CMS:
first months of operation

4th School on the Physics of LHC

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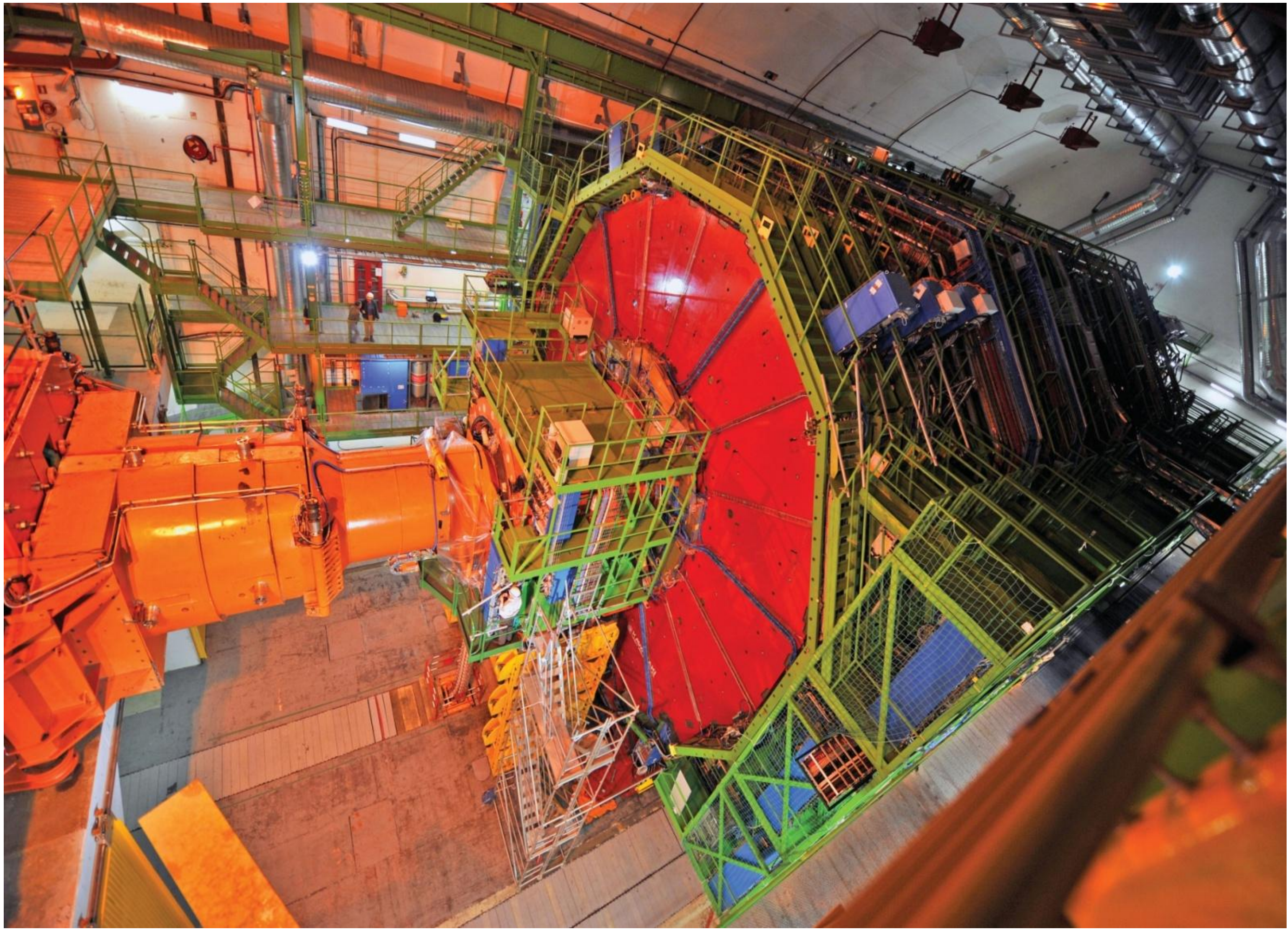
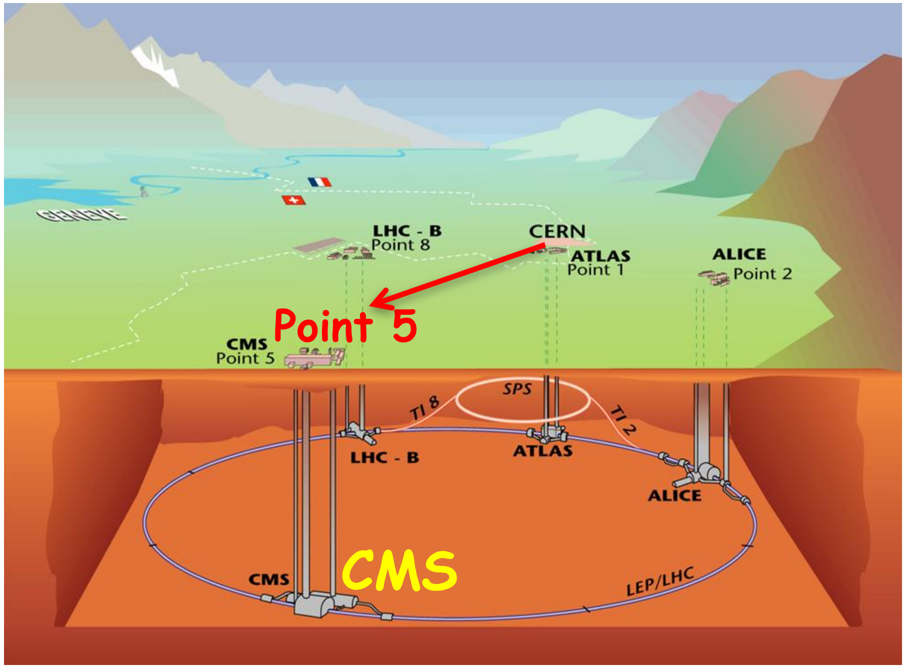
Outline

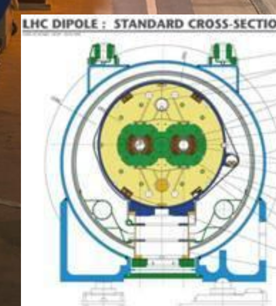
- ✓ The detector
- ✓ Data with Cosmic
- ✓ 0.9 TeV Data
- ✓ 2.36 TeV Data
- ✓ 7 TeV Data
- ✓ Perspectives



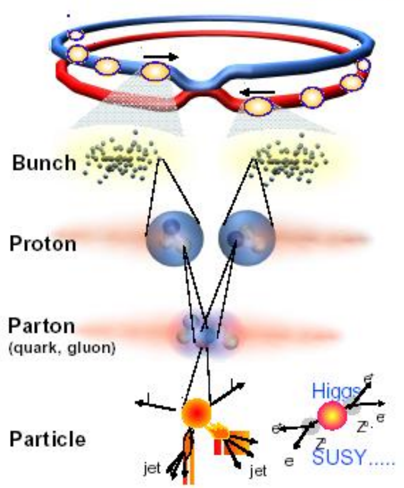
The CERN Large Hadron Collider



9300 Superconductor magnets
1232 Dipoles (15m, 1.9°K) 8.4Tesla 11700 A
448 Main Quads, 6618 Correctors.
Circonference 26.7 km



Collisions at LHC



Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} $cm^{-2}s^{-1}$
Crossing rate	40 MHz
Collisions rate ≈	10^7 - 10^9 Hz
New physics rate ≈	.00001 Hz

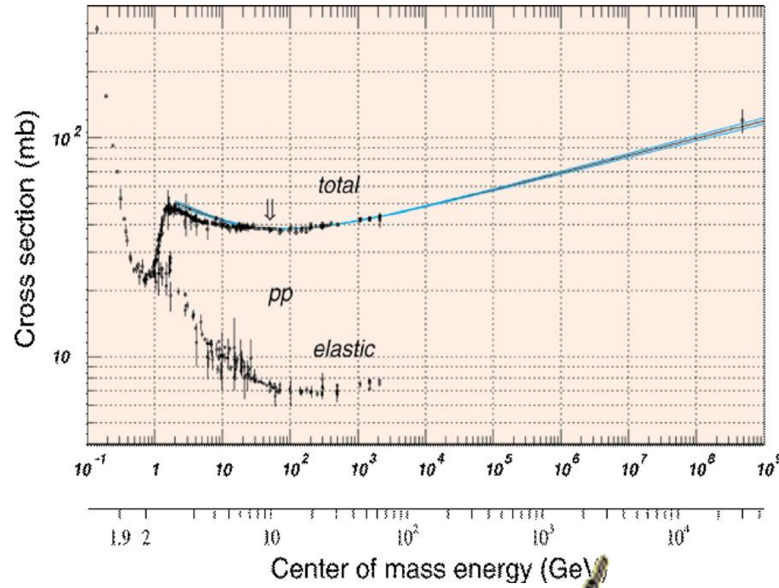
Event selection:
1 in 10,000,000,000,000

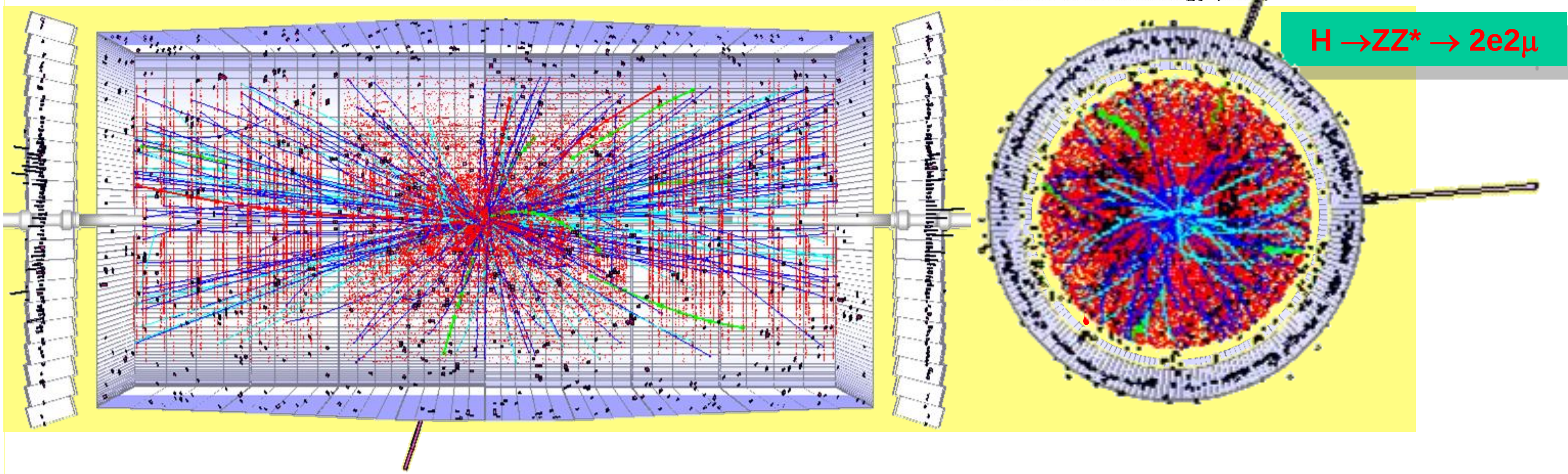
pp cross-sections and minimum bias

\# of interactions/crossing:

- Interactions/s:
  - Lum = 10^{34} $cm^{-2}s^{-1}$=$10^{7}mb^{-1}Hz$
  - $\sigma_{inel}(pp)$ = 80 mb
  - Interaction Rate, R = 8×10^{8} Hz
- Events/beam crossing:
  - Δt = 25 ns = 2.5×10^{-8} s
  - Interactions/crossing=20
- Not all p bunches are full
  - 2835 out of 3564 only
  - Interactions/"active" crossing =
  - = 20 x 3564/2835 = 25

$\sigma_{inel}(pp)\approx$80 mb@14TeV





Impact on detector design

CMS detectors must have fast response

Otherwise will integrate over many bunch crossings

→ large "pile-up"

Typical response time : 20-50 ns

→integrate over 1-2 bunch crossings

→ pile-up of 25-50 min-bias

→ very challenging readout electronics

CMS detectors must be highly granular

Minimize probability that pile-up particles be in the same detector element as interesting object

→ large number of electronic channels

→ high cost

CMS detectors must be radiation resistant:

high flux of particles from pp collisions

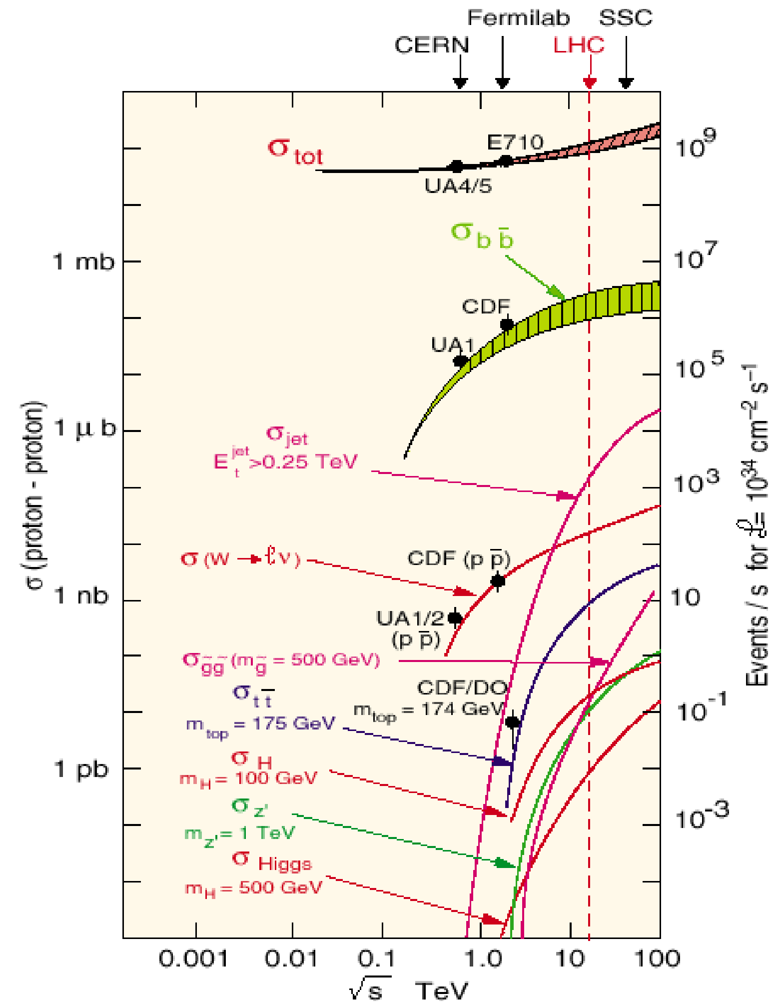
→ high radiation environment

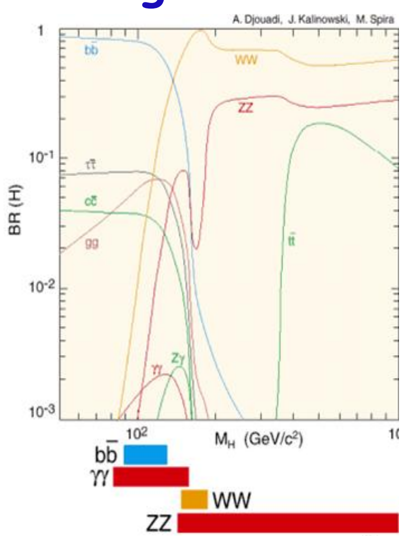
Signal and background → $\mathcal{L}=10^{34}\ \mathrm{cm^{-2}s^{-1}}$

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
$W \rightarrow \ell\nu$: → 10^2 Hz
Inelastic: → 10^9 Hz

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





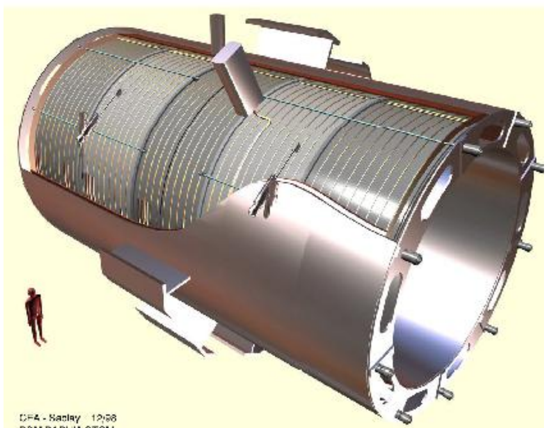
⇒ Needle in a Hay Stack

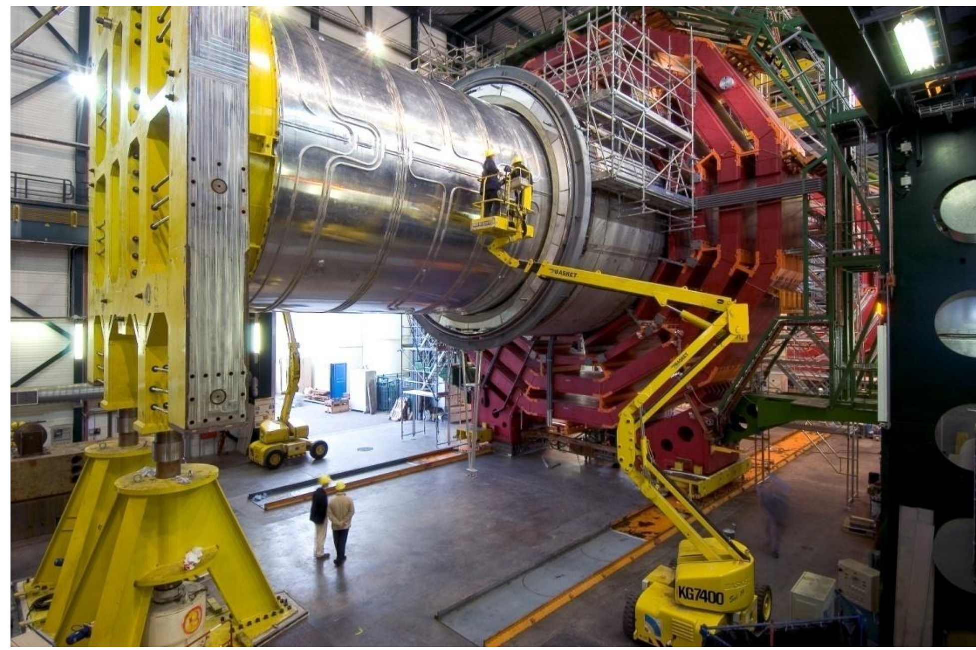
CMS: Detector Requirements

- Excellent muon identification with precise momentum reconstruction
- Efficient and high-resolution tracking for particle momentum measurements, b-quark and τ tagging, vertexing (primary and secondary vertex)
- Very good electromagnetic calorimetry for electron and photon identification
- Ermetic hadronic calorimeter jet reconstruction and missing transverse energy measurement

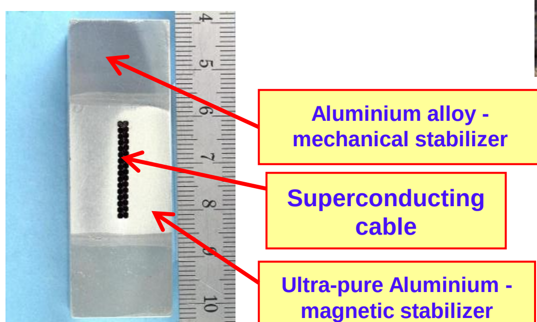
CMS (Compact Muon Solenoid)

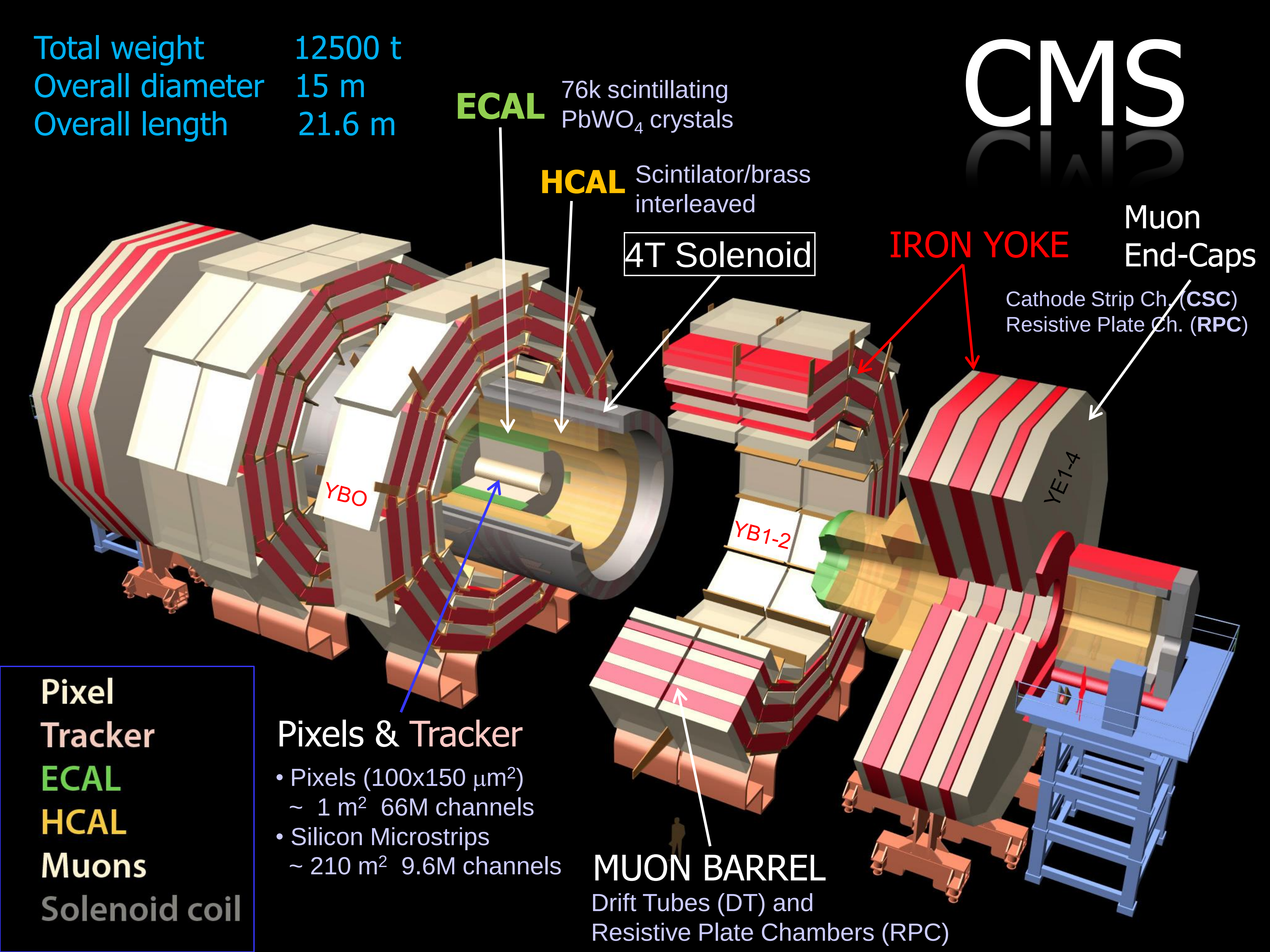
The CMS magnet is a superconducting solenoid around which the full detector has been built. The coil has an overall length of 13m and a diameter of 7m, and a magnetic field about 100,000 times stronger than that of the Earth. The magnet stores enough energy to melt 18 tons of gold and has the largest coil of its type ever constructed and allows the tracker and calorimeter detectors to be placed inside the coil, resulting in a detector that is, overall, “compact”, compared to detectors of similar weight.





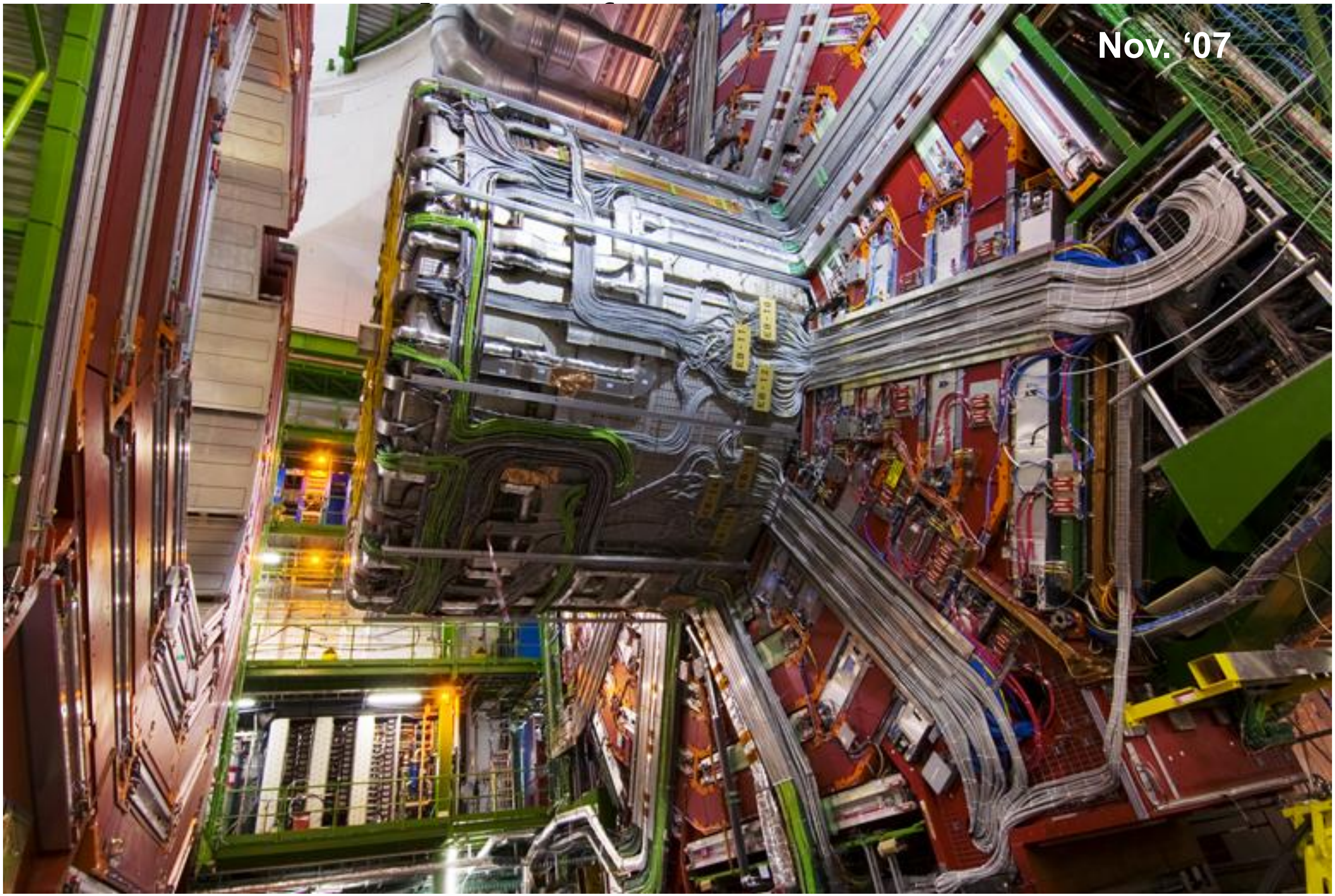
4-layer winding of superconducting cable cooled to ~ 4K to carry a current of ~ 20kA



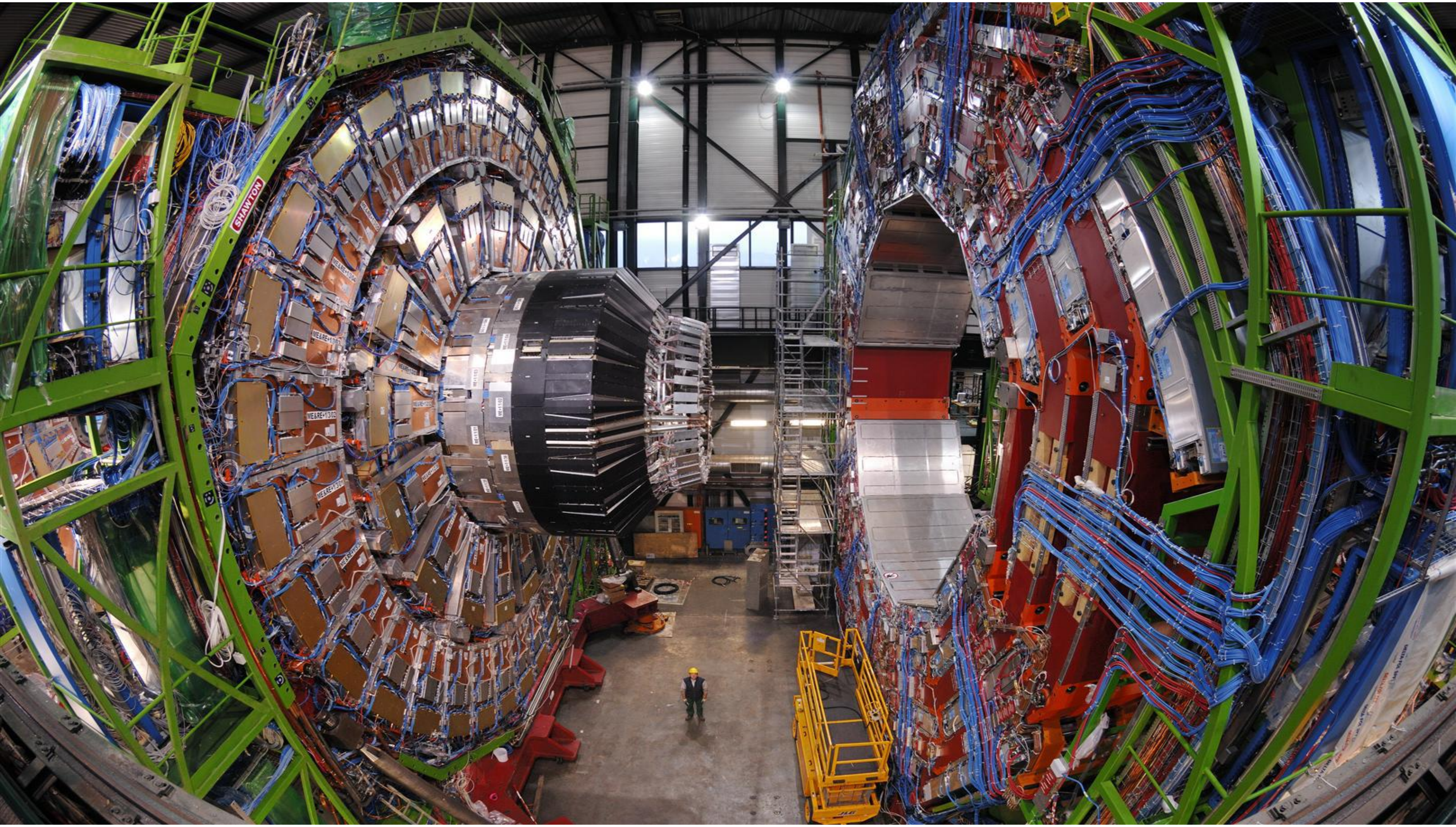


Total weight 12500 t
Overall diameter 15 m
Overall length 21.6 m
CMS
ECAL
76k scintillating PbWO$_4$ crystals
HCAL
Scintilator/brass interleaved
4T Solenoid
IRON YOKE
Muon End-Caps
Cathode Strip Ch. (**CSC**)
Resistive Plate Ch. (**RPC**)
YBO
YB1-2
YE1-4
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm^2)
~ 1 m^2 66M channels
• Silicon Microstrips
~ 210 m^2 9.6M channels
MUON BARREL
Drift Tubes (DT) and
Resistive Plate Chambers (RPC)

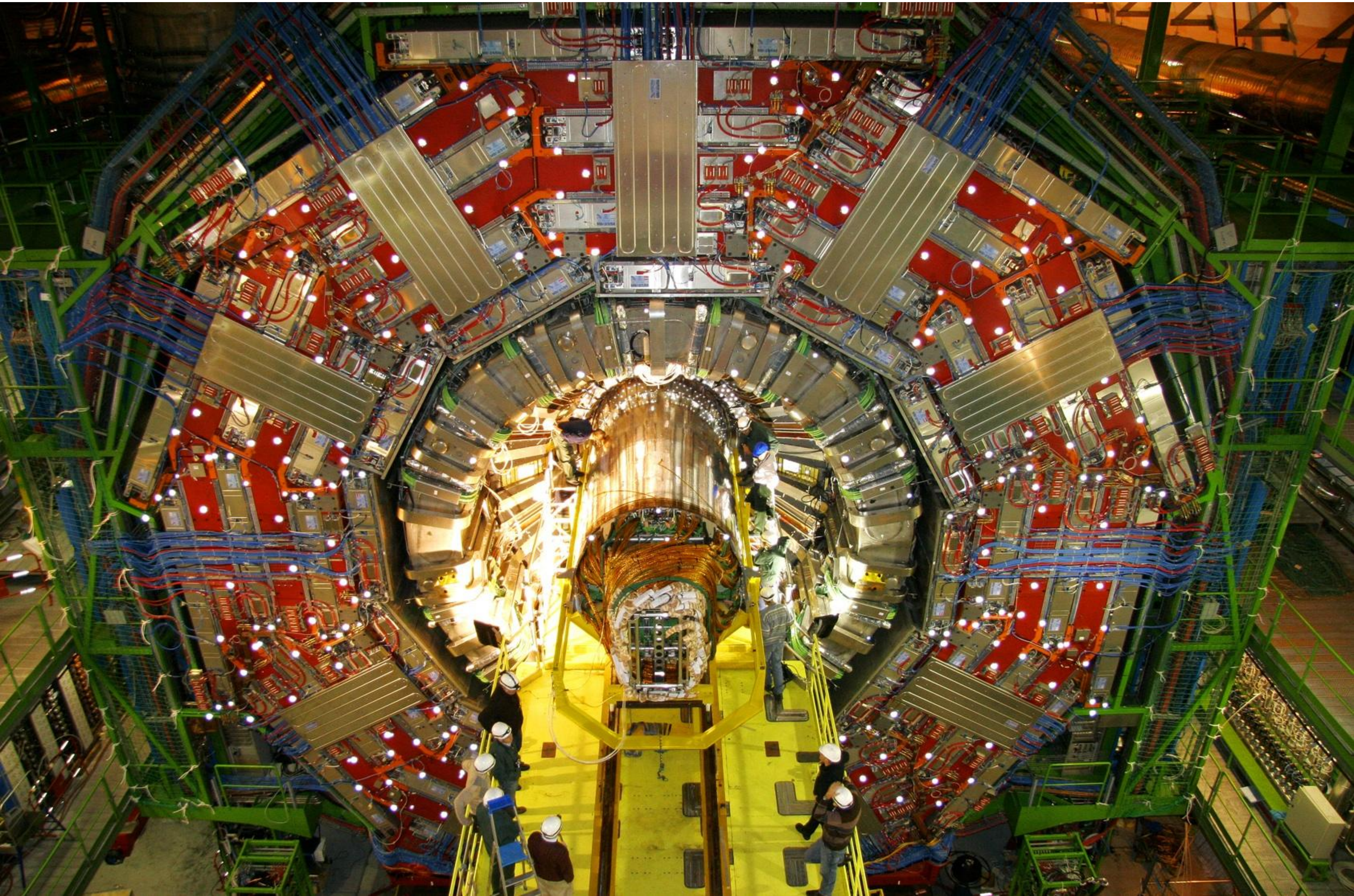
CMS

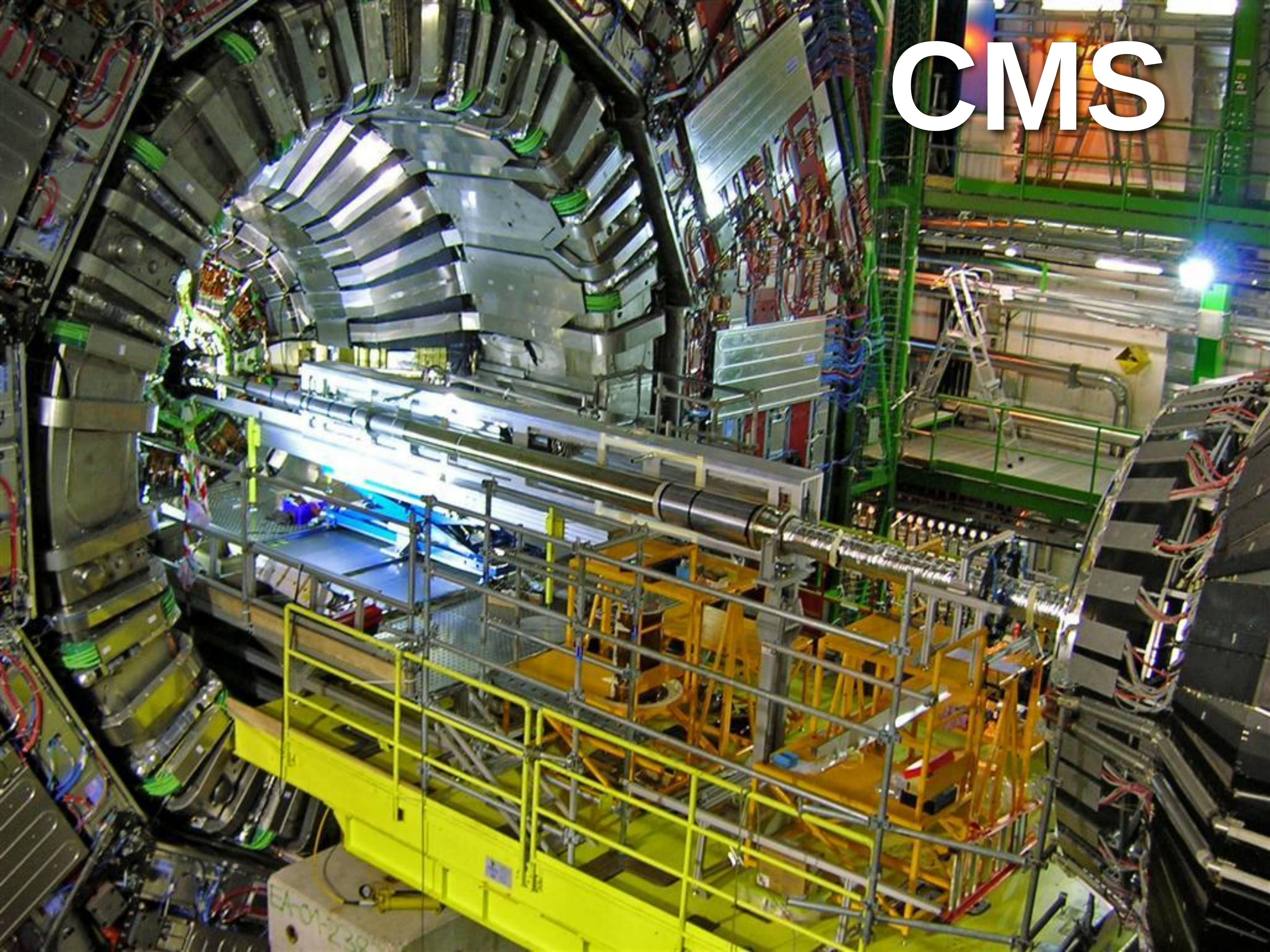


CMS

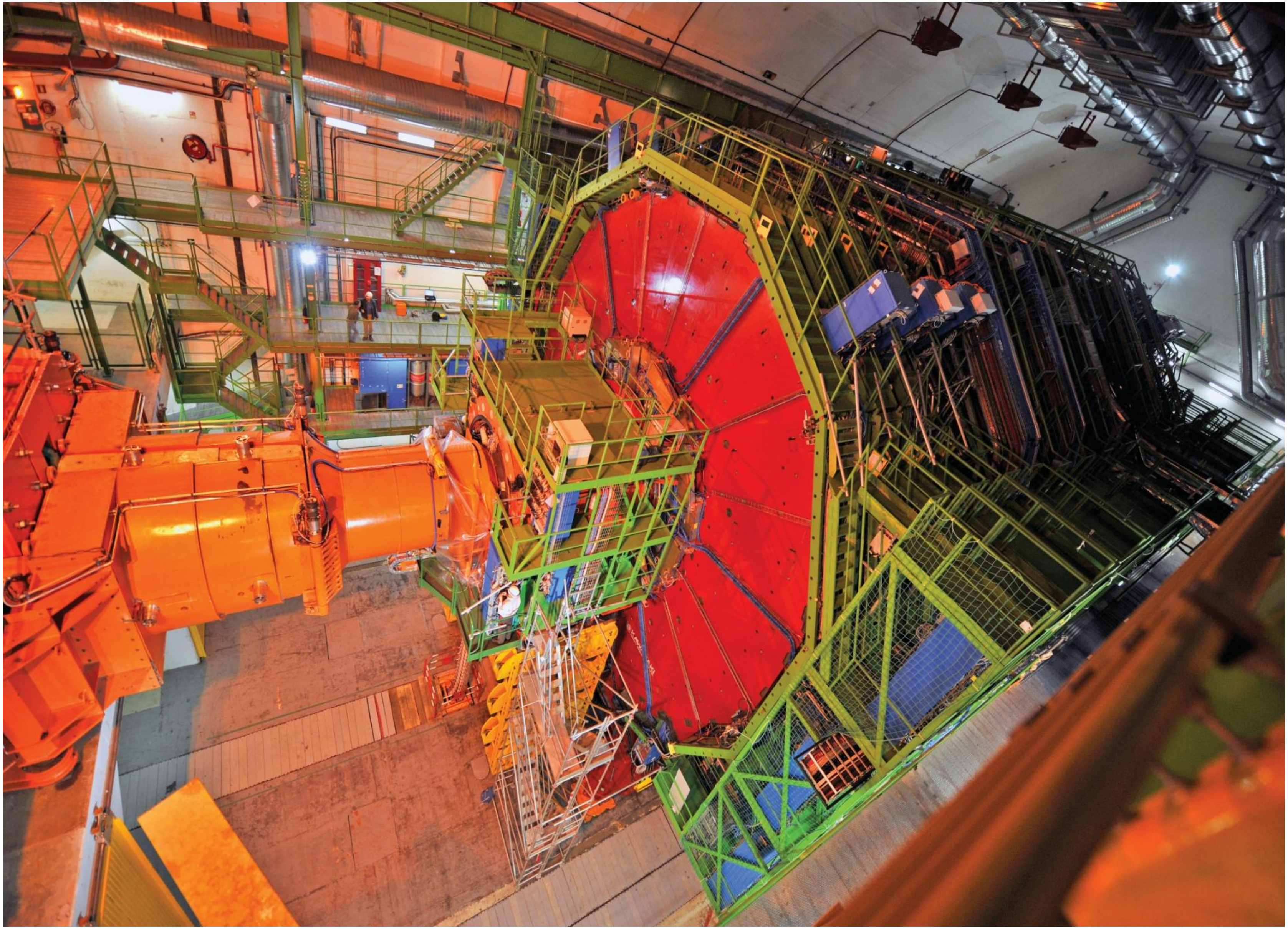


CMS




CMS

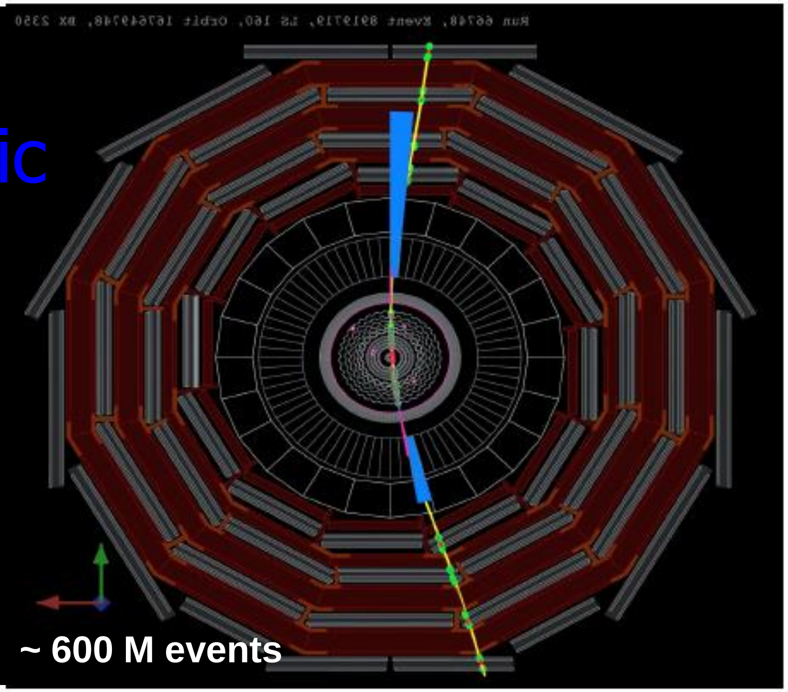
CMS ready to take data



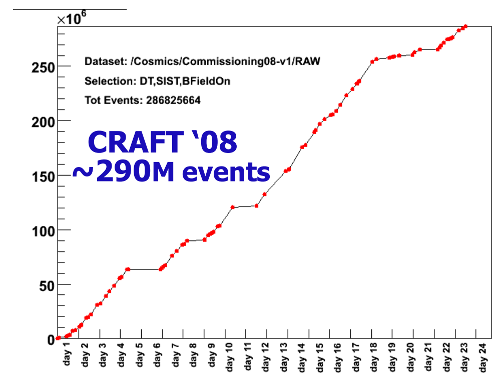
10/09/2008

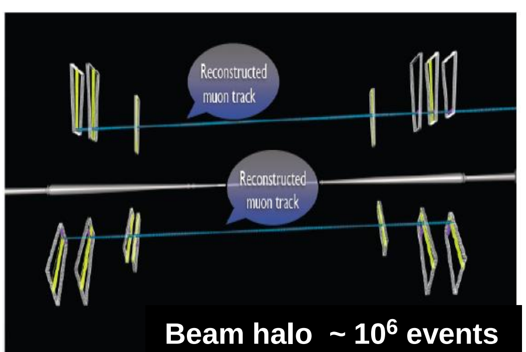
CRAFT: 2008-2009 Commissioning with Cosmics

Cosmic
Runs
At
Four
Tesla

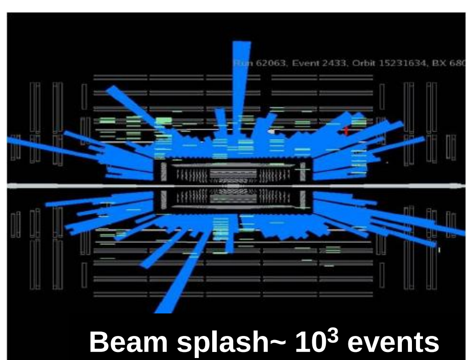


- ✓ Alignements
- ✓ Calibrations
- ✓ Timing
- ✓ Studies of magnetic field

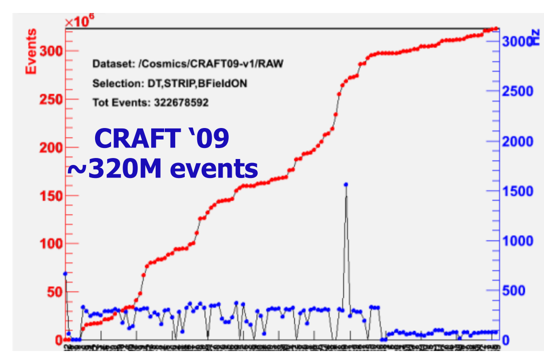




Beam halo ~ 10^6 events

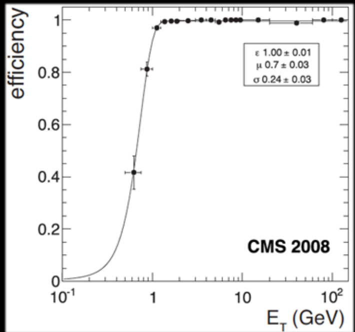


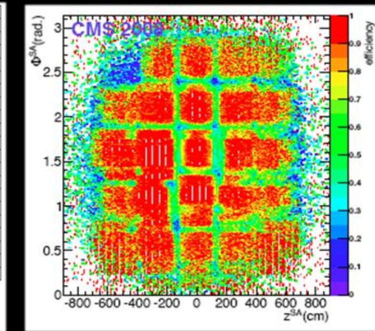
Beam splash~ 10^3 events

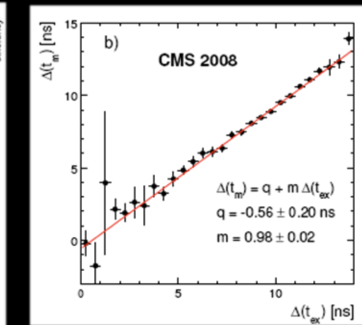


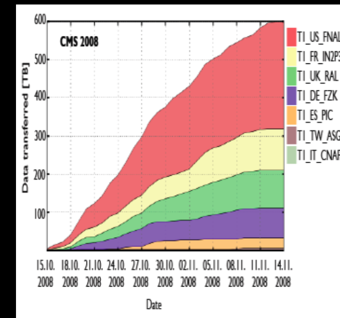
23 "CRAFT" Papers Published in JINST

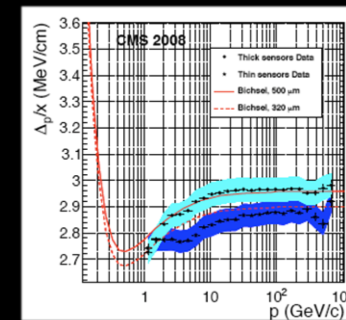
http://iopscience.iop.org/1748-0221/focus/extra.proc6

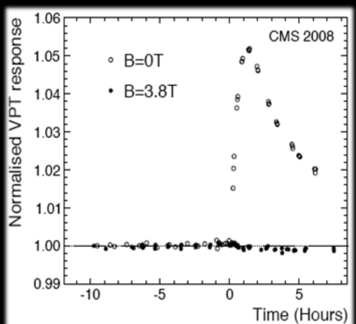


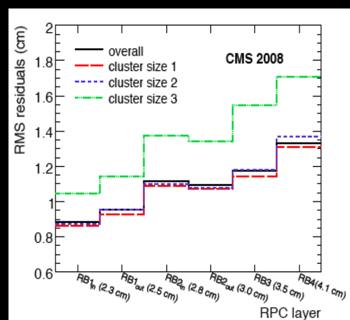


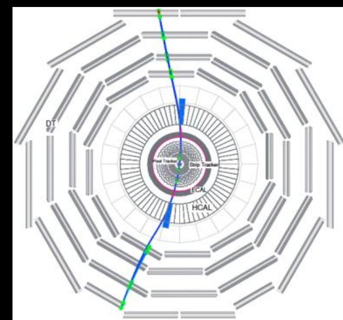


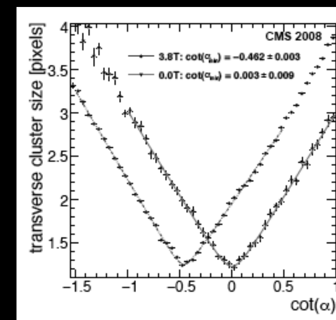


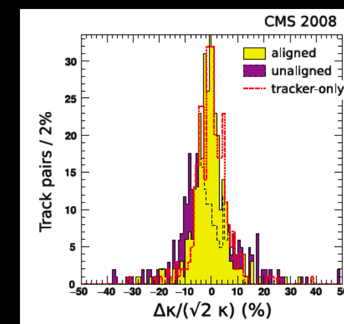


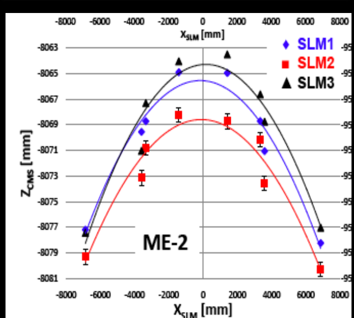


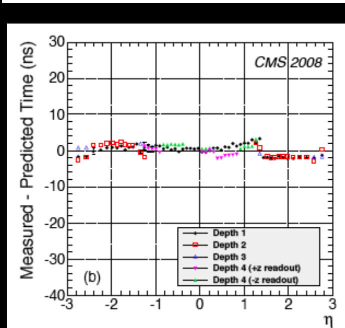


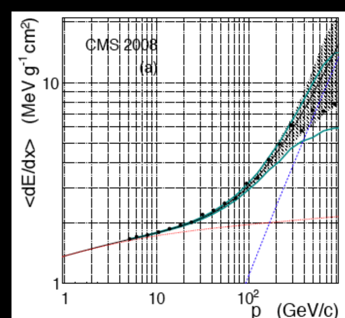


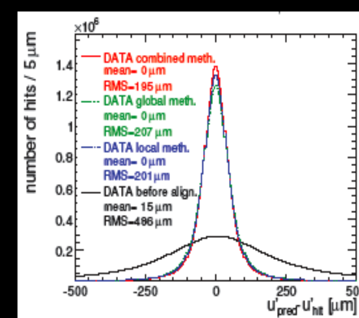


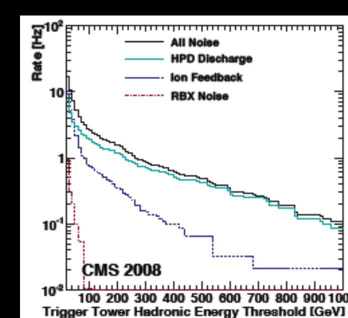


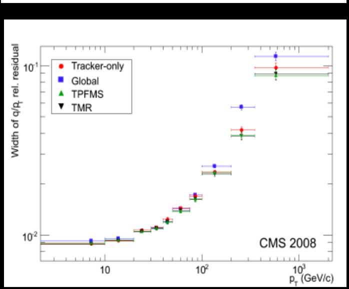


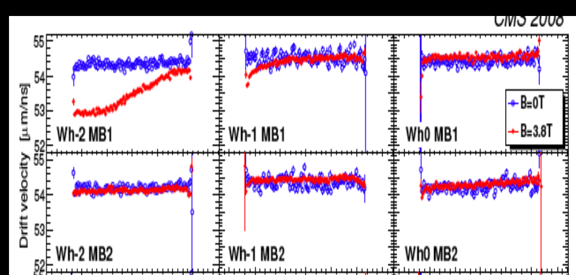


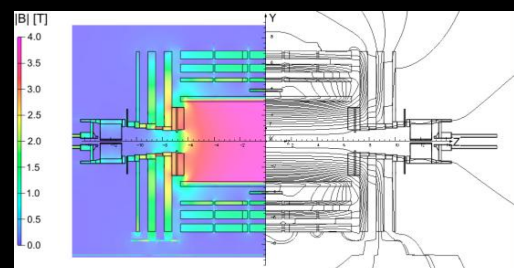


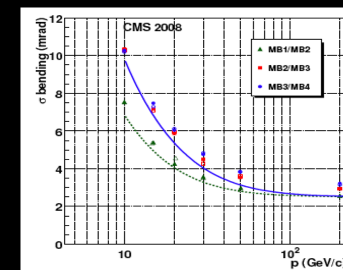






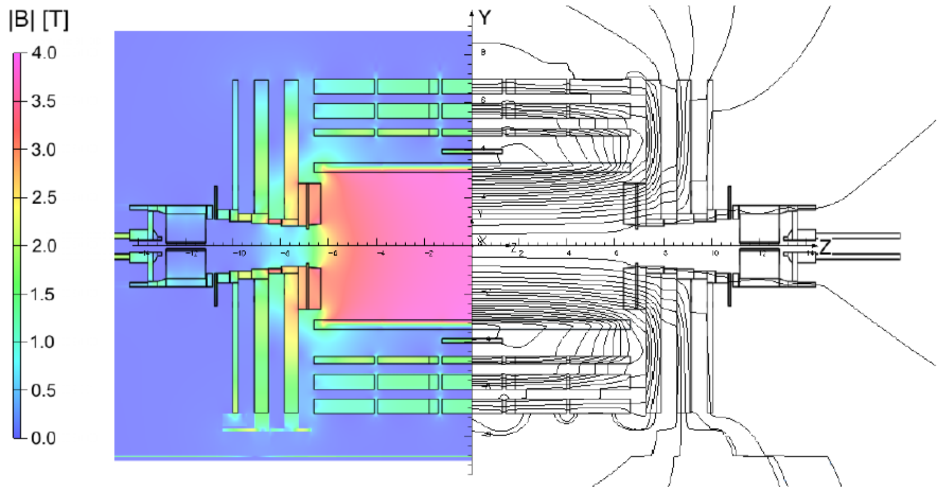




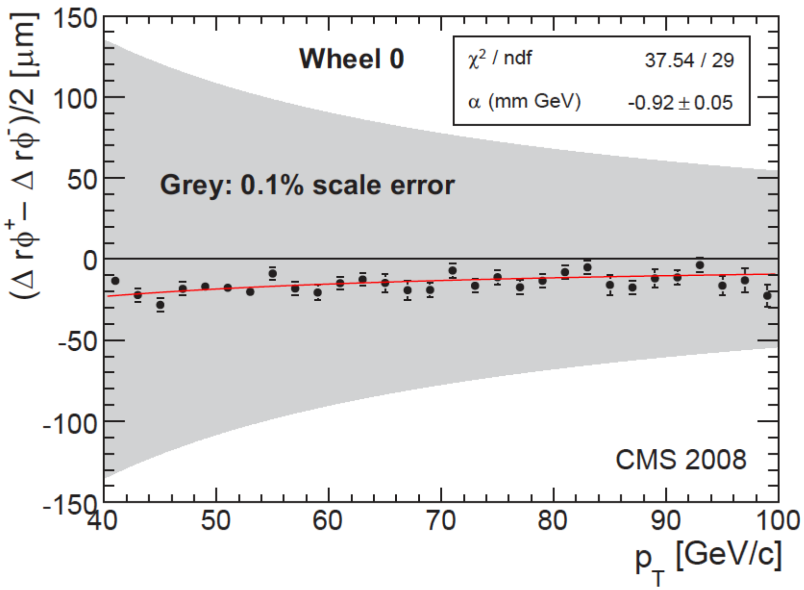


CRAFT:Solenoid Field MAP

2010 *J. Inst.* **5** T03021

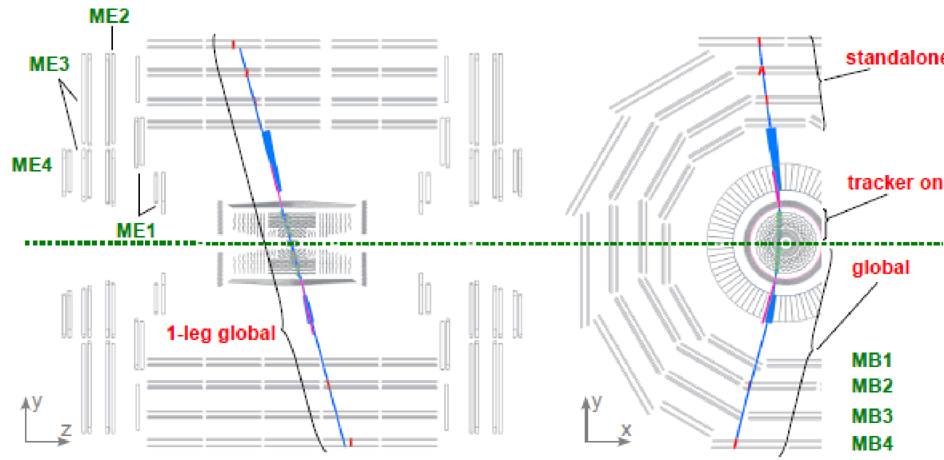


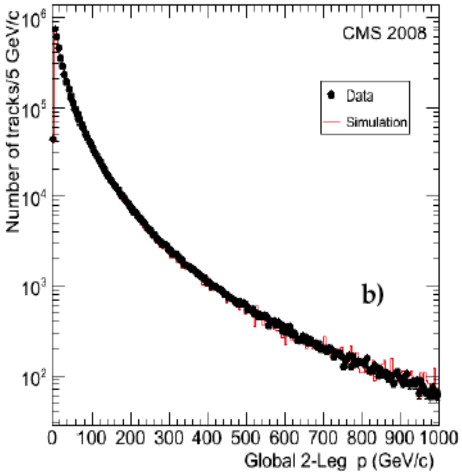
Precision modelling and measurement of the B field
- ➢ implemented in MC model



Extrapolation of track from inner tracker to first layer of barrel muon chamber
- ➢ verity that B field inside solenoid known to < 1‰

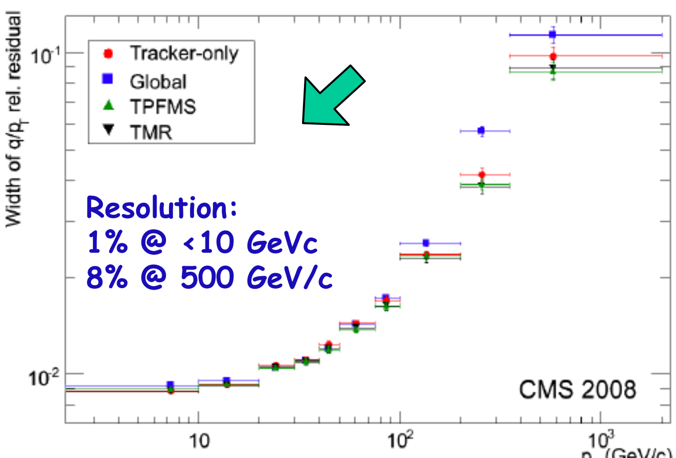
CRAFT: Muon/Tracker commissioning





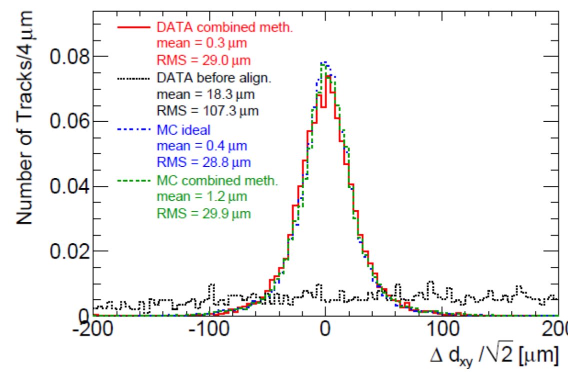
2010 *J. Inst.* **5** T03022

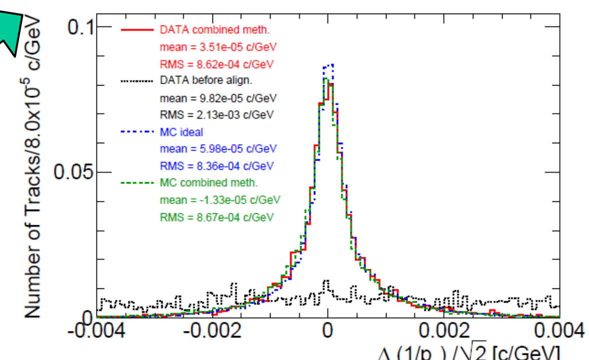
Good understanding of muon reconstruction and resolution

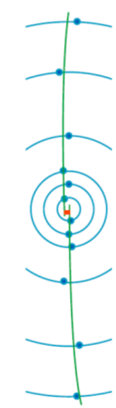


Resolution:
1% @ <10 GeVc
8% @ 500 GeV/c

Alignment already as good as can be obtained with several pb^{-1} of LHC data





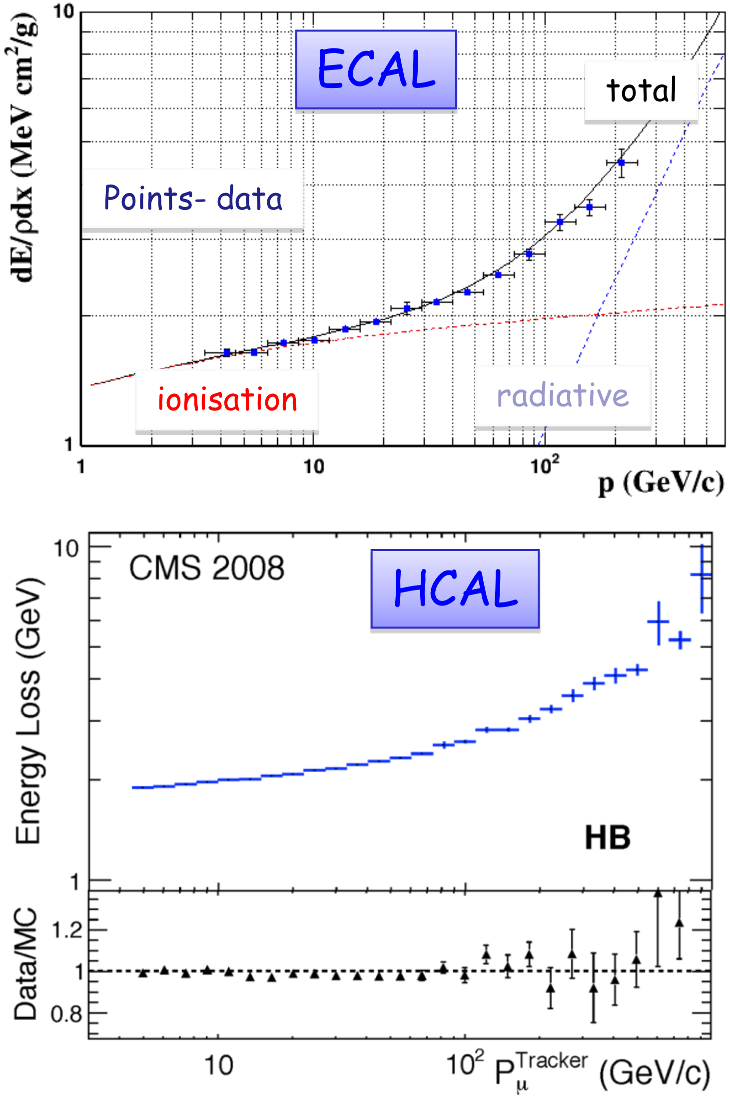


2010 *J. Inst.* 5 T03009

CRAFT: other performance plots

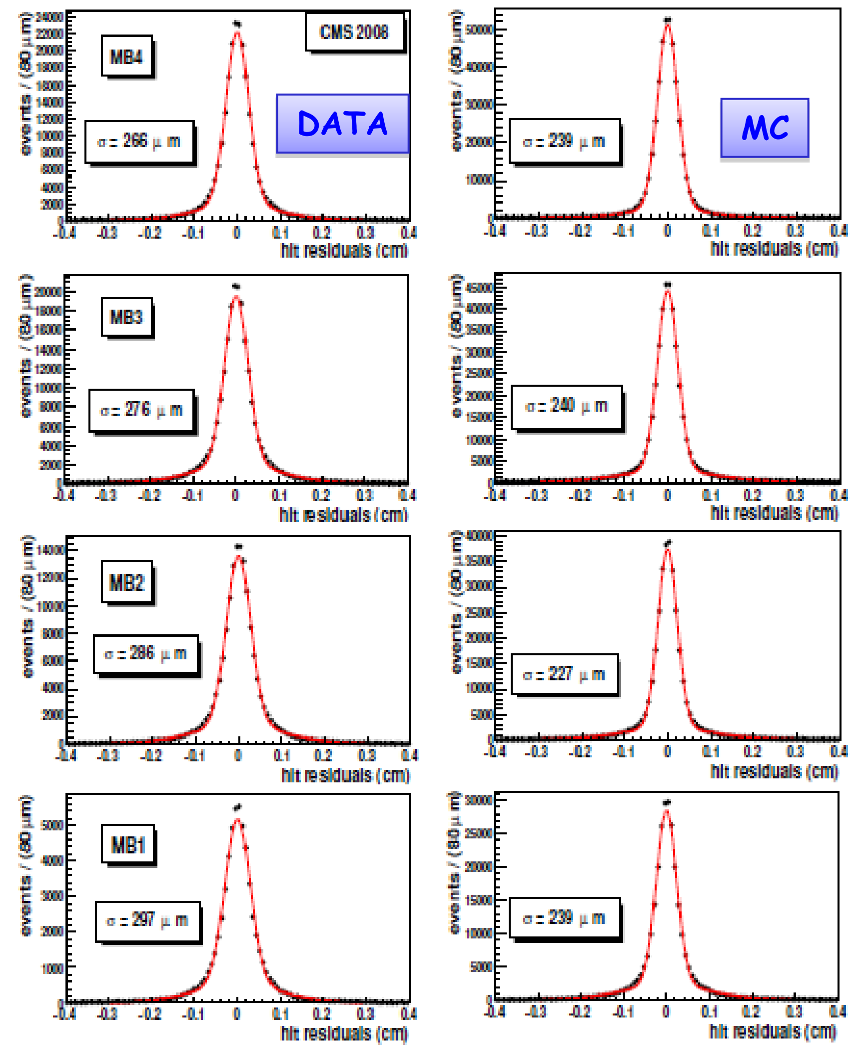
2010 *J. Inst.* **5** P03007

Energy deposited by muons



2010 *J. Inst.* **5** T03015

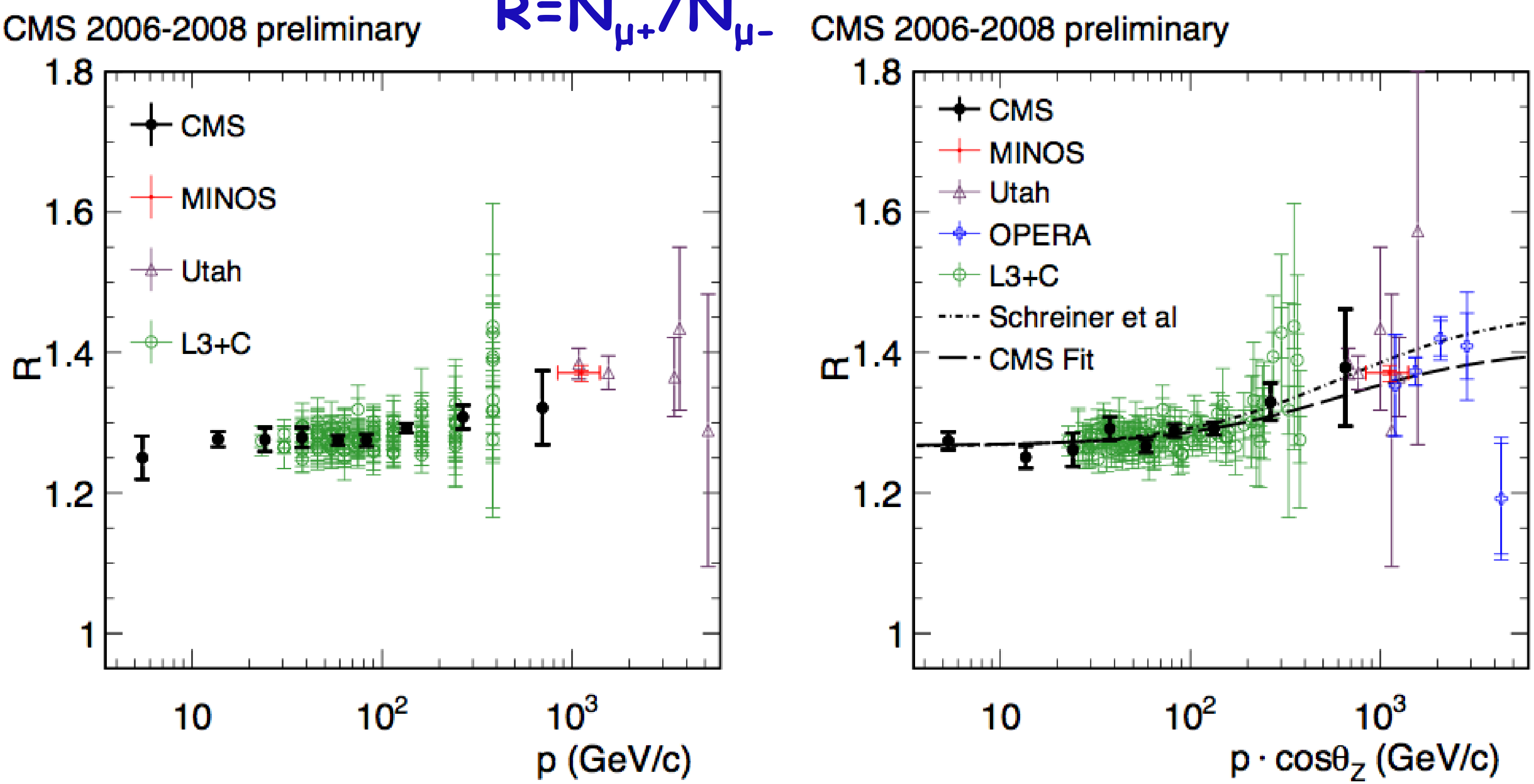
Muon Chambers point resolution



CRAFT: Physics with Cosmics

arXiv:1005.5332

$R = N_{\mu+}/N_{\mu-}$



Measurement of the Charge Ratio of Atmospheric Muons with the CMS Detector.

Submitted to Physics Letters B

Commissioning with Collisions

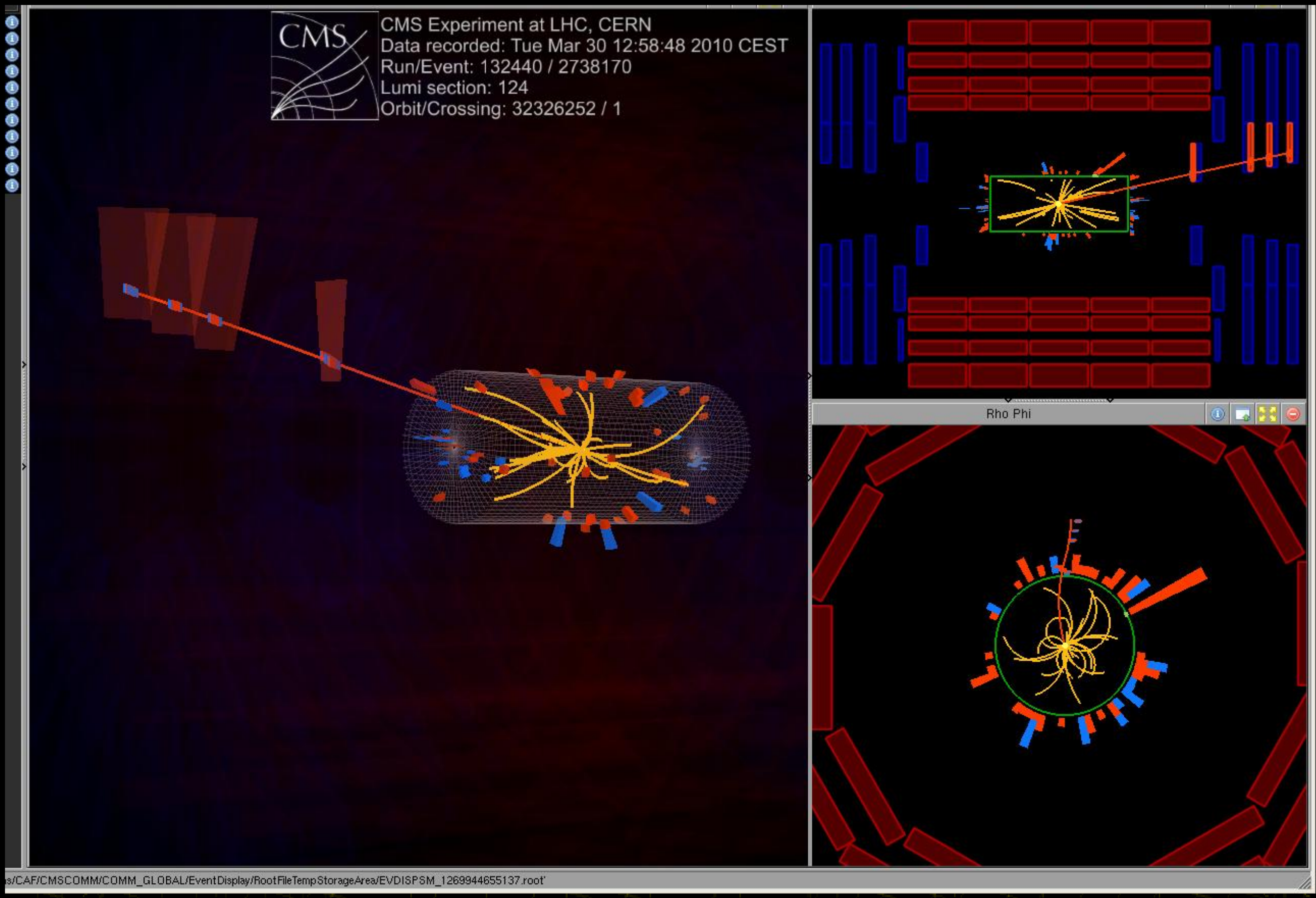
Pilot Runs:

- 23/11/2009
  $\sqrt{s}$ = 0.9 TeV
  $\mathcal{L}$ = 10μb^{-1}
  3.9x10^5 events

- 14/12/2009
  $\sqrt{s}$ = 2.36 TeV
  $\mathcal{L}$ = 0.4 μb^{-1}
  2.0x10^4 events

Physics Run Start-up:

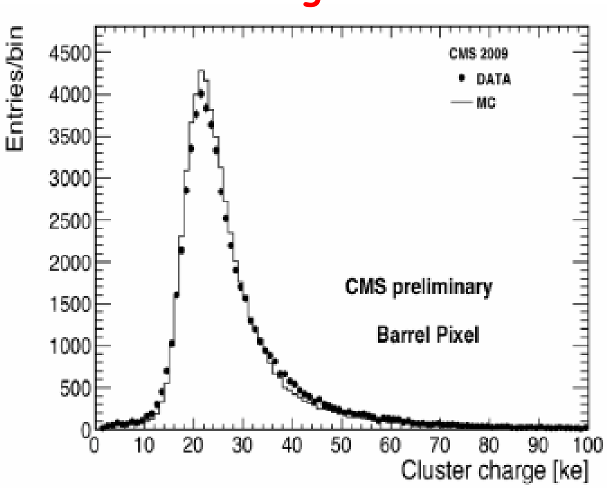
- 30/03/2010
  $\sqrt{s}$ = 7 TeV
  $\mathcal{L}$ ~ 20 nb^{-1} up to now

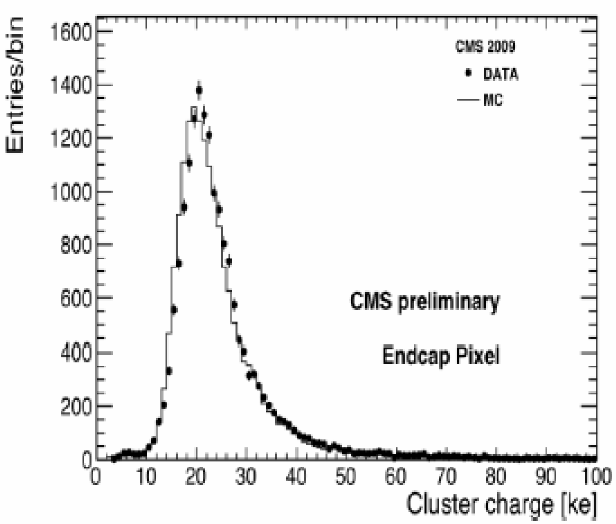


30/03/2010 first collision at $\sqrt{s}$ = 7 TeV

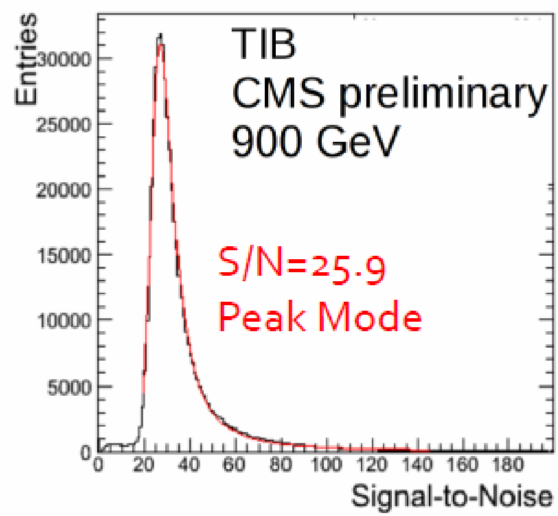
Tracker Performance at √s = 900 GeV

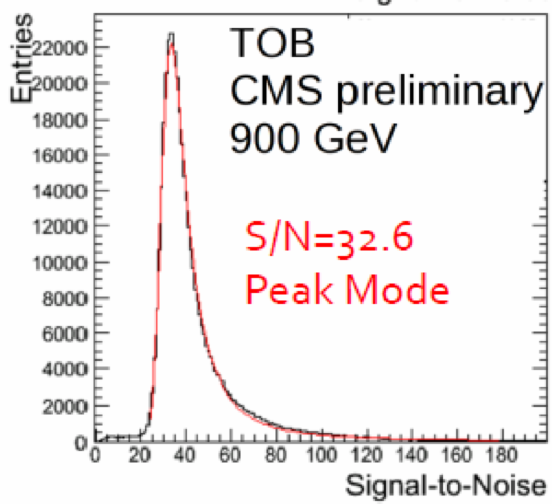
Pixel: Charge Distribution



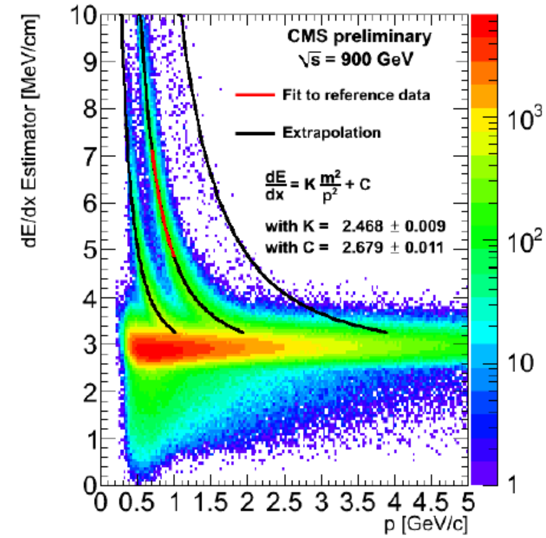


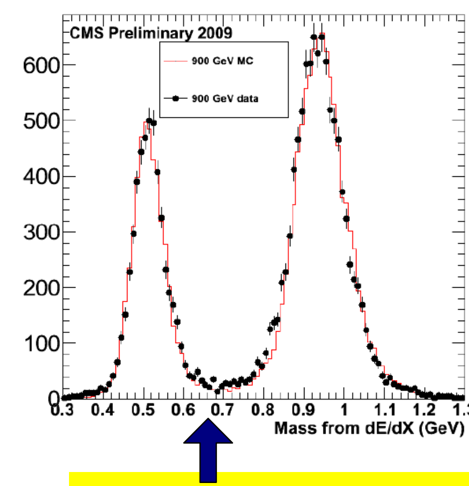
Si-Strip: Charge Distribution





dE/dx

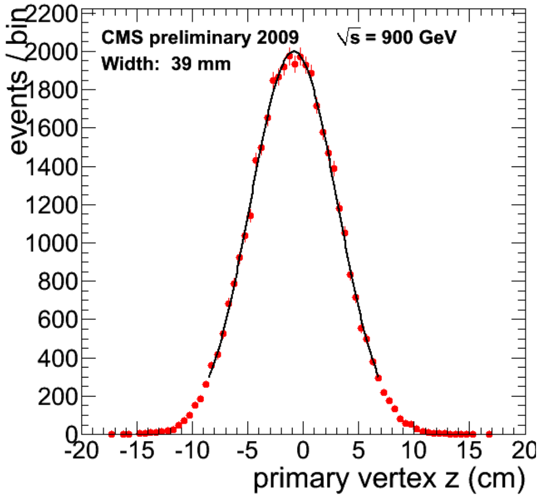




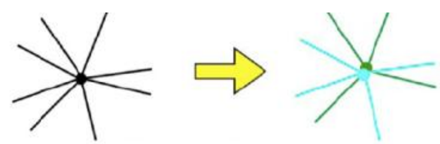
$p < 2$ GeV
$dE/dX > 4.15$ MeV/cm

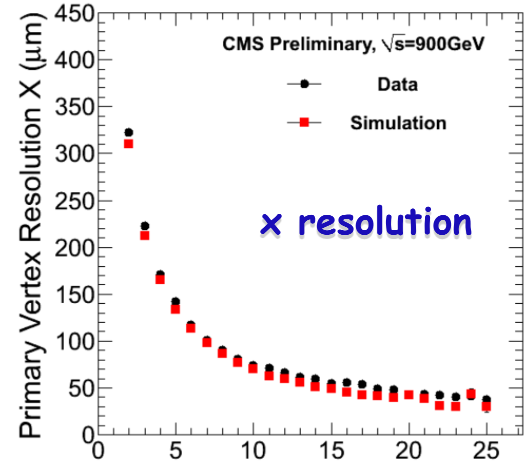
Tracker Performance at √s = 900 GeV

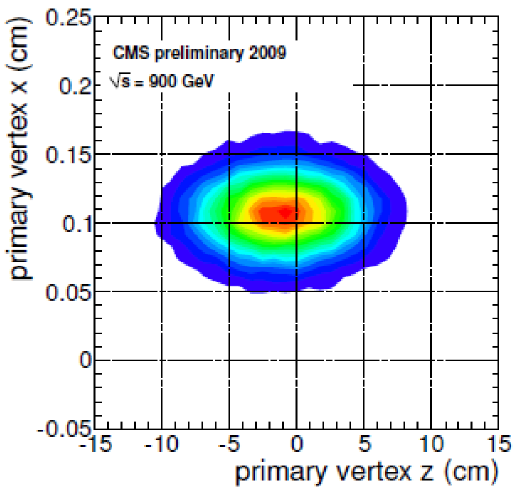
Primary Vertex

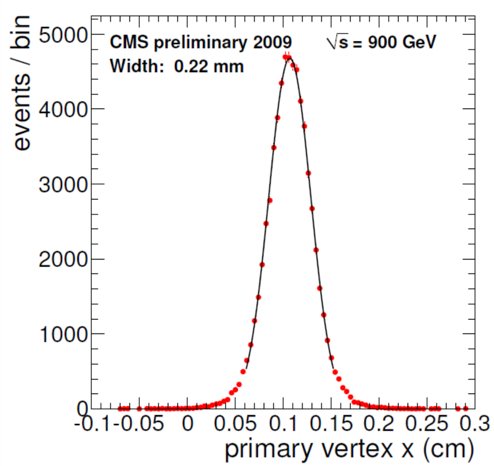


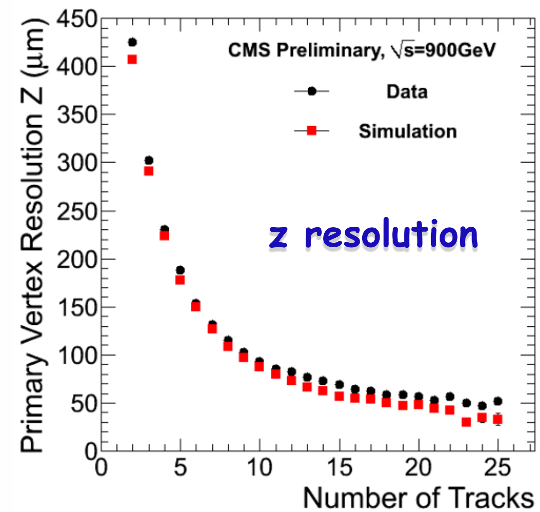
Primary vertex resolution obtained splitting tracks and comparing fits



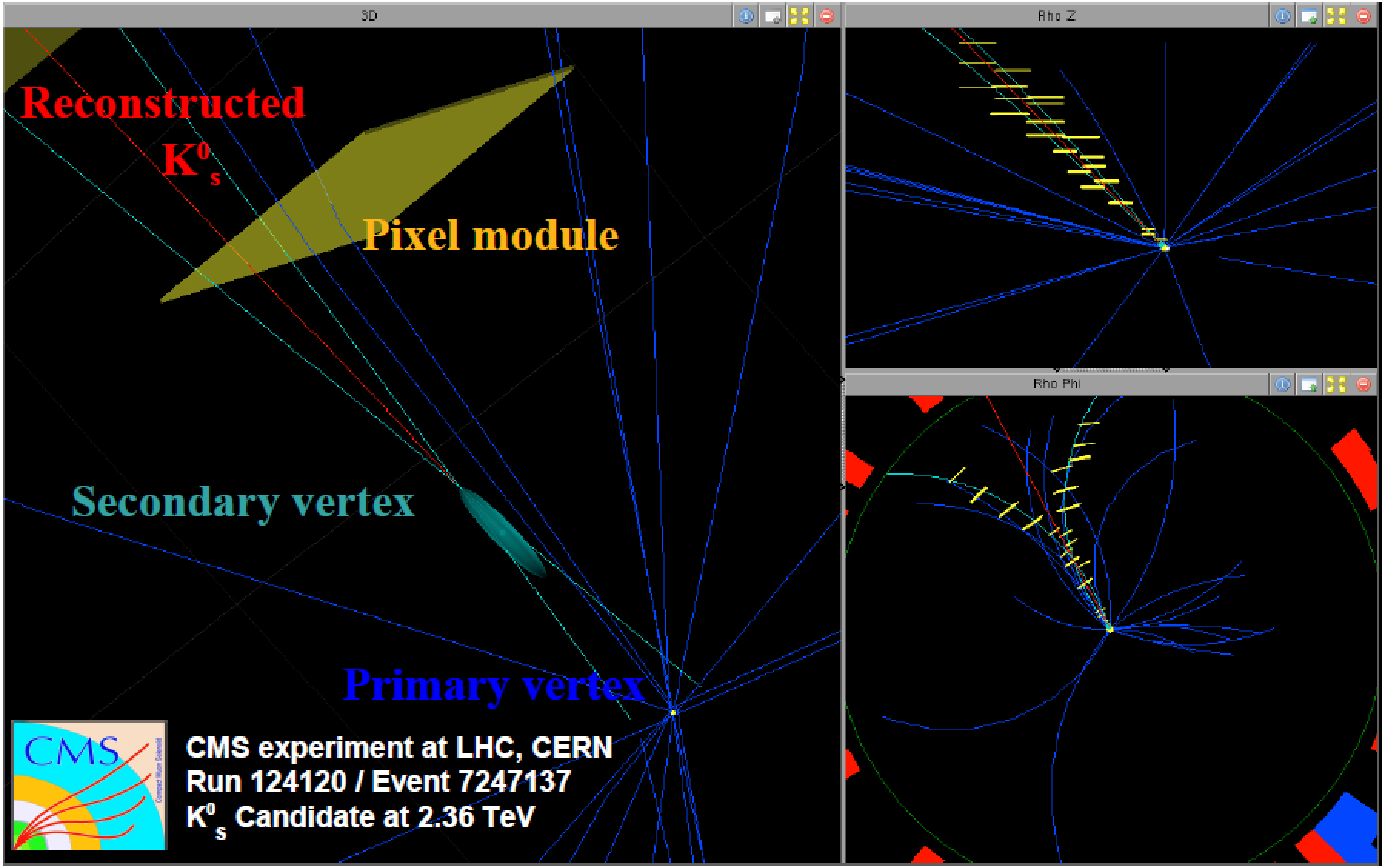




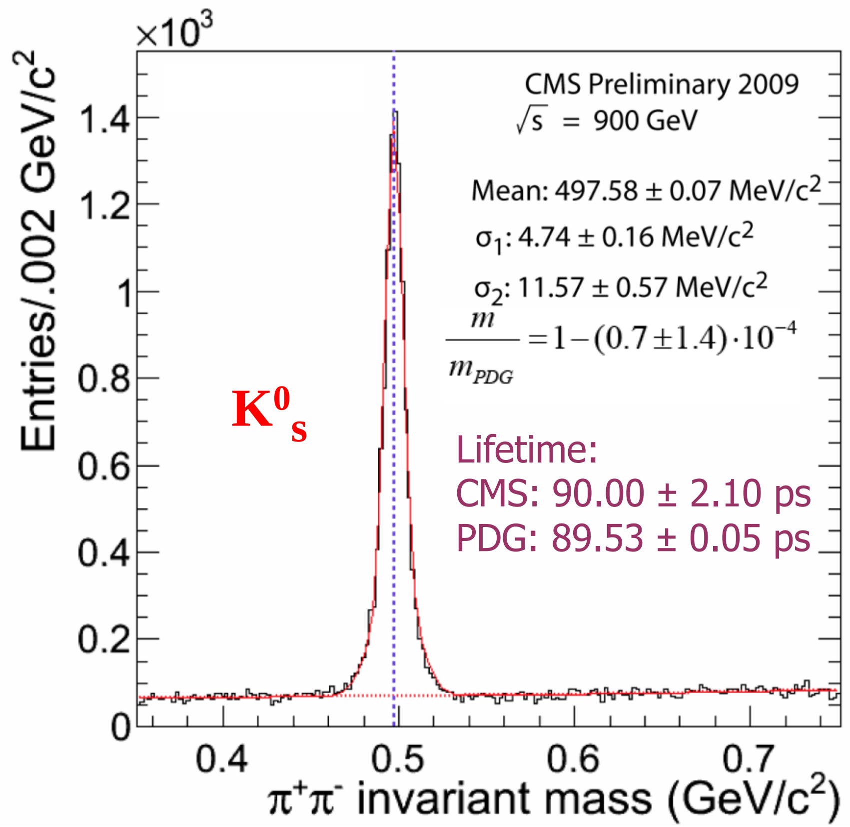


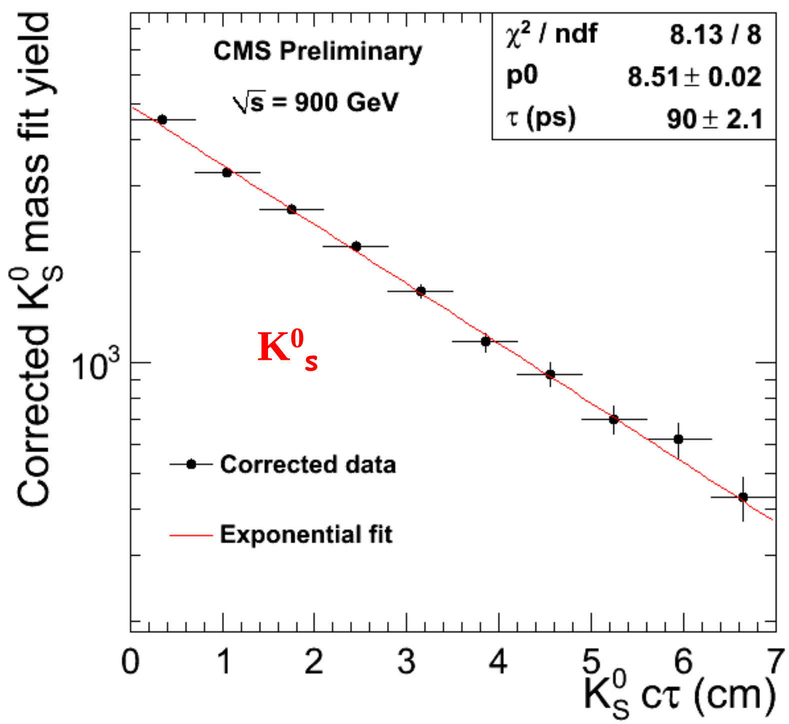


K^0_s candidate event at $\sqrt{s}$ 2.36 TeV



Resonances @ $\sqrt{s}$ = 900 GeV

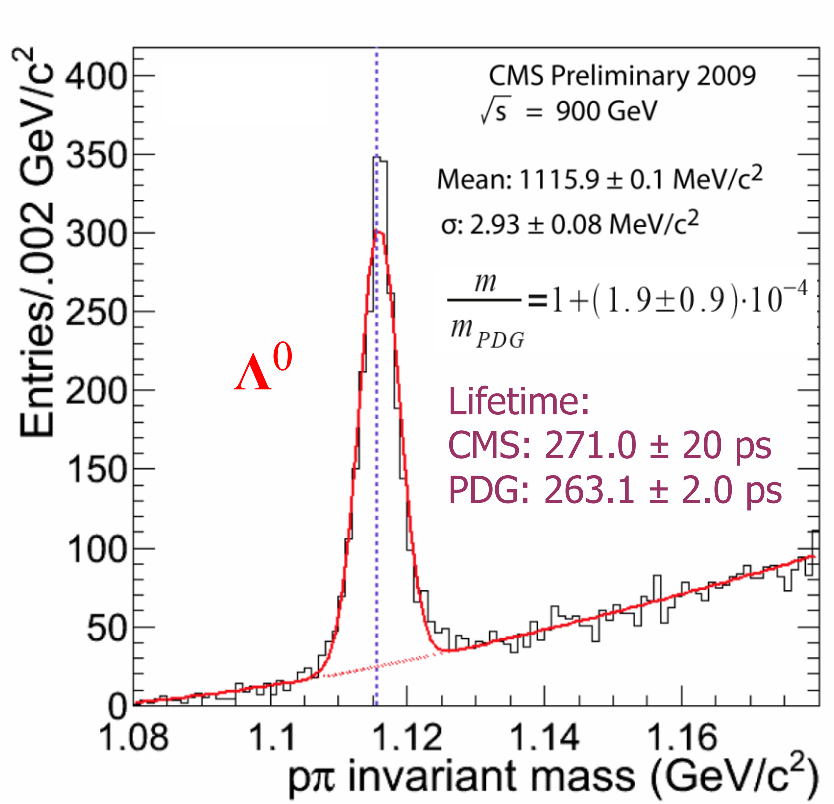


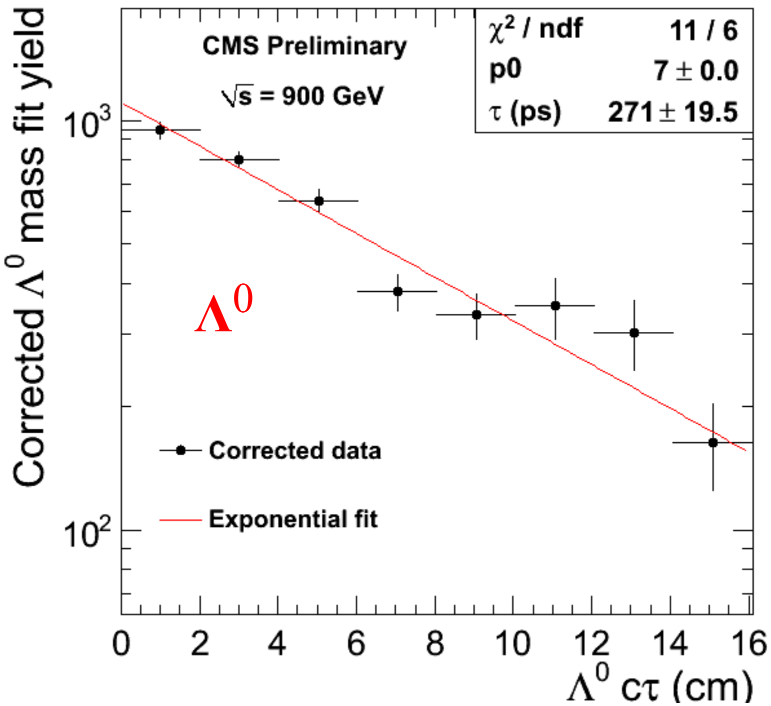


Excellent understanding of the momentum scale for low mass resonances

⇒ Accurate tracking, vertexing, alignment, magnetic field, ….

Resonances @ √s = 900 GeV

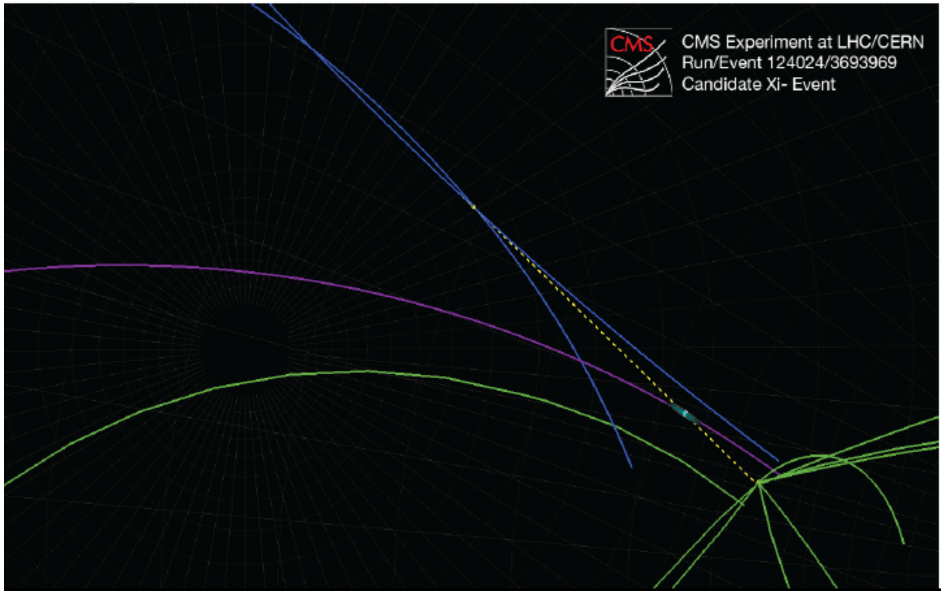


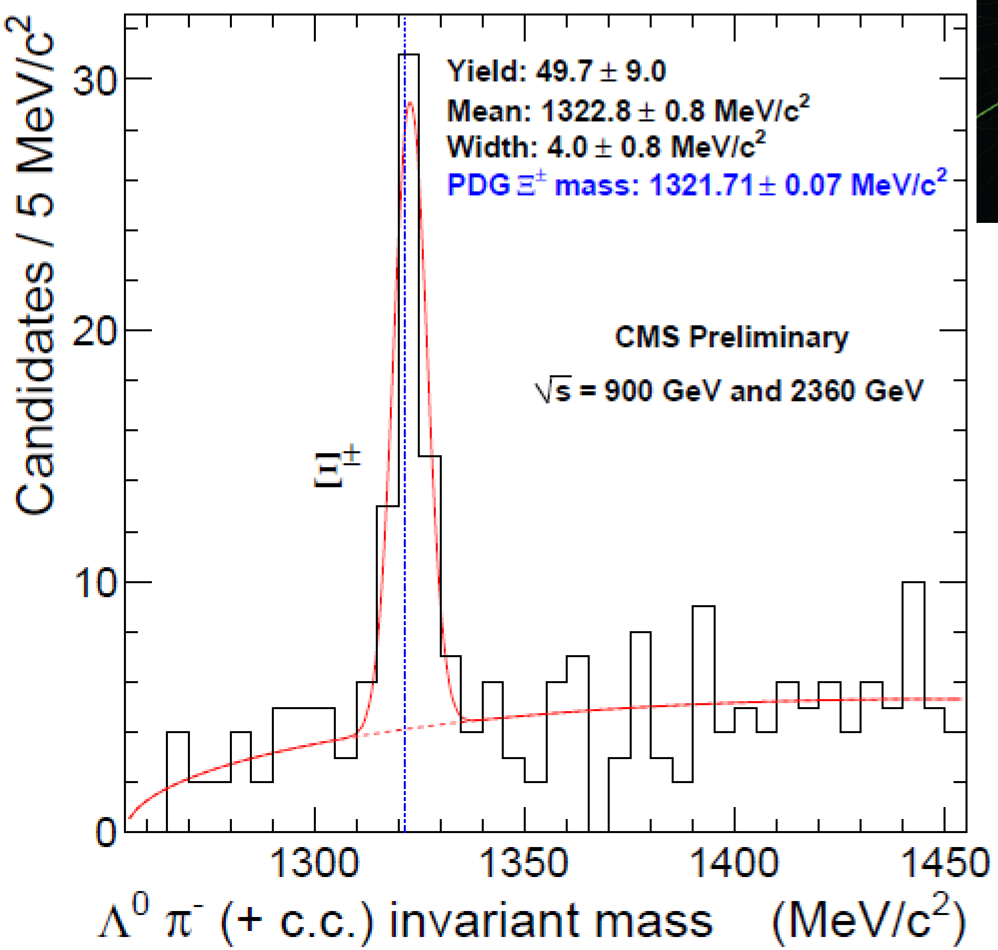


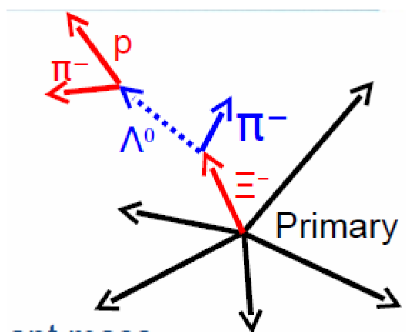
Excellent understanding of the momentum scale for low mass resonances

⇒ Accurate tracking, vertexing, alignment, magnetic field, ….

… and the $\Xi^{\pm}$





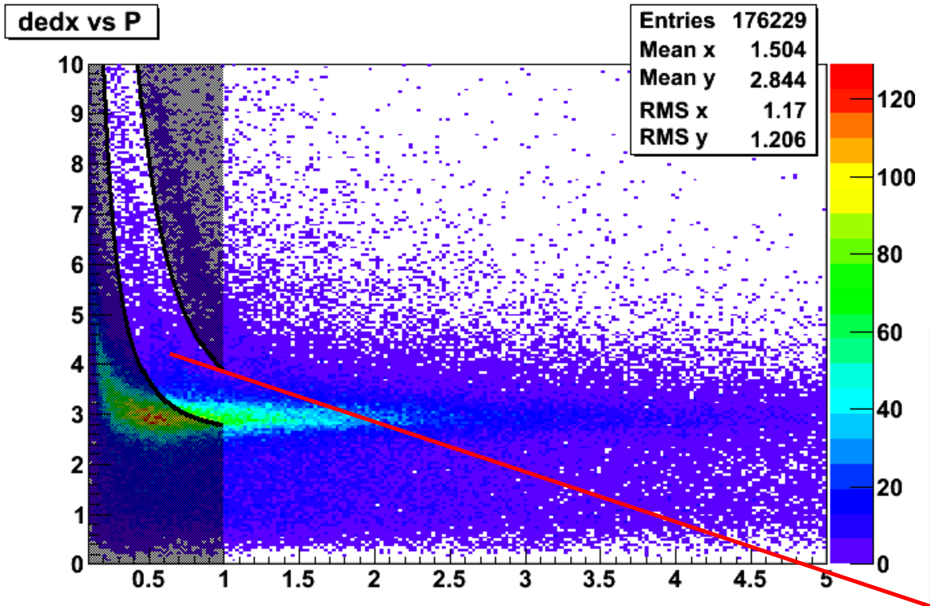


$\Xi^{\pm} \longrightarrow \Lambda\pi^{\pm}$

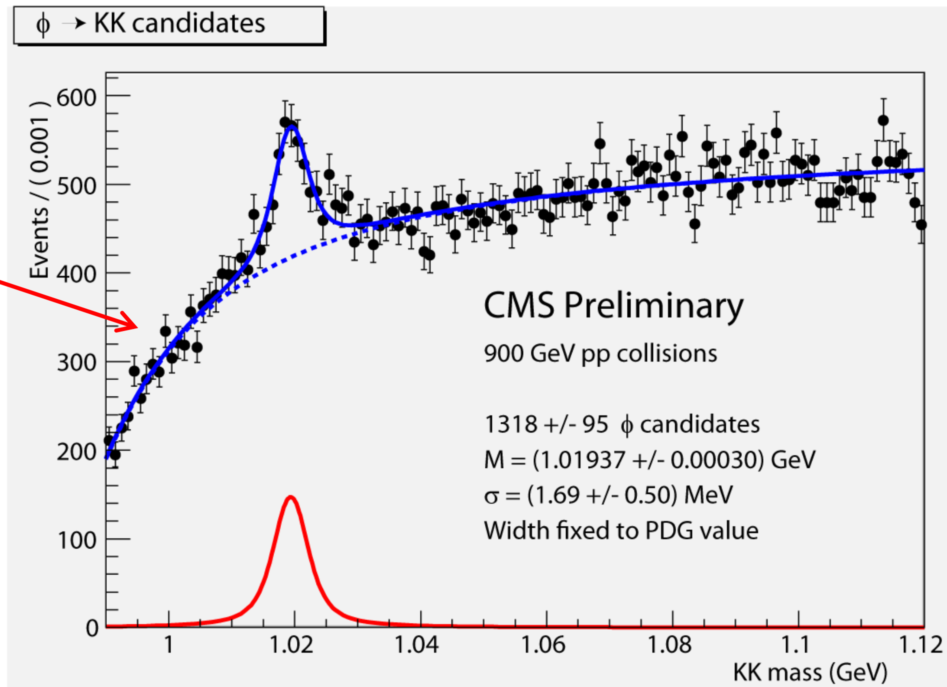
$\Lambda\pi$ Invariant mass

- tracks displaced from primary vertex ($d_{3D} > 3\sigma$)
- constrain Λ mass to PDG world average value in Ξ fit
- require same sign π's

$\phi \rightarrow K^+K^-$ using dE/dx



$\sqrt{s}$ = 900 GeV

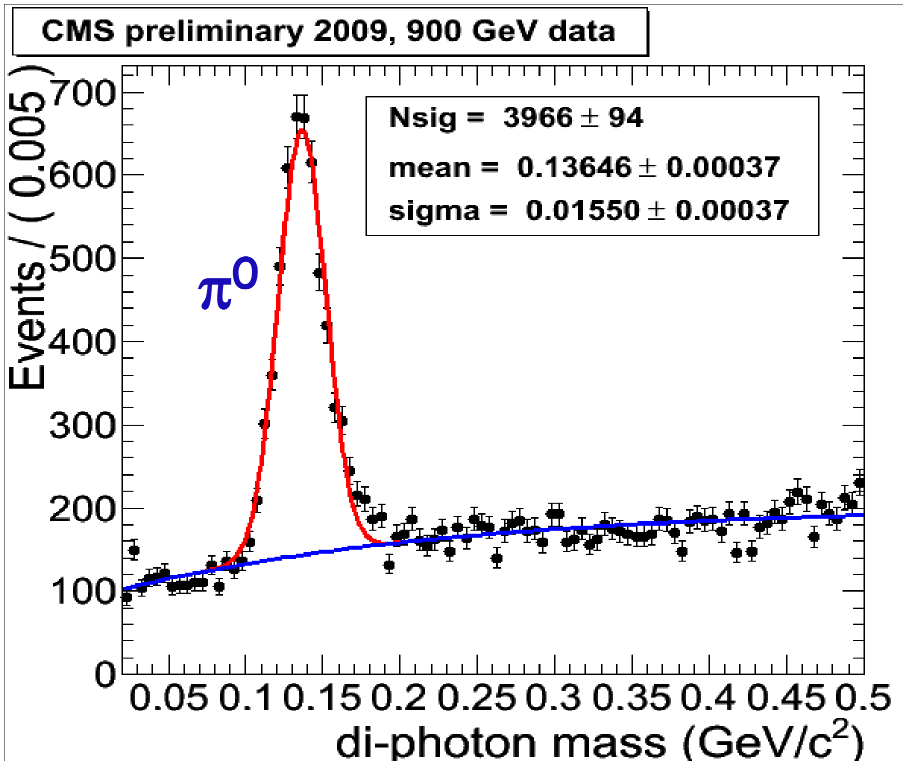


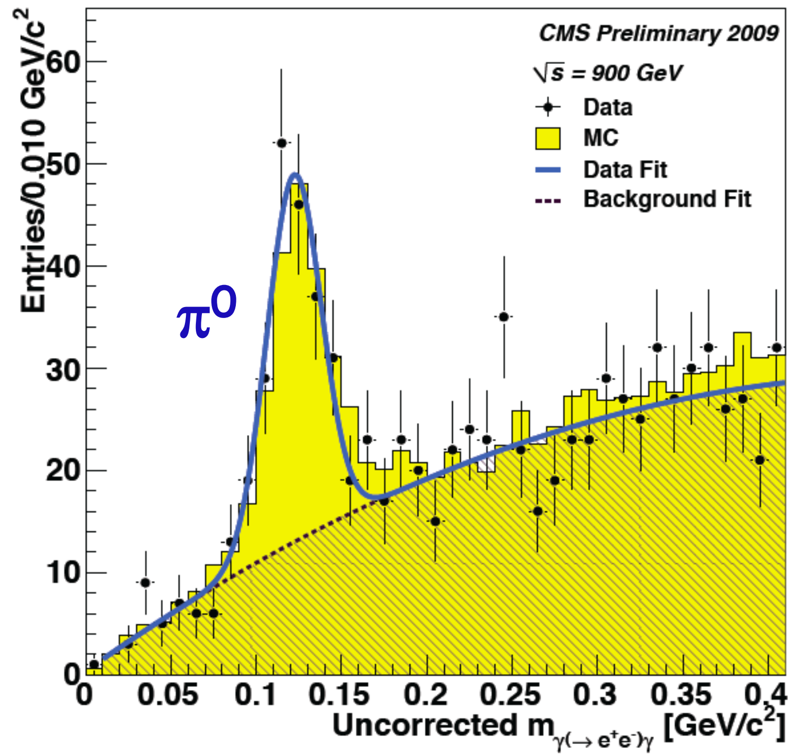
- **Rejection of low P tracks (< 1GeV) with dE/dx incompatible with the hypothesis of a charged K (light band).**
- **Invariant mass reconstruction for events passing the dE/dx cut**

K^0_s, Λ, ϕ …

- **Validate Tracking, Reconstruction, Secondary Vertex Finding, Magnetic Field, Material, Momentum scale**
- **Validation of MC**

First γγ Resonance in CMS

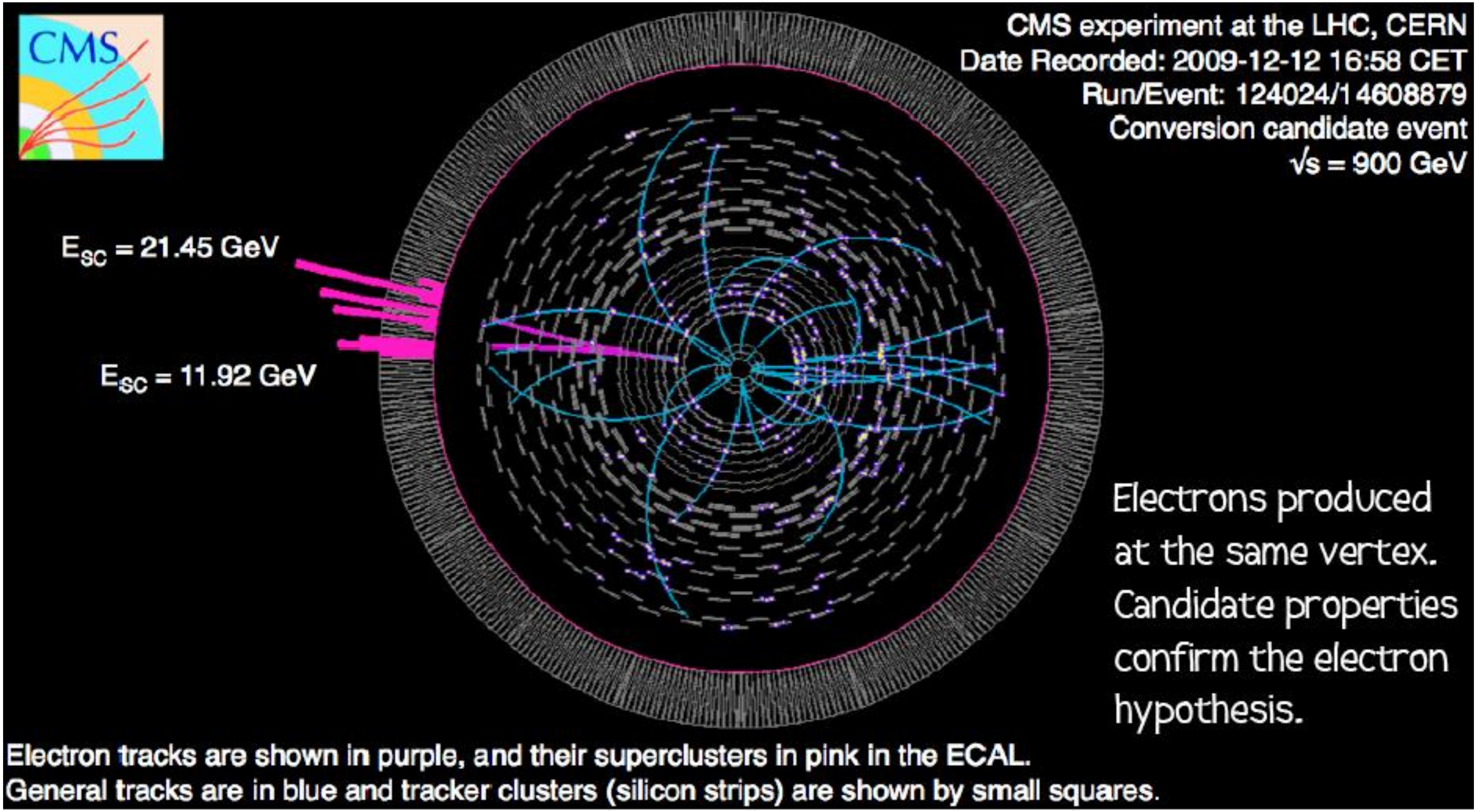




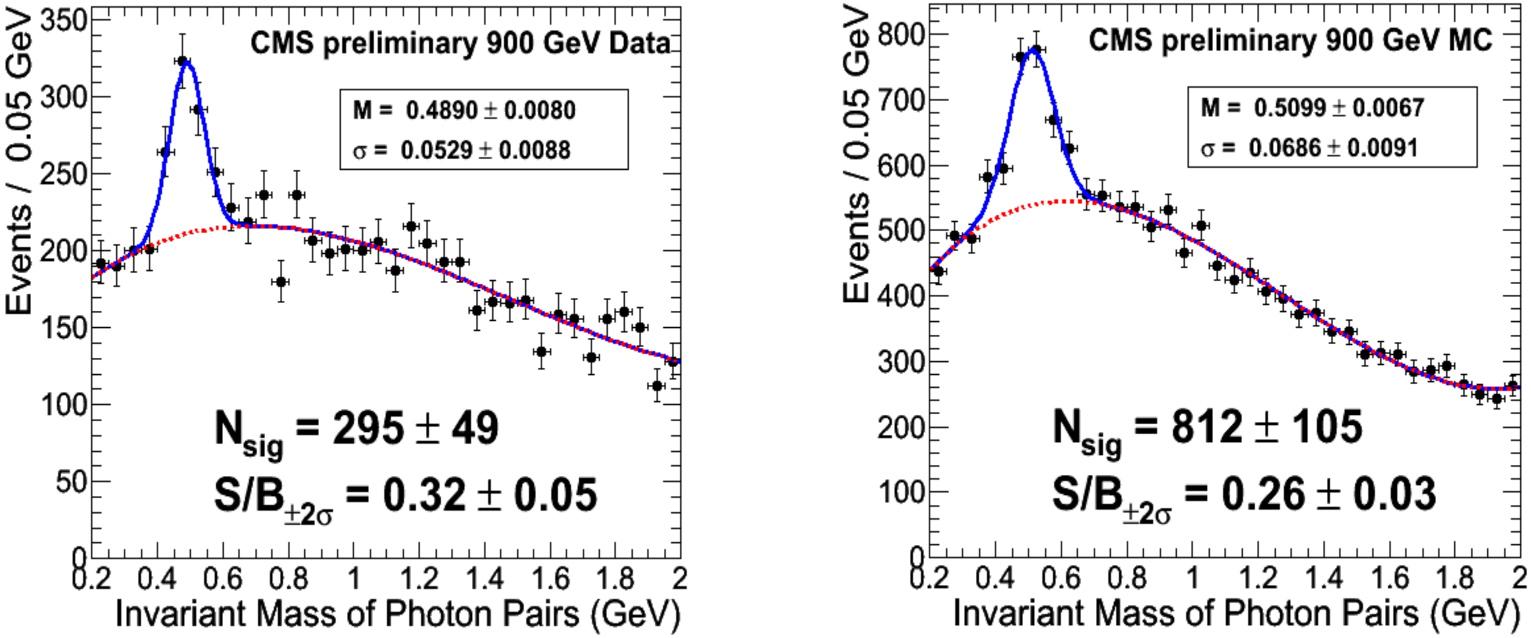
With MC corrections (zero suppression): within 2% of PDG mass …

$\pi^0 \rightarrow \gamma\gamma$ with one leg reconstructed from conversion $\gamma \rightarrow e^+e^-$ candidates

$\gamma \rightarrow e^+e^-$ Conversion candidate

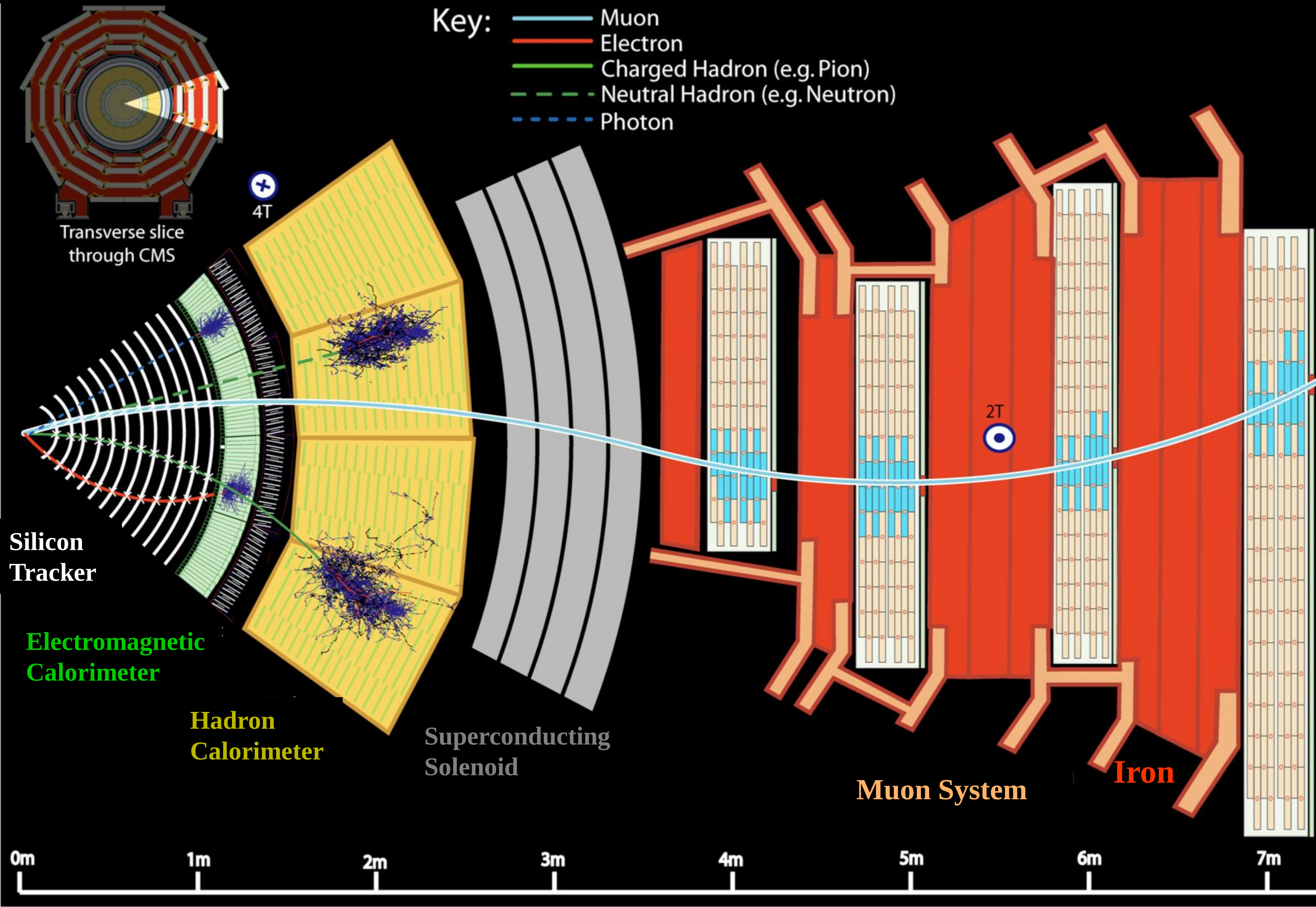


η resonance



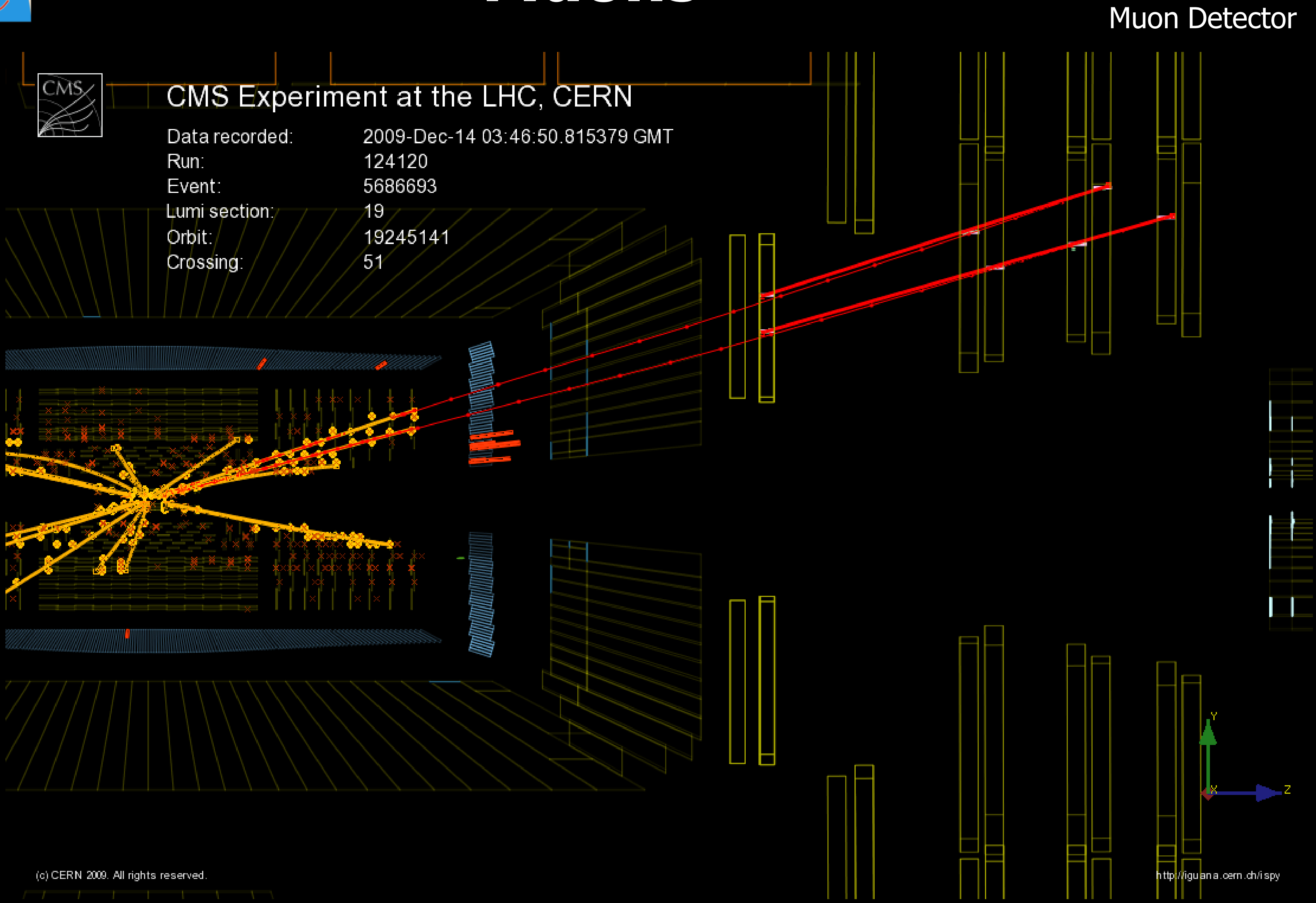
- Mass and width compatible with MC
- η yield scale as expected versus π^0

Transverse slice of CMS



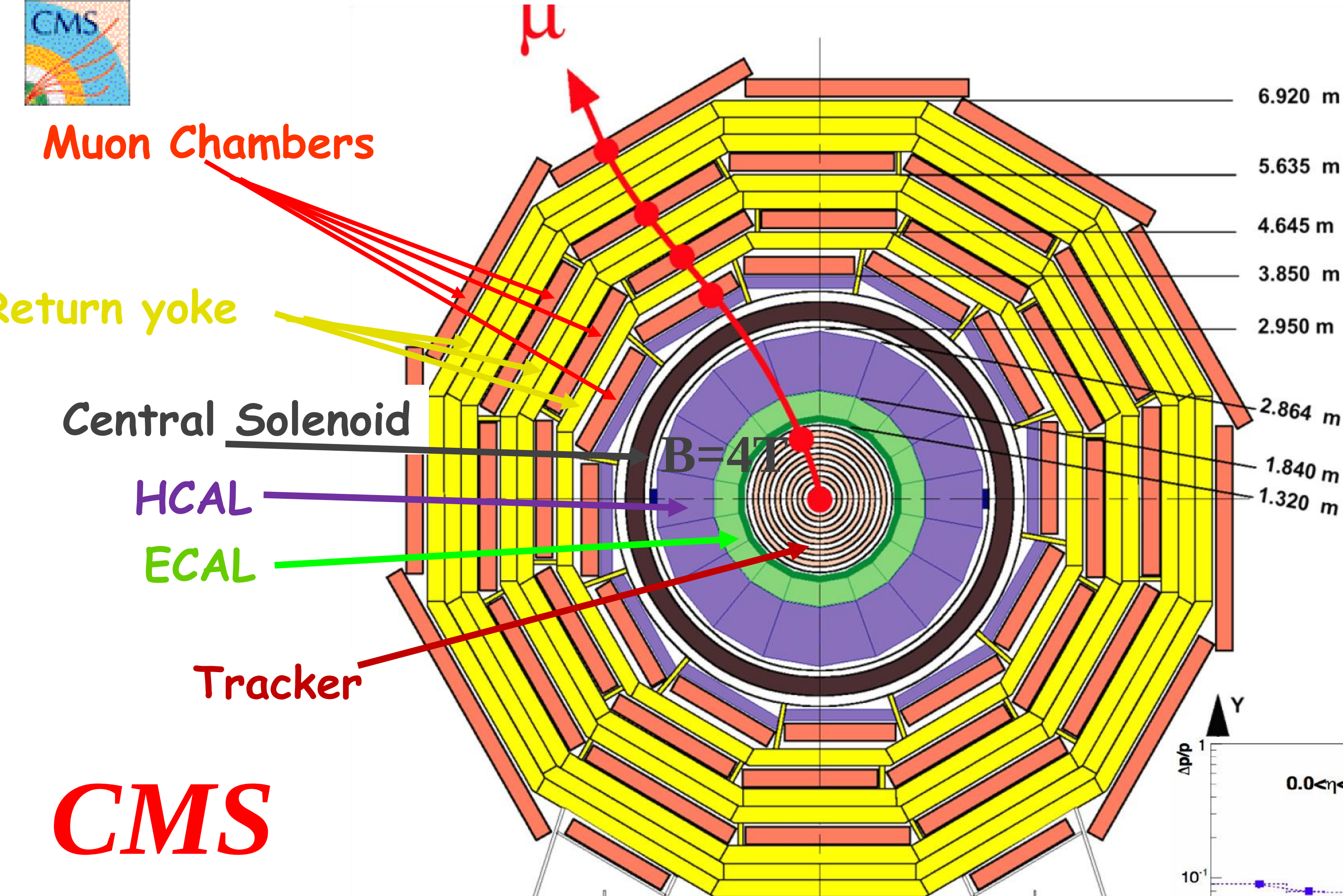
CMS@LHC

Muons

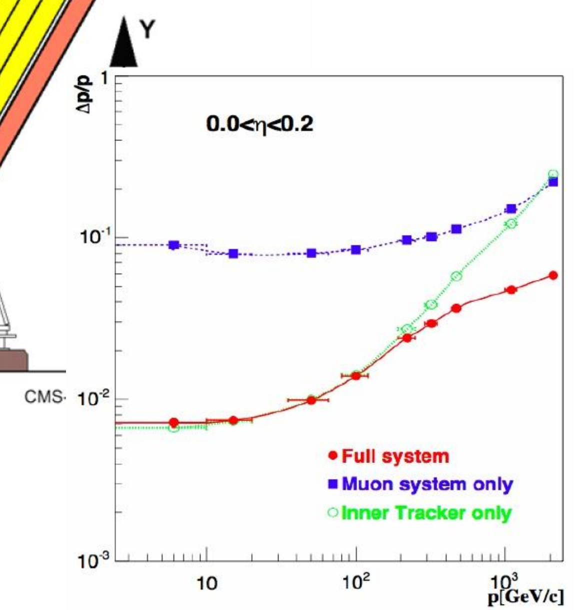


$p_T(\mu_1)$ = 3.6 GeV, $p_T(\mu_2)$ = 2.6 GeV, $m(\mu\mu)$= 3.03 GeV

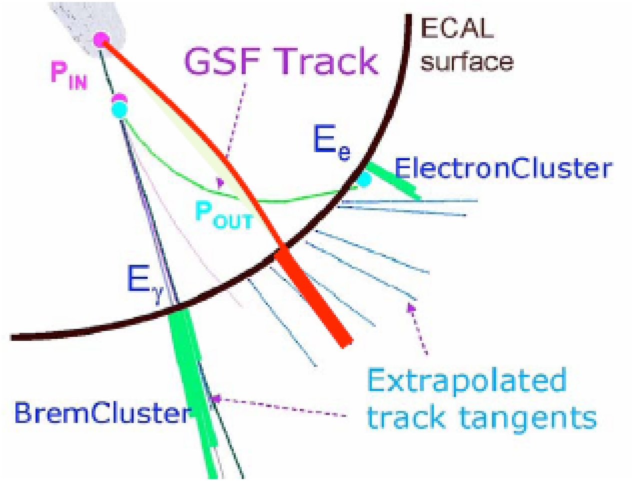
CMS



- High **accuracy momentum** measurement made in the **central tracker**;
- The **external** system **identifies (and trigger) muon tracks** and improves the momentum **Resolution for very high Pt muons**



Electron Particle Flow supercluster algorithm



- The GSF track extrapolation is used to recover the electron cluster
- At each tracker layer a tangent is extrapolated to the ECAL, PreShower and HCAL surface
- ECAL cluster associated to KF tracks non identified from converted brems are vetoed to the PFlow SuperCluster
- <u>The PFlow SuperCluster region is driven by the gsf track</u>

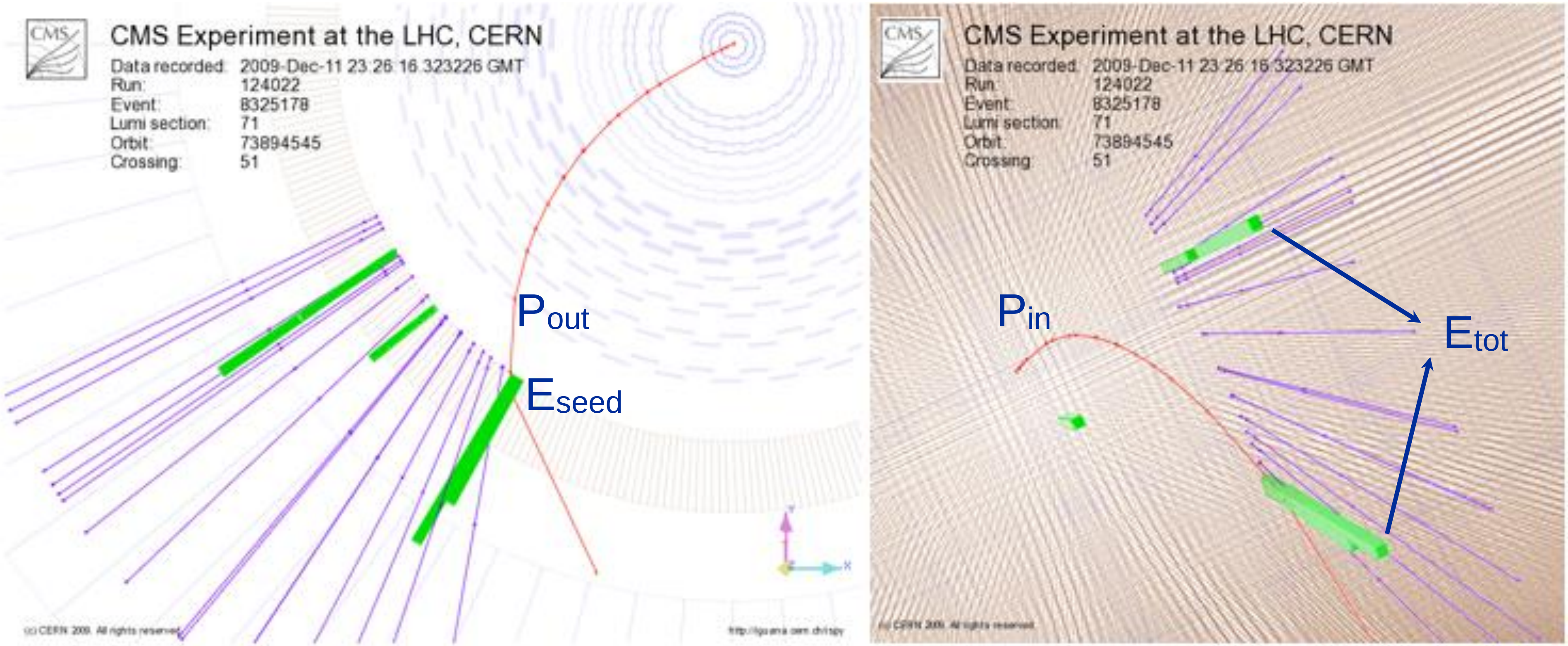
✓ **PF supercluster works better than the e/γ supercluster for electron in jets.**

✓ **It works also at very low P_T: with 4T magnetic field of CMS the radius of curvature is ~1m/GeV P_T (supercluster extend in φ for 0.3 rad).**

Electron candidates in Particle Flow

tracking algorithm: Gaussian-Sum Filter (GSF)

900 GeV data



E_{seed} = 1.26 GeV,
P_{out} = 1.18 GeV/c:
E_{seed}/P_{out} = 1.07

E_{tot} = 2.32,
P_{in} = 2.56 GeV/c:
E_{tot}/P_{in} = 0.91

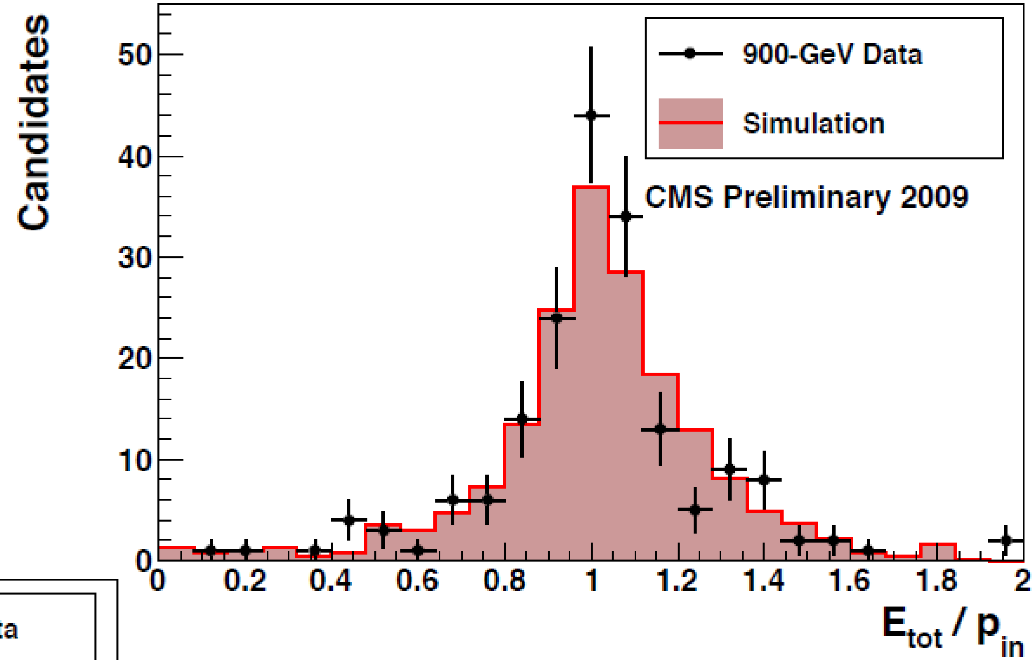
E_{brem}= 1.06 GeV,
P_{in}-P_{out} = 1.38 GeV/c

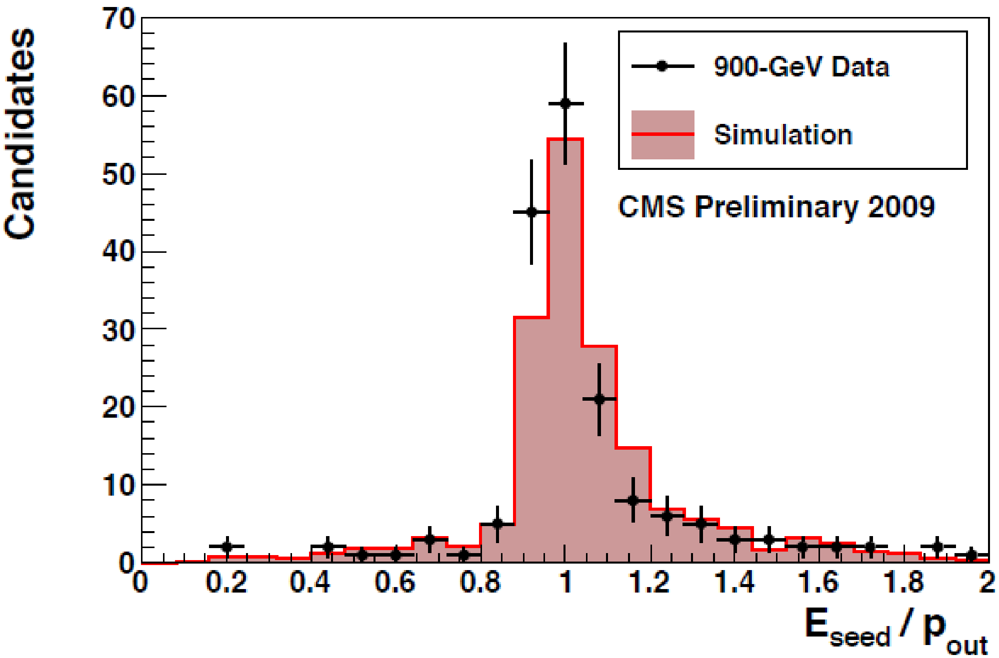
Reconstructed e candidates combines two seeding algorithms:

- "ecal driven" optimized for high E_T isolated clusters (W/Z … H)
- "tracker driven" bringing more for electrons at low p_T or in jets

Electron reconstruction in Particle Flow

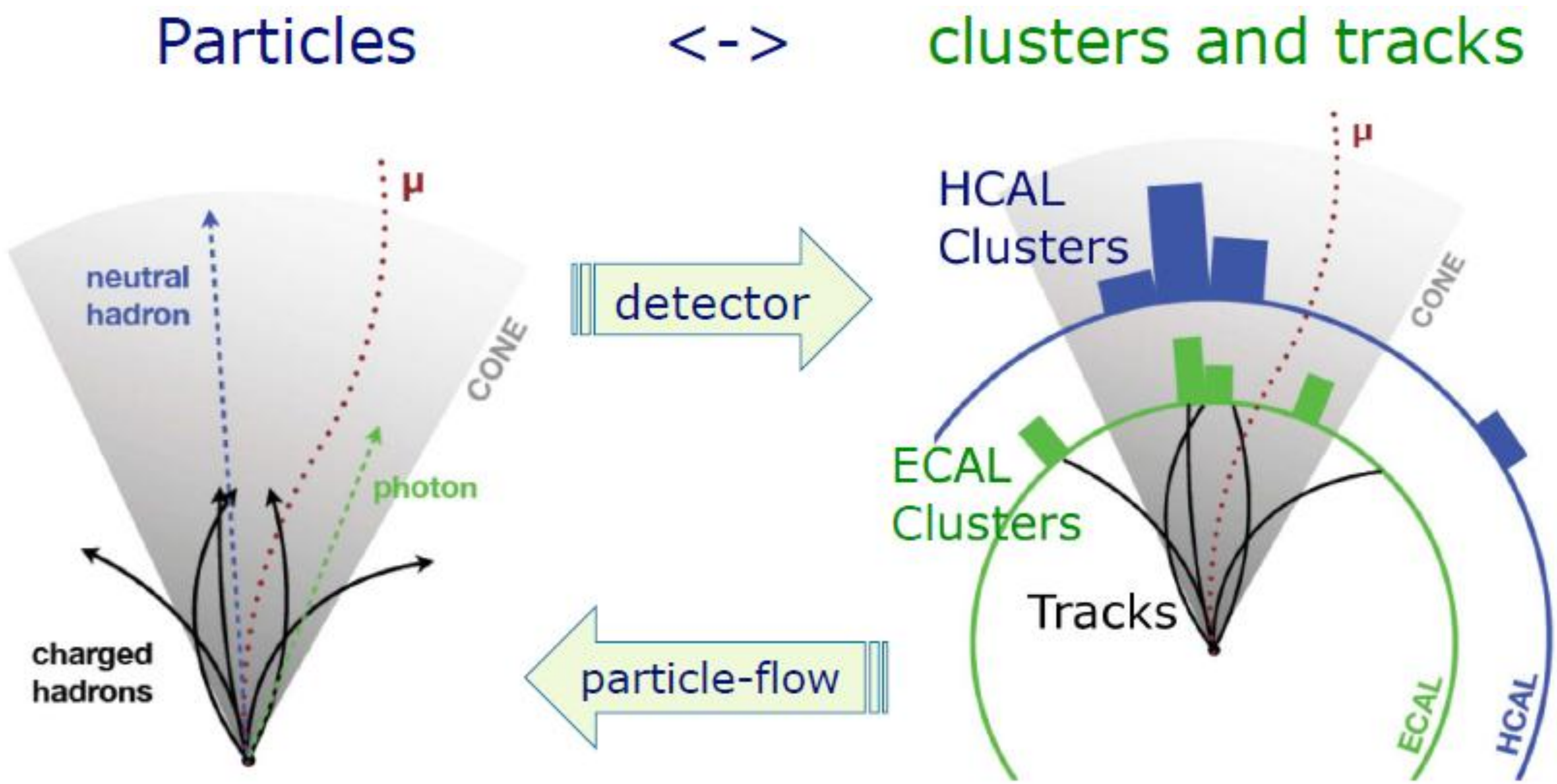
Tracker-ECAL energy matching variables E_{tot}/p_{in} and E_{seed}/p_{out} after identification selection cut.





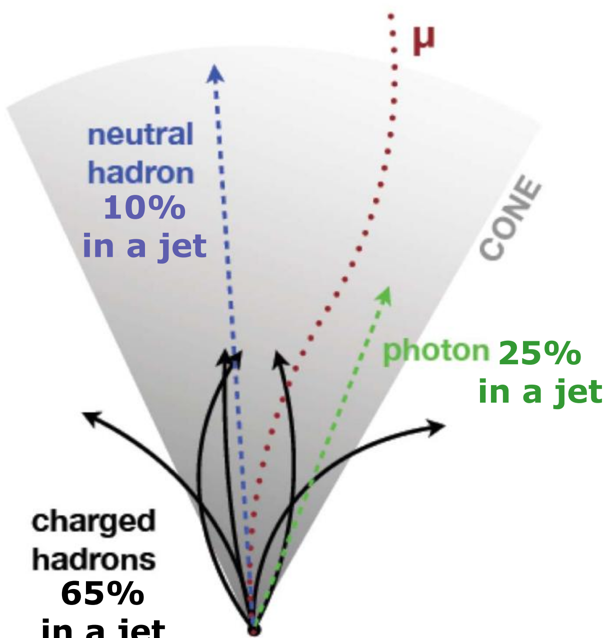
The selection cut is based on a multivariate estimator combining several observables built from tracker and ECAL measurements

The Particle Flow Algorithm



The list of individual particles is then used to build jets, to determine the missing transverse energy, to reconstruct and identify taus from their decay products, to tag b jets …

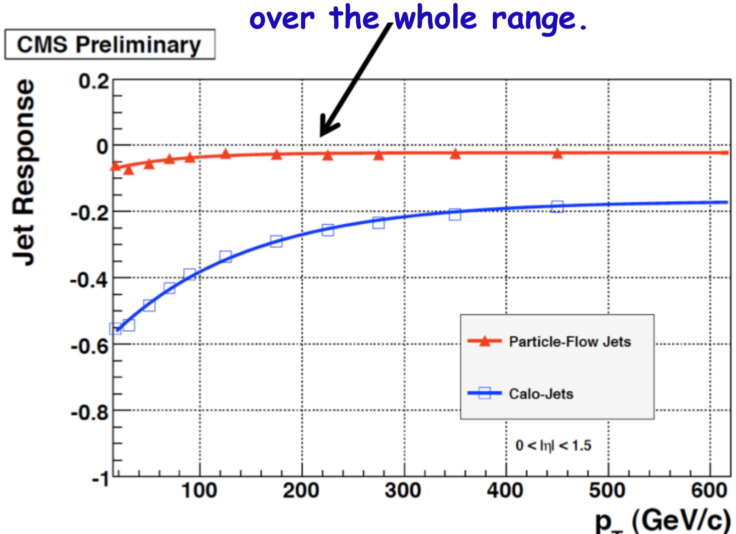
Jet energy response and resolution

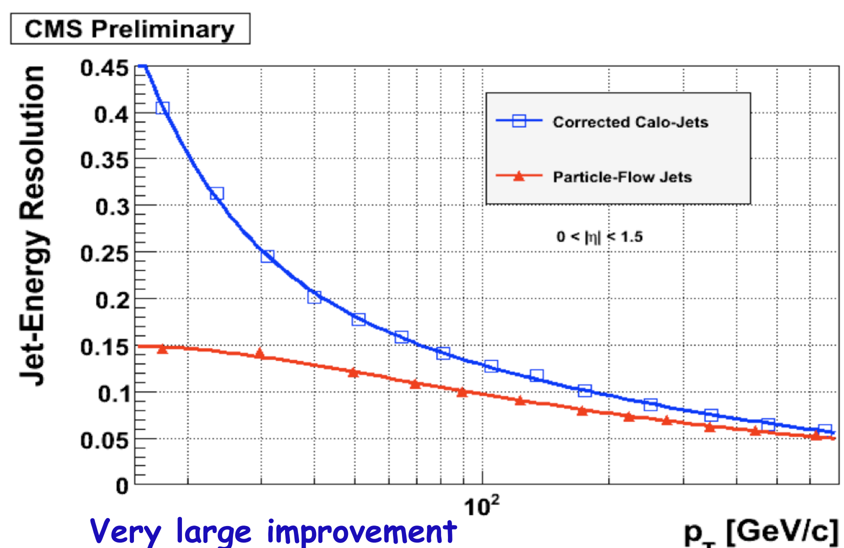


- Even for a jet of p_T = 500 GeV/c the average p_T of the stable particles is of around 10 GeV/c
- ~90% of the jet energy is carried out by charged-hadrons and photons

simulated QCD-multijets events

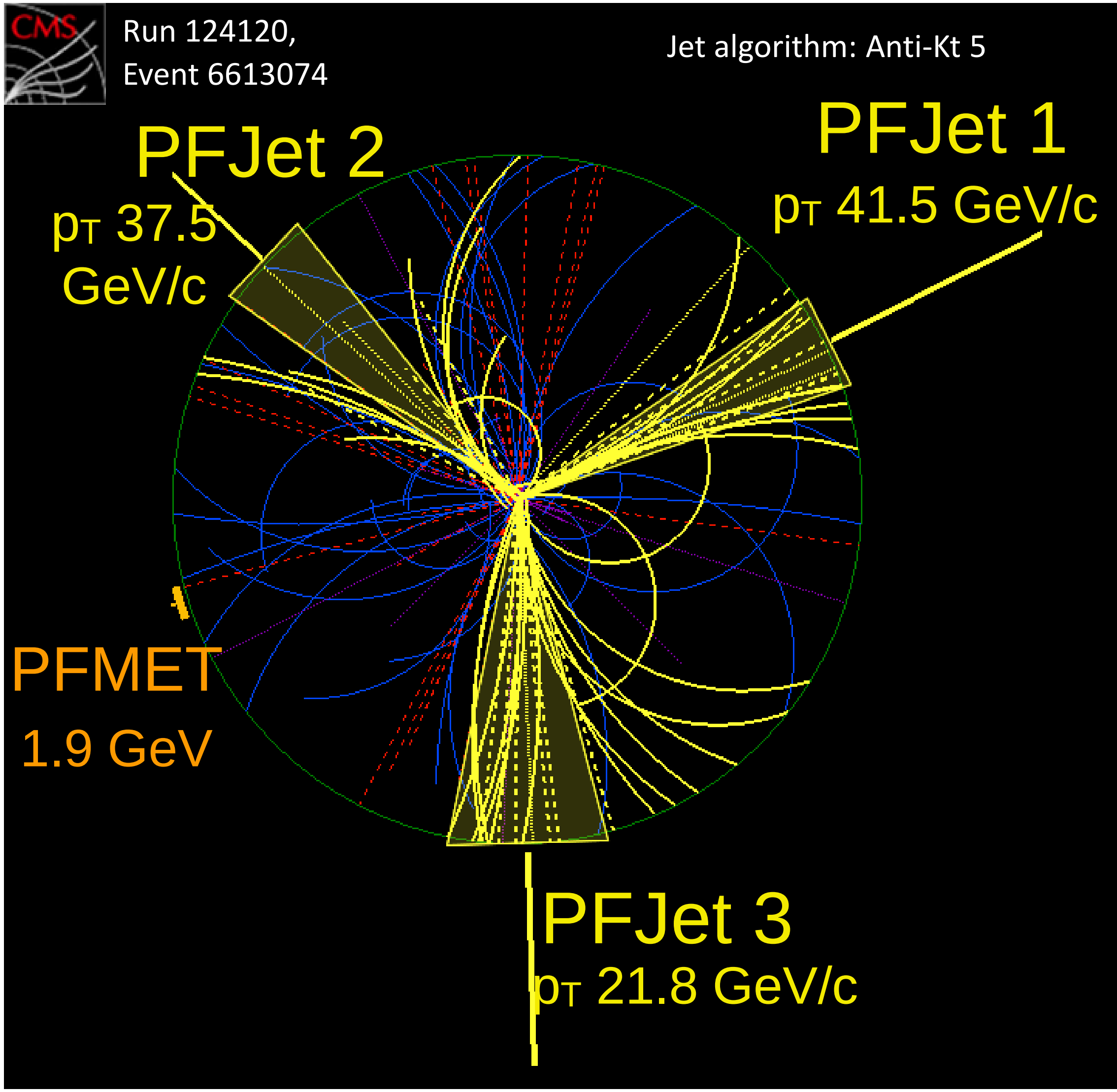
95-97% of the p_T reconstructed, over the whole range.





Very large improvement at low p_T, thanks to tracks

MultiJet event at 2.36 TeV

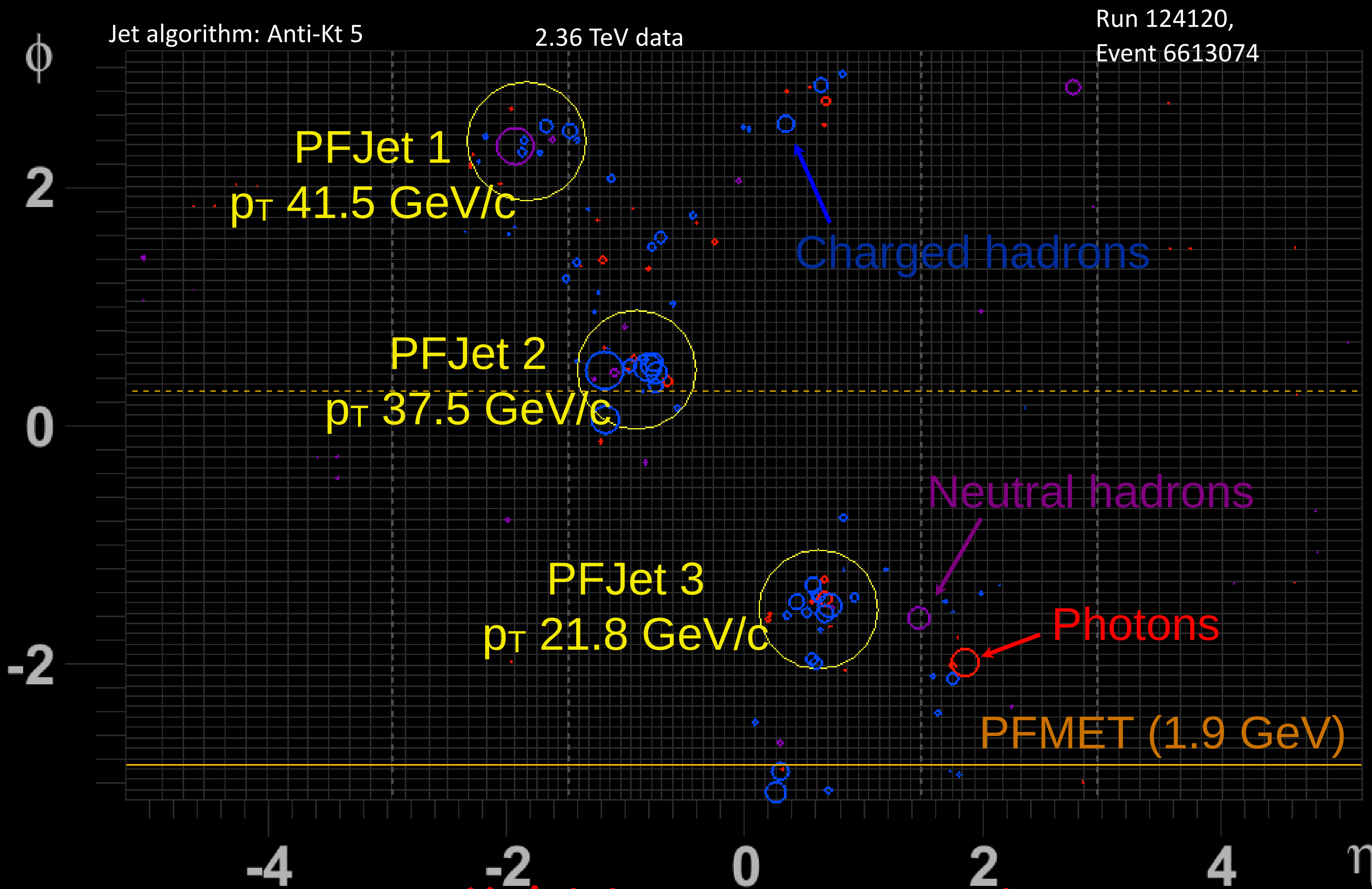


PFJets with (uncorrected) p_T>20 GeV/c

- Particle inside the jet:
- - Charged hadrons
- - Photons
- - Neutral hadrons
- Particles outside the jet:
- - Charged hadrons
- - Photons
- - Neutral hadrons
- PFMET (1.9 GeV) $\overrightarrow{MET} = -\sum_{i=0}^{N_{particles}} \vec{E}_T^i$
- SumE$_T$: 178 GeV

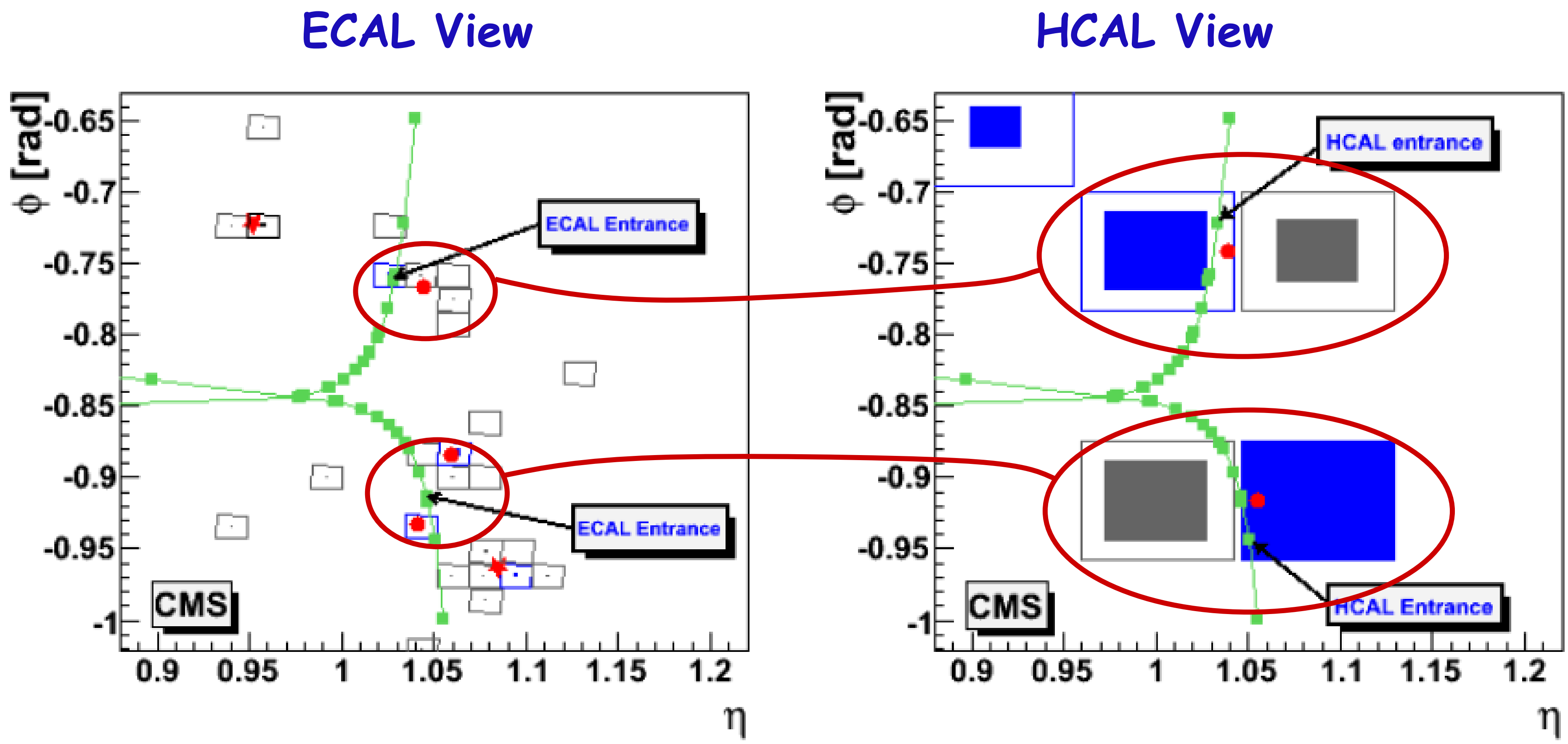
"Particle Flow": reconstruct particle content

Jet reconstruction follows naturally as well as global quantities like E_T^{miss}



Multi jet event: η-φ view

Linking tracks to the calorimeter cells

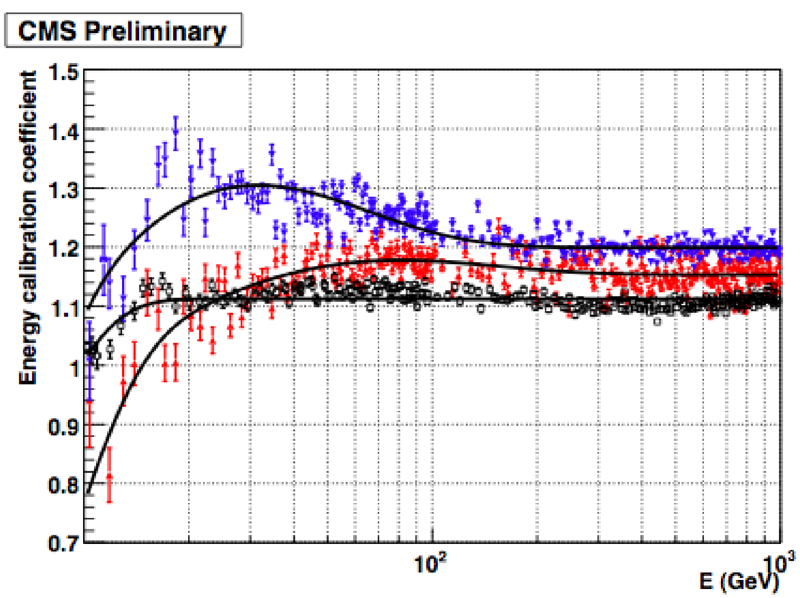


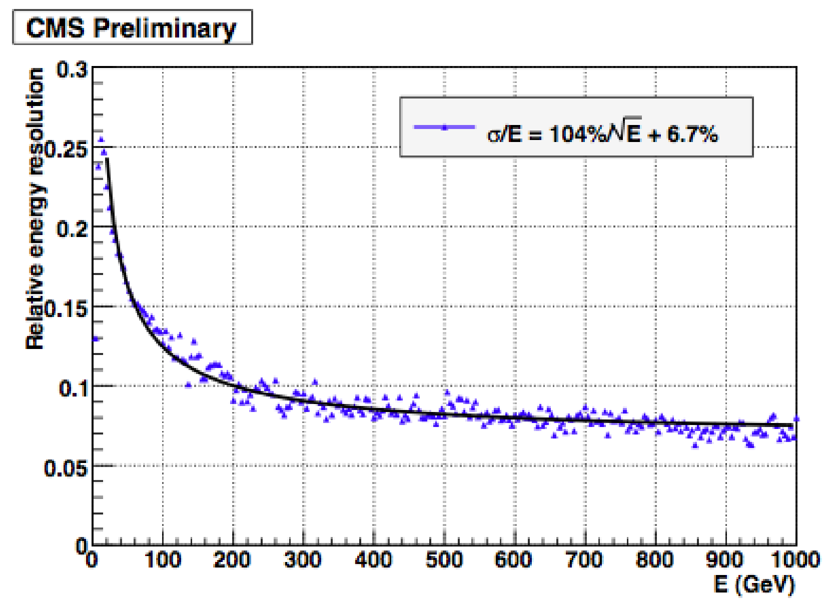
* A not-linked ecal cluster gives birth to a photon
* A not-linked hcal cluster gives birth to a neutral hadron
* A track (not already considered as a muon or an electron) gives birth to a charged hadron
* Any other combination, i.e. blocks formed by more than one object, is analyzed in order to give the complete list of particles

Calibration coefficients from Simulation

- The algorithm needs a calibrated response of the calorimeter
  - So far a Monte Carlo based calibration has been used
    - it works very well also with data! (see next slide)

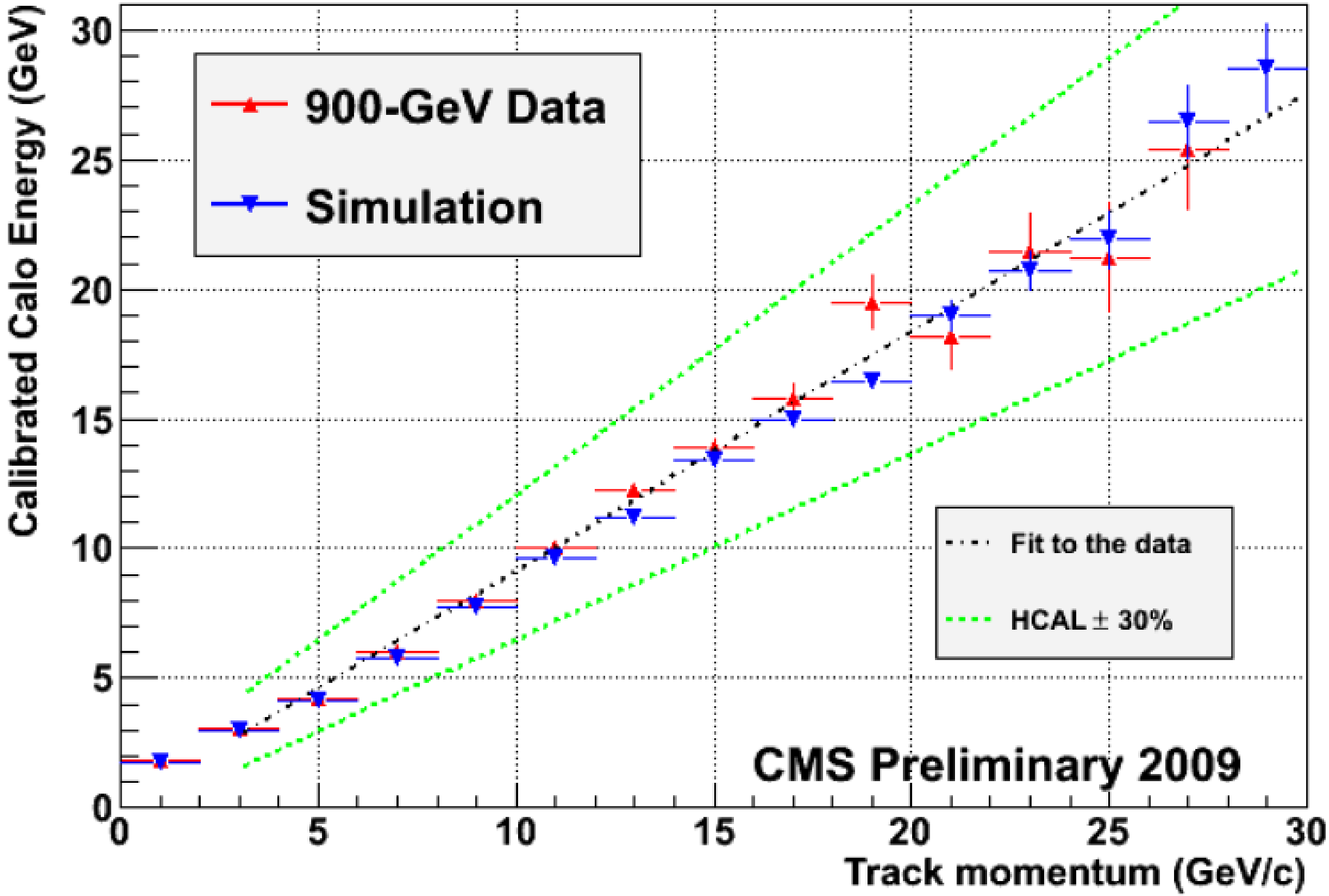
$$E_{\mathrm{calib}} = a(E,\eta) + b(E,\eta)E_{\mathrm{ECAL}} + c(E,\eta)E_{\mathrm{HCAL}}$$





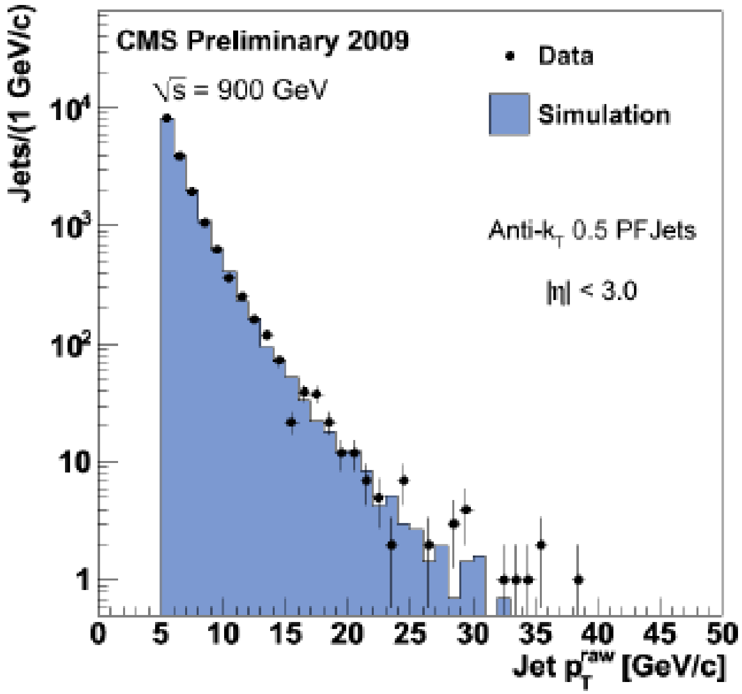
Coefficient for HCAL with particles not interacting in ECAL
Coefficient for ECAL / HCAL with particles interacting in any calorimeter

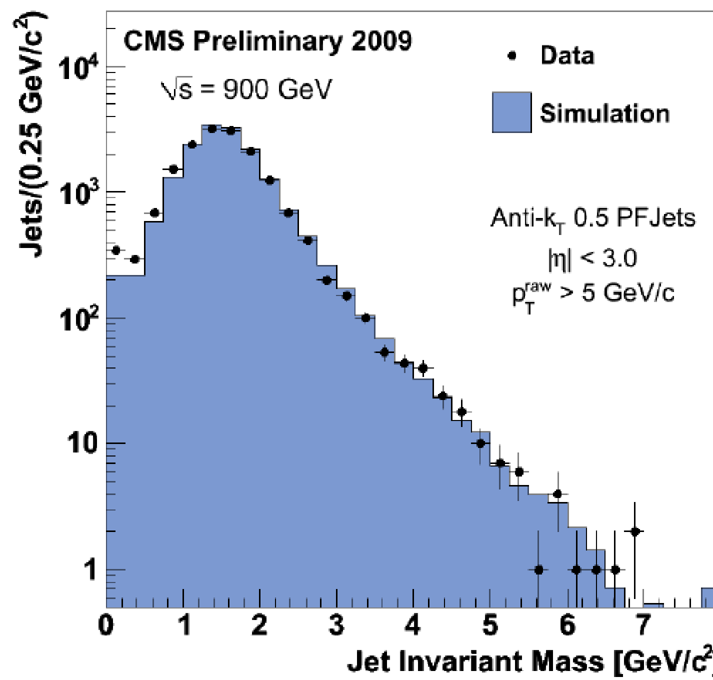
Calorimeter / Tracker response as a function of the track momentum

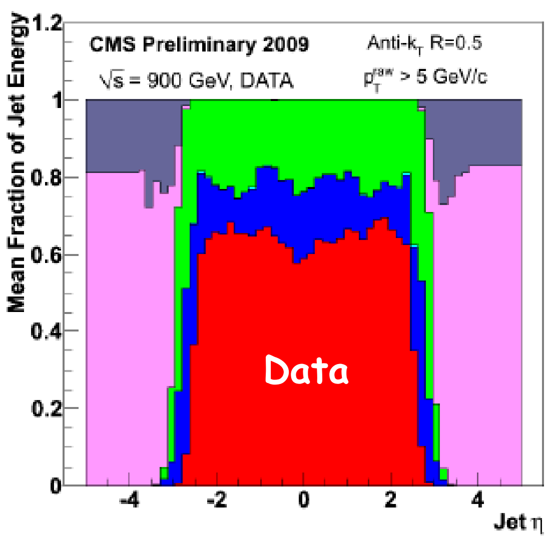


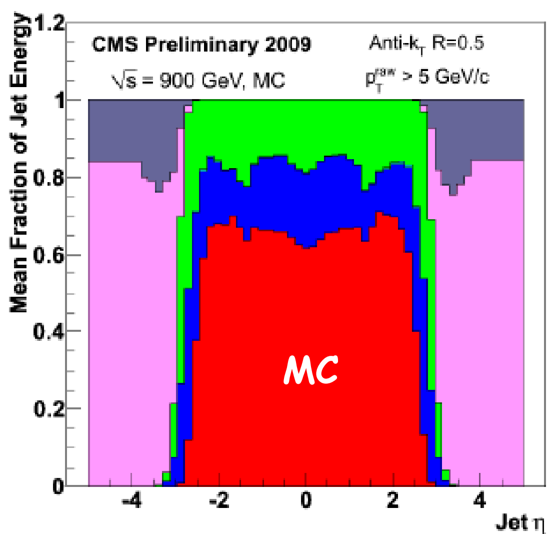
Calorimeter response to hadrons well simulated

Inclusive Jet analyses









Jet-Particle content Data/MC:

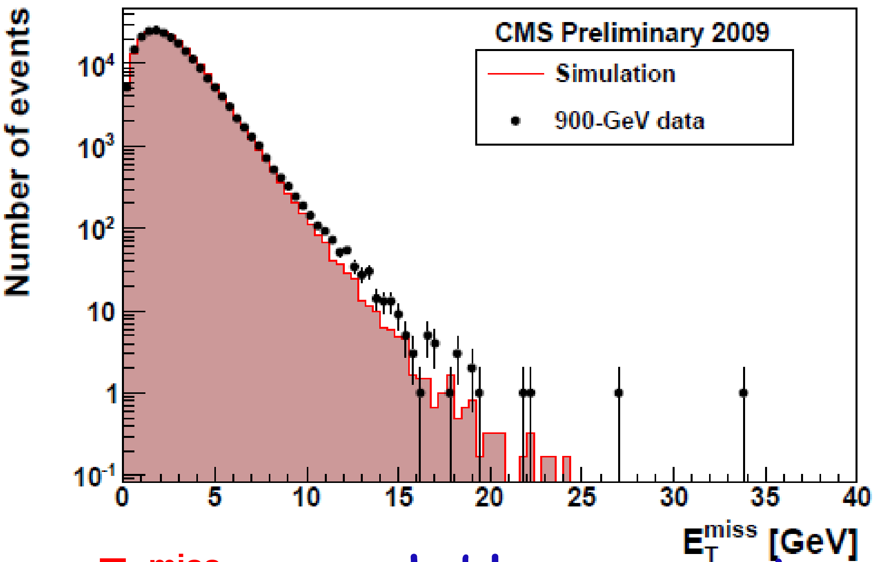
Neutral Hadrons (20%)

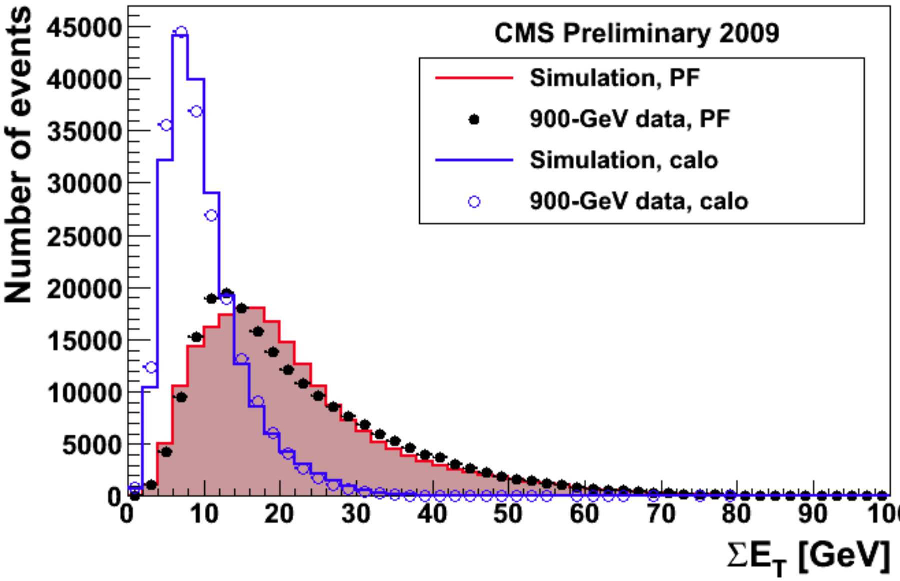
Electron (< 1%)

Photons (15%)

Charged Hadrons (65%)

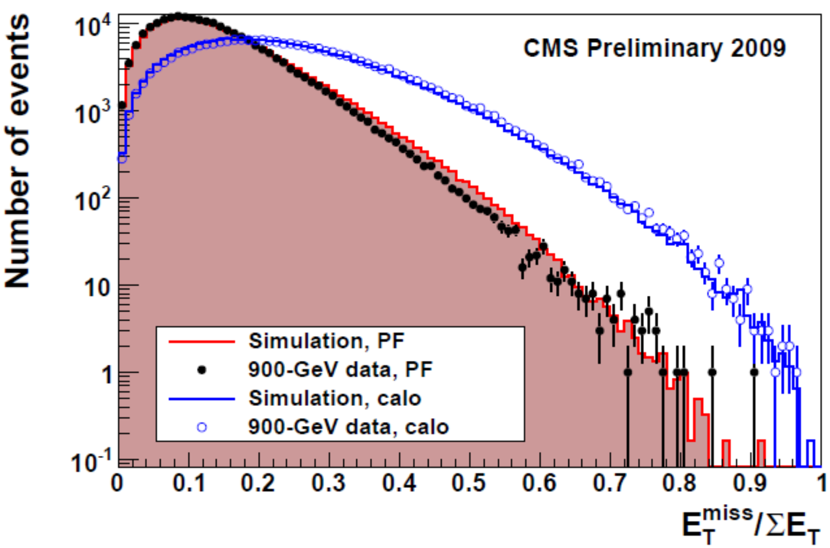
E_T^{miss} and ΣE_T at $\sqrt{s}$ 900 GeV





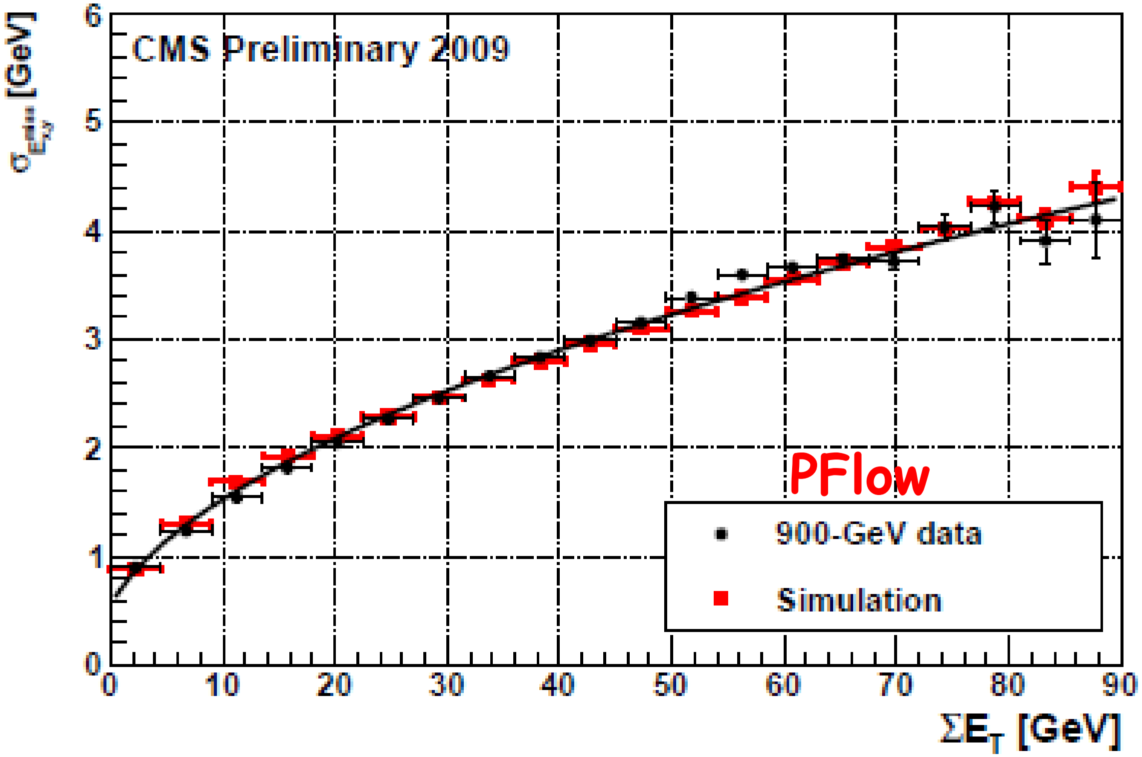
E_T^{miss} : remarkable agreement between Monte Carlo and data

ΣE_T is a very challenging quantity to reconstruct (no cancellation of experimental effects). Also here the simulation gives a remarkable agreement with the data.



$E_T^{miss} / \Sigma E_T$: the improvement of Particle Flow with respect to simple calorimetric methods is remarkable.

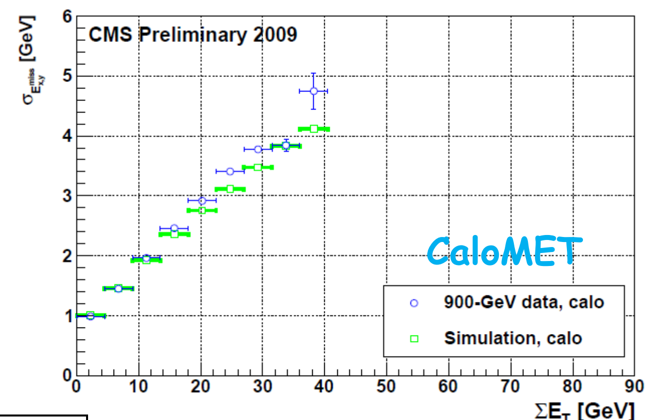
E_T^{miss} resolution versus ΣE_T at $\sqrt{s}$ = 900 GeV

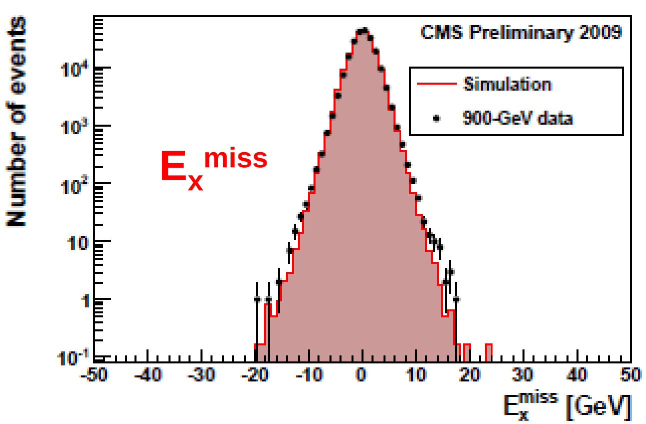


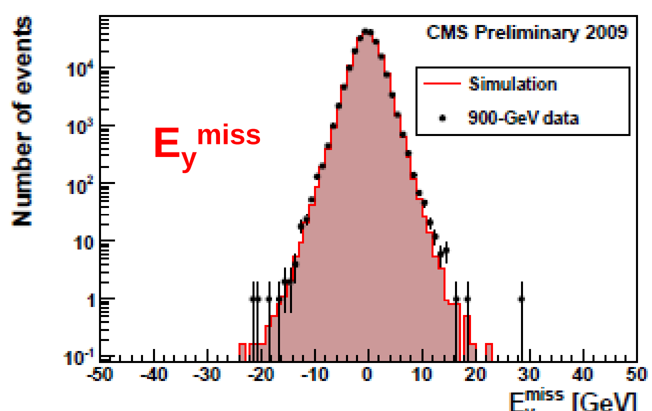
$$\sigma(E_{x,y}^{\mathrm{miss}}) = a \oplus b\sqrt{\sum E_T}$$

a = 0.55 GeV
b = 45 % (PFlow)

ParticleFlow E_T^{miss} relative resolution is about twice as good as for the CaloMET







first CMS paper on pp data: http://arxiv.org/abs/1002.0621

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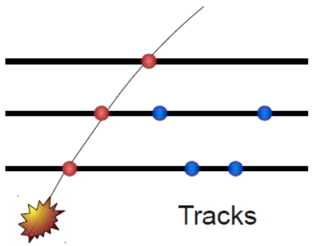
Transverse-momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 0.9$ and 2.36 TeV

CMS Collaboration

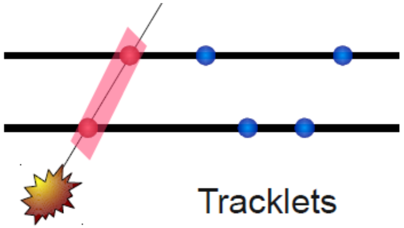
ABSTRACT: Measurements of inclusive charged-hadron transverse-momentum and pseudorapidity distributions are presented for proton-proton collisions at $\sqrt{s} = 0.9$ and 2.36 TeV. The data were collected with the CMS detector during the LHC commissioning in December 2009. For non-single-diffractive interactions, the average charged-hadron transverse momentum is measured to be 0.46 ± 0.01 (stat.) $\pm$ 0.01 (syst.) GeV/c at 0.9 TeV and 0.50 ± 0.01 (stat.) $\pm$ 0.01 (syst.) GeV/c at 2.36 TeV, for pseudorapidities between -2.4 and $+2.4$. At these energies, the measured pseudorapidity densities in the central region, $dN_{ch}/d\eta|_{|\eta|<0.5}$, are 3.48 ± 0.02 (stat.) $\pm$ 0.13 (syst.) and 4.47 ± 0.04 (stat.) $\pm$ 0.16 (syst.), respectively. The results at 0.9 TeV are in agreement with previous measurements and confirm the expectation of near equal hadron production in $p\bar{p}$ and pp collisions. The results at 2.36 TeV represent the highest-energy measurements at a particle collider to date.

JHEP02(2010)041

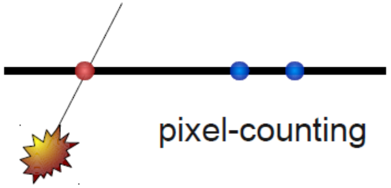
Spectra of charged hadrons: methods



Uses all Tracker (pixel+strip) reconstructing particle trajectories
p_T-reach: down to 100 MeV/c



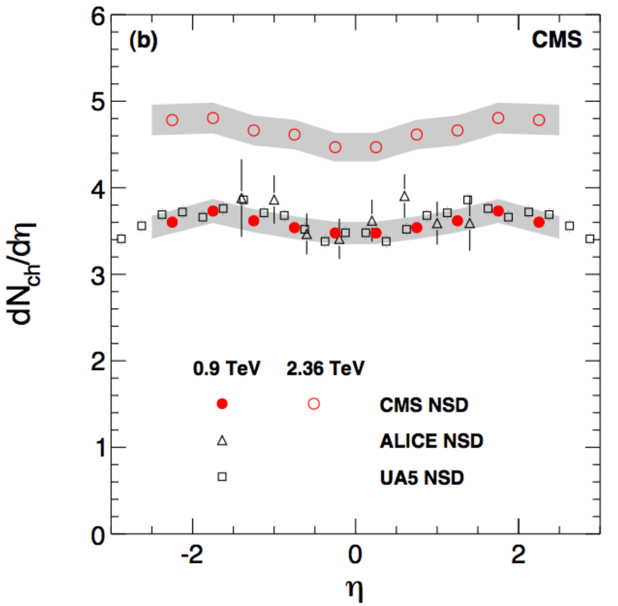
Tracklets: pairs of clusters on different pixel barrel layers
p_T-reach: down to 50 MeV/c

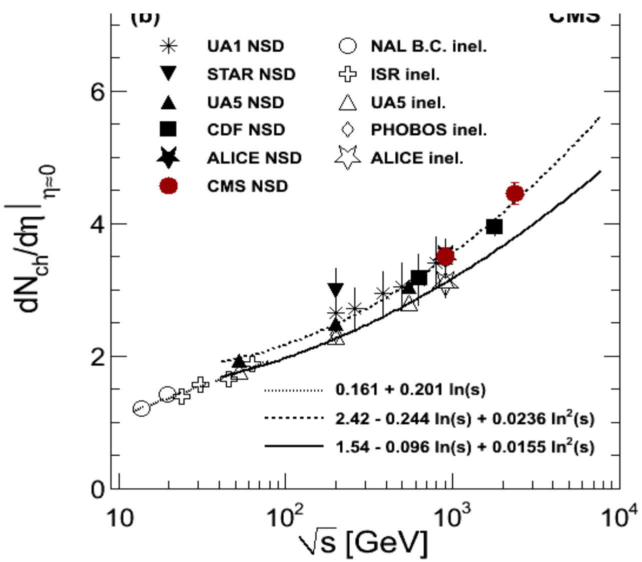


Counting hits (clusters of pixels) in the pixel barrel layers
p_T-reach: down to 30 MeV/c

Spectra of charged hadrons

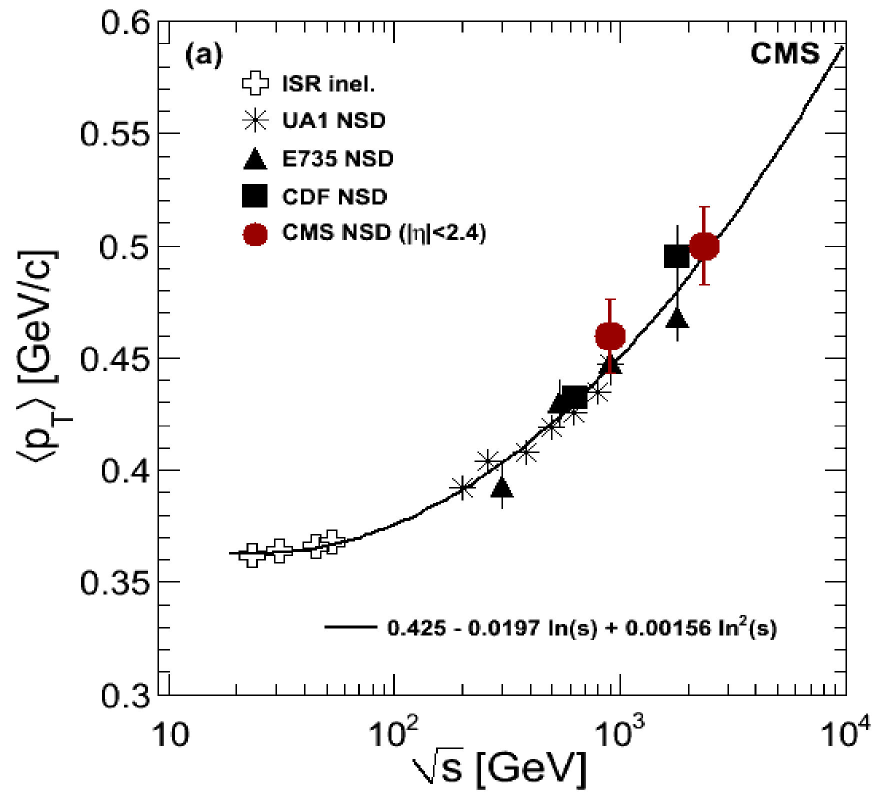
first CMS paper on pp data (http://arxiv.org/abs/1002.0621)





Minimum BiasTrigger
Non Single Diffractive Events

P_T and η distributions of charged hadrons at $\sqrt{s}$ =900 and 2.360 GeV



Charged hadrons p_T-distributions

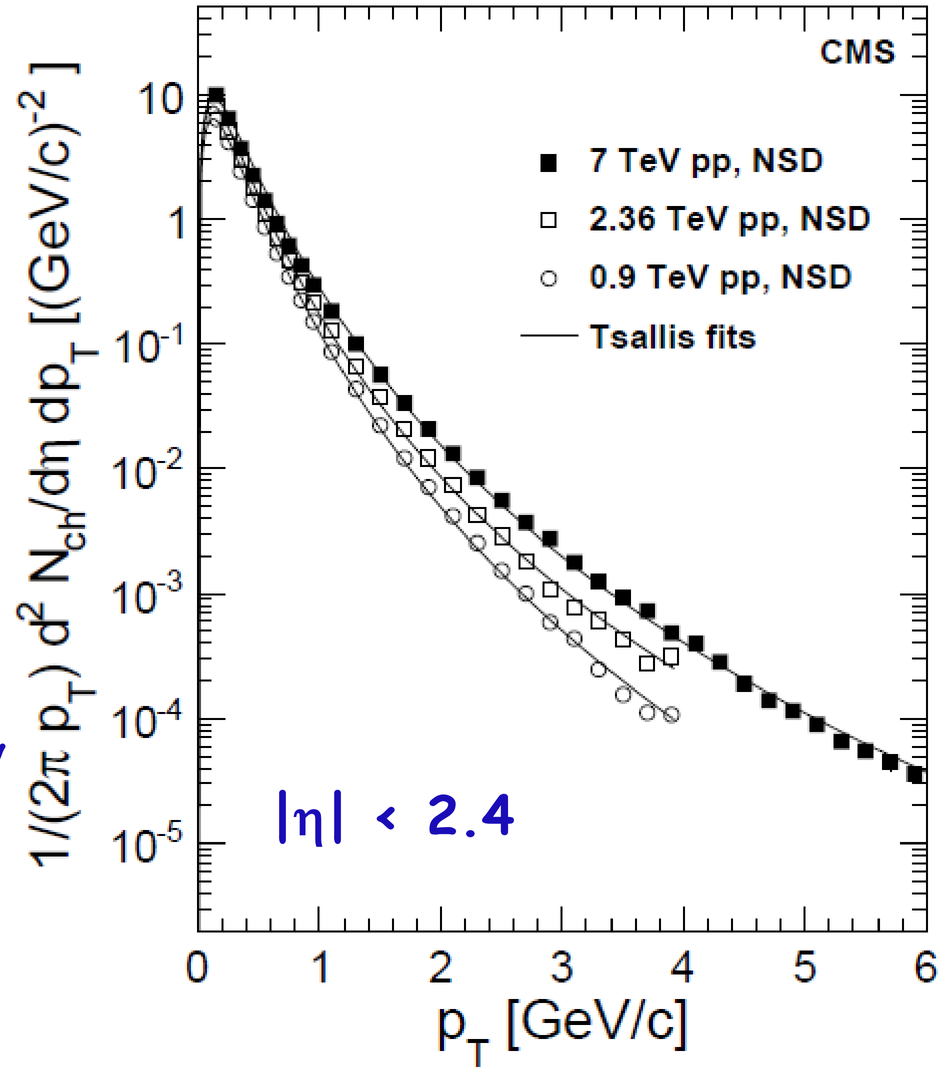
Well described by the Tsallis-function combining a low-p_T exponential with a power-law high-p_T tail

With increasing energy, the p_T-spectrum gets "harder":

$\langle p_T \rangle$=460±10(stat)±10(syst) MeV/c @ 0.9TeV

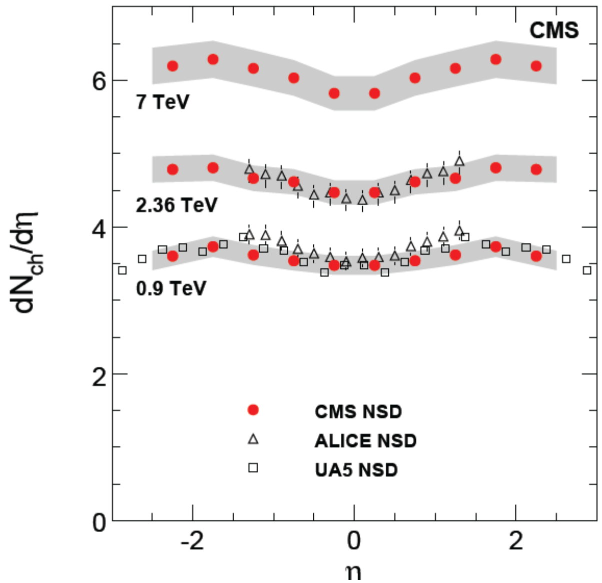
$\langle p_T \rangle$=500±10(stat)±10(syst) MeV/c @ 2.36TeV

$\langle p_T \rangle$=545±5(stat)±10(syst) MeV/c @ 7TeV



Spectra of charged hadrons up to 7 TeV

arXiv:1005.3299



Minimum BiasTrigger

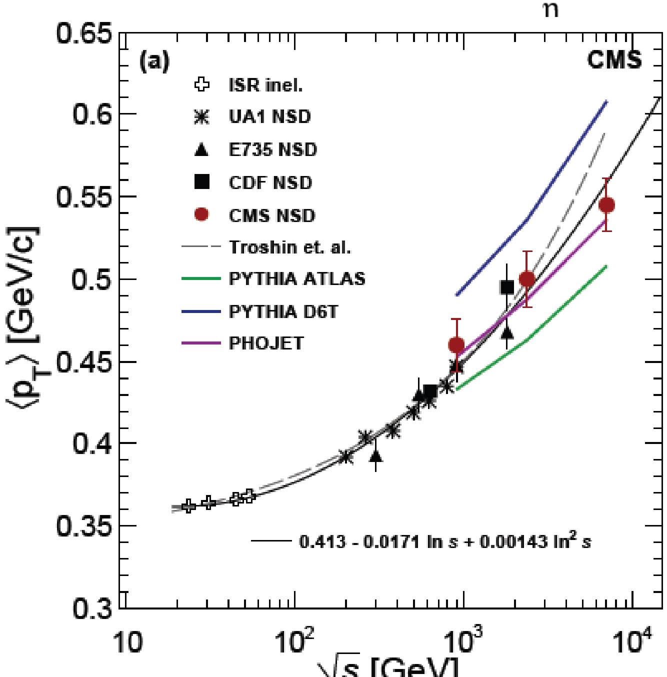
Non Single Diffractive Events

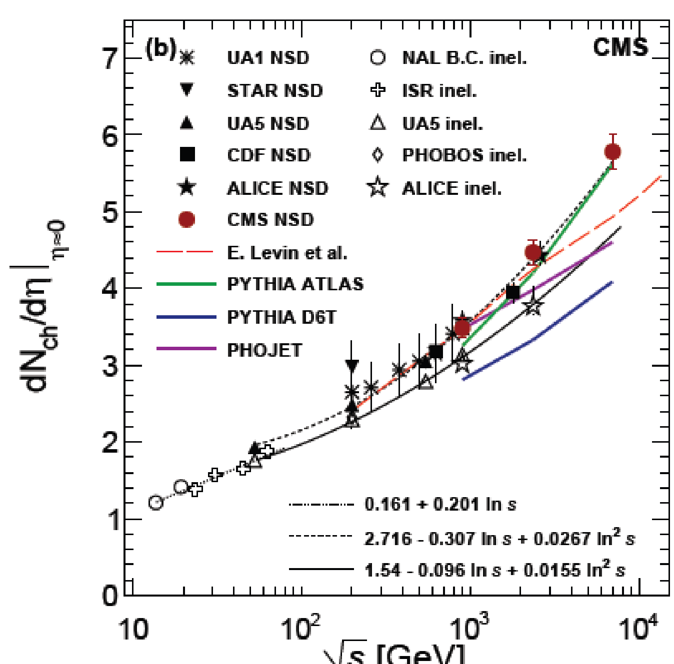
P_T and η distributions of charged hadrons at √s = 0.9, 2.36 and 7 TeV

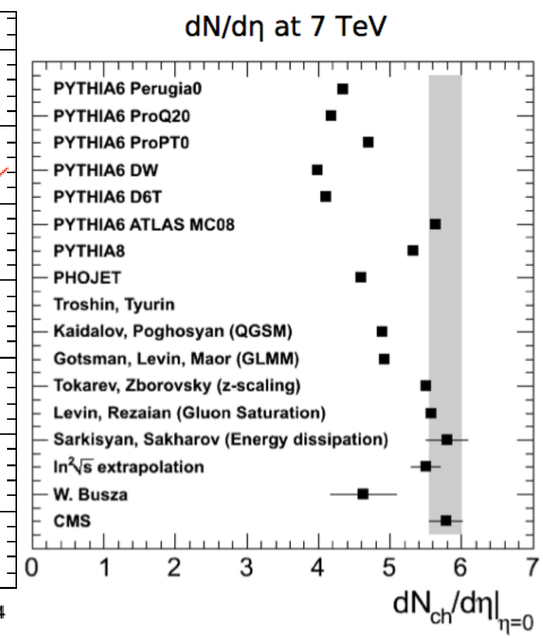
Rise of dN/dη in data stronger than in most currently used tunes

PHOJET describes the $\langle p_T \rangle$ rise rather well but not the dN/dη rise

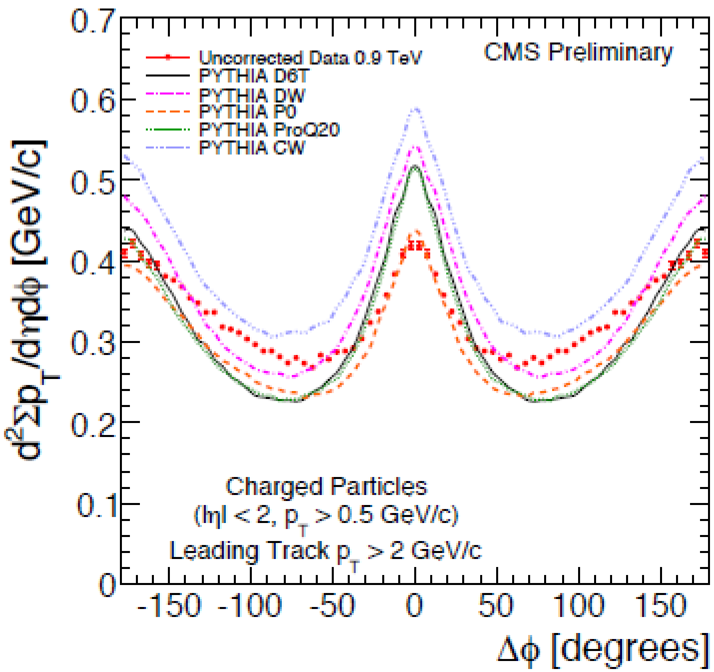
➢ tune better the MC

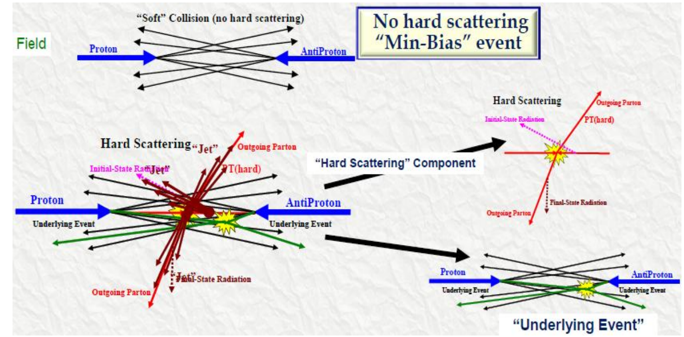


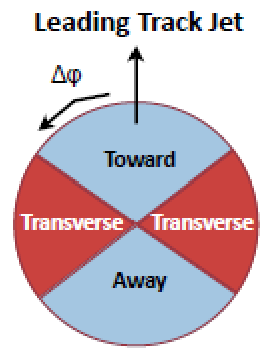




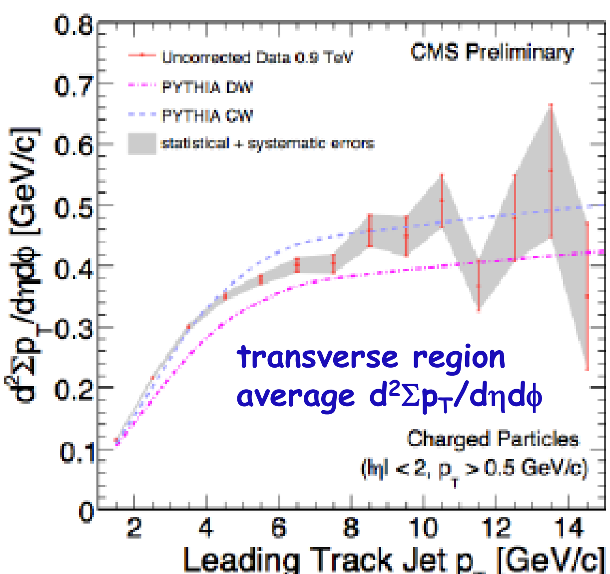
Underlying Event Studies @ $\sqrt{s}$ = 0.9 TeV







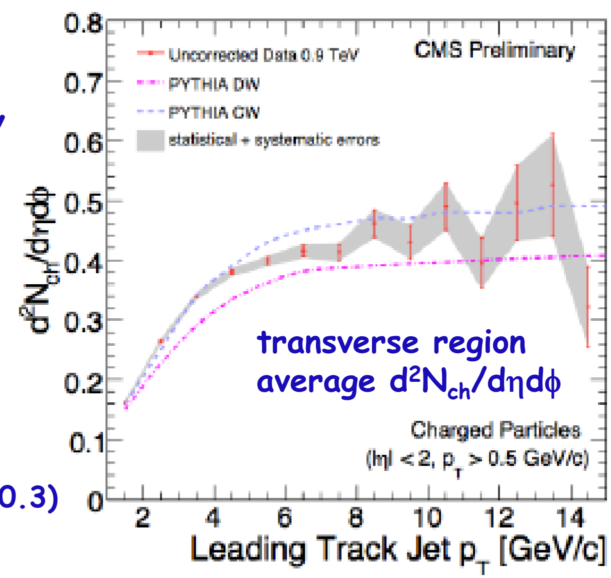
MinBias event selection, with additional requirement of a 'hard' scattering via a leading track-jet with p_T>2 GeV



- ➢ **More data for MC model tuning…**

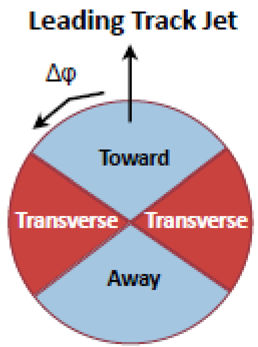
- ❑ **Study the particle density and scalar p_T sum in the transverse region, for particles with |η|<2 and p_T>0.5 GeV (uncorrected data)**

Model Comparison:
DW = Standard Tune
CW = New Tune (p_{T0}=1.8 GeV, ε=0.3)



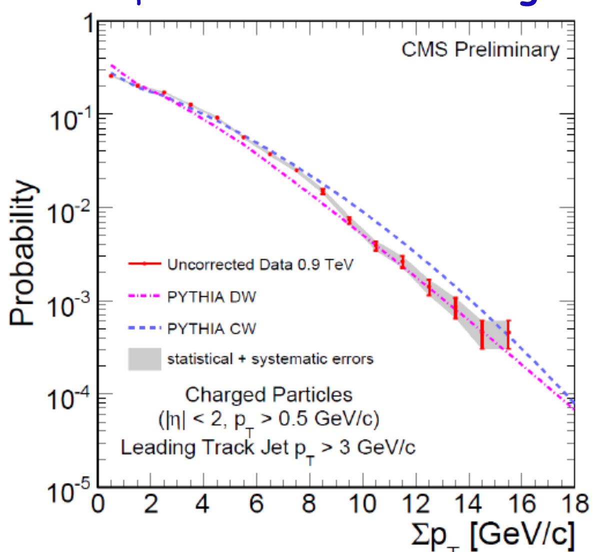
Underlying Event Studies @ √s = 0.9 TeV

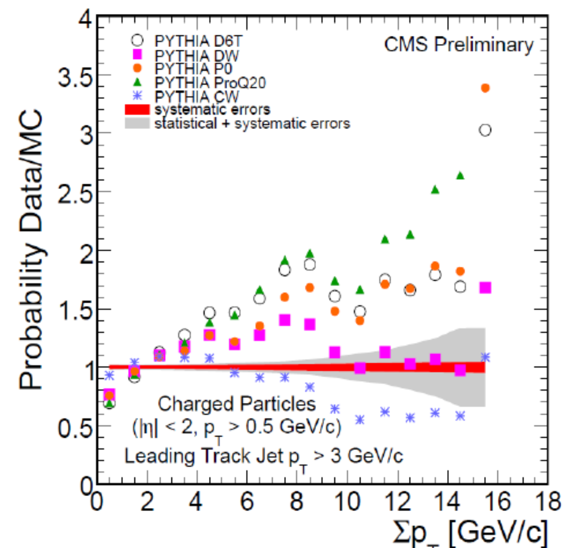
MinBias event selection, with additional requirement of a 'hard' scattering via a leading track-jet with p_T>3 GeV.



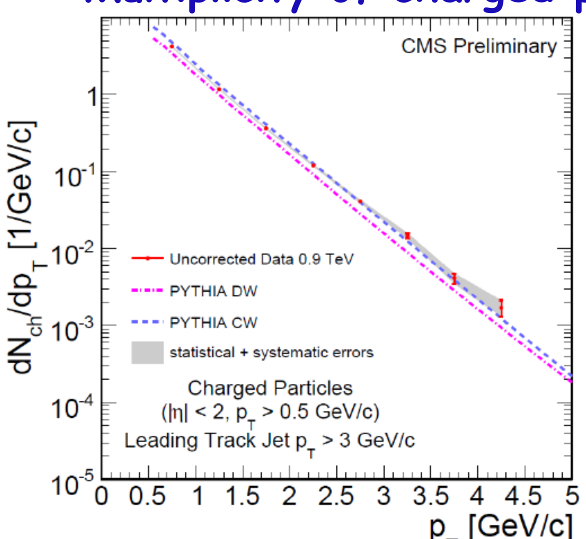
- **More data for MC model tuning...**

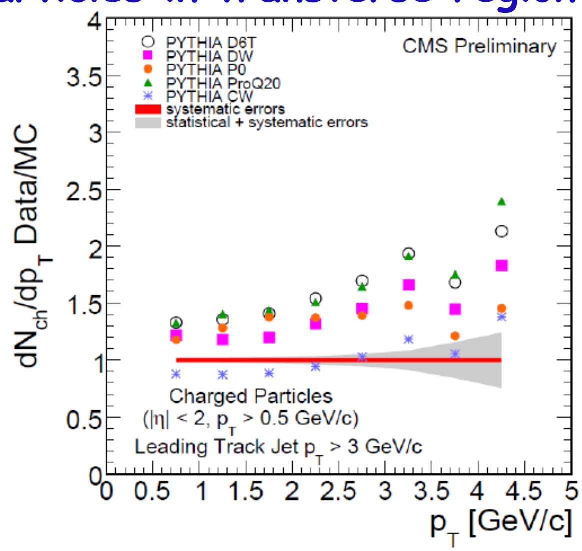
P_T distribution of charged particles in transverse region





Multiplicity of charged particles in transverse region

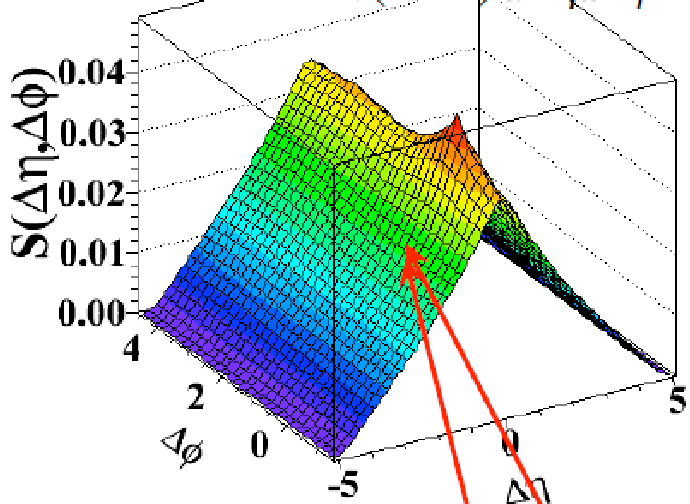




Inclusive two-particle correlations

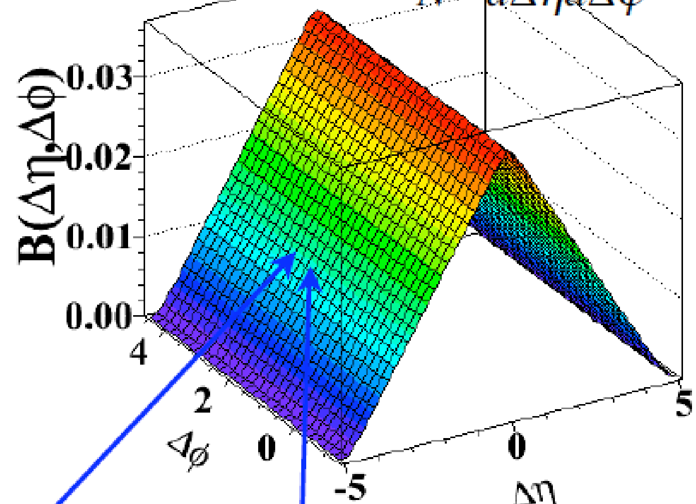
Signal distribution:
(correlated+uncorrelated pairs)

$$S_N(\Delta\eta,\Delta\varphi) = \frac{1}{N(N-1)}\frac{d^2N^{signal}}{d\Delta\eta d\Delta\varphi}$$



Background distribution:
(uncorrelated pairs)

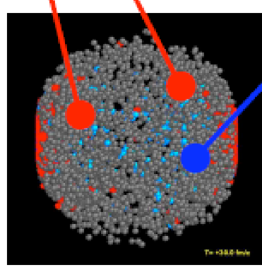
$$B_N(\Delta\eta,\Delta\varphi) = \frac{1}{N^2}\frac{d^2N^{bkg}}{d\Delta\eta d\Delta\varphi}$$



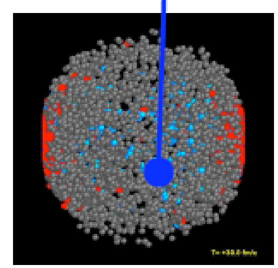
$\Delta\eta = \eta_1 - \eta_2,$

$\Delta\varphi = \varphi_1 - \varphi_2$

N: total multiplicity



Event 1



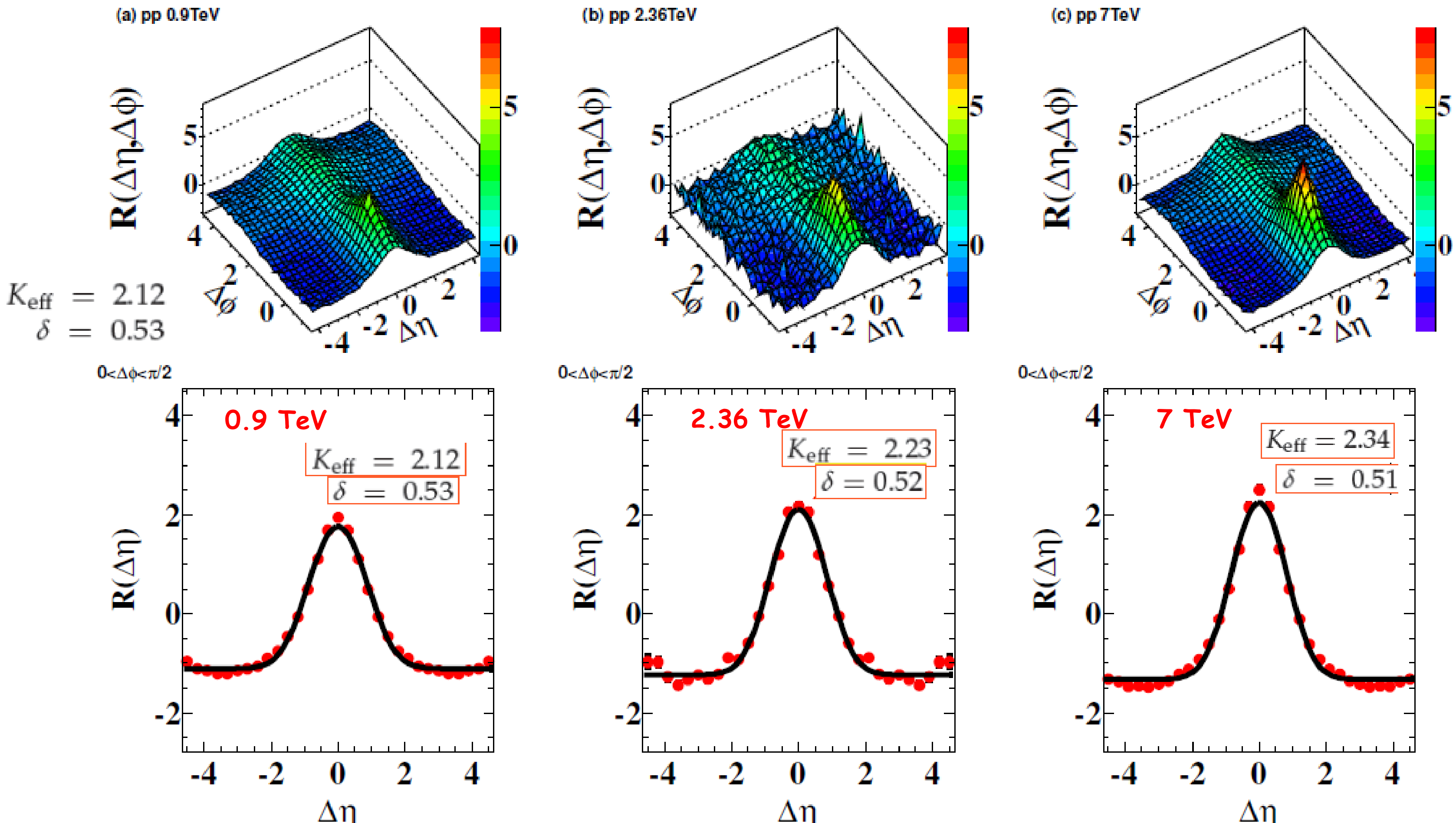
Event 2

mix events with similar vertex and multiplicity

$$R(\Delta\eta,\Delta\varphi) = \langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\varphi)}{B_N(\Delta\eta,\Delta\varphi)} - 1\right) \rangle_{evt}$$

(Convention used by ISR, UA5 and Phobos)

Inclusive two-particle correlations



$$R(\Delta\eta) = (K_{eff} - 1)\left[\frac{\Gamma(\Delta\eta)}{B(\Delta\eta)} - 1\right] \qquad \Gamma(\Delta\eta) \propto \exp\left(-\frac{(\Delta\eta)^2}{4\delta^2}\right)$$

Effective cluster size

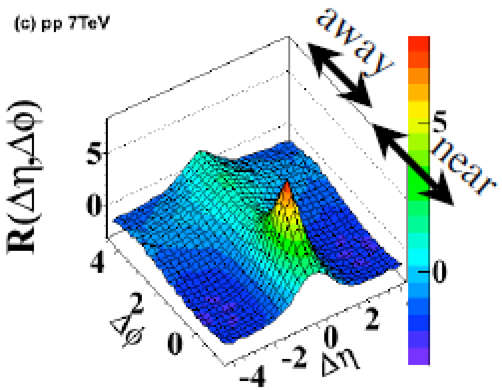
Cluster width

Independent Cluster Model :

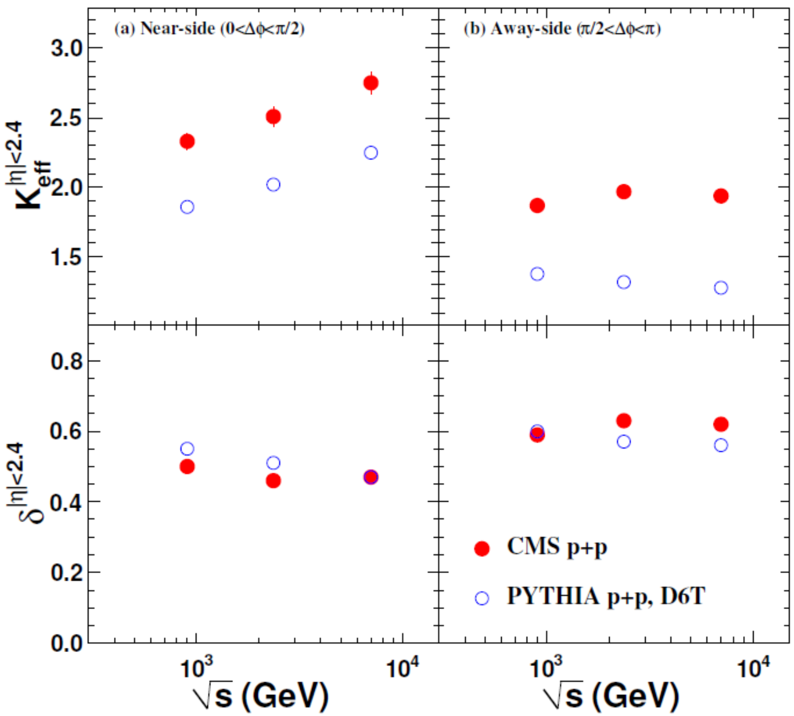
- Independently produced clusters
- Isotropic decay in their c.m.s into hadrons
- On average, every 2-3 charged particles are produced correlated like a cluster

Inclusive two-particle correlations

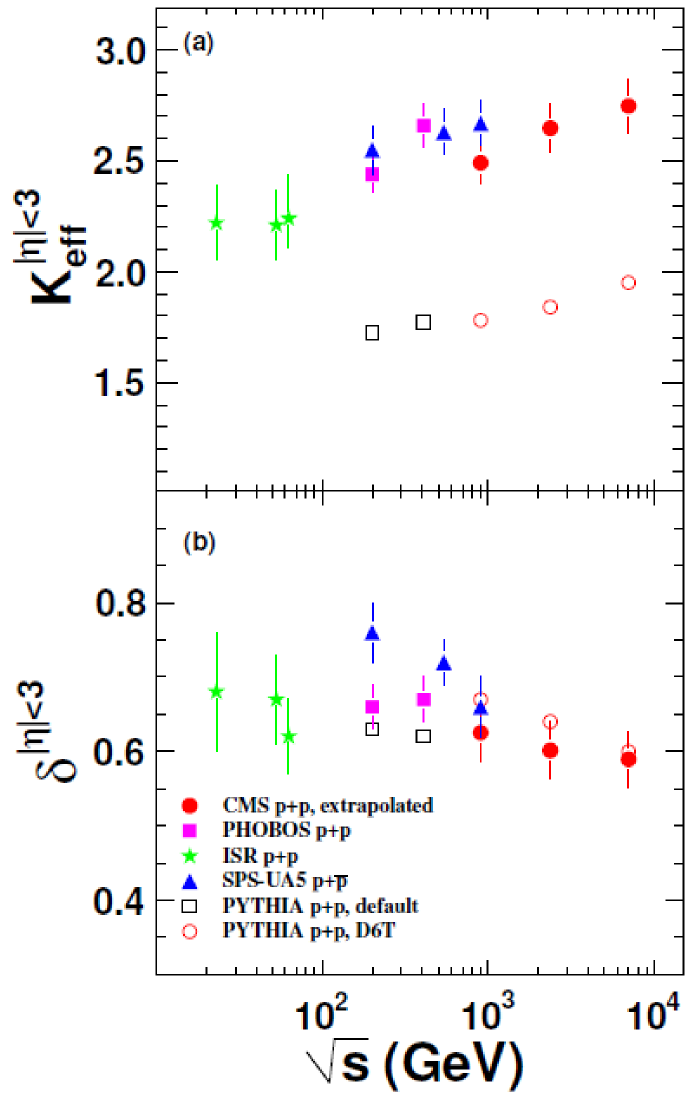
Average in sub-region of $\Delta\phi$



Near-side ($0<\Delta\phi<\pi/2$)   Away-side ($\pi/2<\Delta\phi<\pi$)



Comparison with other experiments



Extrapolate to:
$|\eta|<3.0$
$p_T \sim 0$ GeV/c

- Cluster size K_{eff} increases with energy, Pythia has the right trend but is lower (insensitive to different tunes)
- Cluster width δ remains constant and is reproduced by Pythia

Bose Einstein Correlations

arXiv:1005.3294

- During high-energy collisions, bosons are created at small distance, their wave functions overlap and the Bose-Einstein statistics may change their dynamics
- When identical bosons have comparable four-momenta the global wave function reach the maximum value and enhancement of the correlation function should be observed
- This is essentially the only way to measure the size of a source at the Fermi scale

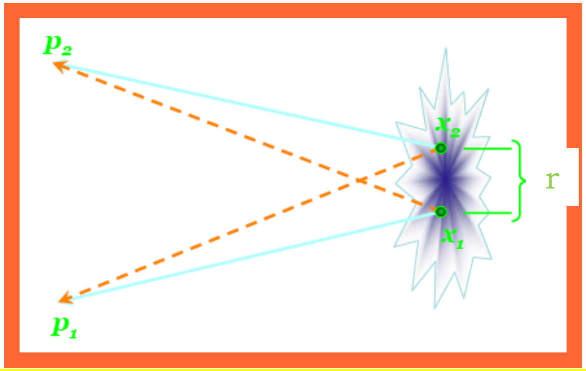
We need to study the ratio between the joint probability of emission of a pair of bosons, and the individual probabilities

$$R = \frac{P(p_1, p_2)}{P(p_1)P(p_2)}$$

Experimentally, we have to produce the distributions of a "proximity" quantity in the data and in a reference sample

$$R = \frac{dN/dQ_{data}}{dN/dQ_{ref}}$$

The proximity in phase space can be quantified (assuming all pions) as: $Q^2 = -(p_1 - p_2)^2 = m_{inv}^2 - 4m_\pi^2$



r : source size
λ : strenght (0 ÷ 1)
C : normalization (~1)
δ : long range effects (~0)

Correlation function used to perform the fit to the data:

$R(Q) = C[1 + \lambda\Omega(Qr)](1 + \delta Q)$

$\Omega(Qr)$ function is interpreted as the Fourier transform of the emission region, whose effective size is measured by r.
Usually it is parametrized as:

$\Omega(Qr) = \exp(-Qr)$ – Exponential, CMS default.

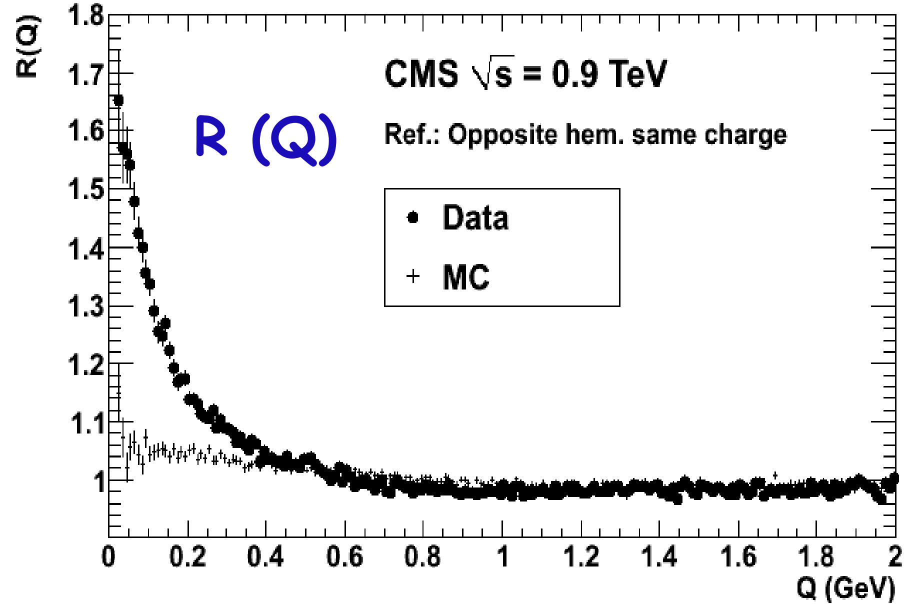
$\Omega(Qr) = \exp(-Q^2r^2)$ – Gaussian, widely used.

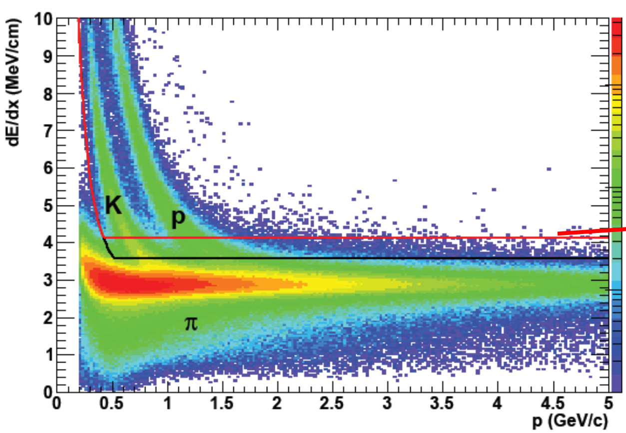
Bose Einstein Correlations

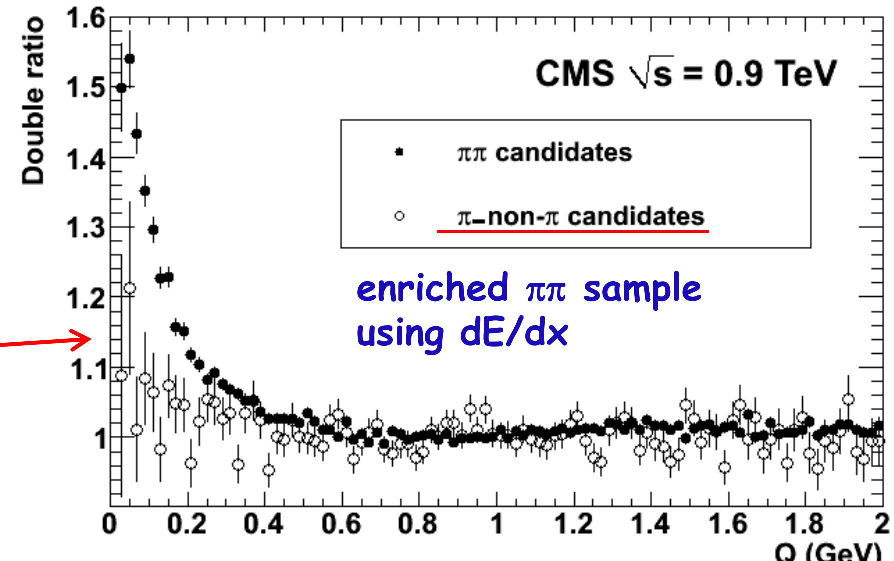
arXiv:1005.3294

To calculate R:
1. Take all (charged) tracks.
2. Construct Q.
3. Repeat for the reference sample
4. Evaluate the ratio: $R = \dfrac{dN/dQ_{data}}{dN/dQ_{ref}}$

Pairs from 7 reference samples:
1. opposite charge (but contains resonances)
2. opposite hemisphere same
3. opposite hemisphere opposite charge
4. rotated
5. mixed events (random)
6. mixed events (similar multiplicity)
7. mixed events (similar invariant mass)







Bose Einstein Correlations

arXiv:1005.3294

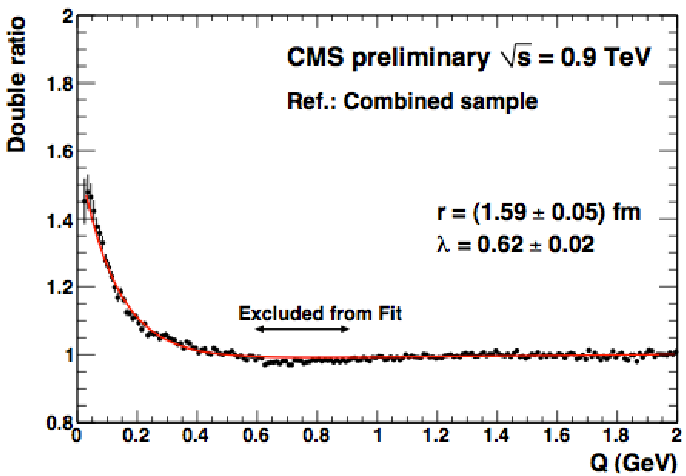
Correlations between identical bosons (pions) @ $\sqrt{s}$ = 0.9 and 2.36 TeV

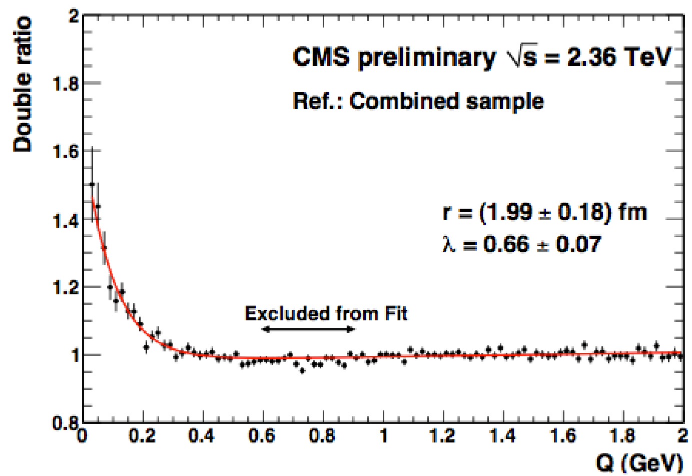
$$R = \frac{P(p_1,p_2)}{P(p_1)\,P(p_2)} = \frac{dN/dQ}{dN/dQ_{ref}} \qquad Q = \sqrt{-(p_1-p_2)^2} = \sqrt{m_{inv}^2 - 4m_\pi^2}$$

$$R(Q) = C\,[1+\lambda\Omega(Qr)]\cdot(1+\delta Q) \qquad \Omega(Qr) = e^{-Qr}$$

Several reference samples for normalization:

opposite charge pairs, rotated particles,
opposite hemisphere, mixed events



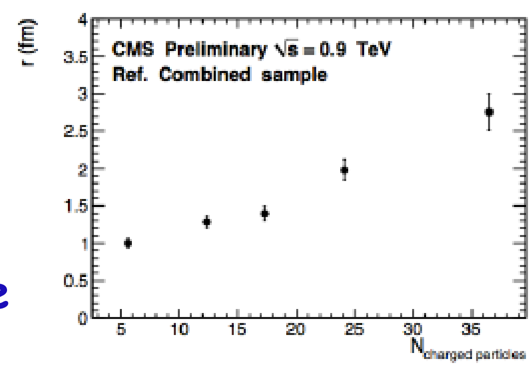


$\sqrt{s}$ = 0.9 TeV $\quad r = 1.59 \pm 0.05$ (stat.) ± 0.19 (syst.) fm and $\lambda = 0.625 \pm 0.021$ (stat.) ± 0.046 (syst.)

$\sqrt{s}$ = 2.36 TeV $\quad r = 1.99 \pm 0.18$ (stat.) ± 0.24 (syst.) fm and $\lambda = 0.663 \pm 0.073$ (stat.) ± 0.048 (syst.)

Results of fits to 0.9 TeV data

Multiplicity range	P-value	C	λ	r (fm)
2 - 9	9.7×10^{-1}	0.90 ± 0.01	0.89 ± 0.05	1.00 ± 0.07 (stat.)± 0.05 (syst.)
10 - 14	3.8×10^{-1}	0.97 ± 0.01	0.64 ± 0.04	1.28 ± 0.08 (stat.)± 0.09 (syst.)
15 - 19	2.7×10^{-1}	0.96 ± 0.01	0.60 ± 0.04	1.40 ± 0.10 (stat.)± 0.05 (syst.)
20 - 29	2.4×10^{-1}	0.99 ± 0.01	0.59 ± 0.05	1.98 ± 0.14 (stat.)± 0.45 (syst.)
30 - 79	2.8×10^{-1}	1.00 ± 0.01	0.69 ± 0.09	2.76 ± 0.25 (stat.)± 0.44 (syst.)

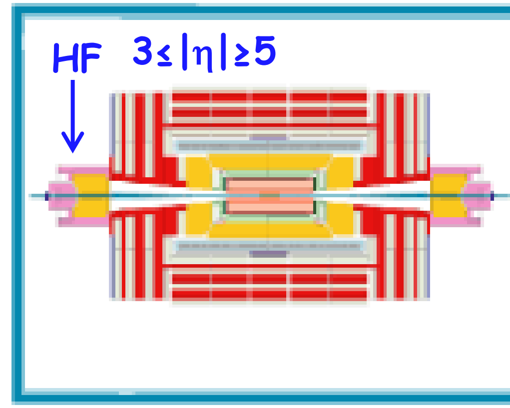


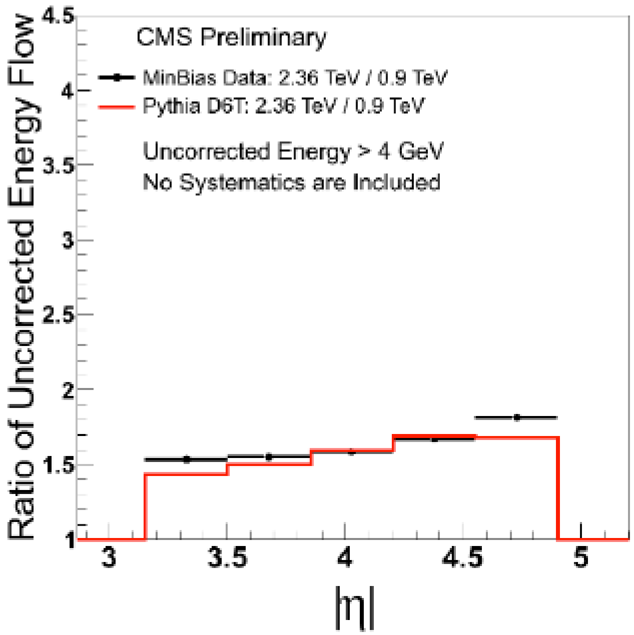
Multiplicity dependence

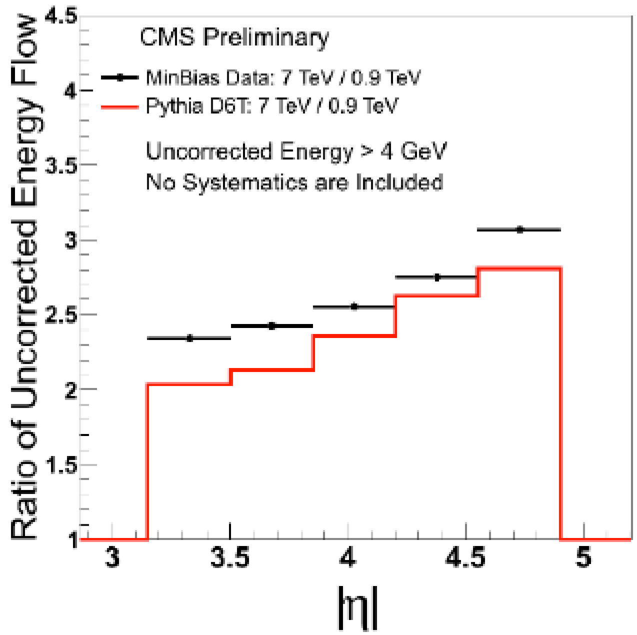
Forward Energy Flow

- ❑ Select minimum bias events with a good primary vertex having at least 4 tracks
- ❑ Measure ratio of uncorrected energy through HF ($3 \leq |\eta| \geq 5$) for different LHC energies:

$$R_{E_{flow}}^{\sqrt{s_1},\sqrt{s_2}} = \frac{\frac{1}{N_{\sqrt{s_1}}}\frac{\Delta E_{\sqrt{s_1}}}{\Delta\eta}}{\frac{1}{N_{\sqrt{s_2}}}\frac{\Delta E_{\sqrt{s_2}}}{\Delta\eta}}$$



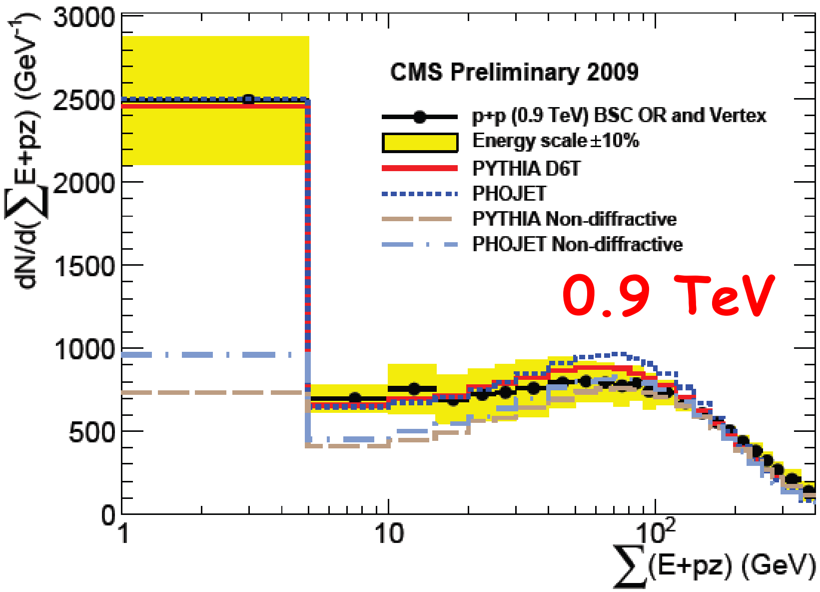


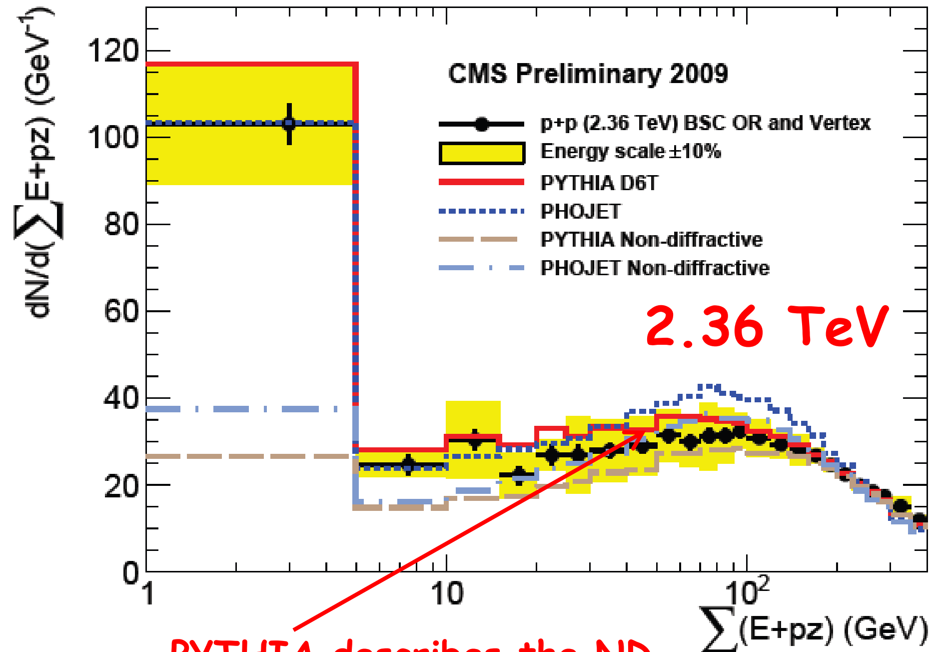


- ➢ Stronger rise with collision energy in data than what foreseen in Pythia (as seen in dN/dη analysis)

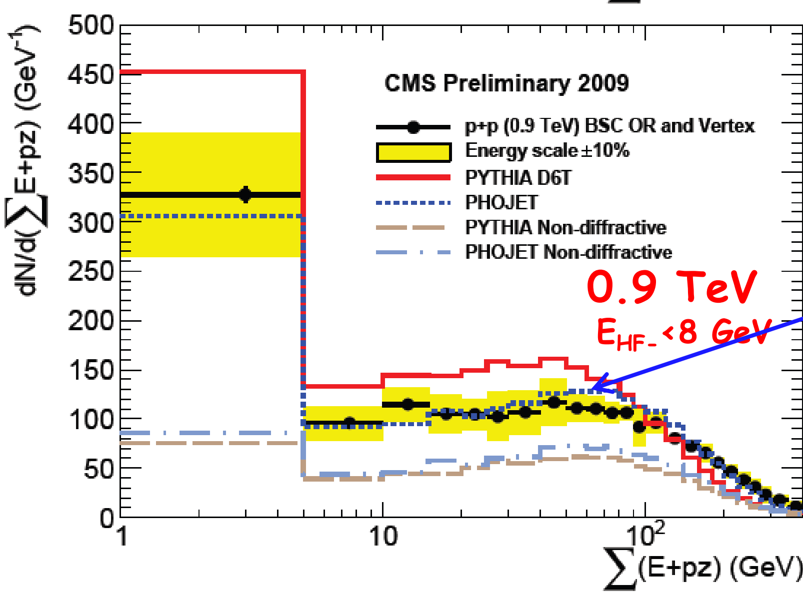
Observation of SD events

Variable used: $\Sigma(E+p_z) = \Sigma E(1+\cos\theta)$
(the sum runs over the full calorimeter acceptance)





PYTHIA describes the ND part better than PHOJET

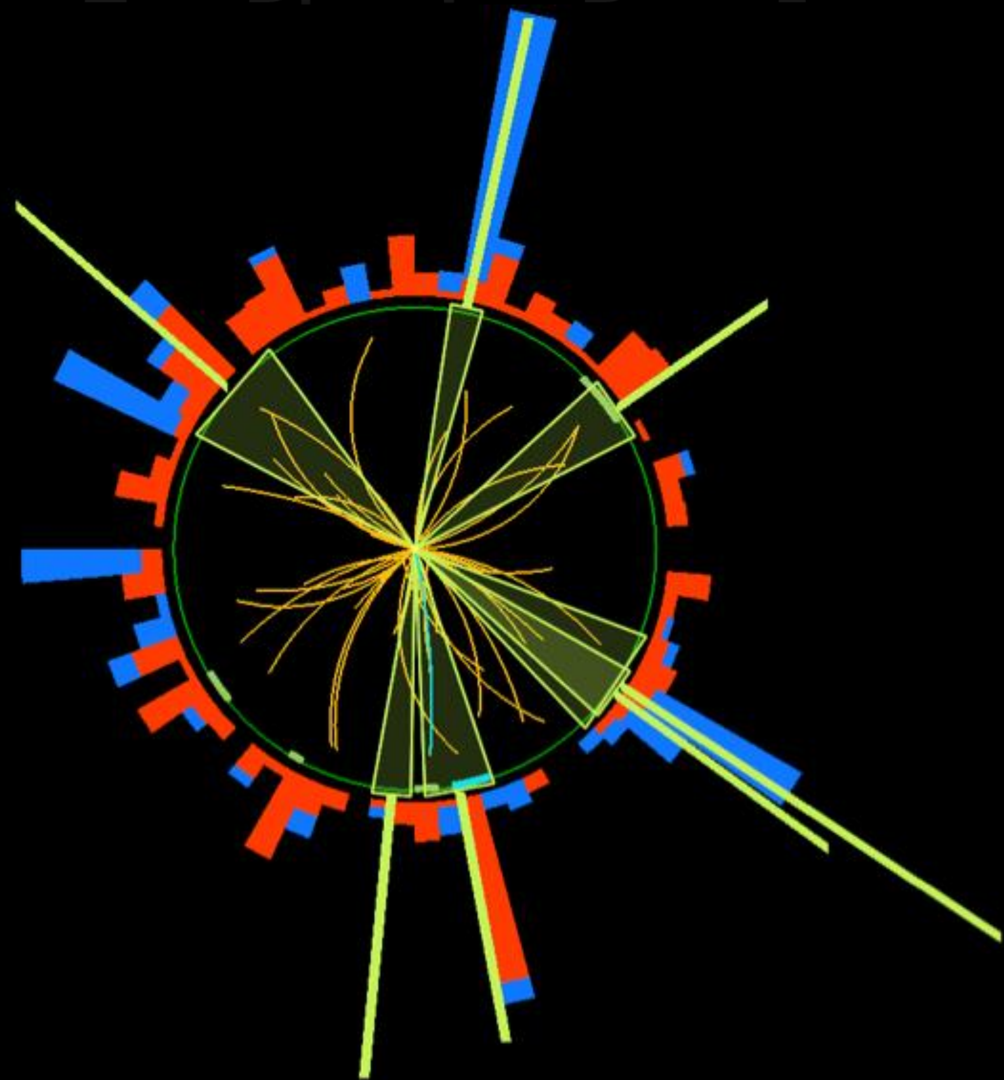


Enhancing SD events:
$E_{HF-}<8$ GeV was required (LRG over HF_-)
PHOJET agrees better with the data
(for high-mass SD)

Prospects For Physics Run I

LHC
Physics Run

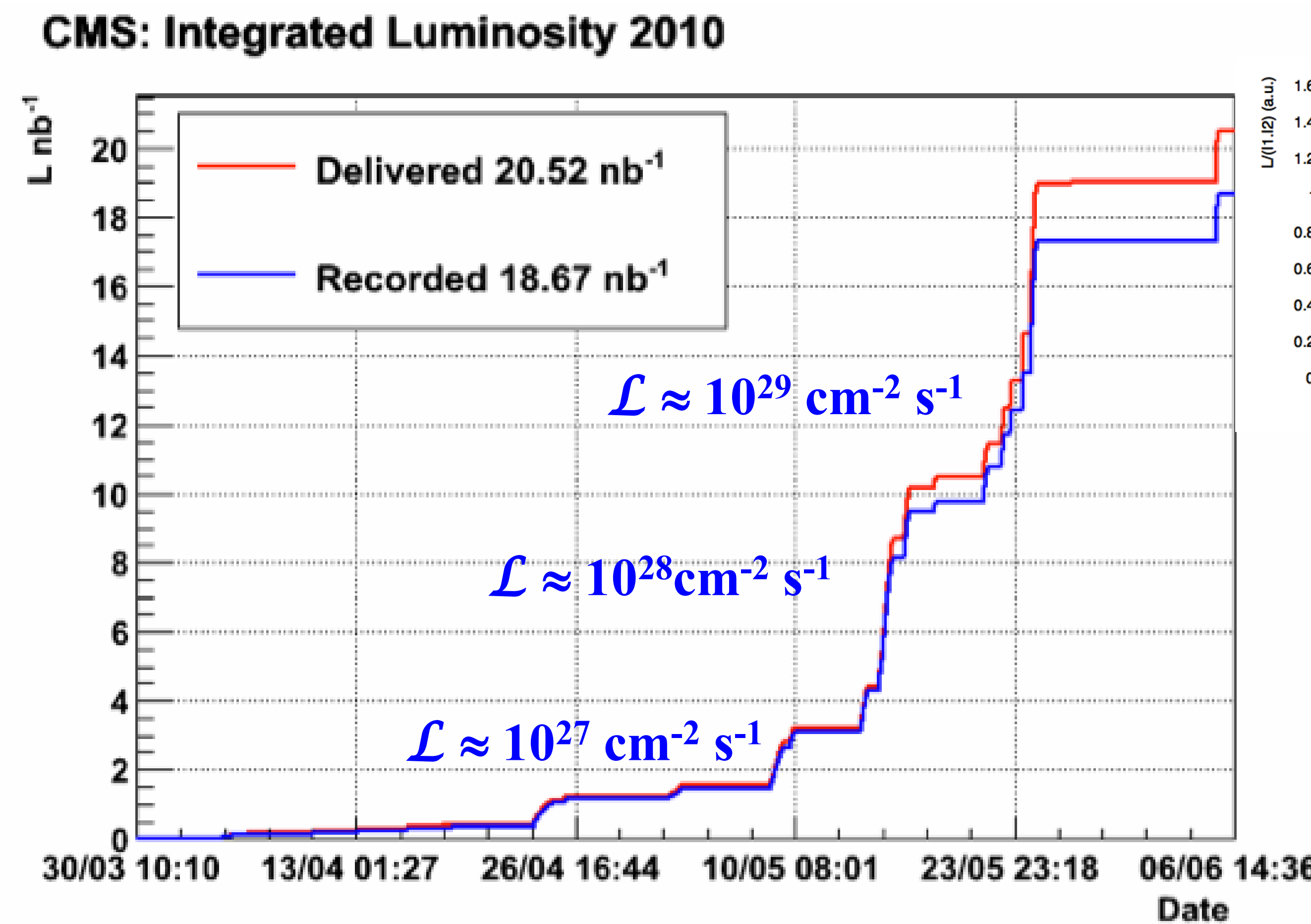
$\sqrt{s} = 7$ TeV
$\mathcal{L} \sim 20\ nb^{-1}$

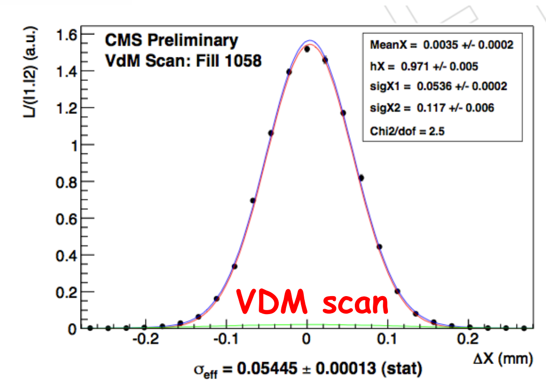


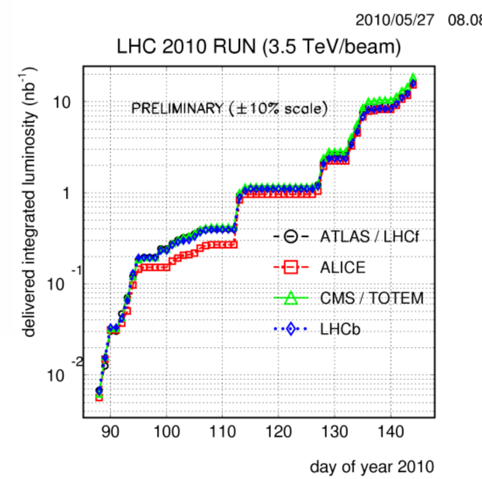
Multi Jet Event at 7 TeV

CMS Integrated Luminosity

Collected so far in 2010:

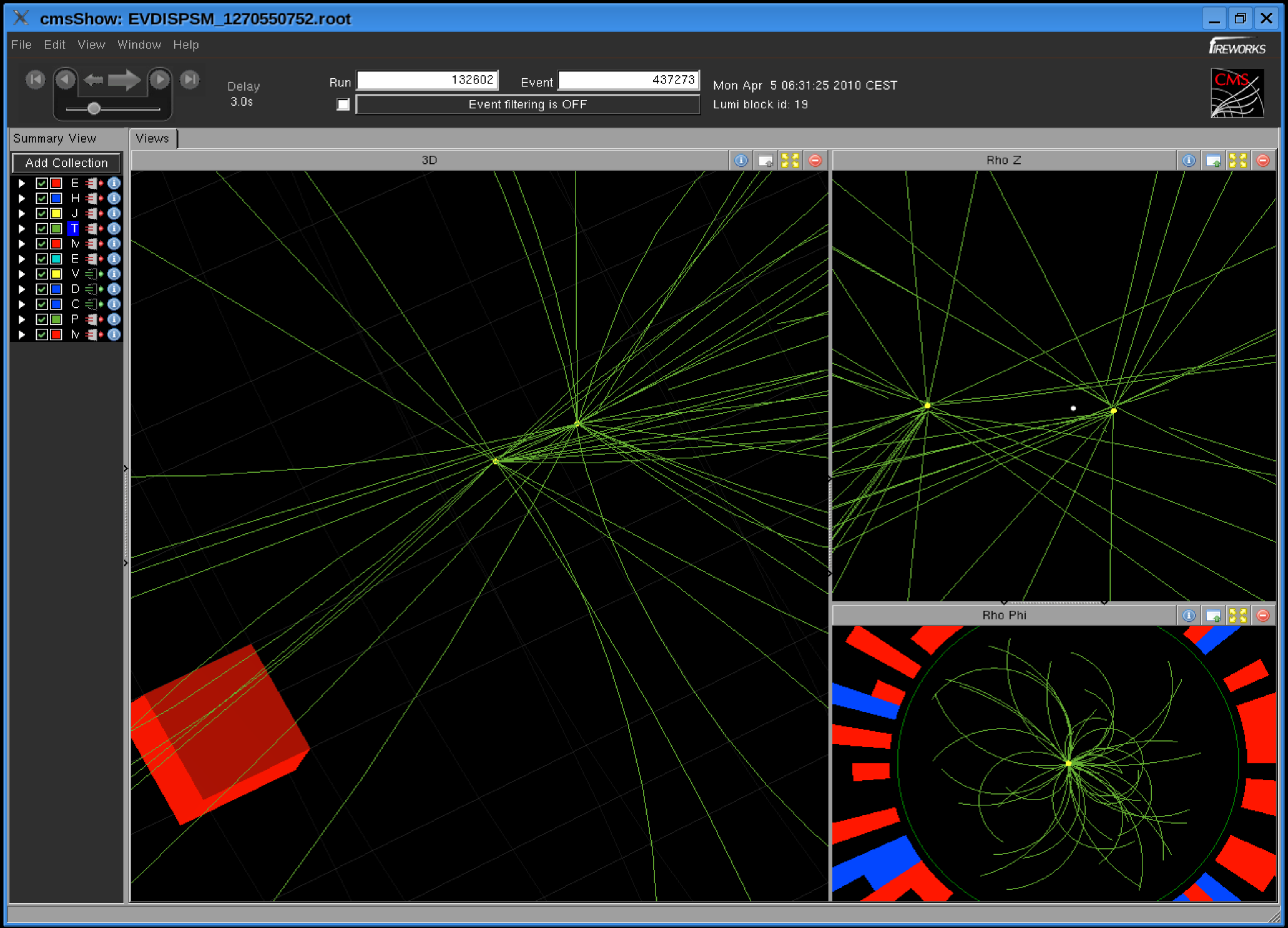






Still Low Luminosity but:

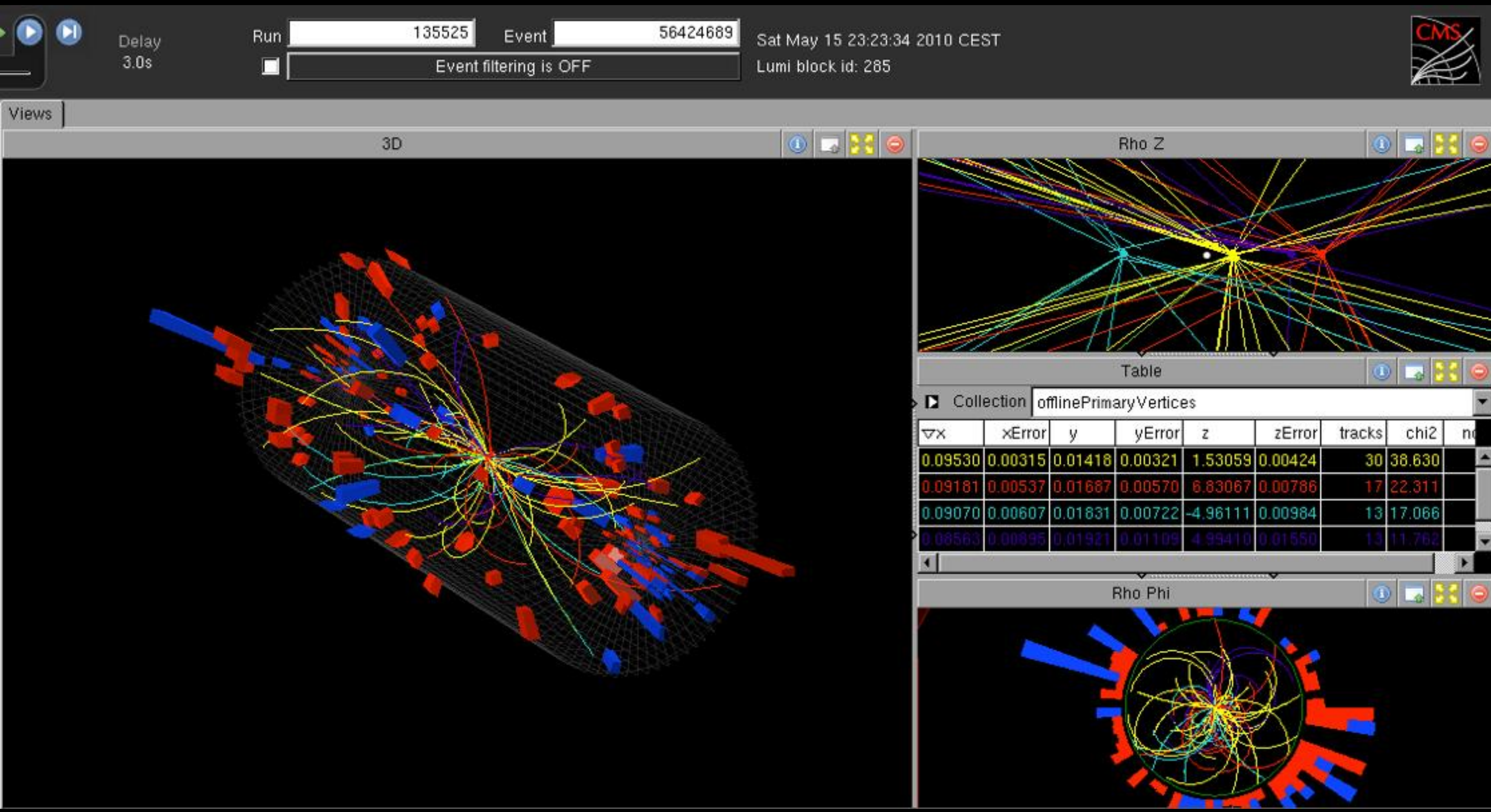
Events with two primary vertices start to occur



It will be an issue for high intensity beams. CMS will be ready for it

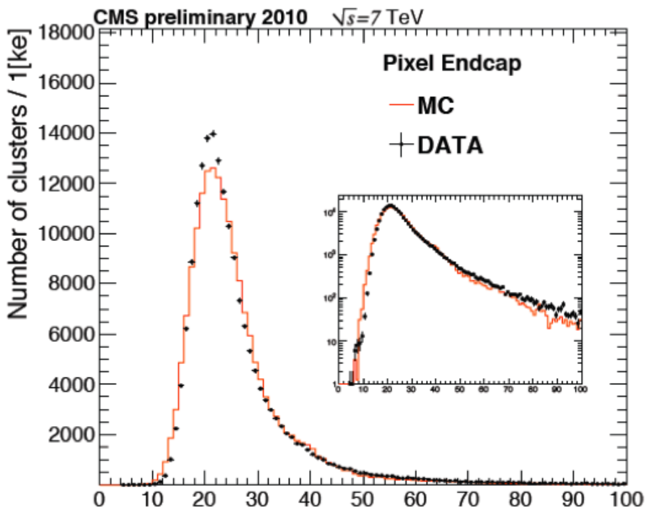
Still Low Luminosity but also…

events with four primary vertices

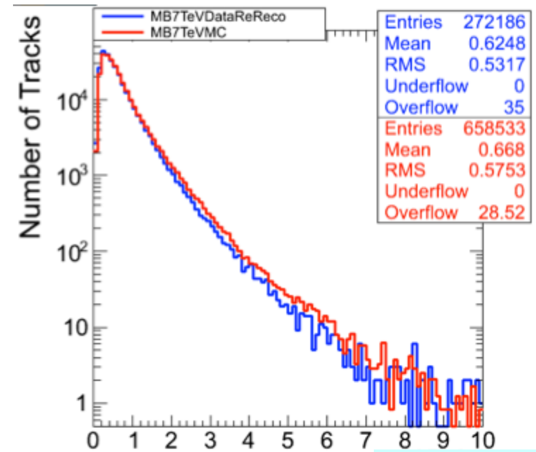


It will be an issue for high intensity beams. CMS will be ready for it

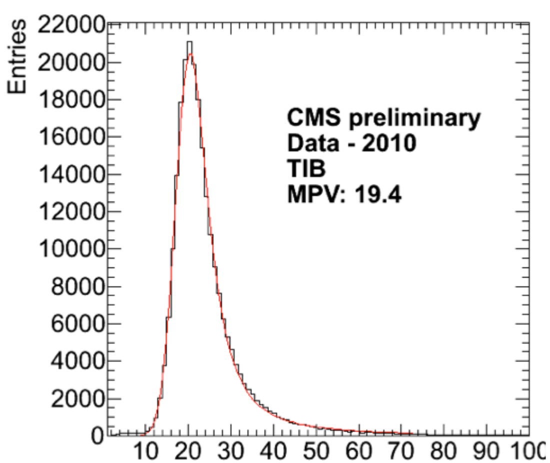
7 TeV Data: Tracker Performance



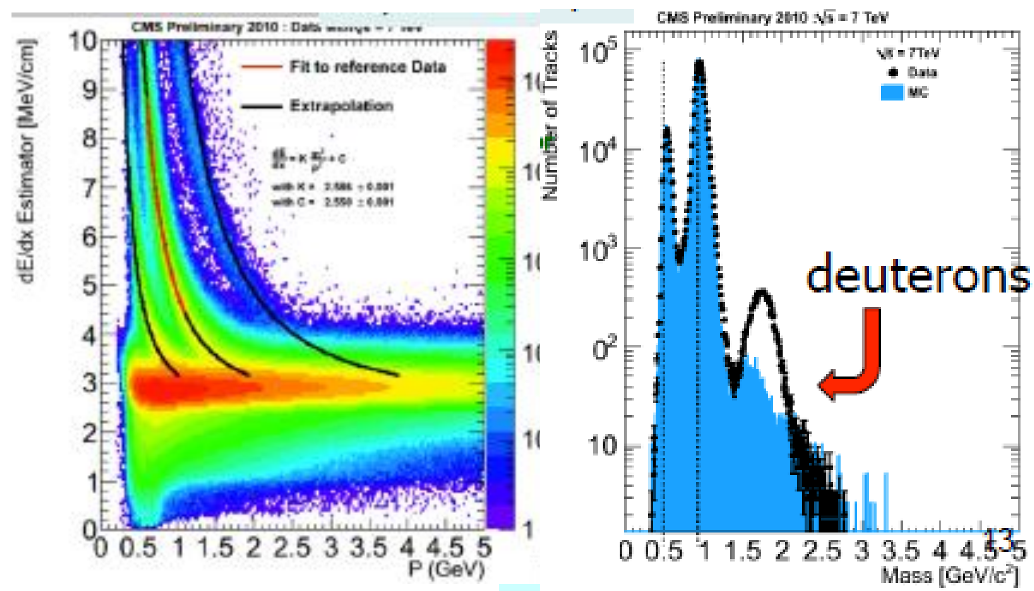
Pixel cluster charge



P_T spectra

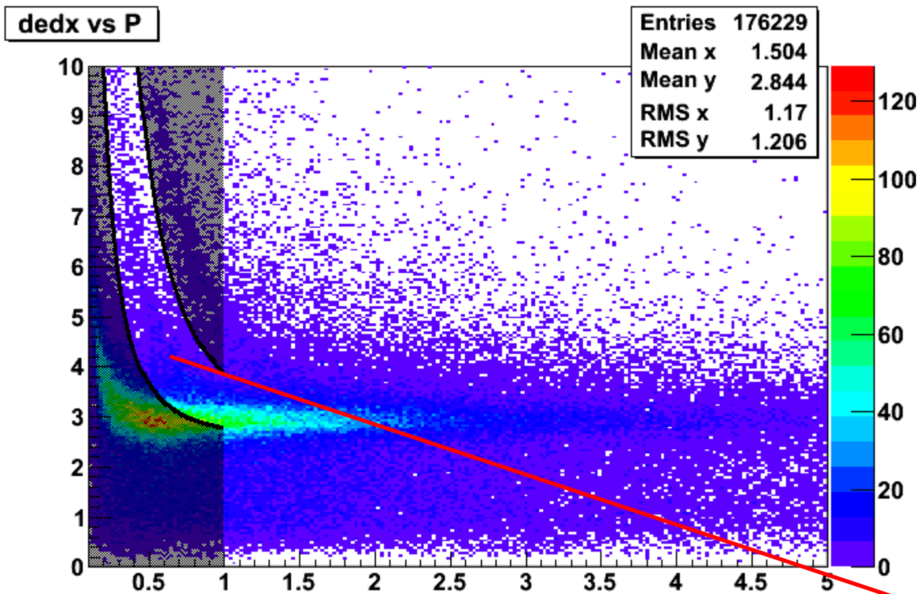


Signal/noise

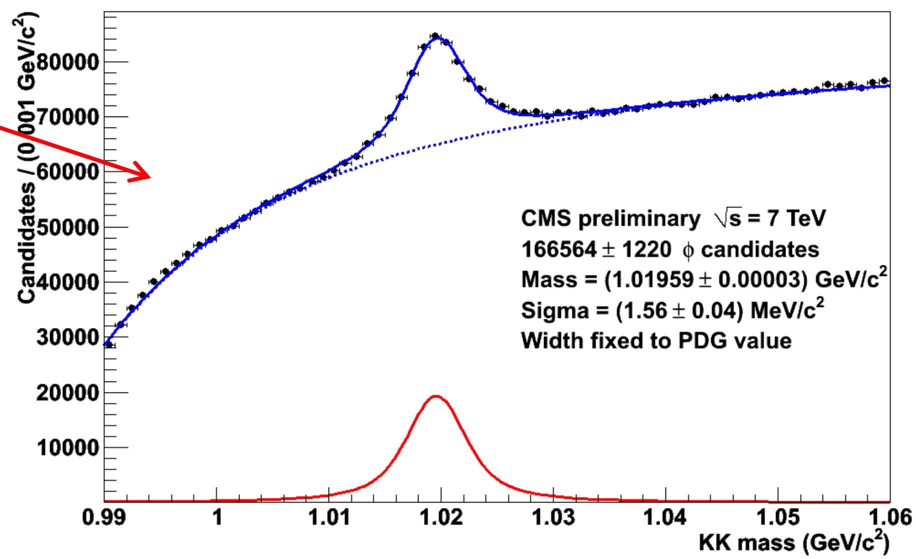


dE/dx

$\phi \rightarrow K^+K^-$ using dE/dx



$\sqrt{s}$ = 7 TeV

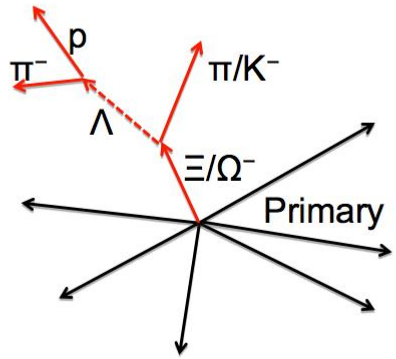


- Rejection of low P tracks (< 1GeV) with dE/dx incompatible with the hypothesis of a charged K (light band).
- Invariant mass reconstruction for events passing the dE/dx cut

K^0_s, Λ, ϕ ...

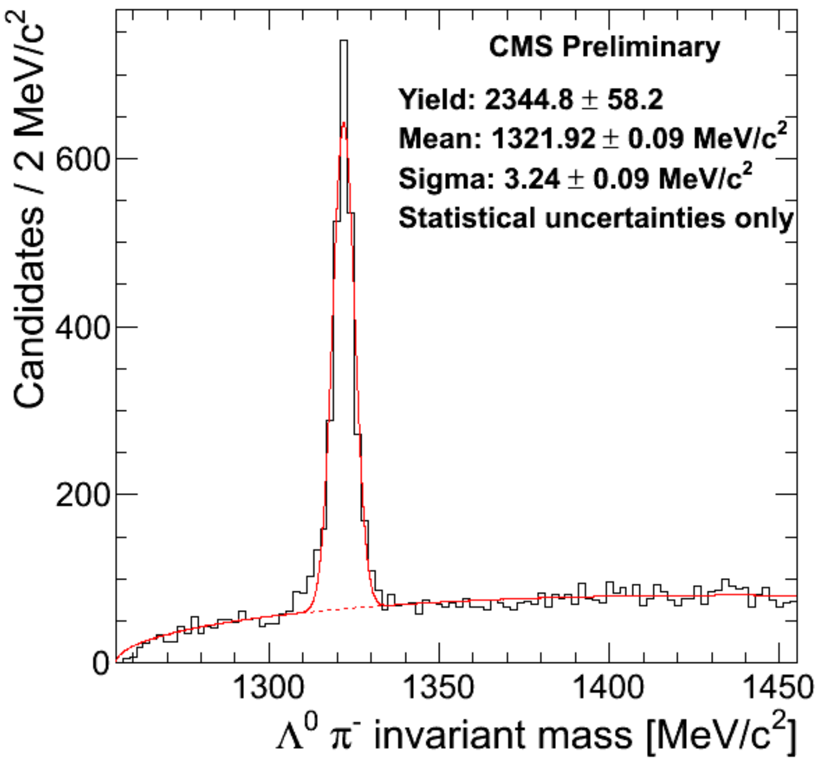
- ➢ **Validate Tracking, Reconstruction, Secondary Vertex Finding, Magnetic Field, Material, Momentum scale**
- ➢ **Validation of MC**

7 TeV Data: Resonances



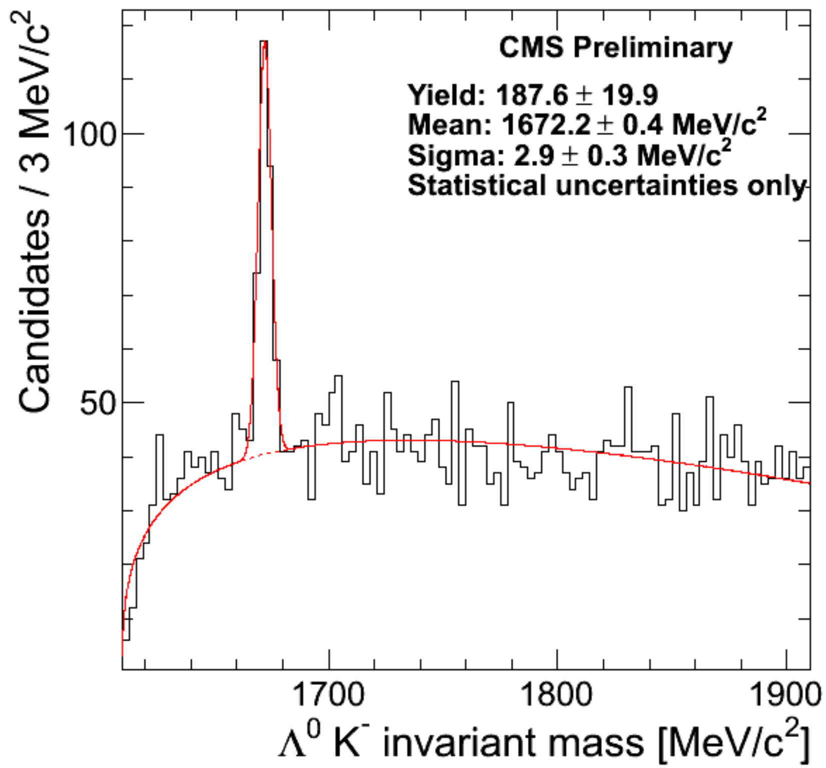
$\Xi^\pm \longrightarrow \Lambda\pi^\pm$

$\Lambda\pi^-$ or anti-$\Lambda\pi^+$ invariant mass



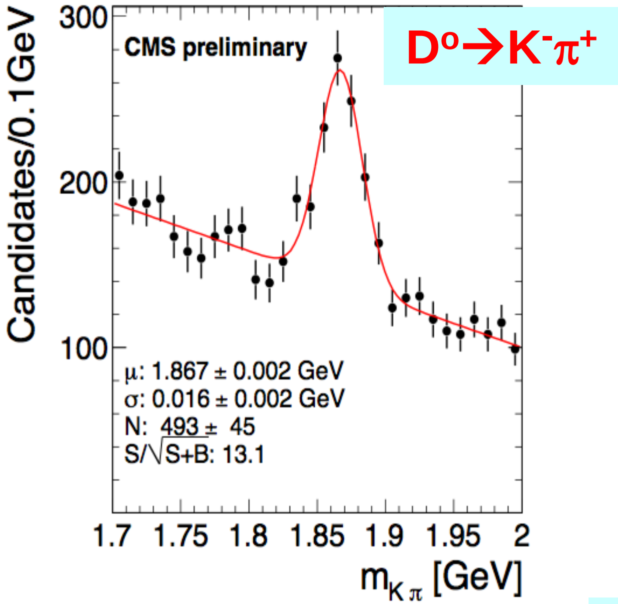
$\Omega^\pm \rightarrow \Lambda K^\pm$

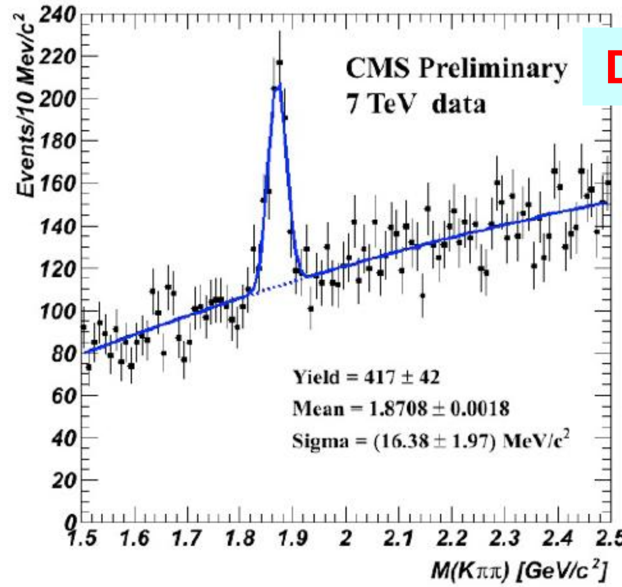
ΛK^- or anti-ΛK^+ invariant mass

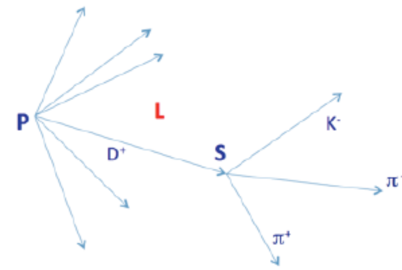


Charm Production

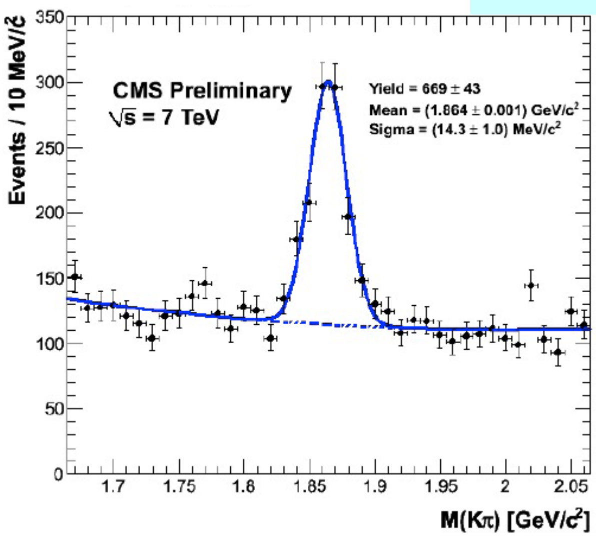
7 TeV DATA

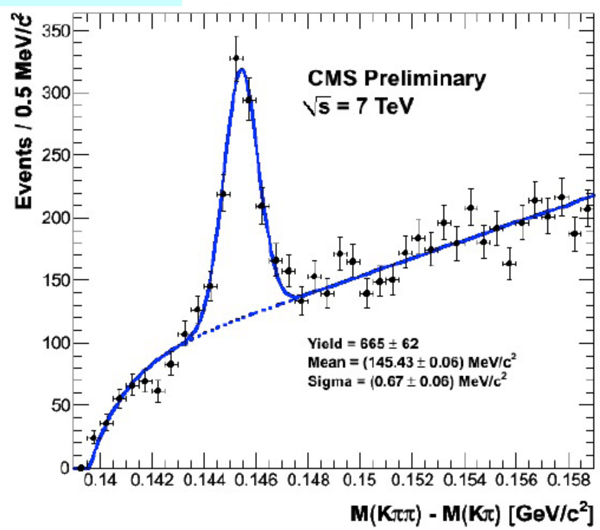






D^{*+}→D^o(K$^-\pi^+$)π^+



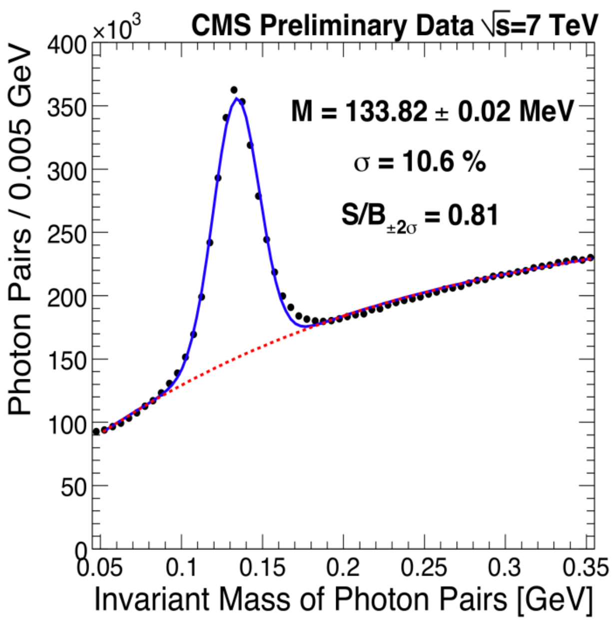


ECAL calibration

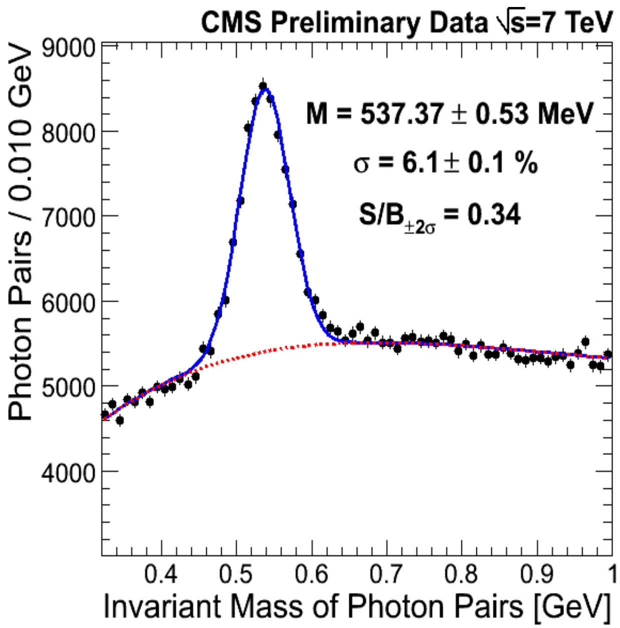
$\mathcal{L} > 1\ \mathrm{nb}^{-1}$: beginning to use π^0's and η's in ECAL calibration.

7 TeV DATA

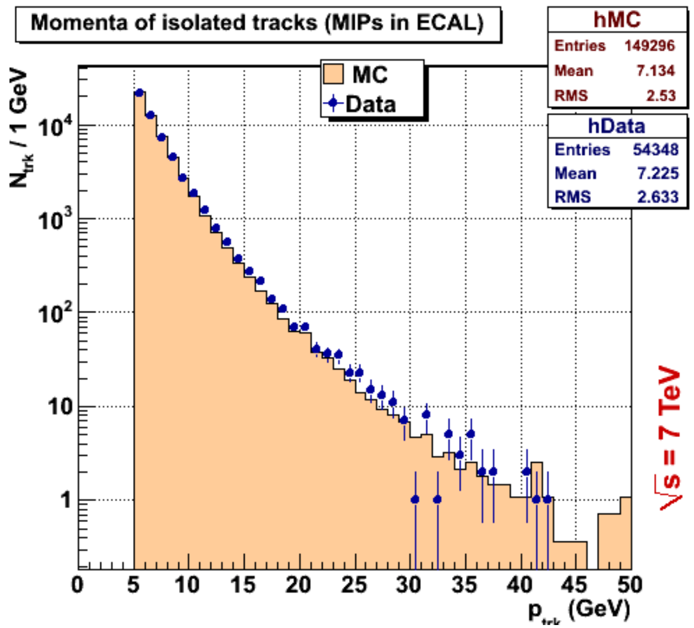
1.46M $\pi^0 \rightarrow \gamma\gamma$ pairs



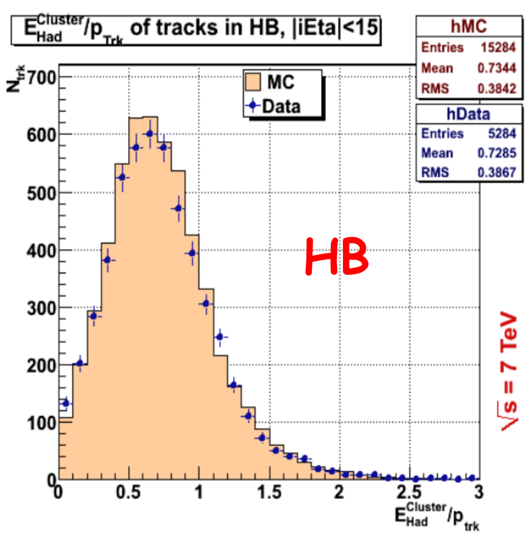
25.5k $\eta \rightarrow \gamma\gamma$ pairs

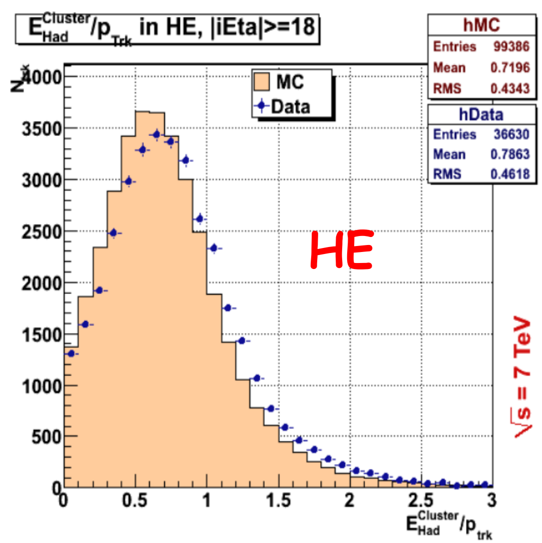


HCAL calibration: response to isolated hadrons



- ~$10pb^{-1}$ needed to determine energy scale using iso-tracks with p_T>40 GeV.
- Studies at lower p_T allow comparison to MC and <u>may</u> provide an initial correction.



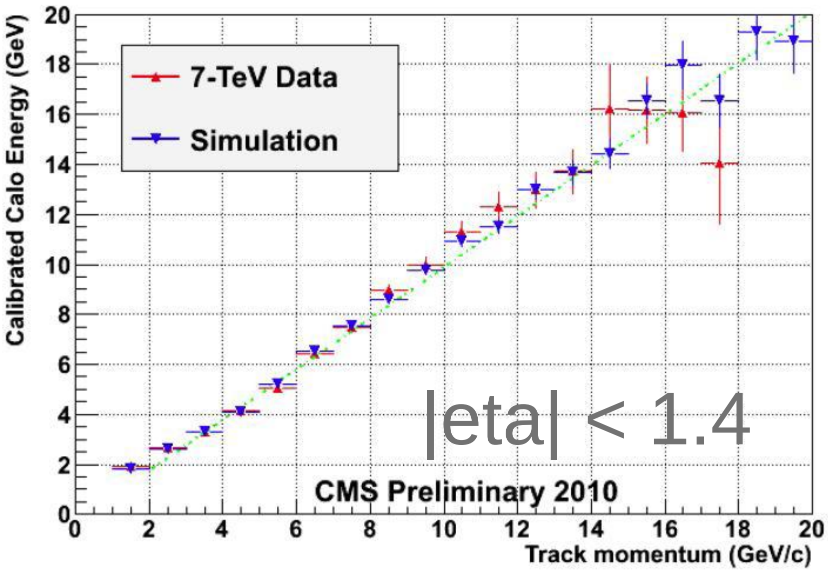


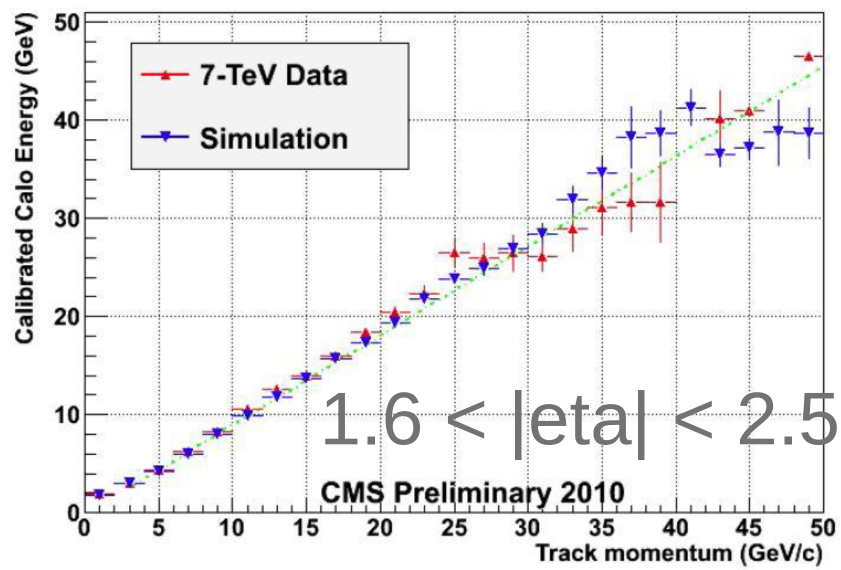
- HB and HE response to isolated minimum ionizing particles integrated over all track momenta.

Calorimeter calibration

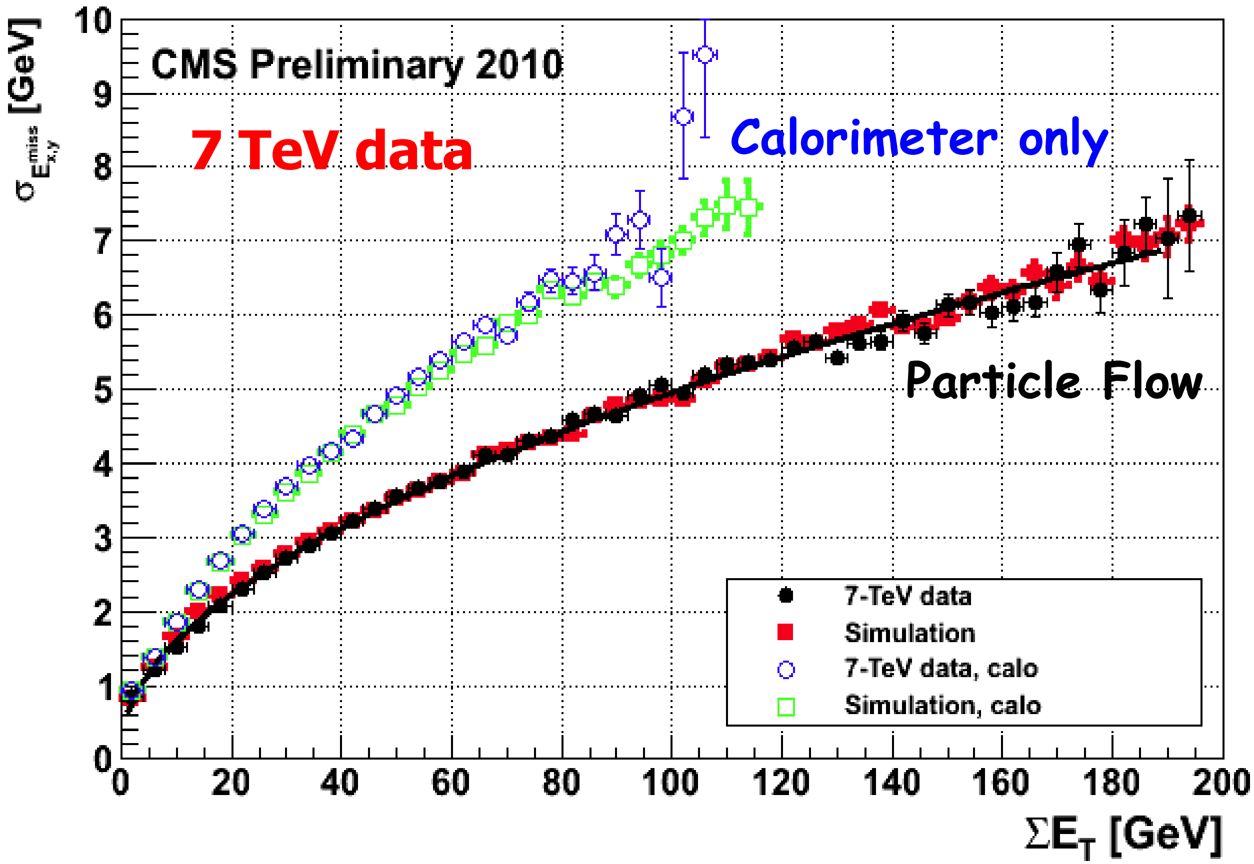
* The PF algorithm needs a calibrated response of the calorimeter
  * So far a Monte Carlo based calibration has been used
    * it has shown to work very well also with data!

$$E_{\mathrm{calib}} = a(E,\eta) + b(E,\eta)E_{\mathrm{ECAL}} + c(E,\eta)E_{\mathrm{HCAL}}$$

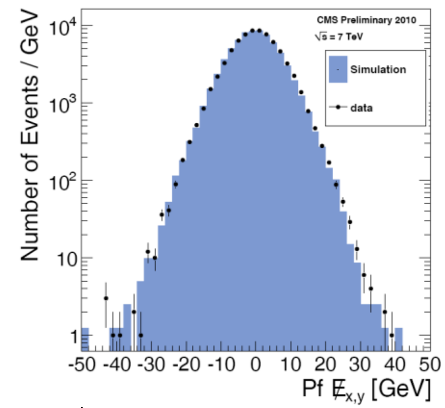




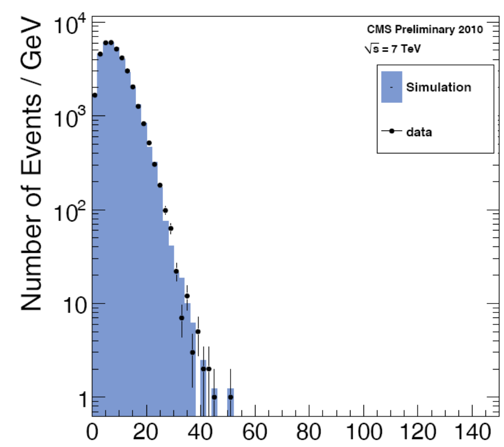
Particle Flow E_T^{miss} resolution vs ΣE_T



$$\sigma(E_{x,y}^{miss}) = \sqrt{0.41^2 + 0.49^2 \sum E_T + 0.008(\sum E_T)^2}$$



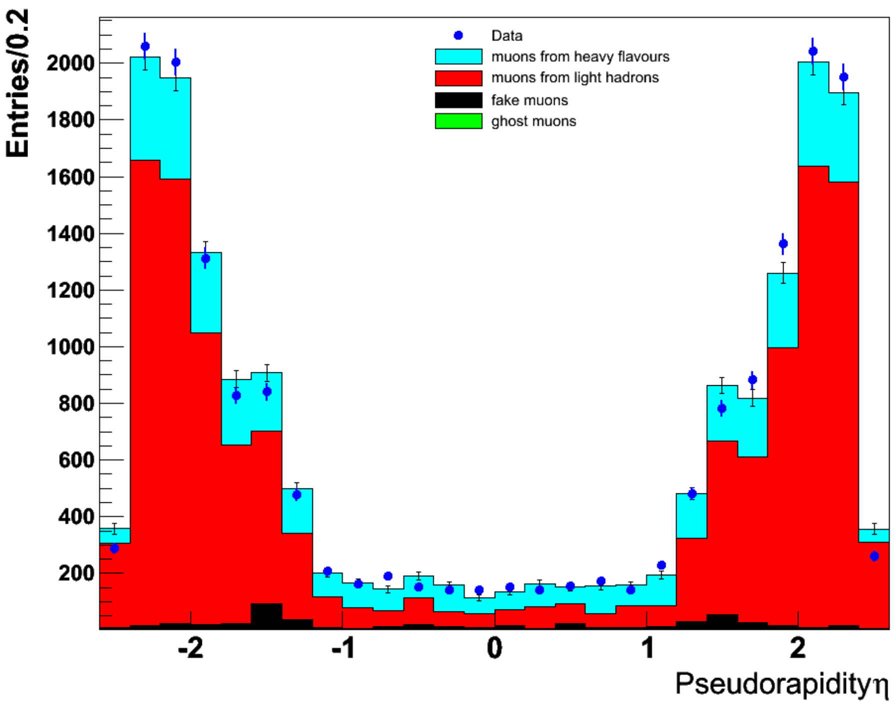
$\not{E}_{x,y}$ in a Di-Jet selection



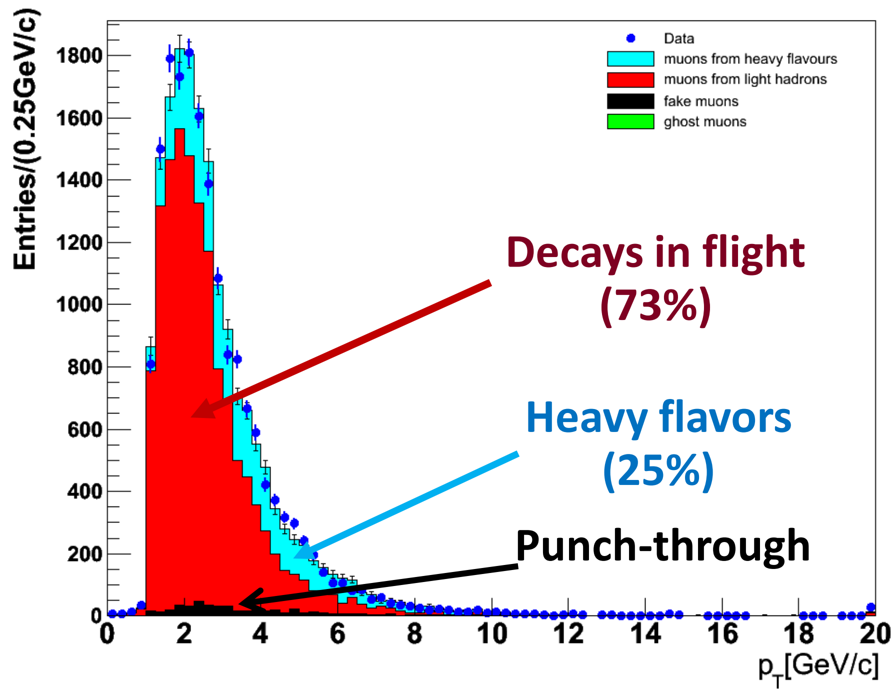
$\not{E}_T$ in a Di-Jet selection

7 TeV Data: Muons

Good data-MC agreement



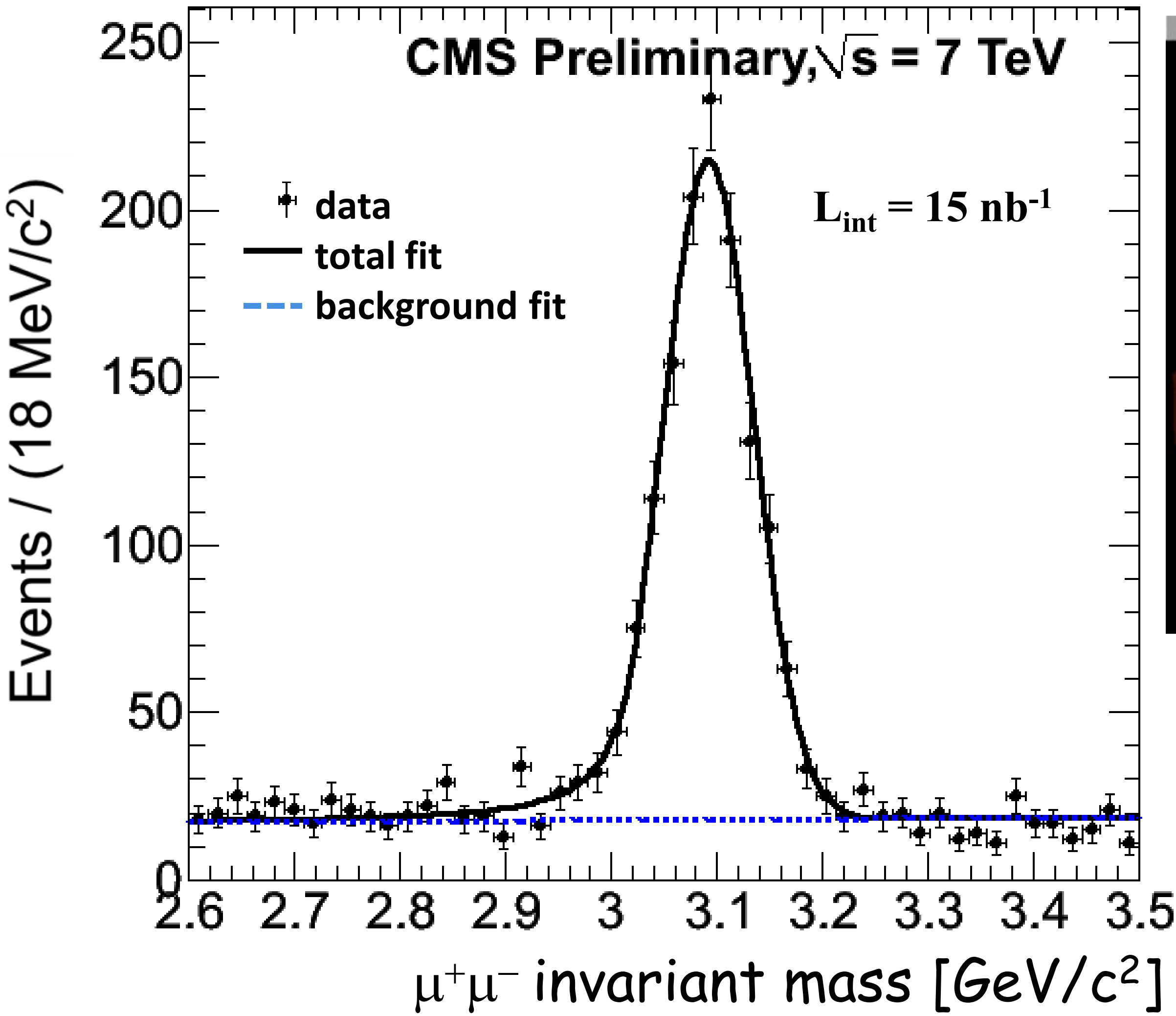
pseudorapidity distribution

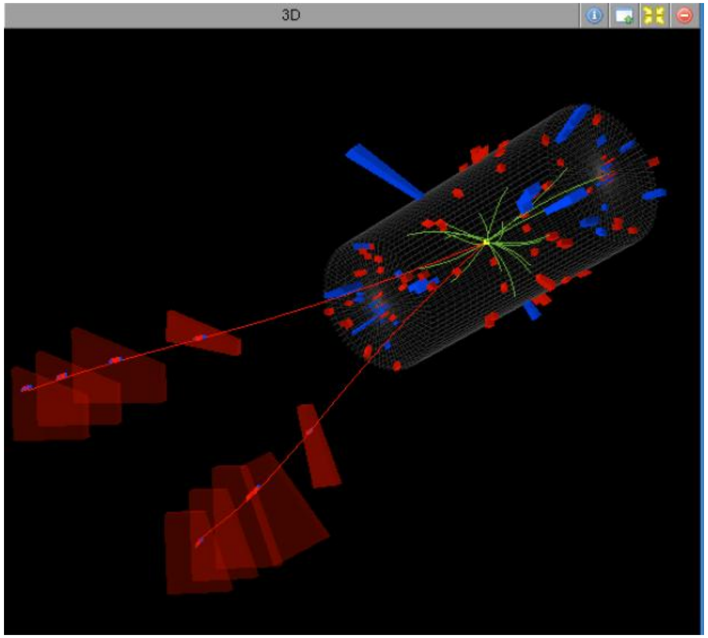


P_T spectra

Di-muon resonances: $J/\psi \rightarrow \mu^+\mu^-$

7TeV data from $\mathcal{L}_{int} \approx 15\ nb^{-1}$





Signal events: 1230 ± 47

Sigma: (42.7 ± 1.9) MeV

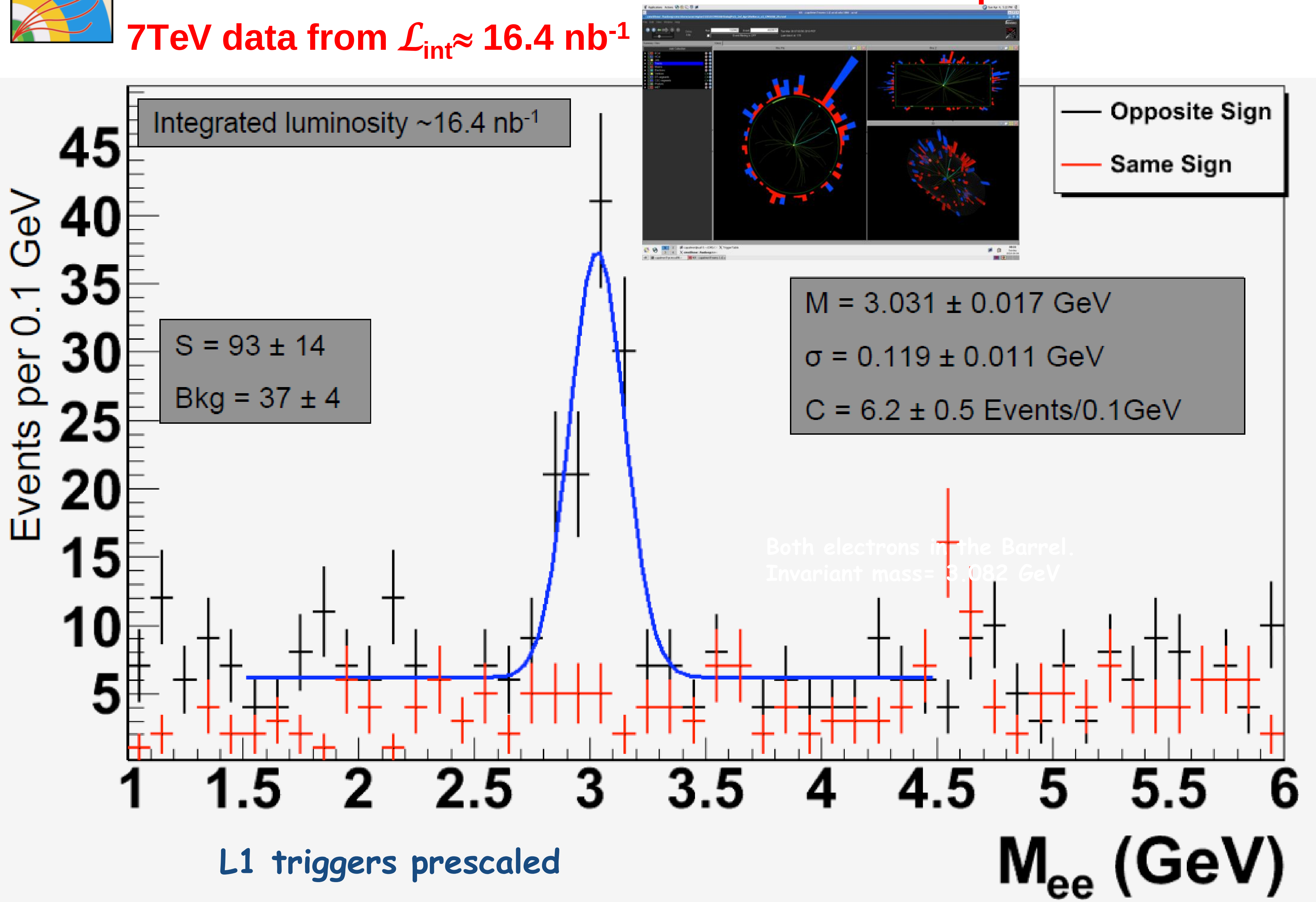
M_0: 3.092 ± 0.001 GeV

S/B = 5.4 (M_0 ± 2.5σ)

χ^2/ndof = 1.1

Di-electron resonances: $J/\psi \rightarrow e^+e^-$

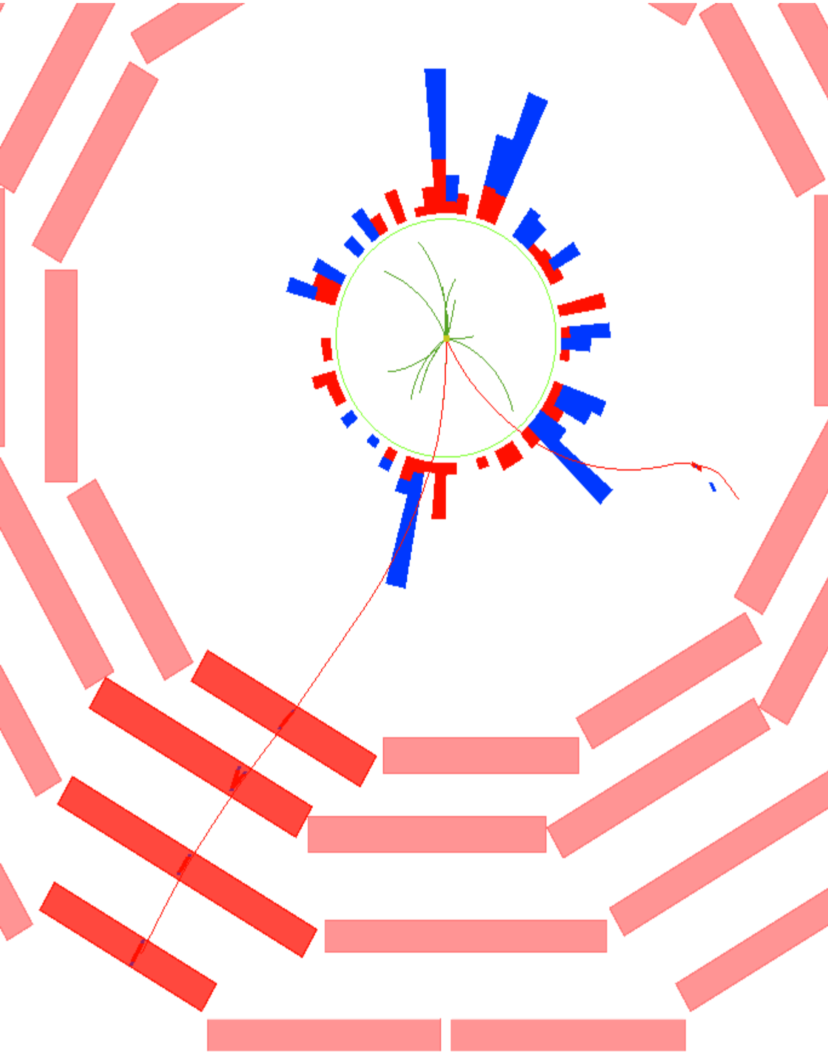
7TeV data from $\mathcal{L}_{int} \approx 16.4\ nb^{-1}$



L1 triggers prescaled

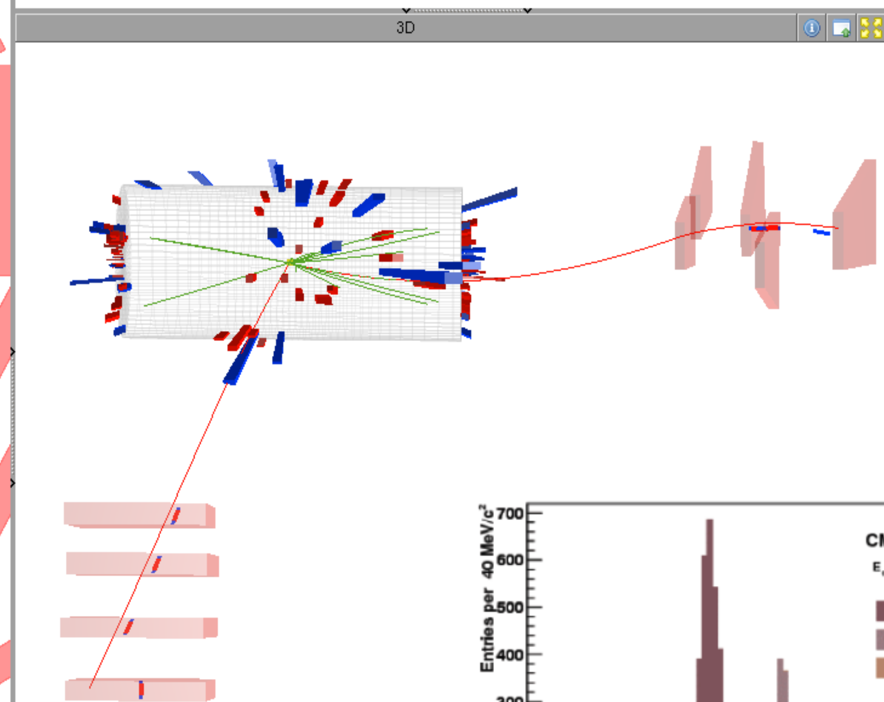
Looking for higher mass di-muon resonances: $\Upsilon \rightarrow \mu^+\mu^-$

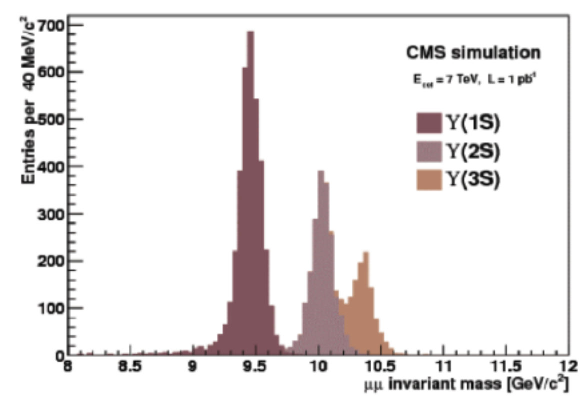
M=9.35GeV; p_t=8.41GeV



Collection Muons

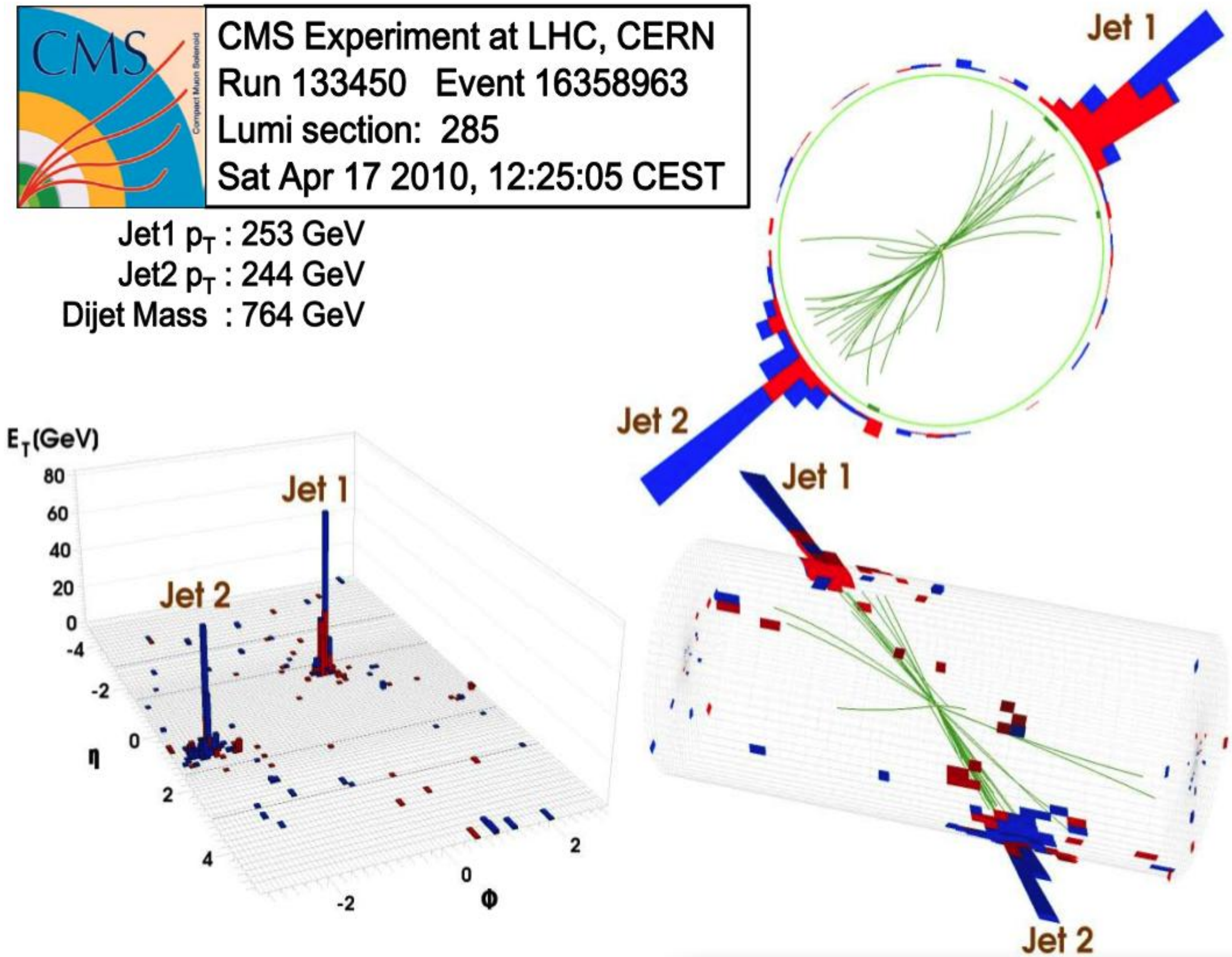
▽pT	global	tracker	SA	calo	tr pt	eta	phi	matches	d0	d0 / d0Err	charge
6.0	true	true	true	false	6.0	0.462	-1.559	4	-0.098	-26.396	1
2.6	true	true	true	false	2.6	-1.527	-1.135	2	-0.096	-13.627	-1



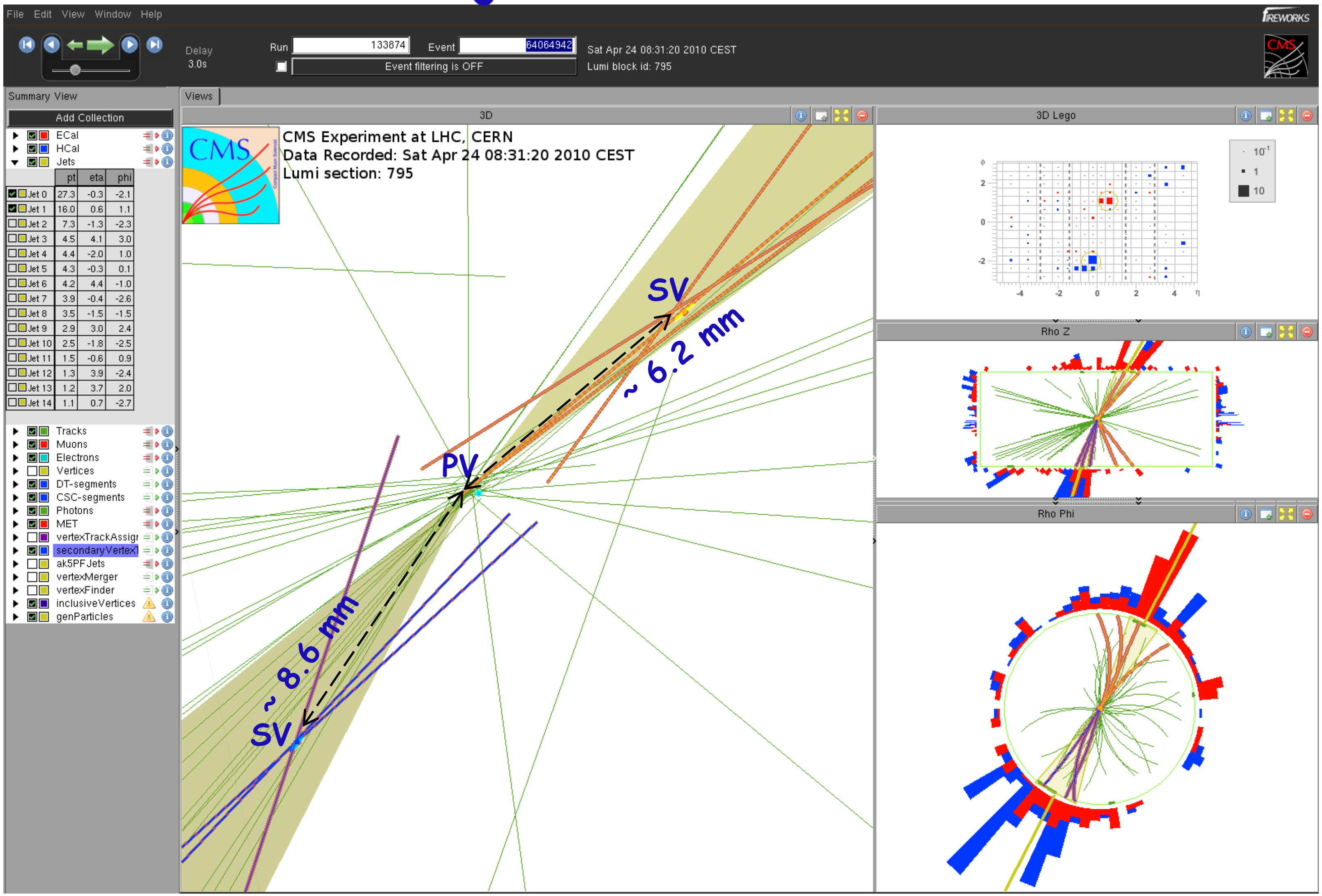


Expecting a few thousand $\Upsilon(nS) \rightarrow \mu^+\mu^-$ in CMS per pb^{-1}

High Dijet Mass Event at 7 TeV



double b-jet candidate



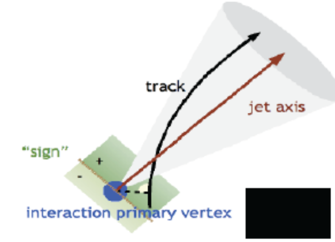
Jets: p_T = 43.7 GeV (top right) / 40.3 GeV (bottom left)

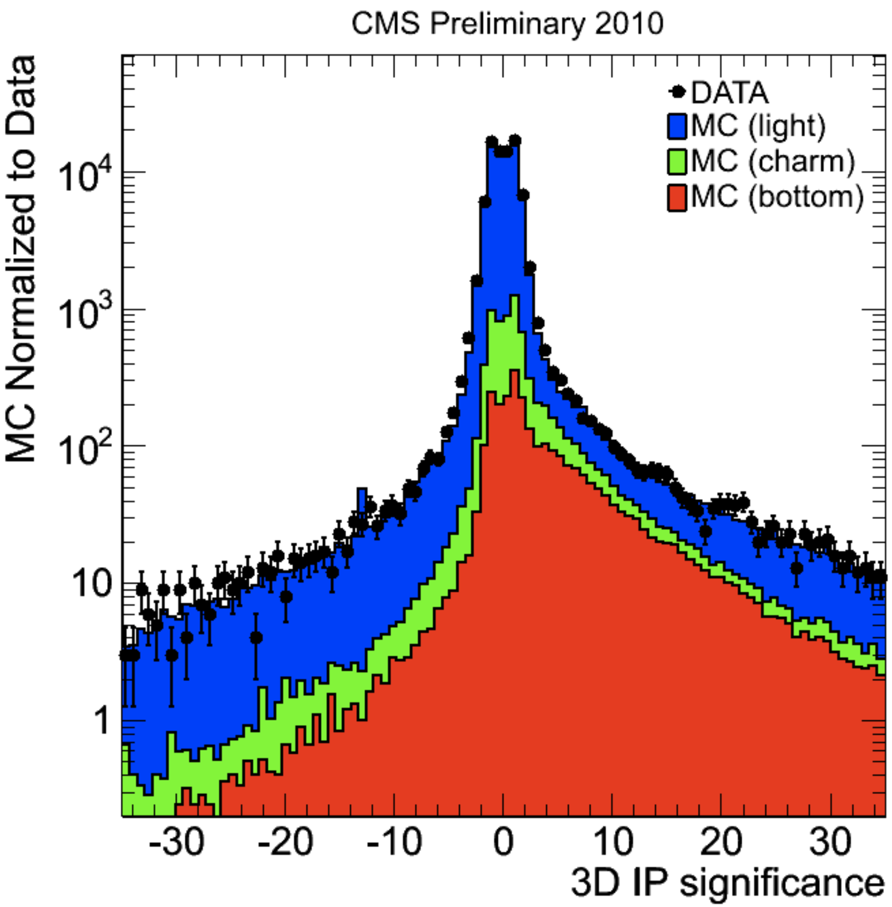
Secondary vertices

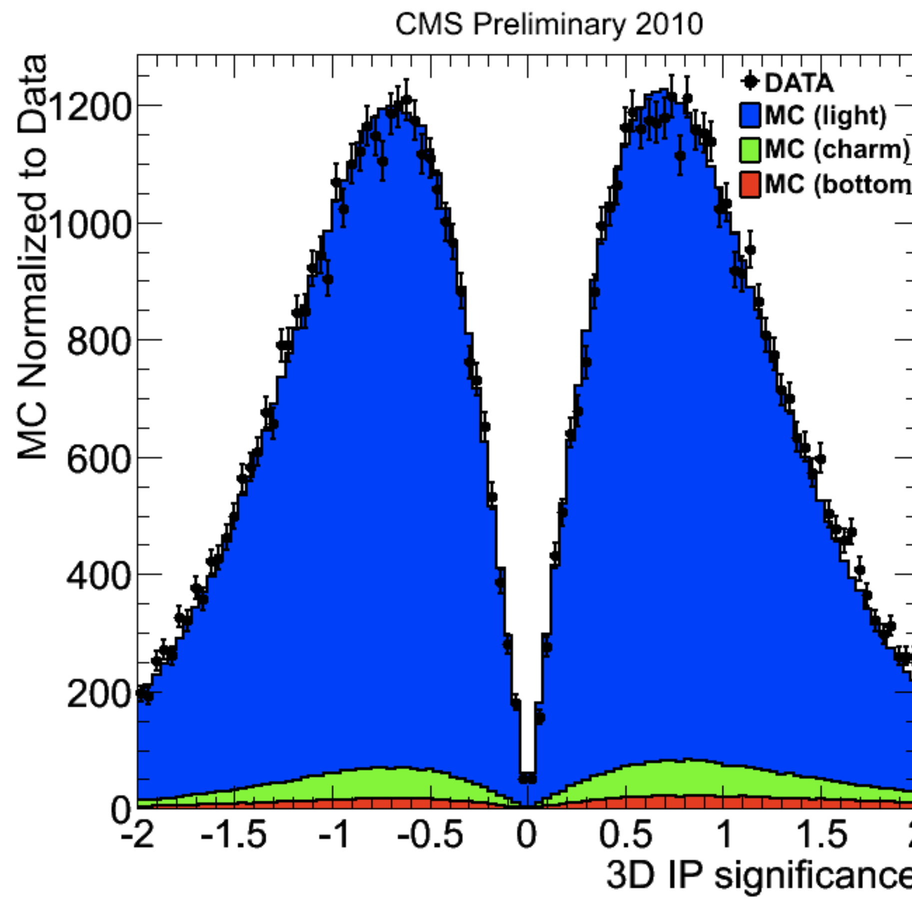
top-right: 3D flight distance (value/ significance) = 6.2 mm / 43 m_{SV} = 2.9 GeV, p_T = 25.7 GeV

bottom left: 3D flight distance (value / significance) = 8.6mm / 55 m_{SV} = 3.1 GeV, p_T = 17.2 GeV

Validation at 7 TeV: b-tagging





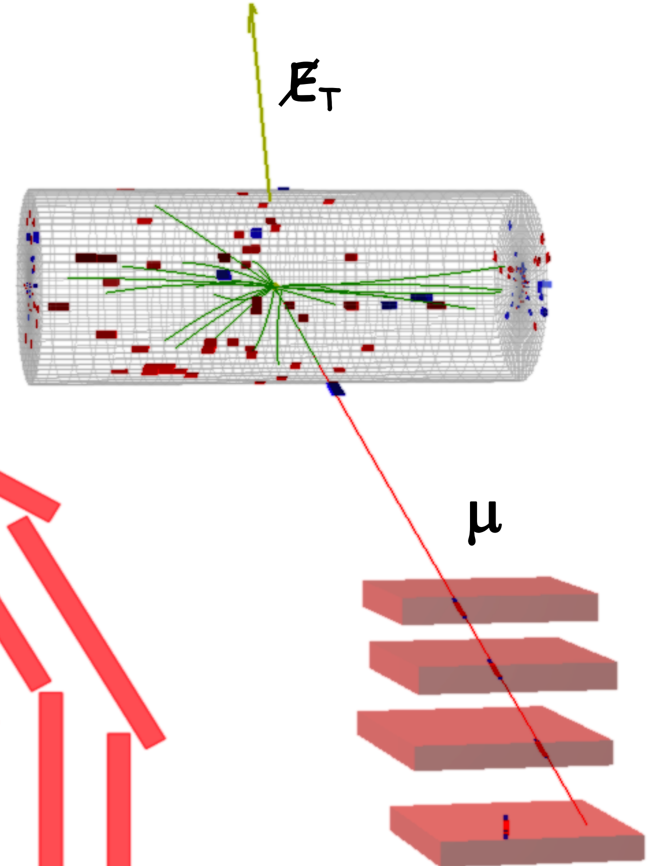


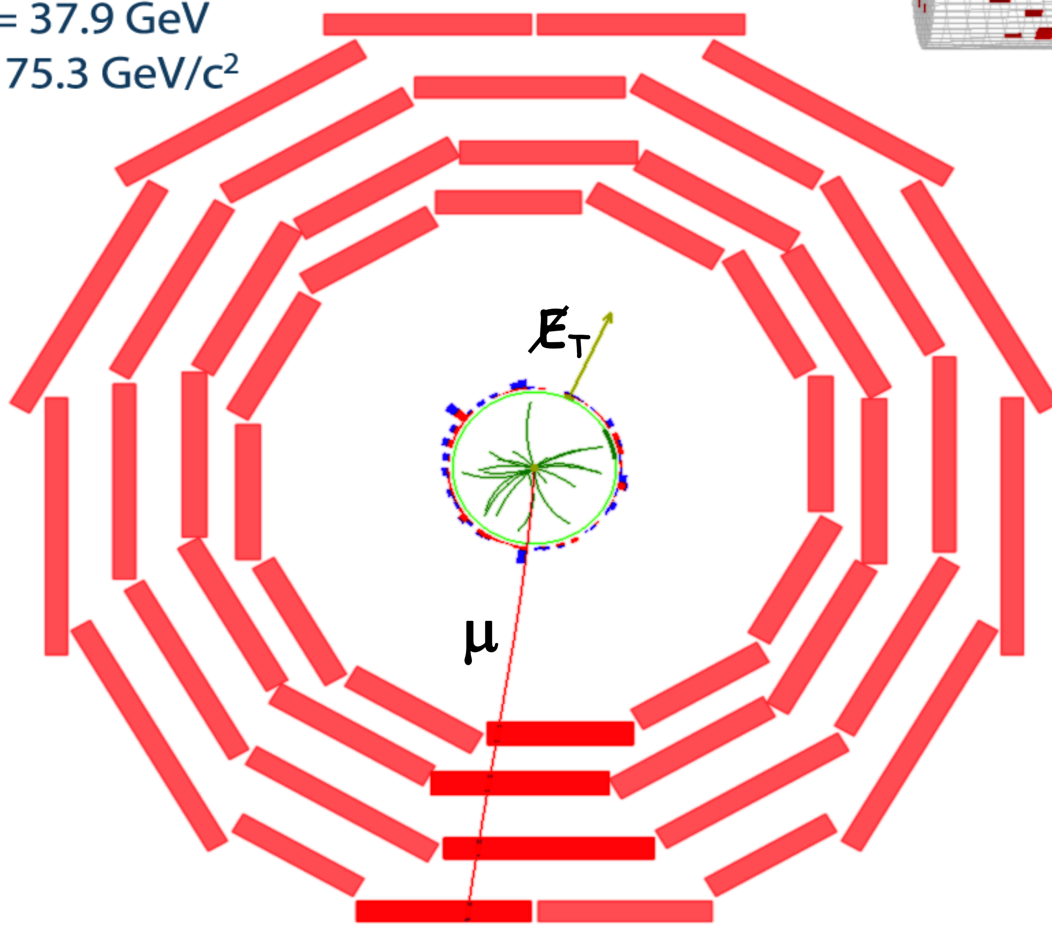
- Left: Significance of the signed 3D impact parameter for all tracks selected for b-tagging, for jets with p_T > 40 GeV and $|\eta|$ < 1.5
- Right: zoom in the region close to 0.
  - ➢ Good agreement between data and MC

W→μν candidate

CMS Experiment at LHC, CERN
Run 133875, Event 1228182
Lumi section: 16
Sat Apr 24 2010, 09:08:46 CEST

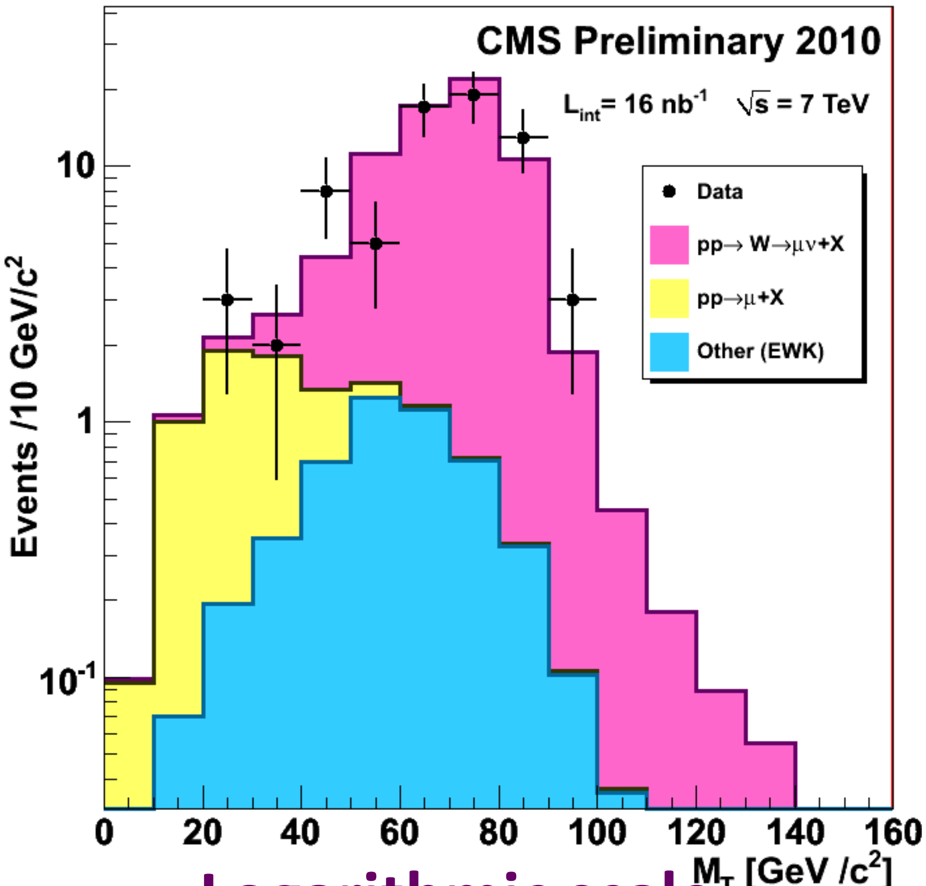
Muon p_T= 38.7 GeV/c
ME_T= 37.9 GeV
M_T= 75.3 GeV/c²



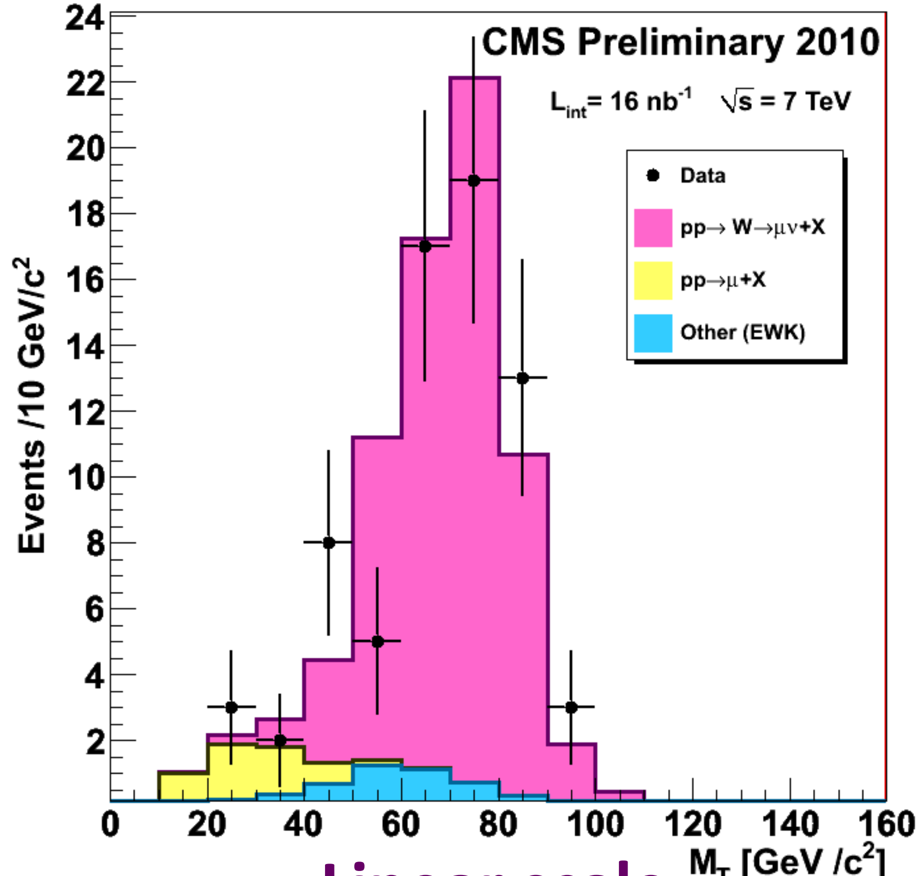


Looking for Vector Bosons: W→μν M_T distribution
7TeV data from $\mathcal{L}_{int} \approx 16\ nb^{-1}$

W→μν candidates extracted on the single muon triggers (p_T>9 GeV non isolated):



Logarithmic scale



Linear scale

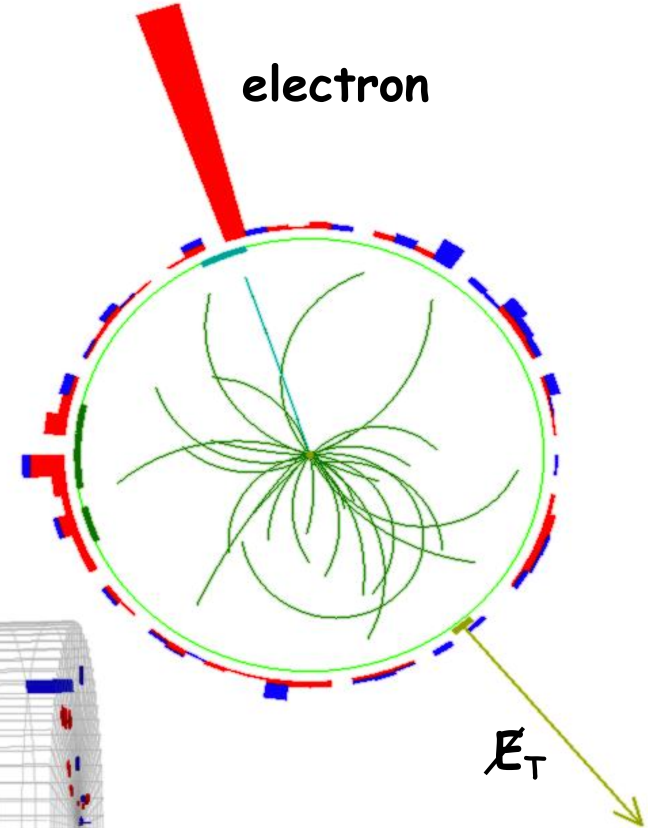
In the plot: 70 events

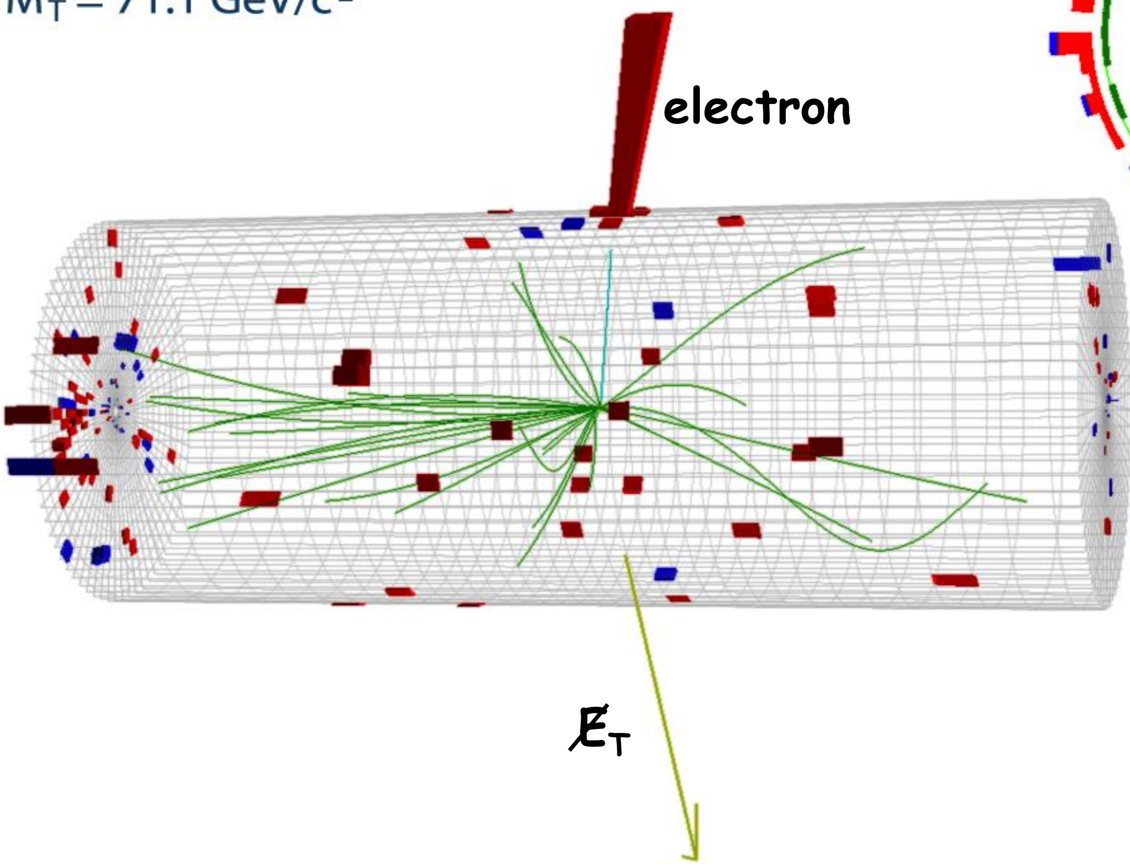
With M_T > 50 GeV: 57 events

W→eν candidate

CMS Experiment at LHC, CERN
Run 133874, Event 21466935
Lumi section: 301
Sat Apr 24 2010, 05:19:21 CEST

Electron $p_T = 35.6$ GeV/c
$ME_T = 36.9$ GeV
$M_T = 71.1$ GeV/c^2

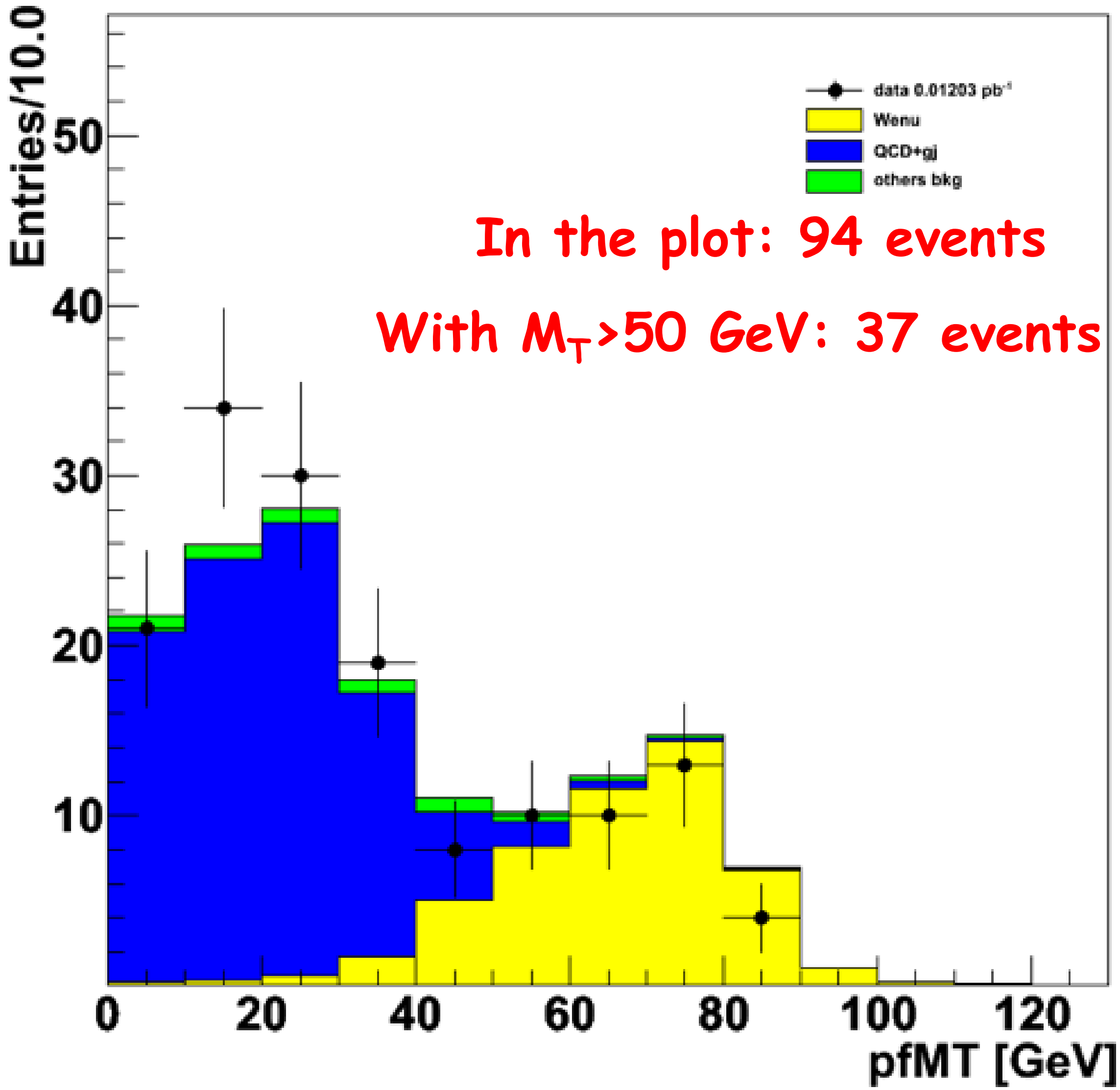




Looking for Vector Bosons: W→eν M_T distribution

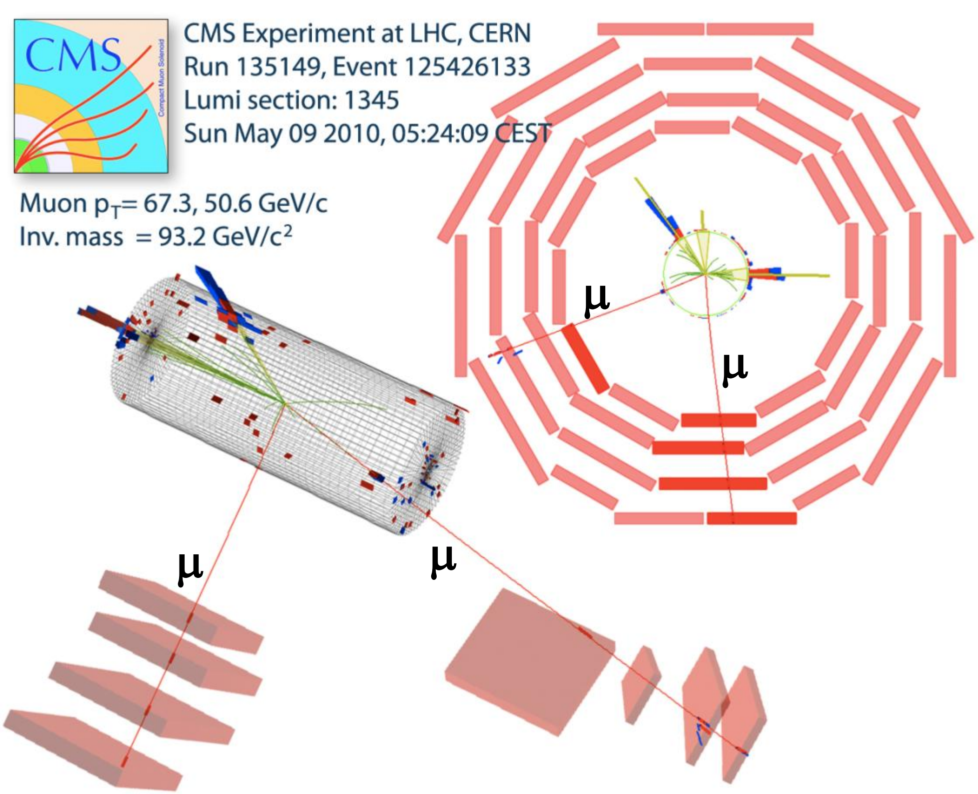
7TeV data from $\mathcal{L}_{int} \approx$ 12 nb^{-1}

W→eν candidates extracted on the single photon trigger (E_T>10 GeV non isolated):

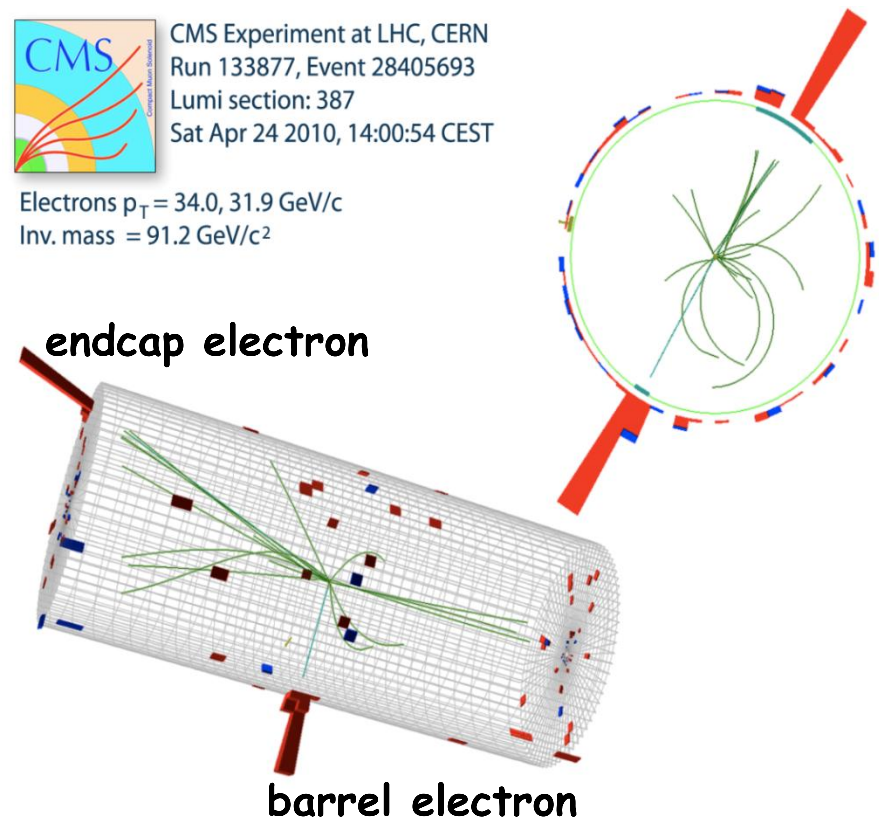


Looking for Z candidates:

$Z \rightarrow \mu^+\mu^-$

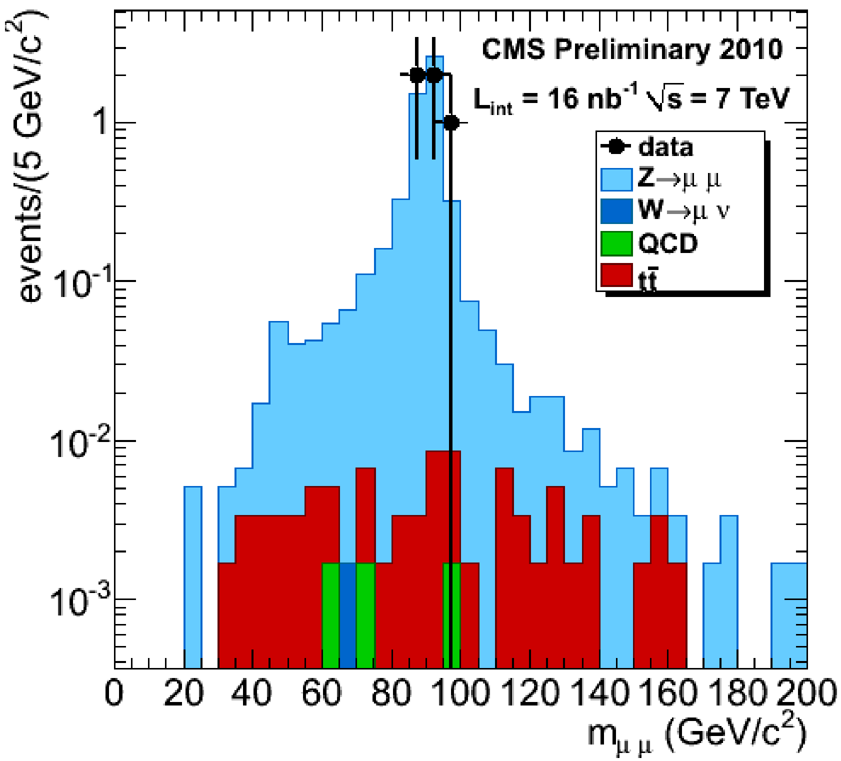


$Z \rightarrow e^+e^-$

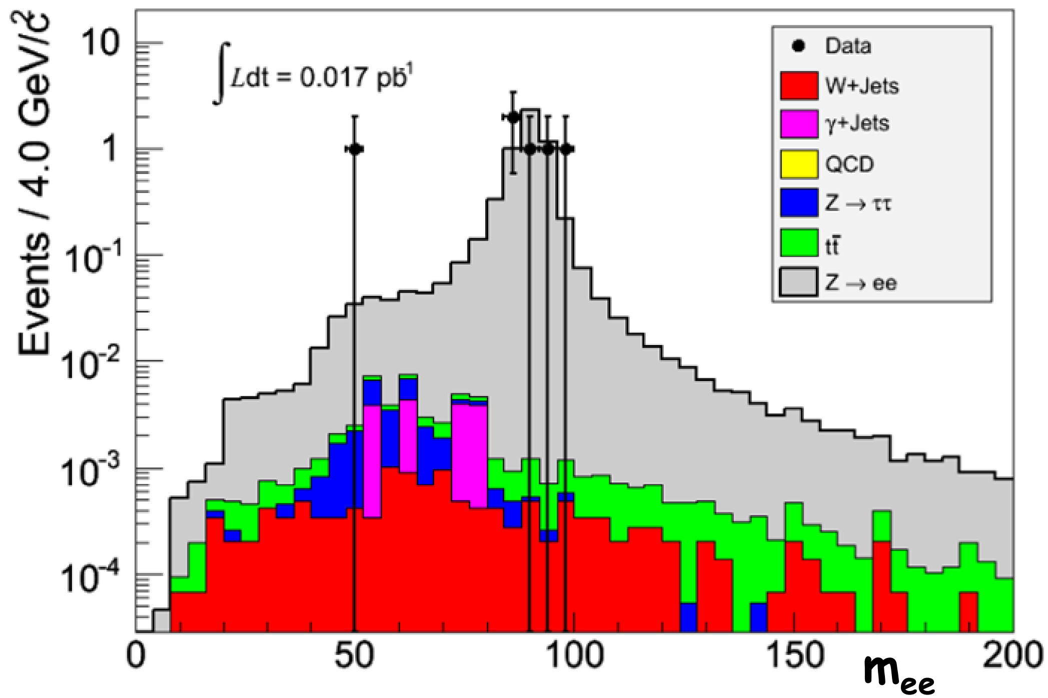


Z candidates at 7 TeV

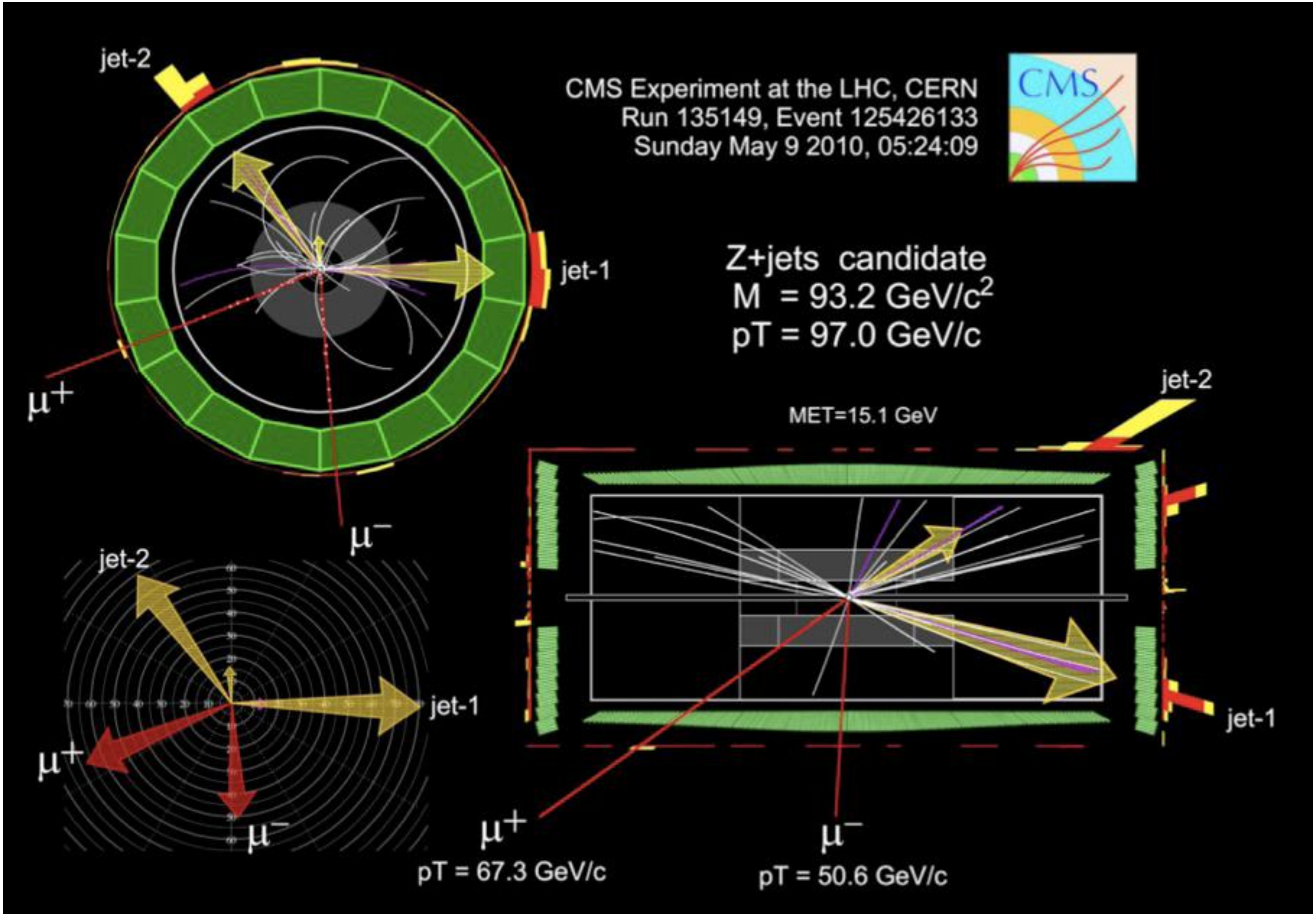
$Z \rightarrow \mu^+\mu^-$: $\mathcal{L}_{int} \approx 16\ nb^{-1}$



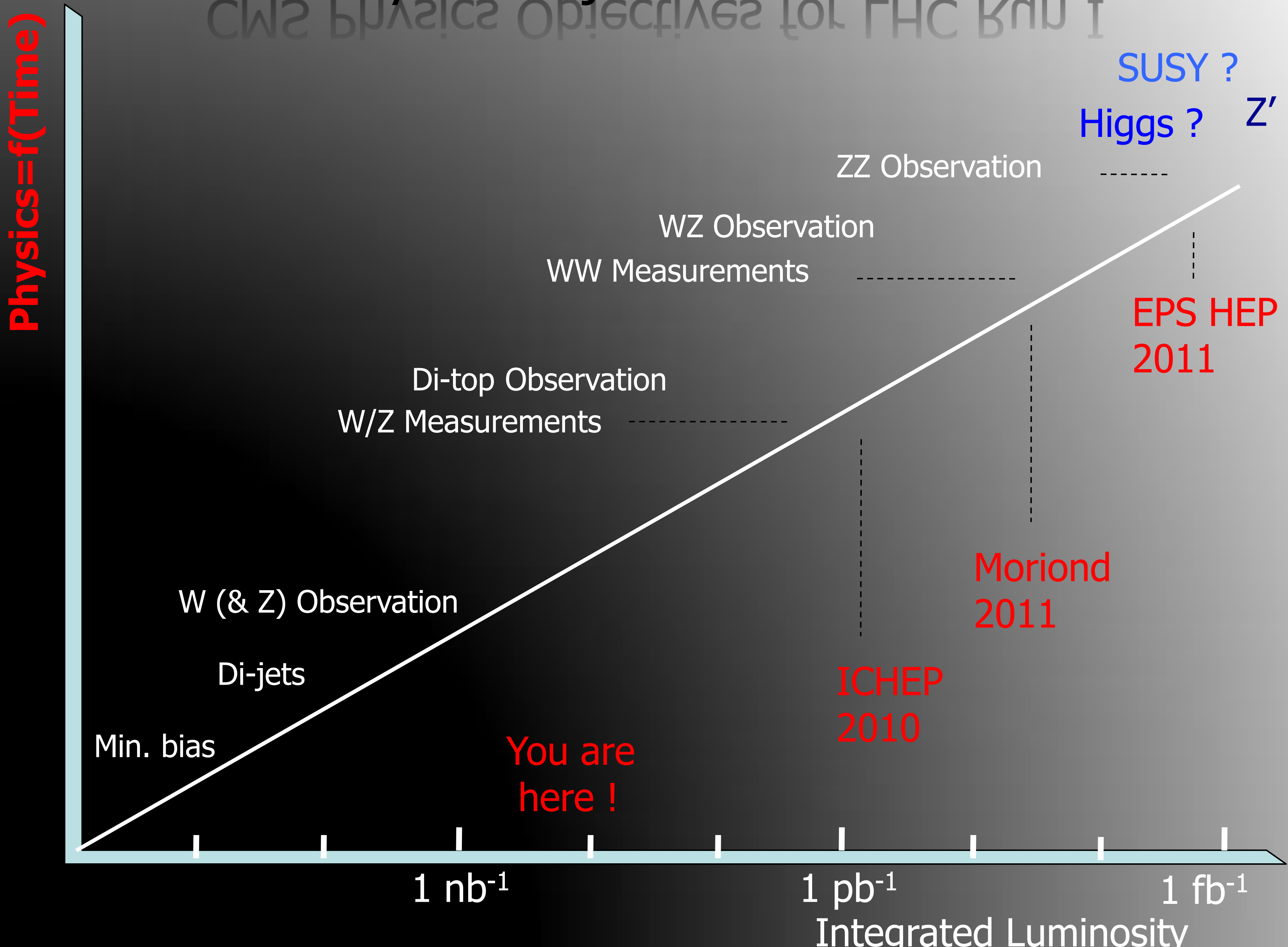
$Z \rightarrow e^+e^-$: $\mathcal{L}_{int} \approx 17\ nb^{-1}$



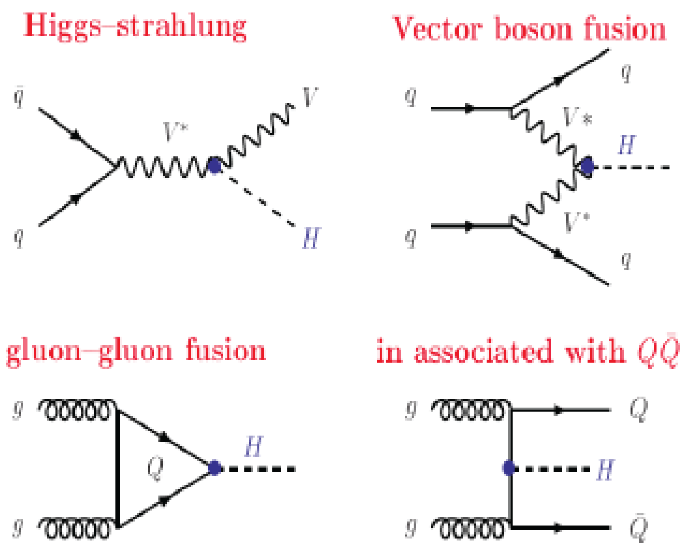
Z+jets candidate

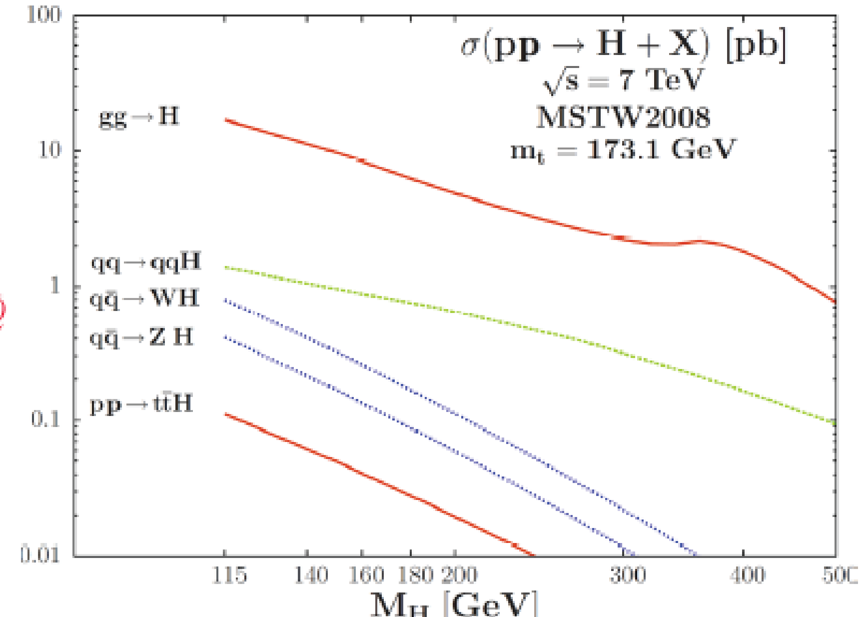


CMS Physics Objectives for LHC Run I

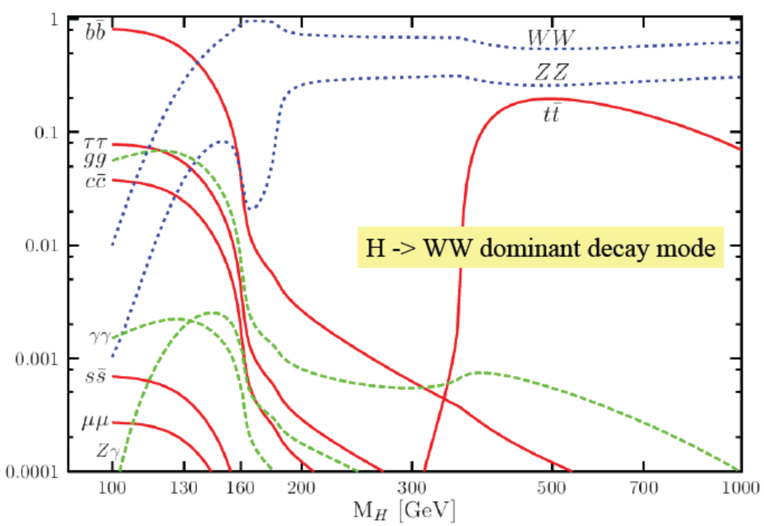


Higgs Production and Decay @ 7 TeV





As at Tevatron, gg -> H is the dominant production mode at LHC

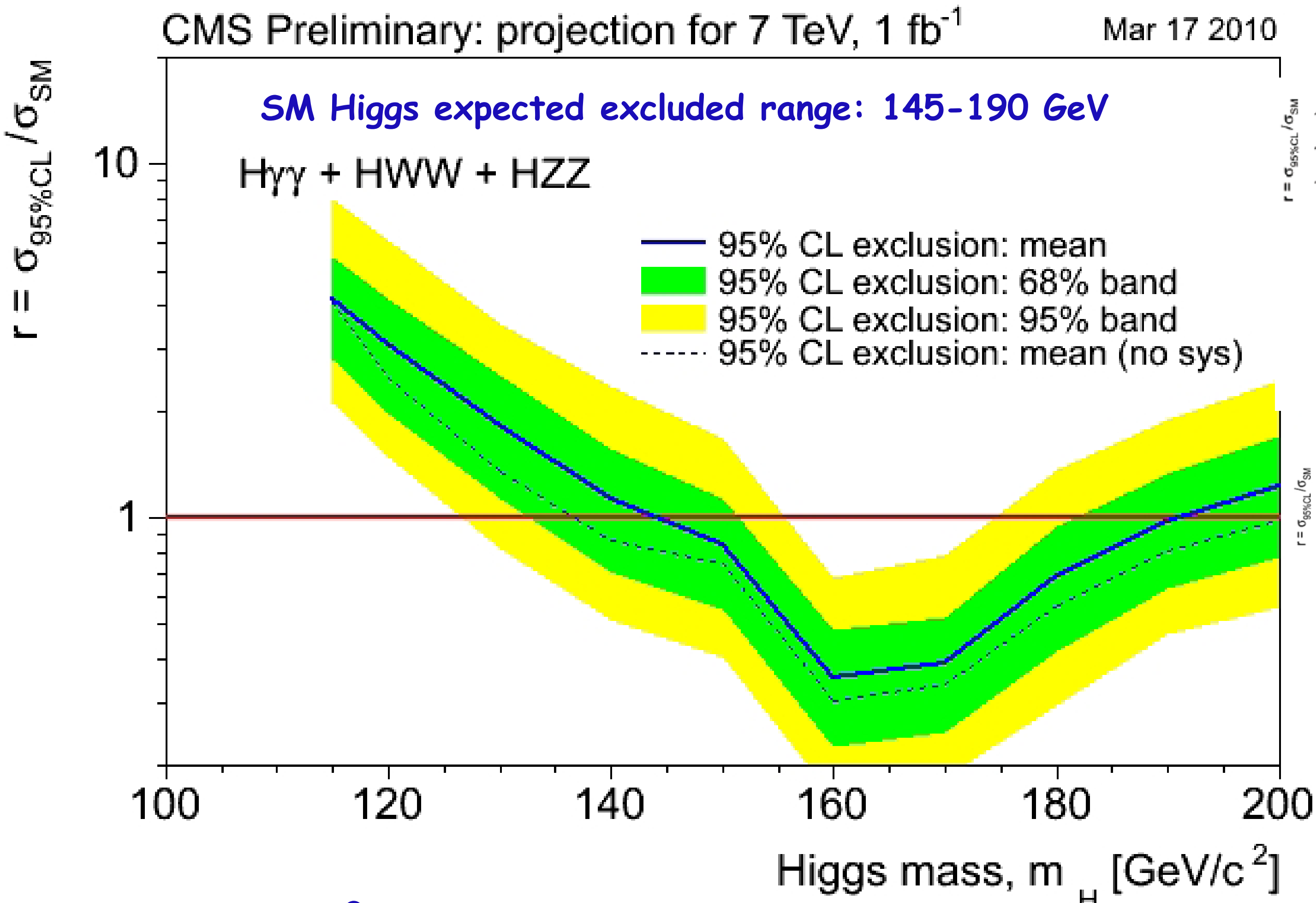


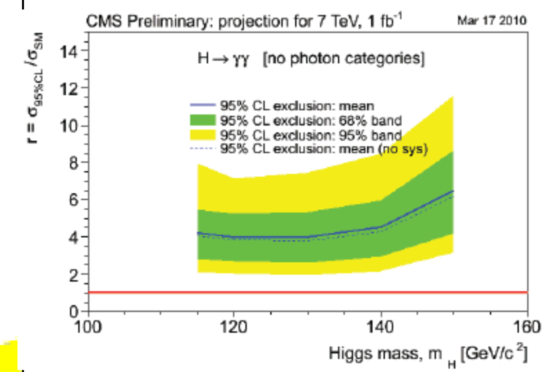
H->WW dominant decay mode for m_H>140 GeV
(BR ≈ 1 at m_H = 160 GeV)

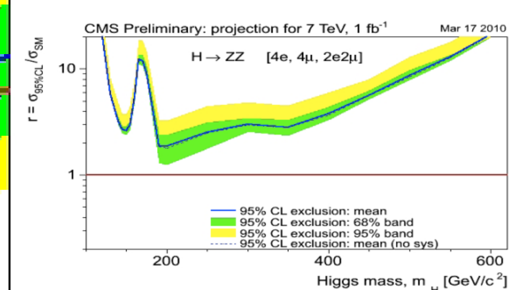
- ✓ bb suffers from the huge QCD background
- ✓ $\tau+\tau-$ is promising at low m_H values
- ✓ $\gamma\gamma$ is relatively easy to detect, but very low BR
- ✓ ZZ has a lower BR than WW, but a clearer signature

SM Higgs Boson

Inclusive Channels for 7 TeV, 1fb^{-1}

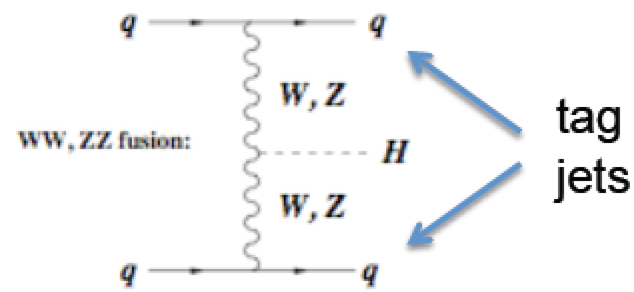






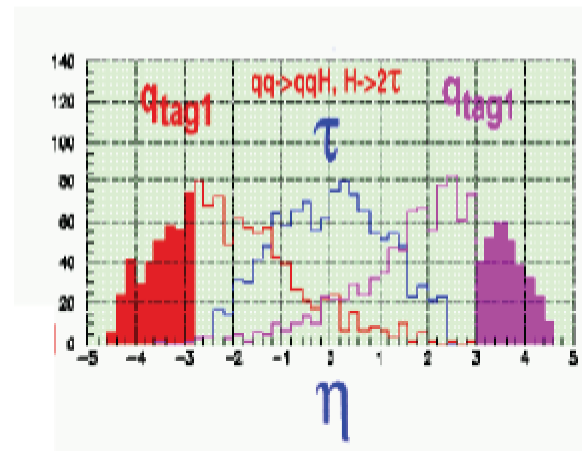
x2:
- SM Higgs expected excluded range approx: 140-200 GeV
- Discovery range approx: 160-170 GeV

VBF $H \to \tau^+\tau^-$

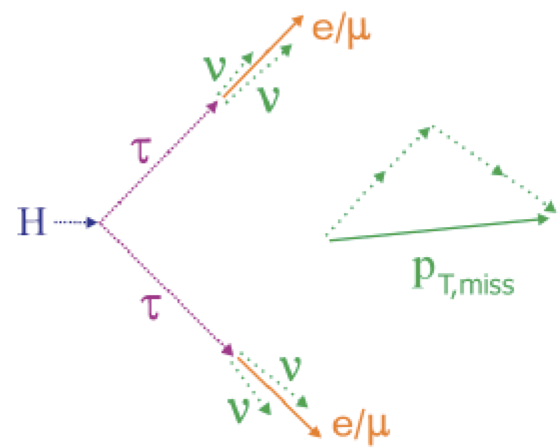


$H \to \tau^+\tau^-$ is promising at low m_H values

- 3 final states: lepton-lepton, lepton-hadron, hadron-hadron
- Signature:
  - ✓ 2 leptons or τ-jets in the central region
  - ✓ MET
  - ✓ 2 forward tag jets in opposite hemispheres (used as tag)

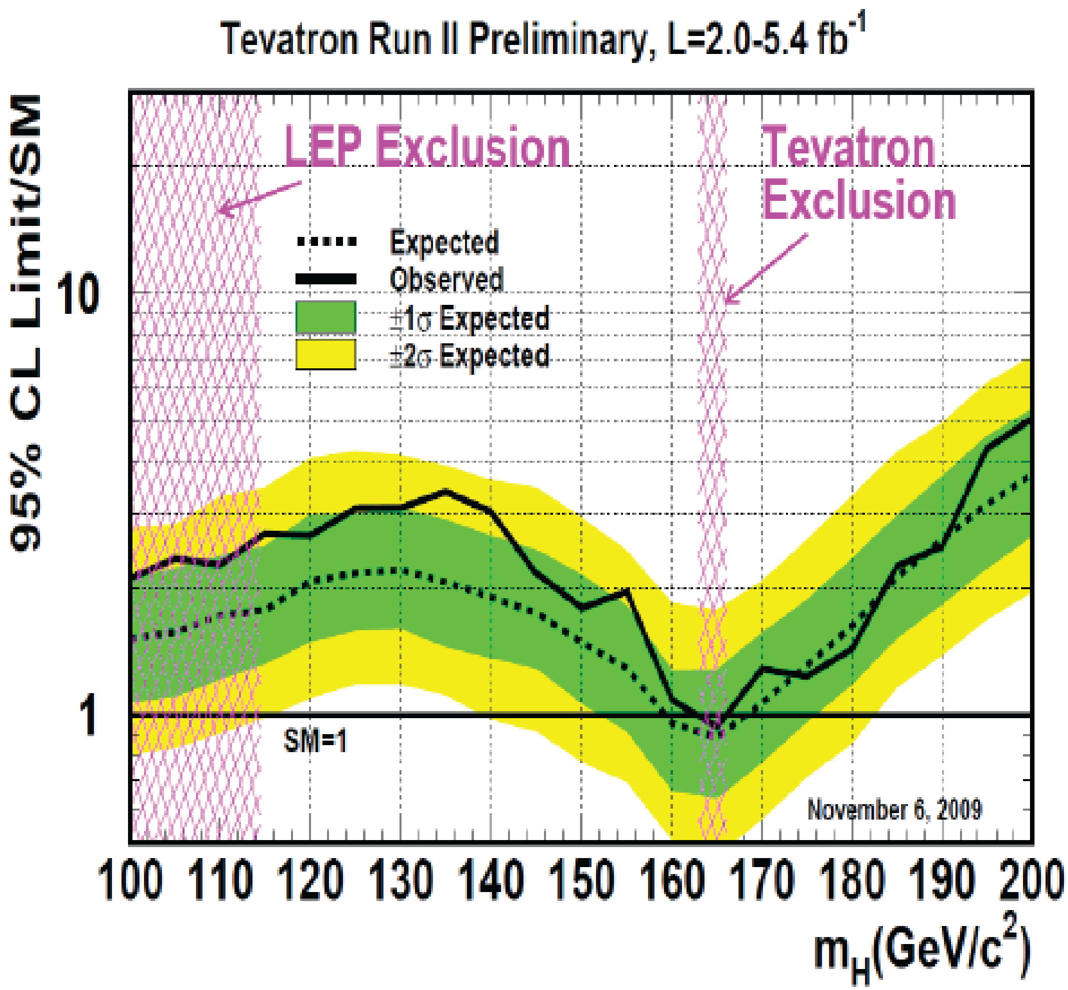


- The invariant mass $M(\tau\tau)$ can be calculated in the collinear approximation: ν's collinear to τ's



- Backgrounds:
  - ✓ QCD, reduced with the Central Jet Veto
  - ✓ W/Z + jets
  - ✓ $Z/\gamma^* \to \tau^+\tau^-$, estimated from $Z \to \mu^+\mu^-$
  - ✓ tt suppressed by performing b-jet ID

SM Higgs Boson at Tevatron



arXiv:1001.4162

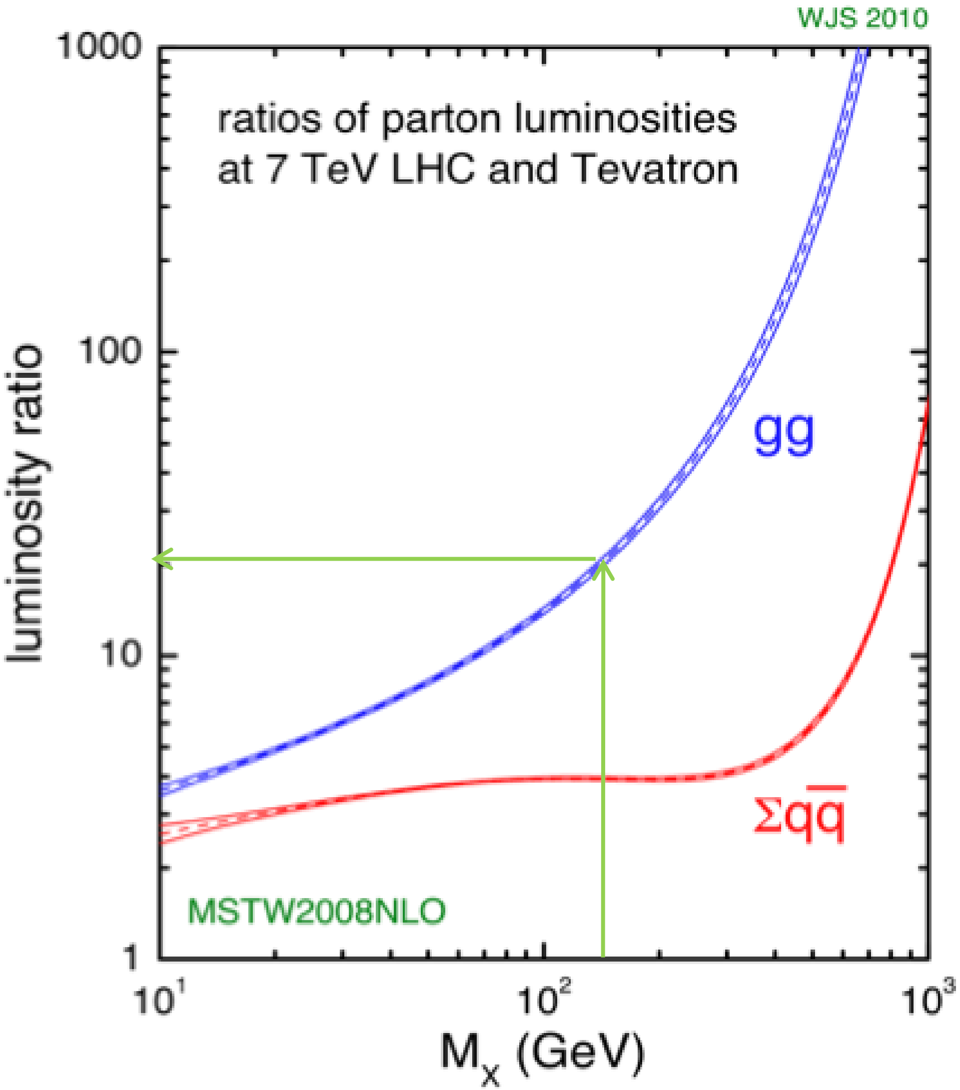
LHC & Tevatron : A Comparison

For M_X > 140 GeV:

- ❑ gg → H at 7 TeV > x15 that at Tevatron
- ➢ Higher rate for Higgs production

- ❑ Irreducible Higgs background (WW, ZZ) originate from qqbar which rises relatively slowly

⇒ S/N rises , LHC competitive @ 1fb^{-1}



For M_X < 140: slow rise in qqbar

- ❑ Higgstrahlung (pp → VH) rate at 7 TeV not much larger than Tevatron
- ❑ Major backgrounds are W/Zbbbar & ttbar which rise sharply due to rapid rise in gg ⇒ smaller rate & S/N
- ❑ gg → H → γγ favored in production but Br(H → γγ) ≈ 0.2%
  ⇒ tiny signal over large QCD γγ

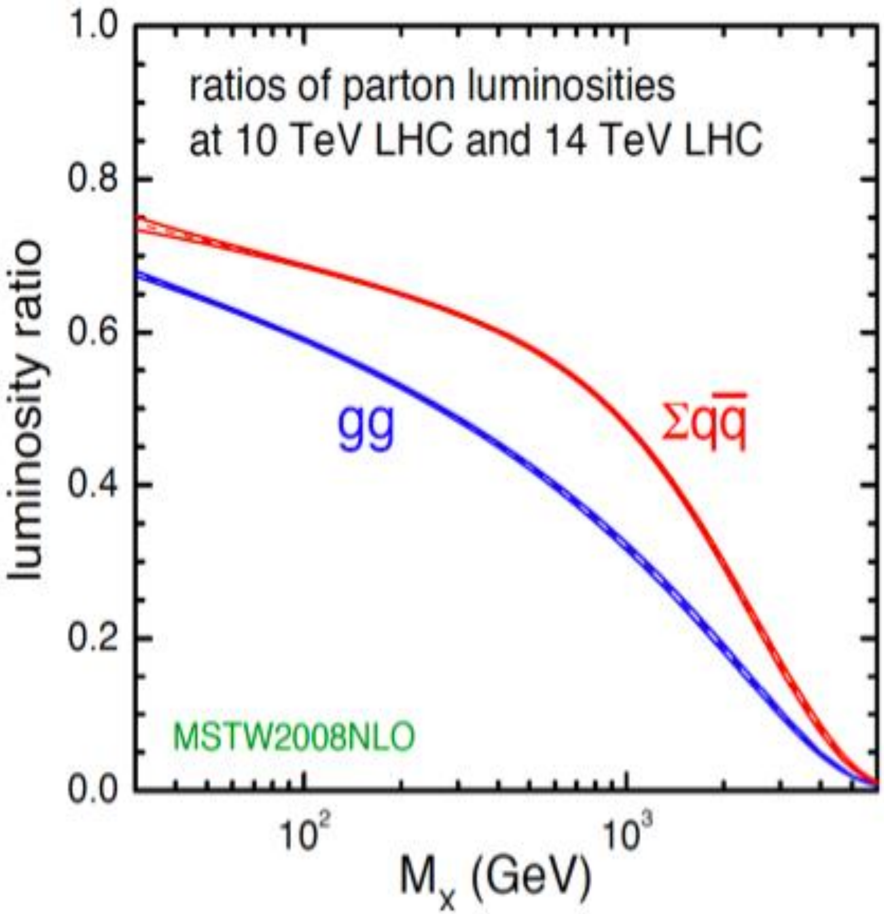
Conclusions

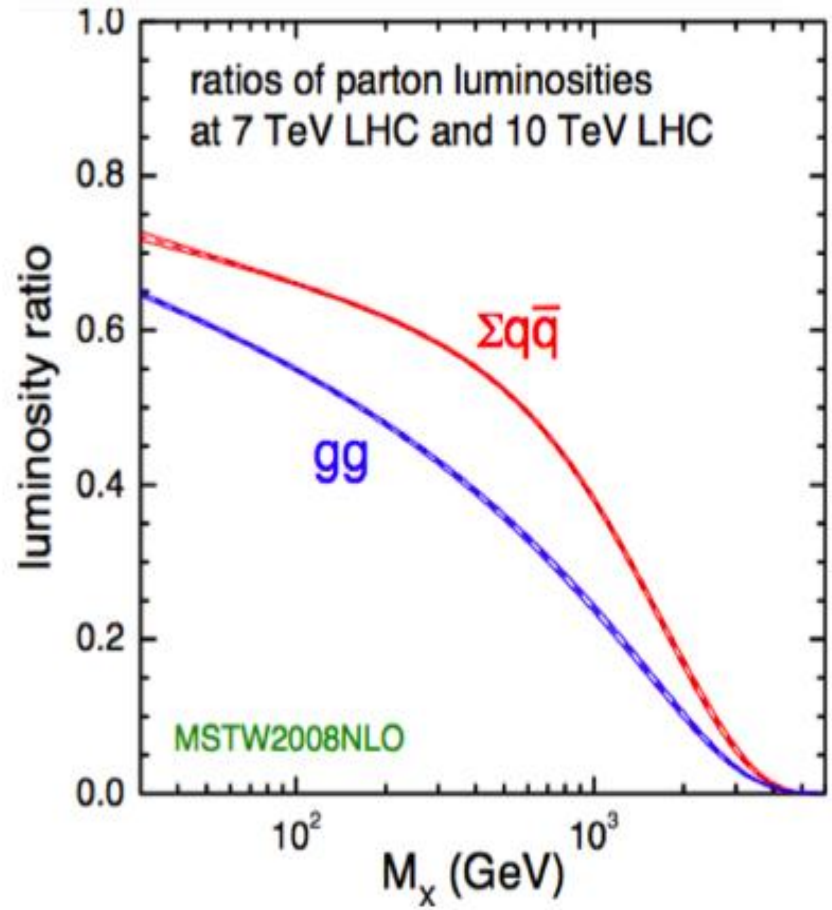
- The full CMS Detector was operational for the first LHC beams in 2008
- CMS could profit from extensive Cosmic Data taking campaigns in 2008 and 2009 for commissioning
- Data taking with LHC pilot runs in December 2009 was a great success, with performances validated within hours, and extensive analyses performed within one day !
- The experiment currently runs with LHC collisions at $\sqrt{s}$ = 7 TeV at a peck luminosity of ~ 2×10^{29} $cm^{2}sec^{-1}$ with 13 bunches…
  and ≈ 100 EWK Boson candidates observed !
- A first production of physics results (EWK, QCD, …) is expected by ICHEP 2010 (with 1-10 pb^{-1} integrated luminosity ?)
- Di-boson observation and first significant constraints (or hints) on the SM Higgs boson are expected in 2011

Special thanks to Simone Gennai for providing me some very useful slides on Particle Flow.

Backup slides

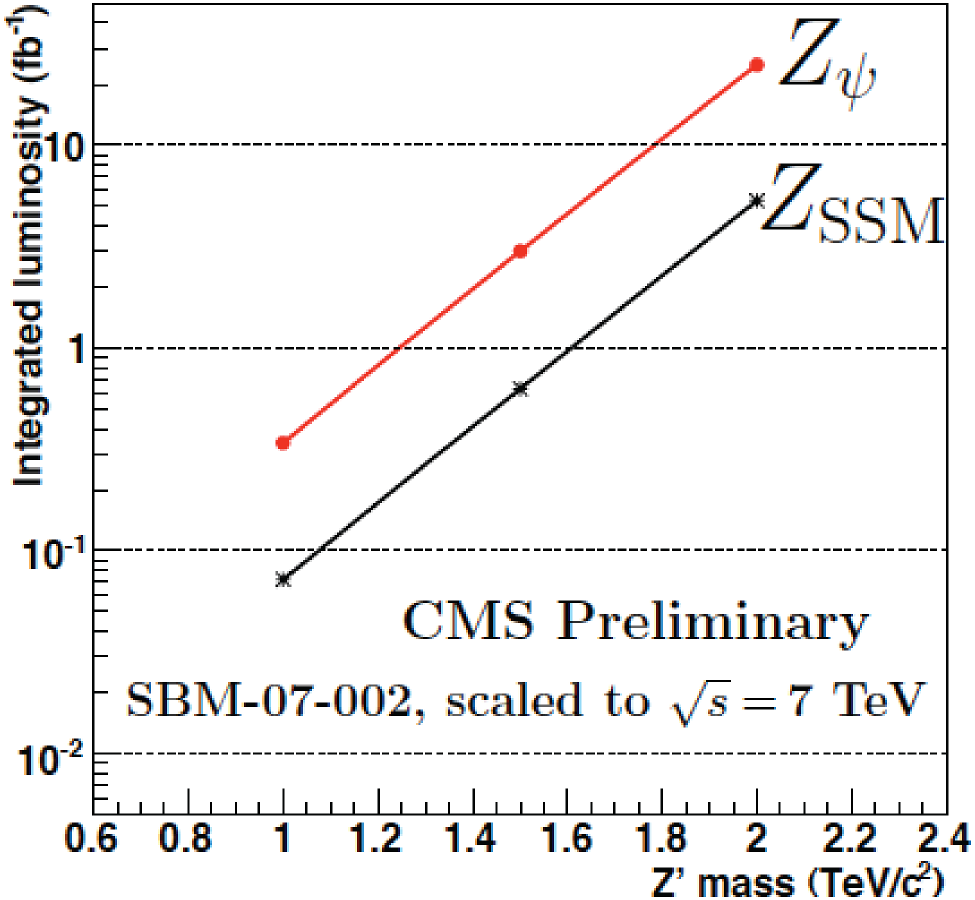
Parton Luminosities





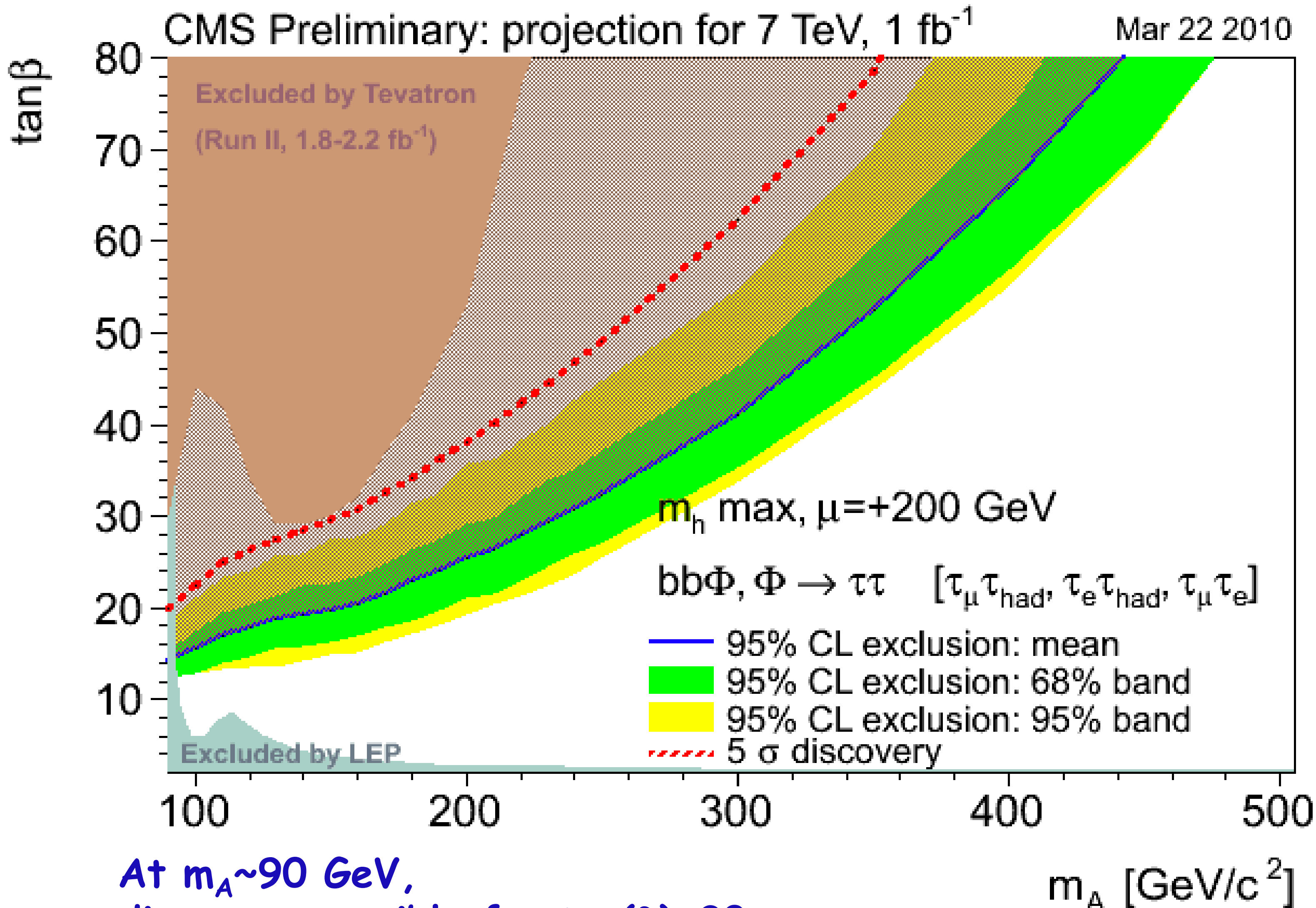
High mass dilepton resonances

5σ discovery reach as a function of mass
μμ channel
(scaled from 10 TeV to 7 TeV)



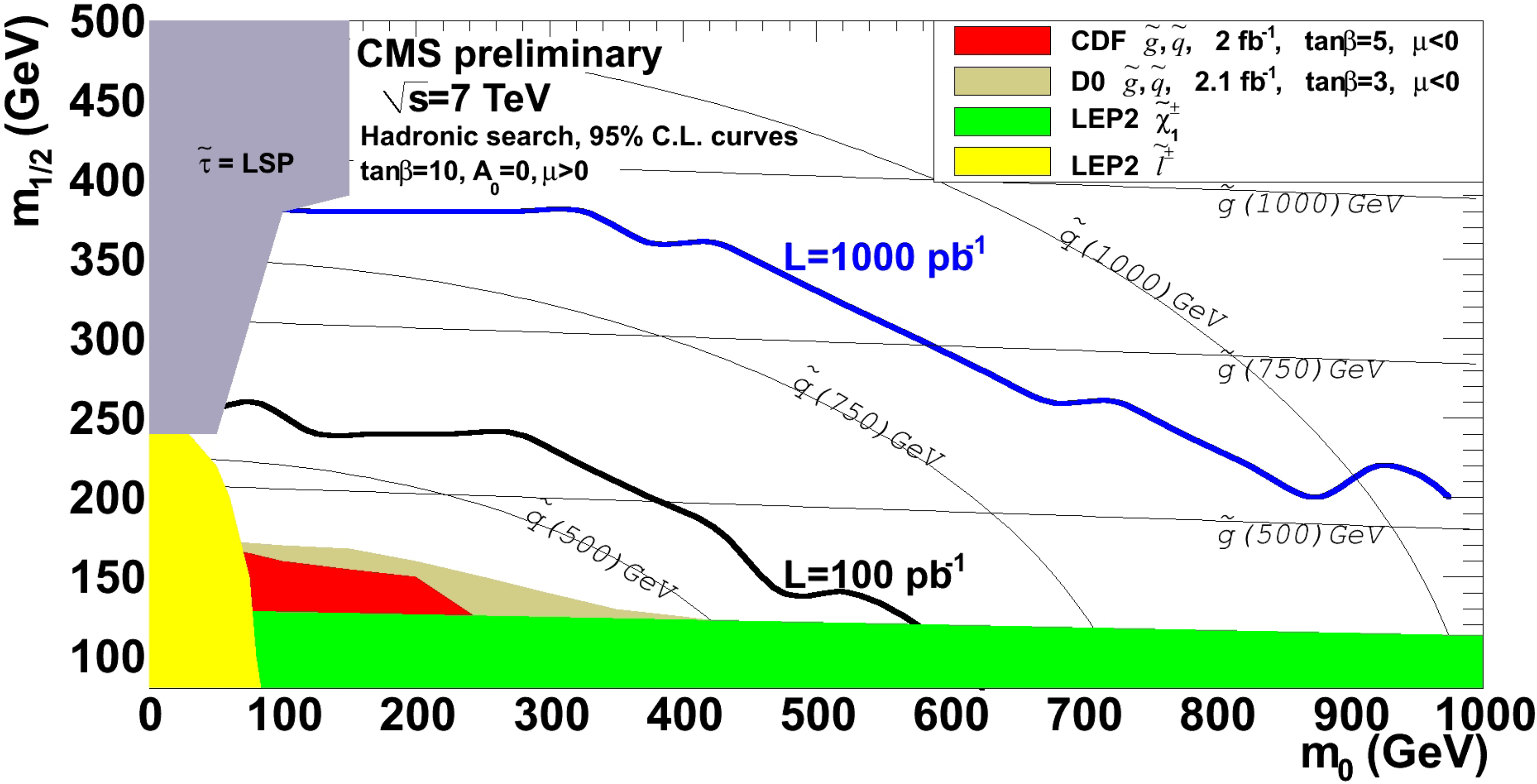
Already sensitivity at 1 TeV with ~ 100 pb^{-1}

MSSM Higgs Boson: pp → bbΦ, Φ →ττ



At m_A~90 GeV,
discovery possible for tan(β)>20,
exclusion for tan(β)~15

Supersymmetry – Jets + MET



95% exclusion limits for inclusive searches with jets and missing energy expressed in the mSugra parameter space
assumes 50% syst. uncertainty on backgrounds