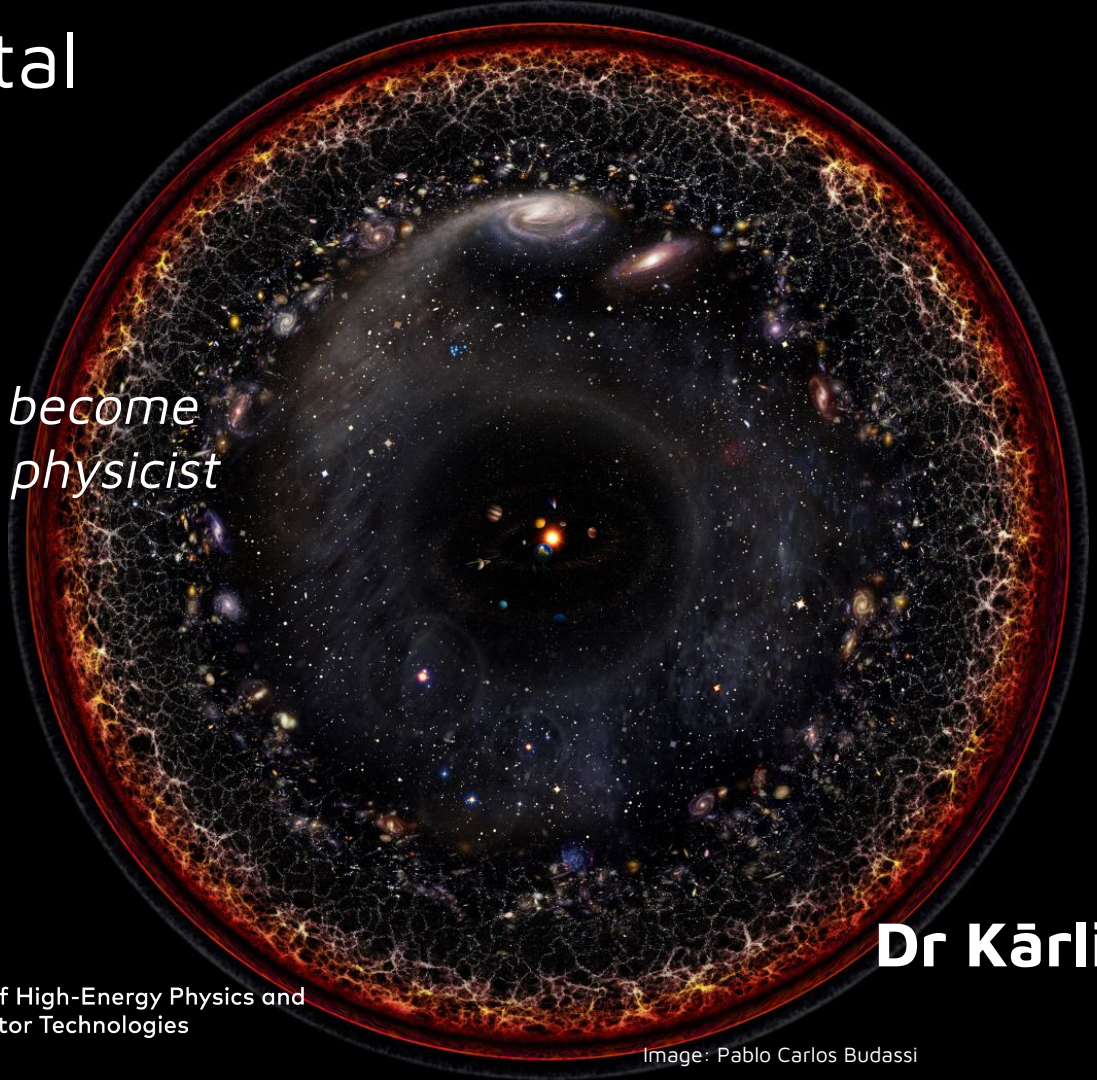
Experimental Particle Physics:

Why should you become an experimental physicist in HEP?



Supported by:
State research programme

RIGA TECHNICAL UNIVERSITY
1862
Centre of High-Energy Physics and Accelerator Technologies

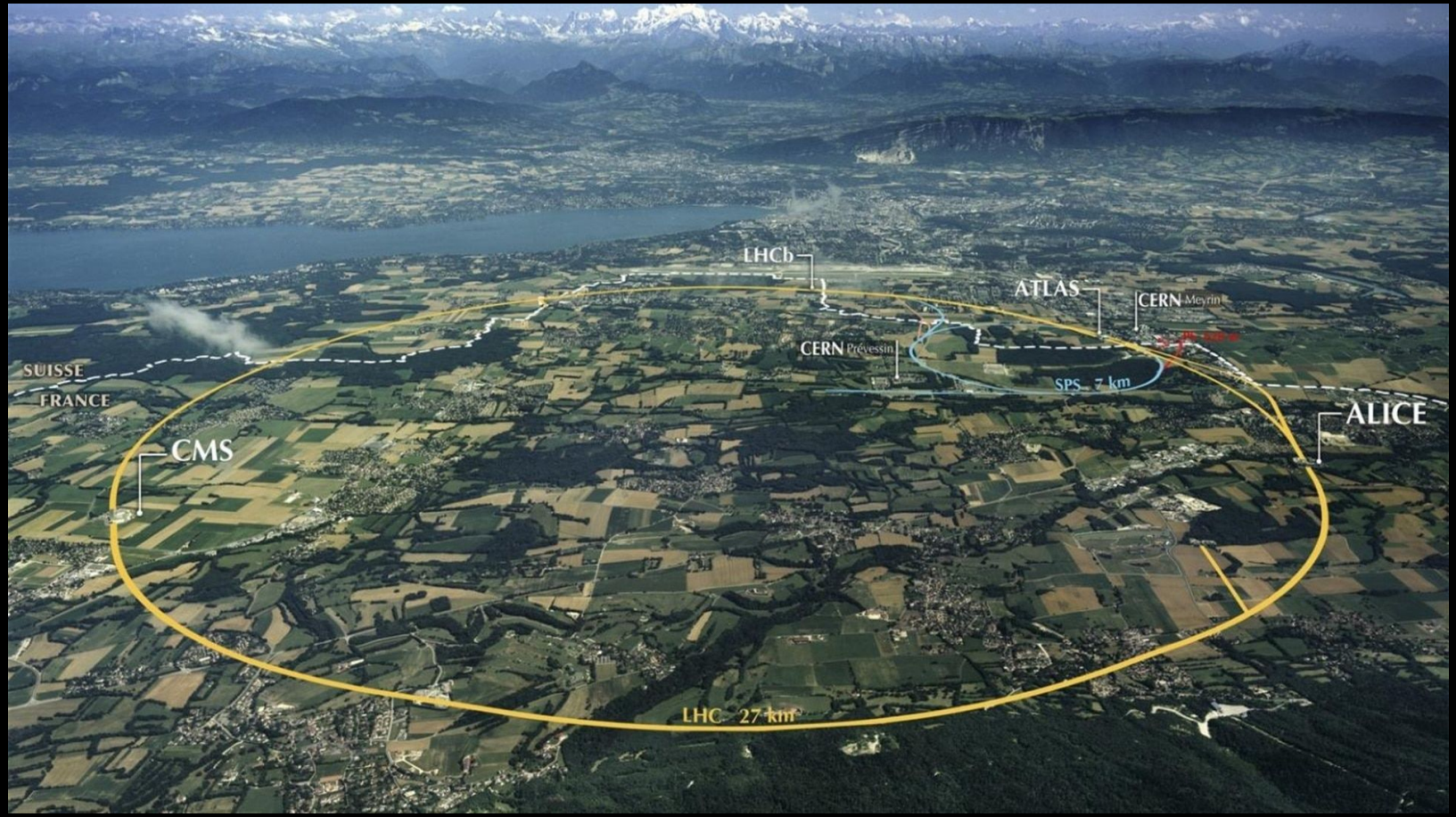
Dr Kārlis Dreimanis

11/08/2022

Image: Pablo Carlos Budassi

Lake Geneva is lovely this time of the year!

The LHC is in its prime!



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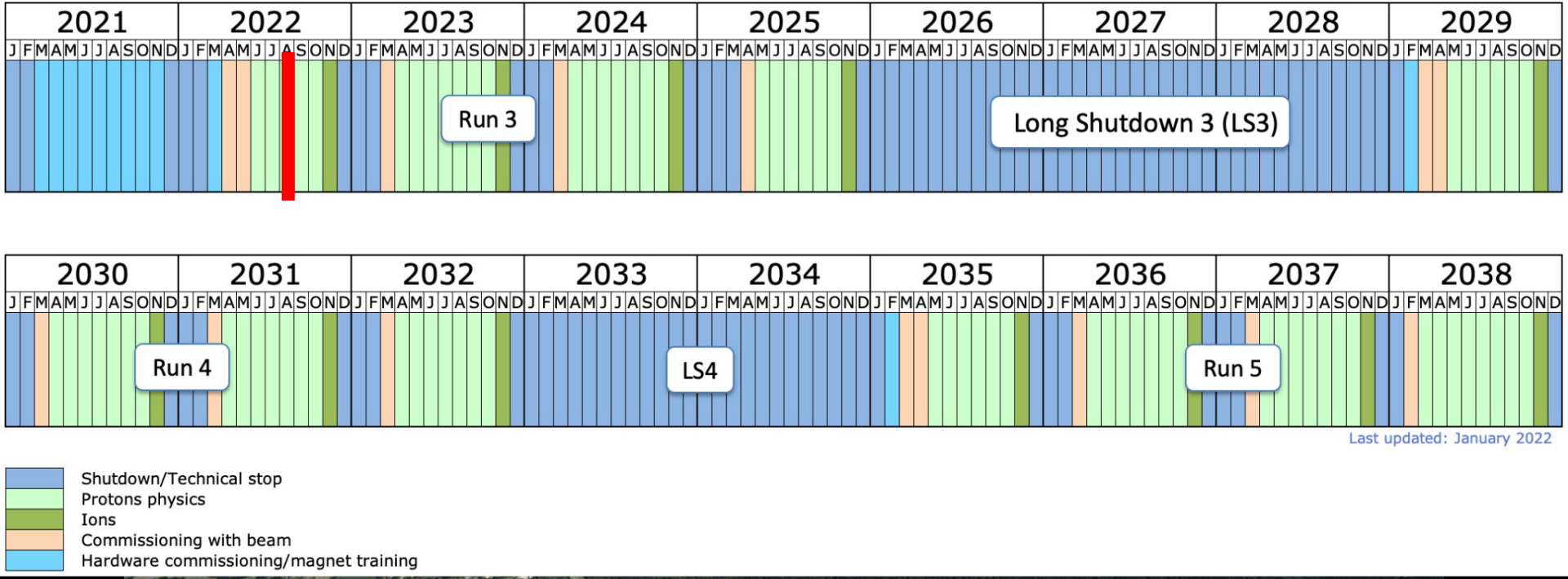
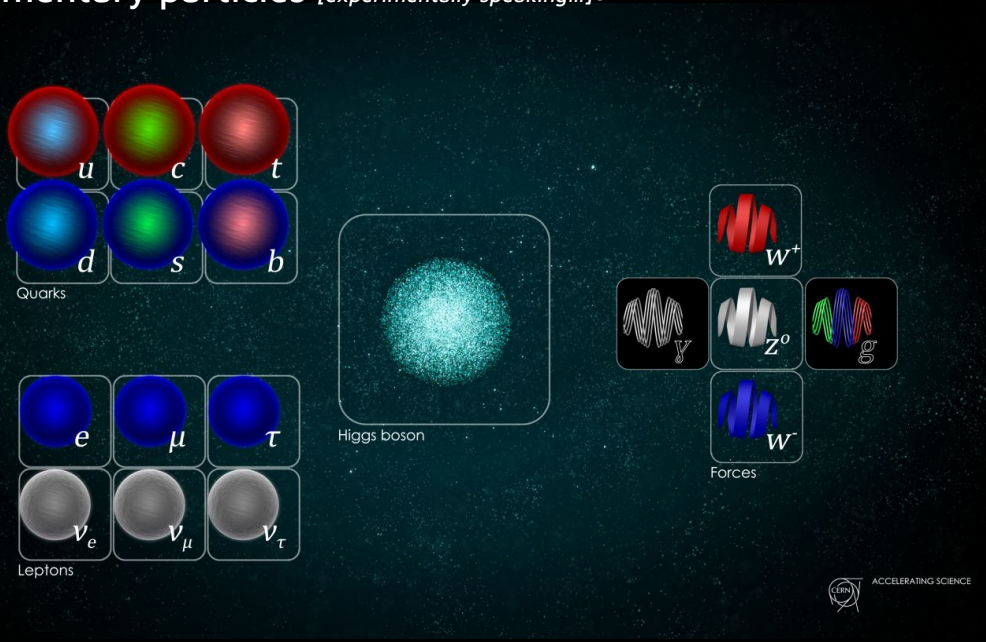


The Standard Model

- 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;



- Just celebrated the 10th anniversary of the discovery of the Higgs!
  - The particle content of the SM is now **complete**!
  - The SM is self-consistent!

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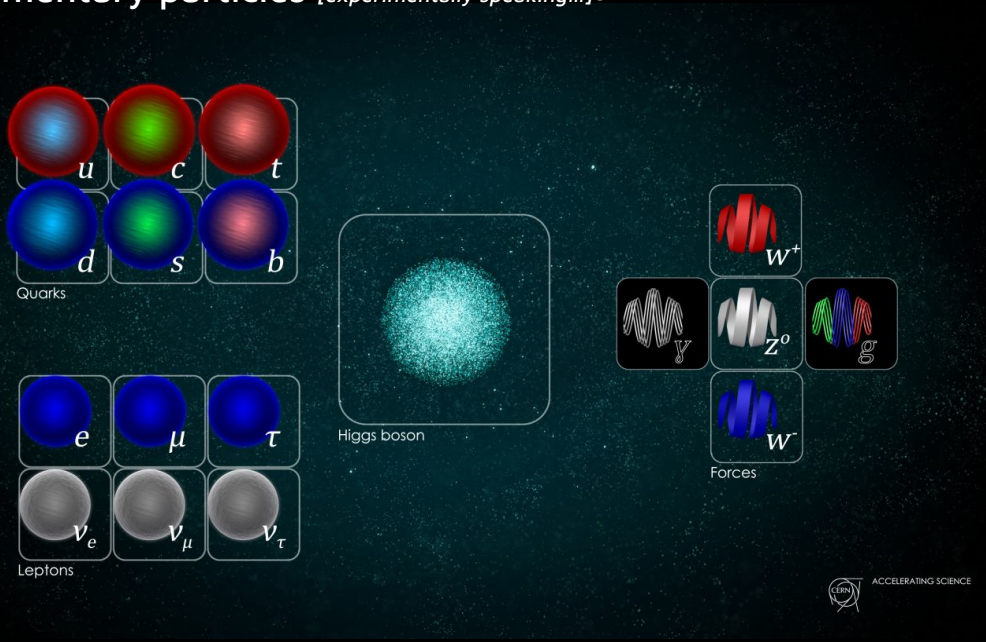

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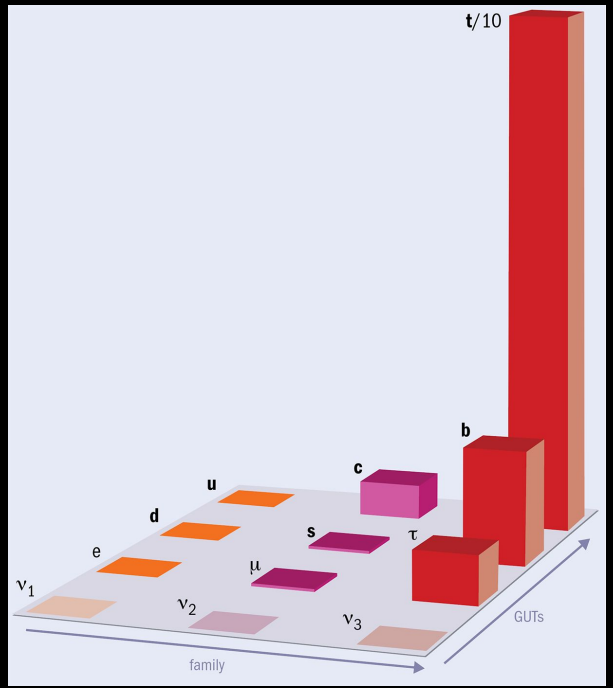
(but incomplete) ◄——————

- Why do we still study particles physics? (and how do we do that?)

The open questions of the SM

- 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?



Source: CERN courier

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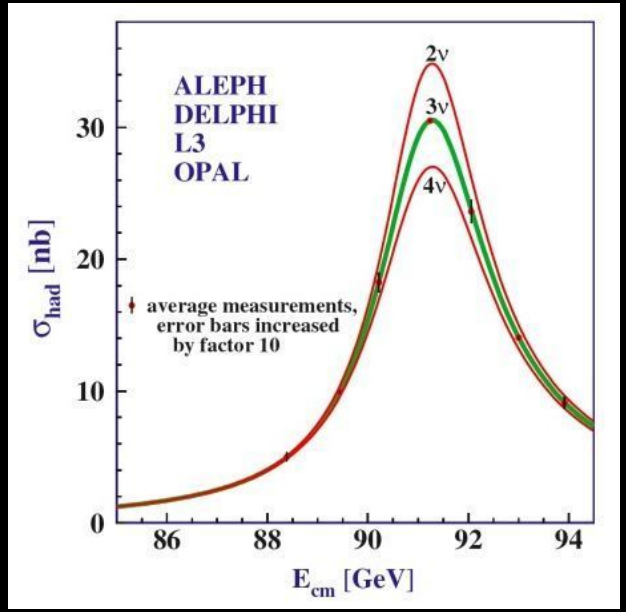

Source: https://www.ppd.stfc.ac.uk/Pages/LEPanniversary.aspx

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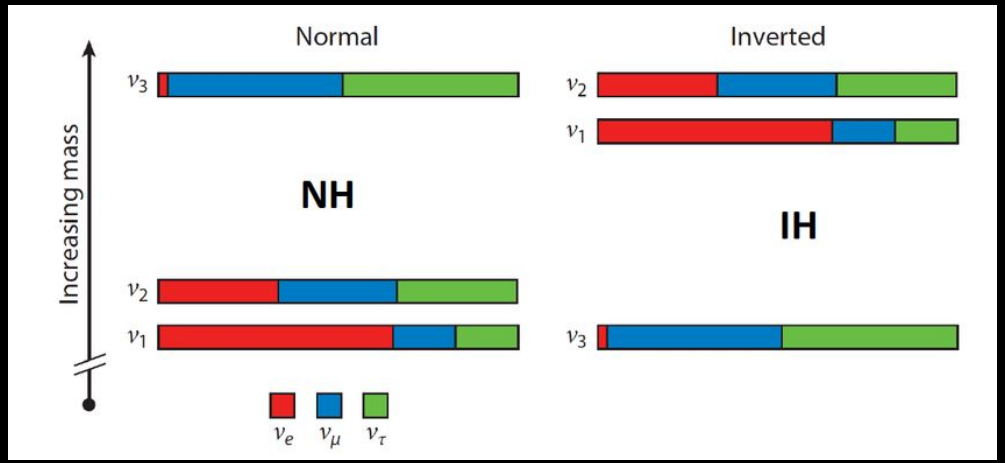

Source: researchgate

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- 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*;

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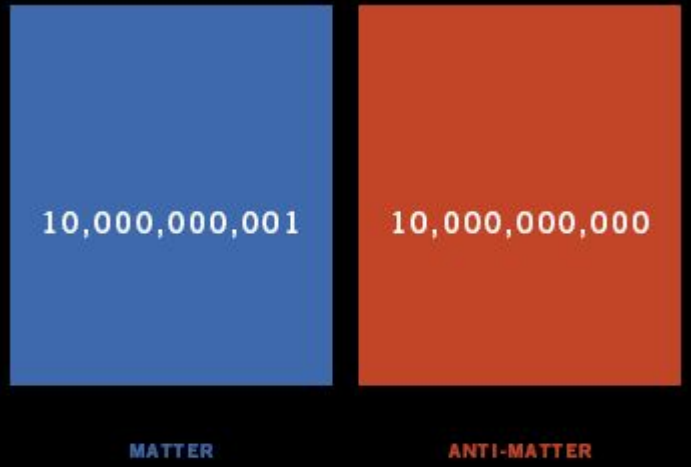
- These must be experimentally determined and input into the SM!

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

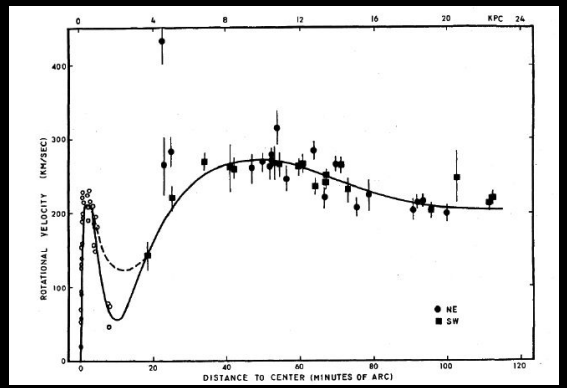
Beyond the SM open questions

- What is the cause of the matter-dominated universe?

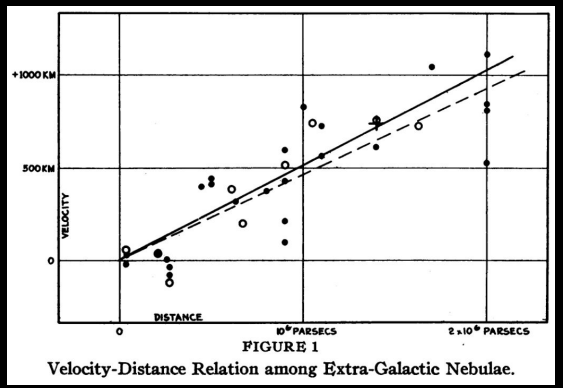


Beyond the SM open questions

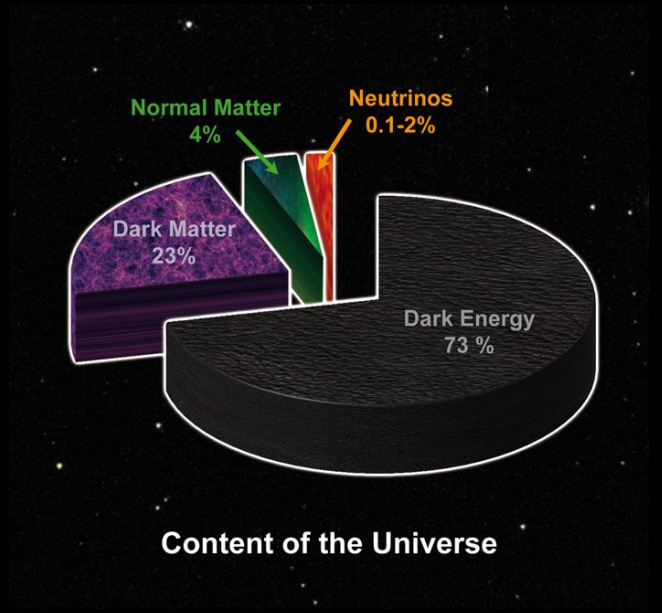
- What is the cause of the matter-dominated universe?
- What is dark matter? What is dark energy?



Source: Rubin & Ford (1970)



Source: E. Hubble (1929)



Source: HAP / A. Chantelauze

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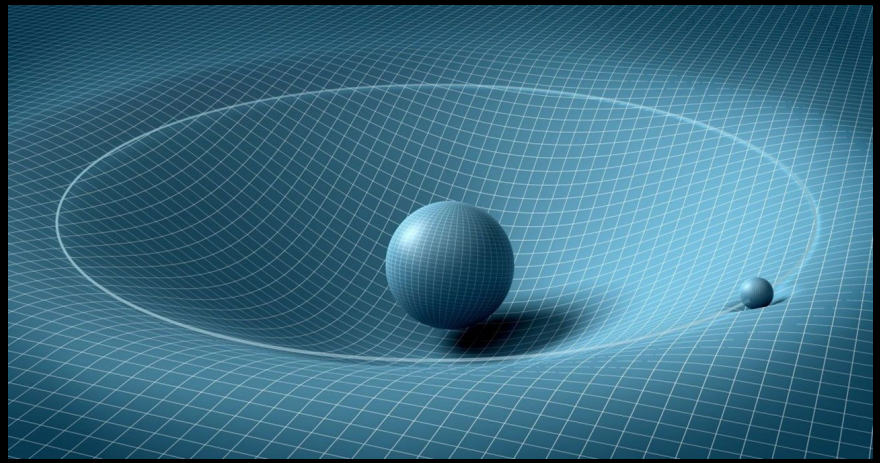
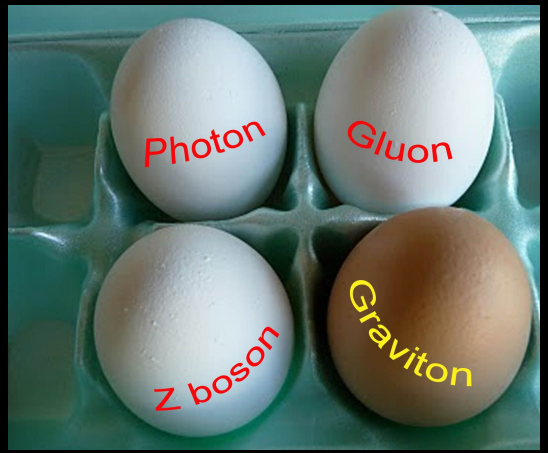


Source: TechExplorist



Source: FNAL

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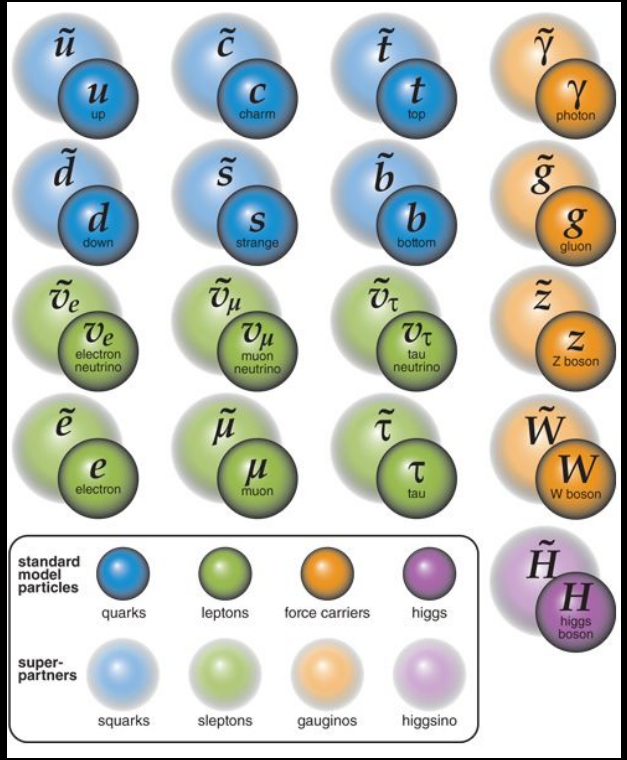
- Does supersymmetry exist?



Source: American Scientist

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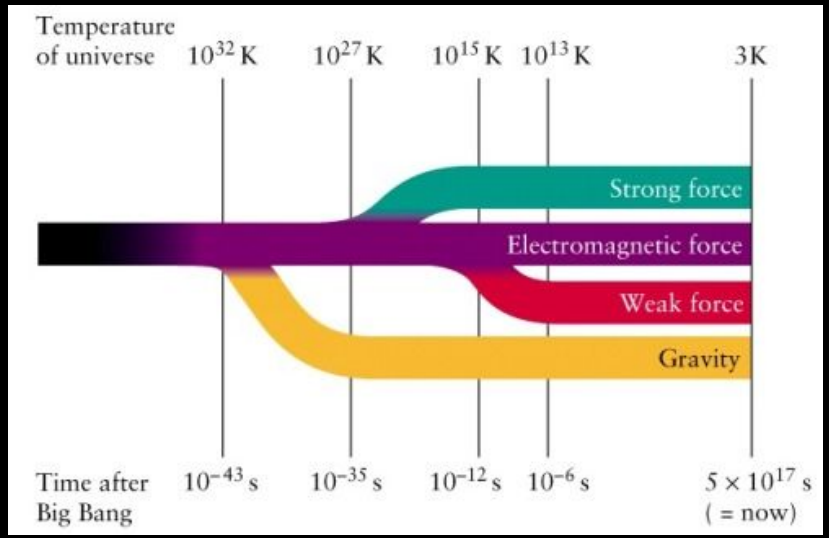

Source: Web

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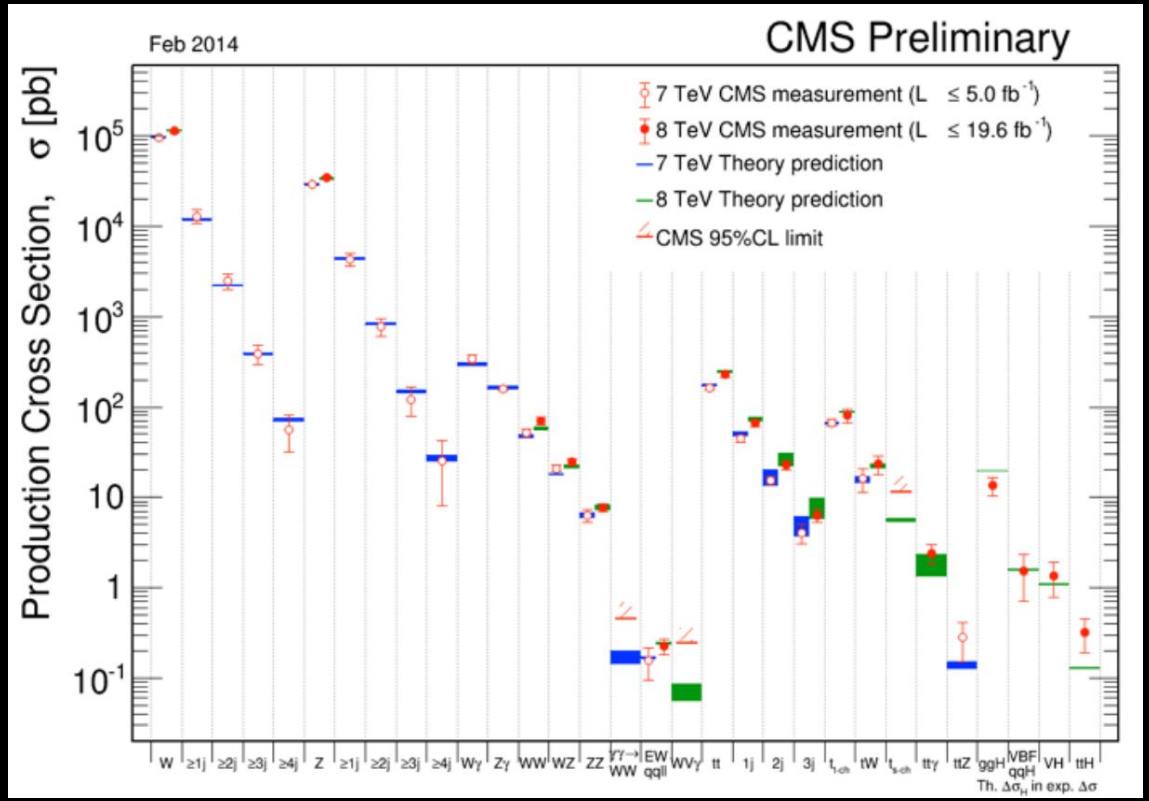
... and many more questions...

Source: 123rf

Observables

- There are a plethora of observables we can measure experimentally to compare with the theoretical predictions:
  - Particle production cross-sections;
  - Particle decay channels and widths;
  - Particle masses;
  - Coupling constants;
  - Angular distributions;

- We perform spectroscopy (*bump-hunting*);
- We do searches and limit setting;



Source: CMS collaboration

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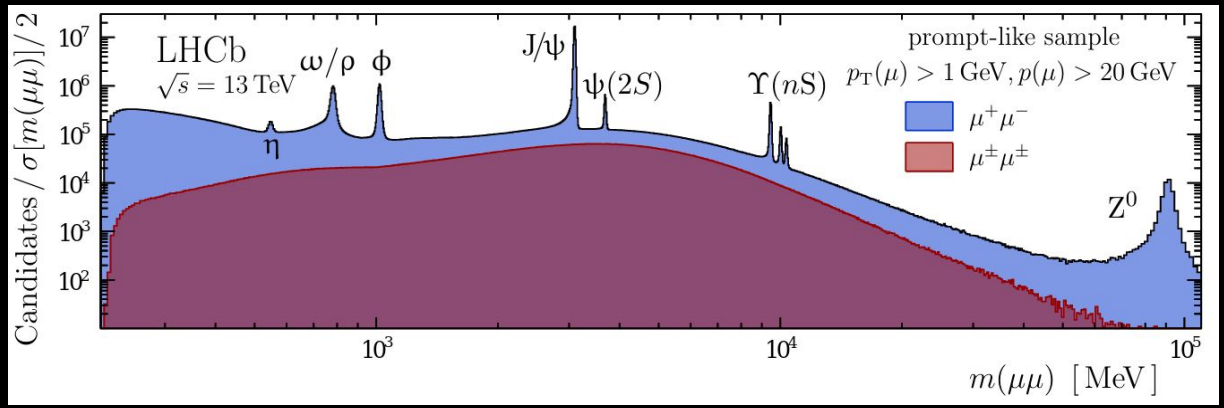
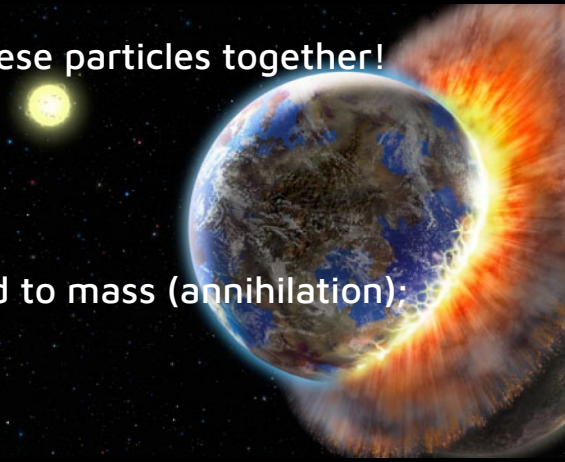


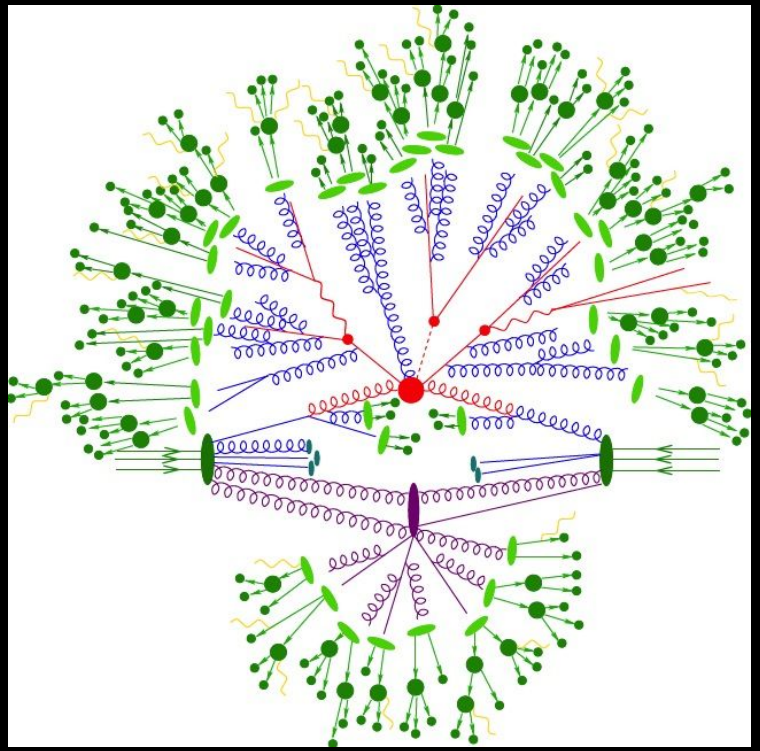
Source: LHCb collaboration

Overall approach



- Use particle colliders to accelerate them to high-energies and smash these particles together!
  - $E = mc^2$: utilise the mass energy equivalence;
- In a lepton collider, like LEP, the entire collision energy can be converted to mass (annihilation);
  - The events are *clean* with fewer highly energetic particles created;
- In a hadron collider, like LHC, only a fraction of the collision energy is converted to mass;
  - *Messier* events with a broad spectrum of outgoing particle energies;
  - Higher overall energy reach;
- We use large-scale experiments (ATLAS, CMS, LHCb, ALICE, others) to **record** the collision products and to reconstruct them back towards their origin and parent-particles;

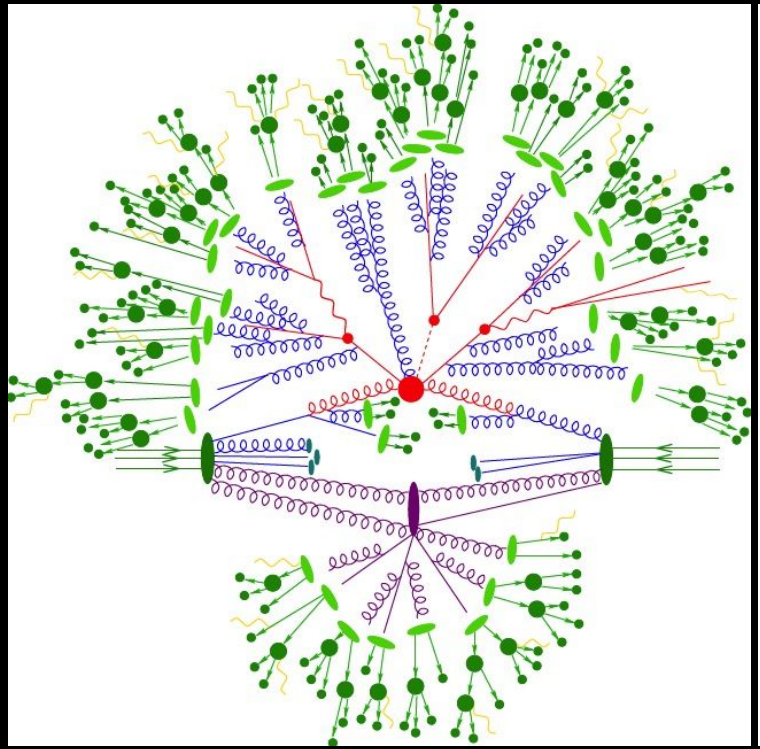
Overall approach



- Red and violet *blobs* - parton collisions;
- Blue, red and purple lines - parton showering;
- Green - hadronisation process;

Source: Sherpa

Overall approach



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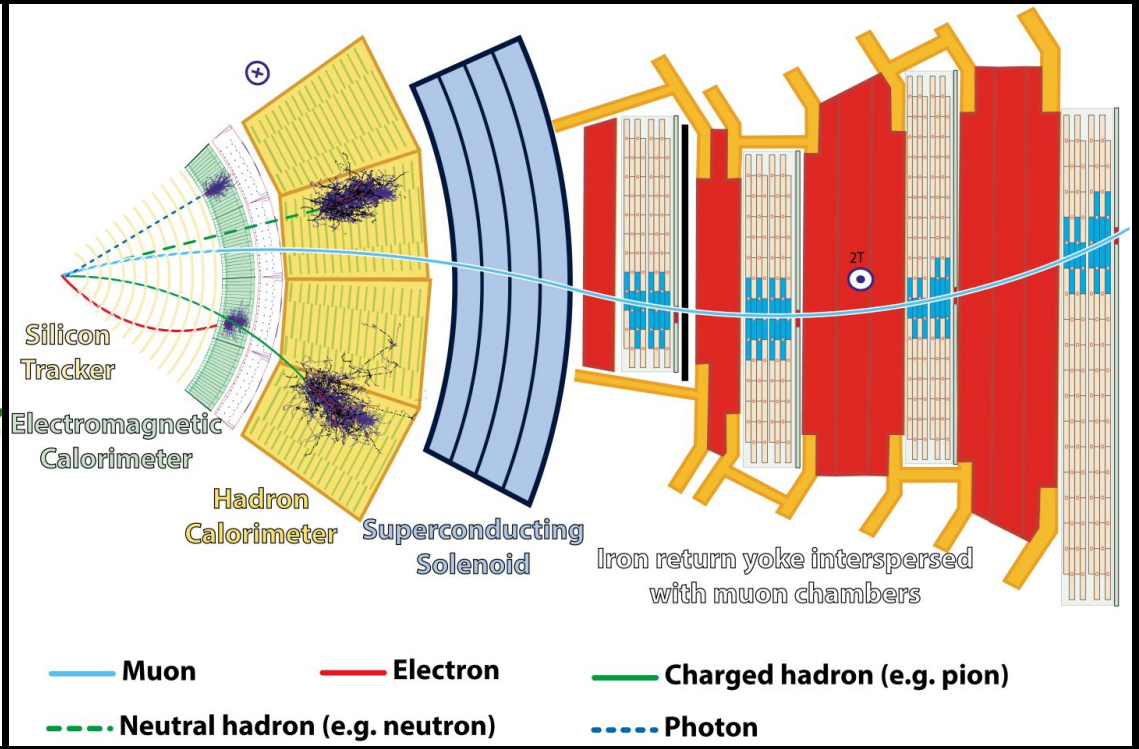

Source: CERN

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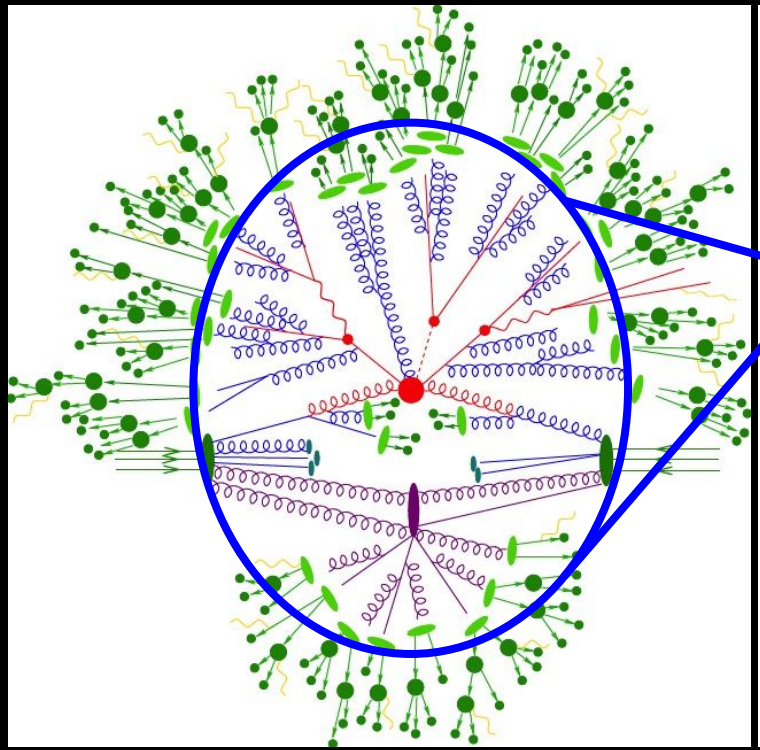

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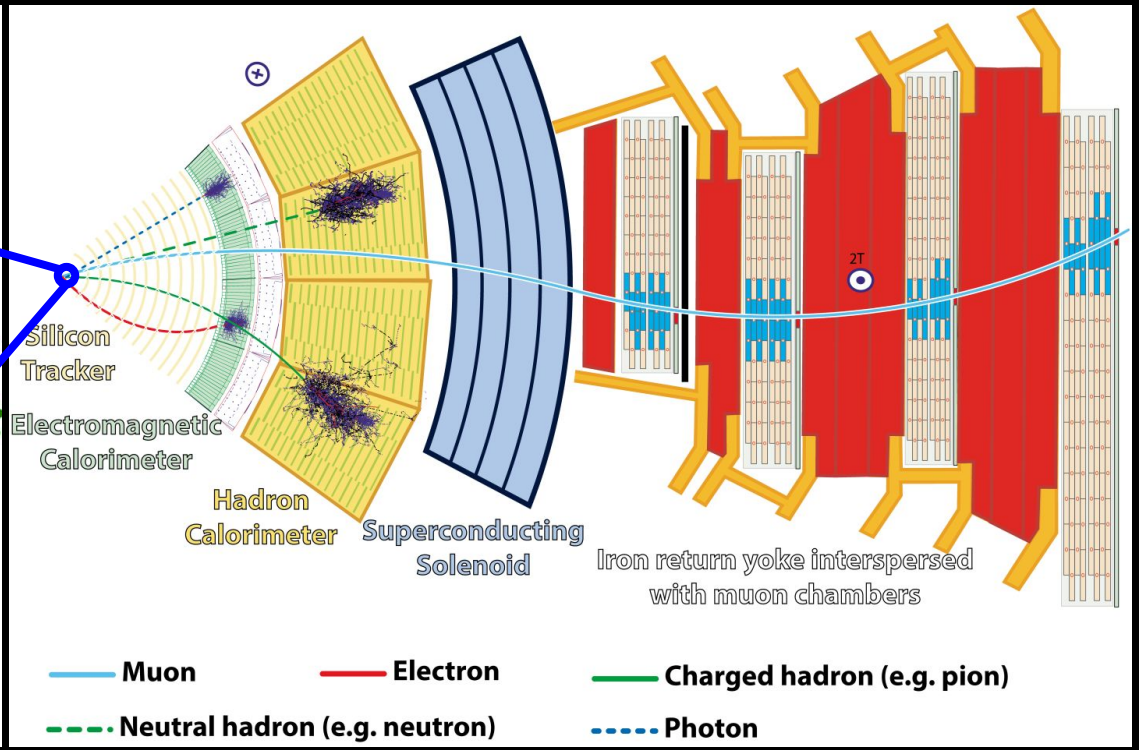
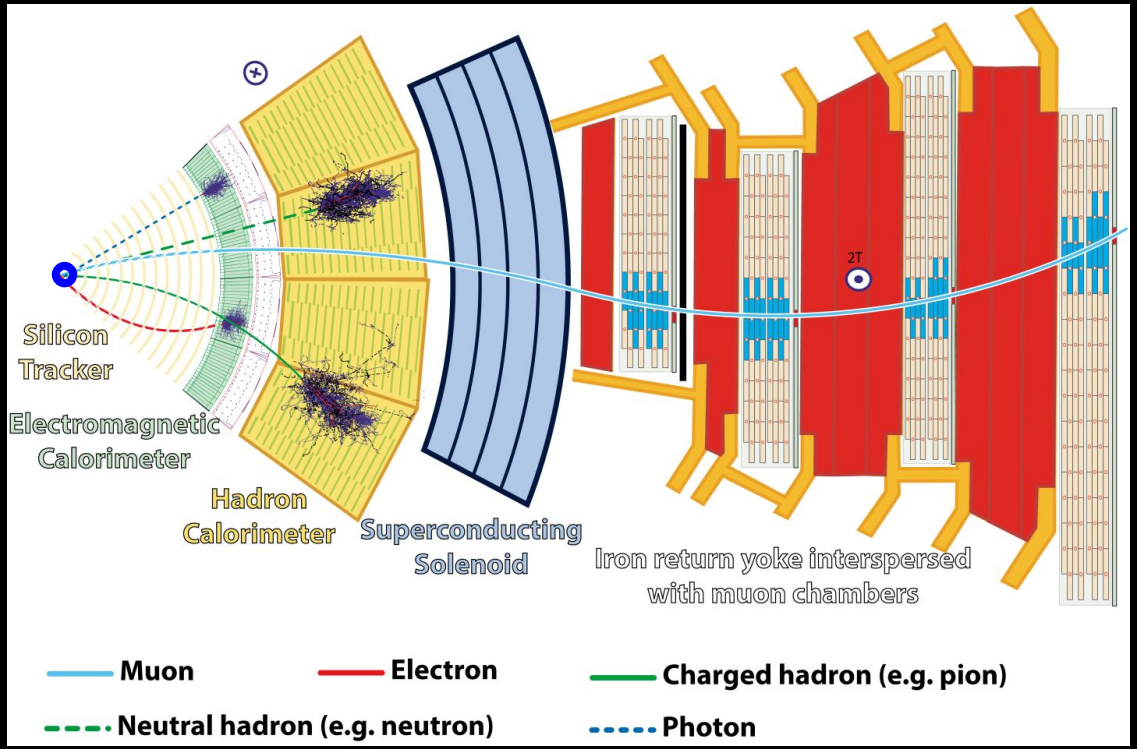


Source: CERN

Overall approach

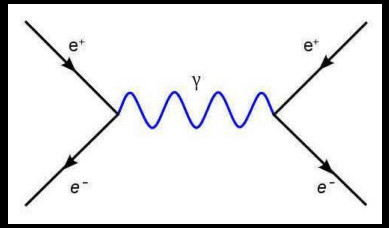
- Almost everything *of interest* occurs **before** the first layer of the detector!
- We must reconstruct particles backwards!
- Must correct for the detector effects!
- **Need excellent simulation**!

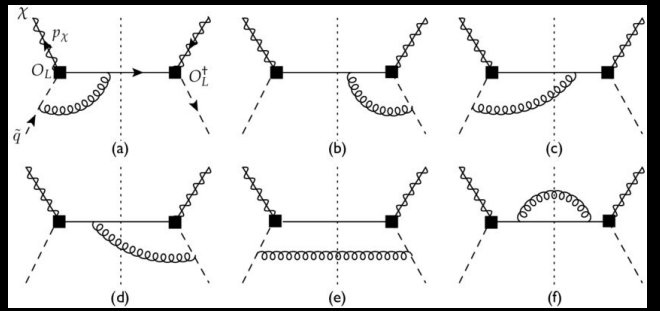


Source: CERN

Monte-Carlo simulation

- Monte-Carlo (MC) simulations are used to compare experimental data to the theory!
- These predictions can be calculated to different levels:
  - Leading-order (LO);
  - Next-to-leading order (NLO);
  - Current cutting-edge:
    N^{3}LO (resource limited process (human & computing)





- Various generators available for MC creation, such as Pythia, Powheg, Sherpa, etc;

- Particles generated by the MC generators undergo the same treatment as the particles obtained in the collisions at LHC!
- Each experiment passes their MC through a fully simulated version of their detector and create the *signal* in the detector, which is then reconstructed by the same software as for the data;

A measurement

- What makes up a measurement …

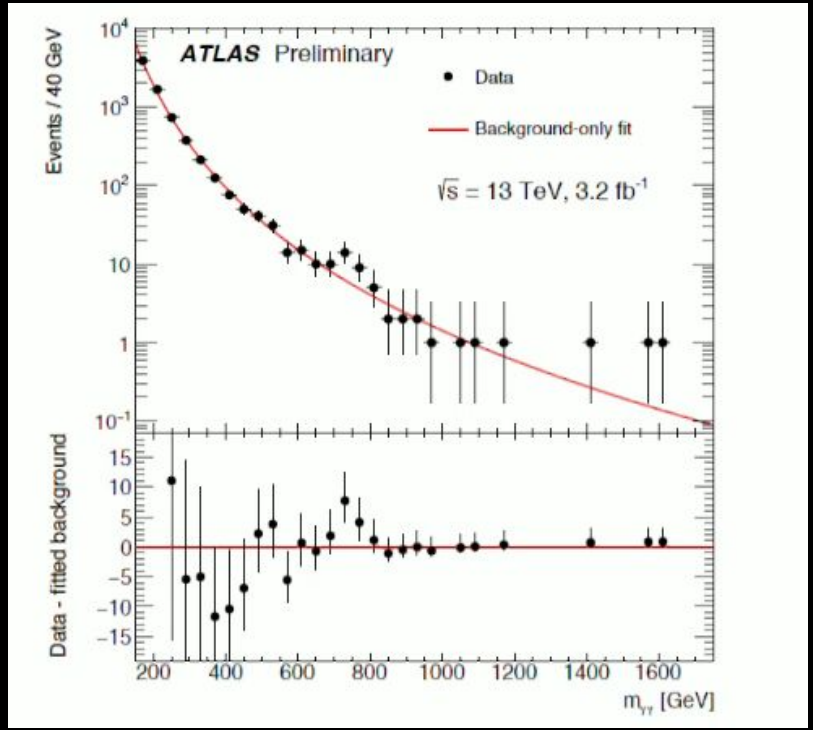
$$X \pm Y$$

central value — uncertainty

- We measure the success/significance of our results in standard deviations, comparing the expected and measured values;
- Threshold for *evidence of something new* is 3σ : 3/1’000 chance of a statistical fluctuation;
- Threshold for *discovery of something new* is 5σ : 6/10’000’000 chance of a stat. fluctuation;

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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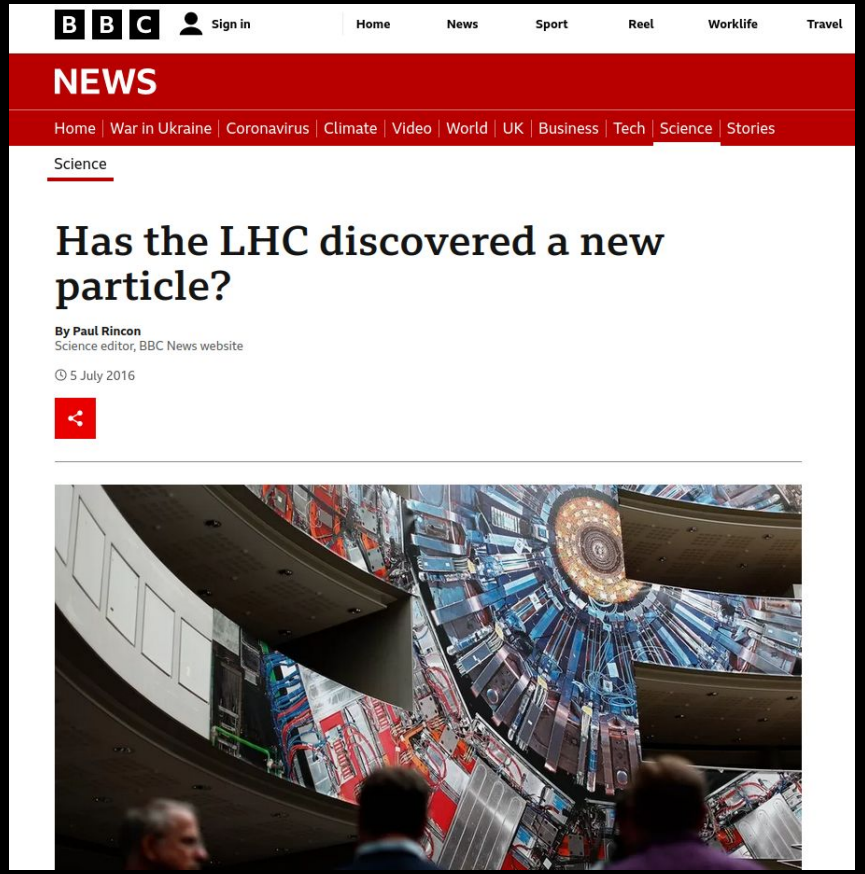

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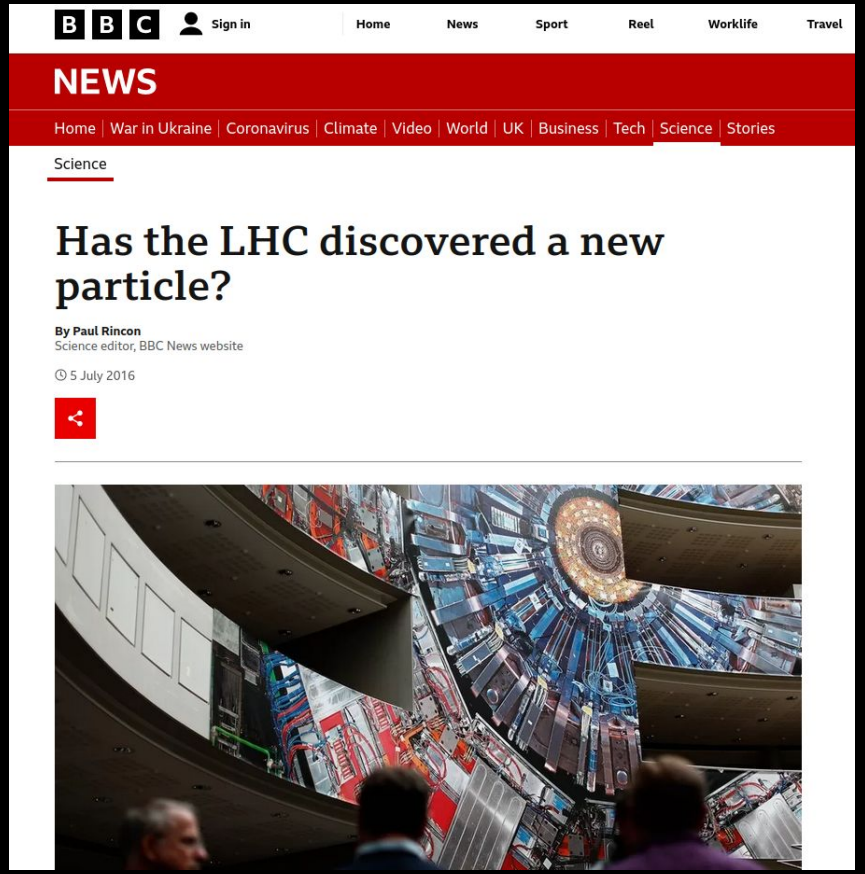
- Alas, with more data taken, the bump disappeared entirely!
- We must be careful with our announcements!



W mass

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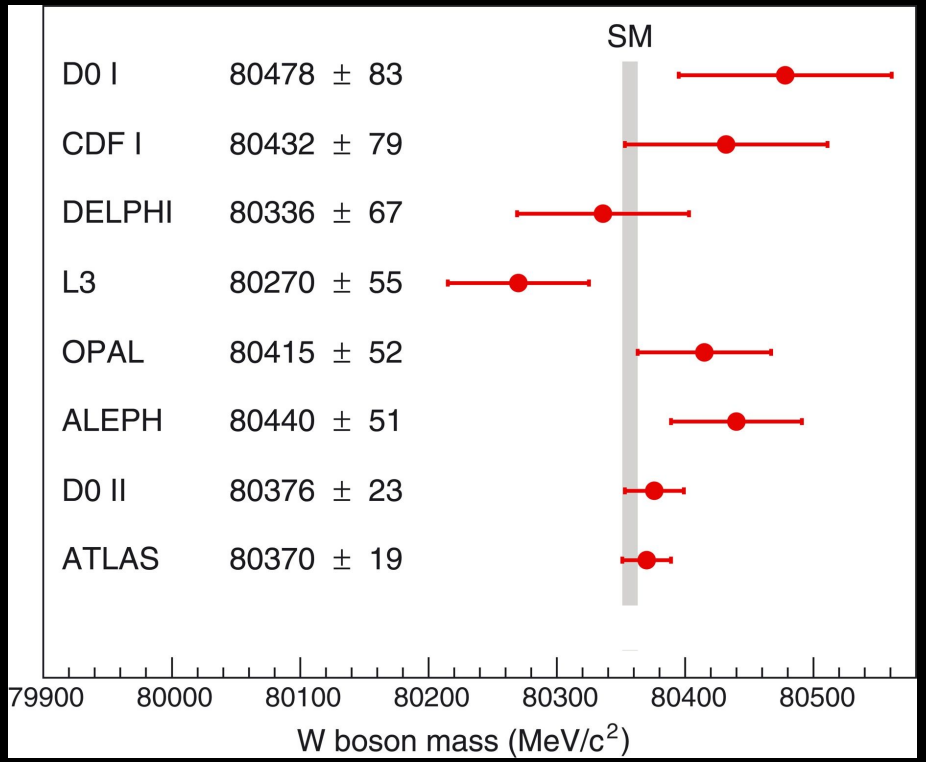
- The hadronic channels are *messy*, the leptonic channels have missing energy carried by the neutrino;
- Performed many times at many experiments, all agreeing with the SM (and each other);



Source: CDF II

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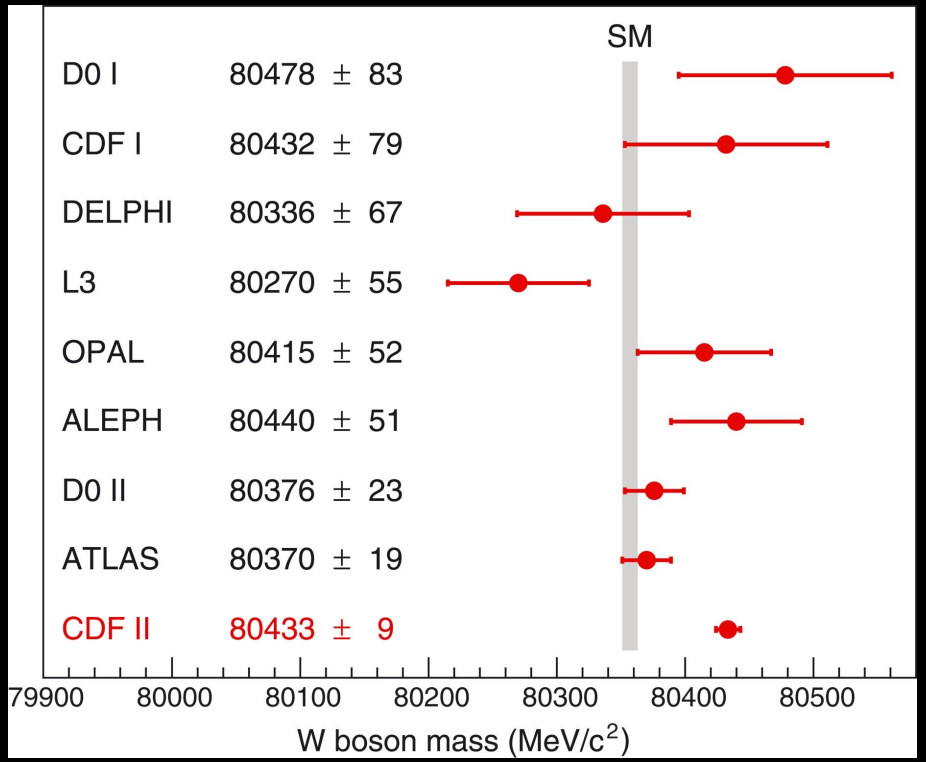
- This has made big news, but the HEP community is extremely cautious!



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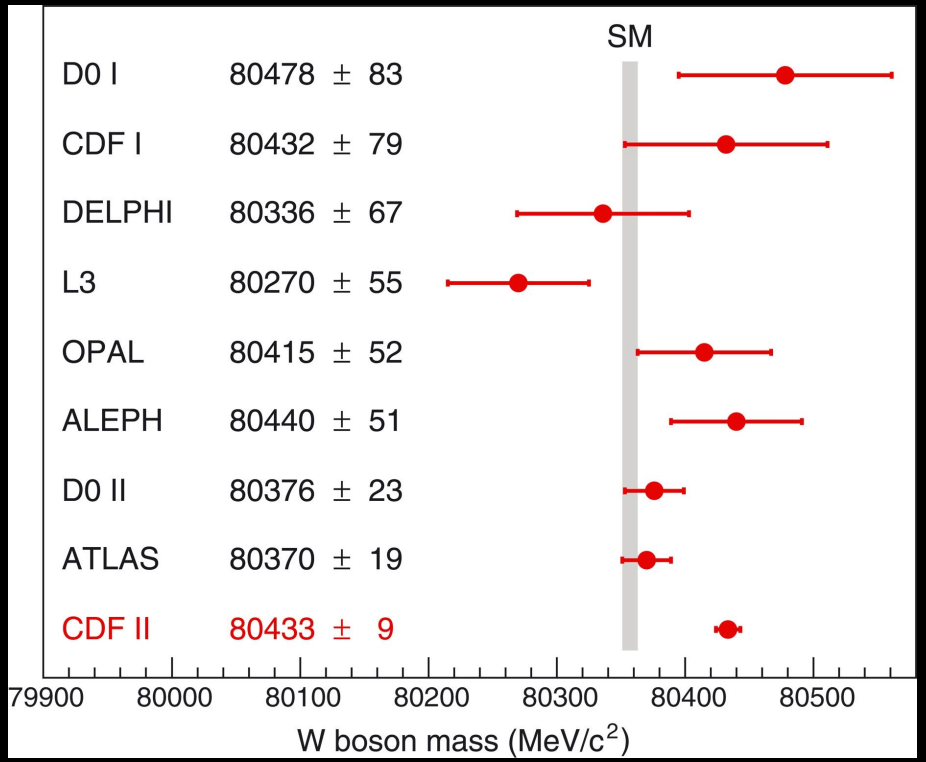


Source: CDF II

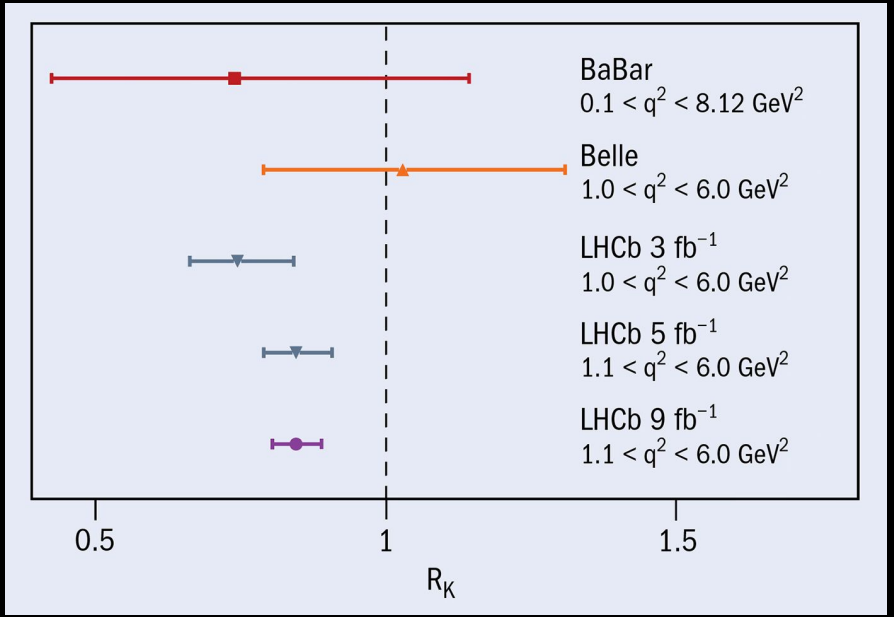
- **Personal opinion** - I do not know where or how, but they have made mistakes! I guess, watch this space ...

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*!



Source: CERN courier

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

The advert!

- The particle physics and accelerator technology development community is growing in the Baltics!

- With the support of our CERN Baltic Group partners, we have developed a doctoral study programme in “Particle physics and accelerator technologies” in Latvia!

- We are keen to expand it to include the universities from our Baltic neighbors! [this takes time!] In the meantime, we are looking towards options of offering some *cotutelle* opportunities.

- The programme already has 7 enrolled students across two years of study and we are looking to enrol more students this year!

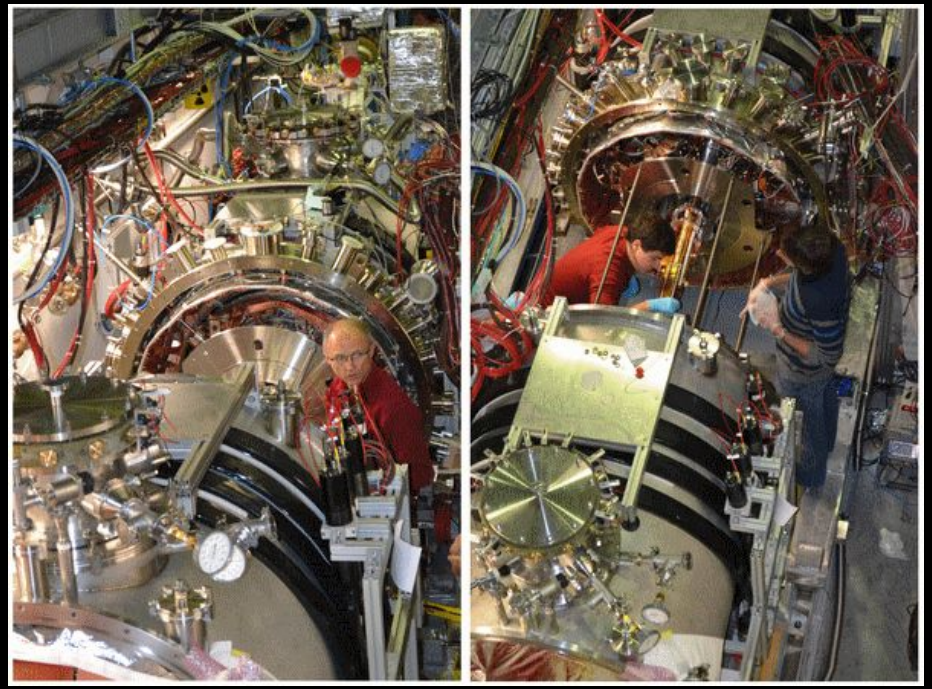
The advert!

- As part of this 4-year PhD, the students have access to excellent lecturers, both from the Baltics and the wider Europe and CERN, who are experts in their field!
- Enrollees can perform their research activities on experiments and projects based or related to CERN:
  - CMS experiment (particle physics);
  - AEgIS (particle/atomic physics);
  - Accelerator development project, such as I.FAST;
  - Medical accelerator projects, such as NIMMS and HITRIplus;
- The students are given an opportunity to spent an extended period of stay at CERN;
- The document submission for 2022 will take place on the week of 22-26th of August!
- If anyone is interested, please, enquire to hep@rtu.lv or contact me directly!
- Tell all your friends!

The advert!

CMS

AEgIS



I.FAST

The advert!

- During LHC Run 3 [2022-2025] we will collect 1.5-2x the data collected in Run 1 and 2 combined!
- Later, during Run 4 we will collect 5x more data then Runs 1-3 together!
- Joining the particle physics community you would join it at a really exciting time, when we are heading into the ultra-precision SM physics and into the unknown outside it!
- For technically minded students, our accelerator group is working on novel manufacturing techniques, which could play an absolutely pivotal role in helping us push the boundaries of physics even further with the Future Circular Collider!

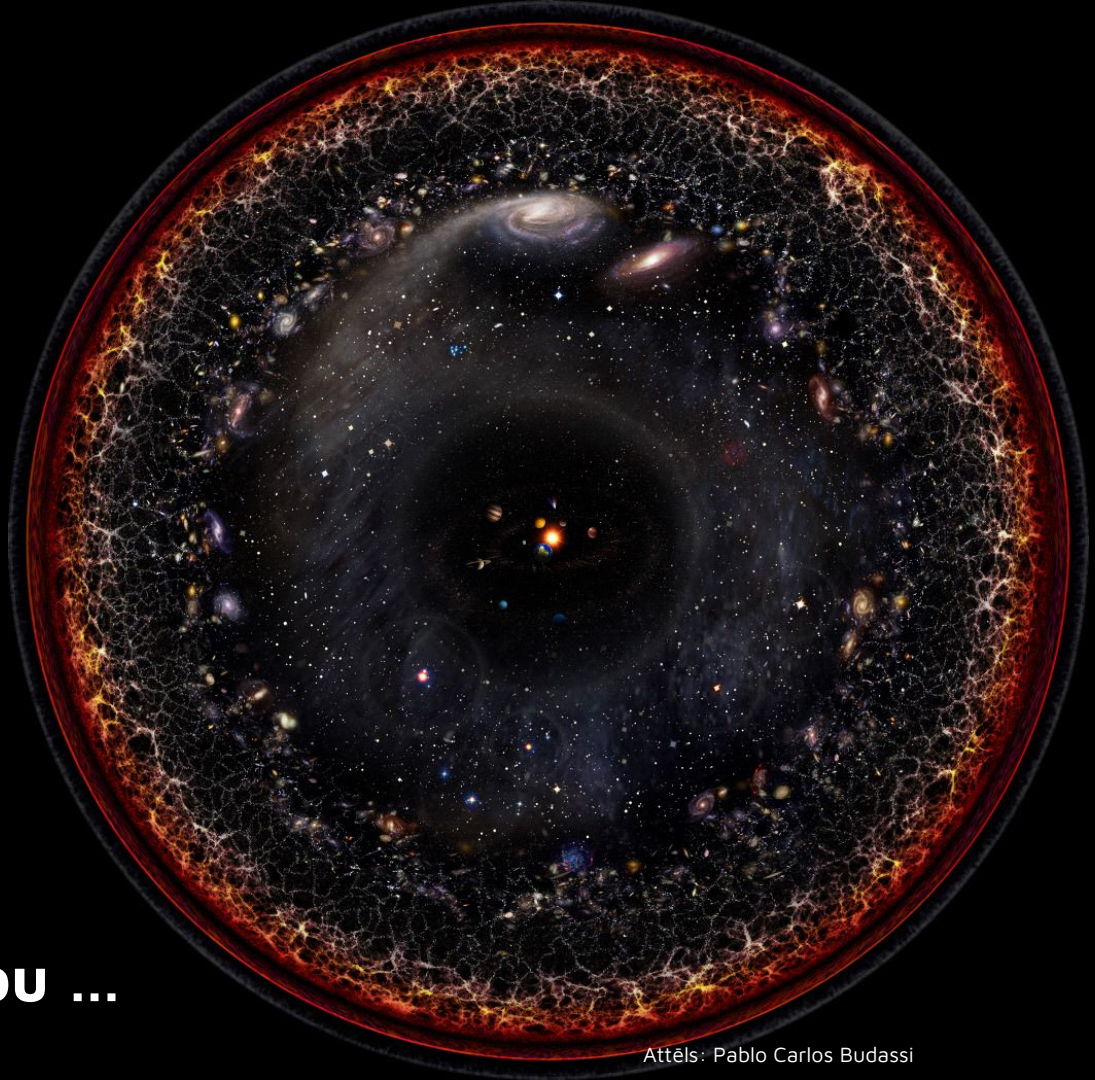
The open questions of the SM

- Despite efforts of thousands of scientists, the SM remains steadfastly unshakeable!

  The open questions still remain!

  - 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?
  - What is the cause of the matter-dominated universe?
  - What is dark matter? What is dark energy?
  - What is gravity? Is there a graviton?
  - Does supersymmetry exist?
  - Is there a GUT? Is there a ToE?

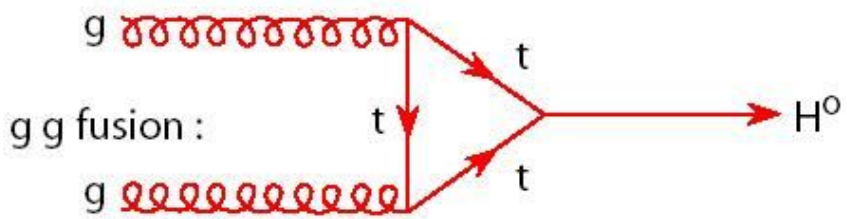
- We need a continued effort from young minds to keep pushing the SM!
- We need people developing the next-generation of tools to make that possible!

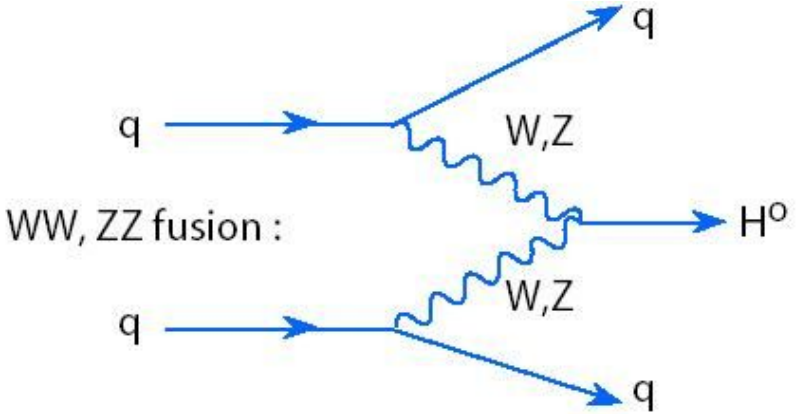


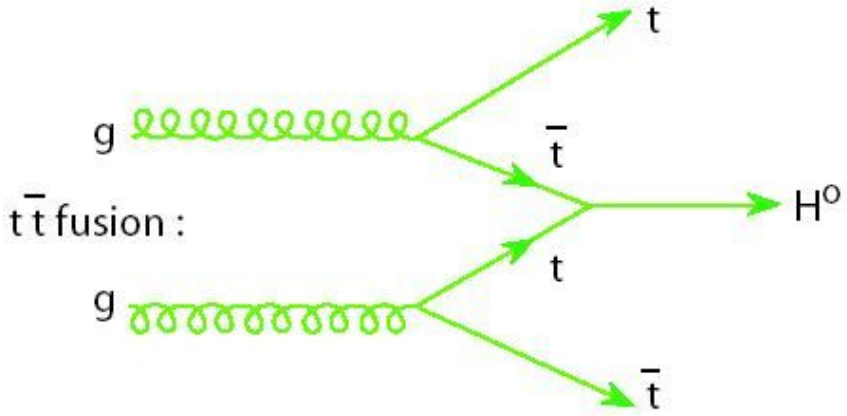
Thank you ...

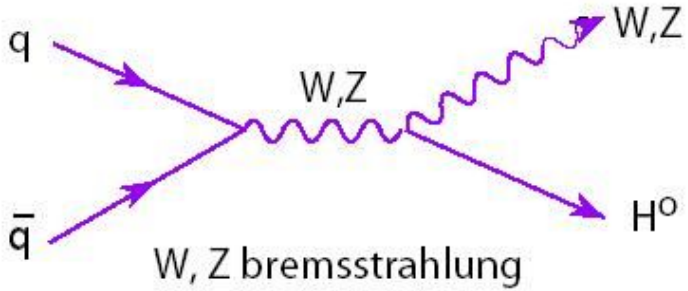
Attēls: Pablo Carlos Budassi

Higgs production mechanisms

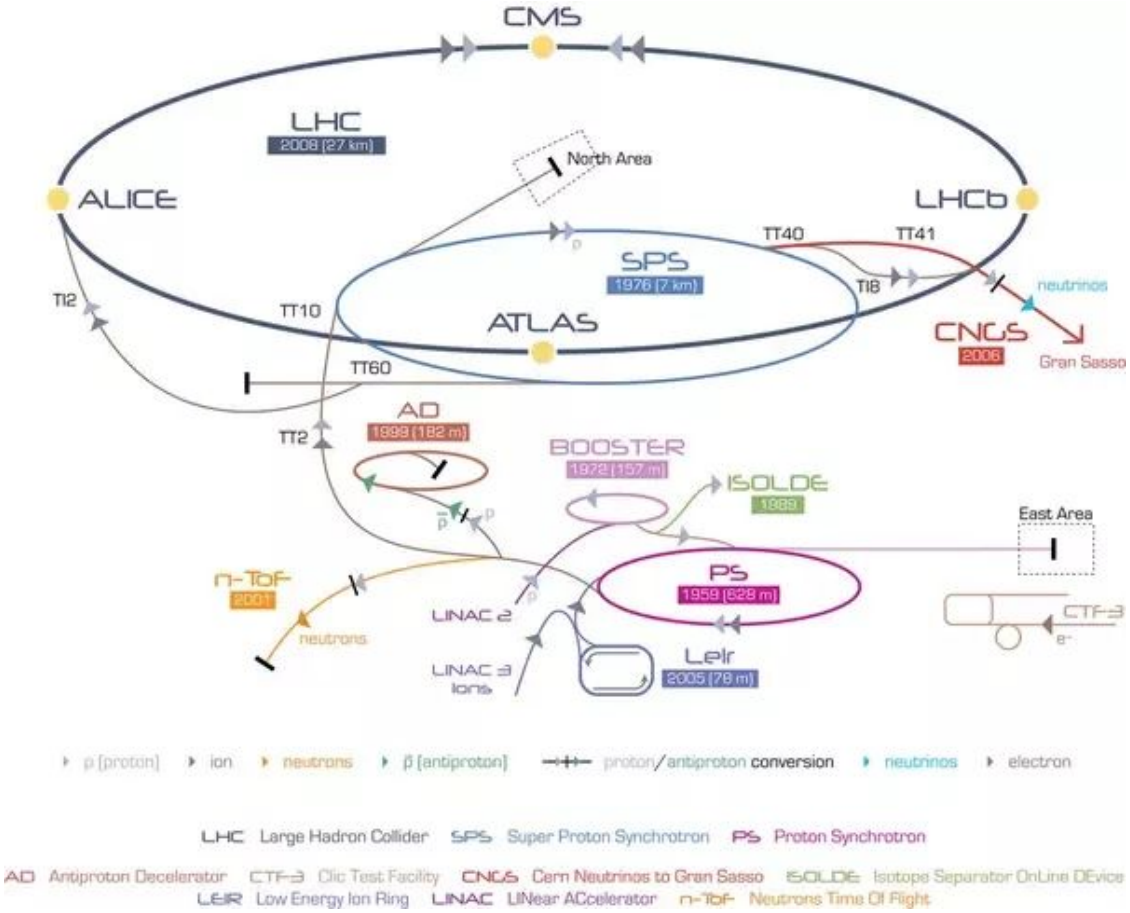








LHC injection chain



Higgs Field

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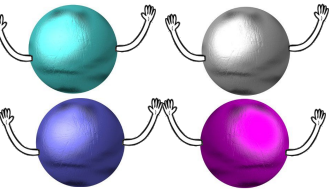

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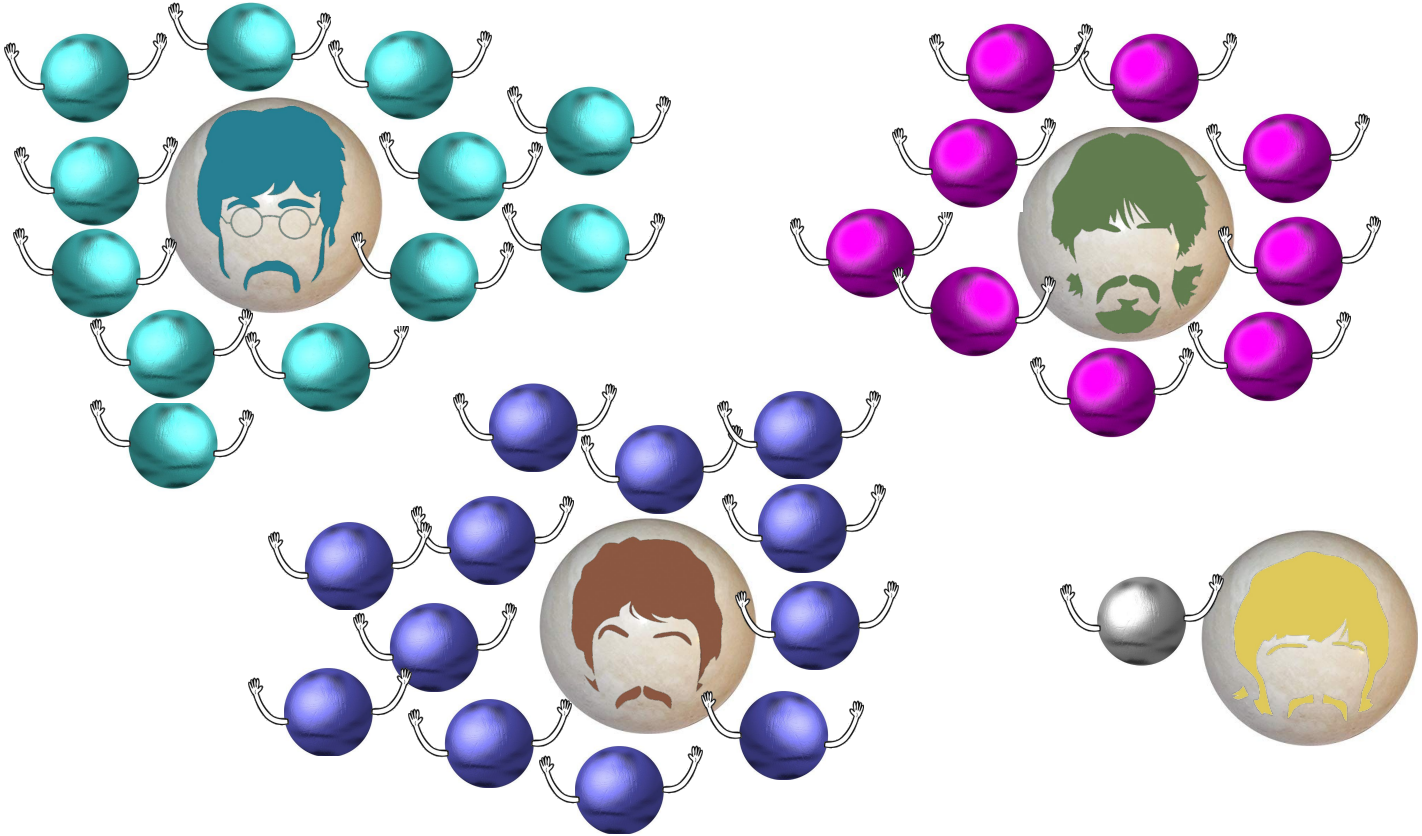

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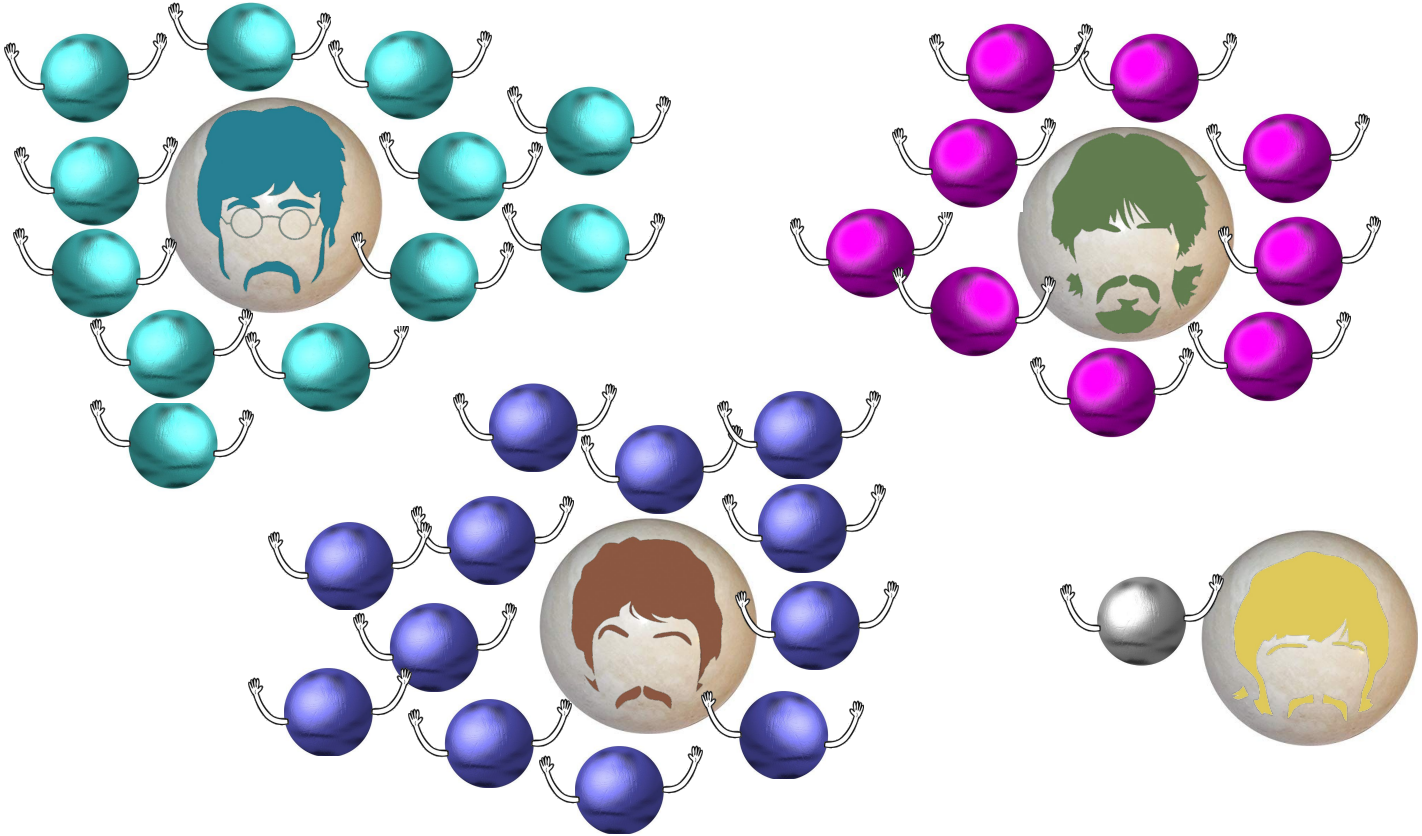
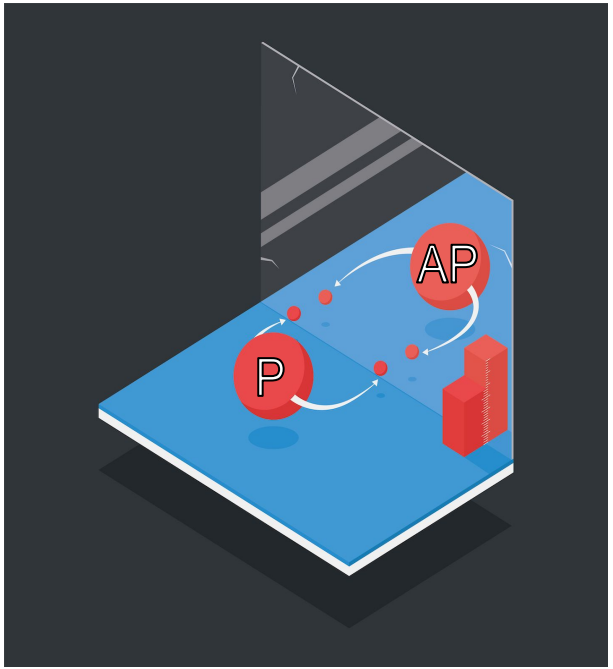


- With this discovery, the Standard Model became complete, but remember..

Flavour physics

- Charge-Parity violation (CPV) was discovered in kaon decays in 1960s;
- Opened ‘flavour’ physics as a doorway to understanding the matter-antimatter asymmetry;
- Largest discrepancy visible in **B**eauty meson decays;
- CPV in **C**harm meson decays was discovered **this** year!
- LHCb and CMS are at the forefront of flavour physics at the LHC.



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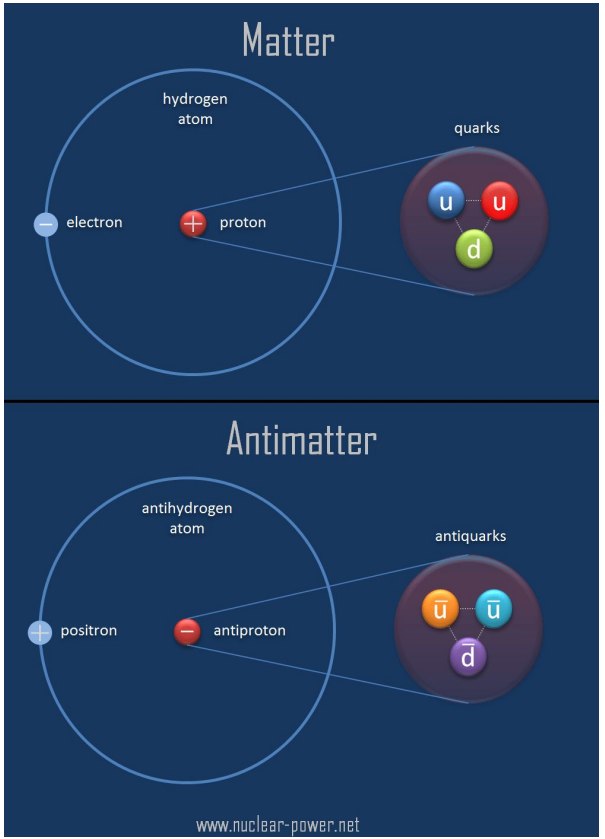
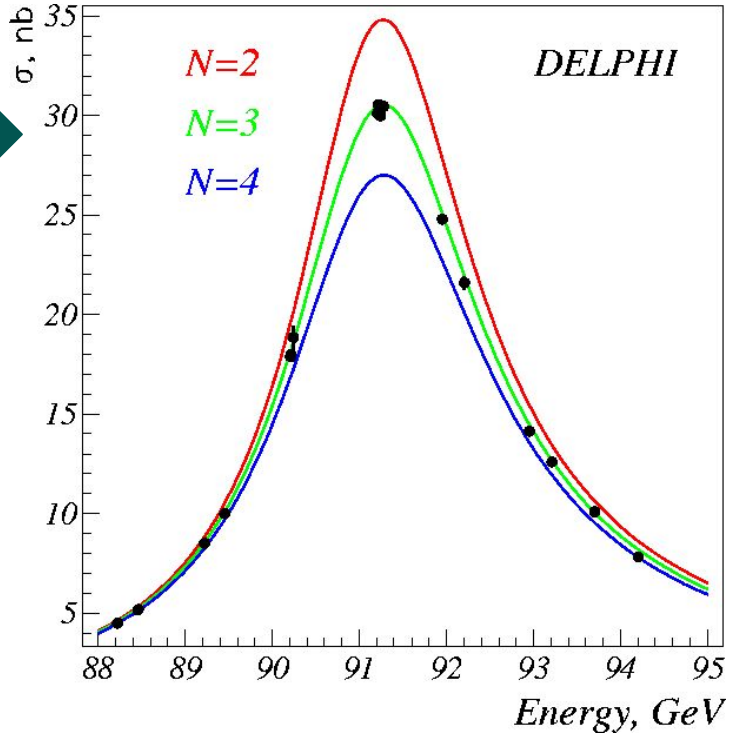


Lepton universality

- Three generations of leptons - electron(*e*), muon(*μ*), tau(*τ*);
- Why are there three families? We don't know! (but we do know there *probably* are exactly 3)
- LU means that, after accounting for their mass, leptons **should** be 'identical';



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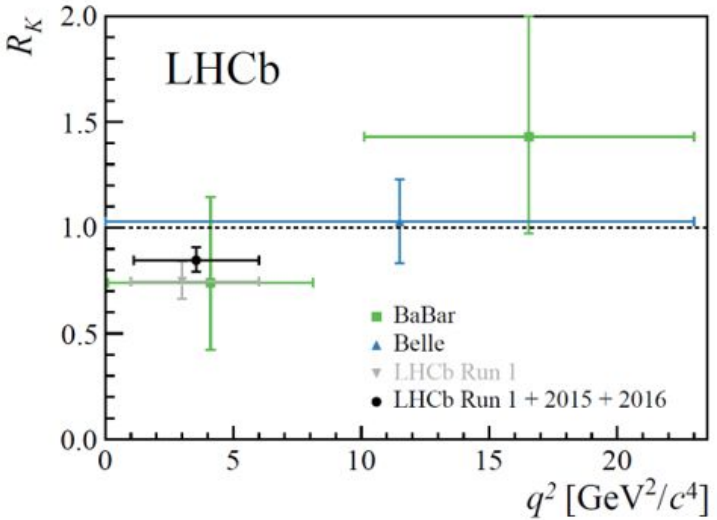
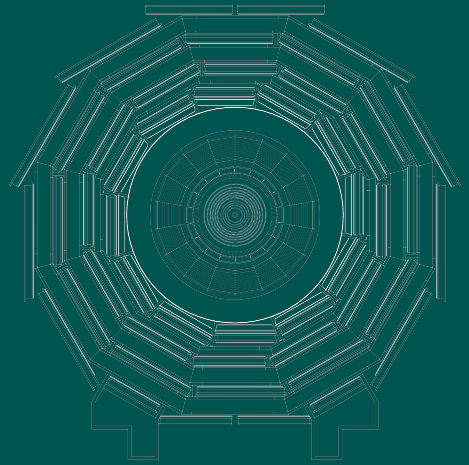
- LU means that, after accounting for their mass, leptons **should** be 'identical';
- Surprising evidence they **might** not be! (2.5σ discrepancy)
- Much (much!) more work is needed!



Above: R(K) BR(B->Kμμ) / BR(B->Kee)
Phys.Rev.Lett. 122 (2019) no.19, 191801



Paldies!