Physics at the Large Hadron Collider

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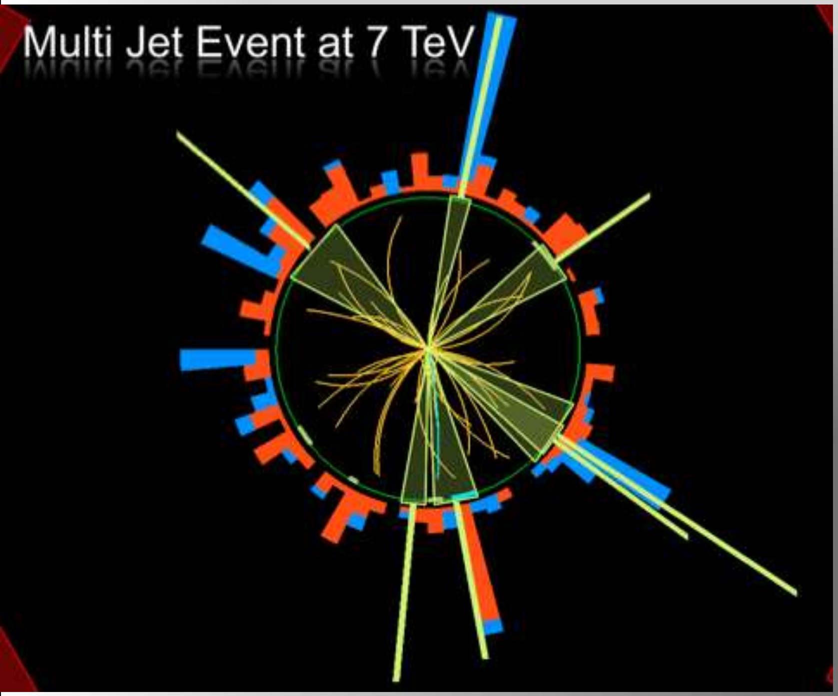
Lecture Plan

Overview of the 2 lectures in the next days

- Lecture 1: Introduction to Experimental Techniques at the LHC & Measurements and test of the Standard Model
- Lecture 2: The Higgs boson and Searches beyond the Standard Model, and a short outlook to the future at the LHC

Outline Lecture I

- Introduction: Experimental Particle Physics
- The Large Hadron Colider
- Experiments at the LHC
- Experimental Challenges
- Experimental Objects
- Basics of experimental pp collisions
- Standard Model Measurements
- Summary



Disclaimer:
ATLAS & CMS have very similar results
Typically one chosen for illustration

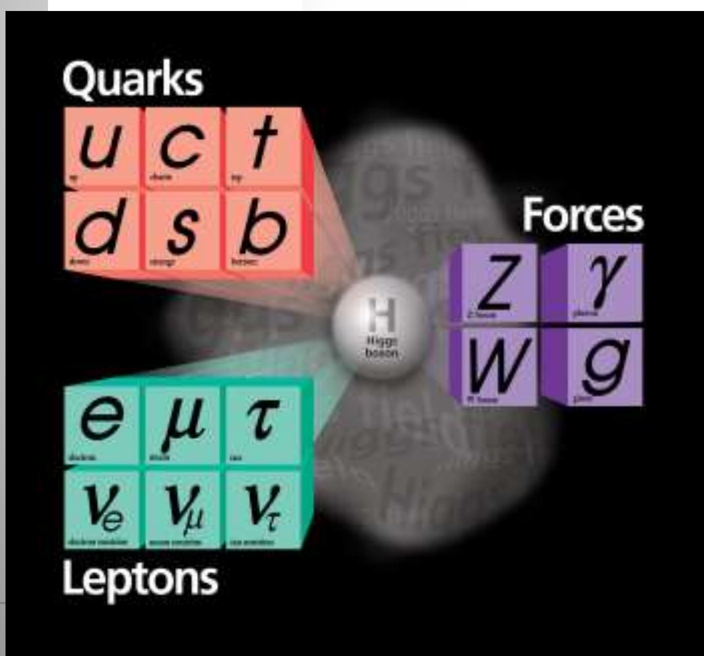

What is the world made of?
What holds the world together?
Where did we come from?

The “Standard Model”

Over the last 100 years: combination of
Quantum Mechanics and Special Theory of relativity
along with all new particles discovered has led to the
Standard Model of Particle Physics.
The new (final?) “Periodic Table” of fundamental elements:

Fermions Bosons

Matter particles



Force particles

The most basic mechanism of the SM, that of granting mass to particles remained a mystery for a long time
A major step forward was made in July 2012 with the discovery of what could be the long-sought Higgs boson!!

Fermions: particles with spin ½
Bosons: particles with integer spin

CERN: founded in 1954: 12 European States

"Science for Peace"

Today: 23 Member States

~ 2500 staff
~ 1800 other paid personnel
~ 13000 scientific users

Budget (2018) ~ 1150 MCHF

Member States: Austria, Belgium, Bulgaria, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, Netherlands, Norway, Poland, Portugal, Romania, Slovak Republic, Spain, Sweden, Switzerland and United Kingdom, Serbia

Associate Members in the Pre-Stage to Membership: Cyprus, Slovenia

Associate Member States: India, Lithuania, Pakistan, Turkey, Ukraine

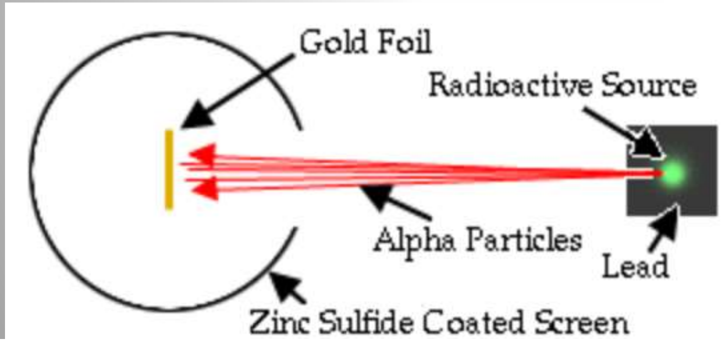
Applications for Membership or Associate Membership: Brazil, Croatia

Observers to Council: Japan, Russia, United States of America; European Union, JINR and UNESCO

High Energy Physics Experiments

First High Energy Physics Experiments:

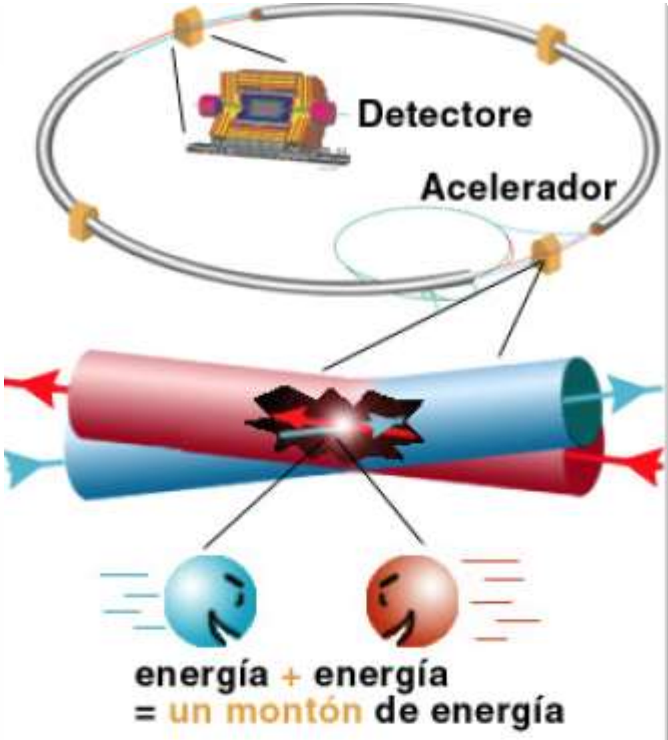
Beam on fixed target!



Rutherford experiment (1909)

High Energy Physics Experiments since mid 70's:

Colliding beams!



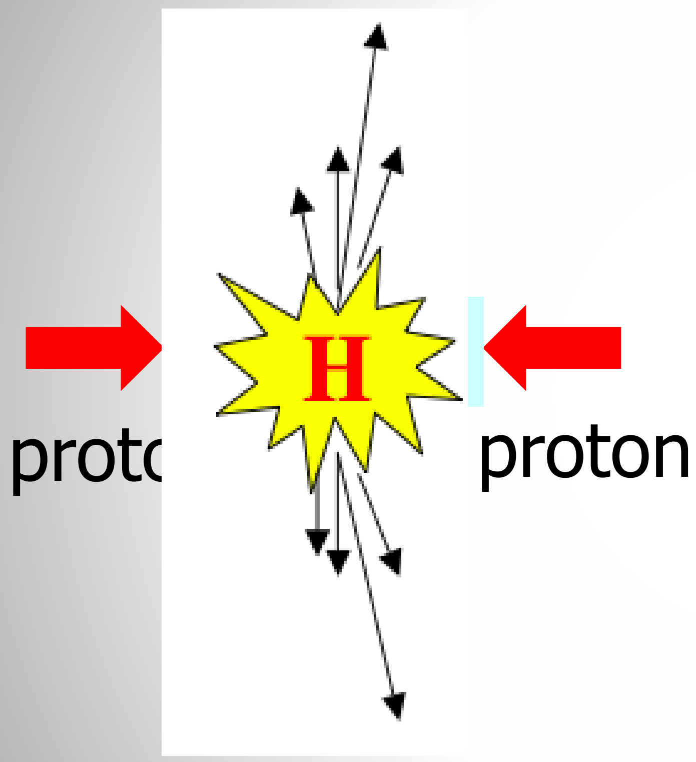
Centre of mass energy squared $s=2E_1m_2$

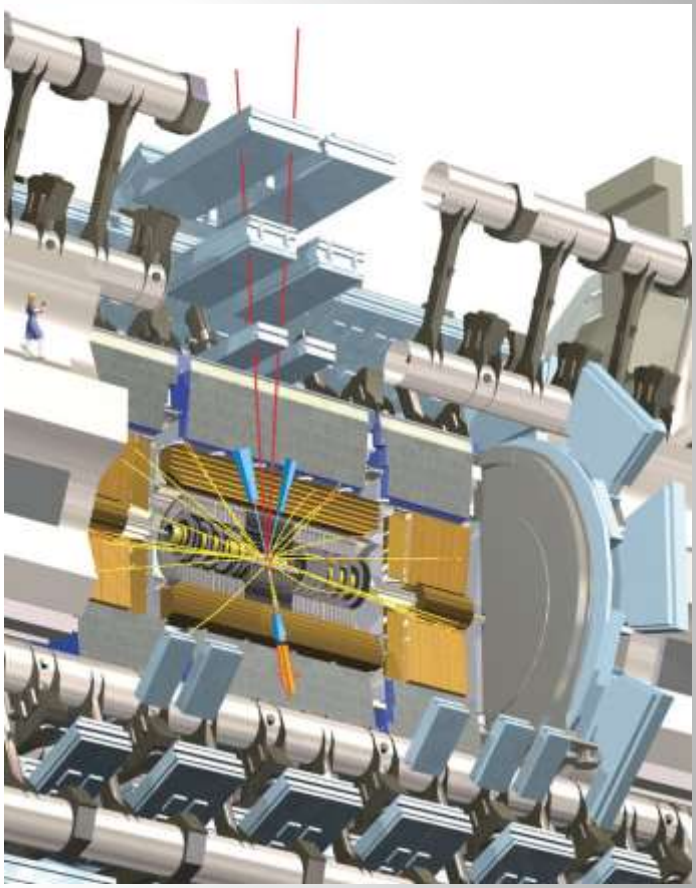
Centre of mass energy squared $s=4E_1E_2$

…plus secondary beams such as neutrinos…

LHC: The Higgs Particle

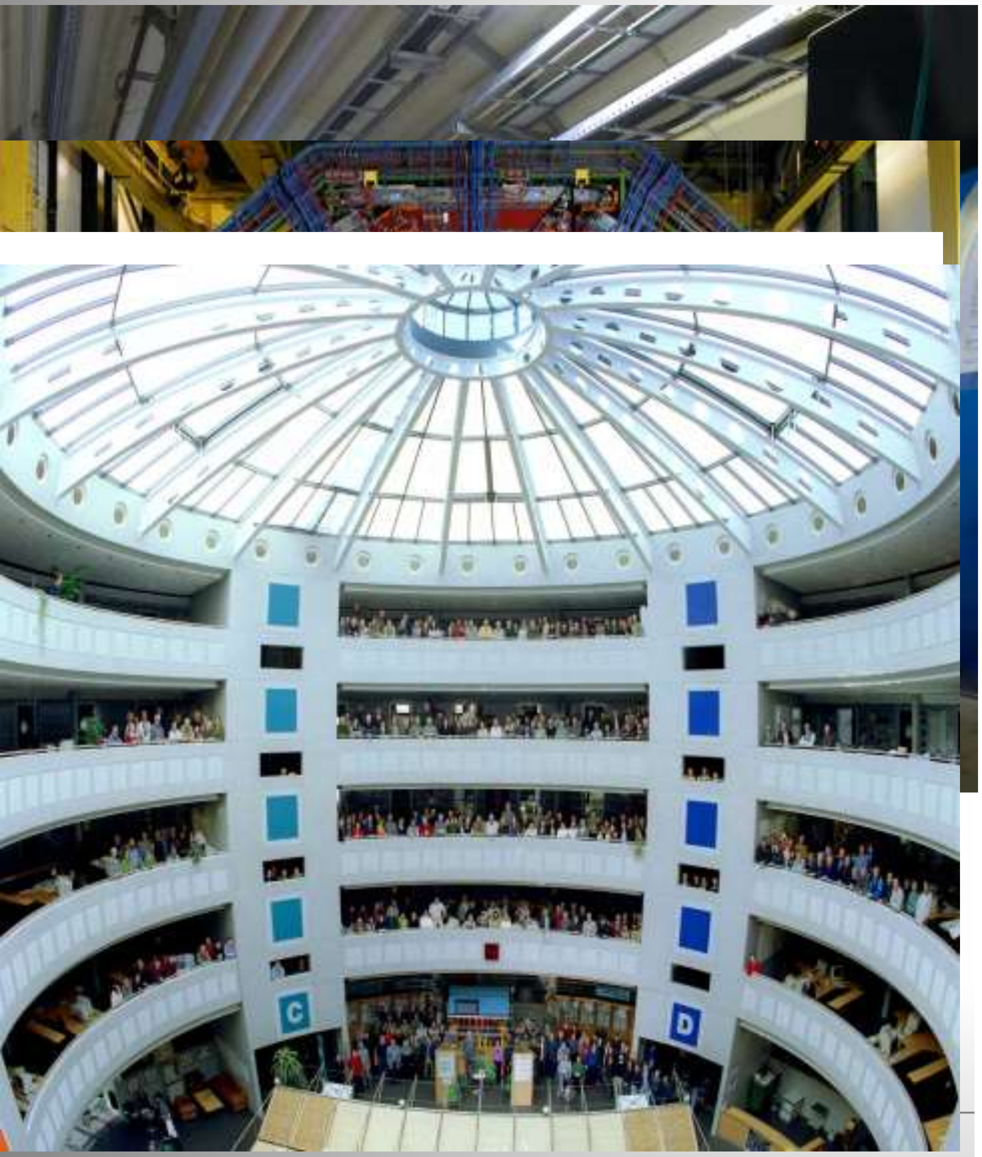
Technique: Produce and detect Higgs Particles at Particle Colliders





Experimental view…

This Search Requires…….



1. Accelerators : powerful machines that accelerate particles to extremely high energies and bring them into collision with other particles

2. Detectors : gigantic instruments that record the resulting particles as they "stream" out from the point of collision.

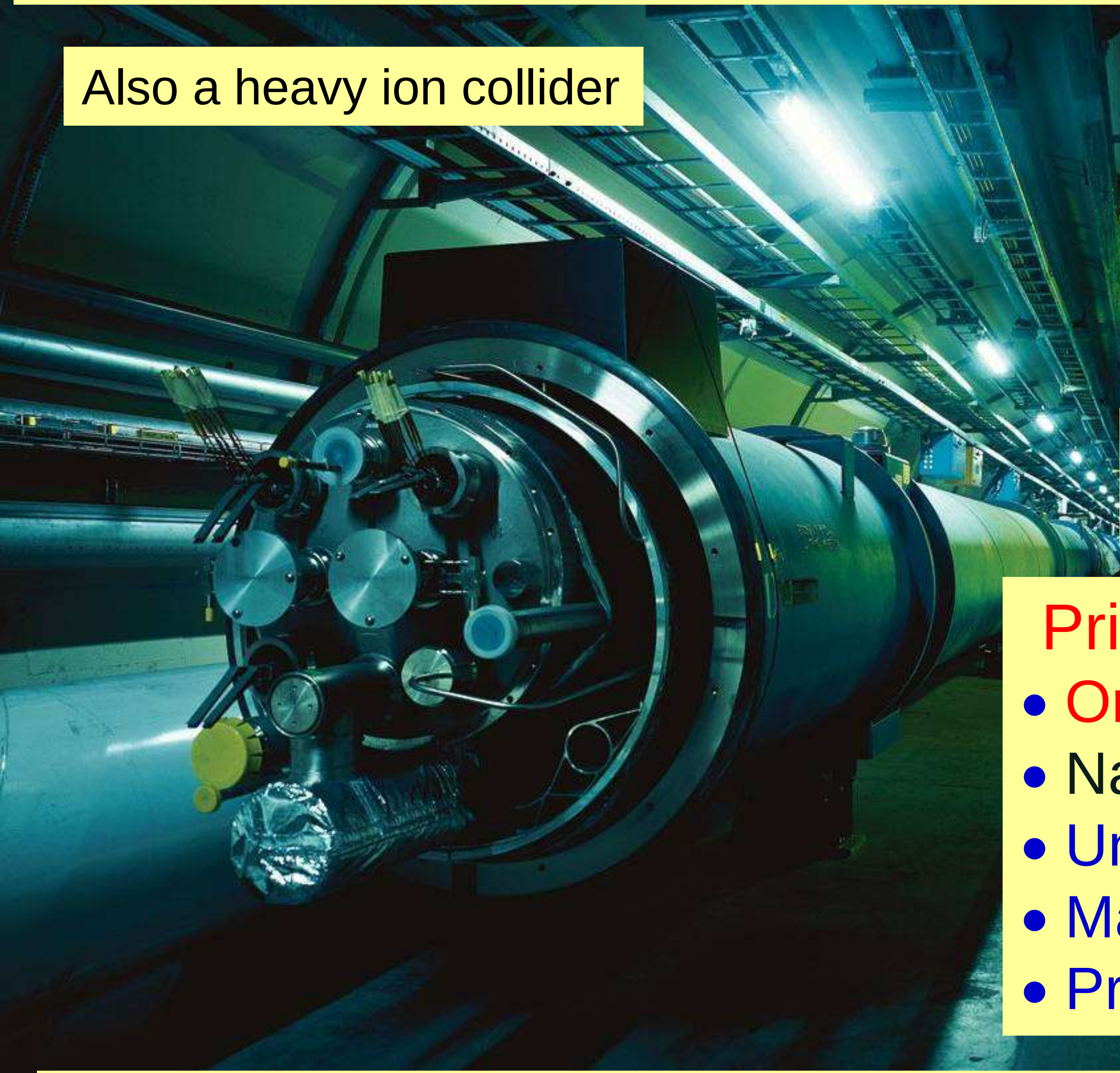
3. Computing : to collect, store, distribute and analyse the vast amount of data produced by these detectors

4. Collaborative Science on Worldwide scale : thousands of scientists, engineers, technicians and support staff to design, build and operate these complex "machines".

The Large Hadron Collider…

The Large Hadron Collider = a proton proton collider

Also a heavy ion collider



7 TeV + 7 TeV
6.5 TeV + 6.5 TeV
(4/3.5 TeV + 4/3.5 TeV)

1 TeV = 1 Tera electron volt
= 10^{12} electron volt

Primary physics targets

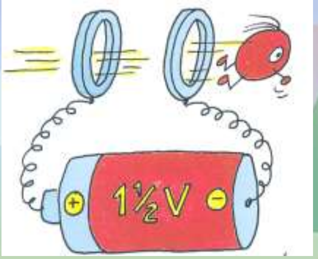
- Origin of mass
- Nature of Dark Matter
- Understanding space time
- Matter versus antimatter
- Primordial plasma

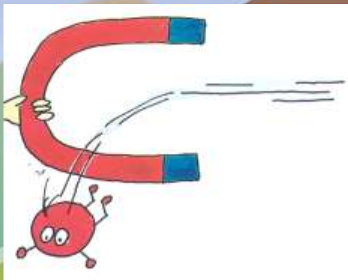
The LHC is a Discovery Machine

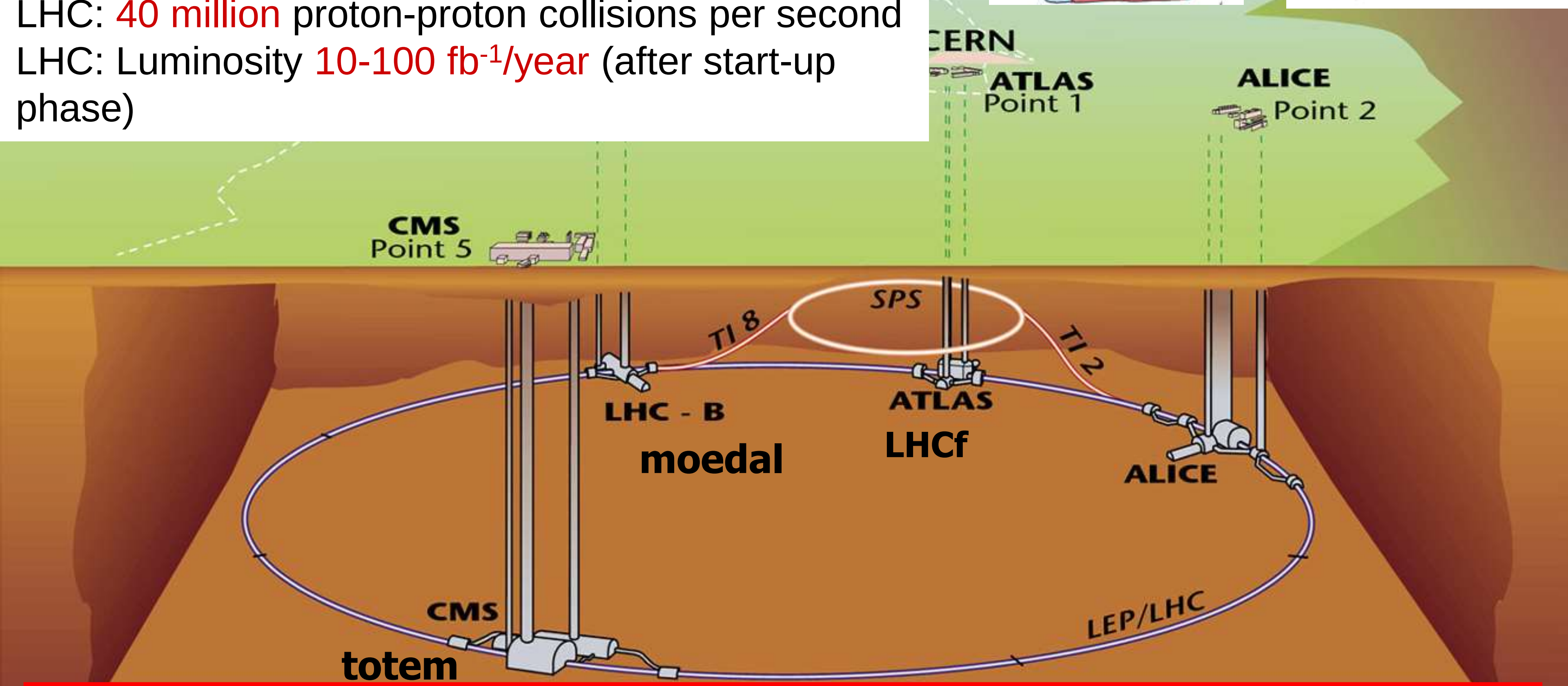
Will LHC determine the future course of High Energy Physics?

The LHC Machine and Experiments

LHC is 100m underground
LHC is 27 km long
Magnet Temperature is 1.9 Kelvin = -271 Celsius
LHC has ~ 9000 magnets
LHC: 40 million proton-proton collisions per second
LHC: Luminosity 10-100 fb^{-1}/year (after start-up phase)

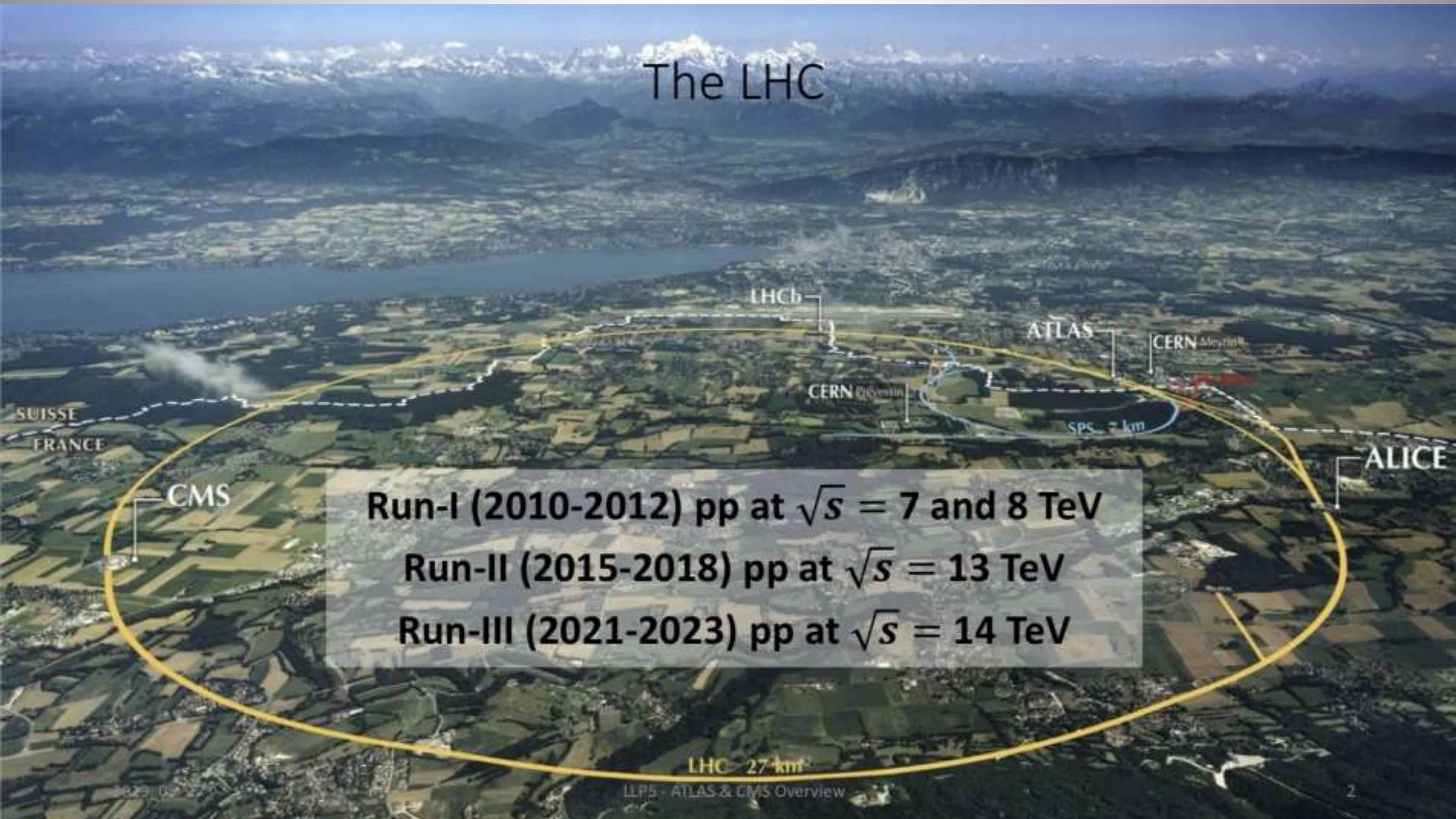


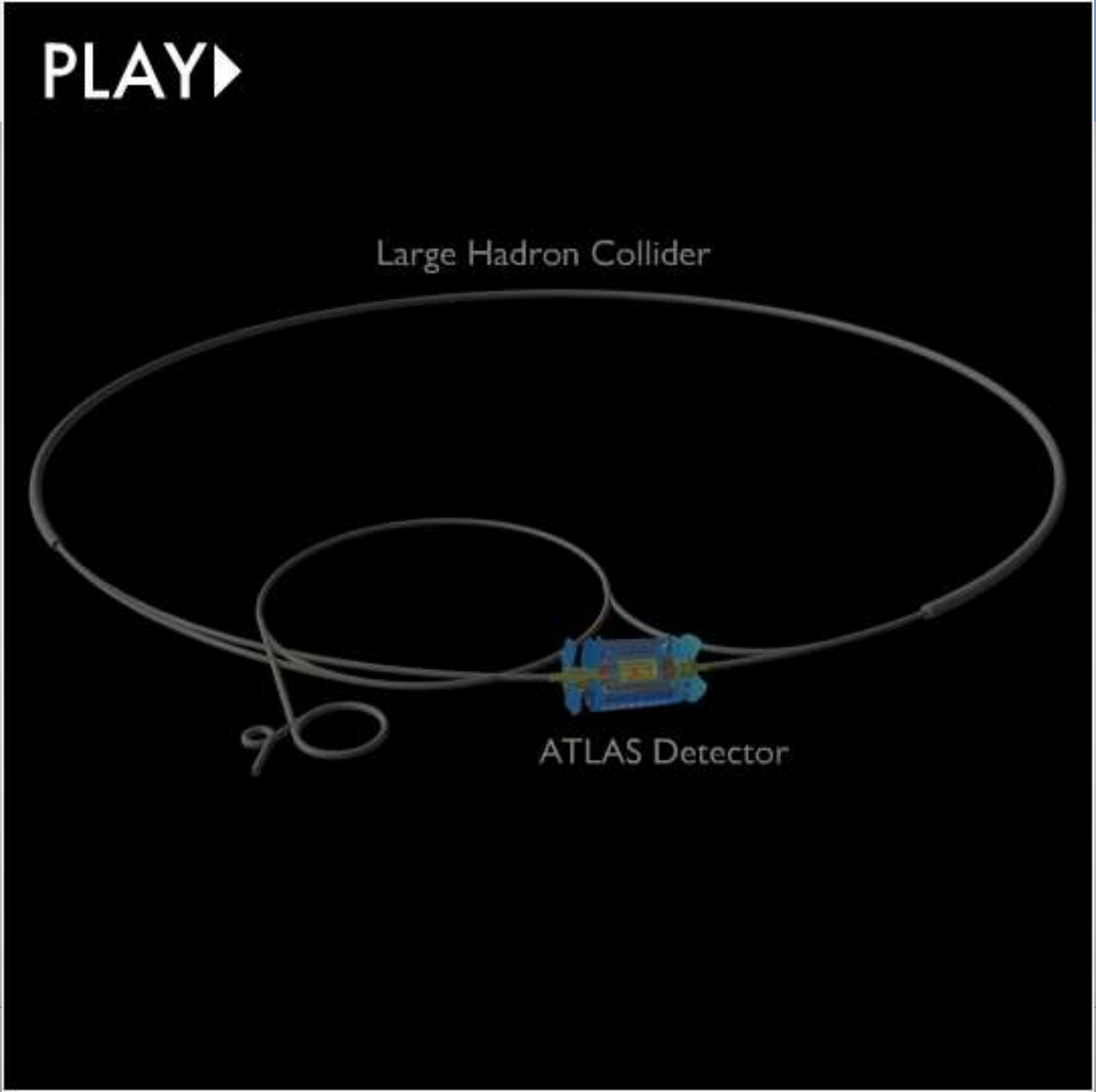




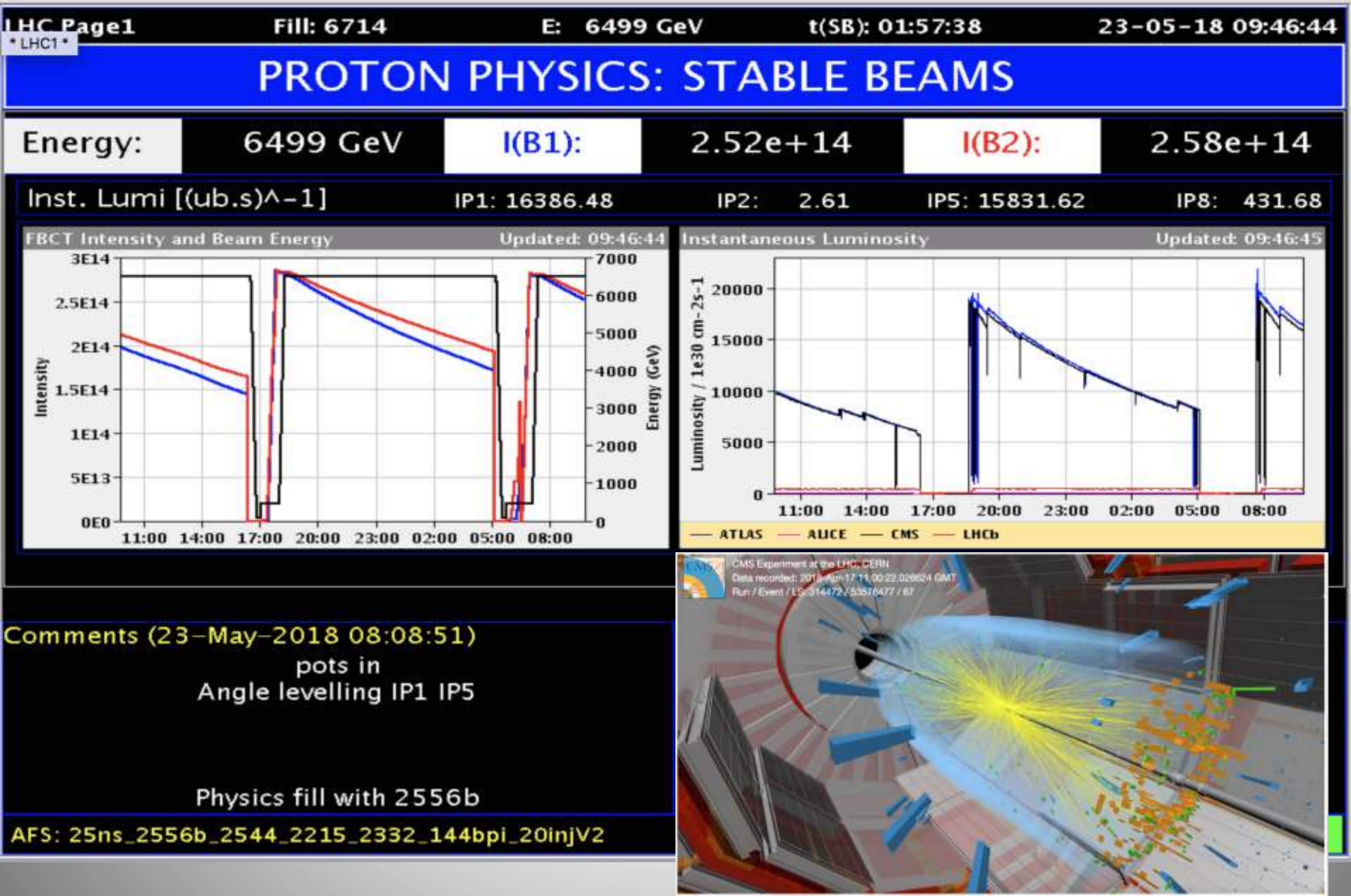
- High Energy ⇒ factor 7 increase w.r.t. past accelerators
- High Luminosity (# events/cross section/time) ⇒ factor 100 increase

LHC Running


The LHC
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
Run-I (2010-2012) pp at $\sqrt{s} = 7$ and 8 TeV
Run-II (2015-2018) pp at $\sqrt{s} = 13$ TeV
Run-III (2021-2023) pp at $\sqrt{s} = 14$ TeV
LHC 27 km
LLP5 - ATLAS & CMS Overview
2

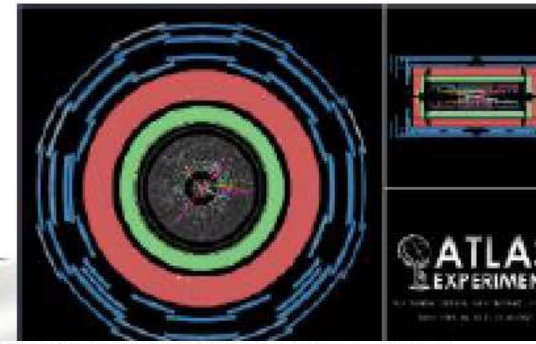

PLAY
Large Hadron Collider
ATLAS Detector

Example: LHC Operation 2018:

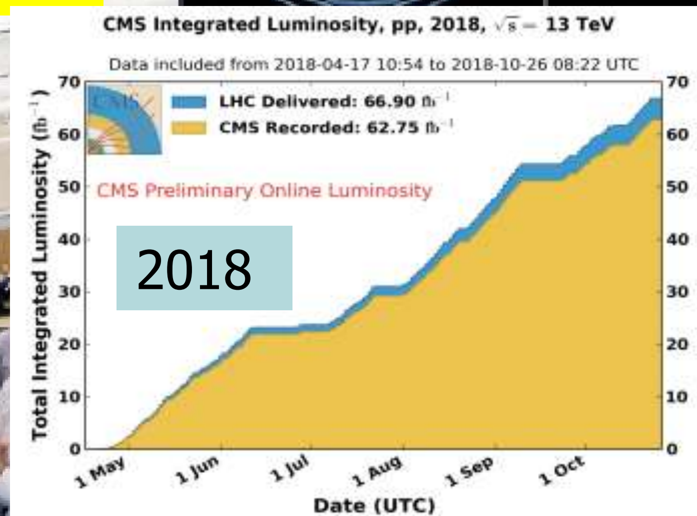


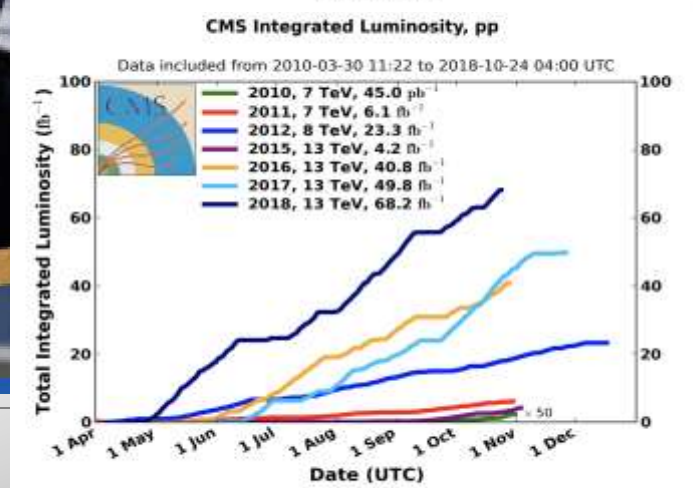
LHC experiments are back in business at a new record energy 13 TeV

3rd June 2015 Run-2 starts



proton-proton Run-2 finished 24/10/18 6:00am





- 2010-2012: Run-1 at 7/8 TeV CM energy
  - Collected ~ 27 fb^{-1}
- 2015-2018: Run-2 at 13 TeV CM Energy
  - Collected ~ 150 fb^{-1}

LHC Highlights

- LHC switched on at 7 TeV in March 2010

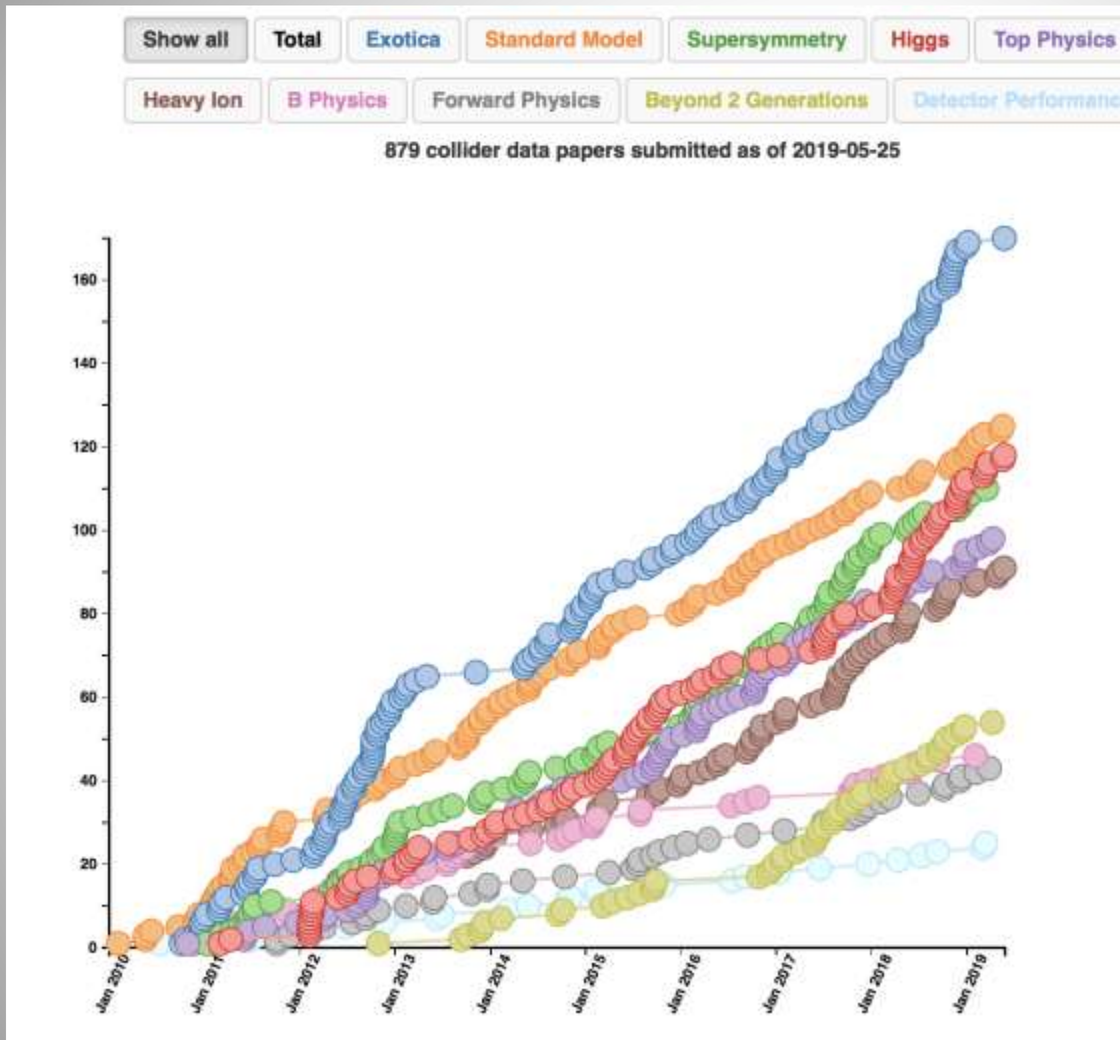
  ->The highest energy in the lab!
- LHC @ 13 TeV from 2015 onwards
- Most important highlight so far:

  The discovery of a Higgs boson
- Many results on Standard Model process measurements, top-physics, b-physics, heavy ion physics, searches, Higgs physics
- Waiting for the next discovery…
  -> Searching beyond the Standard Model

March 30 2010 …waiting..
…since 4:00 am

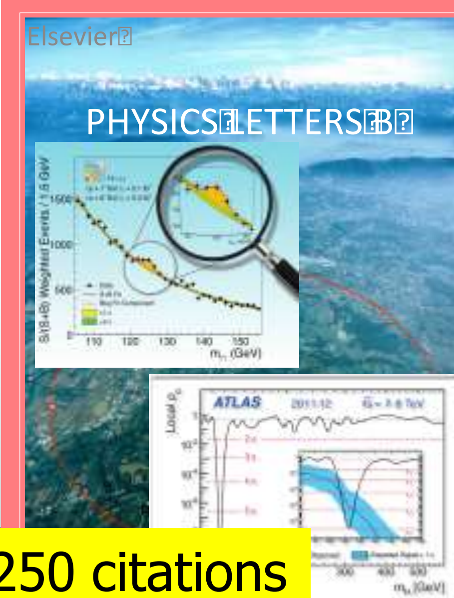
12:58 7 TeV collisions!!!

LHC Publications: Example CMS



~ 880 publications on pp (and pPb/PbPb) physics since 1/2010

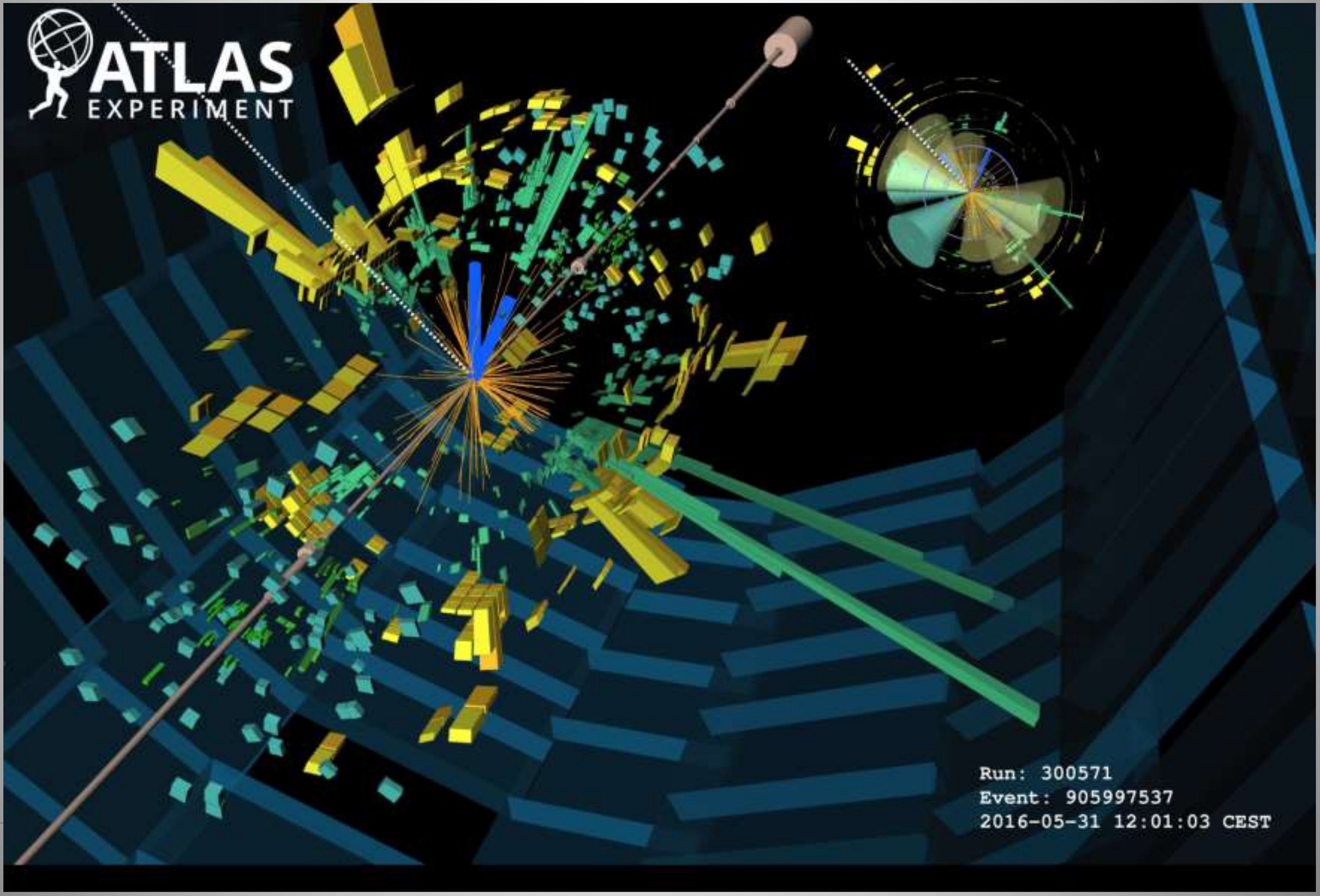
About 100 papers on Higgs studies!!
Paper 16 was the discovery paper!



>9250 citations

http://cms-results.web.cern.ch/cms-results/public-results/publications-vs-time/

Collision in the ATLAS Detector



Experiments at the LHC

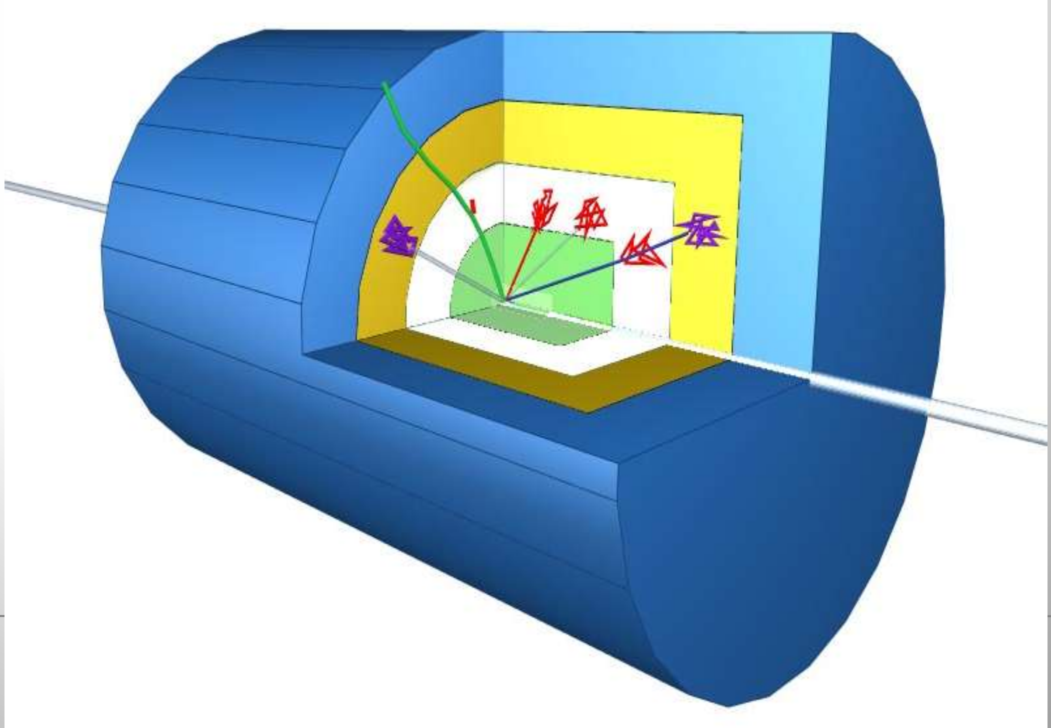
Schematic of a LHC Detector

Physics requirements drive the design!

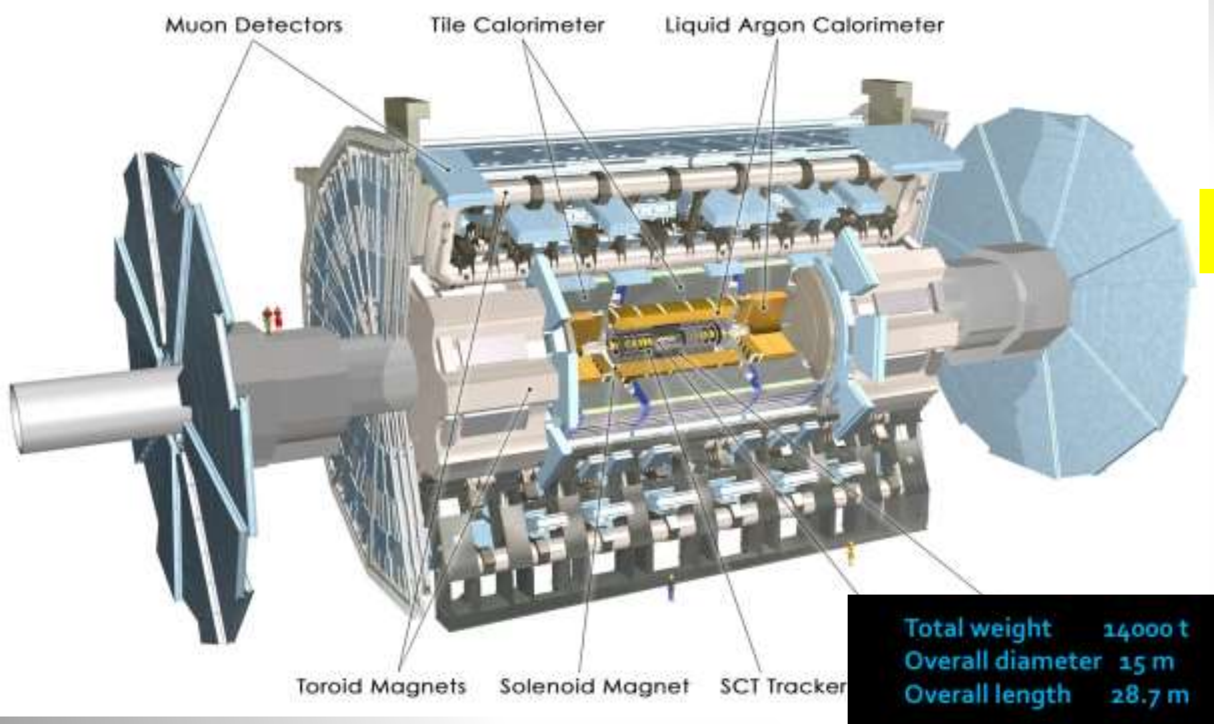
Analogy with a cylindrical onion:

Technologically advanced detectors comprising many layers, each designed to perform a specific task.
Together these layers allow us to identify and precisely measure the energies and directions of all the particles produced in collisions.

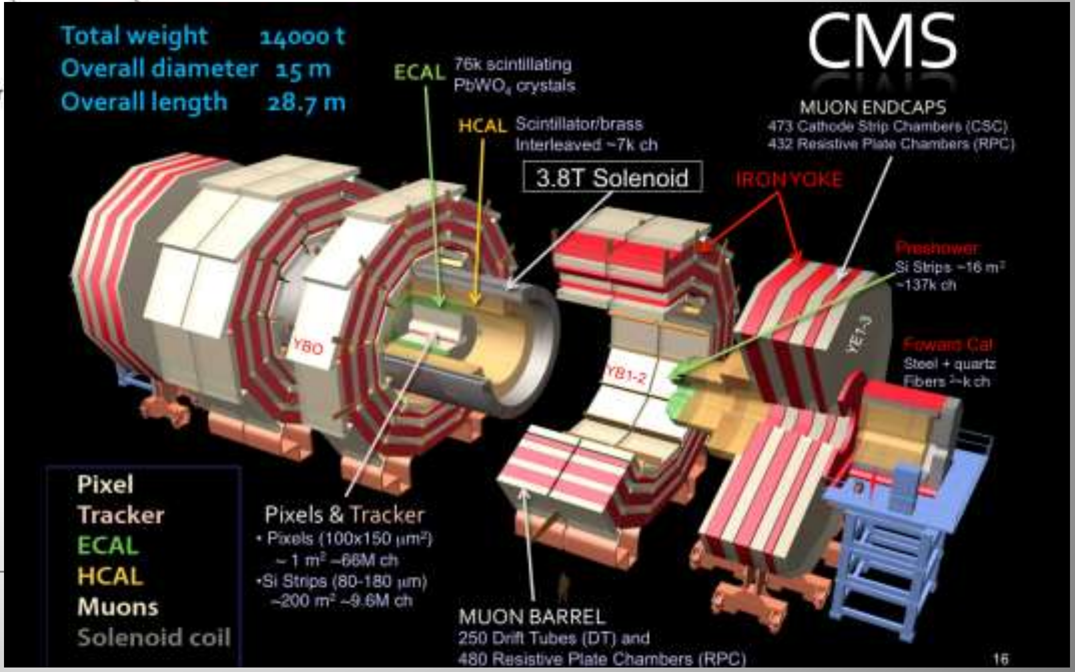
Such an experiment has ~ 100 Million read-out channels!!



The Higgs Hunters @ the LHC



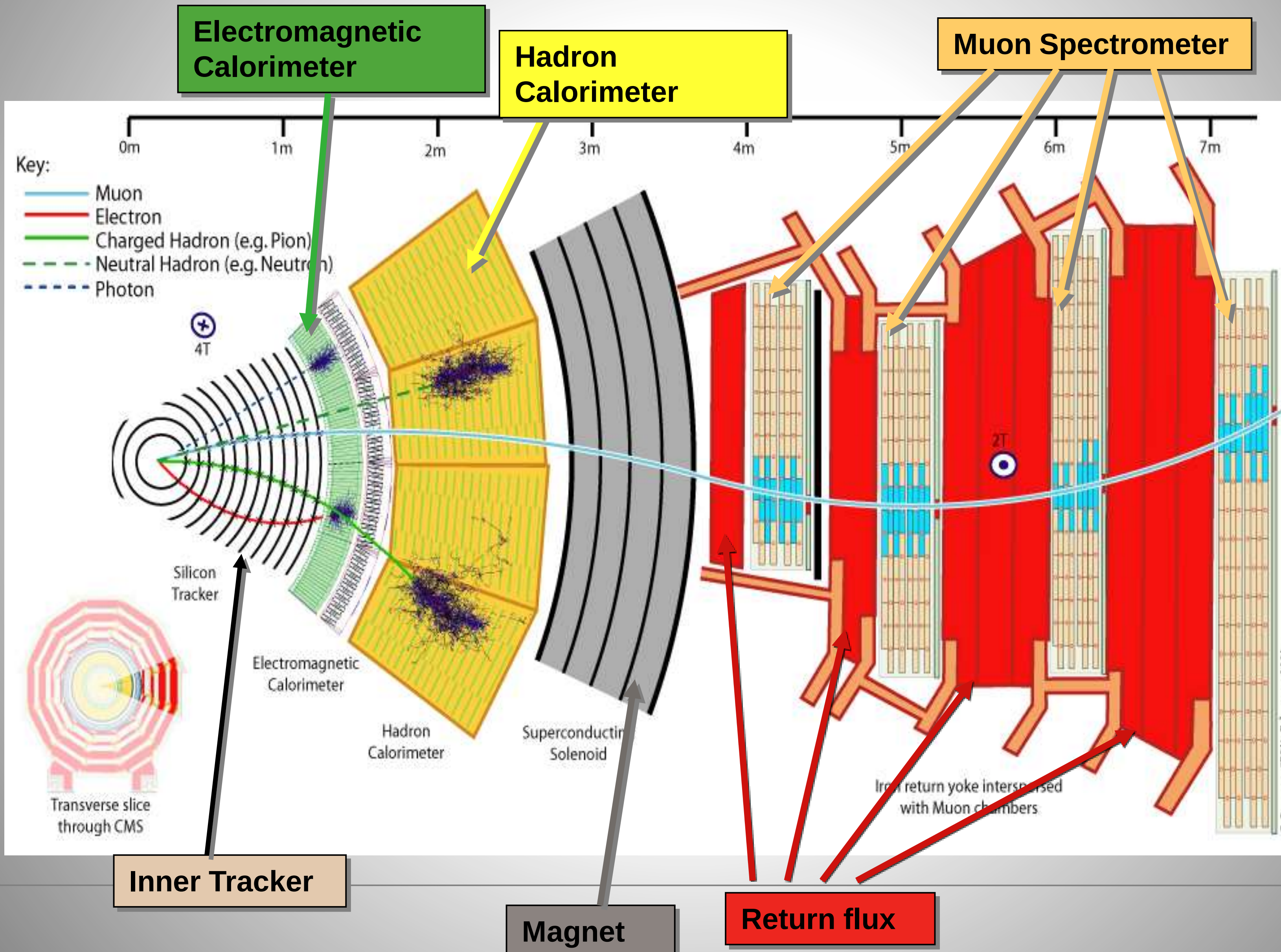
The ATLAS experiment



The CMS experiment

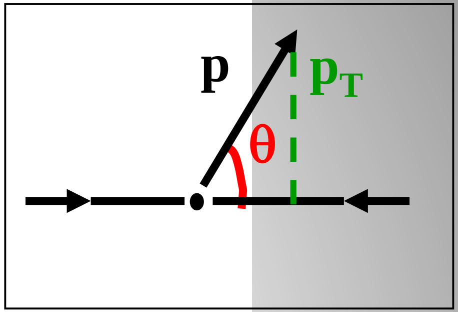
These experiments use different technologies for their detector components

Particles in Detectors



Kinematic Variables for pp Scattering

- Transverse momentum, p_T and $E_T = E \sin\theta$
  - Particles that escape detection (0) have $p_T = 0$
  - Visible transverse momentum =0
    - Very useful variable!
- Longitudinal momentum and energy, p_z and E
  - Particles that escape detection have large p_z
  - Visible p_z is not conserved
    - Not so useful variable
- Angle:
  - Polar angle θ is not Lorentz invariant
  - Rapidity: y
  - Pseudorapidity: η

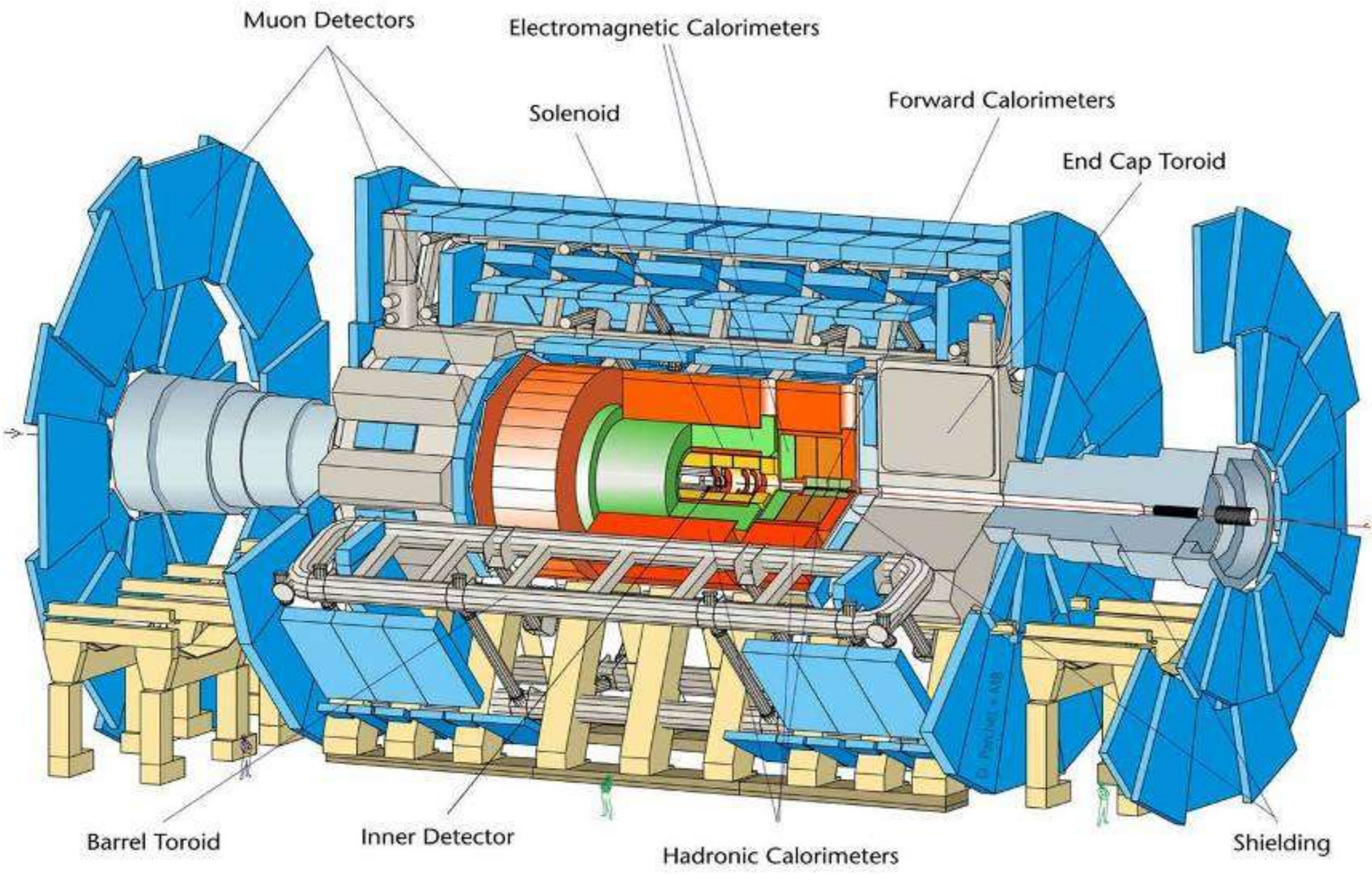


$$y = \frac{1}{2}\ln\frac{E + p_z}{E - p_z}$$

For M=0

$$y = \eta = -\ln(\tan\frac{\theta}{2})$$

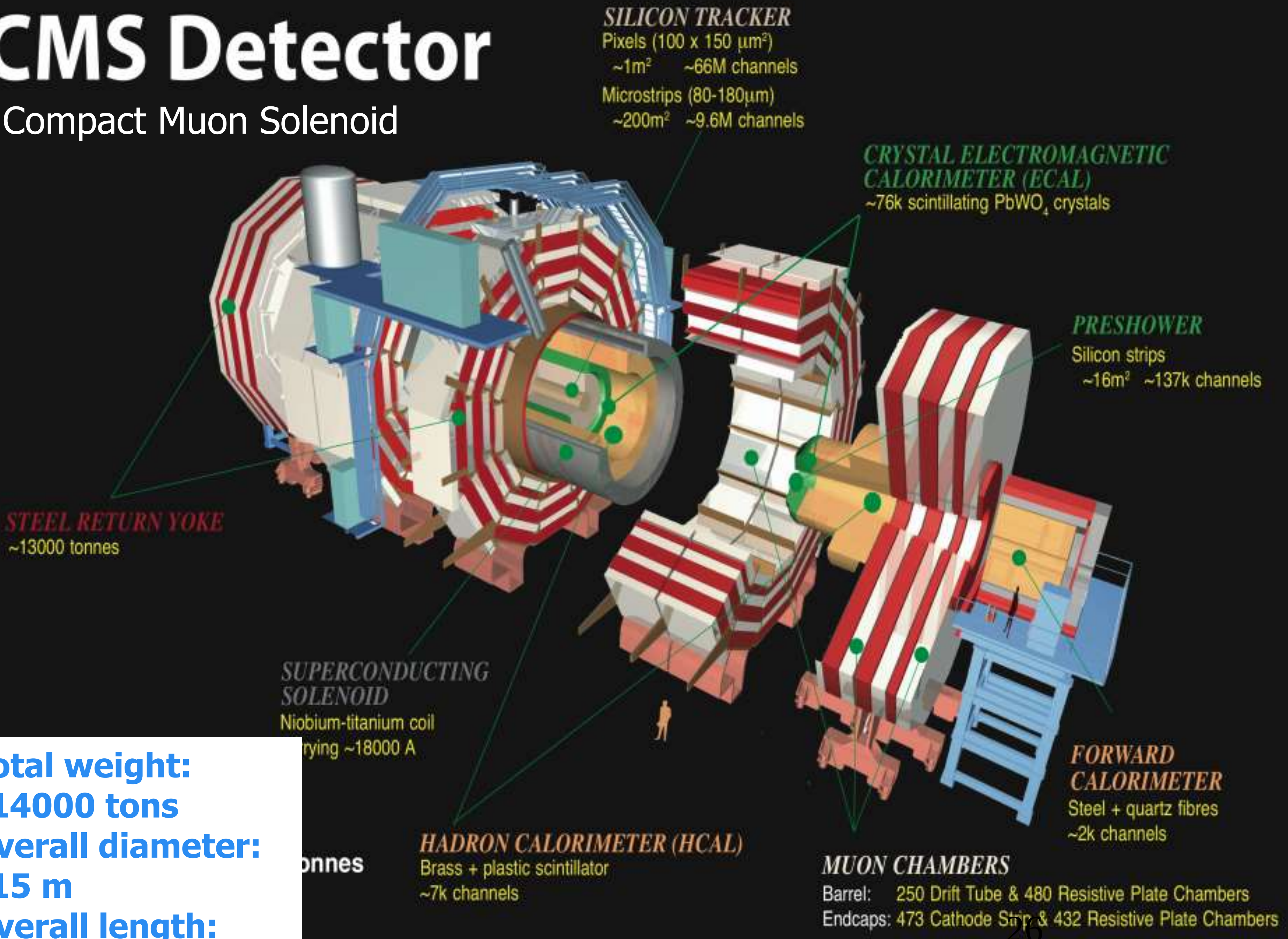
- Missing E_T and P_T: : Vectorial sum of all transverse momenta



Length = 55 m; Width = 32 m; Height = 35 m; but spatial precision ~ 100 μm

CMS Detector

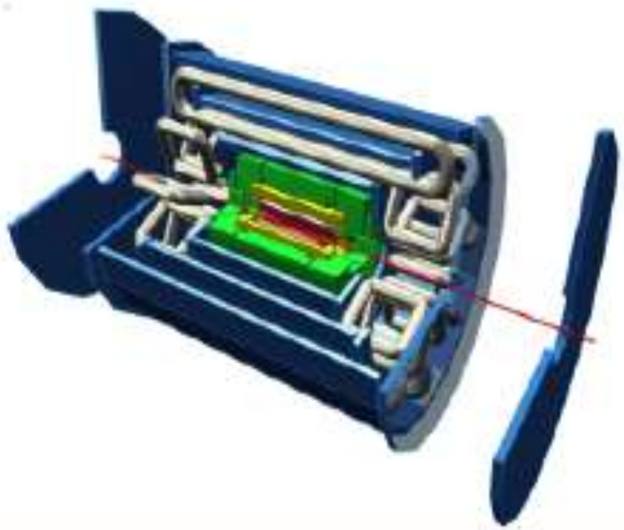
Compact Muon Solenoid



Total weight:
14000 tons
Overall diameter:
15 m
Overall length:
28.7m

General Purpose Detectors at LHC

ATLAS A Toroidal LHC ApparatuS



CMS Compact Muon Solenoid

In total about

~100 000 000 electronic channels

Each channel checked

40 000 000 times per second (collision rate is 40 MHz)

Amount of data of just one collisions

~1 000 000 Bytes

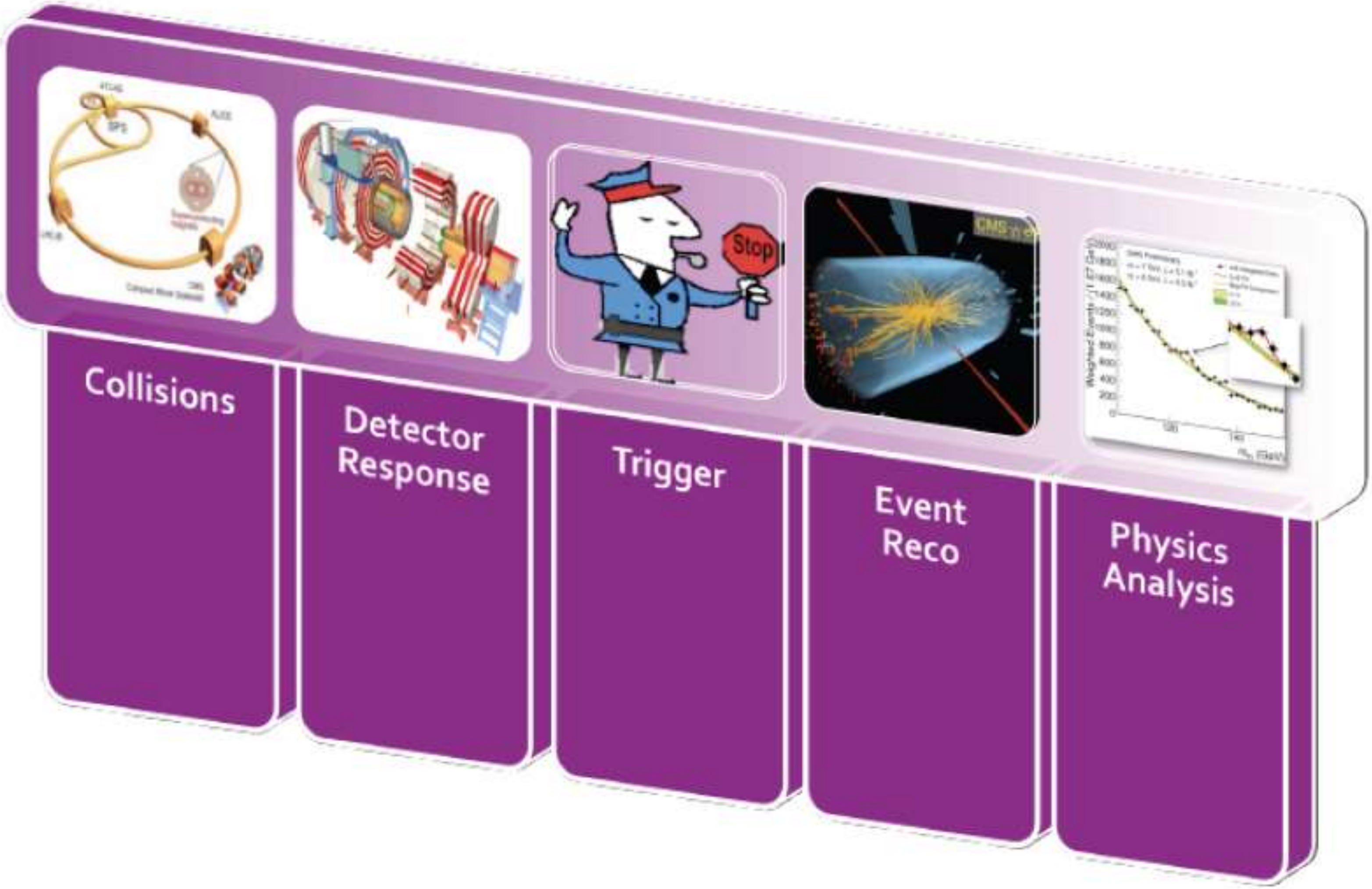
Trigger (online event selection)

Reduce 40 MHz collision rate to ~1 kHz data recording rate

Readout to disk

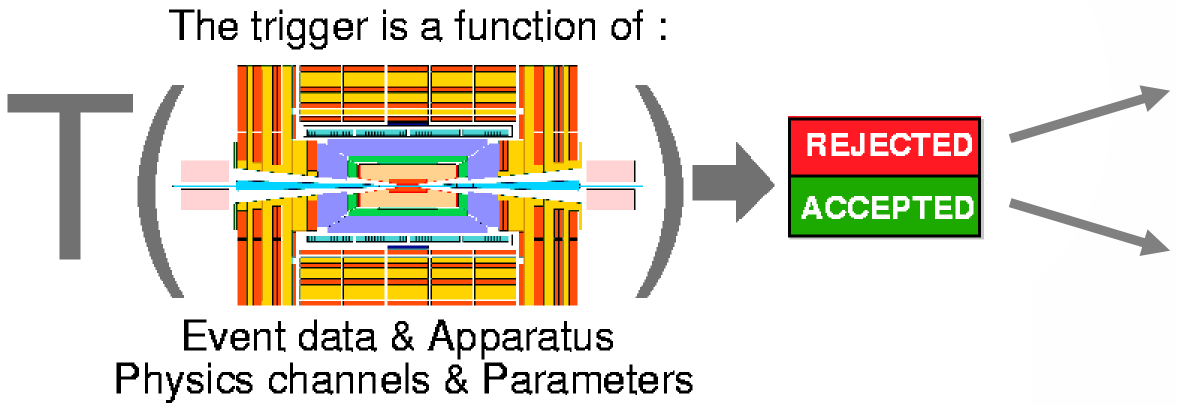
O(1000) collisions/sec $\Rightarrow$ petaBytes of data/year

From Collisions to Papers…



Event Filtering: the Trigger System

Bunch crossing rate is 40 MHz   Event size ~1 Mbyte
2007 technology (and budget) allows only to write a ~1 kHz of events to tape → need a factor ~10^5 online filtering!!



lost forever!!

written to disk for offline analysis

The event trigger is one of the biggest challenges at the LHC
⇒ Based on hard scattering signatures: jets, leptons, photons, missing E_T,…

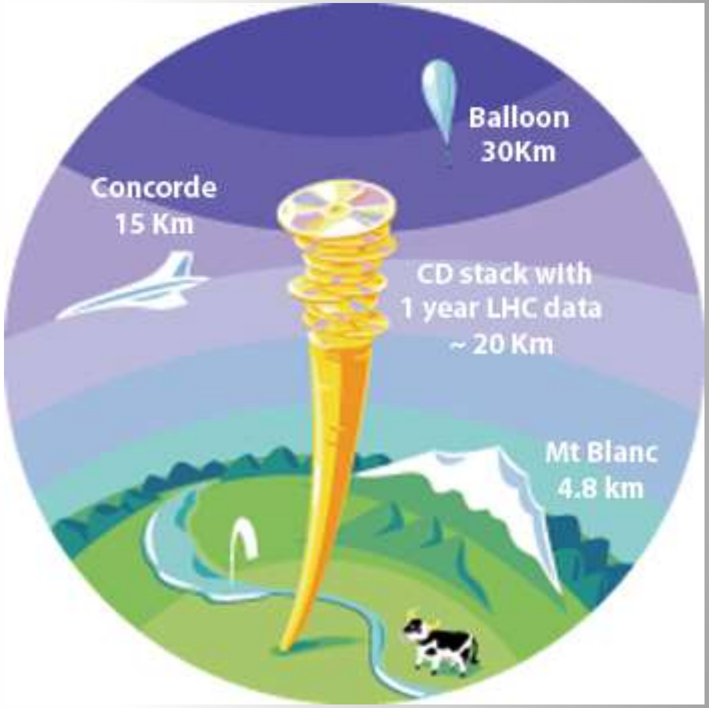
The LHC Data Challenges

Experiments were anticipated to produce about **15 Million Gigabytes** of data each year (~20 million CDs!)

The total volume in eg ATLAS is 5 billion detector events and several billion Monte Carlo events amounting to 100 Million Gigabytes of data in 3 years

LHC data analysis requires a computing power equivalent to **~100,000 of today's fastest PC processors**

=> Requires many cooperating computer centres, as CERN can only provide ~20% of the capacity

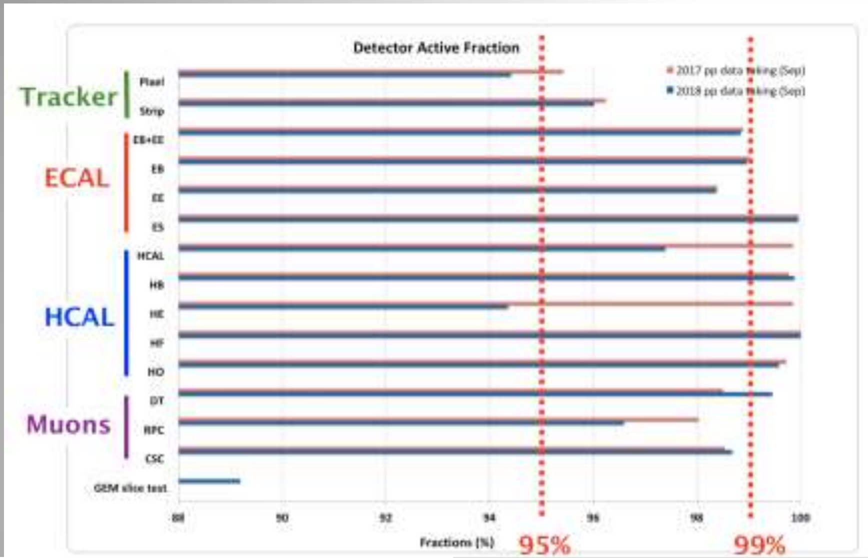


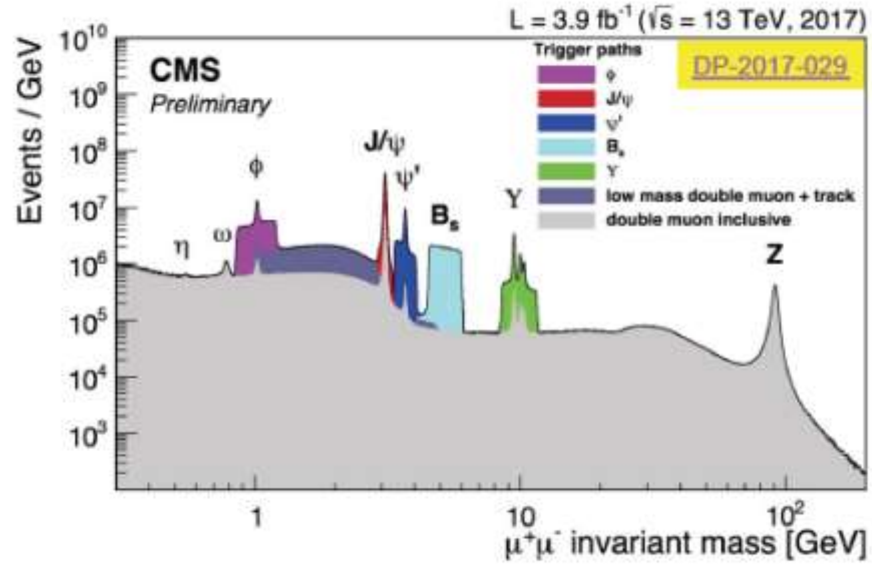
GRID Computing

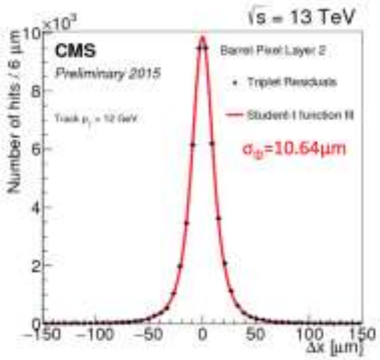
Detector Performance @ 13 TeV

Some examples from the Run-2 data

CMS and ATLAS continue to have an excellent performance

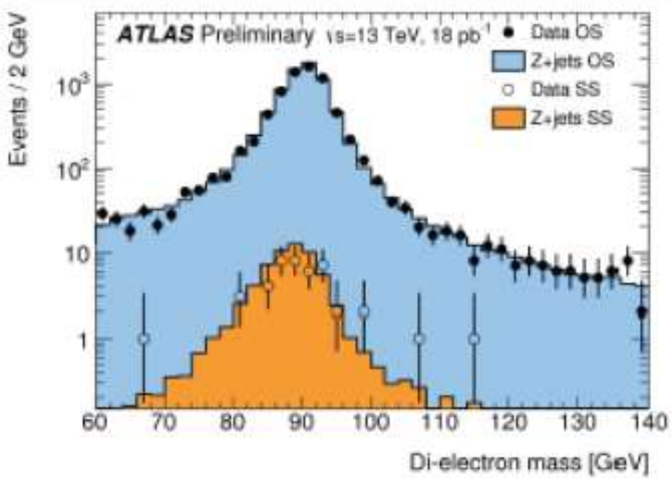


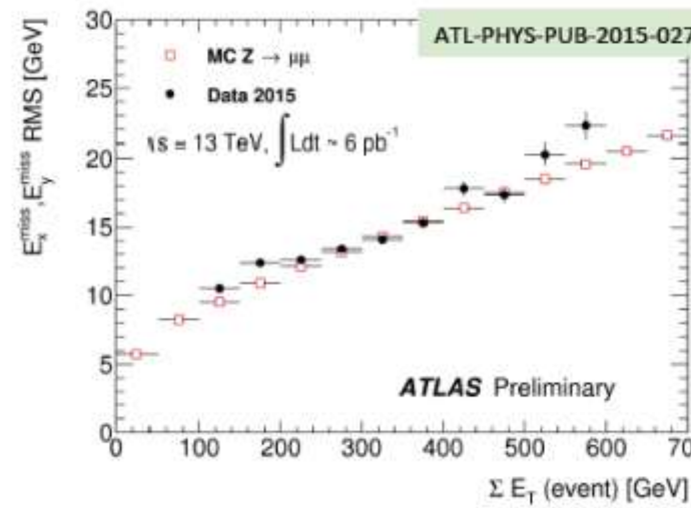




Pixel Detector Resolution:

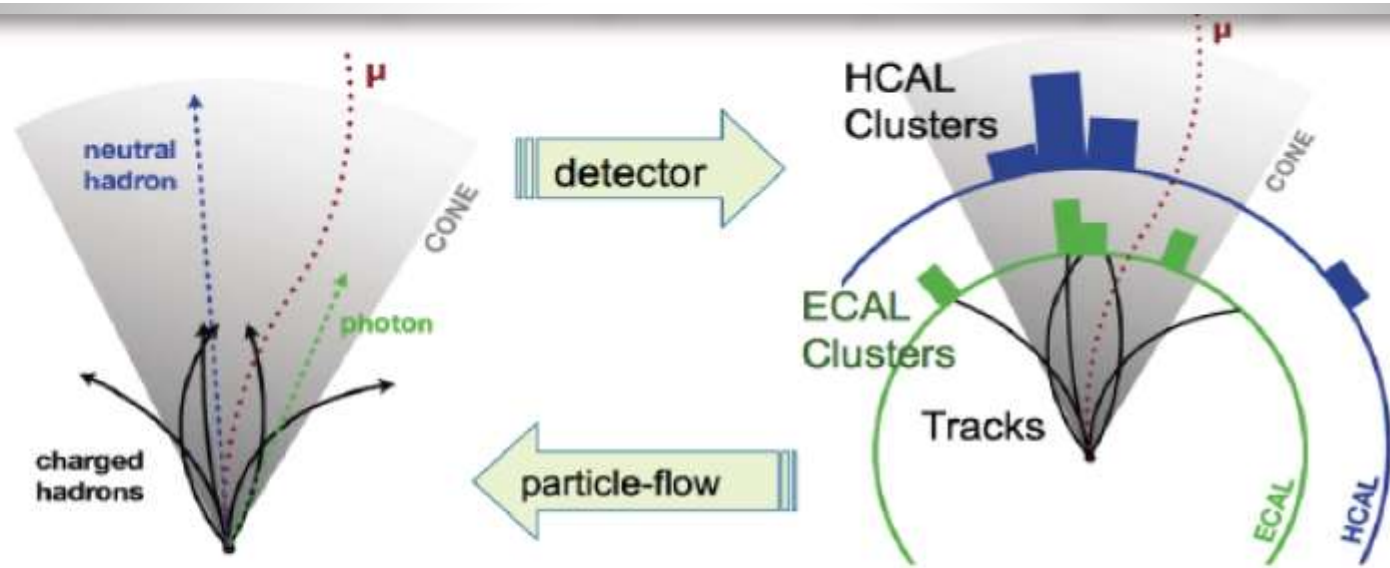
- Transverse to the beam: σ_ϕ=10.64 μm
- Parallel to the beam: σ_z=29.09 μm





Global Event Reconstruction

Using all information of the detector together for optimal measurement



- Optimal combination of information from all subdetectors
- Returns a list of reconstructed particles
  - e,μ,γ, charged and neutral hadrons
    - Used in the analysis as if it came from a list of generated particles
    - Used as building blocks for jets, taus , missing transverse energy , isolation and PU particle identification

Adapted in CMS

B-quark Tagging

Generally: look for jets with displaced vertices (or leptons) from B-meson decays

b-tag efficiency

Two b-jets candidate

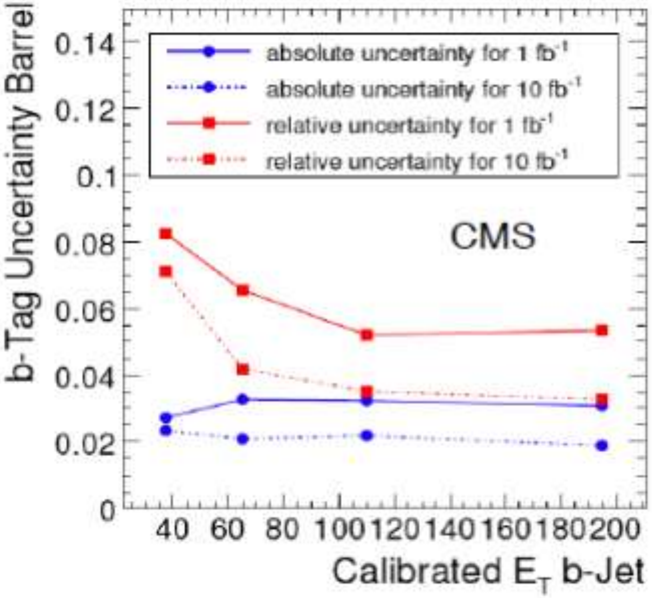
Select b-enriched samples using tt sample

- t → W b ~ 100% → tagging top = tagging b
- Select pure b sample by using tt event topologies
  - 1(2) high p_T leptons, E_{Tmiss}, m_W & m_t constraints
  - 70-80% b-purity after selection

- CMS study 1(10) fb^{-1}
  - Efficiencies 40% to 60% (at $E_{Tb\text{-}Jet}$ > 100) GeV
  - Uncertainty 4-6% for large data samples

- ATLAS study 100 pb^{-1}
  - Similar efficiencies, purities
  - Estimated uncertainty ~10%

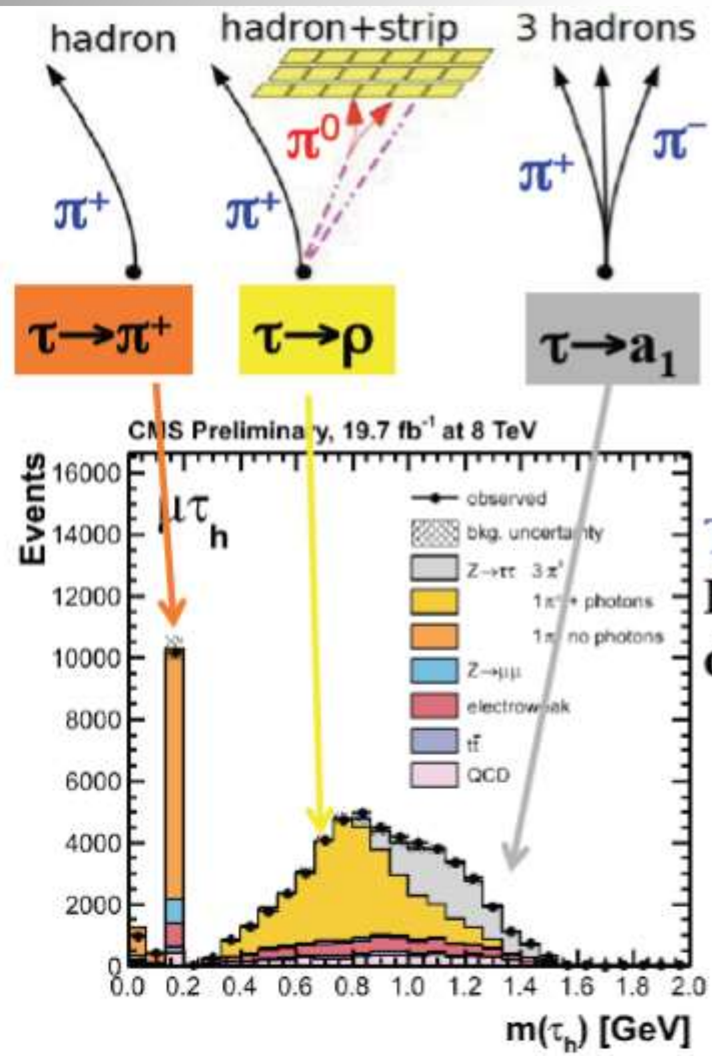
⇨



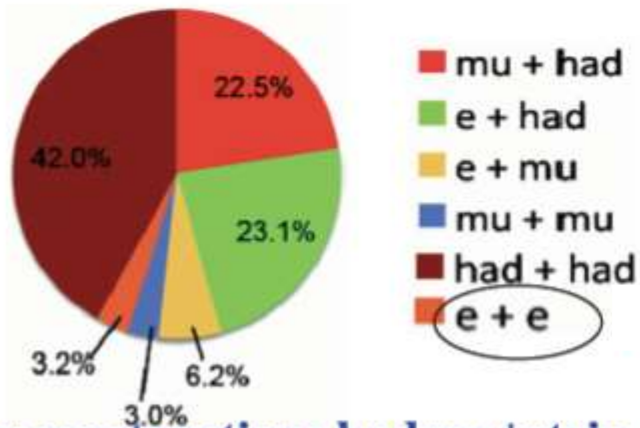
New: Deep Learning NNs..

Tau-finding

Hadronic tau decays are narrow low multiplicity ‘jets’



All di-tau final states used in Higgs search



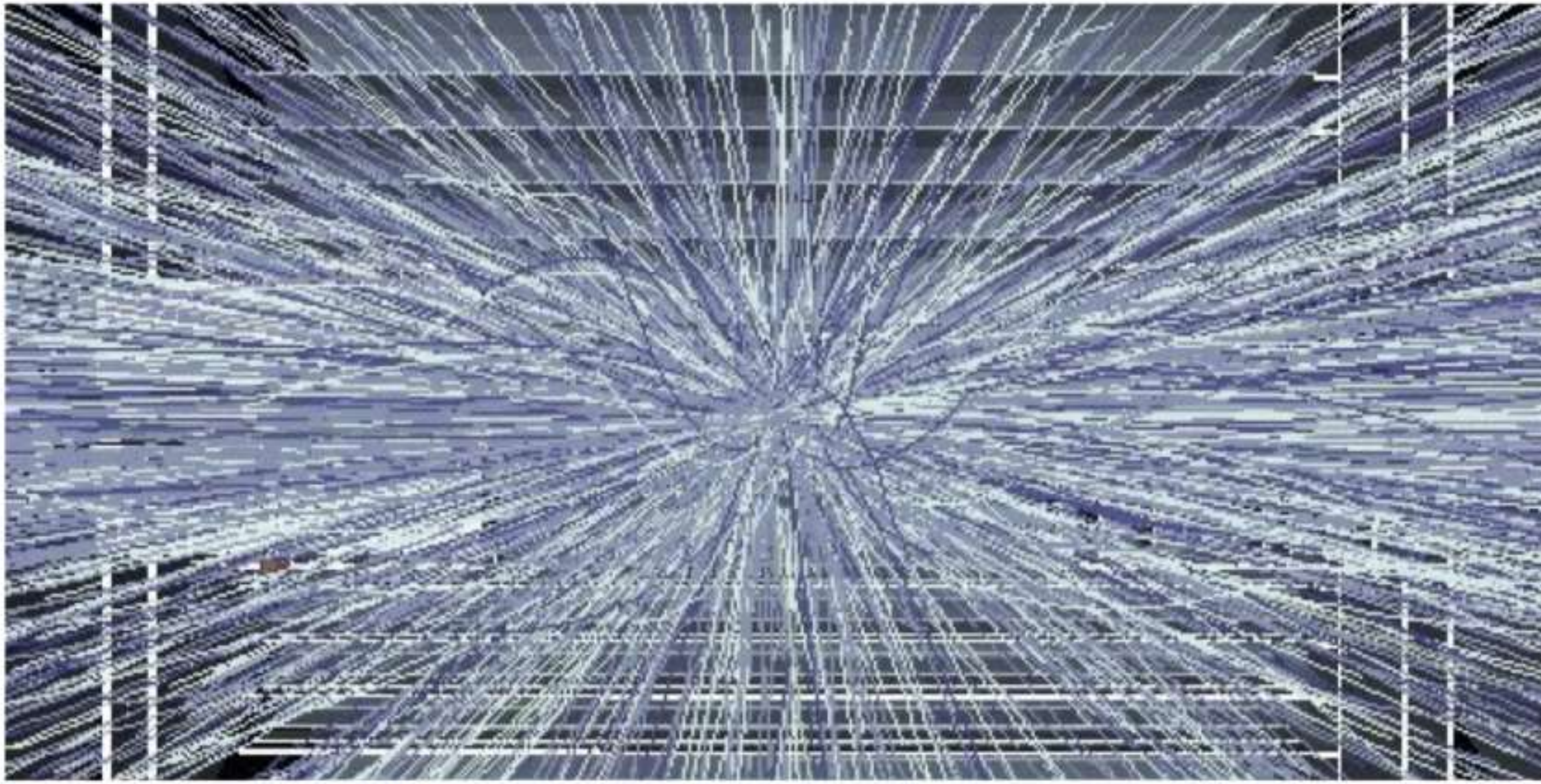
Tau reconstruction: hadron+strip

Particle-flow based algorithm to reconstruct different hadronic tau decay modes

τ_h identification: efficiency ~ 60%
fake rate ~ 1%

The τ_h mass distribution used to control the tau energy-scale within 3% & reconstruction of decay modes

The New Wave: Machine Learning

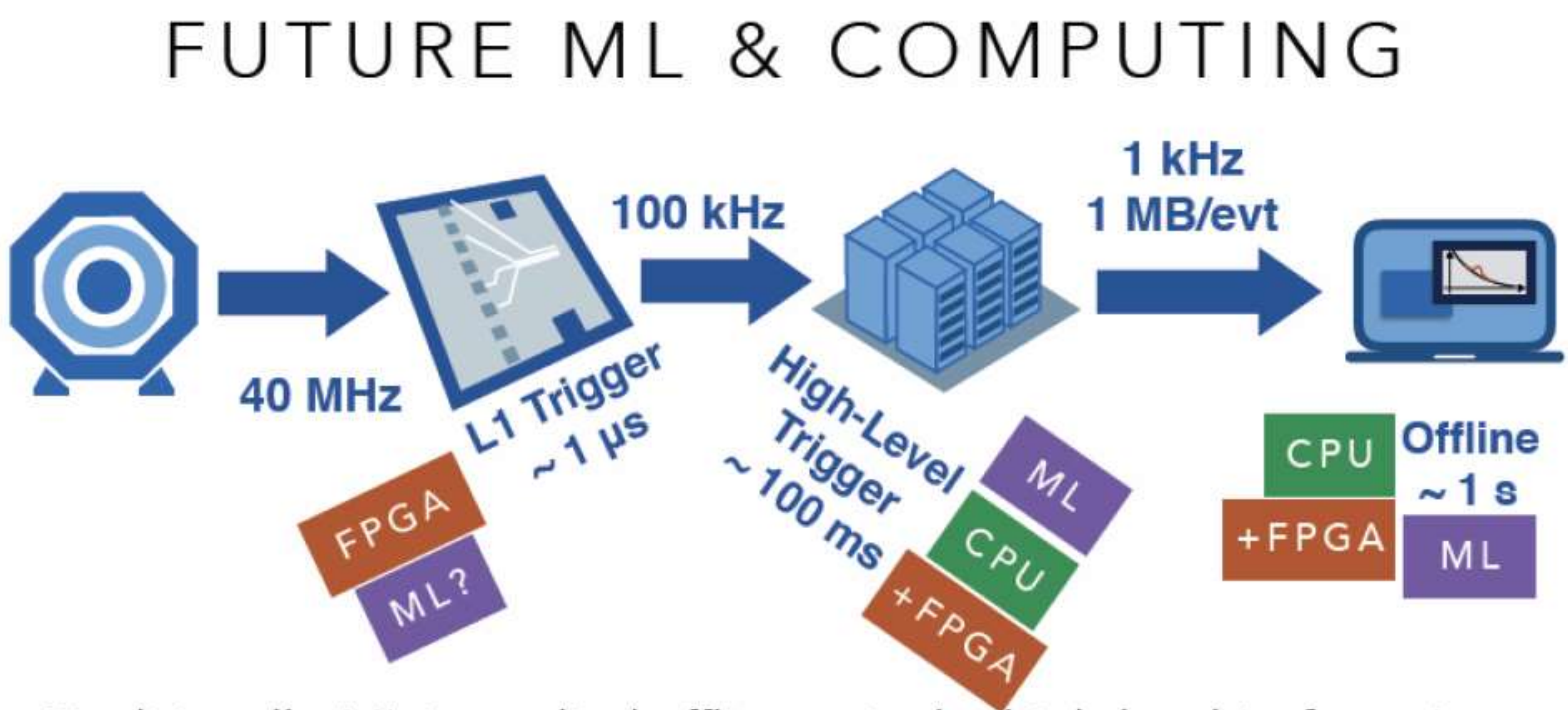


Why do we need Machine Learning?

M. Pierini et al.

European Research Council

The New Wave: Machine Learning



- Traditionally, ML is applied offline or in the high-level (software) trigger in CPUs
  - Can we deploy ML in ultra-fast FPGAs to bring it to L1 trigger?
  - Can we bring FPGA-accelerated ML workflows to HLT and offline?

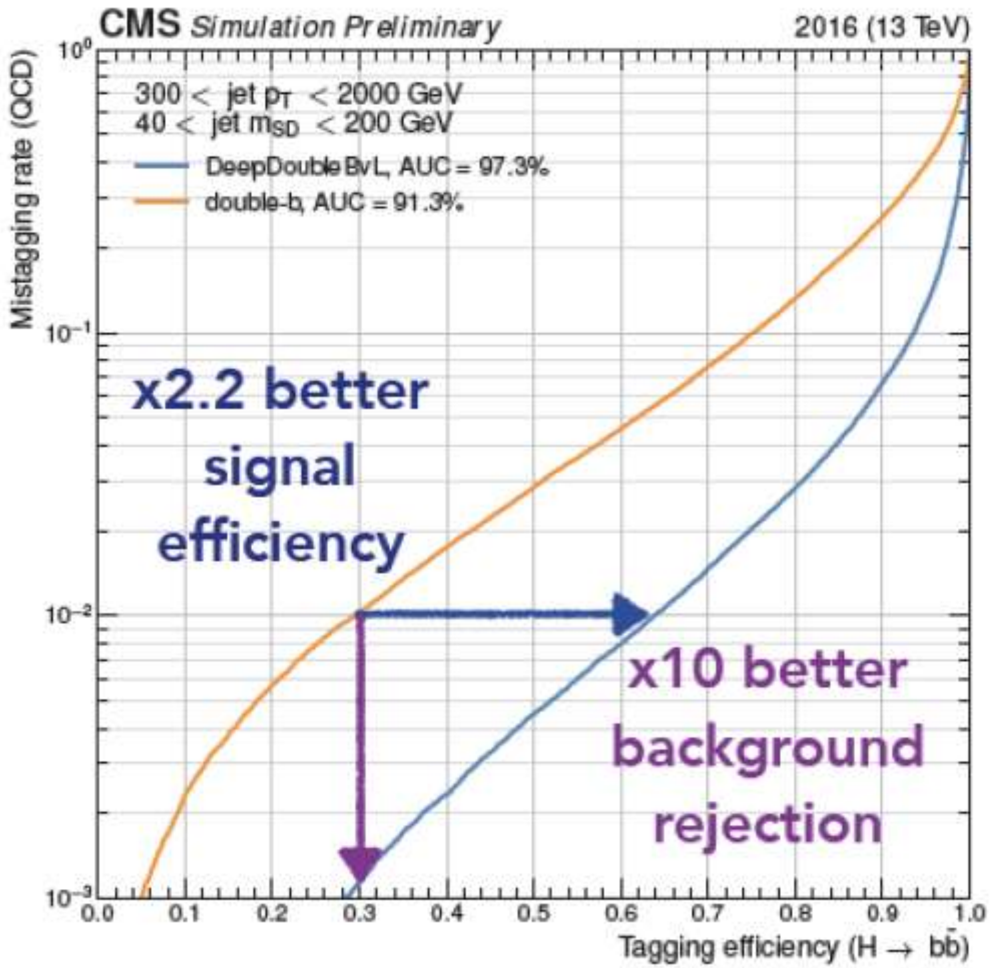
Field Programable Gate Array

The New Wave: Machine Learning

DP-2018/033

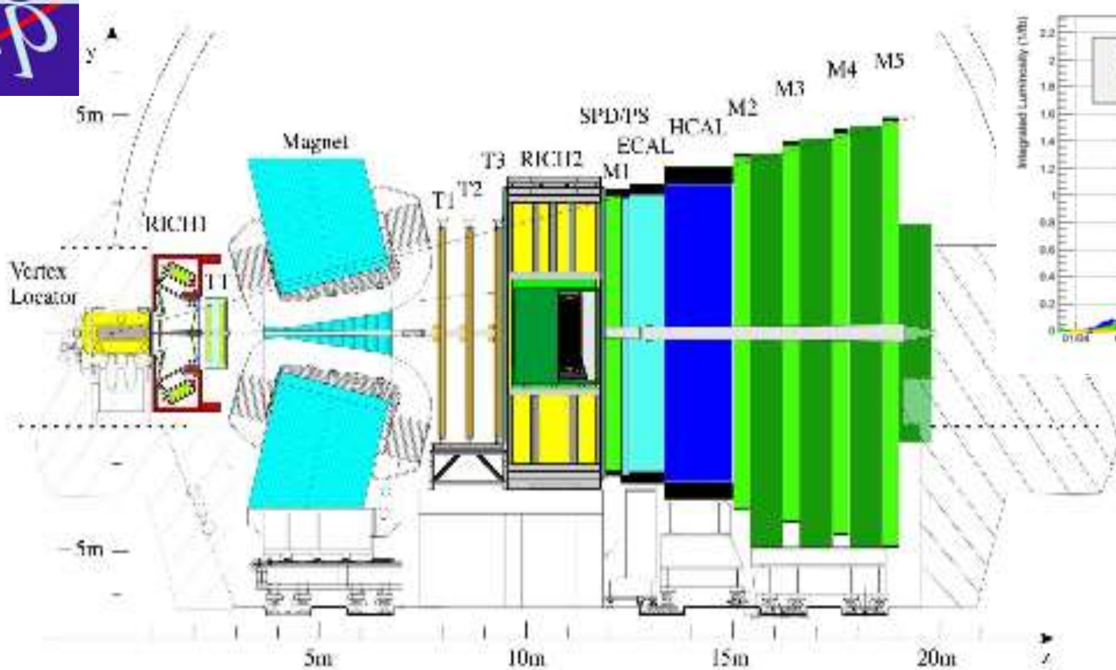
DEEP DOUBLE-B TAGGER

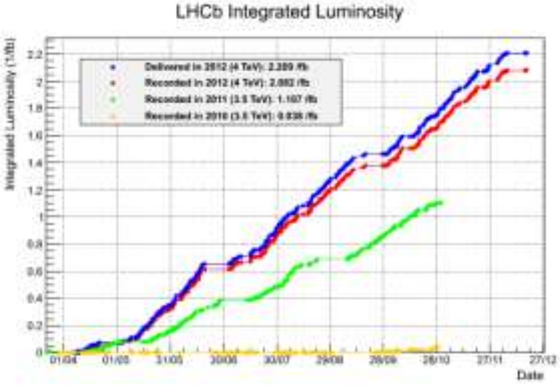
- Large performance gain over previous algorithm



Other Experiments at the LHC

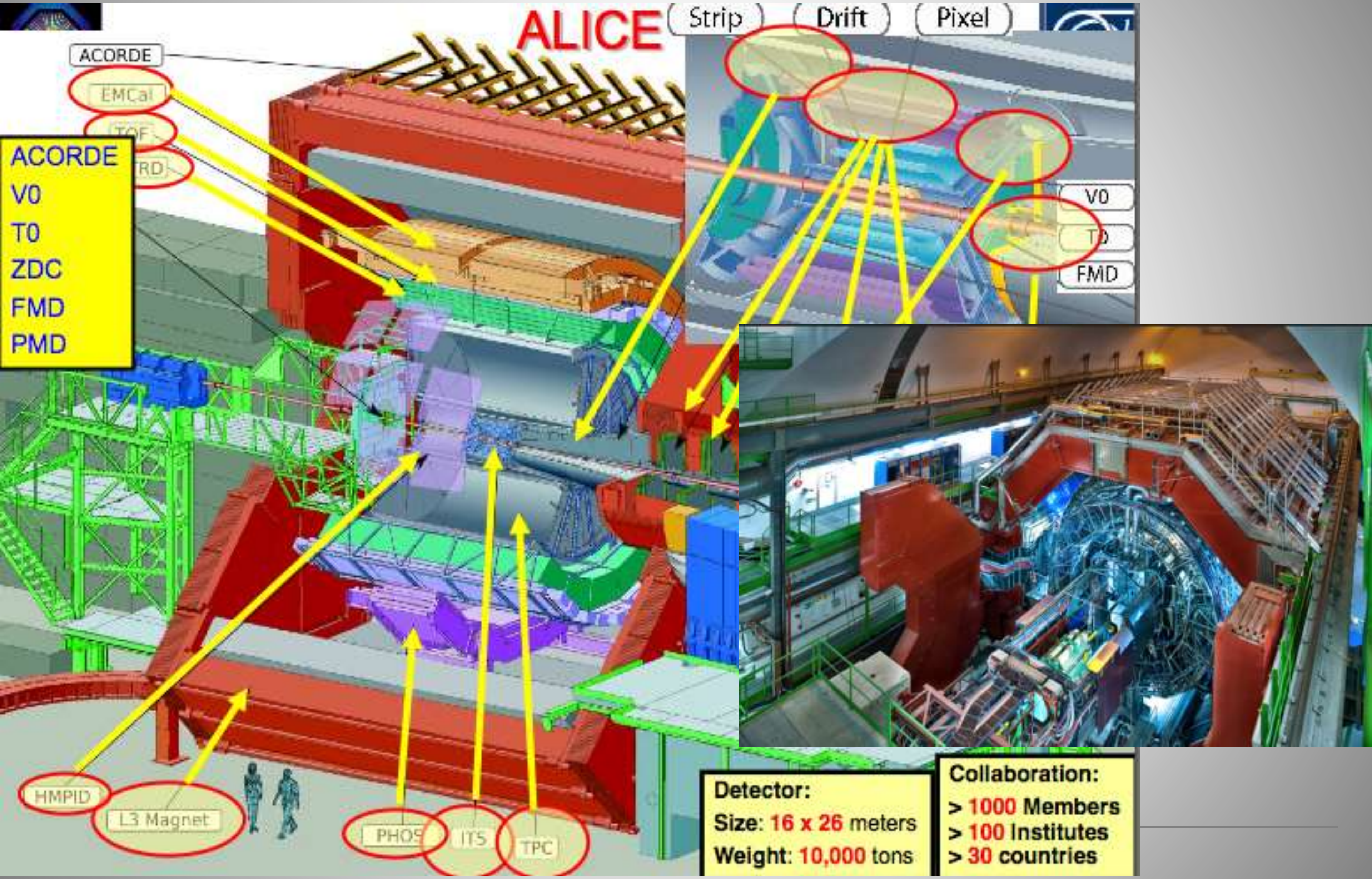
LHCb: Bottom and Charm Physics





- Forward acceptance ($2 < \eta < 5$) and down to very low p_T
- Precise vertexing (VELO) – hit resolution of down to 4 µm achieved; measurements 8mm from beam-line
- RICH system providing hadron id between 2 and 100 GeV/c
- High performance muon system

ALICE: Heavy Ion Physics at the LHC



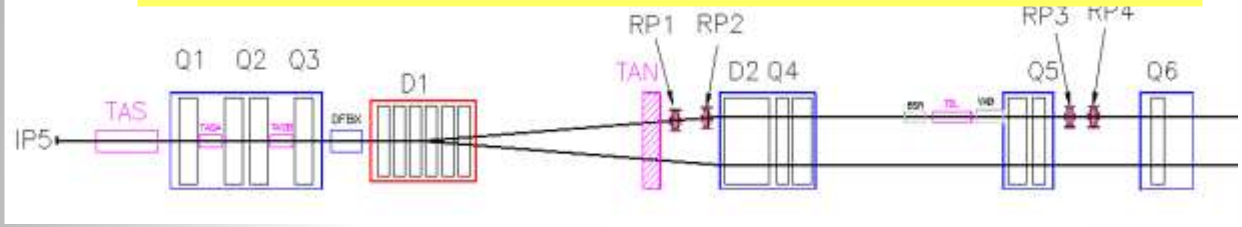
A Few Smaller Experiments: TOTEM & LHCf

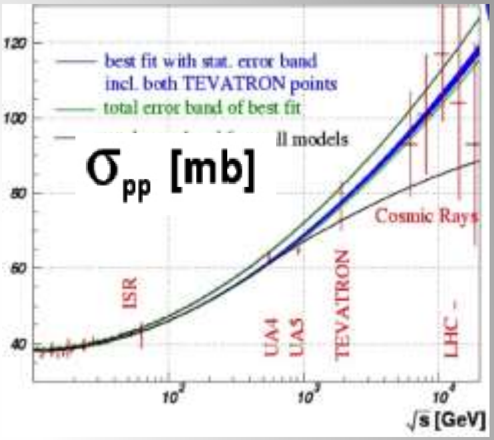
TOTEM: measuring the total, elastic and diffractive cross sections

Add Roman Pots (and inelastic telescope) to CMS interaction regions (200 m from IP)

Recently: common runs with CMS

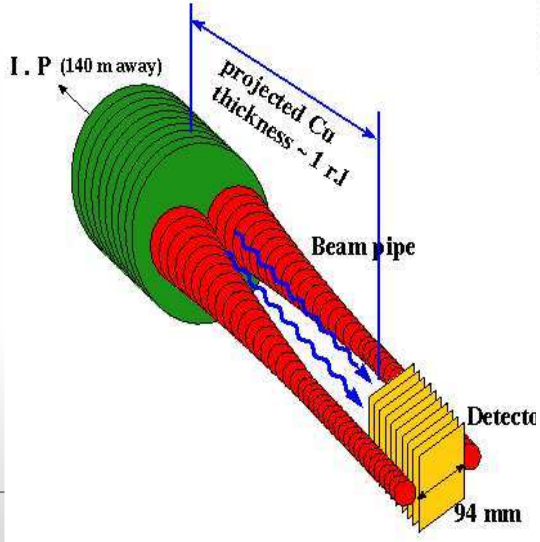
TOTal and Elastic cross section Measurement

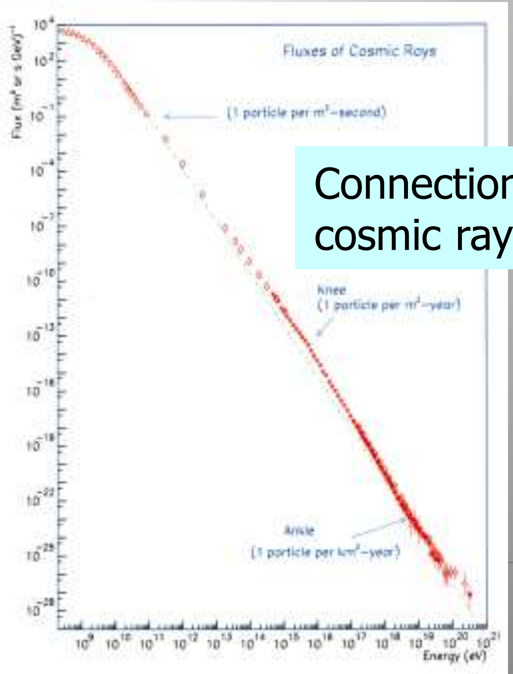




LHCf: measurement of photons and neutral pions in the very forward region of LHC

Add a EM calorimeter at 140 m from the Interaction Point (of ATLAS)

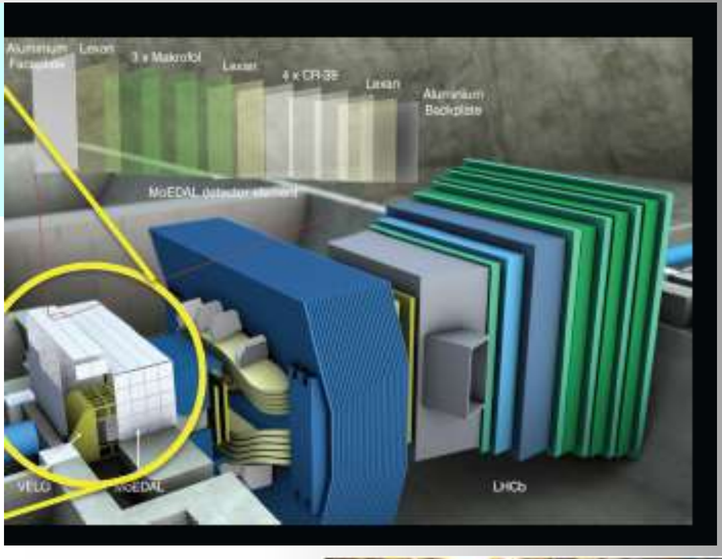




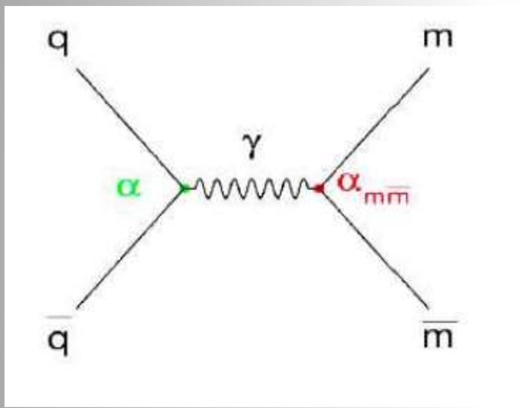
Connection with cosmic rays

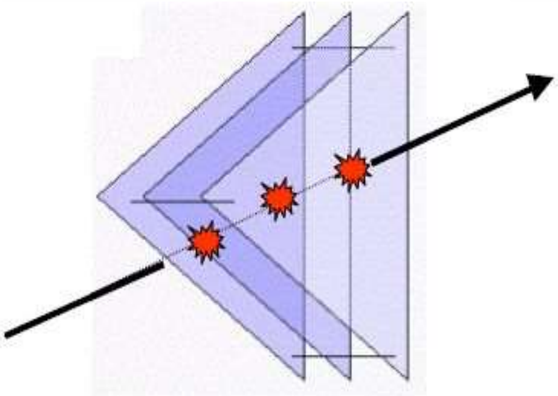
MoEDAL: Monopole and Exotics Detector at the LHC

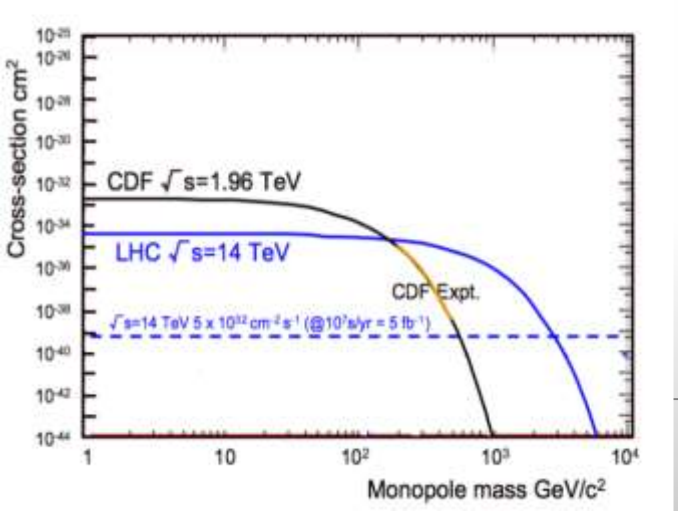
Heavy particles which carry “magnetic charge”
Could eg explain why particles have “integer electric charge”



Monopole production







Remove the sheets after some running time and inspect for ‘holes’

The LHC Detectors are Major Challenges

- CMS/ATLAS detectors have about 100 million read-out channels
- Collisions in the detectors happen every 25 nanoseconds
- ATLAS uses over 3000 km of cables in the experiment
- The data volume recorded at the front-end in CMS is 1 TB/second equivalent to the world wide communication network traffic (2007)
- Data recorded during the 10-20 years of LHC life will be about all the words spoken by mankind since its appearance on earth
- A worry for the detectors: the kinetic energy of the beam is that of a small aircraft carrier of 10^4 tons going 20 miles/ hour


ATLAS pixel detector

>200 m^2 of silicon


CMS silicon tracker

Object	Weight (tons)
Boeing 747 [fully loaded]	200
Endeavor space shuttle	368
ATLAS	7,000
Eiffel Tower	7,300
USS John McCain	8,300
CMS	12,500

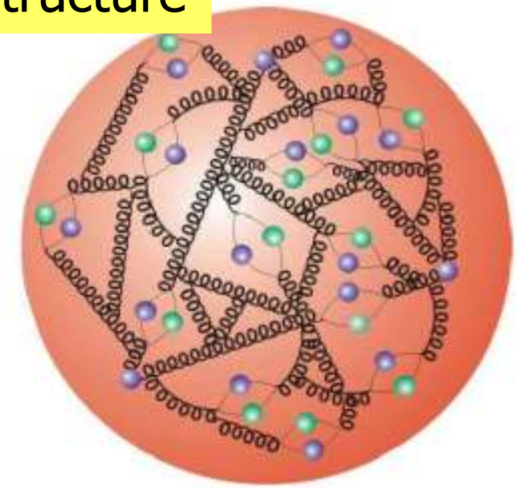
Summary: Challenges@ LHC

- High event rate and pile-up
  - High granularity: typically 10x more channels compared to detectors before the LHC
- Timing/synchronization of 10^8 channels is non trivial
- Event size (> 1 Mbyte)/Computing
  - Limit event rate to a few 100 Hz, use the Grid
- Trigger reduce event rate from 40MHz to a few 100 Hz
  - Multi-layered trigger system and pipelined electronics
- Detectors need excellent hermeticity (missing E_T), lepton identification, B & Tau identification, jet measurements…
- Detectors must be radiation hard and reliable for ~ 10-20 years…

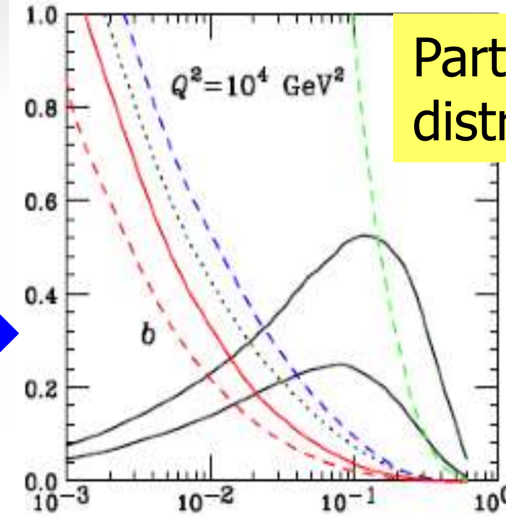
We have these detectors: Let’s look at physics

pp-Collisions : Complications

Protons have structure

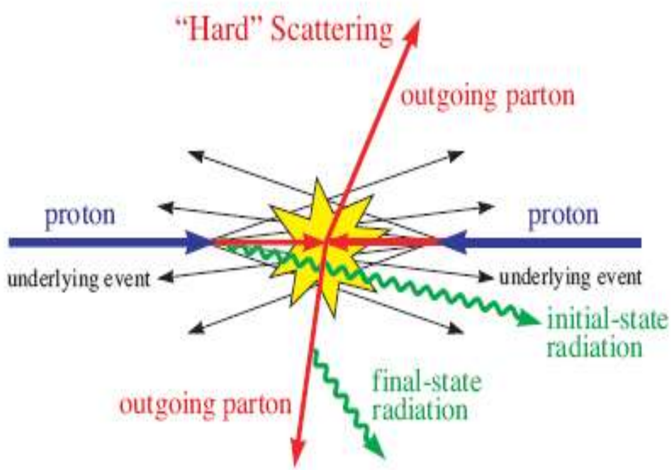


Parton distributions

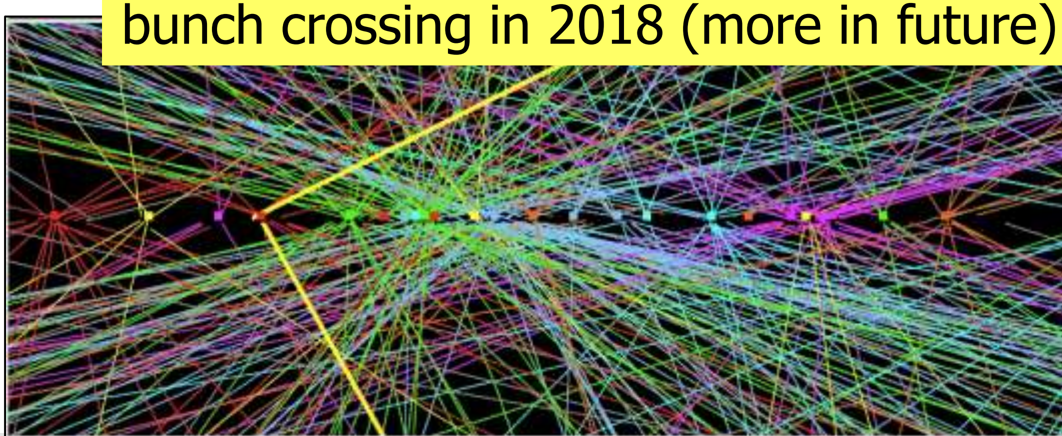


$$\sigma = \sum_{i,j} \int_0^1 dx_1\, dx_2\, f_i(x_1,\mu)\, f_j(x_2,\mu)\, \hat{\sigma}_{ij}$$

Underlying event

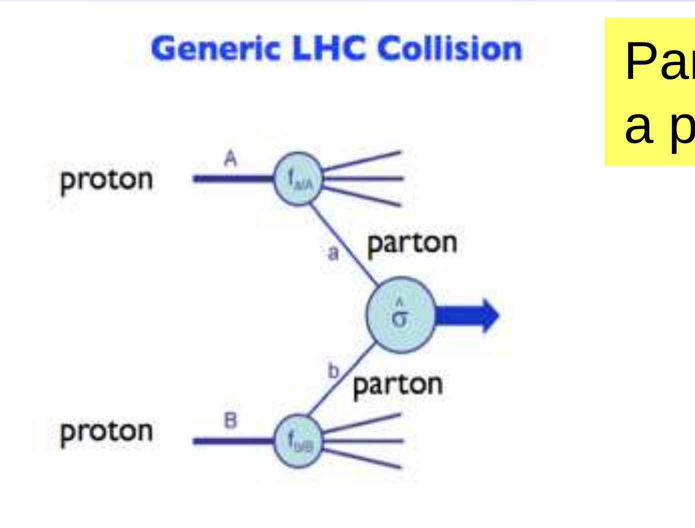


Pile-up: approximate 40 collisions per bunch crossing in 2018 (more in future)

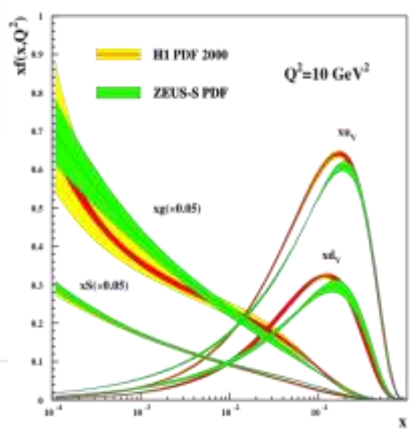


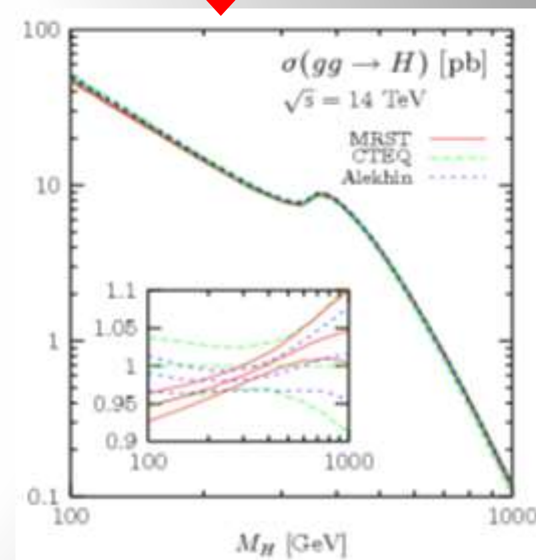
Z→ μμ event with ~20 reconstructed vertices (2012)

Proton-proton collisions and PDFs

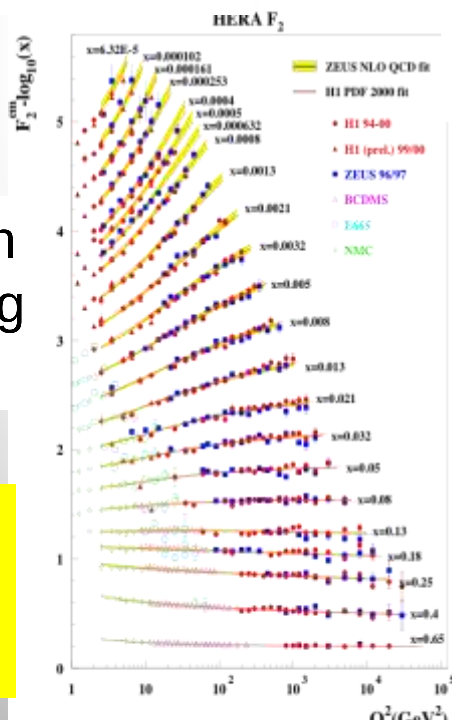


Parton Distribution Functions: the probability of finding a parton with momentum fraction x in the proton





Structure function measurements eg from HERA

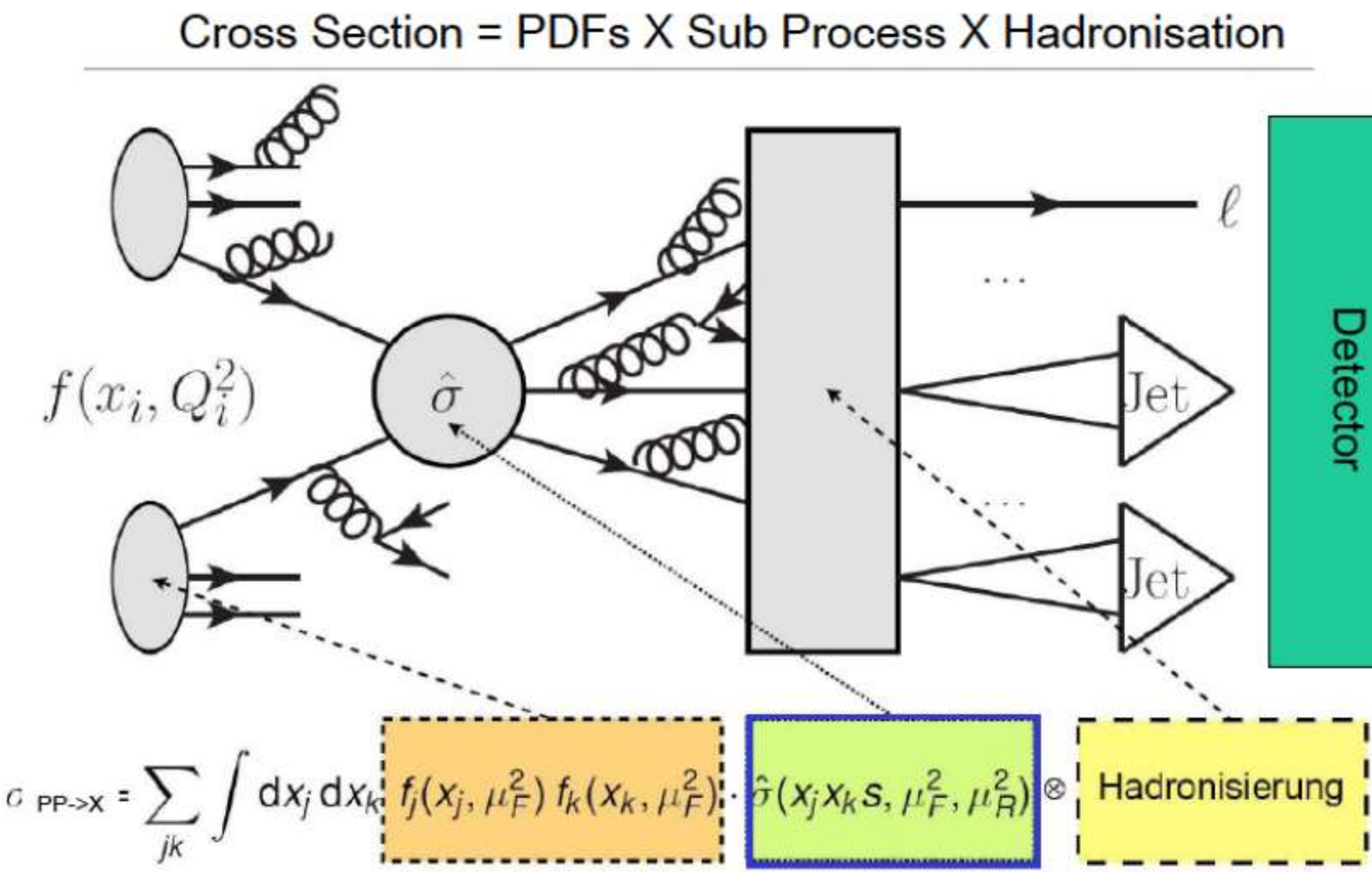


Now also LHC pp data used to constrain PDFs

Simple spread of existing PDFs gives up to 10% uncertainty on Higgs cross section. Possible gain ~ factor of 2 with final HERA data (PDF4LHC)

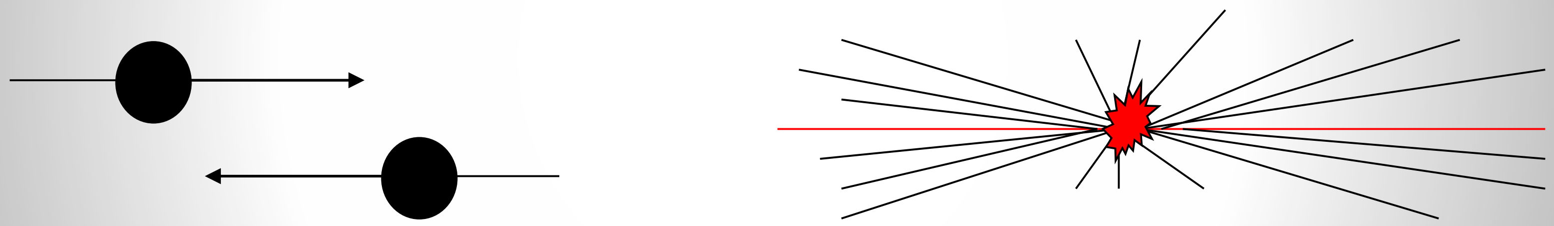
Using also input from LHC data in new fits

Proton-Proton Collisions



Proton-proton Collisions

Most interactions due to collisions at large distance between incoming protons where protons interact as " a whole "
→ small momentum transfer ($\Delta p \approx \hbar / \Delta x$)
→particles in final state have large longitudinal momentum but small
→transverse momentum (scattering at large angle is small)



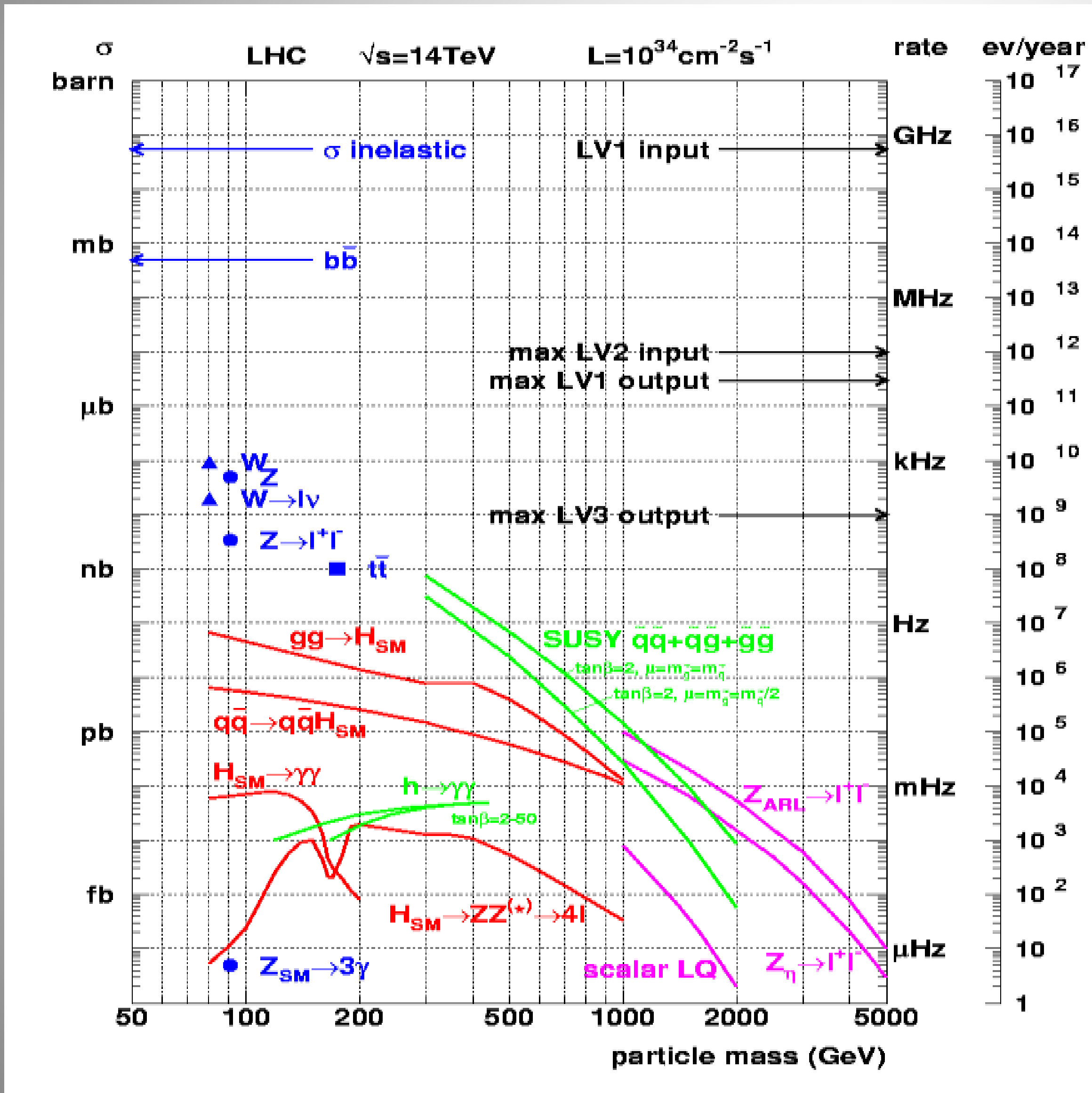
$< p_T > \approx 500$ MeV of charged particles in final state

Most energy escapes down the beam pipe.

These are called soft events…

A minimum bias data event sample is dominated by soft events

Cross sections at the LHC



"Well known" processes, don't need to keep all of them …

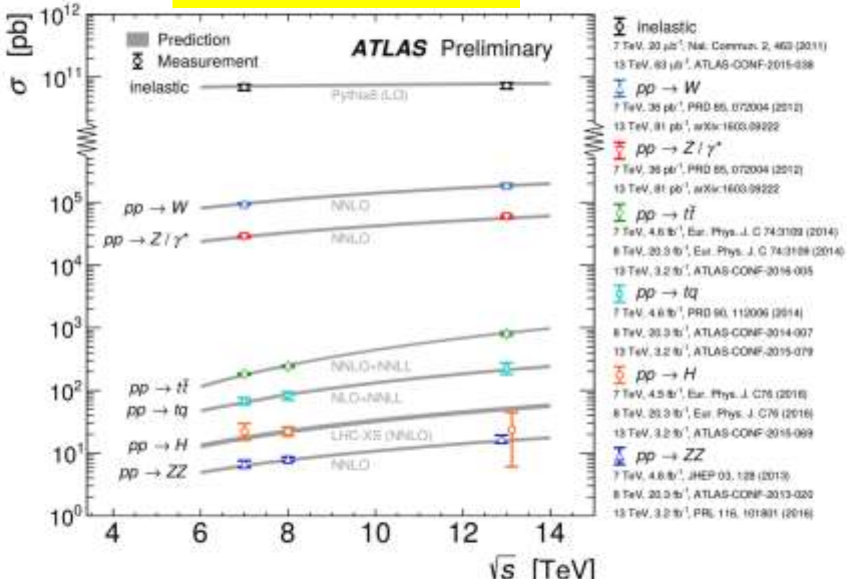
New Physics!!

This we want to keep!!

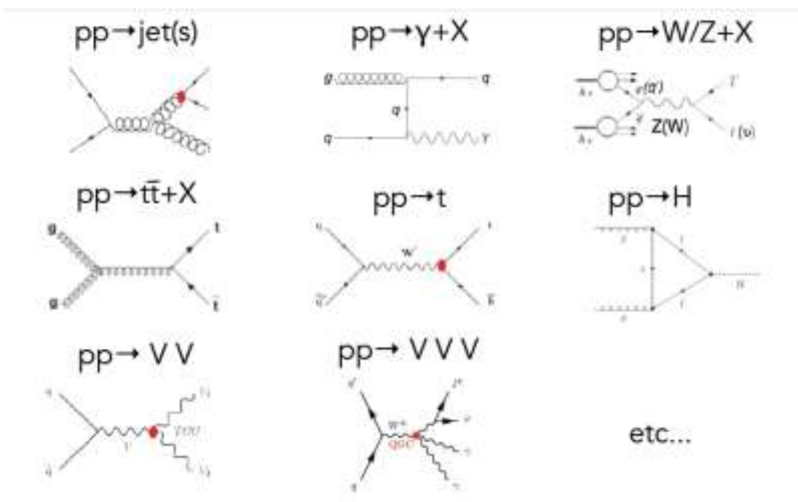
Standard Model Measurements

- Standard Model measurements form an integer part of the physics program of the LHC
- Precision measurements allow test for a wide range of SM predictions, and extract fundamental parameters (eg α_s)
  - Requires matching precision at theory prediction side
- Important to understand backgrounds for searches for new physics

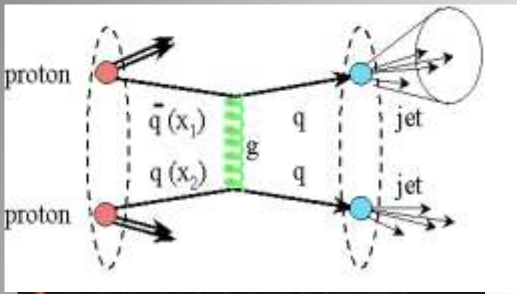
Cross Sections

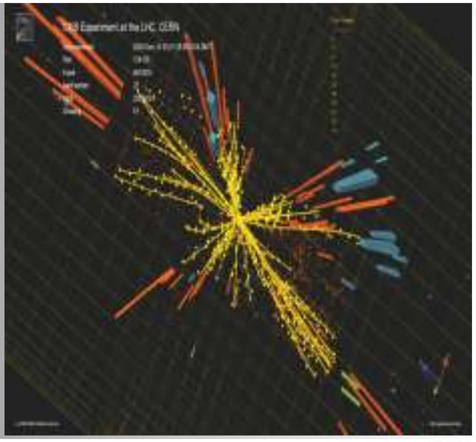


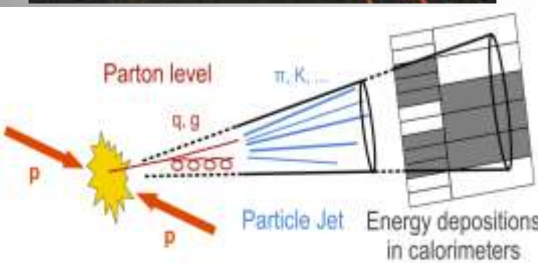
Many processes studied: Examples



Inclusive Jet Production (13 TeV)



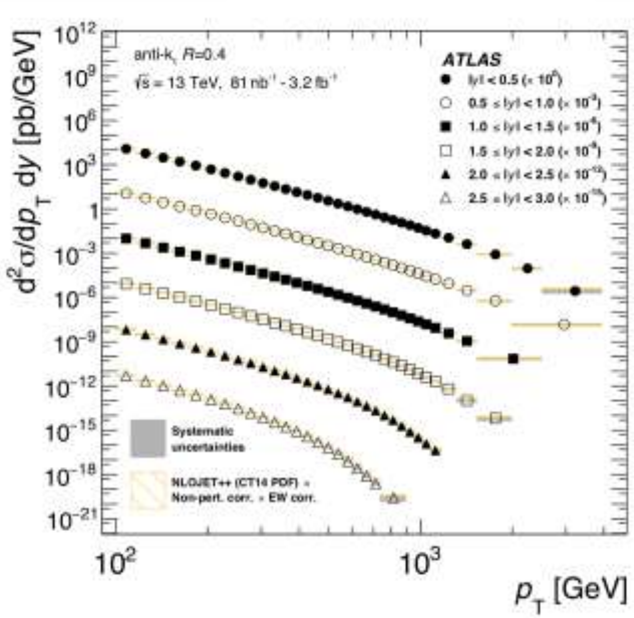


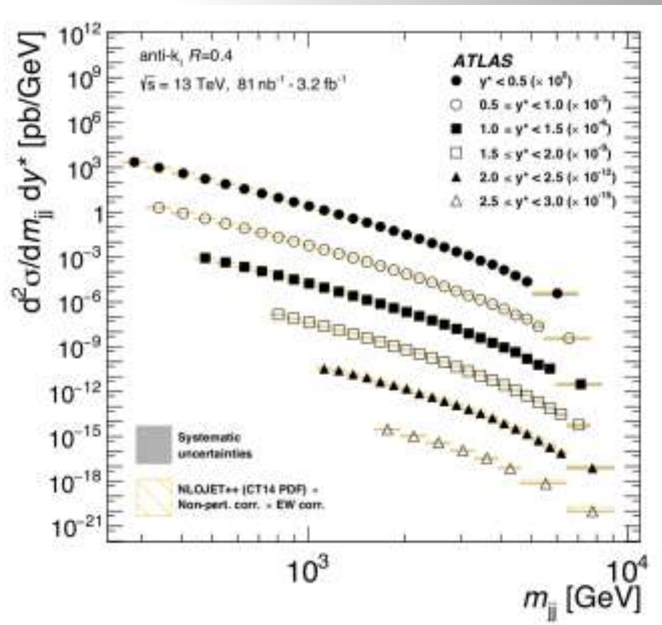


arXiv:1711.02692

Differential cross sections with R=0.4

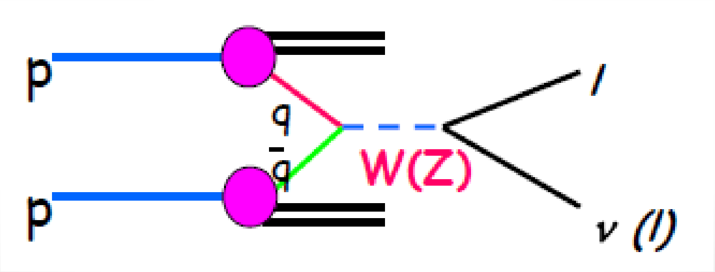
Jet p_T spectrum consistent with predictions from NLOJET++





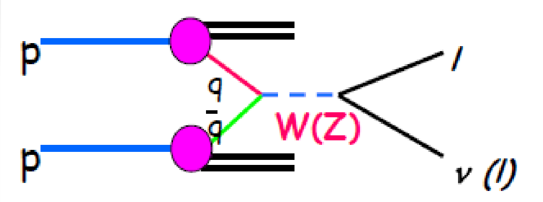
Agreement with NLO calculations over the full range, up to and beyond 2 TeV p_T jets… QCD predictions work well over a large range…

W, Z Production

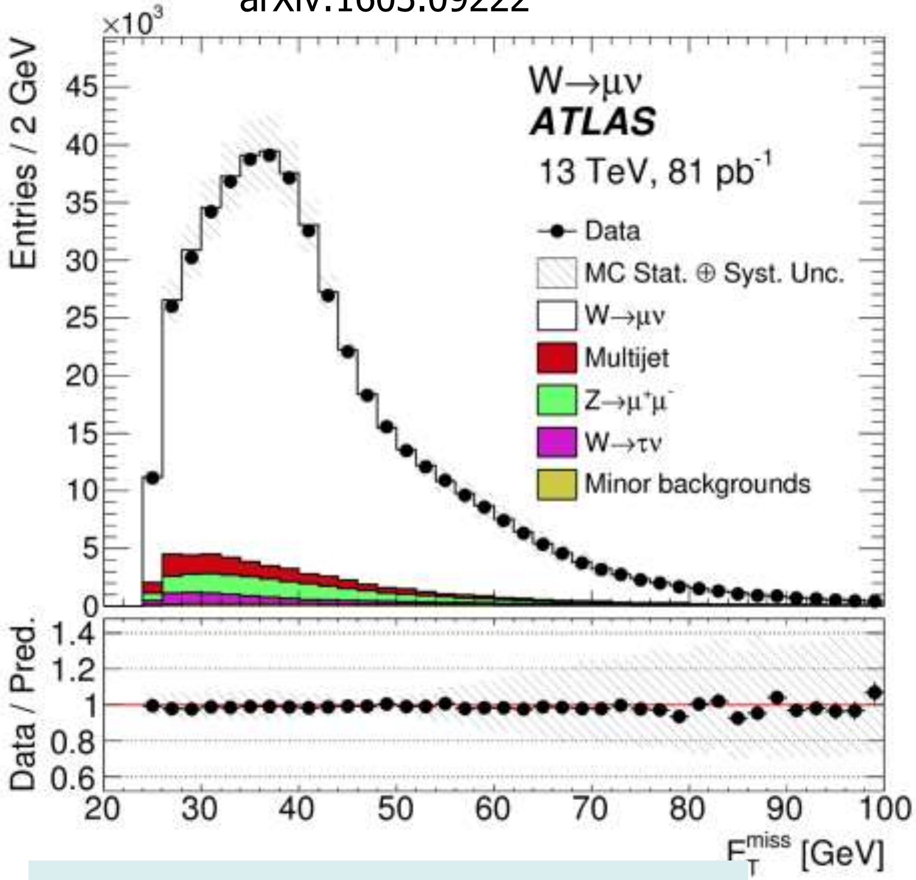


W and Z Boson Production

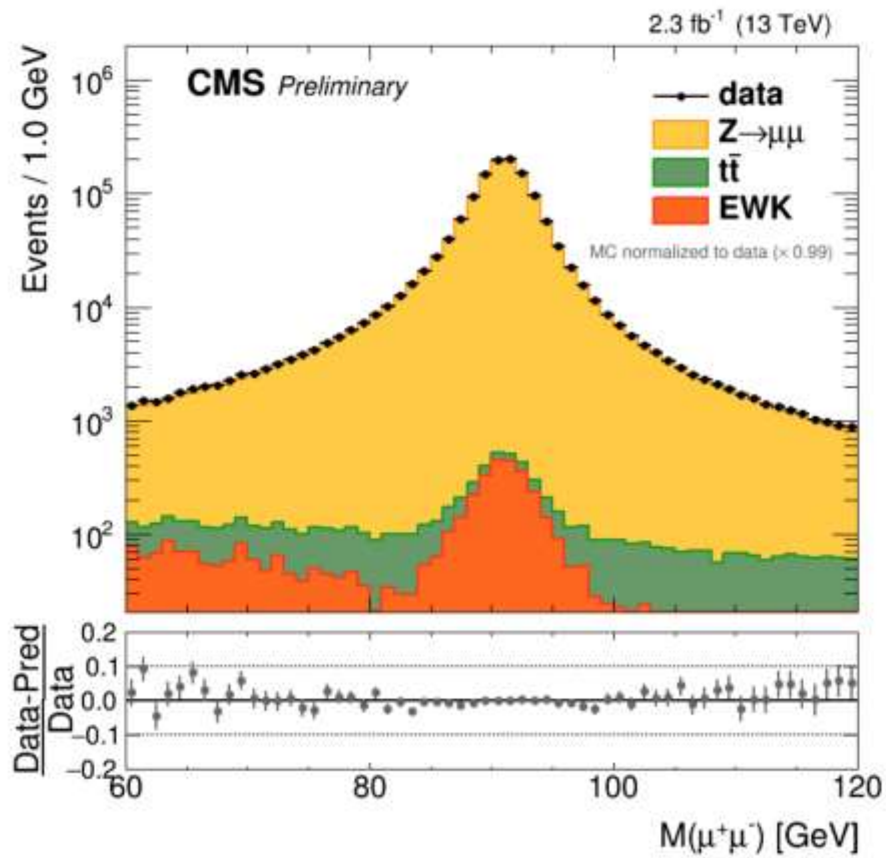
Select final states with leptons



arXiv:1603.09222



CMS-PAS-SMP-15-011

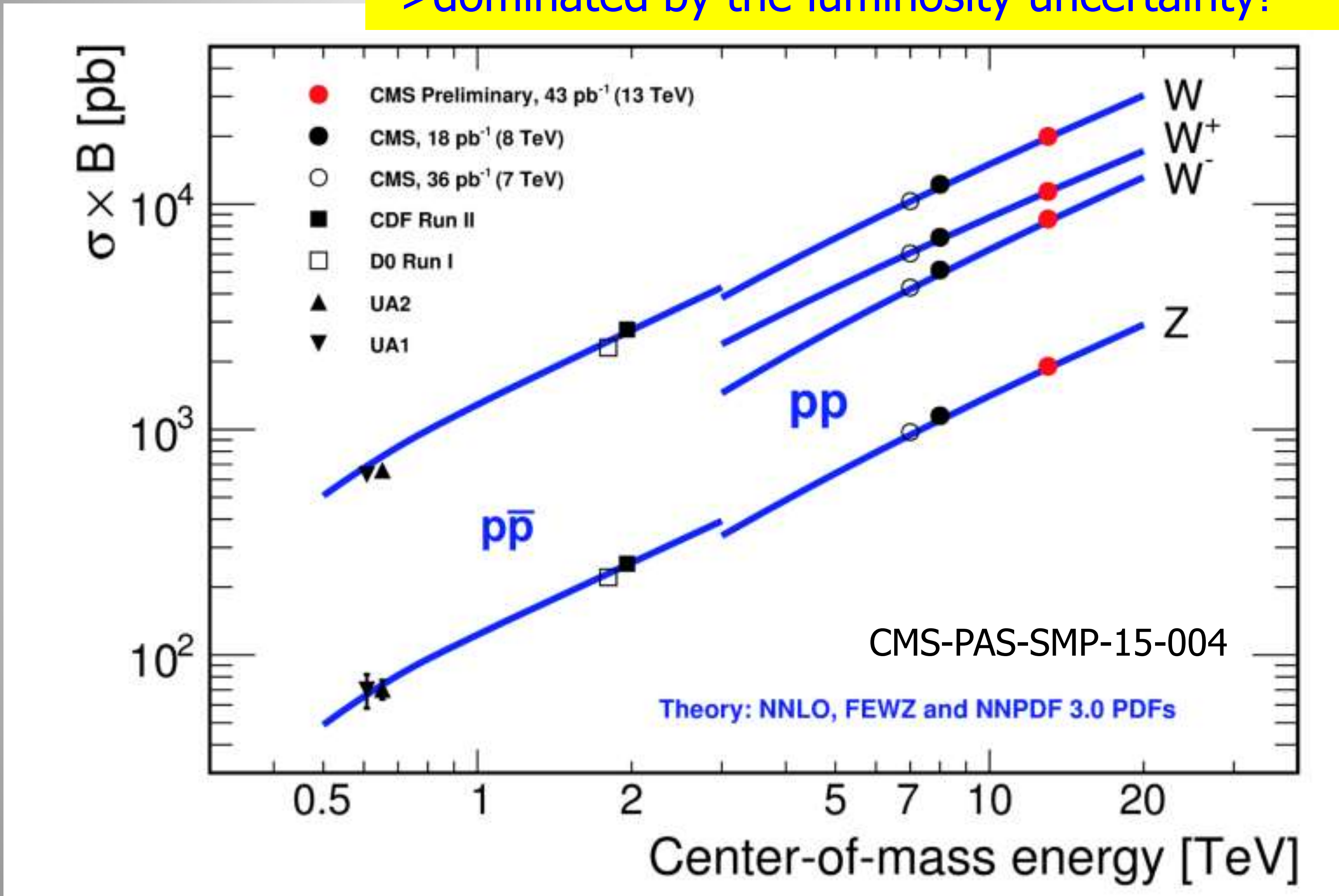


Missing transverse energy from the W → μ+ν decays

Z peak (di-muon pair mass distributions)

W and Z Boson Production

Measurements at 7/8/13 TeV with a precision of 3-4%
->dominated by the luminosity uncertainty!



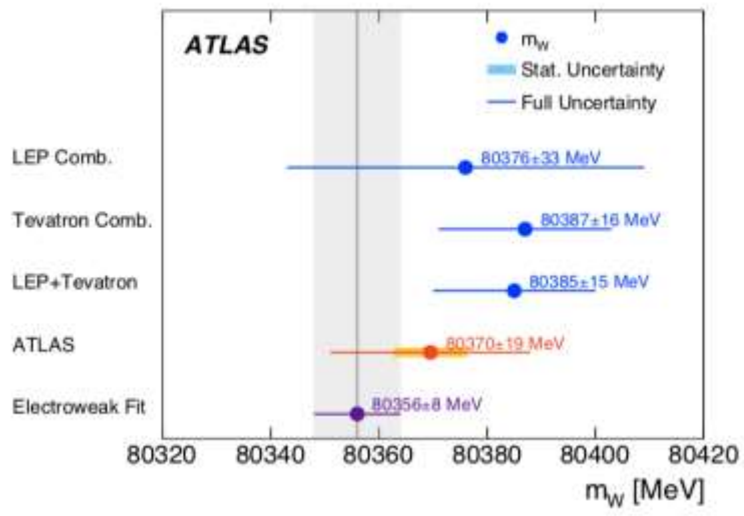
Many detailed EWK studies possible –and done-- with the large Z,W samples

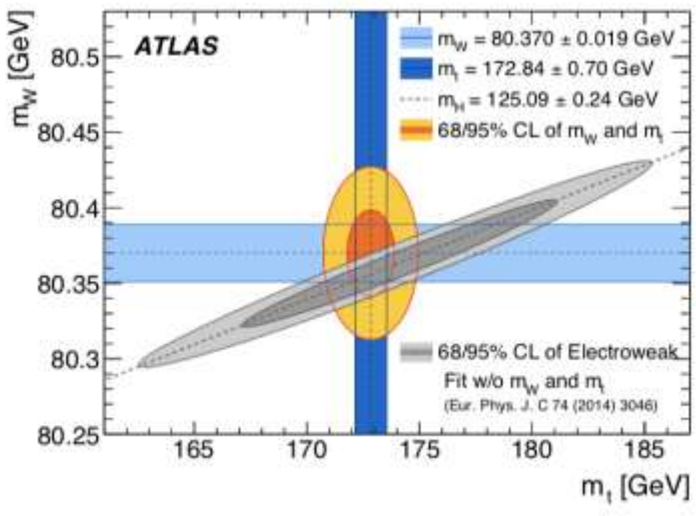
W-Mass Determination

- Measurement based on 7 TeV data (4.6 fb^{-1}). It takes time to get the systematic uncertainties under control for precision!!
- Included ~14.10^6 W leptonically decaying W candidates
- Technique uses template fits to the W p_T and m_T predictions
- Calibration of energy scale, recoil response and efficiency studies using the large Z sample. Modelling of helicity effects constrained by W and Z data.

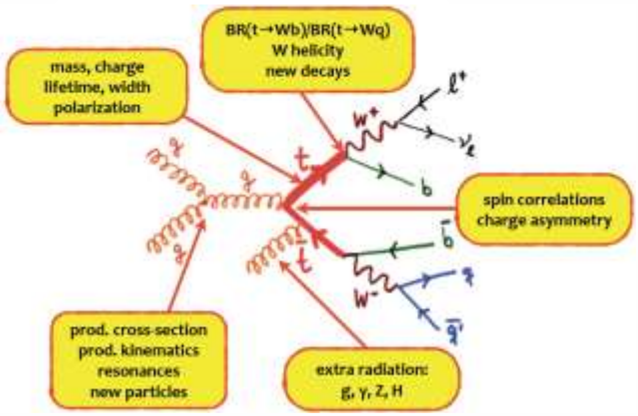
arXiv:1701.07240

$$m_W = 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV}$$
$$= 80370 \pm 19\ \text{MeV},$$





Top Production

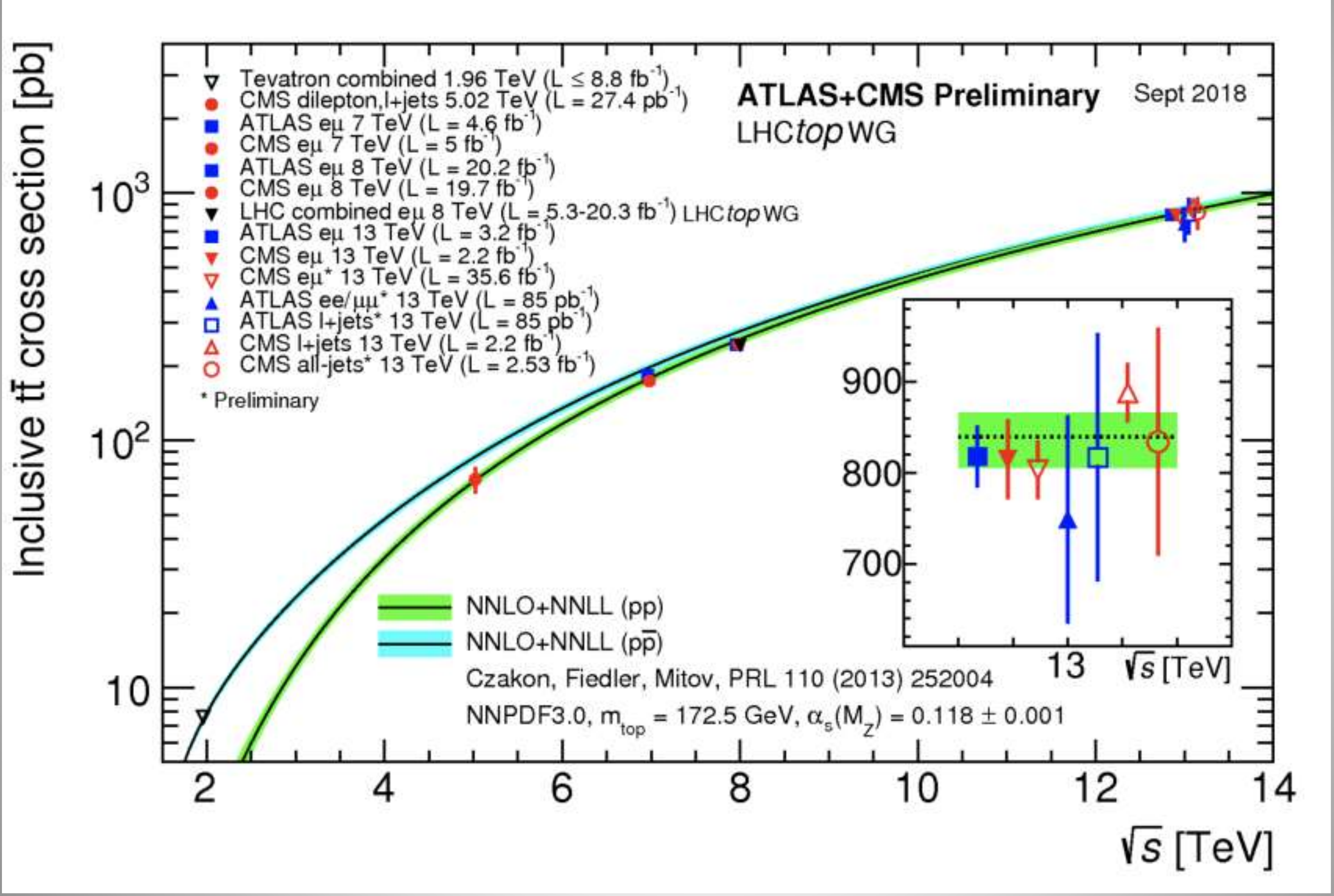


- The heaviest known elementary particle: ~173 GeV
- Coupling to the Higgs ~1 → Special role in EWK symmetry breaking?

LHC is a top factory with ~5.10^6 produced tt-pairs (run-1)

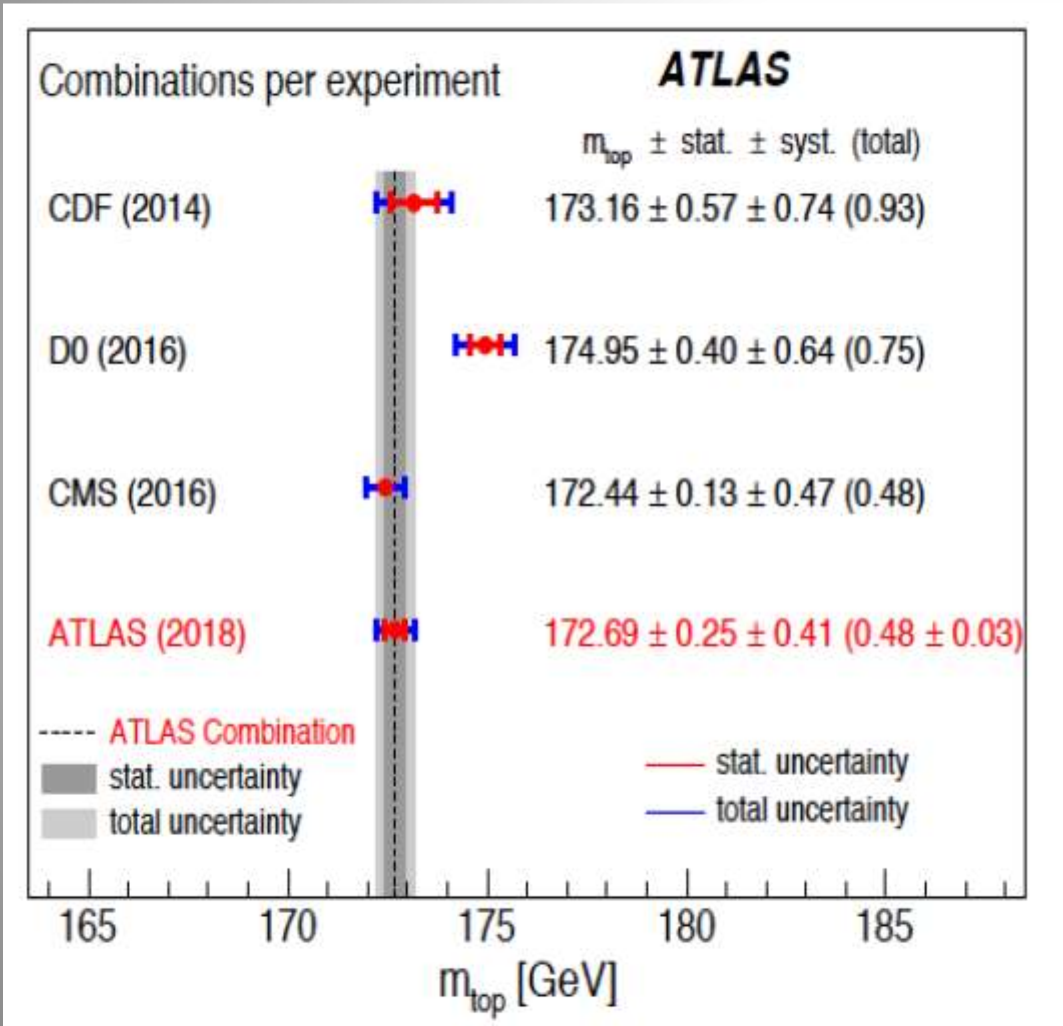
~ 10^8 produced tt-pairs (run-2)

Top Quark Cross Sections



Good agreement with the SM predictions up to the 13 TeV

Top Mass Determination



Steady improvements during run-1 and run-2

Precision reached now ~0.3%

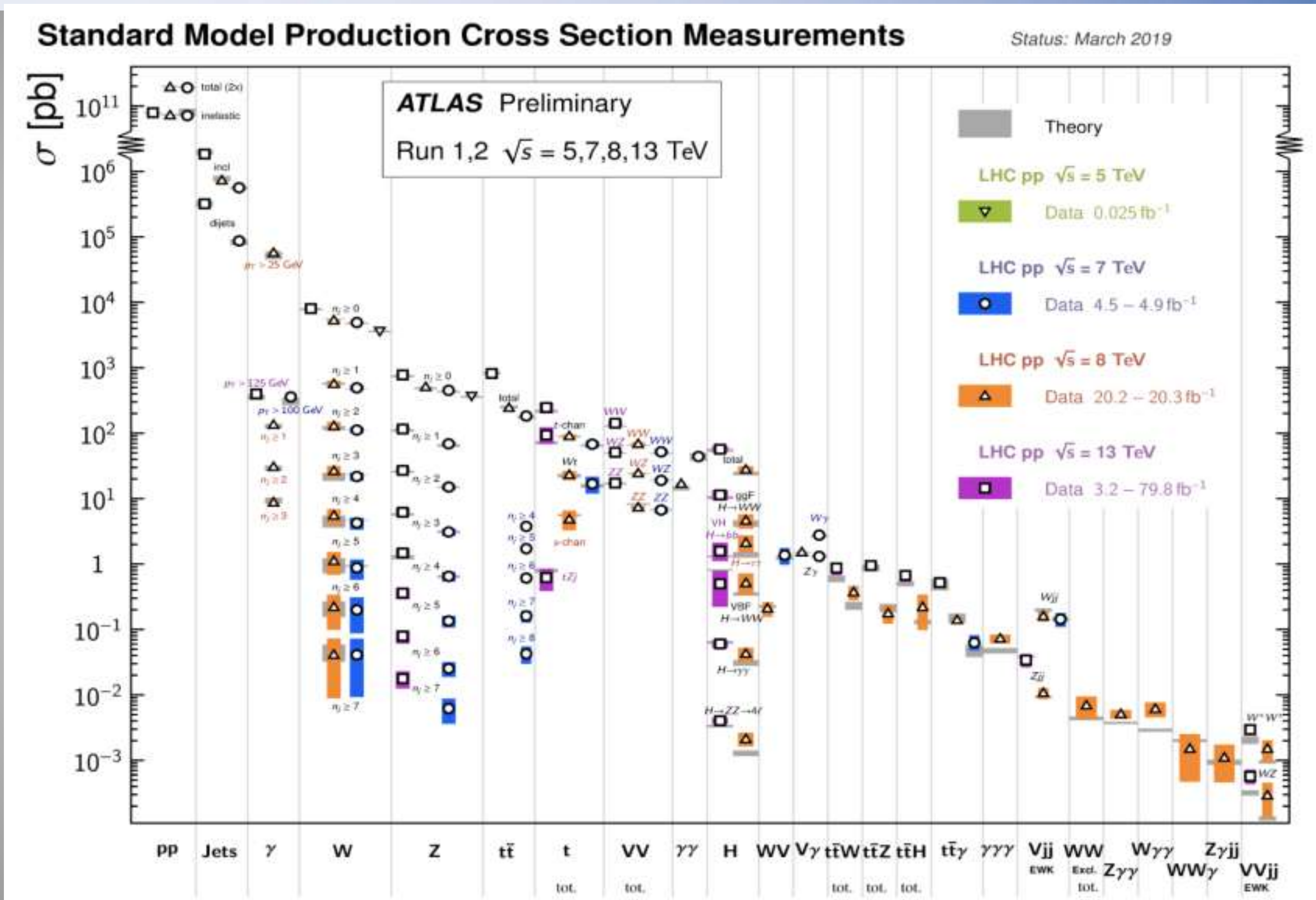
Hadronization model uncertainties one of the main limitations

Several alternative methods have been and are being explored using J/ψ, secondary vertices,...
This is not the final word yet

Experiment combination under way

Note: the average value LHC somewhat lower than Tevatron one: 174.34 $\pm$ 0.64 GeV

Summary: Cross Sections 7/8/13 TeV

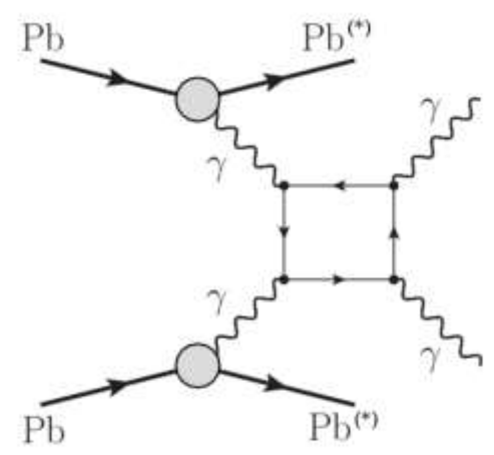


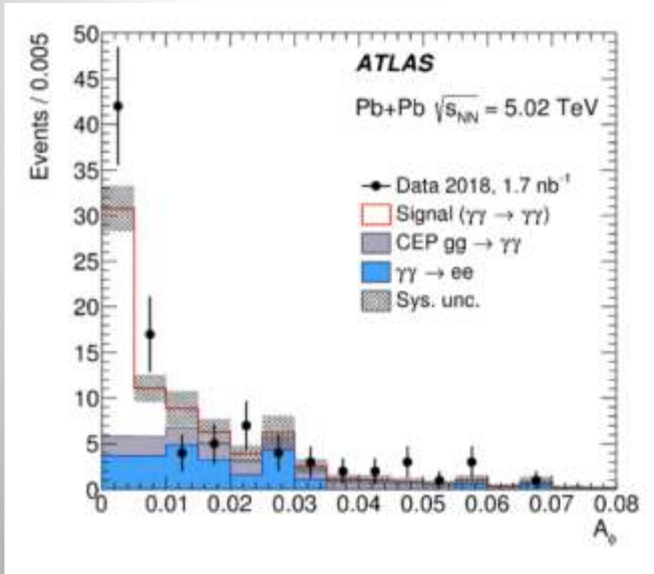
All measurements in good agreement with the Standard Model predictions!!

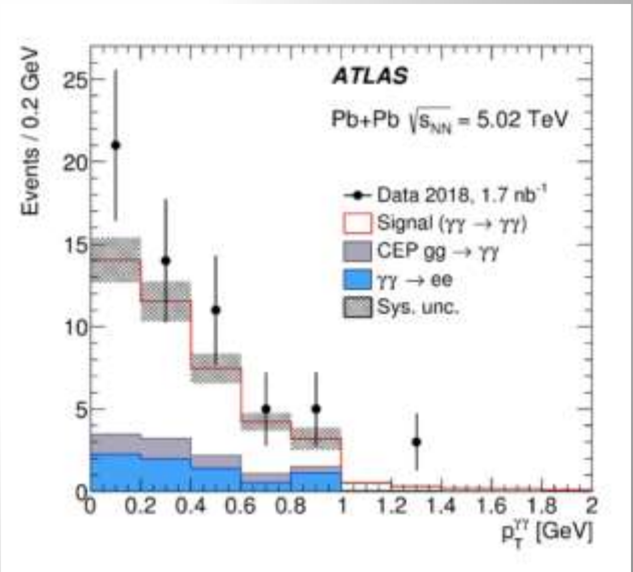
Light-by-light Scattering

arXiv:1904.03536

- Select ultra-peripheral collisions in PbPb
- Exclusive 2-photon final state selection
- Small acoplanarity (< 0.01)
- Small diphoton p_T (< 1 GeV or 2 GeV)
- 42 events found, 6 background events est.
- CMS result: arXiv:1810.04602







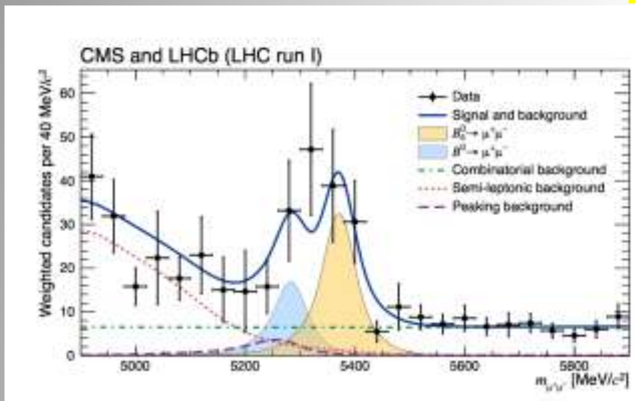
$\sigma_{\text{fid}}(\gamma\gamma \to \gamma\gamma)$ = 78 ± 13 (stat) ± 7 (syst) ± 3 (lumi) nb

8.2σ (6.2σ) obs/exp

Measurements of $B_{s(d)} \rightarrow \mu\mu$

arXiv:1411.4413
Published in Nature

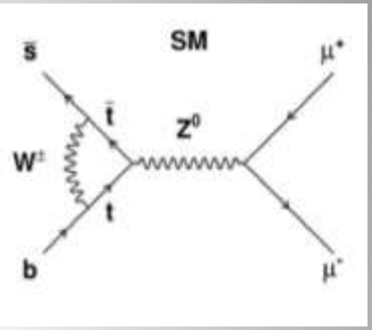
- Three B_s particles in a billion will decay into two muons. This decay has been chased for 30 years!!



- Results:

$$B(B_s^0 \to \mu^+\mu^-) = (2.8\,^{+0.7}_{-0.6}) \times 10^{-9}$$
$$B(B^0 \to \mu^+\mu^-) = (3.9\,^{+1.6}_{-1.4}) \times 10^{-10}$$

- Observed (Expected) significance
  - B_s: 6.2σ (7.4σ)
  - B^0: 3.2σ [WT], 3.0 [FC]σ (0.8σ)



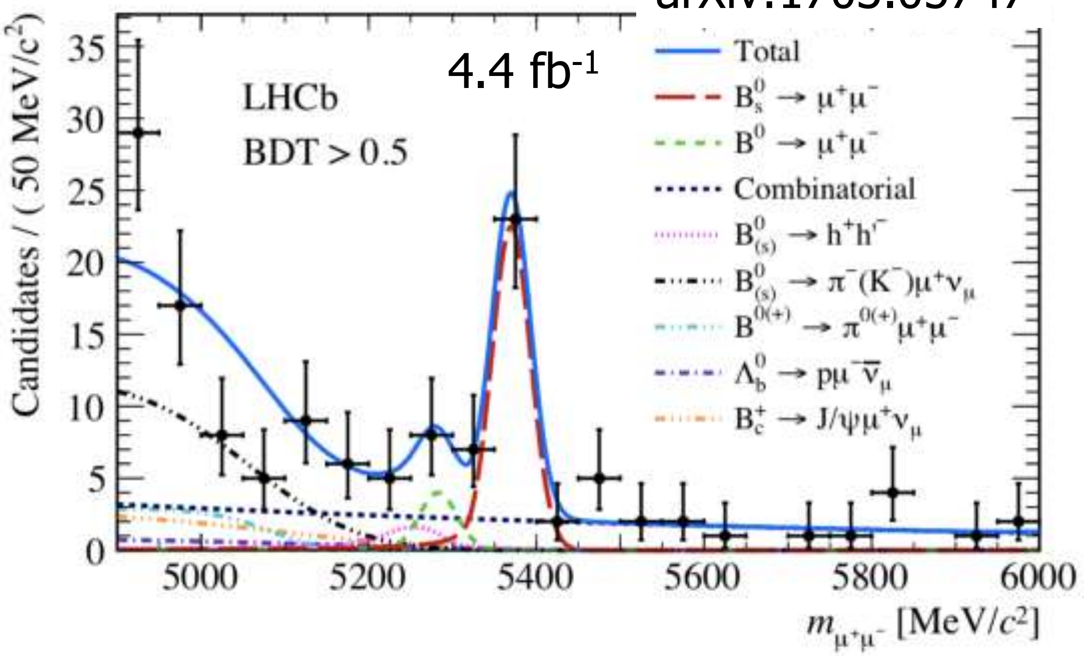
Present most precise results
Significance for B_s to muon decay is 7.8σ

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}$$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{SM} = (3.66 \pm 0.23) \times 10^{-9}$$

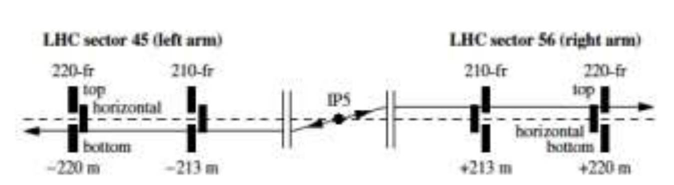
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \text{ at } 95\%$$

arXiv:1703.05747



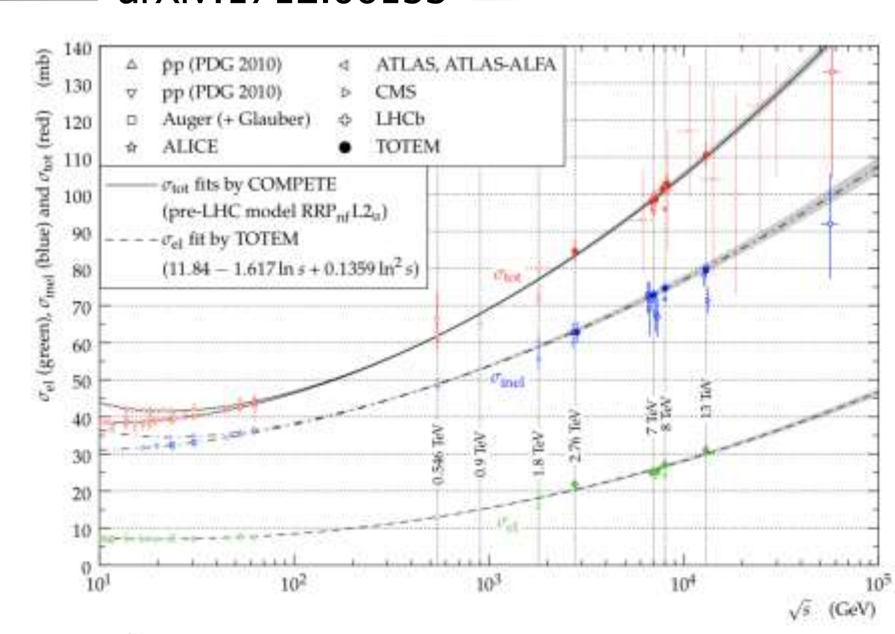
Total and Elastic Cross Sections

TOTEM experiment: Total cross section and elastic/diffractive scattering

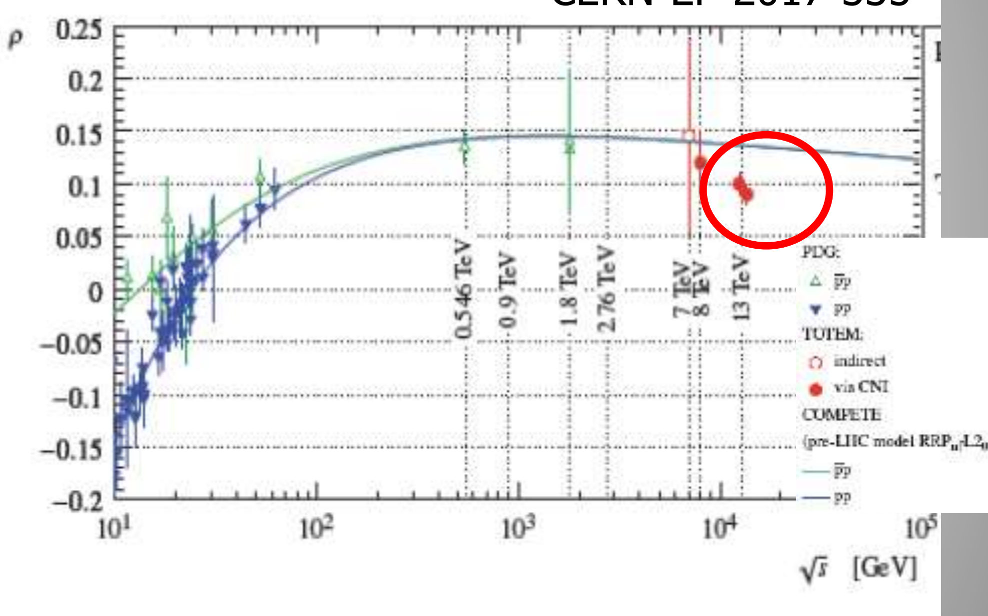


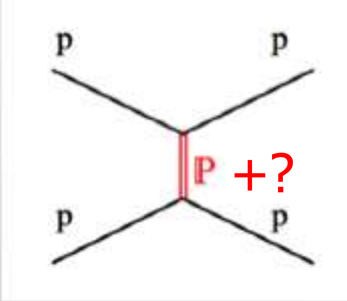
New measurements at 13 TeV

arXiv:1712.06153



CERN-EP-2017-335





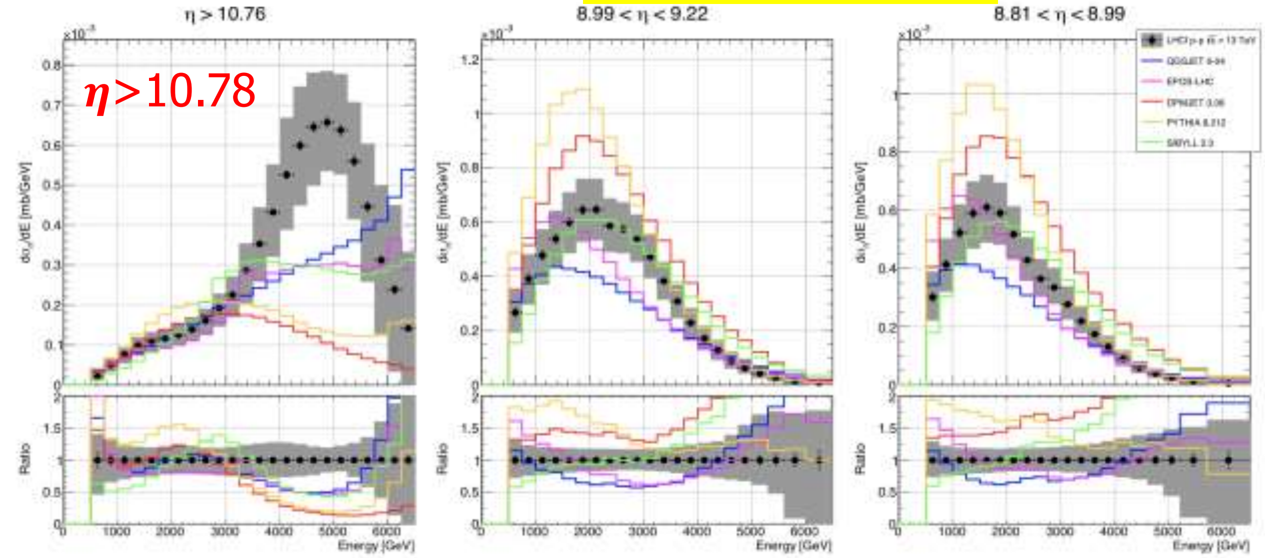
ρ: the ratio of the real to imaginary part of the nuclear elastic scattering amplitude at t=0, is lower that expected

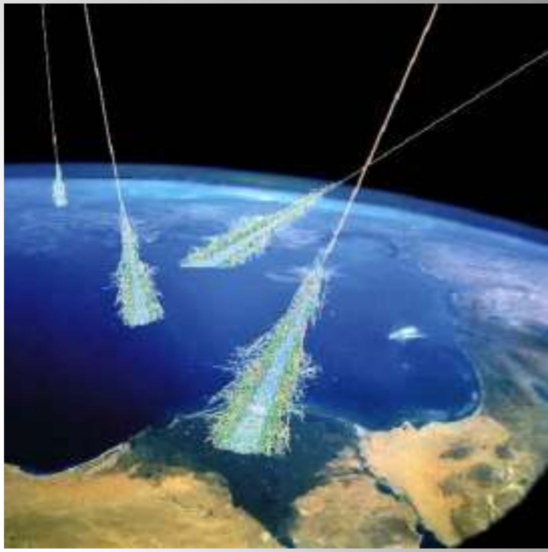
First direct evidence for "odderon" exchange in elastic scattering??

Forward Particle Production

arXiv:1808.09877

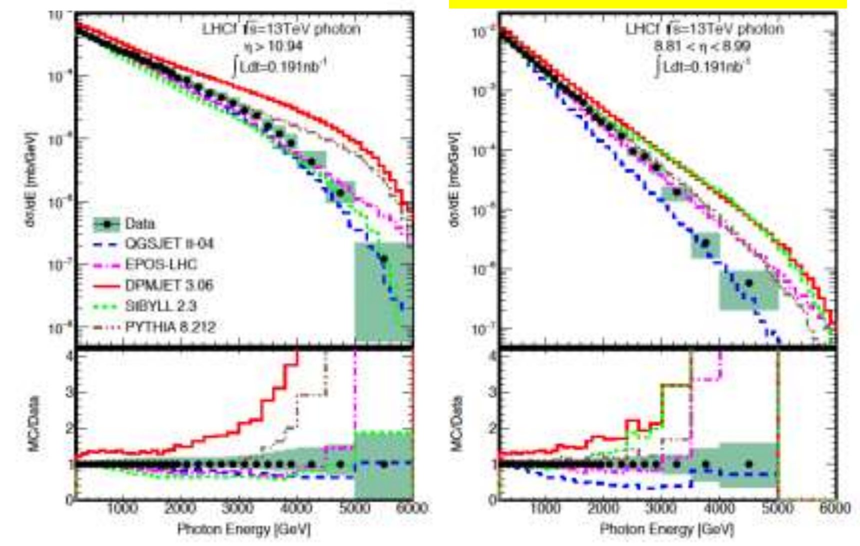
Forward neutrons

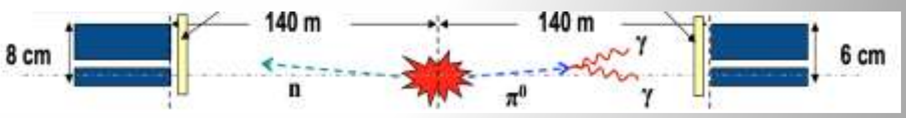




arXiv:1703.07678

Forward Photons





LHCf experiment:
Forward measurements compared to Monte Carlos for Cosmic Ray studies
No model reproduces the data well !!

Summary

- The LHC is the highest energy collider built by mankind so far. Seven experiments are currently collecting and analysis proton-proton (and AA) data.
- The experiments face huge challenges. A very crucial component is the selection trigger
- The physics program at the LHC is very diverse, with general purpose from Standard Model test in the new high energy regime, to searches for new physics
- Measurements of Standard Model processes show good agreement with predictions. Precise measurements require precise calculations.
- We will look at some specific searches for new physics in the next lecture