Journées de Rencontres Jeunes Chercheurs 2018

Beyond the Standard Model (BSM)

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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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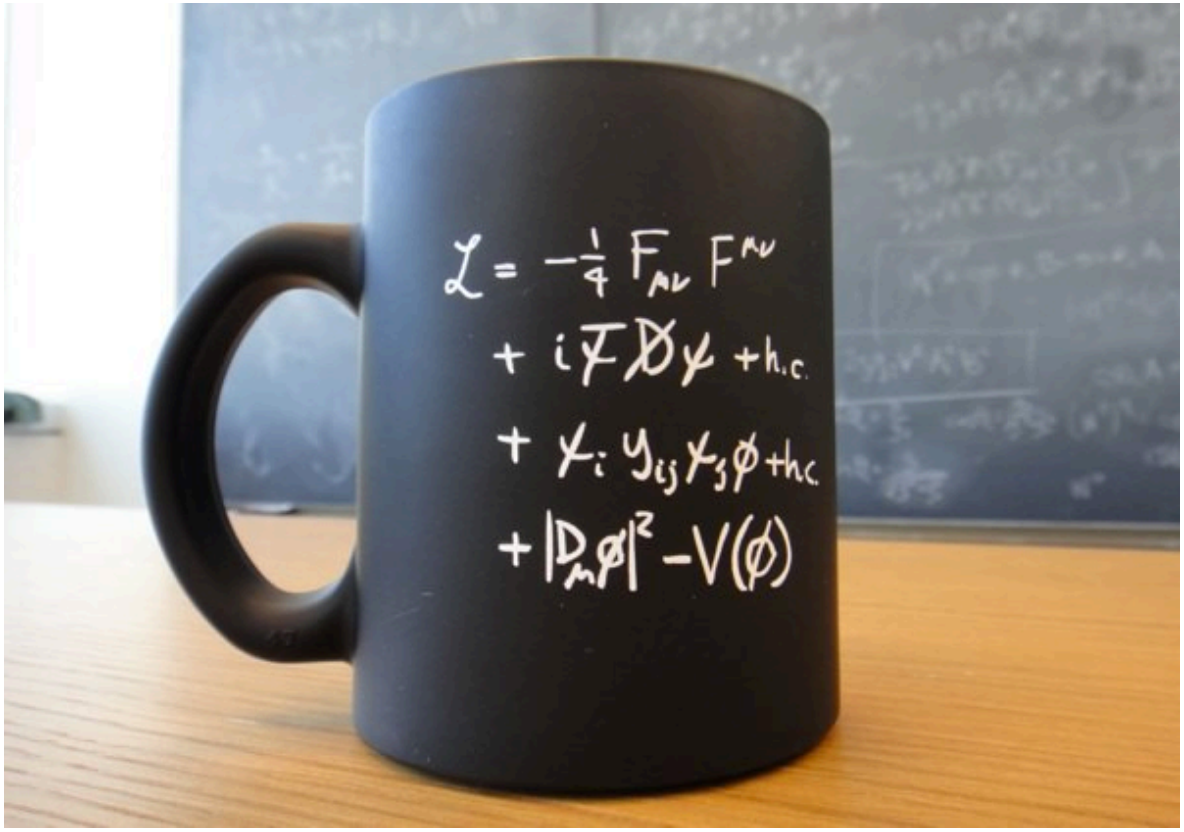
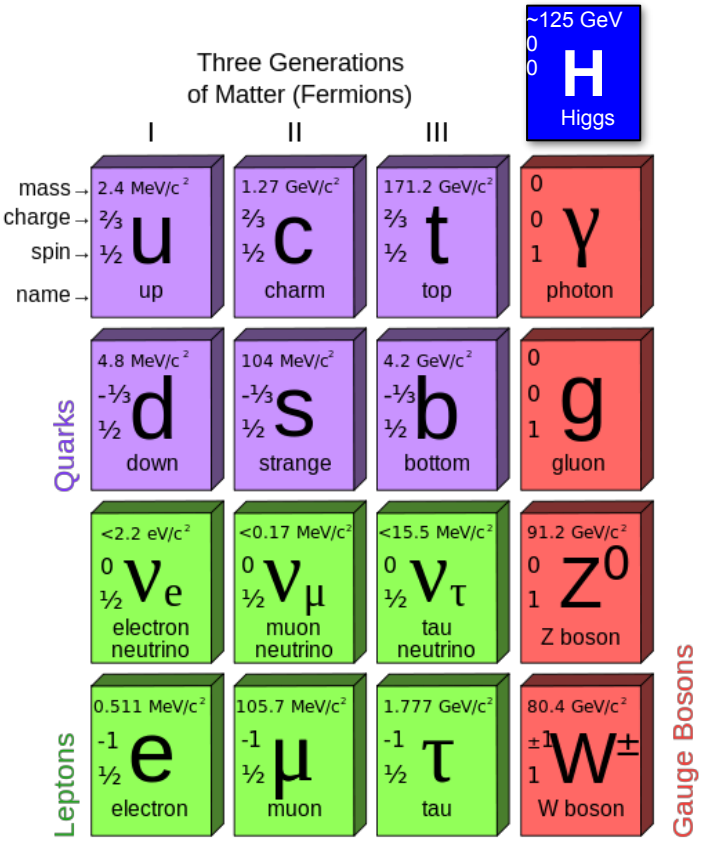
- Not just a formula on a mug …



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
- Thouroughly tested @ LHC
  - And **pretty succesully** so far ☺️ ☹️



The Standard Model: successes (I)

Top quark is very special … Heaviest particle in SM

Will be back later !!

escribe **elementary**

- **Fermions**
  - Elementary constituents of matter
- And **Higgs** boson …
  - Manifestation of mechanism through which particles acquire their masses

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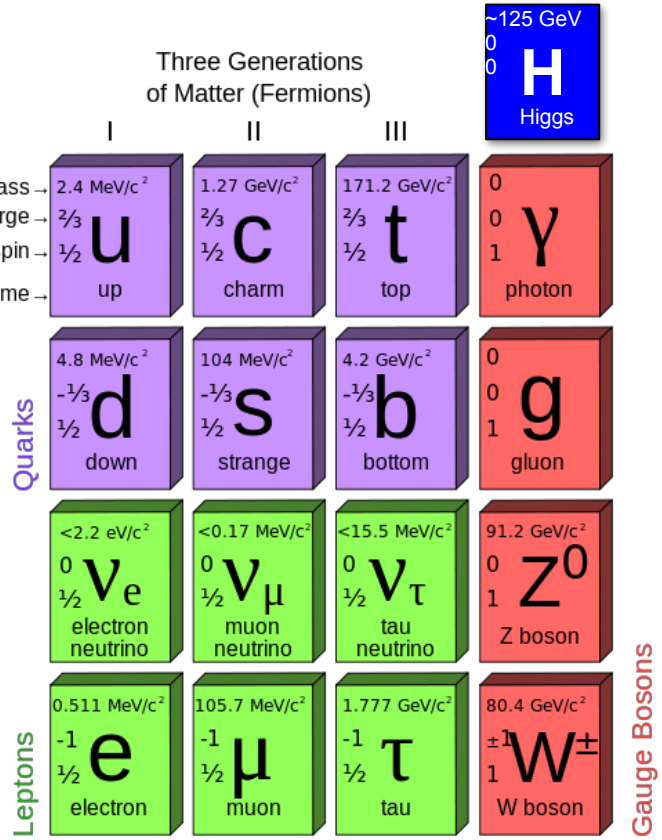
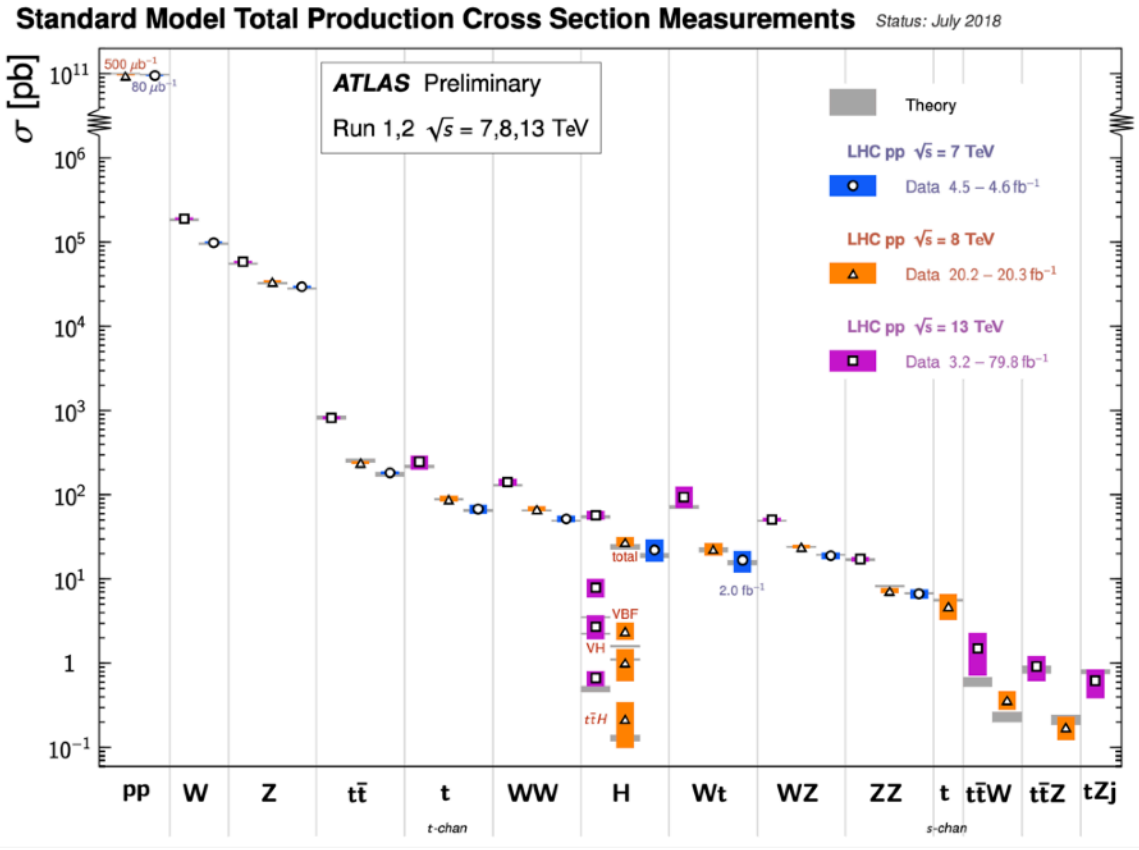


The Standard Model: successes (II)

- Pretty amazing **measurements** done in ATLAS (same in CMS)
  - SM predictions verified over a wide range of cross-section, energies, …
- **Could the SM be the end of the story ?**



But …

Neutrino masses

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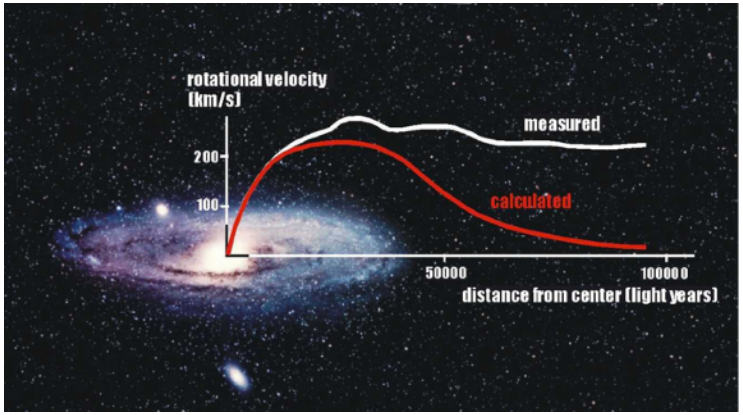

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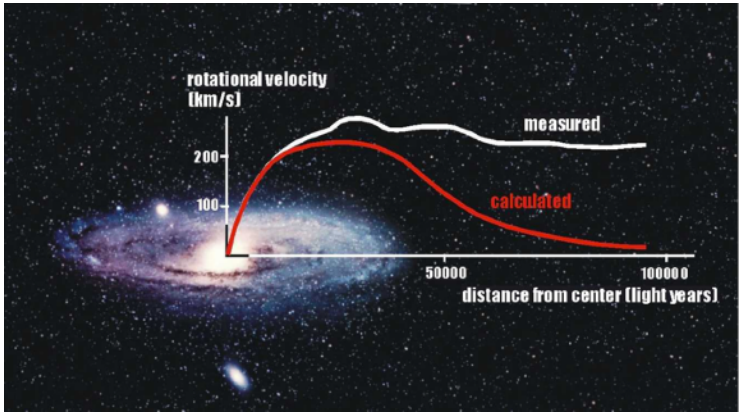
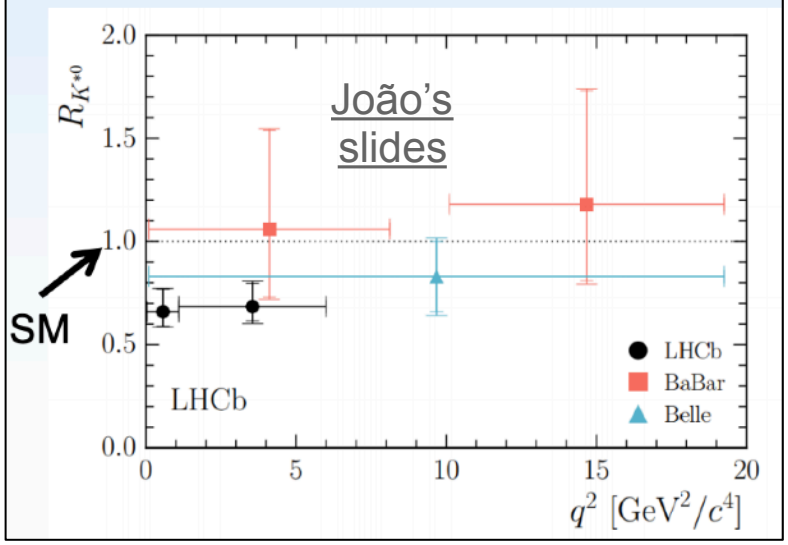


$$R(K^*) = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}$$



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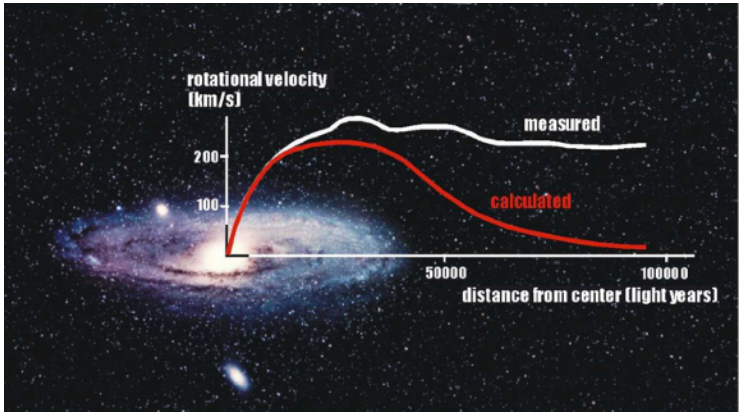

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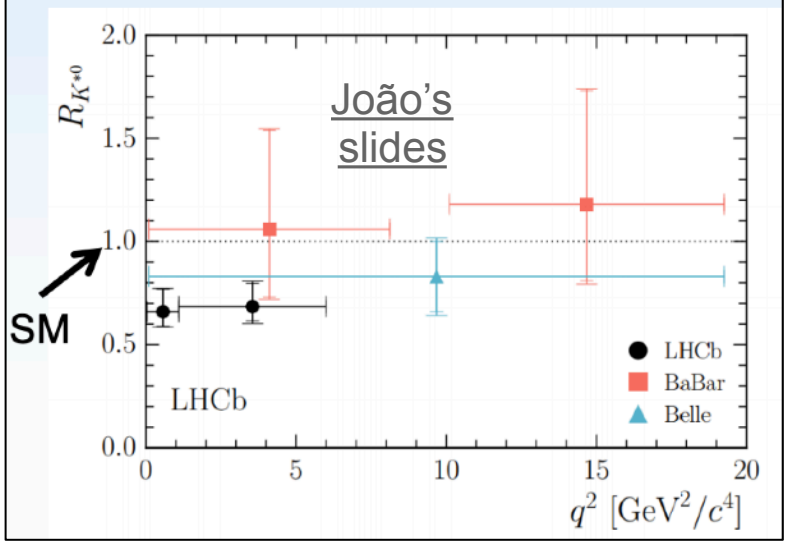

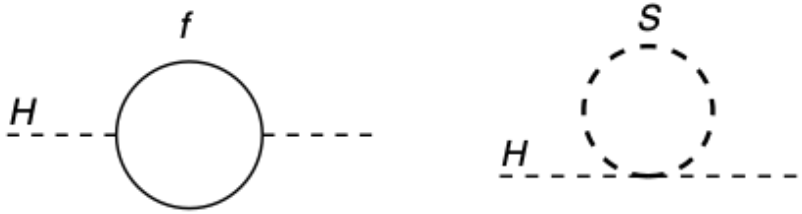

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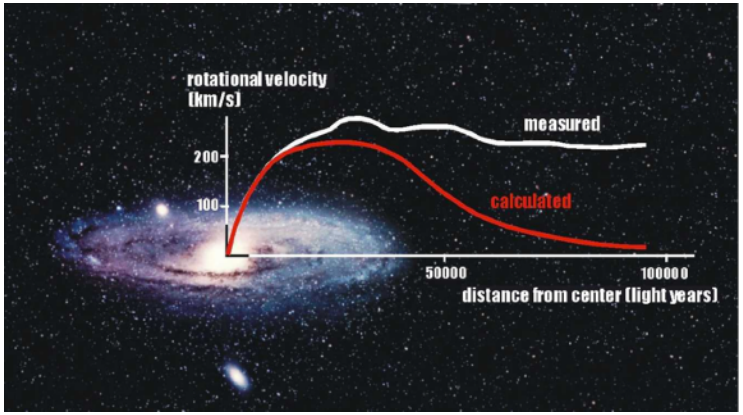

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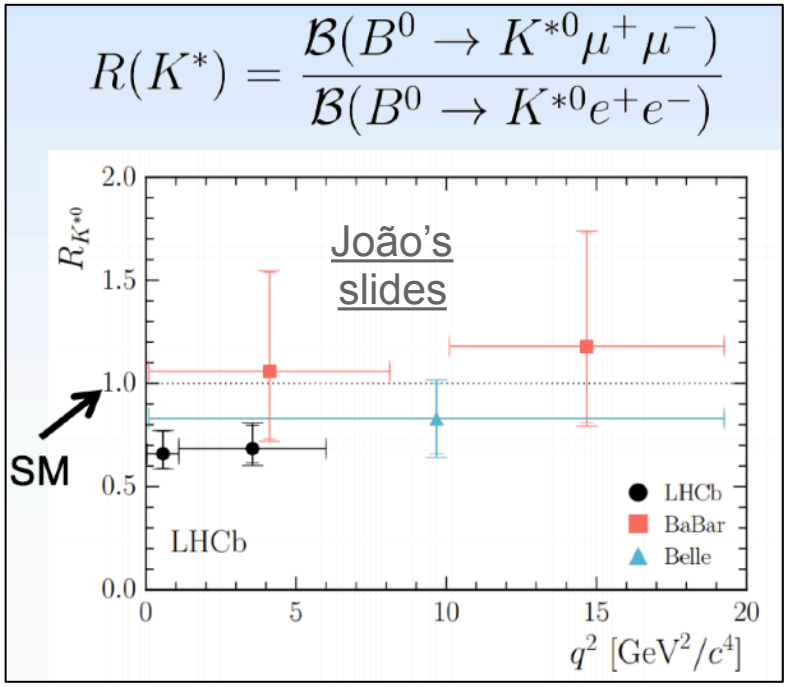
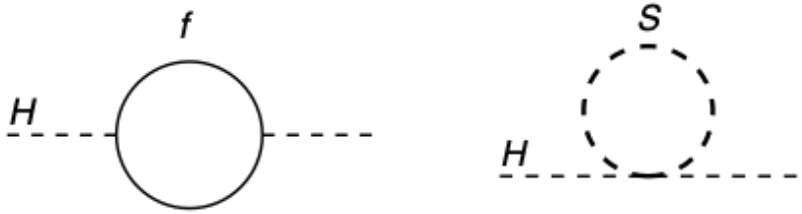


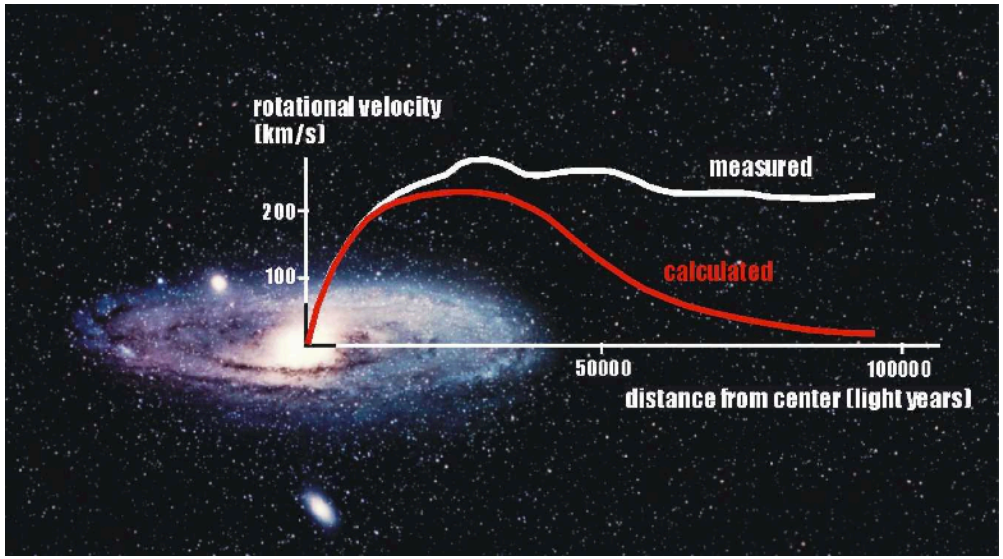


Mass/scale hierarchy

• • •

The Standard Model: limitations (I)

- **Dark matter**
  - Already discussed in previous sessions
  - Astrophysical observations motivate its existence
    - Galaxy rotation velocity: ~ constant for large distance from center
    - Gravitation lensing
    - ...



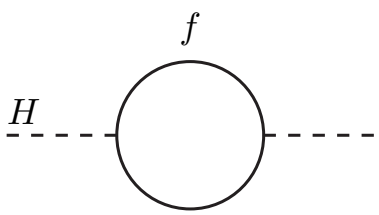
- Dark matter **not described/ predicted** in SM
- *NB/ Actually, gravitation itself is not included in the Standard Model*

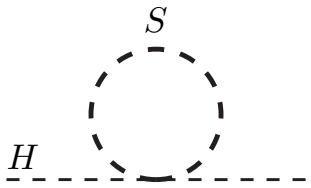
See Chloé's talk in this session

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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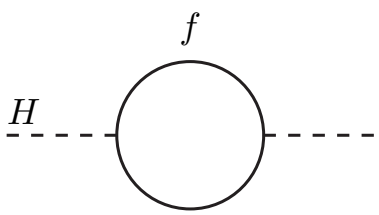

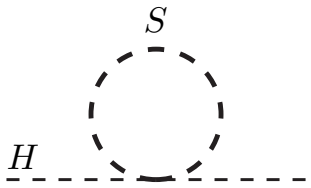

  - *m* measured at ~125 GeV
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- **Where is the problem ?**
  - m_0 and λ_f have to be adjusted up to the 32nd decimal …

How to solve these problems ?

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- **Naturalness problem** as an example
  - Adding **another correction to balance** quadratic divergences
    - For instance:
      - Scalar and fermion corrections to the Higgs mass have opposite signs …
      - If each fermion has scalar partners ... **Divergences should mostly cancel !**
    - This is **supersymmetry** !

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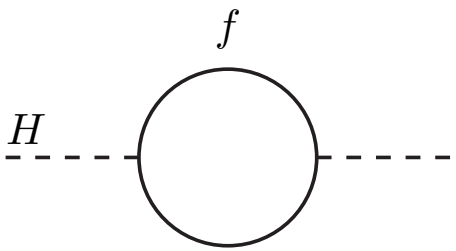

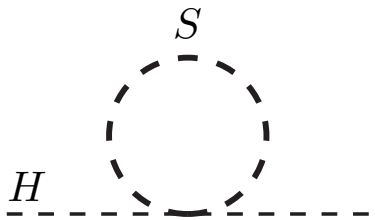

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    - Λ can be large because Planck scale is large ➔ gravitation is *weak* at our scale
    - Because it is propagating through more than 4 dimensions ?
    - So, need for additional dimensions !

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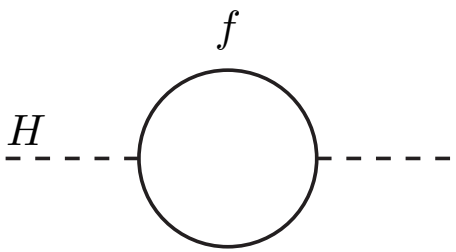

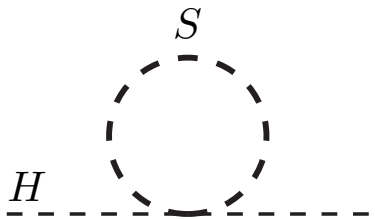

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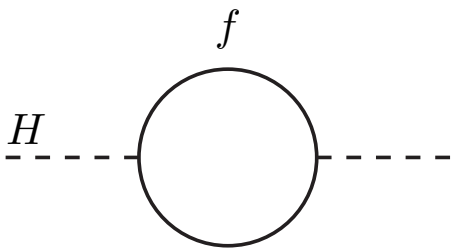
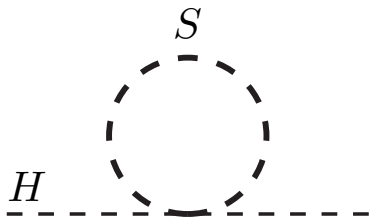
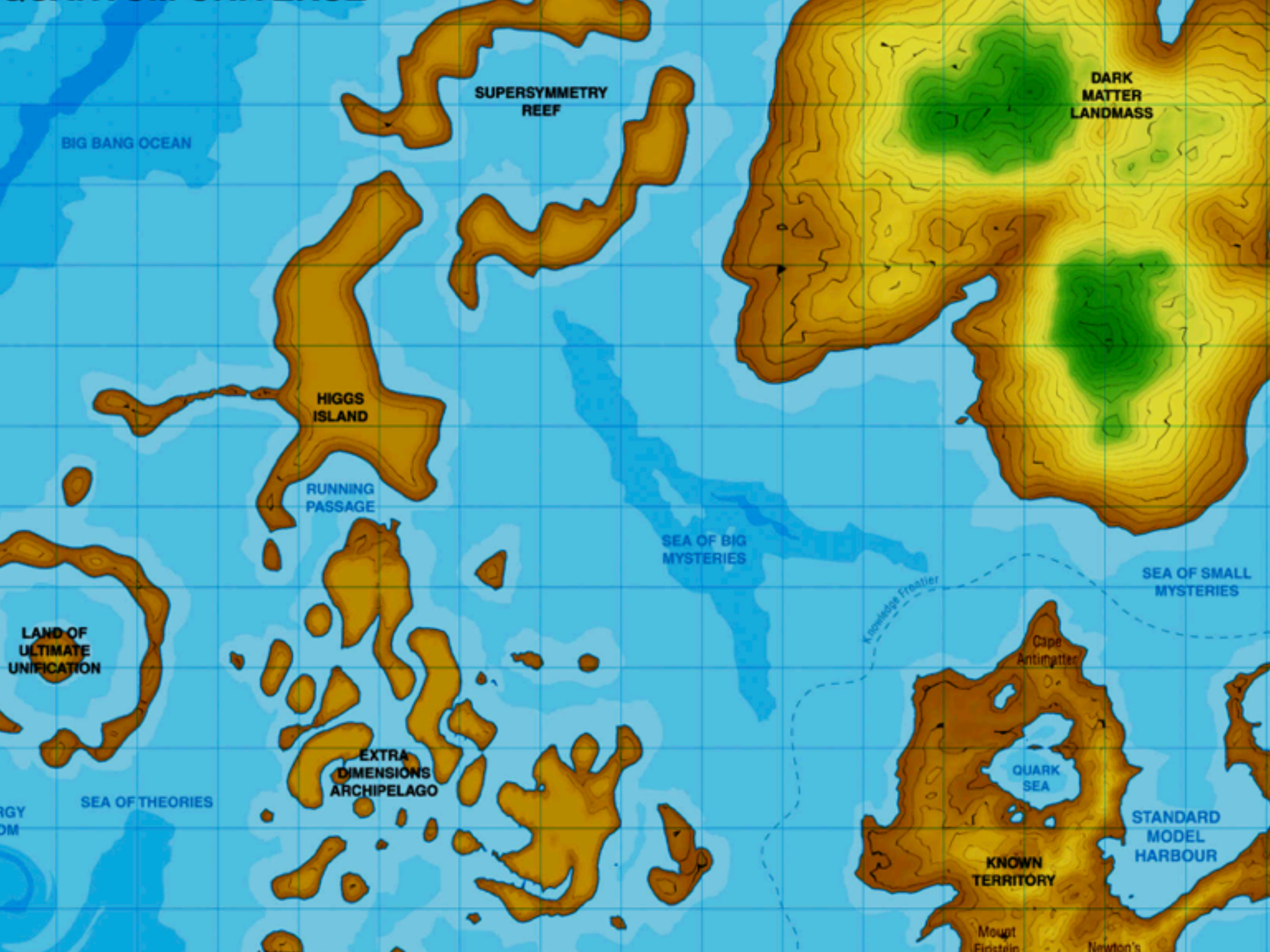
$$F = G_g \frac{m_a m_b}{r_{AB}^{2+d}}$$

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

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






SUPERSYMMETRY REEF
DARK MATTER LANDMASS
BIG BANG OCEAN
HIGGS ISLAND
RUNNING PASSAGE
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Cape Antimatter
QUARK SEA
EXTRA DIMENSIONS ARCHIPELAGO
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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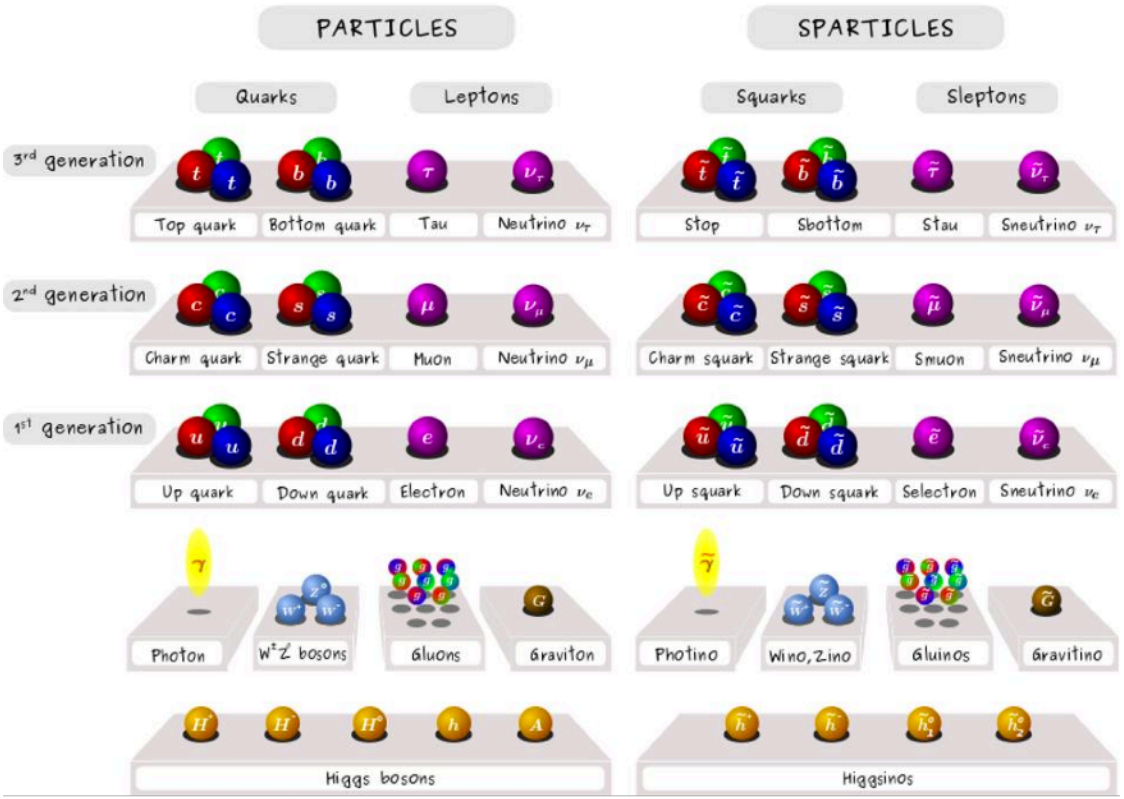

Supersymmetry (I)

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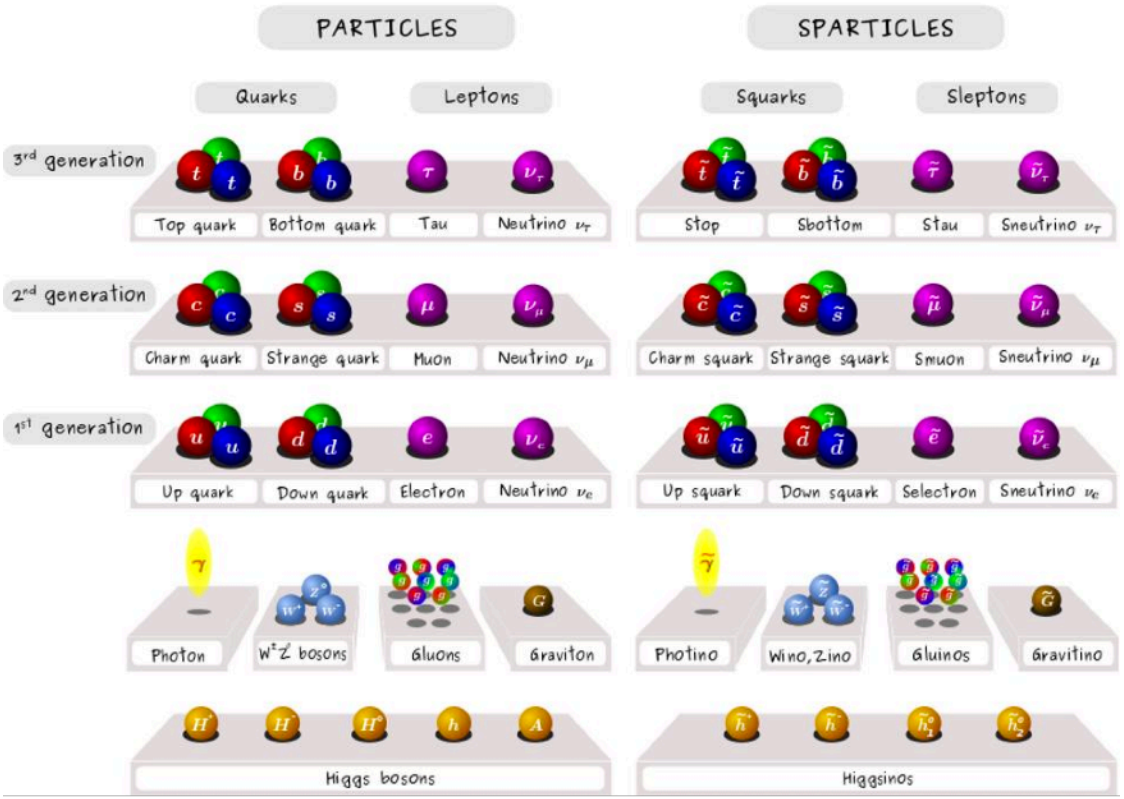
Fermion / Boson symmetry



Particle content: ~factor 2

Supersymmetry (I)

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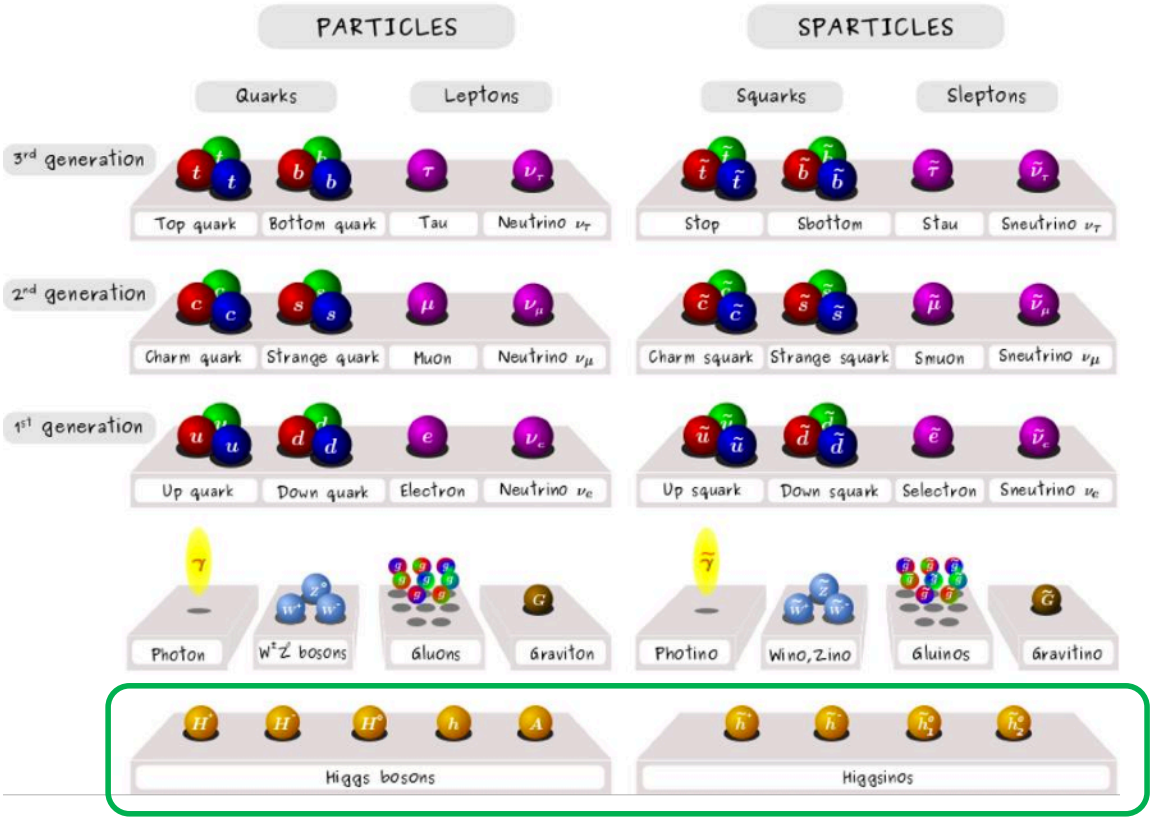
Fermion / Boson symmetry



Particle content: ~factor 2

Extended Higgs sector

Supersymmetry (I)

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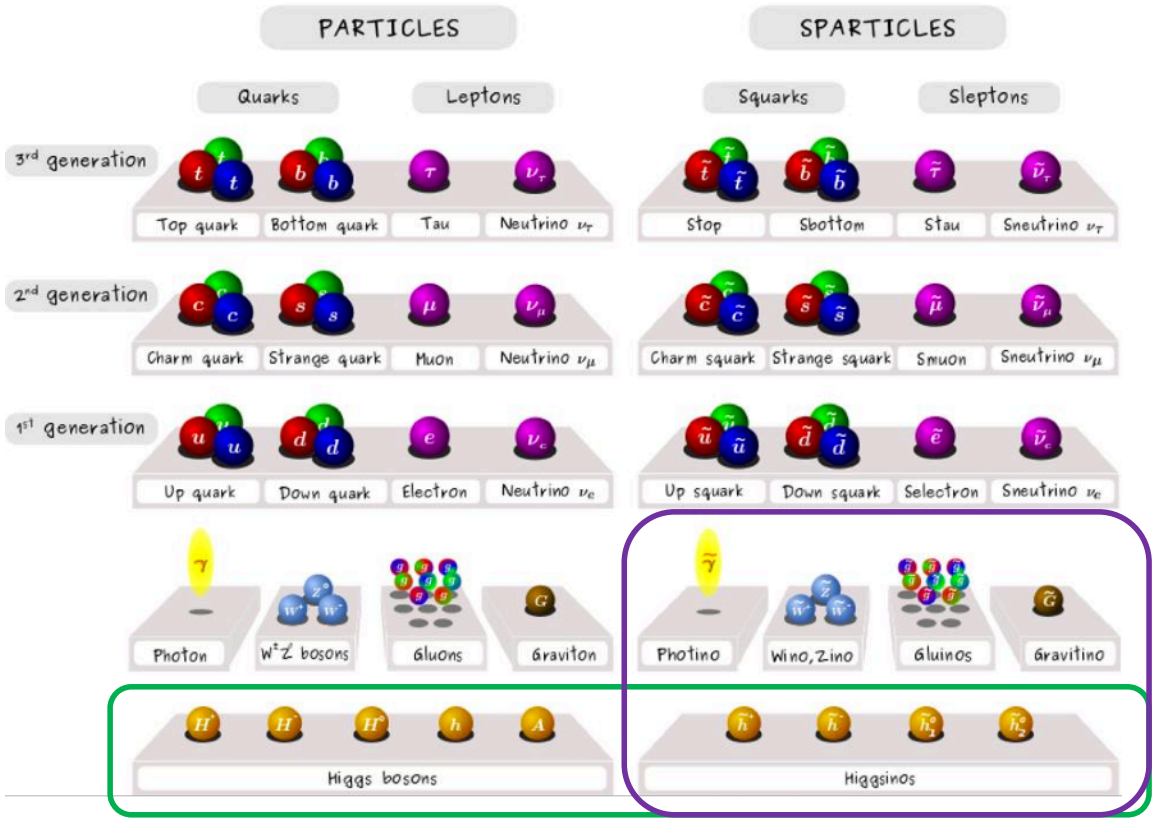
Fermion / Boson symmetry



Particle content: ~factor 2

Mixing: neutralinos and charginos

Extended Higgs sector

Supersymmetry (II)

- **Back to symmetries !**
  - Symmetry exactly realized → identical masses
    - **Experiments: They are not the same !!**
  - **So, SUSY is (softly) broken !**

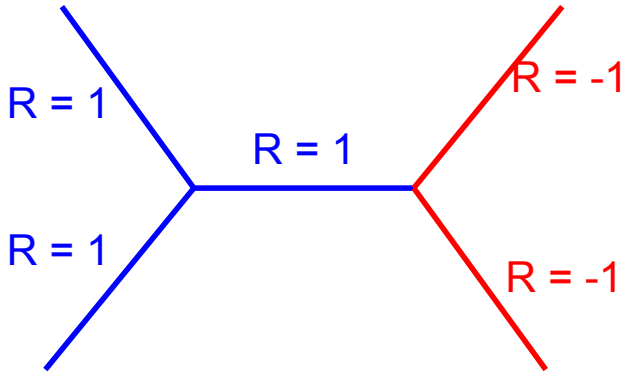
- **Breaking mechanism**: unknown ☹
  - Some proposals exist … but lead to models with >120 parameters
  - Hard to search for ... can be anything/anywhere …
    - Use **phenomenologically-motivated** configurations
    - Use (very) **simplified effective** models
      - Limited number of SUSY particles,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

Supersymmetry (IV)

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

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

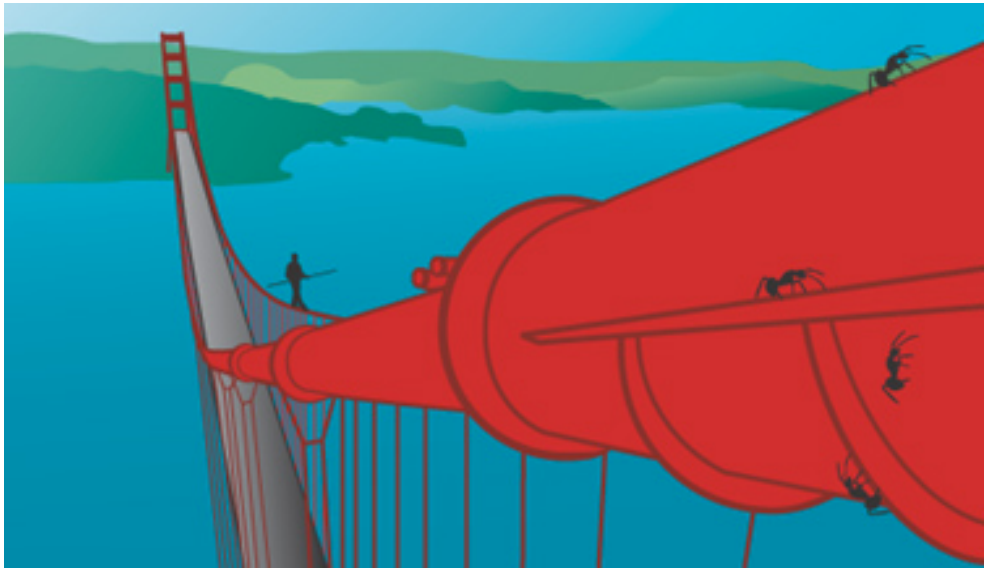
    - B and L the baryonic and leptonic numbers
    - s the spin
    - **Consequence**:
      - R = -1 for SUSY particles
      - R = +1 for SM particles



  - 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**

Extra-dimension theories (I)

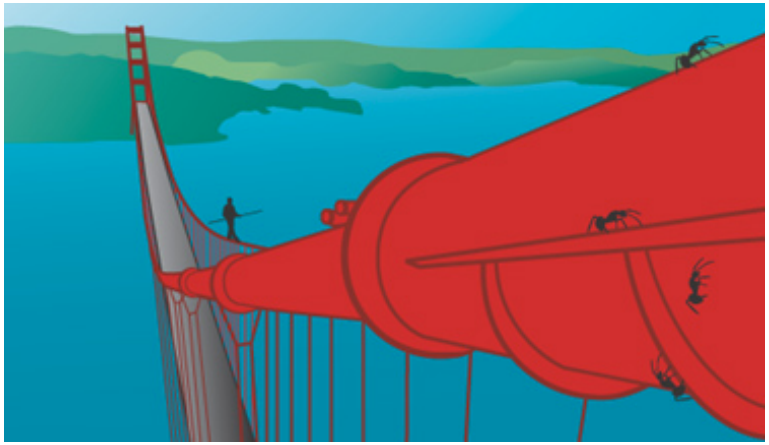
- **General idea**



Extra-dimension theories (I)

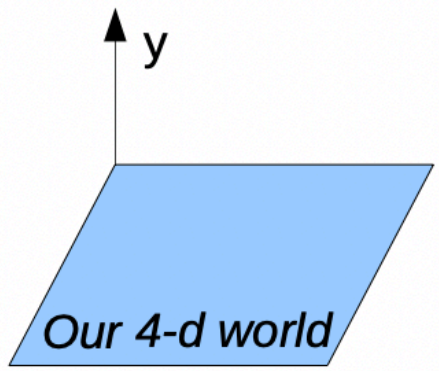
- **General idea**
  - New dimension(s) in which **some interactions would propagate** (gravitation)
  - *Gravitation*
    - Force: $F = G_g \frac{m_a m_b}{r_{AB}^{2+d}}$
    - But of course … planet's orbits are all screwed up ....
  - New dimensions need to be **compactified**

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

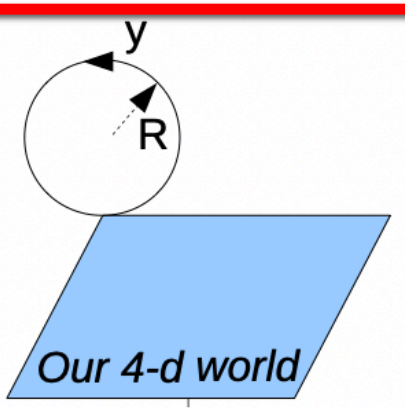


Extra-dimension theories (II)

"Flat"



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



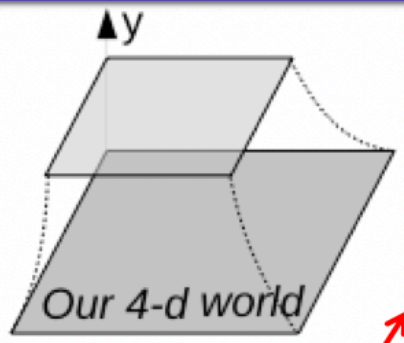
Periodicity conditions on field …
Fourier expansion

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

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 combination** … with different phenomenologies

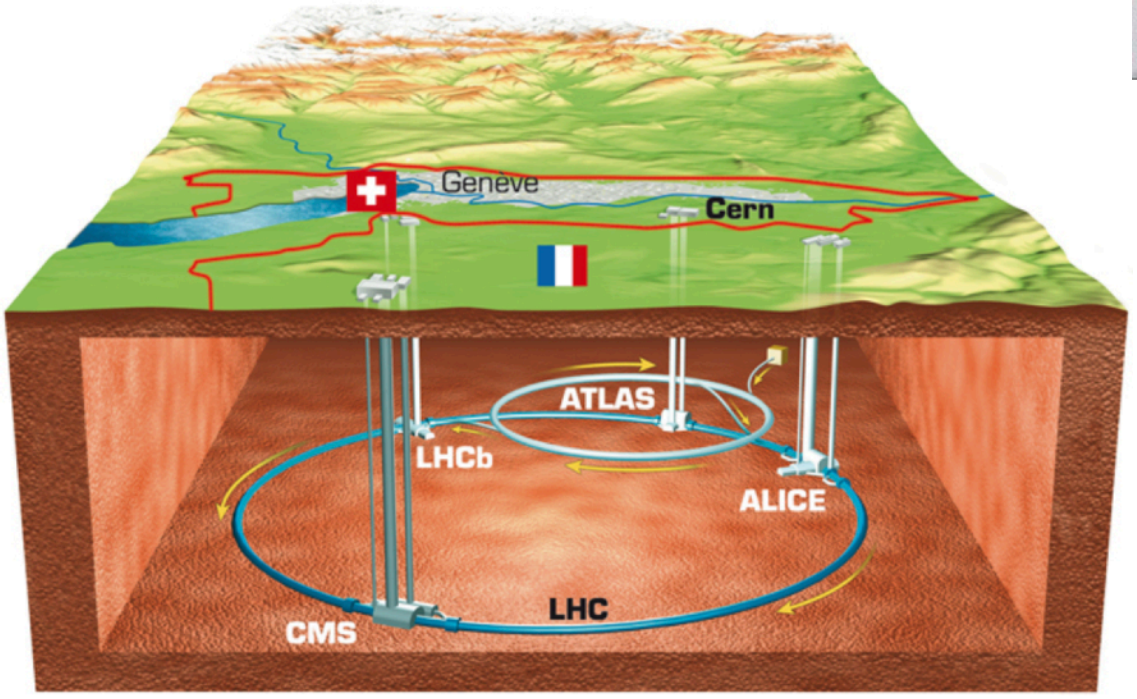
HOW TO LOOK FOR THAT ?

Produce new particles ?

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

Produce new particles ?

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

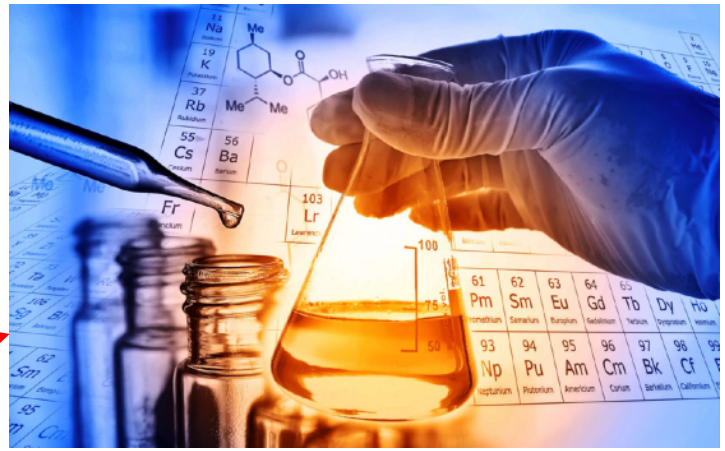


- **Collision energy**: 13 TeV
  - *Proton speed: 99.999% c*
- **Collision rate**
  - *600 millions / second*

Observe new particles ?

Observe new particles ?

Directly



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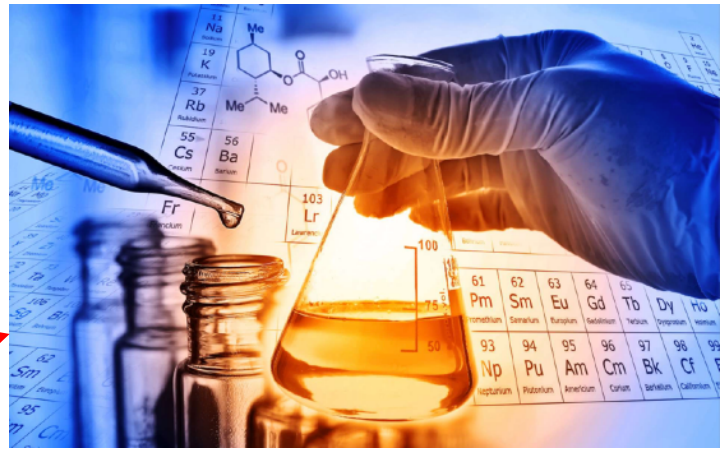

Indirectly

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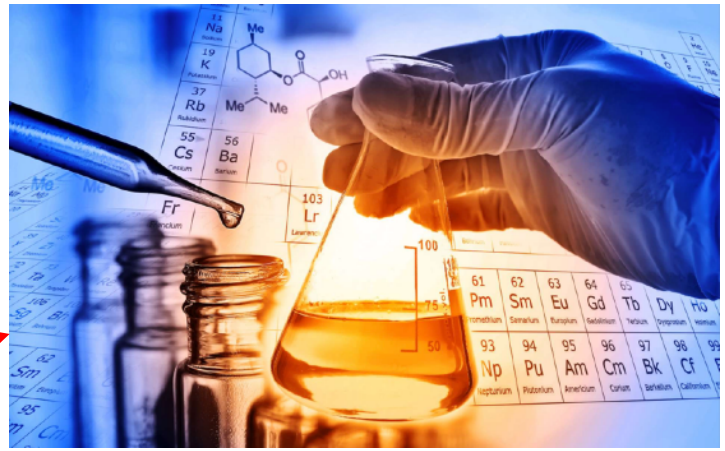

Indirectly

Now a BSM example

Indirect searches

- New processes could increase cross-section of **rare SM processes**
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SM t → Wb

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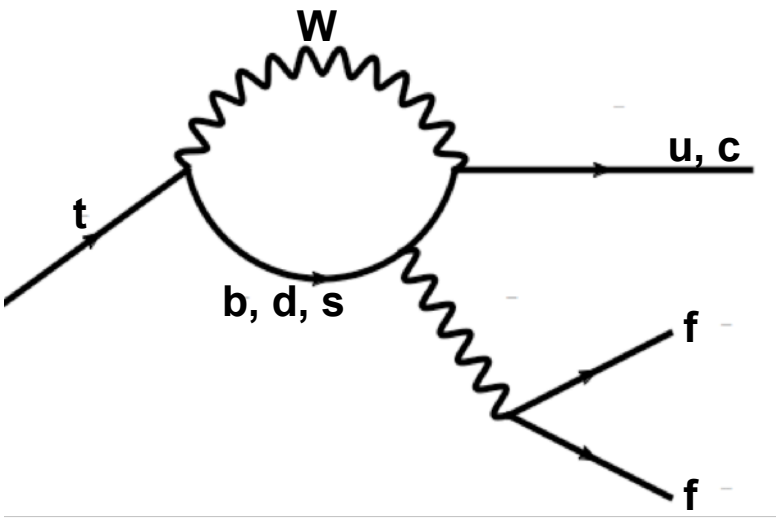

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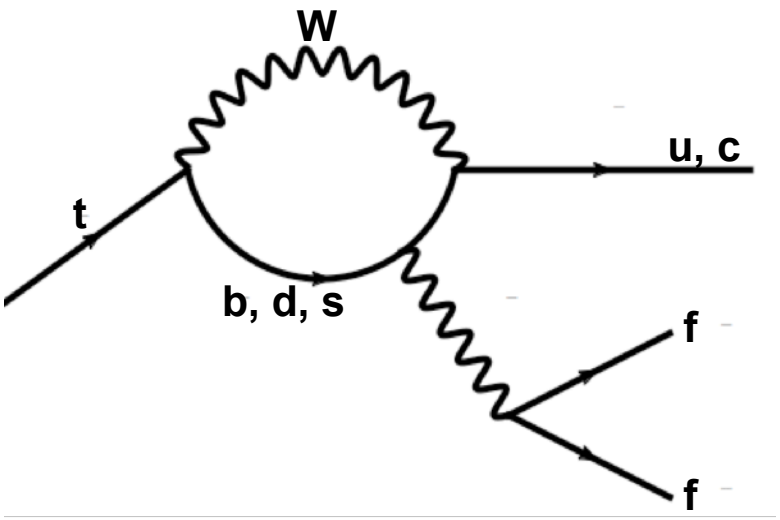
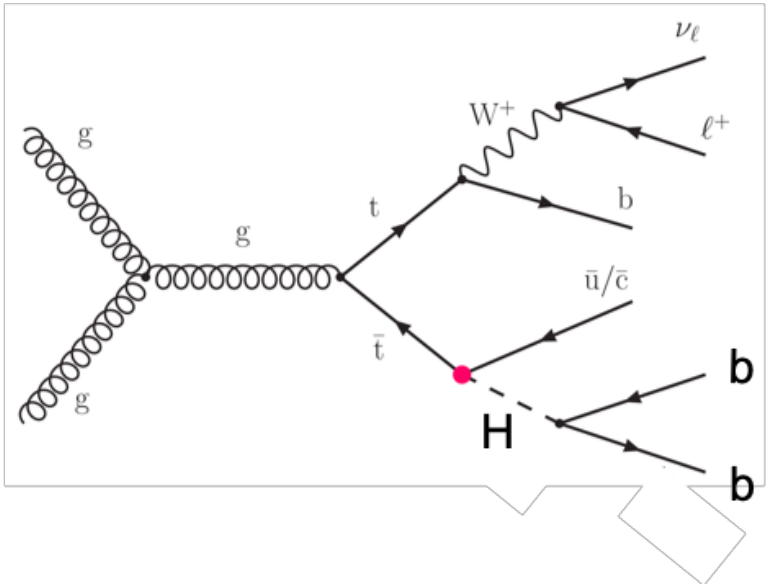
BSM t → Wb

BSM t → Hu, Hc, … ✓ (at tree level)





- Observing such rare processes: **point to new underlying process**

[Statistical break]

[Statistical break]

[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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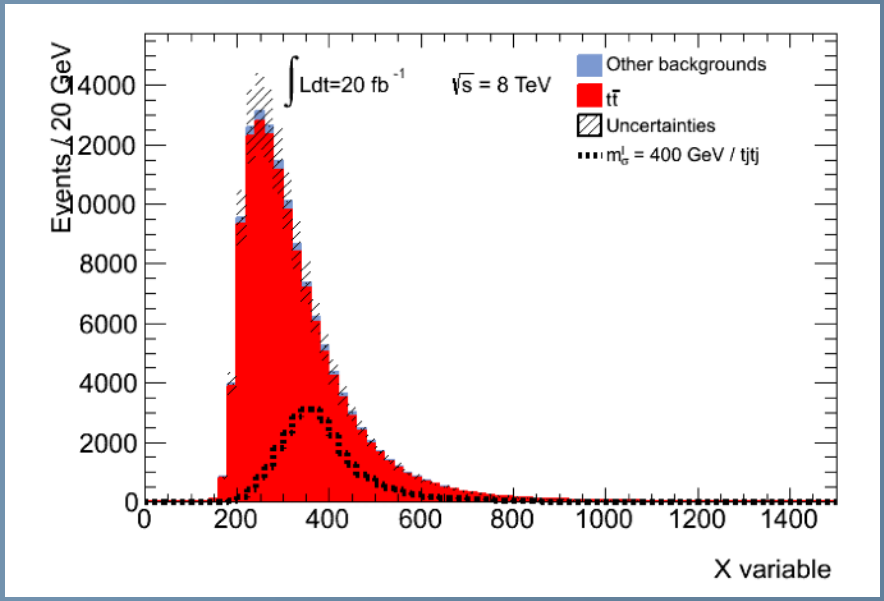

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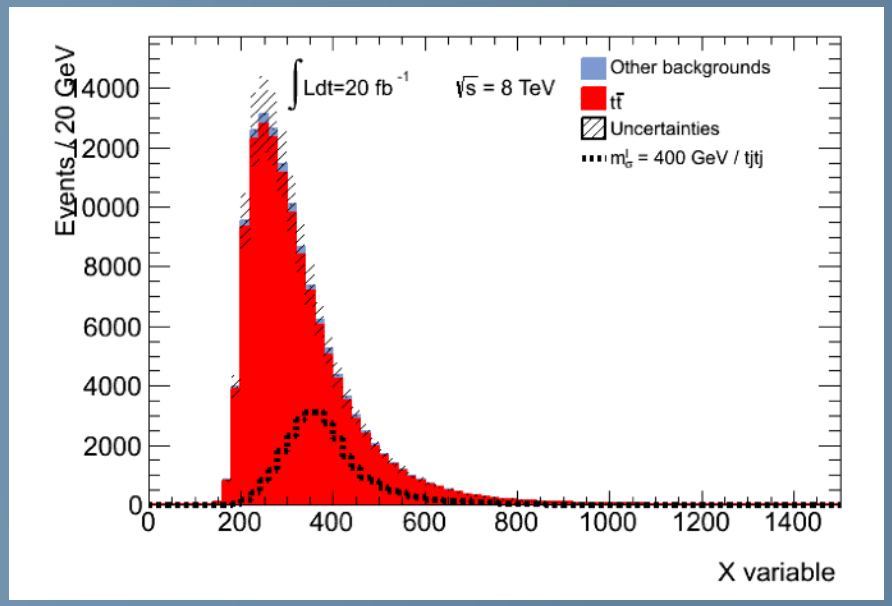

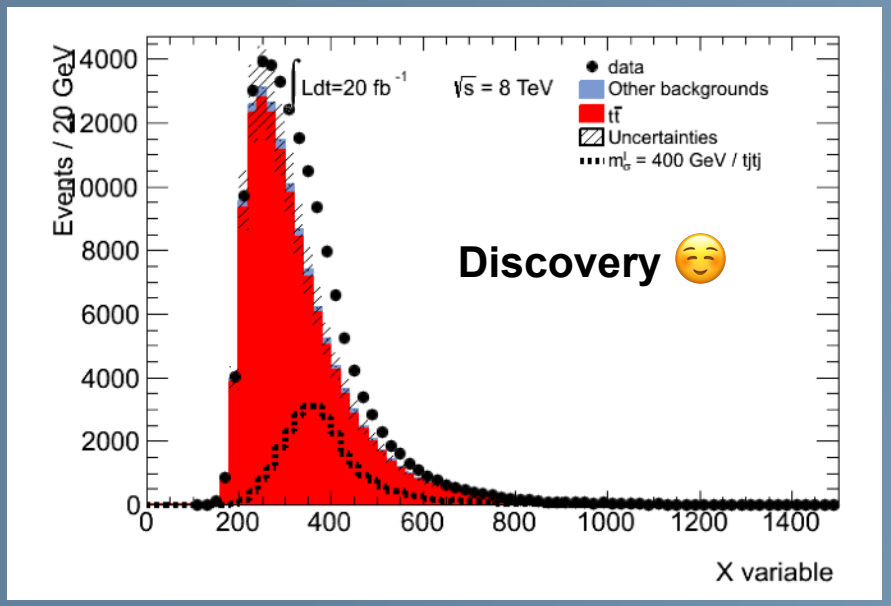

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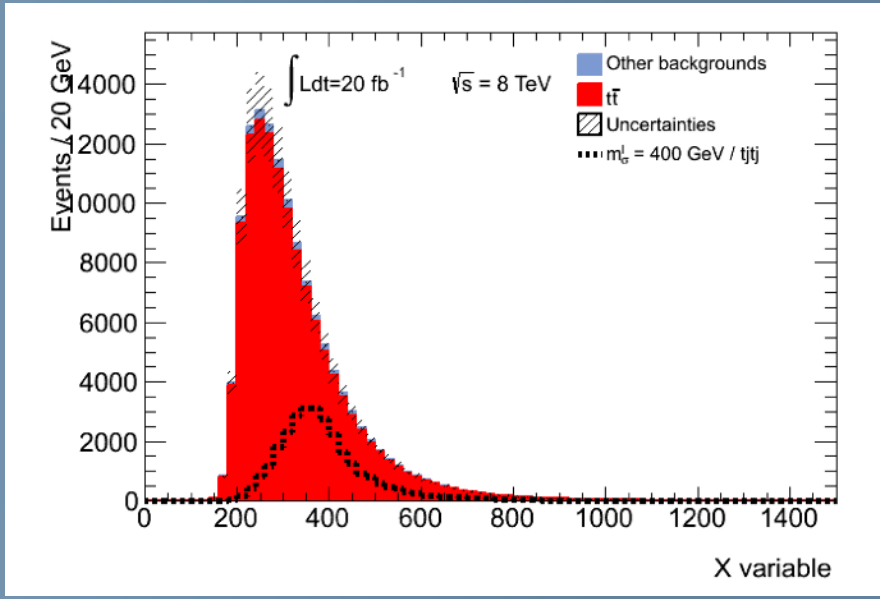
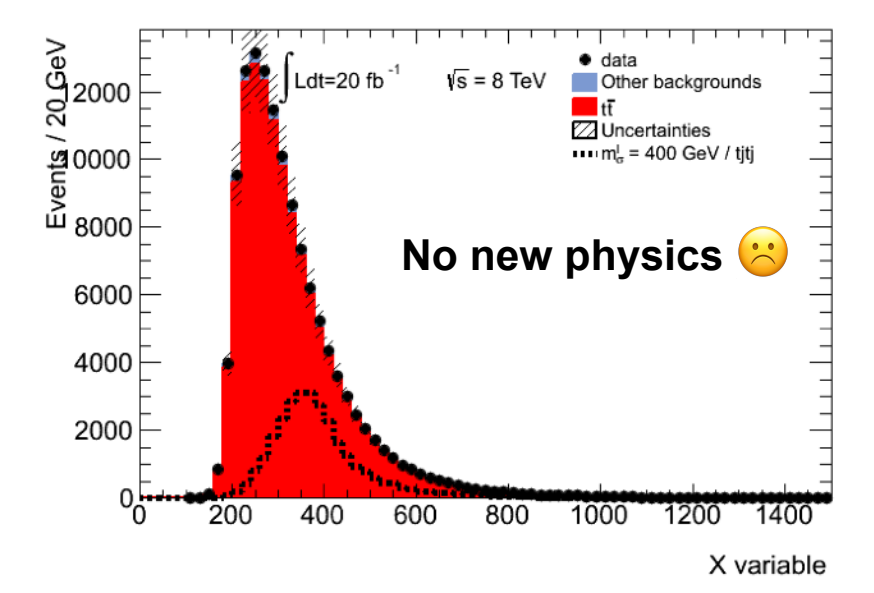
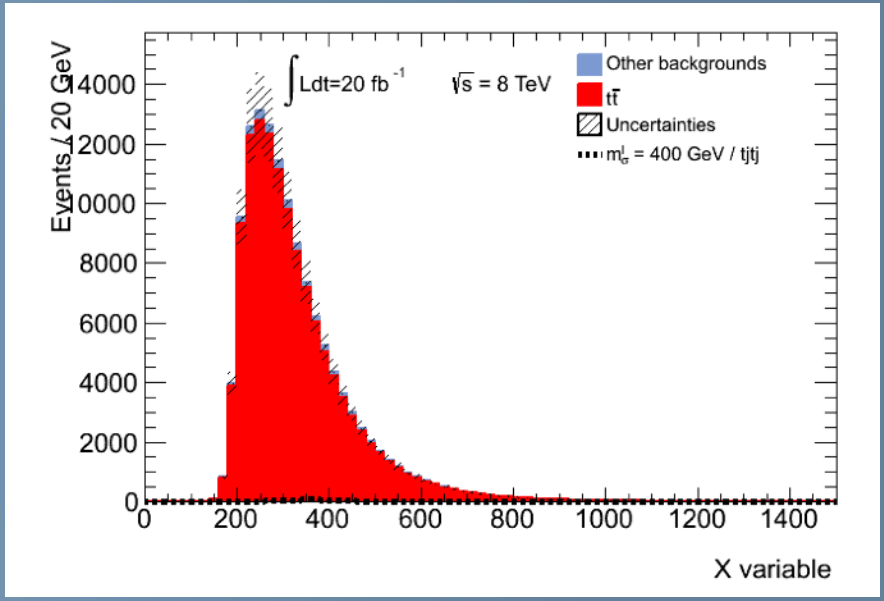




- If this signal existed … we would have seen it !
- **If we don't see anything → signal likely doesn't exist**
  - This signal (at this rate) is **excluded**

[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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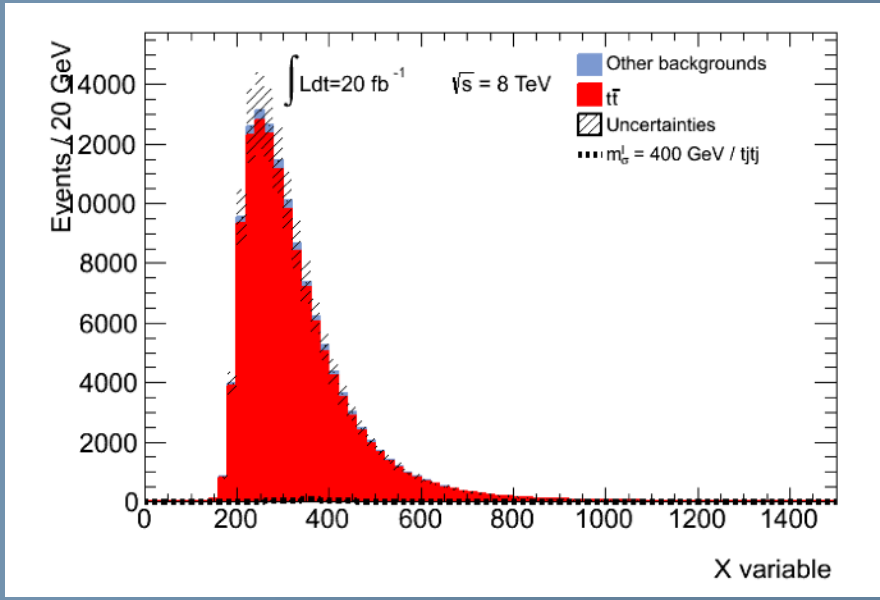

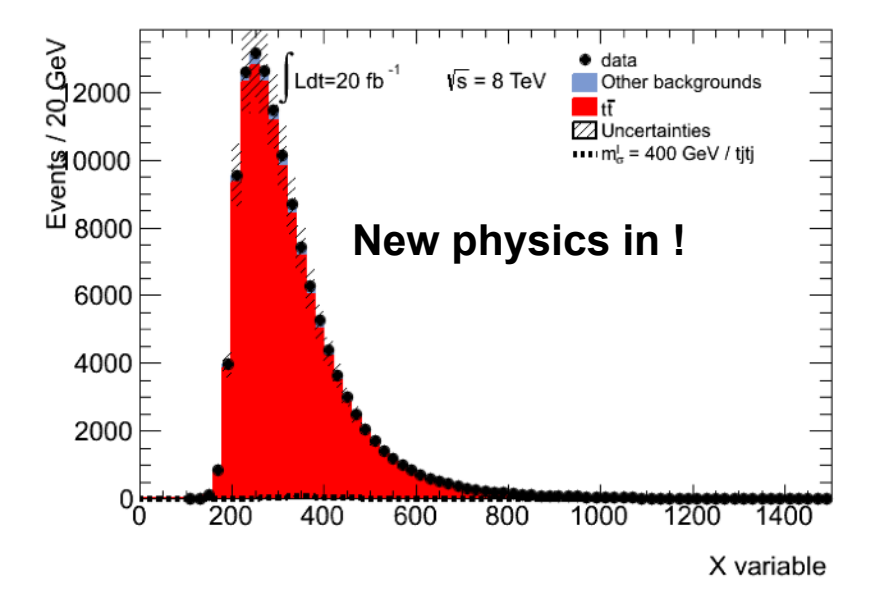

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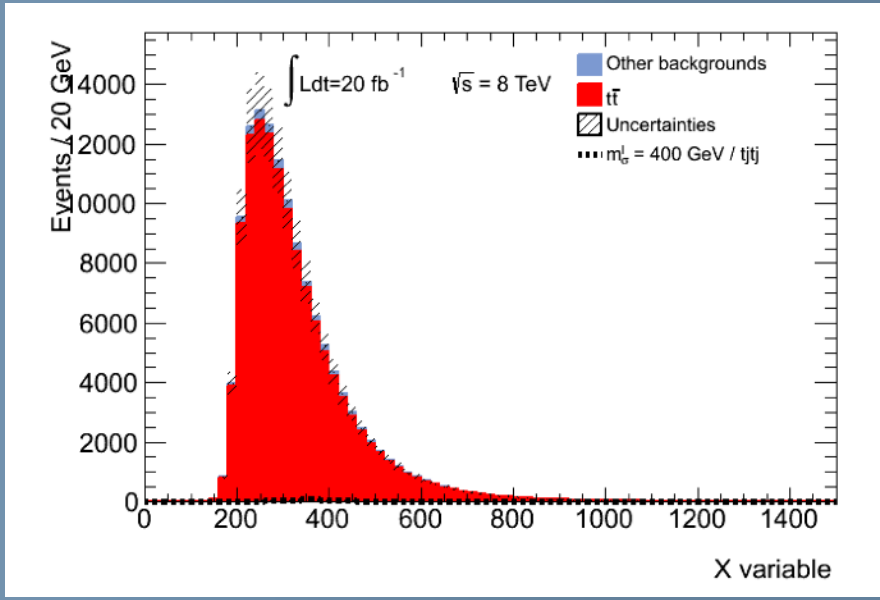
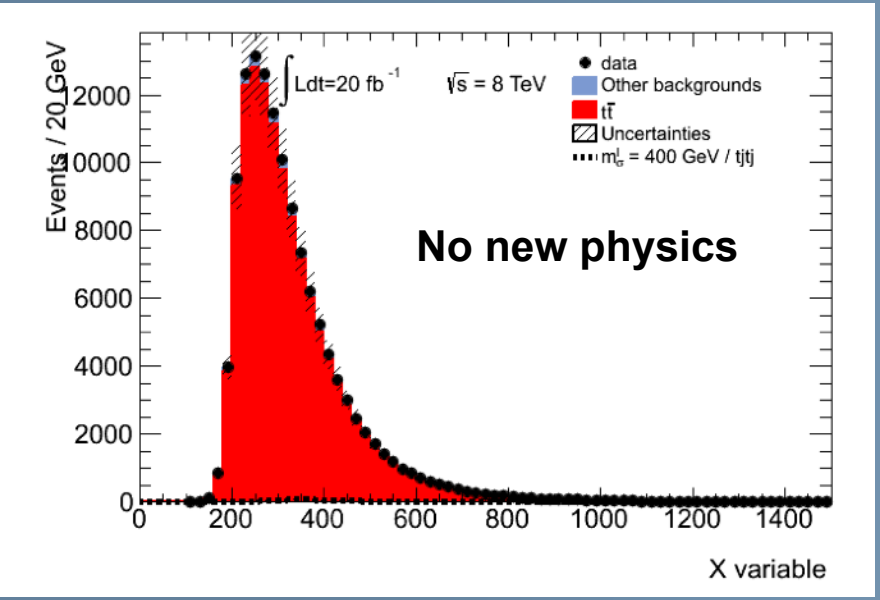
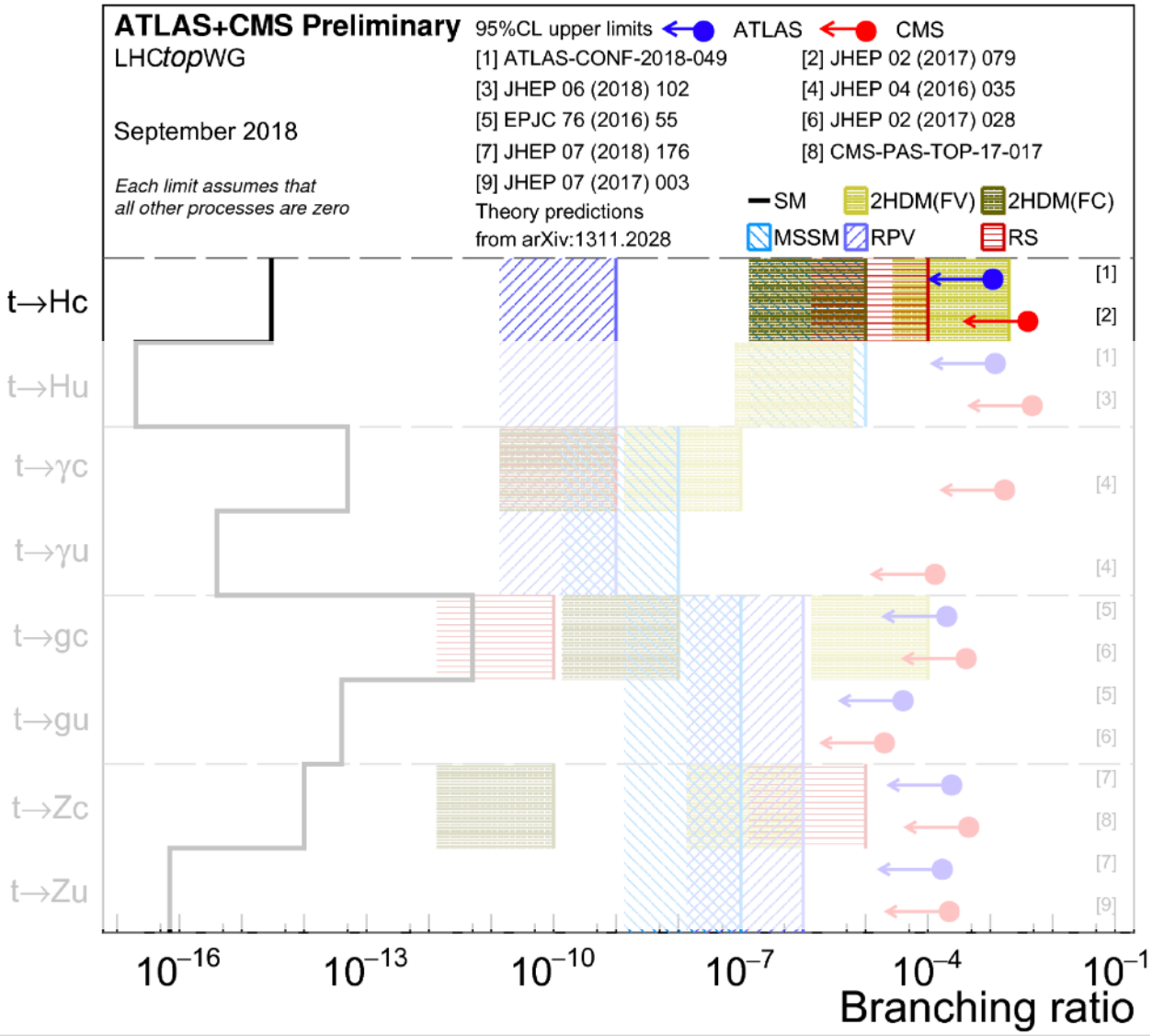




- Even if this signal existed … we couldn't have seen it !
- **No sensitivity** for this signal (at this rate)

Indirect searches



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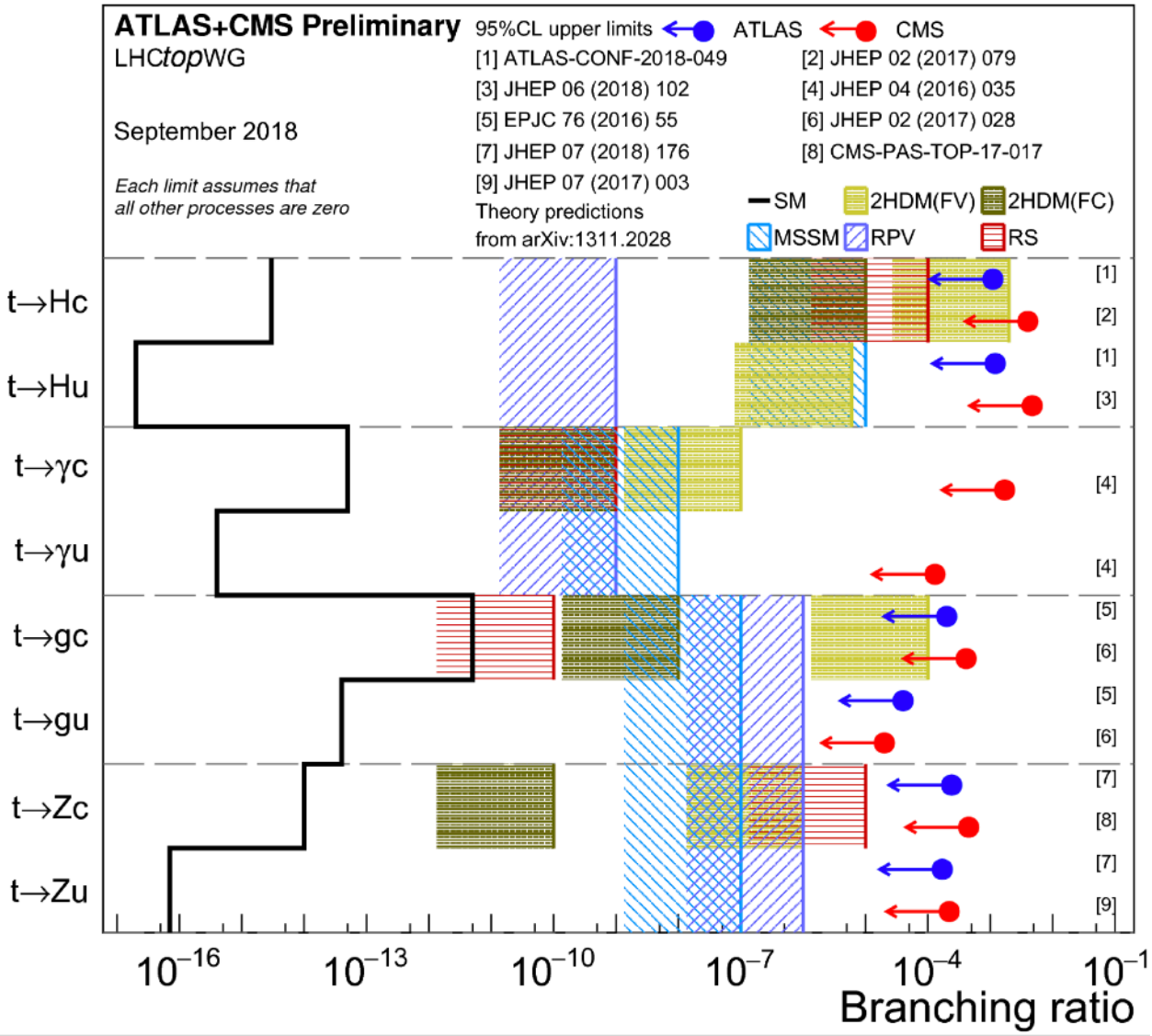
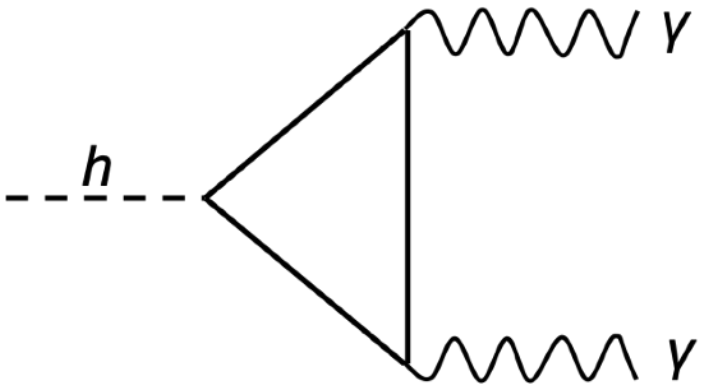
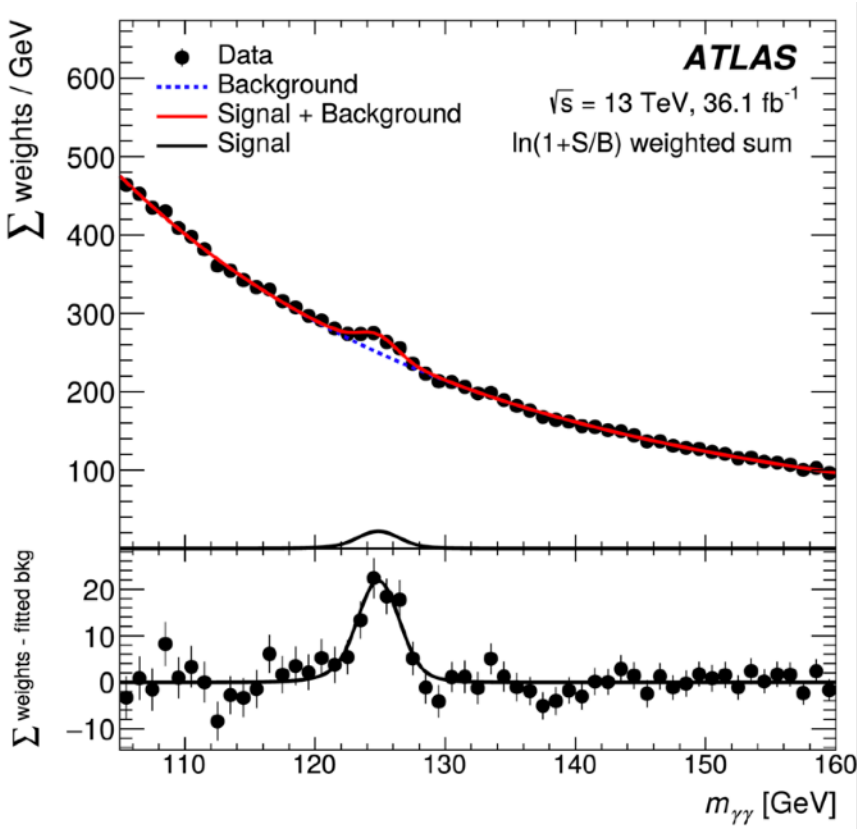


Direct searches

- Directly **search for new particles**
  - e.g. new Higgs bosons decaying to photons





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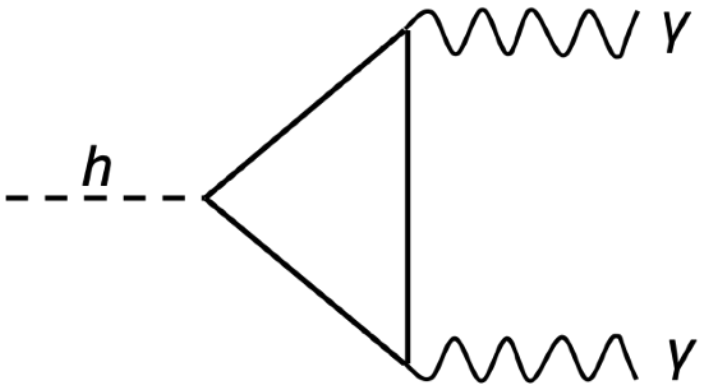


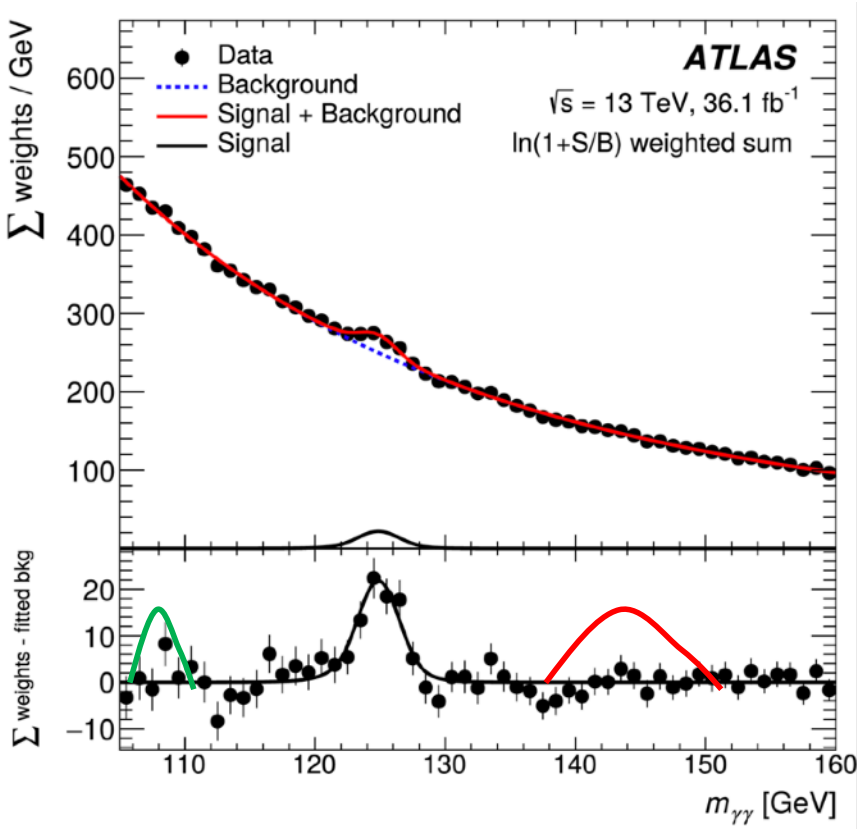
new peaks

⬇

new resonances

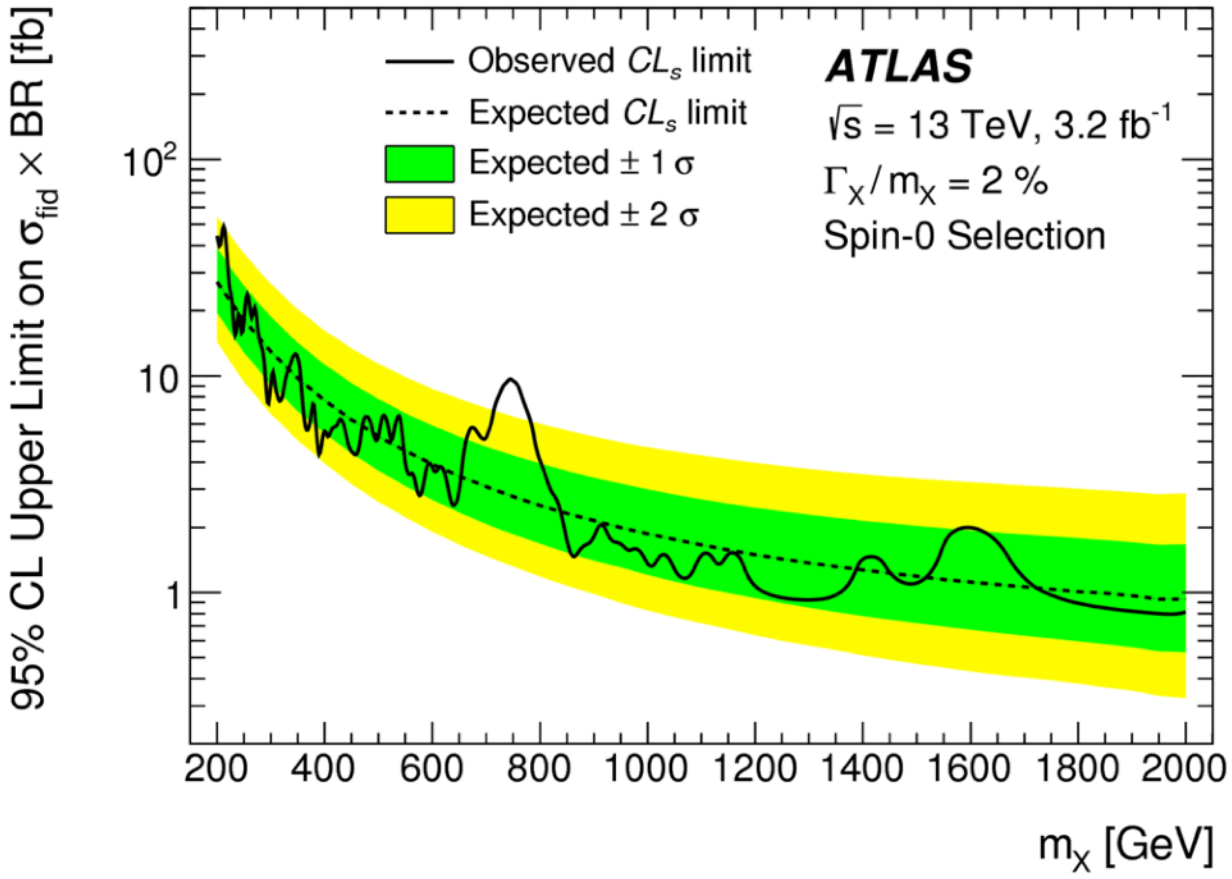
⬇

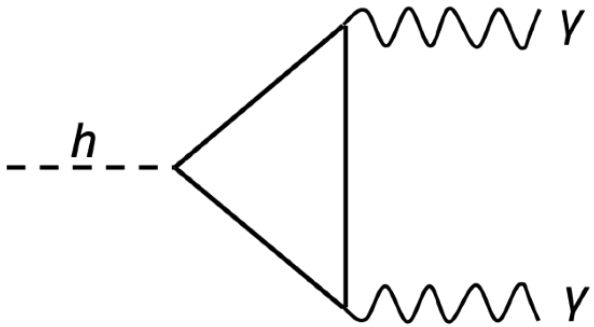
sign of new physics



All presented in Camille's and Yufeng's slides

Direct searches





~3 (local) sigma excess vanished with more data :(

Summary

- **New Physics motivated** by limitations/unnaturalness of SM
  - Dark matter
  - Naturalness problem
  - Hierarchy problem
  - …
- **Many models** can extend SM and cure some limitatations
  - SUSY, extra-dimensions, ...
  - **No real hint yet at LHC** (despite HUGE number of searches in past years)
- **Not all presented today** ... (would have needed days and days)
  - But more presented right now !


Lots of possible needles
In so many real haystacks !


Lots of possible needles
In so many real haystacks !

AND NOW ?

- **Extra-dimension models can predict new particles: branons**
  - Theory and prospective studies @ CMS

Recherche de bosons de Higgs supplémentaires dans le cadre des théories MSSM et 2HDM par l'observation de désintégration $H \to \tau\tau$ dans l'expérience CMS du LHC

Gaël touquet

IPNL

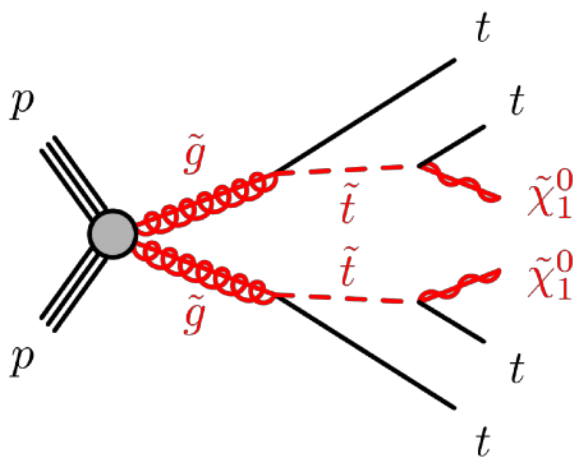
1er Décembre 2017

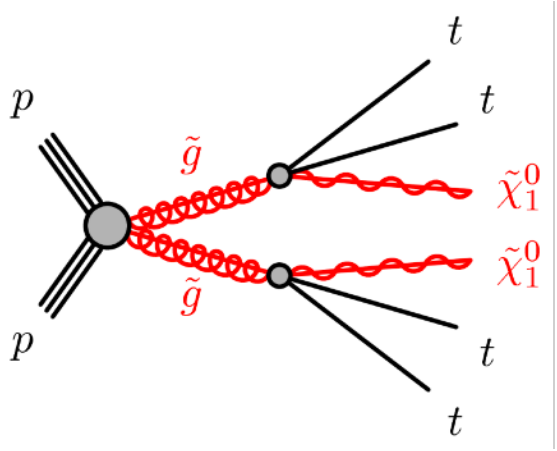
- **SUSY predicts an additional Higgs doublet: why ? how to look for new Higgses ?**
  - Theory and prospective studies @ CMS

Supersymmetry (V)

SUSY vs. LHC

- First data of LHC run 2 very promising for **strong SUSY production**
  - 13 TeV gluino pair-prod cross-section **multiplied by 40 – 2000** wrt 8 TeV
  - Huge discovery power !!
- Probed through **(very) simple benchmarks**

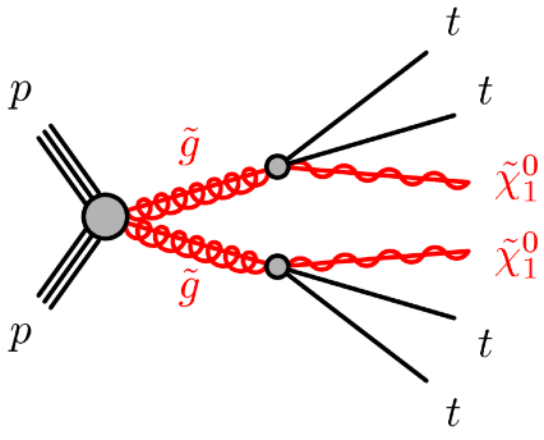




- Only **two parameters**: gluino and neutralino masses
  - Easy !

Supersymmetry (VI)

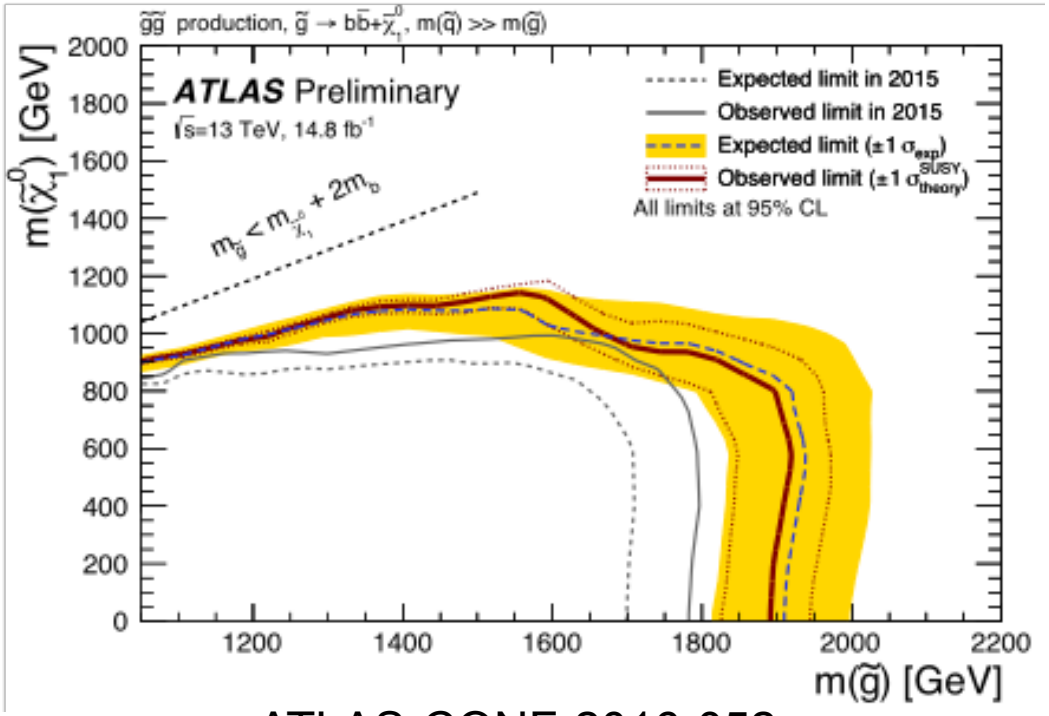
SUSY vs. LHC



- **Limits** set in the mass plane
  - Expected and observed agree (too) well ☹

- **Optimistic**
  - No hint SUSY **yet**
- **Pessimistic**
  - RIP SUSY

- Gluinos (if existing) **should be heavy** …



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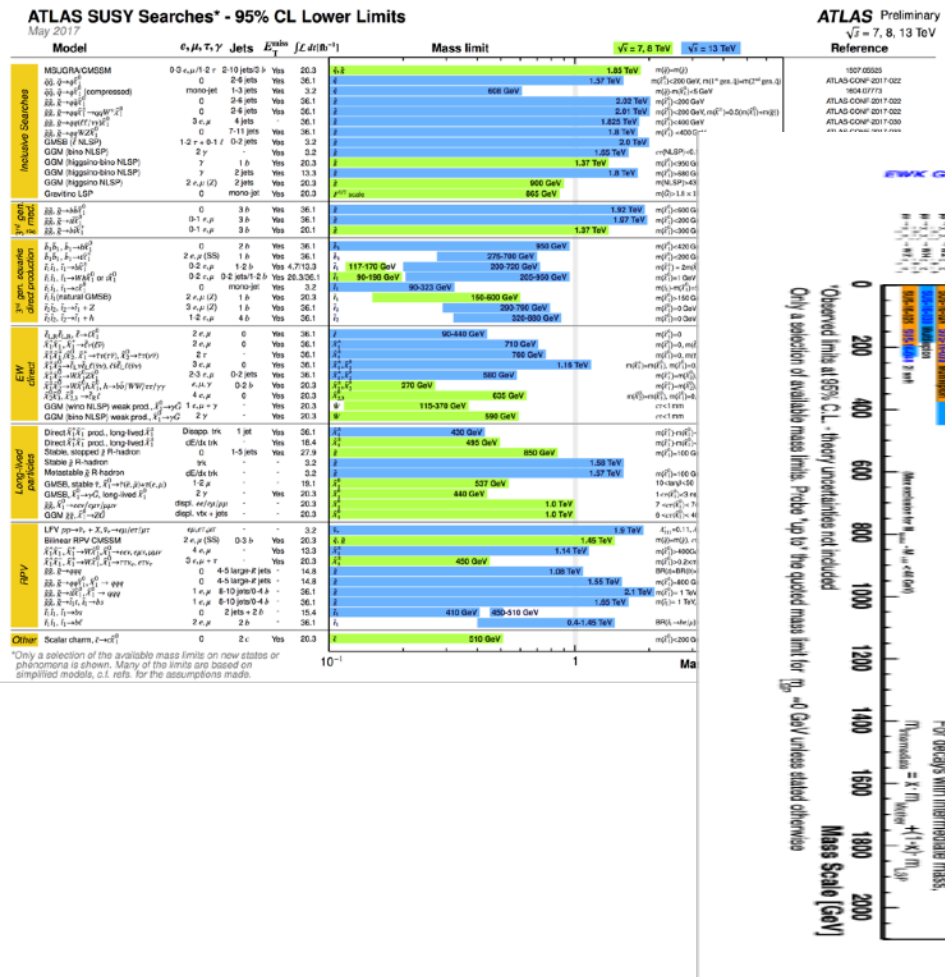
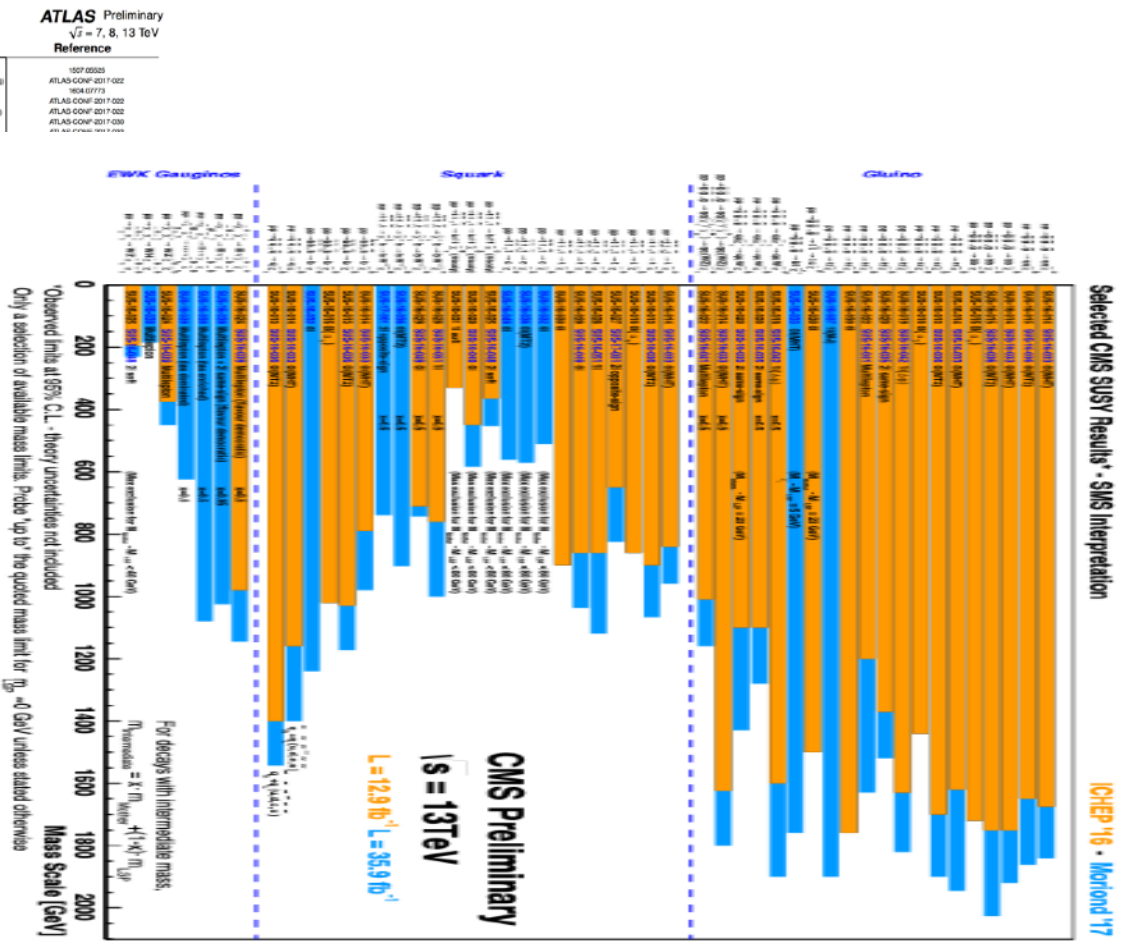
Supersymmetry (VII)

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





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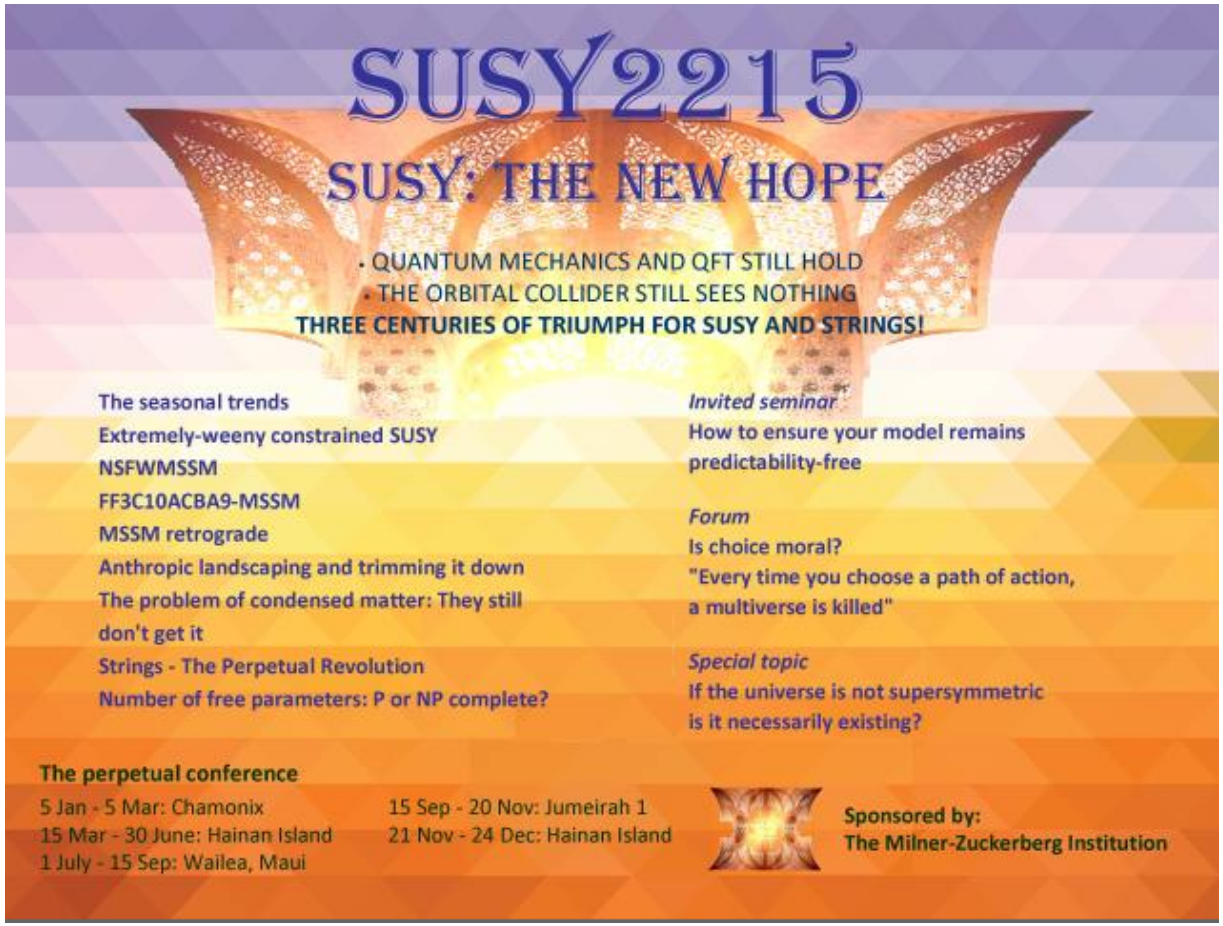

Observe new particles ?

- **Indirect** searches