Beyond the Standard Model

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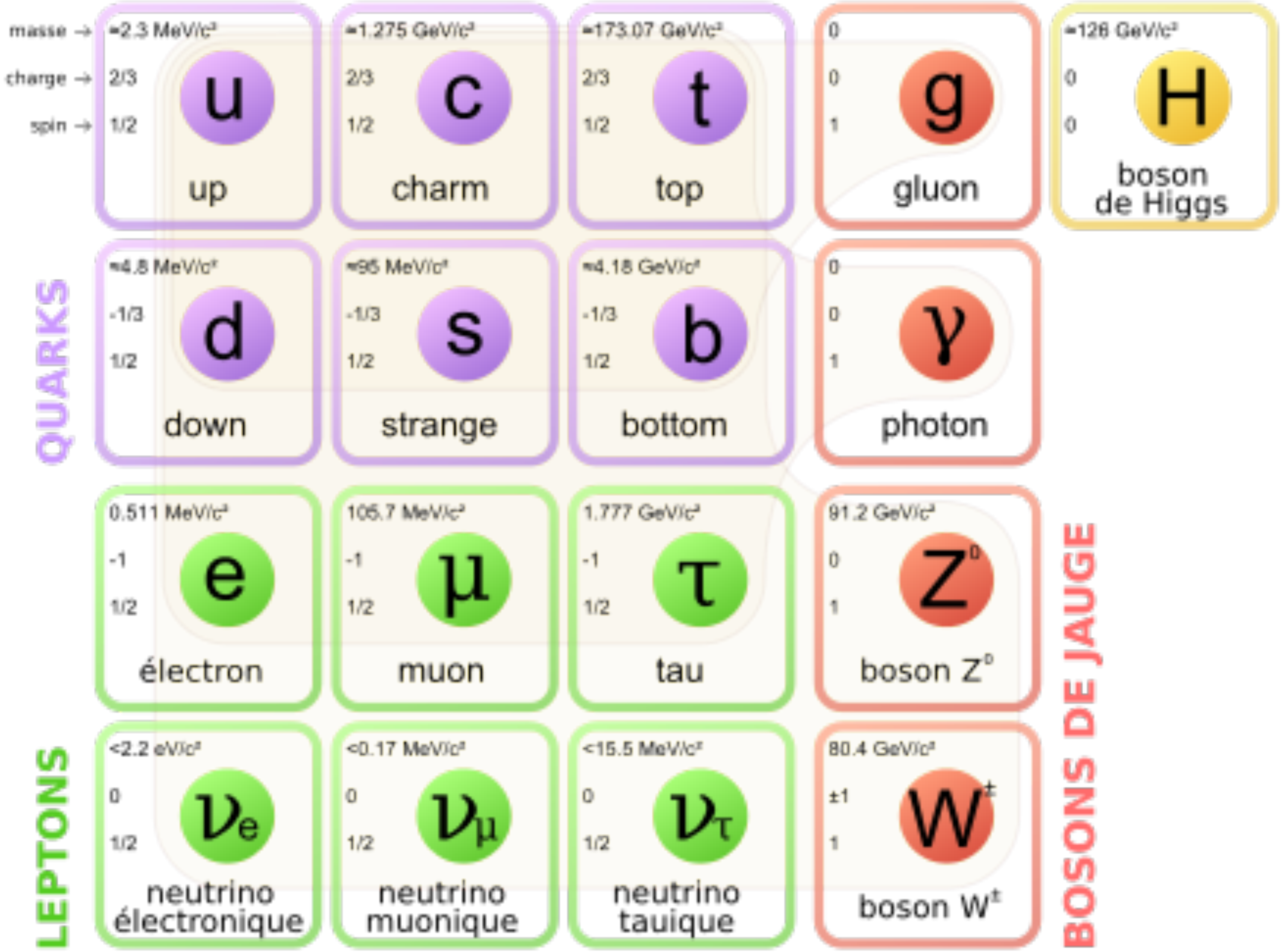
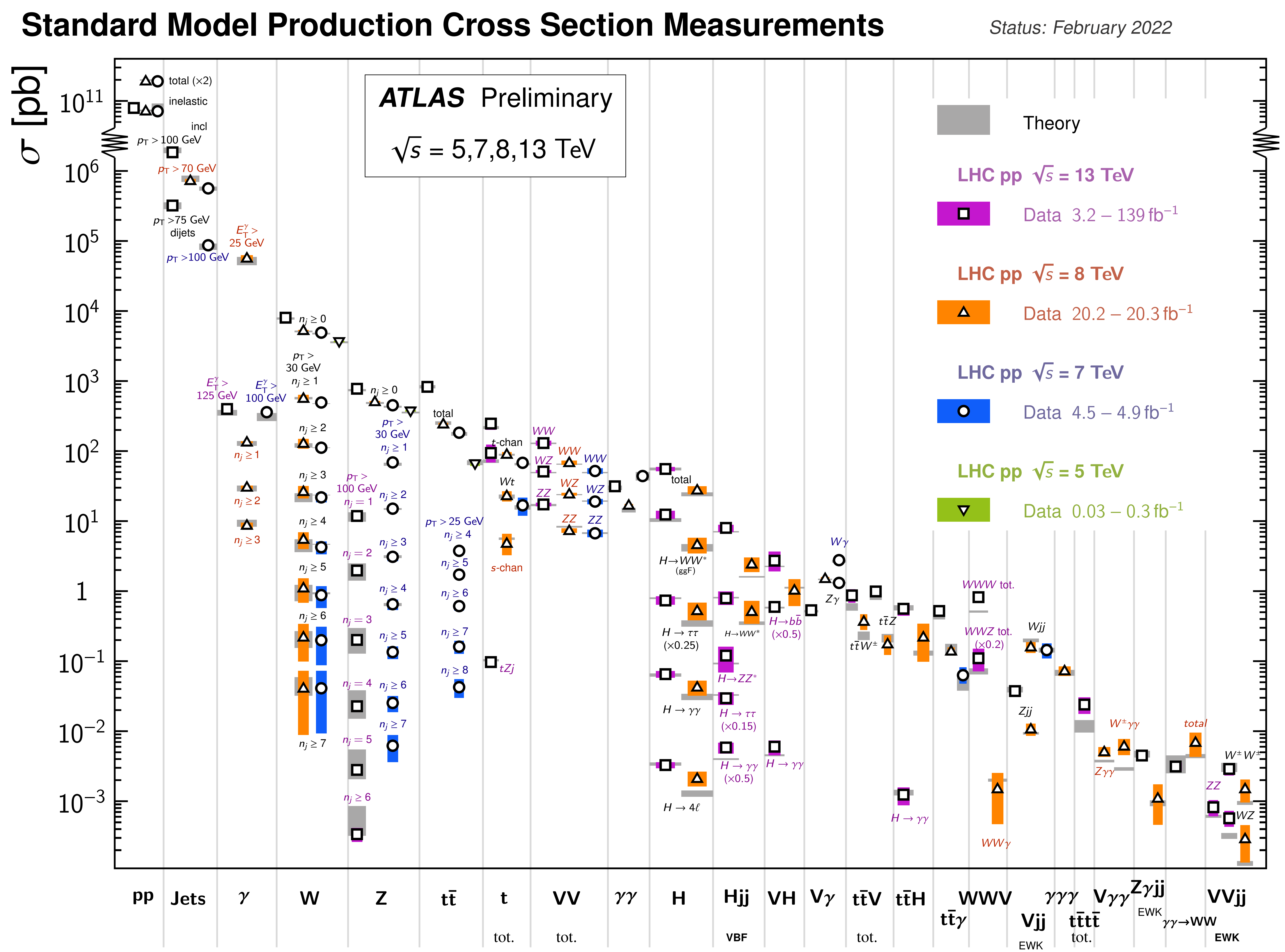
The SM : a theoretical success

- Founded on gauge invariance principles
  - SU(3) × SU(2) × U(1) ⟹ EW and strong interactions
- Is completed with a scalar sector (Higgs)
  - new complex scalar doublet with a potential with a v.e.v. ≠ 0
- Is a renormalizable QFT that is valid up to the Planck scale



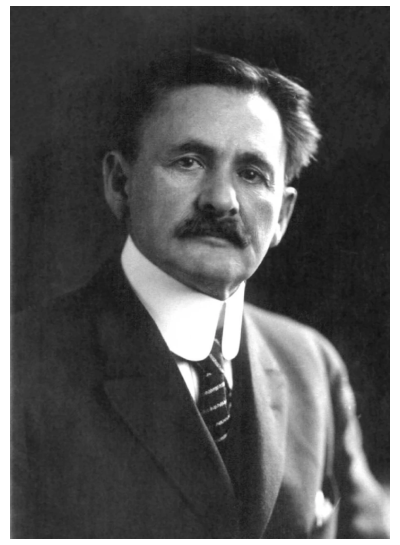
The SM is a beautifully elegant theory of Nature's mechanisms

The SM : an experimental success

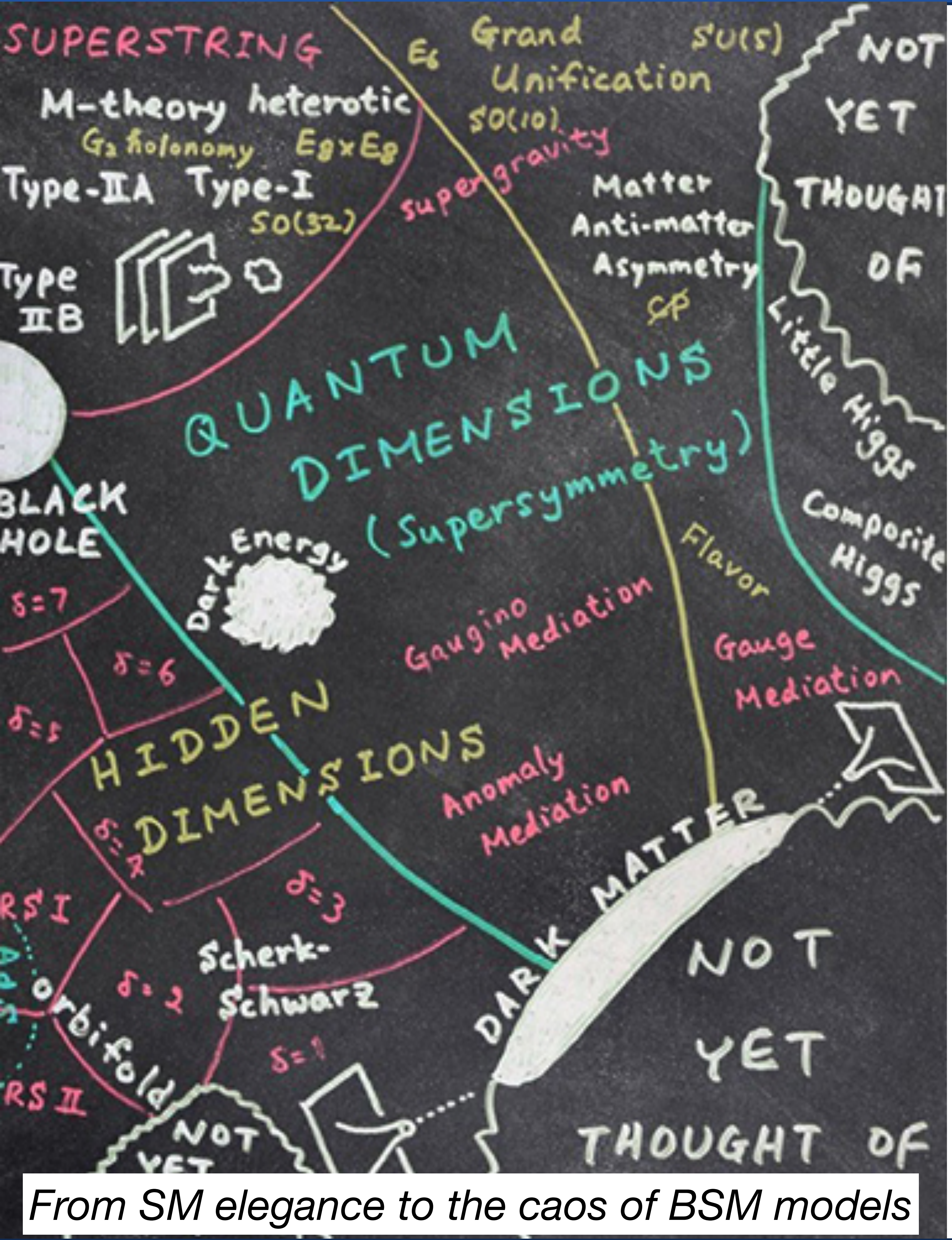


Astonishing capability to describe the observations of collider experiments

- The SM is a solid theory well corroborated by experiments
- Are we back to the end of the XIX century where *“it seems probable that most of the grand underlying principles have been firmly established”* (Albert Michelson) ?



So why BSM?



From SM elegance to the caos of BSM models

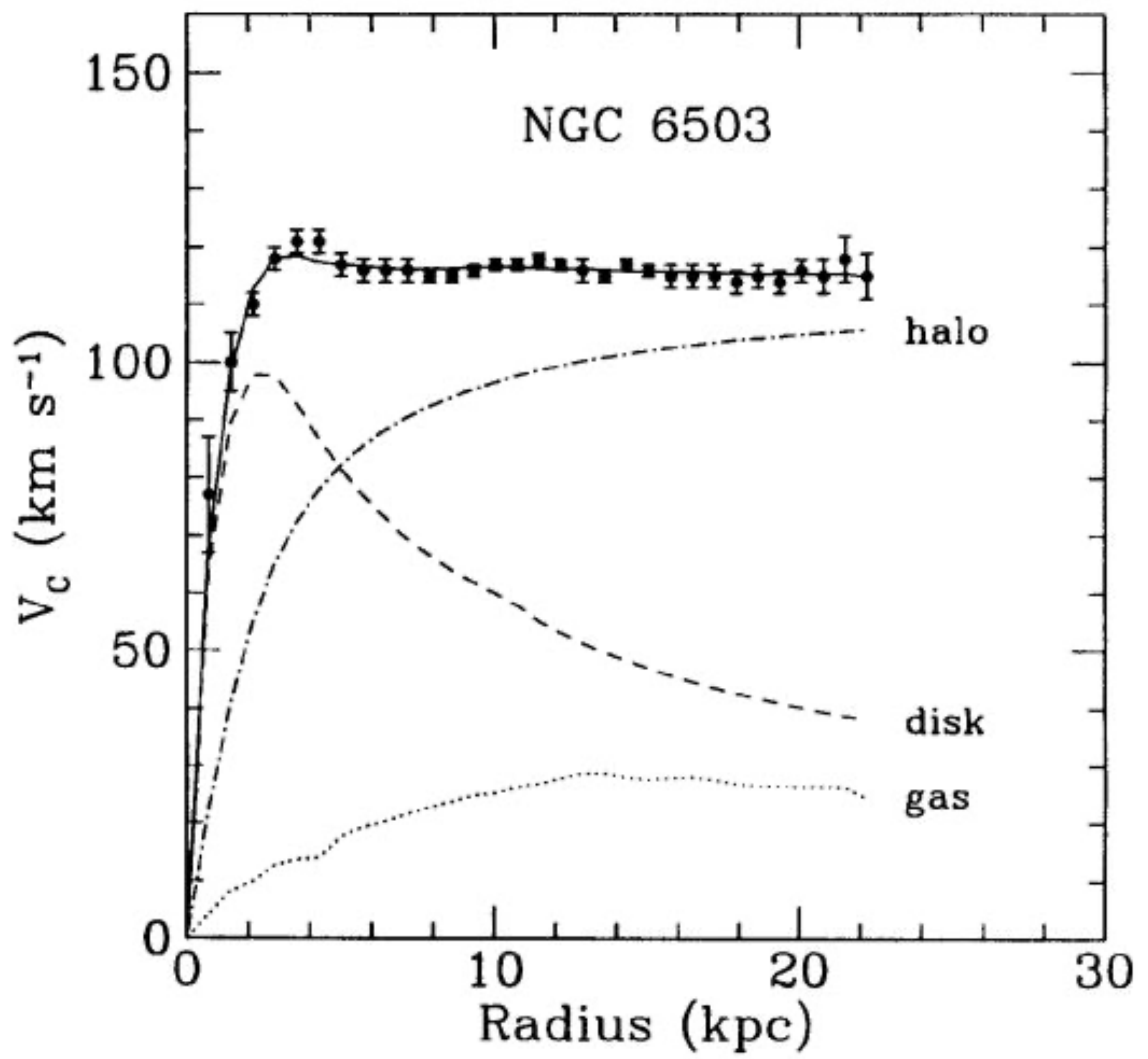
Several limitations of the SM

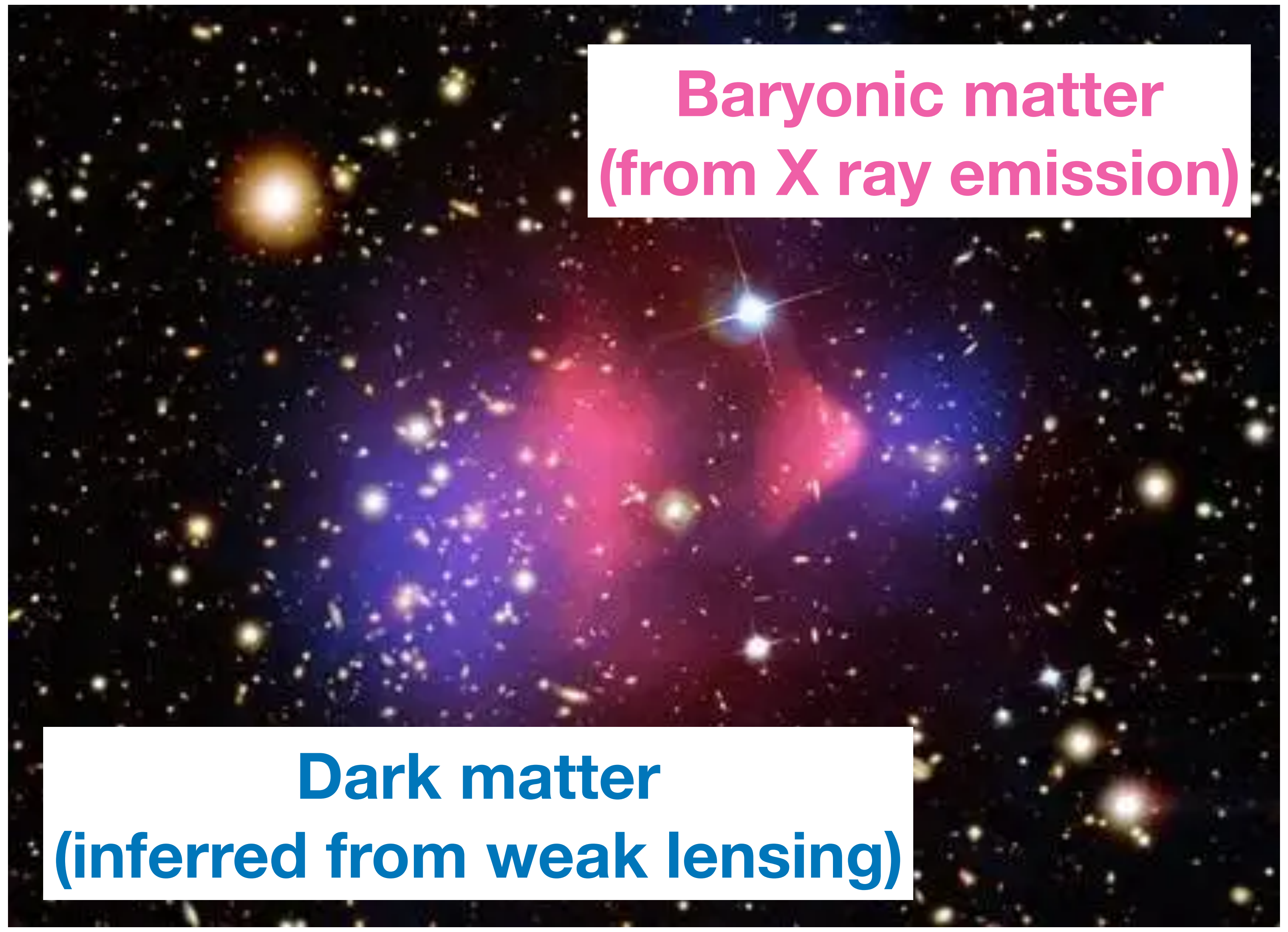
- Astrophysical observations and cosmological considerations
  - dark matter
  - matter/antimatter asymmetry
  - isotropy and homogeneity of early universe (→ inflation)
- Theoretical limitations or puzzles
  - vacuum stability
  - hierarchy problem
  - neutrino masses
  - why 3 families?
  - …

The SM cannot explain our Universe

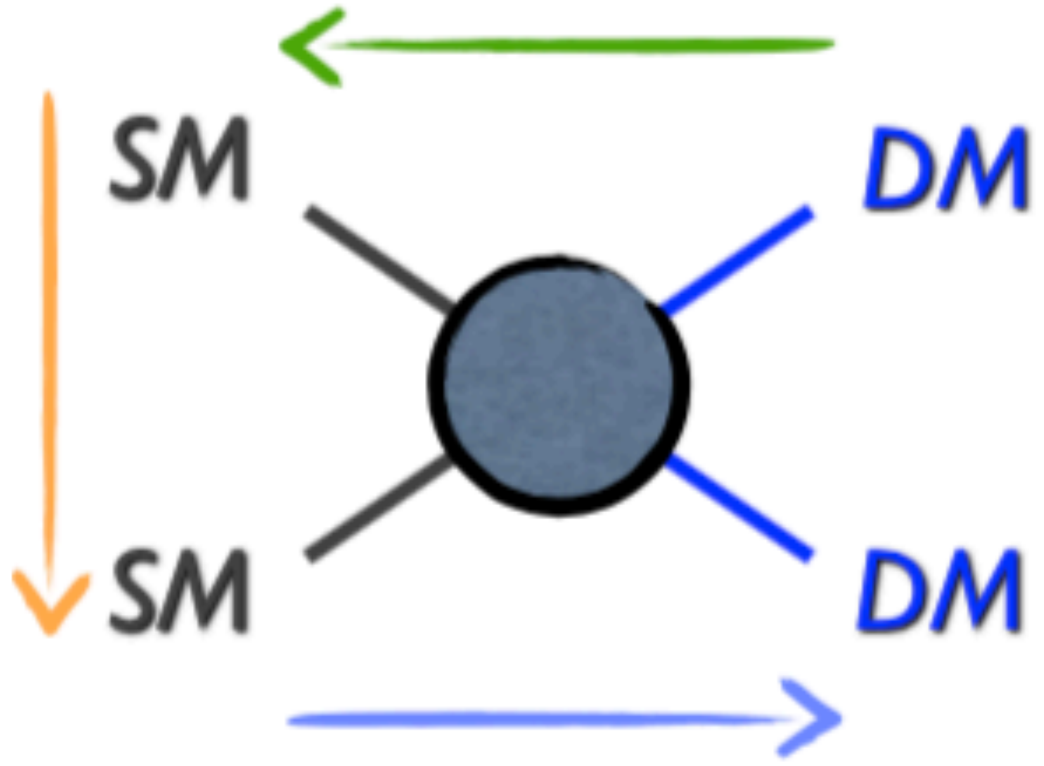
Physics beyond the SM needed to address these questions

Astrophysical motivations: dark matter





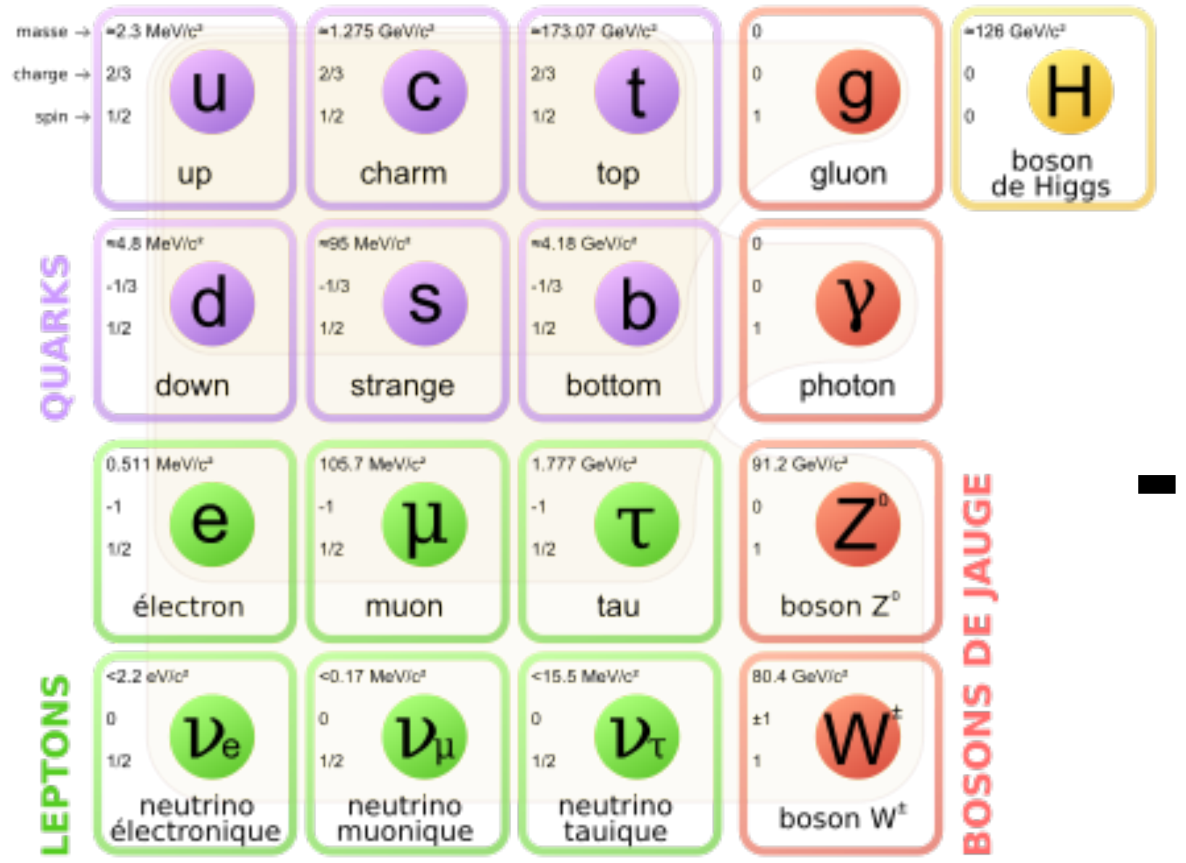
- Clear **astrophysical evidences** for dark matter…
  - the gravitational behaviour differs from the one expected from visibile matter
- … but no suitable dark matter candidate in SM!
- DM is 85% of the total matter in the Universe



- **If** DM is a particle and has minimal interactions with the SM particles, search for
  - its annihilaton (astro)
  - its production (collider)
  - its scattering (direct detection)

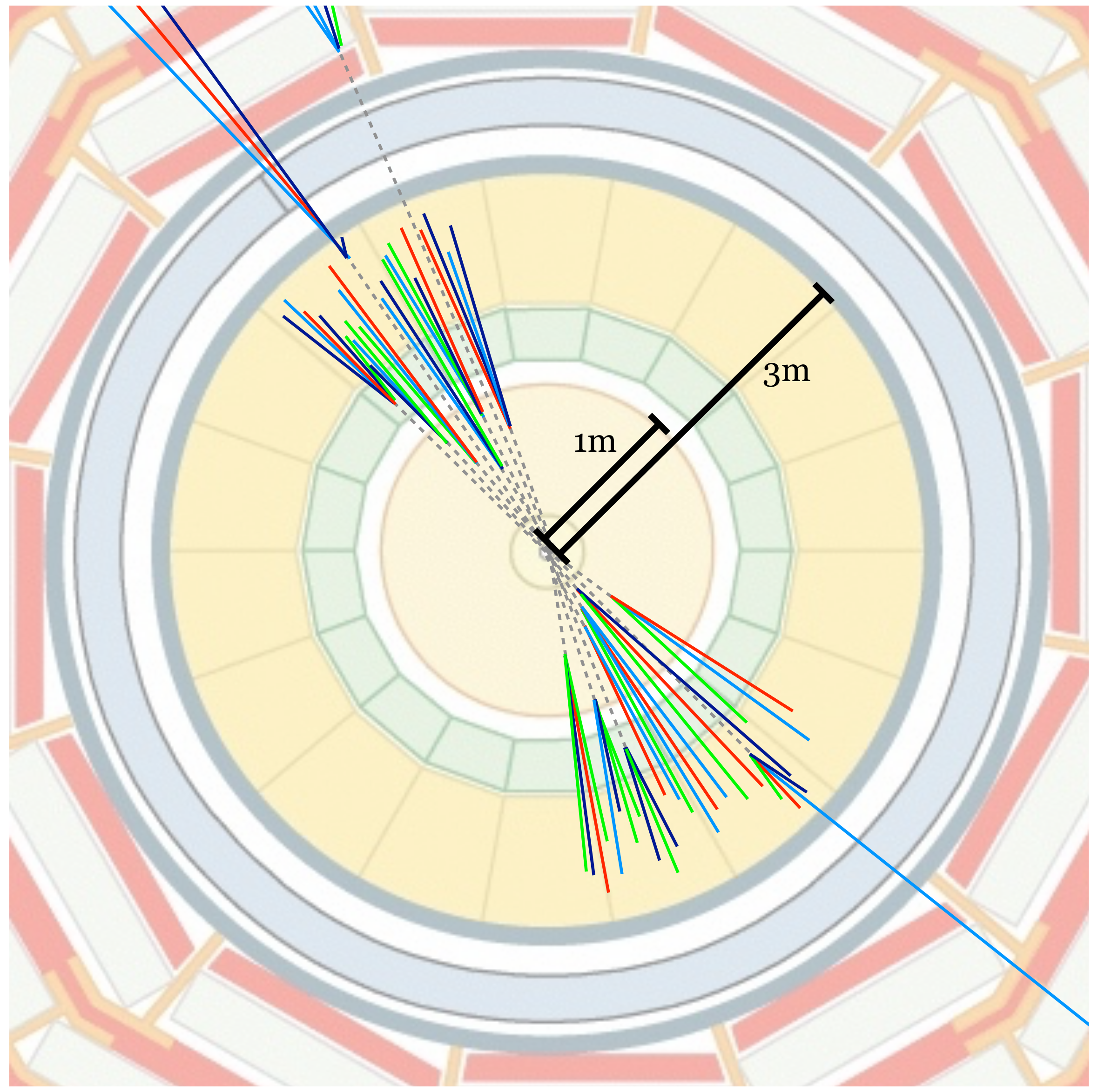
A dark sector of the SM

- Traditional simplified models at the LHC: one DM particle and one mediator
- But a more rich "dark sector" might exist
  - a "dark mirror" or the SM with its own particle content and interactions
  - messengers connect the dark sector to the SM (e.g. Higgs portals models)



SM

Dark sector



- Dark sector and SM weakly coupled → long lifetime of dark particles
- Can be produced at the LHC in pp collisions, decay back to SM particles within the volume of the detector
  $\Longrightarrow$ emerging jets
- Challenging signatures for detectors

→ Talk by Guillaume Albouy

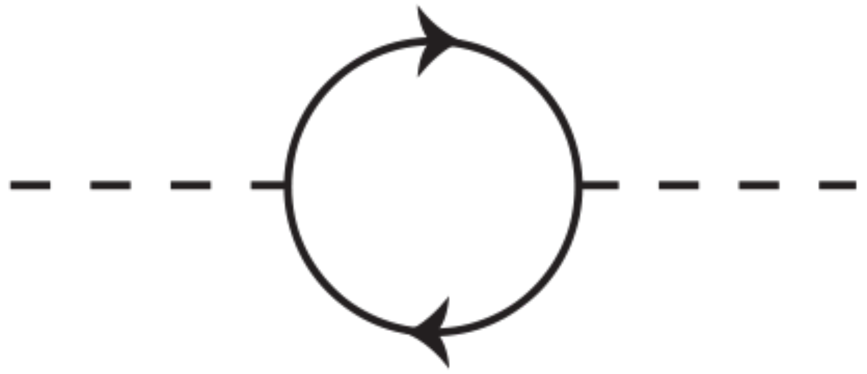
Matter / antimatter asymmetry

- Sakharov conditions
  1. baryon number violation (we expect universe to start symmetric between B and anti-B)
  2. CP violation (treat B and anti-B differently to remove antimatter)
  3. out-of-thermal equilibrium (suppress inverse processes)
- The observed asymmetry between baryons and anti-baryons is 10^{17} larger than the SM prediction
  - no mechanism for baryogenesis can be build within the SM to accommodate this level of asymmetry
- Physics beyond the SM needed to explain the observed imbalance

Where has all antimatter gone?

→ *Talk by Christopher Greenberg*

Theoretical motivations : hierarchy problem



$$\Delta m_H^2 = -\frac{{y_f}^2}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + ...]$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + ...]$$

Loop corrections to m_H are divergent

- Any particle contributing with a large term to m_H
  - other massive SM particles are protected by symmetries
  - but no symmetry protects the Higgs boson itself
- A very accurate cancellation must happen to maintain m_H close to the EW scale

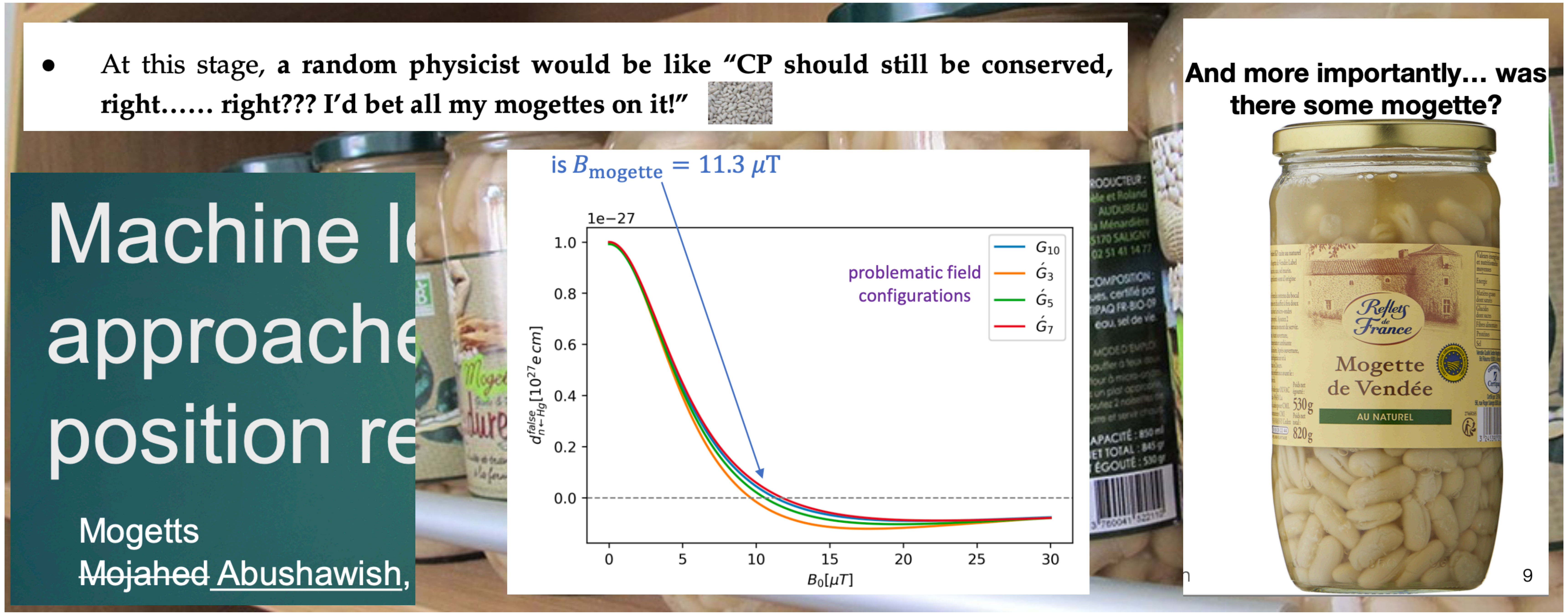
Theoretical motivations : hierarchy problem

It's like finding exactly the same number of mogettes in different jars

Not forbidden, but highly unlikely

- A very accurate cancellation must happen to maintain m_H close to the EW scale

Theoretical motivations : hierarchy problem



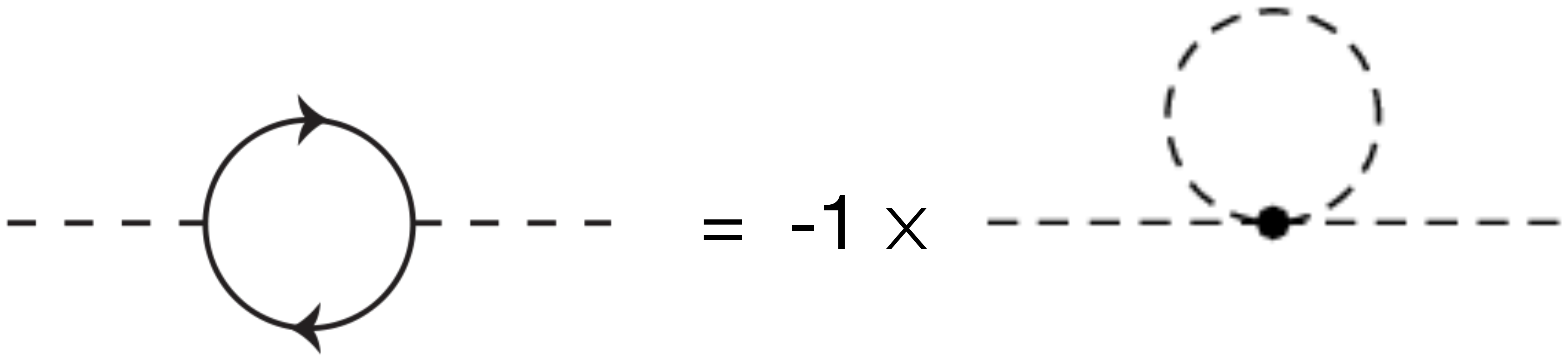
Or like finding a mention of mogettes in several talks in a particle physics meeting

Not forbidden, but there is likely a hidden reason behind

- A very accurate cancellation must happen to maintain m_H close to the EW scale

The Higgs boson mass is *improbably* small

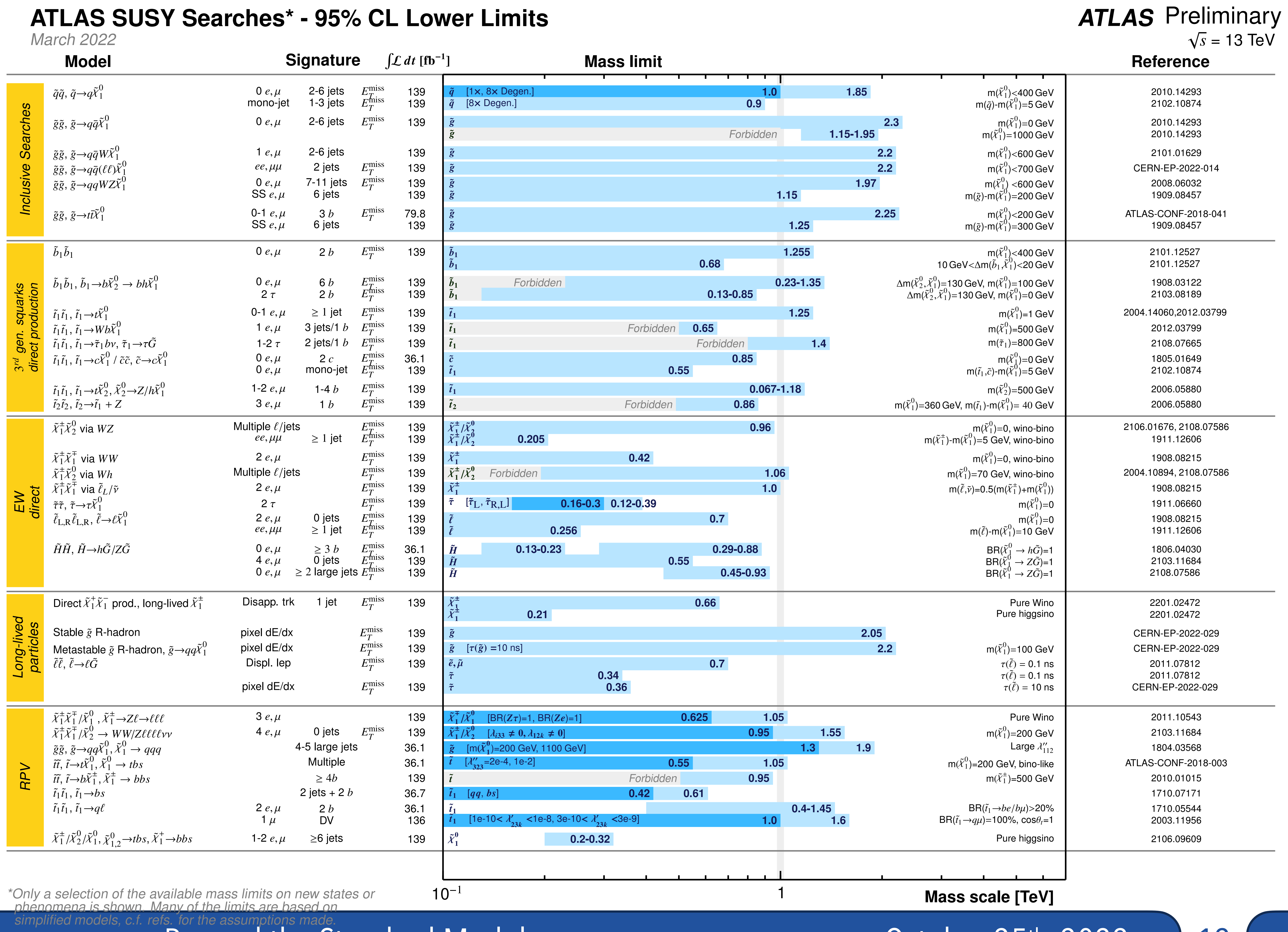
Theoretical motivations : hierarchy problem



A mechanism to ensure that divergent contributions cancels

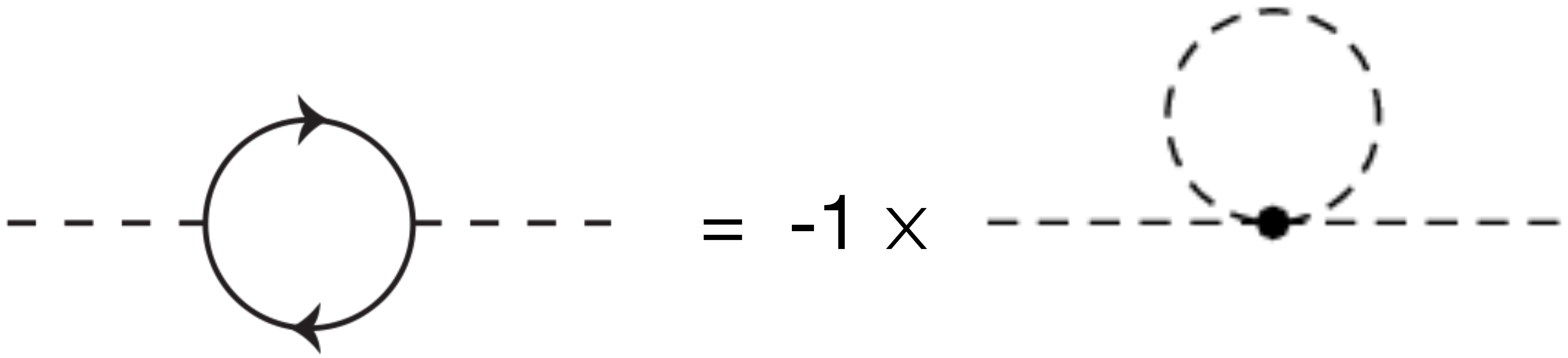
- Supersymmetry: each fermion (boson) has a supersymmetric boson (fermion) partner: **natural cancellation of divergences**

Supersymmetry at the LHC



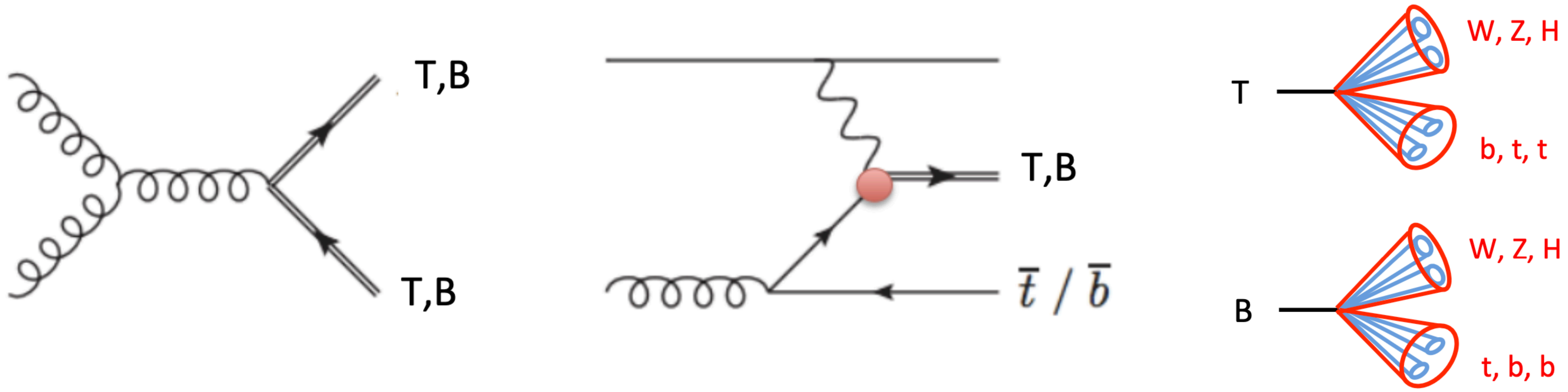
- Thoroughly tested at the LHC in a multitude of signatures
- No sign of SUSY particles

Addressing the hierarchy problem



A mechanism to ensure that divergent contributions cancels

- Supersymmetry: each fermion (boson) has a supersymmetric boson (fermion) partner: **natural cancellation of divergences**
- Vector-like fermions: new quarks that receive mass with direct mass terms and are non-chiral (both L and R charged currents)
  - masses around 1 TeV
  - decays to 1 boson + 1 quark



→ *Talk by Ji Eun Choi*
→ *Talk by Benjamin Blancon*

Searching for BSM physics at colliders

Direct

Detection of new BSM particles

Resonances
New particles

Indirect

Stress-test of the SM predictions searching for deviations

Precision

BSM searches

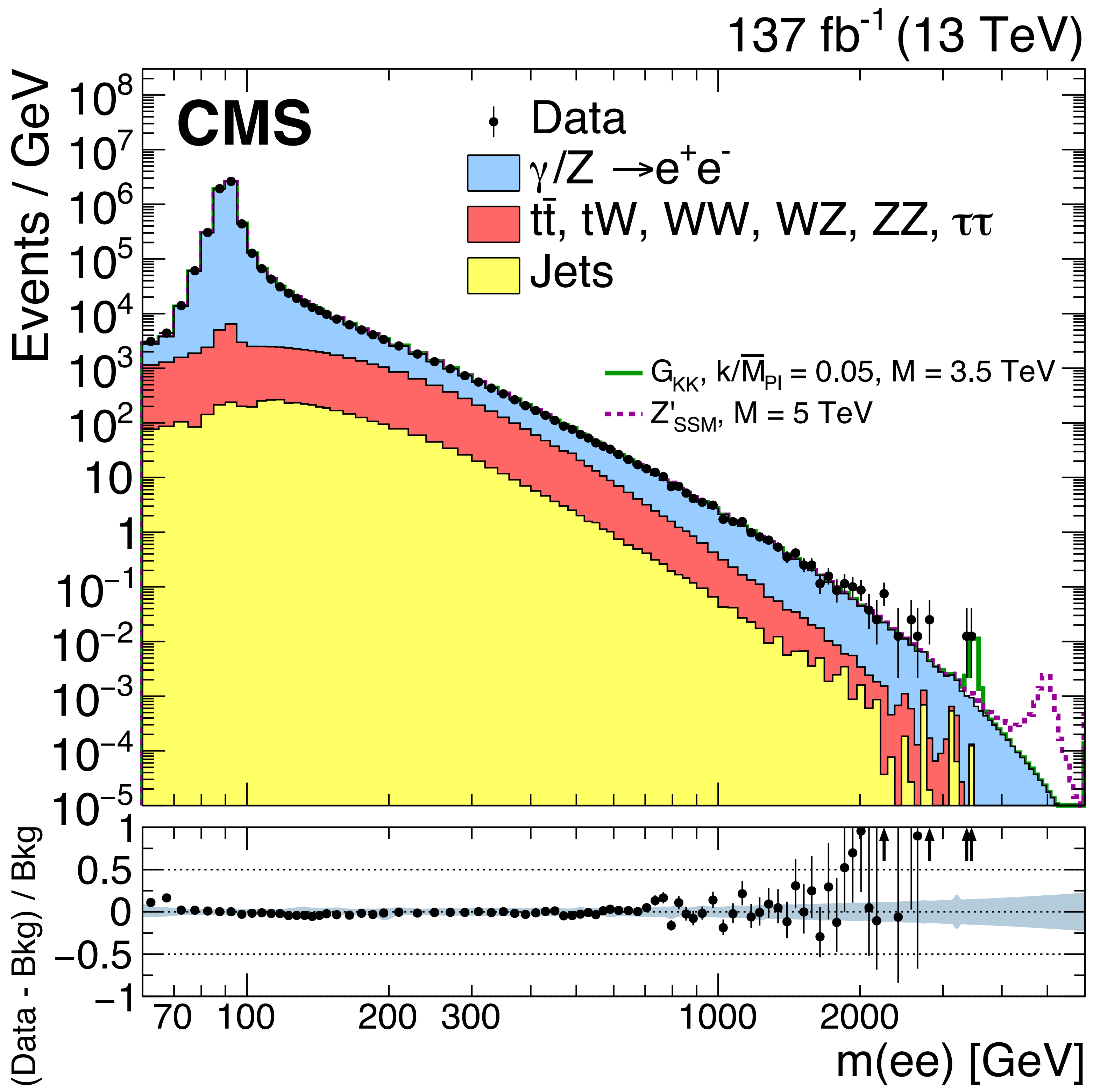
Searching for BSM physics at colliders

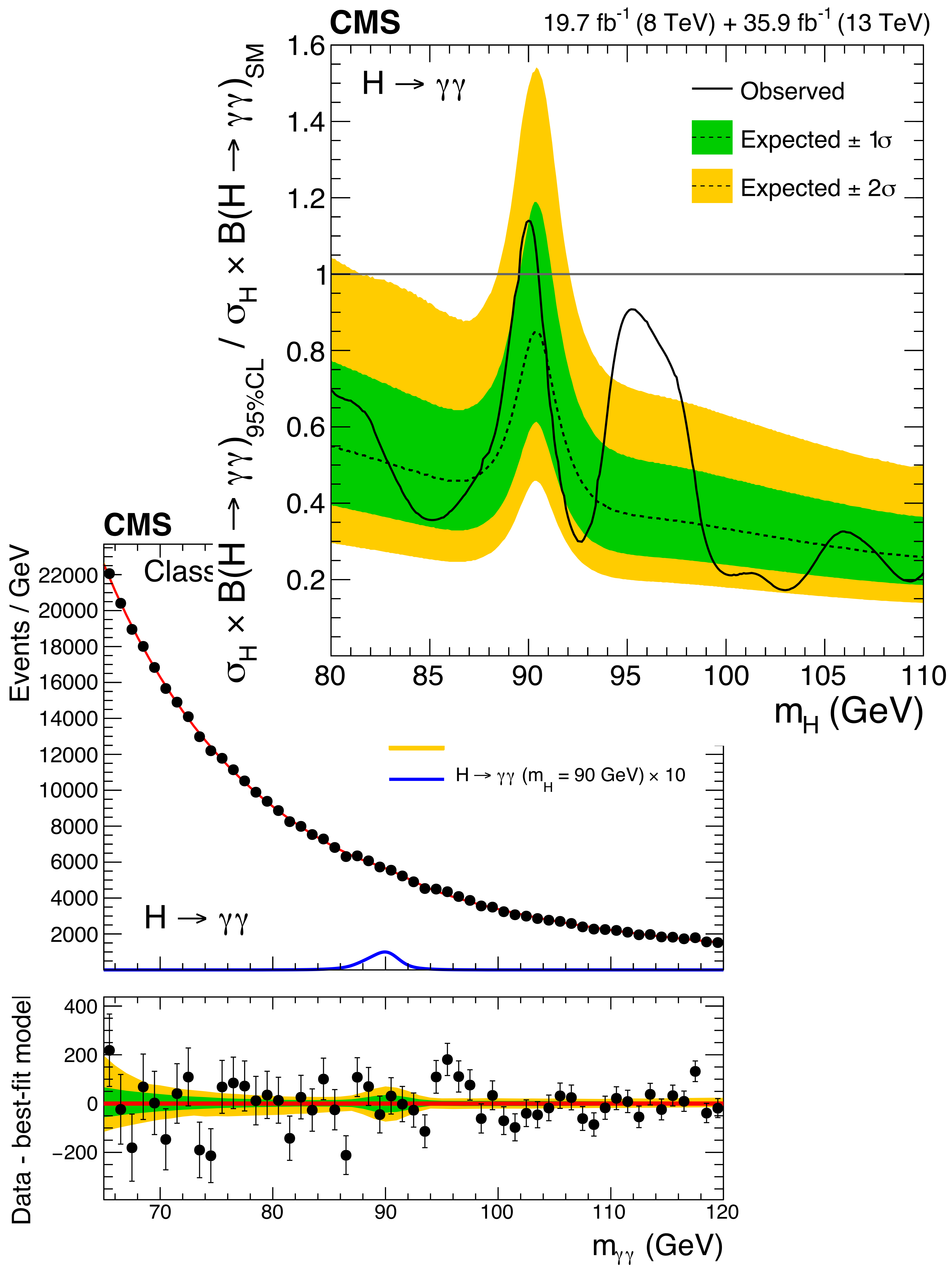
Direct

Detection of new BSM particles

Resonances
New particles

- “Traditional” searches for new states decaying to SM particles (WW, ZZ, HH, μμ, $\tau\tau$, …)

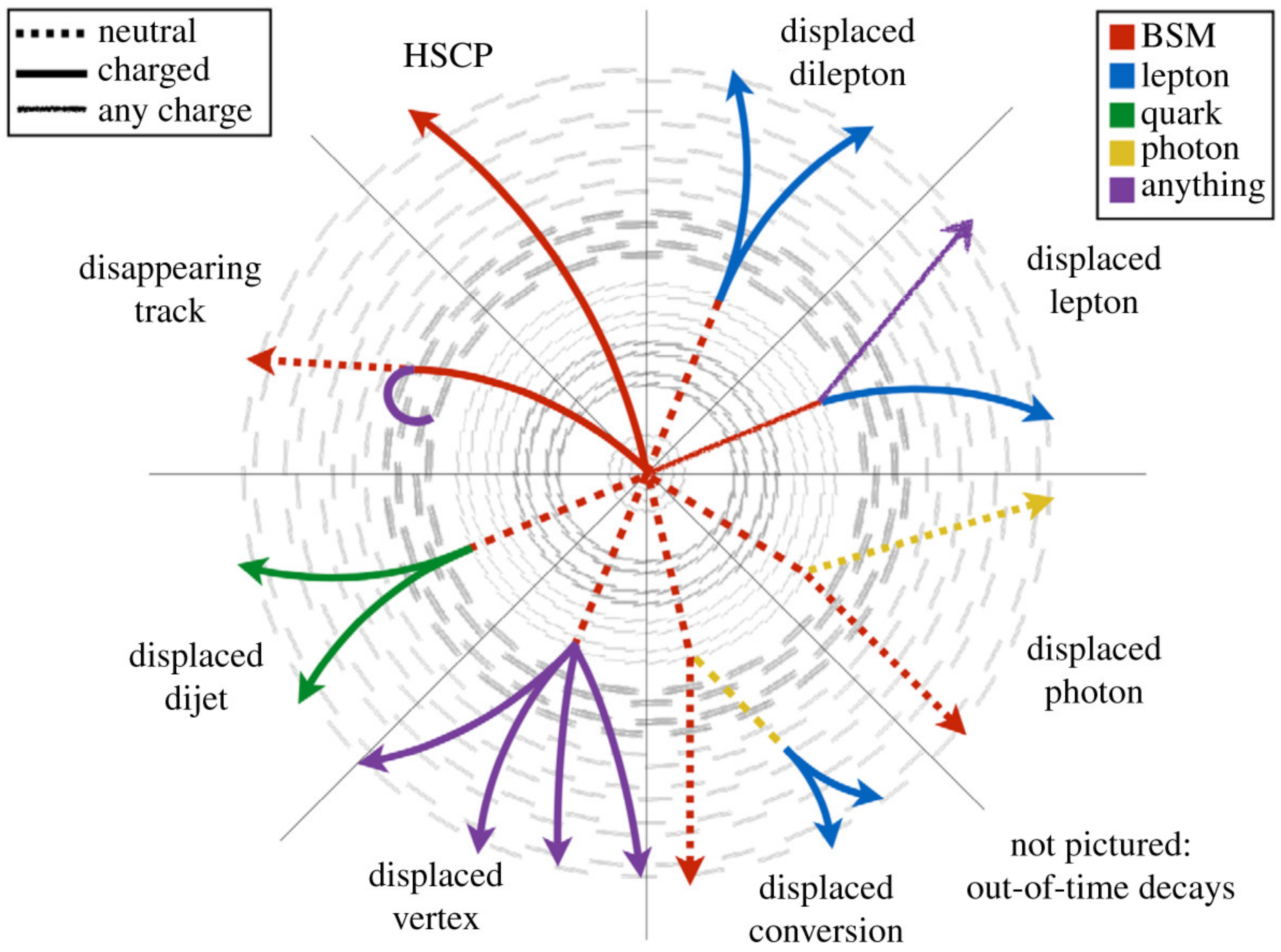




Unconventional signatures

- If BSM decays are suppressed, particles are **long-lived**
  - weak decay interaction
  - very compressed spectra (low density of final state)
- Gives rise to many unconventional signatures that require an usage of detector information beyond its traditional purpose
  - highly displaced vertices / tracks
  - slow charged particles
  - disappearing tracks
- Target dedicates searches are necessary to maximise sensitivity

→ *Talk by Raphael Haeberle*



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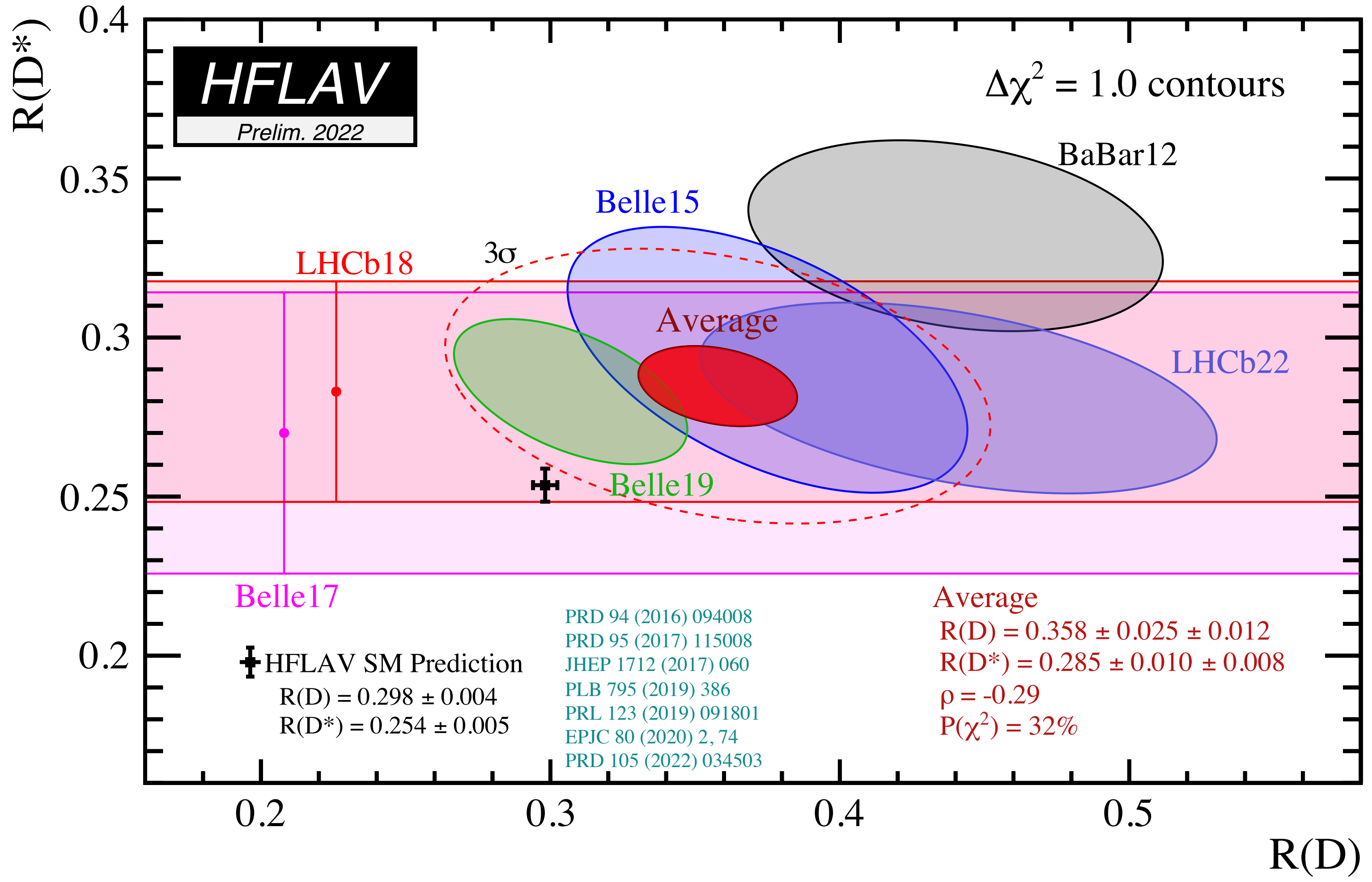
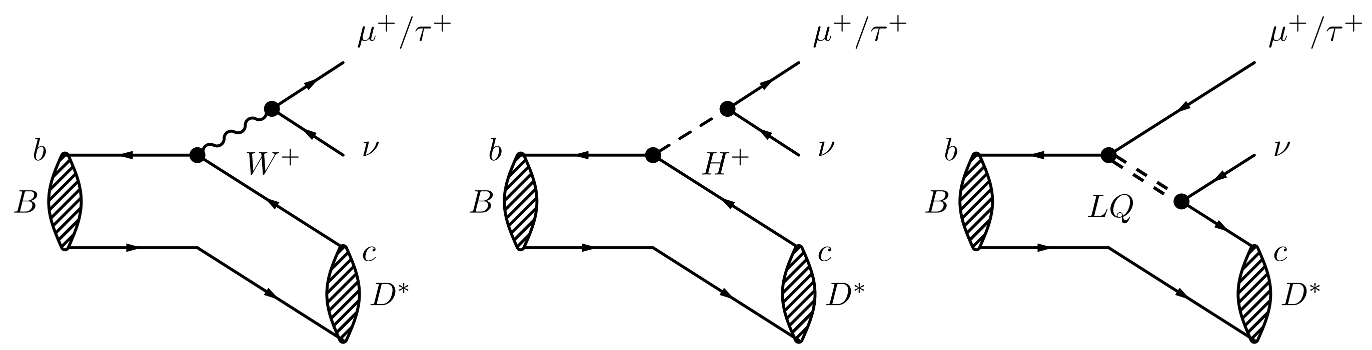
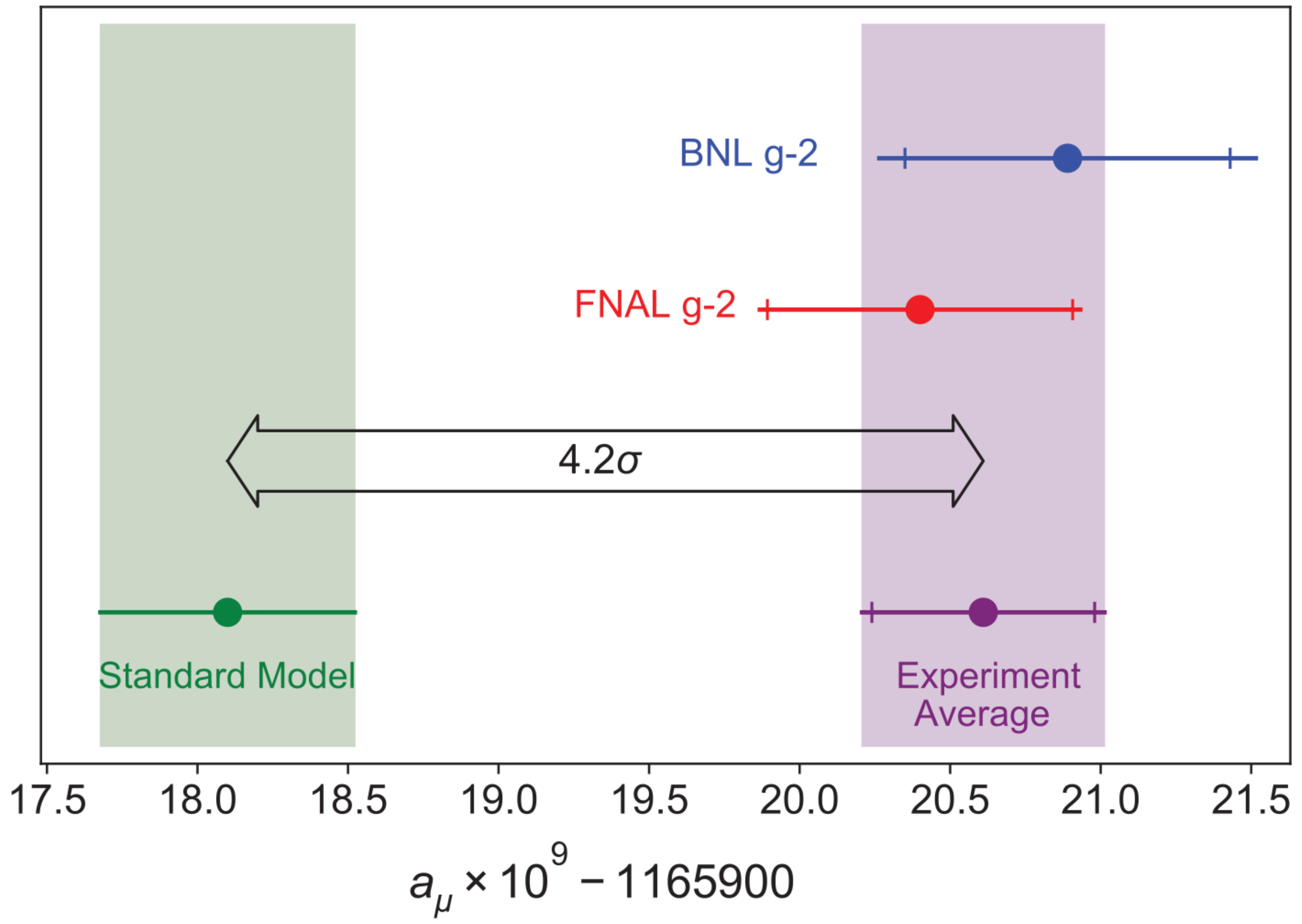
Precision measurements as a probe of BSM

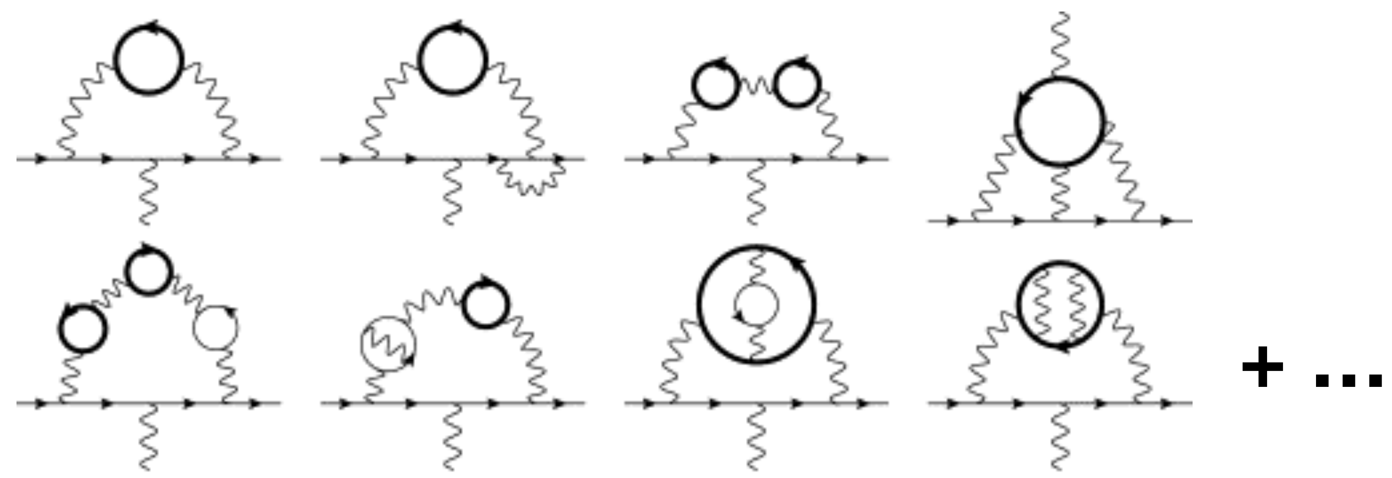
R(D) - R(D*)



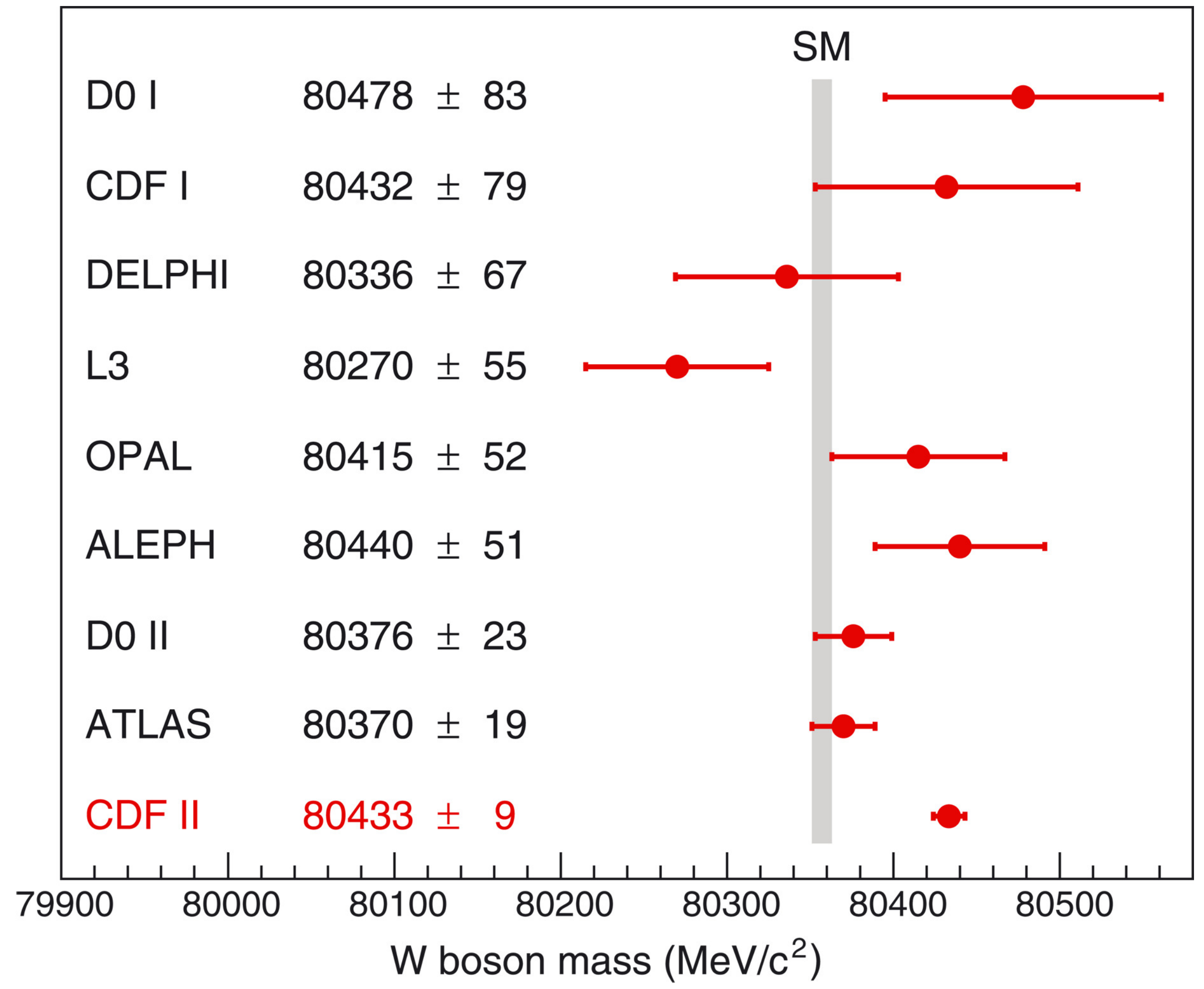


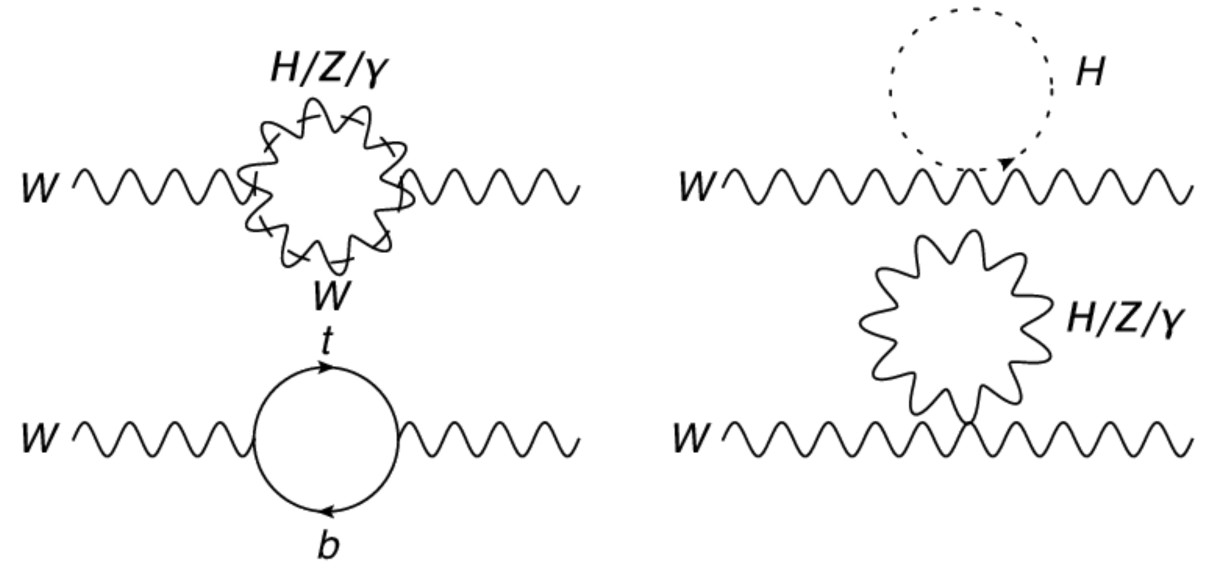
Muon g-2





W mass





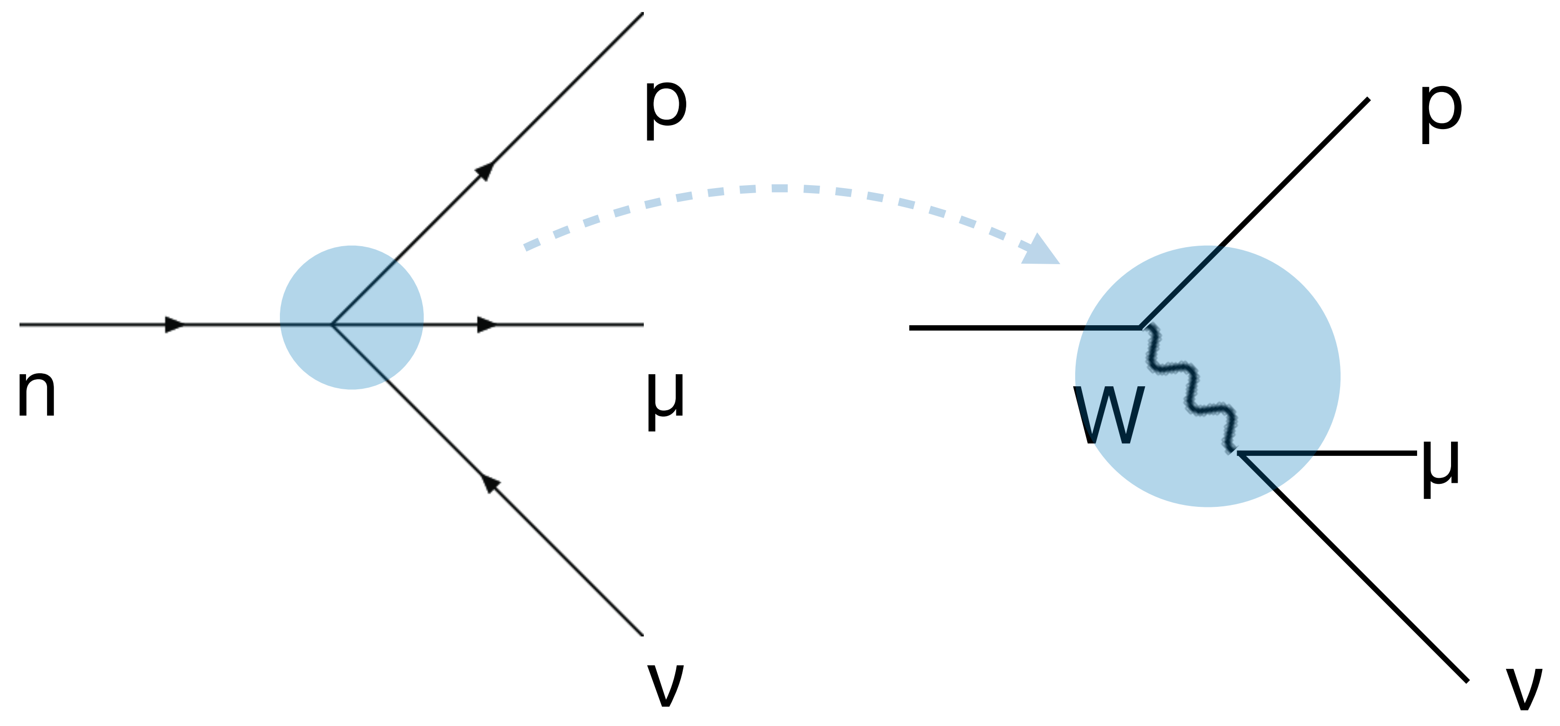
New physics can manifest in quantum loops
Reach scales not directly accessible at the LHC

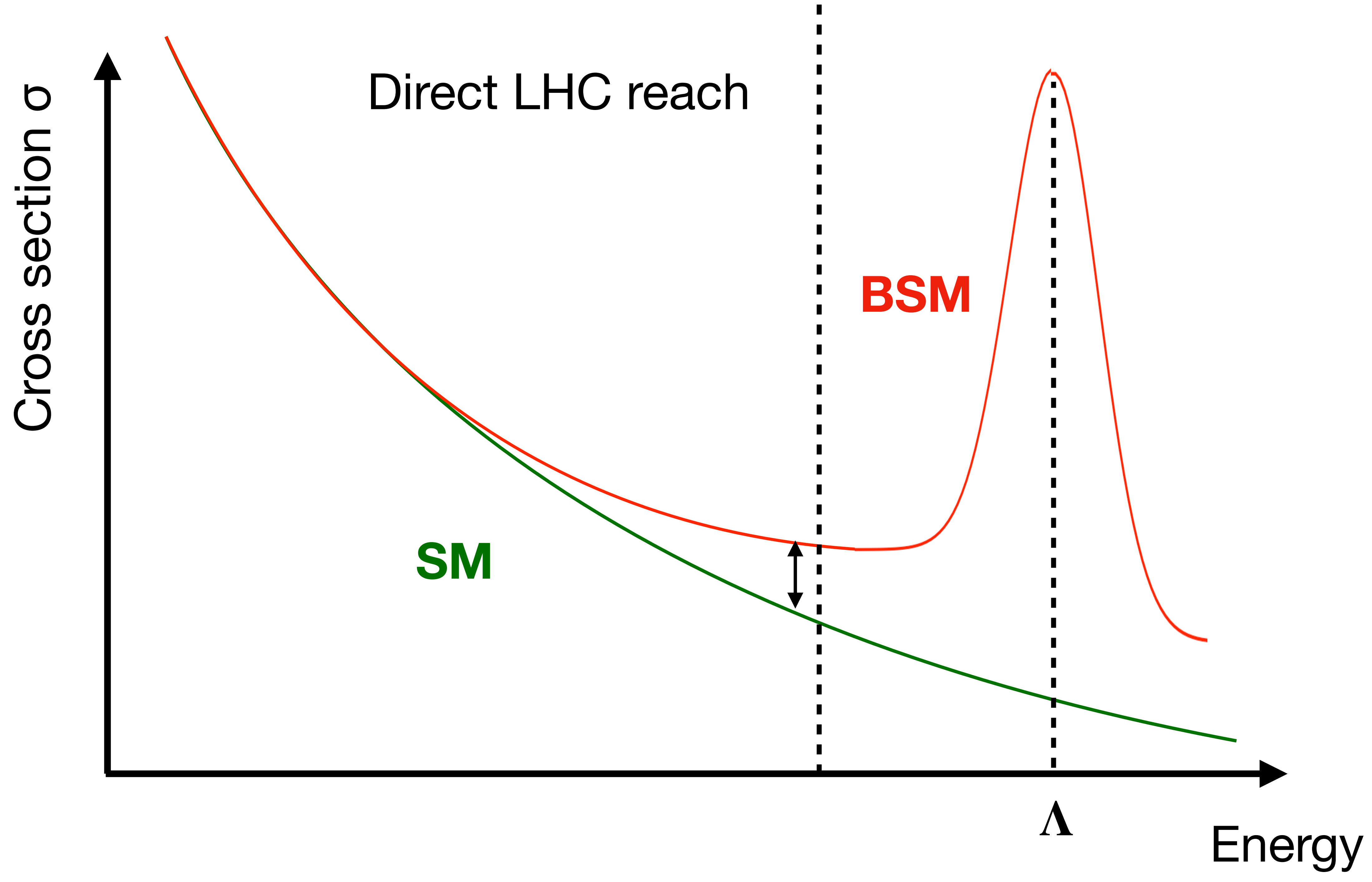
- Requires exceptional control of experimental effects ad thorough validation and cross-checks

Effective field theories

What if new physics is out of the direct reach of a collider?

- Modification of SM predictions modelled with an "effective" theory
  - not a "good" renormalizable theory: breaks when E ~ Λ because new physics appears
  - good "effective" description at low energy
- Analogous to the Fermi theory of a neutron decay





High-scale BSM physics studied from low-energy effects

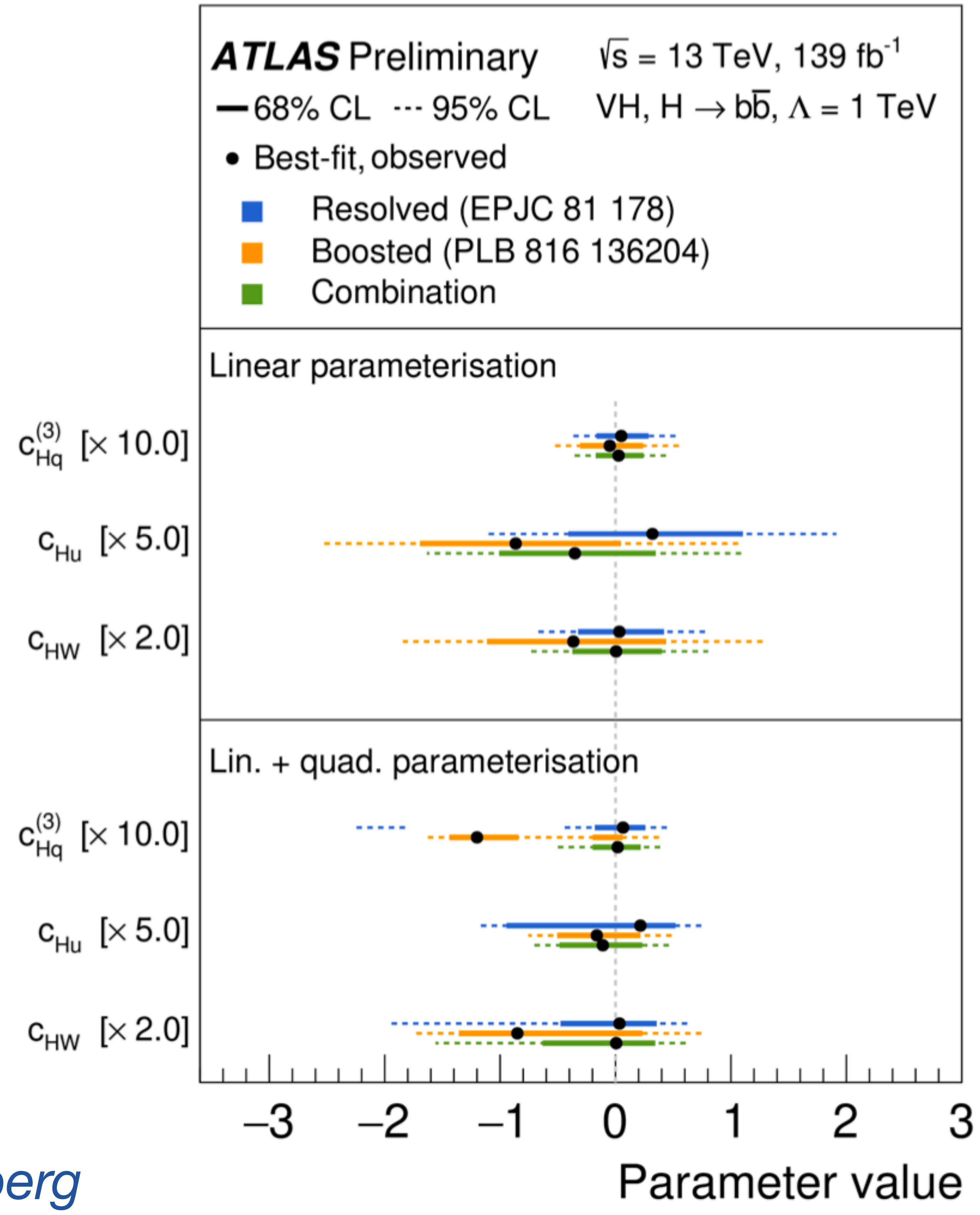
Precision SM measurements are effectively searches for BSM physics

Effective field theories

EFT : expansion of SM Lagrangian (d = 4) with higher order operators

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

- Various choices of the EFT "type" are possible
  - linear (SMEFT: H is a doublet) or non linear (EwChL / HEFT) realisations
  - subsets of SM symmetries can be imposed (e.g. flavour) to restrain number of parameters
- Great tool to coherently treat different measurements
  - theoretically sound combination of Higgs, top, EW, …
  - use the full information from collider data (kinematic, rates, …)
  - specific UV models can be mapped to a EFT
- Highly complex parameter space
  - in SMEFT, 1 dim-5 operator (Maiorana) but O(3000) dim-6 operators!
  - experimentally requires the selection of those with leading effects
  - non trivial treatment of truncation



→ *Talk by Christopher Greenberg*

Violation of the SM symmetries

- Some symmetries in the SM are realised, but not protected by "first principles"
- Lepton number conservation: violated by neutrinos oscillations
- $\mu \rightarrow e$ decay
  - BR ~ 10^{-54} in the SM
  - any LFV process can enhance this - up to 10^{-15} in BSM models!

Neutrinoless $\mu \rightarrow e$ decay

Search with $\mu \rightarrow e+\gamma$ (coincidence)

Search with $\mu N \rightarrow eN$ (mono-energetic e)

Any strong violation of "accidental" SM symmetries is a smoking gun for BSM physics

→ Talk by Nicolas Chadeau

Conclusions

- The SM is a blessing and a curse
  - beautiful and elegant theory, valid up to the Planck scale
  - but astrophysical, cosmological and theoretical considerations call for new physics beyond it
  - no clear theoretical indications of what BSM could be : up to experiments to find new hints
- Broad programme of BSM searches spanning several domains of particle physics
  - direct searches
  - precise verification of the SM predictions
  - search for phenomena forbidden by the SM
- A sea of possibilities to be explored experimentally!