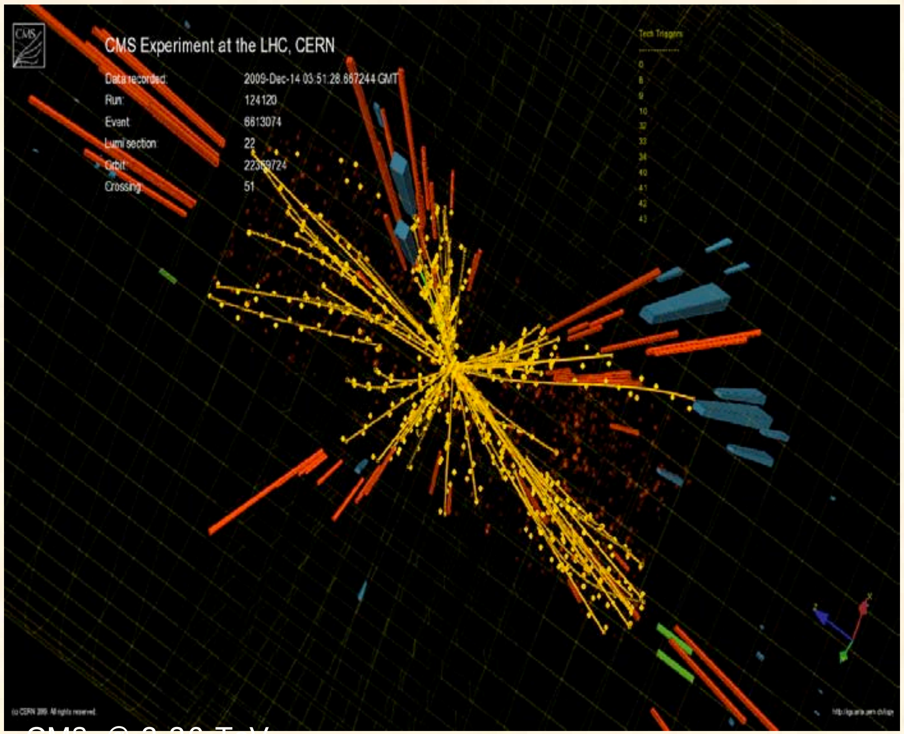
The status of the LHC
-first data, first physics, prospects-



CMS @ 2.36 TeV

- Status of the accelerator
- ATLAS and CMS
  Detector performance with first data
- First physics results
- Prospects for 2010/11 and beyond
  (Standard Model, New Physics,
  Higgs,...

Karl Jakobs
Physikalisches Institut
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The role of the LHC

1. Explore the TeV mass scale

- What is the origin of the electroweak symmetry breaking ?
- The search for “low energy” supersymmetry
- Other scenarios beyond the Standard Model
- …….

Look for the “expected”, but be open for surprises

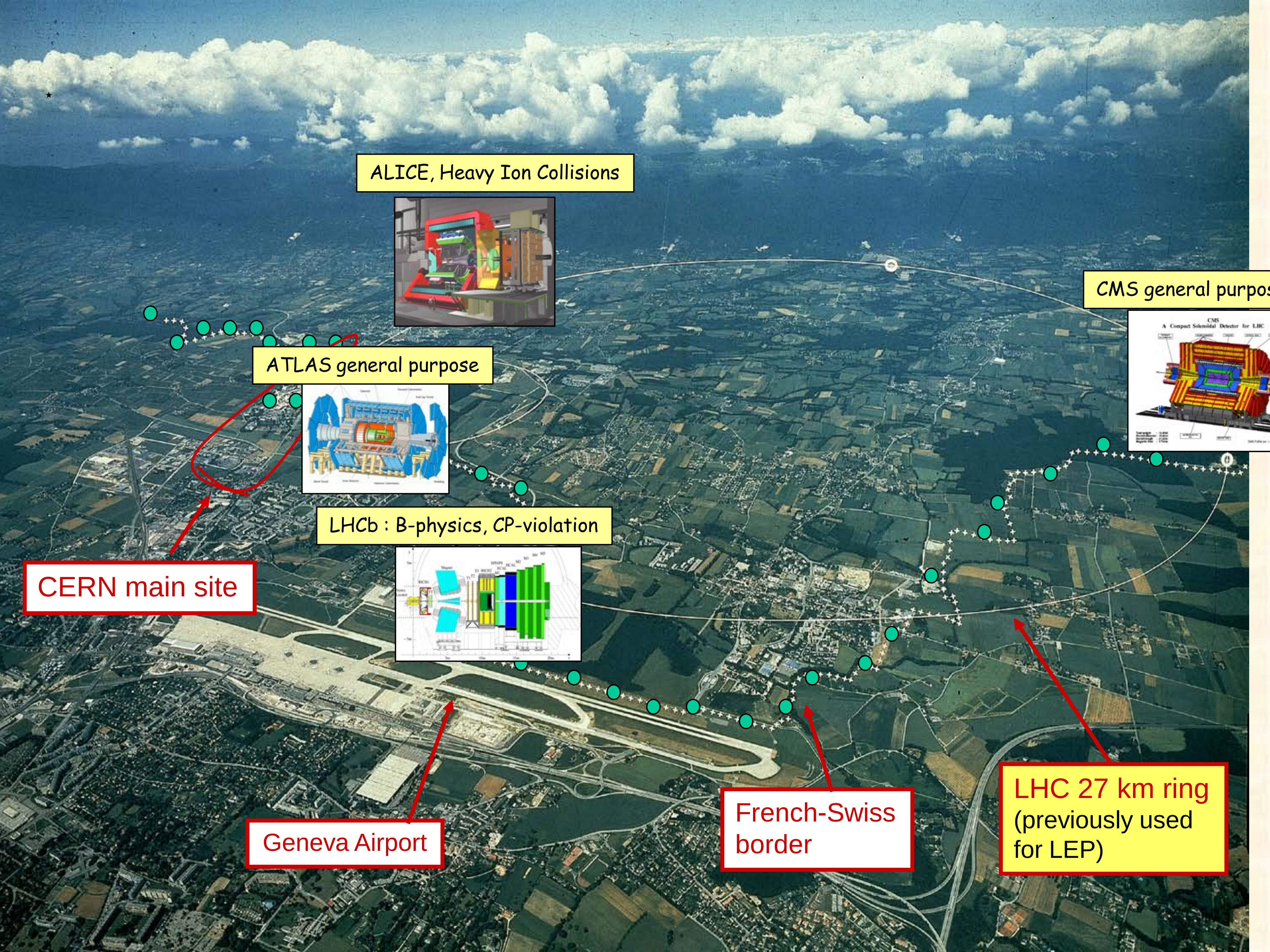
2. Precise tests of the Standard Model

- There is much sensitivity to Physics Beyond the Standard Model in the precision area (m_W, m_t, Flavour physics,….)
- Many Standard Model measurements can be used to test and to tune the detector performance

The LHC machine…

Beam energy	3.5 → 7 TeV
Luminosity (nominal)	10^{32} - 10^{34} $cm^{-2}s^{-1}$
→	**1 - 100 fb^{-1} / year**
Superconducting dipoles	1232, 15 m, 8.33T
Stored energy	350 MJ/beam

… became a reality after ~15 years of hard work


ALICE, Heavy Ion Collisions
CMS general purpos
ATLAS general purpose
LHCb : B-physics, CP-violation
CERN main site
Geneva Airport
French-Swiss border
LHC 27 km ring (previously used for LEP)

Major milestones of the re-start in 2009

20th Nov 09	Injection of both beams, rough RF capture
21st - 22nd Nov 09	Circulating beams
23rd Nov 09	First collisions at injection energy, 450 GeV
30th Nov 09	Ramp to 1.18 TeV (highest beam energy)
1st – 6th Dec 09	Protection system qualified to allow for stable beams
6th Dec	Stable beam at 450 GeV
8th Dec	Ramp two beams to 1.18 TeV, first collisions
11th Dec	Stable beam collisions with bunch intensities at $4x2x10^{10}$
16th Dec	Ramped 4 on 4 bunches to 1.18 TeV, collisions in all four experiments;
16th Dec	End of 2009 run

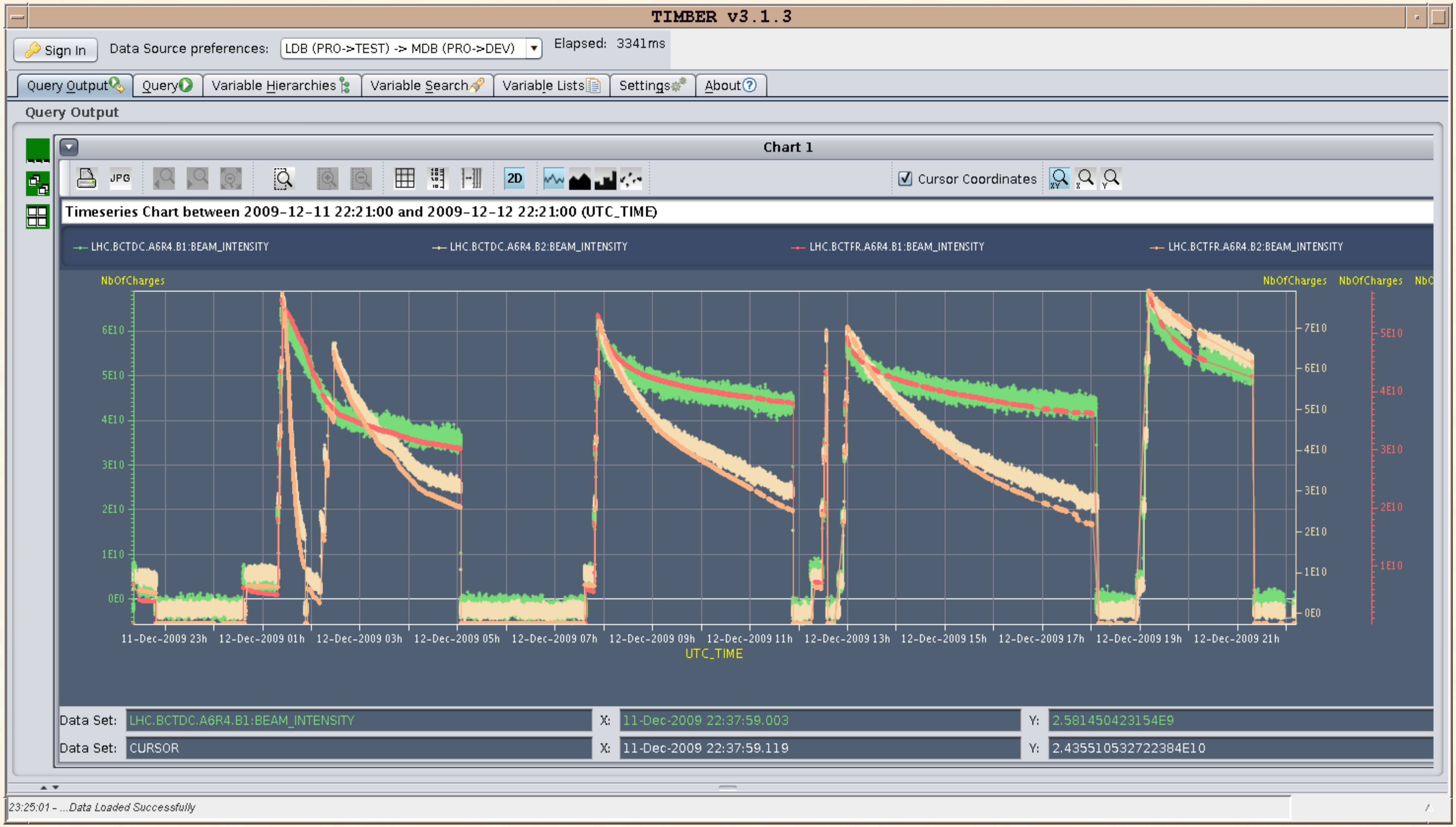
General agreement: Re-start in 2009 was very successful;
A lot was achieved in a short time

LHC sets new world record

Scenes of joy in the CERN Control Centre more photos »

Geneva, 30 November 2009. CERN's Large Hadron Collider has today become the world's highest energy particle accelerator, having accelerated its twin beams of protons to an energy of 1.18 TeV in the early hours of the morning. This exceeds the previous world record of 0.98 TeV, which had been held by the US Fermi National Accelerator Laboratory's Tevatron collider since 2001. It marks another important milestone on the road to first physics at the LHC in 2010.

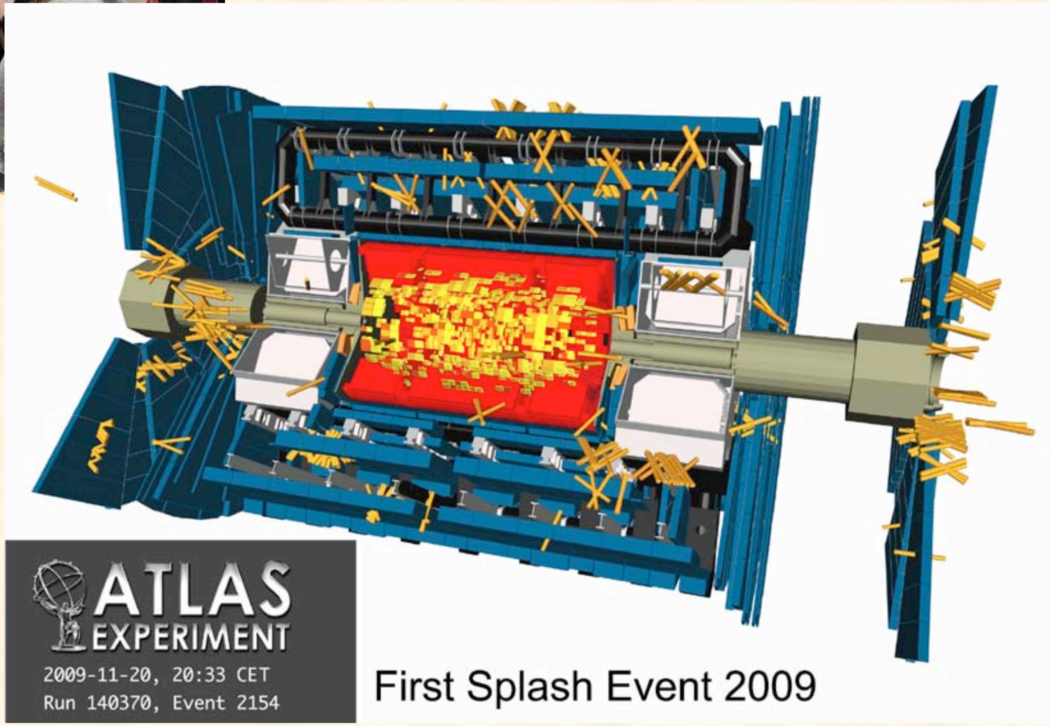
- About 1.5 Mio events were collected by the experiments
- Luminosities of $L = \sim 10^{26} – 10^{27}\ cm^{-2}\ s^{-1}$



LHC re-start as seen from the experiments

Praying for beam

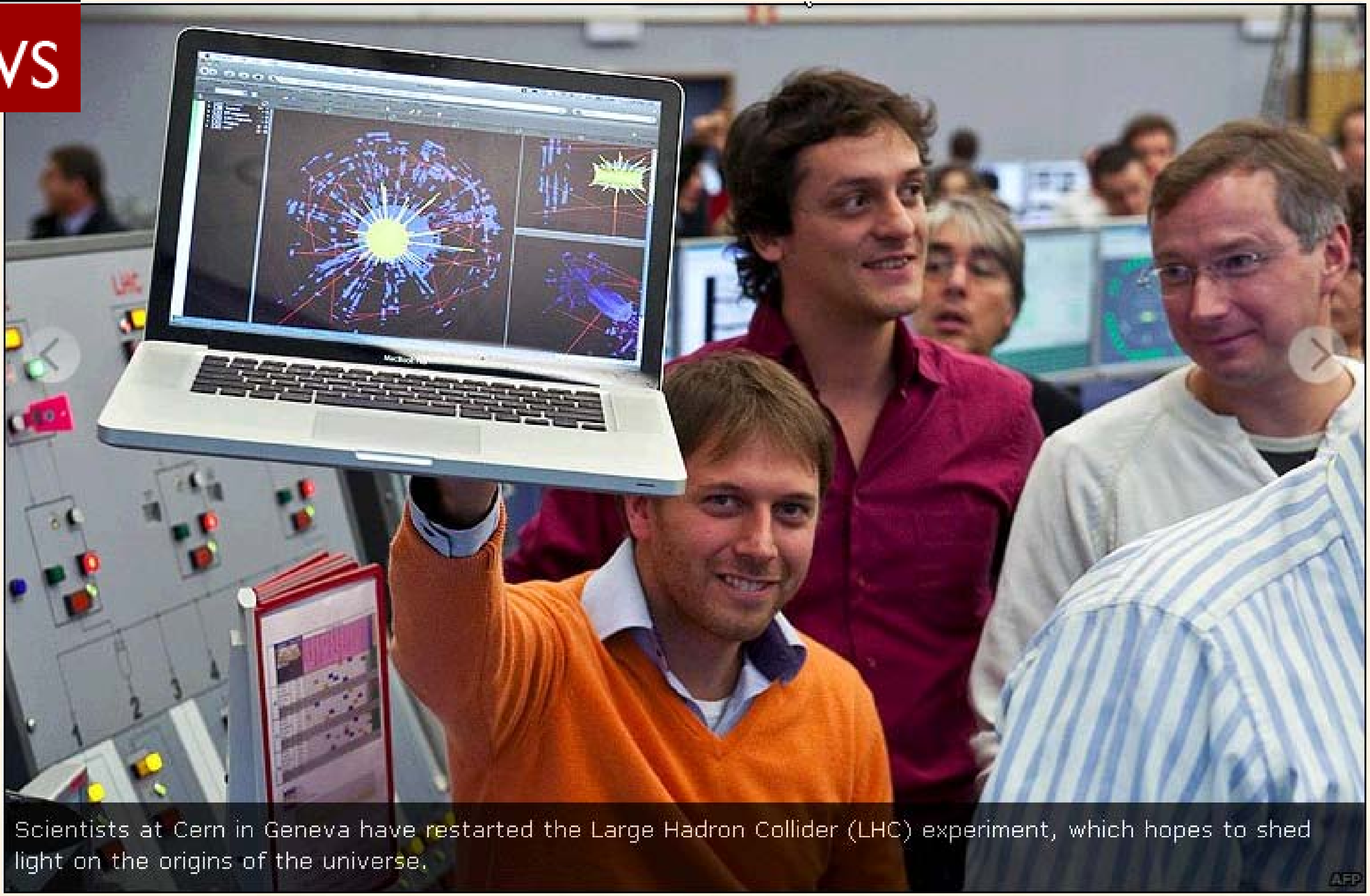
First beam splash events in ATLAS, 20th Nov 2009



CMS re-start in BBC News

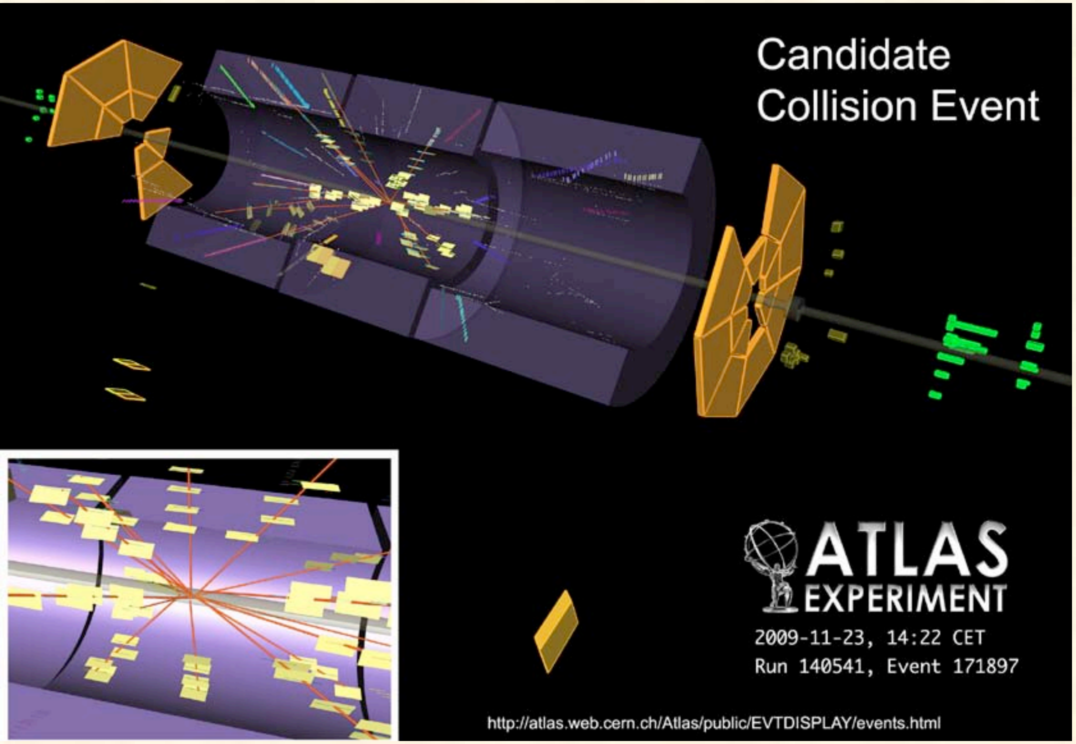
November 21, 2009

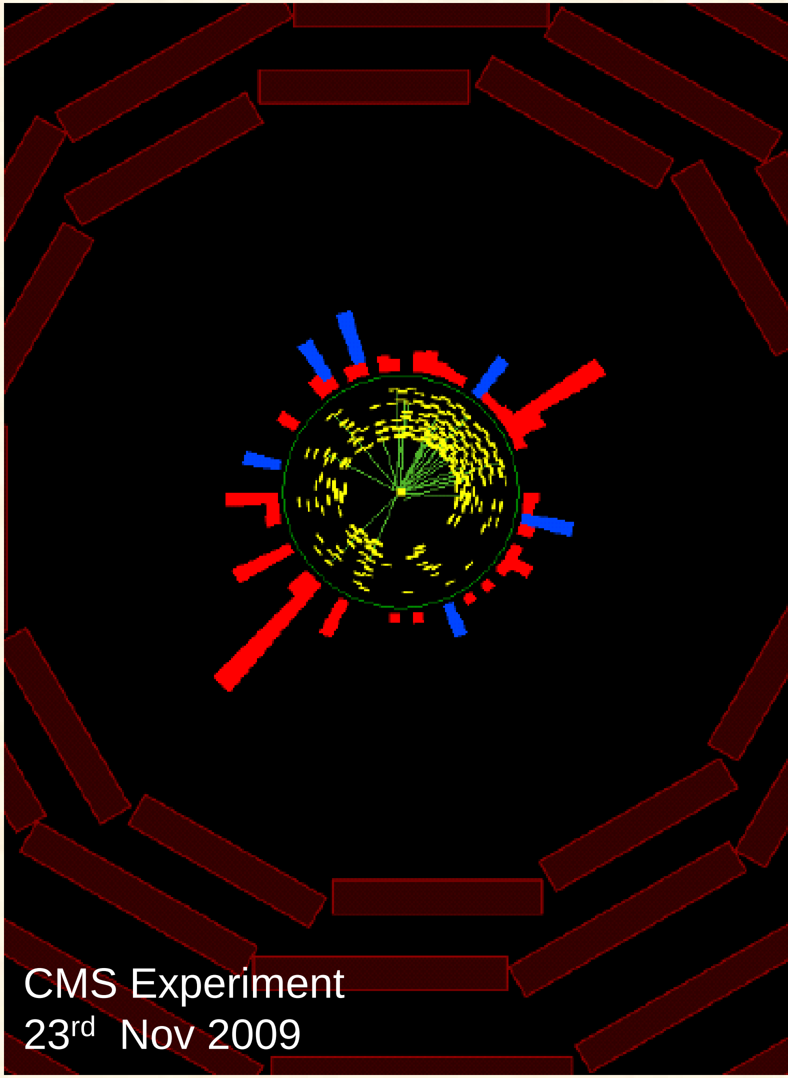
BBC NEWS



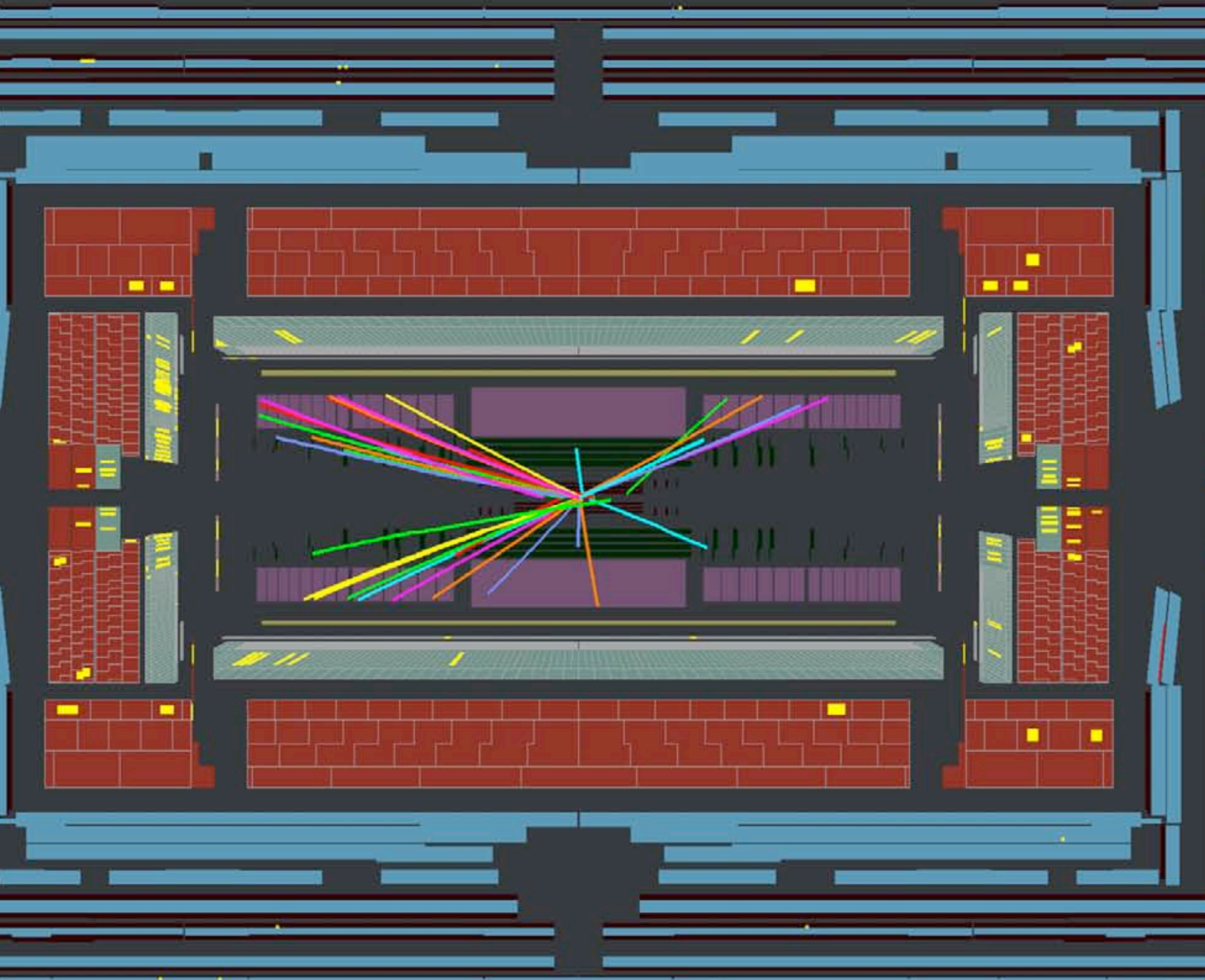
Scientists at Cern in Geneva have restarted the Large Hadron Collider (LHC) experiment, which hopes to shed light on the origins of the universe.

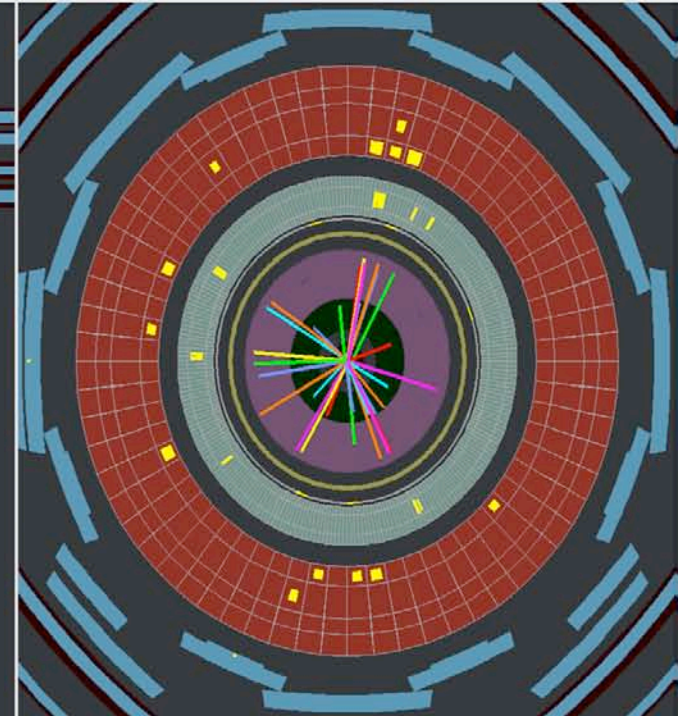
23rd Nov 2009: First collisions at 900 GeV

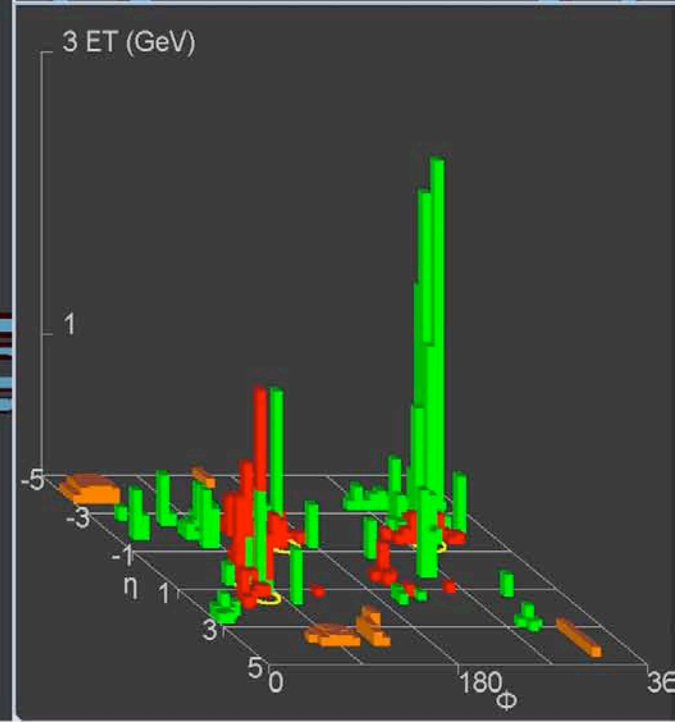




2-Jet Event at 2.36 TeV





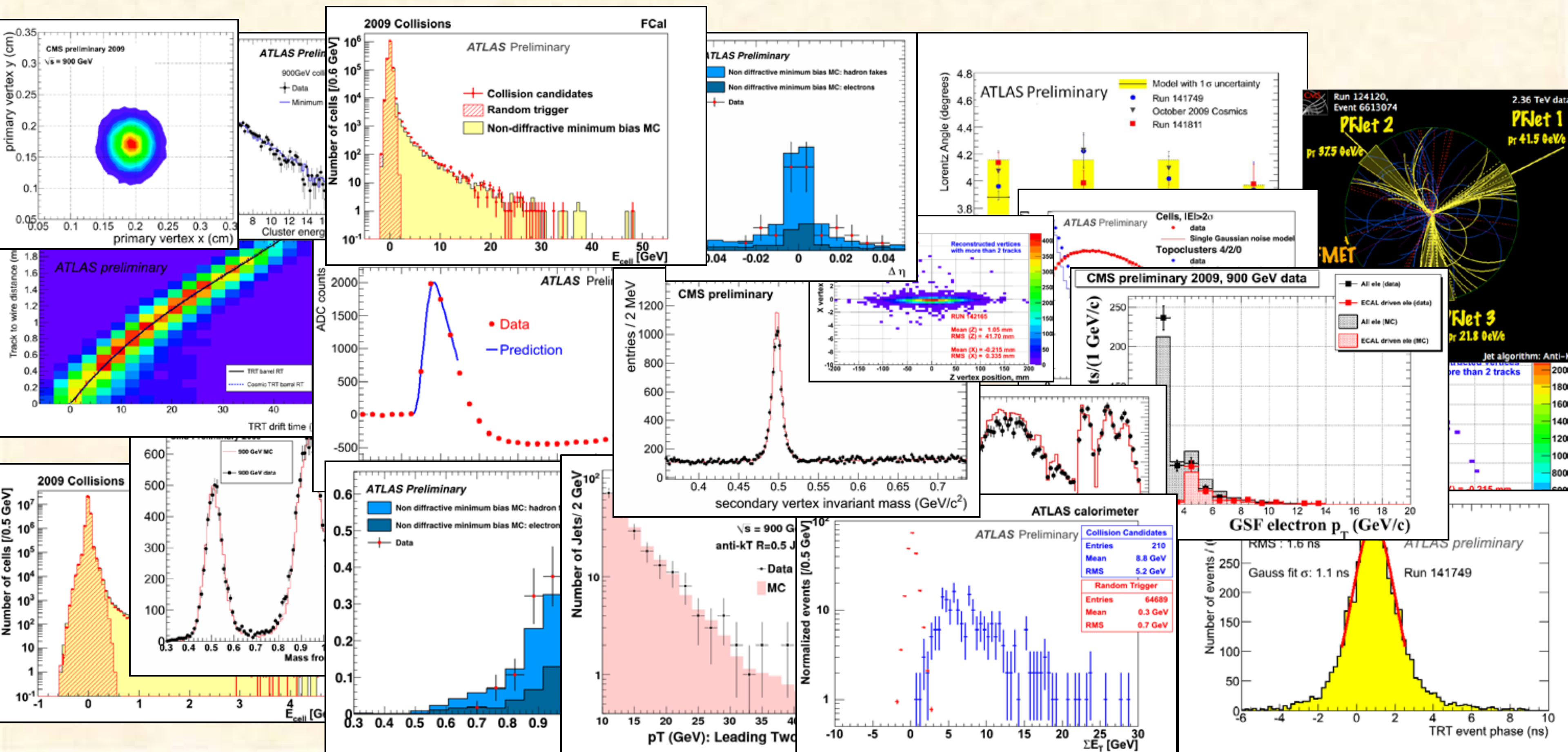


ATLAS EXPERIMENT

2009-12-08, 21:40 CET

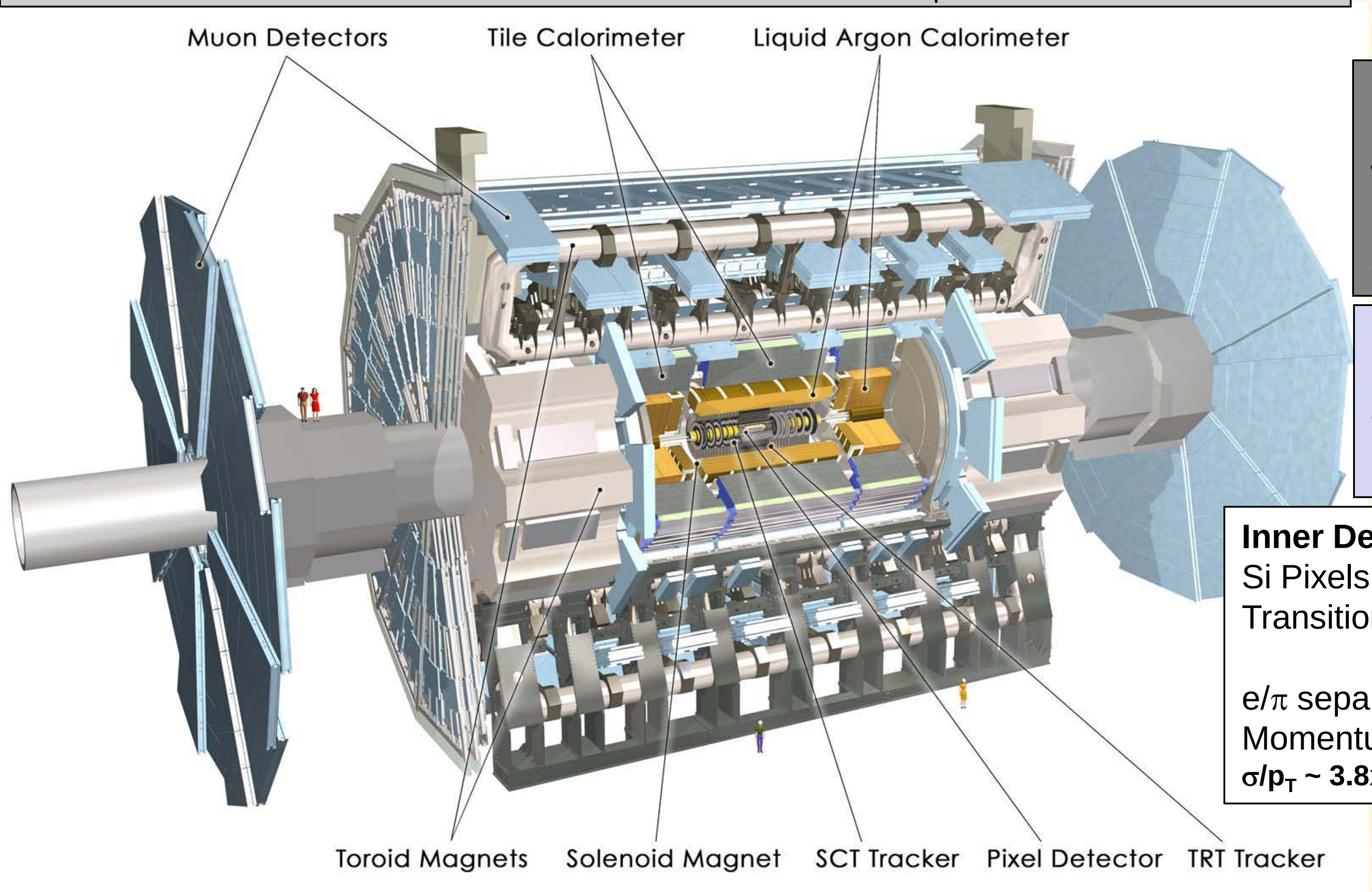
Run 142065, Event 116969

First results on Detector performance



The ATLAS detector

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with **$\Delta p/p$ < 10% up to E_μ ~ 1 TeV**



Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 elec. channels
3000 km of cables

3-level trigger reducing the rate from 40 MHz to ~200 Hz

Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips,
Transition Rad. Tracker

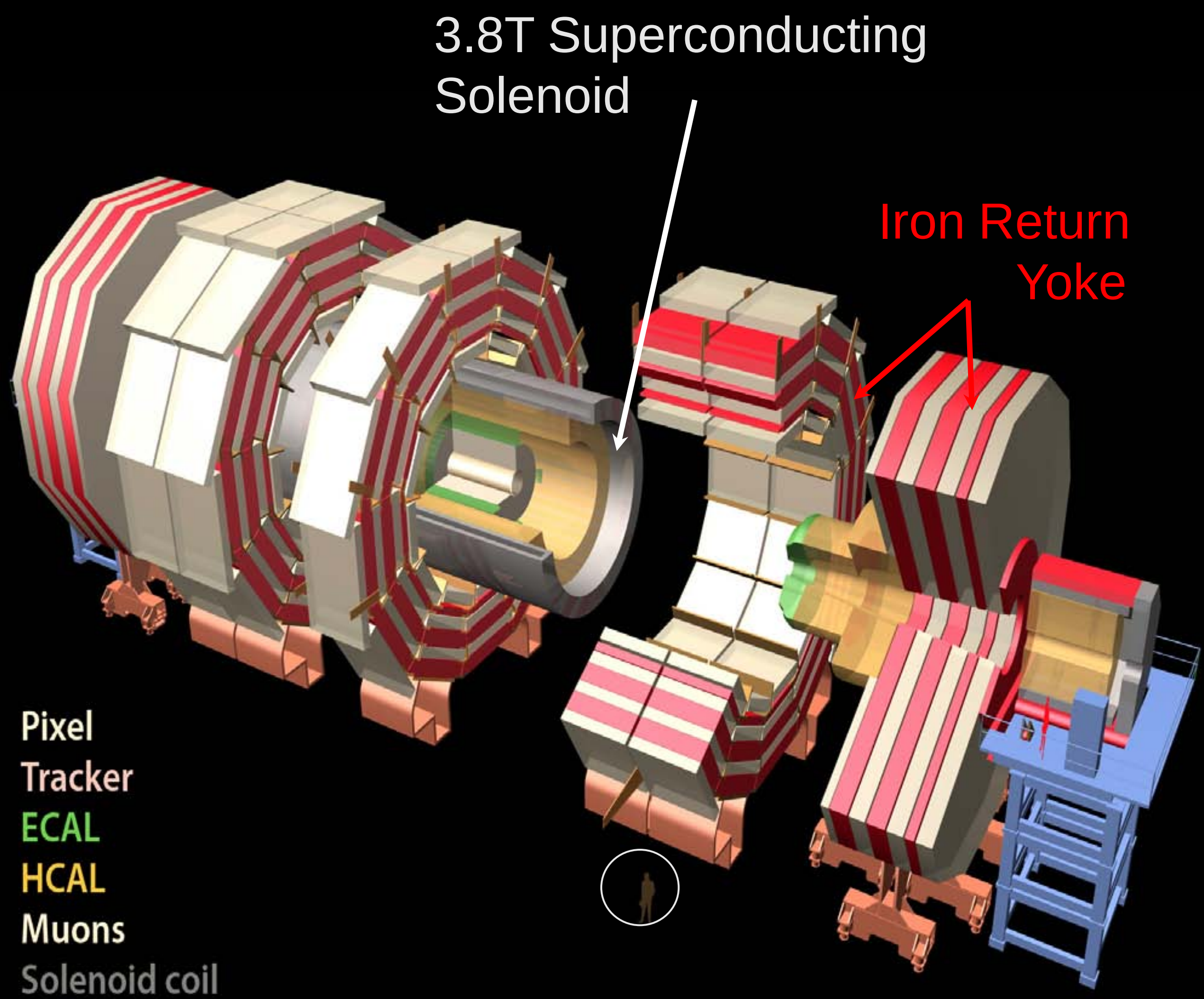
e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T\,(\mathrm{GeV}) \oplus 0.015$

EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

Total weight 12500 t
Overall diameter 15 m
Overall length 21.6 m

The CMS detector



All Silicon tracker (pixels and micro-strips)

Lead Tungstate Crystal EM Calorimeter (ECAL)

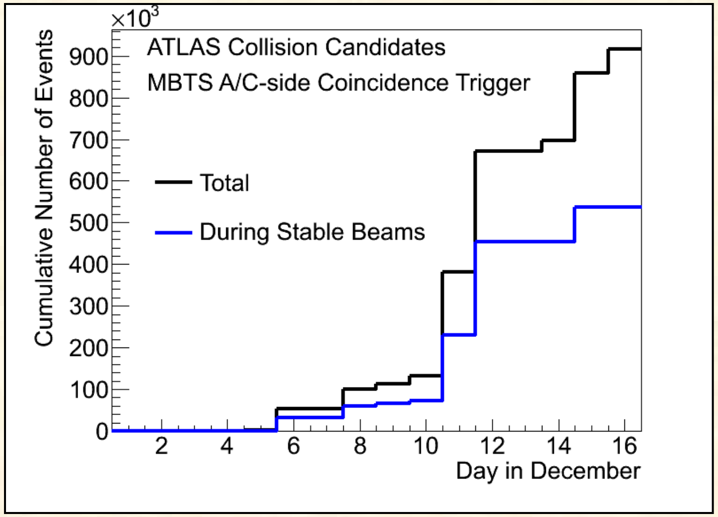
Hermetic (|η|<5.2) Hadron Calorimeter (HCAL)

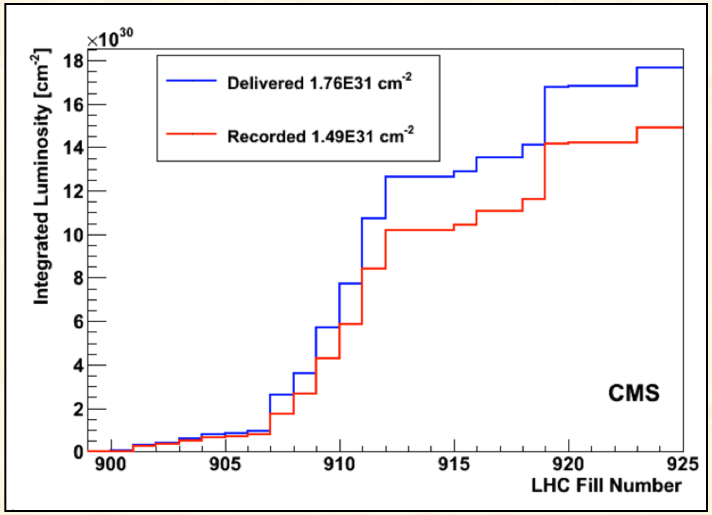
Muon System with high redundancy (RPCs, Drift Tubes, Cathode Strip Chambers)

First LHC pp collisions in ATLAS and CMS

- Detectors sensitive and fully operational from first collisions
- High efficiency for data collection (85 – 90% of luminosity recorded)
- Maximum peak luminosity seen by ATLAS 7×10^{26} cm^{-2} s^{-1}
- Open triggers (beam crossing)
- Trigger rates of about 10 Hz
- Fast analyses delivered preliminary results within hours / days

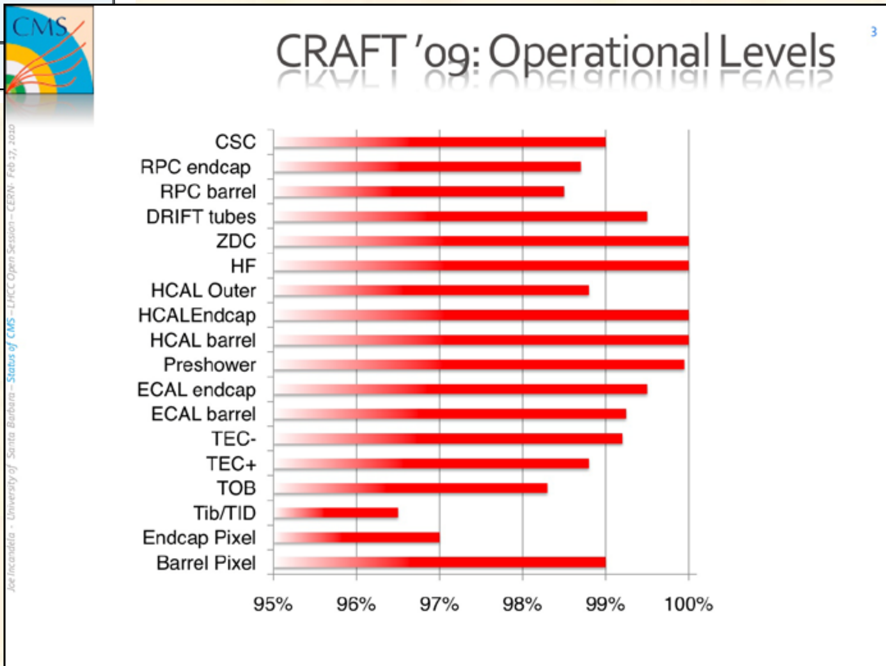
Recorded data samples (ATLAS)	# of events	Int.luminosity (~30% uncertainty)
Total	~ 920k	~ 20 μb^{-1}
With stable beams	~ 540k	~ 12 μb^{-1}
At$\sqrt{s}$=2.36 TeV	~ 34k	~ 1 μb^{-1}



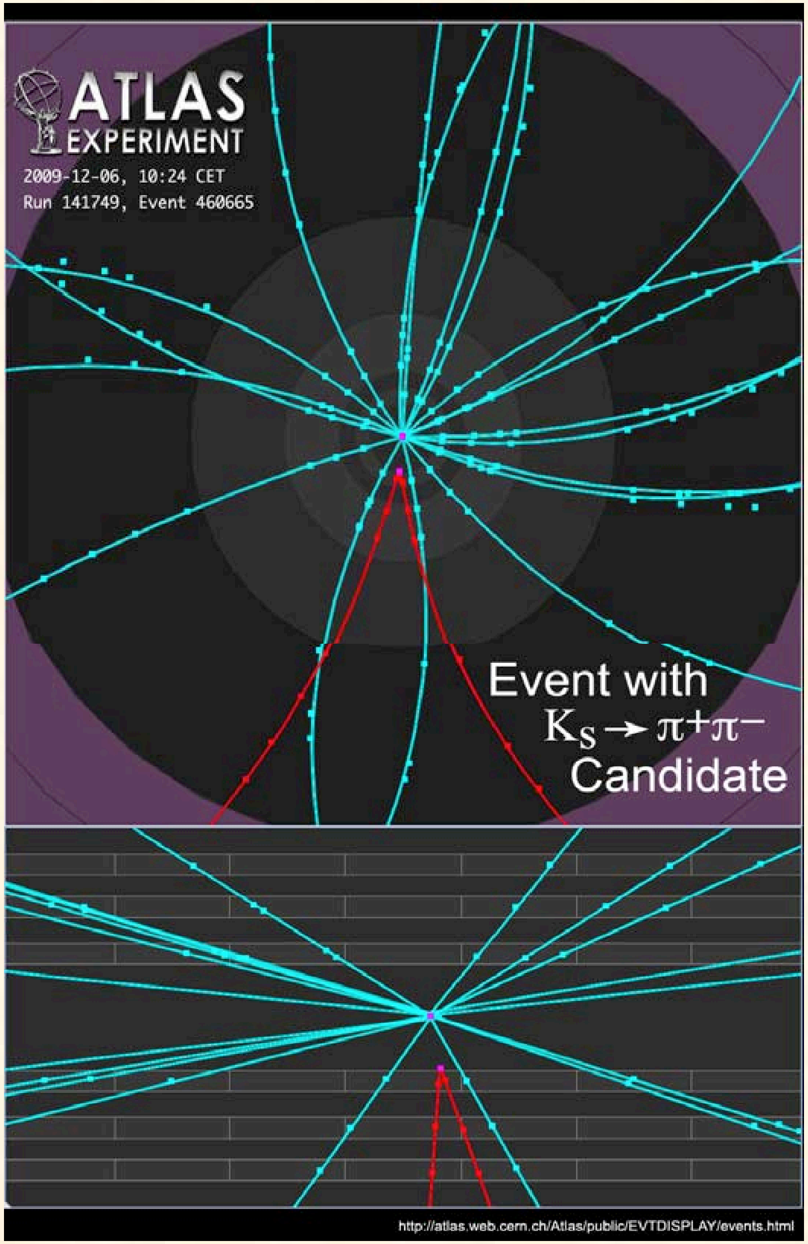


Detector Hardware Status in 2009

Subdetector	Number of Channels	Operational Fraction
Pixels	80 M	97.9%
SCT Silicon Strips	6.3 M	99.3%
TRT Transition Radiation Tracker	350 k	98.2%
LAr EM Calorimeter	170 k	98.8%
Tile calorimeter	9800	99.2%
Hadronic endcap LAr calorimeter	5600	99.9%
Forward LAr calorimeter	3500	100%
MDT Muon Drift Tubes	350 k	99.7%
CSC Cathode Strip Chambers	31 k	98.4%
RPC Barrel Muon Trigger	370 k	98.5%
TGC Endcap Muon Trigger	320 k	99.4%
LVL1 Calo trigger	7160	99.8%



Very small number of non-working detector channels (out of several millions) in both experiments

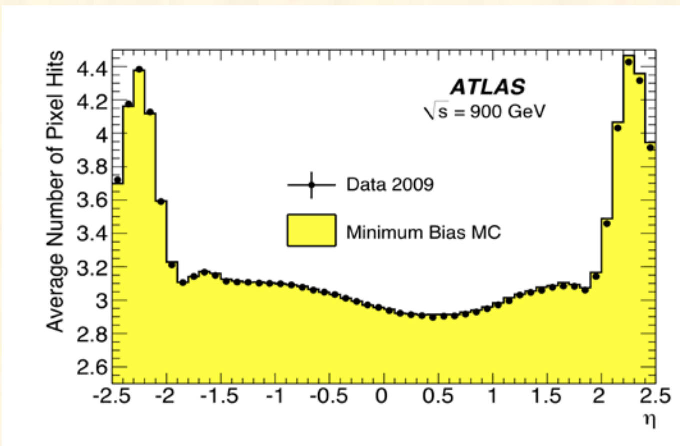

ATLAS
EXPERIMENT
2009-12-06, 10:24 CET
Run 141749, Event 460665
Event with
$K_S \rightarrow \pi^+\pi^-$
Candidate
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

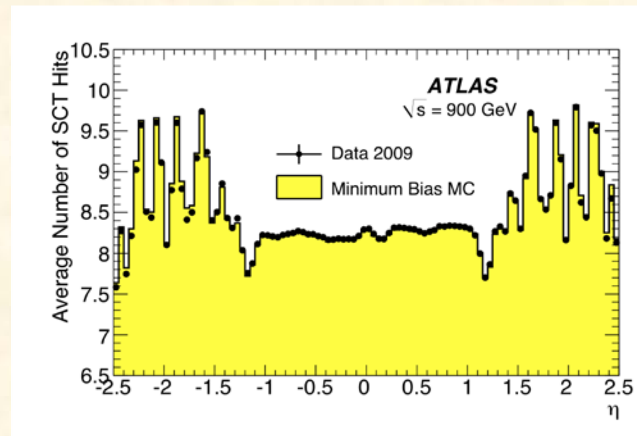
Tracking

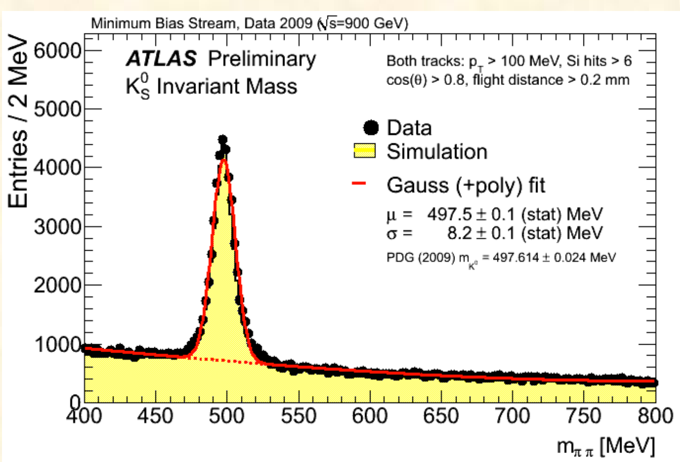
(i) Inner Detector performance: hits, tracks, resonances,...

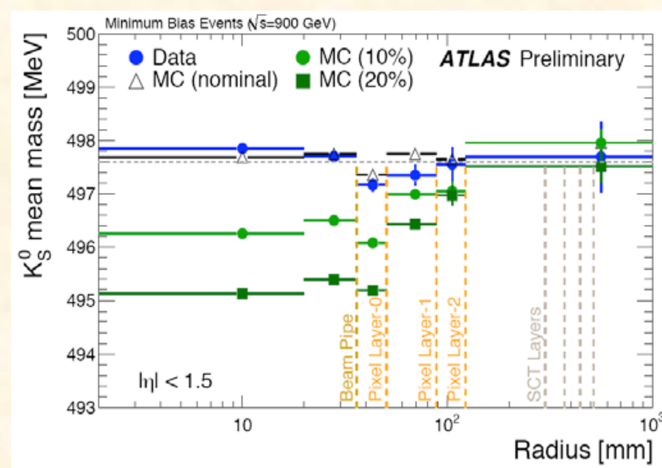
- Very good agreement for the average number of hits on tracks in the silicon pixel and strip detectors

- Material distribution in the inner detector is well described in Monte Carlo (nice cross-check with K^0-mass dependence on radius in the Monte Carlo)

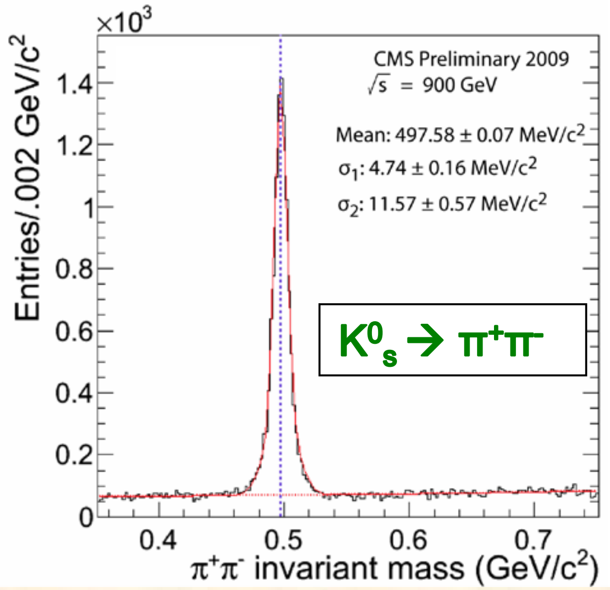


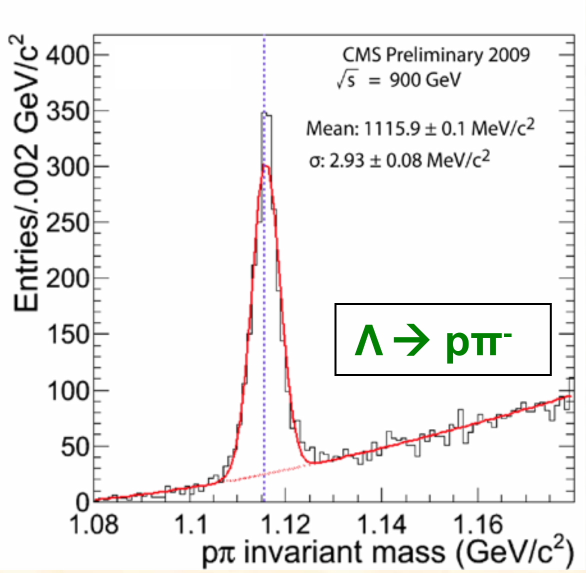


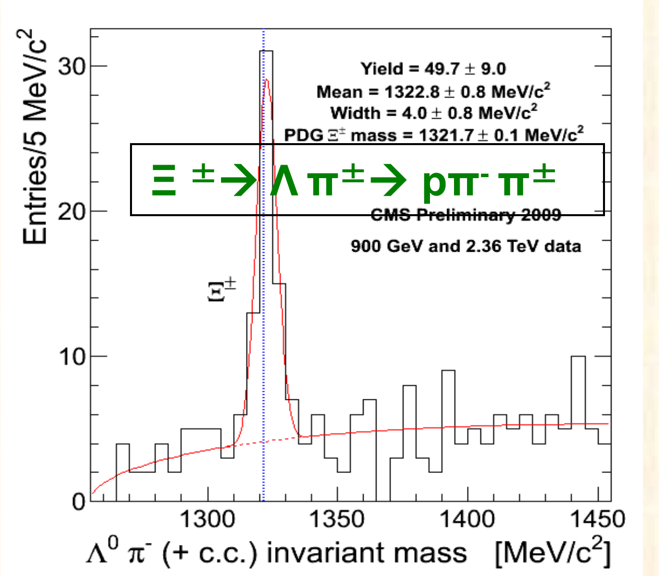


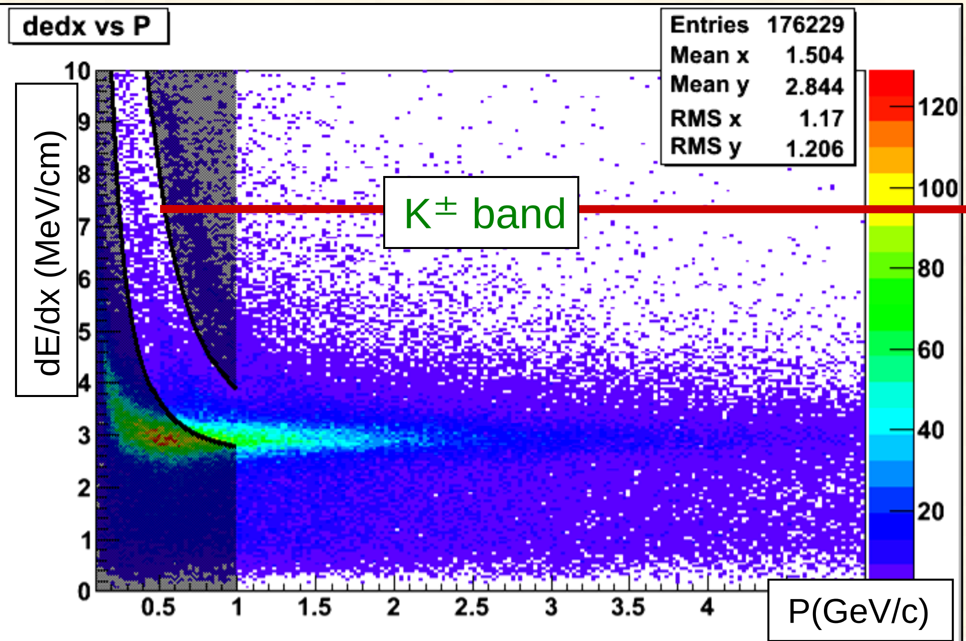


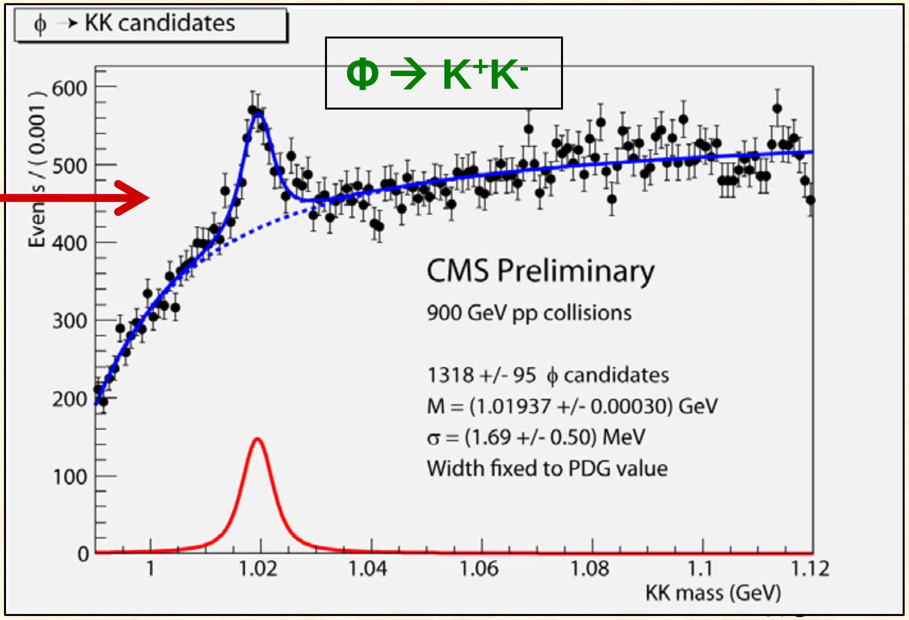
Resonances: CMS tracking detector



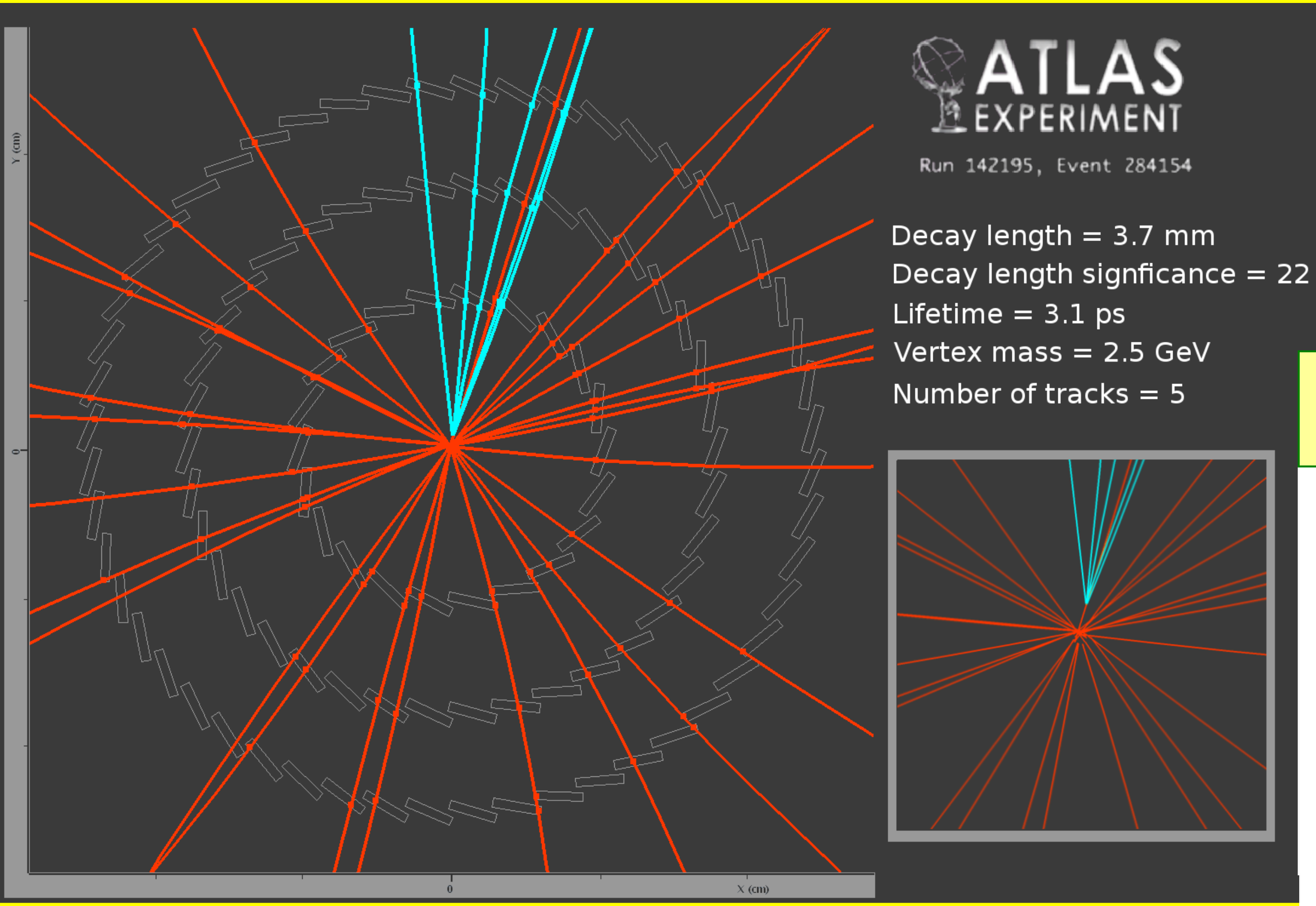




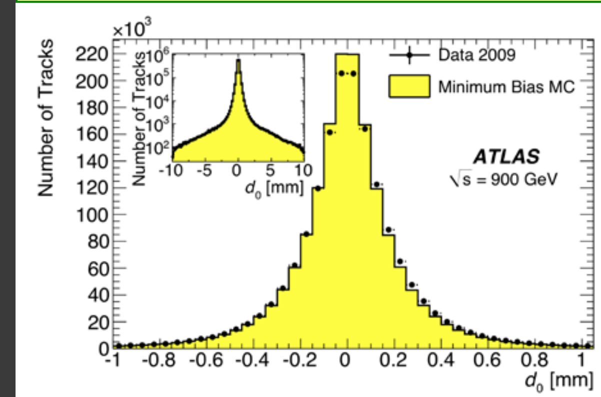


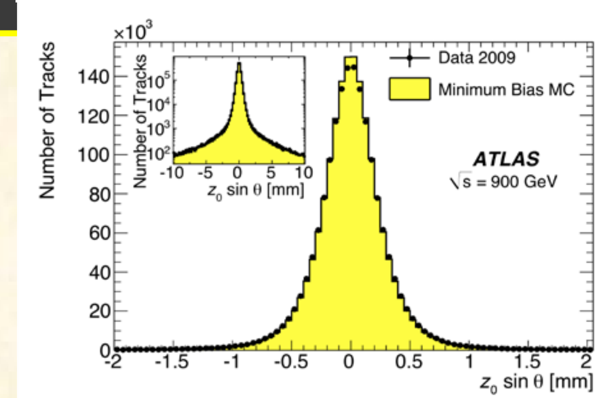


…. towards b-tagging



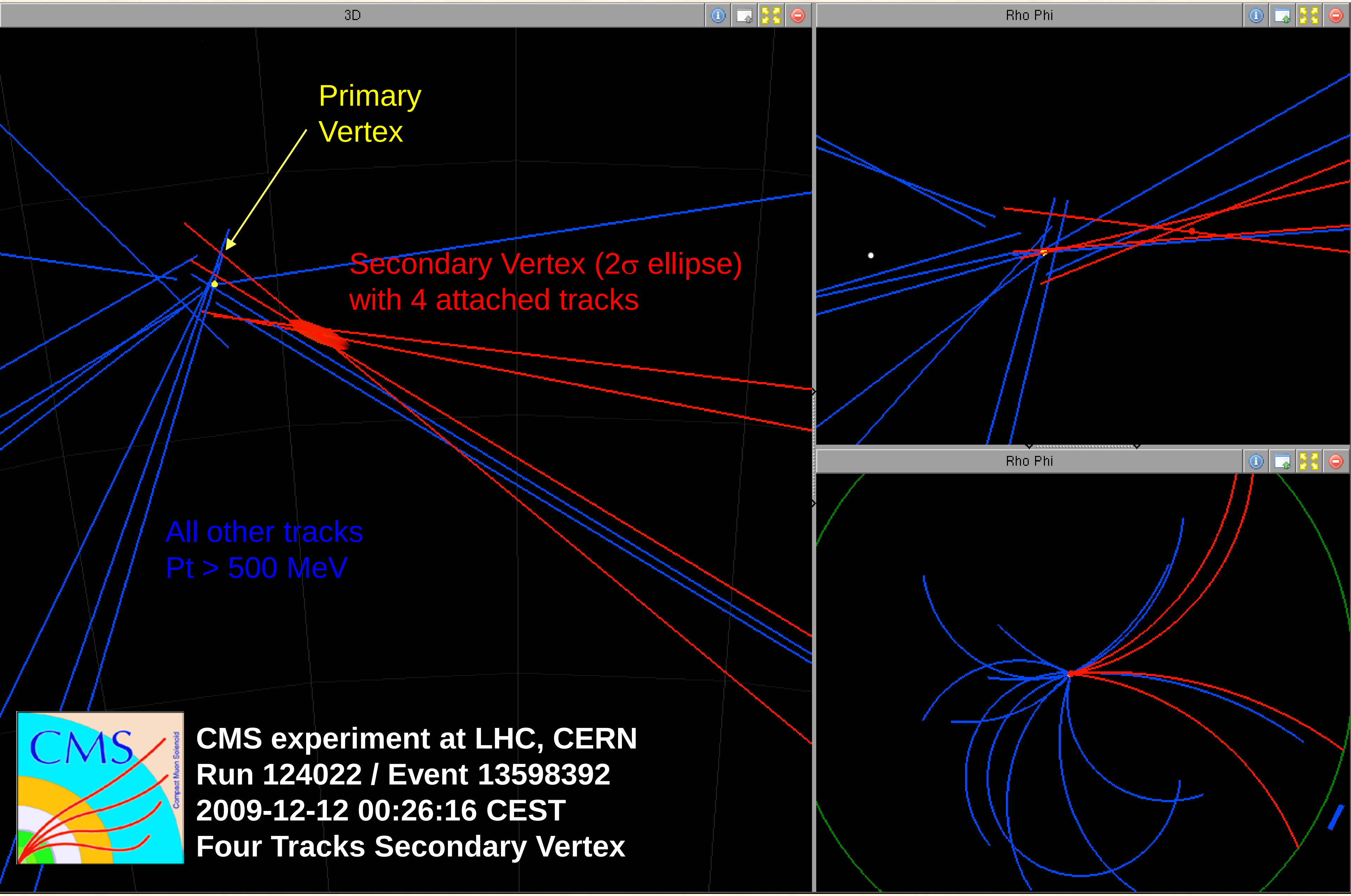
Transverse and longitudinal Impact parameters w.r.t. vertex





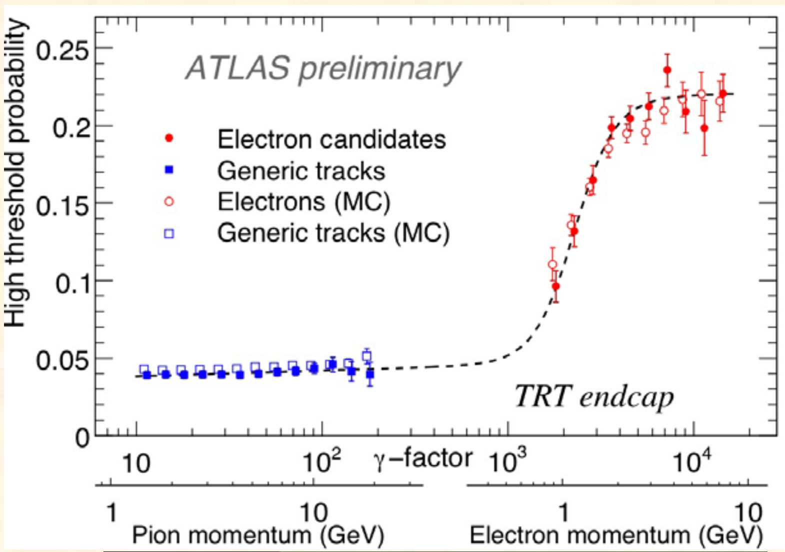
One of the 8 jets tagged with the secondary vertex tagger (SV0) (Light jet probability: 10^{-4})

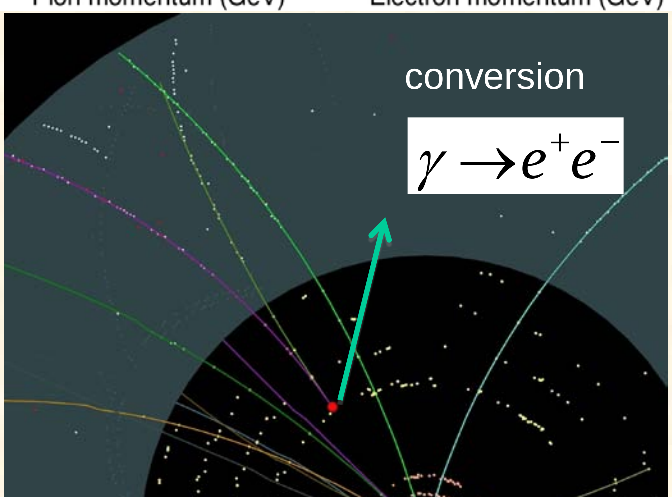
…. CMS b-tagged candidate event

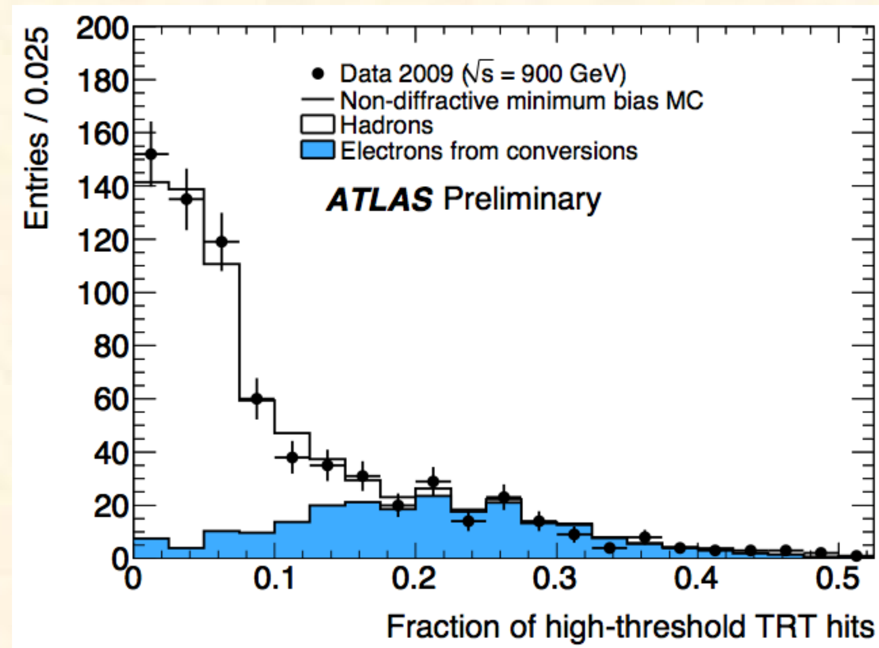


TRT and electron identification

The intensity of the transition radiation in the TRT is proportional to the Lorentz Factor $\gamma = E/mc^2$ of the traversing particle.
Number of high threshold hits is used to separate electrons and pions

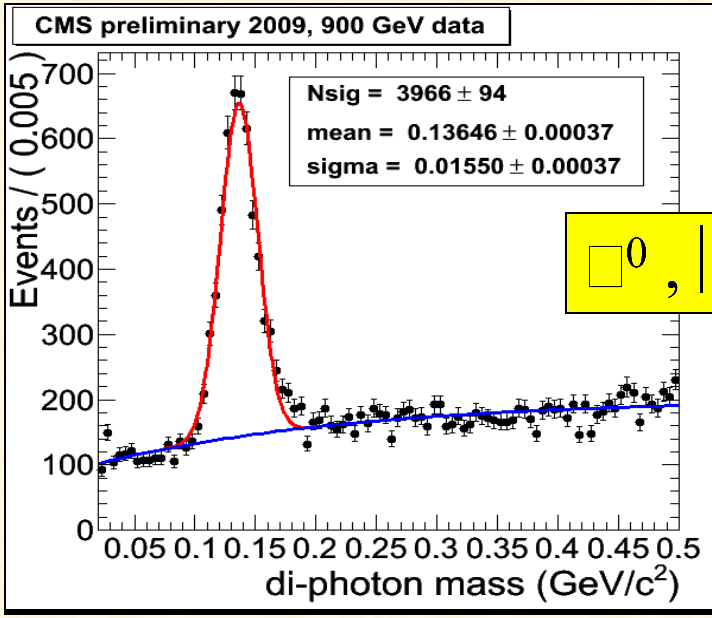




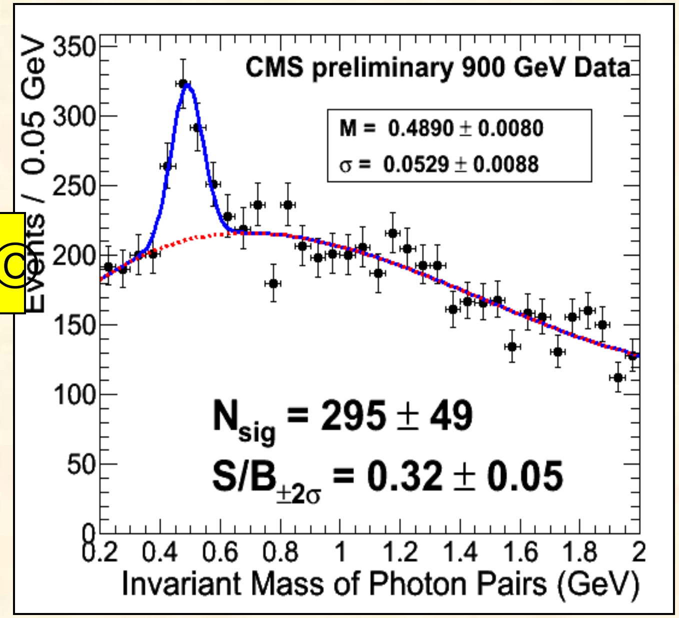


"Tail" towards high-threshold hits is due to electrons from conversion candidates

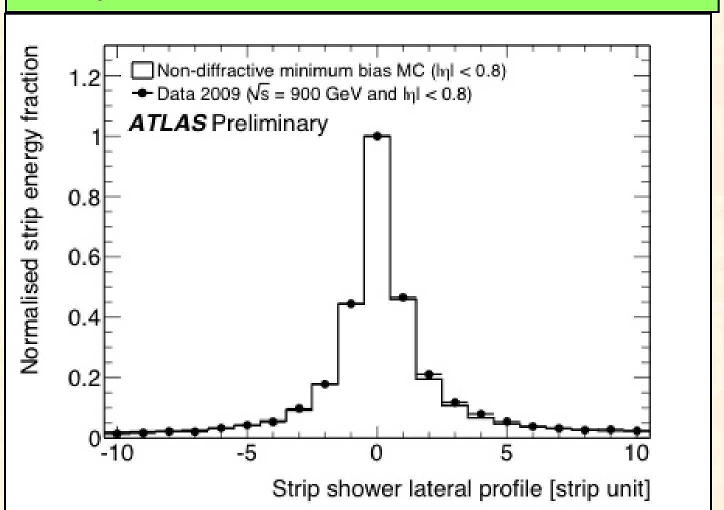
(ii) Calorimeters: resonances in the el.magn. calorimeters

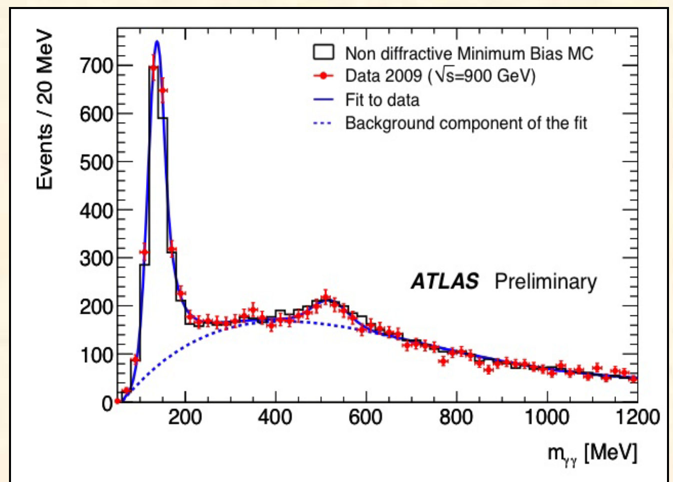


□^{0} , | → ©©



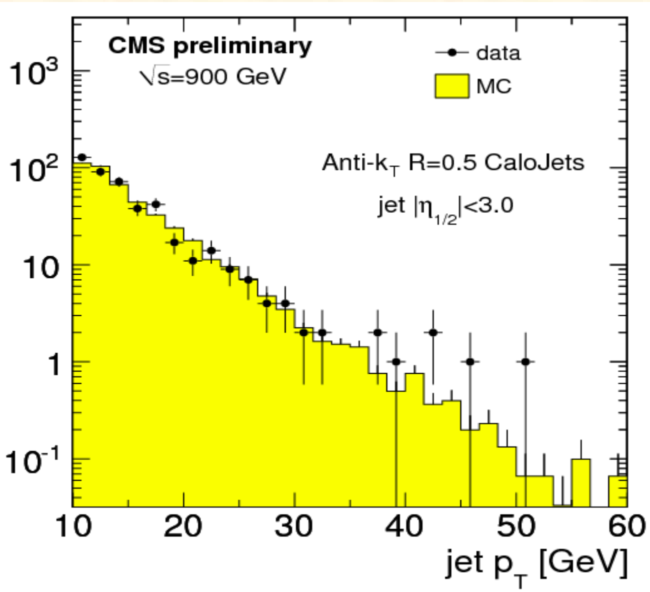
Photon shower shape in the first compartment of ATLAS EM calorimeter

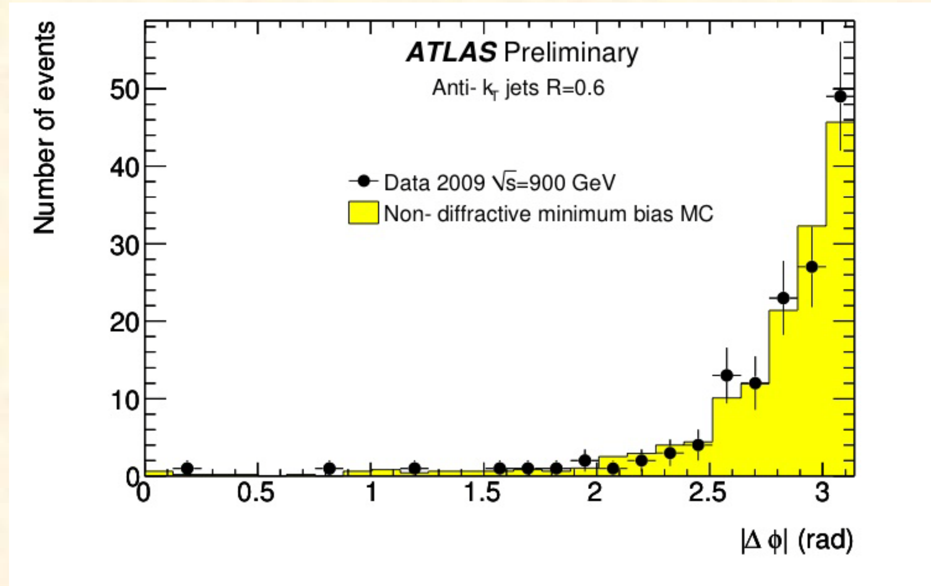


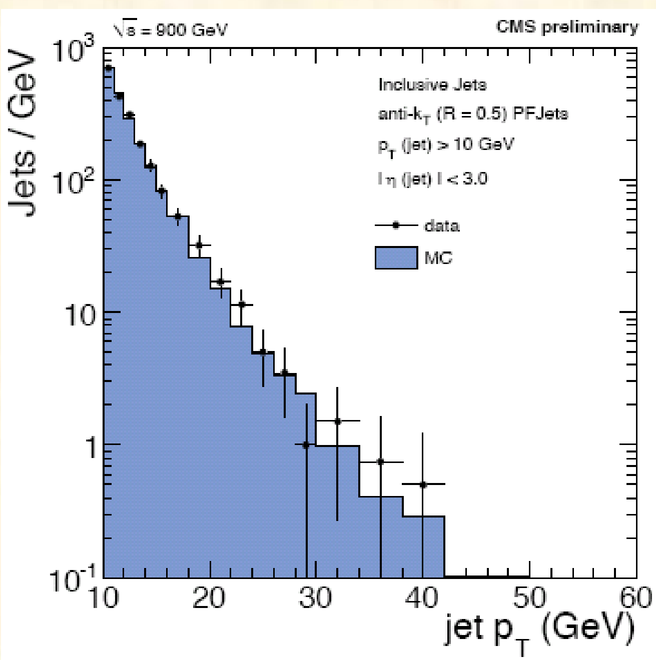


Note: soft photons are challenging in ATLAS: lot of material in front of EM calorimeter (cryostat, coil): ~ 2.5 X_0 at η=0

(iii) Jets and missing transverse energy







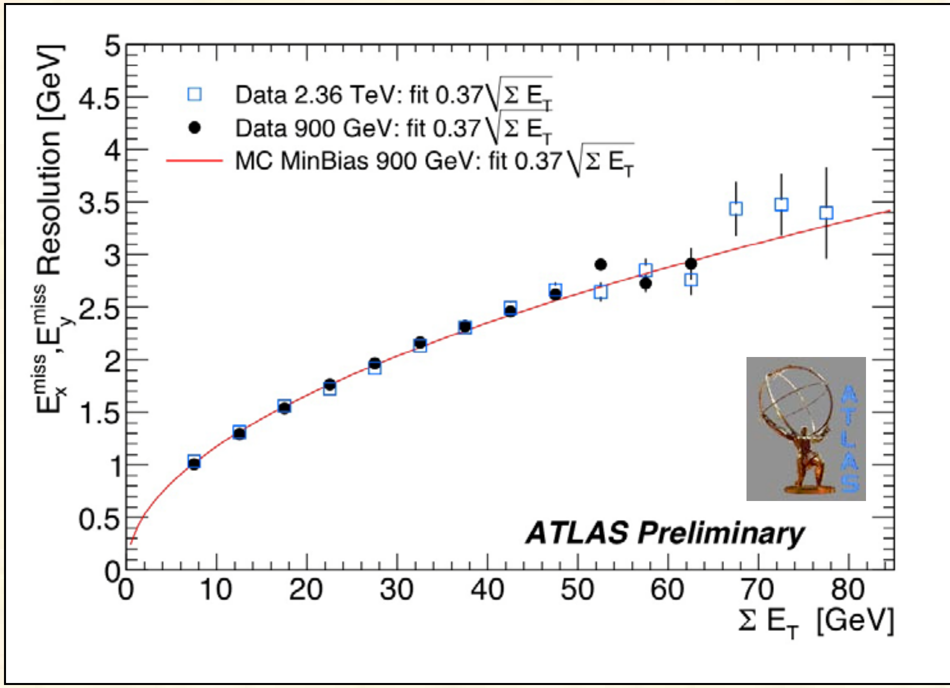
Particle-Flow algorithm:

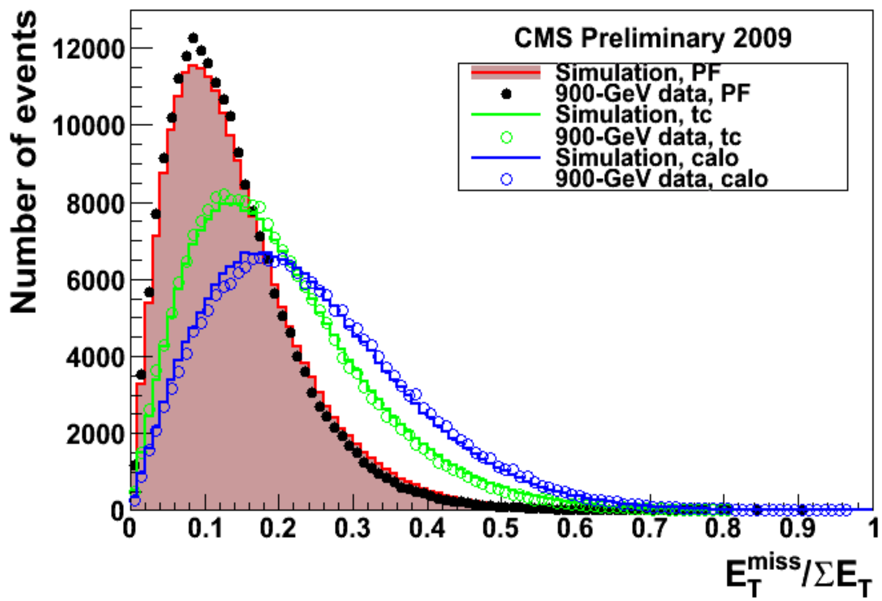
- Identify all type of particles:
• Photons (ECAL only)
• Charged Hadrons (Tracker only)
• Electrons (ECAL+Tracker)
• Neutral Hadrons (CALO only)
• Muons (muon chambers + Tracker)
• And then |, □^{0}, …
- Obtain the best energy estimate for each type of particle

(iv) Missing transverse energy, E_T^{miss}

Sensitive to calorimeter performance (noise, coherent noise, dead cells, mis-calibrations, cracks, etc.) and backgrounds from cosmics, beams, …

Even at this early stage,
the missing E_T
is well described in simulation !





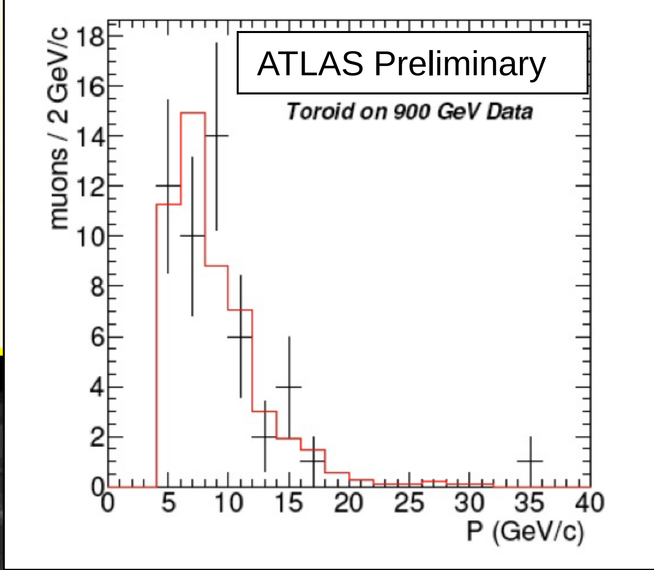
$$\sigma(E_{x,y}^{\text{miss}}) = a \oplus b\sqrt{\sum E_{\text{T}}}$$

Particle-flow based MET:
a = 0.55 GeV, b = 45%

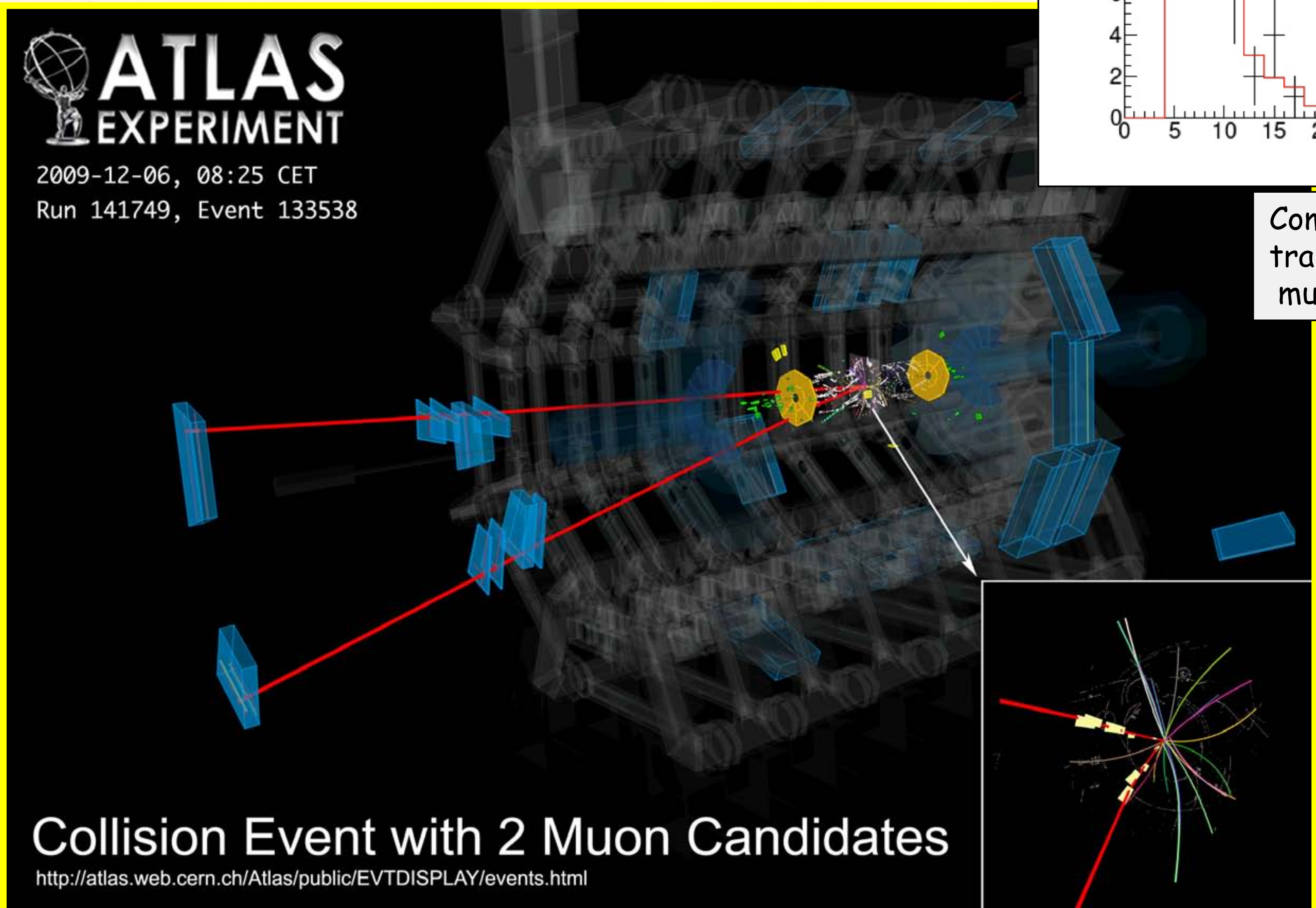
Particle-flow based E_T^{miss} relative resolution is significantly better than calorimeter based E_T^{miss}

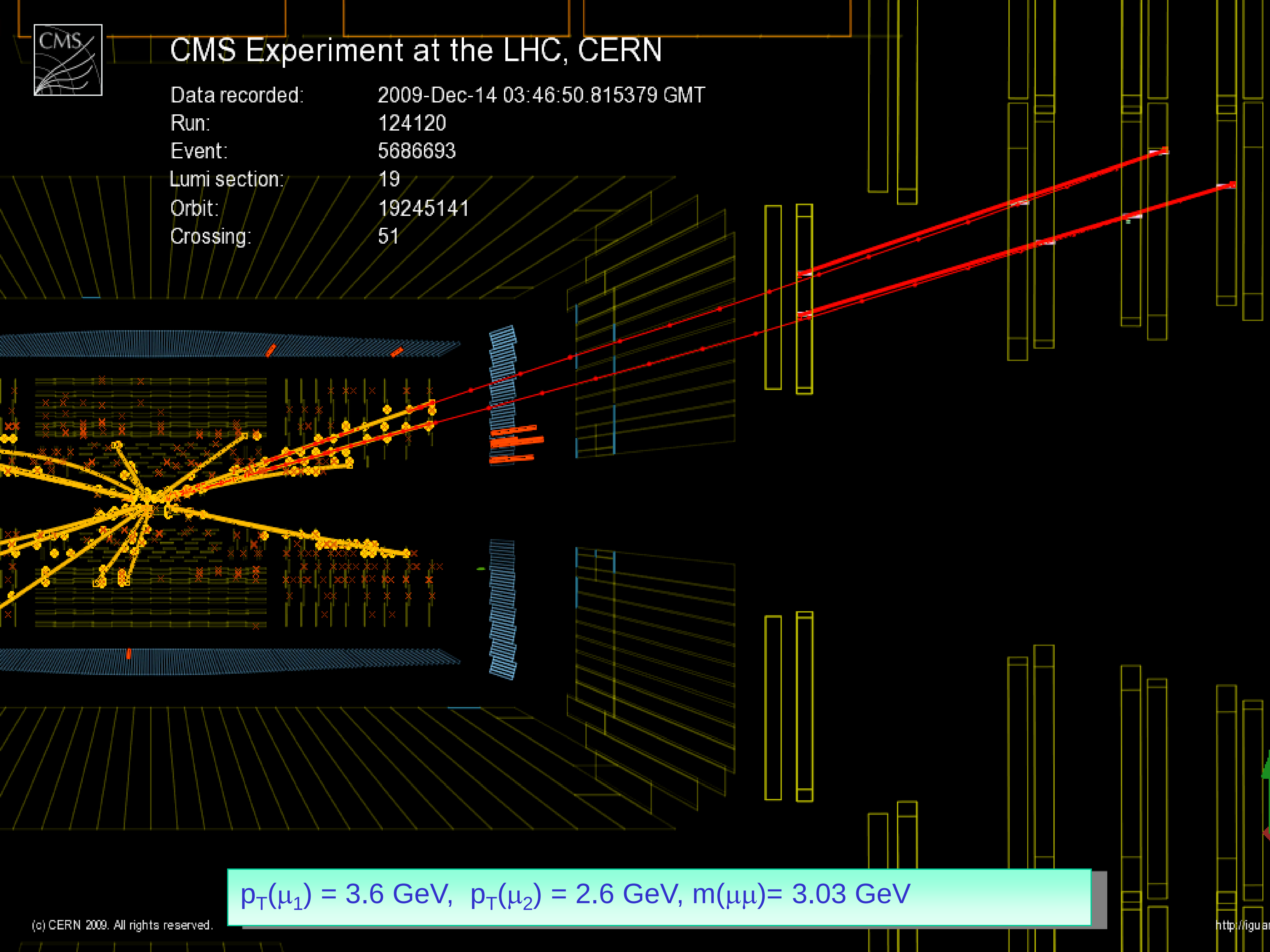
(v) Muons

Only a few muons expected,
mostly from K/□ decays → soft, mostly forward



Combined muons:
tracker +
muon spectrometer

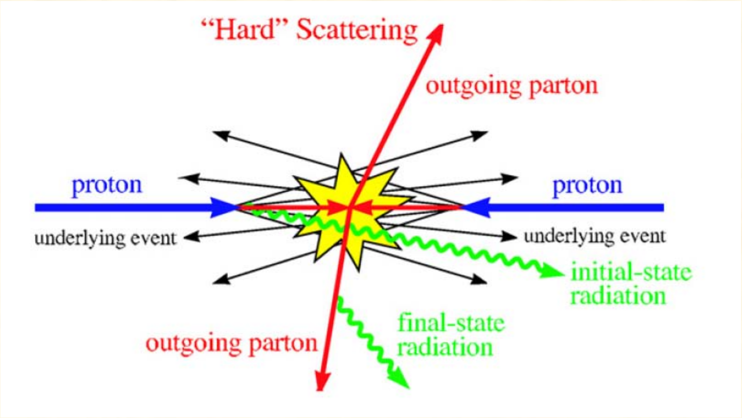


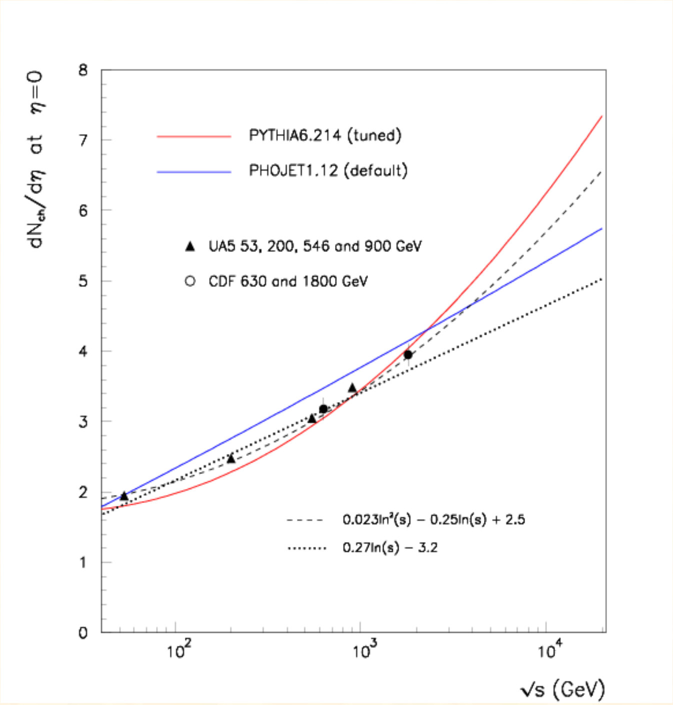


$p_T(\mu_1)$ = 3.6 GeV, $p_T(\mu_2)$ = 2.6 GeV, $m(\mu\mu)$= 3.03 GeV

First Physics

Study of “minimum bias” events



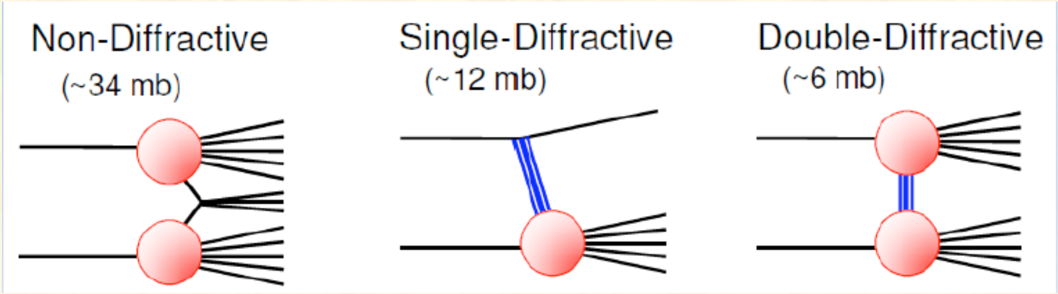


- First physics is dominated by large cross section of inelastic hadronic interactions

- Measurements necessary to constrain phenomenological models of soft-hadronic interactions and to predict properties at higher centre-of-mass energies (underlying event, pile-up of minimum bias events at high luminosity, ….)

Total inelastic pp cross section

- The total inelastic pp cross section has several components:

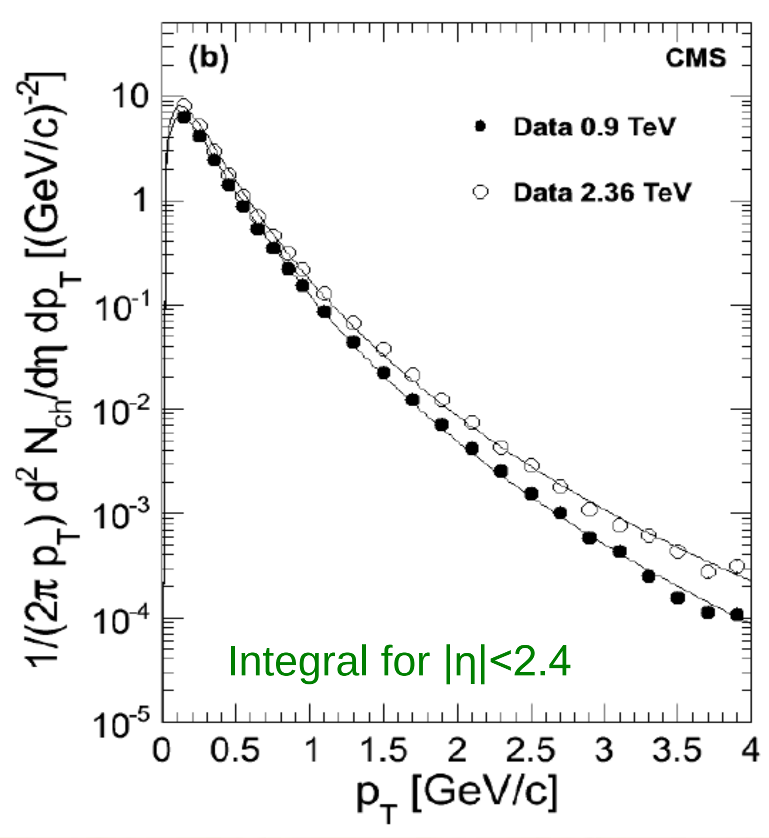


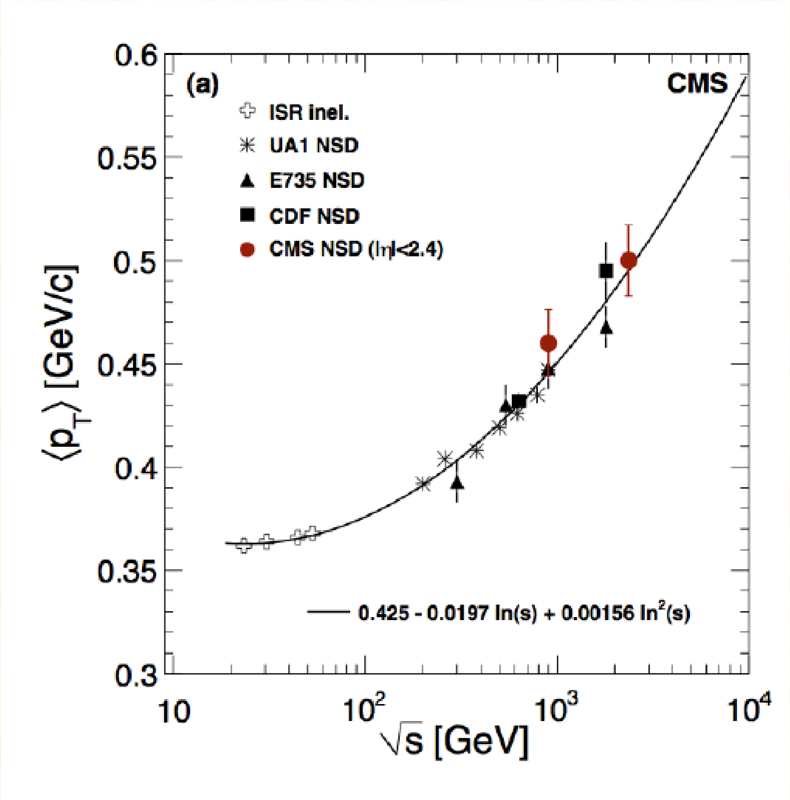
Single **D**iffractive
Double **D**iffractive
Non **D**iffractive

- Use “minimum bias trigger” to study inelastic collisions
  (an “experimental definition”)

- Different definitions can be found in the literature / previous studies:
  (i) Inelastic, non-single diffractive (NSD)
  Trigger selection via double-arm coincidence trigger
  Removal of remaining single-diffractive component, model dependent
  (ii) Inelastic, non-diffractive
  Removal of single- and double-diffractive components, model dependent
  (iii) Inclusive inelastic
  Selection via a single-arm trigger, overlapping with the acceptance of the tracking volume

Charge particle distributions dN/dp_T





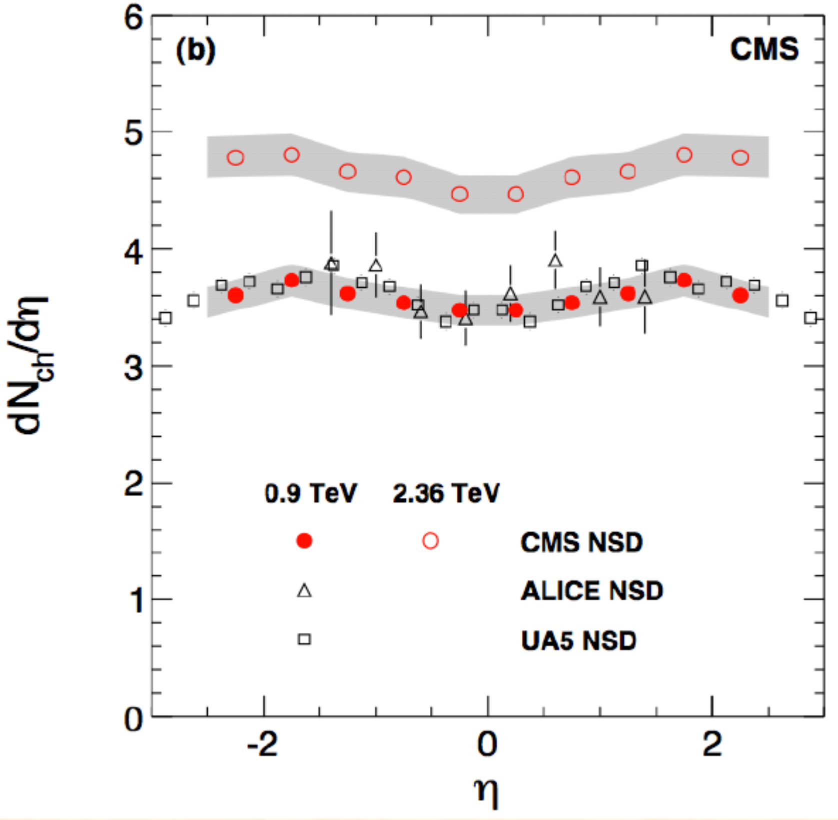
Integral used for $dN/d\eta$ particle count

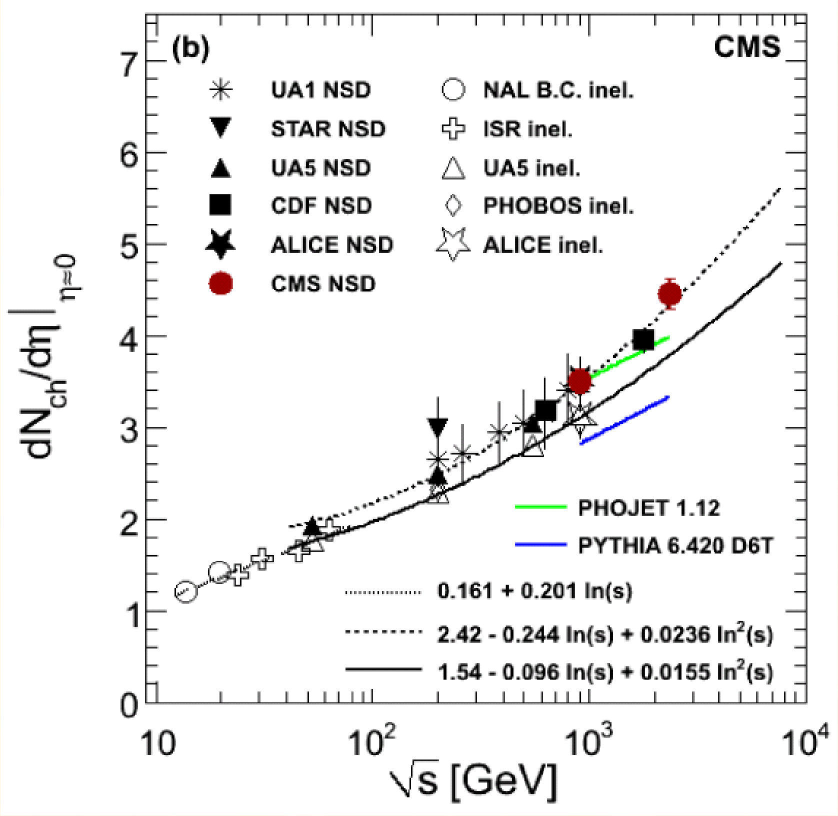
(5% correction at low p_T)

$\langle p_T \rangle = 0.46 \pm 0.01(\mathrm{stat}) \pm 0.01(\mathrm{syst})$ GeV at $\sqrt{s} = 0.90$ TeV

$\langle p_T \rangle = 0.50 \pm 0.01(\mathrm{stat}) \pm 0.01(\mathrm{syst})$ GeV at $\sqrt{s} = 2.36$ TeV

dN/dη distributions





Shaded bands indicate systematic errors (largest part is due to uncertainty in SD/DD contamination (2%))

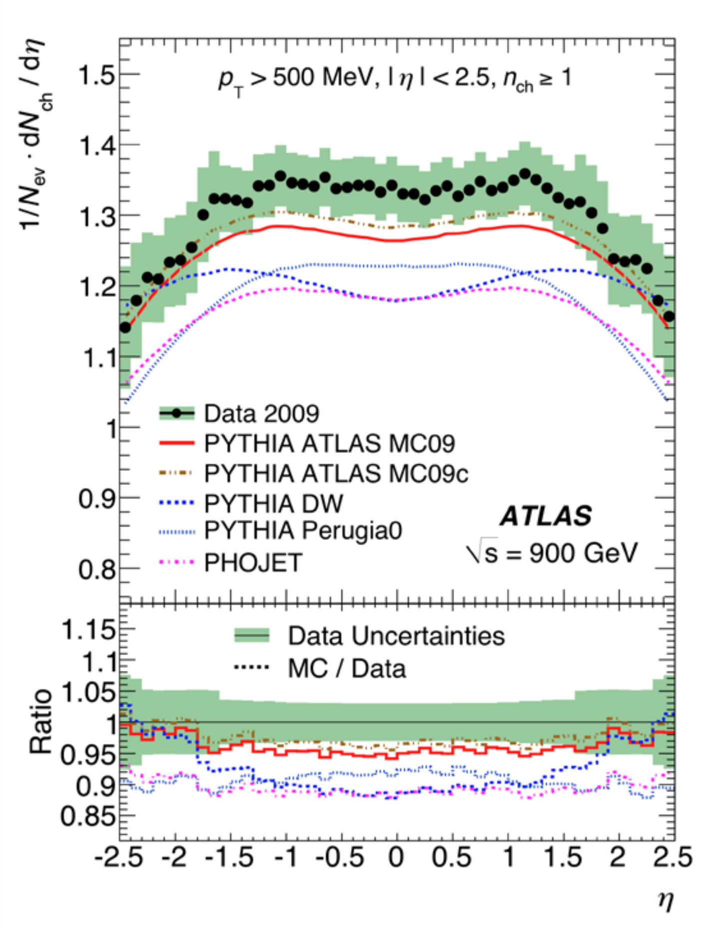
UA5 and CMS results are symmetrised in η. UA5 and ALICE errors are statistical only

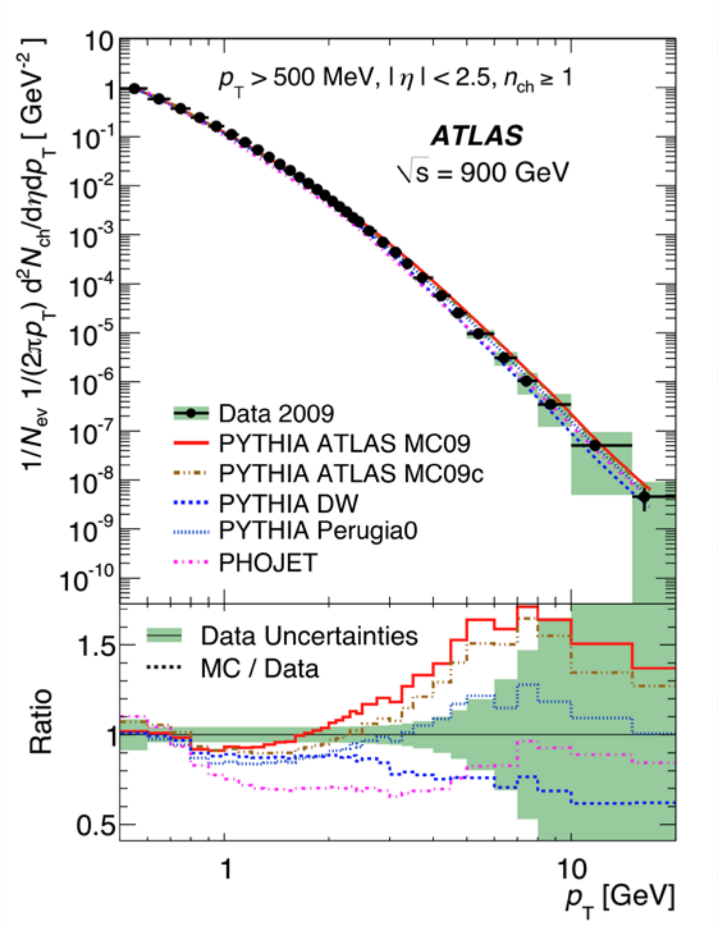
Increase in charged particle multiplicity from 0.9 to 2.36 TeV is significantly higher than predicted by Monte Carlos (PYTHIA, PHOJET)

Charged particle density versus η and p_T

p_T > 500 MeV
|η| < 2.5
N_{ch} ≥ 1

N_{ch}: number of primary charged particles corrected to particle level, normalized to the number of selected events N_{ev}



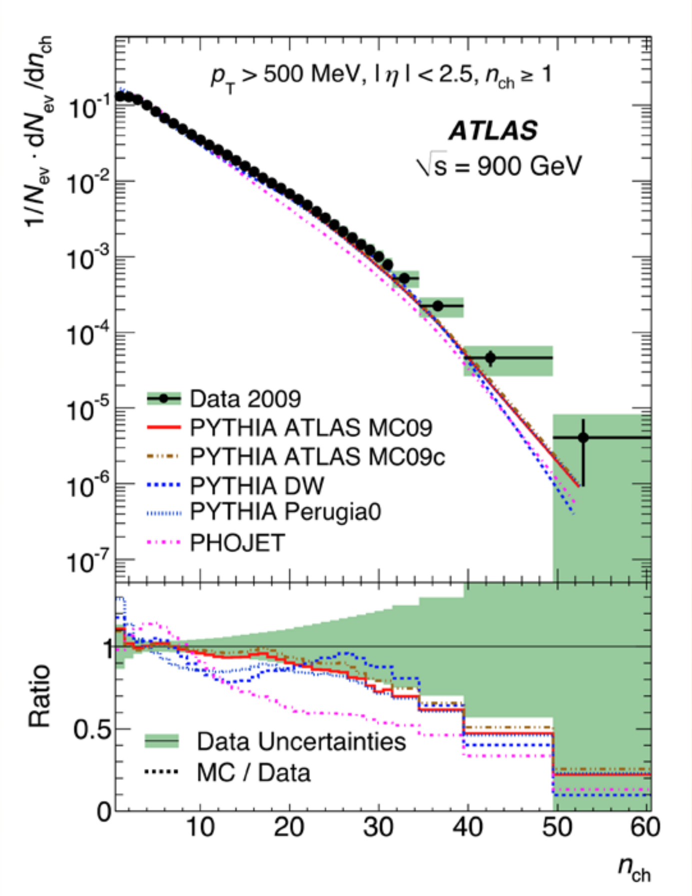


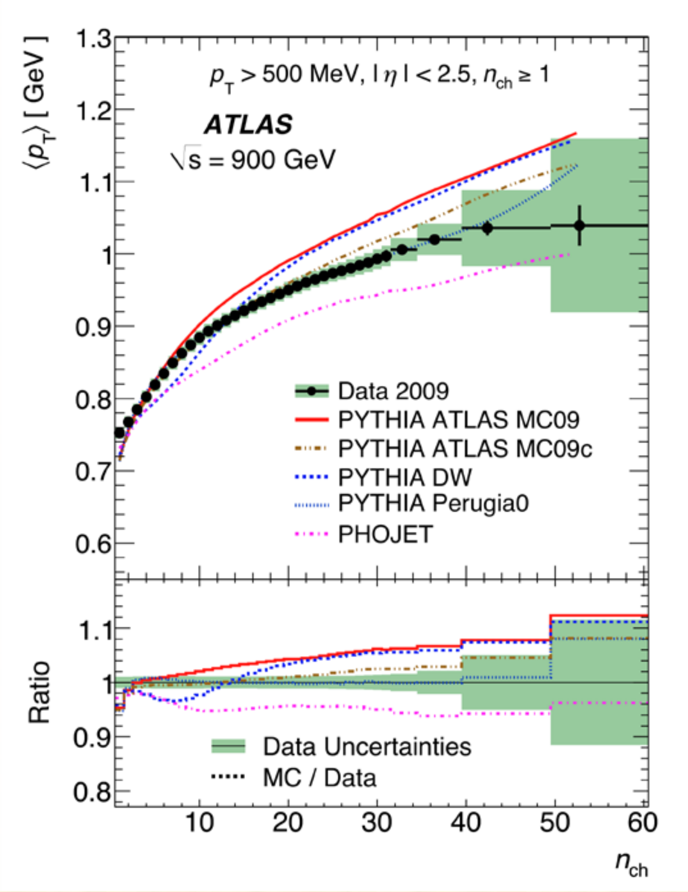
Various Monte Carlo models fail to describe the ATLAS data

Charged particle multiplicities and average P_T

N_{ch}: number of primary charged particles corrected to particle level, normalized to the number of selected events N_{ev}

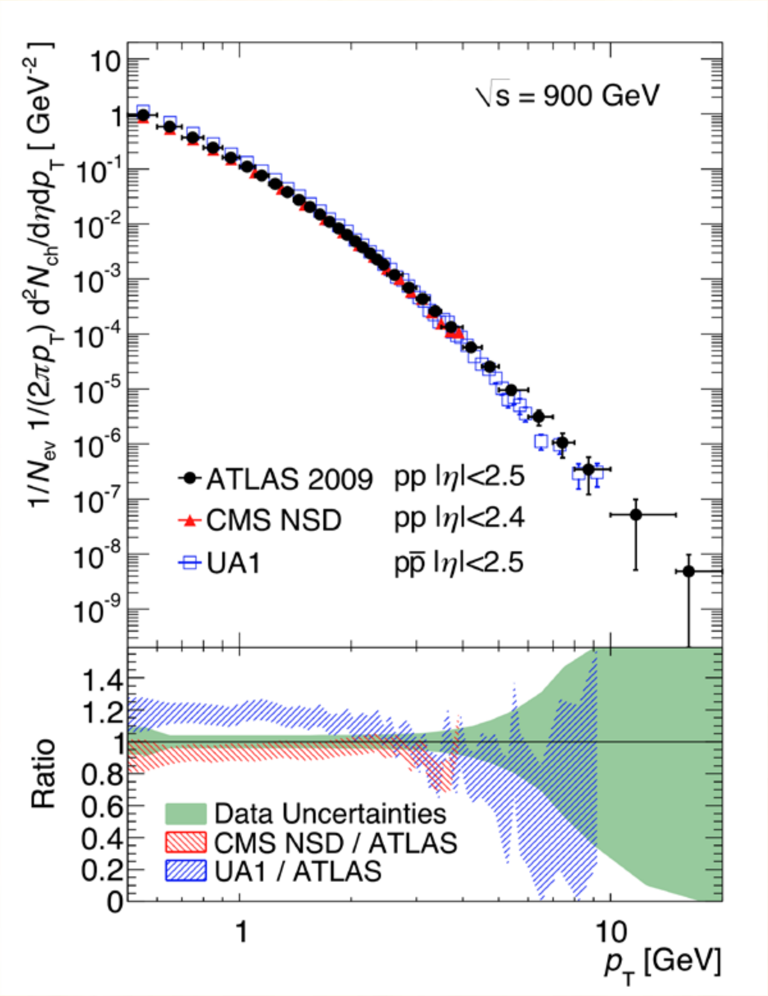
$p_T > 500$ MeV
$|\eta| < 2.5$
$N_{ch} \geq 1$





Monte Carlo models also fail to describe particle multiplicities and the average P_T as function of N_{ch}

Comparison of experimental measurements



ATLAS vs. CMS:

N_{ch} measured to be lower in CMS

CMS measures NSD contributions;
Model-dependent corrections applied

ATLAS vs. UA1:

UA1 data has been normalized by their associated cross-section measurement
N_{ch} ≈20% higher than ATLAS
UA1 used a “double arm” trigger which rejects events with low charged particle multiplicities

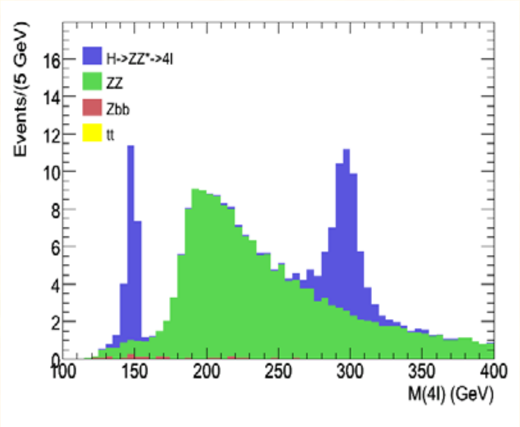
ATLAS Preliminary $<N_{ch}>$	P_T > 500 MeV
$\lvert\eta\rvert$ < 2.5	1.333 ± 0.003(stat) ± 0.040(syst)
NSD $\lvert\eta\rvert$ < 2.4	1.241 ± 0.040
NSD obtained using the PYTHIA DW tune (Tevatron)	

CMS NSD (P_T > 0.5 GeV)	1.202 ± 0.043

Expectations for 2010 / 2011

(i) Machine

(ii) Physics



(i) Machine: expectations for 2010/11

Preliminary outcome from the Chamonix LHC workshop:

- *"The LHC will run at 3.5 + 3.5 TeV in 2010 and 2011, until the experiments collect an integrated luminosity of ~ 1 fb^{-1}. Only a short technical stop is foreseen at the end of 2010 / beginning of 2011. The 2010/11 run will be followed by a long (~1year) shut-down, to redo all splices and thus enable the machine to operate up to the design energy of 7 + 7 TeV"*
- *A firmer plan can only be made around June, after experience is gained with the machine operation and performance (e.g. in terms of luminosity) at 3.5 + 3.5 TeV.*

-

Machine plan in numbers:

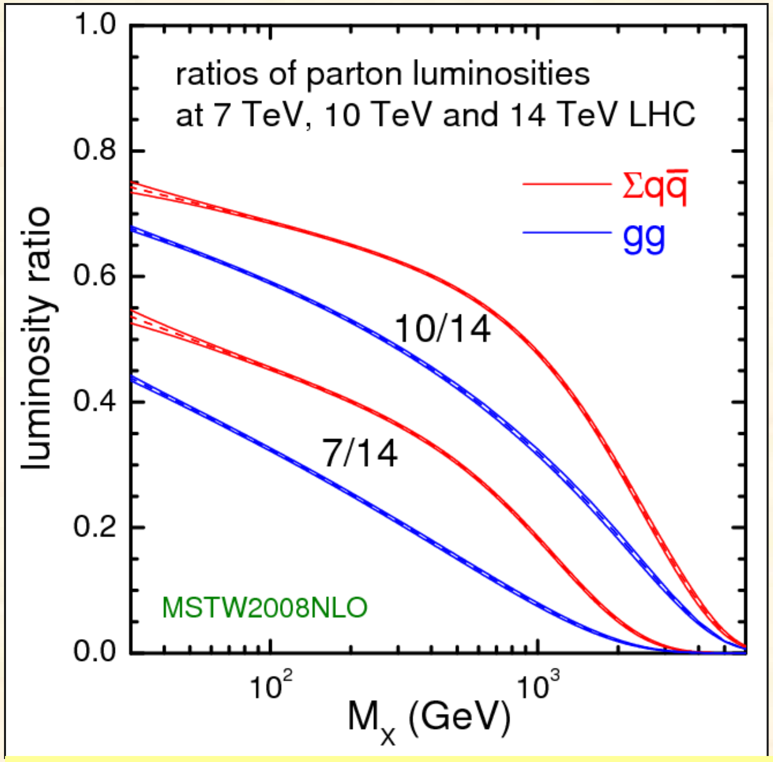
2010: L = ~10^{28} → 10^{32} cm^{-2} s^{-1} → total of 100-200 pb^{-1}

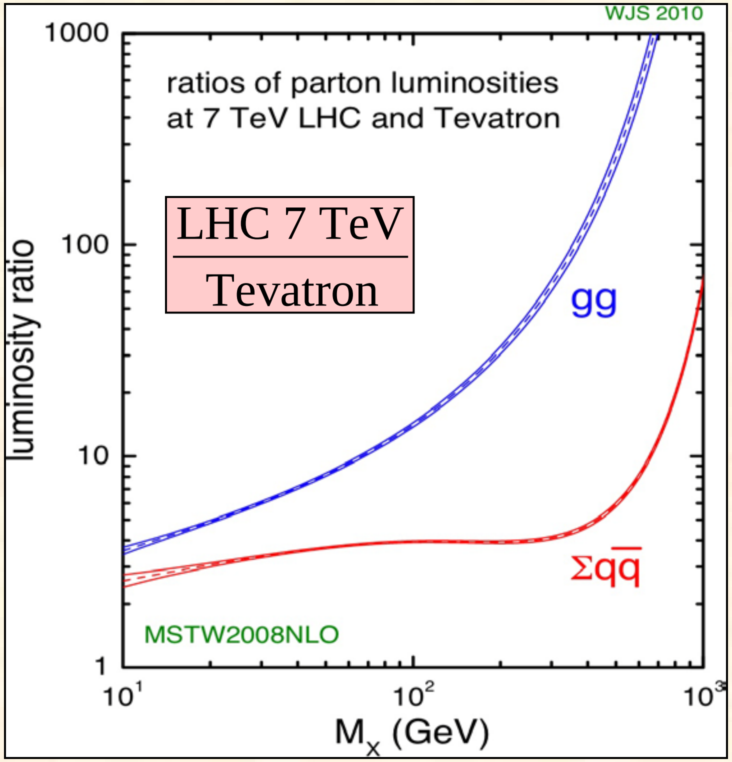
2011: L = 1→ few 10^{32} cm^{-2} s^{-1} → collect ≥ 100 pb^{-1} per month
→ total of ~ 1 fb^{-1}

2012: shut-down

Impact of reduced beam energy

- Ratio of parton luminosities for 7/14 and 10/14 TeV …





J.Stirling
http://projects.hepforge.org/mstwpdf/plots/plots.html

ttbar:
7/14 = 0.2

W' (1.5 TeV):
7/14 = 0.1

W' (1 TeV):
7(pp) / 2(ppbar) ~ 60

...but still large factor compared to the Tevatron ($\sqrt{s}$ =1.96 TeV)

Physics Goals for 2010/11

1. Further understanding of the detector and the reconstruction with collision data (e, μ, τ, jet, E_T^{miss}, b-tagging, …)

   Using well-known physics samples

   - $Z \rightarrow ee, \mu\mu, \tau\tau$
   - $tt \rightarrow bl\nu\ bjj$: jet scale from $W \rightarrow jj$, b-tag performance, …

2. "Re-discovery" of the Standard Model

   - Jets, QCD, W/Z physics, top,....

3. Search for new physics beyond the SM

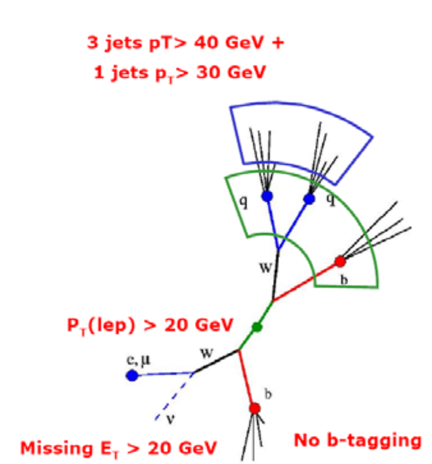
A few examples and **very preliminary estimates** on the 7 TeV physics reach are discussed in the following (7 TeV simulations have just started)

W/Z and top cross sections

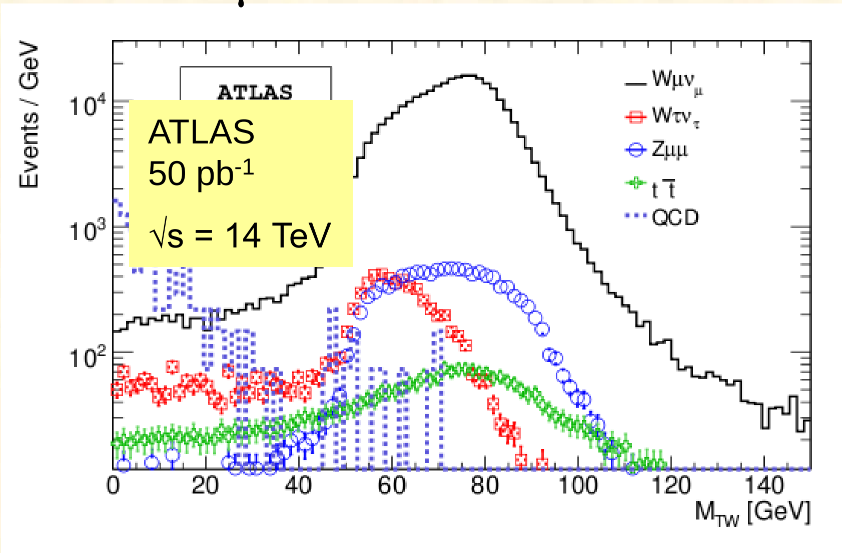
Even with early data (10-50 pb^{-1}), high statistics W and Z samples

→ data-driven cross section measurements

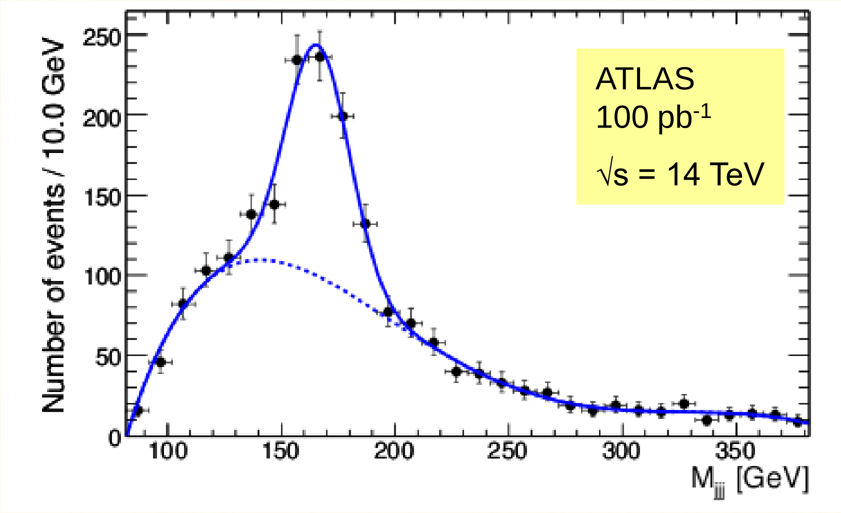
Simple kinematical Selection of tt events;



W → μ ν



Reconstructed mass distribution of
tt → Wb Wb → ℓνb qqb decays (no b-tags)



Cross section measurements (test of perturbative QCD) are limited by systematics (luminosity, jet energy scale (top), …..
Luminosity error: ~ 5-10% in first years,
~ 2- 3% is the longer term goal

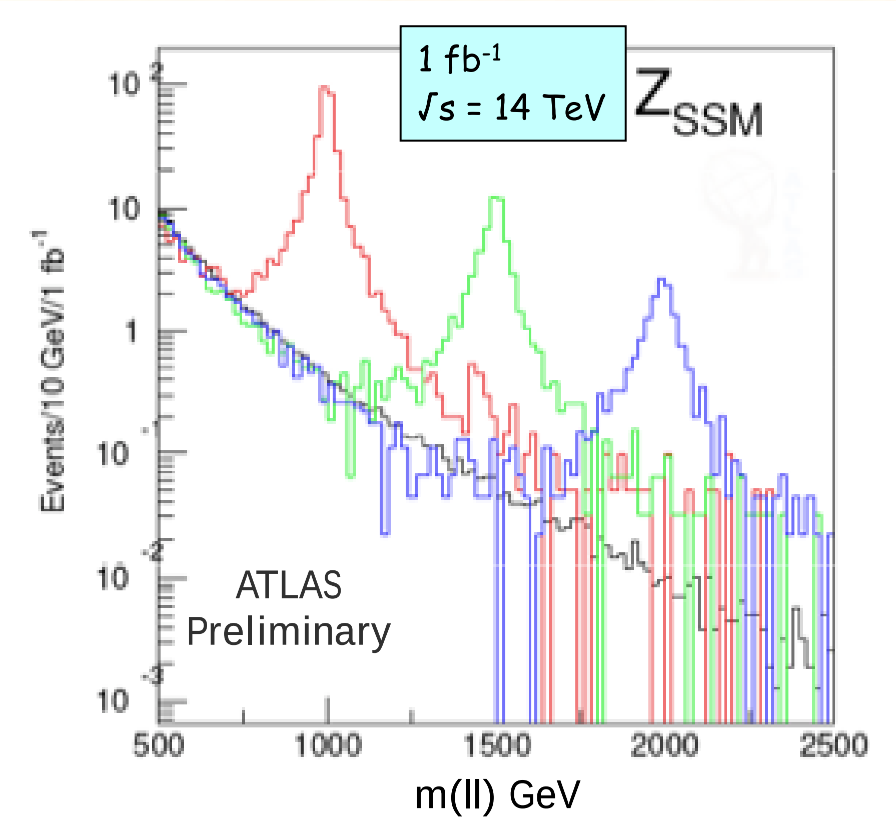
Early Surprises ??

- as already mentioned, the experiments must be open for surprises / unknowns / unexpected discoveries

- requires unbiased measurements of
  - inclusive lepton spectra
  - dilepton spectra……
  - E_T^{miss} spectrum…….
  - ……

One example of many….

$Z' \rightarrow e^+e^-$ with SM-like couplings (Z_{SSM})



Z' (SSM): Tevatron limit ~ 1 TeV (95% C.L)

50 pb^{-1} : exclusion up to ~ 1 TeV (95% C.L.)
500 pb^{-1} : discovery up to ~ 1.3 TeV
exclusion up to ~ 1.5 TeV
1 fb^{-1} : discovery up to ~ 1.5 TeV

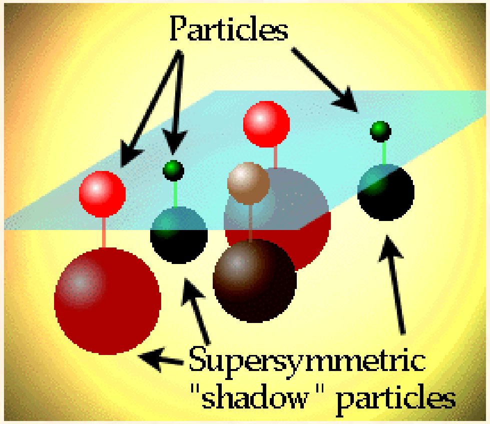
W' : Tevatron limit ~ 1 TeV (95% C.L)

10 pb^{-1} : exclusion up to 1 TeV
100 pb^{-1} : discovery up to ~ 1.3 TeV
1 fb^{-1} : discovery up to ~ 1.9 TeV
exclusion up to ~ 2.2 TeV

Discovery reach above Tevatron limits
m ~ 1 TeV, perhaps in 2010 ?

Search for

Supersymmetry



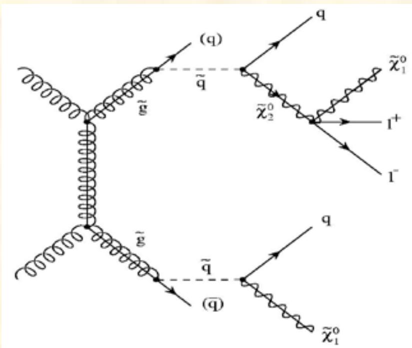
First hints of supersymmetry might show up
already in early data……

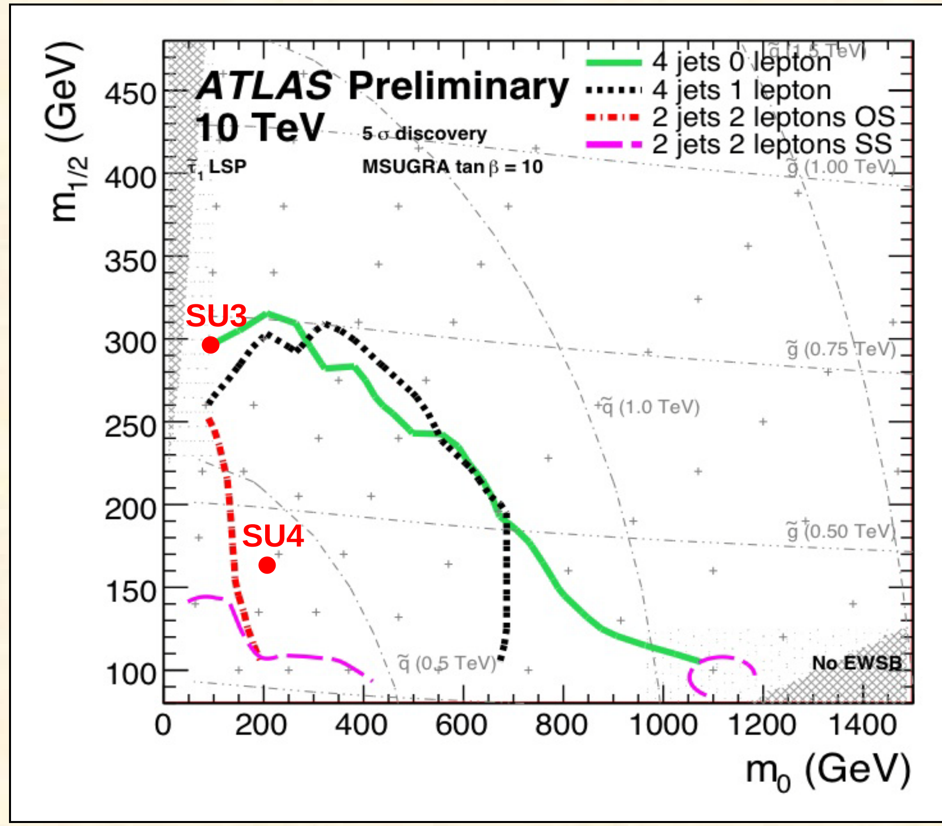
1. Step: Look for deviations from the Standard Model
Example: Multijet + E_T^{miss} signature

2. Step: Determine model parameters (difficult, not for 2010/11)
Strategy: select particular decay chains and use kinematics to determine mass combinations

LHC reach in the m_0 - $m_{1/2}$ mSUGRA plane:

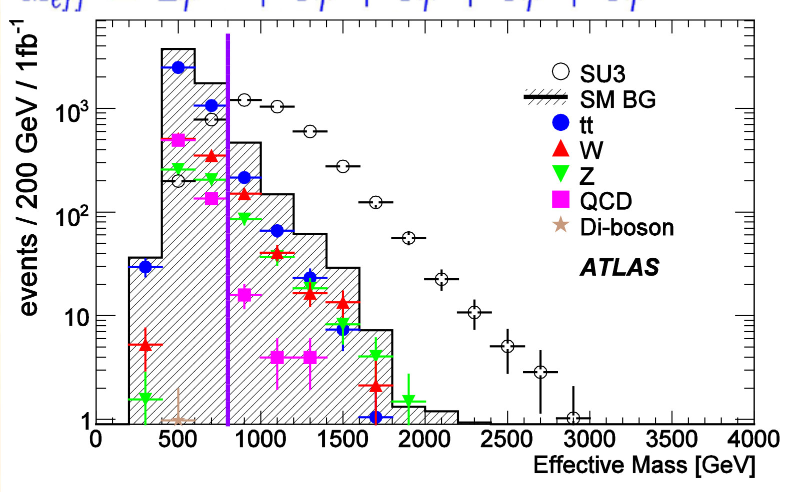
Multijet + E_T^{miss} signature





Distribution of the effective mass:

$$M_{eff} = E_T^{miss} + P_T^1 + P_T^2 + P_T^3 + P_T^4$$

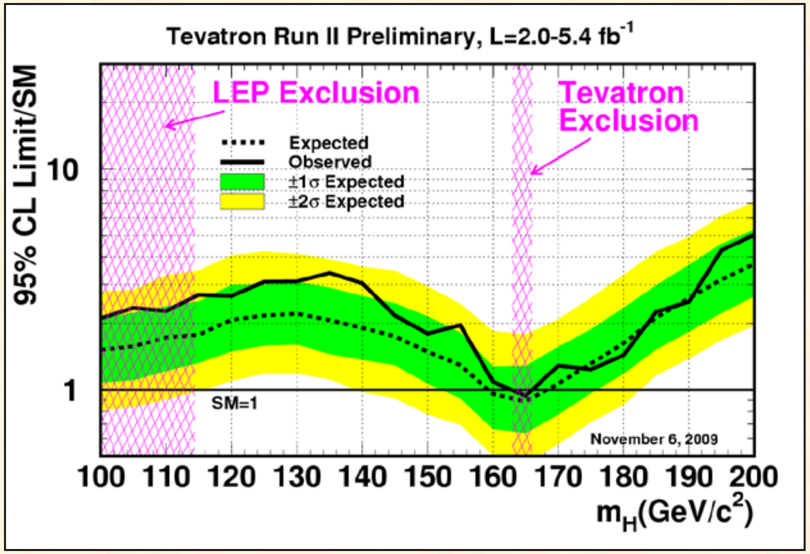


Tevatron squark/gluino limit: ~ 400 GeV (95% C.L)

100 pb^{-1} : discovery up to ~ 400 GeV
1 fb^{-1} : discovery up to ~ 800 GeV

Where is the

Higgs Boson ?

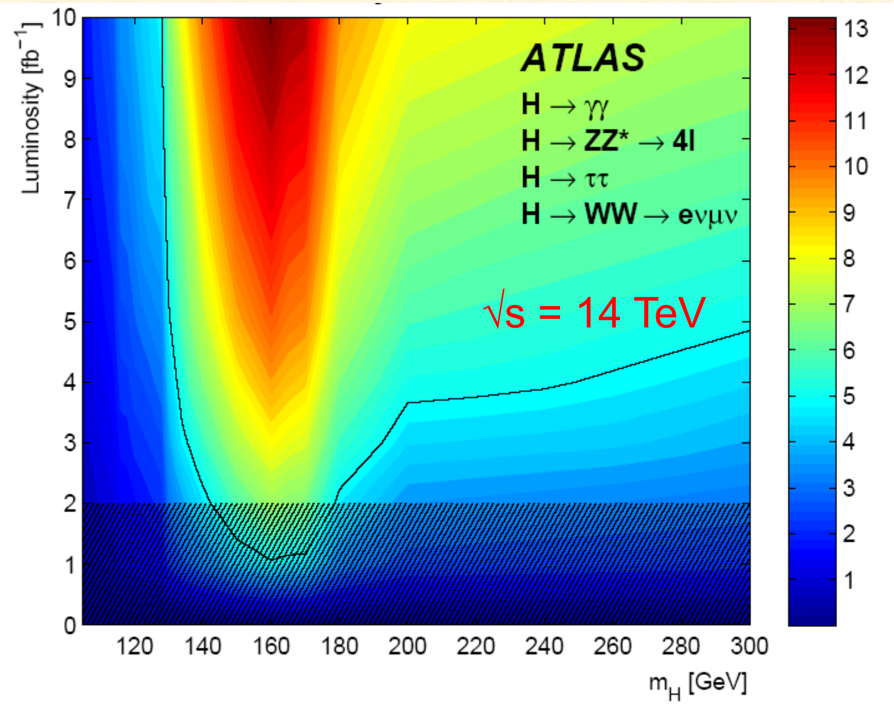


Prospects for the SM Higgs boson discovery

- A long way to go if the Higgs boson mass is around 115 GeV

  Tevatron and LHC are complementary in this mass range

  Tevatron: WH, ZH with H → bb
  LHC: H → $\gamma\gamma$, qqH → qq $\tau\tau$ and
  WH → lν bb (high P_T Higgs, new)



Very preliminary estimates !

$\sqrt{s}$=7 TeV: most sensitive channel H → WW at m_H ~ 160 GeV

300 pb^{-1} per experiment : ~ 3σ sensitivity combining ATLAS and CMS (similar to Tevatron)
1 fb^{-1} per experiment: ~ 4.5 σ combining ATLAS and CMS at 160 GeV
95% C.L. Higgs exclusion: 145 < m_H < 180 GeV

- Exclusion of the full mass range down to m_H~115 GeV requires ~1.5 fb^{-1} per exp. at 14 TeV
- Discovery for m_H ~ 115 GeV requires ~ 10 fb^{-1} per experiment at 14 TeV

Summary / Conclusions

- After more than 15 years of hard work the *Large Hadron Collider* and the experiments have started operation in Dec 2009;

- The ATLAS and CMS experiments have successfully collected first collision data
(thanks also to the exceptional performance of the LHC machine team !).

- The experiments operated efficiently, from data taking at the pit, to data processing and transfer worldwide, to fast delivery of first results.

- Preliminary results indicate that the performance of the detectors, as well as the simulation and reconstruction tools, are far better than expected at this (initial) stage.
(Years of preparation work, testbeam, cosmics, simulations,…. paid off)

- ATLAS and CMS should be able to produce interesting physics results soon !
The physics reach will be competitive with the Tevatron in 2010, but will be superior for an integrated luminosity around 1 fb^{-1}.

Trigger

- Primary physics trigger in 2009:
  - Beam pickup timing devices (BPTX)
    - Electrostatic beam pickup located at ± 175 m from interaction point
  - Minimum Bias Trigger Scintillators (MBTS)
    - located at ± 3.56m in z from the interaction point
    - 32 scintillating counters covering 2.09 < |η| < 3.84
- Average event rate of collision trigger (MBTS + BPTX): ~ 10 Hz