The Large Hadron Collider: The Accelerator and the Experiments

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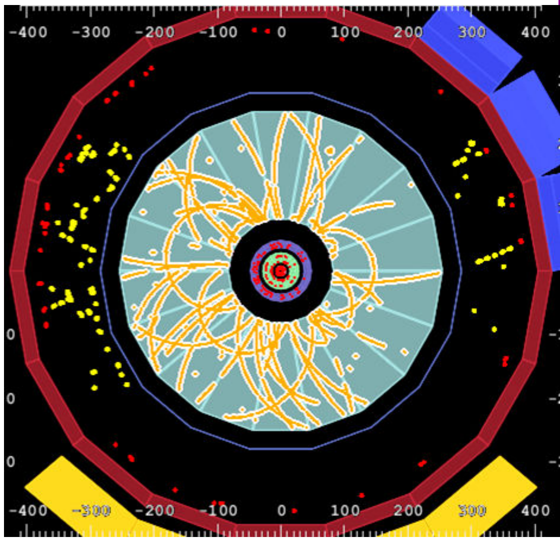
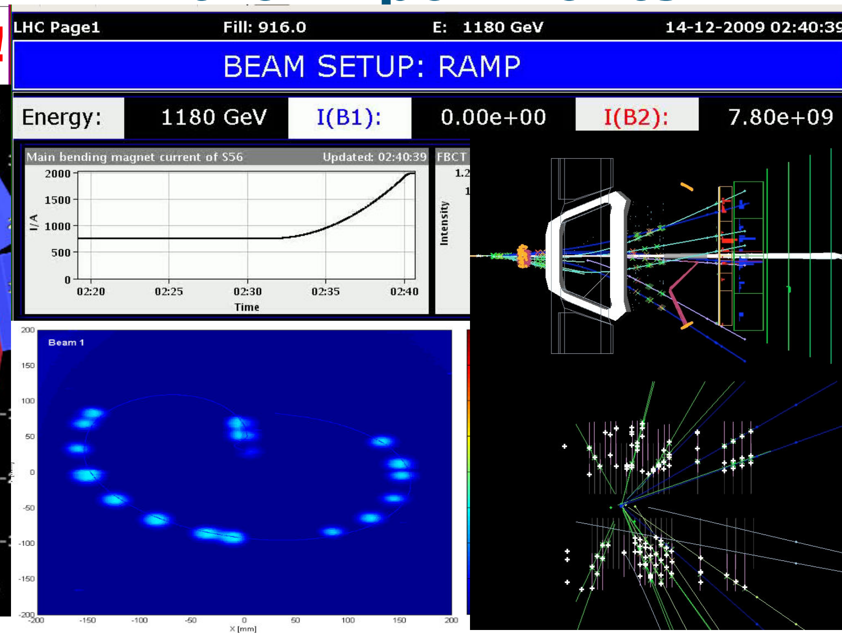
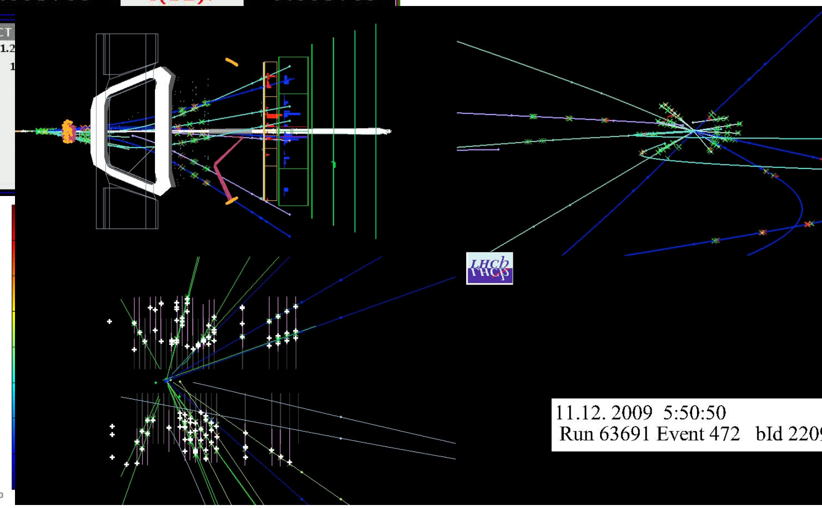
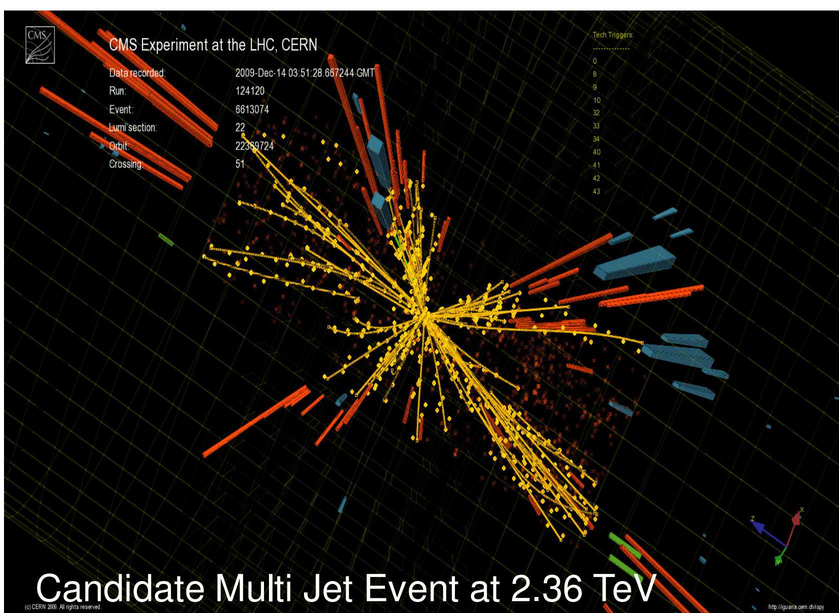
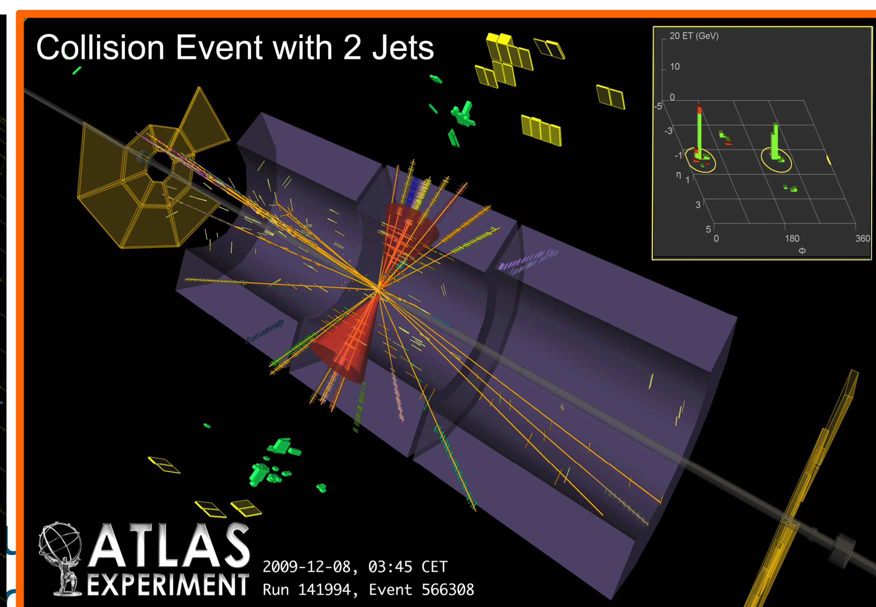
LHC Provides Collisions!











Early 1990's

Reminder from Early 1990's

1. **SM has an unproven element: the generation of mass**

   Answer will be found at $\sqrt{s}$ ~ 1 TeV e.g. why $M_\gamma = 0$, $M_Z \sim 90$ GeV/c^2

2. **SM without Higgs gives nonsense at LHC energies**

At $\sqrt{s} > 1$ TeV probability of $W_L W_L$ scattering > 1 !!

The SM solution: Higgs exchange cancels bad high energy behaviour.

3 **Even if the Higgs exists, all is not 100% well with the SM alone: next question is "why is the (Higgs) mass so low"?**

If SUSY is the answer, it must show up at O(TeV)

4. **SM is logically incomplete**

Does not incorporate gravity. Superstring theory ? ⇨ dramatic concepts : supersymmetry, extra space-time dimensions ?

Experimentally

Search forNew particles/new symmetries/new forces?

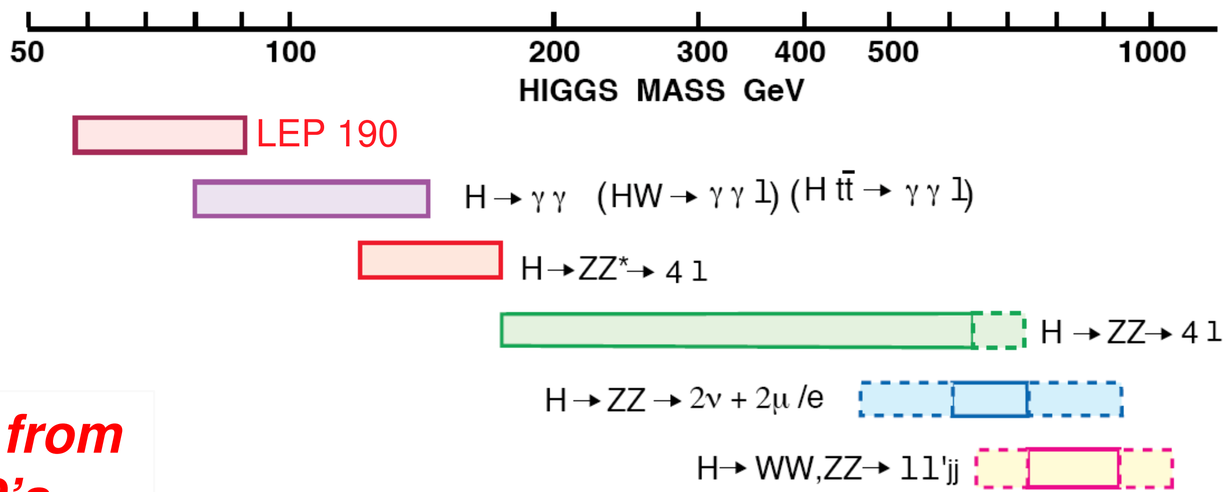
⇨Higgs boson(s), Supersymmetric particles, Z', …unexpected

New: Extra space-time dimensions: gravitons, black holes

Driving the Design of LHC Xpts

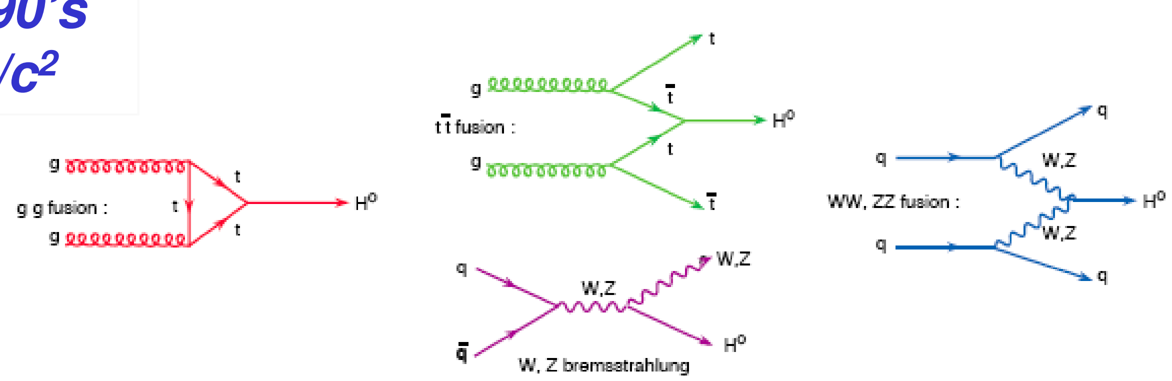
At the LHC the SM Higgs provides a good benchmark to test the performance of a detector

Natural Width 0.01 1 10 100 GeV



Transparency from the early 90's

At the end of 90's $m_H > 114\ GeV/c^2$



Summary of Requirements

What Accelerator?
New Energy Domain
Search for the unexpected in an energy domain $\sqrt{s} > 1$ TeV

Exploratory machine ⇨"Broadband" **The Large Hadron Collider**
Largest possible primary energy (~ 7 TeV)
Largest possible luminosity (~ 10^{34} $cm^{-2}s^{-1}$)

What Detectors? ATLAS and CMS
Very good muon identification and momentum measurement
Trigger efficiently and measure sign of TeV muons $dp/p < 10\%$
High energy resolution electromagnetic calorimetry
~ 0.5% @ E_T ~ 50 GeV
Powerful inner tracking systems
Momentum resolution a factor 10 better than at LEP
Hermetic calorimetry
Good missing E_T resolution
(Affordable detector)

The Large Hadron Collider

LHC Timeline

1984 Workshop on a Large Hadron Collider in the LEP tunnel, Lausanne

1987 Rubbia "Long-Range Planning Committee" recommends Large Hadron Collider as the right choice for CERN's future

1990 ECFA LHC Workshop, Aachen

1992 General Meeting on LHC Physics and Detectors, Evian les Bains

1993 Letters of Intent (ATLAS and CMS selected by LHCC)

1994 Technical Proposals Approved

1996 Approval to move to Construction (ceiling of 475 MCHF)

1998 Memorandum of Understanding for Construction Signed ALICE and LHCb approved.

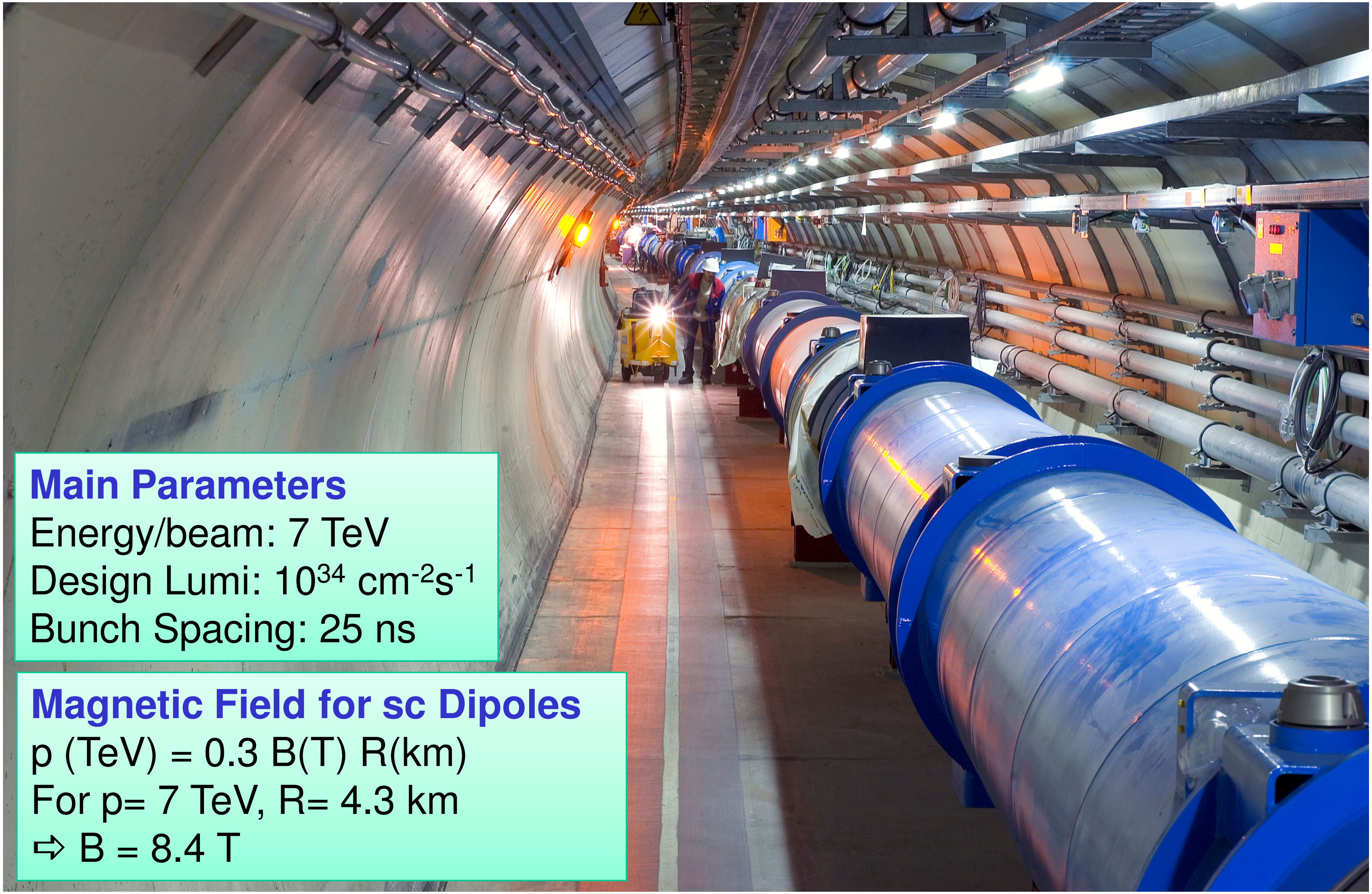
1998 Construction Begins (after approval of Technical Design Reports)

2000 LEP closes

2008 LHC First Operation – September Incident

2009 LHC First Collisions

The Large Hadron Collider



Main Parameters

Energy/beam: 7 TeV

Design Lumi: 10^{34} $cm^{-2}s^{-1}$

Bunch Spacing: 25 ns

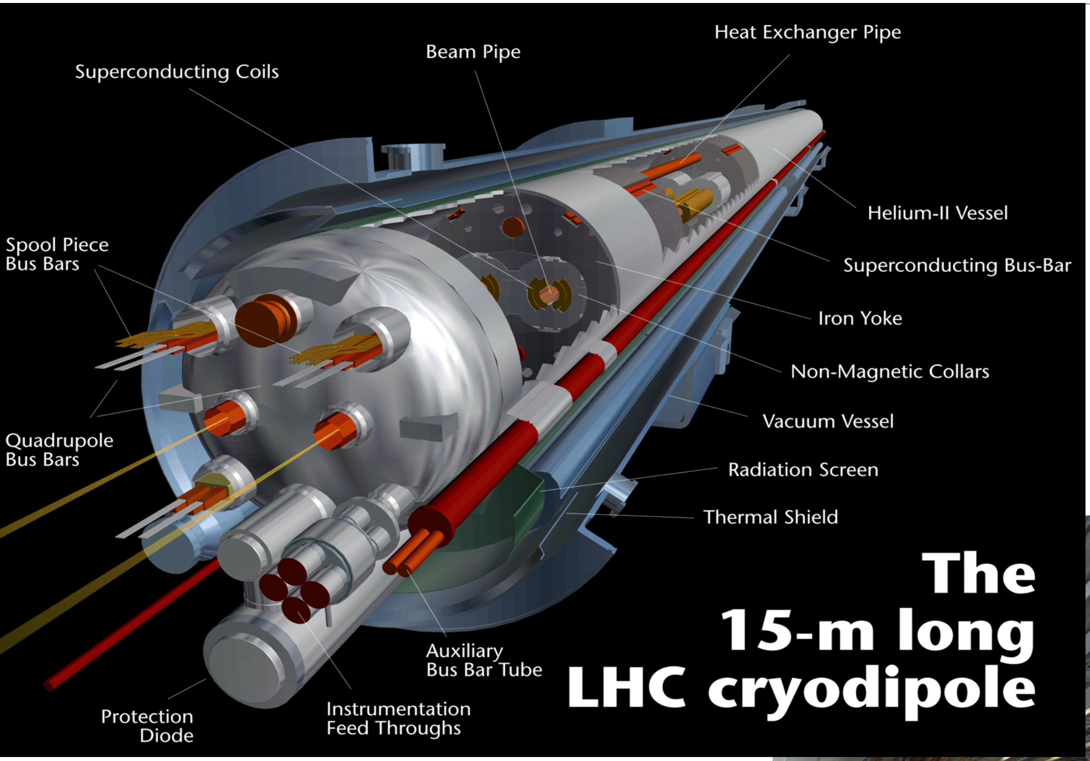
Magnetic Field for sc Dipoles

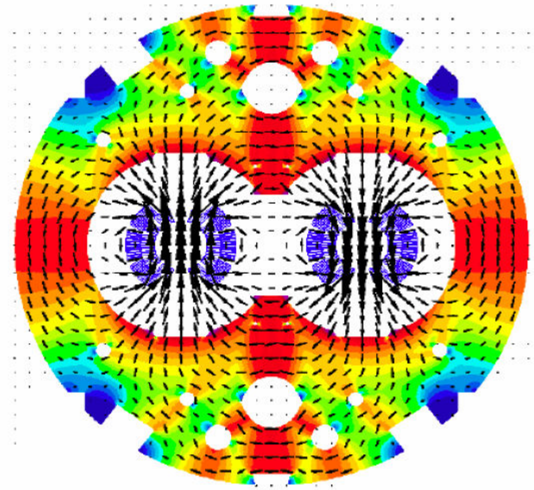
p (TeV) = 0.3 B(T) R(km)

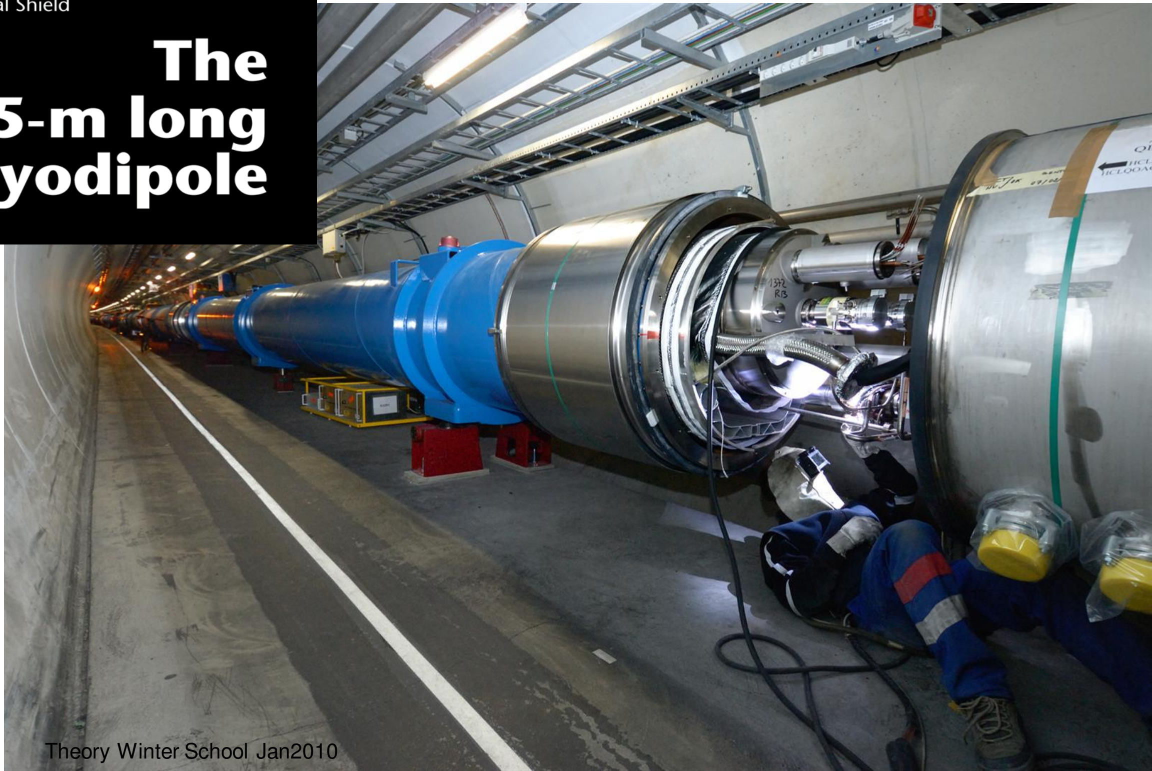
For p= 7 TeV, R= 4.3 km

⇨ B = 8.4 T

LHC Accelerator Challenge: The Dipoles



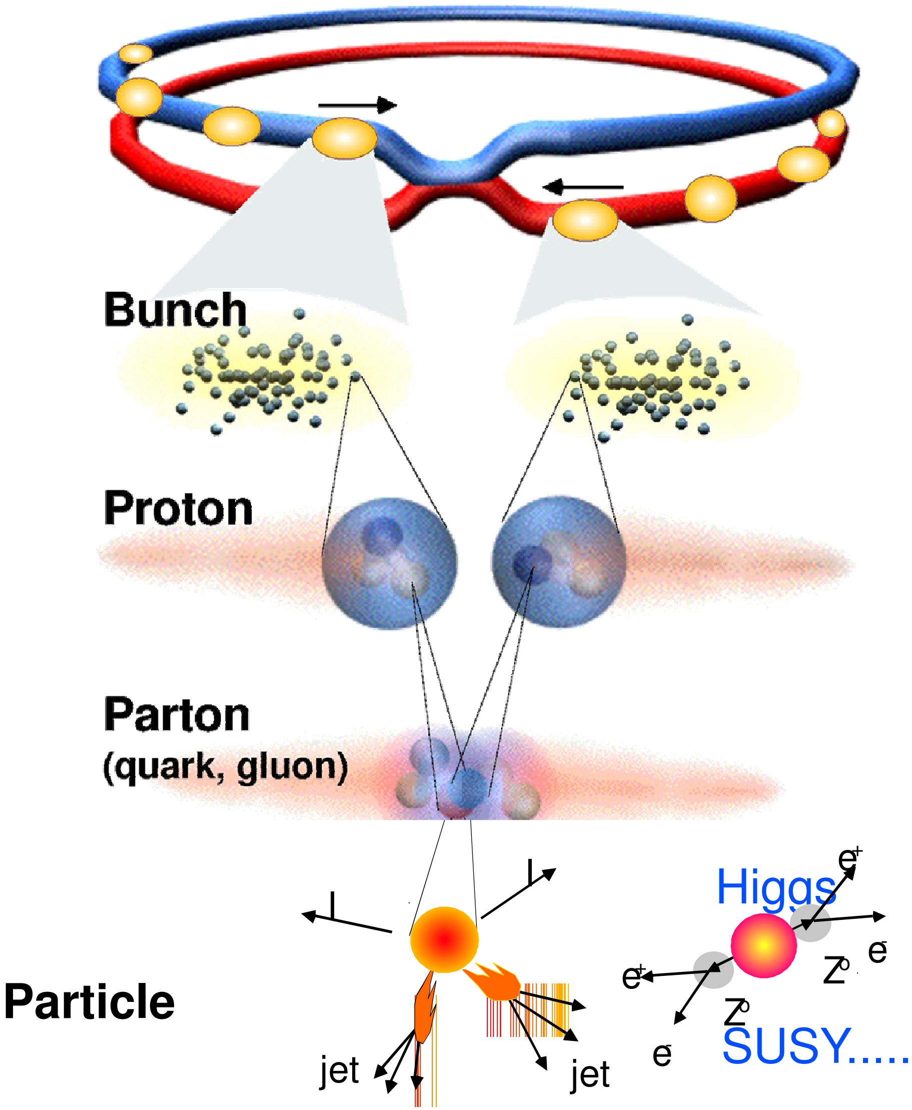




LHC magnets are cooled with pressurized superfluid helium.

The Experiments

Collisions at the LHC: summary



Proton - Proton	2808 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
Collision rate ≈	10^7-10^9

New physics rate ≈ .00001 Hz

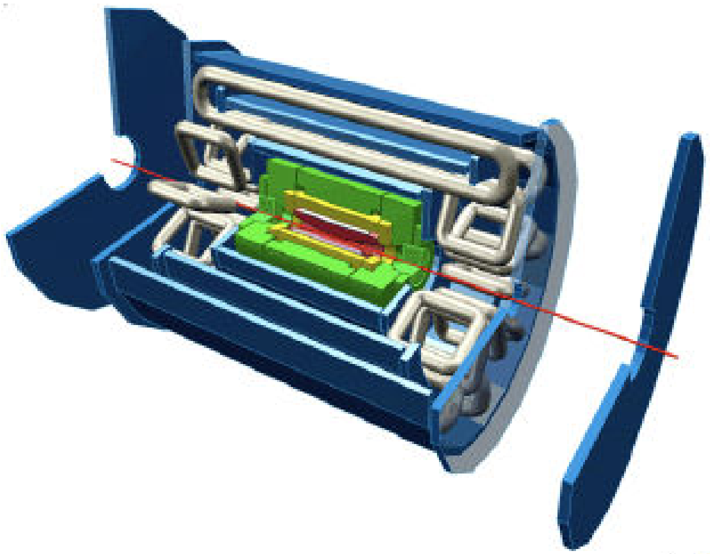
Event selection:
1 in 10,000,000,000,000

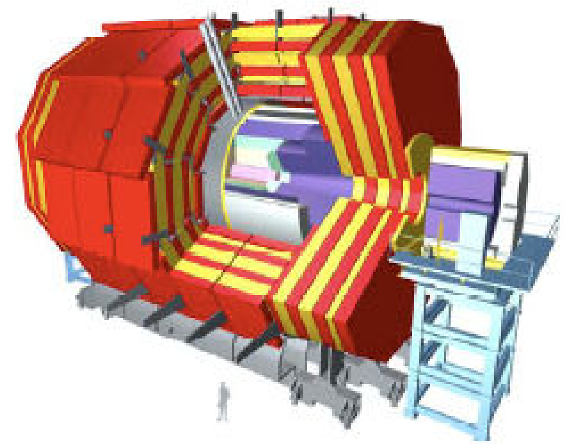
Experimental Challenge

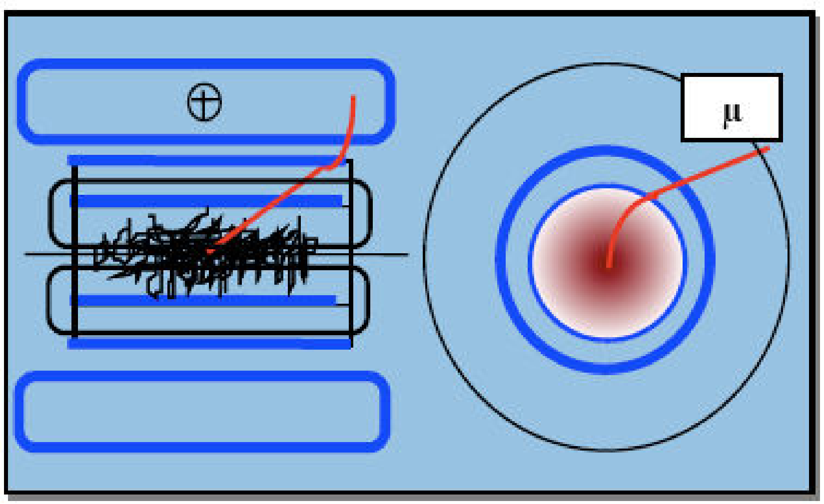
- **LHC detectors must have fast response**
  - Otherwise will integrate over many bunch crossings $\rightarrow$ large "pile-up"
  - Typical response time : 20-50 ns
    - $\rightarrow$ integrate over 1-2 bunch crossings $\rightarrow$ pile-up of 25-50 min-bias
    - $\rightarrow$ very challenging readout electronics
- **LHC detectors must be highly granular**
  - Minimize probability that pile-up particles be in the same detector element as interesting object (e.g. γ from $H \rightarrow \gamma\gamma$ decays)
    - $\rightarrow$ large number of electronic channels
    - $\rightarrow$ high cost
- **LHC detectors must be radiation resistant:**
  - high flux of particles from pp collisions $\rightarrow$ high radiation environment e.g. in forward calorimeters:
    - up to 10^{17} n/cm^2 in 10 years of LHC operation
    - up to 10^7 Gy (1 Gy = unit of absorbed energy = 1 Joule/Kg)

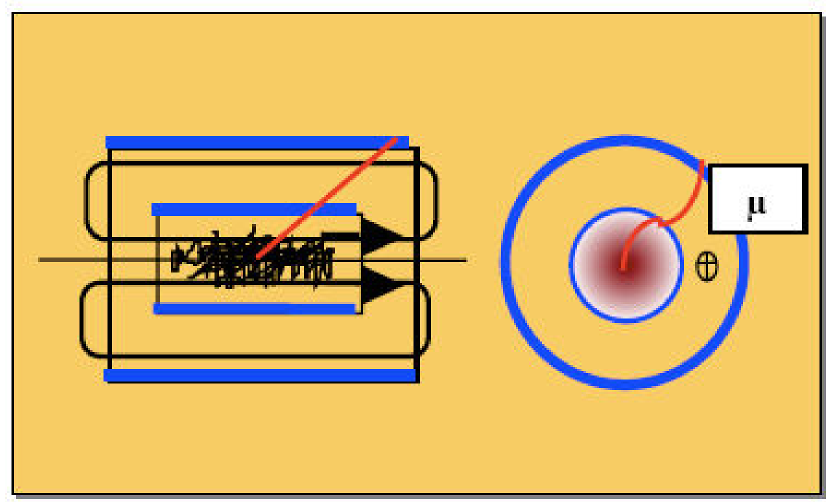
The general-purpose detectors at LHC

A Toroidal LHC ApparatuS Compact Muon Solenoid



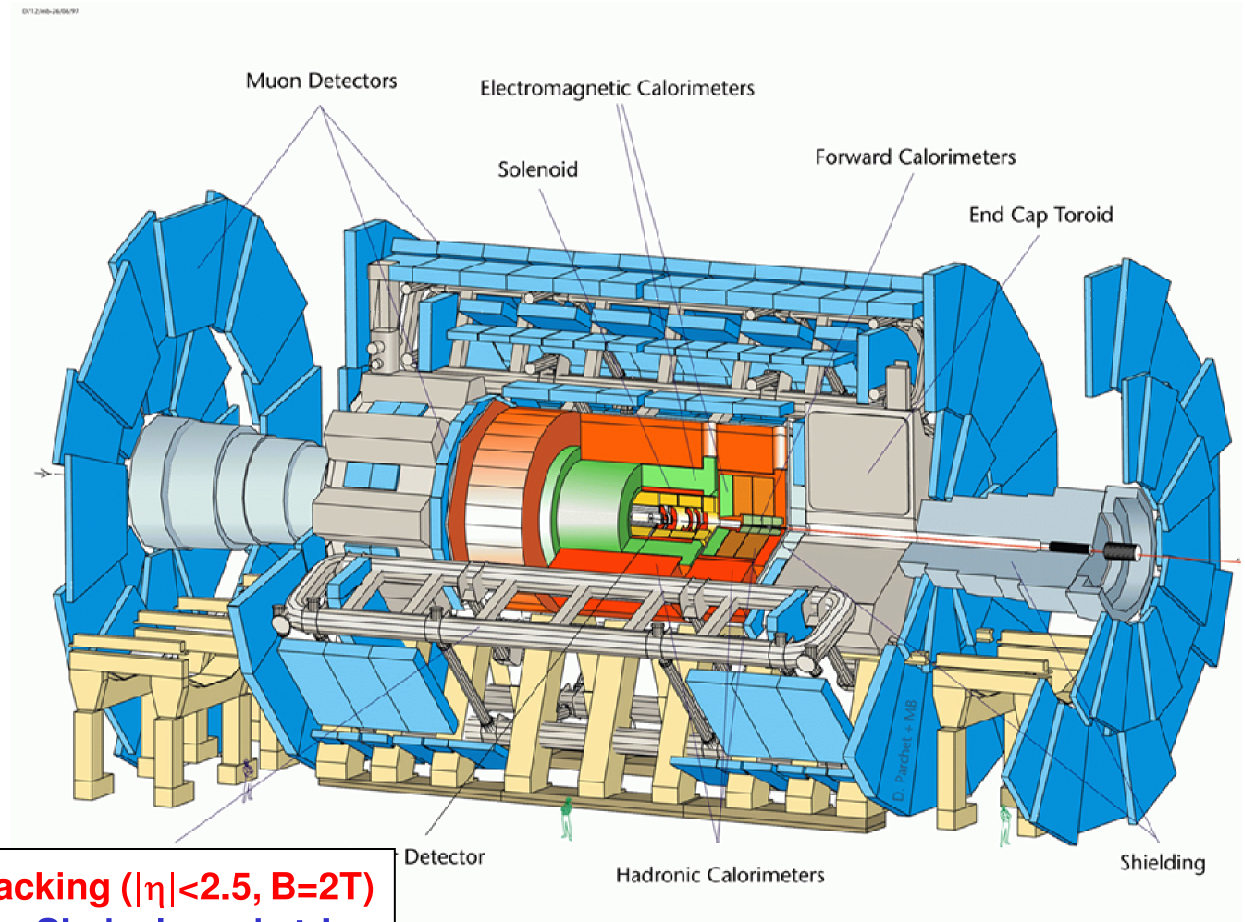






ATLAS Detector

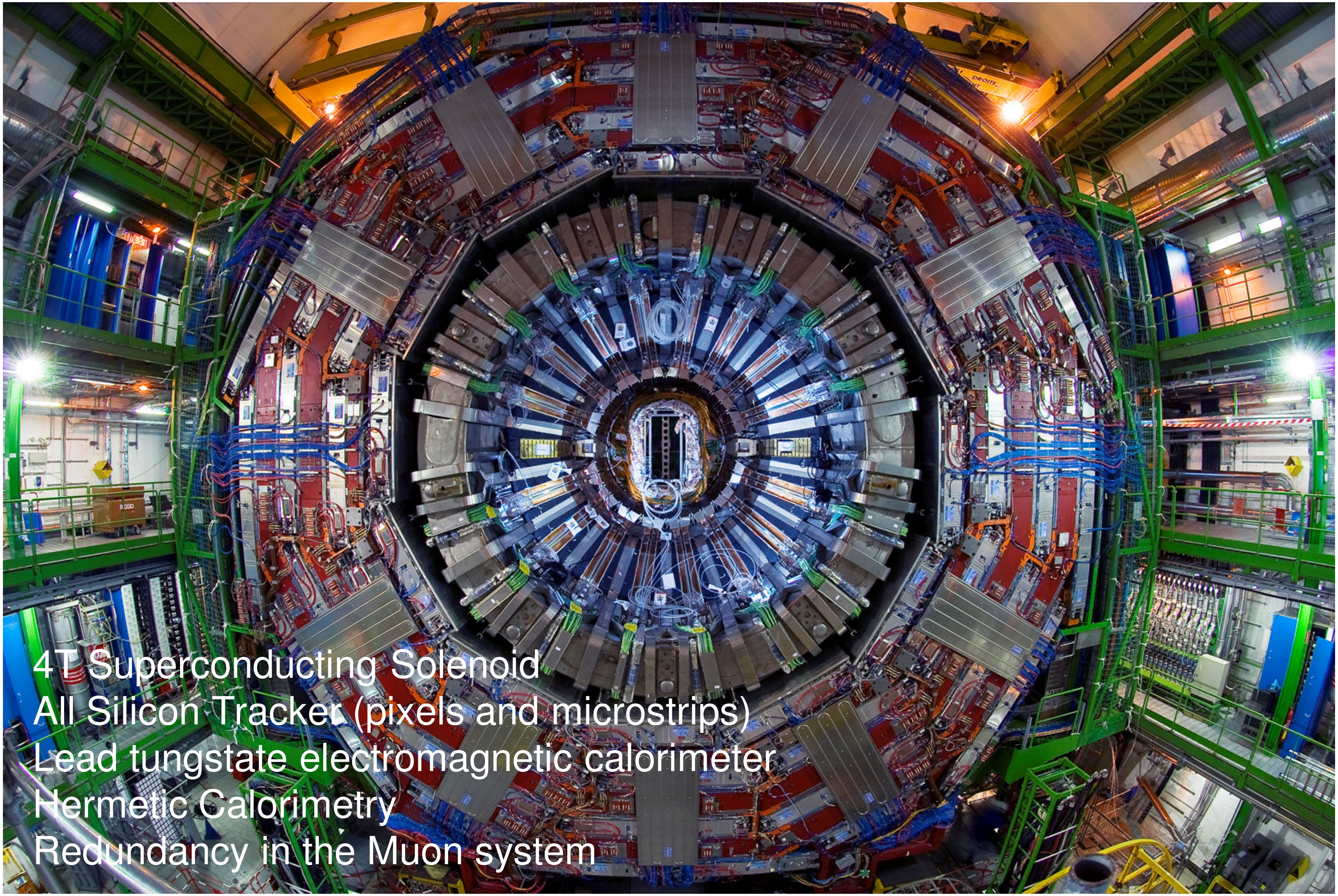
Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
~ 3000 km of cables



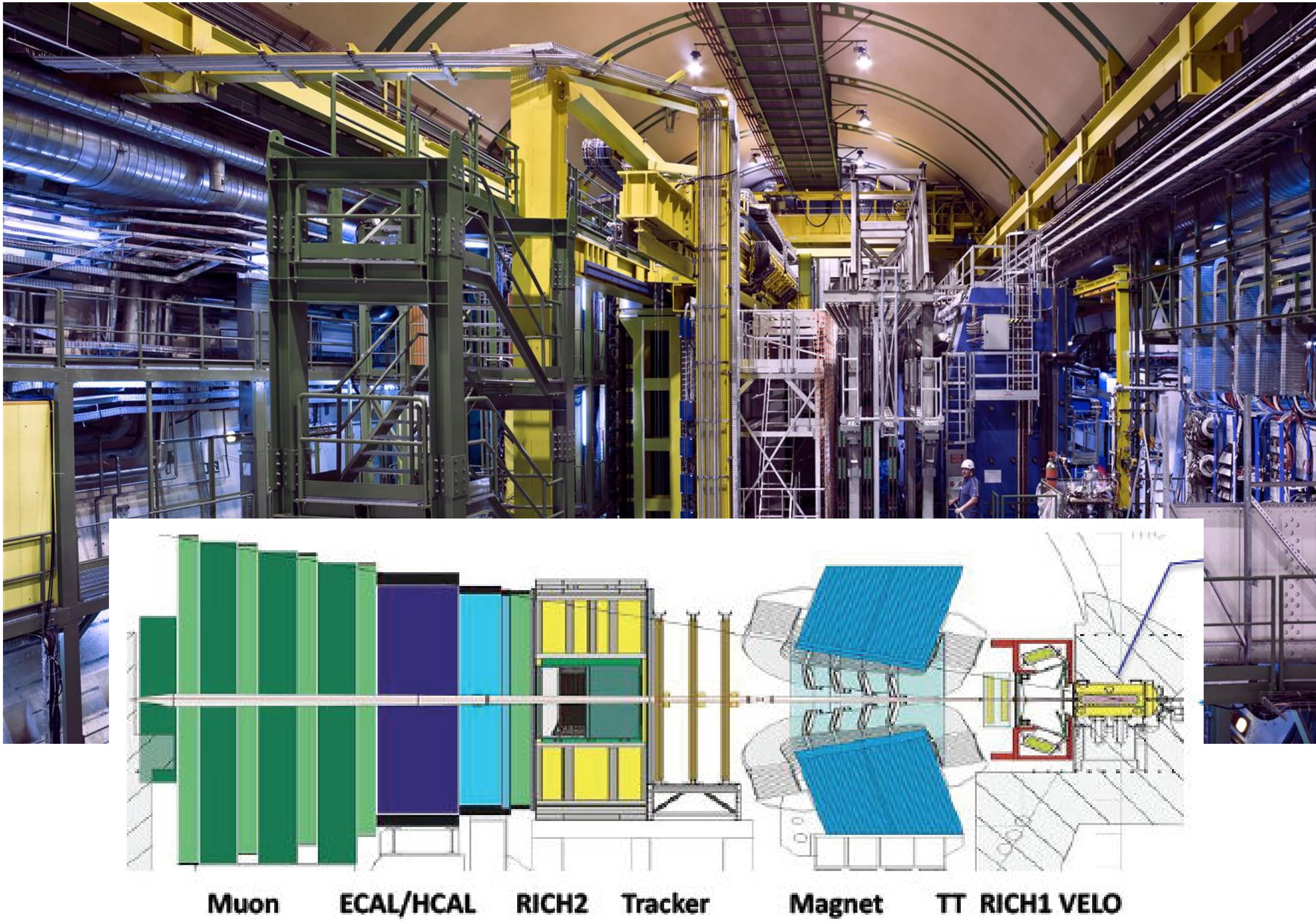
- **Tracking ($|\eta|<2.5$, B=2T)**
  - **Si pixels and strips**
  - **Transition Radiation Detector (e/π separation)**
- **Calorimetry ($|\eta|<5$)**
  - **EM : Pb-LAr**
  - **HAD: Fe/scintillator (central), Cu/W-LAr (fwd)**
- **Muon Spectrometer ($|\eta|<2.7$)**
  air-core toroids with muon chambers

And ~2500 physicists from
167 Institutions
37 countries
5 continents

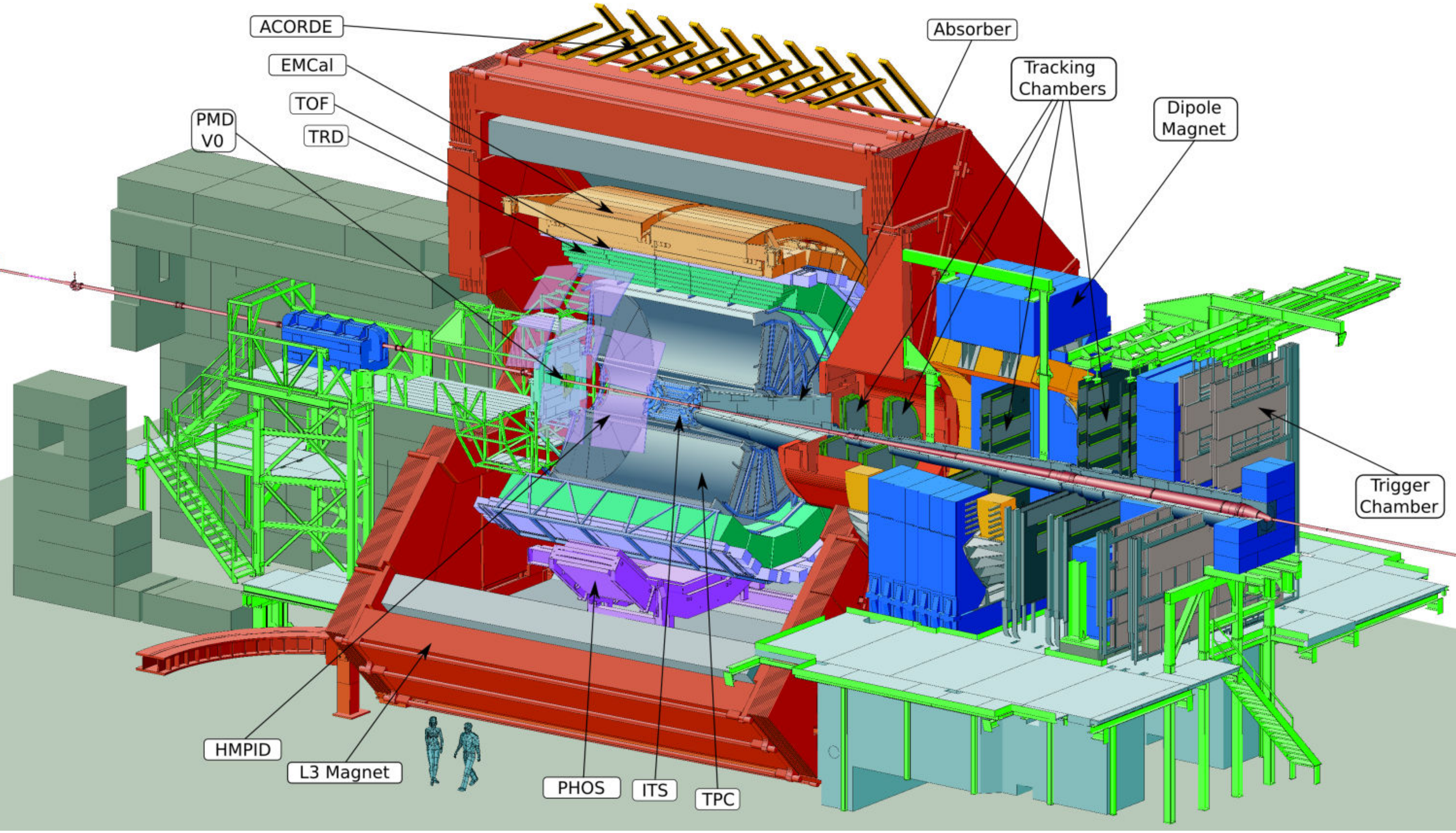
CMS Detector



LHC*b* Detector



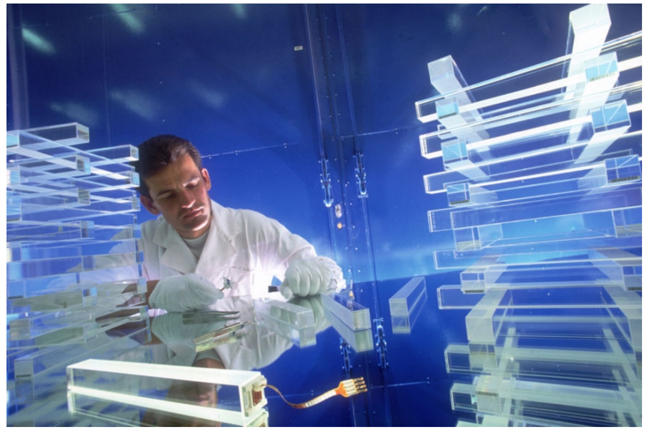
ALICE Detector

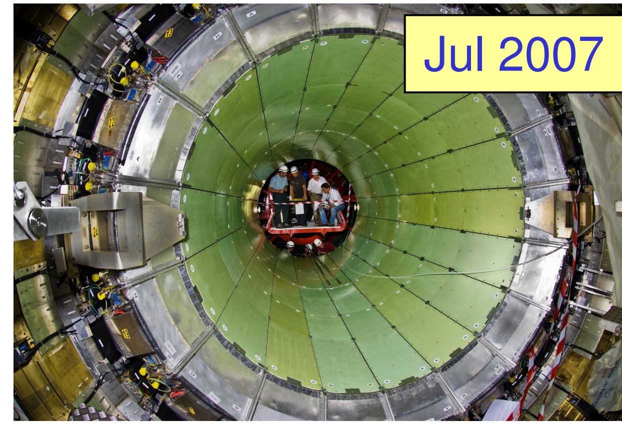


The Constuction of the Experiments

Example of Construction: CMS ECAL

e.g. $PbWO_4$ Crystals for CMS: Physics Driver: H ❼γγ





Idea (1993 – few cm^3 sample)

→ R&D (1993-1998: increase size of crystals, improve rad. hardness,quality)

→ Prototyping (1994-2001: large matrices in test beams, monitoring)

→ Mass manufacture (1997-2005: increase industrial capacity, QC)

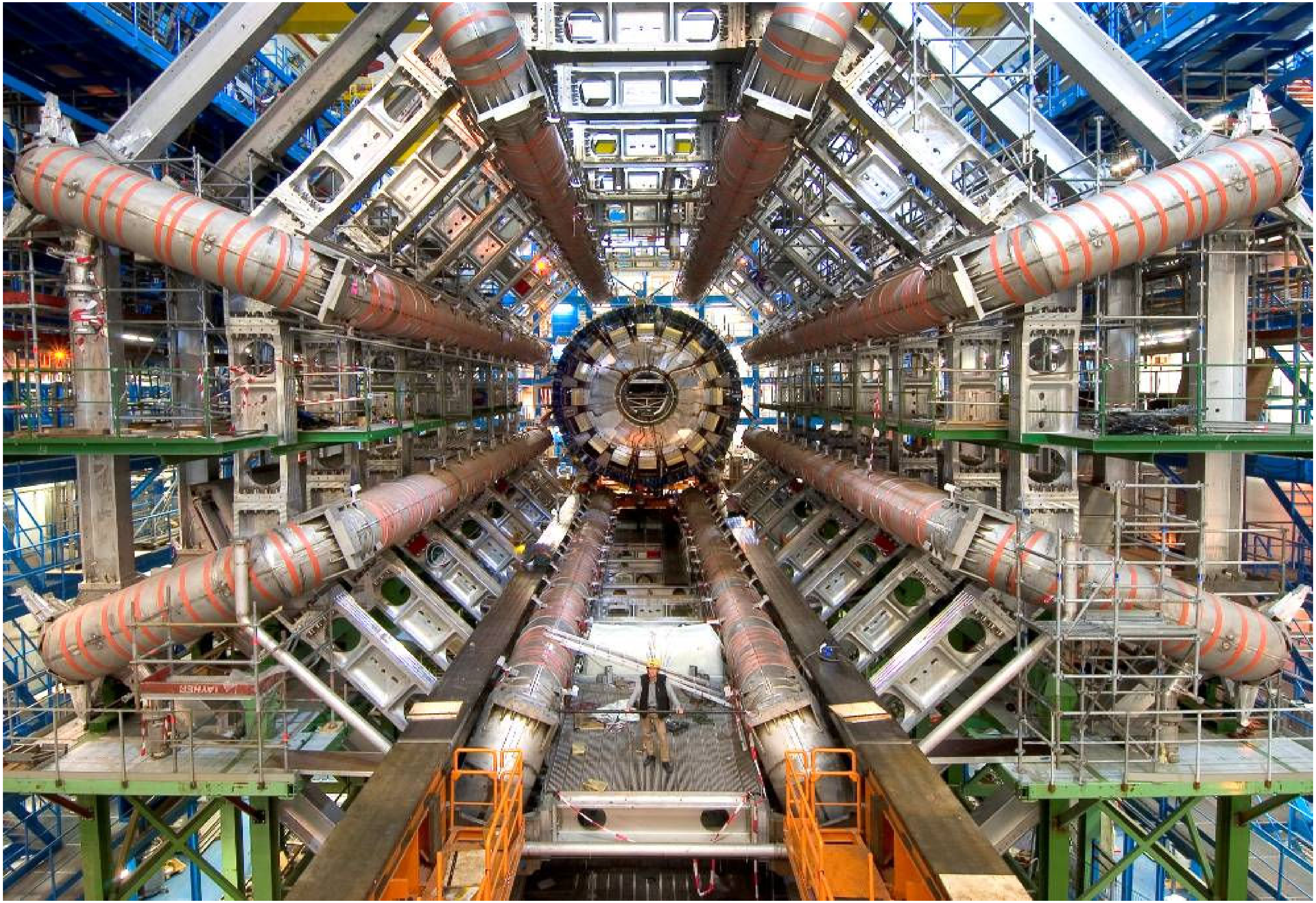
→ Systems Integration (2001-2007: tooling, assembly)

→ Installation and Commissioning (2006-2008)

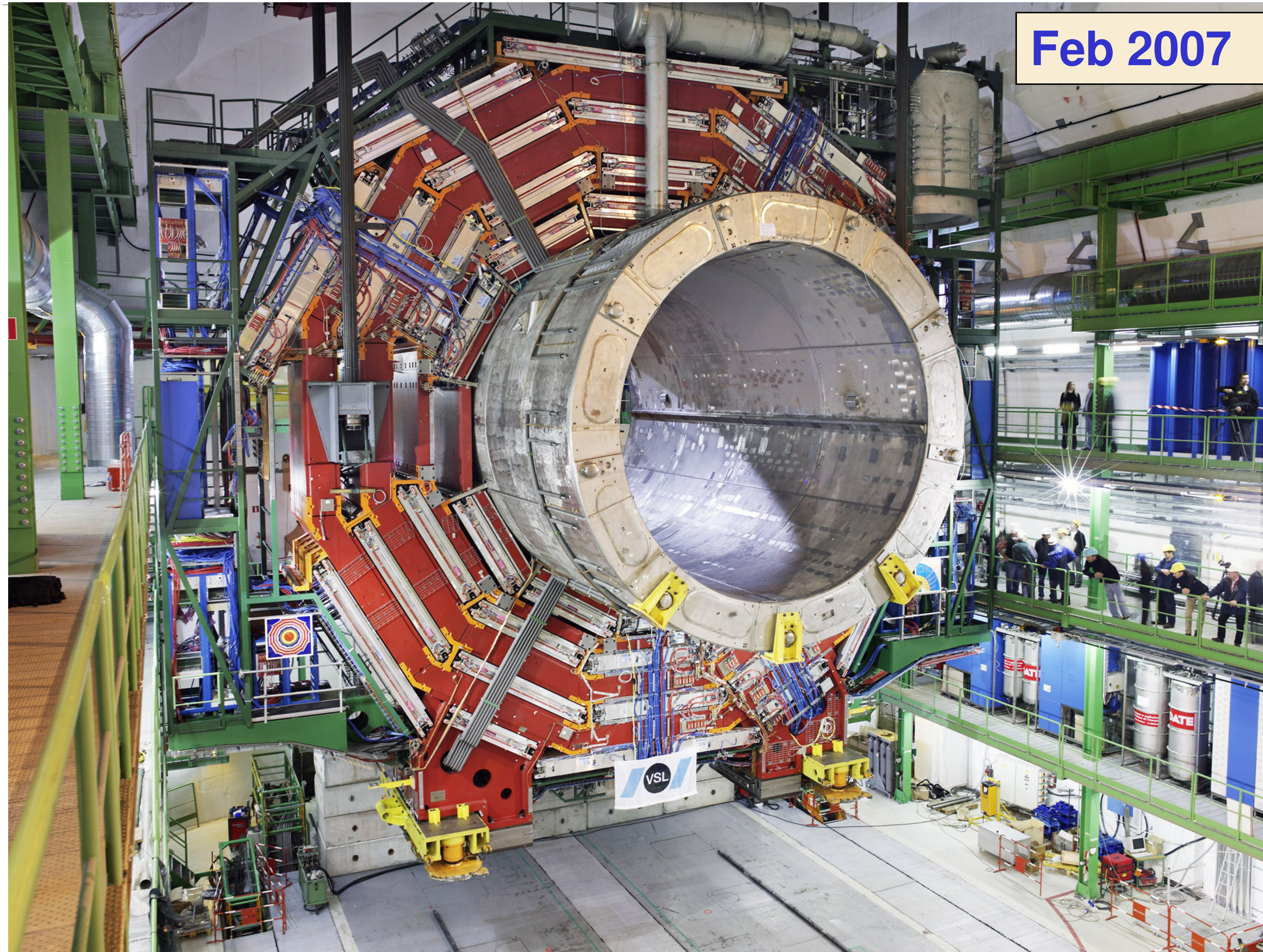
→ Data Taking (>2008)

Δt ~ 15 years !!!

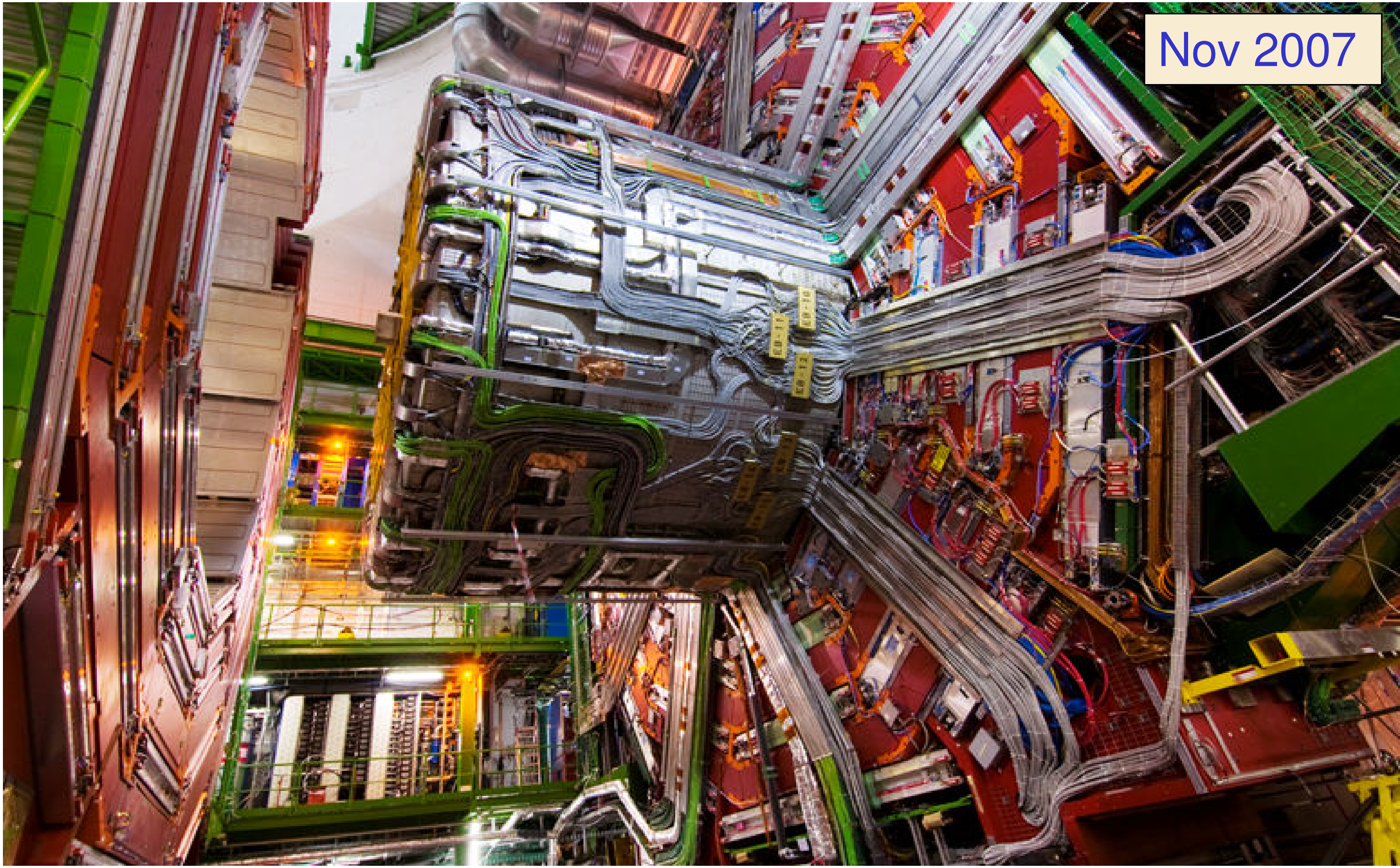
Installation 1: ATLAS (Oct 2005)



Installation 2: CMS



Cabling, Pipes and Optical Fibres !



The Commissioning of the Experiments

Commissioning; e.g. CMS

Since Sept. '08 – extensive tests

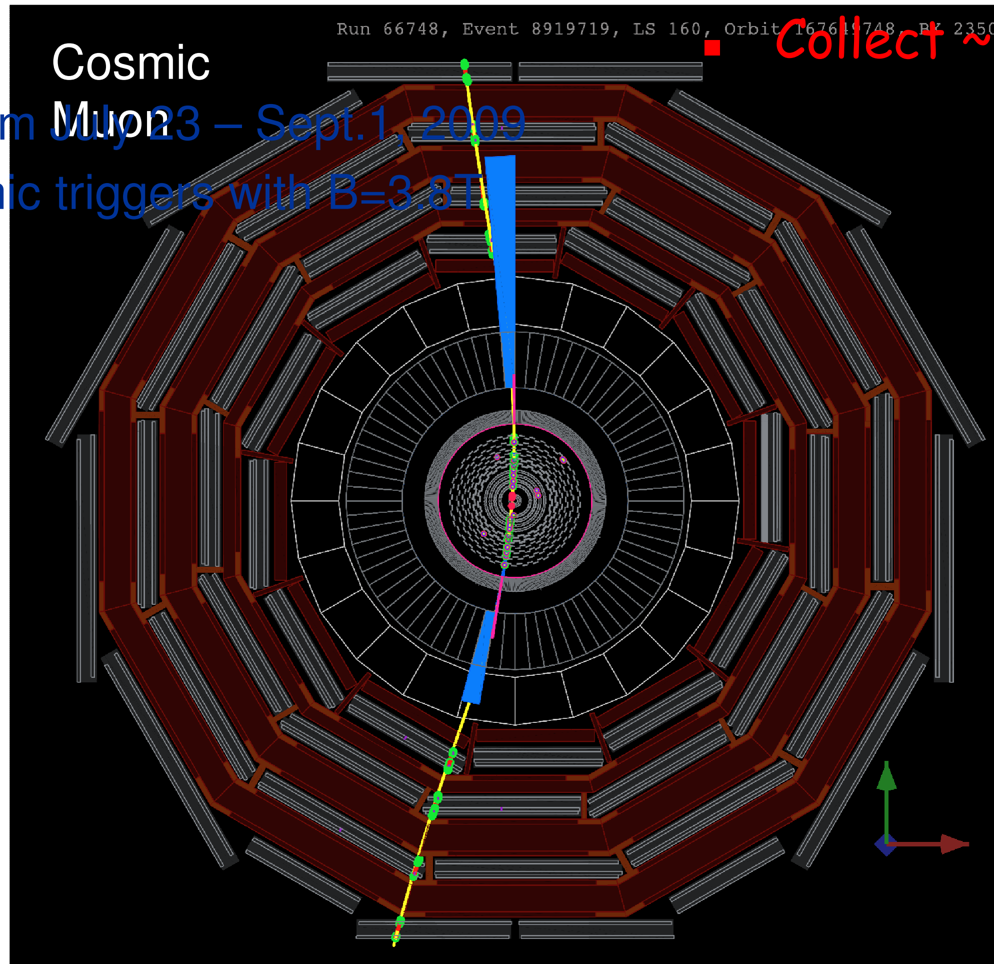
- **1 billion cosmic muosn recorded in Oct'08 and Aug'09 (CRAFT)**
- **Offline and Computing tests**
- **Prompt physics analysis exercise in Oct'09.**

- CRAFT08:
  - 23 days from Oct.13 – Nov.11, 2008
  - 270M cosmic triggers with B=3.8T

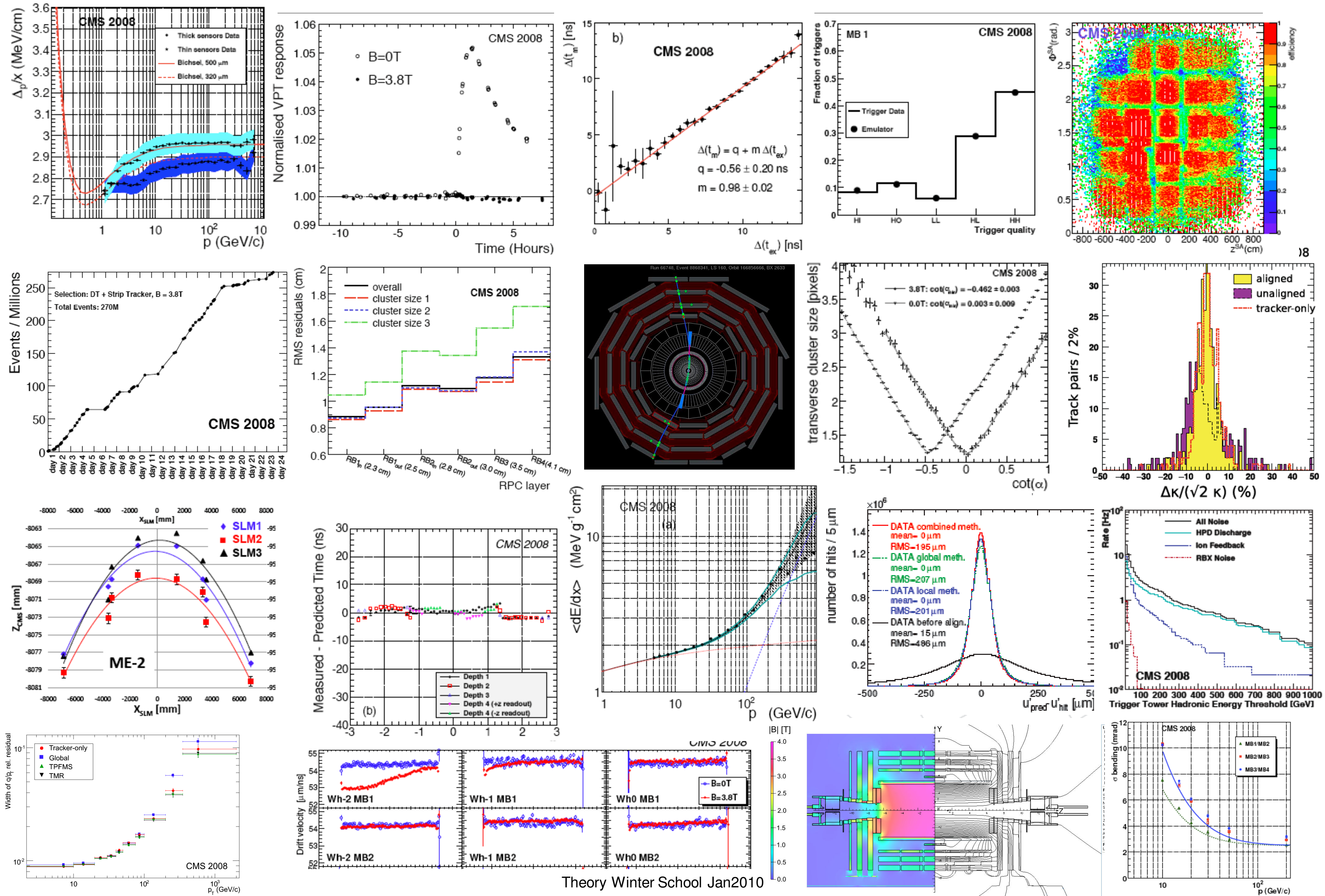
Followed by shutdown, then:

- CRAFT09:
  - 40 days from July 23 – Sept.1, 2009
  - 320M cosmic triggers with B=3.8T

- Commission the experiment with magnet at operating field
- Operate the experiment for an extended period (month)
- Collect ~300M cosmics for detector studies



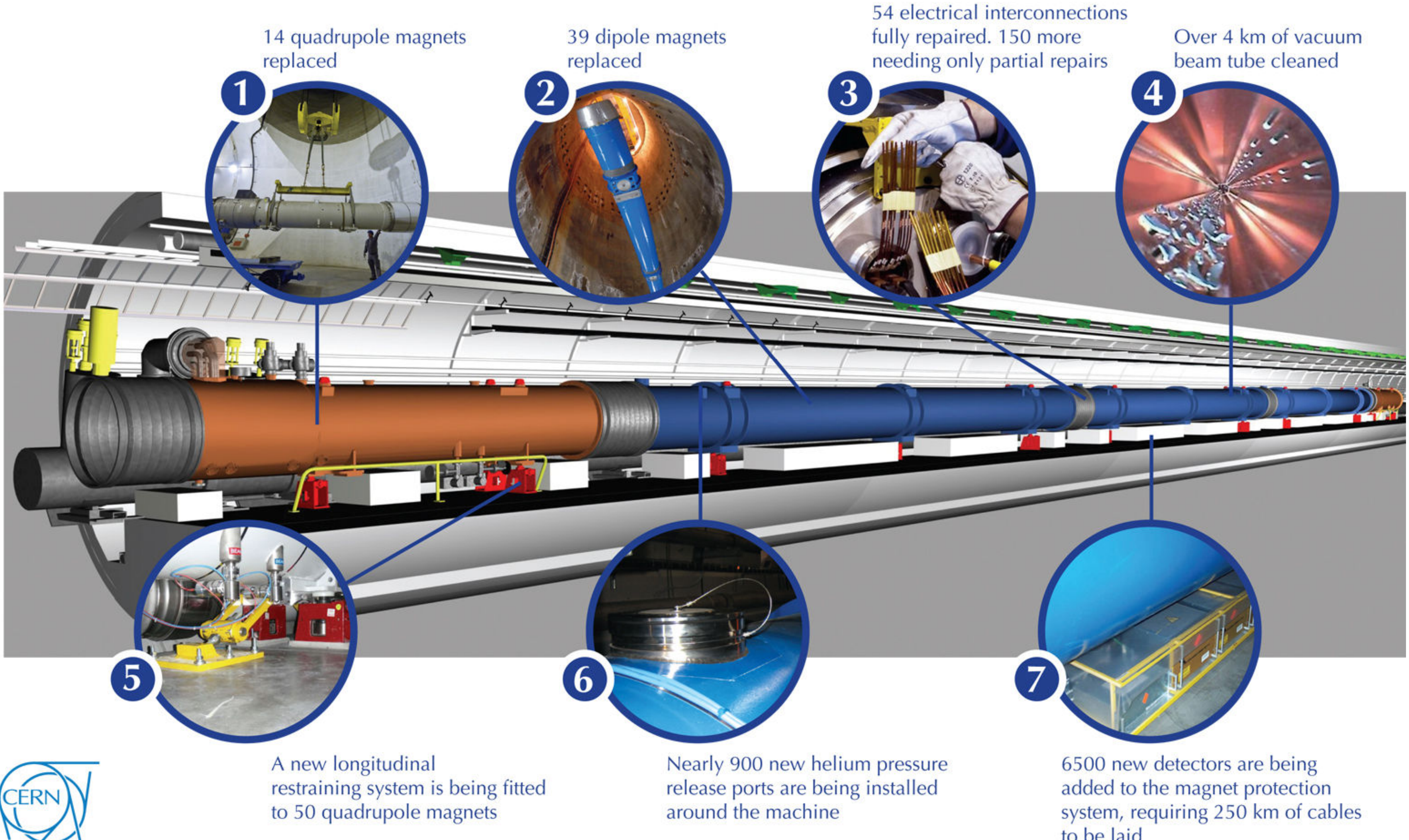
CRAFT: 23 Papers Submitted to JINST



The Operations
The Accelerator

The LHC Accelerator Control Room (10 Sep 2008)

The LHC repairs in detail



LHC Restart 2009: Milestones

1) repair; 2) consolidation; 3) hardware commissioning;
4) preparation for beam; and 5) beam operation.

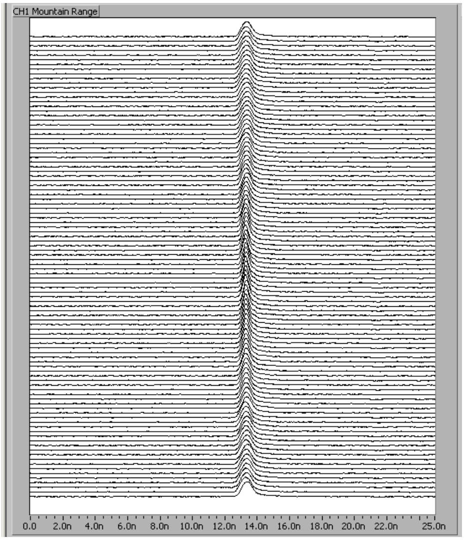
First LHC beams injected on 20 November

- 3 days - first collisions at 450 GeV
- 9 days – first ramp to 1.2 TeV
- 16 days - stable beams at 450 GeV
- 18 days - two beams to 1.2 GeV, first collisions

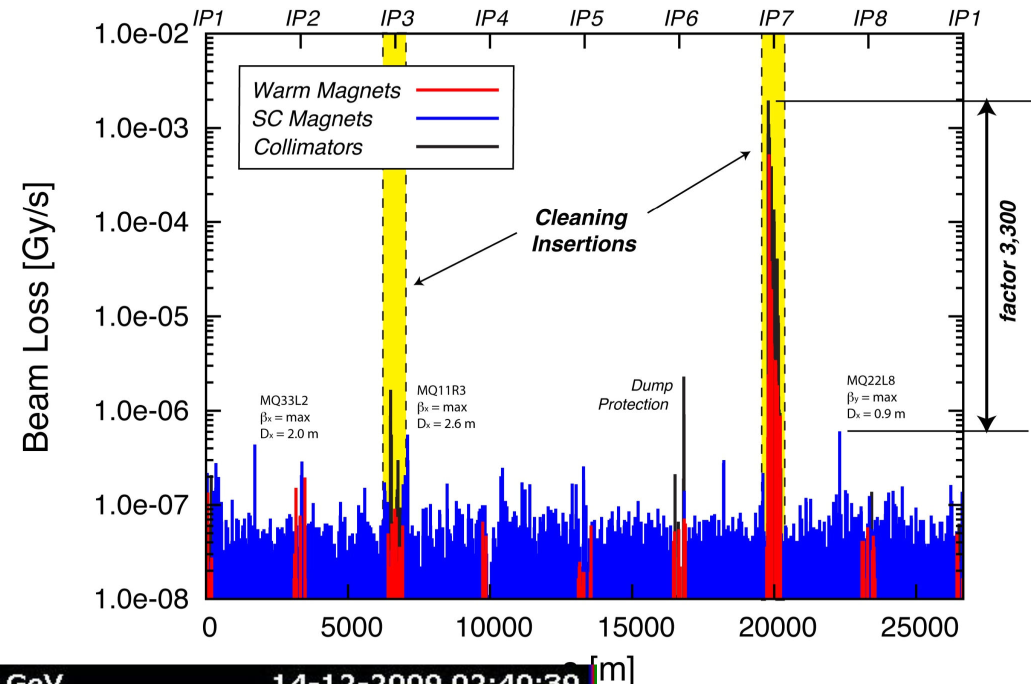
14^{th} Dec	Ramp 2 on 2 to 1.18 TeV - quiet beams - collisions in all four experiments
14^{th} Dec	16 on 16 at 450 GeV - stable beams
16^{th} Dec	Ramped 4 on 4 to 1.18 TeV - squeezed to 7 m in IR5 - collisions in all four experiments
16^{th} Dec	End of run

LHC Perfromance

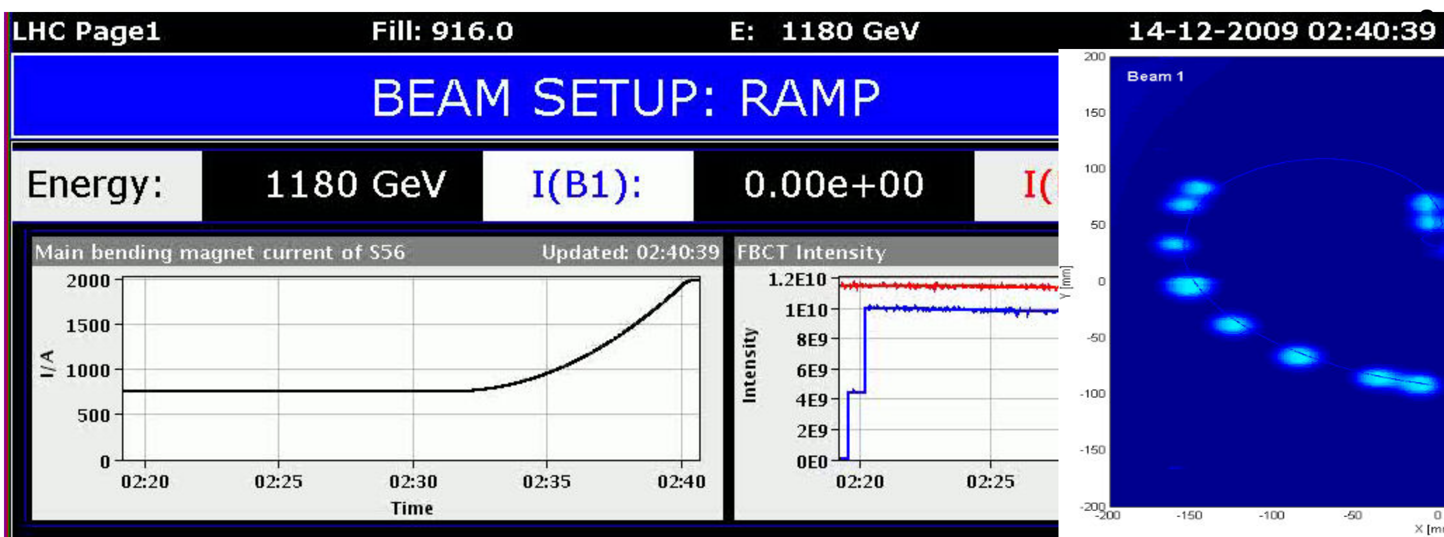
Capturing the Beam

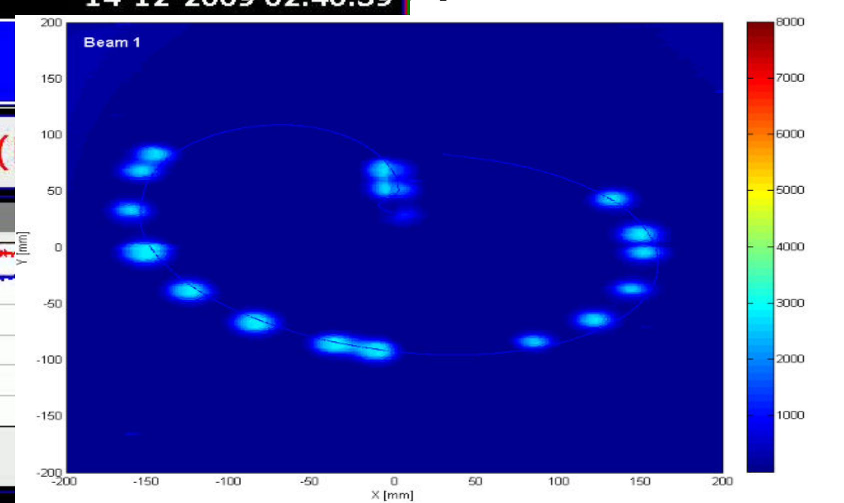


“Cleaning” the Beams: > 99.9%

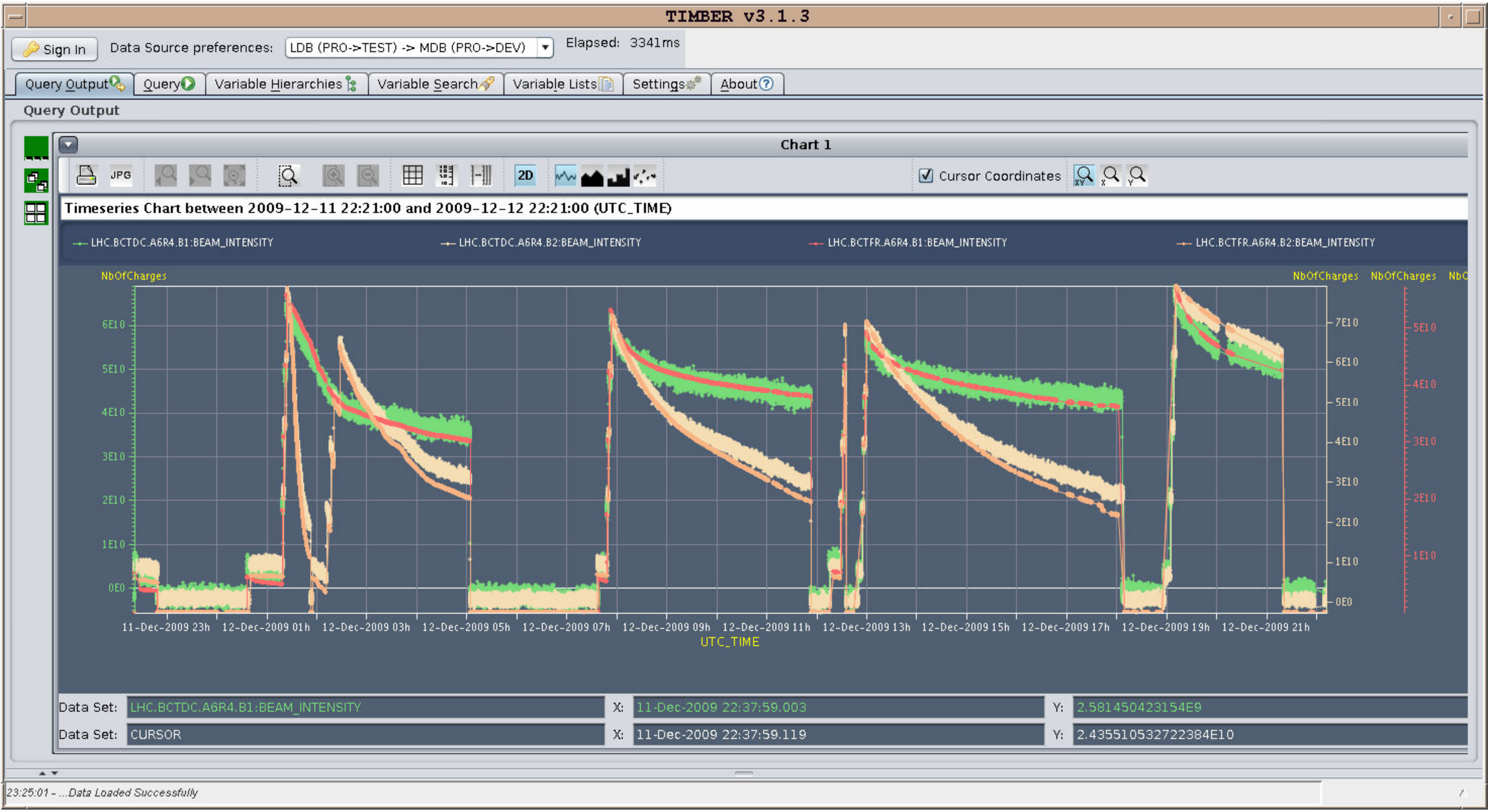


Accelerating the Beam





12.12.2009: 24 hours running - currents



Beam commissioning strategy

Energy	Safe	Very Safe
450	1 e12	1 e11
1 TeV	2.5 e11	2.5 e10
3.5 TeV	3.0 e10	probe

Global machine checkout

Essential 450 GeV commissioning ↔ Trial ramps

Machine protection commissioning 1

Experiments' magnets at 450 GeV

450 GeV collisions

Ramp commissioning to 1.2 TeV

2009

All has been accomplished! +

System/beam commissioning | Machine protection commissioning 2

3.5 TeV beam & first collisions

2010

Full machine protection qualification

System/beam commissioning | Pilot physics

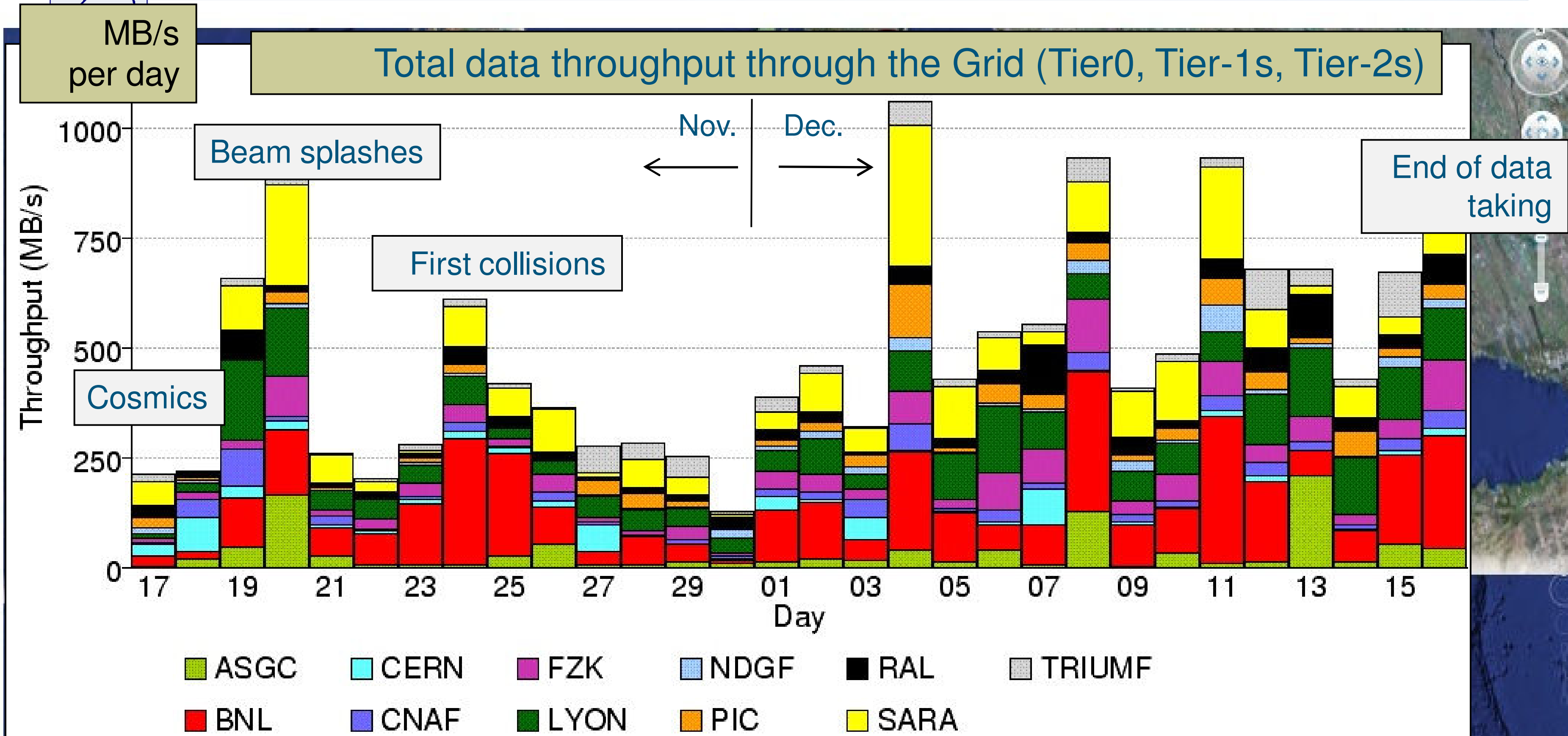
2009 Operations
The Experiments

Detectors are Fully Operational: e.g. ATLAS

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%

- Pixels and Silicon strips (SCT) at nominal voltage only with stable beams
- Solenoid and/or toroids off in some periods

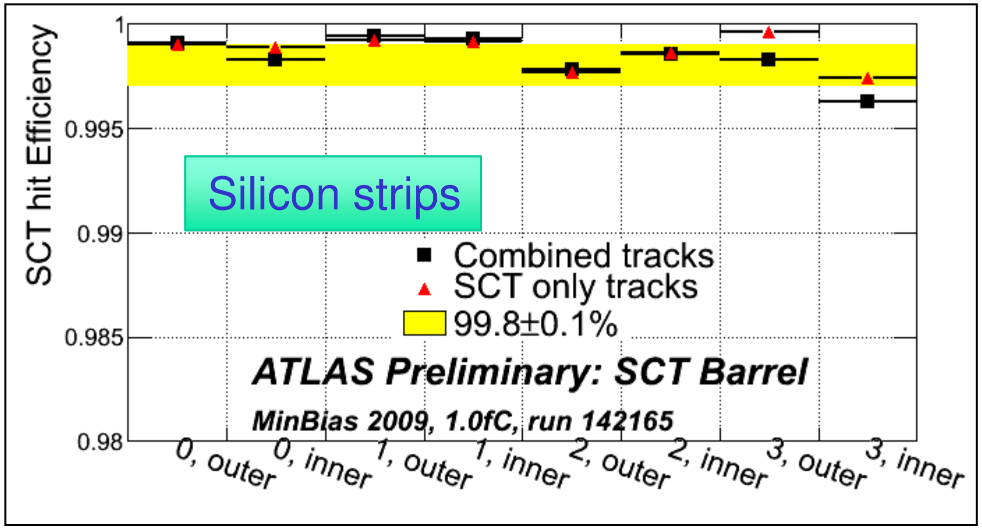
Worldwide LHC Computing Grid: e.g. ATLAS

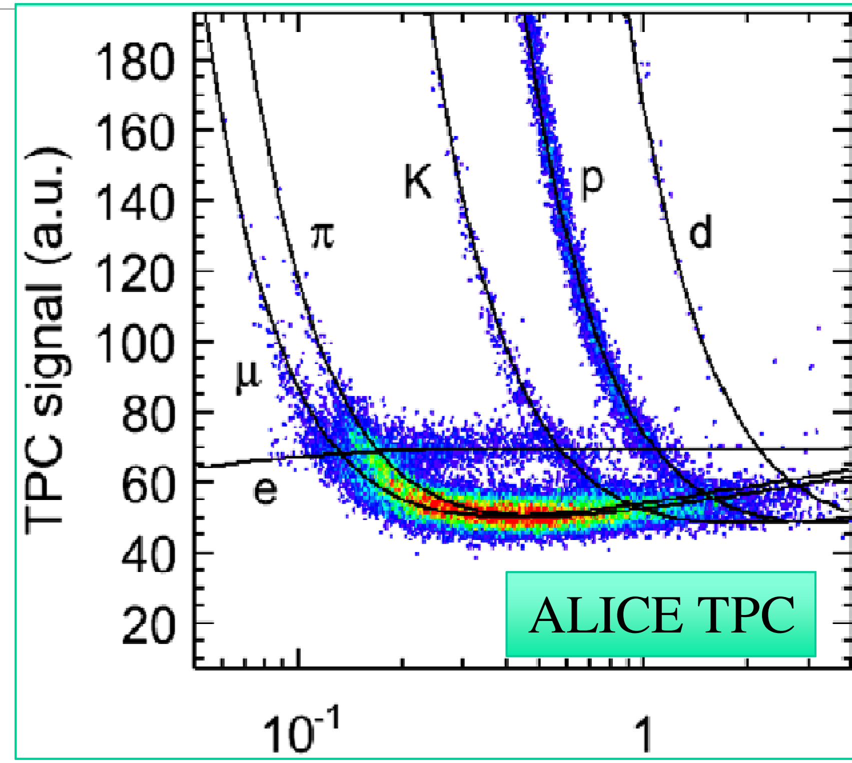


- ~ 0.2 PB of data stored
- ~ 8h between Data Acquisition at the pit and data arrival at Tier2 (including reconstruction atTier0)
- increasing usage of the Grid for analysis

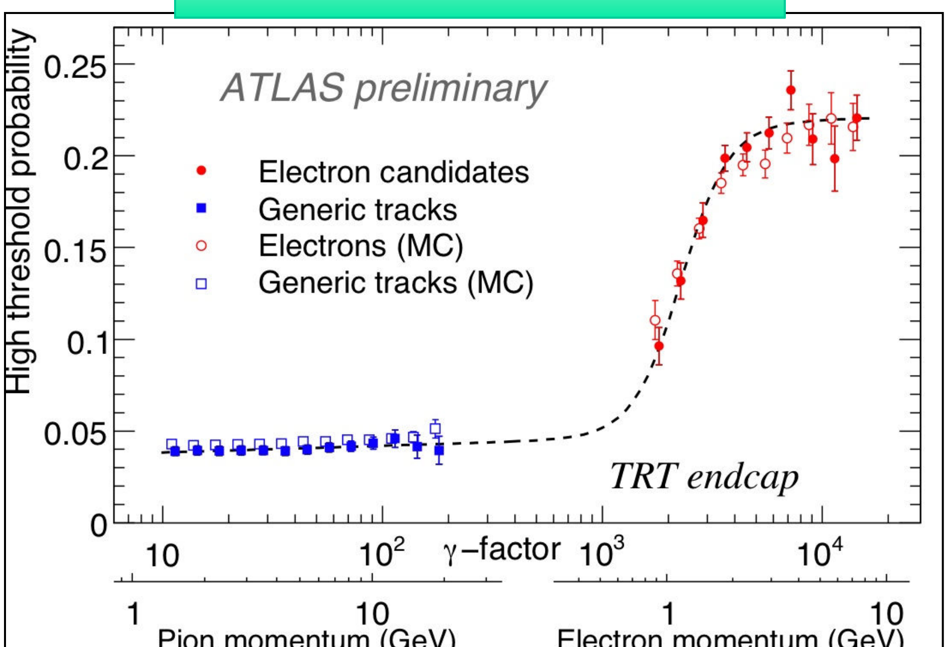
WLCG

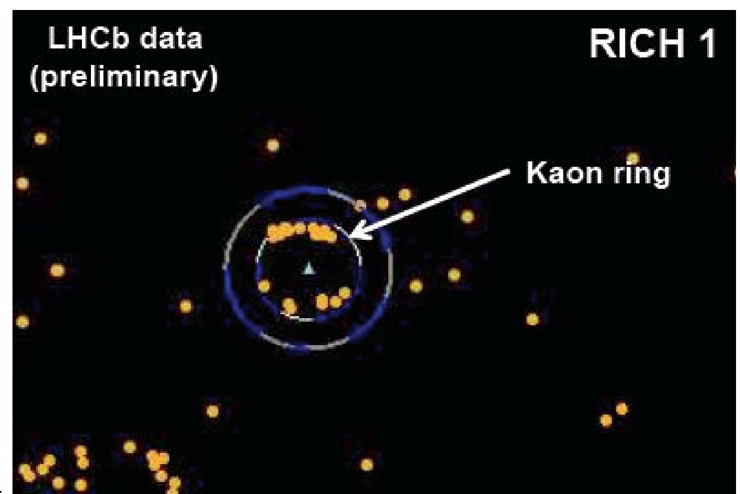
Detector Performance: Tracking/Part id





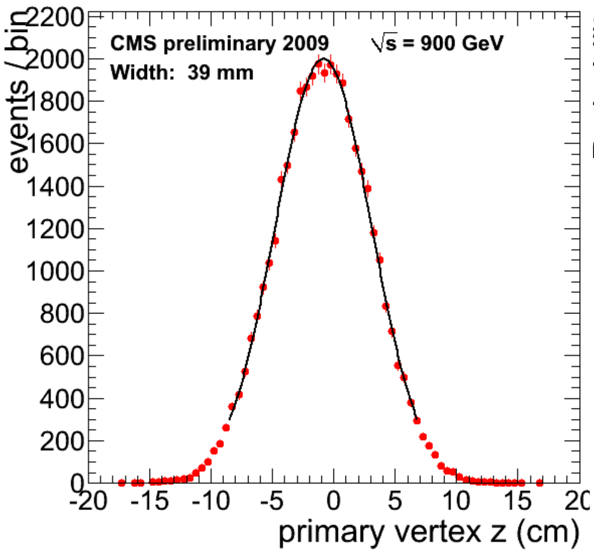
Transition Radiation Tracker

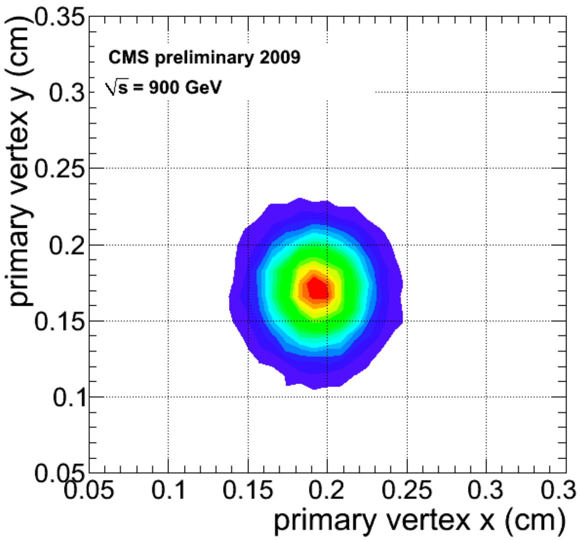




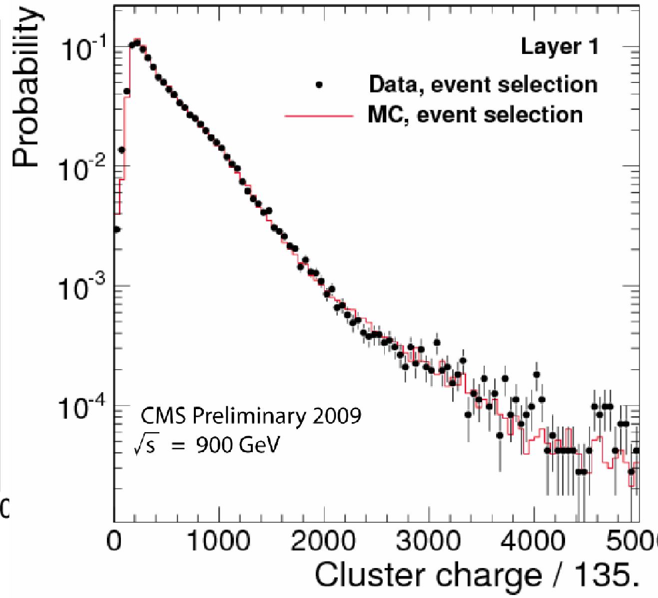
Detector Performance : CMS Tracking/Part id

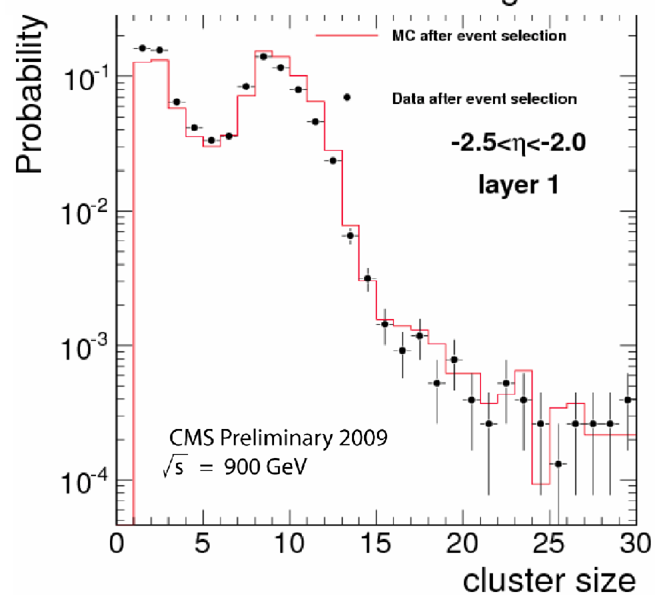
Primary Vertex



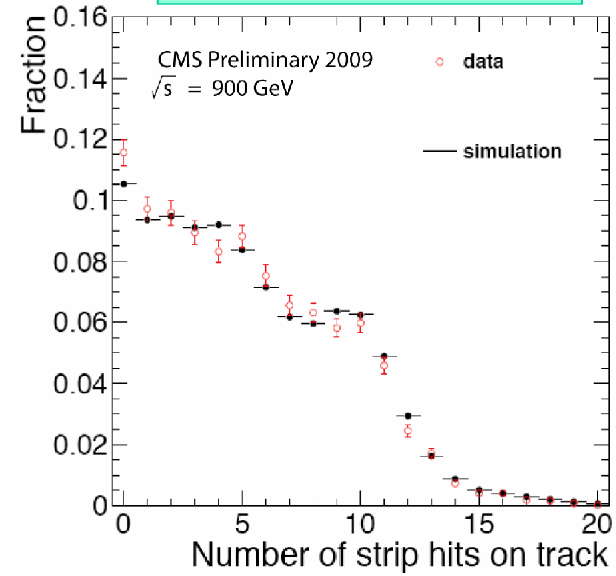


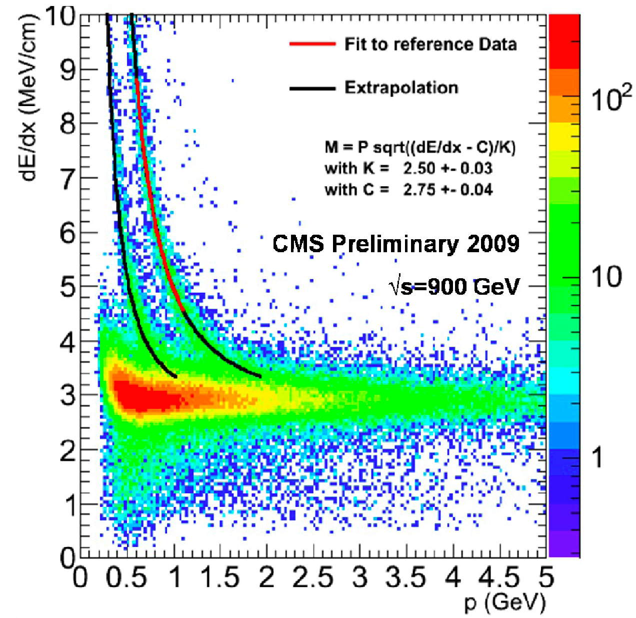
Pixels Clusters



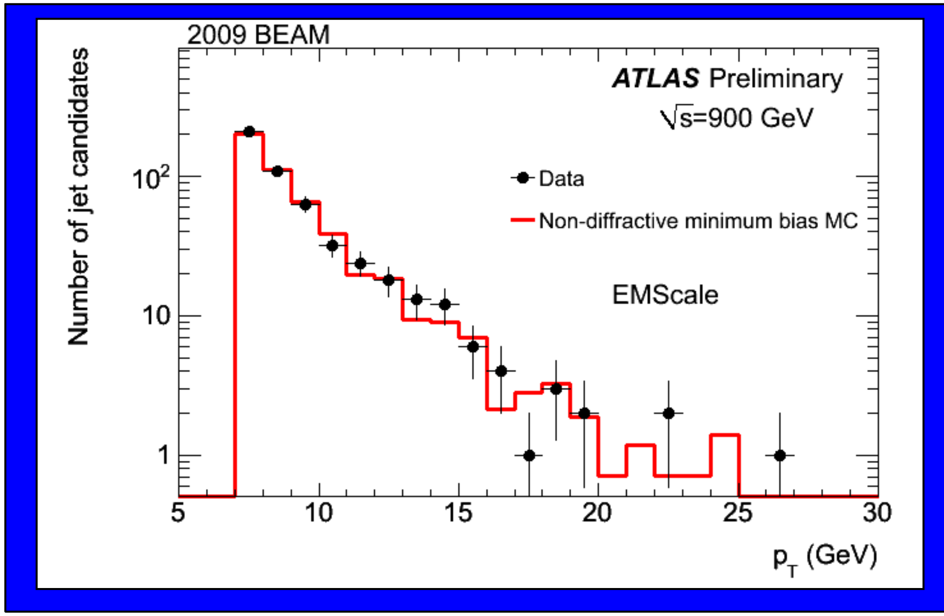


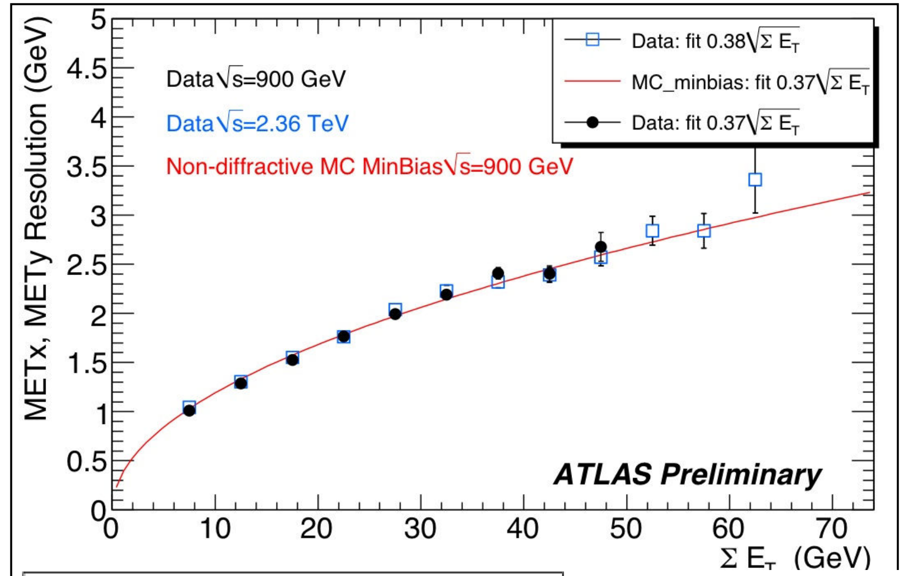
Strip Tracker

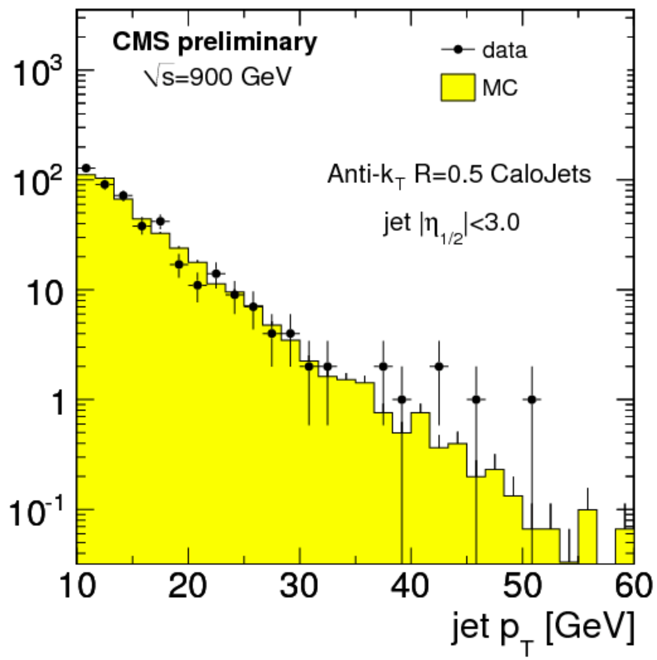


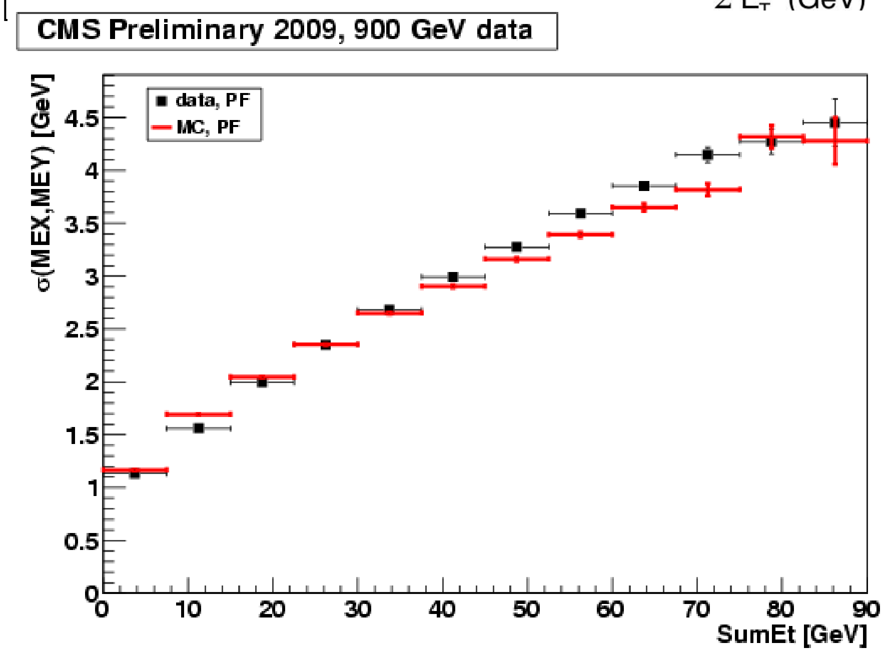


Detector Performance: Calorimetry

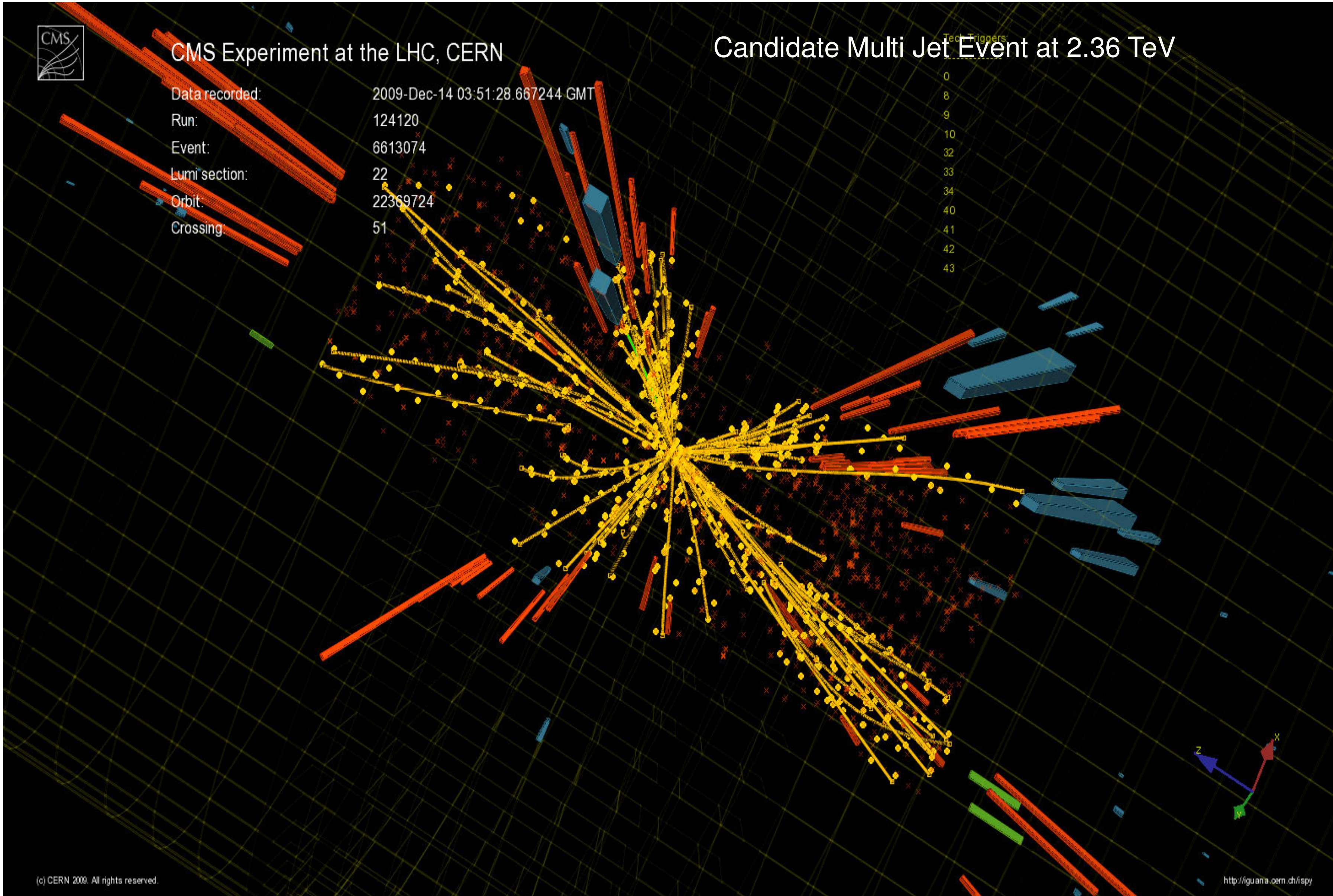




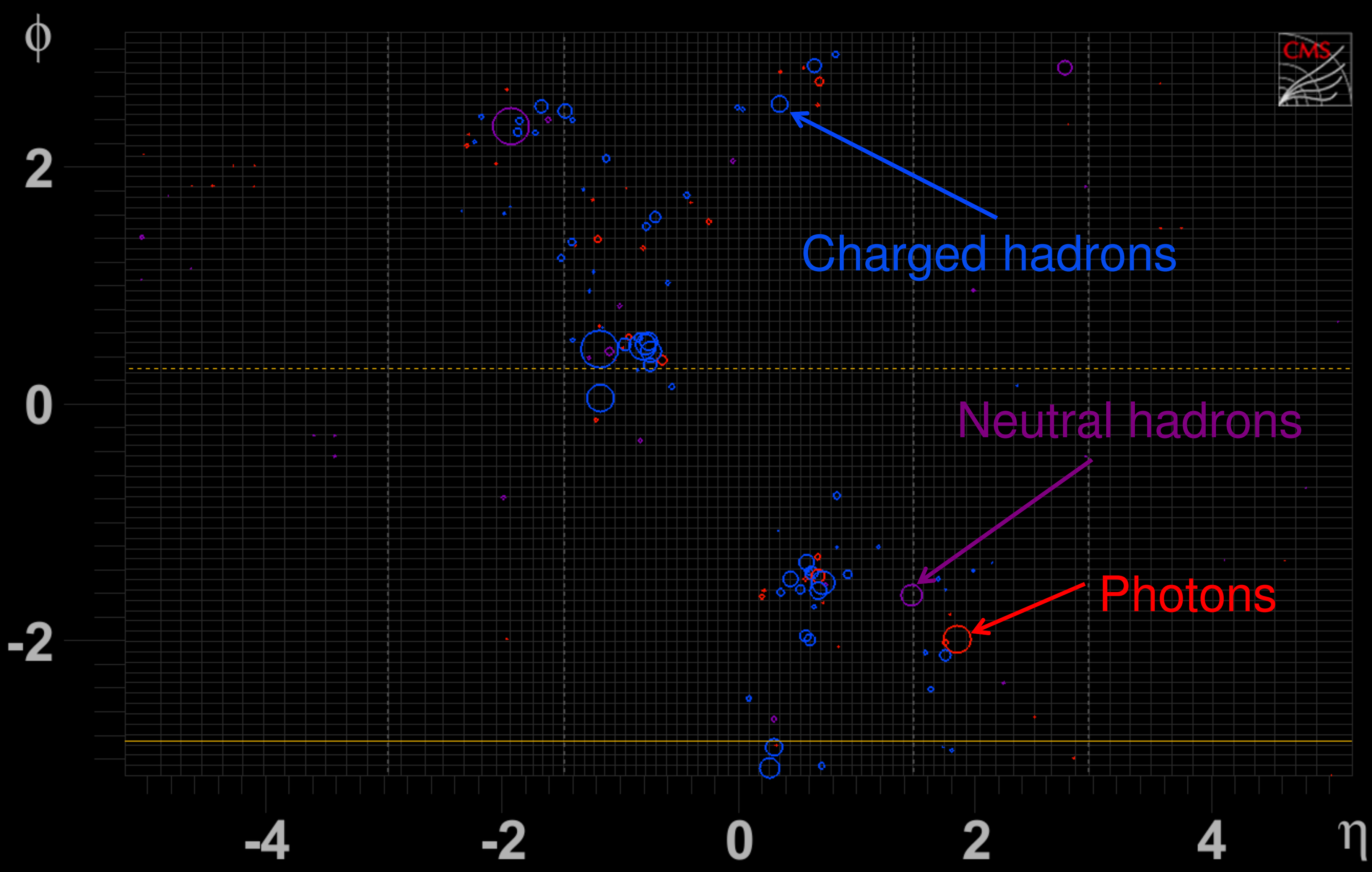




Detector Performance: Particle Flow



Analysing Complex Events



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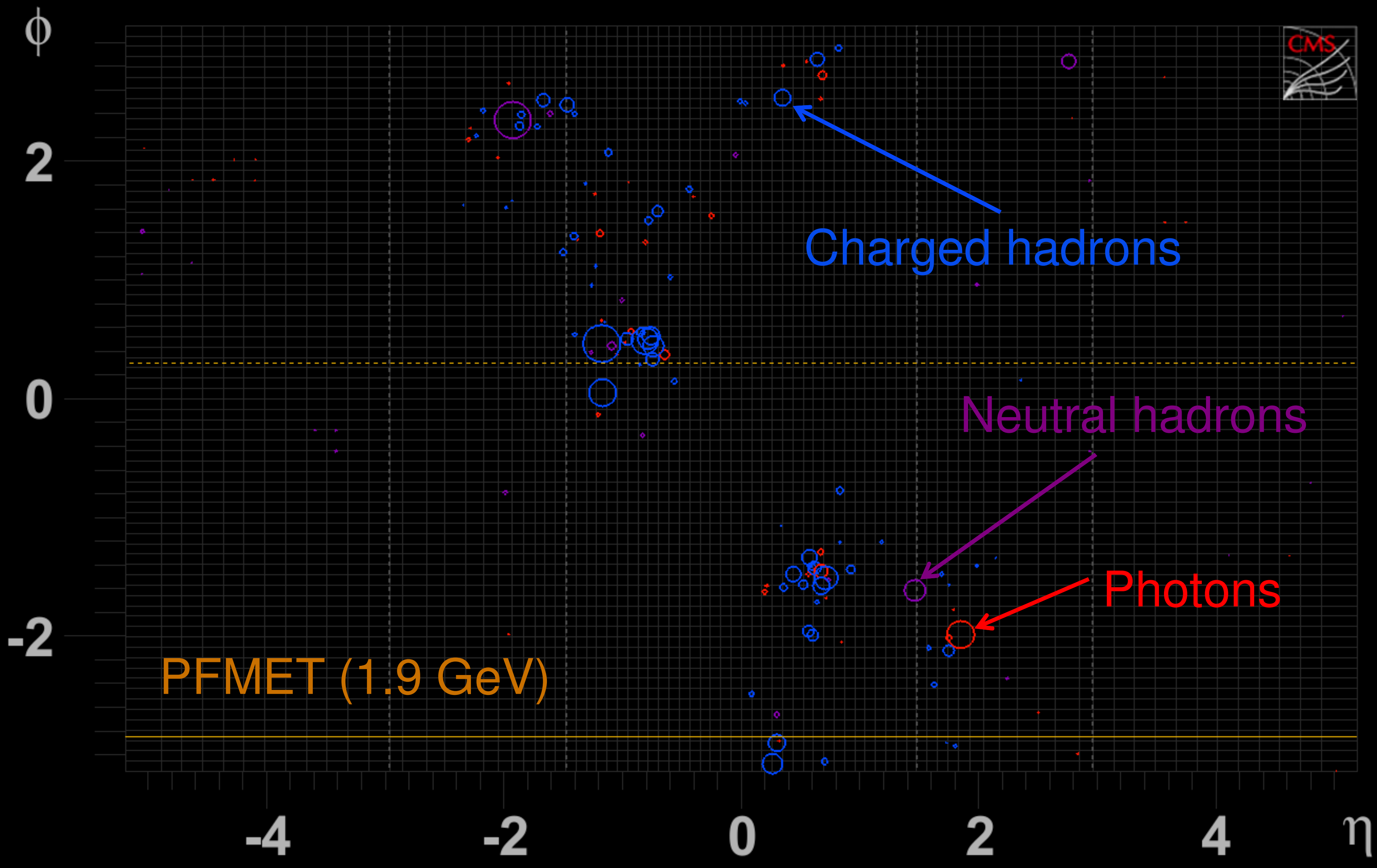
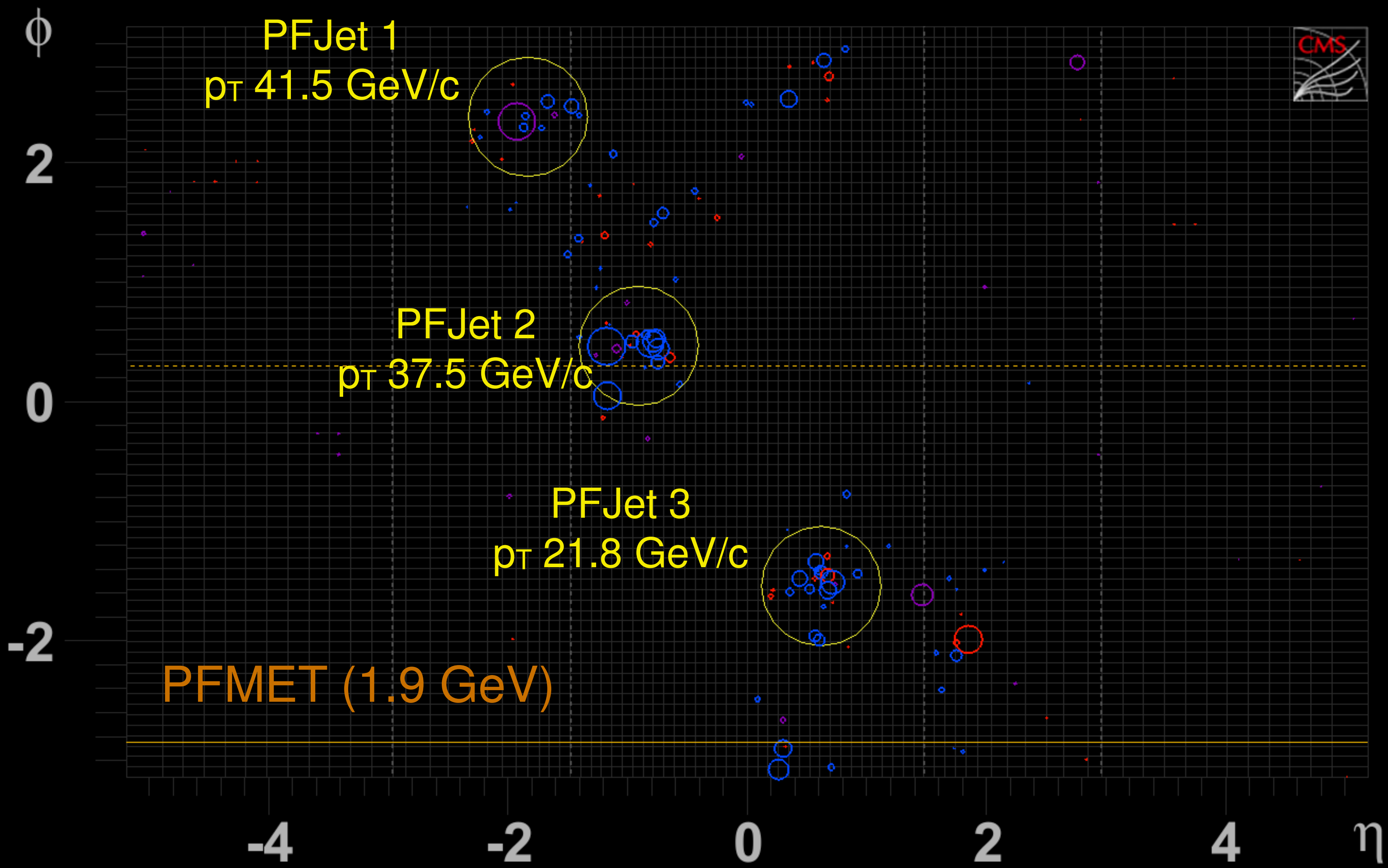
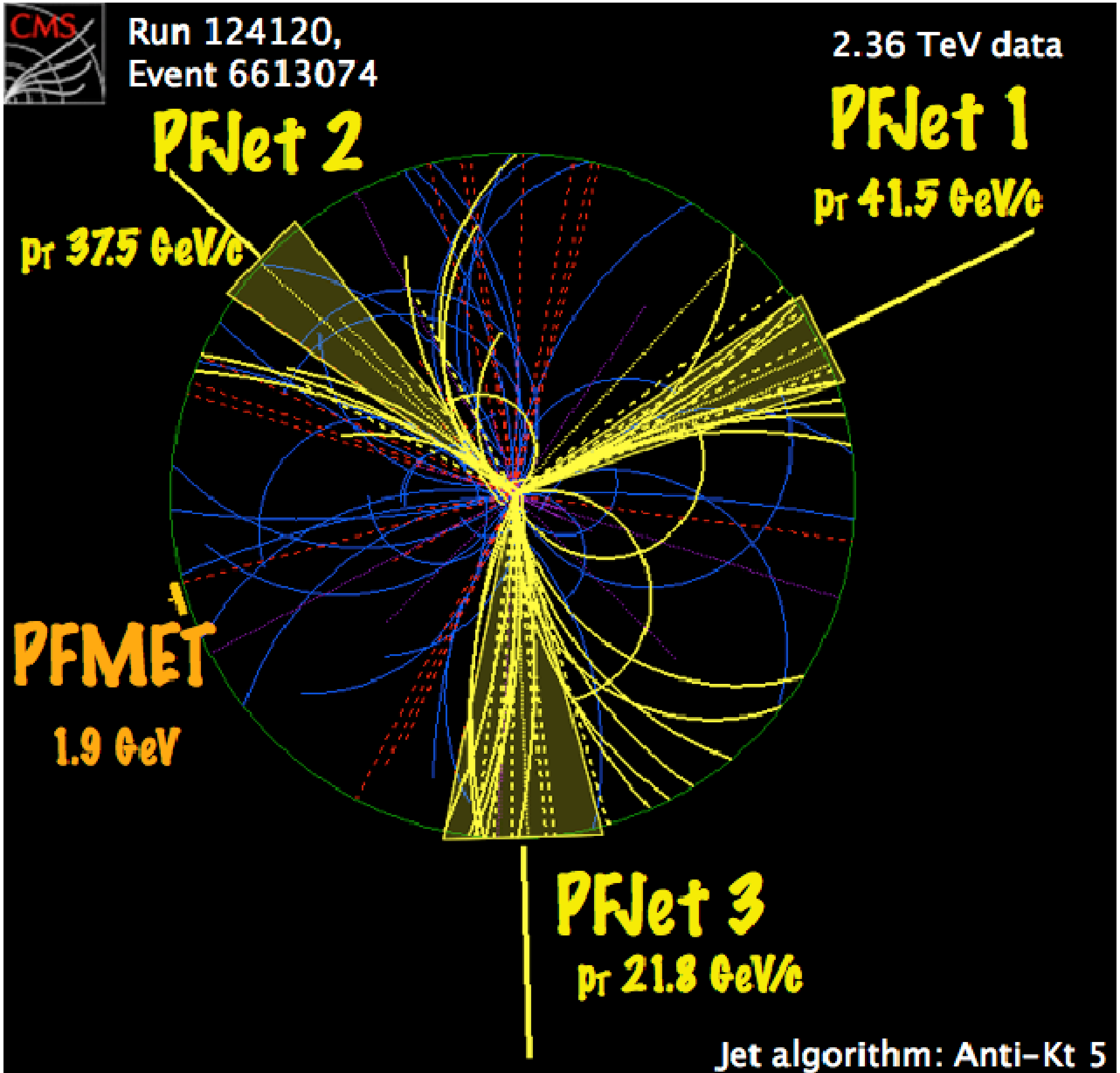
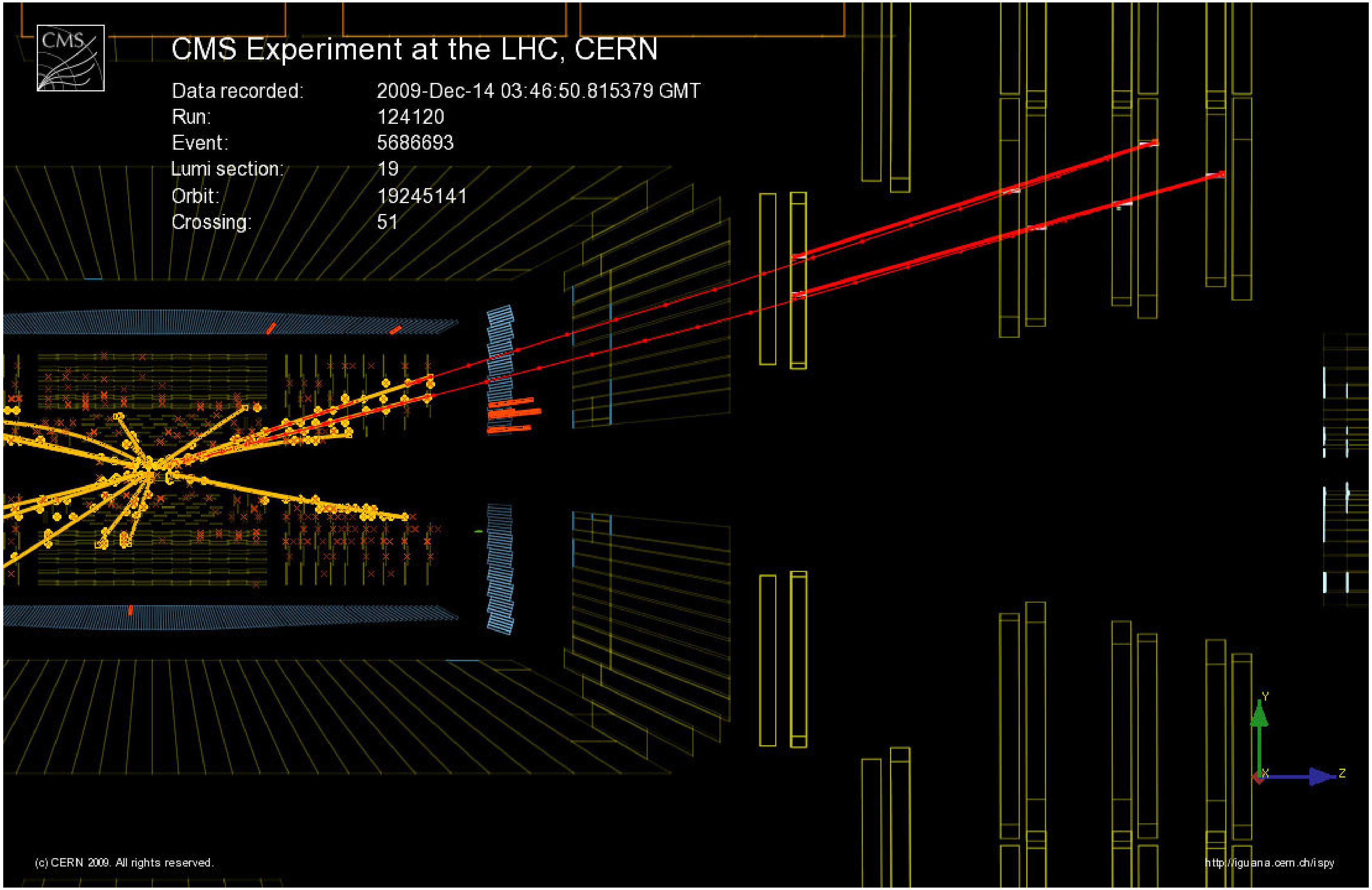


Analysing Complex Events



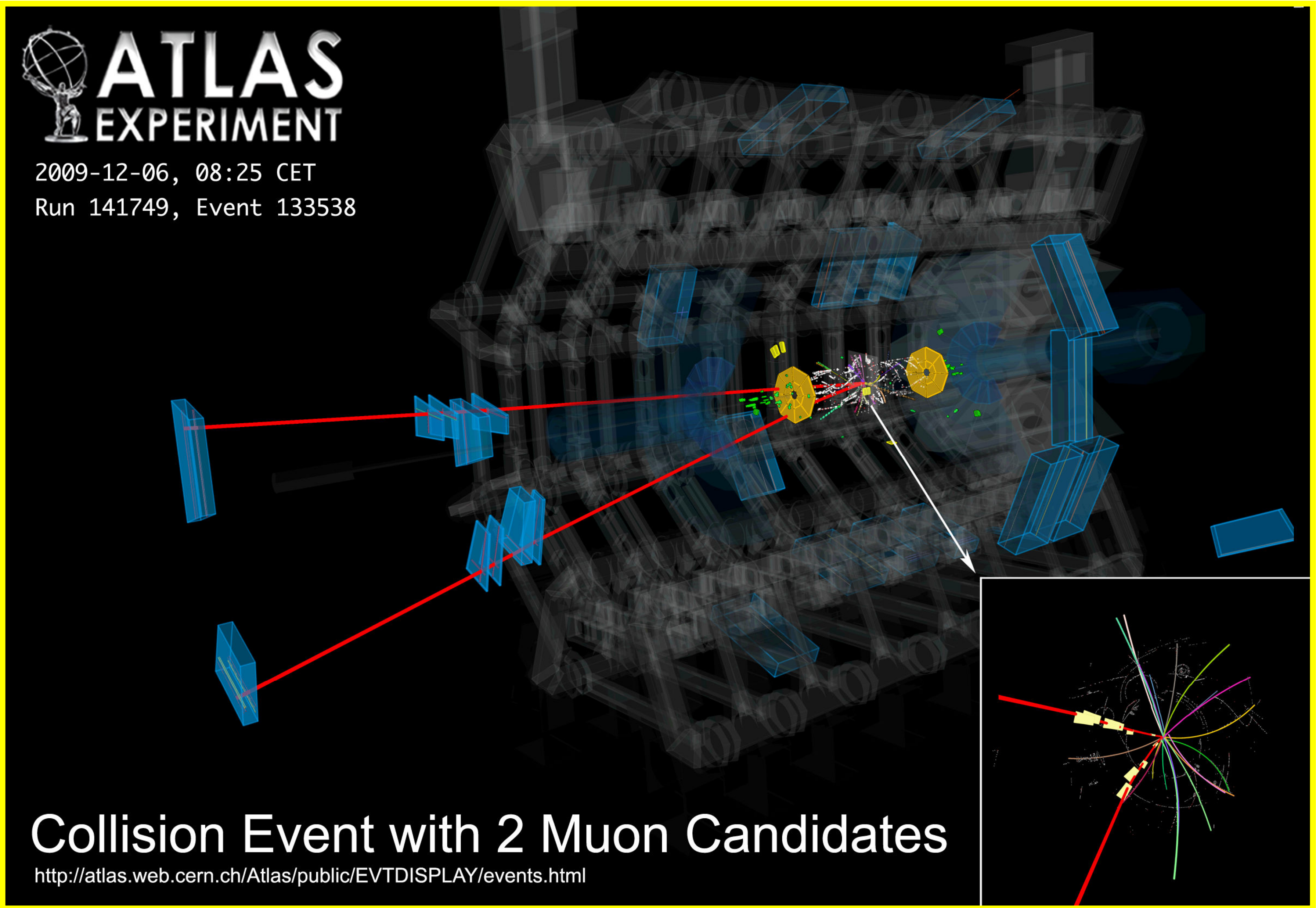

CMS
Run 124120,
Event 6613074
2.36 TeV data
PFJet 1
pT 41.5 GeV/c
PFJet 2
pT 37.5 GeV/c
PFMET
1.9 GeV
PFJet 3
pT 21.8 GeV/c
Jet algorithm: Anti-Kt 5

A Dimuon Event in CMS: 2.36 TeV



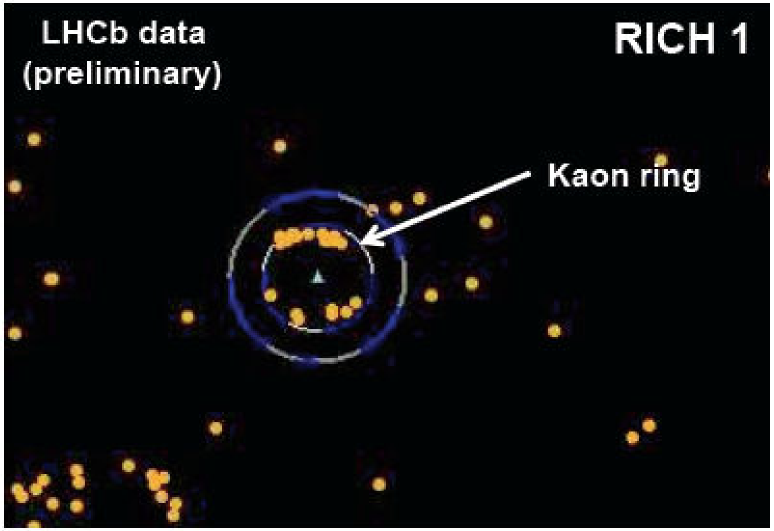
$p_T(\mu_1)$ = 3.6 GeV, $p_T(\mu_2)$ = 2.6 GeV, $m(\mu\mu)$= 3.03 GeV

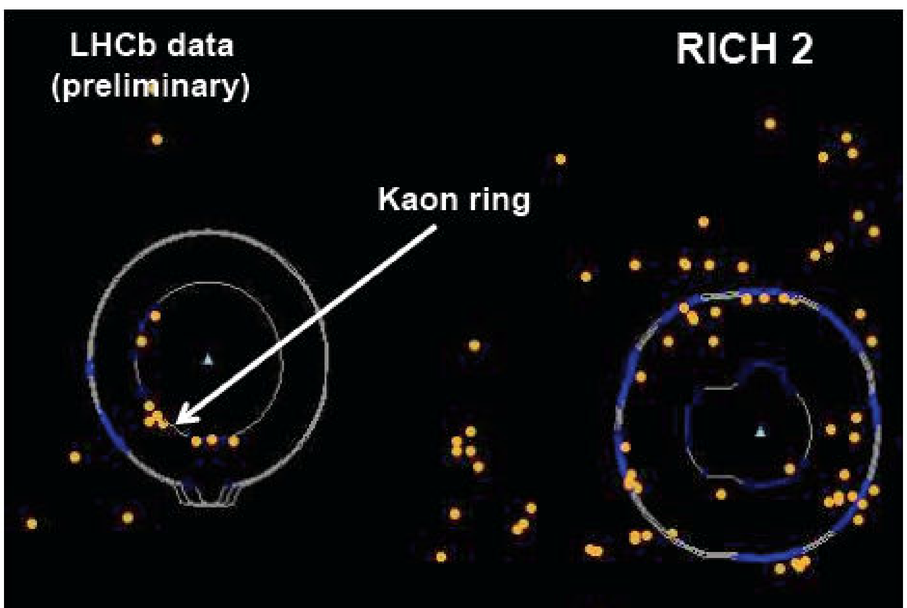
A Dimuon Event in ATLAS



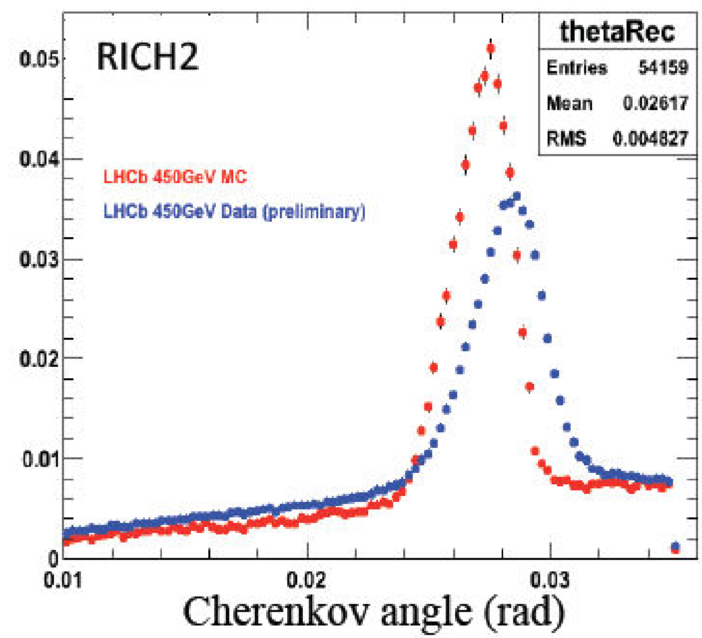
Particle Identification in LHC*b*

RICH identifies charged kaons





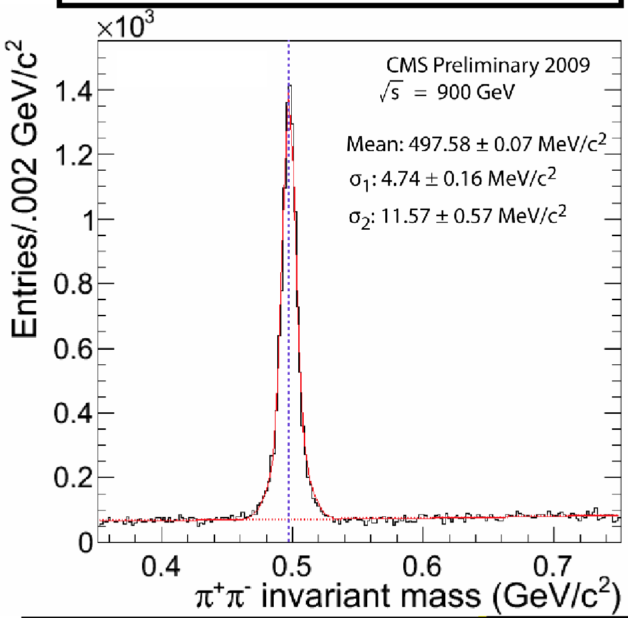
Orange points – photon hits
Continuous lines – expected distribution for each particle hypothesis (proton below threshold)



Detailed calibration and alignment in progress

Rapid Analysis: Known Zoology – K^0_S

M=497.6 MeV/c², σ=4.7 MeV/c²



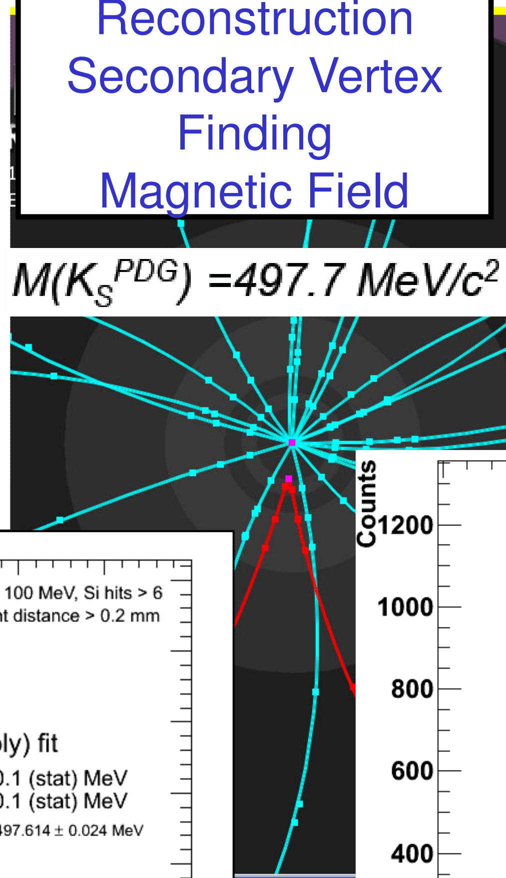
Checks Tracking

Reconstruction

Secondary Vertex Finding

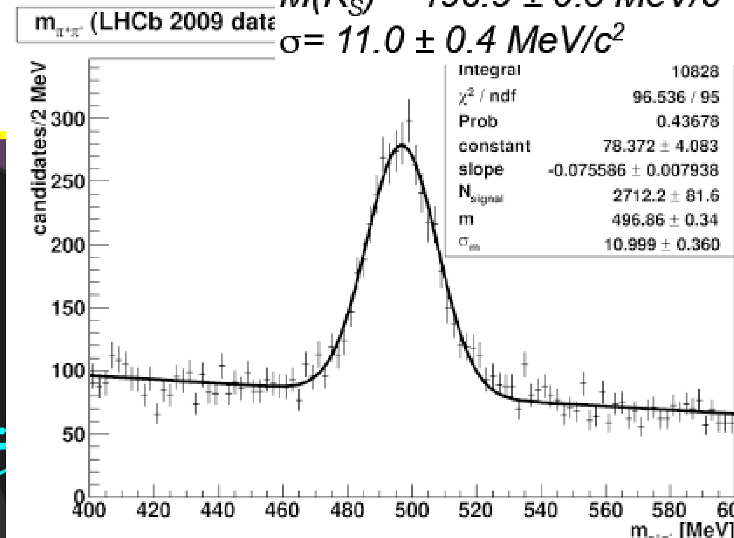
Magnetic Field

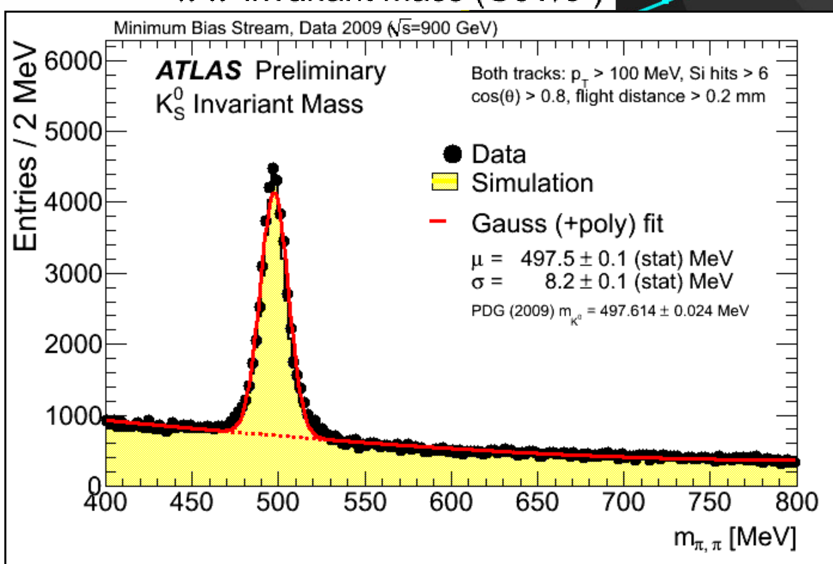
$M(K_S^{PDG}) = 497.7\ MeV/c^2$

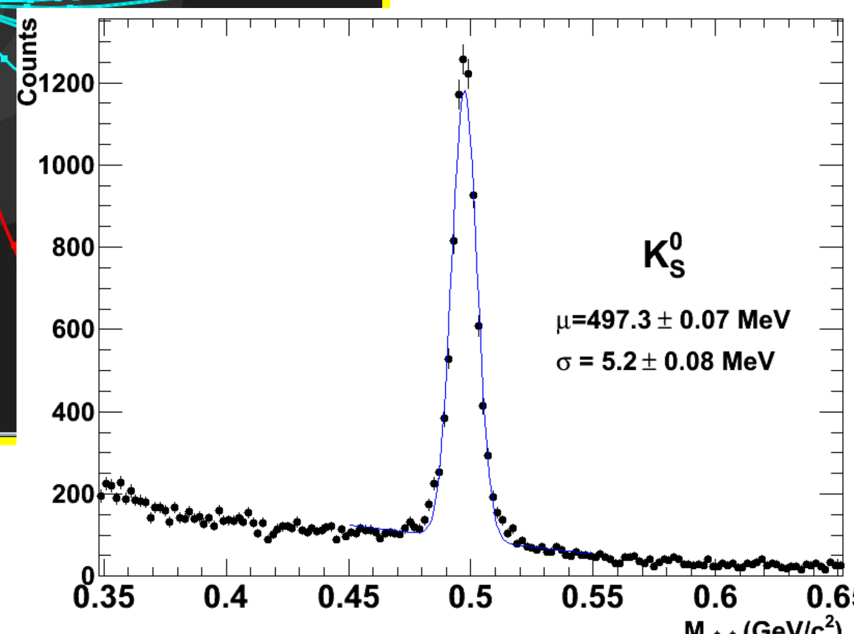


$M(K_S) = 496.9 \pm 0.3\ MeV/c^2$

$\sigma = 11.0 \pm 0.4\ MeV/c^2$

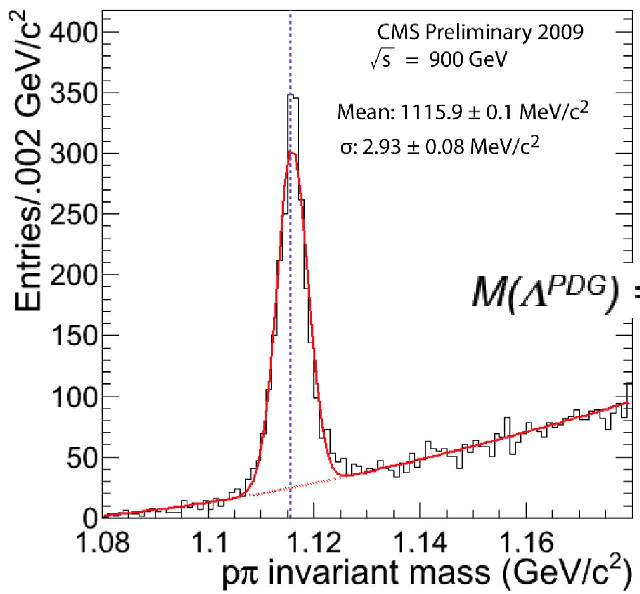






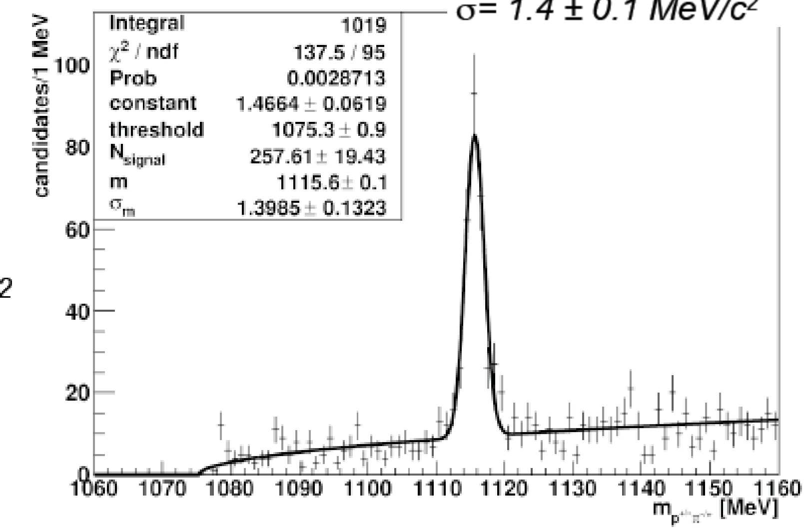
Rapid Analysis: Known Zoology – Λ

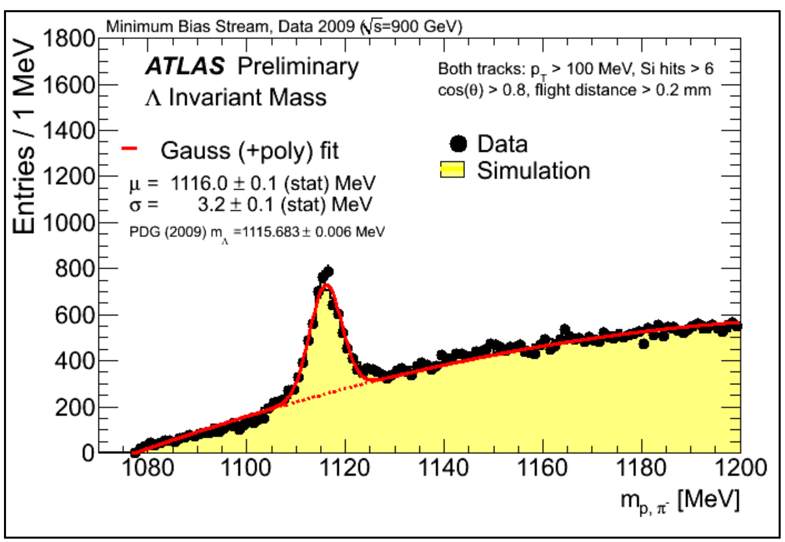
M=1.116 GeV/c^2, σ=2.9 MeV/c^2

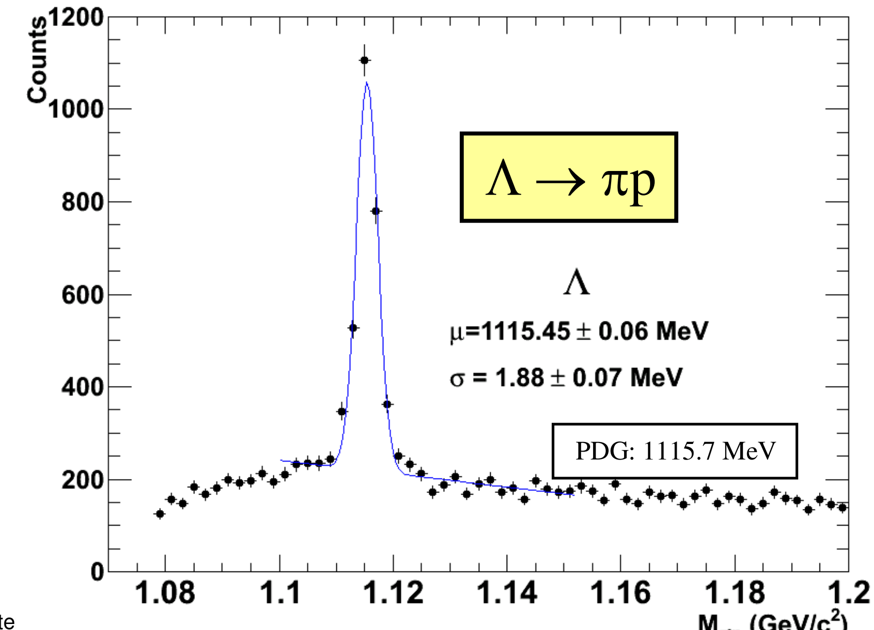


$M(\Lambda^{PDG})$ =1115.7 MeV/c^2

$M(\Lambda)$ = 1115.6 ± 0.1 MeV/c^2
σ= 1.4 ± 0.1 MeV/c^2

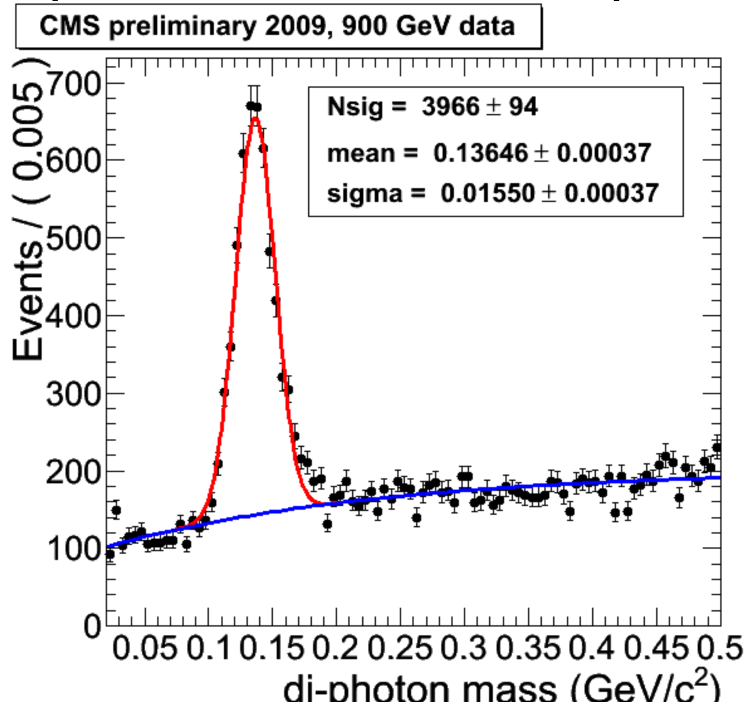


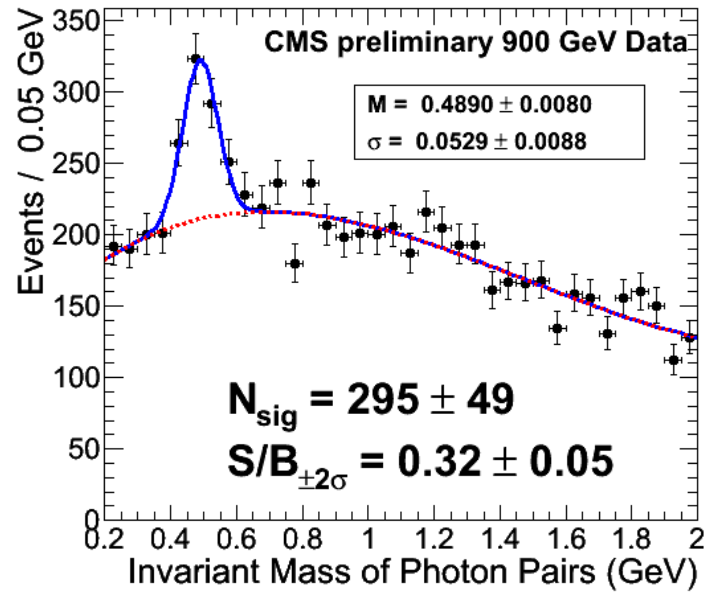


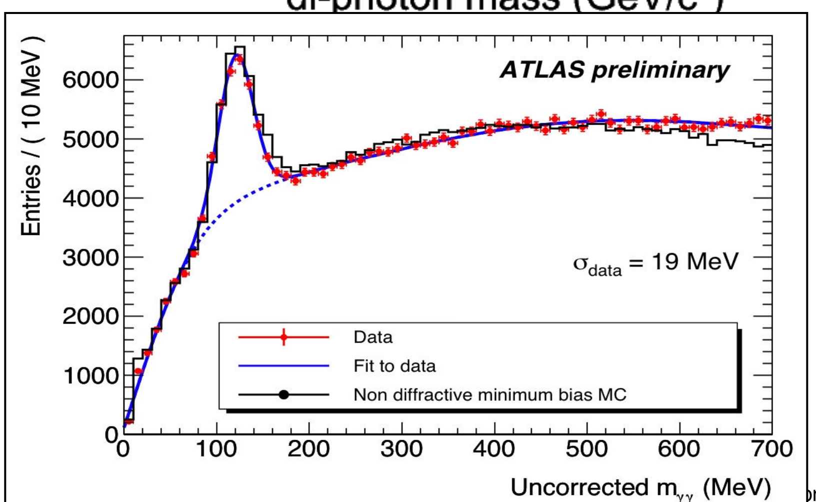


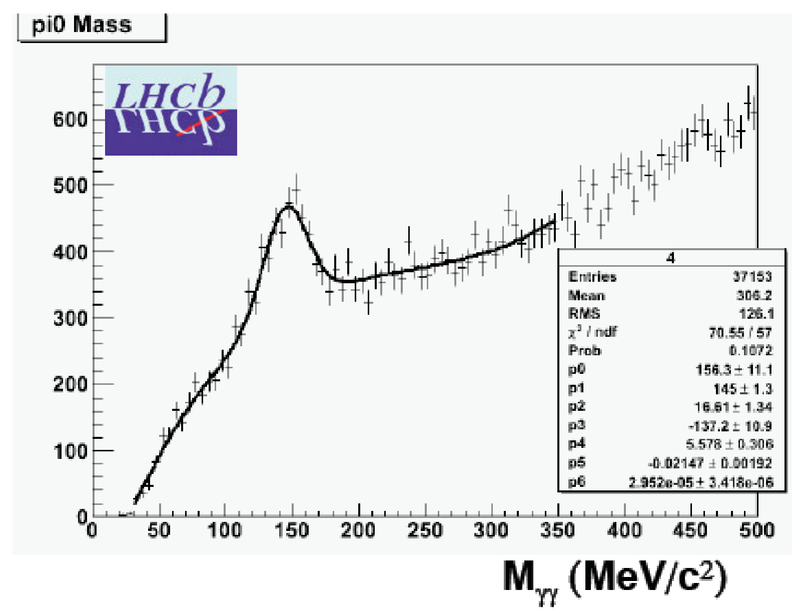
Rapid Analysis: Known Zoology – π^0, η

M=1.116 GeV/c², σ=2.9 MeV/c²



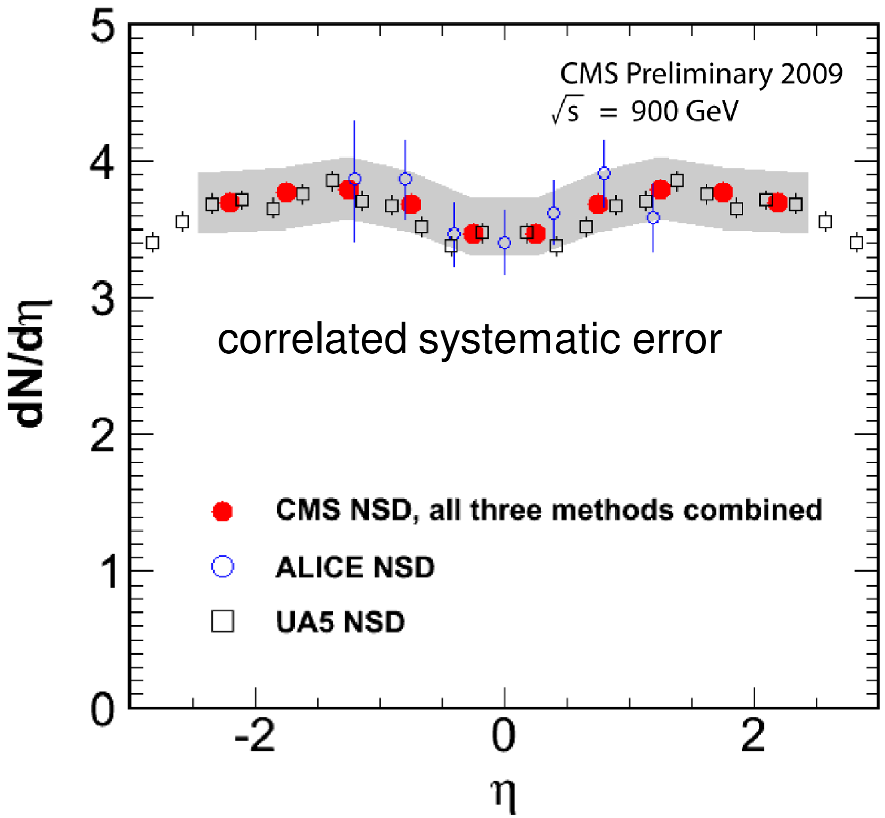




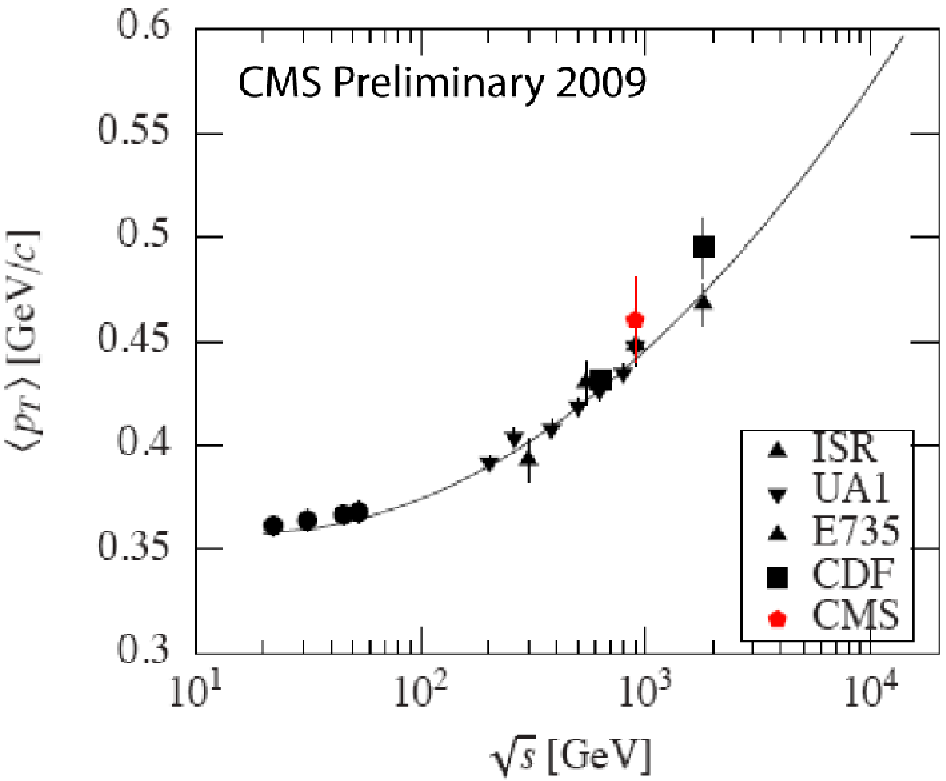


CMS: First Physics Distributions

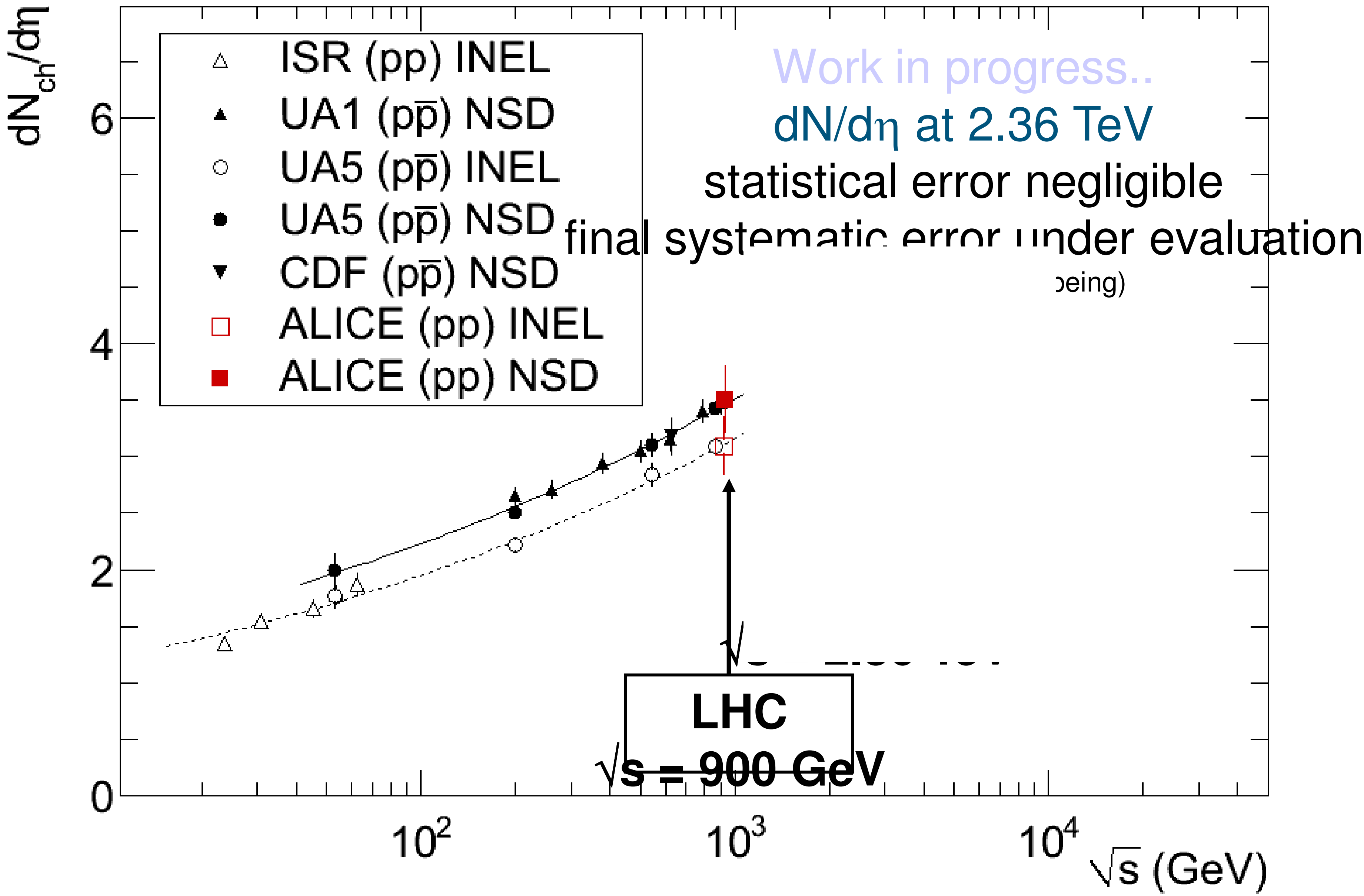
Charged Particle Multiplicity



Average p_T

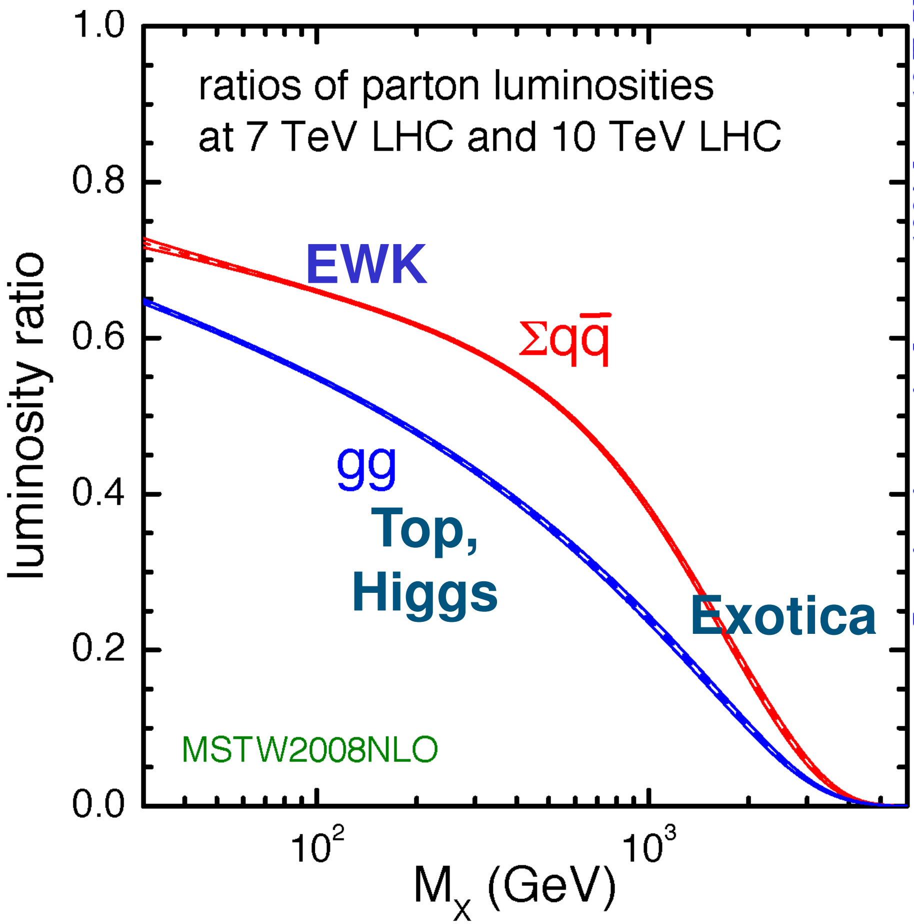


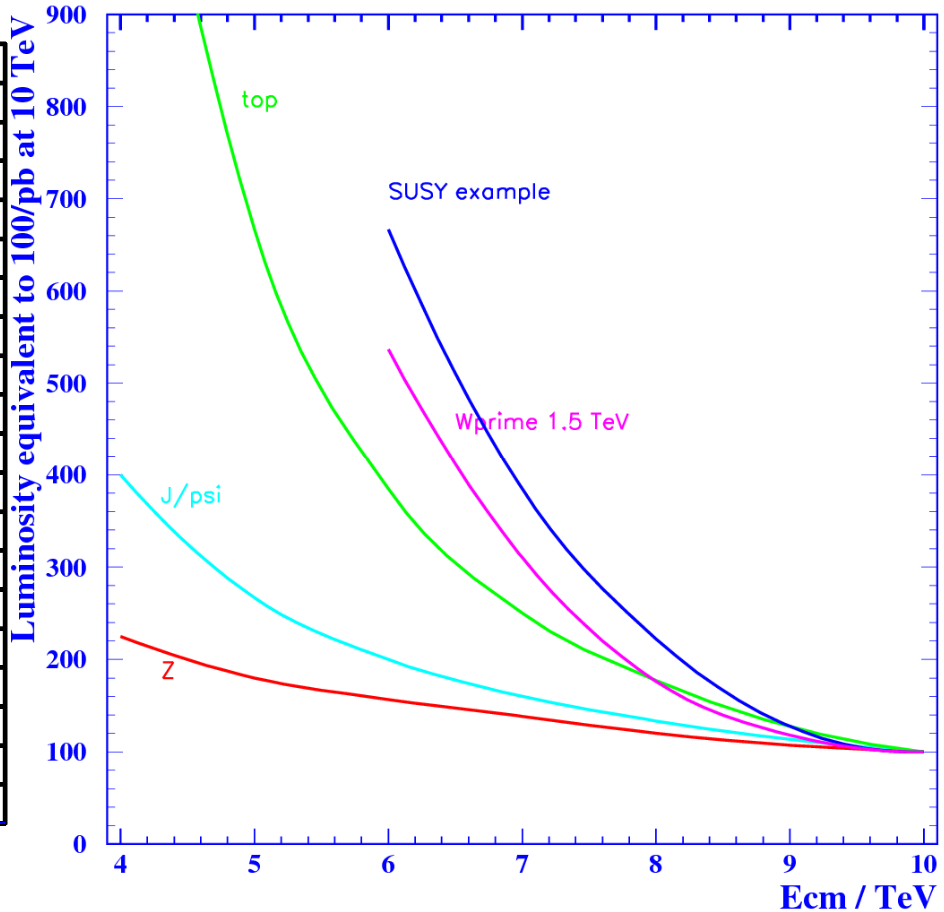
ALICE: First Physics Distributions



2010 Operations

2010: Energy and Luminosity





Prospects for Physics

- **Detector commissioning** – much already done using cosmics and beams in 2009. 0.5Mevts/Xpt at 0.9 TeV and ~20k/Xpt at 2.36 TeV.
- 2010: **collisions at 7 TeV,** 10's of pb^{-1} – "rediscover" & measure S.M., start searches
  - Refine detector synchronization, in-situ alignment and calibration
  - Fully commission triggers, start "physics commissioning"
    - Physics objects; measure jet and lepton rates; observe W, Z, top
    - And, of course, first look at possible extraordinary signatures…
  - Approx per pb^{-1}: 3000 $W \rightarrow \ell\nu$ (ℓ = e,μ); 300 $Z \rightarrow \ell\ell$ (ℓ =e, μ); 5 ttbar $\rightarrow \mu$+X
    - Improved understanding of physics objects; jet energy scale from $W \rightarrow j\, j'$; extensive use (and understanding) of b-tagging
    - Measure/understand backgrounds to SUSY and Higgs searches
  - As data accumulates higher, look for excesses from SUSY & Z′ resonances.
- **Collisions at the higher energy**: extend searches
  - Explore a larger part of SUSY and resonances
  - **~1000 pb^{-1} entering Higgs discovery era**

Prospects for 2010: LHC

- From HCP 2009
- ~ 3 months

Energy limited to 3.5TeV
Intensity limited to 6 10^{13} (20% nominal)
Aperture limited to 2m (3m) without (with) crossing angle

- ~ June decision on going up in energy

Energy < 5TeV
Intensity limited to 3 10^{13} (10% nominal)
Aperture limited to 2m with crossing angle

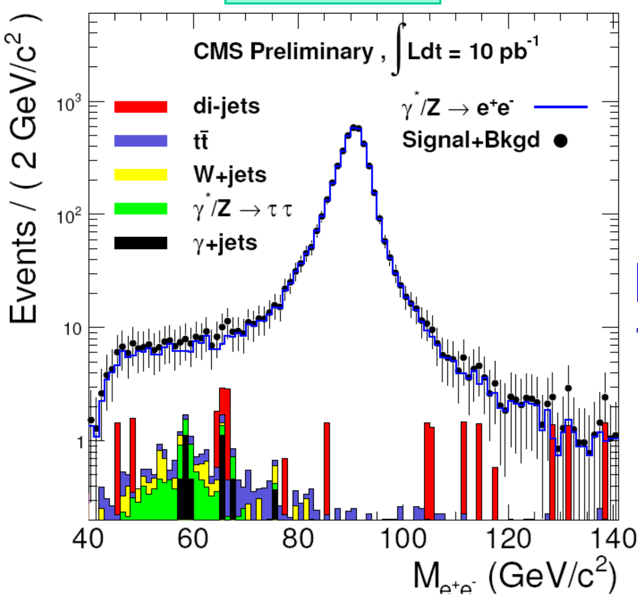
Discussions ongoing in Chamonix as we speak.
The exact 2010 programme will be determined by experience gained during running.

Rediscovering SM: W and Z

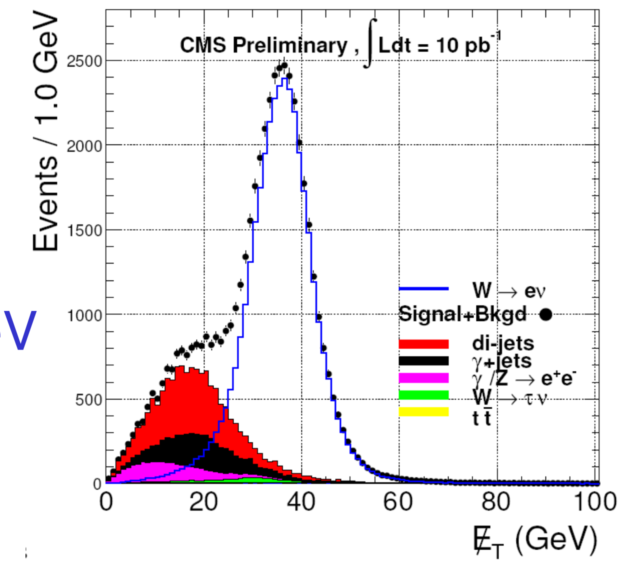
$Z \to ee$

10 TeV

$W \to e\nu$



- Z Selection
$E_T > 20.0$ GeV
both e isolated
$70 < M_{e,e} < 110$ GeV



$N_{selected}$	4273 ± 65
N_{bkgd}	assumed 0.0
Tag&Probe $\varepsilon_{offline}$	90.37 ± 0.32 %
Tag&Probe $\varepsilon_{trigger}$	99.88 ± 0.016 %
Tag&Probe ε_{total}	81.57 ± 0.58 %
Acceptance	40.42 ± 0.18 %
Int. Luminosity	$10\ pb^{-1}$
$\sigma_{Z/\gamma^*} \times BR(Z/\gamma^* \to e^+e^-)$	1296 ± 23 pb
cross section used	1296 pb

Systematic uncertainty
2.4% + 10% for ∫Ldt

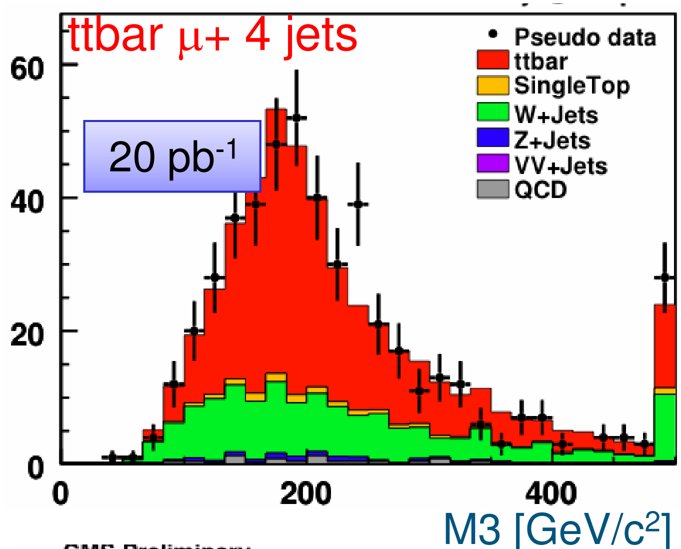
- Use data driven methods e.g. *tag and probe* method to work out efficiencies from “data”

$N_{selected} - N_{bkgd}$	37500 ± 453
Tag&Probe $\varepsilon_{offline}$	74.44 ± 0.59 %
Tag&Probe $\varepsilon_{trigger}$	97.17 ± 0.32 %
Tag&Probe $\varepsilon_{offline \times trigger}$	72.33 ± 0.62 %
Acceptance	36.6 ± 0.074 %
Int. Luminosity	$10\ pb^{-1}$
$\sigma_W \times BR(W \to e\nu)$	14166 ± 212 nb
cross section used	13865 pb

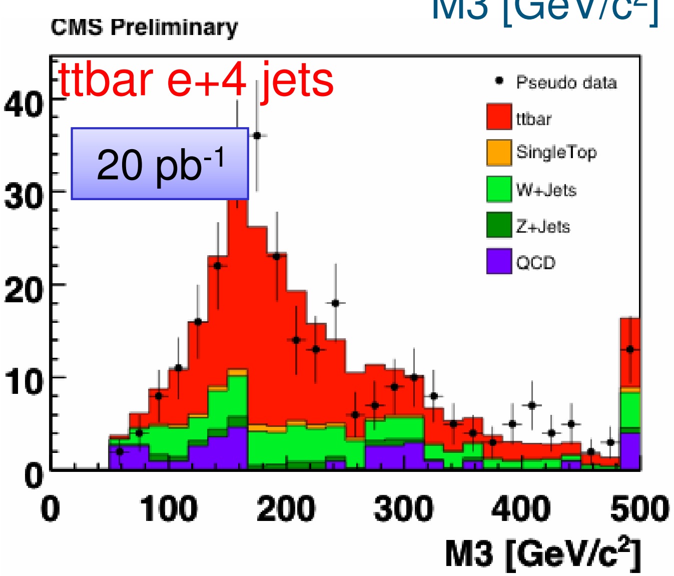
Systematic uncertainty
4.0% + 10% for ∫Ldt;

Top Studies…

Observation and early ttbar cross sections

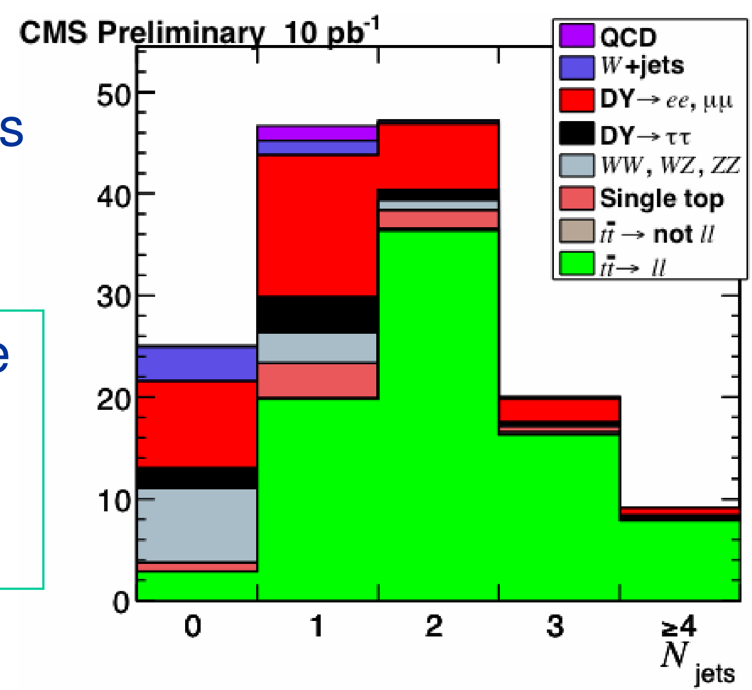


Top production is excellent testbed for the understanding of:
lepton id. (incl. taus), jet corrections, jet energy scale, b tagging, ….



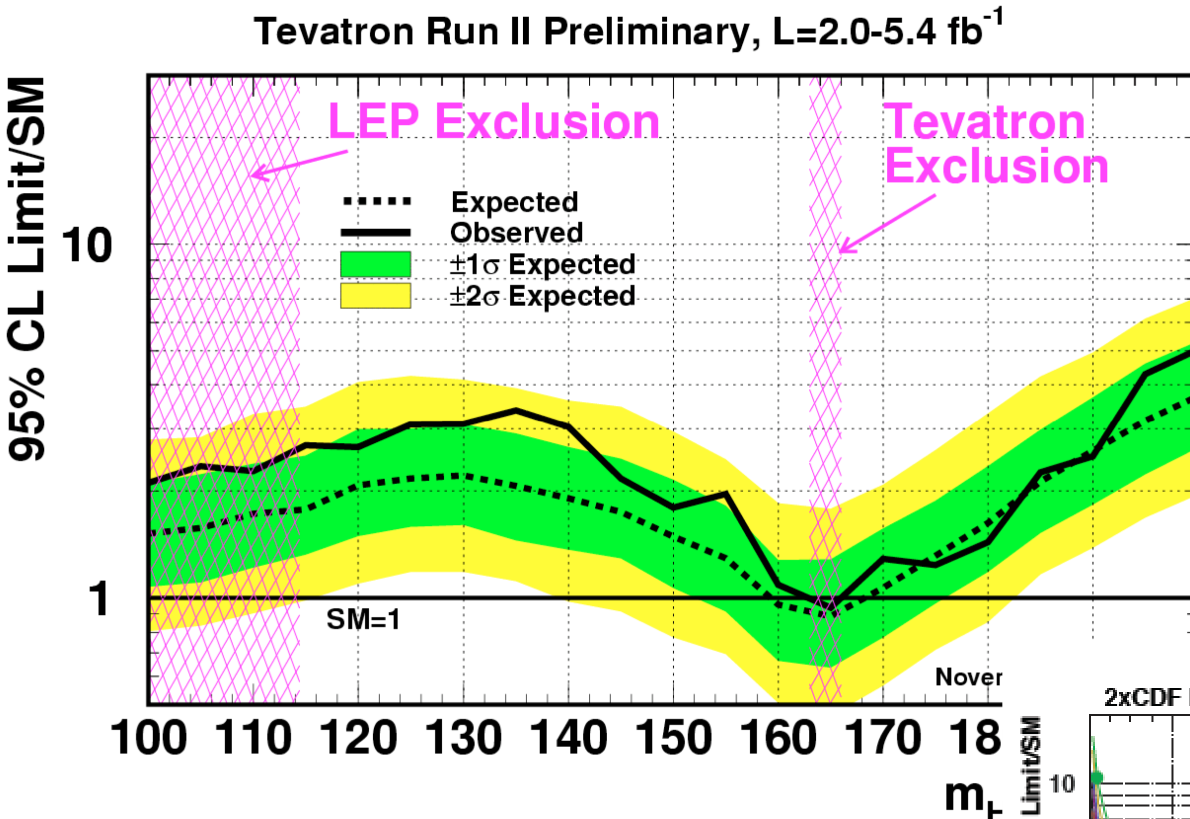
M3 = M of 3 jets with highest vector sum

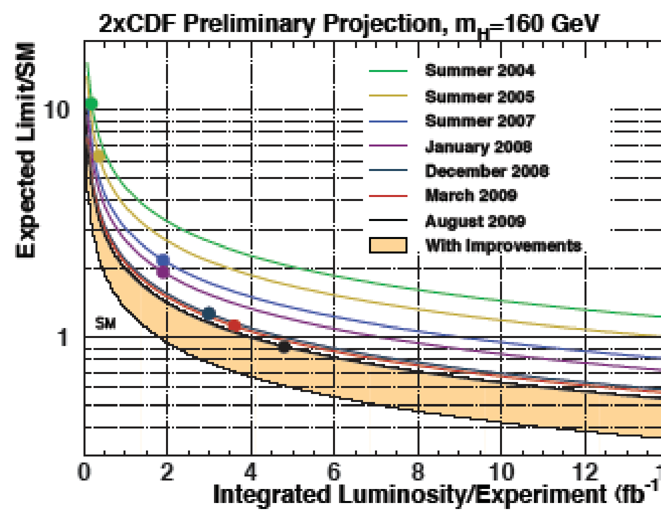
Mostly w/o use of b-tagging, robust selections



σ(ttbar) ~ ±15% Stat) ± 10% (syst) ± 10% (lumi)

SM Higgs at the TeVatron





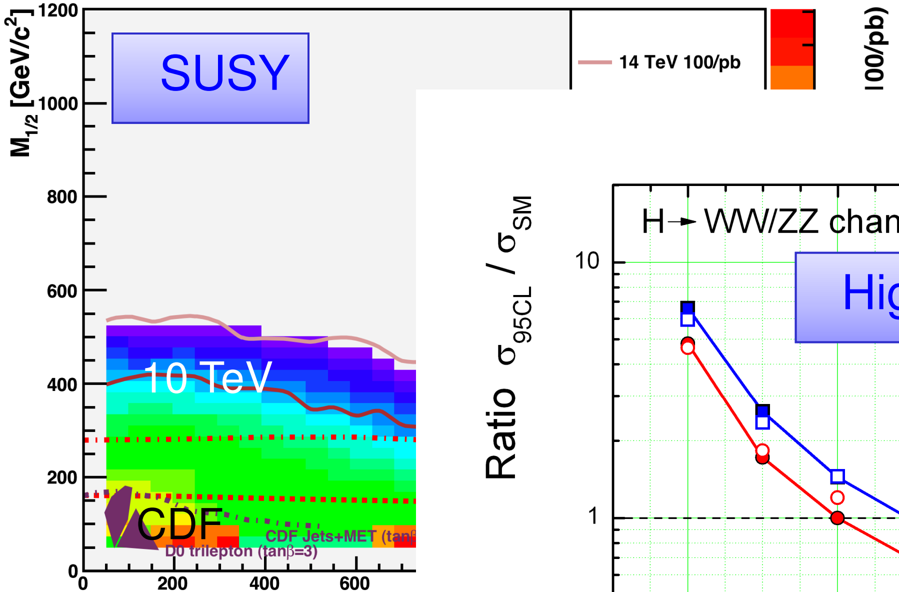
Exclude SM Higgs in mass range

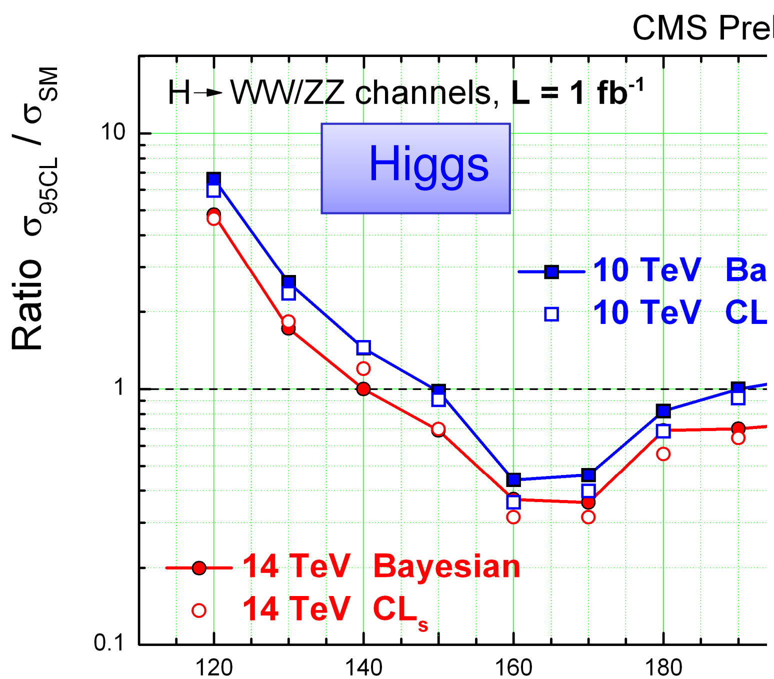
163-166 GeV/c^2 at 95% CL

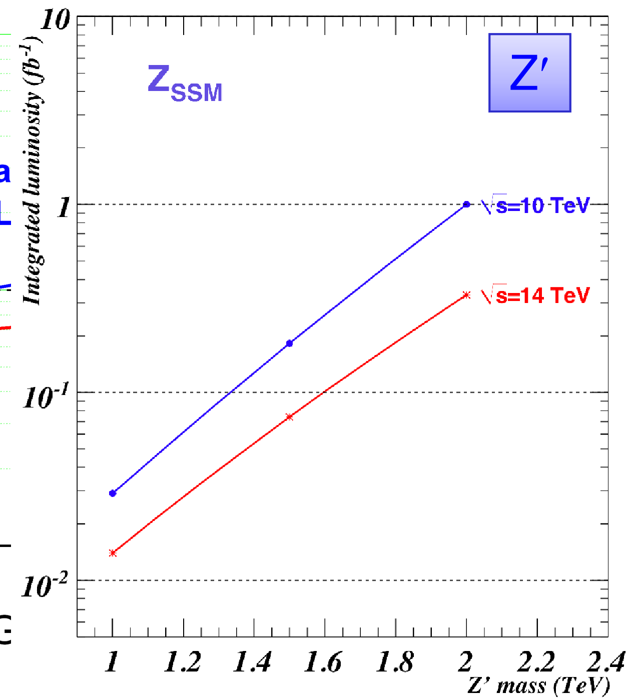
Expected exclusion range 159-168 GeV/c^2

Potential at 10 TeV

Signals and backgrounds are scaled from 14 TeV
Plots are indicative of CMS reach



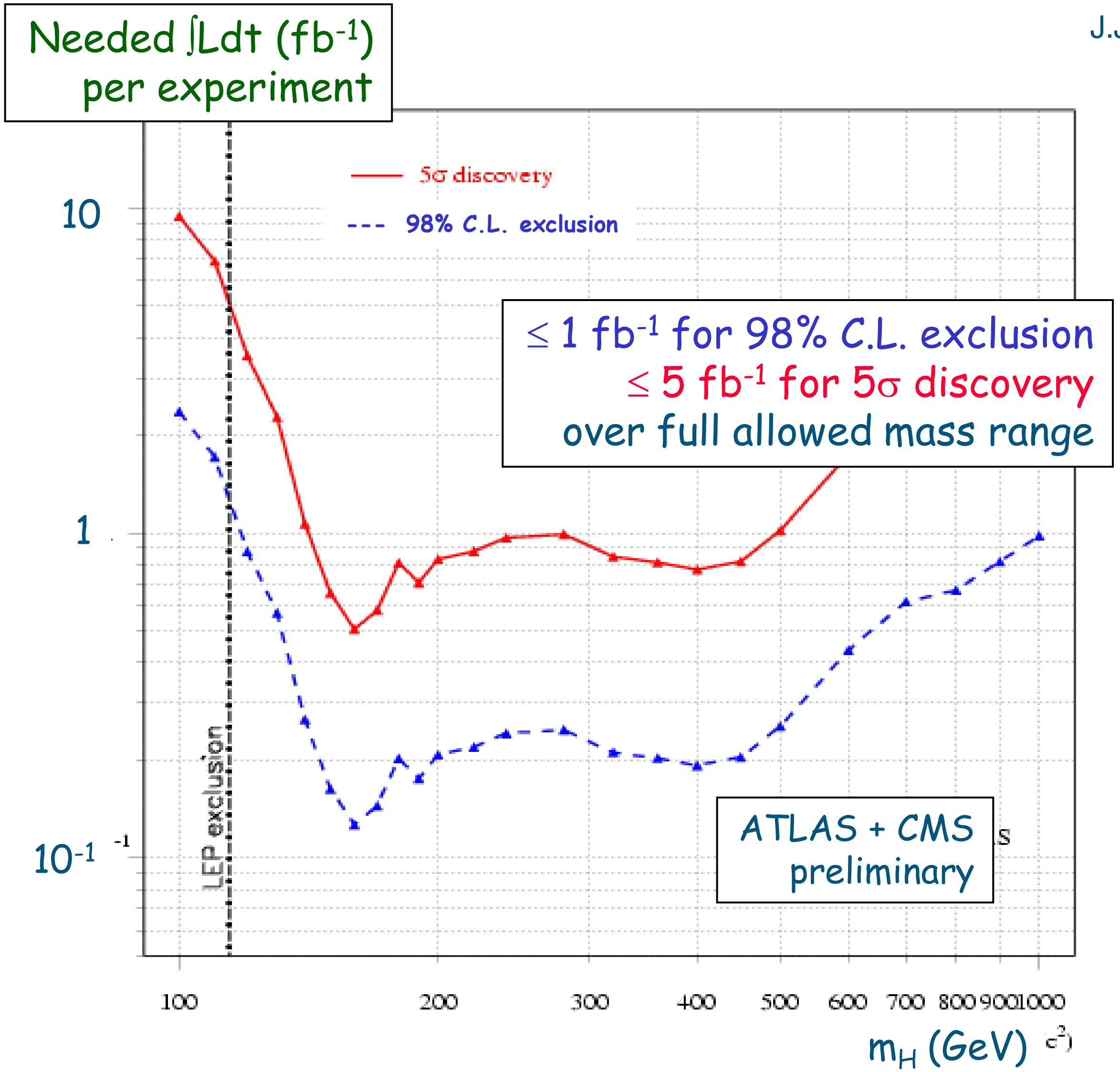




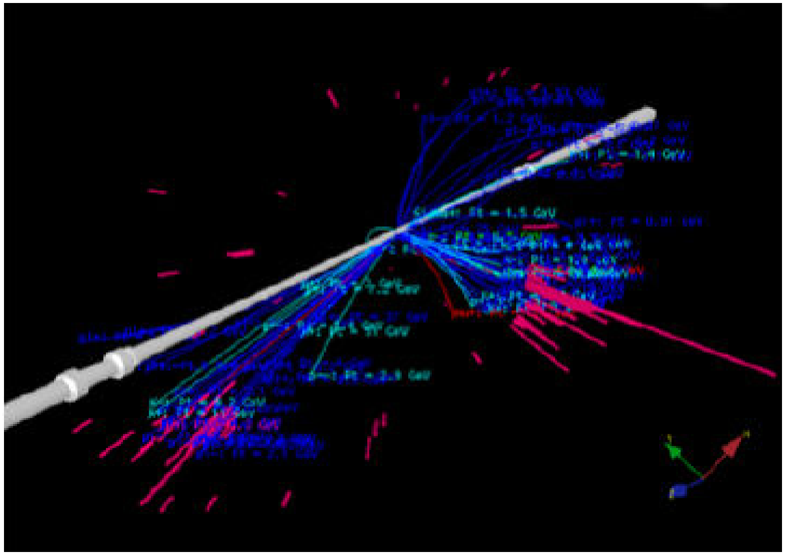
With 200 pb^{-1}, reach current m_H (G
Tevatron sensitivity for
Higgs

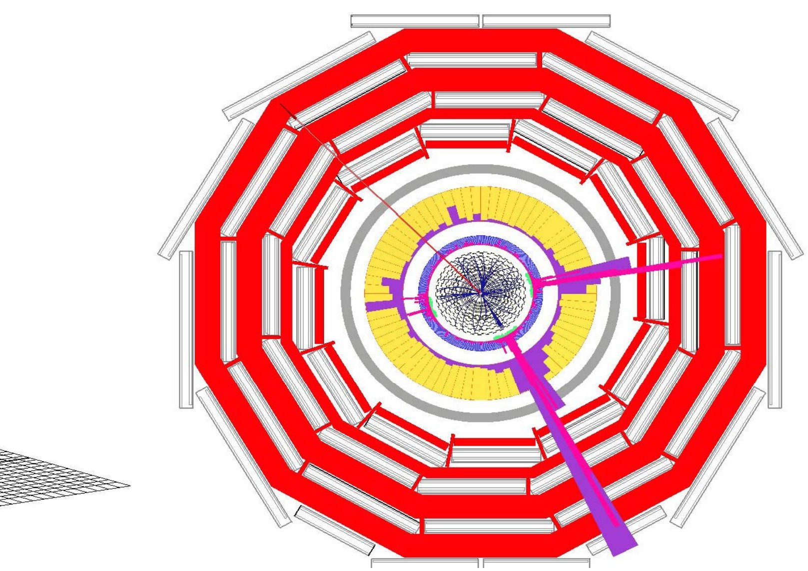
Longer Term: SM Higgs (ATLAS+CMS)

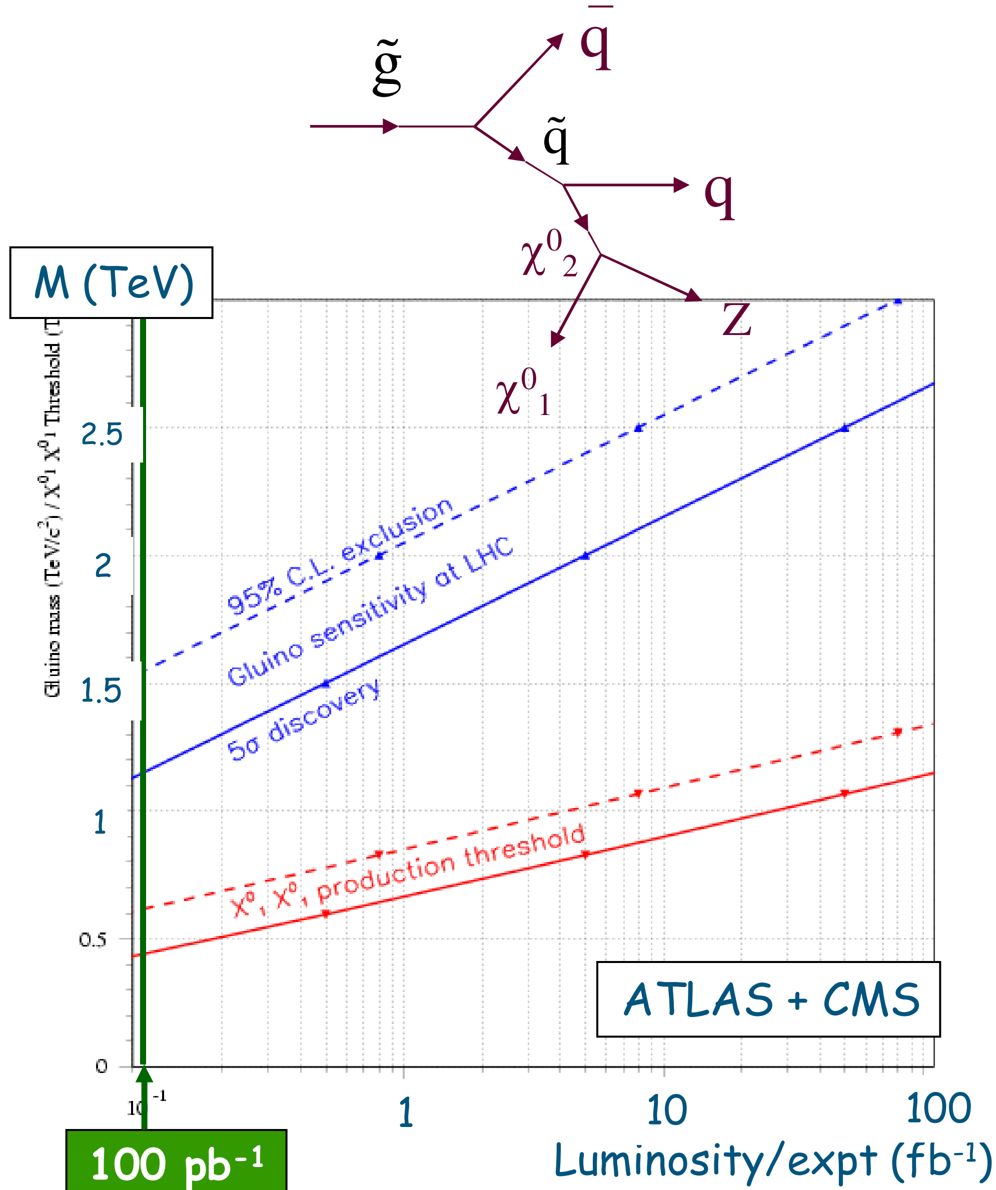
J.J. Blaising et al, input to
Eur. Strategy workshop



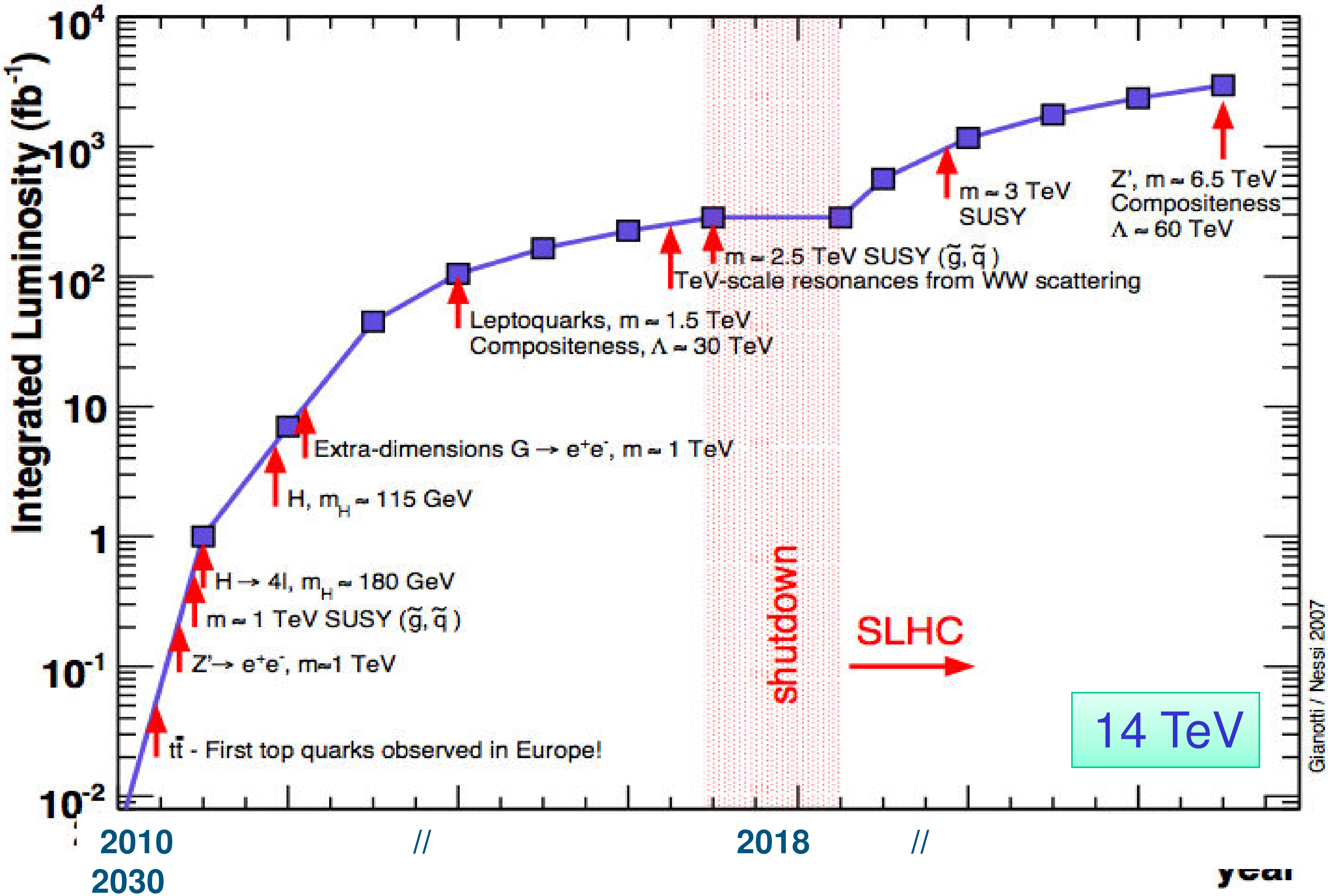
Longer Term: SUSY(ATLAS+CMS)





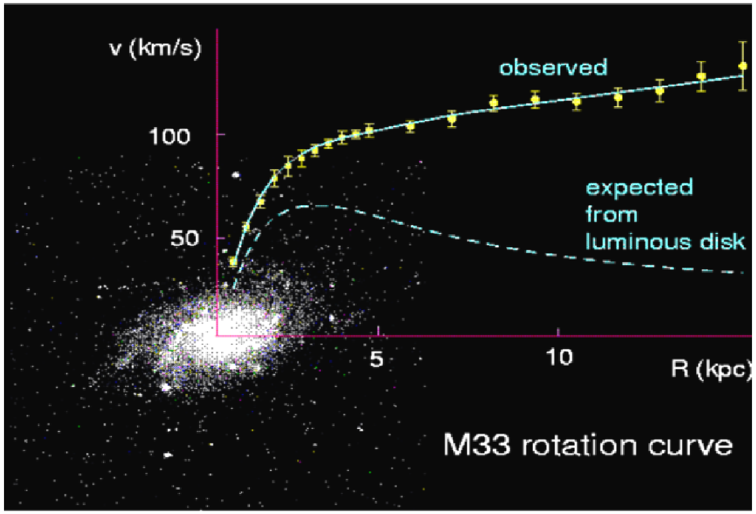


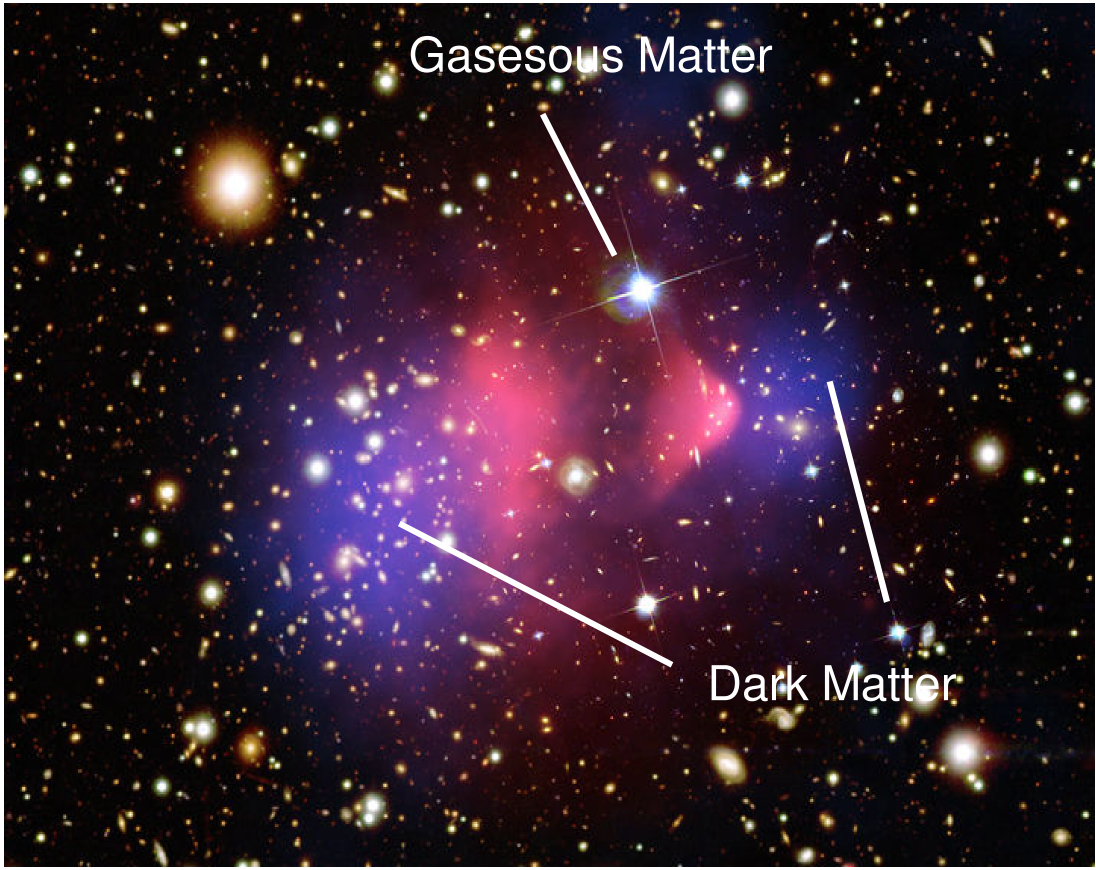
The LHC/sLHC Discovery Reach



The LHC and the Dark Side of the Universe

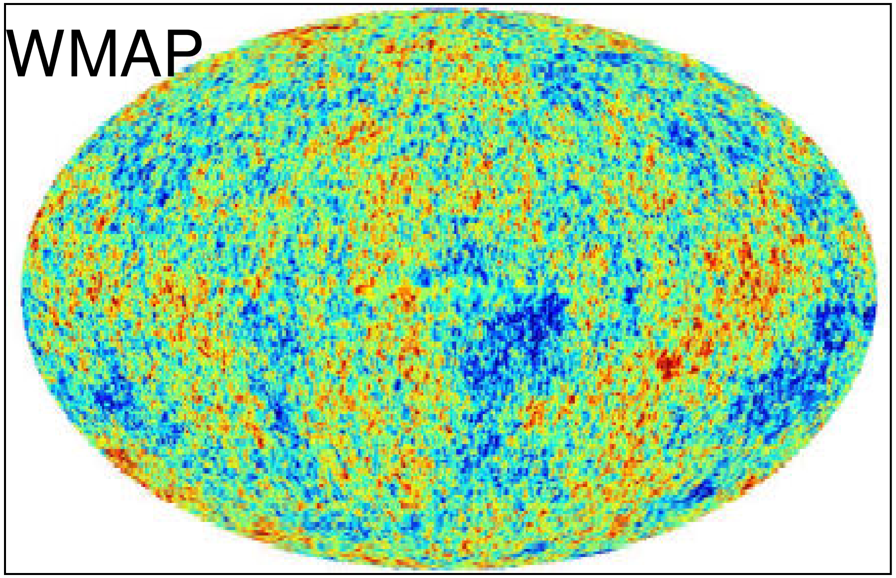
Dark (invisible) matter!



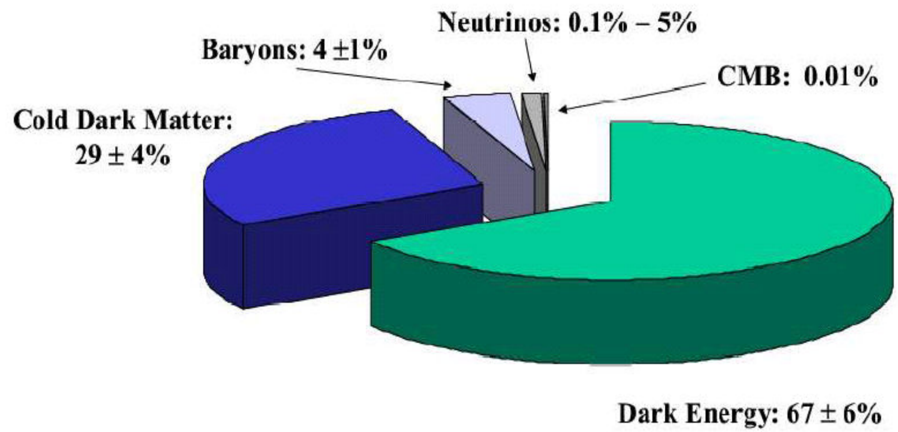


Dark Matter is weakly interacting massive particle
Lightest SUSY particle has these properties !

The LHC and the Dark Side of the Universe



“The Standard Model of Cosmology”
Convergence Model



It appears that the rate of expansion of the universe is accelerating !!
Dark Energy?
Remnant of some elementary scalar field analagous to the Higgs field?

Conclusions

After twenty years of design, construction the 2nd half of the journey of extraction of physics has started in earnest.

The accelerator and the experiments had a good start and functioned very well. The LHC has delivered first pp collisions (at 0.9 and 2.36 TeV)

The accelerator folks are doing things in hours that in previous accelerators took weeks!

Experiments: on the average more than 99% of the sub-detector electronic channels are operational with high data-taking efficiency.
All indications are that:

- **data can be analysed rapidly – all chains are working well,**
- **the performance is according to design (almost all distributions agree well with the simulations at the fine level),**
- **The experiments are starting to produce results from collision data.**
- **This augurs well for the future.**
- **A long and interesting road ahead, we all look forward to revolutionary physics.**