Introduction to the Standard Model

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Introduction

- **The Standard Model is a pillar of modern Science**
  - Most fundamental description of Nature: particles and, most importantly, **their interactions** (everything is interaction)

- It condensates the knowledge gained during centuries of experiments and theoretical work by physicists → ***HUGE*** accomplishment
  - Allows to model what happens in experiments and make predictions about future experiments

- However, it also comes with **limitations**

A history of… reductionism?

- **The Standard Model is the latest attempt to describe the fundamental constituents of matter** (but note that things are fundamental until they aren't anymore…)

~ 450 BC
(later supported by Aristotle)

More sophisticated than it sounds…

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- Today's microscope technology finally allows us to reveal what that element is *today*

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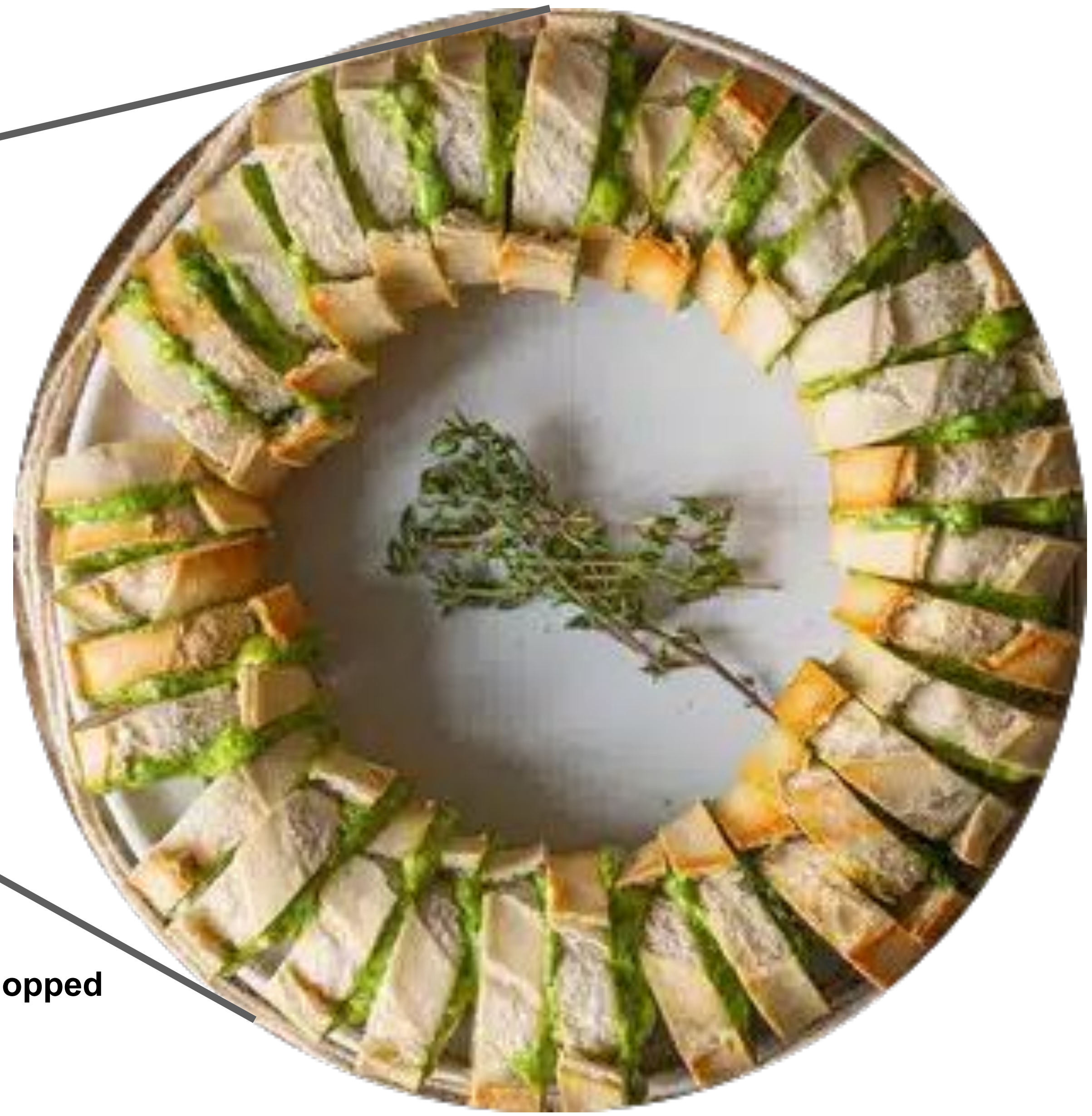
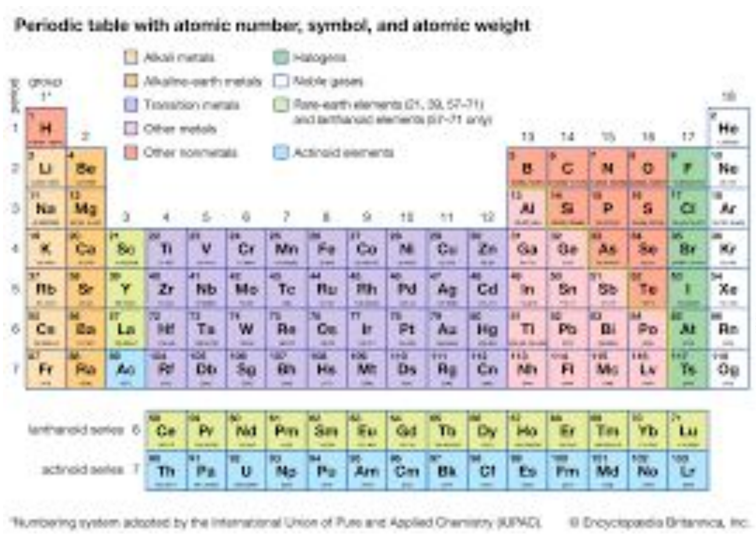


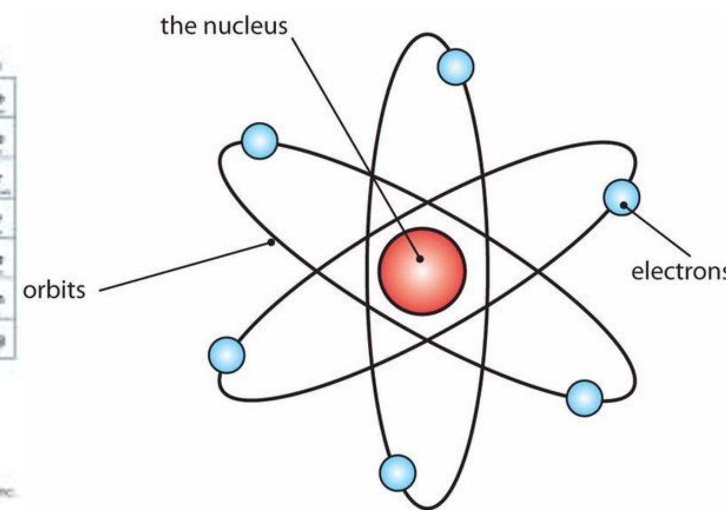
bread garnished with chopped fresh garlic and butter

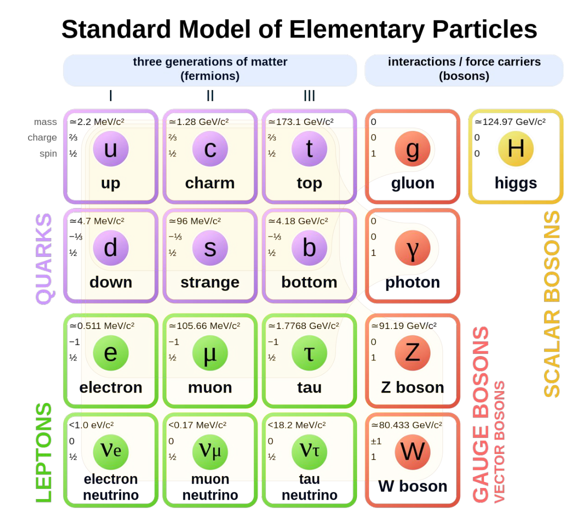
A history of… reductionism?

- **The Standard Model is the latest attempt to describe the fundamental constituents of matter** (but note that things are fundamental until they aren't anymore…)

~ 450 BC	~ 1870	~ 1910	~ 1970
(later supported by Aristotle)	(Mendeleev & others)	(Bohr & others)	(Weinberg, Glashow, Saalam)







More sophisticated than it sounds…

Basis for chemistry

Basis for quantum physics

Latest attempt!

- **There is no reason to expect that this won't evolve further** 😁

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Journey towards the SM (1/4)

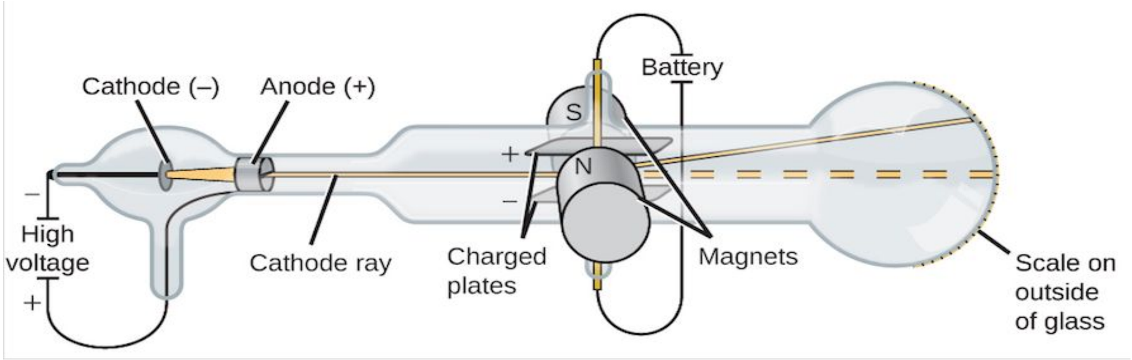
- **Discovery of the electron by J.J. Thomson et al. in 1897**
  - In particular, first to measure the mass and charge, which are independent of the cathode material

  → rest of atom is positively charged

- **Discovery of the nucleus by E. Rutherford in 1911**
  - Most particles undeflected
  - Very few particles are deflected, some at very large angles

- **Discovery of the proton by E. Rutherford in 1919**
  - The hydrogen nucleus is "present" in other nuclei
  - The hydrogen nuclei is produced in some nuclear reactions

  → How can one ensure the nucleus stability? (indirect discovery of nuclear interactions)



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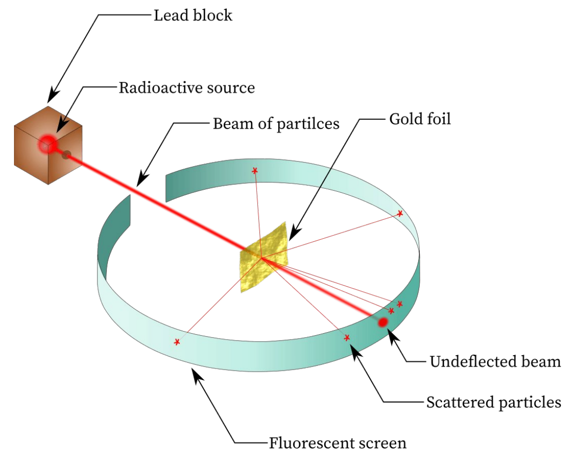
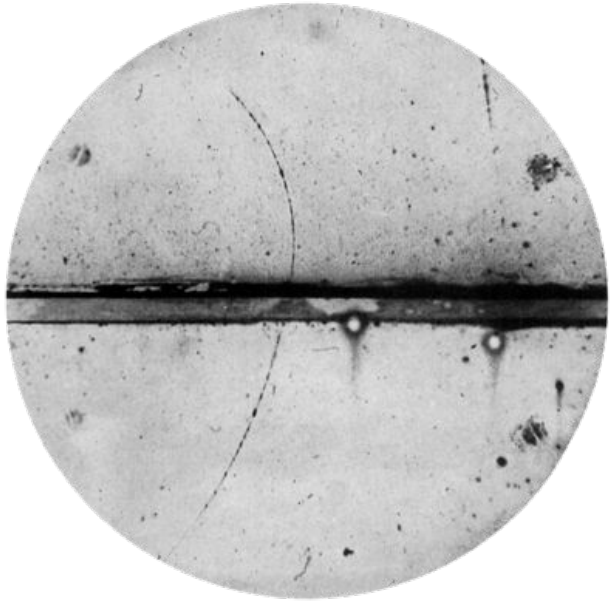


from chemistrygod.com

- **Discovery of the neutron by J. Chadwick in 1932**
  - Neutral radiation emitted in nuclear reactions, but *not* a photon

Journey towards the SM (2/4)



- **Discovery of the positron by C. Anderson in 1932**
  - Cosmic rays in magnetic field, with piece of lead as absorber
  - Same mass to charge ratio as the electron, but opposite charge → antimatter

- **Discovery of the neutrino in two stages**
  - Indirect discovery in 1934 by Fermi in his interpretation of β-decays (along with weak interactions)
  - Direct discovery in 1956 by C. Cowan et al. using a nuclear reactor and the $\nu_e + p^+ \rightarrow n + e^+$ (coincidence of nuclear recoil and ee annihilation)

- **Discovery of the muon and tau leptons**
  - Muon discovered by C. Anderson et al. in 1936 in cosmic radiation
  - Tau discovered (indirectly) by Martin Lewis Perl et al. in 1974-77 at SLAC in e^+e^- collisions (e^+e^- —>$e^+\mu^-$ + missing energy)

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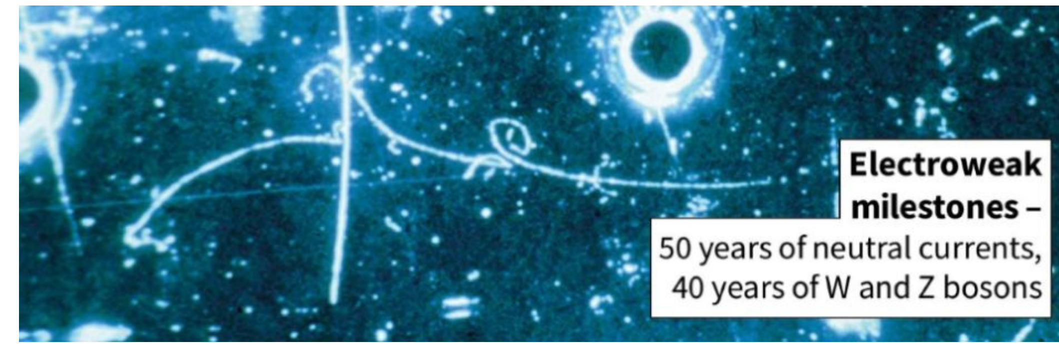
Journey towards the SM (3/4)

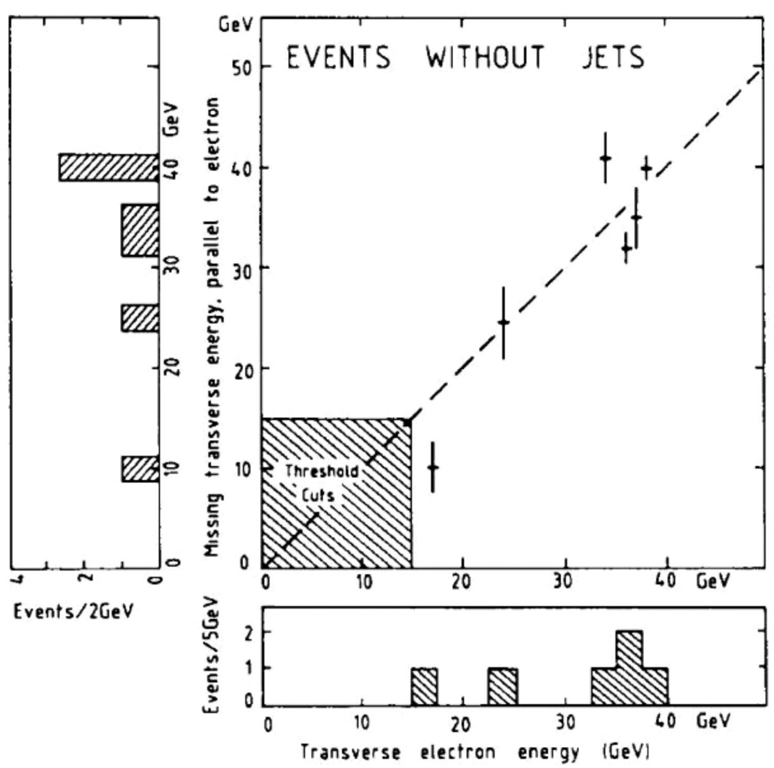
- **Discovery of the quarks & gluons**
  - Indirectly achieved by Gell-Mann & Zweig after discovery of a multitude of hadrons in the 1960's and their explanation of the structure of hadrons in multiplets
  - Discovery of the quark flavours:
    - *up*, *down* and *strange* necessary to explain the *8-fold way* of hadrons already produced (e.g. at SLAC)
    - *charm* discovered at SLAC & BNL (J/ψ) in 1973, as predicted by the GIM mechanism
    - *bottom* discovered at Fermilab by Lederman et al. in 1977
    - *top* discovered at Fermilab's TeVatron by CDF and DO in 1995

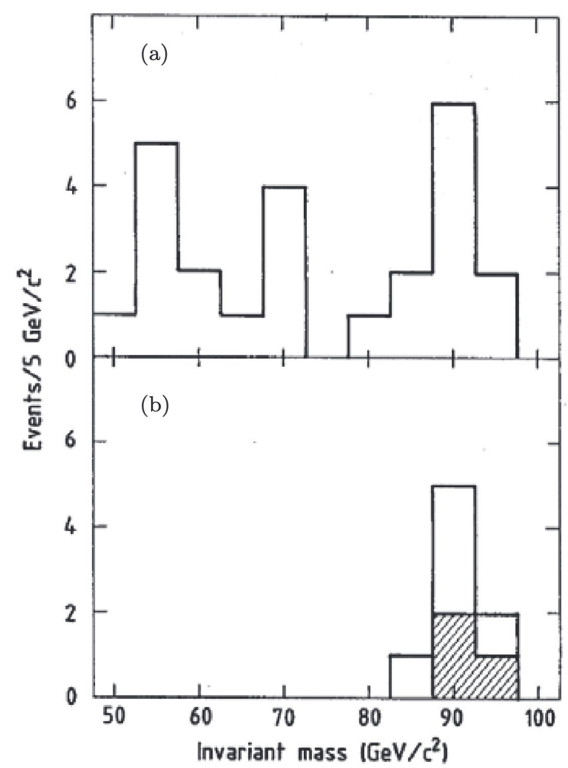
- **Discovery of neutrino flavors**
  - *Muon neutrino* discovered by Lederman, Schwartz, and Steinberger in 1962 at BNL
  - *Tau neutrino* discovered by Fermilab's DONUT experiment in 2000

Journey towards the SM (4/4)

- **Discoveries of the W, Z bosons**
  - Discovery of “neutral currents” by Gargamelle at CERN in 1973
  - Discovery of *W-boson* at SPS at CERN in 1983 by the UA1 and UA2 Collaborations… quickly followed by the *Z-boson* later that same year!
    → Discovery only possible thanks to new accelerator technology (van der Meer)



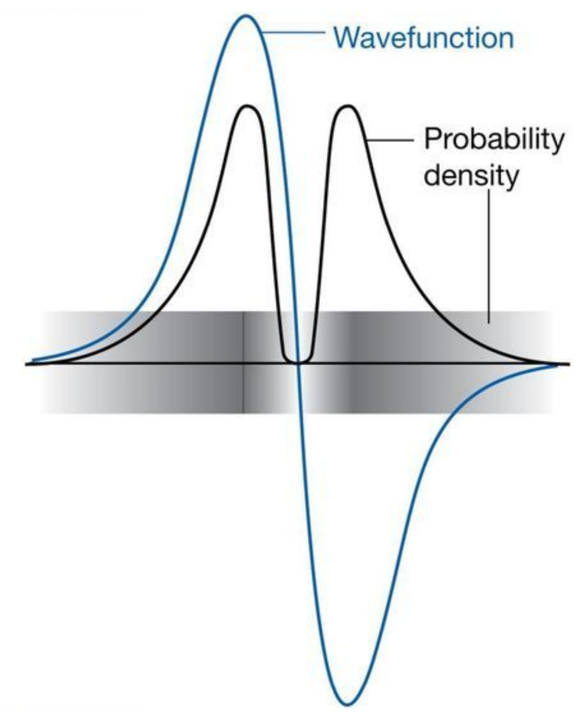


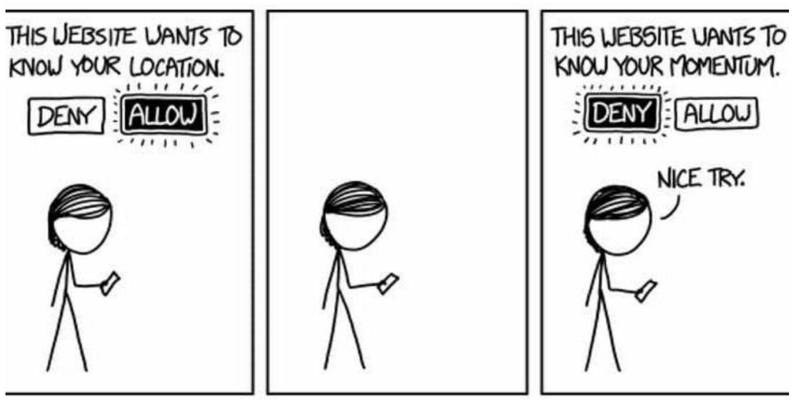


Theoretical ground: quantum mechanics

- Originally developed to address practical issues like atom stability, black body radiation…
- (At fundamental level) phenomena happen in a **probabilistic** way
  - the observed outcome of an experiment belongs to a set of possible outcomes, for which the probability can be computed by squaring complex amplitudes (Born principle) → **mystery of wavefunction collapse**
  - “classical” determinism is an approximate feature that emerges (for example in systems of many particles)
- **Heisenberg uncertainty principle**: certain characteristics of a system cannot be simultaneously measured with arbitrary precision
- Energy levels (and other quantities) in a bound system are **quantized**
- Particles can display corpuscule-like and/or wave-like behaviours (**duality**)

- Original formulations using either matrices mechanics (Heisenberg) or wave mechanics (Schrödinger) → several formulations of QM are possible
- Later came the modern formulation using **path integrals** (Feynman) → generalization of the action principle and allows for a Lagrangian formulation of QM





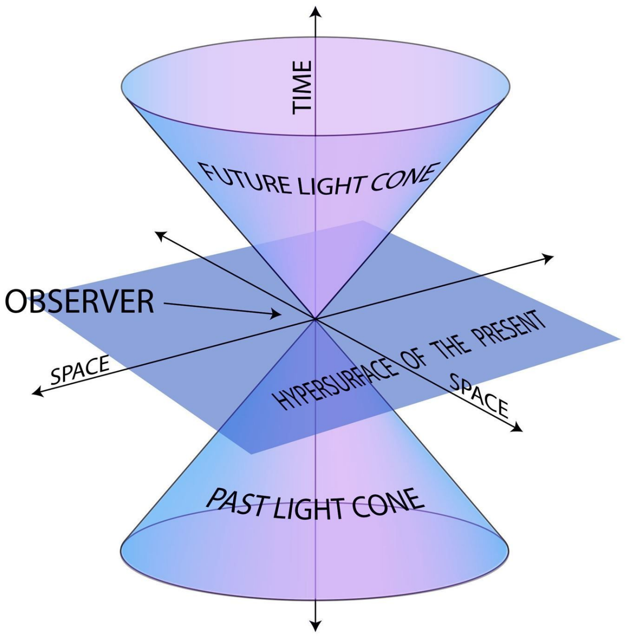
xkcd

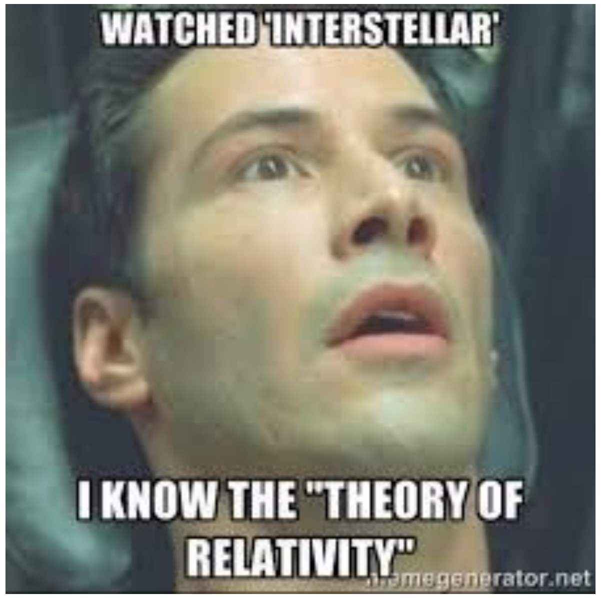
$$\langle x_f, t_f | x_i, t_i \rangle = \int \mathcal{D}x(t) e^{iS[x(t)]/\hbar}$$

Theoretical ground: special relativity

- Originally developed by Einstein (or was it??? let's face it… SR was actually discovered by Poincaré! Me being french has nothing do with it, I'm not biased.) to solve the **incompatibility between Maxwell's equations and Newtonian mechanics**. Essentially:
  - In Maxwell's equations, the speed of light is constant in all inertial reference frames
  - In Newtonian mechanics, the speed of light can change from an inertial reference frame to another…

    → New input needed to resolve the conflict: Poincaré/Lorentz transformations
- **Principle of relativity**
  - laws of physics are the same in all inertial reference frames / speed of light is constant
  - there is no preferred frame of reference
- Other consequences of the theory:
  - Space + time → spacetime (flat); distance → **spacetime interval** (which is conserved); time and space are not independent; duration dilation and length contraction
  - **Energy-momentum relation**: $E^2 = p^2 + m^2$





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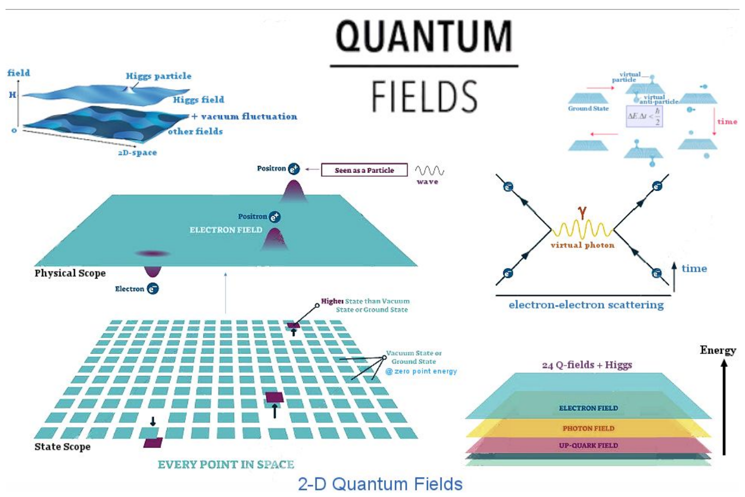
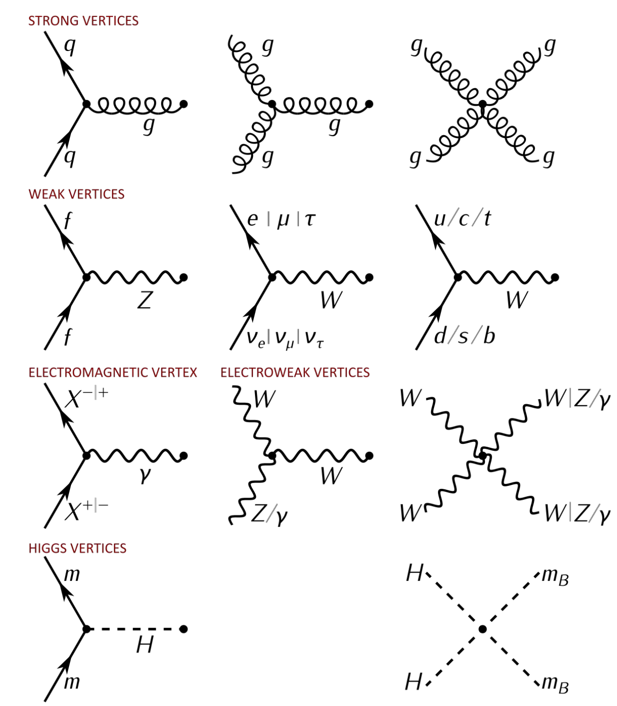
Theoretical ground: quantum field theory

- **QFT** is a combination of classical field theory (interactions occurs through fields), quantum mechanics and special relativity
  - Fundamentally, all that exists are quantum fields that span over the whole space… particles are excited states of the underlying fields
- **Quantum ElectroDynamics** (QED), the first QFT, was actually derived in the 1920s!
  - But it was impossible to make accurate predictions with it due to the appearance of infinities in the computations (from radiative corrections)
- **Symmetries** lead to conserved quantities
  - Translations / rotations → conservation of energy, momentum
  - Gauge symmetries → conserved charges
- **Renormalization** procedure developed by Feynman, Schwinger & Tomonaga (& a few others) in the 1940s: cancelation of infinities in certain classes of QFTs in certain conditions
- **Feynman diagrams** can be seen as a handy tool to represent amplitudes / interactions, but are also very useful computational tools



universe-review.ca

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \mathcal{D}_\mu - m_e)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$



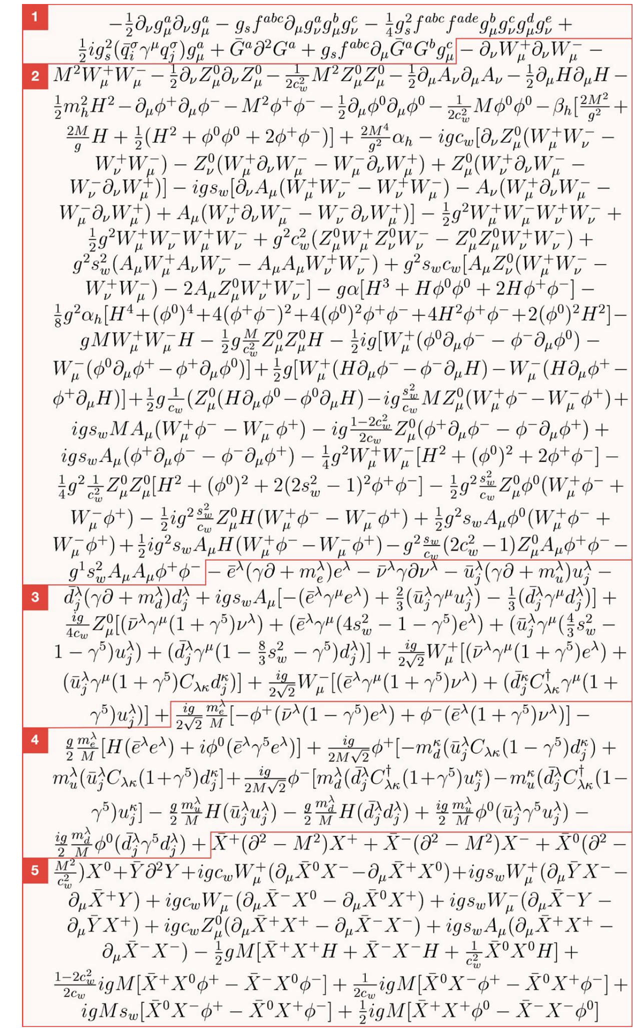
The Standard Model in all its glory

- **<u>3 fermion (spin 1/2) families</u>**
  - Left-handed doublets, right-handed singlets
  - Quarks (QCD-colored and fractionally charged) and leptons (integer-charged)
  - "No" right(left)-handed (anti)neutrinos

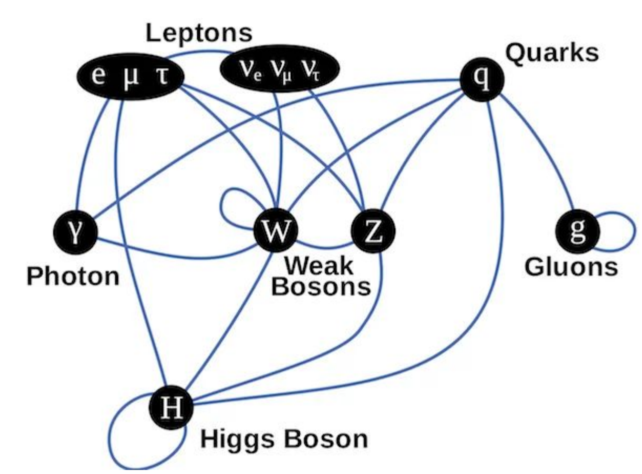
- **<u>Strong interaction</u>***:* non-abelian gauge theory based on the symmetry group SU(3)
  - Mediated by 8 gluons

- **<u>Electroweak interactions</u>**: non-abelian gauge theory based on the symmetry group SU(2) ⊗ U(1), which is broken by Higgs field
  - Resulting in electromagnetism mediated by γ, weak interactions mediated by massive $W^{\pm}$ and Z bosons
  - Only left handed fermions (right handed anti-fermions) sensitive to weak interactions

- **<u>Gravity left out</u> :-(**
  - Unclear at the moment what is the best path forward to achieve a (satisfactory/predictive) quantum theory of gravitation



T.D. Gutierrez



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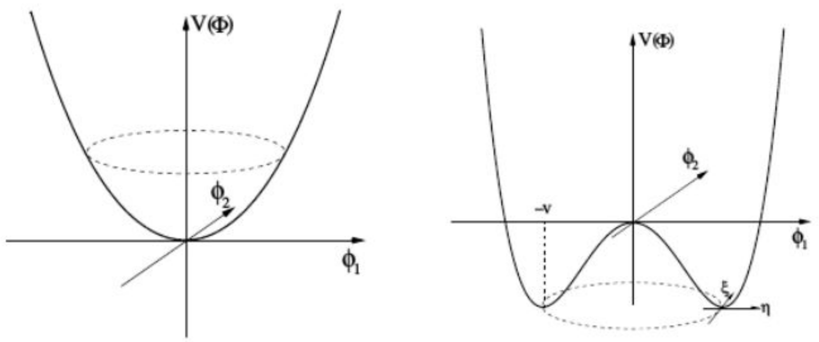
The Higgs mechanism

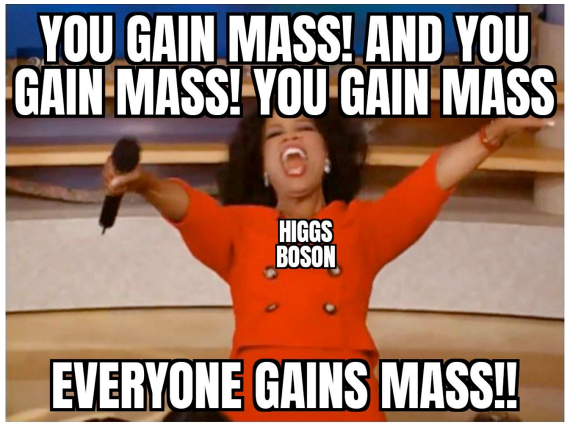
- **Without Electroweak Symmetry Breaking, all particles in the SM are massless (e.g. early universe)**
  - Naive mass terms break Lorentz variance… oops…
  - Obviously in contradiction with observations… need a mechanism to generate masses



Özer Özdal

- **<u>Higgs mechanism</u>** (Brout, Englert, Higgs & others 1964): **dynamical way to provide masses to the SM particles**
  - Higgs field is introduced as a SU(2) doublet
  - In the early universe, Higgs field has a v.e.v. equal to 0
  - As temperature goes down, Universe goes through a phase transition → Higgs field gets a v.e.v. ≠ 0
    - 3 of the 4 degrees of freedom mix with the weak fields and are absorbed in the masses of the $W^{\pm}$ and the Z^0
    - Remaining degree of freedom → Higgs boson
    - Photon remains massless
  - Can also obtain masses for the fermions through Yukawa couplings between Higgs and the L and R chirality fermions
  - Quite remarkable that Higgs et al. were able to theorize this mechanism before the discovery of many of the particles of the SM (in particular W and Z...)

$$\mathcal{L}_{\rm mass} = \overline{d^I_{Li}} M^d_{ij} d^I_{Rj} + \overline{u^I_{Li}} M^u_{ij} u^I_{Rj} + \overline{l^I_{Li}} M^l_{ij} l^I_{Rj} + h.c.$$



Photons :

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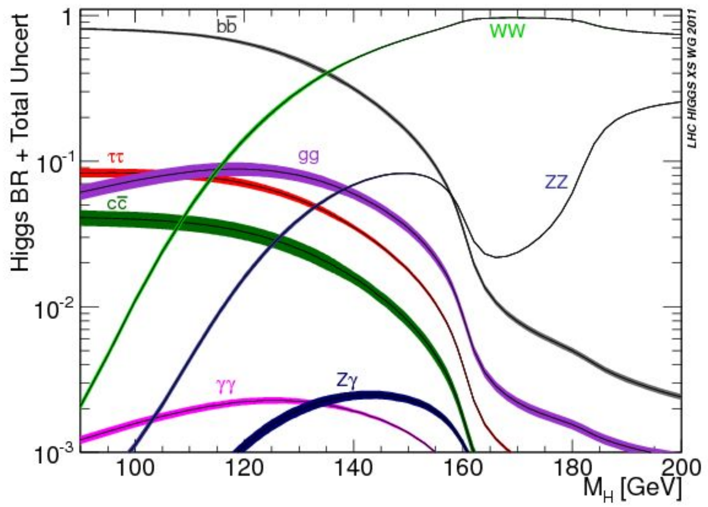
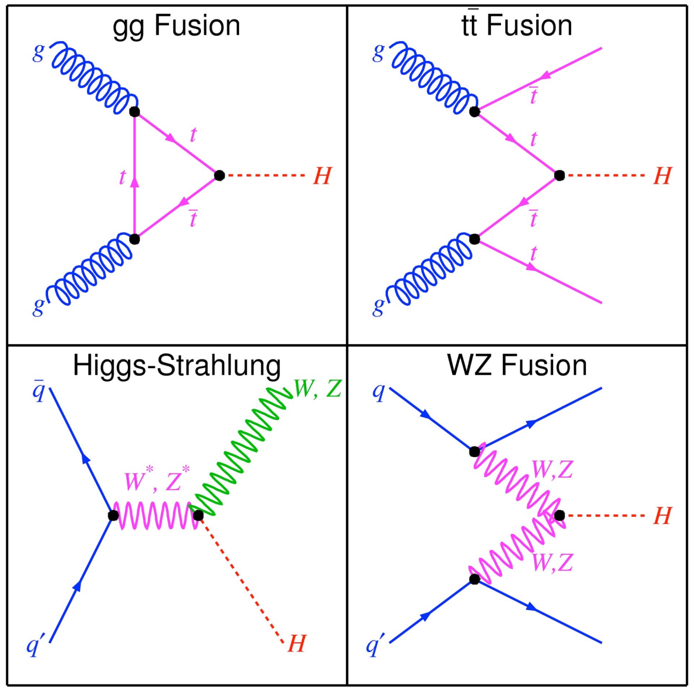
Higgs at colliders / LHC

- **The Higgs mass is a free parameter of the SM** (although some theoretical constraints exist)
- However, if its mass is known, the other SM Higgs boson properties are 100% predictable: tensor structure, (self-)couplings, width, J^P, branching ratios, etc.
- In particular, **one can predict the way it is produced** at different colliders (e^+e^-, proton-proton, proton-antiproton, $\mu^+\mu^-$) and with which cross sections
  - Higgs couples preferentially to heavy particles → production through top-Higgs and W/Z-Higgs vertices
- **At the LHC** (a proton-proton / gluon collider), the Higgs is produced mainly through gluon-gluon fusion, vector boson fusion, or associate production with a vector boson or ttbar pair
  - Some final state topologies (from decay and production) can be used to reduce the backgrounds or access some given properties
- Higgs boson also involved (perturbatively) in some fine SM processes like Vector Boson Scattering
  - Presence of Higgs boson's additional diagrams solves the divergence of $V_L V_L$ production at the TeV scale





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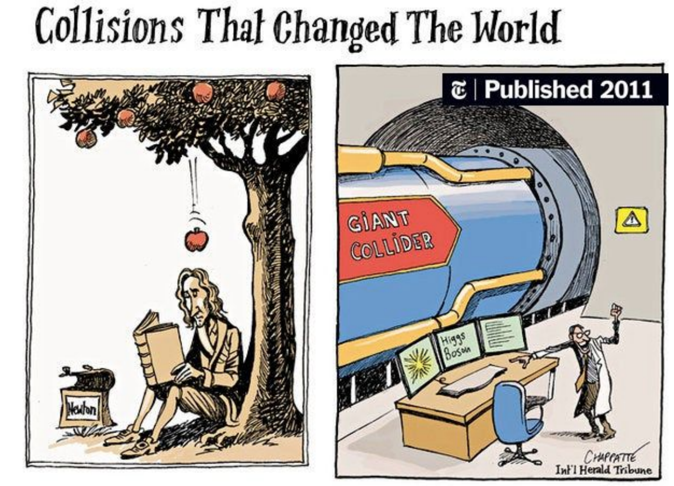
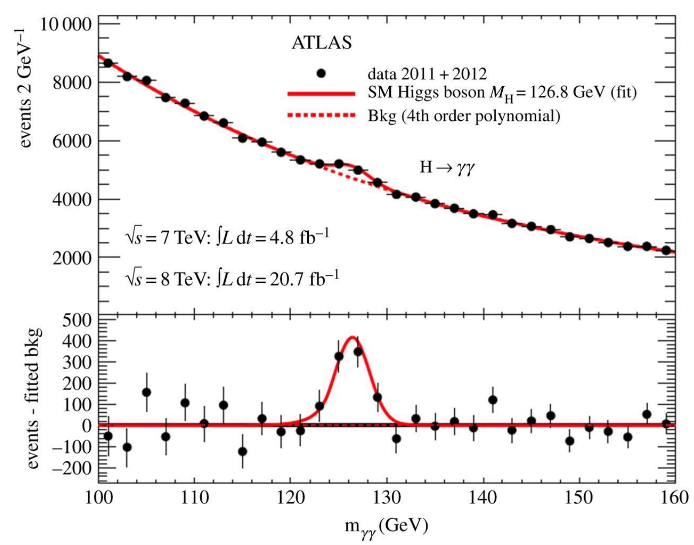
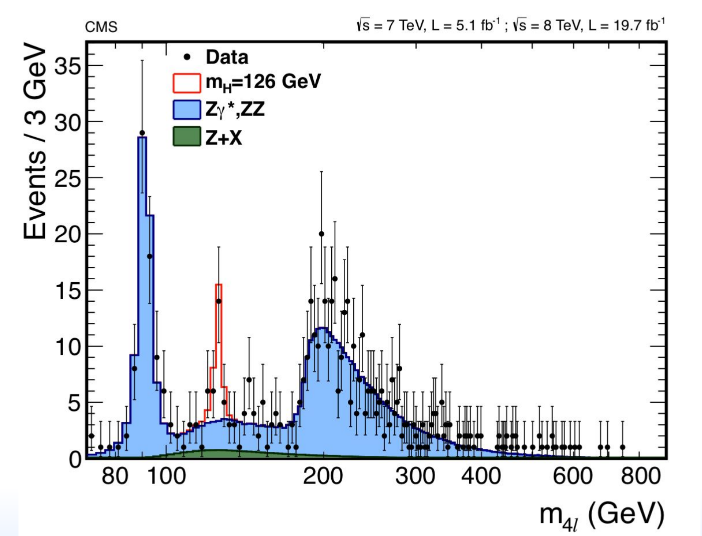
Higgs discovery



- **<u>The Higgs boson was discovered in 2012</u> by the ATLAS and CMS Collaborations**
  - Huge accomplishment by the LHC in the design, construction and operations of the LHC, in order to provide data to the experiments
  - Huge accomplishment by the collaborations in the design, construction, and operations of the detectors, and in carrying out these complex analyses
- **Discovery driven by $H \to Z^0 Z^{0(*)} \longrightarrow 4\ell$, $H \to \gamma\gamma$ and $H \to W^+W^- \to \ell^+\nu\ell^-\nu$ channel**
  - First (very likely) fundamental scalar in Nature!
- **<u>Higgs mass</u> (final free parameter of the SM!) ~125 GeV** (very significant for BSM theories)
- **<u>The "crown jewel" of the SM</u>**, which is now a complete (and over constrained)





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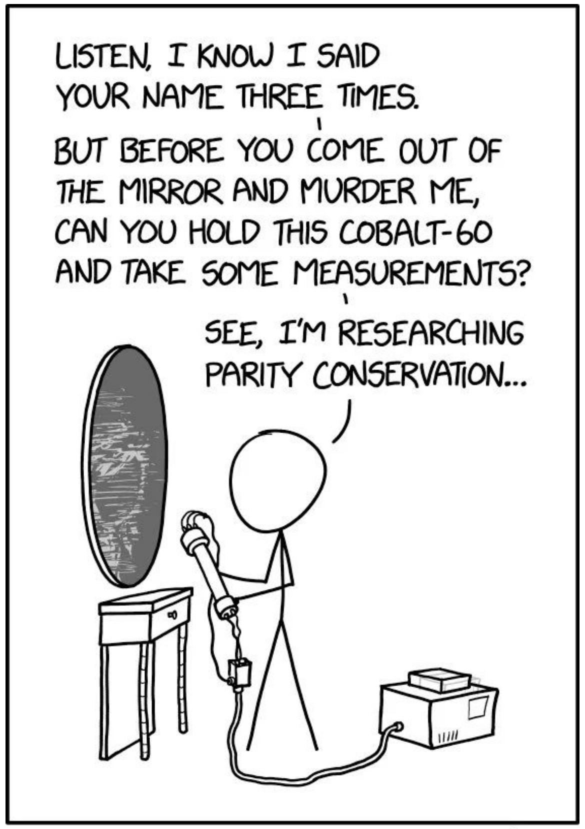
CP violation

- Physicists always assumed that fundamental interactions were invariant under Parity transformations (reversal of all space coordinates) and Charge transformation (reversal of all charges)
  - This is indeed the case for electromagnetism and the strong interaction
- However, analysis of existing data by Lee and Wu in 1956 showed that different rates were observed for some reactions and their mirror image: **P violation**
- A bit later, **C violation** was also measured to be violated (Wu experiments, 1956)

- At this stage, **a random physicist would be like "CP should still be conserved, right…… right???"**
  - But, everything that is not forbidden can happen[*], and **CP is also violated** (indirectly e.g. in kaon oscillation, and directly in some particle decay, e.g. kaon decay) -- indirect CP violation observed in 1964, direct in the 1990s.
  - Indeed… the SM allows for CP to be broken (since it has 3 fermion generations), if a complex phase is introduced in the matrix describing quark (or lepton) mixing.
- **CP violation can be invoked to generate the matter-antimatter asymmetry** observed in the universe (Sakharov's conditions)
  - But CP violation in the quark sector of the SM is minimal… not enough to explain the observed asymmetry[**]… CPV elsewhere?

xkcd

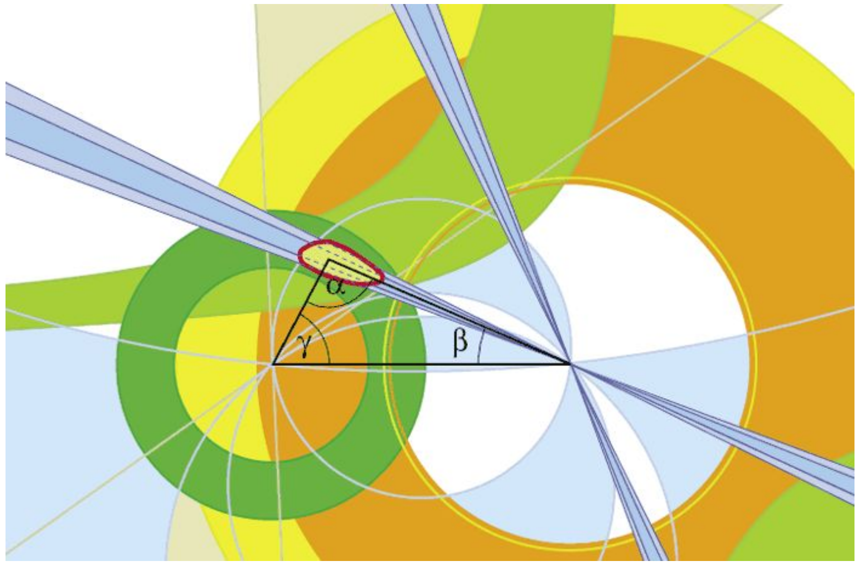


IT TOOK SOME NEGOTIATING, BUT I'VE FINALLY BECOME THE FIRST PERSON TO COAUTHOR A PAPER WITH BLOODY MARY.

[*] however, very strangely (no pun intended), nothing prevents P violation in QCD, but it is not observed.
[**] this is a problem only if we assume the initial condition that matter and antimatter were initially produced in equal quantities…

Two famous 3x3 matrices

- The **<u>CKM matrix</u>** parametrizes the strength of the flavor changing weak interactions in the quark sector:
  - some hadronic decays are more favored than others
  - CP violation: complex phase
- 4 independent parameters fully define the CKM matrix (no known reasons in the SM for their particular values)
- Measurements at colliders (b-factories, hadron colliders) allow to constrain these parameters, test CKM's unitarity

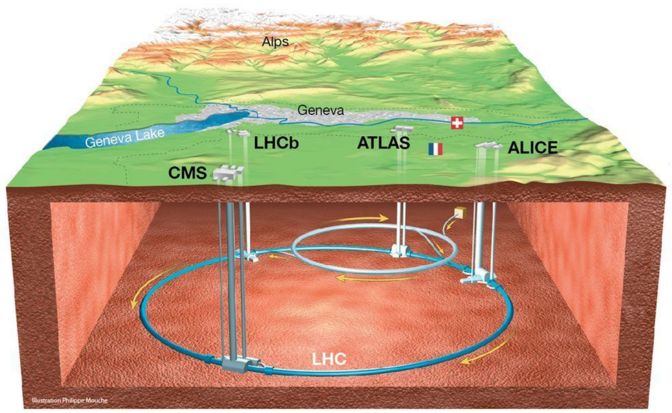


unitarity triangle

- The **<u>PMNS matrix</u>** is the leptonic equivalent of CKM
  - Mass eigenstates (what propagates) ≠ weak flavor eigenstates (what interacts)
  - Neutrinos mix much slower than quarks (lower masses and travel very near the speed of light)
    - (Long range) flavour oscillations can be observed → imply neutrino masses (hierarchy between the 3 masses unknown)
  - **CP violation in the lepton sector** → will be measured at HK and DUNE

$$P_{\nu_\alpha \to \nu_\beta}(t) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2$$
$$= \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\frac{\Delta m^2_{ij} L}{4E})$$
$$+ 2 \sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin(\frac{\Delta m^2_{ij} L}{4E}),$$

The CERN LHC



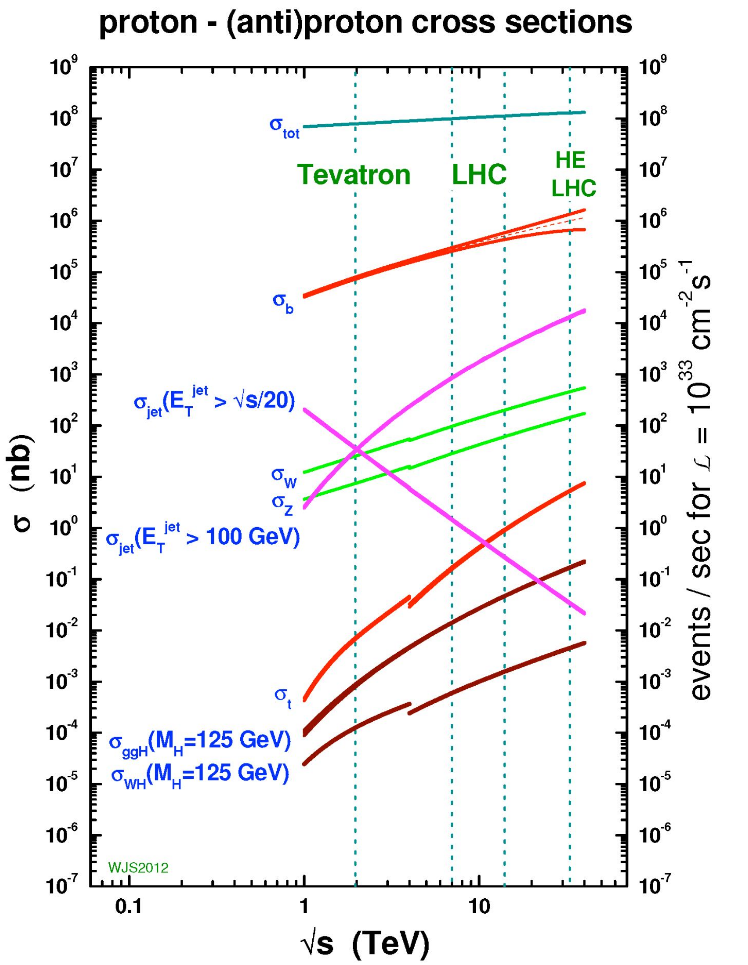
- In order to observe rare processes / new physics, need to maximize

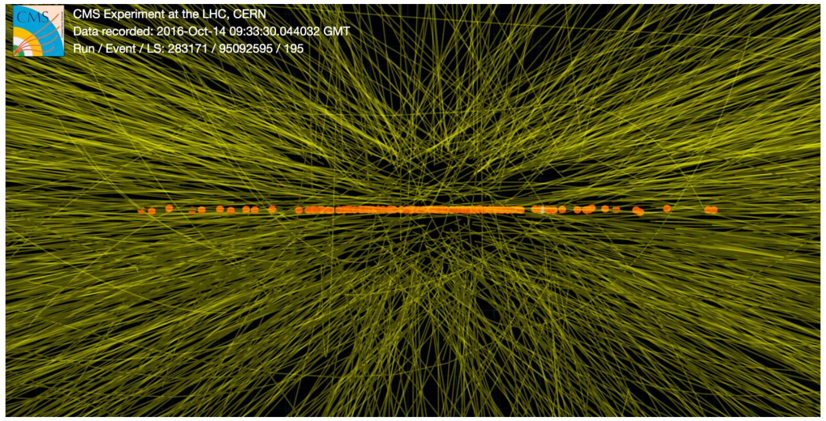
$$N = \sigma \, . \, \mathcal{L}$$

  - N = number of events collected for a given process
  - σ = cross section of that given process
  - $\mathcal{L}$ = integrated luminosity (proportional to the number of collisions performed)

- The LHC (ring ~ 27 km) provides **proton-proton collisions**:
  - At energies up to **13.6 TeV** → higher energies provide higher cross sections for the production of rare processes
  - At unprecedented rates, with $\mathcal{L}_{inst} \sim 2 \times 10^{34}$ cm^{-2} . s^{-1}
    - Already integrated $\mathcal{L}$ ~ 150 fb^{-1}/experiment → 7.5 x 10^6 Higgses produced / experiment

- Bunches of ~ 10^{11} protons **spaced 25 ns**
- The price of high luminosity is therefore that each bunch crossing leads on average to tens of collisions that create physical noise in the detector → the interesting collision needs to be recognized and measured in this **pileup** environment





LHC also provides Heavy Ion collisions for QGP studies

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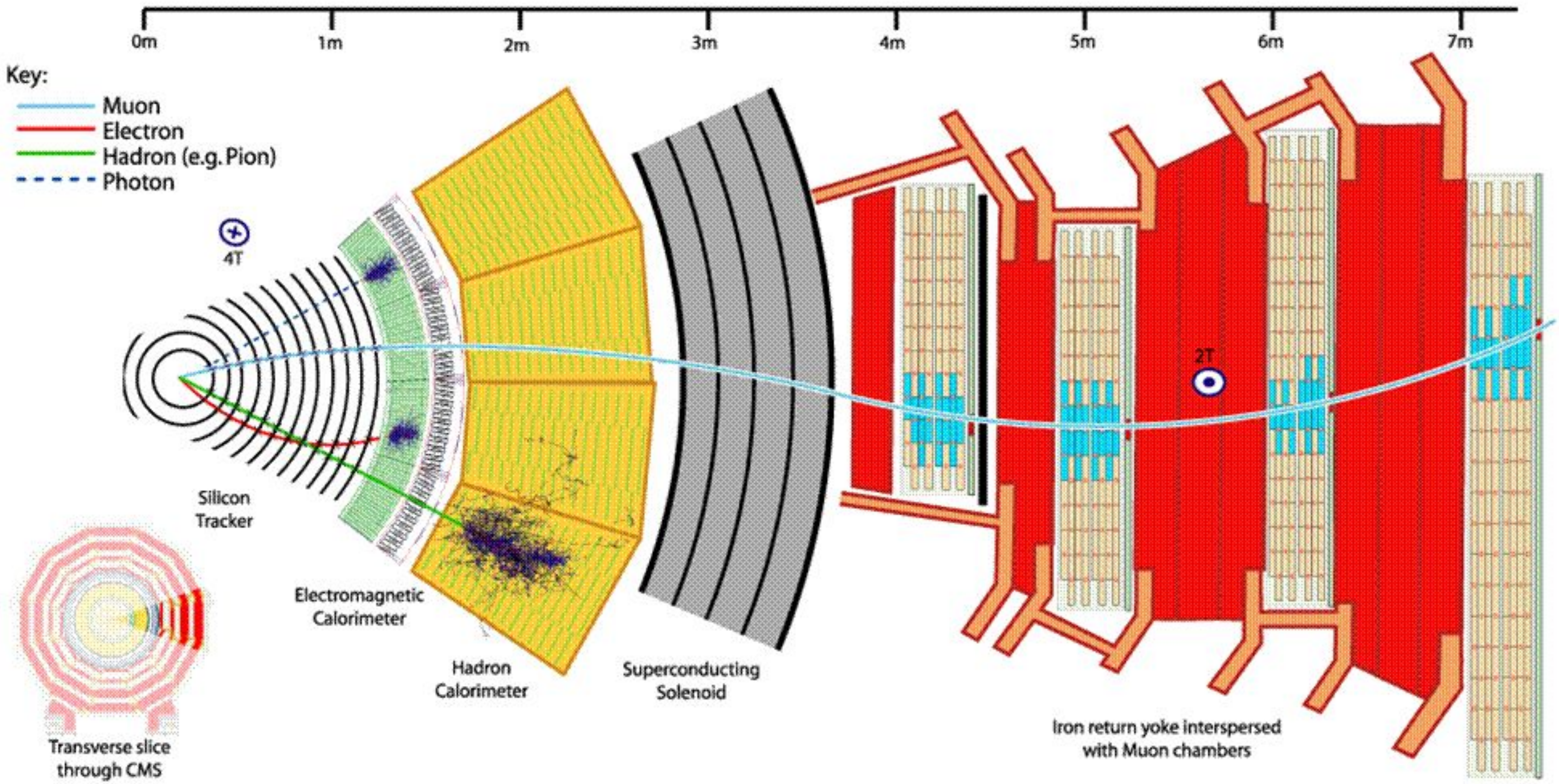
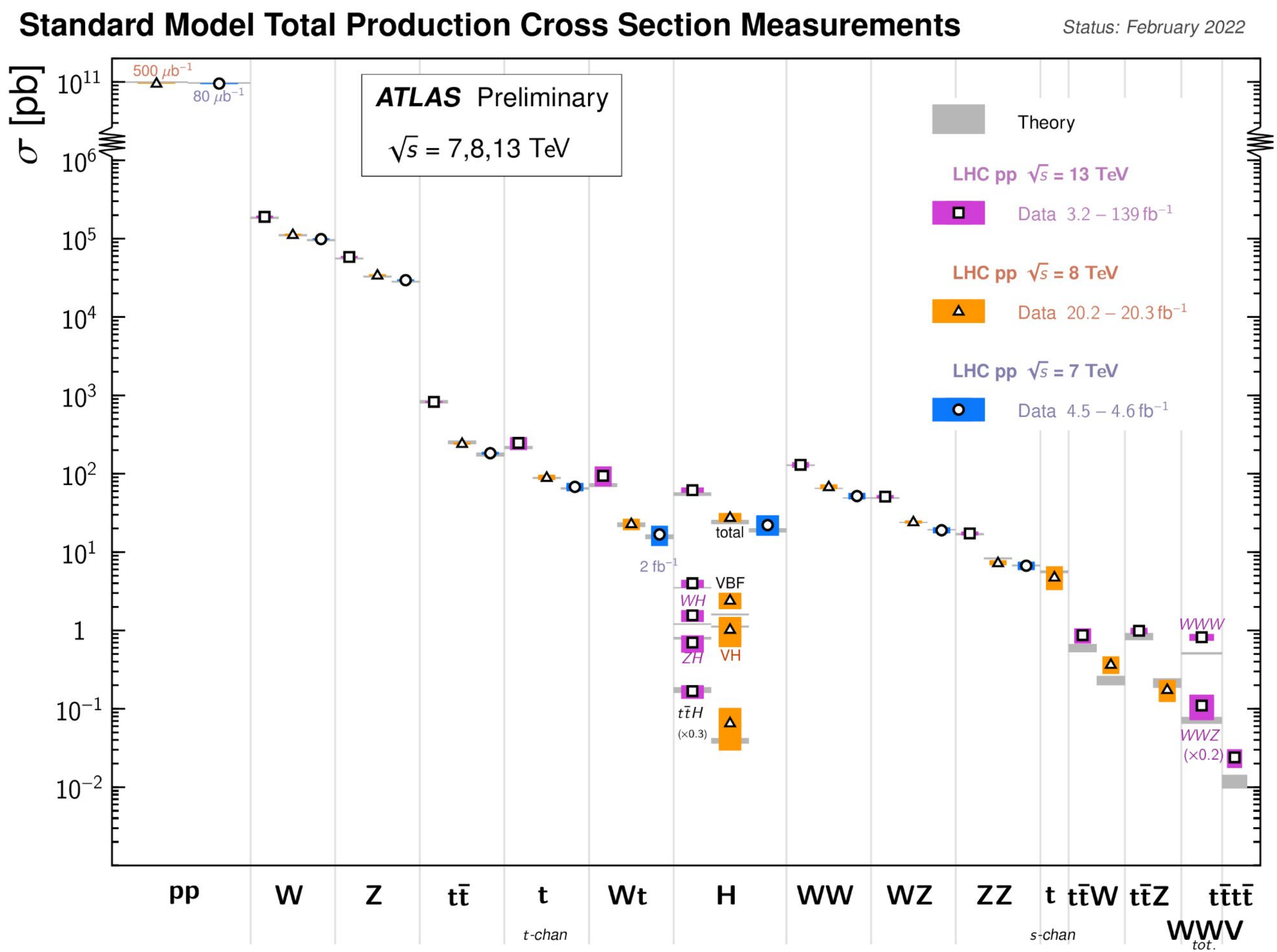
Detecting particles @ the LHC





Standard Model Total Production Cross Section Measurements
Status: February 2022
ATLAS Preliminary
√s = 7,8,13 TeV
σ [pb]
Theory
LHC pp √s = 13 TeV
Data 3.2 – 139 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 7 TeV
Data 4.5 – 4.6 fb⁻¹
500 μb⁻¹
80 μb⁻¹
2 fb⁻¹
total
VBF
WH
ZH
VH
tt̄H
(×0.3)
WWW
WWZ
(×0.2)
pp
W
Z
tt̄
t
t-chan
Wt
H
WW
WZ
ZZ
t
s-chan
tt̄W
tt̄Z
tt̄tt̄
WWV
tot.

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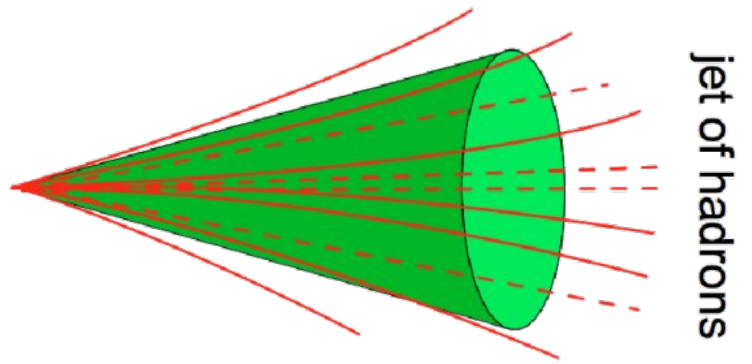
Track, jet and τ_h reconstruction at the LHC

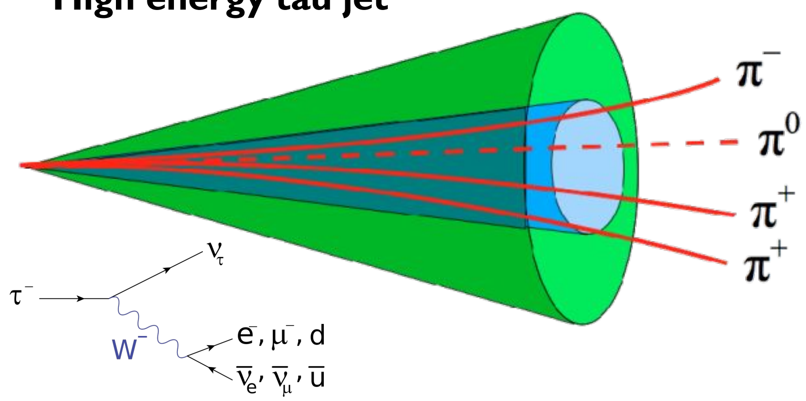
The LHC is a gluon/quark collider, so it's only fair that most of the outgoing particles produced there will be gluons/quarks

- These colored particles are never observed experimentally (color confinement), so they hadronize into (a large collection of) color-neutral particles → **<u>that is what is called a jet</u>**
- Charged components of jets leave tracks in the tracker
- Jet *shower* in the calorimeters
- Hadronically decaying τ_h (τ = only lepton which can decay into hadrons) lead to a similar signature, but much less busy

High energy quark-gluon induced jet



High energy tau jet

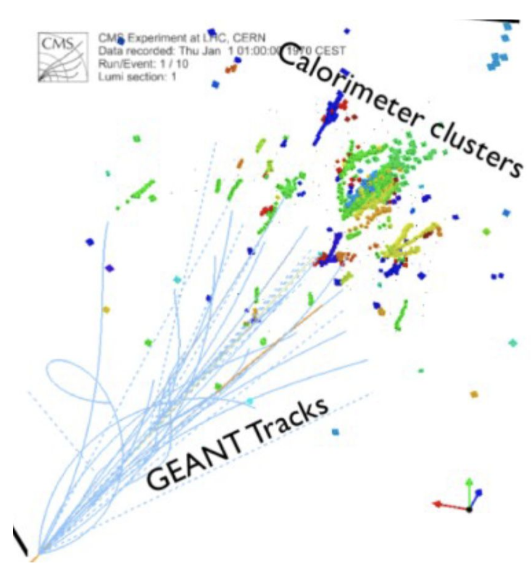


Challenges with tracks / jets / τ_h:

- Tracking → see Fotis Giasemis's and Jeremy Couthures's talks
- Triggering: select the correct objects online
- Reconstruction: building the object from tracks & calo deposits
- Calibration: measure correct energy
- Identification: identify particle type w.r.t. other types, reject fakes

(Triggering and Reconstruction:) see Isaac Ehle's talk

(Reconstruction, Calibration and Identification:) see Line Delagrange's, Laura Sara Boggia's talks (about jets) and Océane Poncet's talk (about τ_h)

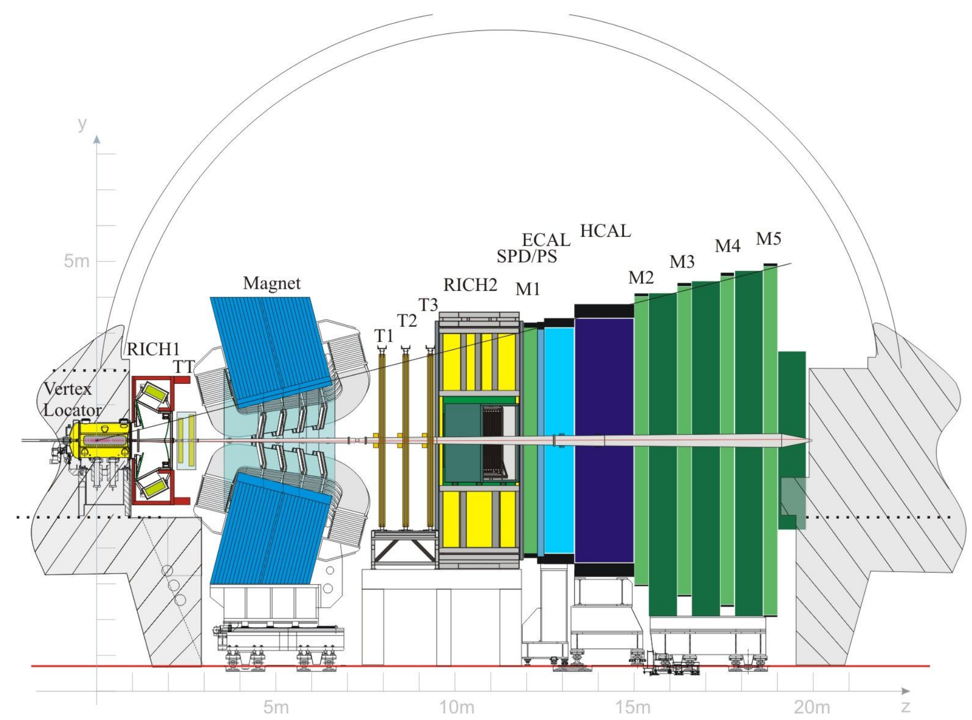


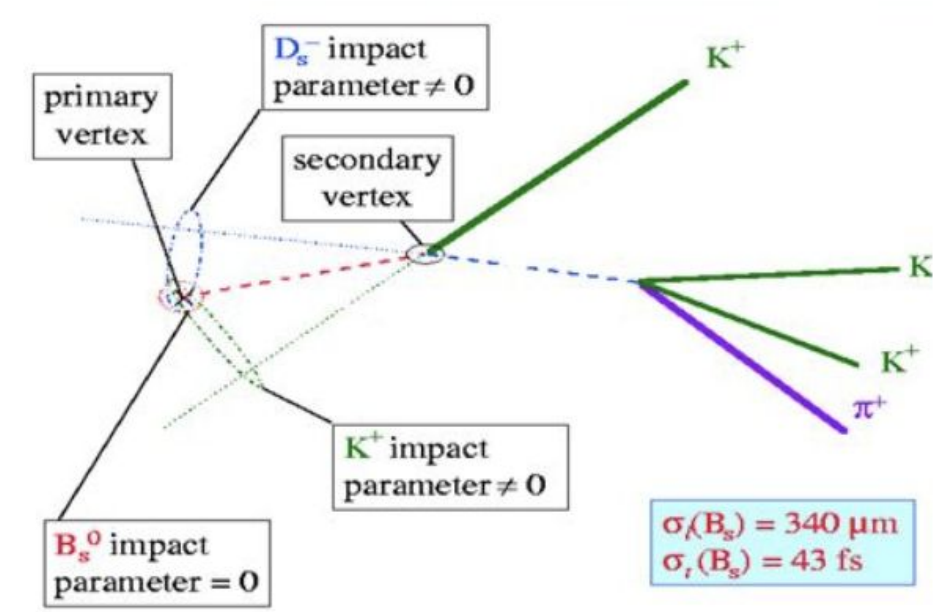
LHCb

- **<u>LHCb</u>**: experiment dedicated to the study of the beauty physics (and also charm physics)
  - Take advantage of the copious production rate of b's at the LHC to explore the rarest processes possible

- LHCb is a single arm spectrometer, covering the high pseudorapidity range $2 < \eta < 5$ (the direction closer to the beam)
  - At the LHC, particles are produced preferably with a direction close to the beam

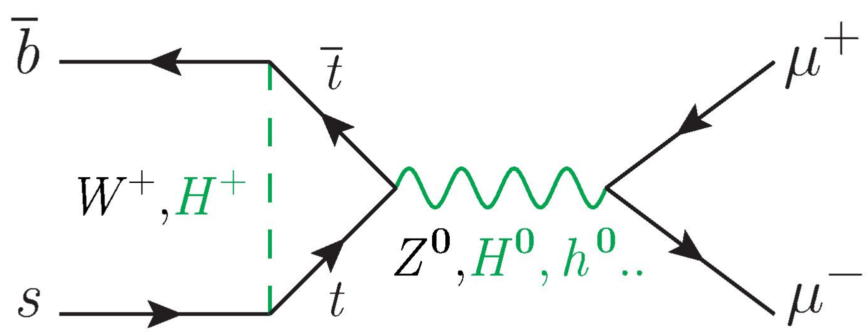
- Reduce the number of interactions per bunch crossing to O(1) in LHCb by splitting the two beams apart from each other
  - Considerably facilitates the reconstruction of the vertex structure which is very important in the study of b decays

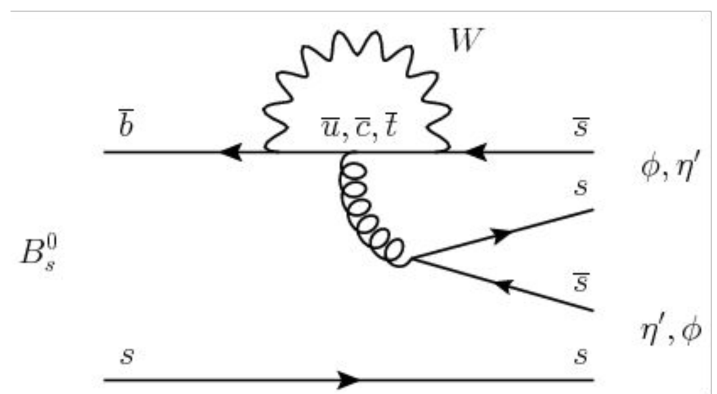


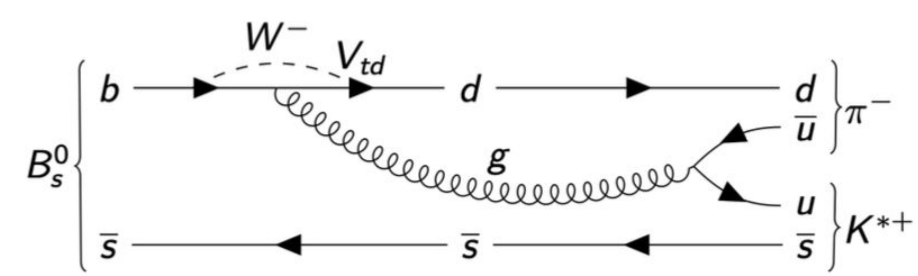


b physics @ LHCb

- Look for the effect of new physics through deviations w.r.t. SM in low energy processes! $A = c_{SM} + 1/\Lambda^2\, c_{NP}$ (where Λ is the scale of New Physics)
  - At LHCb, processes involving b quarks (e.g. b hadron decays, radiative effects, b mixing)
  - Very powerful idea that substantially increases the discovery reach, given a fixed collision energy: use precision of measurements as leverage
  - Need precise channels, ideally clean from backgrounds, and to measure them very accurately
    - Example: radiative decays: see Tristan Miralles' talk

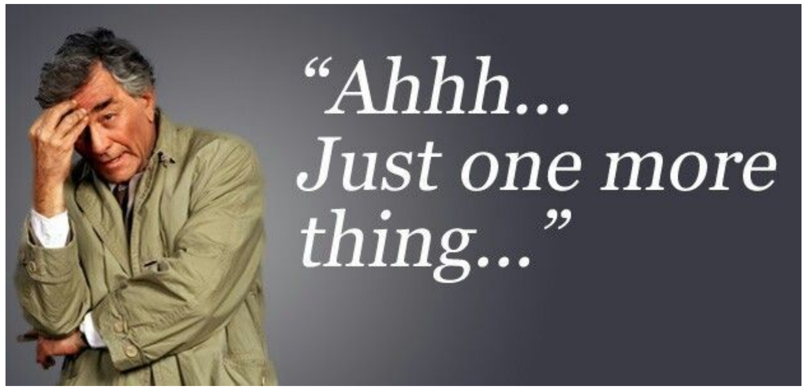






- LHCb tests some key features of the SM
  - CKM / CP violation: see Jessy Daniel's talk
  - Lepton flavour universality: see Bogdan Kutsenko's talk

Problems with the SM (1/2)



- **The SM is a fantastic tool… but is has a few problems…**

1. **<u>The hierarchy problem</u>:**
   - Why is the weak interaction 24 orders of magnitude stronger than gravity?
   - Higgs mass not protected by symmetry… so why is the Higgs mass so light, when radiative quadratic corrections should have a large effect? Fine tuning?

2. **<u>Cosmological constant problem</u>**
   - The quantum vacuum energy contribution to the effective cosmological constant is 50 to 120 orders of magnitude greater than observed (!!!) ("the largest discrepancy between theory and experiment in all of science")

3. **<u>Maths</u>**
   - Self consistency of the SM is not well established mathematically
   - 1 M$ prize if you manage to make progress with it (I'm not the one paying)

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Problems with the SM (2/2)

3. **Neutrino masses**
   - In the classical SM, neutrinos are still massless after the introduction of Higgs
     - Because sterile neutrinos are an inconvenience to some people
   - There are mechanisms (with minimal modifications to the SM or not) available to accommodate these masses

4. Other cosmological-related issues
   - **Dark Matter:** the SM does not naturally provide a DM candidate
   - **CP violation:** the amount of CP violation provided by the SM through CKM and PMNS is not enough to explain the fact we only see matter in the Universe
   - **Inflation**: observations of the isotropy and homogeneity of the early universe, as seen in the CMB, seem to indicate that there was a phase of extremely fast cosmological inflation… SM does not seem to be easily able to provide the field that would be responsible for that.

→ Keep making measurements and theoretical progress so that the SM can either be extended or be replaced by something greater!

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Conclusions

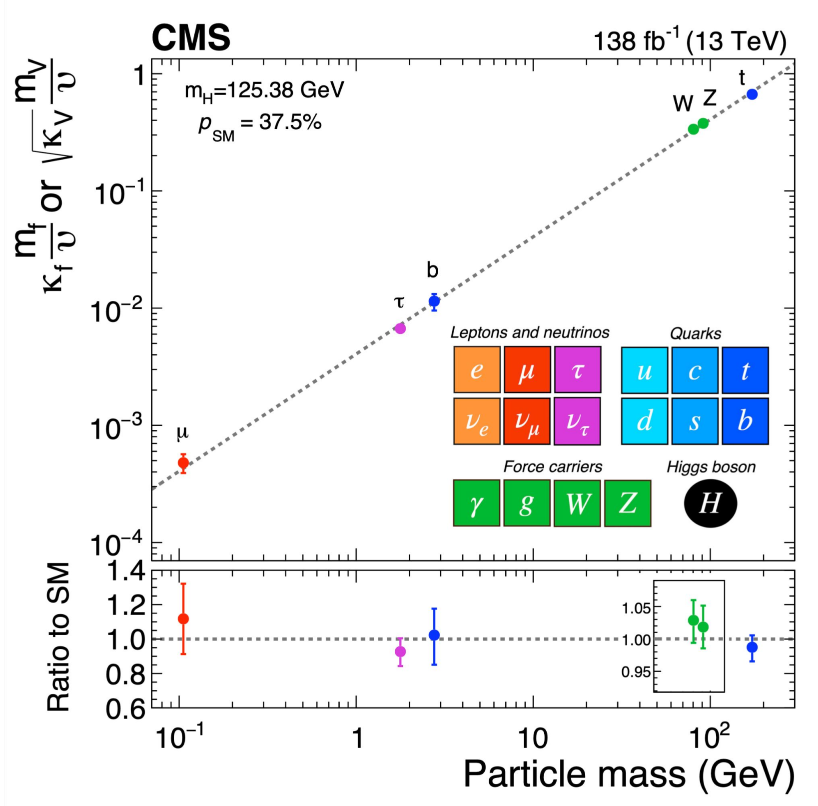
- **The Standard Model is a pillar of modern Science**
  - The culmination of decades of work and discoveries by experimentalists and theorists alike
- **… a good model should be easily tested (yes, I'm looking at you, String Theory)**
  - "Science is the lab bench" as my mentor would say
  - In this session, you will see examples of such tests at LHCb, ATLAS, CMS
  - And preparations for future experiments, including LHC upgrades and FCC
- **The Standard Model has many problems**
  - Some might be serious, some might not be…
  - … but it seems unavoidable that the SM will be seriously challenged by experiments one day or another

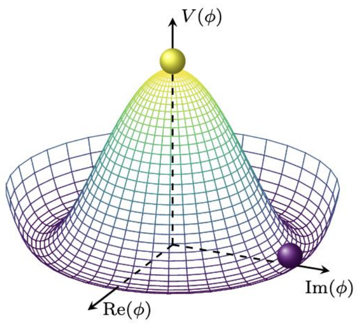
Backup

Higgs properties @ ATLAS & CMS

After the 2012 discovery started an **intensive program to measure the Higgs boson properties**

- **Mass** now known to better than 0.1%:
  - CMS = 125.38 ± 0.14 GeV
  - ATLAS = 125.09 ± 0.21 (stat) ± 0.11 (syst) GeV
- **Spin/parity**: alternative J^P possibilities ruled out at > 99% C.L.
  - Small even-odd mixing still possible
- **Width**: constrained using ratio of off-shell to on-shell Higgs production in H→ZZ→4l
  - Not entirely model independent
  - Invisible width constrained to < 15%
- **Coupling strengths to SM particles**: measured to be compatible with SM prediction, within current uncertainties
  - Coupling to second generation fermions still underway
- Differential measurement of **Higgs cross sections**
  - Performed in the context of Simplified Template Cross Section framework (STXS)
- **Higgs self-coupling**
  - Constraints exist from HH production





$$V(\phi) = -\mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2$$

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