

FYST17 Lecture 5

LHC Physics 1

Thanks to A- Hoecker, V. Hedberg

Today & Monday

- The LHC accelerator
- Challenges
- The experiments (mainly CMS and ATLAS)
- 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

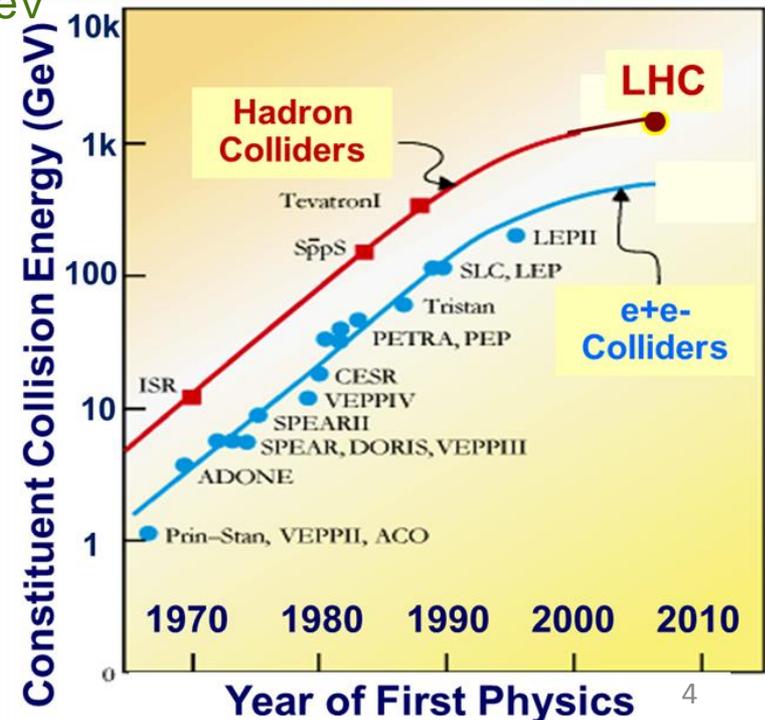
- Can reach higher energies in ring (less synchrotron radiation)

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 → 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 Λ

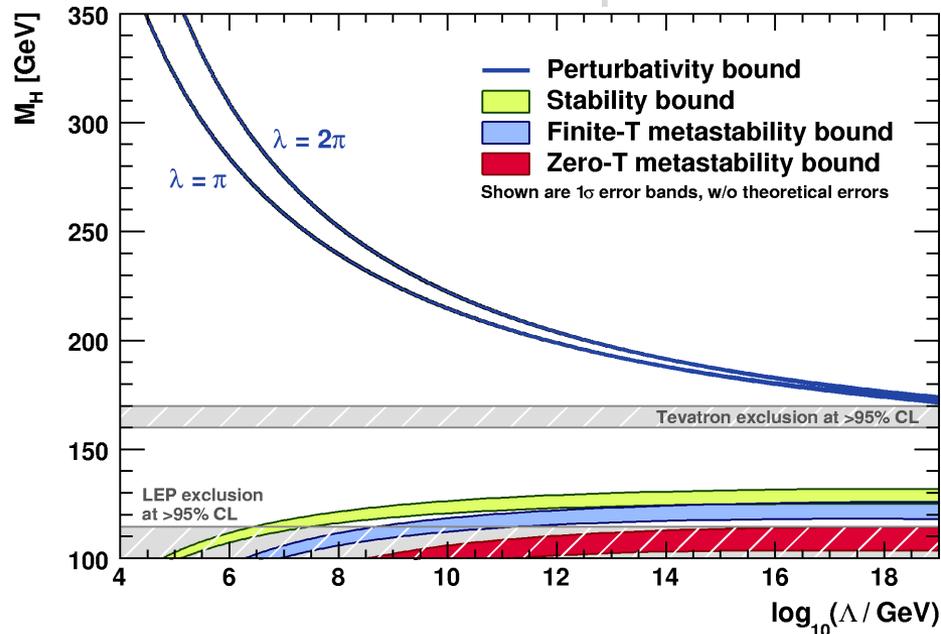
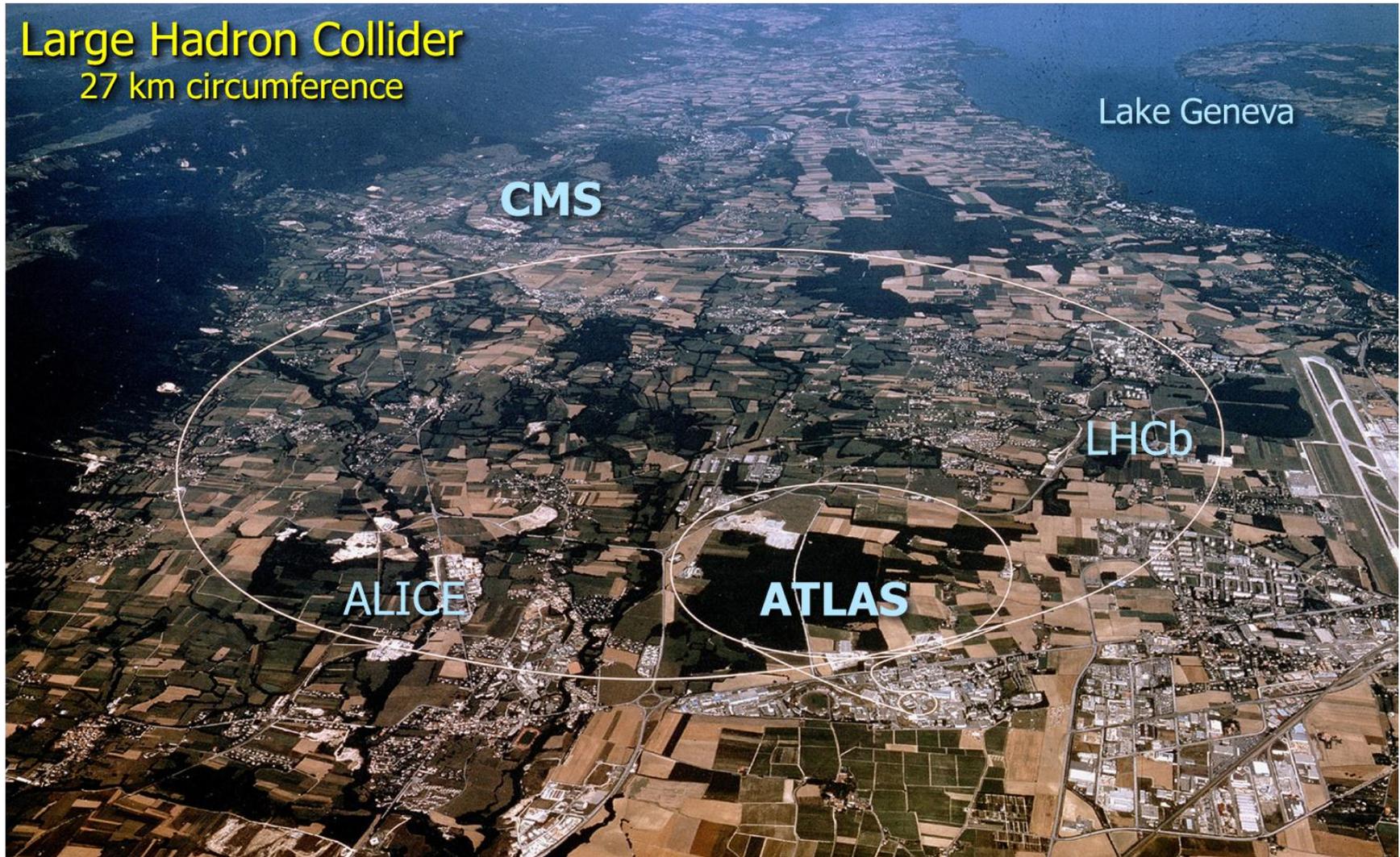


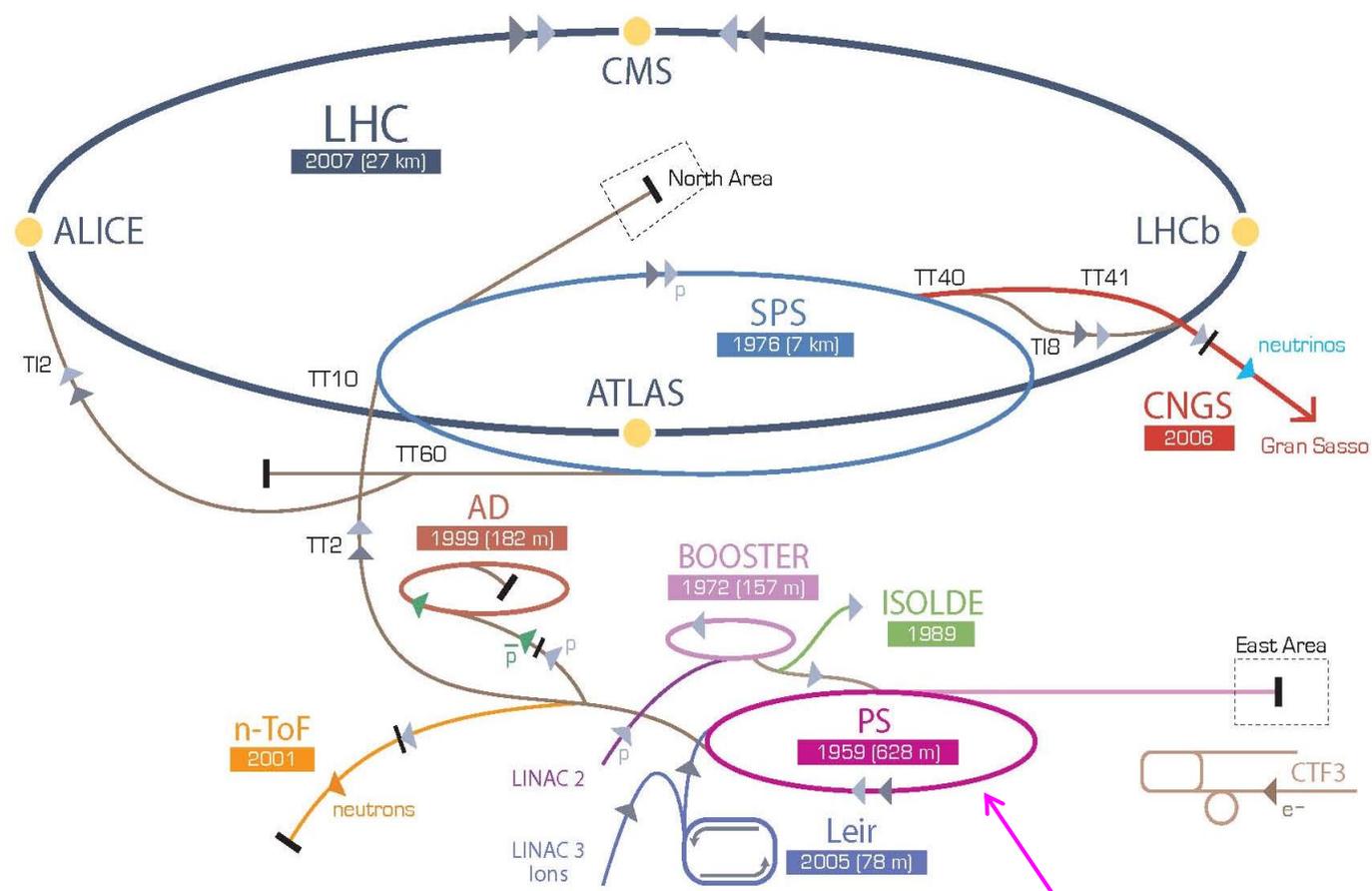
Figure uses NLO Higgs potential. The widths of bands account for errors in α_S , m_t and theory.

The SM Higgs must steer a narrow course between two disastrous situations if it is to survive up to the Planck scale $M_p \sim 2 \times 10^{18}$ 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 x Booster
SPS	450	6'911 = 11 x PS
LHC	7000	26'657 = 27/7 x SPS

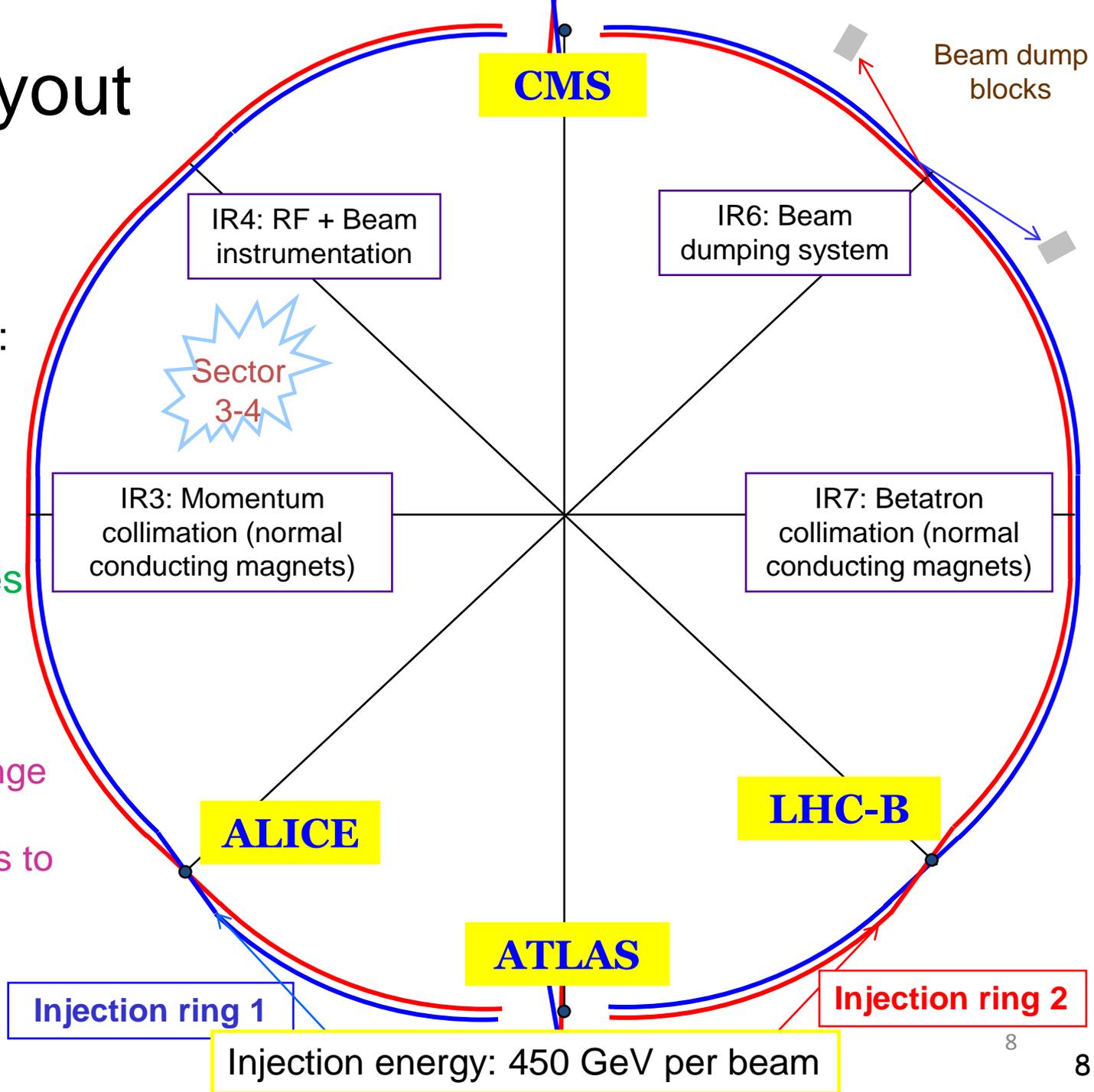
LHC Layout

8 arcs and 8 long (~700 m) straight sections

Each main sector:
154 dipoles
47 quadrupoles.

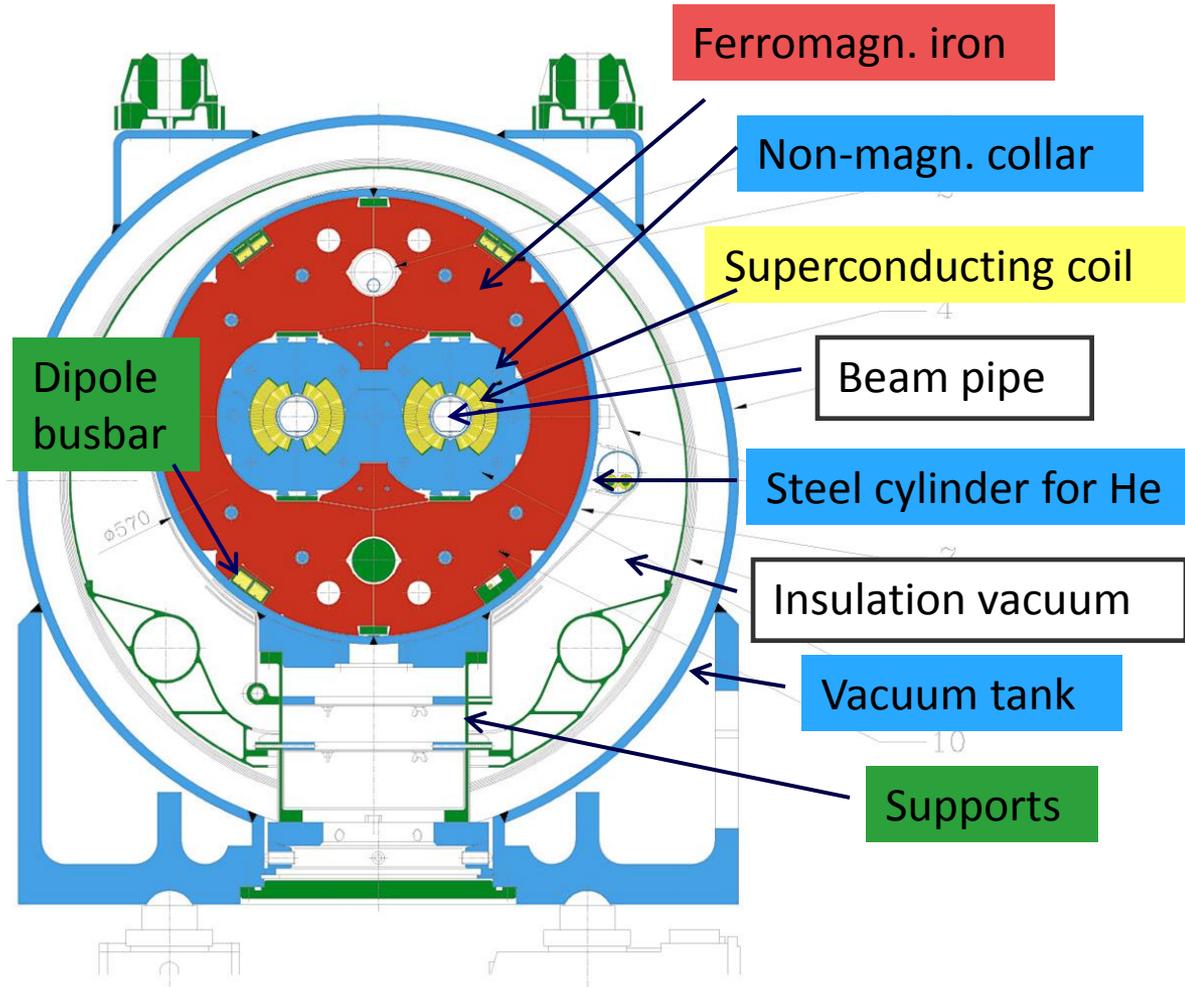
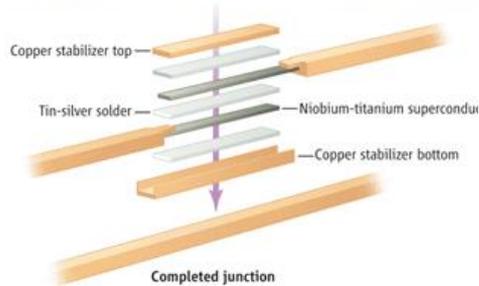
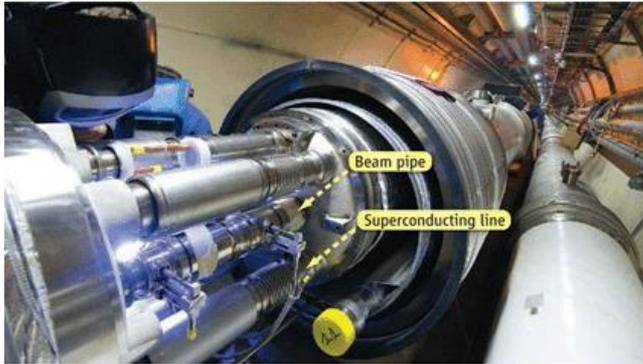
Limits stored energy + facilitates commissioning sector by sector

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



Cross section of dipole magnet

The LHC has > 10000 connections between magnets

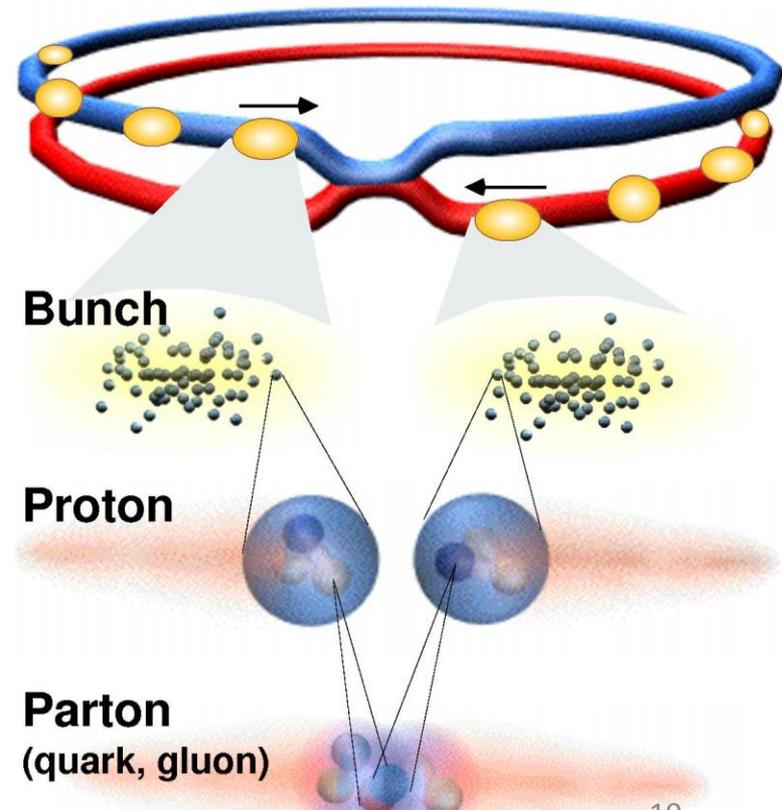


Weight (magnet + cryostat) ~ 30 tons, Length 15 m

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 ($\sim 2/3$)

Protons are circling in bunches, (~ 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!



LHC data handling, GRID computing



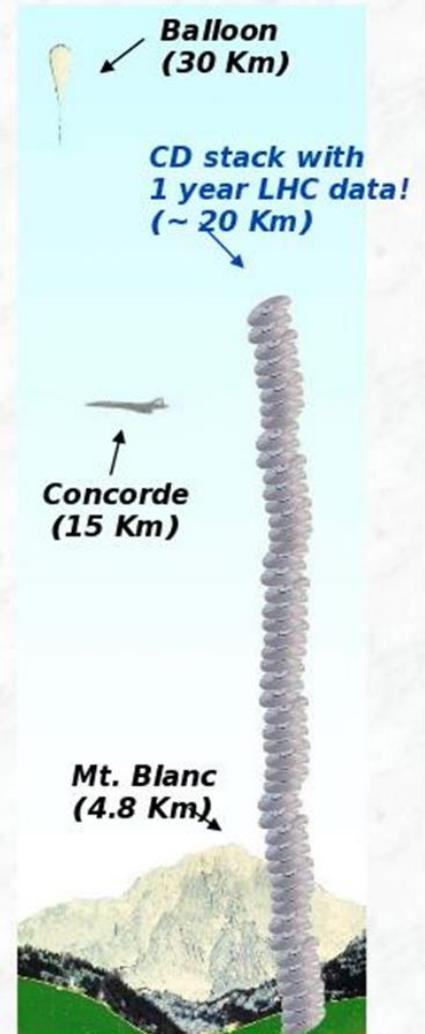
Trigger system selects
~200 "collisions" per sec.

LHC data volume per year:
10-15 Petabytes

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

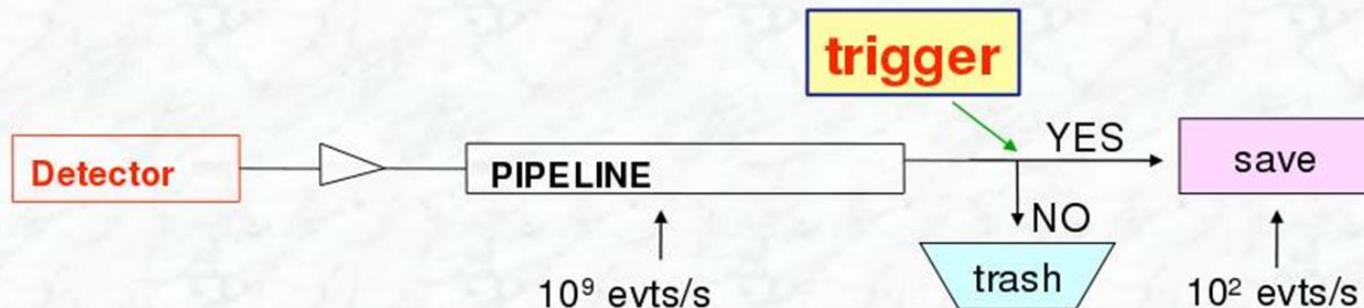


A typical Tier-2 GRID center
(example: Tokyo University)



How to Select Interesting Events?

- Bunch crossing rate: 40 MHz, ~20 interactions per BX (10^9 evts/s)
 - can only record ~200 event/s (1.5 MB each), still 300 MB/s data rate
- Need highly efficient and highly selective TRIGGER
 - raw event data (70 TB/s) are stored in pipeline until trigger decision



- ATLAS trigger has 3 levels (CMS similar with 2 levels)
 - Level-1: hardware, ~3 μ s decision time, 40 MHz \rightarrow 100 kHz
 - Level-2: software, ~40 ms decision time, 100 kHz \rightarrow 2 kHz
 - Level-3: software, ~4 s decision time, 2 kHz \rightarrow 200 Hz

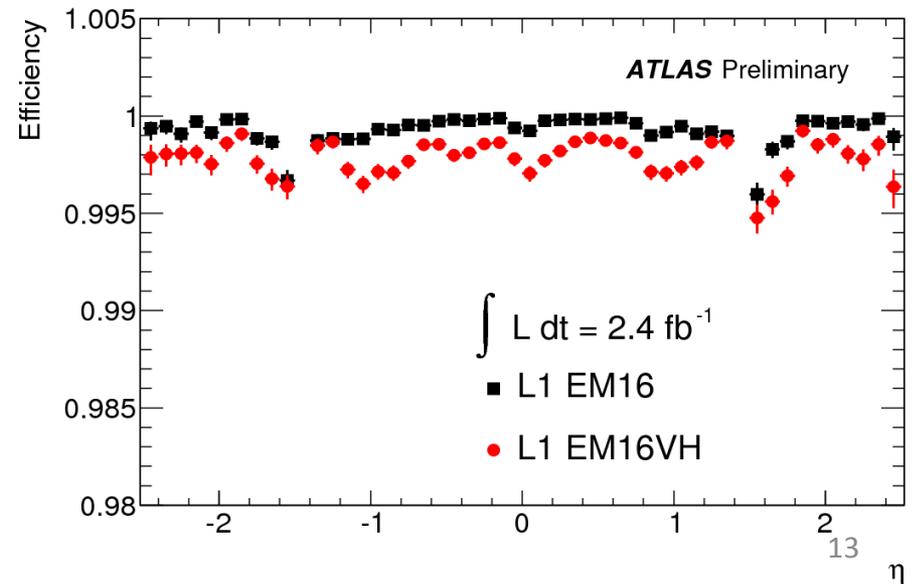
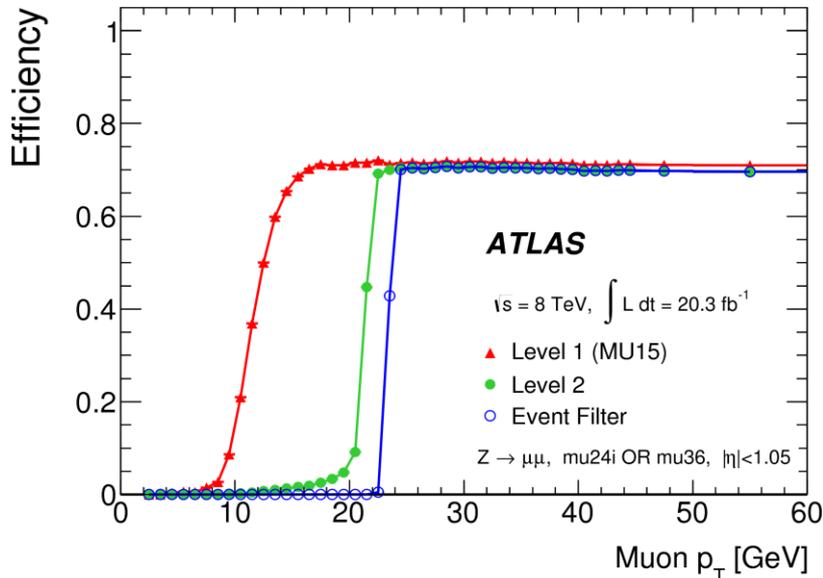
Trigger efficiency

Enters in calculation of cross section:

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

Acceptance → A
Efficiency → ε
Integrated luminosity → $\int L dt$

Examples: ATLAS trigger:



Requirements from Physics Programme

■ Some benchmark analyses

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

➔ W mass

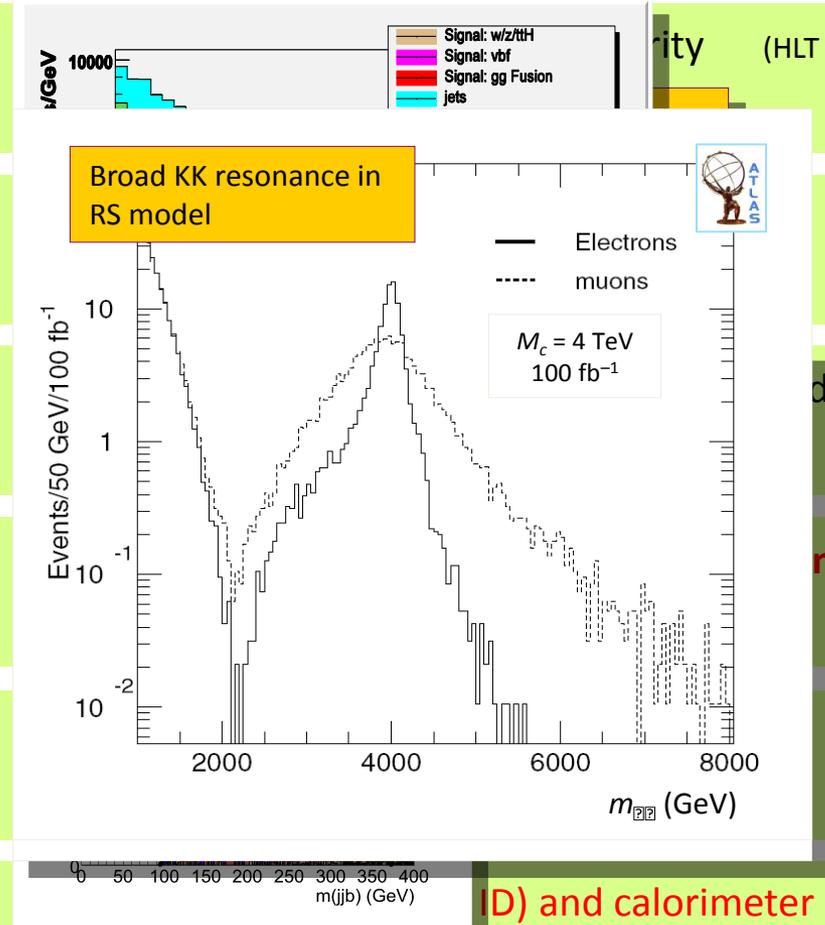
➔ top mass

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

➔ SUSY with R -parity, SUSY Higgs

➔ RS KK modes

■ Design challenges:



(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 μ s

Efficient pattern recognition to reduce: GHz @ L1
 \rightarrow 75 kHz @ HLT \rightarrow 200 Hz to disk

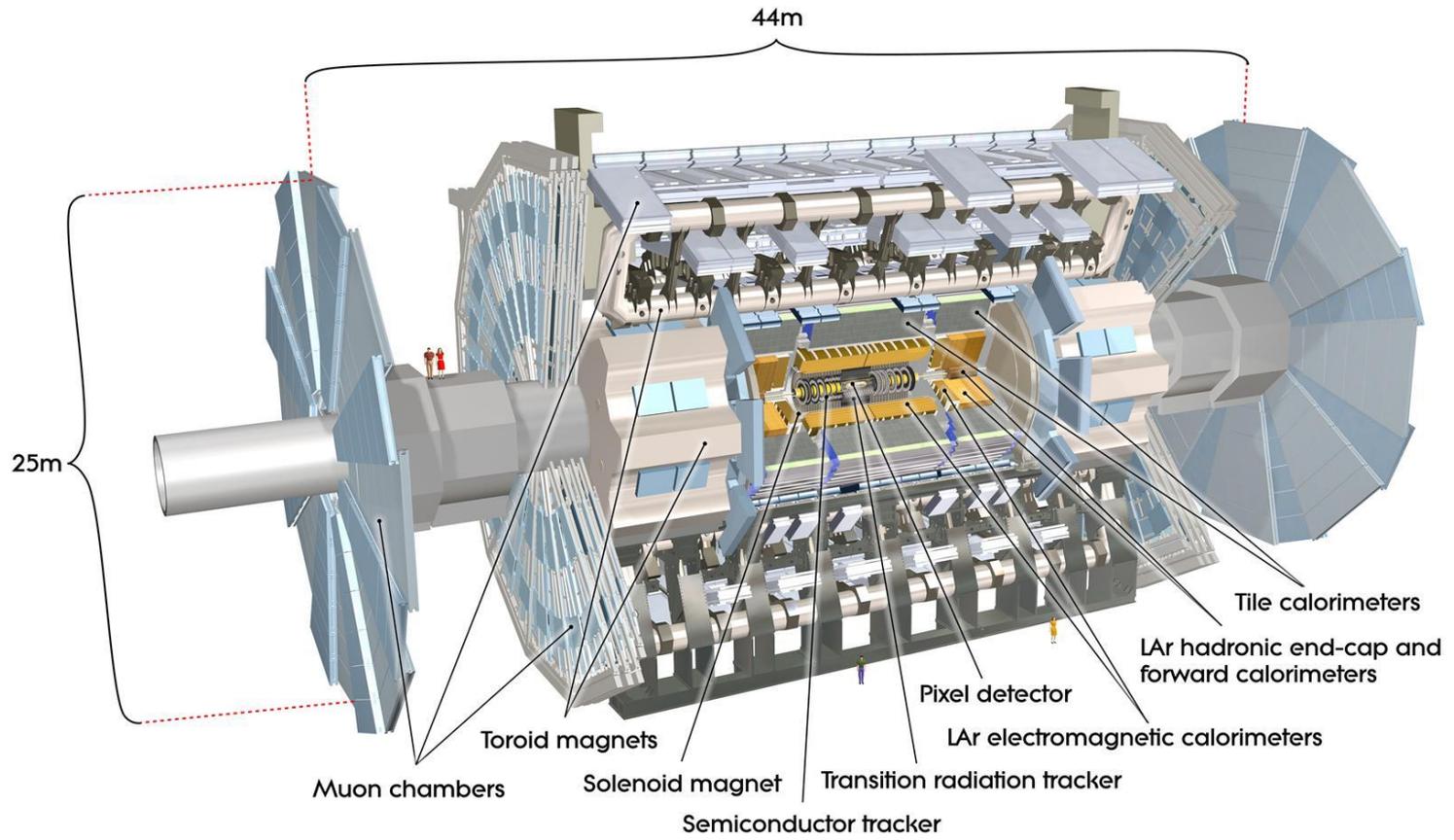
Powerful data processing farms: distribute data analysis to computing centres worldwide

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

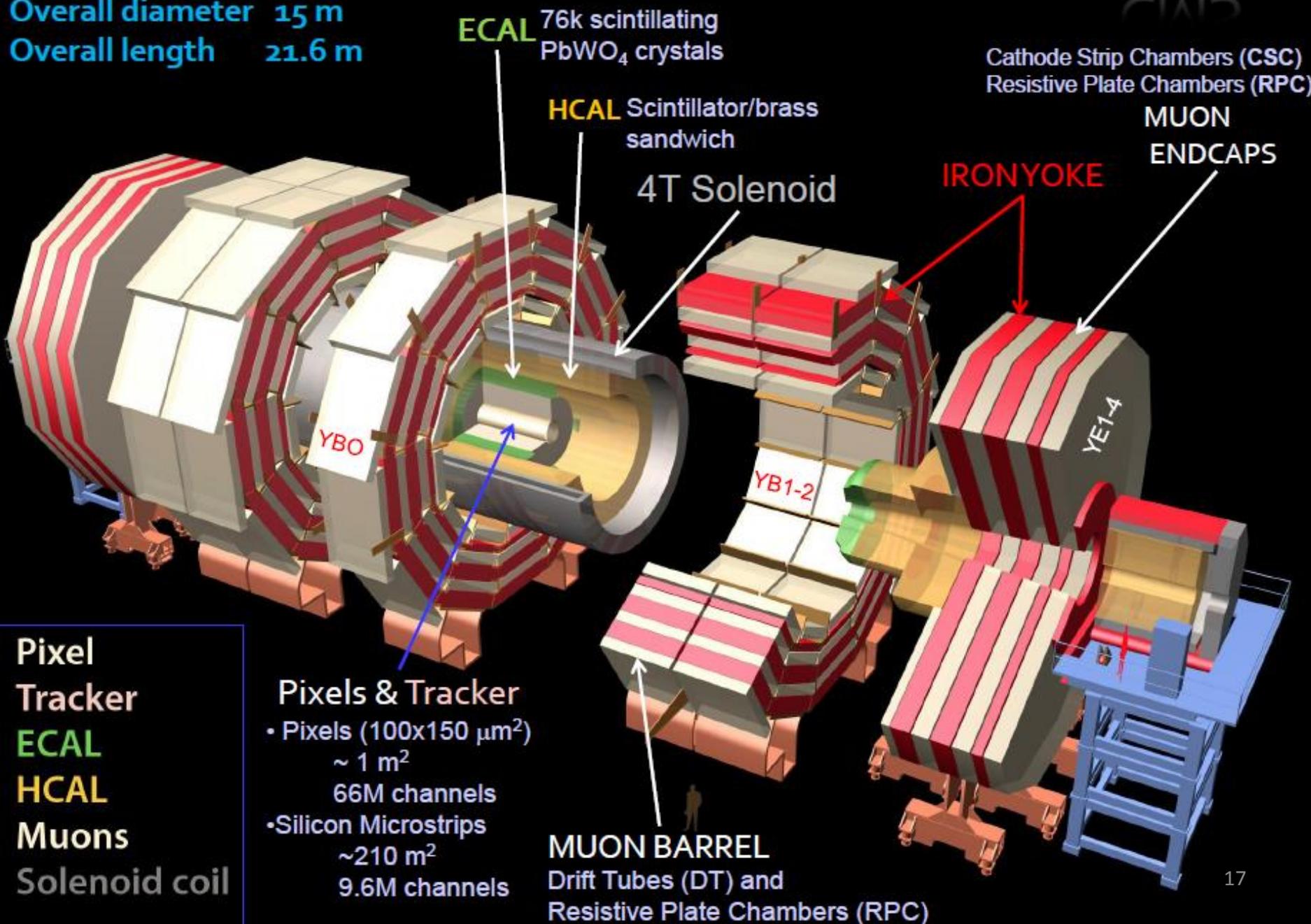
High-granular pixel/silicon or **fine-grained straw tracker** technologies

Precise muon timing, redundant pattern recognition, radiation hardness

ATLAS



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



ECAL 76k scintillating PbWO₄ crystals

HCAL Scintillator/brass sandwich

4T Solenoid

IRONYOKE

Cathode Strip Chambers (CSC)
 Resistive Plate Chambers (RPC)
 MUON ENDCAPS

YBO

YB1-2

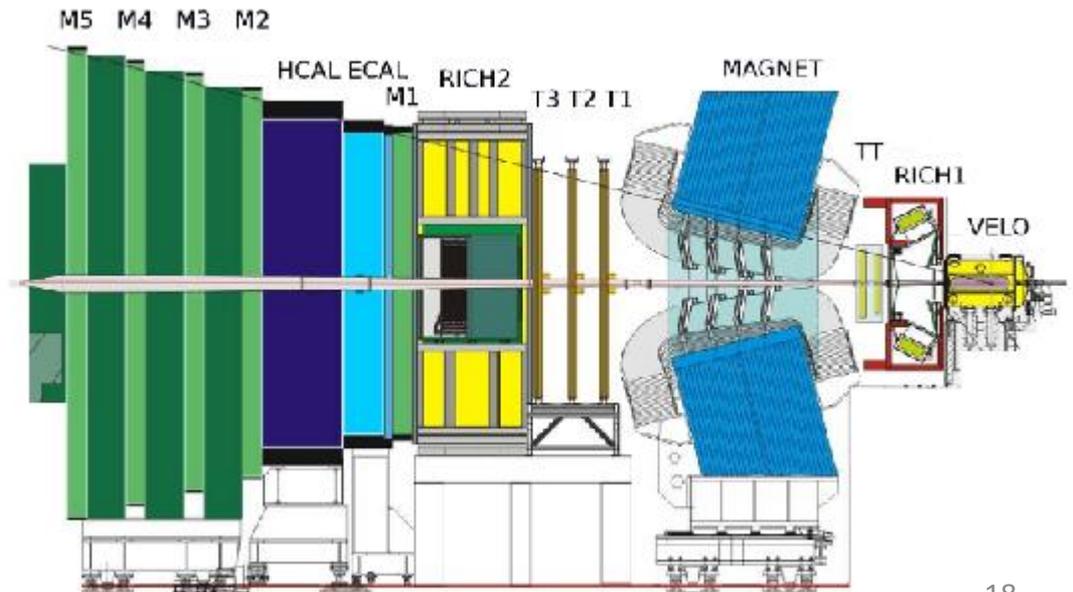
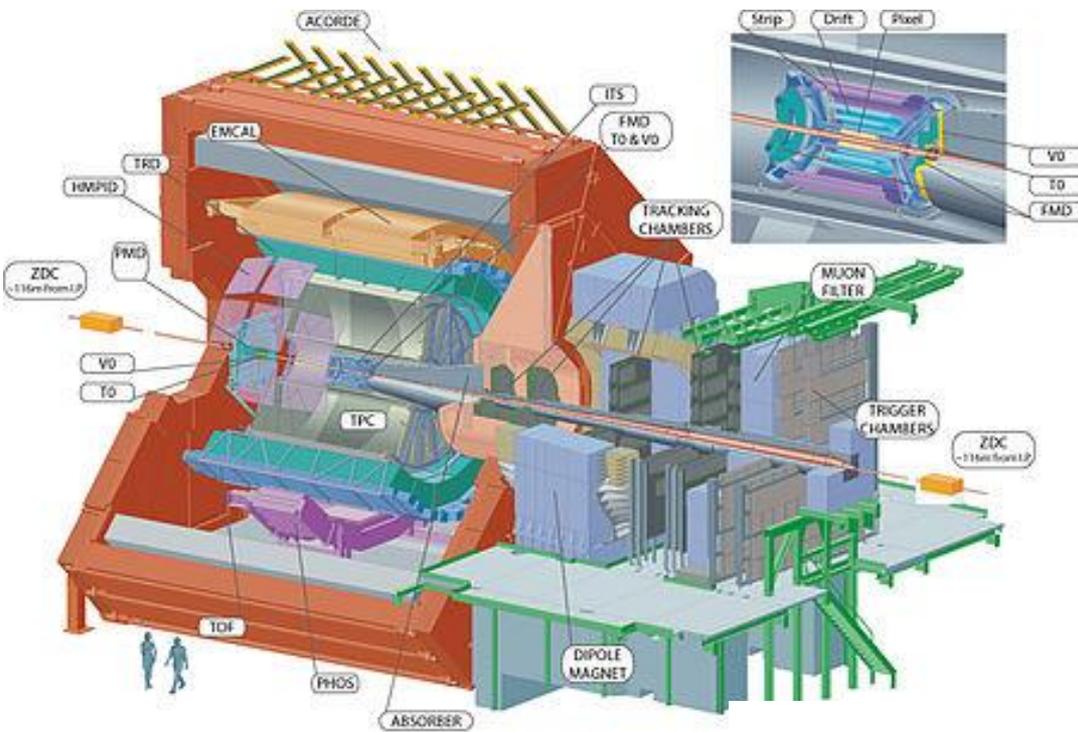
YE1-4

Pixel Tracker
ECAL
HCAL
 Muons
 Solenoid coil

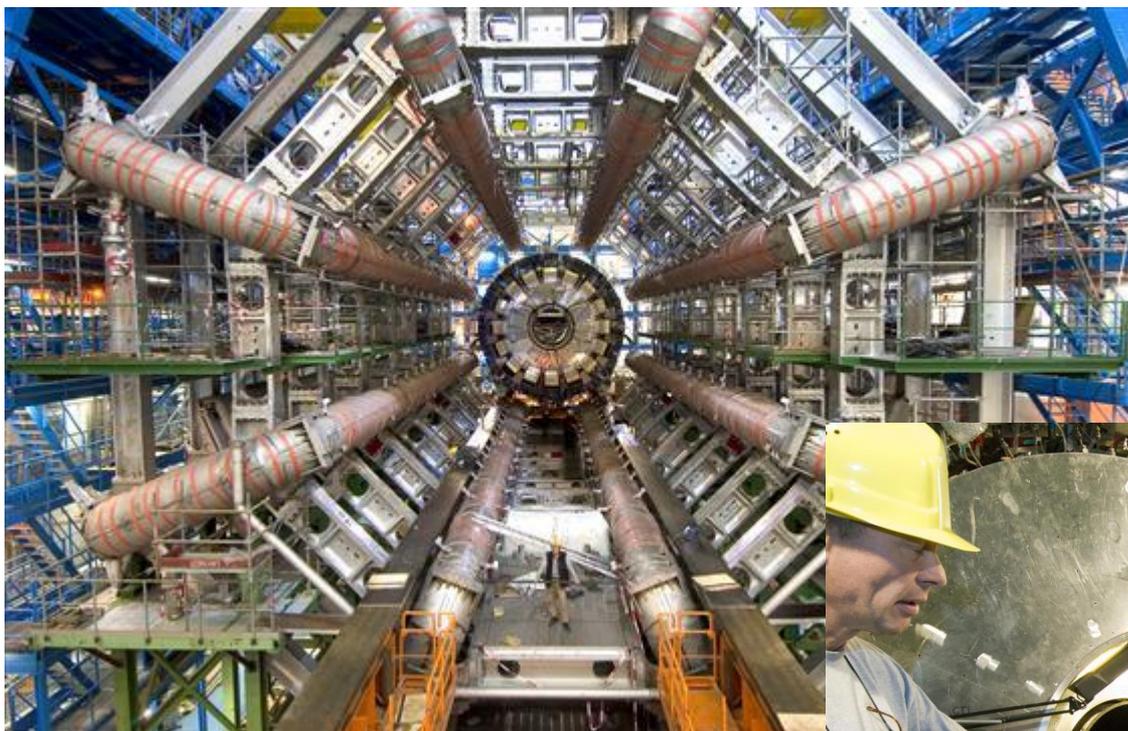
Pixels & Tracker
 • Pixels (100x150 μm²)
 ~ 1 m²
 66M channels
 • Silicon Microstrips
 ~210 m²
 9.6M channels

MUON BARREL
 Drift Tubes (DT) and Resistive Plate Chambers (RPC)

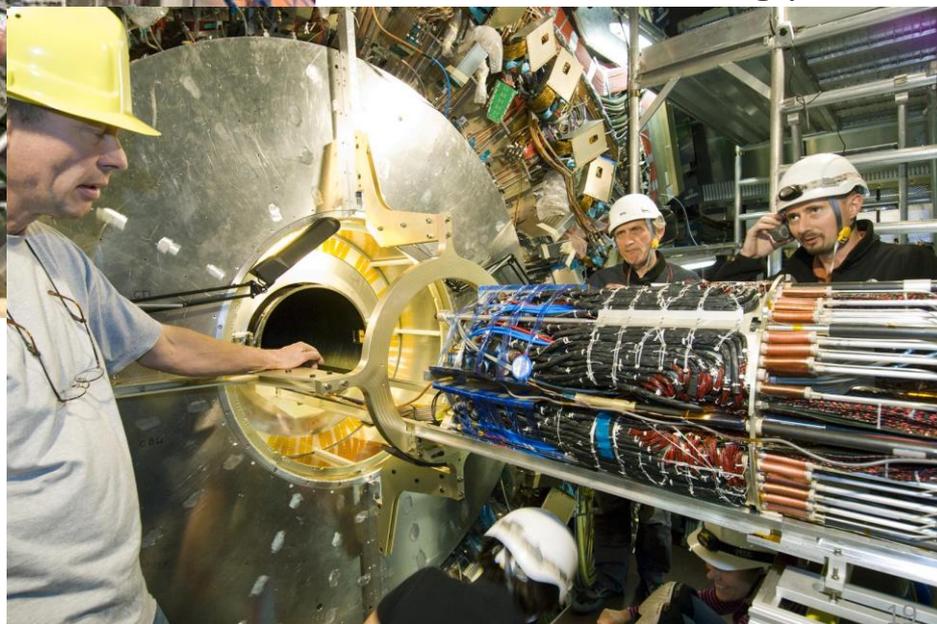
ALICE + LHCb



From the construction of ATLAS

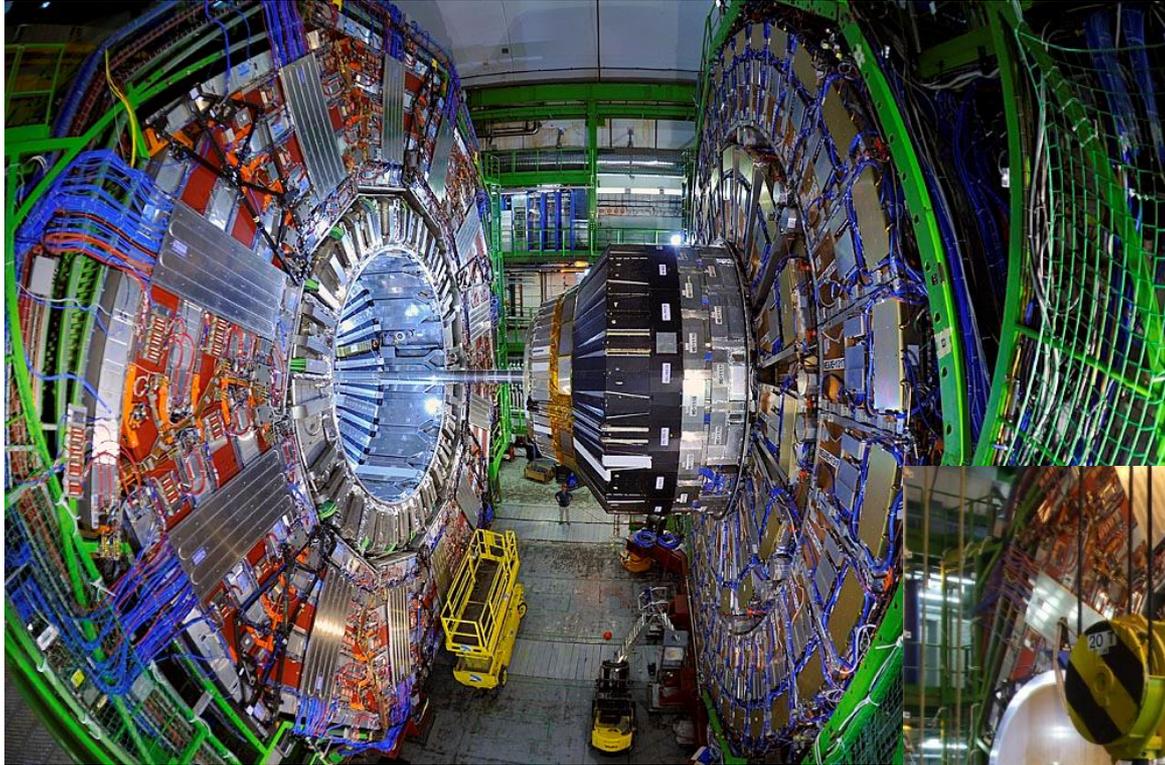


Installing ECAL



Installing pixels

From the installation of CMS

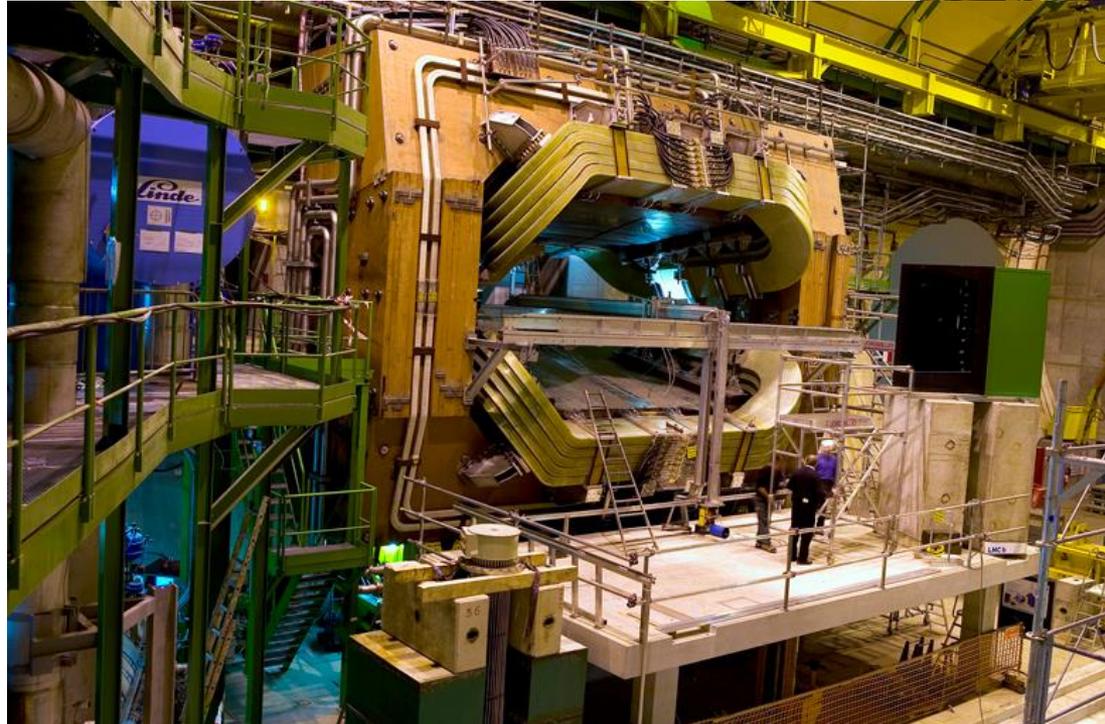


Installing pixels



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	<ul style="list-style-type: none"> • Silicon pixels + strips • TRT with particle identification • $B = 2$ T • $\sigma(p_T) \sim 3.8\%$ (at 100 GeV, $\eta = 0$) 	<ul style="list-style-type: none"> • Silicon pixels + strips • No dedicated particle identification • $B = 3.8$ T • $\sigma(p_T) \sim 1.5\%$ (at 100 GeV, $\eta = 0$)
MAGNETS	<ul style="list-style-type: none"> • 4 Magnets • Solenoid + Air-core muon toroids • Calorimeters outside solenoid field 	<ul style="list-style-type: none"> • 1 Magnet • Solenoid • Calorimeters inside field
EM CALORIMETER	<ul style="list-style-type: none"> • 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 	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • Fe / Scint. tiles (EC: Cu-liquid Ar) • $\sigma(E) \sim 45\% / \sqrt{E} \oplus 1.3\%$ (Barrel) 	<ul style="list-style-type: none"> • Cu (EC: brass) / Scint. tiles • Tail catchers outside solenoid • $\sigma(E) \sim 100\% / \sqrt{E} \oplus 8\%$ (Barrel)
MUON	<ul style="list-style-type: none"> • Drift tubes & CSC (fwd) + RPC/TGC • $\sigma(p_T) \sim 10.5\% / 10.4\%$ (1 TeV, $\eta = 0$) (standalone / combined with tracker) 	<ul style="list-style-type: none"> • 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)

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

- $f_{\text{rev}} = 11245.5$ Hz is the bunch revolution frequency
 - $n_{\text{bunch}} = 1 \dots 2808$ 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
 - $\sigma_{x/y} = 16 \dots 50 \mu\text{m}$ 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**

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

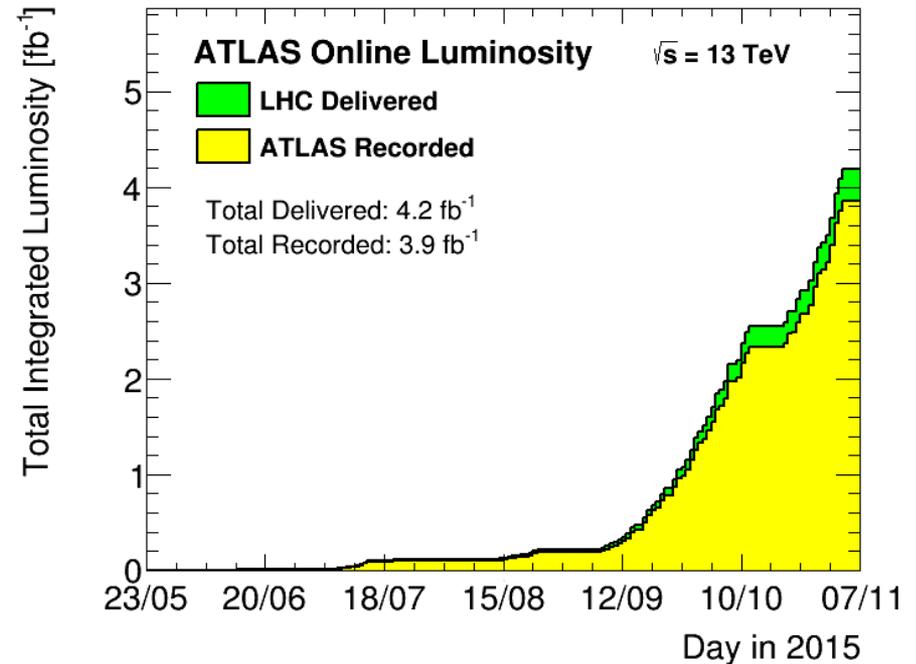
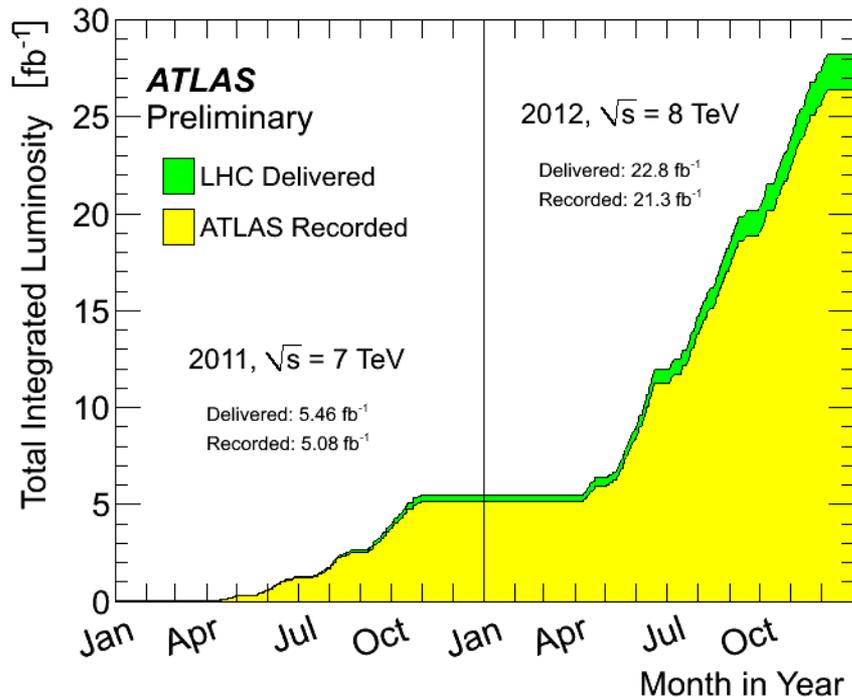
“Cross section” given by Nature

“Efficiency” of detection
optimised by experimentalist

Recorded Luminosity

Measured with forward detectors, calibrated with beam separation scans

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

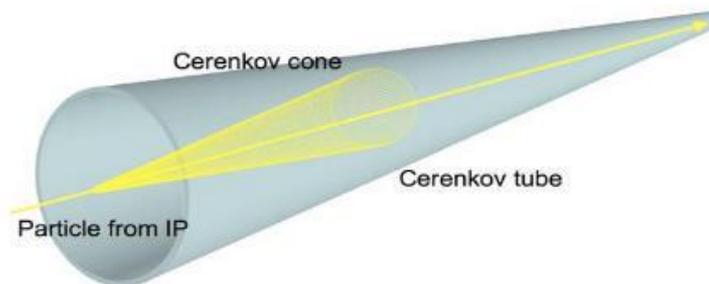


$10^{32} \text{ cm}^{-2}\text{s}^{-1}$ instantaneous luminosity corresponds to an *integrated* luminosity of 0.1 nb^{-1} per second
 $\Rightarrow 180 \text{ pb}^{-1}$ per month (assuming 70% LHC efficiency for physics)

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° 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):

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

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

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

filled BX (pointing to 2808)

total BX (pointing to 3564)

ϵ_{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:

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

Cross Section

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

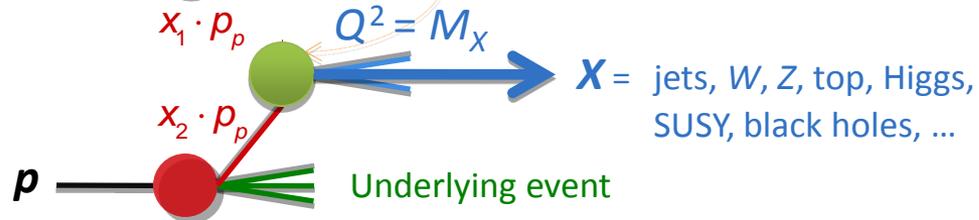
$$\sigma_{pp \rightarrow X} = \sum_{\text{partons}} \text{PDF} \otimes \sigma_{\text{hard scatter}} = \sum_{a,b} \int_0^1 dx_1 dx_2 \cdot f_a(x_1, Q^2) \cdot f_b(x_2, Q^2) \cdot \hat{\sigma}_{ab \rightarrow X}(x_1, x_2, \alpha_{(S)}, Q^2)$$

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

Parton distribution functions
Representing structure of proton



Hard scatter parton cross section
Higher order pQCD correction;
accompanying radiation, jets, ...



- Large α_s requires (complicated) higher order calculations

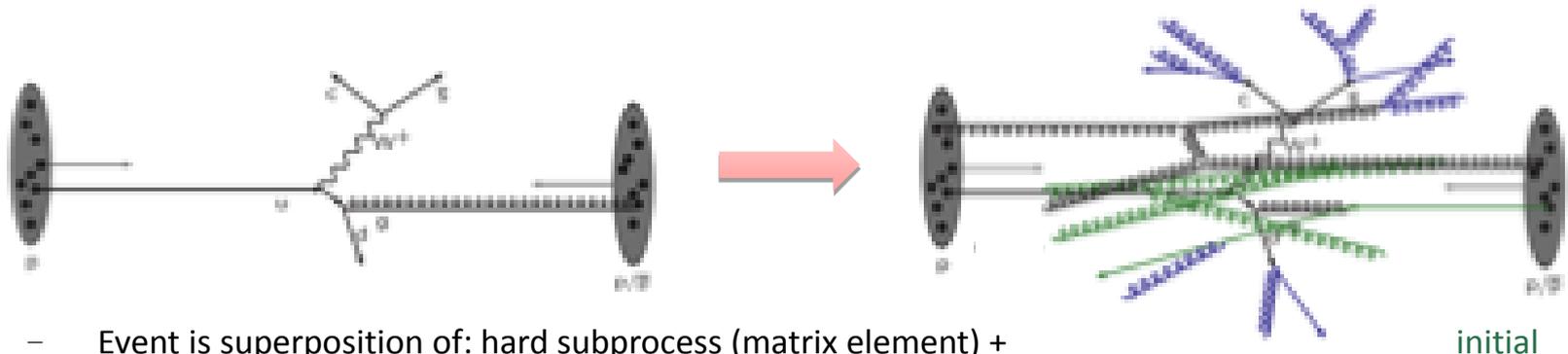
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$$\sigma_{pp \rightarrow X} = \sum_{\text{partons}} \text{PDF} \otimes \sigma_{\text{hard scatter}} = \sum_{a,b} \int_0^1 dx_1 dx_2 \cdot f_a(x_1, Q^2) \cdot f_b(x_2, Q^2) \cdot \hat{\sigma}_{ab \rightarrow X}(x_1, x_2, \alpha_{(S)}, Q^2)$$

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

- Proton–proton events complicated mixture of scattering phenomena



- Event is superposition of: hard subprocess (matrix element) + 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) $\Rightarrow \langle x \rangle = 0.007$ (0.07)

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

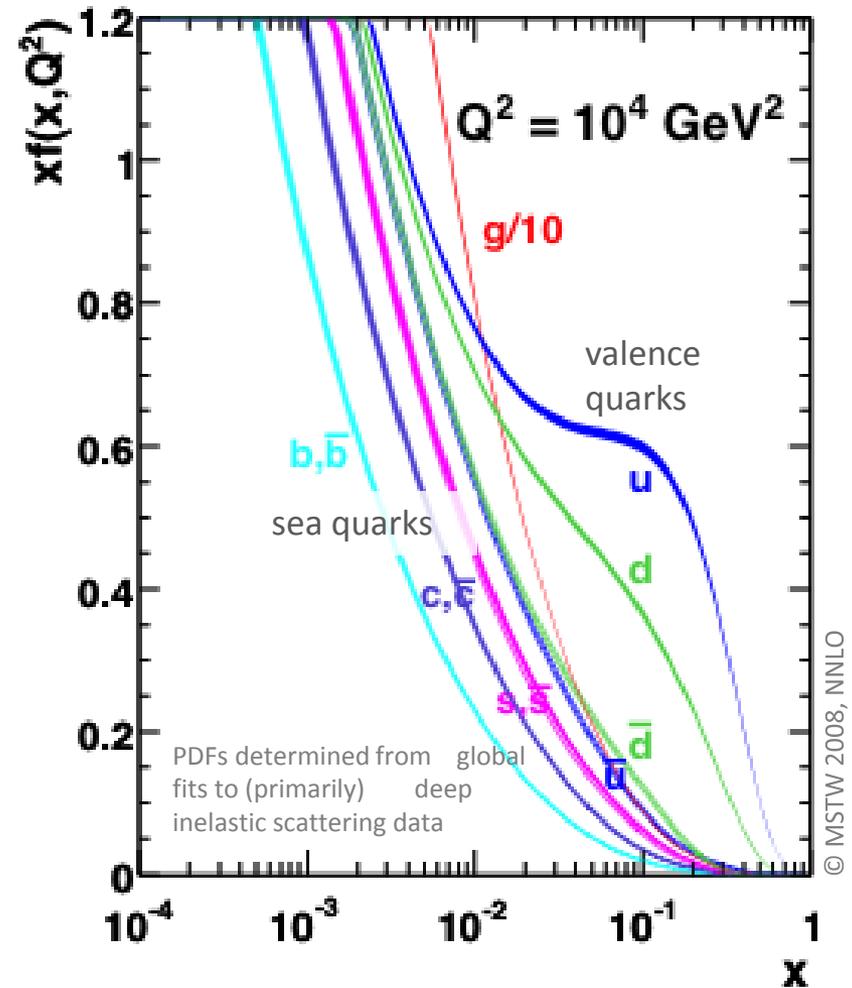
- $M_X = 100$ GeV (1 TeV) $\Rightarrow \langle x \rangle = 0.05$ (0.5)

- PDFs rise dramatically towards low x

\Rightarrow larger cross sections at LHC

\Rightarrow gluon dominated

The LHC is a gluon collider!



Kinematic Constraints and Variables

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

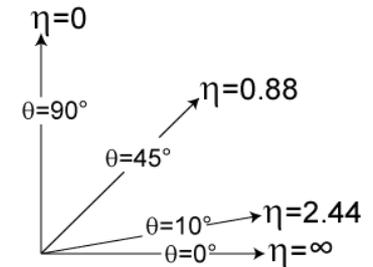
- Particles escaping detection have low p_T
- Visible transverse momentum conserved: $\sum p_{T,i} \approx 0$ **useful variable !**
- Large $E_{T,miss}$ indicates invisible particle (ie, neutrino) escaped detector

- Longitudinal momentum and visible energy: p_z, E

- 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

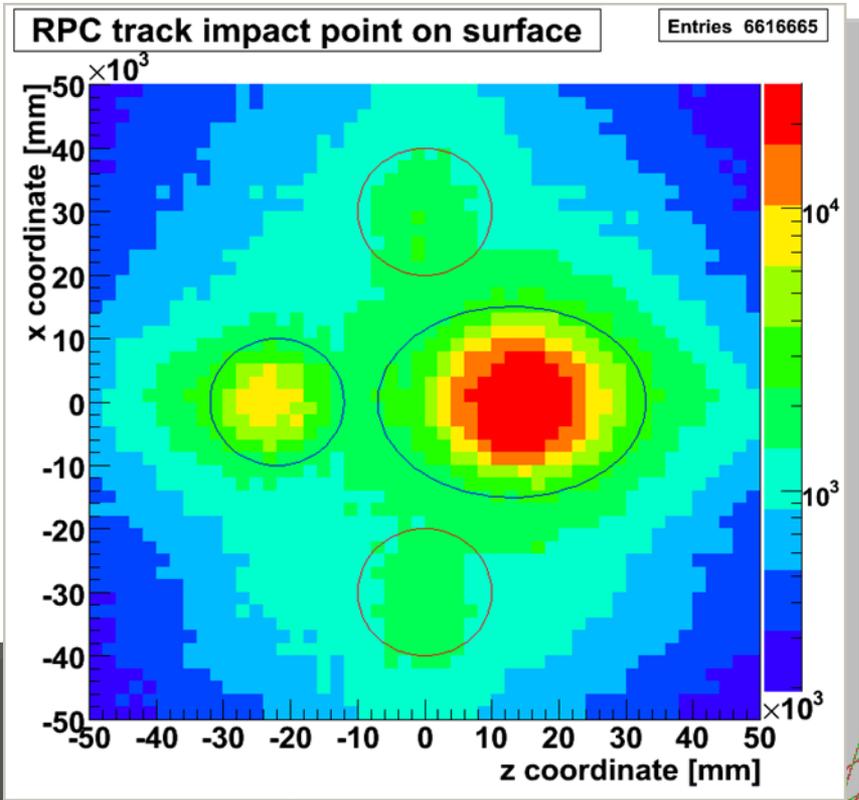
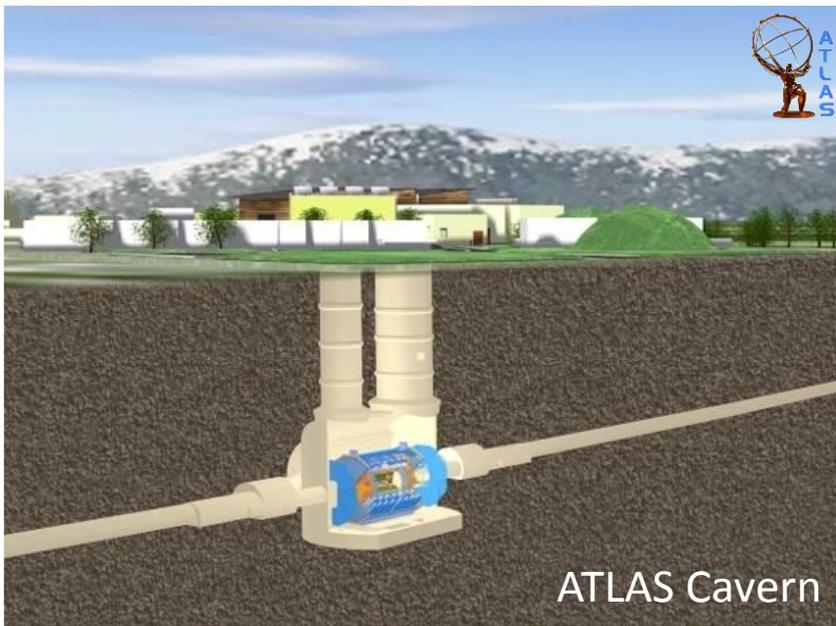
$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right) = \frac{1}{2} \ln \left(\frac{x_1}{x_2} \right) \Rightarrow x_1 = x_2 \cdot e^{2y}, \quad \eta = \frac{1}{2} \ln \left(\frac{|\vec{p}| + p_z}{|\vec{p}| - p_z} \right) = -\ln \left(\tan \frac{\theta}{2} \right) \quad \text{for } M=0$$

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

Starting up an experiment

Data taking: ATLAS control room



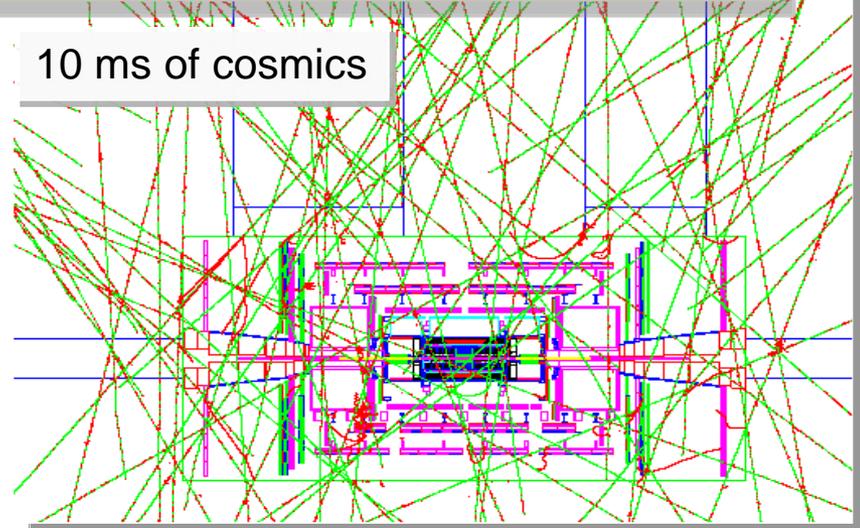


Muon flux at surface:
 $\sim 130 \text{ Hz / m}^2$ for $E_\mu > 1 \text{ GeV}$
 average energy $\sim 4 \text{ GeV}$

Muon flux in ATLAS detector (simulation):
 $\sim 4 \text{ kHz}$ in muon fiducial volume
 $\sim 15 \text{ Hz}$ in TRT barrel

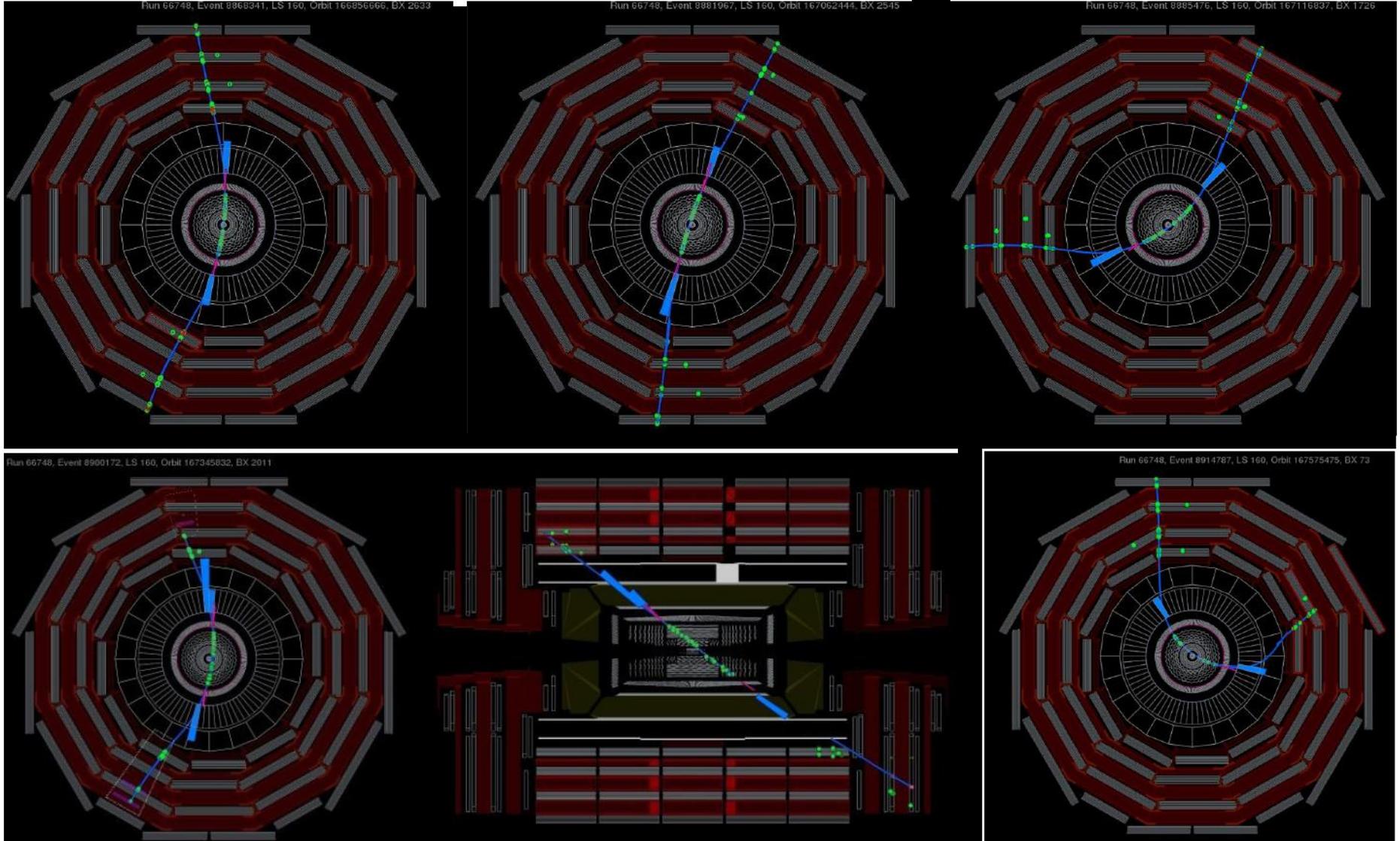
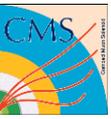
Charge ratio: $\mu^+ / \mu^- \sim 1.27$

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



Simulated cosmic flux in ATLAS cavern: integration over 10 msec

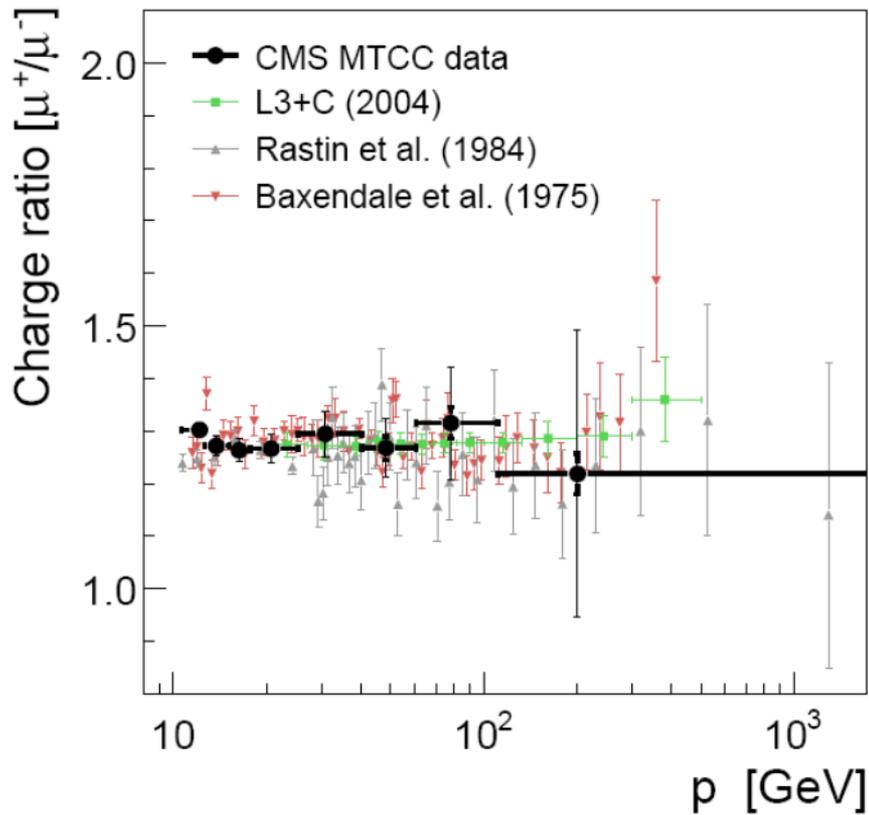
More Cosmic Muons in CMS (both charges!) ...



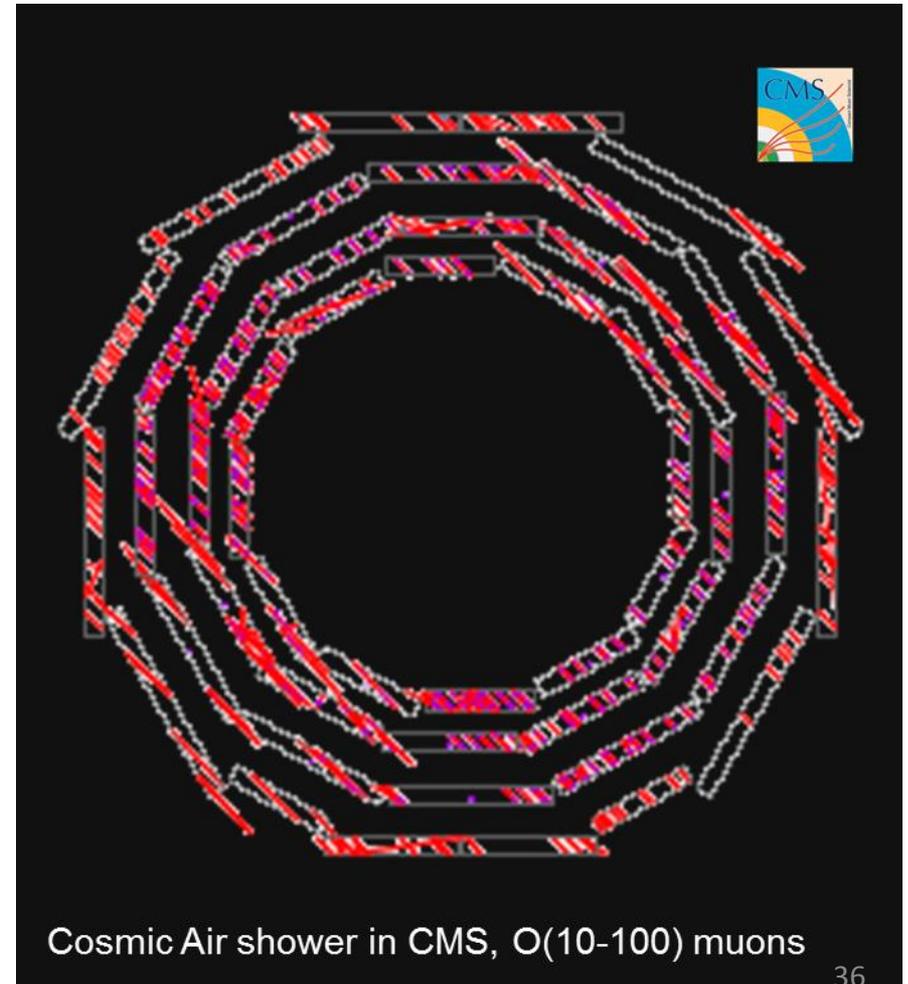
Through barrel and endcap muon detectors

Studying cosmic rays

Charge ratio



Showers of muons

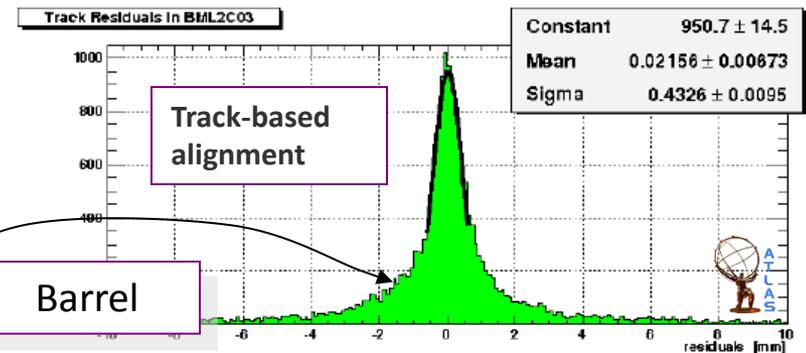
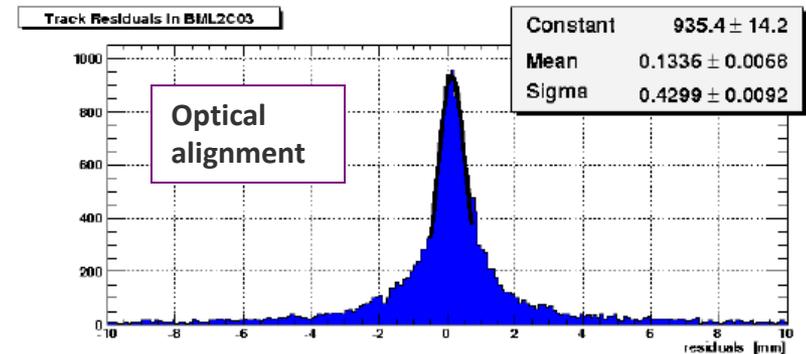
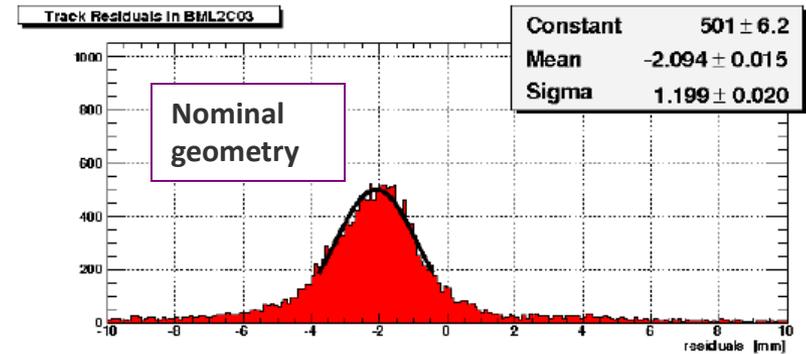
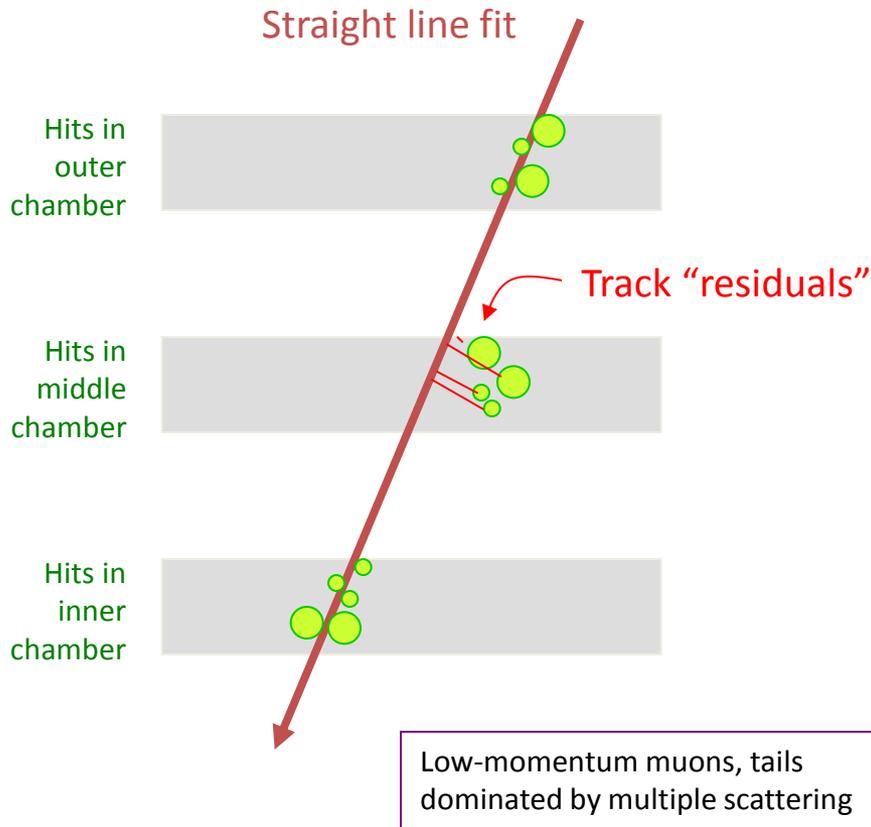


Alignment of detectors

(Another perfect use of cosmic rays)

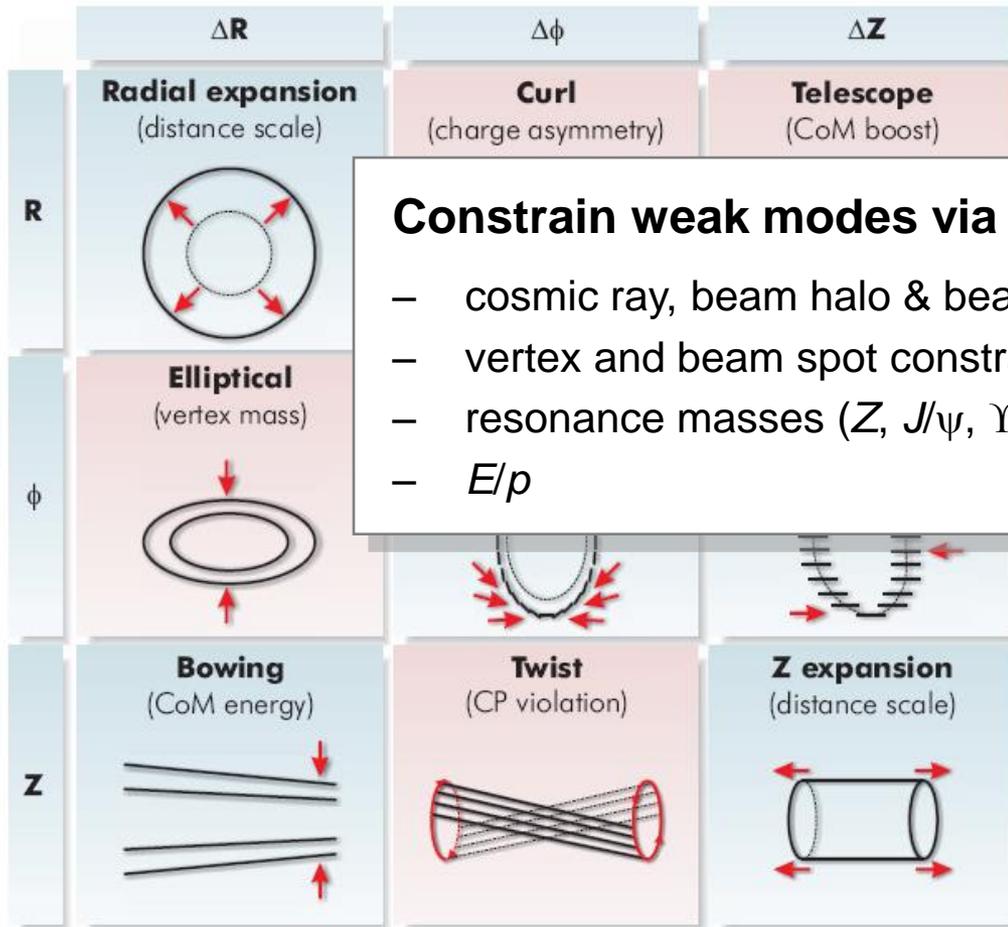
Muon Alignment Also Uses (Straight) Tracks

- Compare residuals for straight cosmic tracks



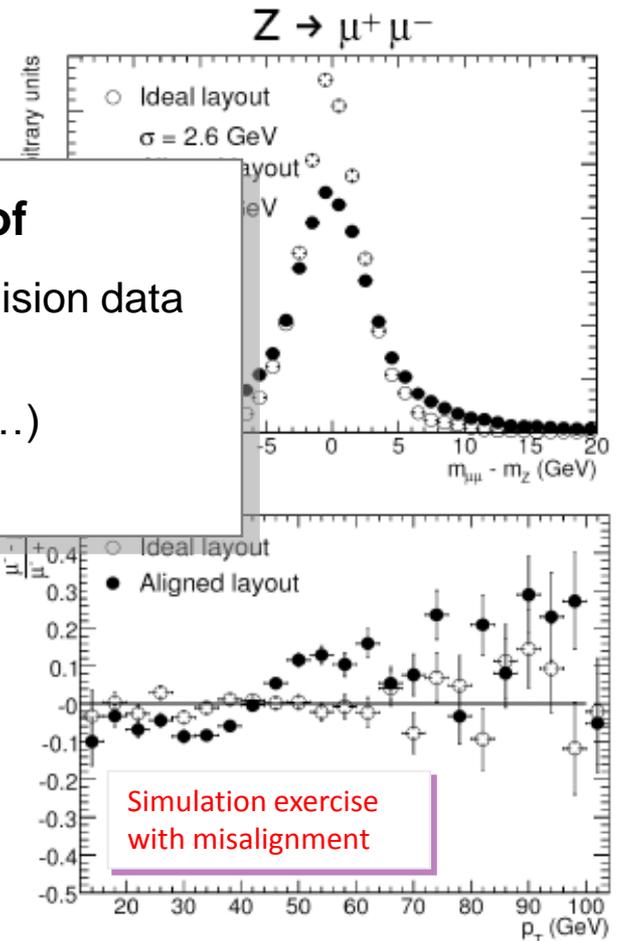
“Weak Modes”

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



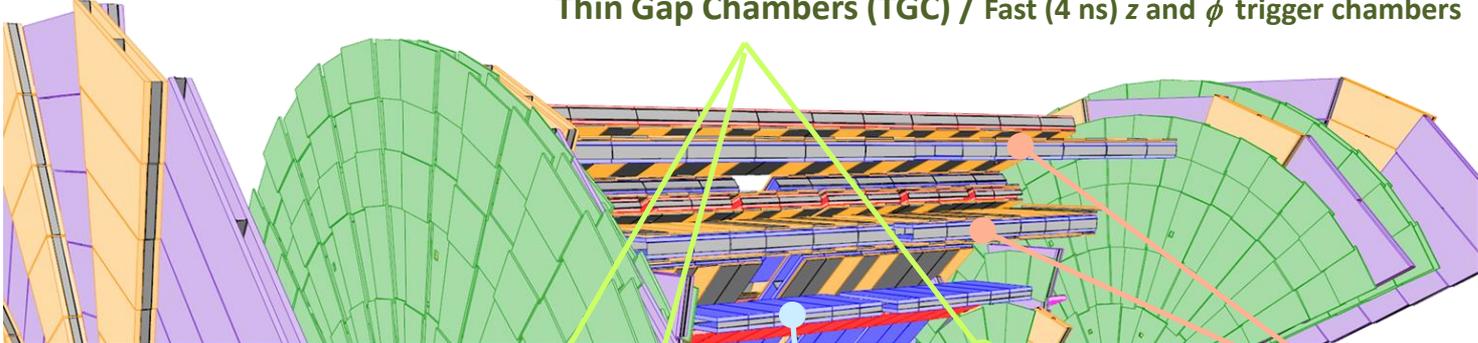
Constrain weak modes via use of

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



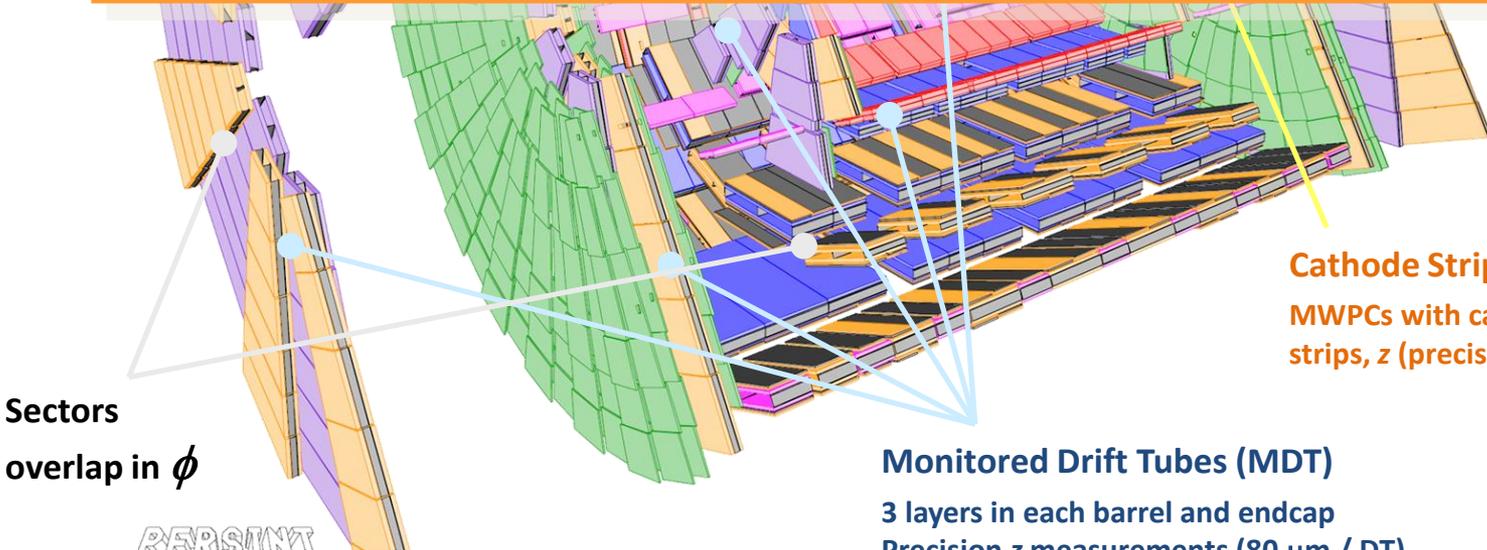
ATLAS Muon System – Active Material

Thin Gap Chambers (TGC) / Fast (4 ns) z and ϕ trigger chambers



Huge volumes – to be aligned at 35 μm !?

te
(PC)
d ϕ
ers



Cathode Strip Chambers (CSC)
MWPCs with cathodes segmented in strips, z (precise) and ϕ info

Sectors
overlap in ϕ

REPRESENT

Monitored Drift Tubes (MDT)
3 layers in each barrel and endcap
Precision z measurements (80 μm / DT)