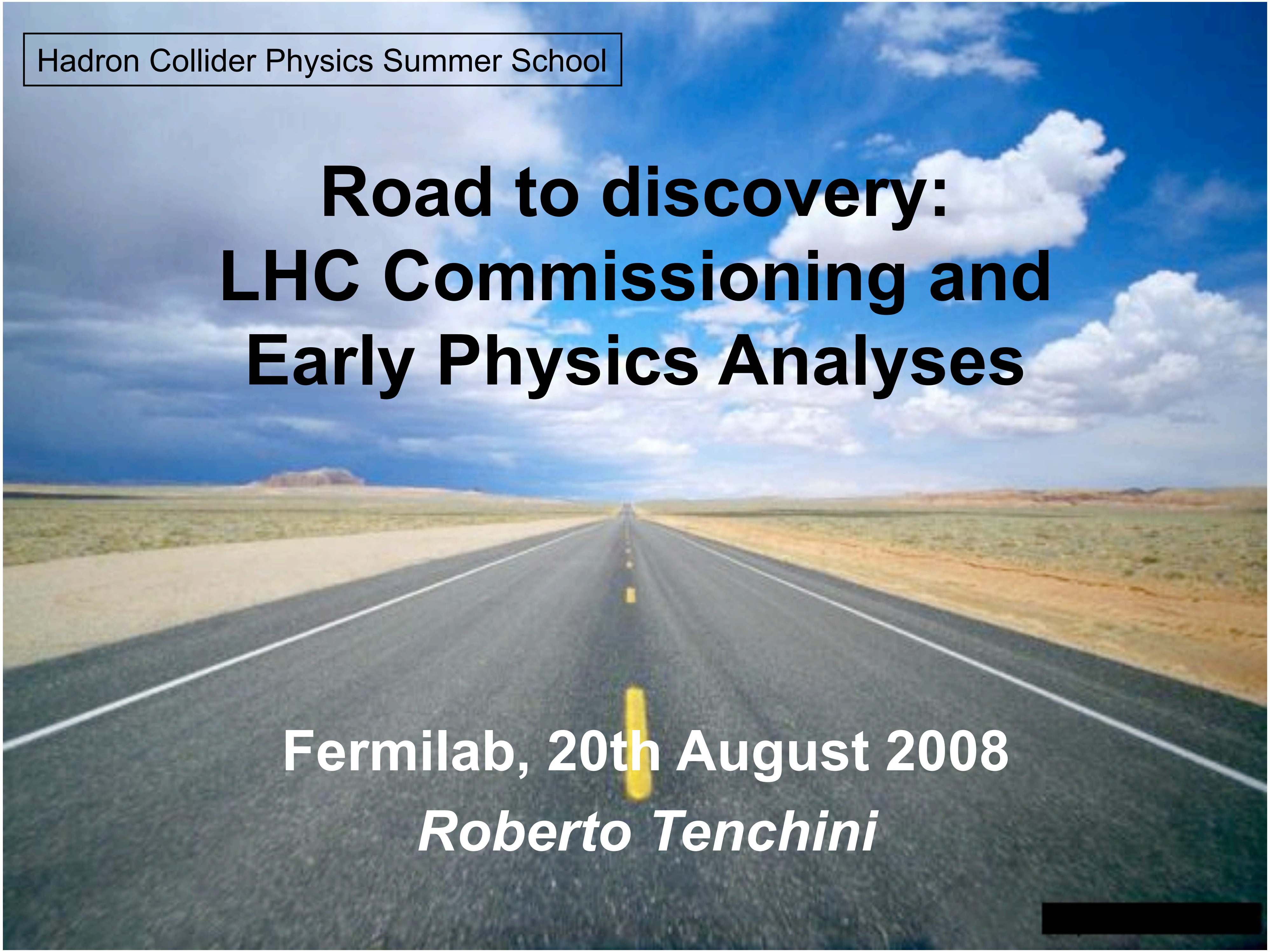


Hadron Collider Physics Summer School

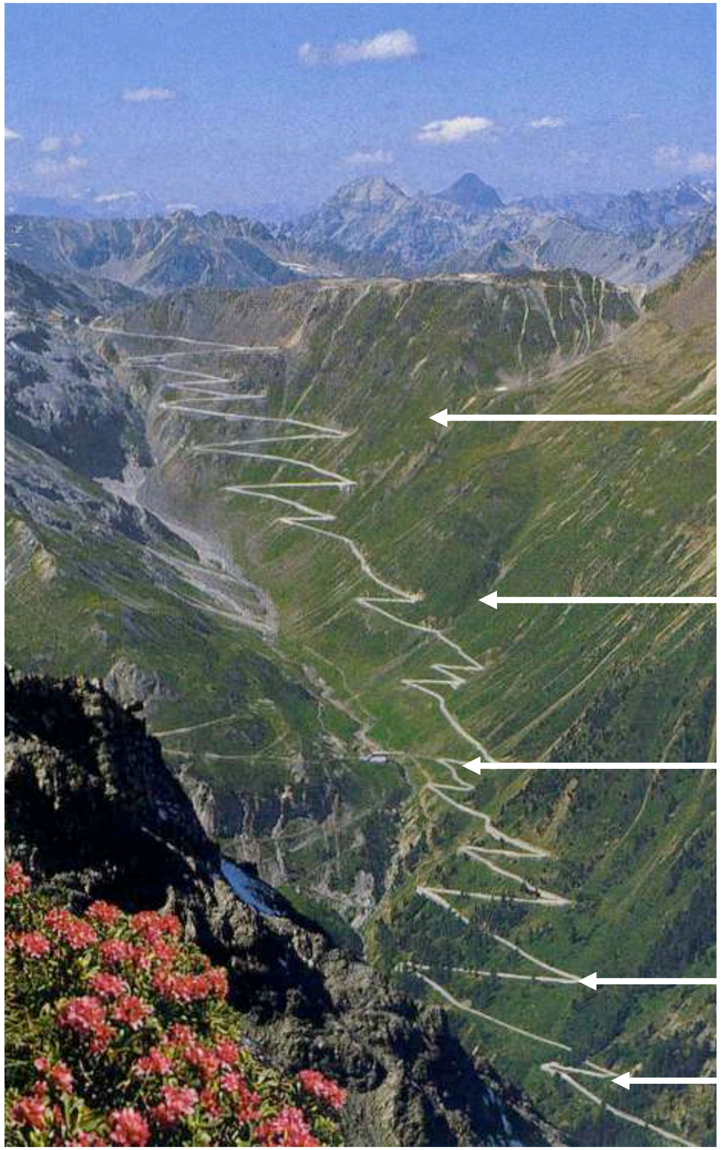
Road to discovery: LHC Commissioning and Early Physics Analyses

Fermilab, 20th August 2008

Roberto Tenchini

[redacted]

A Road to discover next symmetry



2009 ? next symmetry ? $\rightarrow$ $\begin{array}{c} e \\ \tilde{e} \end{array}$ **?**

1973 SU(2) × U(1) $\rightarrow$ $\begin{array}{c} e \\ \nu \end{array}$

1932 antimatter $\rightarrow$ $\begin{array}{c} e^+ \\ e^- \end{array}$

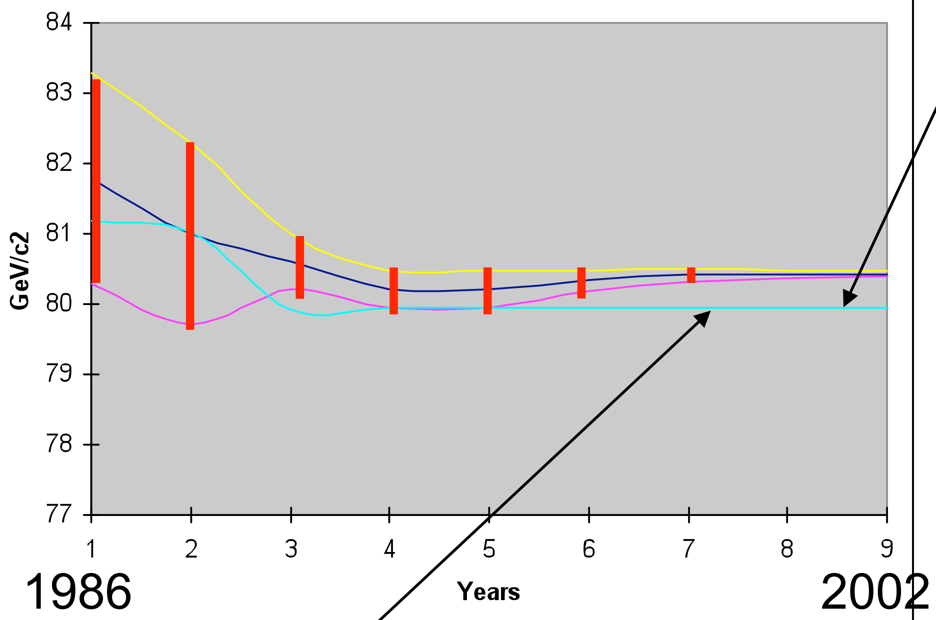
1925 spin $\rightarrow$ $\begin{array}{c} e\downarrow \\ e\uparrow \end{array}$

1897 Discovery of e

broken

Last discovered symmetry [SU(2) X U(1)] works amazingly well

Example: measured W mass vs tree level



Strong Evidence of pure E.W. Higher Order Corrections, dependence on top mass

The SU(2) X U(1) model works at one-loop level, the predicted top mass consistent with Tevatron measurement at 6% level !

E.W. Tree level SM relation

(with running α QED)

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha(M_Z)}{\sqrt{2}}\frac{1}{G_F}$$

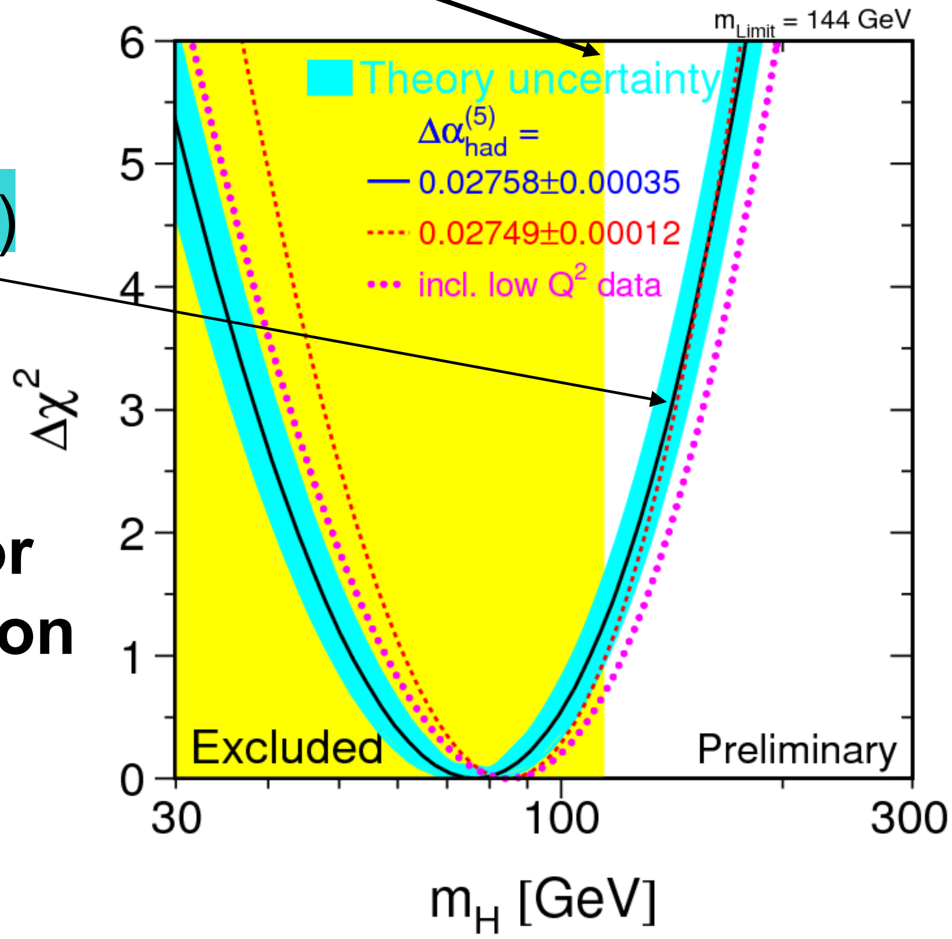
$$\alpha(\sqrt{s}=\mathrm{M_Z})=\frac{1}{128.936\pm 0.046}$$

One closure test on last symmetry still required: find the Higgs Boson

LEP direct searches: $M_{Higgs} \geq 114.4\ \text{GeV}/c^2\ \ 95\%\ \text{CL}$

From LEP, SLC, Tevatron and radiative corrections a light higgs (i.e. below 200 GeV) is expected

A narrow mass region is left for the Standard Model Higgs boson



LHC should shed light on two fundamental questions

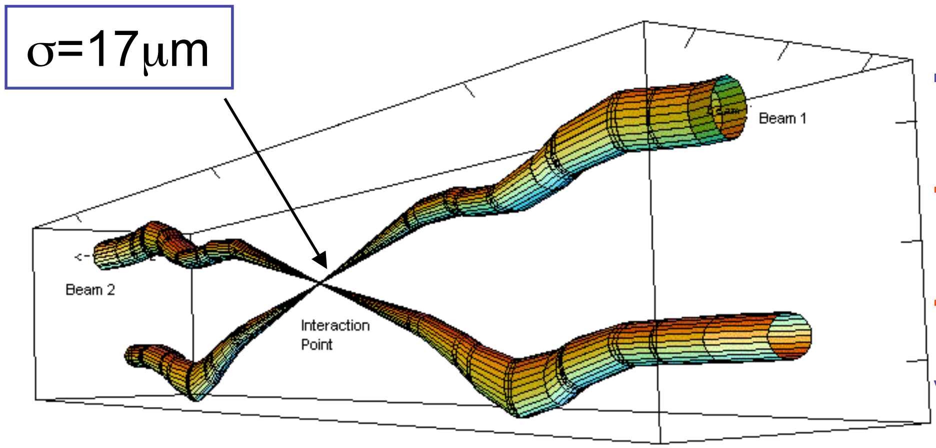
- The **origin of the electroweak symmetry** breaking (Higgs mechanism)
  - Sensitive to the full allowed Higgs boson mass range
- Which **Physics Beyond the Standard Model**
  - For the first time well beyond the Fermi energy scale $G_F^{-1/2} \sim 300$ GeV

The machine

On the road for **pp** collisions

LHC Nominal Parameters, Beam Crossing, Luminosity

Nominal LHC parameters	
Beam energy (TeV)	7.0
Number of particles per bunch	1.15×10^{11}
Number of bunches per beam	2808
Stored beam energy (MJ)	362
Bunch spacing (ns)	25
Bunch length (cm)	7.55



Relative beam sizes around IP1 (Atlas) in collision

- **Crossing angle** = 285 μrad
- **Luminosity = 10^{34} cm^{-2} s^{-1}**
- **Integrated Luminosity per year = 100 fb^{-1}**

LHC: getting the maximum energy for protons in a 27 km Tunnel

Maximum energy is given by the bending magnetic field from dipole magnets

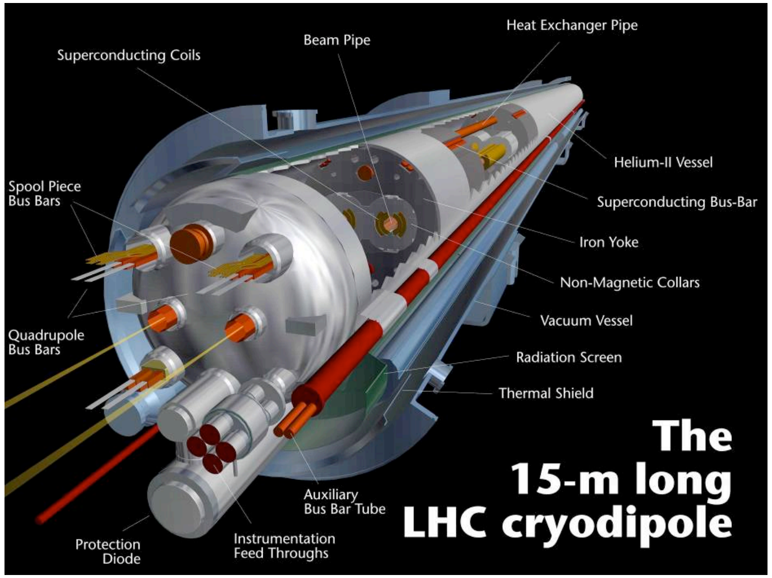
The dipole coverage is limited to 65% of the ring (need other components)

LHC : **B=8.4 Tesla** : **~ 1232 Superconducting dipoles** at **1.9 Kelvin** (by far the largest cryogenic system in the world)

Energy (TeV) = 0.3 B(Tesla) R(km)

= 7 TeV

R= 4.3 km



LHC cross sections and rates

At High Luminosity (10^{34} cm^{-2} s^{-1})

SM Higgs (115 GeV/c^2): → 0.1 Hz

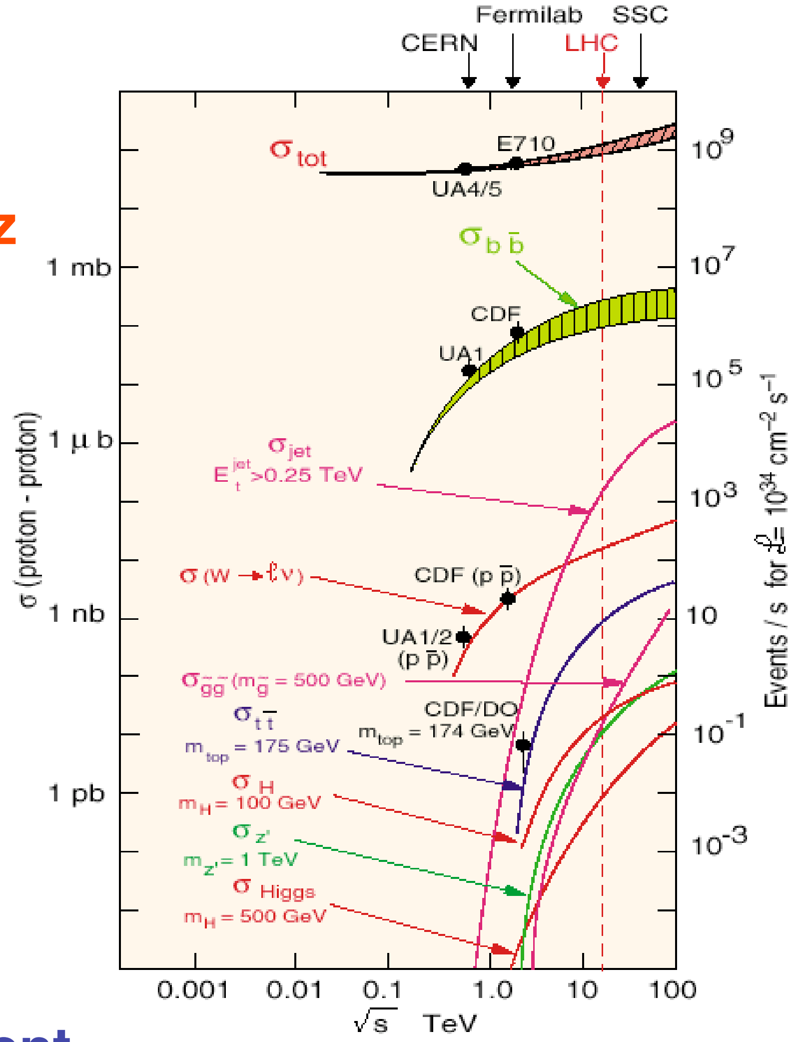
t t production: → 10 Hz

W → $\ell\,\nu$: → 10^2 Hz

Z → $\ell\,\ell$: → 10 Hz

bb production: → 10^6 Hz

Inelastic: → 10^9 Hz



Beam crossing every 25 ns

25 pileup event / beam crossing

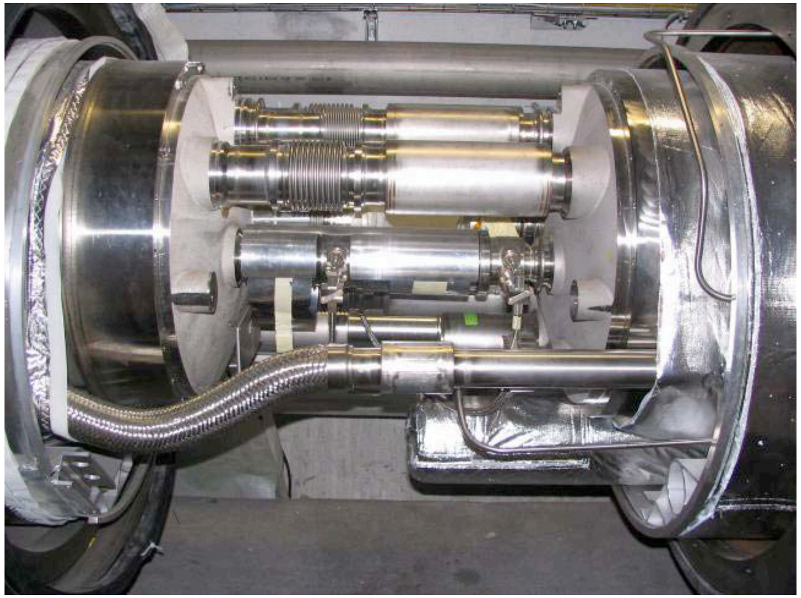
(at High Luminosity)

<u>Experiments: need stringent and efficient online selection criteria (trigger)</u>

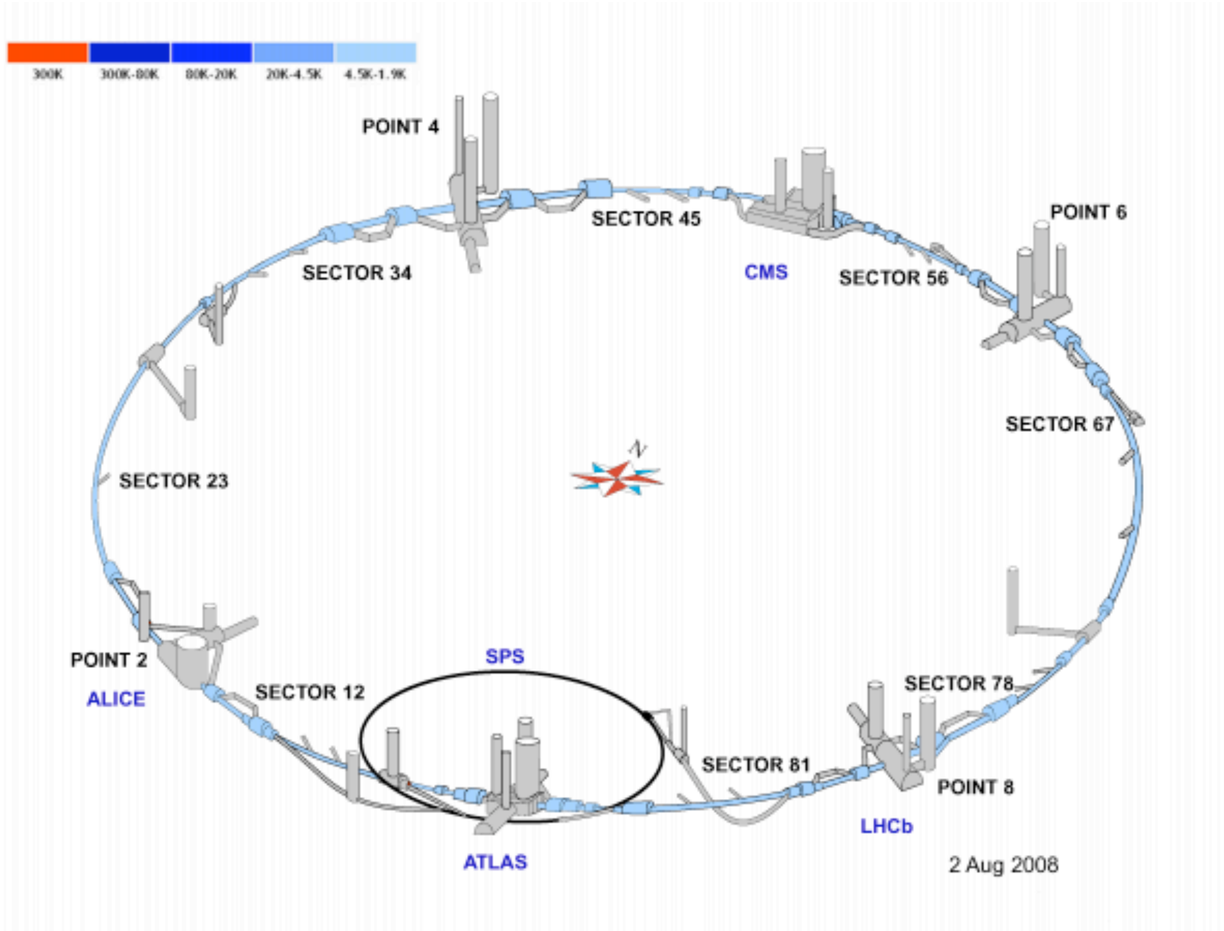

27 November 2006
DIPOLE
n° 1232
... THE LAST ONE

Interconnecting the various LHC sections

Completed 7th November 2007

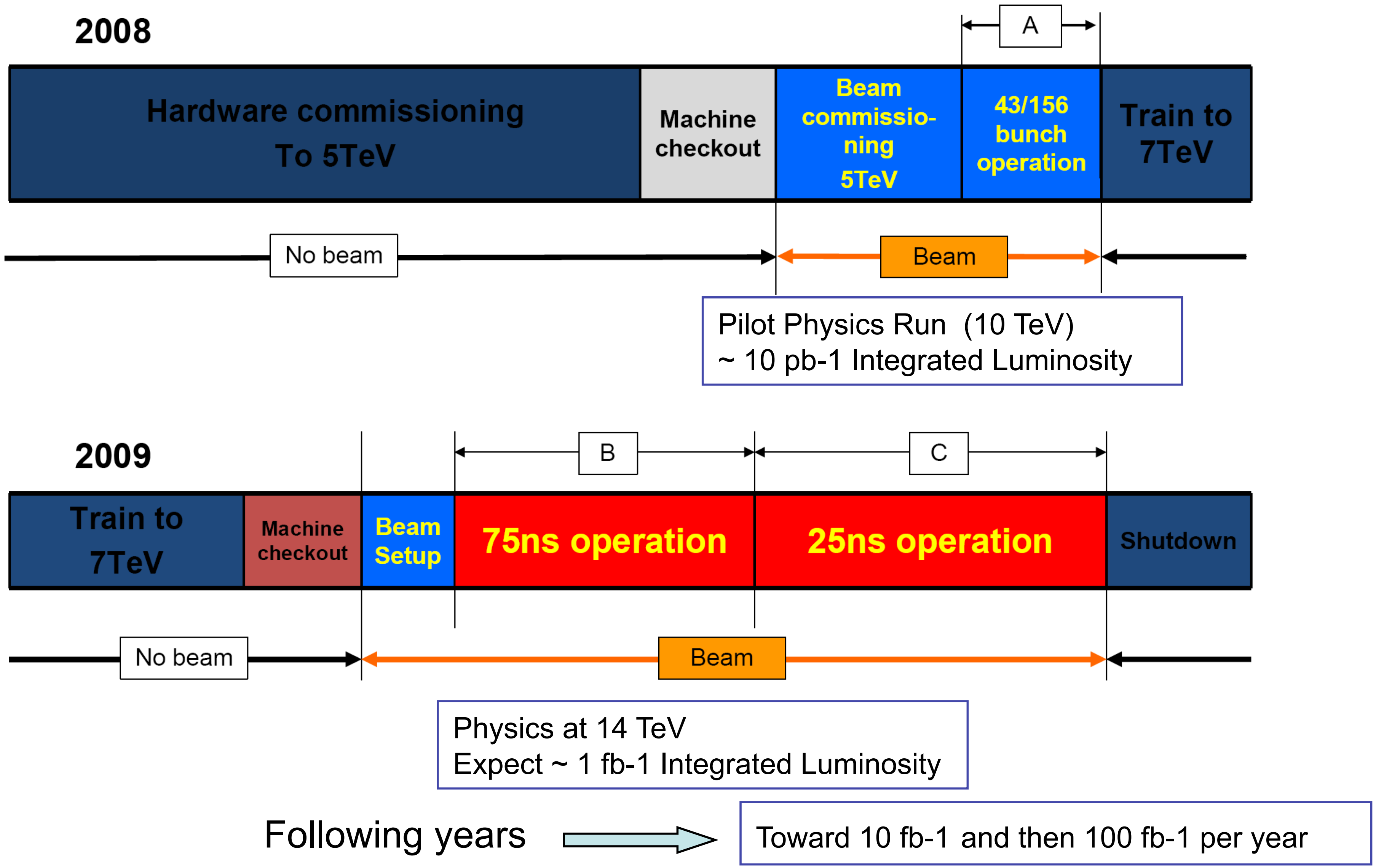


20 Aug 2008 : LHC is cold

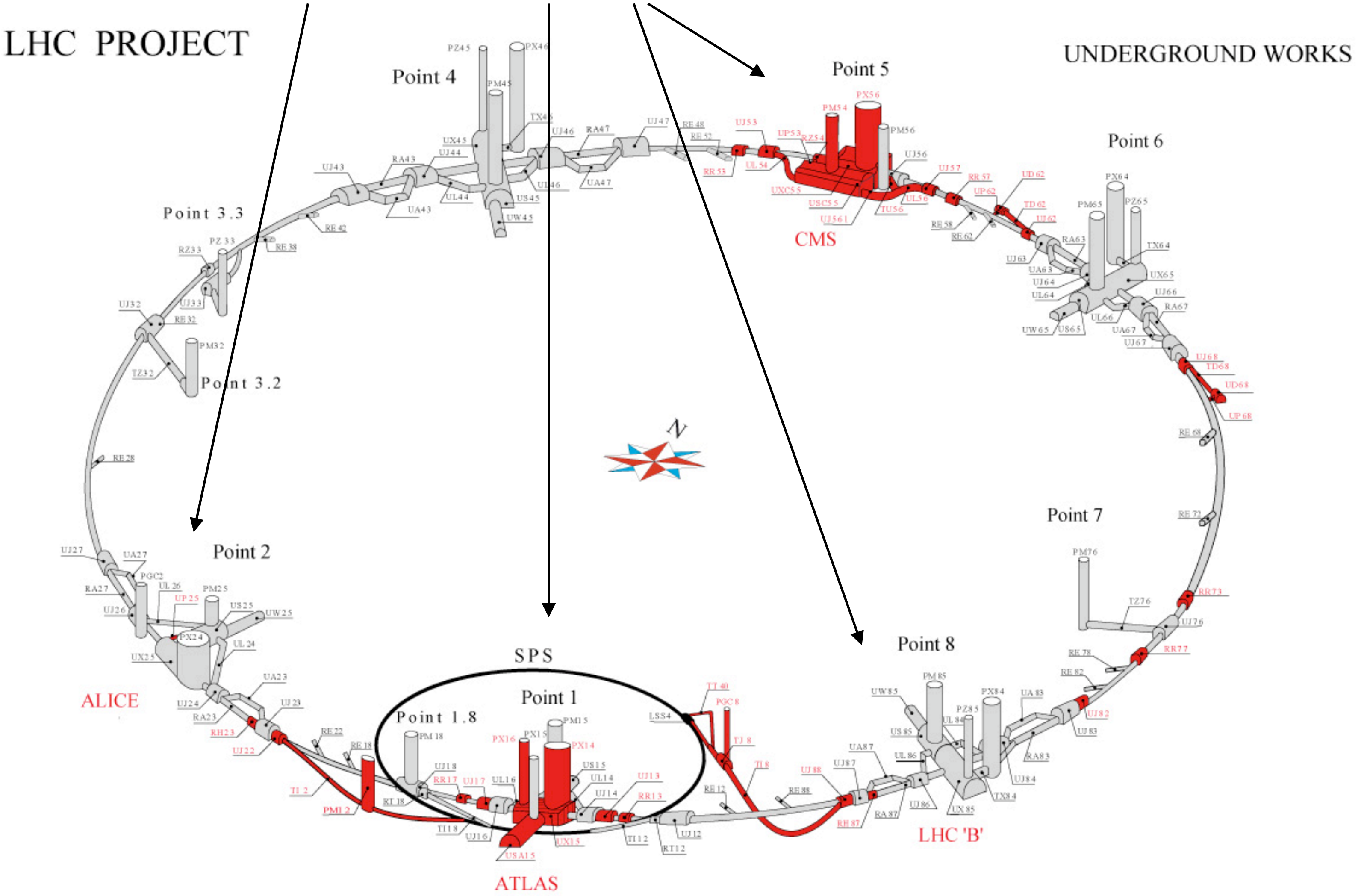


First attempt to circulate beam: 10th September

Program to reach first physics



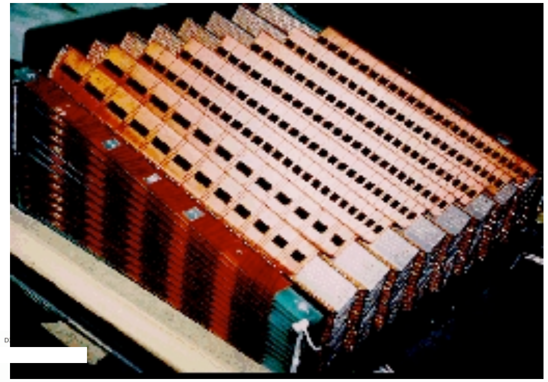
On the road with the Four Experiments (only two discussed today)

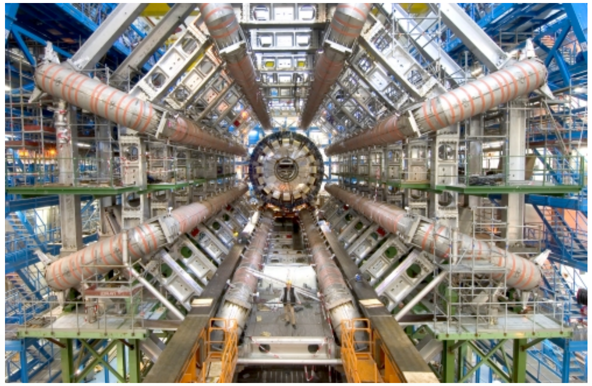


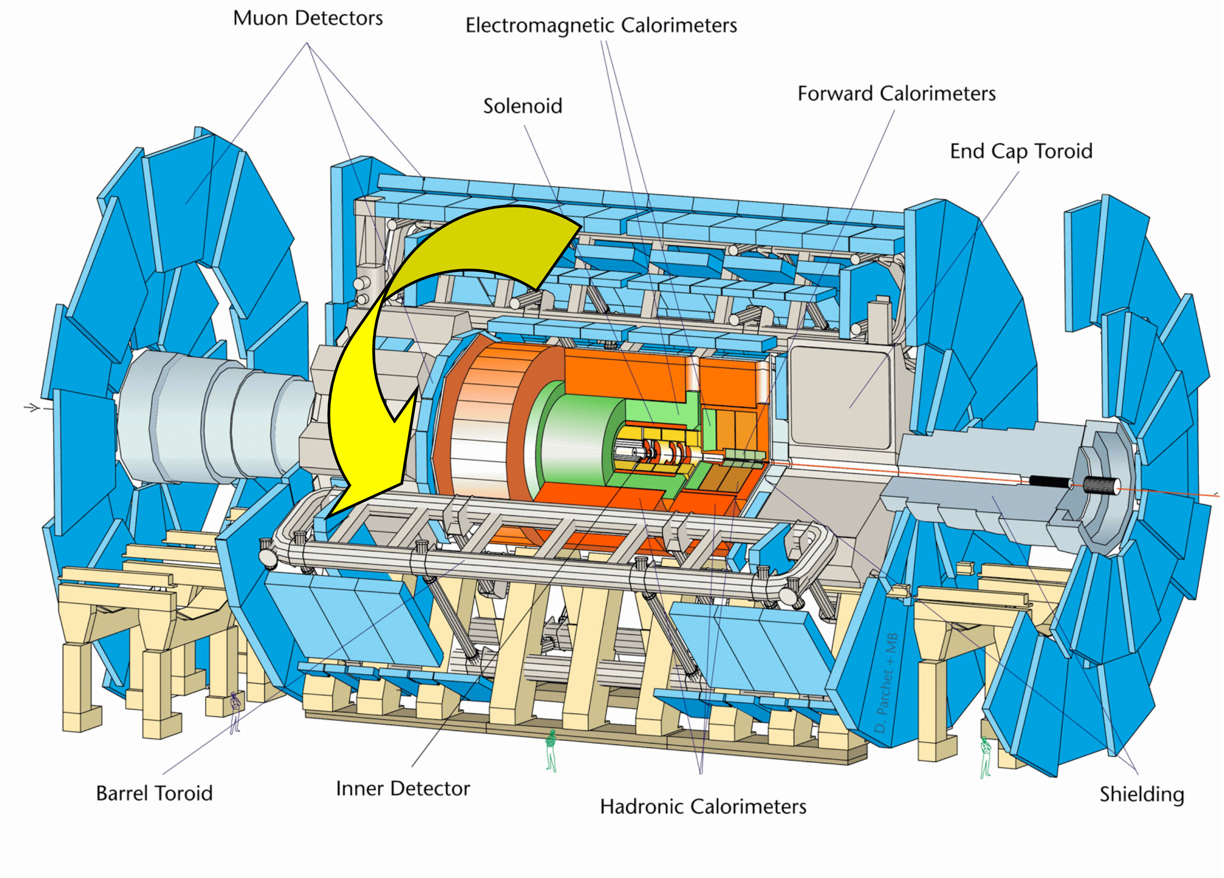
ATLAS A Toroidal LHC ApparatuS (general purpose)
CMS Compact Muon Solenoid (general purpose)
ALICE A Large Ion Collider Experiment (dedicated to heavy ion collisions)
LHCb (Study of CP violation in B mesons)

ATLAS

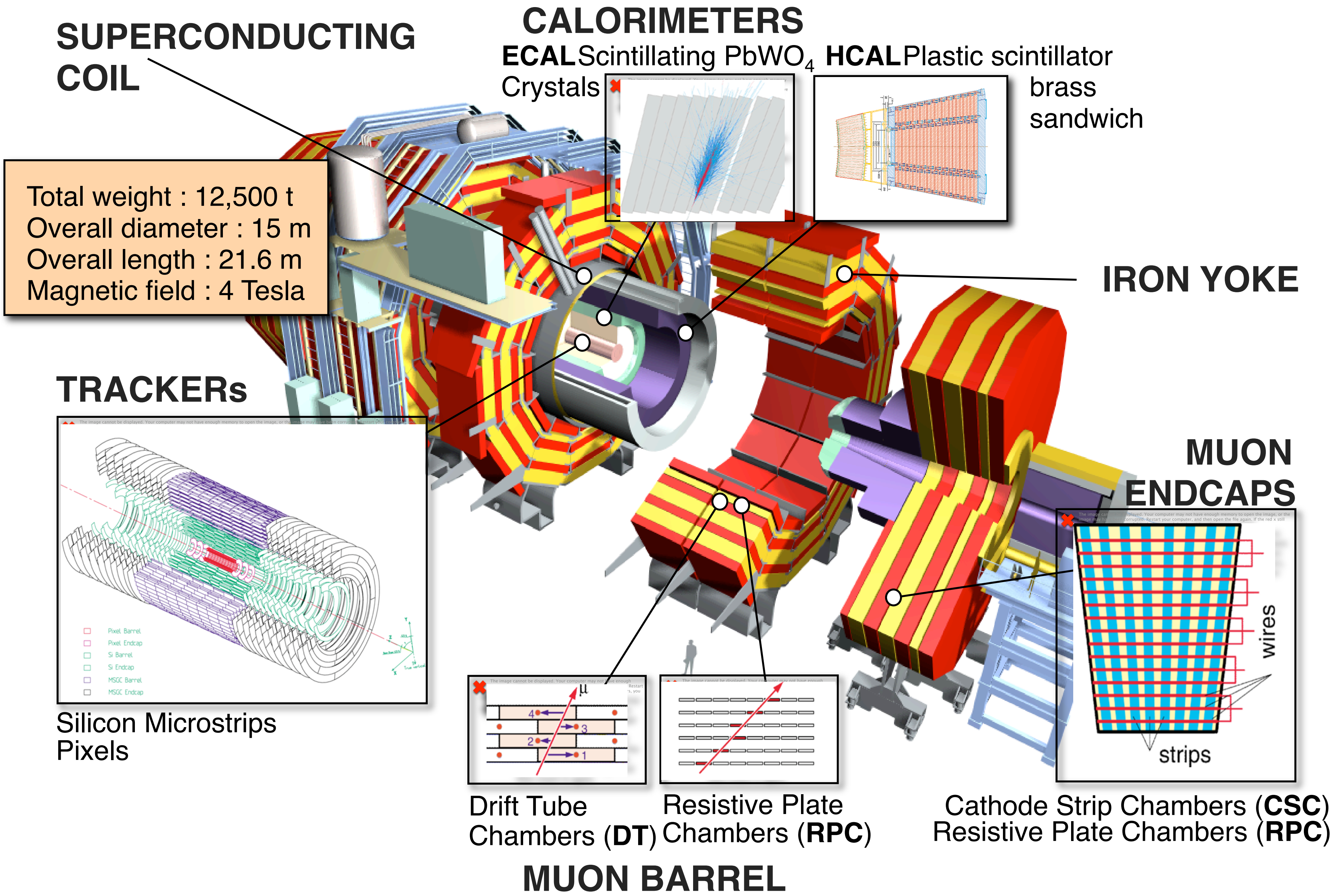
- Large angular coverage ($|\eta|<4.9$; tracking coverage up to $\boldsymbol{\eta \sim 2.5}$)
- Standalone muon spectrometer
- Liquid Argon electromagnetic sampling calorimeter with accordion geometry
- Toroidal magnetic field in muon spectrometer (supercondutor air-core toroids)



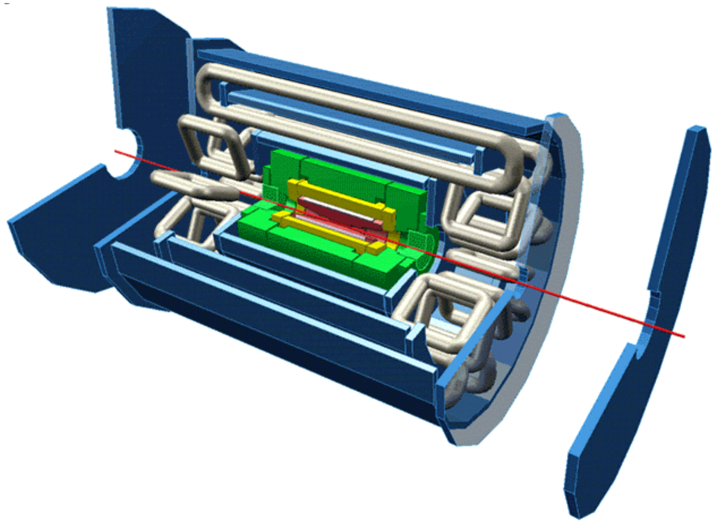


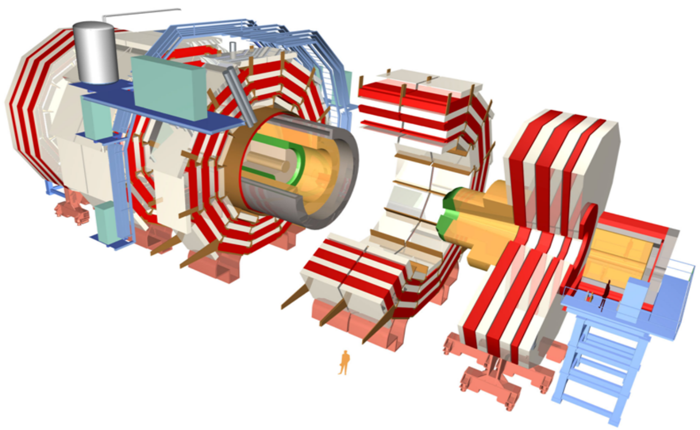


The Compact Muon Solenoid (CMS)



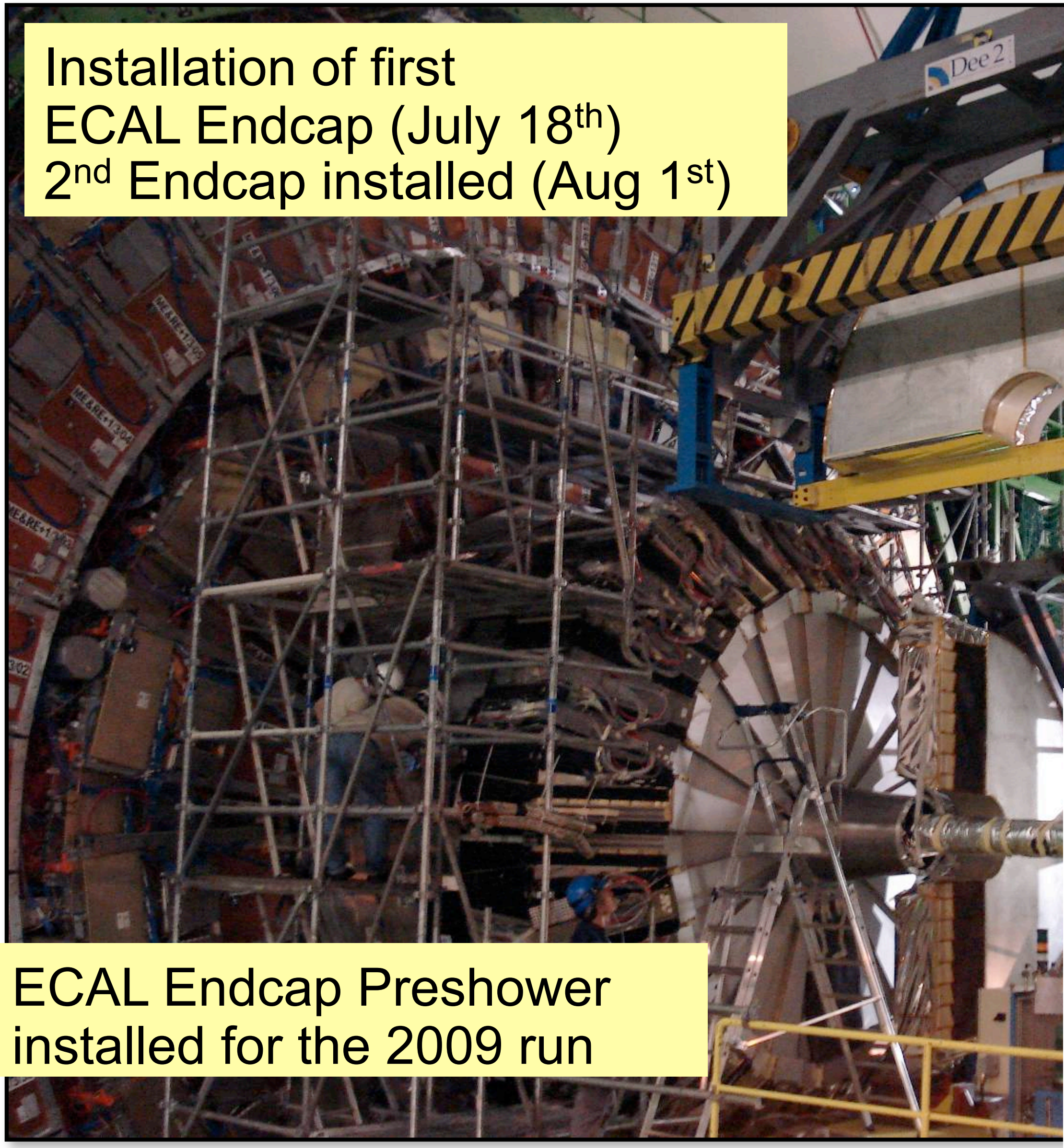
	ATLAS	CMS
Magnetic field	2 T solenoid + toroid (0.5 T barrel 1 T endcap)	4 T solenoid + return yoke
Tracker	Si pixels, strips + TRT $\sigma/p_T \approx 5\text{x}10^{-4} p_T + 0.01$	Si pixels, strips $\sigma/p_T \approx 1.5\text{x}10^{-4} p_T + 0.005$
EM calorimeter	Pb+LAr $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	PbWO4 crystals $\sigma/E \approx 3\%/\sqrt{E} + 0.003$
Hadronic calorimeter	Fe+scint. / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Brass+scintillator (7 λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
Muon	$\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (ID +MS)	$\sigma/p_T \approx 1\%$ @ 50GeV to 10% @ 1TeV (DT/CSC+Tracker)
Trigger	L1 + RoI-based HLT (L2+EF)	L1+HLT (L2 + L3)





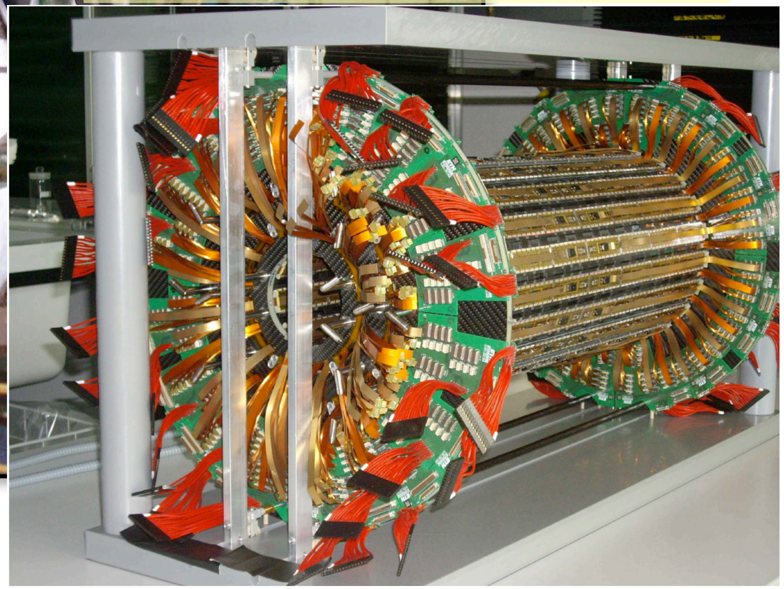
CMS: last "Bits" installed

Installation of first
ECAL Endcap (July 18th)
2nd Endcap installed (Aug 1st)

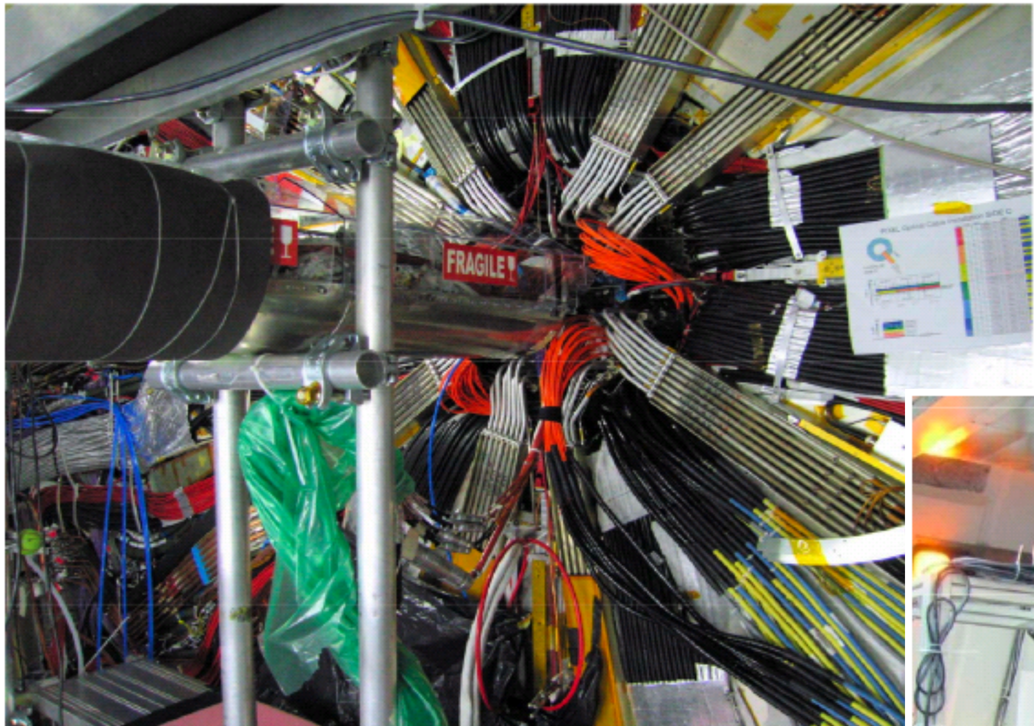


ECAL Endcap Preshower
installed for the 2009 run

Pixels installed Aug 1st

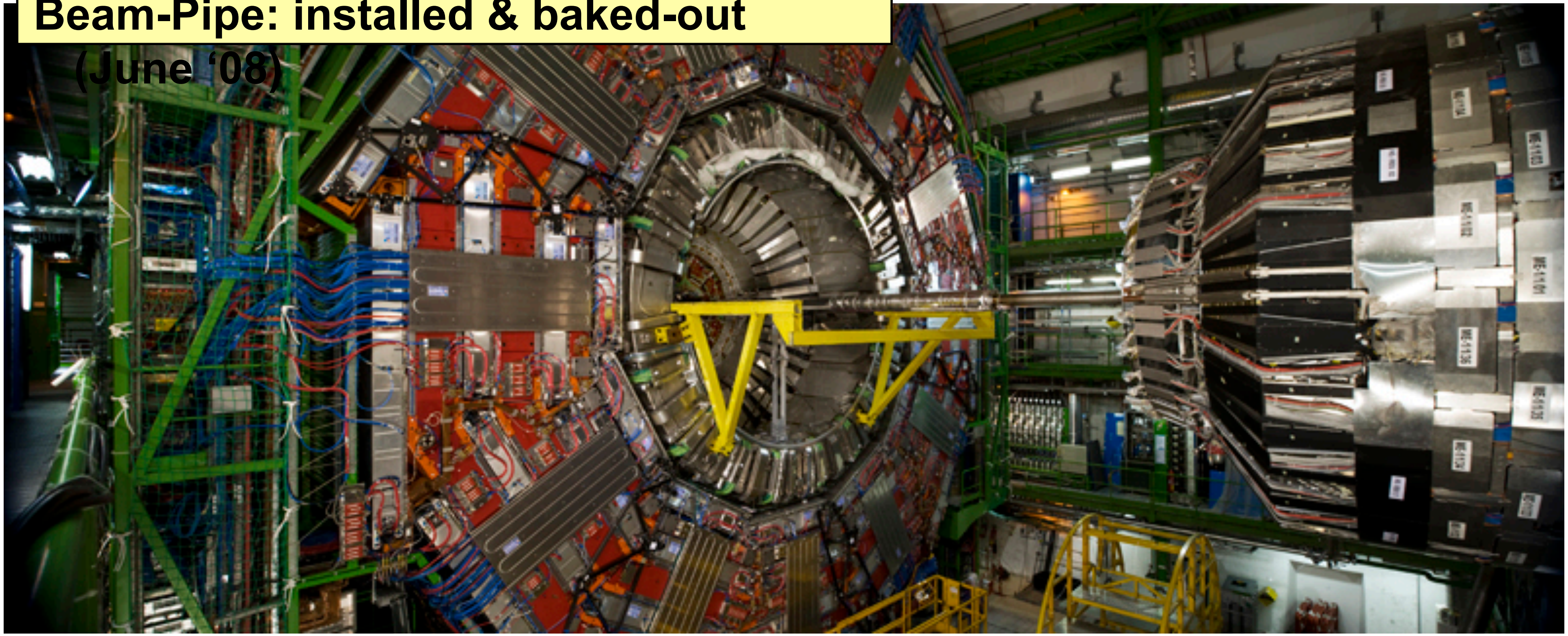


ATLAS completed
last bit (pixels) installed in May 08



CMS Beam Pipe: installed and baked-out (June 08)

Beam-Pipe: installed & baked-out (June '08)



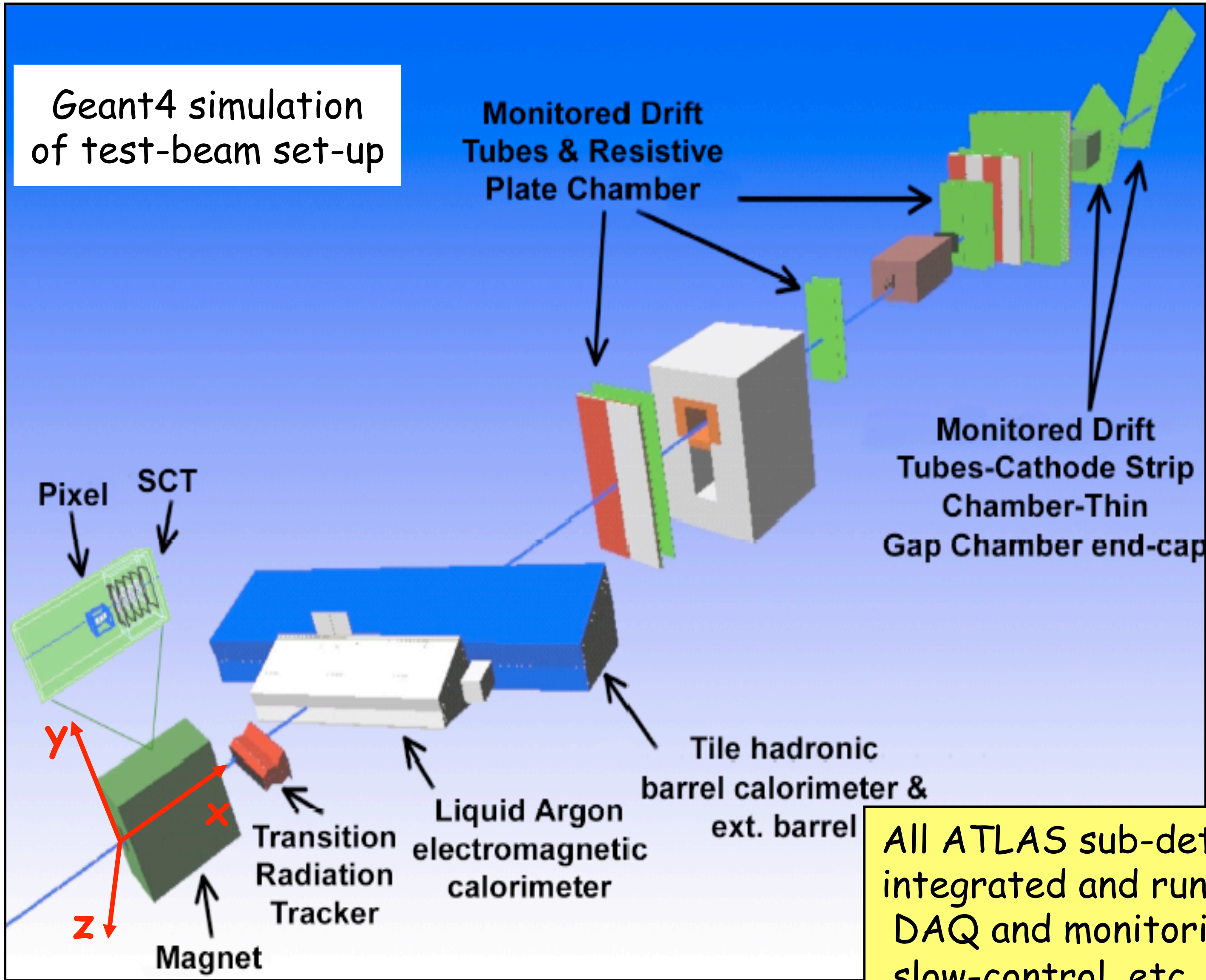
ATLAS Beam Pipe: installed and baked-out July 08

Physics Commissioning: two main phases

- Before data taking starts:
  - Understand and calibrate the detectors with test beams, cosmics, surveys, B-field measurements, etc.
  - Prepare software tools: simulation, reconstruction, calibration and alignment procedures
- With the initial LHC data:
  - Commission and calibrate in situ detector and trigger with physics samples
  - Understand Standard Model physics at 10 and14 TeV
  - Measure background to New Physics

→ **Prepare the road to discoveries**

2004: Atlas combined test beam



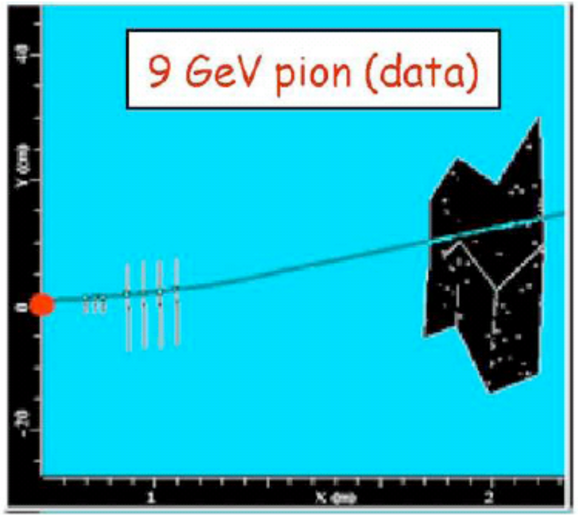
O(1%) of ATLAS

Beam: electrons, muons, pions, Photons of various Energies

With B- field

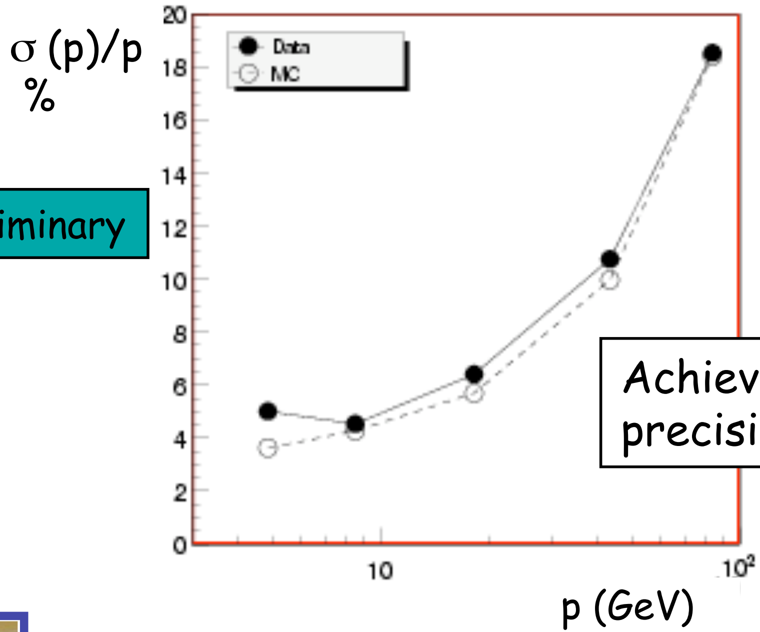
All ATLAS sub-detectors (and LVL1 trigger) integrated and run together with common DAQ and monitoring, "final" electronics, slow-control, etc. Gained lot of global operation experience during ~ 6 month run.

Beam Test: Inner Detector



Pion momentum resolution from 2004 combined test beam using Pixels+SCT

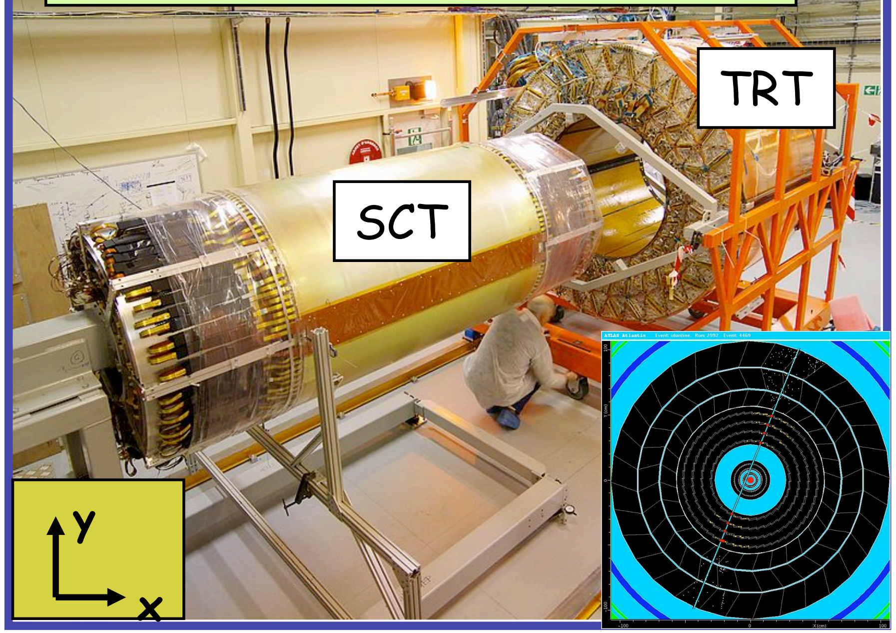
ATLAS preliminary



Note:
no TRT,
B=1.4 T

Achieved alignment precision: 5-10 μm

SCT-TRT integration in surface clean room in Feb 2006



Global SCT-TRT barrel misalignments from survey measurements compared to results from reconstructed cosmics tracks after alignment

Displacement	Survey	Cosmics
Δx (mm)	-0.300 ±.008	-0.290 ±.007
Δrot-y (mrad)	0.221 ±.006	0.285±.021

Atlas Inner Detector at the pit

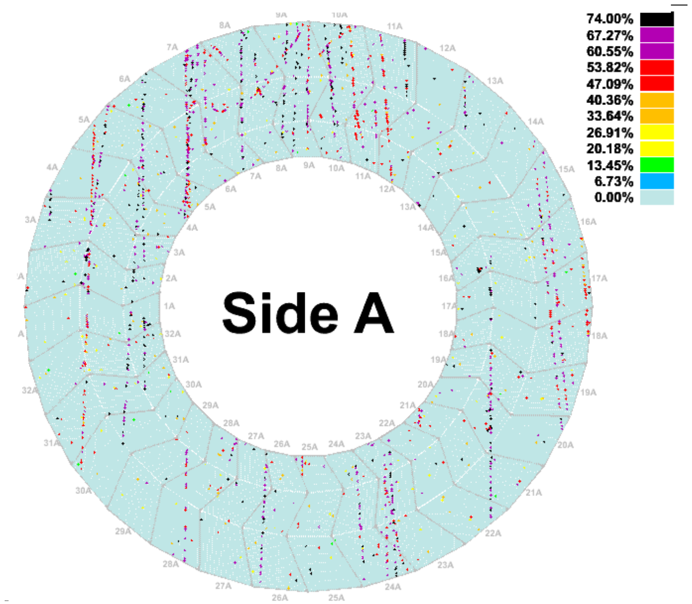
•TRT routinely up and running with other detectors, 2% dead channels

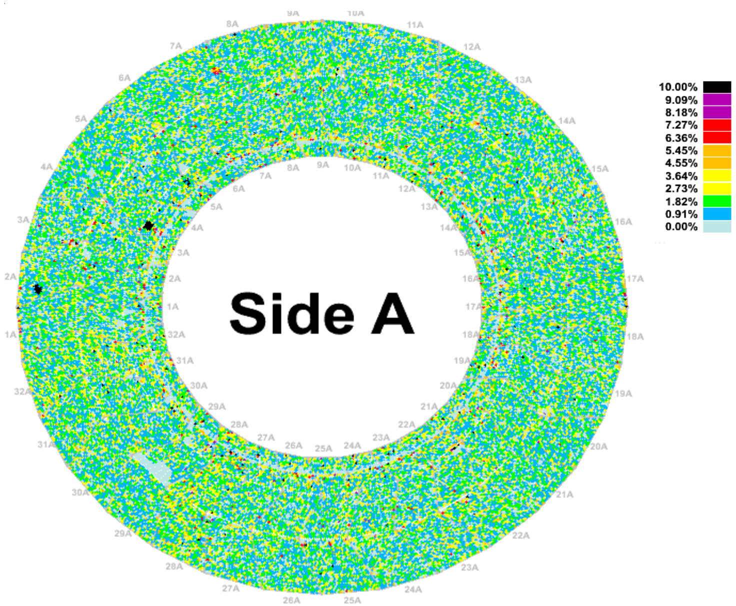
• SCT fully signed off, 0.6% defective channels

•Limited Pixel sign-off: good detector performance

•Require to ramp-up to operational conditions much faster than the other ATLAS sub-detectors

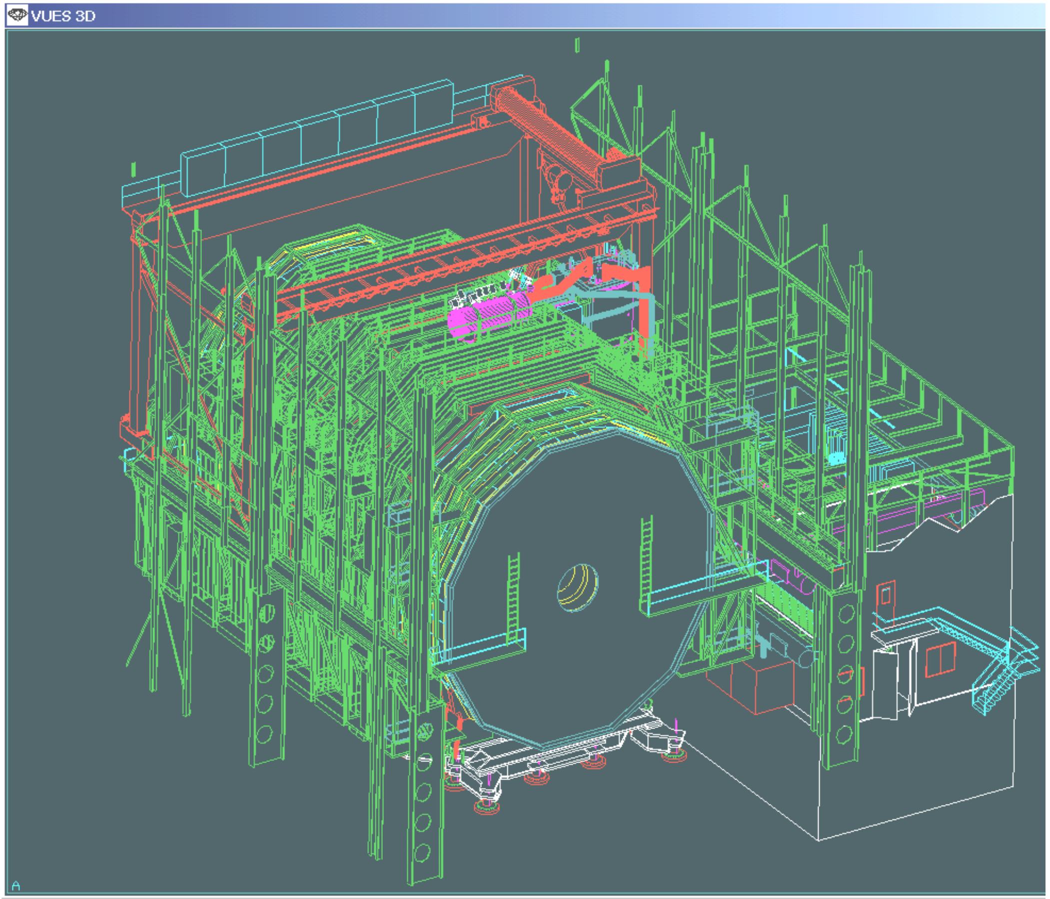
•Pixel will join common ATLAS running in ~4 weeks after beam pipe bake-out





CMS 2006 : Magnet Test - Cosmic Challenge

CMS closed for magnet test in SX5 surface building: winter 05-06



Check closure tolerances, movement under field and **muon alignment system (endcap + barrel + link to Tracker).**

Check installation & cabling of : ECAL/HCAL/Tracker[dummy] inside coil, including cabling test.

Establish stable operation of coil, cryo, power supply and control system.

Map the magnetic field.

Check field tolerance of components within and outside the yoke

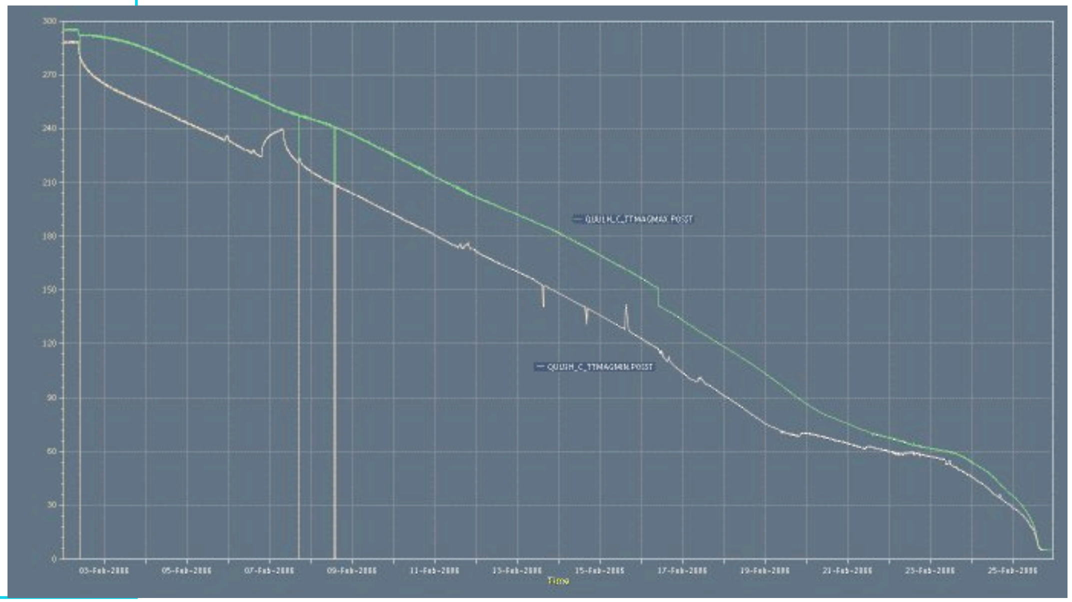
Test individual and combined operation of subdetectors in ~20^o sector of CMS with magnet & central DAQ. **Record cosmics**. Try out 24/7 operation of CMS. = "cosmic challenge"

2006 : Commissioning of the CMS Magnet and B-field

- **B-field Mapping**
- Ramp down to 4.2K ~ 1 month, then 2 months commissioning and 1.5 months of B-field mapping

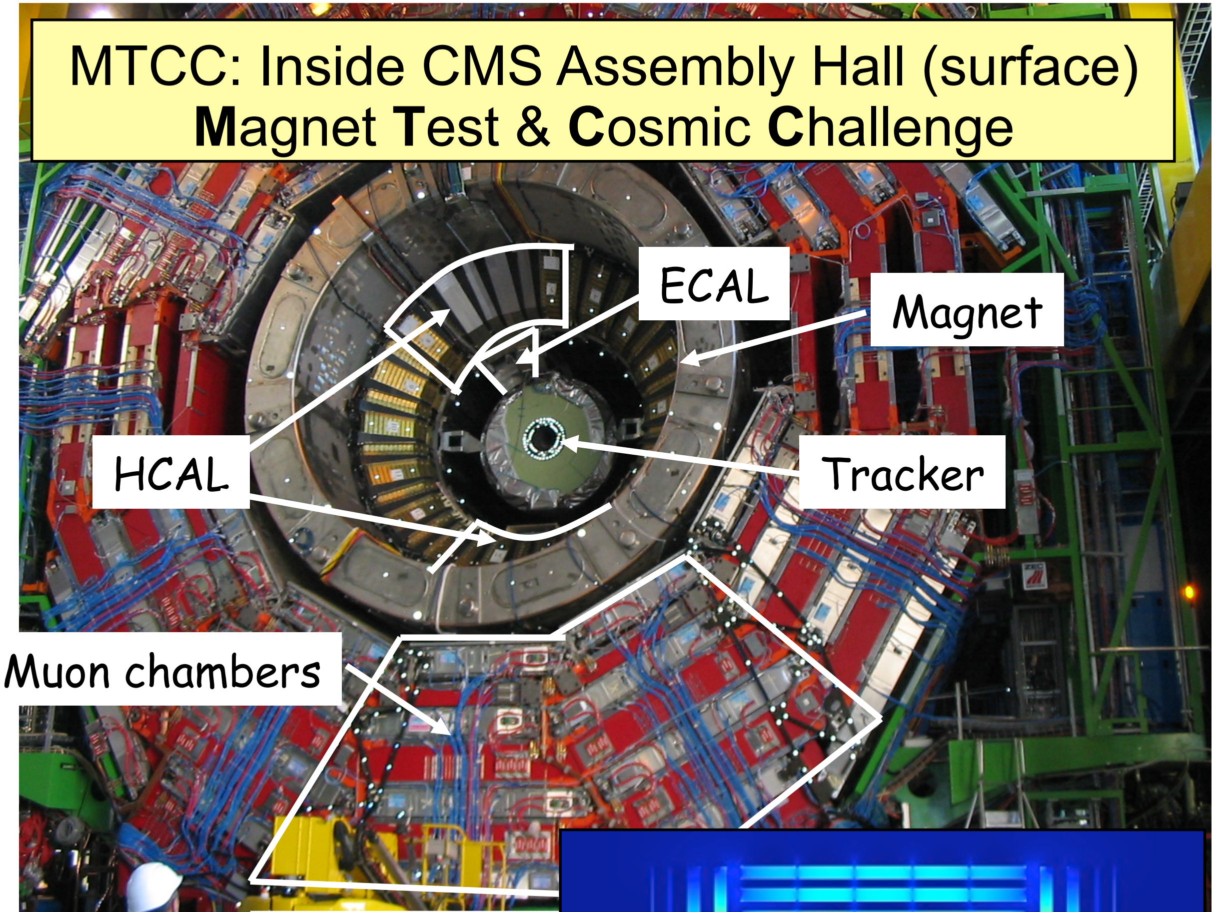
- To achieve 1% Pt resolution at 100 GeV
  - ΔB/B~0.1%-0.5% (tracker volume)
    - (about 1% uniform for construction)
  - ΔB/B~0.4% calorimeters
  - ΔB/B~1% muon chambers

- How:
  - Hall probes + NMR

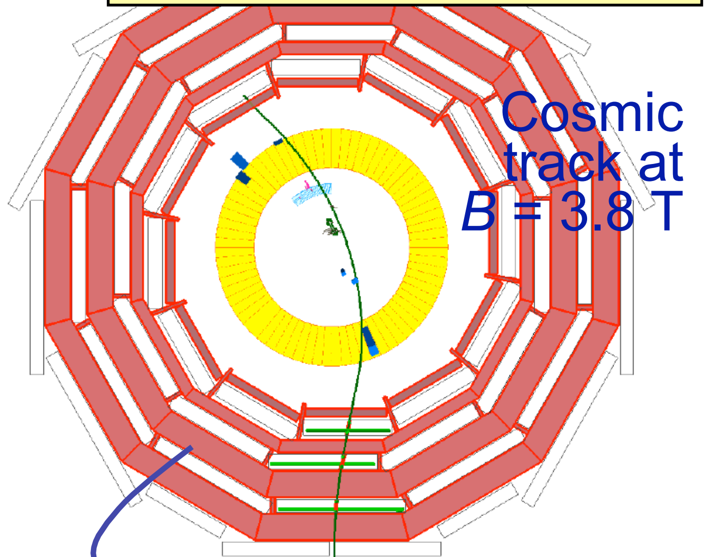


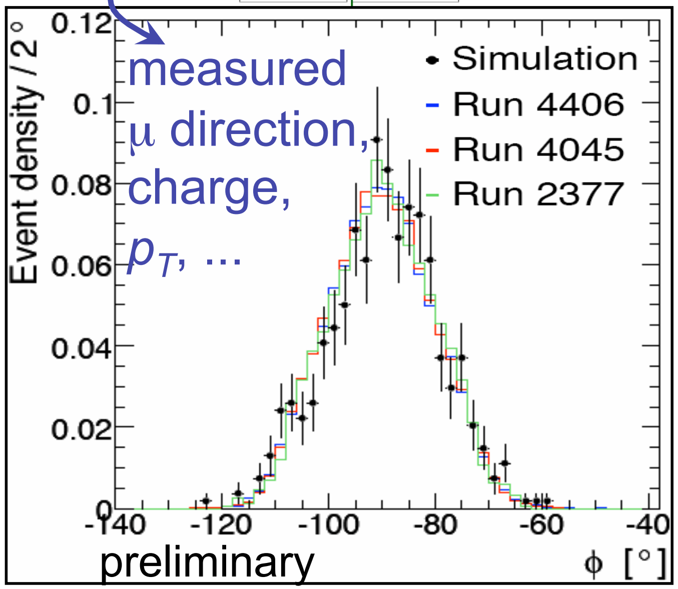
The CMS Magnet today is cold and B=0T, tested to B=4T in 2006

MTCC: Inside CMS Assembly Hall (surface)
Magnet **T**est & **C**osmic **C**hallenge

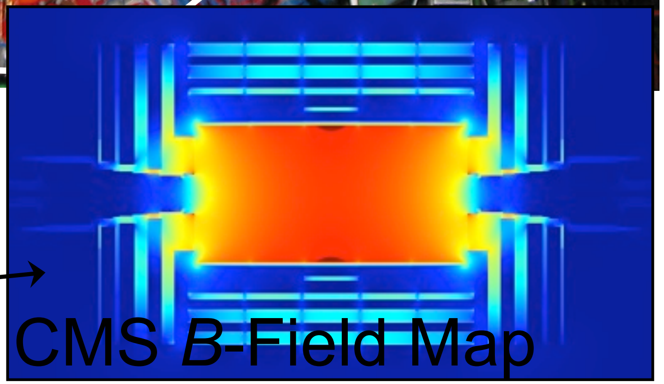


Summer/Autumn 2006



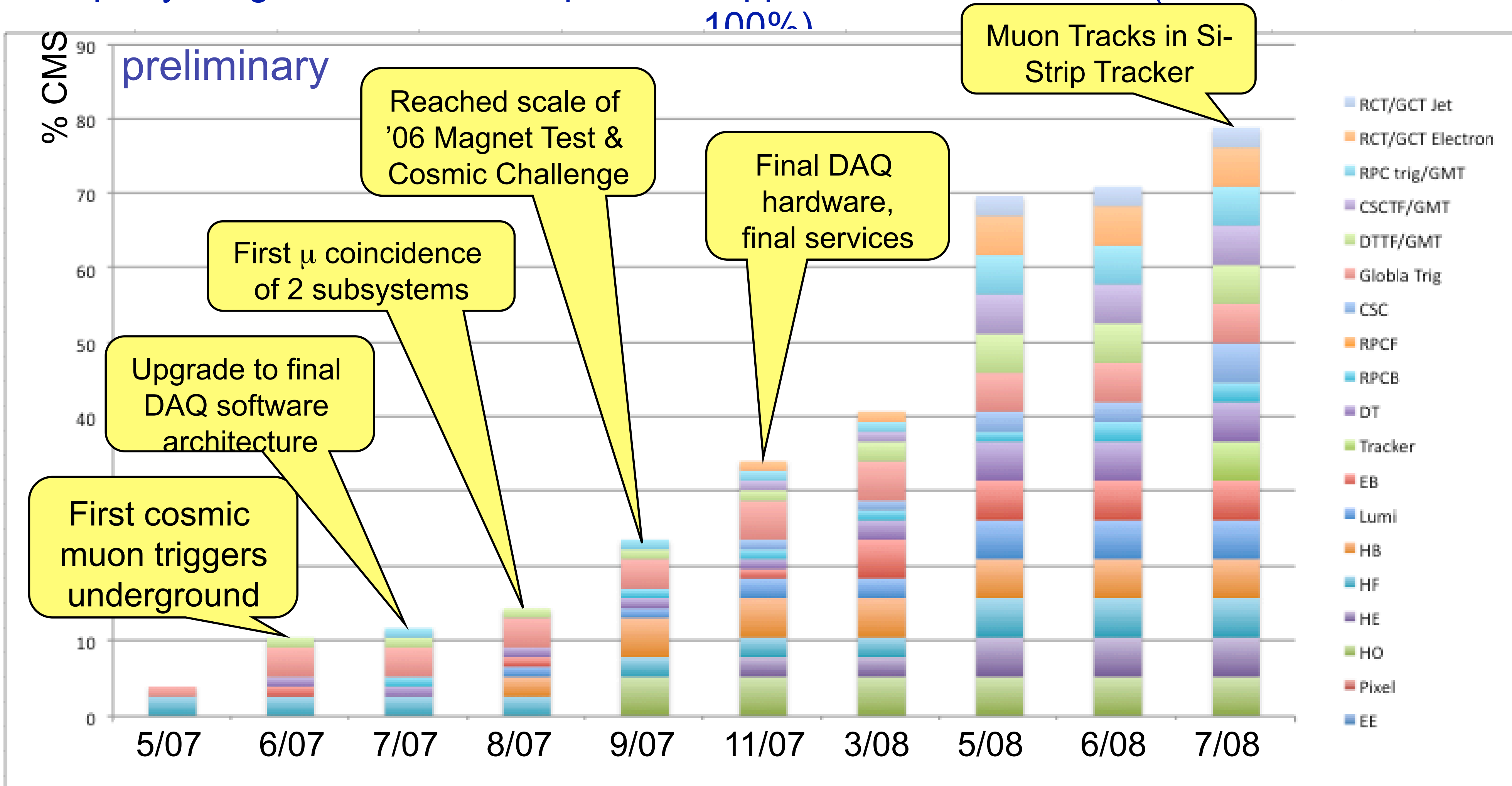


Solenoid:
- tested to B = 4T
- mapped field

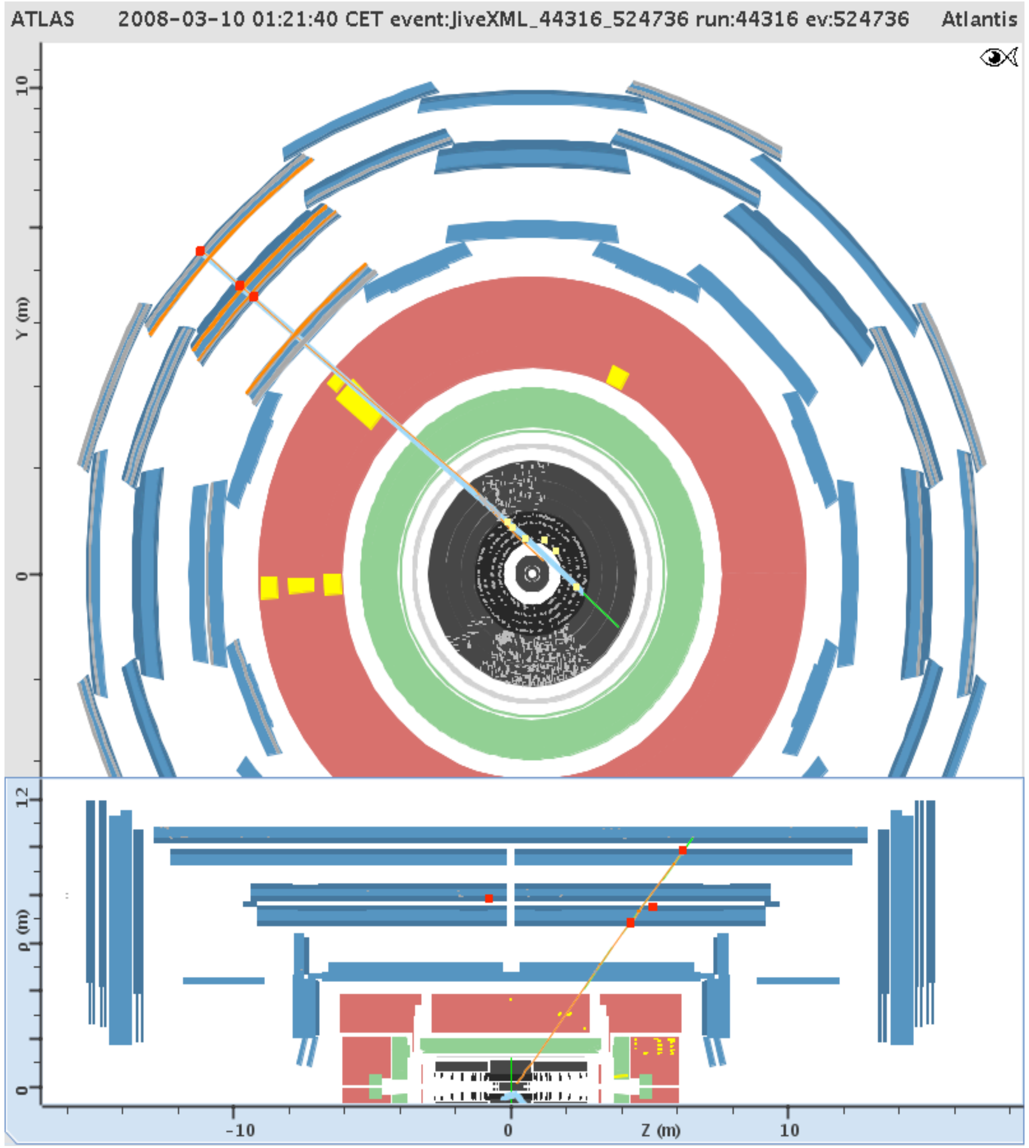


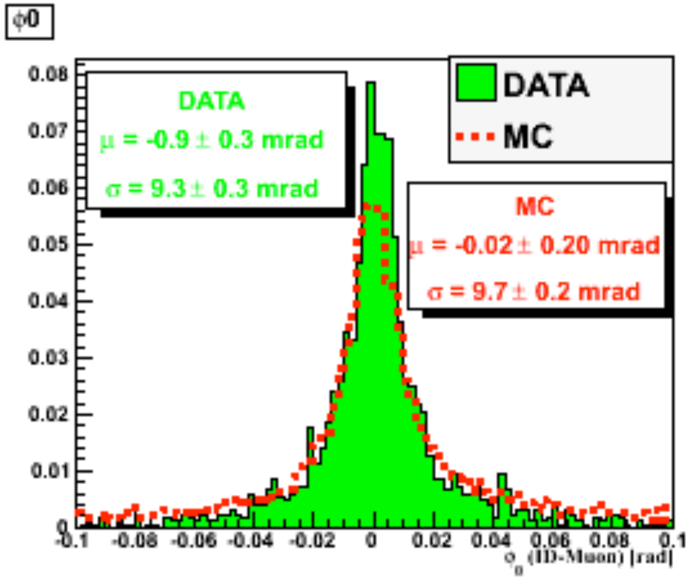
Detector integration: Global Runs

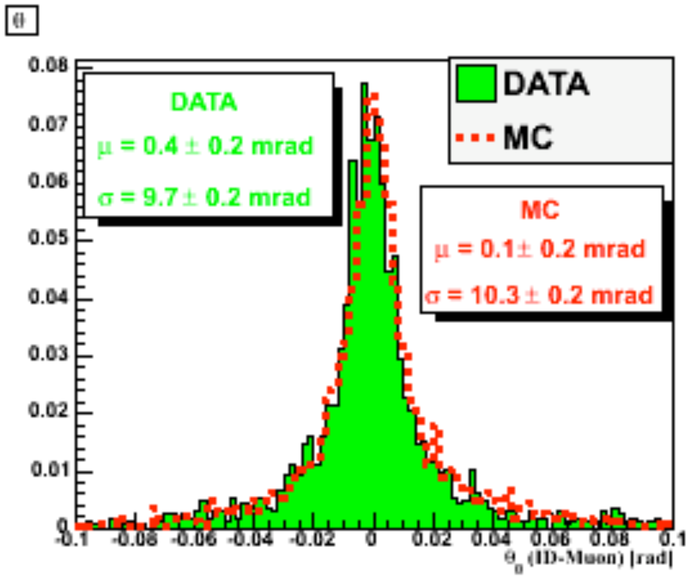
CMS, for Illustration; Subdetector and trigger considered separately - 17 items, each equally weighted - box size represents approx. fraction included (25%, 50%, 75%, 100%)



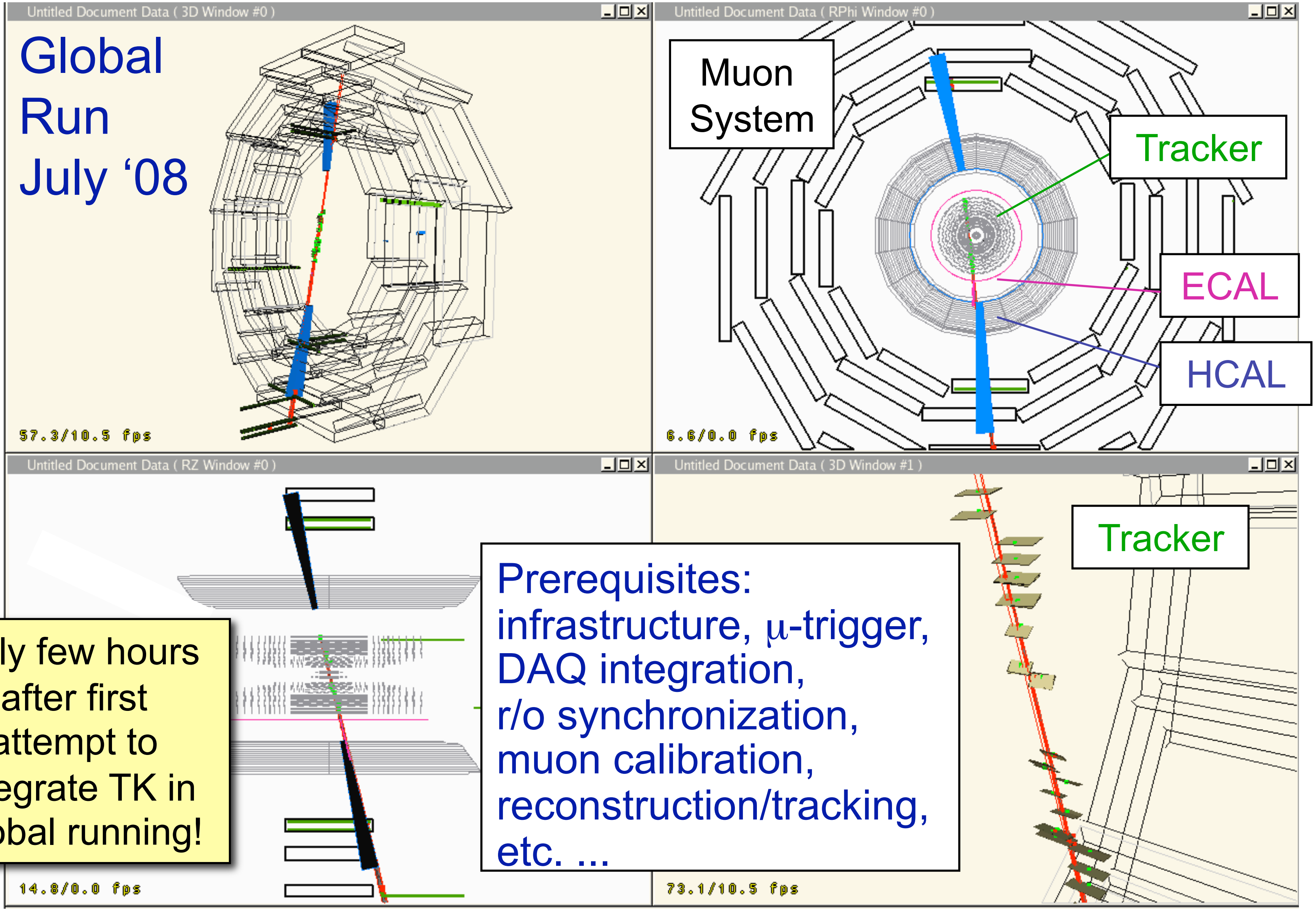
Cross-referencing detectors!







First Global Tracks: Tracker + Drift

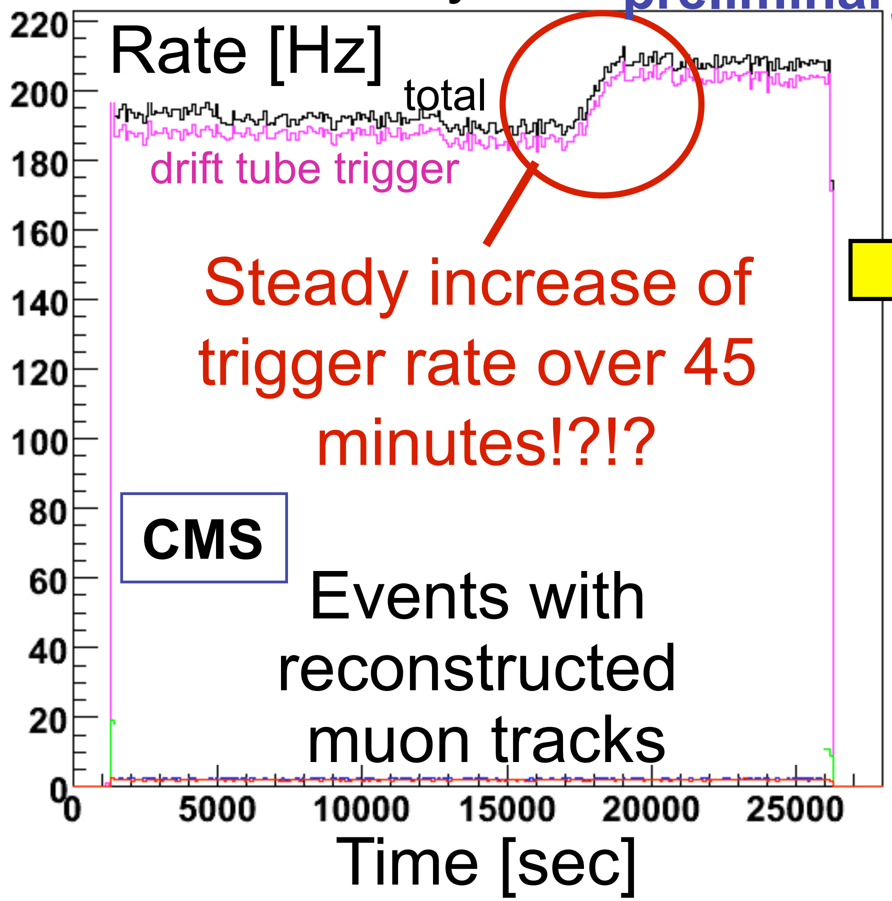


Only few hours after first attempt to integrate TK in global running!

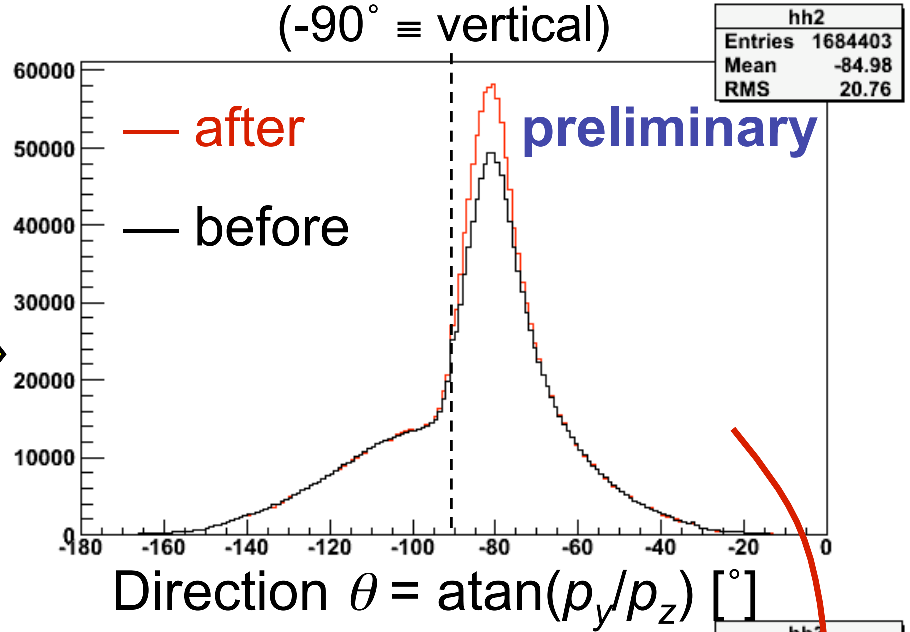
Prerequisites:
infrastructure, μ-trigger,
DAQ integration,
r/o synchronization,
muon calibration,
reconstruction/tracking,
etc. ...

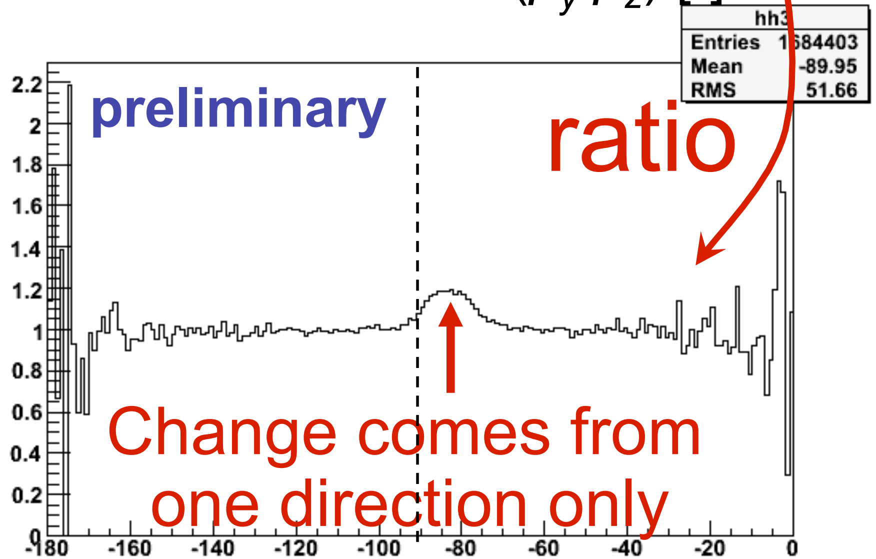
A sofisticated house alarm system

Run 43439, May ‘08



Indeed, increase of cosmic rate correlated with shaft opening!



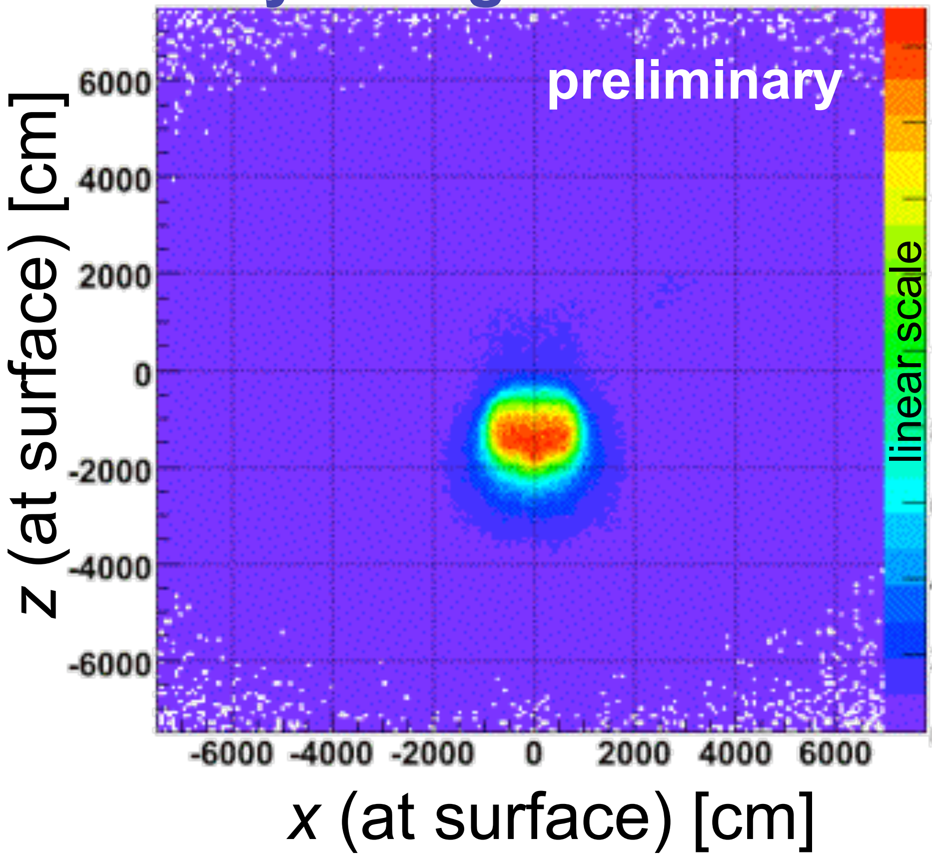


Muon Tag & Probe on Cosmics Data

For cosmics: top muon sectors are timed-in (delayed) w.r.t. bottom sectors → "di-muon"-like signal (here: Drift Tubes)

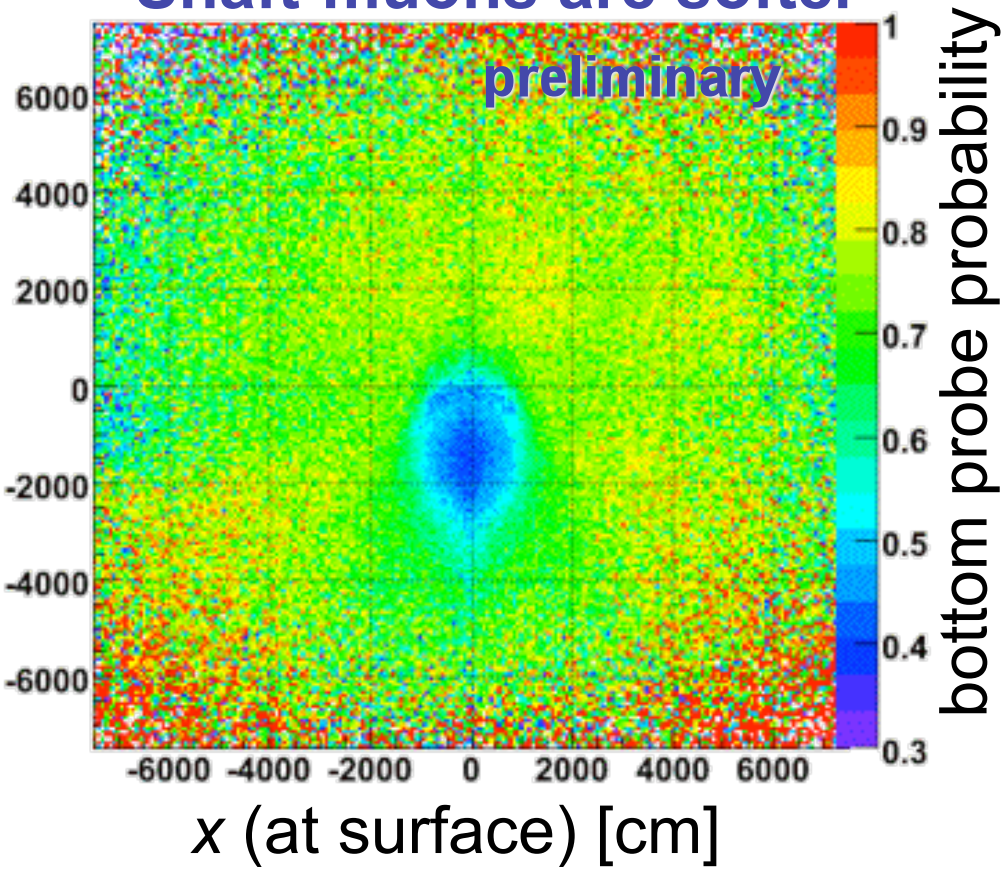
May/June data: muon origin extrapolated to the surface:

"X-ray" image of the shaft

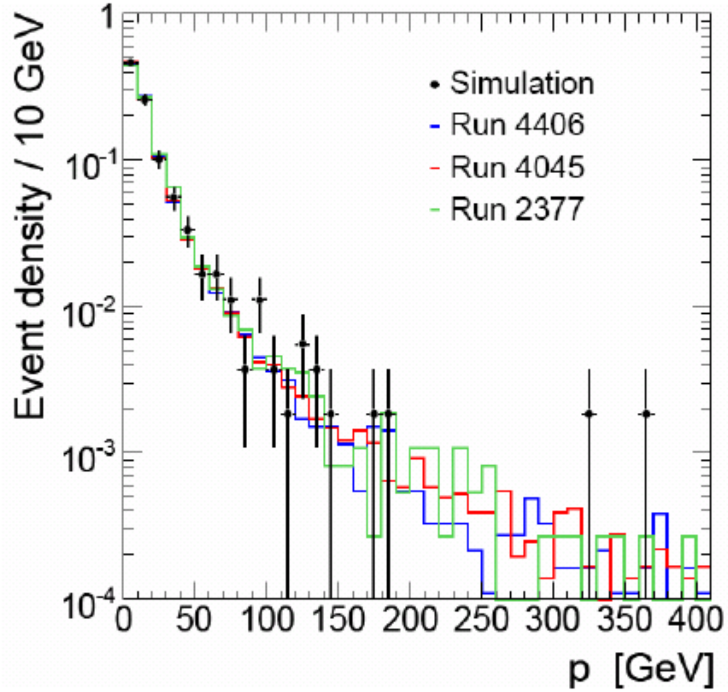


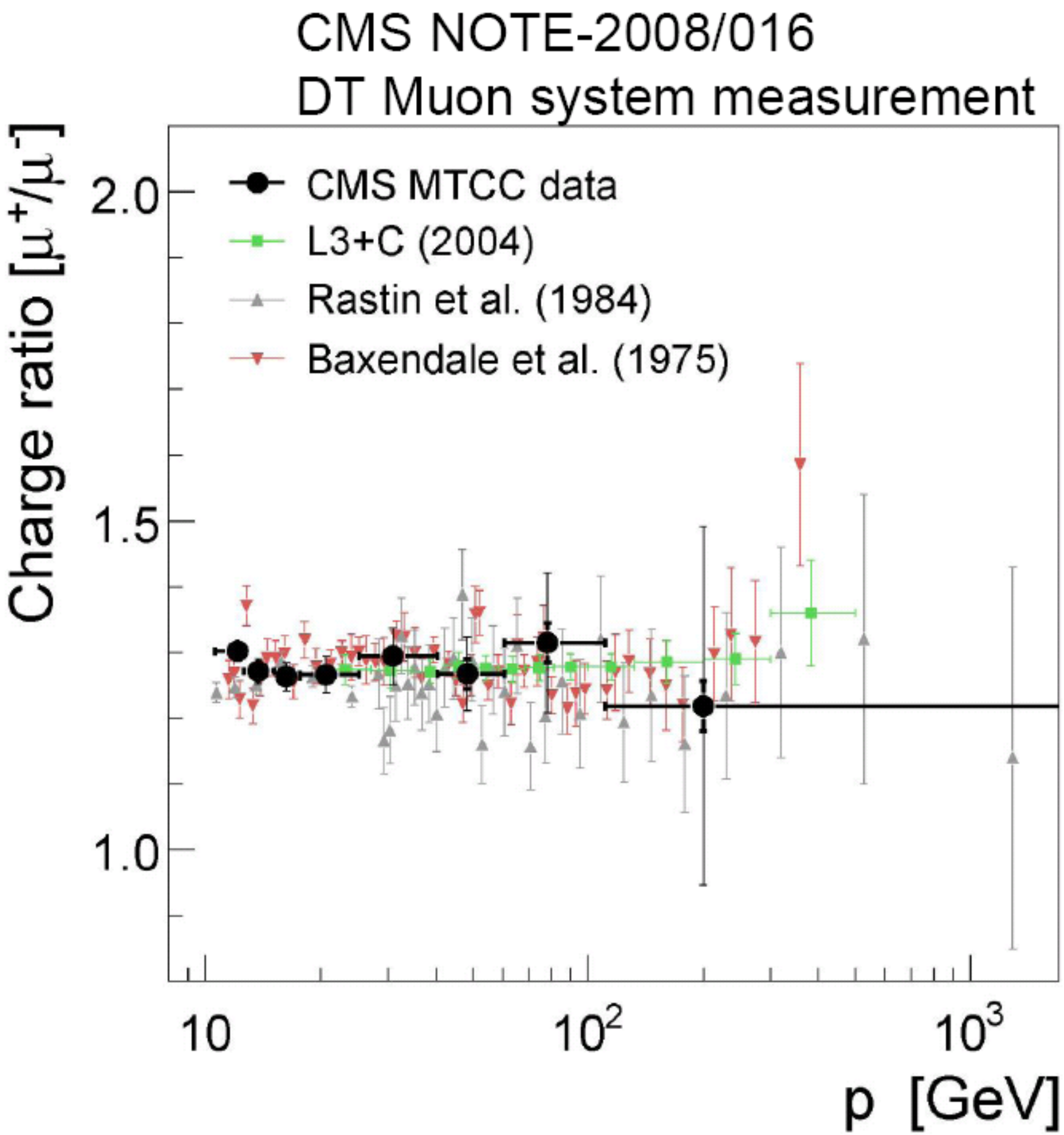
Avg. prob. to find ≥1 segment in bottom sectors - tag (top) & probe (bottom):

Shaft-muons are softer



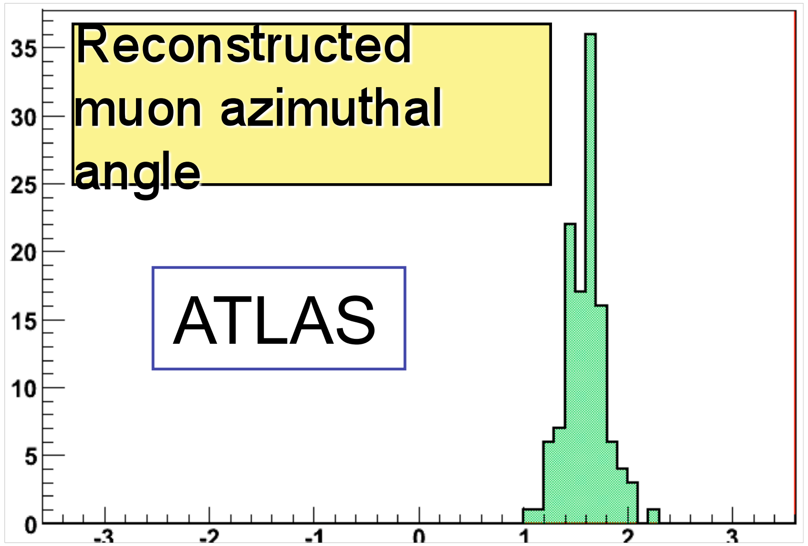
MTCC: Cosmic Charge Ratio Measurement

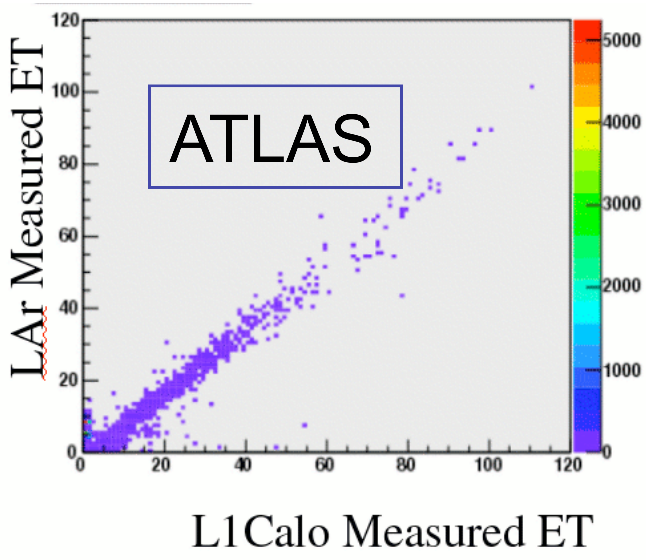


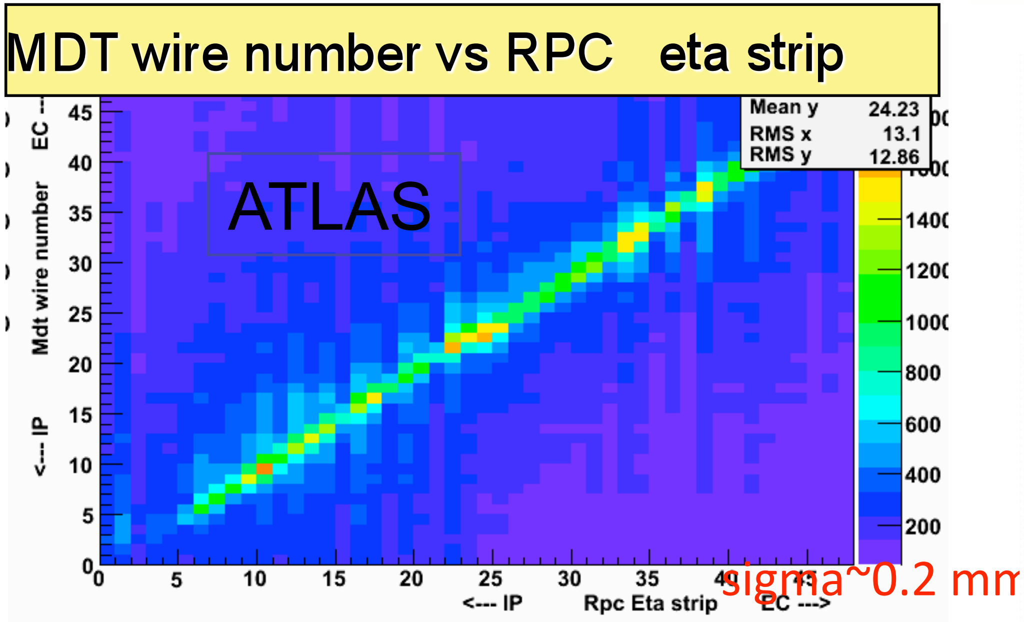


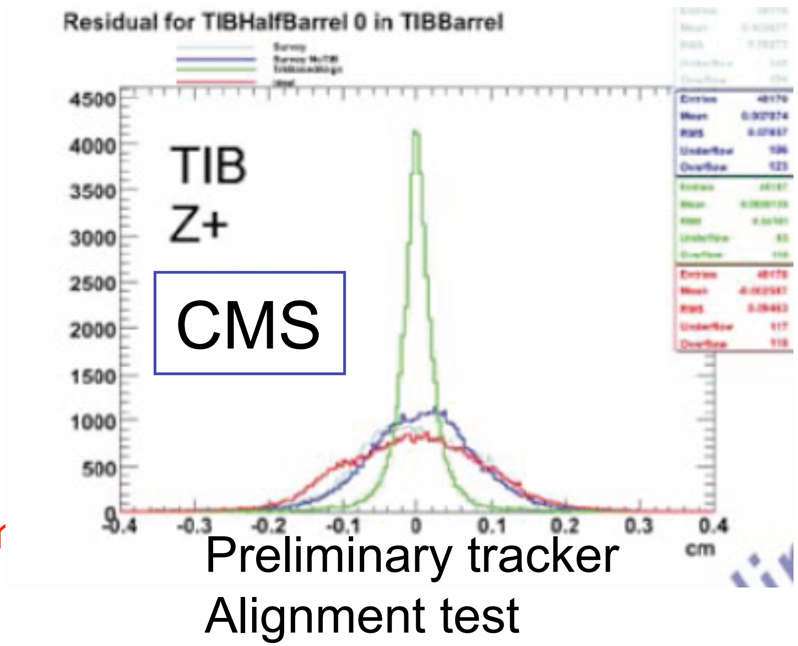
Such measurements push on getting calibration and alignment correct

Offline and trigger algorithms on cosmics









Cosmic and hardware tests: the quality of the detectors is excellent

ATLAS

Sub-detector	# Chan.	Non-working (%)
Pixels	8×10^7	0.2
Silicon Strip (SCT)	6×10^6	0.6
Transition Radiation Tracker (TRT)	3.5×10^5	2
E.M. Calorimeter	1.91×10^5	0.04 (1.5 for now)
Hadronic Calorimeter	10^4	0.1
Forward LAr	3500	0.2
Barrel Muon	7×10^5	0.5
End-cap Muon	3.2×10^5	0.02

Conclusion from Cosmic campaign

- The detectors are in excellent shape
  - Initial expected performance confirmed (<u>sufficient for first day physics</u>)
  - Gaining information for alignment and calibrations
- Integration of various subsystems
  - Global runs regularly taking place
  - Pre-synchronization
  - Trigger commissioning with cosmics

Collisions are next step !

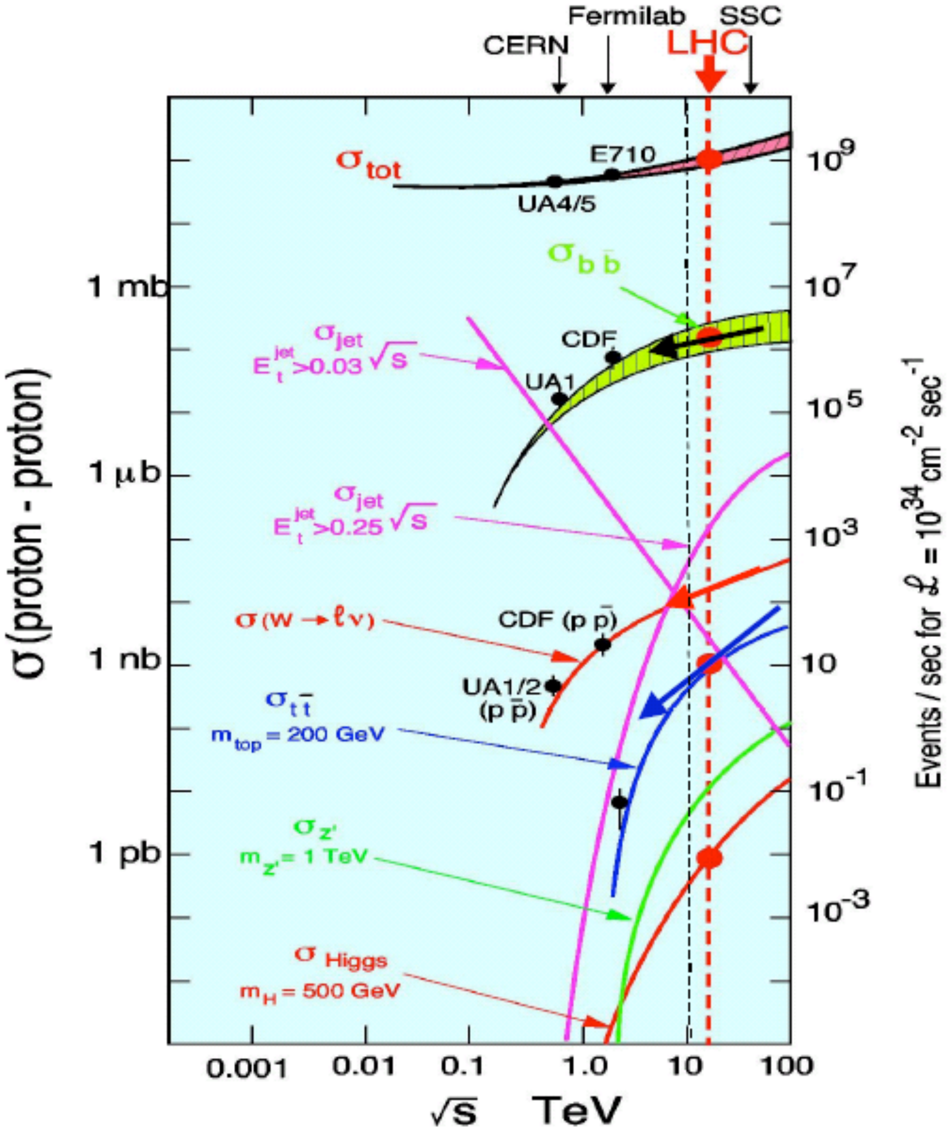
Reminder: 2008 and 2009 runs

Month	Phase	Days physics	Efficiency factor	Peak luminosity	Delivered luminosity
Jan	Cooldown and Hardware Commissioning and Machine checkout				
Feb					
Mar					
Apr					
May					
June					
Jul					
Aug	Beam Commissioning Physics run				
Sep					
Oct					
Nov		40	0.1	$5\ 10^{31}$	20 pb^{-1}
Dec	Shutdown				
Jan					
Feb					
Mar	Machine checkout				
Apr	75ns Commissioning				
May	Physics run	150	0.2	10^{33}	2.5 fb^{-1}
June					
Jul					
Aug					
Sep					
Oct					
Nov					
Dec					

10 TeV

14 TeV

2008: expect to run at 10 TeV



	10 TeV σ_{LO}MadGraph	14 TeV σ_{LO}MadGraph
Top pairs	**317 pb**	**750 pb**
W+jets	**40 nb**	**61 nb**

- Lower reach for searches:
  - Higgs(200 GeV) reduced to ~50%
  - Z'(2 TeV) to ~30%
  - sensitivity to new physics reduced by one order of magnitude for scales >4 TeV
- General rule: background scales less than signal
  - (whatever you call “signal”)

Typical statistics for the 10 TeV run

- Assume 10 pb-1, include acceptance, initial reconstruction and id efficiency
- Can establish Standard Model cross sections and distributions
- Can use to calibrate, align detectors

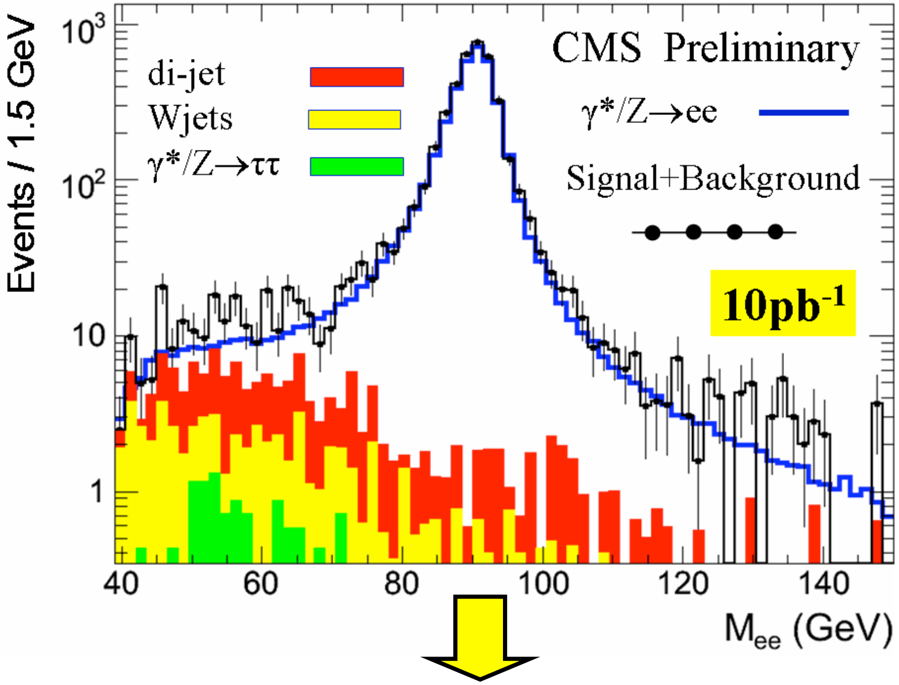
min bias	10^{12}
Jet Et>25	3. 10^{10}
Jet Et>140	3. 10^{6}
γ+Jet Et>20	3. 10^{6}
W ->lν	30000
Z -> ll	3000
tt-> lν4q	100

Stategy for Initial Physics

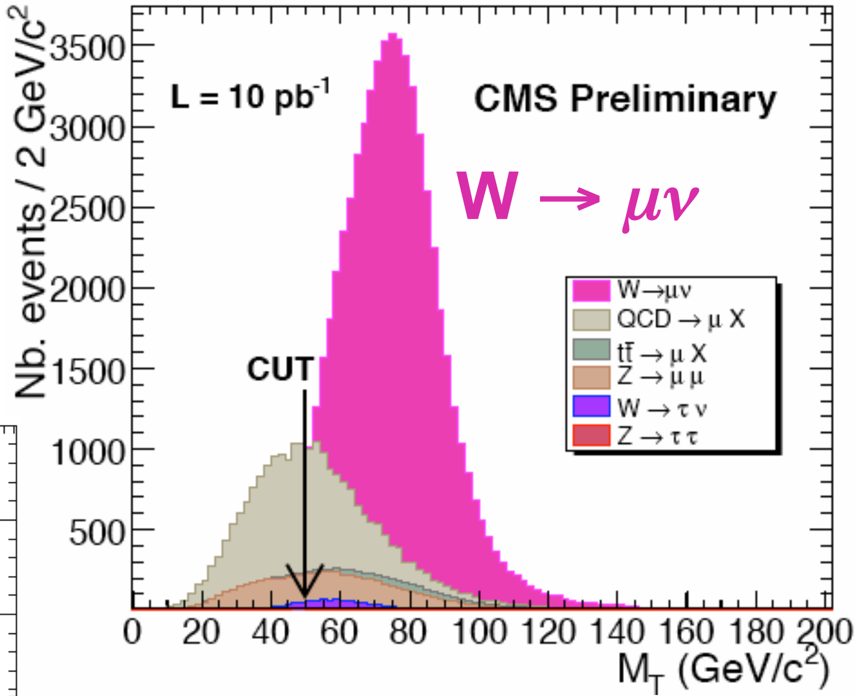
- A. Identify Standard Model process and measure Cross Section
- B. Utilize Standard Model Signal to measure efficiencies and background from data
- C. Search for New Physics with similar signature

- Most plots include realistic initial calibration scenari
- Warning: all plots are at 14 TeV

Z → ee/μμ and W → eν/μν

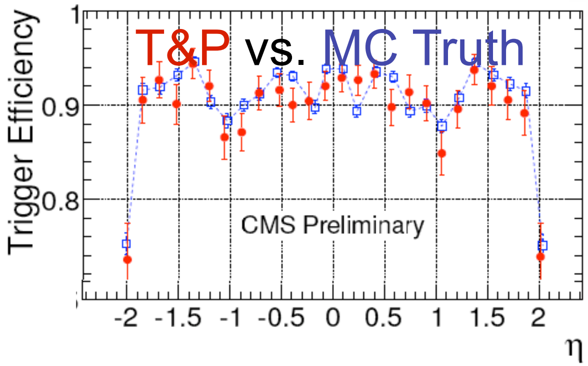


A. The Z and W cross sections are predicted to ~ 5%
  - Can be used to check luminosity
  - Z, W production properties useful to constraint the PDF

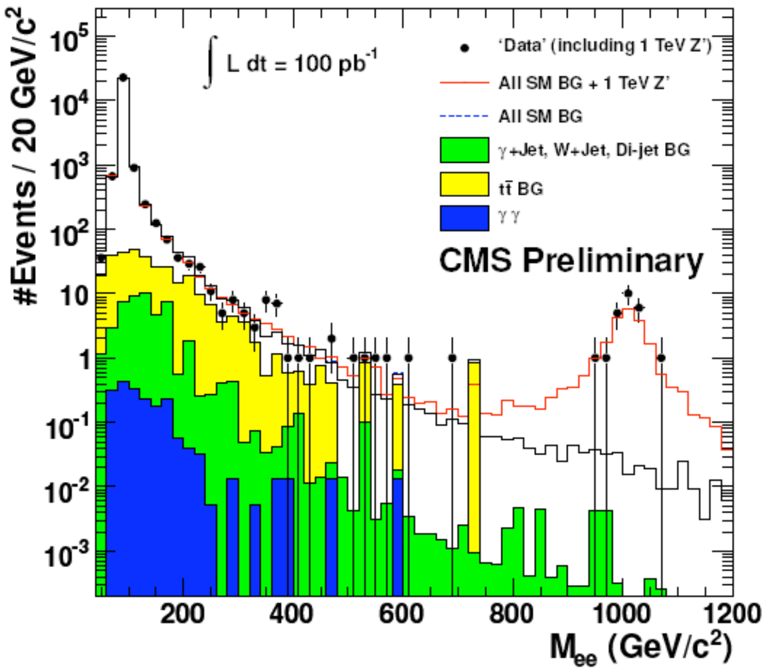


B. Powerful tools for lepton id commissioning
  - Tag & probe methods to determine efficiency from data

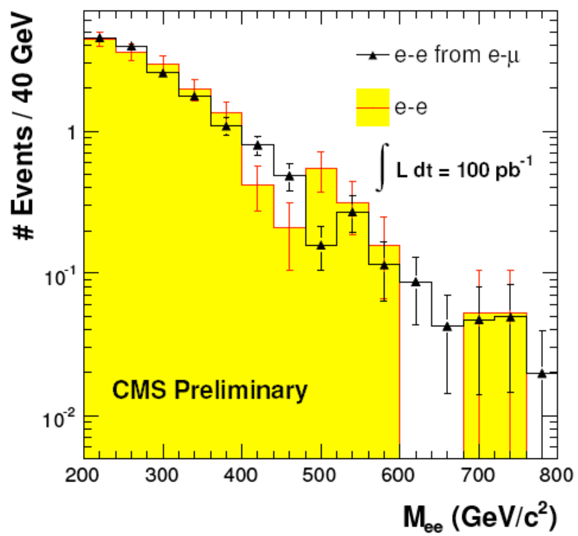
Also background determined from data, e.g. inverting isolation criteria



Same Topology: Search for high mass dilepton resonances



- Lepton id efficiency from tag&probe
- Irreducible Drell Yan background can be fitted
- ttbar background can be estimated from data using b-tagging or different-flavour dileptons

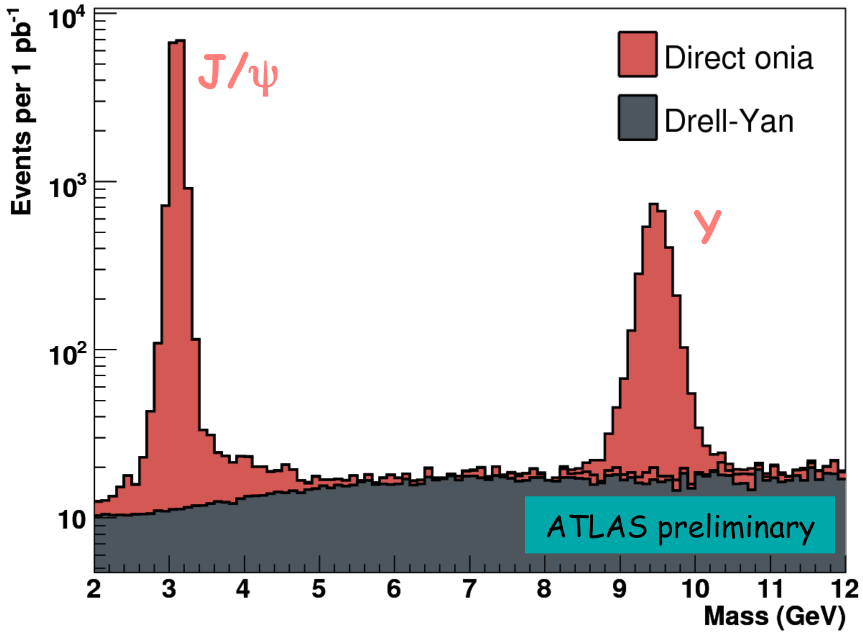


J/psi and Y are also on the list

Atlas example, after all cuts:
~ 4200 (800) J/ψ (Y) $\rightarrow \mu\mu$ evts per day at $L = 10^{31}$
(for 30% machine x detector data taking efficiency)
~ 15600 (3100) events per pb^{-1}

$\rightarrow$ tracker momentum scale, trigger performance,
detector efficiency,
sanity checks, …

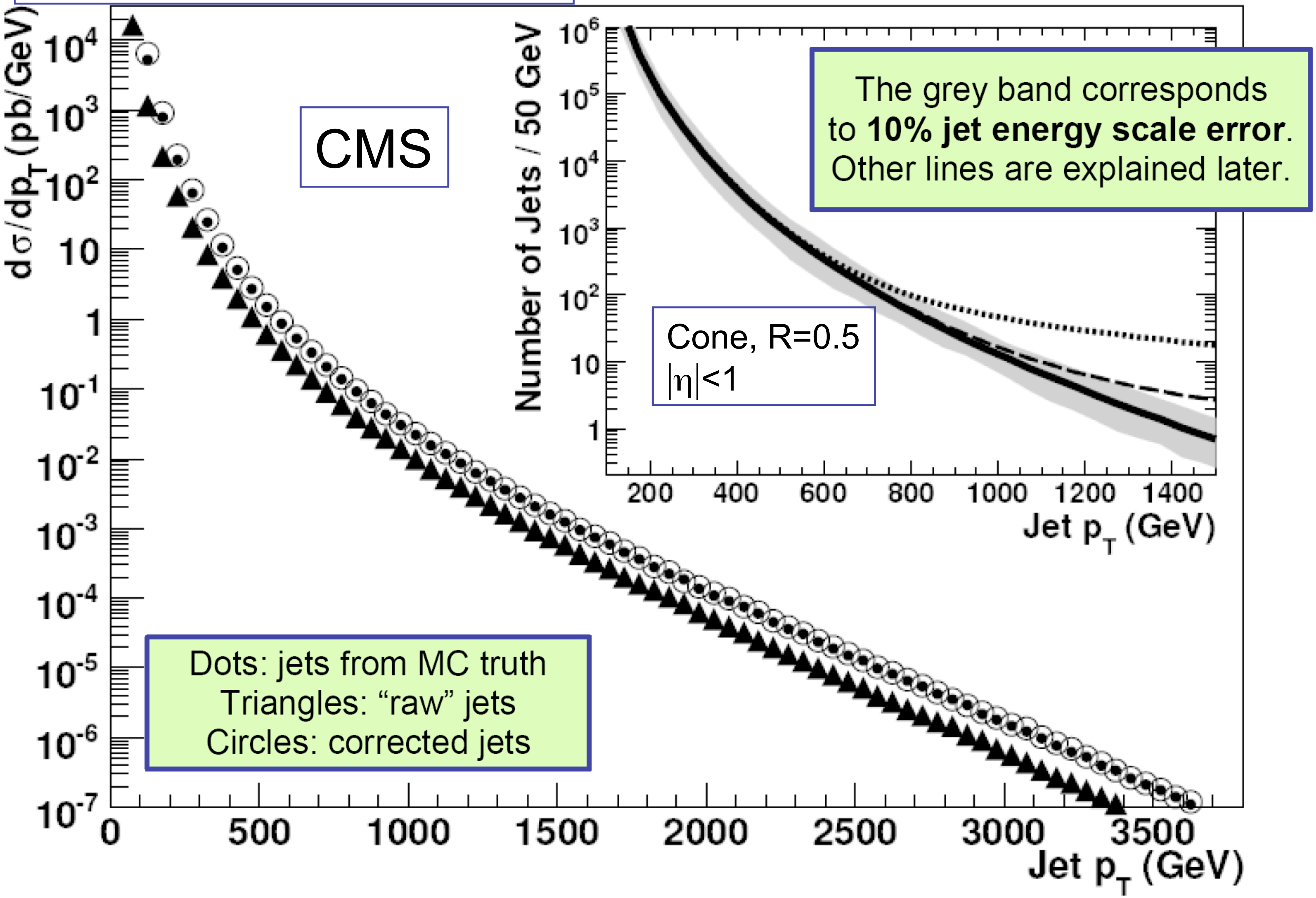
1 pb^{-1}≡3 days at 10^{31} at 30% efficiency



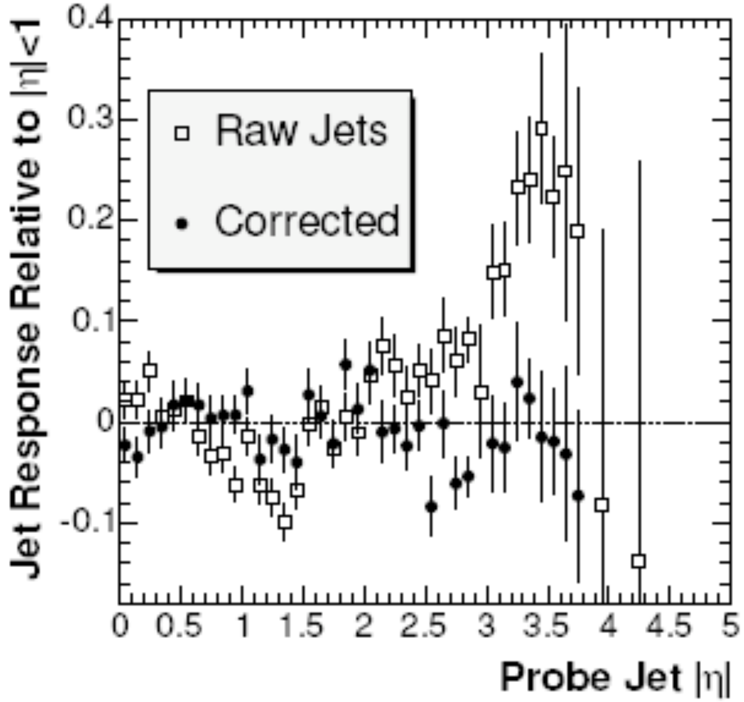
Need to establish Heavy Quark cross section at 10, 14 TeV from first data !

Jets, 10/pb

Measure inclusive jet cross section



Jet Equalization with dijet balancing

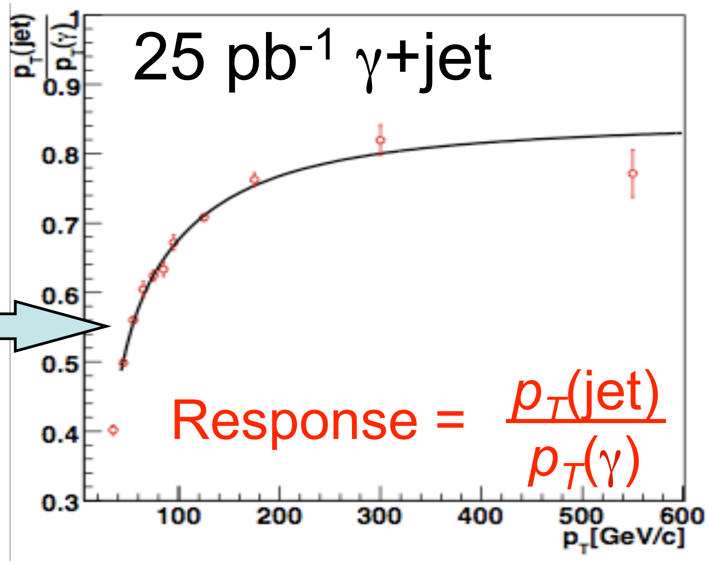


•We can quickly equalize at " low Et" until we run out of statistics

• One must assume equalization holds at higher energy (but data vs MC needed for this)

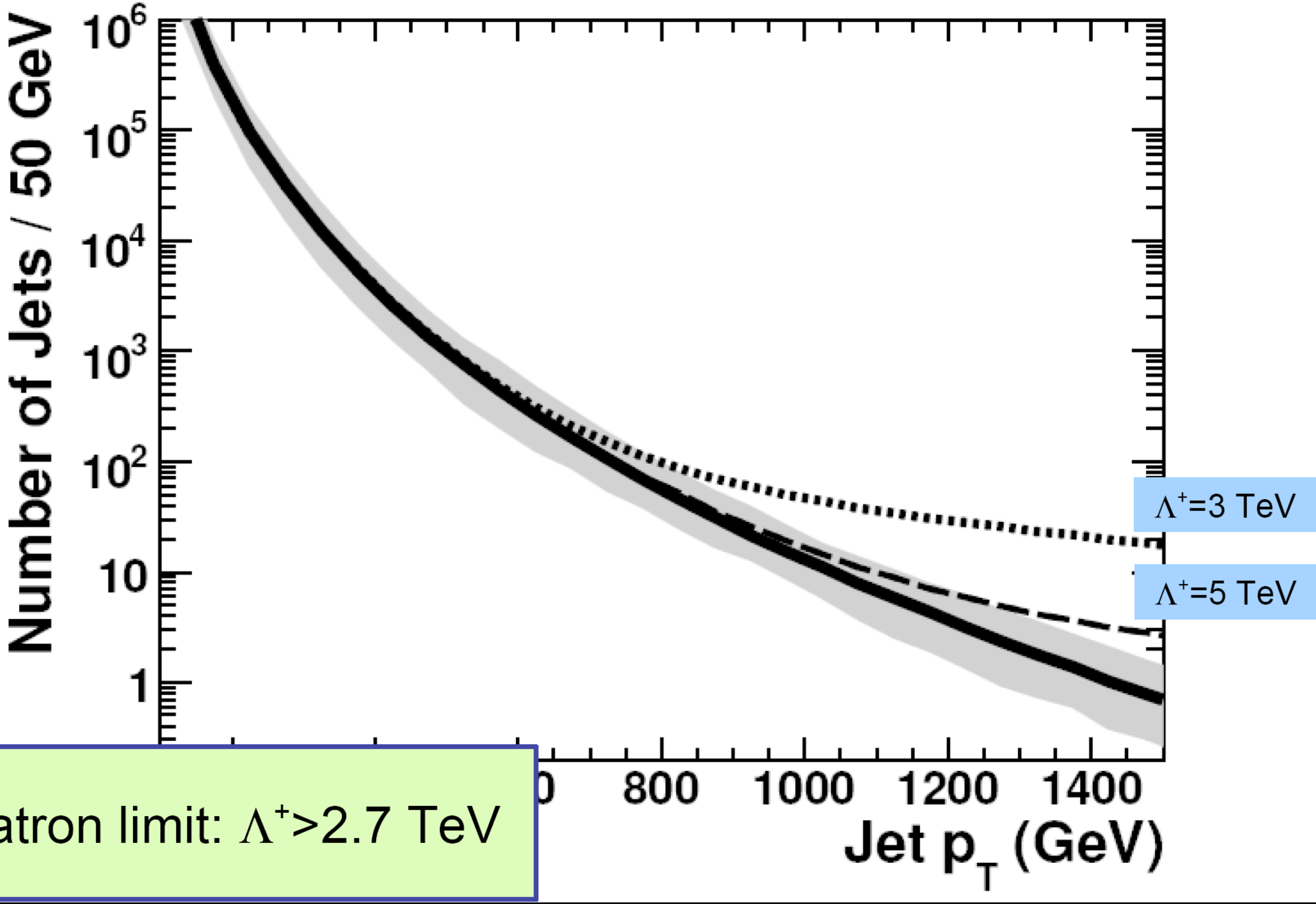
Absolute energy scale:

- we start with a ~ 10% uncertainty
- γ+jet, W's from ttbar will help constraining further and further



Search for New Physics with di-jets:

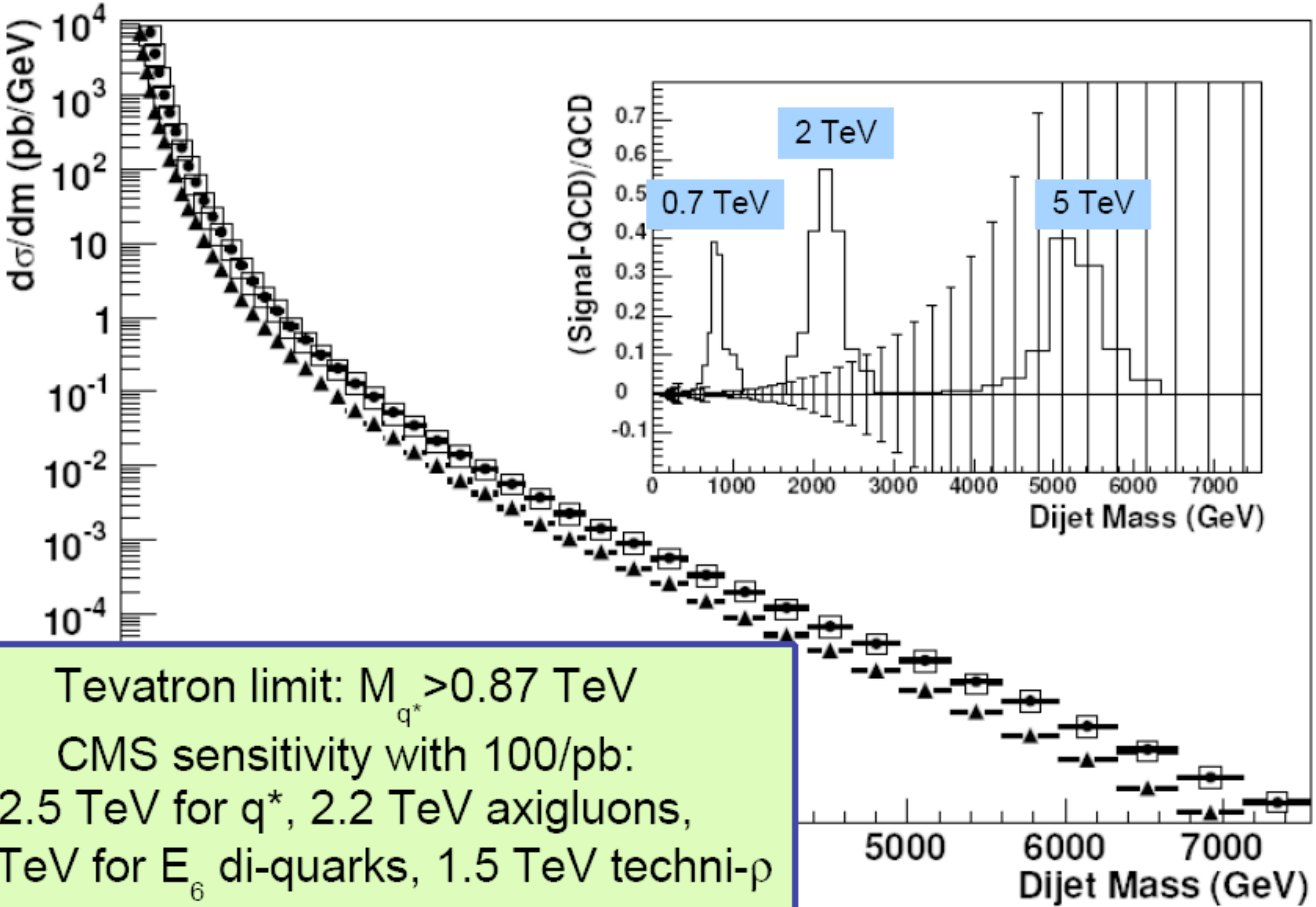
Contact interactions, 10/pb



Tevatron limit: $\Lambda^+ > 2.7$ TeV

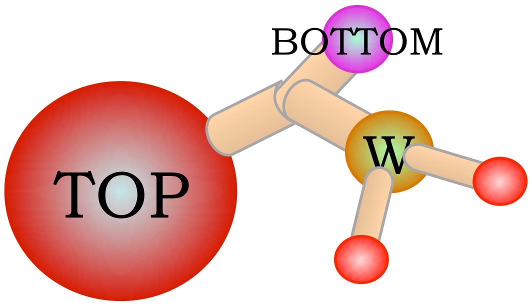
Search for New Physics with di-jets:

Di-jet resonances, 100/pb



Tevatron limit: M_{q^*}>0.87 TeV

CMS sensitivity with 100/pb:
2.5 TeV for q*, 2.2 TeV axigluons,
2.0 TeV for E_6 di-quarks, 1.5 TeV techni-ρ



Early Top at LHC

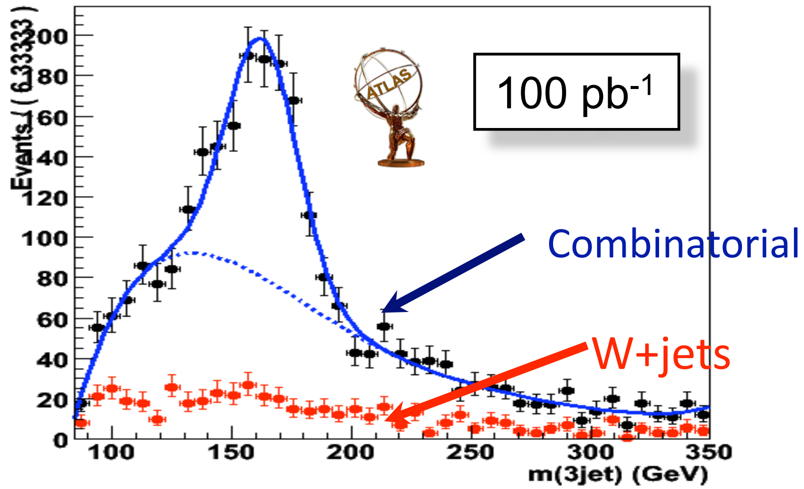
Early measurement

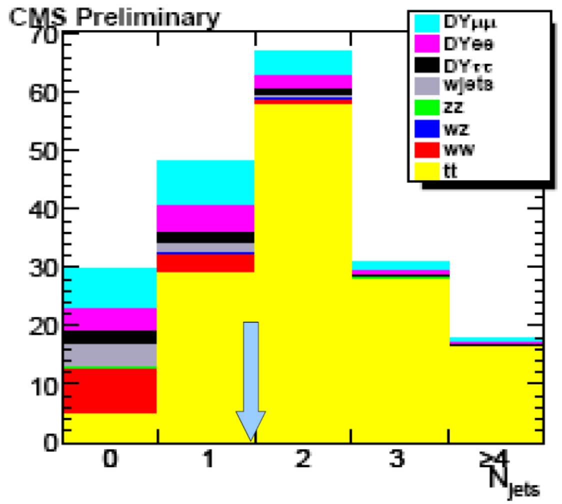
- Establish the ttbar cross section at 14 TeV
- →Check the gluon PDF !

With more luminosity and understood detectors expect a rich program of top physics al LHC

- single top production
- ttbar resonances
- top rare decays
- single top and ttbar spin measurement
- …. eventually precision mass measurement

Semileptonic decays without b-tag

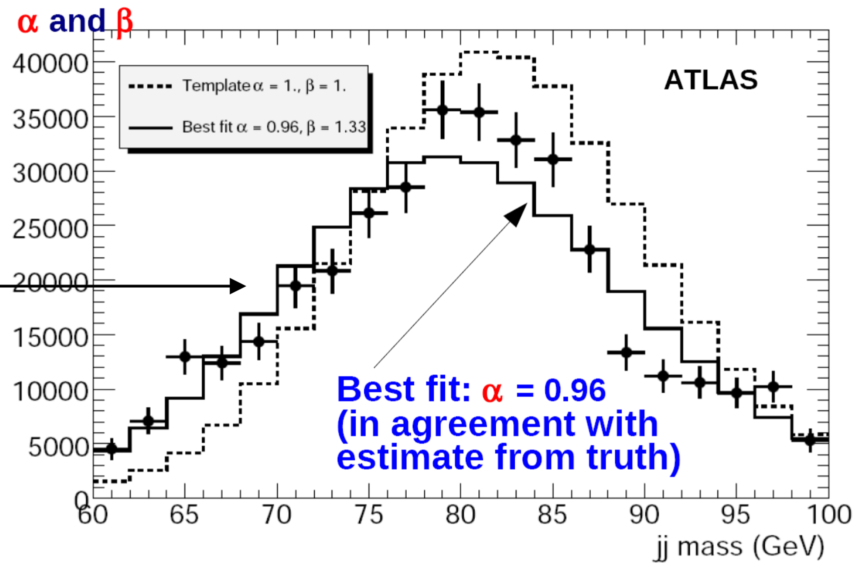




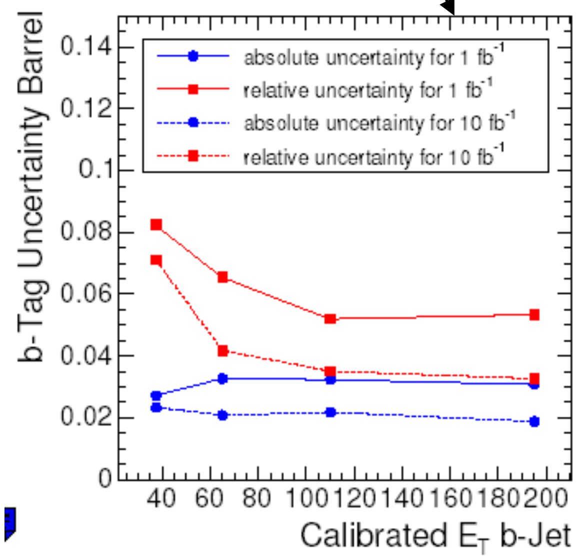
Dileptonic decays without b-tag

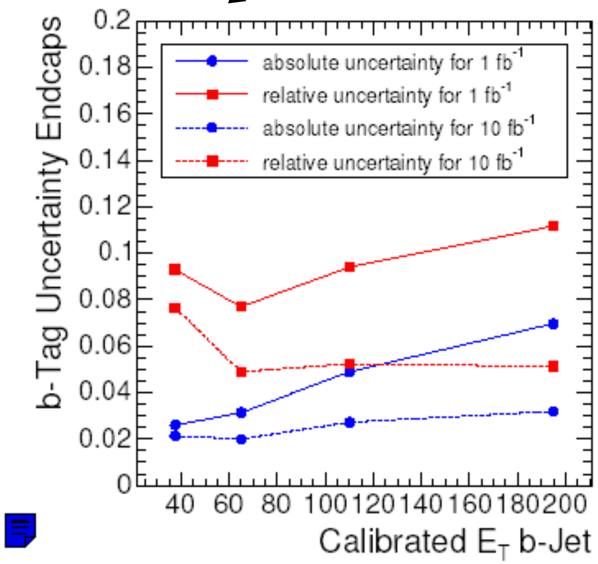
Top as a tool for calibrations

Determine light jet energy scale from W → jj coming from semileptonic top decays



Determine b-tagging efficiencies from b-jets coming from semileptonic top decays

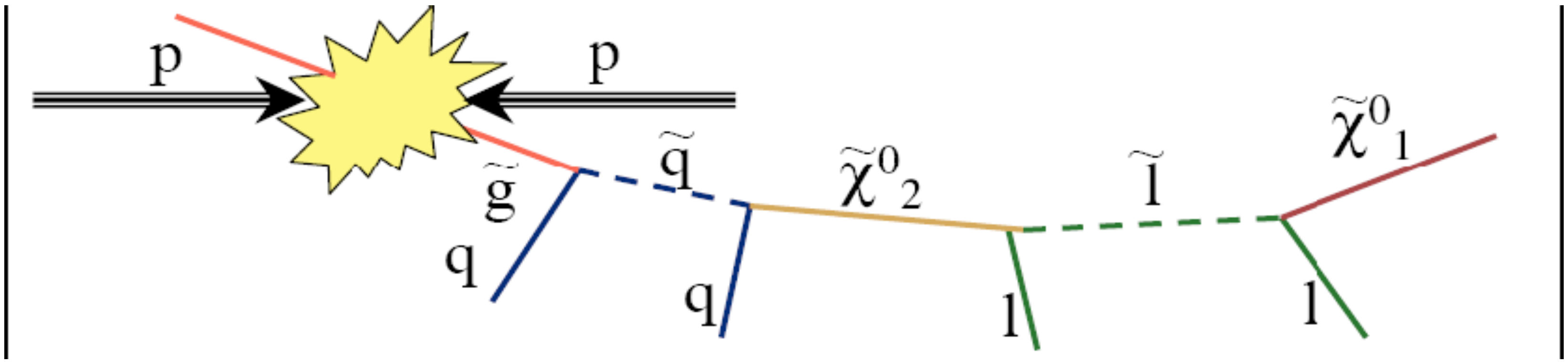




When the Standard Model is established, we can start to be brave …
…………this is just an example

Direct Search for SUSY particles

- Production of Susy Particles at LHC is dominated by gluinos and squarks
- The production is followed by a SUSY+SM cascade.



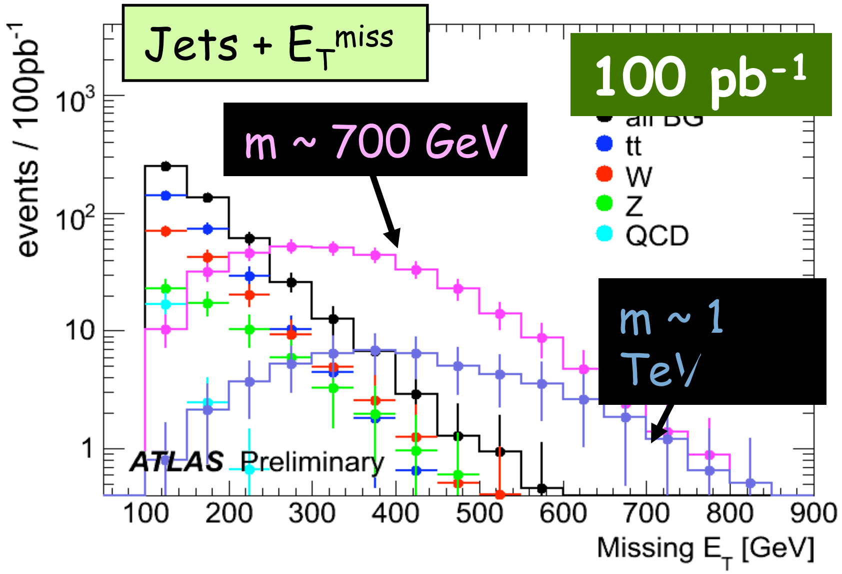
Studying Jets and Missing E_T

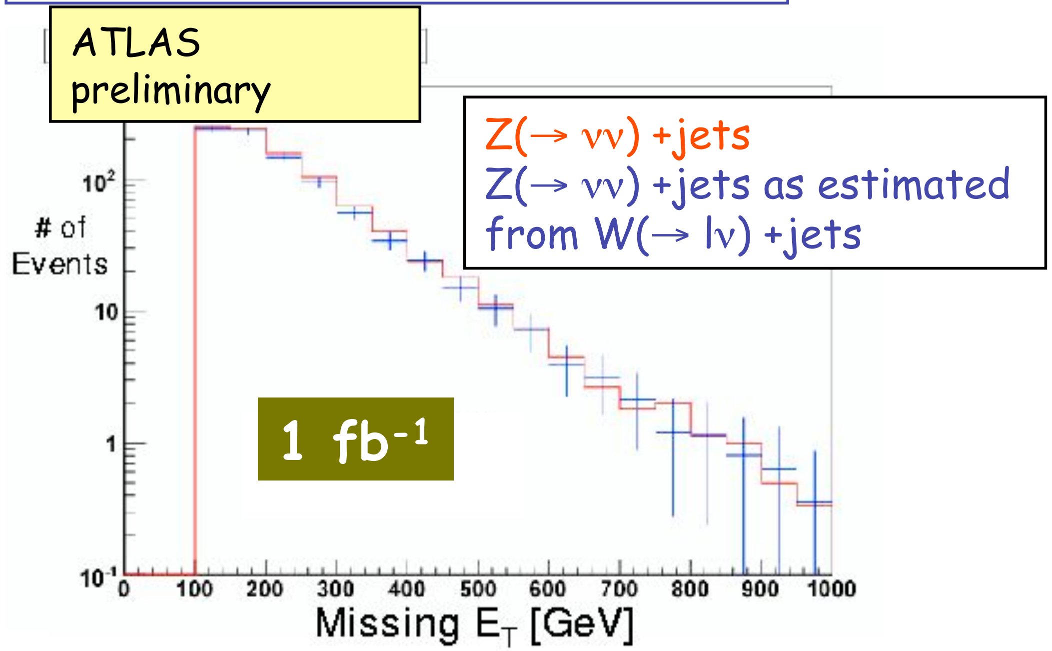
for Low Mass SUSY

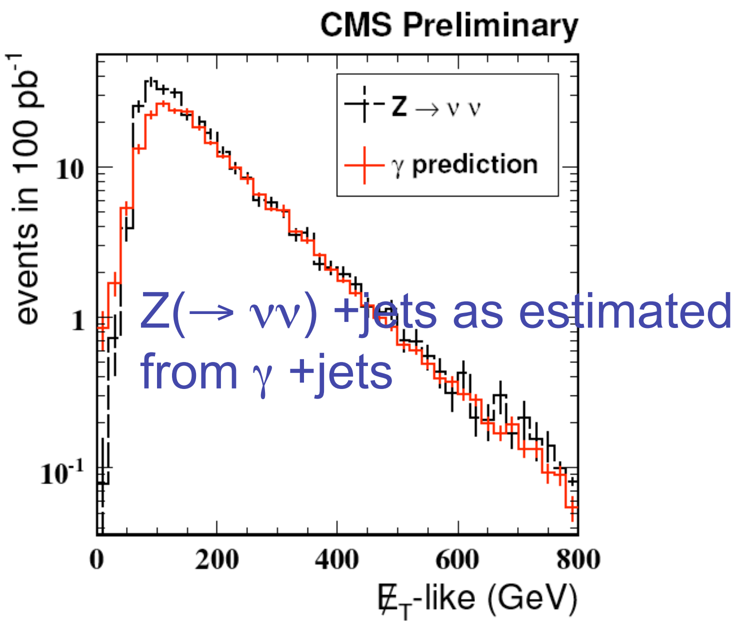
Missing ET :

•Important to monitor instrumental effects (dead channels, non-gaussian tails)

•Important to monitor Standard Model background (e.g Z → νν accompanied by jets)

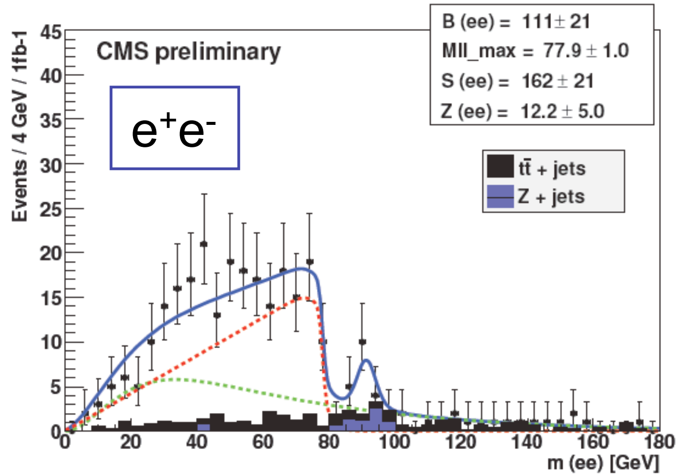




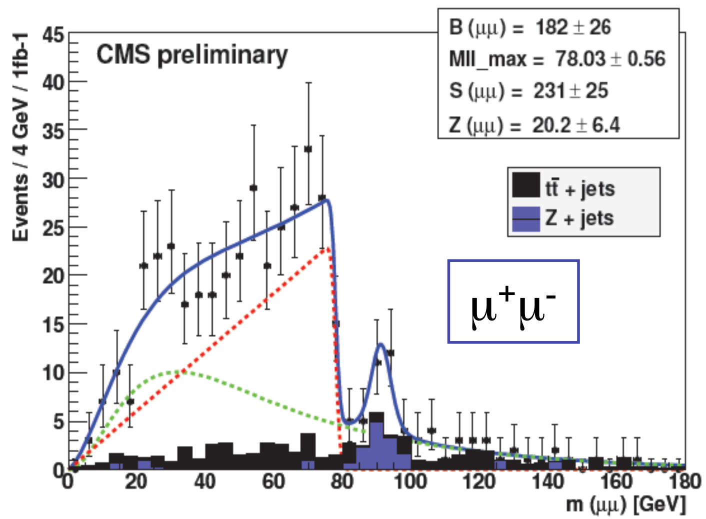


Di-leptonic edges

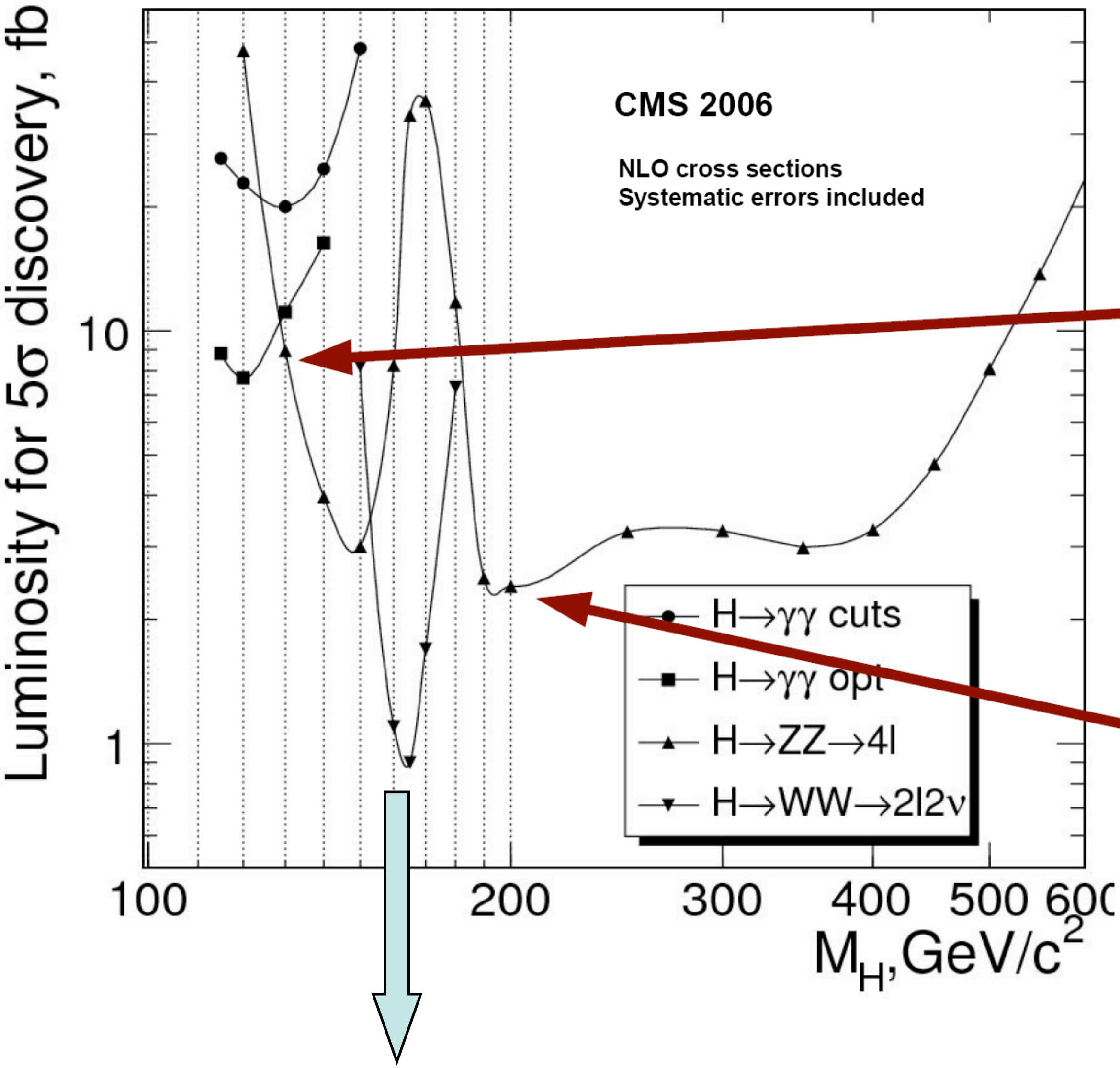
- M_{ll} distrib. in decays $\chi_2^0 \to \tilde{\ell}^+\ell^- \to \chi_1^0 \ell^+\ell^-$
  - SUSY's smoking gun!
  - From edges, information on masses
- Same Flavour, Opposite Sign (SFOS)
  - Lepton flavour uncorrelated in bkg from SM and from SUSY itself
    - Estimated from OFOS leptons ($e^+\mu^-$)
  - Background from fake leptons
    - Estimated from SFSS leptons
- ΔM_{ll}^{max} ~ 0.5 GeV @ 1/fb
  - 5σ (w/ syst) @ 17/pb at LM1 point

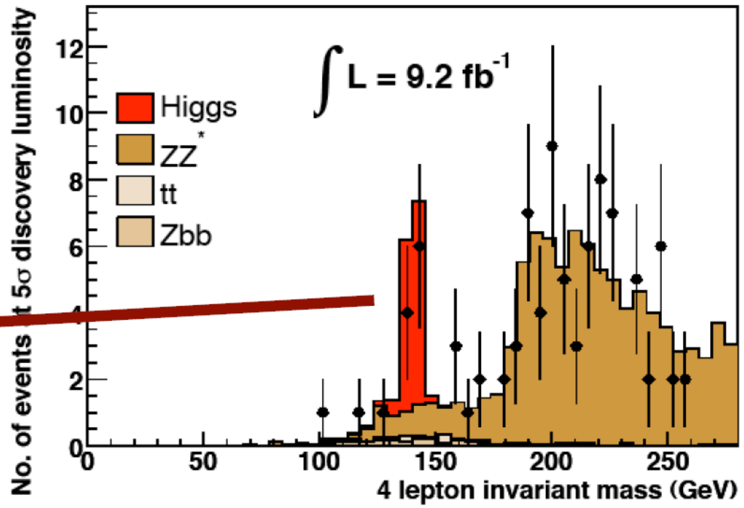


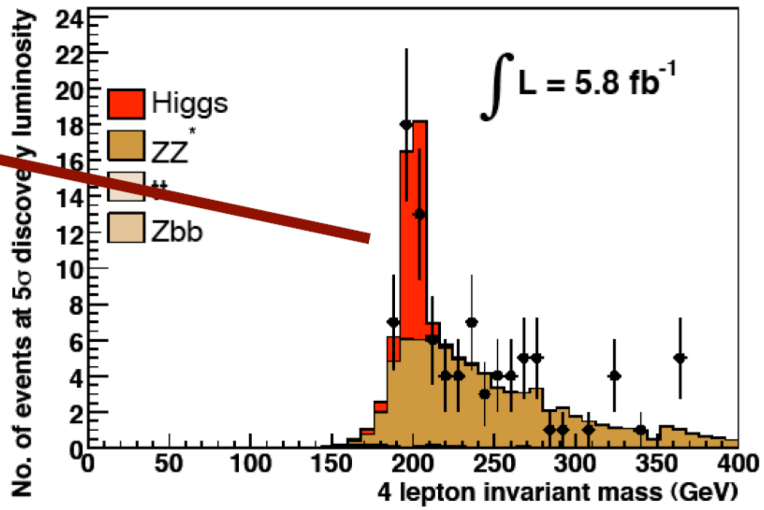
1/fb, LM1 point



And the Higgs?

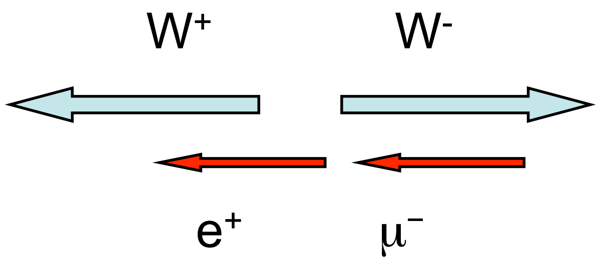




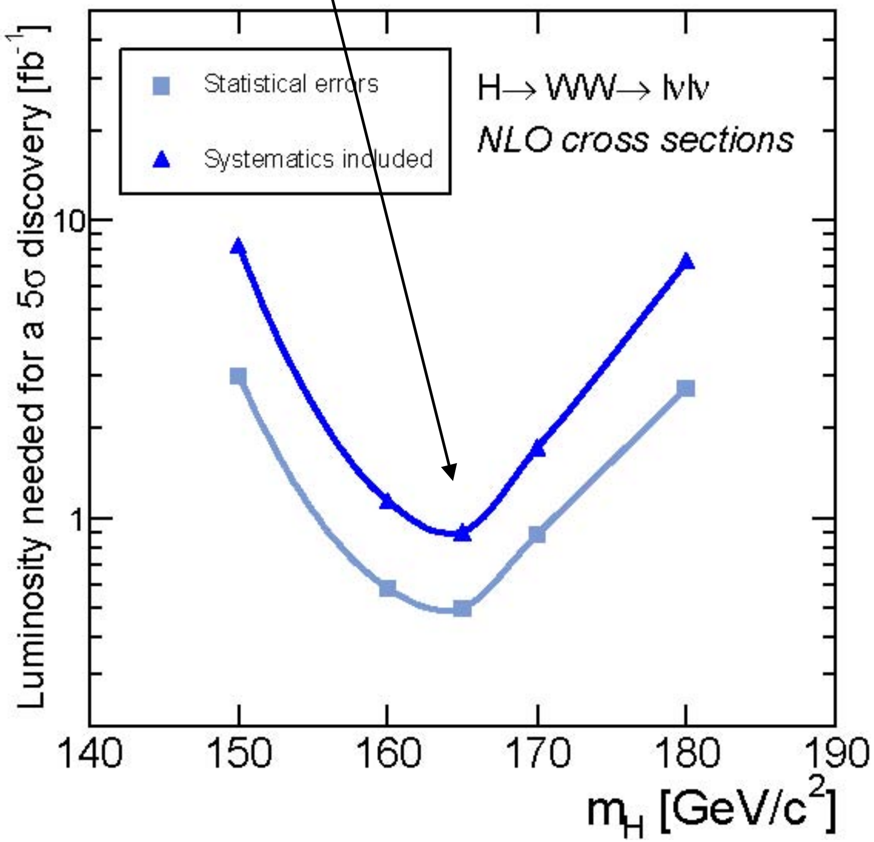


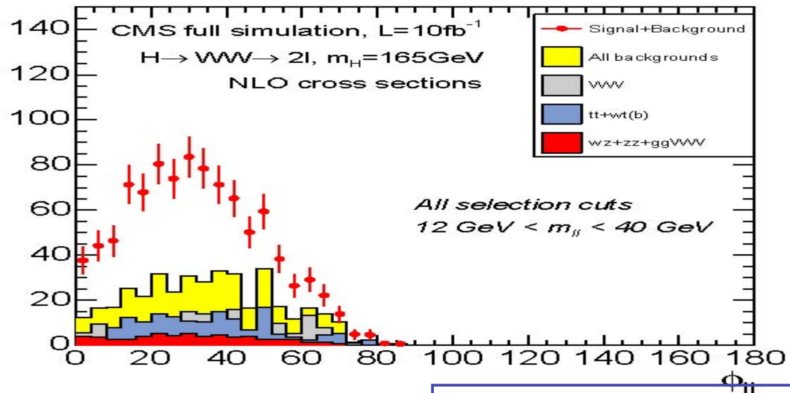
Mass around 160 GeV: H -> WW*

Use the fact that H is spin 0



Counting experiment :
Need to normalize
WW and ttbar background from data !
Predicting effects from, for instance, jet-vetoes from Monte Carlo is dangerous ….

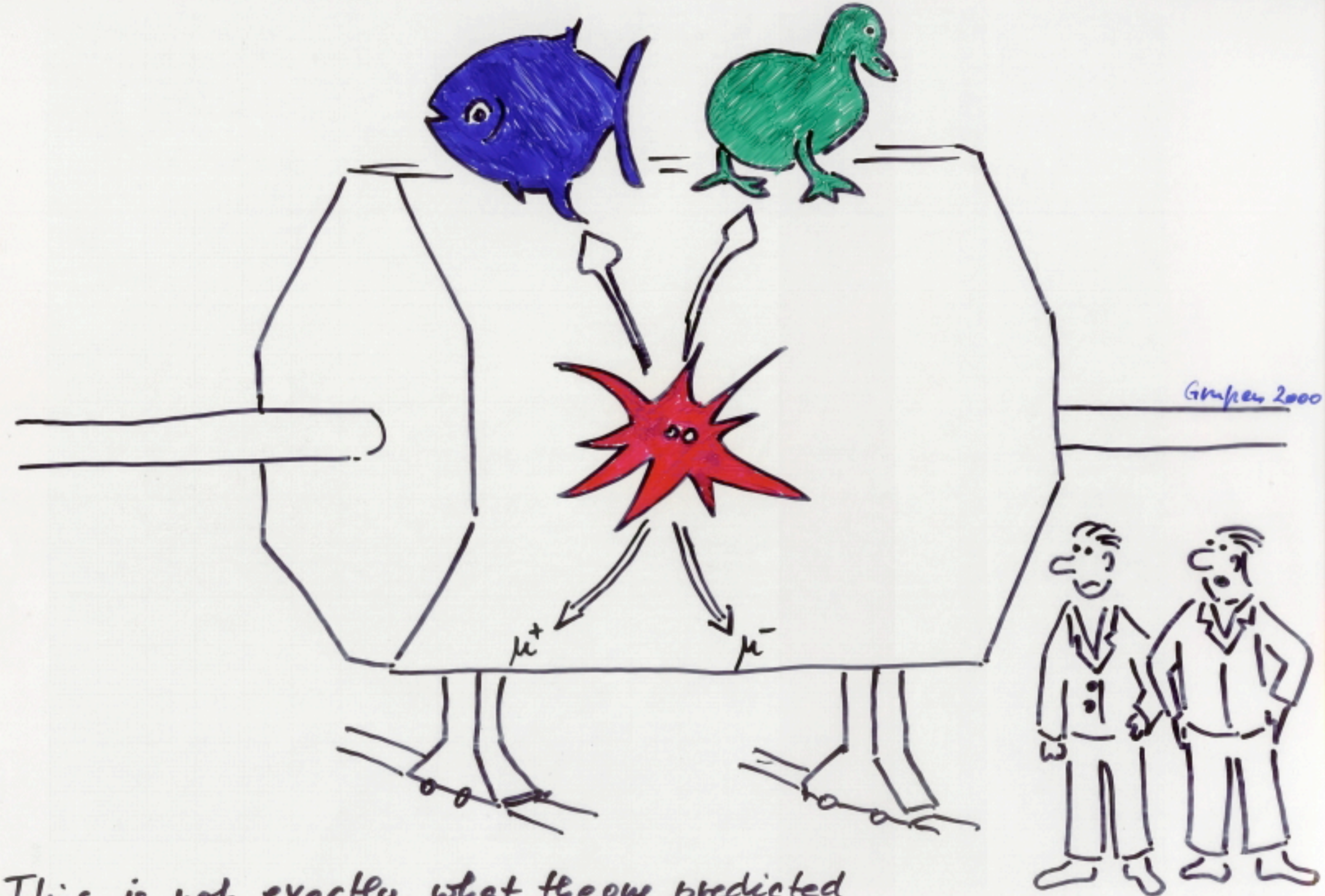




CMS Note-2006/055

The Road Map for discovering Physics Beyond the Standard Model at LHC…..

- … requires re-discovering the Standard Model at LHC
  - Because SM processes are needed to calibrate and align detectors
  - Because SM backgrounds to New Physics need to be measured
- … we must get ready for the unexpected



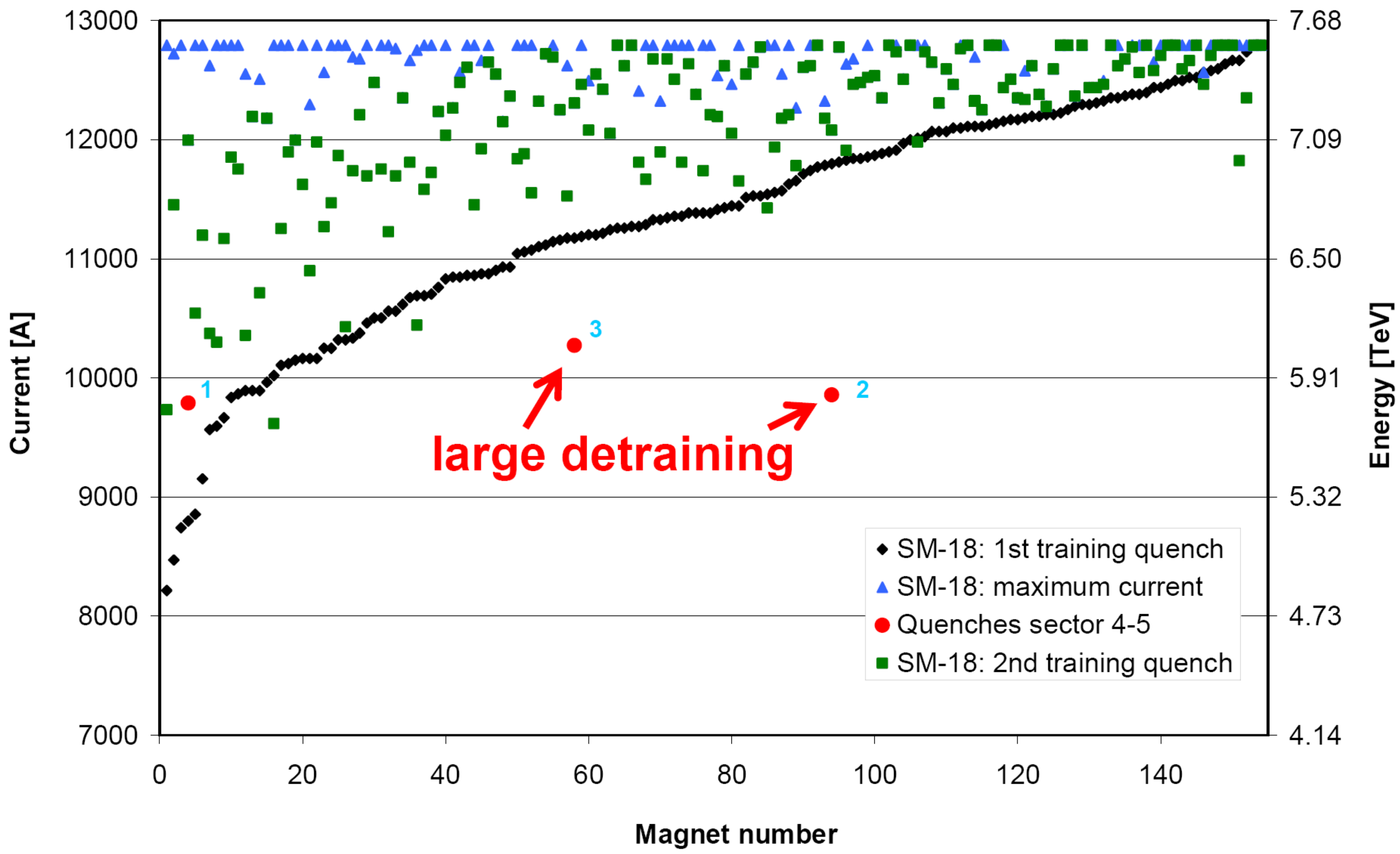
"This is not exactly, what theory predicted for the Higgs decay!"

Acknowledgements

- Roger Bailey
- Riccardo Barbieri
- Alessandro Cerri
- Tim Christiansen
- Andrea Giammanco
- Fabiola Gianotti
- Rob Harris
- and may others …

backup

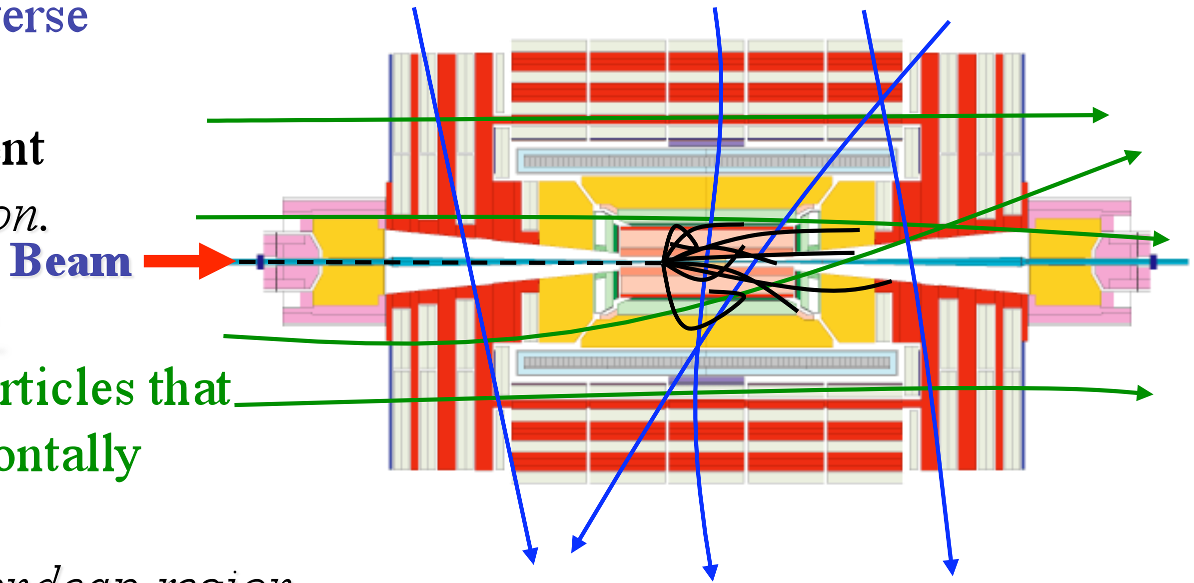
Sector 45 – Powering towards nominal



“Pre-Collision Physics Structures”

Cosmic Muons

High energetic muons that traverse the detector vertically
→particular useful for alignment and calibration - *barrel region.*



Beam Halo Muons (Hadrons)

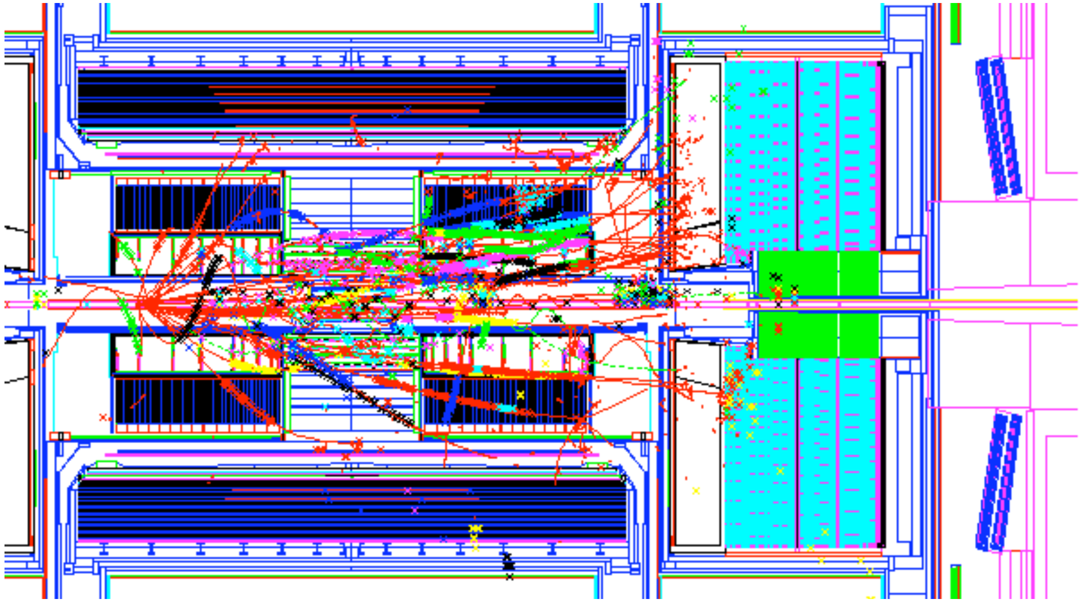
Machine induced secondary particles that cross the detector almost horizontally
→particular useful for alignment and calibration - *endcap region.*

Beam Gas Interactions

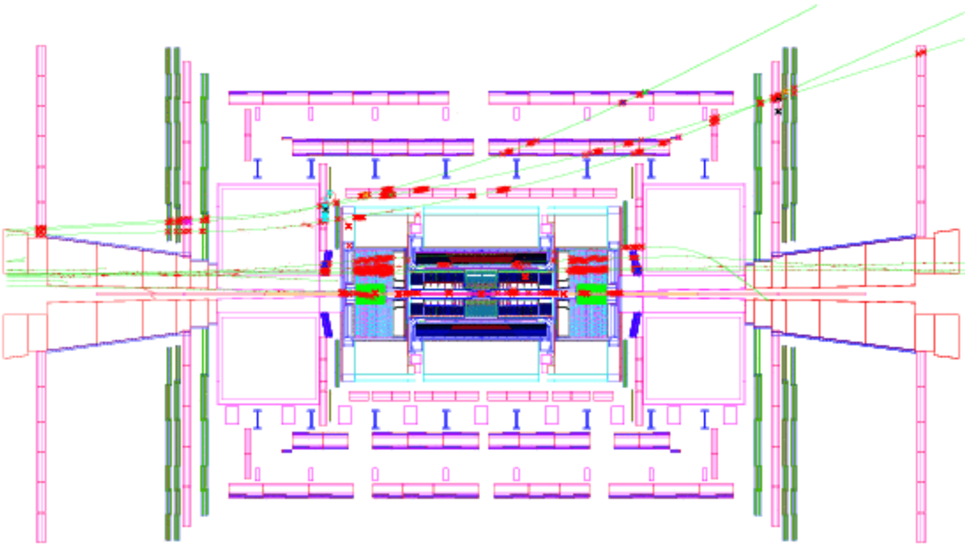
Proton-nucleon interaction in the active detector volume (7TeV→E_{cm}=115 GeV)
→resemble collision events but with a rather soft p_T spectrum (p_T<2 GeV)

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

A beam-gas event in ATLAS (full sim.)



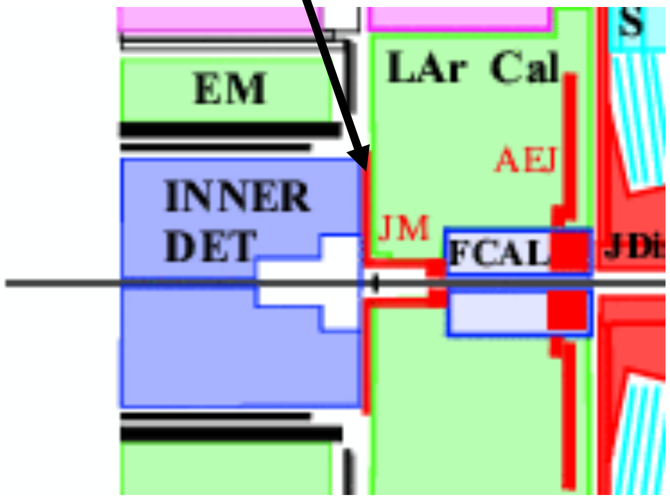
Beam-halo muons in ATLAS (full sim.)



Trigger ?

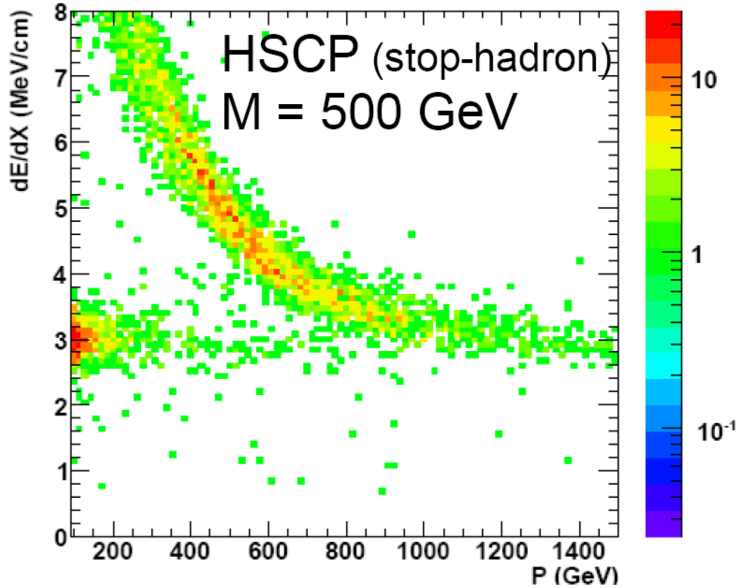
Scintillator counters inside ID cavity, in front of end-cap cryostats (replacing part of moderator), covering R=15→ 90 cm

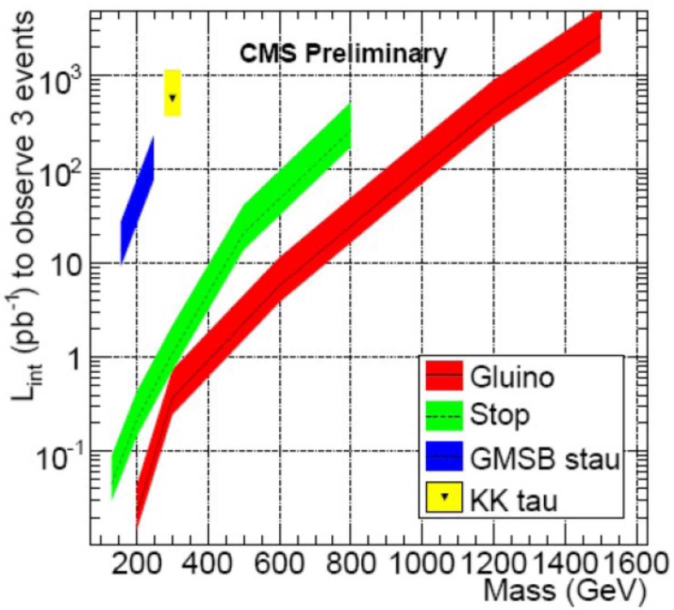
Provide trigger on beam-halo at low R (TGC at large R), beam-gas, and minimum bias for initial LHC operation



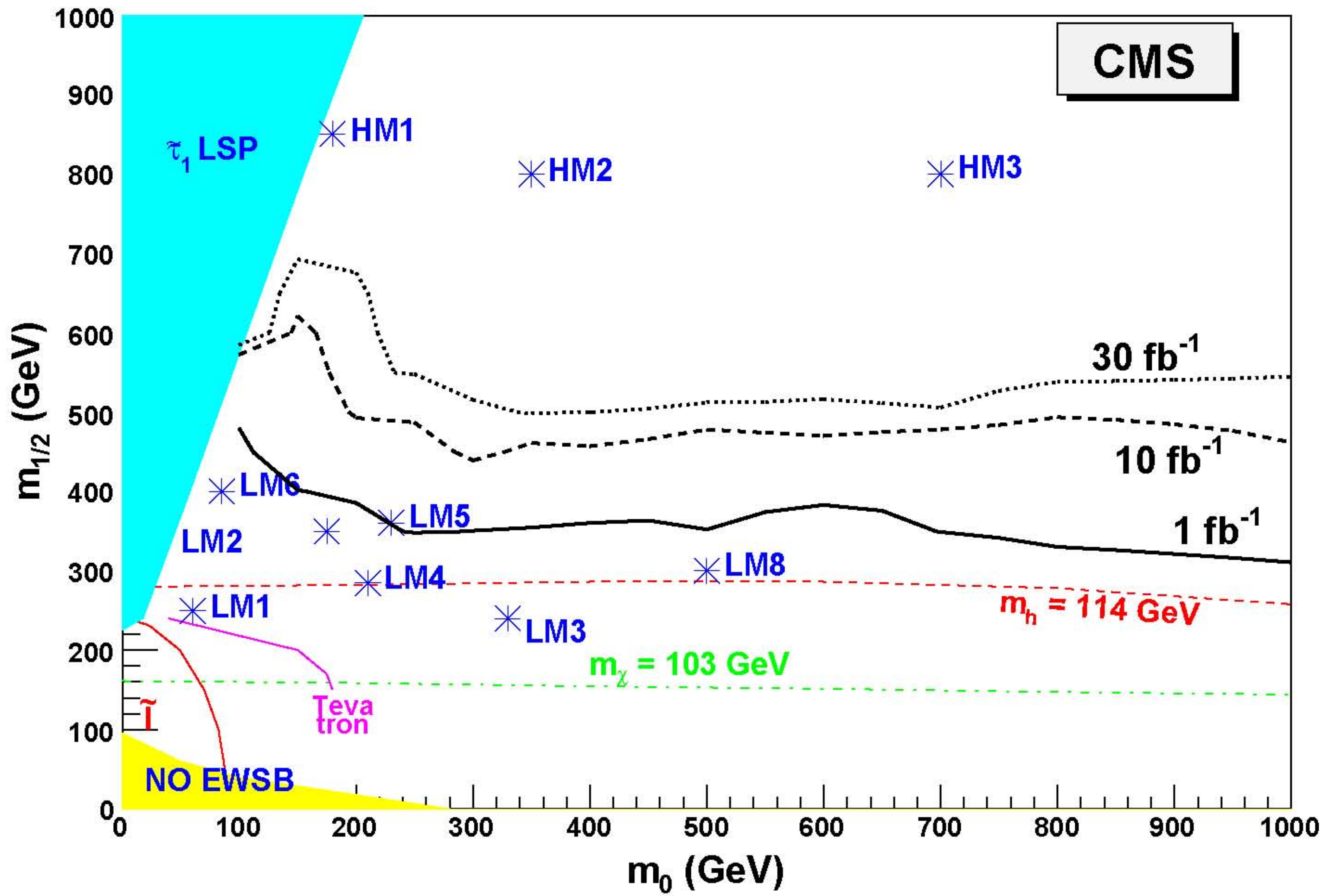
Heavy Stable Charged Particles (HSCP)

- Several SUSY variants predict metastable or stable charged particles
  - Slepton: “heavy muons”
  - Gluino, squark: “R-hadrons”
    - nuclear interactions!
- Signatures: dE/dx, Time Of Flight
- dE/dx: Tracker
  - >10 independent samplings in Si
  - Estimate the Most Probable Value
- TOF: Muon Chambers
  - δt additional parameter in the track fit
  - Main bkg: cosmics



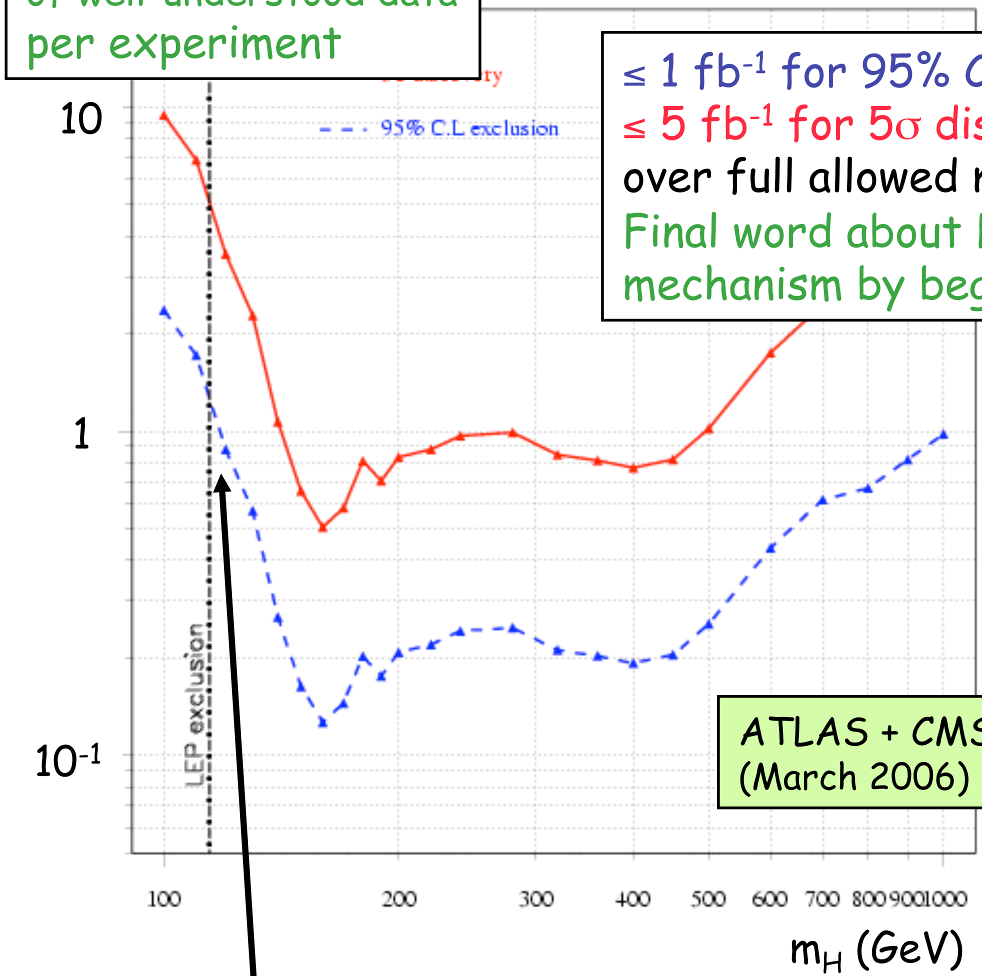


Region explored for Low Mass SUSY



A more difficult case: a light Higgs boson

Needed ∫Ldt (fb^{-1})
of well-understood data
per experiment

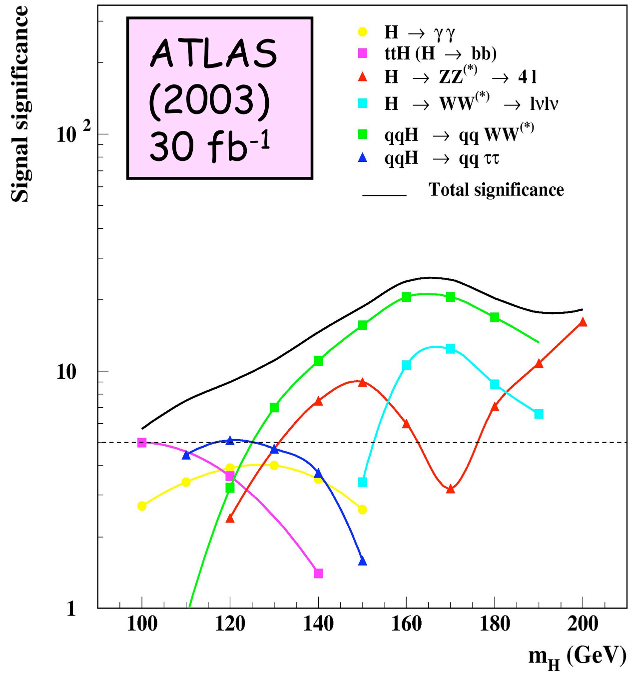


$\leq$ 1 fb^{-1} for 95% C.L. exclusion
$\leq$ 5 fb^{-1} for 5σ discovery
over full allowed mass range
Final word about Higgs
mechanism by beg. 2010 ?

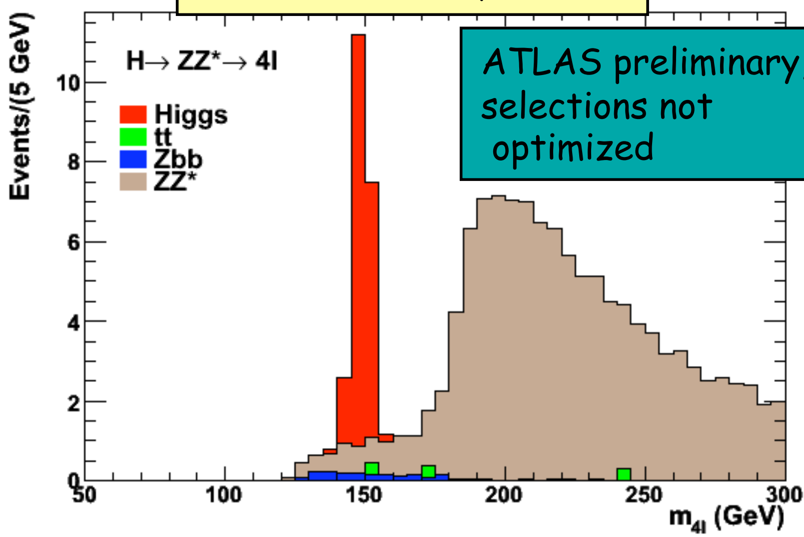
ATLAS + CMS
(March 2006)

Most difficult region:
need to combine many
channels (e.g. $H \rightarrow \gamma\gamma$,
$qqH \rightarrow qq\tau\tau$) with small S/B

ATLAS
(2003)
30 fb^{-1}



$H \rightarrow ZZ^* \rightarrow 4l$, 10 fb^{-1}



ATLAS preliminary,
selections not
optimized

For m_H > 140 GeV discovery easier with $H \rightarrow ZZ^{(*)} \rightarrow 4l$ (narrow mass peak, small B). $H \rightarrow WW \rightarrow l\nu l\nu$ (dominant at 160-175 GeV) is counting experiment (no mass peak)