Status of the LHC

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DESY

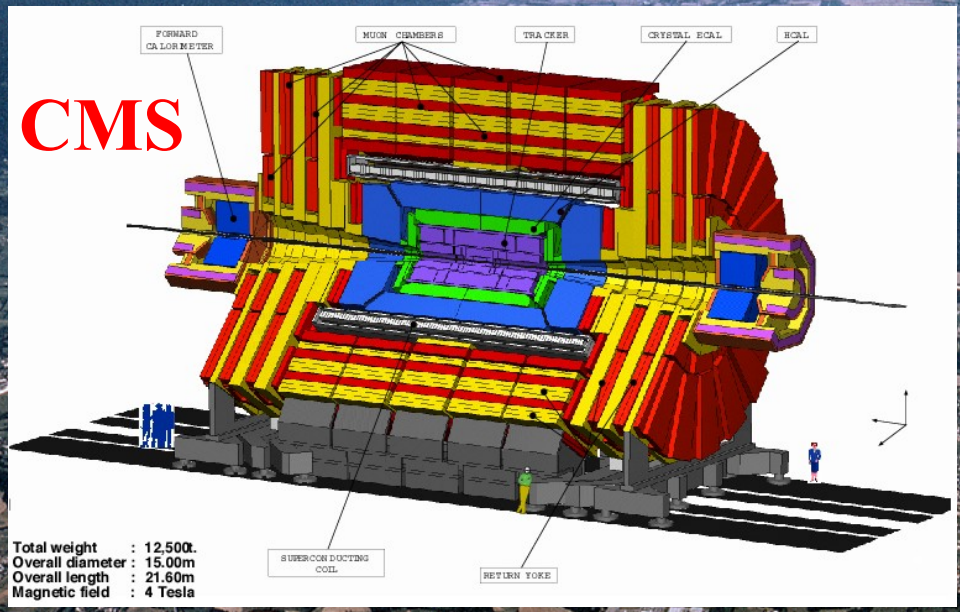
Loops and Legs in Quantum Field Theory
Wörlitz
April 2010

Outline

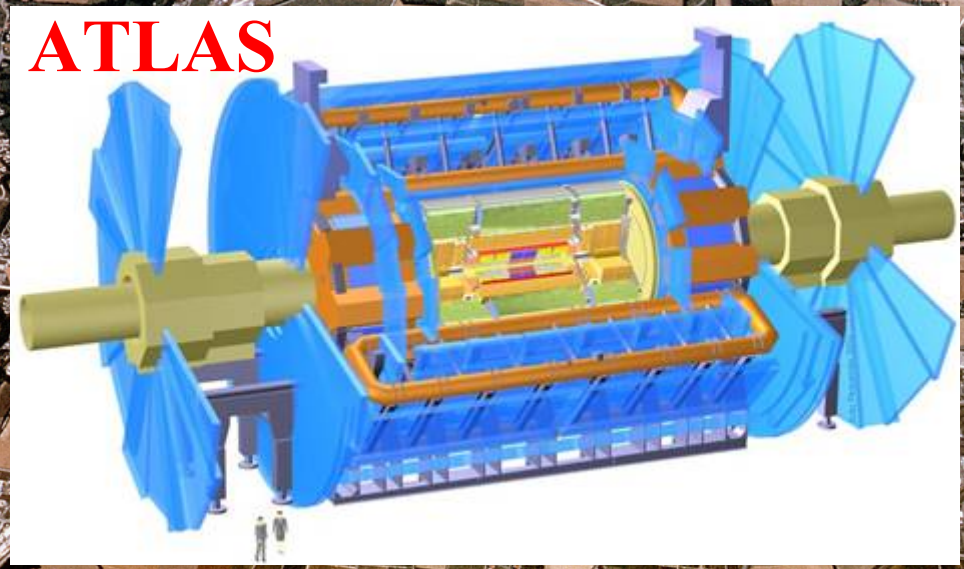
- The Large Hadron Collider
- The Experiments
- First beams & collisions
  - The accident
  - Magnet interconnects
- First results
  - 2009 data at 900 GeV
  - 2010 data at 7 TeV
- Plans & Outlook

The Large Hadron Collider LHC

The Large Hadron Collider LHC



LHCb



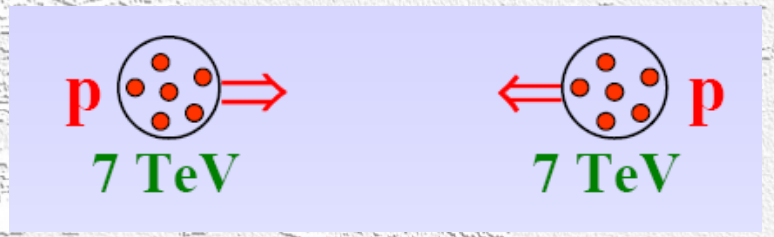
The Large Hadron Collider (LHC)

- Proton-proton collider in the former LEP tunnel
- The LHC uniquely combines the two most important virtues of HEP experiments:
- Highest ever energy per collission

  14 TeV in the pp-system

  cf. Tevatron at 2 TeV
- High luminosity

  up to $10^{34}/cm^2/s$
- 4 experiments:
  - **ATLAS**
  - **CMS**
  - **LHCb** specialised on b-physics
  - **ALICE** specialised for heavy ion collisions

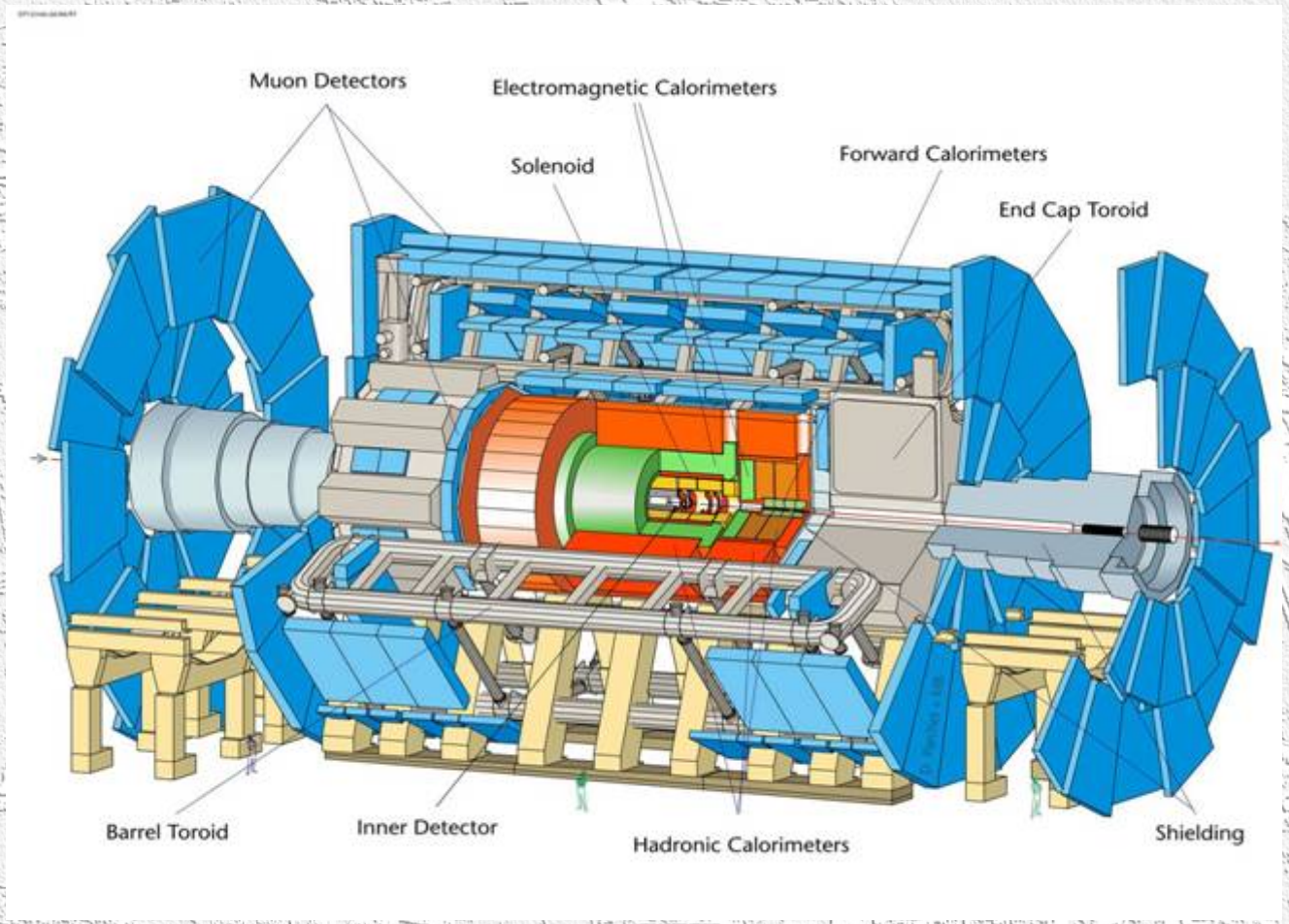


The ATLAS Experiment

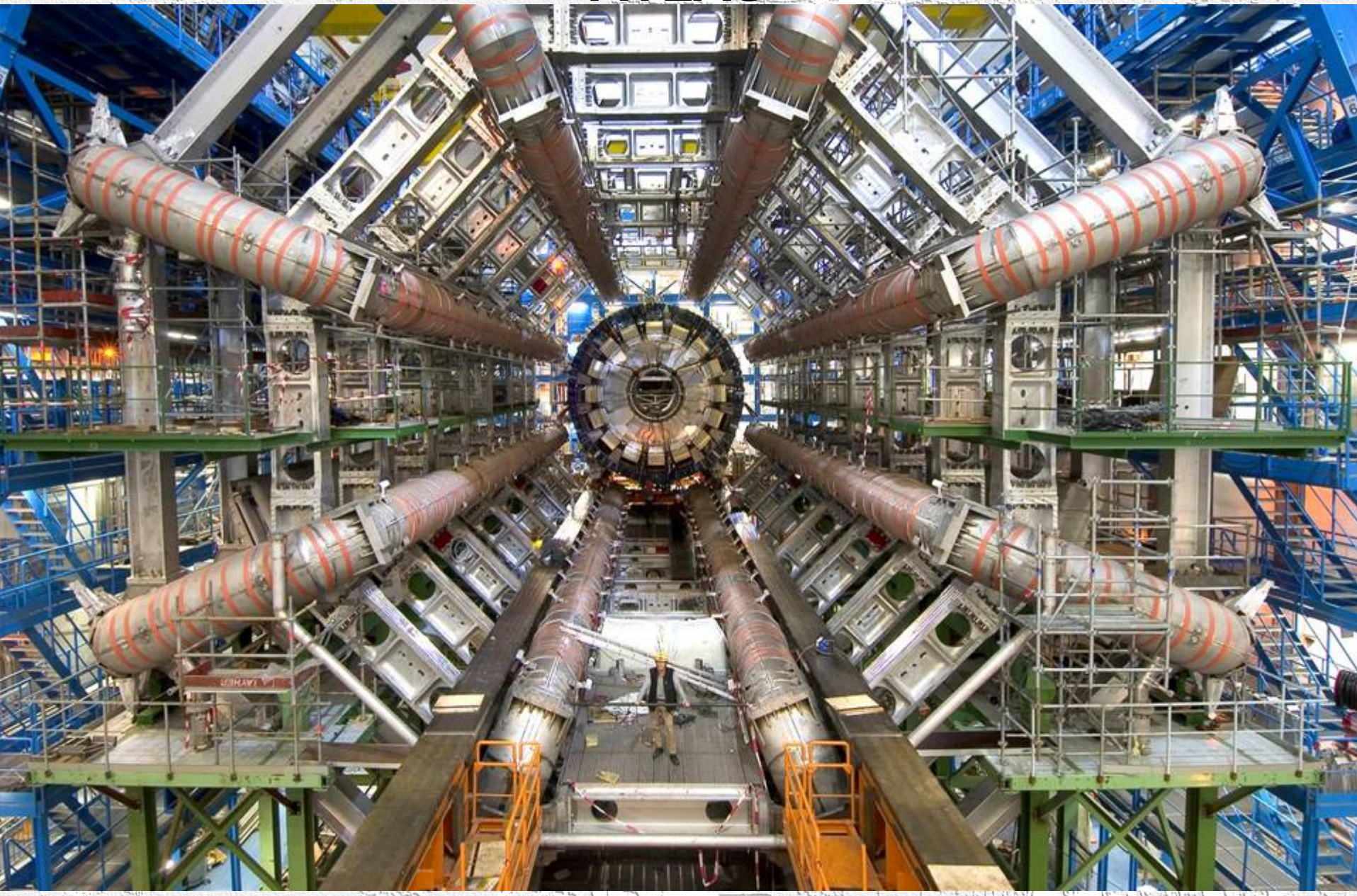
A Toroidal LHC ApparatuS

ATLAS in a nutshell:

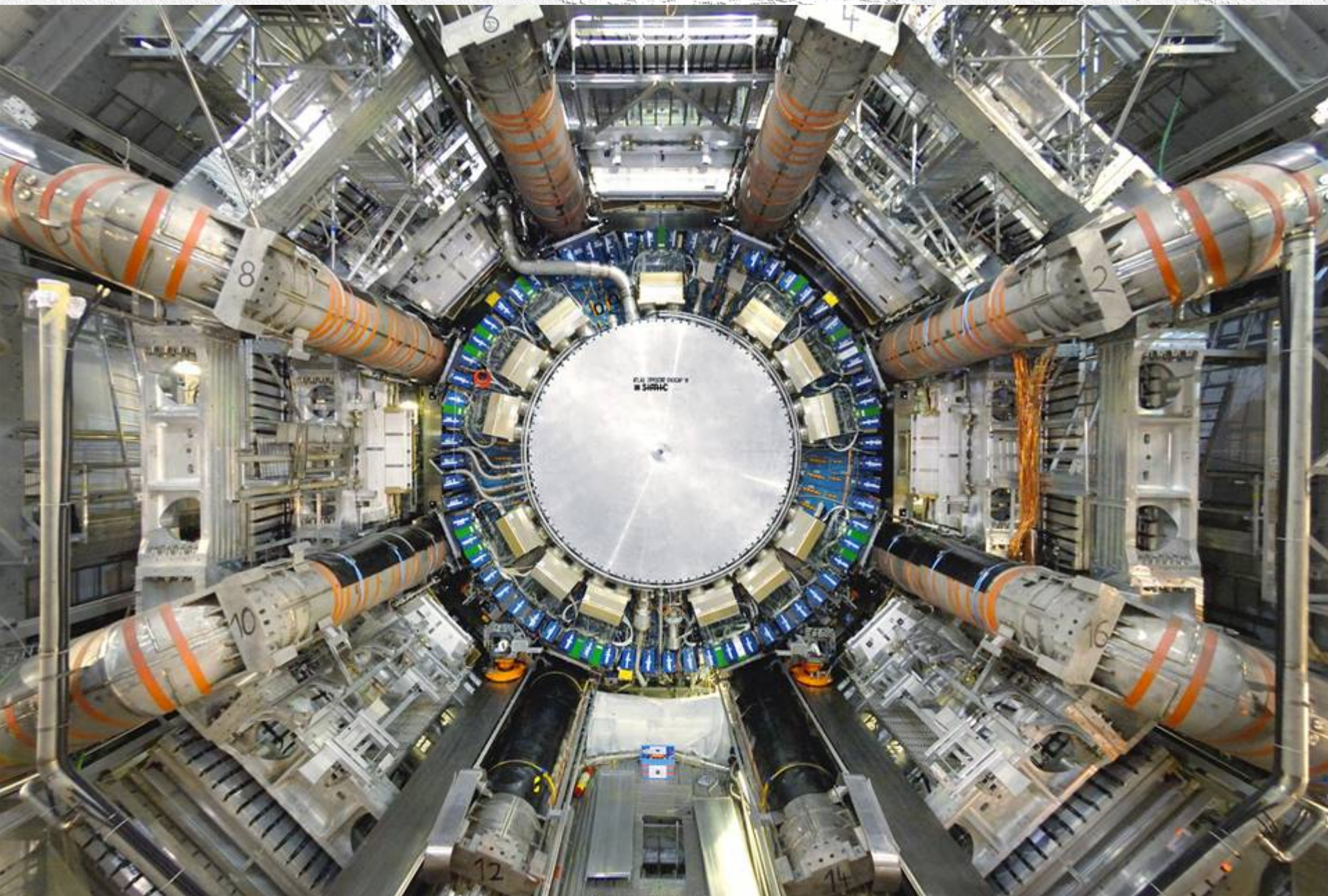
- Large air toroid with μ chambers
- HCAL: steel & scintillator tiles
- ECAL: LAr
- Inner solenoid (2 T)
- Tracker: Si-strips & straw tubes (TRD)
- Si-pixel detector
  10^8 channels
  15 μm resolution



ATLAS



ATLAS with inner Detectors

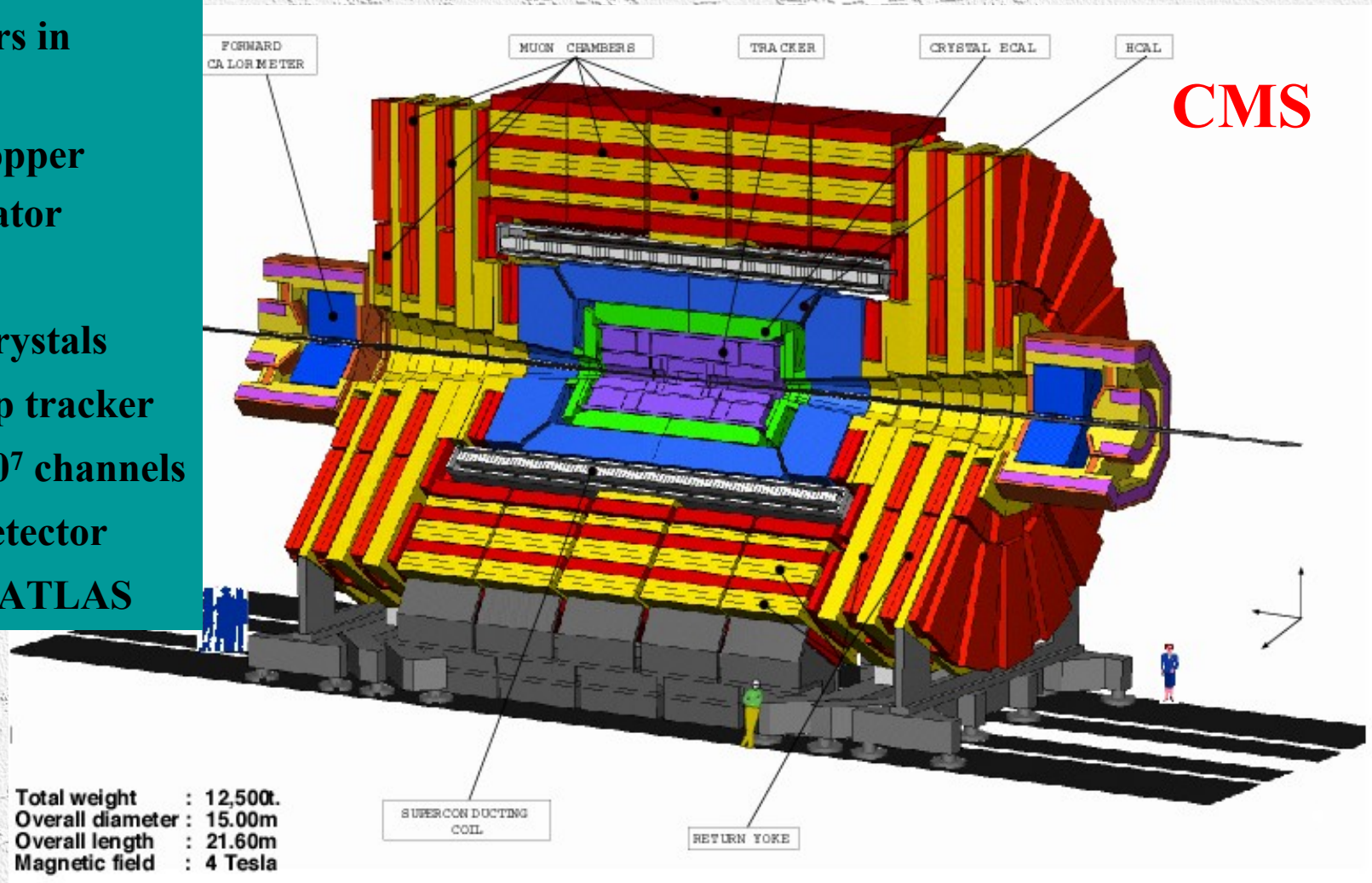


The CMS Experiment

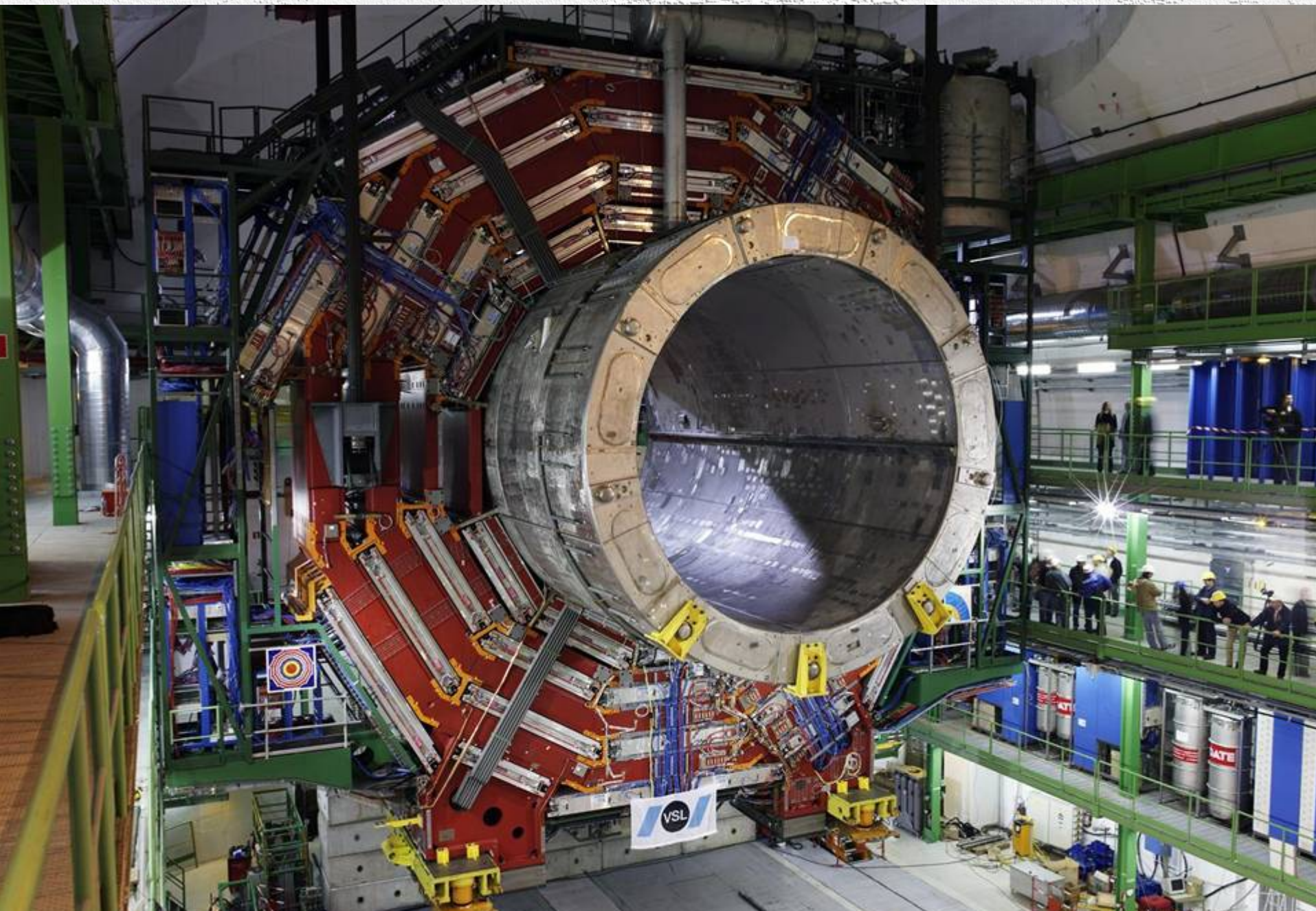
Compact Muon Solenoid

CMS in a nutshell:

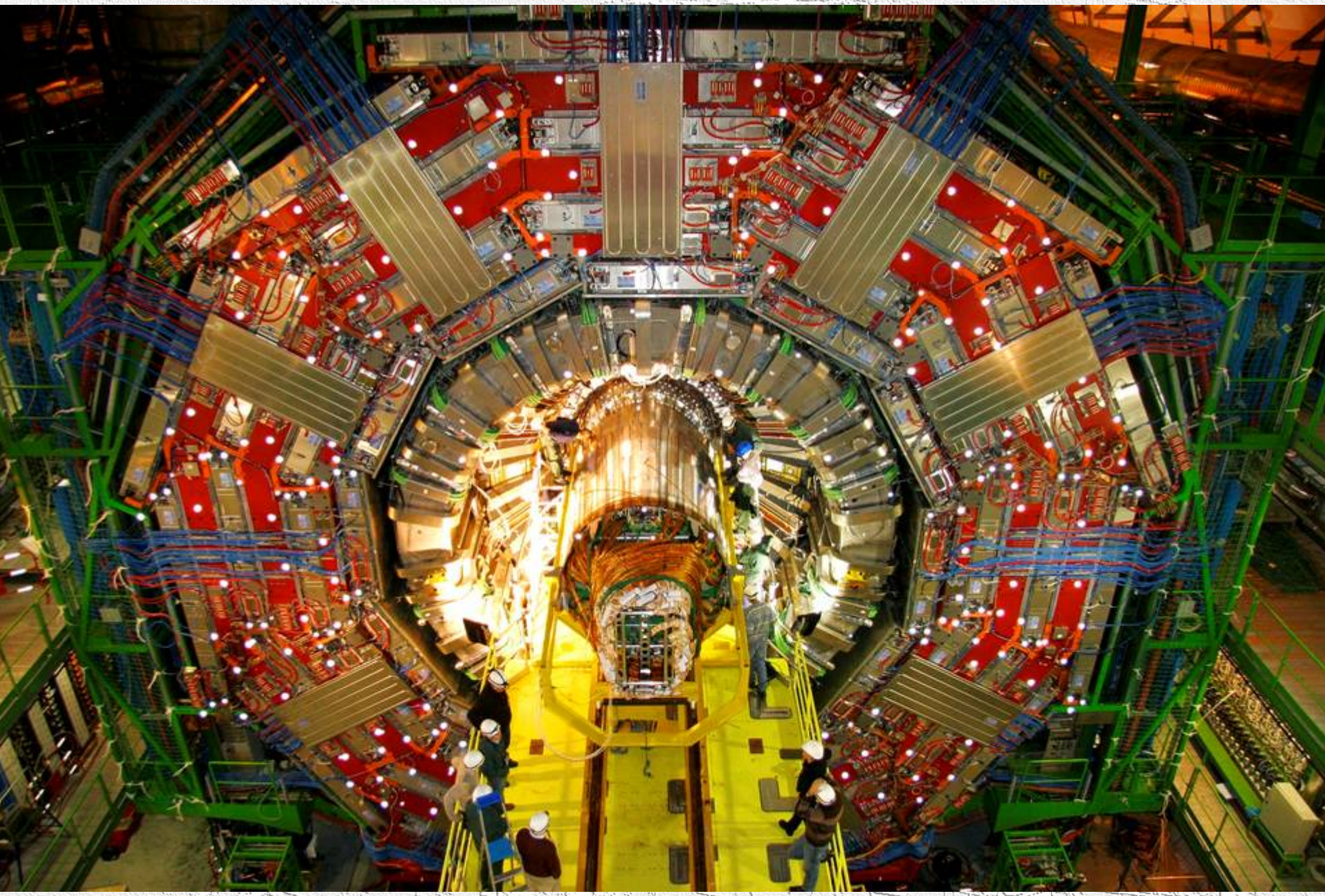
- 4 T solenoid
- μ chambers in iron yoke
- HCAL: copper & scintillator
- ECAL: $PbWO_4$ crystals
- All Si-strip tracker 220 m^2, 10^7 channels
- Si-pixel detector similar to ATLAS



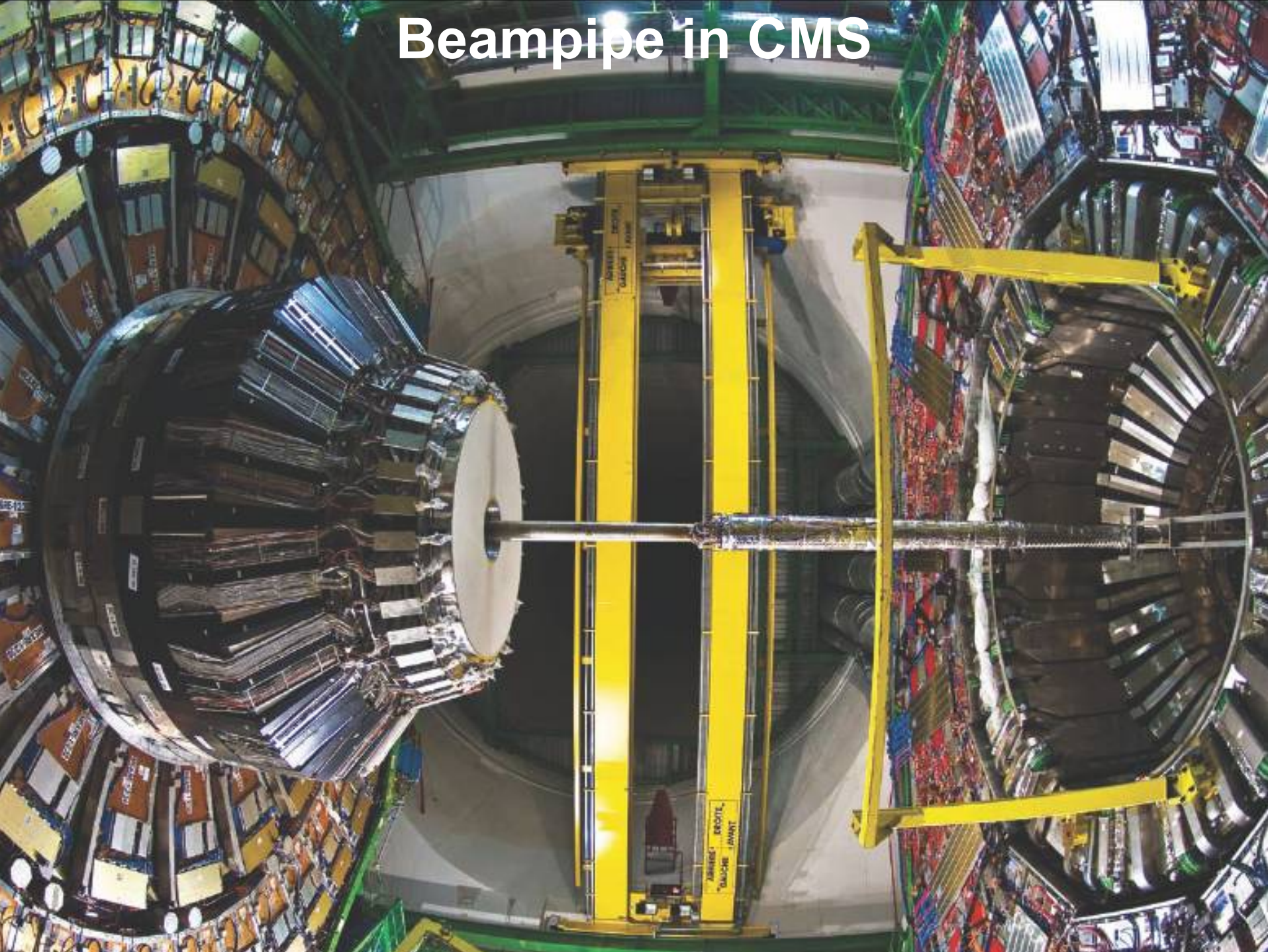
CMS: Compact Muon Solenoid



CMS



Beampipe in CMS



The Large Hadron Collider (LHC)

LHC time table:

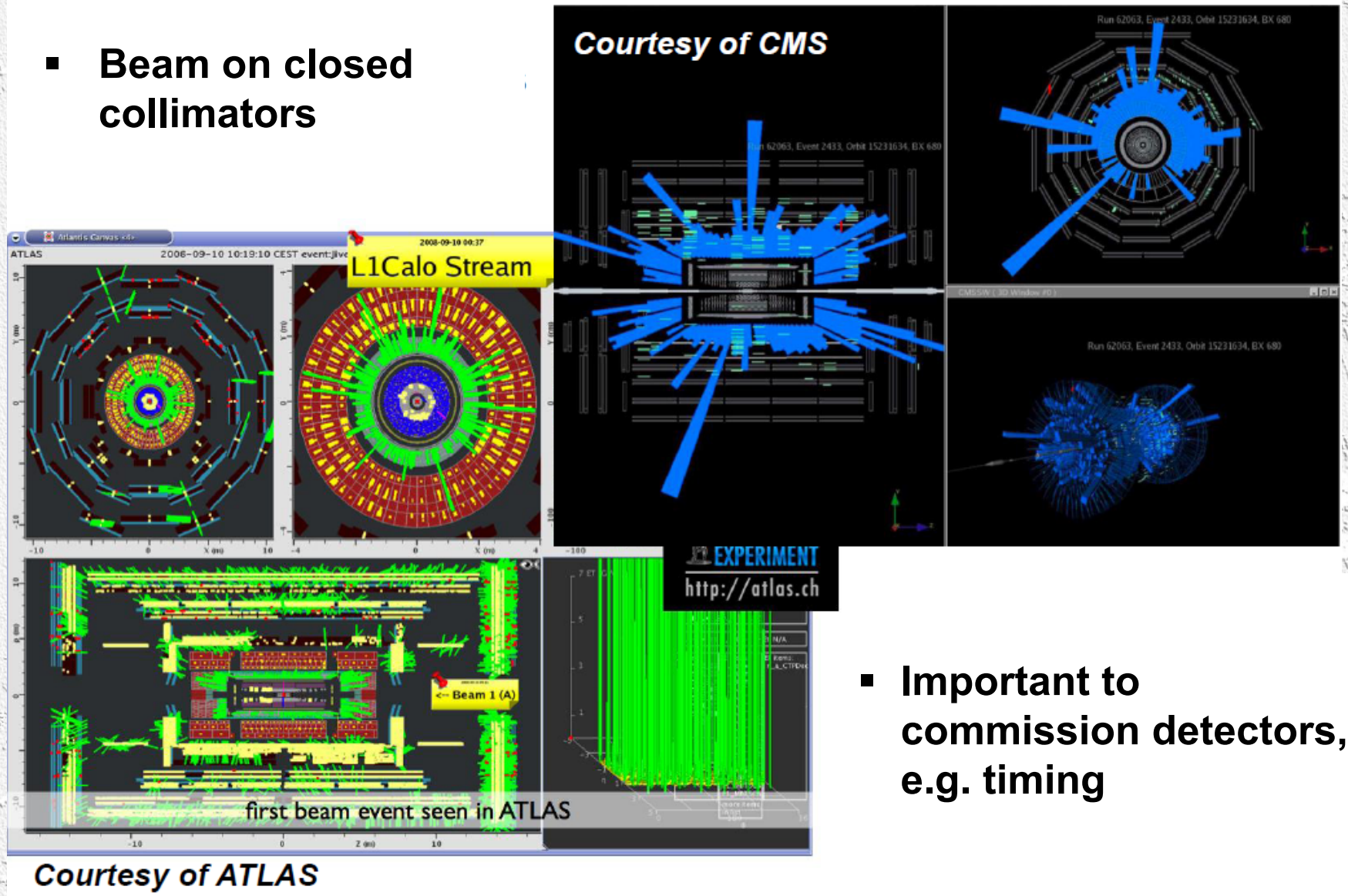
- **Early 1980‘s: first ideas about a multi-TeV proton collider at CERN**
- **Oct 1990: ECFA workshop on LHC in Aachen**
- **16 Dec 1994: CERN council approves the LHC**
- **Feb 1996: approval of ATLAS and CMS**
- **Apr 1998: start civil engineering**
- **7 Mar 2005: first dipole magnet installed**
- **26 Apr 2007: last dipole installed**
- **10 Sep 2008: first circulating beams**
- **Oct 2009: first pp-collisions**
- **Mar 2010: first collissions at 7 TeV**

First Beams & Collisions

- First circulating beams on September 10, 2008

Beam Splash Events

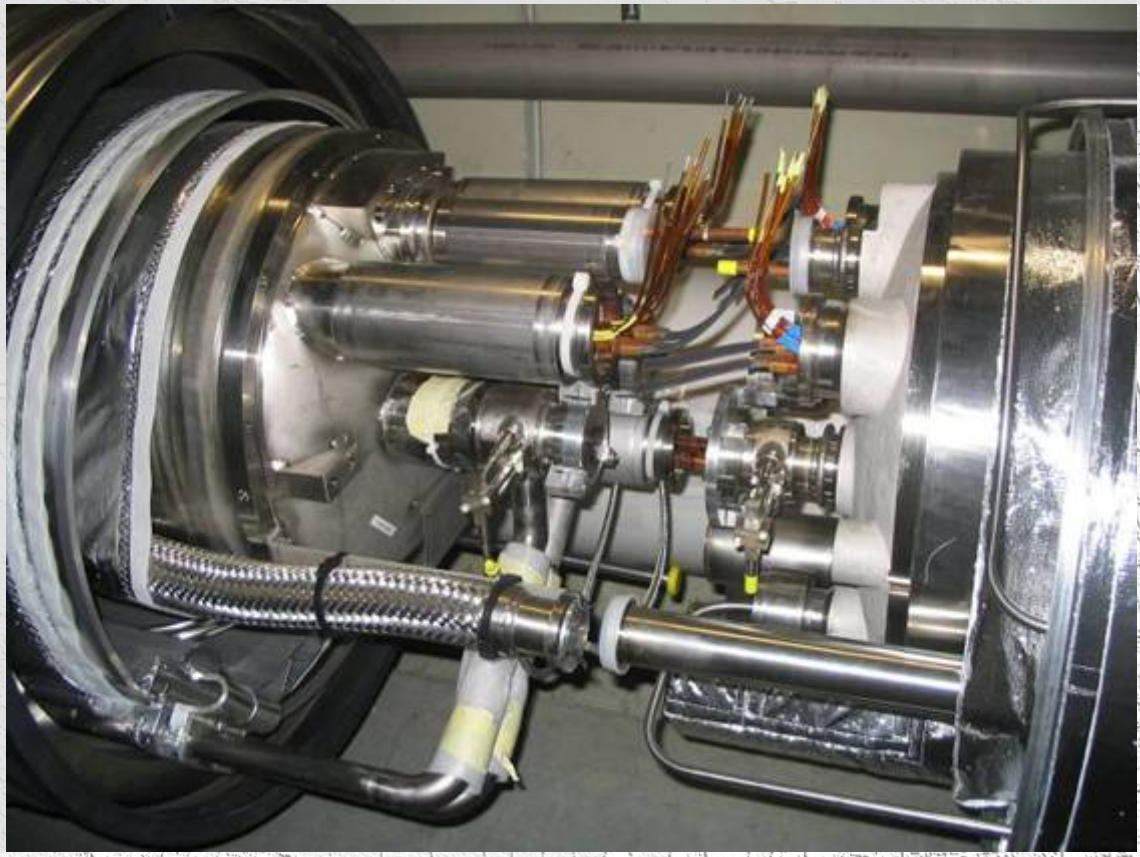
- Beam on closed collimators



- Important to commission detectors, e.g. timing

LHC Accident

- **Major accident on September 19, 2008**
  - **Bad connection between 2 magnets (resistance >> 1 nΩ)**
  - **Heat load ≈ 10 W cannot be cooled away**
  - **Thermal runaway**
- **Quench protection of magnets worked well**
- **But light arc between magnets**
  - **Destroyed a Helium vessel**
  - **2 tons of He effused**
  - **Shock wave in tunnel**

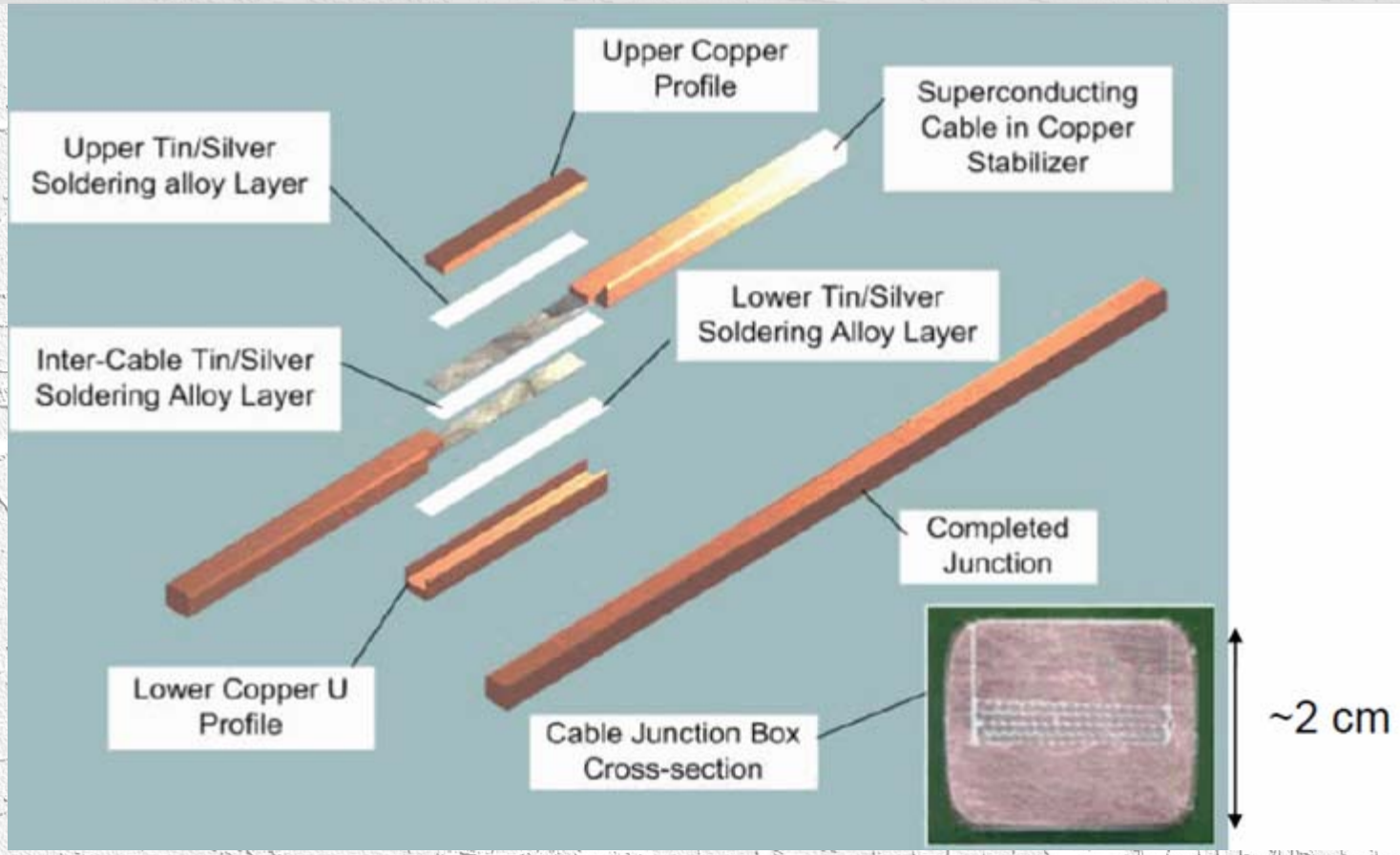


Damage

53 magnets inspected, repaired & reinstalled

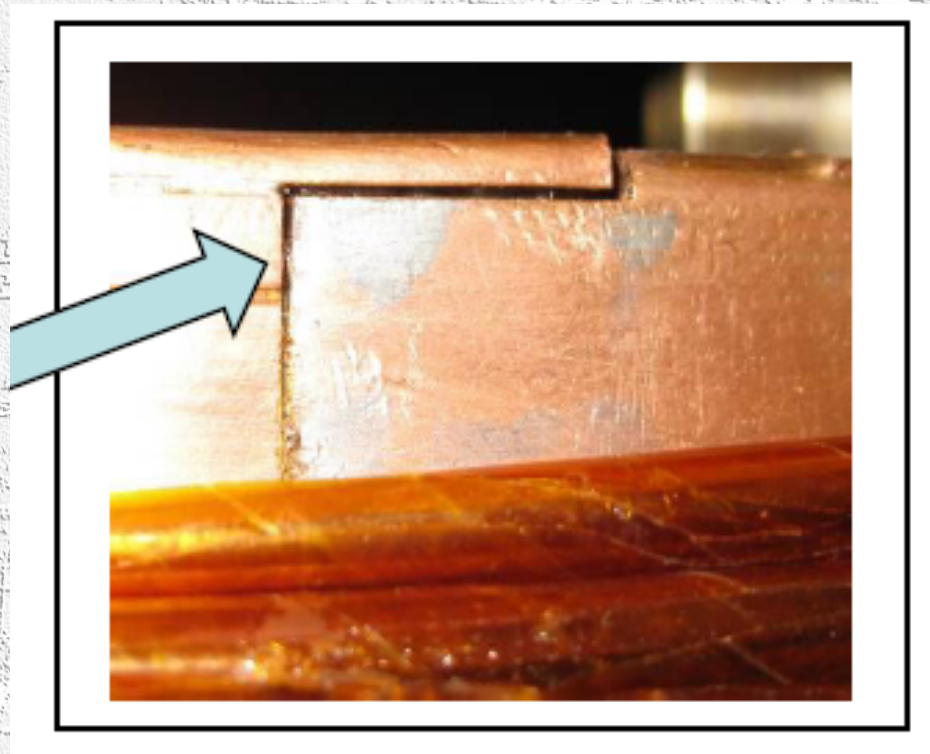
Magnet Joints

- **Superconducting cable embedded in copper stabilizer**
  - **SC resistance ≈ 0.35 nΩ (spec: < 1 nΩ)**
  - **Stabilizer O(μΩ)**



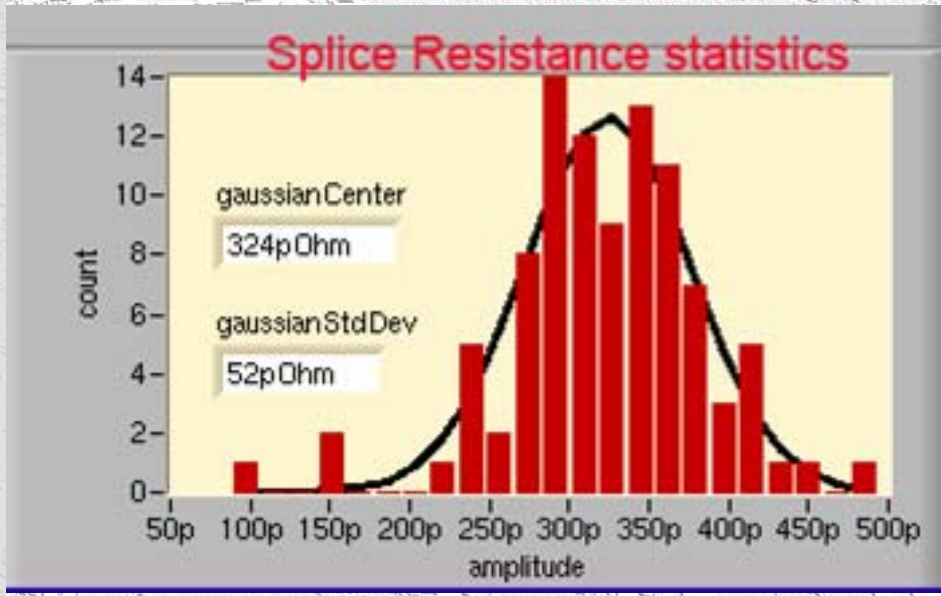
Magnet Joints

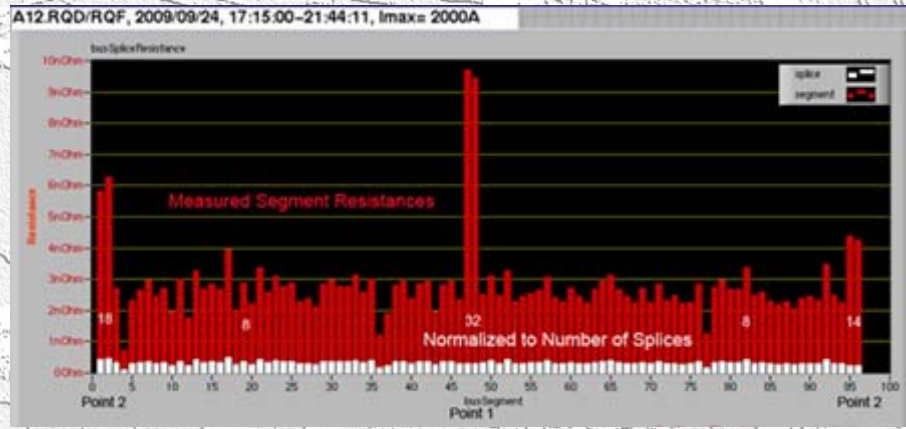
- Evidence for incident destroyed
- But optical inspection showed problems with several joints



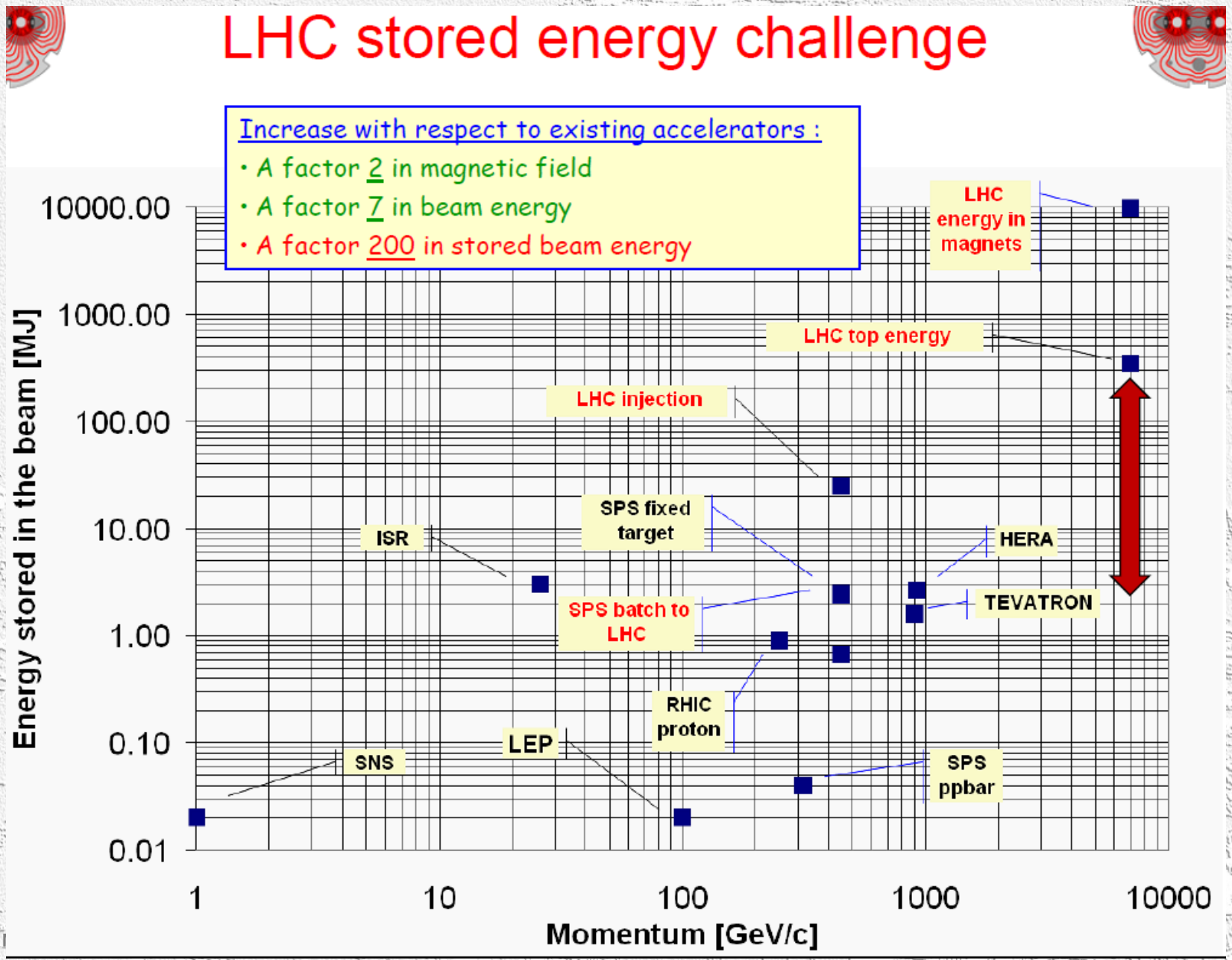
2009: Repair & Improvements

- **Machine repaired**
  - 53 magnets repaired and replaced
  - Cleaning of beam pipe
- **Major improvements of the machine protection system**
  - e.g. magnet interconnections
  - sensitivity ≈ 300 pΩ per splice (factor 1000 improvement)
- **Problem of copper stabilizers**
  - Difficult to measure
  - Several non-conform joint seen
- **Decision:**
  - Redo all joints (clamping) takes time!
  - Run LHC at save energy (3.5 TeV) until then





LHC Stored Energy

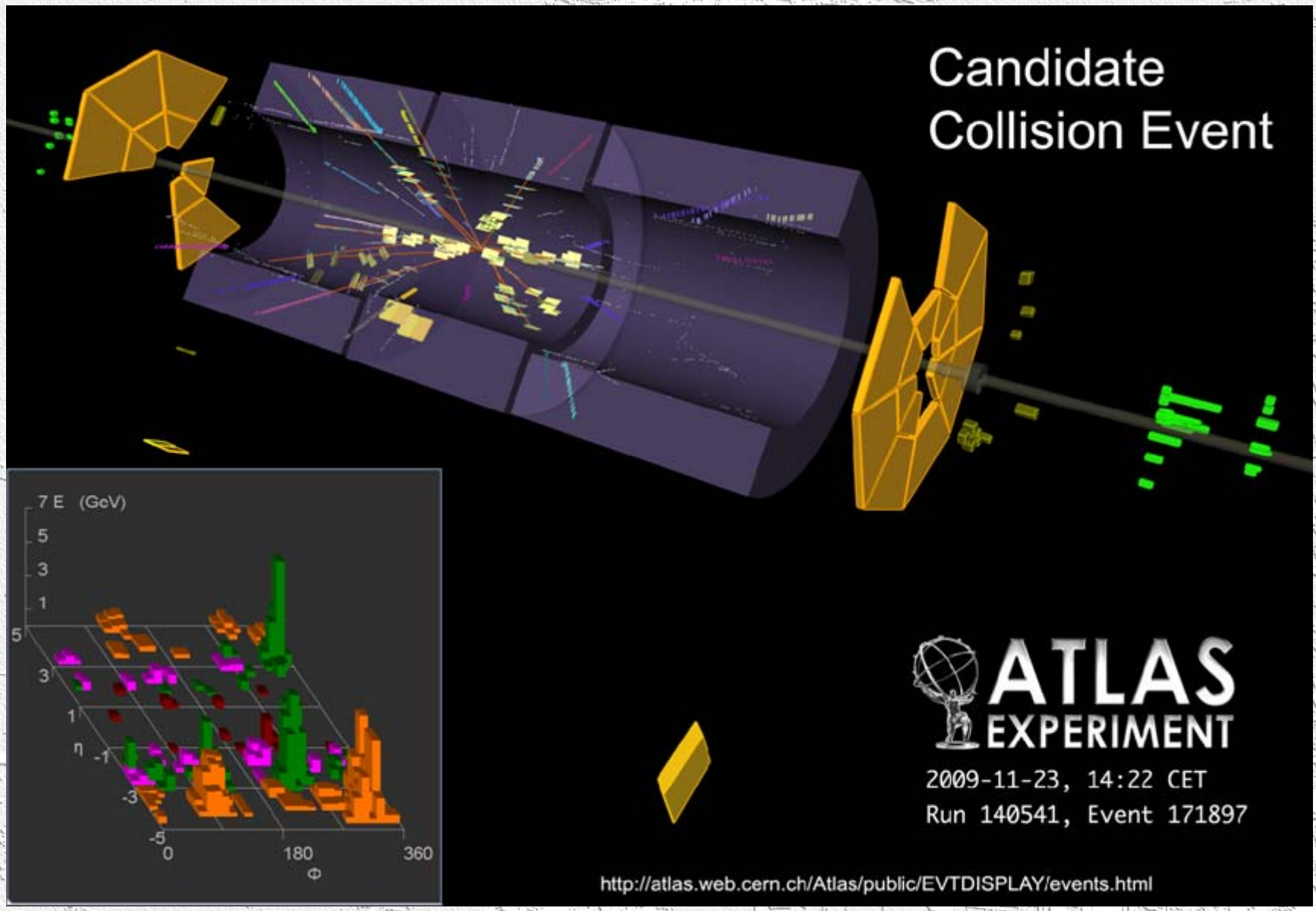


LHC Stored Energy

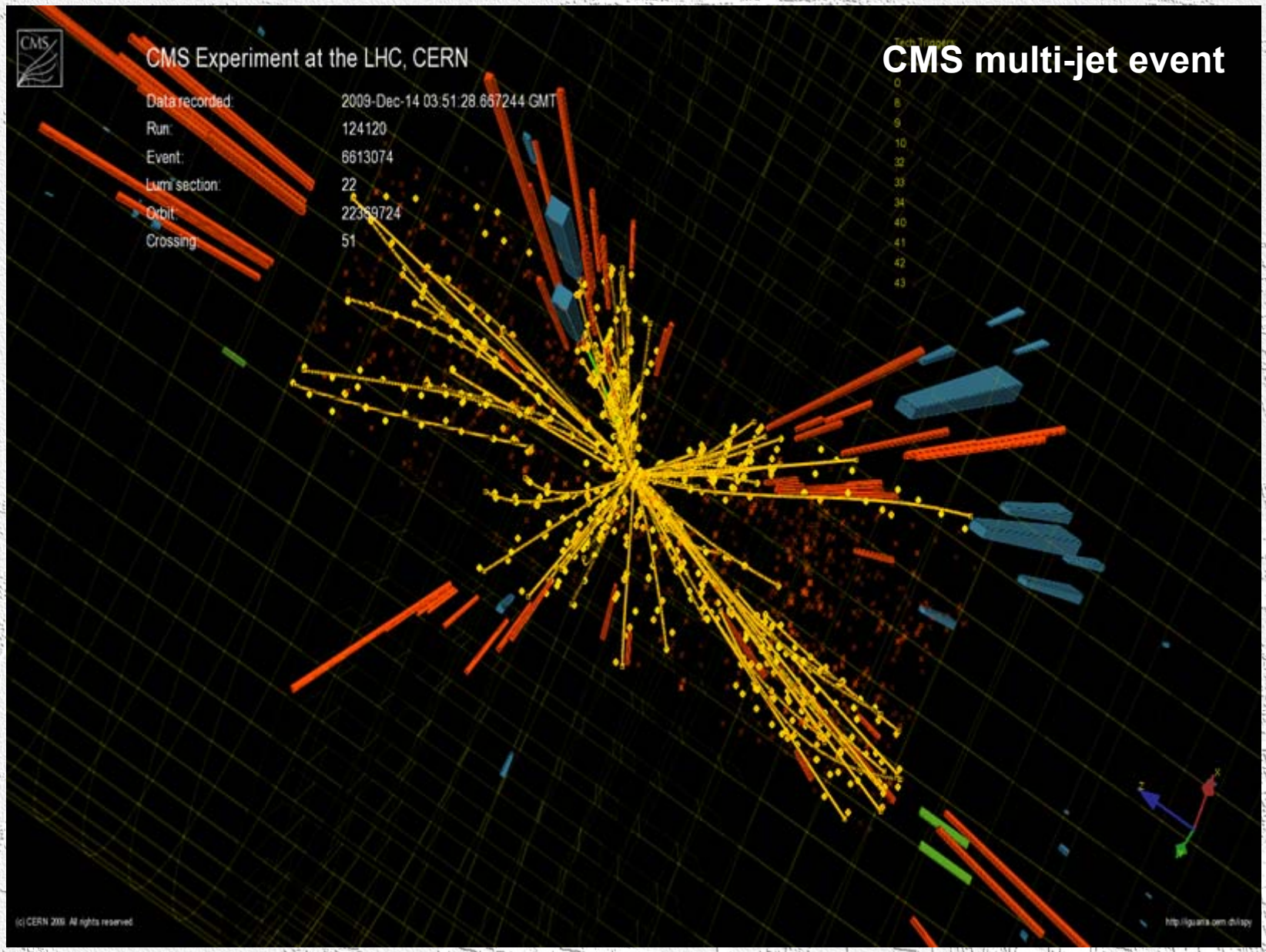
- 350 MJ energy stored in beams (nominal conditions)
- Corresponds to 90 kg TNT

- For illustration:
  - Few cm groove in SPS vacuum chamber
  - Corresponds to ≈ 1% nominal LHC beam
  - 3 days repair
  - Same incident at LHC would cause 3 months shutdown!

23 November 2009: First Collisions at 900 GeV



First Collisions at 900 GeV

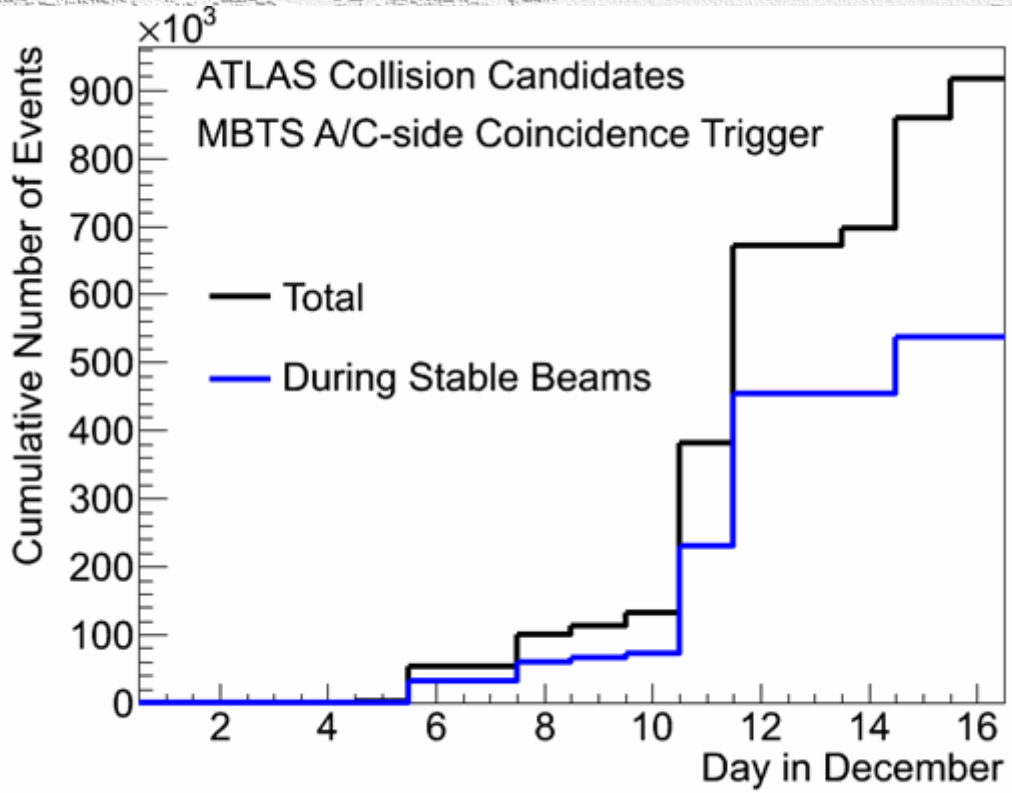


2009 Data

- **Integrated luminosity in 2009 (ATLAS)**
  - **20/μb delivered**
  - **12/μb recorded**
- **≈ 30% error on these numbers**
- **Number of collision candidates:**

  917.000

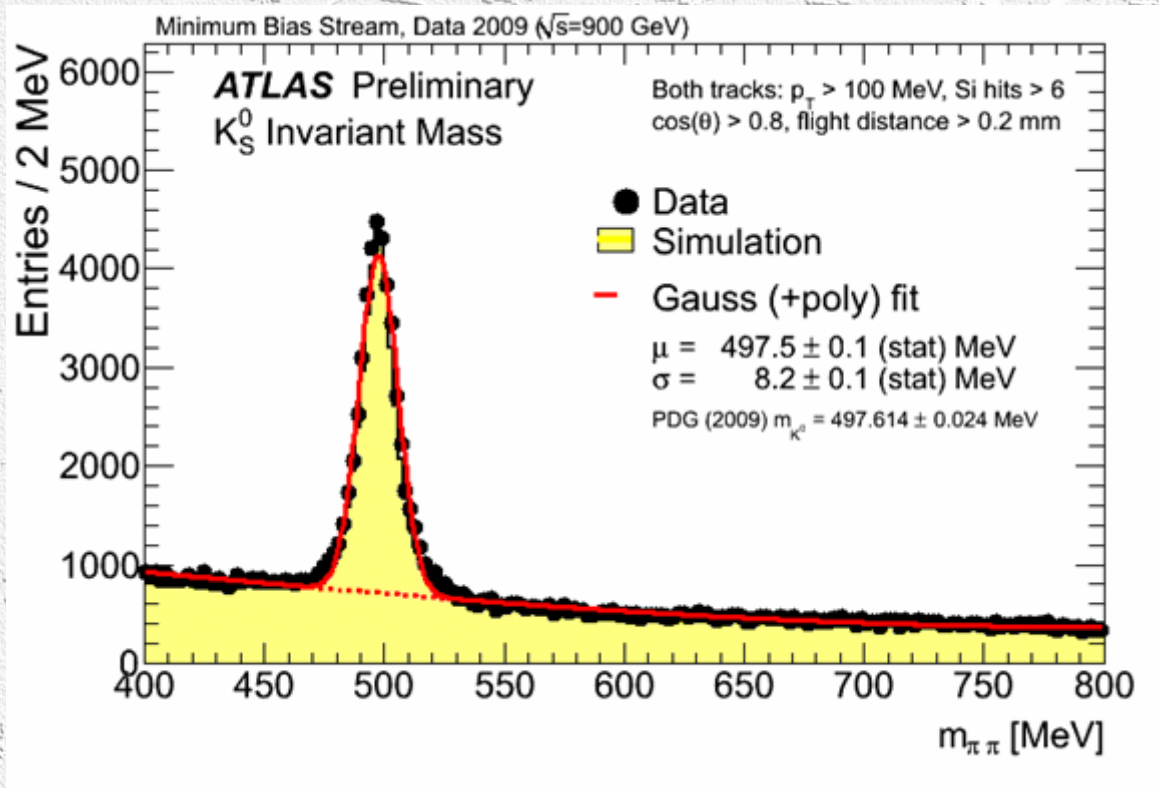
  (34.000 at 2.36 TeV)

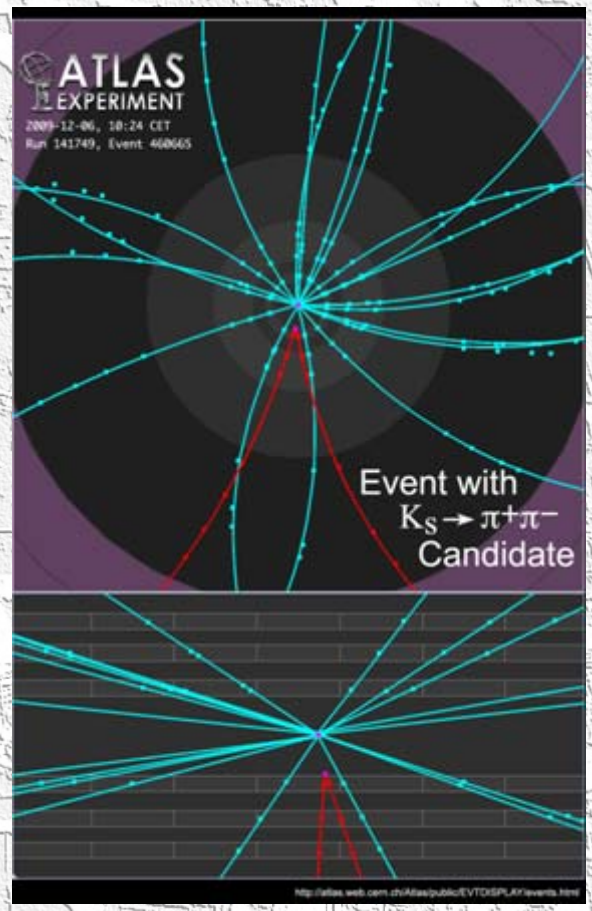


Detector Performance

- 900 GeV data are very important to check and improve the performance of the detectors
- Below a few examples

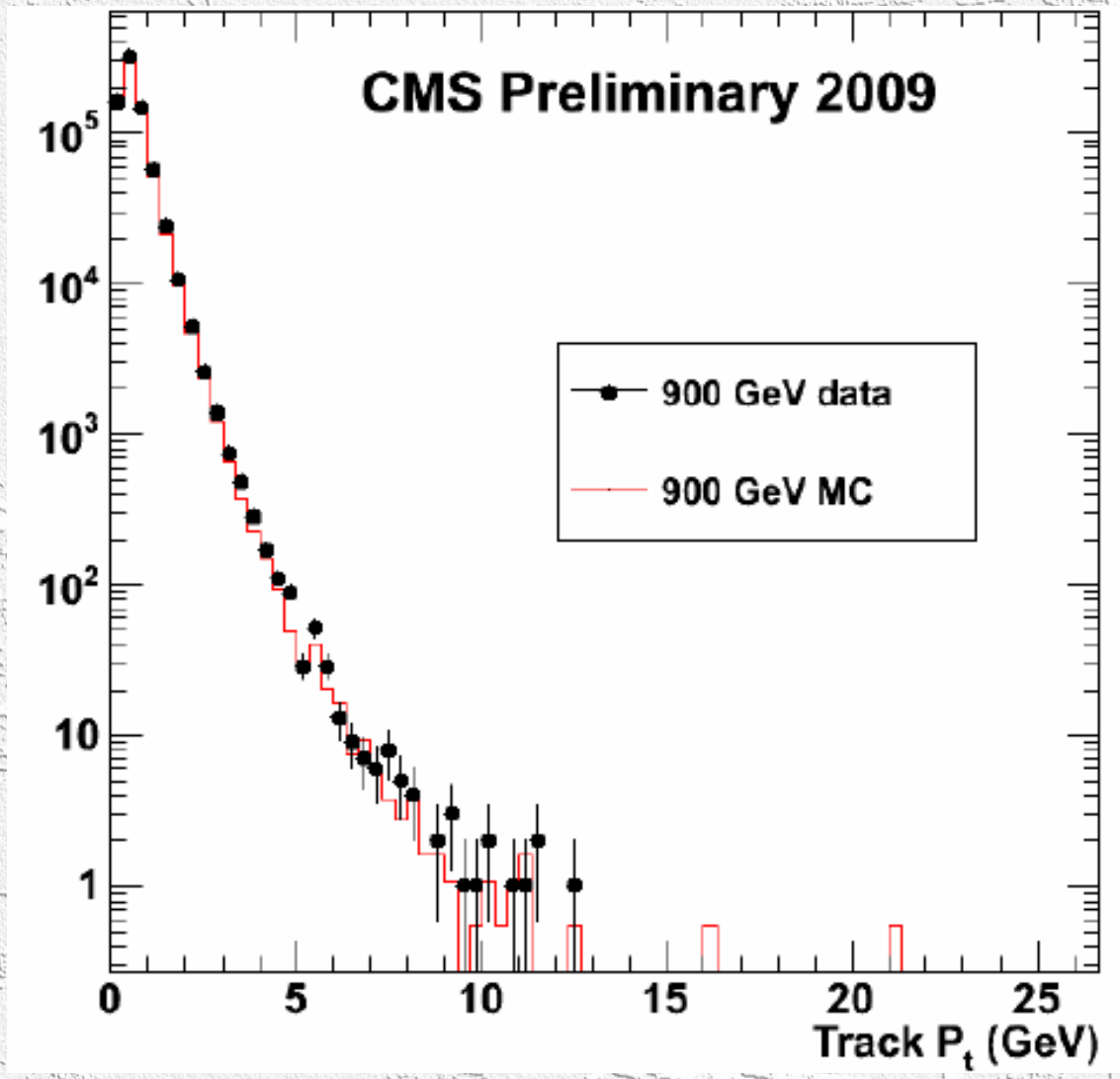
- Tracking: $K_s \rightarrow \pi^+\pi^-$





Tracking

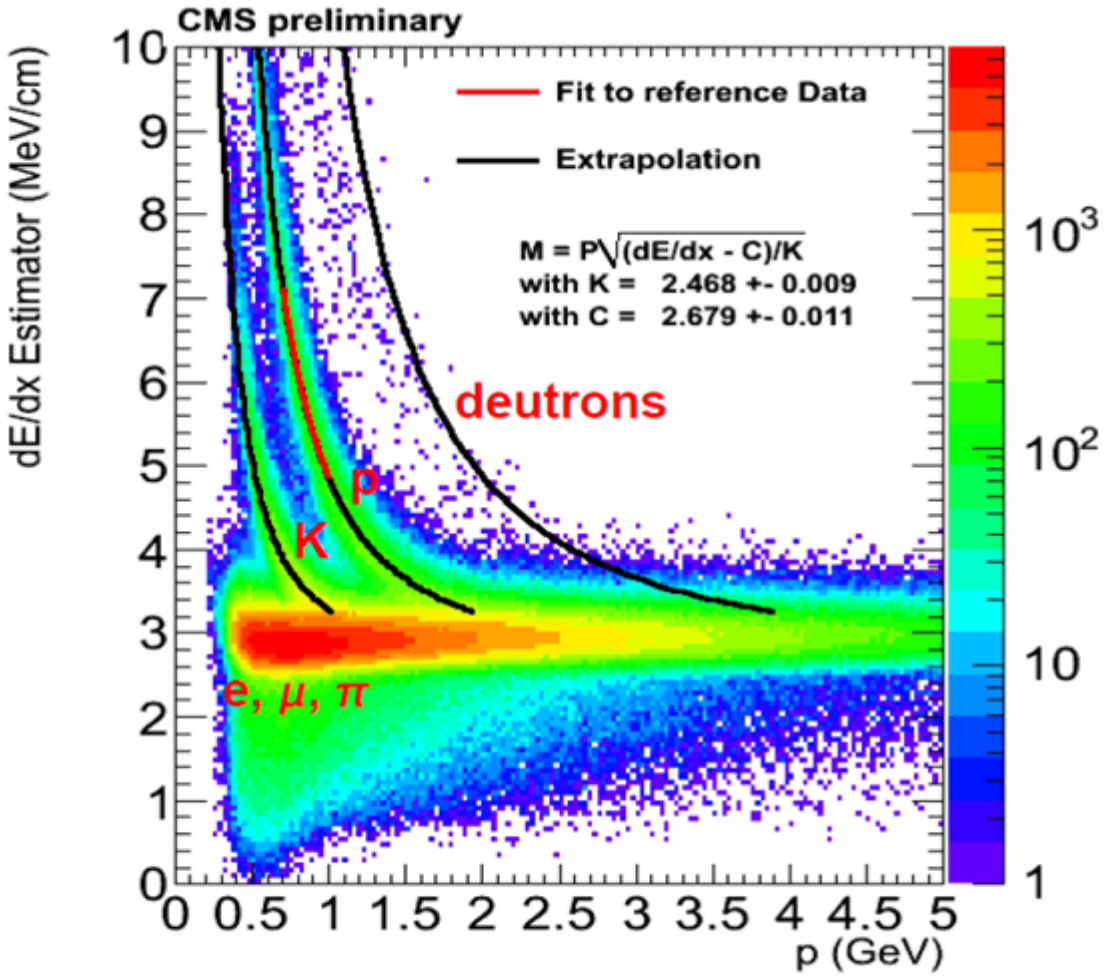
- Charged particle spectrum

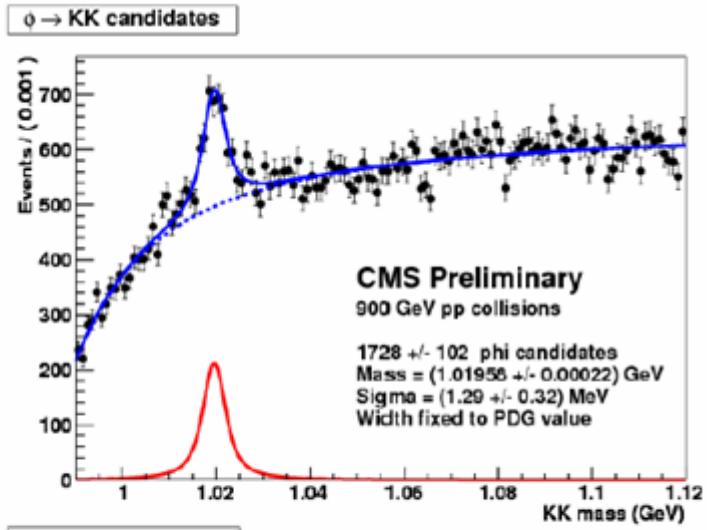


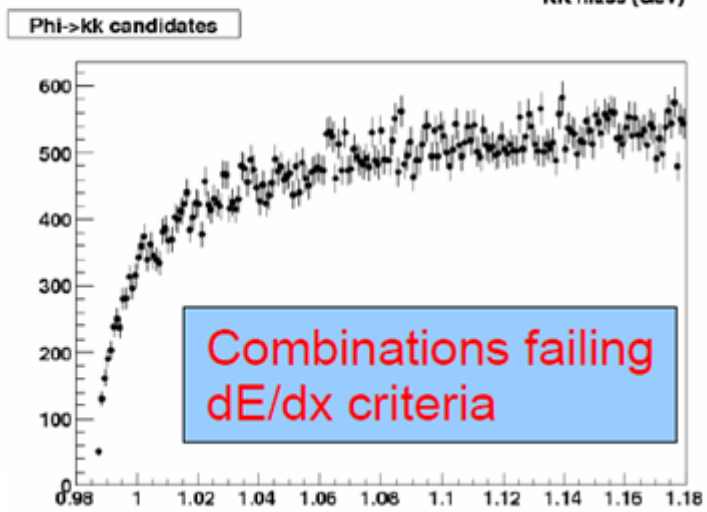
- Agreement to 5 orders in magnitude in rate!

Tracking & dE/dx

- **CMS Φ → KK**

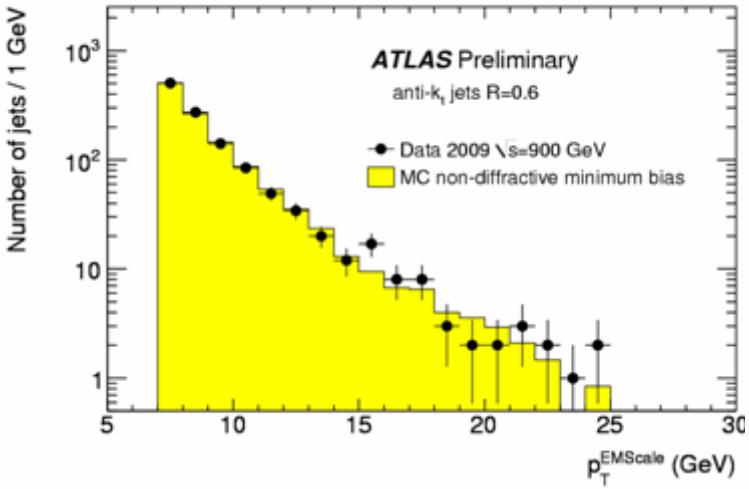


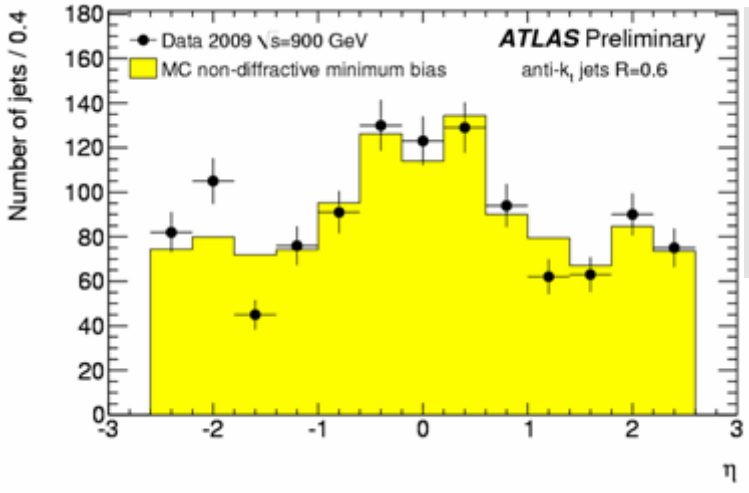




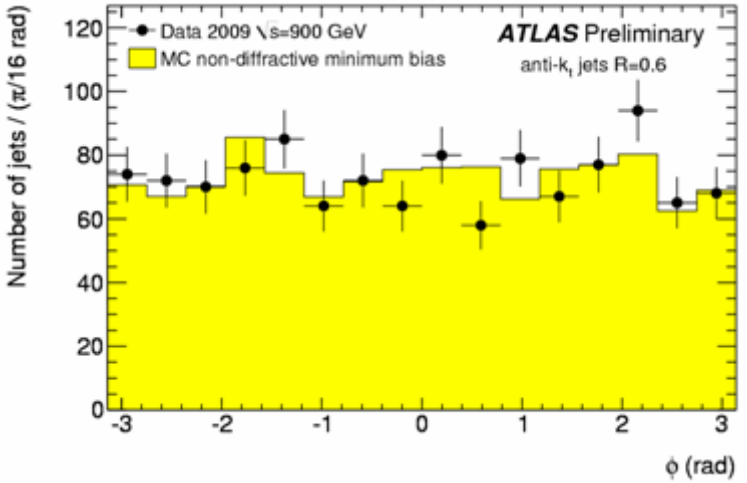
Jet Studies

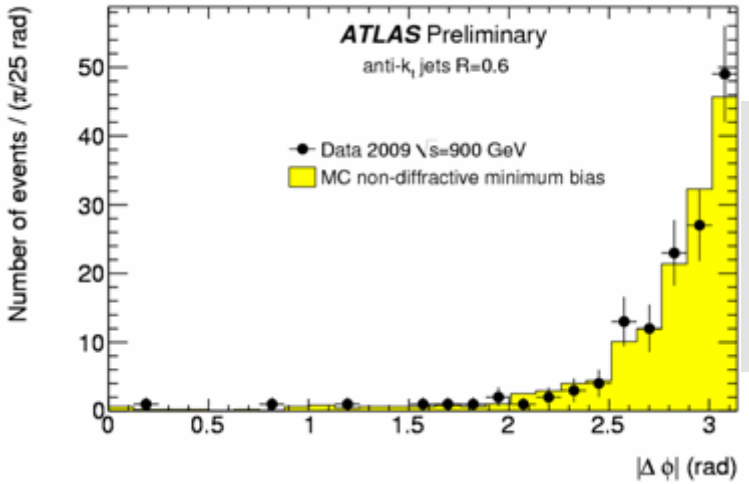
- **Good agreement with Monte Carlo expectations**





- **Anti-kt algorithm with**
  - **D=0.4**
  - **ET>7 GeV**

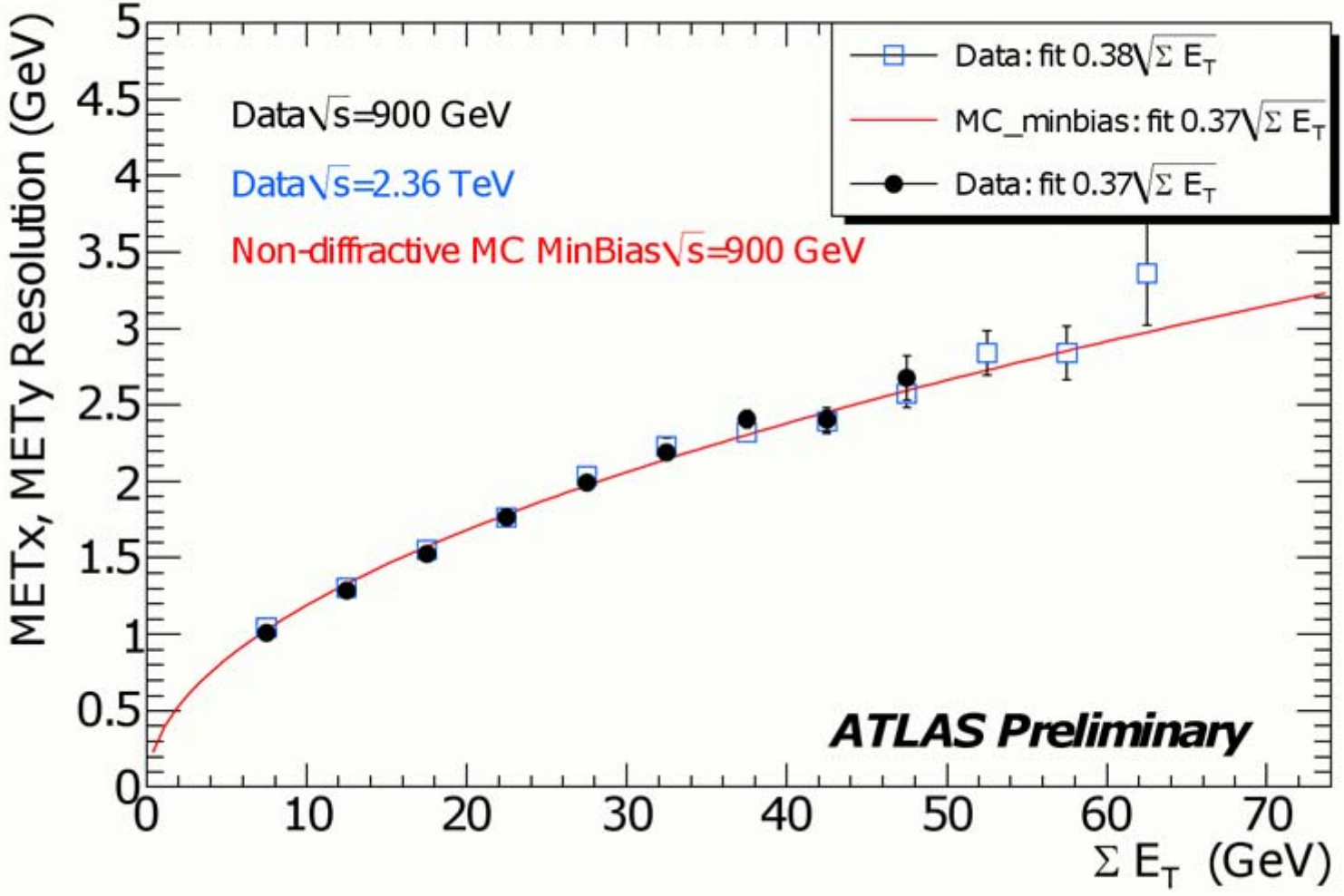




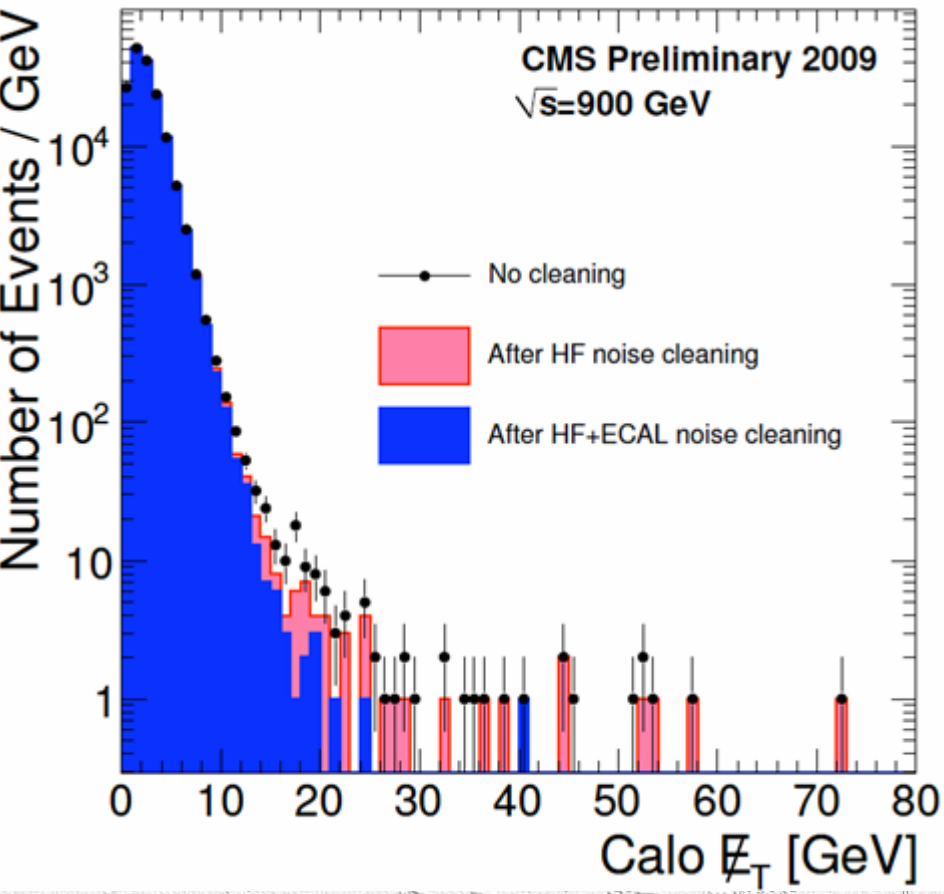
- **ΔR between the two jets (back-to-back)**

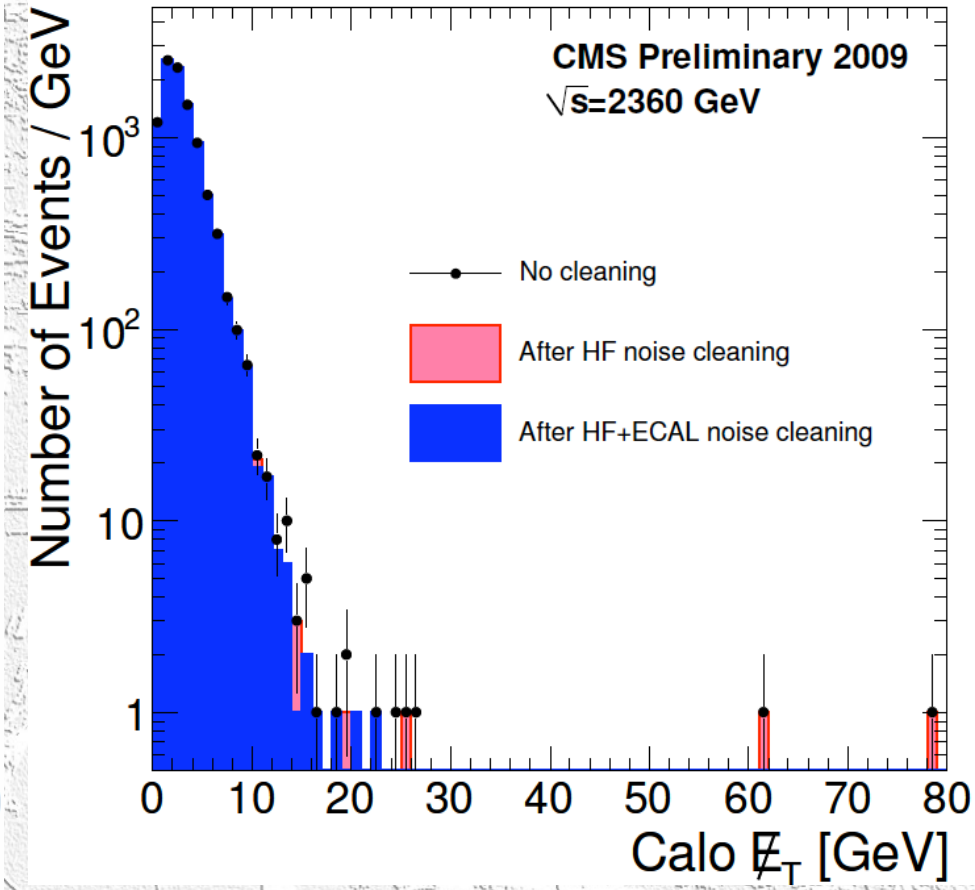
Missing Transverse Energy

$\not\!\!E_T$ resolution vs. $\sum \not\!\!E_T$



Missing Transverse Energy

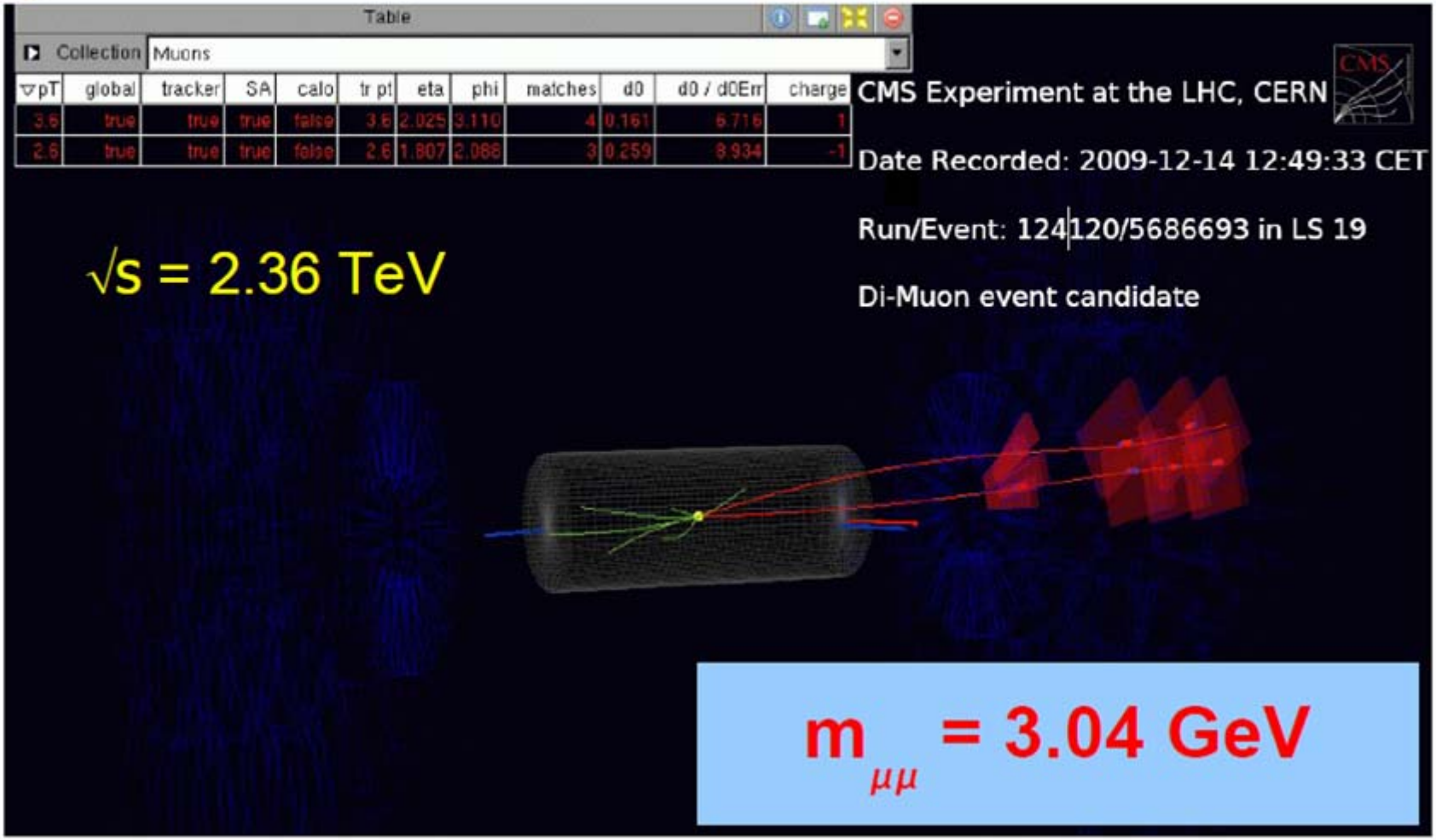




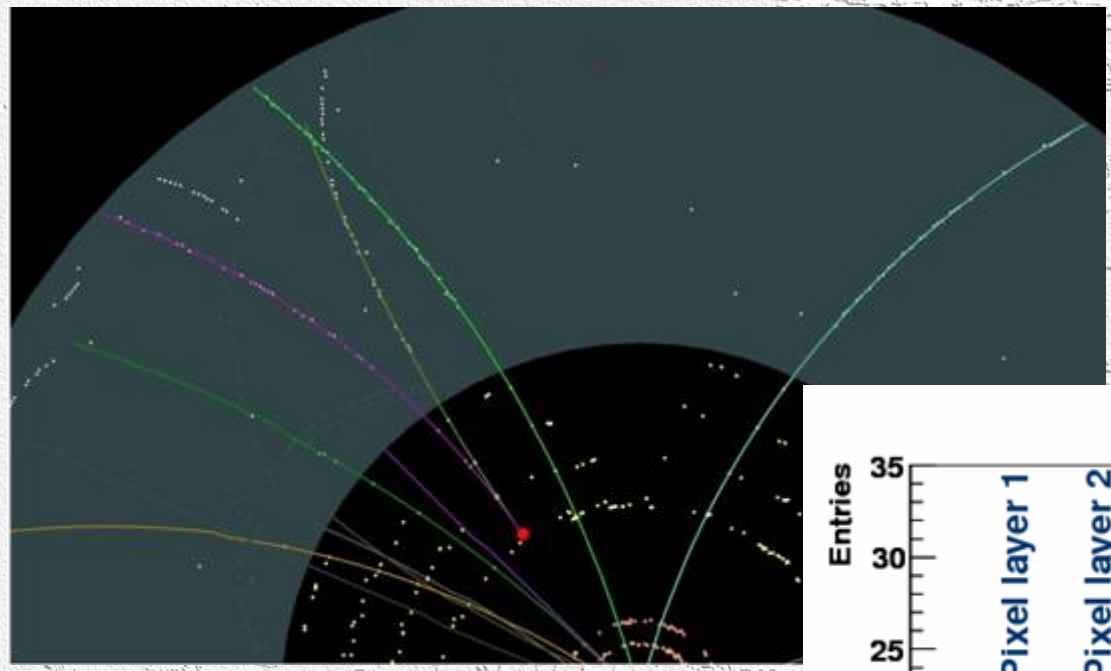
- Good understanding of missing E_T
- Subtle detector effects understood

Muons

$J/\Psi \rightarrow \mu^+\mu^-$ Candidate

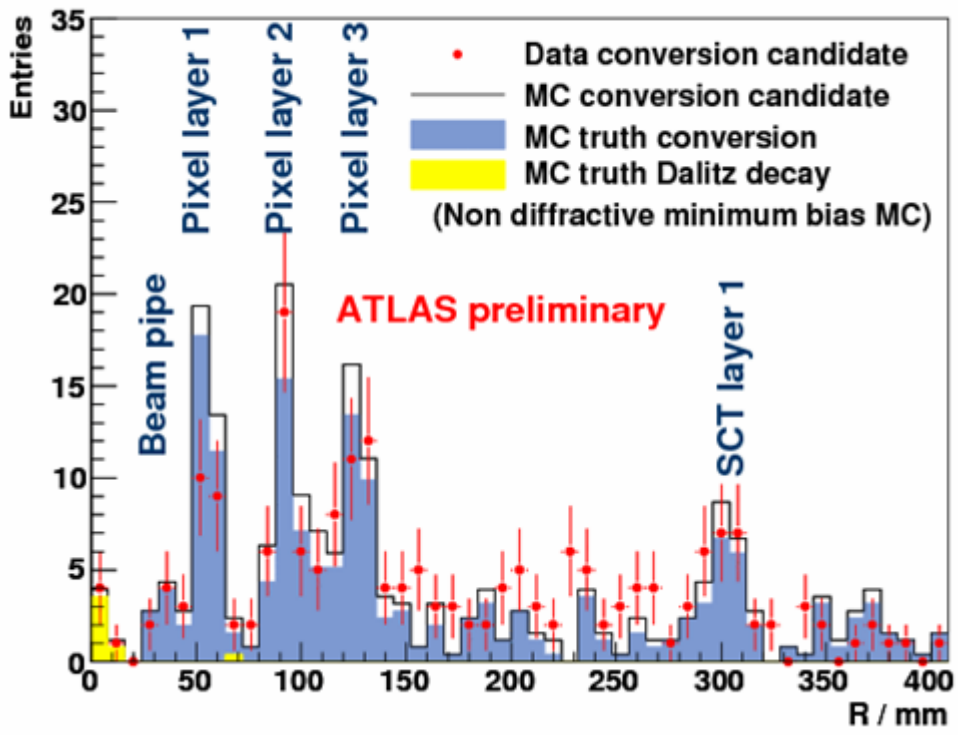


Photon Reconstruction

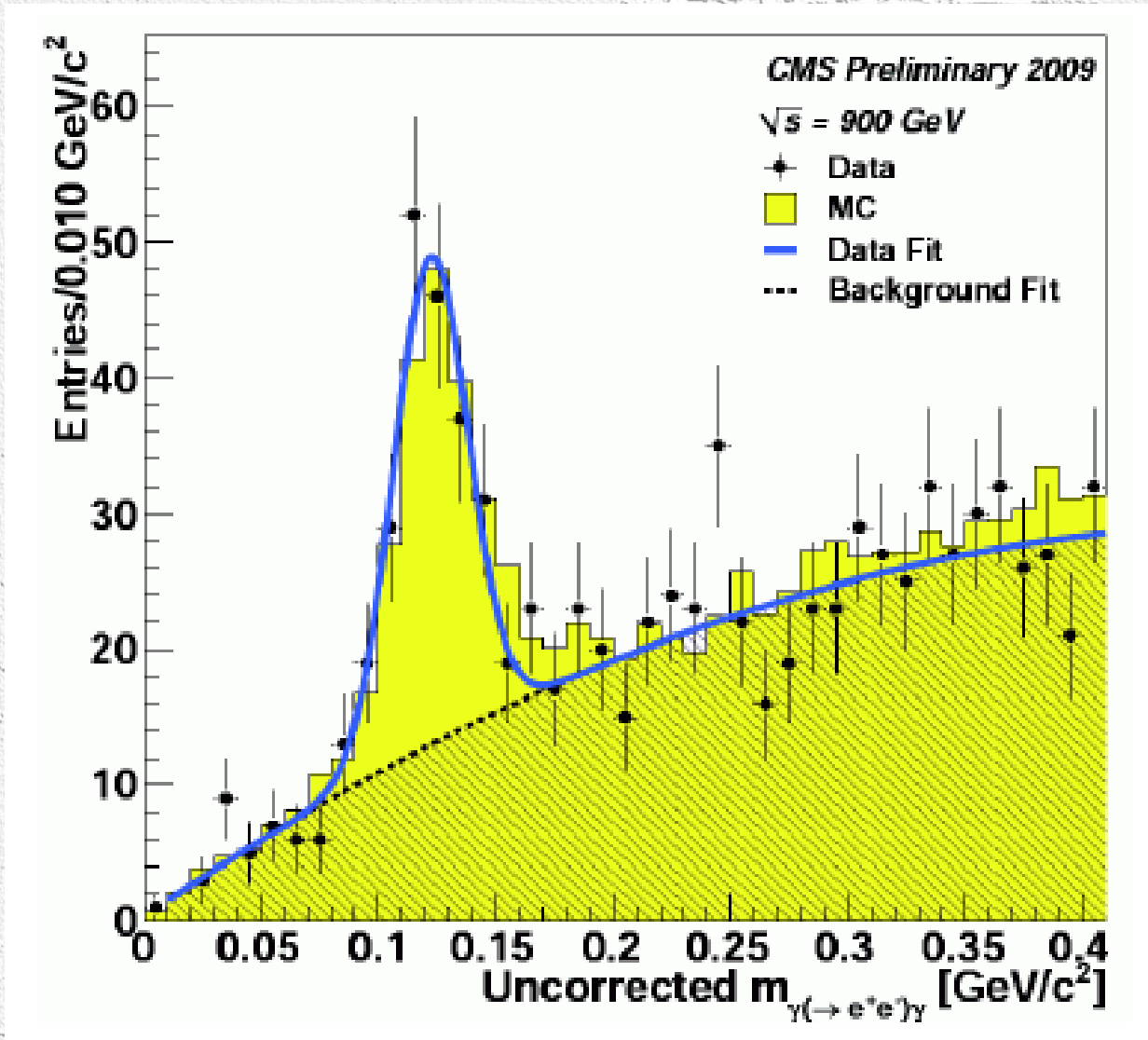


- Photon conversion in ATLAS pixel detector

- Mapping of detector material



π^0 Reconstruction



Including converted photons

First Physics Papers

JHEP

Published for SISSA by Springer

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

CMS Collaboration

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

Keywords: Hadron-Hadron Scattering

ArXiv ePrint: 1002.0621

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP/2010-004
March 15, 2010

Charged-particle multiplicities in pp interactions at $\sqrt{s} = 900$ GeV measured with the ATLAS detector at the LHC

The ATLAS Collaboration

Abstract

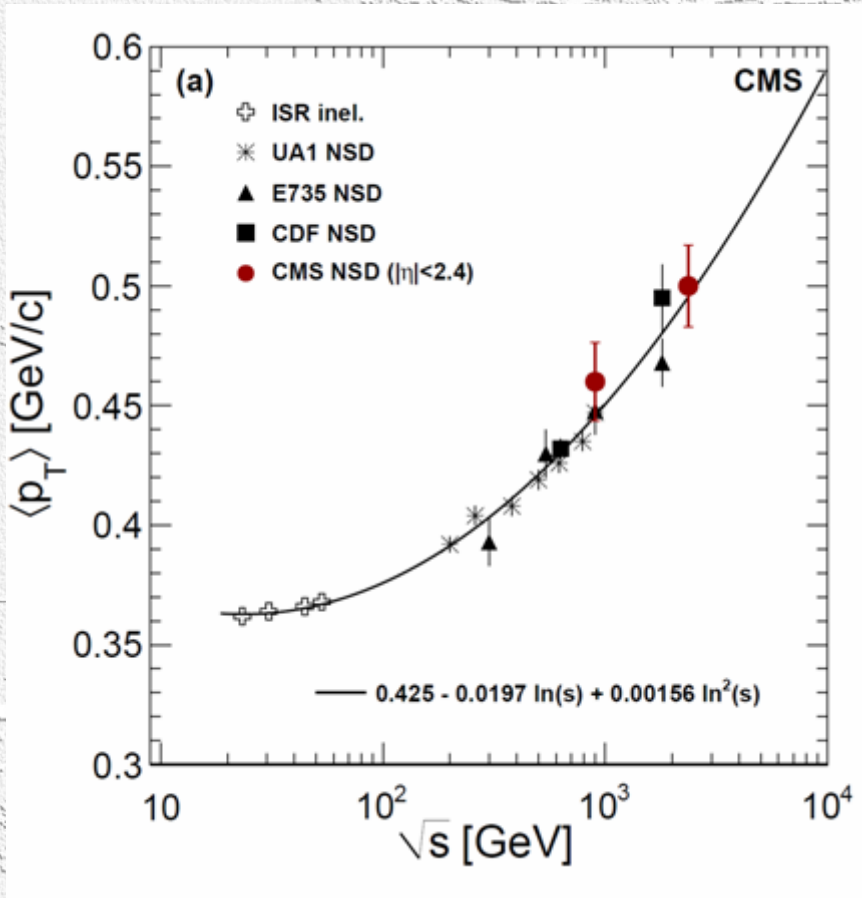
The first measurements from proton-proton collisions recorded with the ATLAS detector at the LHC are presented. Data were collected in December 2009 using a minimum-bias trigger during collisions at a centre-of-mass energy of 900 GeV. The charged-particle multiplicity, its dependence on transverse momentum and pseudorapidity, and the relationship between mean transverse momentum and charged-particle multiplicity are measured for events with at least one charged particle in the kinematic range $|\eta| < 2.5$ and $p_{\rm T} > 500$ MeV. The measurements are compared to Monte Carlo models of proton-proton collisions and to results from other experiments at the same centre-of-mass energy. The charged-particle multiplicity per event and unit of pseudorapidity at $\eta = 0$ is measured to be 1.333 ± 0.003 (stat.) ± 0.040 (syst.), which is 5–15% higher than the Monte Carlo models predict.

Preprint submitted to Phys. Lett. B

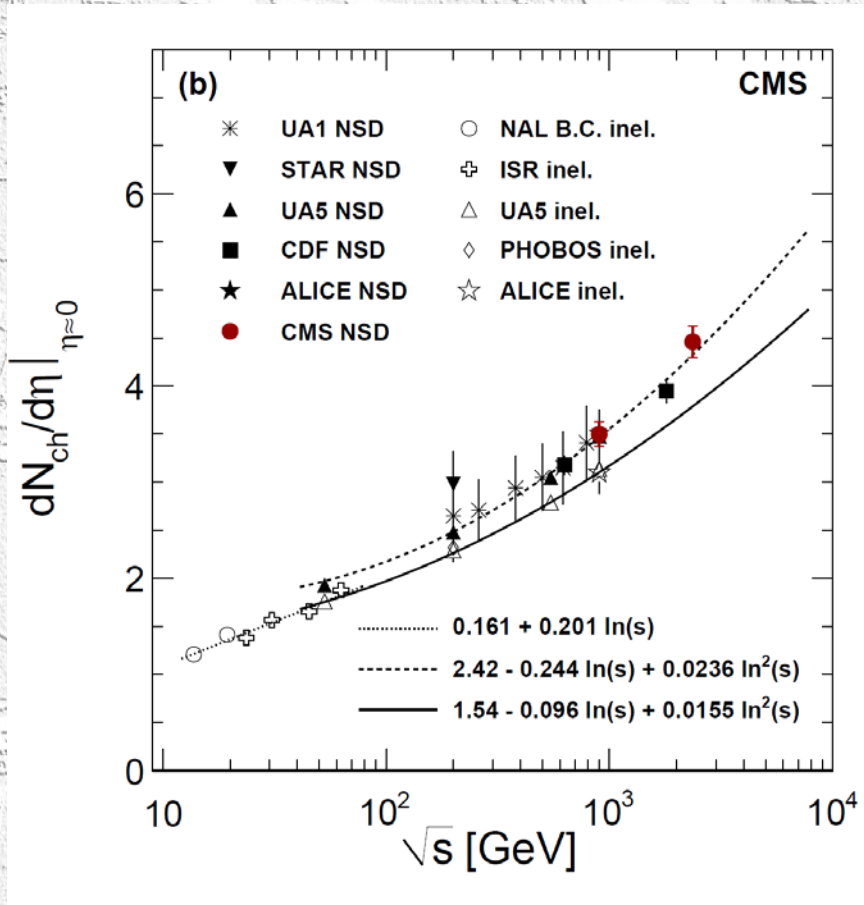
CMS: Energy Dependance

- Comparison to previous experiments

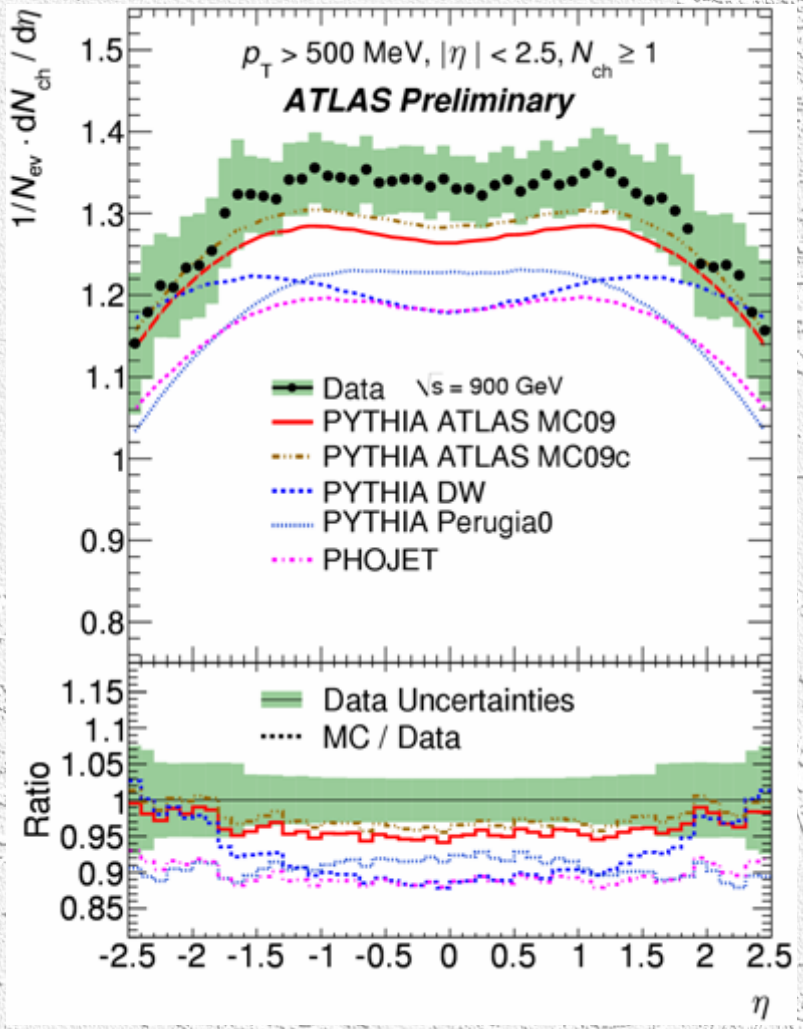
- Average transverse momentum

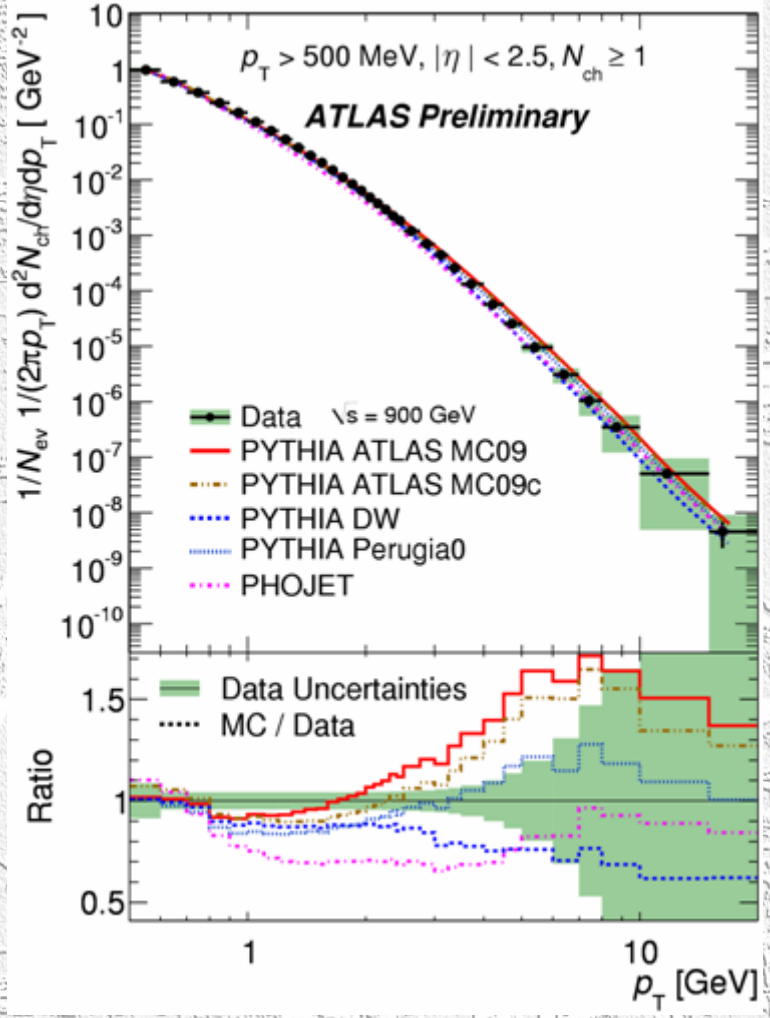


- Pseudo-rapidity density



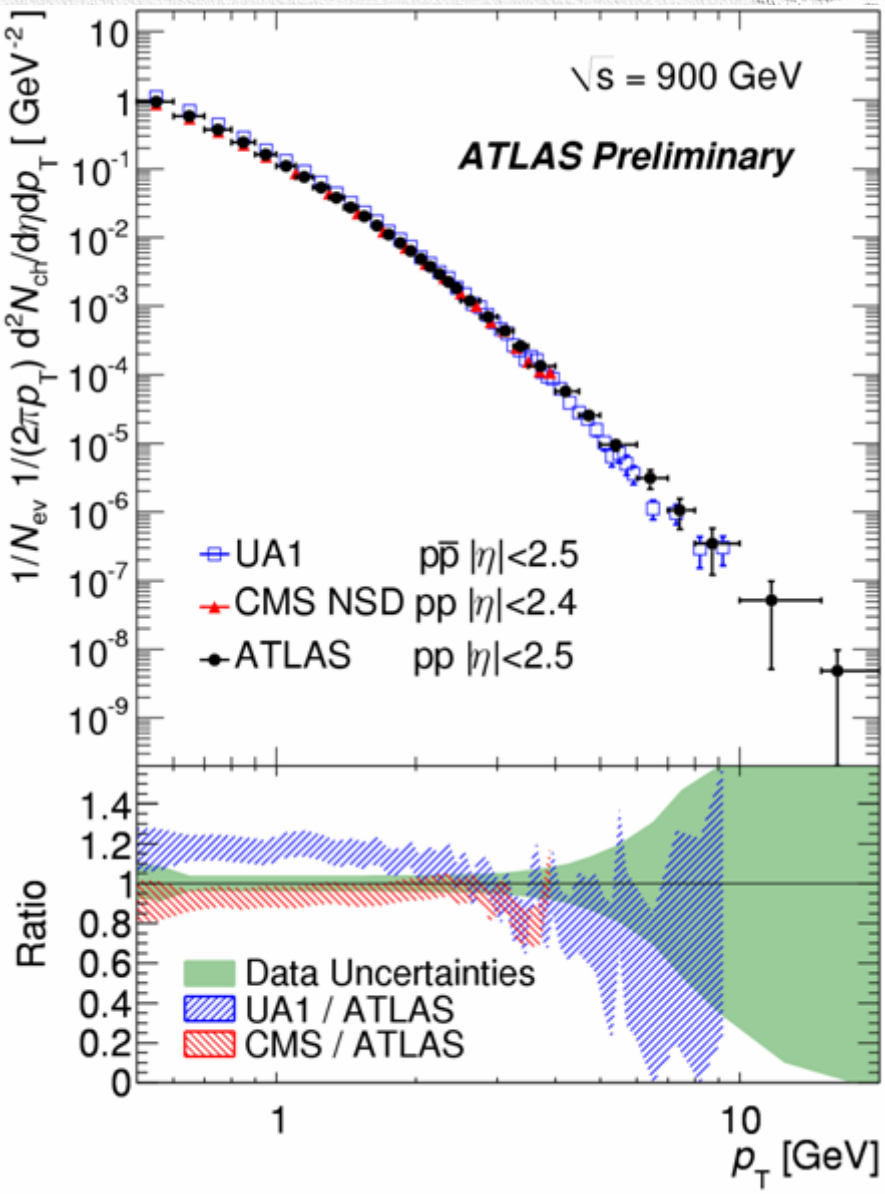
ATLAS: N_{ch} versus p_T and η





- **All MC tunes underestimate ATLAS data**

Comparison Between Experiments



- **Comparison to UA1**
  - **N_{ch} higher than ATLAS data by ~ 20 %**
  - **Consistent with the double-arm trigger requirement used by UA1 which rejects events with low charged particle multiplicities**
- **Comparison to CMS**
  - **N_{ch} consistently lower than ATLAS data**
  - **Different treatment of diffractive components**

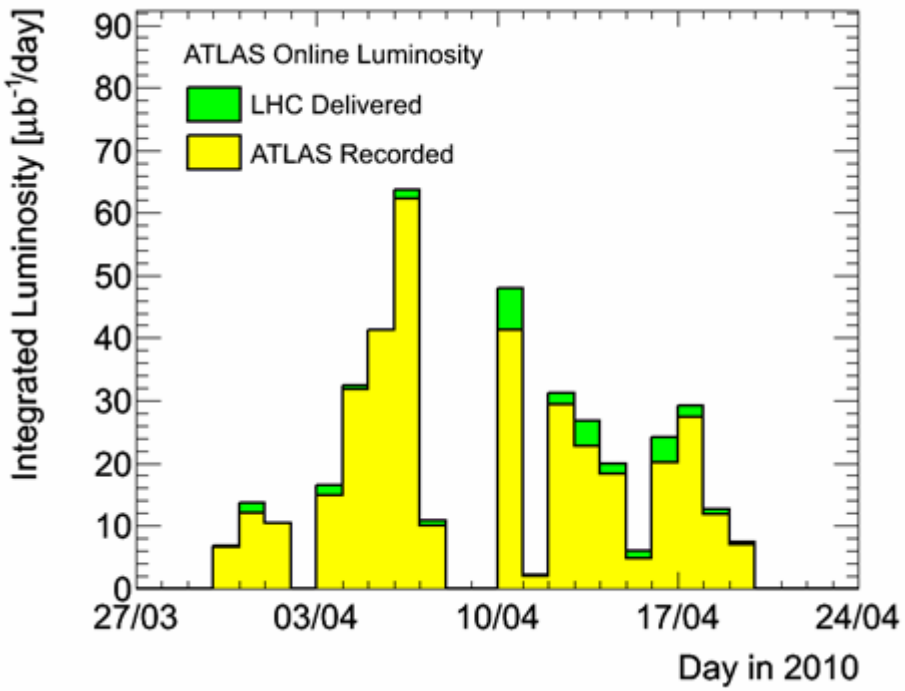
Experience from 2009 Run

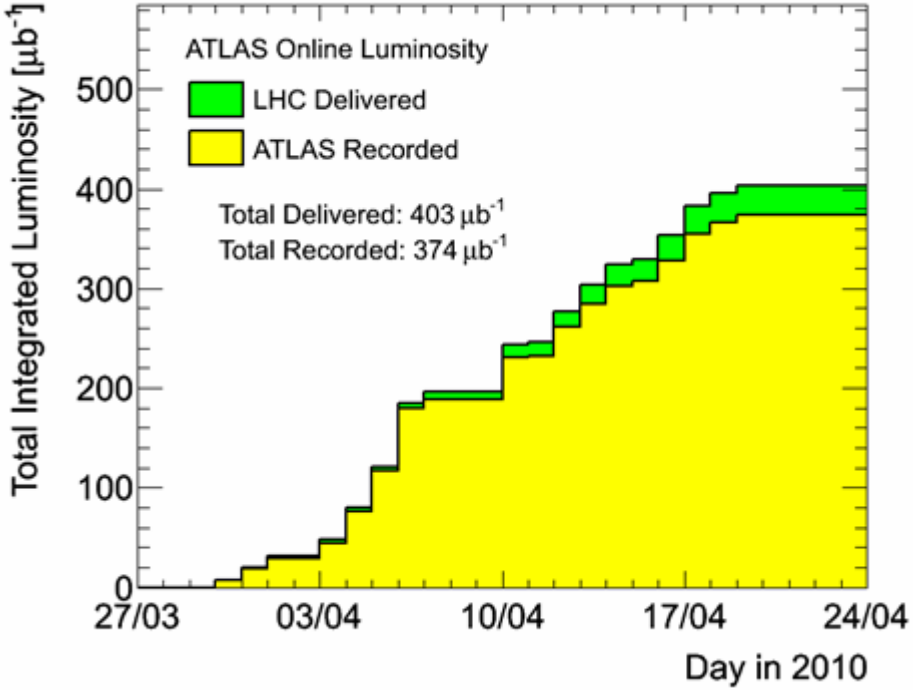
- ATLAS and CMS work very well
  - Only few permille non-operational channels
  - High data taking efficiency
  - Detector performance close to nominal
- Data are well described by Monte Carlo
  - No bad surprises so far
- Results are produced very quickly

2010: Collisions at 7 TeV

2010: 7 TeV running

- **Luminosity derived from total inelastic cross section ≈ 30% uncertainty**





- **Peak luminosity ≈ $2 \cdot 10^{27}/cm^2/s$**

Last Saturday

- Increase of luminosity by factor 10 (>10^{28}/cm^2/s)
  - Double # of bunches
  - Squeeze beams: $\beta^* \approx 10\ m \rightarrow 2\ m$

LHC 2010 - latest news

Week 16: Machine Coordinators: Mike Lamont - Ralph Assmann - M. Meddahi (after Wednesday)

Latest plan: link PDF link XLS (version of 23 April, 18:00)

List of End of Fill studies (in work)

Procedure for Physics fill and recover

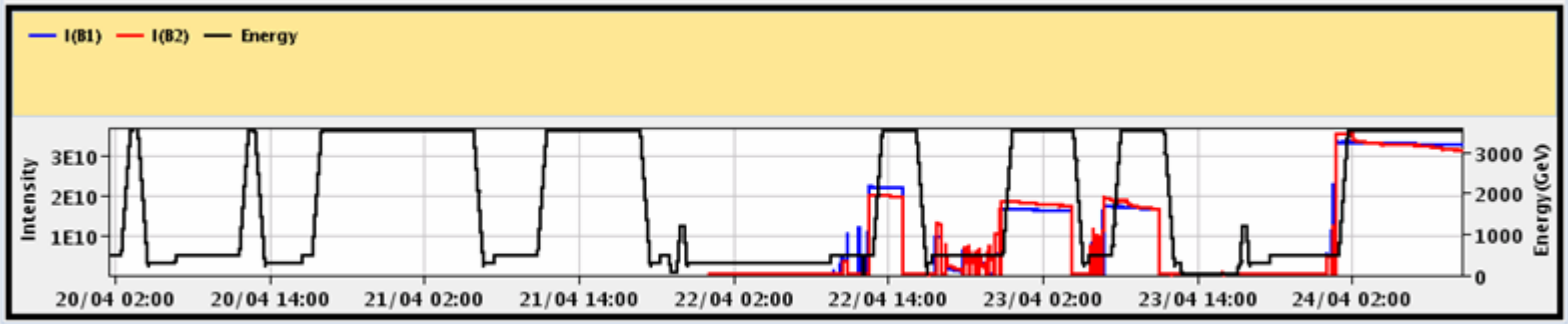
Day	Short summary/plan	Link to reports from 8:30 and 17:00 meetings
Saturday 24th April 2010	• 03:13: First stable beams with beta*=2m. • 05:30: All 4 experiments above 1.1e28 cm-2s-1 after optimization! Factor 10 in luminosity achieved, as predicted! • Plan for next fill: 3.5 TeV, squeezed optics, 2e10/beam (2bx2b) Van der Meer scans • Then: Fill at 3.5TeV, squeezed optics, 3.5e10/beam (3bx3b) - stable beams	Report from 9h00 meeting
Friday 23rd April 2010	• 06:00 - 12:00 : Qualification for 3.5TeV squeezed optics - last check	Report from 8h30 meeting

24-Apr-2010 10:29:52 Fill #: 1058 Energy: 3500.3 GeV I(B1): 3.25e+10 I(B2): 3.12e+10

	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	NOT_R...
Instantaneous Luminosity	7.546e-03	7.292e-03	9.323e-03	1.332e-03
BRAN Count Rate	2.281e+02	8.530e+01	2.263e+02	2.638e+02
BKGD 1	0.017	0.016	0.024	0.131
BKGD 2	1.000	17.480	3.594	3.568
BKGD 3	0.000	0.005	0.003	0.044

LHCf PHYSICS Count(Hz): 3.200 | LHCb VELO Position IN Gap: 0.0 mm | TOTEM: STANDBY

Performance over the last 12 Hrs



Background 1

Background 2

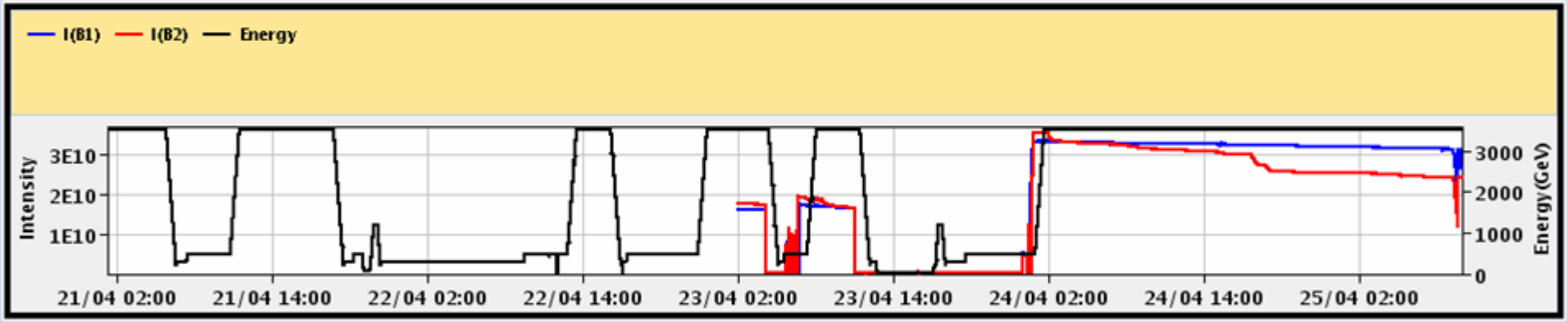
24 hours later…

25-Apr-2010 09:55:14 Fill #: 1058 Energy: 3500.3 GeV I(B1): 2.62e+10 I(B2): 2.41e+10

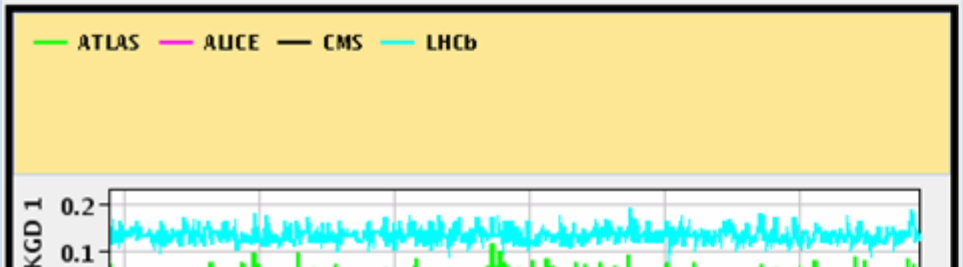
	ATLAS	ALICE	CMS	LHCb
Experiment Status	STANDBY	STANDBY	STANDBY	STANDBY
Instantaneous Luminosity	3.454e-03	0.000e+00	3.958e-03	3.501e-03
BRAN Count Rate	1.004e+02	3.611e+01	9.421e+01	9.831e+01
BKGD 1	0.028	0.014	0.014	0.169
BKGD 2	0.000	0.000	1.482	3.012
BKGD 3	0.000	0.008	0.003	0.043

LHCf STANDBY Count(Hz): 0.000 | LHCb VELO Position OUT Gap: 58.0 mm | TOTEM: STANDBY

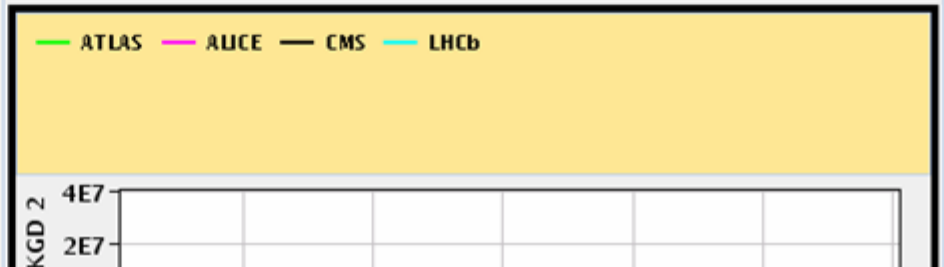
Performance over the last 12 Hrs



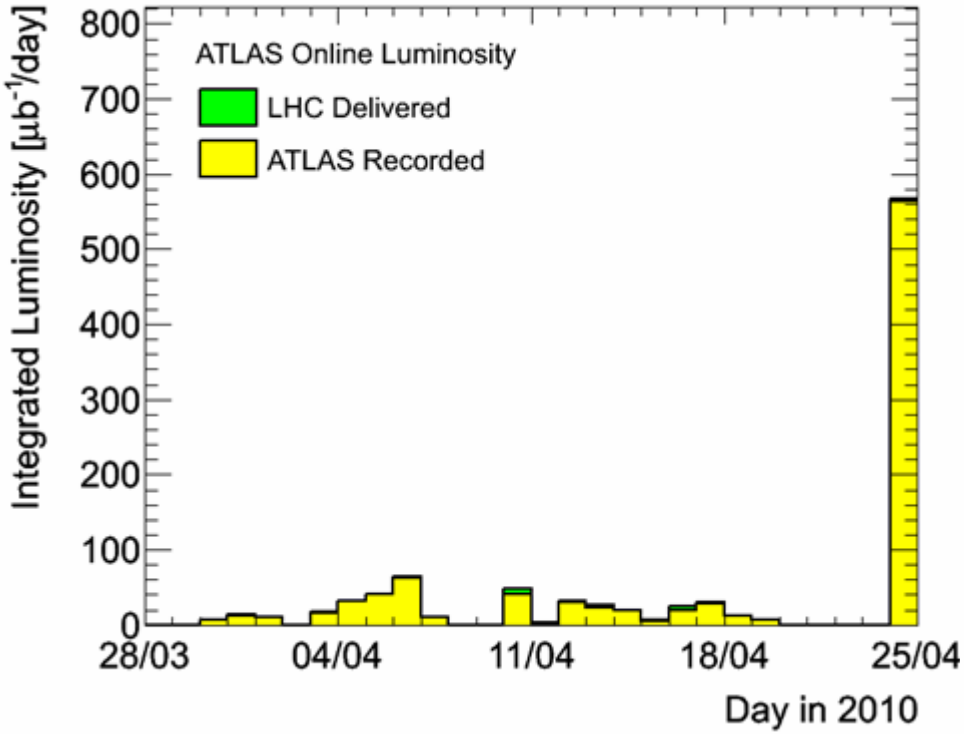
Background 1

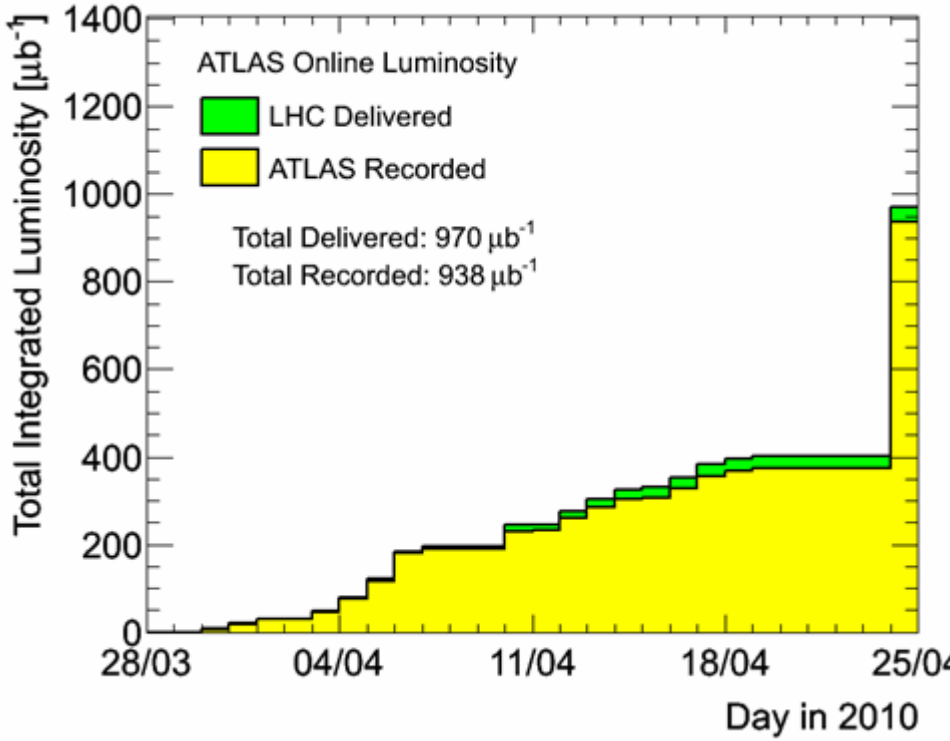


Background 2



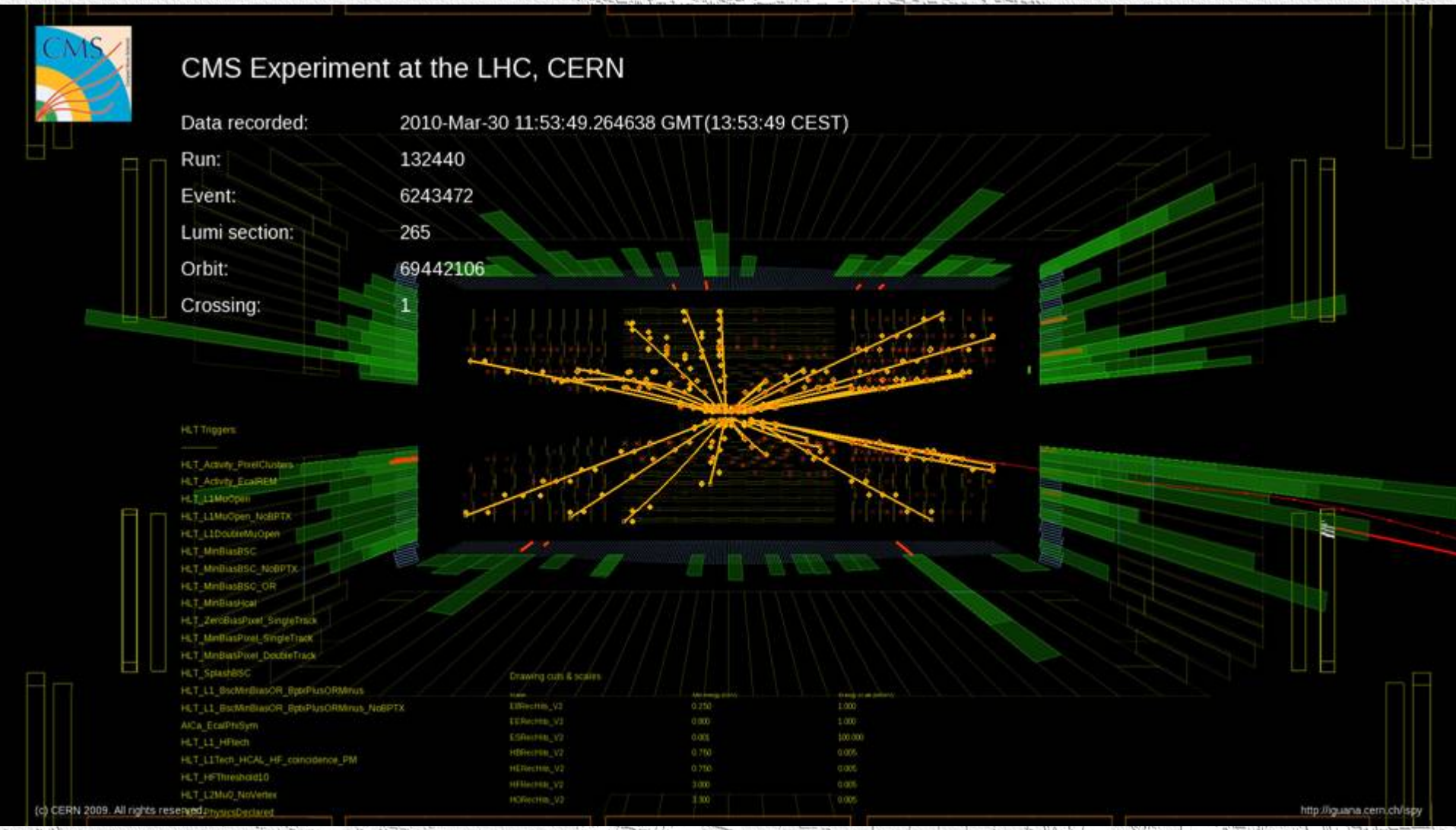
New ATLAS Luminosity Plot



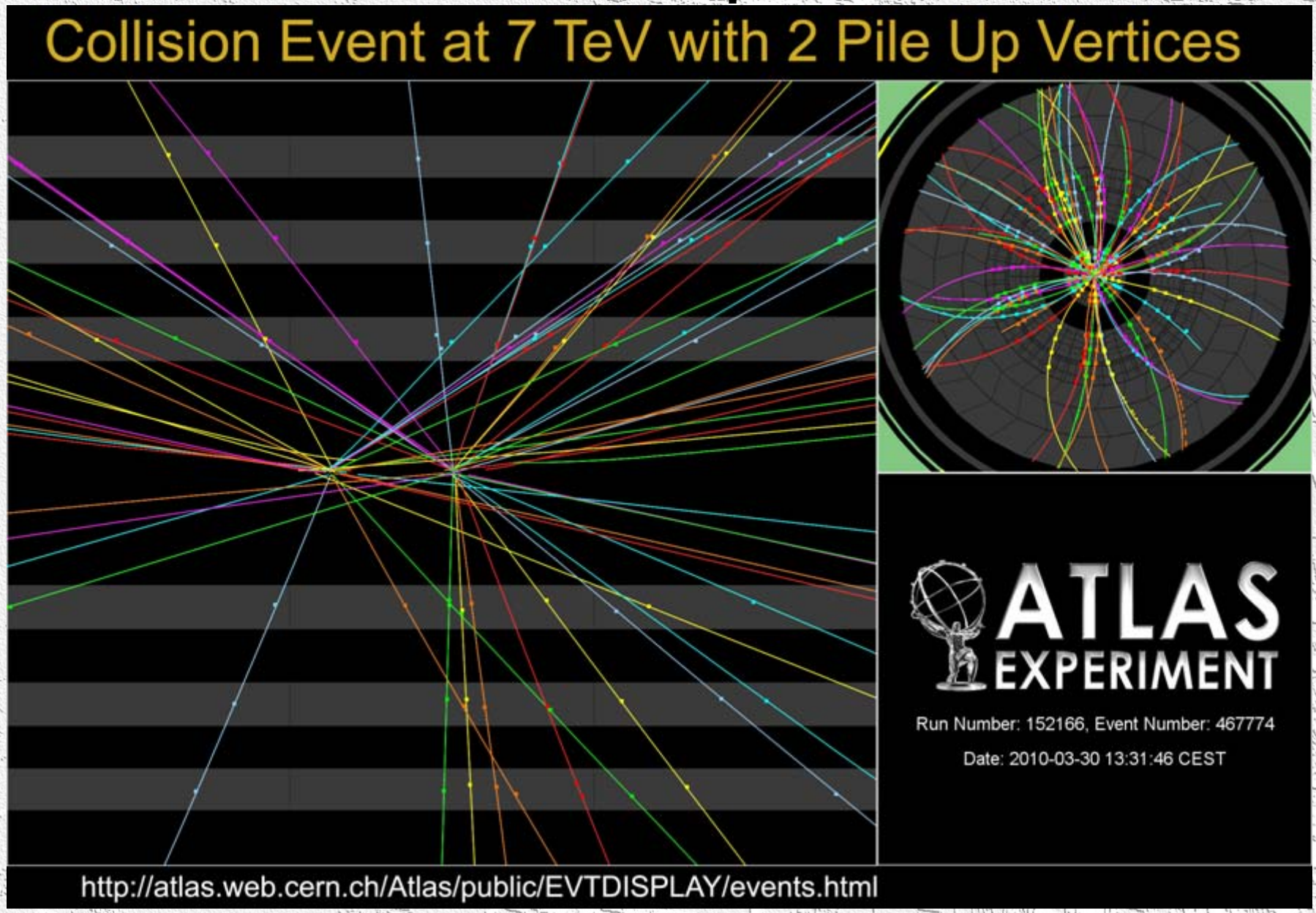


- **Peak luminosity ≈ $12 \cdot 10^{27}/cm^2/s$**
- **But still a long way to go…**

First 7 TeV Events

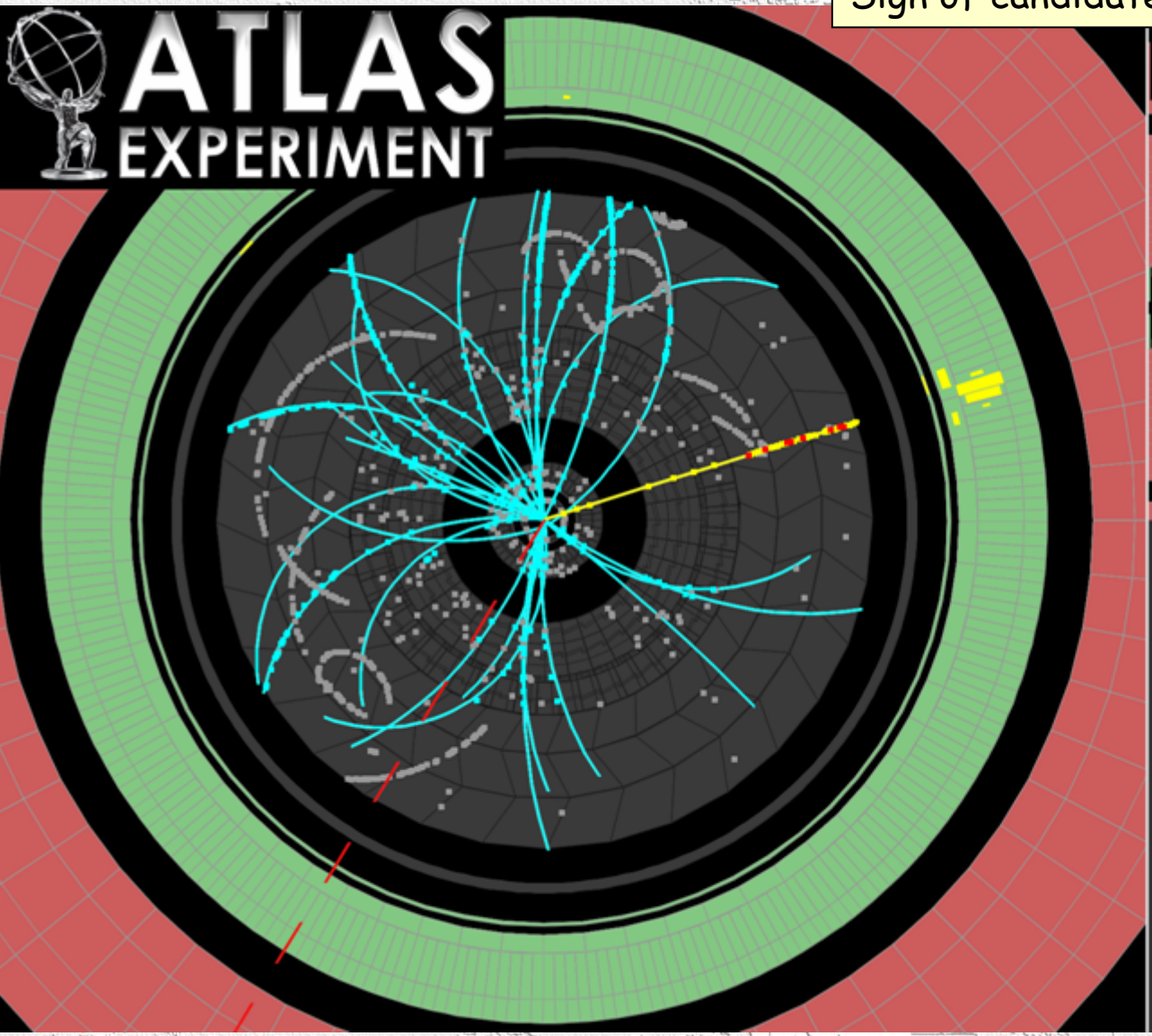


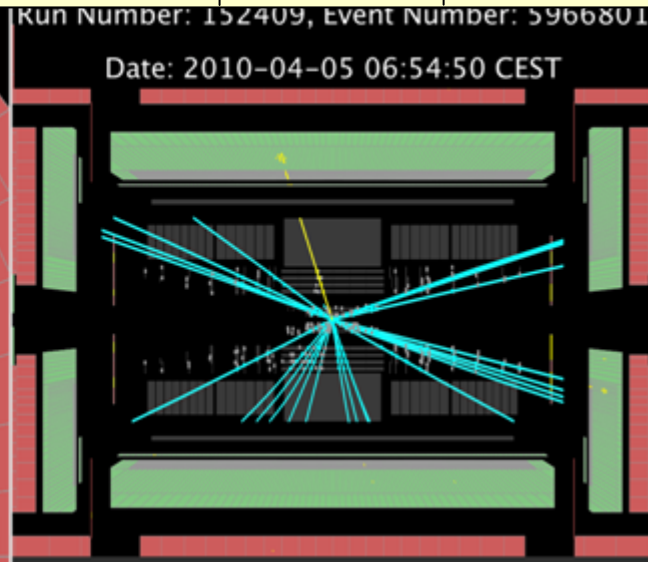
Pile-up

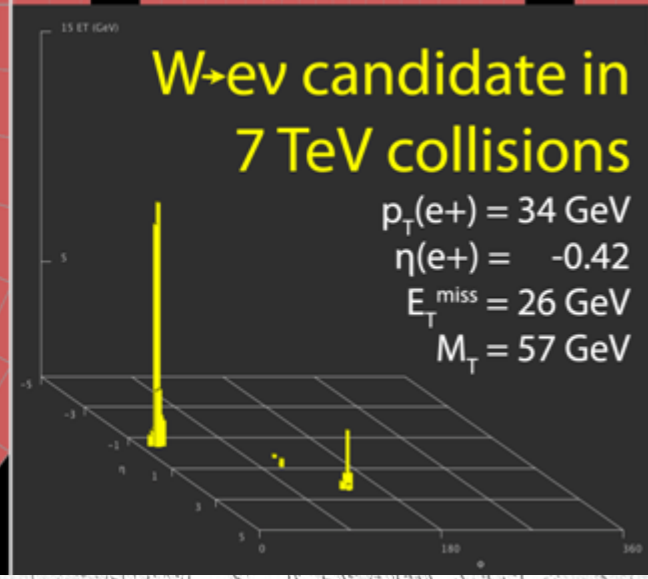

Collision Event at 7 TeV with 2 Pile Up Vertices
ATLAS
EXPERIMENT
Run Number: 152166, Event Number: 467774
Date: 2010-03-30 13:31:46 CEST
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

W candidate

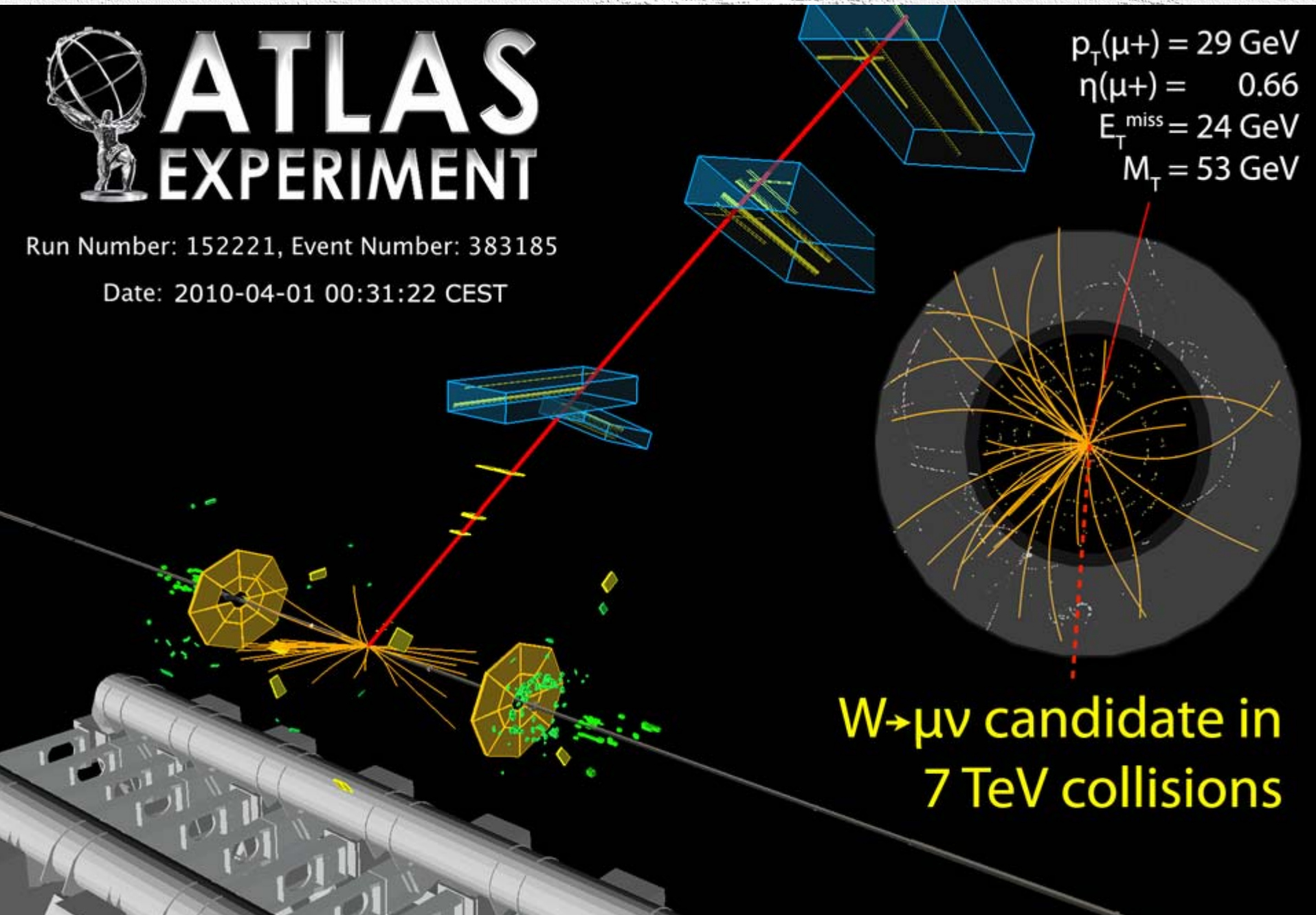
300 μb^{-1} of analysed data	$W \rightarrow e\nu$	$W \rightarrow \mu\nu$
Expected signal	~ 1.5	~ 1.5
Observed candidates	2	2
Sign of candidates	+, +	+, -







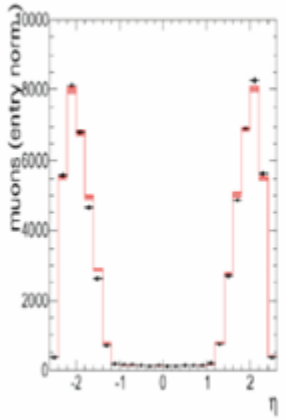
W Candidate

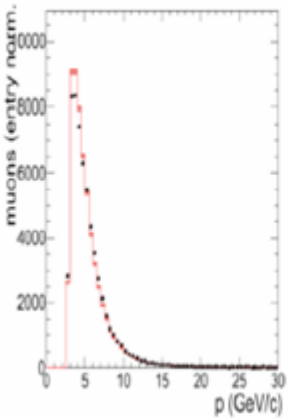

ATLAS
EXPERIMENT
Run Number: 152221, Event Number: 383185
Date: 2010-04-01 00:31:22 CEST
$p_T(\mu+) = 29$ GeV
$\eta(\mu+) = 0.66$
$E_T^{miss} = 24$ GeV
$M_T = 53$ GeV
W→μν candidate in
7 TeV collisions

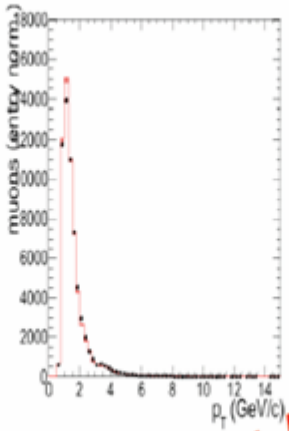
Looking at 7 TeV Data

Tracker muons (60,000 tracks)

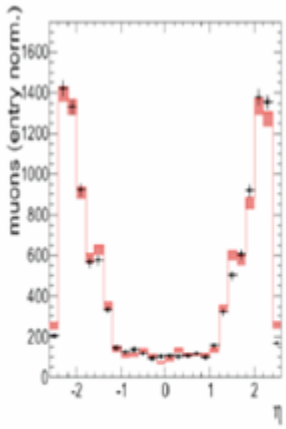
Data
MC

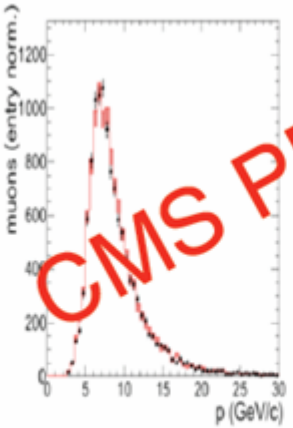


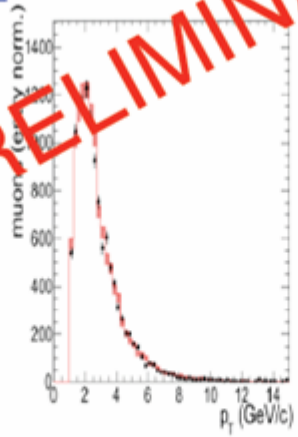




Global muons (12,000 tracks)

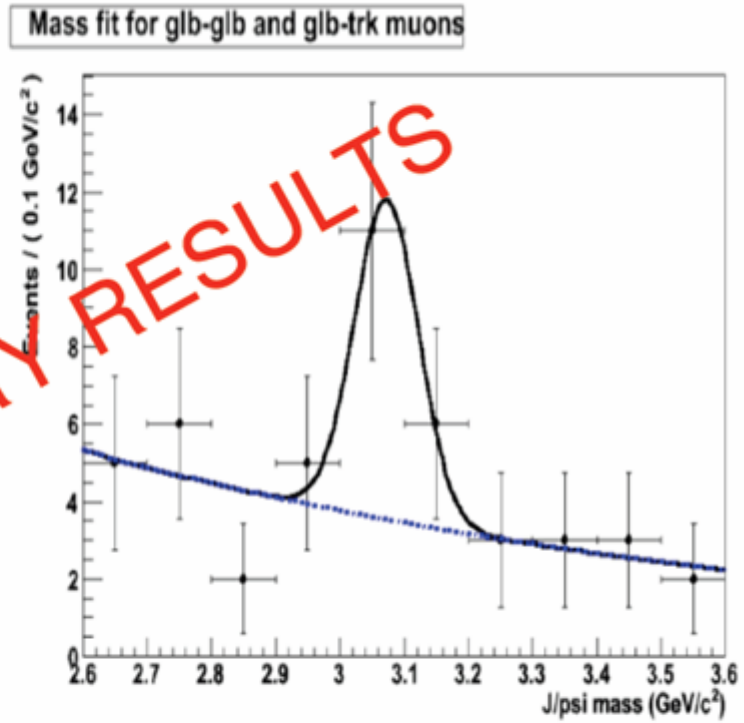






Good MonteCarlo/Data agreement

Nice J/Psi preliminary peak



CMS PRELIMINARY RESULTS

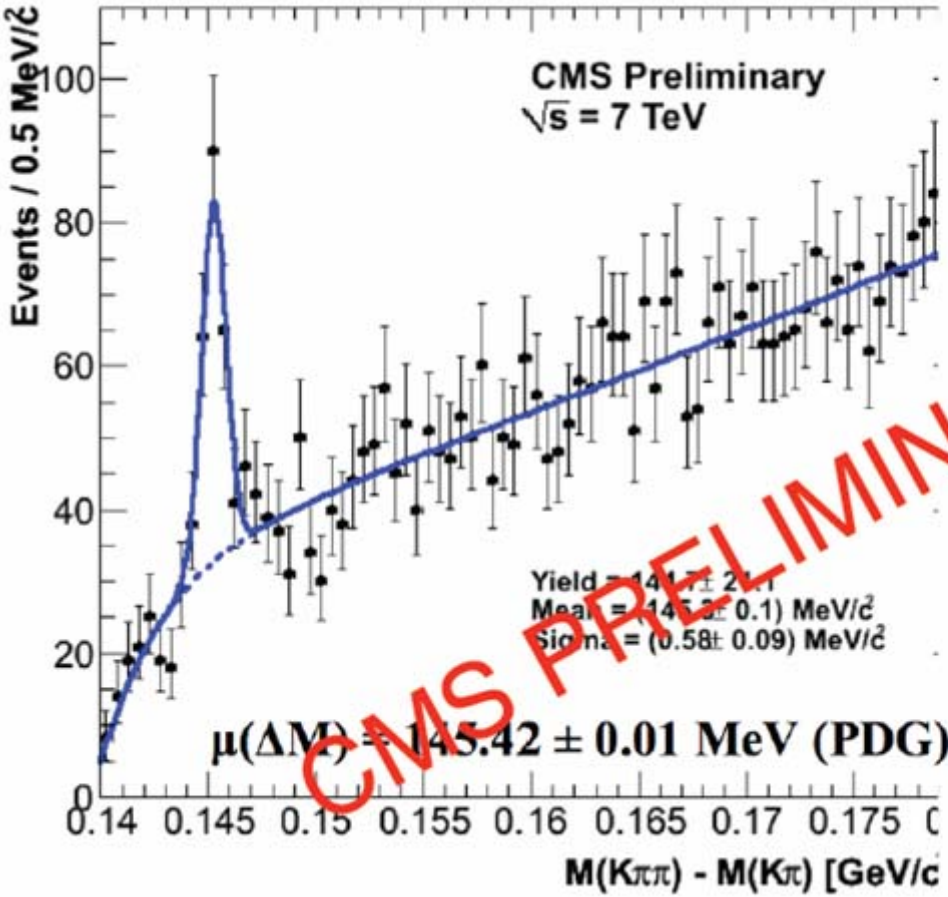
Fitted mass

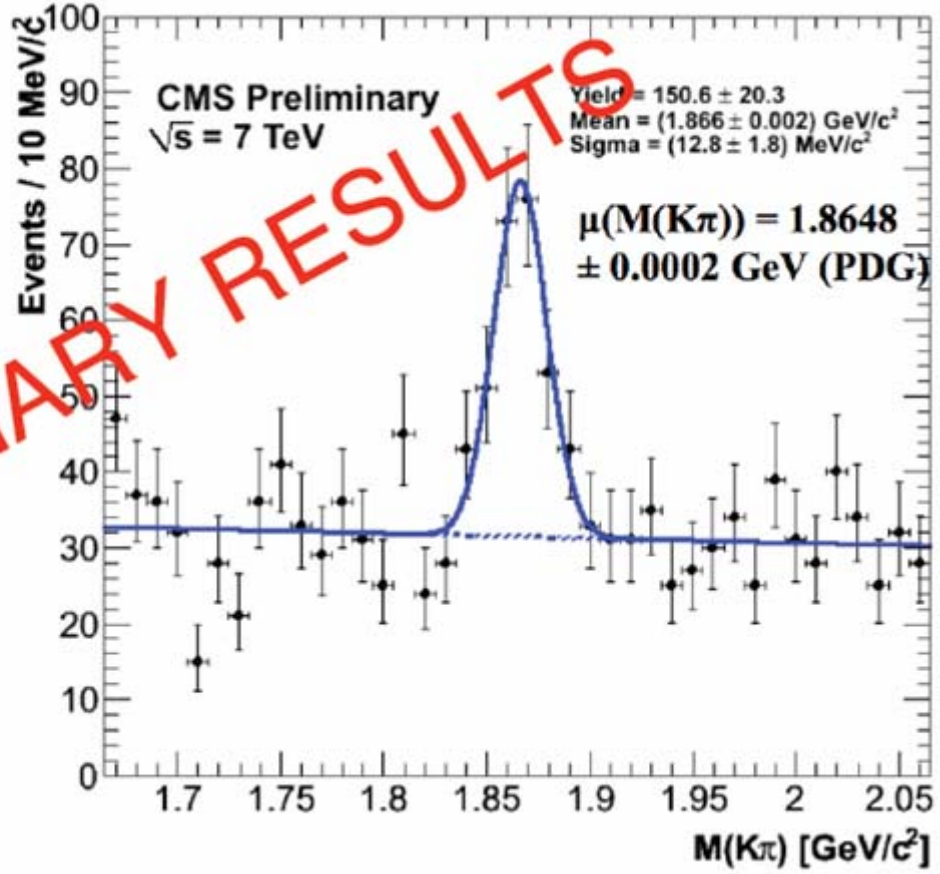
$M_{Jpsi} = (3.073 \pm 0.011)$ GeV

Resolution DATA 51 MeV (MC 37MeV)

Looking at 7 TeV Data

Inclusive D^{*+} production. $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+$

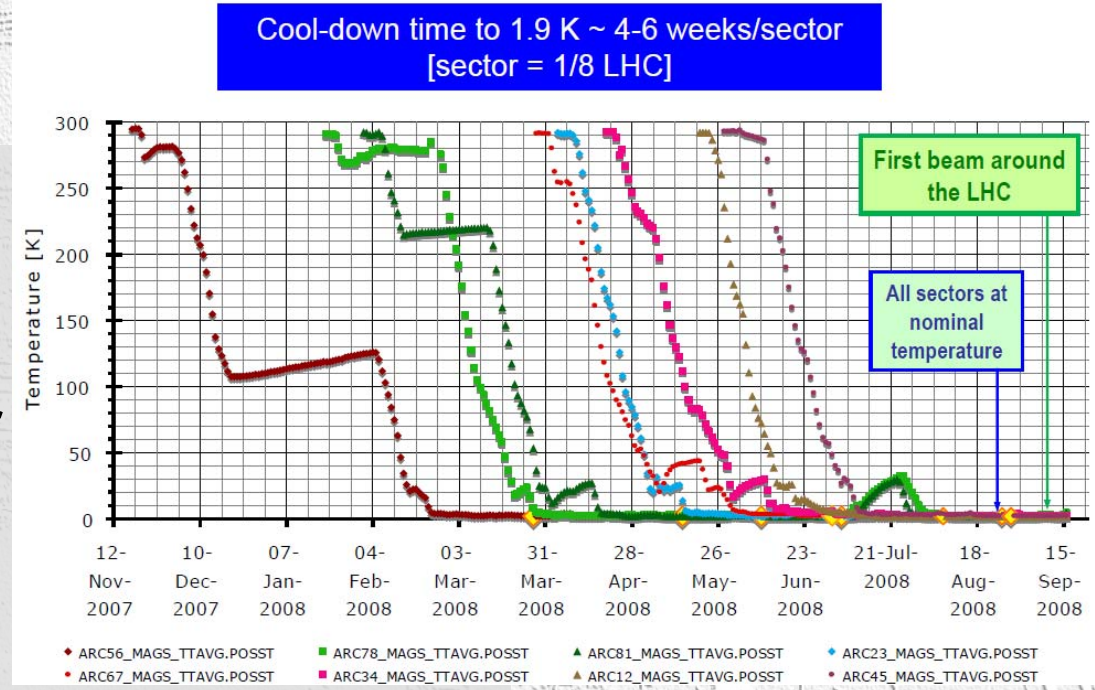




CMS PRELIMINARY RESULTS

Outlook & Plans

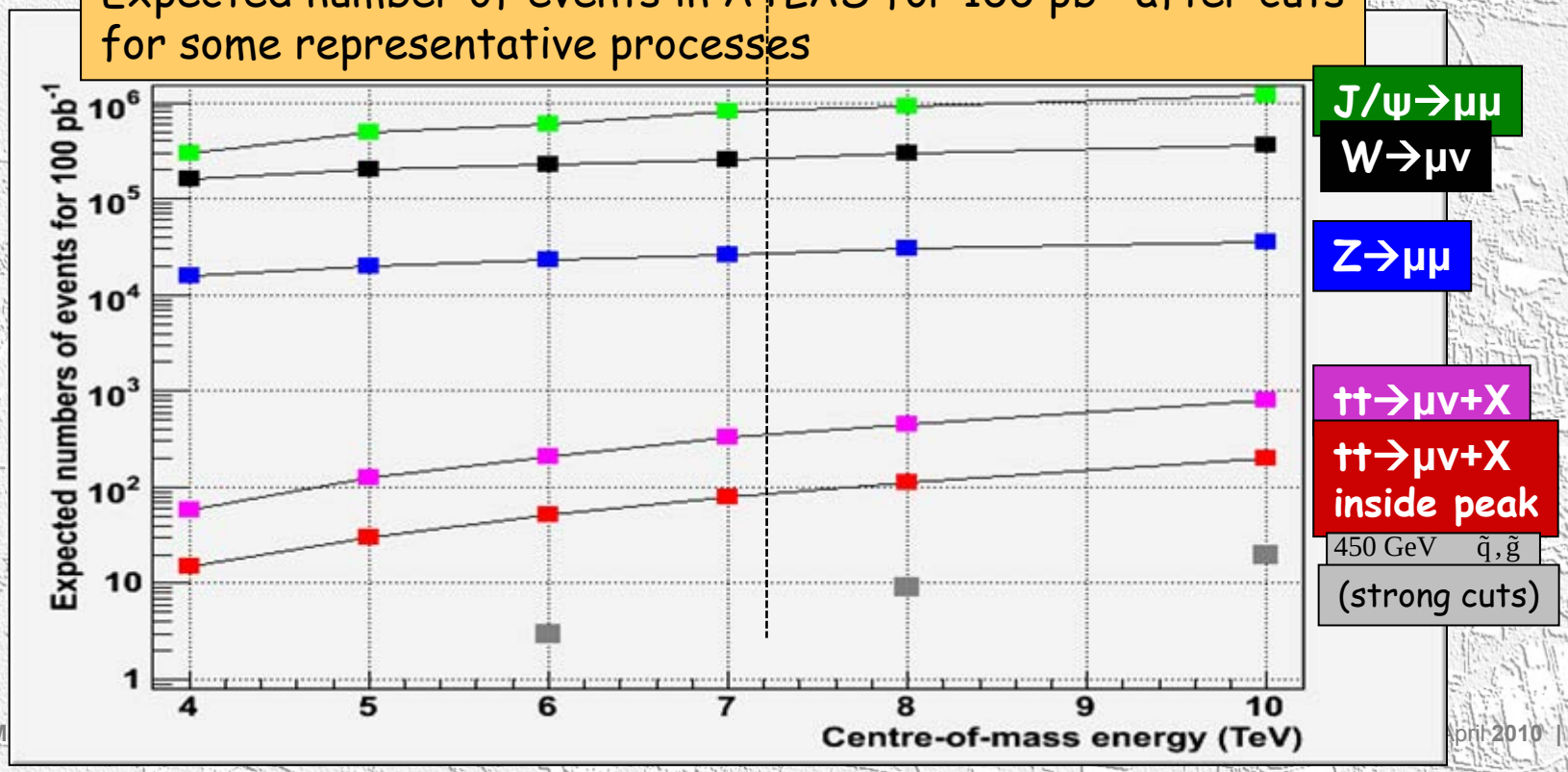
- LHC operation
  - Long running periods (>1 year)
  - Interleaved with longer shut down periods
- 2010 – 2011
  - Run LHC at 7 TeV
  - Goal is to collect 1/fb per experiment until mid/end 2011
  - Then repair all magnet joints takes about 1 year (?)
- 2012/13
  - LHC operation at 14 TeV
  - Open point: magnet training beyond 5 TeV



Prospects for 2010/11 Run

- **Machine planning (7 TeV)**
  - **2010** $L \approx 10^{27} \rightarrow 10^{32}/cm^2/s$ **total of 100 – 200/pb**
  - **2011** $L \approx 10^{32} \rightarrow$ **few** $10^{32}/cm^2/s$ **≥ 100/pb per month (>1 year) total of ≈ 1/fb**
  - **2012** **Shutdown**

Expected number of events in ATLAS for 100 pb^{-1} after cuts for some representative processes



ATLAS New Physics Reach

- **Fabiola Gianotti @ RRB last week**
- **Rough estimates from fast simulations!**

New Physics : approximate LHC reach $\sqrt{s}$ = 7 TeV (one experiment) for some benchmark scenarios

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

SUSY ($\tilde{q}, \tilde{g}$) : Tevatron limit ~ 400 GeV (95% C.L)

100 pb^{-1} : discovery up to ~ 400 GeV
1 fb^{-1} : discovery up to ~ 700 GeV

LHC will start to compete with the Tevatron in 2010, and should take over in 2011 in most cases.

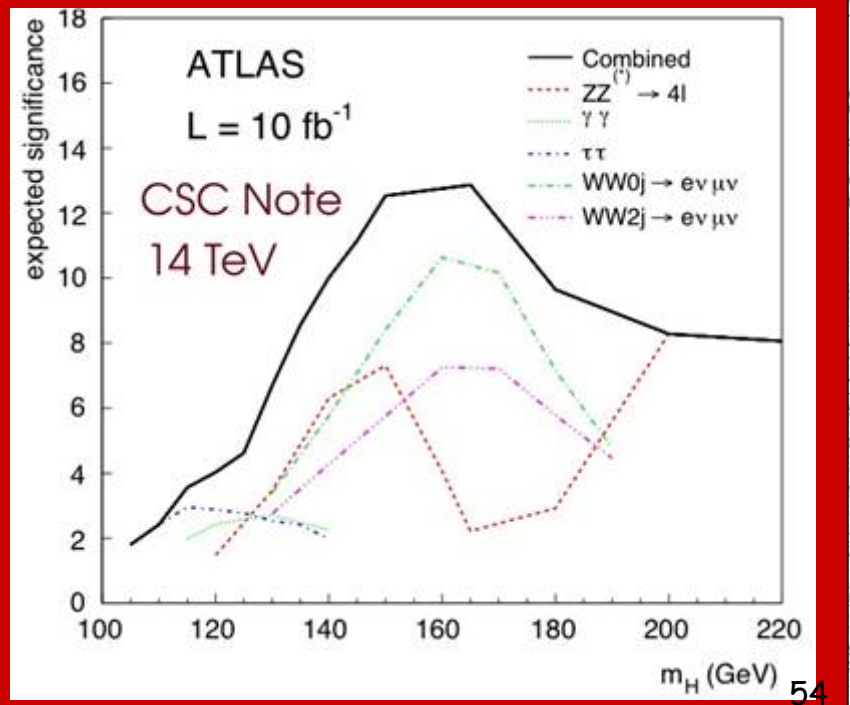
ATLAS Higgs Reach

Higgs $\sqrt{s}$=7 TeV: H → WW, m_H ~ 160 GeV (Tevatron exclusion: 162-166 GeV)

300 pb^{-1} per experiment : ~ 3σ sensitivity combining ATLAS and CMS (similar to Tevatron)
1 fb^{-1} per experiment : could exclude 145 < m_H < 180 GeV
~ 4.5 σ combining ATLAS and CMS

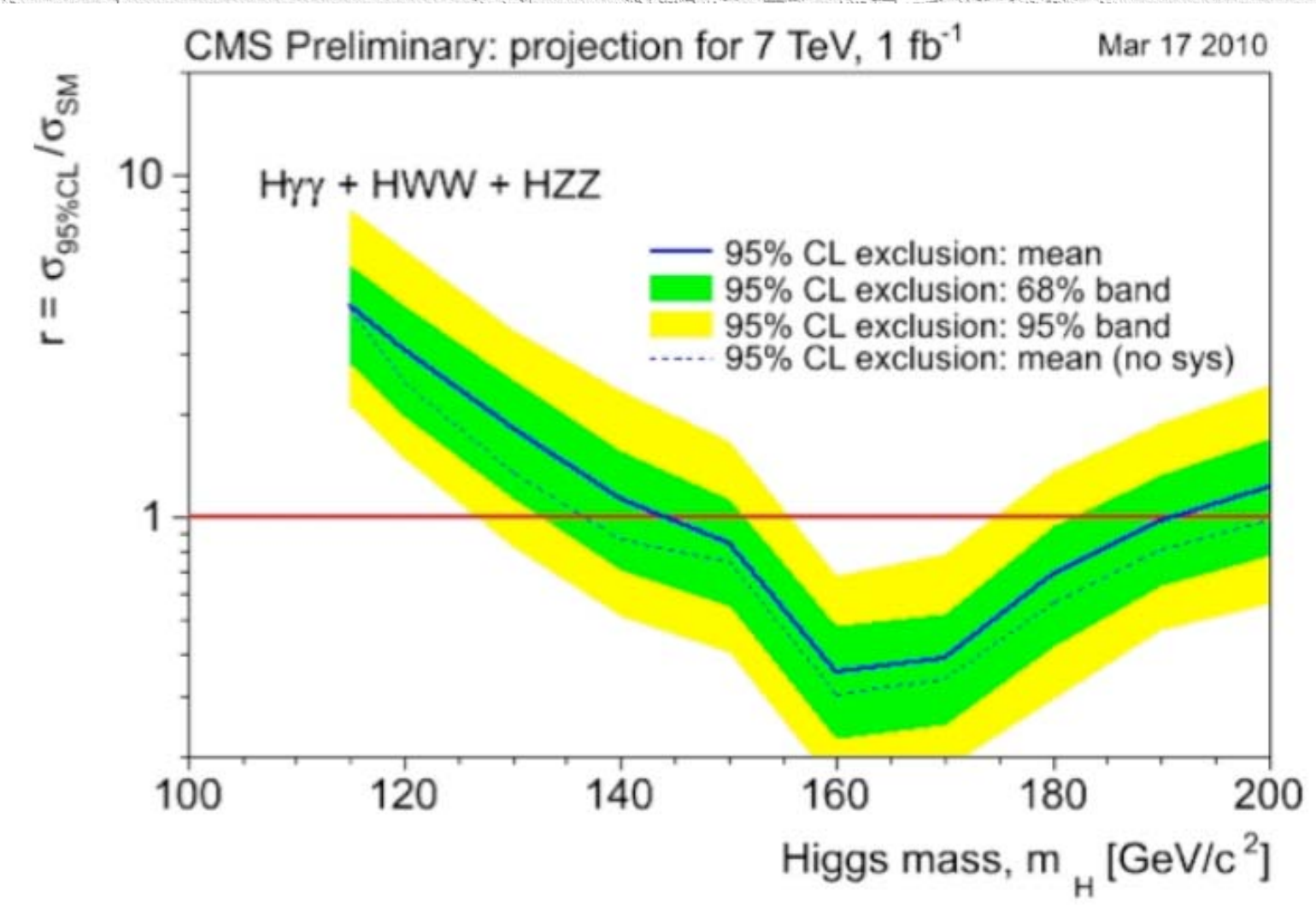
- Exclusion of the full mass range down to m_H~115 GeV requires ~1.5 fb^{-1} per experiment at 14 TeV
- Discovery for m_H ~ 115 GeV requires ~ 10 fb^{-1} per experiment at 14 TeV

A long way to go if the Higgs is just above the LEP2 limit: 2014 ?

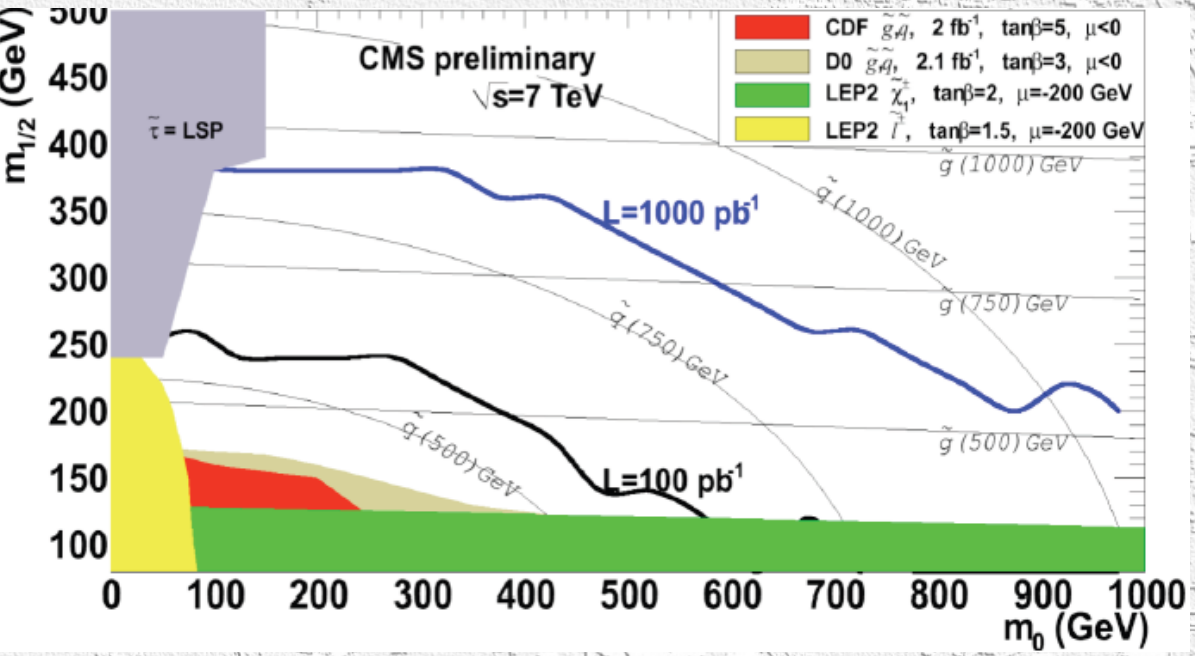


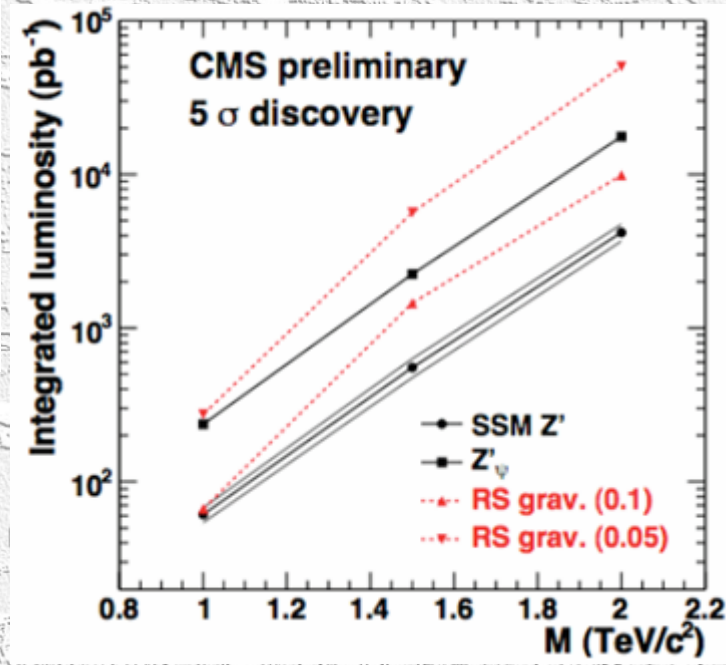
CMS Higgs Sensitivity

- **Guido Tonelli @ RRB last week**



CMS New Physics Reach





Summary & Outlook

- LHC is starting up a little slower than we initially hoped for
  - Very good progress now
- Detectors are working very well and understanding is progressing rapidly
  - Many results on hadron physics available
  - Starting to become sensitive to electroweak physics
- Long physics run 2010/11 at 7 TeV started
  Goal:
  - 100 - 200/pb in 2010
  - 1/fb in 2011
- LHC experiments will surpass Tevatron in 2011

Very exciting times are ahead of us!

Backup slides

Challenges for the LHC: Magnets

- Superconducting dipole magnets to keep 7 TeV protons on a circular path (r ≈ 3 km)

  |B| = 8.33 Tesla

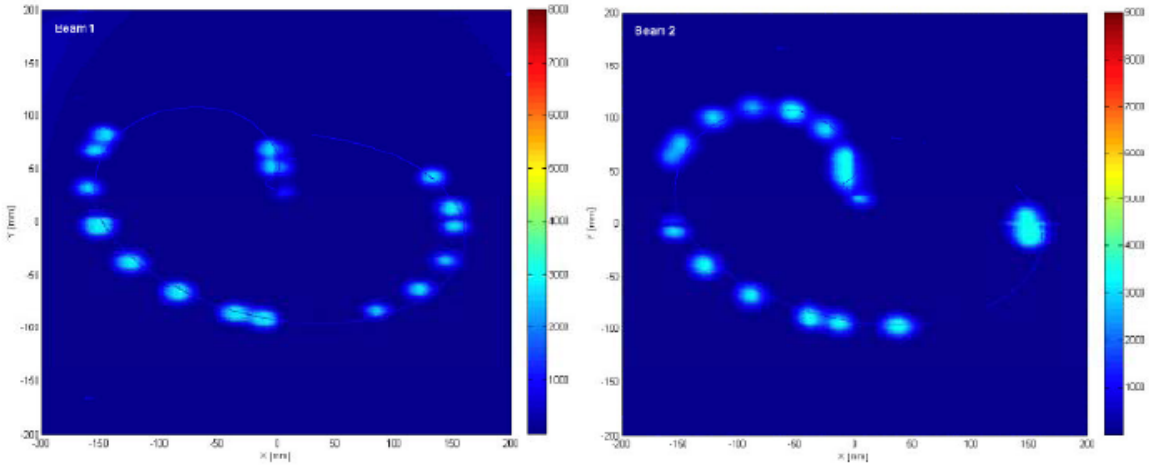
- 1232 dipole magnets needed each is 15 m long
  (+ quadrupoles, sextupoles, etc.)
  - 1.9 K operating temperature
  - Supraliquid Helium
  - Largest cryogenic facility in the world
- Quench protection
  - Stored energy in one dipole: 8 MJ corresponds to a 40 t truck at 50 km/h

- LHC dipole design incorporates reversed field for oppositely rotating proton beams

Dipoles in the LHC Tunnel

LHC Beam Dump System

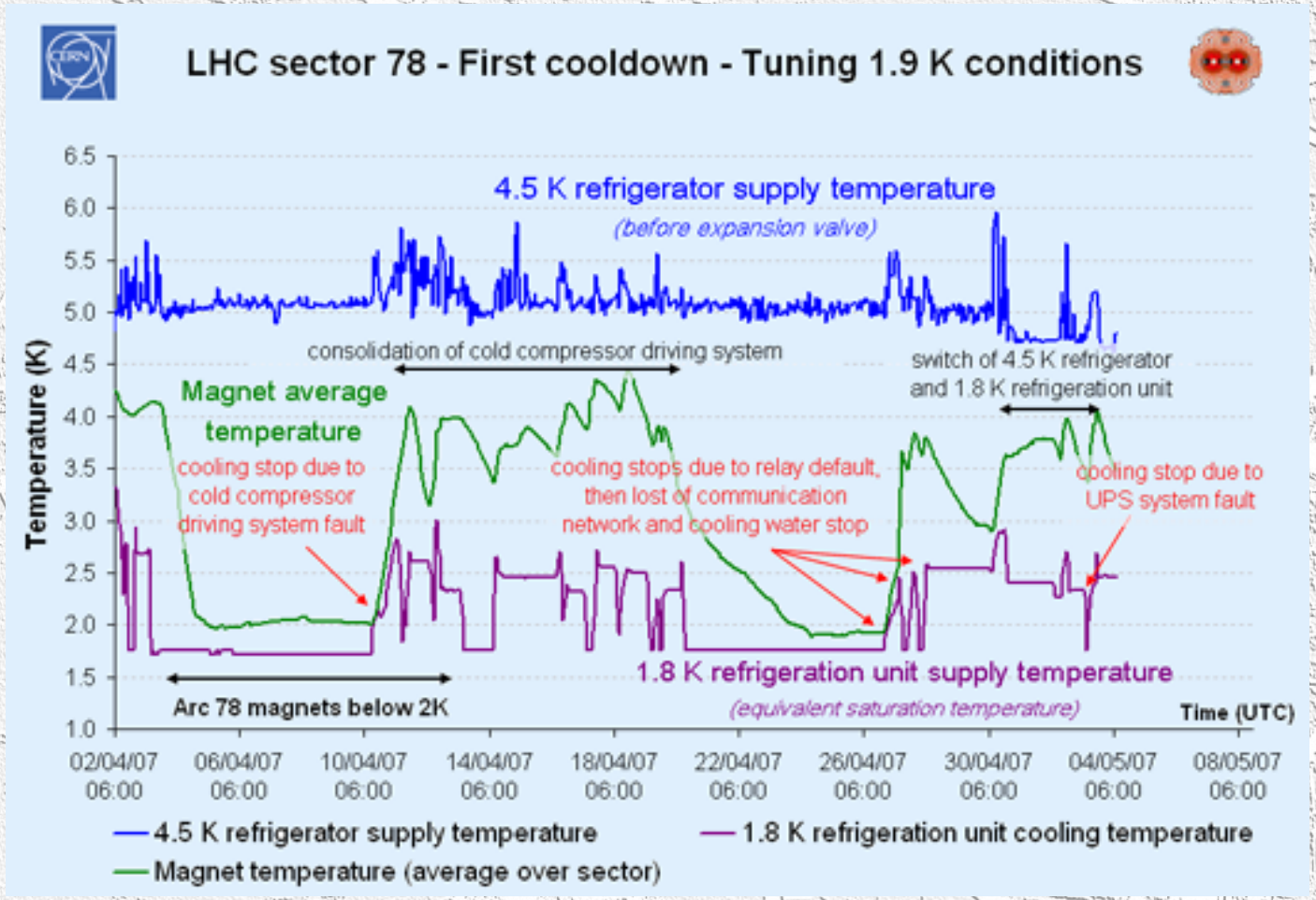
Beams for physics dumped, at the right place! 450 GeV



Beam dumps, 16 bunches + pilot, 14/12/09 around 21:00
BTVDD image = position on beam dump block TDE
Comparison with calculated positions from measured kicker magnet waveforms.

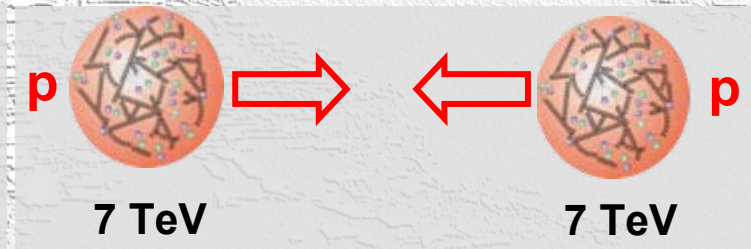
Cryogenics

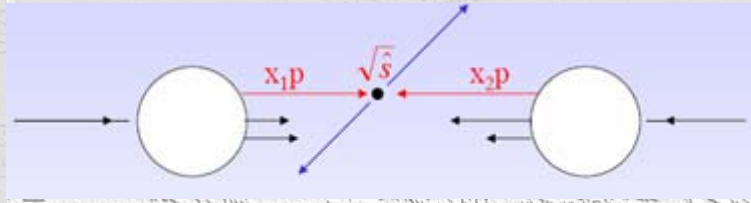
- First cool down of an LHC sector (> 3 km) in April 2007
- Superfluid helium at 1.9 K

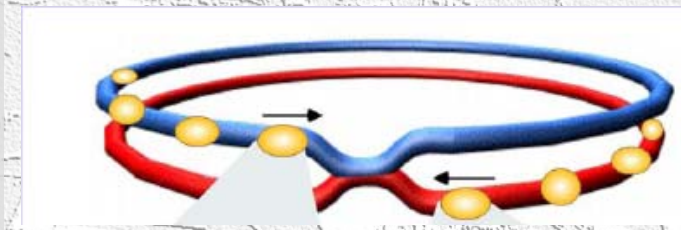


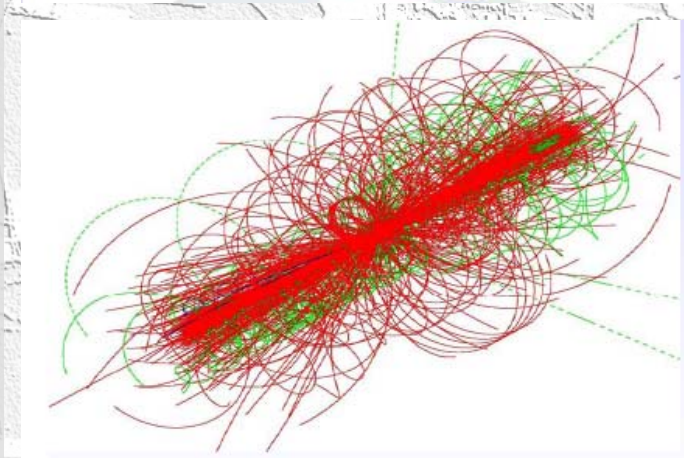
Challenges for LHC Detectors

- Protons are composite particles
  - LHC collides protons on protons
  - But collisions of quarks and gluons are the fundamental processes
  - Screened by interactions of other quarks & gluons (underlying event)
- LHC is filled with 2835 + 2835 proton bunches
  - Collisions every 25 ns
    40 MHz crossing rate
- 10^{11} protons per bunch
  - 25 pp interactions per crossing (pile-up)
  - Each bunch collision produces ≈ 1600 charged particles

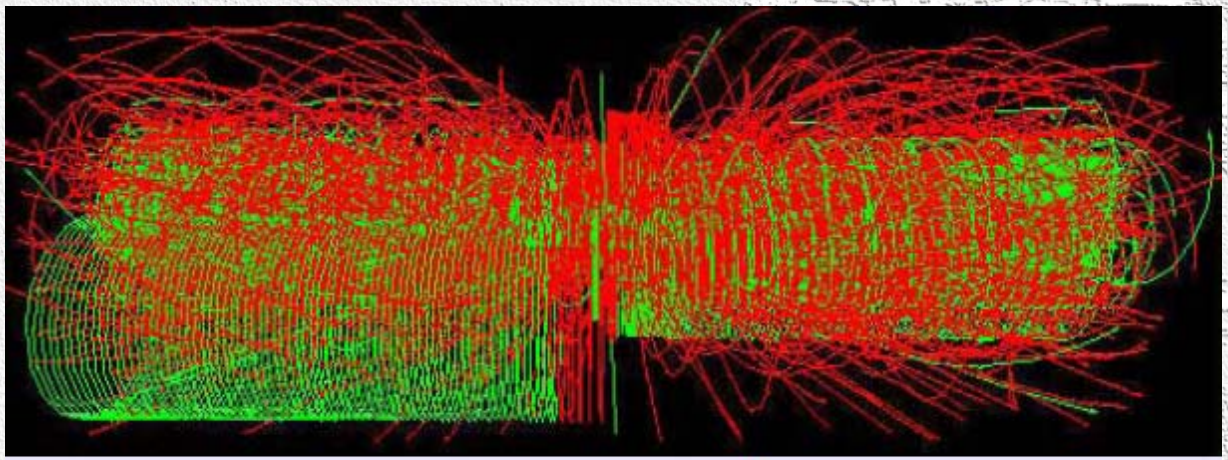




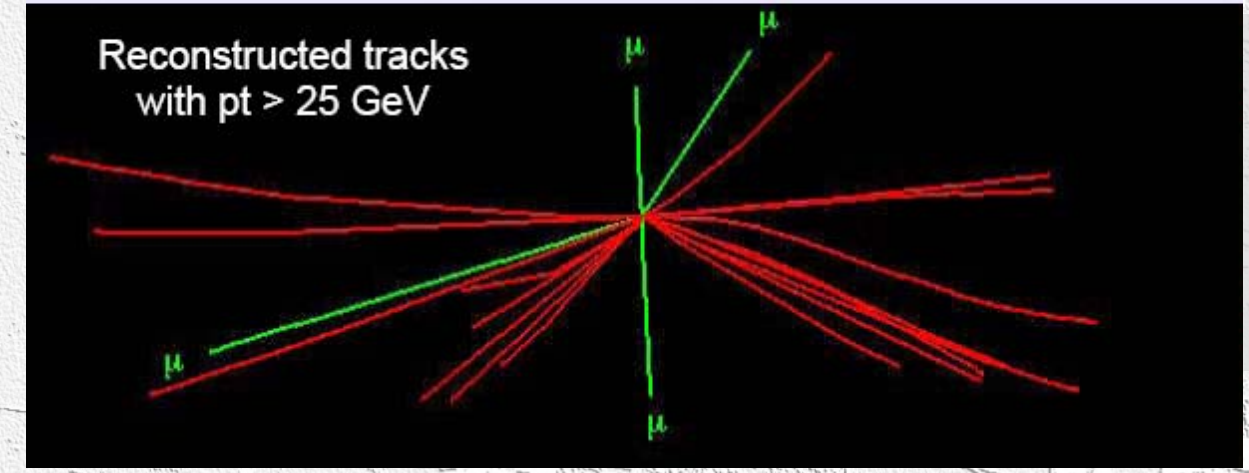




A Collision Producing a Higgs Boson



- with 25 pile-up interactions

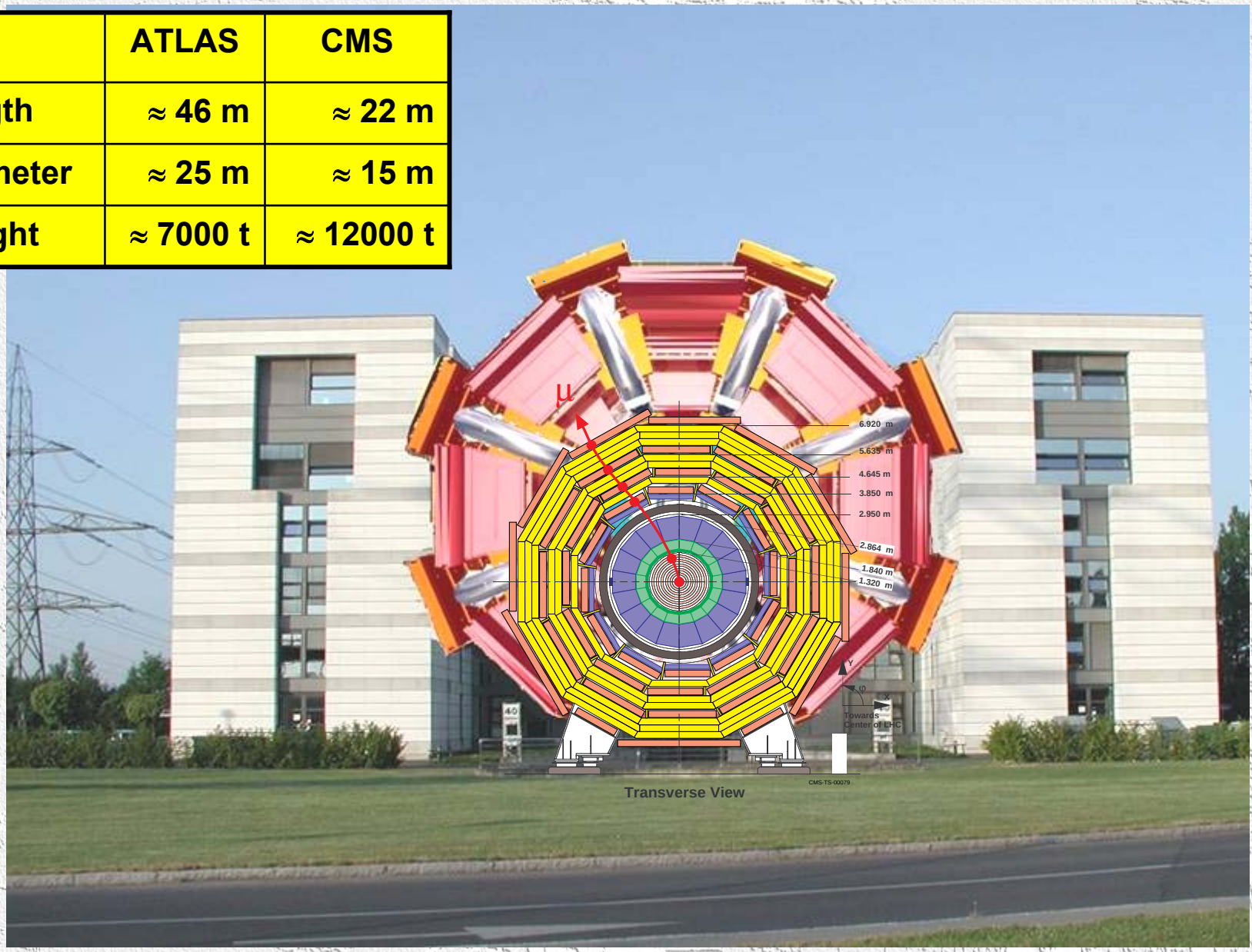


- Remove low energy tracks ($p_T < 25$ GeV)
- $H \rightarrow ZZ \rightarrow 4$ muons

- Identify each track — requires a highly granular detector
- Reconstruct every track — takes a lot of computing power

Comparison ATLAS and CMS

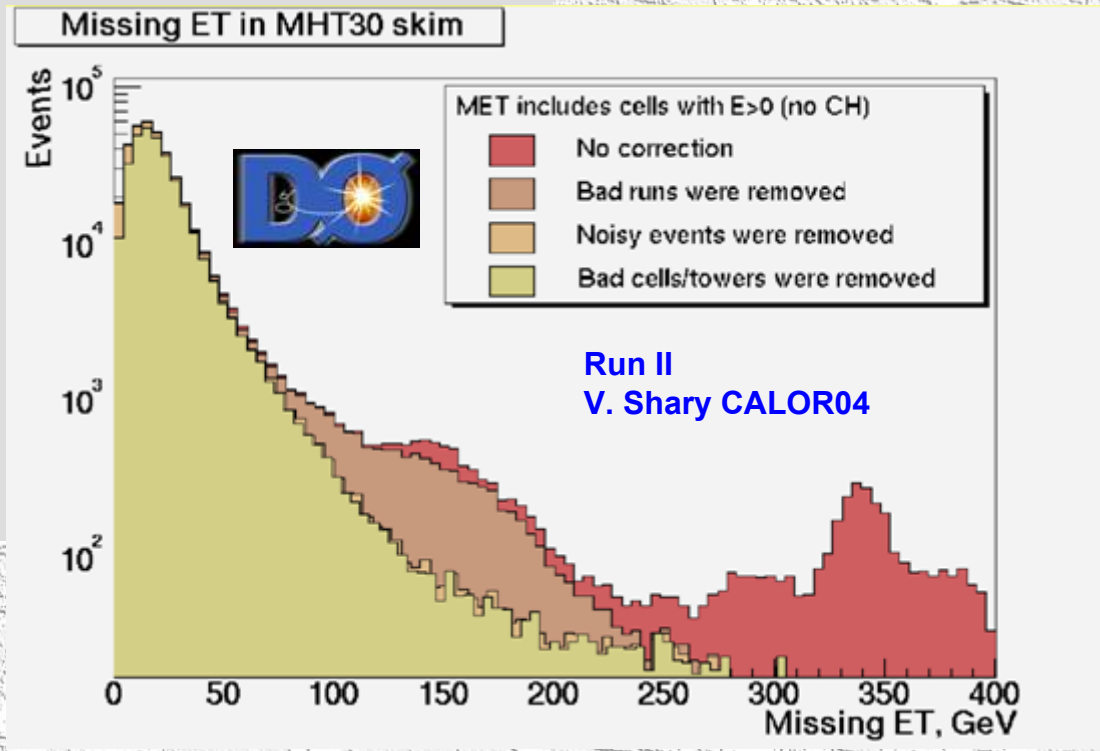
	ATLAS	CMS
length	≈ 46 m	≈ 22 m
diameter	≈ 25 m	≈ 15 m
weight	≈ 7000 t	≈ 12000 t



Understanding of the Detector

Difficult example: missing ET

- **is a very powerful tool to look for new physics**
- **but very complicated variable and difficult to understand:**
- **collison effects**
  - **pile-up**
  - **underlying event**
- **beam related background**
  - **beam halo**
  - **cosmic muons**
- **detector effects**
  - **instrumental noise**
  - **dead/hot channels**
  - **inter-module calibration**



Cross Section of Various SM Processes

⇒ Low luminosity phase

$10^{33}/cm^2/s = 1/nb/s$

approximately

- 10^8 pp interactions
- 10^6 bb events
- 200 W-bosons
- 50 Z-bosons
- 1 tt-pair

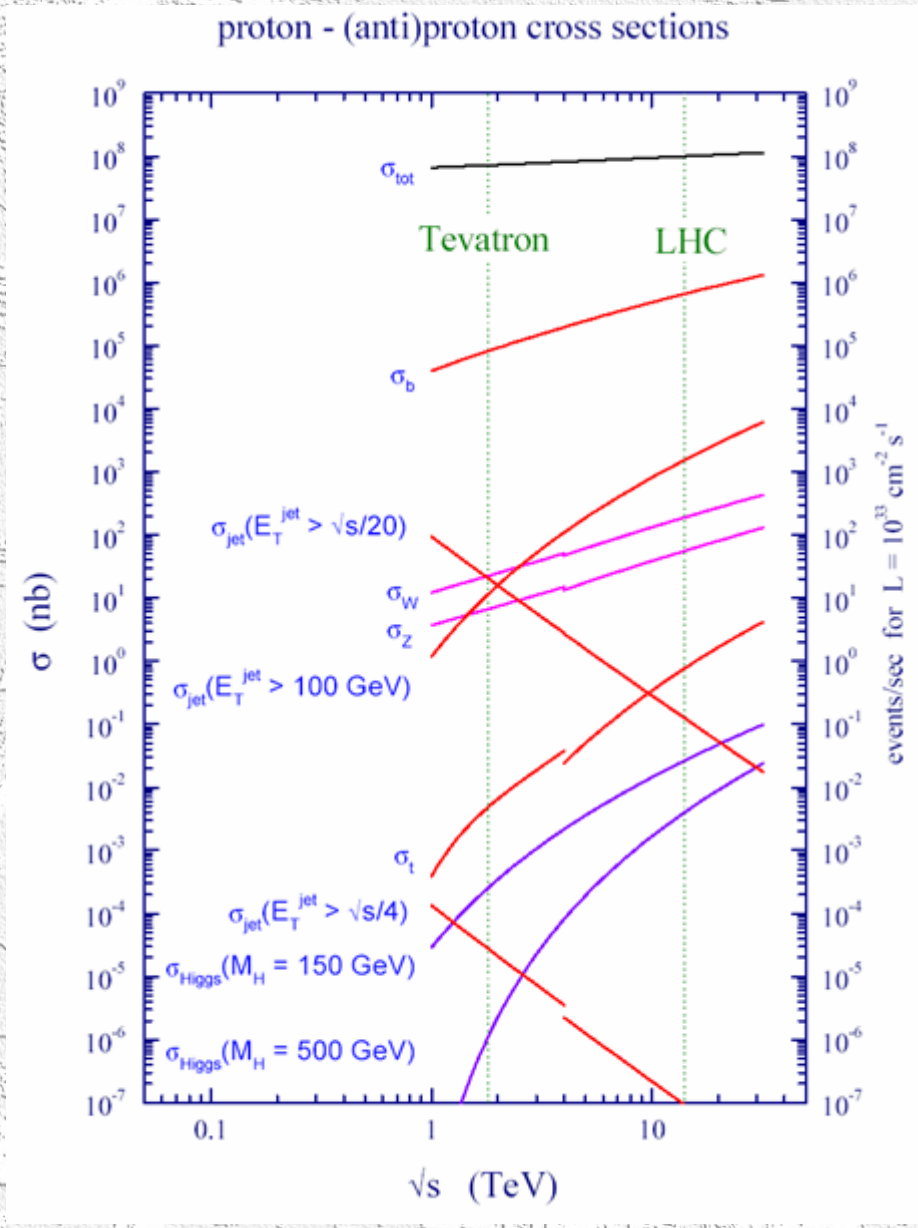
will be produced per second and

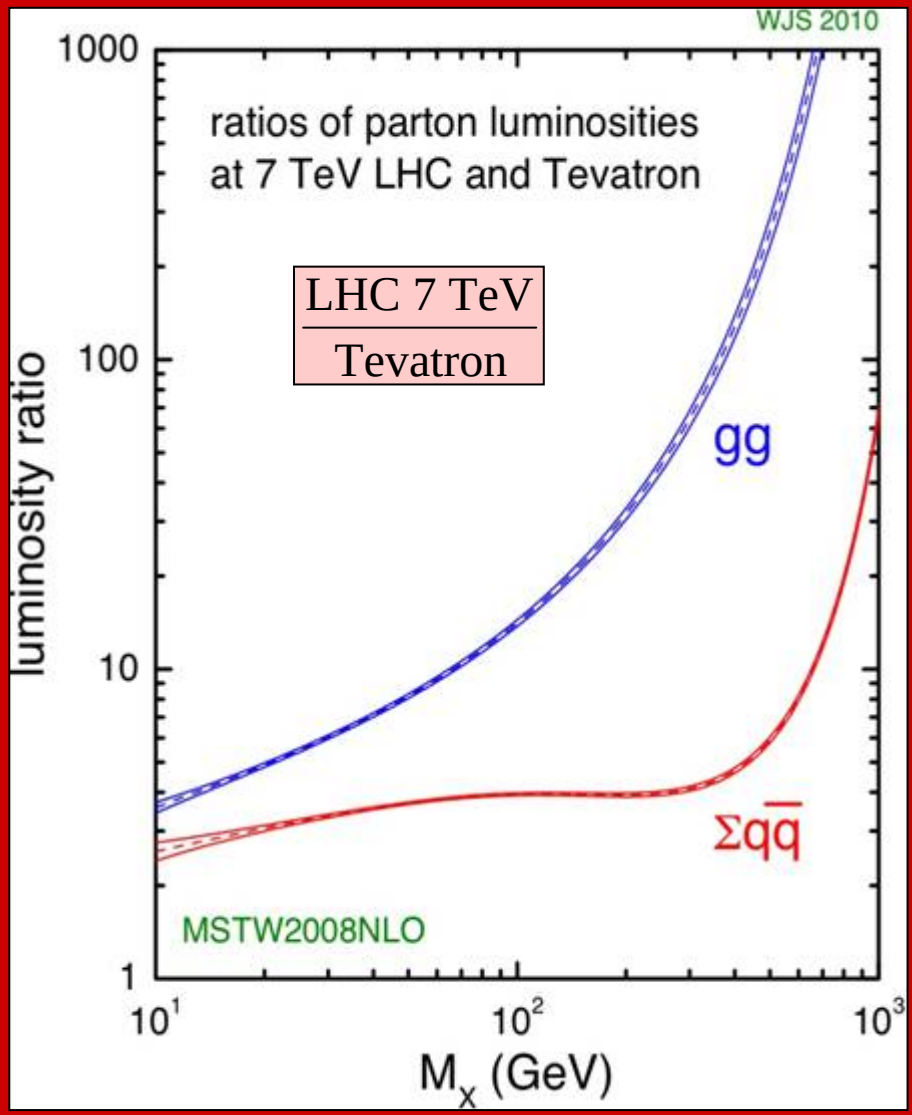
- 1 light Higgs

per minute!

The LHC is a b, W, Z, top, Higgs, … factory!

The problem is to detect the events!





Cross-section	Tevatron	LHC@7TeV/Tevatron	LHC@14TeV/Tevatron
W/Z → lν, ll	2.5/0.25 nb per family	~ 5	~ 10
tt production	7.2 pb	~ 20	~ 100

Resonances in the CMS tracker