



## 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 ?

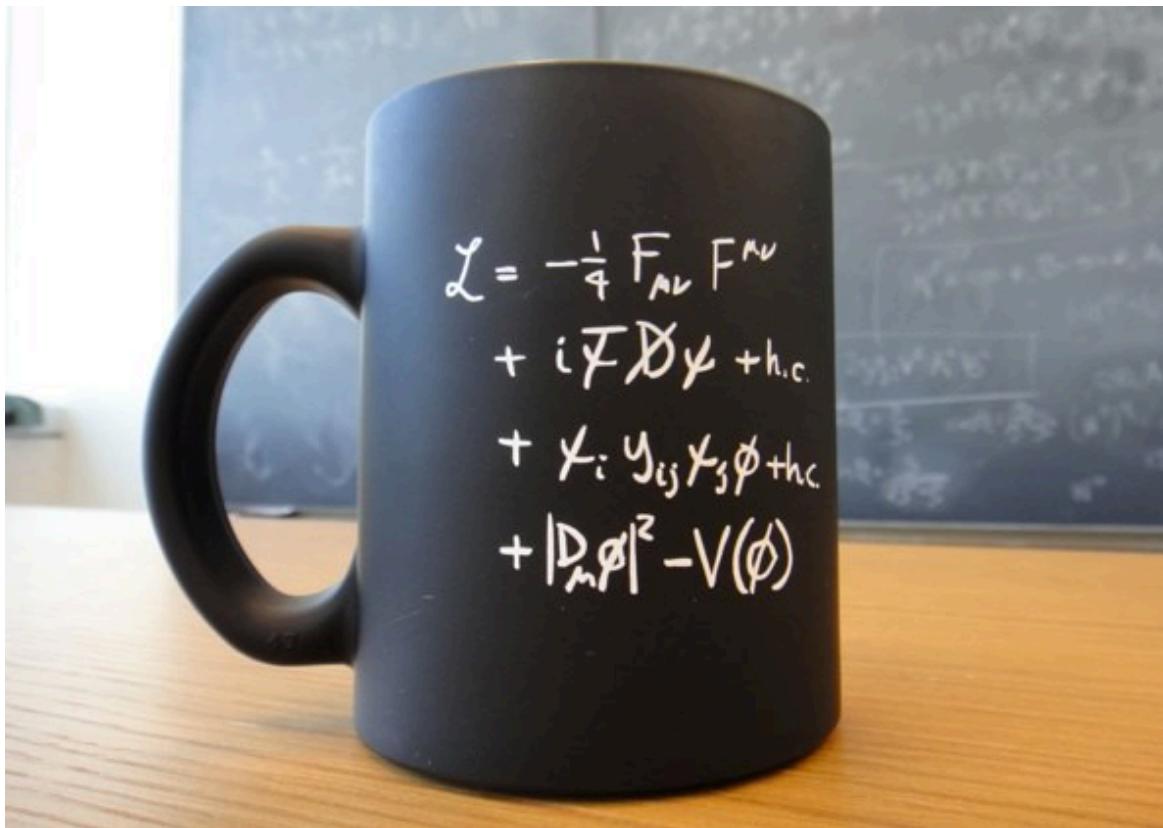
# WHY NEW PHYSICS ?

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# 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 😊 😞

Three Generations of Matter (Fermions)				Quarks	Leptons	Gauge Bosons
I	II	III				
mass → 2.4 MeV/c <sup>2</sup>	1.27 GeV/c <sup>2</sup>	171.2 GeV/c <sup>2</sup>		u charge → 2/3 spin → 1/2 name → up	e charge → -1 spin → 1/2 name → electron	H charge → 0 spin → 0 name → Higgs
charge → 2/3	2/3	2/3		c charge → 2/3 spin → 1/2 name → charm	μ charge → -1 spin → 1/2 name → muon	Z <sup>0</sup> charge → 0 spin → 1 name → Z boson
spin → 1/2	1/2	1/2		t charge → 2/3 spin → 1/2 name → top	τ charge → -1 spin → 1/2 name → tau	W <sup>±</sup> charge → ±1 spin → 1 name → W boson
				d charge → -1/3 spin → 1/2 name → down	ν <sub>e</sub> charge → 0 spin → 1/2 name → electron neutrino	g charge → 0 spin → 1 name → gluon
				s charge → -1/3 spin → 1/2 name → strange	ν <sub>μ</sub> charge → 0 spin → 1/2 name → muon neutrino	
				b charge → -1/3 spin → 1/2 name → bottom	ν <sub>τ</sub> charge → 0 spin → 1/2 name → tau neutrino	

# The Standard Model: successes (I)



*Top quark is very  
special ... Heaviest  
particle in SM*

Feynman diagram showing the decay of a top quark ( $t$ ) into a  $W^+$  boson and a  $b$  quark. The  $W^+$  boson decays into an electron ( $l^+$ ) and a neutrino ( $\nu$ ). The  $t$  quark is shown as a red line, and the  $W^+$ ,  $l^+$ ,  $\nu$ , and  $b$  quarks are shown as wavy red lines.

- **Fermions**
    - Elementary constituents of matter
  - And **Higgs** boson ...
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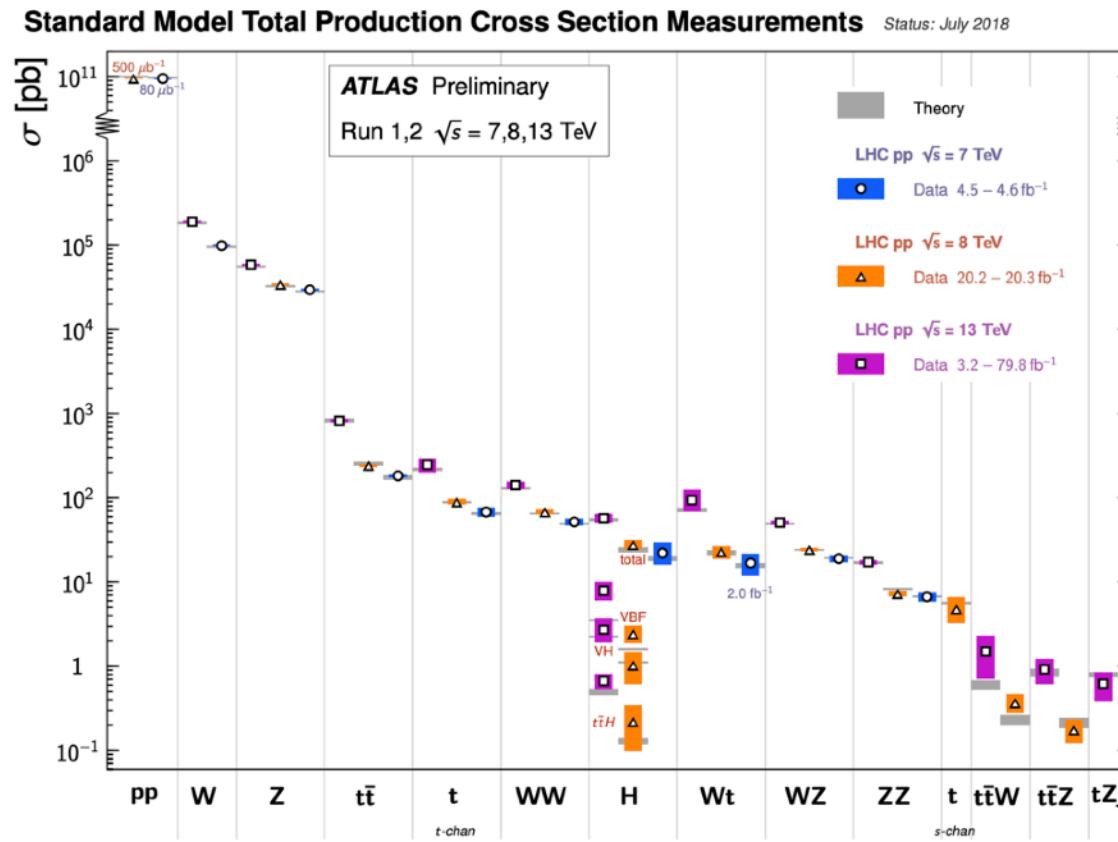
*Will be back later !!!*

# Describe **elementary**

Three Generations of Matter (Fermions)				Higgs
	I	II	III	
mass →	2.4 MeV/c <sup>2</sup>	1.27 GeV/c <sup>2</sup>	171.2 GeV/c <sup>2</sup>	~125 GeV
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	0
name →	up	charm	top	Higgs
<b>Quarks</b>				
	d - $\frac{1}{3}$ $\frac{1}{2}$ down	s - $\frac{1}{3}$ $\frac{1}{2}$ strange	b - $\frac{1}{3}$ $\frac{1}{2}$ bottom	g 0 0 1 gluon
<b>Leptons</b>				
	e 0 $\frac{1}{2}$ electron neutrino	$\nu_\mu$ 0 $\frac{1}{2}$ muon neutrino	$\nu_\tau$ 0 $\frac{1}{2}$ tau neutrino	$Z^0$ 91.2 GeV/c <sup>2</sup> 0 1 Z boson
<b>Gauge Bosons</b>				
	e -1 $\frac{1}{2}$ electron	$\mu$ -1 $\frac{1}{2}$ muon	$\tau$ -1 $\frac{1}{2}$ tau	$W^\pm$ 80.4 GeV/c <sup>2</sup> $\pm 1$ 1 W boson

# 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 ?**

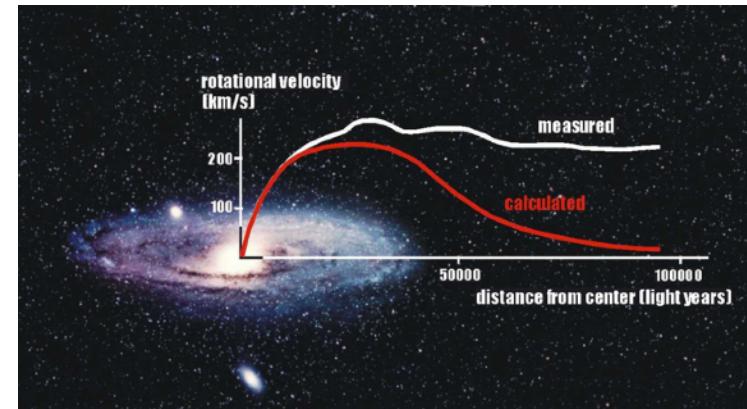


# But ...

Neutrino masses

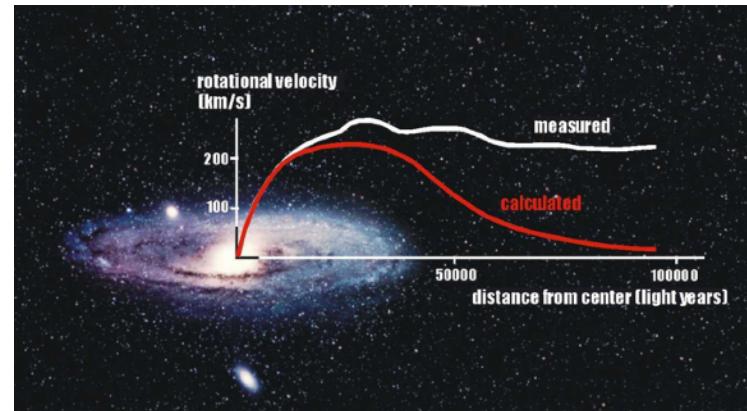
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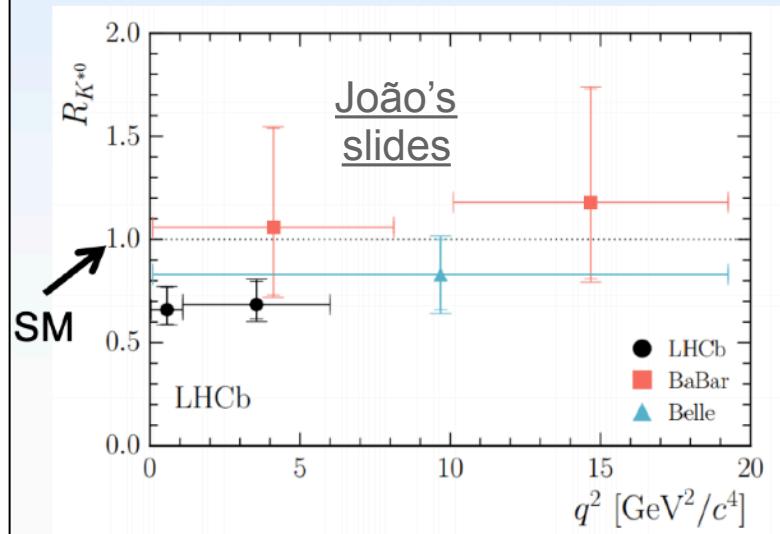


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**Neutrino masses**

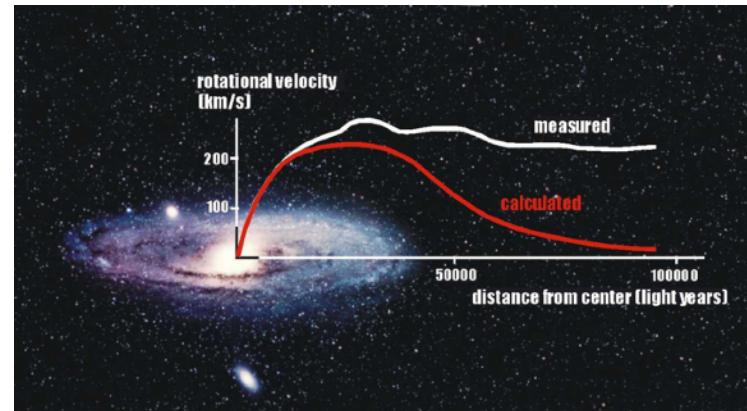


$$R(K^*) = \frac{\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} e^+ e^-)}$$

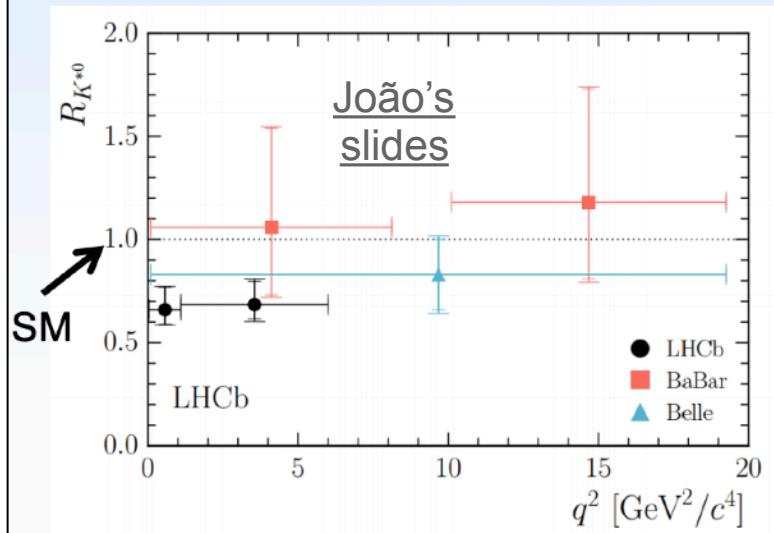


# But ...

## Neutrino masses



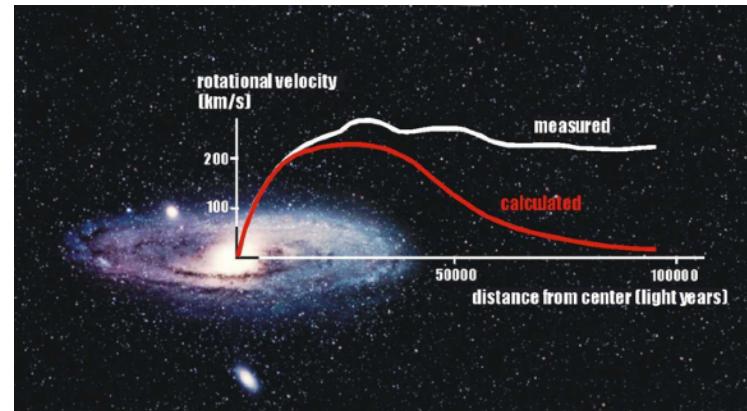
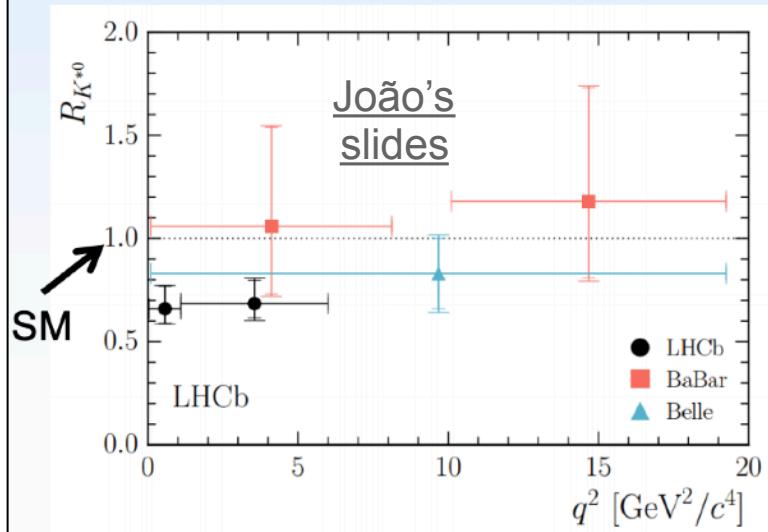
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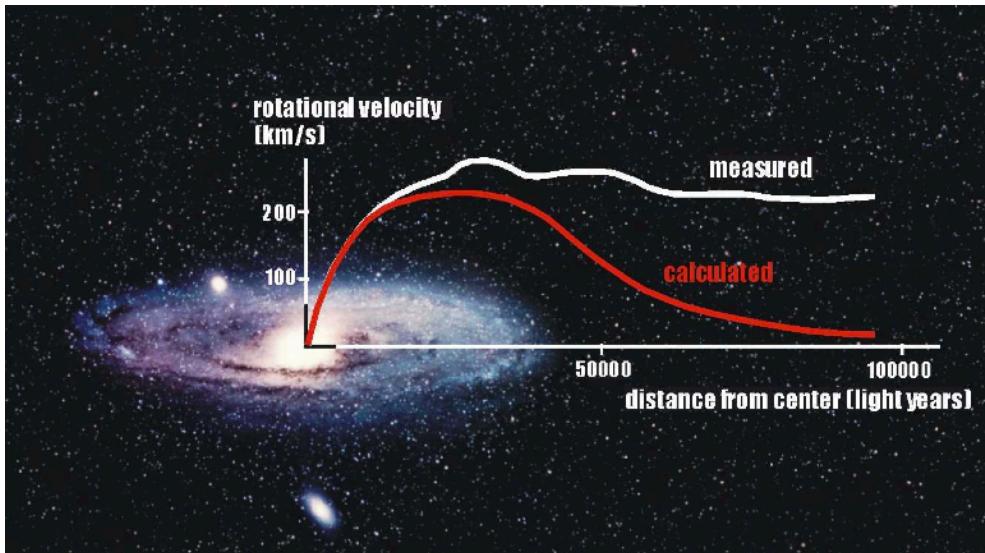
**Mass/scale hierarchy**



# The Standard Model: limitations (I)

- **Dark matter**

- Already discussed in previous sessions
- Astrophysical observations motivate its existence
  - Galaxy rotation velocity:  $\sim$  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**

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



- $m$  measured at  $\sim 125$  GeV
- Standard Model valid until  $\Lambda_c$  (“cut-off scale”)
- $\lambda_f$  the fermion Yukawa coupling (i.e. coupling to the Higgs)

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- **Where is the problem ?**

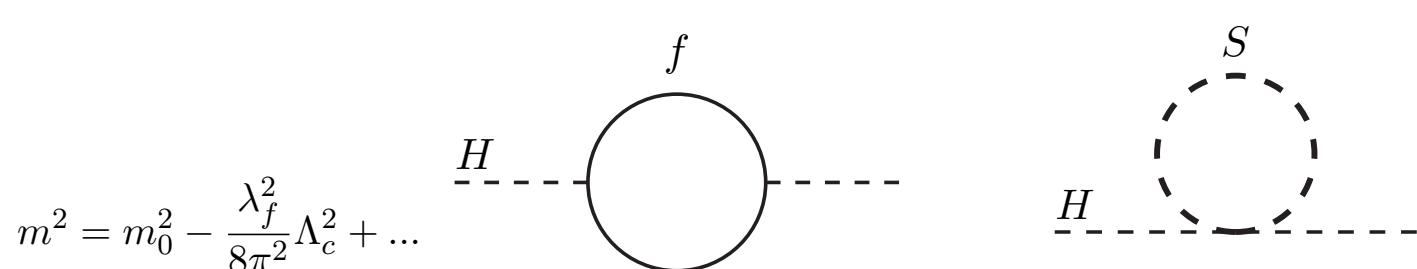
- $m_0$  and  $\lambda_f$  have to be adjusted up to the 32<sup>nd</sup> decimal ...

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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** !

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



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  - **Reducing the scale  $\Lambda$** 
    - $\Lambda$  can be large because Planck scale is large  $\rightarrow$  gravitation is **weak** at our scale
    - Because it is propagating through more than 4 dimensions ?
    - So, need for additional dimensions !

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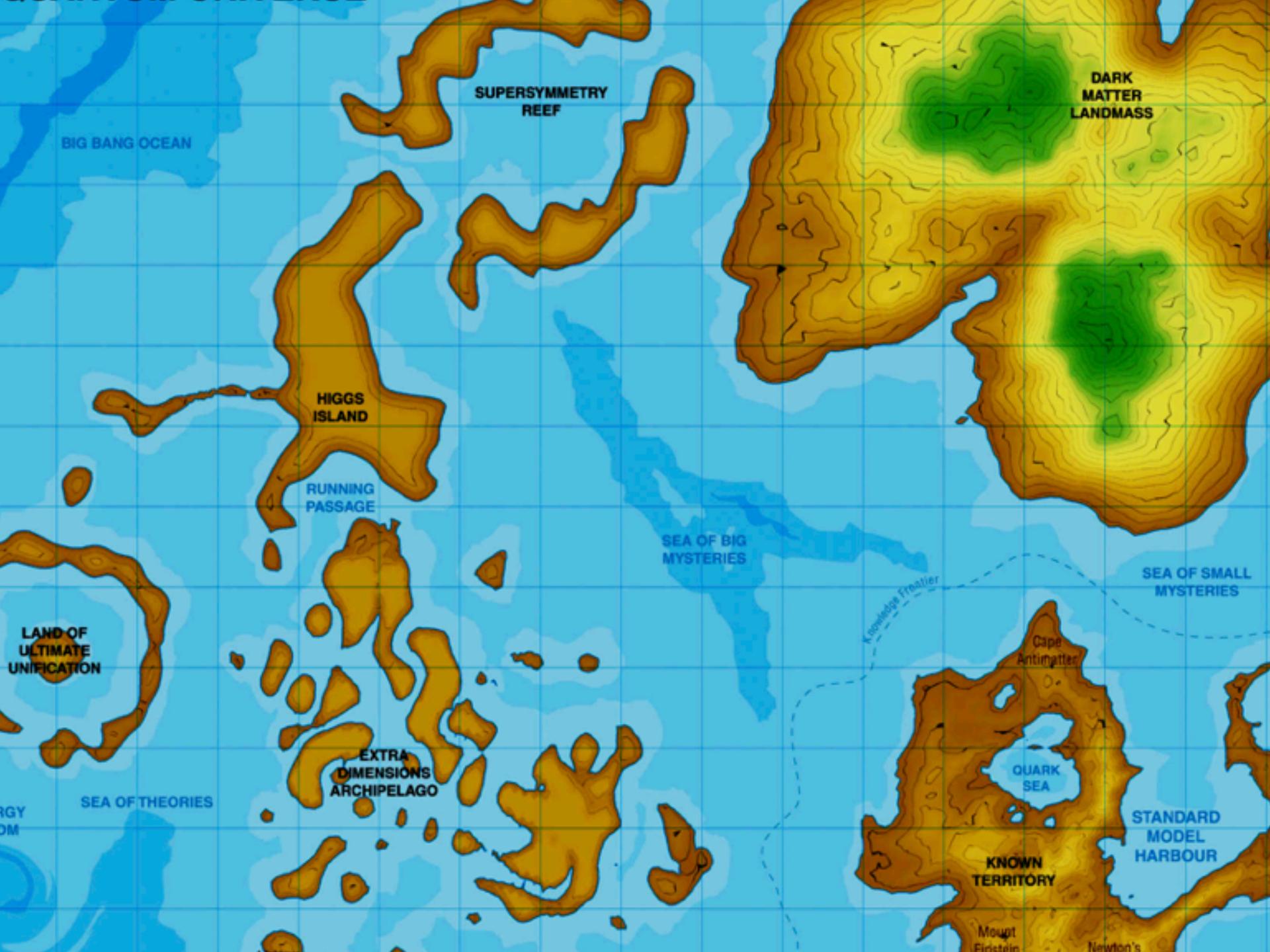


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  - **And what if Higgs was not really the Higgs ?**
    - Composite Higgs ?
    - Additional Higgs doublets

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





# WHAT TO LOOK FOR ?

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# Supersymmetry (I)

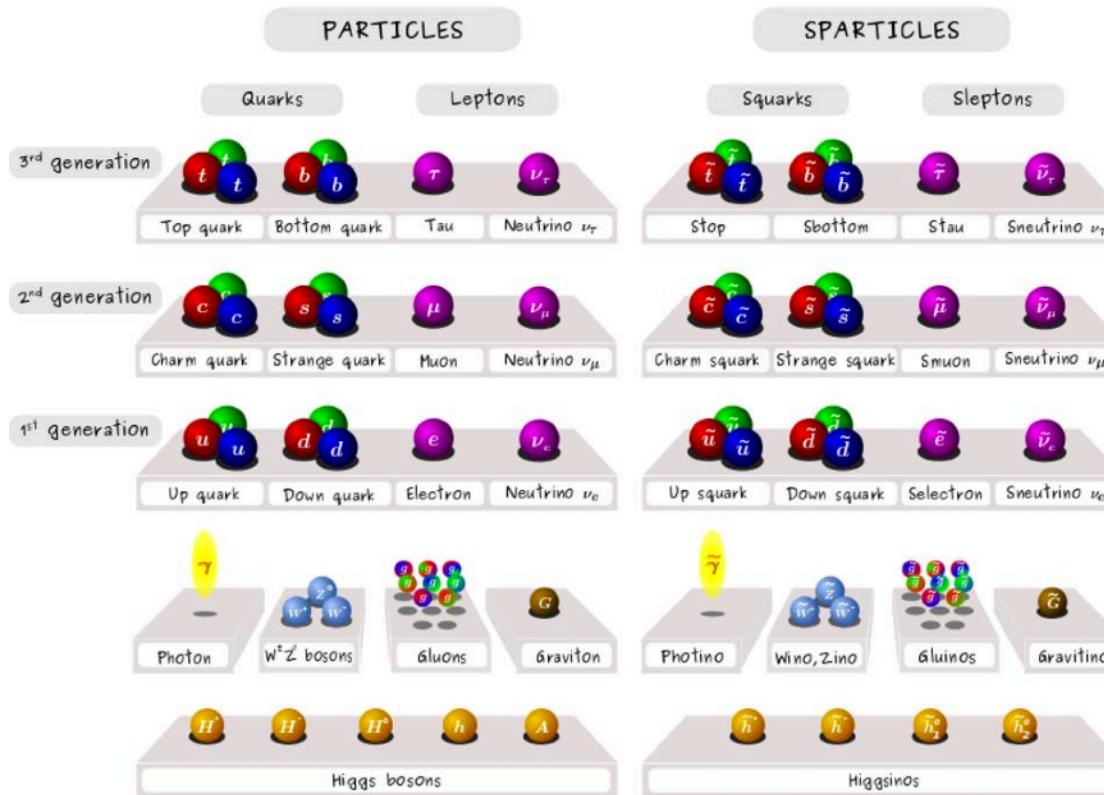
- General idea

Fermion / Boson symmetry

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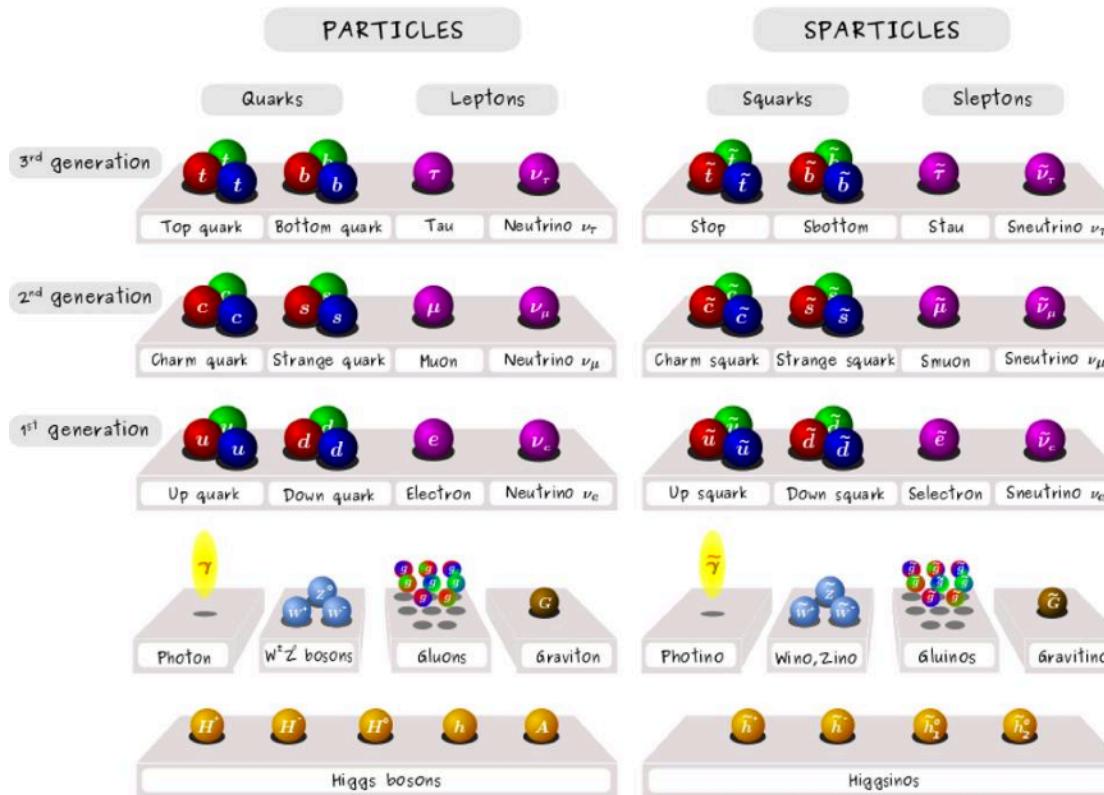
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# Supersymmetry (I)

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## Fermion / Boson symmetry

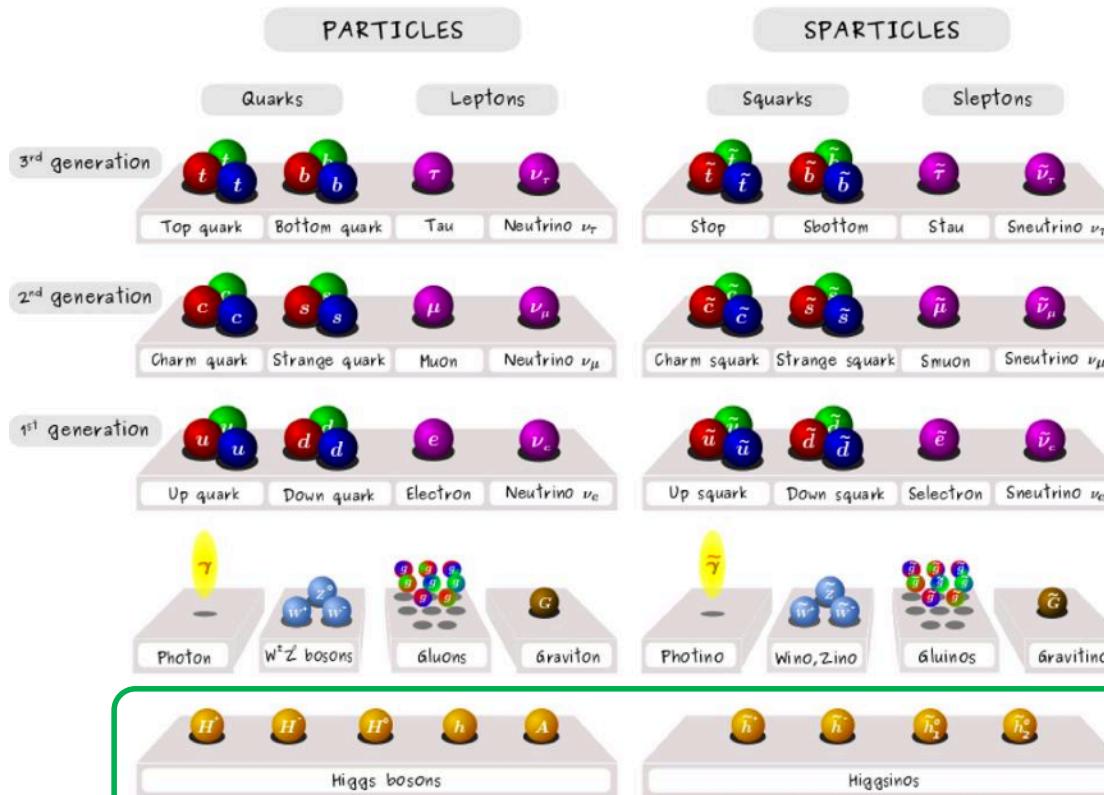


Particle content:  
~factor 2

# Supersymmetry (I)

- General idea

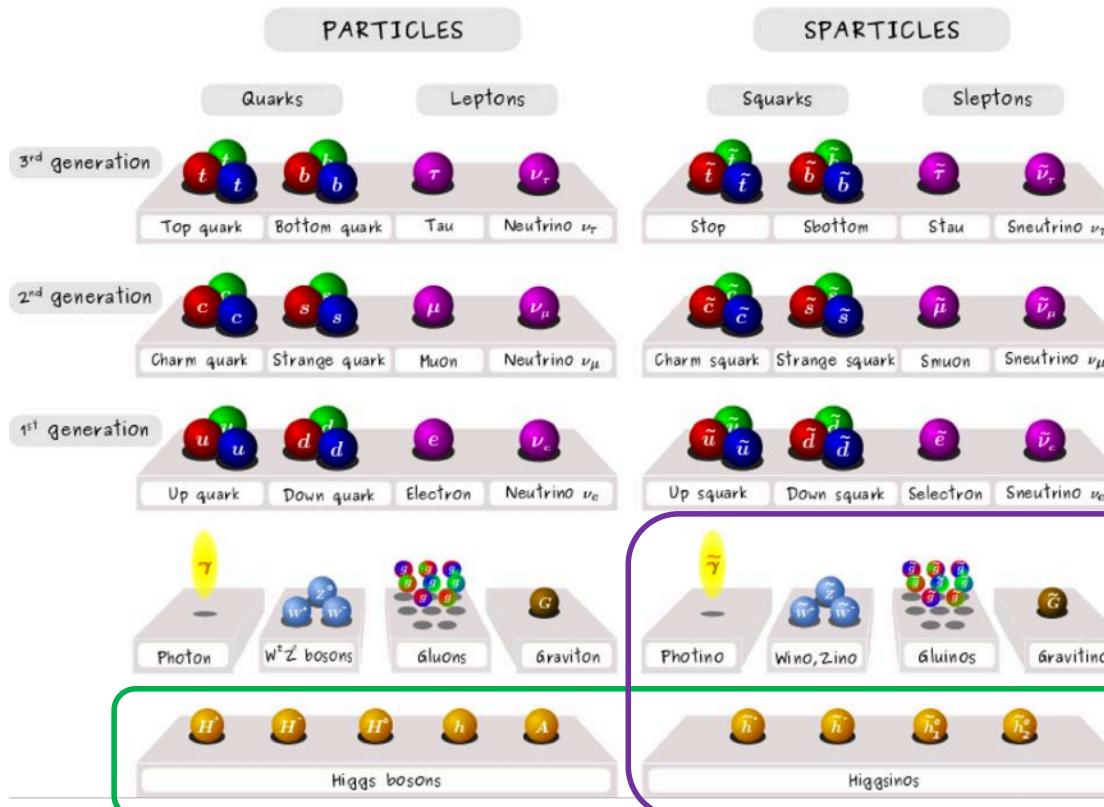
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# Supersymmetry (I)

- General idea

## Fermion / Boson symmetry



# 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

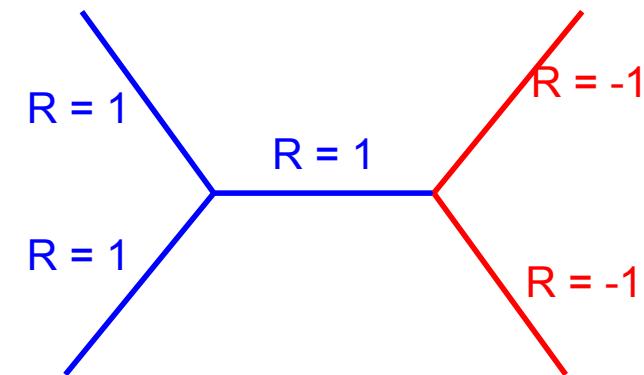
$$R = (-1)^{3(B-L)+2s}$$

- B and L the baryonic and leptonic numbers
- s the spin

- **Consequence:**

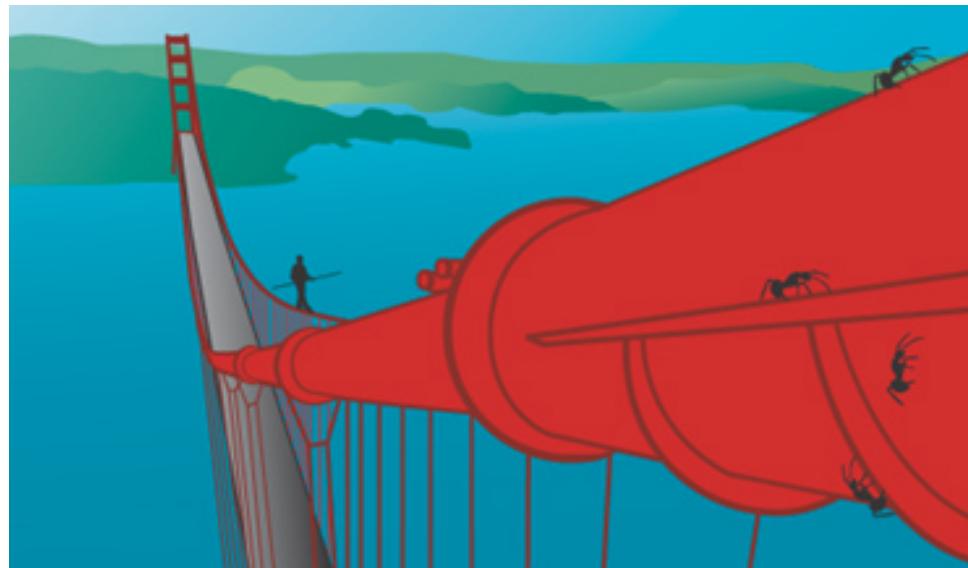
- $R = -1$  for SUSY particles
- $R = +1$  for SM particles

- 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

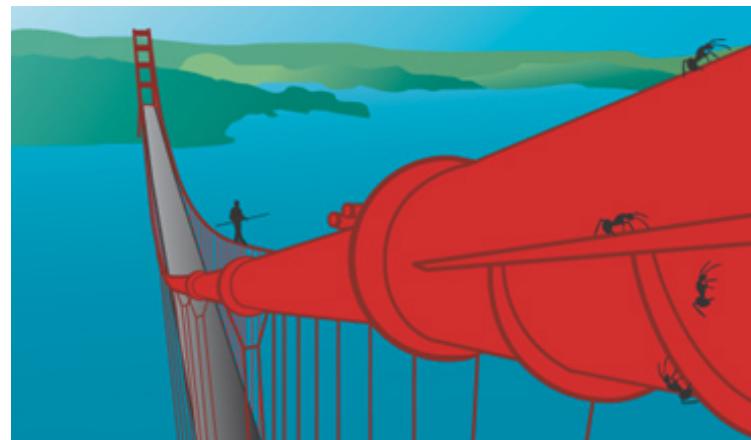


# Extra-dimension theories (I)

- **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**

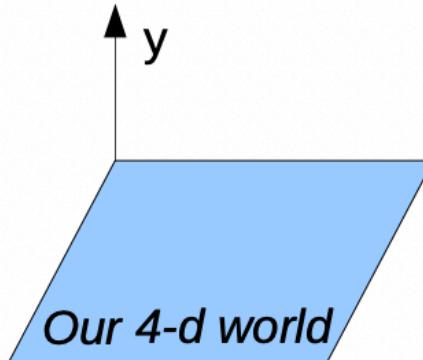
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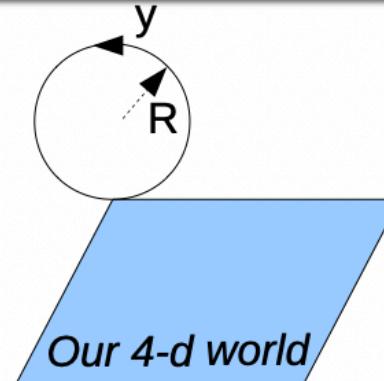
# Extra-dimension theories (II)

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JRJC 2015

**“Flat”**

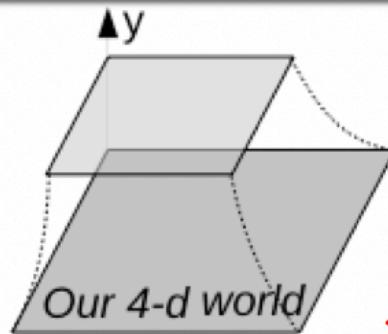


$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu \quad (\mu, \nu = 0, 1, 2, 3 \dots D)$$



Periodicity conditions on field ...  
Fourier expansion

**“Warped”**



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

**Warp factor**

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

Kaluza-Klein modes  
(infinite number)

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

# Extra-dimension theories (III)

- **Types of ED theories**
  - Depend on
    - number of extra-dimensions: 1 or  $\geq 2$
    - topology (flat or warped)
    - fields propagating along new dimensions
  - **Lots of combination ...** with different phenomenologies



# HOW TO LOOK FOR THAT ?

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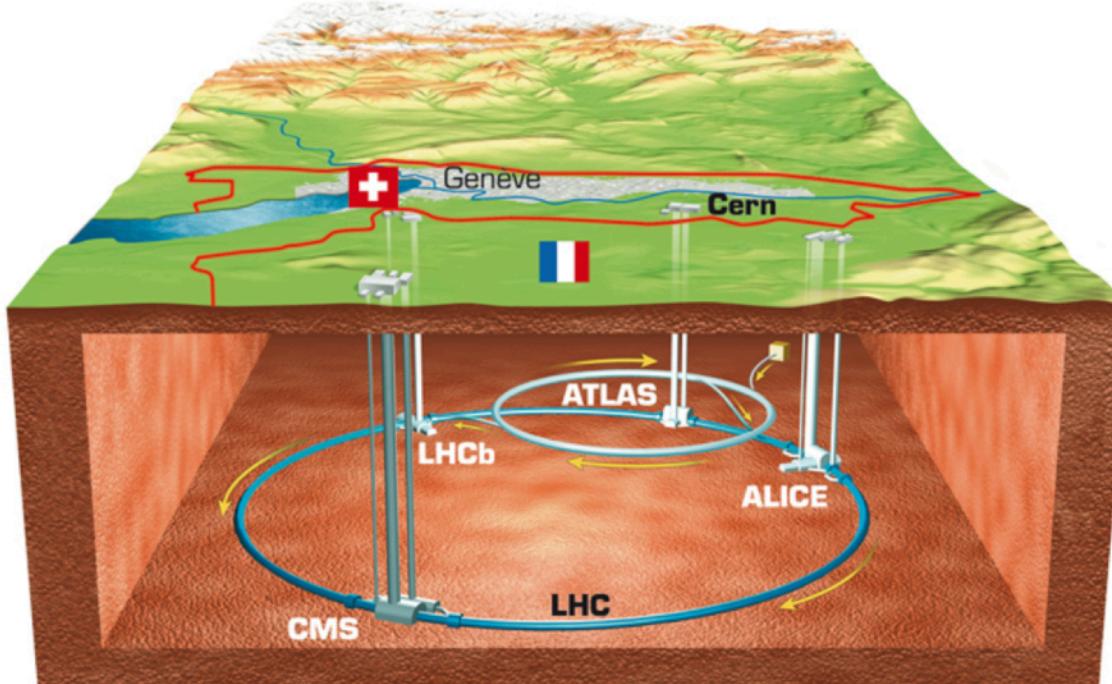
# Produce new particles ?

- 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



# Observe new particles ?

Directly

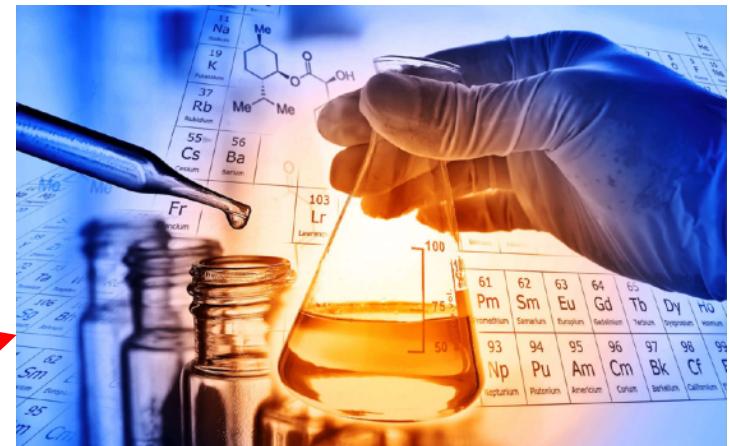


Indirectly



# Observe new particles ?

Directly



Indirectly

Now a BSM example

# Indirect searches

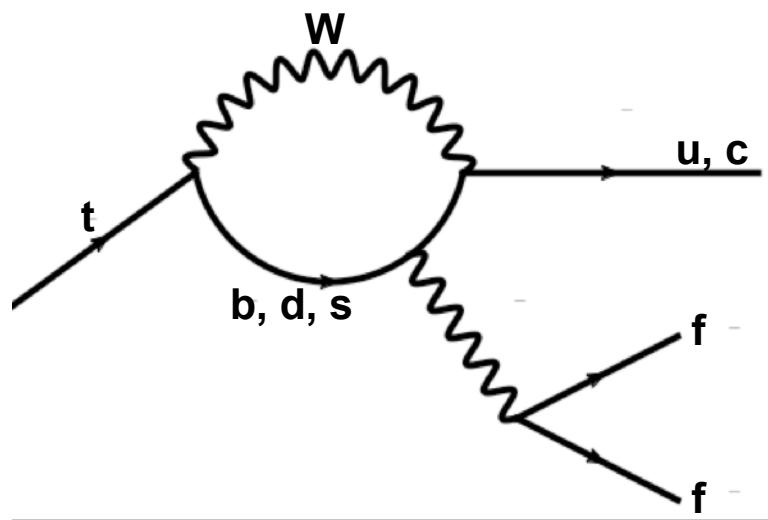
- New processes could increase cross-section of **rare SM processes**
  - e.g. flavour changing neutral currents in top quark sector

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- New processes could increase cross-section of **rare SM processes**
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SM  $t \rightarrow Wb$

SM  $t \rightarrow Hu, Hc, \dots$  X (at tree level)

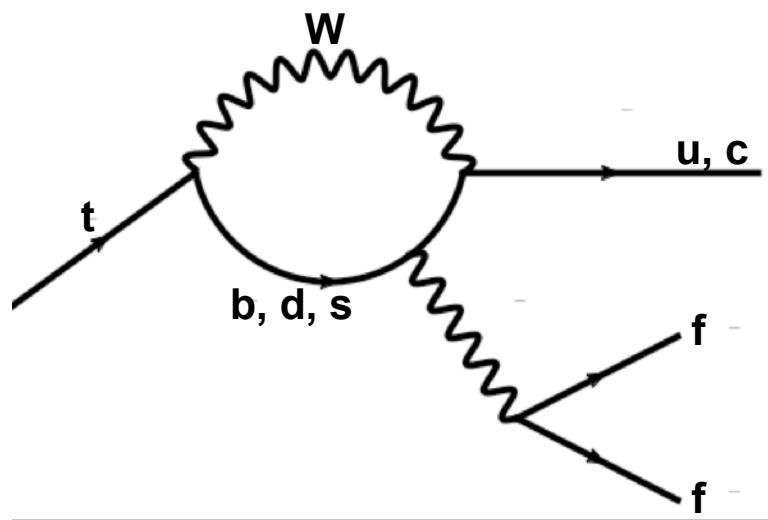


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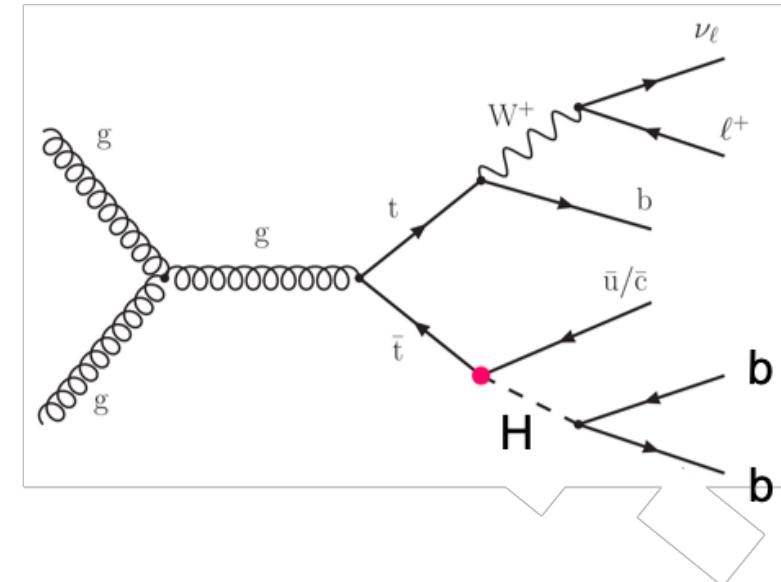
SM  $t \rightarrow Wb$

SM  $t \rightarrow Hu, Hc, \dots$  X (at tree level)



BSM  $t \rightarrow Wb$

BSM  $t \rightarrow Hu, Hc, \dots$  ✓ (at tree level)



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

# [Statistical break]

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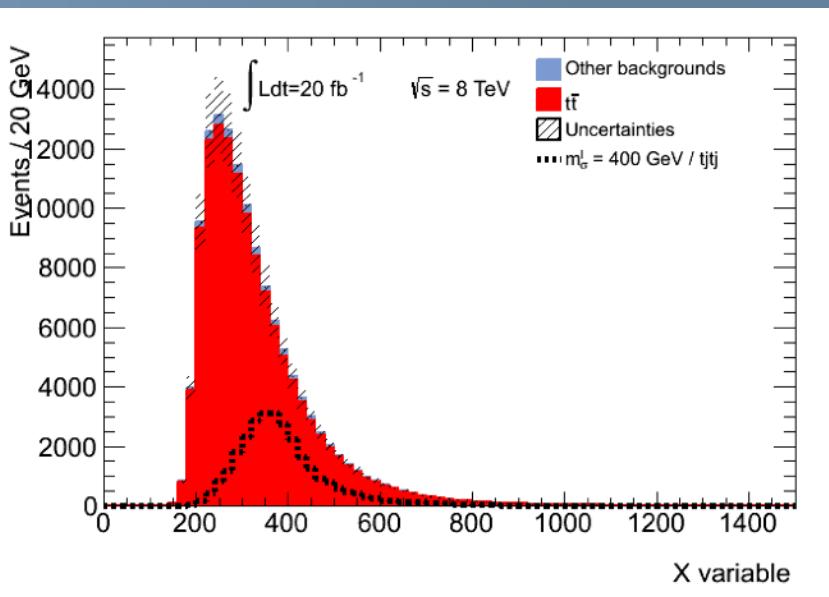
KEEP  
CALM  
AND  
DON'T  
PANIC

# [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**

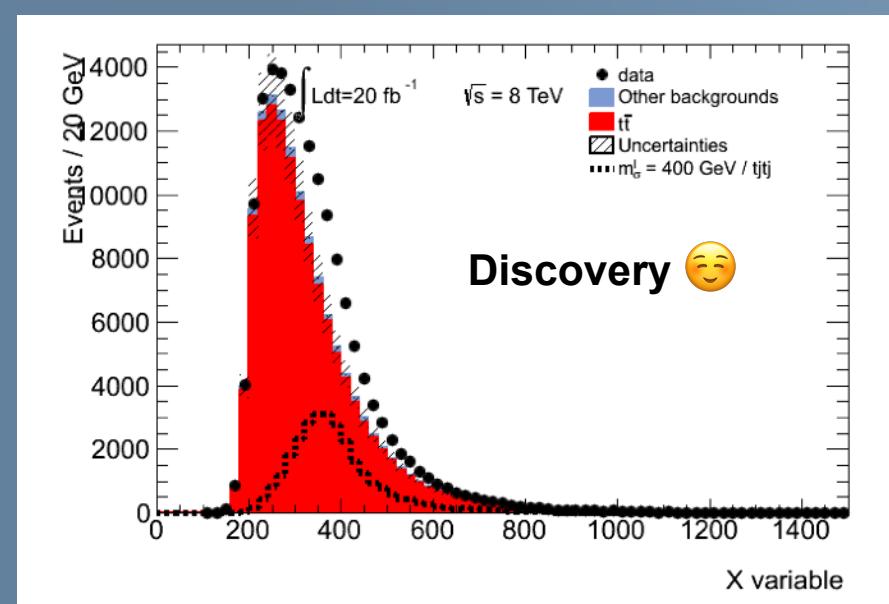
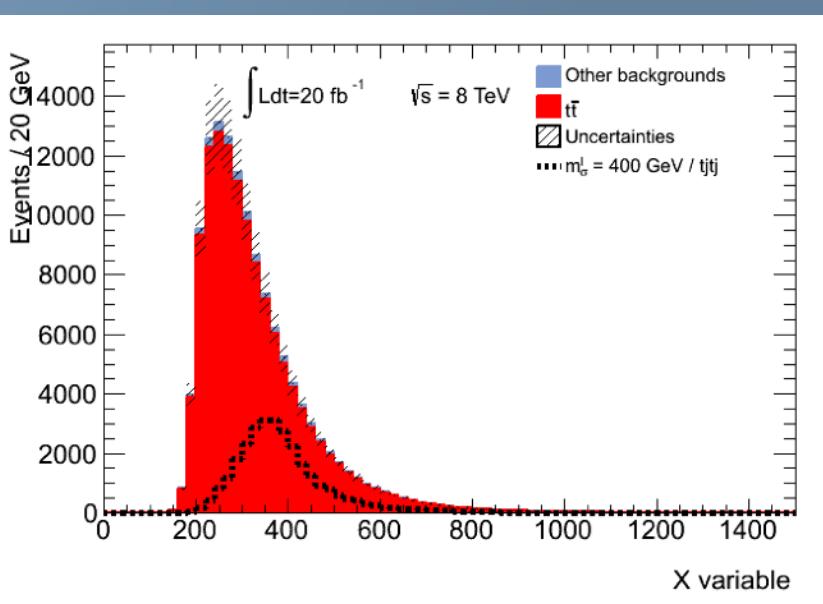
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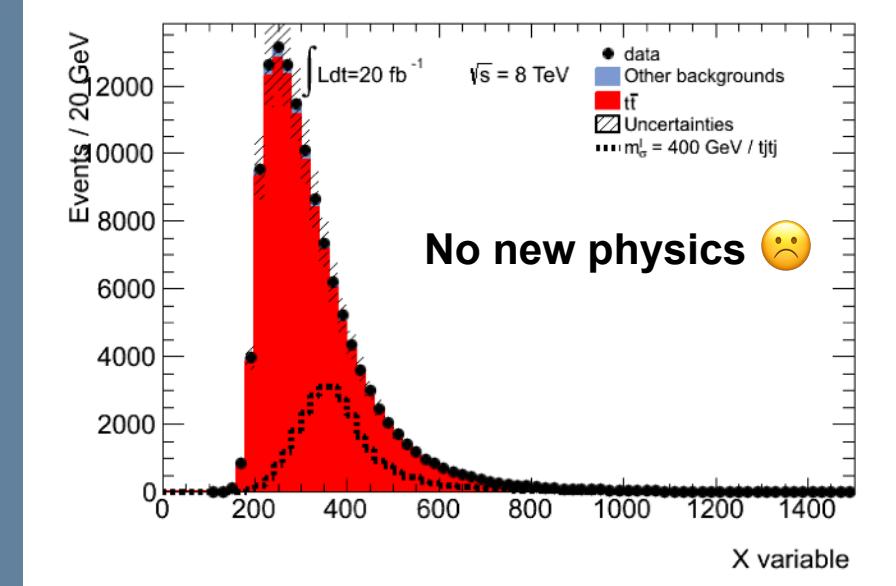
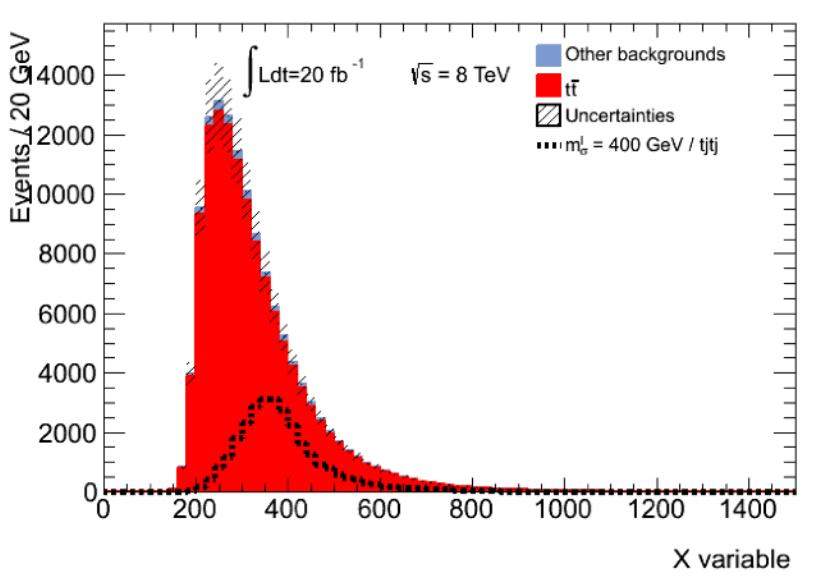
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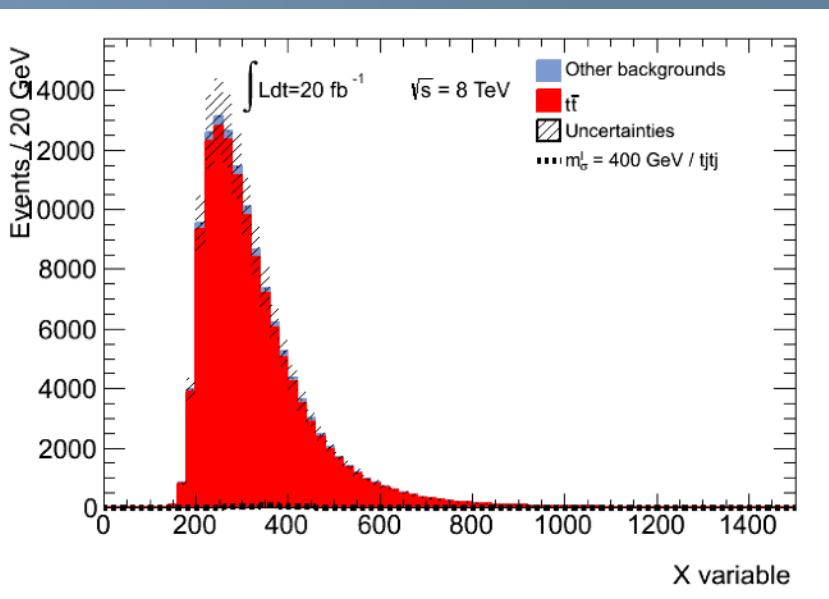
- How big should be an existing signal to be seen ?
- Let's assume that our signal has a **large production rate**



- 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**

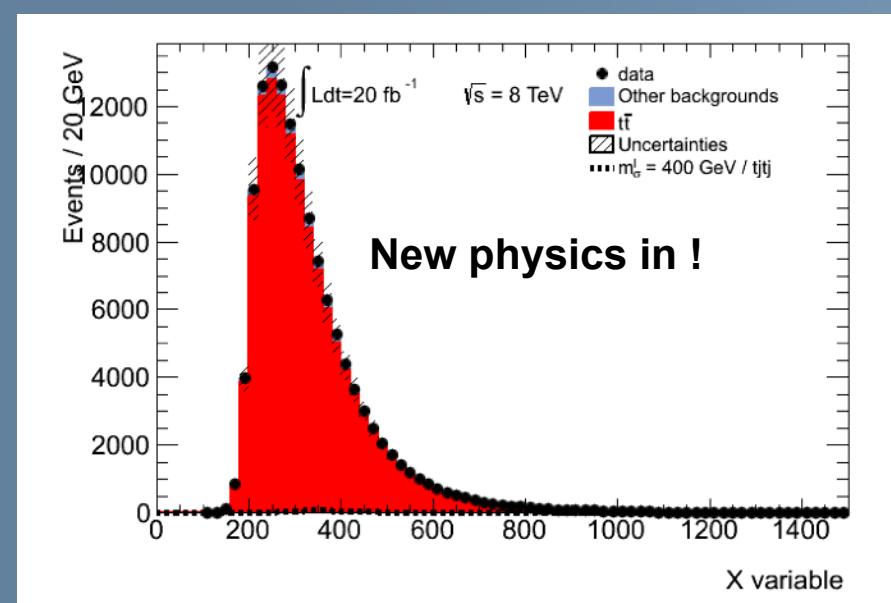
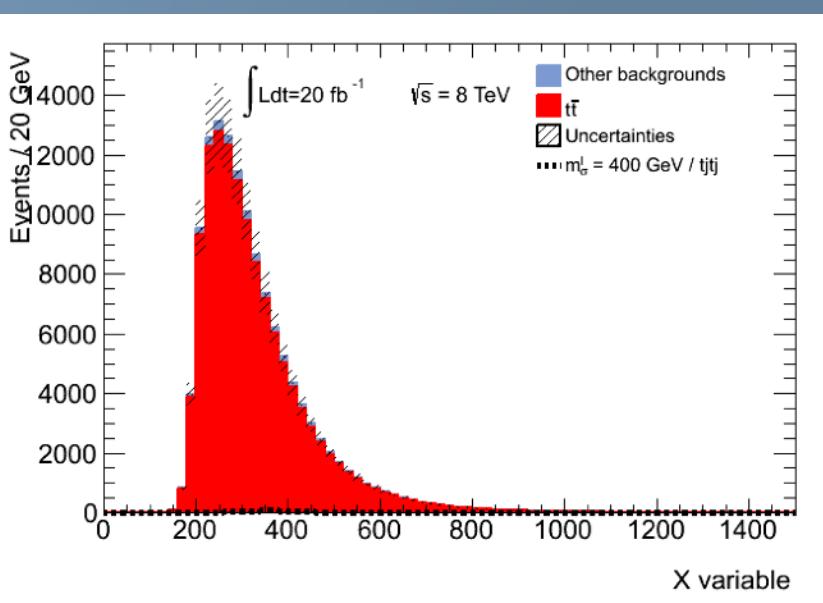
# [Statistical break] Hypothesis test (II)

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



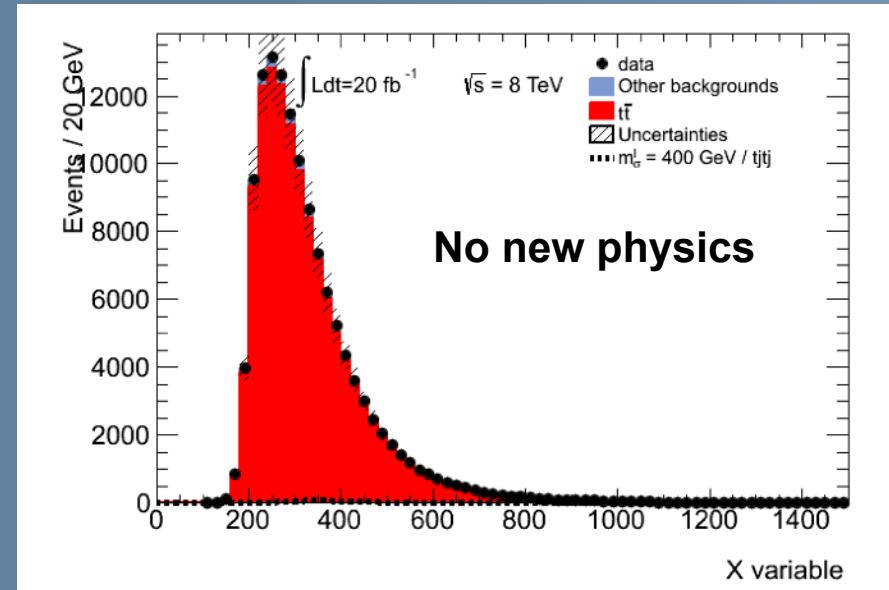
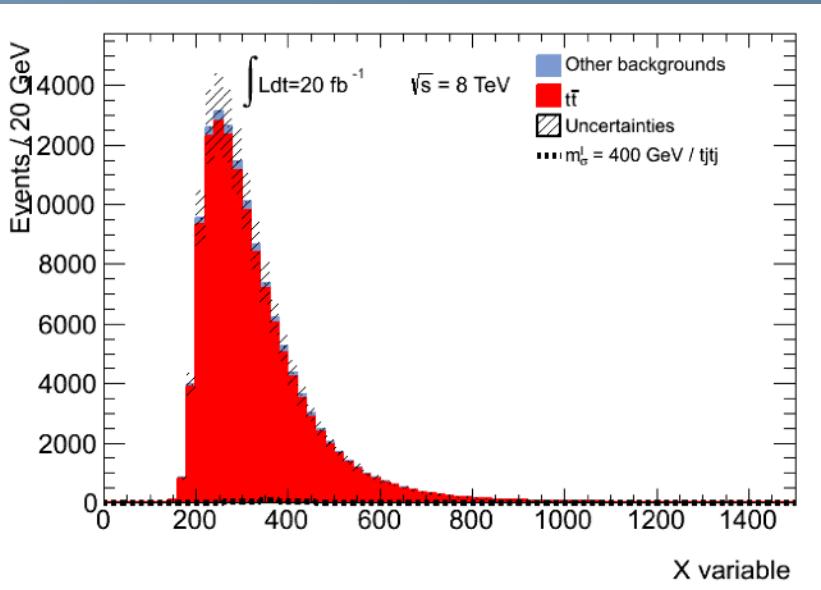
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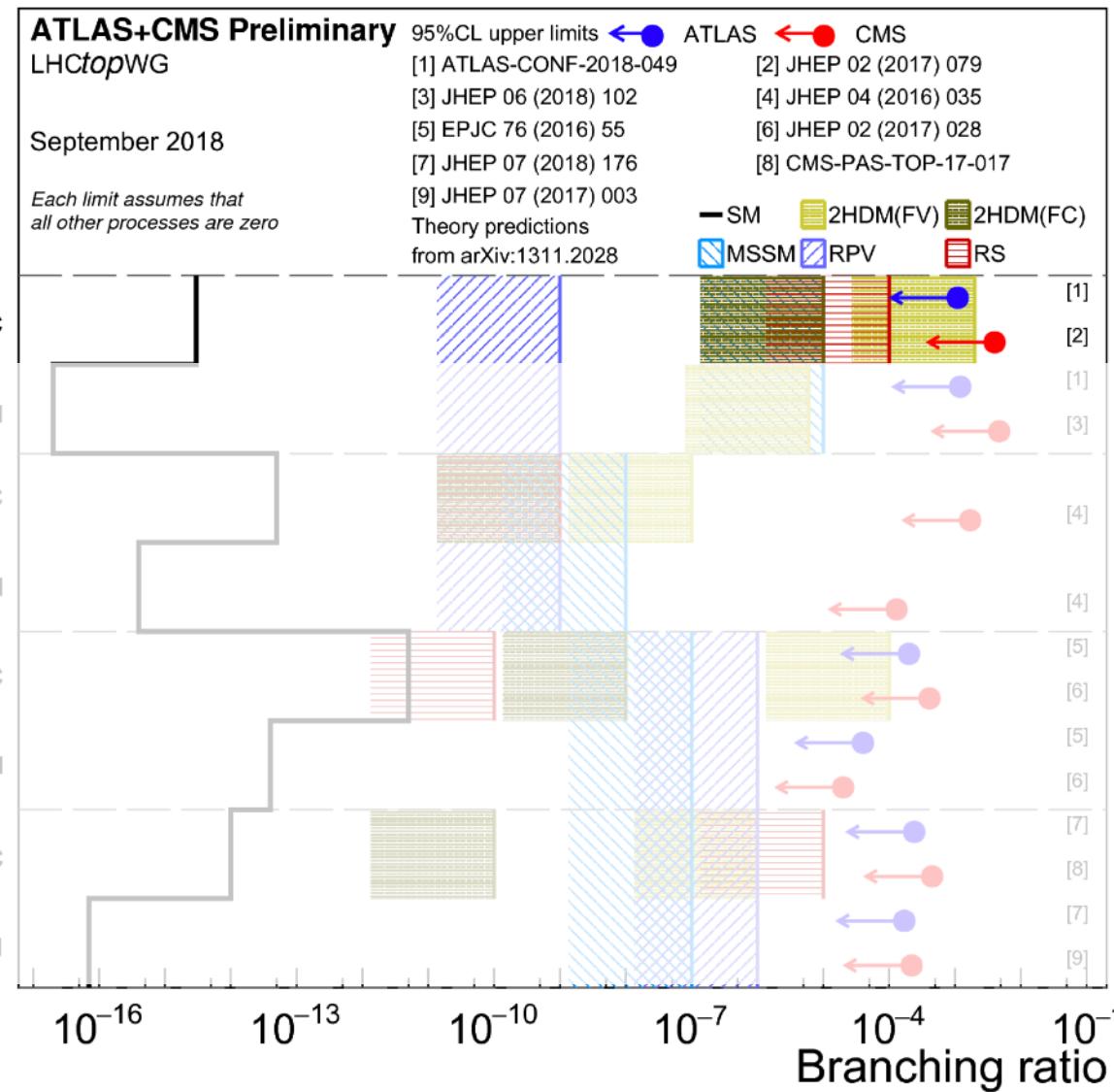
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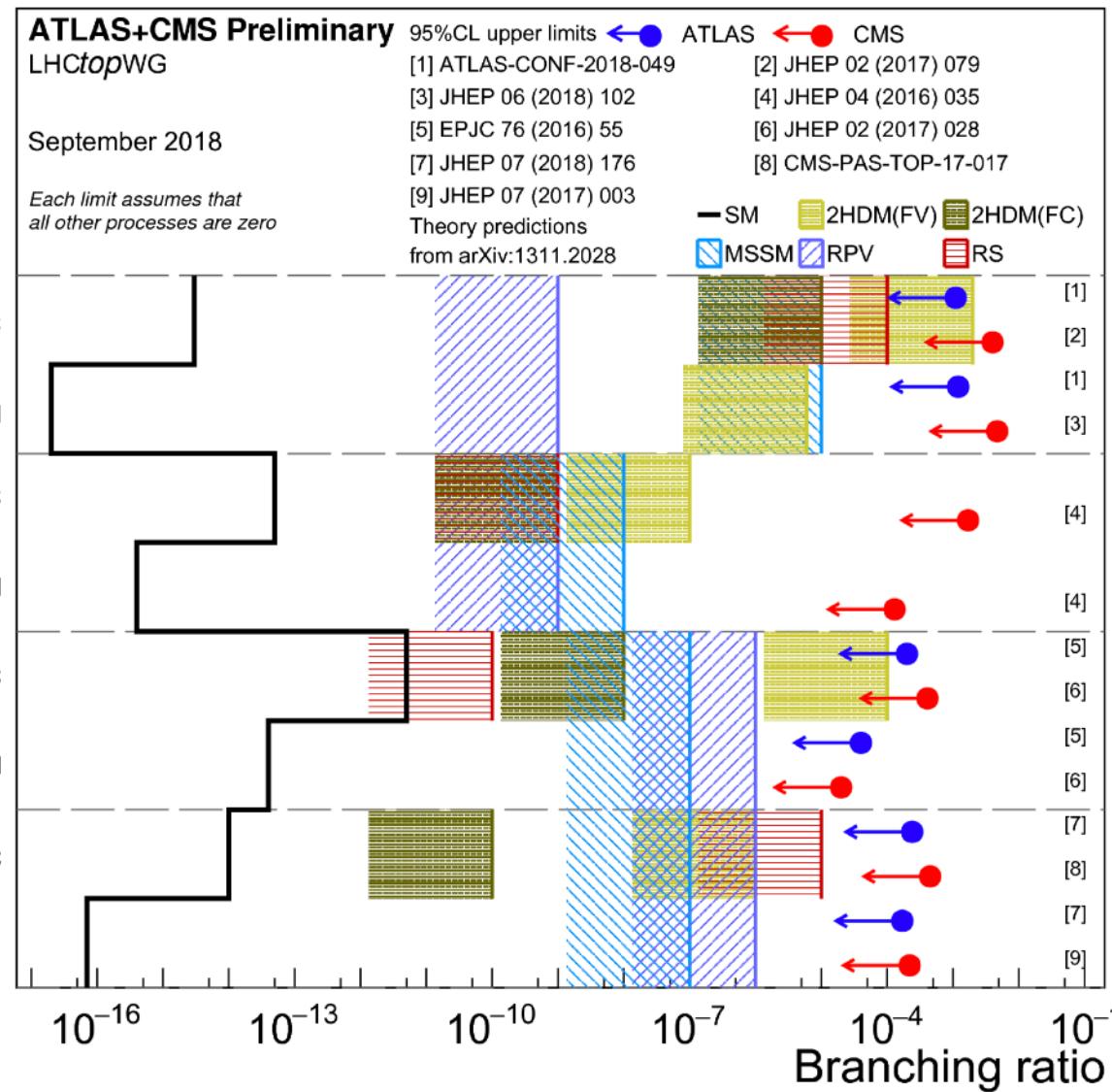


- Even if this signal existed ... we couldn't have seen it !
- **No sensitivity** for this signal (at this rate)

# Indirect searches

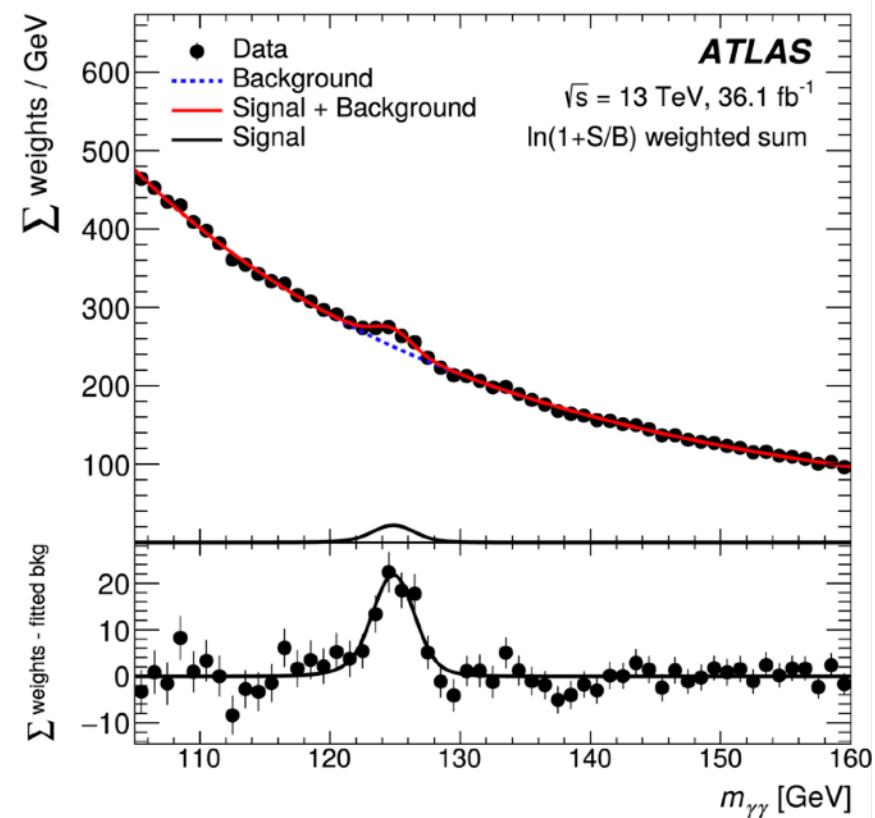
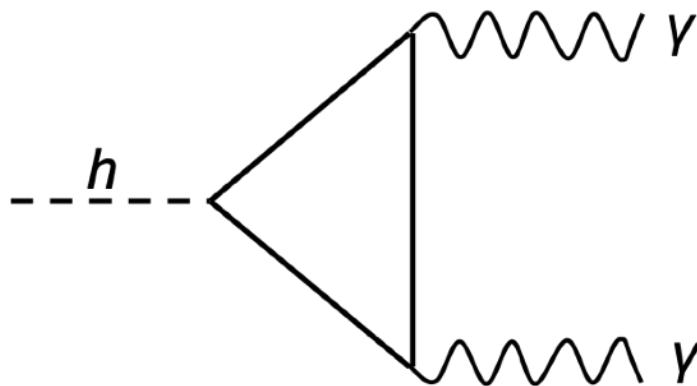


# Indirect searches



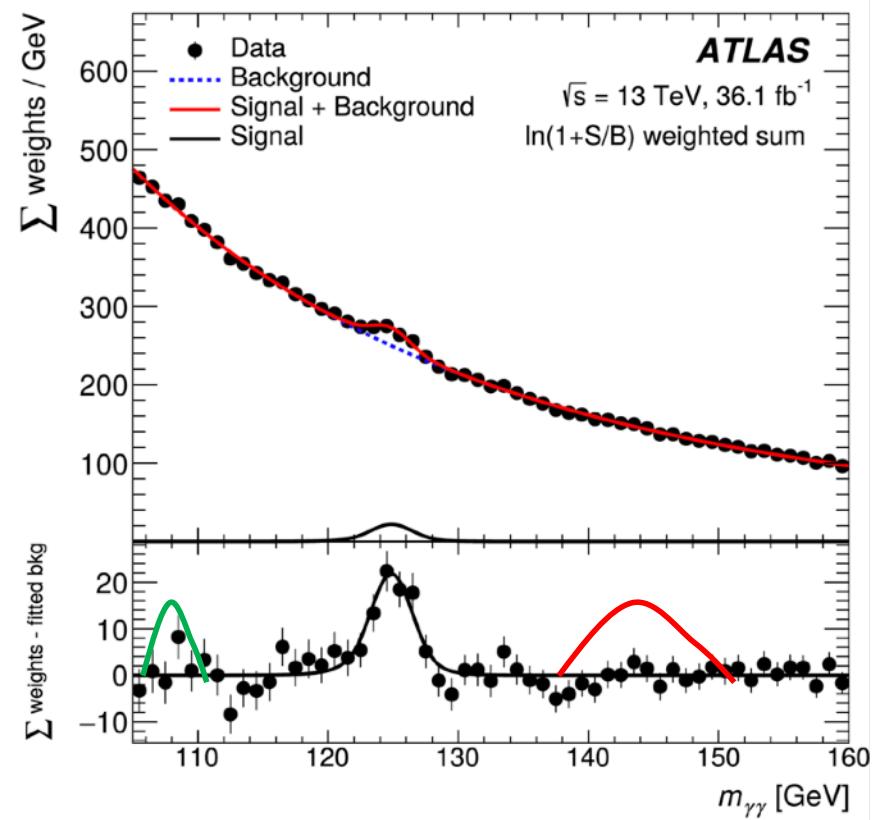
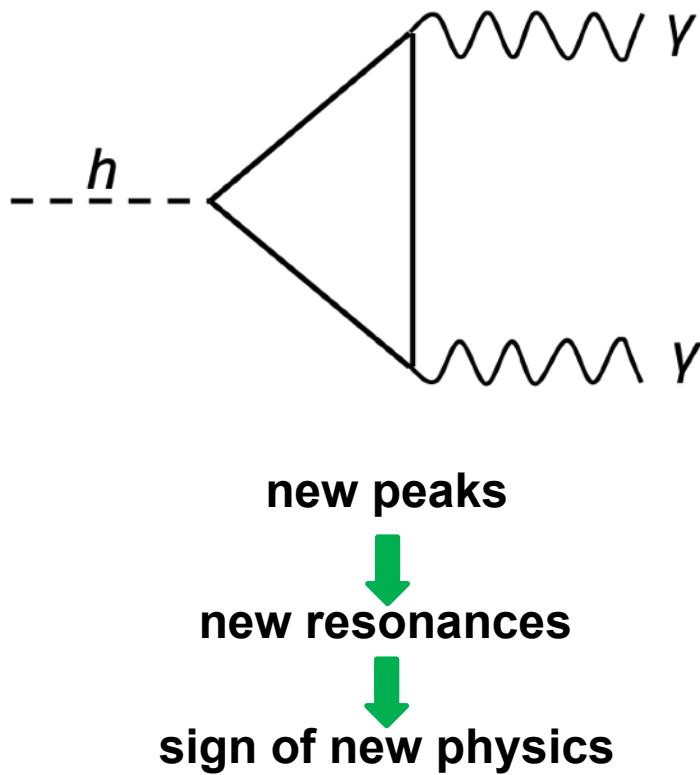
# Direct searches

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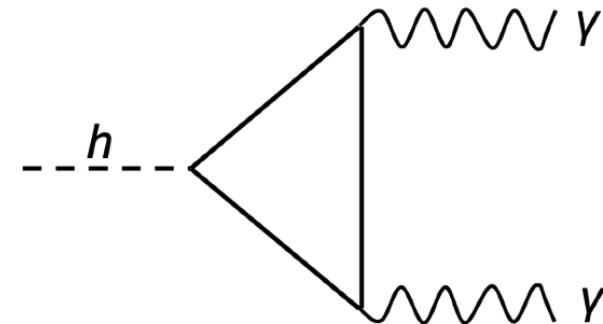
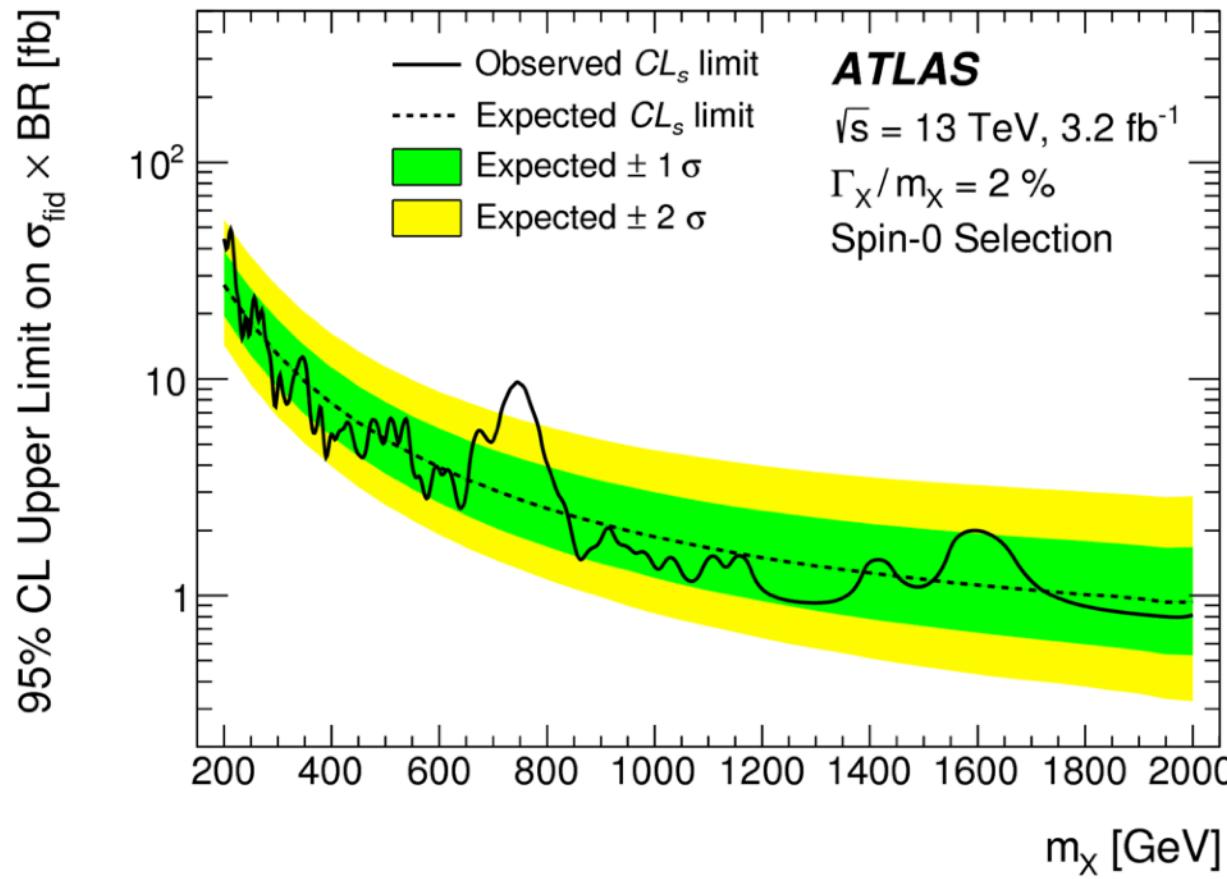
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All presented in Camille's and Yufeng's slides

# 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 limitations
  - 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 ?





## Search for branons in hadronic final states in proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$

- **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  $H \rightarrow \tau\tau$  dans l'expérience CMS du LHC

Gaël touquet

IPNL

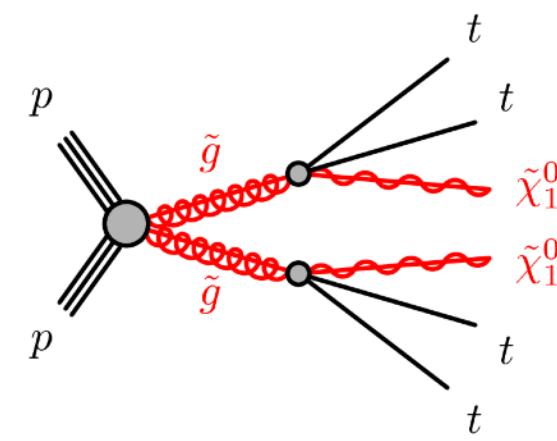
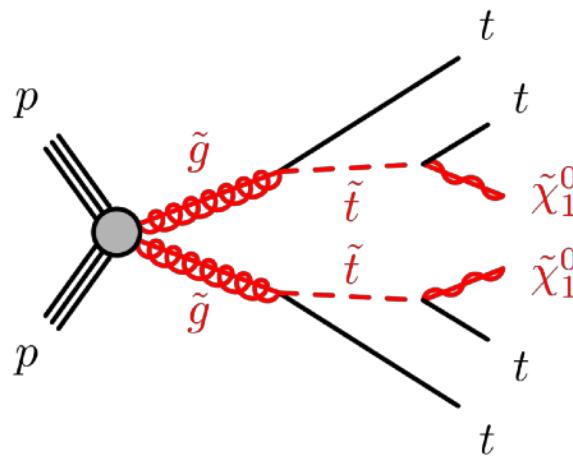
1<sup>er</sup> Décembre 2017

- **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**

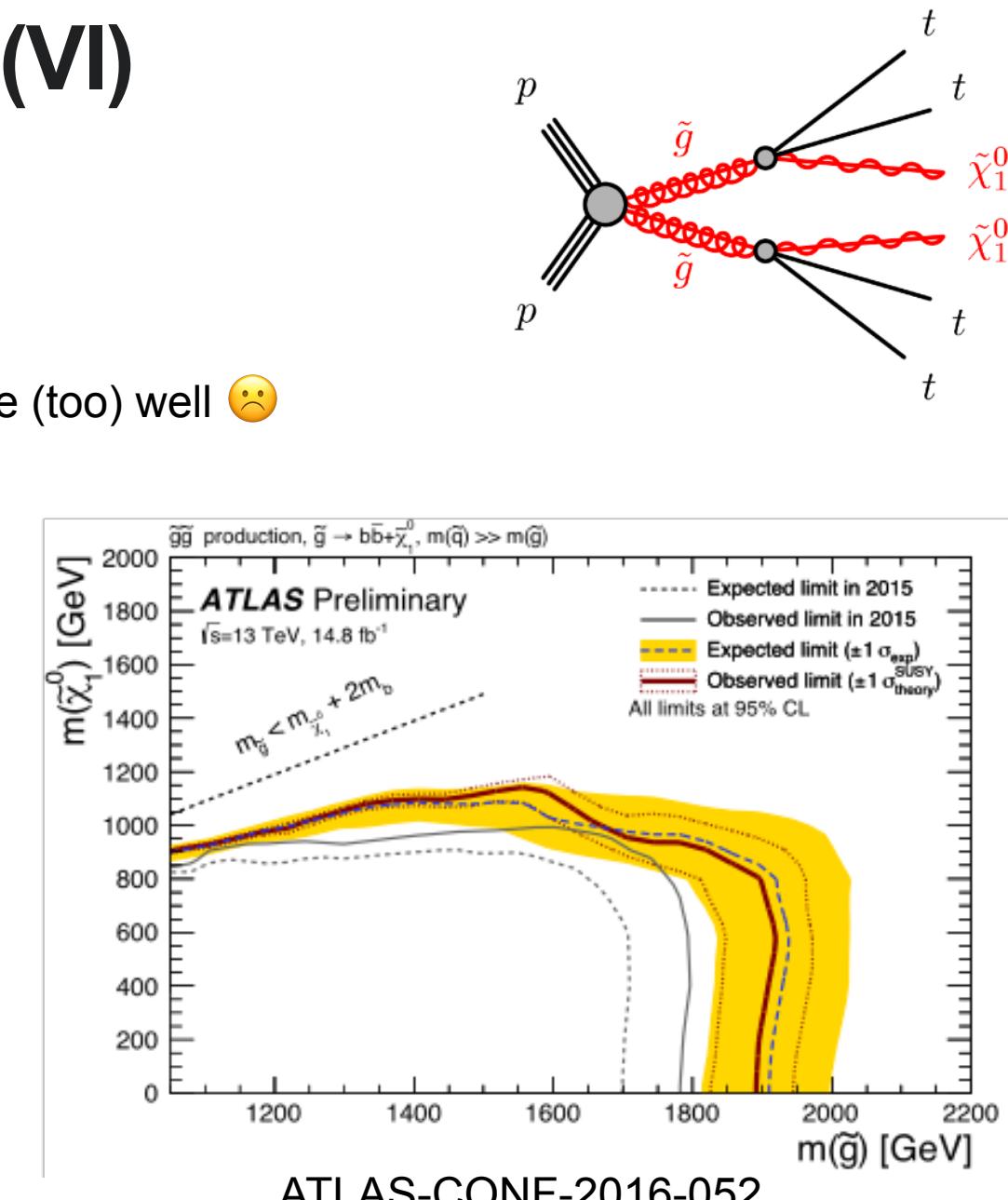


- Only **two parameters**: gluino and neutralino masses
  - Easy !

# Supersymmetry (VI)

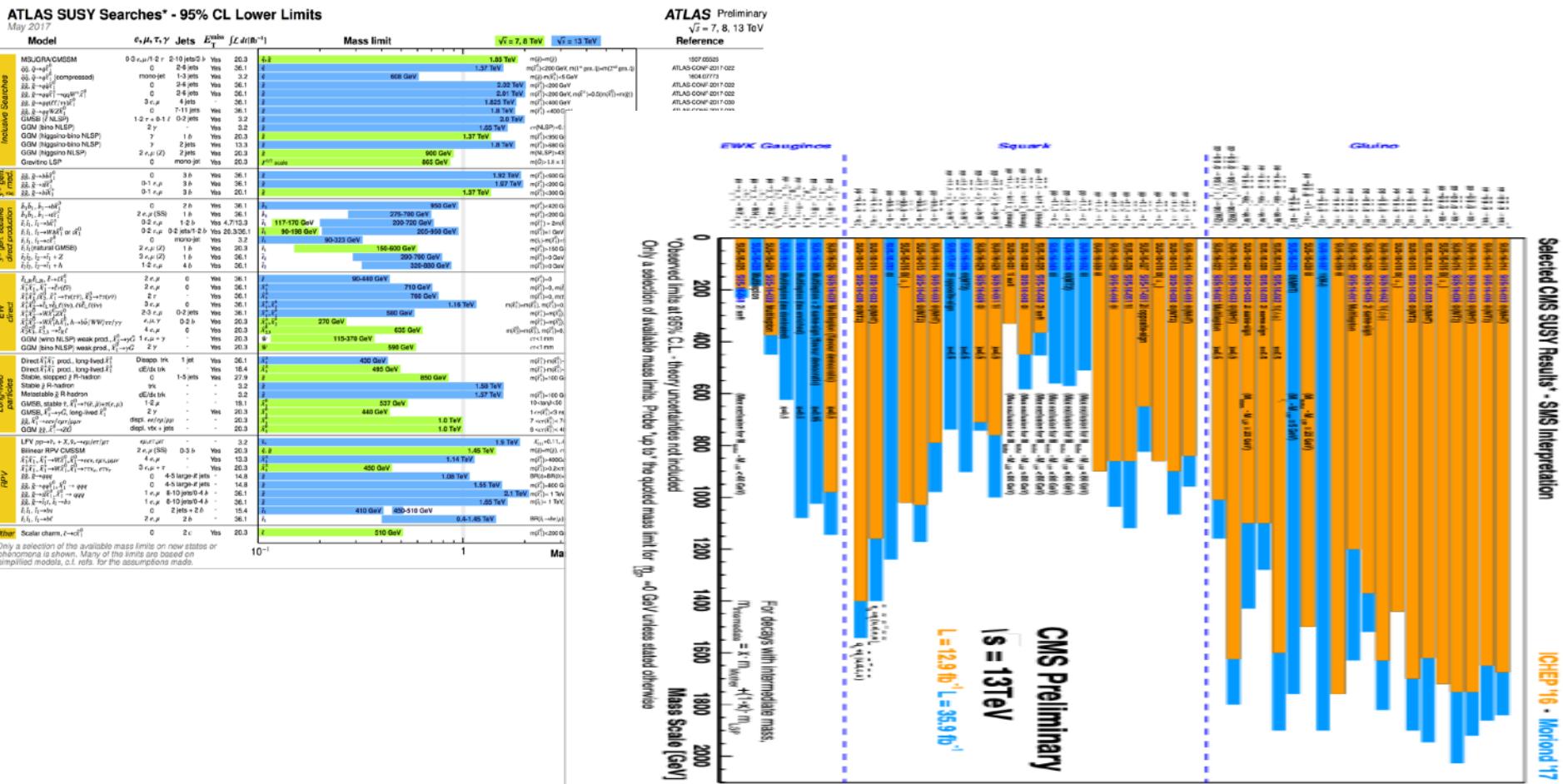
## SUSY vs. LHC

- **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** ...



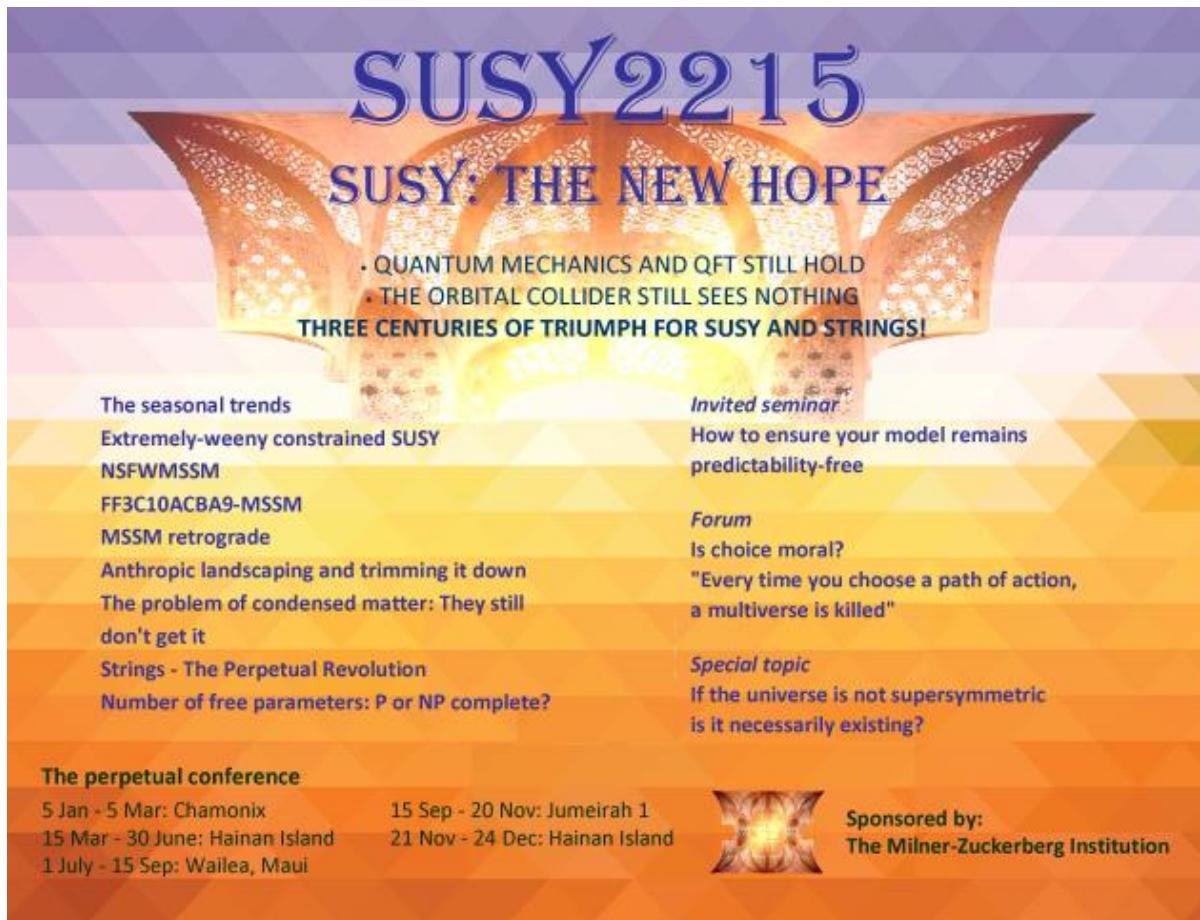
# Supersymmetry (VII)

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



# Supersymmetry (VII)

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



The poster features a purple and orange background with a central graphic of three stylized, glowing wings or petals. The title "SUSY2215" is in large blue serif font, with "SUSY: THE NEW HOPE" below it in a smaller blue serif font. Below the title, there are two bullet points: "QUANTUM MECHANICS AND QFT STILL HOLD" and "THE ORBITAL COLLIDER STILL SEES NOTHING". A banner at the bottom reads "THREE CENTURIES OF TRIUMPH FOR SUSY AND STRINGS!". The poster is organized into several sections:

- The seasonal trends**:
  - Extremely-weeny constrained SUSY
  - NSFWMSSM
  - FF3C10ACBA9-MSSM
  - MSSM retrograde
  - Anthropic landscaping and trimming it down
  - The problem of condensed matter: They still don't get it
  - Strings - The Perpetual Revolution
  - Number of free parameters: P or NP complete?
- Invited seminar**: How to ensure your model remains predictability-free
- Forum**: Is choice moral?  
"Every time you choose a path of action, a multiverse is killed"
- Special topic**: If the universe is not supersymmetric is it necessarily existing?
- The perpetual conference**:
  - 5 Jan - 5 Mar: Chamonix
  - 15 Mar - 30 June: Hainan Island
  - 1 July - 15 Sep: Wailea, Maui
  - 15 Sep - 20 Nov: Jumeirah 1
  - 21 Nov - 24 Dec: Hainan Island

**Sponsored by:**  
The Milner-Zuckerberg Institution

# Observe new particles ?

- **Indirect** searches

