

# FYST17 Lecture 5

## LHC Physics 1

Thanks to A. Hoecker, V. Hedberg

Suggested reading: second half of chap 3, section 4.10, and first part of chap 13



# Today & Next week

- The LHC accelerator and the motivations
- Challenges                      Incl Triggers
- The experiments (mainly CMS and ATLAS)
- More on important variables
- Preparations
- Soft physics
- EWK physics
- LHCb
- A few more recent results

# The LHC Physics Programme

## 1. Mass

- Search for the Higgs Boson, measurement of its properties

## 2. Electroweak unification and strong interactions

- Precision measurements ( $M_W$ ,  $m_{\text{top}}$ ) and tests of the Standard Model
- Tests of perturbative QCD at the highest energy scales

## 3. Hierarchy in the TeV domain

- Search for new phenomena moderating the hierarchy problem

## 4. Flavour

- $B$  mixing, rare decays and  $CP$  violation as tests of the Standard Model

# Motivation behind the Large Hadron Collider

## Advantage of hadron collider

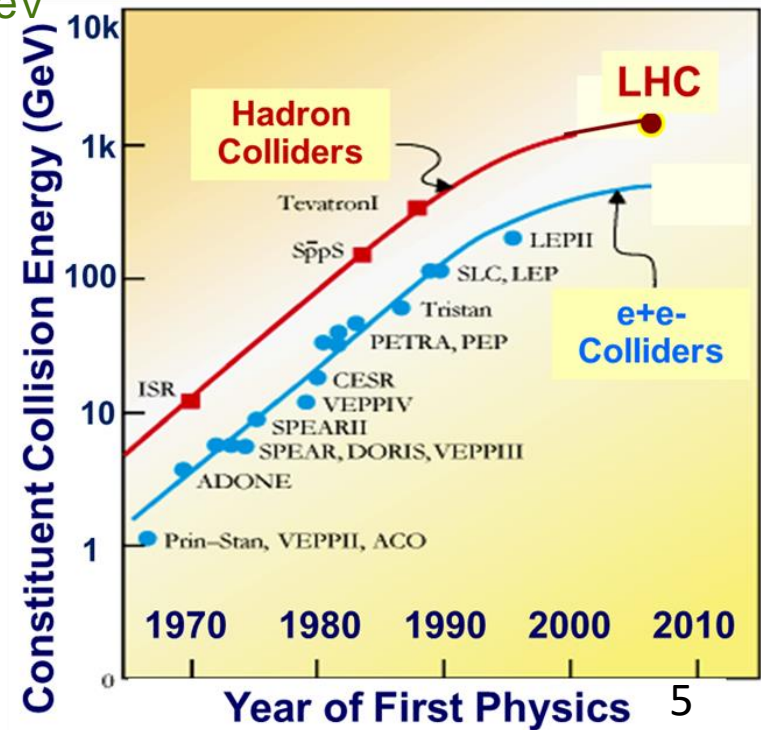
- Can reach higher energies in ring (less synchrotron radiation)

Energy loss per turn:

$$-\Delta E \approx \frac{4\pi\alpha}{3 \cdot R} \left( \frac{E}{m} \right)^4 \approx \begin{cases} 3.5 \text{ GeV for LEP-II at } E_{\text{beam}} = 104.5 \text{ GeV} \\ 6.2 \text{ keV for LHC at } E_{\text{beam}} = 7000 \text{ GeV} \end{cases}$$

## Disadvantages

- Hadrons are composites → parasitic collisions beyond hard parton scattering
- Energy and type of colliding parton unknown → kinematics partially unconstrained



# Driving the SM to the Planck Scale: Or why we expected the Higgs boson to be discovered at the LHC

Perturbativity and (meta)stability bounds versus the SM cut-off scale  $\Lambda$

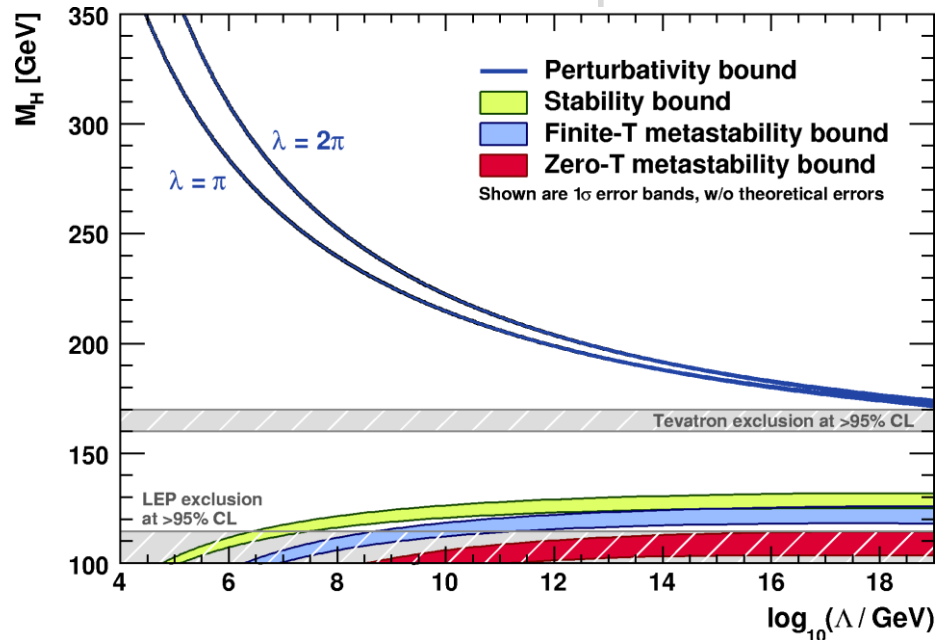
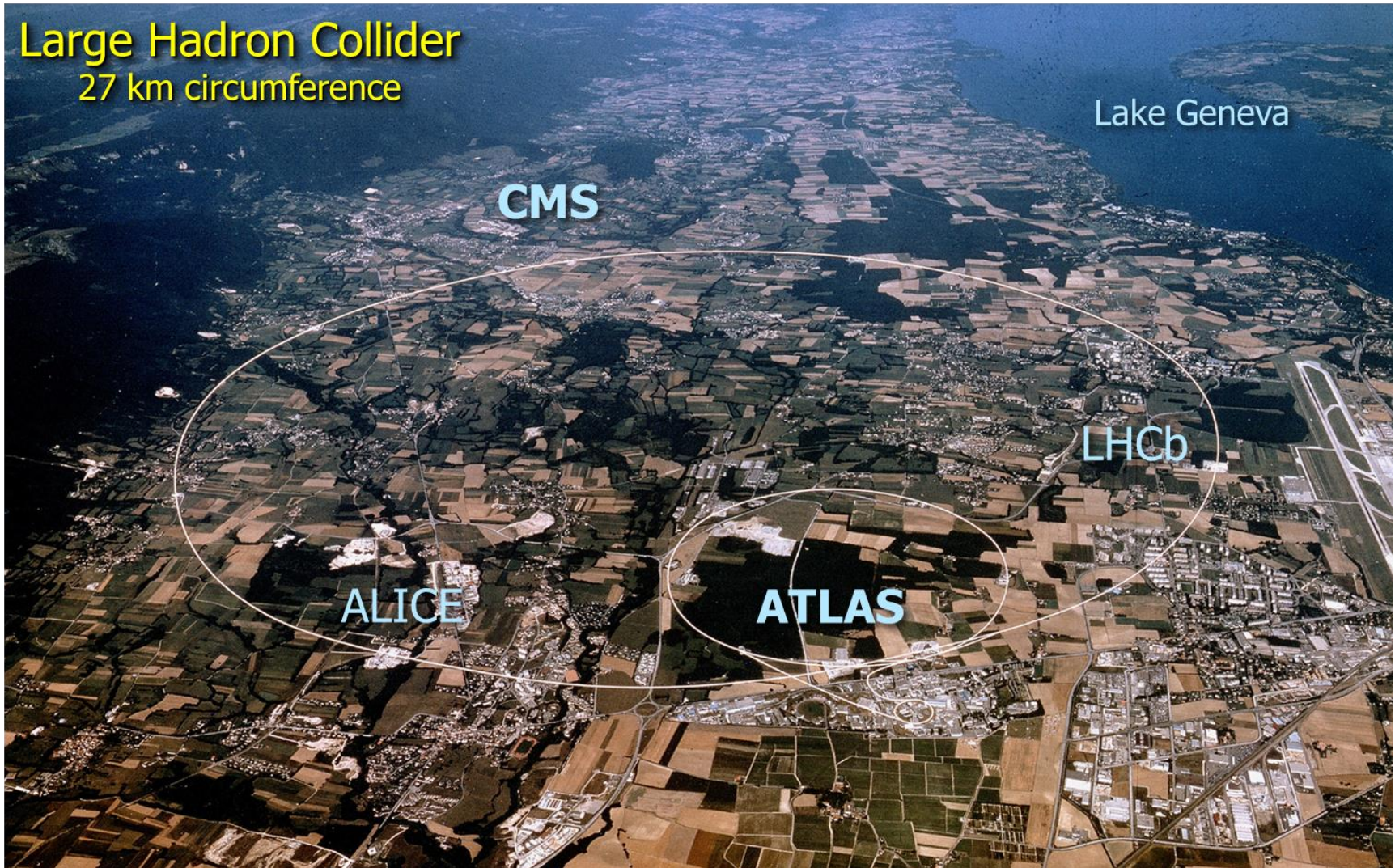


Figure uses NLO Higgs potential. The widths of bands account for errors in  $\alpha_S$ ,  $m_t$  and theory.

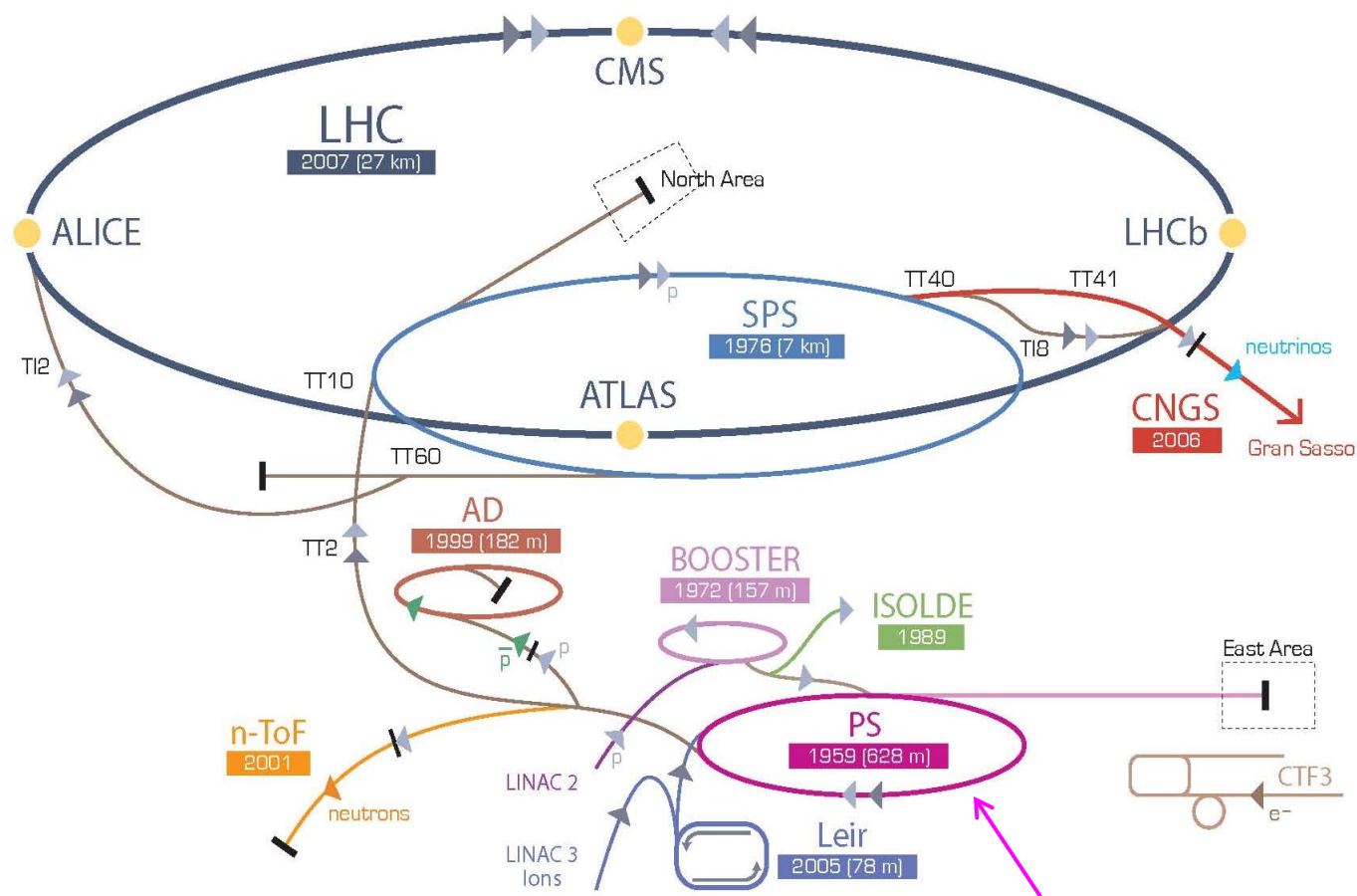
The SM Higgs must steer a narrow course between two disastrous situations if it is to survive up to the Planck scale  $M_p \sim 2 \times 10^{18}$  GeV



# The accelerator



# CERN accelerator complex



(>50 years old! )

	<u>Top energy/GeV</u>	<u>Circumference/m</u>
Linac	0.12	30
Booster	1.4	157
PS	26	$628 = 4 \times \text{Booster}$
SPS	450	$6'911 = 11 \times \text{PS}$
LHC	7000	$26'657 = 27/7 \times \text{SPS}$

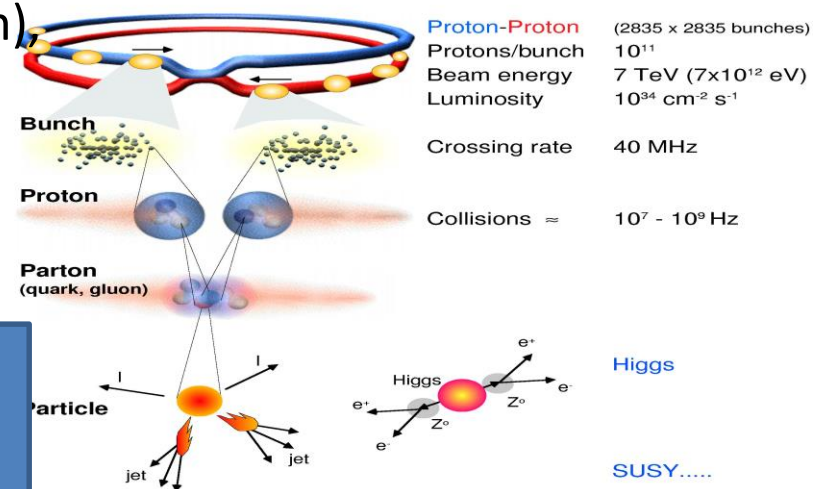


# The LHC environment

- The search for new phenomena exploits **ever smaller distances  $\Rightarrow$  ever larger energies**
- The LHC collides protons at  $E_{\text{CM}} = 13 \text{ TeV} \rightarrow$  probing a distance of  $1 \times 10^{-18} \text{ cm}$  ?  
... not quite, since protons are composites: the energy is distributed among its partons
- **Proton energy is limited by magnets that guide the circular beams**
- $E_{\text{proton}} \sim 0.3 \cdot B \cdot r$  : since radius is fixed (4.3 km), use as strong fields as possible ( $> 8 \text{ T}$ ), and fill all free LHC sections with dipole magnets ( $\sim 2/3$ )



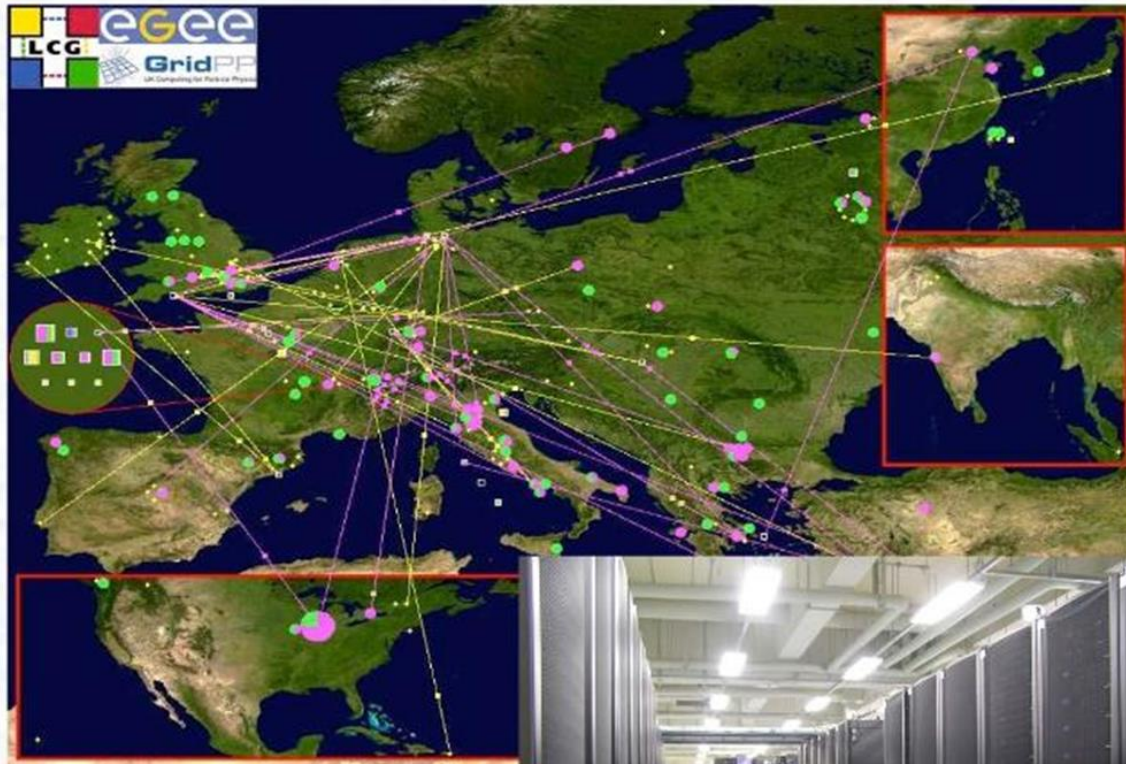
## Collisions at LHC



Protons are circling in bunches, ( $\sim 3000$  at full intensity) with up to  $10^{11}$  protons/bunch  
 Bunch size  $\sim 1 \text{ mm} \times \text{few cm}$   
 $16 \mu\text{m}$  width at collision points  
 Made to collide every 25ns!

Selection of 1 in 10,000,000,000,000

# LHC data handling, GRID computing



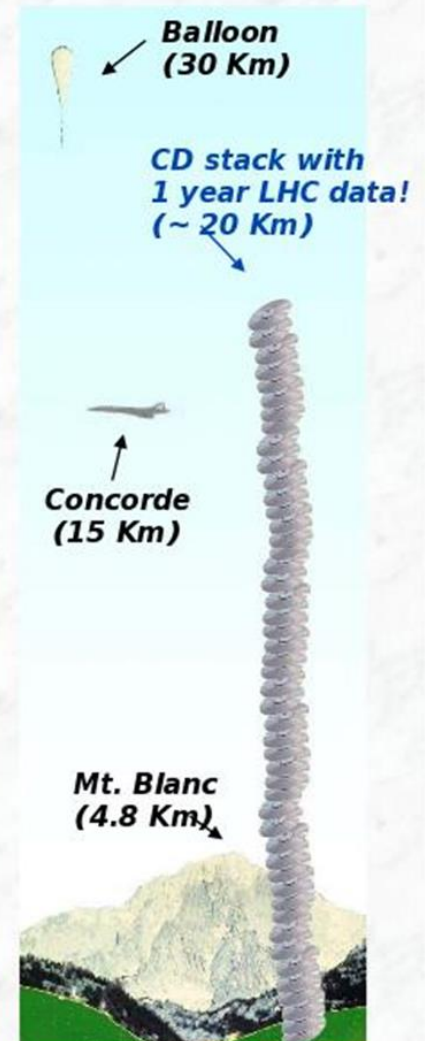
Trigger system selects  
~200 "collisions" per sec.

LHC data volume per year:  
10-15 Petabytes

=  $10-15 \cdot 10^{15}$  Byte

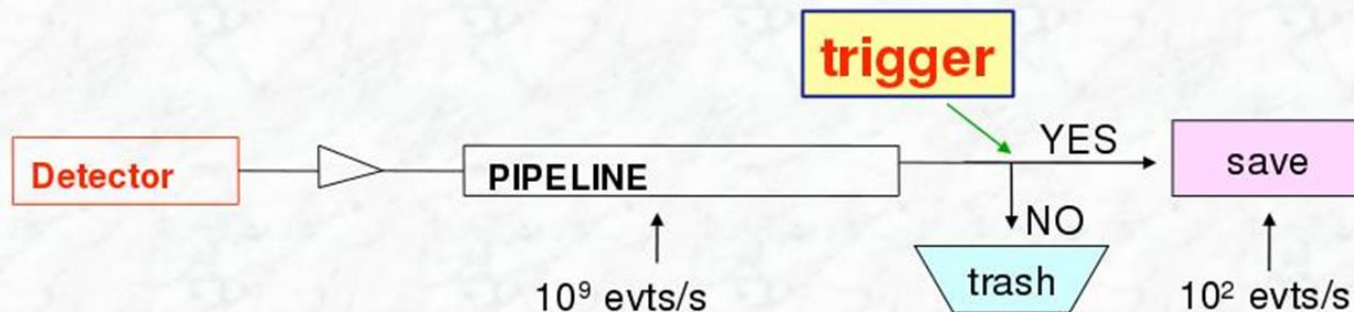


A typical Tier-2 GRID center  
(example: Tokyo University)



## How to Select Interesting Events?

“the trigger does not determine which physics model is right, only which physics model is left” A. Bocci

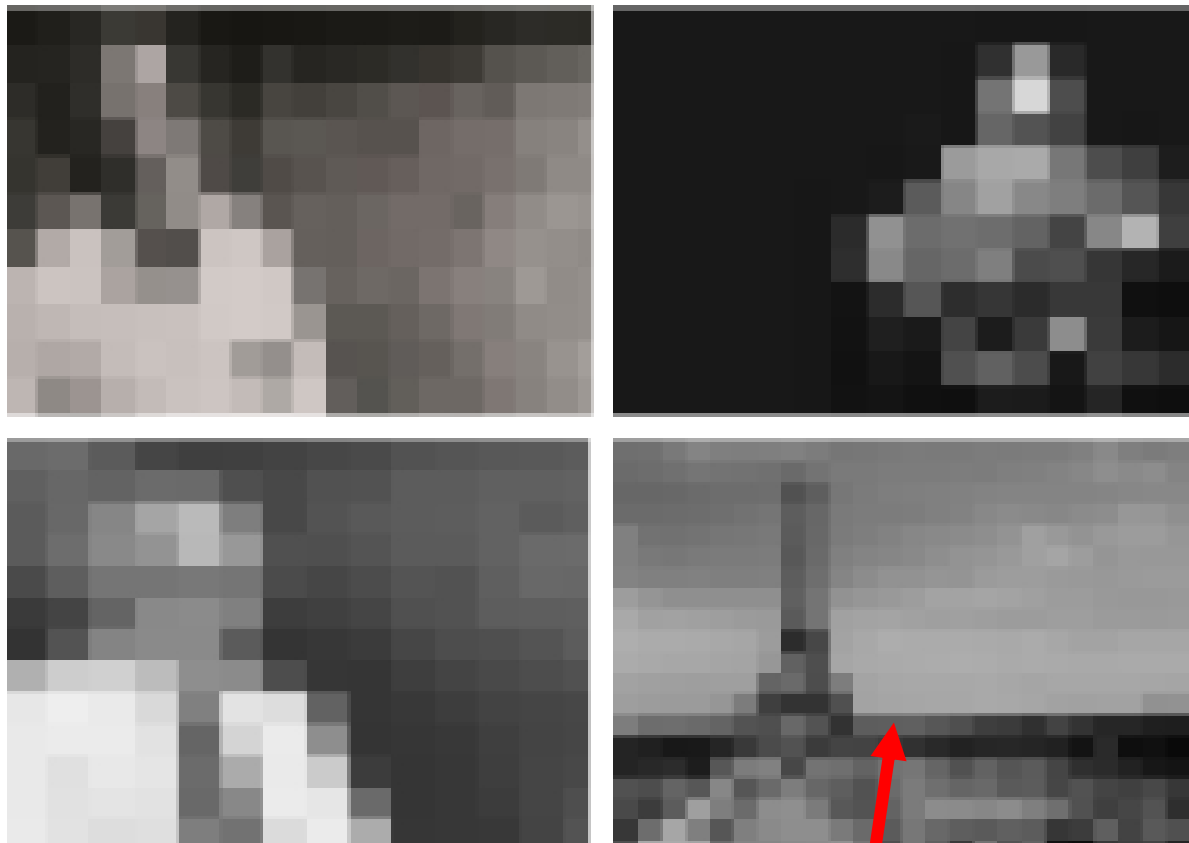


- ATLAS trigger has 3 levels (CMS similar with 2 levels)
  - Level-1: hardware,  $\sim 3 \mu\text{s}$  decision time,  $40 \text{ MHz} \rightarrow 100 \text{ kHz}$  i.e. no time for input from tracking
  - Level-2: software,  $\sim 40 \text{ ms}$  decision time,  $100 \text{ kHz} \rightarrow 2 \text{ kHz}$
  - Level-3: software,  $\sim 4 \text{ s}$  decision time,  $2 \text{ kHz} \rightarrow 200 \text{ Hz}$

## Example: Higgs

• L1

Coarse  
granularity



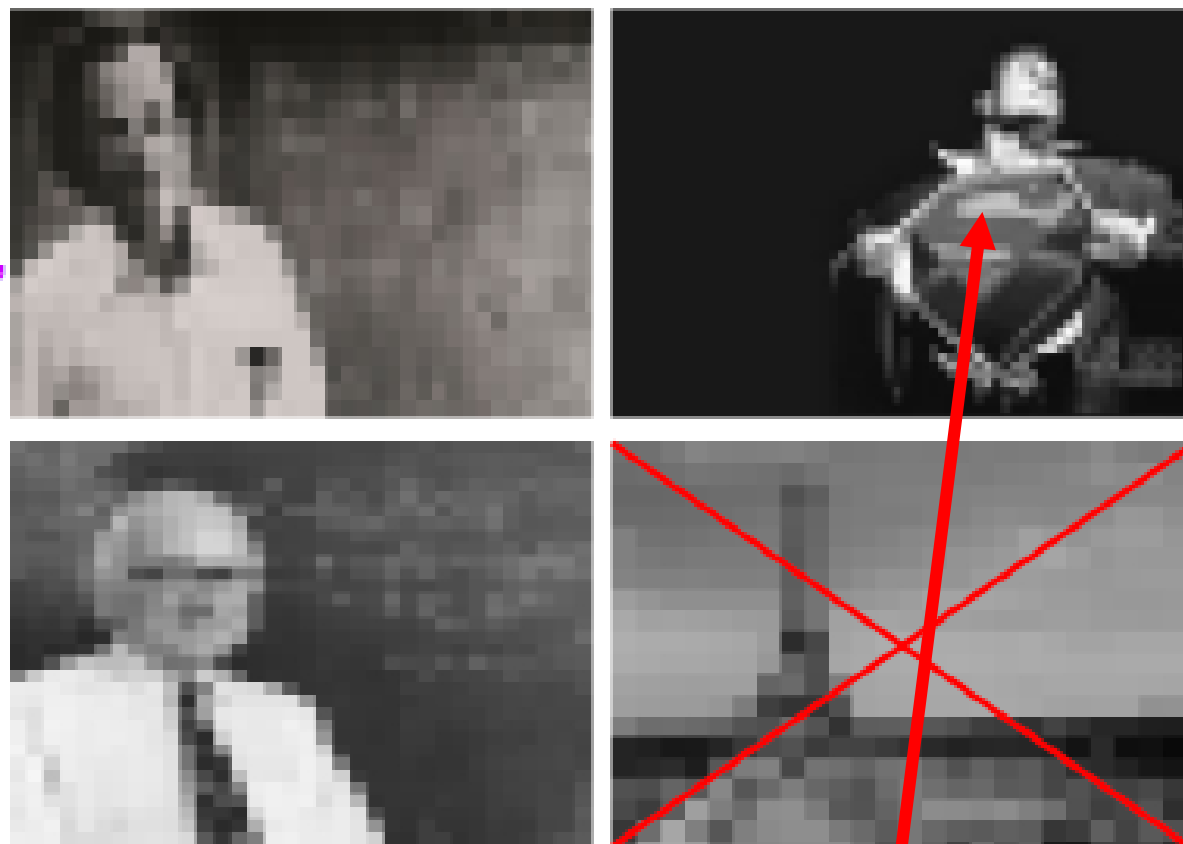
*L1: This is not Higgs*



## Example: Higgs

### • L2

Improved  
reconstruction,  
improved  
ability to reject  
events

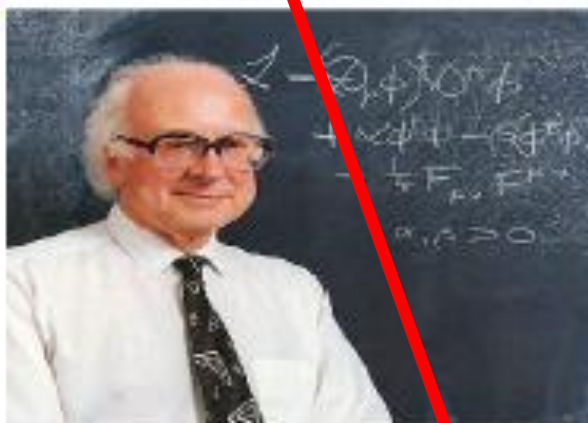
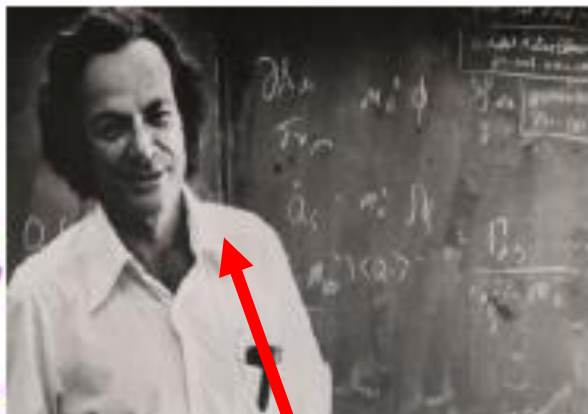


*L2: This is not Higgs*

## Example: Higgs

EF

high quality  
reconstruction,  
improved  
ability to reject  
events



*L3/EF: This is not Higgs*

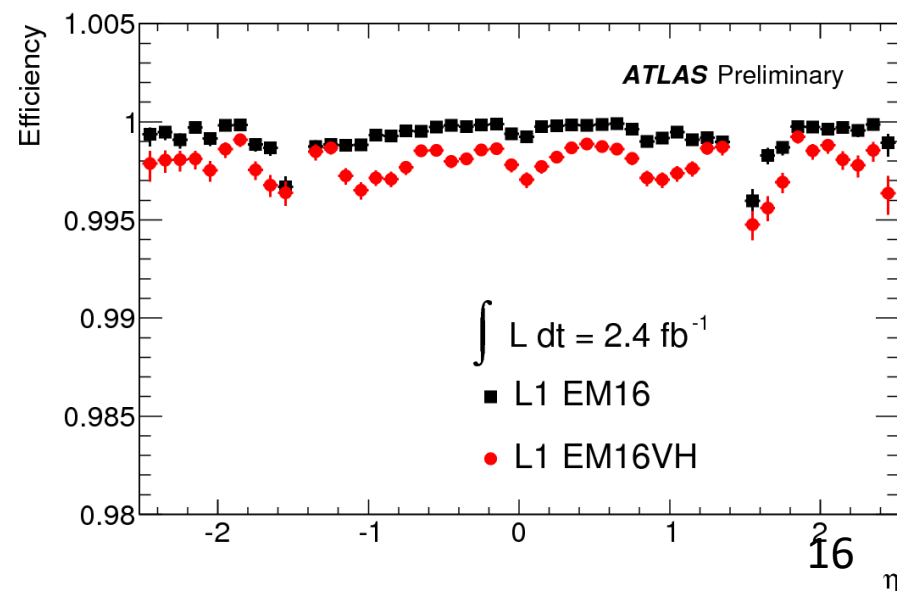
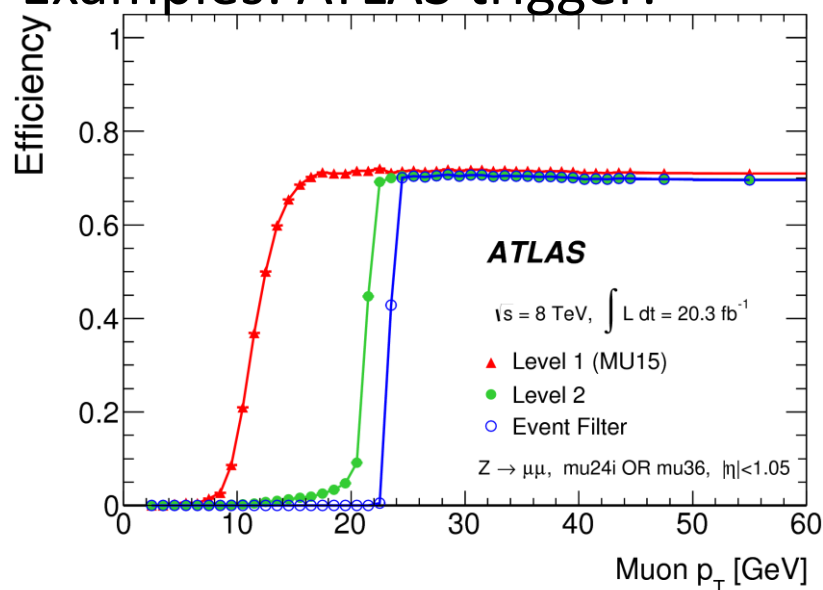
# Trigger efficiency

Enters in calculation of cross section:

$$\sigma = \frac{N}{A \cdot \varepsilon \cdot \int L dt}$$

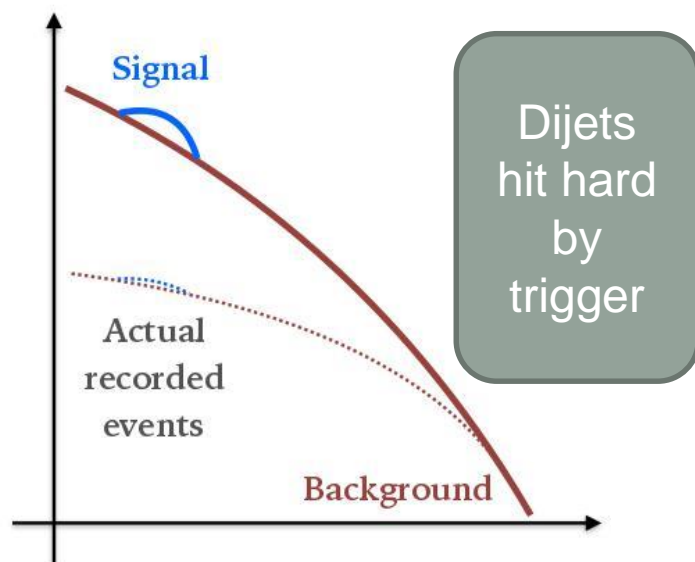
Acceptance  $\rightarrow A$   
 Efficiency  $\rightarrow \varepsilon$   
 Integrated luminosity  $\rightarrow \int L dt$

Examples: ATLAS trigger:



# Online analysis: by-passing the trigger?

Number of events



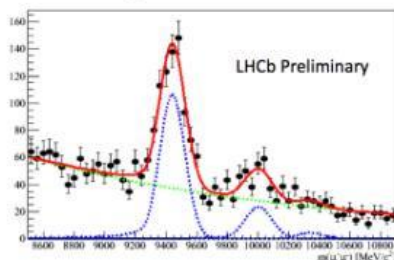
If we relax storage requirement  
Analysis can be done directly on first  
level trigger output

Detector performance/ resolution  
degraded  
-but not always a show stopper

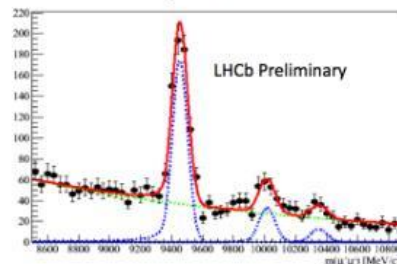
Run 2

Invariant mass distribution for  $\Upsilon \rightarrow \mu^+\mu^-$

First alignment  
 $\sigma_Y = 92 \text{ MeV}/c^2$



Better alignment  
 $\sigma_Y = 49 \text{ MeV}/c^2$



First analyses/ attempts on-going at  
the LHC experiments

Raw data still not 100% stored ...



# Requirements from Physics Programme

■ Some benchmark analyses

➡  $B_{s(d)} \rightarrow \mu\mu$  and  $B_s \rightarrow J/\psi \phi$

➡  $W$  mass

➡ top mass

➡  $H \rightarrow \gamma\gamma, 4e, 4\mu, \tau\tau$  (WBF)

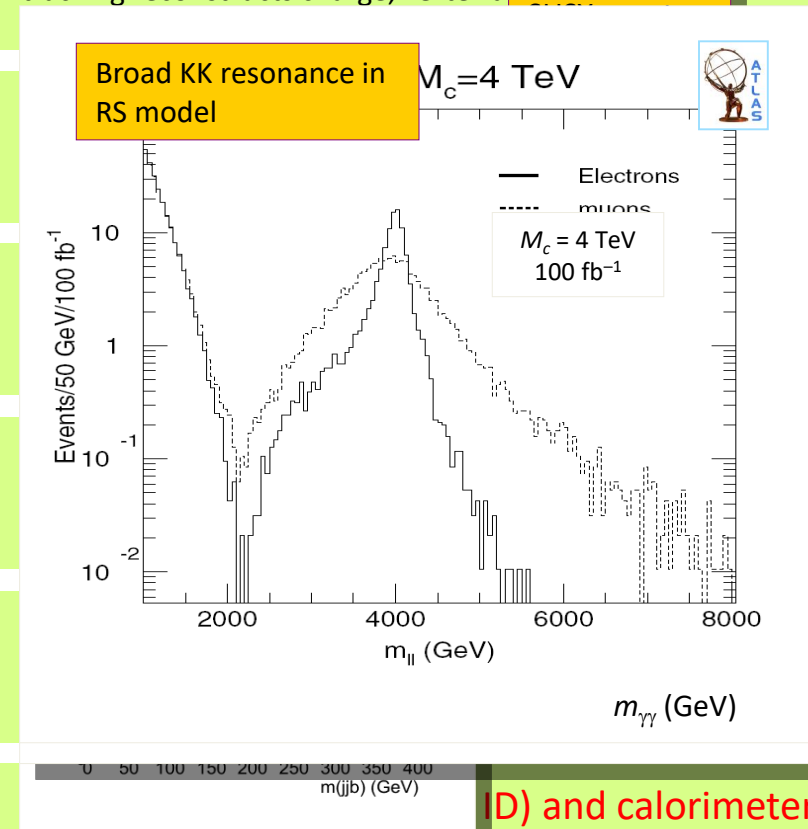
➡ SUSY with  $R$ -parity, SUSY Higgs

➡ RS KK modes

■ Design challenges:



**Trigger efficiency** ( $p_T > 3$  GeV) and purity (HLT tracking reconstructs charge, vertex a [redacted])



**ID) and calorimeter resolution at  $O(\text{TeV})$ , little calo saturation**

# Requirements from LHC Conditions

## ■ LHC and data conditions:

- ➡ **40 MHz bunch crossing rate** (25ns = 7.5m bunch spacing)
- ➡ **~1 GHz interaction rate at  $L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$**  (~25 ias. per bunch crossing)
- ➡ **~300 Mbytes/seconds data rate** (200 Hz  $\Rightarrow O(1.5 \text{ MB/event})$ )
- ➡ **Irradiation rate / 10 LHC years:  $5 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$**  (300 kGray [= J/kg])
- ➡ **High charged multiplicity** ( $O(1000)$  tracks per event,  $10^{12} / \text{sec}$ )
- ➡ **High background rates** (beam halo muons, neutrons, beam-gas collisions)

## ■ Design challenges:



**Fast trigger, precise timing and “pipeline” electronics: Level-1 latency  $< 2.5\mu\text{s}$**

**Efficient pattern recognition to reduce:** GHz @ L1  
 $\rightarrow 75 \text{ kHz @ HLT} \rightarrow 200 \text{ Hz to disk}$

**Powerful data processing farms:** distribute data analysis to computing centres worldwide

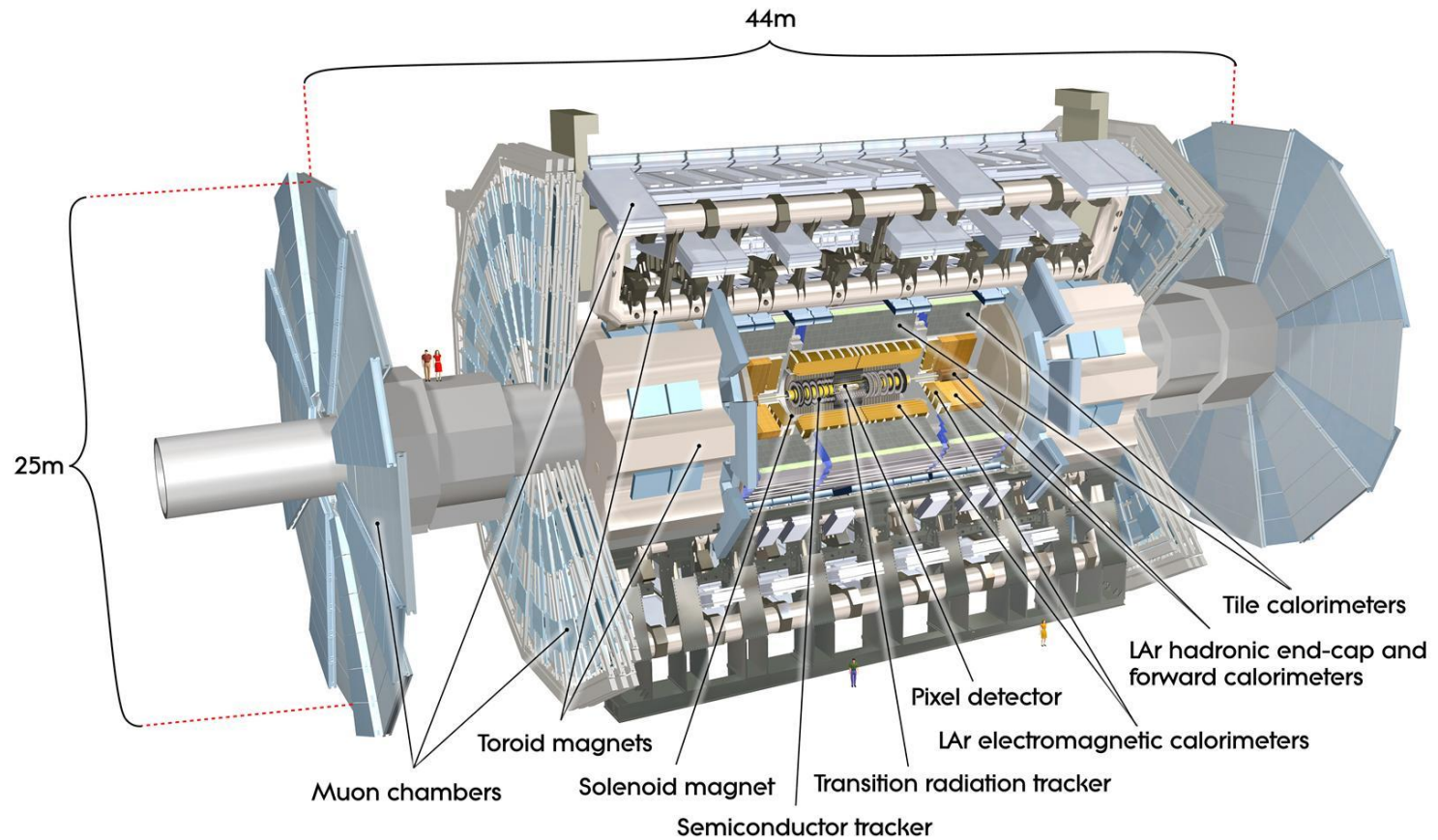
**Radiation hard inner tracker** (pixel with large  $S/B$ )  
**and forward calorimeter technology**

**High-granular pixel/silicon or fine-grained straw tracker** technologies

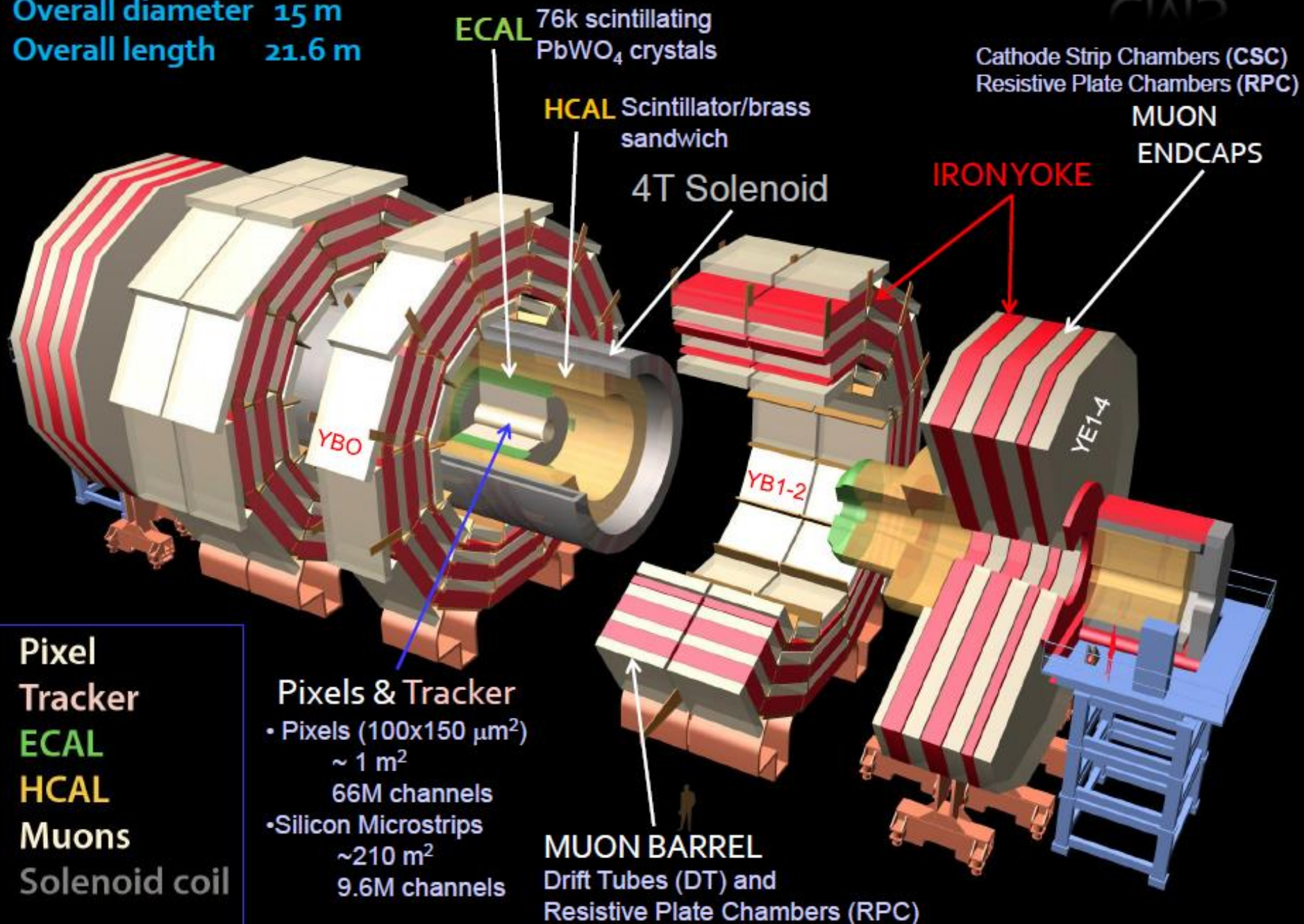
**Precise muon timing, redundant pattern recognition, radiation hardness**

A large Toroidal Lhc ApparatuS

# ATLAS

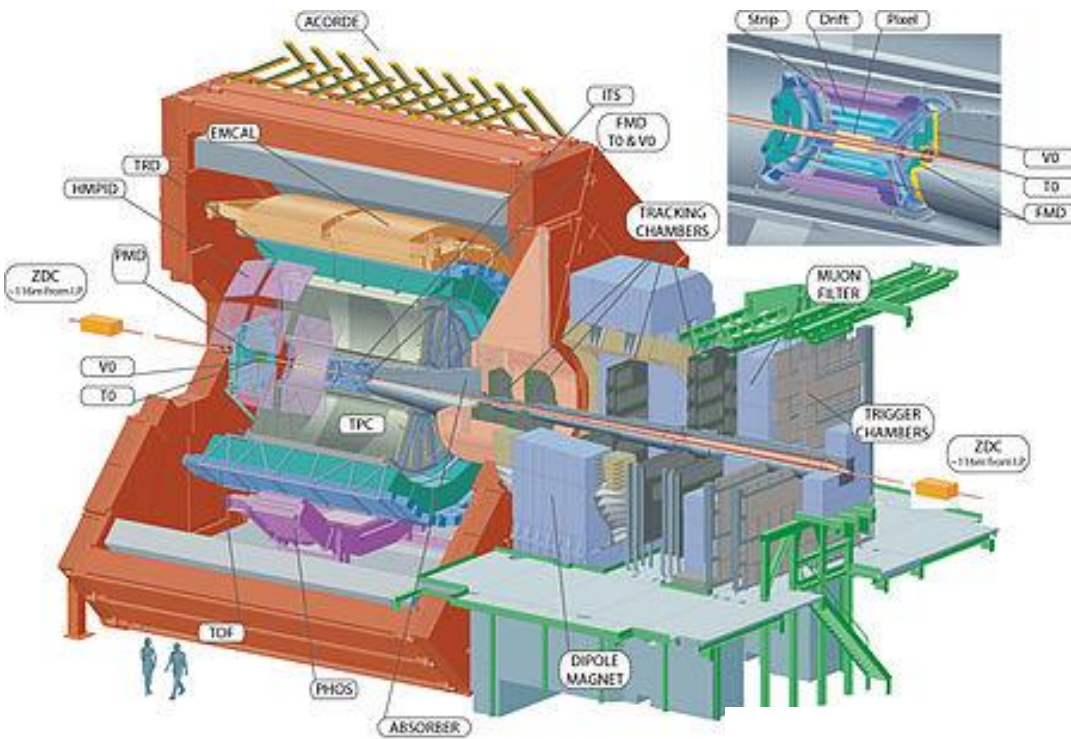


Total weight 12500 t  
Overall diameter 15 m  
Overall length 21.6 m

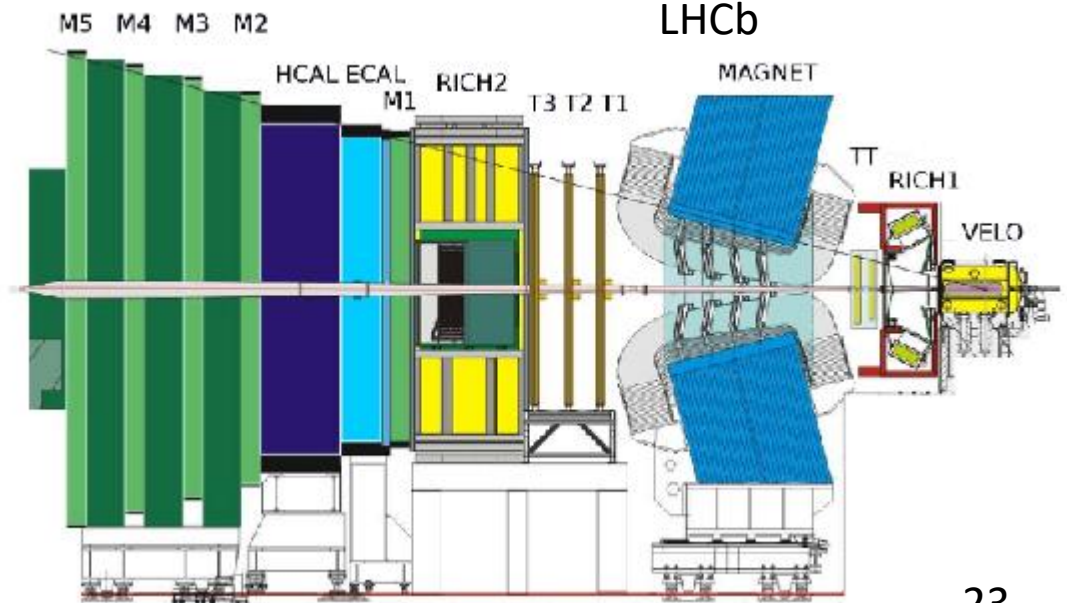




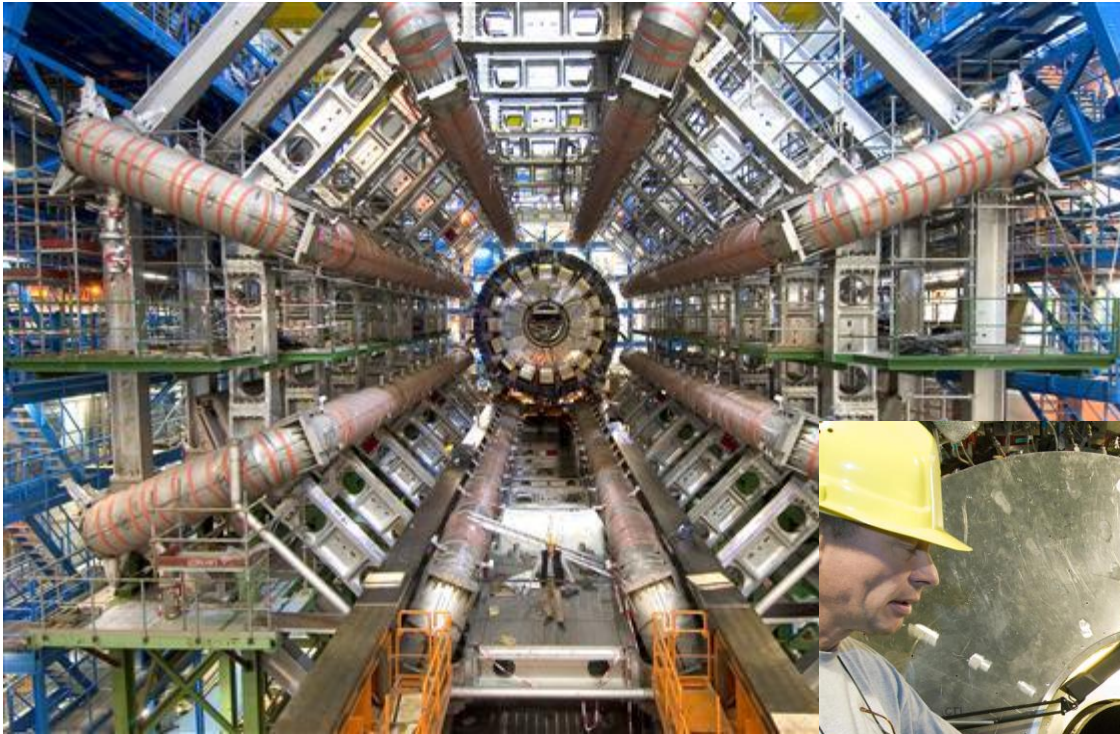
# ALICE + LHCb



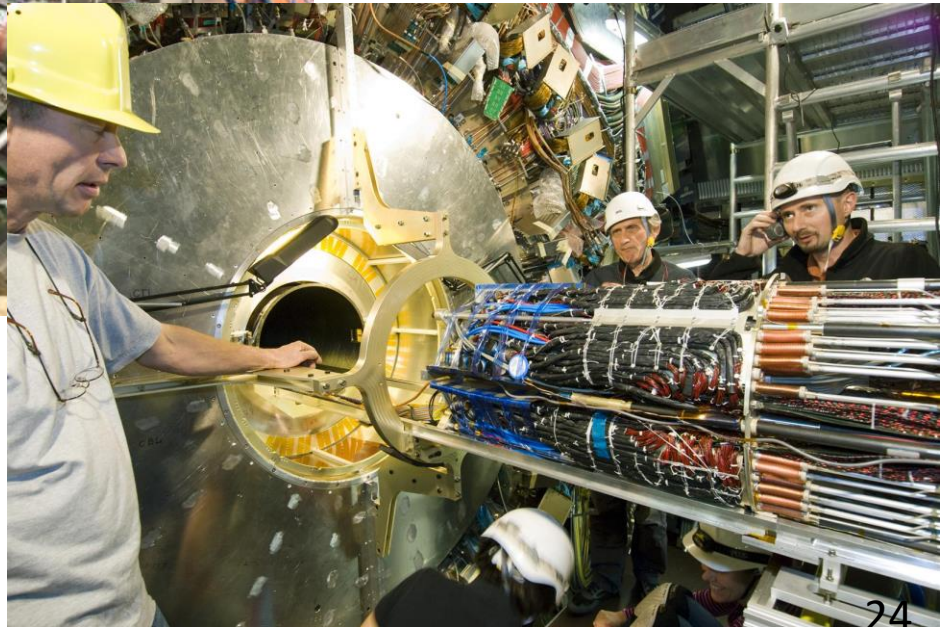
A Large Ion Collider Experiment



# From the construction of ATLAS



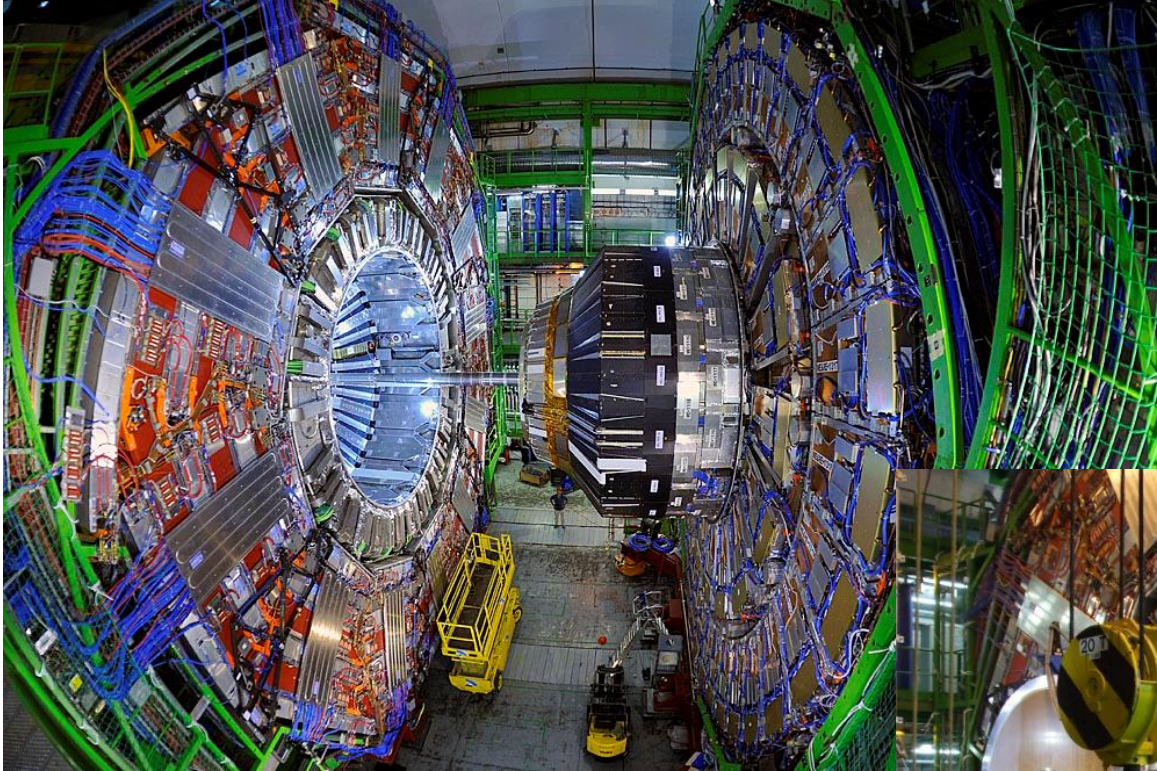
Installing ECAL



Installing pixels



# From the installation of CMS



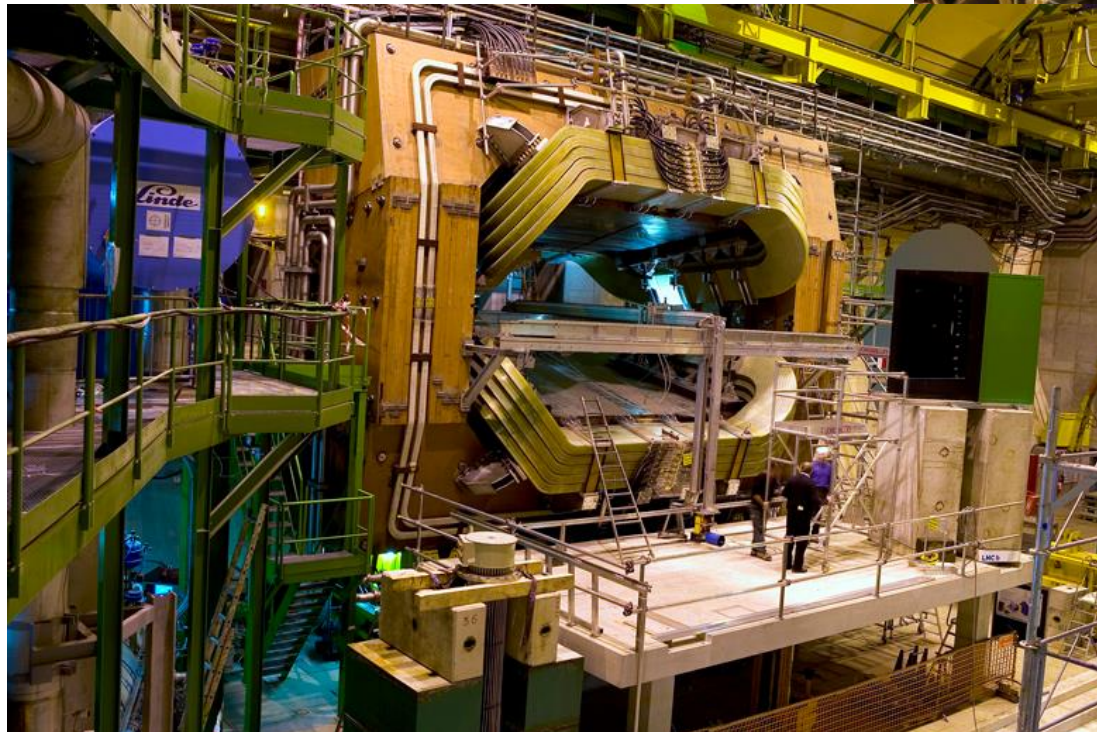
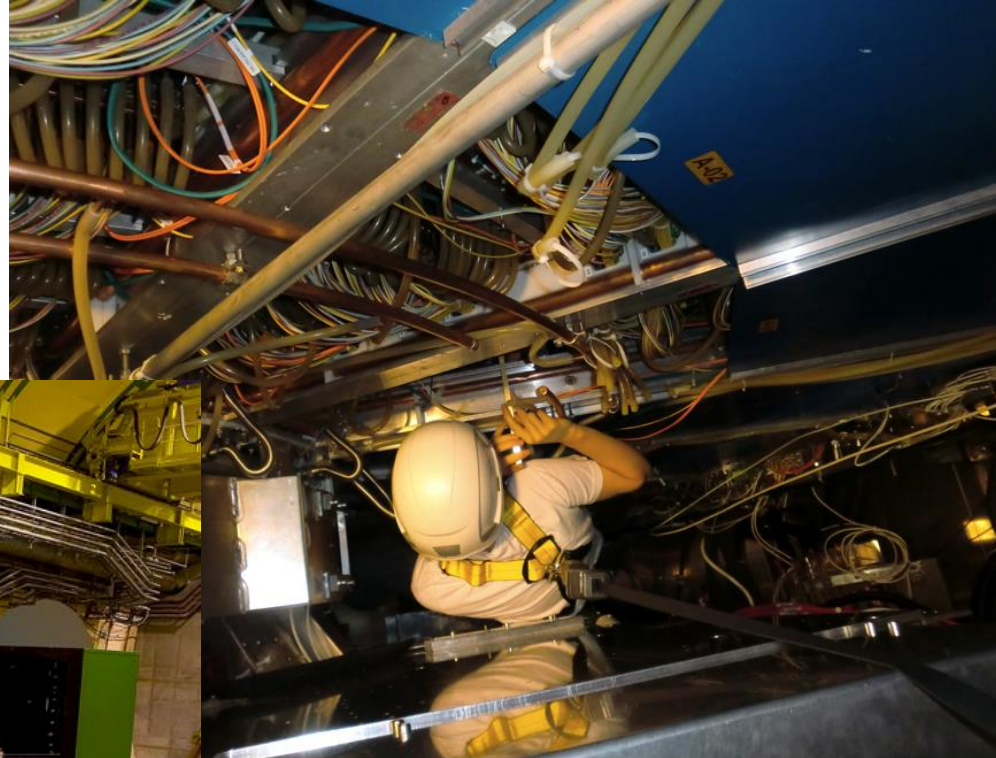
Installing pixels





# LHCb + ALICE

LHCb magnet

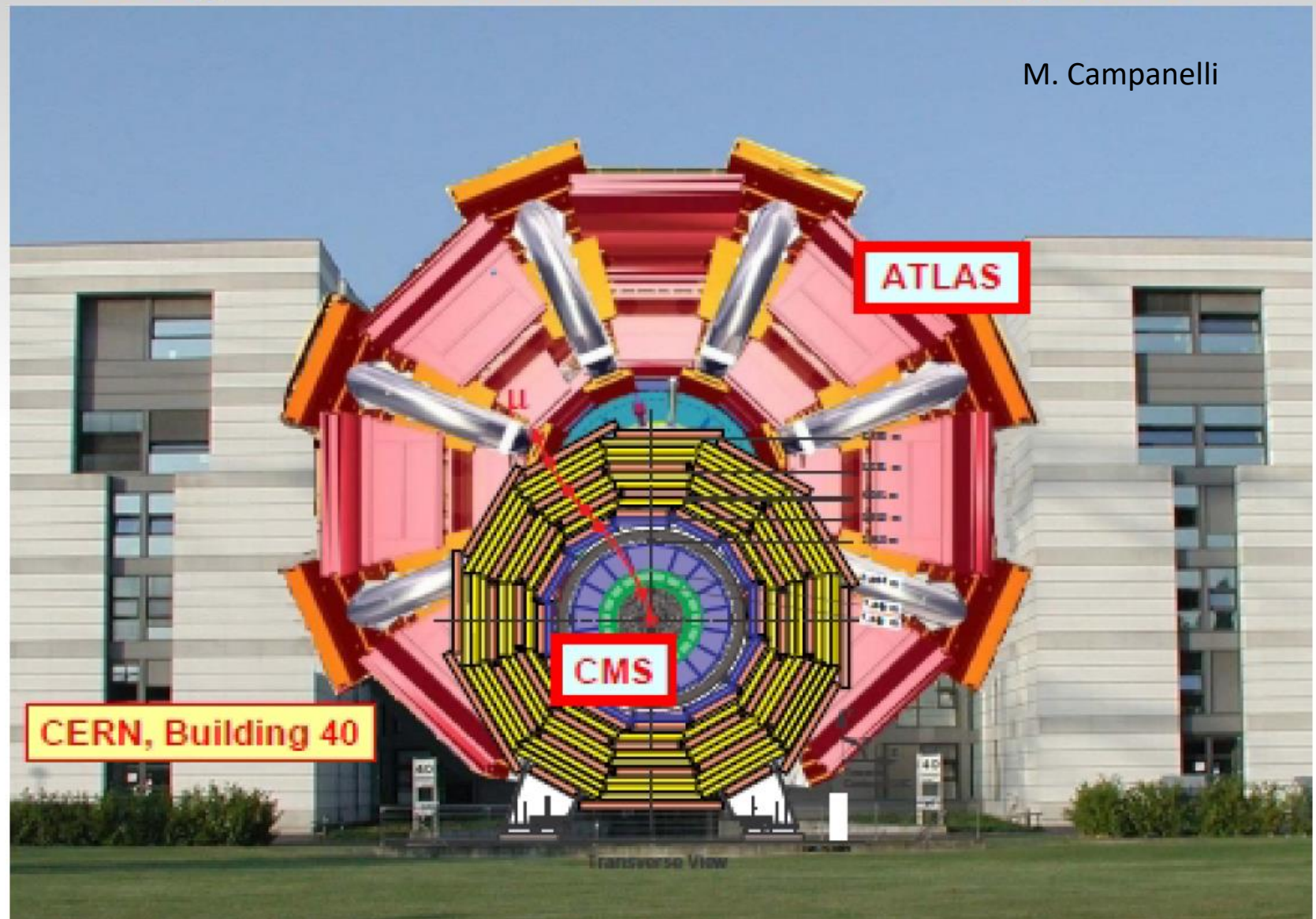


Graduate student Tuva  
pulling cables for ALICE



# Why CMS stands for 'compact'

M. Campanelli



# Luminosity – single most important quantity !

- Luminosity is purely a function of the LHC beam parameters (formula similar to luminosity of stars)

$$L = \frac{f_{\text{rev}} n_{\text{bunch}} N_{p,1} N_{p,2}}{A} = \frac{f_{\text{rev}} n_{\text{bunch}} N_{p,1} N_{p,2}}{4\pi\sigma_x\sigma_y} \quad [L] = \frac{1}{\text{s} \cdot \text{cm}^2}$$

- $f_{\text{rev}} = 11245.5$  Hz is the bunch revolution frequency
  - $n_{\text{bunch}} = 1...2808$  is the number of bunches in the machine
  - $N_{p,1/2} = 1.1 \times 10^{11}$  is the number of protons in each beam
  - $\sigma_{x/y} = 16...50$   $\mu\text{m}$  is the Gaussian transverse beam width
  - $L_{\text{max}} = 1.3 \times 10^{34} \text{ s}^{-1}\text{cm}^{-2}$
- Luminosity** determines the rate of physics processes by unit time and hence **drives our ability to detect new processes**

$$N_{\text{obs}} = \text{cross section} \times \text{efficiency} \times \int L \cdot dt$$

“Cross section” given by Nature

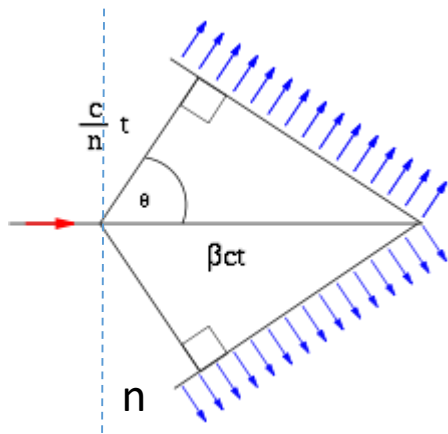
“Efficiency” of detection  
optimised by experimentalist

# Particle ID with Cherenkov detectors

Charged, relativistic particles in dielectric

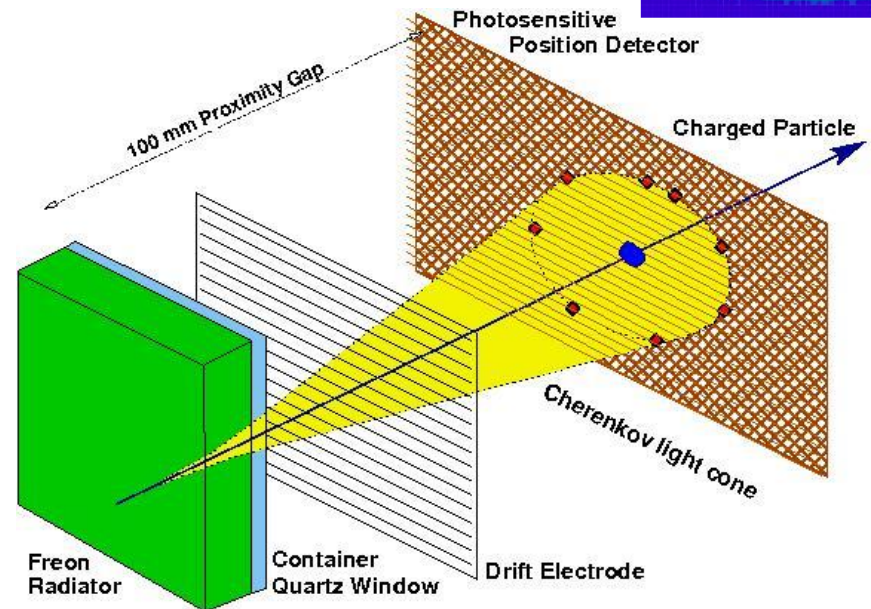
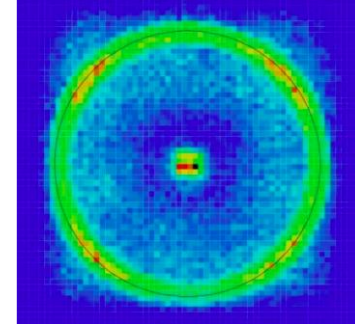
Polarization effect, Cherenkov photons emitted only if

$$v_p > \frac{c}{n(\lambda)}, \text{ where } n(\lambda) \text{ is the refractive index}$$



Simple geometric derivation gives the Cherenkov angle

$$\cos \theta_c = \frac{1}{n(\lambda)\beta}$$



Detector examples: Super-K , IceCube

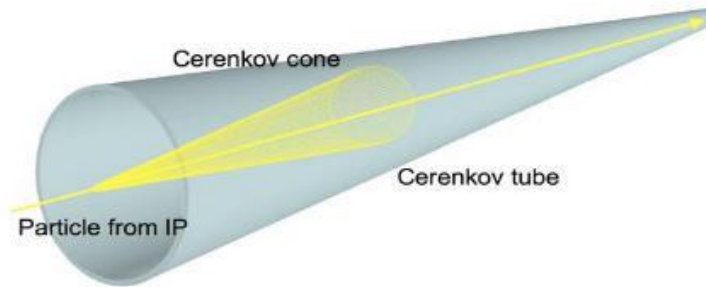




# *The basic concept*



LUCID  
a luminosity  
monitor



An array of **aluminum tubes** filled with  **$C_4F_{10}$  gas** acts as Cherenkov counters.

The **Cherenkov light** is produced with a  **$3^\circ$  angle** and makes typically 3 reflections while passing down the tube.

The **Cherenkov threshold** (10 MeV for elec. and 2.8 GeV for pions) and the pointing of the tubes suppresses background.

**No Landau fluctuations** makes it easier to count several particles going through the same tube.

A good **time resolution** makes it possible to study individual beam crossings.



# The basic concept



The rate of the pp interactions ( $R_{pp}$ ) seen by LUCID is proportional to the luminosity ( $L$ ):

$$R_{pp} = \mu_{LUCID} \cdot f_{BX} = \sigma_{pp} \cdot \epsilon_{LUCID} \cdot L$$

Bunch crossing rate =  $\frac{2808}{3564} \times 40 \text{ Mhz}$

filled BX  
total BX

Number of pp interactions per bunch-crossing (BX) as measured by LUCID.

Efficiency (and acceptance) of LUCID to detect a pp interaction ( $\sim 21\%$  for single sided detection and  $\sim 5\%$  for detection on both the A and C side).

## Zero Counting

Count bunch crossings with no interactions:

$$\mu_{LUCID} = -\ln\left(\frac{N_{zeroBX}}{N_{totalBX}}\right)$$

## Hit Counting

Count the number of tubes with a signal (hit):

$$\mu_{LUCID} = \frac{\langle N_{hits/BX} \rangle}{\langle N_{hits/pp} \rangle}$$

## Particle Counting

Count the number of particles in LUCID by doing several cuts on the pulseheight distributions:

$$\mu_{LUCID} = \frac{\langle N_{particles/BX} \rangle}{\langle N_{particles/pp} \rangle}$$

# Kinematic of Proton Collisions

- Proton is complicated composite of valence quarks, gluons and sea quarks

- PDF depends on 2D mixture of

- $Q^2$  (evolution in  $\ln(Q^2)$  predicted by QCD)
- Bjorken  $x$  momentum fraction

- CM energy of parton

collision:  $\hat{s} = M_X^2 = x_1 \cdot x_2 \cdot s_{\text{LHC}}$

- Typical ' $x$ ' values (assume:  $x_1 = x_2$ )

**LHC ( $\sqrt{s} = 14$  TeV):**

- $M_X = 100$  GeV (1 TeV)  $\Rightarrow \langle x \rangle = 0.007$  (0.07)

**Tevatron ( $\sqrt{s} = 2$  TeV):**

- $M_X = 100$  GeV (1 TeV)  $\Rightarrow \langle x \rangle = 0.05$  (0.5)

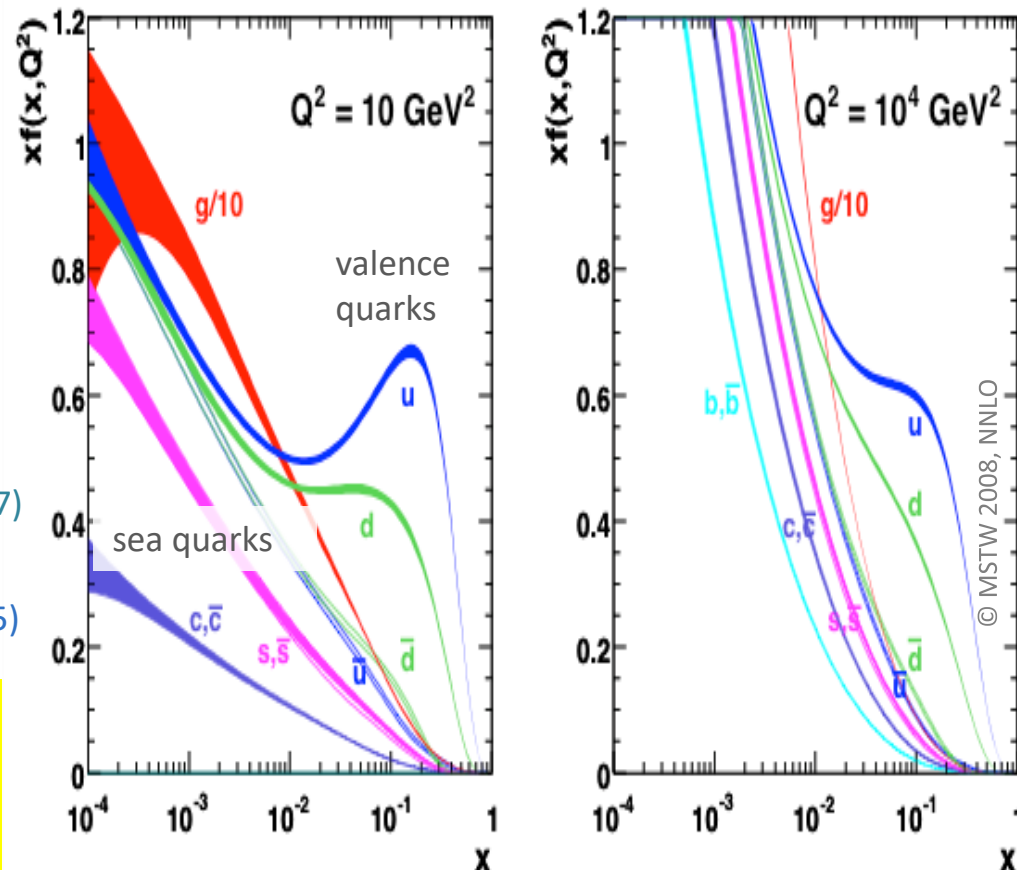
- PDFs rise dramatically towards low  $x$

$\Rightarrow$  larger cross sections at LHC

$\Rightarrow$  gluon dominated

***The LHC is a gluon collider!***

**MSTW 2008 NNLO PDFs (68% C.L.)**



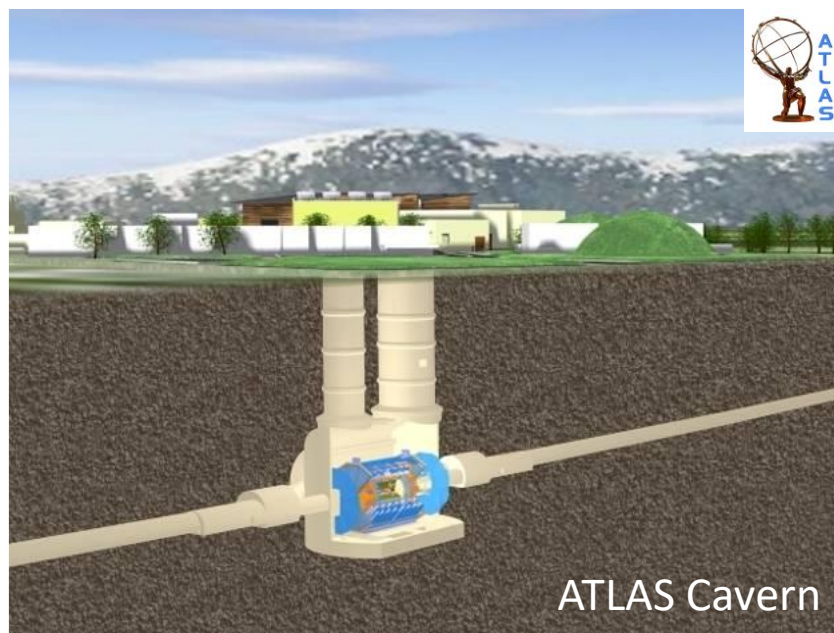
PDFs determined from  
global fits to (primarily)  
deep inelastic scattering data

# Starting up an experiment

# Data taking: ATLAS control room







Muon flux at surface:

$\sim 130 \text{ Hz / m}^2$  for  $E_\mu > 1 \text{ GeV}$   
 average energy  $\sim 4 \text{ GeV}$

Muon flux in ATLAS detector (simulation):

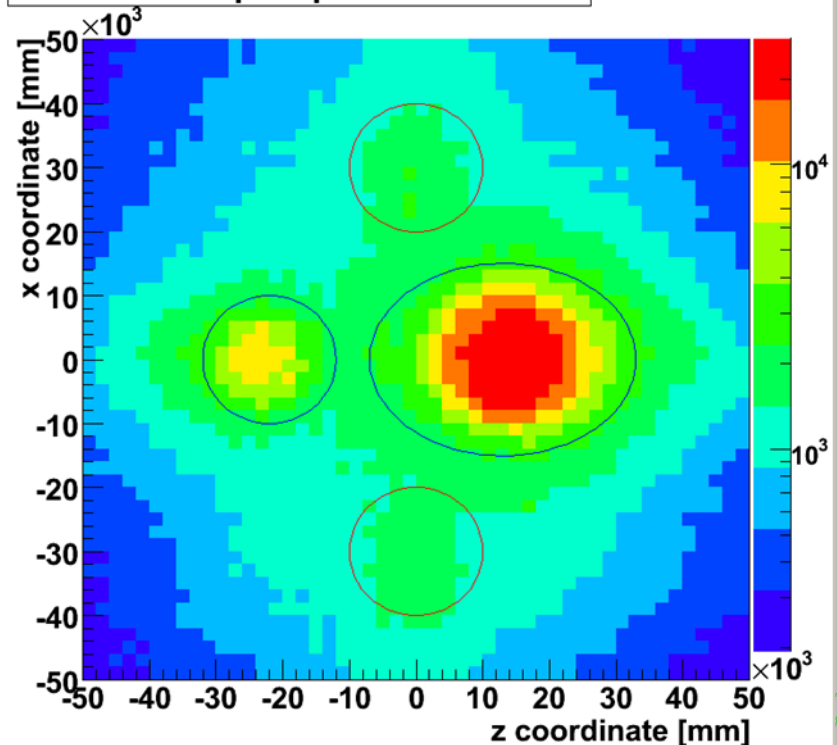
$\sim 4 \text{ kHz}$  in muon fiducial volume  
 $\sim 15 \text{ Hz}$  in TRT barrel

Charge ratio:  $\mu^+ / \mu^- \sim 1.27$

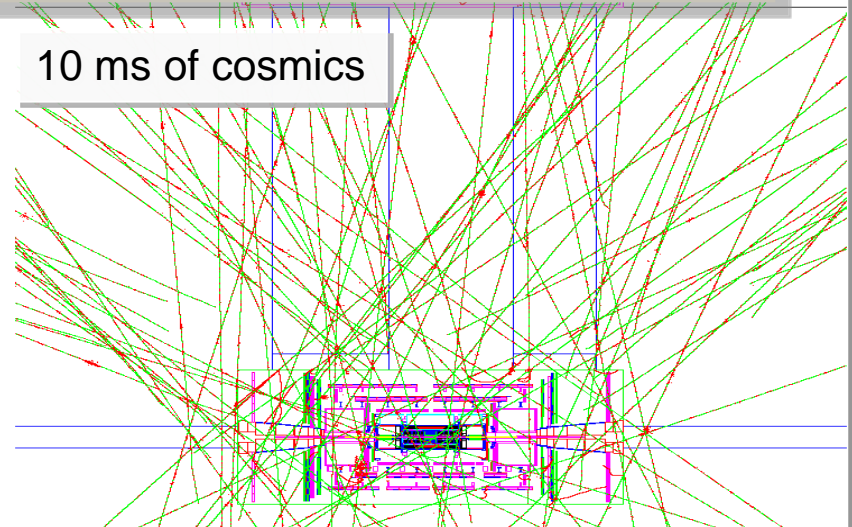
[ T. Hebbeker, C. Timmermans, hep-ph/0102042 ]

RPC track impact point on surface

Entries 6616665

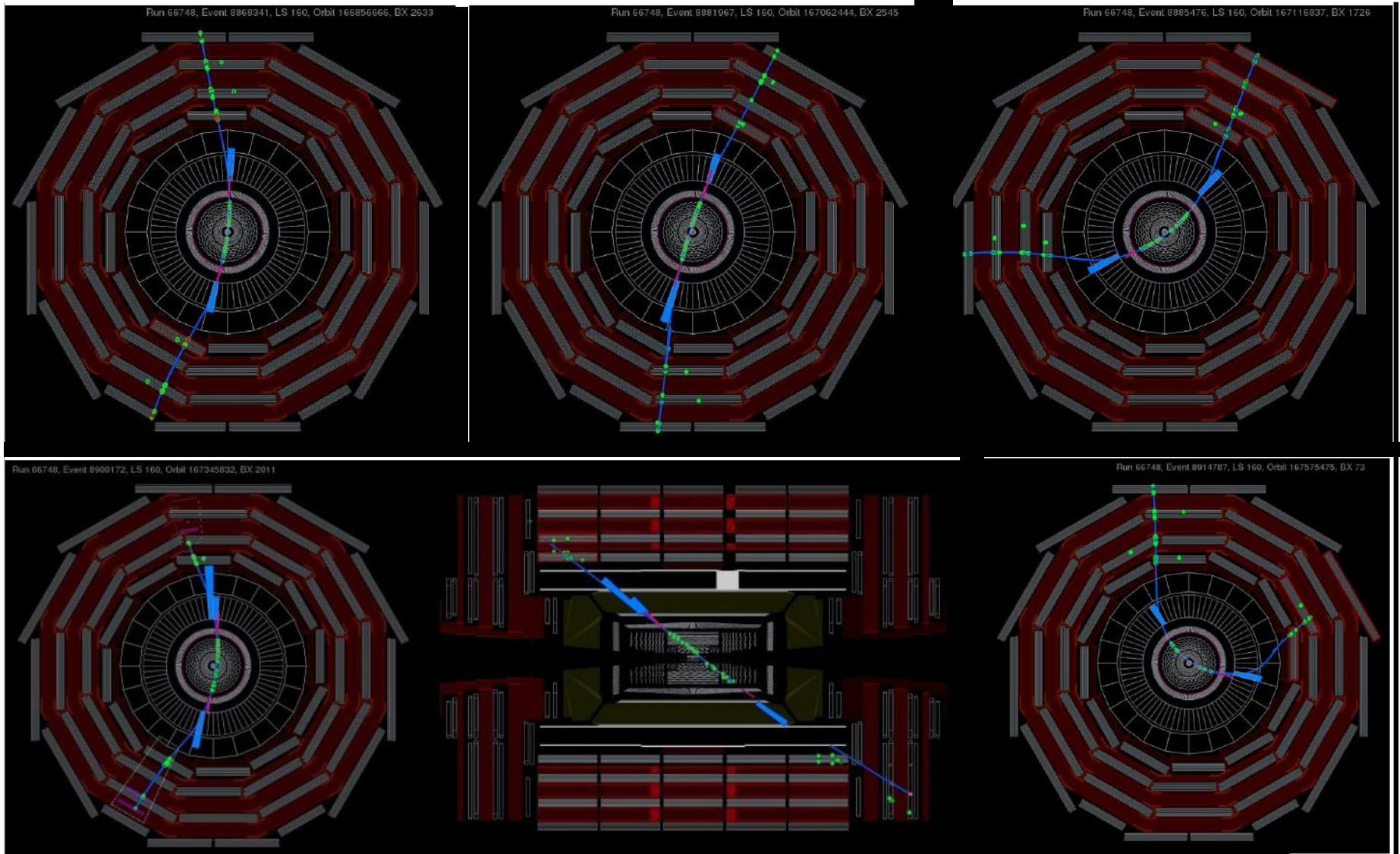


10 ms of cosmics



Simulated cosmic flux in ATLAS cavern: integration over 10 msec

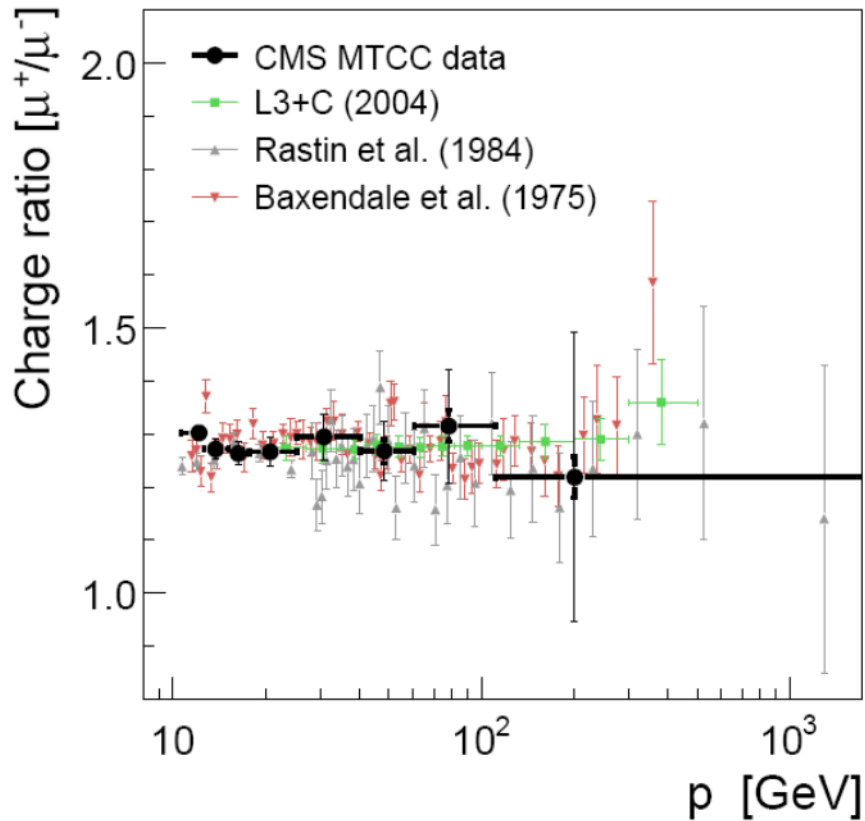
# More Cosmic Muons in CMS (both charges!) ...



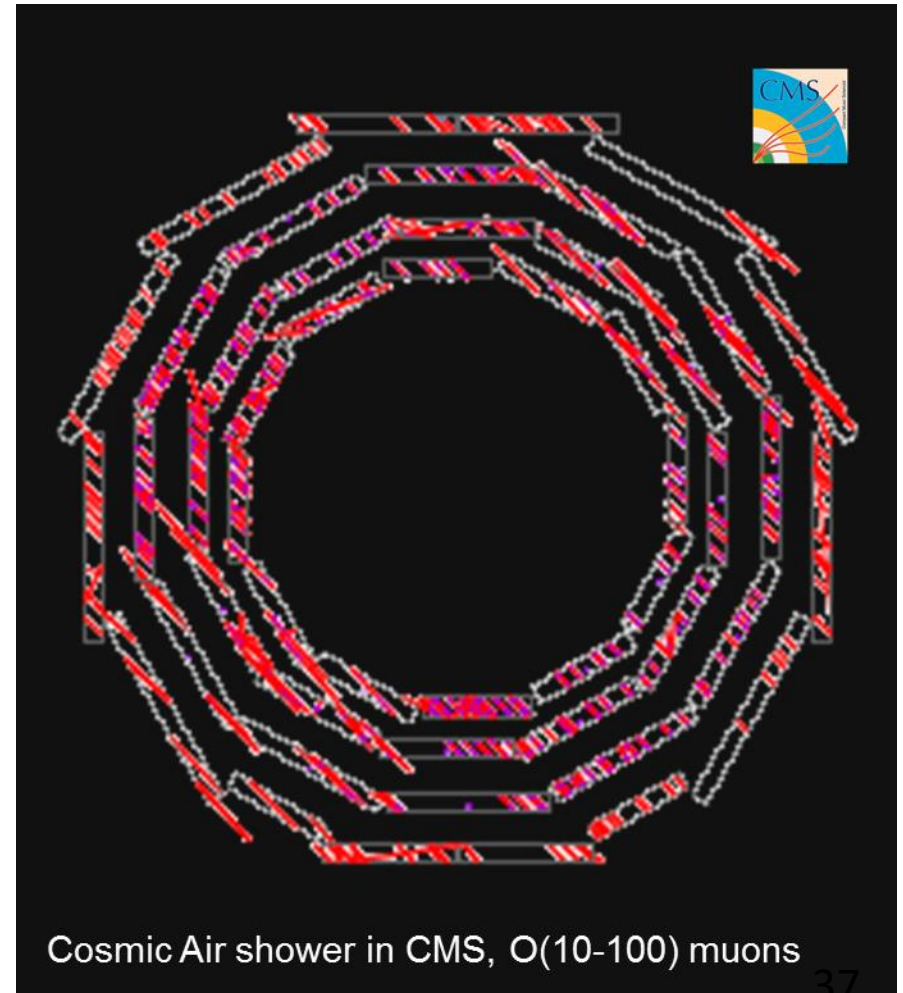
Through barrel and endcap muon detectors

# Studying cosmic rays

Charge ratio



Showers of muons



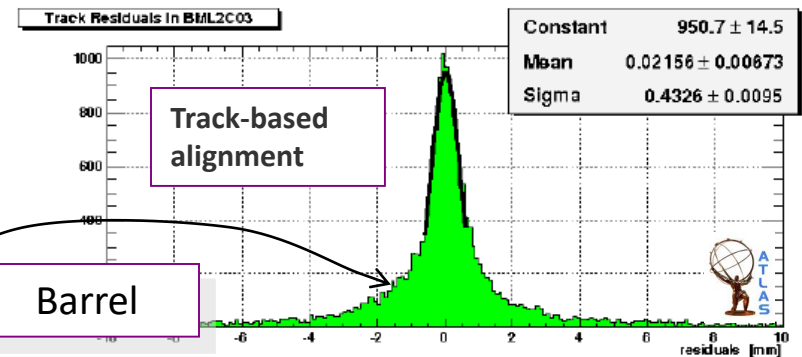
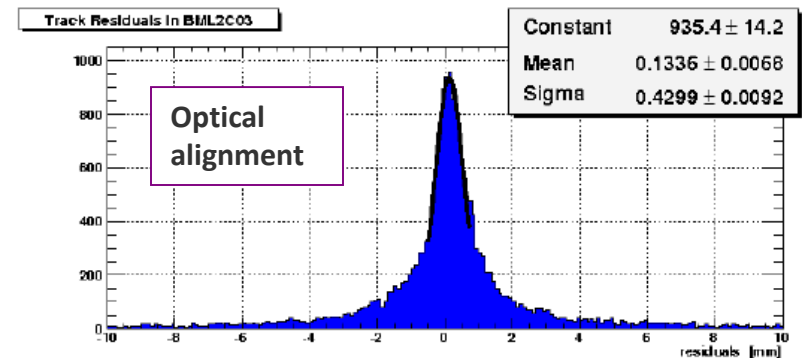
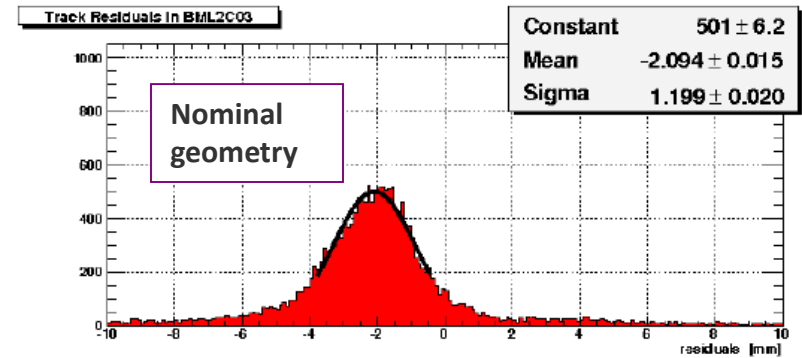
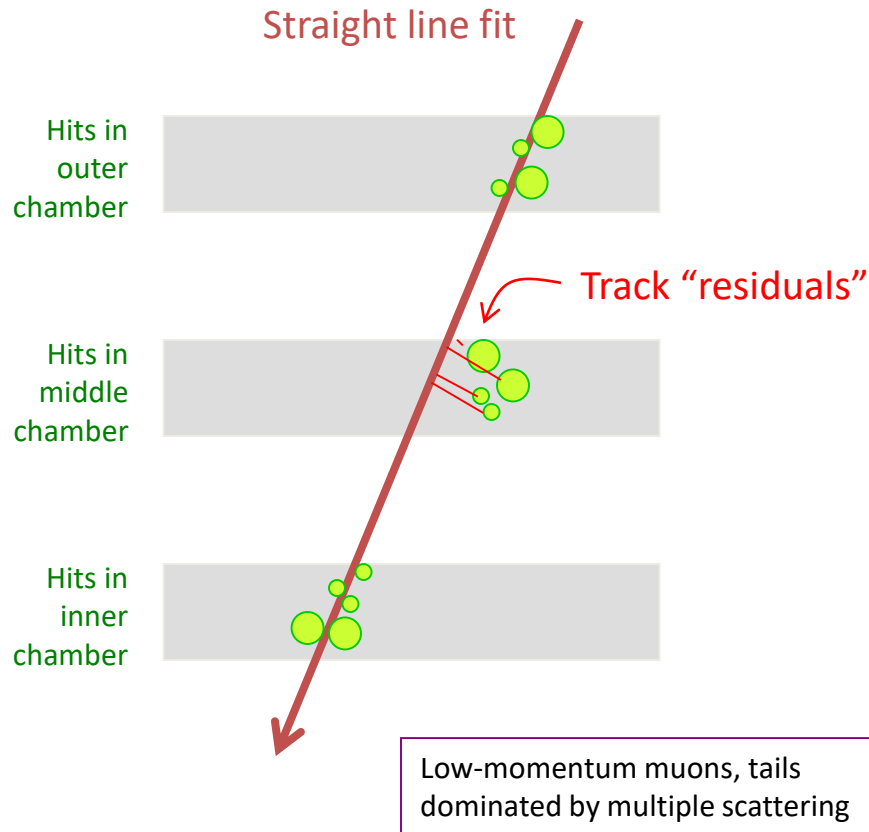
# Alignment of detectors

(Another perfect use of cosmic rays)



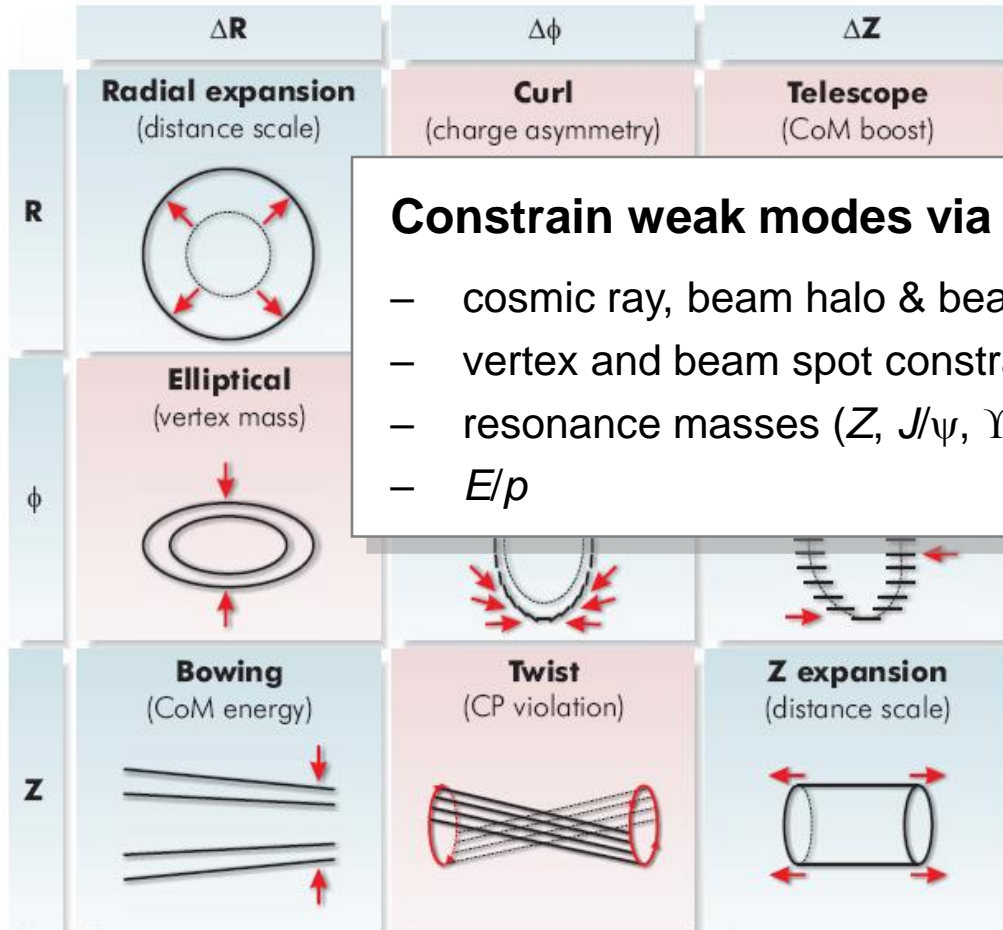
# Muon Alignment Also Uses (Straight) Tracks

- Compare residuals for straight cosmic tracks



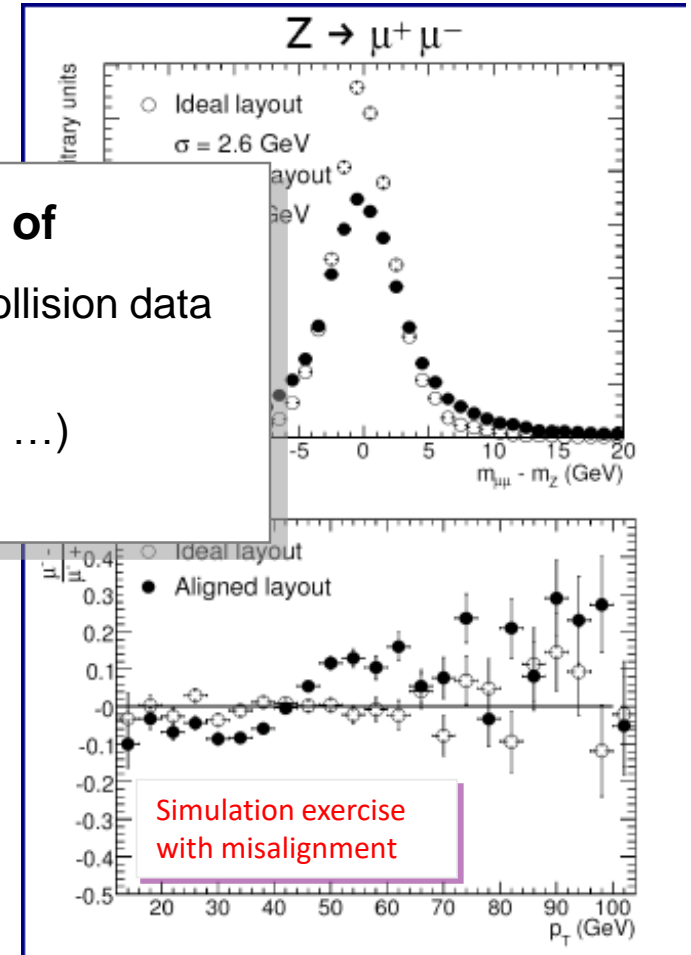
# “Weak Modes”

- Residuals insensitive against some types of misalignment → effect on physics !

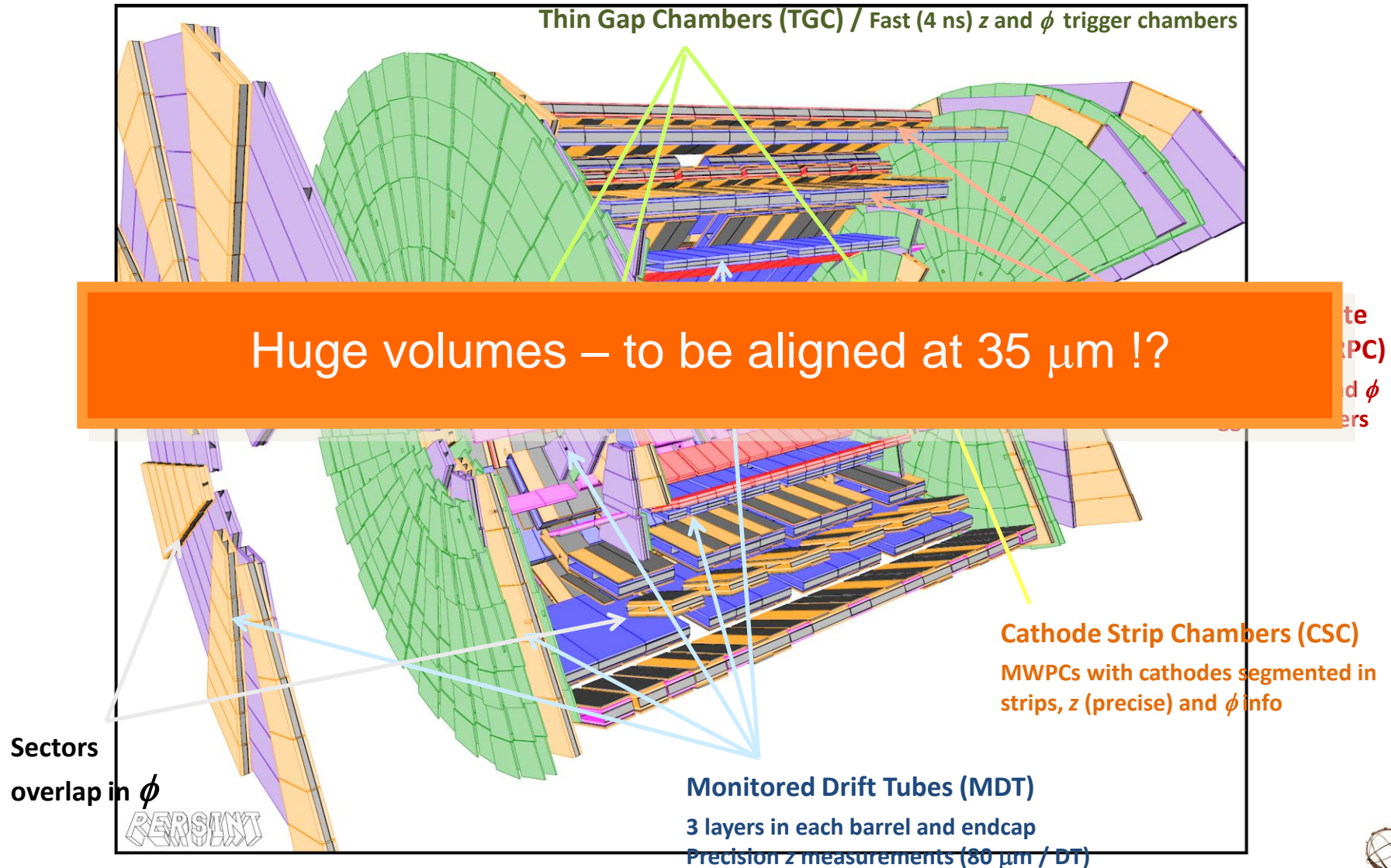


## Constrain weak modes via use of

- cosmic ray, beam halo & beam collision data
- vertex and beam spot constraints
- resonance masses ( $Z$ ,  $J/\psi$ ,  $\Upsilon$ ,  $K^0$ , ...)
- $E/p$



# ATLAS Muon System – Active Material



# Summary of today

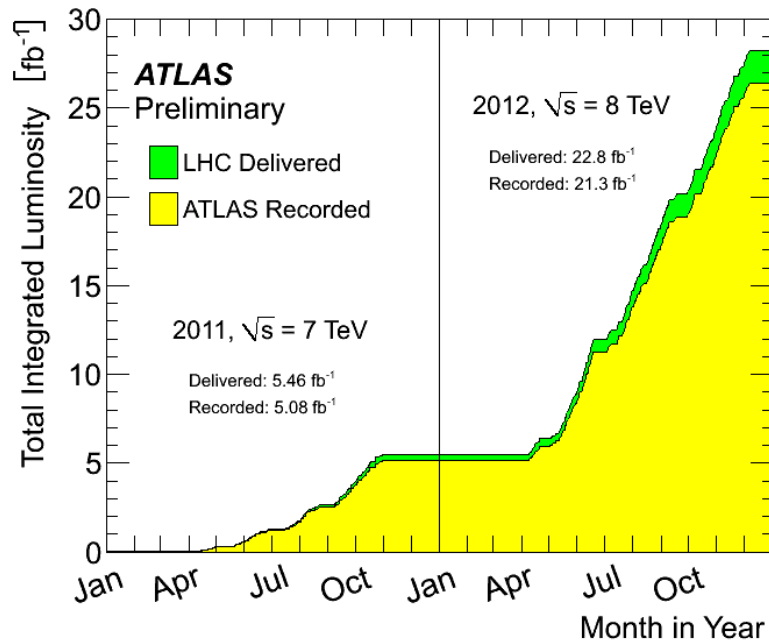
Mostly pretty pictures, more about physics next time!



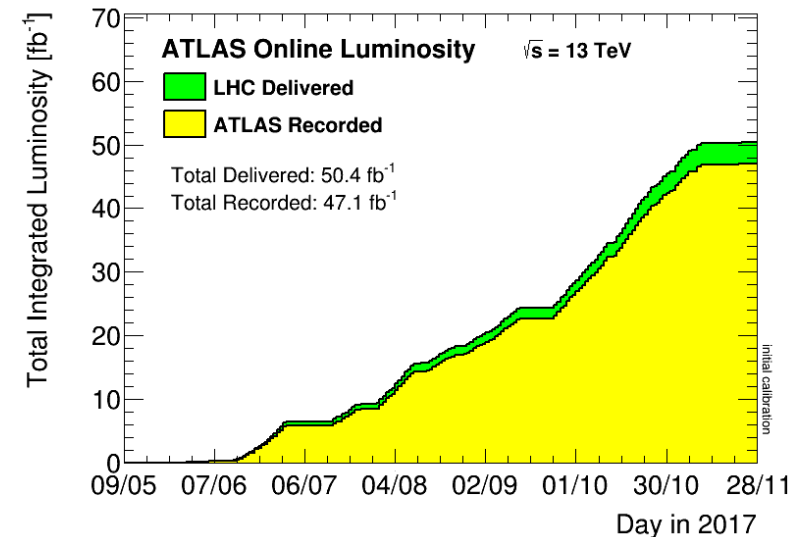
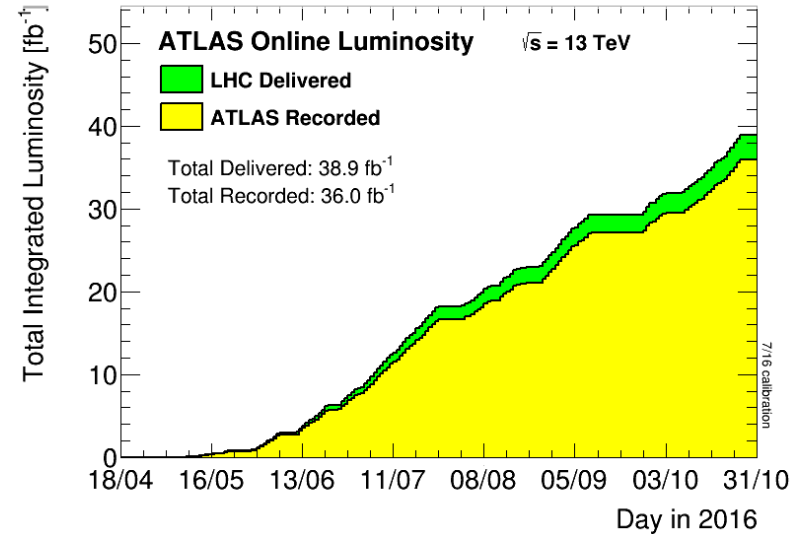
# Recorded Luminosity

Measured with forward detectors, calibrated with beam separation scans

Difference between del. and rec.  
luminosity from trigger deadtime  
and detector inefficiency



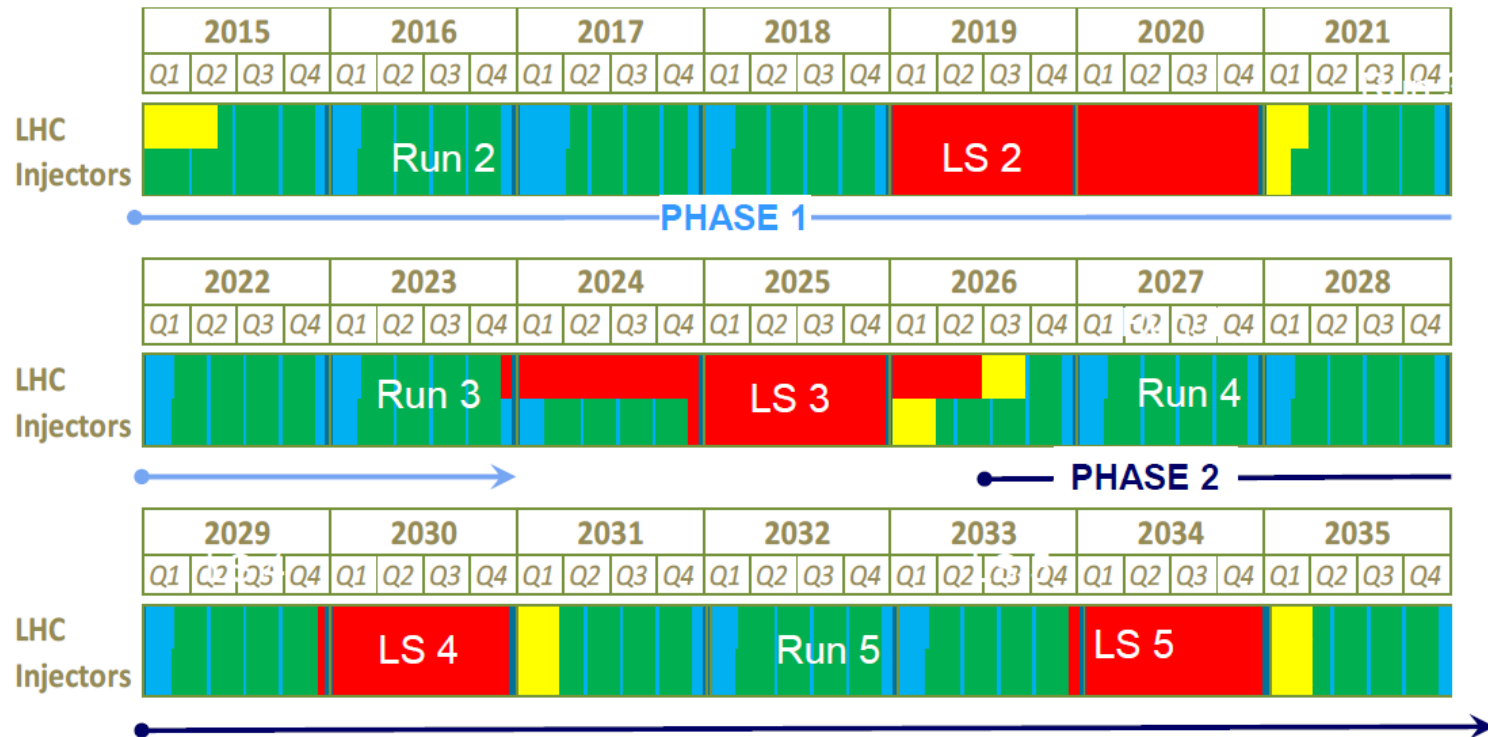
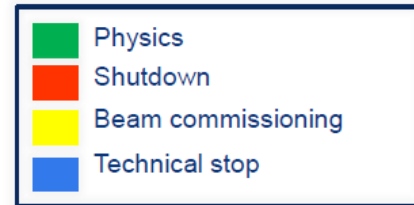
$10^{32} \text{ cm}^{-2}\text{s}^{-1}$  instantaneous luminosity corresponds to an  
*integrated* luminosity of 0.1 nb<sup>-1</sup> per second  
⇒ 180 pb<sup>-1</sup> per month (assuming 70% LHC efficiency for  
physics)



# Schedule (preliminary)

## LHC roadmap: according to MTP 2016-2020 V1

LS2 starting in 2019 => 24 months + 3 months BC  
 LS3 LHC: starting in 2024 => 30 months + 3 months BC  
 Injectors: in 2025 => 13 months + 3 months BC





Heavy ion runs most Novembers (not this year, though)



Frederick Bordry to the SPC

# ATLAS & CMS: Design & Performance Overview

	<b>ATLAS (7 ktons)</b> 	<b>CMS (12.5 ktons)</b> 
<b>INNER TRACKER</b>	<ul style="list-style-type: none"> <li>• Silicon pixels + strips</li> <li>• TRT with particle identification</li> <li>• <math>B = 2 \text{ T}</math></li> <li>• <math>\sigma(p_T) \sim 3.8\%</math> (at 100 GeV, <math>\eta = 0</math>)</li> </ul>	<ul style="list-style-type: none"> <li>• Silicon pixels + strips</li> <li>• No dedicated particle identification</li> <li>• <math>B = 3.8 \text{ T}</math></li> <li>• <math>\sigma(p_T) \sim 1.5\%</math> (at 100 GeV, <math>\eta = 0</math>)</li> </ul>
<b>MAGNETS</b>	<ul style="list-style-type: none"> <li>• 4 Magnets</li> <li>• Solenoid + Air-core muon toroids</li> <li>• Calorimeters outside solenoid field</li> </ul>	<ul style="list-style-type: none"> <li>• 1 Magnet</li> <li>• Solenoid</li> <li>• Calorimeters inside field</li> </ul>
<b>EM CALORIMETER</b>	<ul style="list-style-type: none"> <li>• Pb / Liquid Ar sampling accordion</li> <li>• <math>\sigma(E) \sim 10\text{--}12\% / \sqrt{E} \oplus 0.2\text{--}0.35\%</math></li> <li>• Longitudinal segmentation</li> <li>• Saturation at <math>\sim 3 \text{ TeV}</math></li> </ul>	<ul style="list-style-type: none"> <li>• <math>\text{PbWO}_4</math> scintillation crystals</li> <li>• <math>\sigma(E) \sim 3\text{--}5.5\% / \sqrt{E} \oplus 0.5\%</math></li> <li>• No longitudinal segmentation</li> <li>• Saturation at 1.7 TeV</li> </ul>
<b>HAD CALORIMETER</b>	<ul style="list-style-type: none"> <li>• Fe / Scint. tiles (EC: Cu-liquid Ar)</li> <li>• <math>\sigma(E) \sim 45\% / \sqrt{E} \oplus 1.3\%</math> (Barrel)</li> </ul>	<ul style="list-style-type: none"> <li>• Cu (EC: brass) / Scint. tiles</li> <li>• Tail catchers outside solenoid</li> <li>• <math>\sigma(E) \sim 100\% / \sqrt{E} \oplus 8\%</math> (Barrel)</li> </ul>
<b>MUON</b>	<ul style="list-style-type: none"> <li>• Drift tubes &amp; CSC (fwd) + RPC/TGC</li> <li>• <math>\sigma(p_T) \sim 10.5\% / 10.4\%</math> (1 TeV, <math>\eta = 0</math>) (standalone / combined with tracker)</li> </ul>	<ul style="list-style-type: none"> <li>• Drift tubes &amp; CSC (EC) + RPC</li> <li>• <math>\sigma(p_T) \sim 13\% / 4.5\%</math> (1 TeV, <math>\eta = 0</math>) (standalone / combined with tracker)</li> </ul>

# Kinematic Constraints and Variables

- Transverse momentum and missing transverse energy:  $p_T, E_{T,miss}$

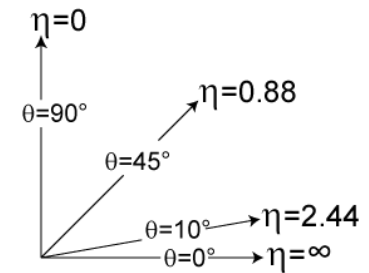
- Particles escaping detection have low  $p_T$
- Visible transverse momentum conserved:  $\sum p_{T,i} \approx 0$  **useful variable !**
- Large  $E_{T,miss}$  indicates invisible particle (ie, neutrino) escaped detector

- Longitudinal momentum and visible energy:  $p_z$

- Particles escaping detection have large  $p_z$
- Visible  $p_z$  not conserved  $\Rightarrow$  not a useful variable

- Polar angle  $\theta$  (angle between beam axis and particle)

- Not Lorentz invariant, depends on longitudinal boost of system



- Rapidity  $y$  and Pseudorapidity  $\eta$

$$y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right) = \frac{1}{2} \ln \left( \frac{x_1}{x_2} \right) \Rightarrow x_1 = x_2 \cdot e^{2y}, \quad \eta = \frac{1}{2} \ln \left( \frac{|\vec{p}| + p_z}{|\vec{p}| - p_z} \right) = -\ln \left( \tan \frac{\theta}{2} \right) \quad \text{for } M=0$$

- $dN/dy$  distribution independent of Lorentz boosts along the beam axis
- Particle production in hadron colliders is  $\sim$  constant in  $y$