Introduction session
Beyond the Standard Model

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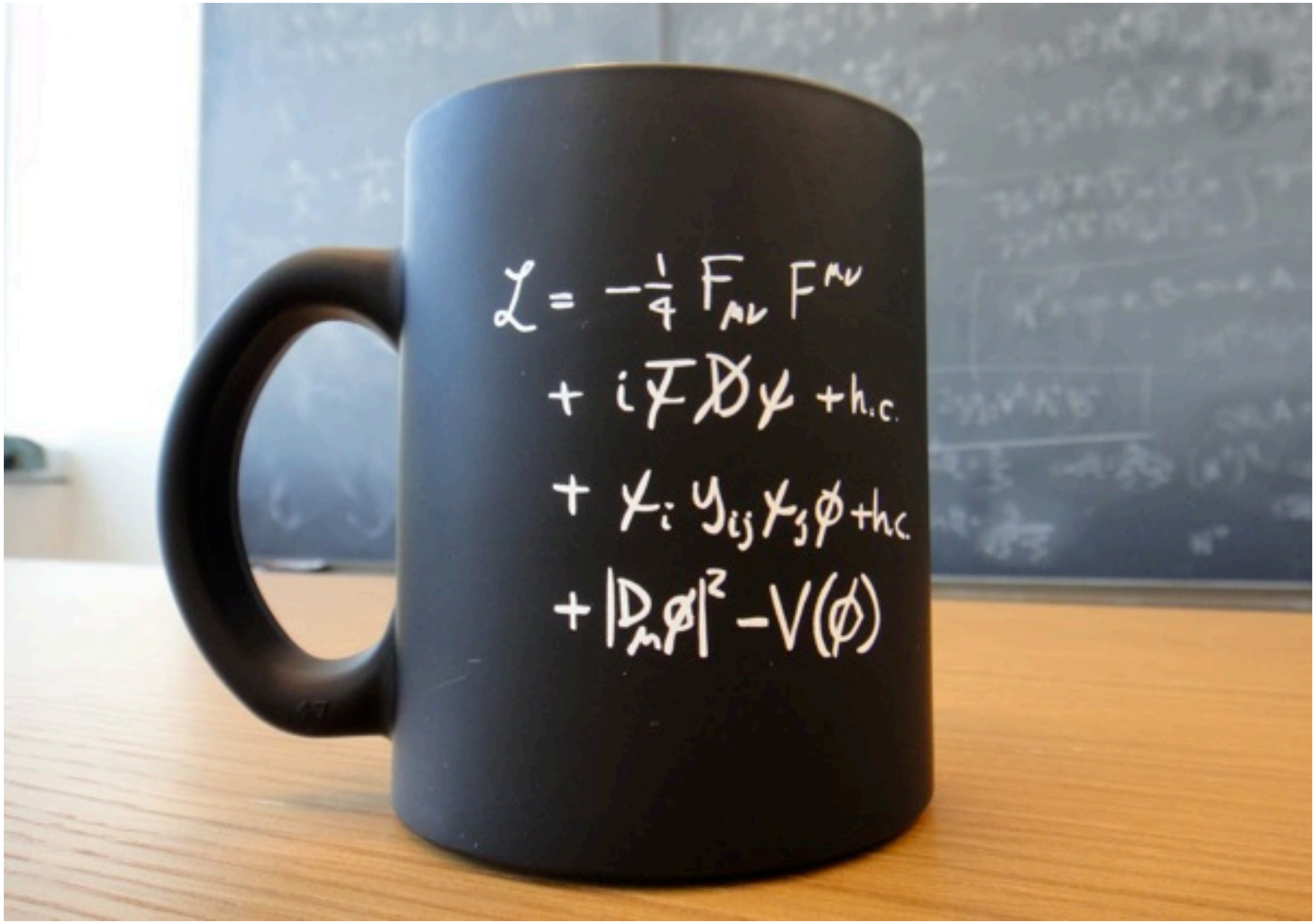
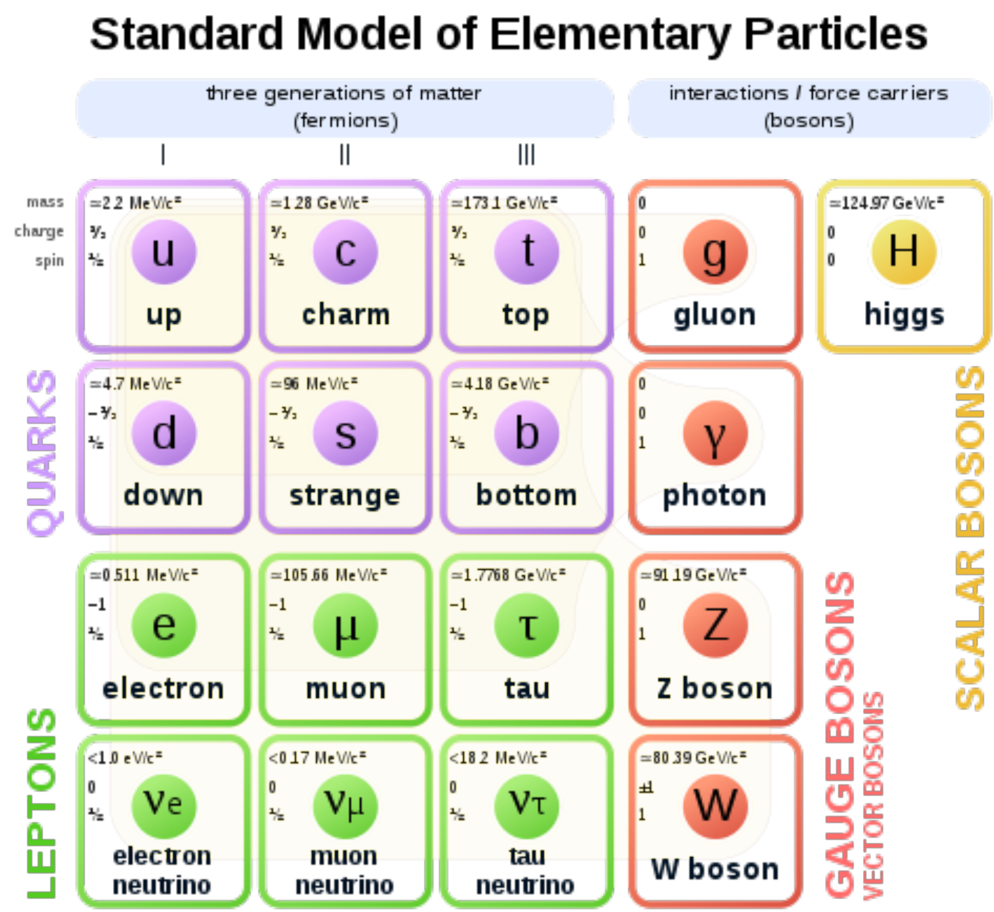
- **Not just a formula on a mug…**



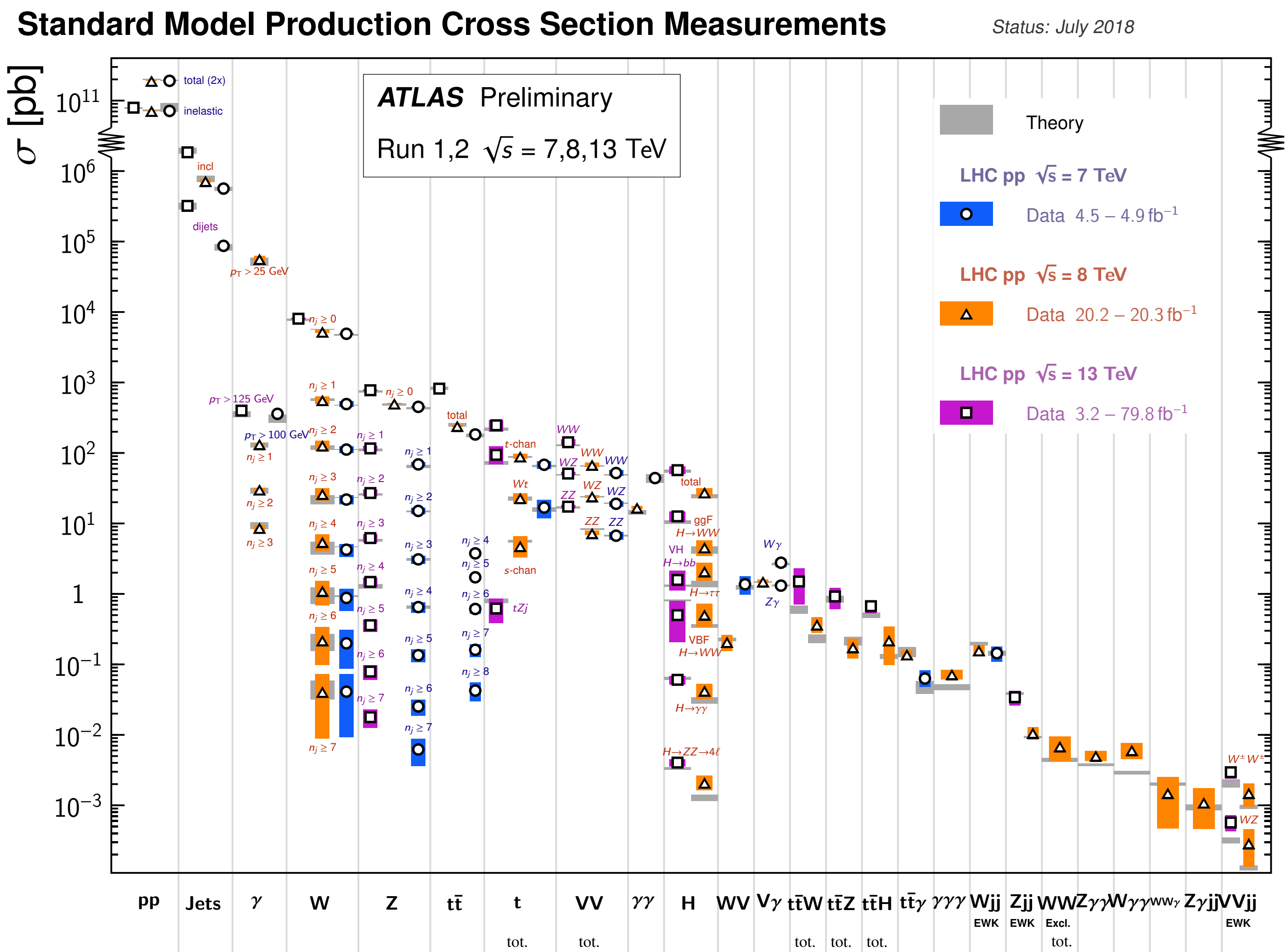
The Standard Model success story

- **A** **complete theory** **to describe** **elementary particles** **and their** **interactions:**
  - **fermions**: three families with matter + antimatter, left/right components with different interactions
  - **gauge bosons**: carry interaction, associated with symmetry group
  - Higgs boson: (only) scalar particle, associated with mass generation mechanism through symmetry breaking



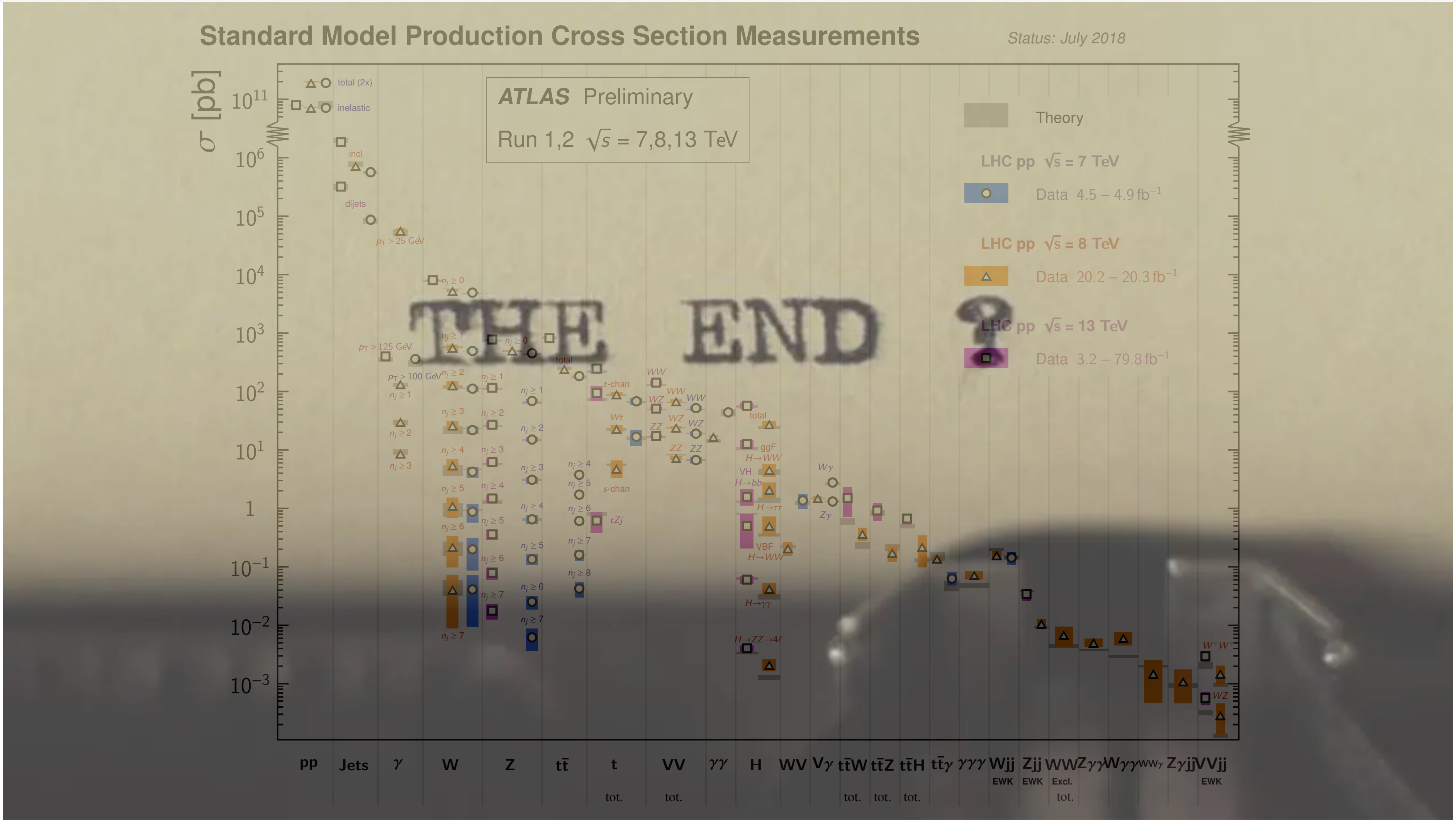
- **Can be used to** **predict any process** after a finite set of measurements to determine 25 parameters (renormalizable theory)

The Standard Model success story



- **Ever-growing set of measurements at LHC consistent with SM:** over wide range of energies, final states…

The Standard Model success story

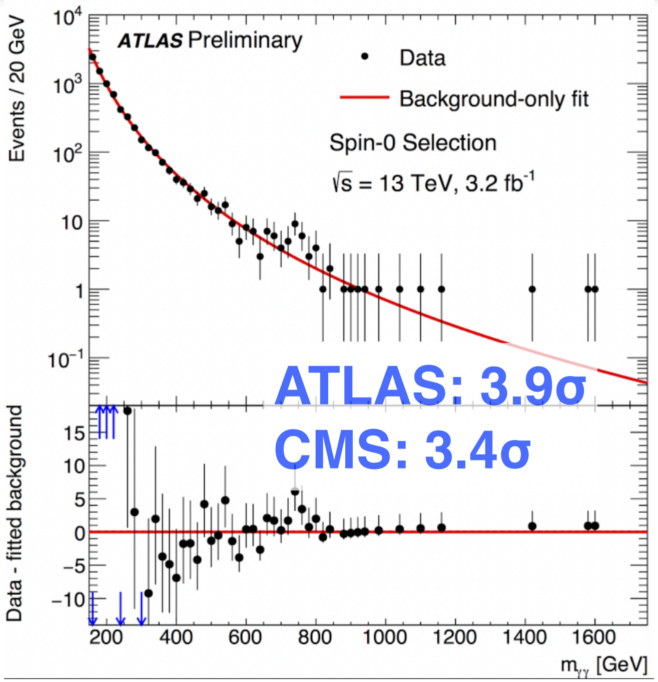


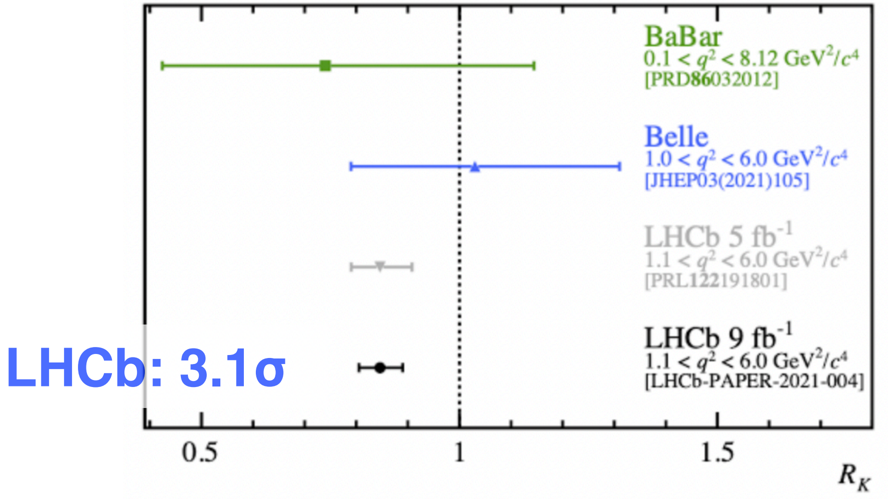
- **Ever-growing set of measurements at LHC consistent with SM:**
  over wide range of energies, final states…

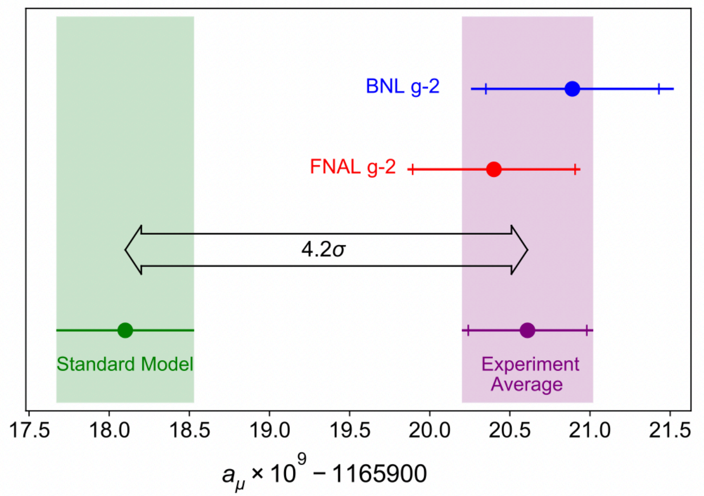
Some experimental tensions

- Several results available in the last years with **measurements inconsistent with SM prediction**
- **Possible causes:**
  - statistical fluctuations
  - flawed SM predictions
  - experimental biases
  - **new physics**

  => often source of a bunch of arXiv theory papers following public results



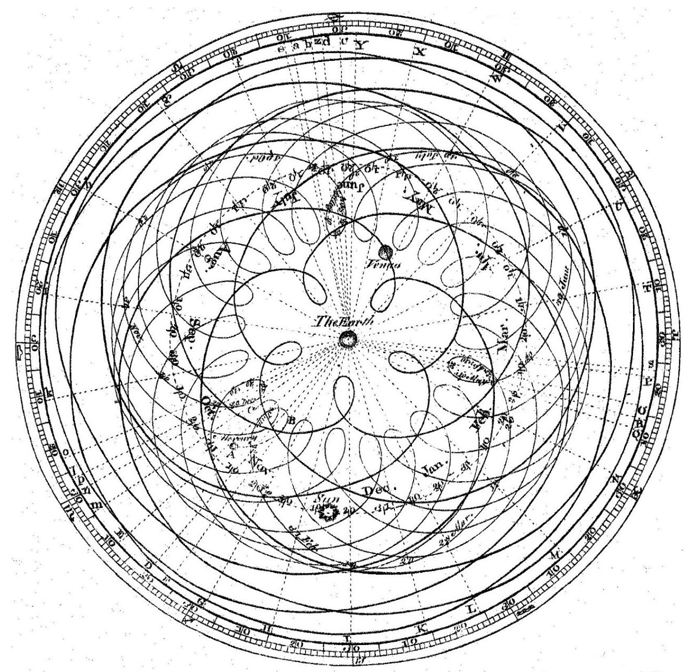


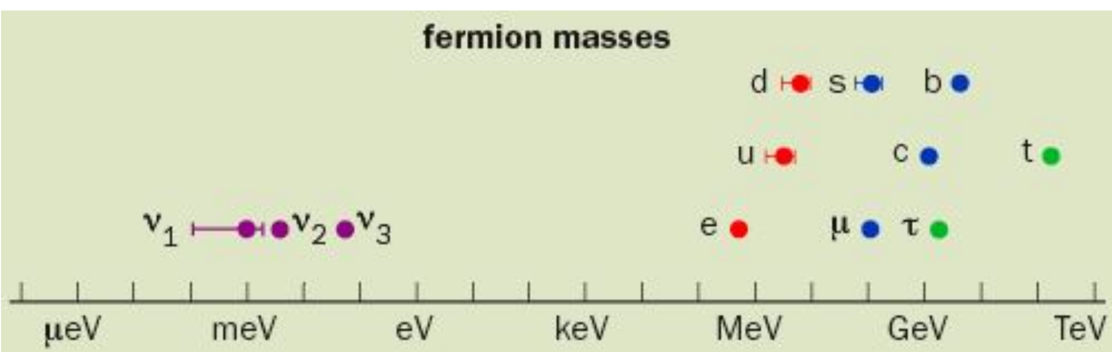


The Standard Model flaws

- **Still need 25 parameters** (assuming massive Dirac neutrinos): **is SM the new epicycle?**

- **Many unanswered fundamental questions:**
  - why three families of fermions?
  - any lepton/quark connection?
  - why the CP asymmetry? why none in QCD?
  - why the SU(3)xSU(2)xU(1) gauge symmetry?
  - are neutrinos Dirac or Majorana?
  - why such a large mass hierarchy?



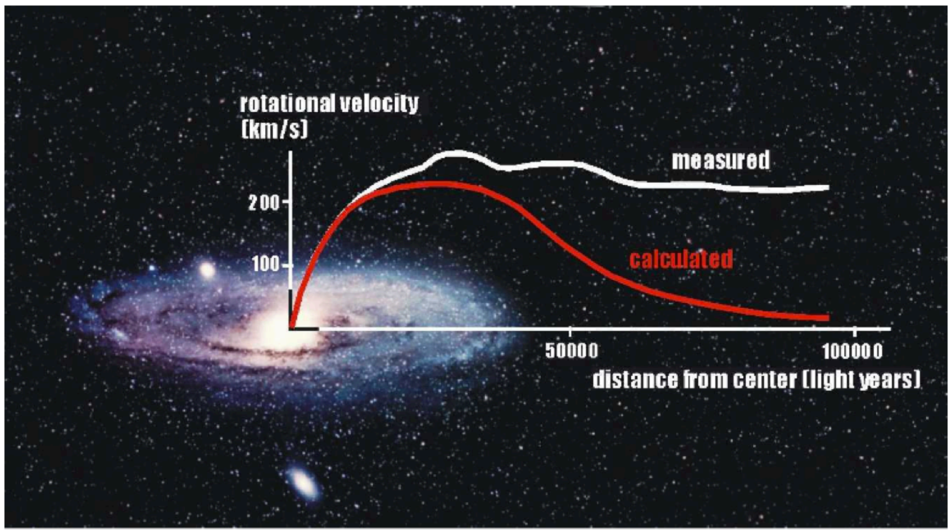


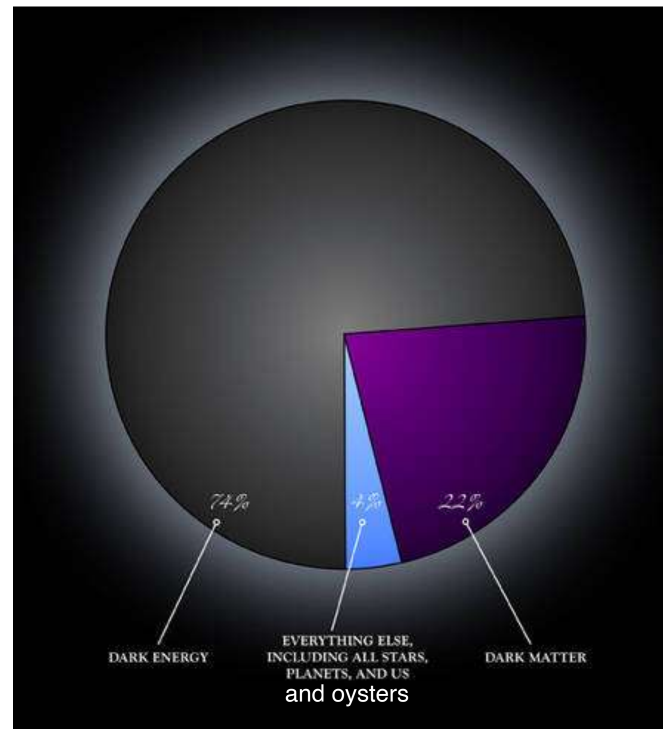
- **Many BSM models on the market to try to address those questions**

Standard Model and gravitation

- **Gravitation not described within SM** (nor in any QFT derived from it): Einstein's equations not renormalizable

- **Several experimental evidences of dark matter** (which does not interact through strong or EM interaction): **new BSM particle? interactions with SM particles?**



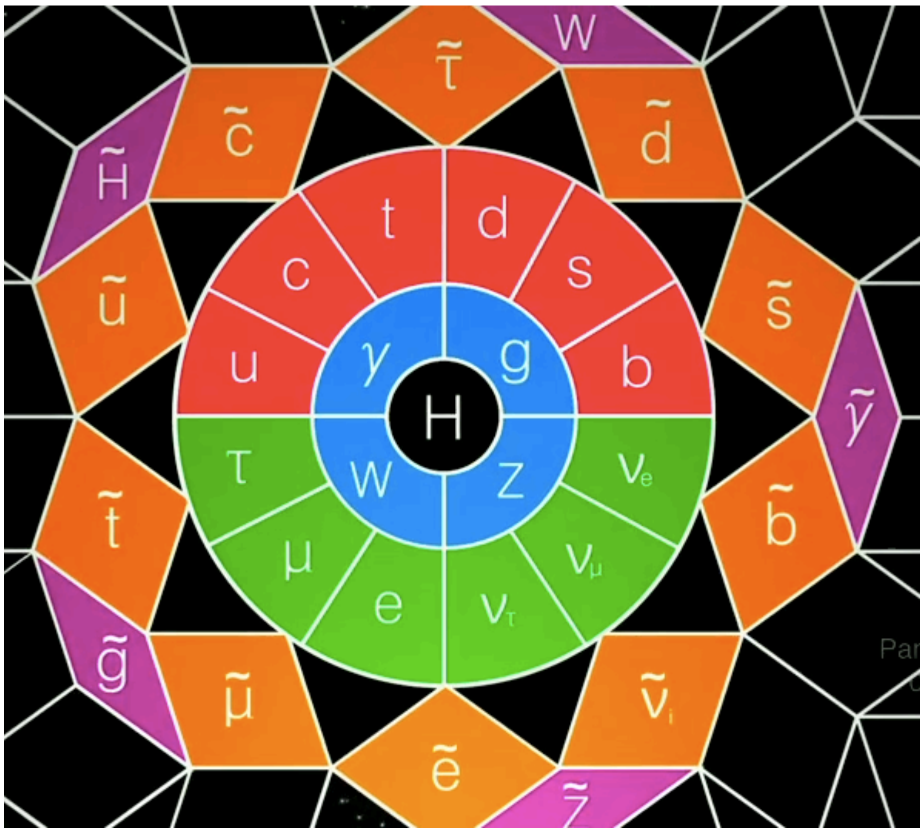


- **Dark energy** (= cosmological constant) **not embedded in SM either:** link with Higgs vev?

BSM models

- **Broadly two kinds of approaches for possible BSM studies**

- **Model-dependent approach:** try to start from a complete theory, which embeds the SM + addresses some SM flaws or unanswered questions



- **Example of supersymmetry:**
  - SM + extended particle content
  - potential DM candidate
  - solves naturalness problem (= unnatural fine-tuning in Higgs mass quantum corrections)

- **Needs to make sure that existing measurements do not contradict model predictions:** non-observation of proton decay or flavor-changing neutral currents

BSM as an Effective Field Theory

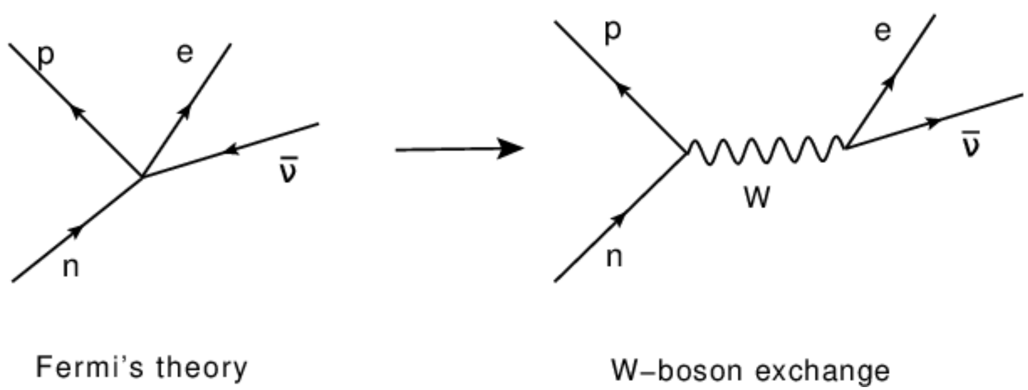
- **Model-independent approach:** treats the SM as a low-energy Effective Field Theory (EFT) of some unknown UV-complete theory

- **Study SM-scale low-energy perturbations introduced by new operators** with a generic parametrised Lagrangian

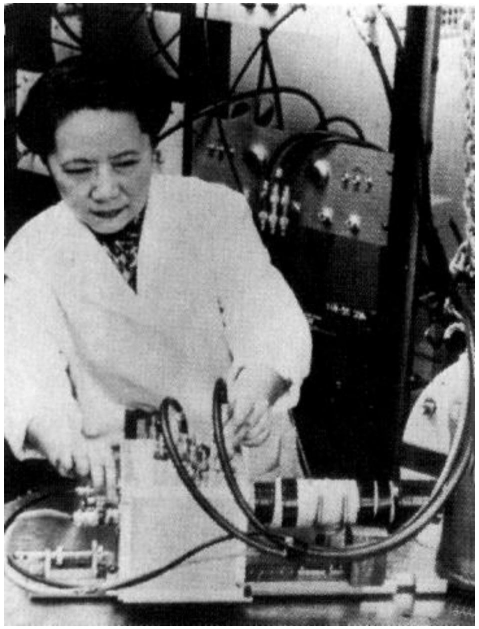
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\sum_i c_i^{(5)} \mathcal{O}_i^{D=5} + \frac{1}{\Lambda^2}\sum_i c_i^{(6)} \mathcal{O}^{D=6} + \dots$$

- **1 d=5 operator** (= Majorana's neutrinos) **+ 2499 d=6 operators!**
  Not all of them respect SM accidental symmetries (B-L conservation, lepton flavour universality…) => assumptions sometimes made to restrict numbers of operators by imposing some symmetries

- **Treatment valid as long as energy-scale of processes ≪ Λ = scale of new physics:** see Fermi's theory example

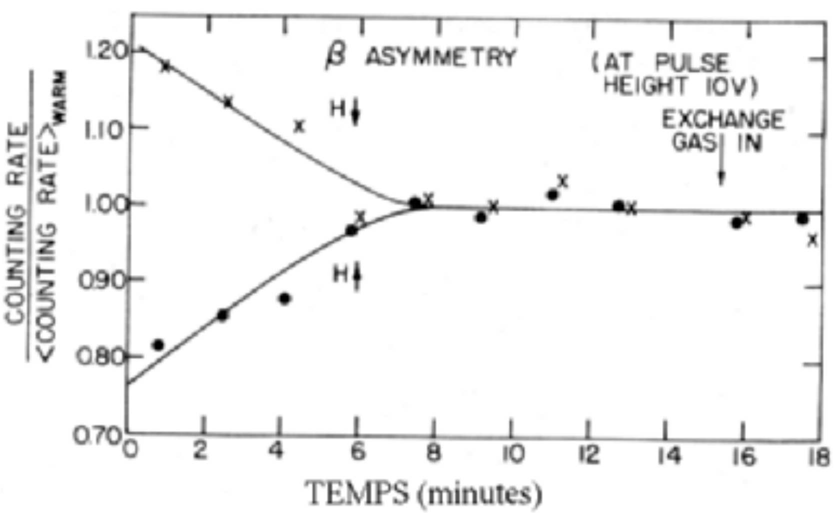


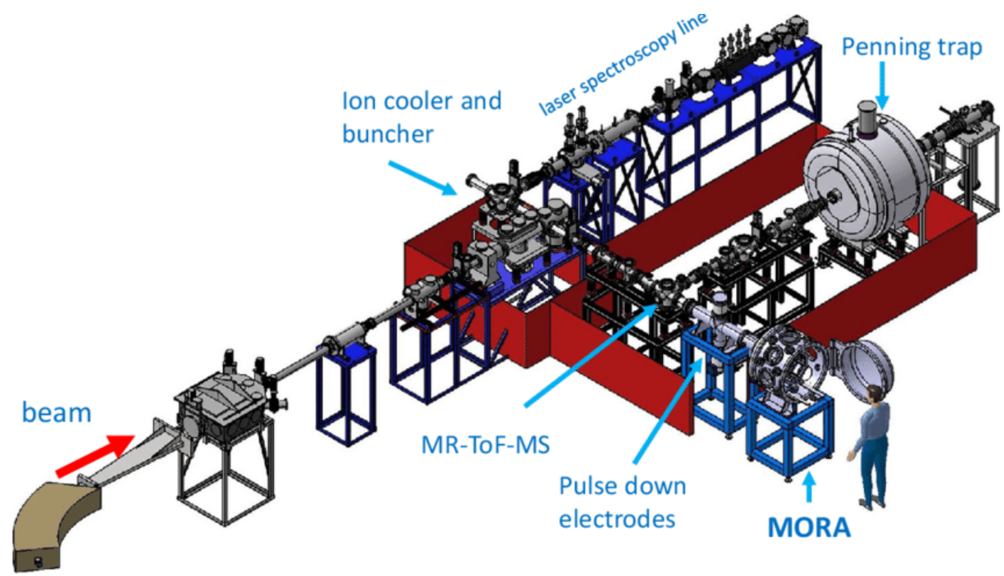
BSM search in low-energy observables



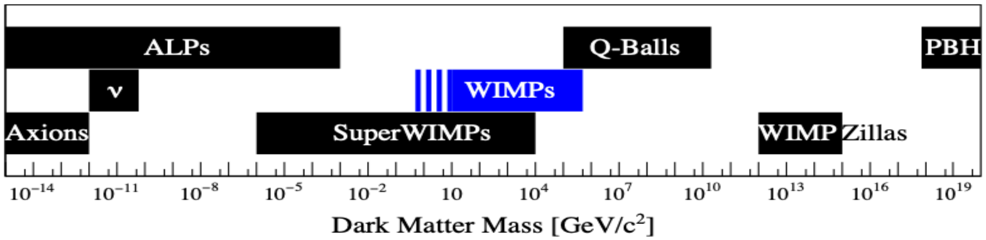
- **Many BSM theories exist and of course no single experiment can probe them all**
- **Some low-energy observables sometimes more sensitive to new physics that measurements at the energy frontier:** following Co60 Wu's experiment, precise measurements of β spectrum can be sensitive to new physics

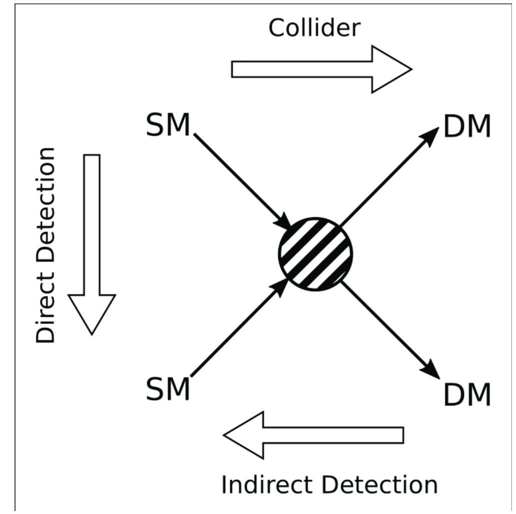
see Mohamad's and Sasha's talk



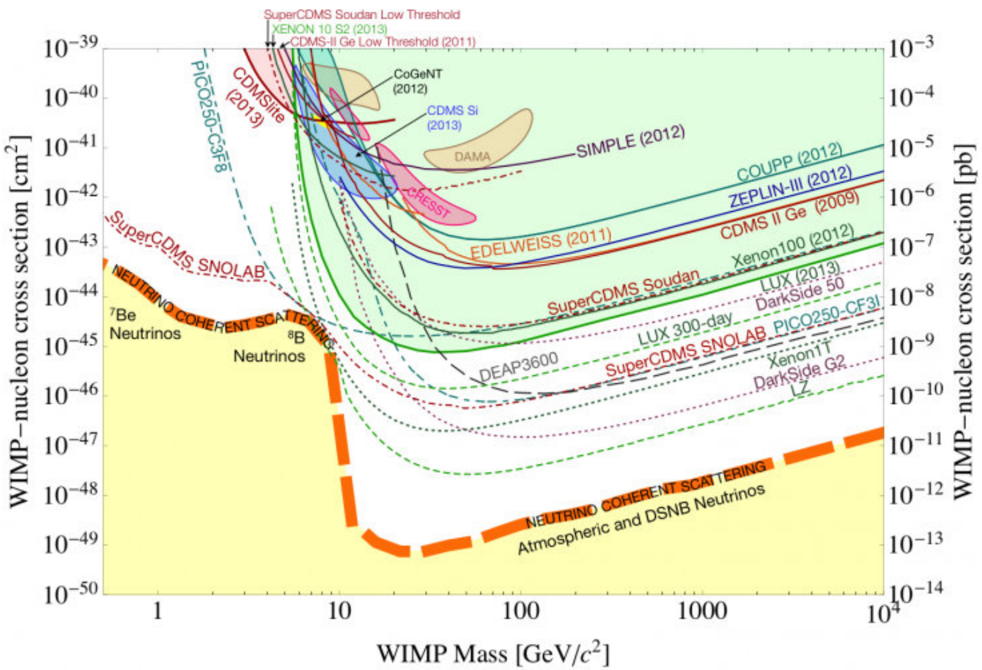


Dark matter searches





- **Several models predict for dark matter candidates** with different properties: sterile neutrinos, axions, weakly interactive massive particles (WIMPs)…



- **Different ways to detect dark matter particles**

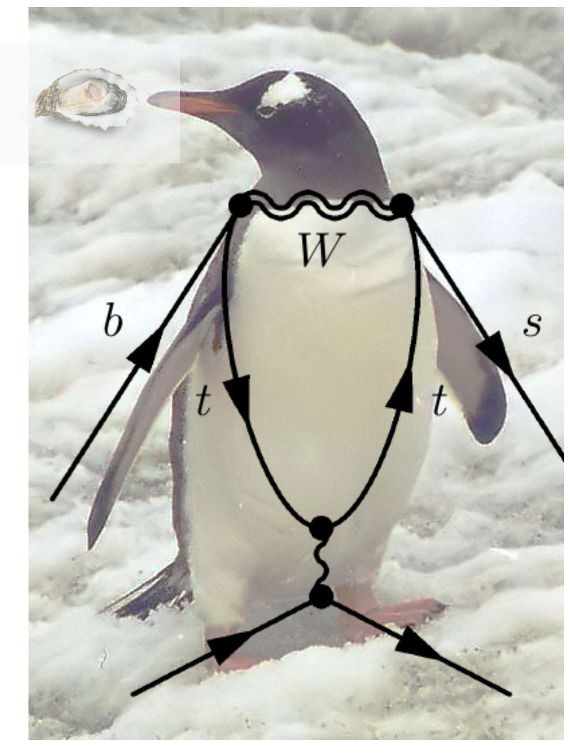
- **Several generations of detectors with increased sensitivity to WIMPs:** exploit nuclear recoil from DM interaction, different technologies to probe different mass ranges

see Claudia's talk

BSM in colliders

- **Lepton or hadron colliders** have the advantage of a large spectrum of possible interactions: can produce **B hadrons with high luminosity**

- **B-factories at lepton colliders** (Belle-II at KEK) **or b-physics experiments at hadron colliders** (LHCb at LHC)



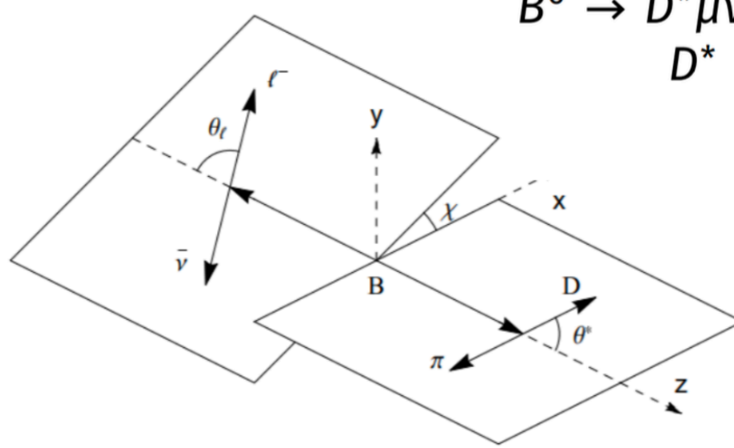
- **Probe new physics in loop diagrams:** particles too heavy to be directly observed can still impact decay rates or angular properties of decay products

see Vlad's talk

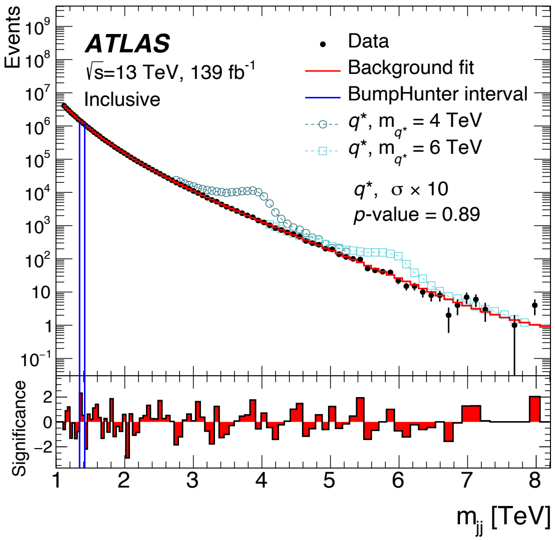
$B^0 \to D^* \mu \nu$

$D^* \to D^0 \pi_s$

$D^0 \to K\pi$

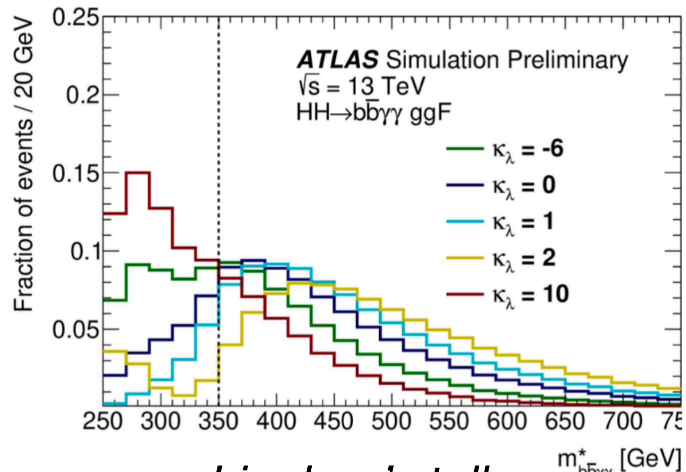


BSM in colliders

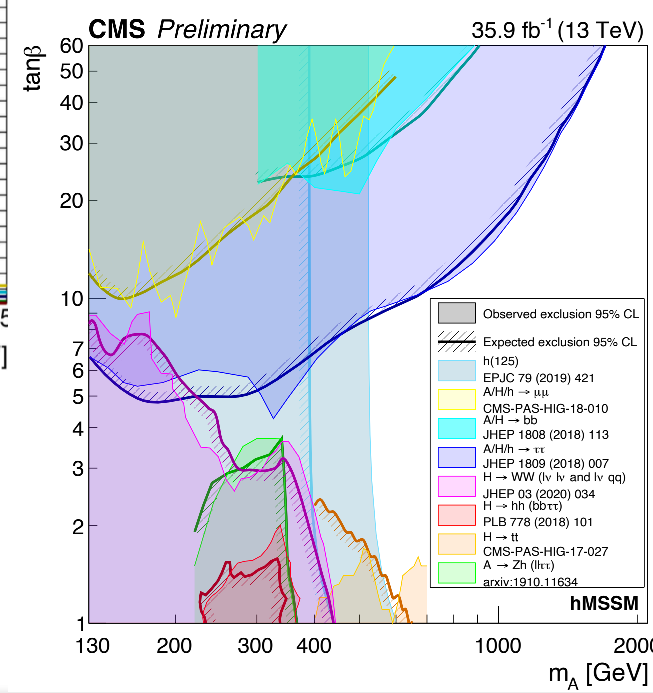


- **Lepton or hadron colliders** have the advantage of a large spectrum of possible interactions: can produce **heavy BSM resonances**

- **Interpretation more or less involved depending on number of free parameters in the model**

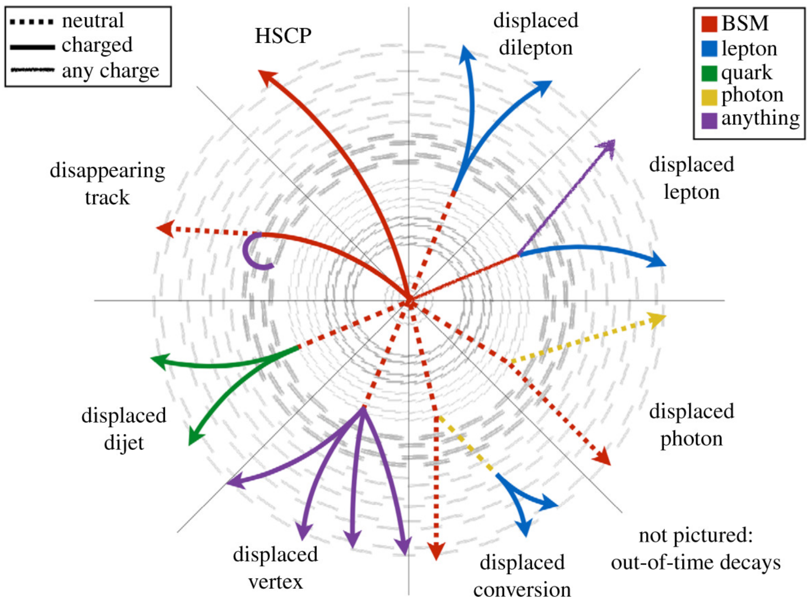


see Linghua's talk

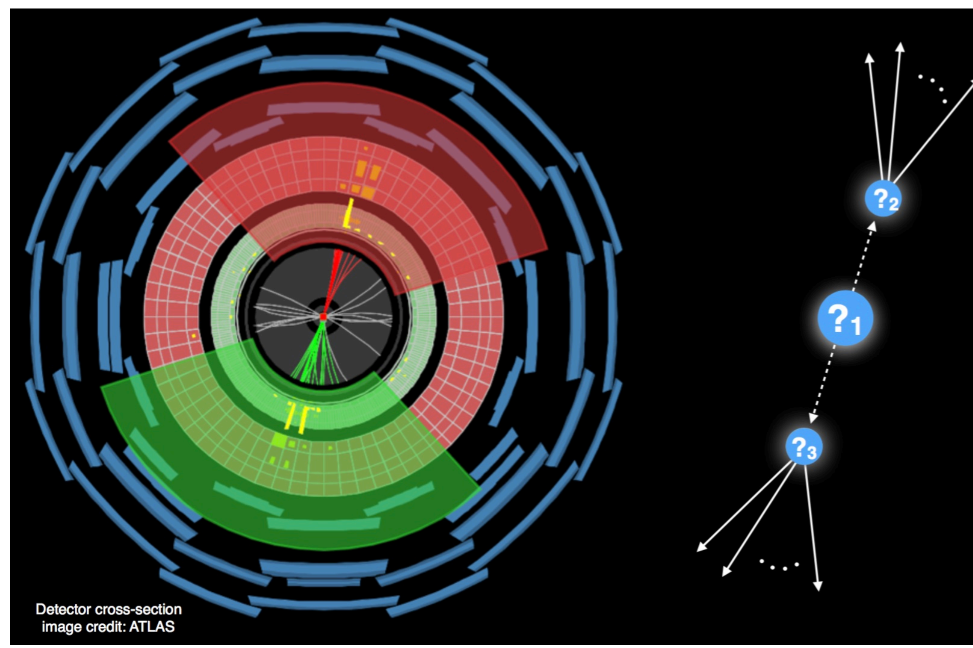


- **From search for a bump in mass spectrum,** with or without intermediate SM/BSM resonances, to more involved MVA analysis

BSM in colliders



- Given absence of clear evidence for BSM physics, LHC physicists have started to wonder if **we might have missed it just because we've been blind to it**
- **Alternative techniques** developed to compensate for **limitations of standard reconstruction techniques:** large radius tracking, ECAL timing, LLP-jet tagging…



- **What if we don't even have the proper model yet to describe new physics?**
  => development of anomaly detection using unsupervised Machine Learning

see Louis's talk

Conclusion

- We know that the **Standard Model is not the end of the story**

- **Several ways to describe physics Beyond the Standard Model:** complete models or SM as Effective Field Theory

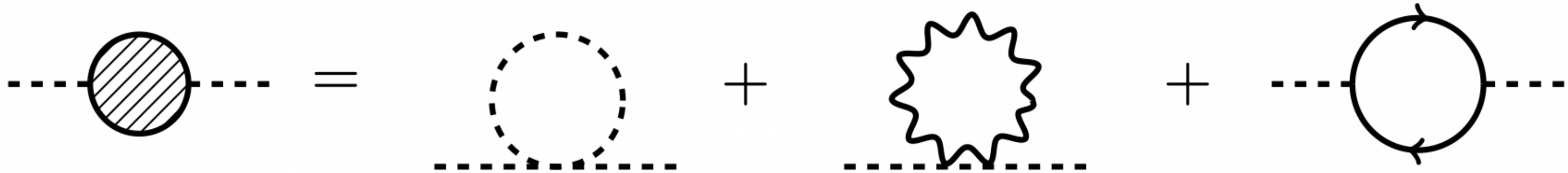
- **Many avenues to explore to try to put the Standard Model in default:**
  - low-energy observables
  - dark matter searches
  - intensity frontier
  - energy frontier
  - …

  => each of them would deserve an introduction of their own

- **No convincing experimental evidence yet but who knows:** sometimes just need the right idea and right experiment, **physics is your oyster!**

Back up

The naturalness problem



- **Higgs mass quantum corrections quadratically sensitive to cut-off scale** (= energy where SM breaks down, at most Planck scale)

$$\delta m_H^2 = \frac{\Lambda^2}{32\pi^2}\left[6\lambda + \frac{1}{4}\left(9g^2 + 3g'^2\right) - y_t^2\right]$$

$$\delta m_H^2 \gg m_H^2$$ by ~10^{32}

$$\Delta m_e \sim m_e \ln\left(\frac{\Lambda}{m_e}\right)$$

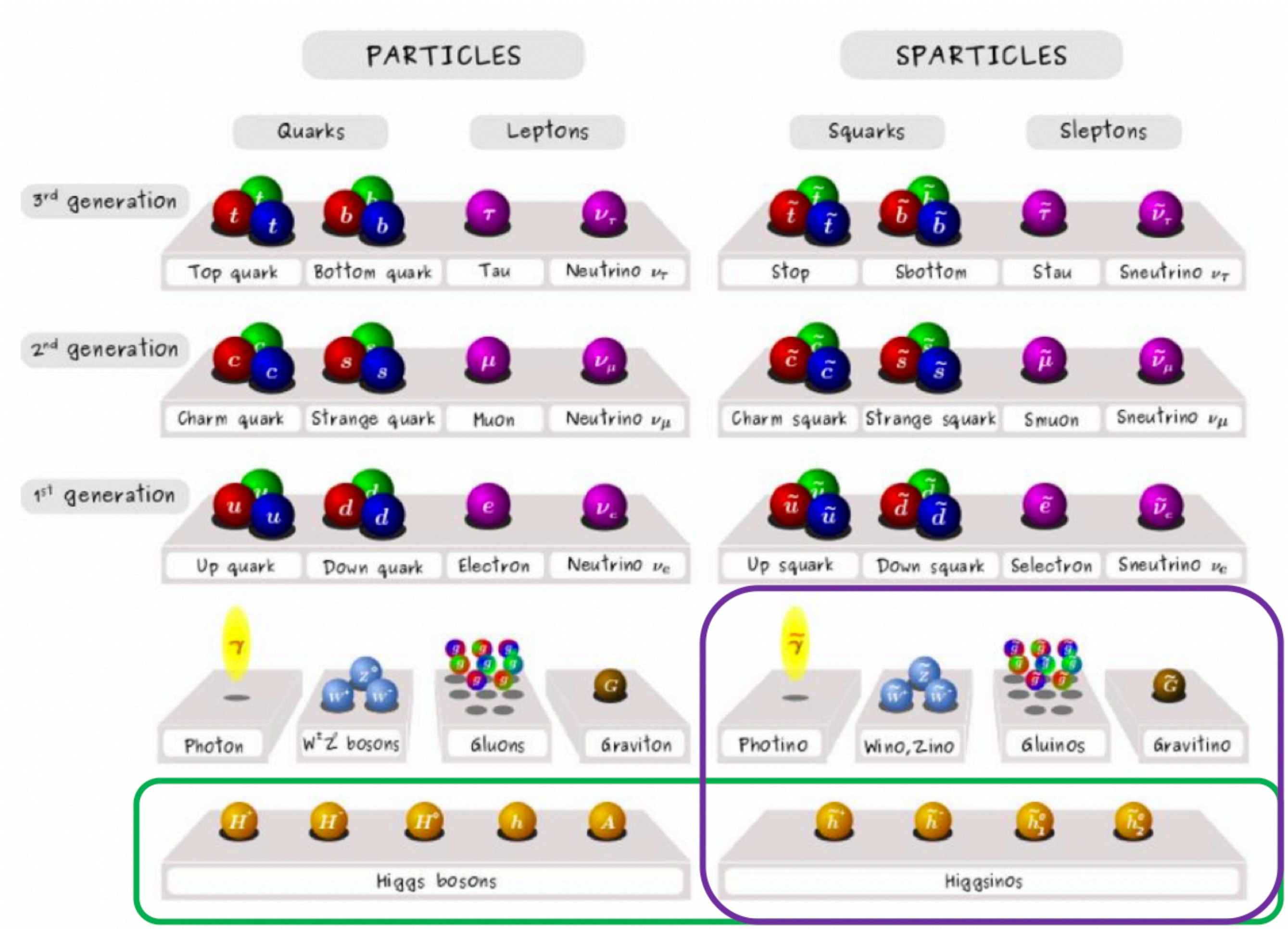
$$\Delta M_W^2 \sim M_W^2 \ln\left(\frac{\Lambda}{M_W}\right)$$

- Not the case for fermions or gauge bosons, as **corrections protected through chiral symmetry or gauge symmetry**

- **Motivation to consider BSM models where:**
  - new symmetry introduced to protect Higgs mass (SUSY)
  - cut-off scale reduced wrt Planck scale (extra-dimensions for instance)
  - composite Higgs (similar to pions with quark chiral-flavour symmetry)

Supersymmetry

- **Example of new symmetry:** fermions-bosons symmetry, new SUSY particles contributions to Higgs mass correction cancel SM ones



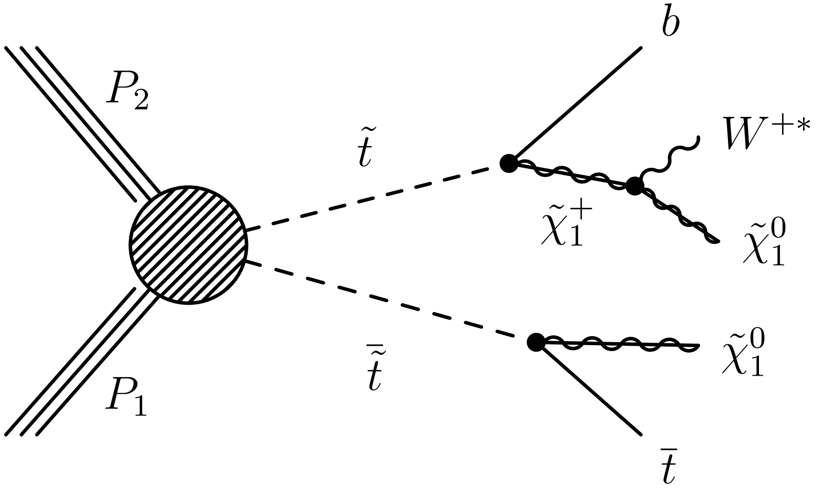
Scalar partners of fermions = sfermions

Mixing of fermion partners of gauge bosons + Higgs bosons = neutralinos + charginos

Extended Higgs sector (2HDM)

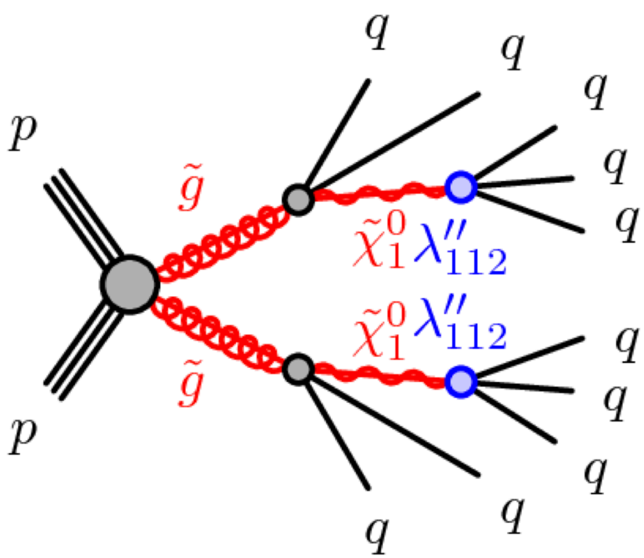
Supersymmetry

- General SUSY extension of SM allows for **proton decay** unless extra symmetry introduced, for instance **R-parity = +1 for SM particles, -1 for SUSY partners**



- **With R-parity:**
  - SUSY particles produced in pair
  - Lightest SUSY-particle (LSP) stable

  => possible DM candidate

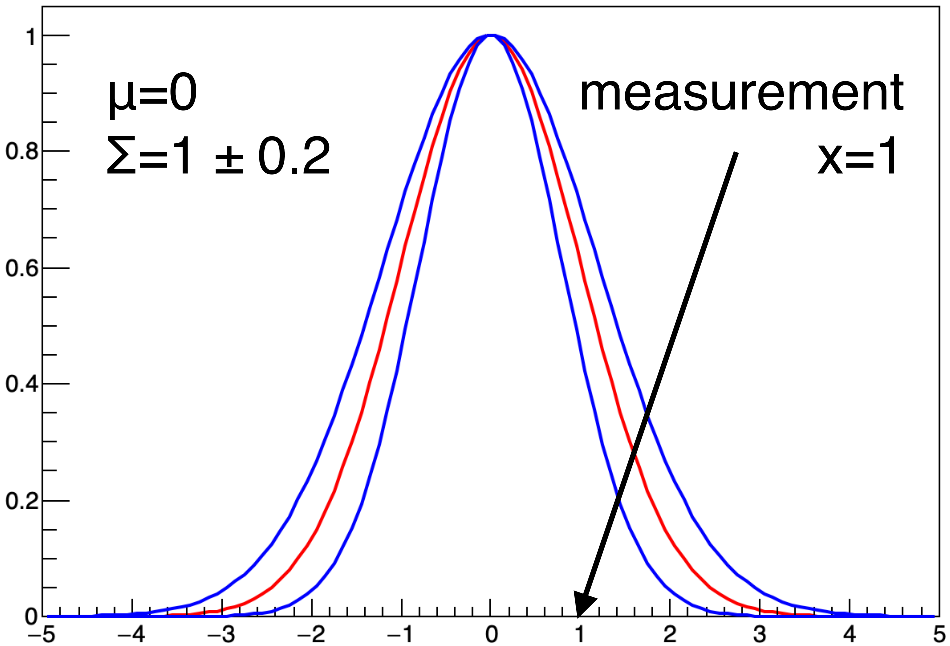


- **R-parity violating SUSY models** also considered:
  - allows for baryon (B) or lepton (L) number violation (but not B-L)
  - wide range of LSP lifetime possible

Statistical break: limit settings

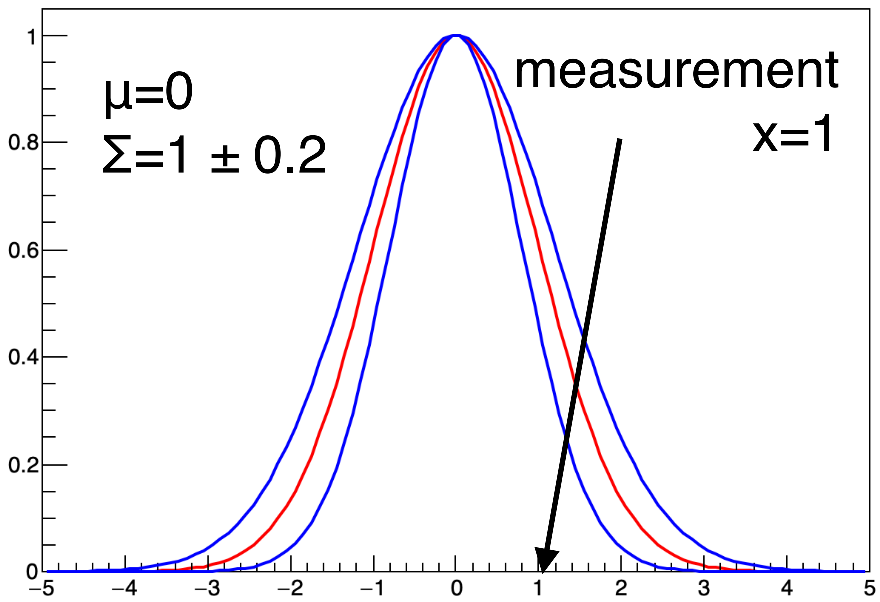
- Typical approach for BSM searches is to **check if data are more compatible with SM or BSM** (often as a function of some parameters associated to the model)

- Base tool for this is the **likelihood i.e. the probability to observe a given set of data assuming a particular theory** (not the probability of a theory given a particular set of data)



- **Toy-example:**
  BSM theory has 1 unconstrained **parameter of interest μ**, SM = μ=1
  + extra-parameter Σ **constrained** from auxiliary measurements = **systematics**
  Gaussian likelihood for **observable x** (in general from fit of multi-dim binned distribution)
  Experiment = measure of x

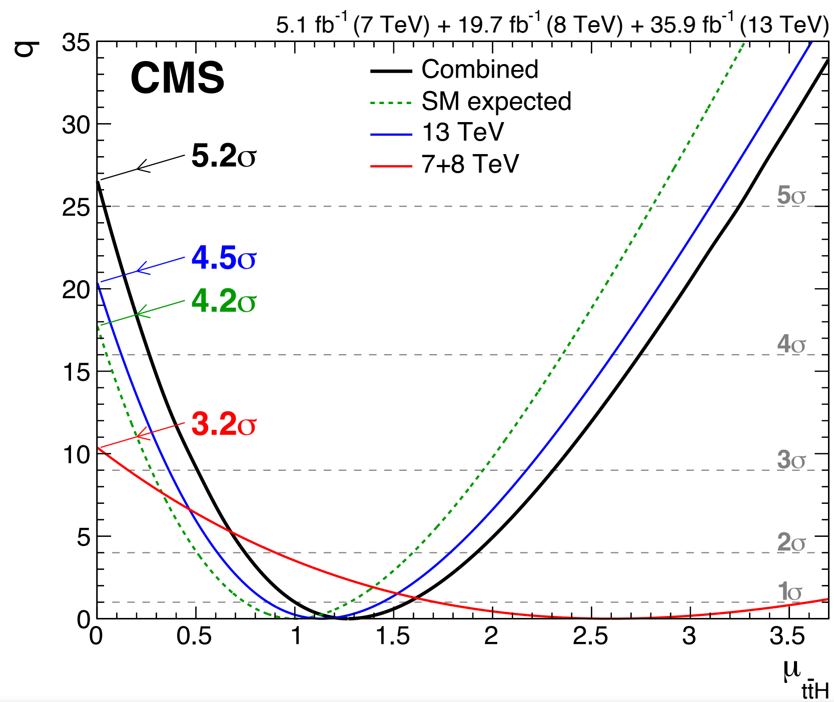
Statistical break: limit settings



- **Which value of μ can I exclude considering my measurement x=1?**
  Convention: determine which values of μ are such that
  P(x=1 | μ) / P(x=1 | SM μ=1) = profile likelihood ratio < y% (or z σ)

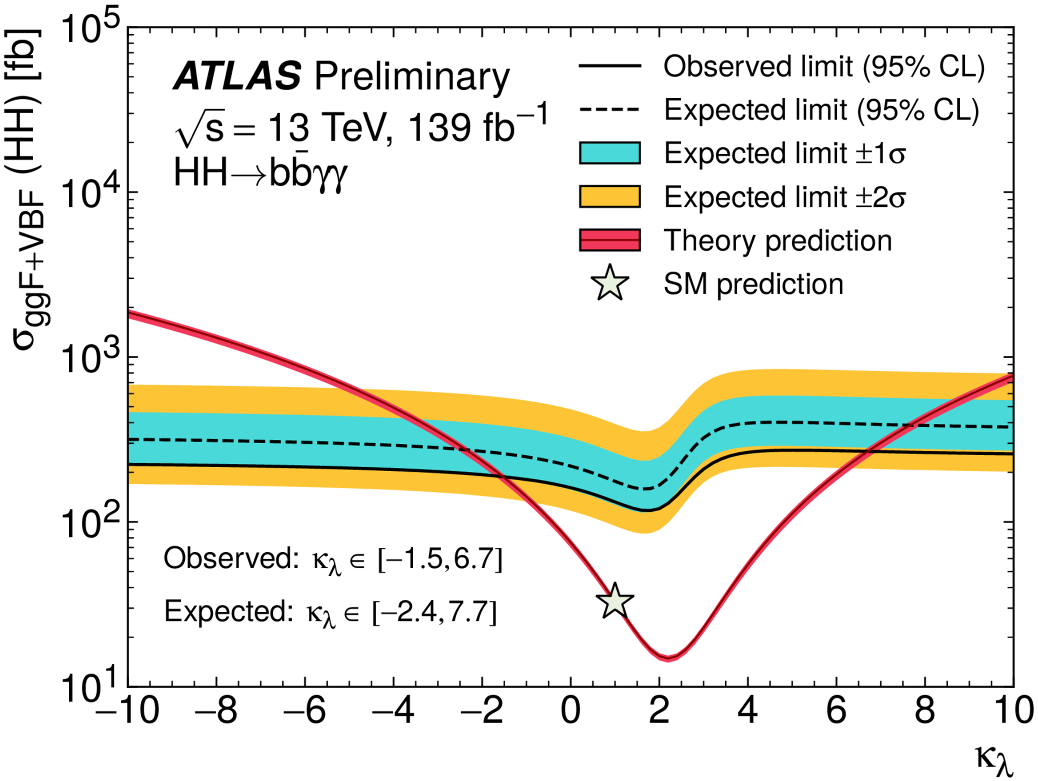
- **For each value of μ compute p.l.r.** (+ profile systematics)

- **Example from real analysis:**
  μ=0 excluded at 5.2σ
  0.65<μ<1.9 95% confidence interval



q=-2 log(p.l.r.)

Statistical break: limit settings



- **Limit on HH production cross-section σ** (=μ in previous example) **as a function of a theory parameter κ_λ**
- **Observed limit** computed using observed data, **expected limit** computed using simulated data generated from **SM prediction = Asimov dataset**

- Using **relation between σ and κ_λ** in the model, can translate **95% CL exclusion limits on σ** into **95% CL interval on κ_λ**