Au-delà du Modèle Standard

Más allá del Modelo Estándar

Über das Standardmodell hinaus

Πέρα απ'το Καθιερωμένο πρότυπο

Além do Modelo Padrão

Beyond the Standard Model

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JRJC 2019

Outline

- **Why** beyond the Standard Model ?
- **What** to look for ?
- **How** to look for New Phenomena ?

WHY NEW PHYSICS ?

The Standard Model: successes (I)

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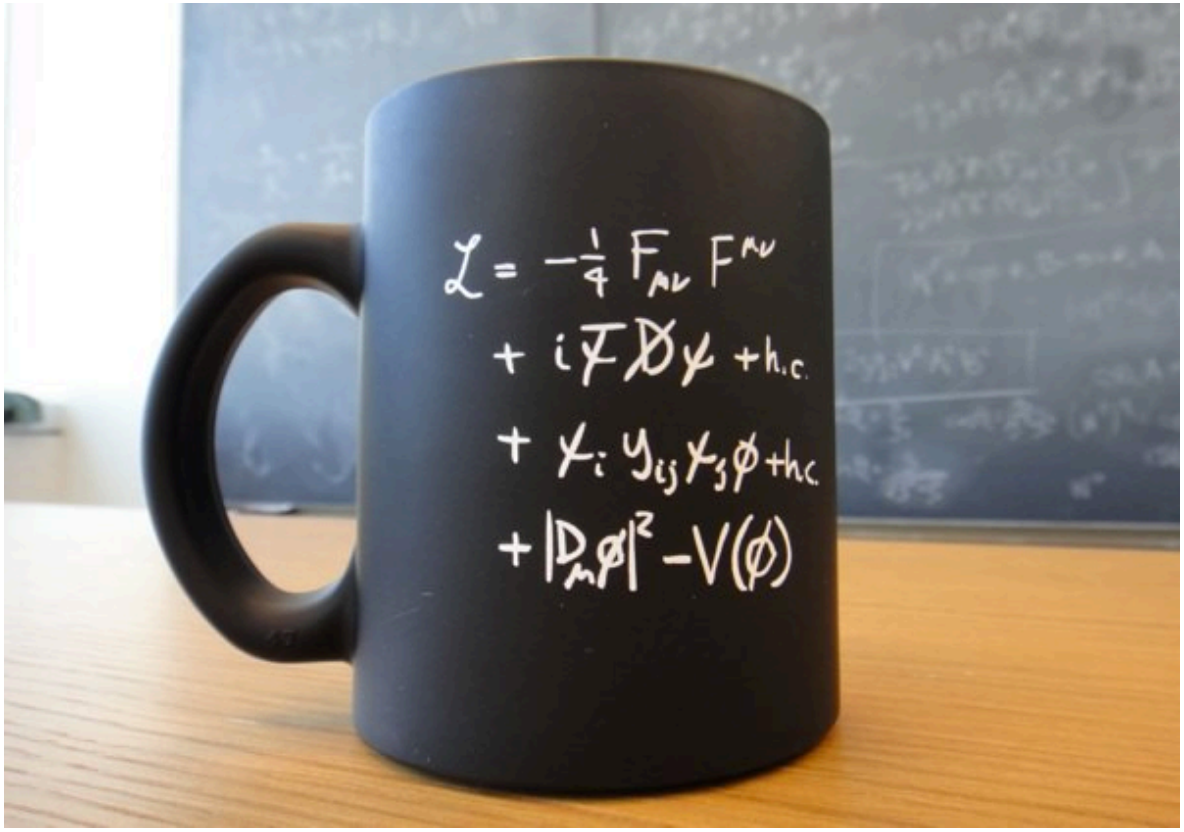
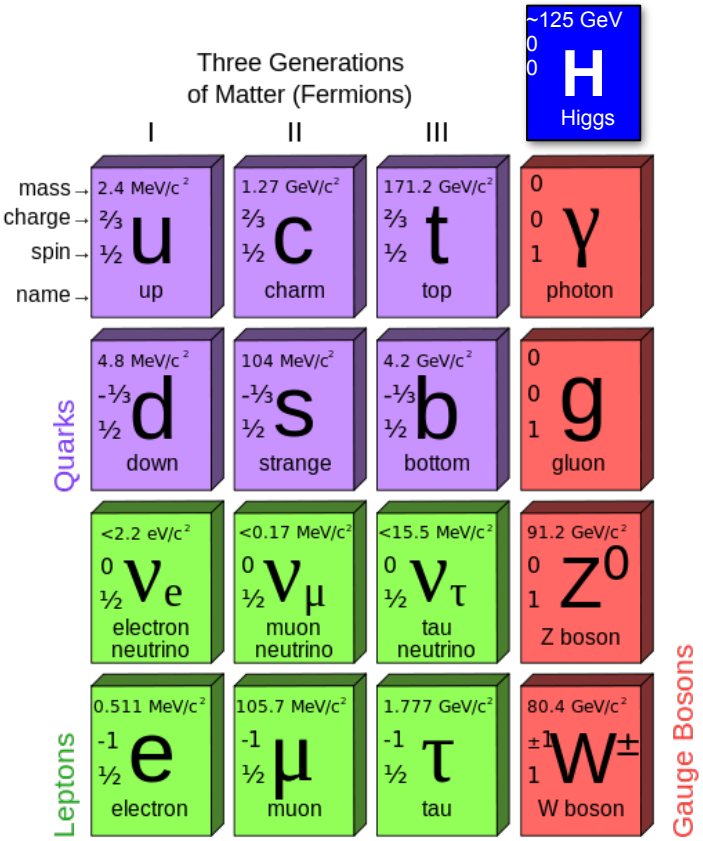
- Not just a formula on a mug …



The Standard Model: successes (I)

- Not just a formula on a mug …
- But a *complete theoretical framework* to describe **elementary particles** and **interactions**
  - **Gauge bosons**
    - Carry interactions
  - **Fermions**
    - Elementary constituents of matter
  - And **Higgs** boson …
    - Manifestation of mechanism through which particles acquire their masses
- Thoroughly tested @ LHC
  - And **pretty successfully** so far ☺ ☹



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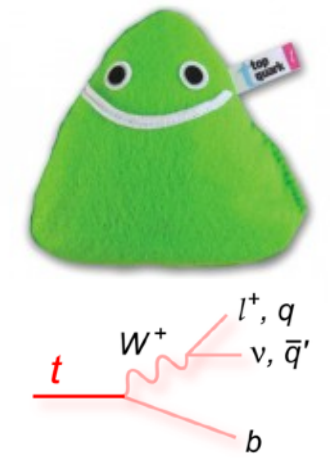

Top quark is very special … Heaviest particle in SM

Will be back later !!

escribe **elementary**

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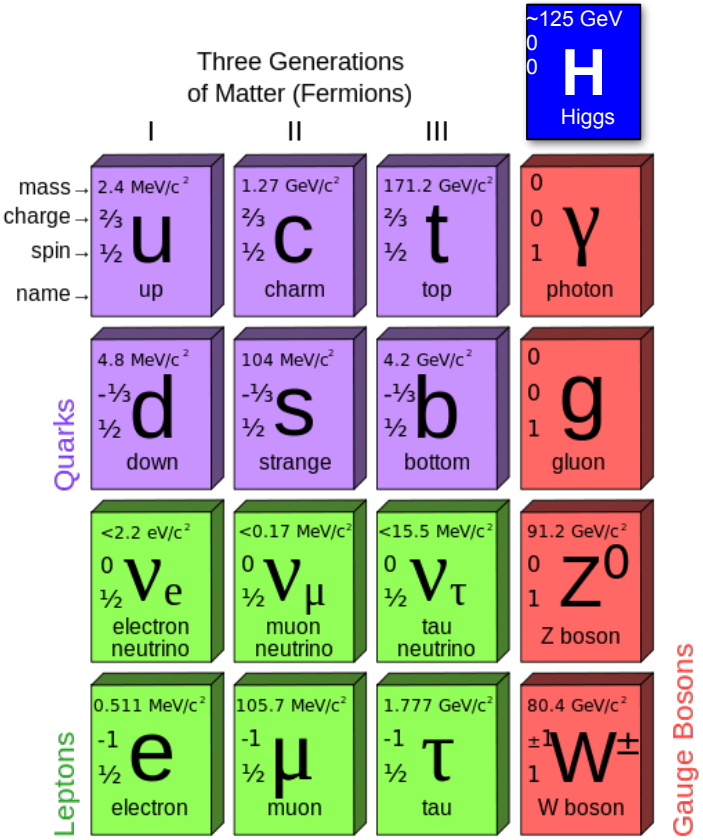

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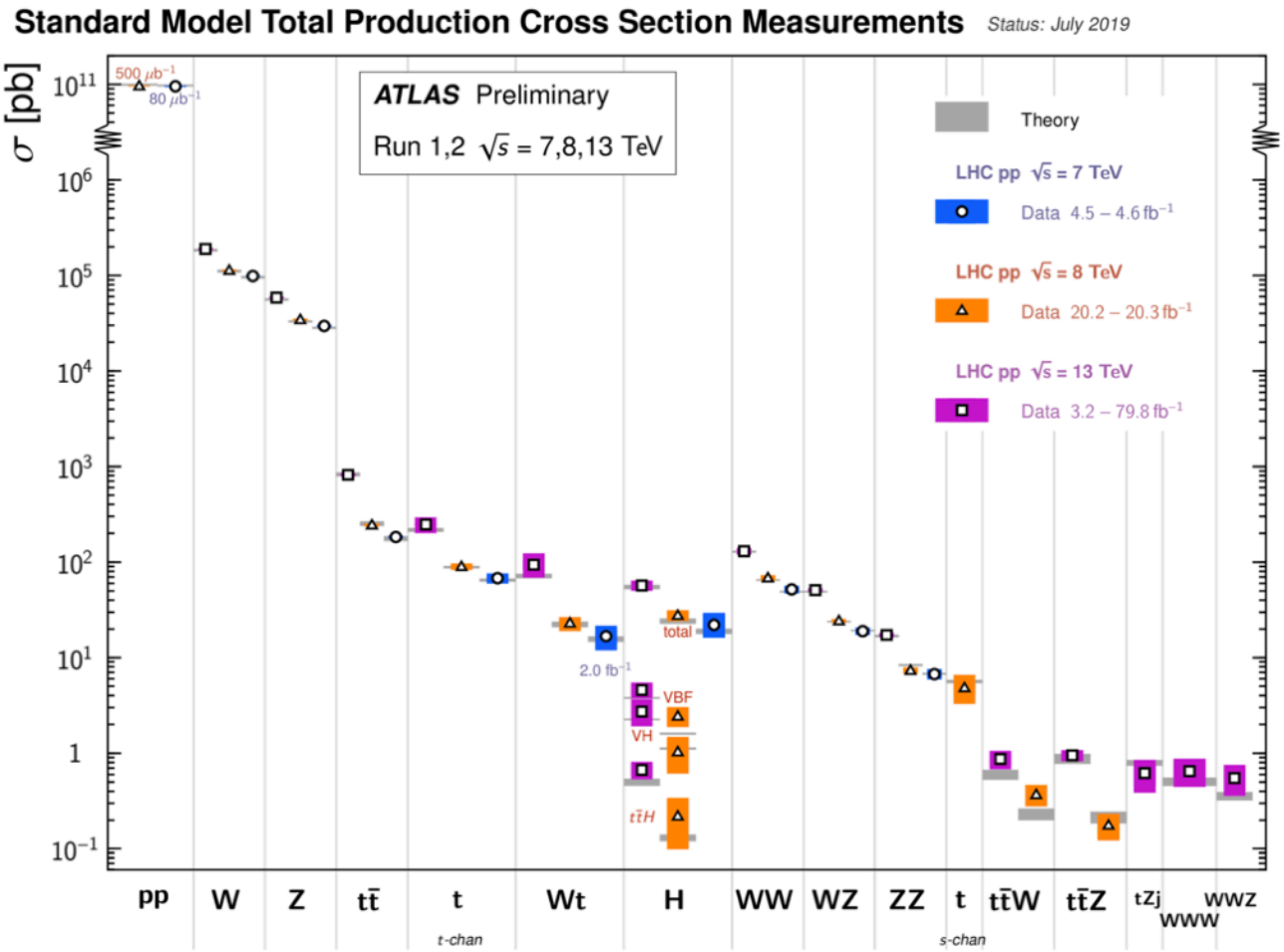
  - SM predictions verified over a wide range of cross-section, energies, …



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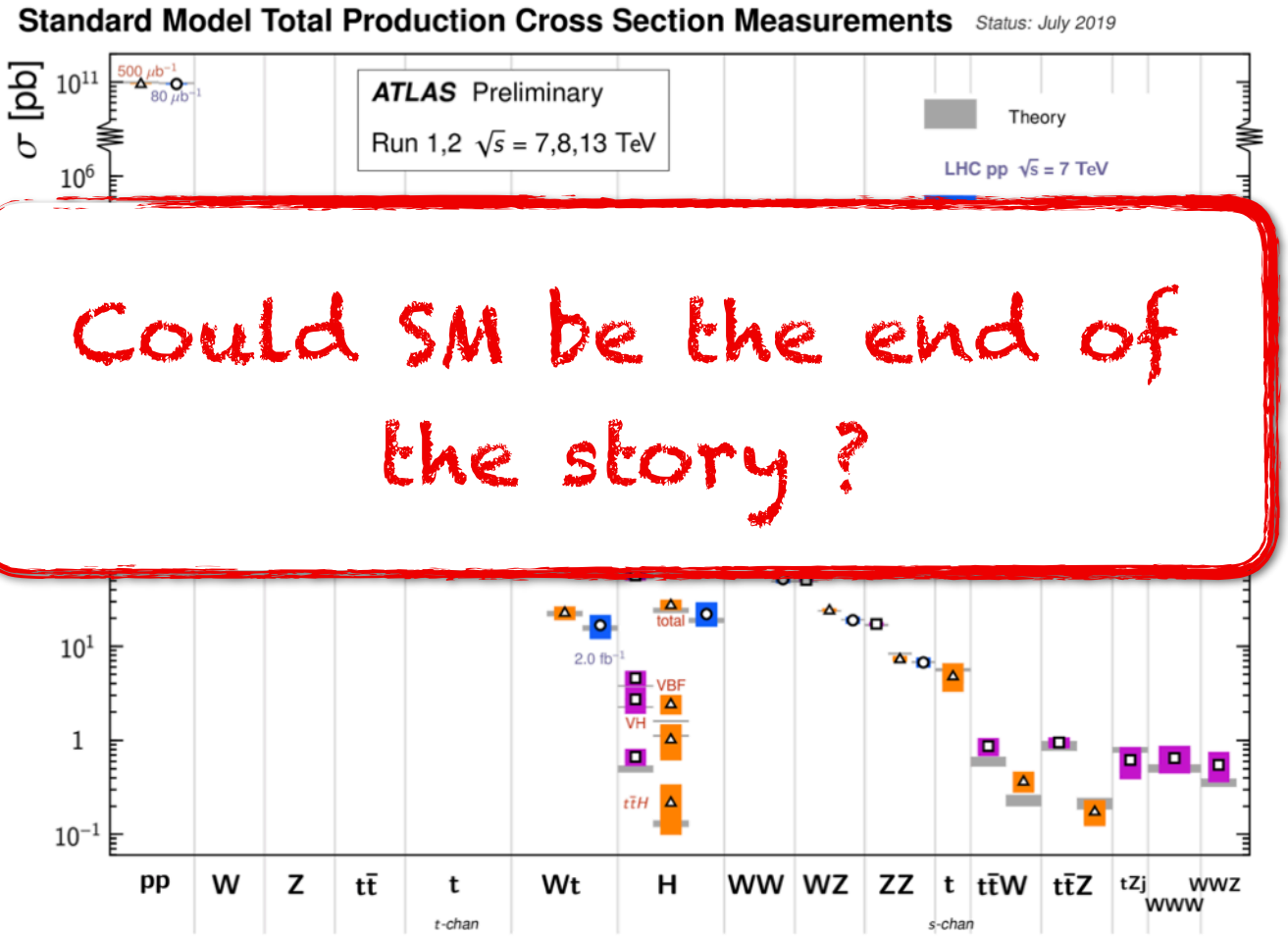

But …

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Neutrino masses

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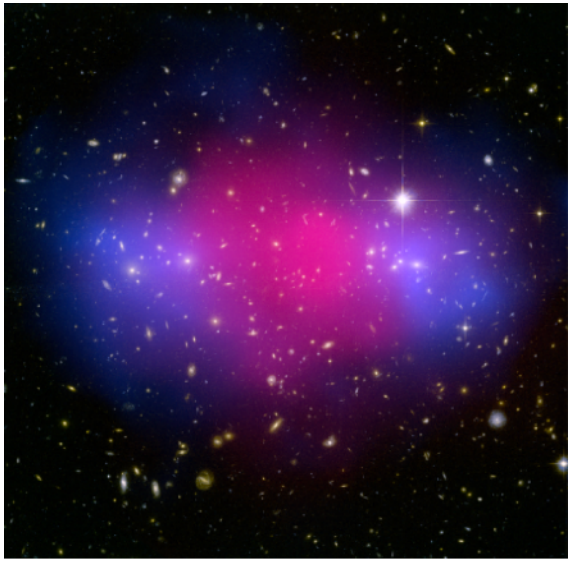

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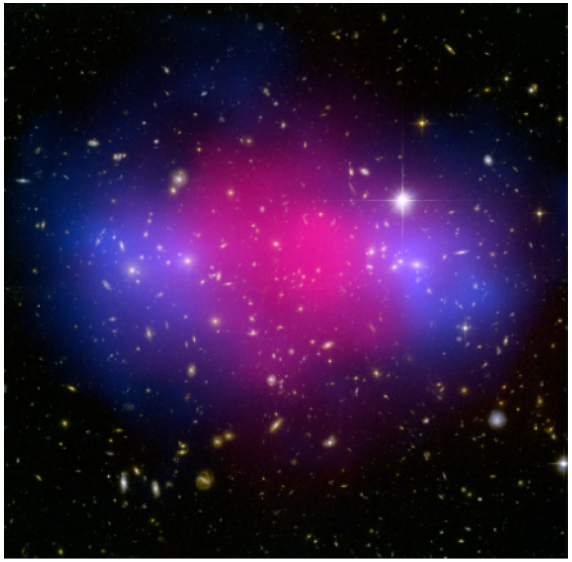

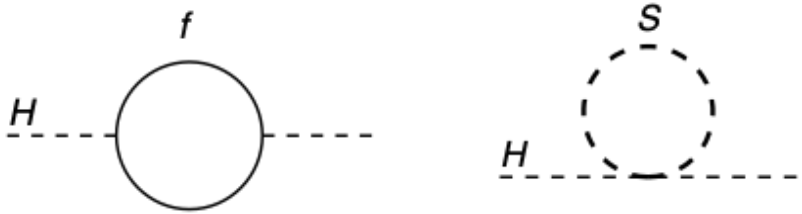

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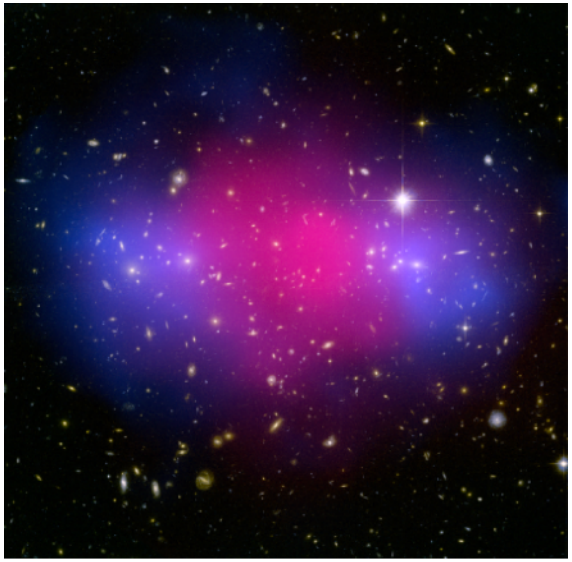

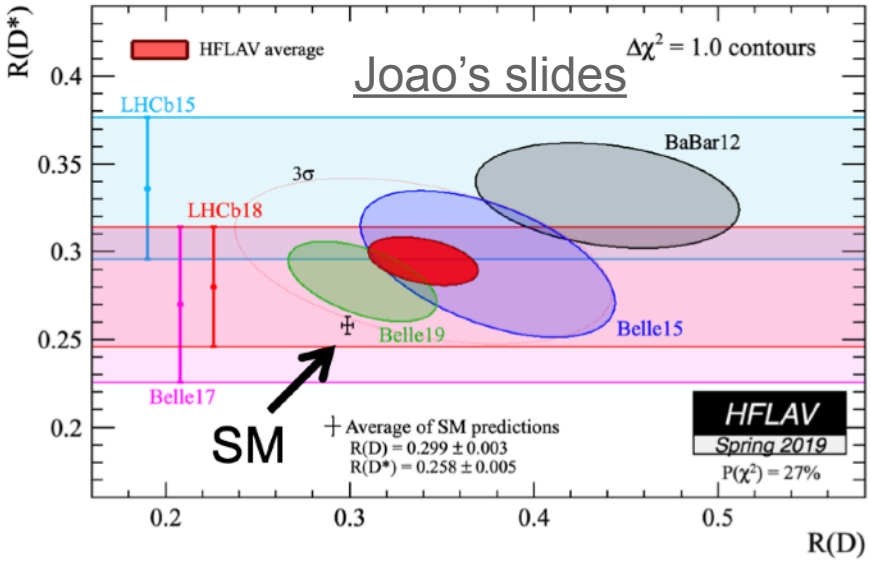

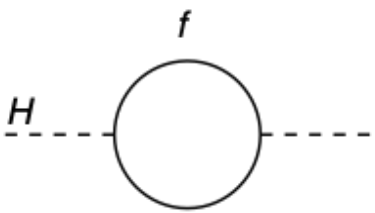

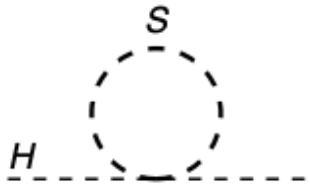

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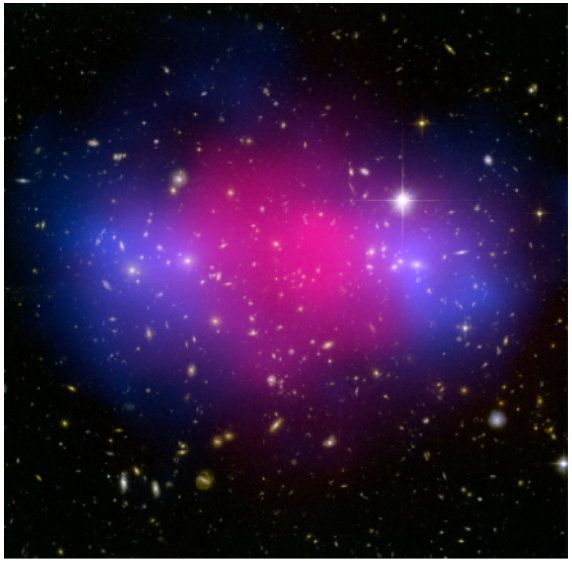
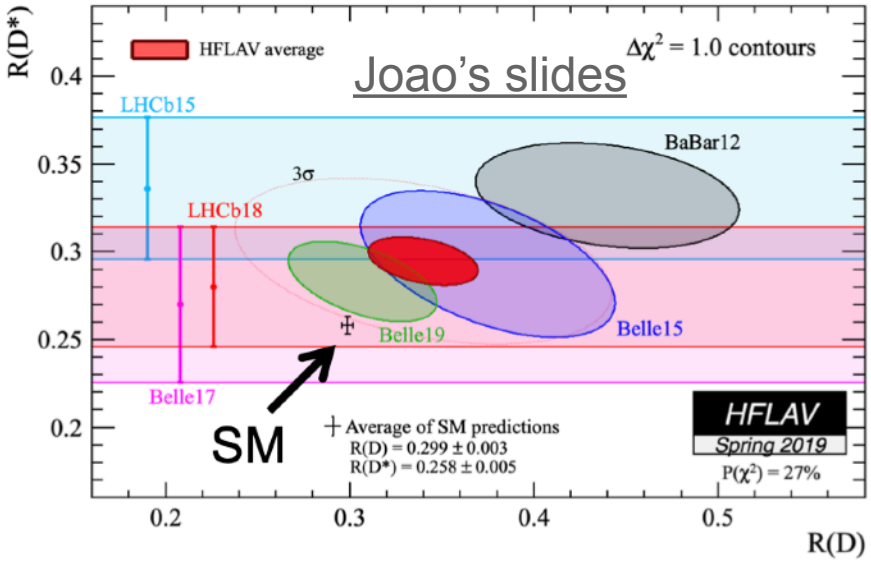
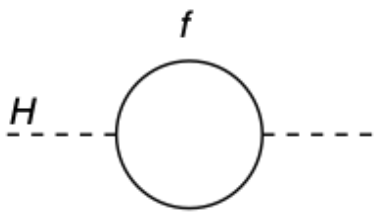
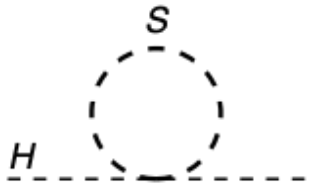






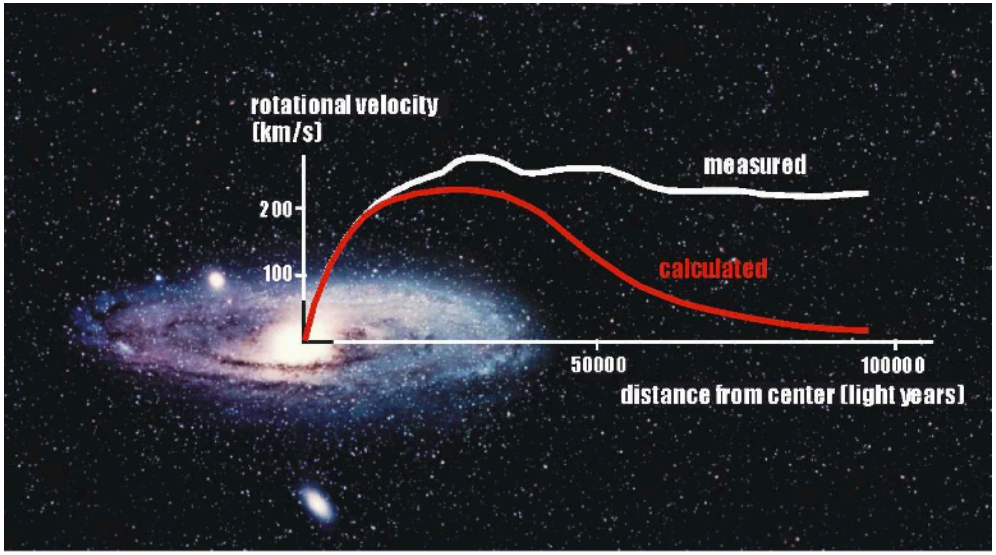


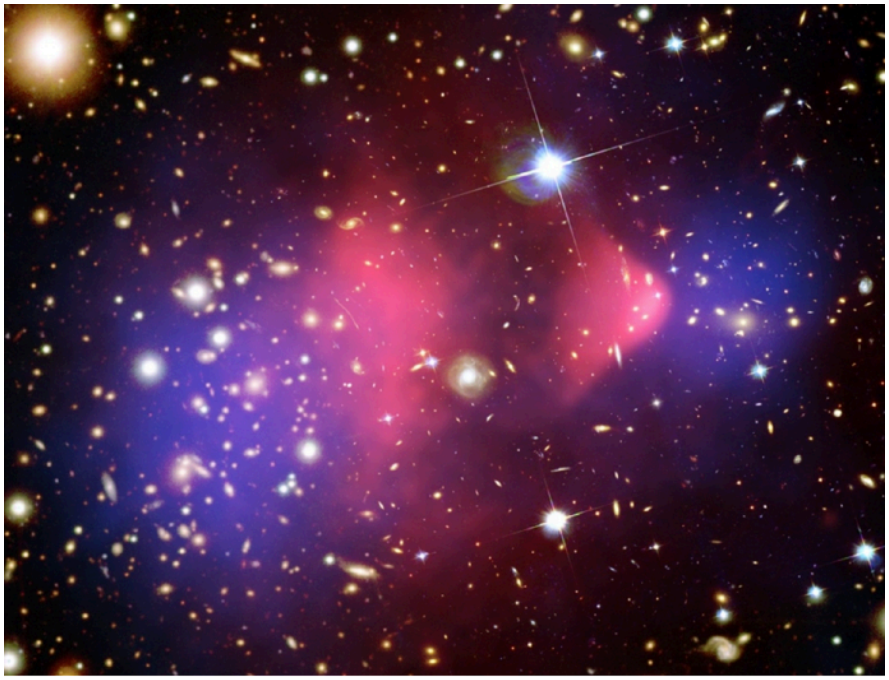
Mass/scale hierarchy

• • •

The Standard Model: limitations (I)

- **Dark matter**
  - Already discussed in previous sessions
  - Several indications of its existence … but **not described/predicted in the SM**
  - Dark matter **not described/predicted** in SM
    - *Nor is gravitation*

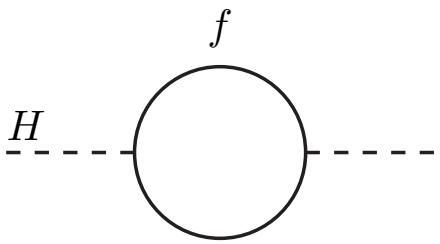


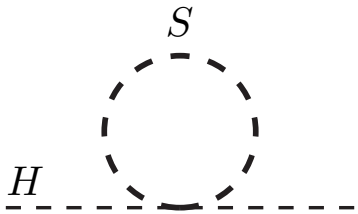


The Standard Model: limitations (II)

- **Naturalness problem**

$$m^2 = m_0^2 - \frac{\lambda_f^2}{8\pi^2}\Lambda_c^2 + \ldots$$





  - *m* measured at ~125 GeV
  - Standard Model valid until Λ_c (“cut-off scale”)
  - λ_f the fermion Yukawa coupling (i.e. coupling to the Higgs)

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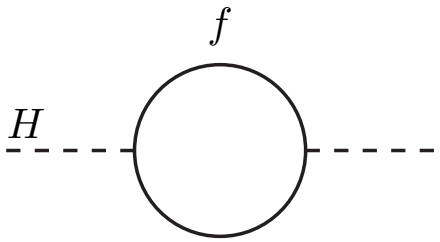

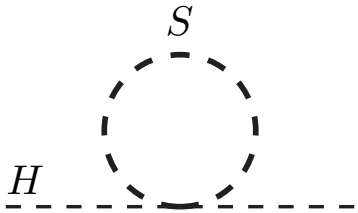

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- **Where is the problem ?**
  - m_0 and λ_f have to be adjusted up to the 32nd decimal …
  - **Not "natural" ?**

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- **Naturalness problem** as an example

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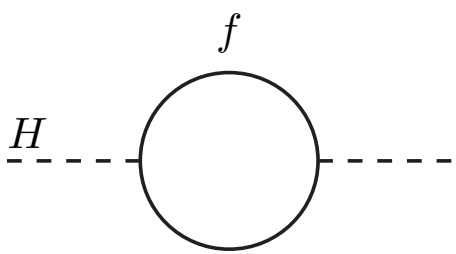

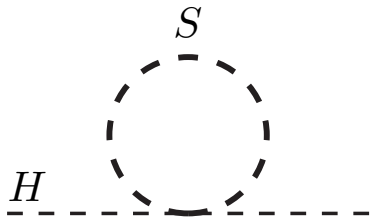

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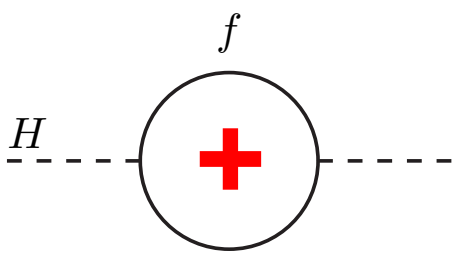

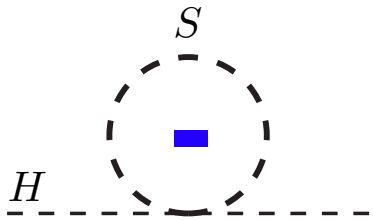

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    - Λ can be large because Planck scale is large ➔ gravitation is *weak* at our scale
    - Because it is propagating through more than 4 dimensions ?
    - So, need for **additional dimensions** !

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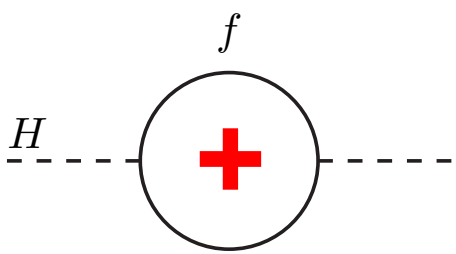

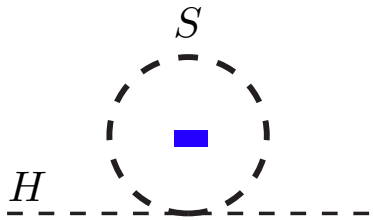

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  - **And what if Higgs was not really the Higgs ?**
    - Composite Higgs ?
    - Additional Higgs doublets

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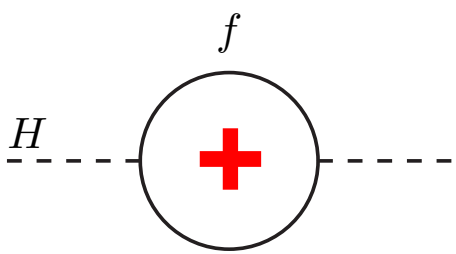

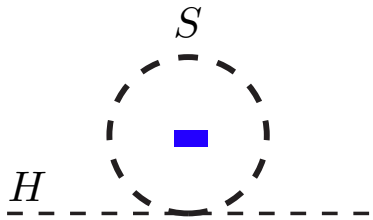

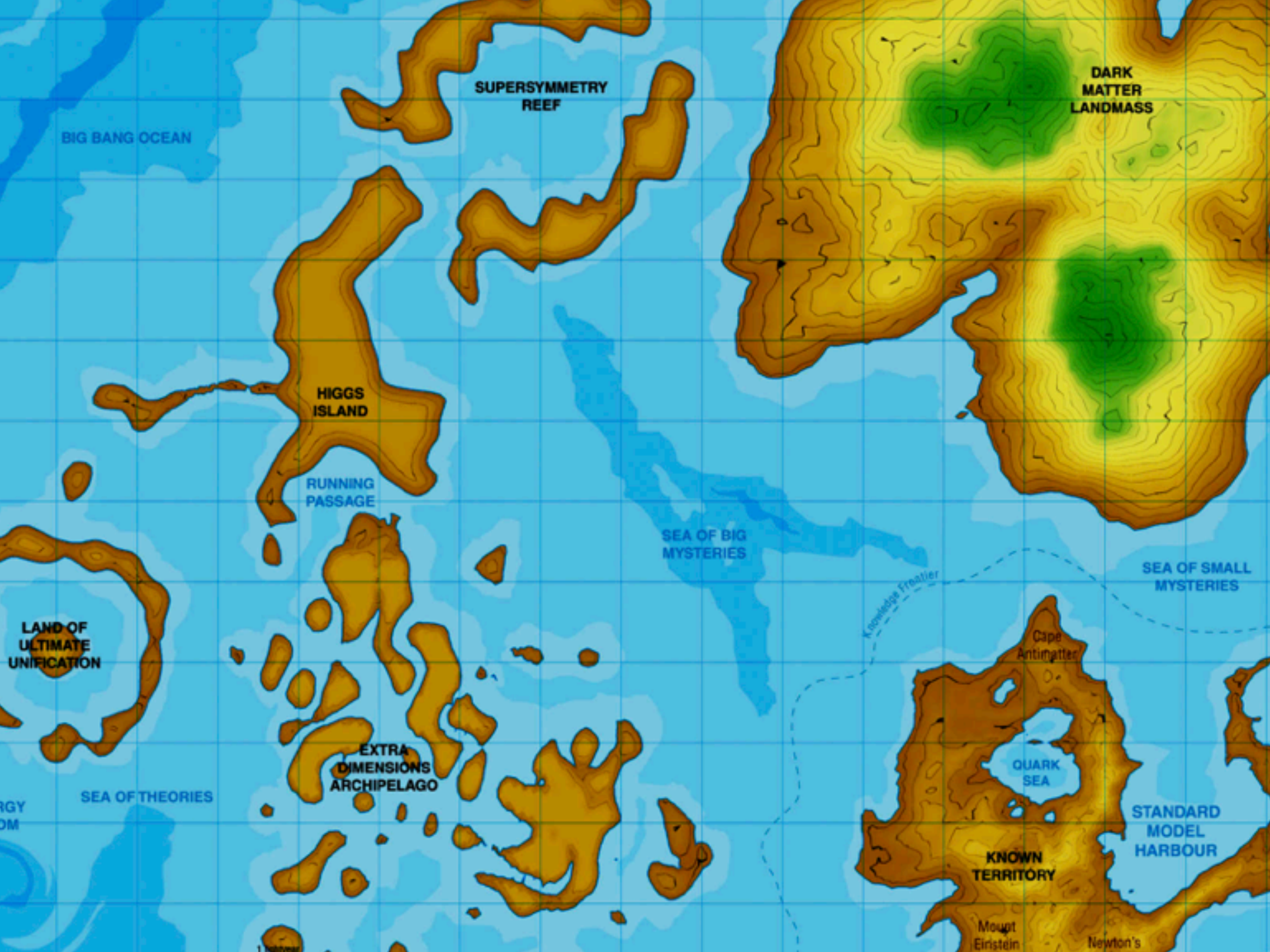
SUPERSYMMETRY REEF
DARK MATTER LANDMASS
BIG BANG OCEAN
HIGGS ISLAND
RUNNING PASSAGE
SEA OF BIG MYSTERIES
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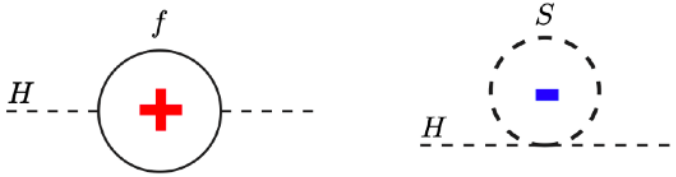
Knowledge Frontier
LAND OF ULTIMATE UNIFICATION
Cape Antimatter
EXTRA DIMENSIONS ARCHIPELAGO
QUARK SEA
SEA OF THEORIES
STANDARD MODEL HARBOUR
KNOWN TERRITORY
Mount Einstein
Newton's

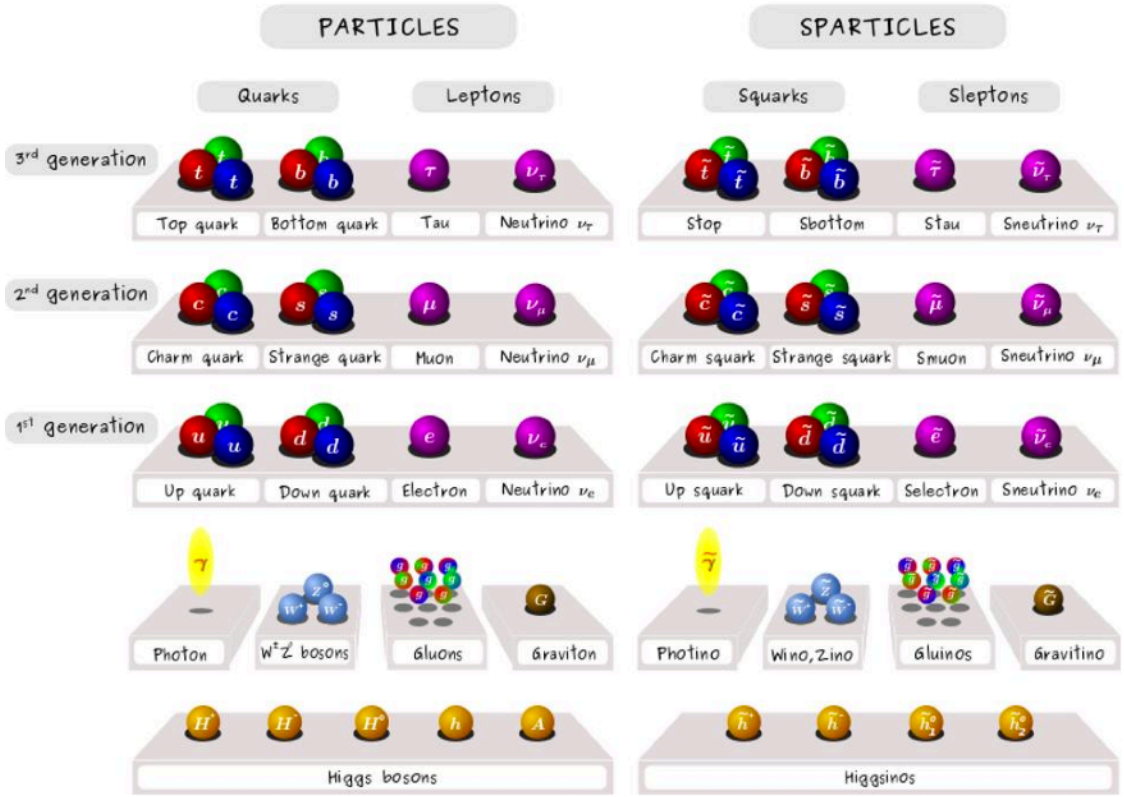
WHAT TO LOOK FOR ?

Supersymmetry (I)



- **General idea**

Fermion / Boson symmetry



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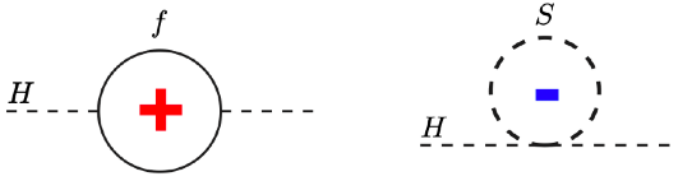

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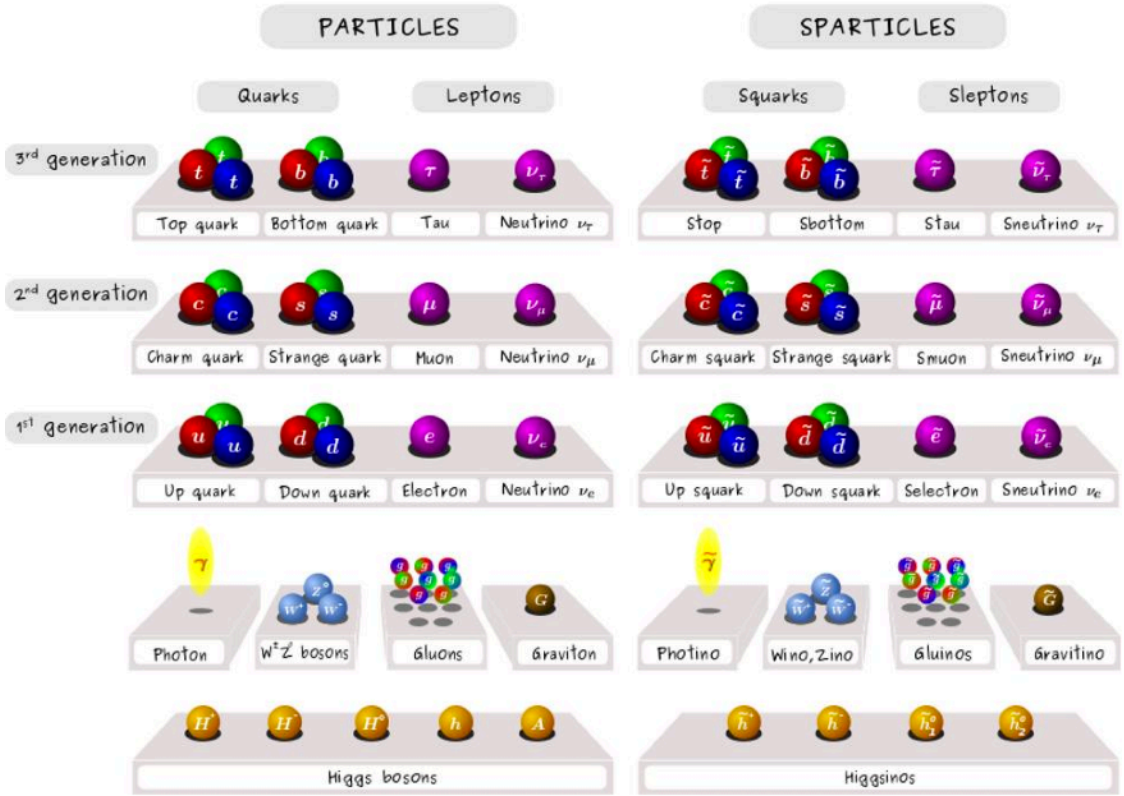

Particle content: ~factor 2

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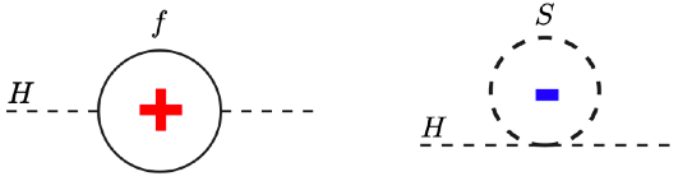

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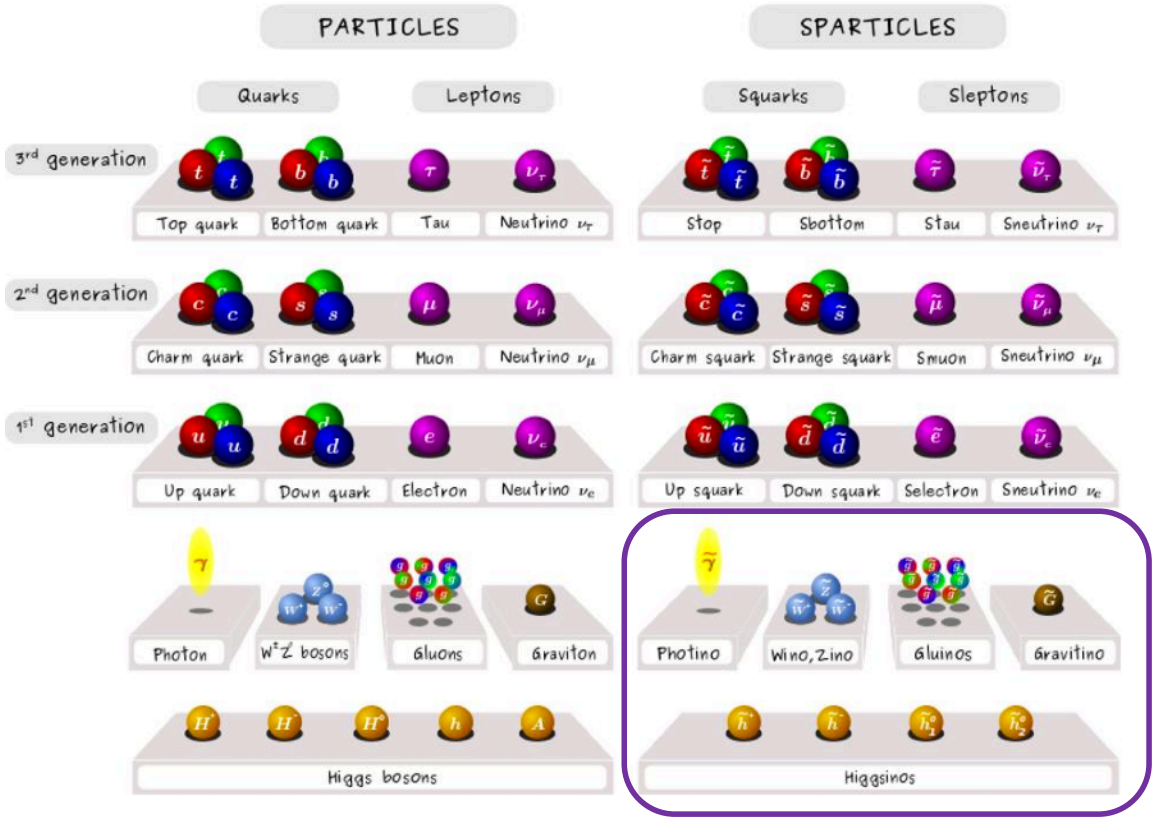

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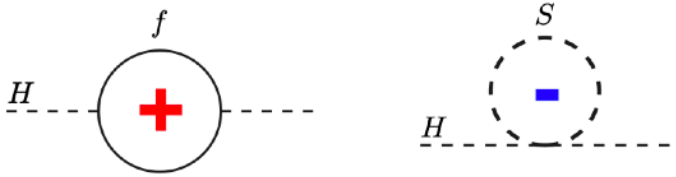

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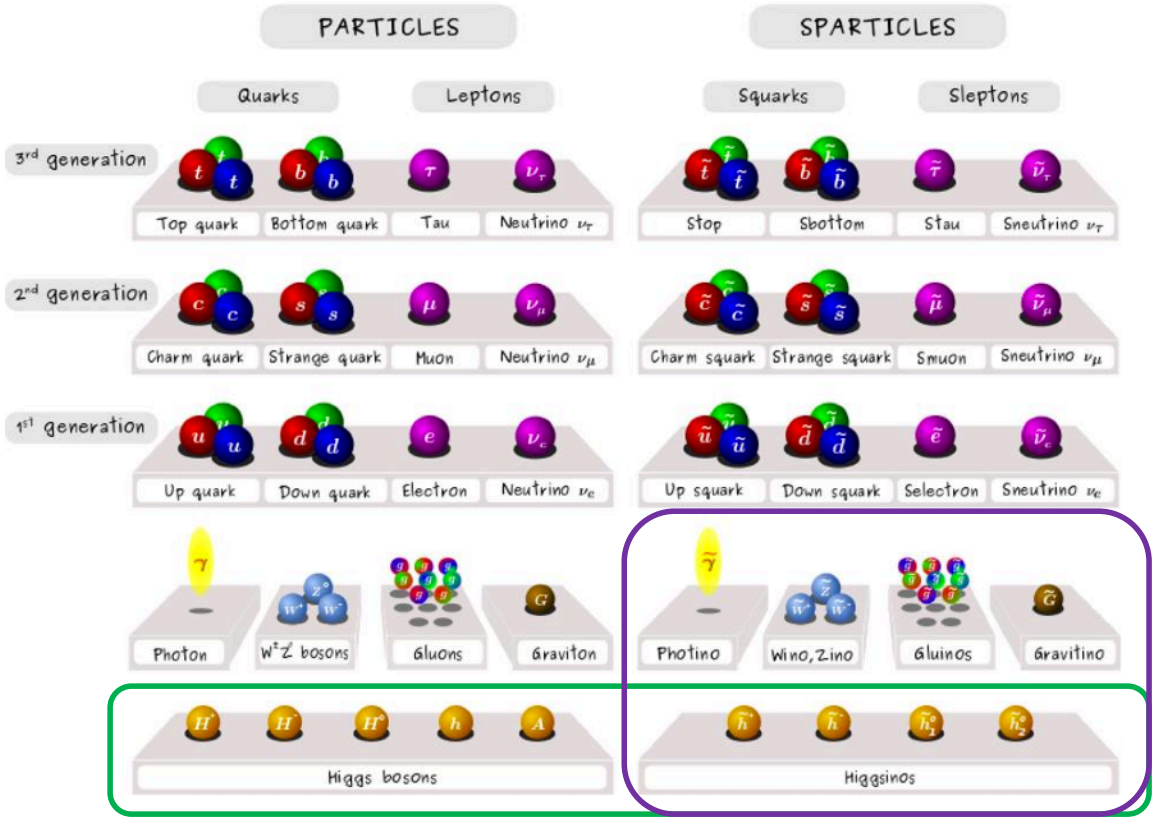

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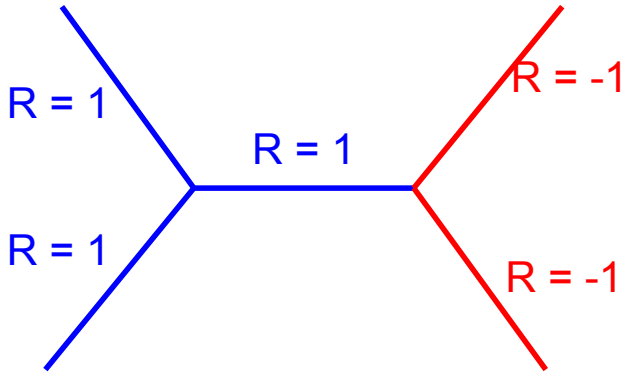
Extended Higgs sector

Supersymmetry (II)

- **R-parity and dark matter**
  - R-parity defined as

$$R = (-1)^{3(B-L)+2s}$$

    - B and L the baryonic and leptonic numbers
    - s the spin
    - **Consequence**:
      - R = -1 for SUSY particles
      - R = +1 for SM particles



  - Experimental constraints (protect proton lifetime) ➔ **R-parity conserved**
  - **Consequences**
    - SUSY particles **pair-produced**
    - SUSY particle decays have to contain one SUSY particle
      - **Dark matter candidate**

Supersymmetry (III)

- **Back to symmetries !**
  - Symmetry exactly realised → identical masses

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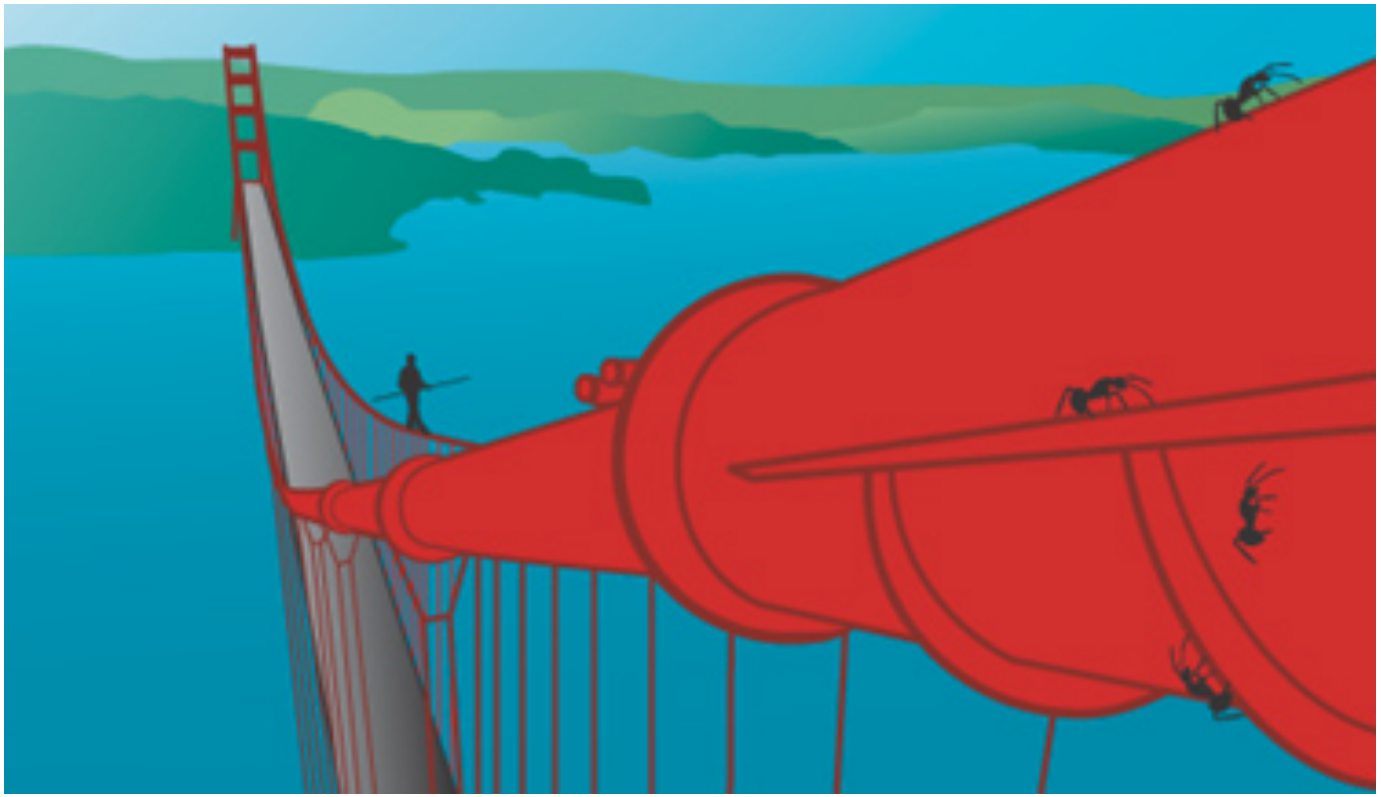
Experiments announce that no SUSY particles were found.

- **Solution: SUSY is (softly) broken**
- **Breaking mechanism**: unknown ☹
  - Some proposals exist … but lead to models with >120 parameters
  - Hard to search for ... can be anything/anywhere …
    - Use **phenomenologically-motivated** configurations
    - Use (very) **simplified effective** models
      - Limited number of SUSY particles, fixed branching ratios, ...

Extra-dimension theories (I)

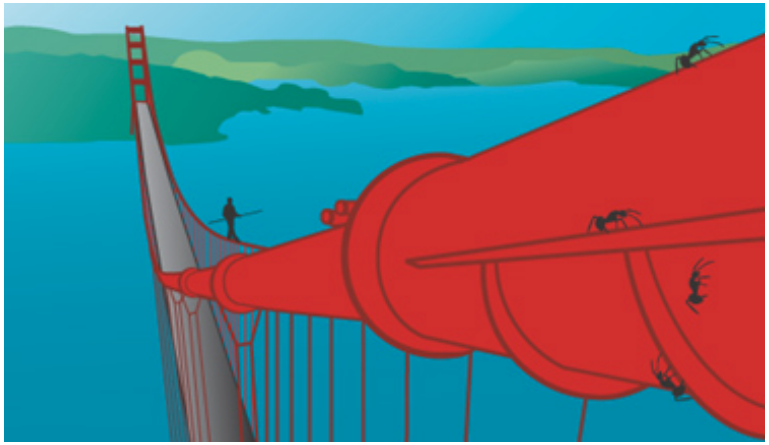
- **General idea**



Extra-dimension theories (I)

- **General idea**
  - New dimension(s) in which **some interactions would propagate** (gravitation)
  - *Gravitation*
    - Force: $F = G_g \frac{m_a m_b}{r_{AB}^{2+d}}$
    - But of course … planet's orbits are all affected ....
  - New dimensions need to be **compactified**

$$F = G_g \frac{m_a m_b}{r_{AB}^2 R^d}$$



Extra-dimension theories (II)

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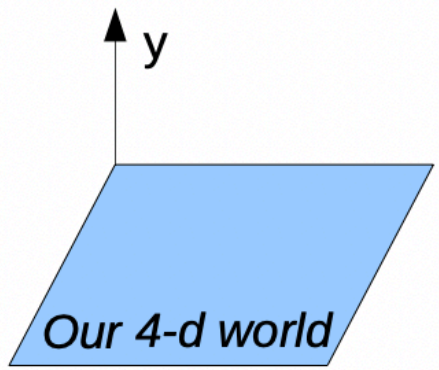
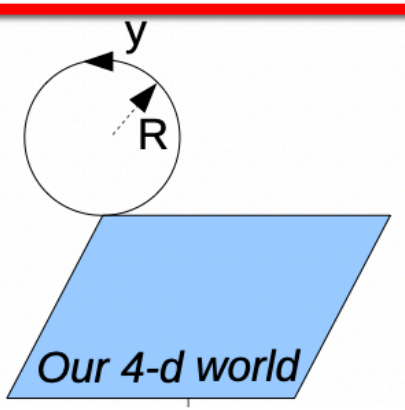
"Flat"



$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu \ (\mu,\nu = 0,1,2,3...D)$$



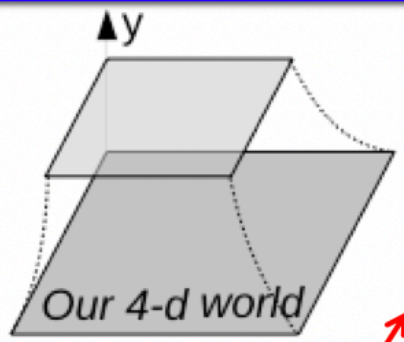
Periodicity conditions on field …
Fourier expansion

$$\phi(x_\mu, y) = \sum_{k=-\infty}^{+\infty} \phi^{(k)}(x_\mu) e^{\frac{iky}{R}}$$

Kaluza-Klein modes
(infinite number)

$$m_k^2 = m_o^2 + \frac{k^2}{R^2}$$

"Warped"



Warp factor

$$ds^2 = a(y)(\eta_{\mu\nu}dx^\mu dx^\nu) + dy^2$$

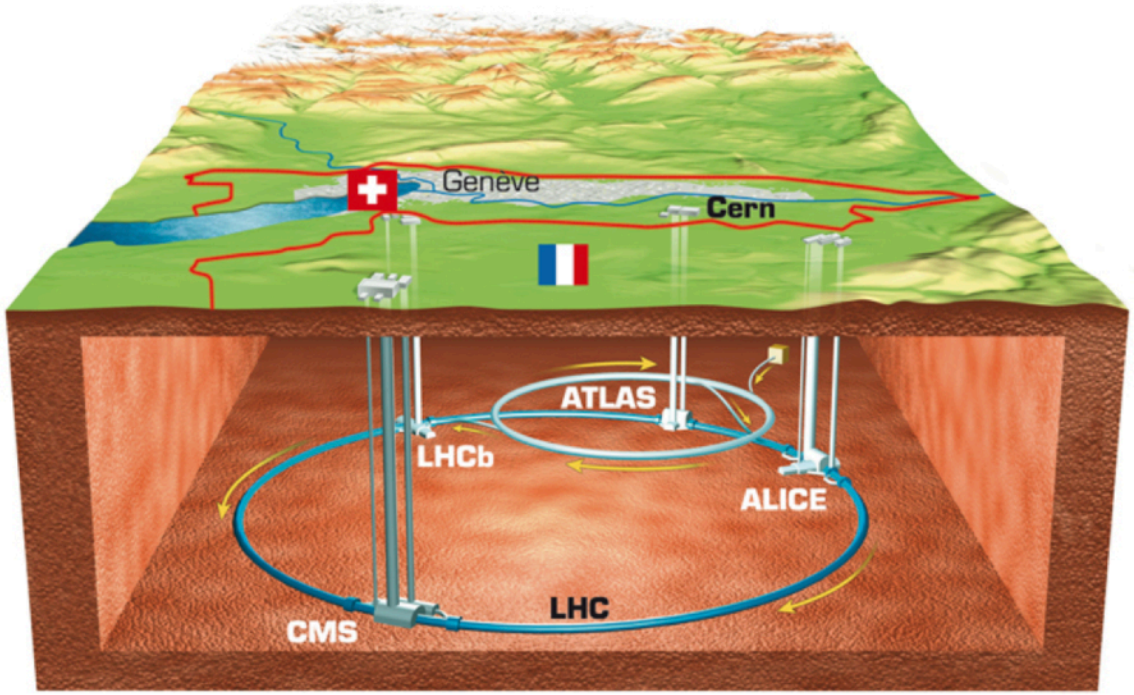
Extra-dimension theories (III)

- **Types of** ED theories
  - Depend on
    - number of extra-dimensions: 1 or ≥2
    - topology (flat or warped)
    - fields propagating along new dimensions
  - **Lots of combinations** … with different phenomenologies …

HOW TO LOOK FOR BSM ?

Produce new particles ?

- New physics = **high-energy** and **rare**



- **Collision energy**: 13 TeV
  - *Proton speed: 99.999% c*
- **Collision rate**
  - *600 millions / second*

Observe new particles ?

~~Observe new particles ?~~

Are we in Brittany ?

~~Observe new particles ?~~

Are we in Brittany ?

Direct way

GPS coordinates

~~Observe new particles ?~~

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Kouign amann density theorem

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(also works with salted butter)

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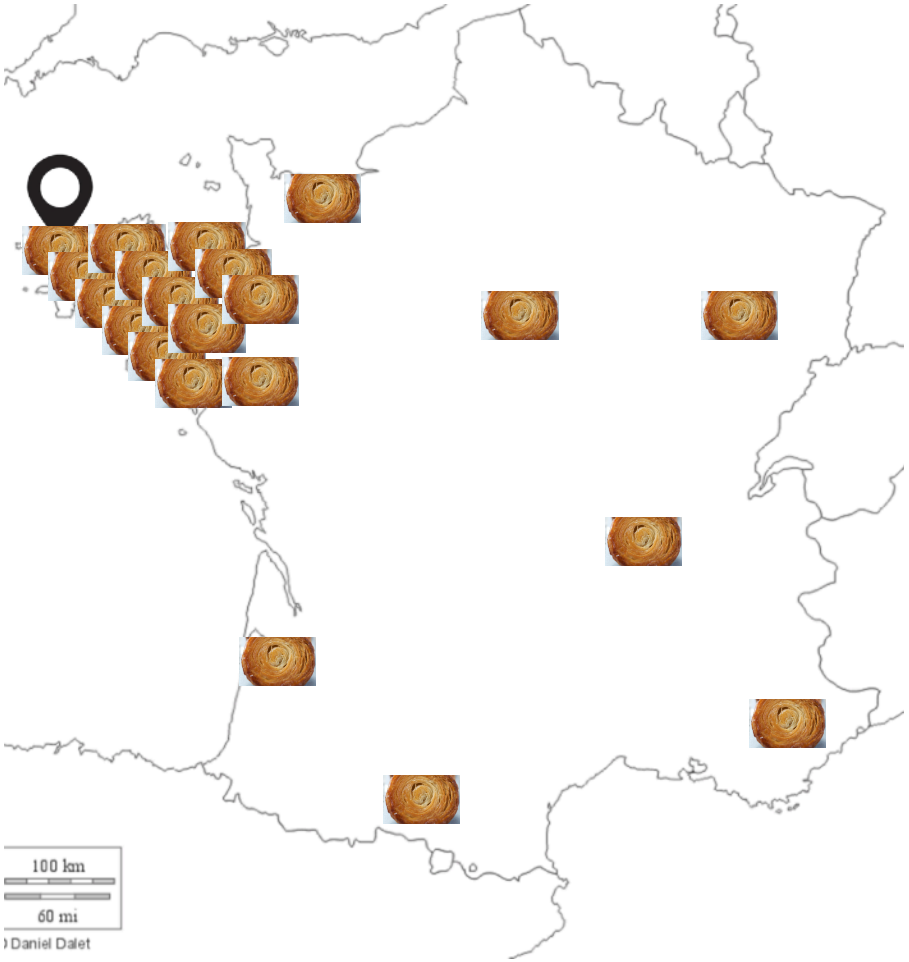

Direct way

GPS coordinates

Indirect way

Kouign amann density theorem
(also works with salted butter)

BSM searches: new Higgs bosons ?

- Could be detected **directly/indirectly**

BSM searches: new Higgs bosons ?

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Directly

We can “see” the new Higgs boson(s)

BSM searches: new Higgs bosons ?

- Could be detected **directly/indirectly**

Directly

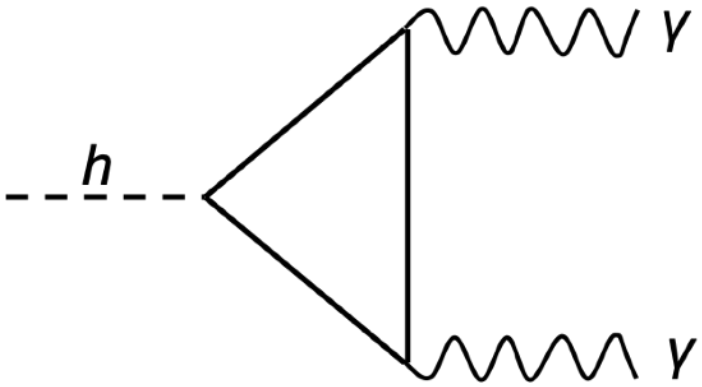
We can “see” the new Higgs boson(s)

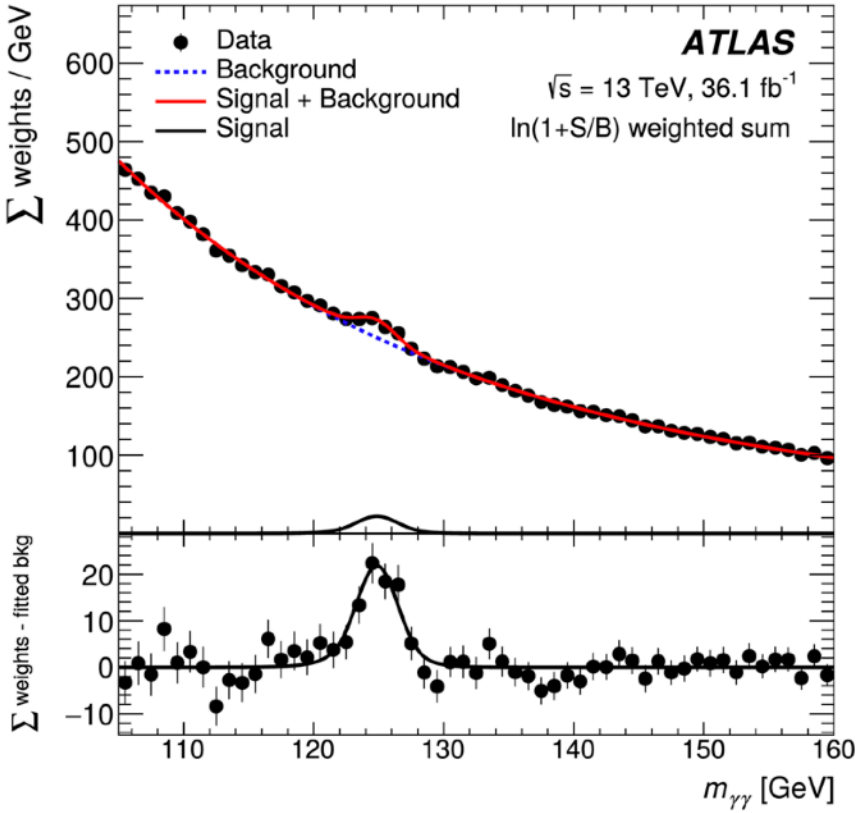
Indirectly

We can “see” some effects of new Higgs boson(s)

Direct search

- Look for a **“bump” on a spectrum**





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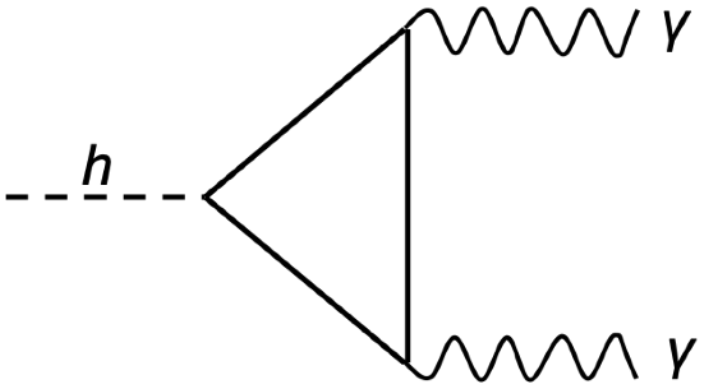
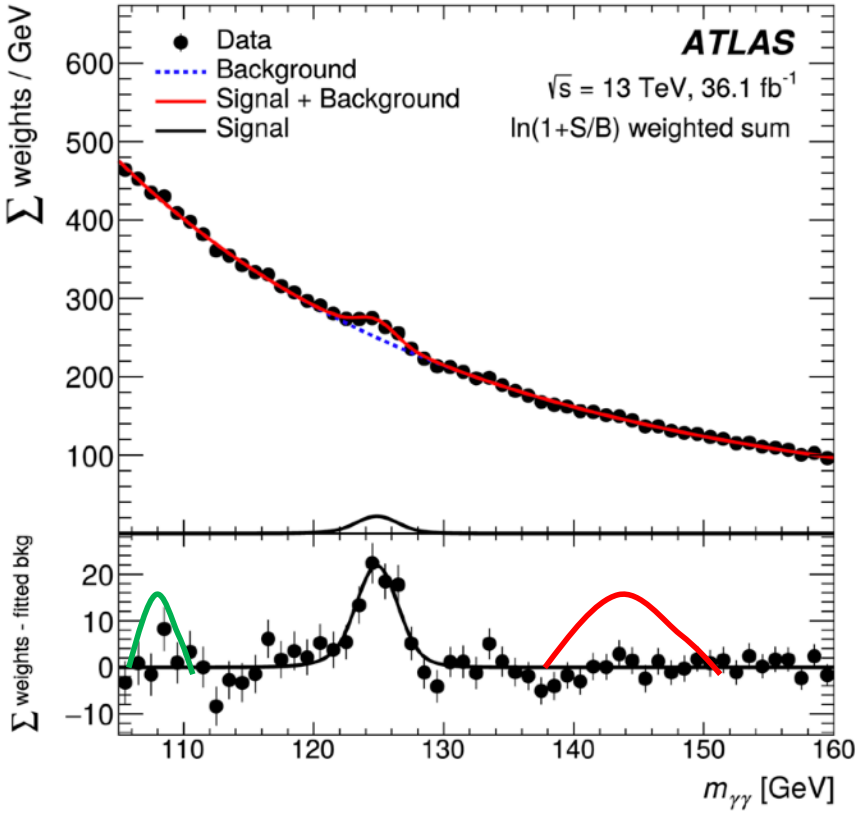


new peaks

new resonances

sign of new physics



Direct search

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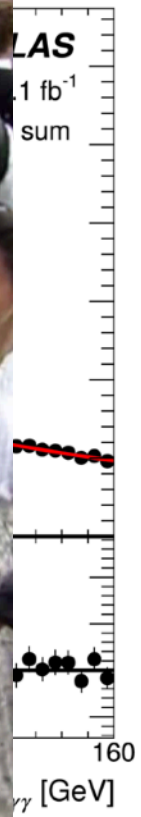

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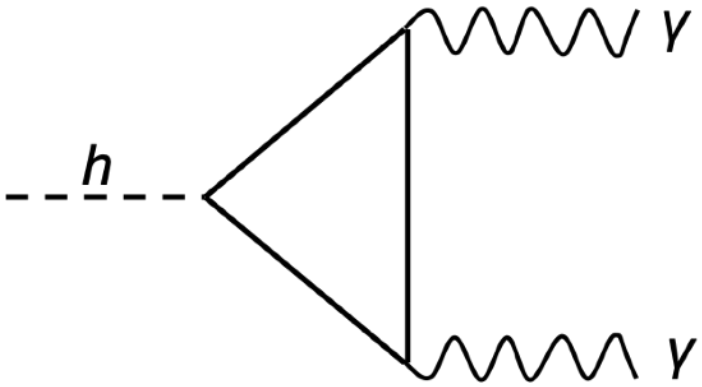

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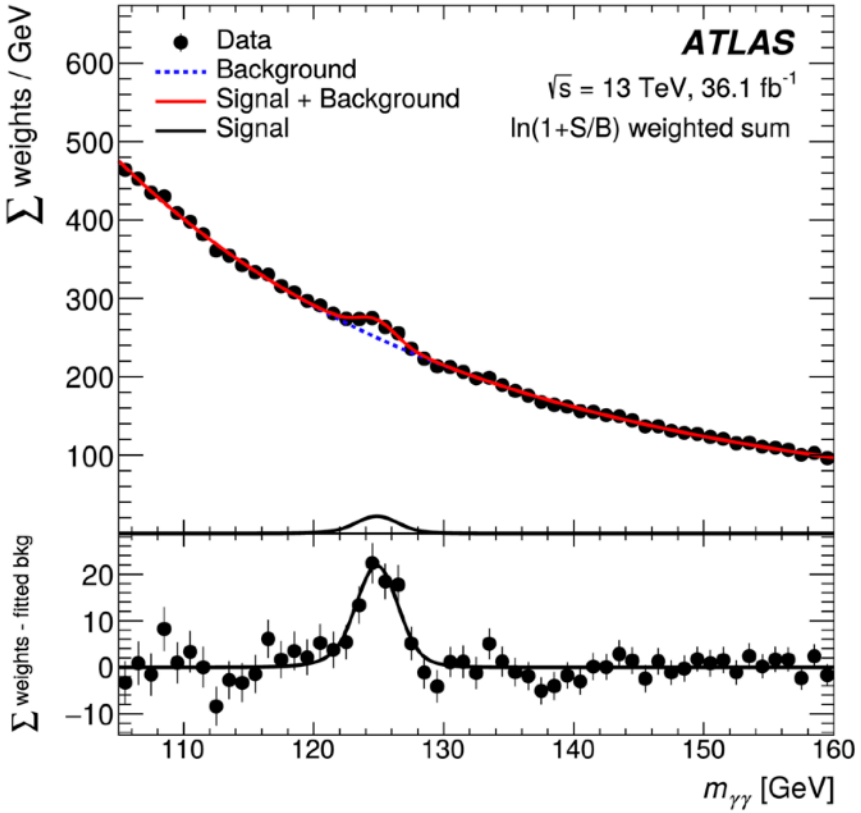

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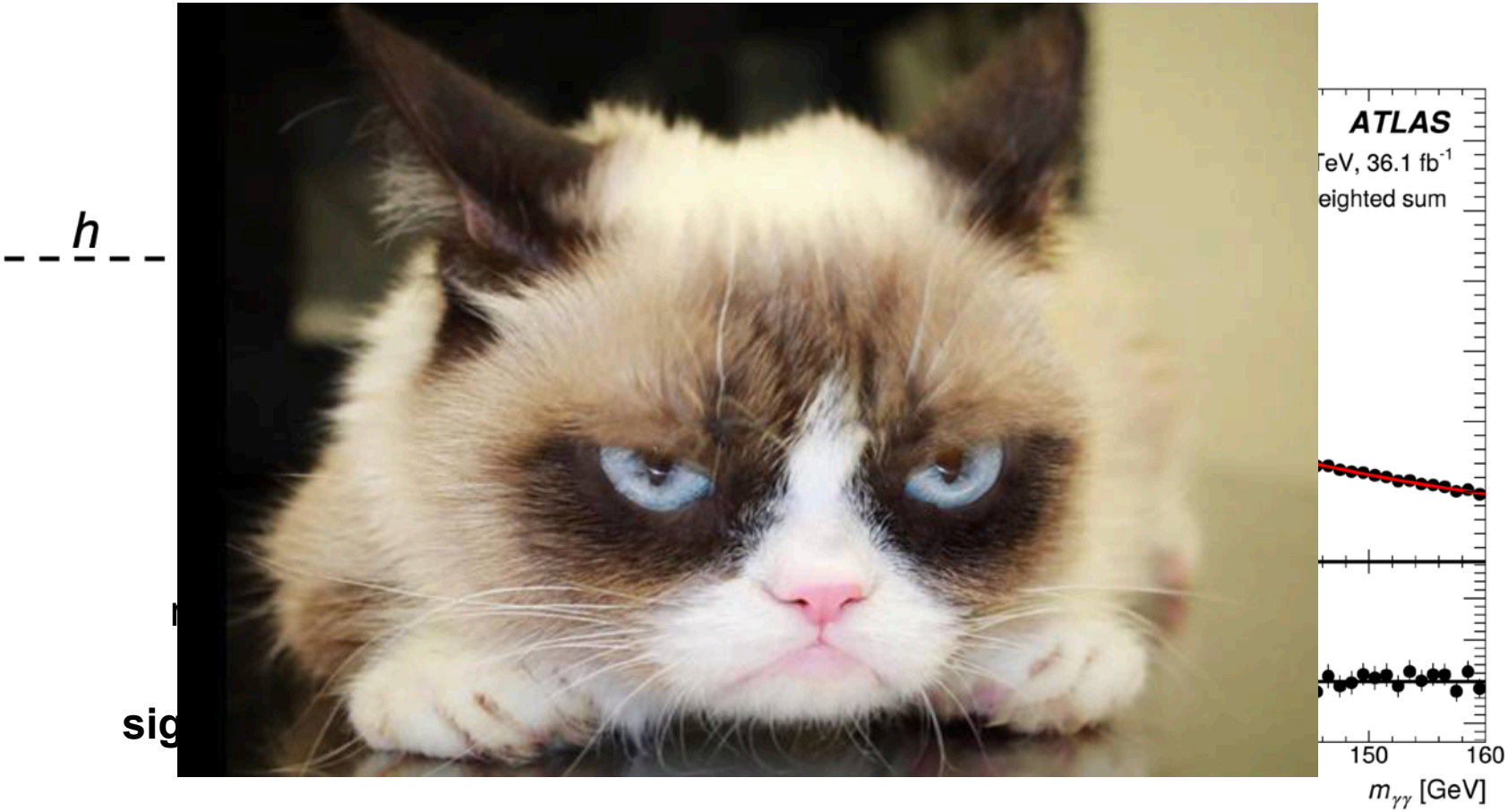

[Statistical break]

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[Statistical break] Hypothesis test (I)

- *How big should be an existing signal to be seen ?*
- Let's assume that our signal has a **large production rate**

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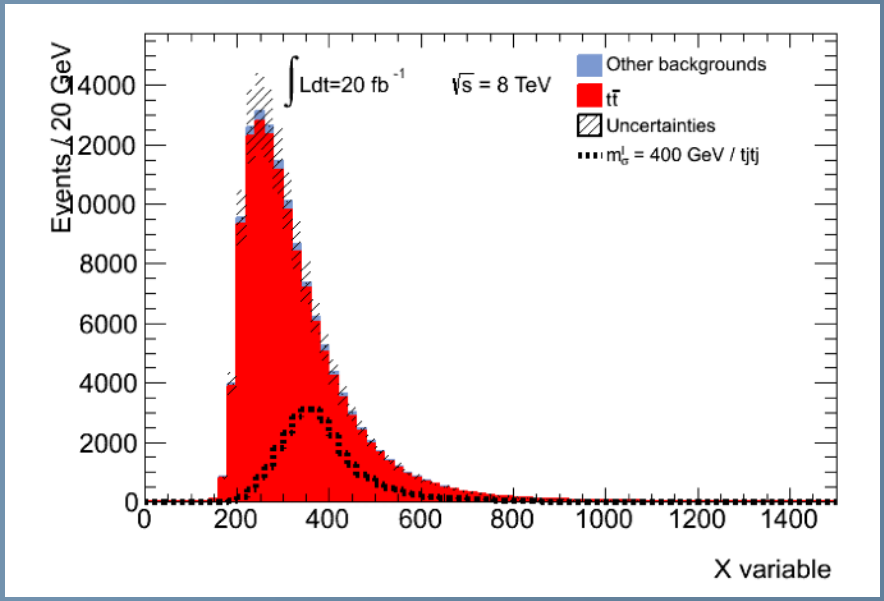

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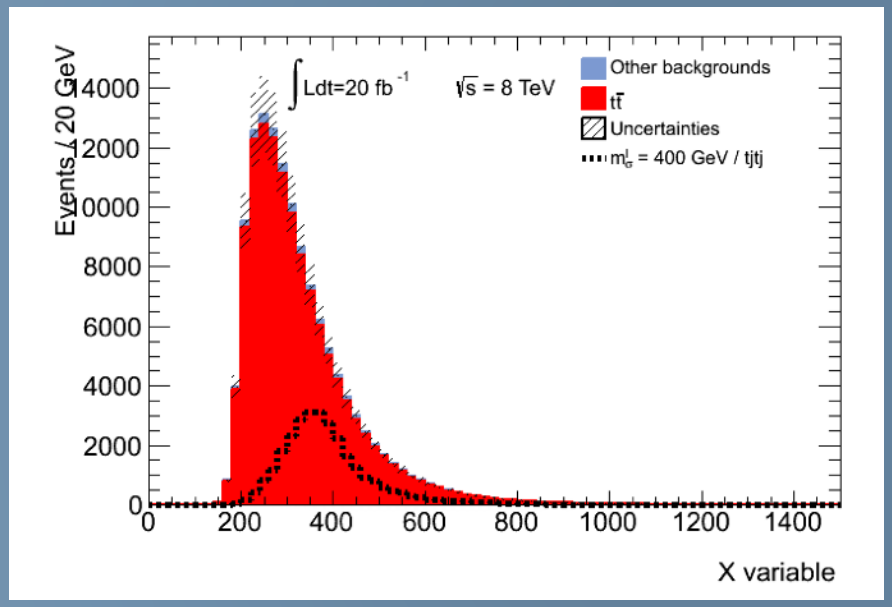

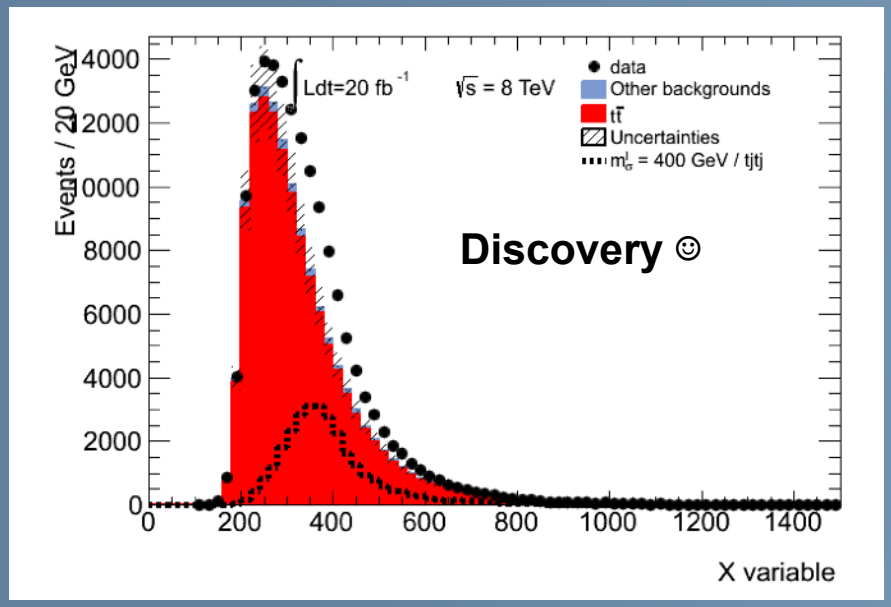

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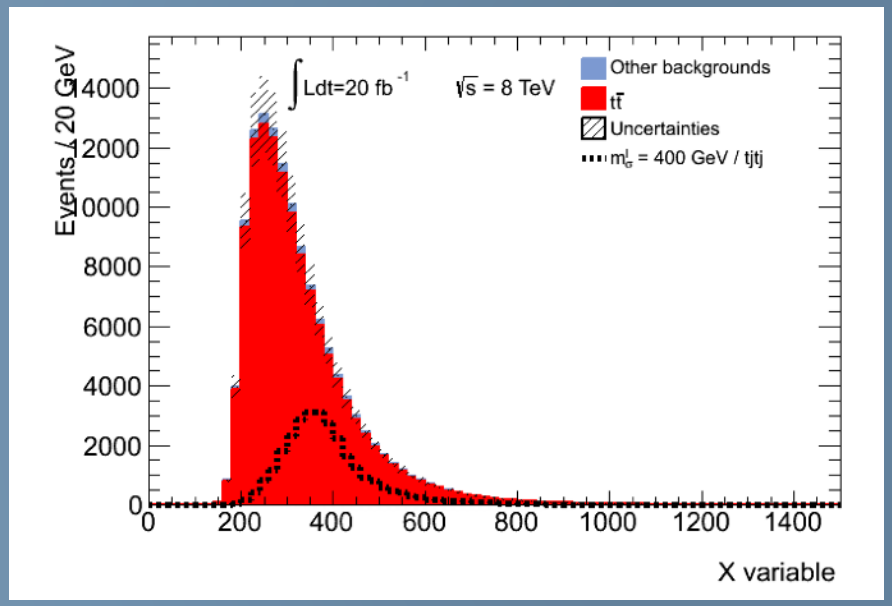
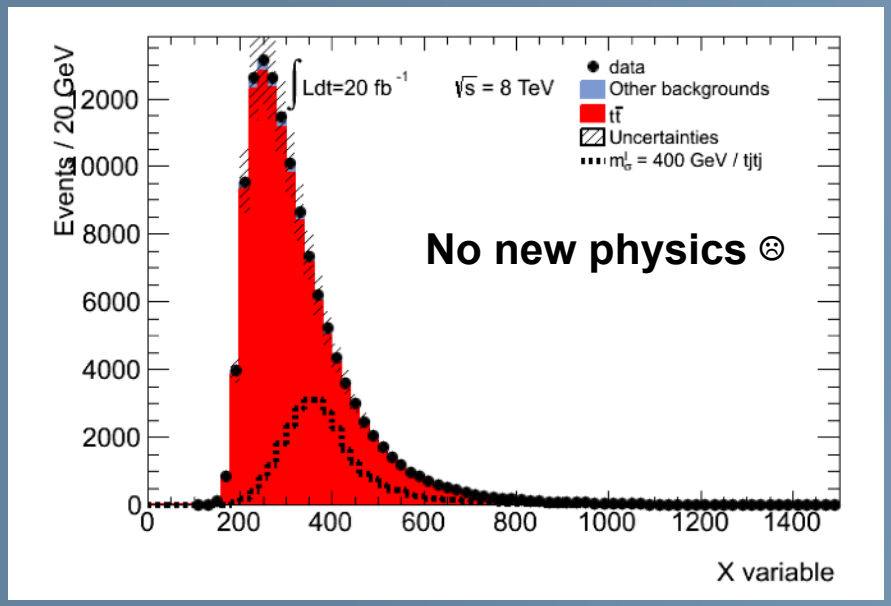
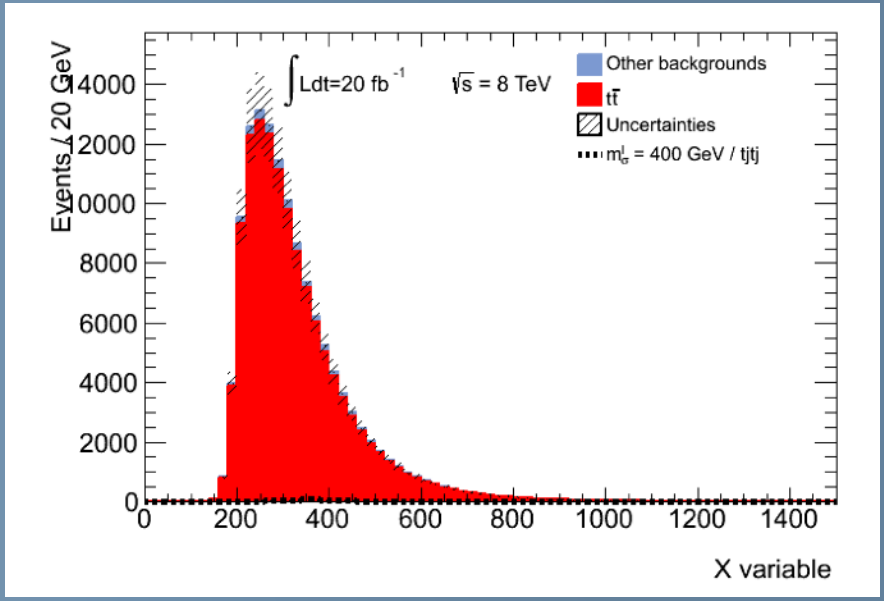




- If this signal existed … we would have seen it !
- **If we don't see anything ➔ signal likely doesn't exist**
  - This signal (at this rate) is **excluded**

[Statistical break] Hypothesis test (II)

- *How big should be an existing signal to be seen ?*
- Let's assume that our signal has a **tiny** **production rate**



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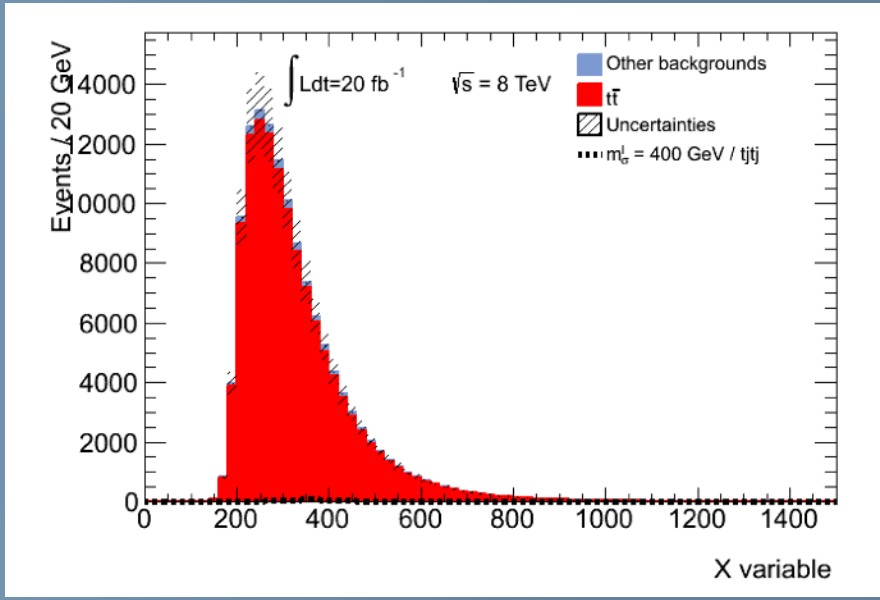

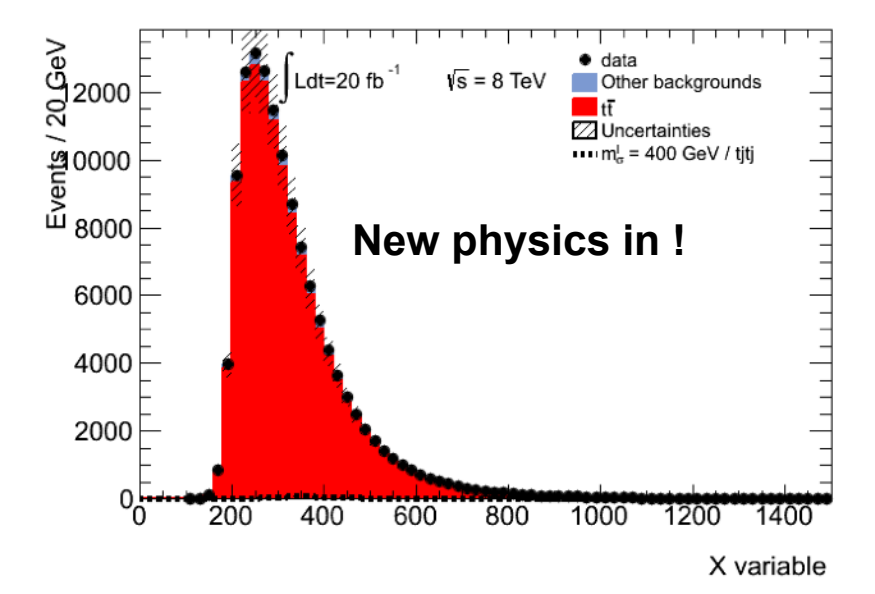

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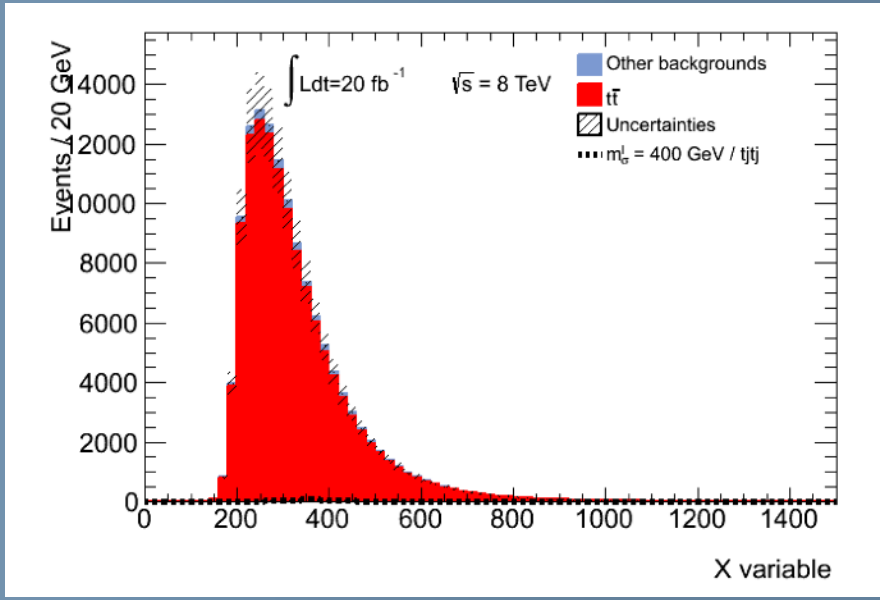
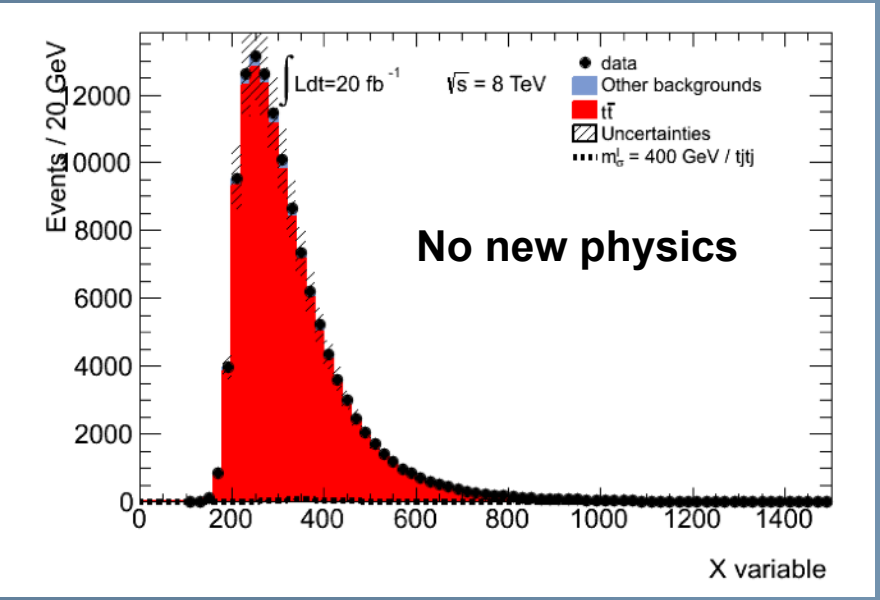
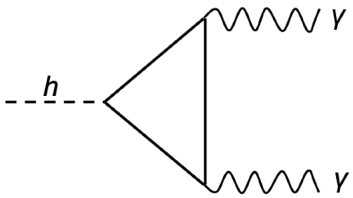




- Even if this signal existed … we couldn't have seen it !
- **No sensitivity** for this signal (at this rate)

Direct search



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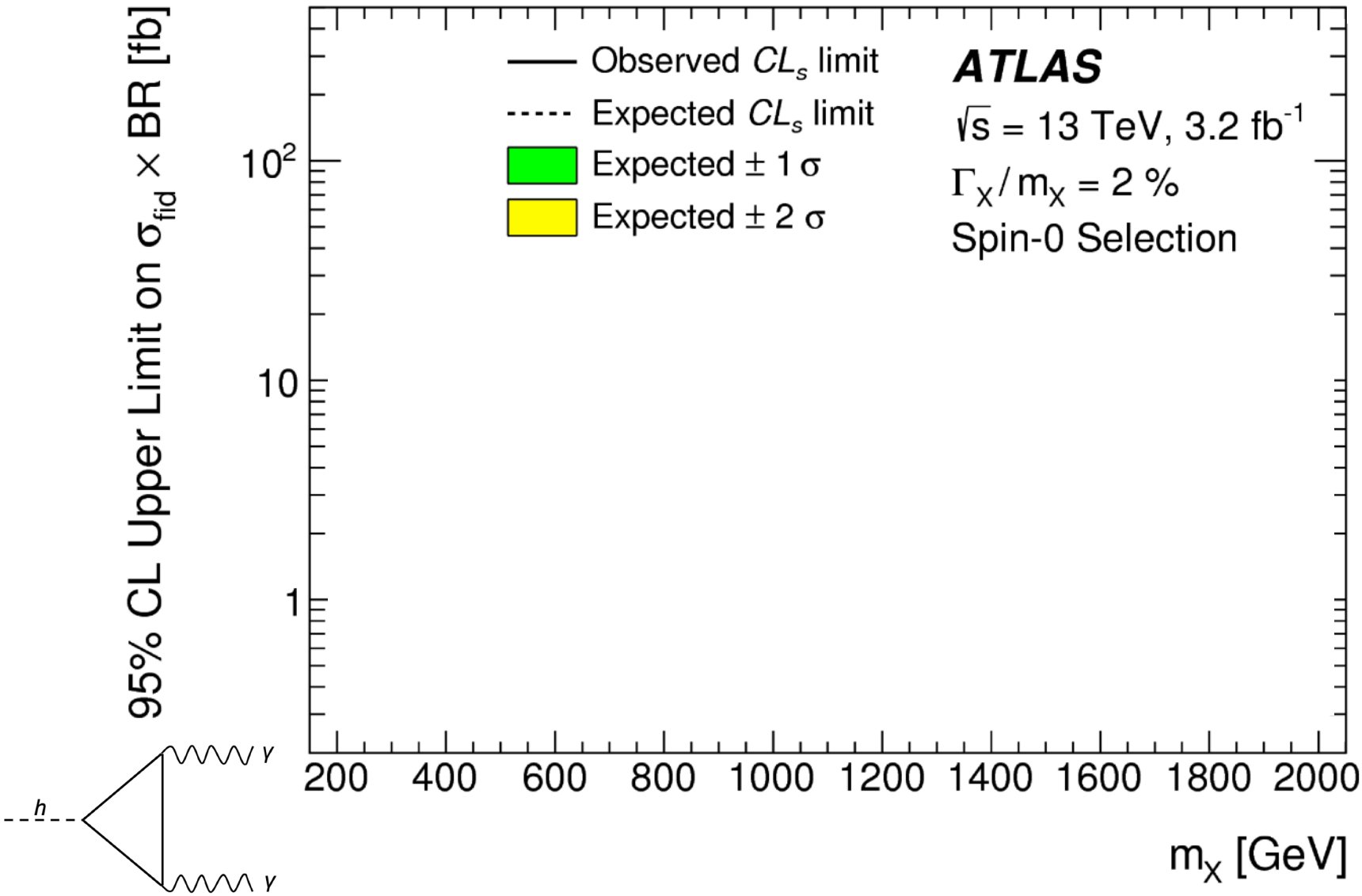

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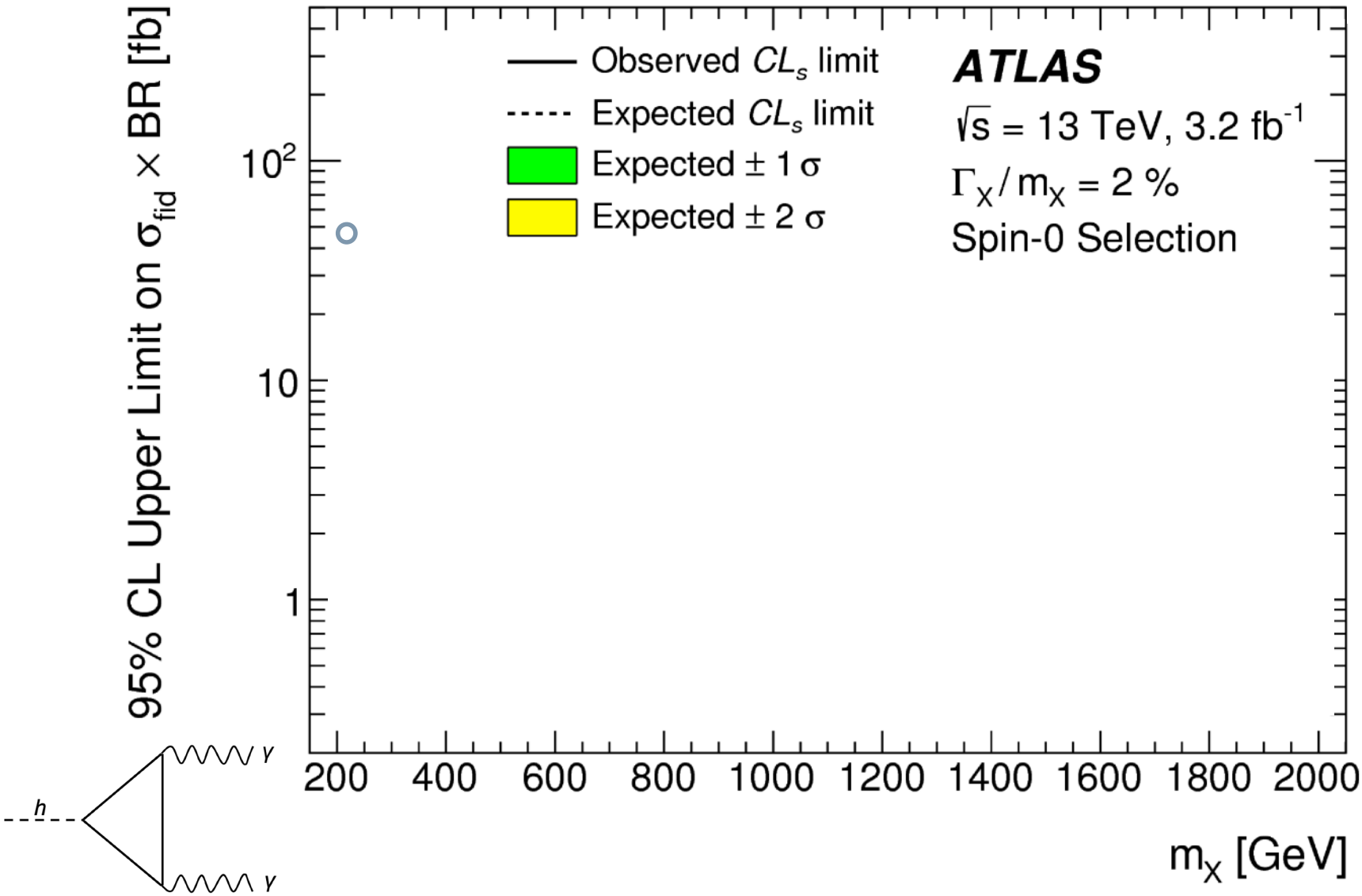

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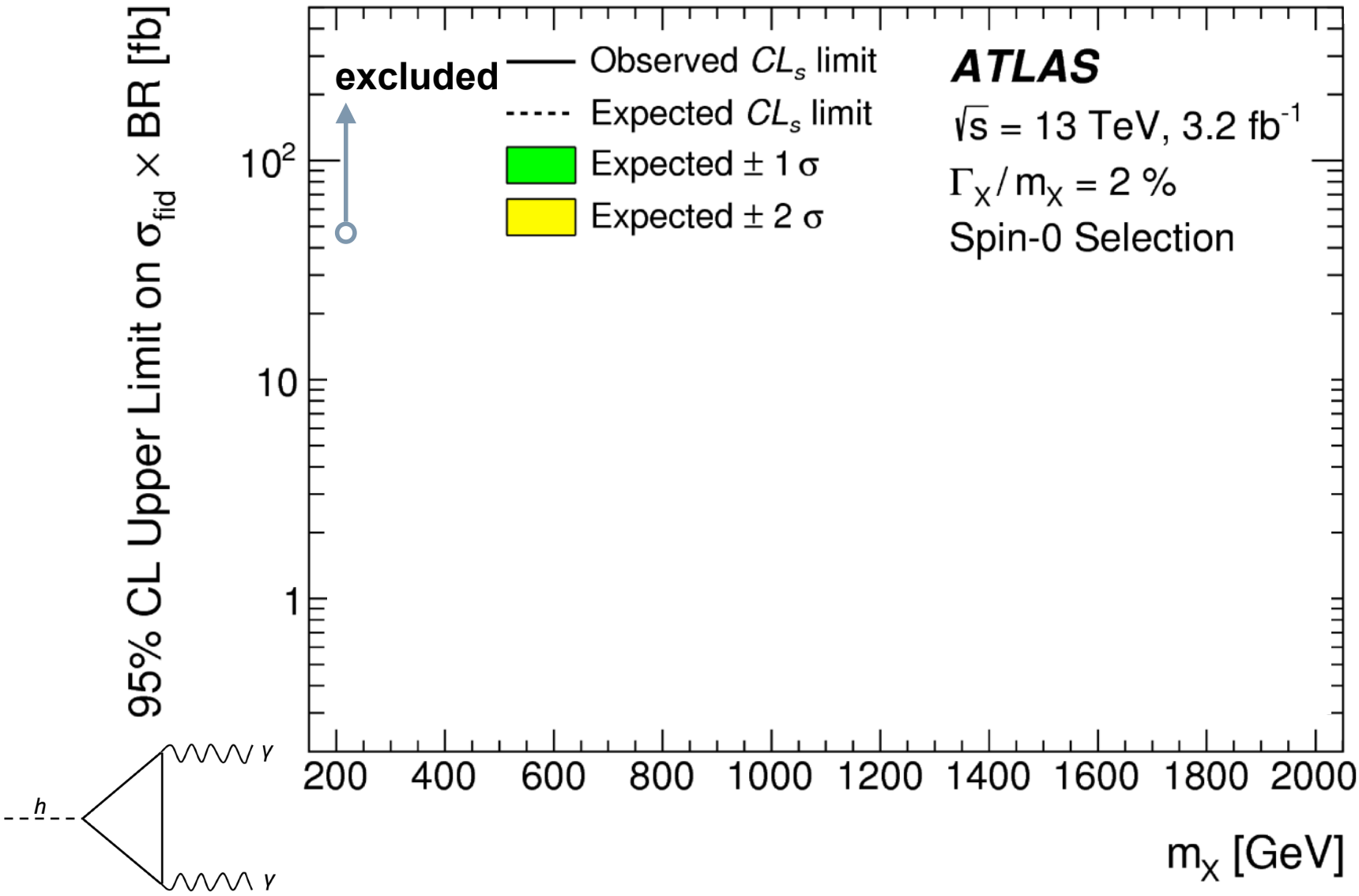

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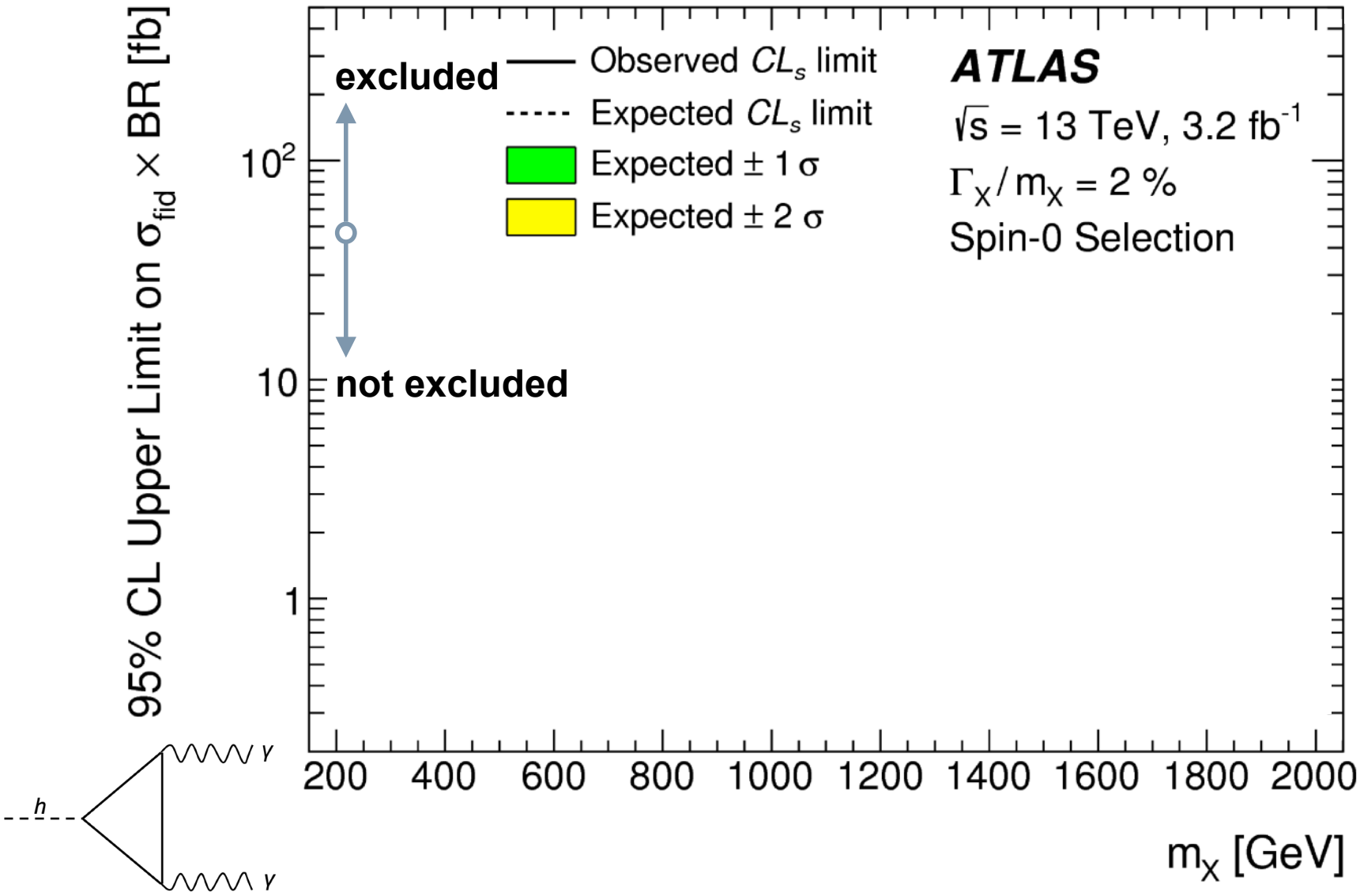

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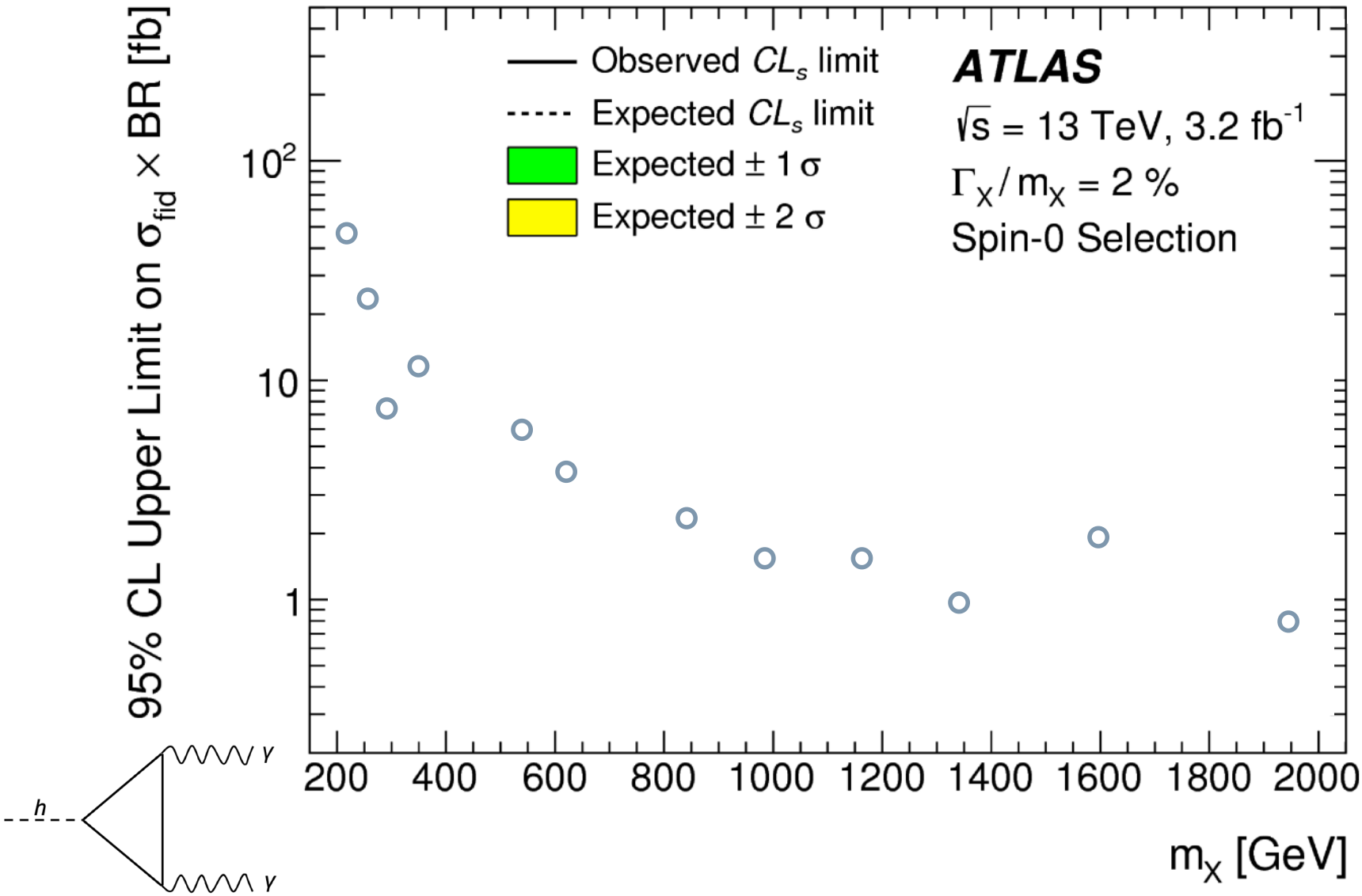

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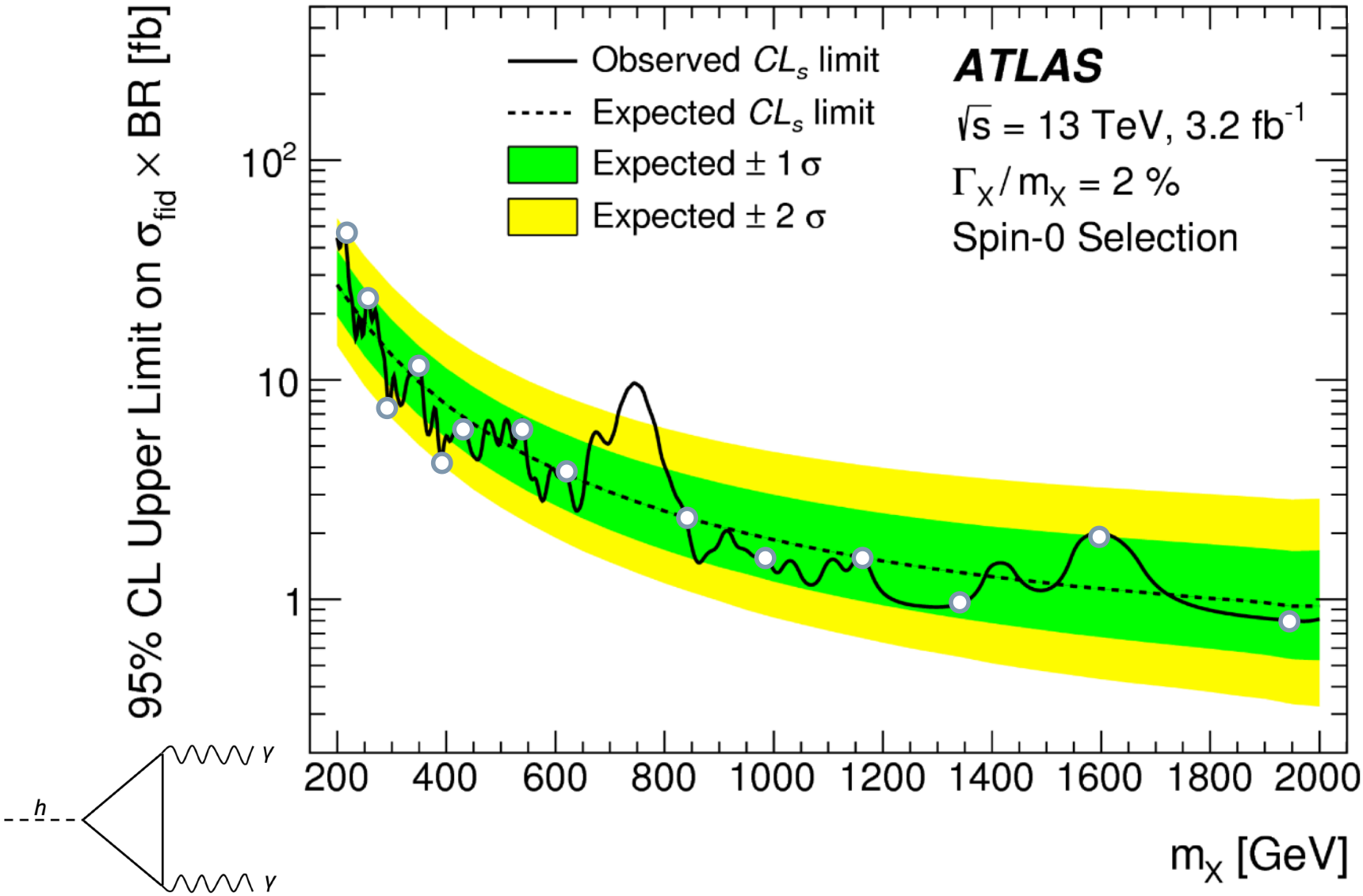
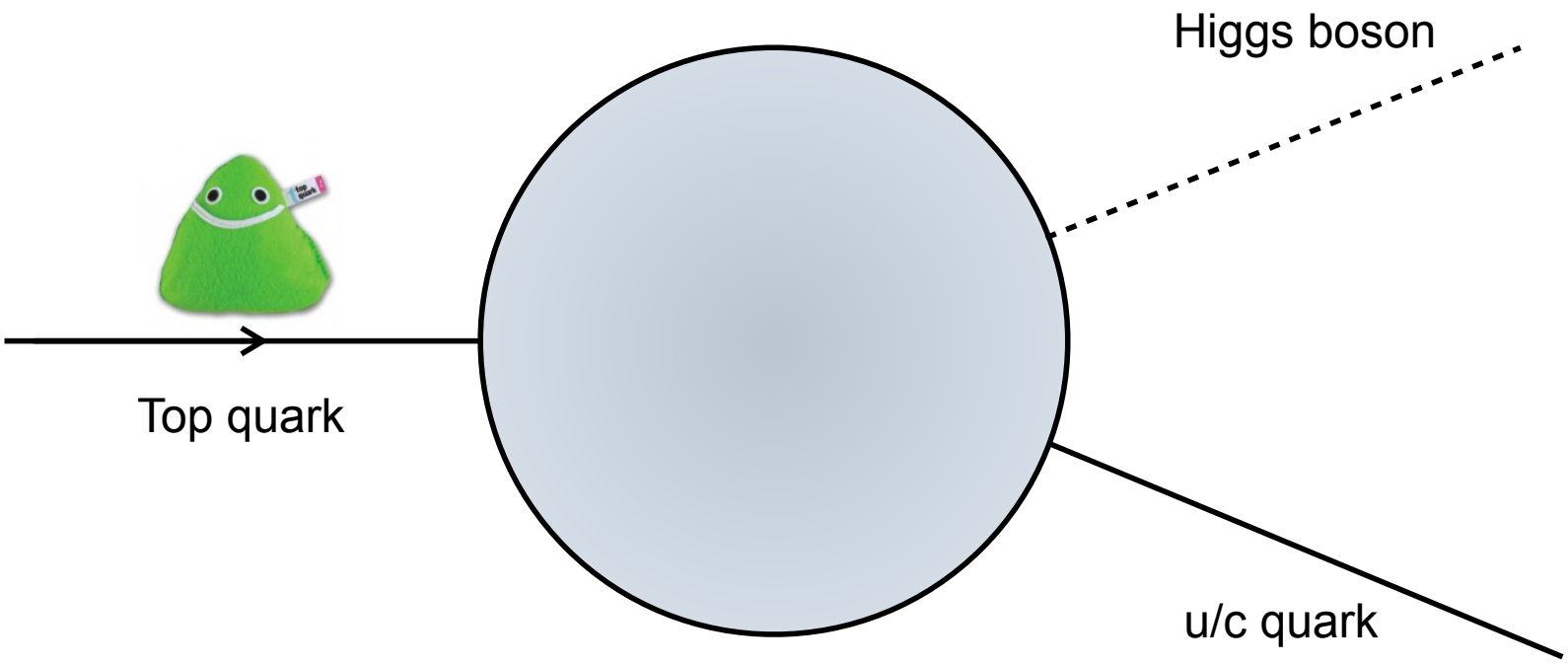


Indirect search

- BSM could increase cross-section of **rare SM processes**
  - e.g. flavour changing neutral currents

$$t \rightarrow Hc$$

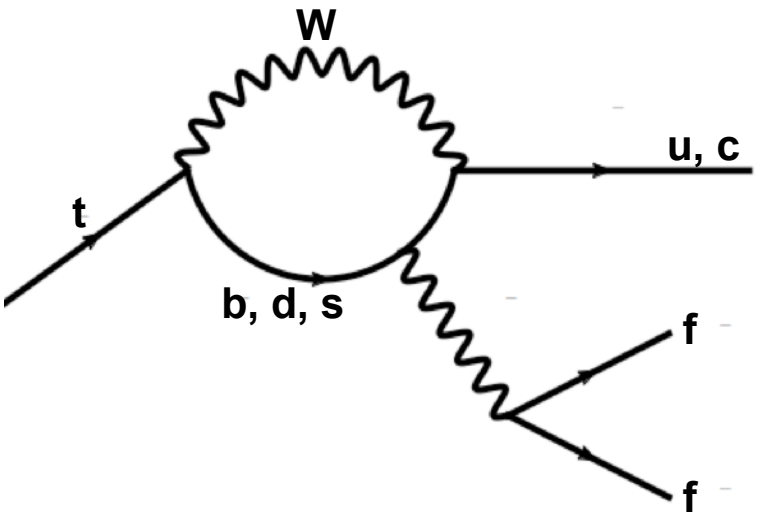


Indirect search

In total, about 2.10^8 top quarks produced at LHC since 2011

SM

t → Hu, Hc, … ✗ (at tree level)



$$\mathscr{P}(t \to Hu) \approx 10^{-15}$$

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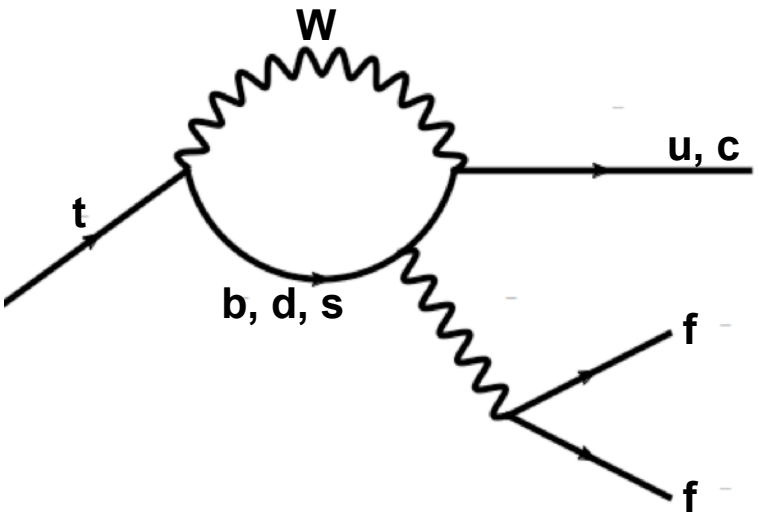

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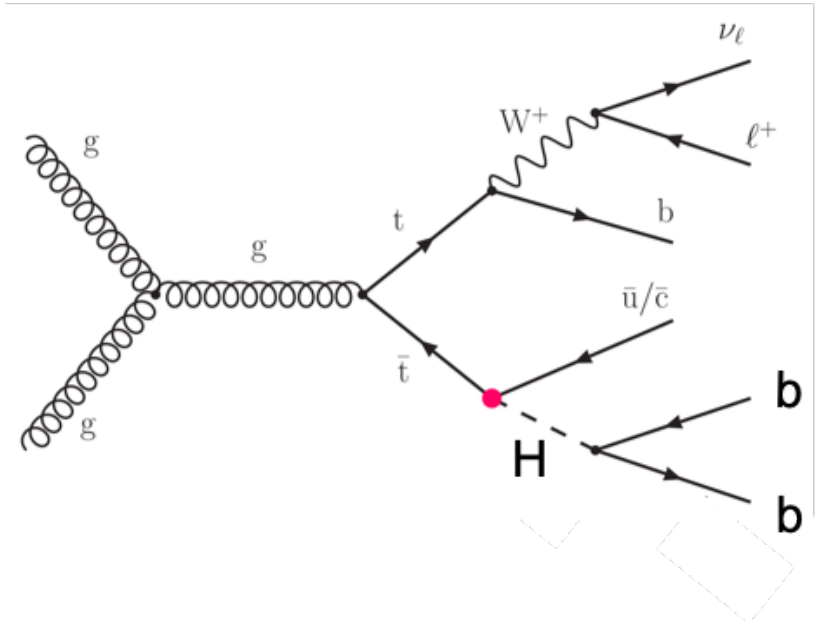
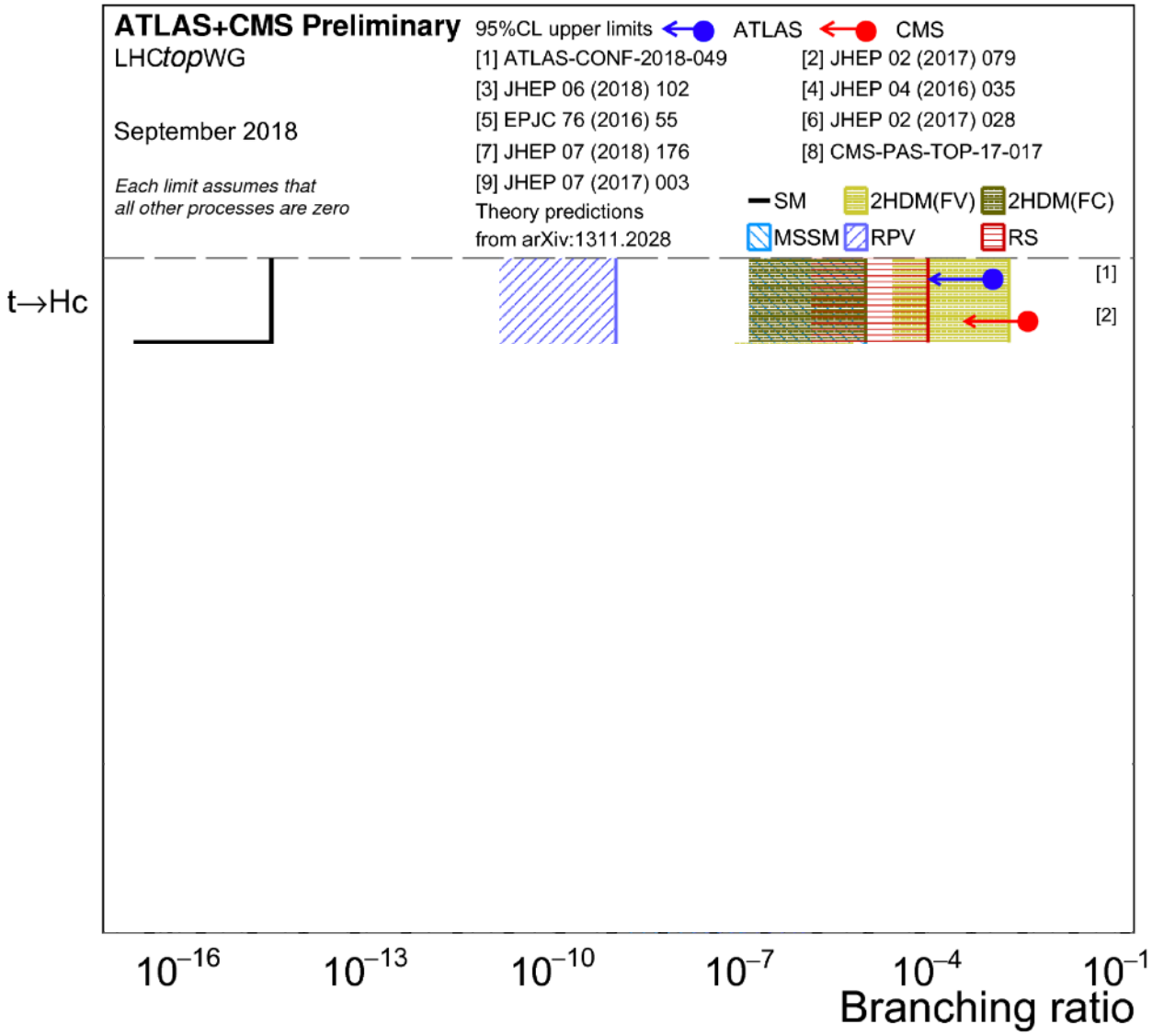


$$\mathscr{P}(t \to Hu) \leq 10^{-5}$$

Indirect search



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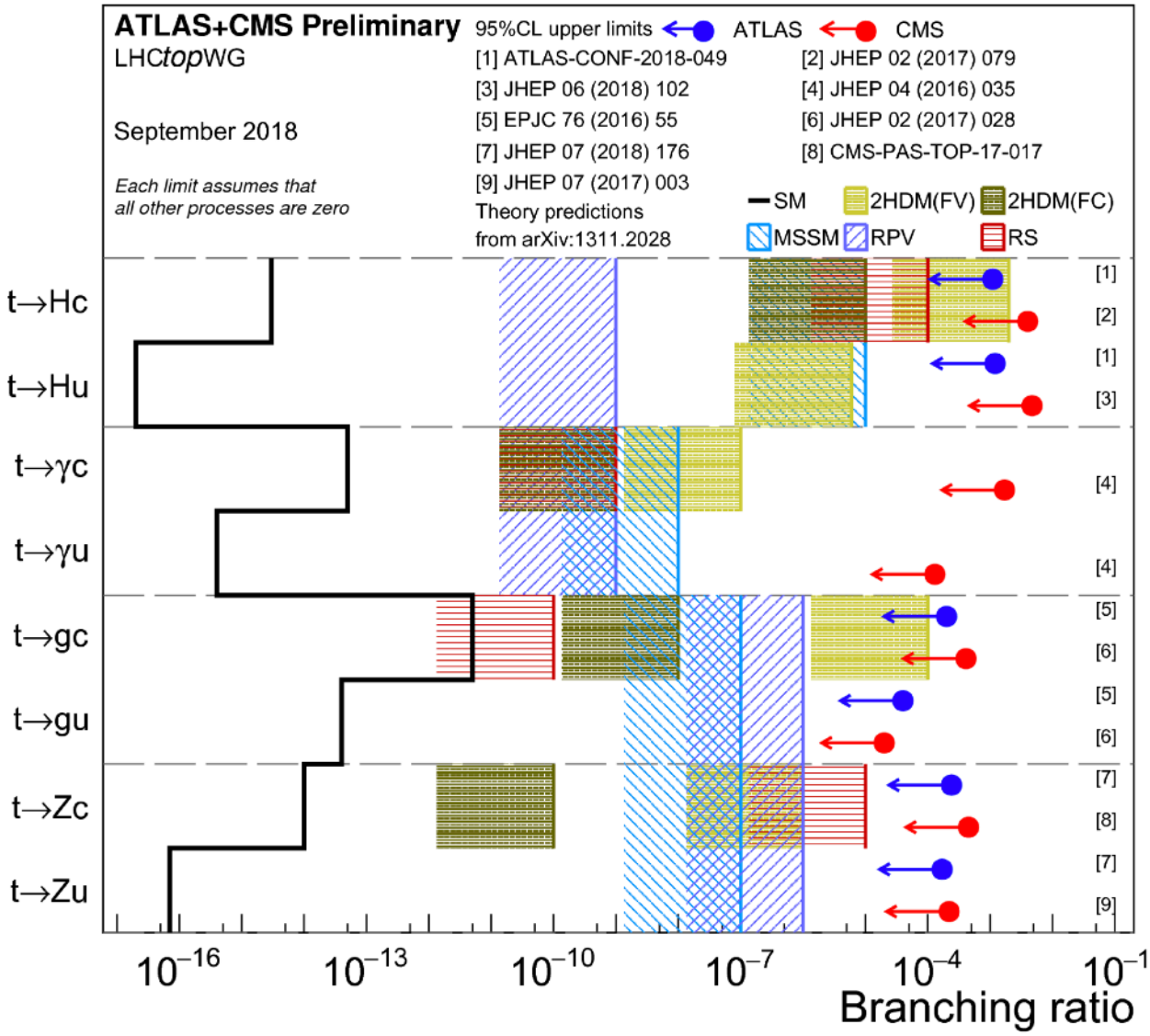
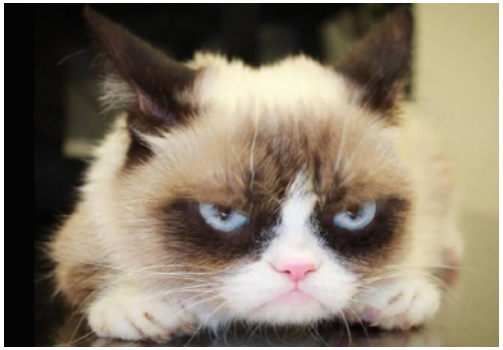


Summary

- **New Physics** motivated by limitations/unnaturalness of SM
  - Dark matter
  - Naturalness problem
  - Hierarchy problem
  - …
- **Many models** can extend SM and cure some limitations
  - SUSY, extra-dimensions, ...
- **Many searches: no real hint (yet)**



- **Not all presented today** ... (would have needed days and days)
  - **But more presented right now (and tomorrow morning from 8:30)!**

Supersymmetry (VII)

- **MANY results in Run 2** from ATLAS and CMS …
  - **Not really in favour of SUSY** ☹