THE UNIVERSITY OF WARWICK

LHC Run 2 Prospects: Experimental Overview YETI 2016

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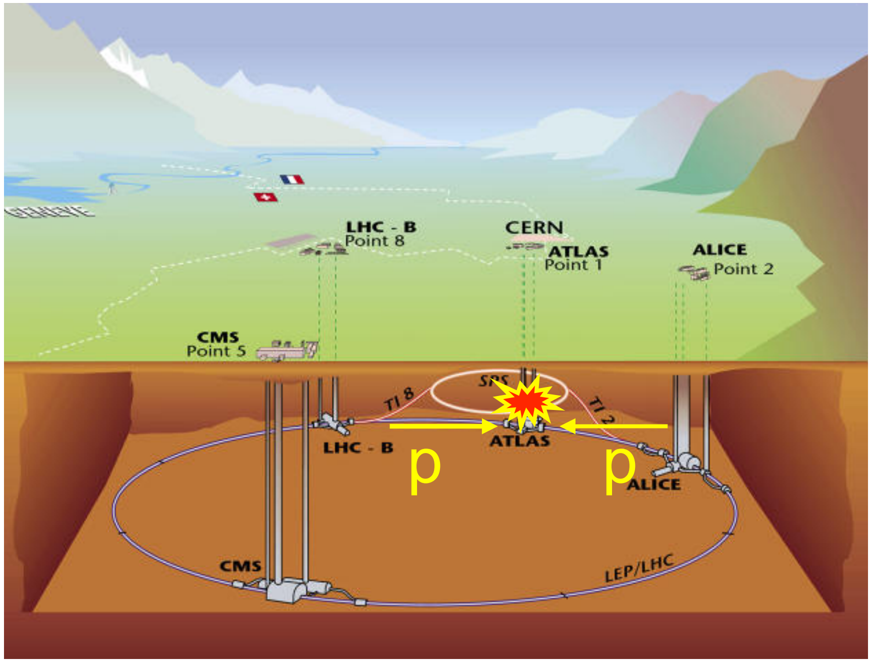
12th January 2016

Outline

- **What I will cover:**
  - Recap the goals of the LHC
  - Look at how the LHC experiments are designed
  - Summarise what was achieved in Run 1
  - Describe the upgrades done in the shutdown between Run 1 & 2
  - Summarise some of the Physics prospects for Run 2
  - Look at some early hints from Run 2

- **What I will not cover:**
  - Details of any given Physics topic
    - In the next days you will have 2 hours dedicated to individual topics, with a detailed look at the theory and experiment behind each topic
    - This talk is an overview of many topics so touches on them briefly
- **Final caveat:**
  - I'm on ATLAS so may use it to describe things more often than CMS simply because I'm more familiar with it – there is no intended bias

The Large Hadron Collider

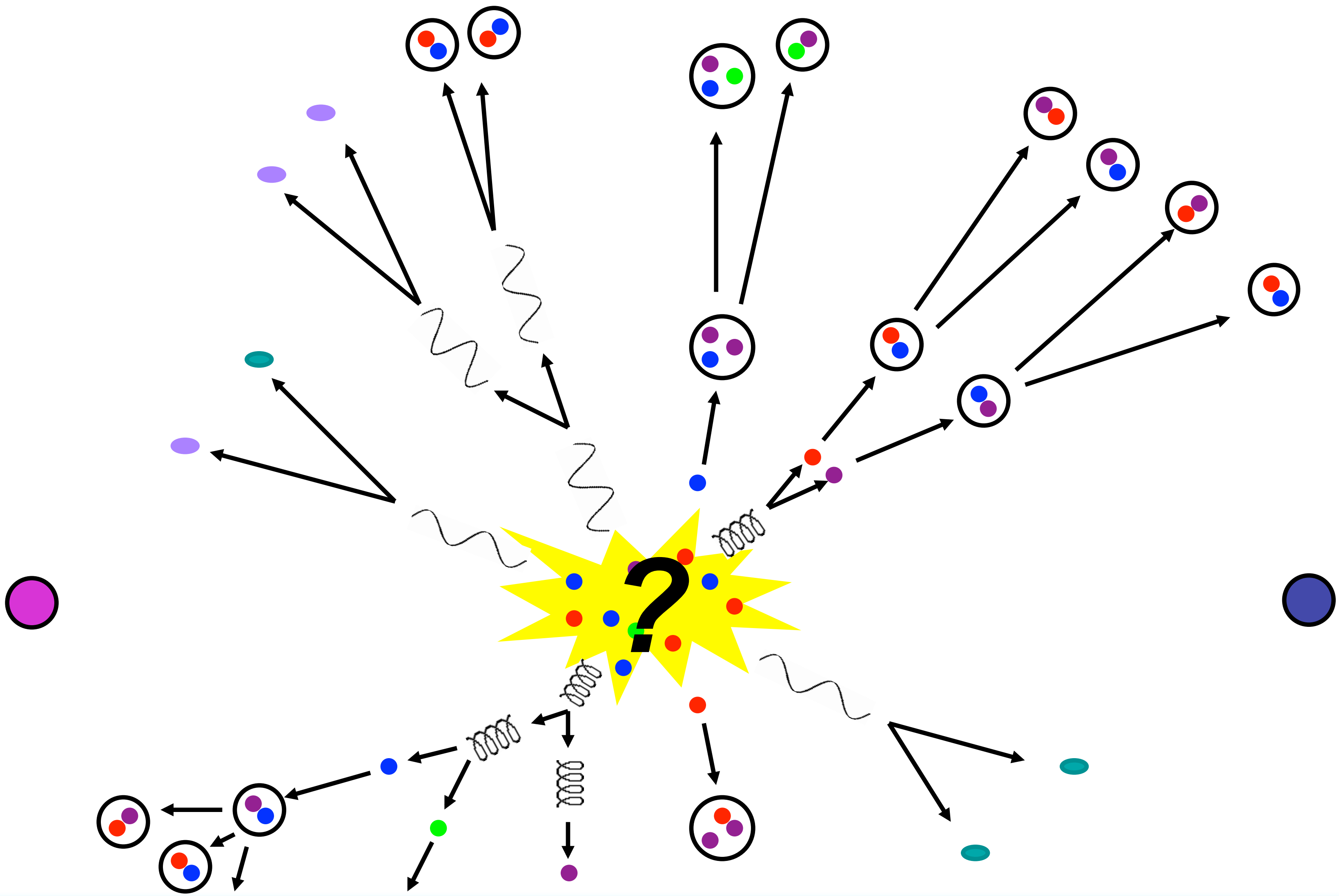


- Collisions of proton bunches travelling at high energy
- Superconducting dipole magnetic field 8.3 Tesla
- 2808 bunches, 10^{11} particles in each
    - 99.9999991% x speed of light, 11000 revolutions per second
    - Interactions between beams every 25 nanoseconds

Particle Collisions

Two particles collide at very high energy

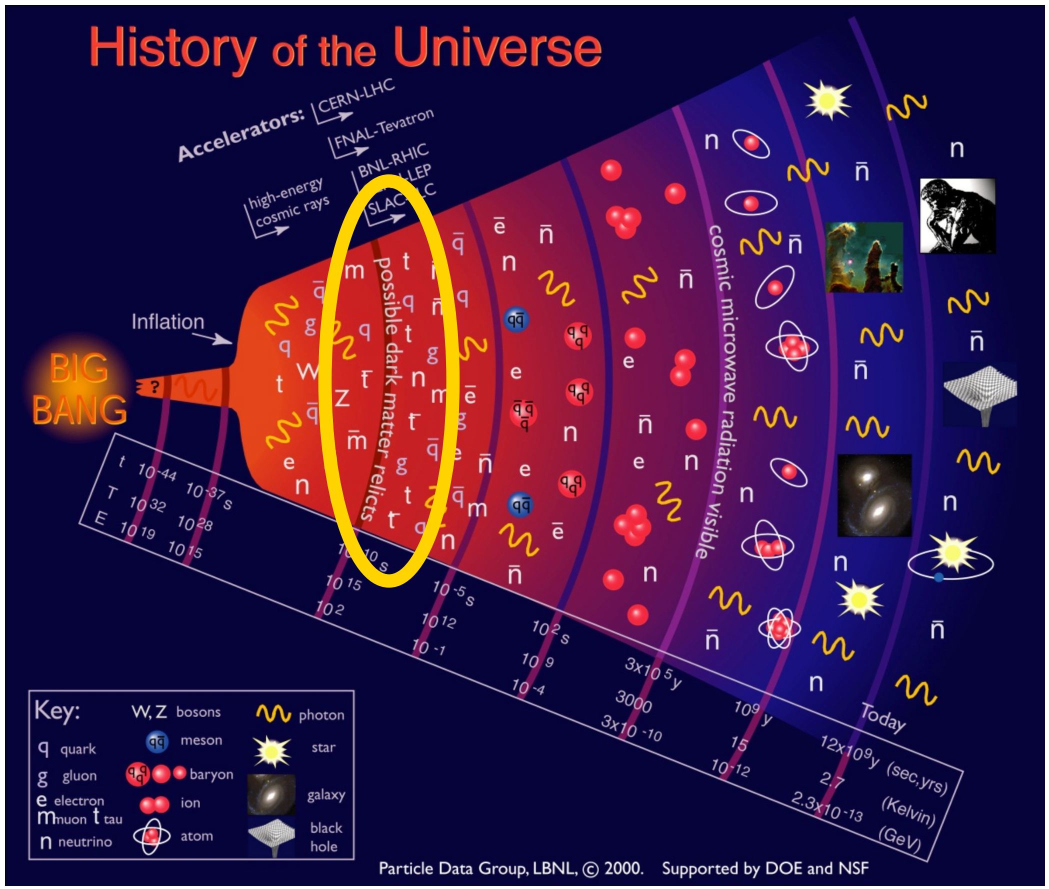
New particles are produced which we detect and study



Why?

Understanding the Universe

Big Bang

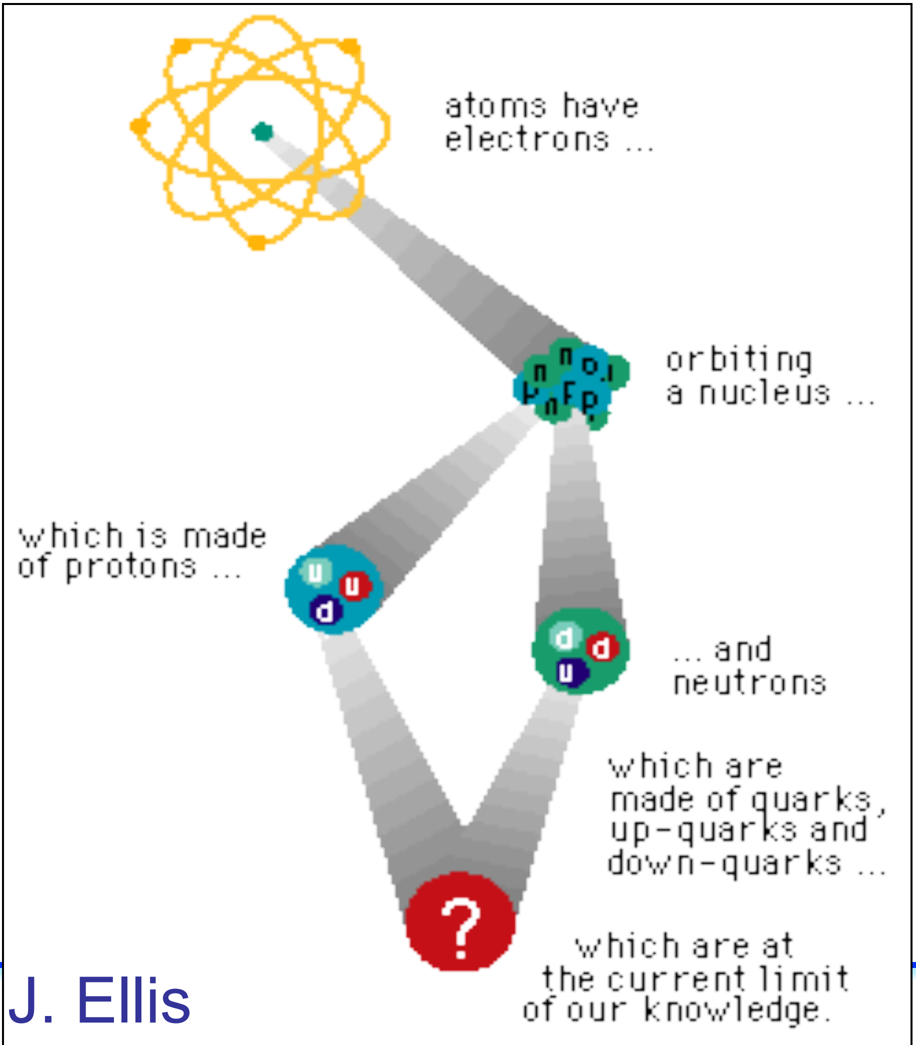


now

Older ….. larger … colder ….less energetic

How do we do it?

- **To probe the conditions of the early universe we smash particles together**



The Energy Frontier

- Size of structure we can probe with a collider like LHC

$$= h / p \qquad \text{(de Broglie, 1924)}$$

h = Planck's constant = 6.63×10^{-34} Js

p = momentum of protons

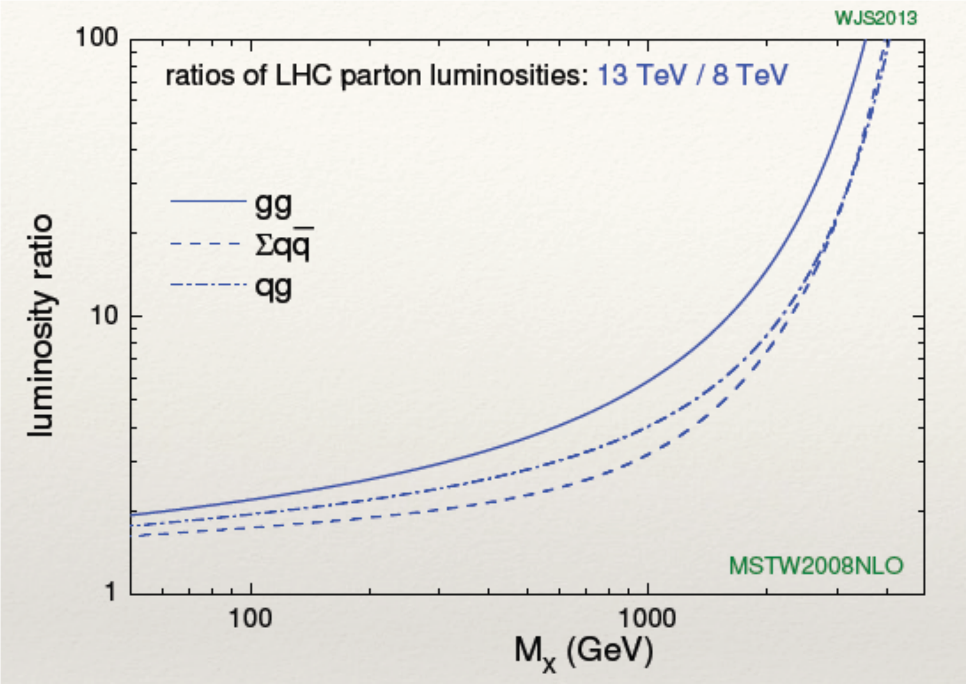
- The larger the momentum (energy), the smaller the size probed

- AND $E=mc^2$

Run 1 to Run 2 Energy Increase

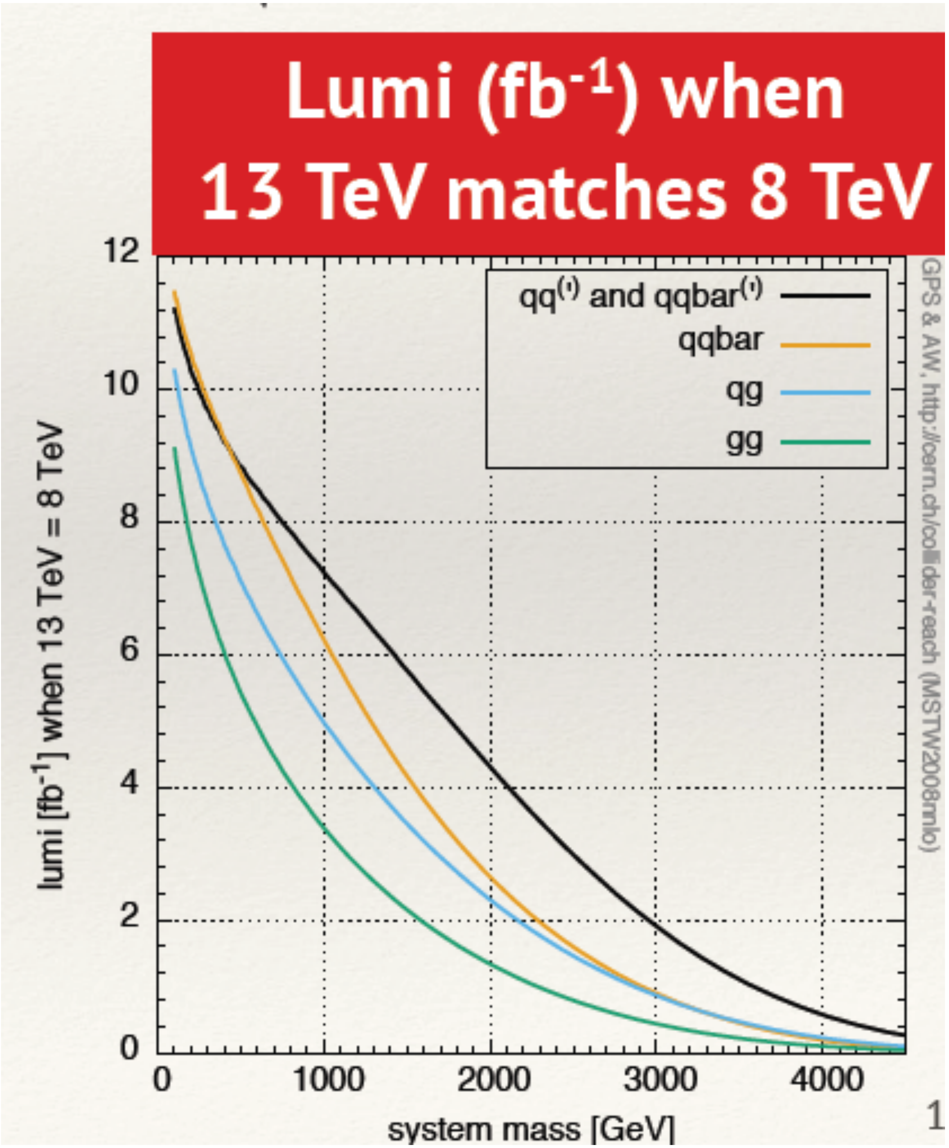
- Linear relation between energy of collision and mass of particles that can be produced

- But the extra luminosity is not shared equally among parton-pair interactions, so the reach depends on production mechanism



Integrated lumi comparison

- (From G. Salam talk)



Goals of the LHC

- **Understanding the generation of mass**

- **Understanding origin of CP violation**
  - In quantities large enough to explain CP asymmetry of universe

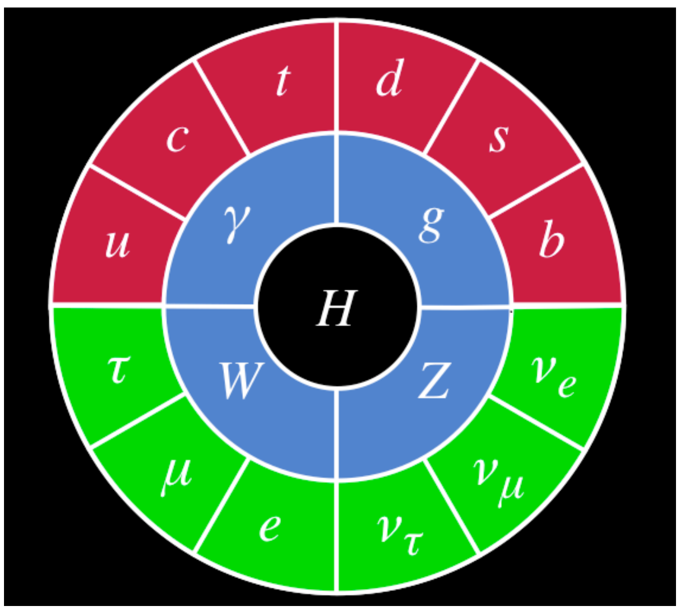
- **Searching for new phenomena to rule in or out new theories**

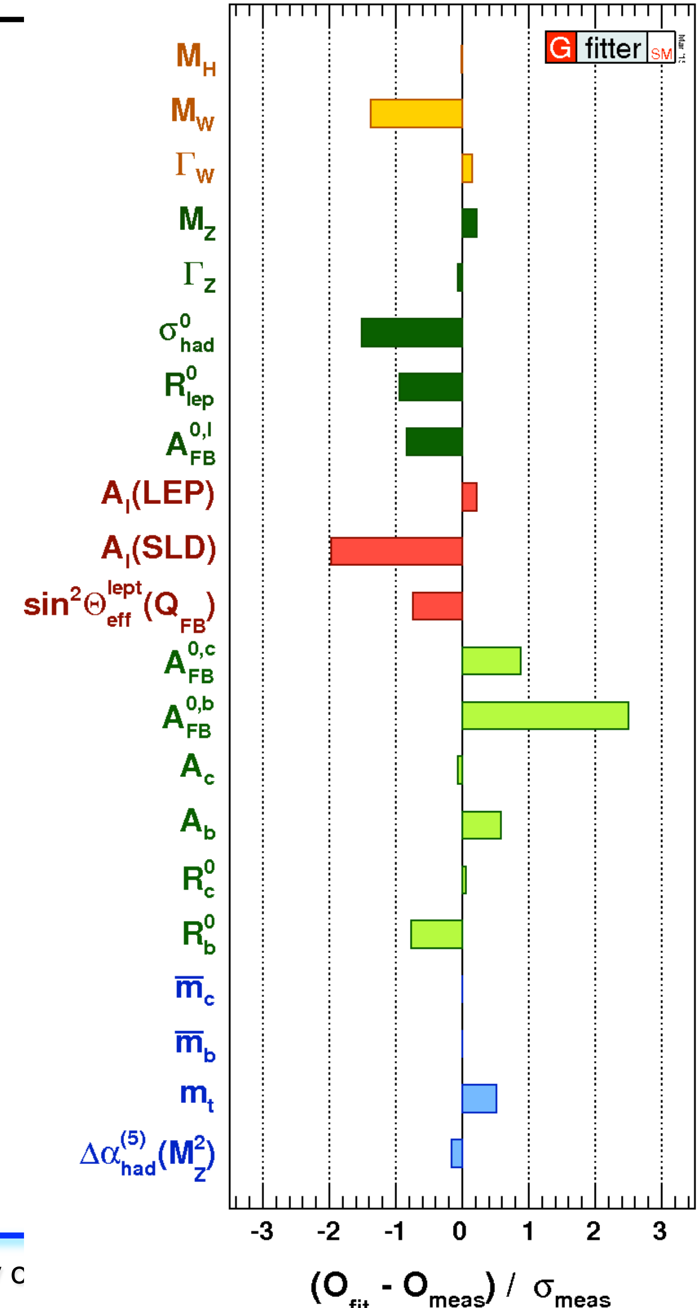
- **Searching for whatever is out there**

- **Joining up our understanding of the very large (galaxies) with the very small: what is dark matter?**

Probe the Standard Model and look for processes beyond it

- Strong, weak and Electromagnetic forces
- Describes interaction of matter particles by the means of force carrier particles





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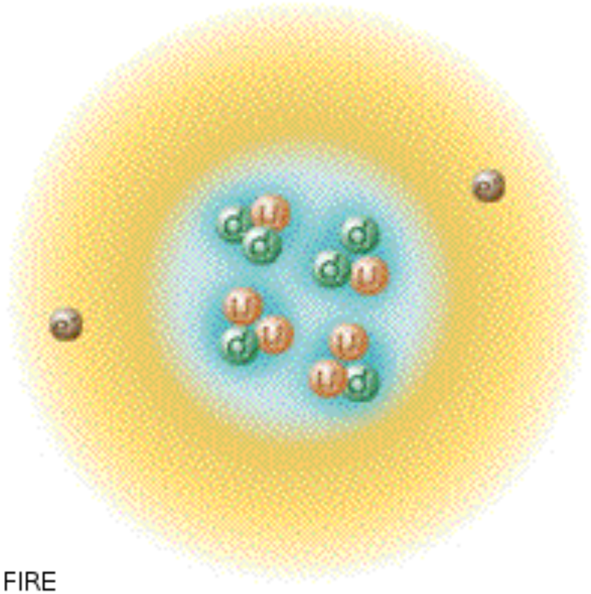
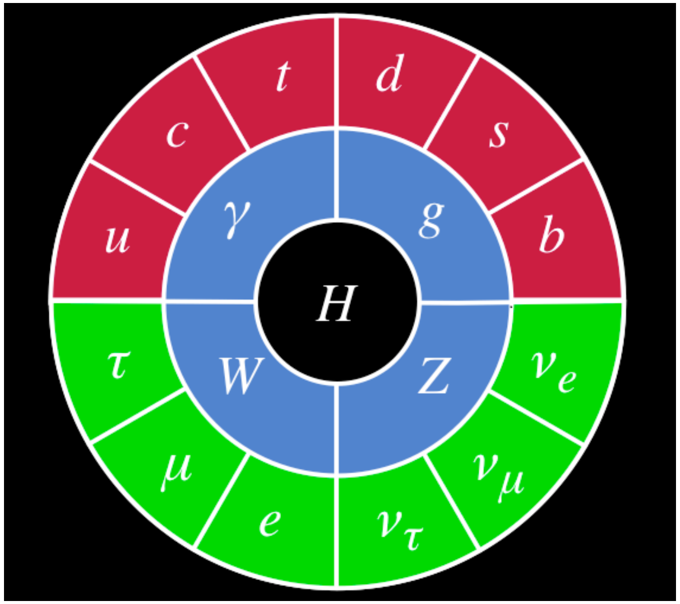
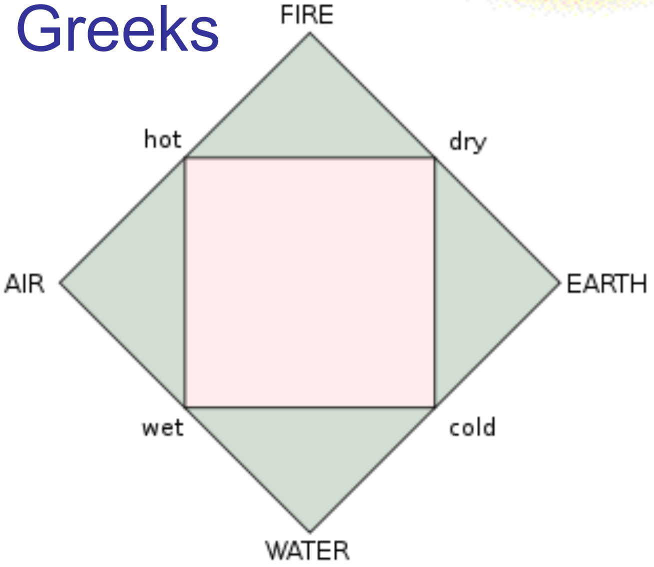




Greeks

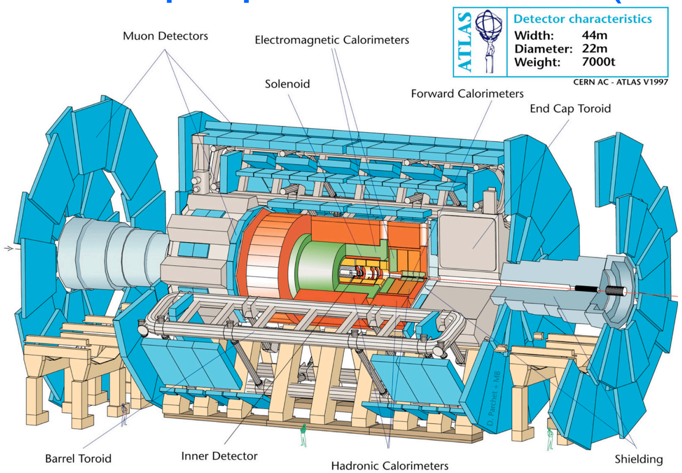


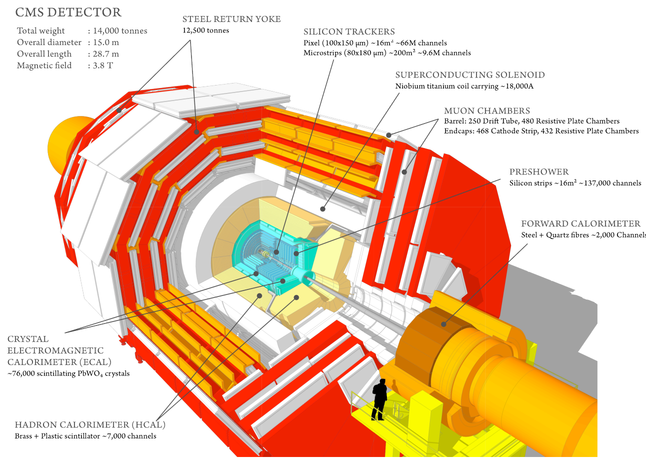
Goals of the LHC

- How do we, as experimentalists, go about achieving those goals?
- How far did we get in Run 1?

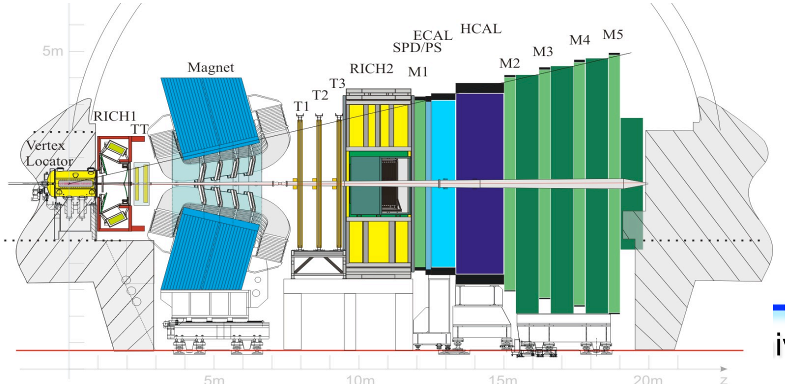
LHC Experiments

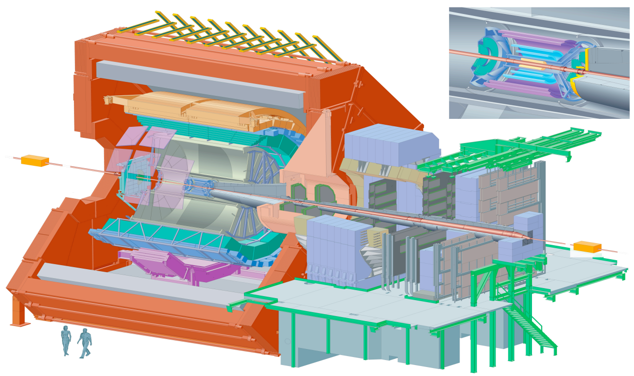
- **To achieve LHC goals, there are two approaches, built using the same detector principles**
  - General purpose detectors (ATLAS and CMS)





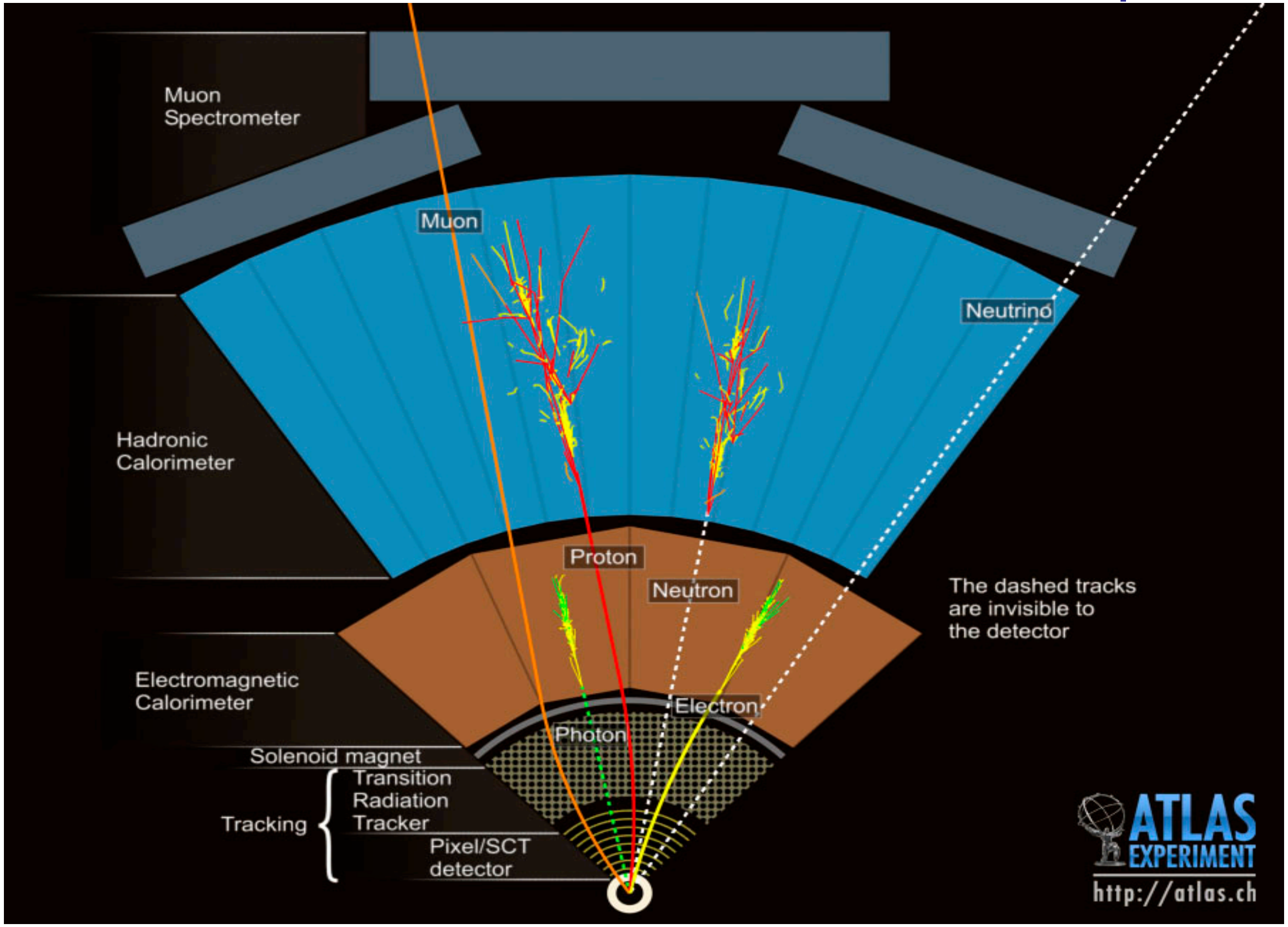
  - Dedicated experiments for flavour physics (LHCb) and Heavy Ion (ALICE) – I will not cover ALICE detector or Physics





ATLAS Detector

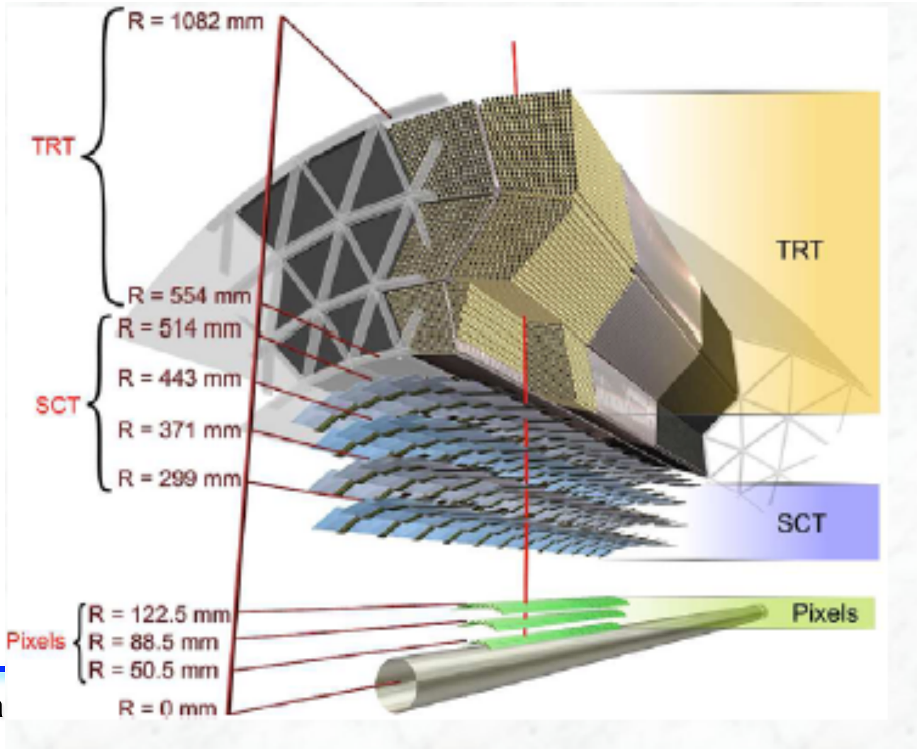
"Onion shell" structure enables reconstruction of particles



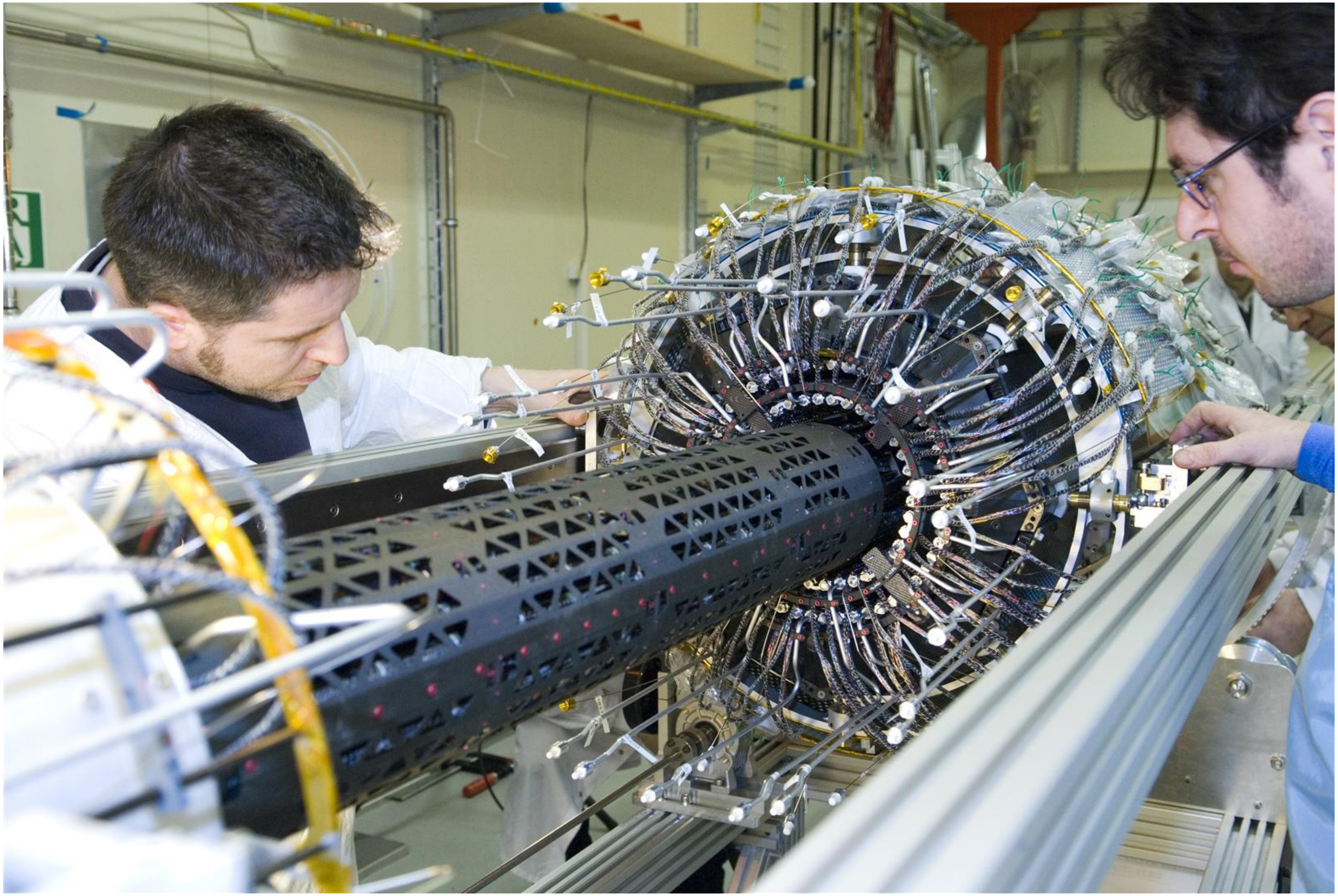
Use this capability to reconstruct particle interactions of special interest

ATLAS Tracker

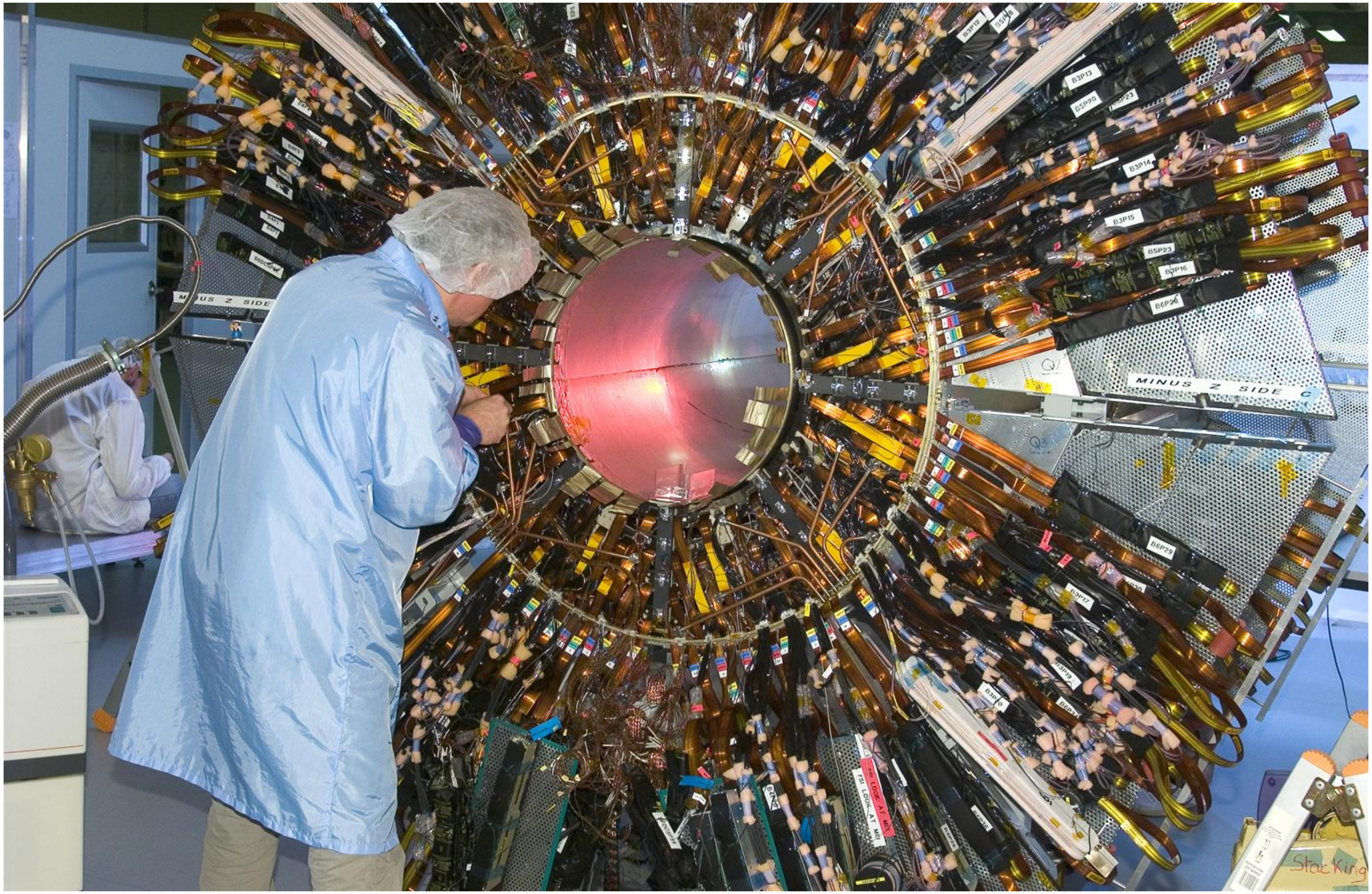
- **Silicon strips and pixels (~62m^2 of silicon)**
  - In 2 Tesla field
  - High granularity and resolution for charged particle trajectories
- **Transition Radiation Tracker**
  - Continuous tracking of charged particles – Xe-filled tubes
  - Less material
    than silicon tracking



The ATLAS experiment

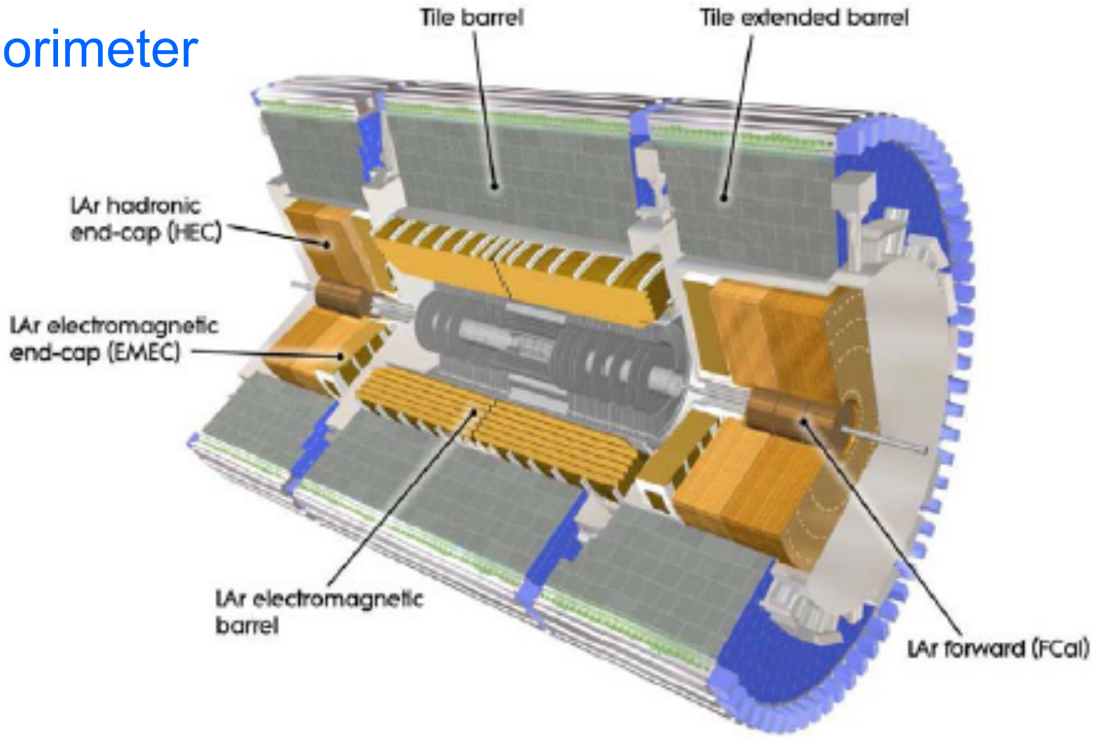


The ATLAS experiment



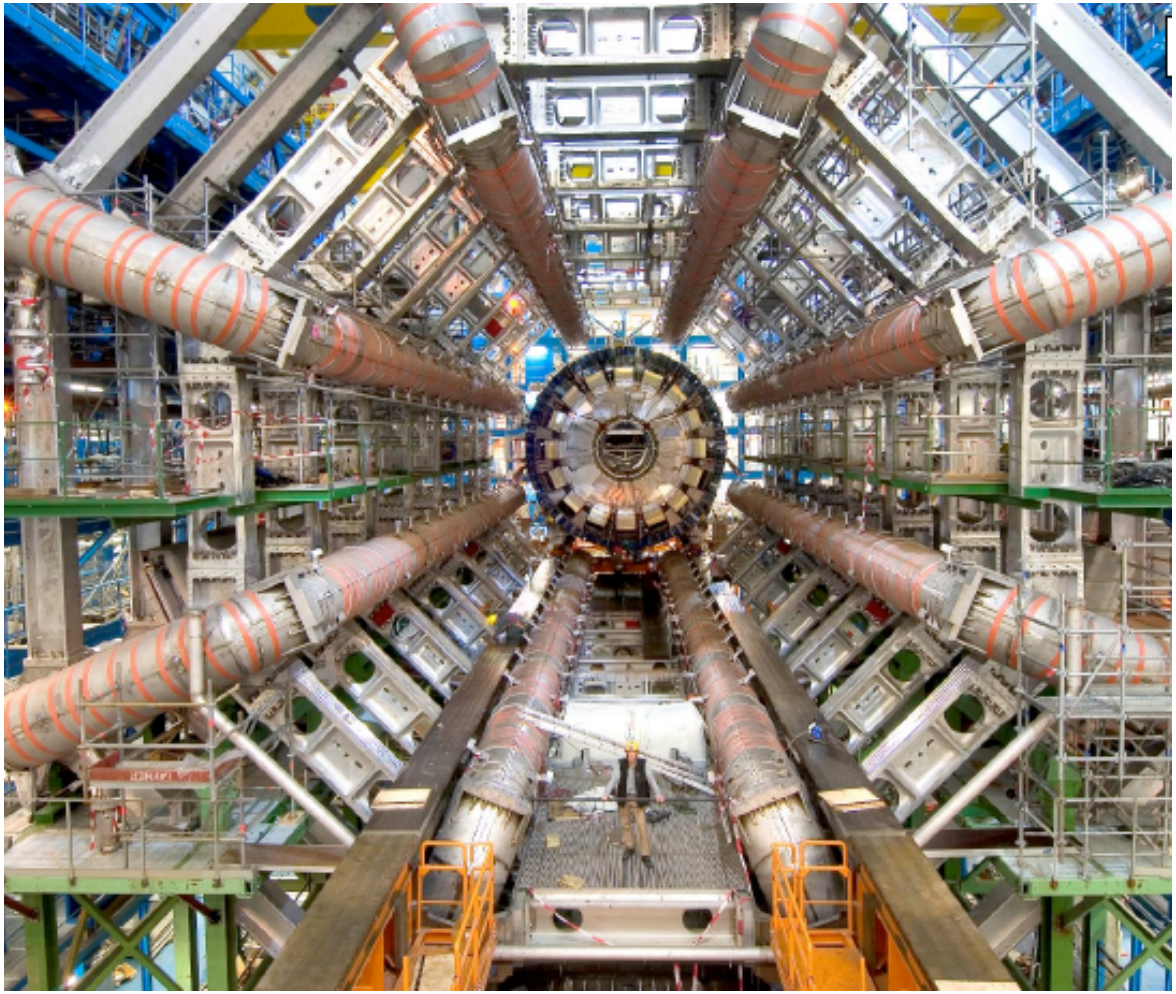
ATLAS Calorimeters

- **Liquid Argon calorimeter**
  - Barrel Electromagnetic calorimeter and end-cap of Hadronic calorimeter
  - Fast response time, fine “granularity”
- **Tile**
  - Barrel of Hadronic Calorimeter
- **Outside B-field**



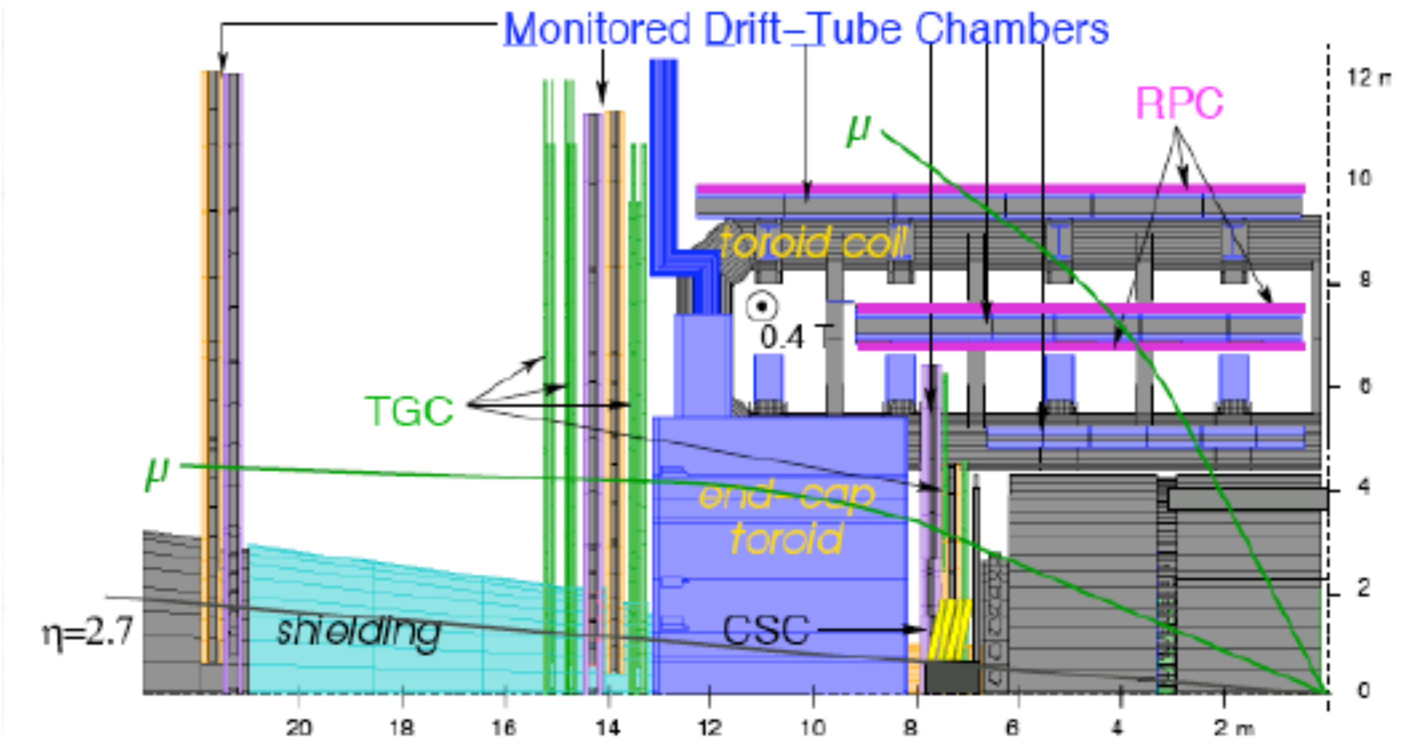
ATLAS Muon Chambers

- **ATLAS=A ToroidaL ApparatuS**

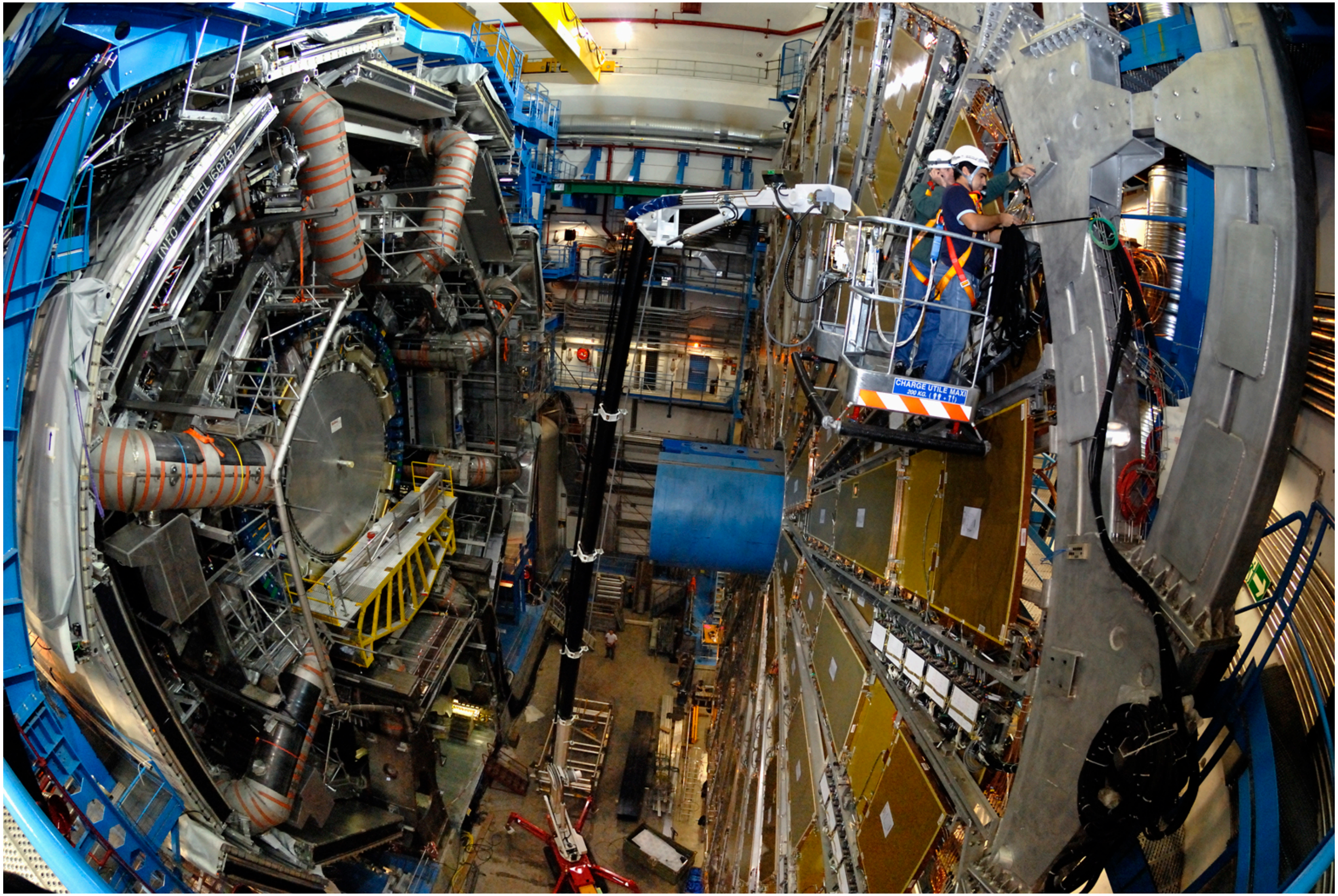


ATLAS Muon Chambers

- Independent muon spectrometer
  - Standalone capabilities
  - Monitored Drift Tube chambers measure momentum and position of muons

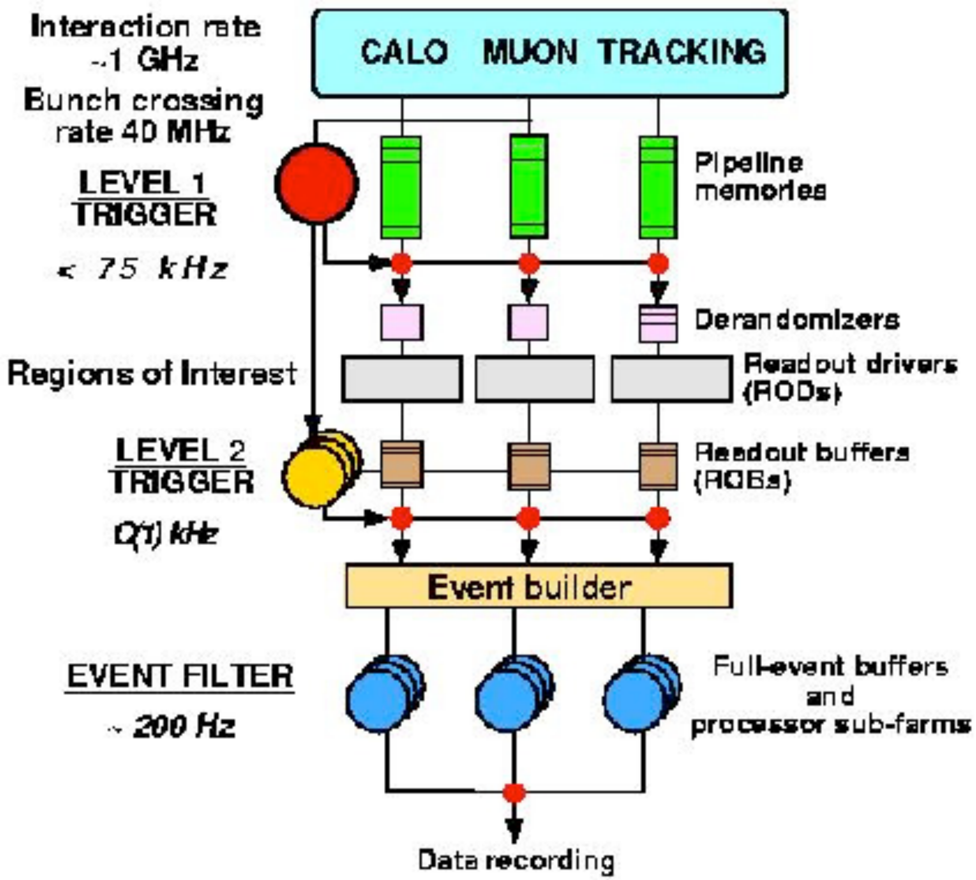


The ATLAS Experiment

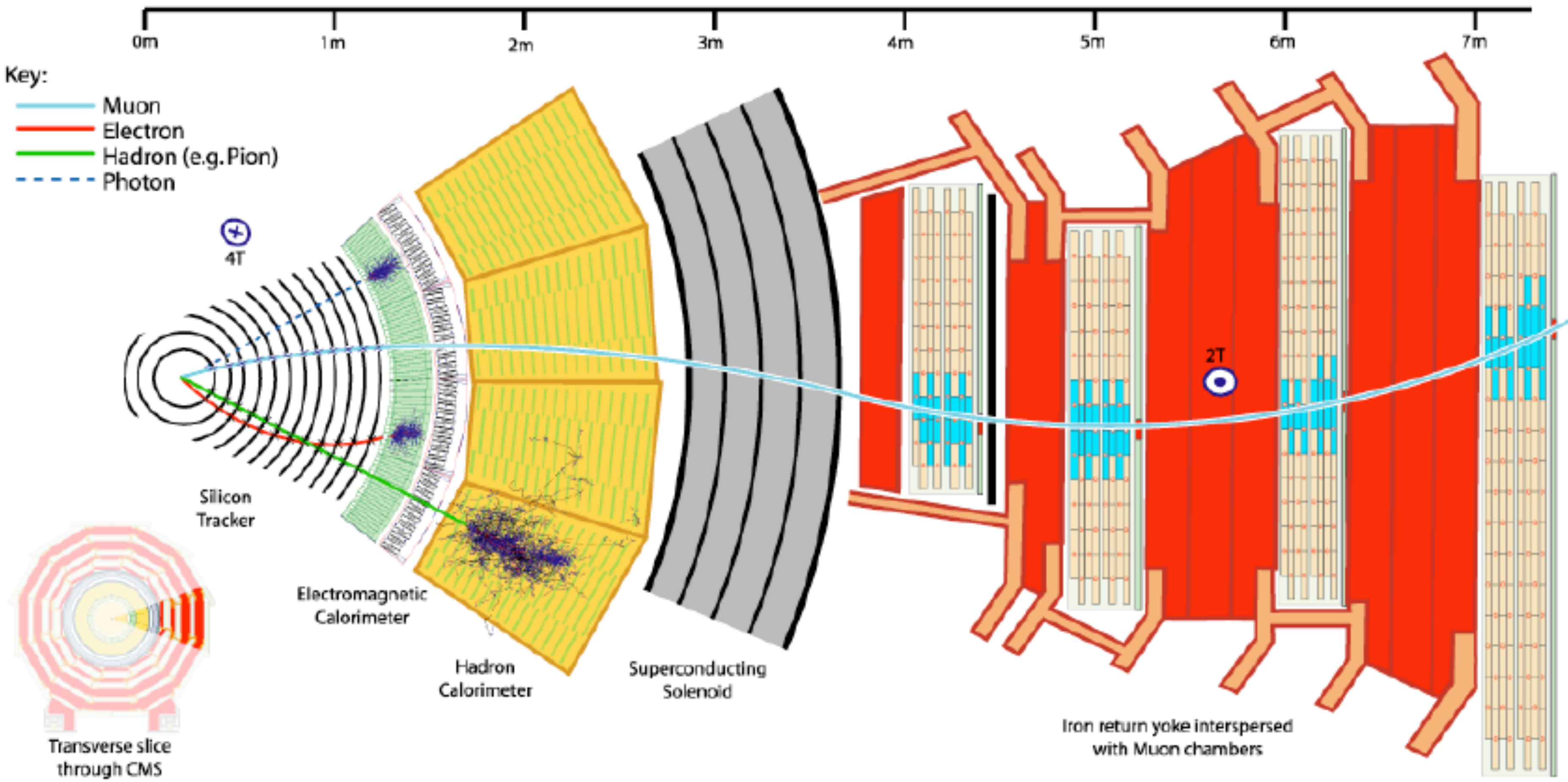


ATLAS Trigger

- Three distinct levels during Run 1
- Reduce rate from bunch crossing ~40 MHz to output rate of order 1 kHz

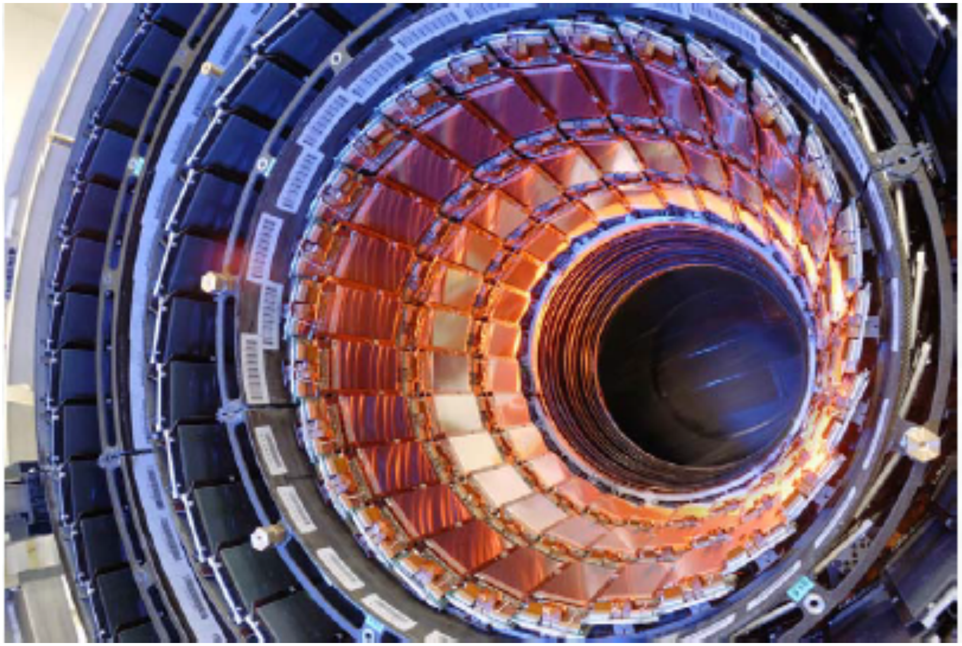
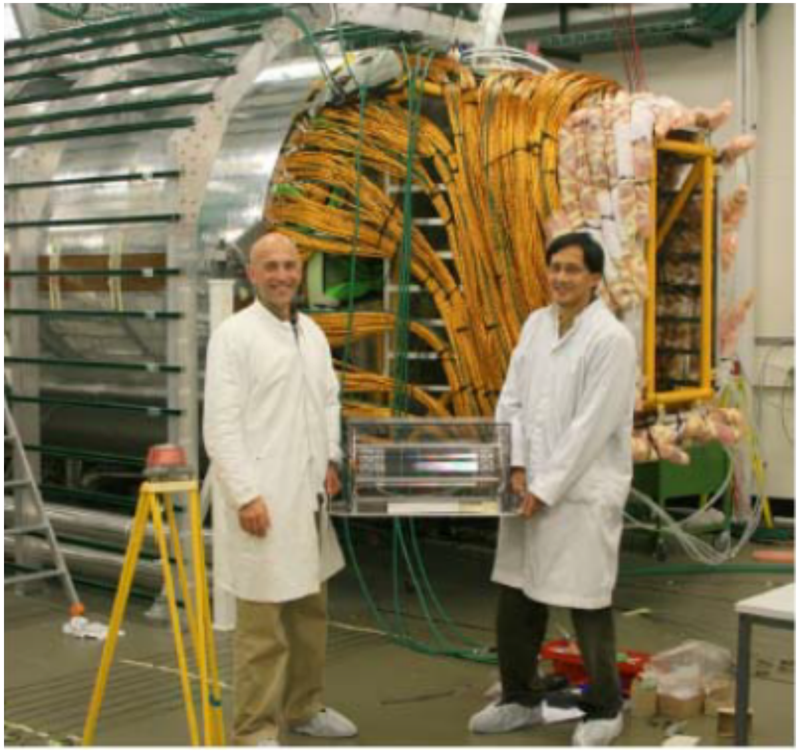


CMS Detector



CMS Tracker

- 200m^2 of silicon detector
- 4 Tesla magnetic field

ATLAS/CMS Comparison

Main performance characteristics of the ATLAS and CMS trackers

	ATLAS	CMS
Reconstruction efficiency for muons with $p_T = 1$ GeV	96.8%	97.0%
Reconstruction efficiency for pions with $p_T = 1$ GeV	84.0%	80.0%
Reconstruction efficiency for electrons with $p_T = 5$ GeV	90.0%	85.0%
Momentum resolution at $p_T = 1$ GeV and $\eta \approx 0$	1.3%	0.7%
Momentum resolution at $p_T = 1$ GeV and $\eta \approx 2.5$	2.0%	2.0%
Momentum resolution at $p_T = 100$ GeV and $\eta \approx 0$	3.8%	1.5%
Momentum resolution at $p_T = 100$ GeV and $\eta \approx 2.5$	11%	7%
Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (μm)	75	90
Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (μm)	200	220
Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 0$ (μm)	11	9
Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 2.5$ (μm)	11	11
Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (μm)	150	125
Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (μm)	900	1060

From K. Jakobs

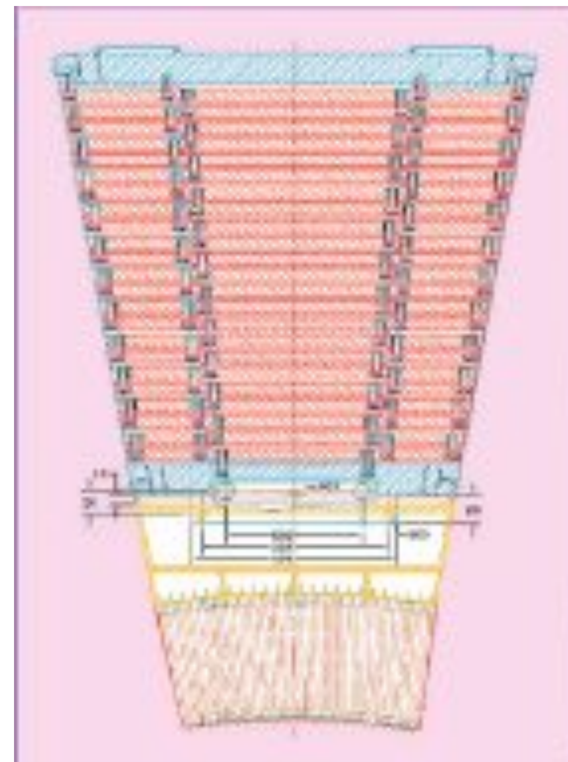
- Performance of CMS tracker is undoubtedly superior to that of ATLAS in terms of momentum resolution.
- Vertexing and b-tagging performances are similar.
- However, impact of material and B-field already visible on efficiencies.

CMS Calorimeters

- **Electromagnetic calorimeter and part of hadronic calorimeter are inside the solenoid coil and form its return yoke**

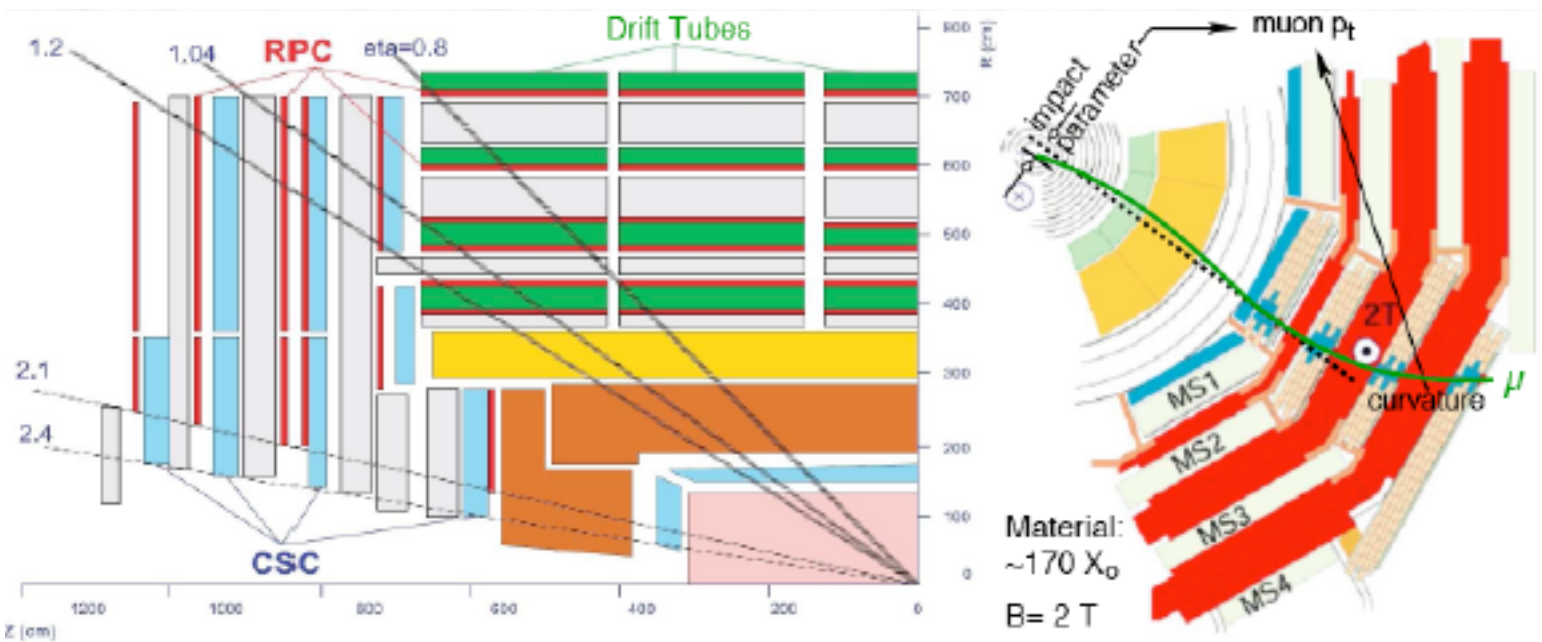
$PbWO_4$ crystals
$\sigma/E \approx 3\%/\sqrt{E} + 0.003$

Brass + scintillator (7 λ + catcher)
$\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV



CMS Muon Chambers

- **Excellent momentum resolution combined with tracking detector in central region**
  - Less good standalone, making muon triggering a bit more challenging e.g. unprescaled thresholds

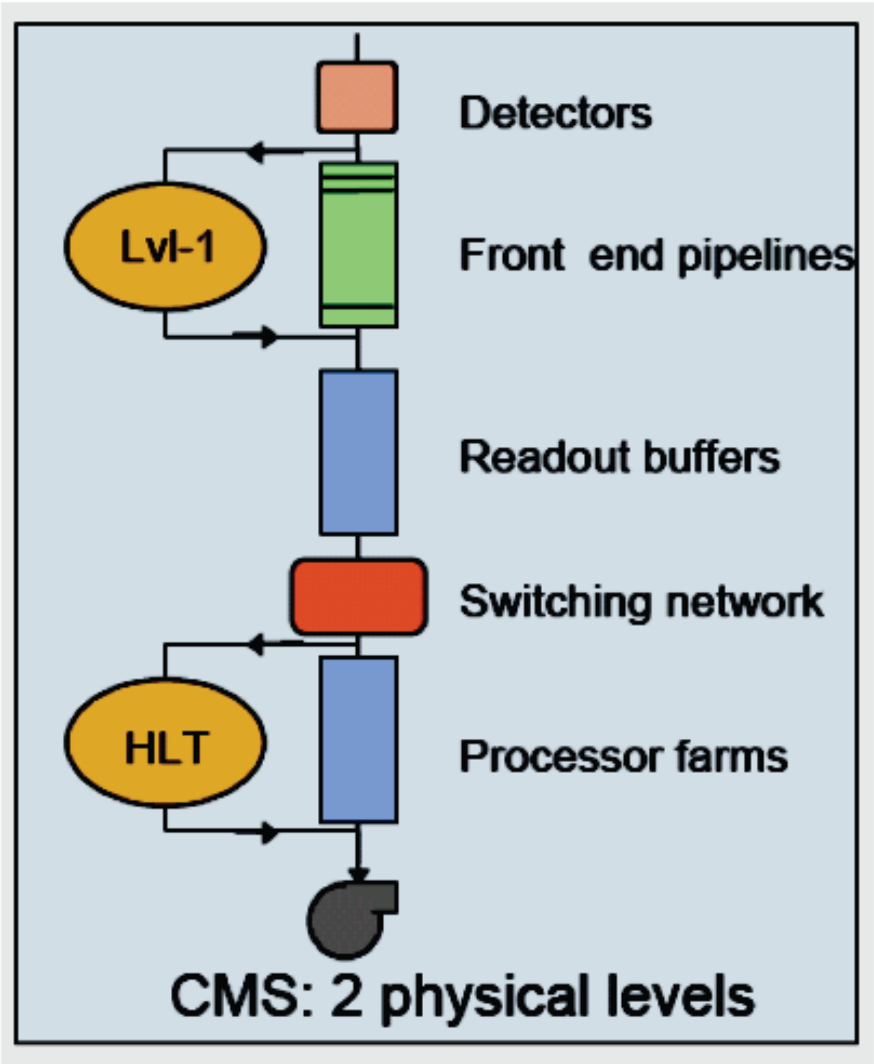


ATLAS/CMS muon chambers

Main parameters of the ATLAS and CMS muon measurement systems as well as a summary of the expected combined and stand-alone performance at two typical pseudorapidity values (averaged over azimuth)

Parameter	**ATLAS**	**CMS**
Pseudorapidity coverage		
-Muon measurement	$\|\eta\| < 2.7$	$\|\eta\| < 2.4$
-Triggering	$\|\eta\| < 2.4$	$\|\eta\| < 2.1$
Dimensions (m)		
-Innermost (outermost) radius	5.0 (10.0)	3.9 (7.0)
-Innermost (outermost) disk (z-point)	7.0 (21–23)	6.0–7.0 (9–10)
Segments/superpoints per track for barrel (end caps)	3 (4)	4 (3–4)
Magnetic field B (T)	0.5	2
-Bending power (BL, in T· m) at $\|\eta\| \approx 0$	3	16
-Bending power (BL, in T· m) at $\|\eta\| \approx 2.5$	8	6
Combined (stand-alone) momentum resolution at		
-p = 10 GeV and $\eta \approx 0$	1.4% (3.9%)	0.8% (8%)
-p = 10 GeV and $\eta \approx 2$	2.4% (6.4%)	2.0% (11%)
-p = 100 GeV and $\eta \approx 0$	2.6% (3.1%)	1.2% (9%)
-p = 100 GeV and $\eta \approx 2$	2.1% (3.1%)	1.7% (18%)
-p = 1000 GeV and $\eta \approx 0$	10.4% (10.5%)	4.5% (13%)
-p = 1000 GeV and $\eta \approx 2$	4.4% (4.6%)	7.0% (35%)

CMS Trigger

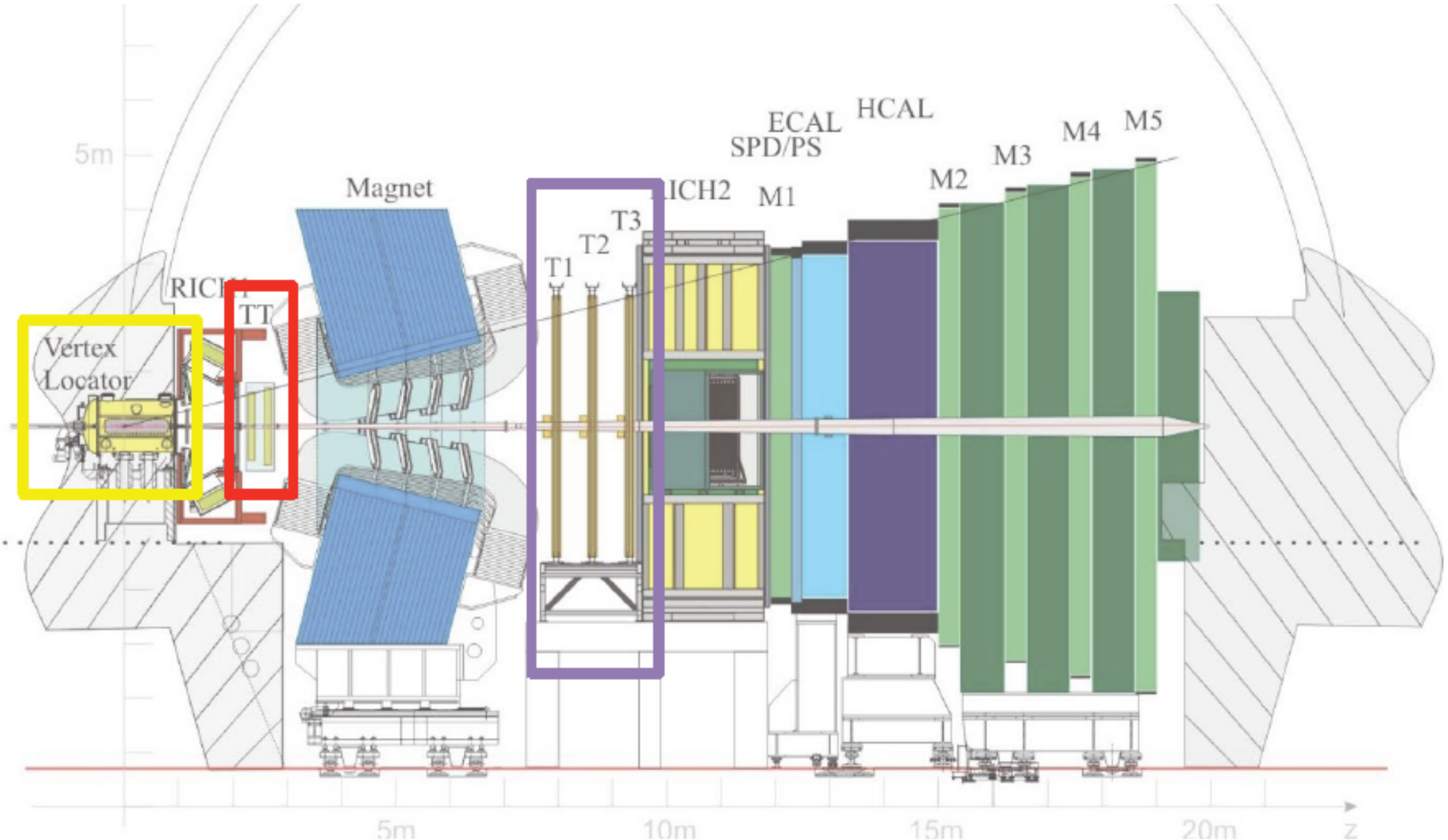


- 40 MHz input rate to Level 1
- Selection cannot be done in 25ns so pipelined trigger
- 100 KHz Level 1 output rate
- 100 Hz written at the output
- Event Size 1-2 Mbytes

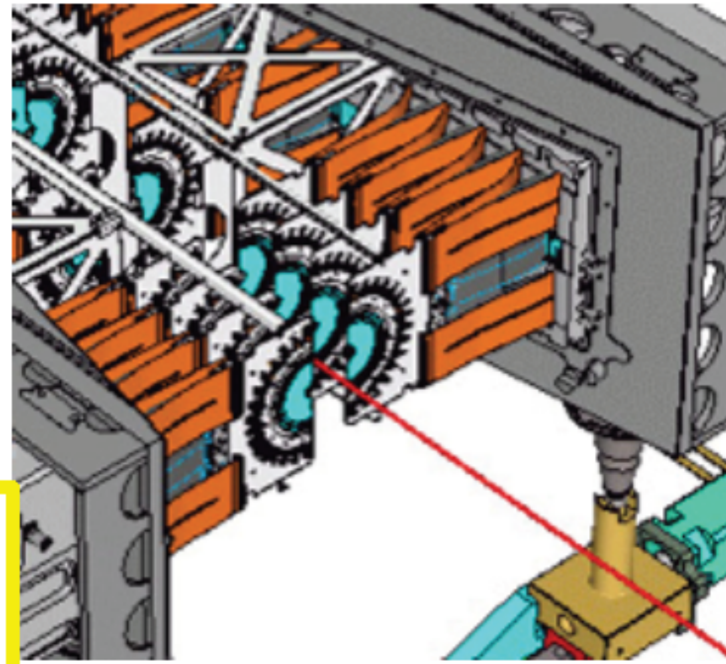
Level-1 Trigger:
$\Rightarrow$ Custom made hardware system

High Level Trigger:
$\Rightarrow$ PC farm (~1000 units) using reconstruction software and event filters similar to the offline analysis.

LHCb Detector



LHCb Tracker



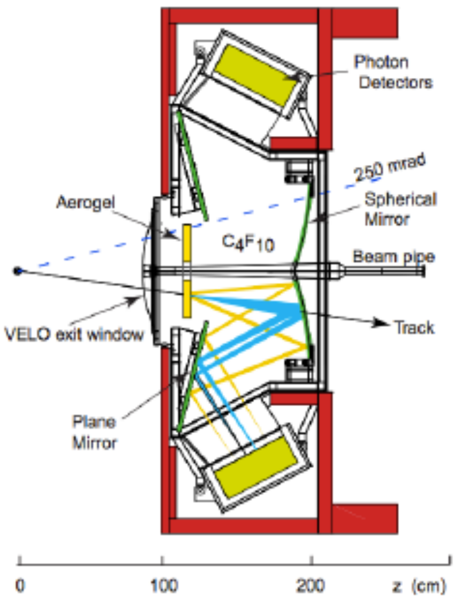
Vertex Locator (VELO):

- 42 silicon micro-strip stations with r-Phi sensors
- Surrounding interaction point
- Two retractable halves, 8 mm from beam when closed
    - **Closed when is declared “stable beam”**
- **Possibility to inject gas (like He, Ne, Ar) for special data taking**

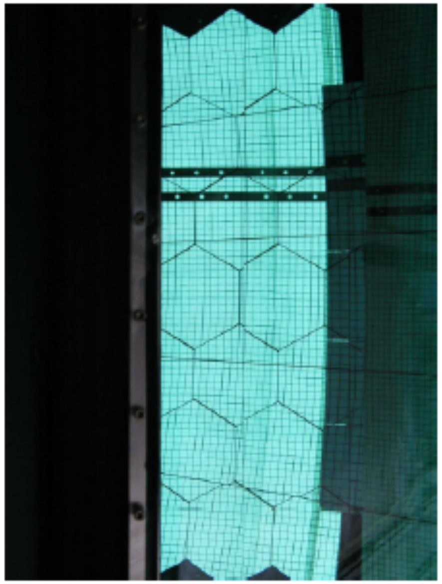
From B. Storaci

LHCb Particle Identification

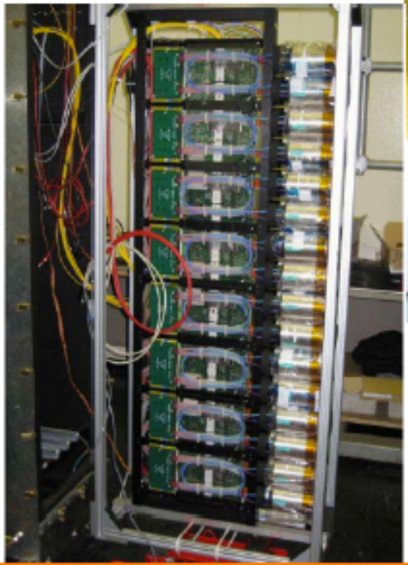
RICH1

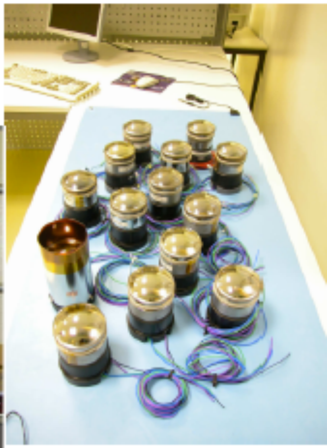


RICH2 spherical mirrors



Hybrid Photon Detectors





Ring Imaging CHerenkov detectors (RICH1 and RICH2)

- RICH1:
  - Upstream of the magnet
  - C_4F_{10} radiator
  - 2<p<40 GeV/*c*
- RICH2:
  - Downstream of the magnet
  - CF_{10} radiator
  - 15<p<100 GeV/*c*

From B. Storaci

LHCb Calorimeter, Muon Chambers

Electromagnetic and hadronic calorimenters (ECAL and HCAL)

- Scintillator planes + absorber material planes
- Provide the Level 0 signature for events with hadrons above a certain E_T
- Offline PID for photons, electrons and hadrons

ECAL

Muon multi-wire proportional chambers

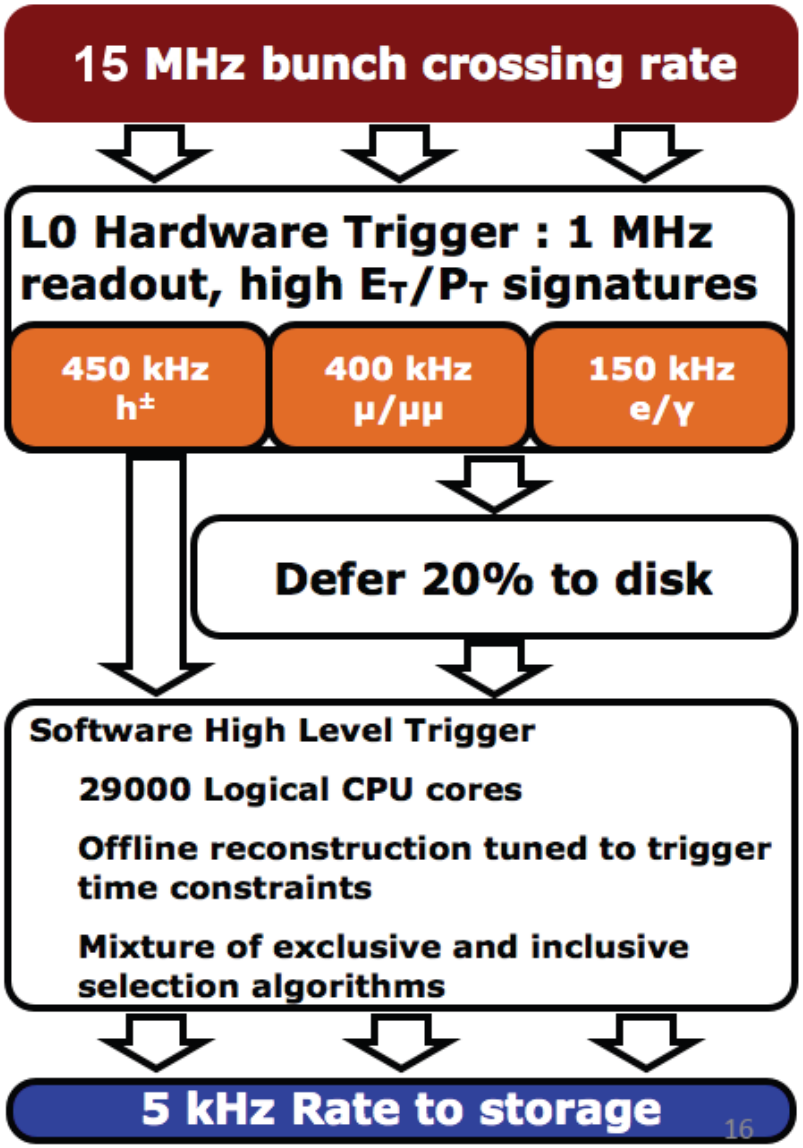
Muon system

- 5 stations, each equipped with 276 multi-wire proportional chambers
  - Inner part of the first station equipped with 12 GEM detectors
- Level 0 trigger selection of tracks with high p_T
- Offline PID of muons

From B. Storaci

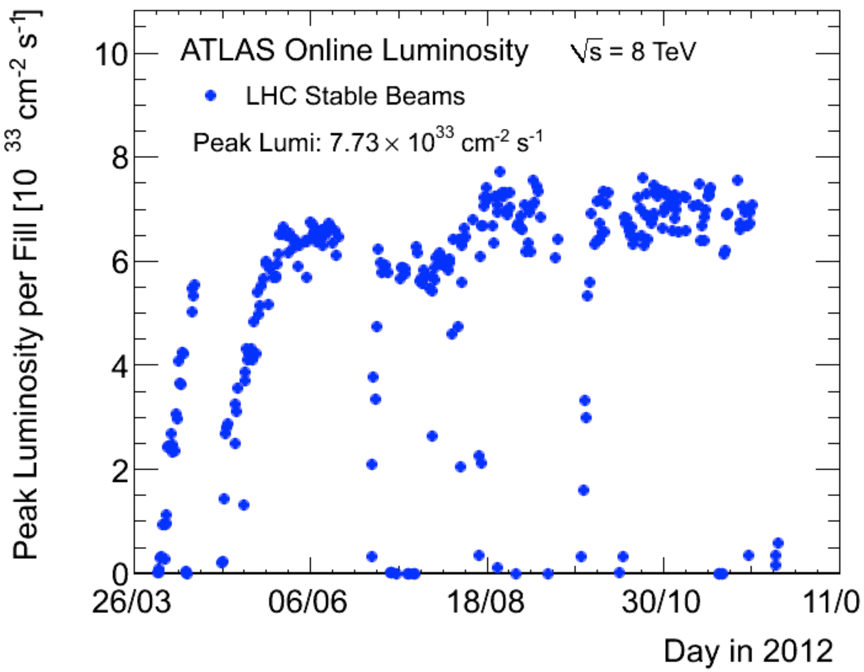
LHCb Trigger

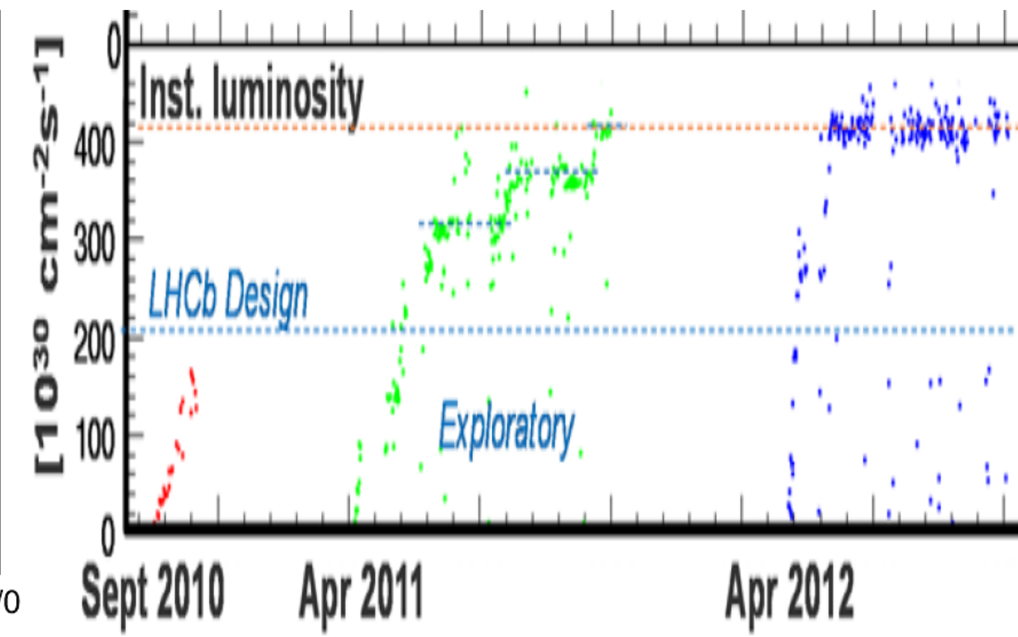
- In Run 1:



Run 1 Dataset

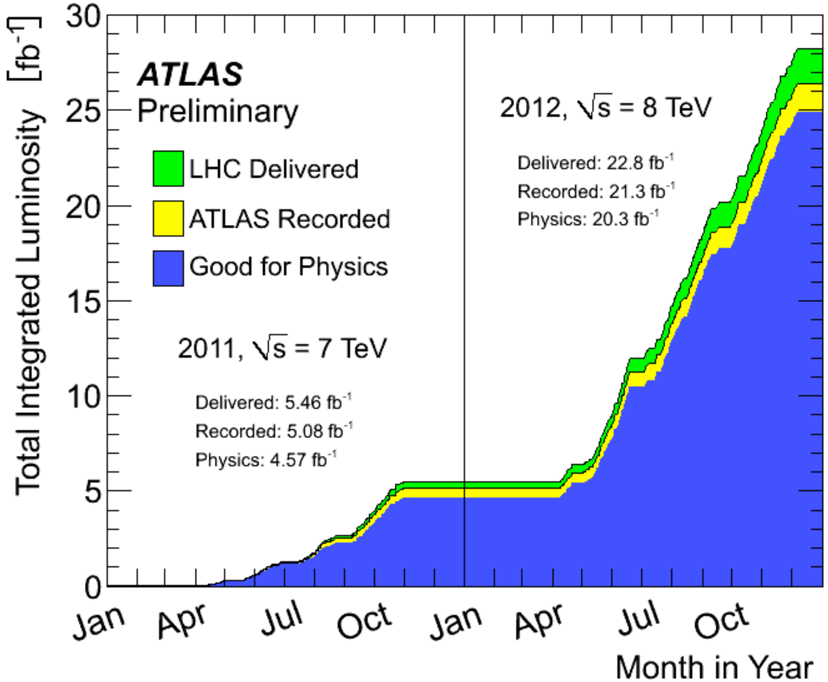
- **7/8 TeV centre of mass collisions**
- **Instantaneous luminosity:**
  - ATLAS/CMS: ~7x10^{33}cm^{-2}s^{-1}, event pile-up ~ 20.7
  - LHCb luminosity levelling: ~4x10^{32} cm^{-2}s^{-1}, event pile-up ~ 1.7 events
    - Much harder to resolve vertex structure of b decays with pile-up

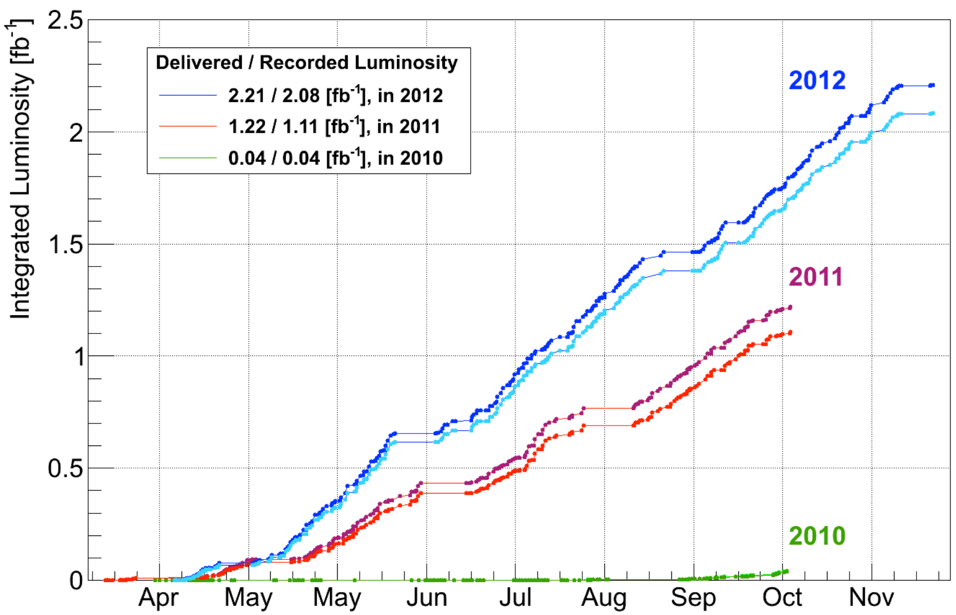




Run 1 Dataset

- **7/8 TeV centre of mass collisions**
- **Integrated luminosity:**
  - ATLAS/CMS: ~4fb^{-1} at 7 TeV, 20 fb^{-1} at 8 TeV
  - LHCb:~1fb^{-1} at 7 TeV, ~2fb^{-1} at 8 TeV



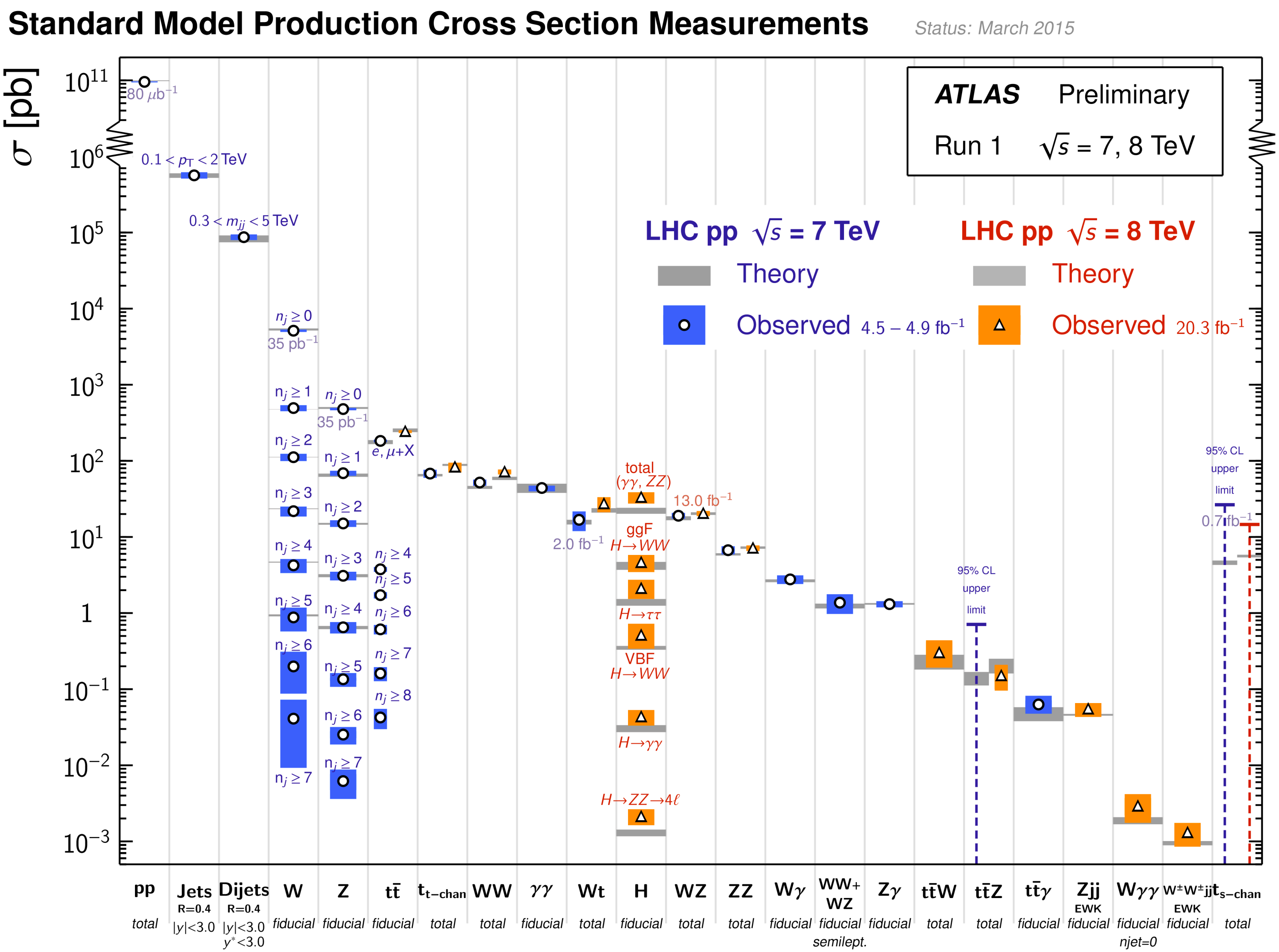


Run 1 Analysis Highlights

- **Impossible to summarise Run 1 in a couple of slides**
  - But I'm going to try…
  - Selecting highlights
- **Lumping ATLAS and CMS together**
  - In general they search for and measure the same physics (though not always)

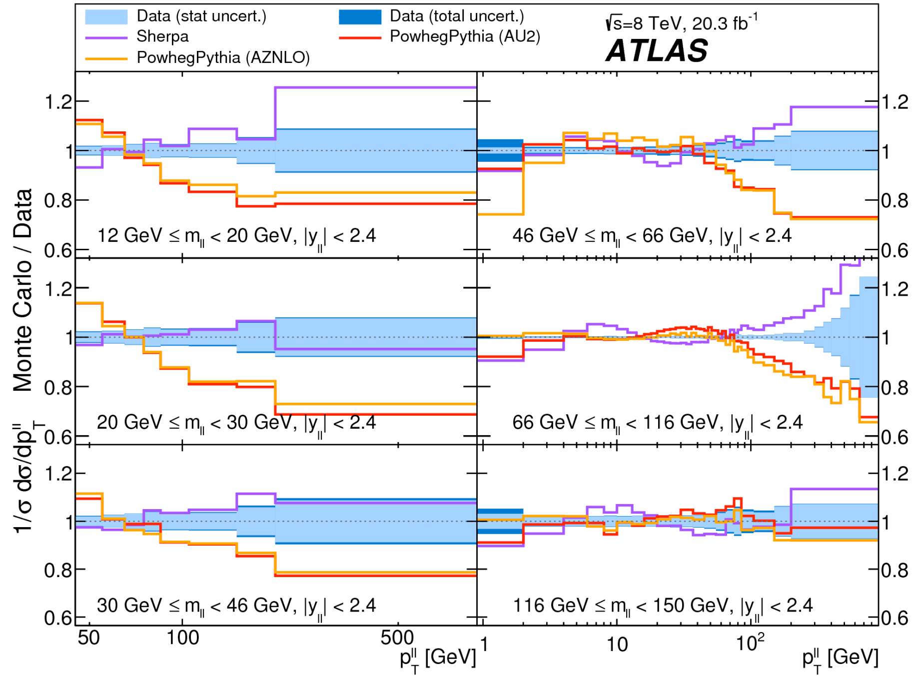
Run 1 Dataset

- Copious production of SM particles and the Higgs

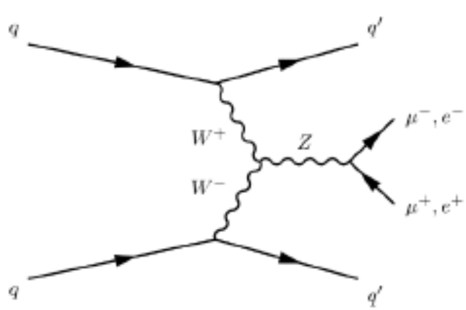


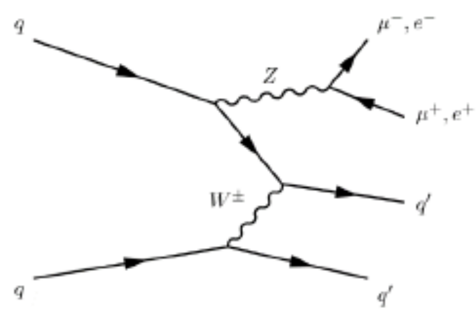
Run 1 Achievements: ATLAS/CMS

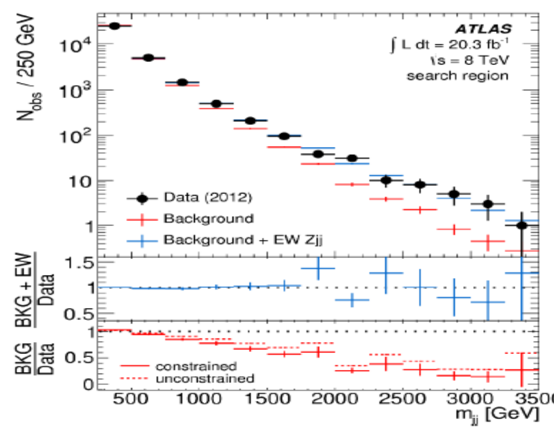
- **Standard Model**
  - Large range of results
  - Some (re)establish e.g. boson production and give momentum distributions to pin down Monte Carlo tunings



  - Some are first observations of new phenomena (or are stronger than previous signals at Tevatron thus allowing probing of their kinematics)

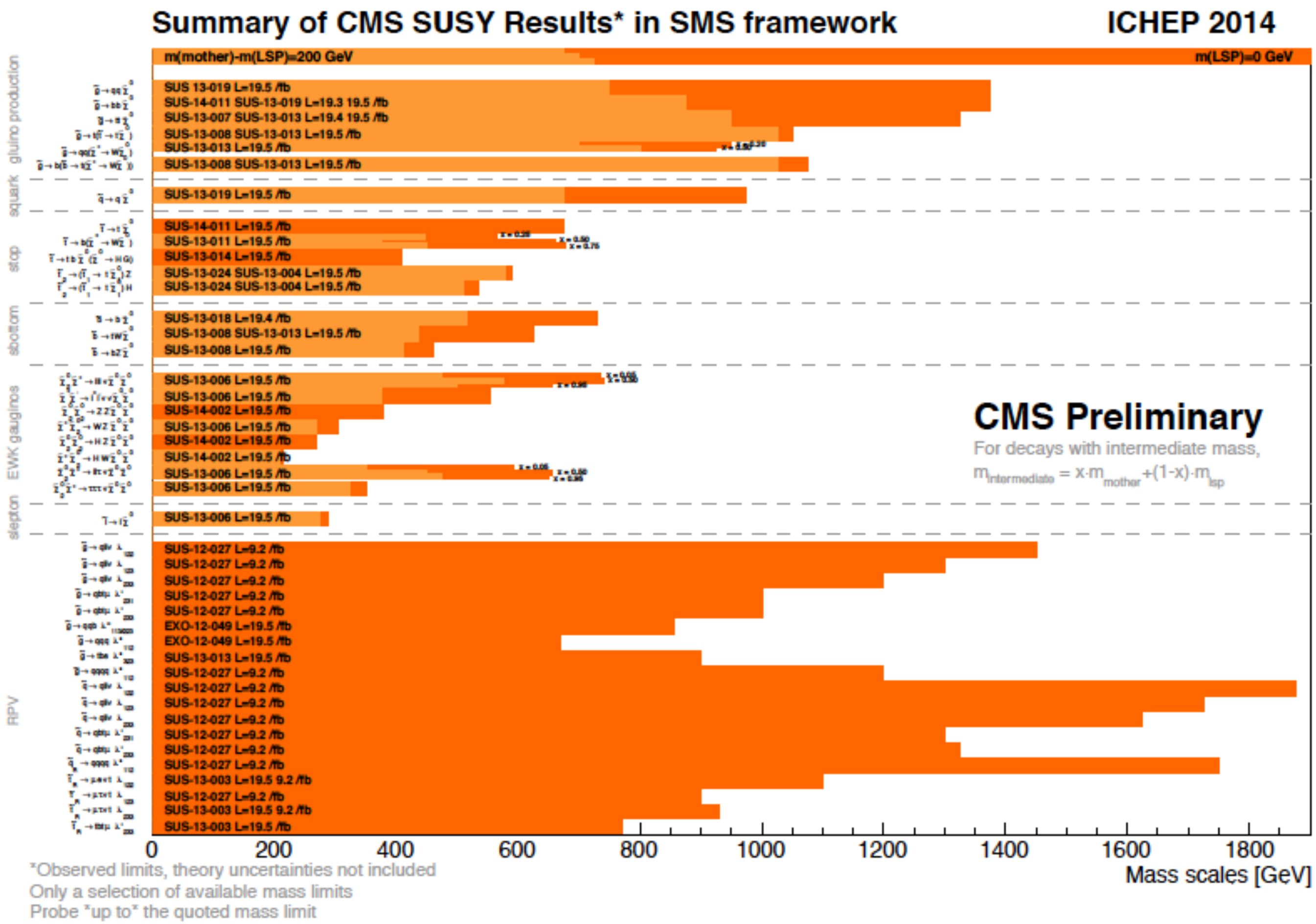






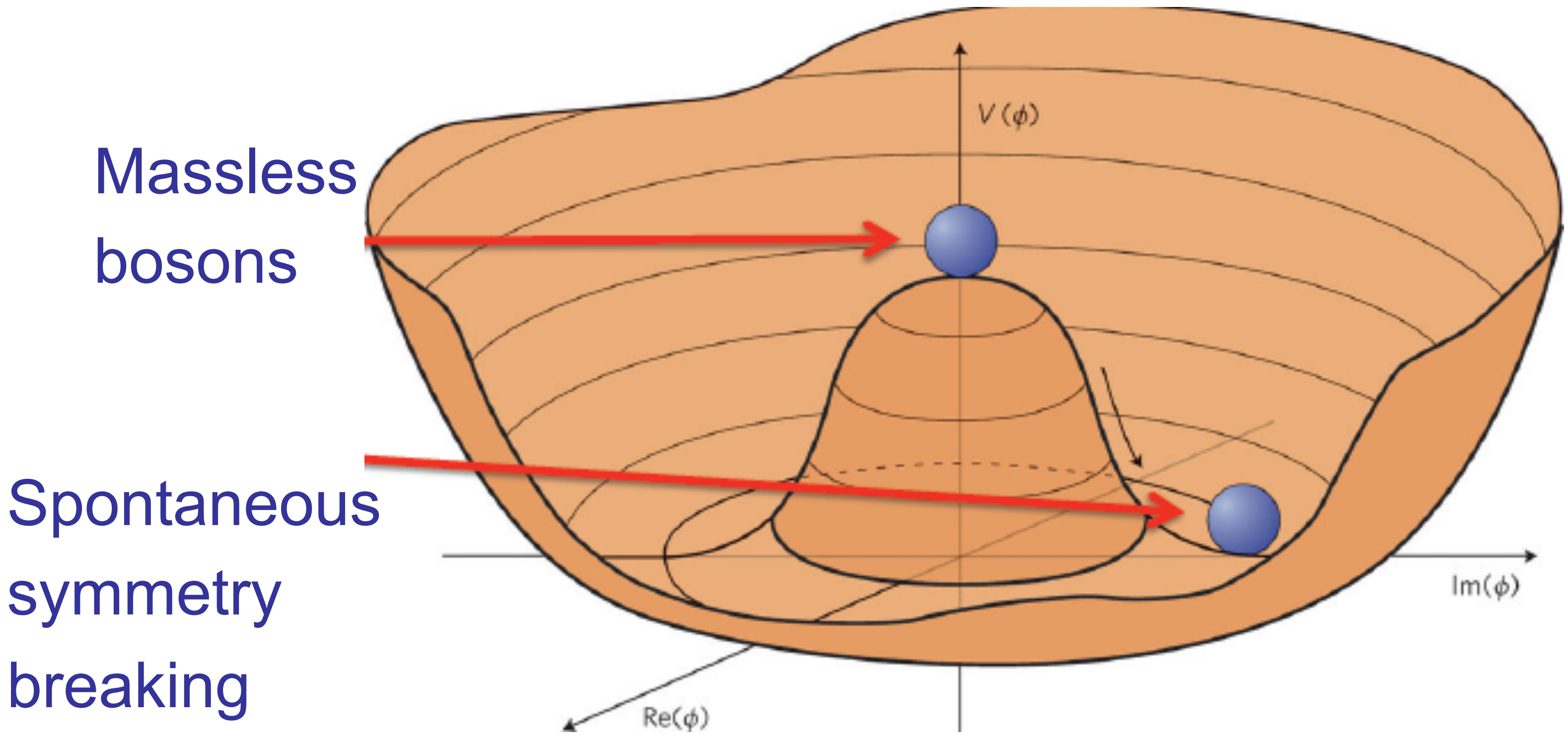
Run 1 Achievements: ATLAS/CMS

- **Supersymmetry Searches**
  - CMS summary of limits and final states
  - Prolific searches and honing of techniques but no evidence (yet)



Higgs Boson

- **Introduced to give mass to W and Z bosons**
  - Requires a new potential to be added to the Standard Model
  - Introduction of "complex doublet" implies 4 new degrees of freedom, 3 of which are the W^+, W^- Z boson mass
  - Fourth is the Higgs boson itself



EPJC 74(2014) 3076, PRD 92 012006(2015),PRD 91 012006(2015), PRD 90 112015(2014), JHEP 01 (2014) 096, PRD 89 (2014) 092007

Higgs Decaying to Bosons

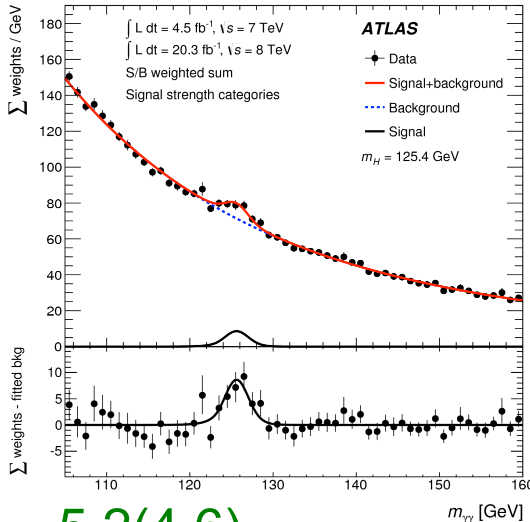
- **Observation in γγ**

ZZ*

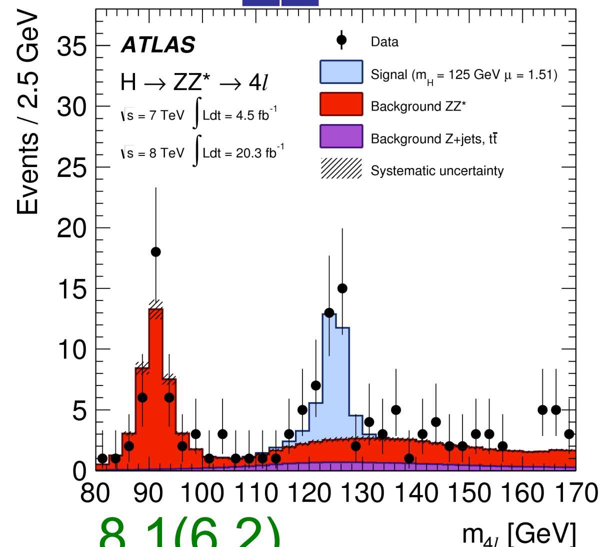
WW*

ATLAS

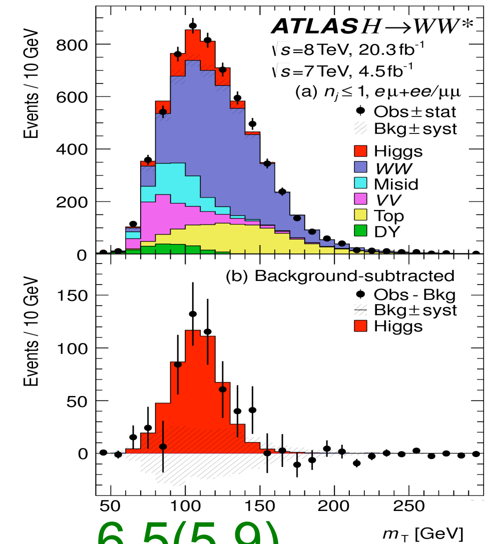
obs(expected) significance



5.2(4.6)

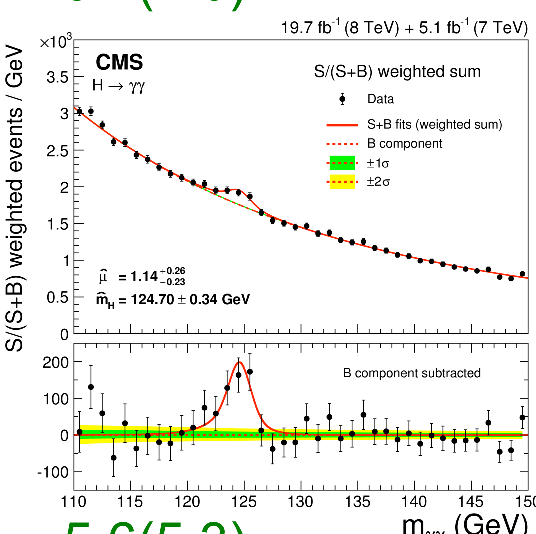


8.1(6.2)

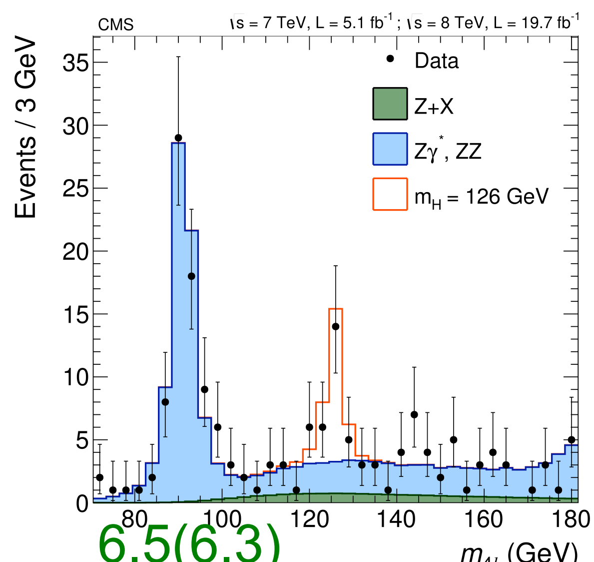


6.5(5.9)

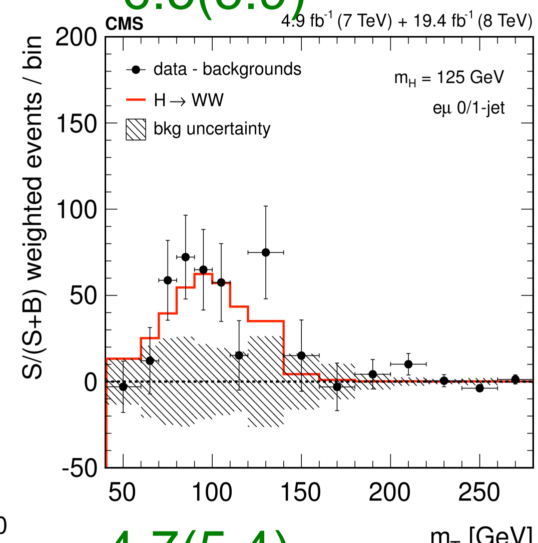
CMS



5.6(5.3)



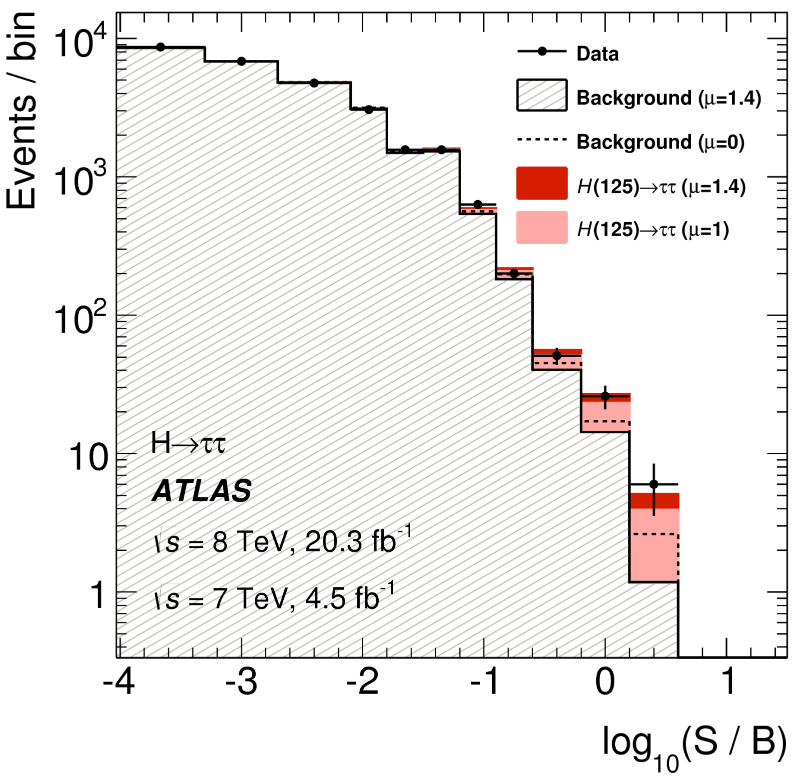
6.5(6.3)

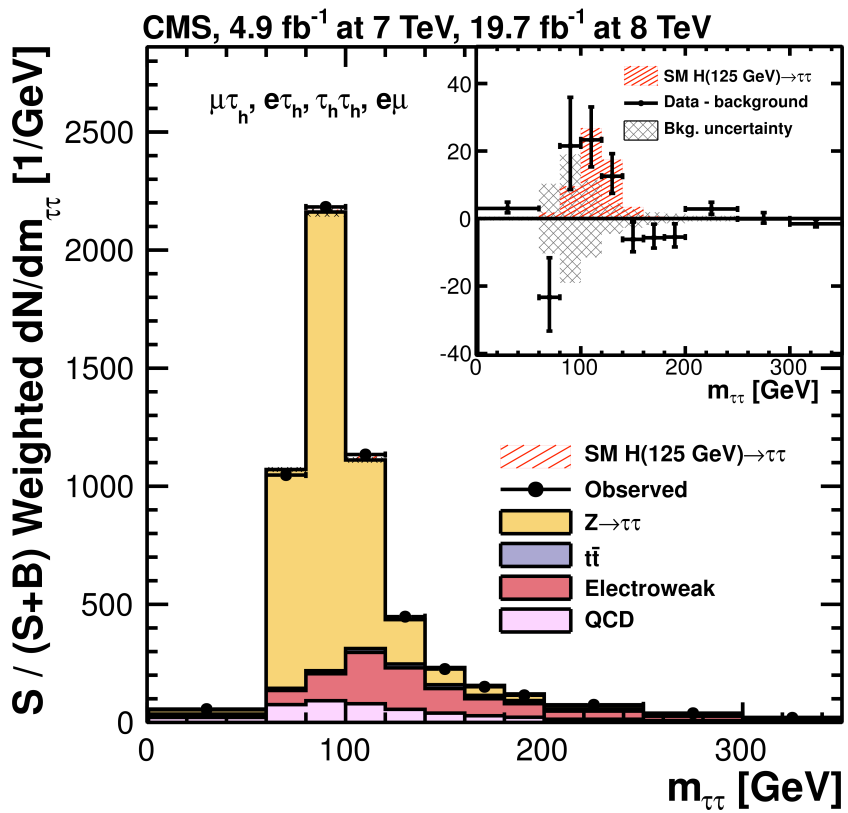


4.7(5.4)

Higgs Decaying to Fermions

- **Tau leptons**





JHEP 04 (2015) 117

σ Observed (Expected)

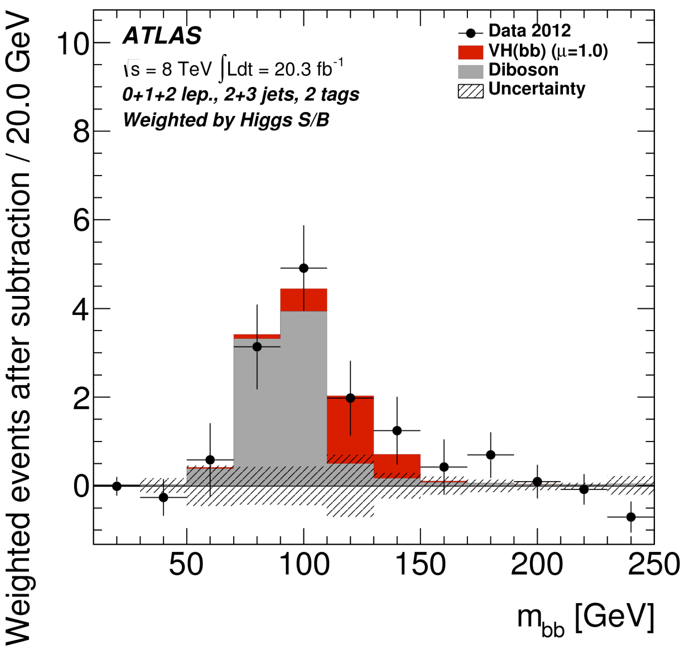
JHEP 05 (2014) 104

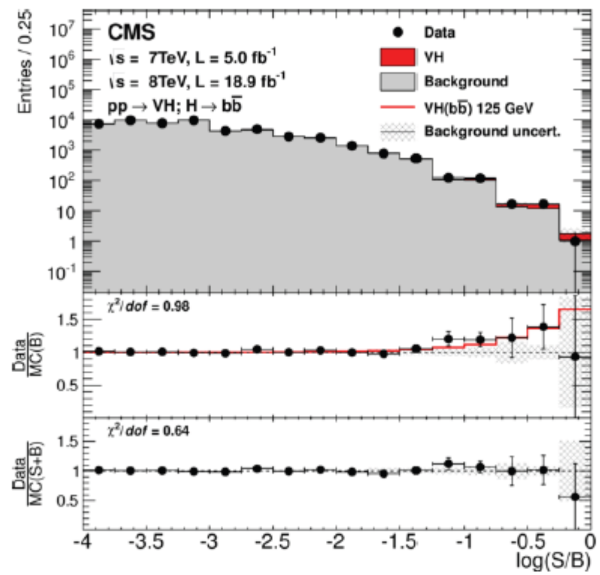
4.5 (3.4)

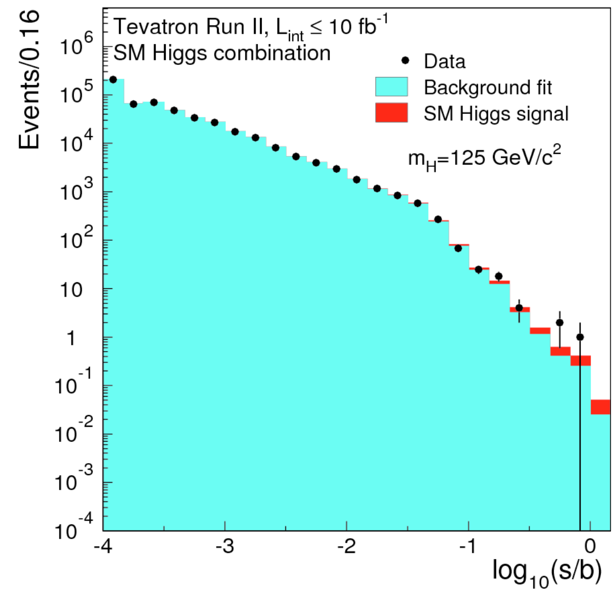
3.2 (3.7)

Higgs Decaying to Fermions

- **b quarks**







JHEP01(2015)069

arXiv:1506.01010

PRD 88, 052014 (2013)

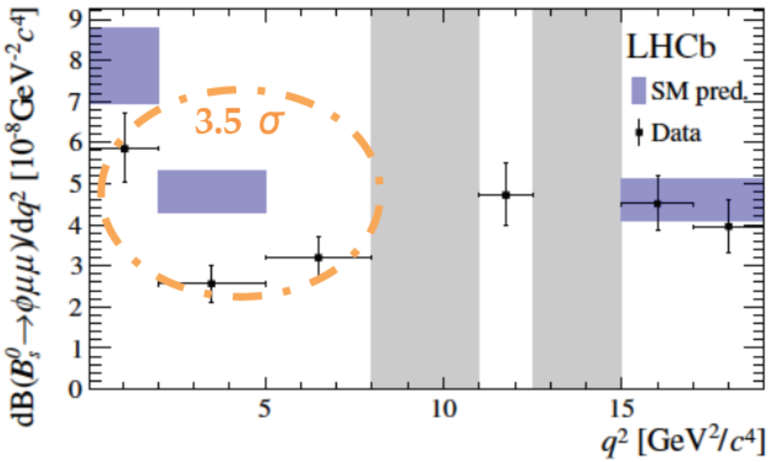
σ Observed (Expected)

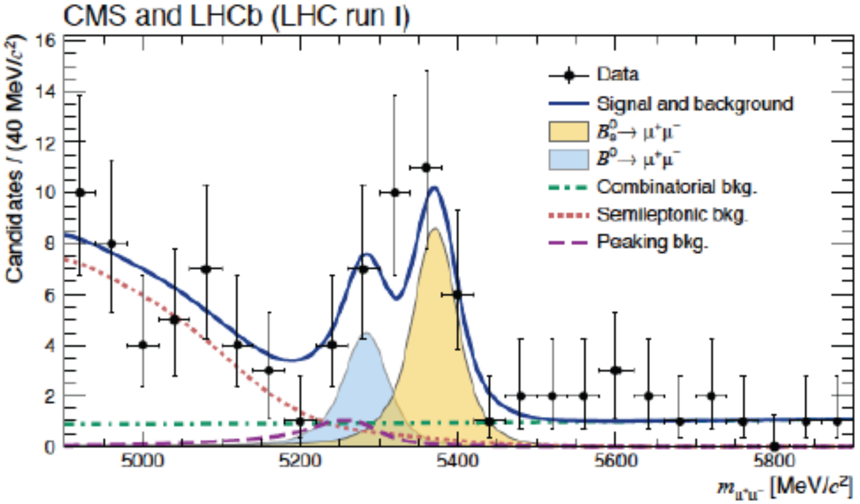
1.8 (2.8) **2.6 (2.7)** **2.2(1.4)**

Run 1 Achievements: LHCb

- **Probed rare decays and found some interesting discrepancies**

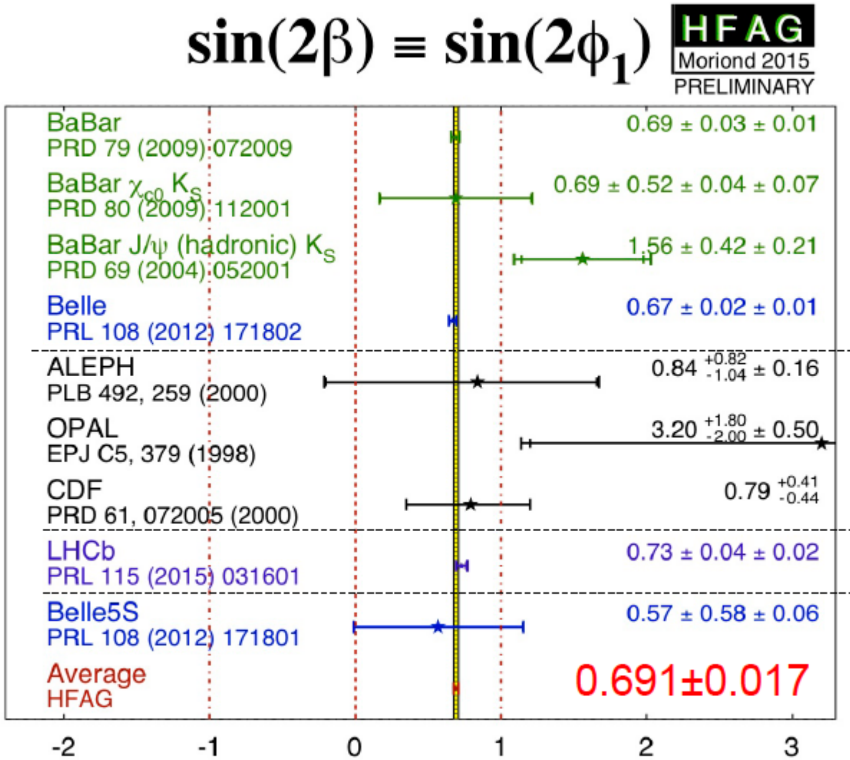
LHCb, arXiv:1506.08777, submitted to JHEP





- **Observed B to mumu (BR ~10^{-9})**

Run 1 Achievements: LHCb

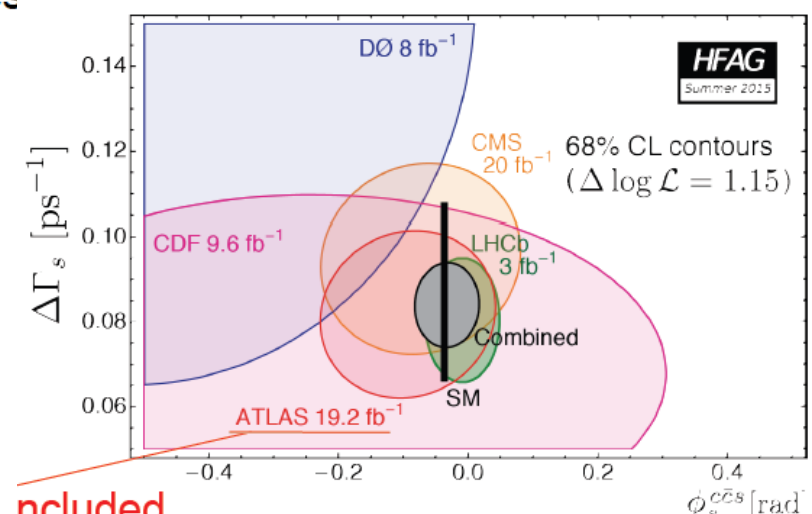


Measurements by B-factories

From K. Miyabayashi

Measurements before B-factories

LHCb starts to bring competitive results with B-factories



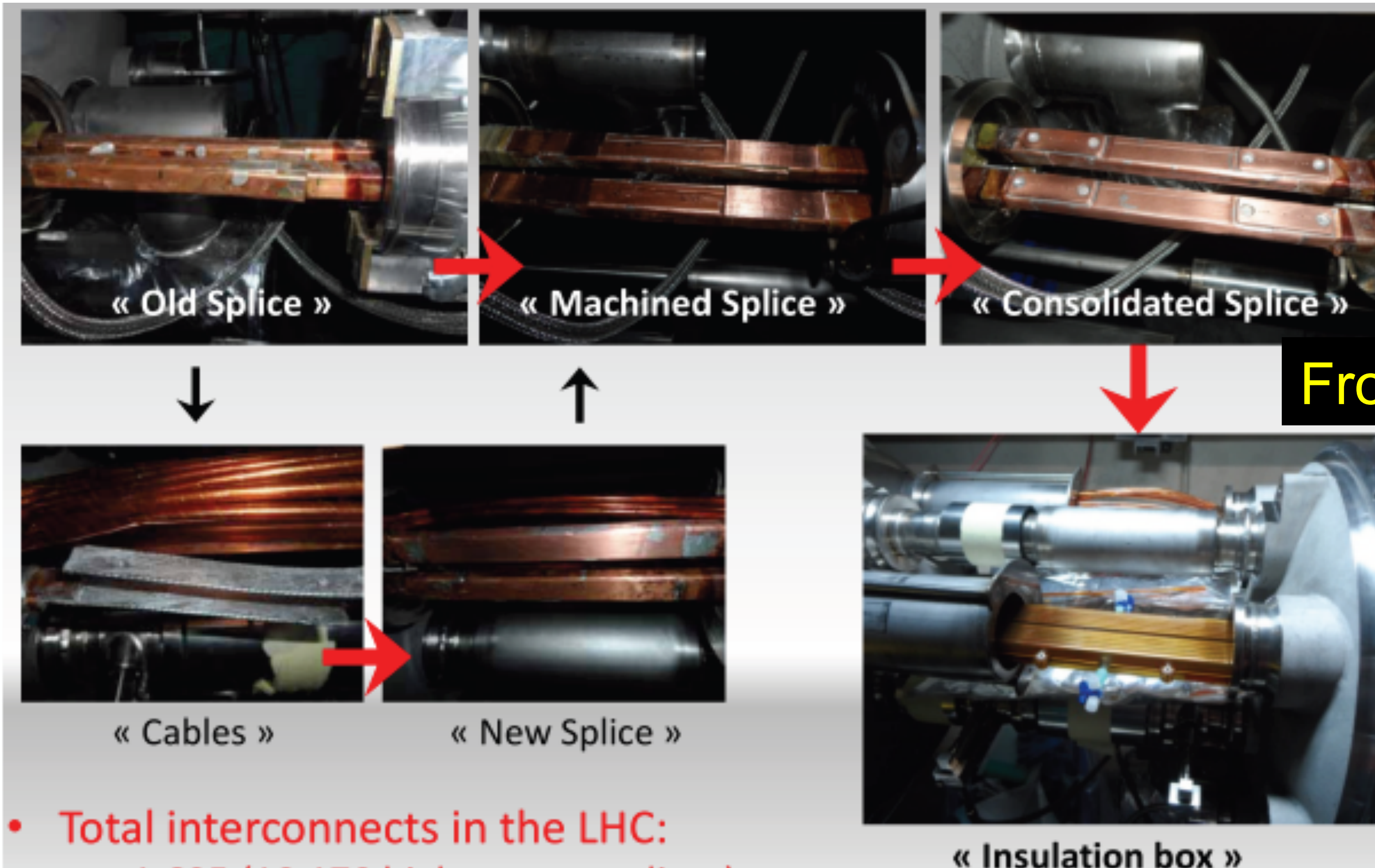
ncluded.

Upgrades for Run 2

- Long Shutdown 1: 14th Feb 2013 – 23rd March 2015
- LHC work: 10,000 high-current splices between LHC magnets opened and consolidated

- Experiments also installed new detectors and performed maintenance during this time

LHC in the Shutdown



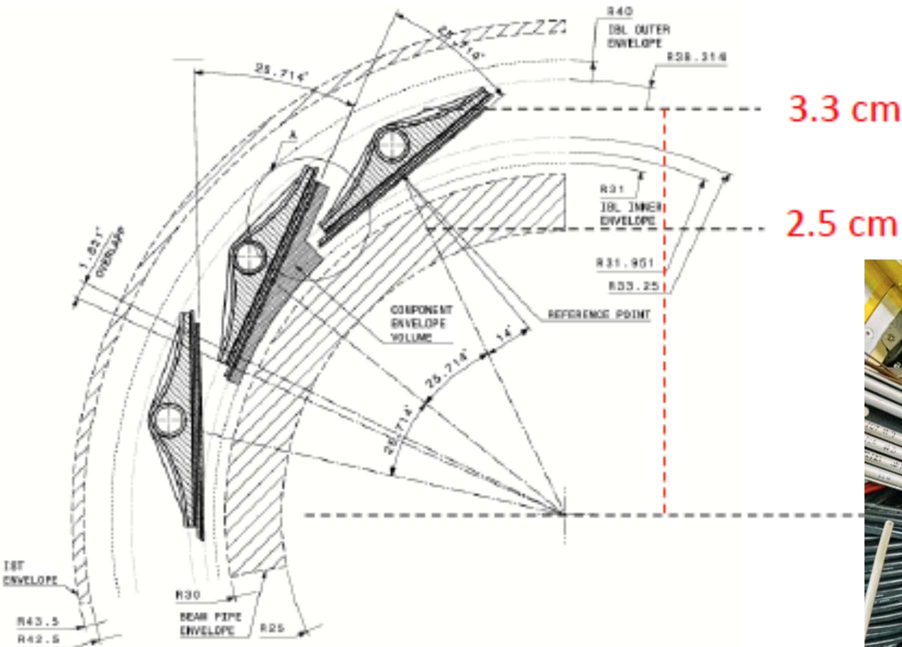
From M. Lamont

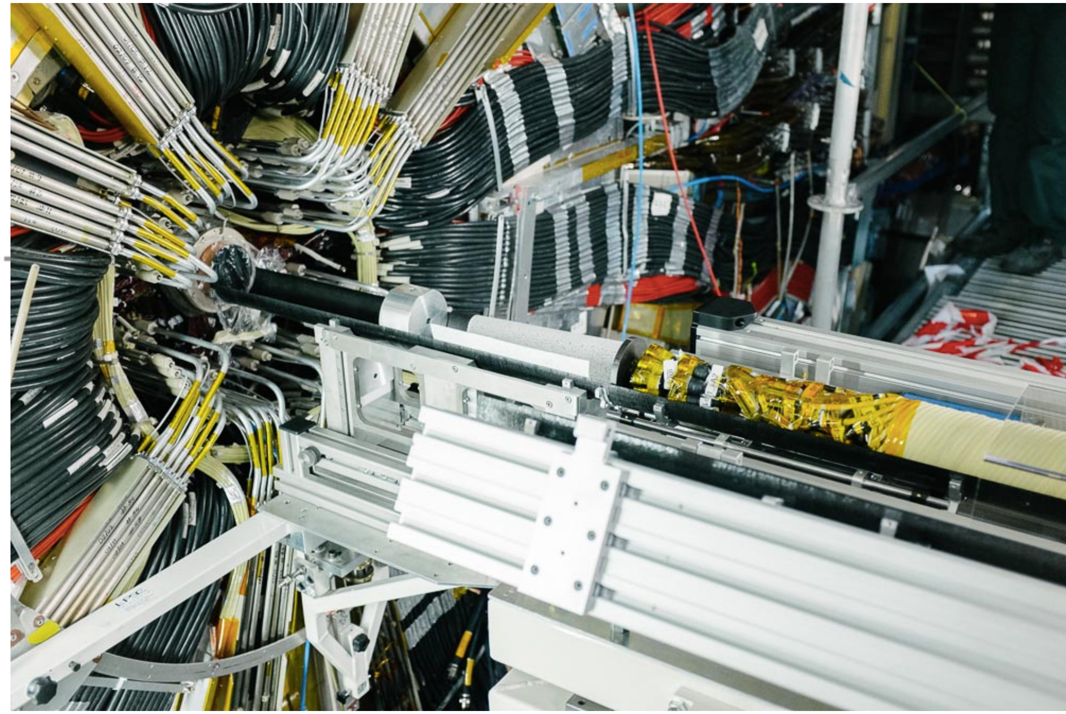
- Total interconnects in the LHC:
  - 1,695 (10,170 high current splices)
- Number of splices redone: ~3,000 (~ 30%)
- Number of shunts applied: > 27,000

And a lot more besides…

ATLAS in the shutdown

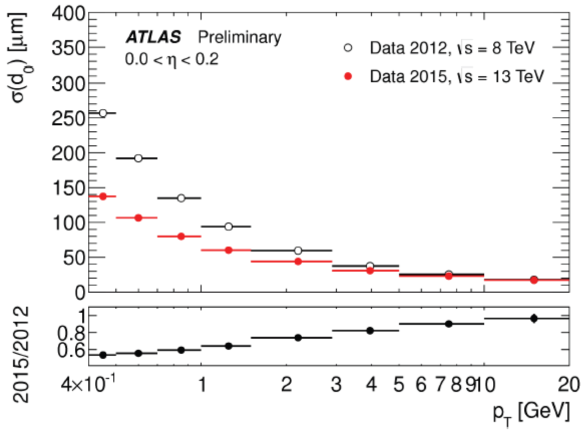
- 4th silicon pixel detector layer (IBL)
  - Innermost Pixel detector layer at R=3.3 cm from beam



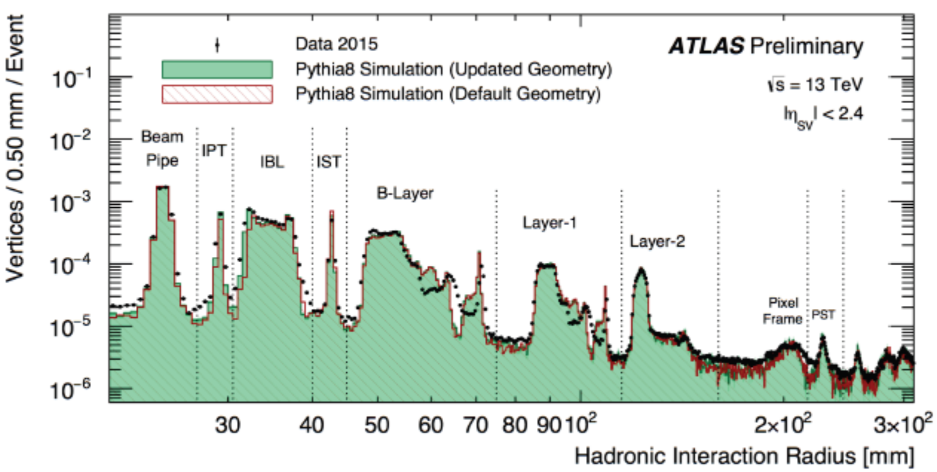


IBL silicon layer

- Improved tracking performance (impact parameter resolution)



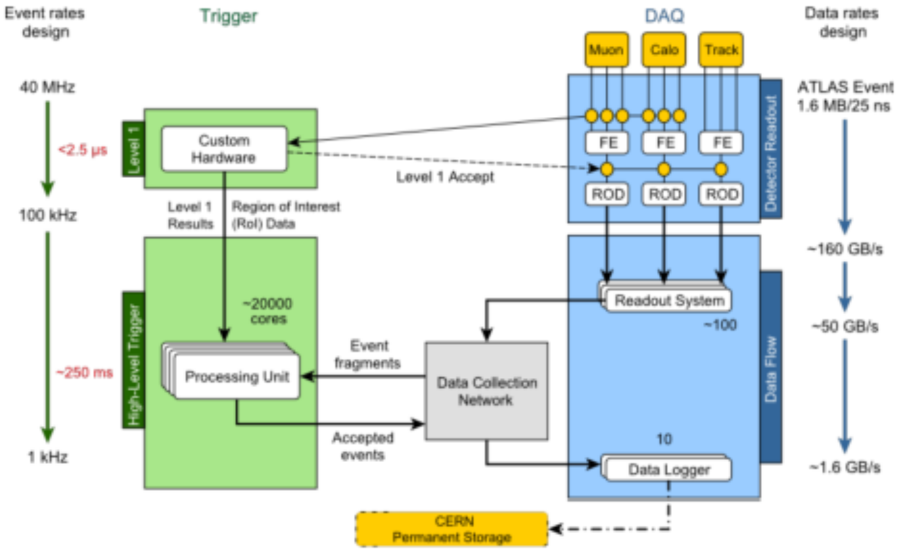
- Extra material demands a new geometry for ATLAS:



ATLAS in the shutdown

- Trigger improvements
  - New Topological L1 trigger, new central trigger processor, coincidence between Tile and muons, merge of high-level trigger, new Fast TracK Trigger (FTK), improved L1 calorimeter trigger

- TDAQ system redesigned for Run-2 to improve:
  - Read-Out Buffers
  - Data flow network performance
  - High level trigger (HLT)
  - Online calibration farm
  - Control & Operational monitoring
  - Trigger rate up to 100 kHz at L1, on average 1kHz HLT



ATLAS in the Shutdown

- Infrastructure:
  - New beampipe, improvements to magnet & cryogenic system
- Detector consolidation
  - Muon chambers completion ($|\eta|=1.1-1.3$) and repairs, improved readout of various systems (L1 rate 100 kHz), repair of pixel modules and calorimeter electronics, new pixel services, new luminosity detectors, new MBTS detector
- Software improvements to simulation, reconstruction, grid and analysis software

CMS in the shutdown

- **Level 1 Trigger:**
  - Upgraded calorimeter trigger – better isolation and pile-up subtraction
- **Added a muon chamber**
- **Run tracker colder (strips at -15 C, pixels at -10 C)**
  - Detector suffers less radiation damage at cooler temperatures
- **HCAL new calibration strategies**

CMS in the Shutdown

Pixel Luminosity Telescope

Brand new luminosity detector

16/16 PLT telescopes (8 telescopes per end)

48/48 PLT sensors

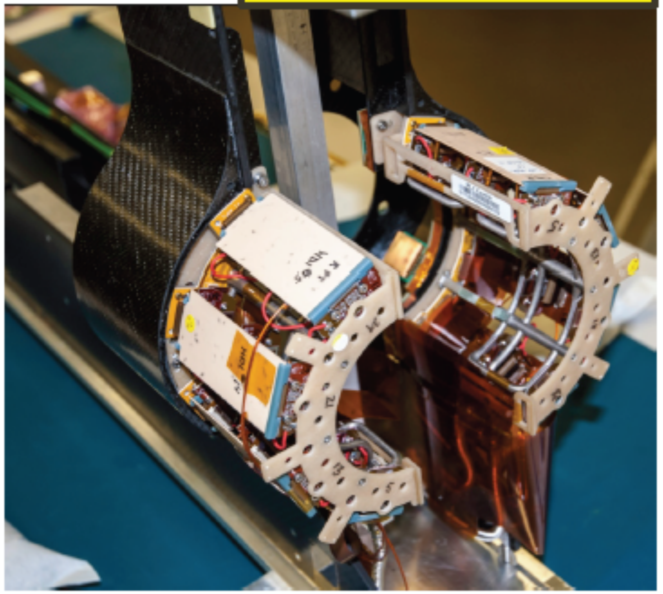
Target is 1% Statistical error/Bunch/s

Coincidence fast-OR of 3-plane telescopes.

Online and Offline luminometer

Innovative use of Titanium 3D Printed integrated cooling/support structu

PLT IP side of carriage



From W&C seminar Olsen, Malgeri

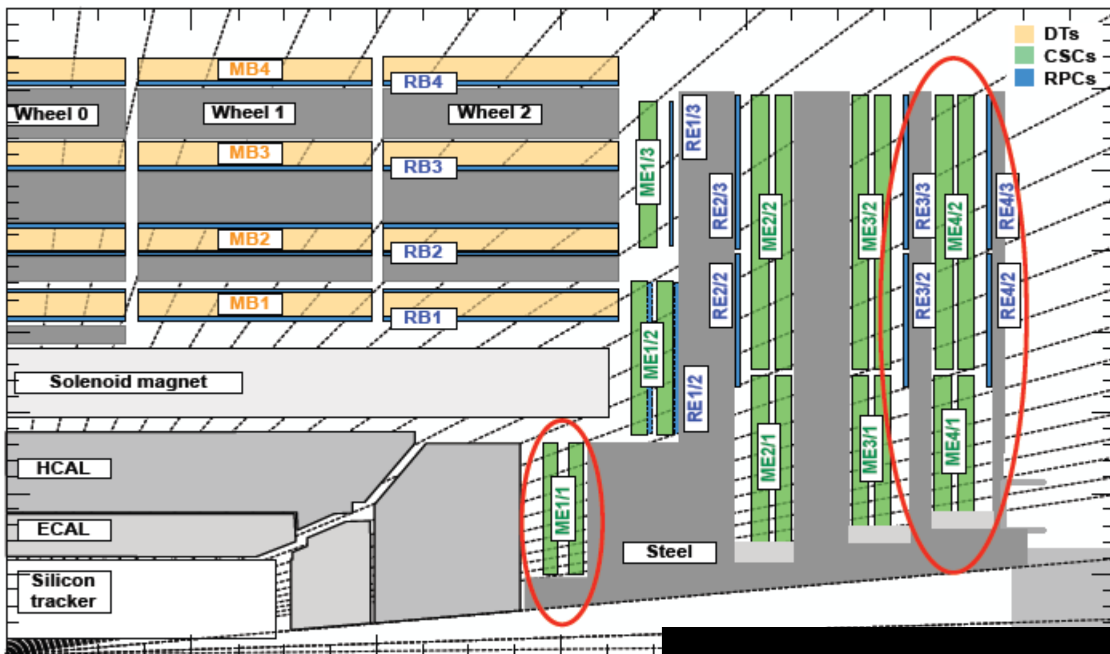
CMS in the Shutdown

Muon System

CMS Muon System has three sub-systems: Drift Tubes (DT), Cathode Strip Chambers (CSC), Resistive Plate Chambers (RPC)

Removal, revision, re-installation of ME1/1 chambers

4th muon station added: 72 (144) new CSC (RPC) chambers



From W&C seminar Olsen, Malgeri

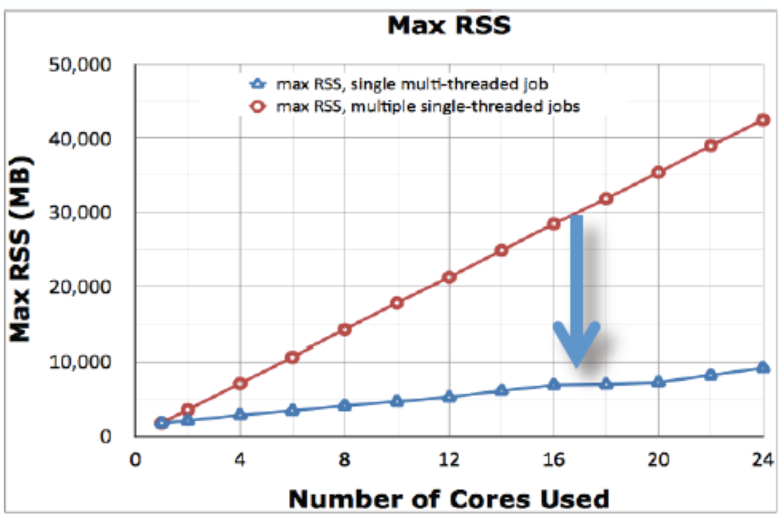
CMS in the Shutdown

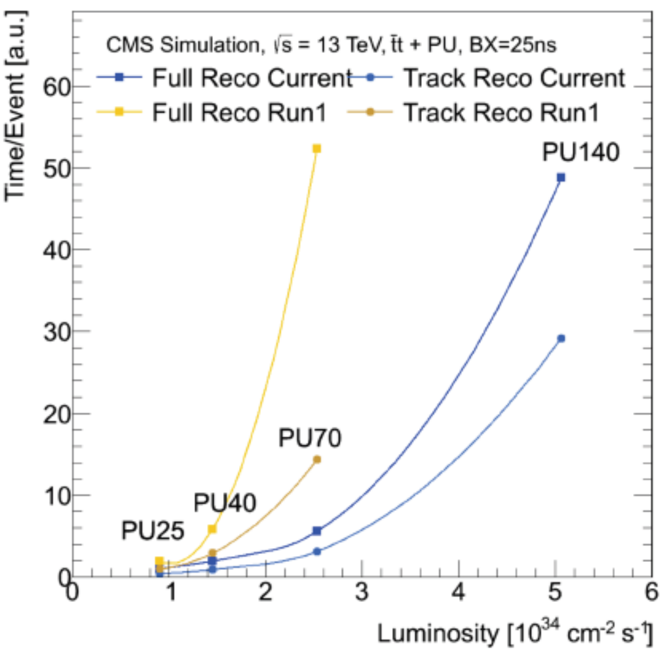
Computing/Offline for Run 2

Next-generation framework based on multi-threading approach
Processing higher Run 2 trigger rates efficiently; lower memory usage

Developed "miniAOD" data format ~10 times smaller than what was used in Run 1: target ~80-90% of users

Several technical improvements in the reconstruction code (not impacting physics performance) allowed to reduce drastically the CPUtime/event (x2 reduction)



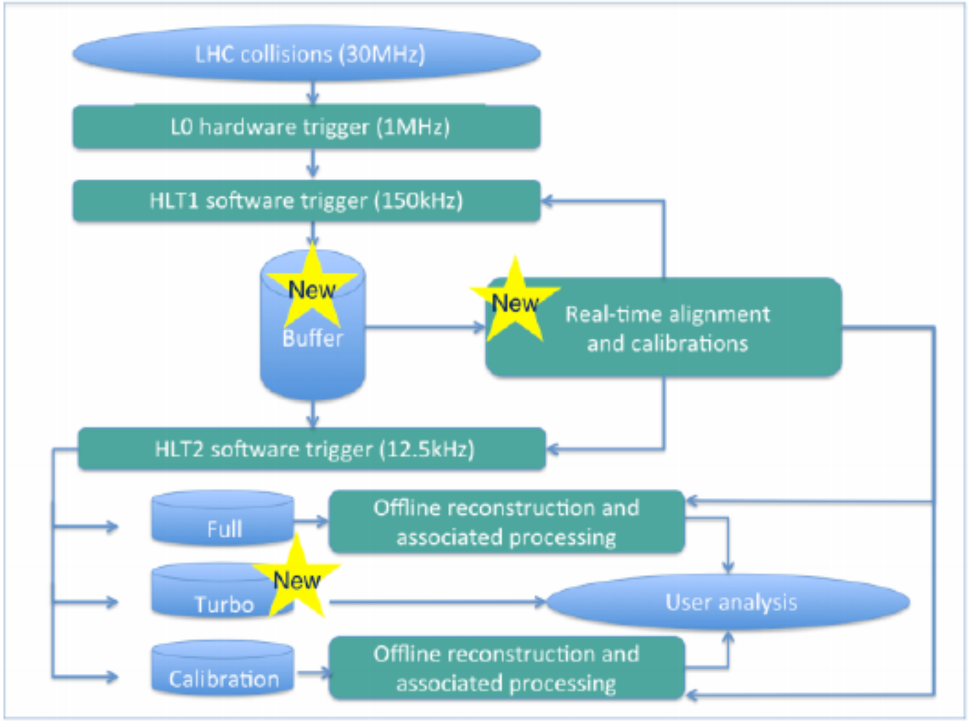


J. Olsen, L. Malgeri - Wine&Cheese - 17/04/2015

LHCb in the shutdown

Trigger in RunII

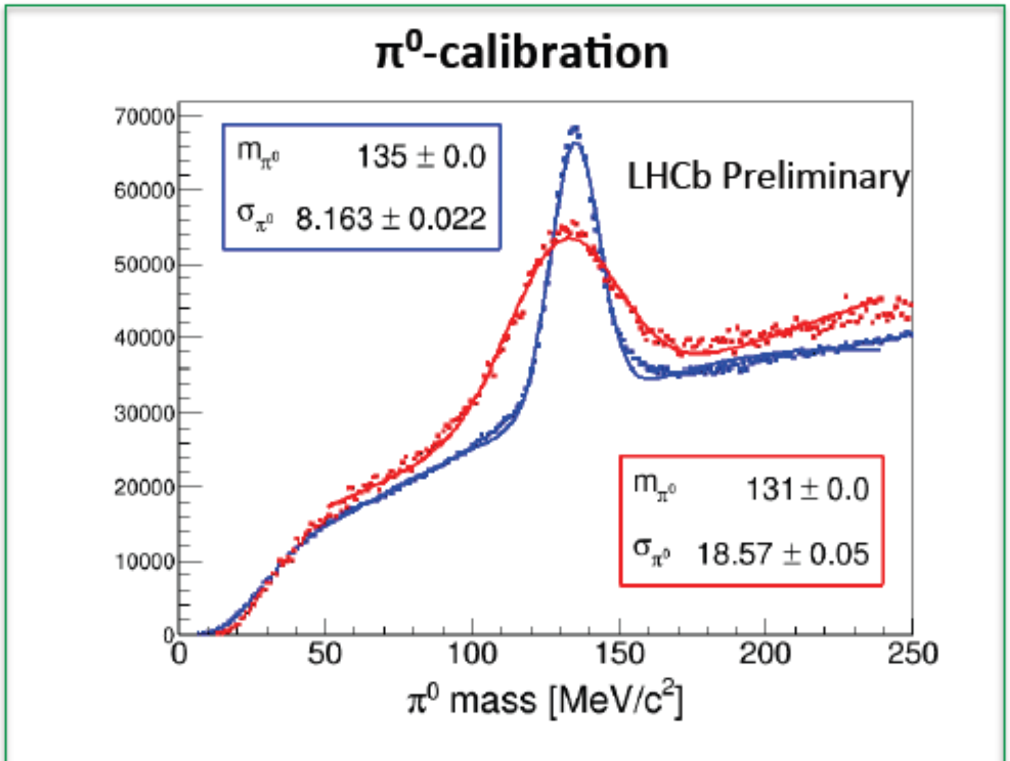
- Events from lower trigger levels can **be buffered on disk while performing real-time alignment and calibration**
- Last trigger level uses the **same reconstruction** as offline
- **Same alignment and calibration constants** used by the trigger and the offline reconstruction
- Some analysis performed directly on the trigger output



From CERN seminar B. Storaci

LHCb in the Shutdown

- **Challenging to perform calibration and alignment in real time, but has been successful e.g.**
  - π^0 calibration done every months: now it takes only few hours to produce the results



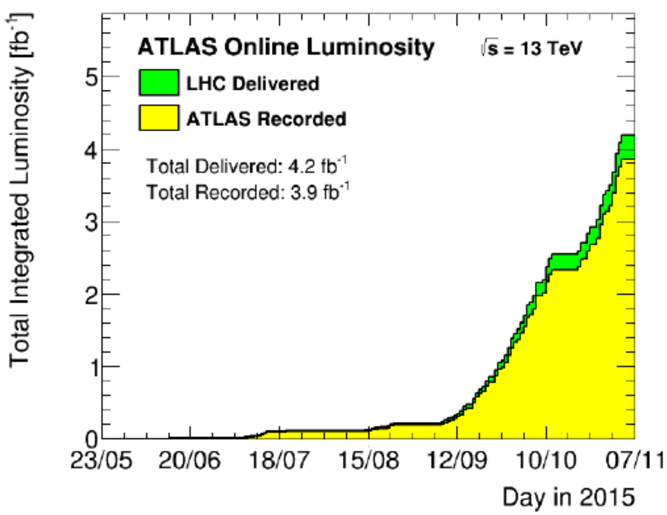
From CERN seminar B. Storaci

Prospects for Run 2

- **Expected performance in 2016:**

	Peak lumi E34 $cm^{-2}s^{-1}$	Days proton physics	Approx. int lumi [fb^{-1}]
2015	~0.5	~50	4
2016	1.2	160	~35

Goal remains to collect 100 fb^{-1} per expt (ATLAS/CMS) in Run

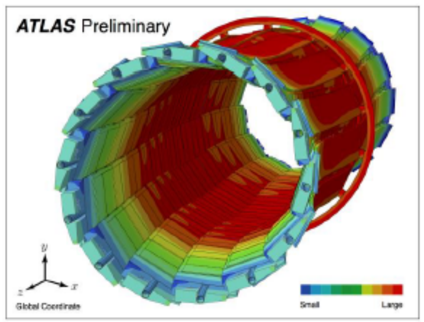


•For a full overview of the public Run 2 results see the talks at the CERN seminars for CMS and ATLAS: https://indico.cern.ch/event/442432/

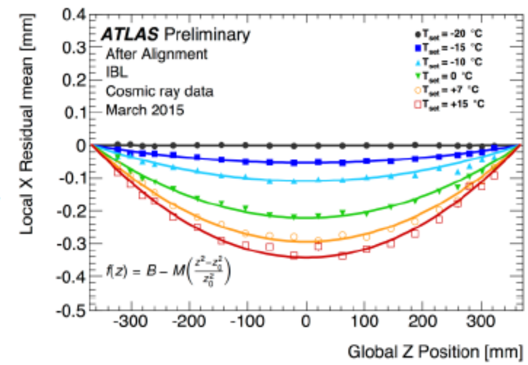
Prospects for Run 2: ATLAS and CMS

- **Some hardware challenges**
- **ATLAS**

IBL – Thermomechanical Distortion



- Issue discovered early in 2015
- Temperature dependency exhibited - O(10 μm/K)
- Direct impact on the tracking performance
- Temperature and cooling stability ok until September
- Static alignment correction was sufficient to mitigate the effects



- **CMS**

Robustness of Cryogenic system for CMS Magnet

- Much has been understood about the erratic behavior but mysteries remain.
- The first focus of the joint CMS-CERN TE task force has been increasing tolerance to contamination to maximise the "Up-Time" of the CMS magnet for Physics
  - Changes to cold-box absorbers, filters &turbines plus regular elective regeneration/ maintenance of the filters, absorbers and first heat exchanger
- This effort has resulted in:
  - ~ 3/4 of the 13 TeV luminosity delivered with the magnetic field ON
  - All reference p-p and all Pb-Pb (except today) luminosity delivered so far, with the magnetic field ON

Slides from LHCC open session

A few slides

- **Following few slides attempt to give the briefest of highlights of what will be discussed in the next three days**
  - I am sure to miss out many people's favourite topics, so take this as a sketch!

Higgs: What precision is necessary?

- **SM couplings can be modified by new physics**

$$\Gamma_i = \kappa_i^2 \, \Gamma_i^{SM}$$

- **Modifications can be small depending on the BSM scenario (Snowmass report)**
  - For new physics at the 1TeV mass scale:

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

arXiv:1310.8361

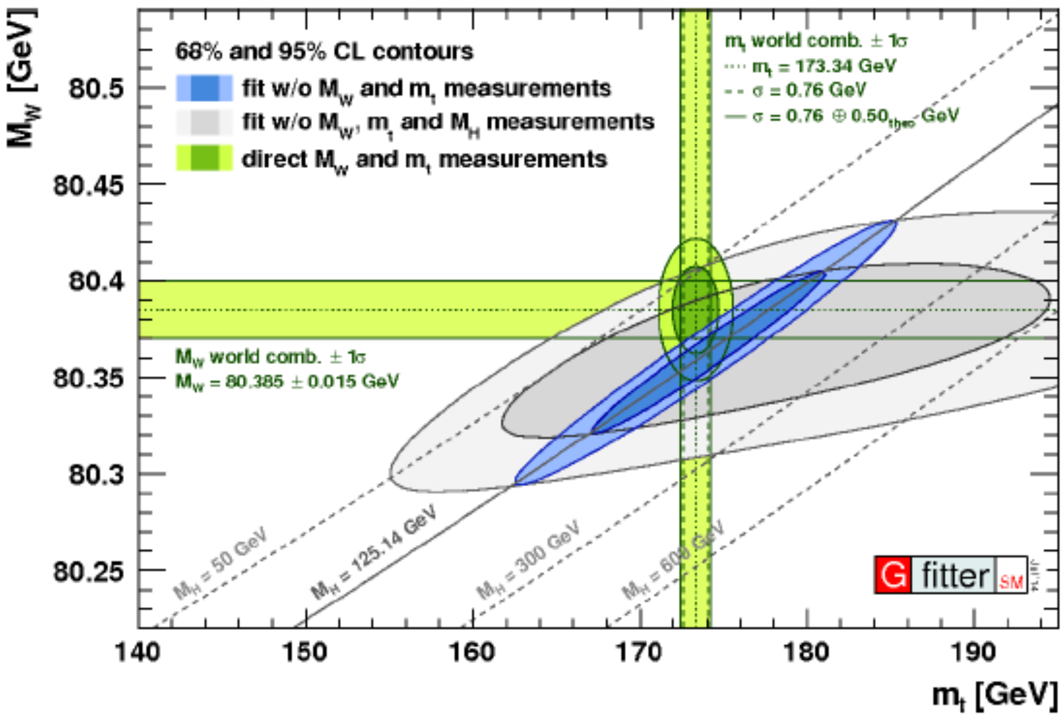
  - Higher scales imply smaller effects

Higgs: Prospects for ATLAS and CMS

- **Full measurement of the key properties of this new boson will take some time to establish**
  - The Higgs-fermion sector is relatively unknown but Run 2 will close in on it
- **Key to characterising this particle are**
  - Production and decay rates (to greater precision)
    - Original discoveries of order 10-20% uncertainties
    - Run 2 will take us to order 5-7% uncertainties and theory predictions improving all the time too
    - Probe fermion sector not only with higher statistics but with new mechanisms e.g. ttH, Look for Higgs to mumu
  - Intrinsic quantum numbers
- **Switch from search mode to precision physics**
  - Emphasis on publishing what we measure in pure form (think about EFT, simplified cross-section)

Top/Searches prospects for Run 2

- **Top**
  - Measure cross-section and properties more accurately, especially single top
- **Searches**



- We (LHC/CMS) are already doing pretty well in M_{top}.
- M_W might be the next (big) challenge. Tevatron did great and much better than expected
- Need to keep an eye on it and prepare for Run2!

CMS wine and cheese, Olsen and Malgeri

ck

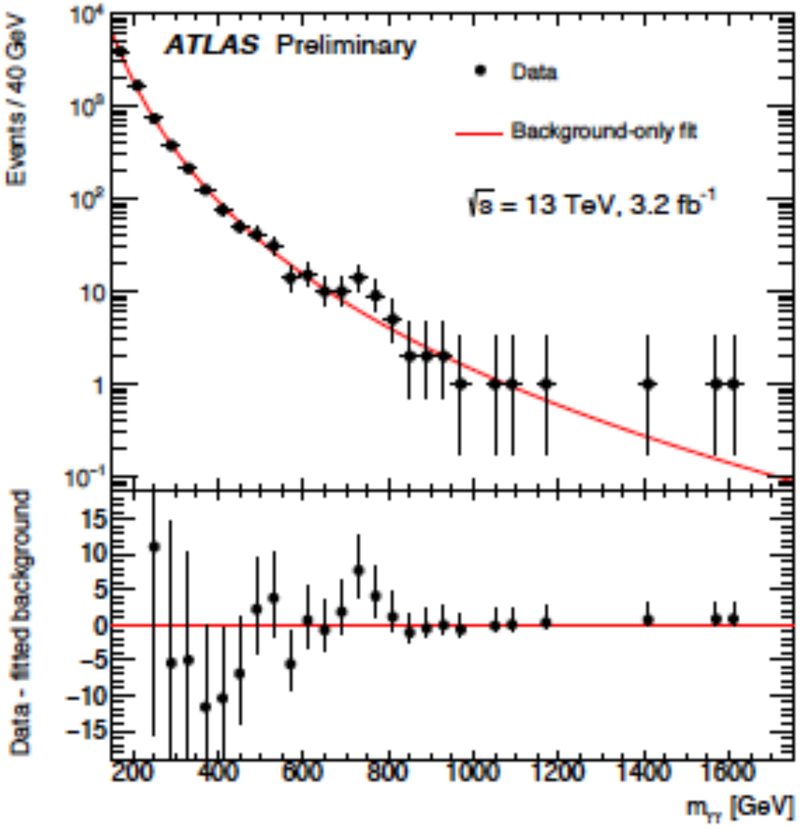
Prospects for Run 2: LHCb

- Will go impressively further into precision SM measurements
- Statistical uncertainties for Run 2

Type	Observable	LHC Run 1	LHCb 2018
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025
	$\phi_s(B_s^0 \to J/\psi\ f_0(980))$ (rad)	0.068	0.035
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13
	$2\beta^{\rm eff}(B^0 \to \phi K_{\rm S}^0)$ (rad)	0.30	0.20
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020
	$q_0^2\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°
	$\beta(B^0 \to J/\psi\,K_{\rm S}^0)$	1.7°	0.8°
Charm CP violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2
	ΔA_{CP} (10^{-3})	0.8	0.5

Hints from Early Run 2

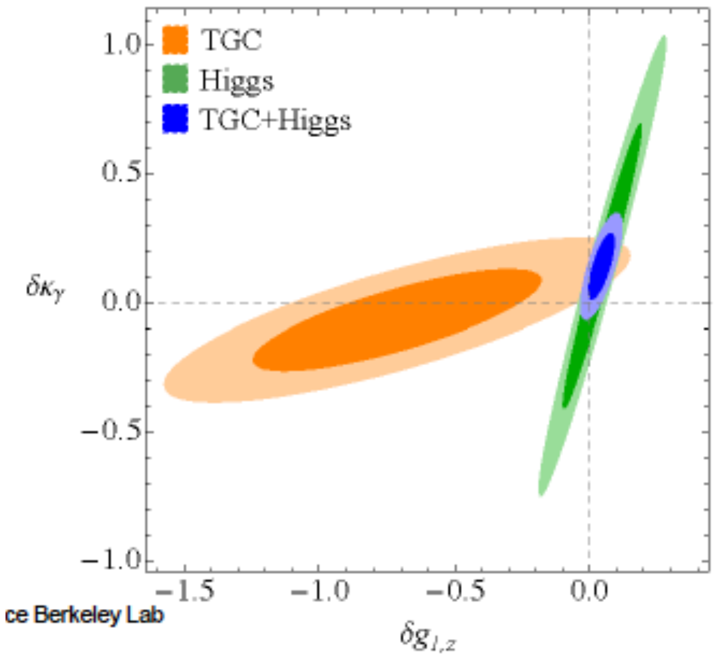
- **Diphotons**
  - See 2 σ bump around 750 GeV
    - But two sigma effects come and go… (e.g. dijets excess was 2.5 σ in run 1 and has gone in run 2)

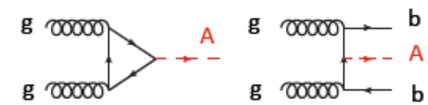


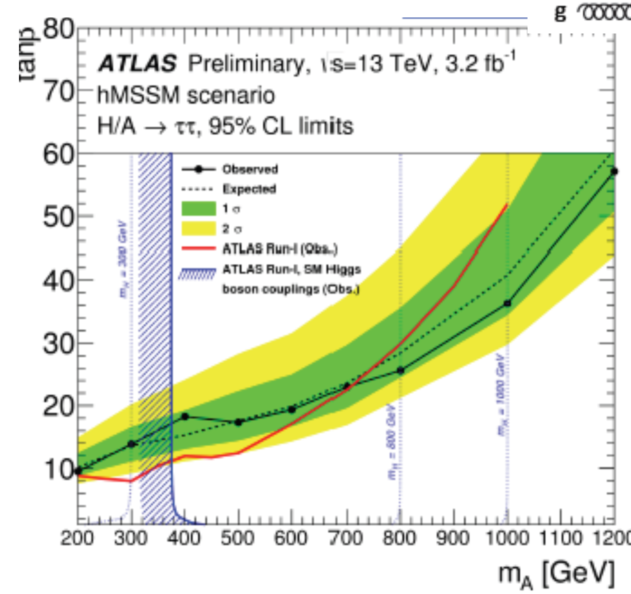
Final Remarks

- **LHC continues to live up to its role as the energy frontier collider and deliver results that constitute**

  - Precision measurements -Powerful searches (with relatively small amounts of data)







- **The next couple of days here at YETI will be very interesting**
  - Impossible to predict which sector will yield the interesting results

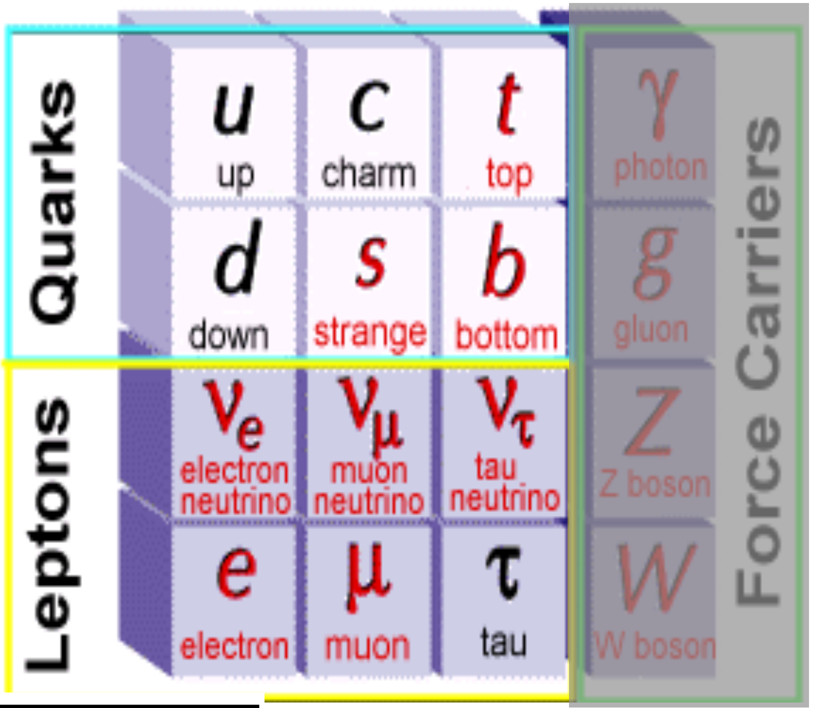
Thanks to Tim Gershon (LHCb) and Sam Harper (CMS) for help finding material

Discussion Topics

- What sets the scale of the detectors?
- Why have a dedicated flavour physics detector?
- Why is LHCb a forward-only detector (and why only one arm?)?
- What sets the lifetime of the detectors?
- What constitutes a useful measurement (from a theorist perspective)?

Matter Particles

- We see three generations
  - Undergoing similar interactions
  - Mass hierarchy
  - Each has an antiparticle



First Generation		2nd Generation		3rd Generation		Charge e
Electron Neutrino	ν_e	Muon neutrino	ν_μ	Tau neutrino	ν_τ	0
Electron	e-	Muon	μ-	Tau	τ-	-1
Up quark	u	Charm quark	c	Top quark	t	+2/3
Down quark	d	Strange quark	s	Bottom quark	b	-1/3

Forces

• In the Standard Model, we depict (and calculate) forces as the exchange of a force-carrier boson, between particles