Experimental physics at the LHC:
from collisions to results

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Kārlis Dreimanis
Baltic School of High-Energy Physics
and Accelerator Technologies

Palanga, Lithuania
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1862
RIGA TECHNICAL
UNIVERSITY
Institute of Particle Physics and
Accelerator Technologies

What is experimental HEP?

- Broadly speaking, experimental HEP has two tasks:

  1) **To measure** precisely the various parameters and predictions of the **Standard Model** (SM);

  2) **To search for** signals of yet-undiscovered ***New Physics***, *lurking* Beyond the SM.

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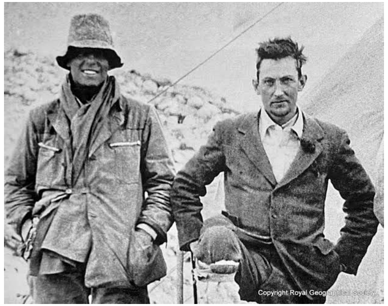
“Why climb Mount Everest?”

“Because it’s there!”

(George Mallory)



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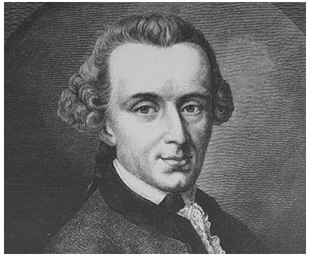
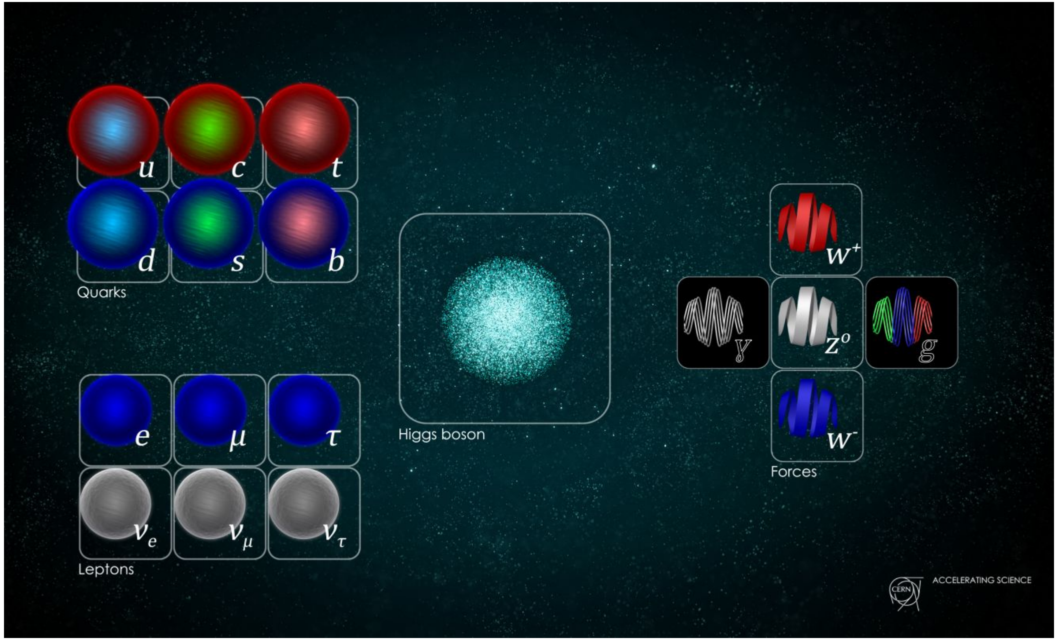
“Experiment without theory is blind, but theory without experiment is a mere intellectual play”

(Immanuel Kant)



The Standard Model

- The Standard Model consists of 27 unique elementary particles *[experimentally speaking…]*:
    - 6(+6) (anti-)quarks;
    - 3(+3) charged (anti-)leptons;
    - 3 neutral leptons;
    - 6 force carriers;



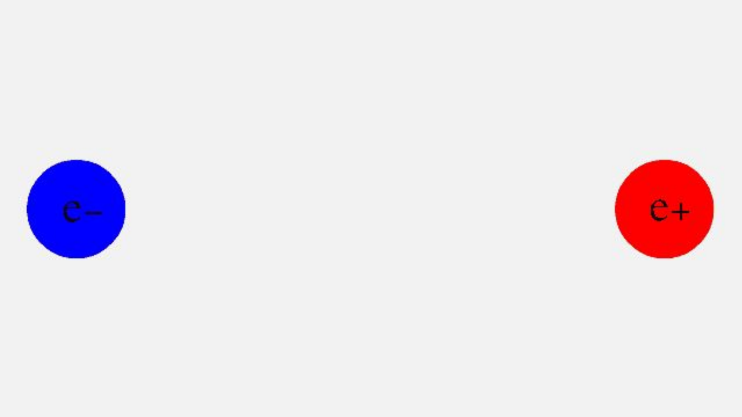
- Since the discovery of the Higgs, its proposed particle content is complete!

- However, as a most fundamental theory of Nature, the SM is still lacking!

- To study the SM experimentally, we need to study all of its constituent particles! To do that we must first create them in particle colliders!

When beams in a collider cross …

- In an e+e- collider (such as LEP) *life is "simple"*:
  - The *entire particle* participates in the collision;
  - The full energy is converted into *pure energy*;
  - Collisions can be tuned for a specific resonances:
    - bb{bar} (SuperKEKB*);
    - Z, WW, ZZ (LEP);
    - ZH, tt{bar} (FCC-ee**);
  - Clean signatures!



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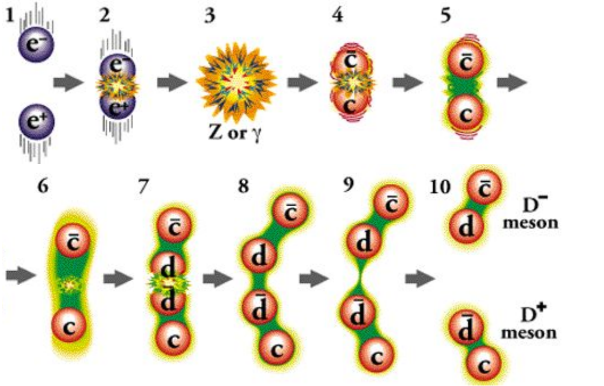

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* using asymmetric {energy} beams.
** hopefully, all of you will contribute to the creation of this!

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Energy loss per revolution: $P \propto \gamma^4$

$$\gamma = E/mc^2$$

$$m_e = 511keV, \quad m_p = 938MeV$$

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  - Greater synchrotron radiation losses → energy limit!
  - Cannot be solved *simply* by stronger bending magnets → need larger radii!

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$$\frac{P_e}{P_p} \sim 10^{13}$$

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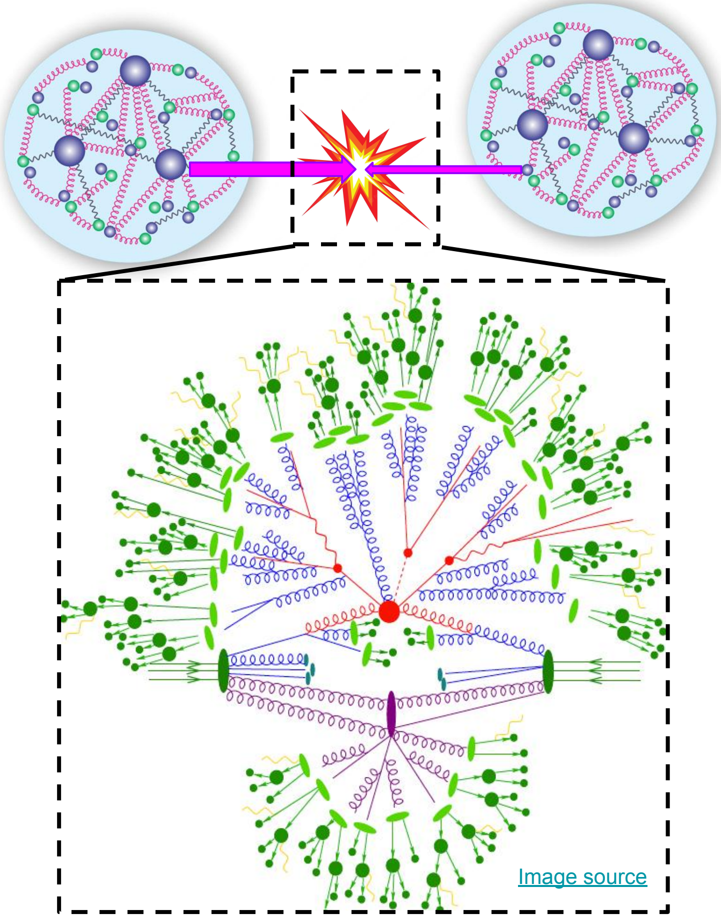
When beams in a collider cross …

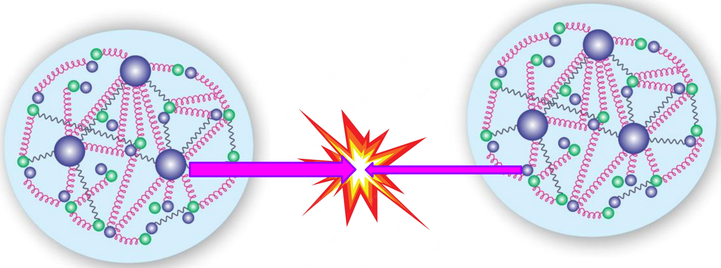
- Collisions in a hadron collider are much more complicated:
  - Only a fraction of the particle participates in the collision;
  - Extremely *messy* environment;
  - *Impossible* to tune the collision energy for certain resonances.

- But hadron colliders have their up-sides:
  - Low synchrotron radiation losses:
    - Higher achievable centre-of-mass energies;
    - Increased luminosity → higher statistics;
    - Further energy gains available with further magnet development!

- Hadron collision process can be broken down to its main parts:
    - **Main hard scattering**
    - **Underlying event**
    - **Collision product decay**
    - **Hadronization and hadron decays**



Interlude - PDFs



- Protons are constituent particles;

- We tend to think them as consisting of 3 quarks (uud), but in truth these 3 quarks are just the *valence* quarks, held together by gluons, whilst swimming in a quark-gluon sea!

- The greater the energy with which one probes the proton (ie. the greater the Q^2), the greater the chance of *encountering* a non-valence constituent of the proton!

- These constituents are called partons and their distributions (likelihood of being encountered with a given Bjorken-x at a given Q^2) are governed by the parton distribution functions (PDFs).

Interlude - PDFs

- PDFs can be measured best at ep experiments, where e deeply probes the proton;

- PDFs measured at given Q^2 can then be evolved to other Q^2 values using the DGLAP equations;

  (and I'll leave it at that here!)

- But, importantly, this leads to LHC being, essentially, a gluon-gluon collider!

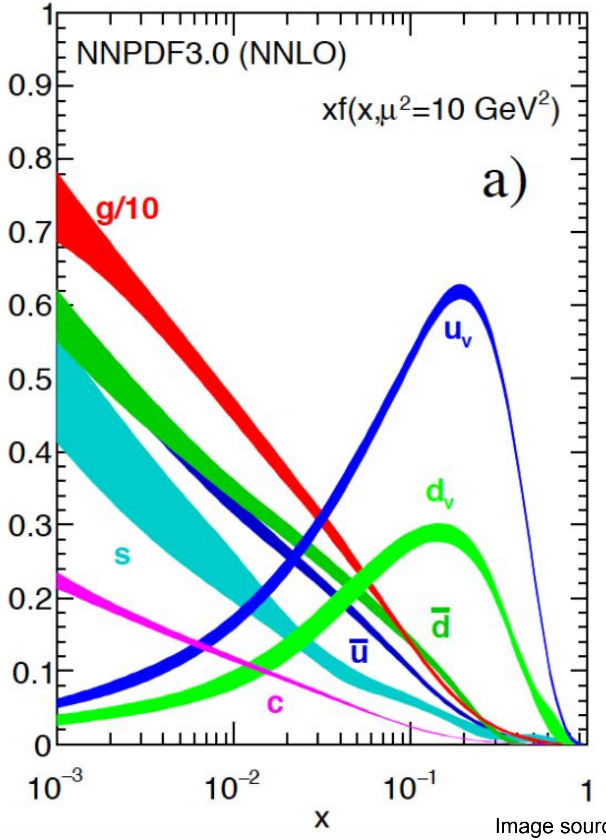


Image source: PDG 2016

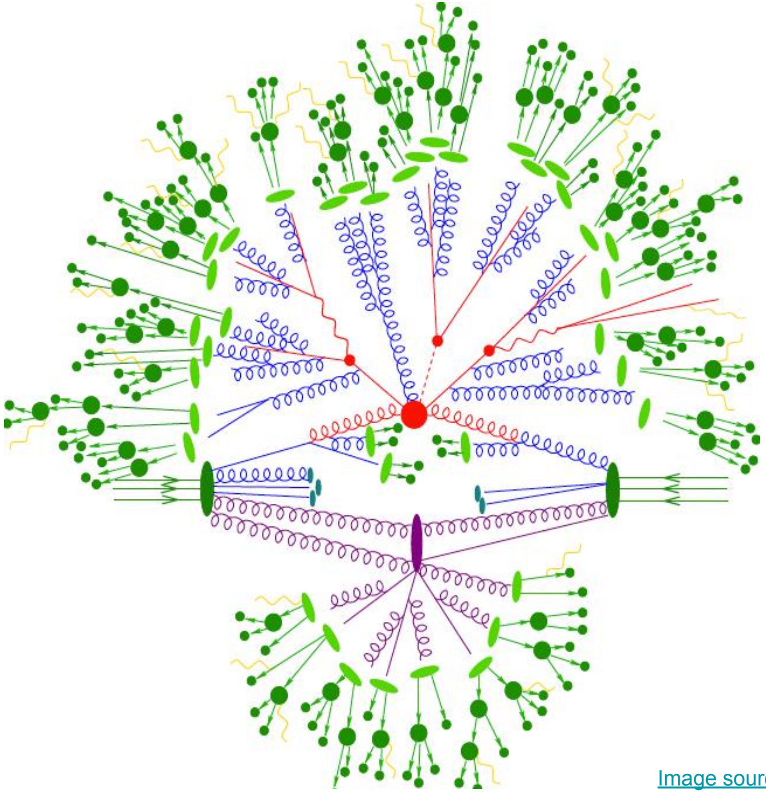
When beams in a collider cross ...

- Main (hard) scattering event:
  - Large momentum transfer (Q^2);
  - Perturbatively calculable!

- Secondary (underlying) event/-s:
  - Small Q^2;
  - *Impossible* to calculate using perturbative methods!
  - Must be *provided* by the experiment!

- Our detectors can see only the green and yellow!
  - Hadron decays;
  - Photon emission;

  [and prompt and non-prompt leptons (not shown)].



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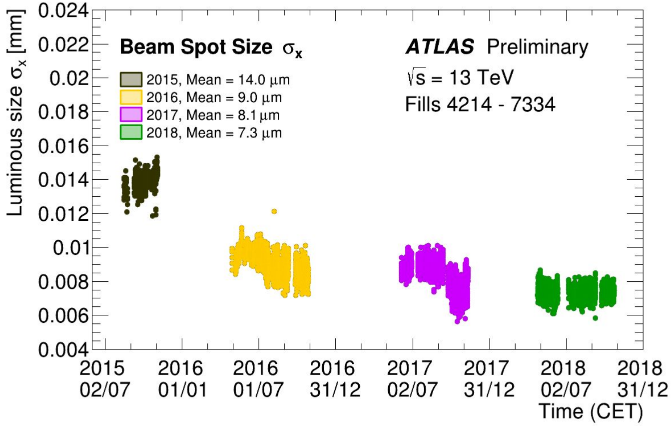
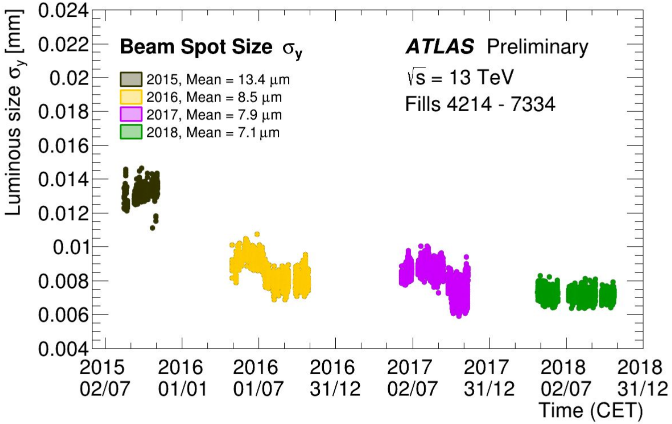
“Detecting particles” at LHC

- The aim of the LHC experiments is to study *exotic* particles.
- In HEP, *exotic* often means more massive.
- Such particles are extremely *fickle* - they decay into more *mundane* particles very quickly:
  - Z,W±: $\tau \sim 10^{-25}$s;
  - t: $\tau \sim 10^{-25}$s;
  - H: $\tau \sim 10^{-22}$s.
- These particles *travel* infinitesimally small distances from the primary vertex (PV) before decaying.

- Example: the LHC beam-spot at ATLAS →





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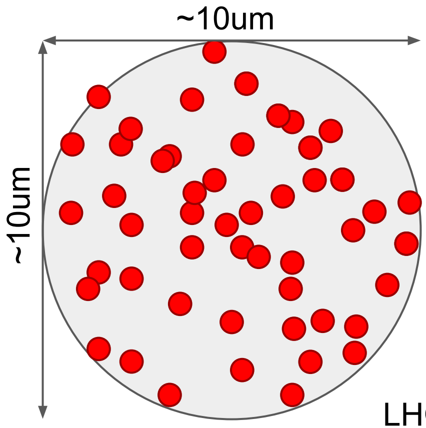
- The beam-spot contains all the pp interactions within it (both transversely & longitudinally);



LHC beam-spot
(head-on/transverse view)

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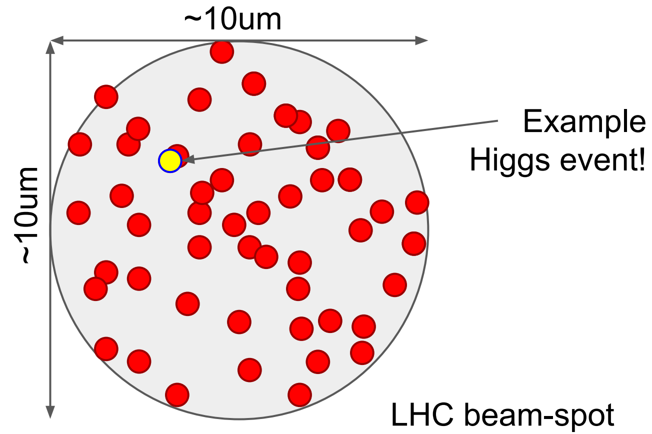
- The velocity at which any this H would have to travel to even escape the beam-spot is **0.9999999999999999c**; (protons accelerated by LHC to 0.999999991c are ~100x less massive!)



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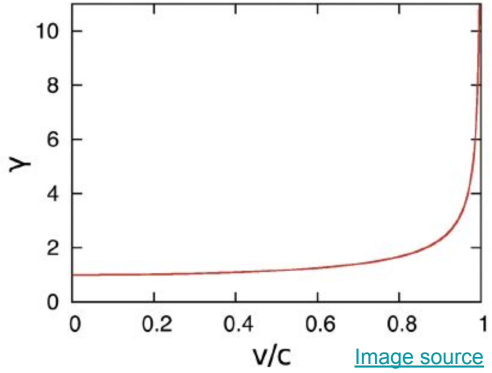
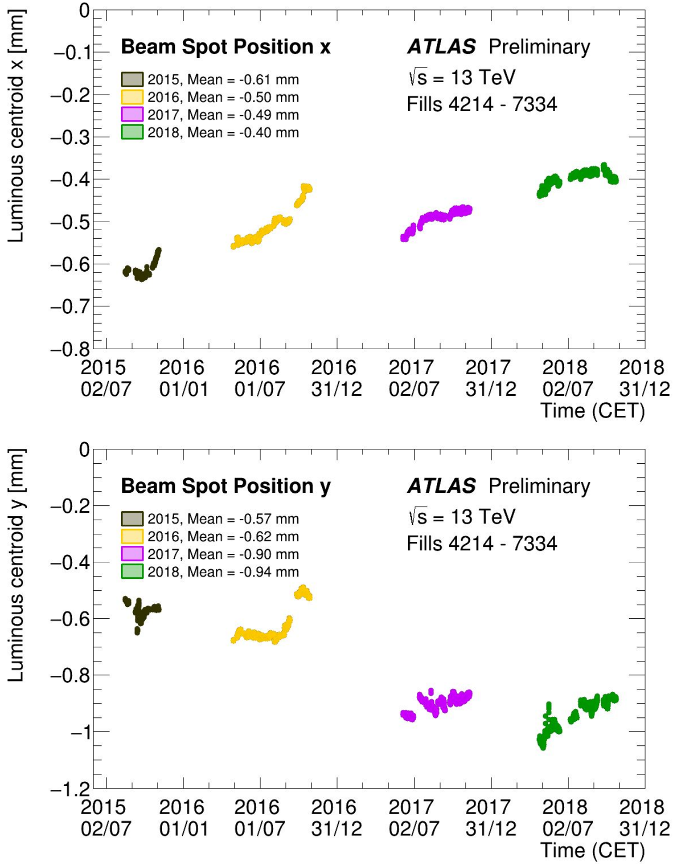


Image source

"Detecting particles" at LHC

- In fact, it is even worse that!
- LHC beams are not perfectly uniform nor is the beam position always the same;
- The detectors must be placed a safe distance from the beam to avoid costly damage;
- At the LHC, this safe distance is ~3 cm;



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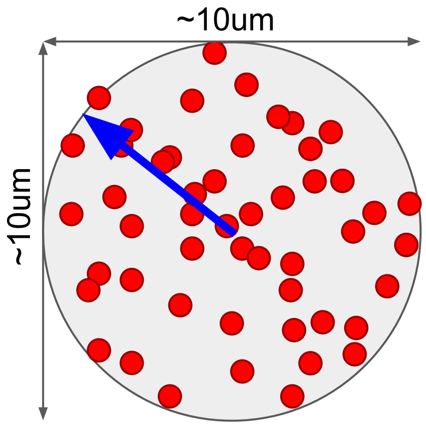

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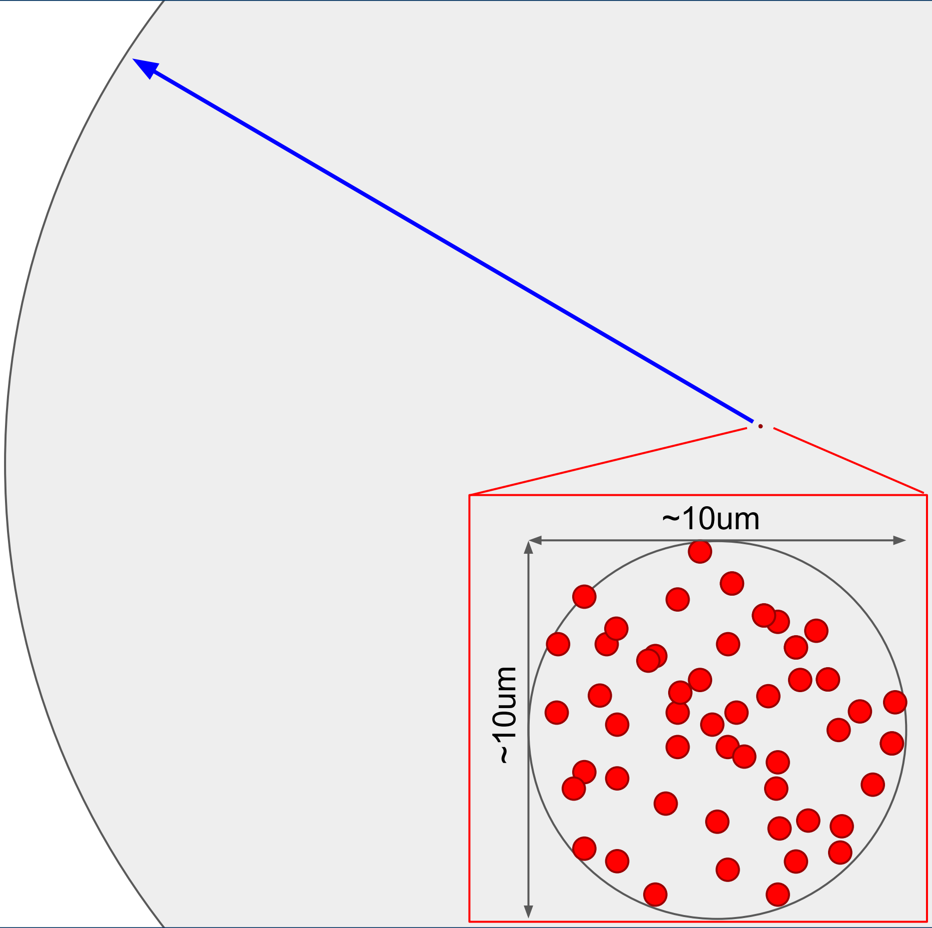
… but rather something like **THIS**!

Which is not really viable!



“Detecting particles” at LHC

- We never actually detect these heavy particles!
- We only detect their decay products!
  (and decay products of decay products of …)
- Here, ttH production via a **gluon-gluon** collision process at a hadron collider (like LHC) is shown;
- **t** quarks and **H** boson are produced;
- These decay in **W** bosons, **τ** leptons and **b** quarks;
- These then further decay into various **leptons** and **hadrons**.

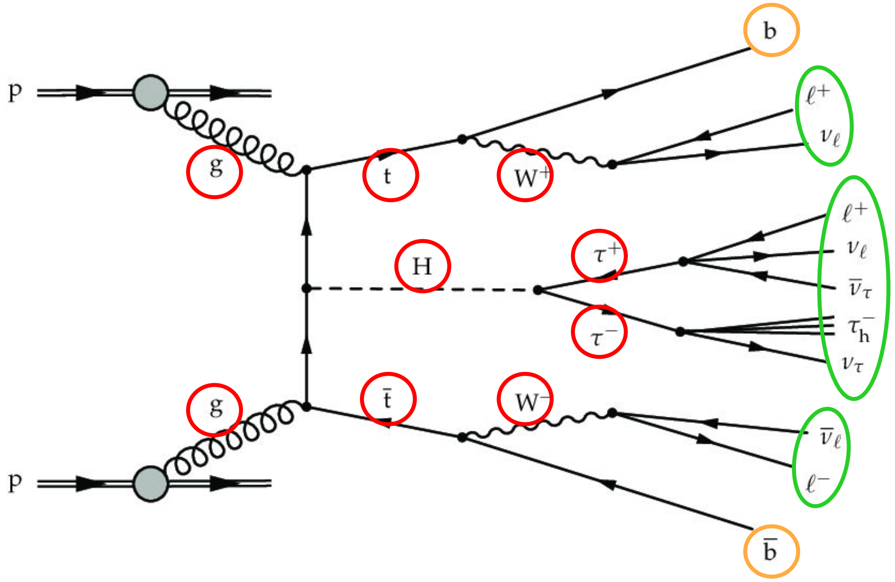


Image source

"Detecting particles" at LHC

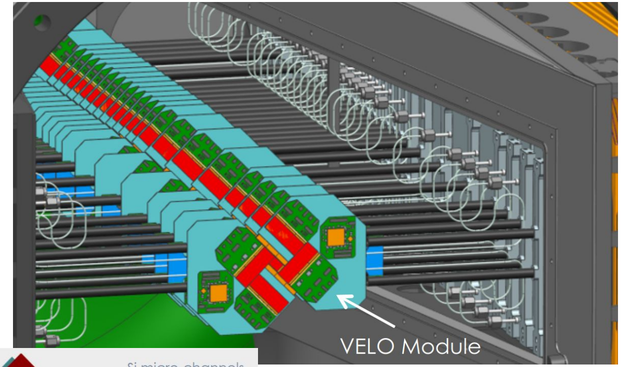
- Thankfully, some *exotic* particles are more *compliant*:
  - τ leptons: $\tau \sim 10^{-13}$s;
  - D mesons: $\tau \sim 10^{-13}$s;
  - B mesons: $\tau \sim 10^{-12}$s.

- At the LHC, B mesons can travel as far as ~1 cm!

- One detector at the LHC can, in theory, "see" these particles *directly*;

- LHCb's VELO detector can be moved-in towards the collision point to a distance of 5 mm;

- **VELO** stands for **VE**rtex **LO**cator, as the detector specialises in precise reconstruction of secondary vertices.



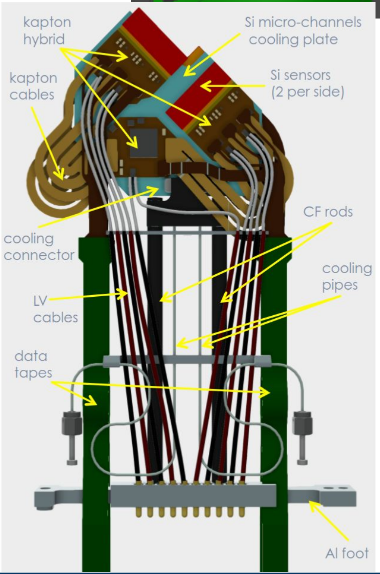
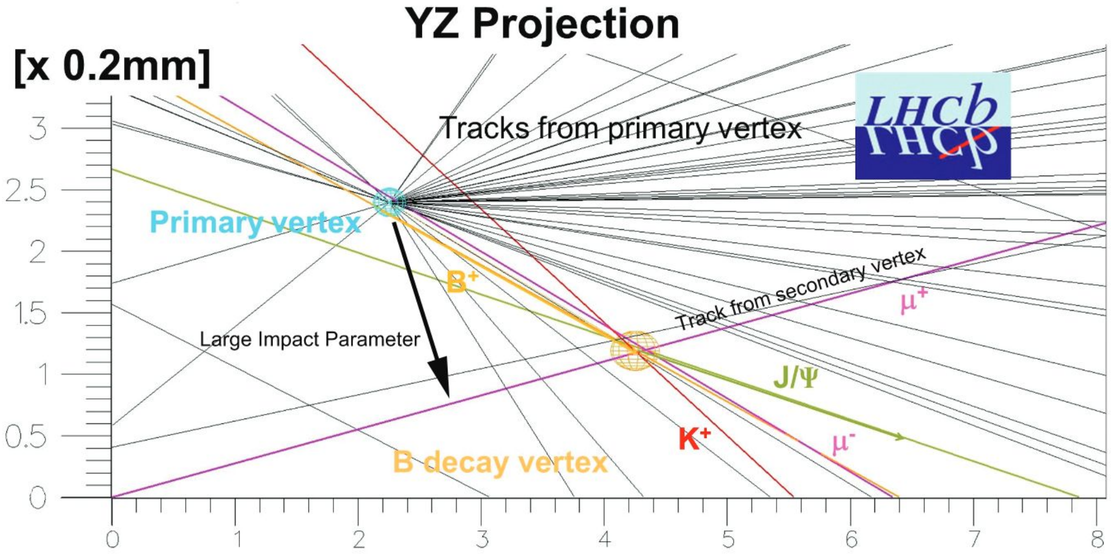


Image source:
LHCb collaboration

Vertexing at LHCb

- In truth, the tracks are still reconstructed from the decay product interaction with the detector;



Signature of B decay products from a $B^+ \to J/\psi K^+$ candidate event in LHCb data.

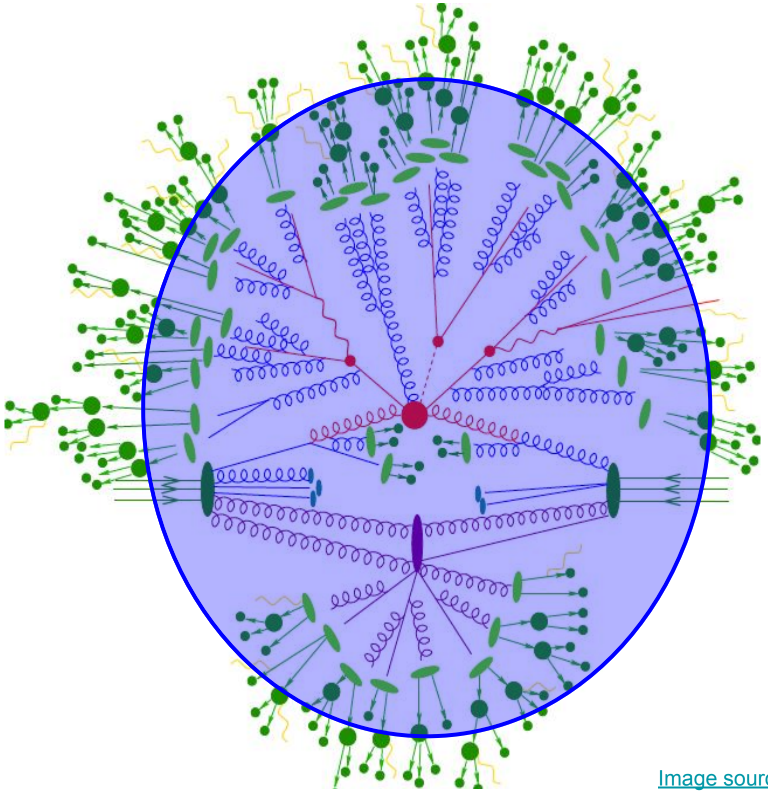
Image source: LHCb collaboration

- But the closer to can start the decay product detection, the better your vertex resolution!

Vertexing at the GPDs

- For ATLAS and CMS, the first detecting layer is 3.3 and 2.9 cm from the beam-spot, respectively.

- The challenge of precise secondary vertex reconstruction is even higher!



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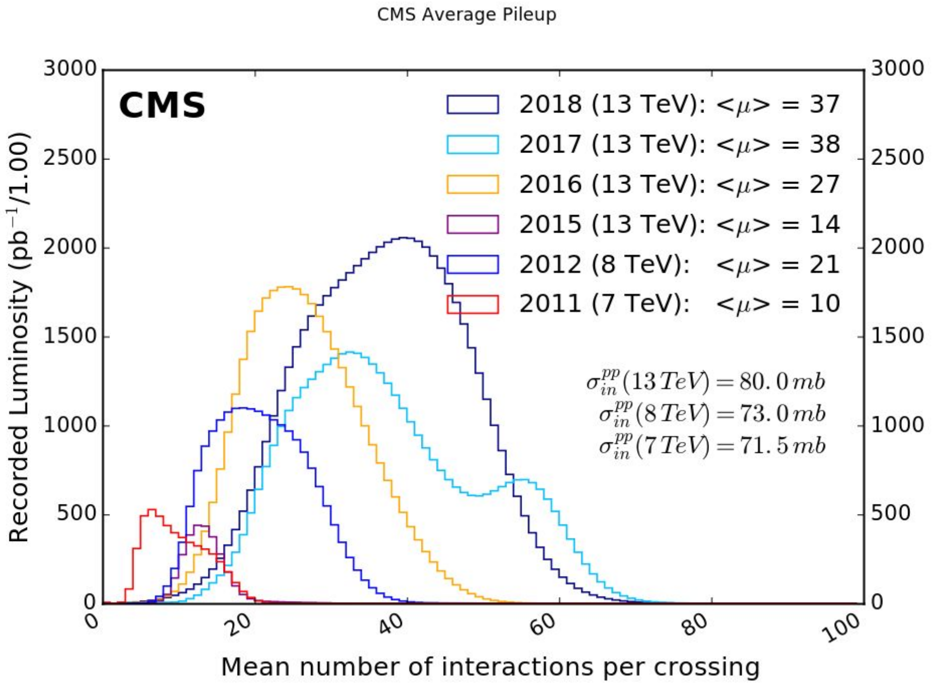

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- Here, the n_{PV} is *only* ~100;
- At **HL-LHC** it will be up to **200**!

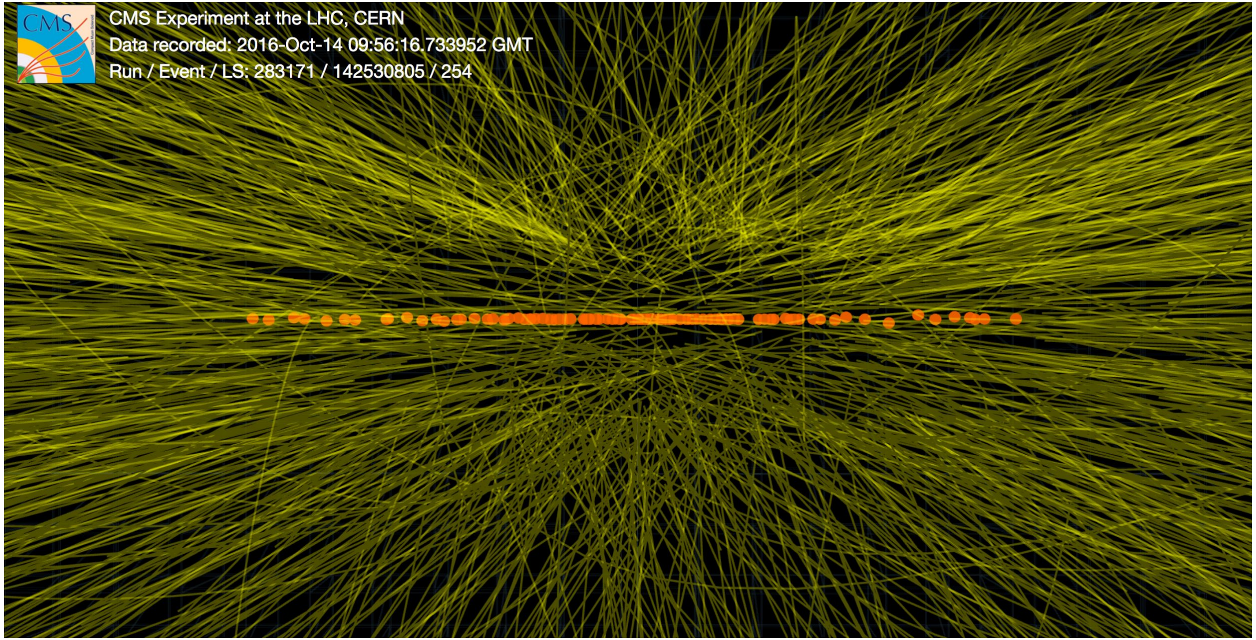


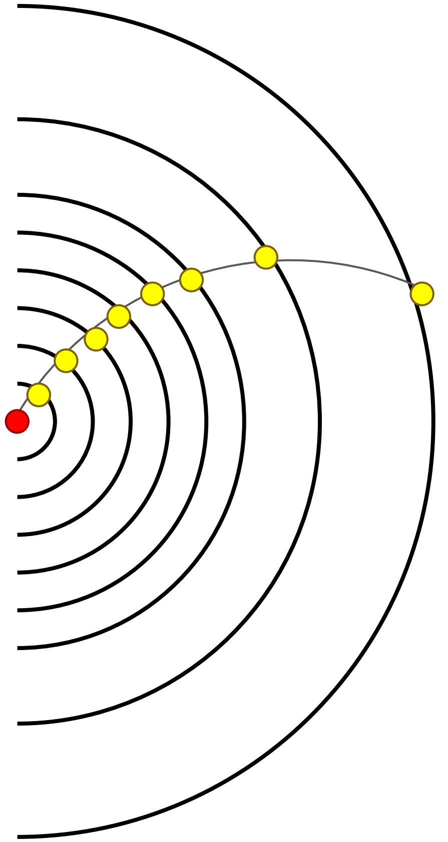
Image source: CMS collaboration

Track reconstruction

- Precise track reconstruction is vital for good quality physics results.
- Trackers are usually* the nearest-to-beam instrumentation at the LHC;
- Trackers are immersed in a B-field, which bends the particle paths:

$$R = \frac{mv}{qB}$$

- The bending radius is used to measure charged particle **momentum**.
- An ideal tracker is infinitesimally thin to avoid 'corrupting' the measured particle path through material interactions;
- Ideally, the tracker would also be infinitely granular, but in reality, understanding of your the B-field can be the driver of the momentum uncertainty with a modern pixel tracker.



* muon stations are, essentially, also trackers, but are the farthest.

Calorimetry

- As the name suggests, calorimeters aim to measure the *total calories* (the total energy) of the incident particles;
- Thus, completely opposite to trackers, calorimeters *want* to maximally 'corrupt', or stop, the detected particles;
- Usually split into ECAL and HCAL to allow for a separation between e/γ and the hadronic particles.

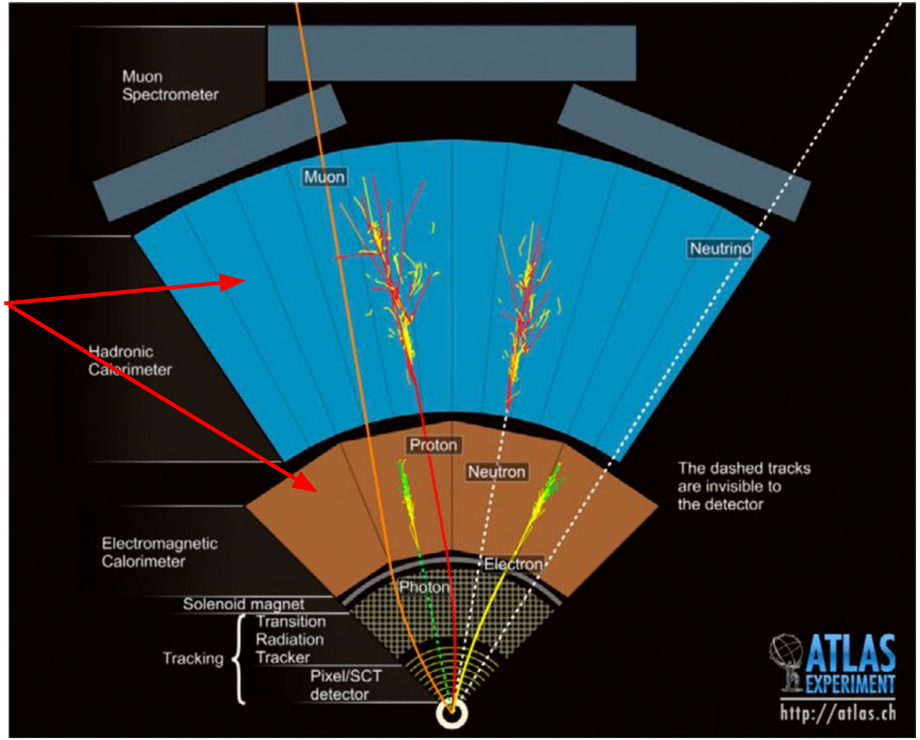


Image source: ATLAS collaboration

Particle Identification

- Particle Identification (PID) is usually a combined effort of multiple detector layers and technologies.

- As before, ECAL/HCAL split allows to separate e/γ from the hadrons.

- Adding the tracking information allow to split electrons from γ and charged hadrons from neutral hadrons.

- Finally, placing muon stations as the outermost layer, allows to identify muons (and their tracks in the tracker).

- But this approach struggles to separate, various hadronic particles from each other → particularly relevant for flavour physics at LHCb!

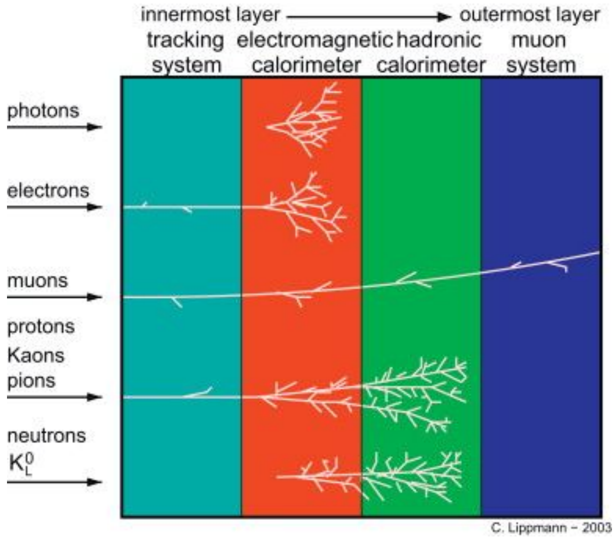


Image source: https://doi.org/10.1016/j.nima.2011.03.009

- Use ingenuity - Cherenkov light!

- Cherenkov light is produced when a charged particle moves in a medium faster than the speed of light in that medium;

- It creates a light-cone with an angle related to the particle's velocity:

$$cos\theta_C = \frac{1}{\beta n}$$

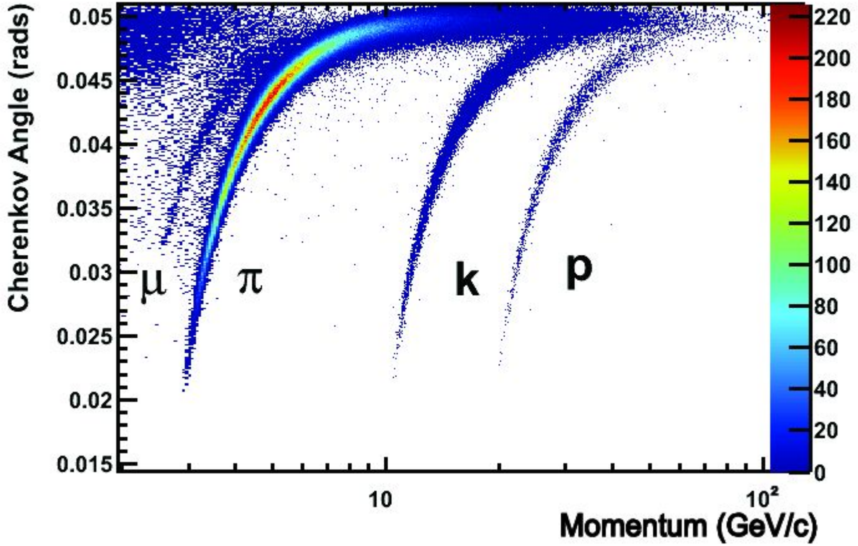


Image source: LHCb collaboration

- Combining this information with the momentum information from the tracking system, one can extract the particle's mass!

Correcting the measurements

- All particles are *detected* with a given efficiency, ε_{det};

- Various parameters need to be corrected for,
like reconstruction efficiency, ID efficiency, etc. …

- This is usually done by binning your distributions against some relevant variable:

  - Total momentum, p;
  - Transverse momentum, pT;
  - Pseudorapidity, η;

    … etc.

  … and finding the ε_{det} in each bin.

- Another tricky correction is accounting for bin migrations.

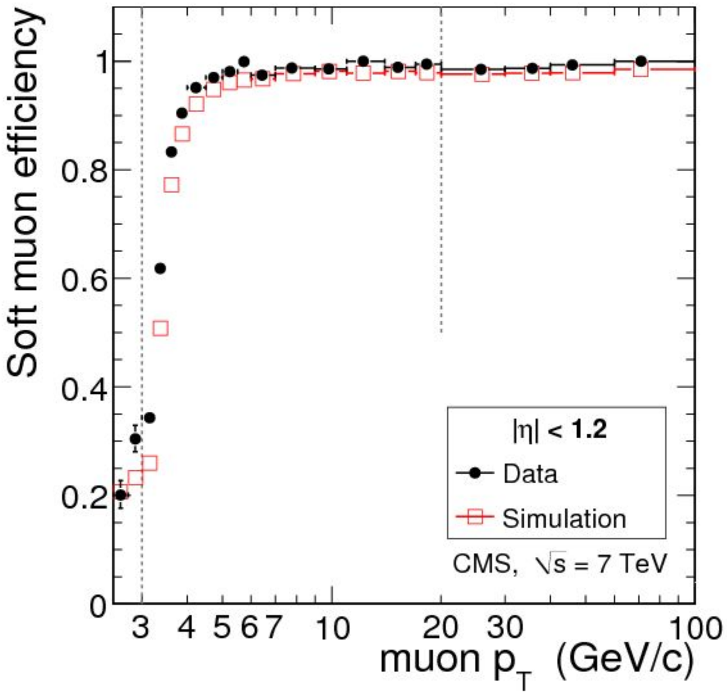


Image source: CMS collaboration

Monte-Carlo simulations

- A vital part of particle physics experiment is the *Monte-Carlo* (MC) simulation; MC, broadly speaking, is a theory prediction of particle behaviour.

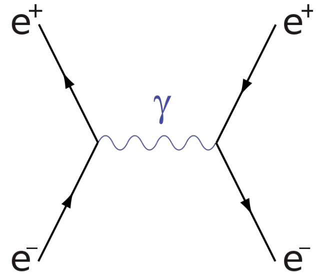
- MC generator *precision* is limited by the *order* to which the particle interactions are simulated:
  - Leading order (LO), a.k.a. tree-level;
  - Next-to-leading order (NLO);
  - Next-to-next-to-leading order (NNLO);

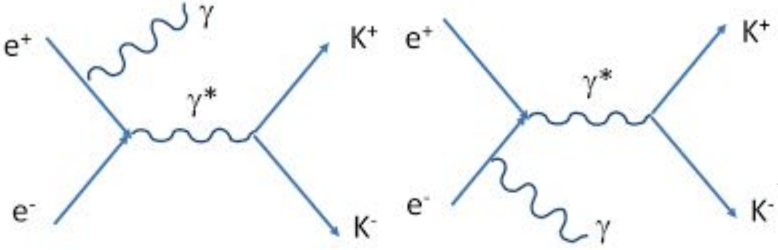
    ...

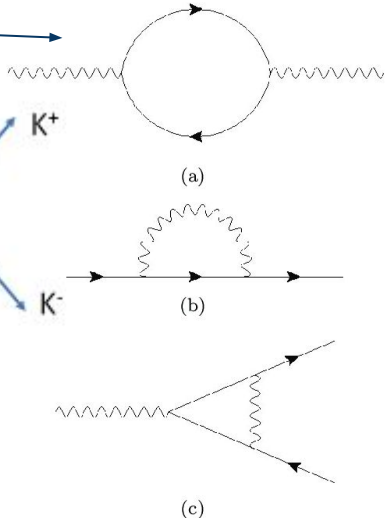
- The current state-of-the-art is N^3LO;

- There are many MC generators in use:
  - PYTHIA;
  - Powheg;
  - Sherpa;

  … among others.







Monte-Carlo simulations

- MC simulation on its own gives us the physical processes at the ***truth*** or ***generator*** level.

- A particle collision as it *truly* happened, from the hard scattering itself, to the potentially observable physics objects.

- Notice, it also includes non-perturbative soft components, such as the MPIs.

- Generator level MC is very powerful, but not immediately useful for the experiment on its own.

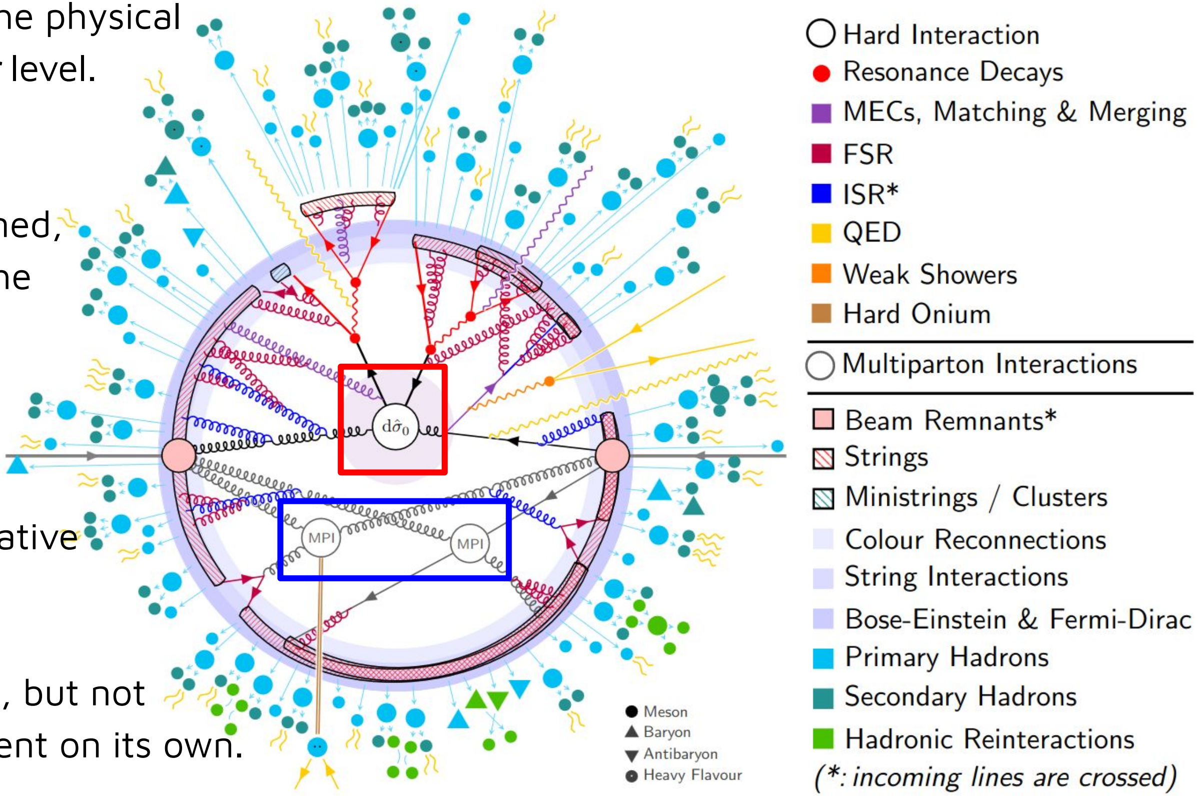


Image source: https://arxiv.org/pdf/2203.11601.pdf

Detector simulation

- Detecting == interfering!

- We must have a complete (!) understanding of what the generated particles encounter;

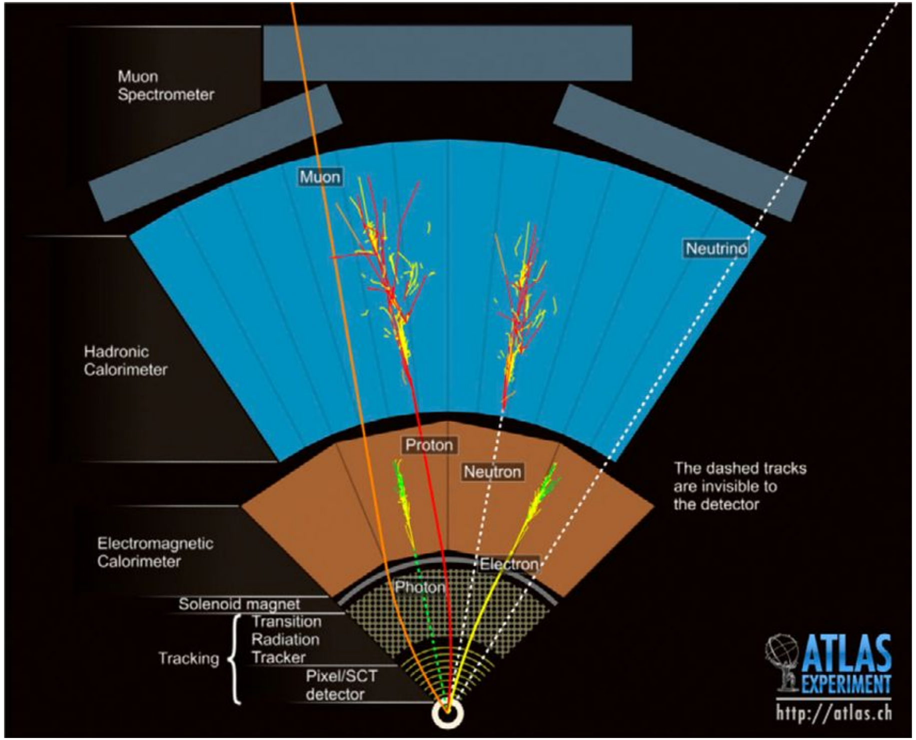


Image source: ATLAS collaboration

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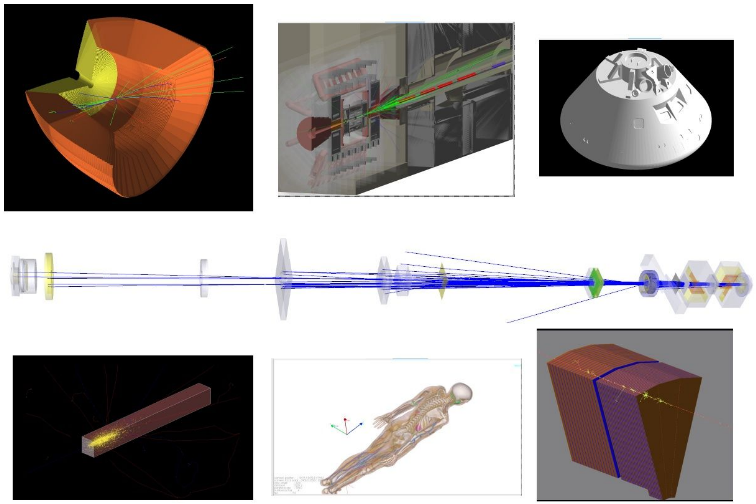
- We use a tool* called Geant4, to fully simulate our detectors, including both active and passive materials within them.



* other tools, such as FLUKA are also used for more specialised needs.

Image source: Geant4 collaboration

Combination: full simulation!

- To get to how *nature* shows-up in our detector, one must combine the physics generator with the detector simulation …
  … and add digitisation and other steps …

- All HEP experiments have their own huge software packages, painstakingly built, continuously updates and improved:
  - ATLAS → Athena;
  - CMS → CMSSW;
  - LHCb → Gauss.

- Finally, at the end of all this, we arrive at our ***reconstruction*** or ***detector*** level MC simulation.

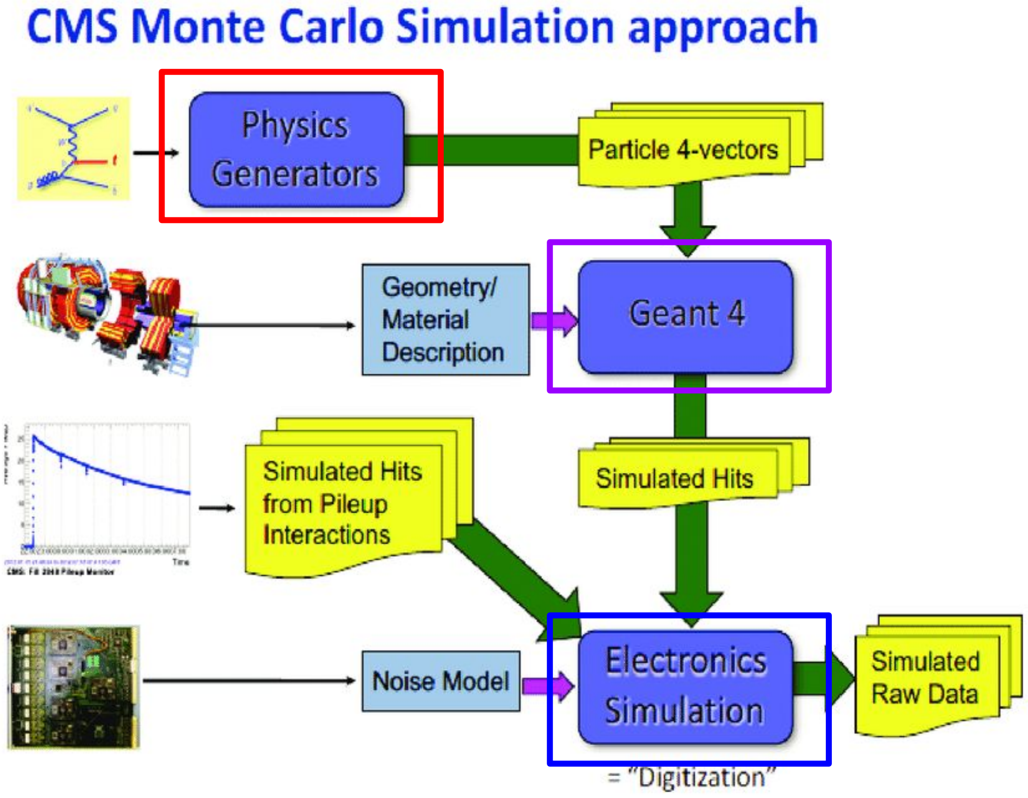


Image source: CMS collaboration

MC simulation versus collision data

What *information* is *readily* accessible?

Monte-Carlo simulation	**Collision data**
Detector / reconstruction level information	Detector / reconstruction level information
Generator / truth level information	Generator / truth level information

MC simulation versus collision data

What *information* is *readily* accessible?

Monte-Carlo simulation	Collision data
Detector / reconstruction level information ✔	Detector / reconstruction level information
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MC simulation versus collision data

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Detector / reconstruction level information	✔	Detector / reconstruction level information	✔
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MC simulation versus collision data

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Monte-Carlo simulation	Collision data
Detector / reconstruction level information ✔	Detector / reconstruction level information ✔
Generator / truth level information ✔	Generator / truth level information ✗

But the truth level information in real collision data is exactly what we seek!

Catastrophe!!!

MC simulation versus collision data

What *information* is *readily* accessible?

Monte-Carlo simulation		Collision data	
Detector / reconstruction level information	✓	Detector / reconstruction level information	✓
Generator / truth level information	✓	Generator / truth level information	✗

- To avoid the catastrophe, we must correct the measured distributions for detector effects;
- We must also understand our backgrounds very well;
- In fact, the vast majority of time it takes to complete a physics analysis at LHC goes to understanding backgrounds, correcting your distributions, etc. …

MC simulation versus collision data

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- In fact, the vast majority of time it takes to complete a physics analysis at LHC goes to understanding backgrounds, correcting your distributions, etc. …

… and convincing your collaborators that you have done everything correctly!

Unfolding

- The knowledge of MC reco, MC truth and data reco distributions can be used to *recover* data truth, via a process called detector unfolding.

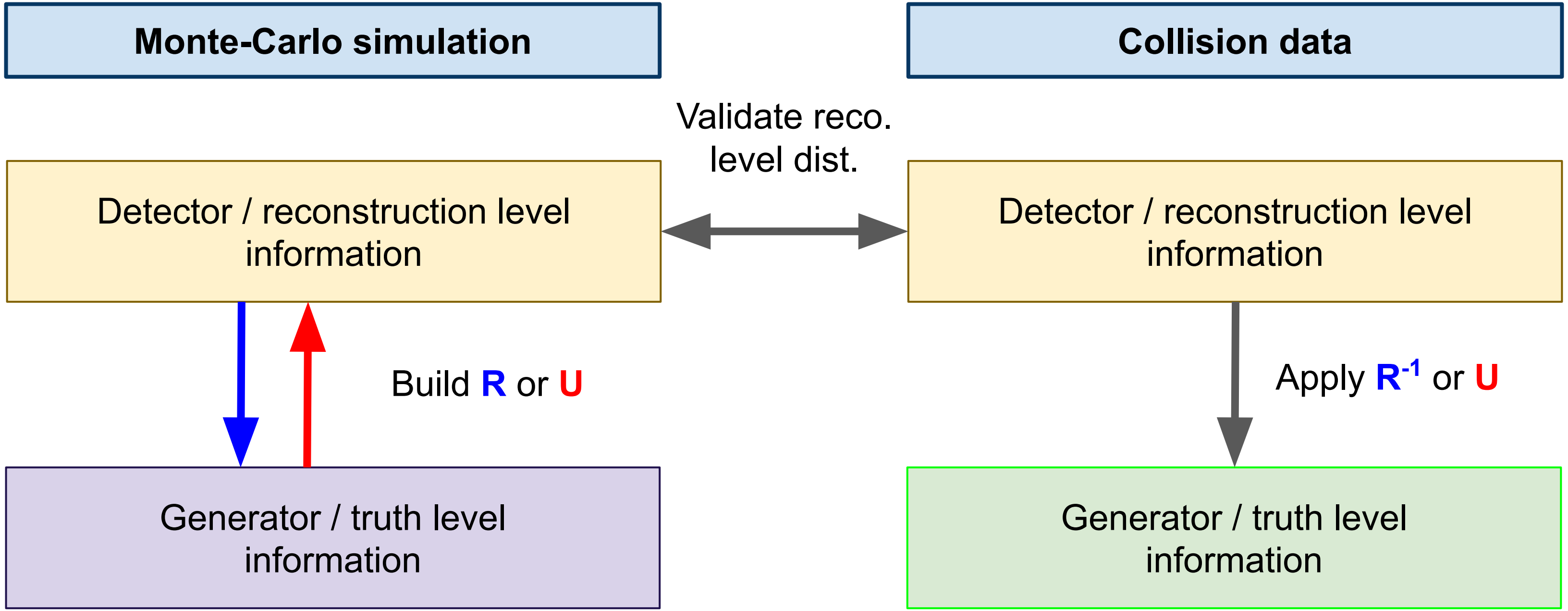
- Consider a reconstructed distribution, $\mathbf{M}_{\mathbf{r(MC)}}$, and a true distribution, $\mathbf{M}_{\mathbf{t(MC)}}$; these can be related to each other through *some* response matrix **R** via $\mathbf{M}_{\mathbf{r(MC)}}=\mathbf{R}\mathbf{M}_{\mathbf{t(MC)}}$.

- Hence, by definition, the relation $\mathbf{M}_{\mathbf{t(MC)}}=\mathbf{R}^{-1}\mathbf{M}_{\mathbf{r(MC)}}$ also holds true; $\mathbf{R}^{-1}$ is what one calls the unfolding matrix **U**, which can be obtained directly from MC and applied to $\mathbf{M}_{\mathbf{r(data)}}$ to get find $\mathbf{M}_{\mathbf{t(data)}}=\mathbf{U}\mathbf{M}_{\mathbf{r(data)}}$

- For MC, the link between truth and reco particles can be retained, ie. one can identify:
    - *Correctly* reconstructed particles (exist at both the truth and reco levels);
    - Missed particles (exist only at the truth level);
    - Ghost particles (exist only at the reco level).

- Using this information one can easily construct both **R** and **U**.

Unfolding



Monte-Carlo simulation
Collision data
Validate reco. level dist.
Detector / reconstruction level information
Detector / reconstruction level information
Build R or U
Apply R-1 or U
Generator / truth level information
Generator / truth level information

Unfolding

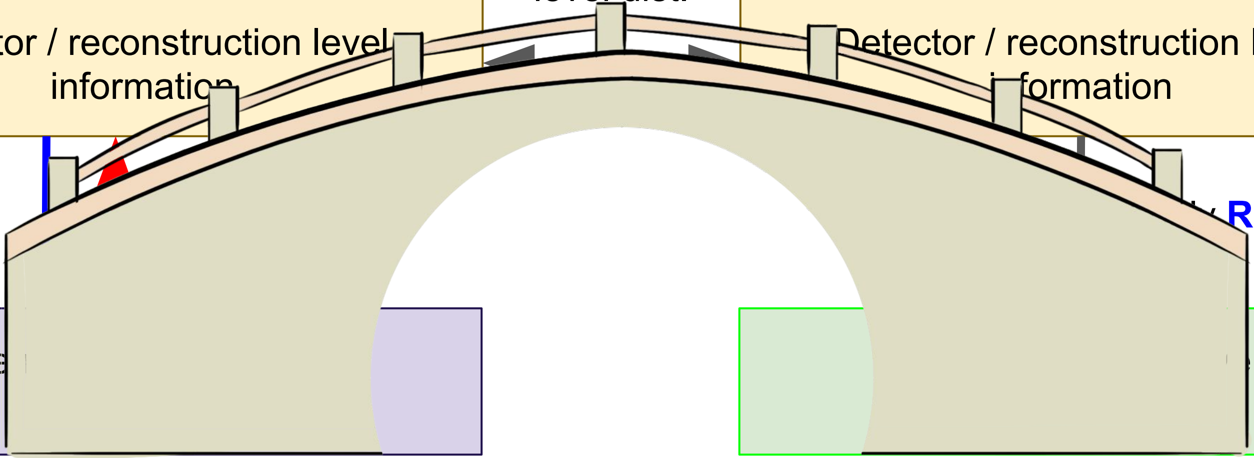
Monte-Carlo simulation

Collision data

Validate reco. level dist.

Detector / reconstruction level information

Detector / reconstruction level information



R^{-1} or U

Unfolding example

- Multiplicity distributions in (e×η) **[LHCb unpublished]**:

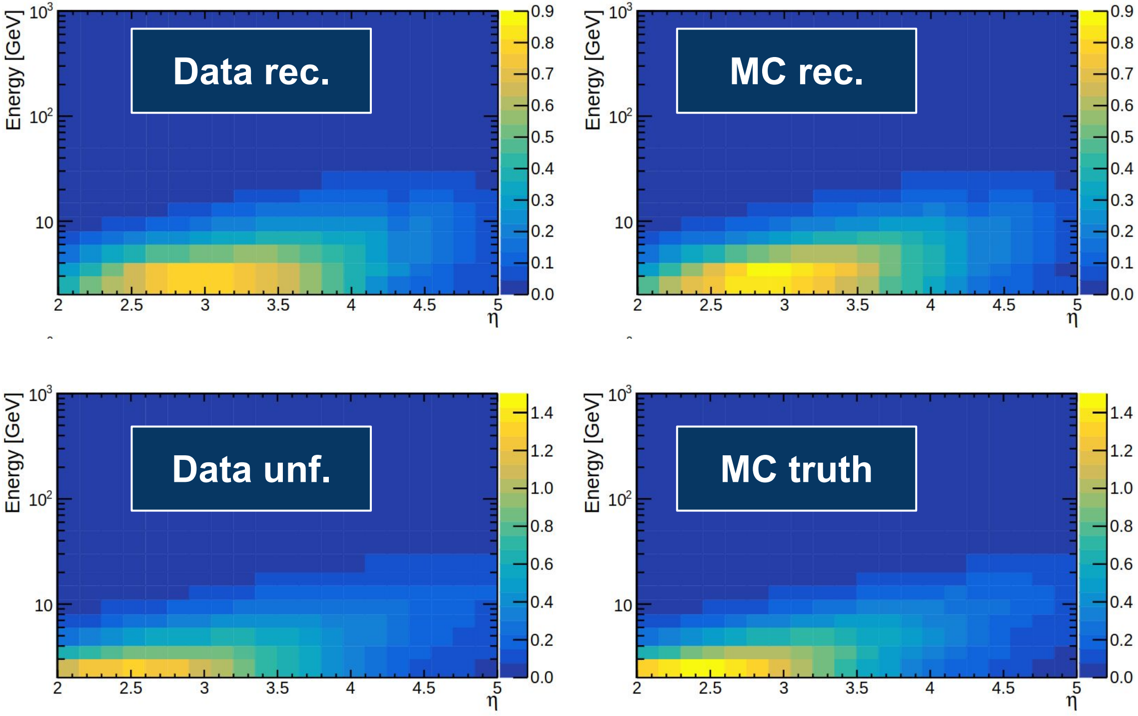


Image source: https://cds.cern.ch/record/2304736/

Unfolding example

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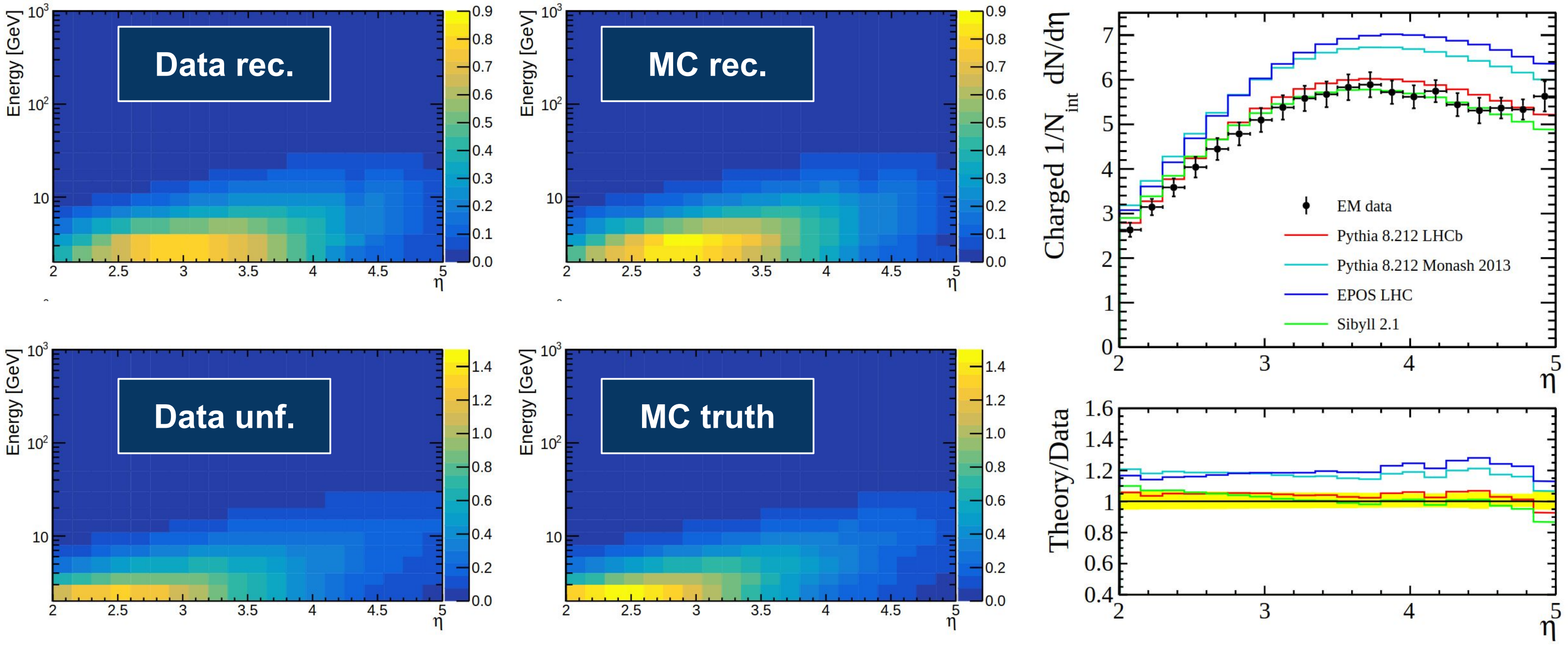

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The goal - physics

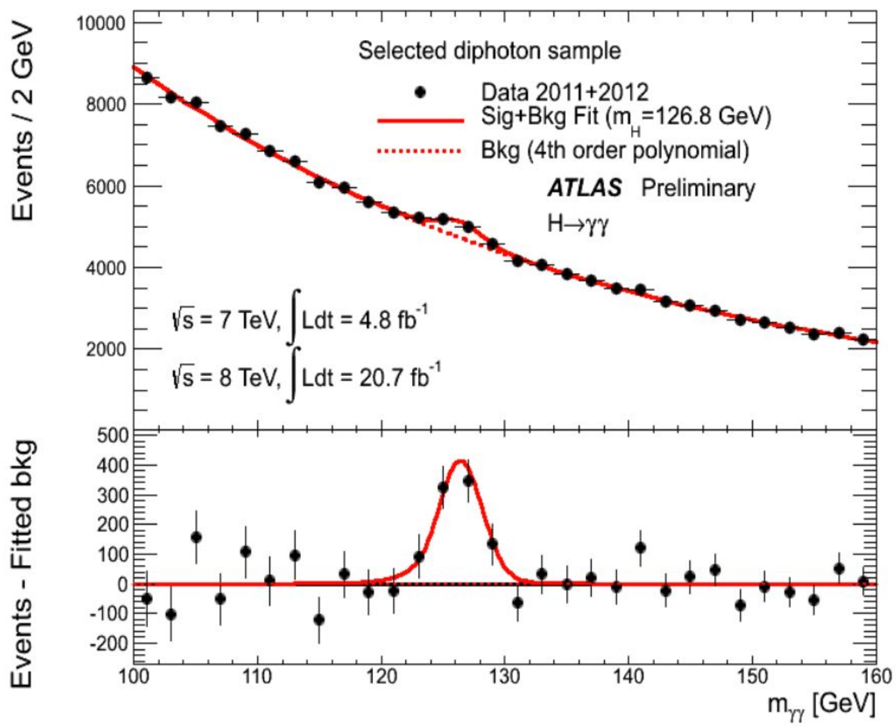

Image source: ATLAS collaboration

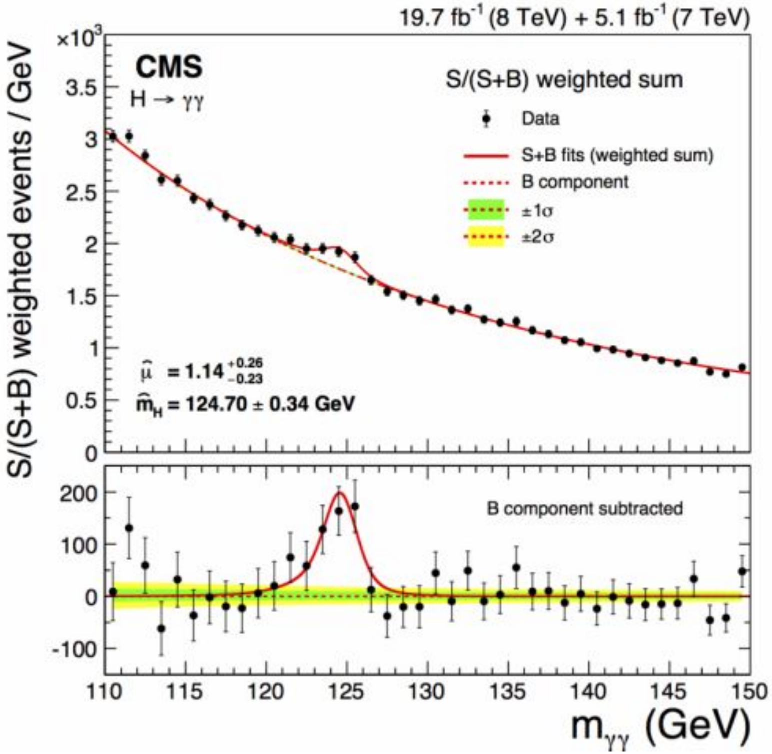

Image source: CMS collaboration

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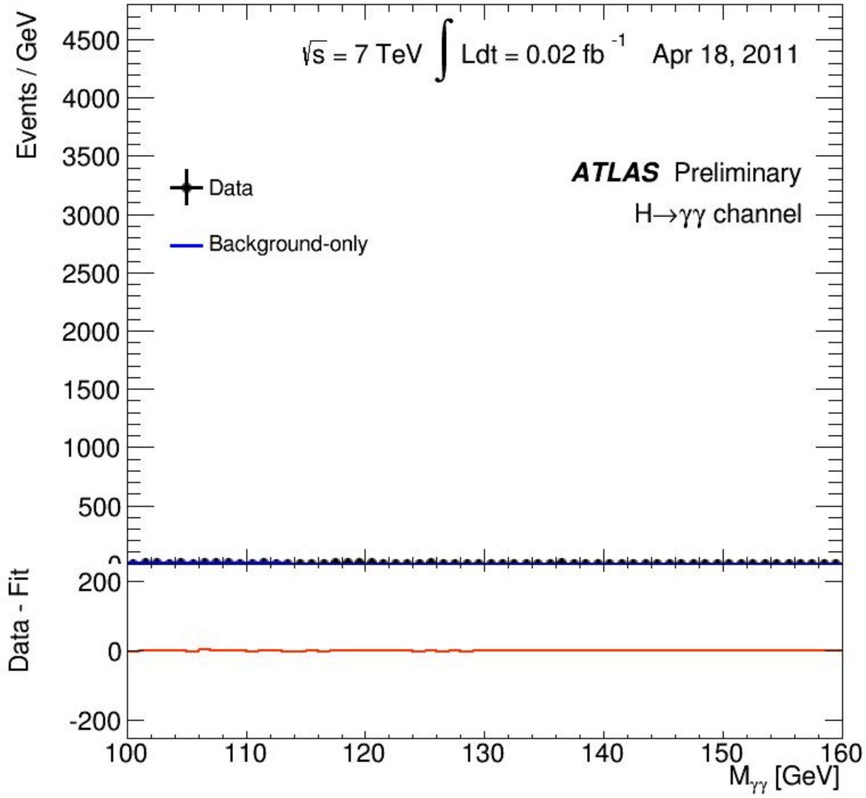


Image source: ATLAS collaboration

The goal - physics

- There are a vast array of various physics **measurements** to be done to further validate (or finally discredit!) the **SM**!
  - Particle production cross-sections;
  - Particle decay channels and widths;
  - Particle masses;
  - Coupling constants;
  - Angular distributions;

    … etc. …
- But we also perform spectroscopy (bump-hunting) and many (many!) **NP searches** !

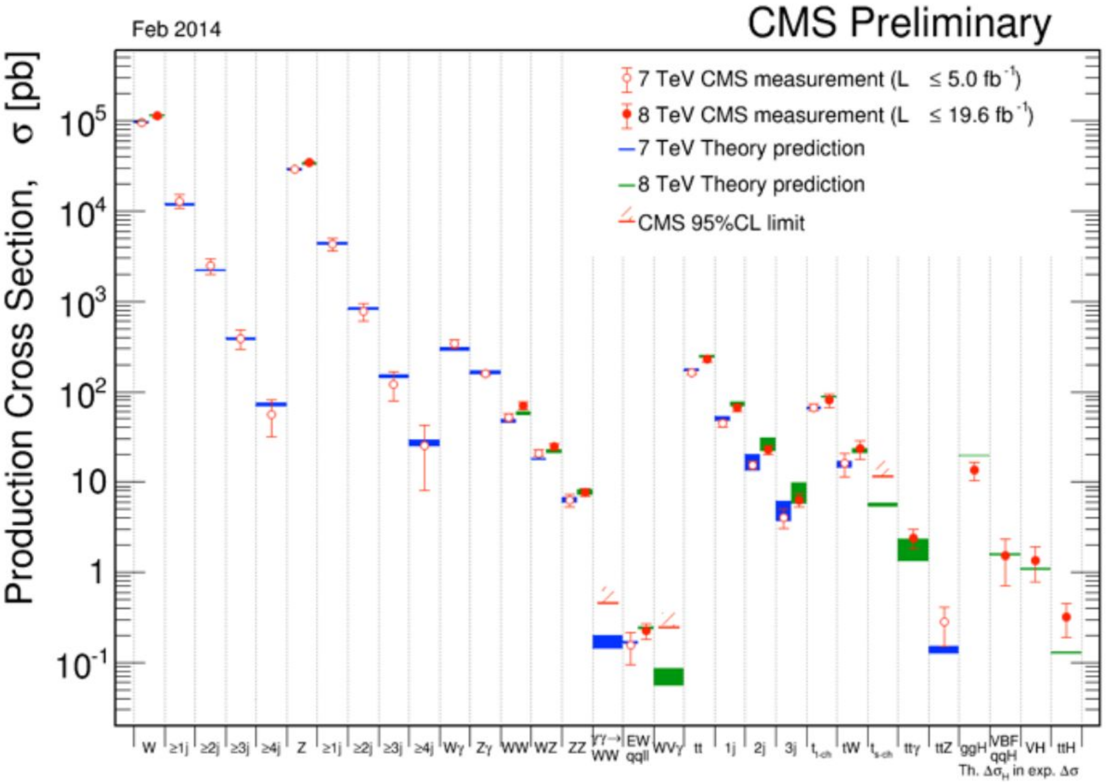
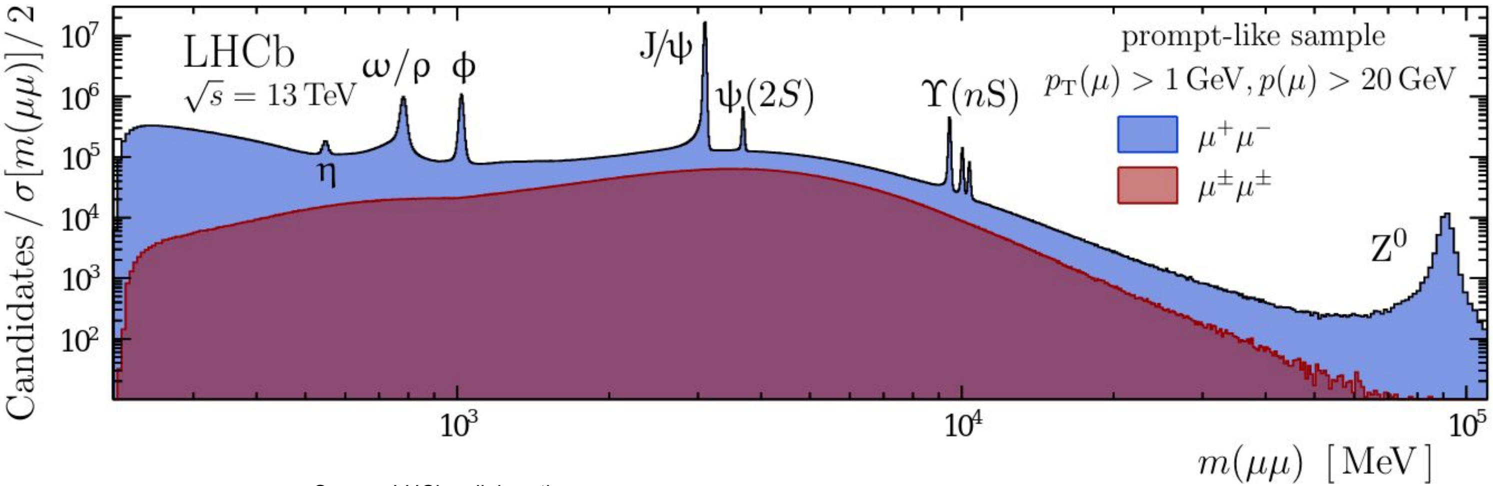


Image source: CMS collaboration

The goal - physics



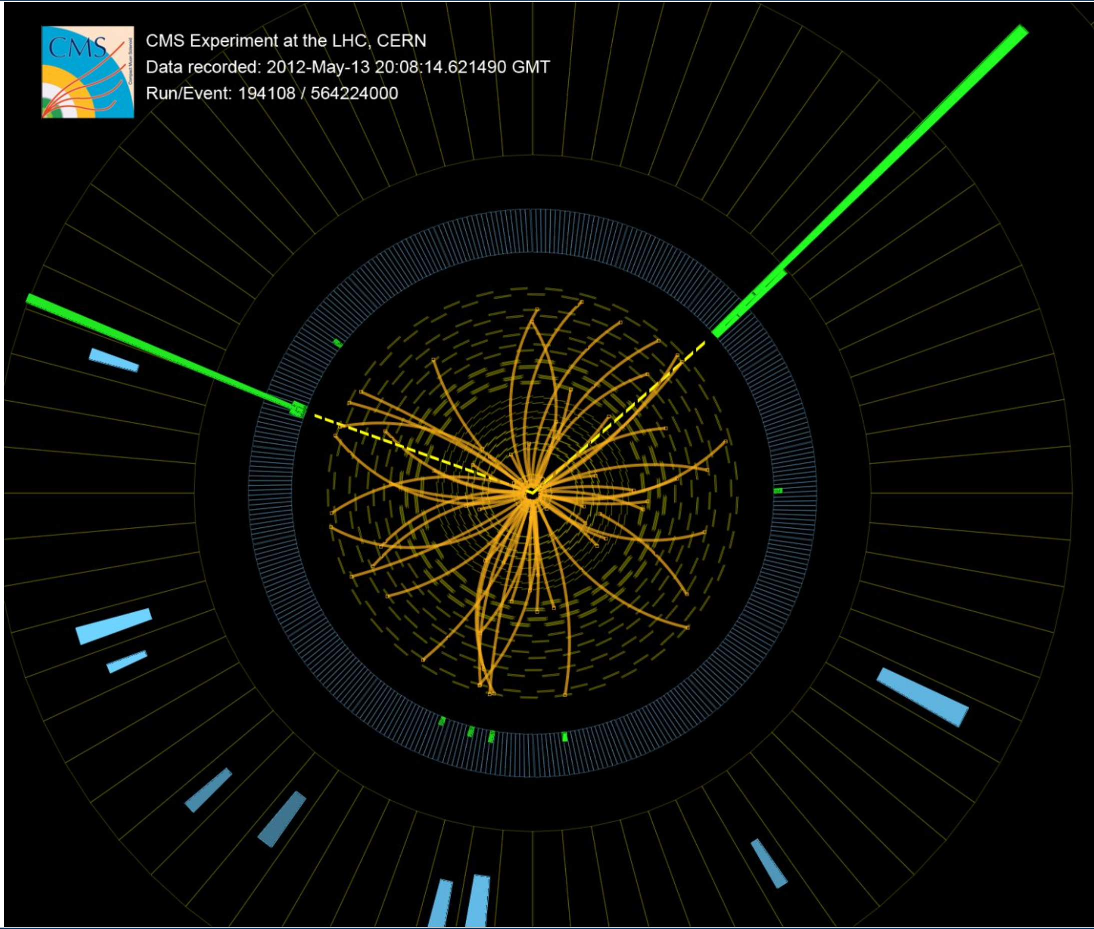
Source: LHCb collaboration

- Spectroscopy can be exciting, but has very little discovery potential without a considerable jump in collision energies (or theory suggestion/model for some odd particle-combinations!).
- Alternatively, we need MUCH MORE data!

An event recorded by the CMS experiment

- Two reconstructed high-p_T **photons**:
  - Pointing towards a **single vertex**;
  - Combined mass ~**124.7 GeV/c²**.

- What was, **more likely than not**, produced in **this** collision event?



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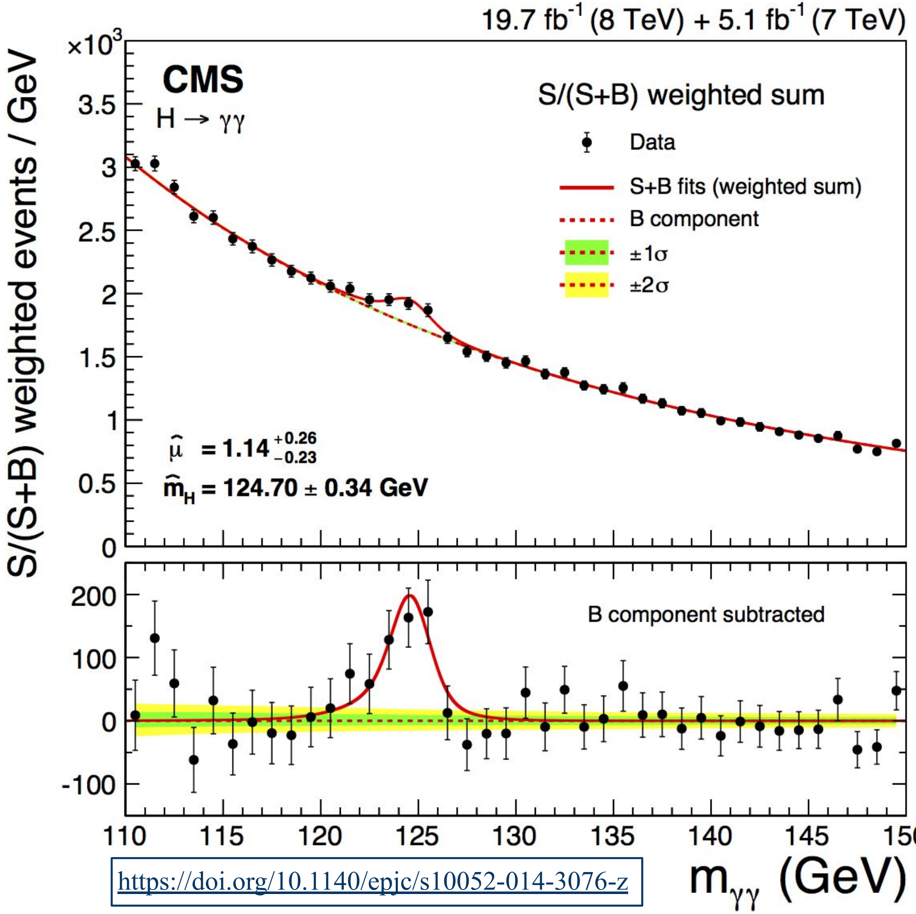
  Let's see!



https://doi.org/10.1140/epjc/s10052-014-3076-z

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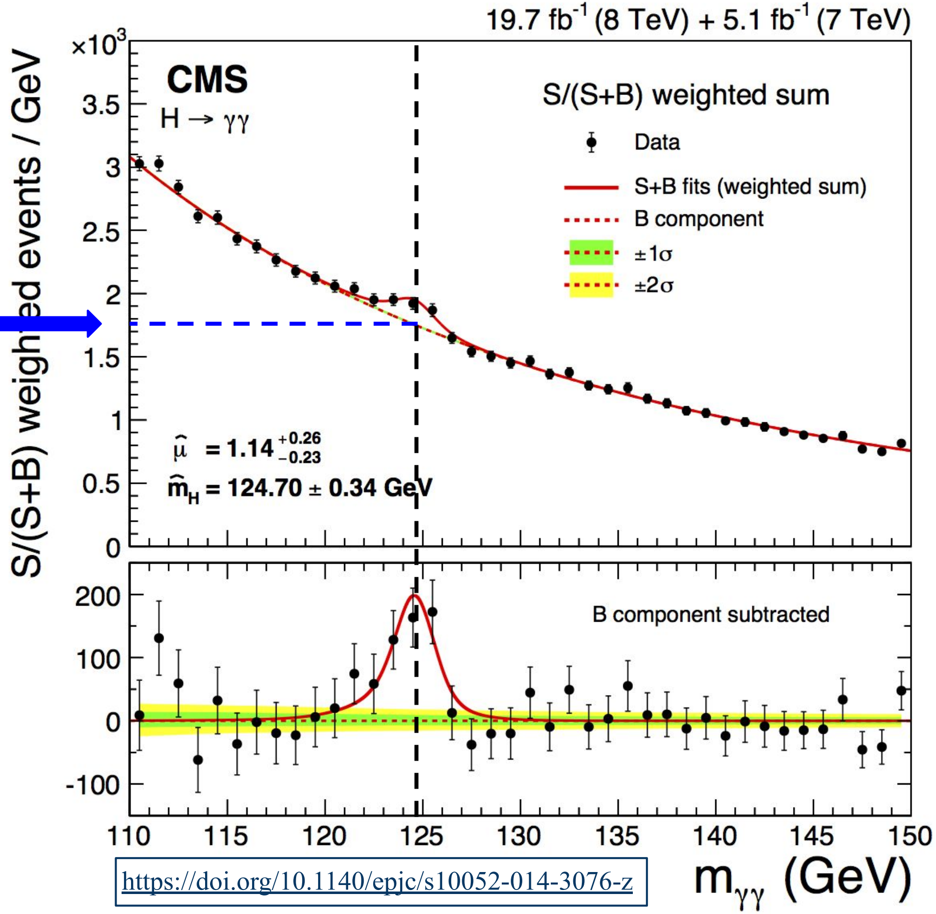
  … the # of SM background events **~1.75x10³**;



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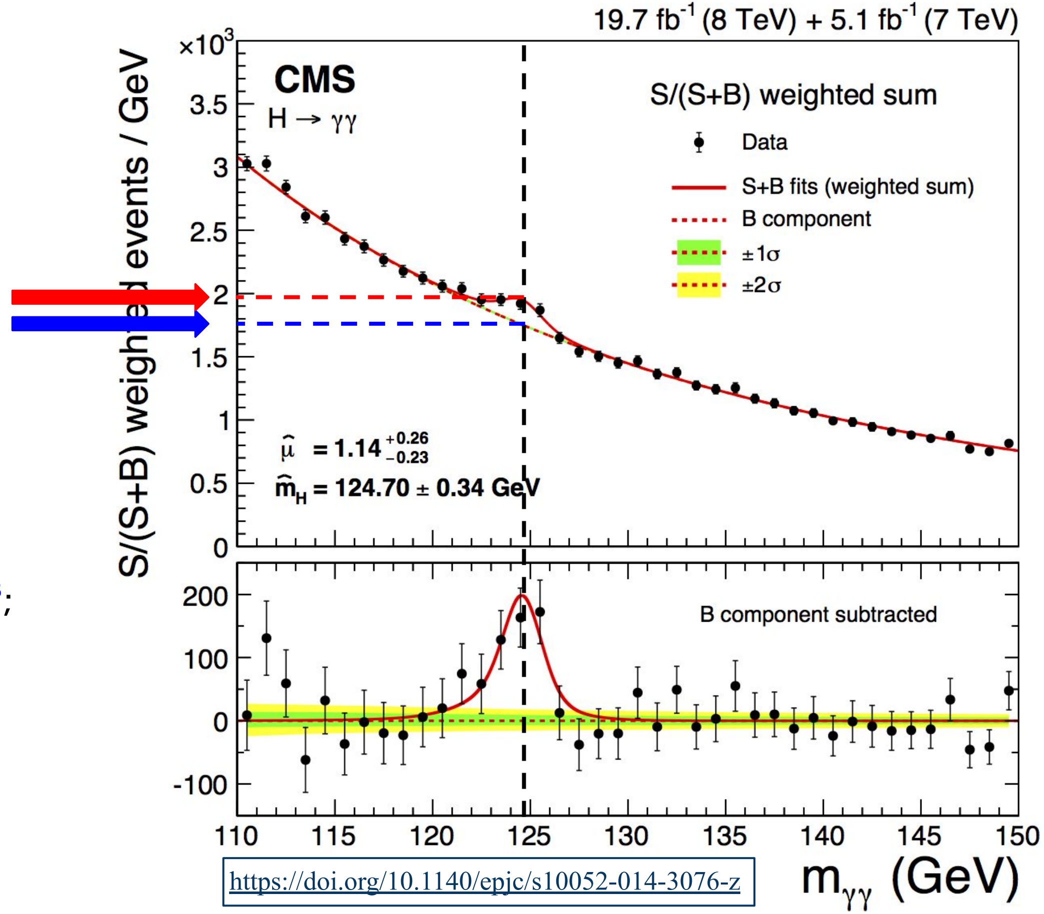
  … the # of Higgs decay events ~**0.2×10^3**;



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Example

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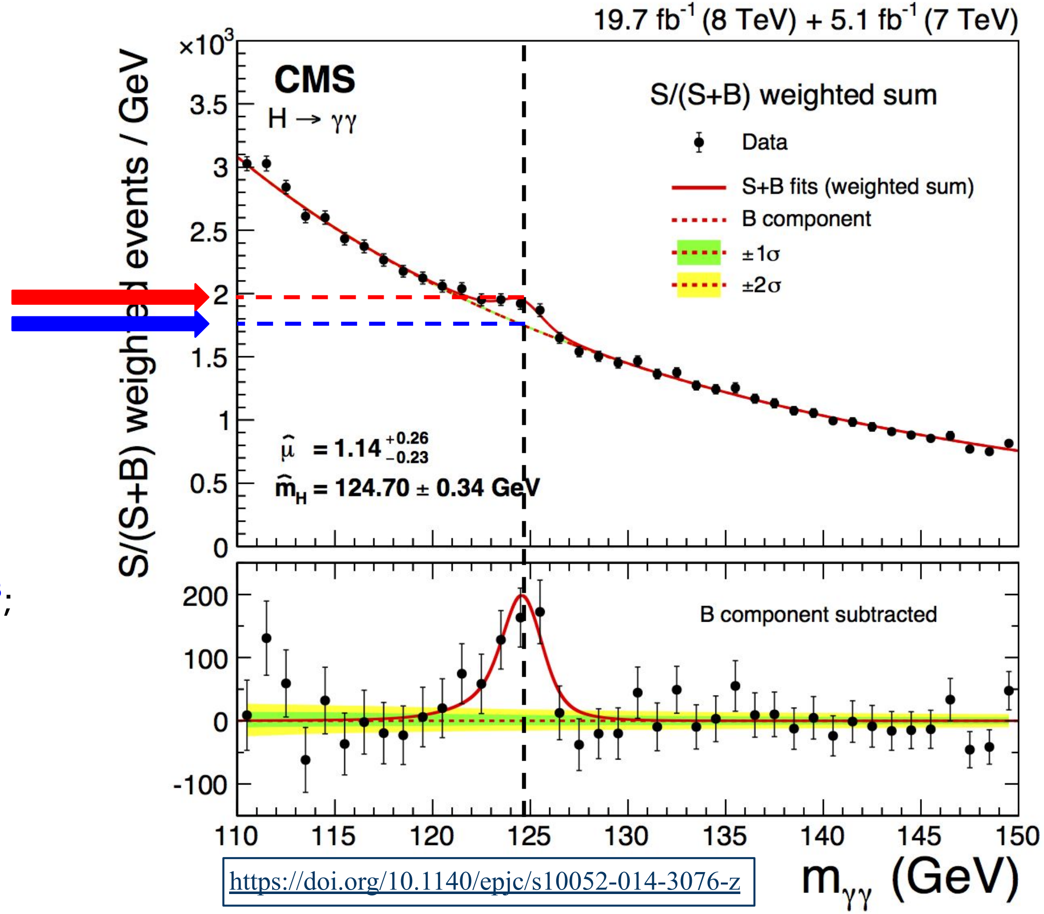
- What was, **more likely than not**, produced in **this** collision event?

  Let's see!: at 124.7 GeV/c^2 …

  … the # of SM background events ~**1.75x10³**;
  … the # of Higgs decay events ~**0.2x10³**;

- This single event is ~**9x more likely** to be a *random* SM background event!



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The goal - finding the answers!

- The SM may by self-consistent, but it still has internal unanswered questions;
  - What is the origin of the specific masses of the fermions?
  - Why are said masses so different between generations?
  - Why are there (and, indeed, are there?) *only* three generations of fermions?
  - Are the neutrinos Majorana or Dirac; is their mass-hierarchy normal or inverted?*

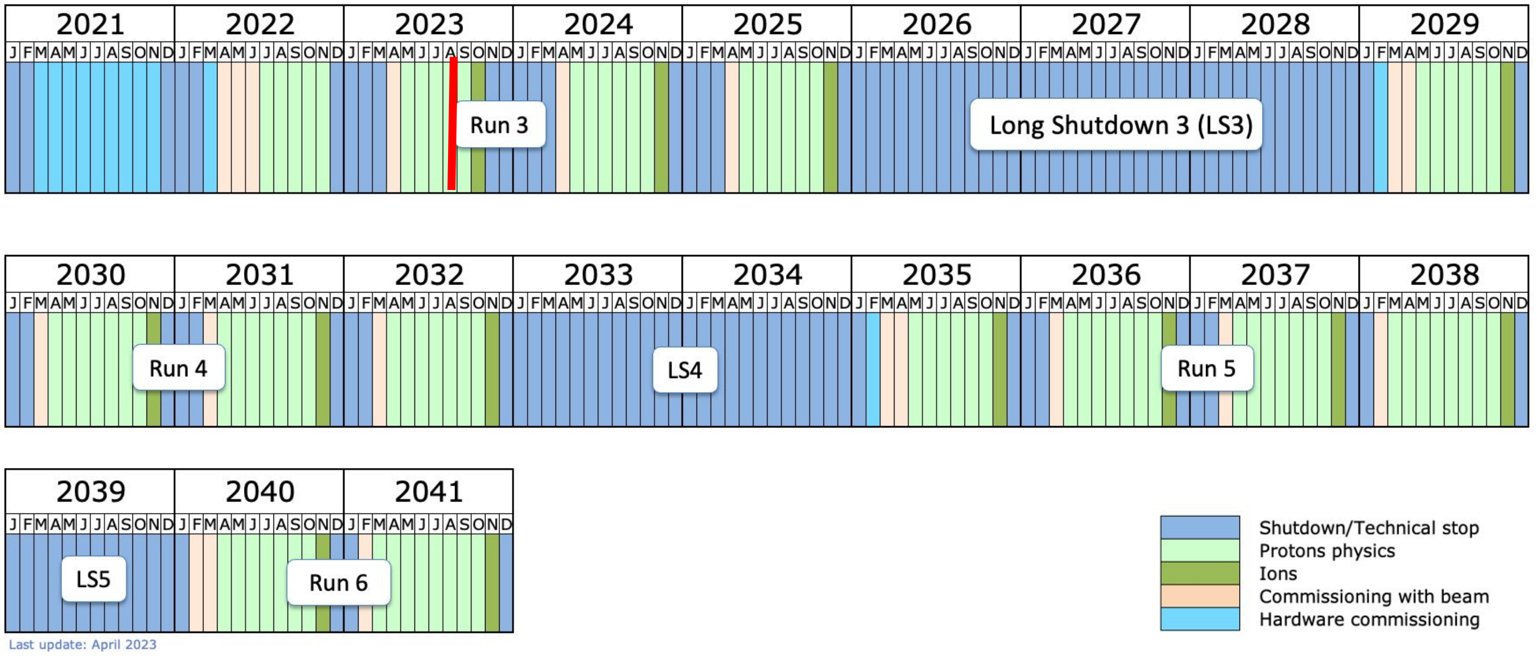
- In total the SM has 19 (26*) free parameters:
  - Irreducible sets of 7 free parameters from the electroweak sector;
  - 6 quark masses and the 3 angles and 1 complex phase of the CKM matrix;
  - QCD renormalization scale and the Θ-parameter, arising from the strong CP problem;
  - 3 masses and 4 parameters from the PMNS matrix from the neutrino sector*;
- These must be experimentally determined and input into the SM!

* - technically the neutrino sector is already an extension to the SM!

LHC Run 3 - a great time to join *hep-ex*

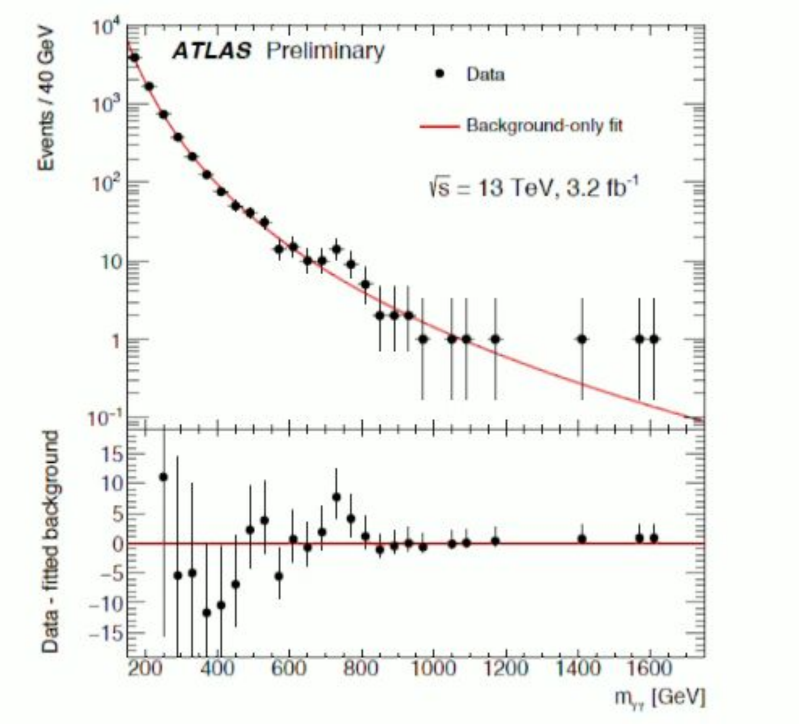
You are here

LHC: Runs 1 to 3 will total ~300 fb^{-1}
HL-LHC: Runs 4 to 5 will total ~3000 fb^{-1} !!!



F particle

- In 2015, ATLAS reported a 3.6σ excess at 750 GeV in the di-photon spectrum!
- Could this have been a heavy Higgs?
  Could this be proof of Supersymmetry?
- CMS data reported an excess at 2.6σ!
- Surely this is a major discovery!



Source: ATLAS collaboration

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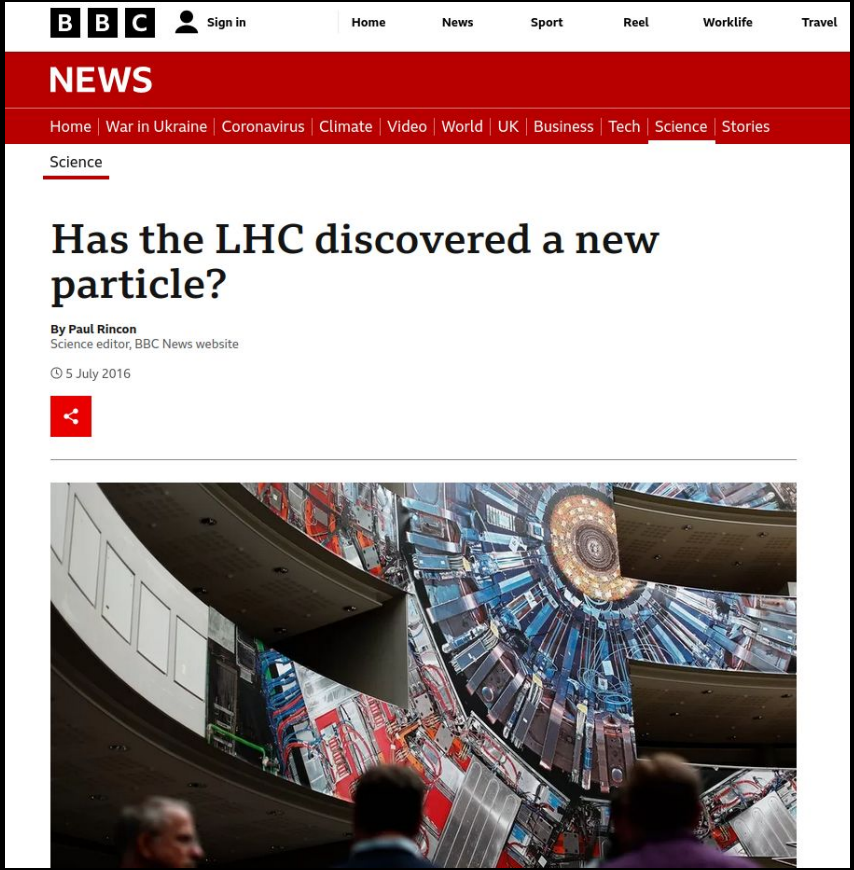

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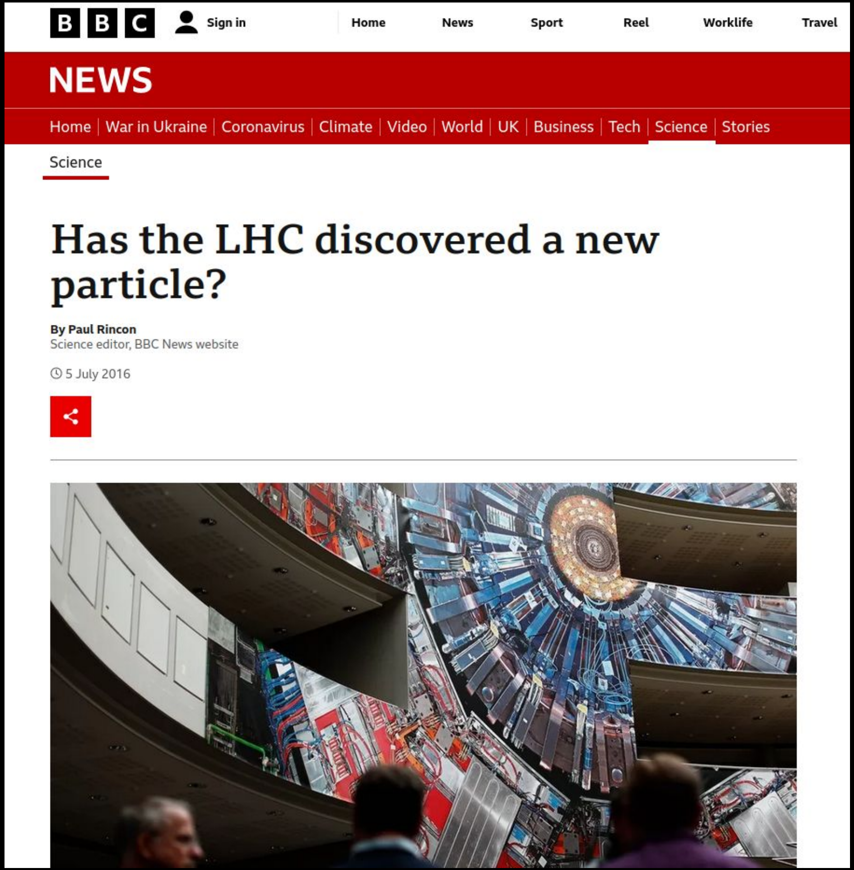
- Alas, with more data taken, the bump disappeared entirely!
- We must be careful with our announcements!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Science

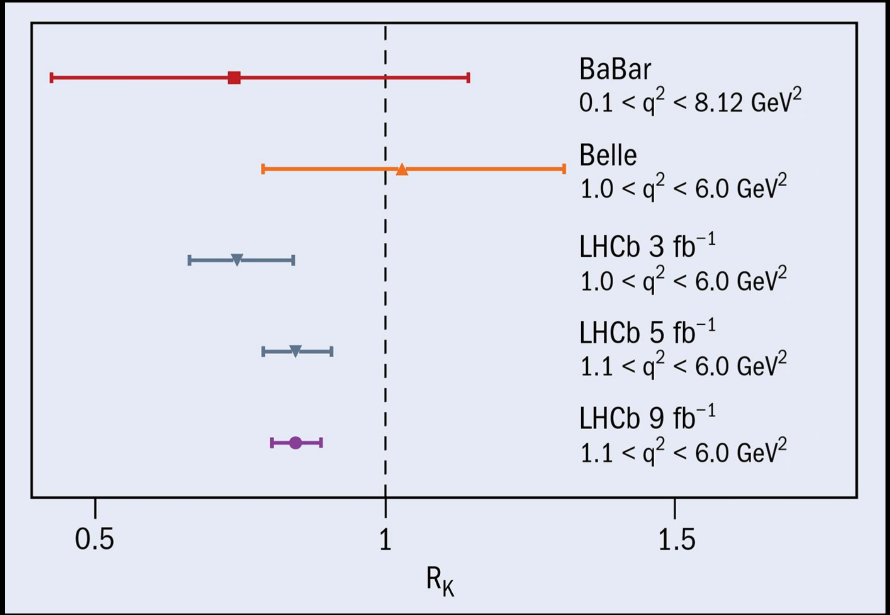
Has the LHC discovered a new particle?

By Paul Rincon
Science editor, BBC News website

5 July 2016

A true discrepancy?

- Measurement of the ratio of B-meson decays into a kaon+muons and a kaon+electrons;
- Corrected for mass should be == 1;
- Multiple measurements pointing in the same direction; >3σ significance;
- This is a tentative evidence of BSM physics! Lepton non-universality;
- Must be cautious as this could also *go away*!
- **Personal opinion** - tantalising! A genuine chance of *New Physics*! (but rumours are swirling that this is less prominent in higher q^2 regions)



Source: CERN courier

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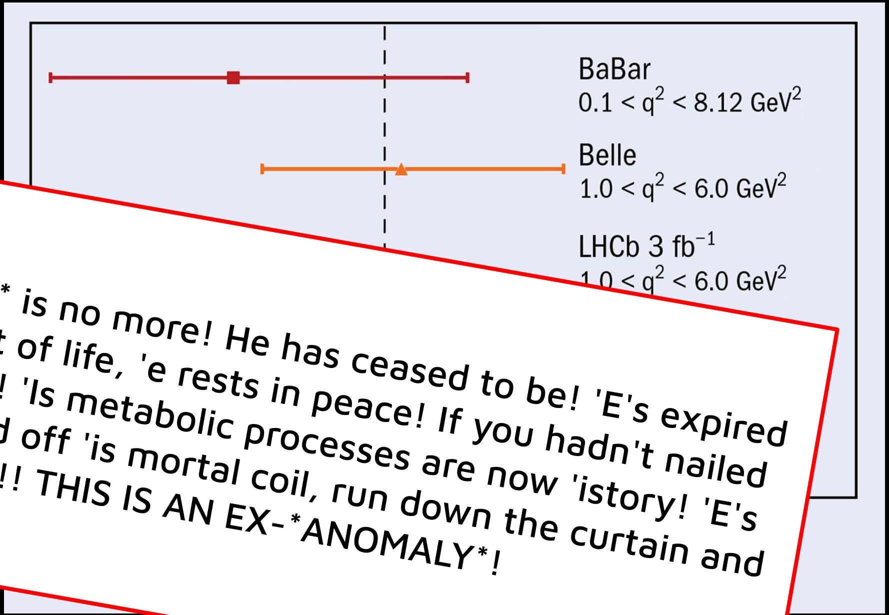
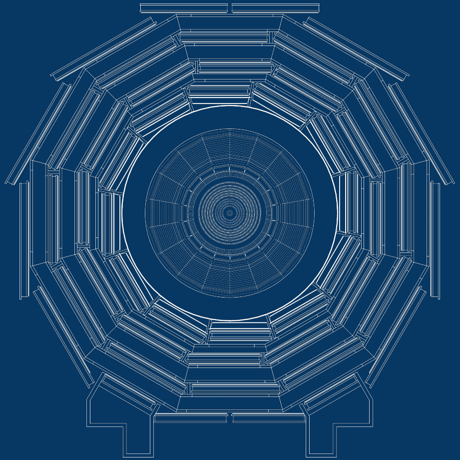


Source: CERN courier

'E's not pinin'! 'E's passed on! This *ANOMALY* is no more! He has ceased to be! 'E's expired and gone to meet 'is maker! 'E's a stiff! Bereft of life, 'e rests in peace! If you hadn't nailed 'im to the perch 'e'd be pushing up the daisies! 'Is metabolic processes are now 'istory! 'E's off the twig! 'E's kicked the bucket, 'e's shuffled off 'is mortal coil, run down the curtain and joined the bleedin' choir invisible!! THIS IS AN EX-*ANOMALY*!

- **Personal opinion** - tantalising! A genuine chance of *New Physics*! (but rumours are swirling that this is less prominent in higher q^2 regions)



Thank you

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Institute of Particle Physics and Accelerator Technologies