FYST17 Lecture 5
LHC Physics 1

Thanks to A. Hoecker, V. Hedberg

Today, (tomorrow) & 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_{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

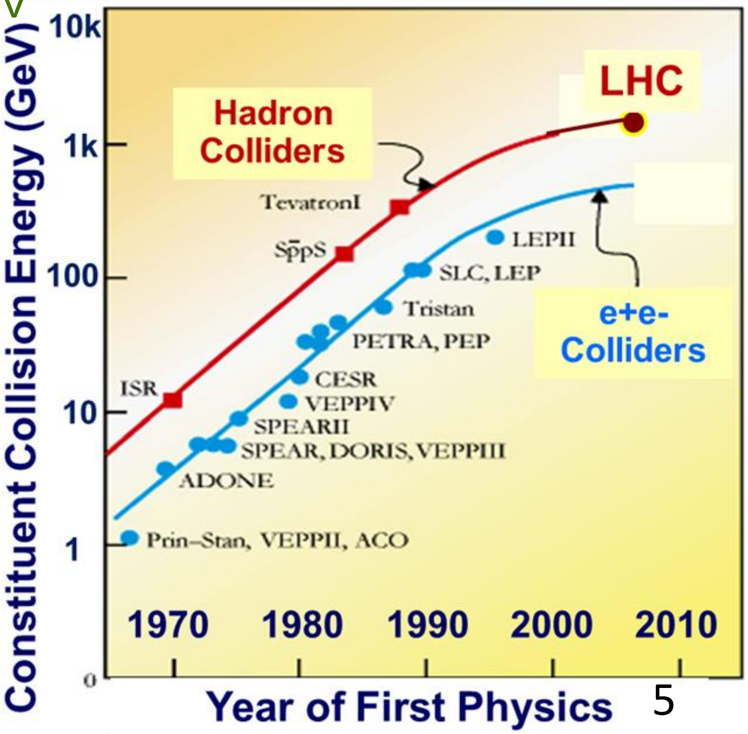
- Can reach higher energies in ring (less synchrotron radiation)

  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 $\rightarrow$ parasitic collisions beyond hard parton scattering
- Energy and type of colliding parton unknown $\rightarrow$ 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 Λ

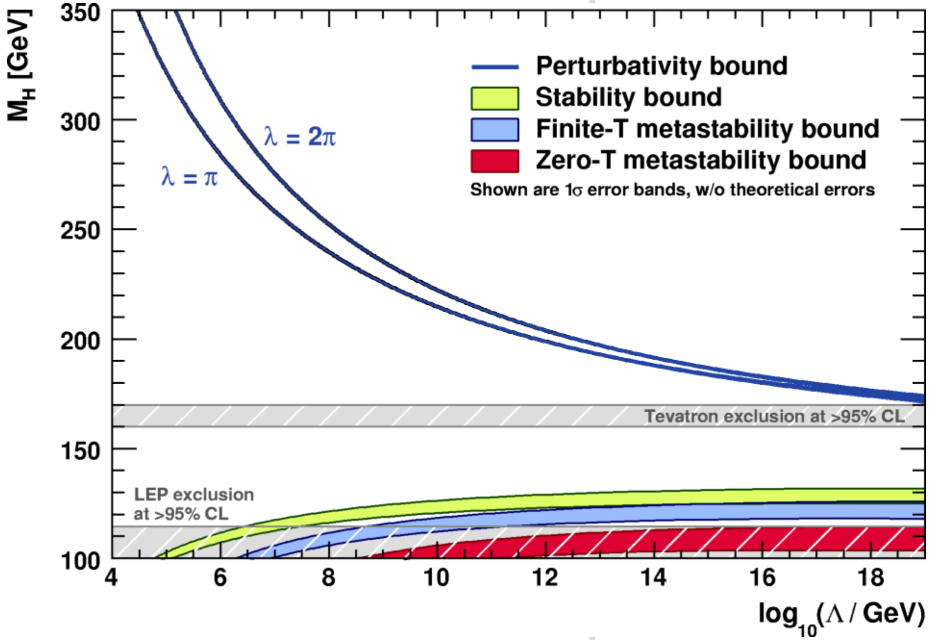
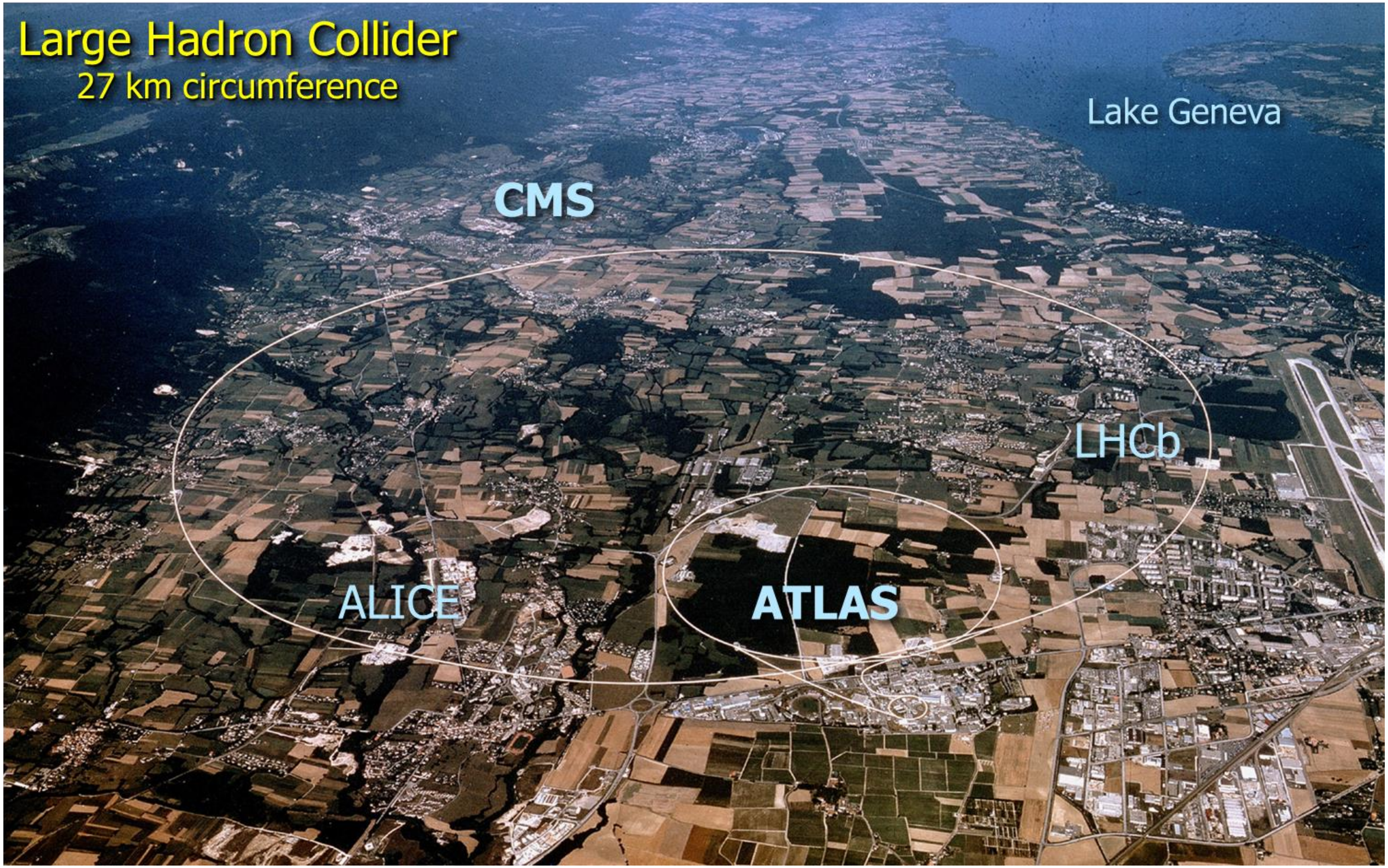


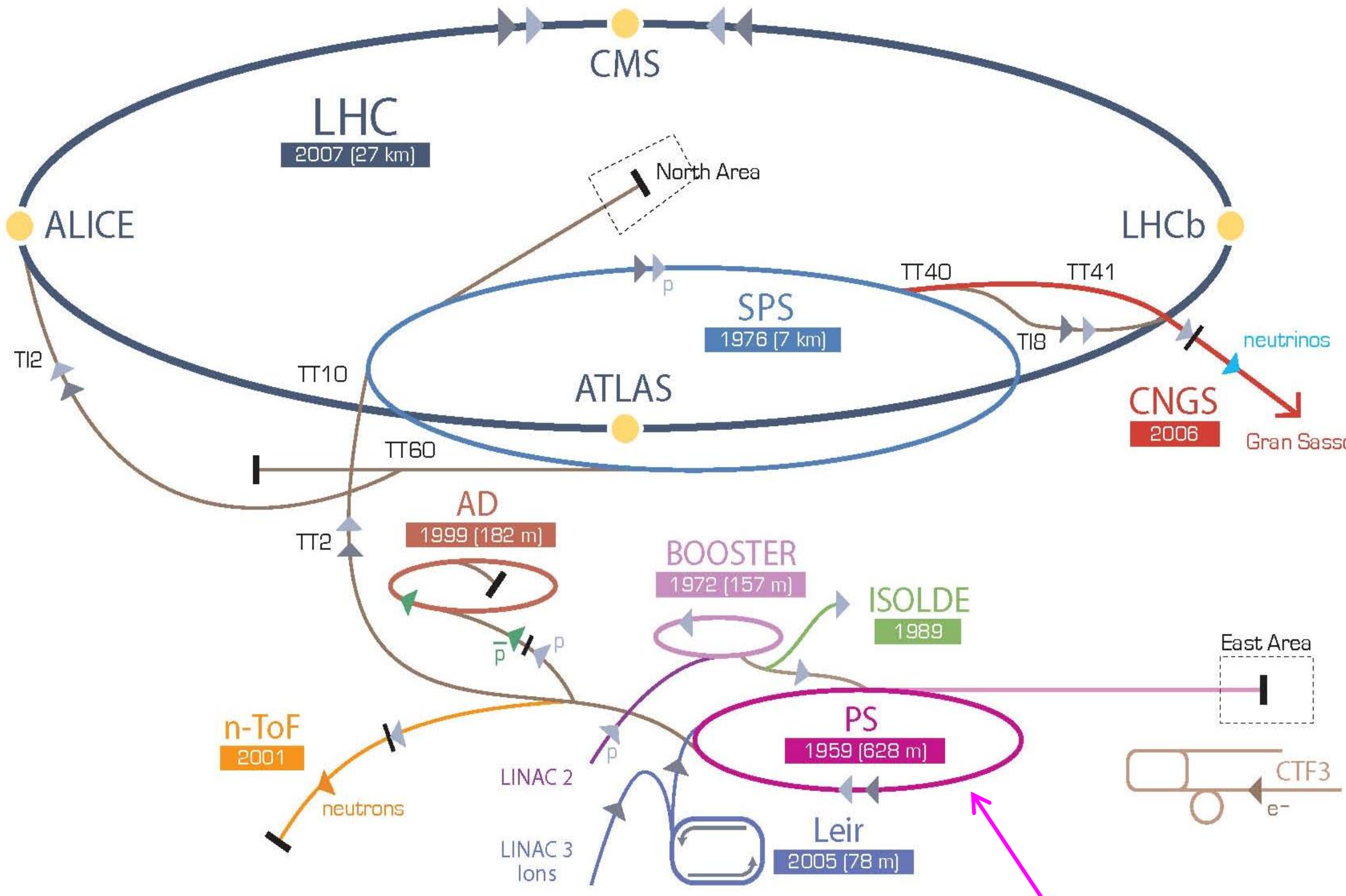
Figure uses NLO Higgs potential. The widths of bands account for errors in α_S, m_t and theory.

The SM Higgs must steer a narrow course between two disastrous situations if it is to survive up to the Planck scale $M_P \sim 2\times10^{18}$ GeV

The accelerator



CERN accelerator complex



(>50 years old!)

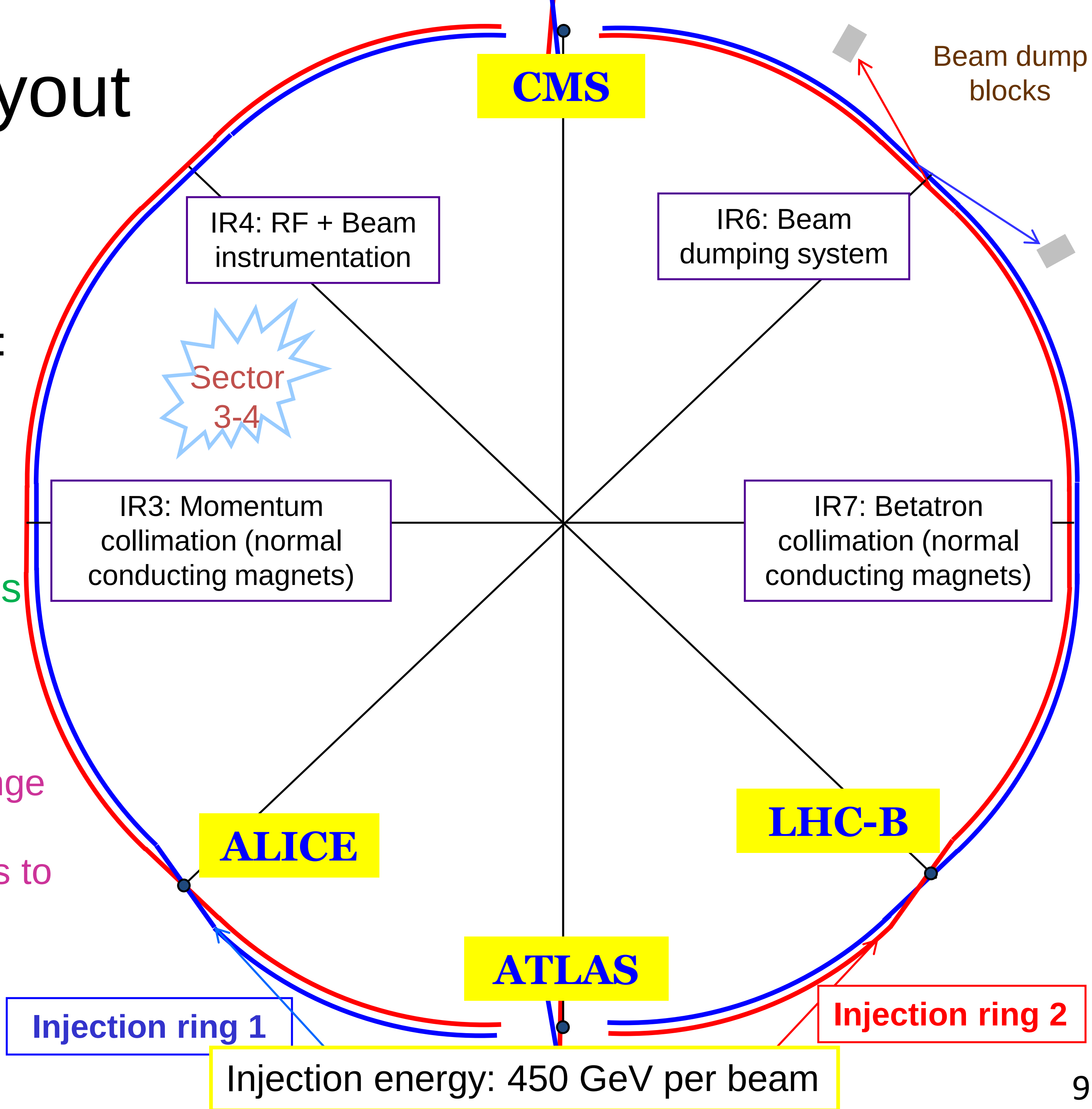
	Top energy/GeV	Circumference/m
Linac	0.12	30
Booster	1.4	157
PS	26	628 = 4 x Booster
SPS	450	6'911 = 11 x PS
LHC	7000	26'657 = 27/7 x SPS

LHC Layout

8 arcs and 8 long **(~700 m)** straight sections
Each main sector:
 154 dipoles
 47 quadrupoles.

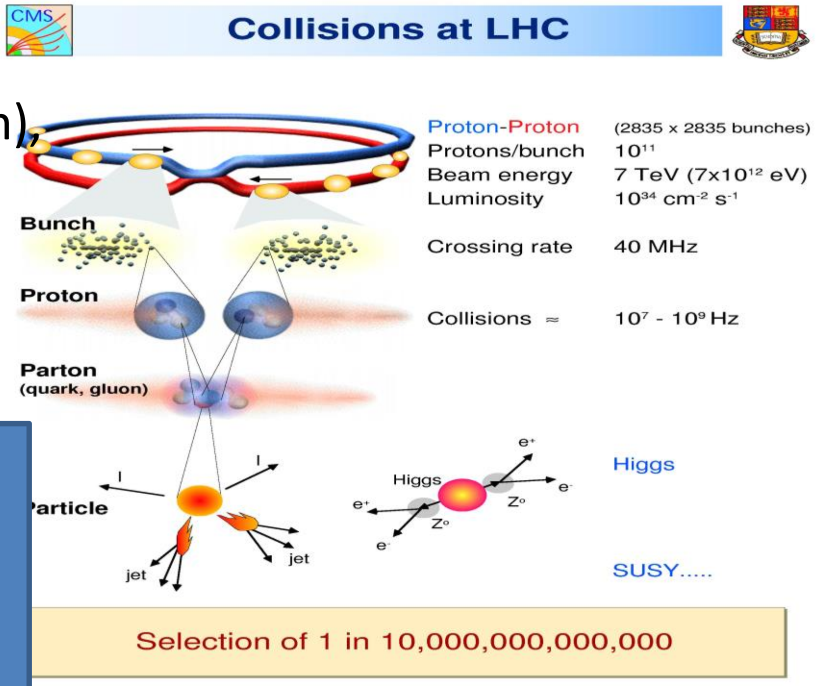
Limits stored energy + facilitates commissioning sector by sector

The beams exchange positions (inside /outside) in 4 points to ensure both rings have the same circumference!



The LHC environment

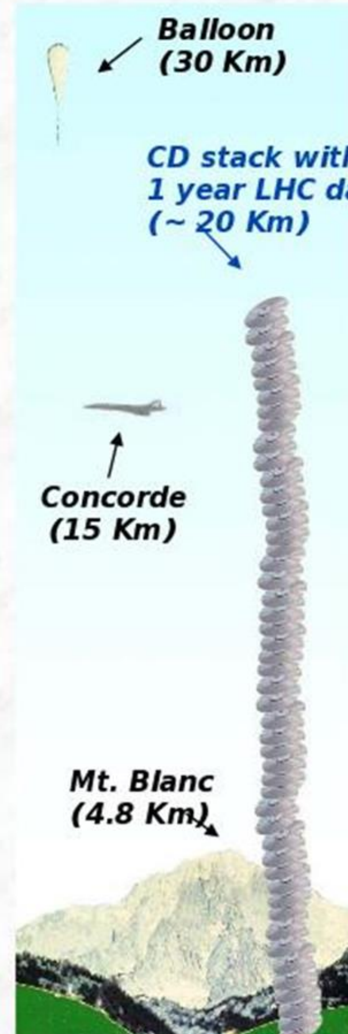
- The search for new phenomena exploits **ever smaller distances ⇒ ever larger energies**
- The LHC collides protons at E_{CM} = 13 TeV → probing a distance of 1 x 10^{-18} cm ?
  … not quite, since protons are composites: the energy is distributed among its partons
- **Proton energy is limited by magnets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



Protons are circling in bunches, (~3000 at full intensity) with up to 10^{11} protons/bunch
Bunch size ~1mm x few cm
16μm width at collision points
Made to collide every 25ns!

LHC data handling, GRID computing

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

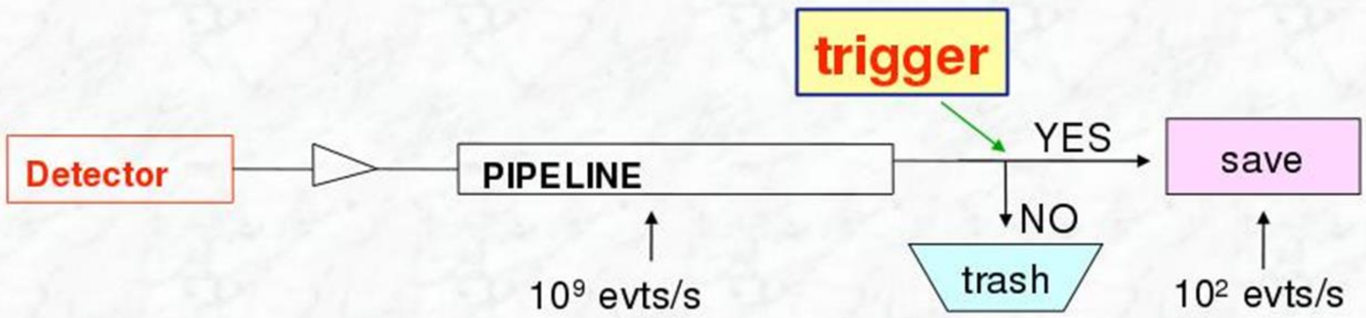


Trigger system selects
~200 "collisions" per sec.

LHC data volume per year:
10-15 Petabytes
= 10-15 $\cdot 10^{15}$ Byte

How to Select Interesting Events?

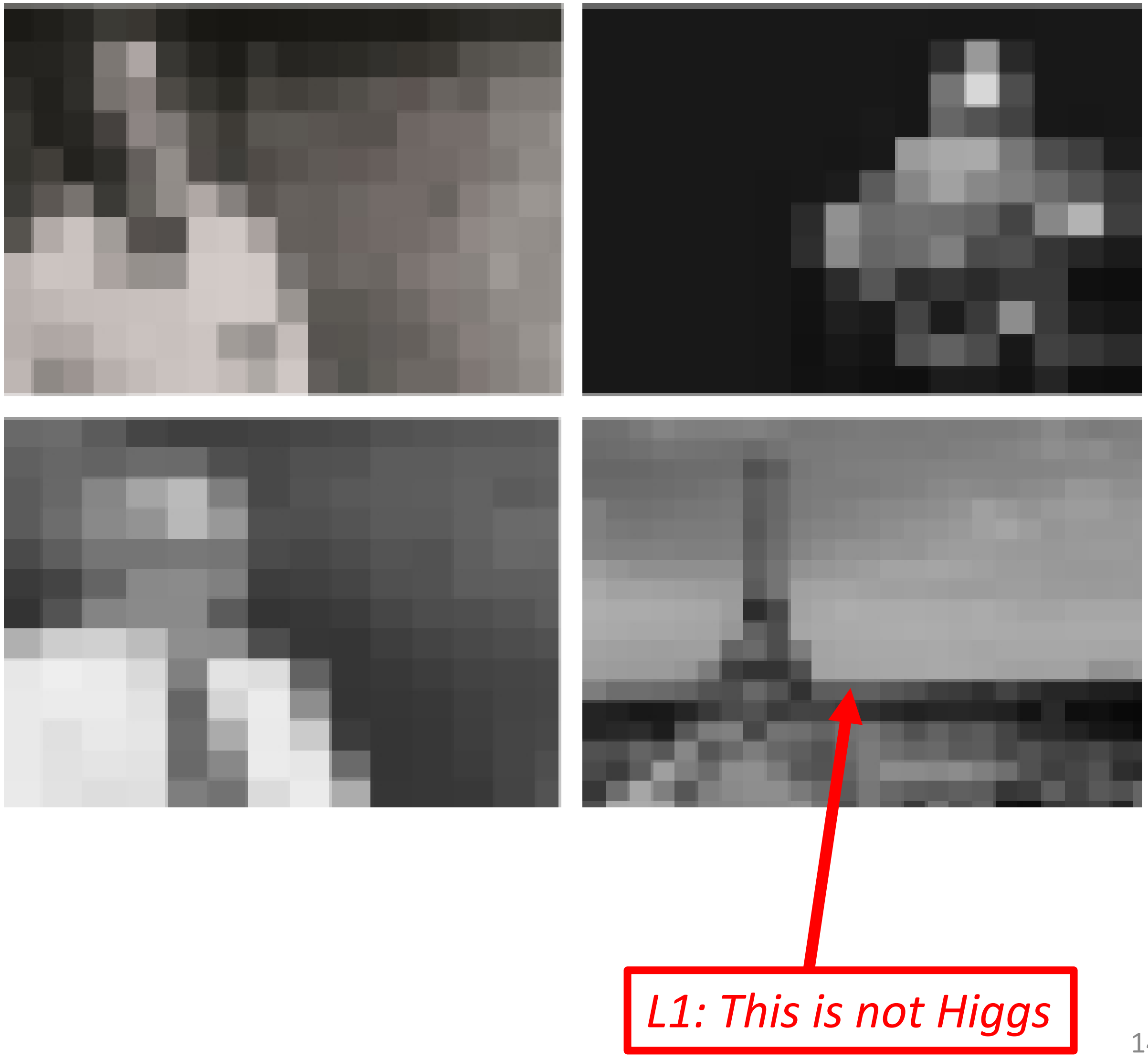
"the trigger does not determine which physics model is right, only which physics model is left" A. Bocci



- ATLAS trigger has 3 levels (CMS similar with 2 levels)
  - Level-1: hardware, ~3 μs decision time, 40 MHz → 100 kHz   i.e. no time for input from tracking
  - Level-2: software, ~40 ms decision time, 100 kHz → 2 kHz
  - Level-3: software, ~4 s decision time, 2 kHz → 200 Hz

Example: Higgs

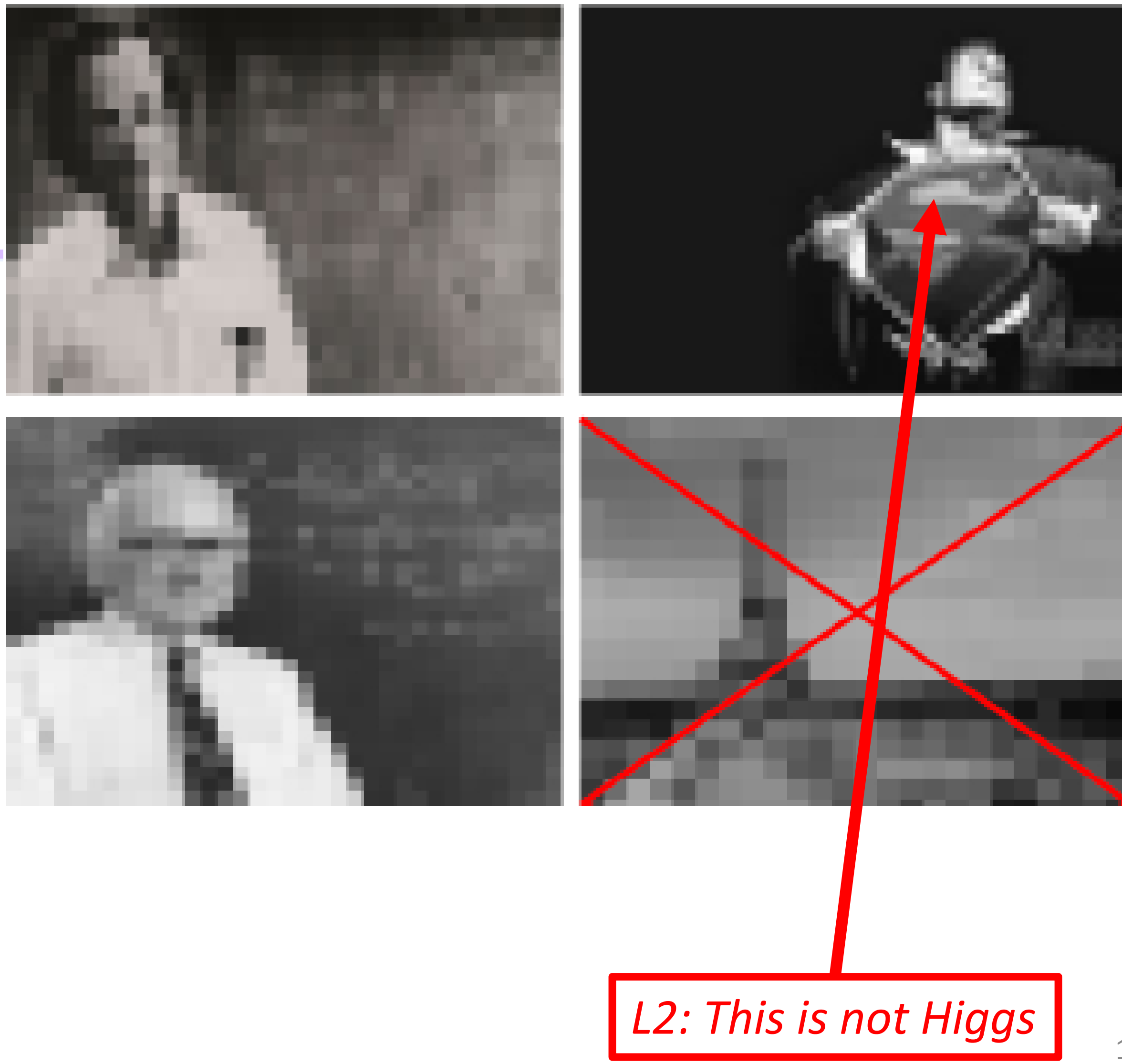
- L1
  Coarse granularity



Example: Higgs

- L2

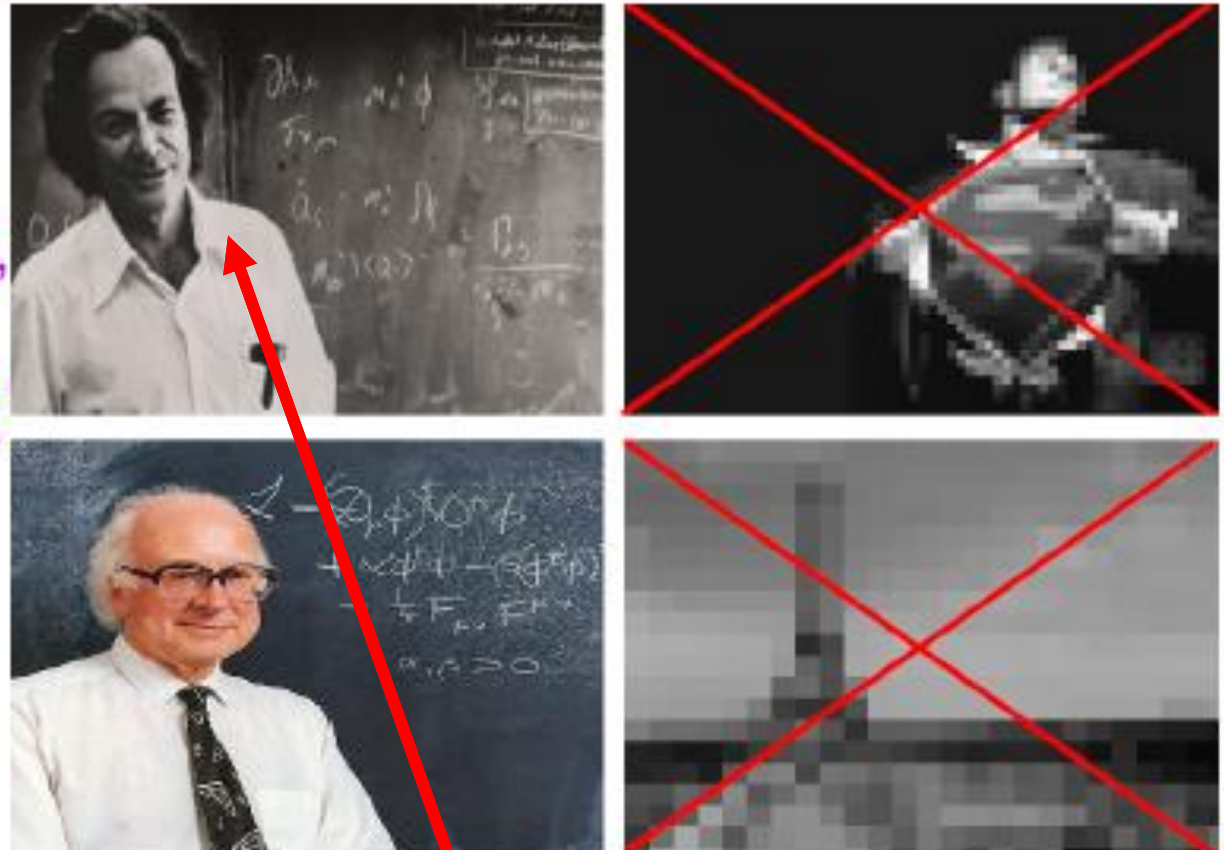
  Improved reconstruction, improved ability to reject events



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:

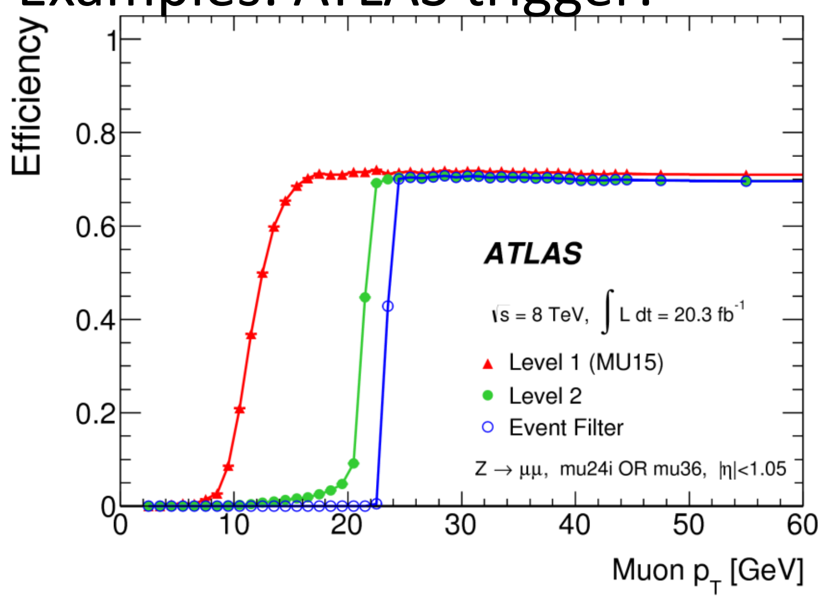
$$\sigma = \frac{N}{A \cdot \varepsilon \cdot \int L\, dt}$$

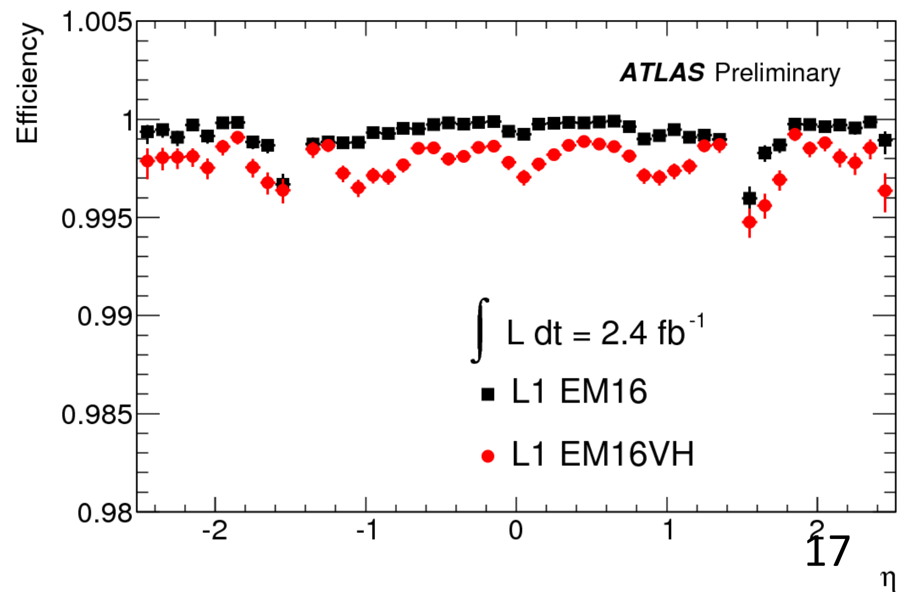
Acceptance

Efficiency

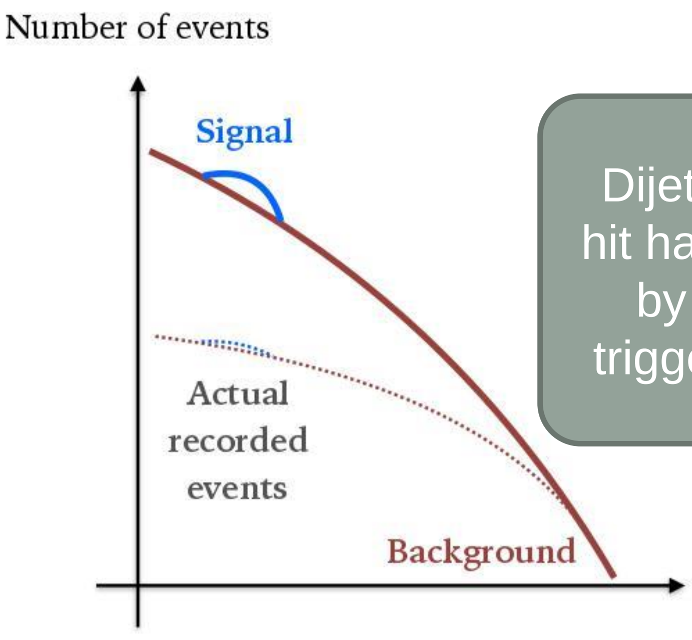
Integrated luminosity

Examples: ATLAS trigger:





Online analysis: by-passing the trigger?



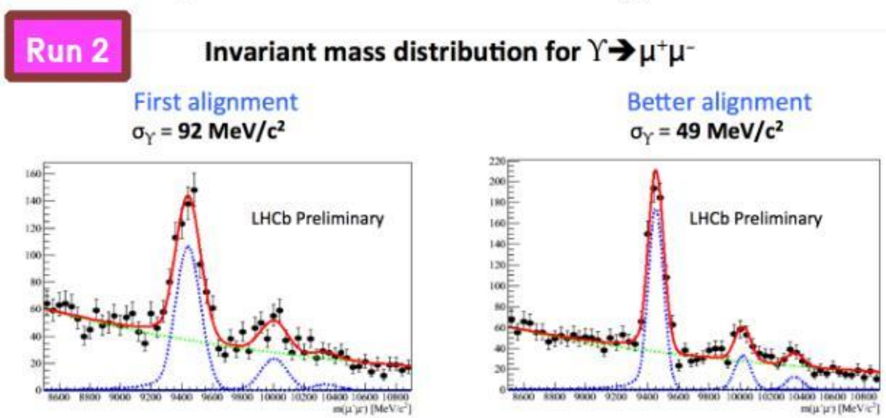
Dijets hit hard by trigger

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

First analyses/ attempts on-going at the LHC experiments

Raw data still not stored …



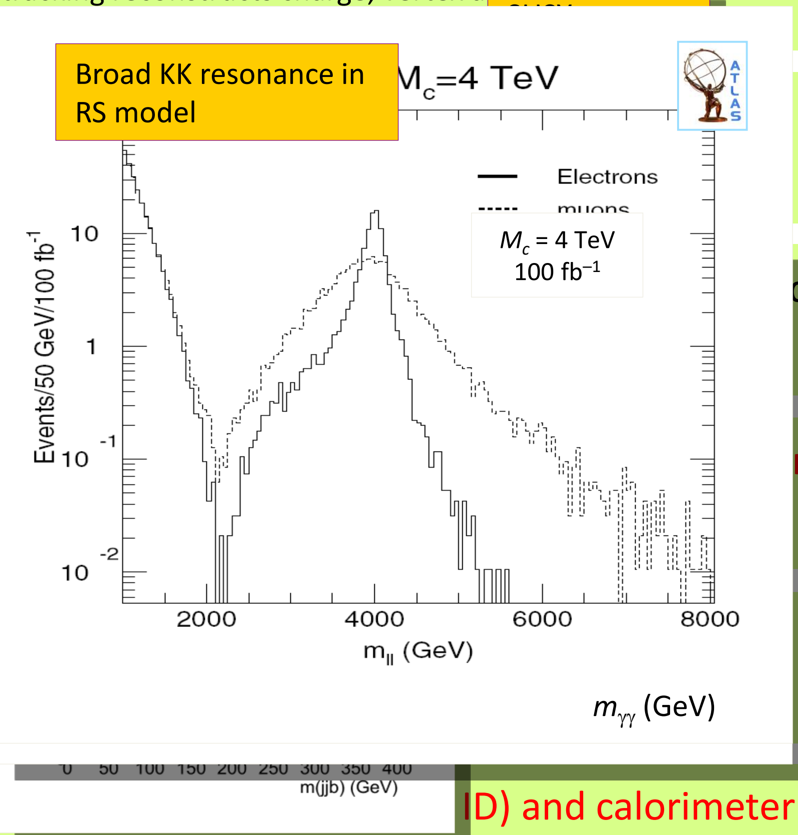
B. Storaci, CERN Seminar

Requirements from Physics Programme

- Some benchmark analyses
  - **$B_{s(d)} \rightarrow \mu\mu$ and $B_s \rightarrow J/\psi\ \varphi$**
  - **W mass**
  - **top mass**
  - **$H \rightarrow \gamma\gamma$, 4$e$, 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



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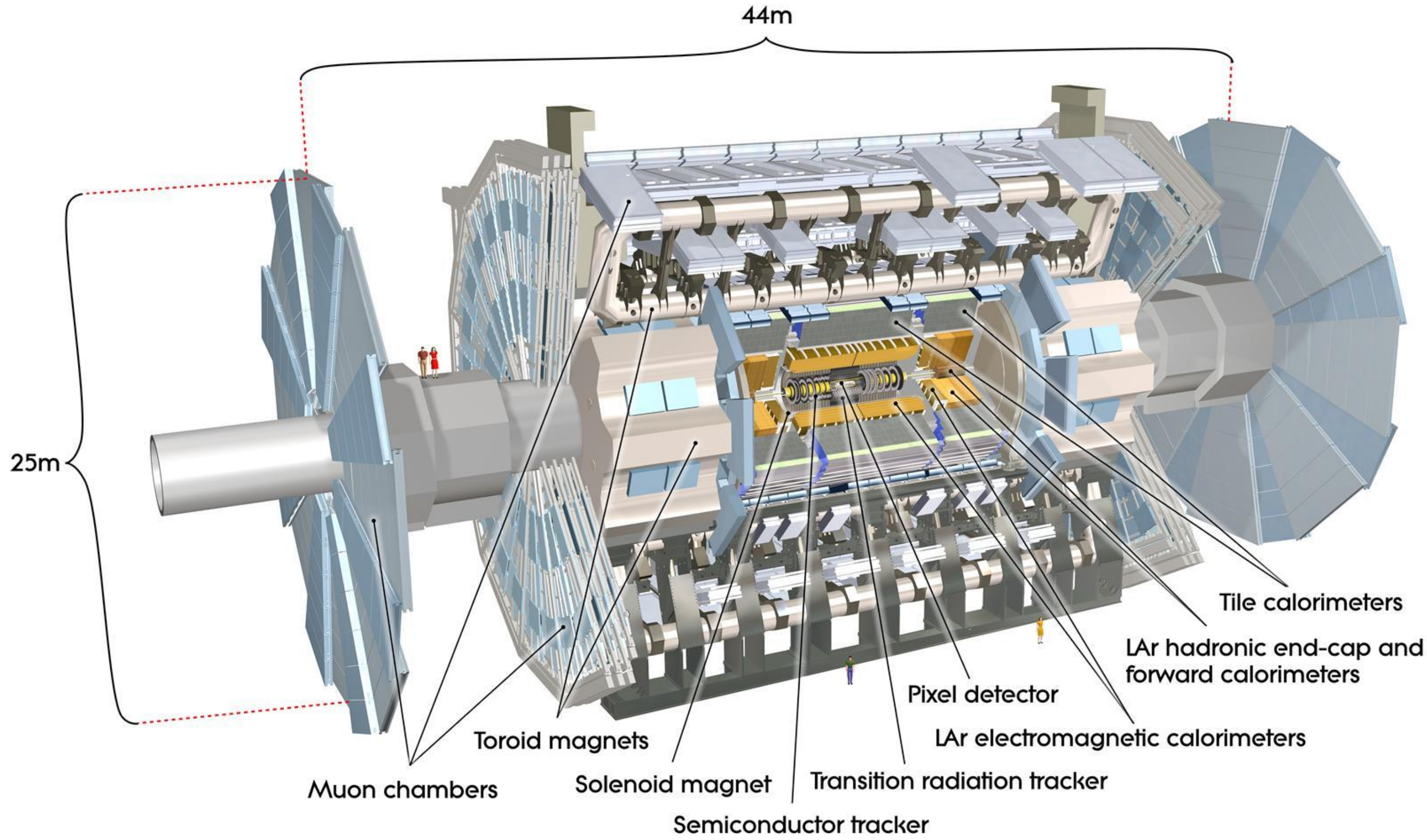
ID) and calorimeter resolution at O(TeV), little calo saturation

Requirements from LHC Conditions

LHC and data conditions:	Design challenges:
40 MHz bunch crossing rate (25ns = 7.5m bunch spacing)	**Fast trigger, precise timing and "pipeline" electronics: Level-1 latency < 2.5μs**
~1 GHz interaction rate at $L = 10^{34}$ cm^{-2}s^{-1} (~25 ias. per bunch crossing)	**Efficient pattern recognition to reduce:** GHz @ **L1** $\rightarrow$ 75 kHz @ **HLT** $\rightarrow$ 200 Hz to disk
~300 Mbytes/seconds data rate (200 Hz $\Rightarrow$ O(1.5 MB/event))	**Powerful data processing farms**: distribute data analysis to computing centres worldwide
Irradiation rate / 10 LHC years: 5x10^{14} n_{eq}/cm^2 (300 kGray [= J/kg])	**Radiation hard inner tracker** (pixel with large S/B) **and forward calorimeter technology**
High charged multiplicity (O(1000) tracks per event, 10^{12} / sec)	**High-granular pixel/silicon** or **fine-grained straw tracker** technologies
High background rates (beam halo muons, neutrons, beam-gas collisions)	**Precise muon timing**, redundant pattern recognition, radiation hardness

A large Toroidal Lhc ApparatuS

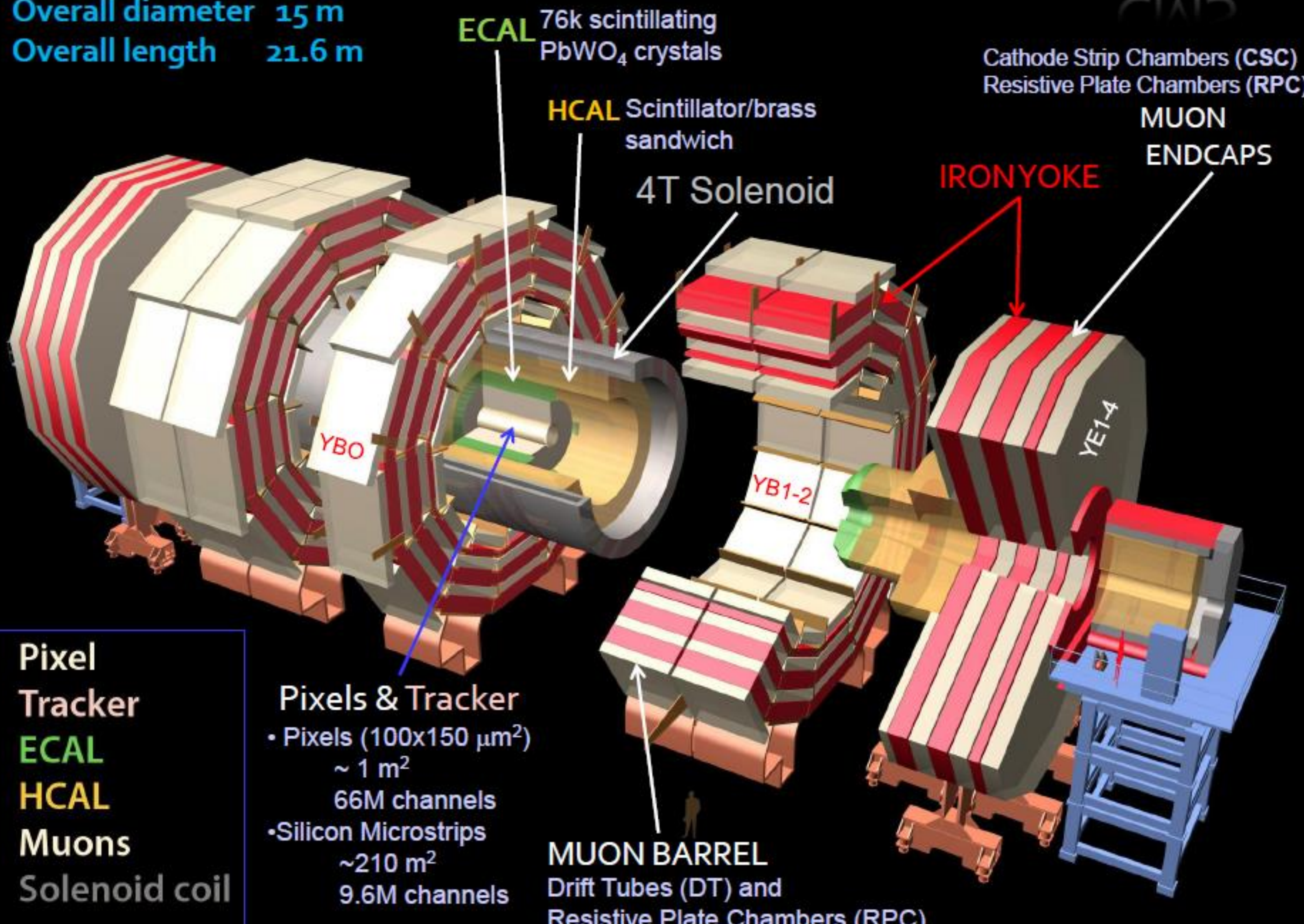
ATLAS



Compact Muon Solenoid

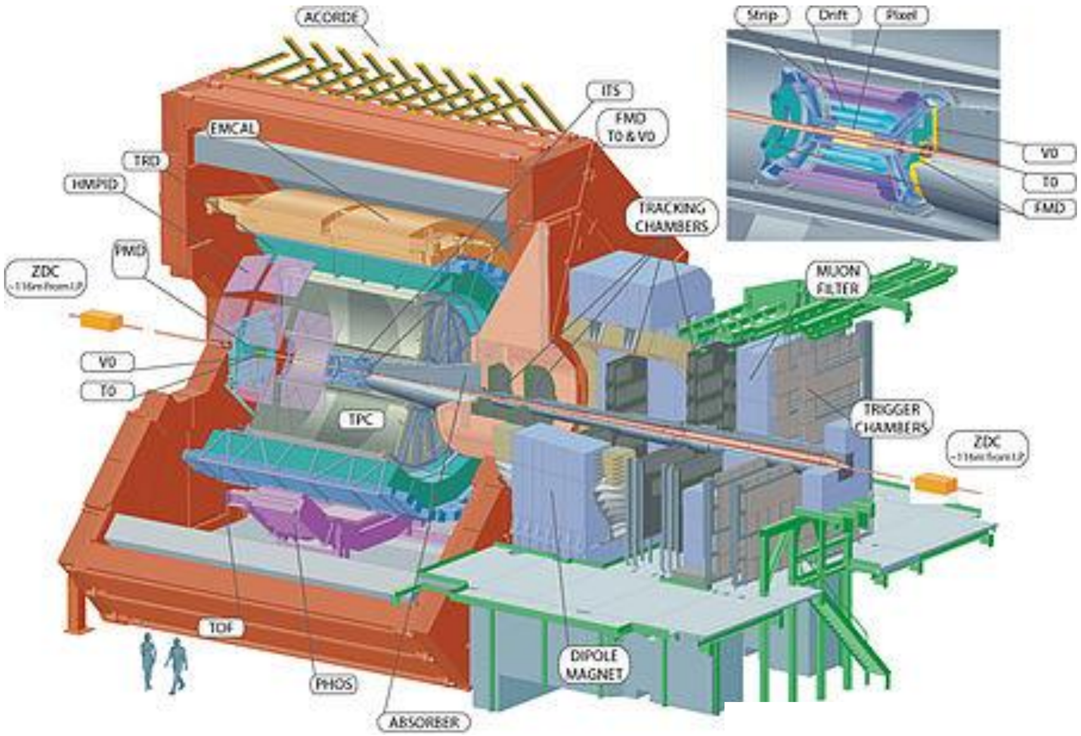
CMS

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



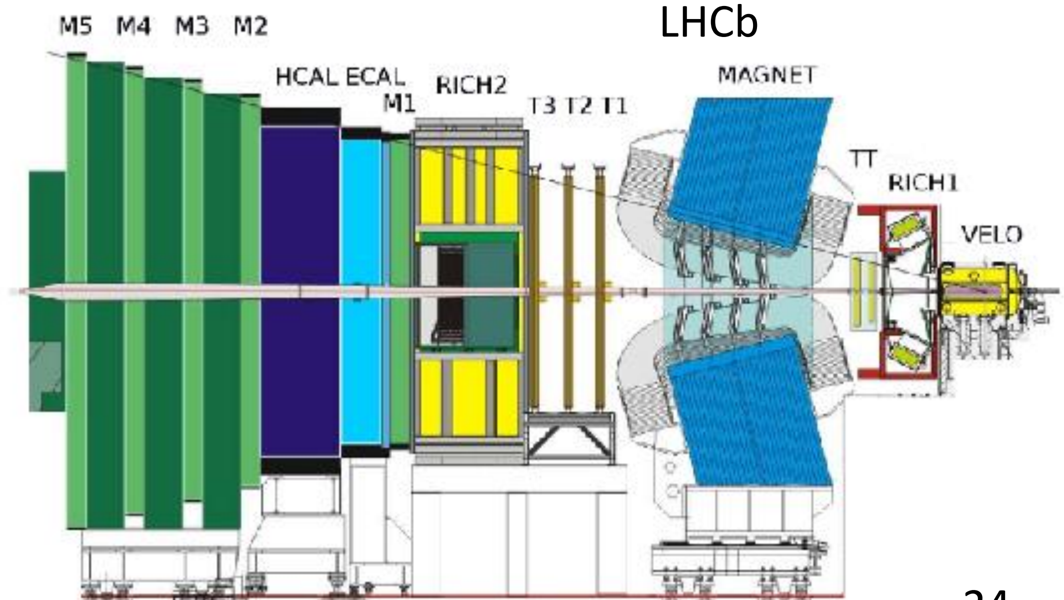
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

ALICE + LHCb

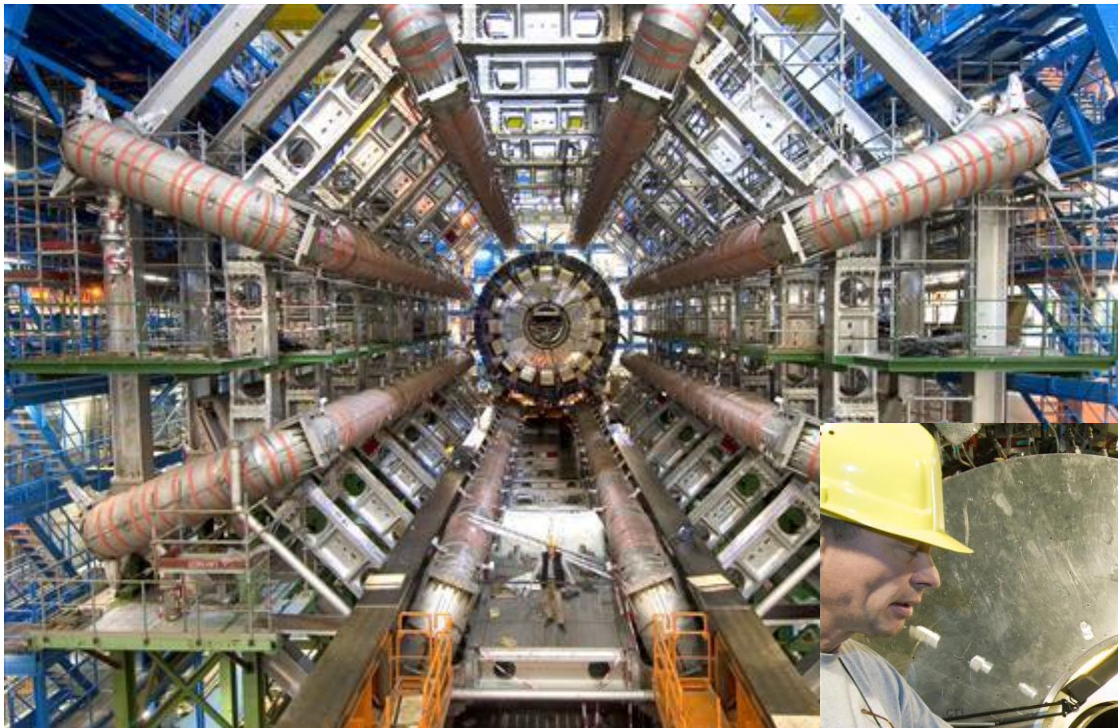


A Large Ion Collider Experiment

LHCb

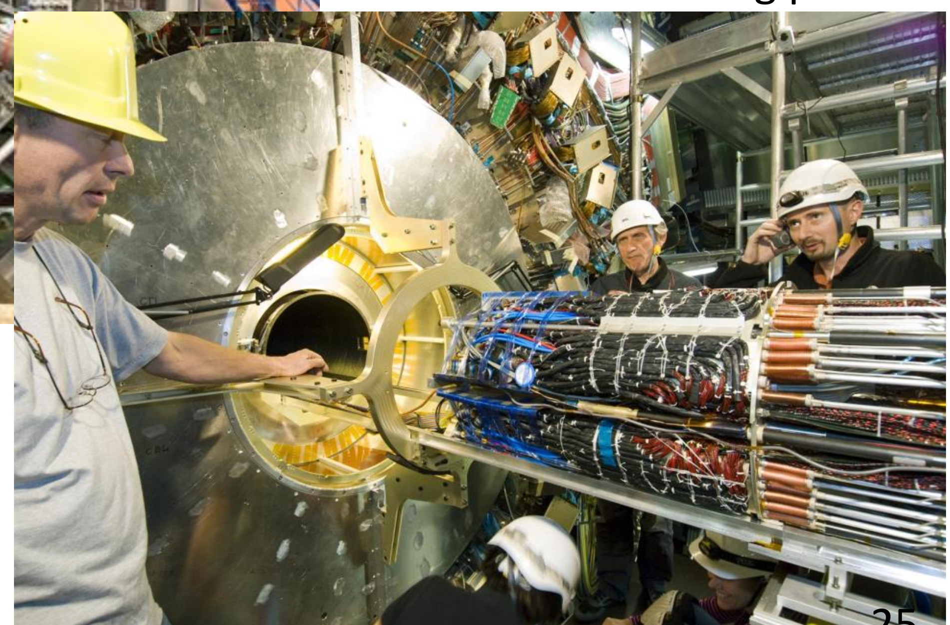


From the construction of ATLAS

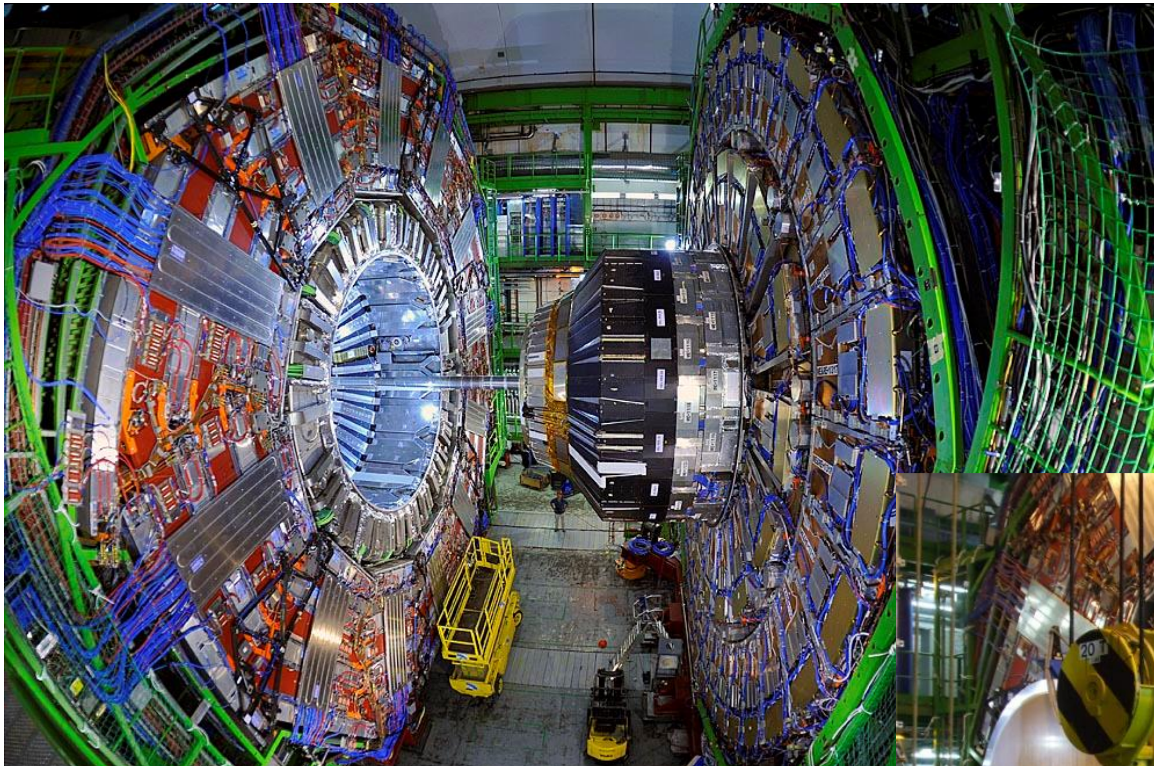


Installing ECAL

Installing pixels



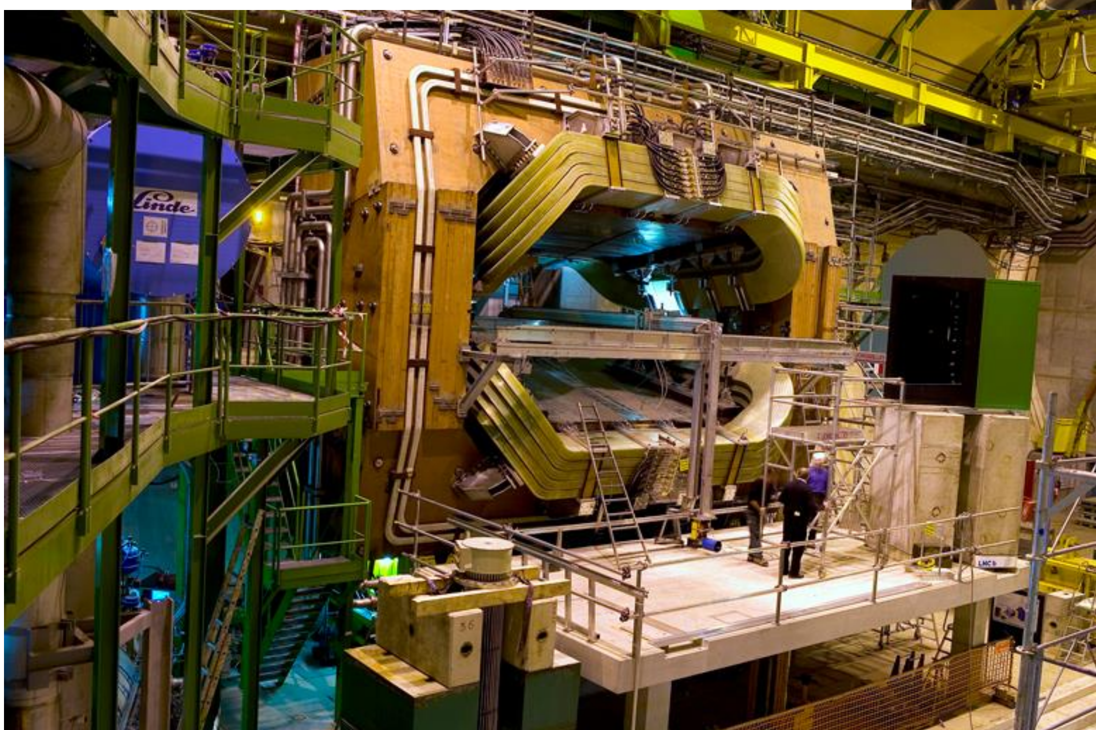
From the installation of CMS



Installing pixels

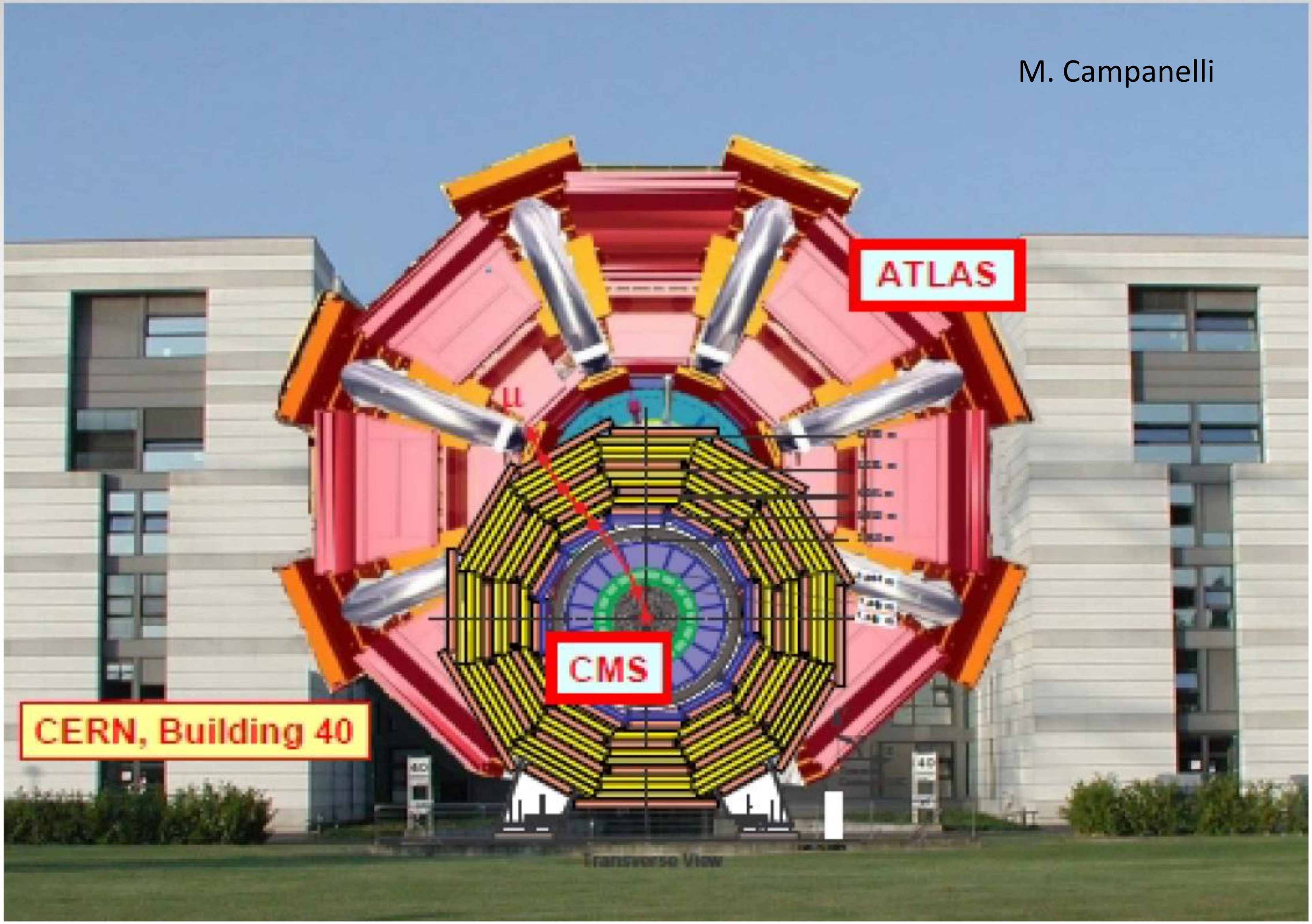
LHCb + ALICE

LHCb magnet



Graduate student Tuva
pulling cables for ALICE

Why CMS stands for 'compact'



ATLAS & CMS: Design & Performance Overview

	ATLAS (7 ktons)	CMS (12.5 ktons)
INNER TRACKER	• Silicon pixels + strips • TRT with particle identification • B = 2 T • $\sigma(p_T) \sim 3.8\%$ (at 100 GeV, $\eta = 0$)	• Silicon pixels + strips • No dedicated particle identification • B = 3.8 T • $\sigma(p_T) \sim 1.5\%$ (at 100 GeV, $\eta = 0$)
MAGNETS	• 4 Magnets • Solenoid + Air-core muon toroids • Calorimeters outside solenoid field	• 1 Magnet • Solenoid • Calorimeters inside field
EM CALORIMETER	• Pb / Liquid Ar sampling accordion • $\sigma(E) \sim 10\text{–}12\% / \sqrt{E} \oplus 0.2\text{–}0.35\%$ • Longitudinal segmentation • Saturation at ~ 3 TeV	• $PbWO_4$ scintillation crystals • $\sigma(E) \sim 3\text{–}5.5\% / \sqrt{E} \oplus 0.5\%$ • No longitudinal segmentation • Saturation at 1.7 TeV
HAD CALORIMETER	• Fe / Scint. tiles (EC: Cu-liquid Ar) • $\sigma(E) \sim 45\% / \sqrt{E} \oplus 1.3\%$ (Barrel)	• Cu (EC: brass) / Scint. tiles • Tail catchers outside solenoid • $\sigma(E) \sim 100\% / \sqrt{E} \oplus 8\%$ (Barrel)
MUON	• Drift tubes & CSC (fwd) + RPC/TGC • $\sigma(p_T) \sim 10.5\% / 10.4\%$ (1 TeV, $\eta = 0$) (standalone / combined with tracker)	• Drift tubes & CSC (EC) + RPC • $\sigma(p_T) \sim 13\% / 4.5\%$ (1 TeV, $\eta = 0$) (standalone / combined with tracker)

Luminosity – single most important quantity !

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

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

  - f_{rev} = 11245.5 Hz is the bunch revolution frequency
  - n_{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 μm 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

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

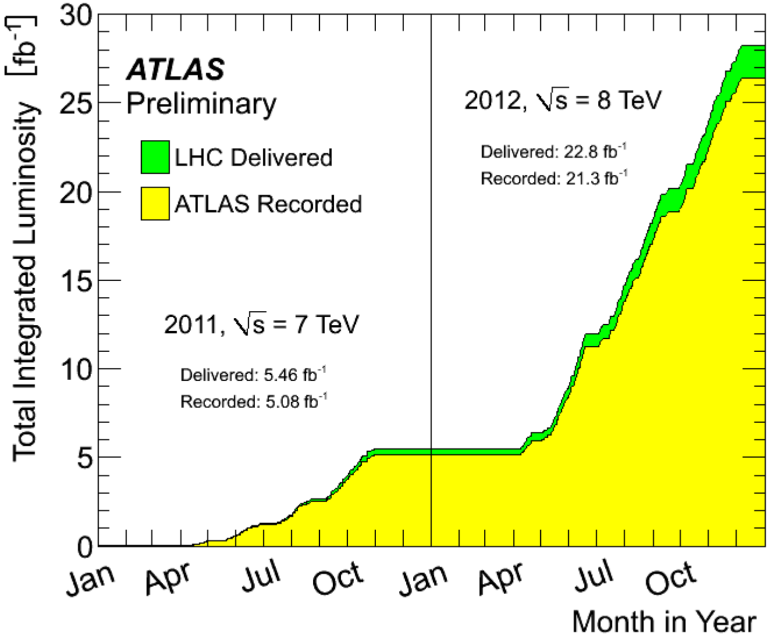
"Cross section" given by Nature

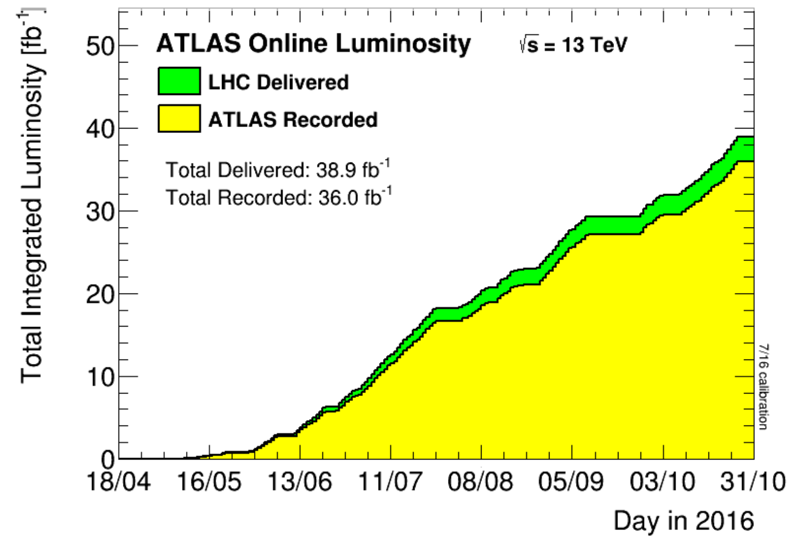
"Efficiency" of detection optimised by experimentalist

Recorded Luminosity

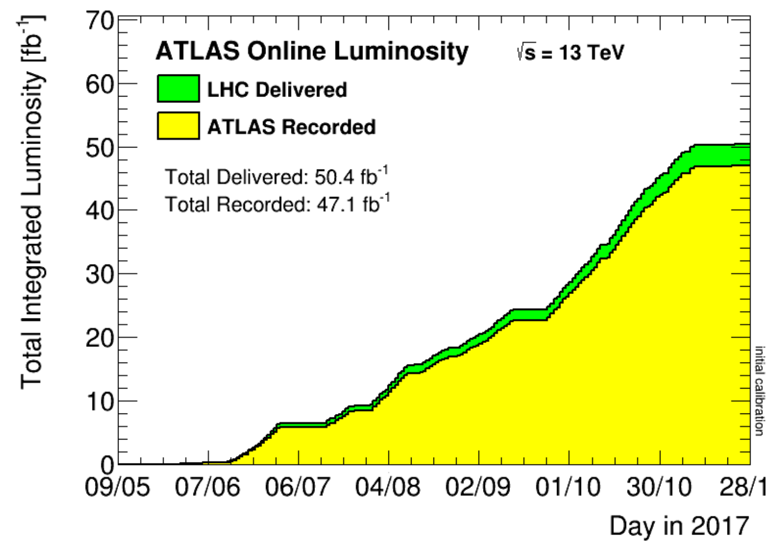
Measured with forward detectors, calibrated with beam separation scans

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

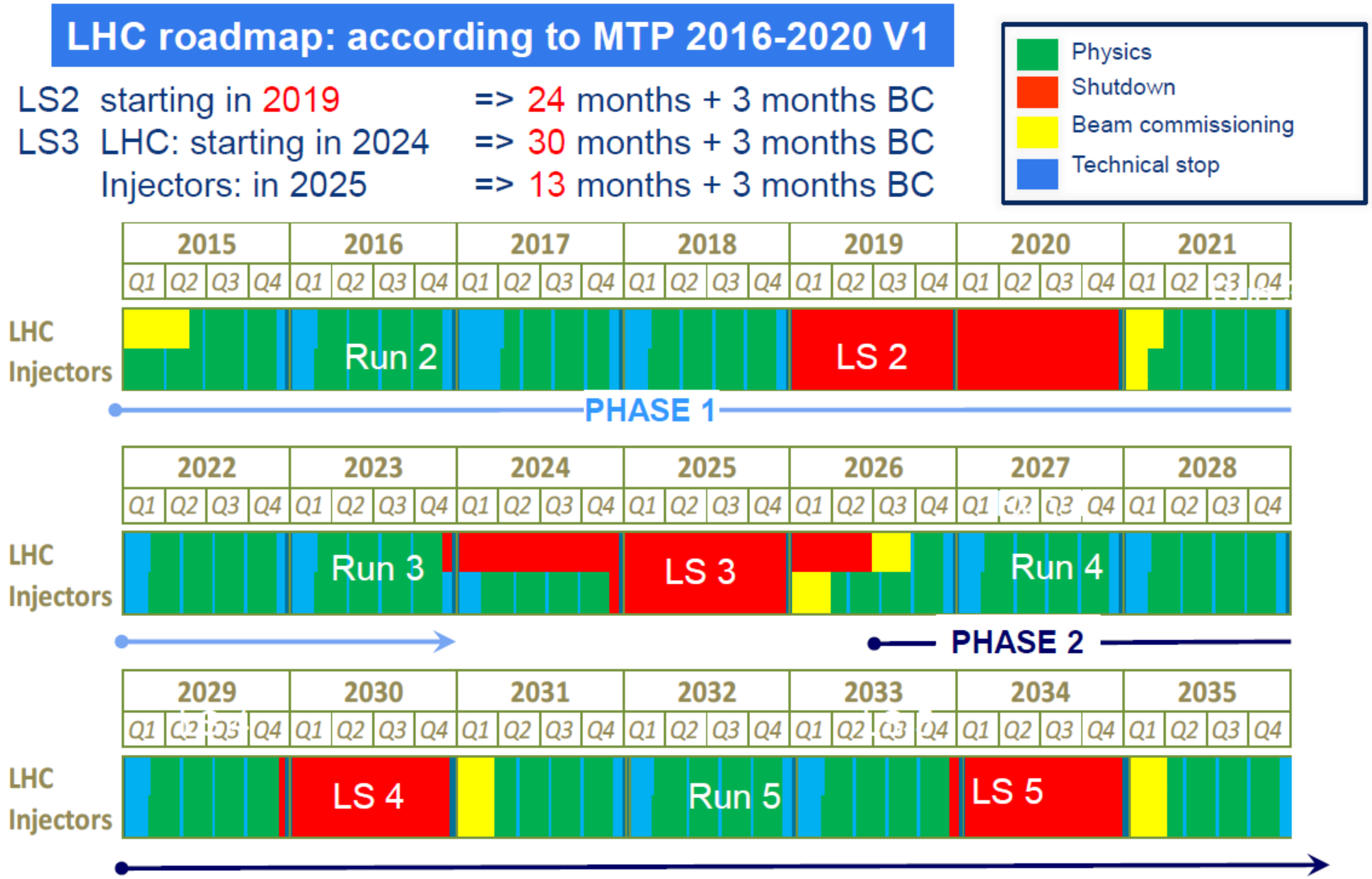




10^{32} cm^{-2}s^{-1} *instantaneous* luminosity corresponds to an *integrated* luminosity of 0.1 nb^{-1} per second
$\Rightarrow$ 180 pb^{-1} per month (assuming 70% LHC efficiency for physics)



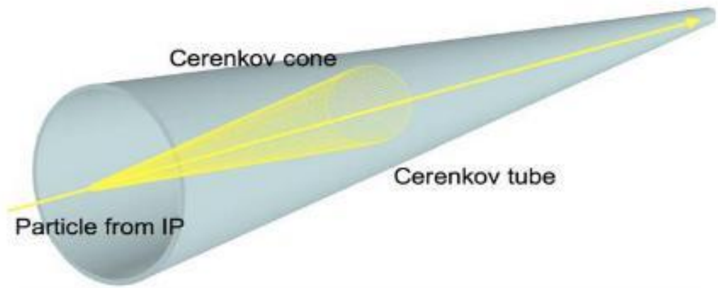
Schedule (preliminary)



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

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^o 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 supresses 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.

ATLAS LUCID

The basic concept

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

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

Bunch crossing rate = $\frac{2808}{3564}$ x 40 Mhz (2808: filled BX; 3564: total BX)

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

Efficiency (and acceptance) of LUCID to detect a pp interaction (~21% for single sided detection and ~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:

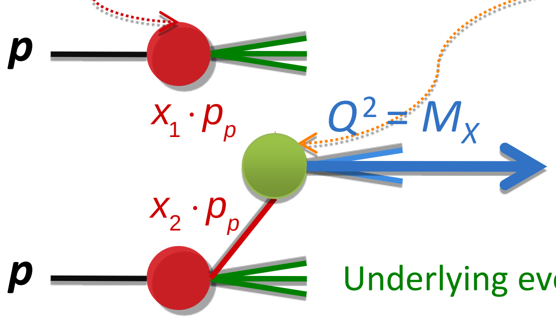
$$\mu_{LUCID} = \frac{\langle N_{particles/BX} \rangle}{\langle N_{particles/pp} \rangle}$$

Cross sections at a hadron collider

- For proton collisions, cross section is convolution of Parton Density Functions (PDF) with parton scattering Matrix Element
- For inclusive processes and at short distance, $\sigma(pp \to X)$ can be computed in pQCD with factorization theorem, separating hard scattering and PDFs

$$\sigma_{pp\to X} = \sum_{\text{partons}} \text{PDF} \otimes \sigma_{\text{hard scatter}} = \sum_{a,b} \int_0^1 dx_1\, dx_2 \cdot f_a(x_1, Q^2) \cdot f_b(x_2, Q^2) \cdot \hat{\sigma}_{ab\to X}\left(x_1, x_2, \alpha_{(S)}, Q^2\right)$$

here chose: $Q = \mu_F = \mu_R$



- Large α_S requires (complicated) higher order calculations

p-p event is superposition of: hard subprocess (matrix element) +
initial and final state radiation, multiple parton–parton interactions with additional radiation

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) ⇒ <x> = 0.007 (0.07)

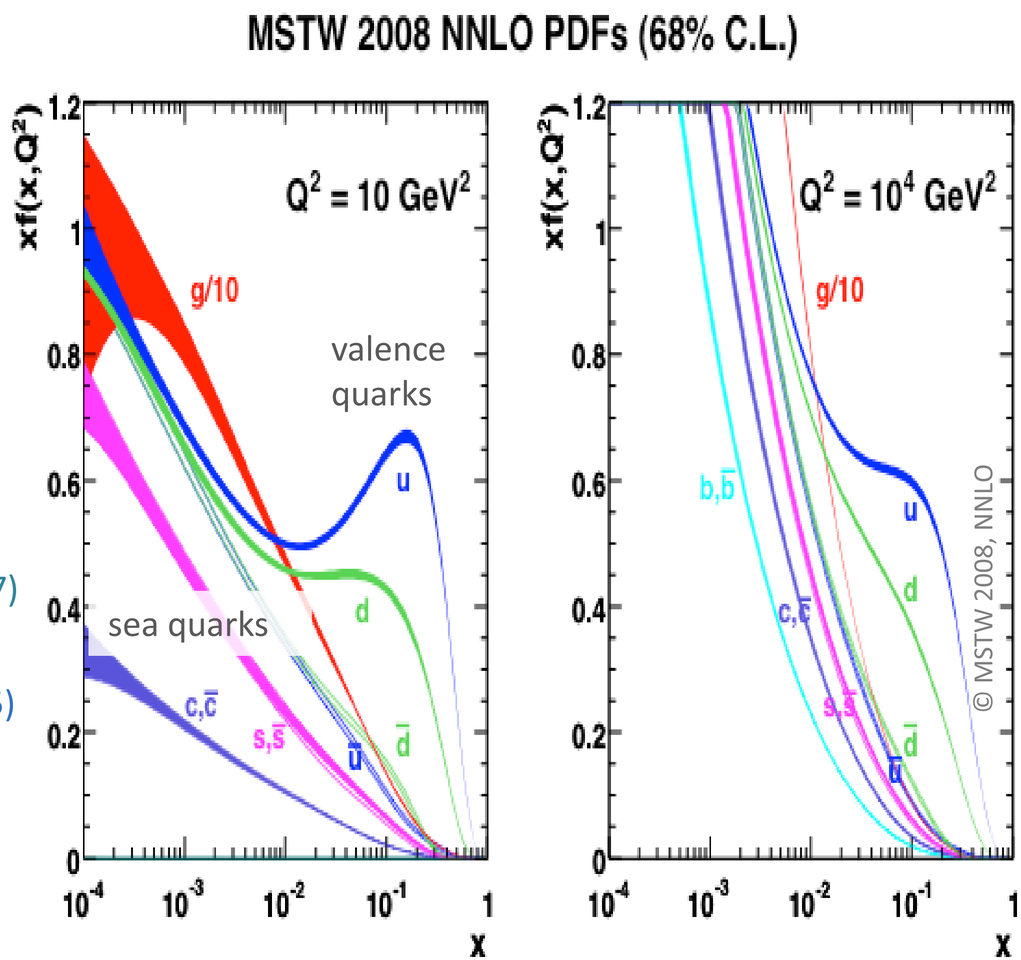
  Tevatron ($\sqrt{s}$ = 2 TeV):
  - M_X = 100 GeV (1 TeV) ⇒ <x> = 0.05 (0.5)

- PDFs rise dramatically towards low x

  ⇒ larger cross sections at LHC

  ⇒ gluon dominated

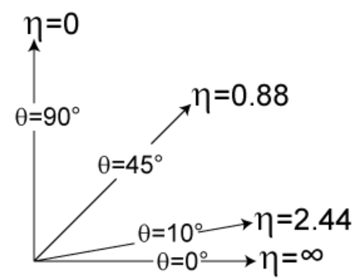
The LHC is a gluon collider!



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

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: $\sum_i \vec{p}_{T,i} \approx 0$ **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 θ (angle between beam axis and particle)
  - Not Lorentz invariant, depends on longitudinal boost of system



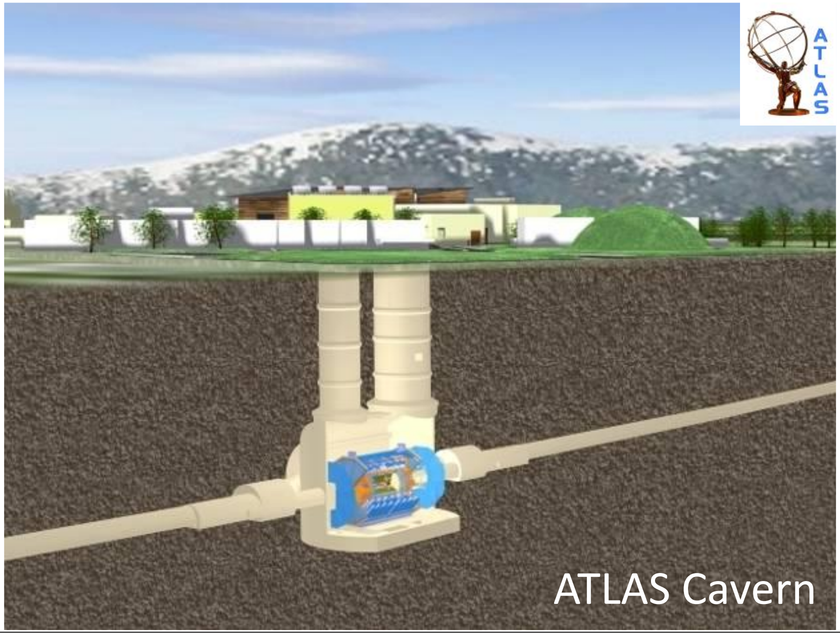
- Rapidity y and Pseudorapidity η

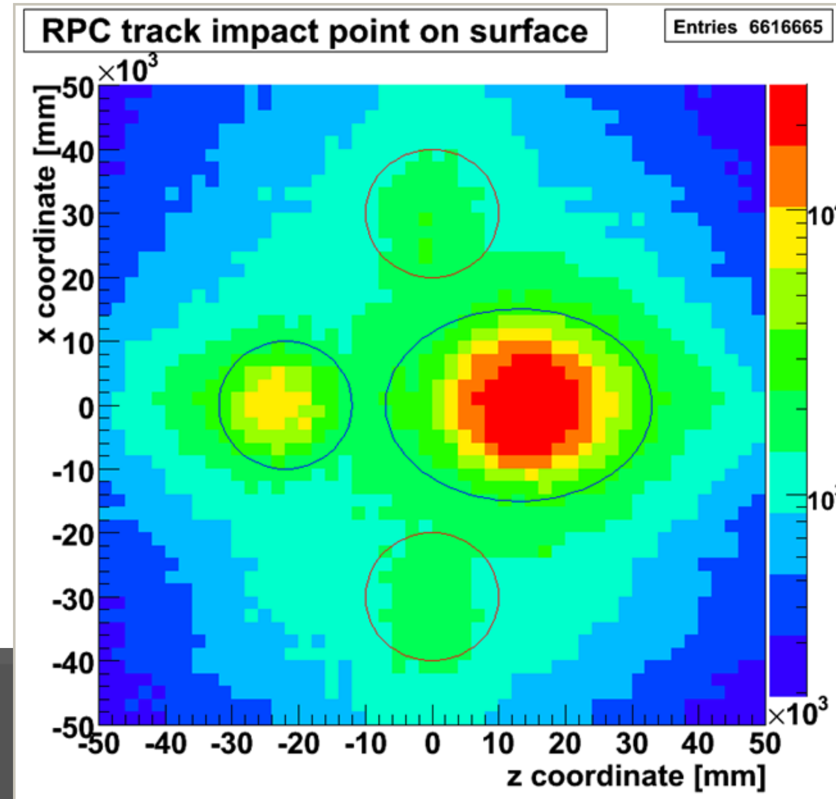
$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) = \frac{1}{2}\ln\left(\frac{x_1}{x_2}\right) \Rightarrow x_1 = x_2 \cdot e^{2y} \quad , \quad \eta = \frac{1}{2}\ln\left(\frac{|\vec{p}|+p_z}{|\vec{p}|-p_z}\right) = -\ln\left(\tan\frac{\theta}{2}\right) \underset{M=0}{=} y$$

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

Starting up an experiment

Data taking: ATLAS control room





Muon flux at surface:

~130 Hz / m^2 for E_μ > 1 GeV

average energy ~4 GeV

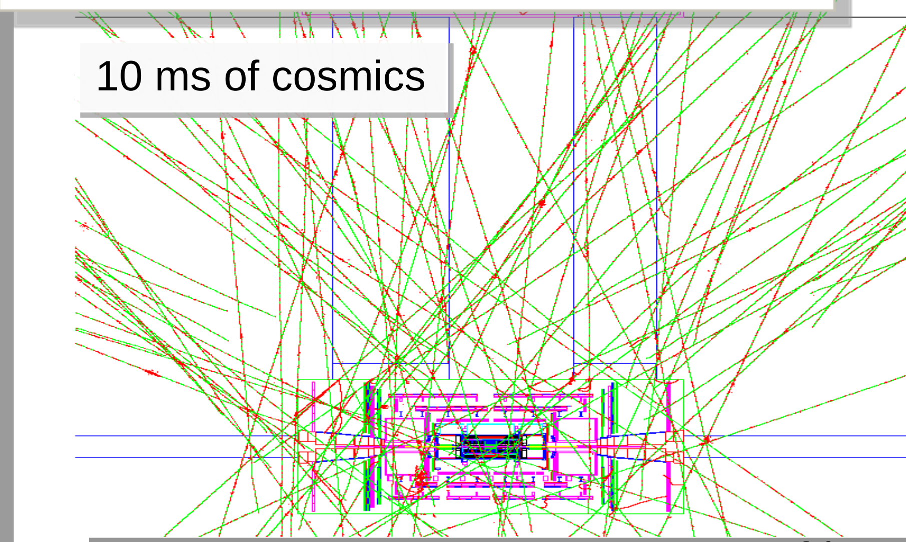
Muon flux in ATLAS detector (simulation):

~4 kHz in muon fiducial volume

~15 Hz in TRT barrel

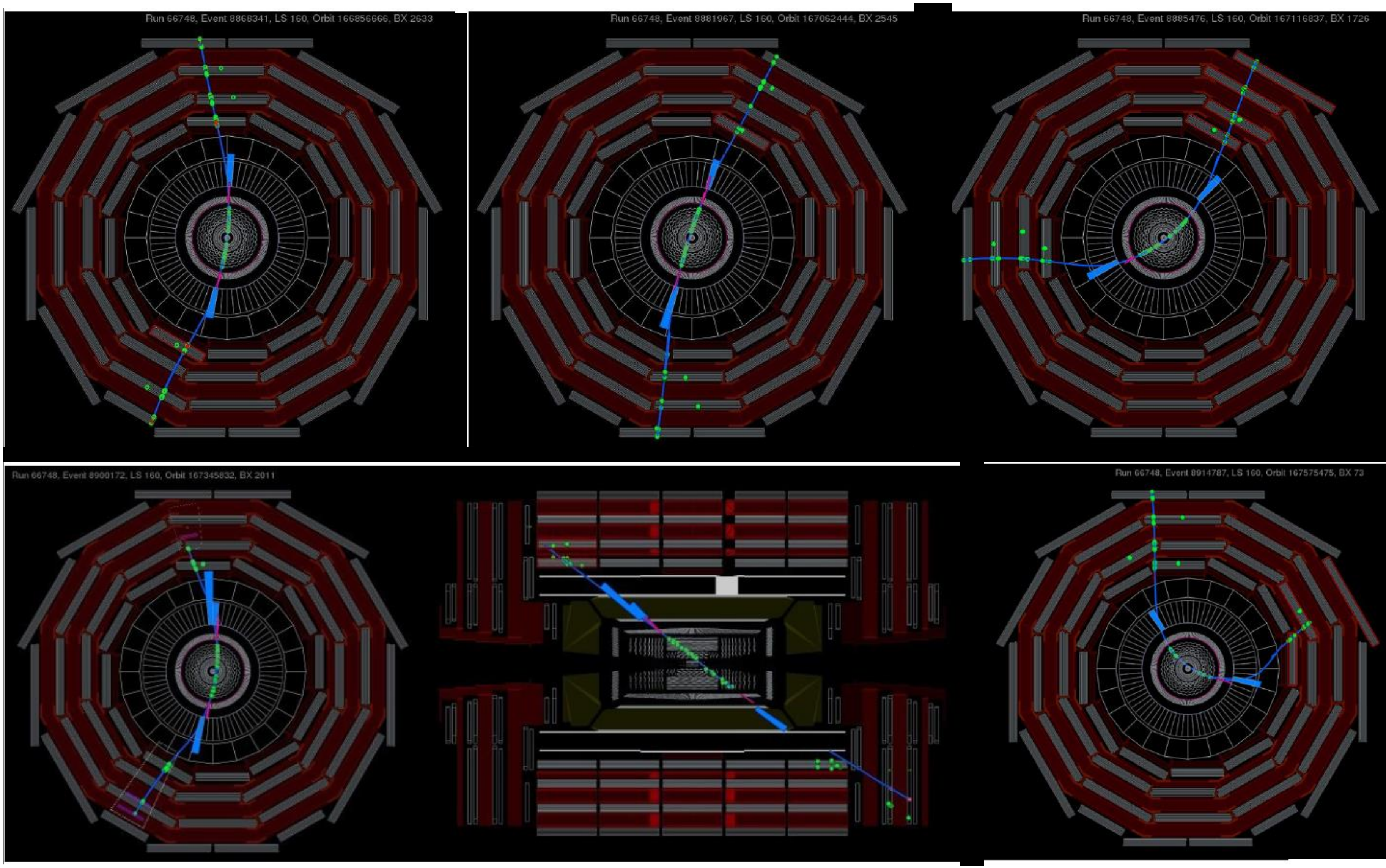
Charge ratio: $\mu^+ / \mu^- \sim 1.27$

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



Simulated cosmic flux in ATLAS cavern: integration over 10 msec

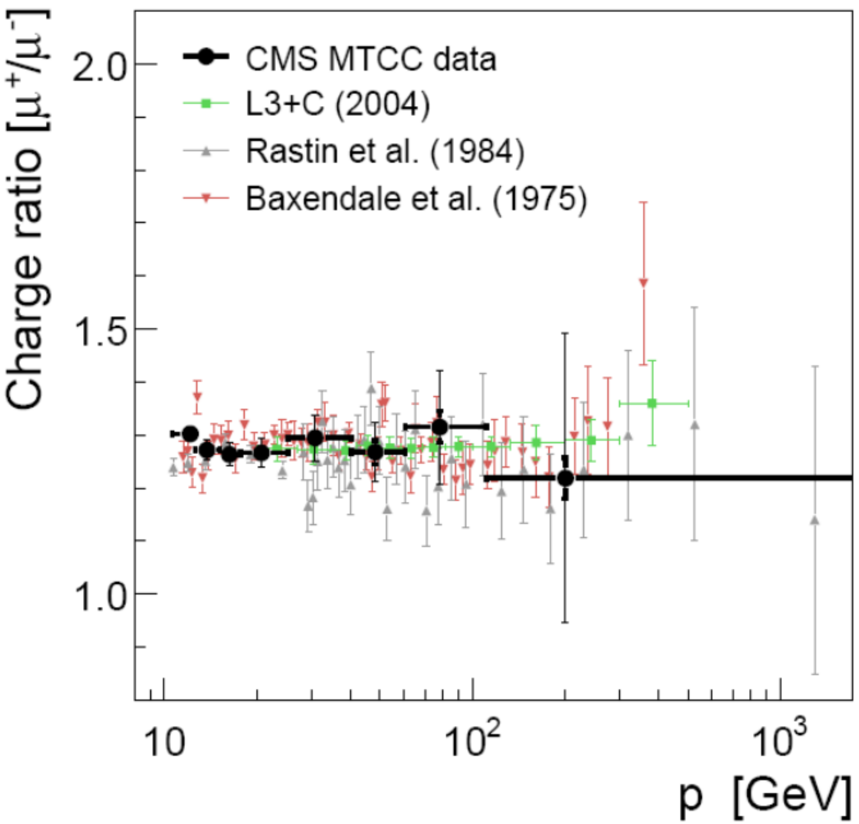
More Cosmic Muons in CMS (both charges!) ...



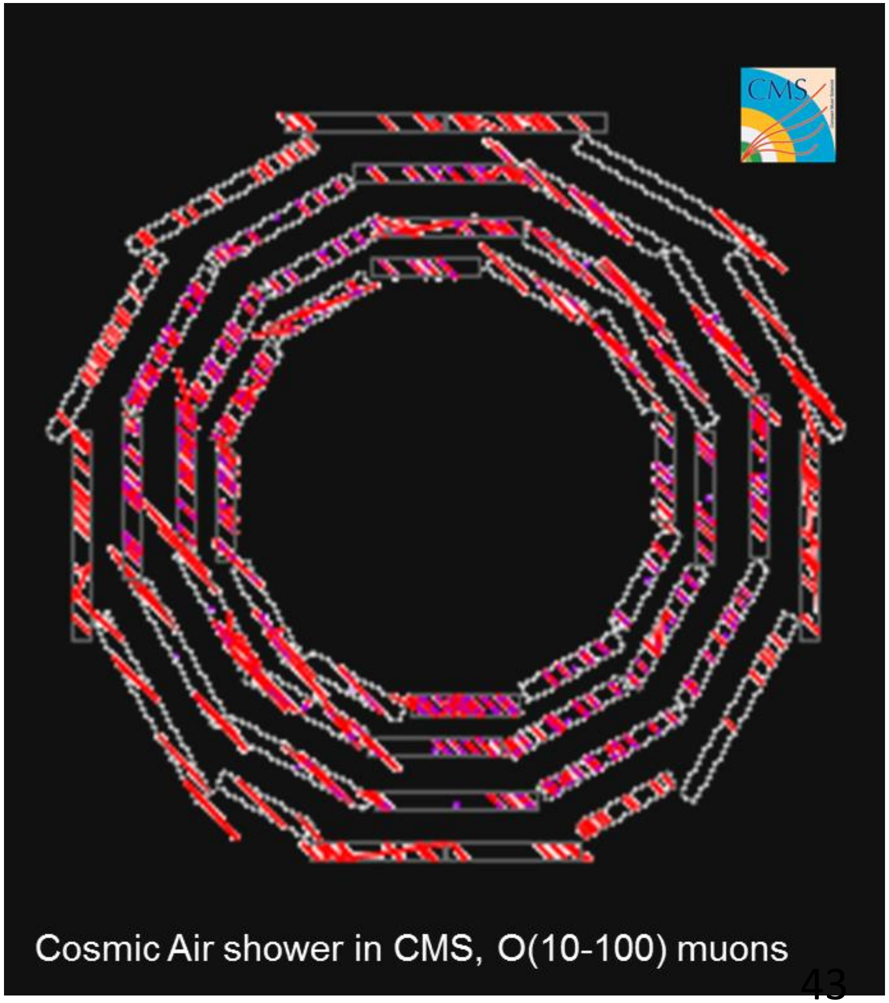
Through barrel and endcap muon detectors

Studying cosmic rays

Charge ratio



Showers of muons

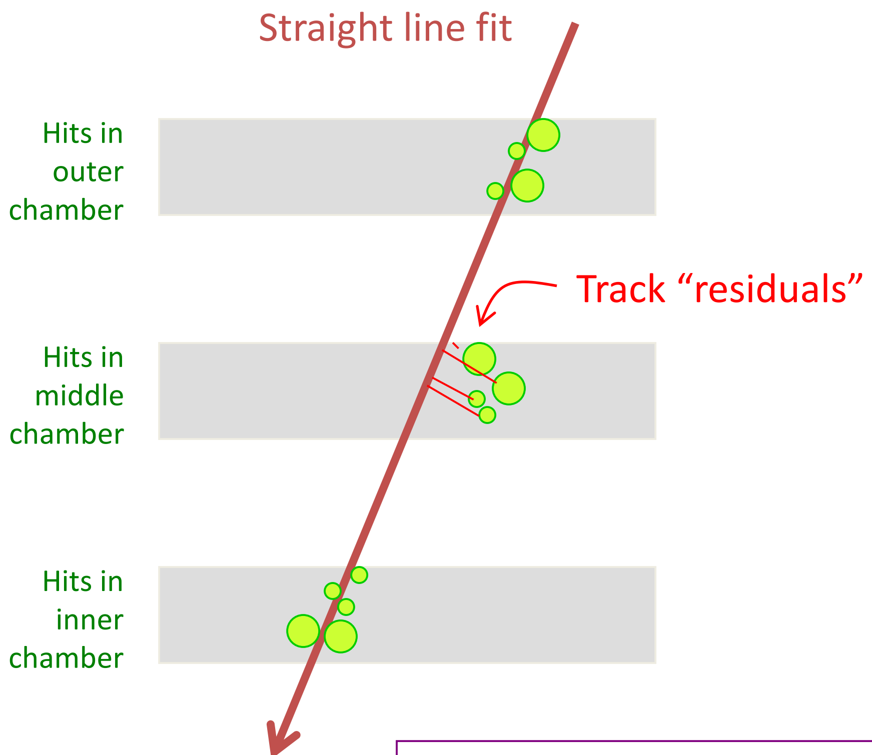


Alignment of detectors

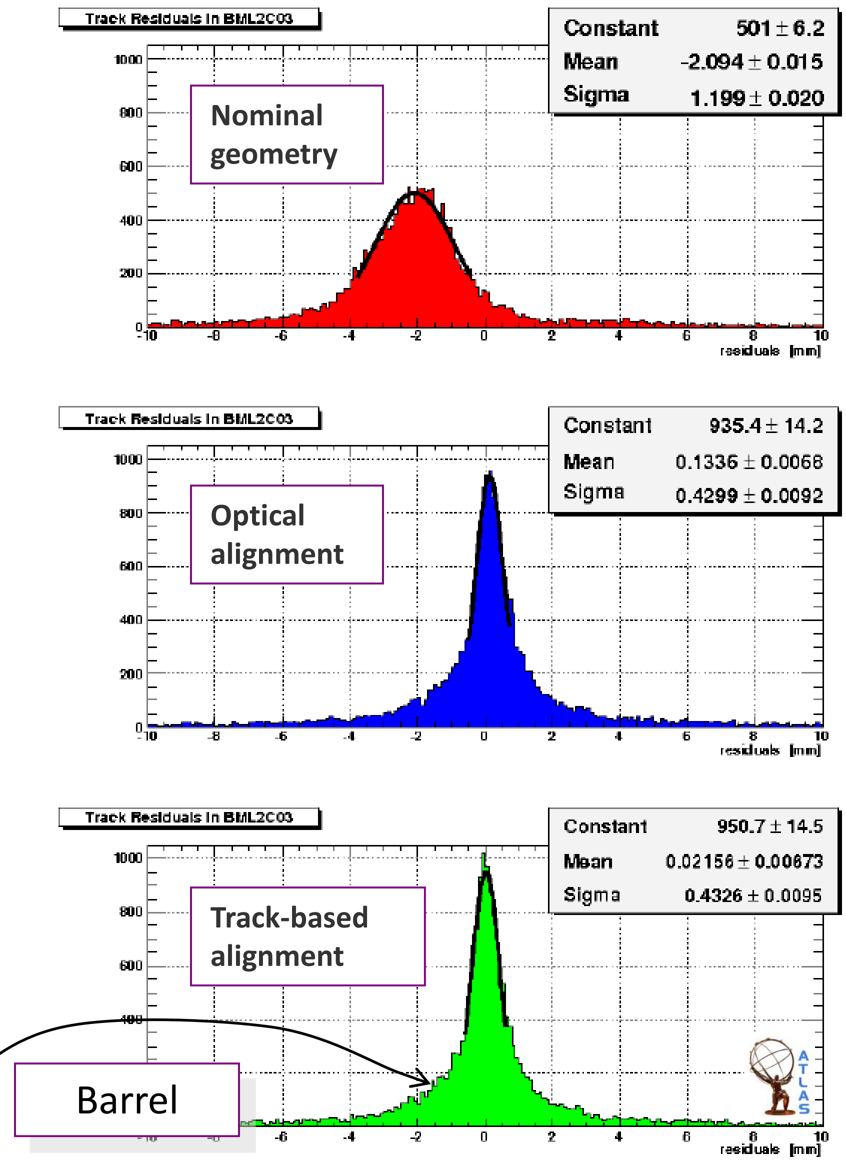
(Another perfect use of cosmic rays)

Muon Alignment Also Uses (Straight) Tracks

- Compare residuals for straight cosmic tracks

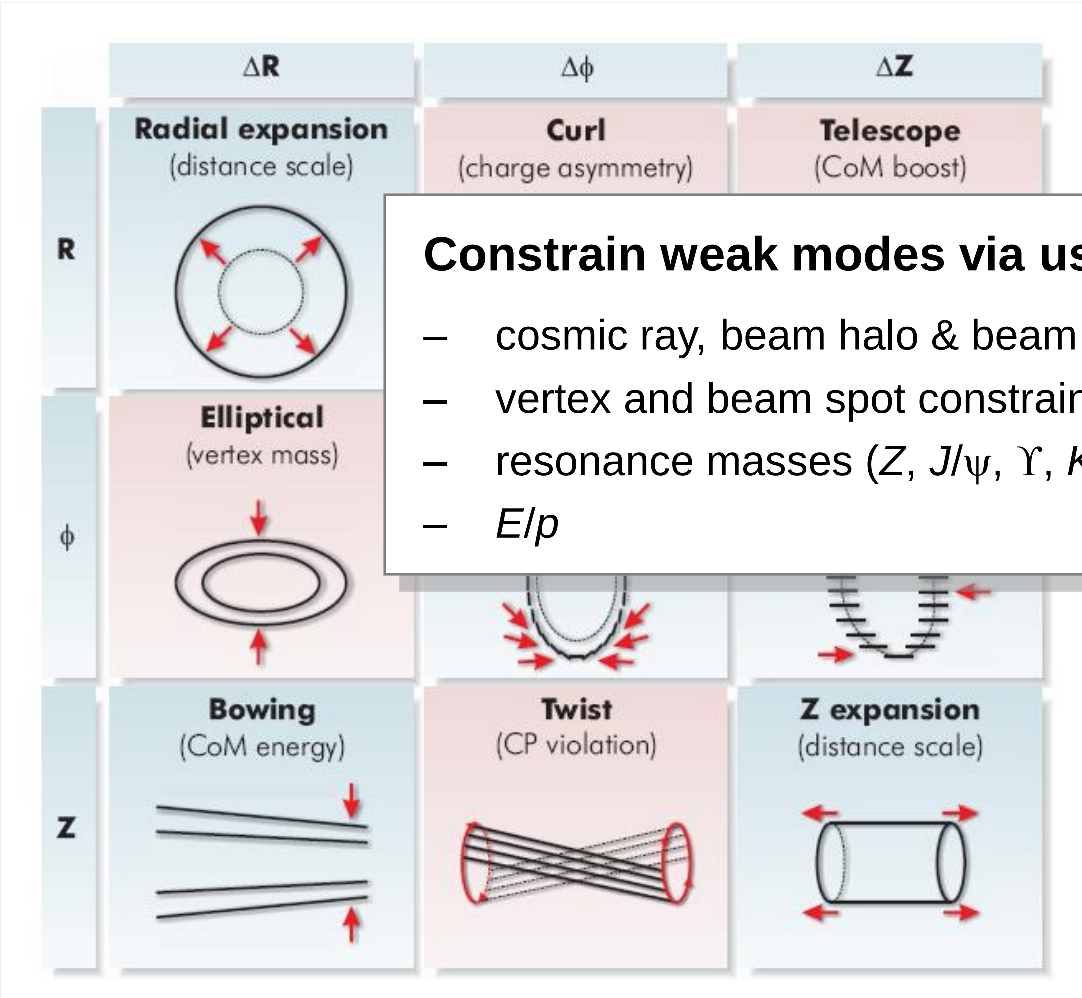


Low-momentum muons, tails dominated by multiple scattering



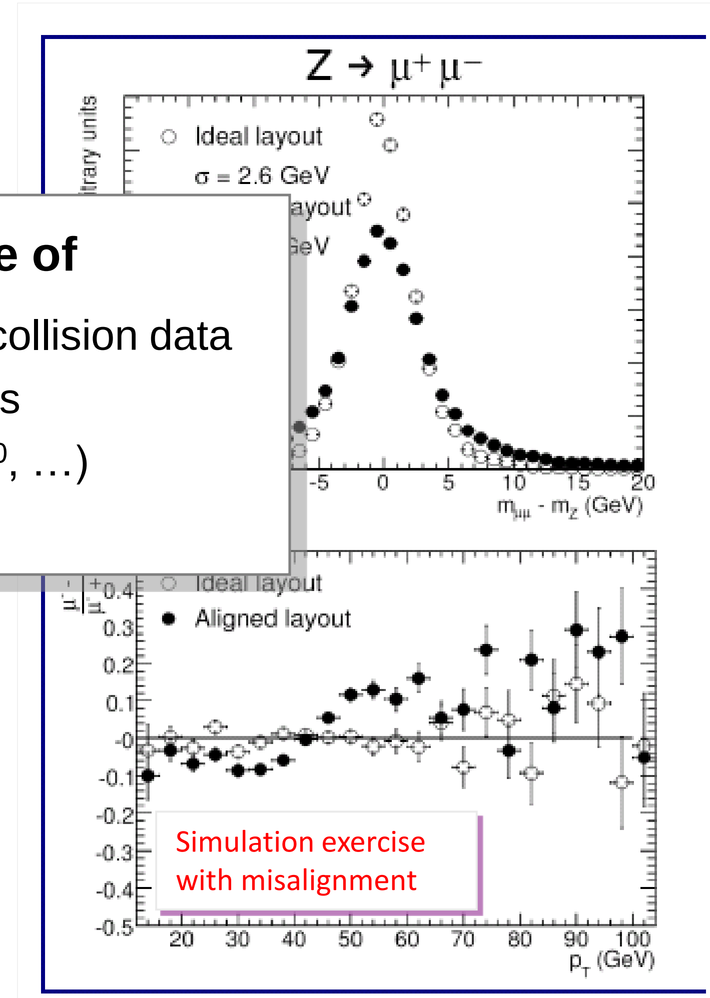
“Weak Modes”

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

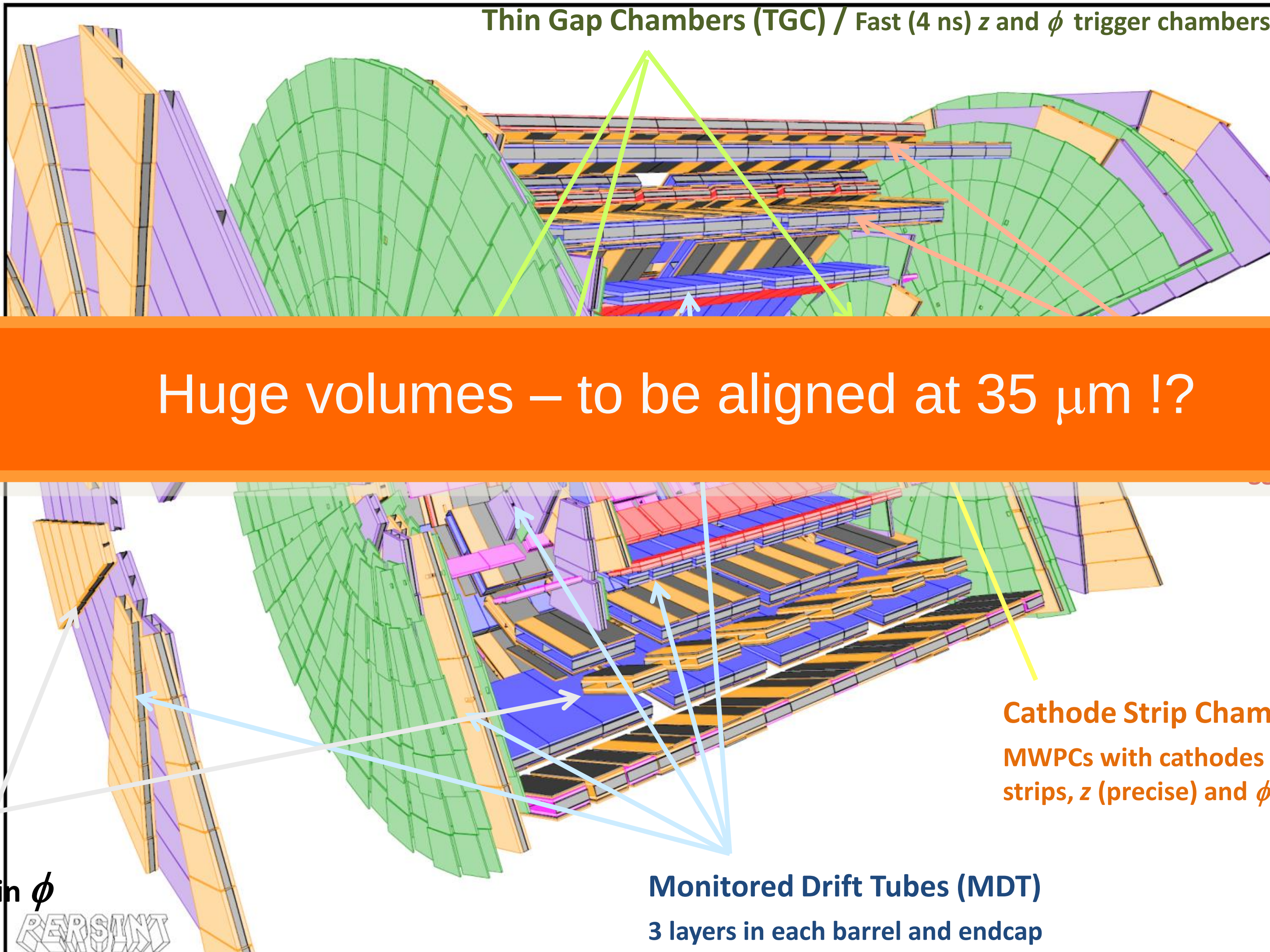


Constrain weak modes via use of

- cosmic ray, beam halo & beam collision data
- vertex and beam spot constraints
- resonance masses (Z, J/ψ, Υ, K^0, …)
- E/p



ATLAS Muon System – Active Material



Huge volumes – to be aligned at 35 μm !?

Summary of today

Mostly pretty pictures, more about physics tomorrow!