The Large Hadron Collider LHC
A New Era in Particle Physics

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DESY

50^{th} Anniversary Particle and Nuclear Physics at KIT

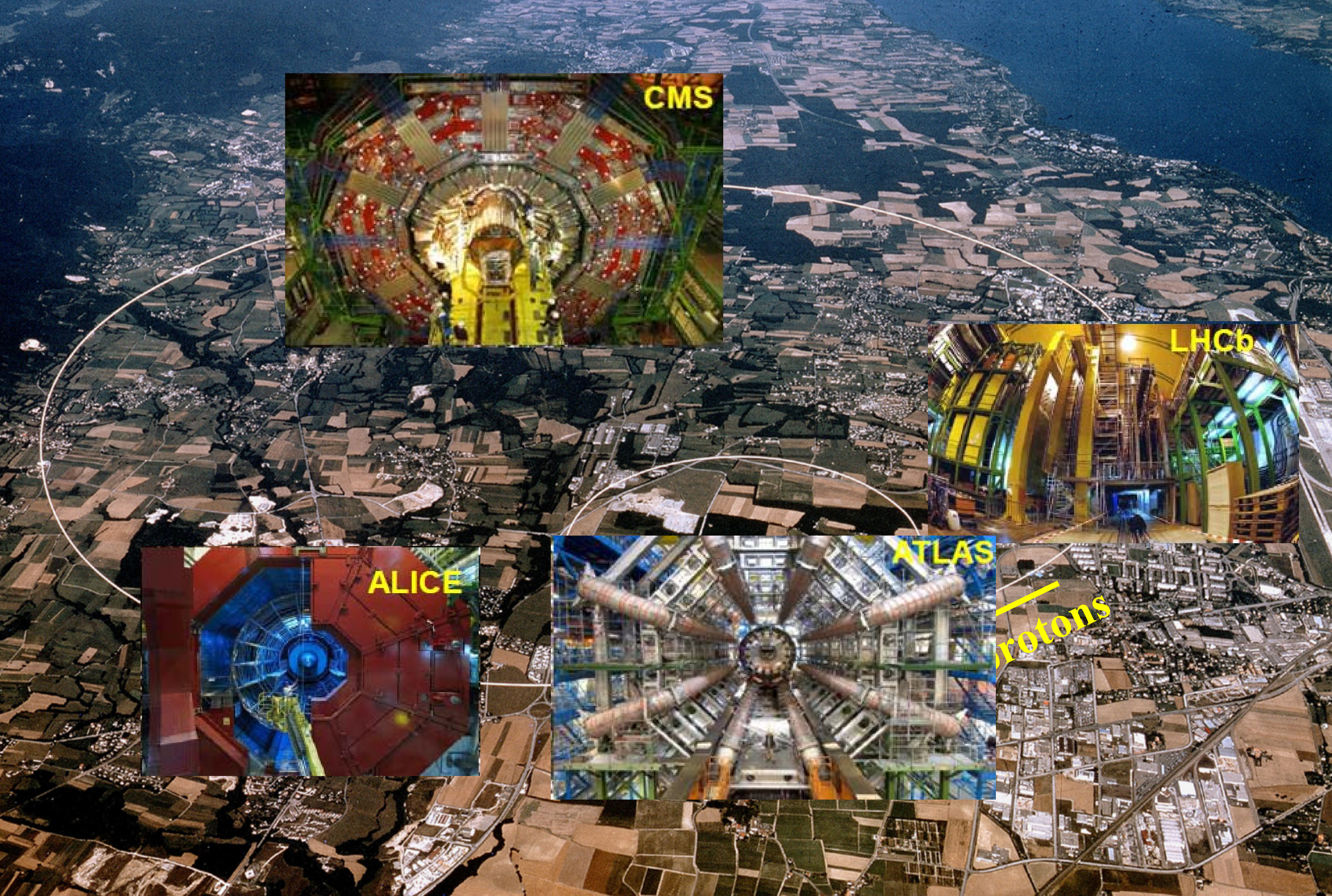
Karlsruhe
December 14, 2010

Outline

- The Large Hadron Collider
- The Experiments
- LHC physics
- First beams & collisions
- 2010 results*
- Plans & prospects

*results mostly from open LHCC session Nov 17, 2010

The Large Hadron Collider (LHC)



The Large Hadron Collider (LHC)

- Proton-proton collider in the former LEP tunnel
- The LHC <u>uniquely</u> combines the two most important virtues of HEP experiments:

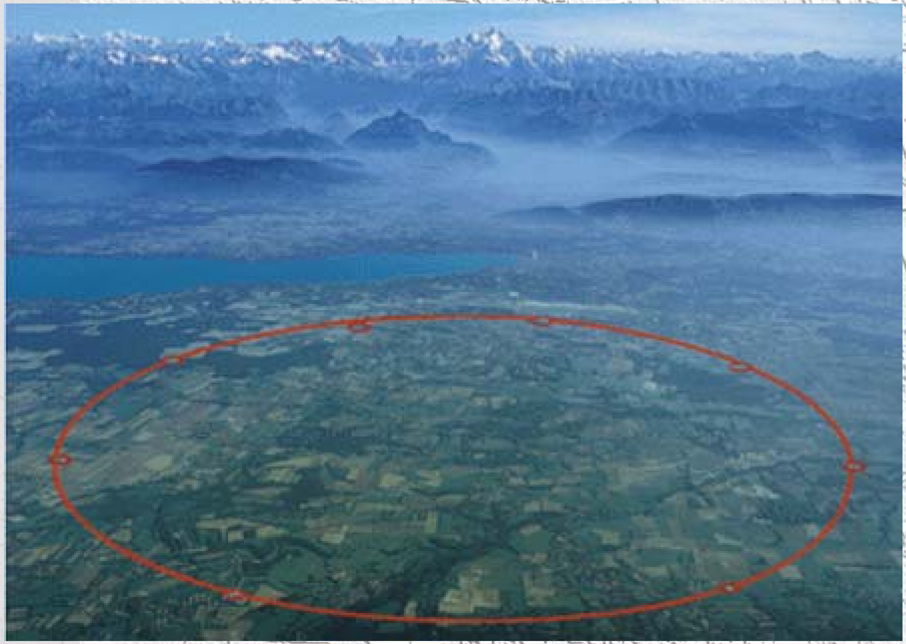
  1. Highest ever energy per collission

     up to 14 TeV in the pp-system
     cf. Tevatron at 2 TeV

  2. High luminosity

     up to $10^{34}/cm^2/s$

- 4 experiments:
  ATLAS large multi-purpose detector
  CMS large multi-purpose detector
  LHCb specialised on b-physics
  ALICE specialised for heavy ion collisions



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**

The LHC Project: Dipoles

- **First dipole prototype reached 8.73 Tesla on April 14, 1994**

- **Last of 1232 dipoles lowered on April 26, 2007**

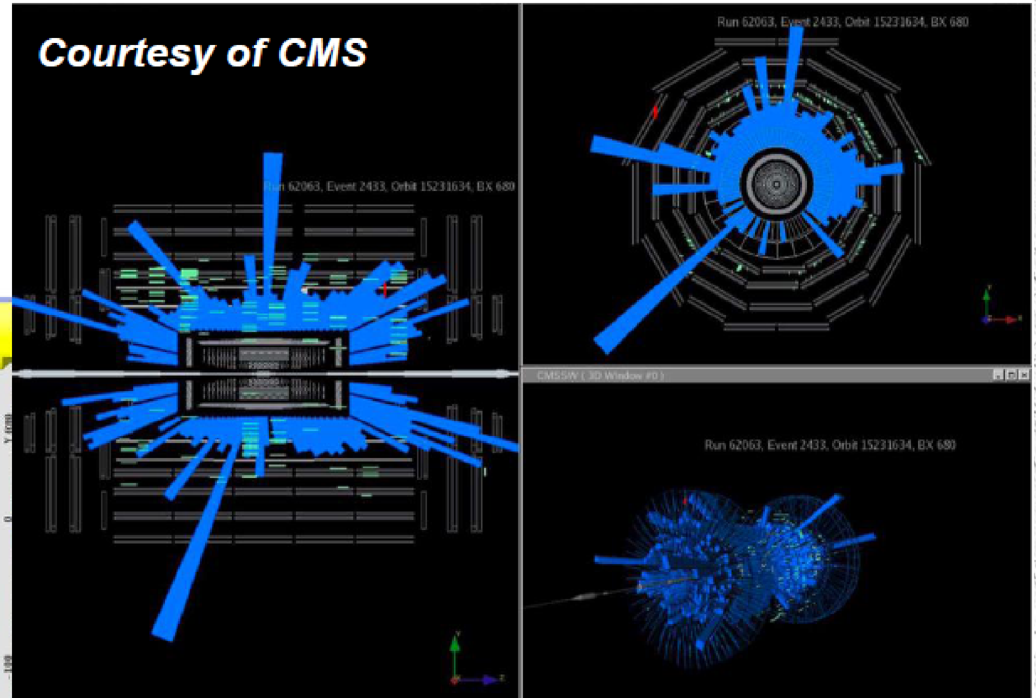
The LHC Today

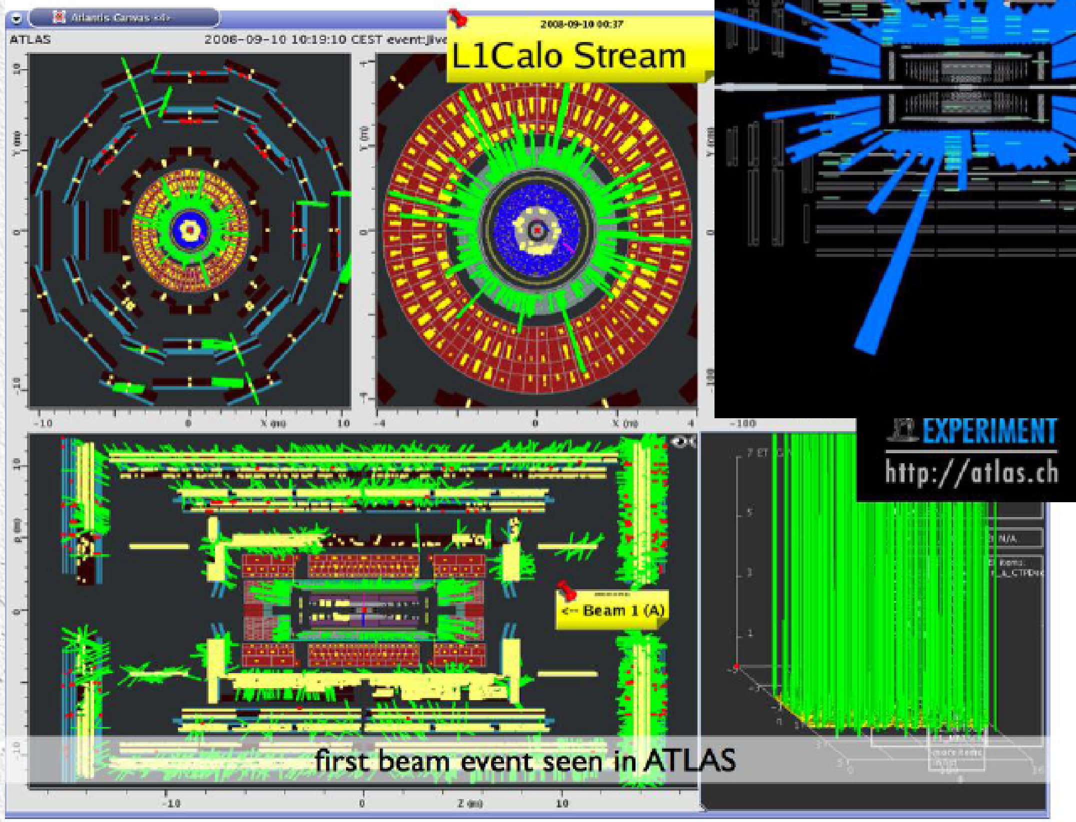
First Beams & Collisions

- **First circulating beams on September 10, 2008**

Beam Splash Events

- **Beam on closed collimators**





Courtesy of ATLAS

- **Important to commission detectors, e.g. timing**

The Accident

- **Major set-back on September 19, 2008**
  - **bad connection between two magnets**
  - **thermal runaway**
  - **light arc between magnets destroyed a He vessel**
  - **shock wave in tunnel**

- **Consequences:**
  - **delayed first collisions by 1 year**
  - **max. beam energy 3.5 TeV**
  - **1 year shutdown needed to stabilize magnet interconnects**

53 magnets to be repaired & reinstalled

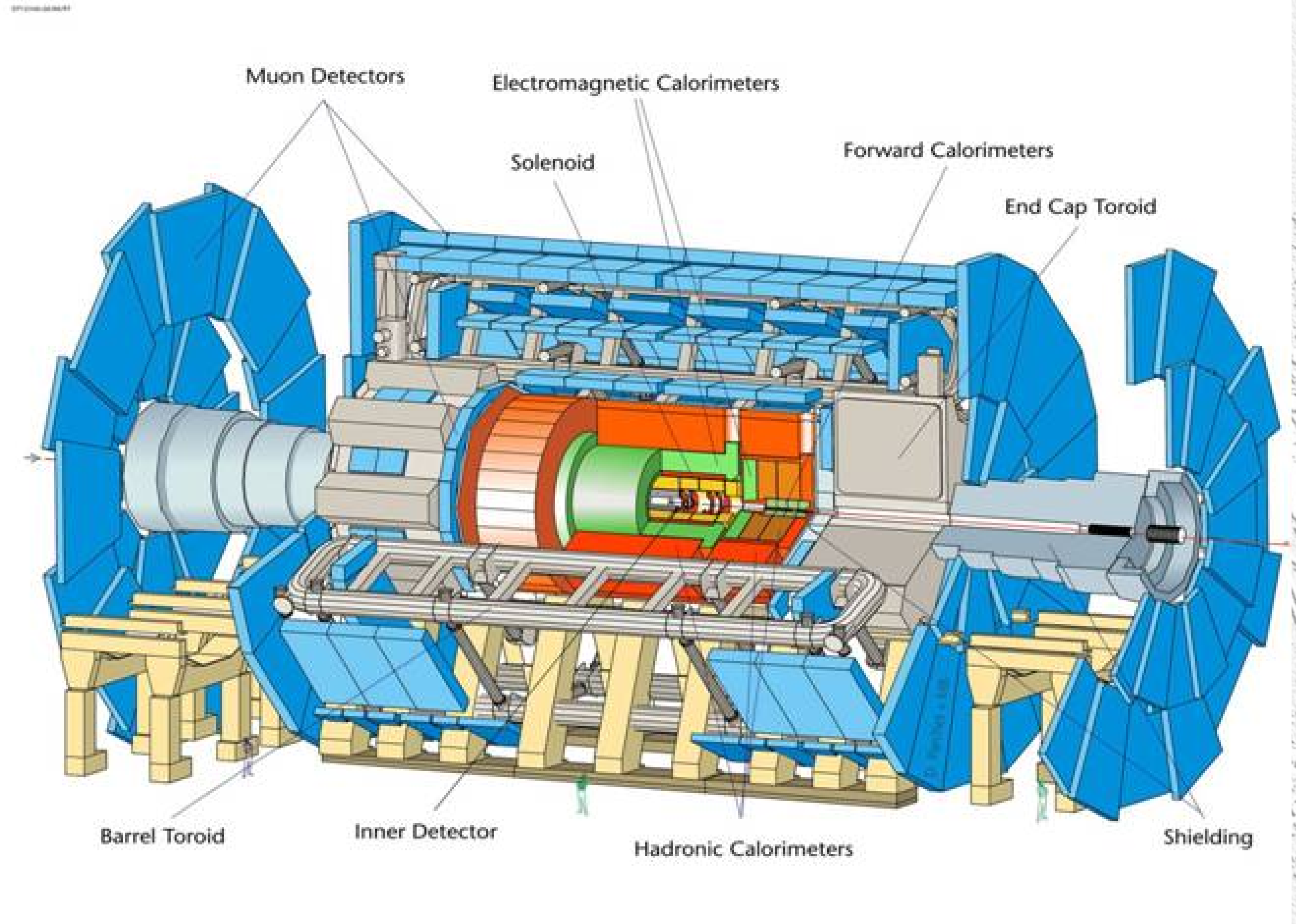
The ATLAS Experiment

A Toroidal LHC ApparatuS

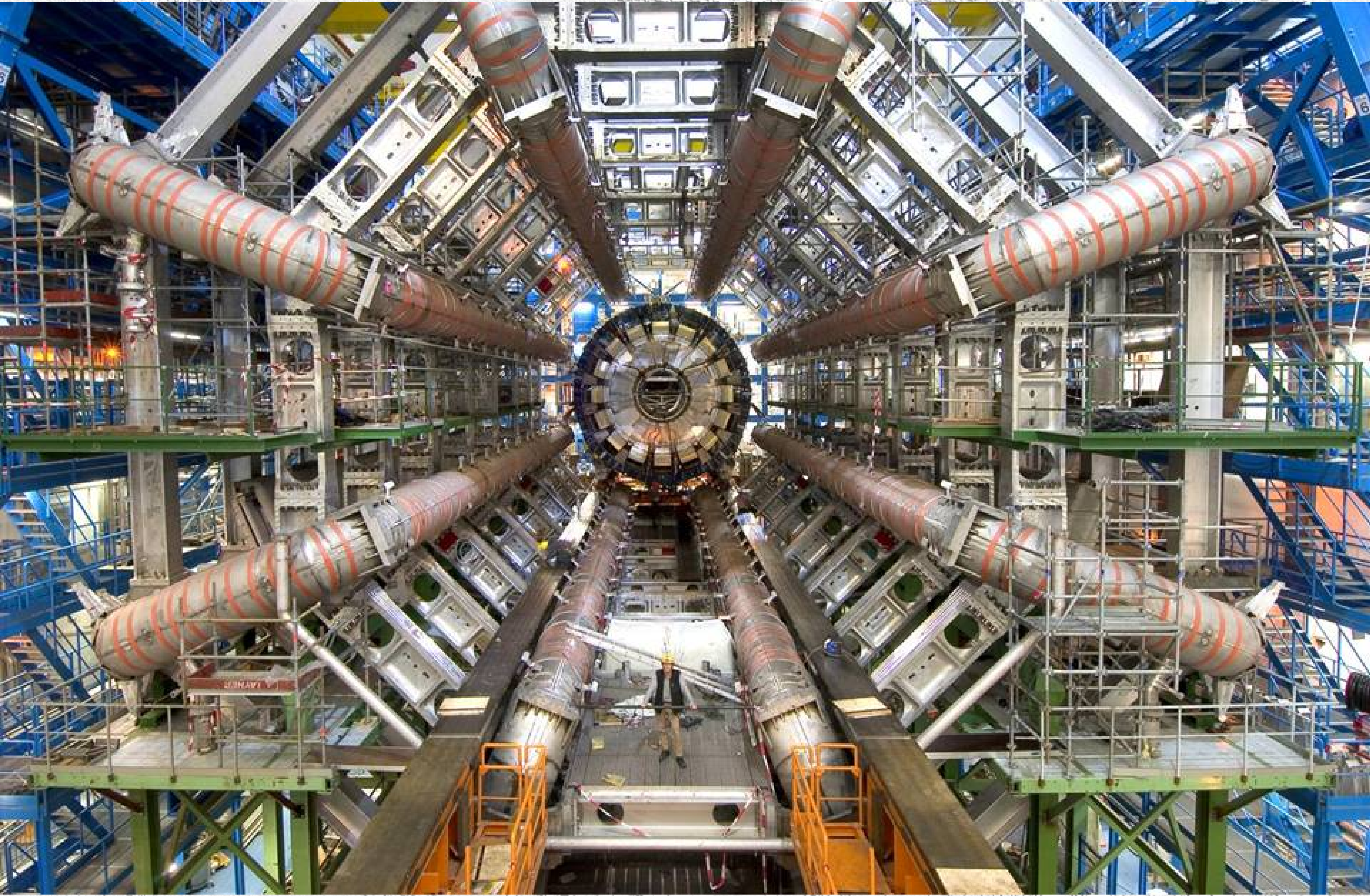
ATLAS in a nutshell:
- Large air toroid with μ chambers
- HCAL: steel & scintillator tiles
- ECAL: LAr
- Inner solenoid (2 T)
- Tracker: Si-strips & straw tubes (TRD)
- Si-pixel detector

10^8 channels

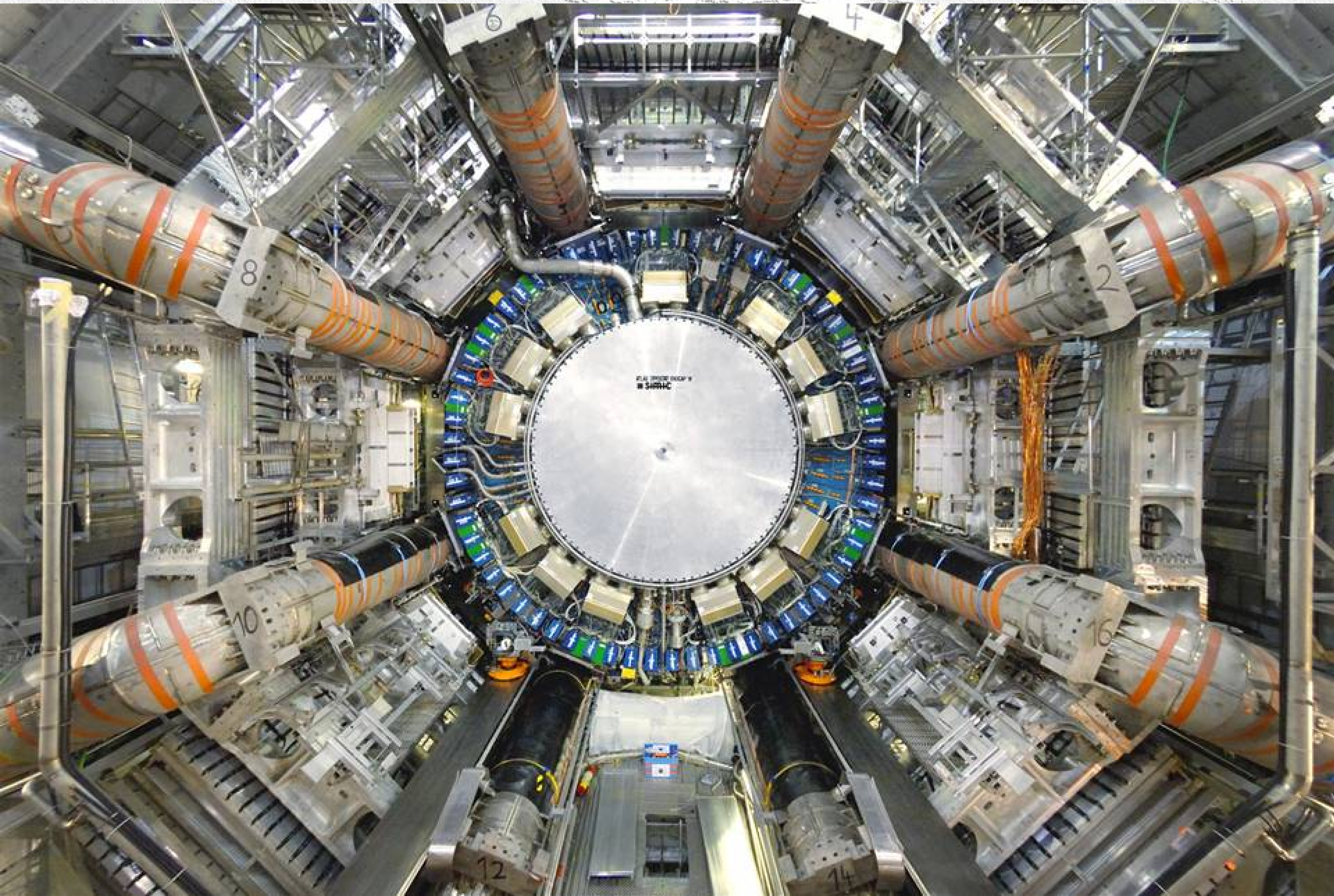
15 μm resolution



ATLAS



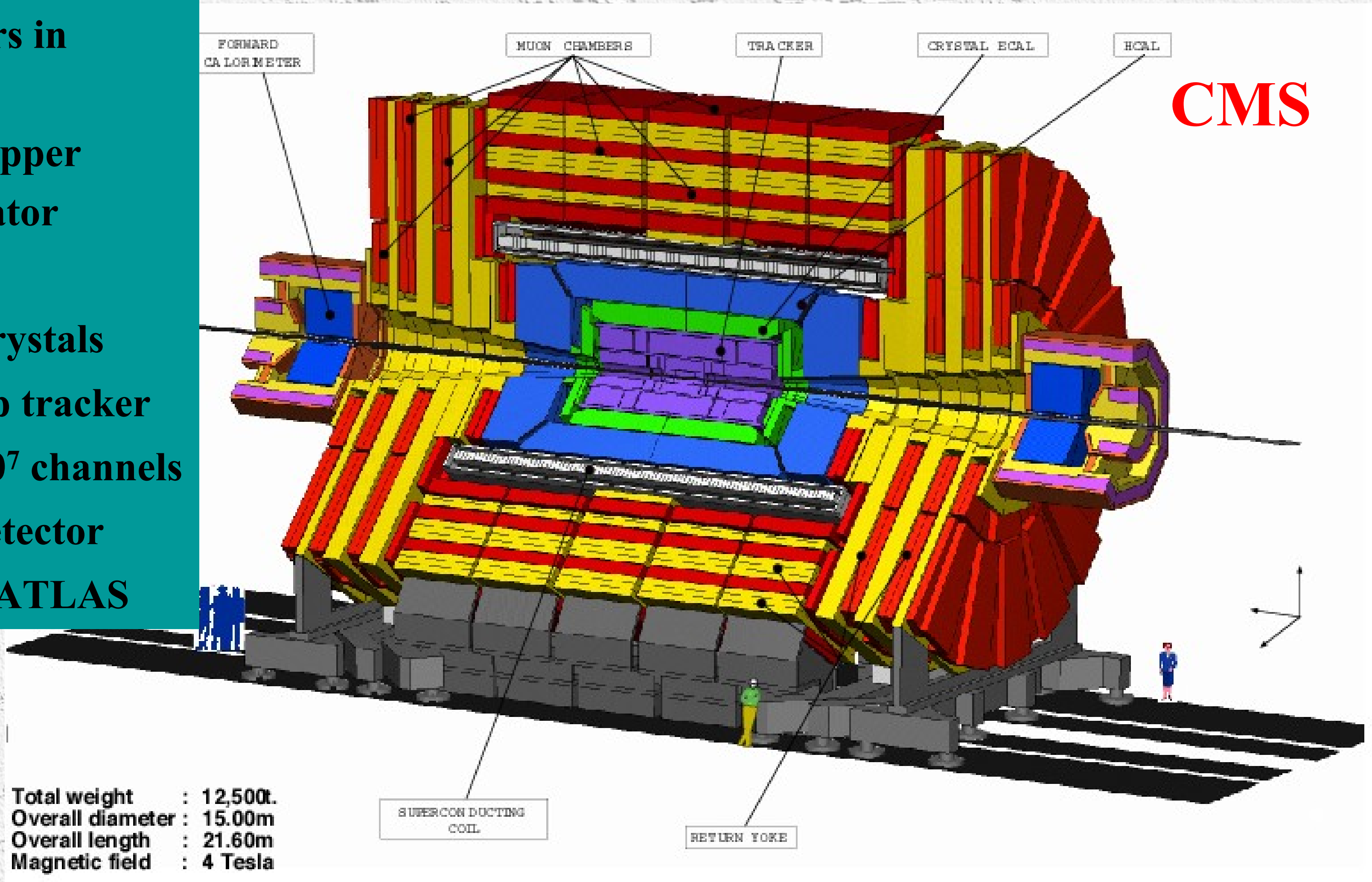
ATLAS with inner Detectors



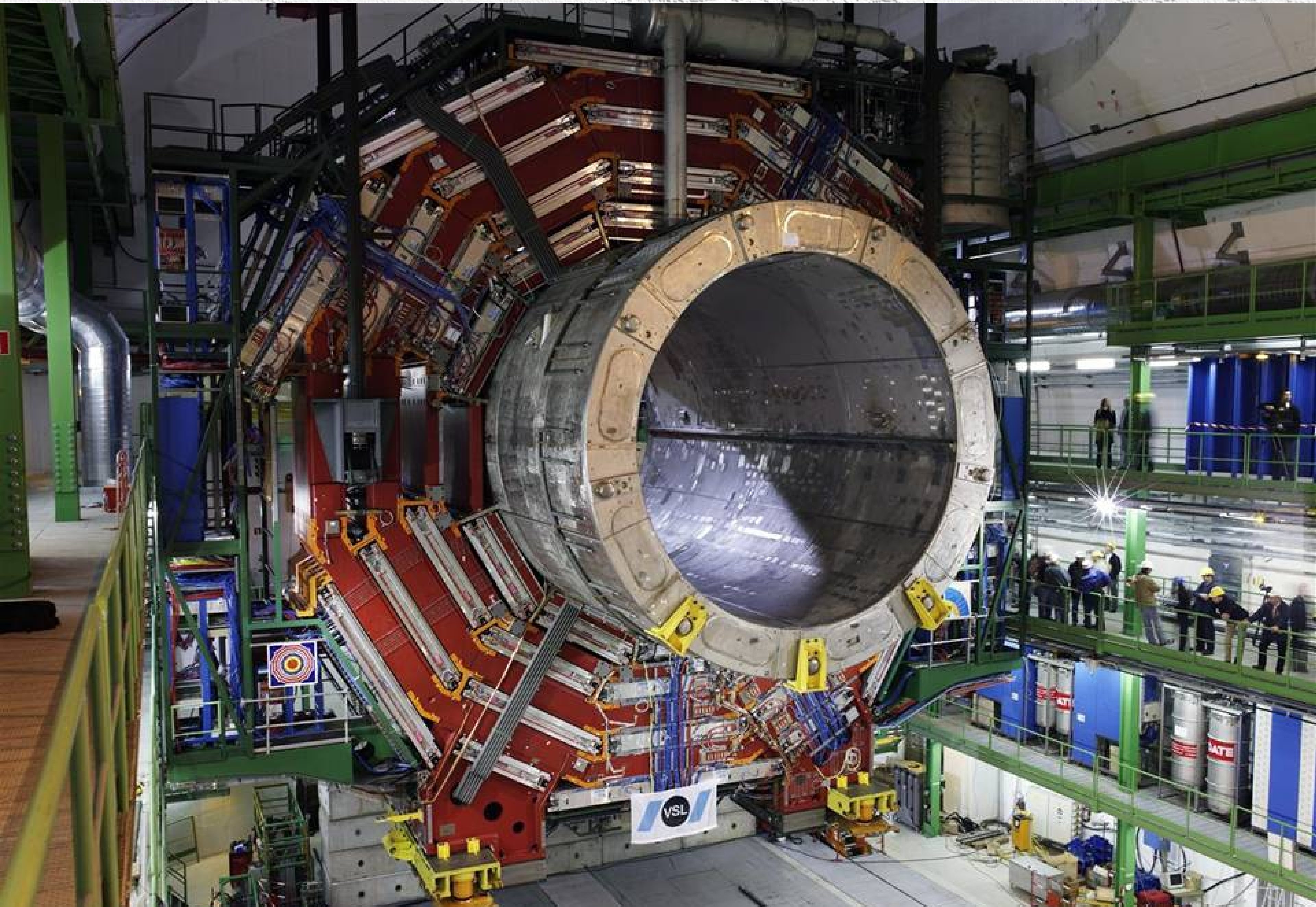
The CMS Experiment

Compact Muon Solenoid

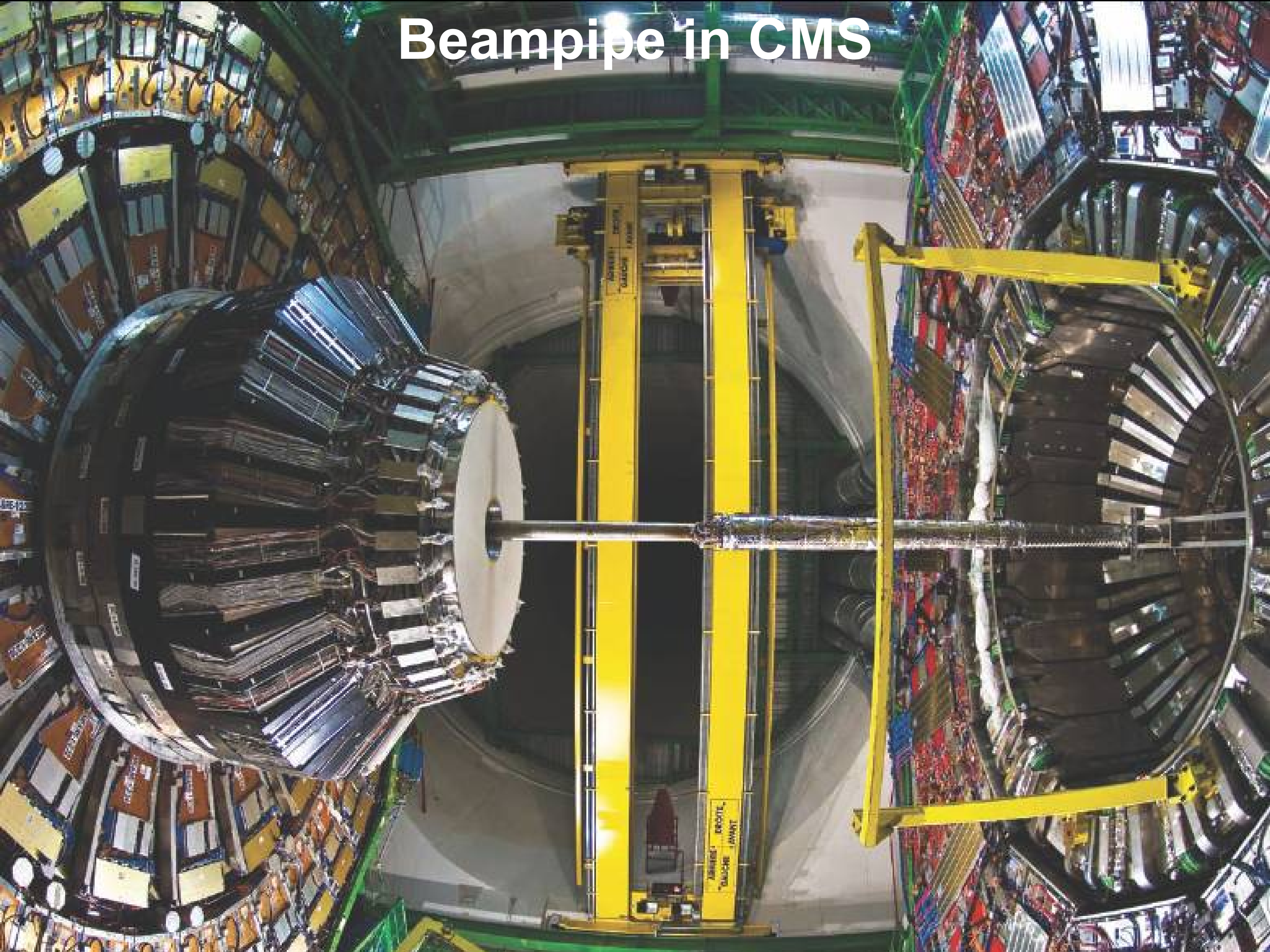
CMS in a nutshell:
- 4 T solenoid
- μ chambers in iron yoke
- HCAL: copper & scintillator
- ECAL: $PbWO_4$ crystals
- All Si-strip tracker $220\ m^2$, 10^7 channels
- Si-pixel detector similar to ATLAS



CMS: Compact Muon Solenoid

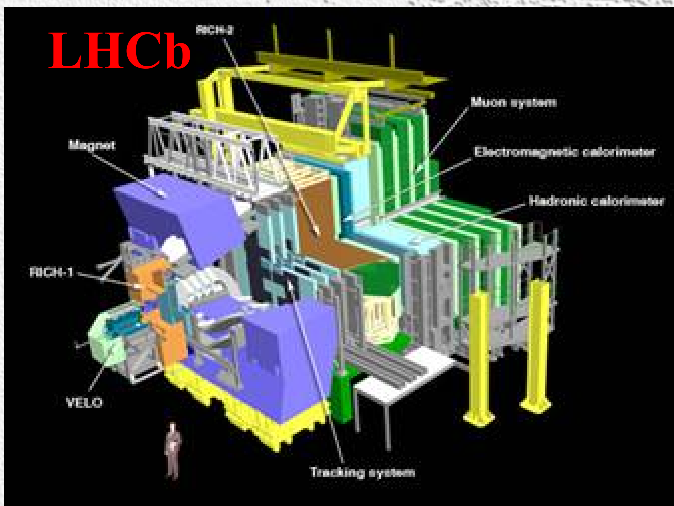


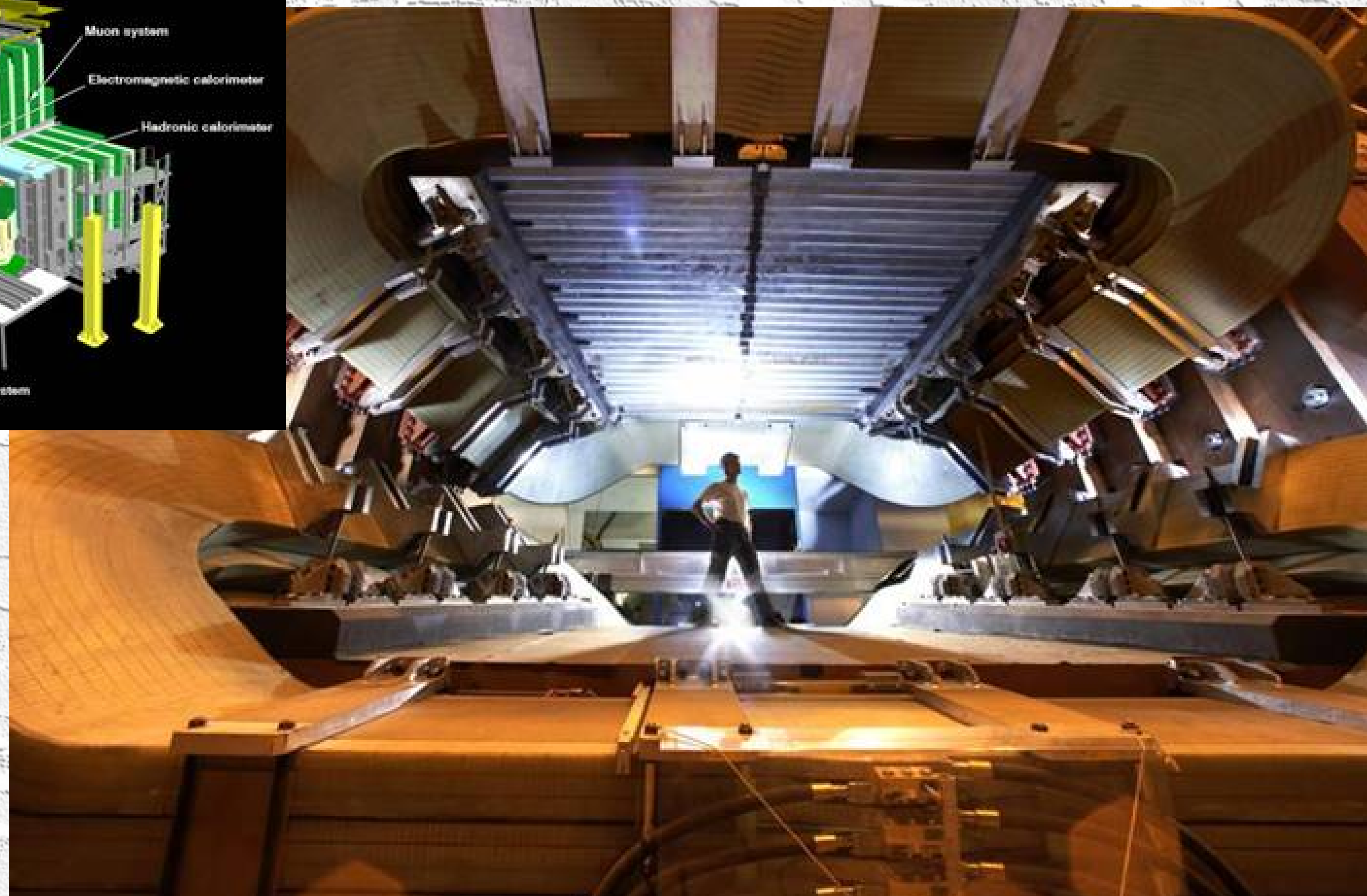
Beampipe in CMS



LHCb

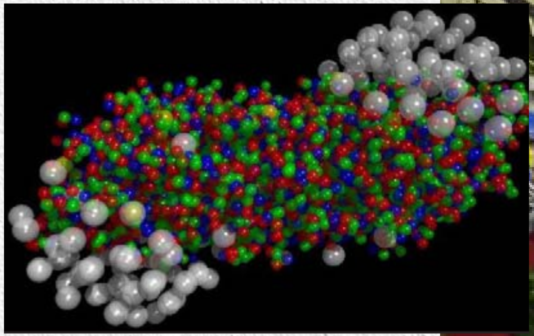
- **Forward spectrometer for B-physics**
- **addressing the question of matter-antimatter asymmetry**



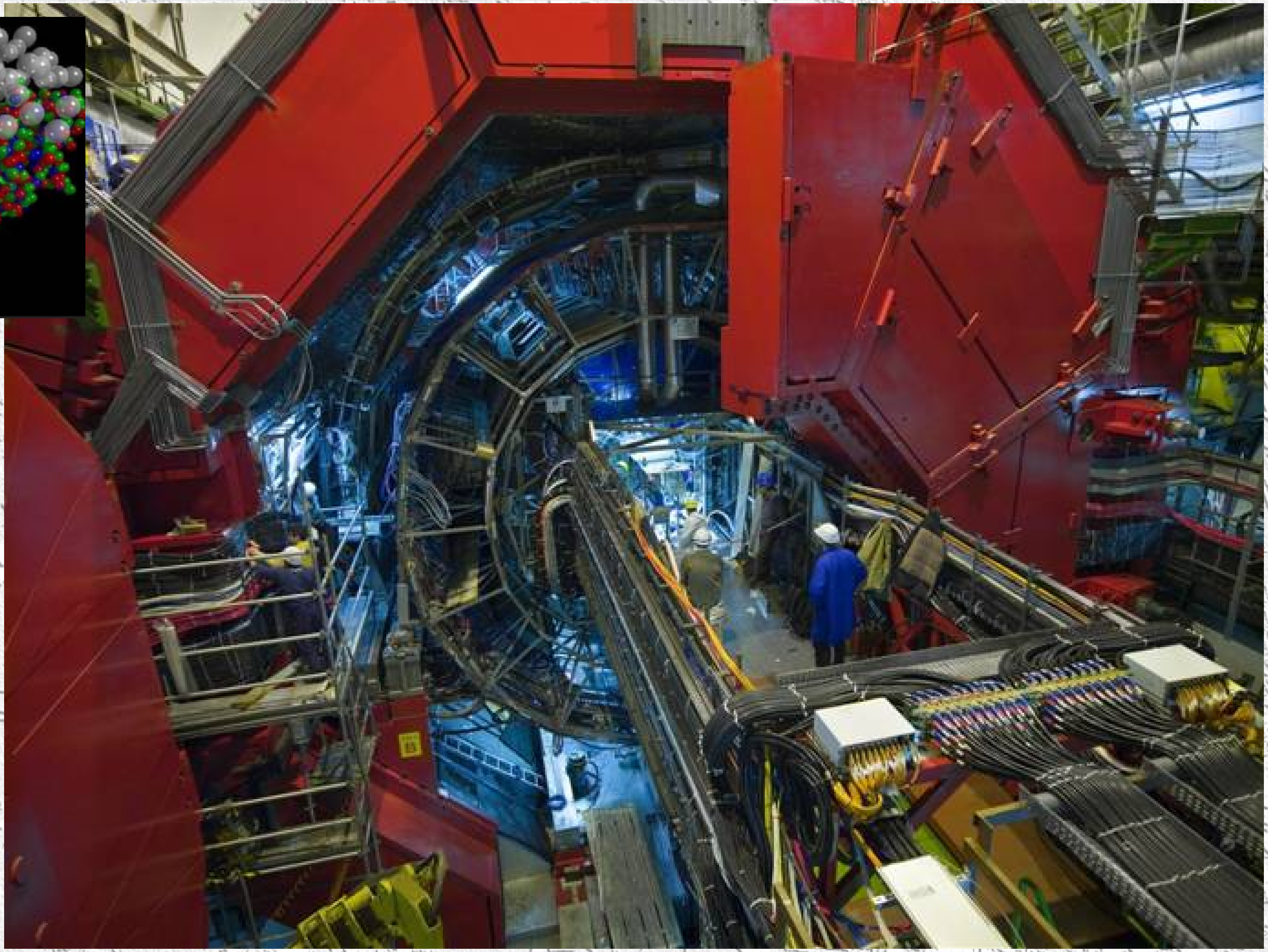


ALICE

- **Experiment addresses new state of matter: the quark-gluon plasma**

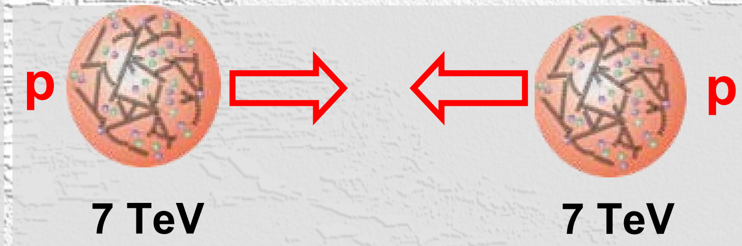


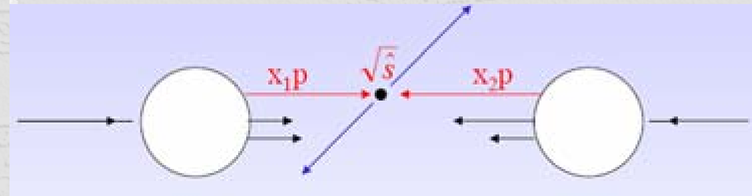
- **Heavy ion collisions, eg. Pb-Pb**
- **Using L3 magnet**

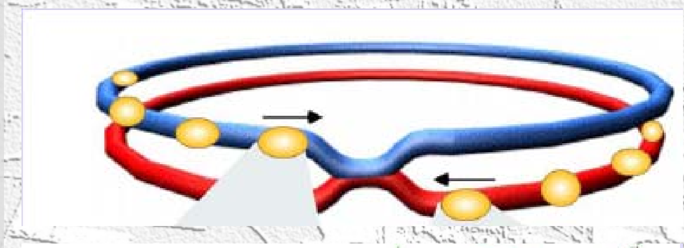


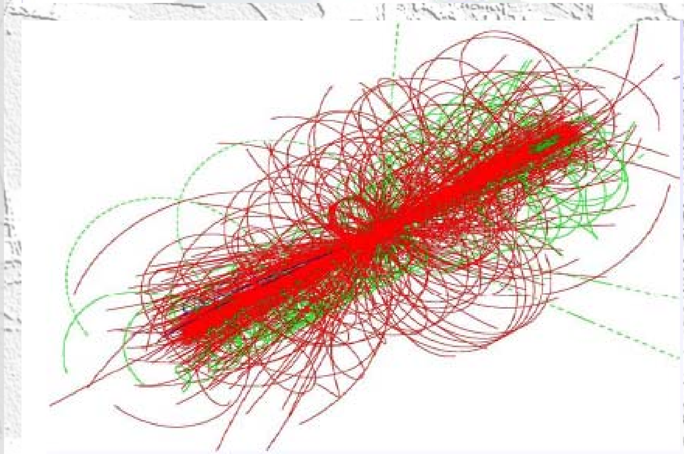
Challenges for LHC Detectors

- **Protons are composite particles**
  - Bags filled with quarks and gluons
  - Quark-quark and gluon-gluon collisions are the fundamental processes
  - Screened by interactions of other quarks & gluons
- **LHC is filled with 2835 + 2835 proton bunches**
  - Collisions every 25 ns, i.e. 40 MHz crossing rate
- **10^{11} protons per bunch**
  - 25 pp interactions per crossing (pile-up)
  - Each bunch collision produces ≈ 1600 charged particles

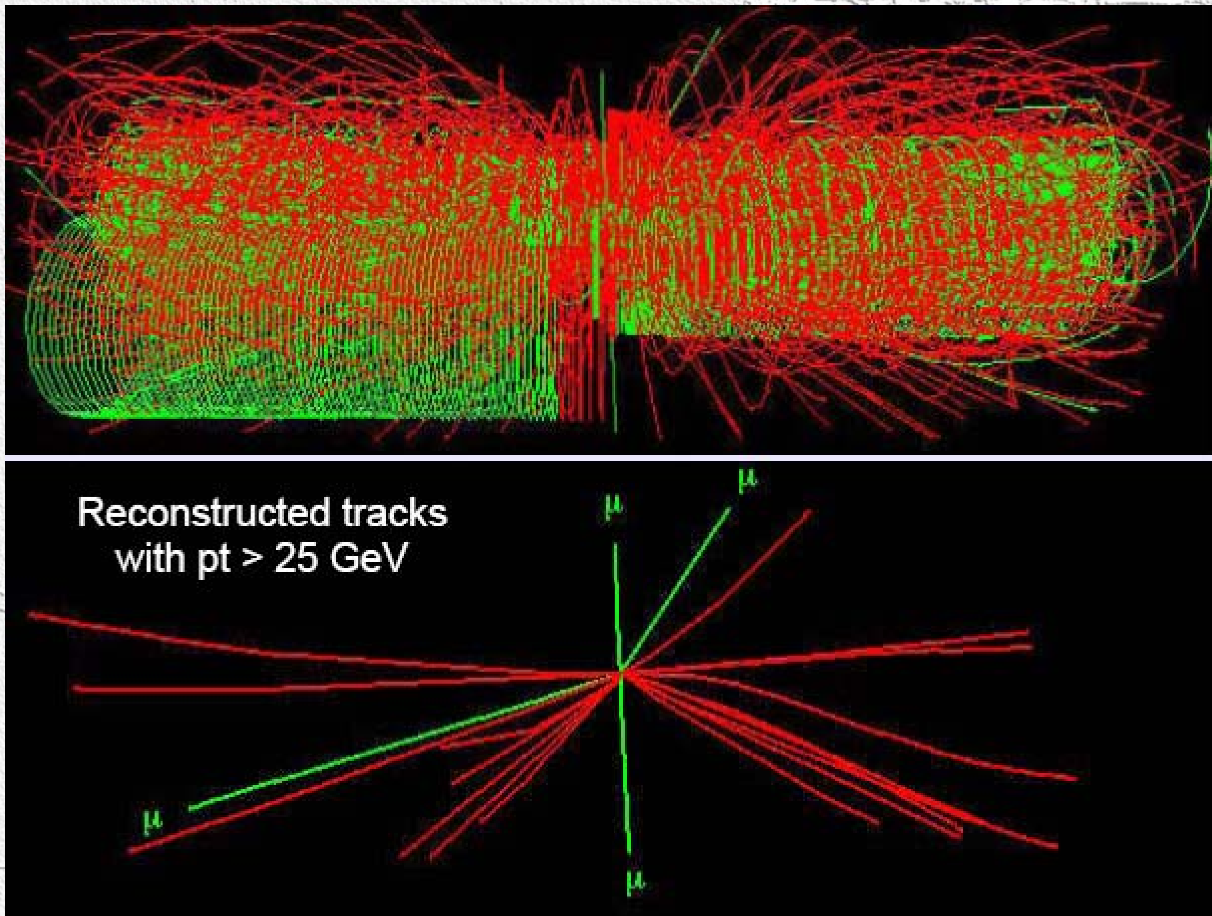








A Collision Producing a Higgs Boson



- with 25 pile-up interactions
- Remove low energy tracks (p_T < 25 GeV)
- H → ZZ → 4 muons

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

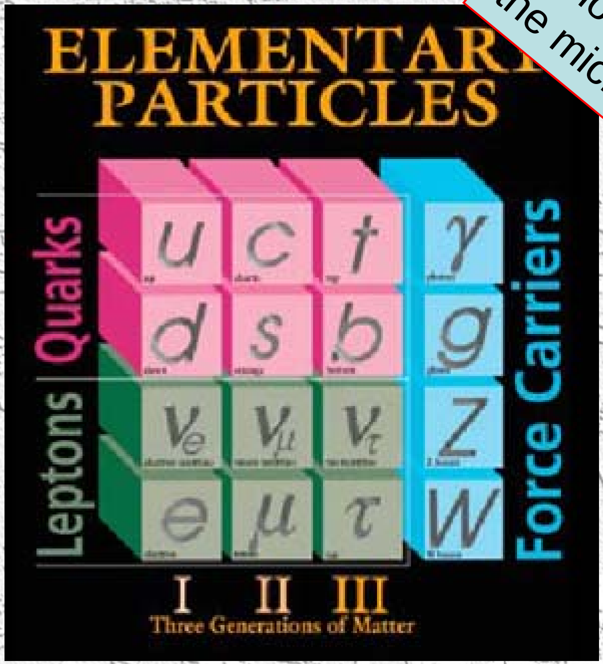
Particle Physics at the Energy Frontier

- **Progress in theory and experiment over the past decades**

Standard Model of Particle Physics

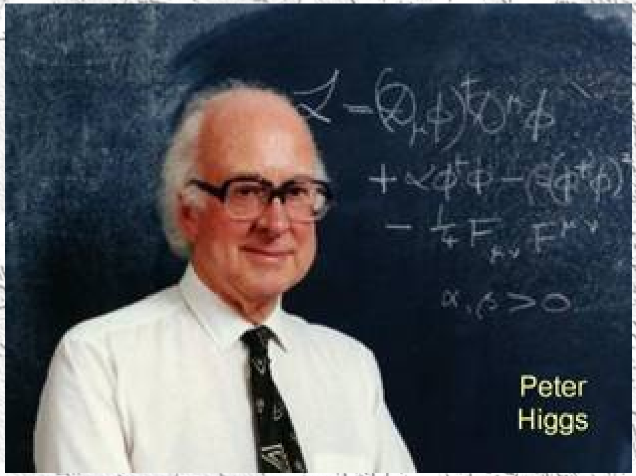
  - **Matter particles: Quarks and Leptons**
  - **Force carriers: Gauge Bosons**

- **Excellent theory tested down to 10^{-18} m**

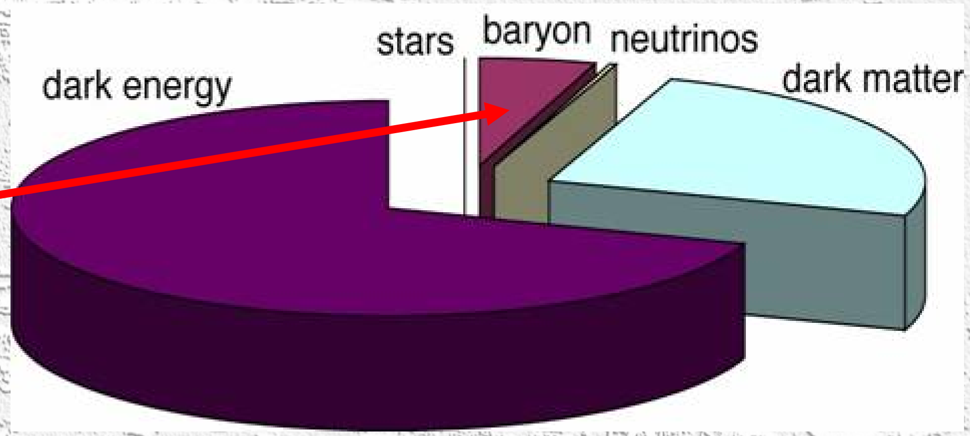


Periodic system of the microcosm

- **However**
  - **Missing corner stone: Higgs-Boson**
  - **Many open questions to be addressed at the Terascale**



Particle Physics at the Energy Frontier



- **Standard Model valid only for about 5% of the universe**

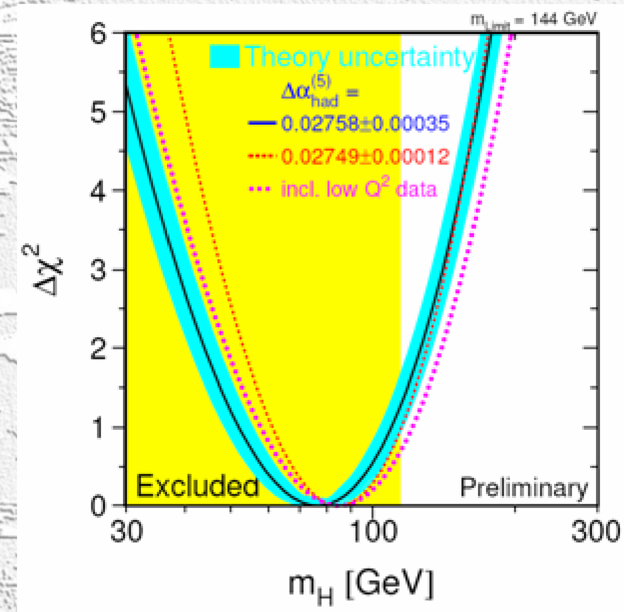
Experimental and theoretical evidence for new physics at scale of 1 TeV

→ LHC

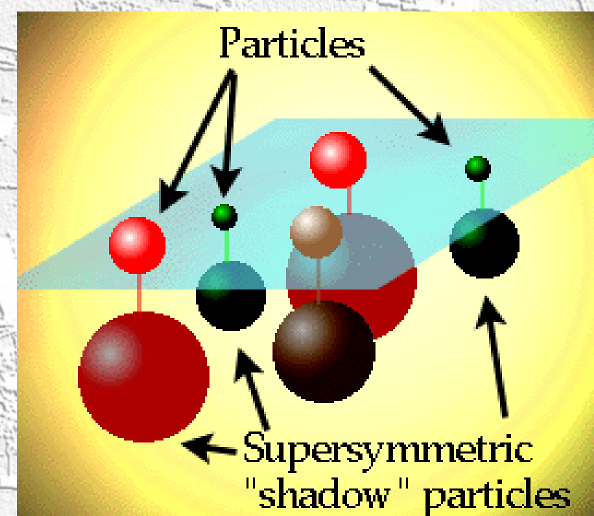
- **Mystery of Dark Matter**
  - **What is the universe made of?**
  - **Particles produced copiously at the big bang?**
  - **Supersymmetry provides a candidate for Dark Matter to be discovered at the LHC**

Origin of Mass and Supersymmetry

- **Higgs Particle**
  - What is the origin of mass?
  - Do fundamental particles acquire their mass through the Higgs mechanism?
  - Is space filled with an omnipresent energy field?
- If so it can be studied at the Terascale
- If not new phenomena must appear

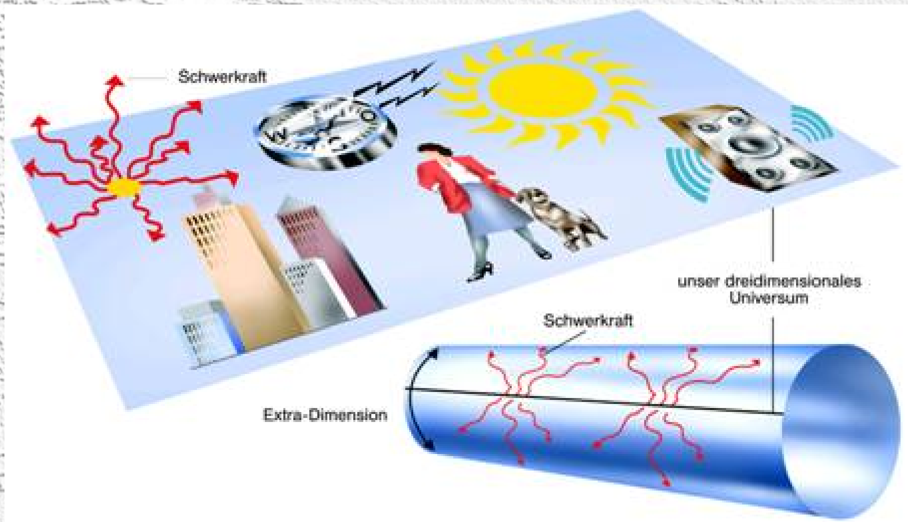


- **Supersymmetry**
  - Symmetry between forces and matter?
  - Mirror world of new supersymmetric particles?
  - New shadow world like antimatter?
  - Supersymmetry as key to resolve clash between Einstein's general relativity and quantum mechanics, i.e. the worlds of large and small scales?
- Experiments at the LHC will provide answers

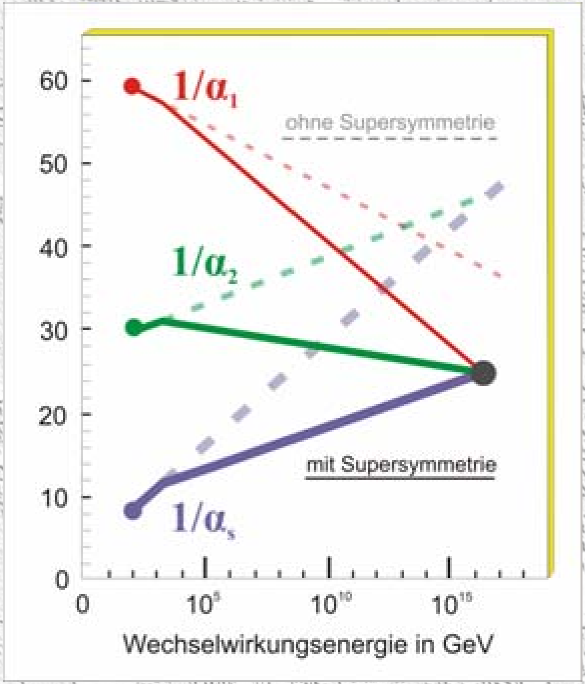


Extra Dimensions and Grand Unification

- **Extra Space Dimensions:**
  - Mystery of vastly different scales of electroweak force (0.1 TeV) and gravity (10^{16} TeV)
  - Gravity scale lowered through extra spatial dimensions to 1 TeV? Curled up on small distances?
- Particles living in extra dimensions could be detected at the LHC

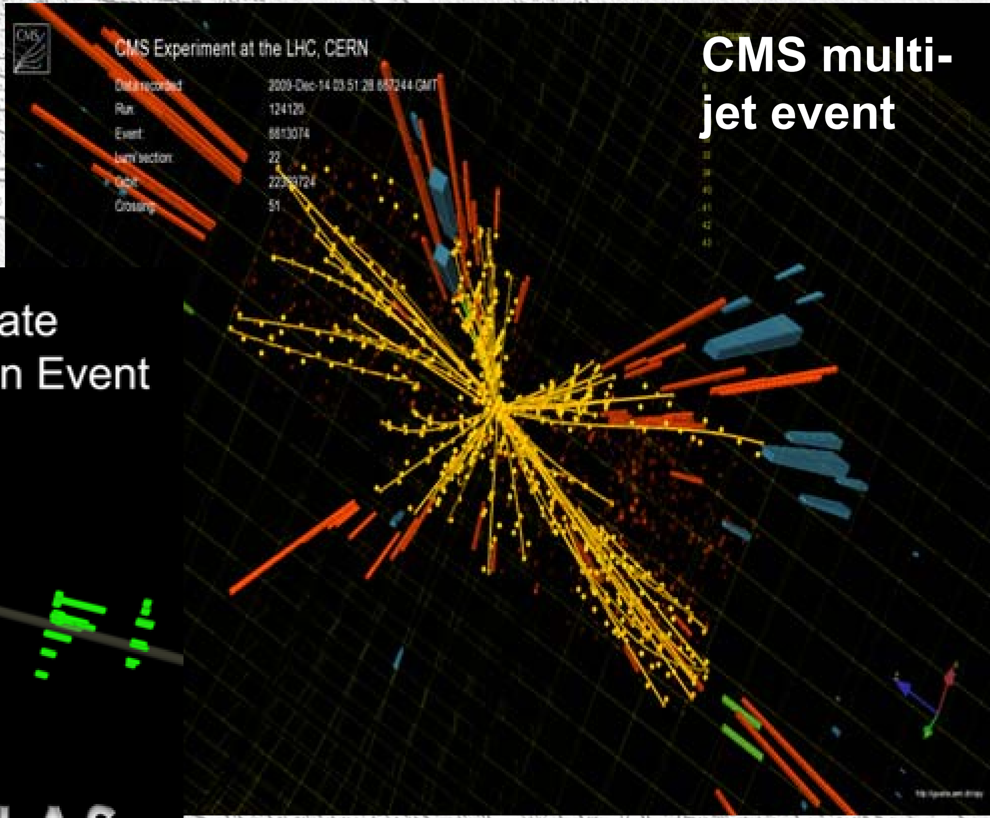


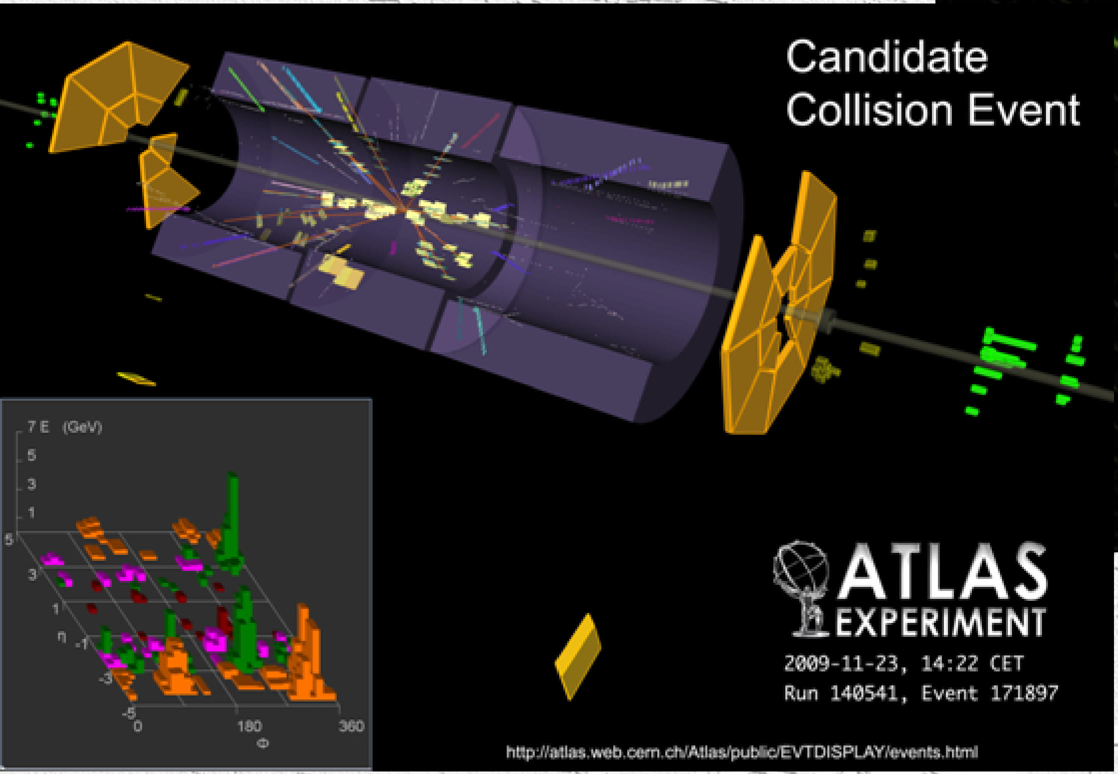
- **Grand Unification:**
  - Why are there three different fundamental interactions?
  - Only one truly fundamental interaction of universal strength?
- Insight to be gained at the LHC



LHC: The Start of the Experimental Programme

- **23 November 2009: First Collisions at 900 GeV**
- **Followed by collisions at 2.36 TeV (world record)**

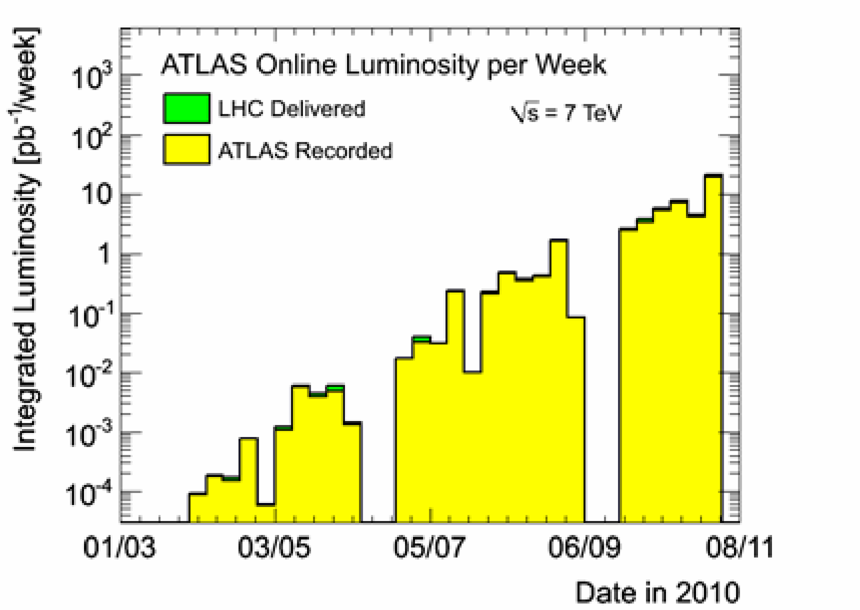


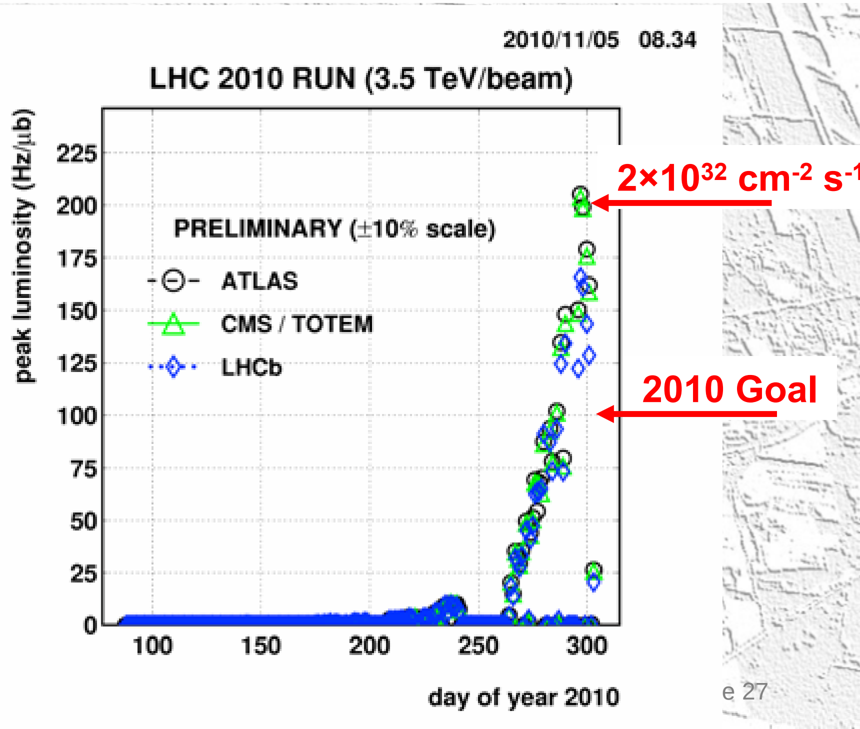


2010: Collisions at 7 TeV

LHC Operation in 2010

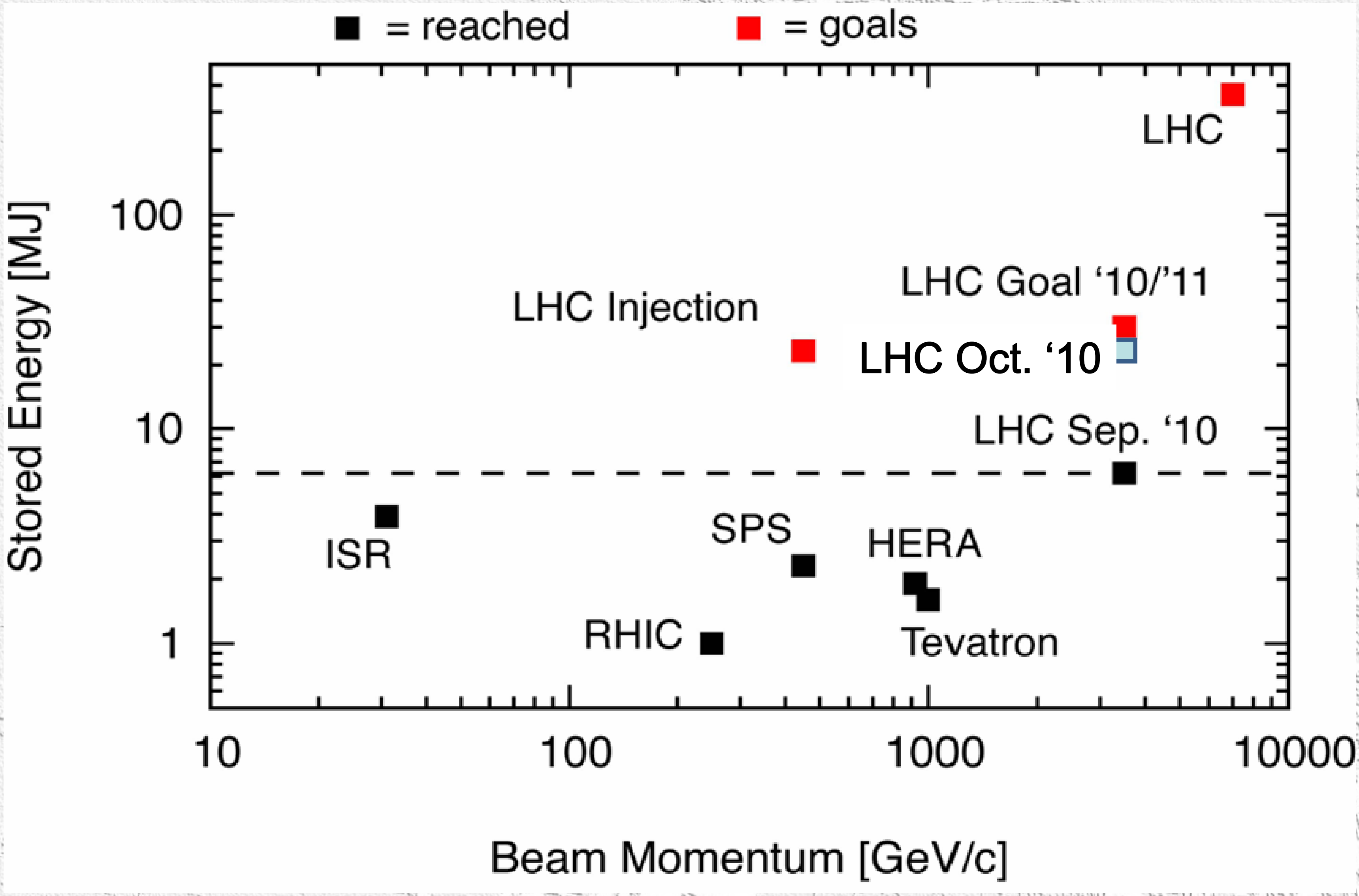
- **About 200 days of very successful machine commissioning and pp-running**
  - Steady increase of luminosity
  - Bunch trains with 150 ns bunch spacing
  - Up to 348 colling bunches
  - Nominal bunch charge
- **Peak luminosity of 2× 10^{32}/cm^2/s achieved**
  - exceeding goal for 2010 by factor 2
- **50 pb^{-1} integrated luminosity per experiment**





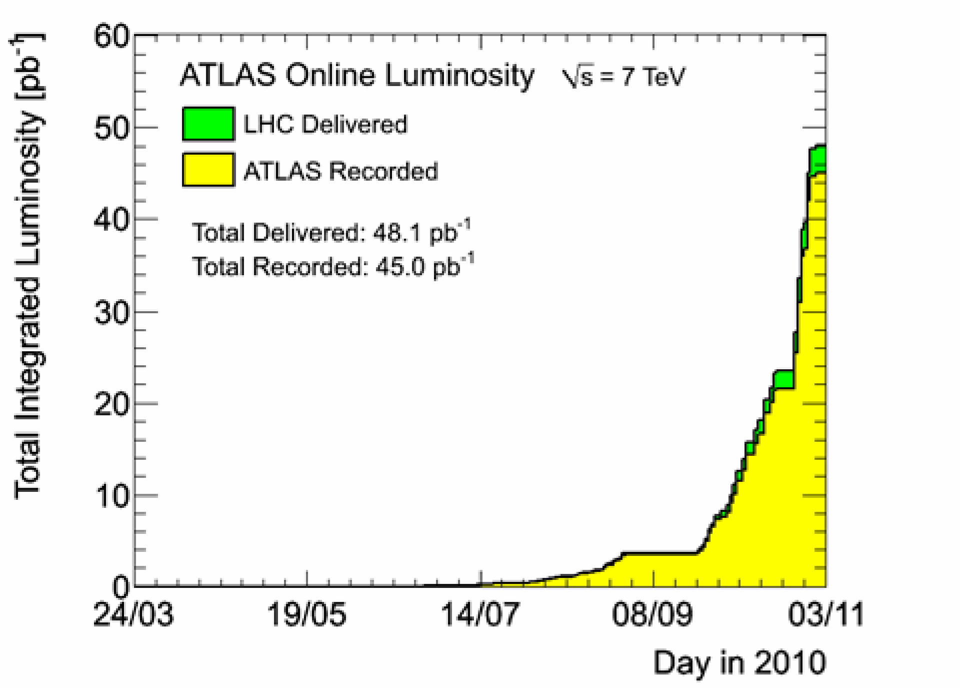
LHC Stored Energy

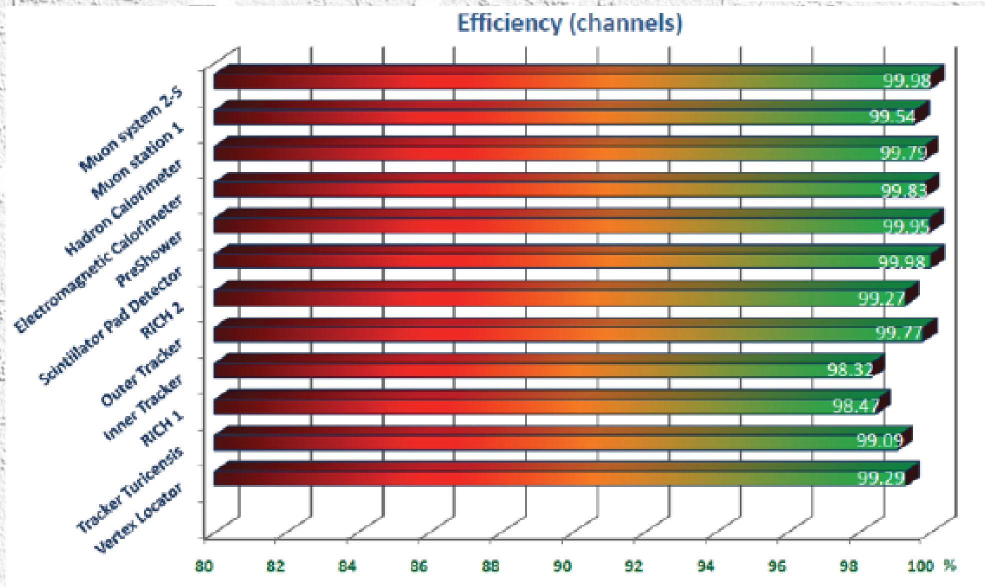
- **LHC pushes the limits of particle accelerators**



Performance of the Experiments

- **All experiments are extremely well prepared**
  - **DAQ effciencies >> 90%**
  - **Already well alignmed & calibrated**
  - **Performance often already close to design**

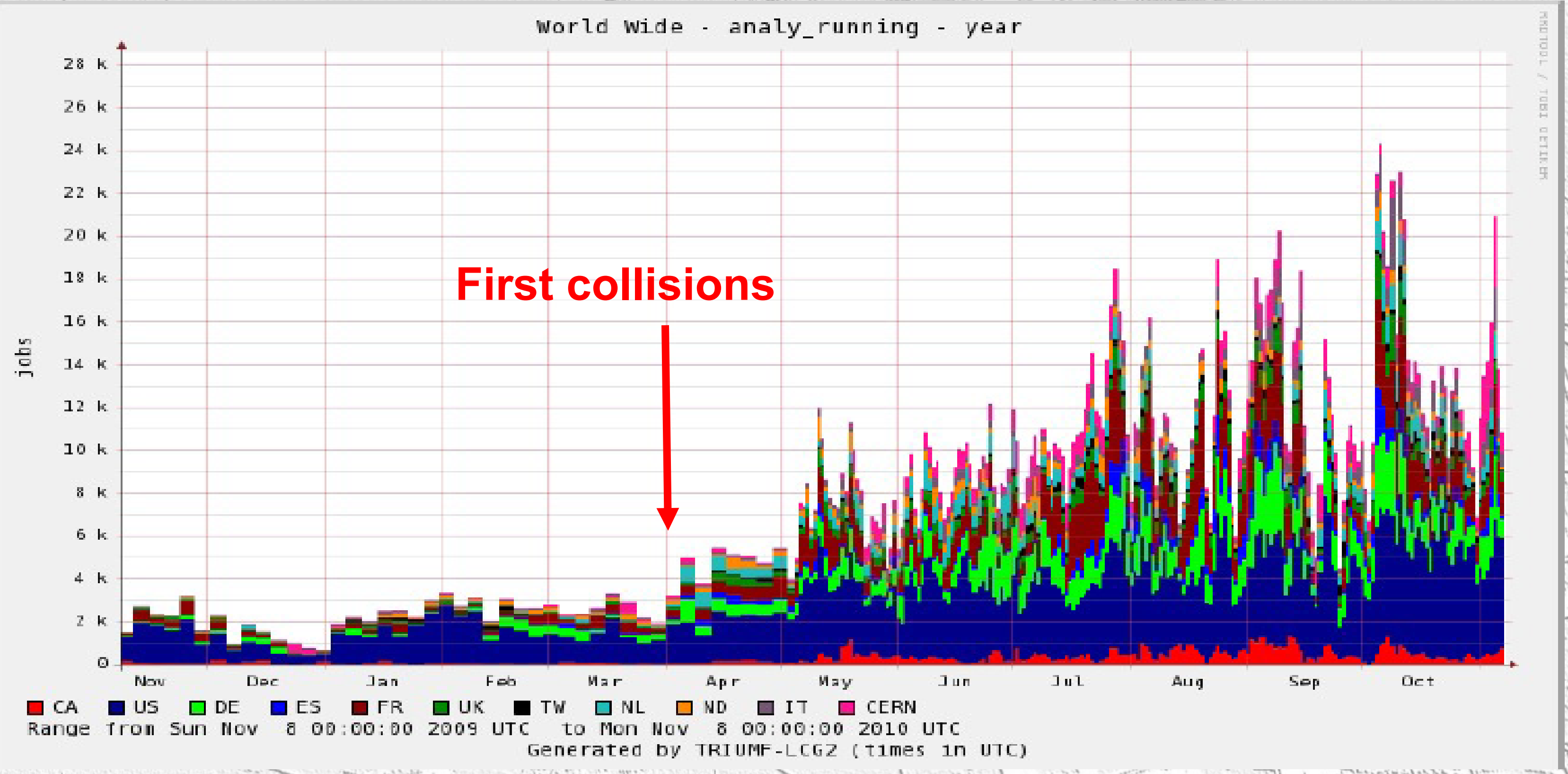




- **Example: LHCb sub-detector efficiencies**

The LHC Computing Grid

- **Computing Grid jobs (example from ATLAS)**

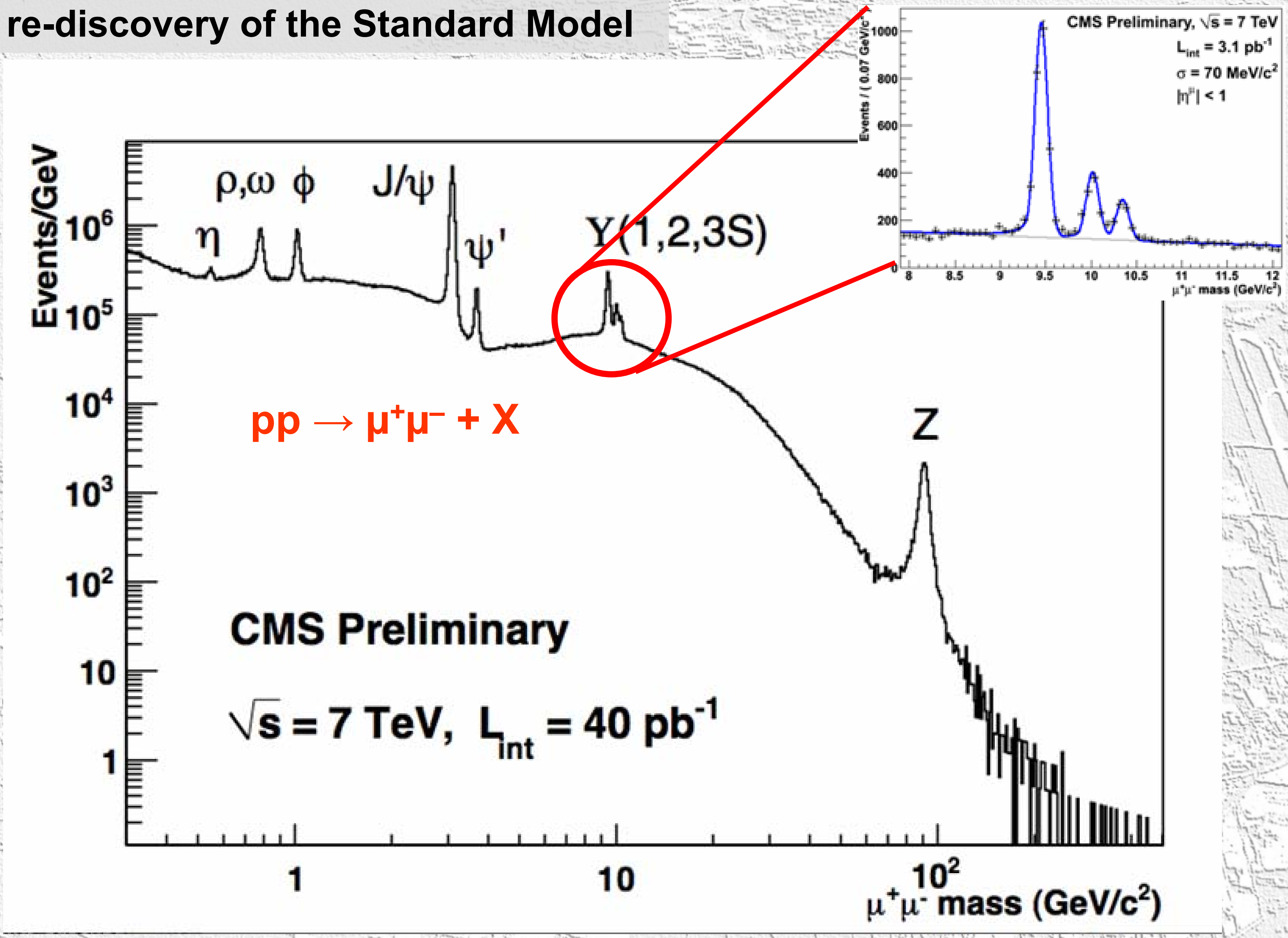


- **Working very reliably**
- **Pre-requisite for LHC data analysis**
- **Important role of GridKa**

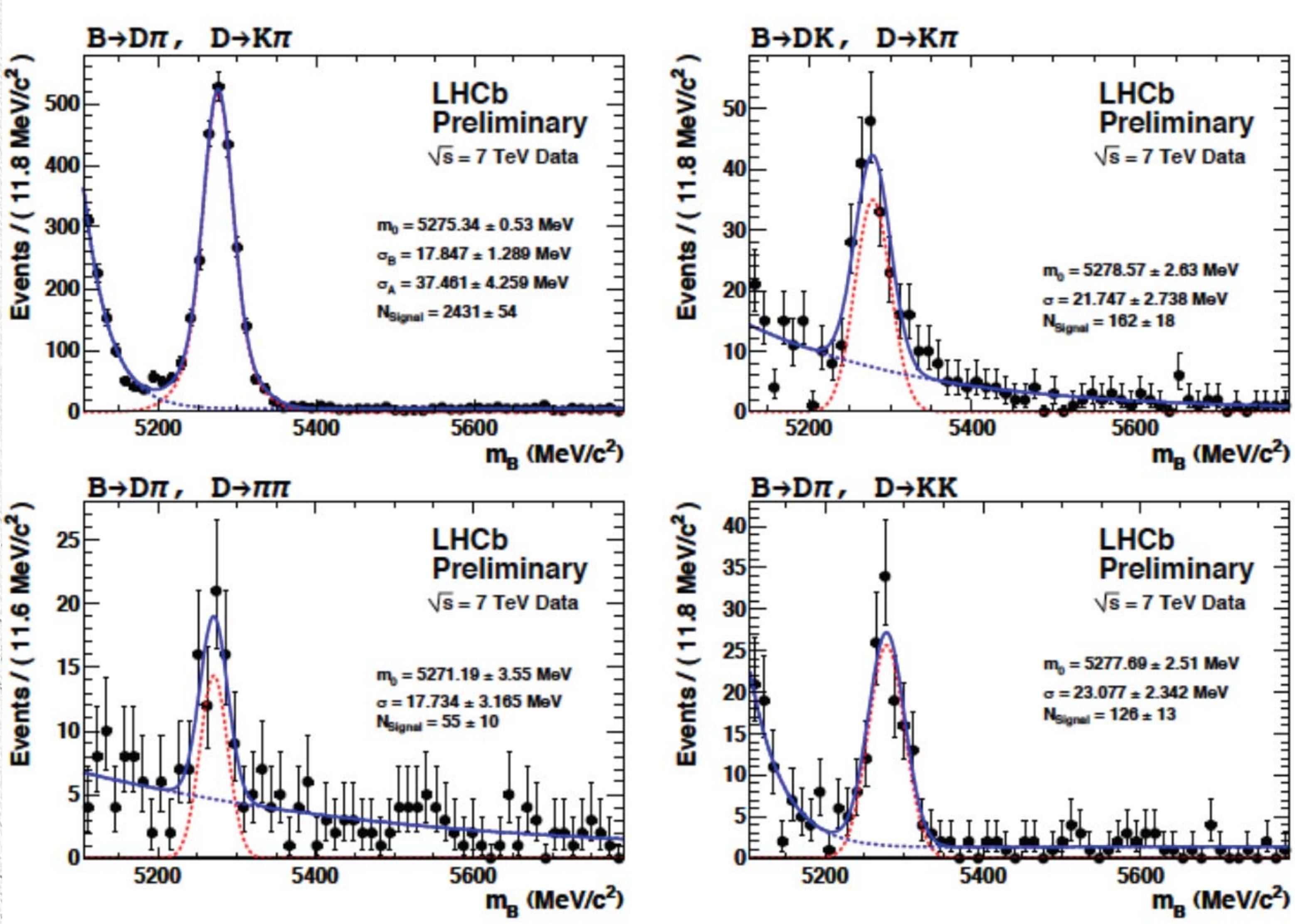
A few first physics results of 2010

First LHC Results

- **The re-discovery of the Standard Model**



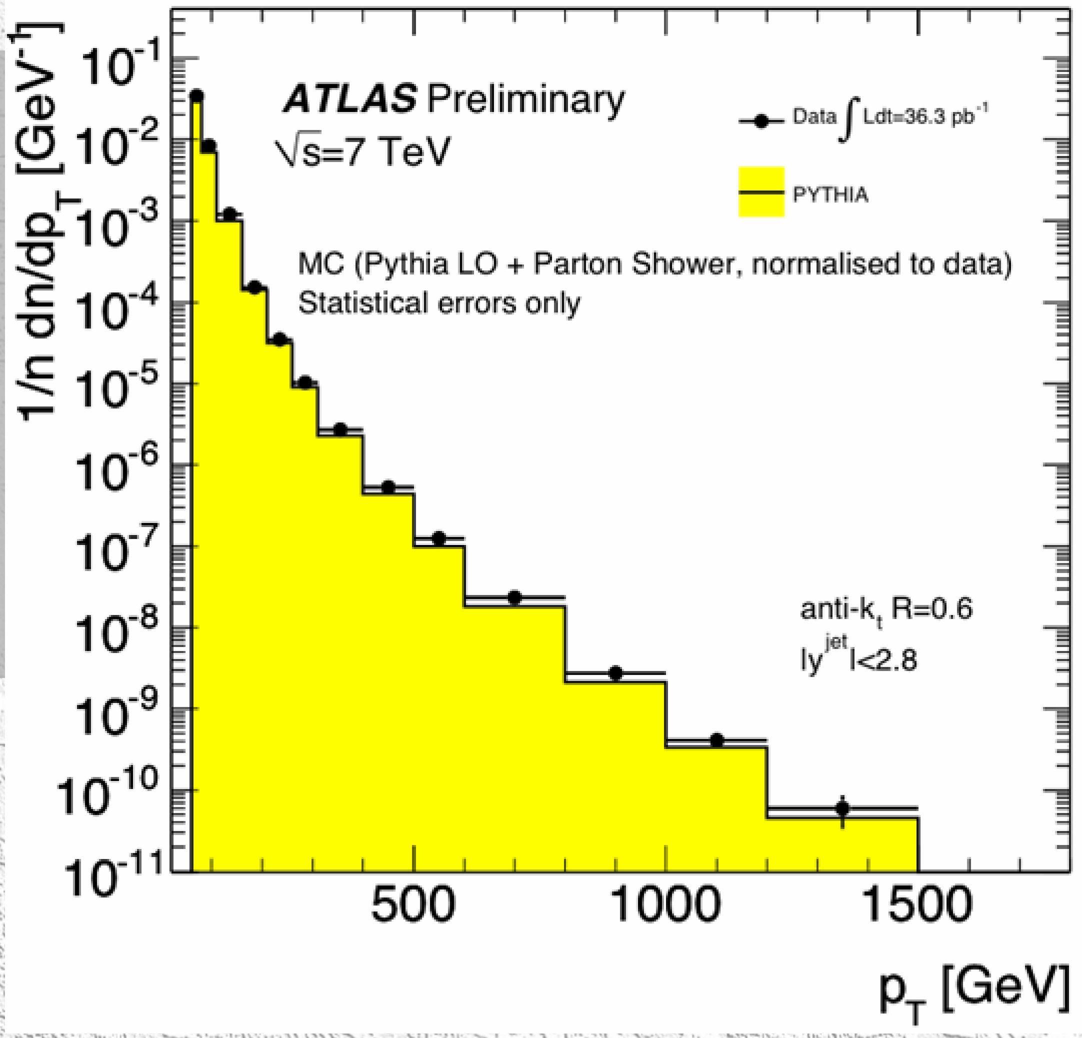
LHCb: Exclusive B-Decays



- **Important milestone in LHCb physics programme**

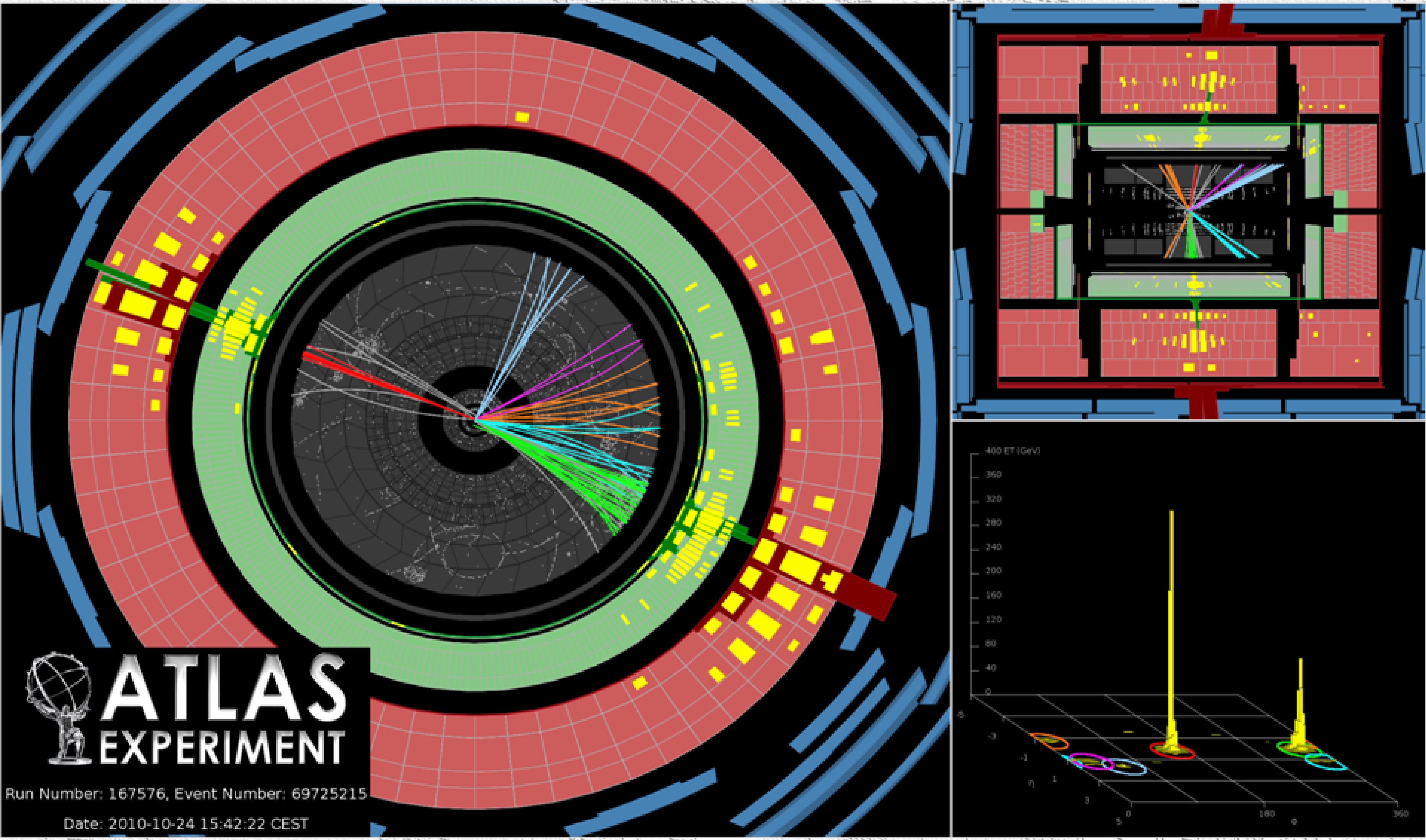
QCD and Jets

- Inclusive jet rates
- Combination of various triggers
- Good understanding over 9 orders of magnitude in rate
- Highest p_T jet observed: 1.3 TeV

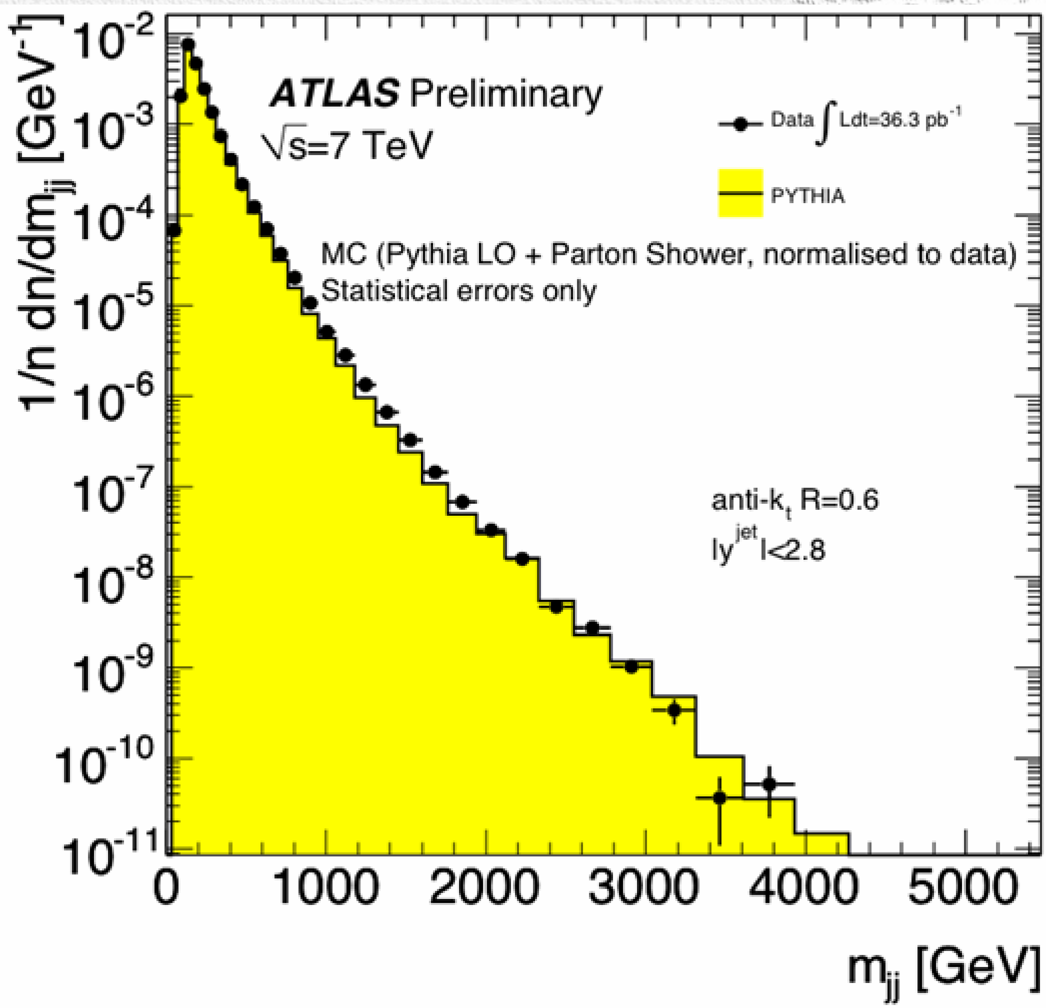


Highest p_T jet

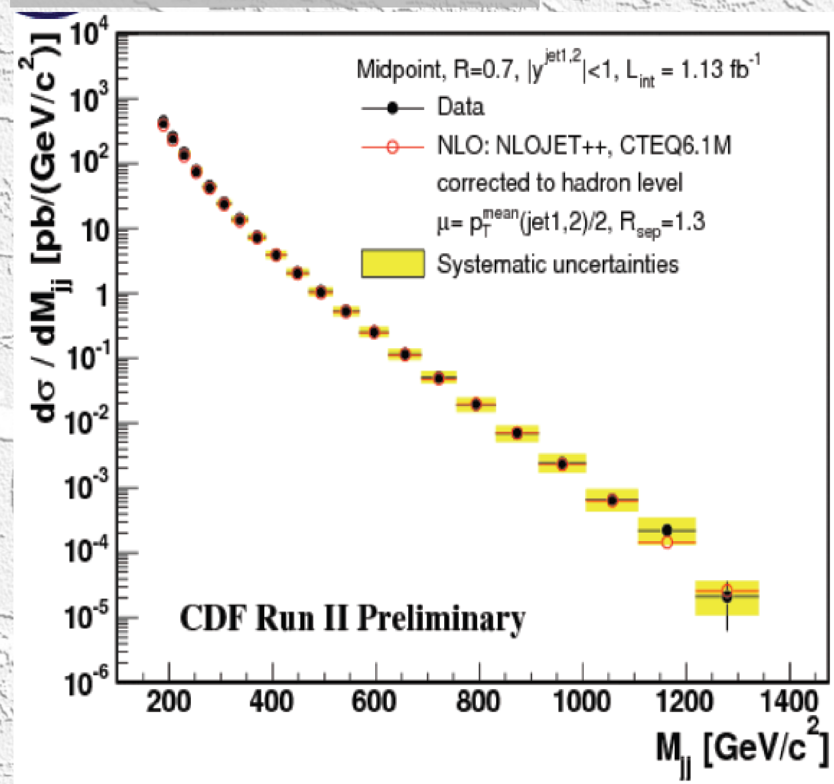
p_T jet1 = 1.3 TeV
p_T jet2 = 1.2 TeV
m_{jj} = 2.6 TeV



Di-jet Events

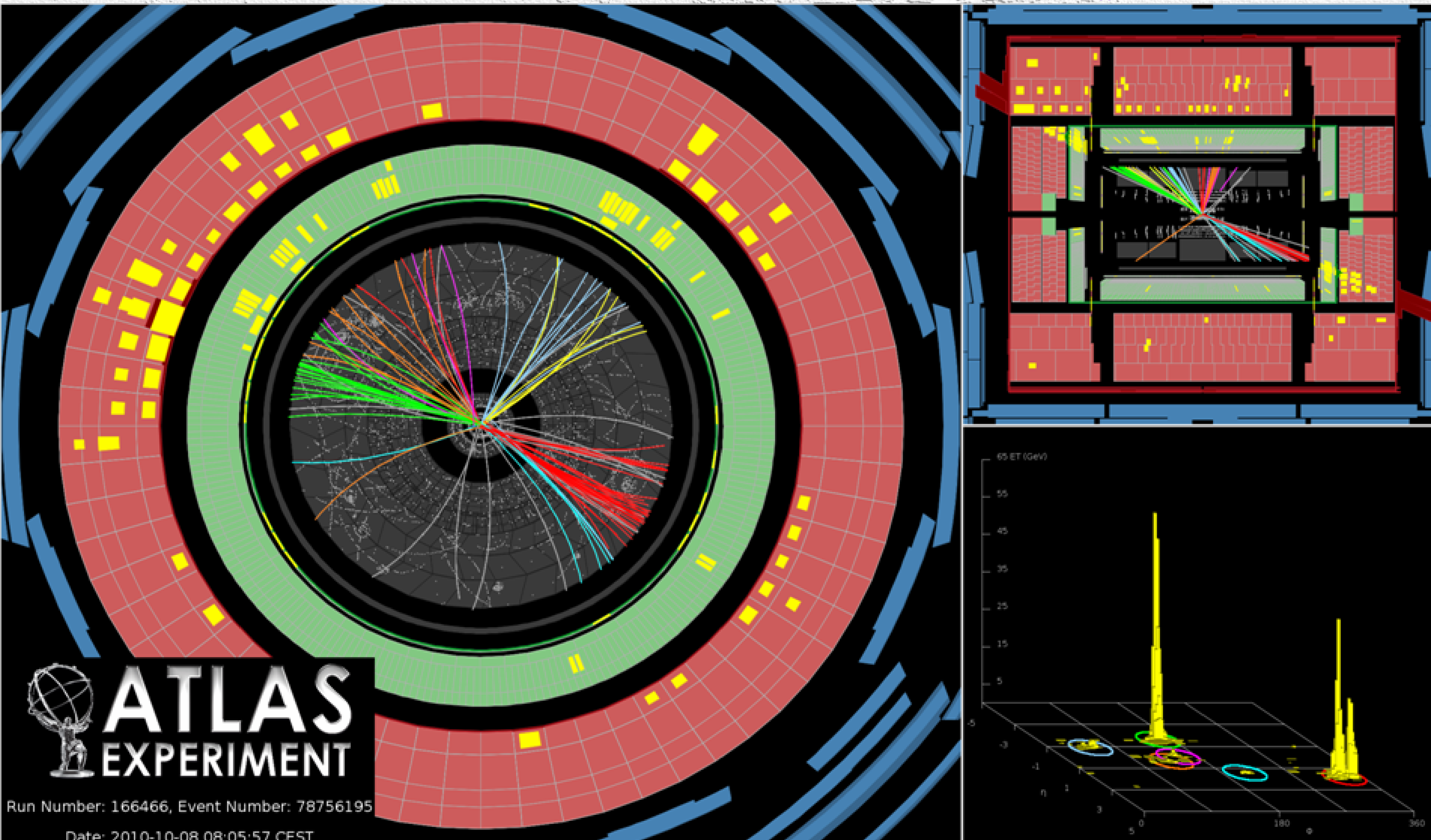


- **Highest di-jet mass 3.7 TeV**
- **For comparison Tevatron result:**



Highest mass di-jet

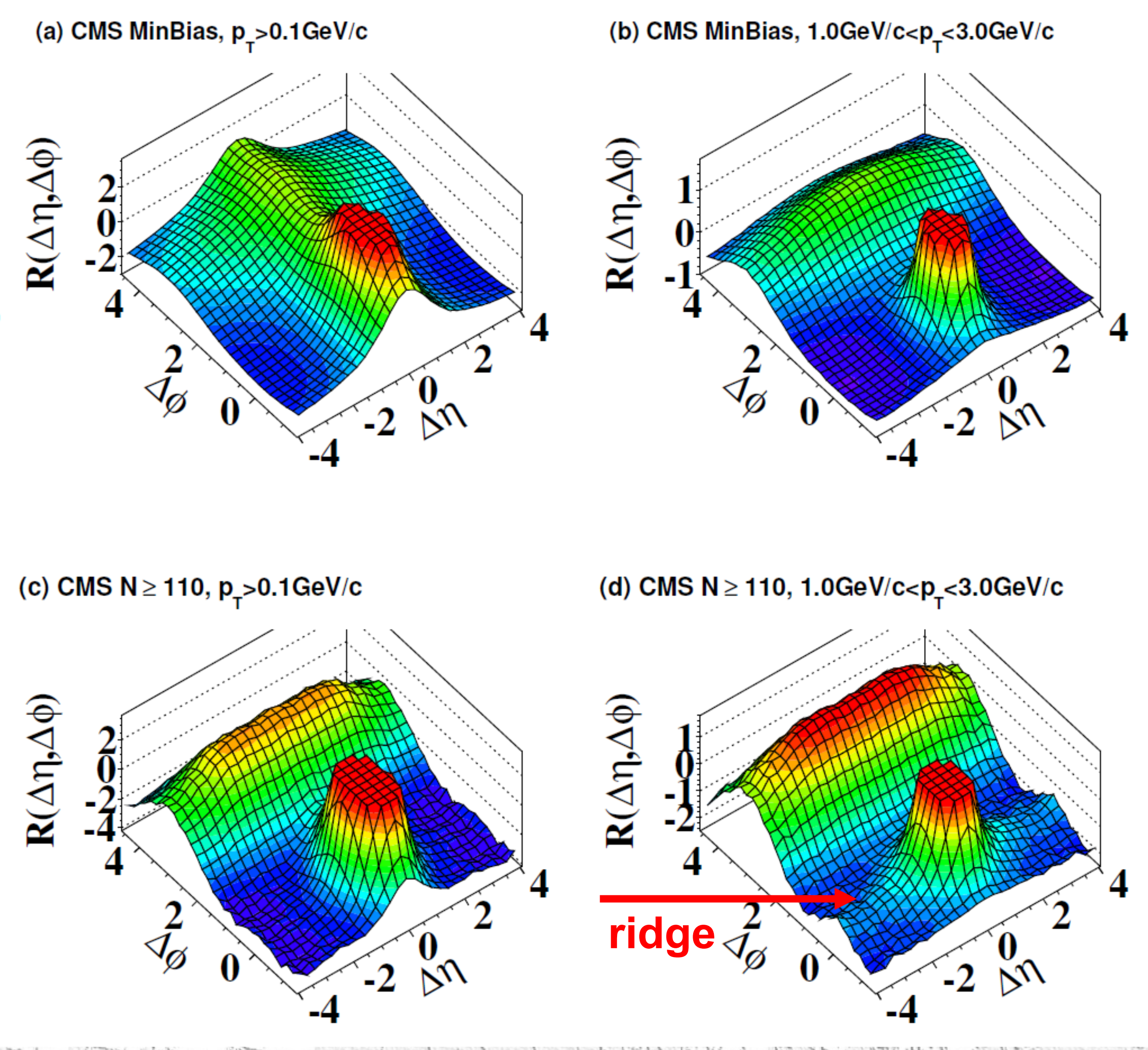
p_T jet1 = 670 GeV
p_T jet2 = 610 GeV
m_{jj} = 3.7 TeV



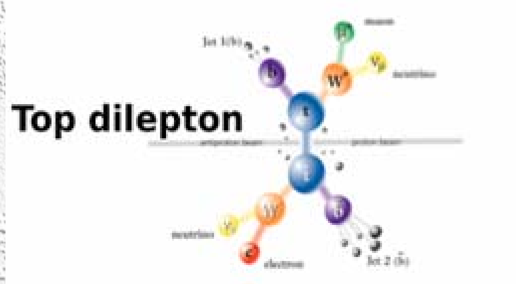
Soft QCD

- **Long range two-particle correlations in pp collisions at 7 TeV**

- **Two-particle correlation function R**
- **Same side correlation (ridge structure) observed for high multiplicity events at ΔΦ = 0**
- **Most evident in intermediate p_T range**
- **Resembles features seen in Heavy Ion collisions**

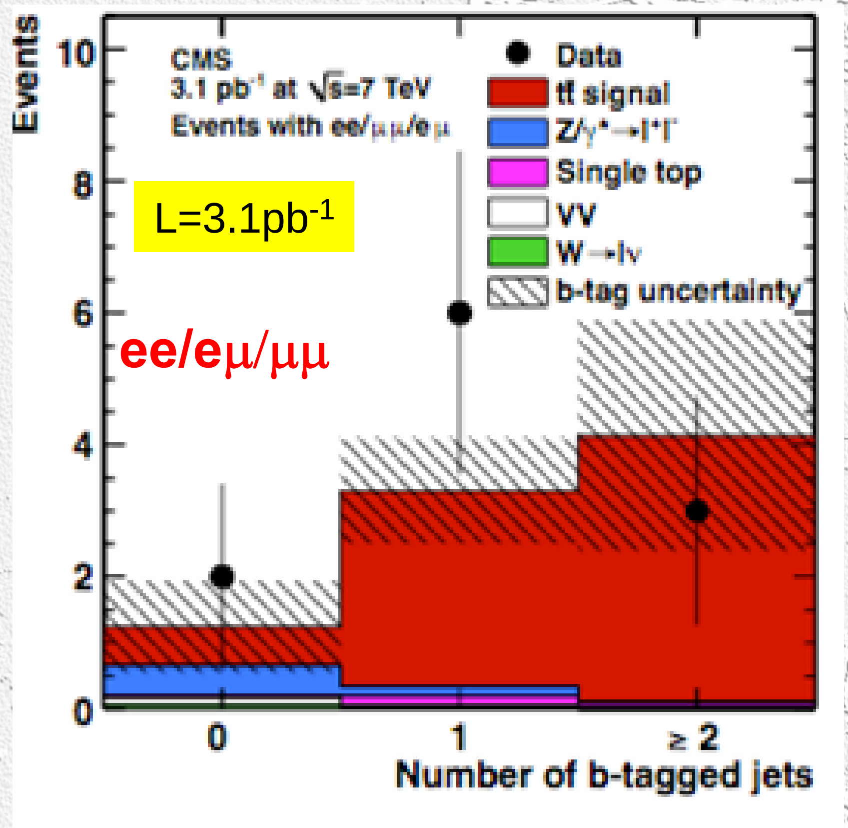


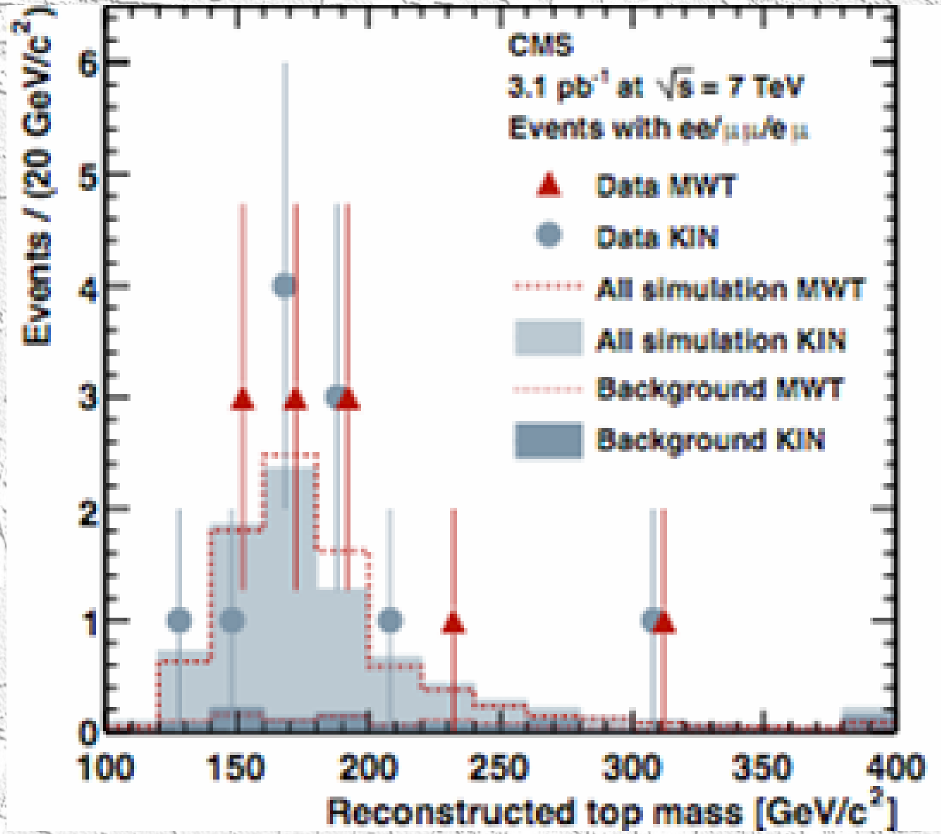
Top Quark Physics



- **CMS: di-lepton channel**

$$\sigma(pp \rightarrow t\bar{t}) = 194 \pm 72(\text{stat.}) \pm 24(\text{syst.}) \pm 21(\text{lumi.})\ \text{pb}$$

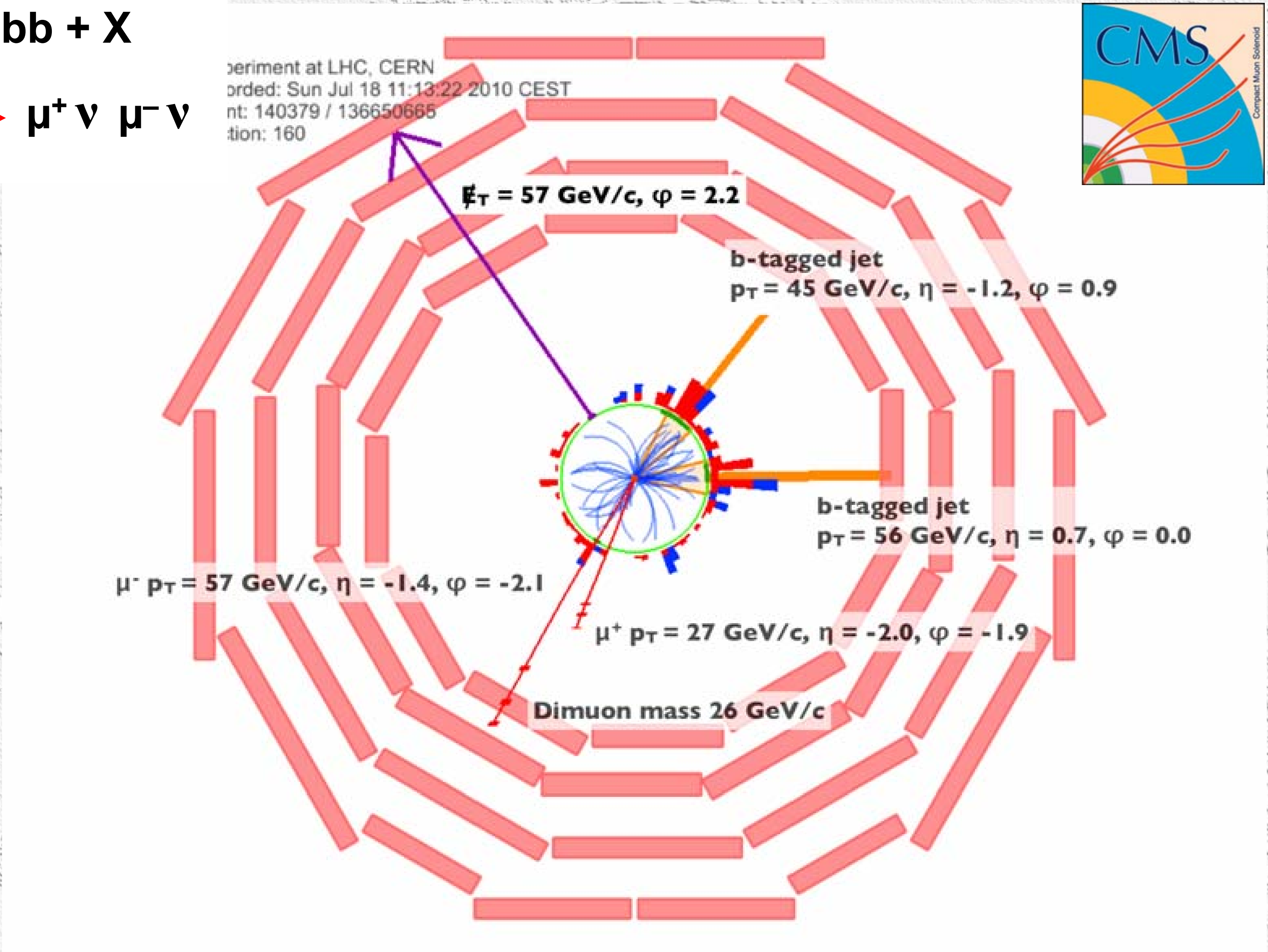




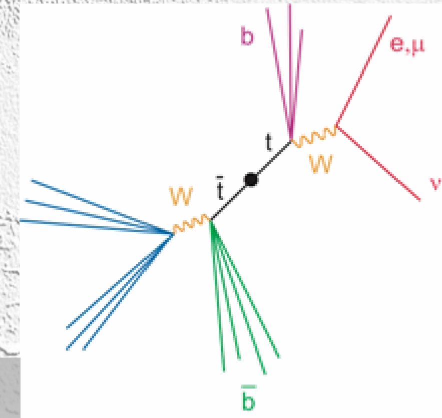
Top Di-lepton Candidate

$pp \rightarrow WW\ bb + X$

$\quad\quad \hookrightarrow \mu^+ \nu\ \ \mu^- \nu$

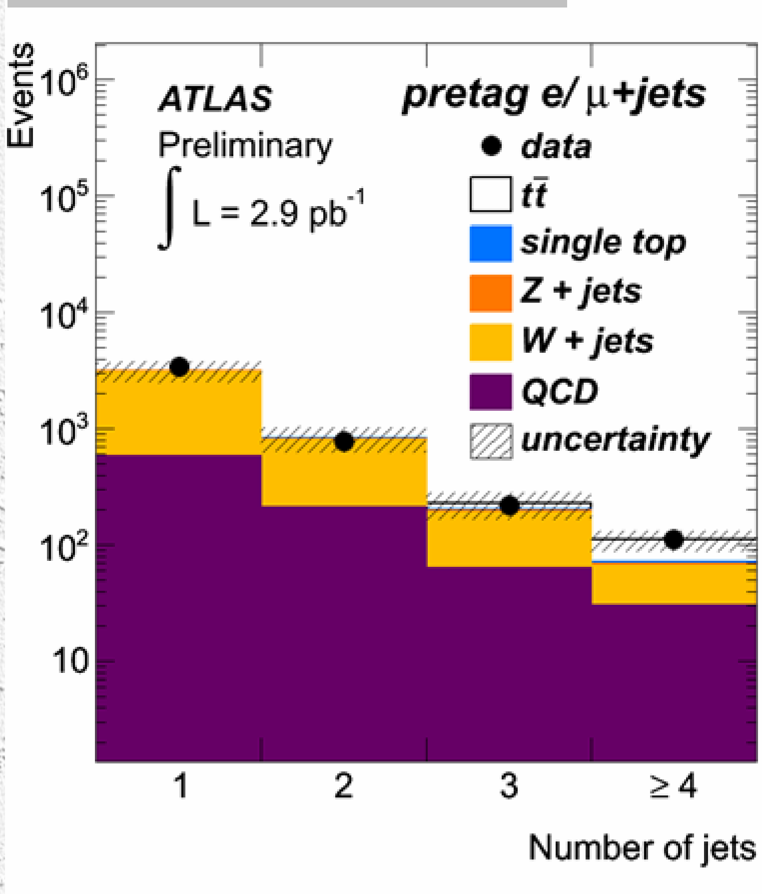


Top Quark Physics

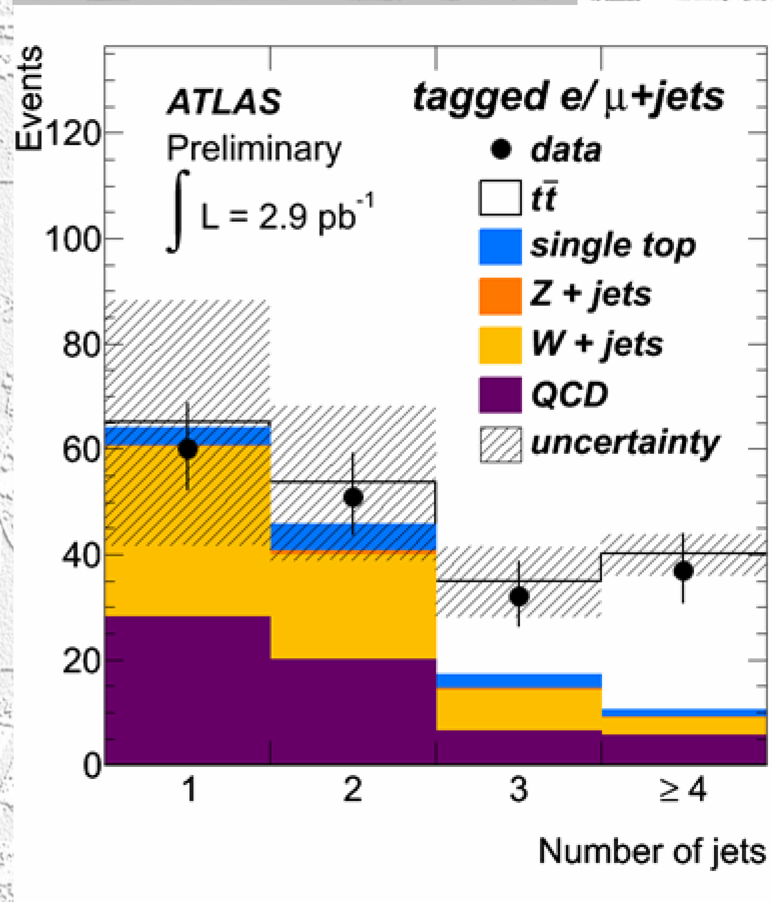


- **ATLAS: Lepton + jets channel**

- **Lepton + jets:**



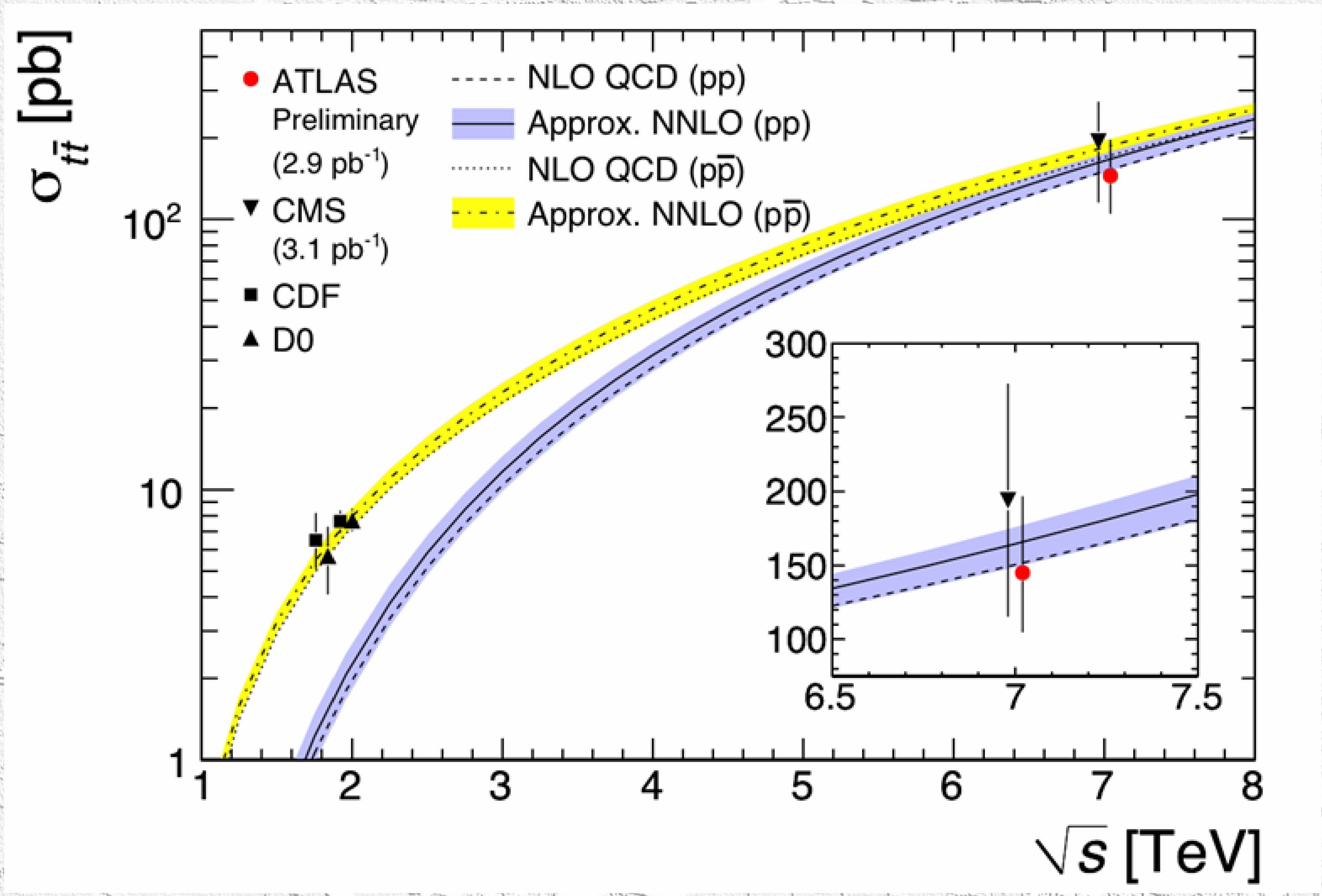
- **Requiring 1 b-tag:**



Top-pair Cross Section at 7 TeV

- **Based on ≈ 3 pb^{-1}**
- **Good aggrement with expectation**

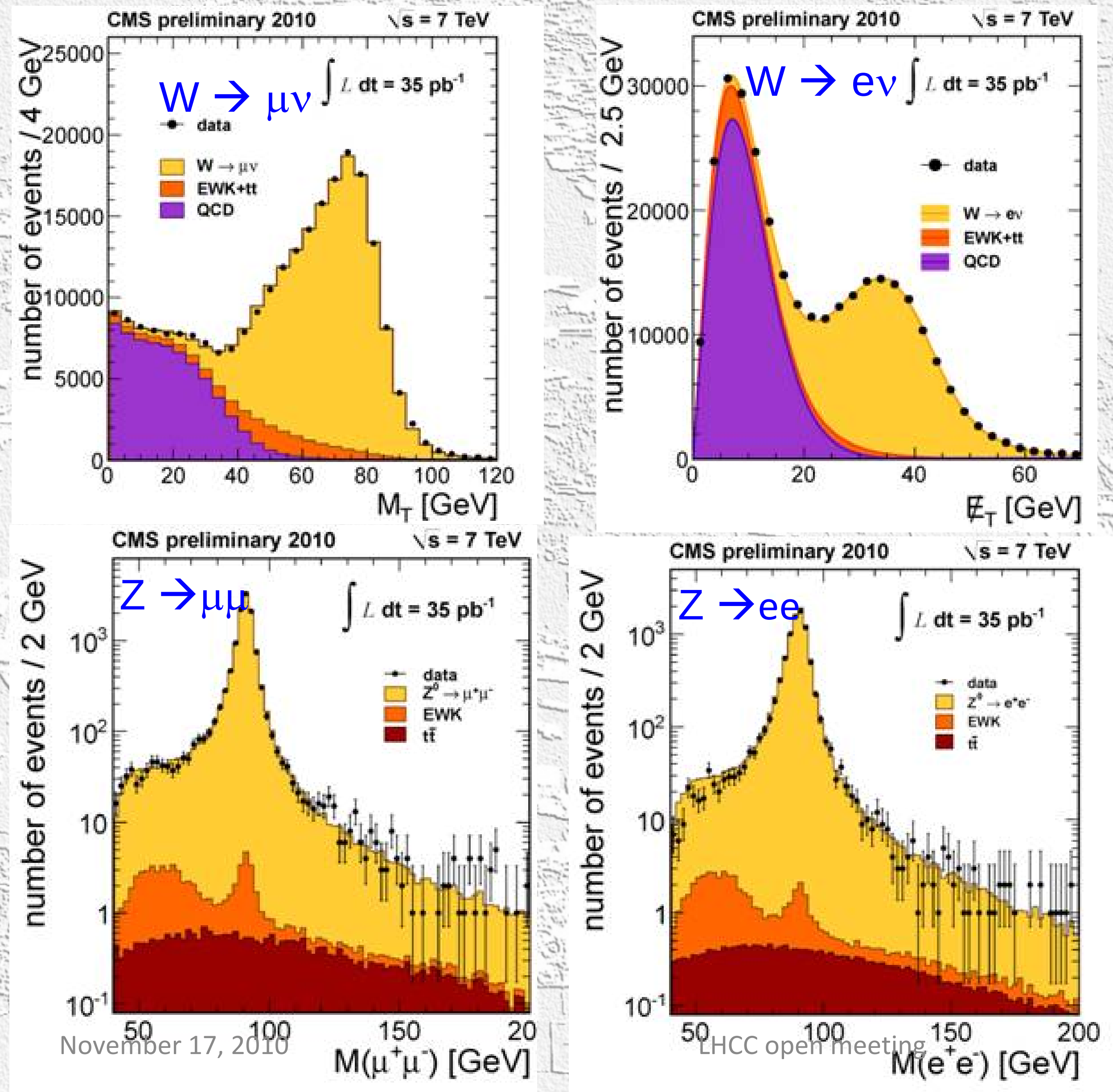
ATLAS: $\sigma_{t\bar{t}} = 145 \pm 31^{+42}_{-27}$ pb

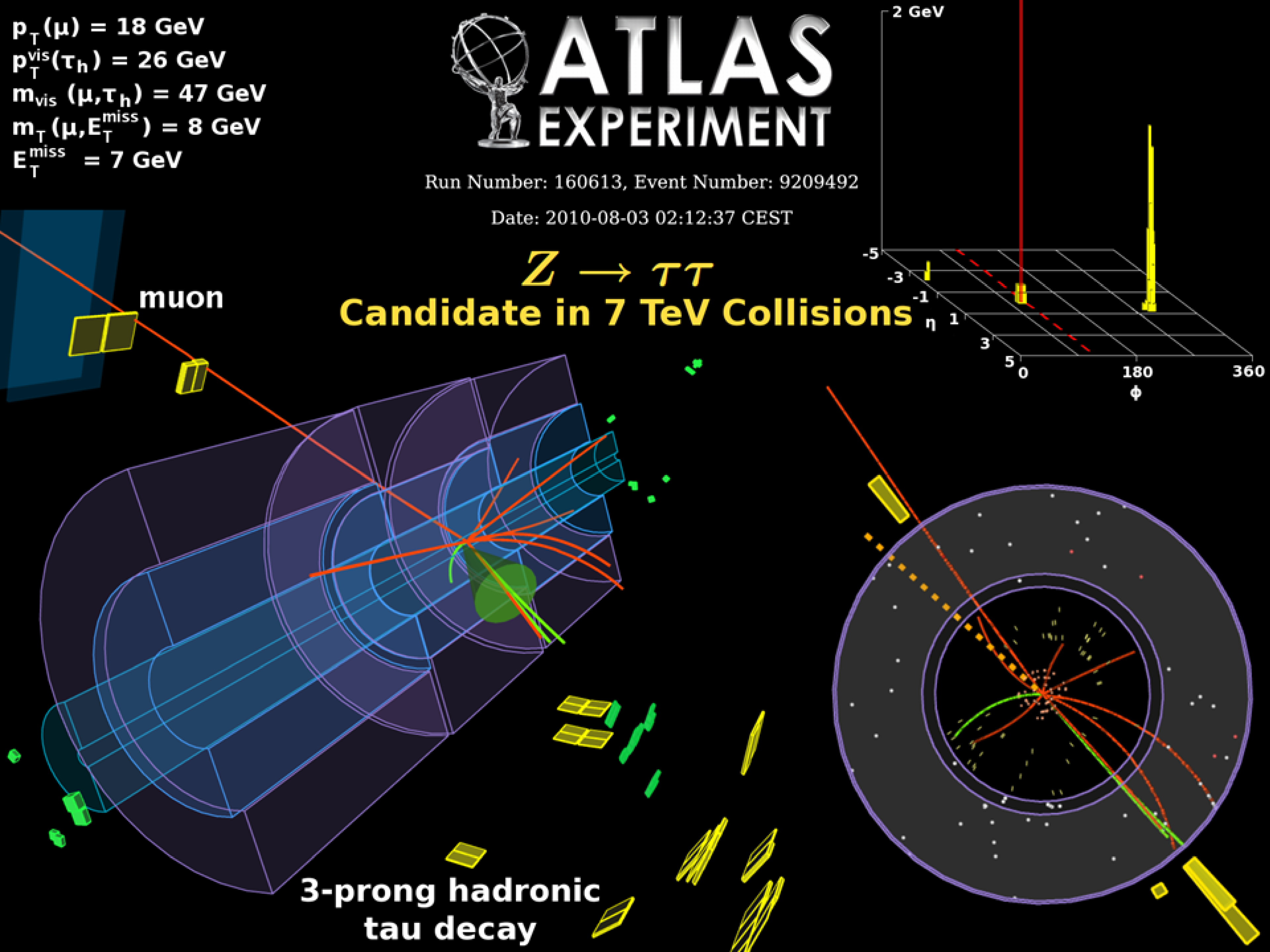


Electroweak Physics

- W and Z bosons
  - ≈ 250k W-events
  - ≈ 25k Z-events

  per experiment
- CMS results based on 35 pb^{-1}

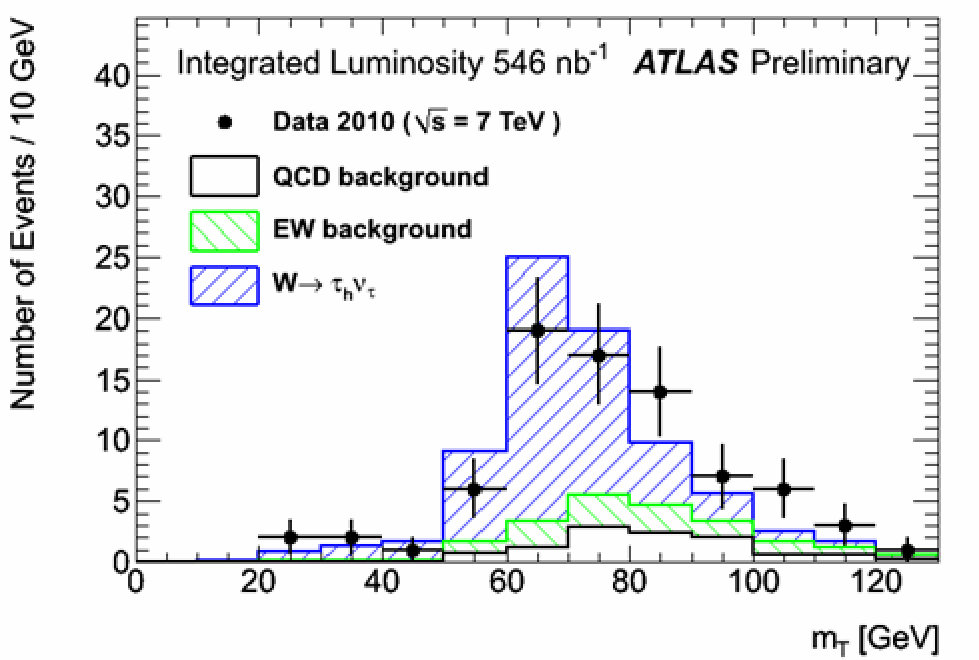


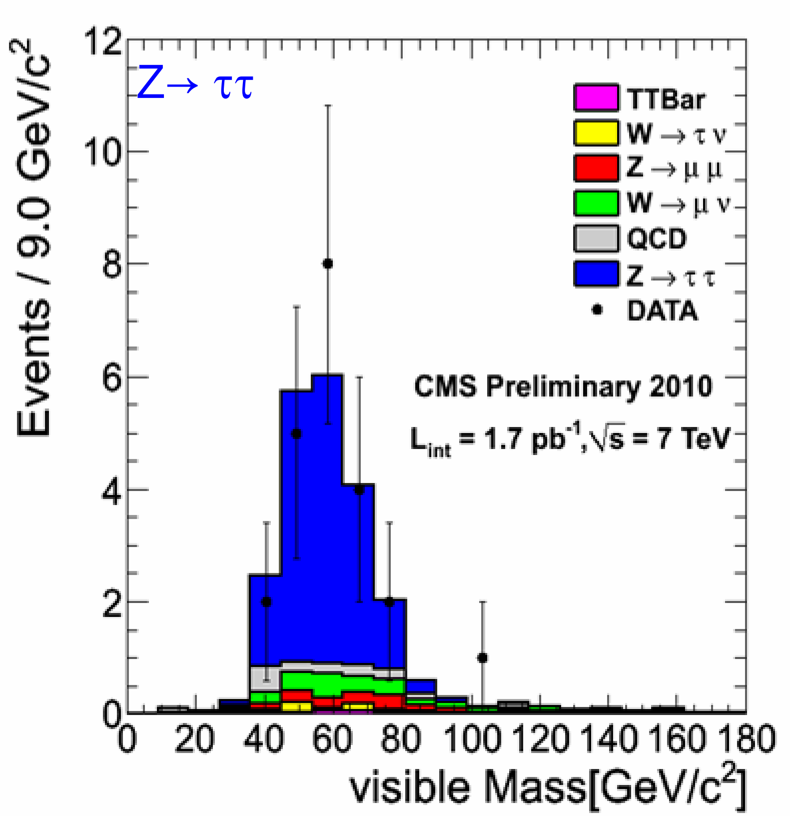

$p_T(\mu)$ = 18 GeV
$p_T^{vis}(\tau_h)$ = 26 GeV
m_{vis} (μ,τ_h) = 47 GeV
$m_T(\mu,E_T^{miss})$ = 8 GeV
E_T^{miss} = 7 GeV
ATLAS EXPERIMENT
Run Number: 160613, Event Number: 9209492
Date: 2010-08-03 02:12:37 CEST
$Z \rightarrow \tau\tau$
Candidate in 7 TeV Collisions
muon
3-prong hadronic tau decay
2 GeV
-5
-3
-1
1
3
5
η
0
180
360
φ

W→τν and Z →ττ observation

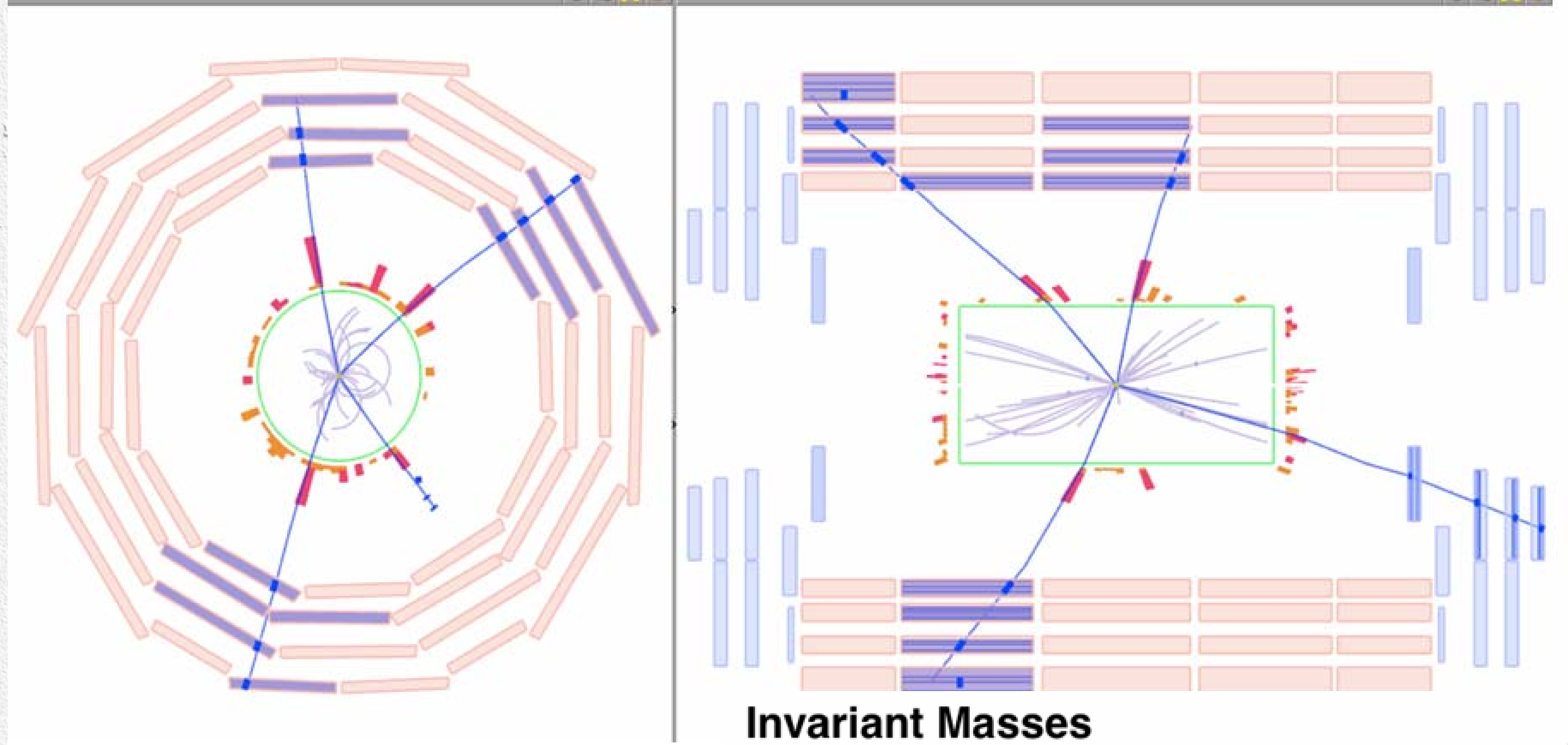
- ATLAS observation of W → τν based on 550 nb^{-1} (1% of total statistics)
- 78 events with hadronic τ decay candidates
- 23 background events

- CMS Z → ττ candidates





A Beautiful ZZ Event



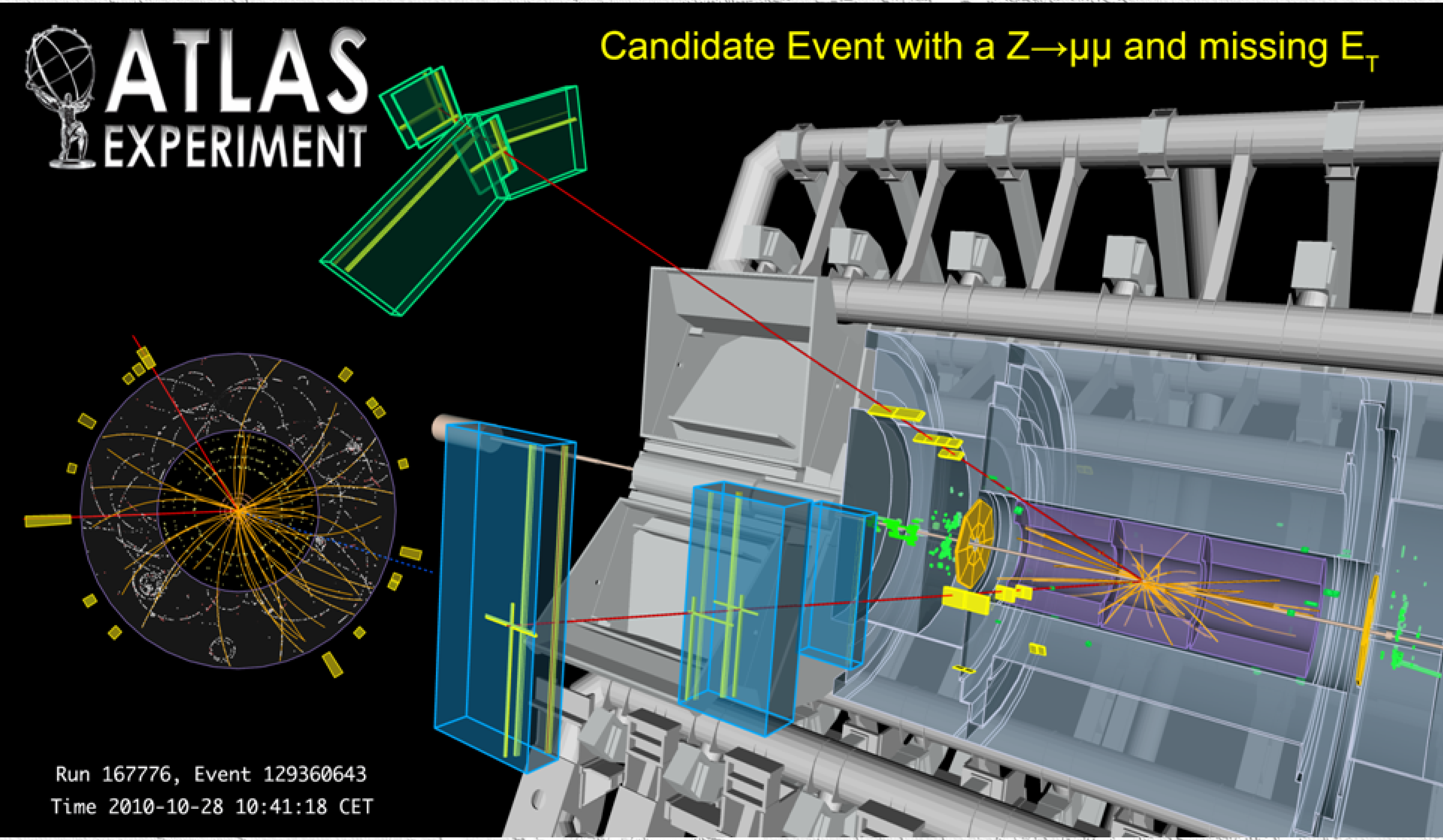
Invariant Masses

$\mu_0 + \mu_1$: 92.15 GeV (total(Z) p_T 26.5 GeV, ϕ -3.03),
$\mu_2 + \mu_3$: 92.24 GeV (total(Z) p_T 29.4 GeV, ϕ +.06),
$\mu_0 + \mu_2$: 70.12 GeV (total p_T 27 GeV),
$\mu_3 + \mu_1$: 83.1 GeV (total p_T 26.1 GeV).

Invariant Mass of 4μ: 201 GeV

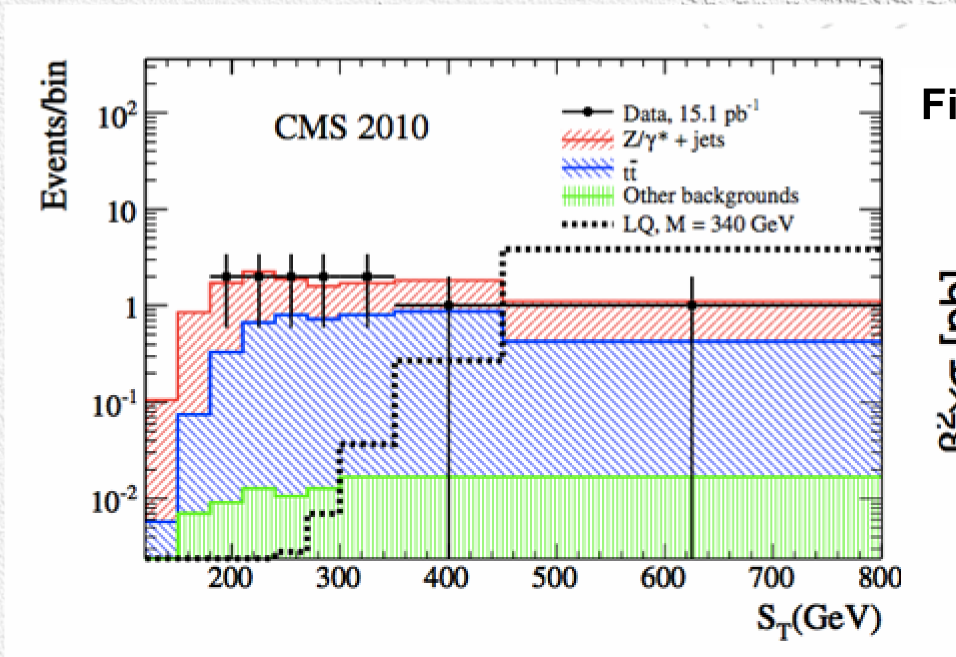
Candidate for ZZ→μμνν

- $m_{\mu\mu}$ 94 GeV, E_T^{miss} = 161 GeV



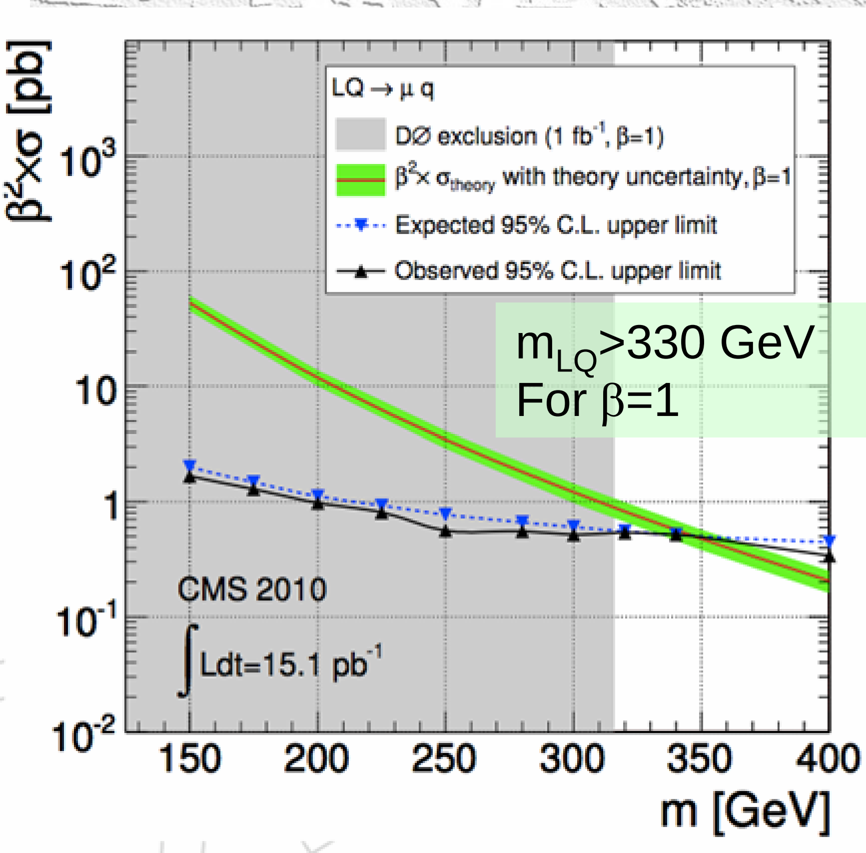
Searches for New Physics

- **Search for pair produced Lepto-Quarks decaying β % in μ+jet**



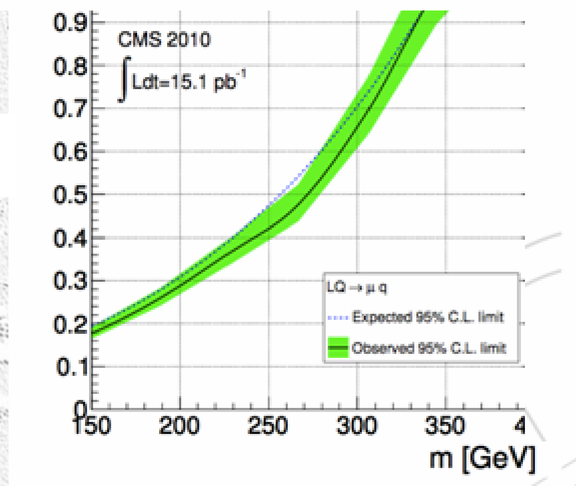
Final discri variable

$$S_T = \sum_{\mu_{1,2}} p_t^{\mu} + \sum_{Jet_{1,2}} p_t^{jet}$$



m_{LQ}>330 GeV
For β=1

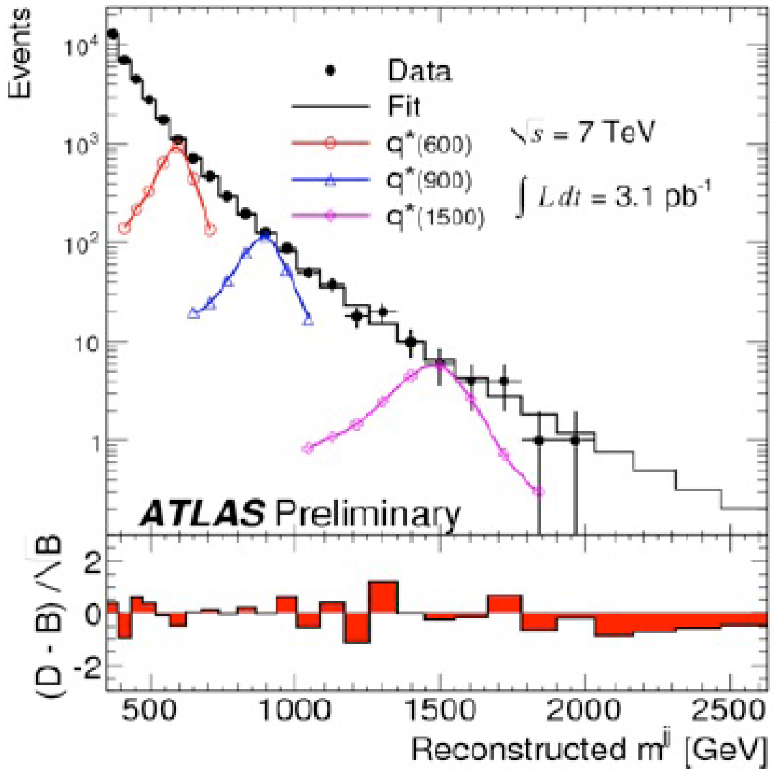
As a function of β

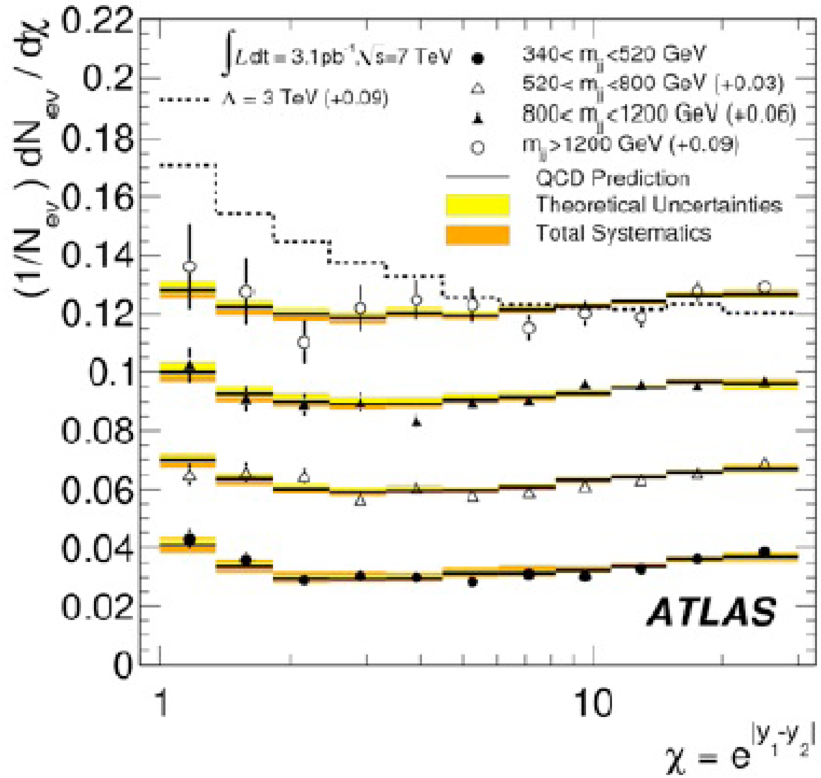


ATLAS: Di-jet Mass & Angular Distribution

excluded:
0.50 < m(q*) < 1.53 TeV @ 95% CL

Quark contact interactions with scale Λ < 3.4 TeV @ 95% CL



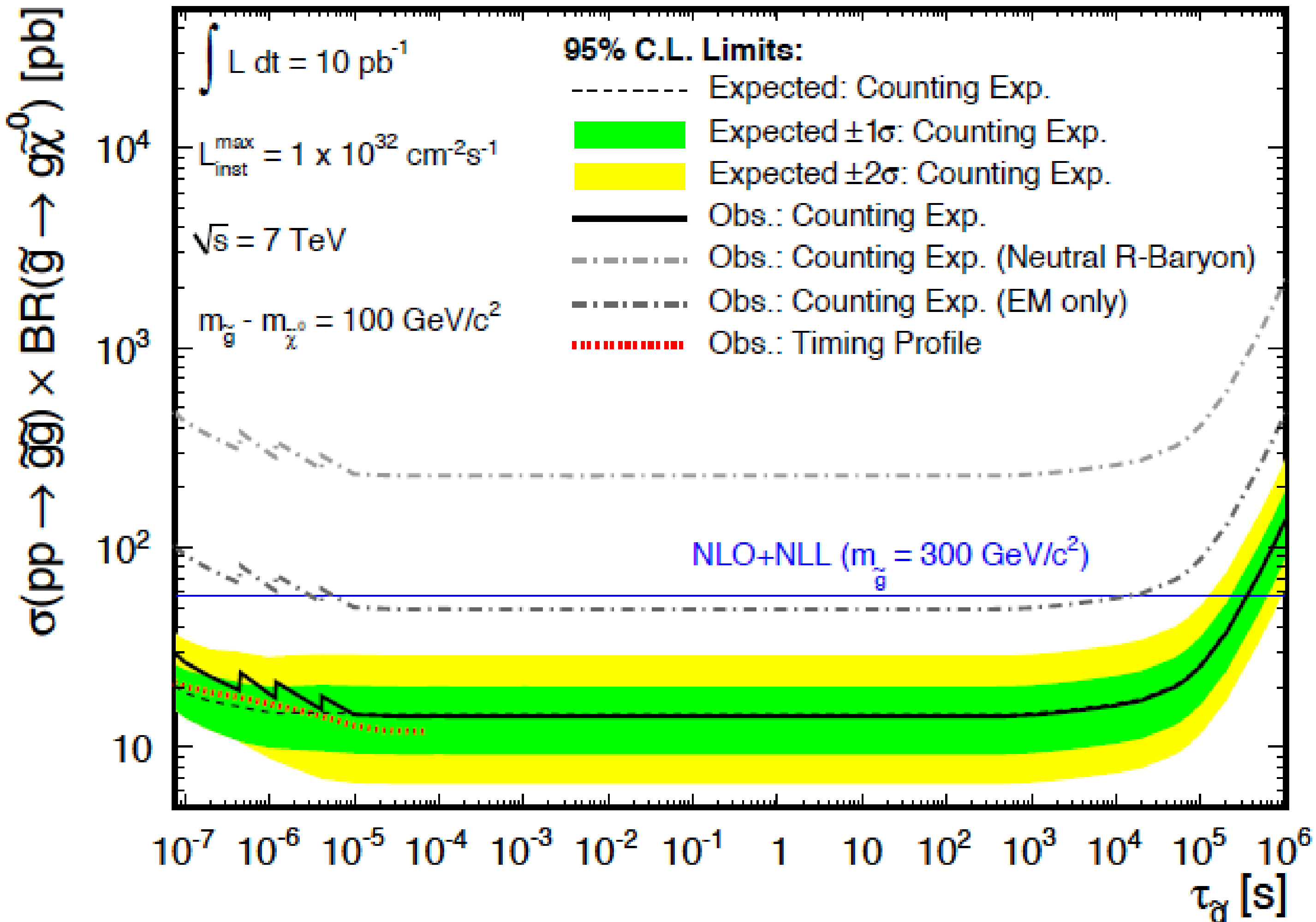


Search for New Particles in Two-Jet Final States in 7 TeV Proton-Proton Collisions with the ATLAS Detector at the LHC, Phys. Rev. Lett. 105, 161801 with 315 nb^{-1}

Search for Quark Contact Interactions in Dijet Angular Distributions in in 7 TeV Proton-Proton Collisions with the ATLAS Detector at the LHC, Accepted by PLB

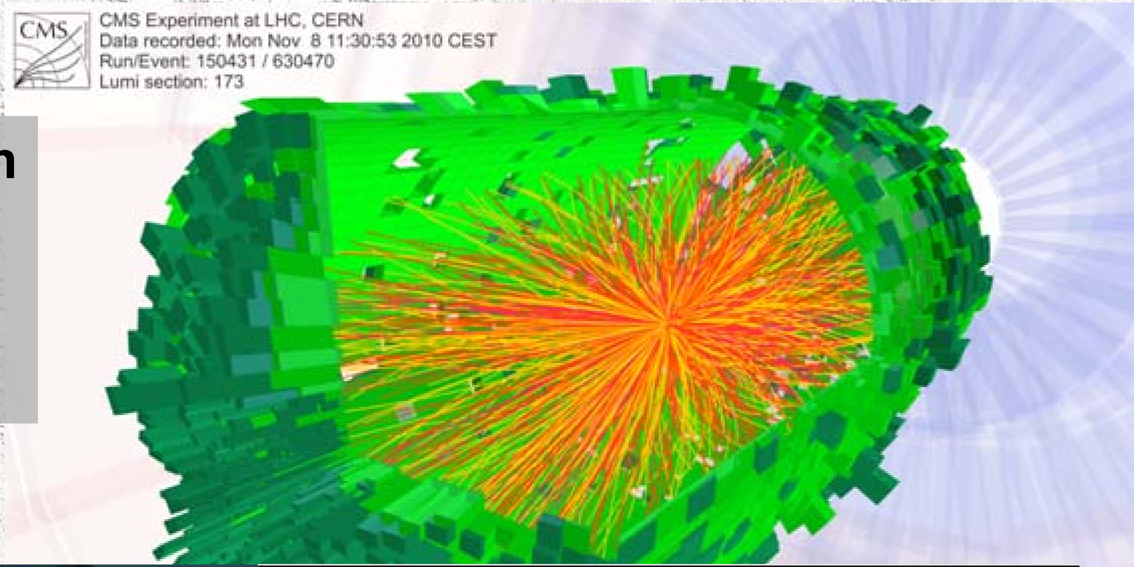
CMS: Limits on Stopped Gluinos

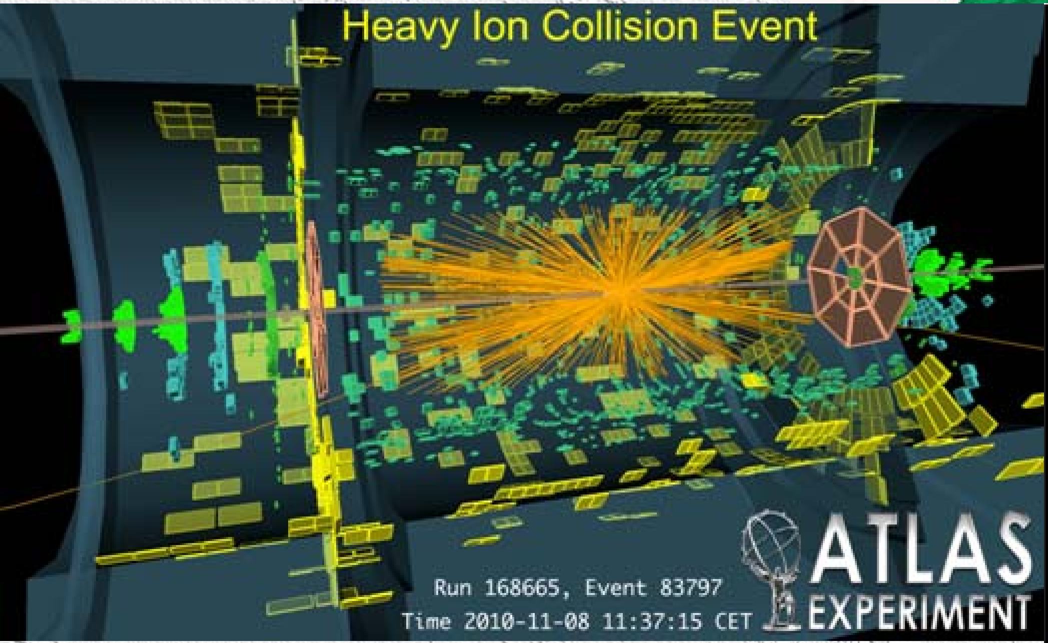
Search for decays of stopped long lived R-hadrons (gluino-meson, gluino-baryon, gluino-gluon bound states) during time intervals without LHC crossing.

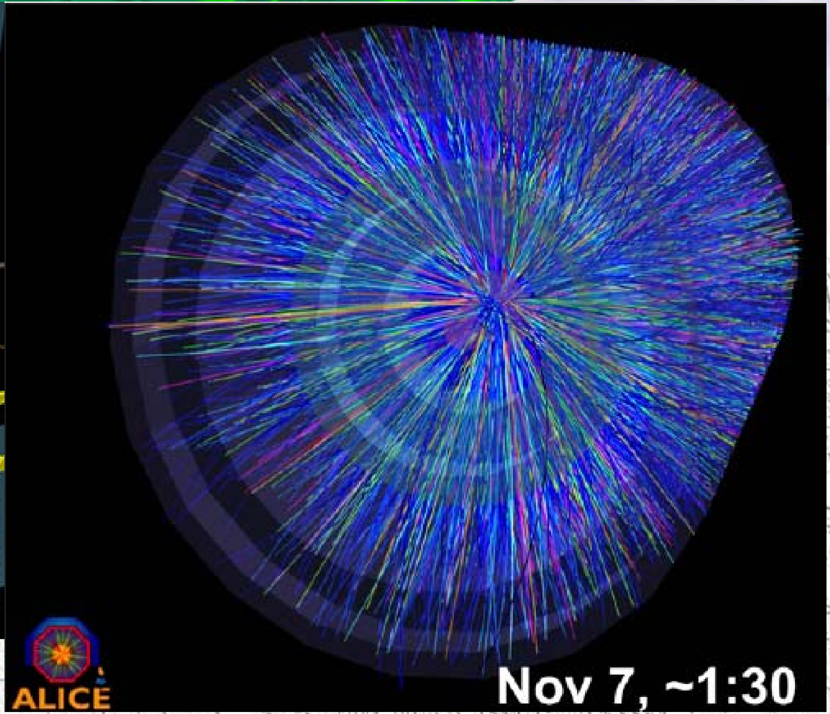


Heavy Ion Collisions

- **4 weeks of Pb-Pb running in Nov/Dec 2010**
- **Up to 10 000 tracks per events observed**

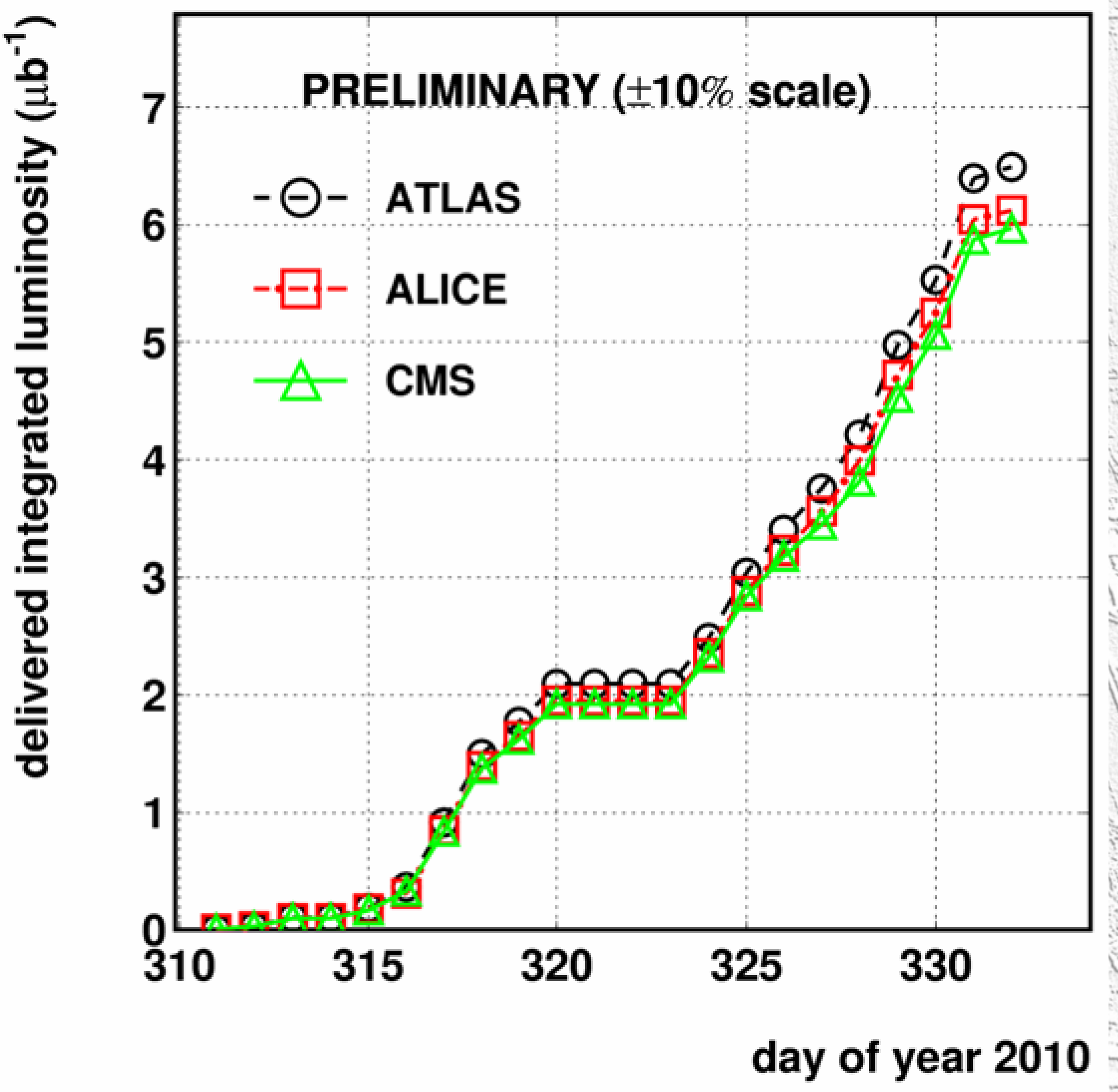






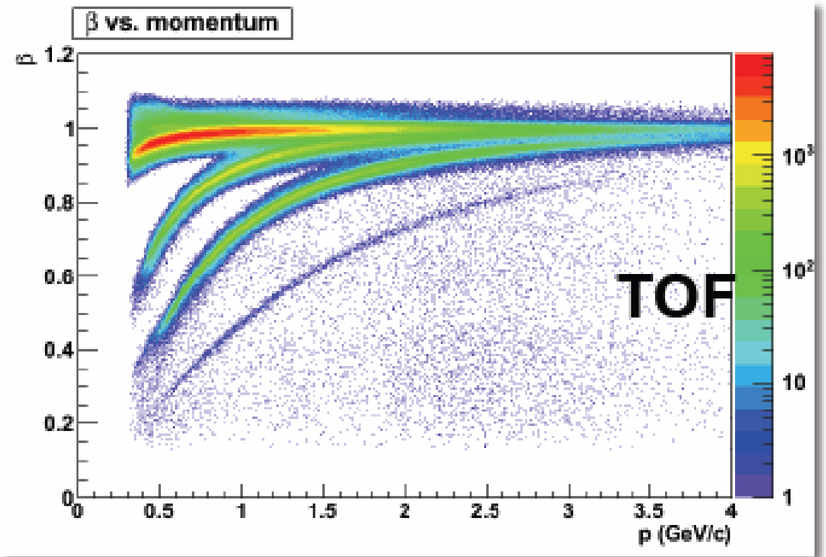
Luminosity in Heavy Ion Run

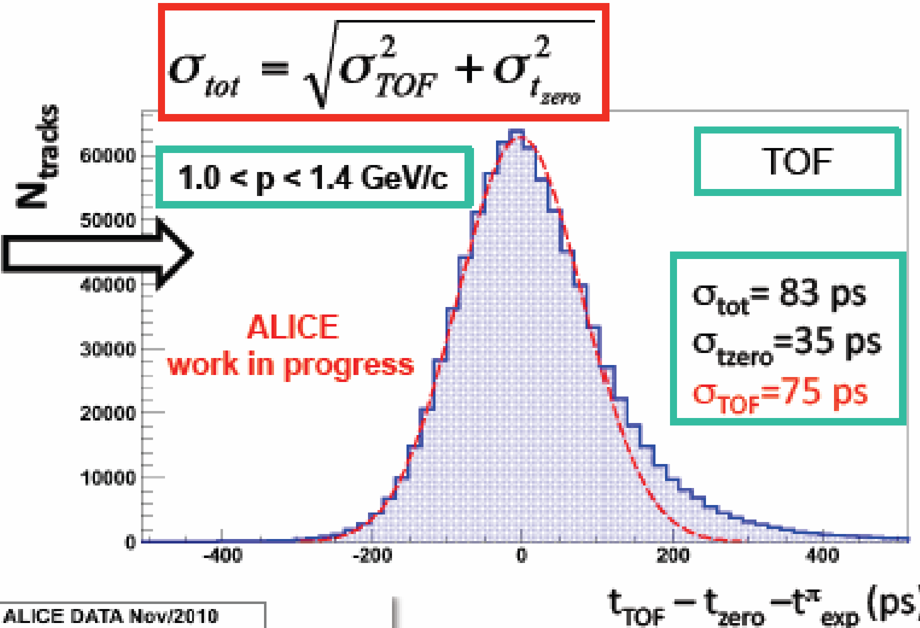
- **Steady progress**
- **≈ 8 μb^{-1} per experiment delivered**



Detector Performance in Pb-Pb Collisions

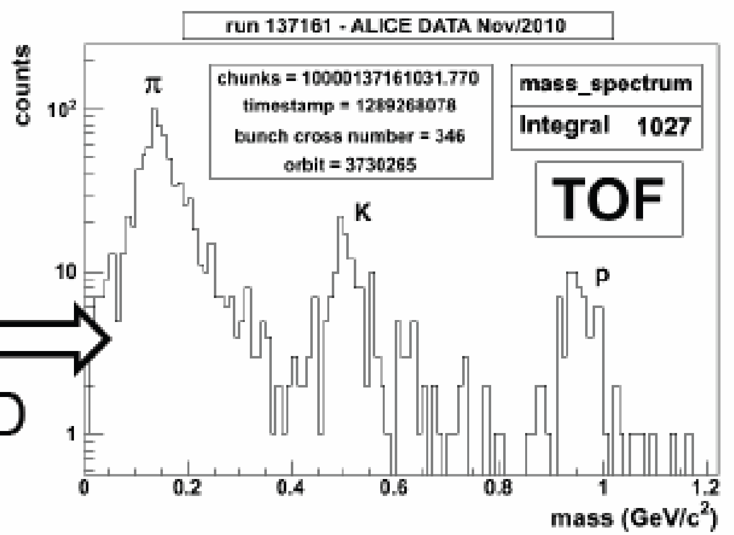
- **Particle ID by ALICE**



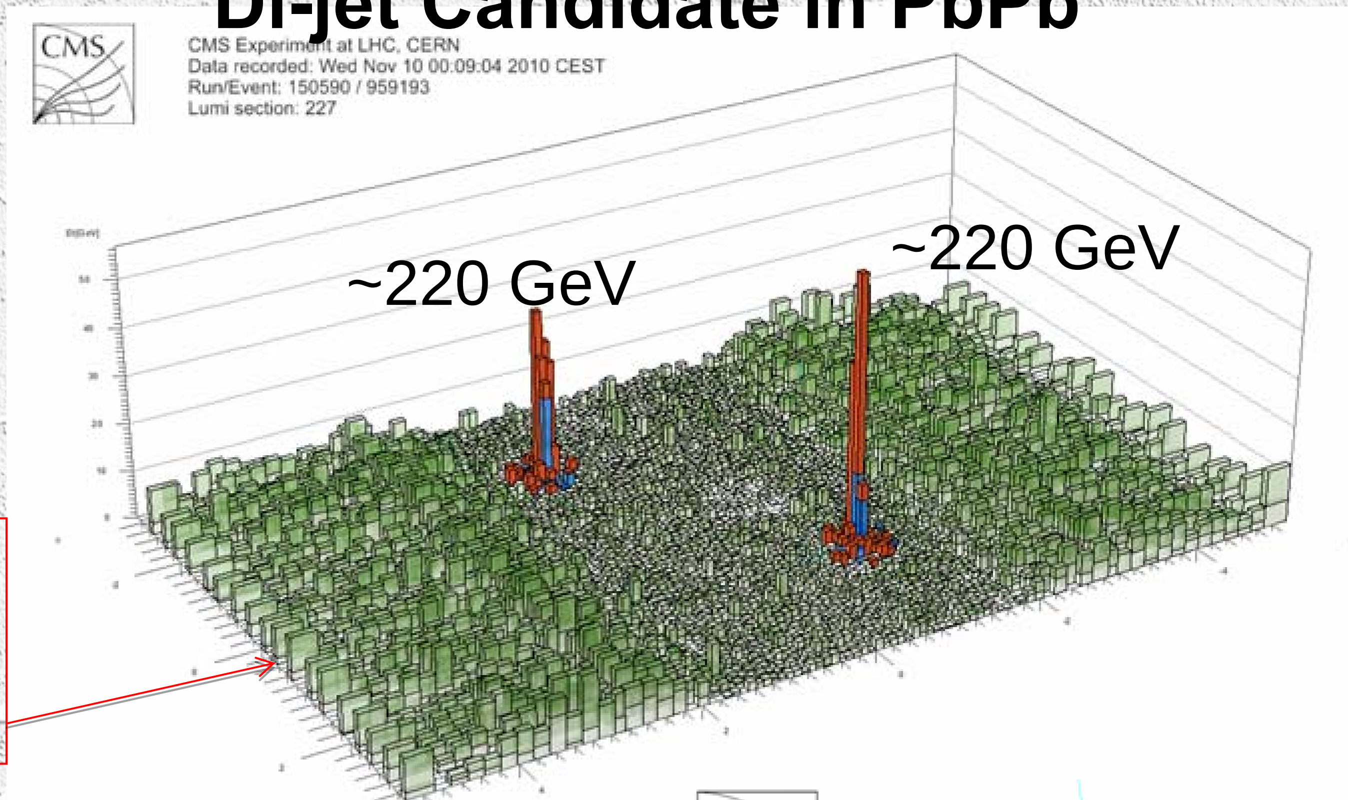


<80 ps (design) resolution seems within reach!

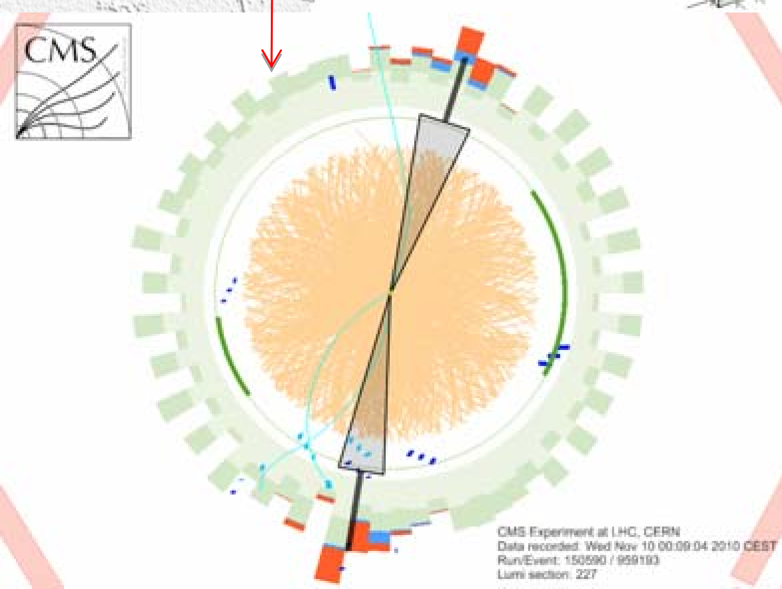
A single Pb-Pb collision!
Event-by-event PID

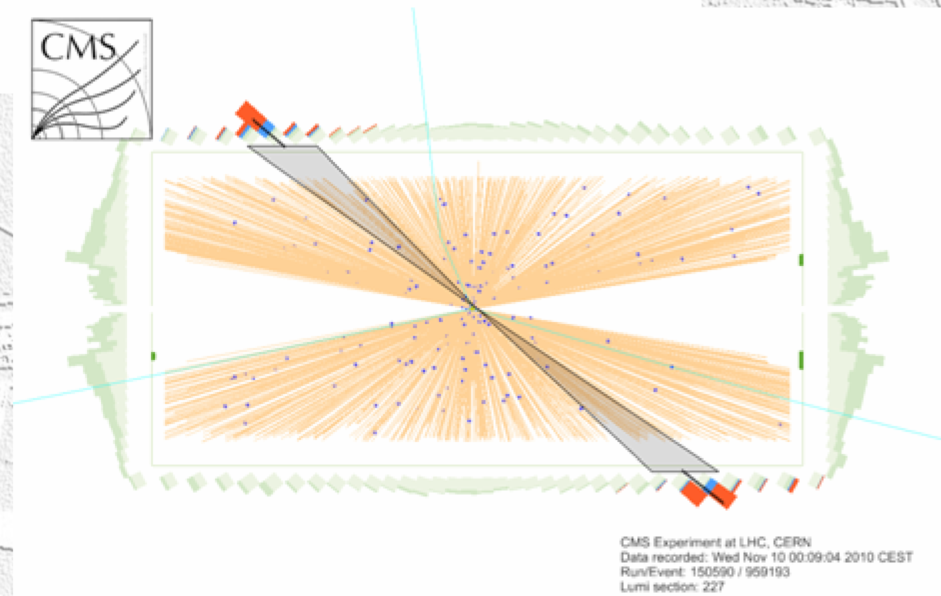


Di-jet Candidate in PbPb



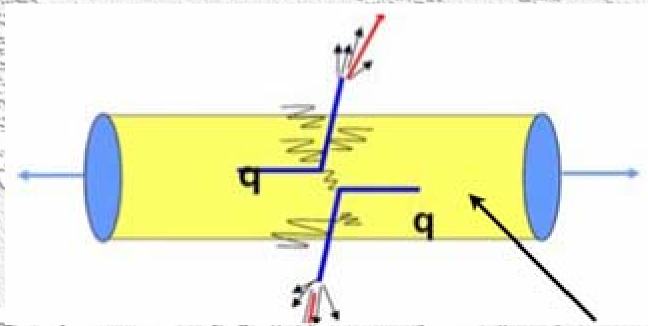
Cog-wheel effect due to projection of ϕ structure of fwd calo

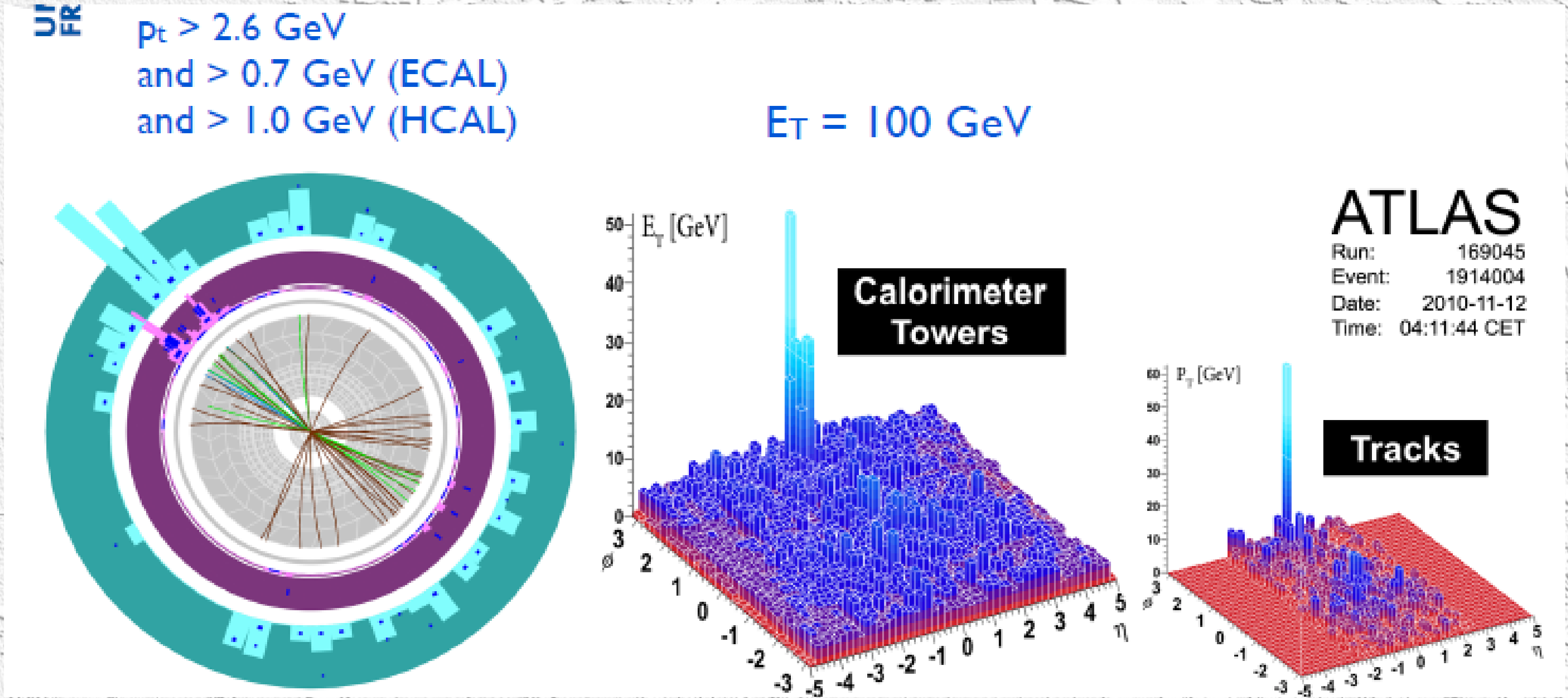




Jet-Quenching

- **Jets are expected to loose momentum traversing dense colore medium**
- **Asymmetric jets if produced at the edge**



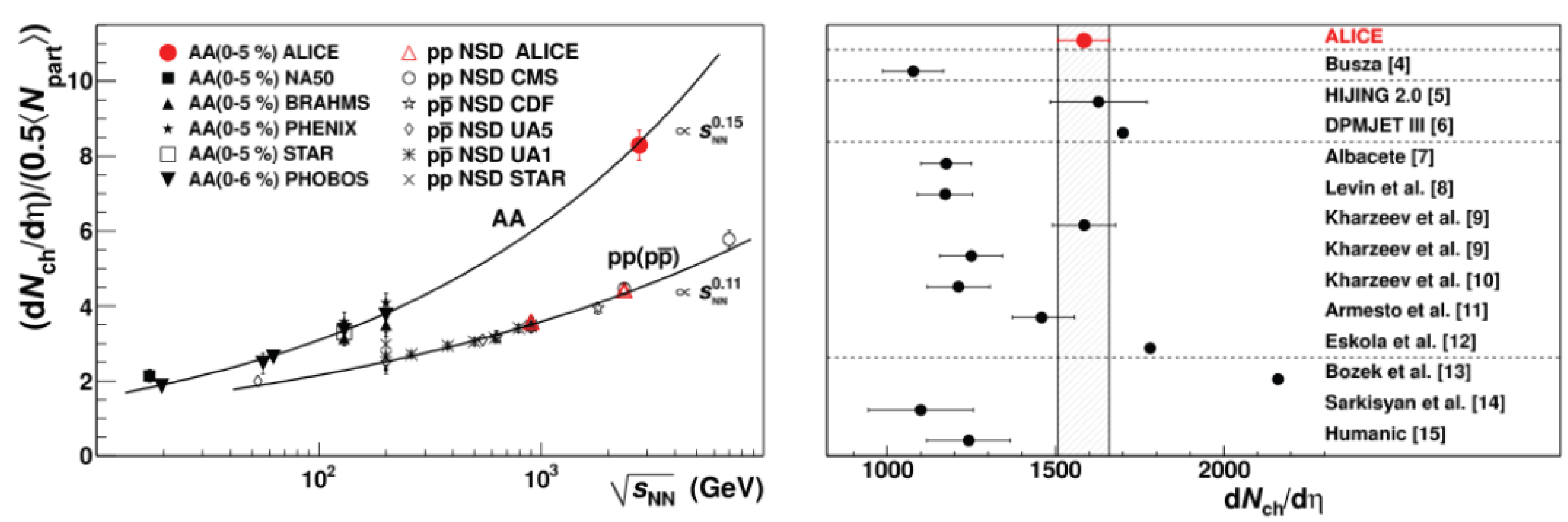


- **Many events with asymmetric di-jets observed**

Charged Track Multiplicity

- **ALICE:**

$$dN_{ch}/d\eta = 1584 \pm 4\ (stat.) \pm 76\ (syst.)$$



- **Increase by factor 1.9 wrt pp collisions at same energy**
- **Increase by factor 2.2 wrt RHIC Au-Au at 200 GeV**

Outlook for 2011

- **LHC will resume in February after the technical stop**
- **200 days pp physics plus 4 weeks heavy ion scheduled**
- **Goal:**

1 fb^{-1} per experiment at 7 TeV

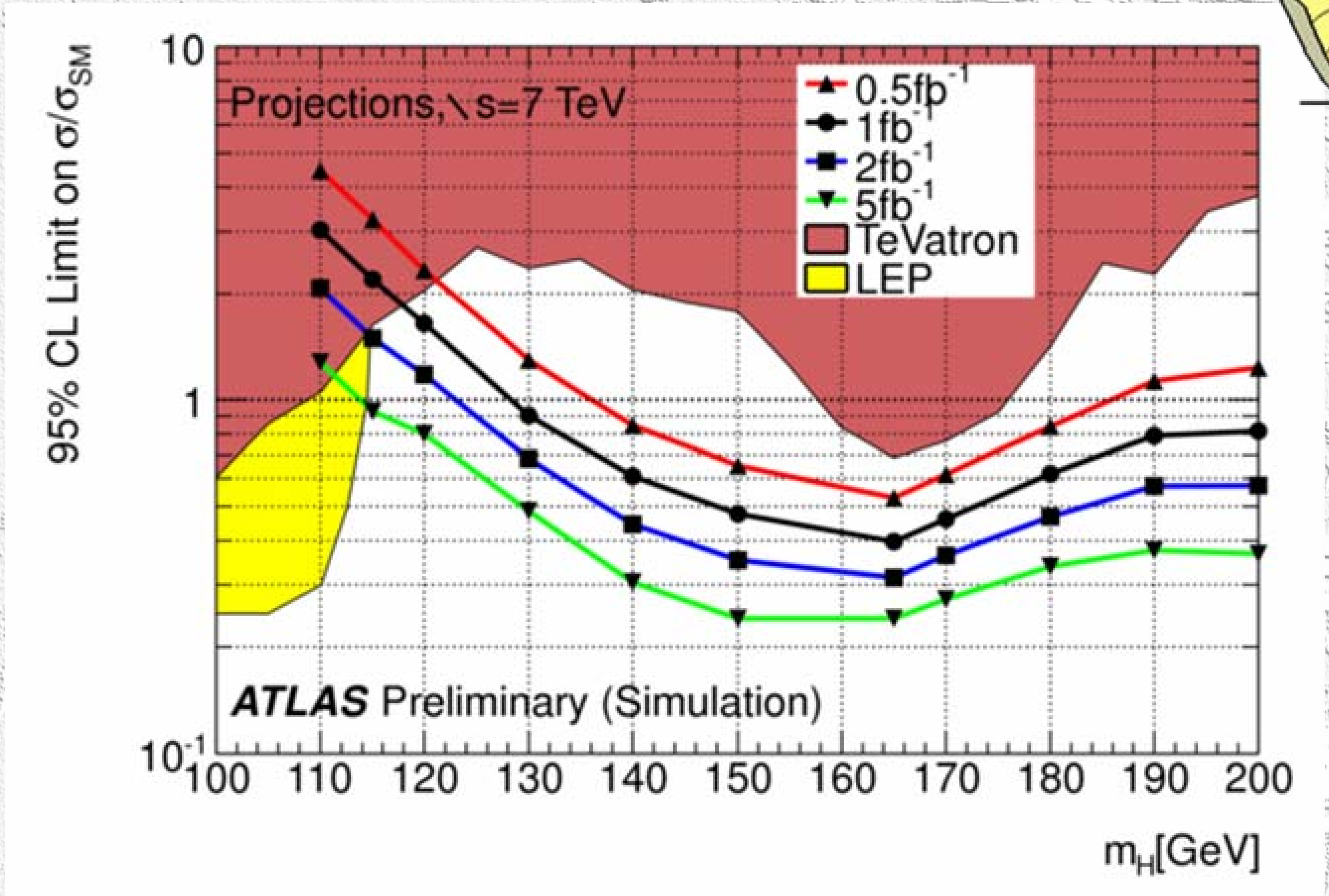
- **Based on very positive experience in 2010 goals might be revised**
  - **increase cms energy to 8 TeV**
  - **peak lumi ≈ $6\times10^{32}/cm^2/s$ resulting in integrated lumi of ≈ 2 fb^{-1}**
  - **LHC running in 2012?**

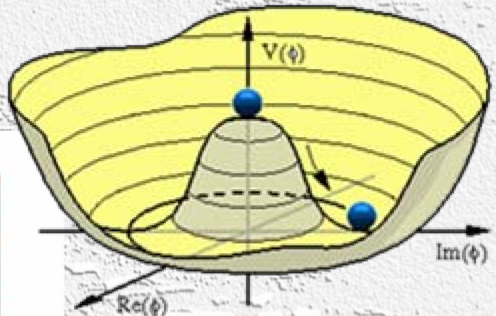
more news early February

- **Opens bright perspective for the Higgs particle hunt in 2011/12**

The Hunt for the SM Higgs

- **ATLAS simulation at 7 TeV**





- **5 fb^{-1} enough to close gap with LEP**
- **Expected 3σ observation from 123 to 550 GeV**

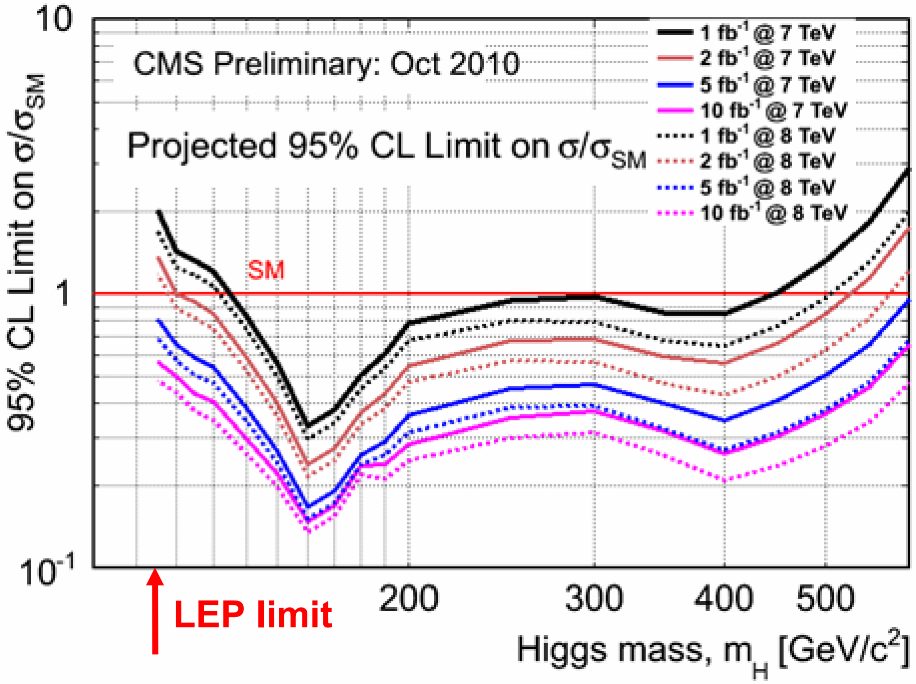
The Hunt for the SM Higgs

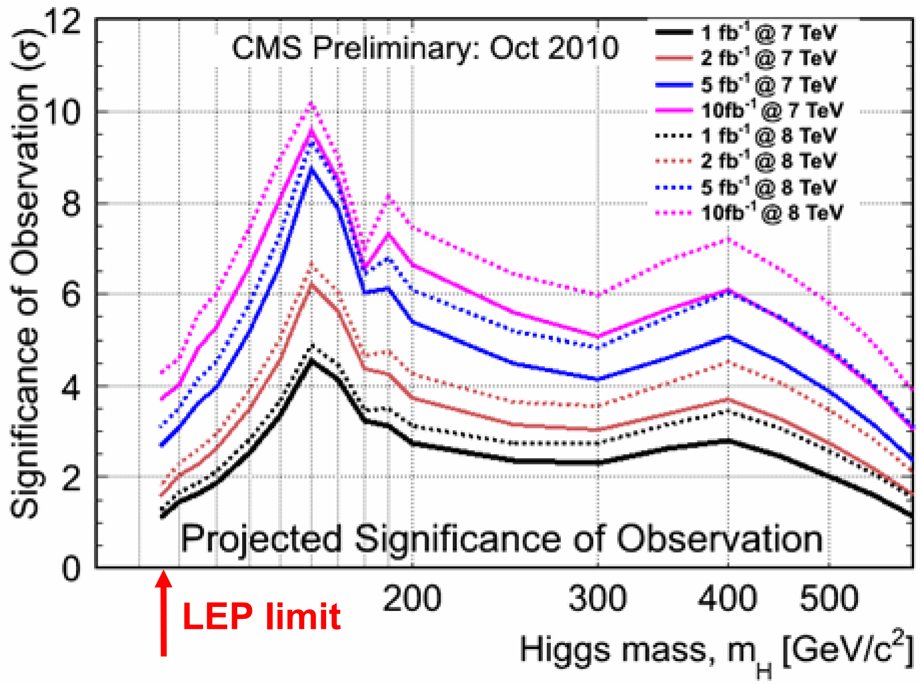
- **CMS simulations at 7 TeV and 8 TeV**

7 TeV (solid)	8 TeV (dashed)
1 fb^{-1}	1 fb^{-1}
2 fb^{-1}	2 fb^{-1}
5 fb^{-1}	5 fb^{-1}
10 fb^{-1}	10 fb^{-1}

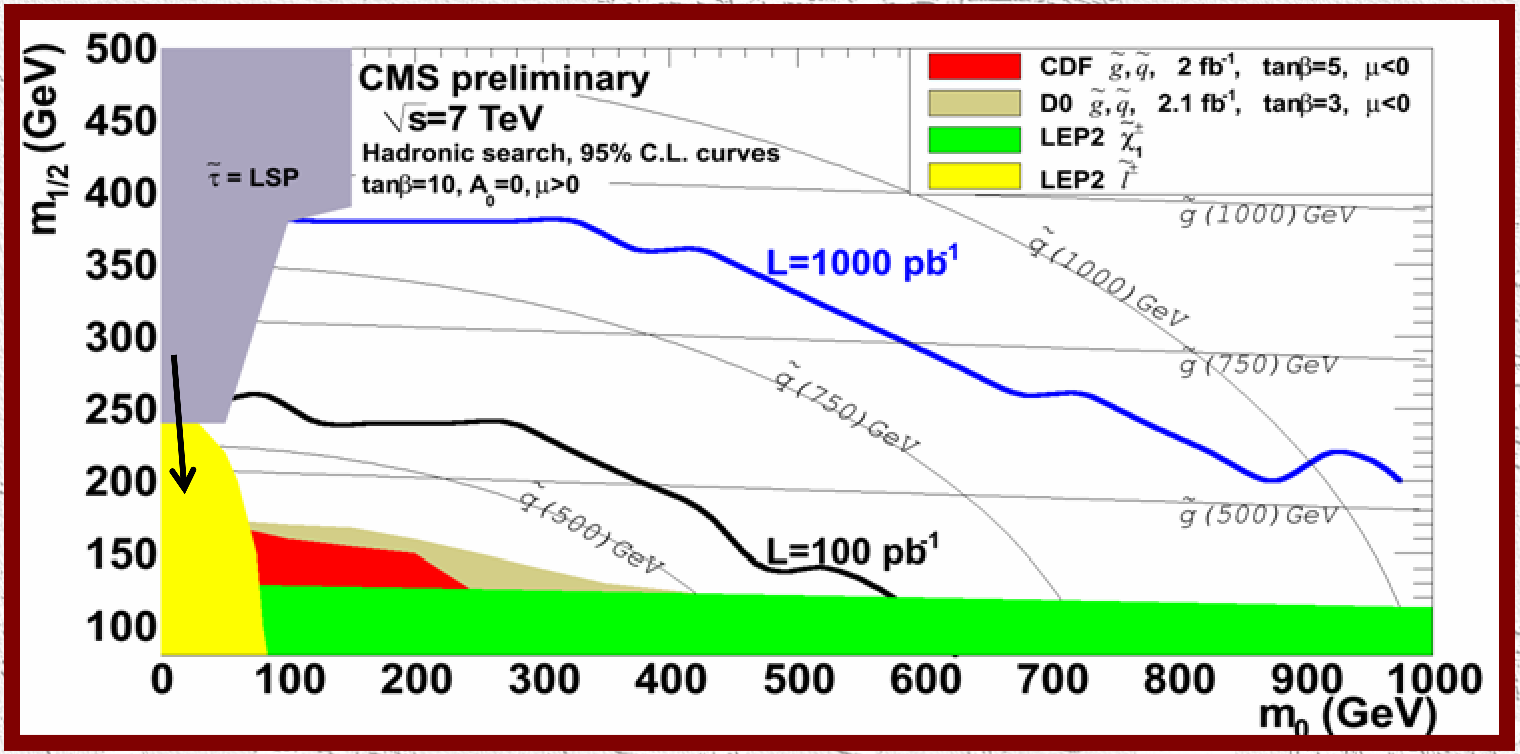
@ 7 TeV   @ 8 TeV

With 5 fb^{-1} can exclude or have 3 σ evidence from 114 to 600 GeV





Search for Supersymmetry



LHC discovery reach for $\tilde{q}$, $\tilde{g}$ pair production, 1 experiment

M (TeV)	1 fb^{-1}	2 fb^{-1}	5 fb^{-1}
√s=7 TeV	0.7	0.8	1
√s=8 TeV	0.8	0.9	1.1

Tevatron exclusion reach: ~ 450 GeV

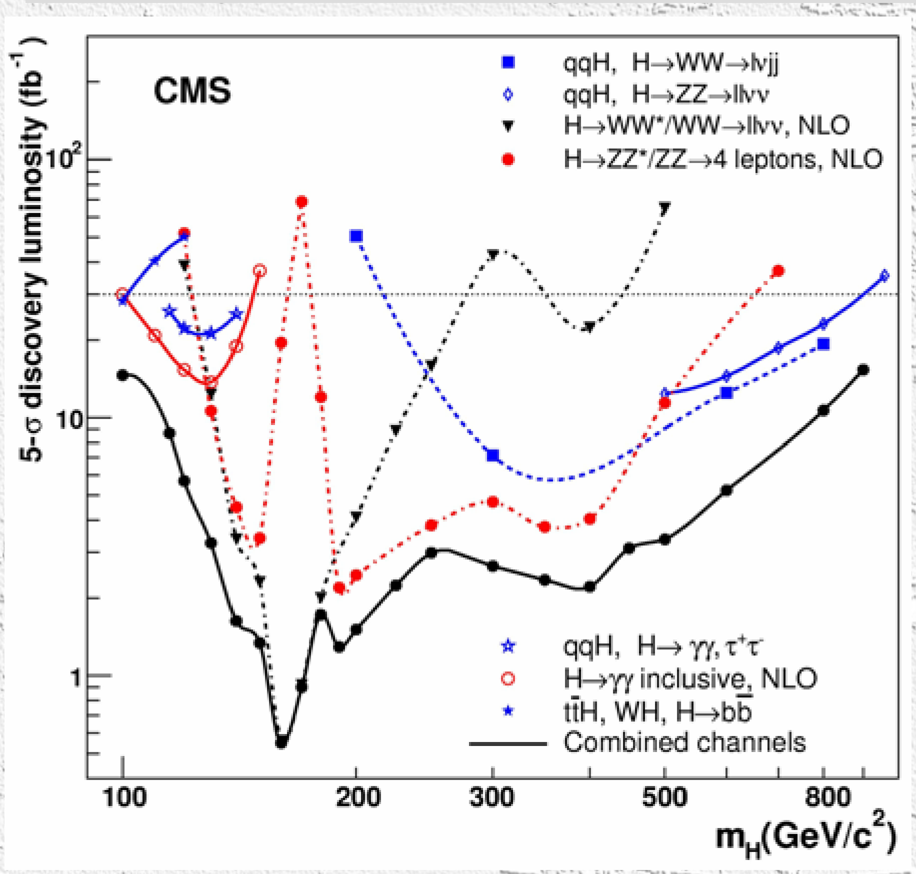
Outlook beyond 2011

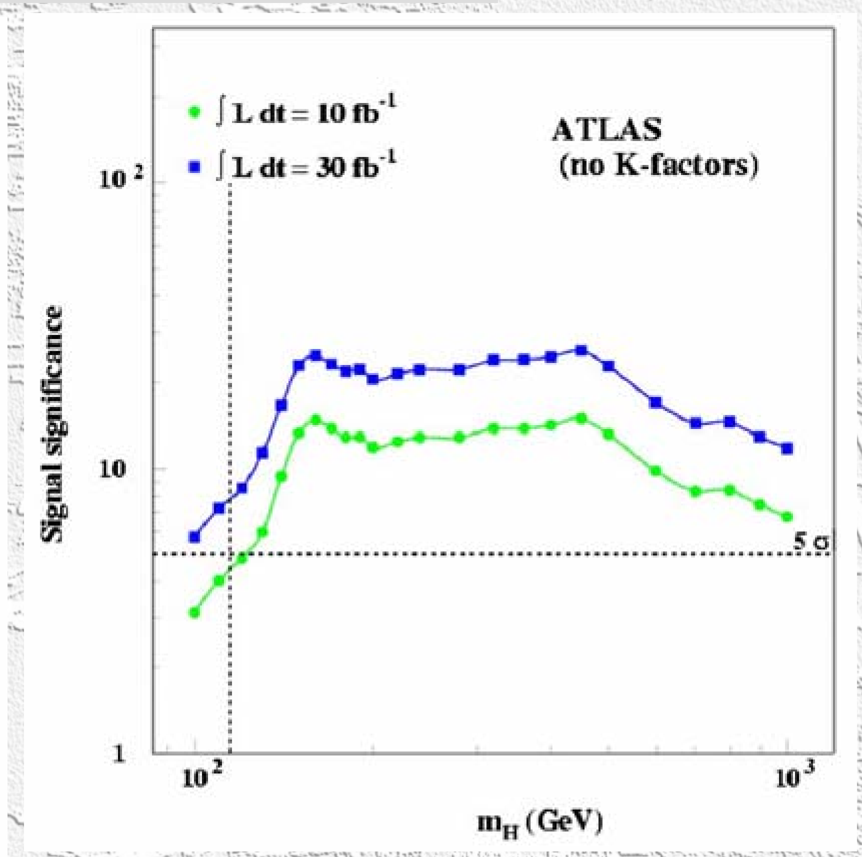
Long term planning

- **2012:**
  - shutdown to repair
    might be postponed to 2013
- **2013 – 2020:**
  - running at 14 TeV
  - two years running interleaved with 1 yerar shutdown
  - push luminosity to 10^{34}/cm^2/s
  - collect ≈ 300 fb^{-1} per experiment
- **2020+:**
  - plans to upgrade the luminosity (High-lumi LHC) to ≈ 5×10^{34}/cm^2/s
  - major upgrades of detector

Search for the Higgs Boson at the LHC

Combine all search channels and determine expected significance as function of the luminosity and Higgs mass:

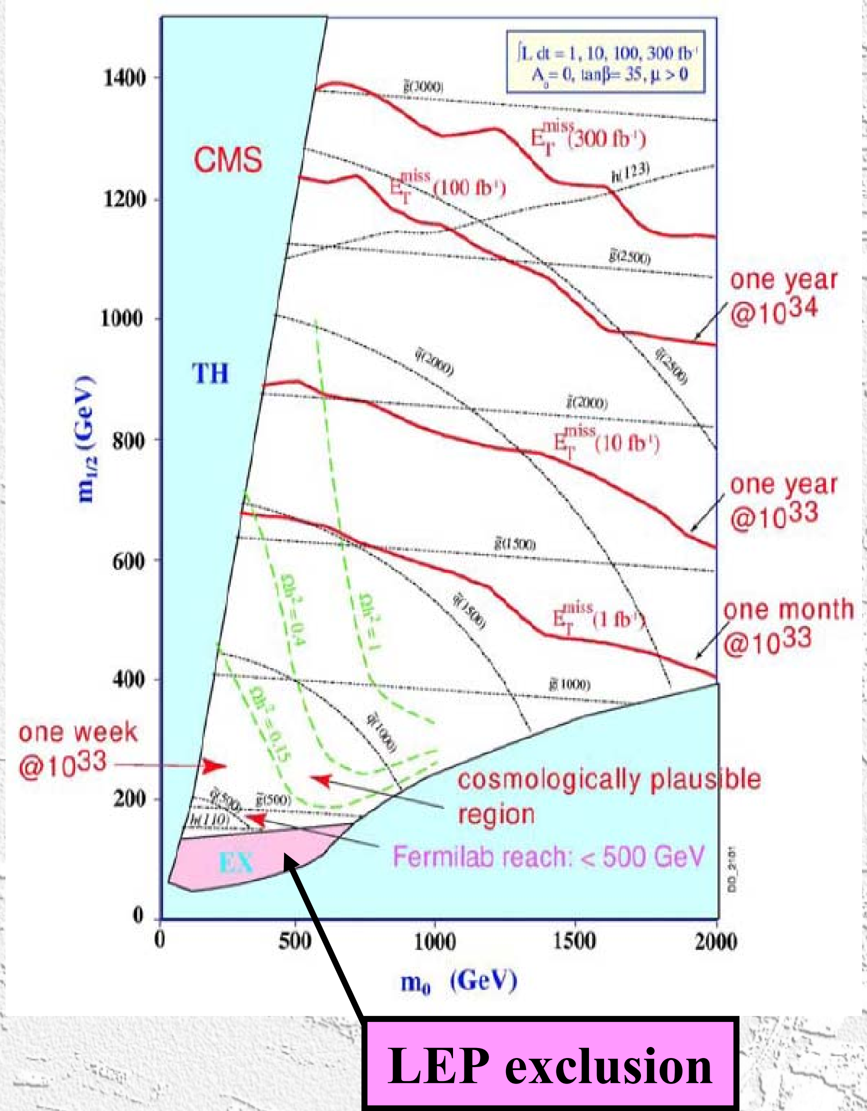




10 fb^{-1} sufficient for 5 σ discovery of the Higgs
LHC will definitely tell if there is a Higgs or not

SUSY Search at LHC

Example: discovery reach as function of luminosity and model parameters which fix the mass scale of SUSY parameters



- achievable limits exploiting E_T^{miss} signatures
- requires very good understanding of detectors

Conclusion:
- LHC will eclipse today's limits on SUSY particles and parameters
- or discover SUSY if it exists at the TeV scale

Summary

- **Phantastic start of the LHC physics programme**
  - **very good perfomance of the machine**
  - **and of the detectors**
  - **Successful stress tests of computing, analysis tools etc.**

- **Excellent prospects**
  - **many SM measurements on top quarks, W/Z bosons and others**
  - **entering uncharted territory next year**
  - **extending mass regions for SUSY and other particles**
  - **the hunt for the Higgs will start**

- **LHC will revolutionize the understanding of our world**

Very exciting times are ahead of us!