Higgs Searches at LEP, Tevatron and LHC

Particle Physics Course

"Dottorato di Ricerca Internazionale"

LECTURE 3.

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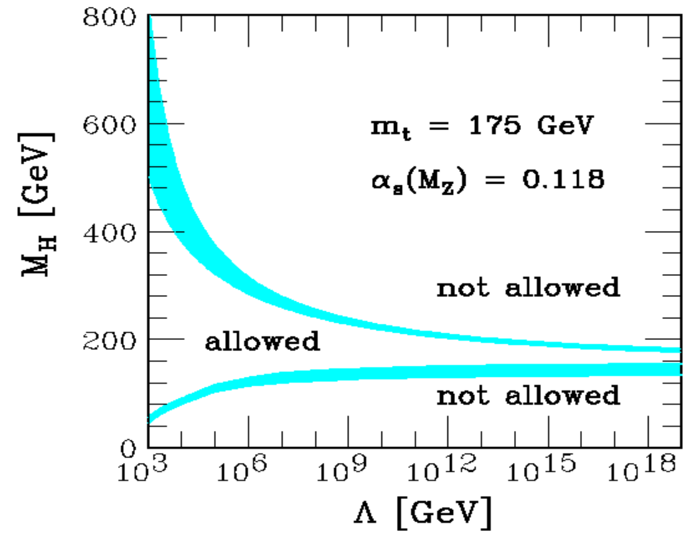
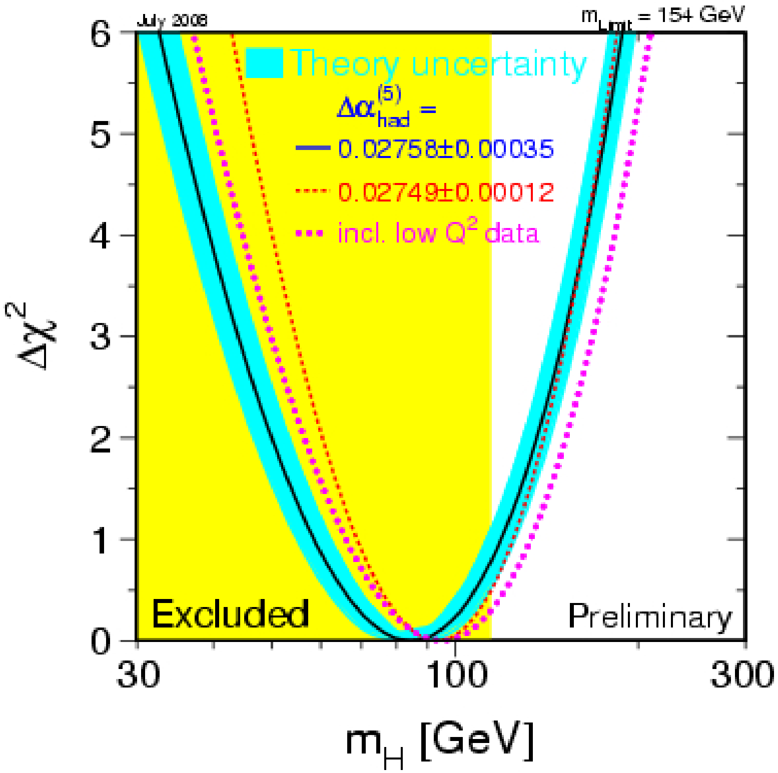
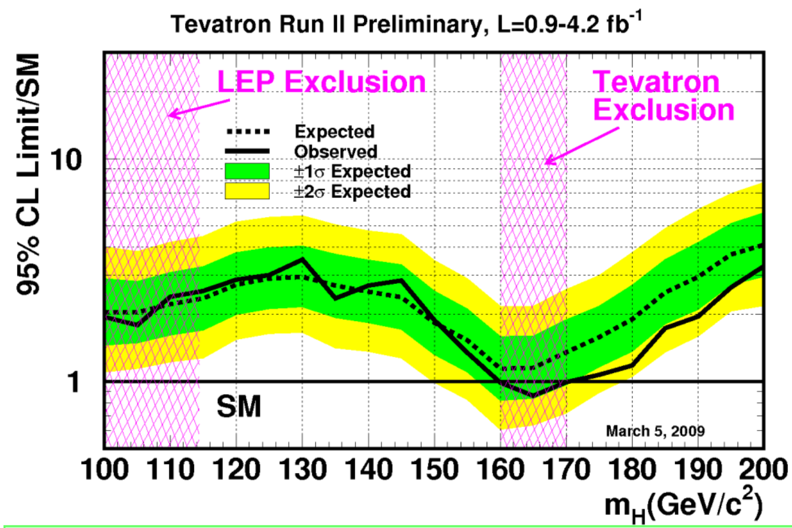
Higgs current limit

- **Teoretical limits**
  vacuum stability
  renormalizability







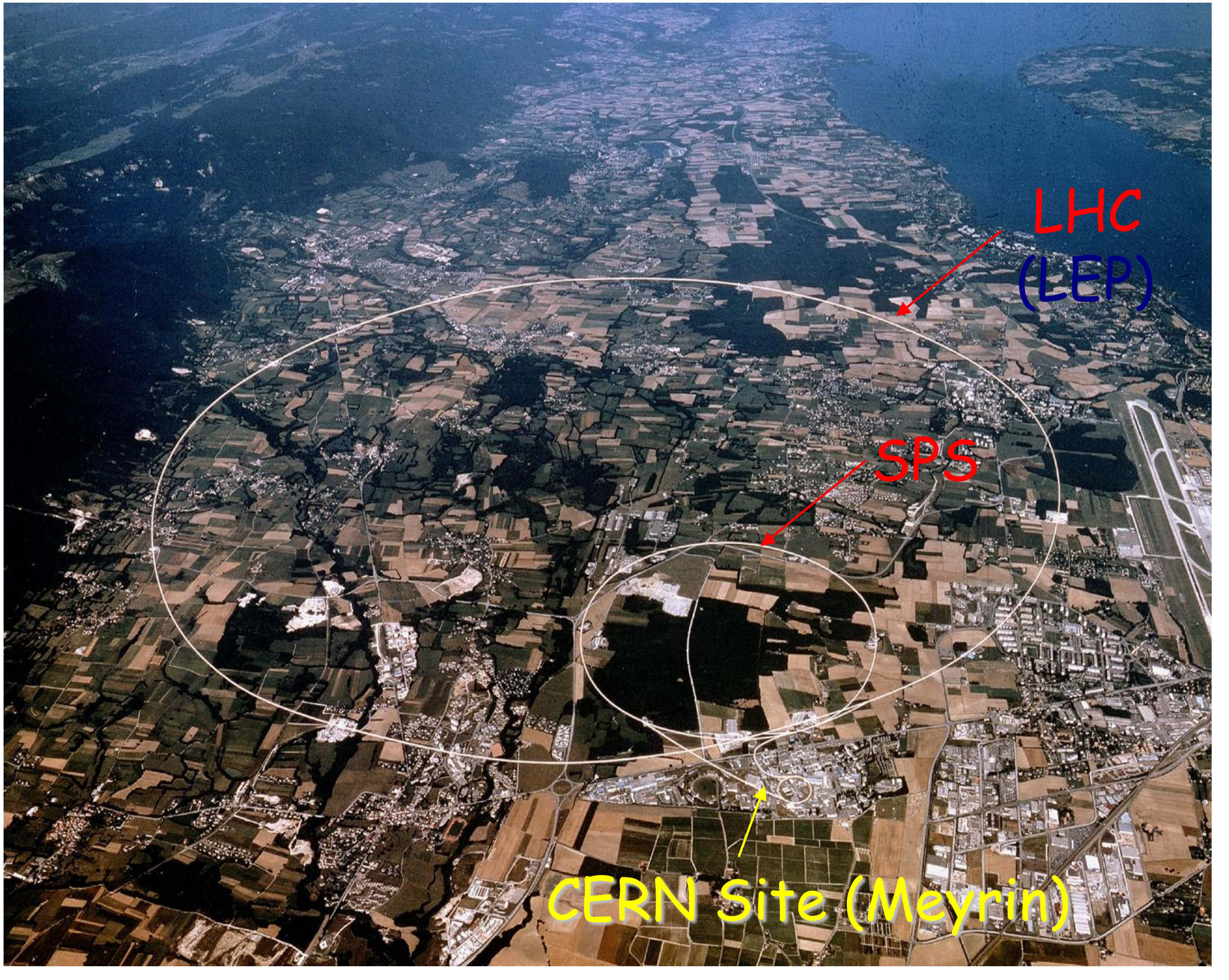
- **Indirect searches derived from precise EWK measurements:**

$M_H = 91^{+45}_{-32}$ <186 GeV @ 95% C.L.

- **Experimental limits:**

LEP: m_H> 114.4 GeV/c^2 at 95% CL
Tevatron: Excluded the mass range of 160 GeV/c^2 to 170 GeV/c^2 at 95% CL

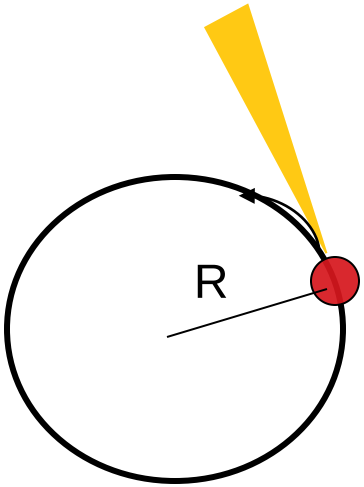
LHC (LEP) @ CERN



Lepton vs Hadron Colliders

Synchrotron Radiation

- Energy loss per revolution



$$\Delta E = \frac{e^2}{3\varepsilon_0}\frac{\beta^3\gamma^4}{2\pi R} \qquad \beta = \frac{\mathrm{v}}{c} \qquad \gamma = \frac{\mathrm{E}}{m} \qquad R = \text{orbit radius}$$

$$\Delta E[GeV] = 5.7\times10^{-7}\frac{E^4[GeV]}{R[km]}$$

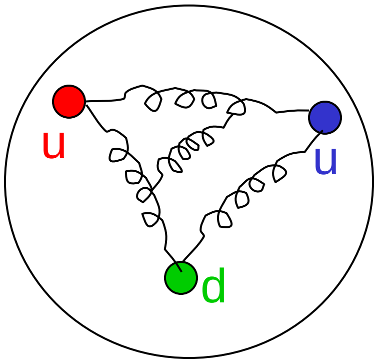
- Example : LEP, $2\pi R$=27km, E=100 GeV (in 2000)
  - **ΔE = 2 GeV!!**
  - LEP at limit, need more and more energy just to compensate energy loss

- Note : for ultrarelativistic protons/electrons ($\beta \simeq 1$)

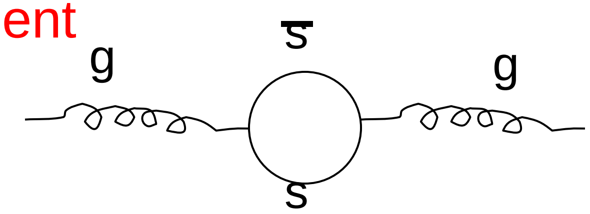
$$\Delta E[p]/\ \Delta E[e] = (m_e/m_p)^4 = \mathbf{10^{-13}\ !!}$$

Proton structure

- (Anti-) Protons are a quark-gluon soup
  - 3 valence quarks bound by exchange of gluons
  - Gluons are colored and interact with other gluons
  - Virtual quark pair loops can pop-up generating additional quark content (sea-quarks)
  - Proton momentum is shared among all constituent partons (quarks& gluons)



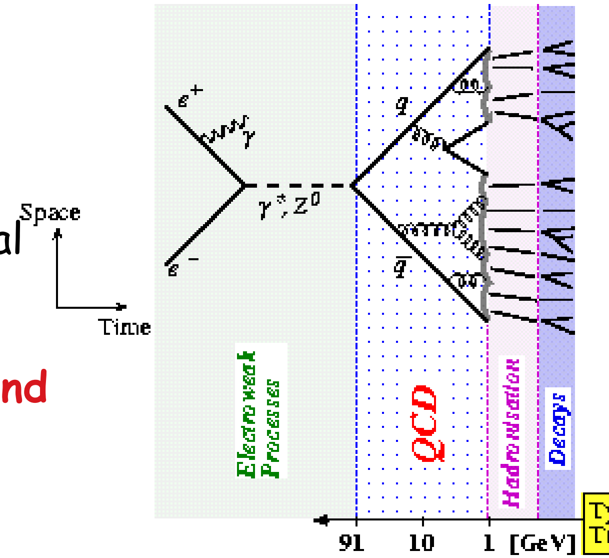
Proton

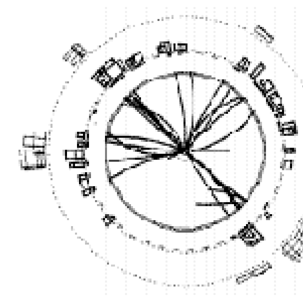


Virtual quark loop

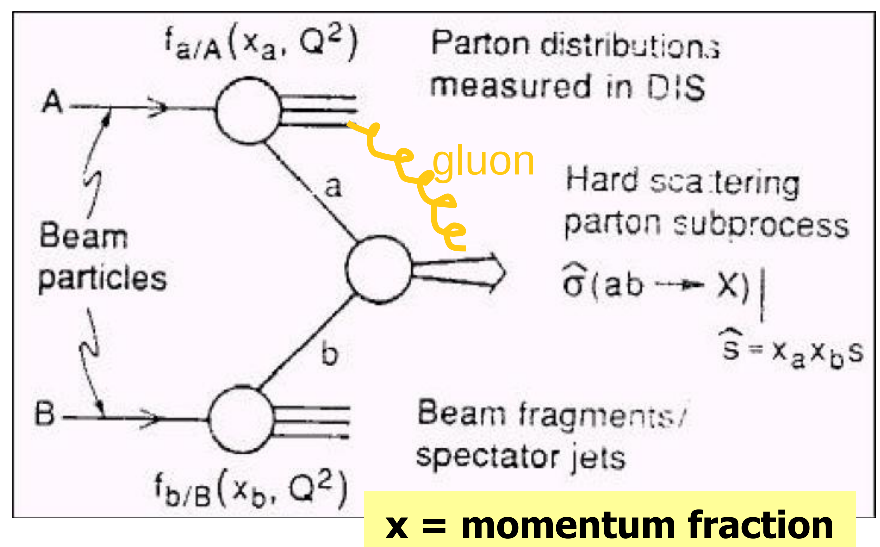
e^+e^- versus pp

- take e^+e^- annihilation to quarks
  - e^+, e^- are **point-like** particles (to our present knowledge)
  - colliding particles do **not carry colour** charge ⇒ no interference between initial and final state because of strong interaction (gluon emission)
  - ⇒ theoretical calculations are **"easy" and precise**



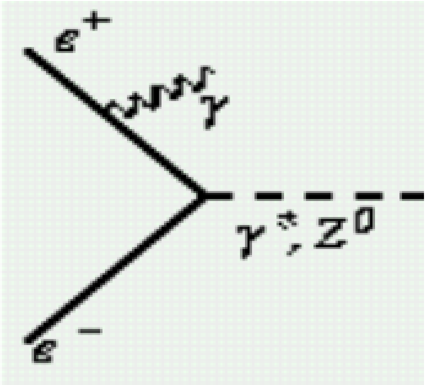


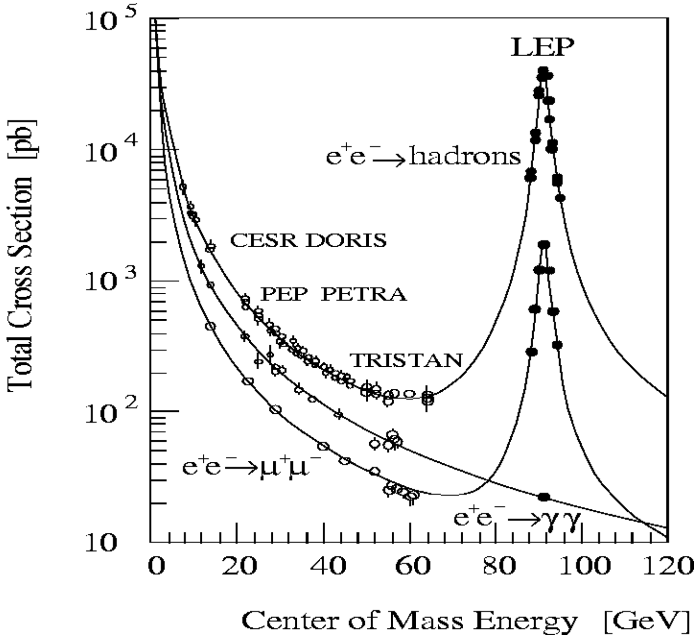
- take proton-proton collisions:
  - protons are **made out of quarks and gluons**, actual interaction is between these partons
  - parton distributions cannot be computed from first principles, only determined from experiments
  - colliding particles carry **colour charge** ⇒ interference
  - ⇒ theoretical calculations are very **"difficult", and not very precise**



How much beam energy is really available for producing new particles?

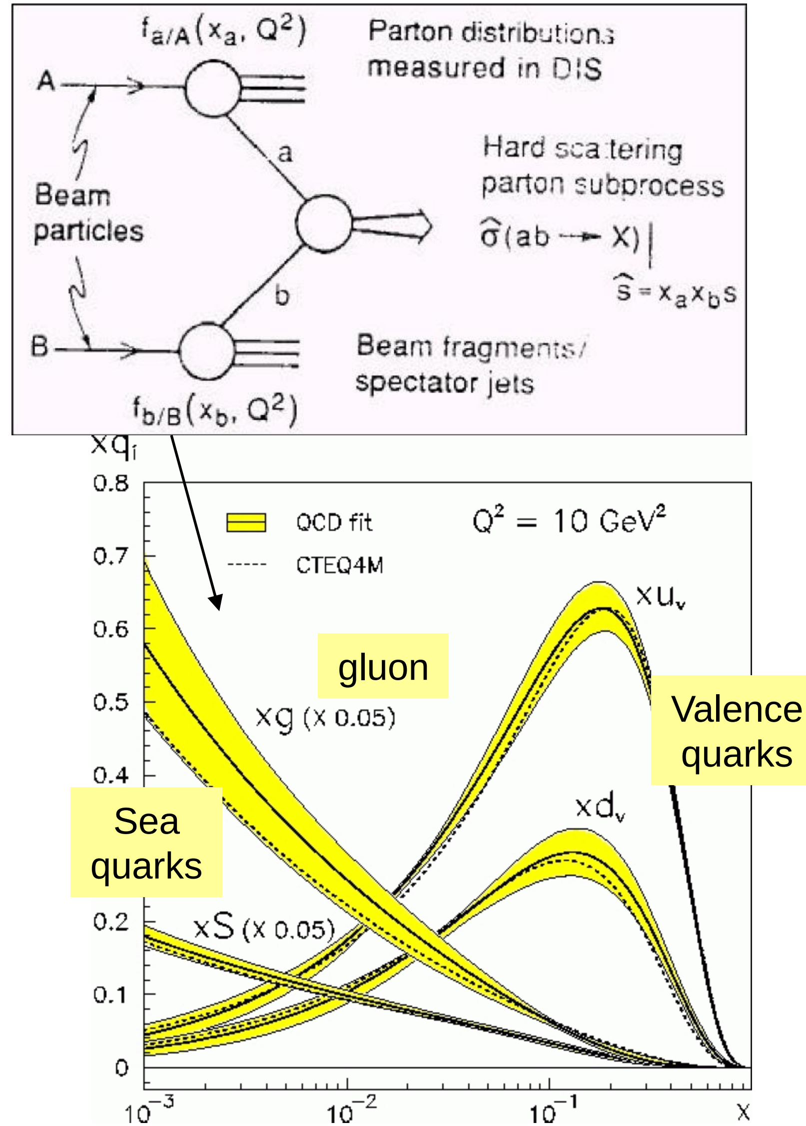
- In an e^+e^- collider :
  - practically all of it
  - However: Photon radiation in the initial state can reduce the effective E_{CM}
  - particularly important when close (in energy) to a resonance
- Advantages:
  - energy very precisely adjustable, for example, to be at a resonance (e.g. Z: 91 GeV, Upsilon: 9.46 GeV) where the cross section is large
- Disadvantages:
  - When looking for new particles with unknown mass: Have to scan “manually” the beam energy





How much beam energy is really available for producing new particles?

- In an proton collider :
  - hard interaction due to partons
  - **Effective $E_{CM}^2 = x_a\, x_b\, E_{CM}^2$**
  - x_a, x_b << 1
- Advantages:
  - because in every collision the x_i are chosen "at random", there is a natural scan of effective E_{CM} : good for exploration of new energy regime (for new particles)
- Disadvantages:
  - effective E_{CM} not adjustable by operator
  - since in general $x_a \neq x_b$: centre-of-mass system boosted w.r.t. to lab system



LHC parameters

$$L = \frac{\gamma f k_b N_p^2}{4\pi \varepsilon_n \beta^*} F$$

f	revolution frequency
k_b	no. of bunches
N_p	no. of protons/bunch
ε_n	norm transverse emittance
β^*	betatron function
F	reduction factor xing angle

Magnetic Field

p (TeV) = 0.3 B(T) R(km)

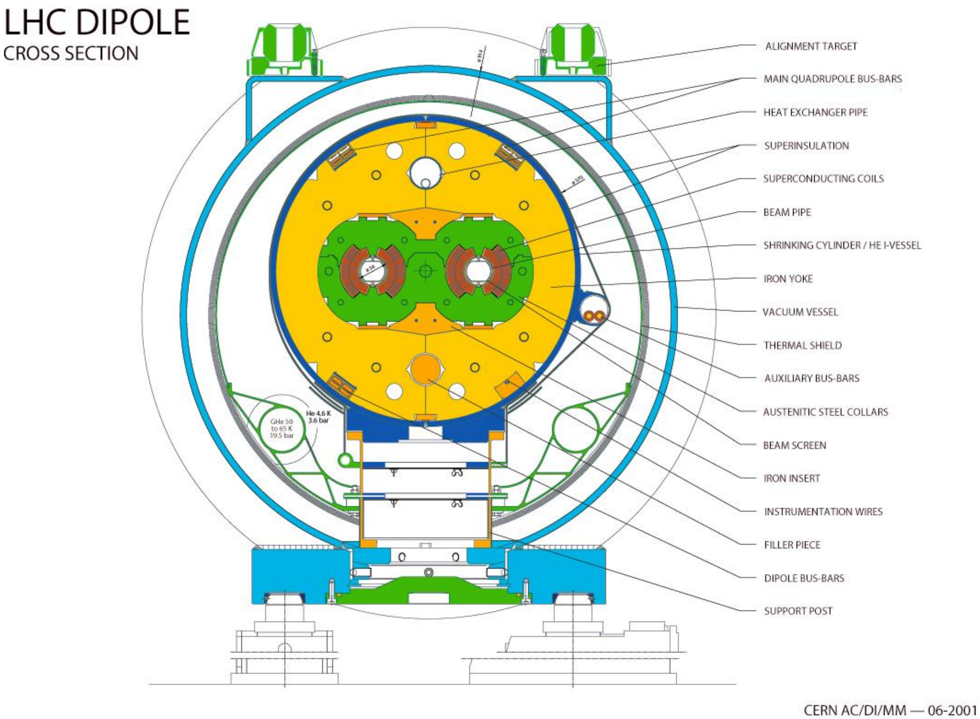
For p= 7 TeV, R= 4.3 km

⇨ **B = 8.4 T**

Beam-beam tune shift $\xi = \frac{N r_p}{4\pi \varepsilon_n}$

Energy at collision	E	7	TeV
Dipole field at 7 TeV	B	8.33	T
Luminosity	L	10^{34}	$cm^{-2}s^{-1}$
Beam beam parameter	ξ	3.6	10^{-3}
DC beam current	I_{beam}	0.56	A
Bunch separation		24.95	ns
No. of bunches	k_b	2835	
No. particles per bunch	N_p	1.1	10^{11}
Normalized transverse emittance (r.m.s.)	ε_n	3.75	μm
Collisions			
β-value at IP	β^*	0.5	m
r.m.s. beam radius at IP	σ^*	16	μm
Total crossing angle	ϕ	300	μrad
Luminosity lifetime	τ_L	10	h
Number of evts/crossing	n_c	17	
Energy loss per turn		7	keV
Total radiated power/beam		3.8	kW
Stored energy per beam		350	MJ

p-p collisions at LHC

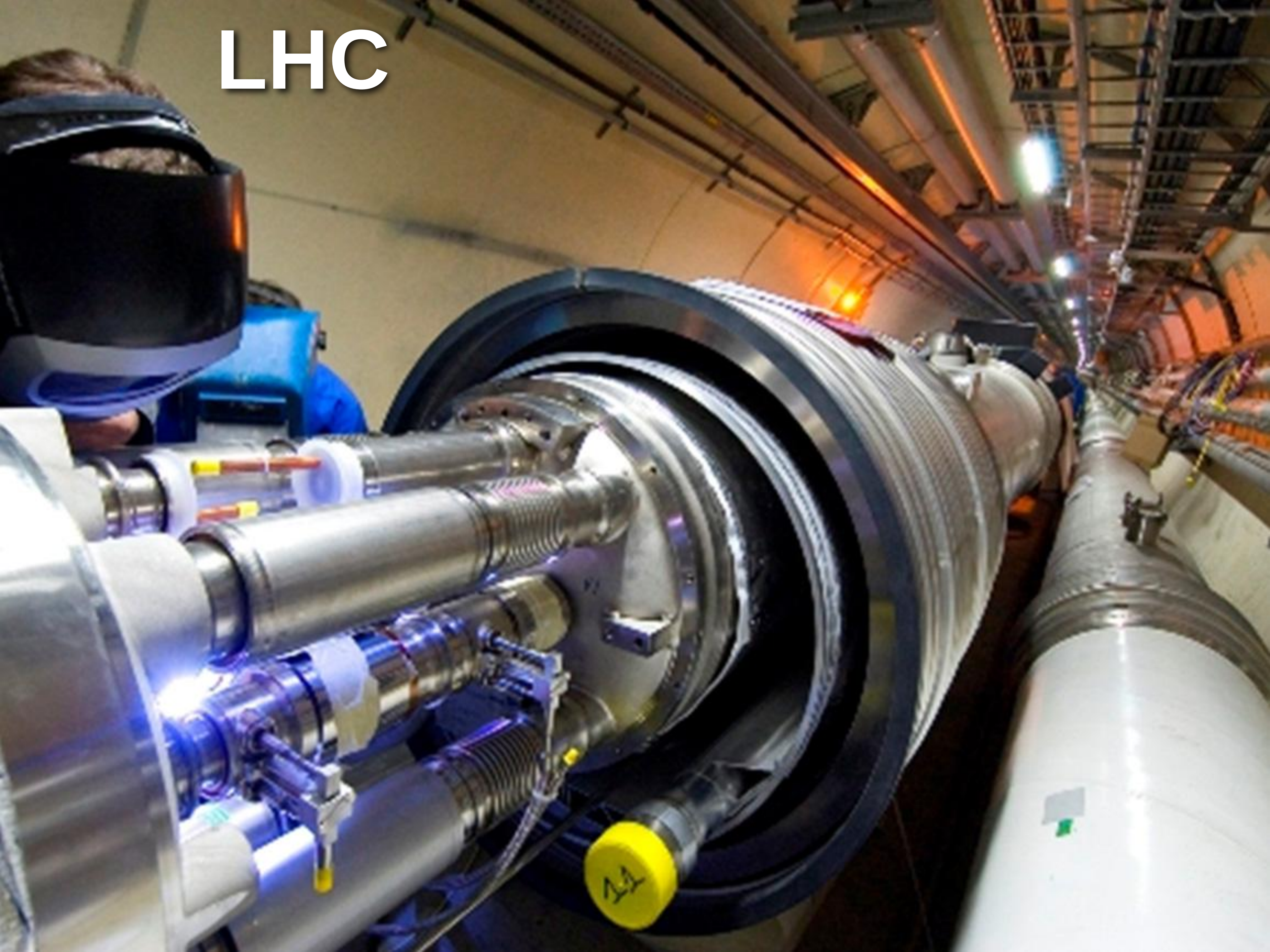


9300 Superconducting Magnets
1232 Dipoles (15m), 448 Main Quads, 6618 Correctors.

Operating temperature: 1.9^{o} K

26.7 km tunnel

LHC



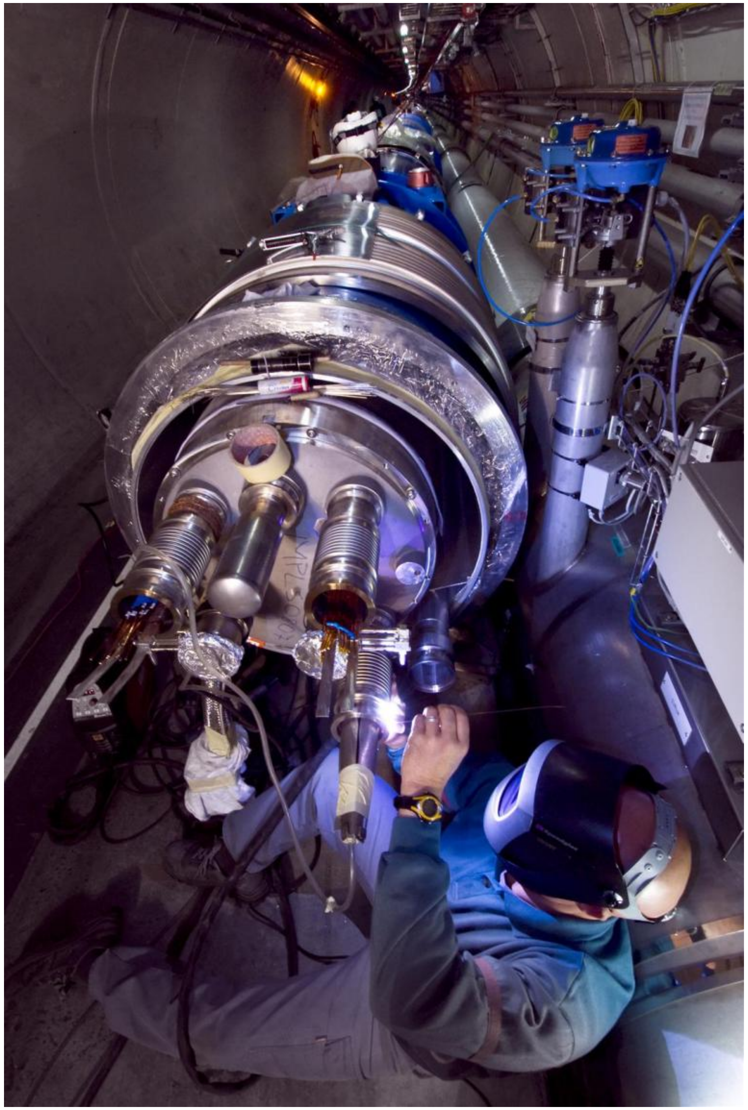
The Large Hadron Collider (LHC)

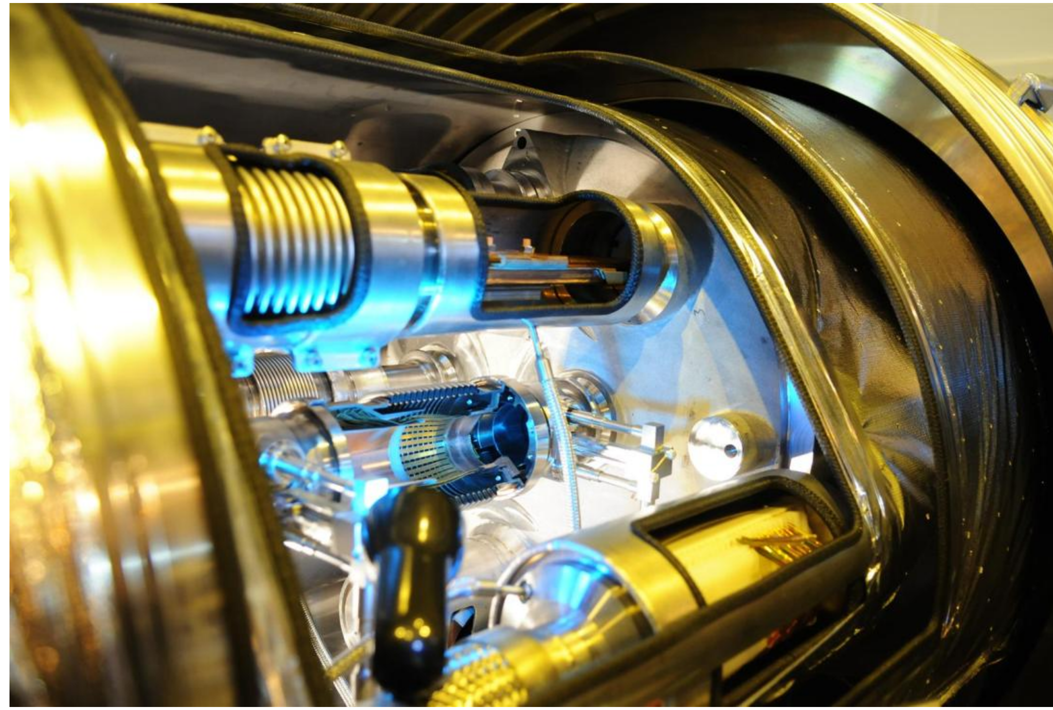
Lowering one of the 1232
15m long dipoles 100m down into the LHC
There are another 8000 magnets of
different types as well
1st magnet lowered in March 2005

The last dipole magnet makes its descent towards its final destination in the LHC tunnel.

18 | CERN

The Large Hadron Collider (LHC)

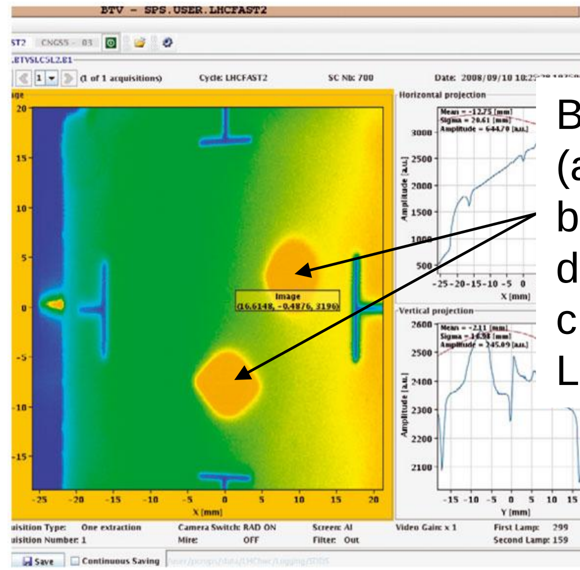




Preparing to connect the magnets together – and a cutaway showing the multiplicity of complex services from one magnet to another
There are over 2000 of these magnet-to-magnet joints to make around the ring

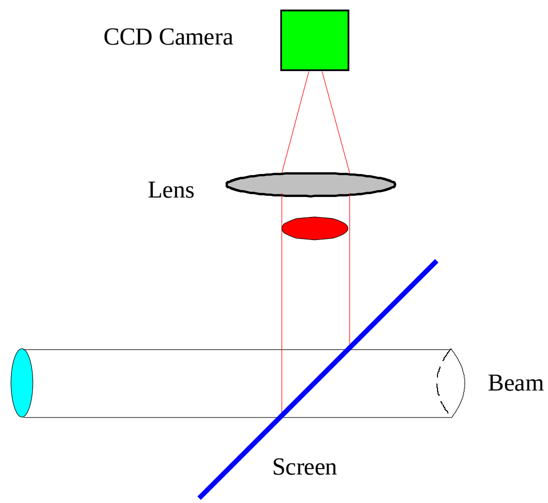
First beams around the LHC

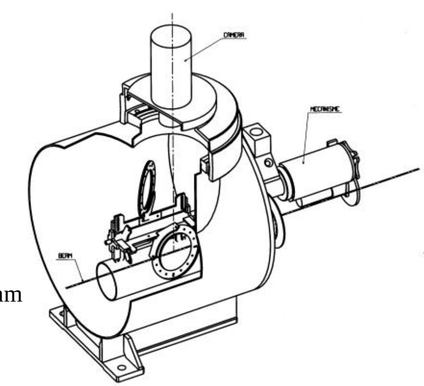
Joyous faces on 10 Sep 2008 at 10.23



Beam (a single proton bunch) enters and does a complete circle around the LHC ring

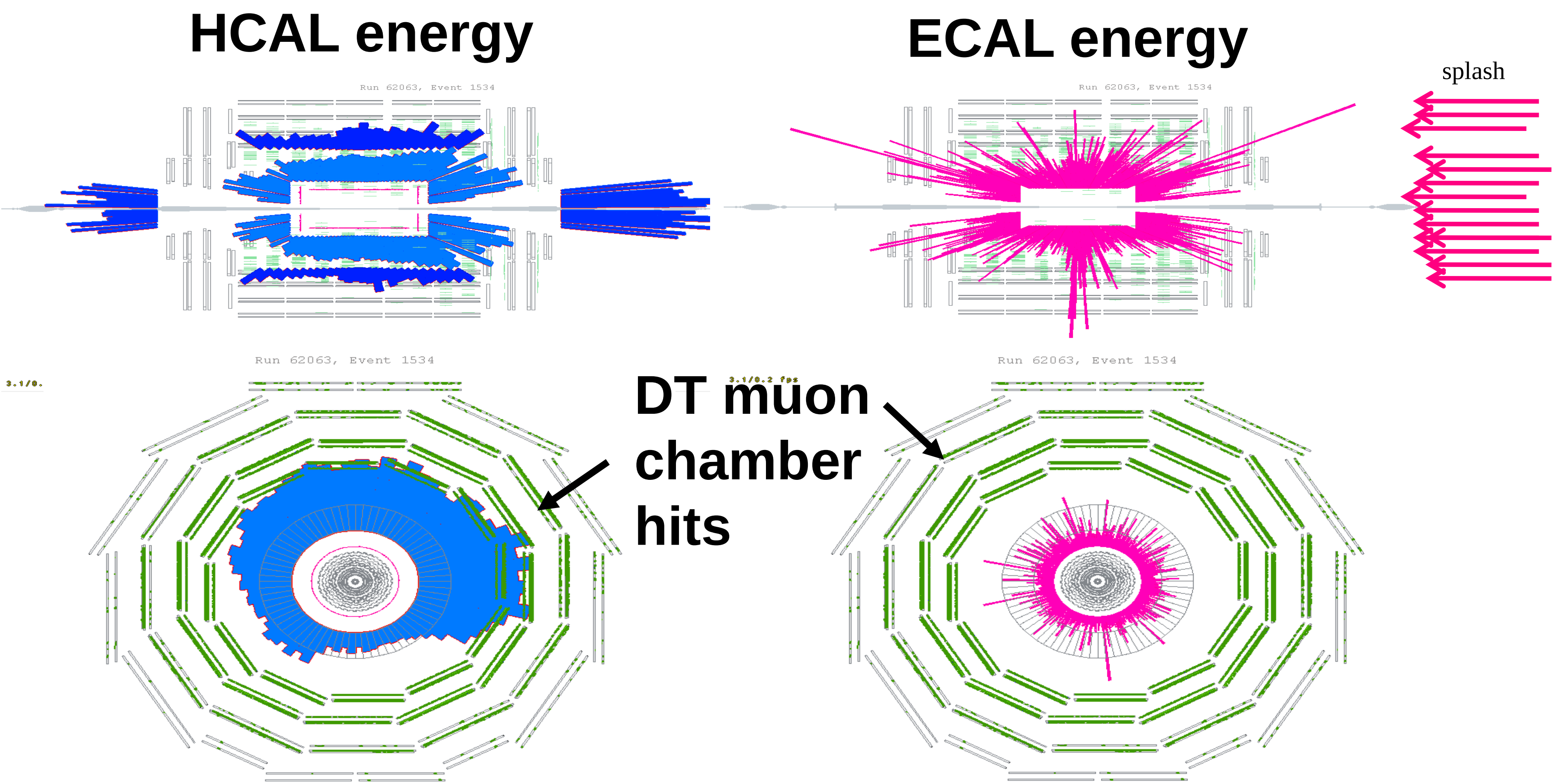
Fluorescent screen to detect the beam – like that in a CRT television



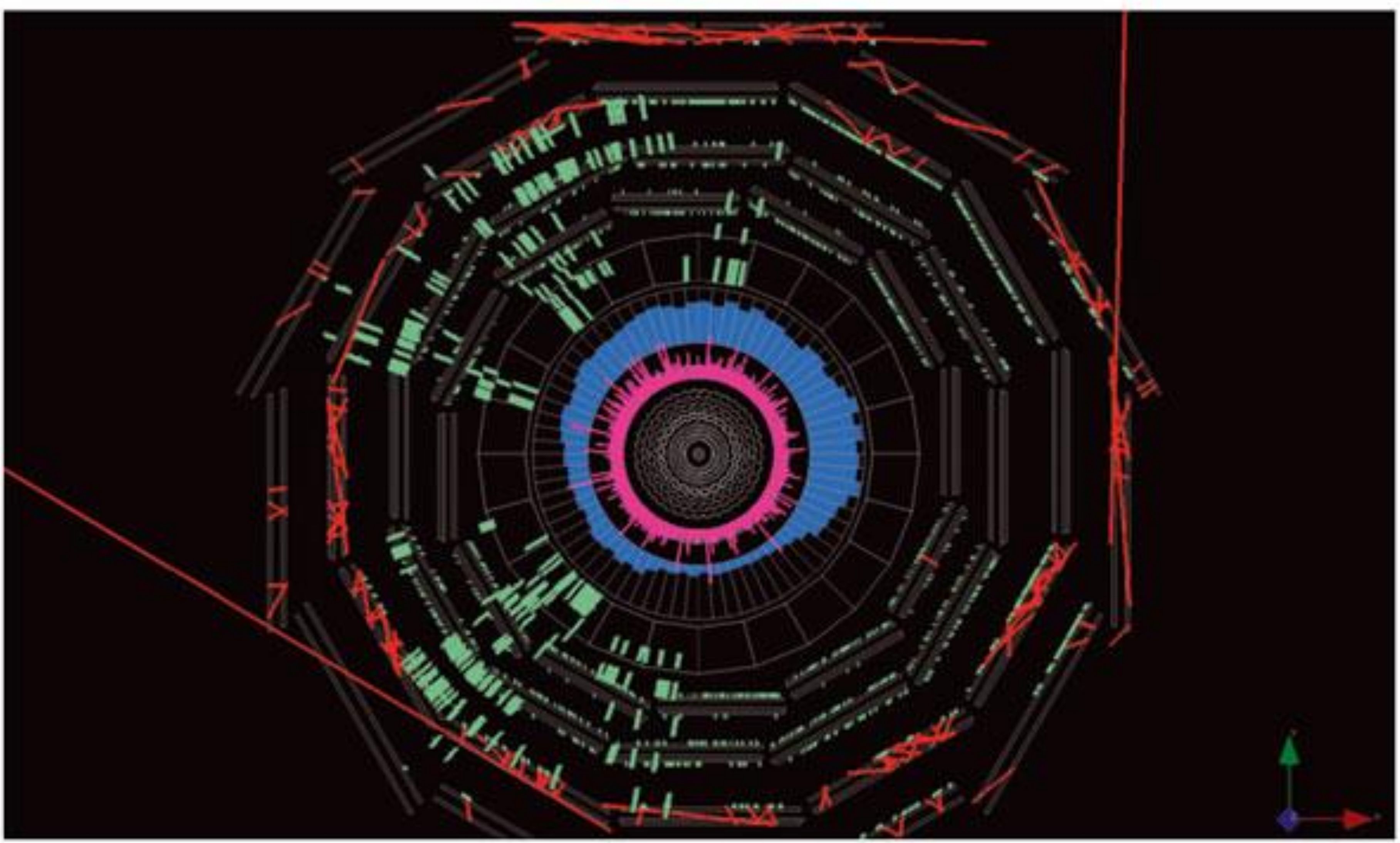


Beam splashes at CMS

- 10^9 protons at 450 GeV dumped on collimator 150 m upstream of the CMS experiment. ECAL total energy: 150–250 TeV

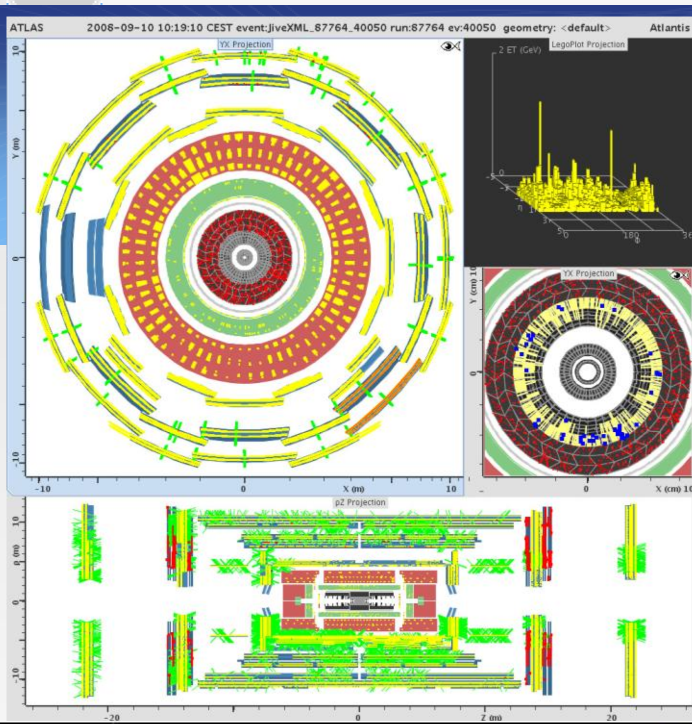


First beams around the LHC in CMS

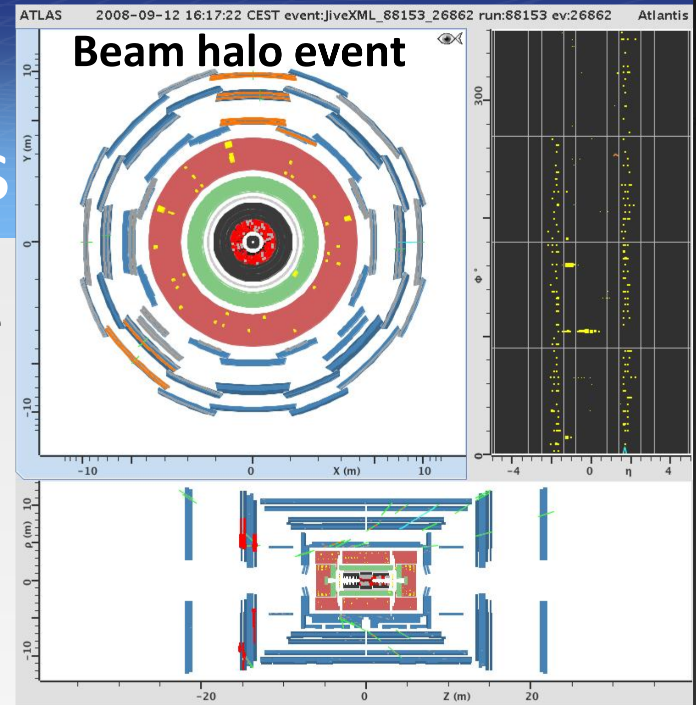


ATLAS

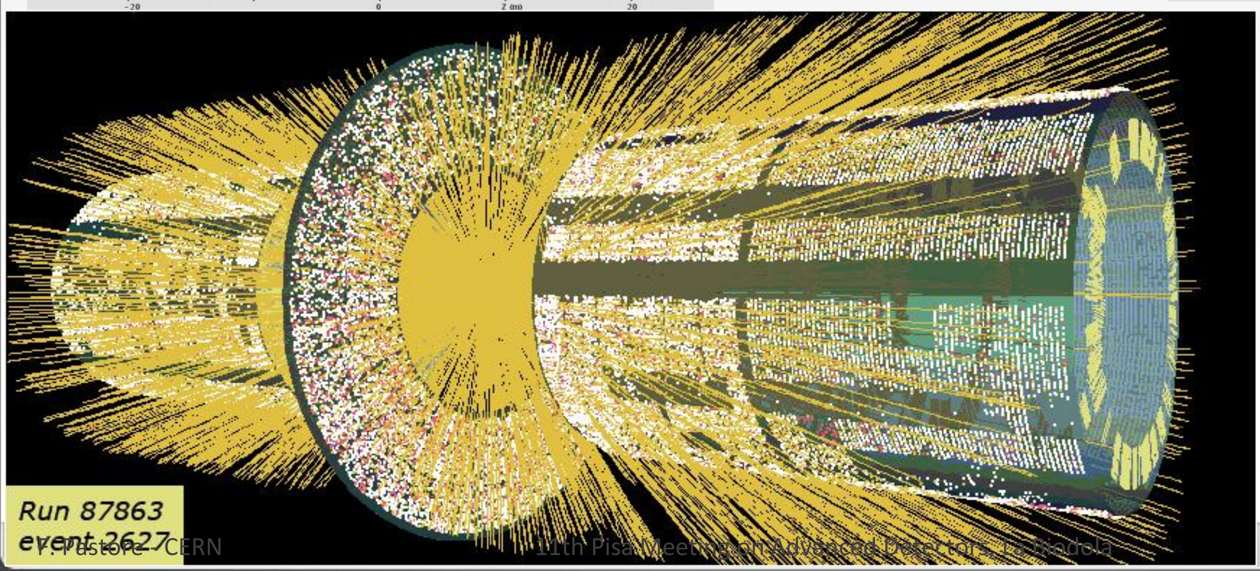
Some LHC events



Beam halo events are important for Endcaps calibrations

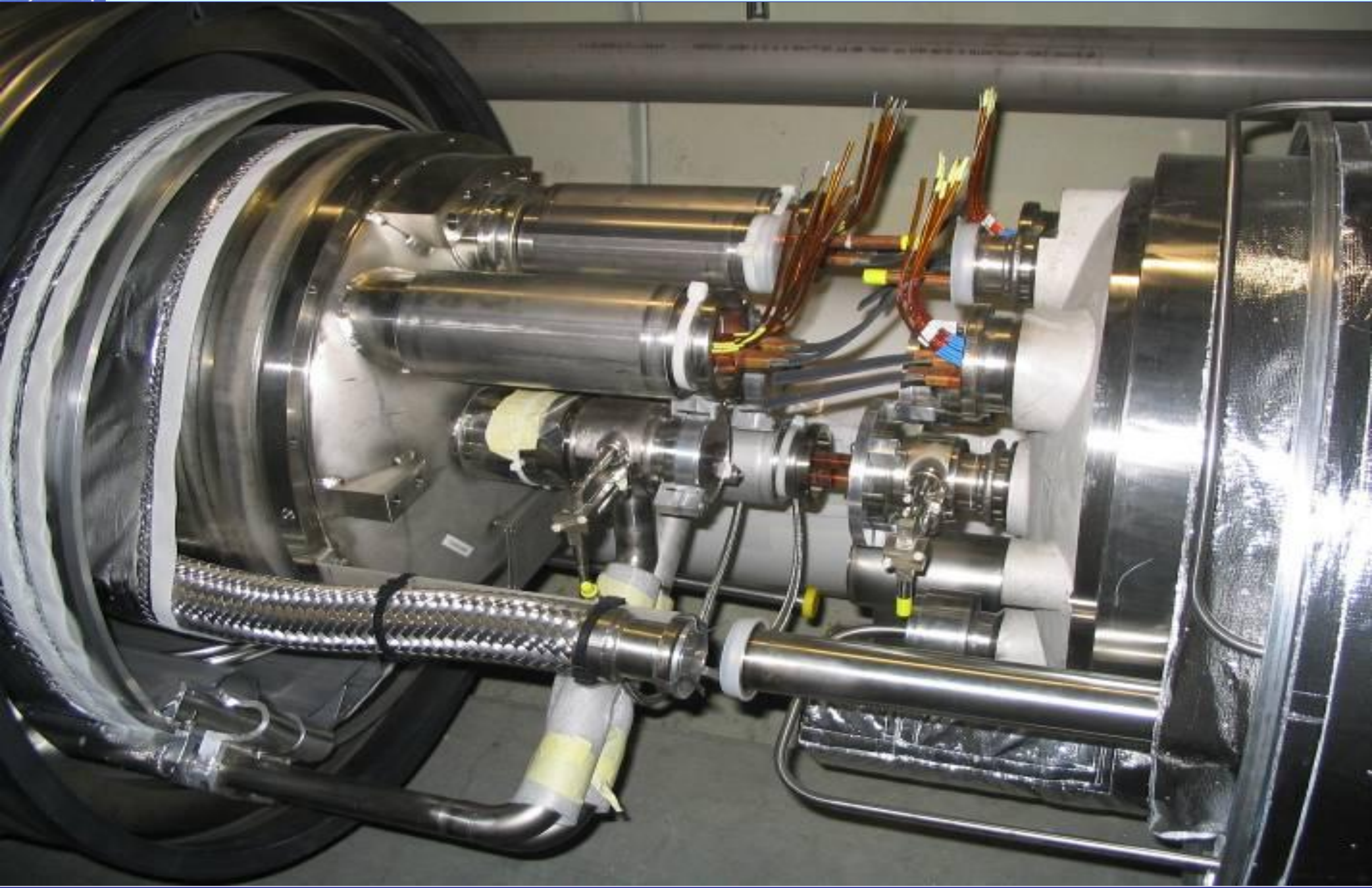


Splash event

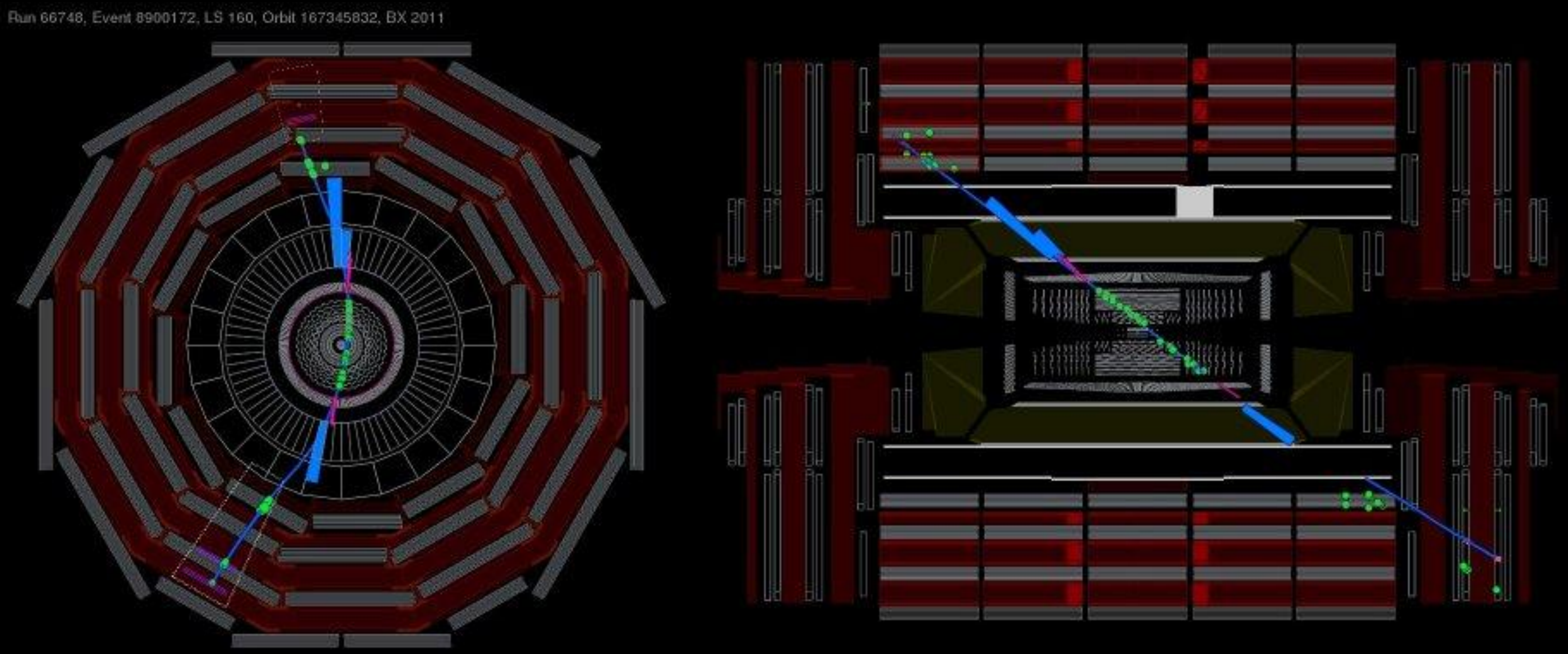


Beam dumped on closed collimators 140 m far from the IP, produced a **splash of particles,** useful for timing-in the L1 systems

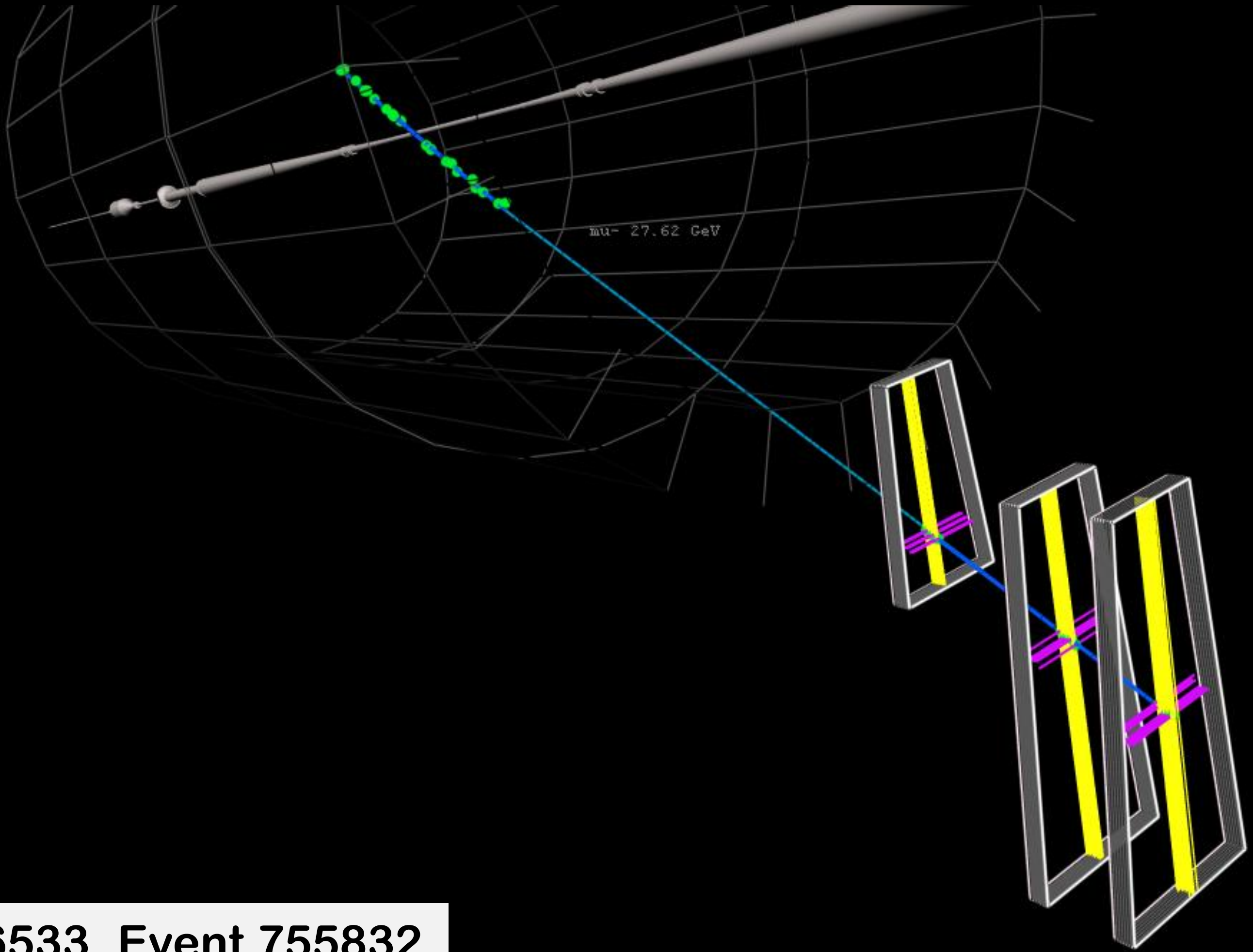
One of ~1700 interconnections: busbars and tubes



CMS: cosmic ray event

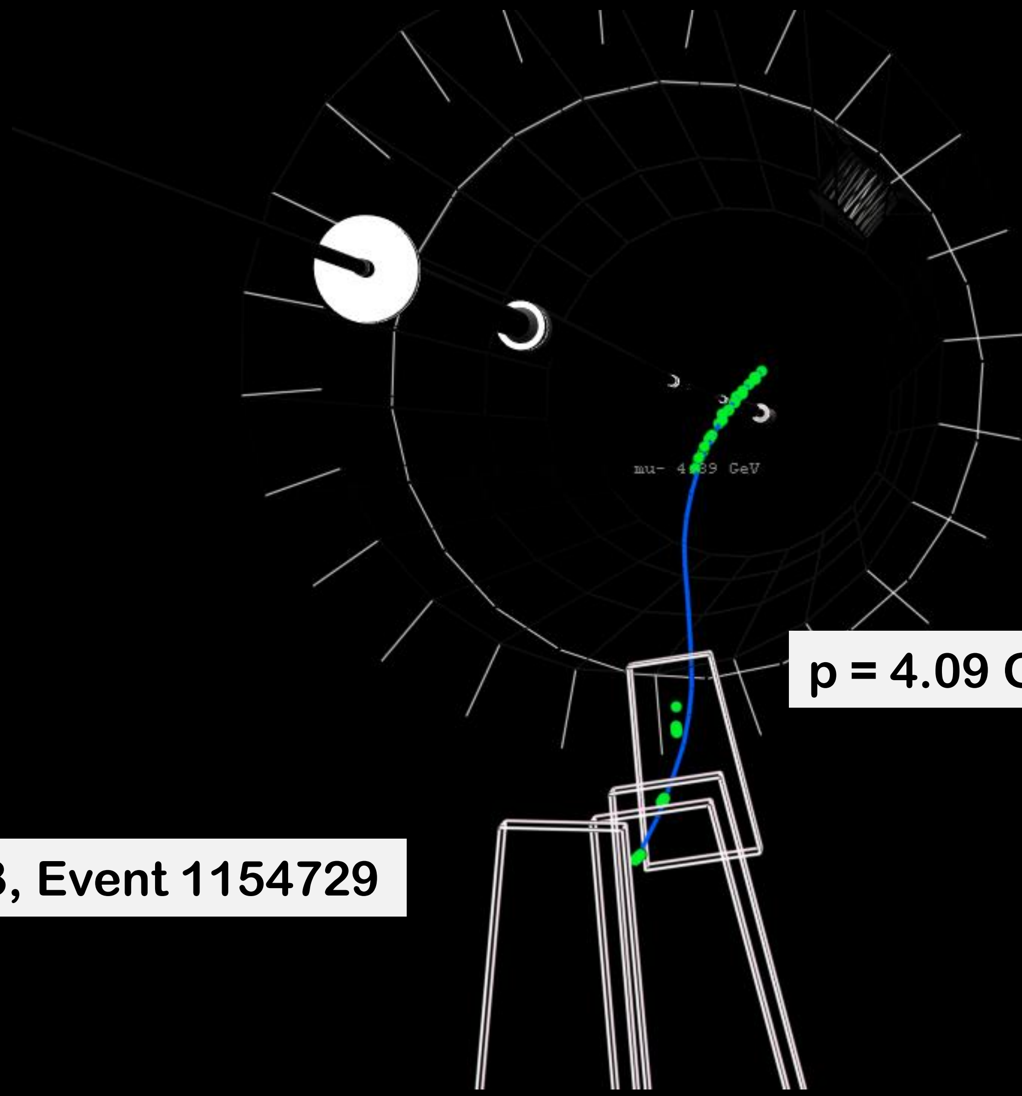


CMS: cosmic ray event



Run 66533, Event 755832

CMS: cosmic ray event

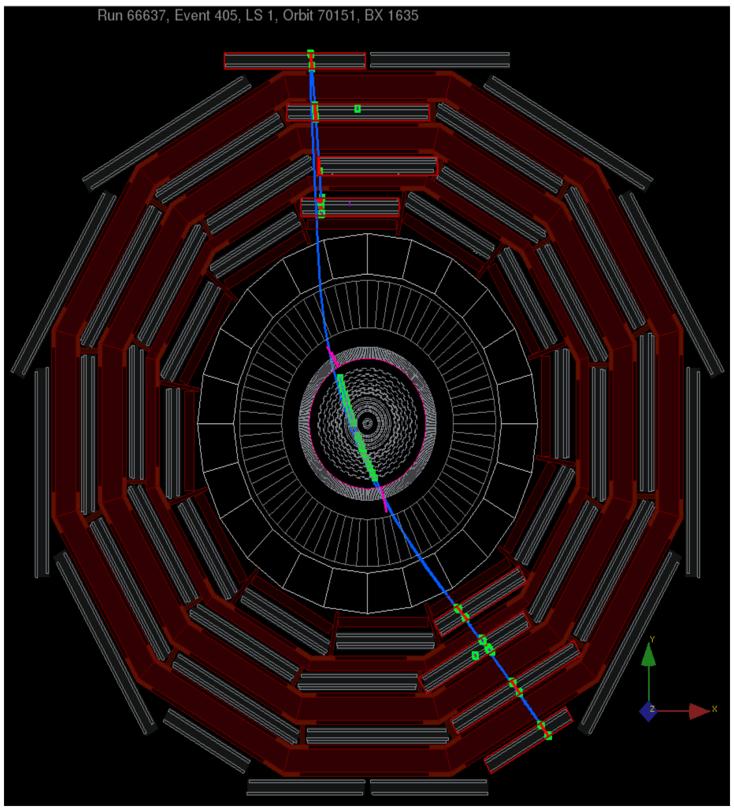


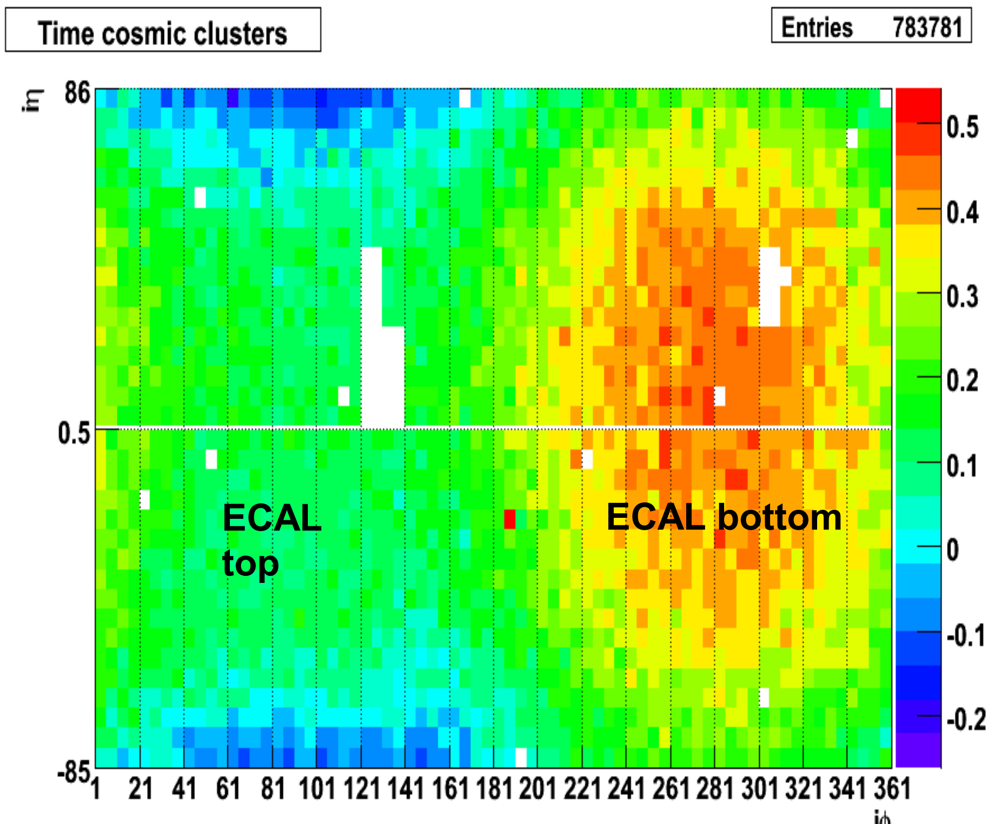
p = 4.09 GeV/c

Run 66533, Event 1154729

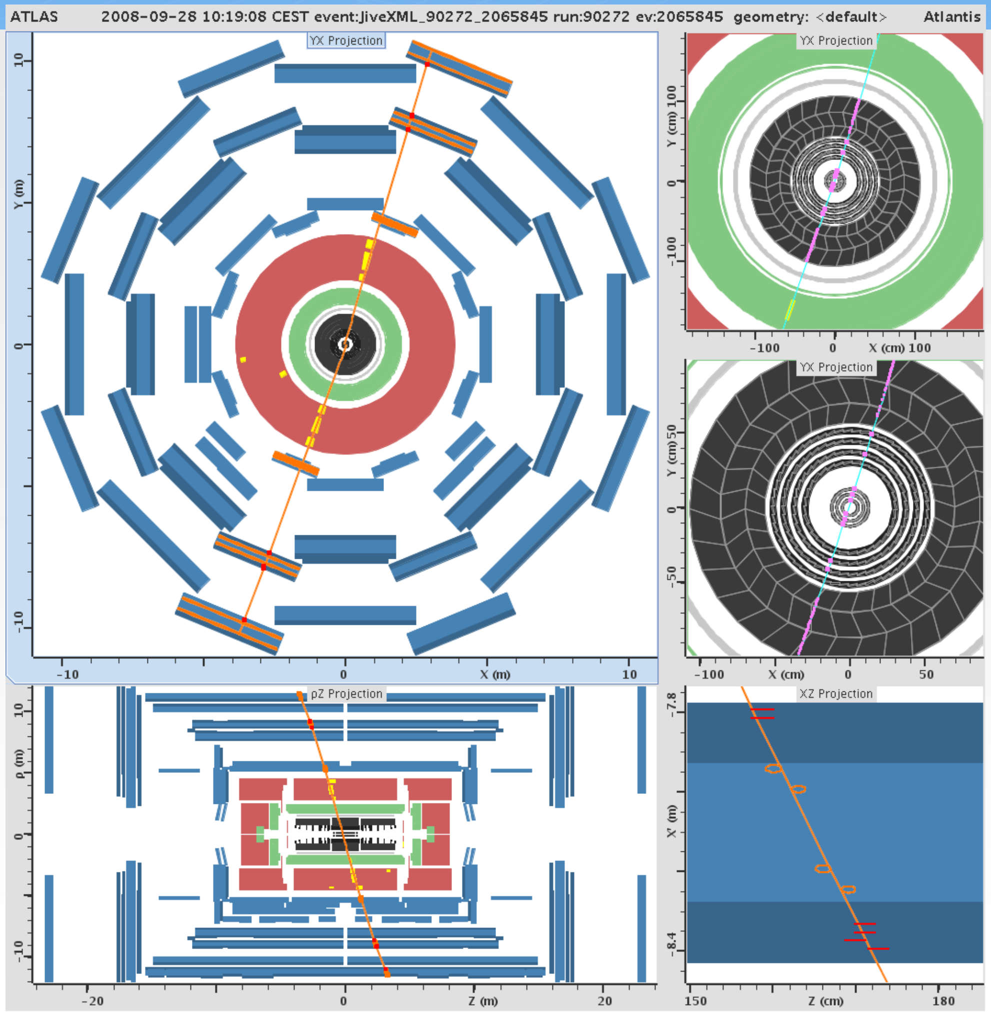
CMS: Cosmic rays signal in ECAL

- Minimum ionizing particles deposit 250 MeV in ECAL. Increase efficiency: signal/noise enhanced (x4) in EB to the value of 20, by increasing the gain of the APD.
- Pattern in reconstructed time: time of flight top➔bottom and internal synchronization schema for collision events



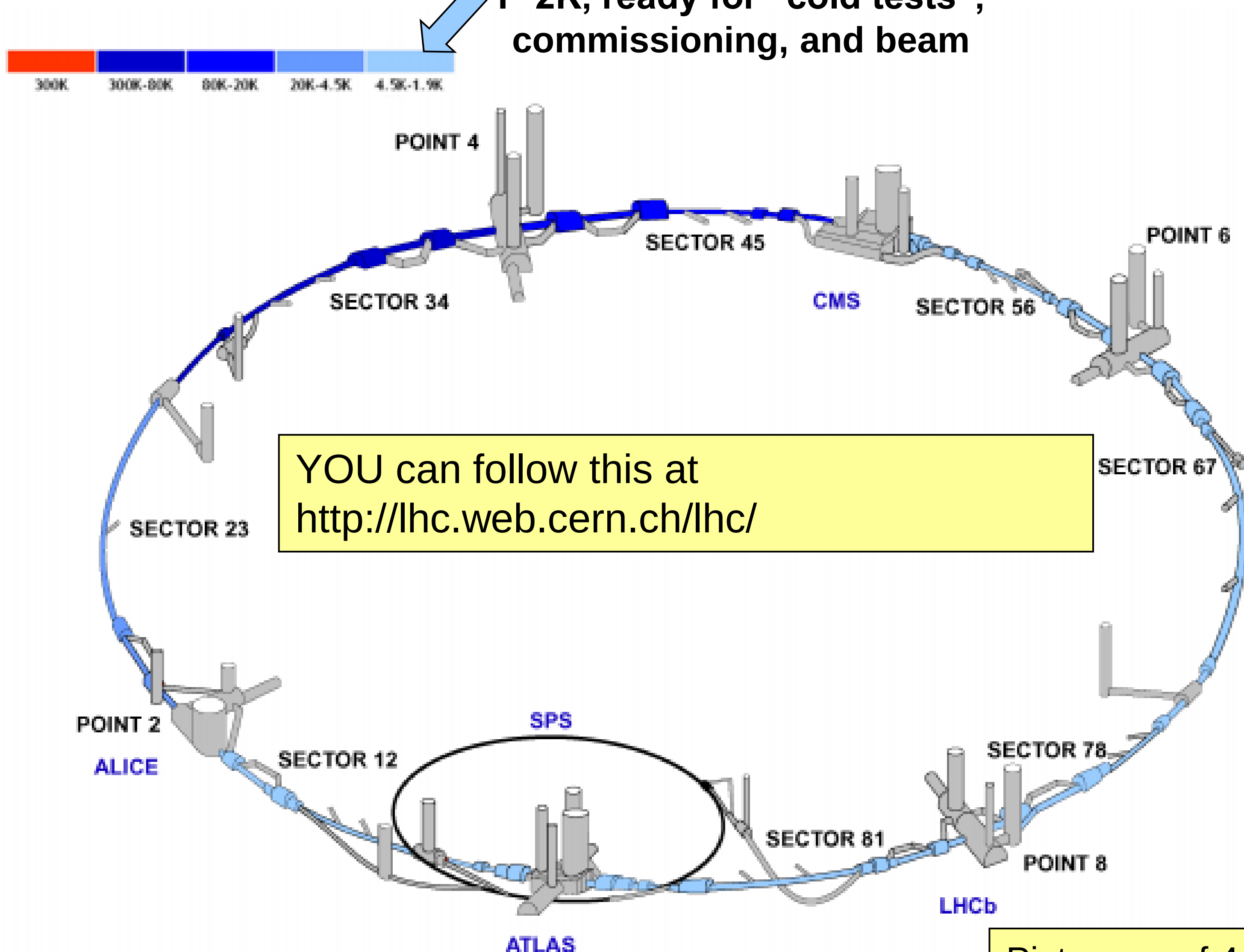


ATLAS: cosmic ray event



Temperatures around the LHC ring

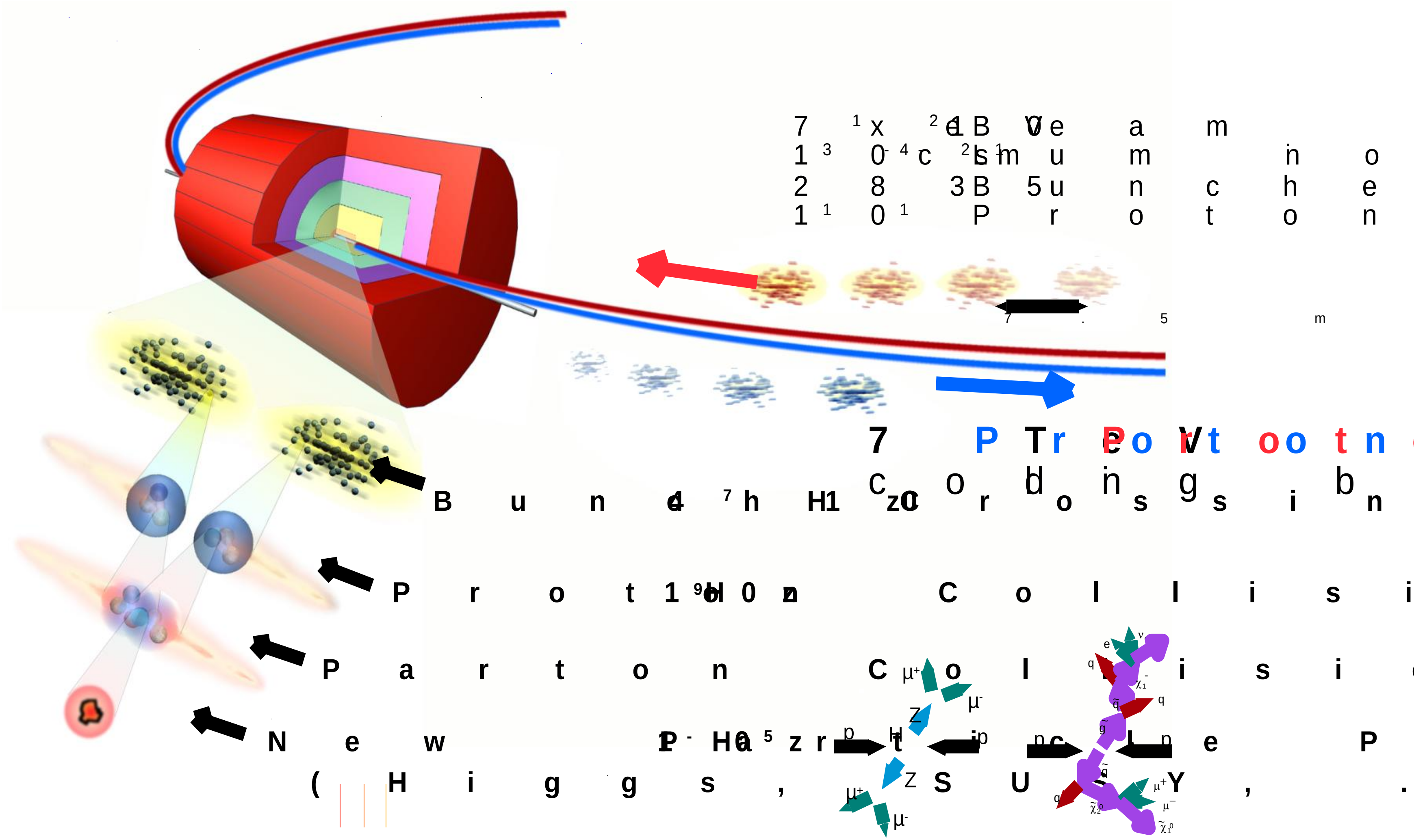
T~2K, ready for “cold tests”, commissioning, and beam



YOU can follow this at
http://lhc.web.cern.ch/lhc/

Picture as of 4 Nov 2008

Collisioni protone-protone at LHC



Selection of 1

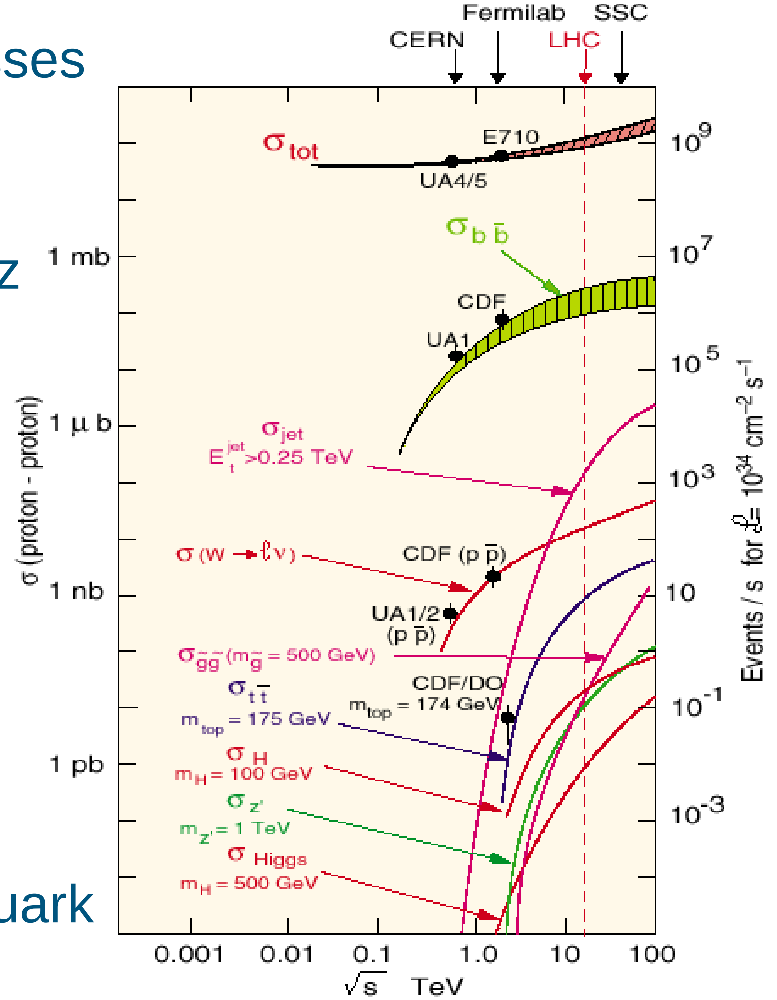
Signal and background→10^{34}

Cross sections for various physics processes vary over many orders of magnitude

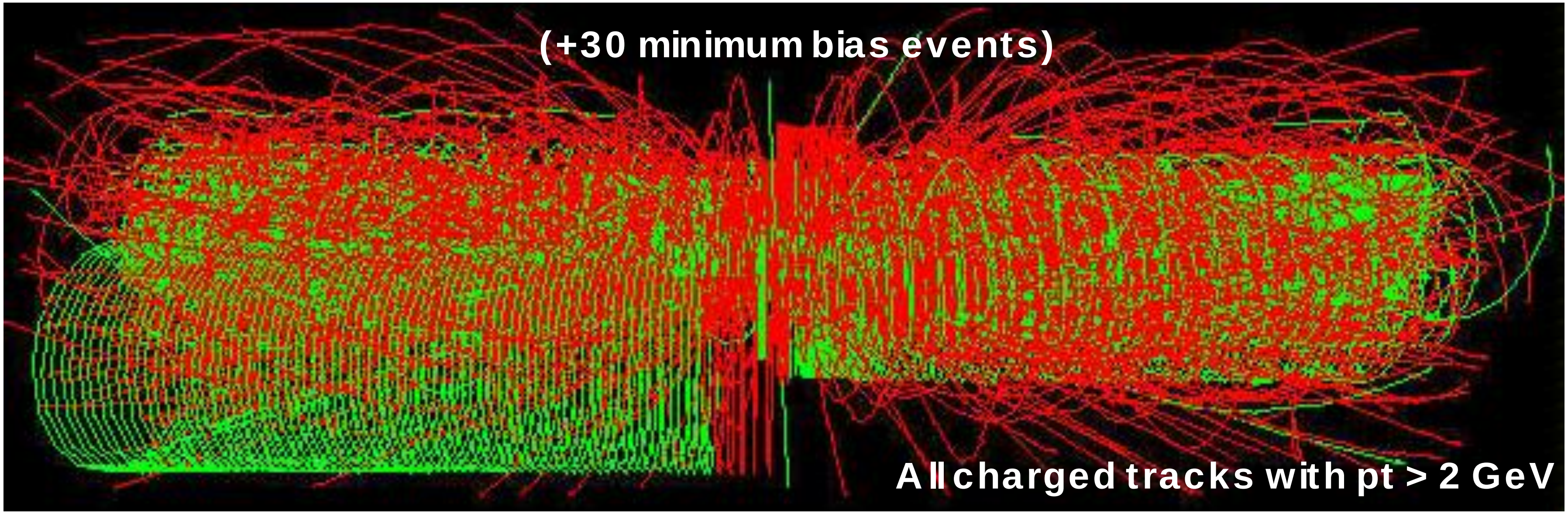
Higgs (600 GeV/c^2): 1pb @10^{34} →10^{-2} Hz
Higgs (100 GeV/c^2): 10pb @10^{34}→0.1 Hz
t t production: →10 Hz
W→ ℓ ν: →10^2 Hz
Inelastic: →10^9 Hz

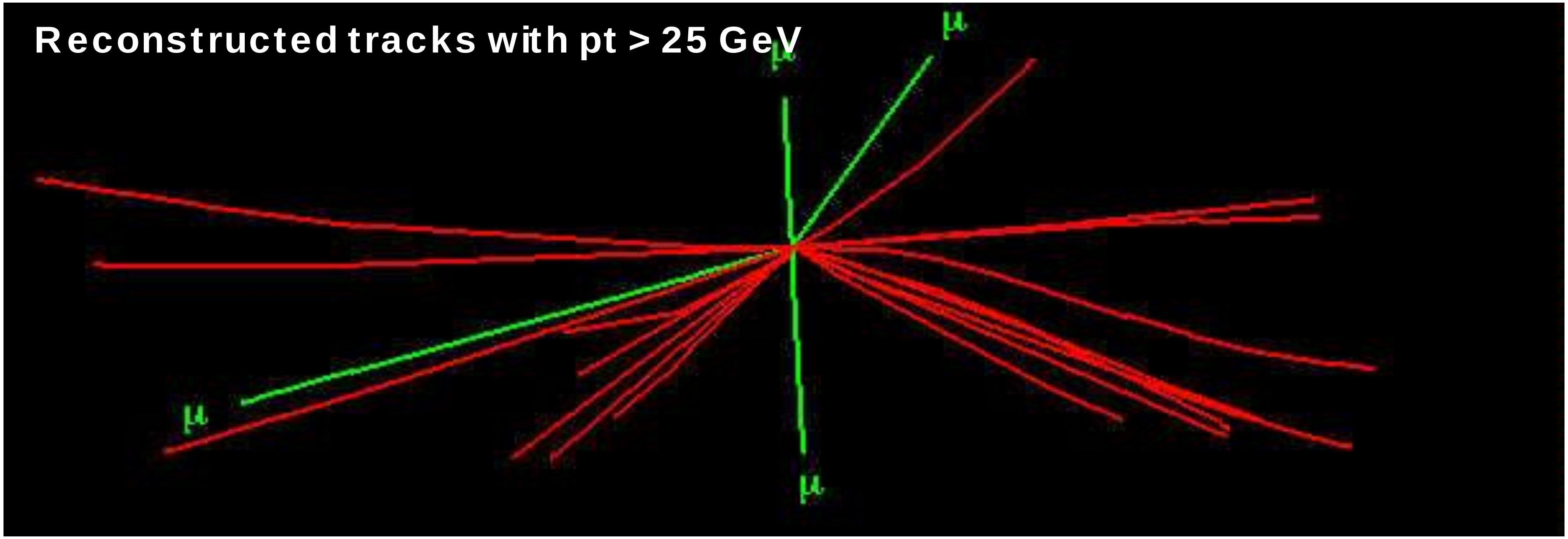
Selection needed: 1:10^{10-11}
Before branching fractions...

CDF and D0 successfully found the top quark facing similar rejection factors



Higgs decay in 4 muons





Impact on detector design

LHC detectors must have fast response

- Otherwise will integrate over many bunch crossings $\rightarrow$ large "pile-up"
- Typical response time : 20-50 ns
  - $\rightarrow$ integrate over 1-2 bunch crossings $\rightarrow$ pile-up of 25-50 min-bias
  - $\rightarrow$ very challenging readout electronics

LHC detectors must be highly granular

- Minimize probability that pile-up particles be in the same detector element as interesting object (e.g. γ from $H \rightarrow \gamma\gamma$ decays)
  - $\rightarrow$ large number of electronic channels
  - $\rightarrow$ high cost

LHC detectors must be radiation resistant:

- high flux of particles from pp collisions $\rightarrow$ high radiation environment e.g. in forward calorimeters:
  - up to 10^{17} n/cm^2 in 10 years of LHC operation

Basic principles

Need "general-purpose" experiments covering as much of the solid angle as possible ("4π") since we don't know how New Physics will manifest itself

$\rightarrow$ detectors must be able to detect as many particles and signatures as possible: e, μ, τ, ν, γ, jets, b-quarks, ….

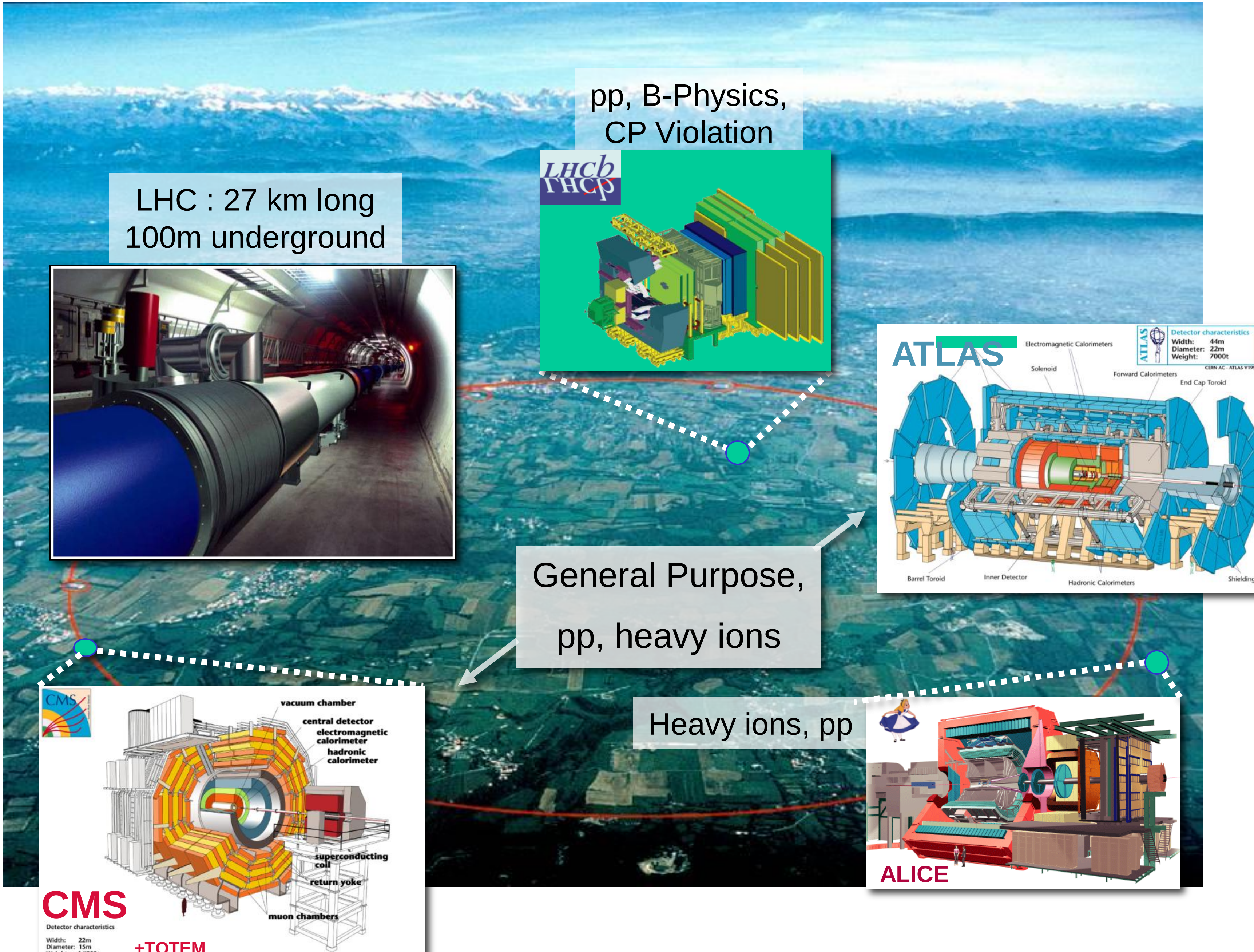
Momentum / charge of tracks and secondary vertices (e.g. from b-quark decays) are measured in central tracker (Silicon layers).

Energy and positions of electrons and photons measured in electromagnetic calorimeters (+central tracker).

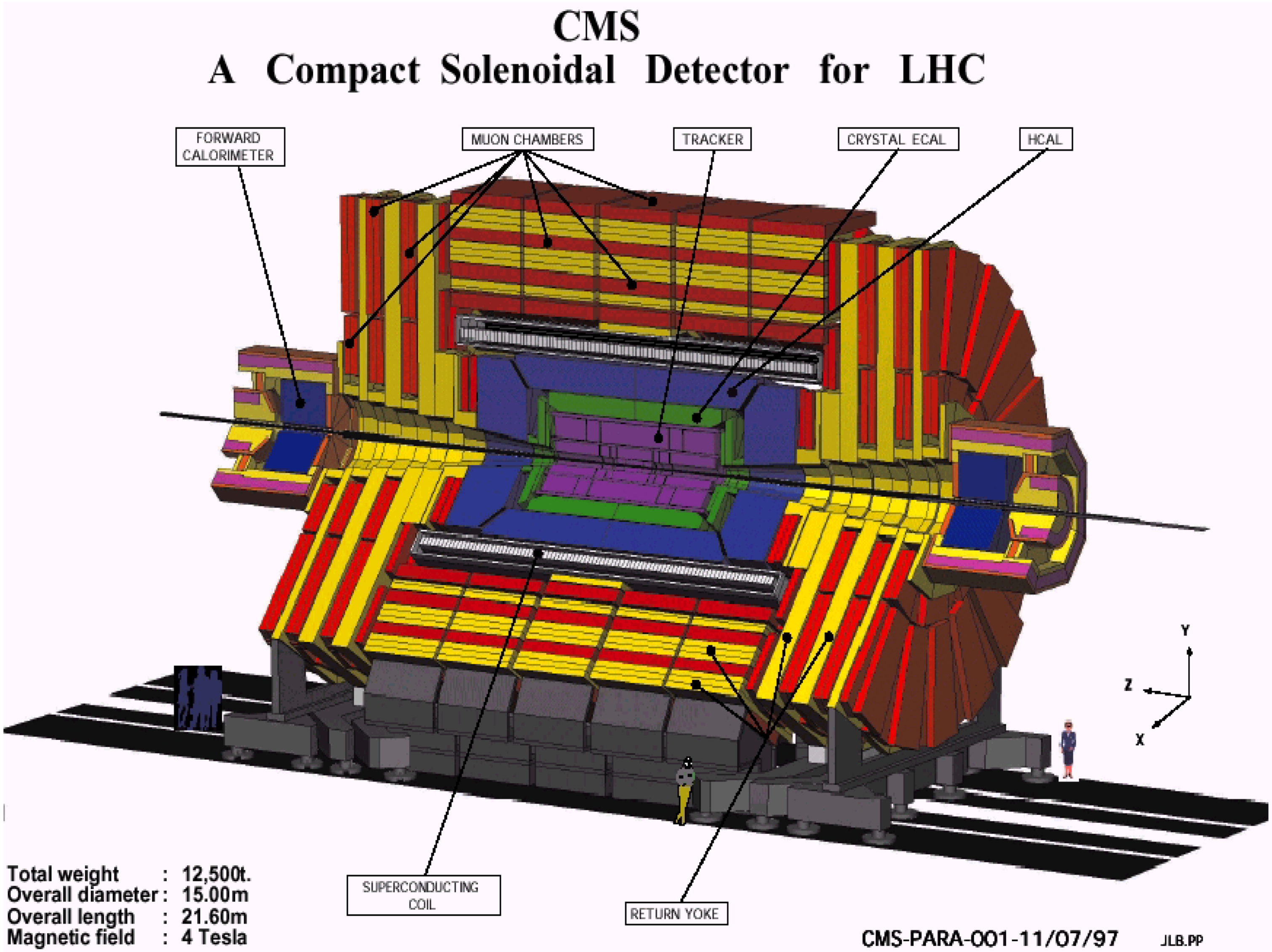
Energy and position of hadrons and jets measured mainly in hadronic calorimeters (+central tracker for charged hadrons).

Muons identified and momentum measured in external muon spectrometer (+central tracker).

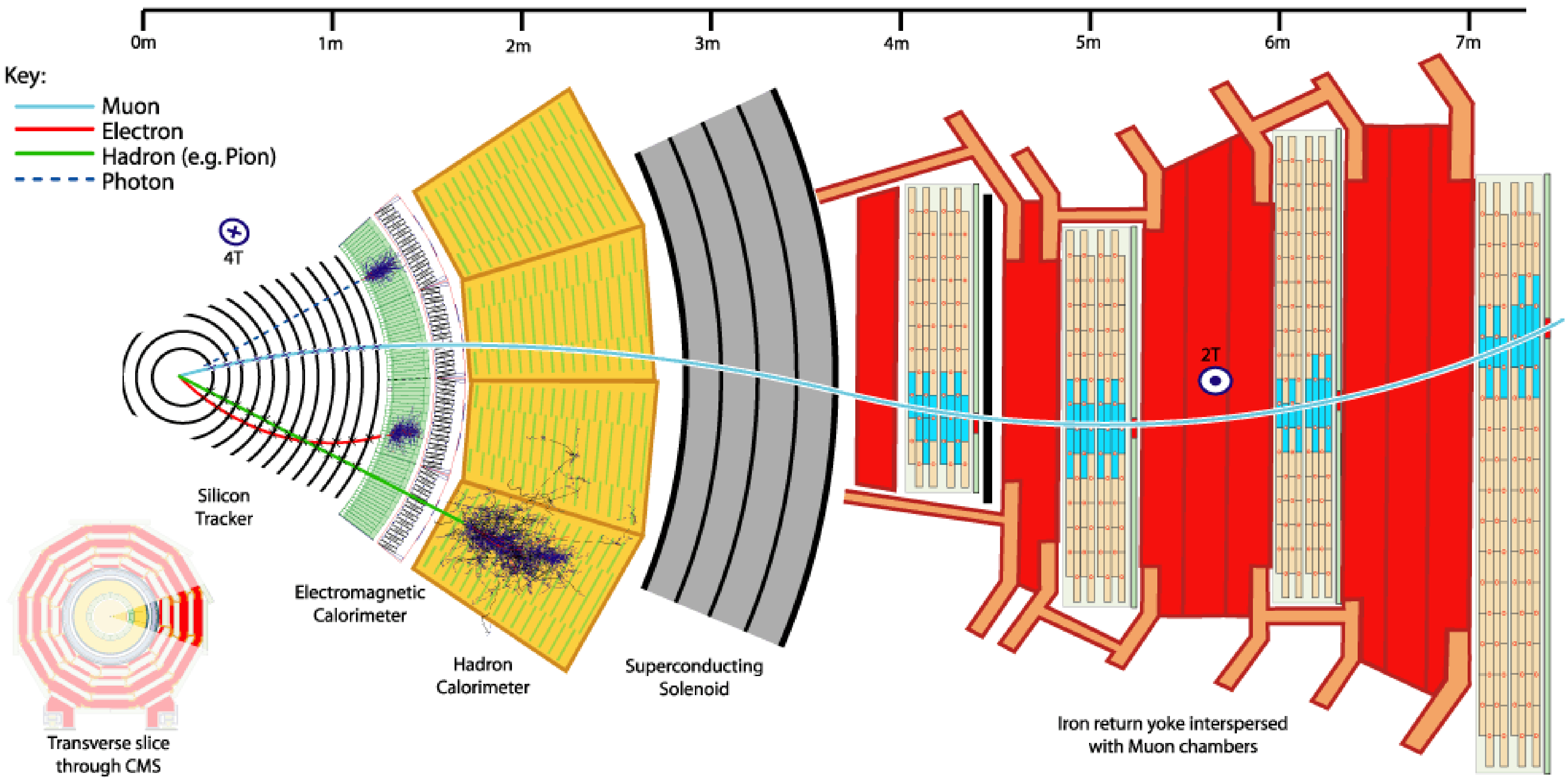
Neutrinos "detected and measured" through measurement of missing transverse energy (ET^{miss}) in calorimeters (+central tracker).


pp, B-Physics,
CP Violation
LHCb
LHC : 27 km long
100m underground
ATLAS
Electromagnetic Calorimeters
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
General Purpose,
pp, heavy ions
Heavy ions, pp
ALICE
vacuum chamber
central detector
electromagnetic calorimeter
hadronic calorimeter
superconducting coil
return yoke
muon chambers
CMS
Detector characteristics
Width: 22m
Diameter: 15m
Weight: 14'500t
+TOTEM

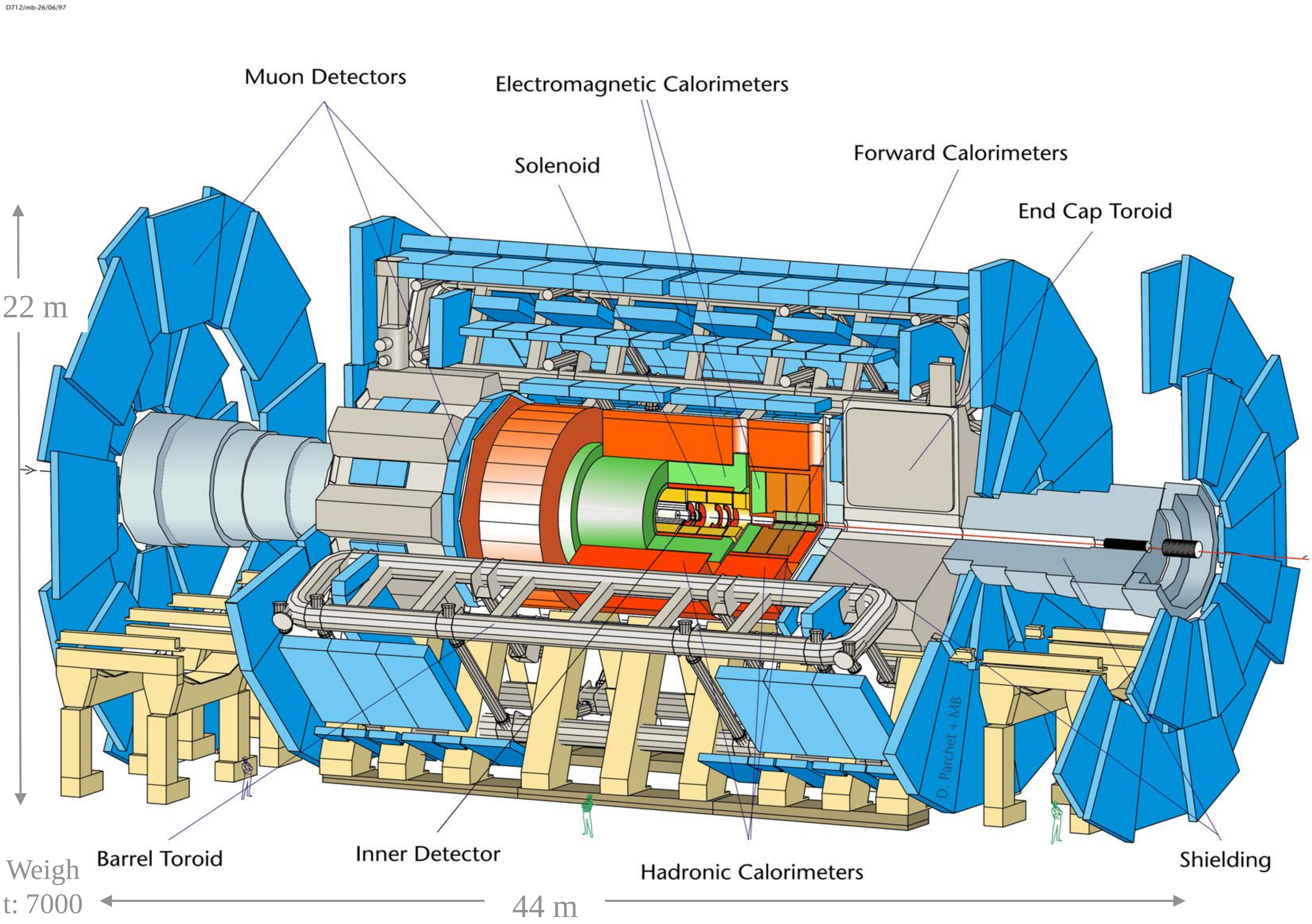
The CMS Detector



Particles as seen in CMS

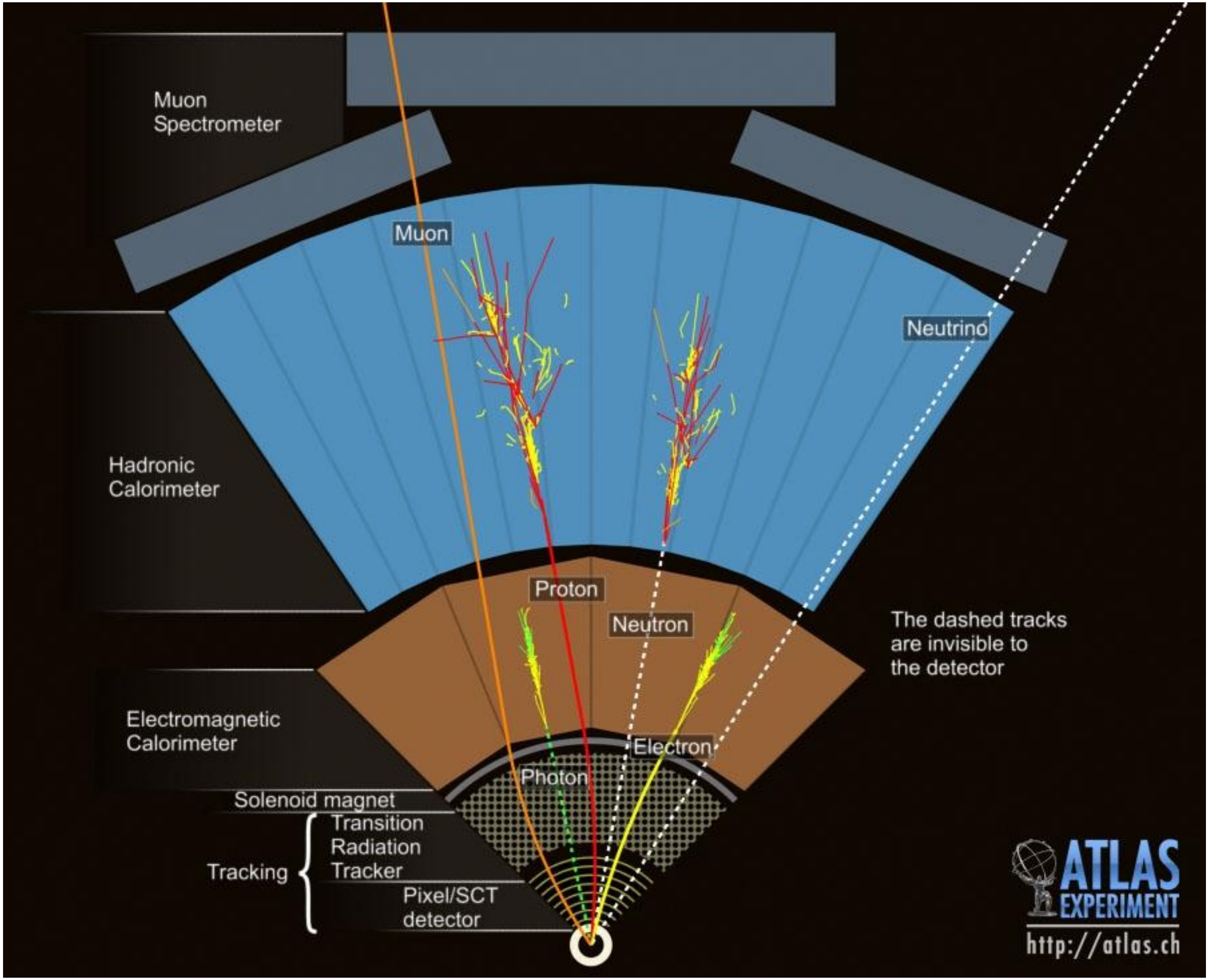


The ATLAS Detector



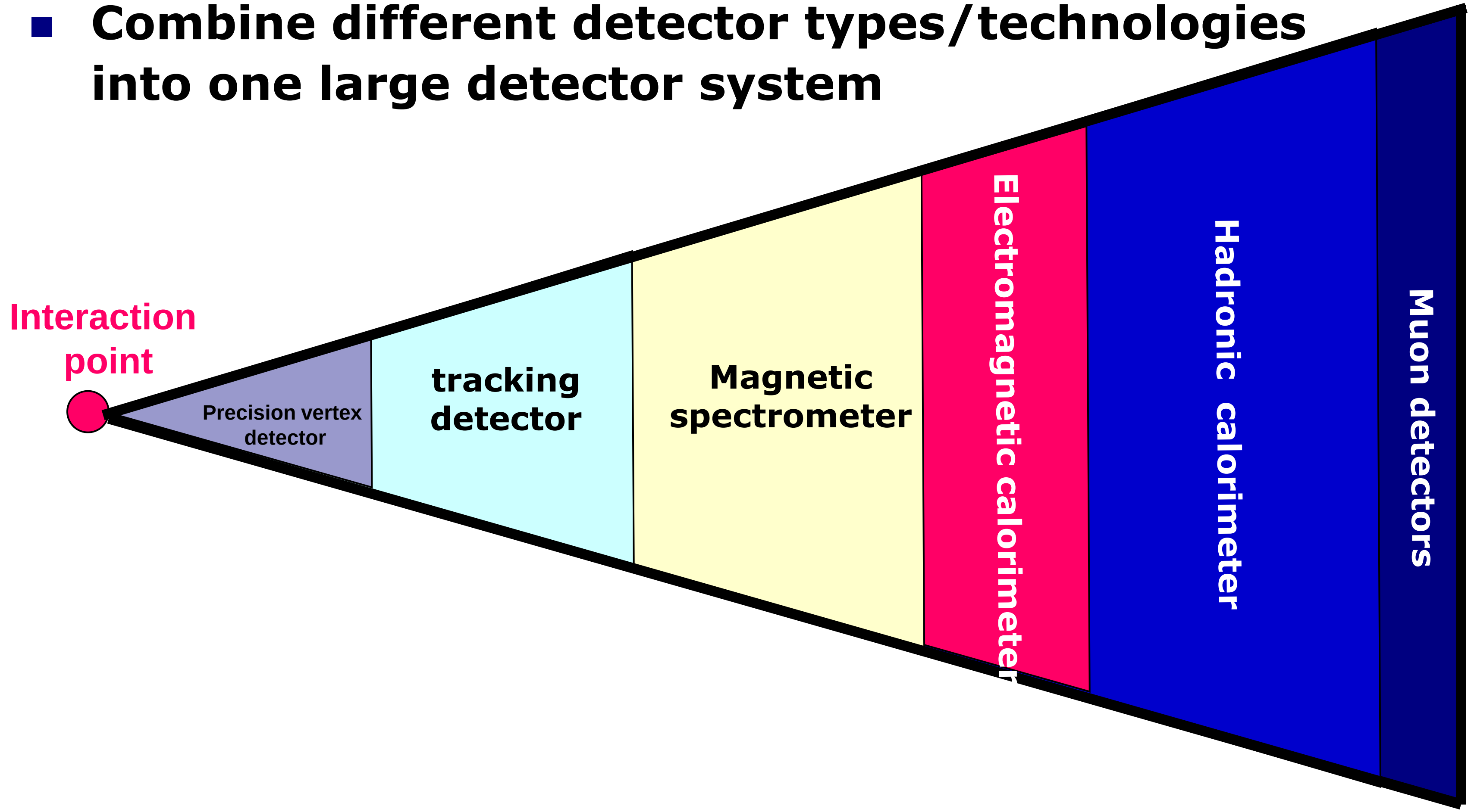
Weight: 7000 t

Particles as seen in ATLAS



Typical detector concept

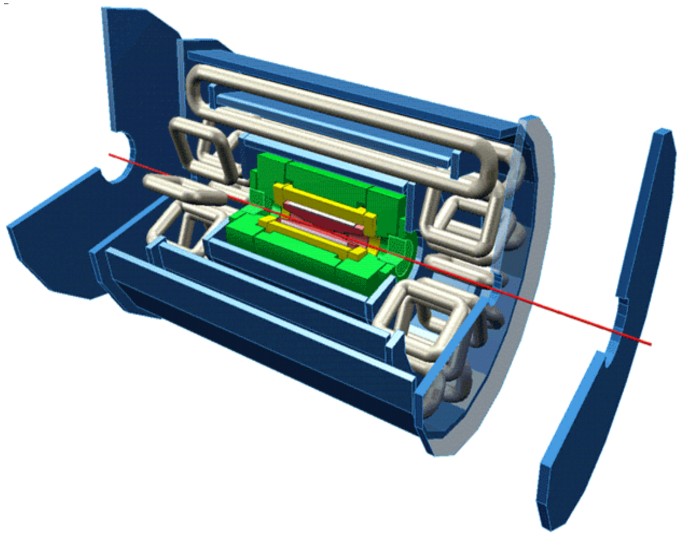
- **Combine different detector types/technologies into one large detector system**

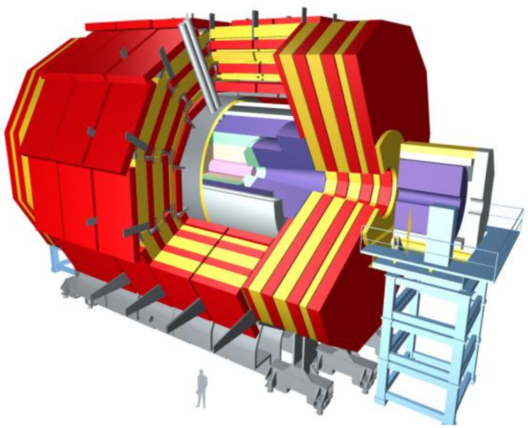


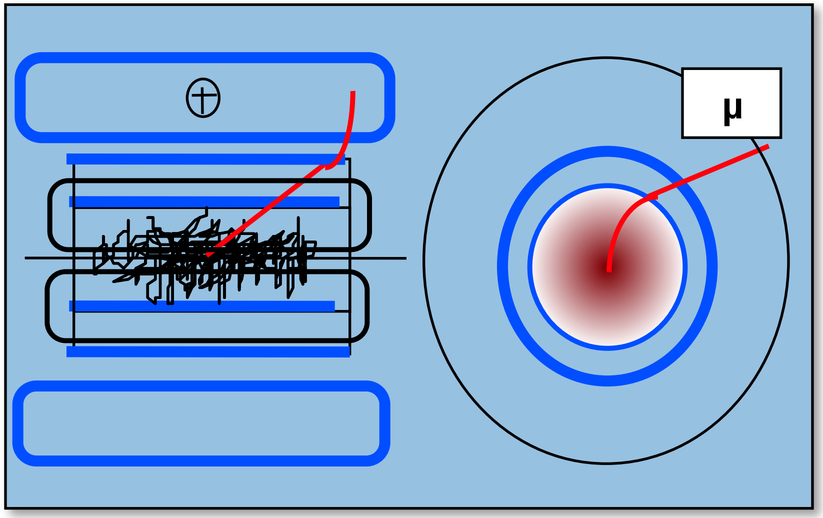
LHC pp experiments

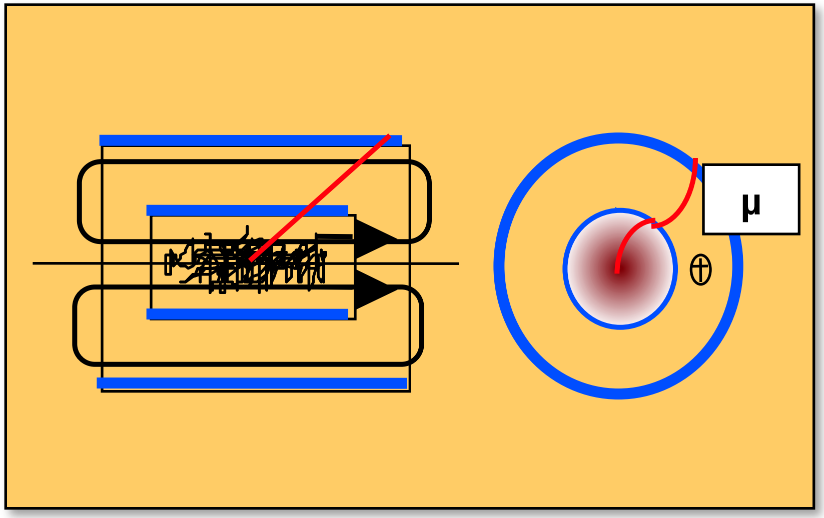
ATLAS A Toroidal LHC ApparatuS

CMS Compact Muon Solenoid

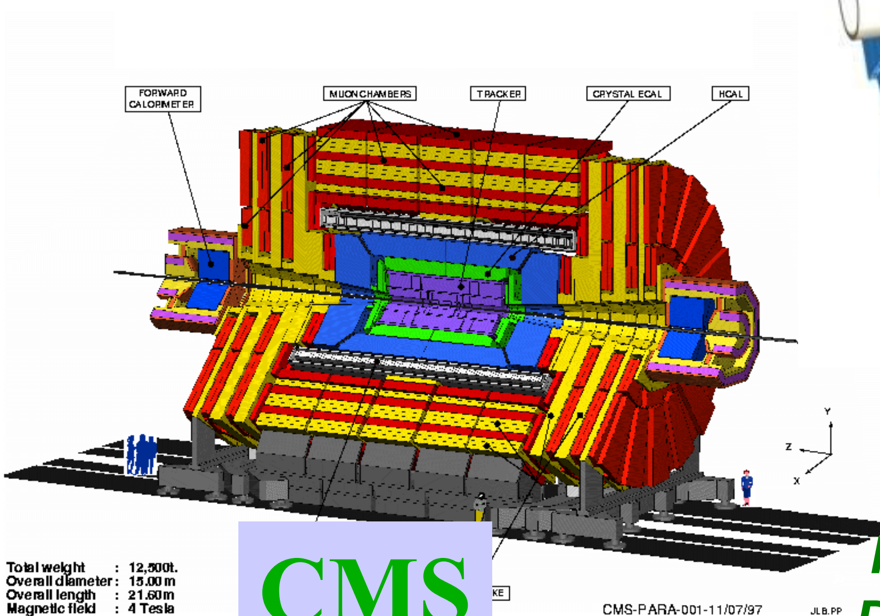




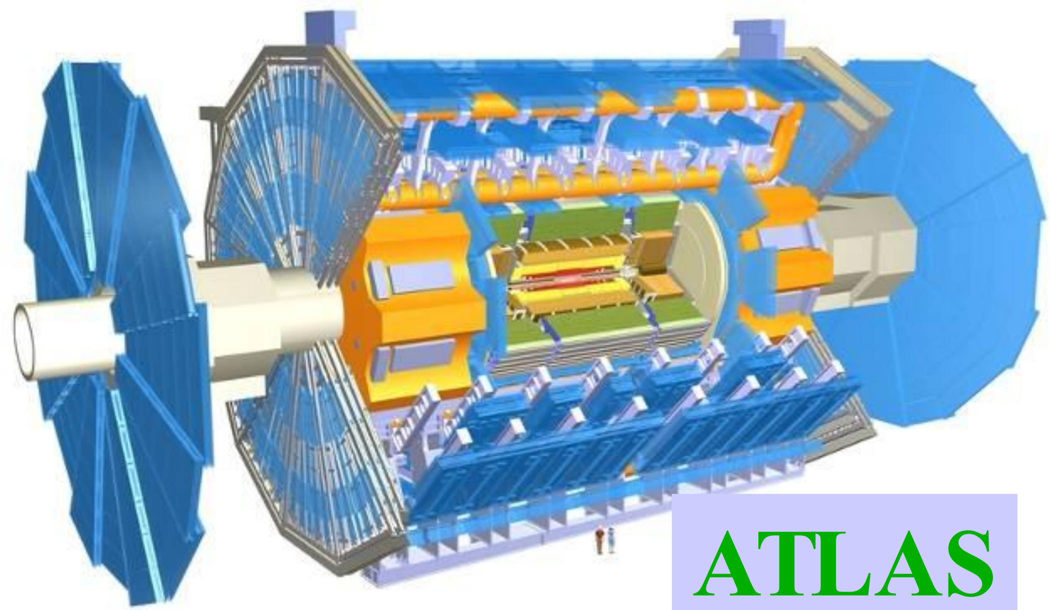




Quanto sono grandi ATLAS e CMS?



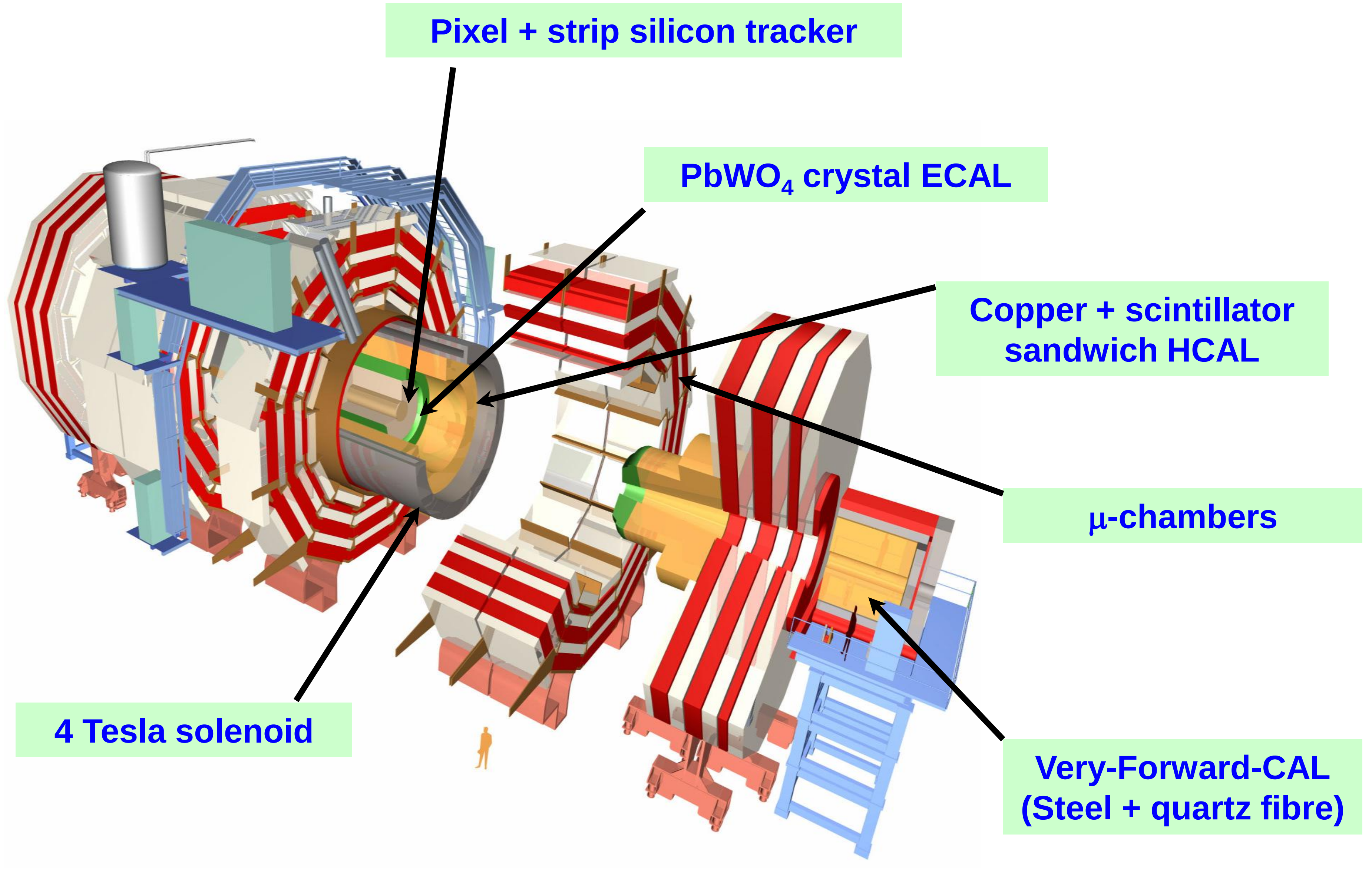
CMS



ATLAS

	ATLAS	CMS
Peso totale (tons)	*7000*	*12500*
Diametro	*22 m*	*15 m*
Lunghezza	*46 m*	*22 m*
Campo magnetico	*2 T*	*4 T*

The CMS Detector



Lavori di scavo a “Point 5”

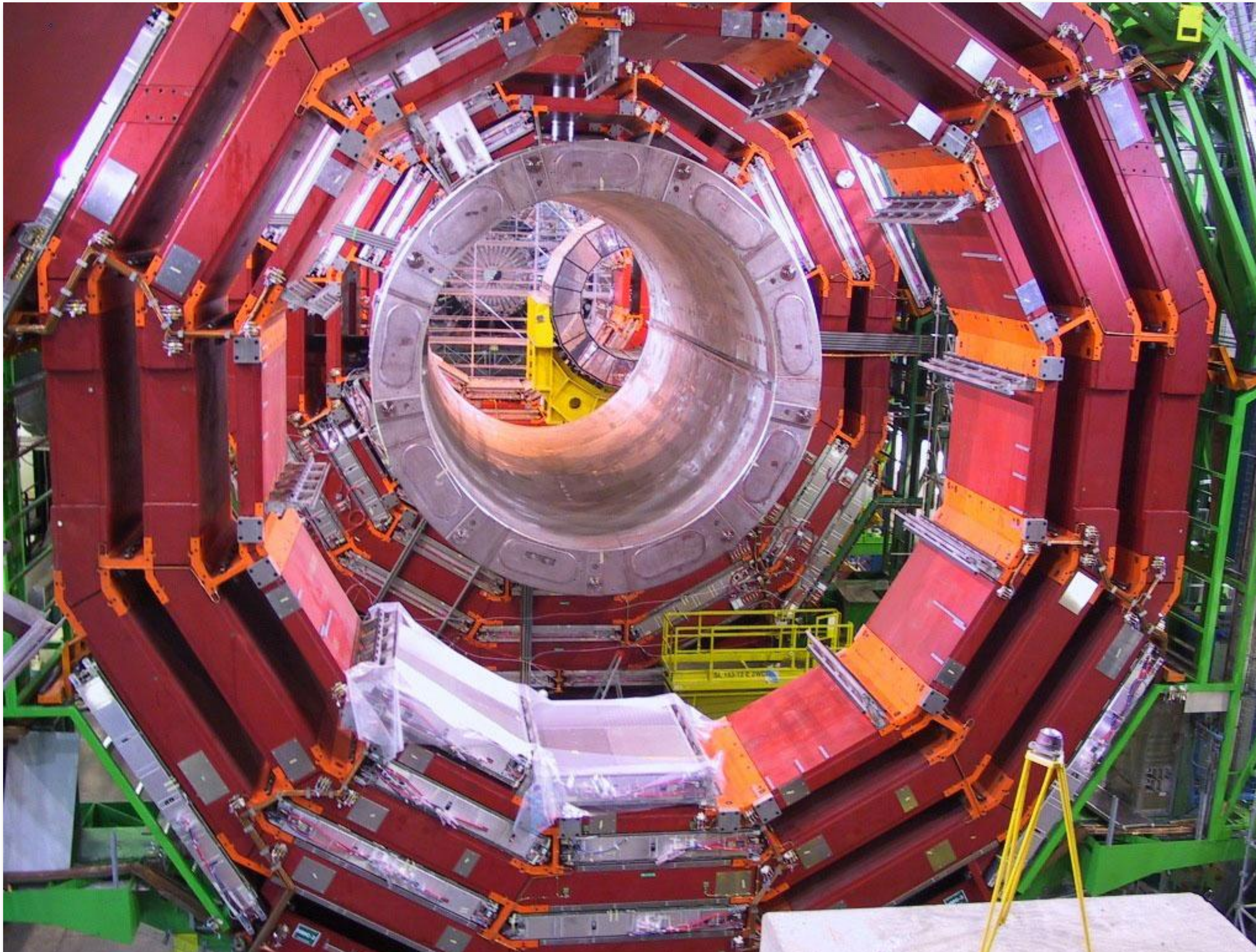

Point 5 - Excavation of pillar - November 22, 2000 - CERN ST-CE

Point 5 - Installation ventilation in PM54 - September 18, 2000 - CERN ST-CE

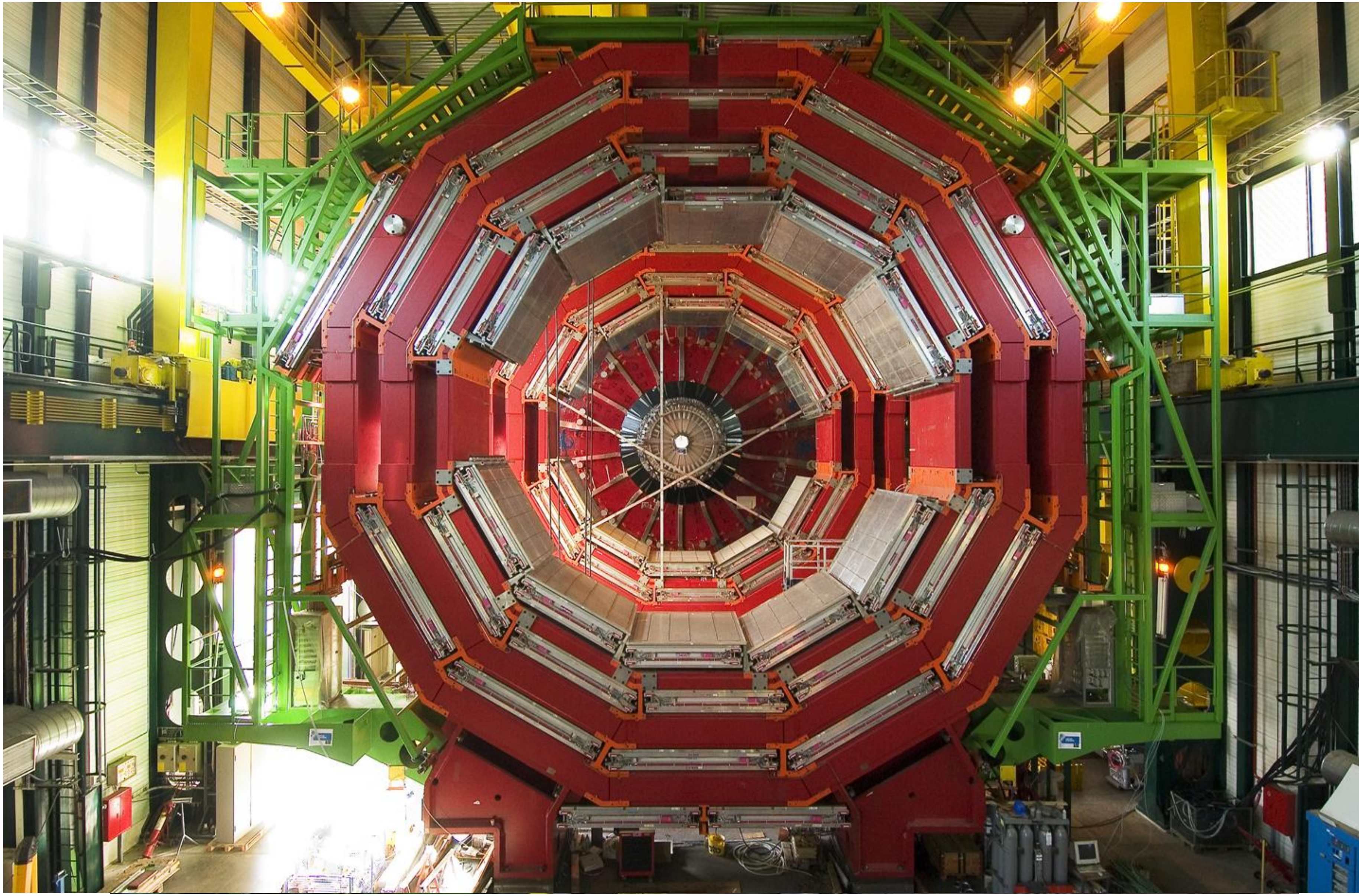
UXC/USC5: CMS caverns

Delivered to the experiment on February 1-st 2005.

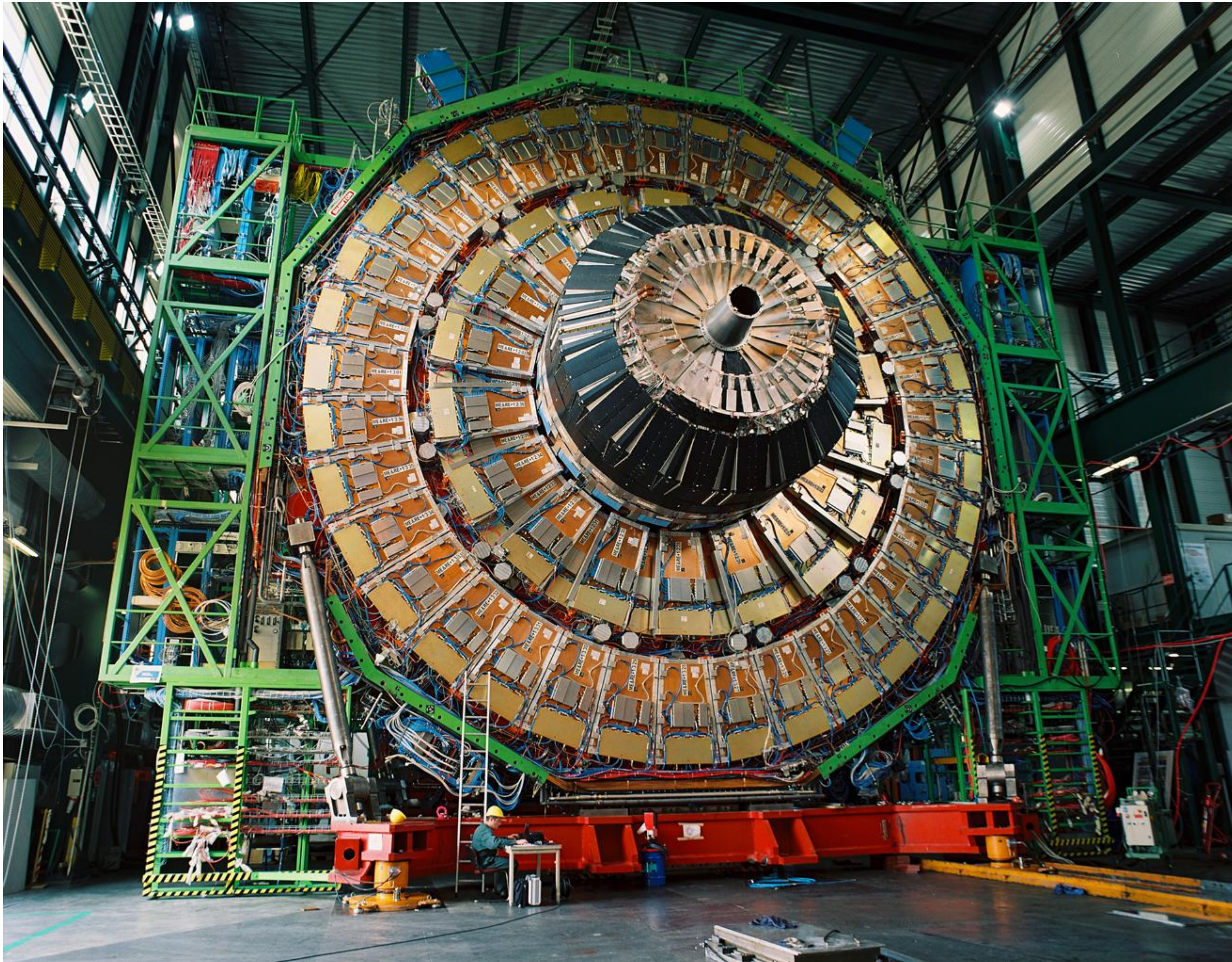
CMS Surface Hall in Feb 2006



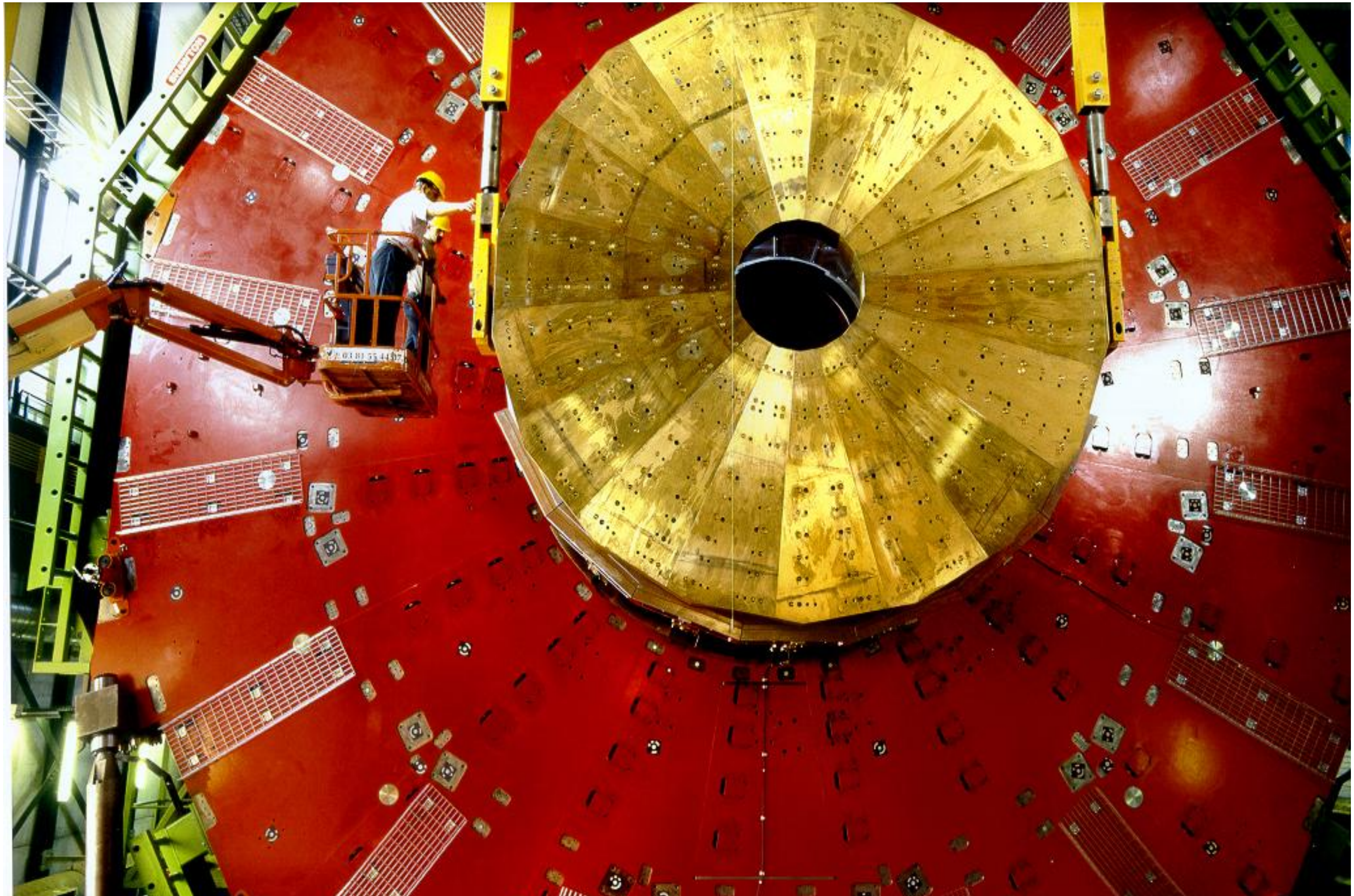
Surface Hall: Barrel Muons



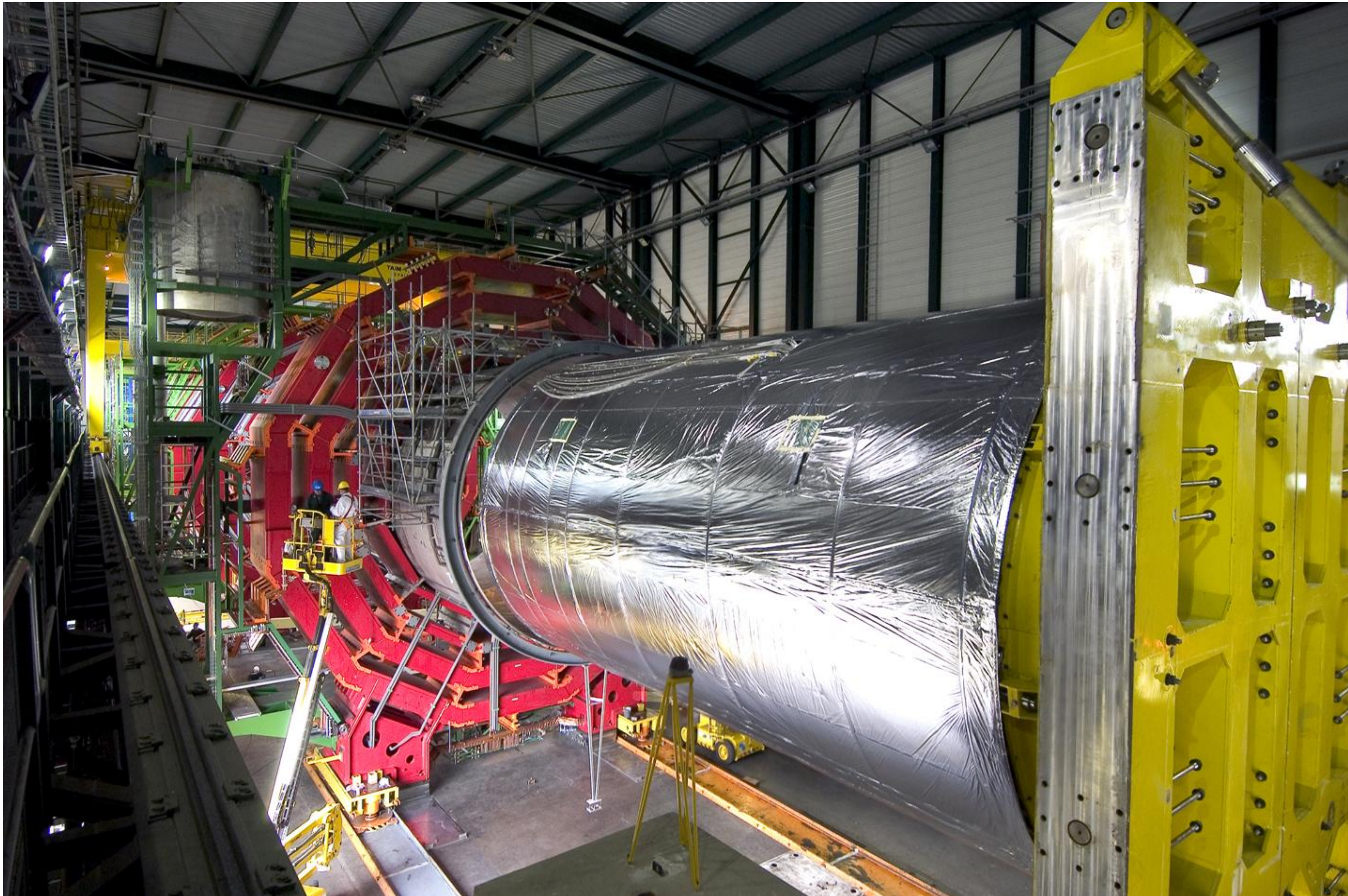
Surface Hall: Endcaps



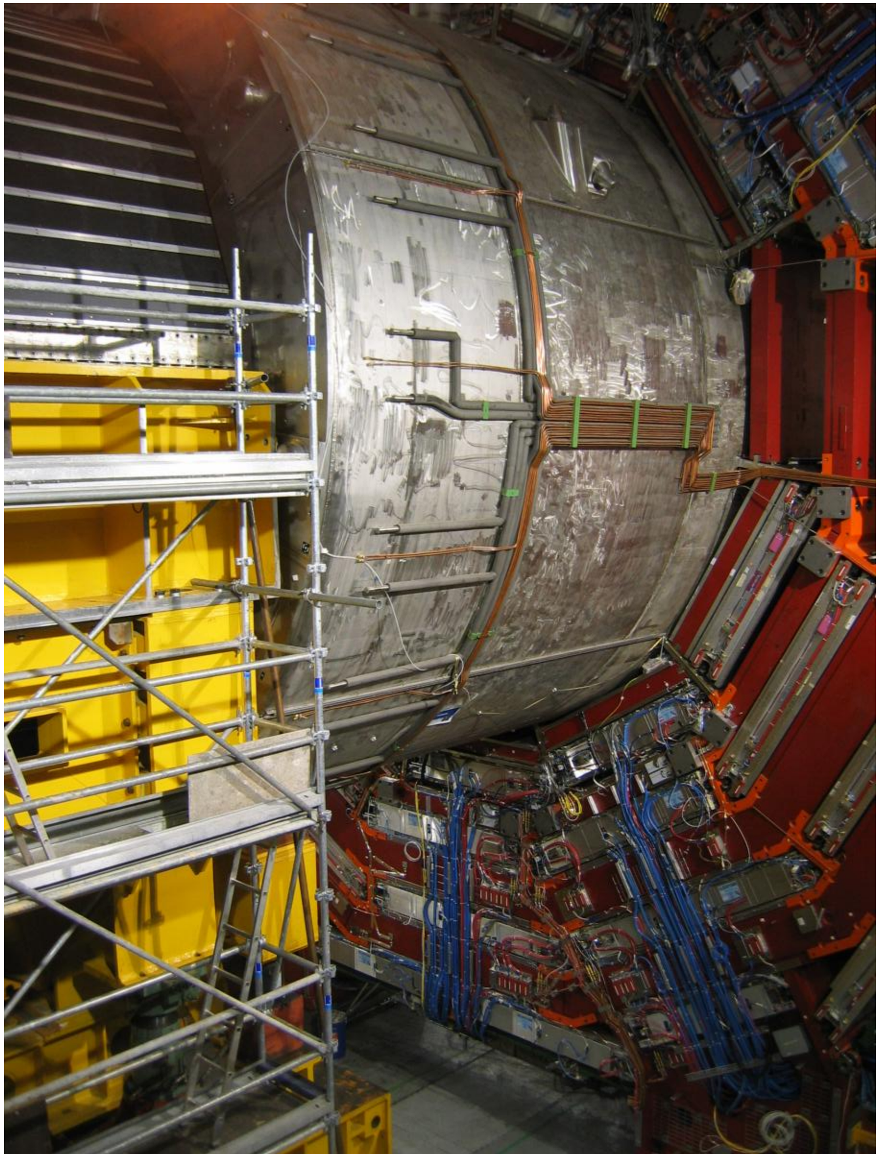
HCAL Endcap

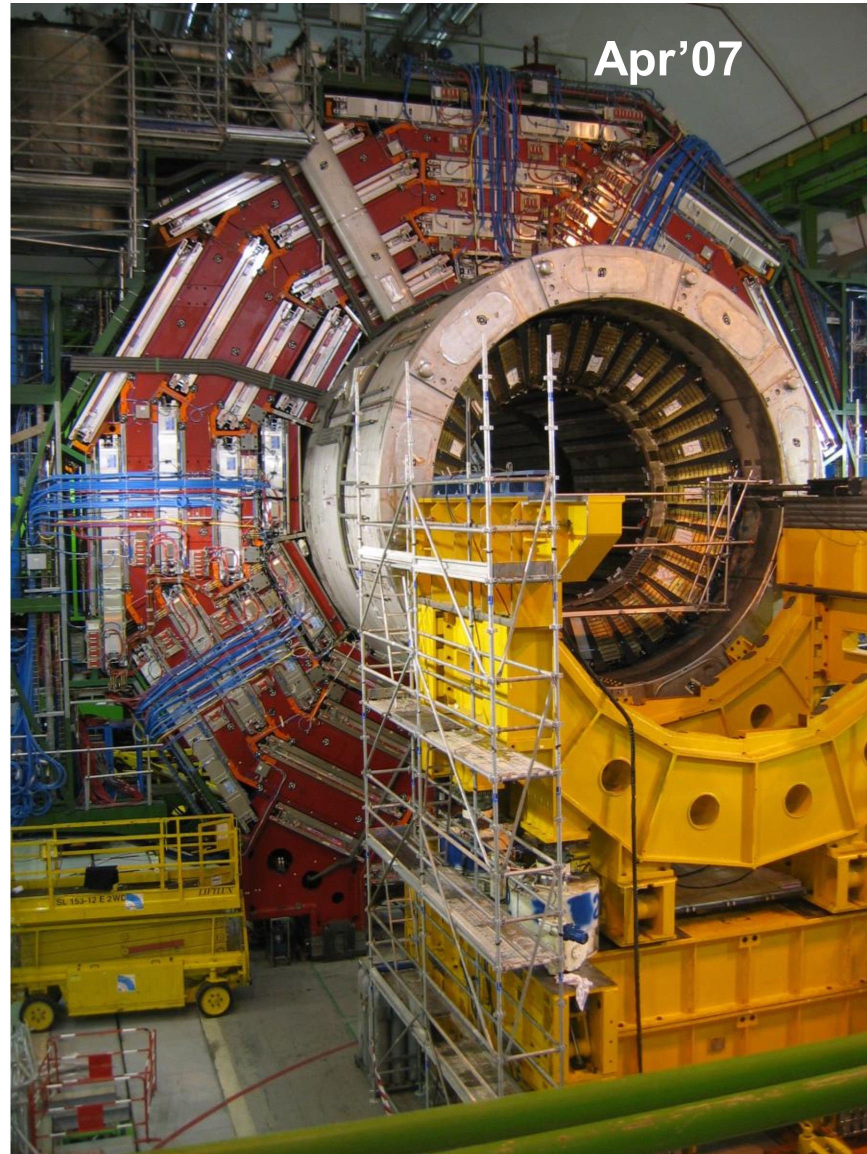


Assembly of the Coil

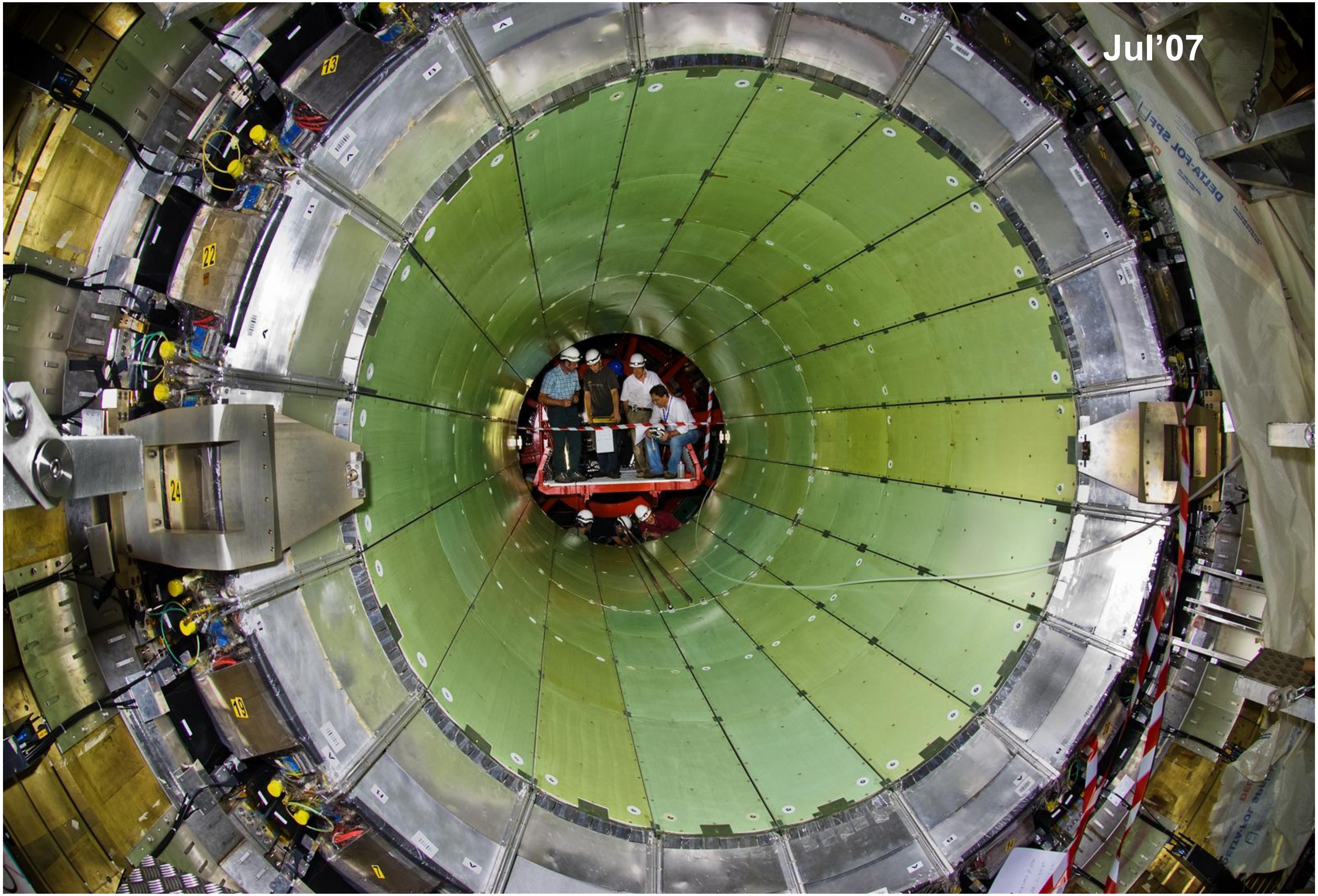


Insertion of HCAL Barrel



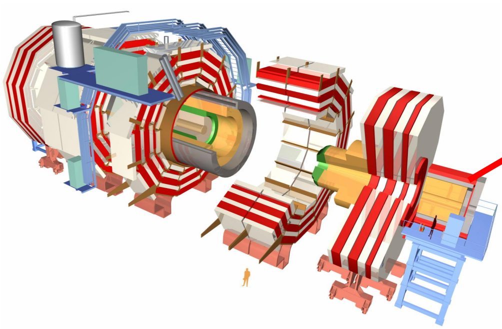


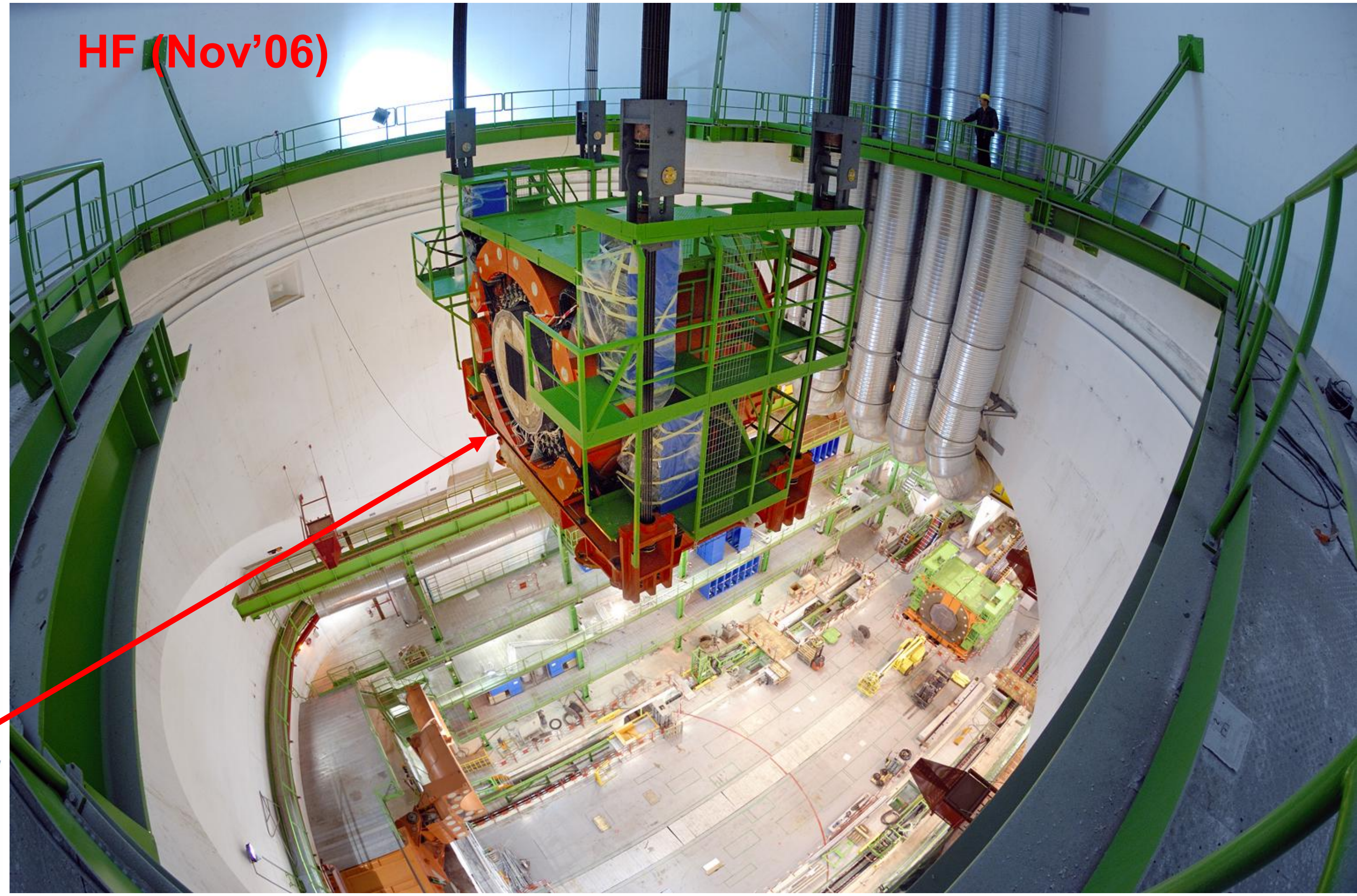
Insertion of Barrel ECAL



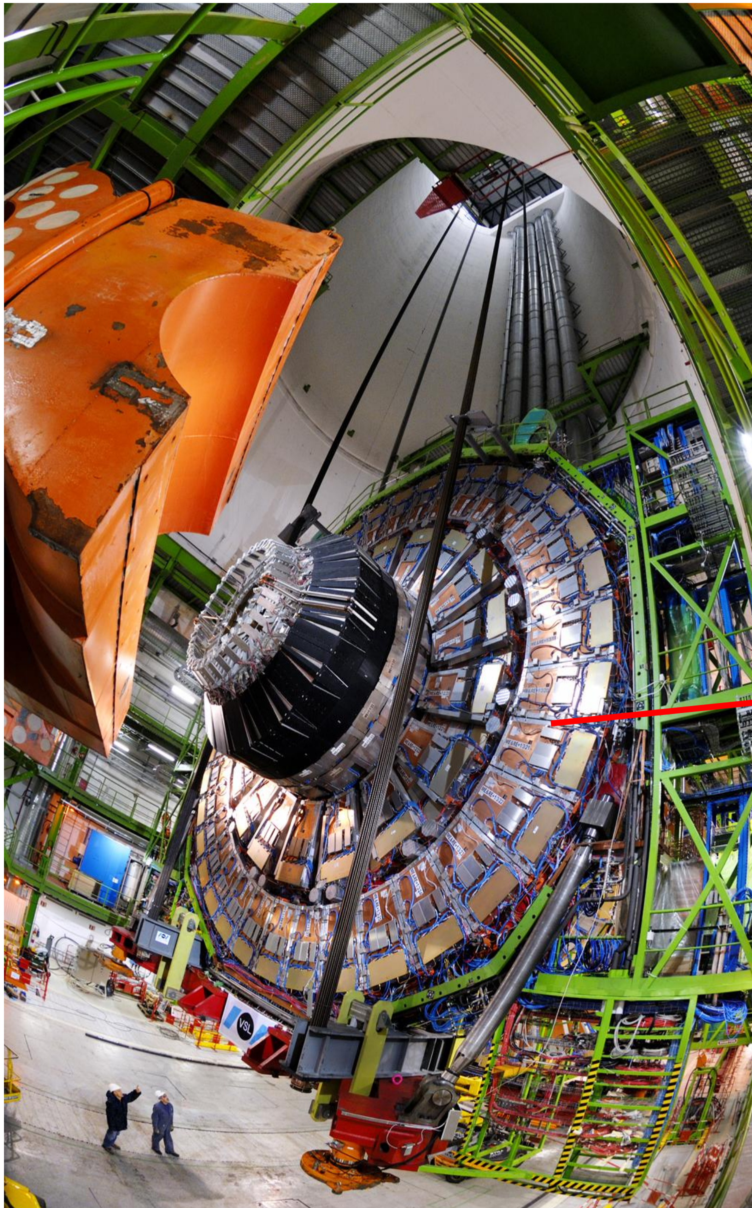
First HF landing into UXC55 (2 Nov 06)

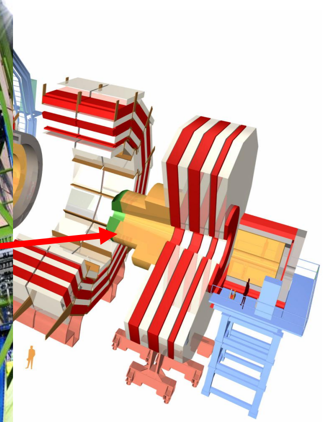
Lowering of Heavy Elements

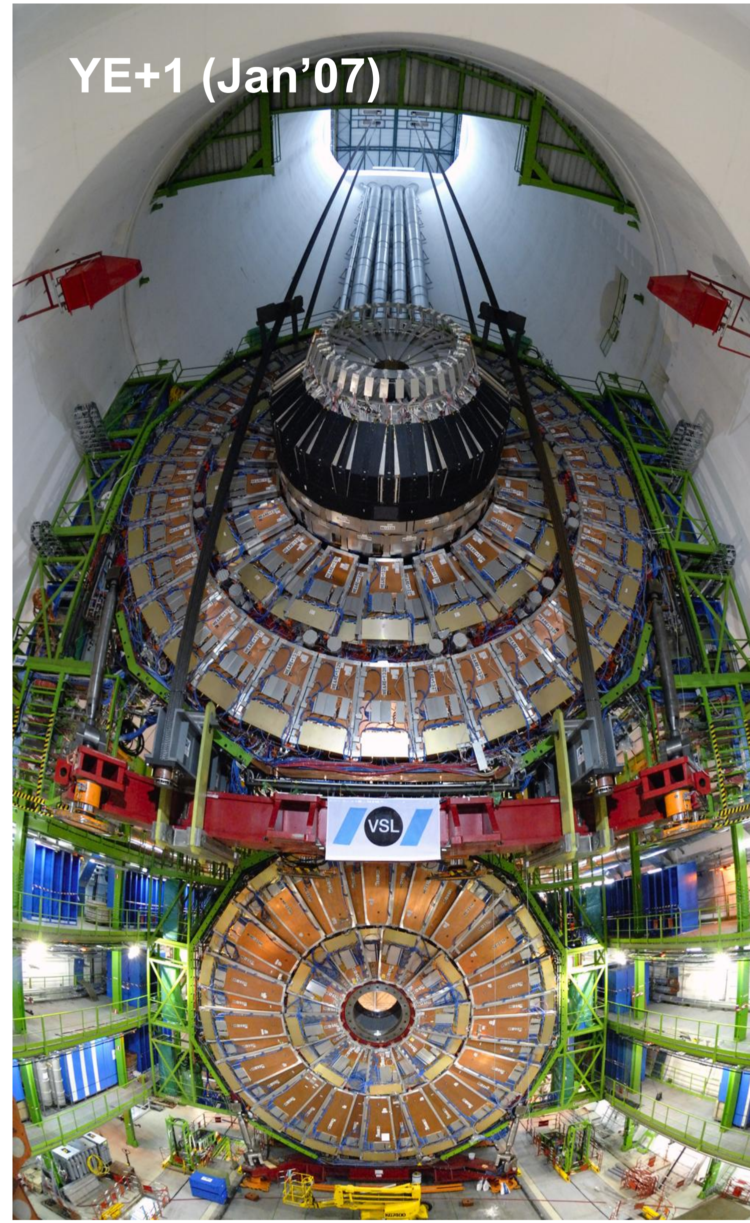




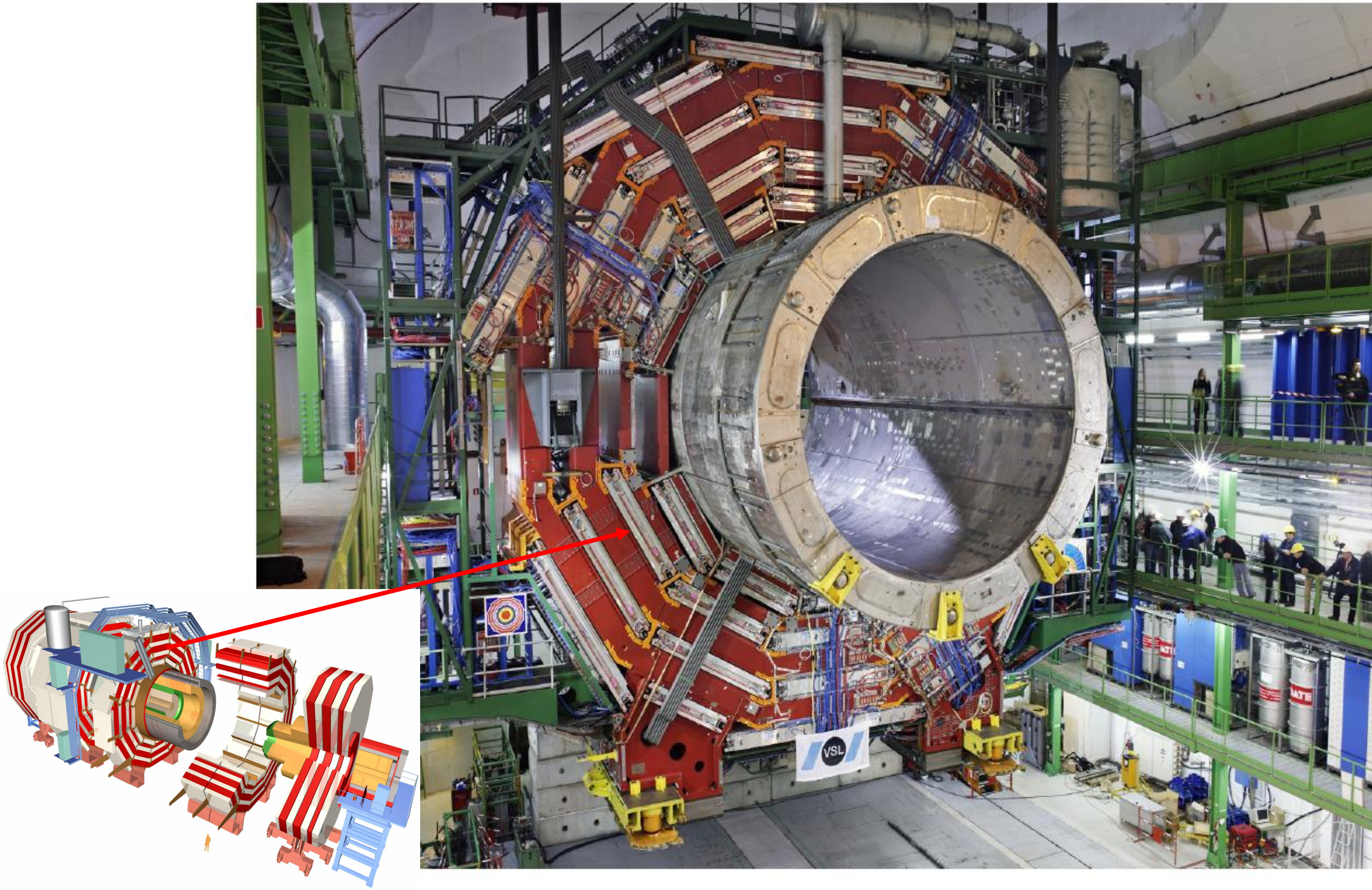
Lowering of Heavy Elements





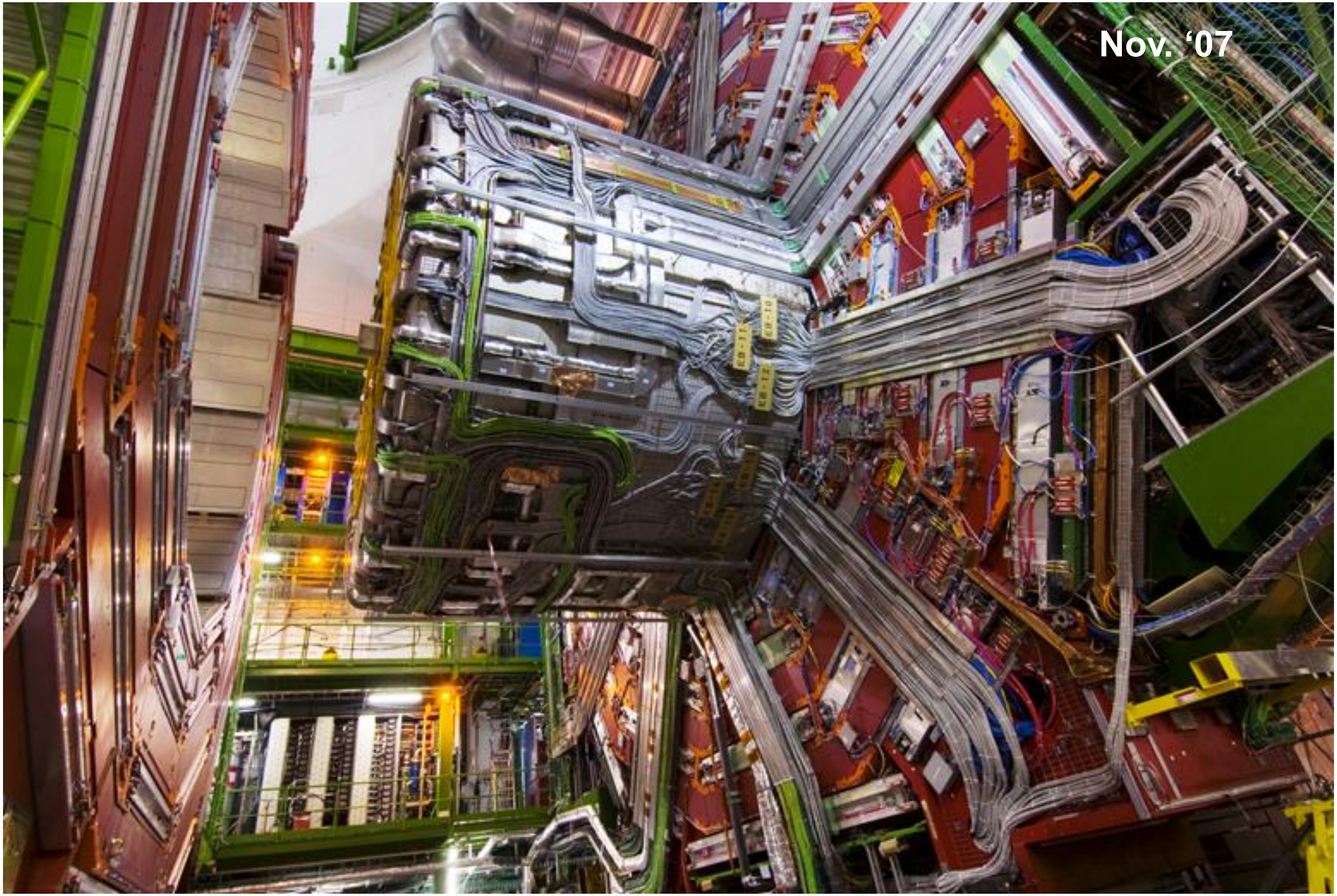


Lowering of Heavy Elements

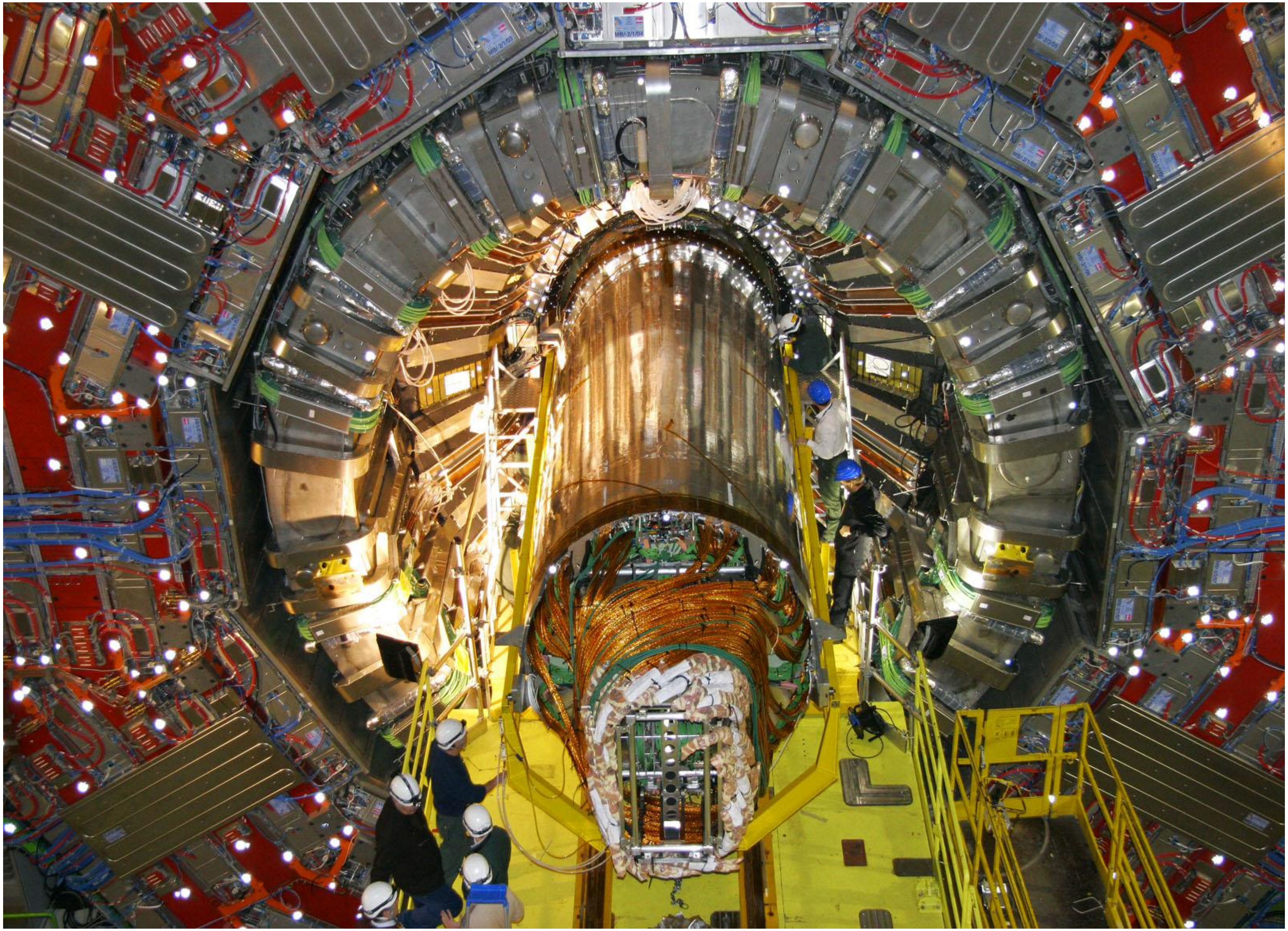


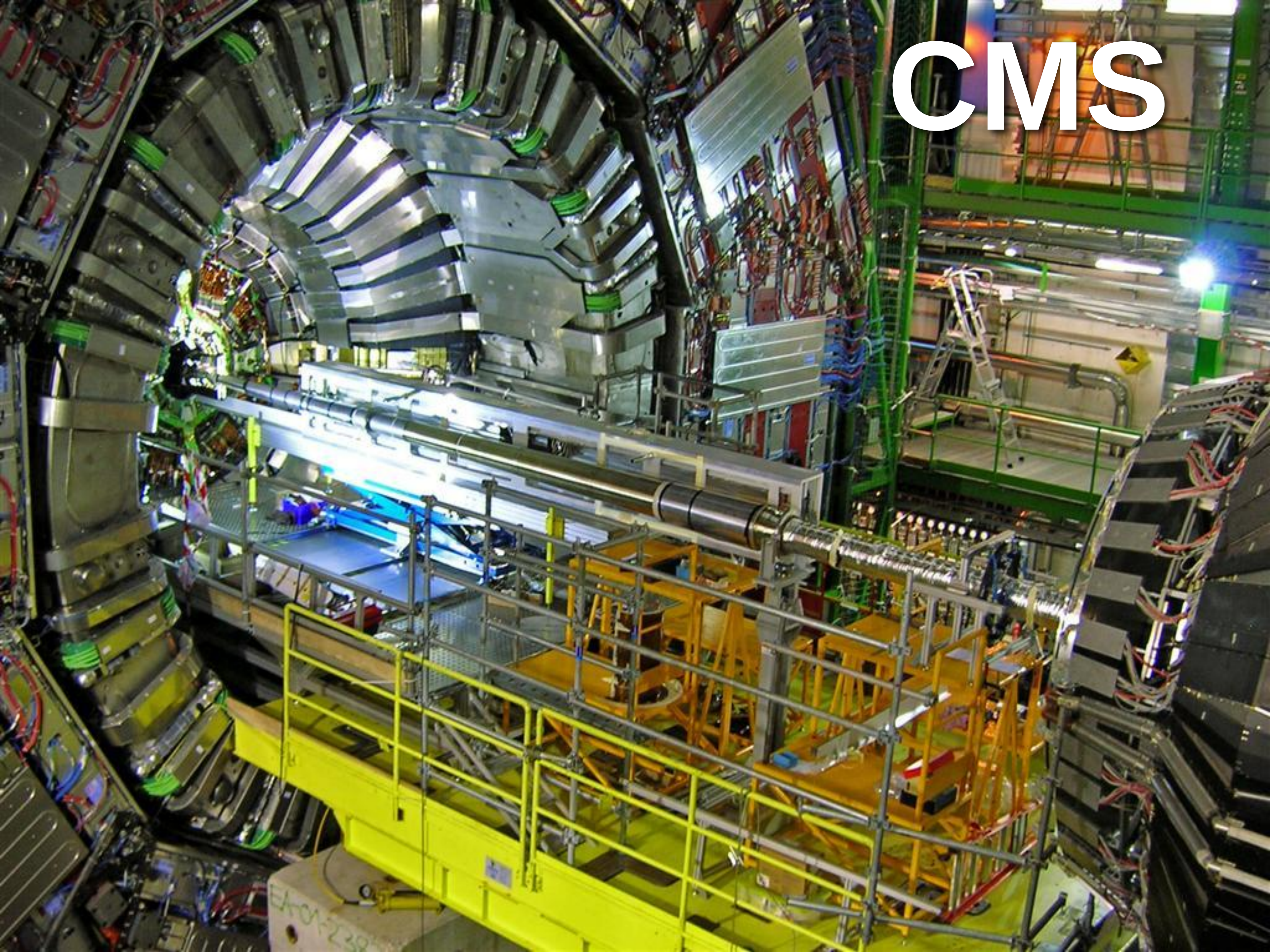
YB0 landing in the CMS experiment hall

Completion of Services on YB0

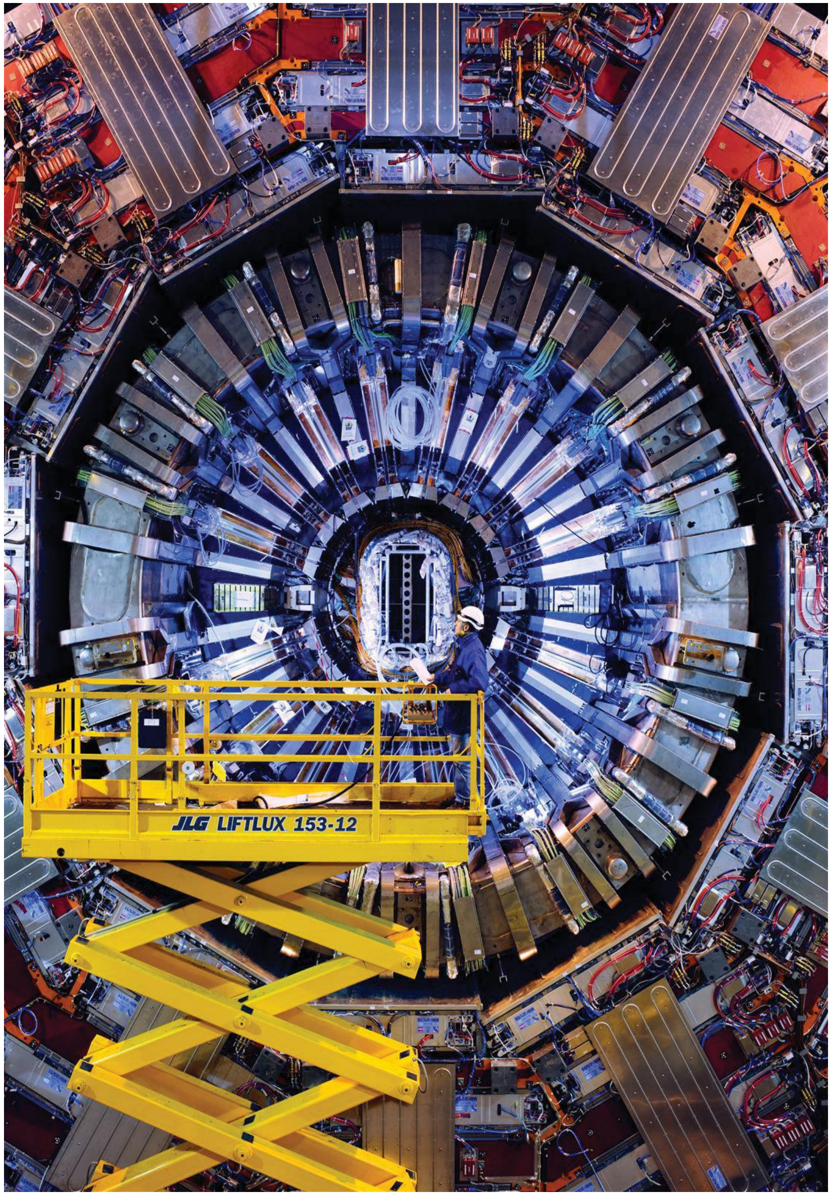


Tracker Insertion

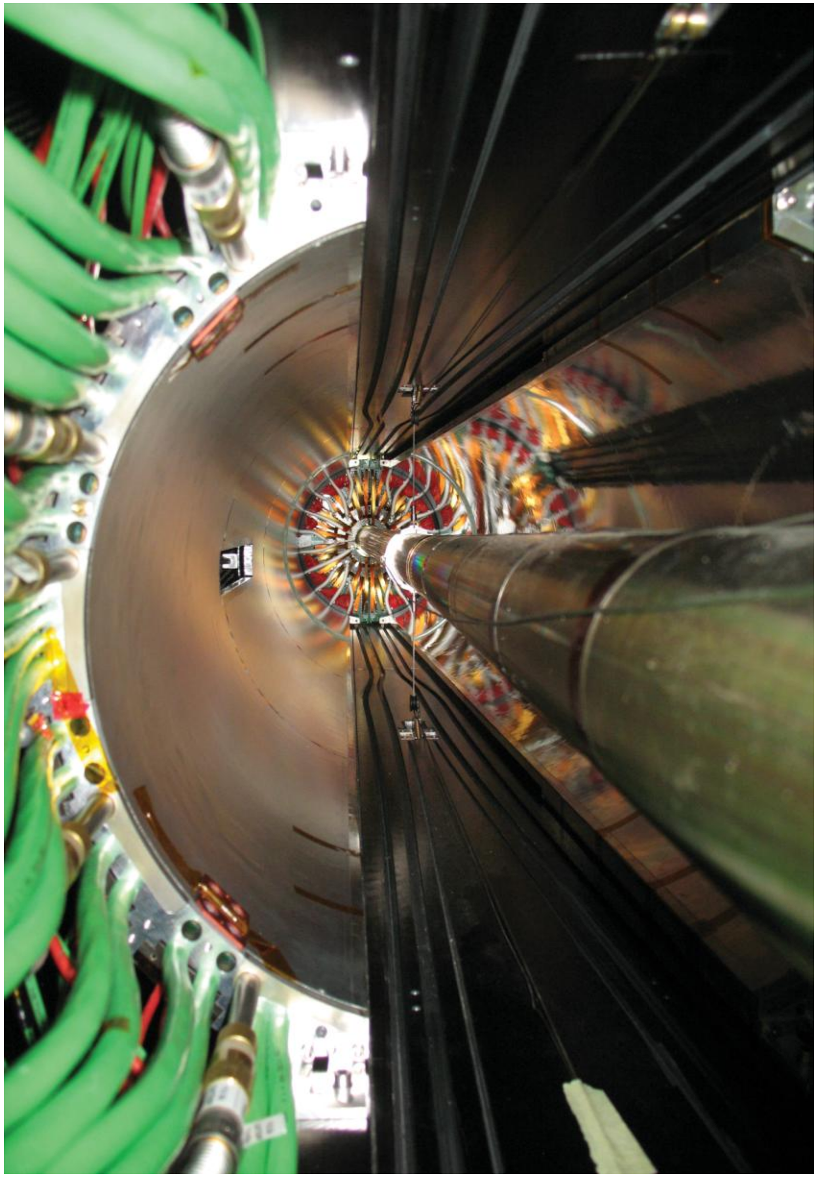



CMS

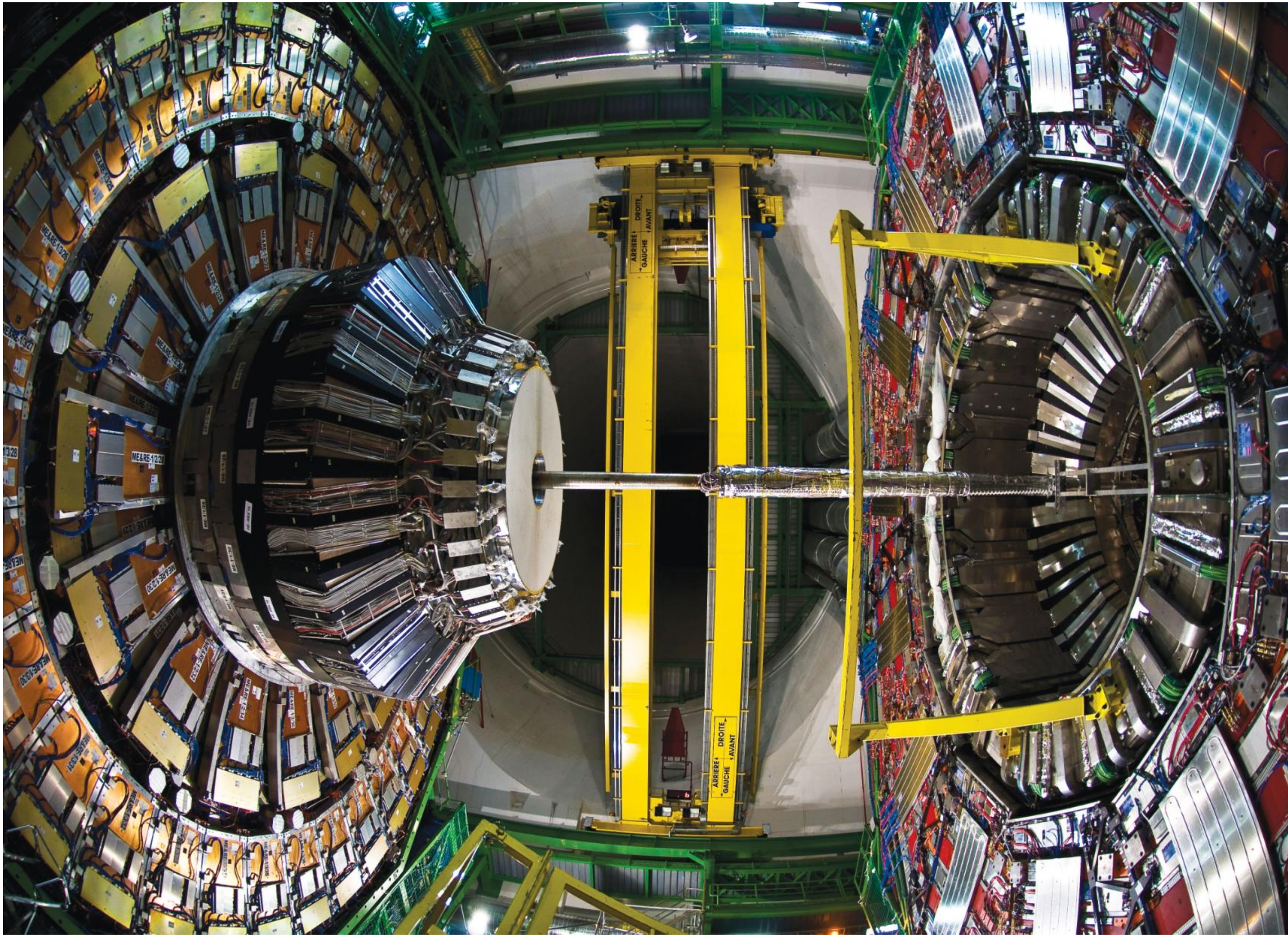
After Tracker insertion



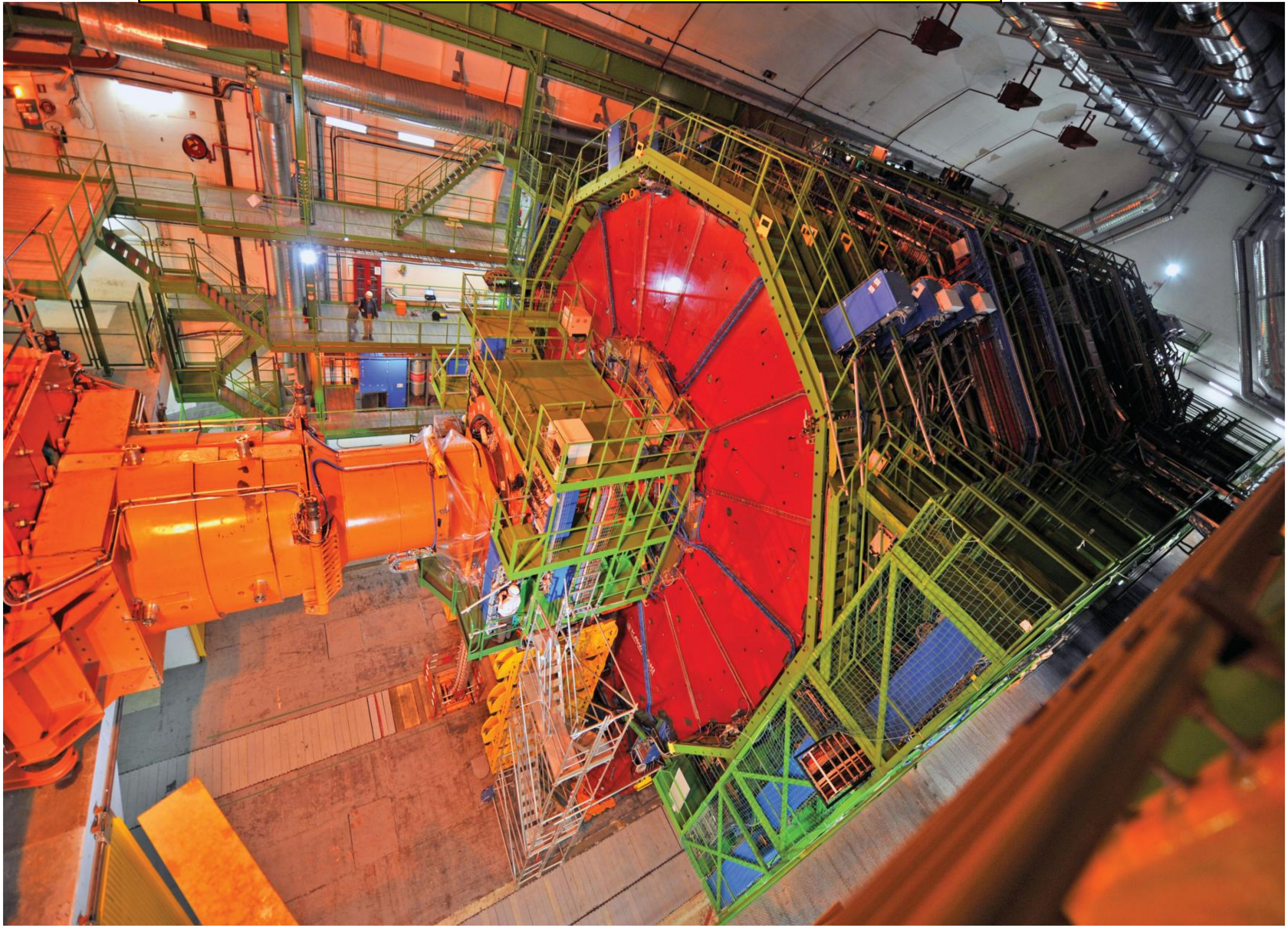
Pixel insertion



Beam Pipe installation

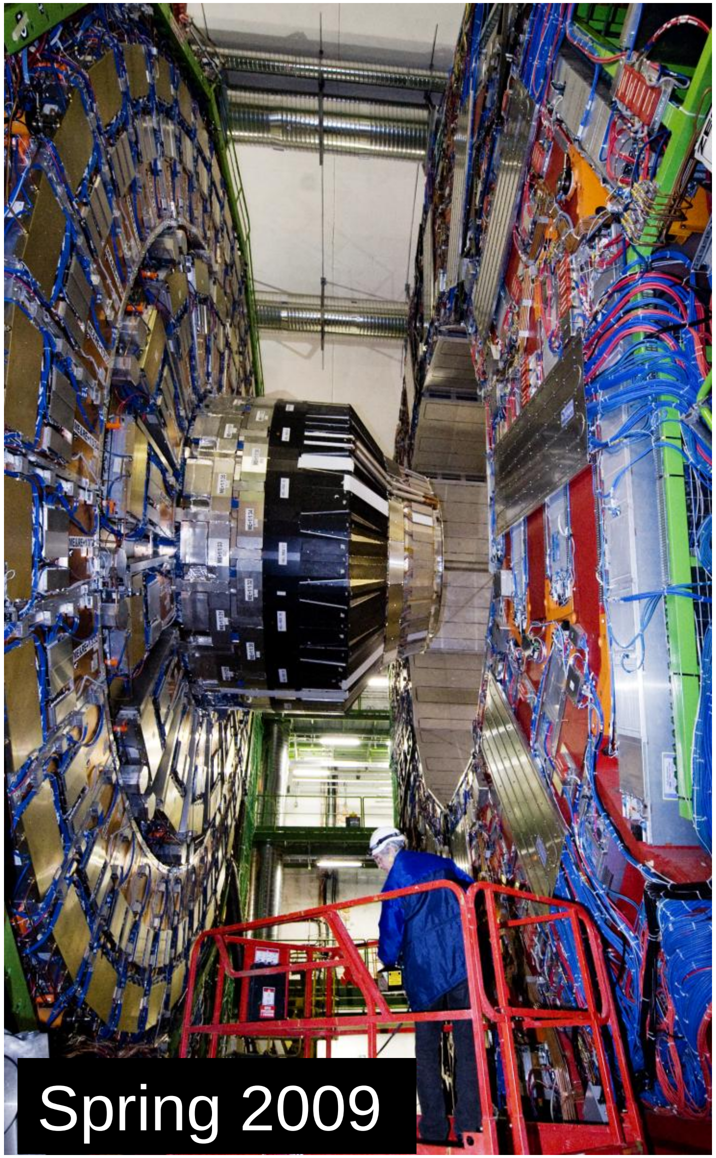


CMS closed and ready for data



Cabling and re-cabling one year later

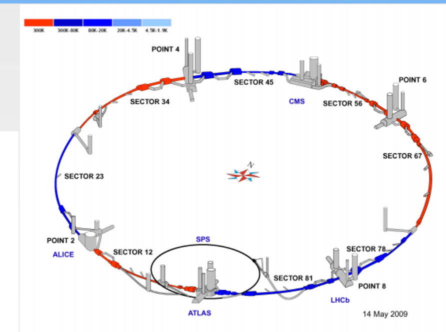
Spring 2008

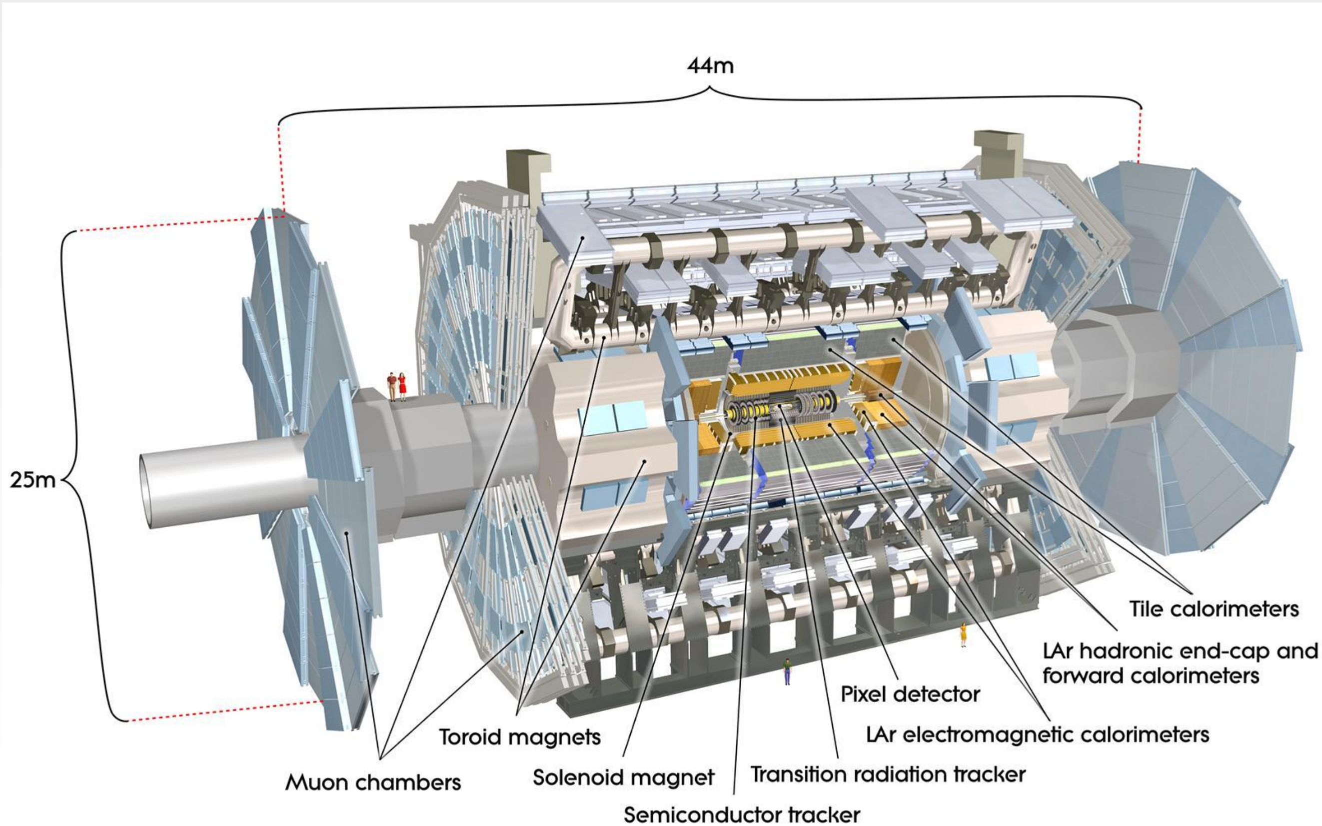


Spring 2009

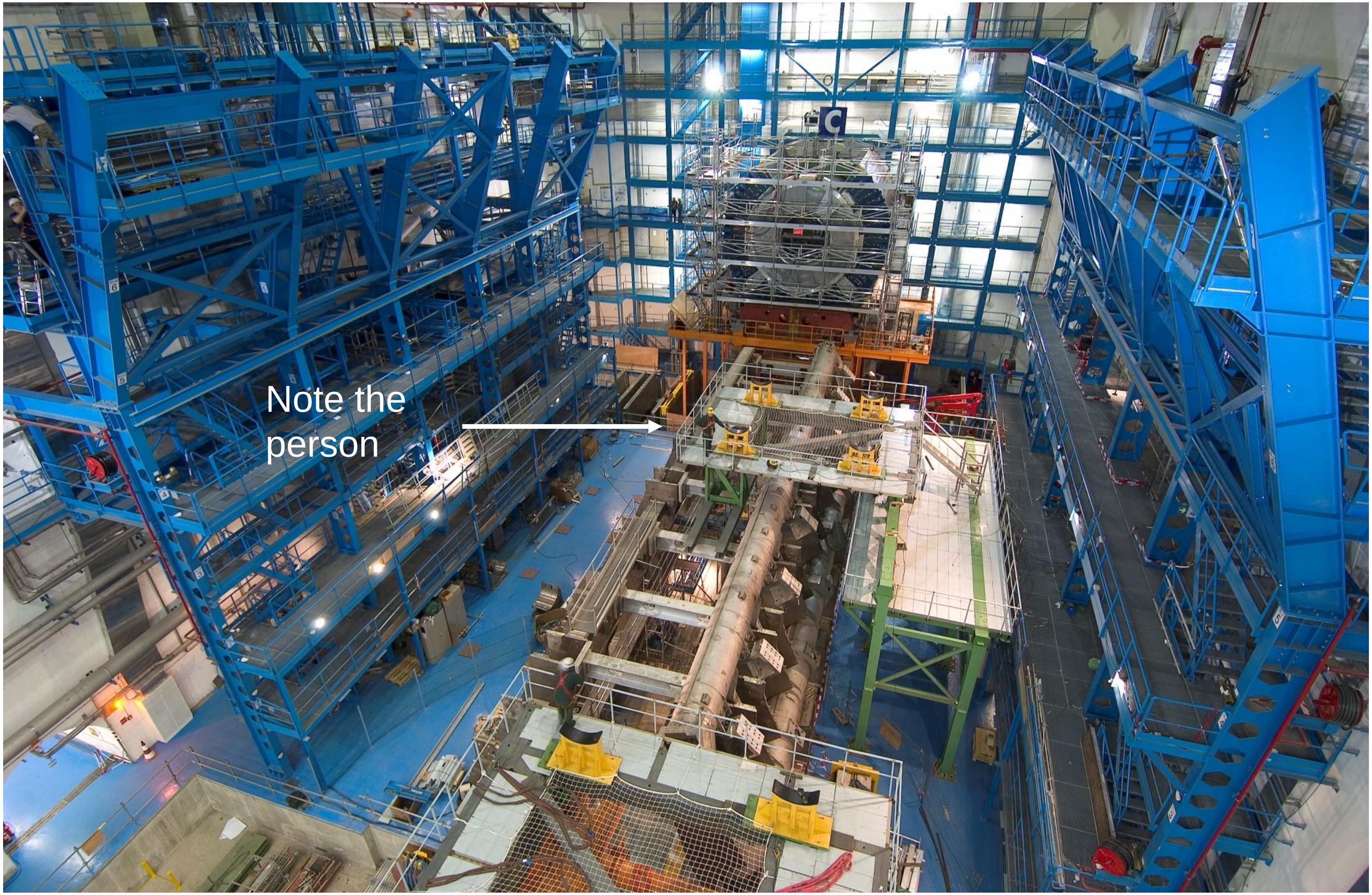
The ATLAS detector

- pp collisions @ 14 TeV and $L=10^{34}\ cm^{-2}s^{-1}$
- LHC collision rate = 40 MHz



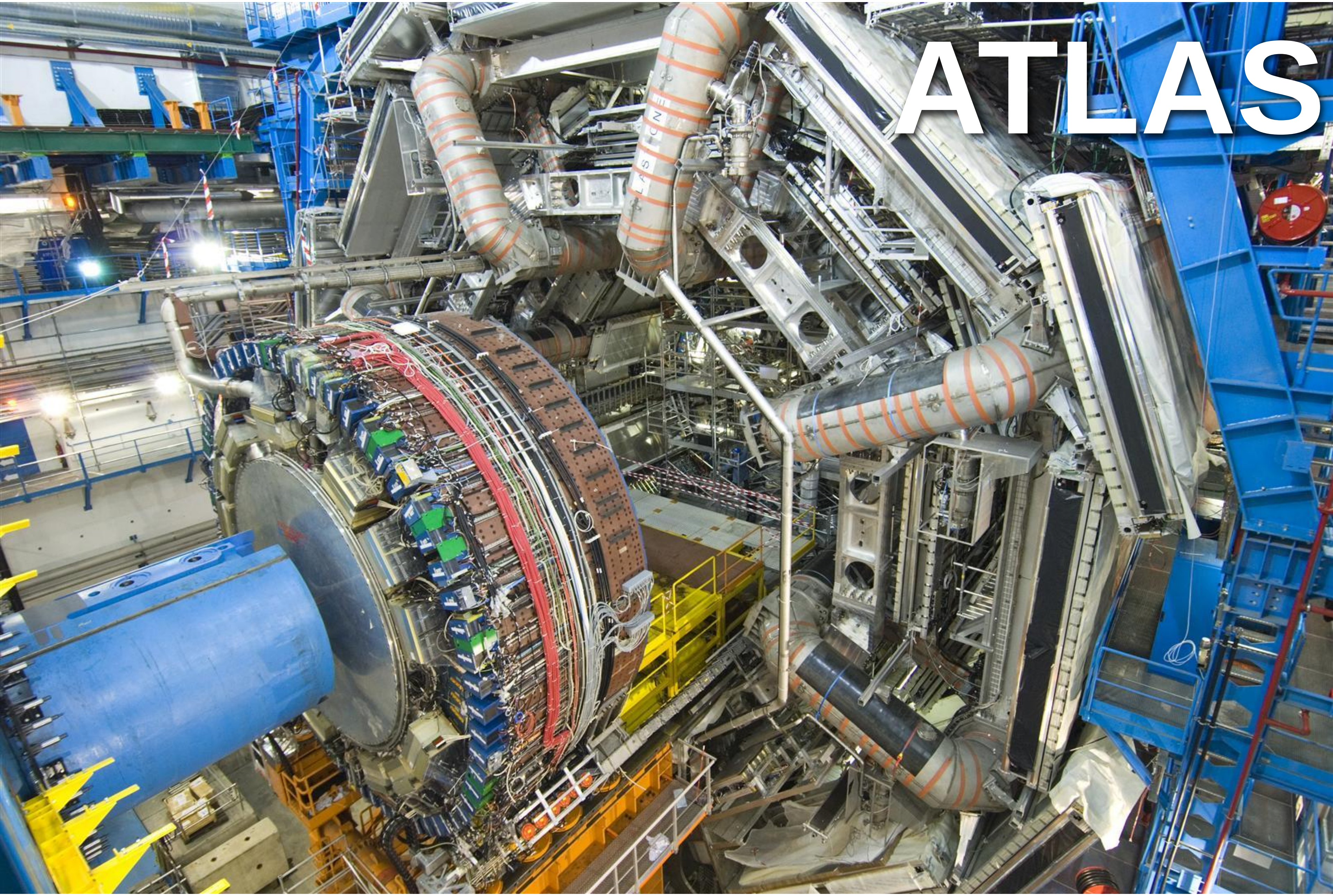


ATLAS – A Toroidal LHC ApparatuS

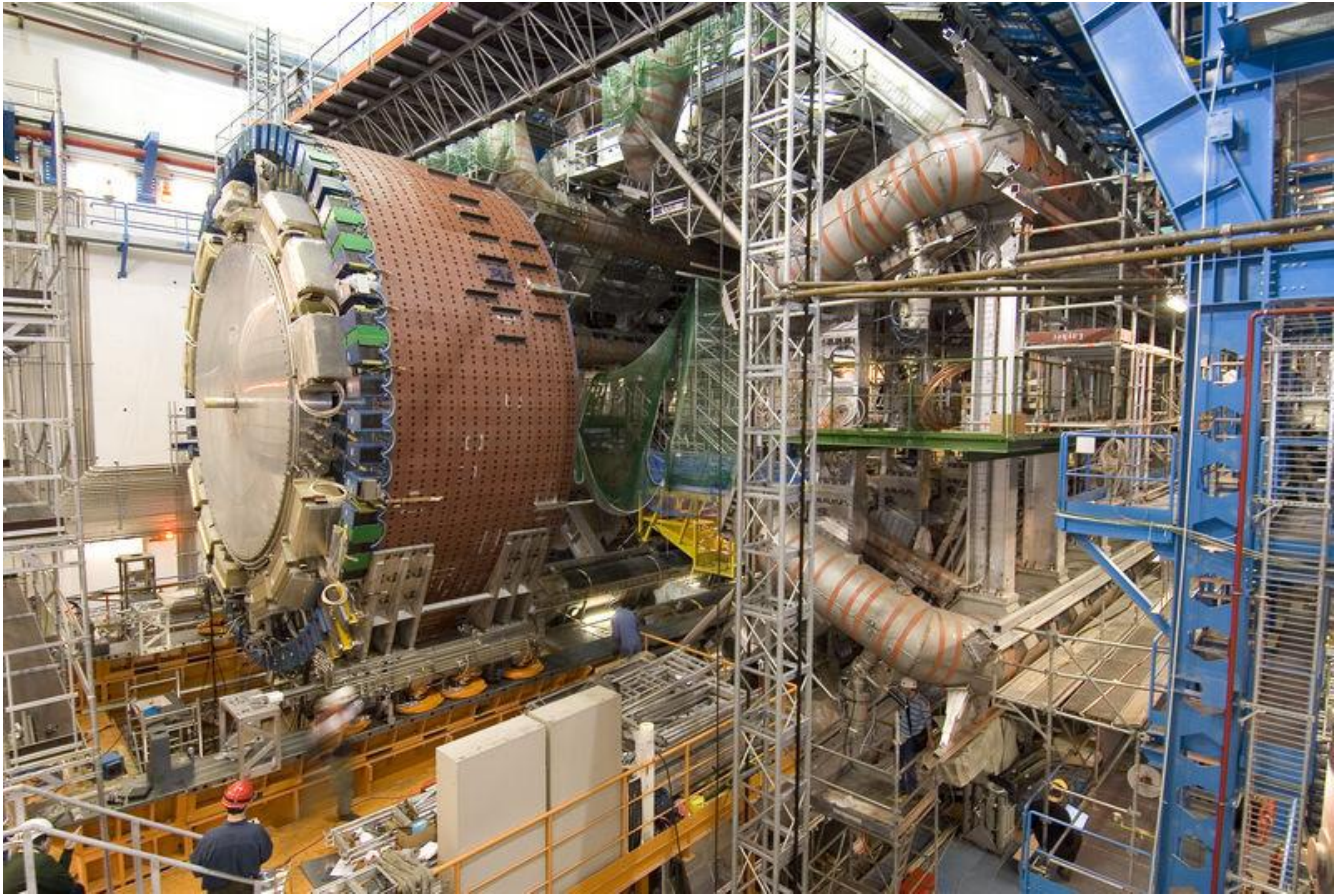


the vast ATLAS cavern

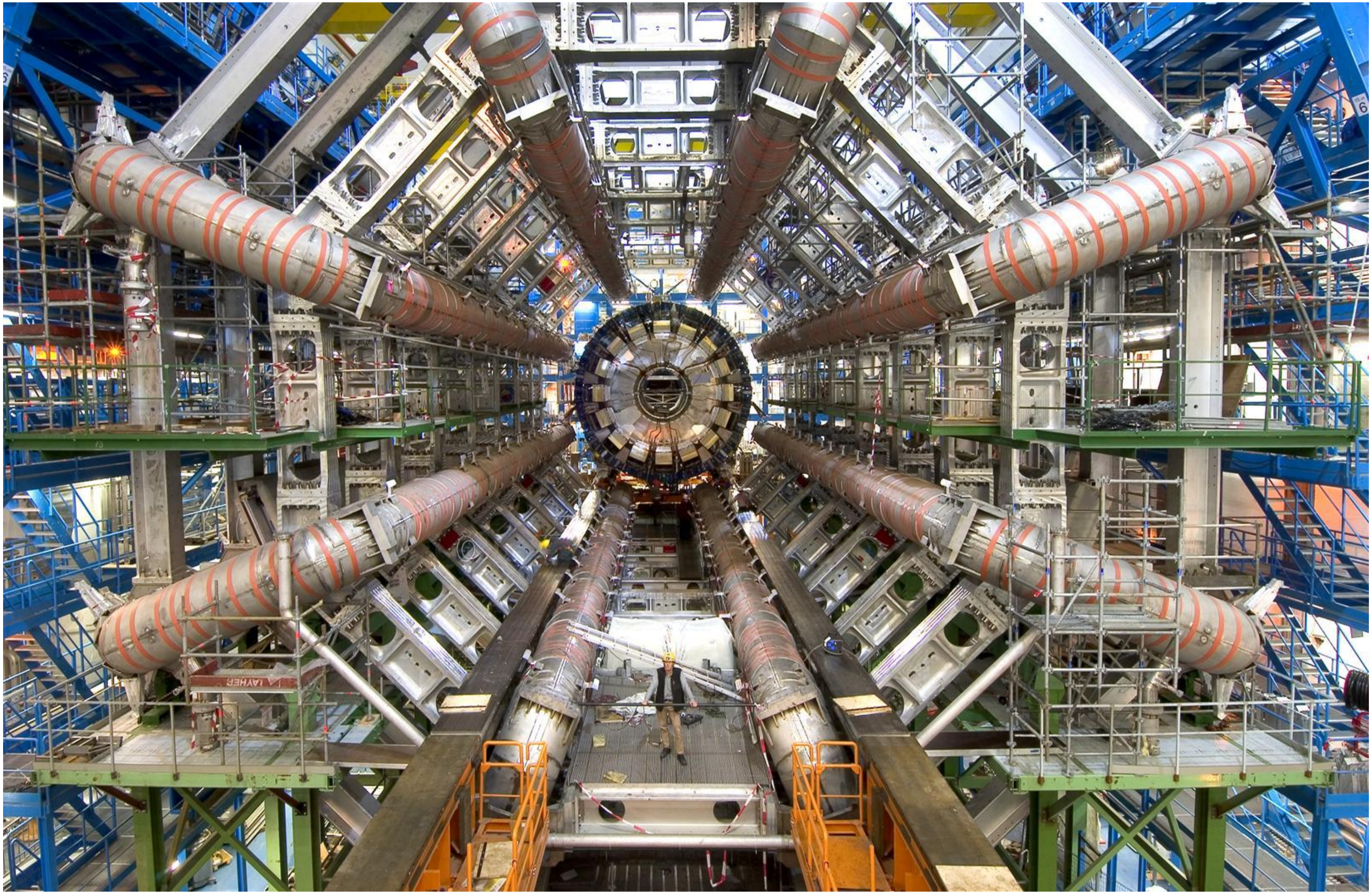
ATLAS – from high up


ATLAS

ATLAS

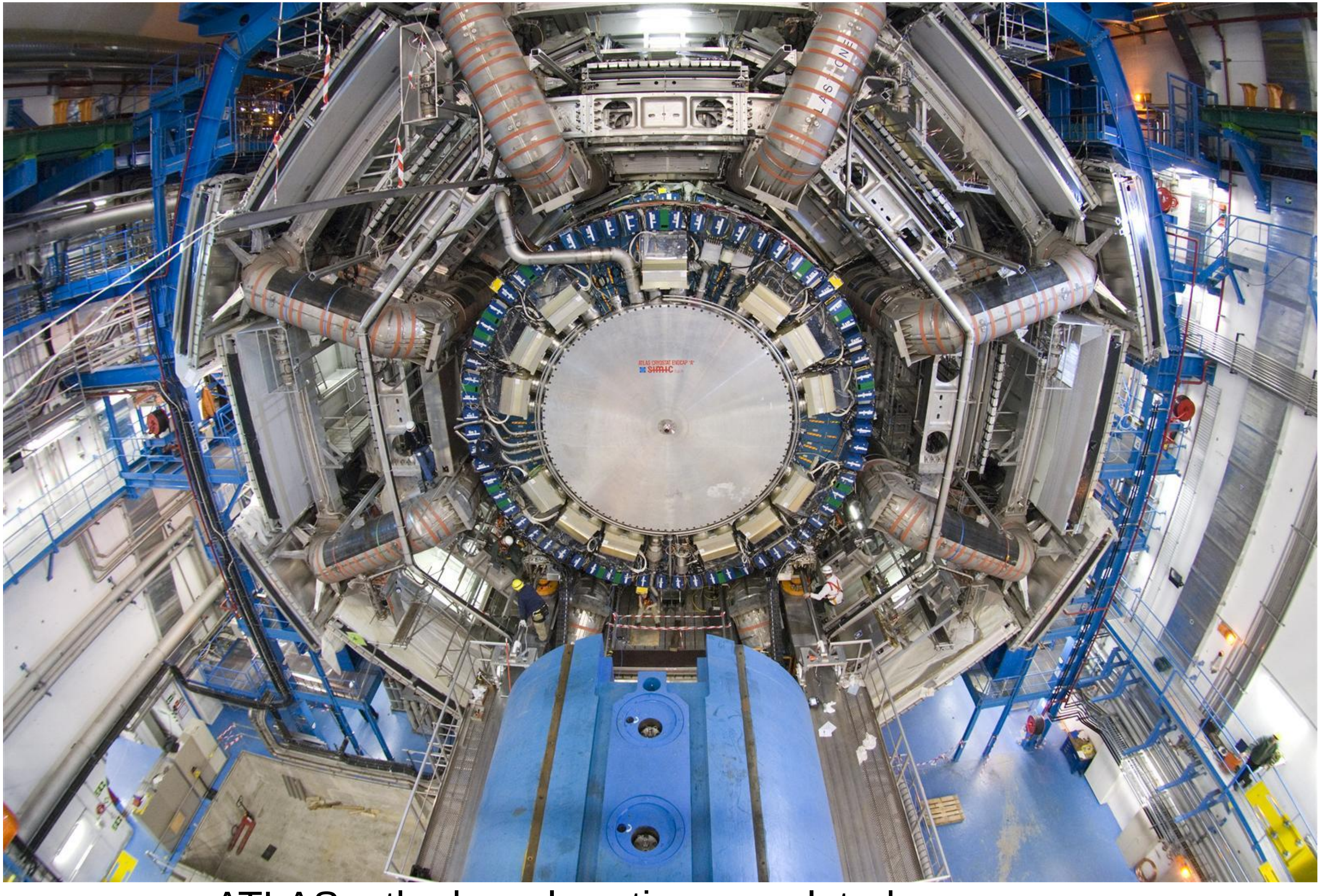


ATLAS – The Toroids



ATLAS – the 8 huge Toroidal magnets in place

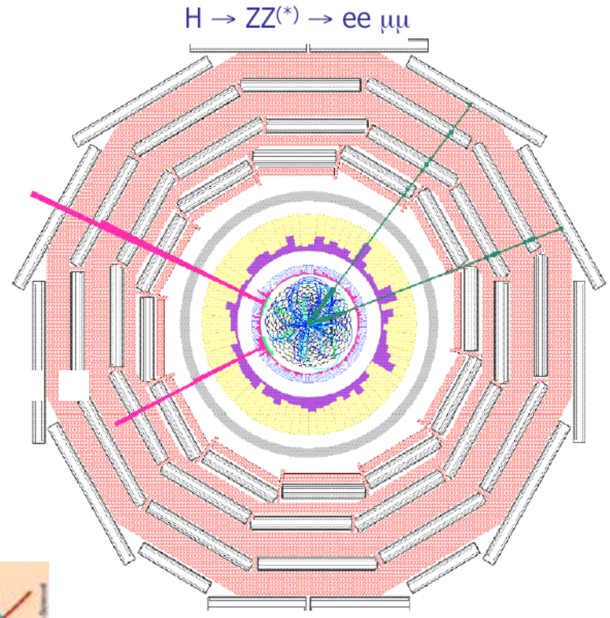
ATLAS – barrel complete

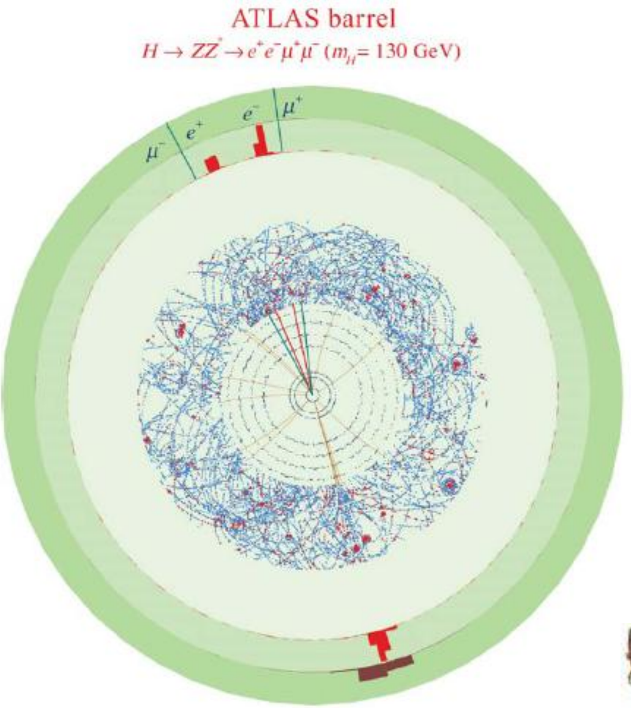


ATLAS – the barrel section completed

Some slides are from a presentation at CMS Italia, Bari 2008 (C. Botta –N. De Filippis)

SM Higgs @ CMS
vs
SM Higgs @ ATLAS





Detection strategies: CMS vs ATLAS

"No particle of interest should escape unseen"

Need to absorbe energy of 1 TeV electrons (30 X_0 or 18 cm Pb), of 1 TeV pions (11λ or 2m Fe)
Particle are produced over all the solid angle, need to limitate crack in acceptance. ($|\eta| < 2.5$)
Efficient identification in addiction to excellent purity of muons, electrons, photons arising from the hard scattering are as important as the accuracy with which their four-momenta can be determined
(for pt 40 GeV the electron/jet ratio decrease from 10^{-3} to 10^{-5} from Tevatron to LHC)

Different answers to these needs by the 2 collaborations expecially in the choice of the magnet system which has shaped the experiment in a major way

ATLAS e CMS chose different way to maximize the factor BL^2 determining the resolution on the momentum of the muons (goal: 10% for 1TeV muon)

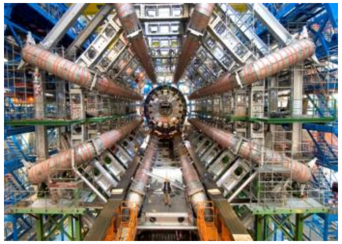
Different design concepts

THE MAGNET SYSTEM

Parameter	CMS Solenoid	ATLAS Solenoid	ATLAS Barrel toroid	ATLAS End-cap toroids
Inner diameter	5.9 m	2.4 m	9.4 m	1.7 m
Outer diameter	6.5 m	2.6 m	20.1 m	10.7 m
Axial length	12.9 m	5.3 m	25.3 m	5.0 m
Number of coils	1	1	8	8
Number of turns per coil	2168	1173	120	116
Conductor size (mm^2)	64×22	30×4.25	57×12	41×12
Bending power	$4\ T \cdot m$	$2\ T \cdot m$	$3\ T \cdot m$	$6\ T \cdot m$
Current	19.5 kA	7.7 kA	20.5 kA	20.0 kA
Stored energy	2700 MJ	38 MJ	1080 MJ	206 MJ

THE CMS CHOICE:

one magnet for high magnet field in the tracker volume and high enough return flux for muon momentum measurement.



THE ATLAS CHOICE:

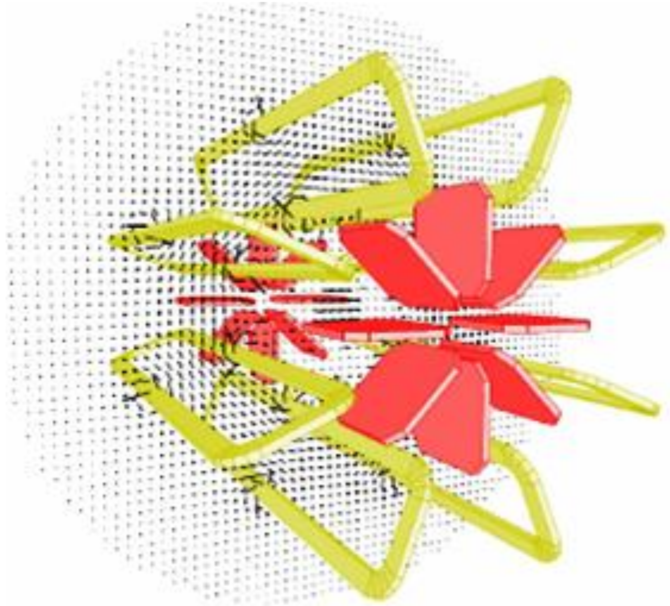
-small-radius thin-wallet superconducting solenoid integrated into the cryostat of the barrel ECAL that provide a 2T field

-Barrel Toroid: 8 flat superconducting race-track coils, each 25 metres long and 5 metres wide, grouped in a torus shape. The 8 coils in the torus are kept by 16 support rings.

-Two EndcapToroid positioned inside the Barrel Toroid at both ends of the Solenoid, provide the required high magnetic field across a radial span of 1.5 to 5 metres.

Different design concepts

THE MAGNET SYSTEM (2)



ATLAS PROS: the muon spectrometer provides indipendent and high accuracy measurement of muons over full coverage ($|\eta| < 2.7$)

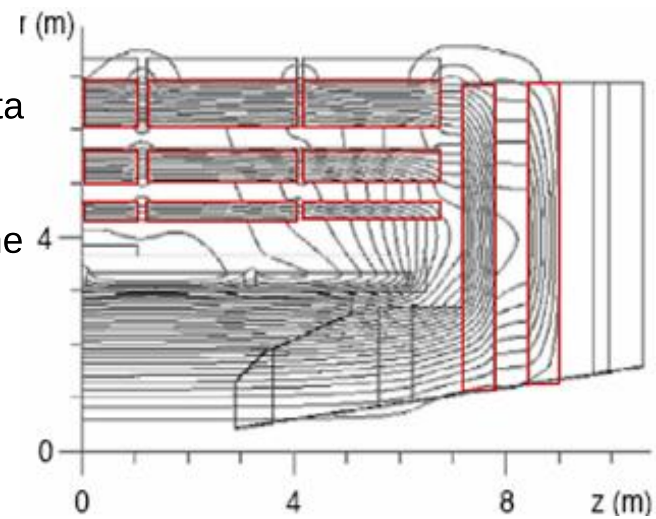
ATLAS CONS: not uniform field in the limits of the tracker volume (because of the lenght of the solenoid)

ATLAS CONS: the position of the solenoid in front of the barrel ECAL limited in some extent the energy resolution in the region $1.2 < |\eta| < 1.5$

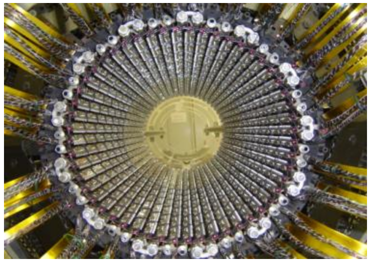
CMS PROS: the higher field strenght and uniformity of CMS solenoid provide better momentum resolution and better uniformity over the full eta coverage

CMS CONS: the position of the solenoid outside the calorimeter limits the number of interaction lenghts to absorbe hadronic shower for $|\eta| < 1$

CMS CONS: the muon spectrometer system has limited stand-alone measurement capabilities (problem for triggering with the LHC upgrade)

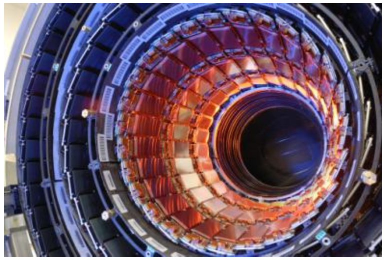


Different design concepts



THE TRACKING SYSTEM

For robust and redundant pattern recognition / High level trigger capabilities for e, μ, tau and b-jets / secondary vertices and impact parameters/ electrons Id by matching cluster and tracks…



Same geometrical coverage (over $|\eta| < 2.4 - 2.5$)

Similar near the interaction vertex but differ in technological choices at larger radii

- **small radii: PIXEL DETECTOR-> 3 hits, pixel size ($(\mu m) R\varphi \times (\mu m) z$) = 50x400 (ATLAS) /100x150 (CMS)**
- **intermediate radii: SILICON STRIP ($\approx 300\,\mu m$, pitch $80 - 120\,\mu m$). SCT (ATLAS) -> 8 hits (30- 60 cm) / TIB,TID and first rings of the TEC (CMS) -> 6 hits (20-55 cm)**
- **outer radii: (CMS) silicon strip technology with TOB and TEC->8 hits (55-107 cm) ($\approx 300\,\mu m$, pitch $120 - 180\,\mu m$). (ATLAS) TRT (56-107) cm (set of 4 mm in diameter straw-tube detectors operating at room temperature)**

similar inner and outer dimensions (107 cm (ATLAS) – 110 cm (CMS))

serious problem of the material budget that increased during the years ((CMS) it reaches 1.8 X_0 at $\eta \approx 1.7$)

Different design concepts

THE TRACKING SYSTEM (2)

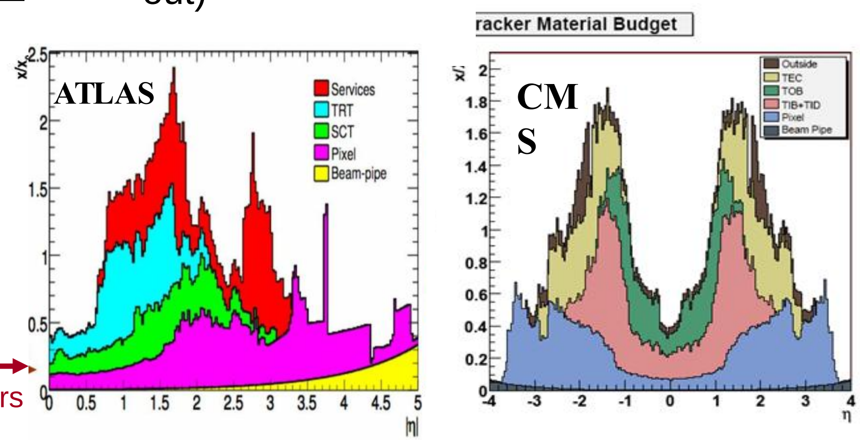
	ATLAS	CMS
Reconstruction efficiency for muons with $p_T = 1$ GeV	96.8%	97.0%
Reconstruction efficiency for pions with $p_T = 1$ GeV	84.0%	80.0%
Reconstruction efficiency for electrons with $p_T = 5$ GeV	90.0%	85.0%
Momentum resolution at $p_T = 1$ GeV and $\eta \approx 0$	1.3%	0.7%
Momentum resolution at $p_T = 1$ GeV and $\eta \approx 2.5$	2.0%	2.0%
Momentum resolution at $p_T = 100$ GeV and $\eta \approx 0$	3.8%	1.5%
Momentum resolution at $p_T = 100$ GeV and $\eta \approx 2.5$	11%	7%
Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (μm)	75	90
Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (μm)	200	220
Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 0$ (μm)	11	9
Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 2.5$ (μm)	11	11
Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (μm)	150	125
Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (μm)	900	1060
Longitudinal i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 0$ (μm)	90	22–42
Longitudinal i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 2.5$ (μm)	190	70

Performance of CMS tracker is undoubtely superior to that of ATLAS in term of **momentum resolution**
(more uniform and higher field and more accurate measurements at large radii)

Vertexing and b-tagging performance are similar
(the smaller pixel size is counterbalanced by the charge sharing and the analog read-out)

Impact of material and B field is visible on **efficiencies**
(the problem is more visible in CMS because of the higher magnetic field which enhance effect owing to interaction with material)

Lep Detectors

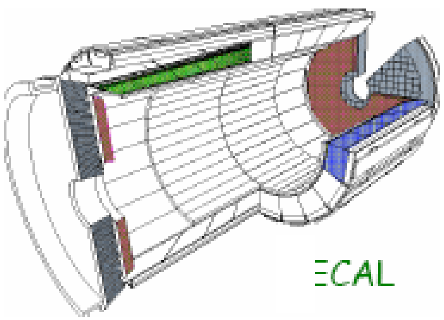


Different design concepts

THE CALORIMETER SYSTEM

Elettromagnetic calorimeter

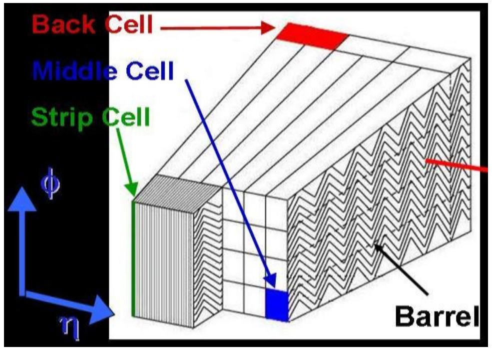
CMS

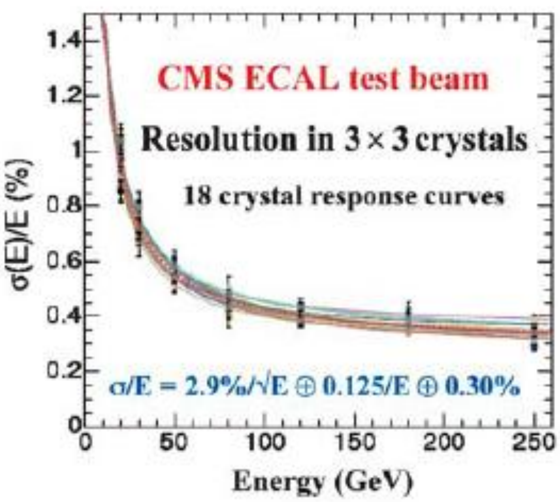


ATLAS uses LAr sampling calorimeter with good energy resolution and excellent lateral and longitudinal segmentation

CMS use PbWO4 scintillating crystals with excellent energy resolution and lateral segmentation but no longitudinal segmentation

ATLAS

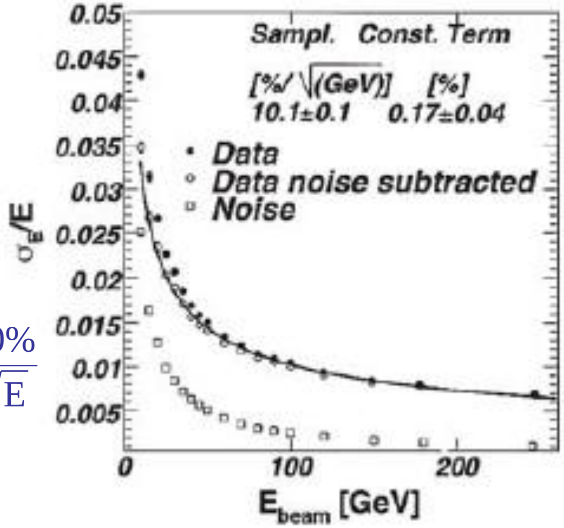




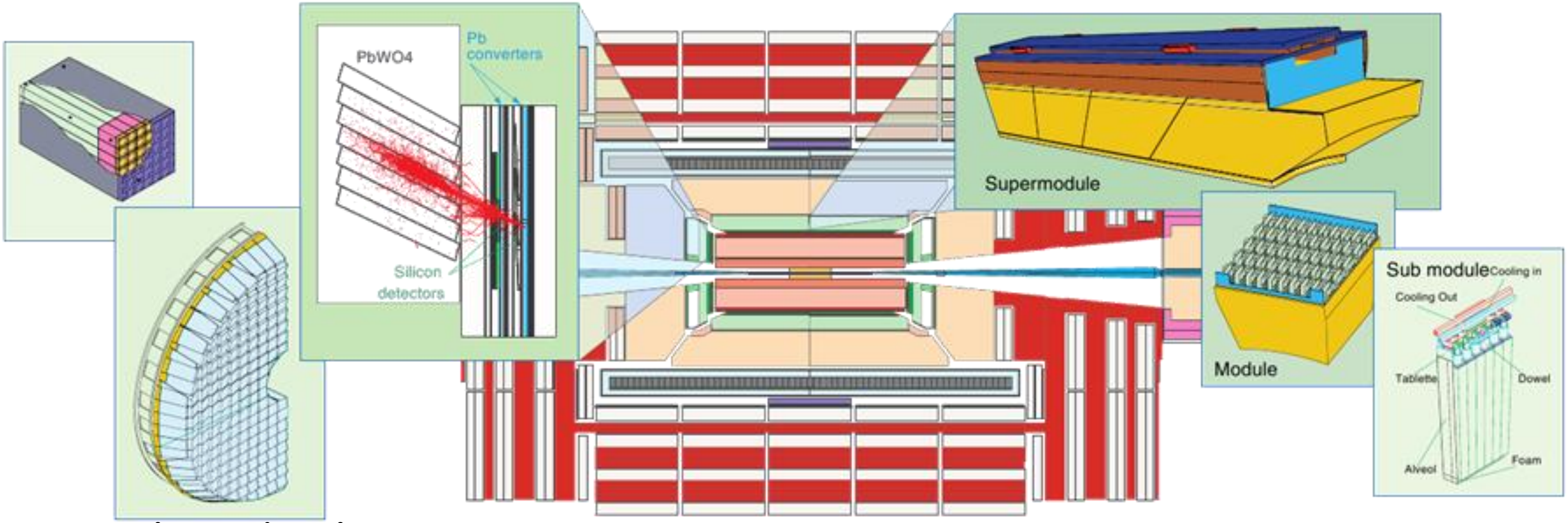
Test beam:
CMS superior intrinsic resolution
ATLAS excellent uniform response

$$\frac{\sigma(E)}{E} \approx \frac{3\text{-}5\%}{\sqrt{E}}$$

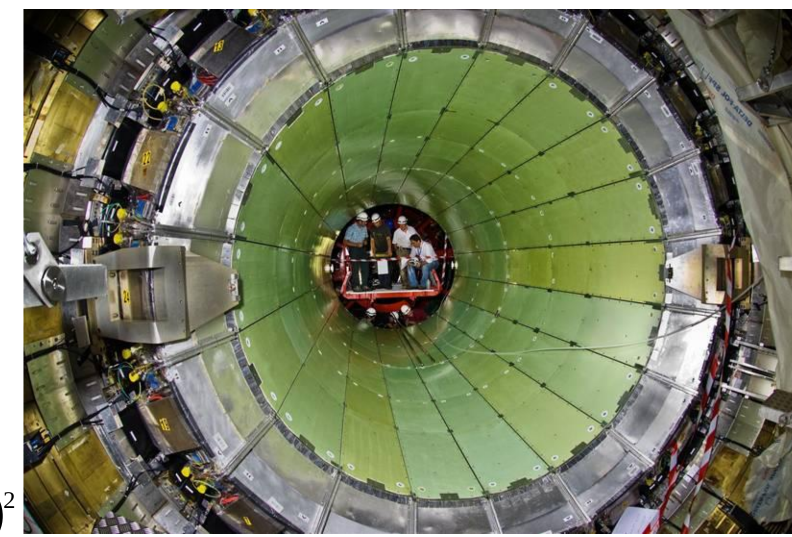
$$\frac{\sigma(E)}{E} \approx \frac{10\%}{\sqrt{E}}$$



Electromagnetic Calorimeter



- Crystal Technology
  - Lead Tungstate Crystals (~76000)
    - High density (8.2 g/cm^3)
    - Short radiation length (8.9 mm)
    - Small Moliere radius (22 mm)
- High segmentation for precise position measurement
- Acceptance to $|\eta|<3.0$
- Resolution: $\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.83\%}{\sqrt{E}}\right)^2 + \left(\frac{124\,MeV}{E}\right)^2 + (0.26\%)^2$



Different design concepts

THE CALORIMETER SYSTEM

Hadronic calorimeter

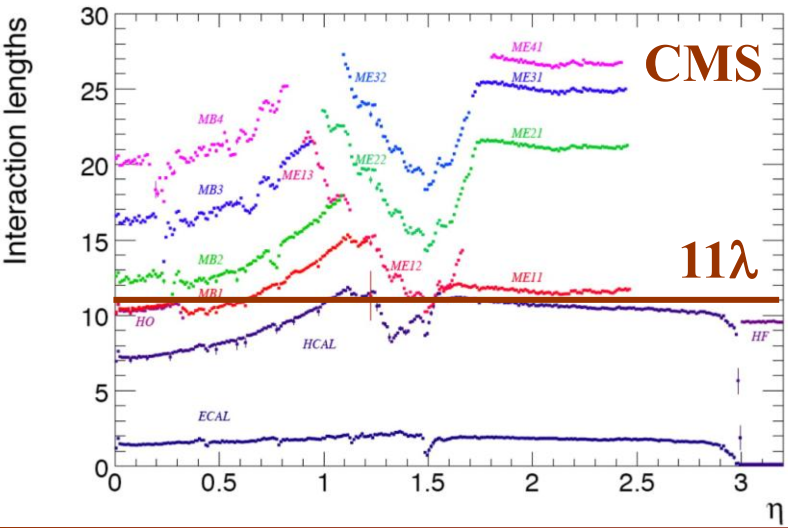
ATLAS: Made by Fe-scintillator (barrel) and Cu-liquid argon (end-caps) for a total of 11 λ_I
relative good energy resolution: $\sigma_E / E \approx 50\% / \sqrt{E/GeV} \oplus 0.03$

CMS: Made of Cu-scintillator with energy resolution

$\sigma_E / E \approx 100\% / \sqrt{E/GeV} \oplus 0.05$

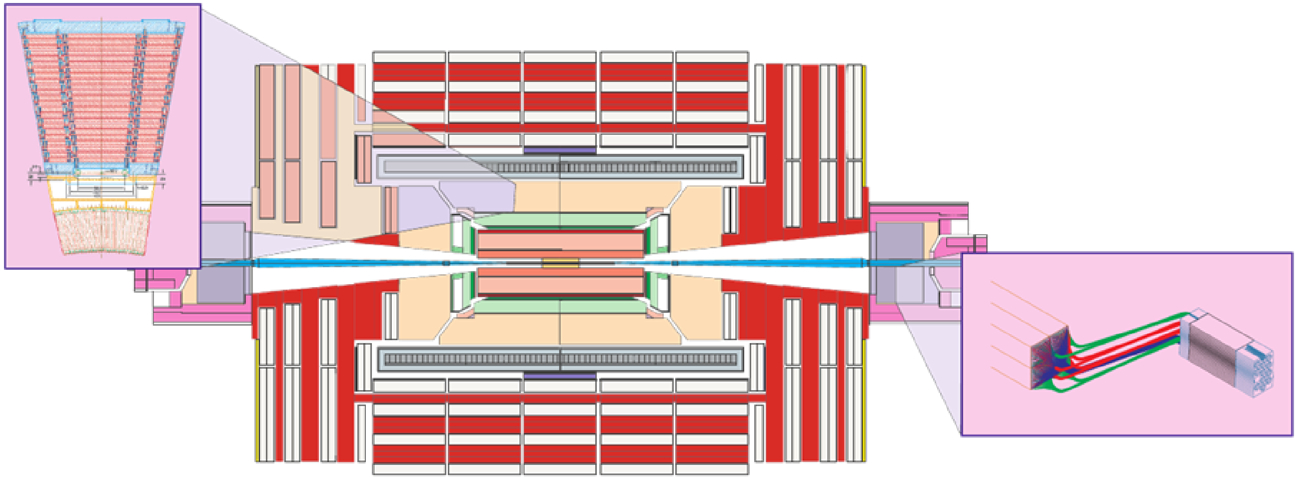
Due to the constrain of beeing inside the magnet is not long enough -> HO $(7.2\lambda_I (\eta \cong 0))$

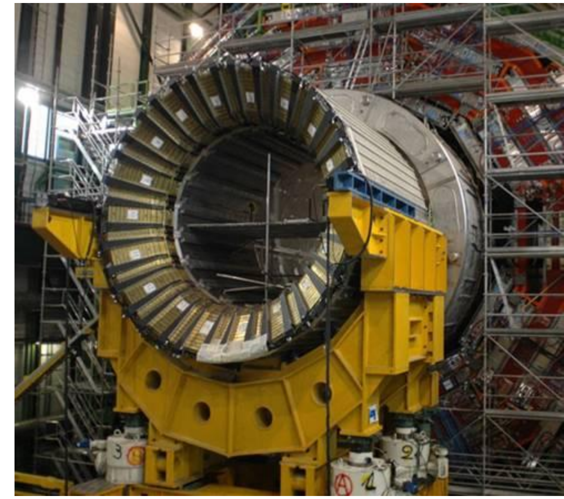
→ CMS Sampling fraction 3 time worse than ATLAS
(fraction of ionizing energy deposited in active medium for MIP)



	ATLAS	CMS
Technology		
Barrel/Ext. barrel	14 mm iron/3 mm scint.	50 mm brass/3.7 mm scint.
End caps	25–50 mm copper/8.5 mm LAr	78 mm brass/3.7 mm scint.
Forward	Copper (front) - Tungsten (back)/0.25–0.50 mm LAr	Steel/0.6 mm quartz
Abs. lengths (min.-max.)		
Barrel/Ext. barrel	9.7–13.0	7.2–11.0 10–14 (with coil/HO)
End caps	9.7–12.5	9.0–10.0
Forward	9.5–10.5	9.8

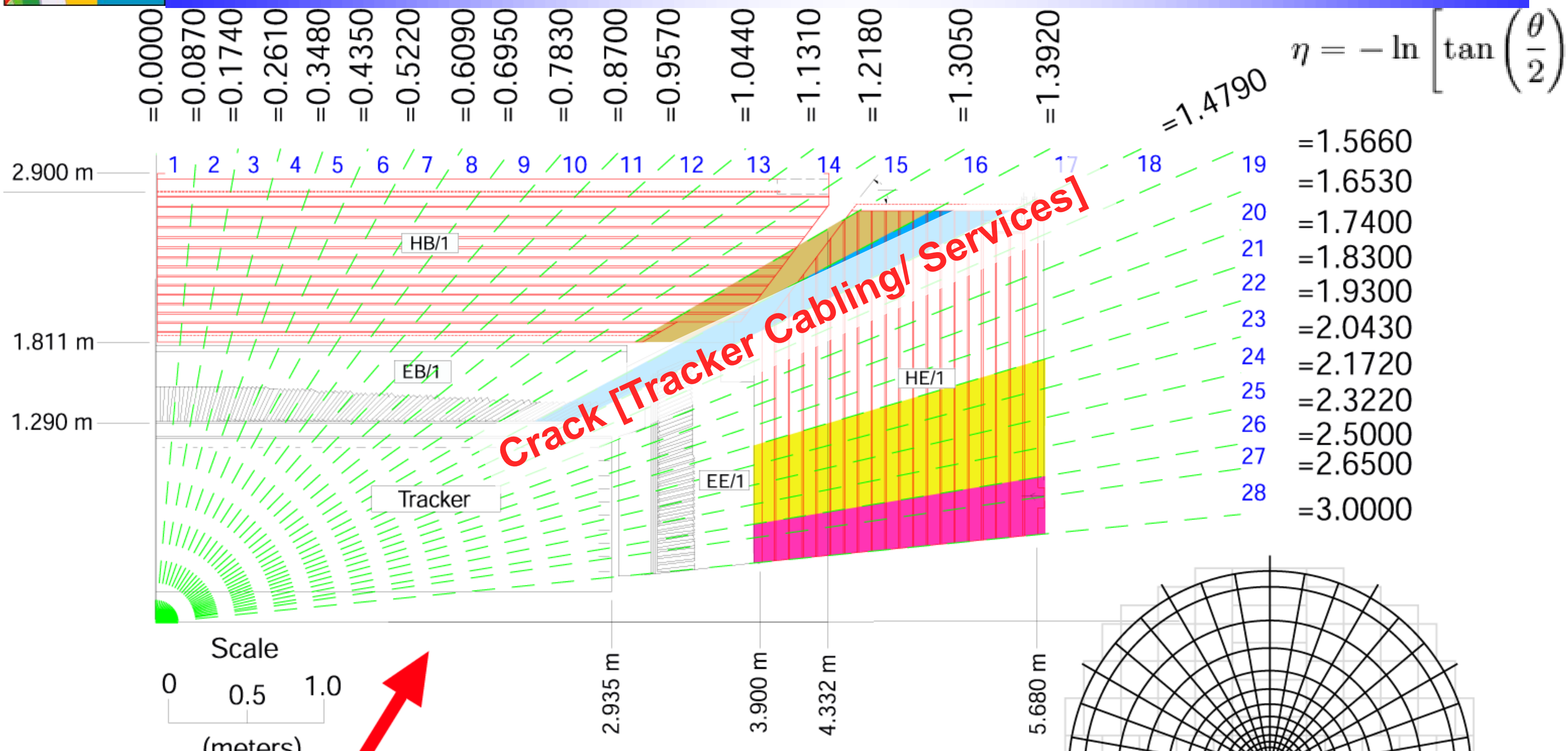
Hadronic Calorimeter



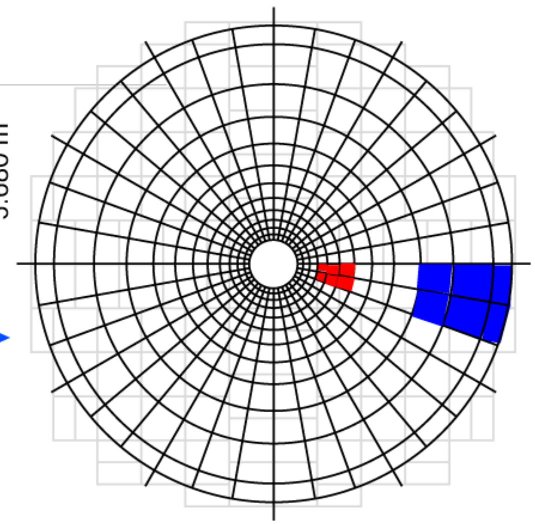


- Barrel and Endcap part ($|\eta|<3$)
  - Brass / Scintillation layers Resolution: $\left(\frac{\sigma}{\mathrm{E}}\right)^2 = \left(\frac{115\%}{\sqrt{E}}\right)^2 + (5.5\%)^2$
- Forward Region ($3<|\eta|<5$)
  - Steel plates / Quartz fibers Resolution: $\left(\frac{\sigma}{\mathrm{E}}\right)^2 = \left(\frac{280\%}{\sqrt{E}}\right)^2 + (11\%)^2$
- Absorber geometry
  - 7 Interaction lengths at $\eta = 0$
  - 11 Interaction lengths at $\eta = 1.3$

Calorimeter Geometry

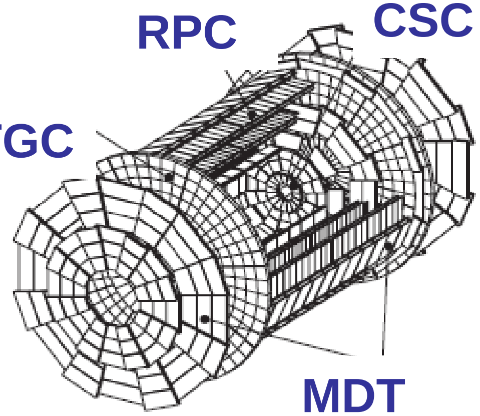


Barrel & Endcap:
E & H: 72 x 56
(|η| < 3.0)



Forward:
H only: 18 x 4
(3.0 < |η | < 5.0)

Different design concepts



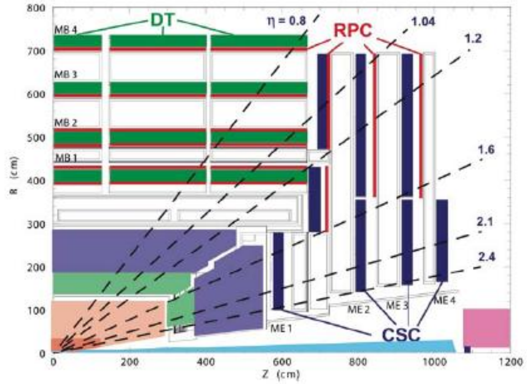
THE MUON SYSTEM

the golden decay $H \rightarrow ZZ \rightarrow 4\mu$ requires a resolution of 1% of the two-muon states

both experiments aim at a 10% momentum resolution for 1TeV muon

wide rapidity region (2/3 of Higgs decay in 4μ have at least one μ with $\eta > 1.4$)

Trigger: ability to measure and select on line μ with pt > 5-10 GeV



ATLAS: $|\eta|<1$: large toroidal magnet with 8 coils , 3 cilyndrical layers of chambers (MDT and RPC)

$1.4<|\eta|<2.7$: muon tracks are bent in two smaller toroidal, 3 wheels (CSC, TGC and MDT)

$1<|\eta|<1.4$: the magnetic fields partially overlap reducing the bending, chamber strategically placed

TRIGGER with RPC e TGC

CMS: chambers installed between the iron slabs that provide the return yoke for the field (big enough to have 4 station in the barrel and 4 perpendicoular disk in the endcap)

TRIGGER with CSC,DT and RPC

Pseudorapidity coverage CMS < 2.5 – ATLAS <2.7

Different design concepts

THE MUON SYSTEM

- ATLAS opted for a high-resolution stand-alone measurement (large volume with low material density)

- The required precision on muon momentum implies an excellent knowledge on the magnetic field (modest in all the region (0.5T) but inhomogeneus → must be measured and monitored with high precision (to 20G))

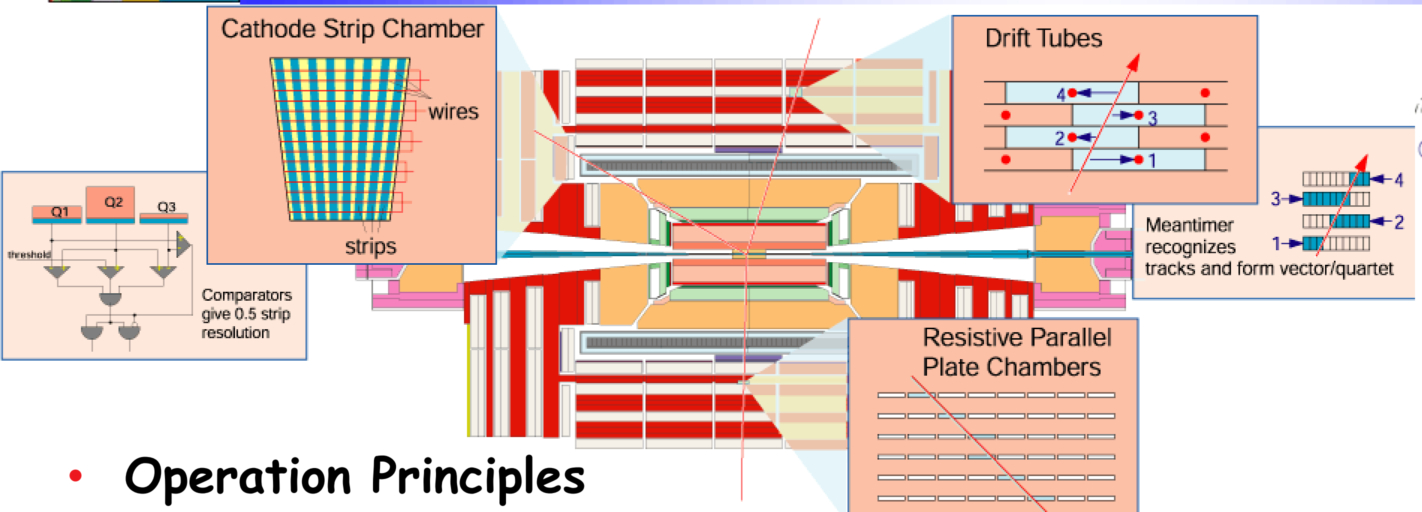
- The high accuracy stand-alone measurements necessitates a high precision on the alignment (30 μm w.r.t 100-500 μm requires by CMS)

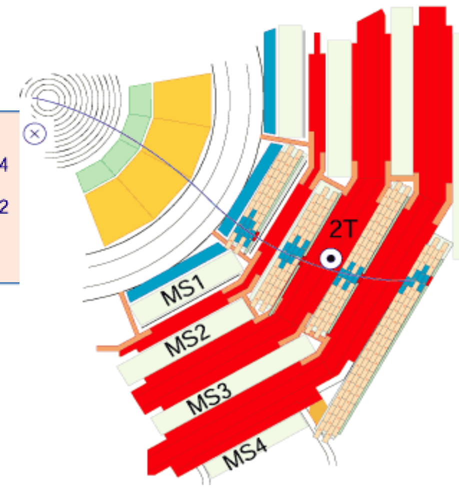
- Finally these measurements relay on a detailed knowledge of the material-distribution in the spectrometer, expecially for reconstructing with high accuracy intermediate-momentum muons without a high fake rate (the corresponding effect in CMS is much smaller)

- The CMS muon system strong point is the effective matching with the tracker. The solenoidal field outside the coil bends the tracks in the transverse plane effectively adding points to tracker track

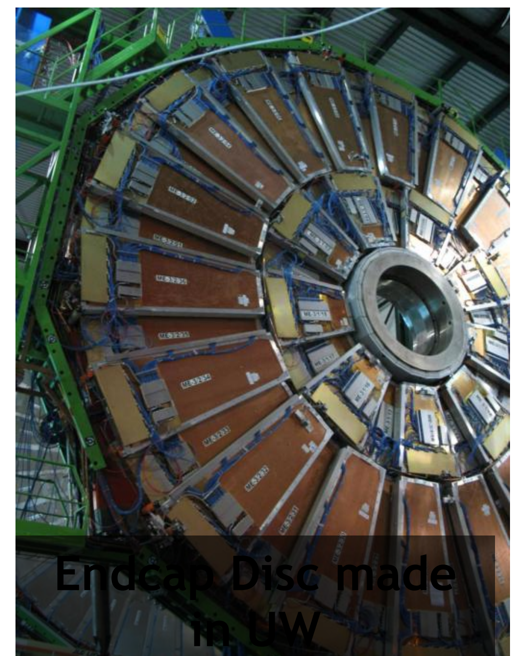
- The limited stand-alone muon resolution of CMS is dominated by MULTIPLE SCATTERING in iron, while in ATLAS by calibration and alignment

Muon System



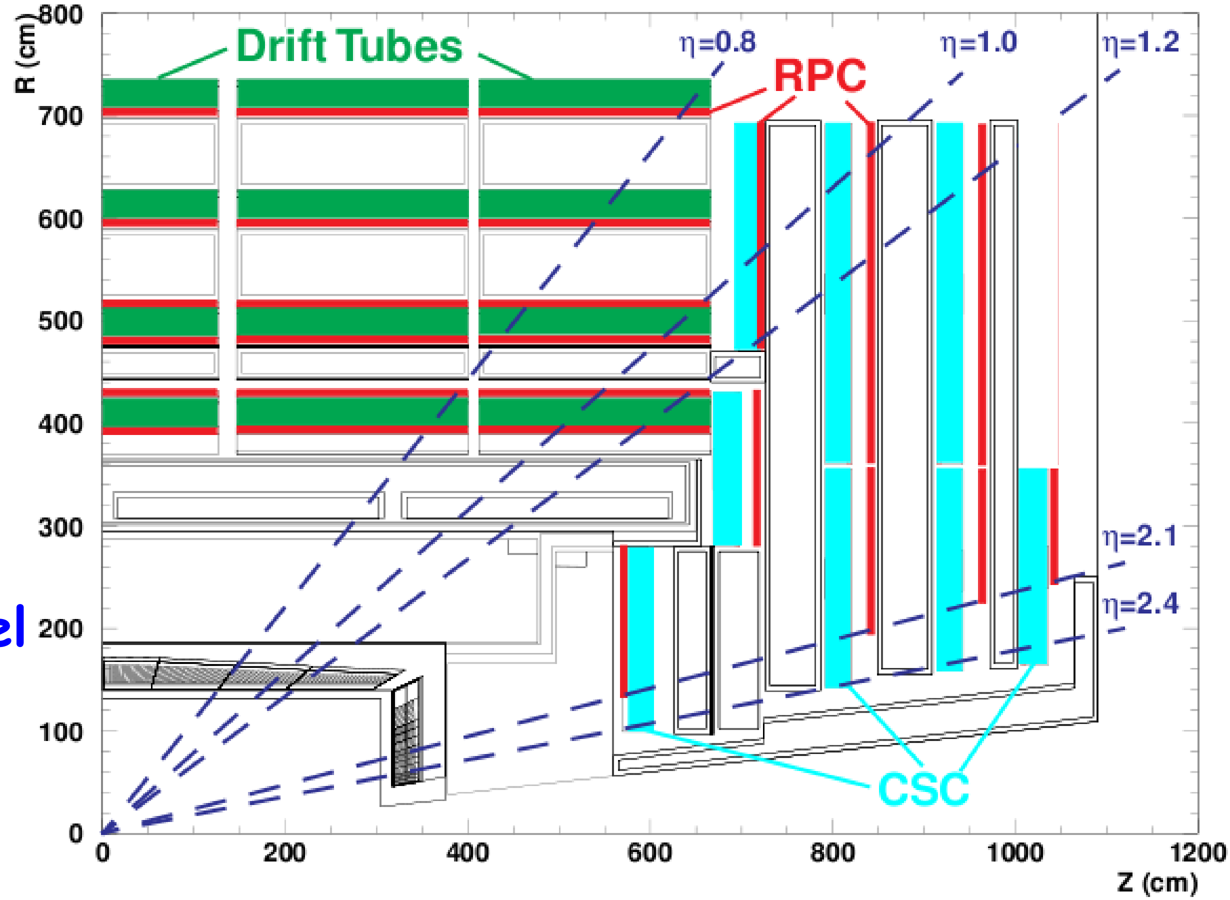


- Operation Principles
  - Muons are identified in Muon System
  - For low P_t muons, P_t is assigned by the tracker
  - For high P_t muons, Muon system contributes to the measurement
  - All muon sub-detectors contribute to the trigger
- Layout
  - Barrel
    - Drift Tube chambers (DT) $|\eta|<1.3$
    - Resistive Plates (RPC) $|\eta|<1.3$
  - Endcap
    - Cathode Strip Chambers (CSC) $0.9<|\eta|<2.4$
    - Resistive Plate Chambers (RPC) $|\eta|<2.1$



Muon Geometry

- Full coverage to $|\eta|<2.4$
  - Overlaps with Tracker Coverage.
- Three main coverage regions
  - $|\eta|<0.8$: Barrel only
  - $0.8<|\eta|<1.3$: Barrel and endcap
  - $1.3<|\eta|<2.4$: Endcap only.

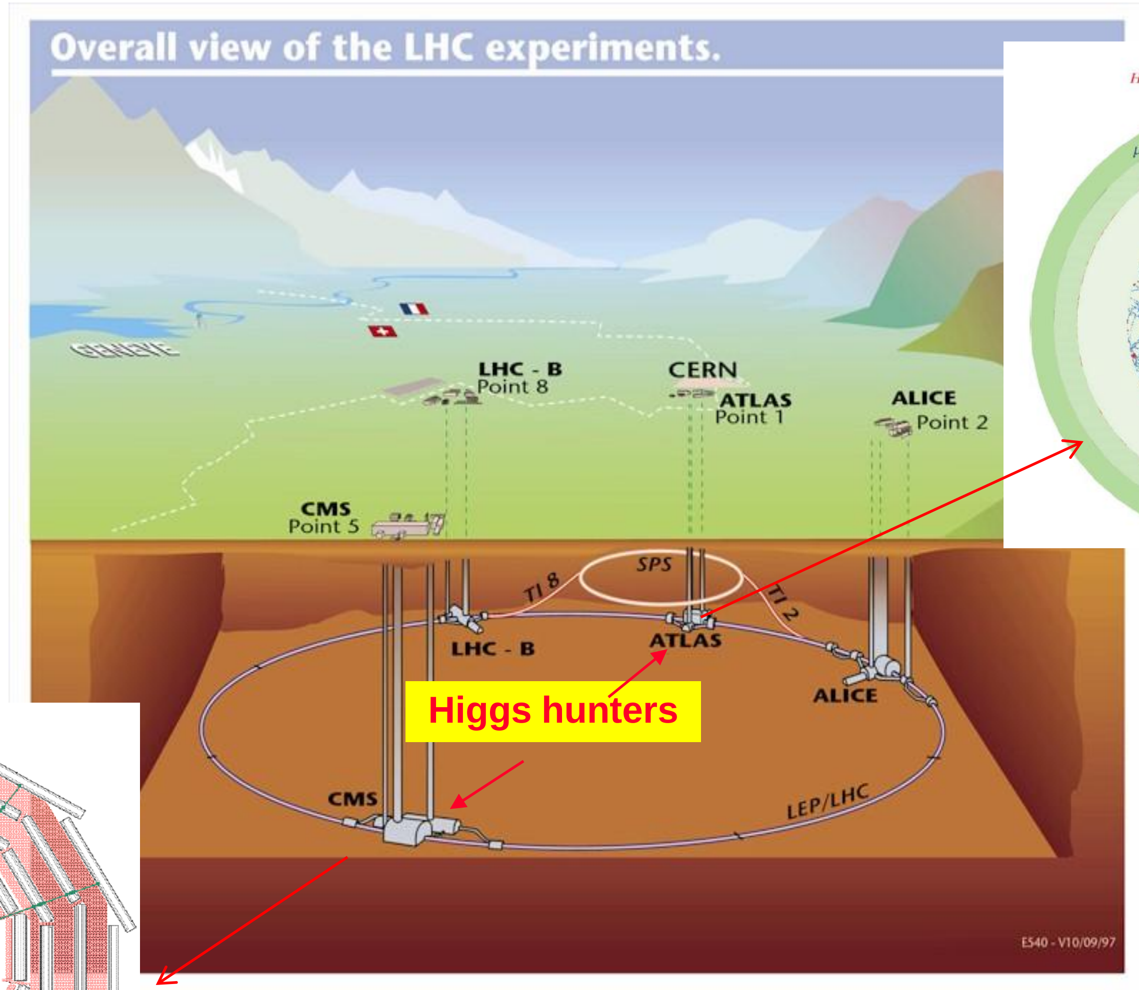


$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

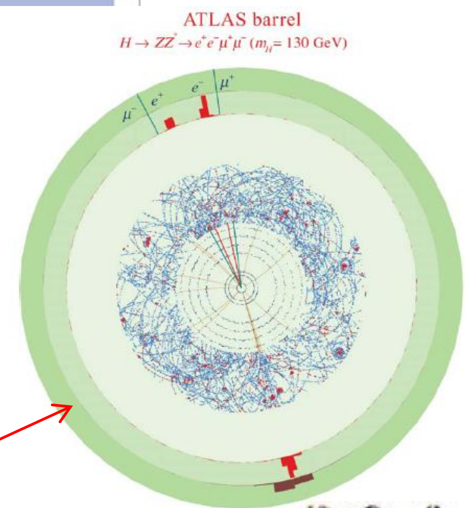
ATLAS vs CMS

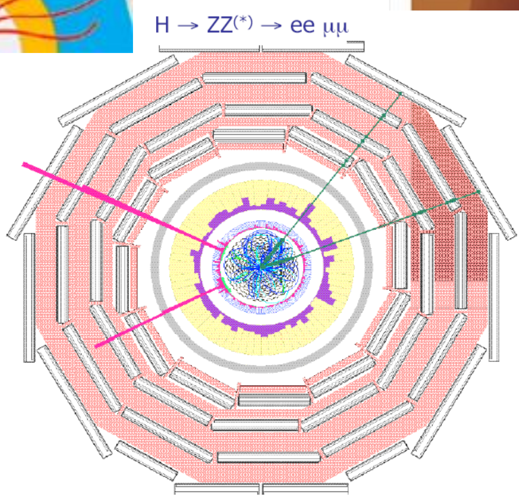
	ATLAS	CMS
Magnetic field	2 T solenoid + toroid (0.5 T barrel 1 T endcap)	4 T solenoid + return yoke
Tracker	Si pixels, strips + TRT $\sigma/p_T \approx 5\times10^{-4} p_T + 0.01$	Si pixels, strips $\sigma/p_T \approx 1.5\times10^{-4} p_T + 0.005$
EM calorimeter	Pb+LAr $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	PbWO4 crystals $\sigma/E \approx 2\text{-}5\%/\sqrt{E} + 0.005$
Hadronic calorimeter	Fe+scint. / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Cu+scintillator (5.8λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
Muon	$\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (ID+MS)	$\sigma/p_T \approx 1\%$ @ 50GeV to 5% @ 1TeV (ID+MS)
Trigger	L1 + RoI-based HLT (L2+EF)	L1+HLT (L2 + L3)

Higgs Hunting at LHC

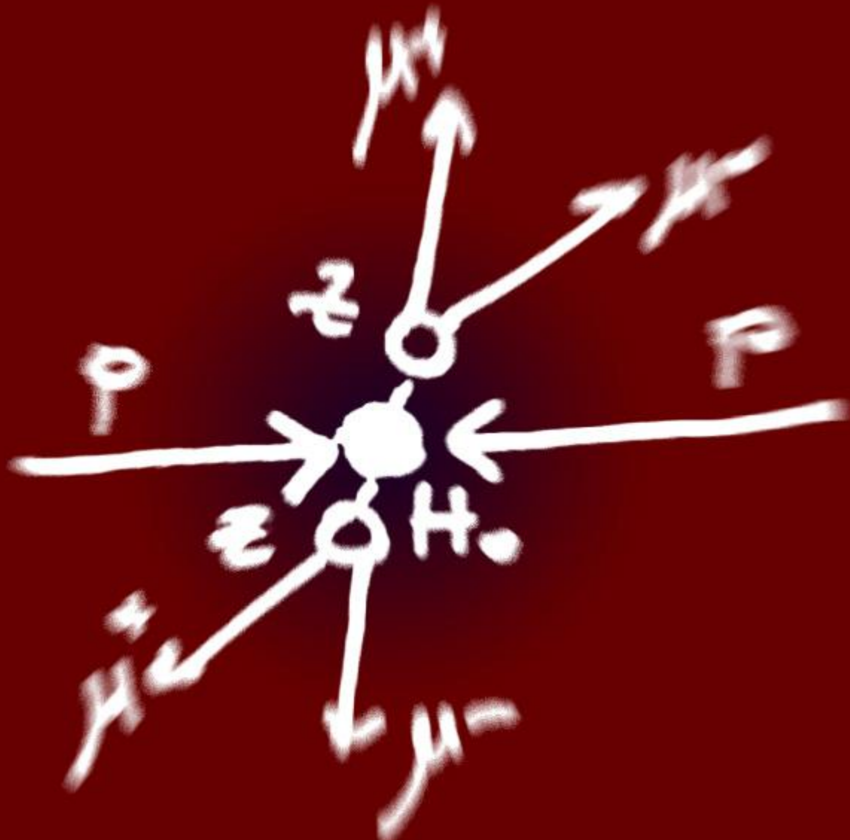


Higgs hunters





Higgs search prospects



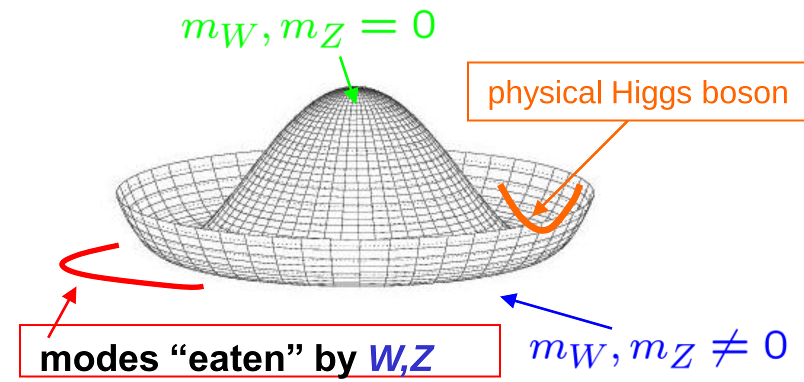
SM Higgs: what we know from theory

One pseudo-scalar doublet Φ (4 degrees of freedom)

Potential $V = \lambda|\Phi|^4 - \mu^2|\Phi|^2$

After spontaneous symmetry breaking:
- **$W^{\pm}$ and Z acquire masses (3 degrees of freedom)**
- **the last remaining degree of freedom (4-3=1):**

scalar CP-even Higgs of unknown mass
$m^2_H = \lambda v^2/3$



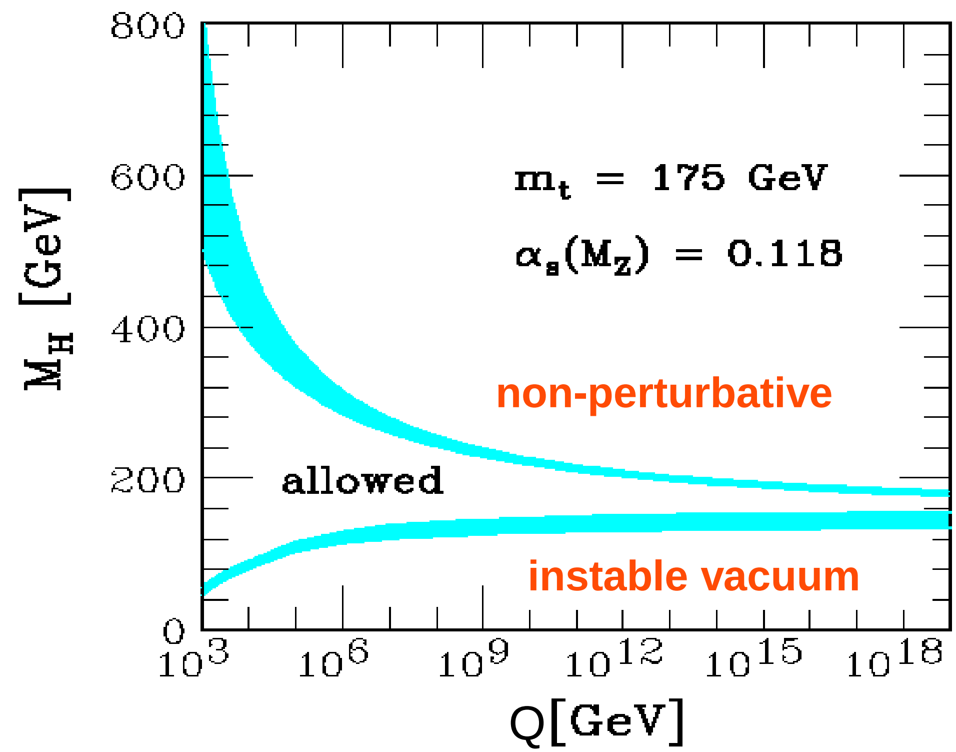
λ, as any other coupling constant, runs up to a scale Q at which the model is not longer valid:
- **small m_H at 1-TeV scale**

at some Q, $\lambda(Q) < 0$ V has no minimum (vacuum breaks loose)
- **large m_H at 1-TeV scale**

at some Q, $\lambda(Q) = \infty$ theory becomes non-perturbative

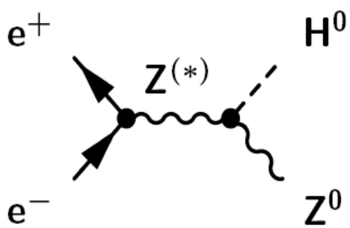
$\rightarrow$ chimney

m_H must be within ~ 50-600 GeV range (if the SM is valid up to Q ~ 1 TeV scale)

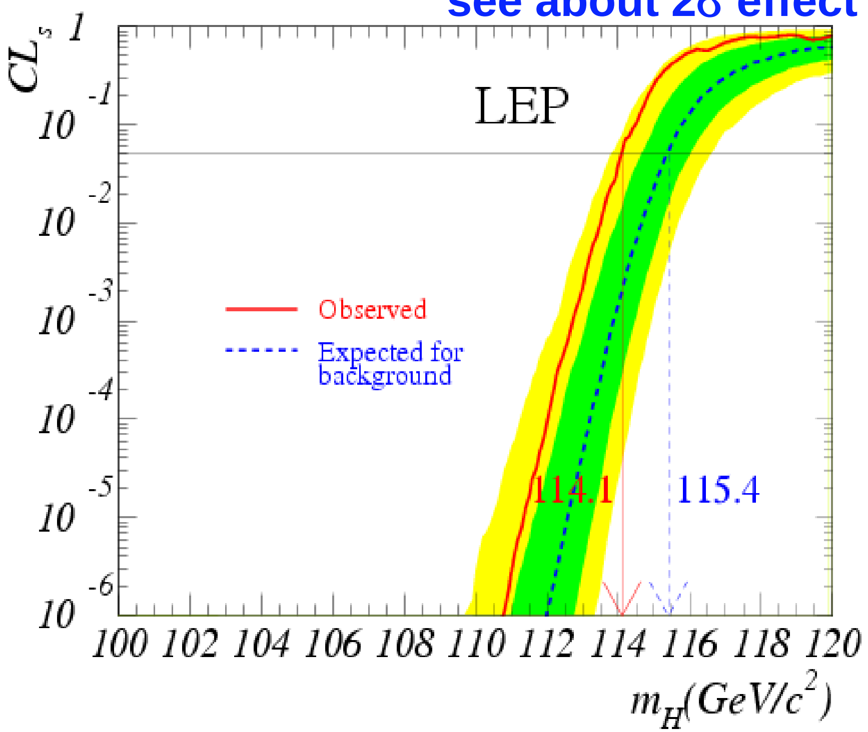


Direct searches at LEP, e^+e^- collisions, (1989-2000)

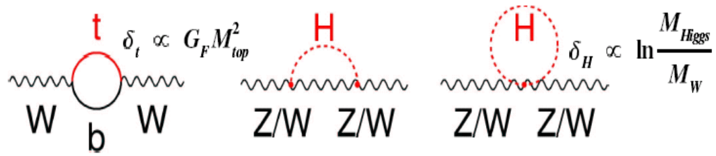
Indirect evidence is driven by radiative corrections



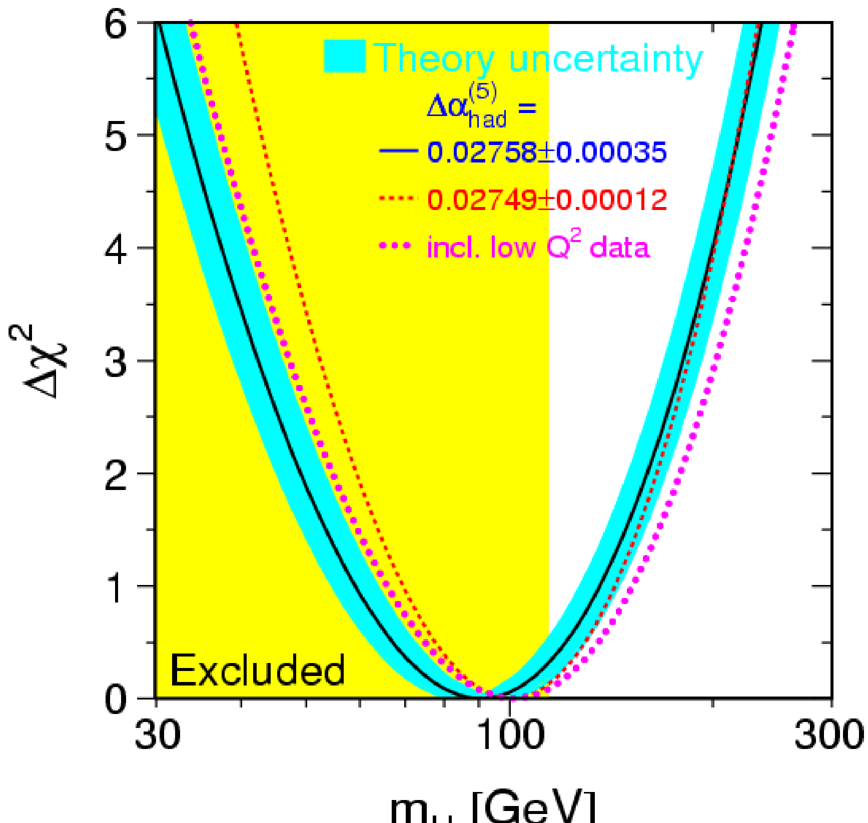
First Hint of Higgs boson with mass 115 GeV observed by ALEPH. LEP experiments together see about 2σ effect



M_H>114.1 GeV @ 95% C.L.

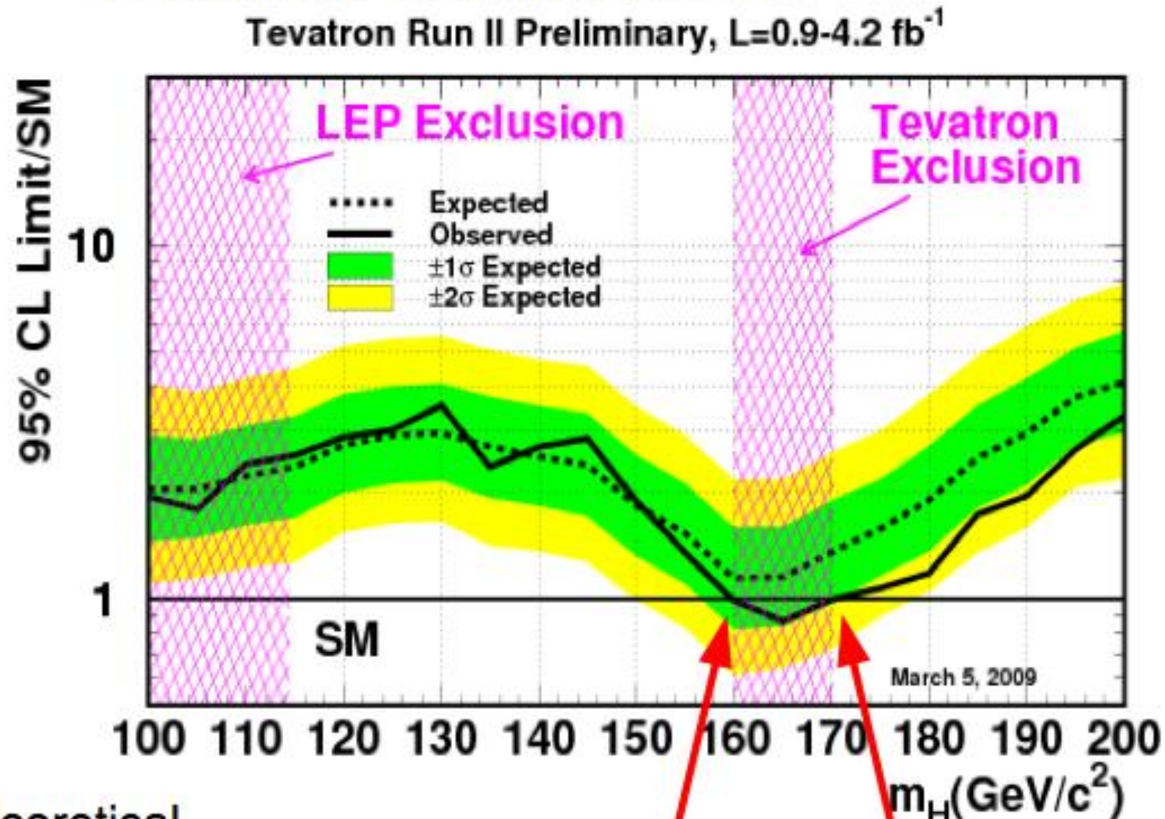


CDF+D0 Top Quark Mass = 172.7 ± 2.9 GeV



$M_H=91^{+45}_{-32}$ <186 GeV @ 95% C.L.

Tevatron Combination

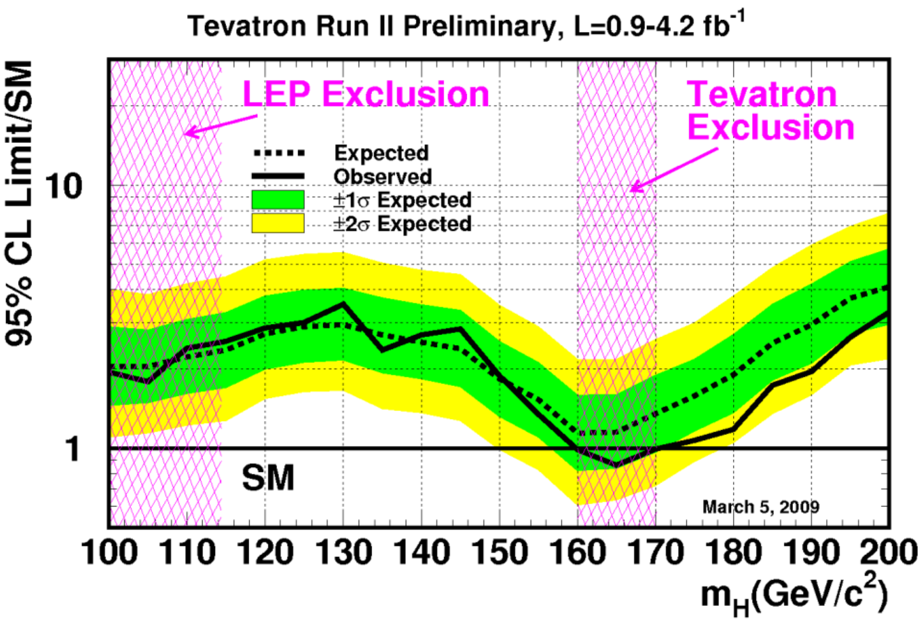


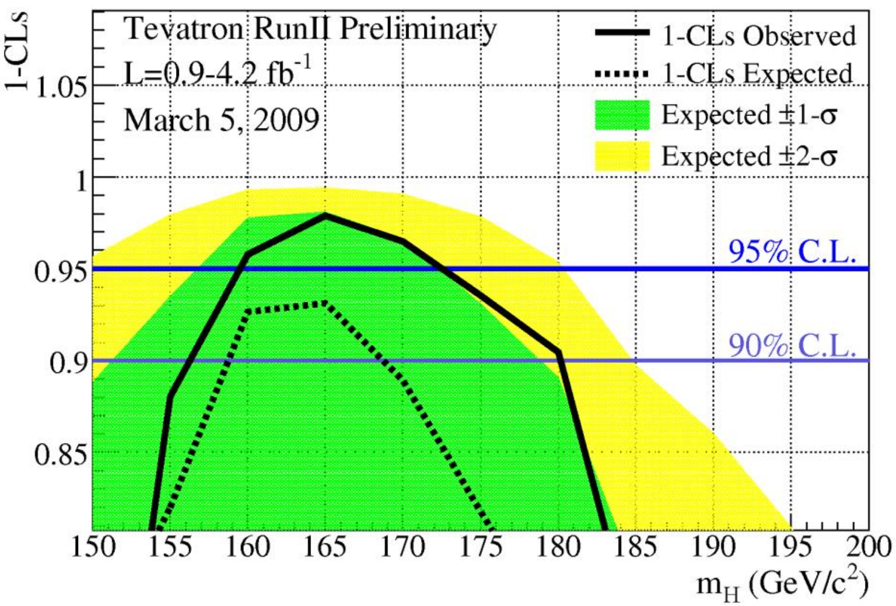
2009 Moriond

Use latest theoretical inputs including: σ(gg→H) by de Florian & Grazzini w/ MSTW 2008 NNLO PDF set

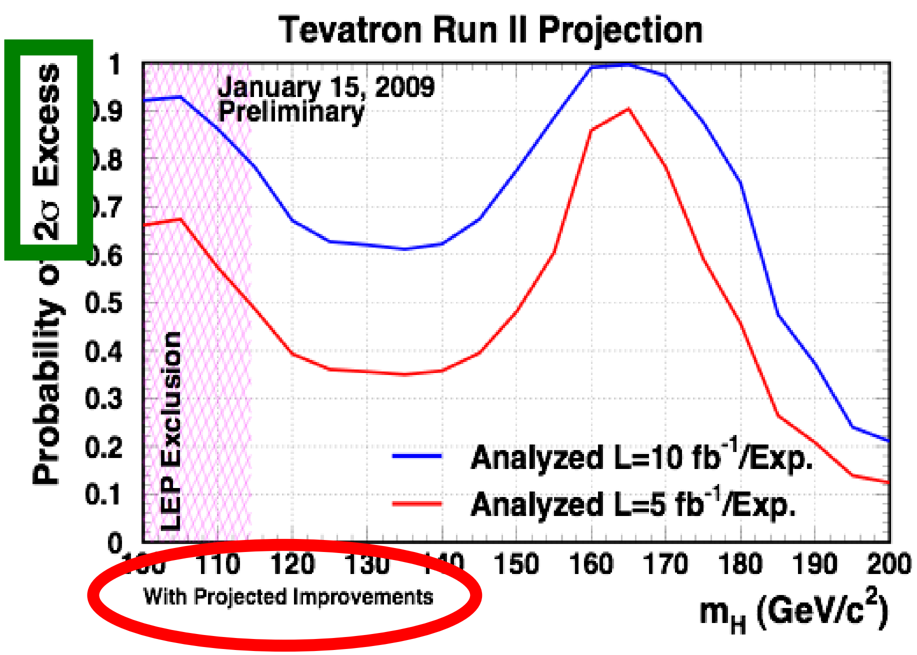
Bayesian	155	160	165	170	175	180	185	190	195	200
Expected	1.5	1.1	1.1	1.4	1.6	1.9	2.2	2.7	3.5	4.2
Observed	1.4	0.99	0.86	0.99	1.1	1.2	1.7	2.0	2.6	3.3
Cls	155	160	165	170	175	180	185	190	195	200
Expected	1.5	1.1	1.1	1.3	1.6	1.8	2.5	3.0	3.5	3.9
Observed	1.3	0.95	0.81	0.92	1.1	1.3	1.9	2.0	2.8	3.3

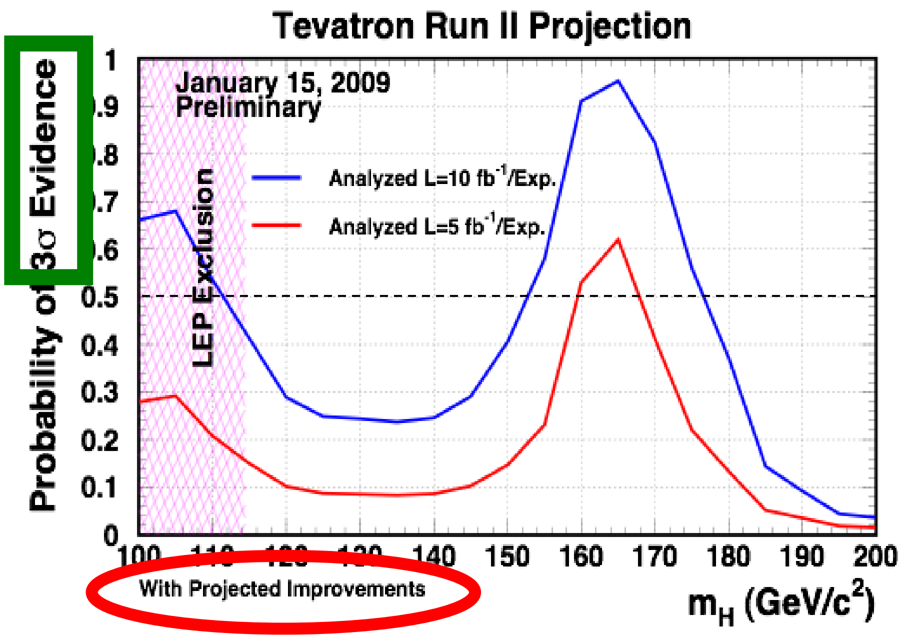
What we know experimentally:
Tevatron CDF & D0 combined (March 2009)





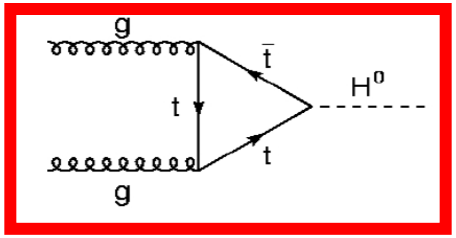
Tevatron exclusion projections



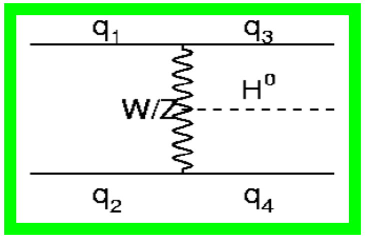


- Improvement factor of 1.5 is assumed (besides plain increase in Lumi)
- Projections do not take into account the current actually observed limits

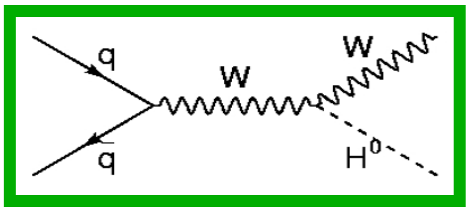
Production cross-section @ √s = 14 TeV



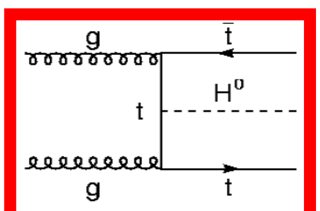
GF H → WW, ZZ , γγ



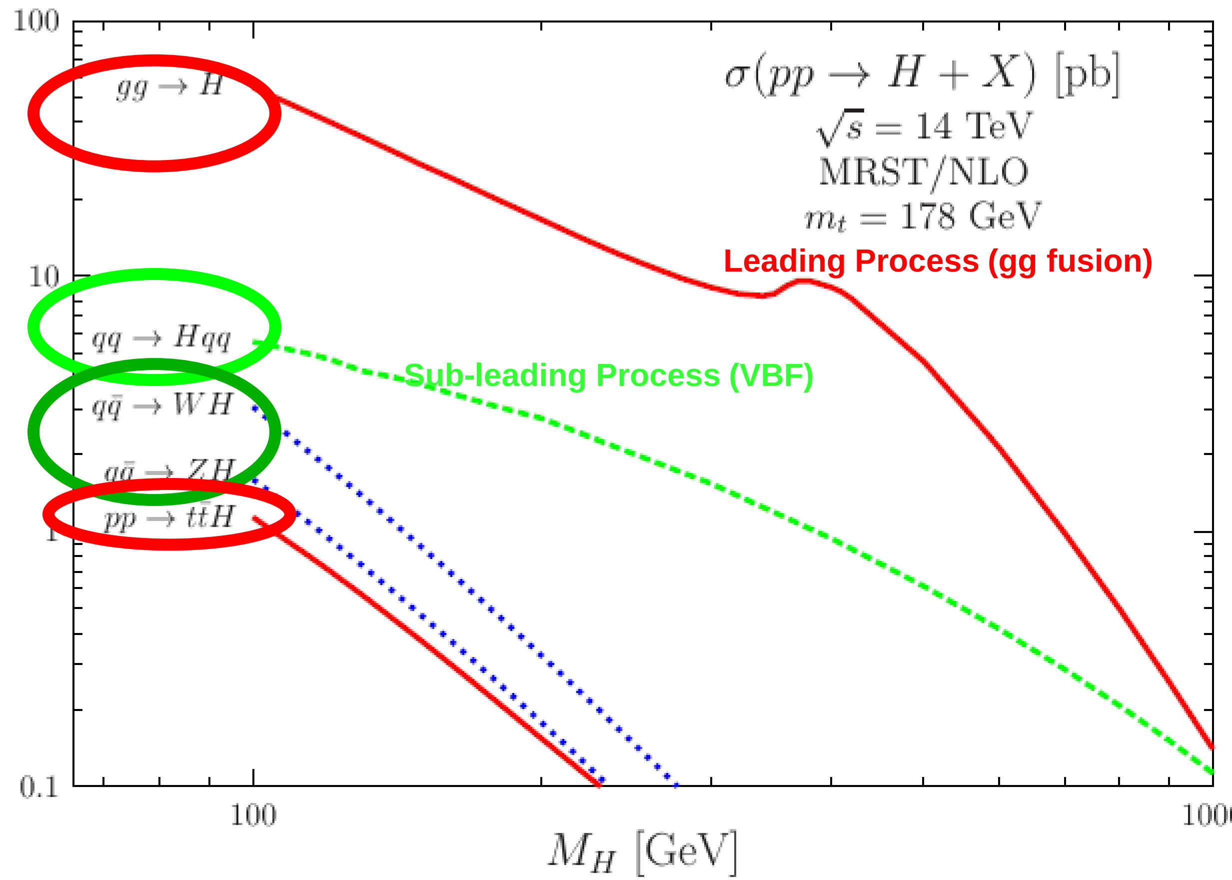
VBF H → WW , γγ , ττ



H → WW, γγ



H → WW, γγ, bb



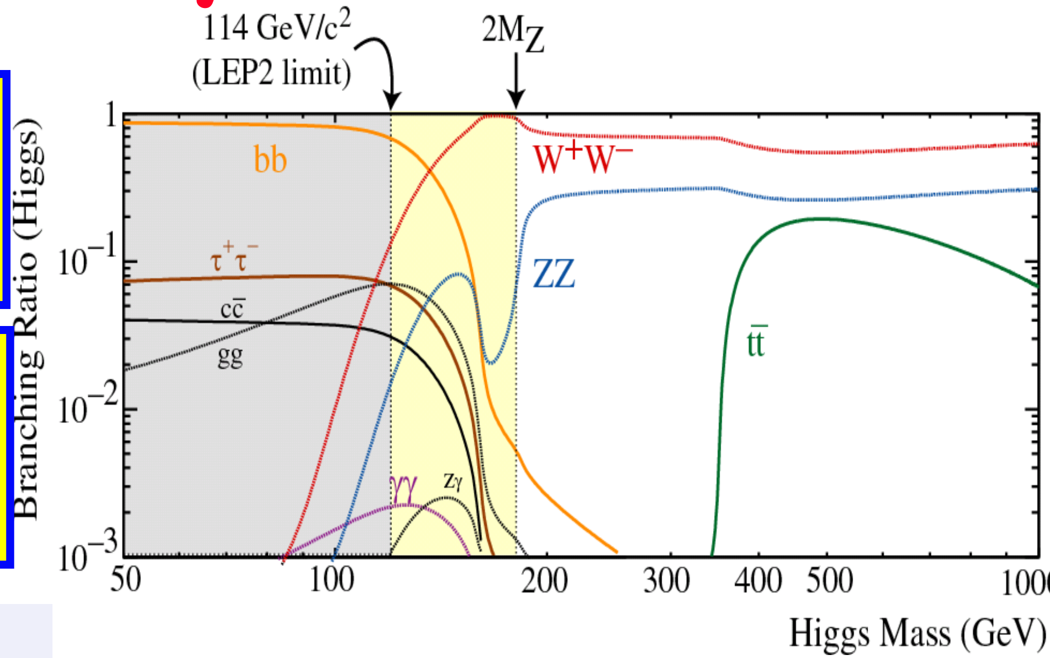
A.Djouadi Phys.Rept.457:1-216

Typical uncertainties on cross-section		
gg	10 %	NNnLO
VBF	5%	NLO
WH,ZH	5%	NNLO
ttH	15%	NLO

Main Decay Modes

Close to LEP limit: $H \rightarrow \gamma\gamma, \tau\tau, bb$

For $M_H > 140$ GeV: $H \rightarrow WW^{(*)}, ZZ^{(*)}$



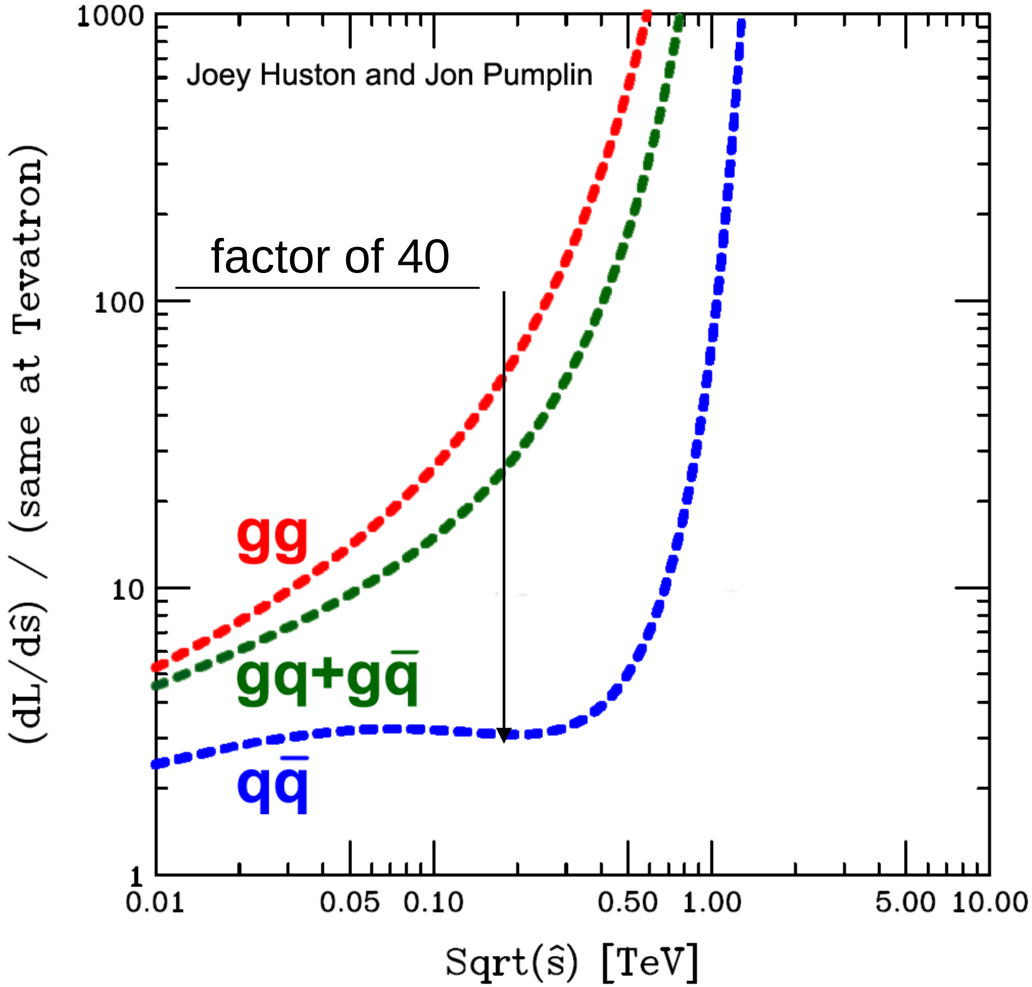
❖ ***At Low mass*** ***($m_H < 2m_Z$)***

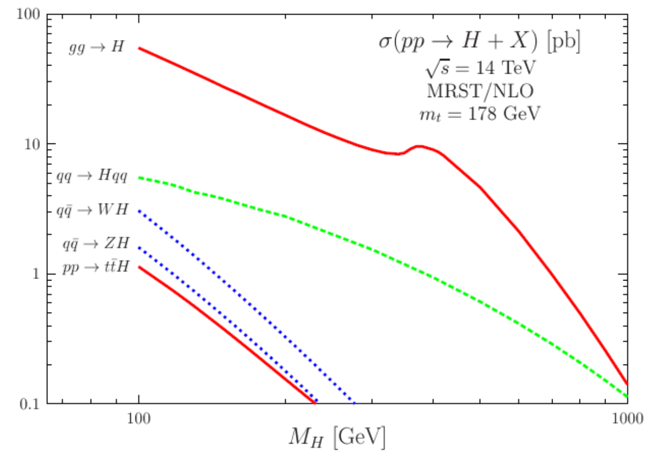
- **$H \rightarrow bb$** : BR ~0.85 but huge QCD background
- **$H \rightarrow \tau\tau$** : accessible through VBF
- **$H \rightarrow \gamma\gamma$** : very important despite the low BR (~0.002) due to the excellent γ/jet separation and γ resolution
- **$H \rightarrow WW^* \rightarrow 2l2\nu$** : accesible through gg fusion and VBF, BR~1 at m_H ~160 GeV/c²
- **$H \rightarrow ZZ^* \rightarrow 4l4\nu$** : also accesible

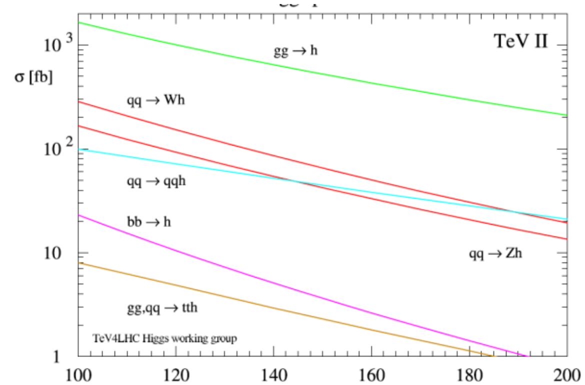
❖ **For Higher masses**

$H \rightarrow WW^* \rightarrow 2l2\nu$ and **$H \rightarrow ZZ^* \rightarrow 4l$**

TEVATRON vs LHC
at the end of 2010: 8 fb^{-1} vs 200 pb^{-1}
factor of 40 in x-sections?





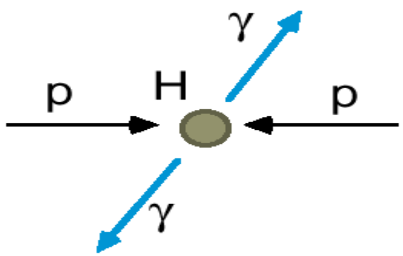


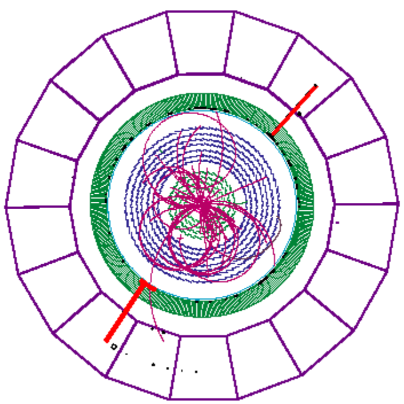
Very roughly,

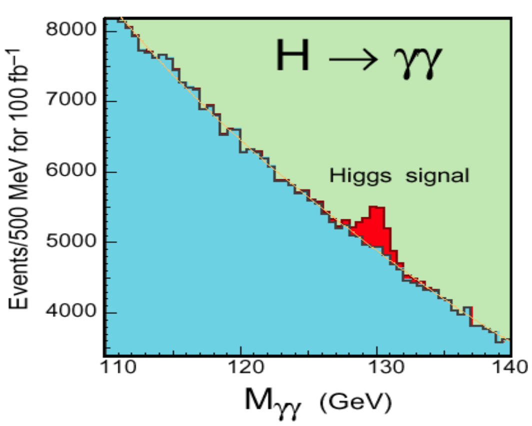
- **for gg-induced processes, one can compete at m_{inv}>150 GeV**
- **for qqbar-induced processes, one can compete at m_{inv}>1 TeV**

Higgs Events in CMS

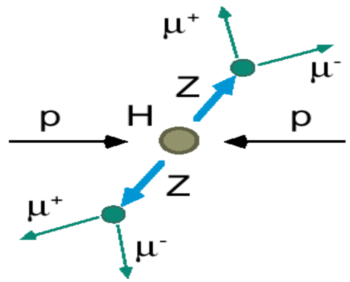
M_H < 150 GeV

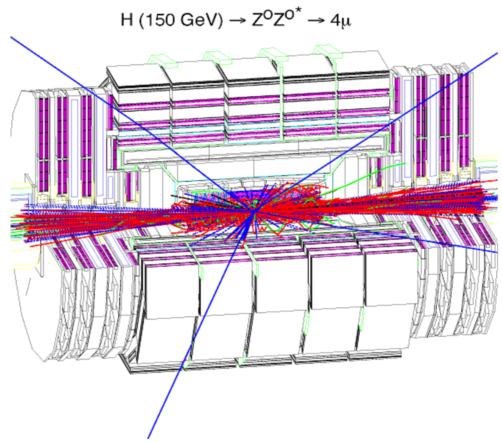


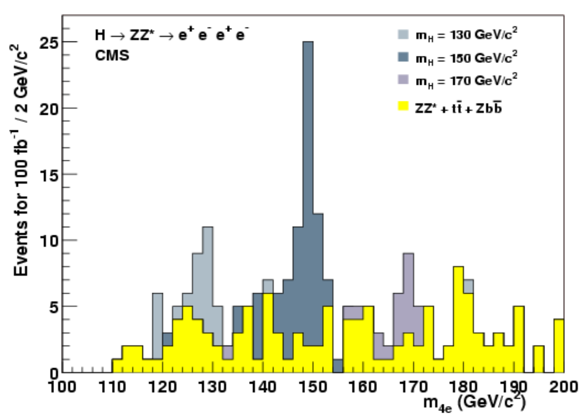




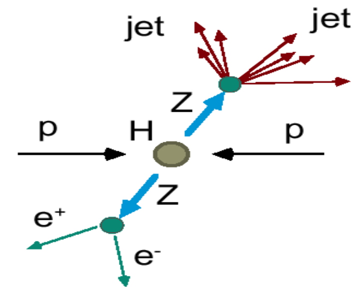
130<M_H<500 GeV

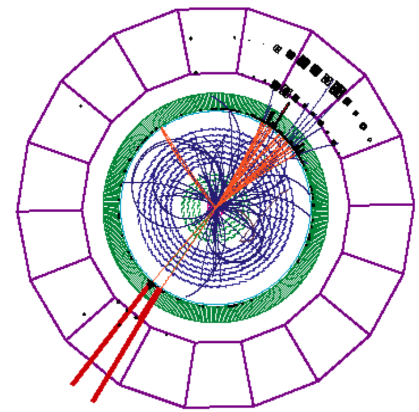


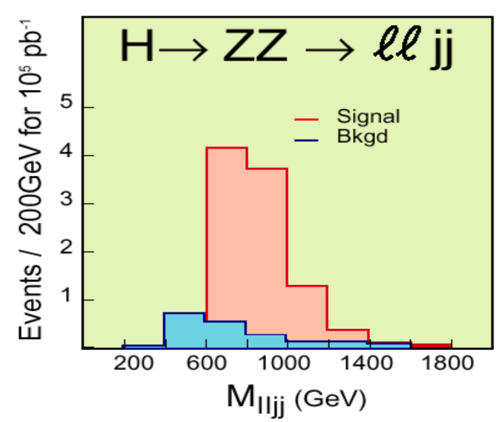




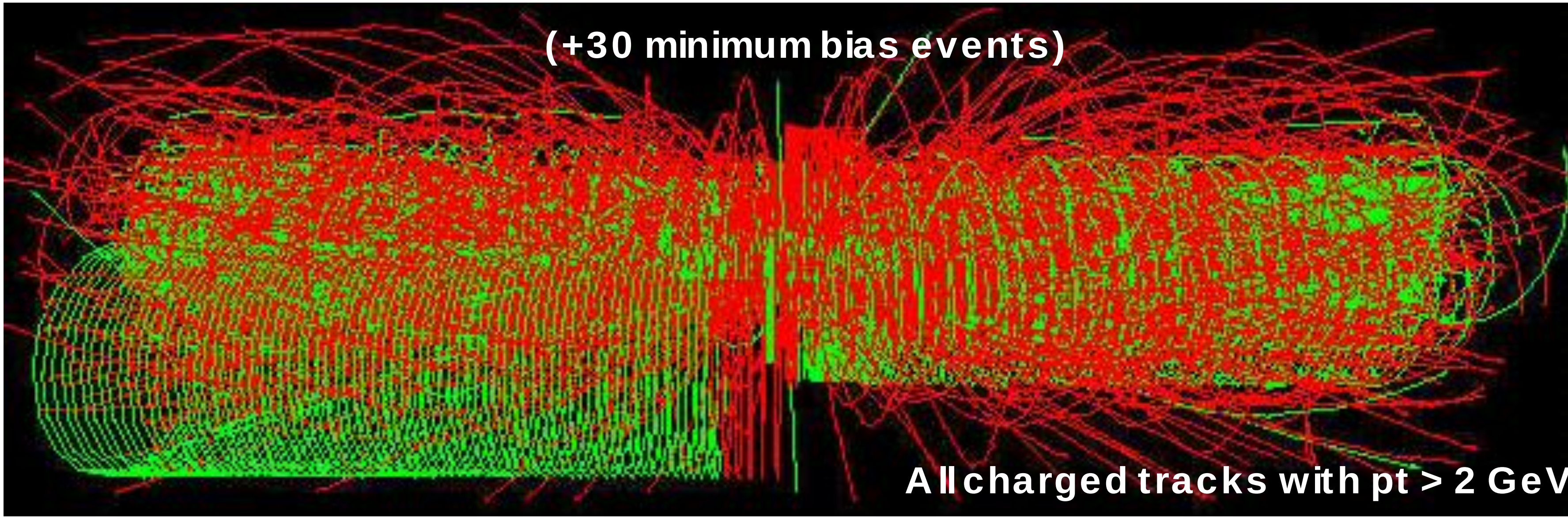
M_H > ~500 GeV

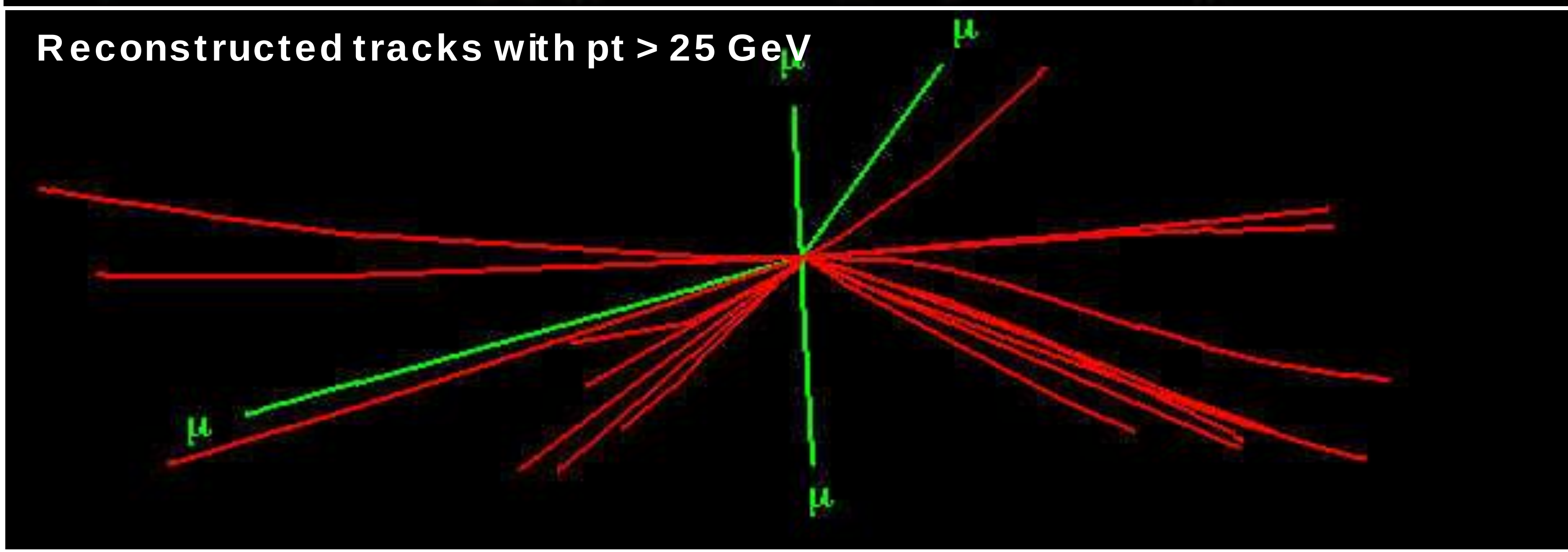






Higgs decay in 4 muons



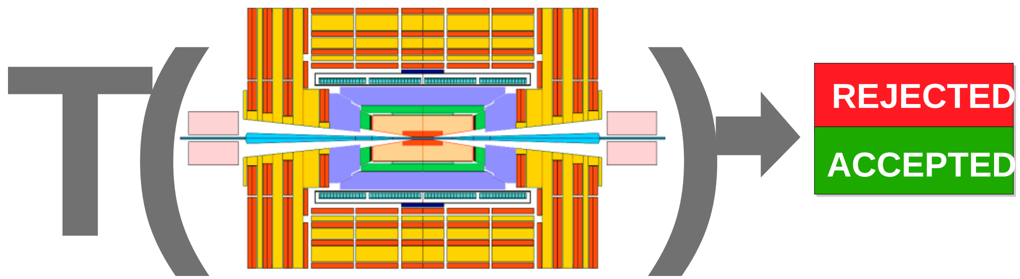


Event selection: The trigger system

Mandate:

"Look at (almost) all bunch crossings, select most interesting ones, collect all detector information and store it for off-line analysis"

The trigger is a function of :



Event data & Apparatus
Physics channels & Parameters

Since the detector data are not all promptly available and the function is highly complex, T(...) is evaluated by successive approximations called :

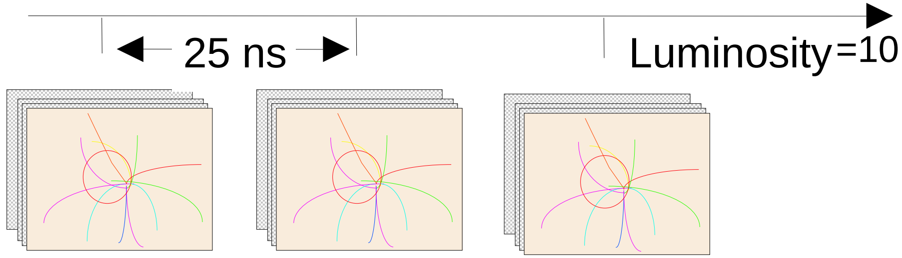
TRIGGER LEVELS

(possibly with zero dead time)

Trigger and readout structure at LHC

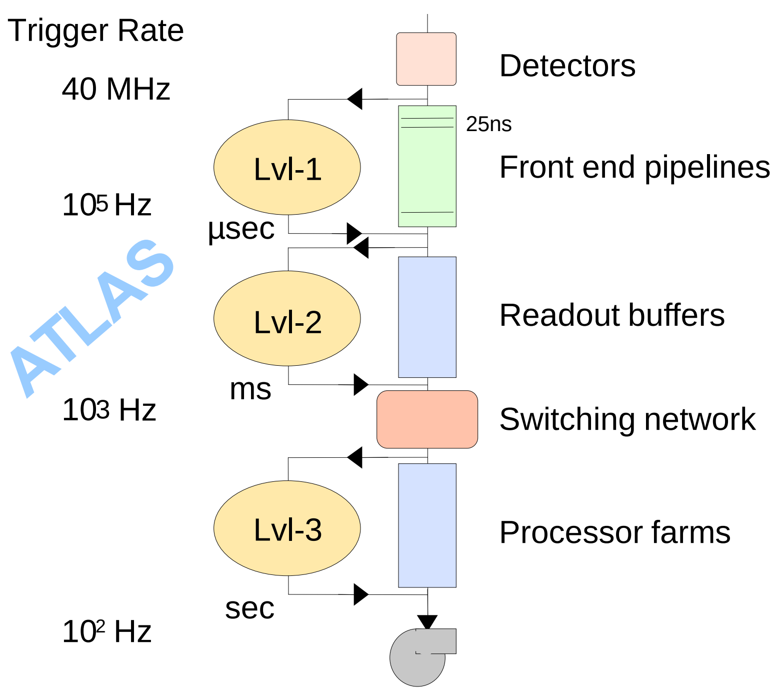
- 30 Collisions/25ns
(10^9 event/sec)

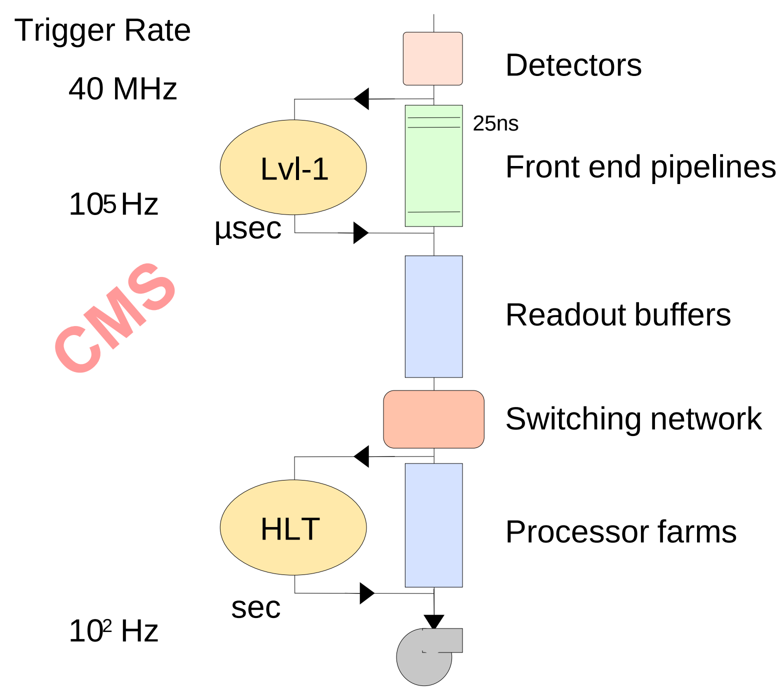
10^7 channels
(10^{16} bit/sec)



Luminosity=10^{34} cm^{-2} sec^{-1}

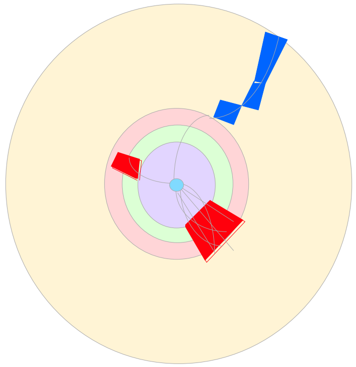
Multilevel trigger and readout systems



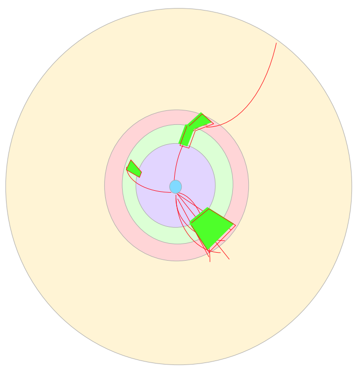


Trigger levels at LHC (the first second)

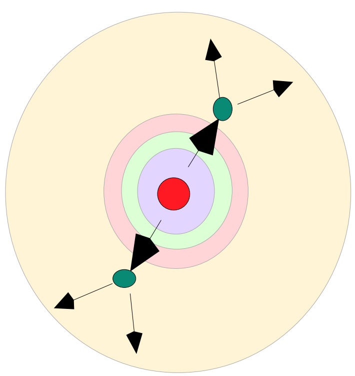
10^{-7} s



10^{-6} s



10^{-3} s



10^{0} s

Collision rate 10^9 Hz

Channel data sampling at 40 MHz

Level-1 selected events 10^5 Hz

Particle identification (High p_T e, μ, jets, missing E_T)

- Local pattern recognition
- Energy evaluation on prompt macro-granular information

Level-2 selected events 10^3 Hz

Clean particle signature (Z, W, ..)

- Finer granularity precise measurement
- Kinematics. effective mass cuts and event topology
- Track reconstruction and detector matching

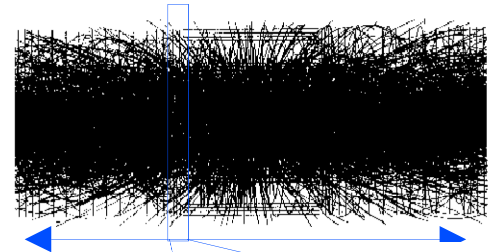
Level-3 events to tape 10..100 Hz

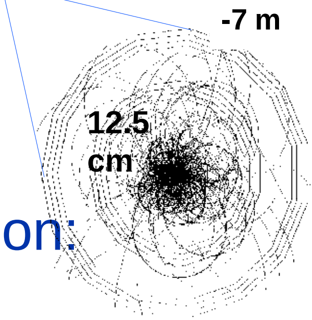
Physics process identification

- Event reconstruction and analysis

CMS Level-1 : calorimeters and muons

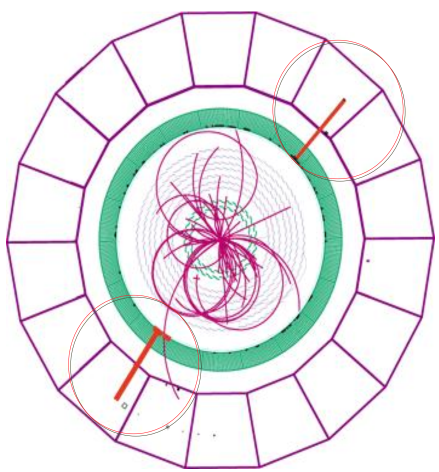
Compare to Central tracking at L =10 ^{34}
(50 ns integration, -1000 tracks)

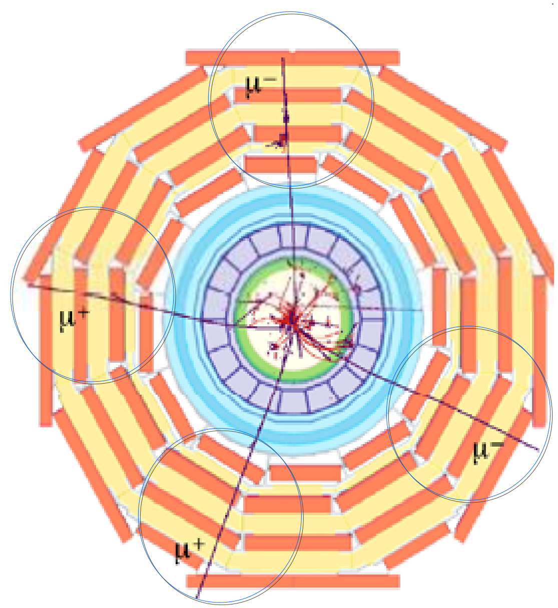




Algorithm Complexity + huge amount of data

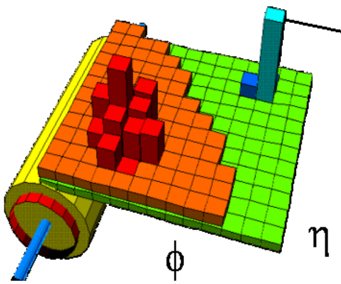
Pattern recognition much easier on calo & muon:





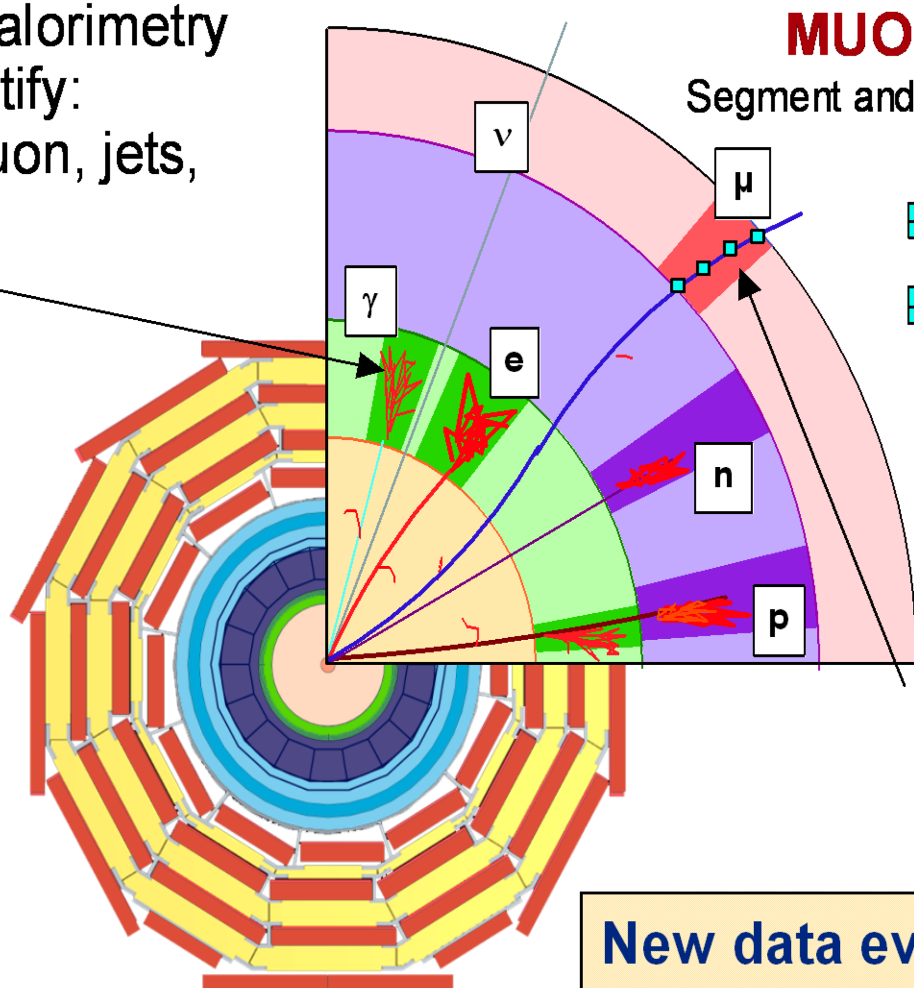
Particle identification

Use prompt data (calorimetry and muons) to identify:
High p_t electron, muon, jets, missing E_T



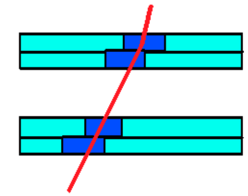
CALORIMETERs

Cluster finding and energy deposition evaluation



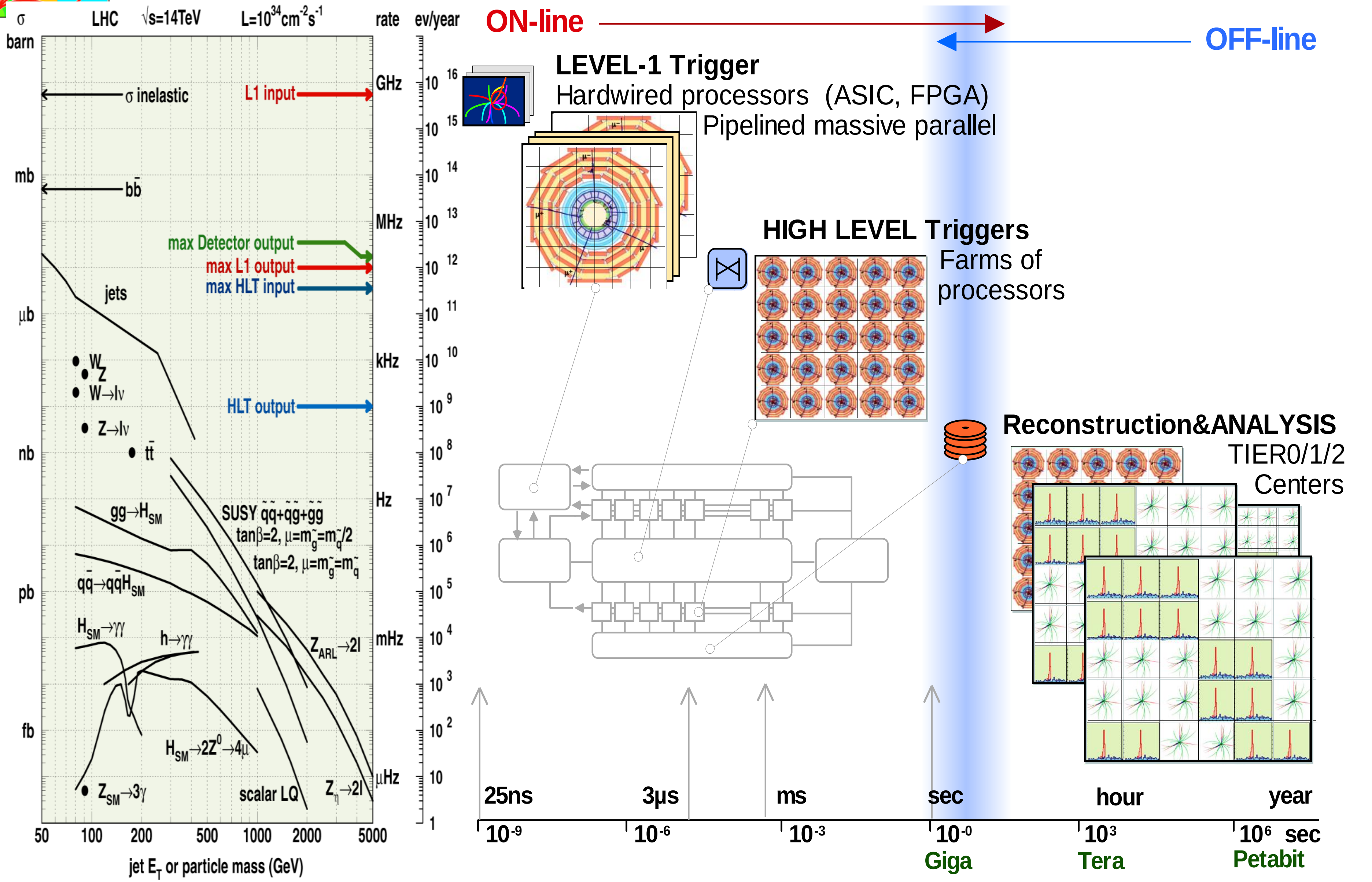
MUON System

Segment and track finding



New data every 25 ns
Decision latency ~ μs

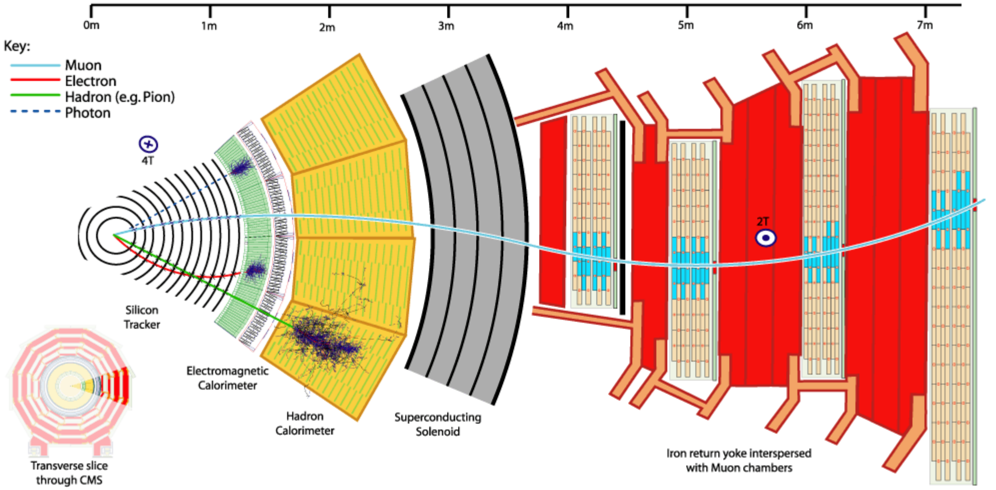
Event selection and computing stages



Particle-Flow Event Reconstruction

Reconstruct and
identify all particles

- Charged hadrons
- Photons
- Neutral hadrons
- Electrons (also non isolated)
- Muons

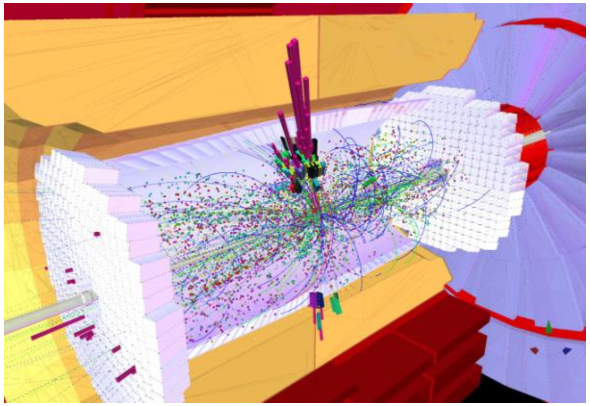


Identify and utilize an optimal combination of all (CMS) sub-detector information

Provide a unique list of particles

- for a global, coherent, accurate event description

Particle-based objects: MET, Jets, taus, b jets, ...



Physics Object: Photons

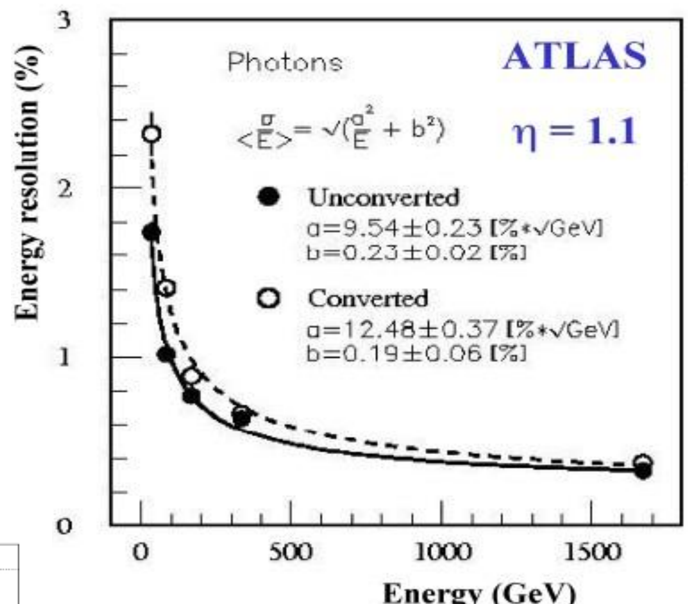
<u>Photons at 100 GeV</u>

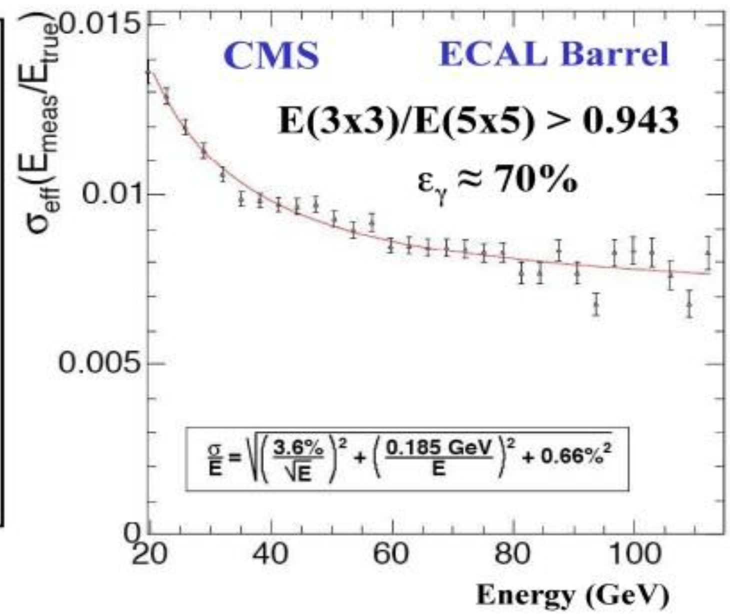
ATLAS: 1-1.5% energy resol. (all γ)

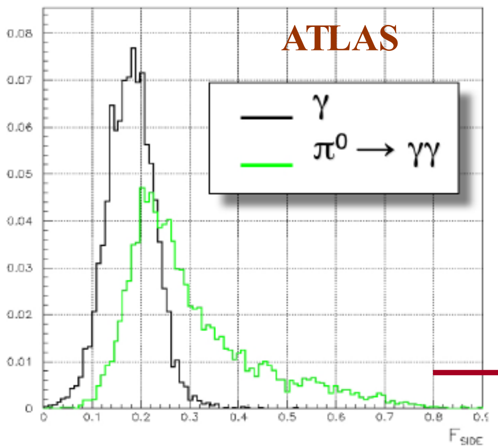
CMS: 0.75% energy resol. (ε_γ ~ 70%)

ATLAS: ~30% photons convert in the barrel

CMS: 42% in the barrel, **59.5%** in the endcap







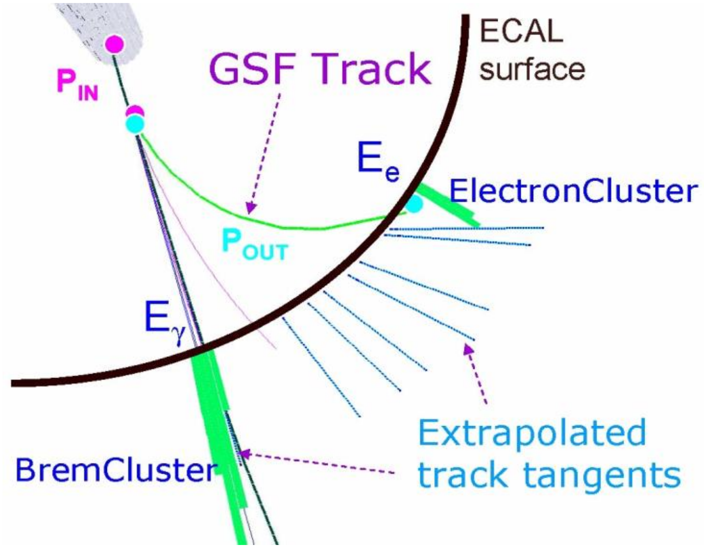
<u>Broadly speaking:</u>

CMS has a better energy resolution

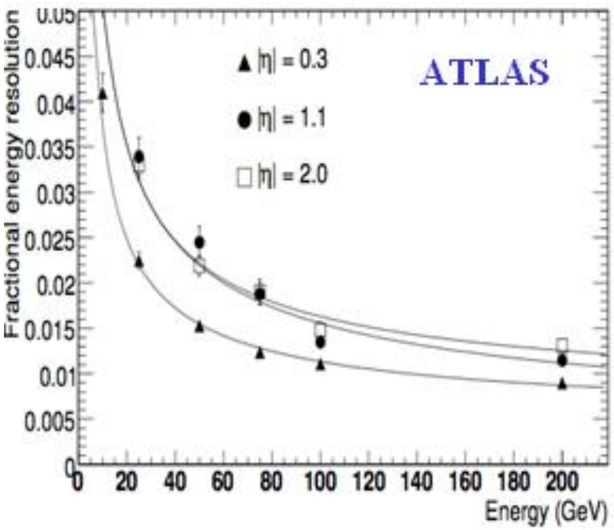
CMS is probabily worse then ATLAS in the π^0 rejection.

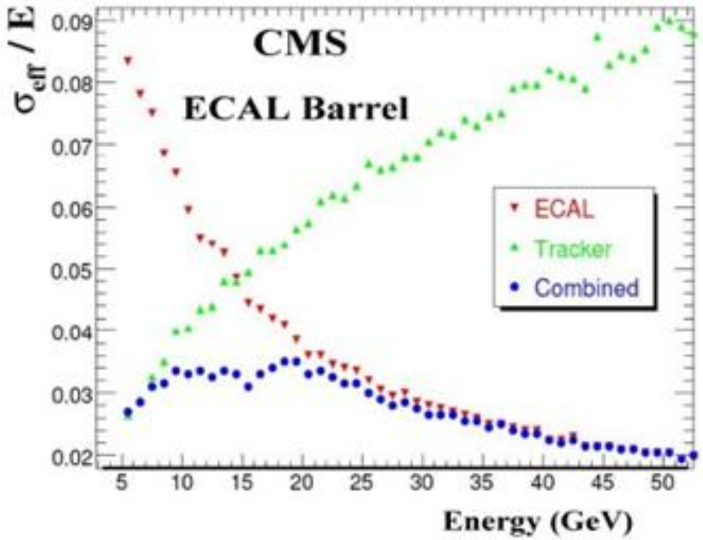
A rejection factor of 3.2 against π^0 is found for a 90% of photon efficiency

Physics objects: Electrons



Electrons:
at 50 GeV in the barrel region:
- theCMS **effective** resolution is estimated to be **2%**
- the ATLAS **energy resolution** varies between 1.3% (at η = 0.3) and **1.8%** (at η = 1.1)

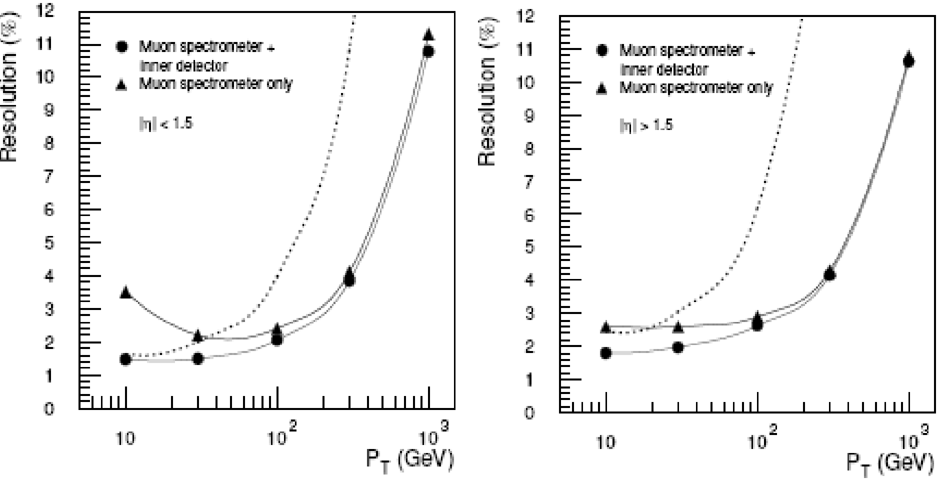




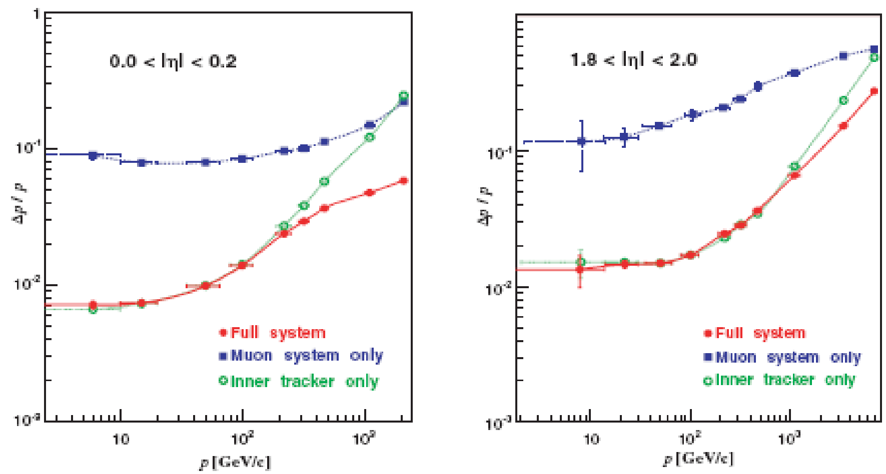
Physics objects: muons

Combined (stand-alone) momentum resolution at	ATLAS	CMS
- p = 10 GeV and $\eta \approx 0$	1.4% (3.9%)	0.8% (8%)
- p = 10 GeV and $\eta \approx 2$	2.4% (6.4%)	2.0% (11%)
- p = 100 GeV and $\eta \approx 0$	2.6% (3.1%)	1.2% (9%)
- p = 100 GeV and $\eta \approx 2$	2.1% (3.1%)	1.7% (18%)
- p = 1000 GeV and $\eta \approx 0$	10.4% (10.5%)	4.5% (13%)
- p = 1000 GeV and $\eta \approx 2$	4.4% (4.6%)	7.0% (35%)

ATLAS



CMS



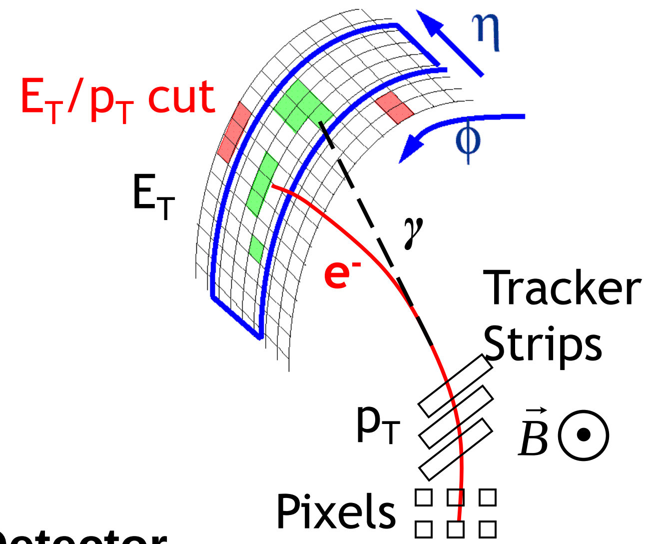
ATLAS: almost indipendence of the resolution from η
CMS: degradation of resolution at higher η

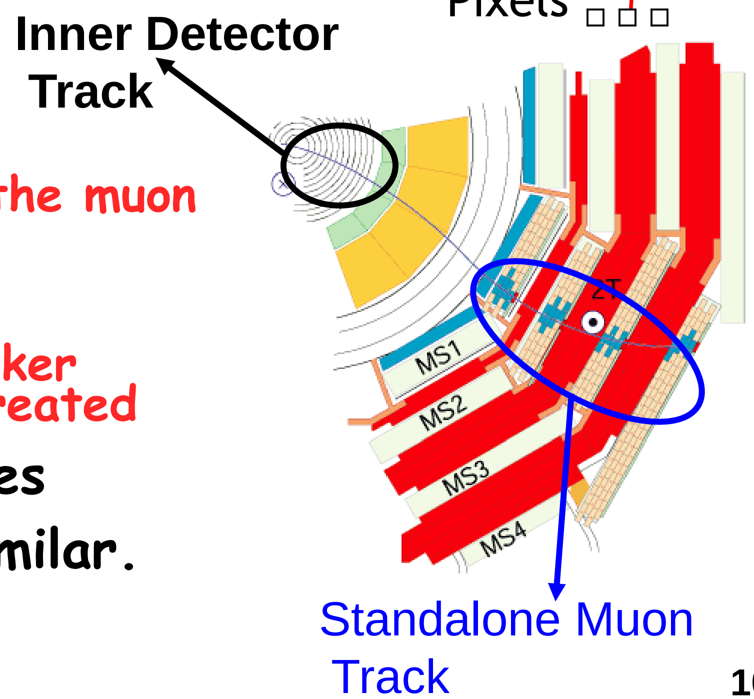
CMS : Superior combined momentum resolution in central region ->higher resolution tracking system
ATLAS: Superior combined momentum resolution in forward region -> better coverage toroidal system

Together with a recostruction efficiency of about 99% over almost all the pseudorapidity range, these numbers are very important for the Higgs discovery golden channel

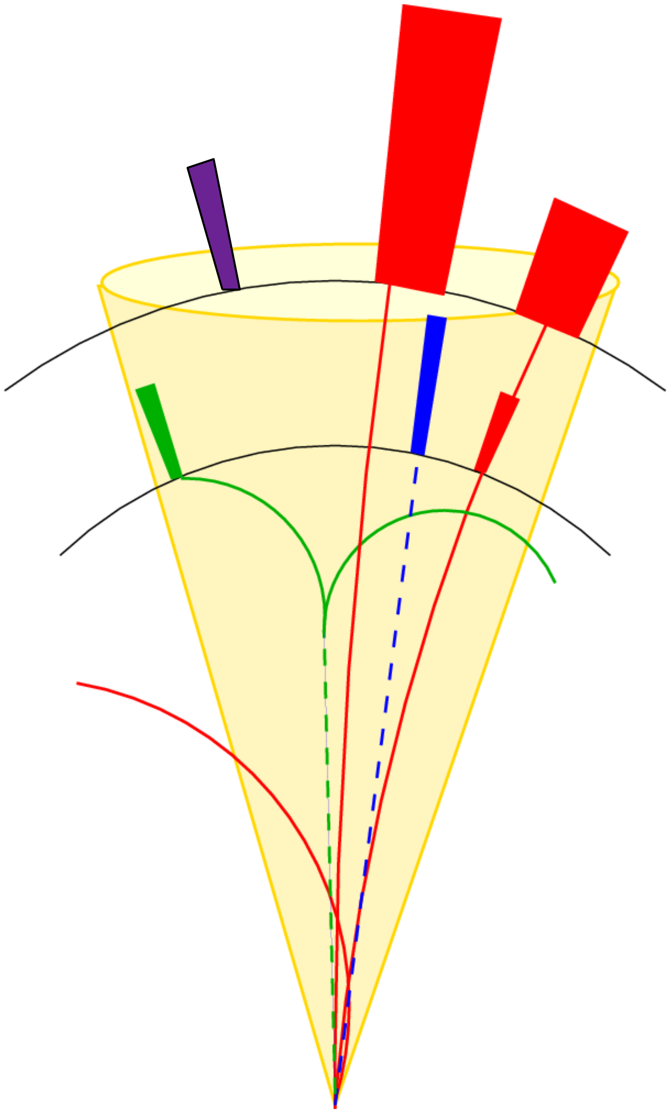
e/μ Offline Reconstruction

- **Electrons**
  - Calorimeter Reconstruction
    - Create "super-clusters" of clusters to include radiated photons
    - Apply E_t thresholds
  - Tracker Reconstruction
    - Electron is matched to a track.
  - Cuts are applied on e/p and HCAL energy deposits
- **Muons**
  - Standalone Reconstruction
    - Muon tracks reconstructed from the muon system
  - Combined Reconstruction
    - Muon Tracks are matched to tracker tracks and combined muons are created
- Isolation can be applied in both cases
- High Level trigger algorithms are similar.





Physics objects: Jets



Particle Flow Algorithm

Photons

- **20% of the jet energy**
- **ECAL cluster → Ecal resolution**

Charged hadrons

- **70% of the jet energy**
- **Track + ECAL + HCAL → Tracker resolution**

Neutral hadrons

- **10% of the jet energy**
- **HCAL (+ECAL) cluster → HCAL resolution**

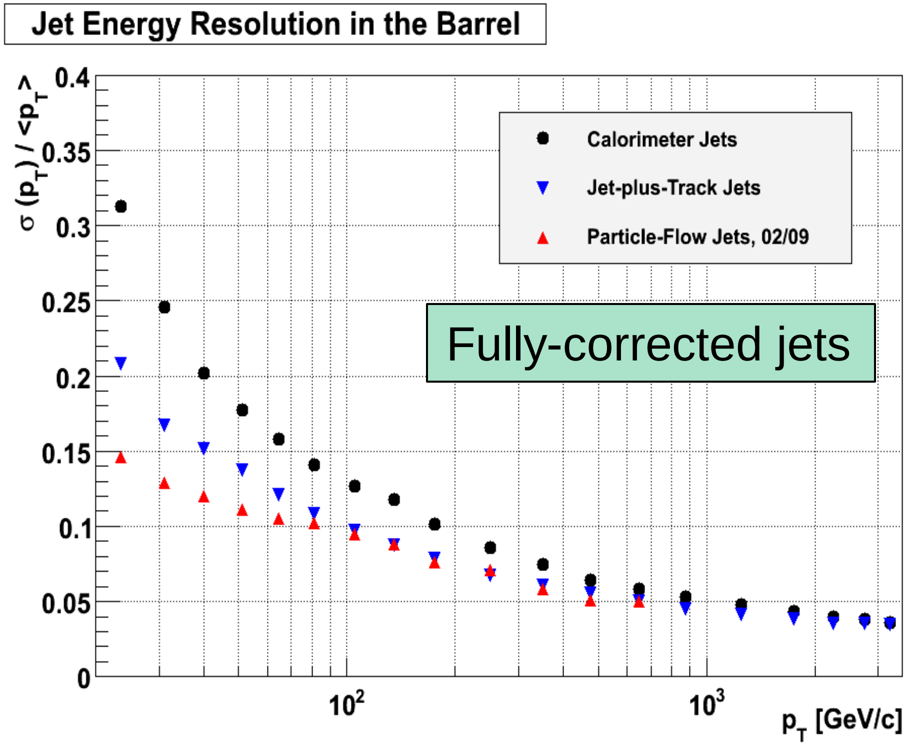
Muons

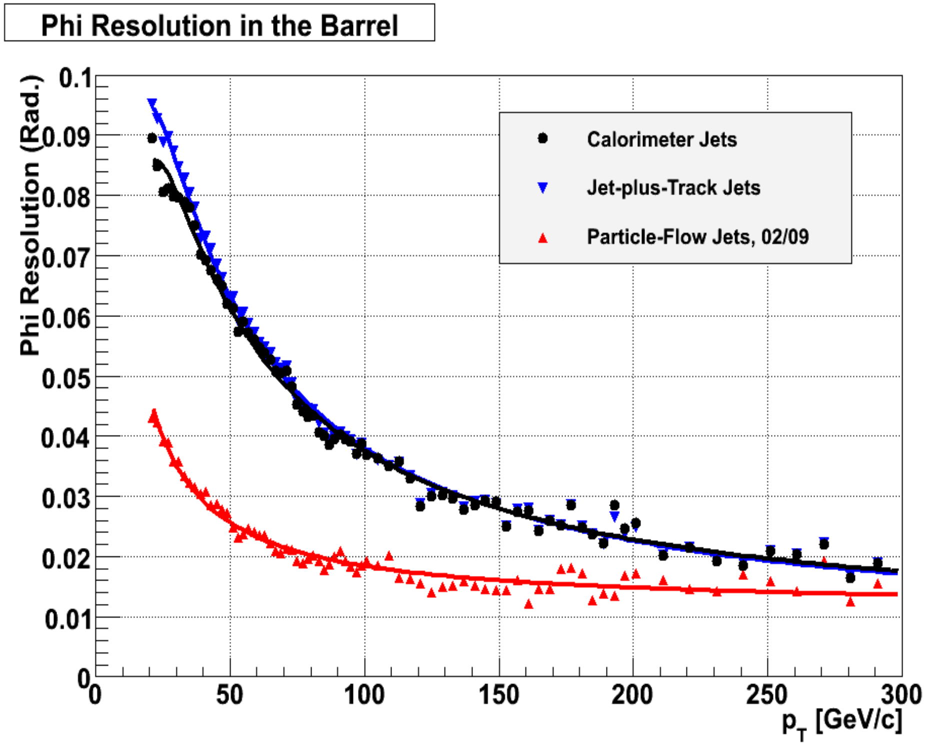
- **Track + muon resolution**

Electrons

- **Tracker + ECAL resolution + brem recovery**

Reconstructing Jets With Particle Flow





Latest performance with cluster calibration and improved tracking

- **Particle Flow Jet Energy and Angular Resolutions**
  - **Substantial improvement over calorimetric jets all the way to ~1 TeV**
    - ~ Much smaller Jet-Energy-Scale corrections/uncertainties

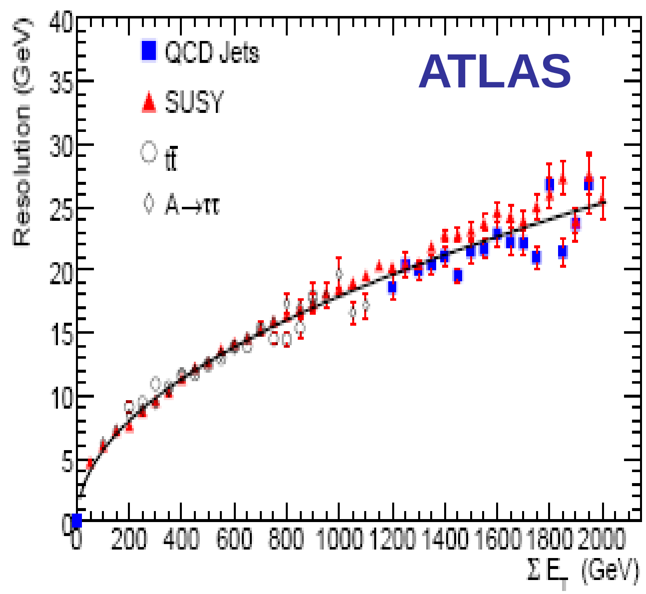
Physics objects: Missing energy

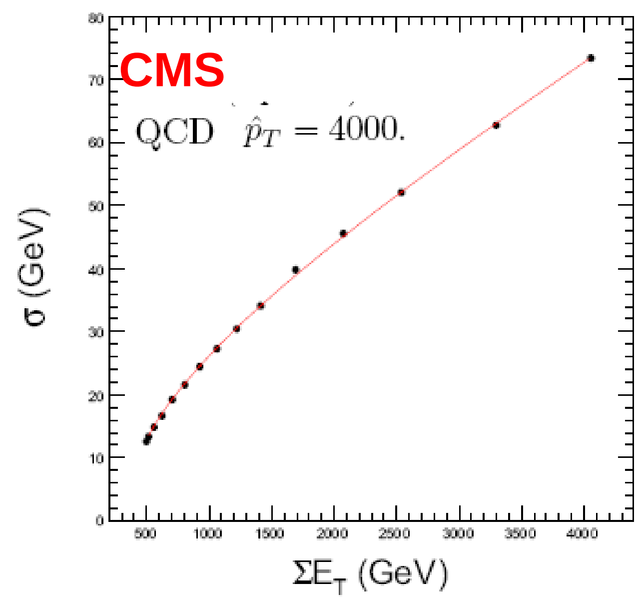
The missing transverse energy is defined by the vector sum of the energy deposits in the calorimeter towers (or cells):

$$\vec{E}_T^{miss} = -\sum_n (E_n \sin\theta_n \cos\phi_n \hat{\imath} + E_n \sin\theta_n \sin\phi_n \hat{\jmath}) = (E_x^{miss} \hat{\imath} + E_y^{miss} \hat{\jmath})$$

eventually corrected for muons →

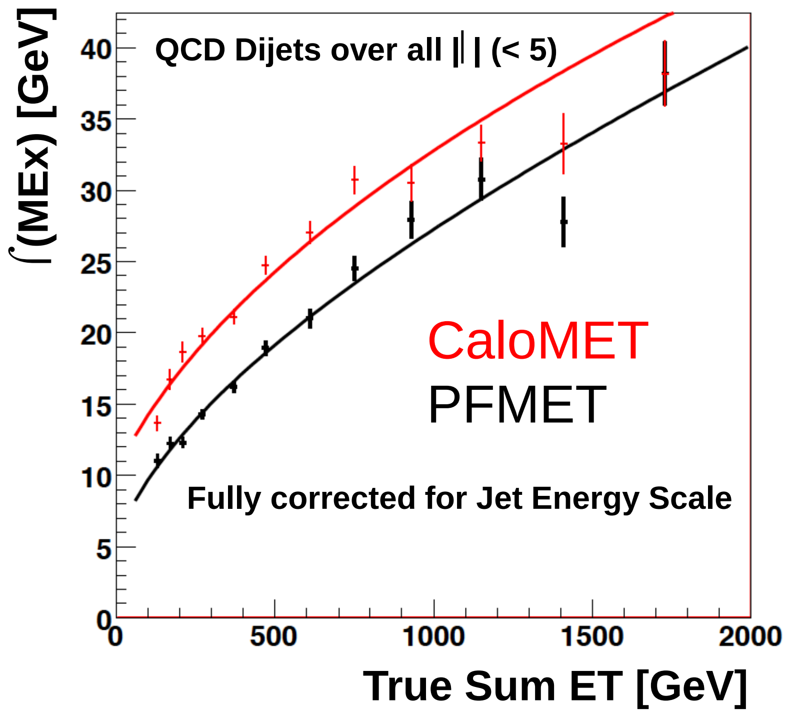
$$\vec{E}_T = -\sum_{\text{towers}} \vec{E}_T^i - \left(\sum_{\text{muons}} \vec{p}_T^{\,i} - \sum_{\text{mu deposits}} \vec{E}_T^i \right)$$

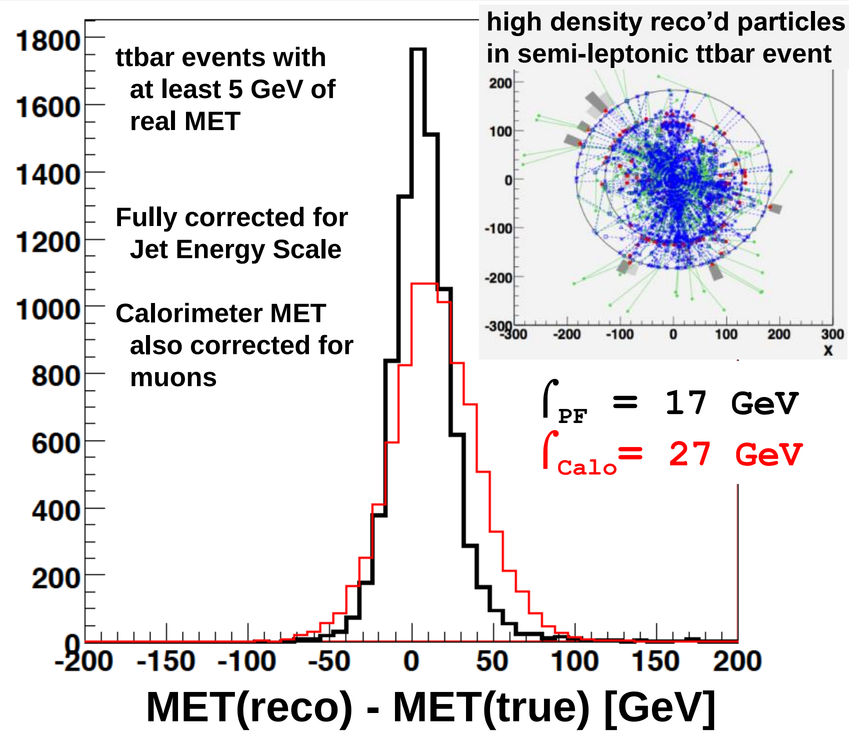




<u>At $\Sigma E_T = 2000$ GeV</u>
- **ATLAS: σ ~ 25 GeV**
- **CMS: σ ~ 40 GeV**

Reconstructing MET with Particle Flow





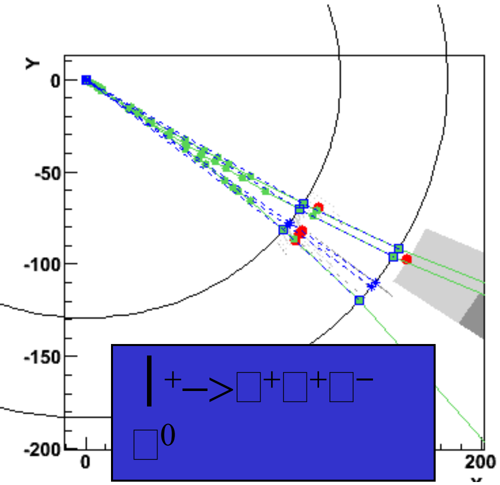
P-Flow MET in QCD (zero MET) & ttbar (real MET) events

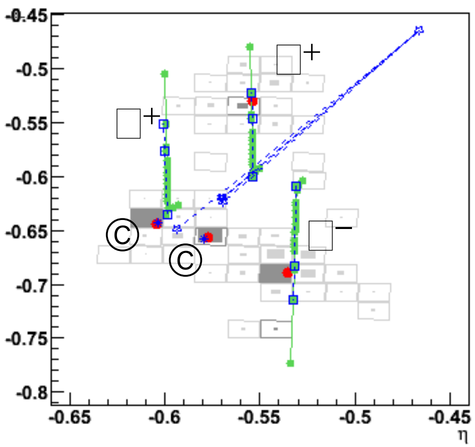
- Substantial improvement in absolute resolution over calo MET
    - Both for events with zero MET (QCD) and for events with real MET (ttbar); result does not yet include latest cluster calibration or improved tracking
        - ~ Improvements in p-flow MET performance expected

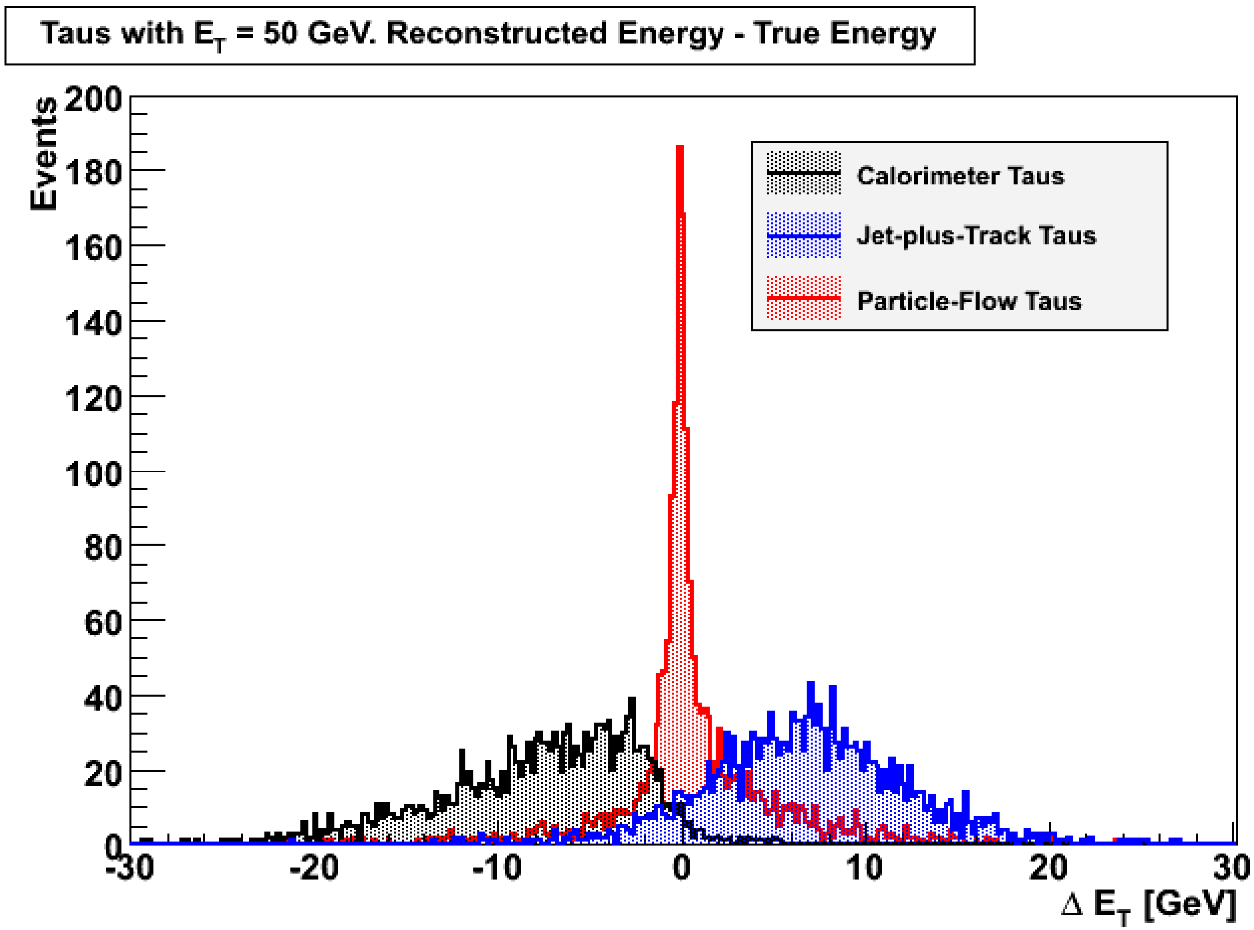
Reconstructing Taus With Particle Flow

Optimal use of the tracker and of the granularity of the ECAL in Particle Flow Reco

- **Reconstruct all charged hadrons and photons from □^{0}'s**





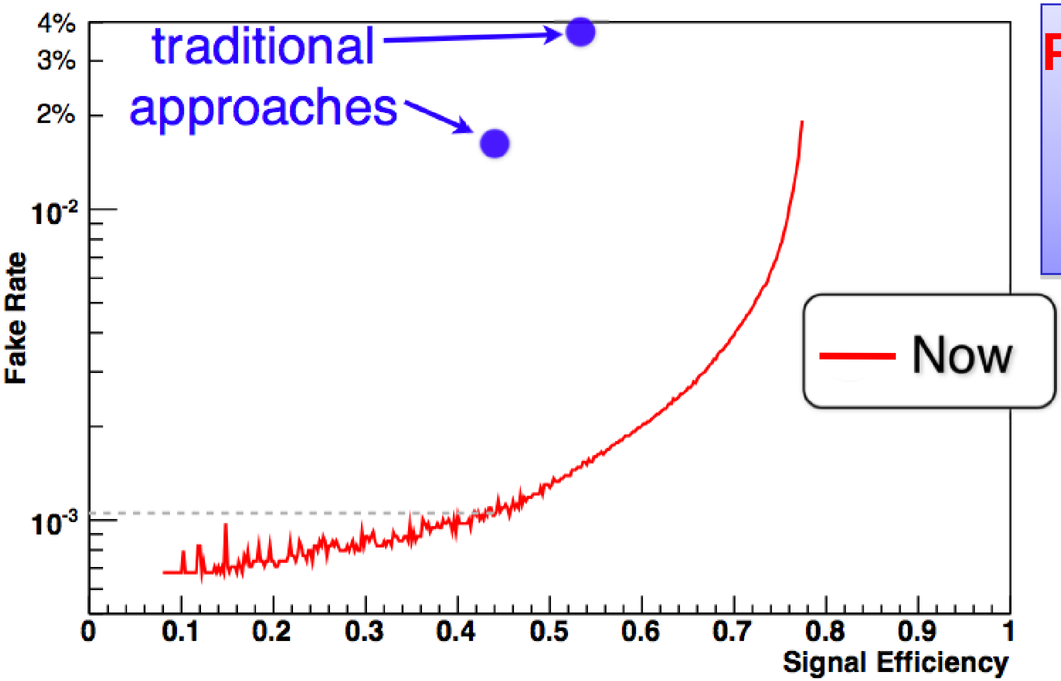


Identifying taus with Particle Flow

P-flow reconstruction: new possibilities in tau ID

- Use of □[0]'s as leading particles
- Exclusive reconstruction of tau decays
- Improved tracking efficiency at low p_T

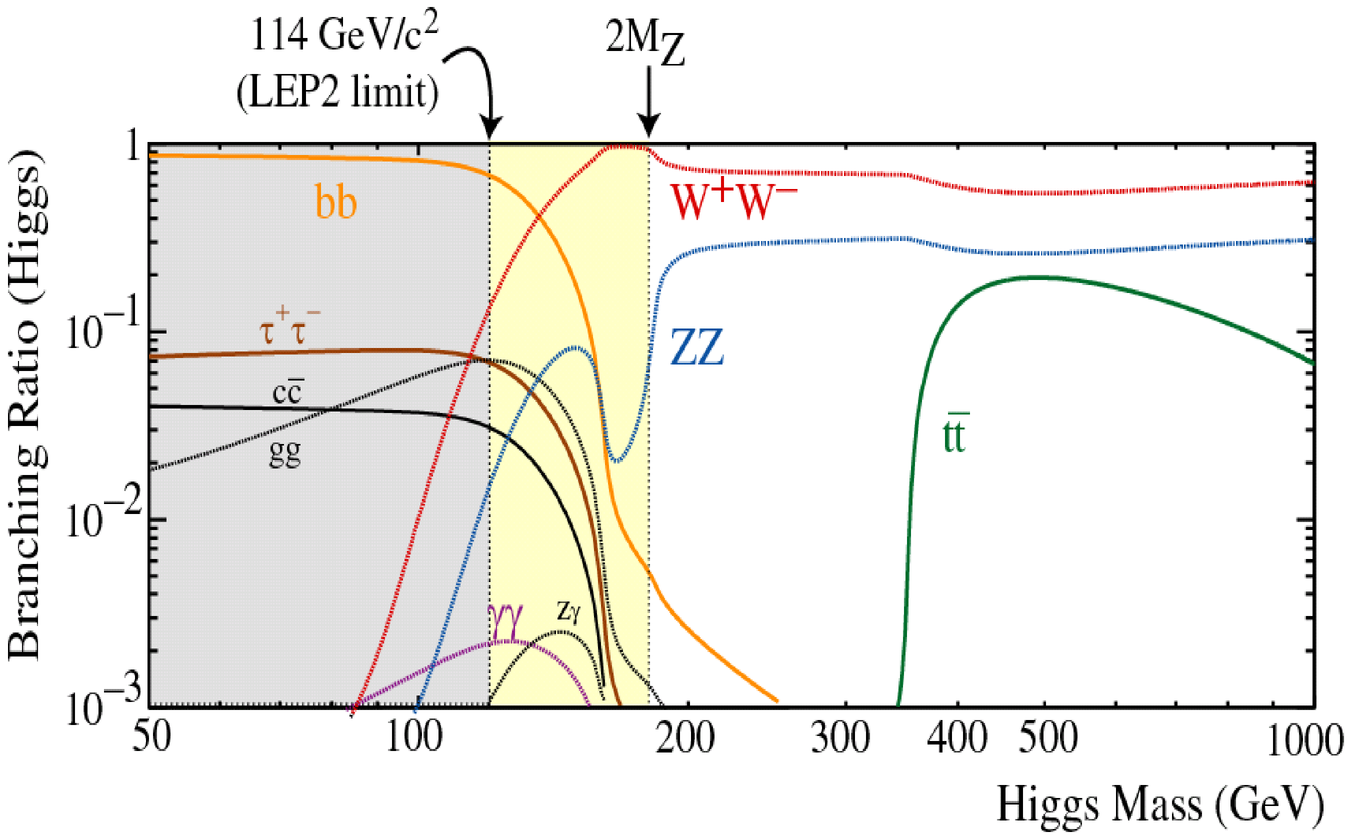
Combined in a NN



Performance for jets with $20 < p_T < 50$ GeV/c:
efficiency (per tau): 60%
efficiency (per QCD jet): 0.2%

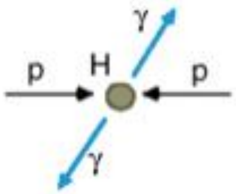
Background rejection: factor 20 larger than with traditional tau ID

Main Decay Modes

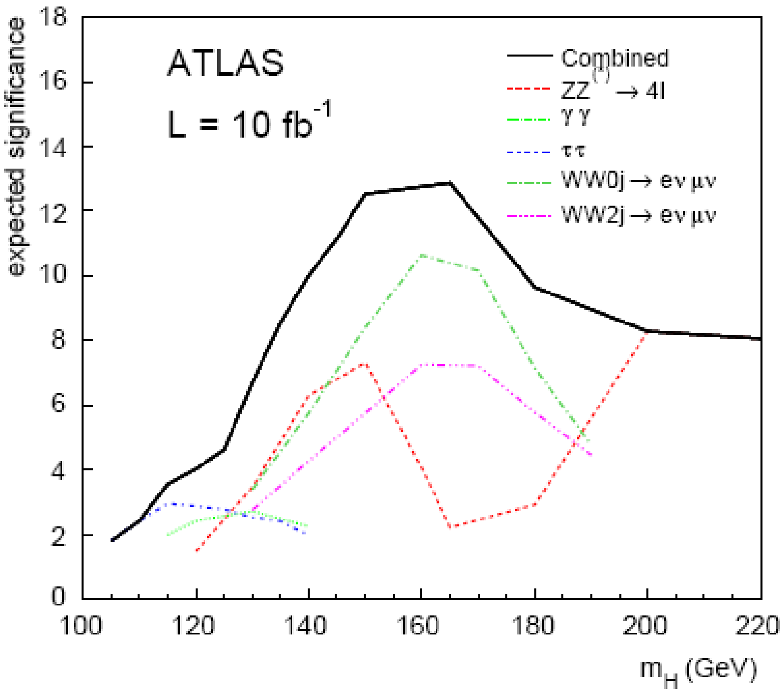


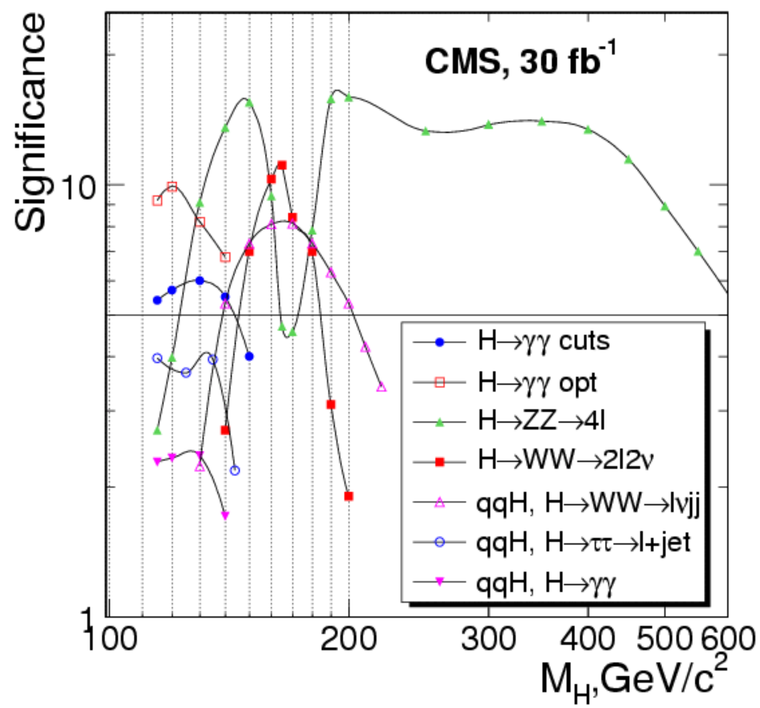
Close to LEP limit:
$H \rightarrow \gamma\gamma, \tau\tau, bb$

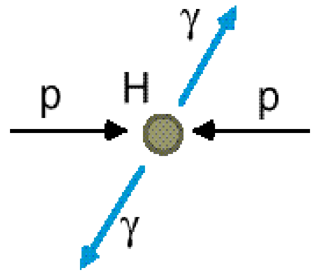
For $M_H > 140$ GeV:
$H \rightarrow WW^{(*)}, ZZ^{(*)}$



Low Mass SM Higgs: $H \rightarrow \gamma\gamma$

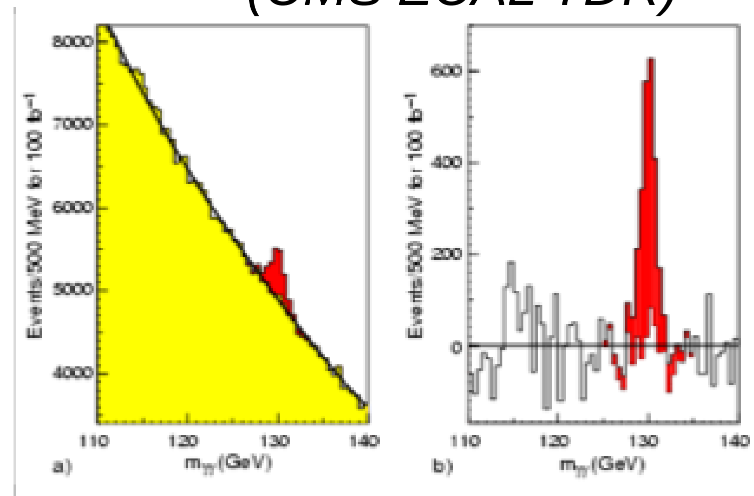




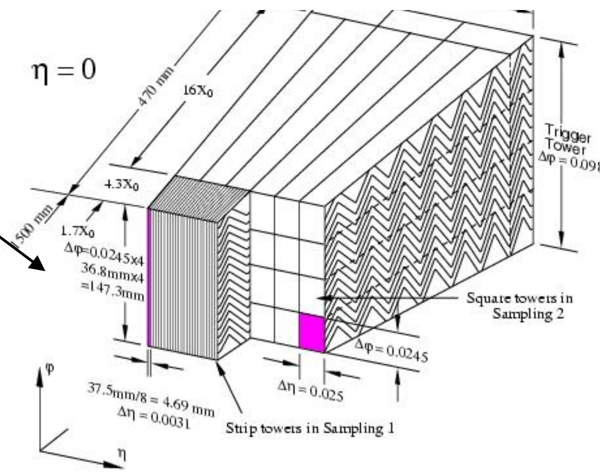


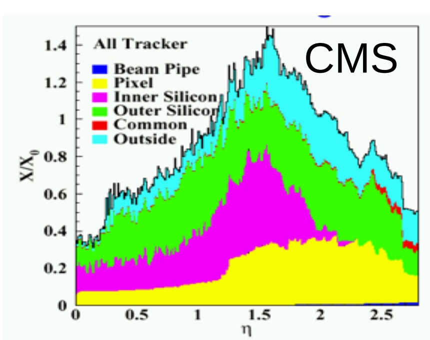
$H \rightarrow \gamma\gamma$

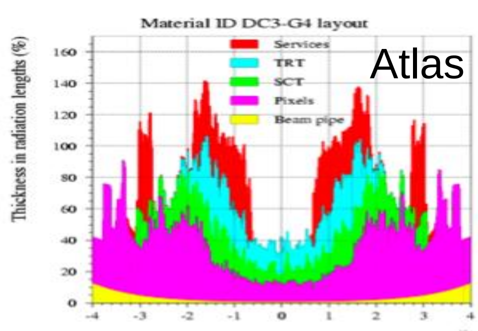
(CMS ECAL TDR)



- Narrow peak over "smooth" background
- Key points:
  - Good mass resolution (Intrinsic width is negligible) => Energy resolution of e.m. calorimeter + primary vertex determination
  - Good photon identification: To reduce jet background below true photon background
    - Very fine segmentation (*ATLAS*) to allow photon/π^0 separation event by event
    - Isolation cuts
    - Recovery of conversions:
      - ~30% of photons convert in tracker







If vertex unknown add 1.4 GeV to mass resolution
Calo pointing in ATLAS gives vertex resolution of 1.7 cm while σ(beam) = 5.6 cm

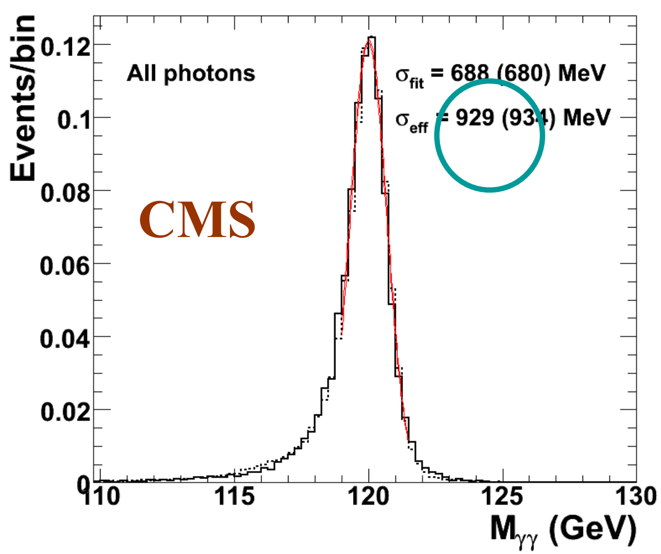
$H \rightarrow \gamma\gamma$

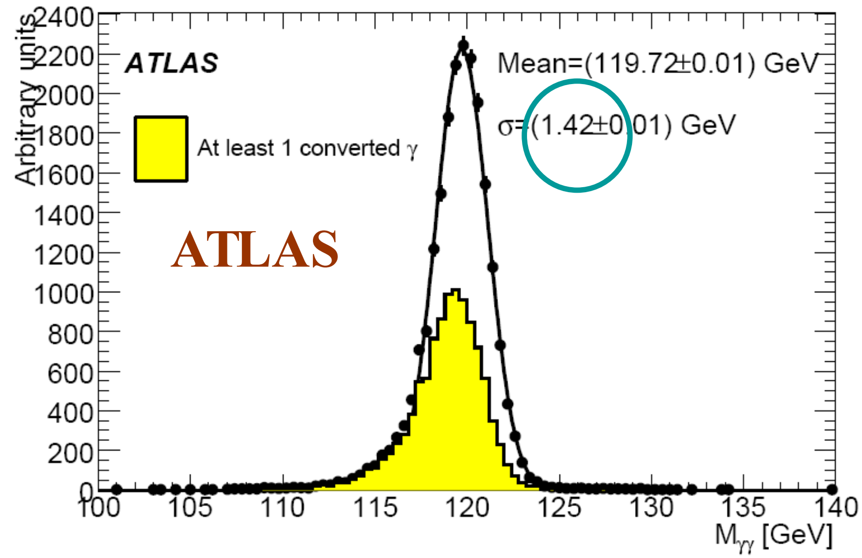
Most important channel for Higgs discovery (from LEP limit to 150 GeV) because clear signature with respect to bb decay but small B.R. (0.2%)

Cross section x BR: 99.3 fb (M(H)=115 GeV), 41.5 fb (M(H) = 150 GeV)

Mass resolution: $M_{\gamma\gamma}^2 = 2\, E\gamma_1 E\gamma_2 (1-\cos\theta_{12}) \longrightarrow$

- Intrinsic resolution of calo
- Calibration/uniformity of calo
- Meas. of interaction primary vertex



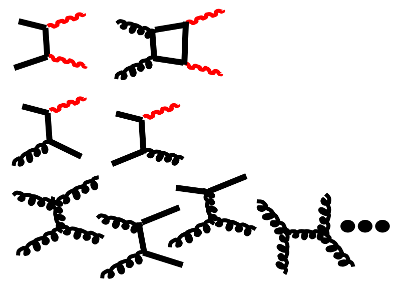


Significances@30fb^{-1}:
CMS: 6.0 (cut based), 8.2 NN
ATLAS: 6.3 cut based

SM Higgs: H→γγ

Backgrounds:

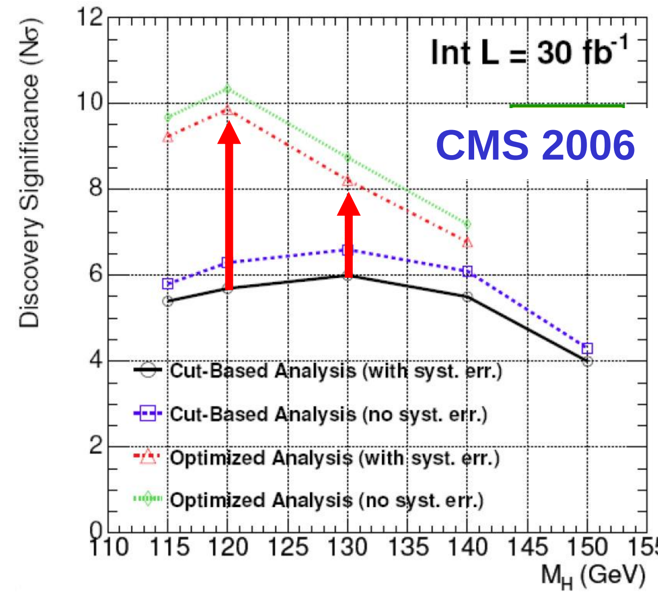
- prompt γγ
- prompt γ + jet(brem γ, $\pi^0 \to \gamma\gamma$)
- dijets

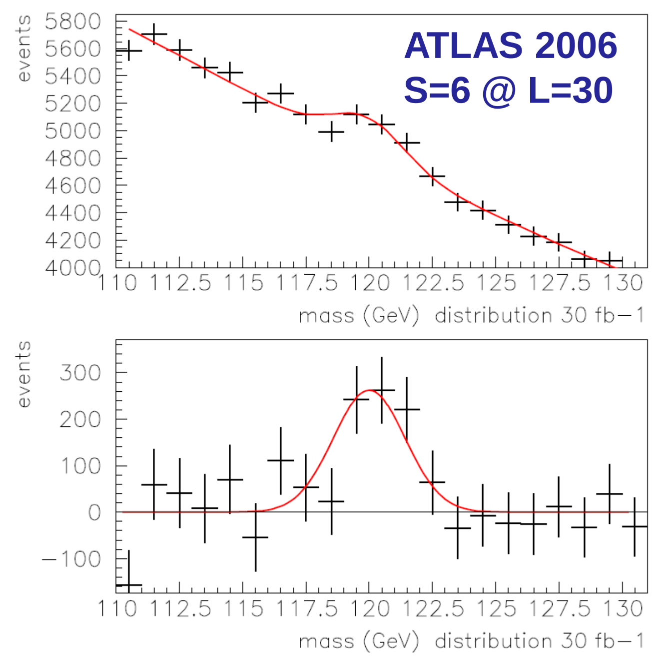


CMS-2006 analysis:

- cut-based
  - events sorted by “em shower quality”
  - kinematics, isolation, $M_{\gamma\gamma}$-peak
- optimized
  - loose sorting and kinematical cuts
  - Neural net and Likelihood Ratio

    with bkgd pdf taken from sidebands, signal pdf from MC



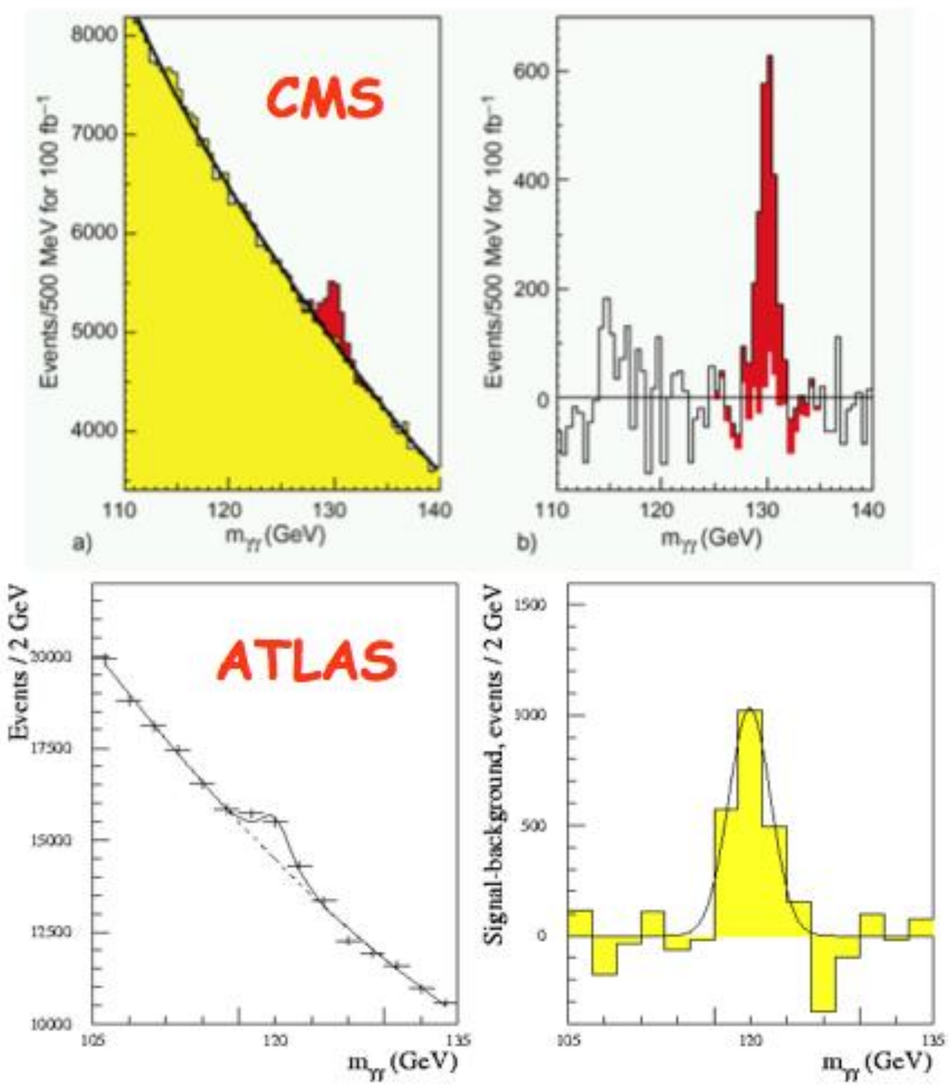


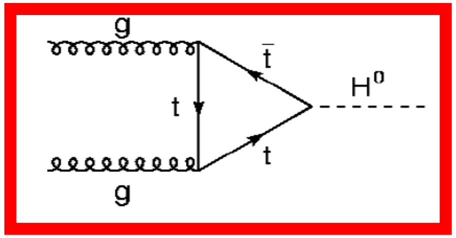
m_H=130 GeV	CMS	NLO cut based (TDR-2006)	6.0 σ
		NLO neural net (TDR-2006)	8.2 σ
	ATLAS	LO cut based (TDR-1999)	3.9 σ
		NLO cut based (2006, stat. err. only)	6.3 σ
		NLO likelihood (2006, stat. err. only)	8.7 σ

agree

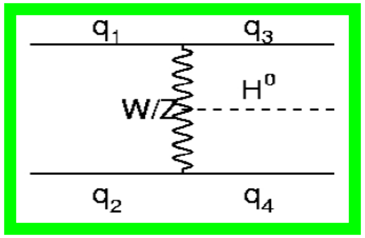
Higgs → γγ (100 fb^{-1})

CMS and ATLAS analyses for 100 fb^{-1}

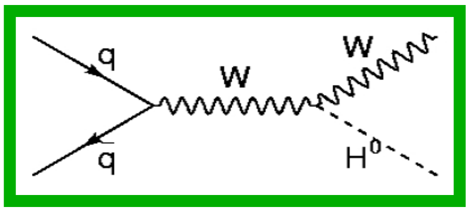




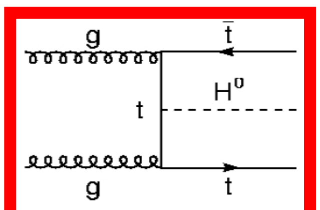
GF $H \to WW, ZZ, \gamma\gamma$



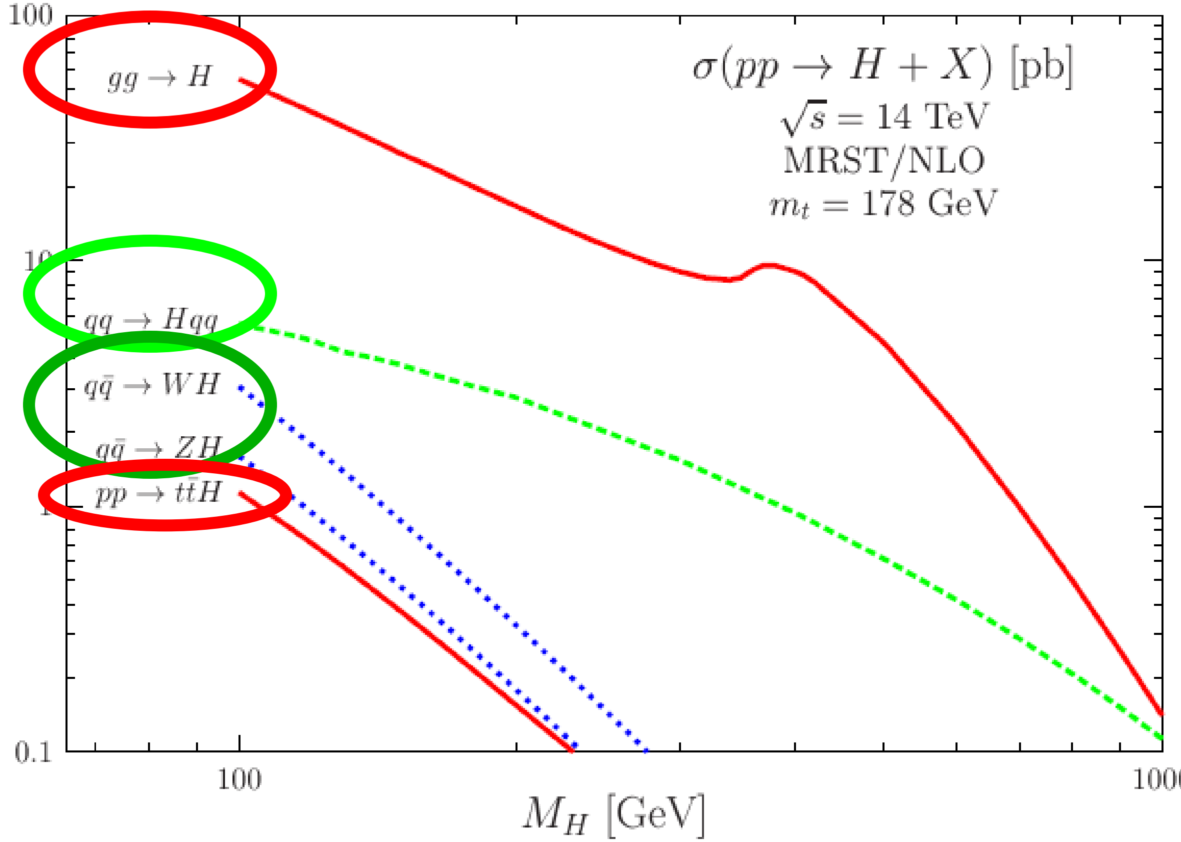
VBF $H \to WW, \gamma\gamma, \tau\tau$



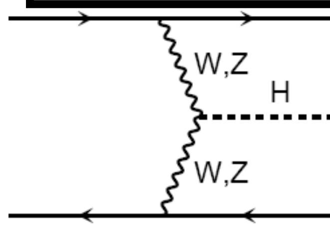
$H \to WW, \gamma\gamma$

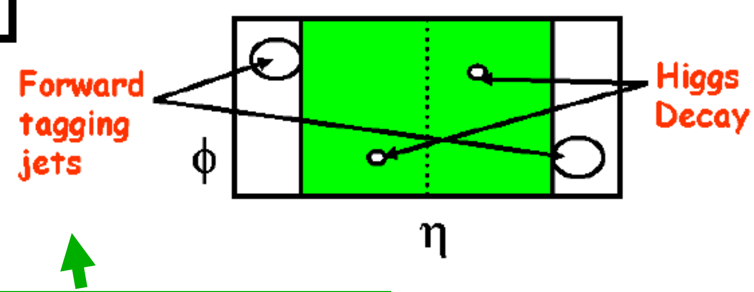


$H \to WW, \gamma\gamma, bb$



VBF $H \to \gamma\gamma$

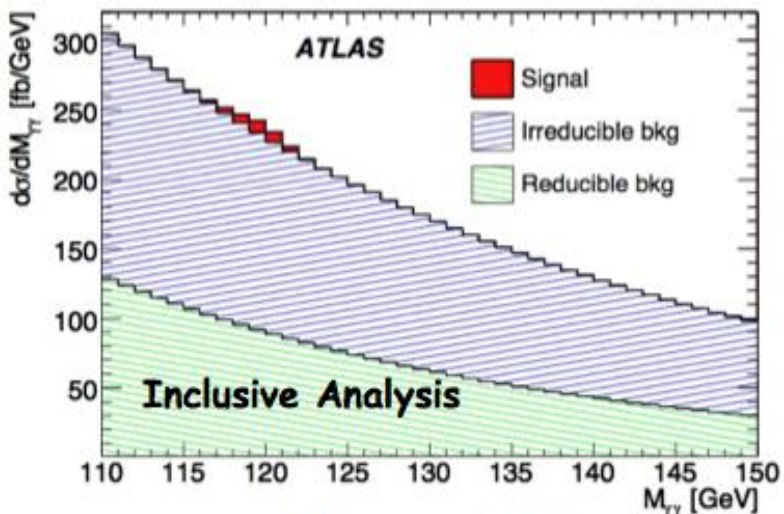


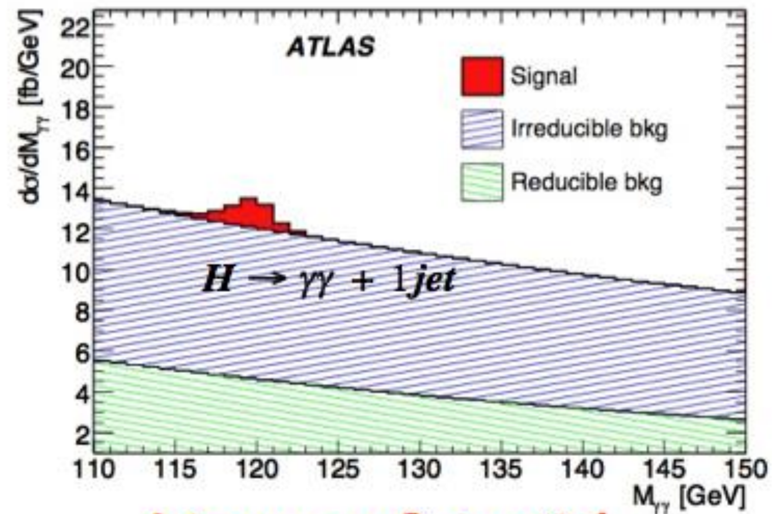


2 high p_T tag jets at large rapidity

ATLAS

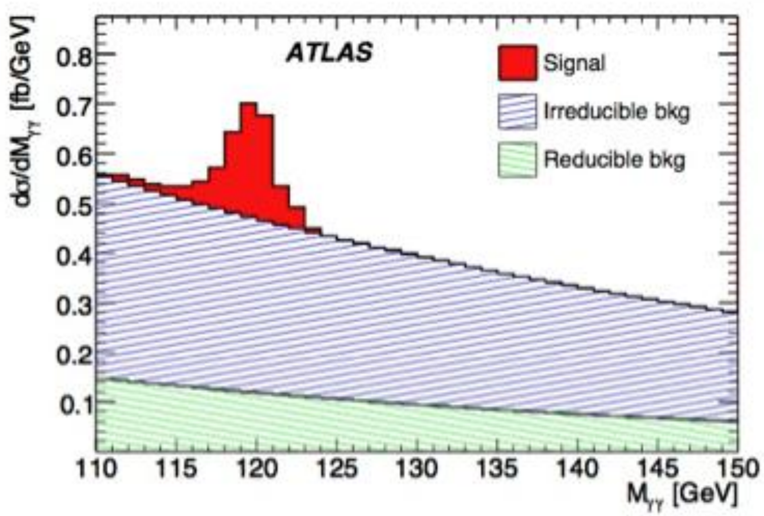
Discovery potential of H→γγ

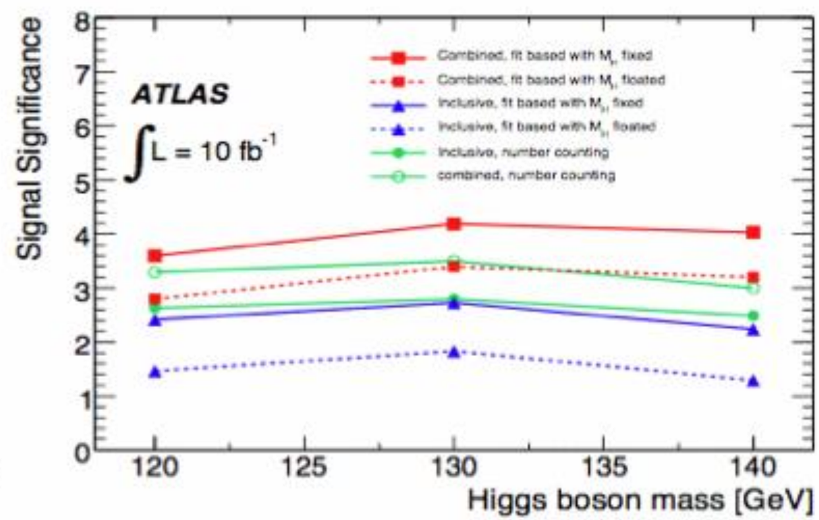




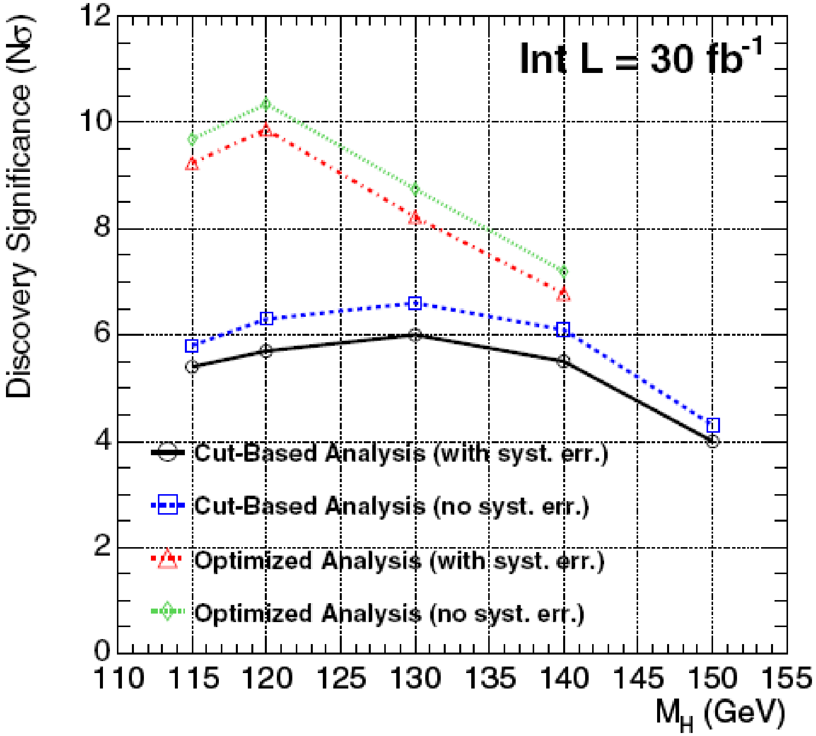
$H \rightarrow \gamma\gamma + 2jet$

Discovery Potential

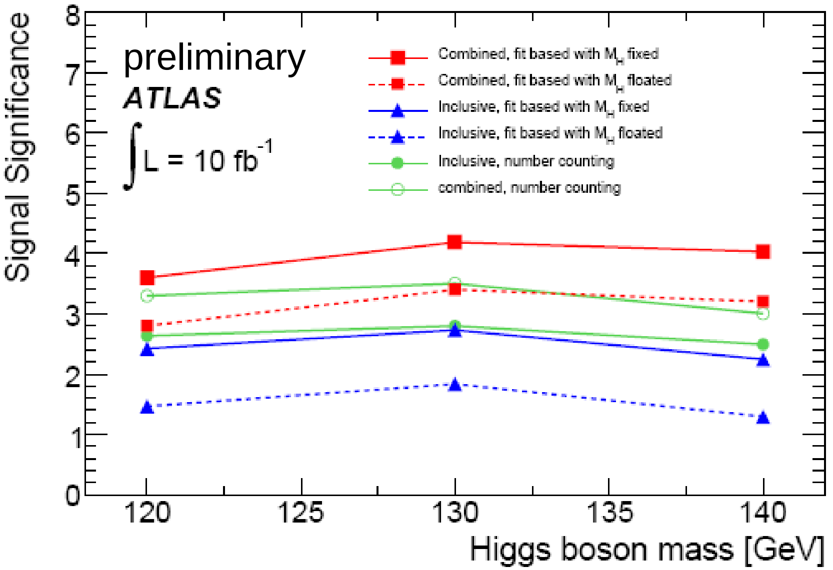




Results for H→γγ



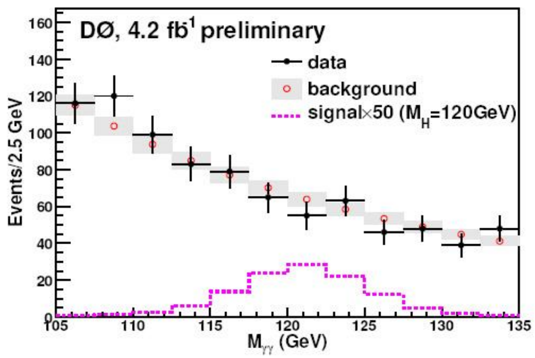
CMS optimized : NN with kinematics as input ,
(η , cluster size, conversions)

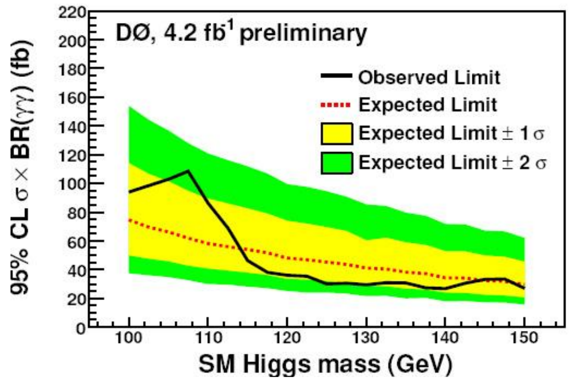


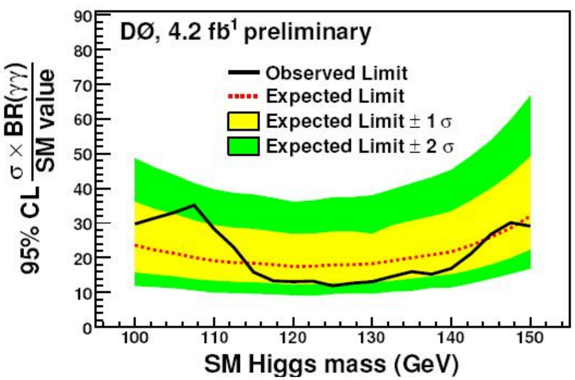
ATLAS : combined fit using
variables (p_T ,# jets , cosθ*)
and categories (η , conversions)

Low mass $X \to \gamma\gamma$

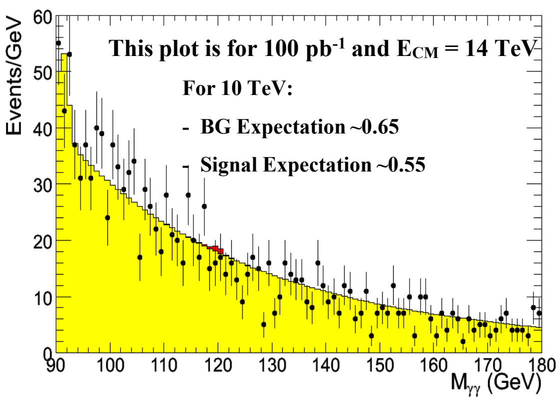
- **Tevatron limits in terms of the expectation for SM Higgs:**
  - **D0 limit r~12 for 4.2 fb^{-1} (lucky stat. fluke, expected r~18)**
  - **with additional 4 fb^{-1}, expect r~10**



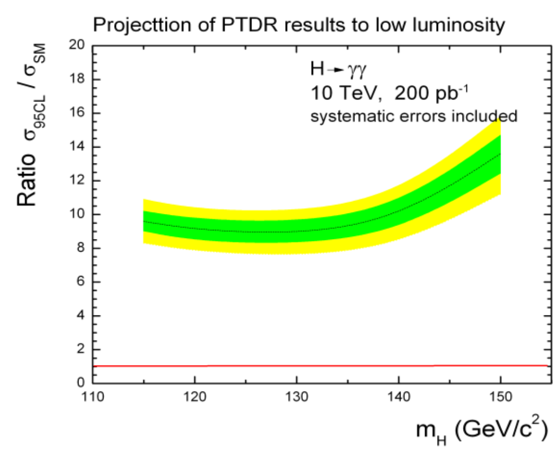




- **CMS expectation (200 pb^{-1}, 10 TeV)**



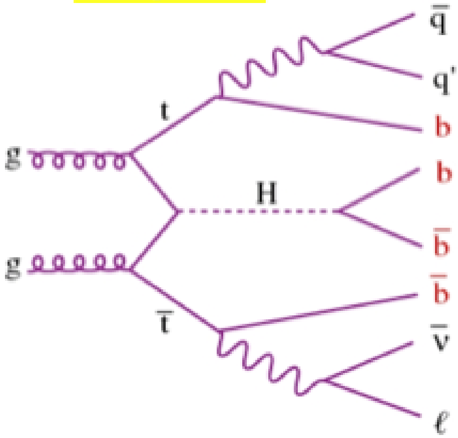
simple counting
(should do better)



Low Mass SM Higgs: ttH→bb

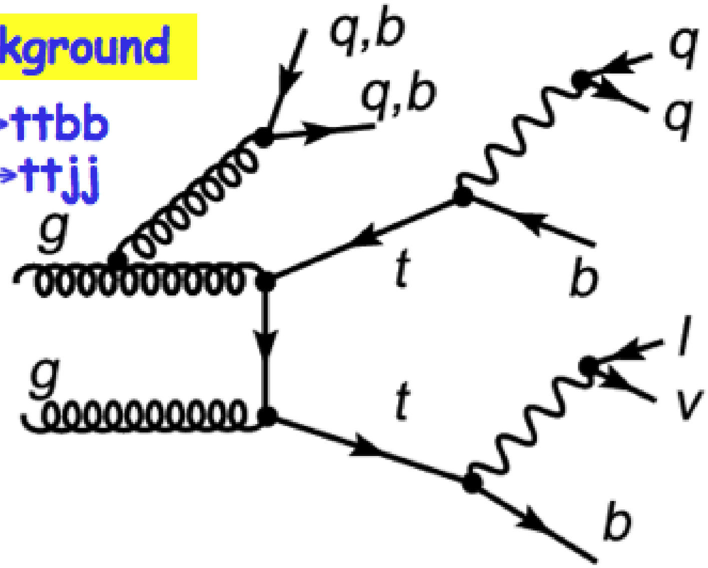
Complex final state: ttH(→bb)→lepton+ν+bbbb+jj

Signal



Background

pp→ttbb
pp→ttjj

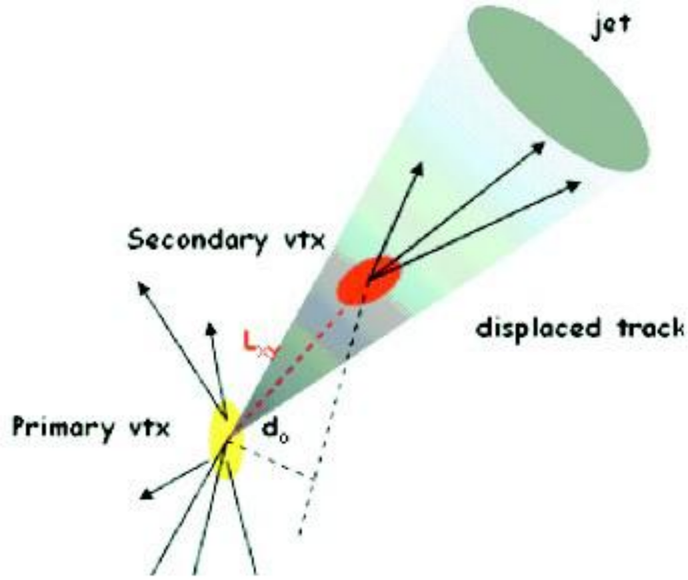


- Analysis very sensitive to b-tagging efficiency (ε_b^4)
  - Parton/Hadron level studies → $\varepsilon_b \geq 60\%$ needed
- Need ~100 times rejection against light jets and ~10 times against charm to suppress ttjj

b tagging

B hadron properties can be exploited to tag b-jets:

- long B lifetime (1.57±0.01 ps)
  - Can travel few millimeters before the decay
  - Secondary vertex displaced few millimeters from the interaction vertex
- high mass (~ 5.2 GeV/c^2)
- high charged decay multiplicity (4.97 ± 0.06)

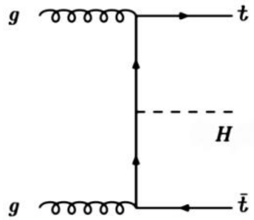


A variety of algorithms is available

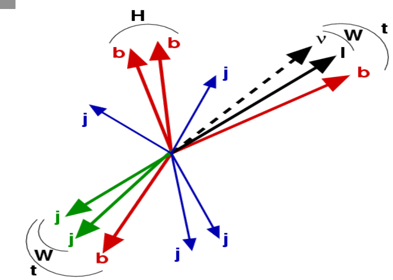
IP- & sec. vertex based; combined with kinematics; soft leptons

Identified robust subset for startup; tagging available at HLT

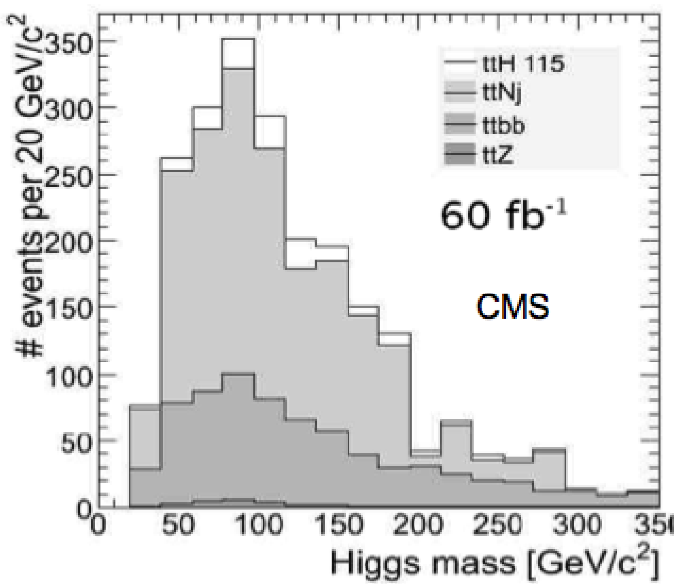
ttH is (was?) the best bet to see H→bb



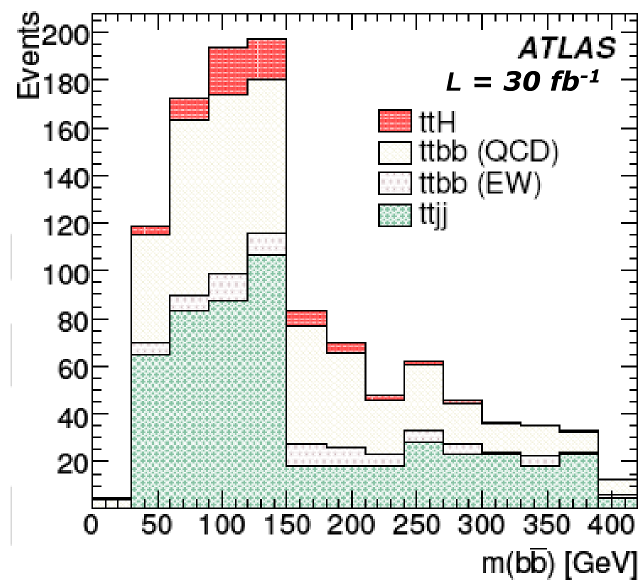
ttH, H→bb



CMS
(M_H=115 GeV)



ATLAS
(M_H=120 GeV)

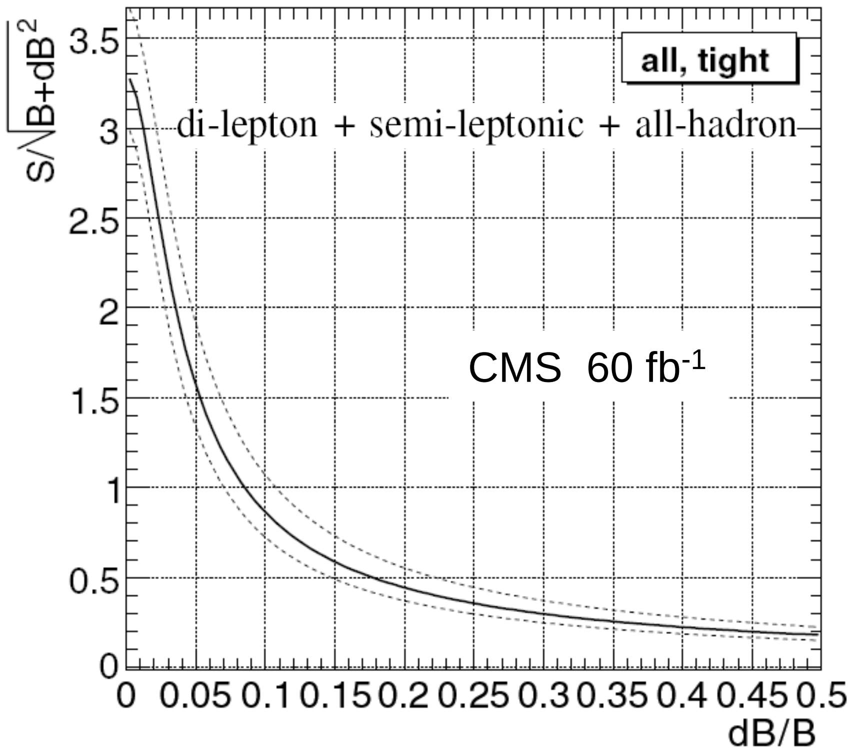


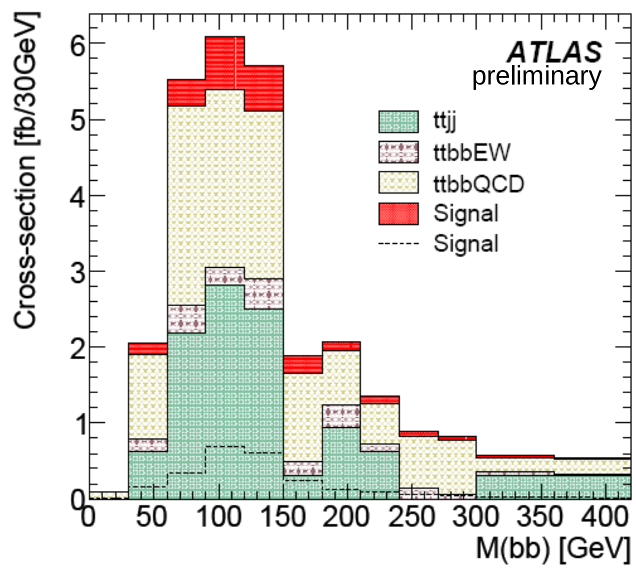
Early projections: might be observable already at L=30 fb^{-1}

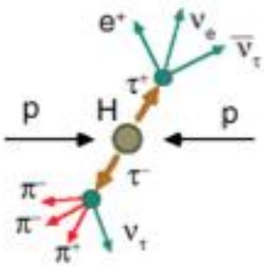
More recent analysis (CMS & ATLAS):
systematic error control at a percent level is needed—not feasible...

ttH, H→ bb

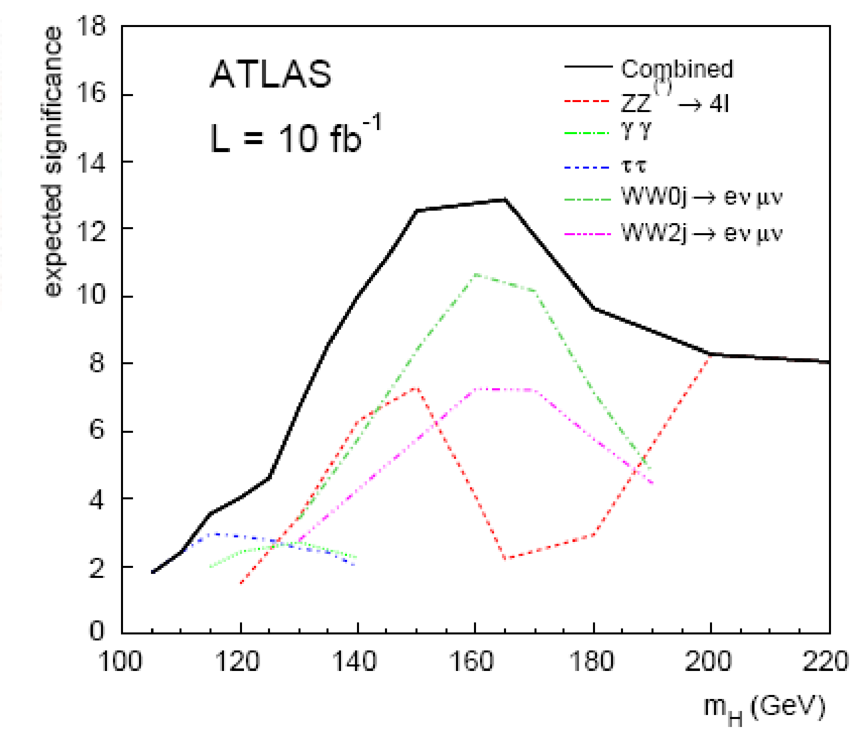
Very difficult
large background , similar to signal

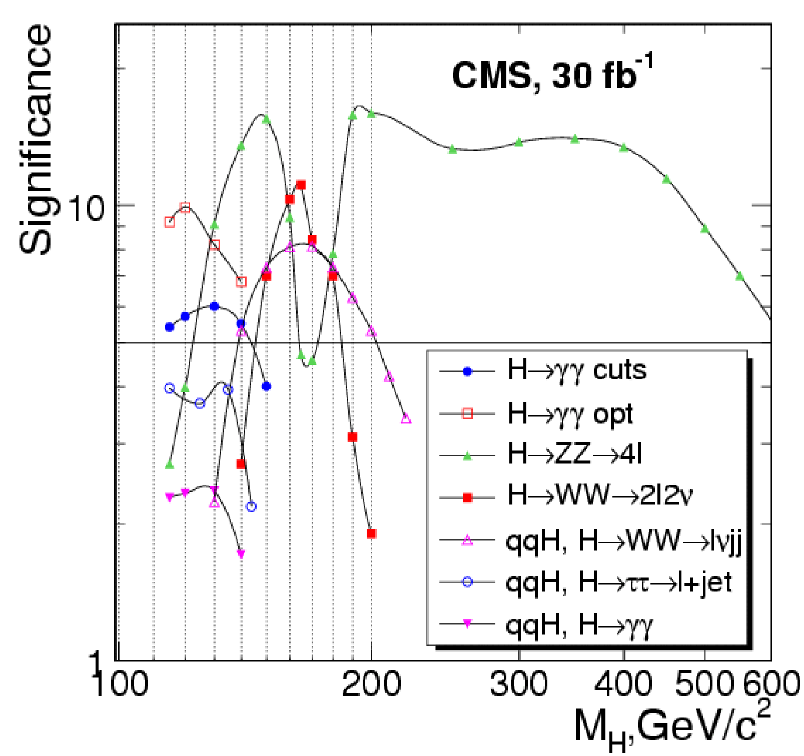





p
H
p
e^+
ν_e
$\bar{\nu}_\tau$
τ^+
τ^-
π^-
π^-
π^+
ν_τ

H→ττ


ATLAS
L = 10 fb^{-1}
Combined
ZZ$^{(*)}$ → 4l
γ γ
τ τ
WW0j → eν μν
WW2j → eν μν
expected significance
m_H (GeV)


CMS, 30 fb^{-1}
Significance
H→γγ cuts
H→γγ opt
H→ZZ→4l
H→WW→2l2ν
qqH, H→WW→lνjj
qqH, H→ττ→l+jet
qqH, H→γγ
M_H,GeV/c^2

Tau lepton decays & identification

- **Leptonic decay mode**

$\tau \to \nu_\tau + \nu_e + e$ (17.4%)

$\tau \to \nu_\tau + \nu_\mu + \mu$ (17.8%)

Tau identification=
electron/muon identification
(ε=80/90%, rejection q(g) jet ~ 0.1%)

- **Hadronic decay mode**

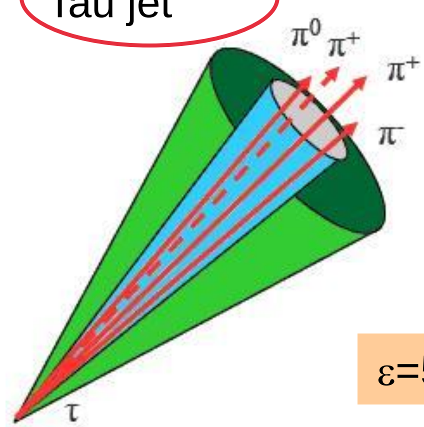
1 prong

$\tau \to \nu_\tau + \pi^\pm$	(11.0%)
$\tau \to \nu_\tau + \pi^\pm + \pi^0$	(25.4%)
$\tau \to \nu_\tau + \pi^\pm + \pi^0 + \pi^0$	(10.8%)
$\tau \to \nu_\tau + \pi^\pm + \pi^0 + \pi^0 + \pi^0$	(1.4%)
$\tau \to \nu_\tau + K^\pm + n\pi^0$	(1.6%)

3 prong

$\tau \to \nu_\tau + 3\ \pi^\pm + n\pi^0$ (15.2%)

Tau jet



Tau jet identification

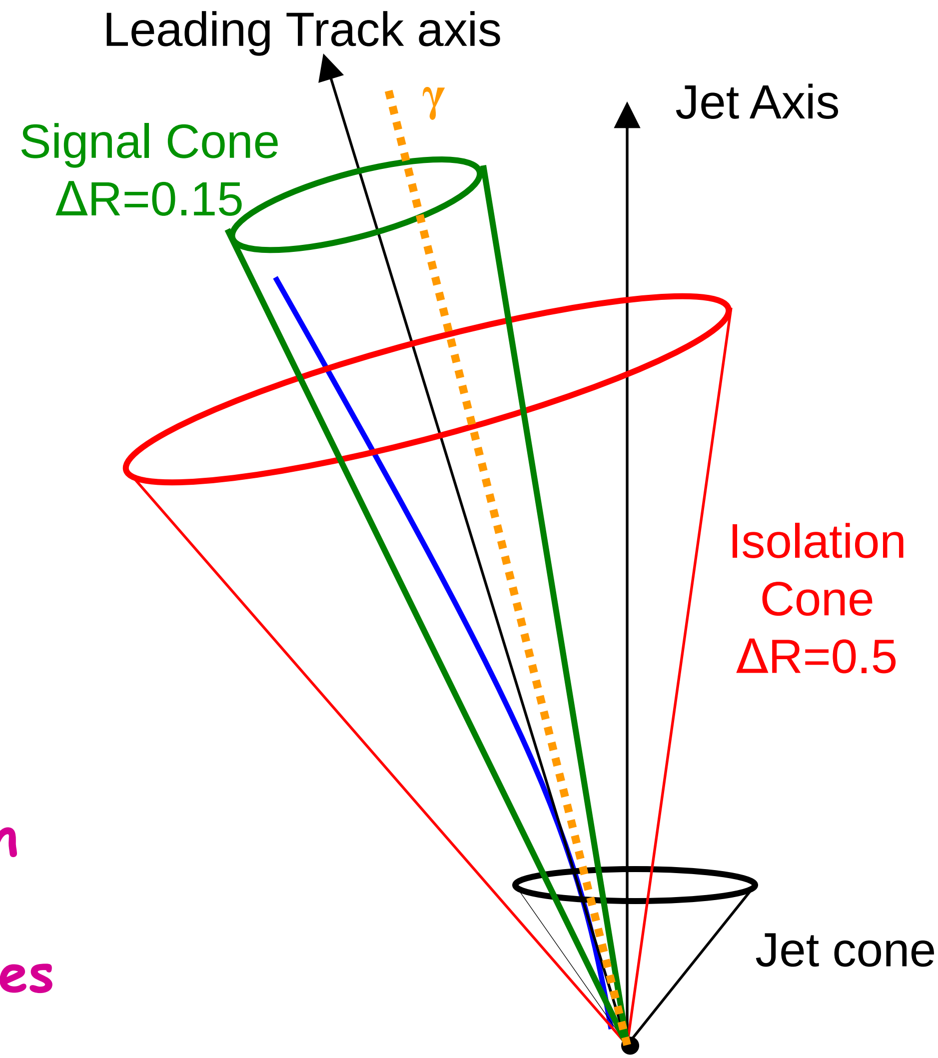
1 - 3 tracks ,
impact parameter,
shower shape,
secondary vertex,
energy sharing of neutral and charged pion component

ε=50%, rejection q(g) ~ 1%

τ Identification with Cone Isolation

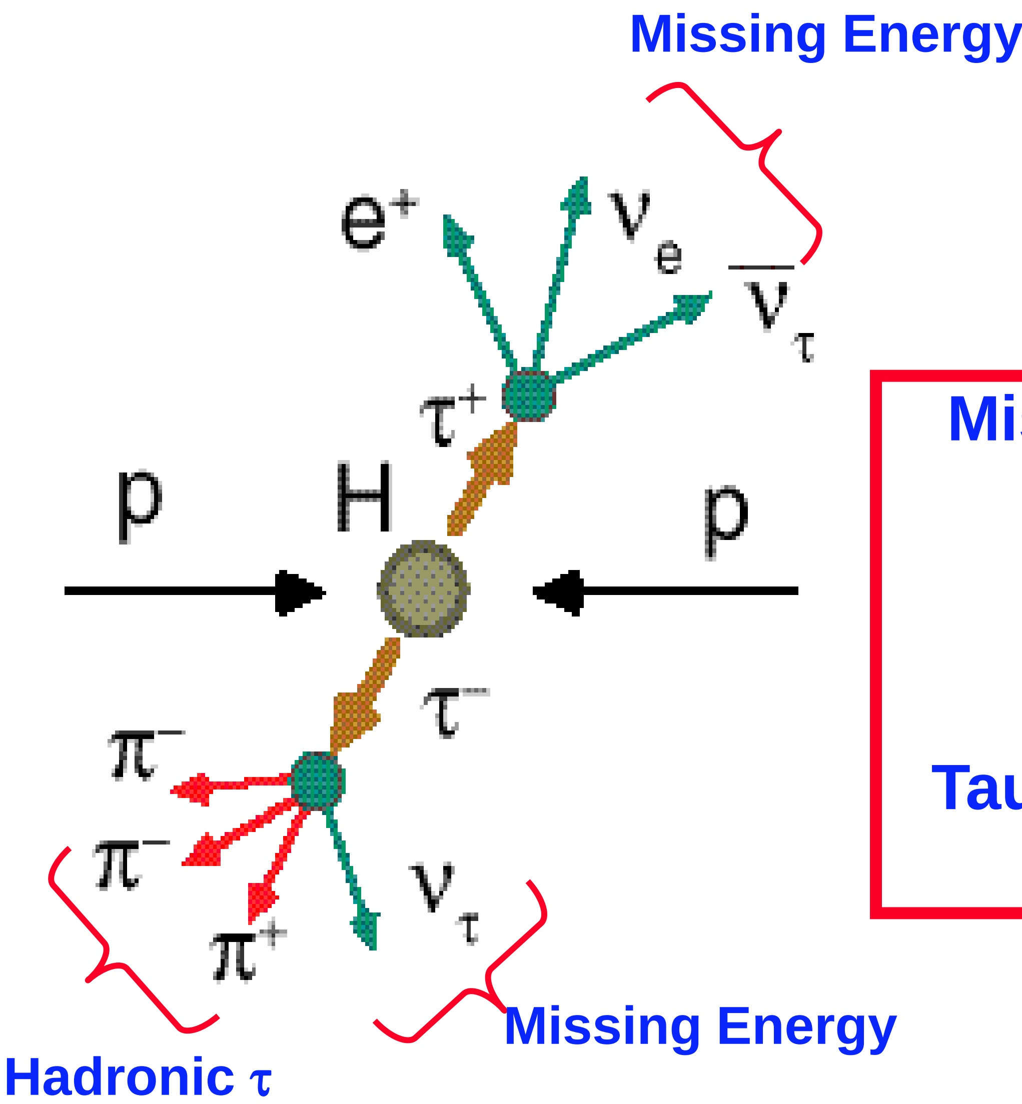
Two algorithms

- CaloTau Algorithm
  - Associates tracks to jets
  - Identifies τ by track isolation
- Particle Flow
  - The algorithm
    - Reconstructs particles
    - Applies Pt corrections in particle level
    - Forms jets from particles



Require no charged, γ candidates in isolation annulus

Low Mass Higgs: $H \rightarrow \tau\tau$



Outstanding issues

Missing E_T reconstruction

Lepton Identification

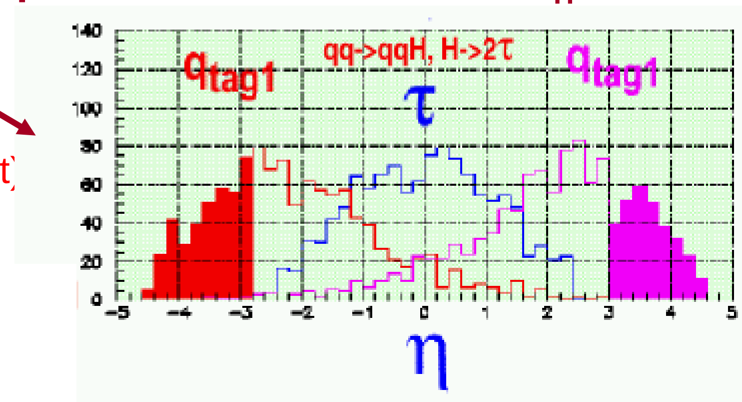
Tau tagging (likelihood, NN methods)

VBF qqH, H $\rightarrow \tau\tau \rightarrow$ l+jets

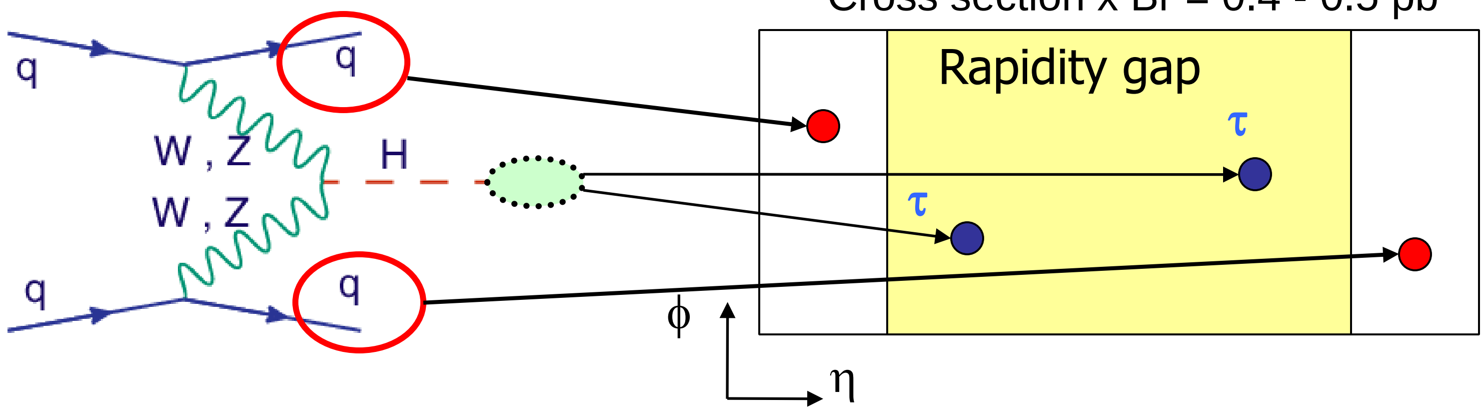
- Both experiments are focusing on VBF production channel, since it allows to improve s/b ratio.
- ATLAS performed studies on all final states (l l, l + jet, jet jet)
- CMS focused in the recent past on l + jet decay channel
- Main backgrounds:

  Z + jets, W + jets, tt and QCD → detailed study done in CMS about background estimate from data

Important channel in 115 < m_H < 145 GeV.



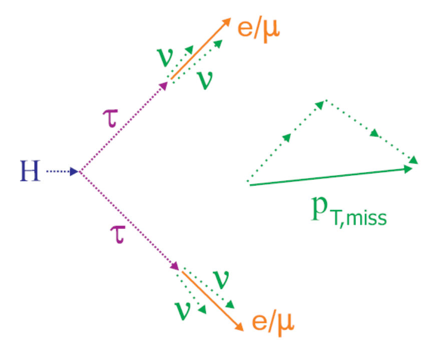
Cross section x Br = 0.4 - 0.5 pb



Characteristics of signal :

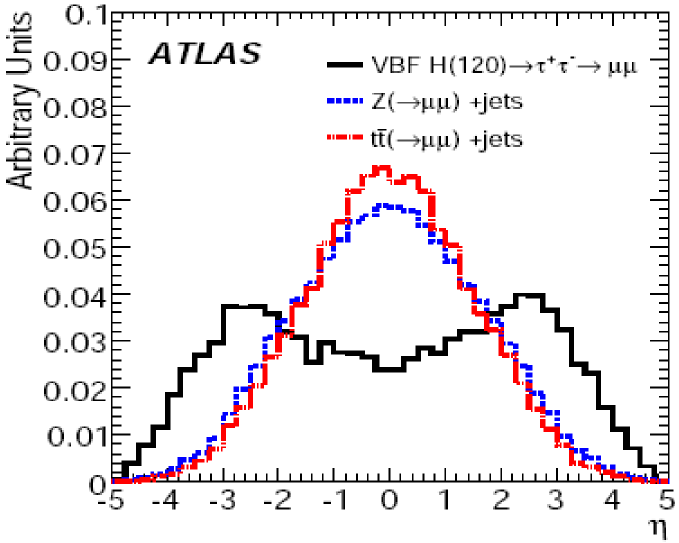
+ Central tau decay products
+ high p_T forward quark initiated jets, separated in η
+ other jets between the two quark initiated jets suppressed (no colour flow between two quark jets)
+ missing energy in the transverse plane (due to taus)

Invariant mass of the τ pair reconstructed via the collinear approximation

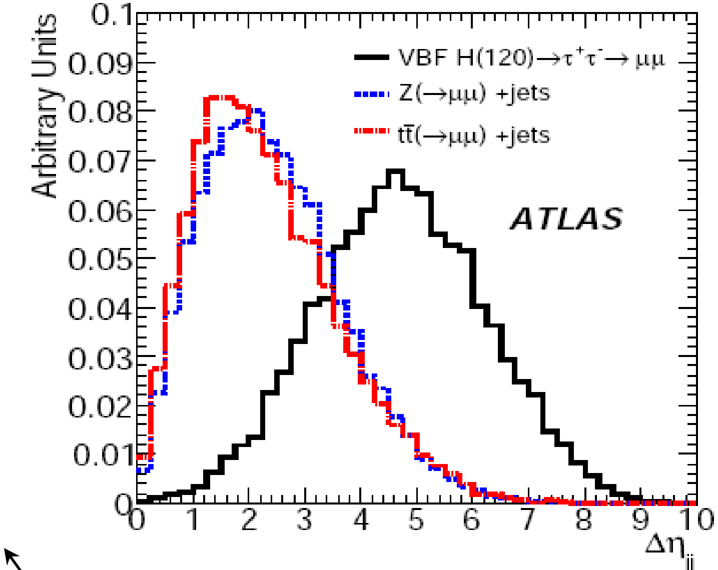


Rapidity gap in VBF processes

PRELIMINARY

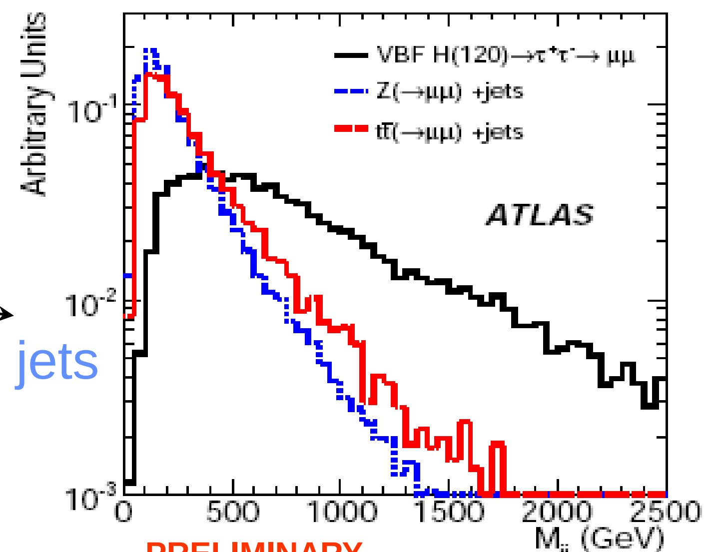


PRELIMINARY



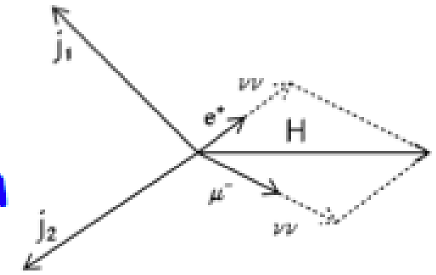
- Find central taus
- Look for first and second highest pT jet in the event

High pT forward jets



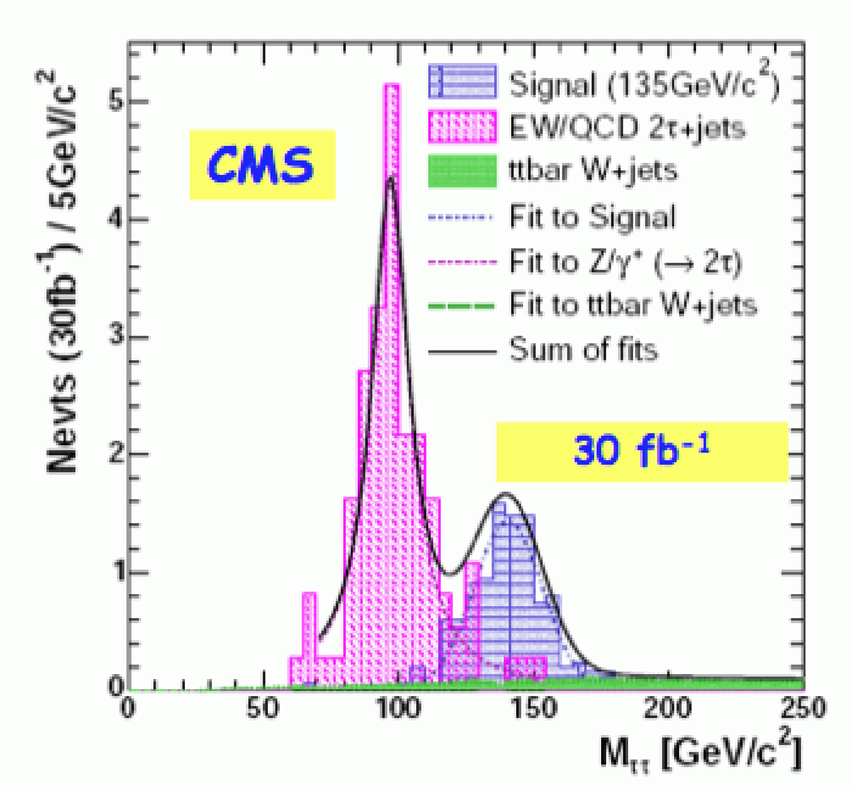
PRELIMINARY

Low Mass SM H→ττ+jets

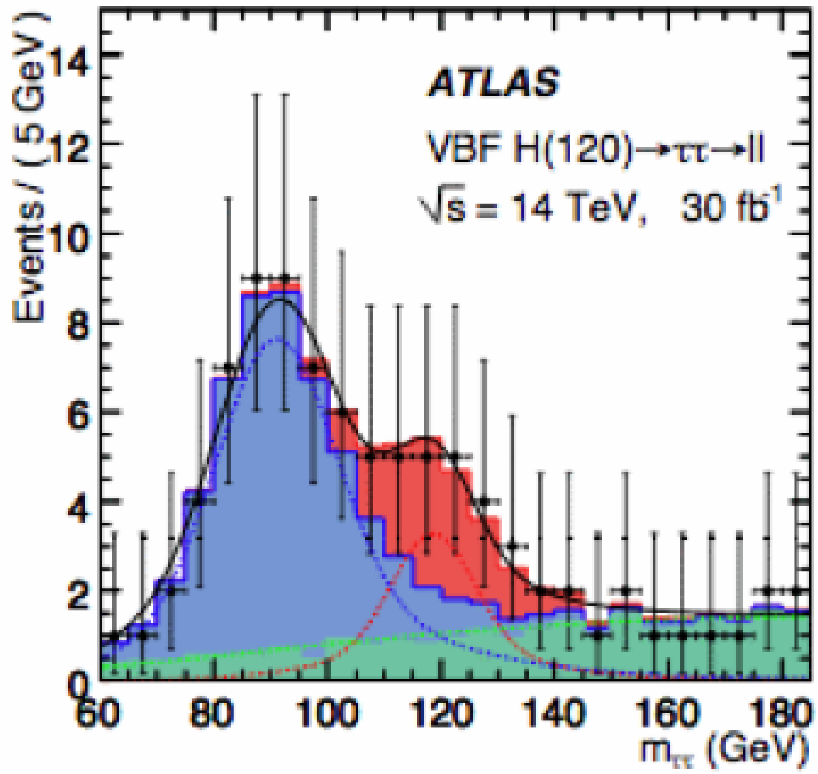


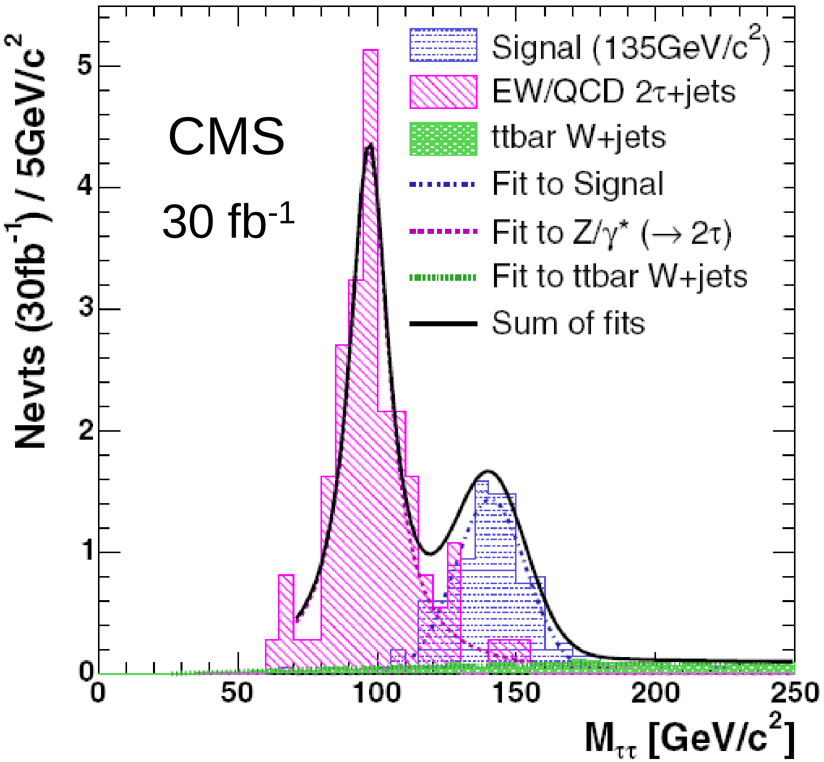
- Reconstruct Higgs mass with collinear approxim

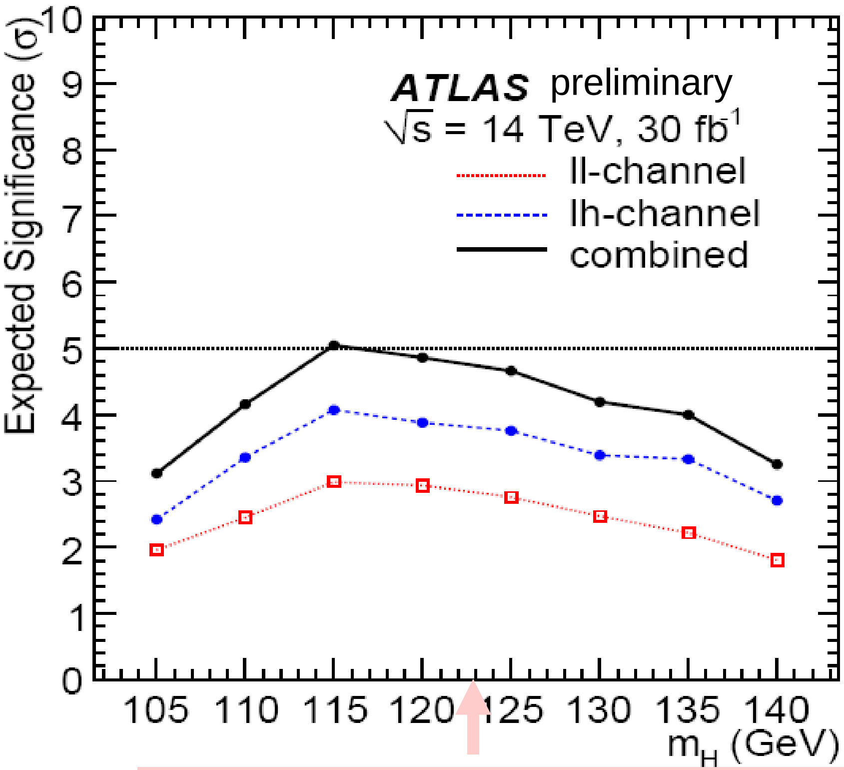
H(→ττ→lh) +≥2jets



H(→ττ→2l) +≥2jets



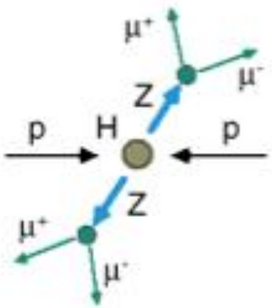




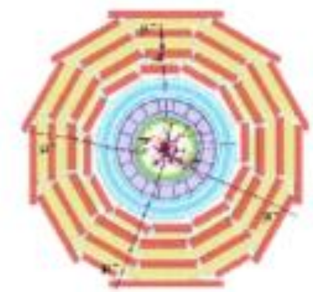
similar in CMS , slightly tighter cuts (pile-up included $L = 2\ 10^{33}\ cm^{-2}\ s^{-1}$)

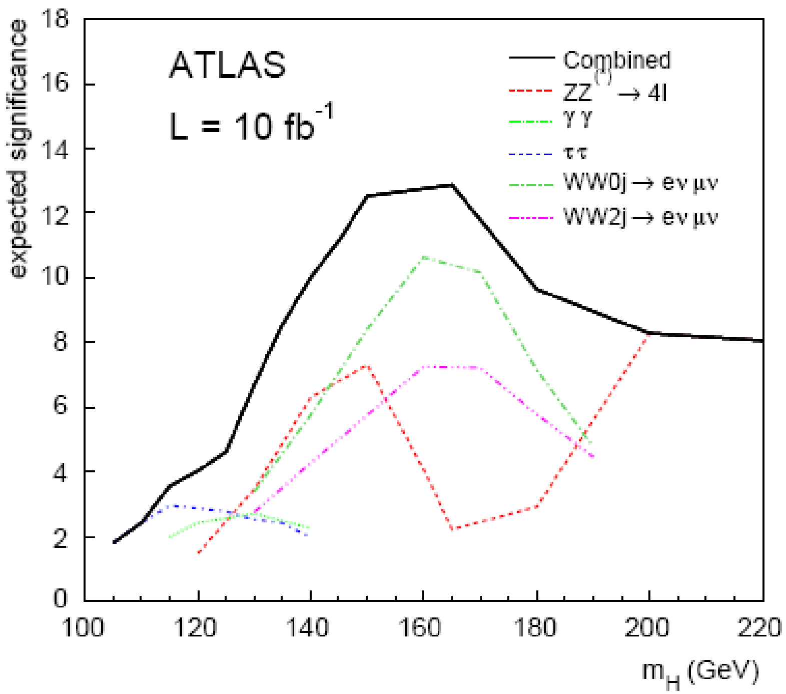
Significance at 30 fb^{-1}:

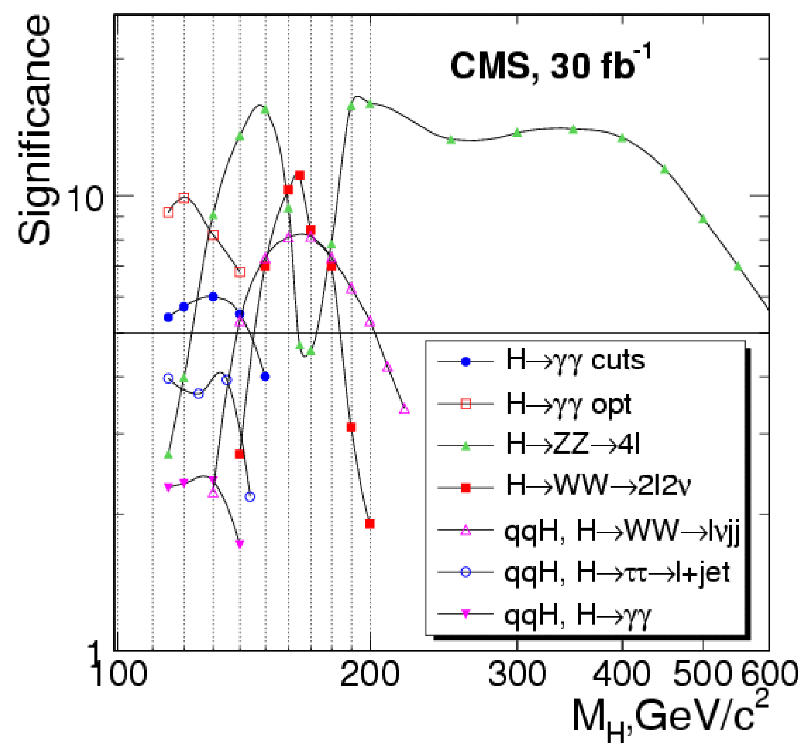
- ATLAS: $\tau\tau \rightarrow$ l + jet M_H=130 GeV , Sign. 4.4
- CMS: $\tau\tau \rightarrow$ l + jet M_H=135 GeV , Sign. 3.98



SM Higgs: $H \rightarrow ZZ^{(*)} \rightarrow 4l$

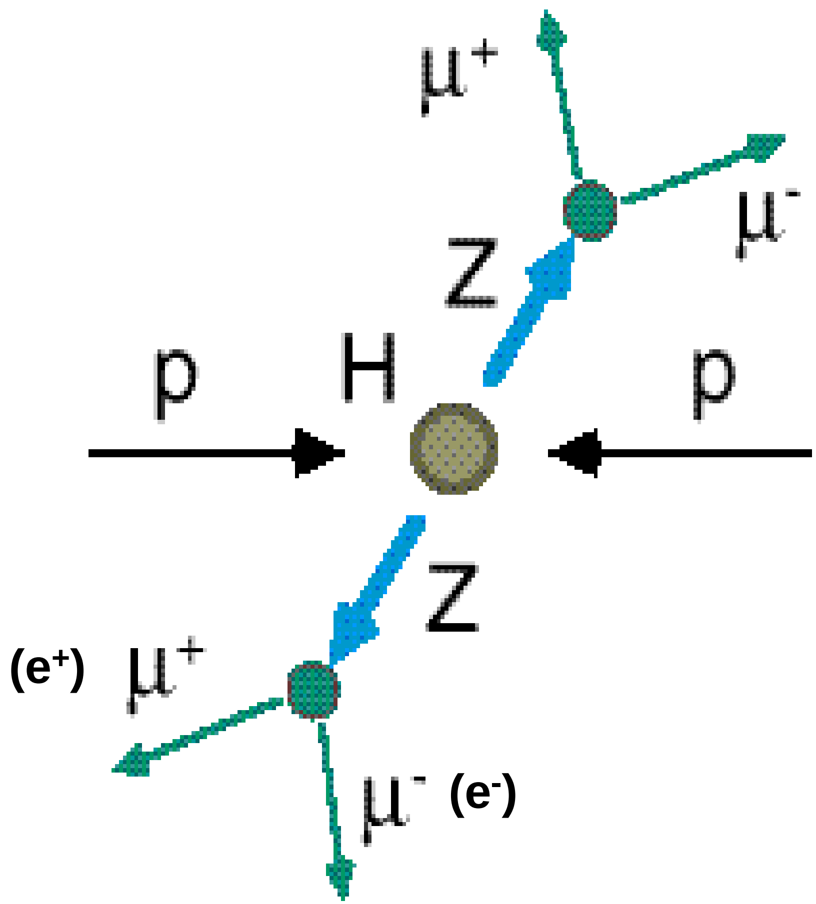






Intermediate and Heavy Higgs:
(M_H>140 GeV) $H \to ZZ^{(*)} \to 4l$

Fully reconstruct Higgs kinematics



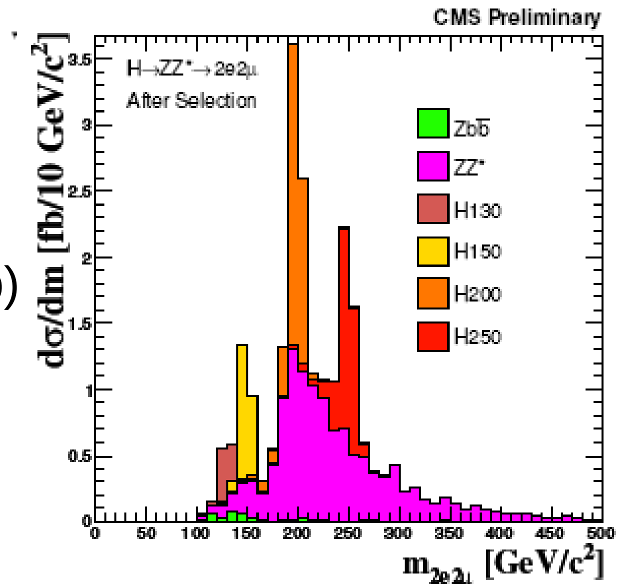
Outstanding issues

Lepton Identification and Isolation

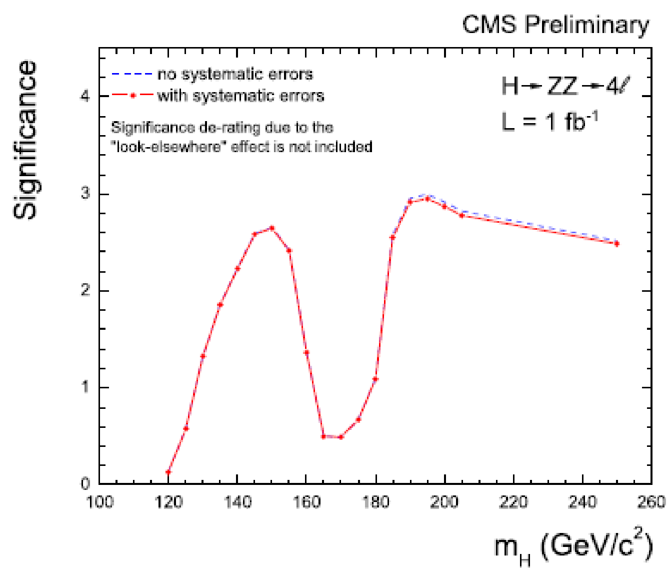
Suppression of backgrounds coming from tt and Zbb

H → ZZ → 4l analysis

- **Signatures:** 4e,4mu and 2e2mu final state
- **Backgrounds:**
  - *irreducible* ZZ (each virtual or real Z in $\mu^+\mu^-$)
  - *reducible* Zbb (Z in $\mu^+\mu^-$ and semilept. decay of b)
  - *reducible* tt (each t in bW and semilept. decay of b)
  - and tt+jets, Z+jets, W+jets, QCD



- **Preselection strategy:** (to get rid of QCD bkg with fake leptons)
  - Single & double lepton triggers
  - 4 loose isolated leptons opp. charge and eleId
  - m_{ll}>12 GeV, m_{4l}>100 GeV



- **Main selection observables:**
  - tight isolation (against tt, Zbb)
  - impact parameter (against Zbb and tt)
  - 50<m_Z<100 GeV, 20<m_{Z*}< 100 GeV

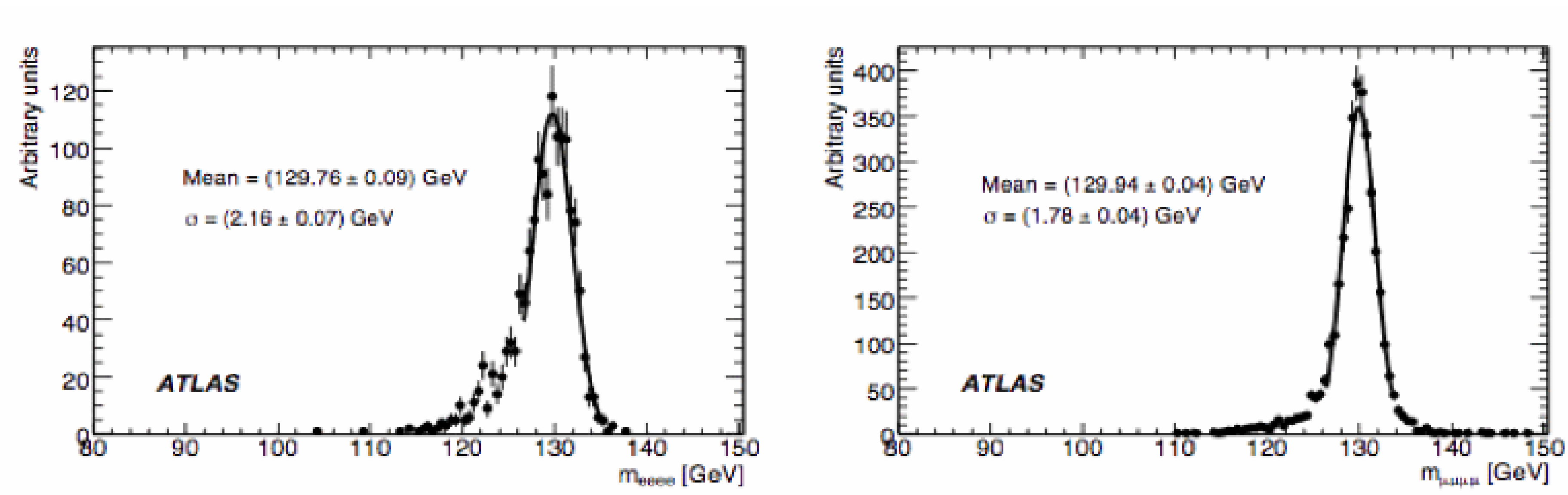
→ Baseline cut-based analysis, m_H-independent, able to get rid of main bkg → first observation with reasonable lumi

SM Higgs→ZZ$^{(*)}$→4l

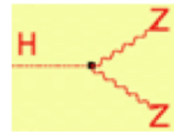
- Able to reconstruct a narrow resonance, with mass resolution close to 1%. Can achieve excellent signal-to-background > 1
  - Major issue: Lepton ID and rejection of semi-leptonic decays of B decays. Suppress reducible background Zbb,tt→4l

H[130 GeV]→4e

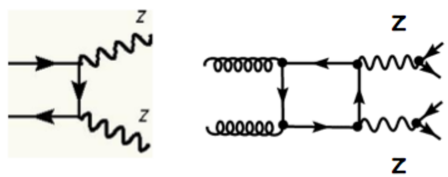
H[130 GeV]→4μ



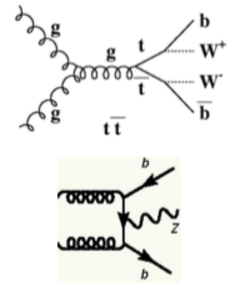
Higgs decay to Z^0Z^0

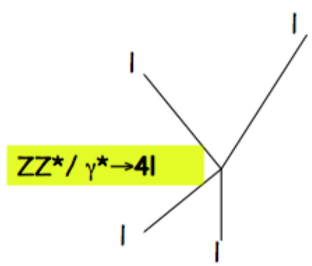


Irreducible Z^0Z^0 backgrounds

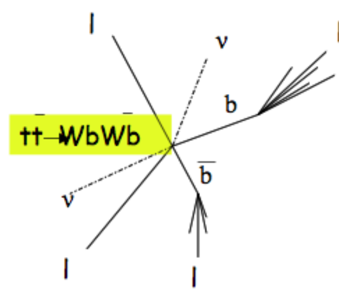


Reducible 4l backgrounds

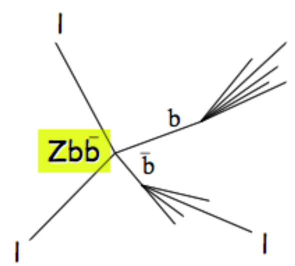




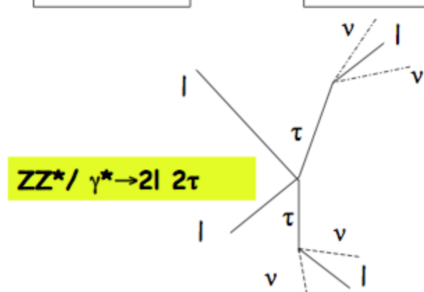
Continuum Irreducible



Non-Resonant reducible

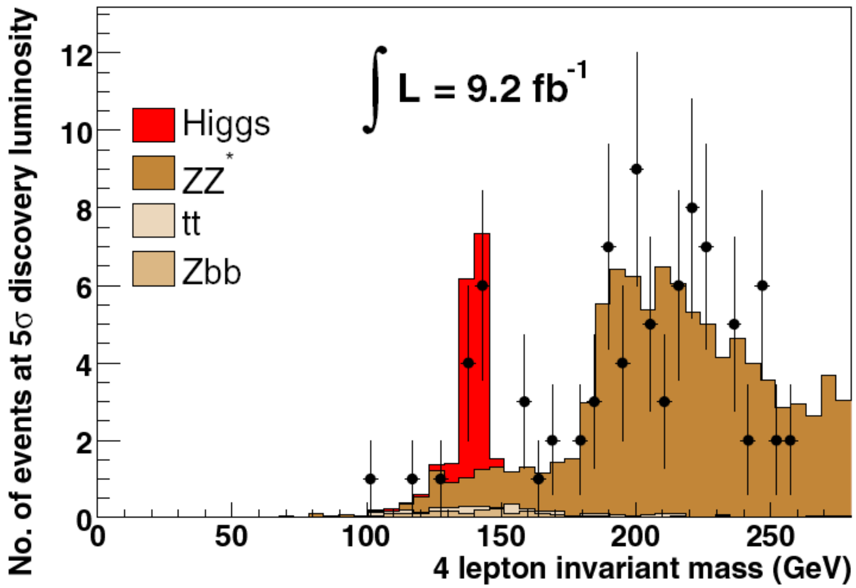


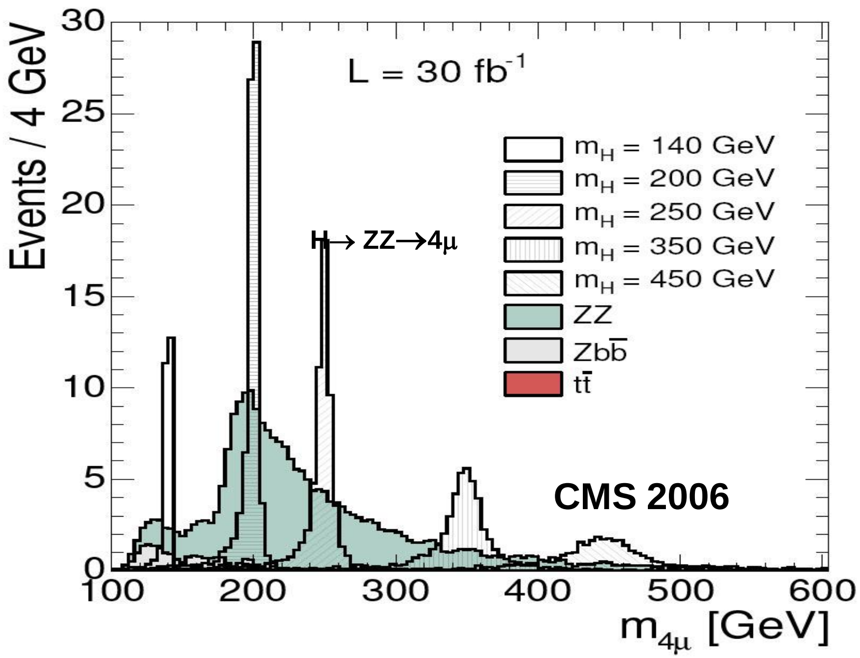
Resonant reducible

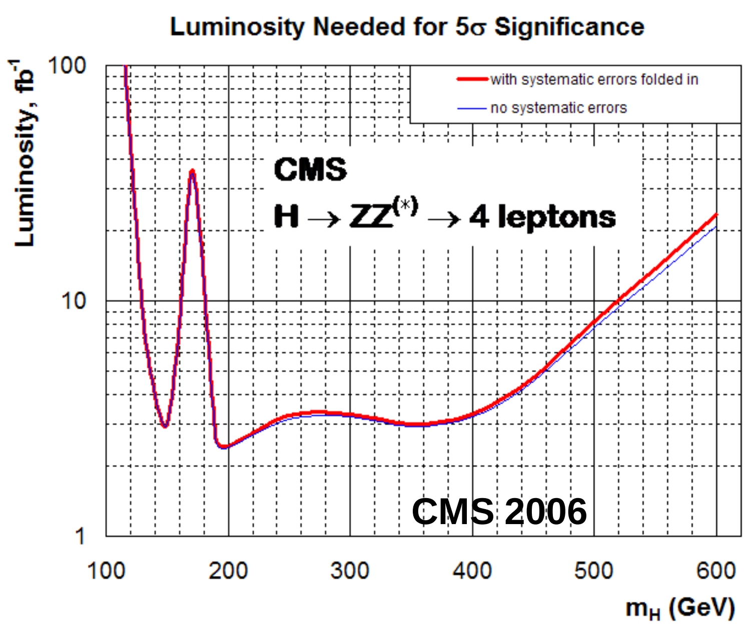


Backgrounds Higgs→$ZZ^{(*)}$→4l ($l=e\mu$)

SM Higgs: H→ZZ→4l





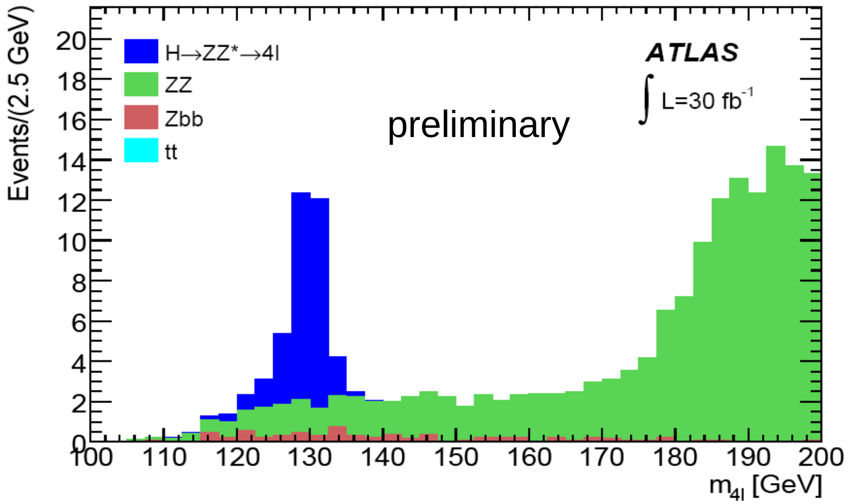


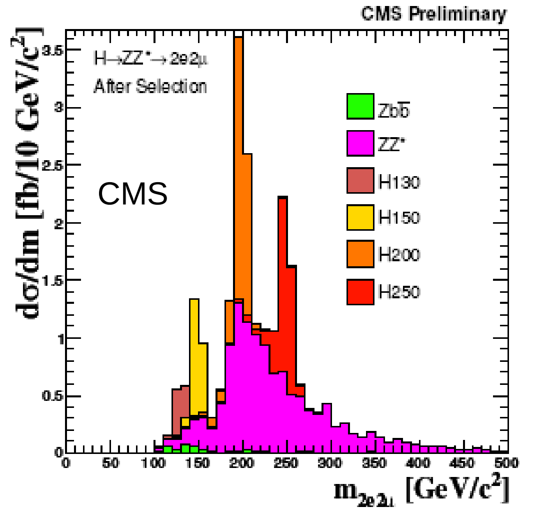
$H \to ZZ \to 4l$, update 2008

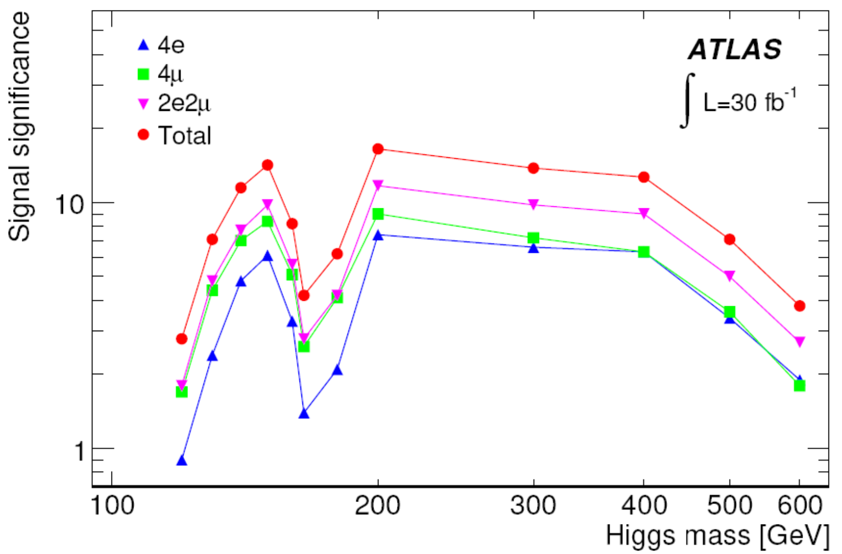
eeμμ 4μ 4e

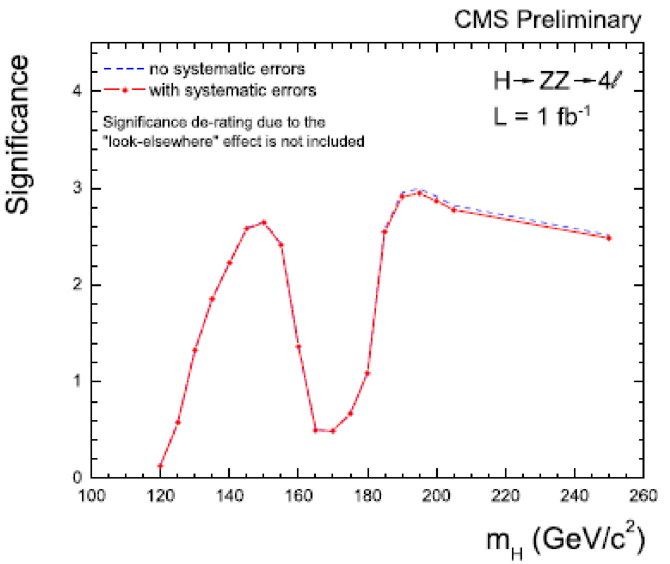
Main backgrounds : ZZ (irreducible) , tt and Zbb (reducible)

Tools for background suppression : lepton isolation and impact parameter





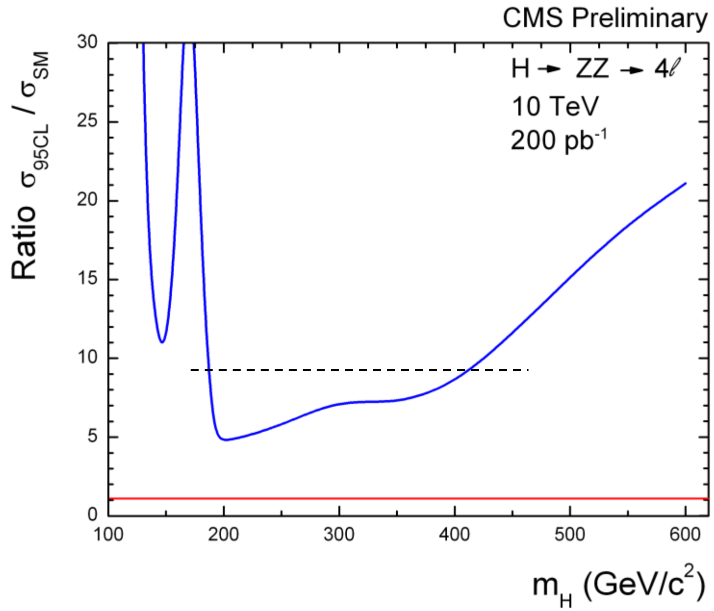




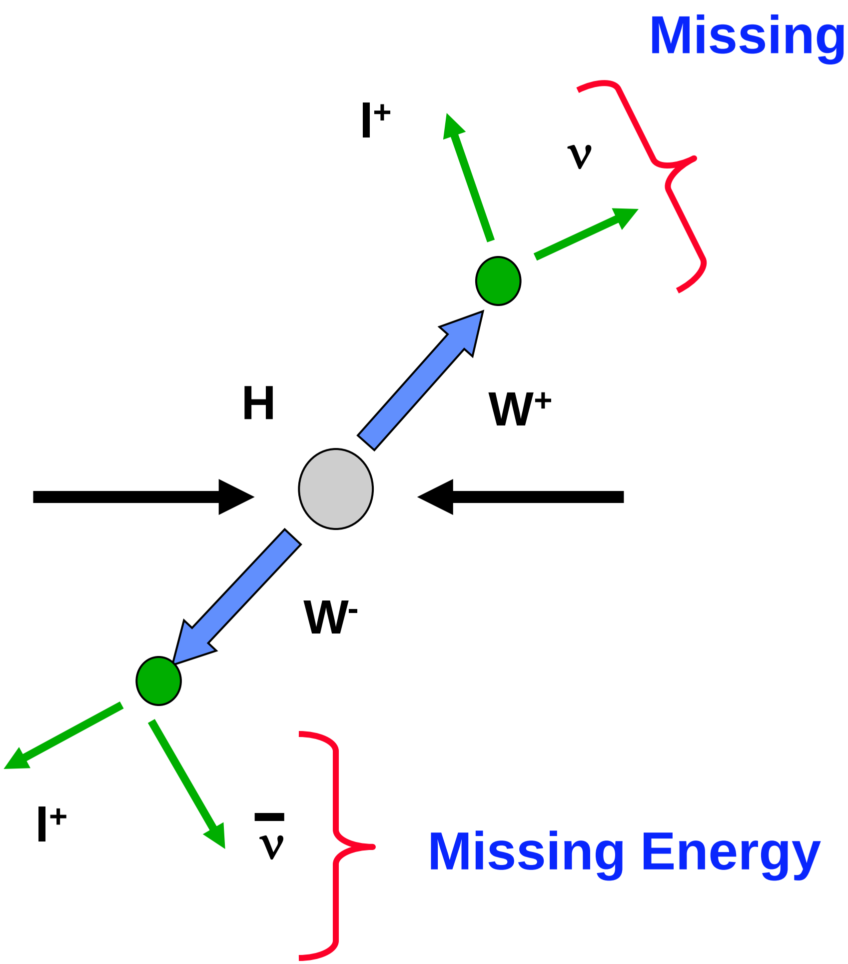
$H \to ZZ \to 4l$ (10 TeV 200 pb^{-1})

- **currently no limits from Tevatron**
- **for m_H>200 GeV, LHC10 x-section >40 x (Tevatron)**
- **projection: we can reach limit r = $\sigma_{95\%CL}/\sigma_{SM}$ ~ 5-10** (m_H~200-400)
- **meaningful in context of 4-generation models**
  which boost the gg-fusion x-section by a factor of ~9
  (4^{th} generation with Higgs m_H<200 is excluded by Tevatron)

scaling down PTDR
and CMS-AN2008/050
down to 10 TeV and 200 pb^{-1}
- ~3 bkgd events in the full spectrum
- 0.7 signal events for the best m_H~200



Intermediate mass Higgs: $(140<m_H<200\ \text{GeV})$ $H\rightarrow WW^{(*)}\rightarrow 2l2\nu$



Main search channel for range $140 < m_H < 2m_Z$

Highest branching ratio for $m_H > 140$ GeV/c^2: 95% at $m_H = 160$ GeV/c^2

Signal: 2 high p_T isolated leptons, missing E_T and no central jets

Background: WW, tt, W+jets, Z+jets, tW, WZ, ZZ..

No mass peak (undetected ν's)➔needs a good background understanding

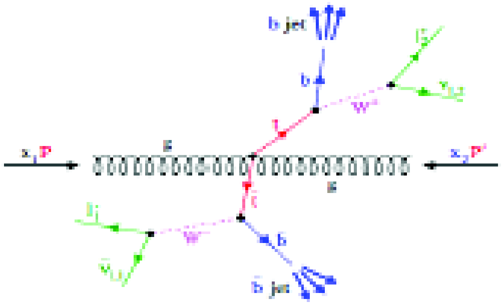
$H \to WW^*$

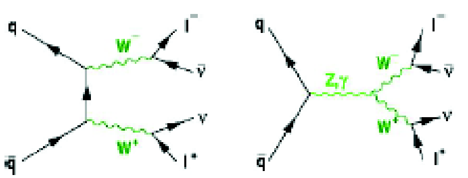
Difficulty:

- **Counting experiment, essentially no mass reconstruction and no mass peak**
- **Rely on accurate estimate of background rate**
- **Strategy: Use control region(s) to estimate background(s) and extrapolate to signal region**

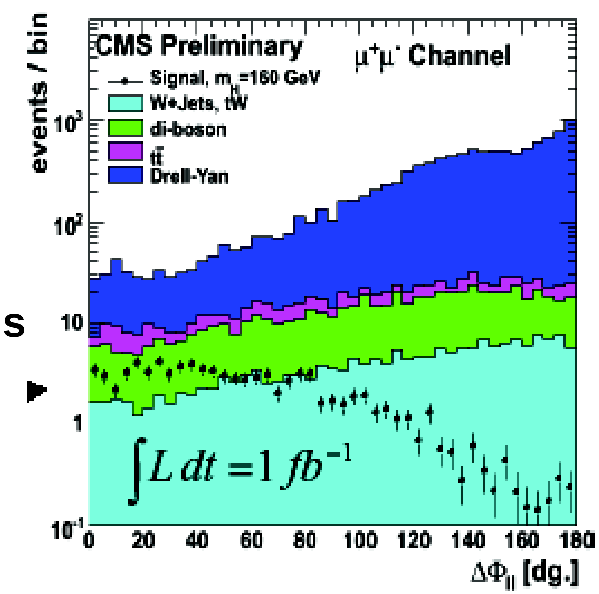
Backgrounds: two main discriminants

- **t-tbar production: rejected by jet-veto** (i.e. reject events with central jets since ttbar process slightly favors central jets)
- **WW continuum: Use spin correlation to distinguish signal from background**

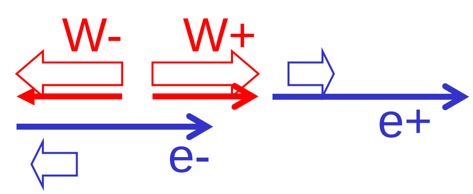


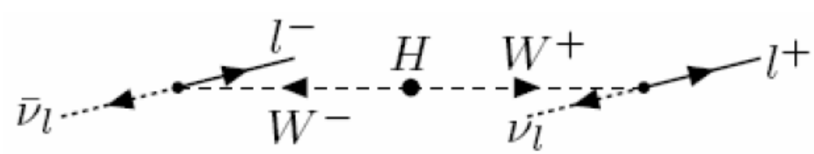


Angle between leptons in transverse plane (small opening angle for the signal due to spin correlations)



Spin 0 decay





$H \to WW \to \mu e + \nu\nu$

H →W W(*) is the dominant Higgs decay mode in a wide mass range
for: $\mathbf{2m_W < m_H} < \mathbf{2m_Z}$ the BR is ~ 1.

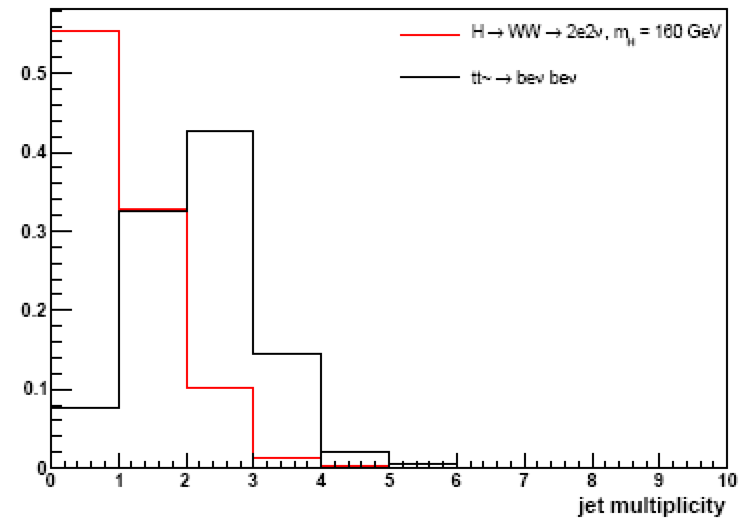
$pp \to H \to WW \to l\nu l\nu$	
m_H [GeV]	σ_{NLO} [pb]
160	2.34
170	2.26
180	1.99

Signal: clean signature of two high pT leptons and missing energy

Main backgrounds:
Di-boson production, especially **WW** (but also **WZ, ZZ**) ,
ttbar (**tW** and **bb** also),
Drell-Yan, **W + jets** (jets faking electrons)…

Process	WW	WZ	ZZ	ttbar	tW
σ_{NLO} [pb]	114,4	49,9	15,2	840	62

- The jet reconstruction is **fundamental** to ensure an efficient background rejection.
- The kinematics of the ttbar process slightly favors central jets → **jet veto (i.e. reject events with central jets)**



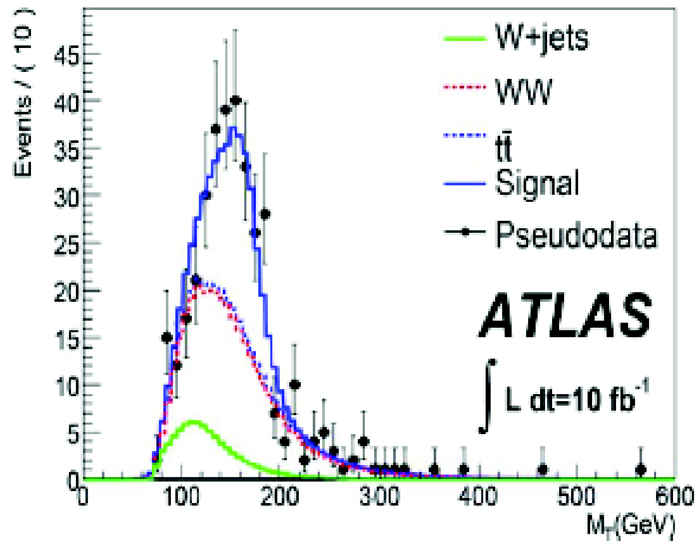
Other cuts on: lepton isolation, p_T of leptons, MET, $\Delta\Phi_{ll}$, Inv. m of lept

$H \to WW^* \to ll\nu\nu$ analysis strategy

ATLAS **(eμ final state, H+ 0j, H+2j analysis)**

- **Preselection:**
- **2 opposite-sign isolated and identified leptons**
- **Cuts on m_{ll}, MET, $\Delta\varphi_{ll}$, Z | | removal**
- **Central Jet veto & b-tag veto**
- **Final selection:**

2D Fit of transverse mass and p_T in 2 bins of di-lepton azimuthal angle $\Delta\varphi_{ll}$ to extract S/B ratio in signal region



CMS **(ee, μμ, eμ final states, H+0j analysis)**

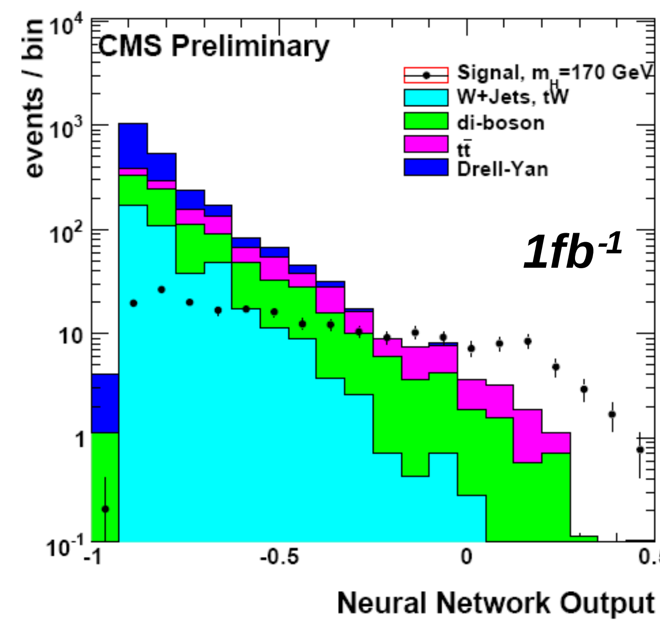
- **Preselection:**
- **2 opposite-sign isolated and identified leptons**
- **Cuts on m_{ll}, MET**
- **Central Jet Veto**
- **Variables used to reduce background :**

p_T of the leptons, m_{ll}, $\Delta\varphi_{ll}$, MET

- **Final selection:**

Mass dependent cut based & multivariate analysis

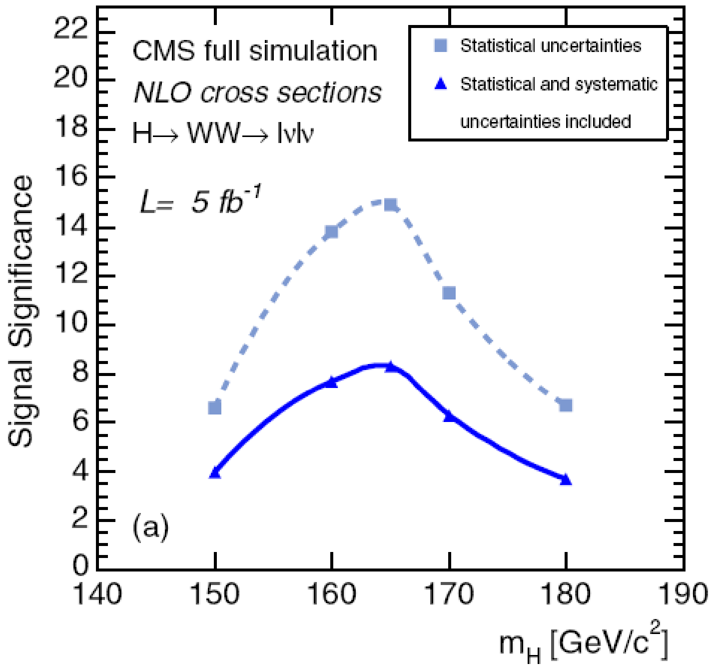
- ***Control regions: fake leptons, background normalization***



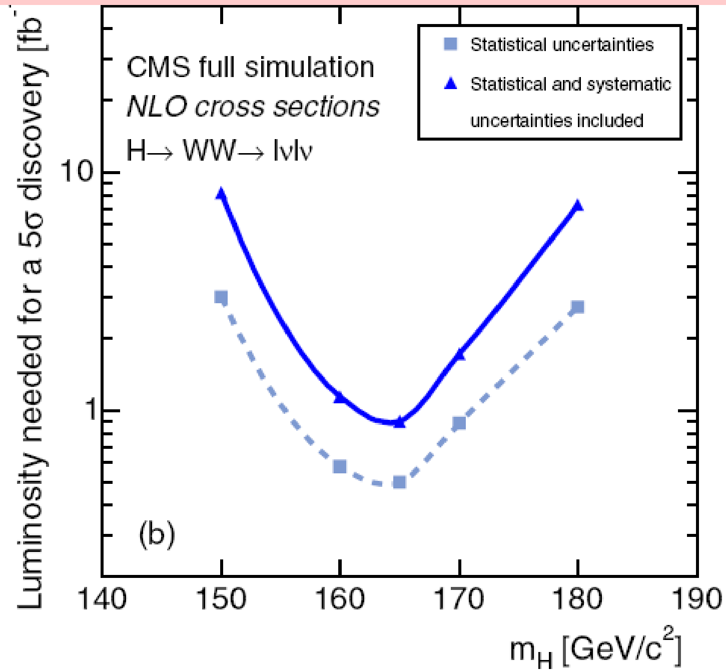
CMS Results for H → WW* → llνν

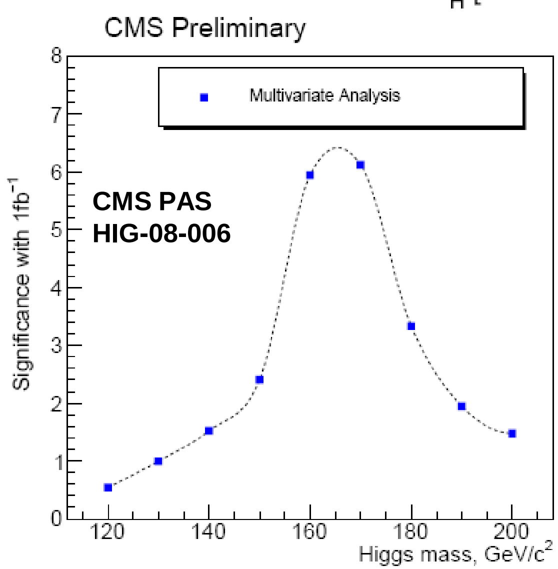
could be a discovery channel at modest L

systematic effects important (especially at high L)



CMS 2005





Updated CMS result:

Sensitivity to a SM Higgs improved using a mass dependent multivariate analysis

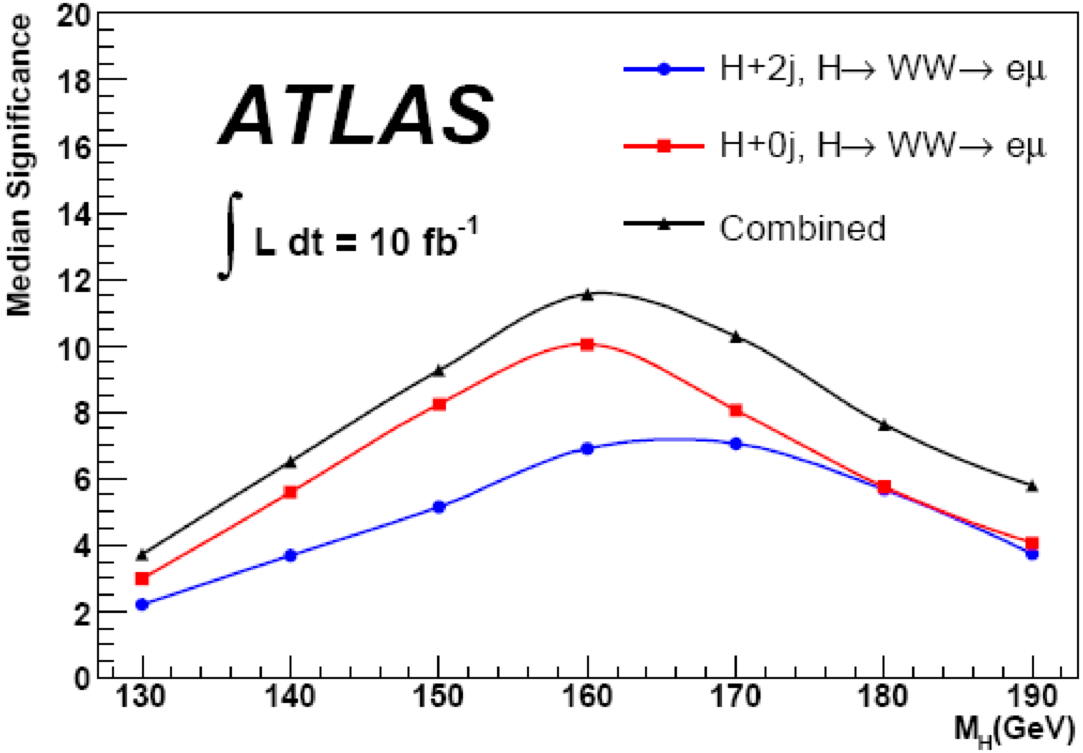
Improvements on Lepton ID ,
mass dependent cuts,
more data driven approaches

Cuts have been optimized separately for $1fb^{-1}$ maximizing the expected statistical significance.

H→WW*→ eμ νν, ATLAS update 2008

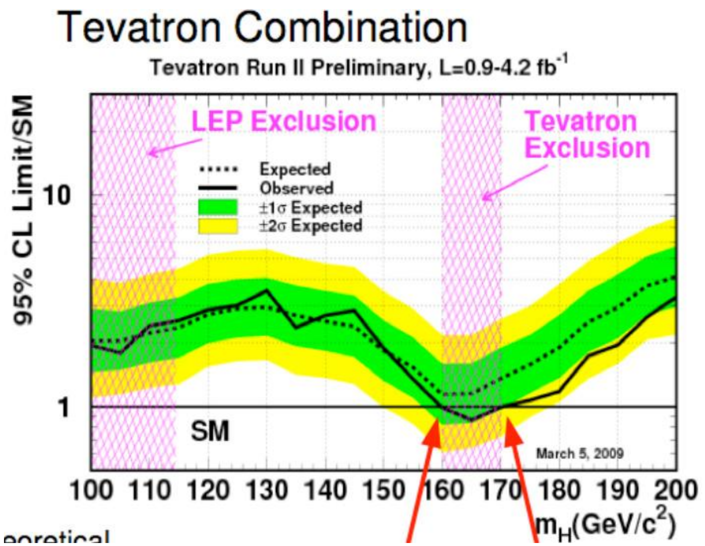
ATLAS updated only eμ-channel

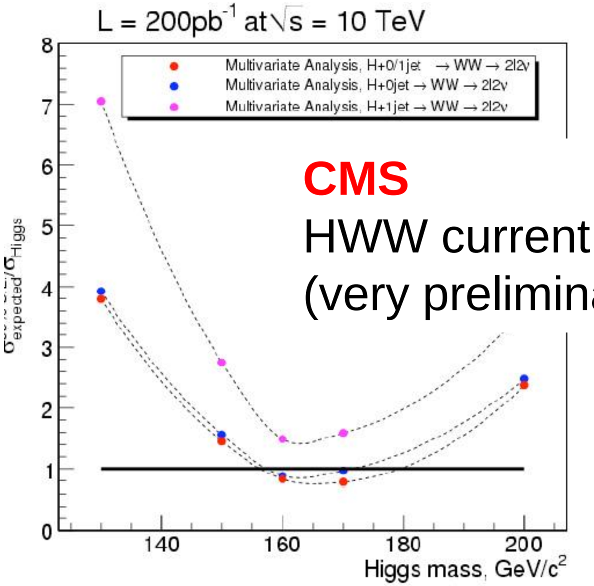
- **inclusive WW is now better than VBF**
  - this order now agrees with CMS
  - is reverse to ATLAS simulations in 2003
- **Combined significance (10 fb^{-1} @ 14 TeV) above 5σ level for ≈ m_H> 140 GeV/c^2**



$H \to WW \to 2l2\nu$ (10 TeV 200 pb^{-1})

- **Tevatron (CDF+D0) just excluded m_H=160-170**
- **CMS vs Tevatron:**
  - **CMS can exclude m_H=160-180** (important crosscheck)
  - **for m_H=200-500, limit r~2.5-5**
    - expected to be even better than ZZ for exclusions at low luminosity
    - certainly outperforms Tevatron in this mass range

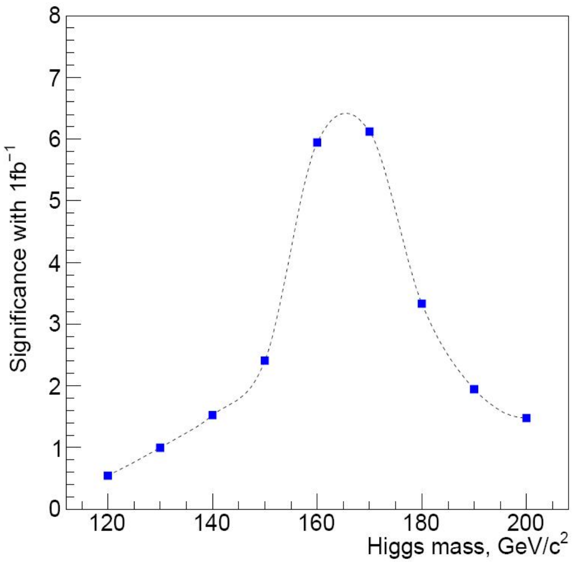




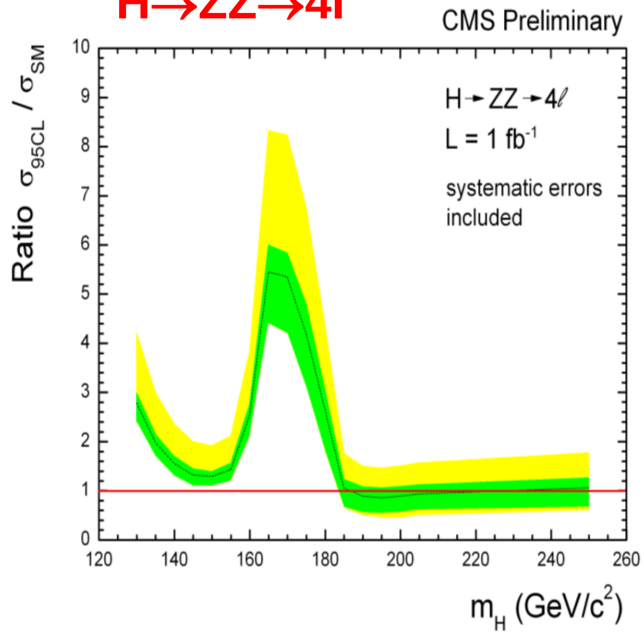
CMS
HWW current status
(very preliminary!)

CMS last updated analyses (1 fb^{-1} @ 14 TeV)

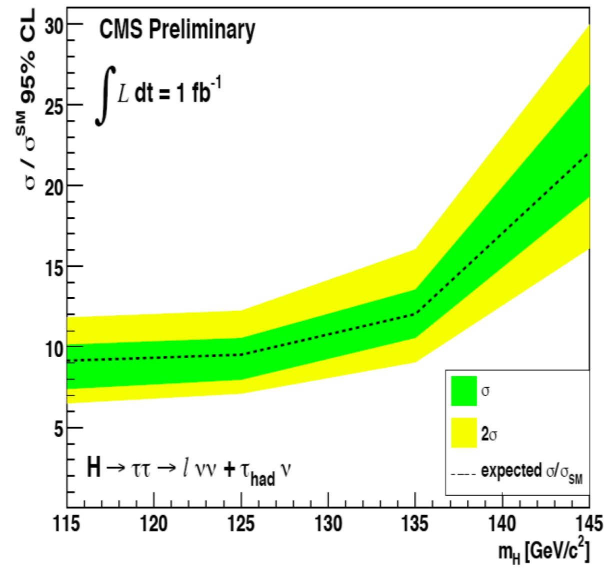
$H \to WW \to 2l2\nu$



$H \to ZZ \to 4l$



VBF $H \to \tau\tau \to l + \tau_{jet}$ +MET



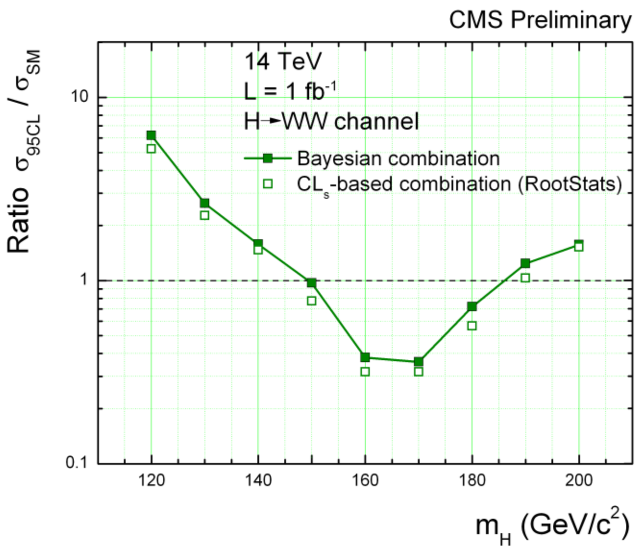
1 fb^{-1} @ 14 TeV

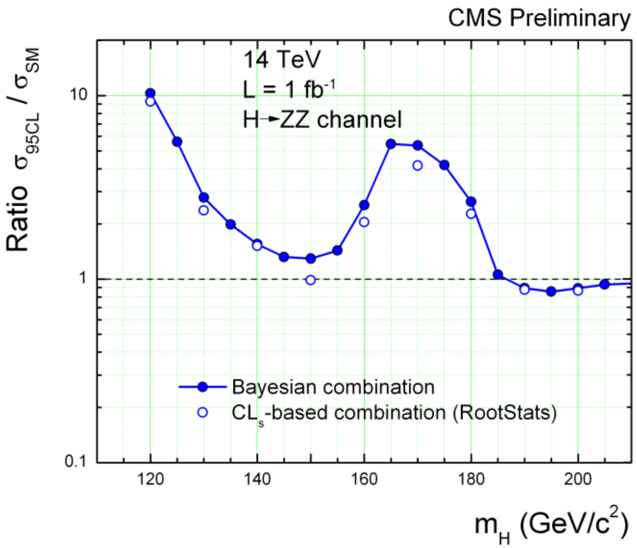
WW: has enough sensitivity for a discovery (160-170 GeV)

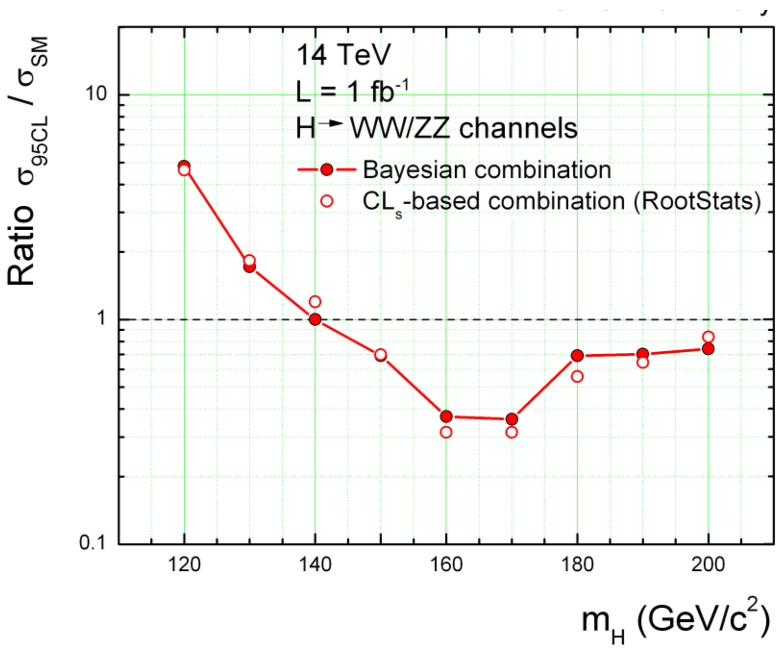
ZZ: has enough sensitivity for exclusion (190-230 GeV)

ττ: only high upper limits are possible

Combining channels







$\sqrt{s}$: 14 TeV→10 TeV

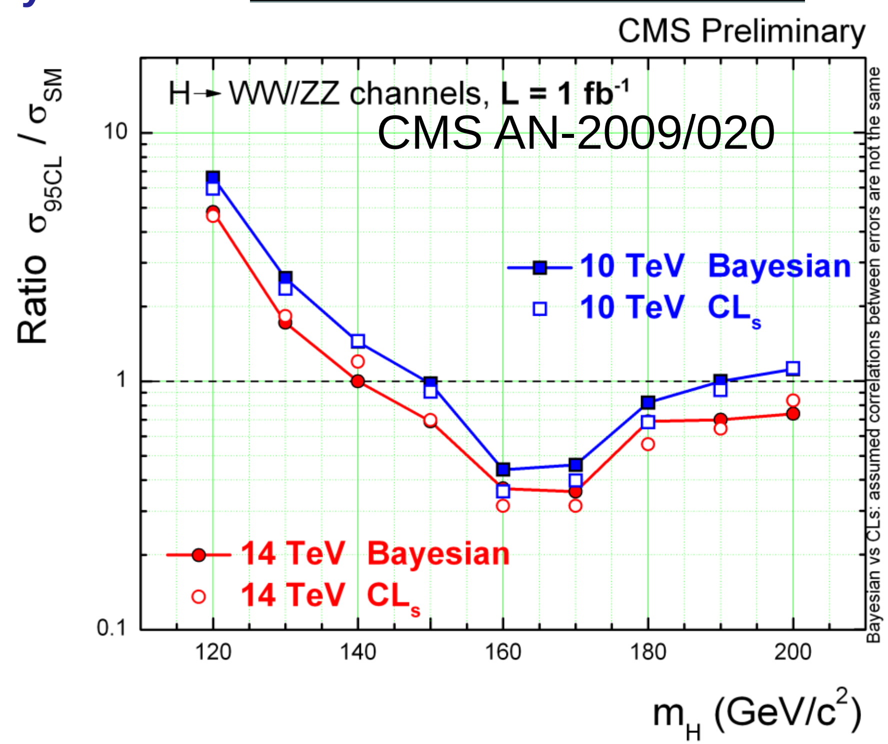
LHC will start working with $\sqrt{s}$ lower than 14 TeV (around 10 TeV)

- **Cross section for signals and background goes down**
- **Signal (Higgs production) goes down slightly faster:** ***Higgs is mainly produced from gg and backgrounds from qq***
- **Higgs decay products become relatively more central for smaller LHC energies**

Process	$\frac{\sigma_{\sqrt{s}=10TeV}}{\sigma_{\sqrt{s}=14TeV}}$	$\frac{\sigma_{\sqrt{s}=6TeV}}{\sigma_{\sqrt{s}=14TeV}}$
$t\bar{t}$	0.450	0.113
Wt	0.450	0.113
WW	0.650	0.320
WZ	0.650	0.320
ZZ	0.650	0.320
$Z \to \ell\ell$	0.681	0.371
$W \to \ell\nu$	0.681	0.371
$gg \to H$	0.540	0.190

Example : HWW + HZZ combined

$\int L$ for 5σ	14 TeV	10 TeV
m_H=200 GeV	0.6 fb-1	1.3 fb-1

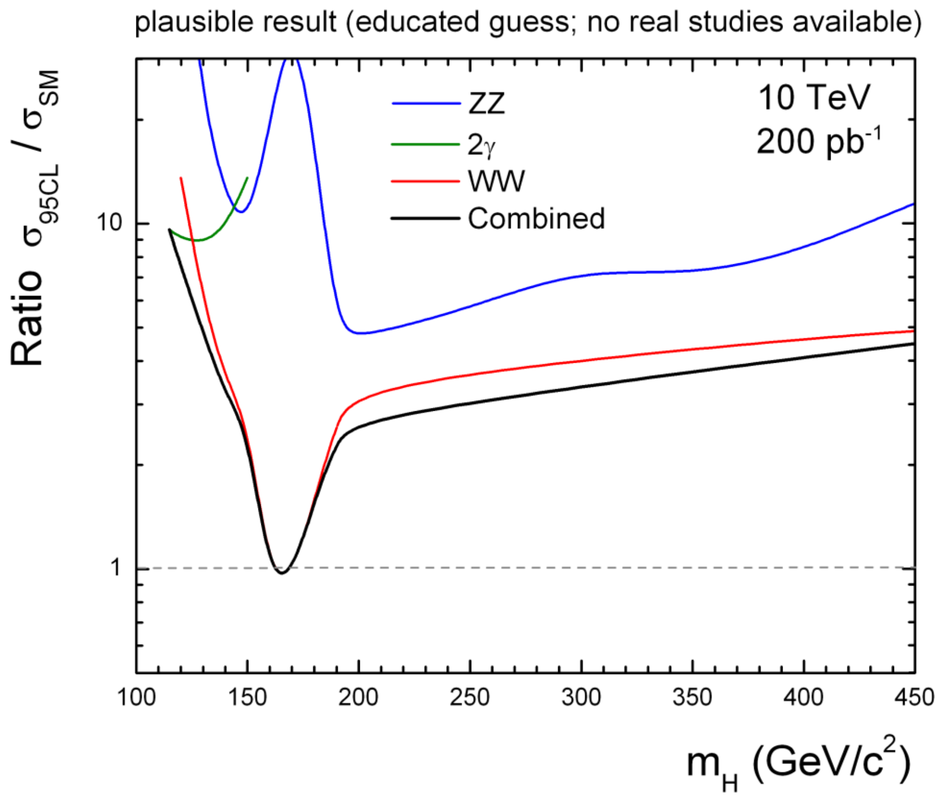


Signal and bkgd yields re-scaled $\sqrt{s}$: 14 TeV→10 TeV:

- **loss of a factor of 1.5 in sensitivity, or a factor of 2 in luminosity**
- **with roughly ~200 pb^{-1}, reach sensitivity for a SM Higgs with m_H~160-170 GeV** ***(but region just excluded by Tevatron)***

SM Higgs CMS combined (10 TeV 200 pb^{-1})

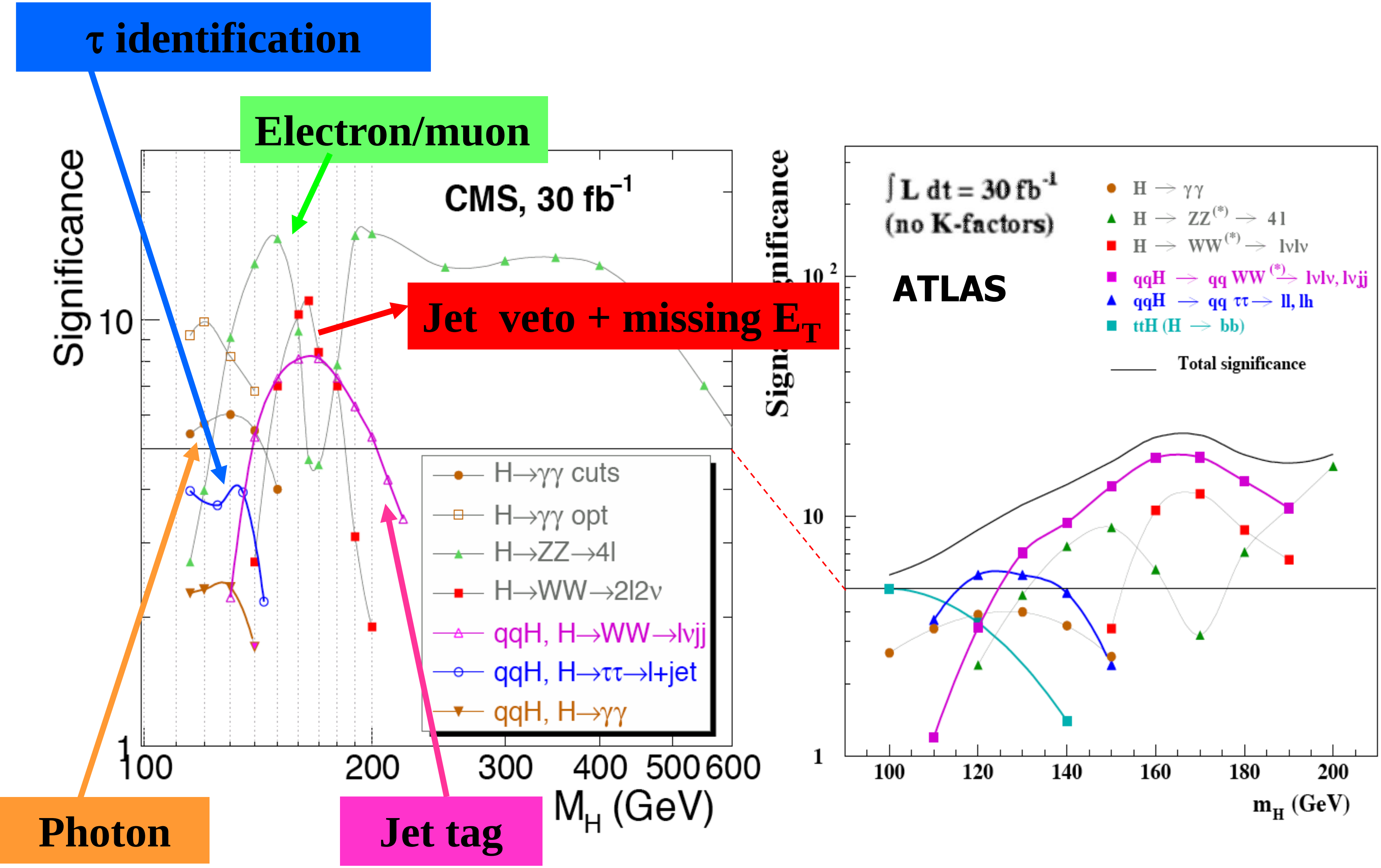
But a lot of work still to be done to combine all channels…



we need to

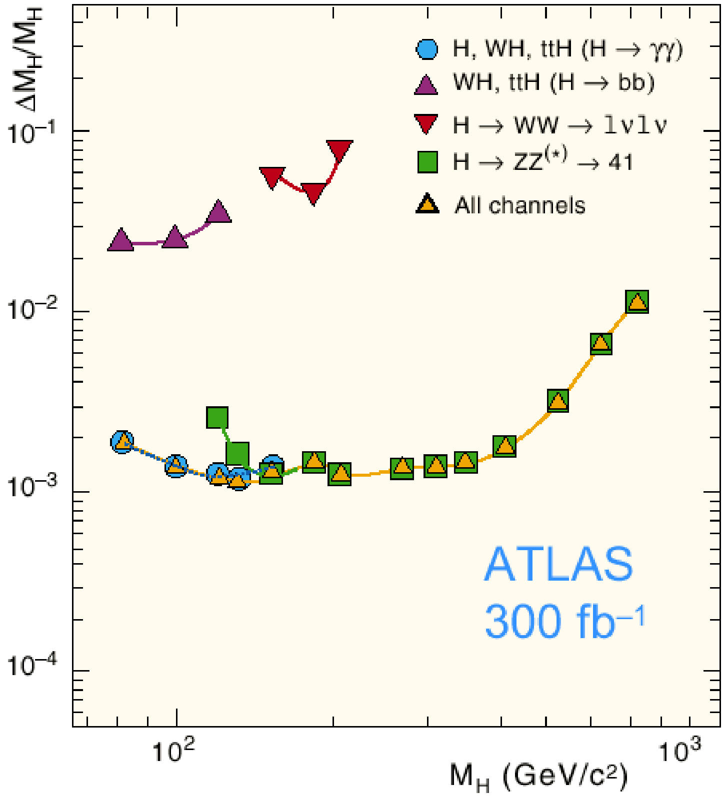
- put in place tools for proper treatment of cross-channel correlations
- coordinate the three analyses to ease the combination exercise

SM Higgs discovery potential



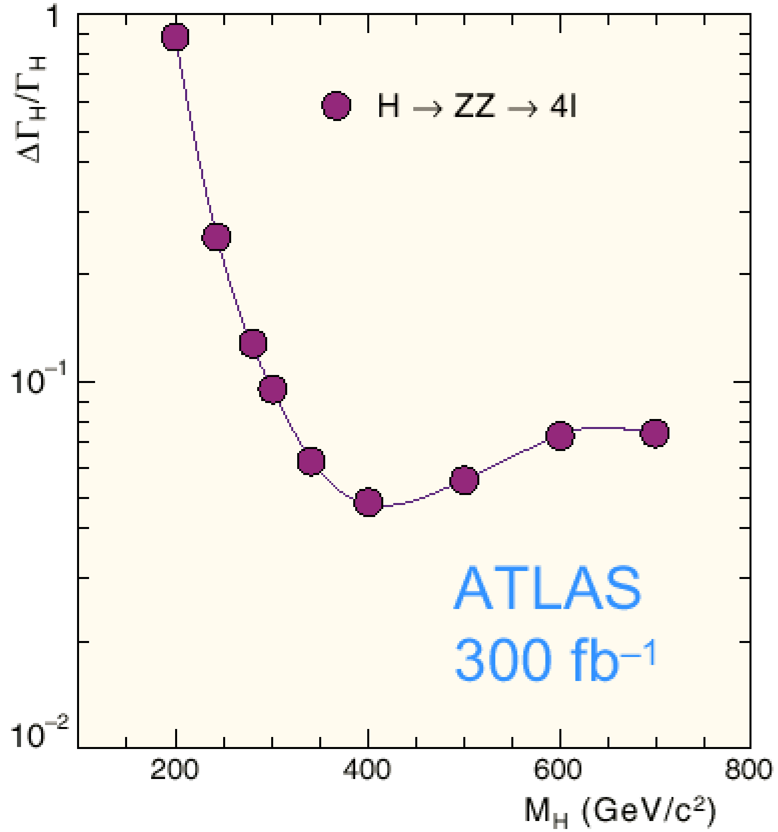
SM Higgs properties: mass

- **Mass measurement**
  - Limited by absolute energy scale
    - leptons & photons: 0.1% (with Z calibration)
    - Jets: 1%
  - Resolutions:
    - For $\gamma\gamma$ & $4\ell \approx 1$ GeV/c^2
    - For bb ≈ 15 GeV/c^2
  - At large masses: decreasing precision due to large Γ_H
  - CMS ≈ ATLAS



SM Higgs properties: width
(for M_H>200 Gev)

- **Width:**
  - **Direct measurement for M_H>200 using golden mode (4ℓ)**



Conclusions

- If the Higgs boson is there, ATLAS and CMS are ready to find it…
  …unless it is discovered or excluded first at the Tevatron!!!

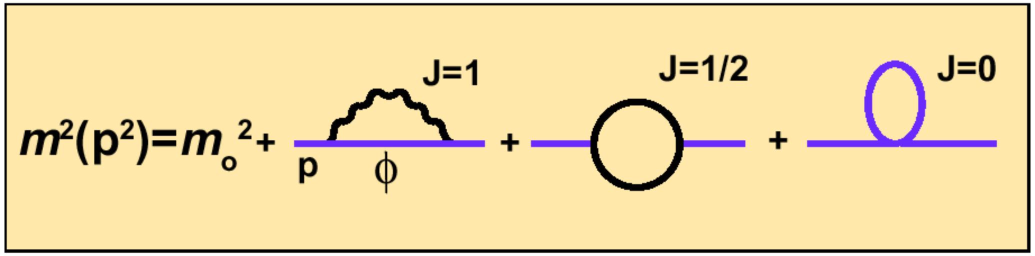
- To find a SM Higgs, with a combination of ATLAS & CMS @14TeV, between ~ 1 and 5 fb^{-1} are needed depending on mass value.
  Benchmark luminosities:
  - *~0.1 fb^{-1} ➔ exclusion limits will start carving into SM Higgs cross section*
  - *~0.5 fb^{-1} - 1 fb^{-1} ➔ discoveries start to become possible in the region near the one excluded by Tevatron (M_H~160-170 GeV/c^2)*
  - *~5 fb^{-1} - 10 fb^{-1} ➔ SM Higgs could be discovered (or excluded) in full mass range (~110-500 GeV/c^2)*

- Post-discovery questions that would need to be answered…..
  - what is the Higgs mass, width, quantum numbers?
  - is it a Standard Model Higgs? Is there only one Higgs? or MSSM or other models…?

- If the Higgs is not found, the ATLAS and CMS detectors are anyhow able to search for signatures of a new physics

Problems with the SM Higgs

- Quadratic divergence of its mass



$$m^2\left(p^2\right) = m^2\left(\Lambda^2\right) + Cg^2 \int_{p^2}^{\Lambda^2} dk^2$$

  - Λ is a cutoff momentum
  - In other words: why is the Higgs mass low?
- With SUSY, quadratic divergences disappear:
  - As long as $M_p = M_{sp}$
- SUSY requires more Higgs-like particles

MSSM Higgses: choice of parameters

- 5 Higgses in Minimal Supersymmetry ($H^{\pm};H^0,h^0,A^0$)
- 2 charge, 3 neutral: 2 CP – even (light h and heavy H), and one CP – odd (heavy A)
- SUSY has a lot of parameters, but only 4 are important for the Higgs sector in MSSM!
  - At tree level, all masses & couplings depend on only two parameters (usually M_A & $\tan\beta$)
  - Modifications to tree-level mainly from top loops
  - Additional parameters:

    1: SUSY particle masses:

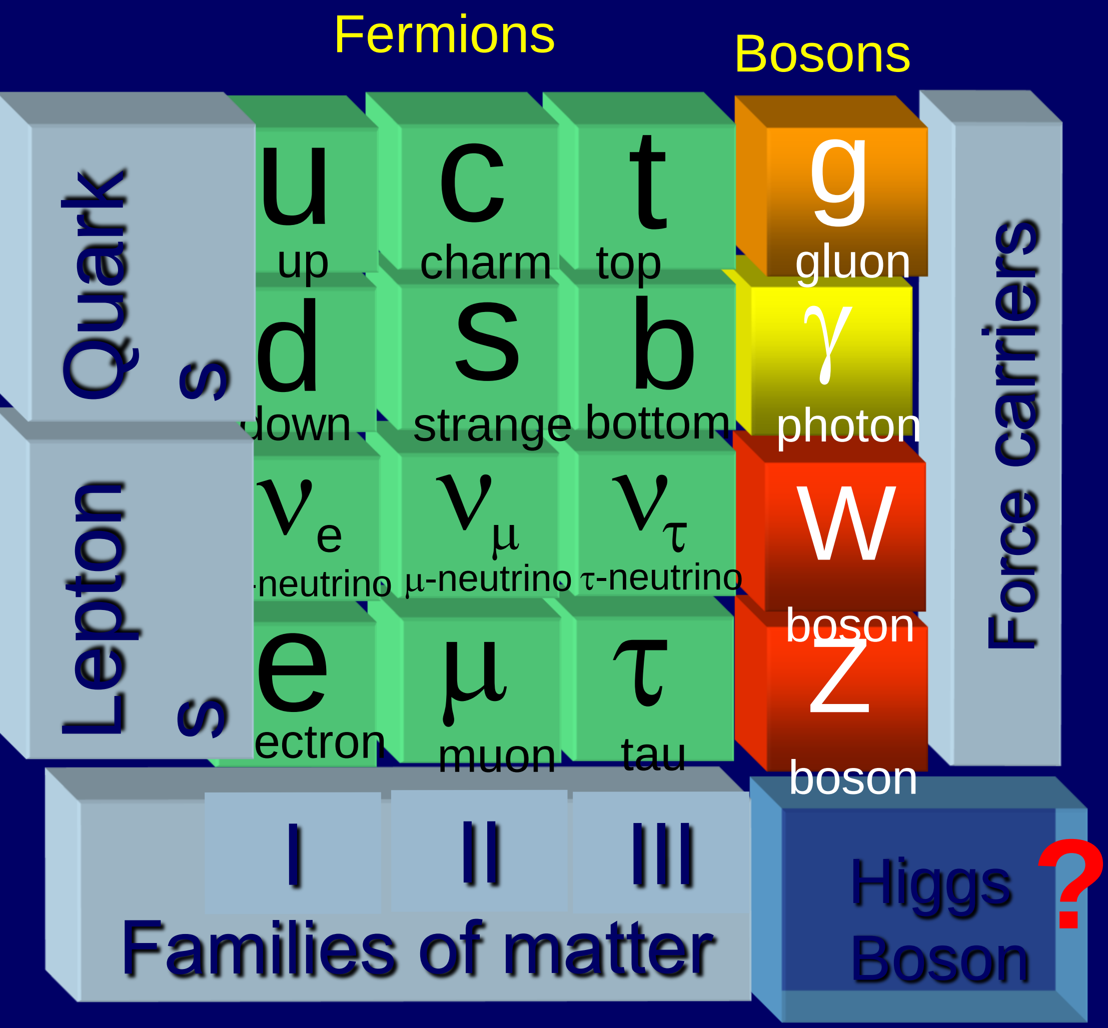
    (a) M>1 TeV (i.e. no decays of the Higgses to sparticles); well-studied

    (b) M<1 TeV (i.e. allows decays of the Higgses to sparticles); “new”

    2: stop mixing:

    Maximal–No mixing

The Standard Model



Questions:
why masses of matter particles and forces carriers are so different ?
The bare SM could be consistent with massless particles but matter particles range from almost 0 to about 170 GeV while force carriers range from 0 to about 90 GeV.

The simplest solution:
all particles are massless !!
A new scalar field pervades the Universe (the Higgs field). Particles interacting with this field acquire mass: the stronger the interaction the larger the mass...

BUT

the Higgs boson have not yet been found !

The Standard Model is one of the most successful theories tested so far but many questions are still without an answer.

** What is the origin of the mass of quarks, leptons and force carriers ?*

** What is the origin of the mass of quarks, leptons and force carriers ?*

** What is the dark matter (and dark energy), which pervades the Universe ?*

** Why our World is made with matter and how the antimatter disappeared ?*

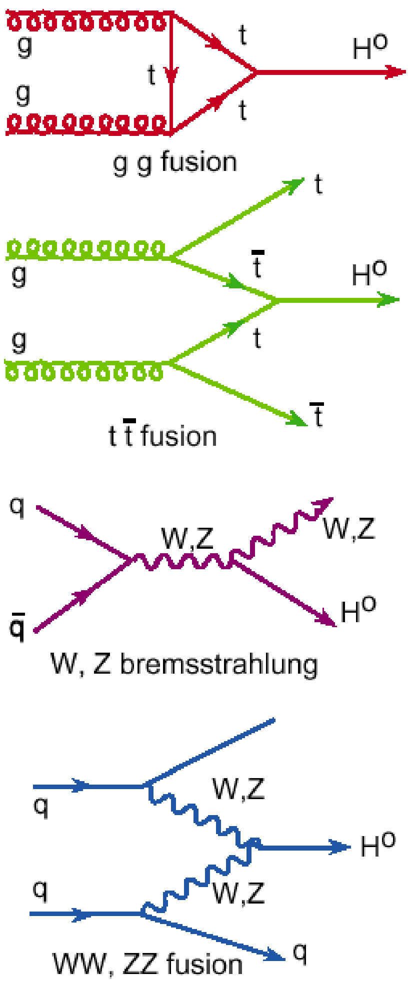
** Why the interactions are so different in strenght and why Gravity cannot be included in our SM theory?*

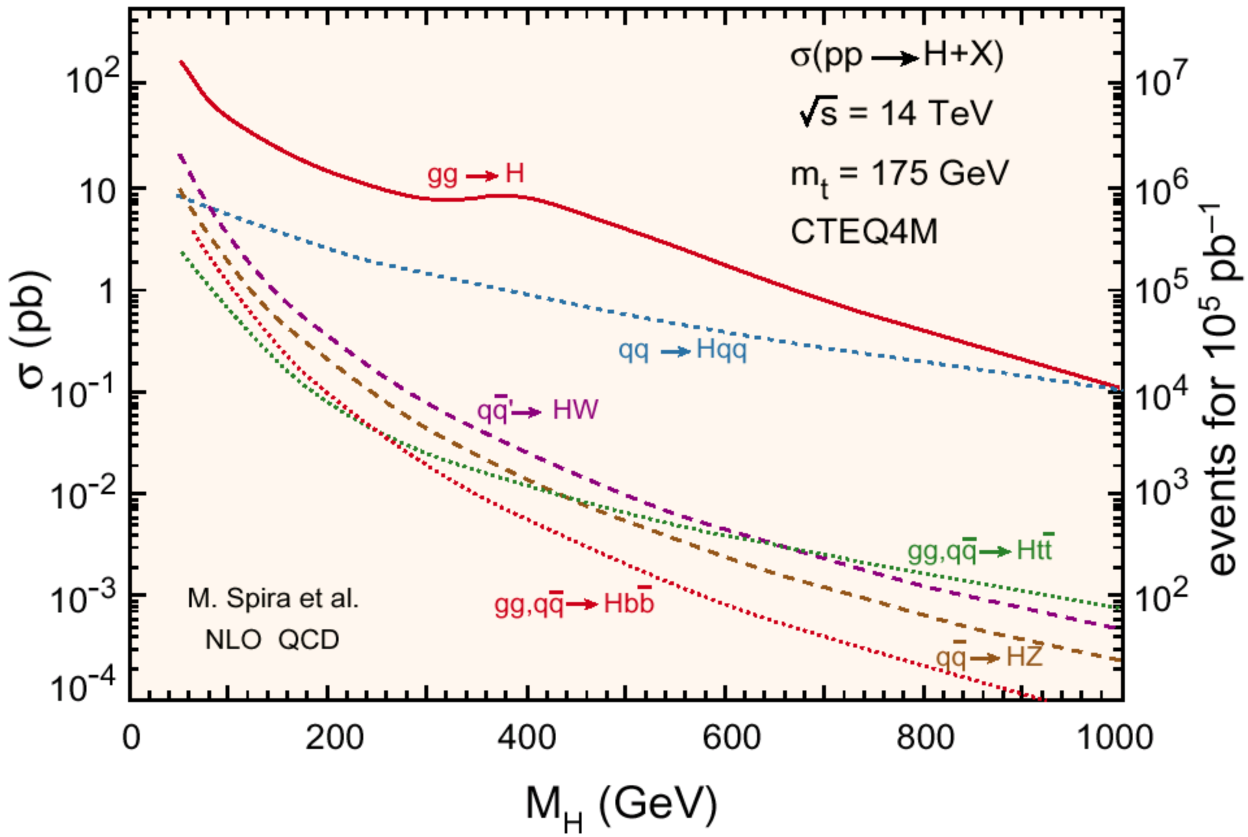
** Are quarks and leptons fundamental particles or have they internal structures ?*

We believe that the answer to some of these questions is probably hidden in the so far unexplored TeV region which will become accessible with the CERN Large Hadron Collider (LHC)

SM Higgs: production

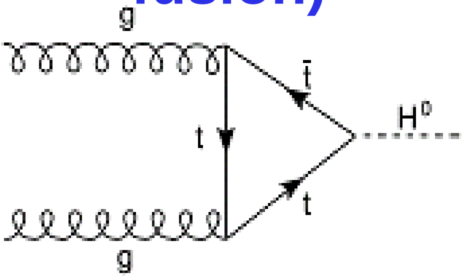
- **Production mechanisms & cross section**
- **10 000- 100 000 Higgses produced /year at high lumi**





Higgs Production Cross-sections

Leading Process (gg fusion)



Sub-leading Process (VBF)