Getting Ready for the LHC

Albert De Roeck
CERN

Les Rencontres de Physique de la Vallée d'Aoste

Contents

- Introduction: The LHC machine & schedule
- The CMS and ATLAS experiment at day one
- Preparing for physics at ATLAS and CMS
- First physics at the LHC
- Summary

(*) ALICE, LHCb and TOTEM well on track too…

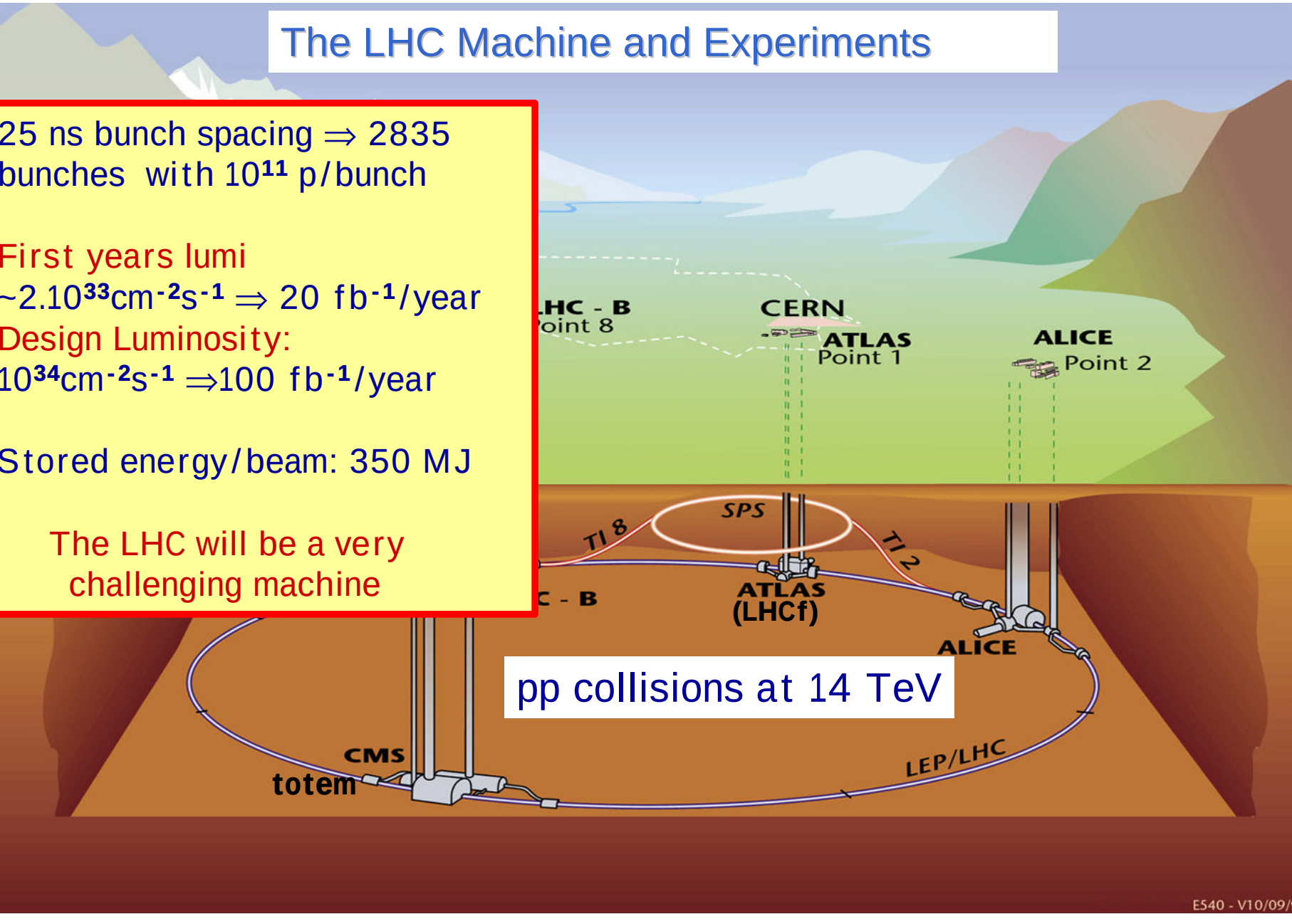
The LHC Machine and Experiments

25 ns bunch spacing ⇒ 2835 bunches with 10^{11} p/bunch

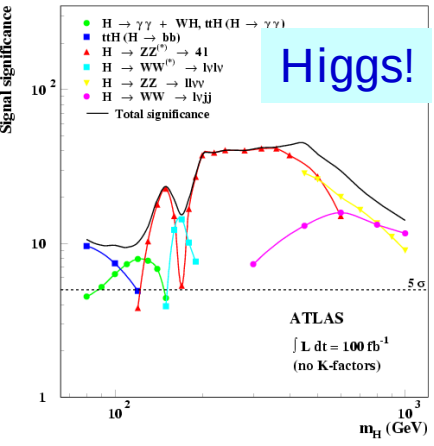
First years lumi
~$2.10^{33}cm^{-2}s^{-1}$ ⇒ 20 fb^{-1}/year
Design Luminosity:
$10^{34}cm^{-2}s^{-1}$ ⇒100 fb^{-1}/year

Stored energy/beam: 350 MJ

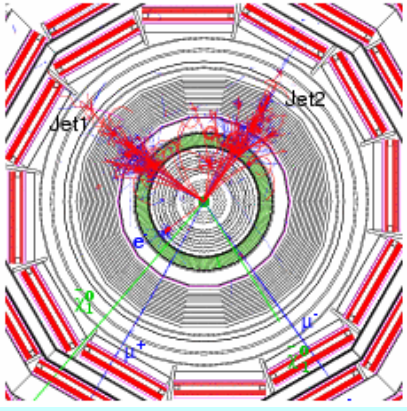
The LHC will be a very challenging machine



Physics at the LHC: pp @ 14 TeV

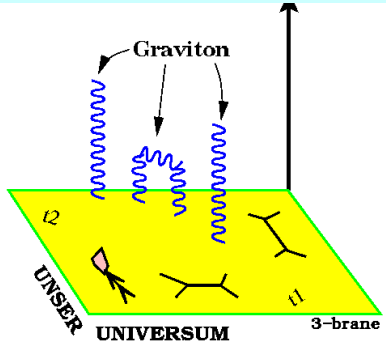


Higgs!

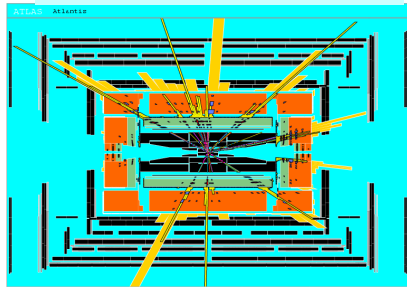


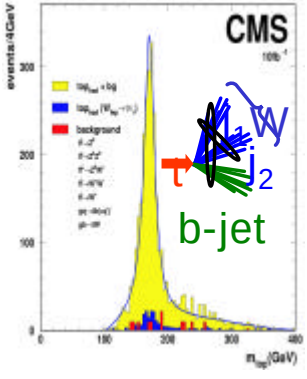
Supersymmetry?

Extra Dimensions?

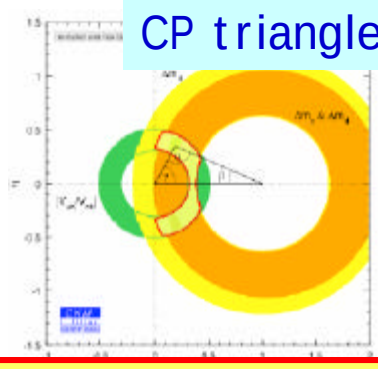


Black Holes???



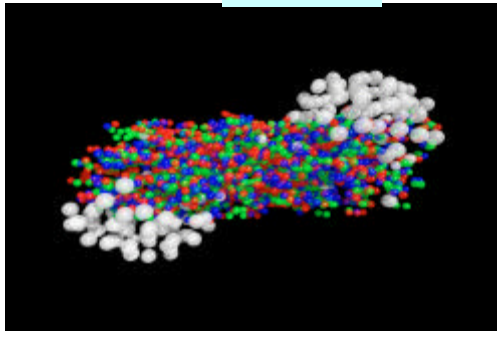


Precision measurements e.g top!



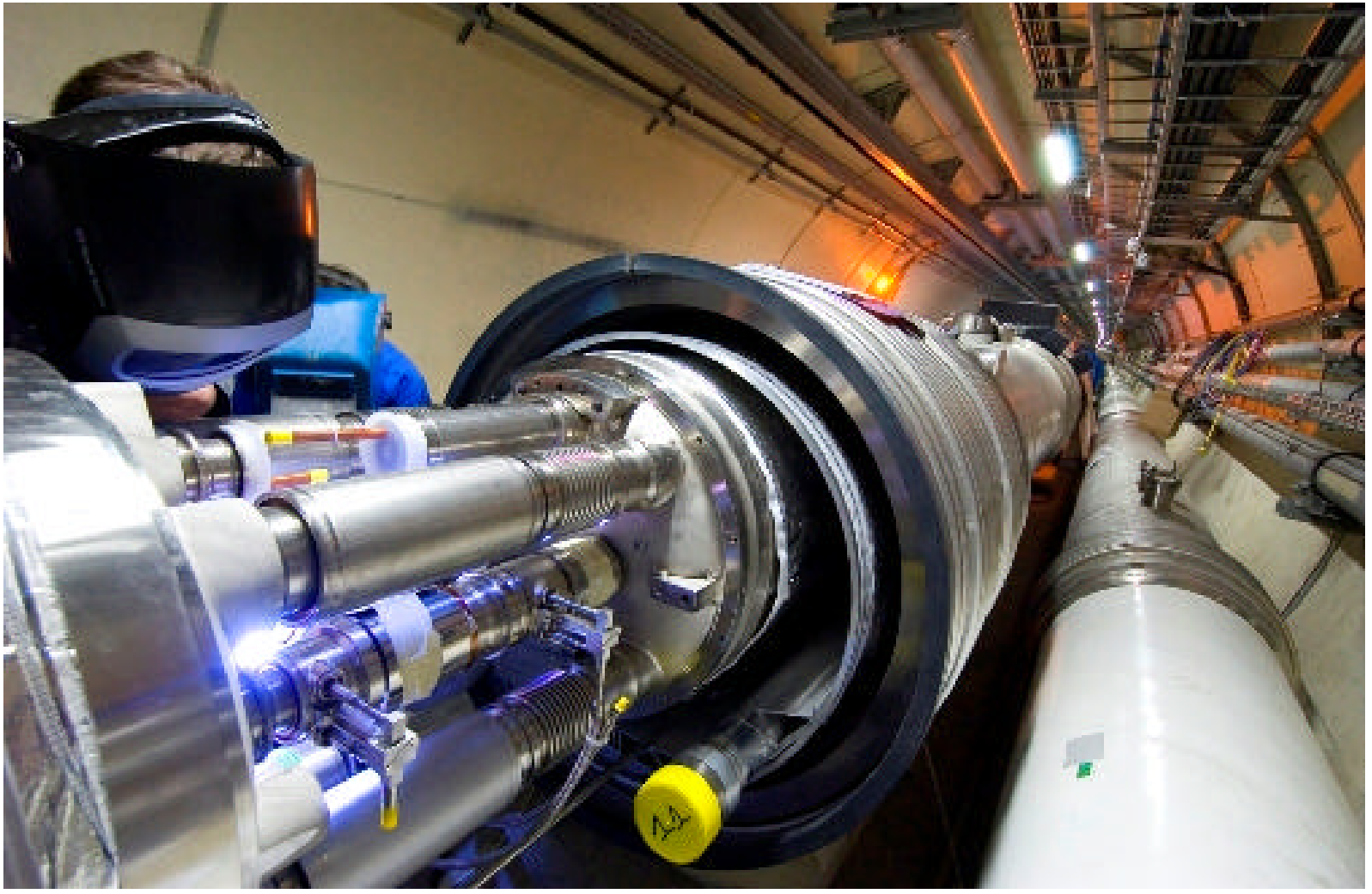
CP triangle!

QGP?



- LHC will explore directly the highly-motivated TeV-scale and say the final word about the SM Higgs mechanism and many TeV-scale New Physics predictions
- Also LHC will be a great machine for: QCD, B-physics, Heavy Ions, EW precision

The LHC is Coming!

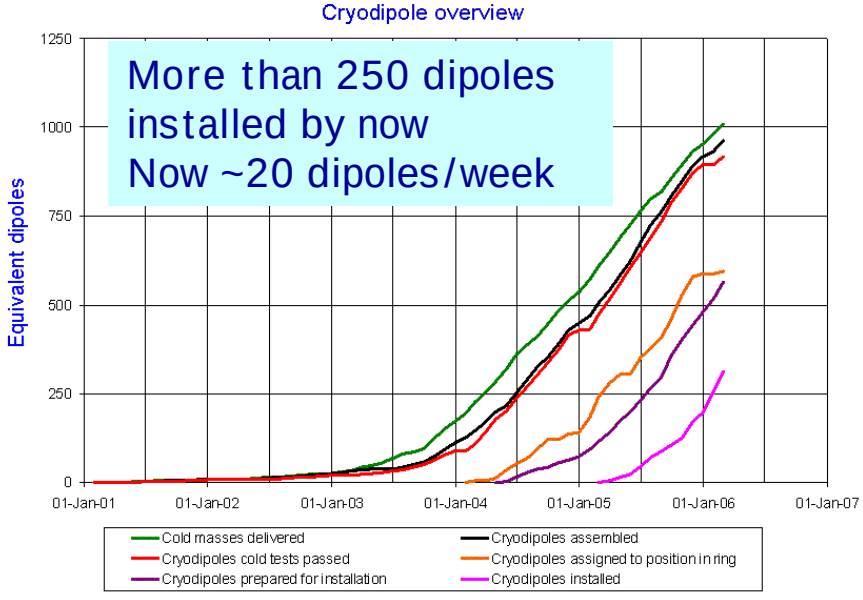


The LHC Progress & Schedule

Crucial part: 1232 superconducting dipoles
Can follow progress on the LHC dashboard
http://lhc-new-homepage.web.cern.ch/lhc-new-homepage/

LHC Progress Dashboard

Accelerator Technology Department



The LHC Schedule(*)

- LHC will be closed and set up for beam on 1 July 2007
- First beam in machine: August 2007
  LHC commissioning will take time!
- First collisions expected in October/November 2007
  Followed by a short pilot run
  O(10) pb^{-1} ?
- First physics run in 2008
  one to a few fb^{-1}?
- Physics run in 2009 +...
  10-20 fb^{-1}/year $\Rightarrow$100 fb^{-1}/year

(*) eg. M. Lamont et al, April 2005.
Achtung! Lumi estimates are mine, not from the machine
Update expected in June-July 2006

Conclusions from Lyn Evans' recent presentation at the CERN Scientific Policy Committee, on 12th December 2005

(Available via the official LHC Web: http://lhc.web.cern.ch/lhc/)

All key objectives have been reached for the end of 2005

- End of repair of QRL, reinstallation of sector 7-8 and cold test of sub -sectors A and B
- Cool-down of full sector 8-1
- Pressure test of sector 4-5
- Endurance test of full octant of power converters

Magnet installation rate is now close to 20/week, with more than 200 installed

This, together with interconnect work, will remain the main bottleneck until the end of installation

First Collisions: Fall 2007?

43 on 43 Bunches with 3 to 4 x 10^{10} ppb to 7 TeV

- No parasitic encounters
  - No crossing angle, No long range beam, Larger aperture
- Instrumentation (testing)
- Good beam for RF, Vacuum…
- Lower energy densities
  - Reduced demands on beam dump system
  - Collimation
  - Machine protection
- Luminosity 2 x 10^{31} $cm^{-2}s^{-1}$ at a β^* of 1 m

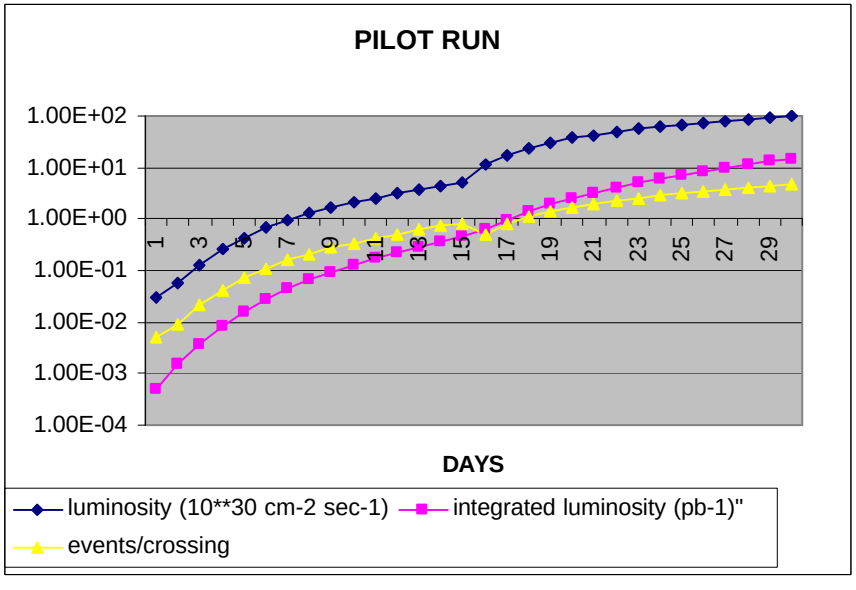
Lumi numbers are my private guesses. Not official numbers released by the machine group

Pilot run ⇒ maybe a few weeks of collisions in 2007: ~10-20 pb^{-1}?

2008: 75 nsec + low intensity 25ns ⇒ expect O(1) fb^{-1}
2009: 25ns half intensity ⇒ expect 10-20 fb^{-1}

Expected Evolution of LHC Parameters

	Pilot run 2007	First Physics 2008
Number of bunches	43→156	936→2808
β^*	18 m→2 m	2 m→ 0.55 m
Protons per bunch	$10^{10} \rightarrow 4 \times 10^{10}$ (10^{11})	4×10^{10}
Luminosity	$3 \times 10^{29} \rightarrow 2 \times 10^{31}$ (10^{32})	$10^{32} \rightarrow 2 \times 10^{33}$
Integrated Luminosity	10 pb^{-1}	< 5 fb^{-1}



For an efficiency = 20%

Total collect luminosity

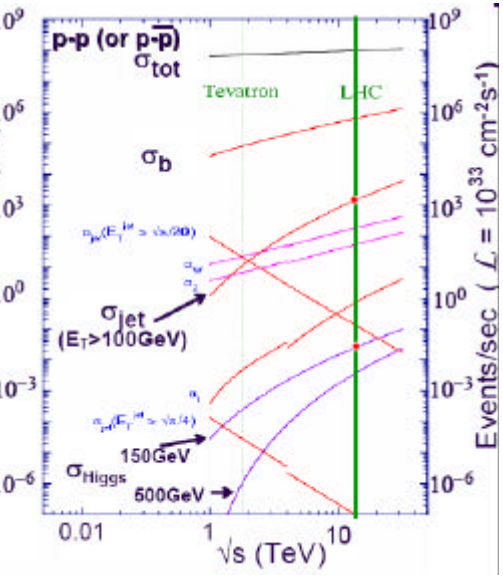
~10-20 pb^{-1}

Note: Already pile up…

G. Rolandi

Pilot Run Challenge

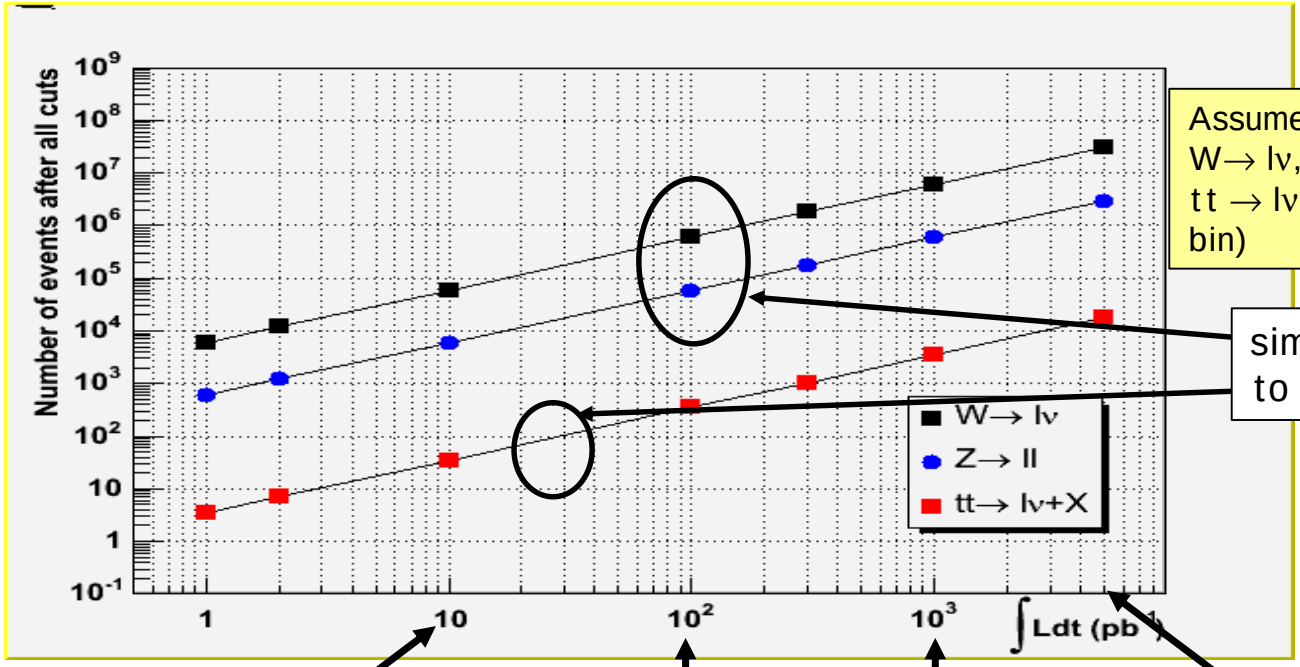
- The pilot run could provide a large statistics of interesting data
- We have to make sure that we can make the best use of these data for
  - detector performance/detector commisioning
  - physics measurements and feedback.



Process	σxBR	ε (estimate)	Events selected in 10 pb^{-1}
$W \rightarrow l\ \nu$	20 nb	~20%	~40000
$Z \rightarrow l\ l$	2 nb	~20%	~4000
$t\bar{t} \rightarrow l\ \nu + X$	370 pb	~1.5%	<100
Jet E_t>25GeV	400 μb	100%	~4×10^9 x prescale factor
Jet E_t>140GeV	340 nb	100%	~3.4×10^6
Minimum bias	100 mb		~10^{12} x prescale factor

Event Rates at Start-up

F. Gianotti



Assumed selection efficiency:
W→ lν, Z→ ll : 20%
tt → lν+X : 1.5% (no b-tag, inside mass bin)

similar statistics to CDF, D0 today

10 pb^{-1} ≡ 1 month at 10^{30} + < 2 weeks at 10^{31}, ε=50%

100 pb^{-1} ≡ few days at 10^{32} , ε=50%

1 fb^{-1} ≡ 6 month at 10^{32}, ε=50%

5 fb^{-1} ≡ 3 month at 10^{32} + 3 month at 10^{33}, ε=50%

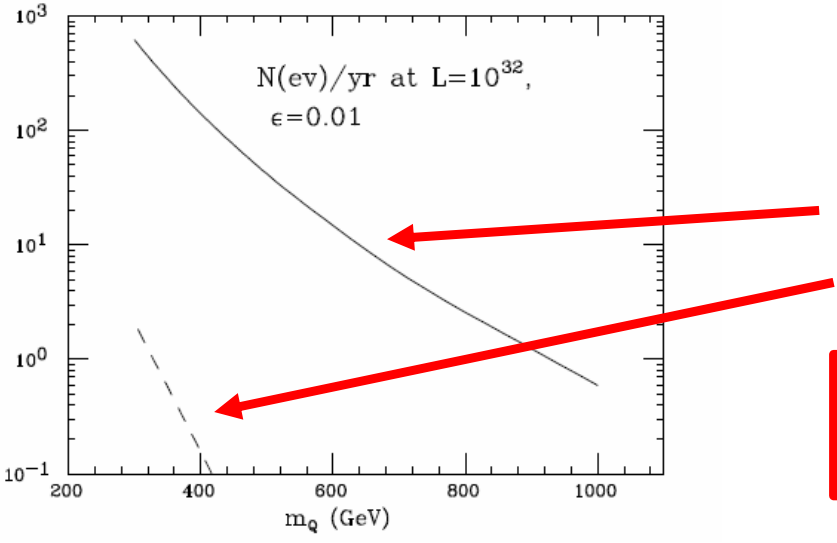
® end 2007 ?

® end 2008 ?

Historical perspective

1982: first run of UA1/UA2 (CMS energy 10x higher than ISR)
30 days with $5 \bullet 10^{28} cm^{-2} s^{-1}$ (~ 1% of final one) $\Rightarrow$ 20 nb^{-1}
$\Rightarrow$ W,Z Discovery!

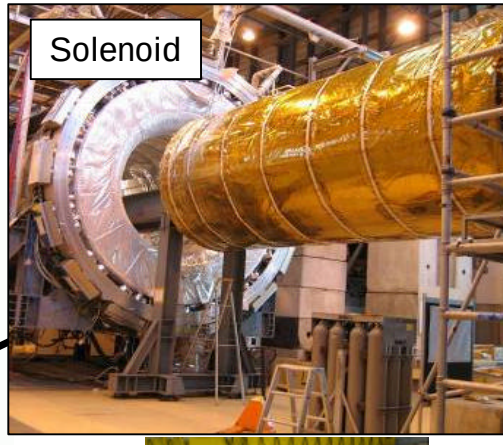
1987: first run of CDF (CMS energy 3x times higher than SppS)
30 days with $5 \bullet 10^{28} cm^{-2} s^{-1}$ (~ 1% of design one) $\Rightarrow$ 20 nb^{-1}
Þ No Early discoveries

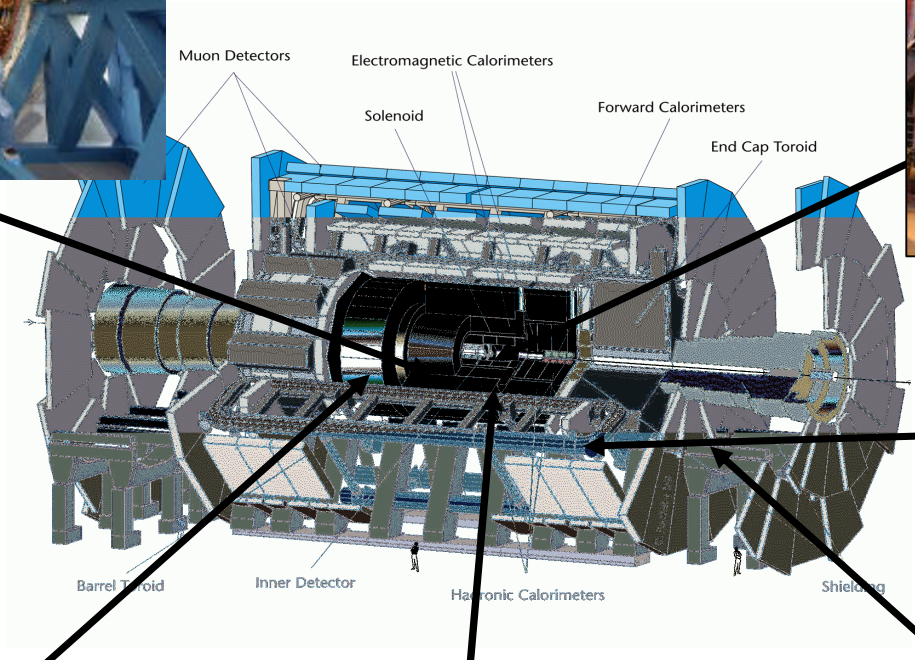


Production rate for new heavy (s)quarks as function of mass for
LHC (14TeV)
Tevatron (2TeV)

LHC energy 7 times higher than Tevatron $\Rightarrow$???

ATLAS



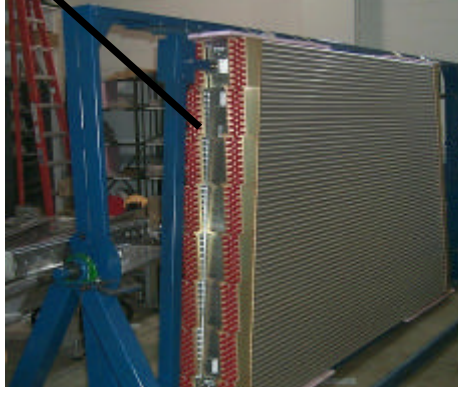


Barrel LAr ECAL

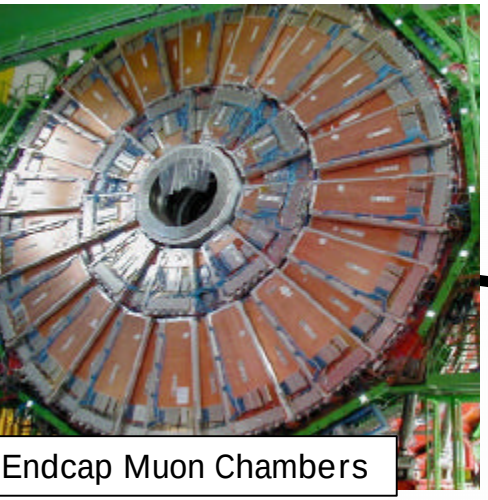
Length : ~40 m
Radius : ~10 m
Weight : ~ 7000 tons

Barrel coil cryostat

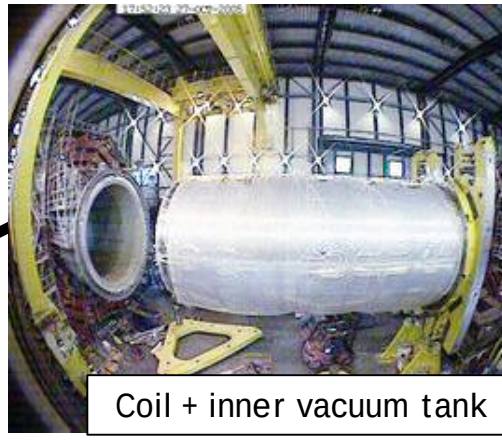
TRT end-cap wheel



CMS

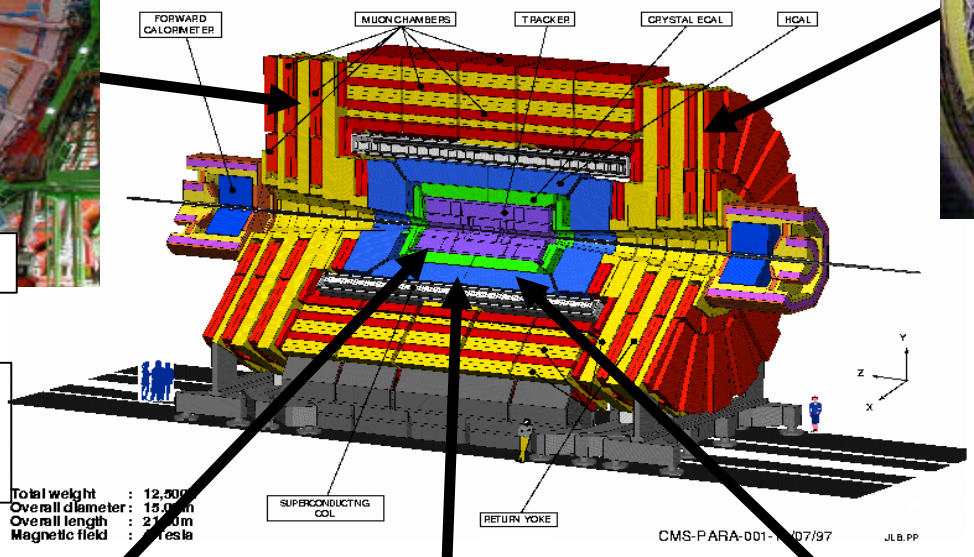


Endcap Muon Chambers

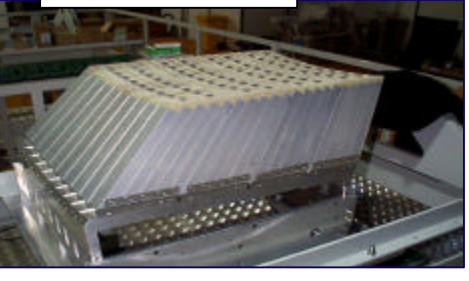


Coil + inner vacuum tank

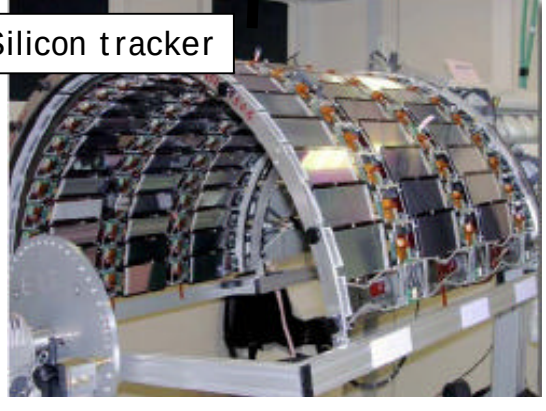
Length : ~20 m
Radius : ~7 m
Weight : ~ 13000 tons



ECAL crystals



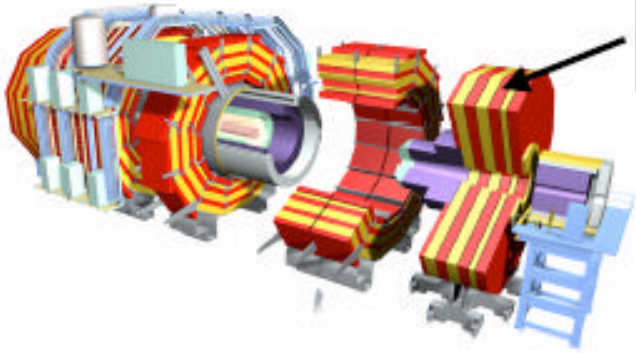
Silicon tracker



Barrel HCAL

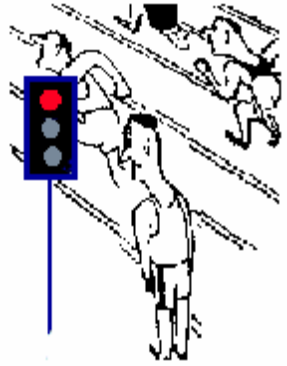
Start-up Detectors

❷ Which detectors the first year ?



RPC over $|\eta|<1.6$ (instead of $|\eta|< 2.1$)
4^{th} layer of end-cap chambers missing

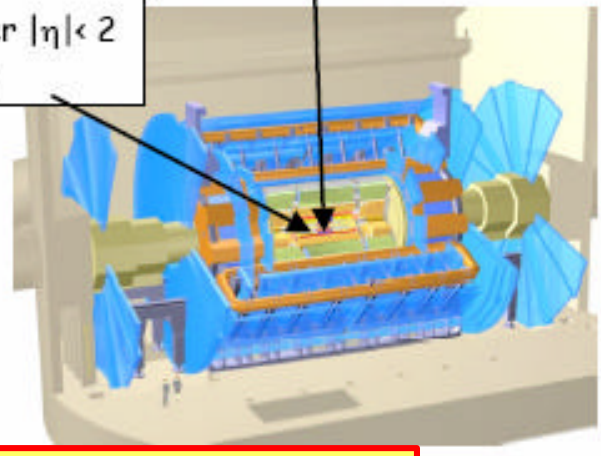
Pixels and end-cap ECAL
installed during first shut-down



2 pixel layers/disks instead of 3 ?

Detectors, including LHCb and Alice will be fairly complete at start-up

TRT acceptance over $|\eta|< 2$
(instead of $|\eta|< 2.4$)

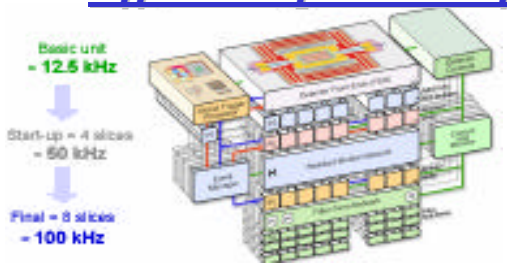


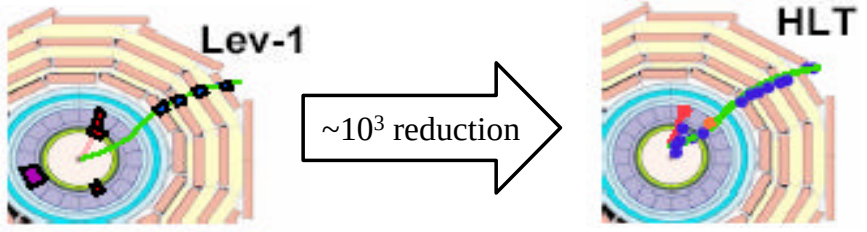
Both experiments:
deferrals of high-level Trigger/DAQ processors
→ LVL1 output rate limited to
~ 50 kHz CMS (instead of 100 kHz)
~ 40 kHz ATLAS (instead of 75 kHz)

⇒ Complete detector instalation and prepare for detector commissioning with cosmics, single beams etc.

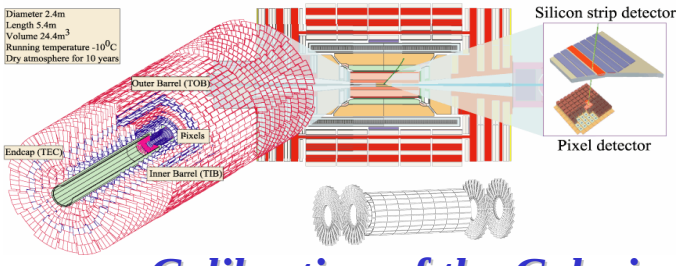
Major Commissioning Challenges

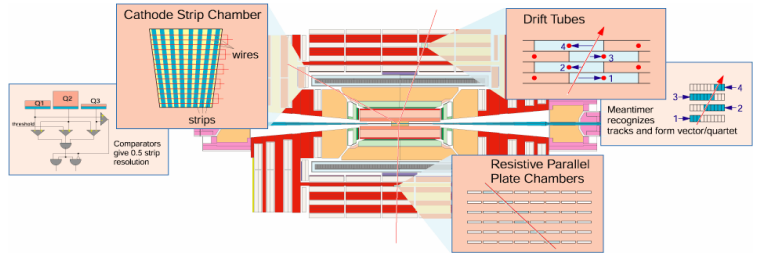
Efficient operation of Trigger (Level1/HLT) and DAQ System



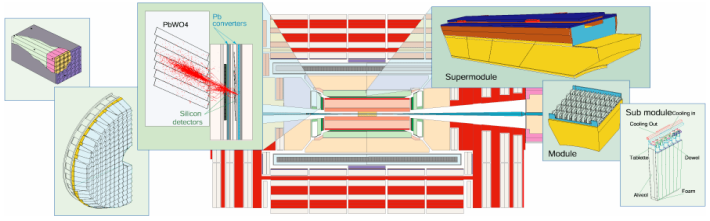


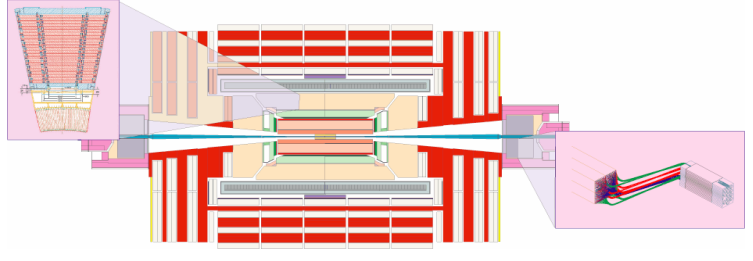
Alignment of the tracking devices Tracker(PIXEL,Strip) and Muon System





Calibration of the Calorimeter Systems ECAL and HCAL





→form the base for the “commissioning of physics tools” like b and τ tagging, jets, missing E_T …

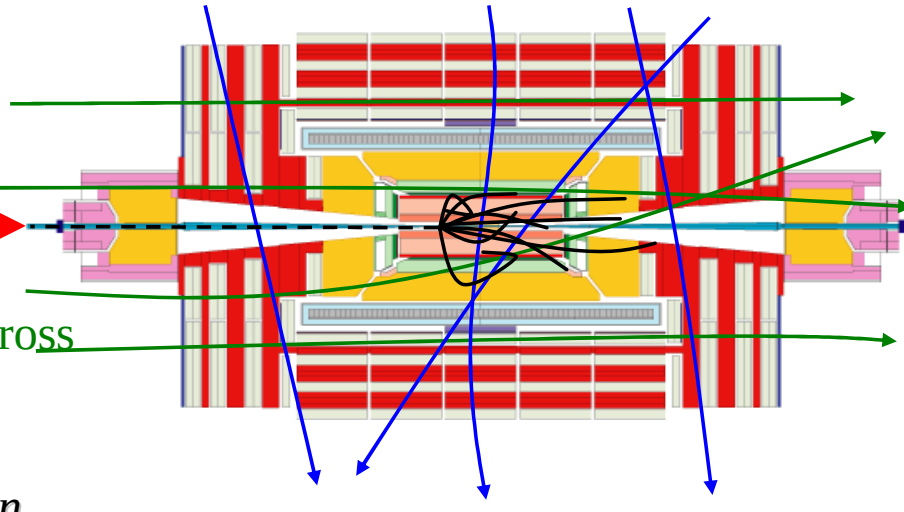
Calibrating/Alignment Before Collisions

Experiments will have ~3-4 months before collisions

Cosmic Muons

High energetic muons that traverse the detector vertically

→particular useful for alignment and calibration - *barrel region.*



Beam Halo Muons (Hadrons)

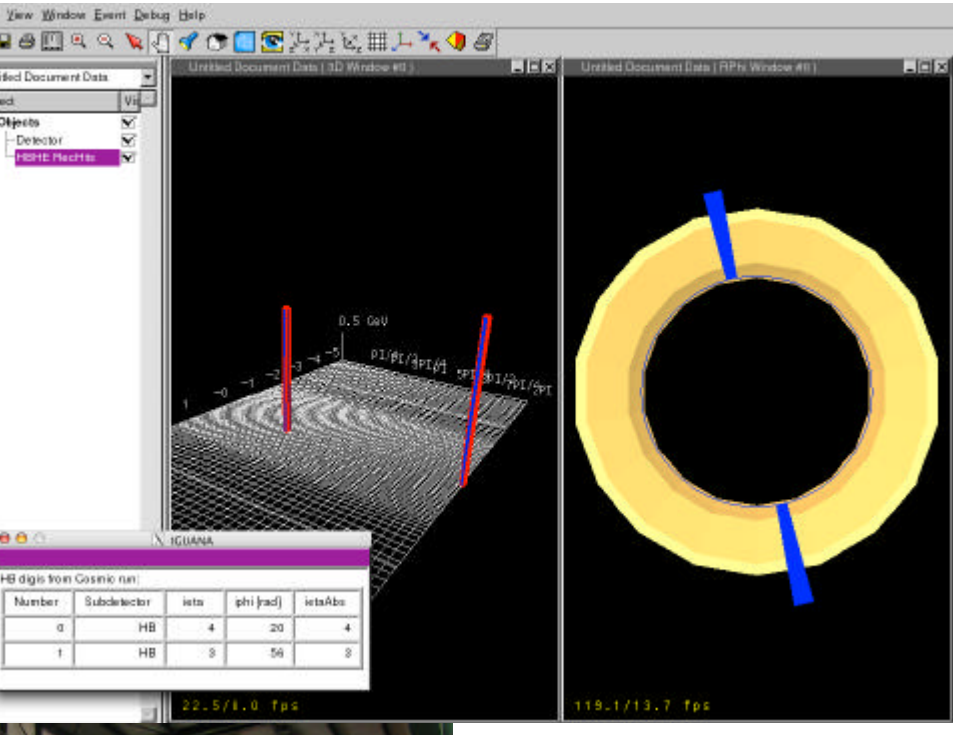
Machine induced secondary particles that cross the detector almost horizontally

→particular useful for alignment and calibration - *endcap region.*

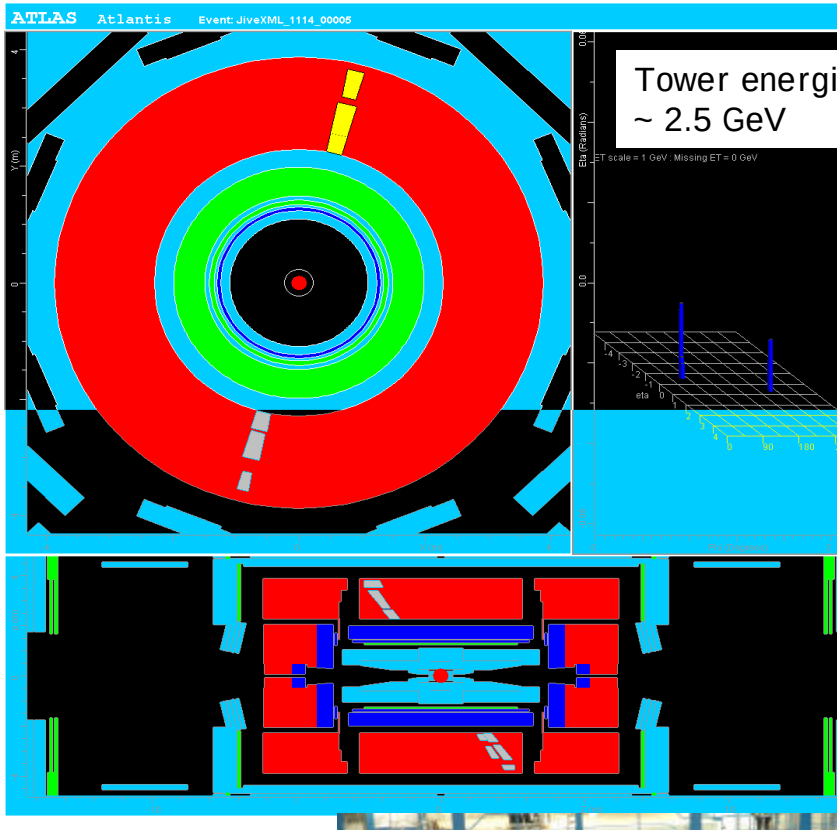
Beam Gas Interactions

Proton-nucleon interaction in the active detector volume (7TeV→E_{cm}=115 GeV)
→resemble collision events but with a rather soft p_T spectrum (p_T<2 GeV)

All three physics structures are interesting for alignment, calibration, gain operational experience, dead channels, debug readout, etc …



Cosmic muons observed by CMS at IP5 (recorded by hadron barrel calorimeter)

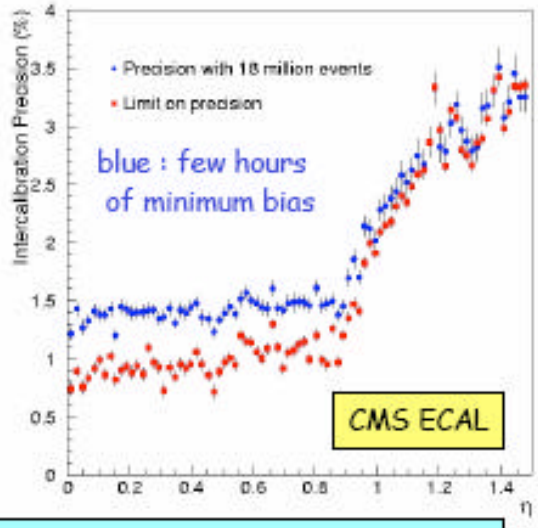


Cosmic muons observed by ATLAS in the pit (recorded by hadron Tilecal calorimeter)

Detectors at Start-up for Physics

Which detector performance on day one ?

A few examples and educated guesses
based on test-beam results and simulation studies



	Expected performance day 1	Physics samples to improve (examples)
ECAL uniformity	~ 1% (ATLAS), 4% (CMS)	Minimum-bias, Z→ ee
e/γ scale	1-2 % ?	Z → ee
HCAL uniformity	2-3 %	Single pions, QCD jets
Jet scale	< 10%	Z (→ ll) +1j, W → jj in tt events
Tracking alignment	20-500 μm in Rφ ?	Generic tracks, isolated μ , Z → μμ

Ultimate statistical precision achievable after few days of operation. Then face systematics ….
E.g. : tracker alignment : 100 μm (1 month) → 20μm (4 months) → 5 μm (1 year) ?

Strategy at Start-up

Goal # 1

Understand and calibrate detector and trigger in situ using well-known physics samples

e.g. - $Z \rightarrow ee, \mu\mu$ tracker, ECAL, Muon chambers calibration and alignment, etc.

- $t\bar{t} \rightarrow b l\nu\, bjj$ 10^3 evts/day after cuts → jet scale from W→jj, b-tag perf., etc.

Understand basic SM physics at $\sqrt{s}$ = 14 TeV → first checks of Monte Carlos (hopefully well understood at Tevatron and HERA)

e.g. - measure cross-sections for e.g. minimum bias, W, Z, $t\bar{t}$, QCD jets (to ~ 10-20 %), look at basic event features, first constraints of PDFs, etc.

- measure top mass (to 5-7 GeV) → give feedback on detector performance

Note : statistical error negligible after few weeks run

Goal # 2

Prepare the road to discovery:

-- measure backgrounds to New Physics : e.g. $t\bar{t}$ and W/Z+ jets (omnipresent ...)

-- look at specific "control samples" for the individual channels:

e.g. $t\bar{t}jj$ with $j \neq b$ "calibrates" $t\bar{t}b\bar{b}$ irreducible background to $t\bar{t}H \rightarrow t\bar{t}b\bar{b}$

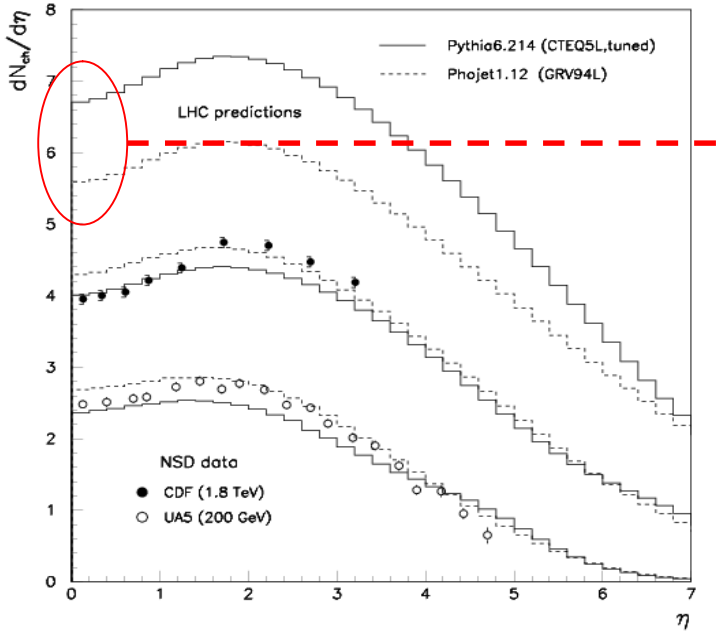
Goal # 3

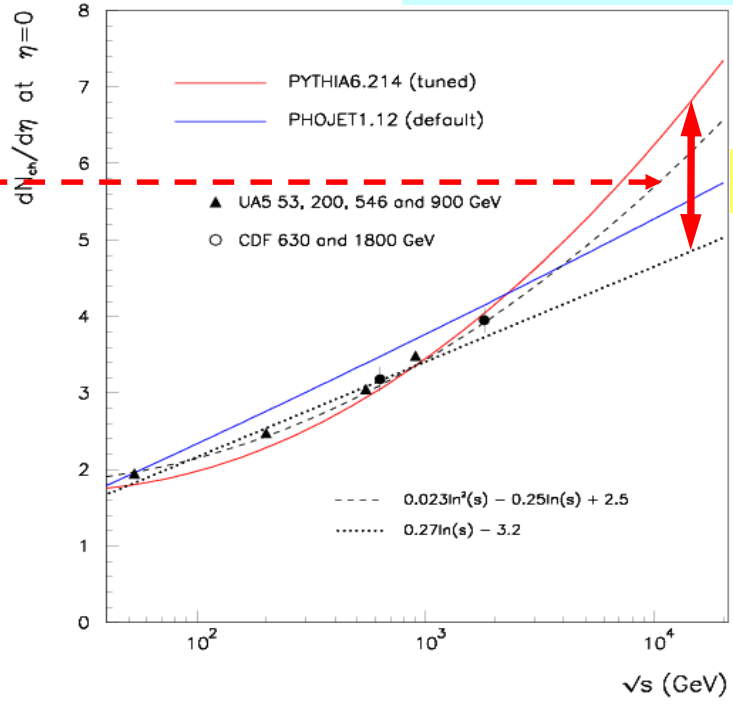
Look for New Physics potentially accessible in first year (e.g. SUSY, some Higgs ? ...)

Early Minimum-Bias Measurements

Charged particle density

The pile-up for the future





LHC?

- Energy dependence of dN/dη ?
- Vital for tuning UE model (see later)
- Only requires a few thousand events.

- **PYTHIA models favour $\ln^2(s)$;**
- **PHOJET suggests a $\ln(s)$ dependence.**

Likely the First Paper…

1 December 2007

Charged particle multiplicity in pp collisions at $\sqrt{s}$ = 14 TeV

Pilot Run

CMS collaboration

Abstract

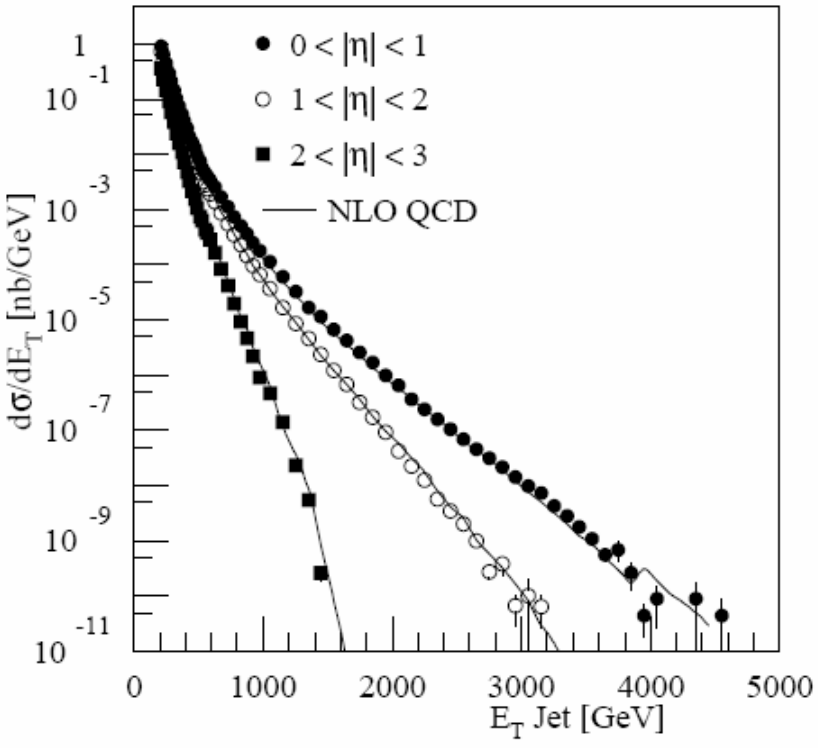
We report on a measurement of the mean charged particle multiplicity in minimum bias events, produced in the central region $|\eta| < 1$, at the LHC in pp collisions with $\sqrt{s}$ = 14 TeV, and recorded in the CMS experiment at CERN. The events have been selected by a minimum bias trigger, the charged tracks reconstructed in the silicon tracker and in the muon chambers. The track density is compared to the results of Monte Carlo programs and it is observed that all models fail dramatically to describe the data.

Submitted to *European Journal of Physics*

QCD Studies

E.g. Jet Physics

Huge cross sections:
Eg for 1 fb^{-1} ~ 10000 events with $E_T > 1$ TeV
100 events with $E_T > 2$ TeV



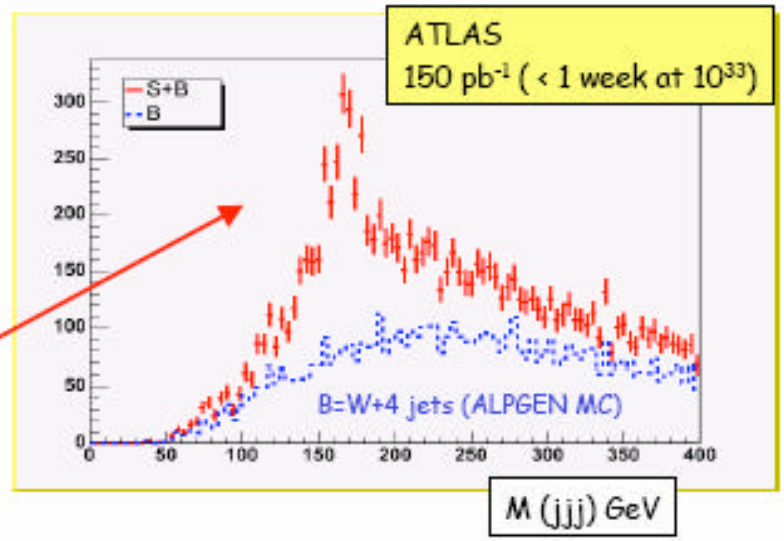
- PDFs
- Jet shape
- α_s
- New physics?

Understanding QCD at 14 TeV will be one of the first topics at LHC
Then: precise measurements of W,Z, tt, Drell-Yan production
Then: W,Z+1 jet; W,Z+2 jets etc
⇒ Use to tune Monte Carlos

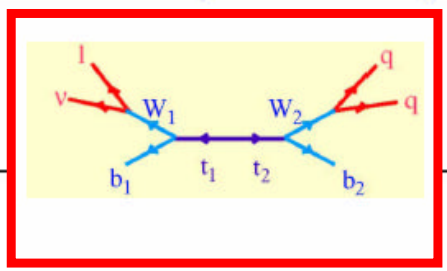
Top Quarks

Example of initial measurement : top signal and top mass

- Use gold-plated $t\bar{t} \rightarrow bW\,bW \rightarrow bl\nu\,bjj$ channel
- Very simple selection:
  - -- isolated lepton (e, μ) $p_T > 20$ GeV
  - -- exactly 4 jets $p_T > 40$ GeV
  - -- no kinematic fit
  - -- no b-tagging required (pessimistic, assumes trackers not yet understood)
- Plot invariant mass of 3 jets with highest p_T



Time	Events at 10^{33}	Stat. error δM_{top} (GeV)	Stat. error $\delta\sigma/\sigma$
1 year	3×10^5	0.1	0.2%
1 month	7×10^4	0.2	0.4%
1 week	2×10^3	0.4	2.5%



- top signal visible in few days also with simple selection and no b-tagging
- cross-section to ~ 20% (10% from luminosity)
- top mass to ~7 GeV (assuming b-jet scale to 10%)
- get feedback on detector performance :
  m_{top} wrong → jet scale ?
  gold-plated sample to commission b-tagging

What about early discoveries ?

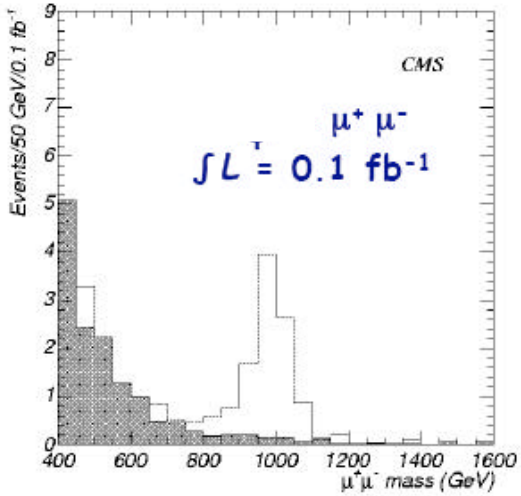
An easy case : a new resonance decaying into e+e-, e.g. a Z ' → ee of mass 1-2 TeV

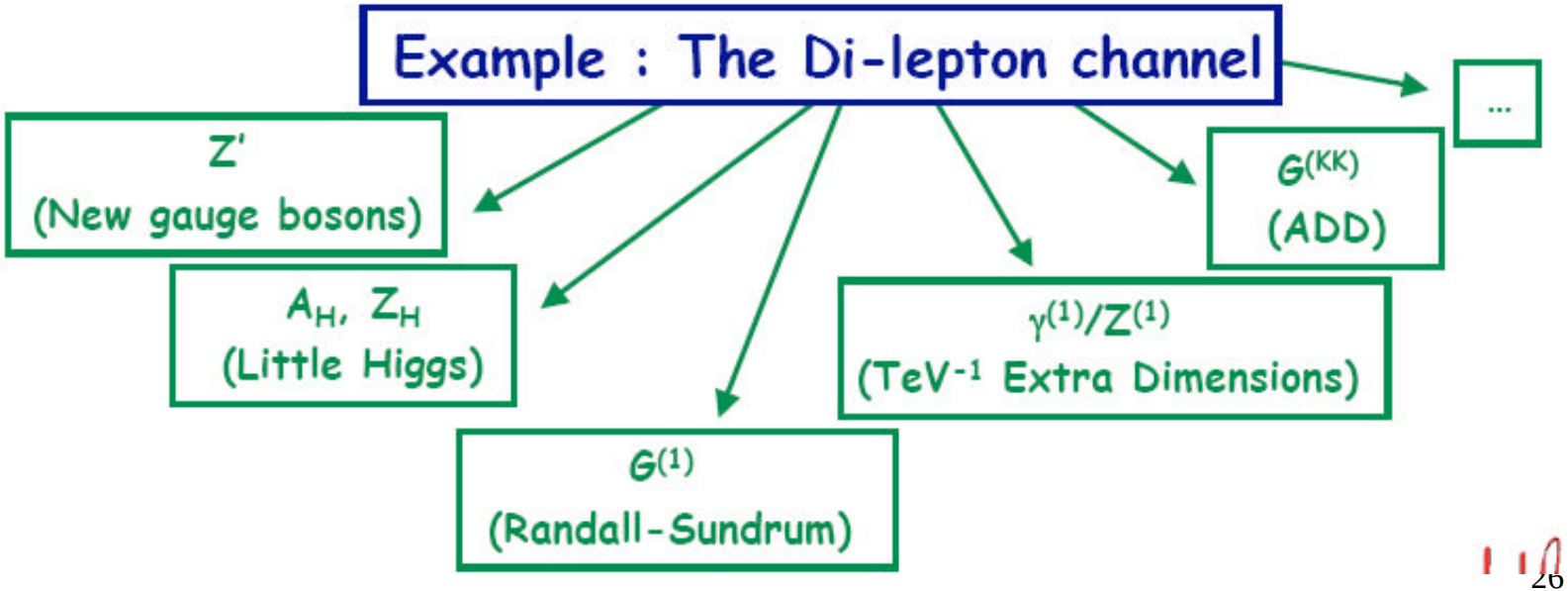
An intermediate case : SUSY

A difficult case : a light Higgs (m ~ 115 GeV)

Example: Di-lepton Resonance

May be seen very early: first weeks



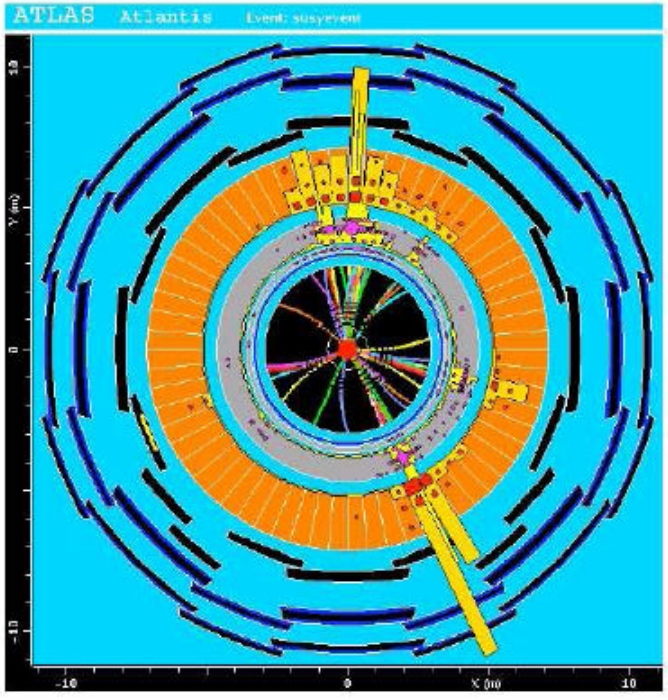


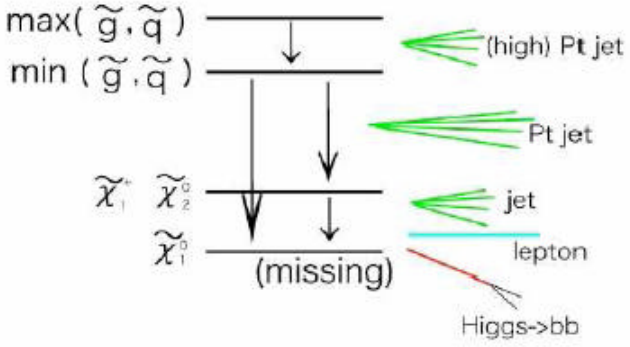
Supersymmetry:

SUSY could be at the rendez-vous very early on!

M_{sp}(GeV)	s (pb)	Evts/yr
500	100	10^6-10^7
1000	1	10^4-10^5
2000	0.01	10^2-10^3

$10 fb^{-1}$





event topologies of SUSY

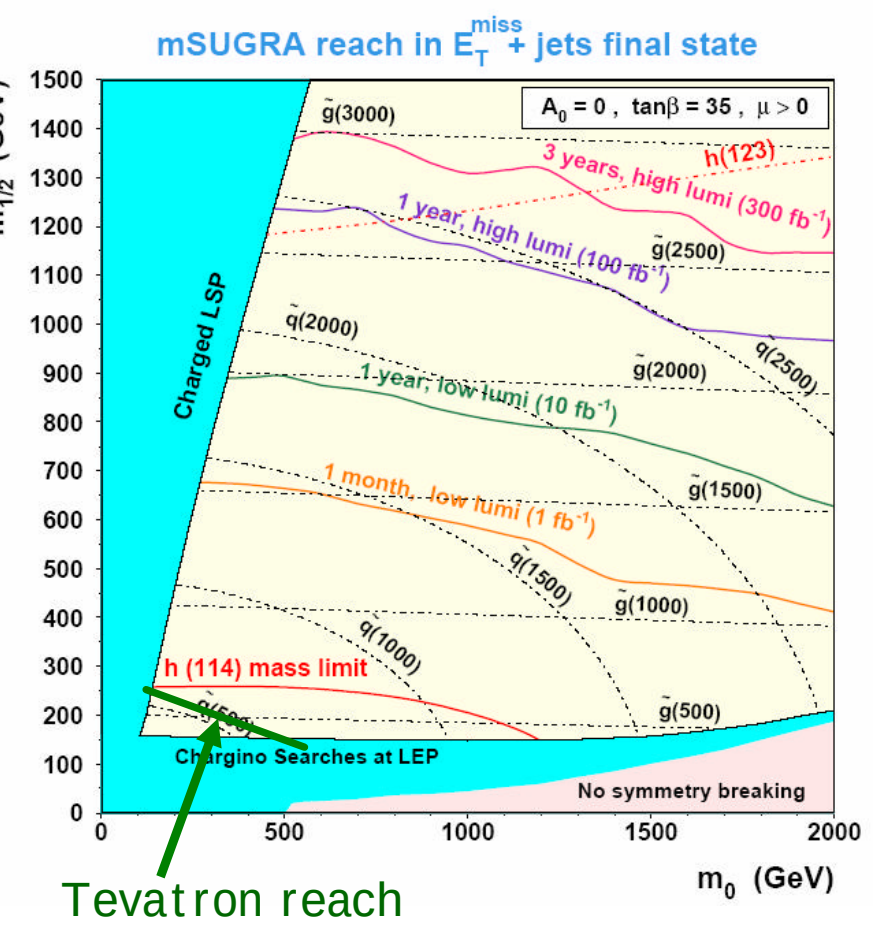
$$\not{E}_T + \text{High } P_T \text{ jets} + \begin{matrix}\text{multi} \\ \text{b-jets} \\ \tau\text{-jets}\end{matrix} \text{ leptons}$$

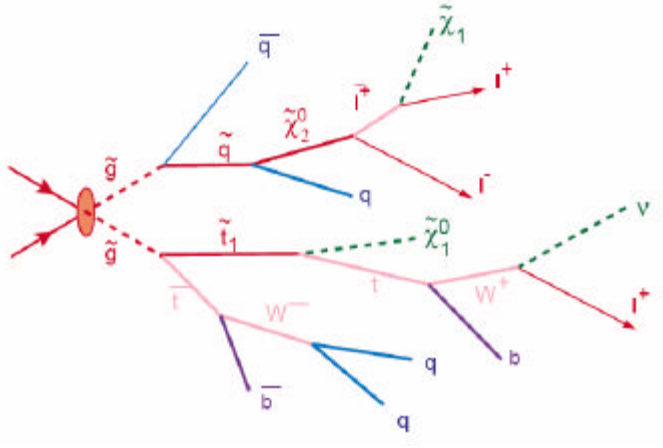
Therefore:
SUSY one of the
priorities of the
"search" program

Main signal: lots of activity (jets, leptons, taus, missing E_T)

Note: establishing that the new signal is SUSY will be more difficult!

SUSY Reach vs Integrated Luminosity





- If low energy Supersymmetry exists, LHC will almost certainly observe it
- Squarks and Gluinos detectable up to 1.5-2.0 TeV mass with 10 fb^{-1}

Recent Studies: New Signatures

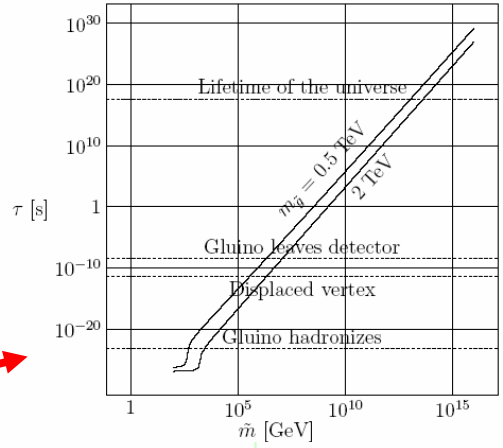
Arkani-Hamed, Dimopoulos hep-th/040515

Split Supersymmetry

- Assumes nature is fine tuned and SUSY is broken at some high scale
- The only light particles are the Higgs and the gauginos

- Gluino can live long: sec, min, years!
- R-hadron formation: slow, heavy particles containing a heavy gluino.

Unusual interactions with material

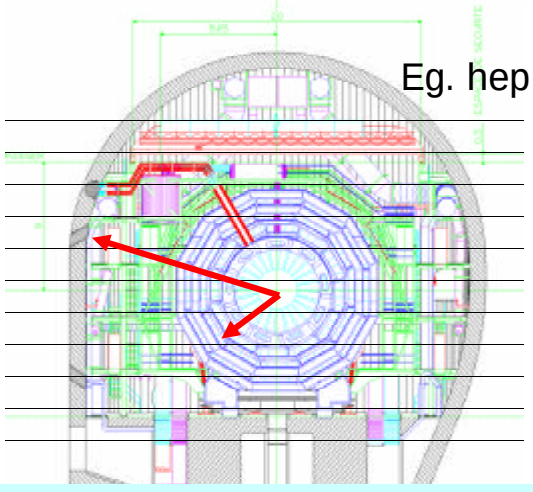


Gravitino Dark Matter and GMSB

- In some models/phase space the gravitino is the LSP
- Then the NLSP (neutralino, stau lepton) can live 'long'

⇒Challenge to the experiments!

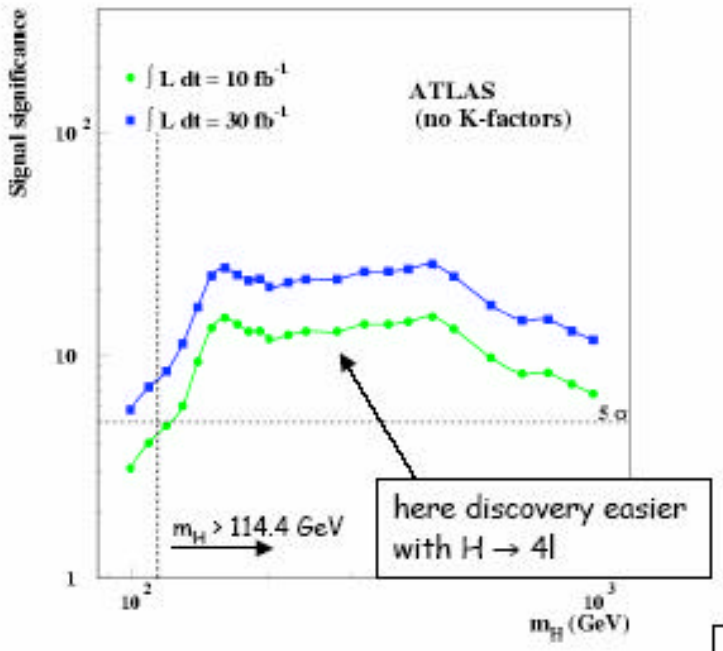
Eg. hep-ph/050819

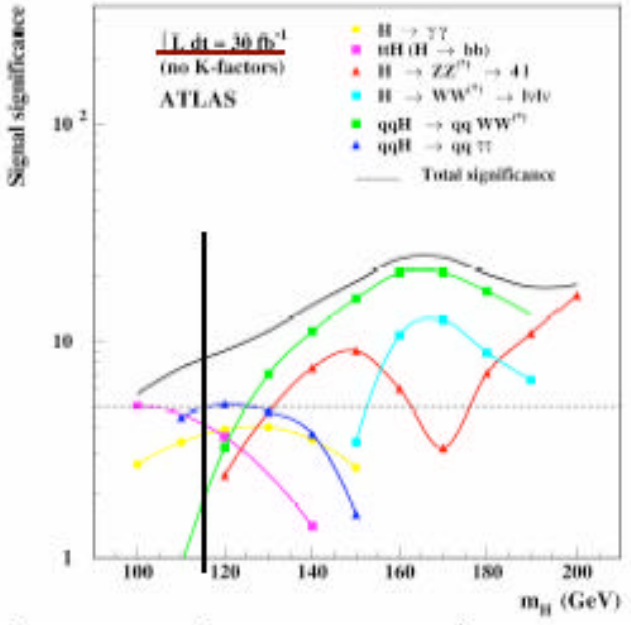


Sparticles stopped in the detector or walls around of the cavern.
They decay after hours---months…

Higgs Discovery

A difficult case: a light Higgs ($m_H \sim 115$ GeV) ...





$m_H \sim 115$ GeV 10 fb^{-1}

total $S/\sqrt{B} \approx 4^{+2.2}_{-1.3}$

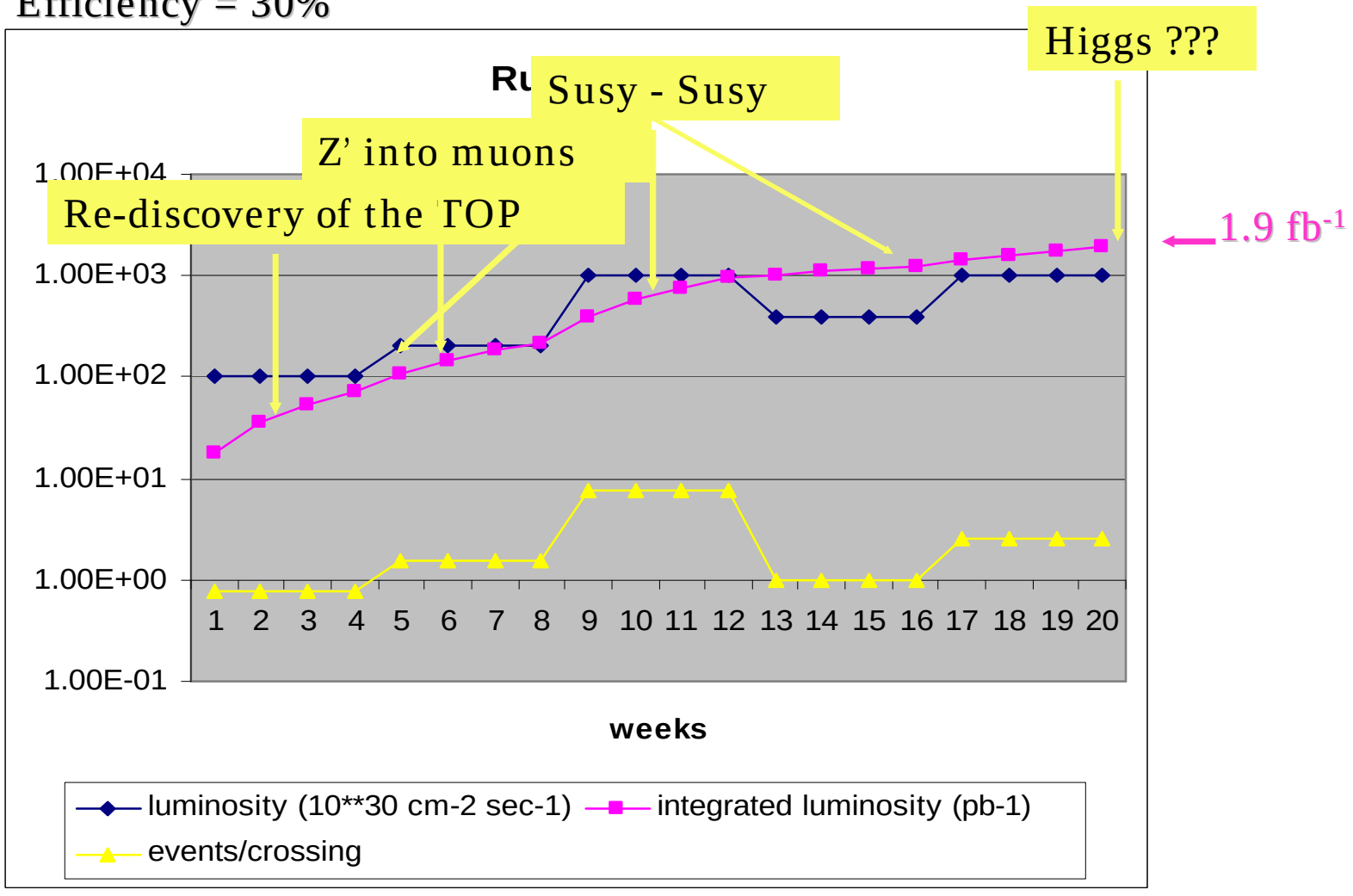
ATLAS	H → γγ	ttH → ttbb	qqH → qqττ (ll + l-had)
S	130	15	~ 10
B	4300	45	~ 10
S/ √B	2.0	2.2	~ 2.7

K-factors ≡ σ(NLO)/σ(LO) = 2 not included

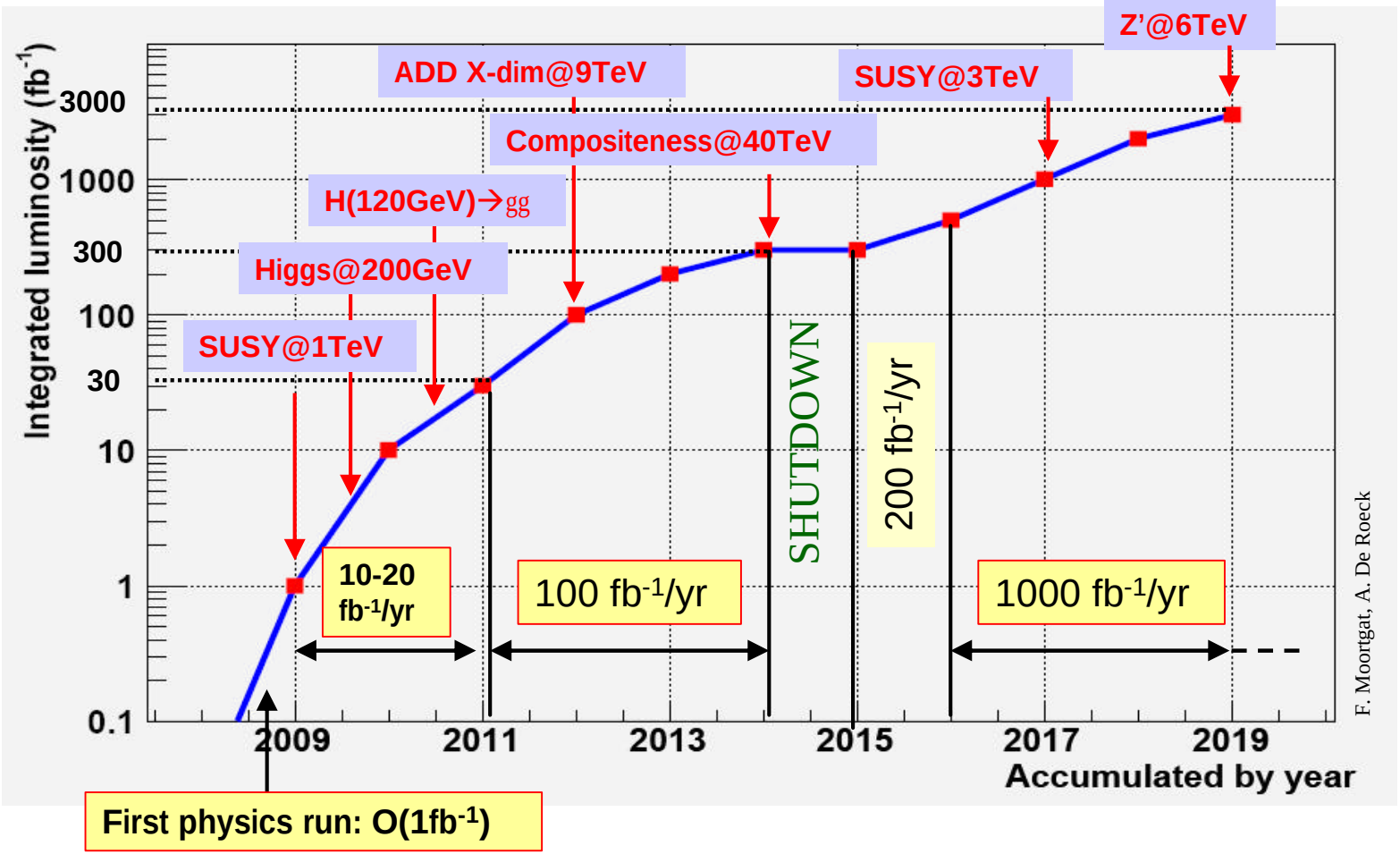
Full GEANT simulation, simple cut-based analyses

The First Physics Run (2008)

Efficiency = 30%



LHC Luminosity/Sensitivity Evolution?



Summary

- LHC promises (still) first collisions in 2007, but at low luminosity:
  - Commissioning of detectors; QCD physics? Watch out for large signal new phenomena…
- First physics run in 2008: expect of O(1) to a few fb^{-1}.
  - Low mass SUSY reach extended far beyond Tevatron reach. Open new windows for extra dimension searches, black holes, new gauge bosons,… Top quark/W mass measurements already dominated by systematics. Standard model Higgs may be still difficult to establish, especially in the low mass region
- Physics run in 2009: expect 10-20 fb^{-1}.
  - SM Higgs mass range fully covered
    high mass SUSY…
- Schedules are tight/lots of work ahead for us in the next two years
  $\Rightarrow$ But it will be rewarding at the end

And Maybe…

6 December 2008

Evidence for squark and gluino production in pp collisions at $\sqrt{s}$ = 14 TeV

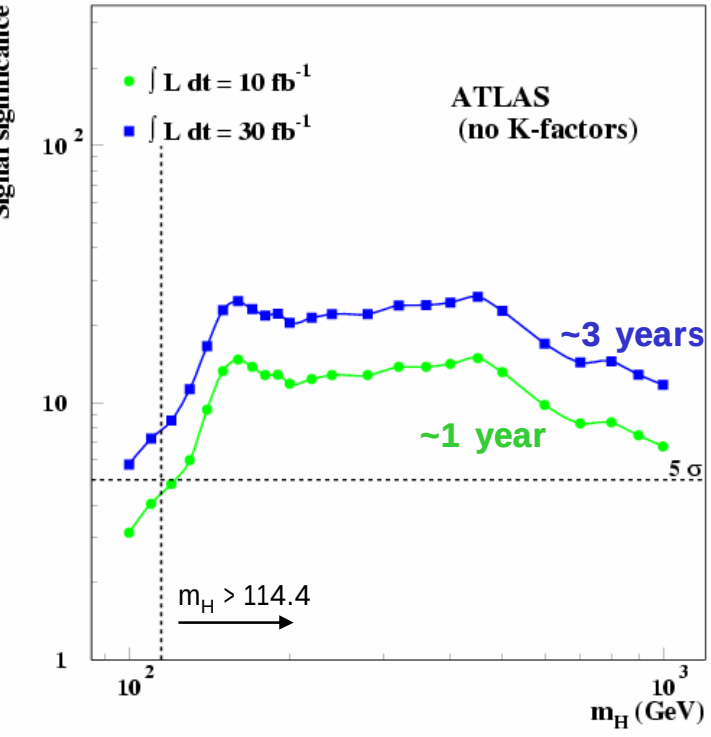
CMS collaboration

Abstract

Experimental evidence for squark and gluino production in pp collisions $\sqrt{s}$ = 14 TeV with an integrated luminosity of 97 pb^{-1} at the Large Hadron Collider at CERN is reported. The CMS experiment has collected 320 events of events with several high E_T jets and large missing E_T, and the measured effective mass, i.e. the scalar sum of the four highest P_T jets and the event $\not{E}_T$, is consistent with squark and gluino masses of order of 650 GeV/c^2. The probability that the measured yield is consistent with the background is 0.26%.

Submitted to *European Journal of Physics*

Higgs Reach



5σ ≡ dis

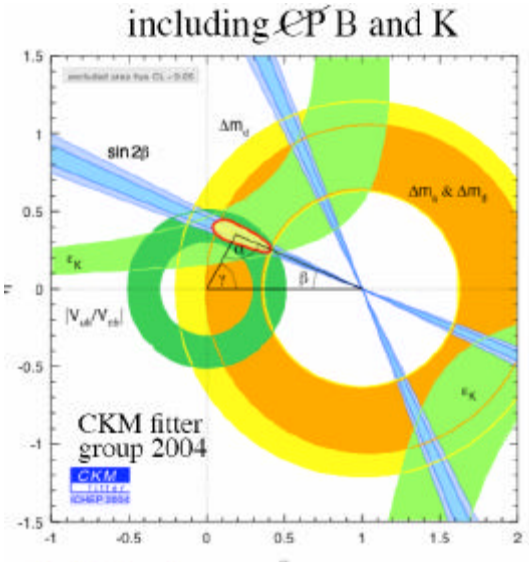
- Higgs can be discovered over full allowed mass range in 1 year of good LHC operation
  → final word about SM Higgs mechanism by 2009 or so
- However: it will take time to understand and calibrate ATLAS and CMS …
- In most difficult region m_H < 130 GeV ≥3 different channels observable → robustness

Important test for theories requiring a light Higgs (SUSY, Baryogenesis)

LHCb: b-physics at the LHC

Examples

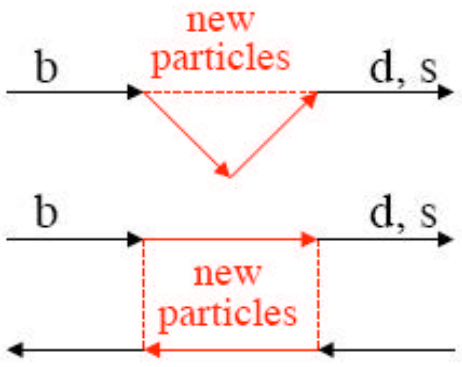
CKM triangle



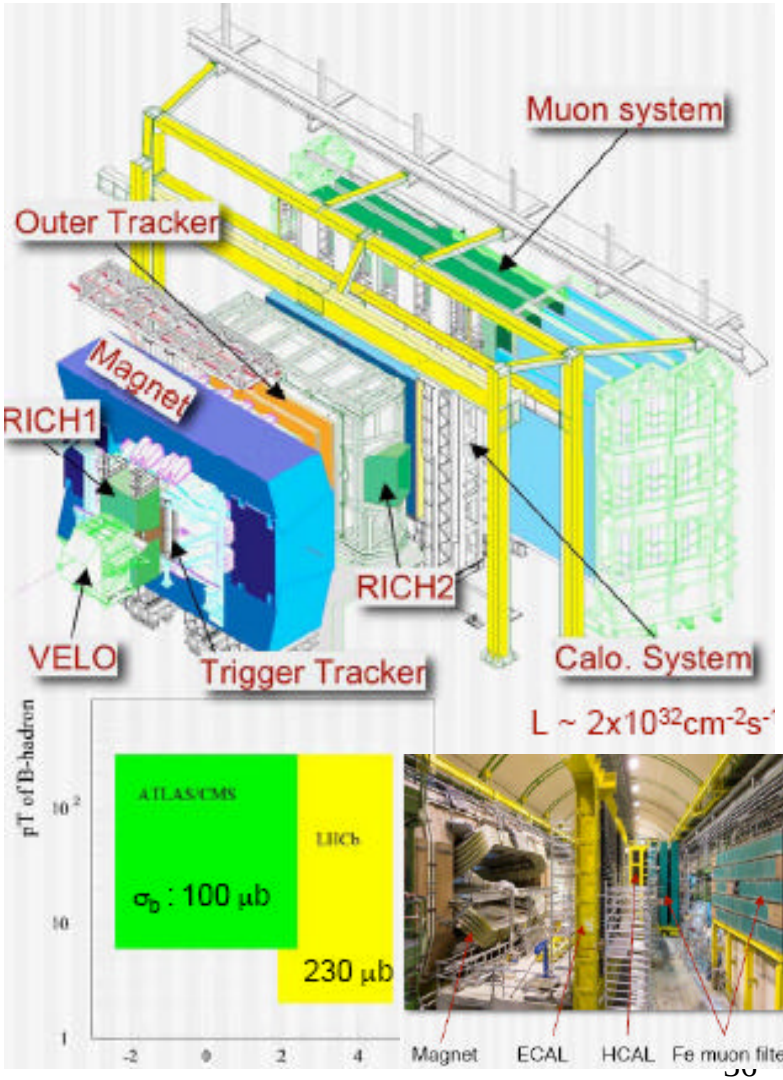
$B_s \to J/\psi\phi$ 120k signal events/year in LHCb

$\sigma(\sin\phi_s) \sim 0.06,\ \sigma(\Delta\Gamma_s/\Gamma_s) \sim 0.02$

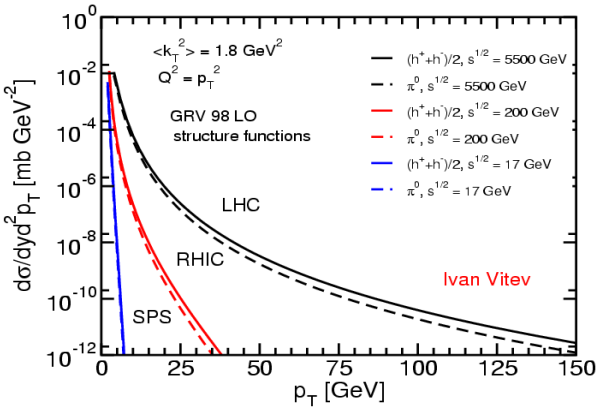
observation of B_s–$\bar{B}_s$ oscillation



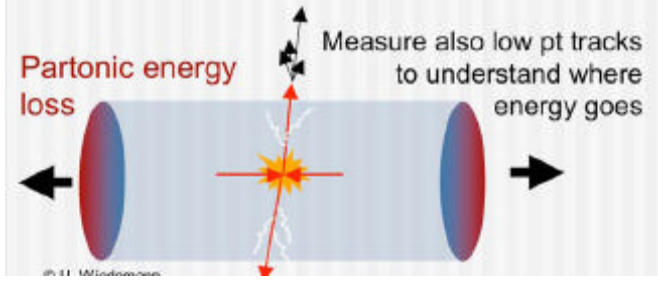
Sensitive to new physics complementary to ATLAS/CMS



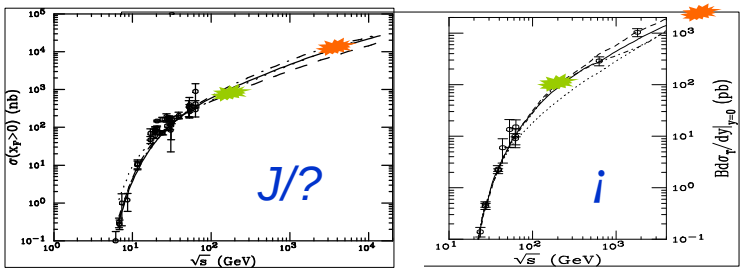
Heavy Ion Physics at the LHC



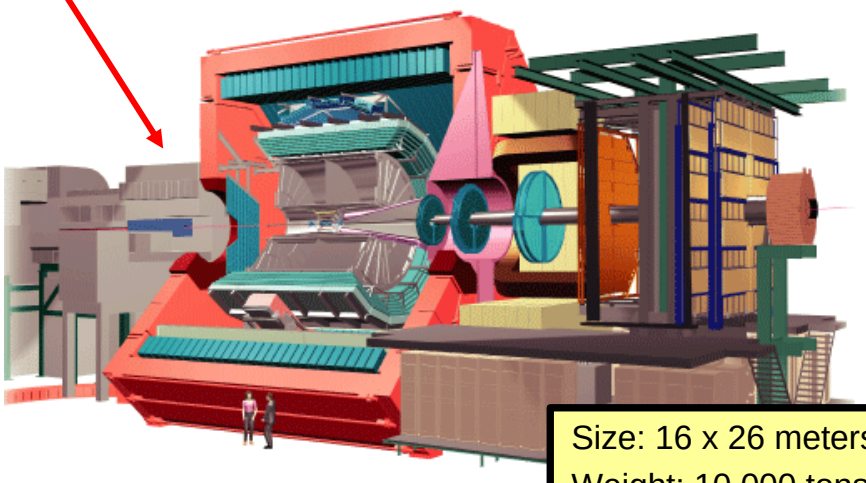
High P_T particle and jet production Jet-quenching



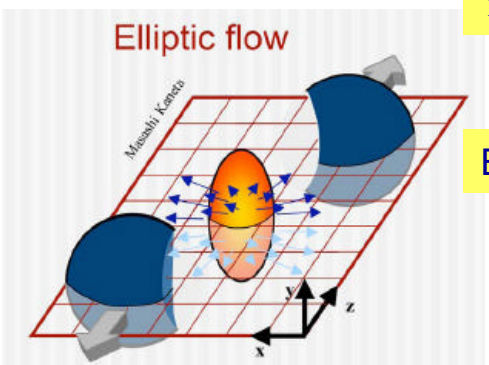
Heavy ions part of the LHC physics program with ALICE, but also CMS and ATLAS



Y melt down



Size: 16 x 26 meters
Weight: 10,000 tons

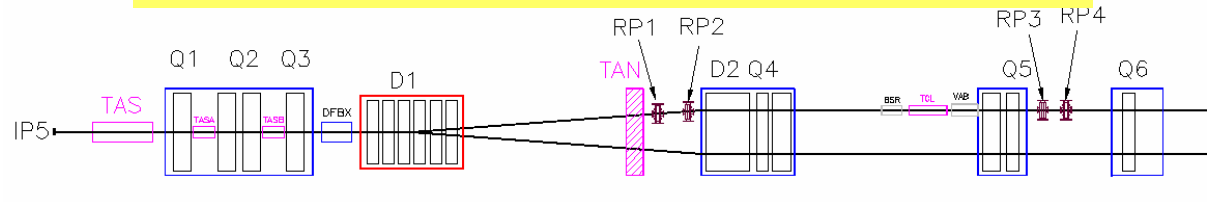


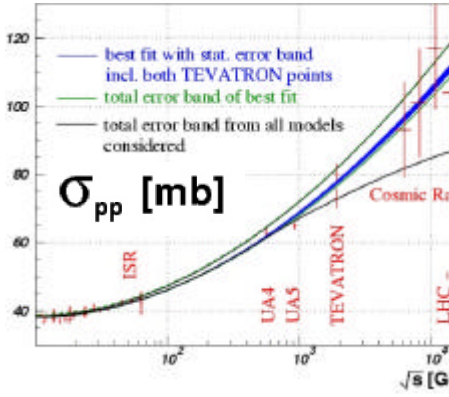
Event shapes

LHC ready for heavy ions in 2008?

Forward Coverage: TOTEM/LHCf

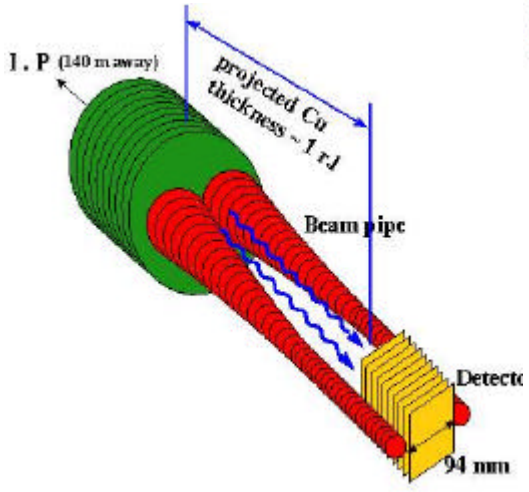
TOTEM: measuring the total, elastic and diffractive cross sections
Add Roman pots (and inelastic telescope) to CMS interaction regions.
Common runs with CMS planned

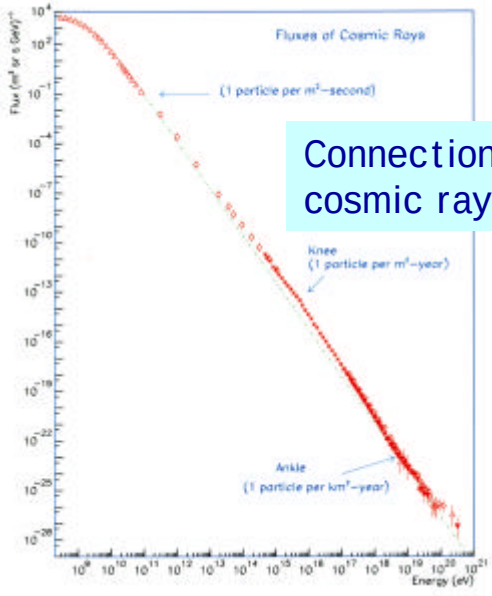




LHCf: measurement of photons and neutral pions in the very forward region of LHC

Add a EM calorimeter at 140 m from the Interaction Point (of ATLAS)





Connection wit cosmic rays