



Au-delà du Modèle Standard Más allá del Modelo Estándar Über das Standardmodell hinaus Πέρα από το Καθιερωμένο πρότυπο Além do Modelo Padrão Beyond the Standard Model

Loïc Valéry
DESY
lvalery@cern.ch

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Outline

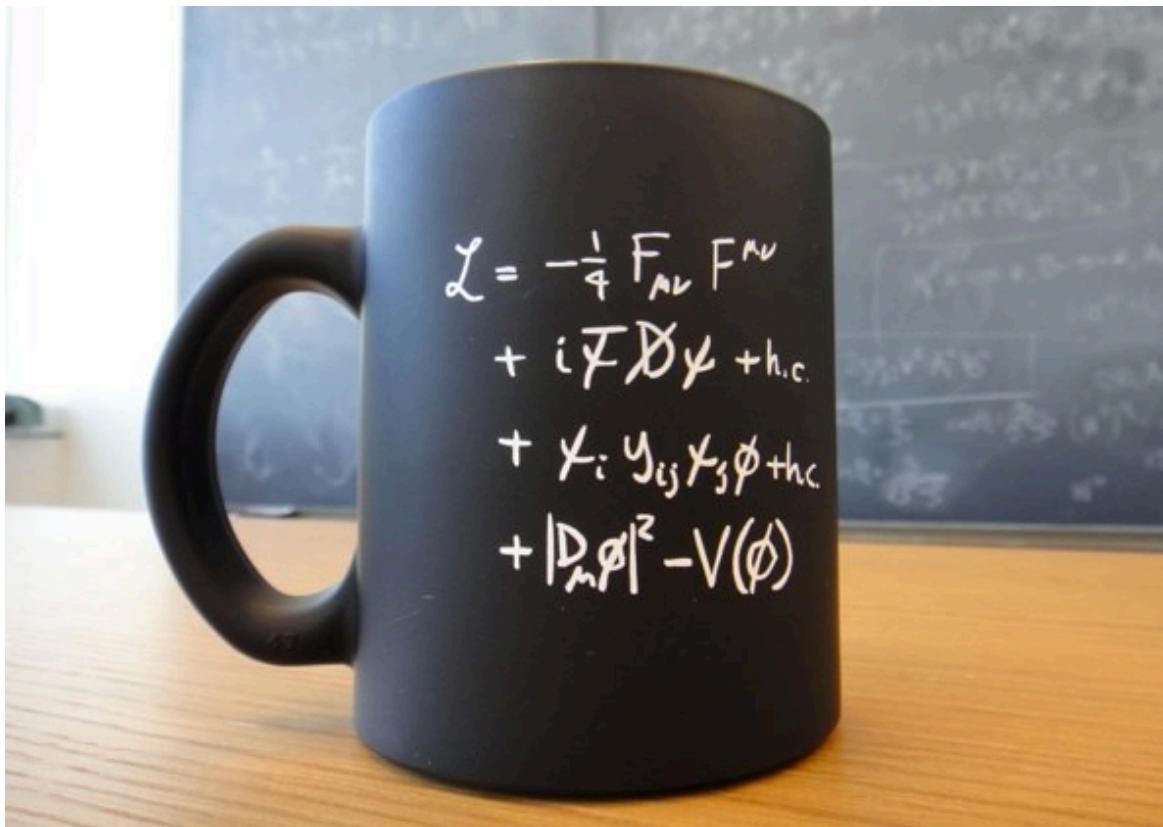
- **Why** beyond the Standard Model ?
- **What** to look for ?
- **How** to look for New Phenomena ?

WHY NEW PHYSICS ?

The Standard Model: successes (I)

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- Not just a formula on a mug ...

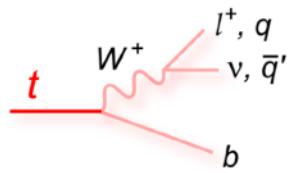


The Standard Model: successes (I)

- 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
- Thoroughly tested @ LHC
 - And **pretty successfully** so far ☺ ☺

Three Generations of Matter (Fermions)			
Quarks	Leptons		Gauge Bosons
mass → 2.4 MeV/c ² charge → $\frac{2}{3}$ spin → $\frac{1}{2}$ name → u up	mass → 1.27 GeV/c ² charge → $\frac{2}{3}$ spin → $\frac{1}{2}$ name → c charm	mass → 171.2 GeV/c ² charge → $\frac{2}{3}$ spin → $\frac{1}{2}$ name → t top	mass → ~125 GeV charge → 0 spin → 0 name → H Higgs
mass → 4.8 MeV/c ² charge → $-\frac{1}{3}$ spin → $\frac{1}{2}$ name → d down	mass → 104 MeV/c ² charge → $-\frac{1}{3}$ spin → $\frac{1}{2}$ name → s strange	mass → 4.2 GeV/c ² charge → $-\frac{1}{3}$ spin → $\frac{1}{2}$ name → b bottom	mass → 0 charge → 0 spin → 1 name → γ photon
mass → <2.2 eV/c ² charge → 0 spin → $\frac{1}{2}$ name → ν _e electron neutrino	mass → <0.17 MeV/c ² charge → 0 spin → $\frac{1}{2}$ name → ν _μ muon neutrino	mass → <15.5 MeV/c ² charge → 0 spin → $\frac{1}{2}$ name → ν _τ tau neutrino	mass → 91.2 GeV/c ² charge → 0 spin → 1 name → Z ⁰ Z boson
mass → 0.511 MeV/c ² charge → -1 spin → $\frac{1}{2}$ name → e electron	mass → 105.7 MeV/c ² charge → -1 spin → $\frac{1}{2}$ name → μ muon	mass → 1.777 GeV/c ² charge → -1 spin → $\frac{1}{2}$ name → τ tau	mass → 80.4 GeV/c ² charge → ±1 spin → 1 name → W [±] W boson

The Standard Model: successes (I)



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

Will be back later !!

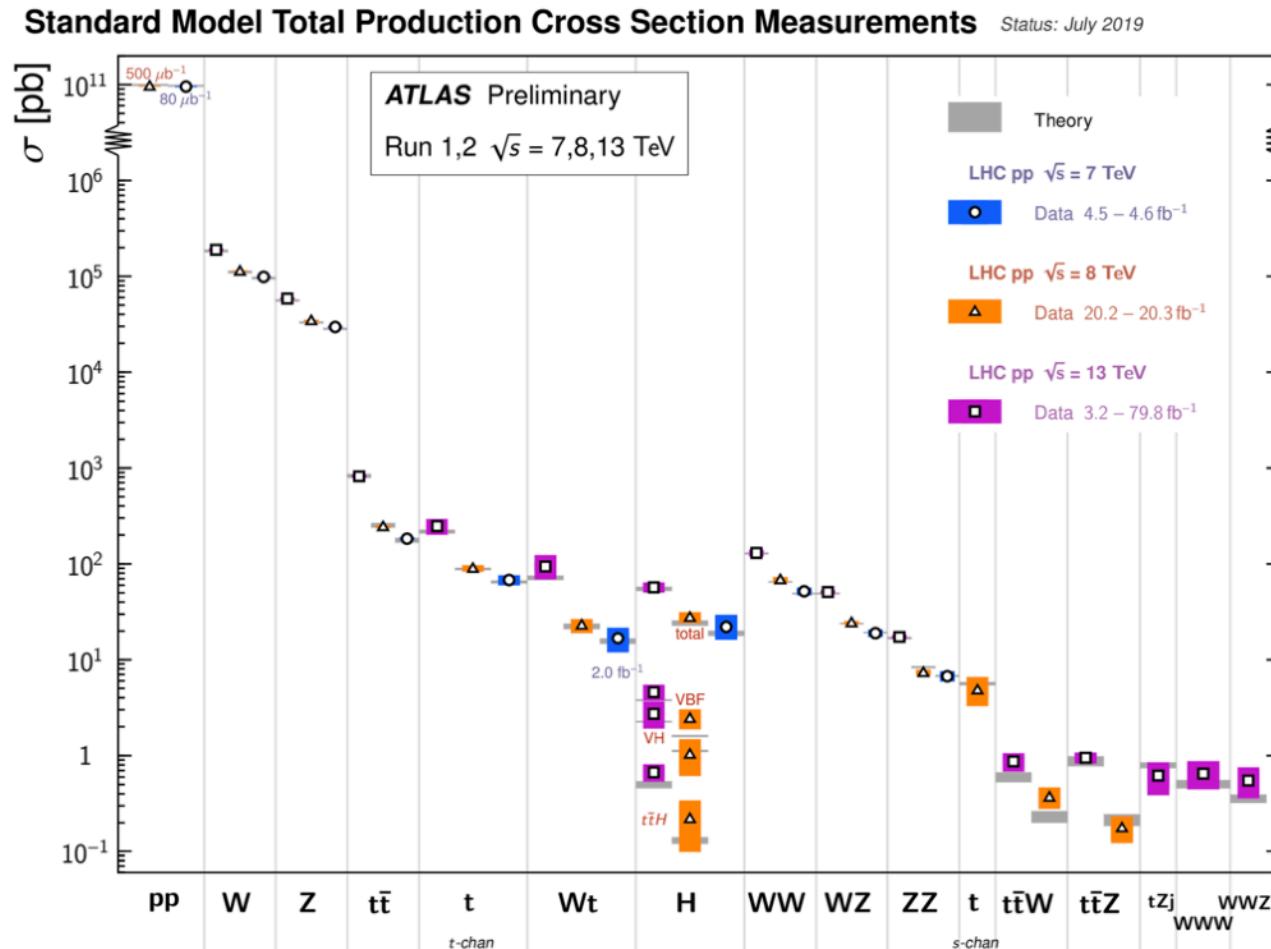
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describe **elementary**

Three Generations of Matter (Fermions)			
I	II	III	
mass → 2.4 MeV/c ²	1.27 GeV/c ²	171.2 GeV/c ²	~125 GeV
charge → 2/3	2/3	2/3	0 0
spin → 1/2	1/2	1/2	H Higgs
name → u	c	t	γ
up	charm	top	photon
Quarks			
mass → 4.8 MeV/c ²	104 MeV/c ²	4.2 GeV/c ²	0 0
charge → -1/3	-1/3	-1/3	1
spin → 1/2	1/2	1/2	g
d	s	b	gluon
down	strange	bottom	
Leptons			
mass → <2.2 eV/c ²	<0.17 MeV/c ²	<15.5 MeV/c ²	91.2 GeV/c ²
charge → 0	0	0	0
spin → 1/2	1/2	1/2	1
e	μ	τ	Z ⁰
electron	muon	tau	Z boson
Gauge Bosons			
mass → 0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²	80.4 GeV/c ²
charge → -1	-1	-1	±1
spin → 1/2	1/2	1/2	1
e	μ	τ	W [±]
electron	muon	tau	W boson

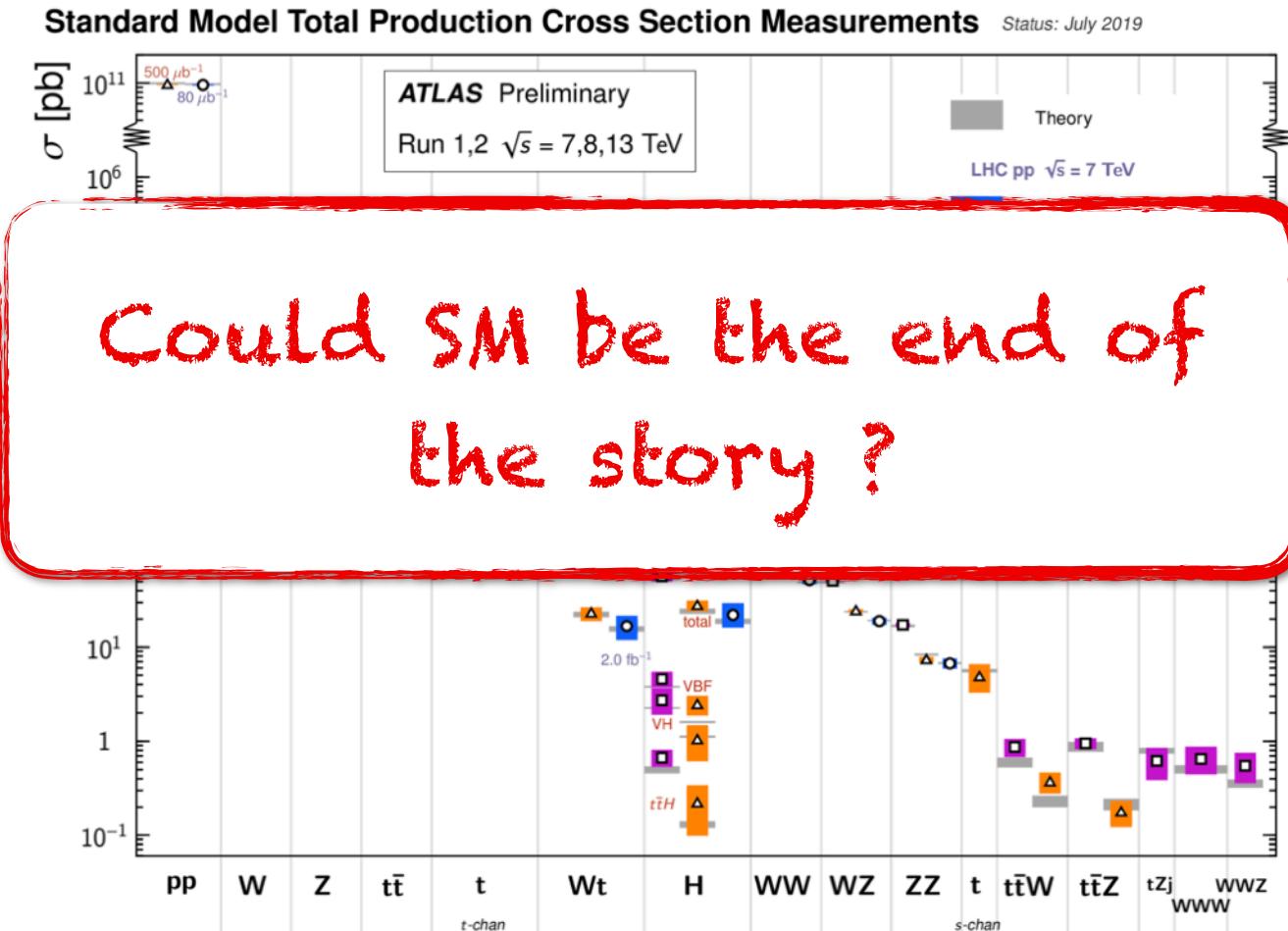
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- Pretty **amazing measurements** done in ATLAS (same in CMS)
 - SM predictions verified over a wide range of cross-section, energies, ...



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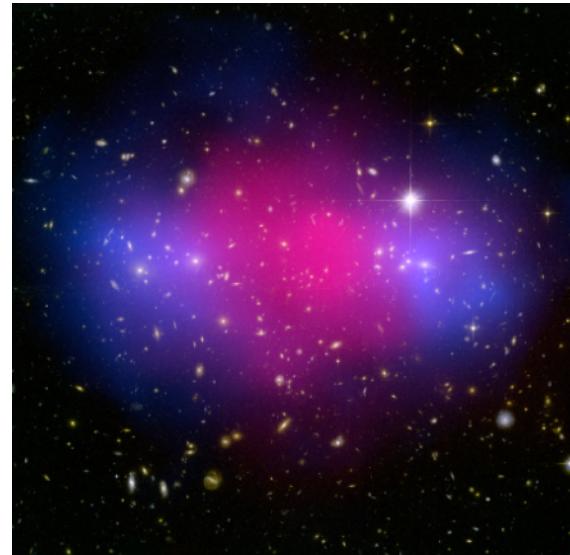
But ...

But ...

Neutrino masses

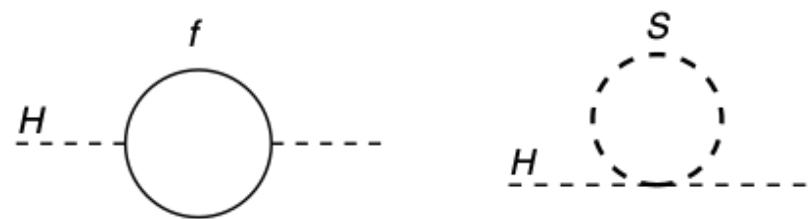
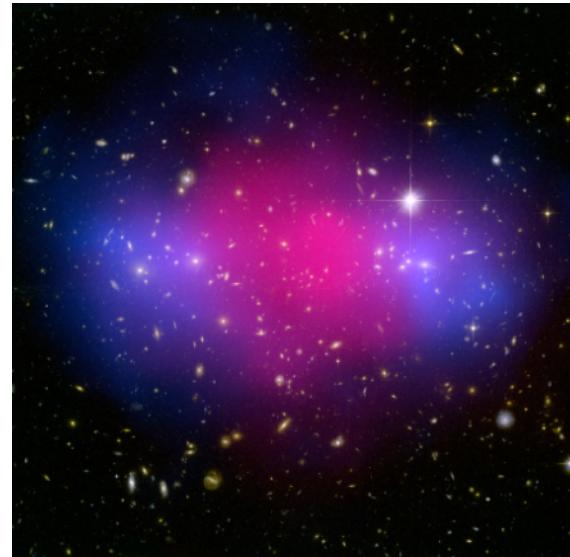
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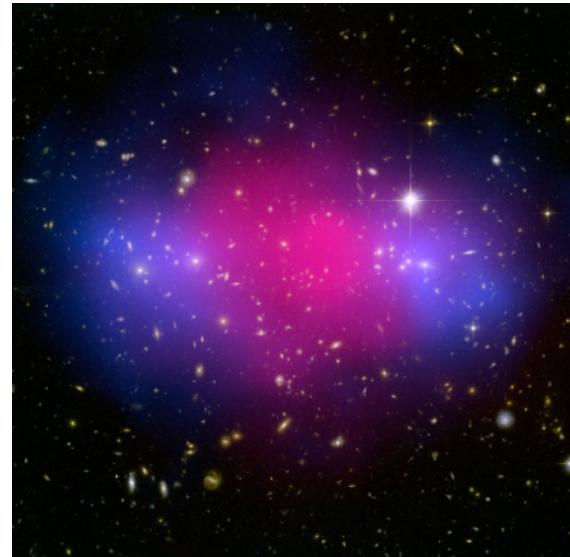


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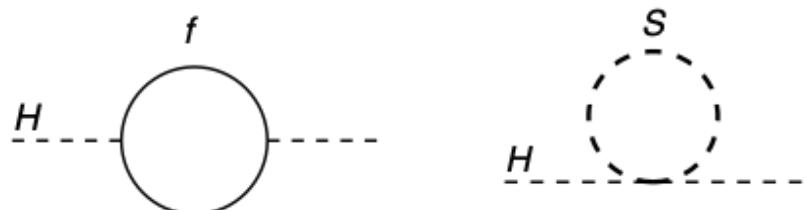
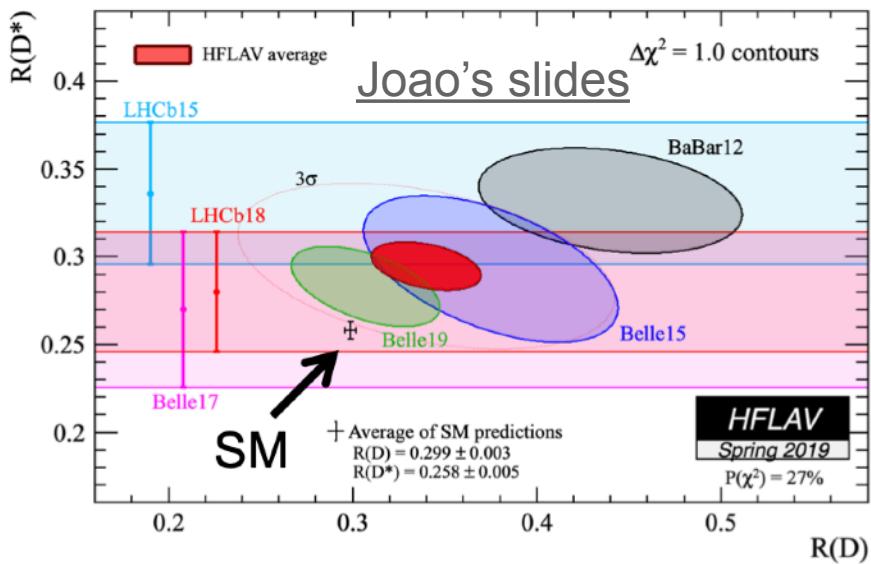
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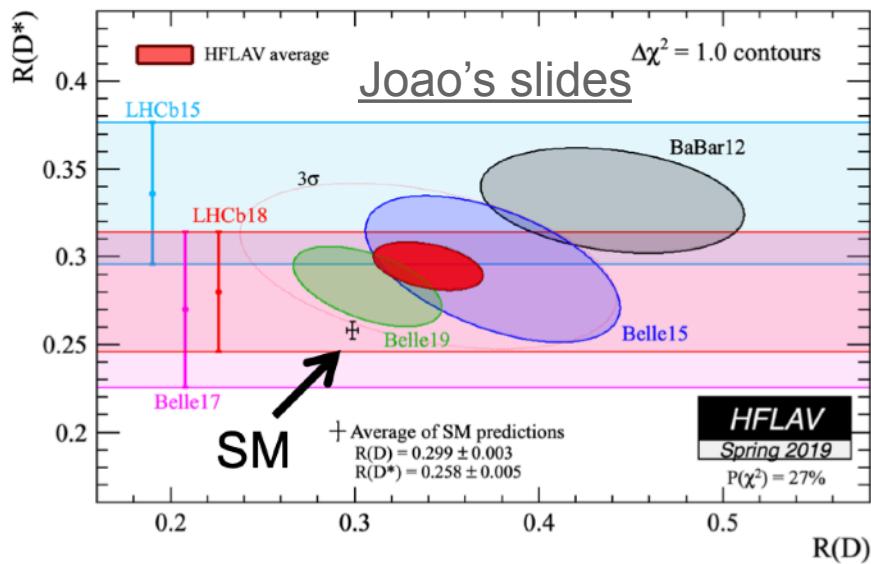
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Neutrino masses



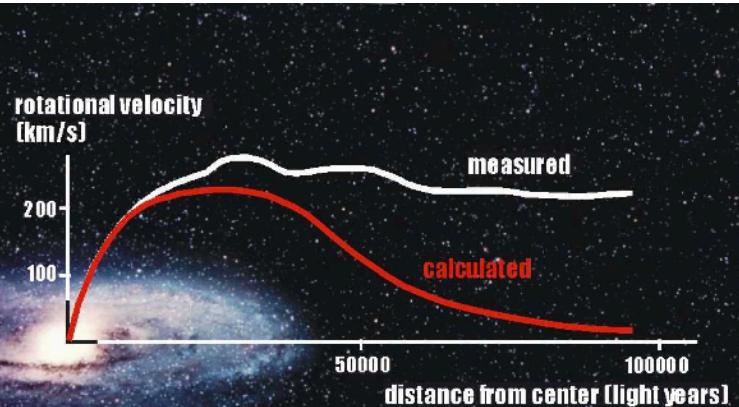
Mass/scale hierarchy



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**

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



- 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
- Standard Model valid until Λ_c (“cut-off scale”)
- λ_f the fermion Yukawa coupling (i.e. coupling to the Higgs)
- **Where is the problem ?**
 - m_0 and λ_f have to be adjusted up to the 32nd decimal ...
 - **Not “natural” ?**

How to solve these problems ?

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- **Naturalness problem** as an example

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



How to solve these problems ?

- **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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 - **Reducing the scale Λ**
 - 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 !**

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

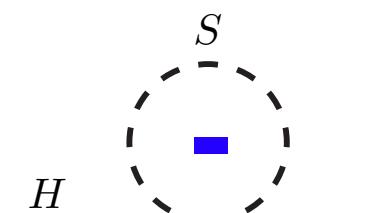
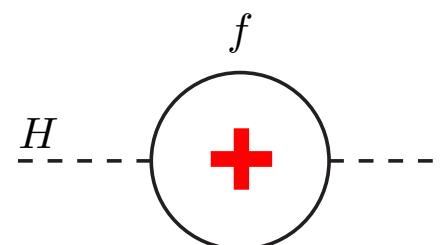
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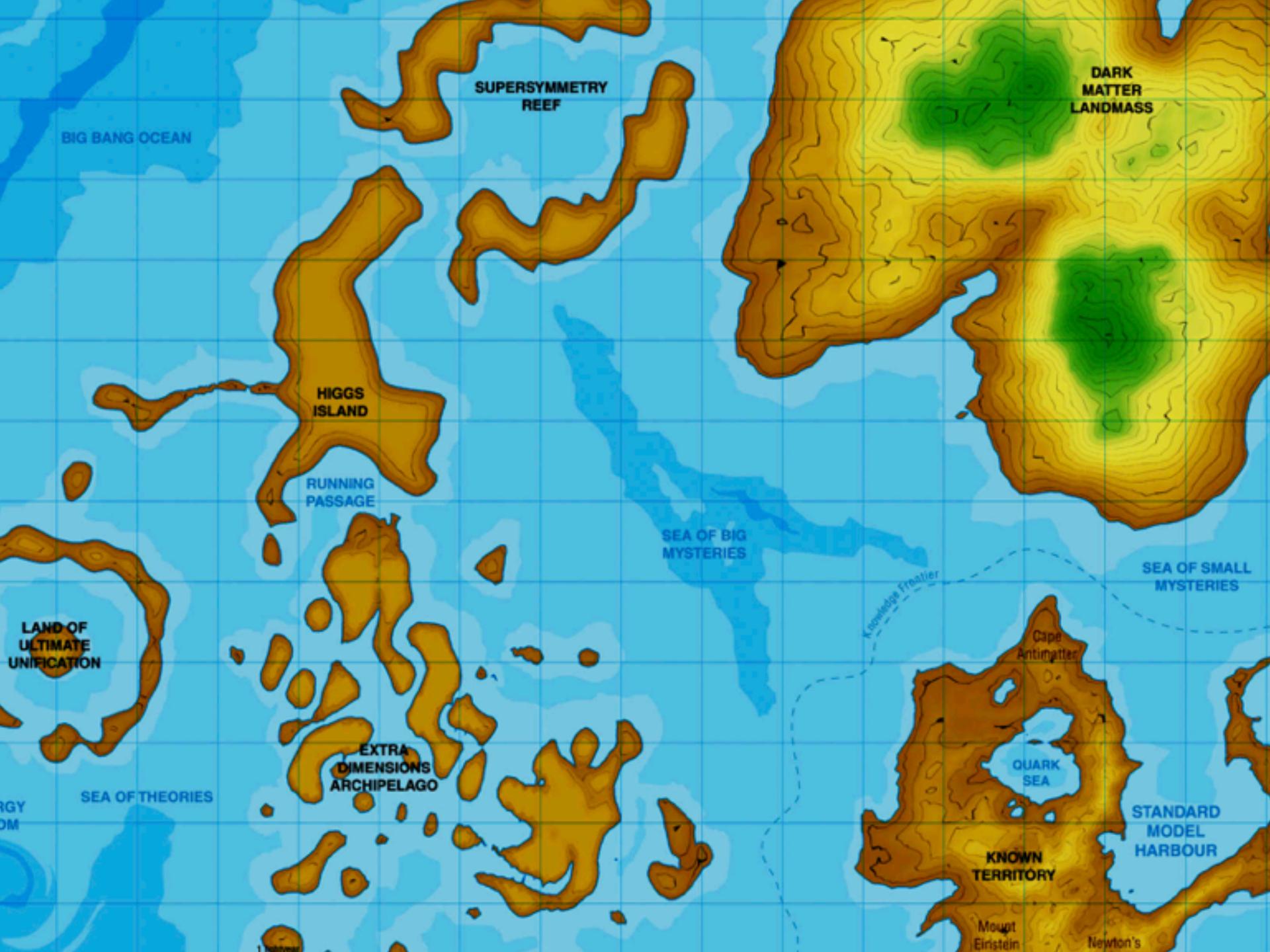


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 - **And what if Higgs was not really the Higgs ?**
 - Composite Higgs ?
 - Additional Higgs doublets

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





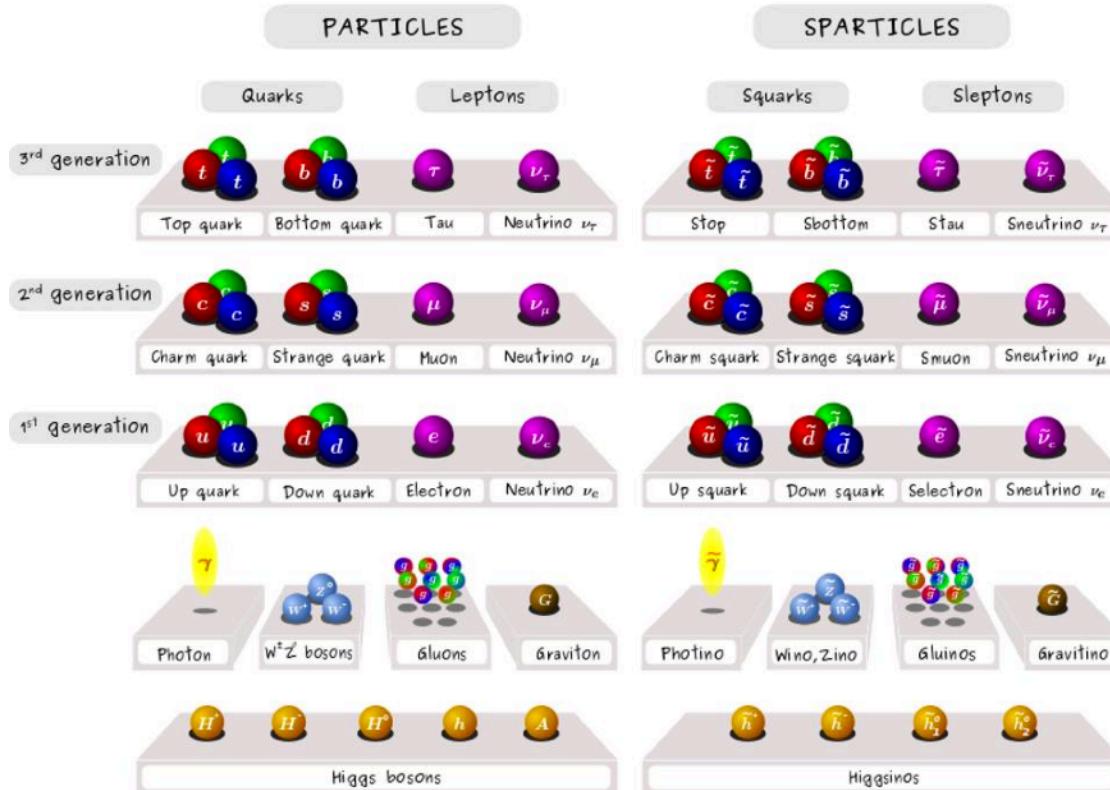
WHAT TO LOOK FOR ?

Supersymmetry (I)



- General idea

Fermion / Boson symmetry



Supersymmetry (I)



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Fermion / Boson symmetry

PARTICLES				SPARTICLES			
Quarks		Leptons		Squarks		Sleptons	
3 rd generation	t t Top quark	b b Bottom quark	τ Tau	ν _τ Neutrino ν _τ	tilde{t} tilde{t} Stop	tilde{b} tilde{b} Sbottom	tilde{τ} tilde{ν _τ } Stau Sneutrino ν _τ
2 nd generation	c c Charm quark	s s Strange quark	μ Muon	ν _μ Neutrino ν _μ	tilde{c} tilde{c} Charm squark	tilde{s} tilde{s} Strange squark	tilde{μ} tilde{ν _μ } Smuon Sneutrino ν _μ
1 st generation	u u Up quark	d d Down quark	e Electron	ν _e Neutrino ν _e	tilde{u} tilde{u} Up squark	tilde{d} tilde{d} Down squark	tilde{e} tilde{ν _e } Selectron Sneutrino ν _e
	Photon γ	W [±] Z bosons W [±] Z ⁰	Gluons G	Graviton G	Photino tilde{γ}	Wino, Zino tilde{W}, tilde{Z}	Gluinos tilde{G}
	H ⁰ H ⁰	H ¹ h	A ⁰ h	Higgs bosons	tilde{h} 1 tilde{h} 2	tilde{h} 2 tilde{h} 3	Higgsinos tilde{h} 3

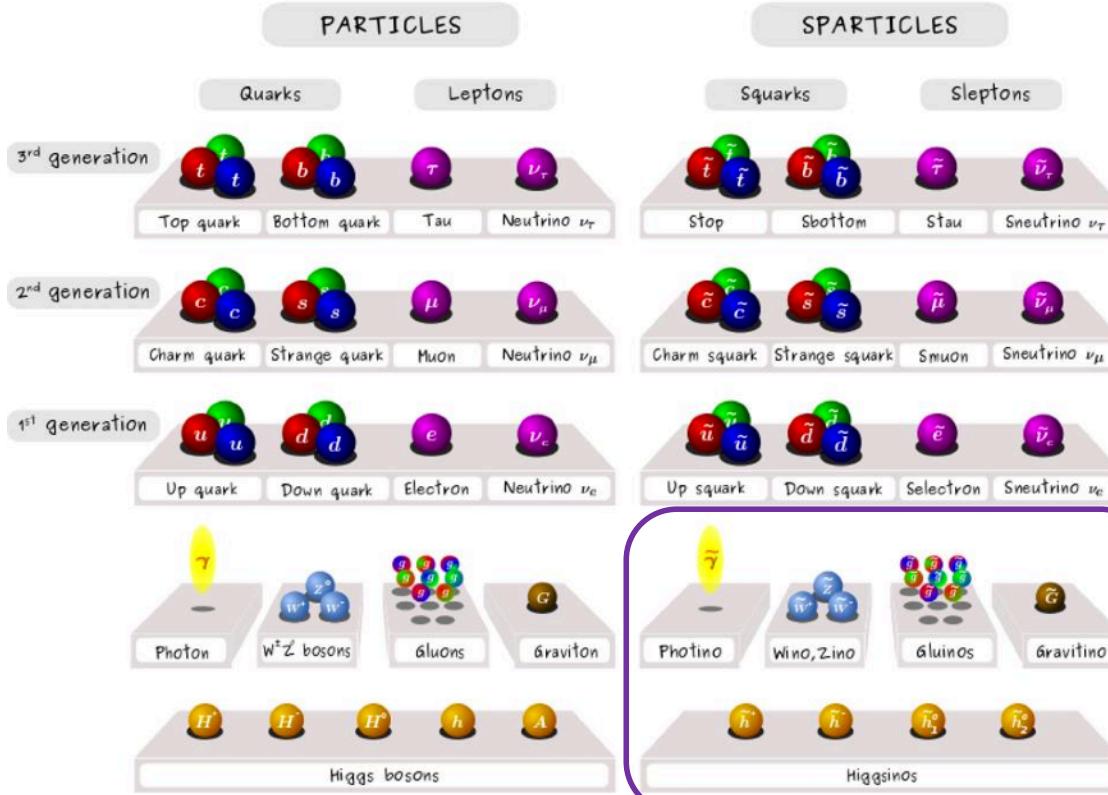
Particle content:
~factor 2

Supersymmetry (I)



- General idea

Fermion / Boson symmetry

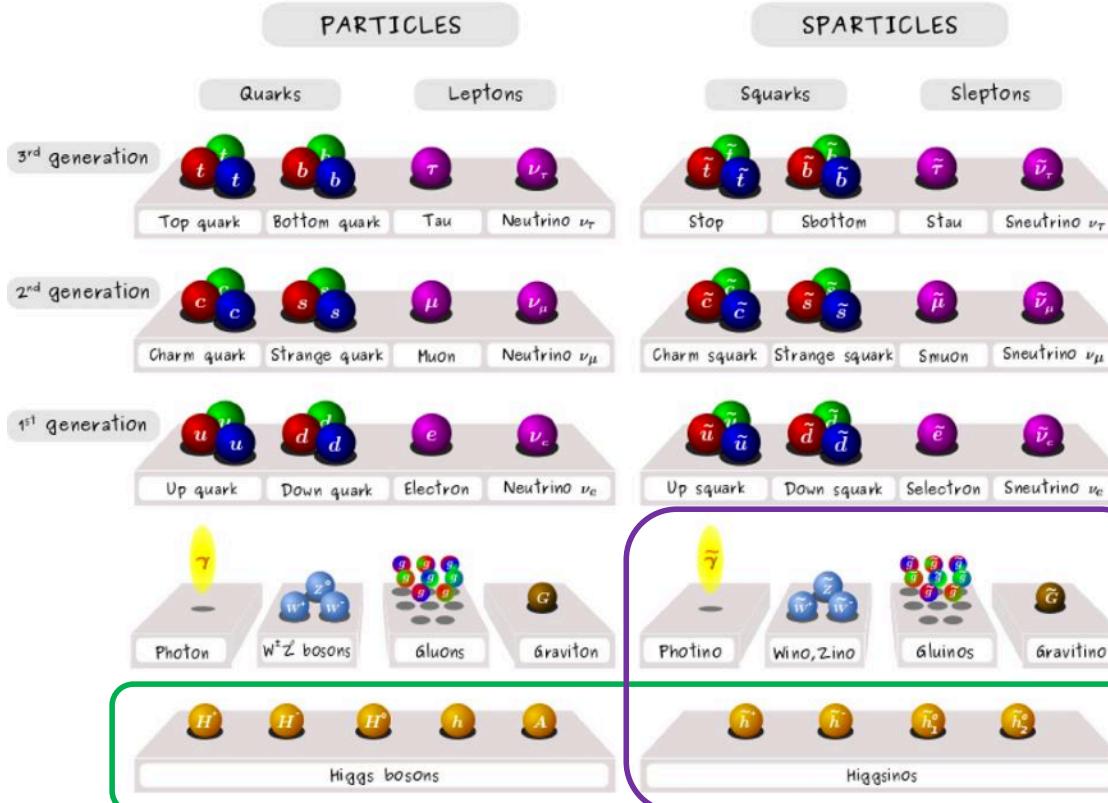


Supersymmetry (I)



- General idea

Fermion / Boson symmetry



Supersymmetry (II)

- **R-parity and dark matter**

- R-parity defined as

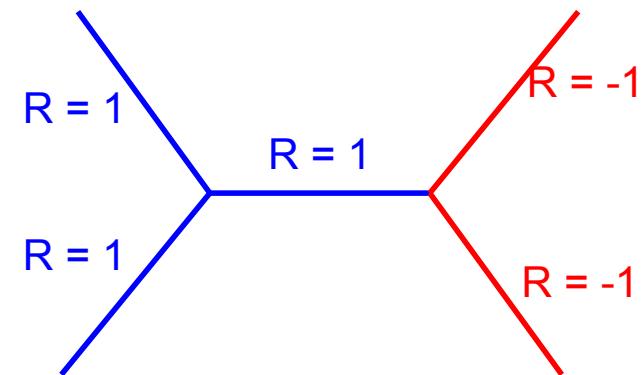
$$R = (-1)^{3(B-L)+2s}$$

- 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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Supersymmetry (III)

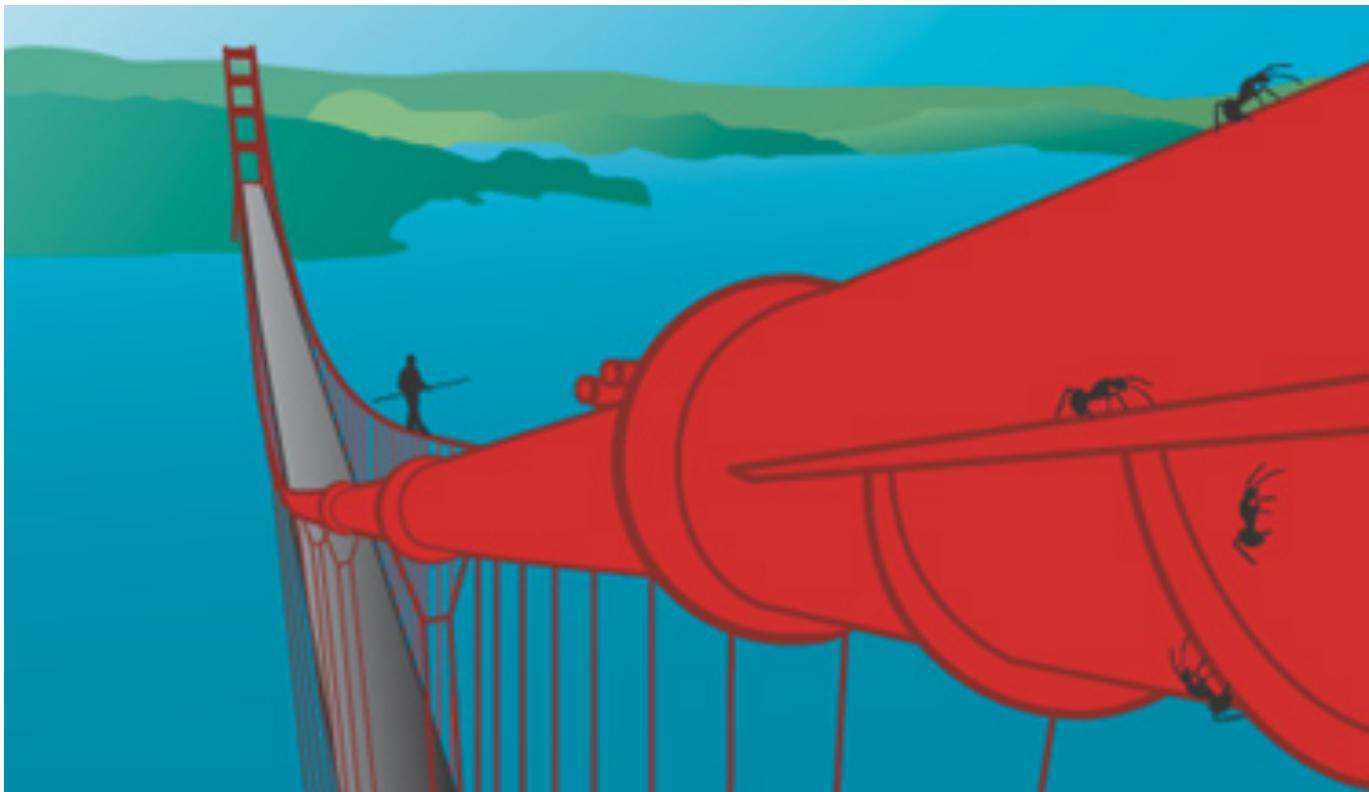
- **Back to symmetries !**
 - Symmetry exactly realised → identical masses



- **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**

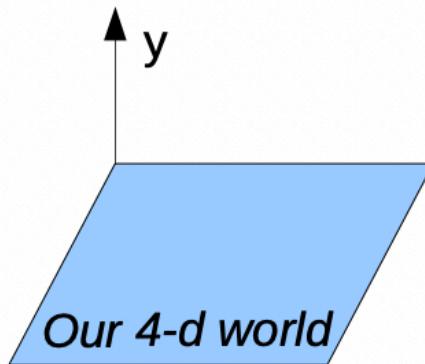
$$F = G_g \frac{m_a m_b}{r_{AB}^2 R^d}$$



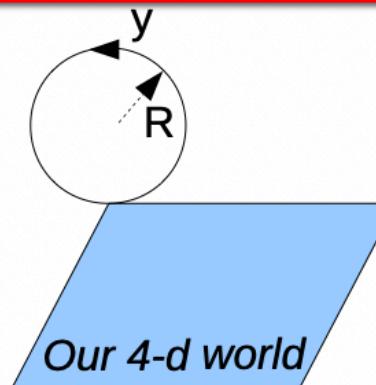
Extra-dimension theories (II)

© S. Calvet

“Flat”

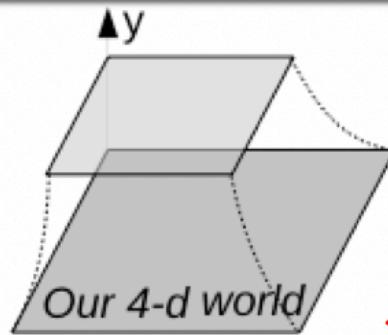


$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu \quad (\mu, \nu = 0, 1, 2, 3 \dots D)$$



Periodicity conditions on field ...
Fourier expansion

“Warped”



Warp factor

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

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

Kaluza-Klein modes
(infinite number)

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

Extra-dimension theories (III)

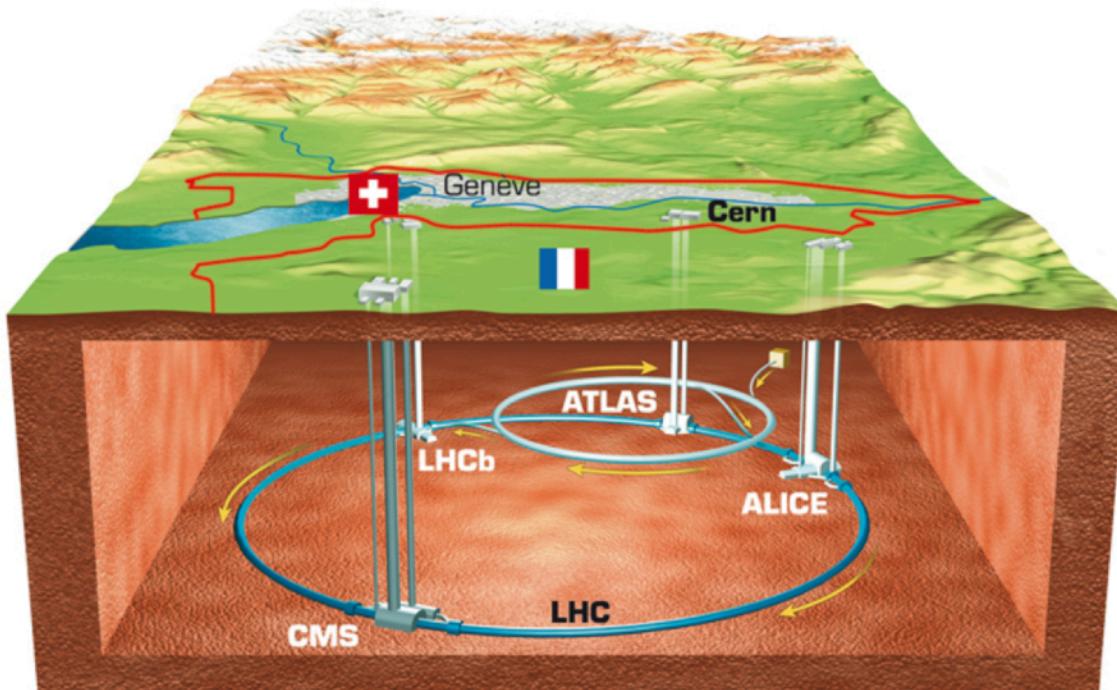
- **Types of ED theories**
 - Depend on
 - number of extra-dimensions: 1 or ≥ 2
 - topology (flat or warped)
 - fields propagating along new dimensions
 - **Lots of combinations** ... with different phenomenologies ...



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



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GPS
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Indirect way



*Kouign
amann
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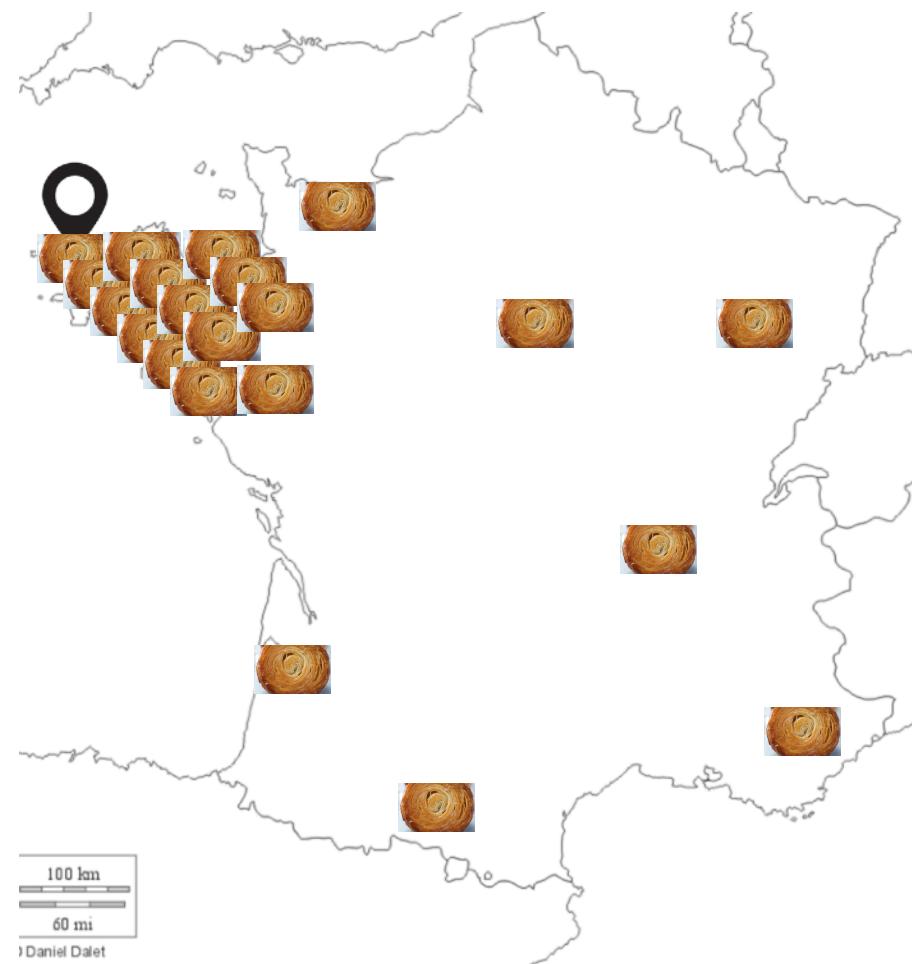
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(also works with
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BSM searches: new Higgs bosons ?

- Could be detected **directly/indirectly**

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Directly

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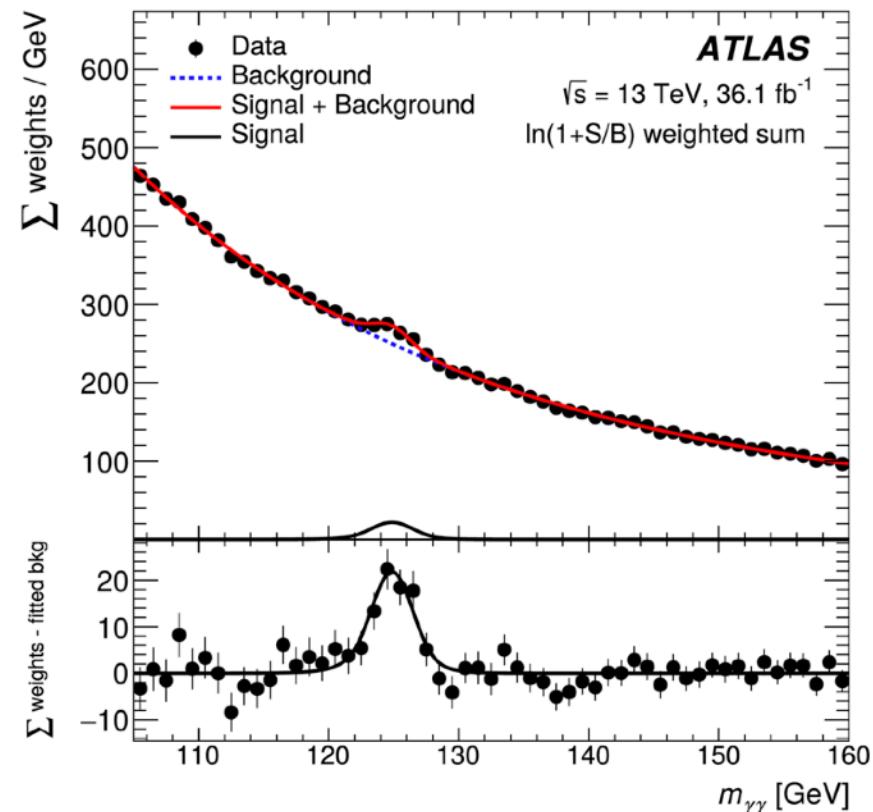
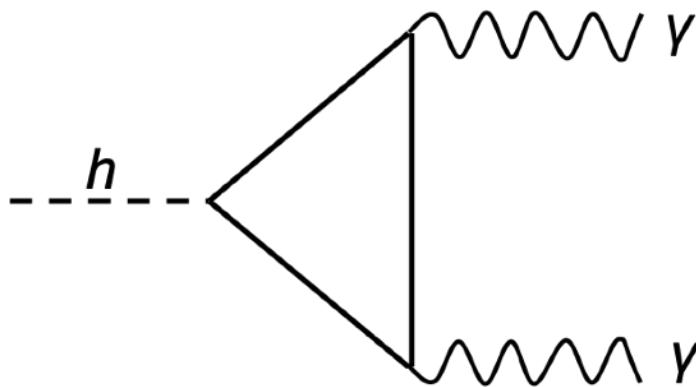
We can “see” some effects
of new Higgs boson(s)



Direct search



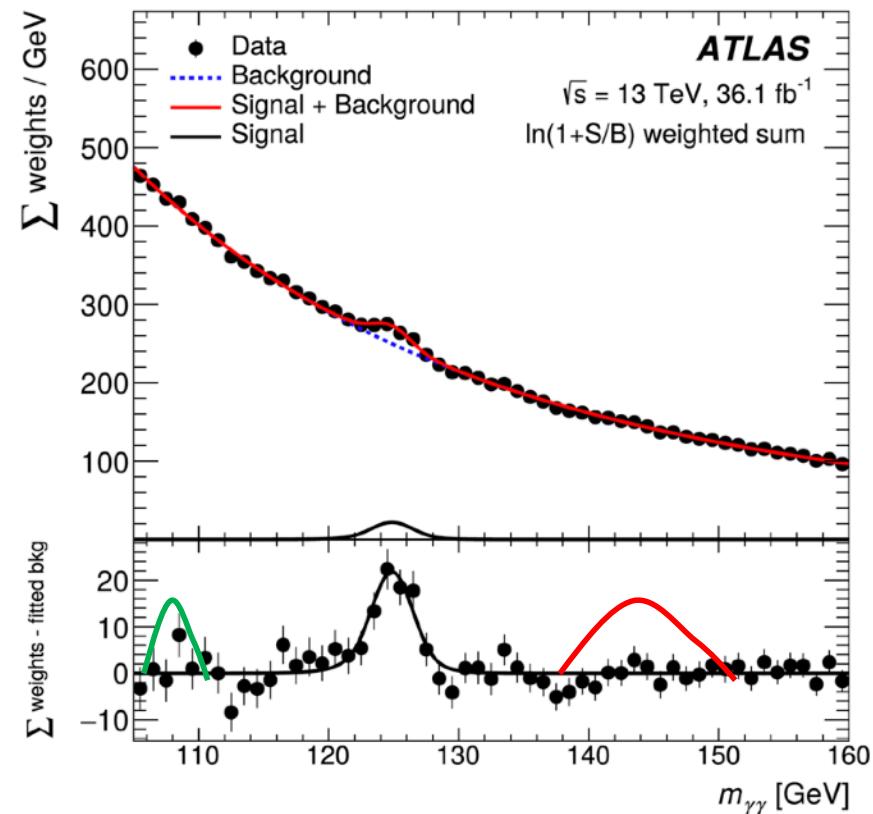
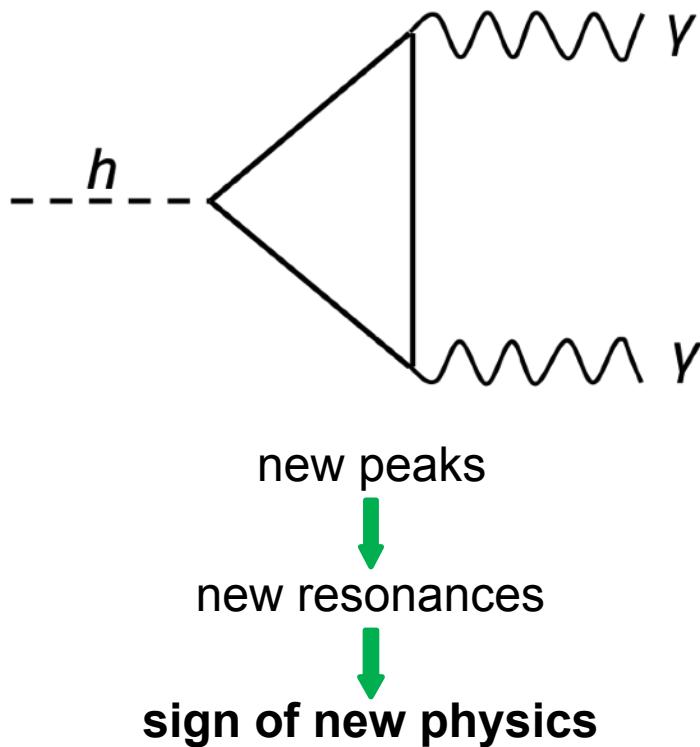
- Look for a “bump” on a spectrum



Direct search



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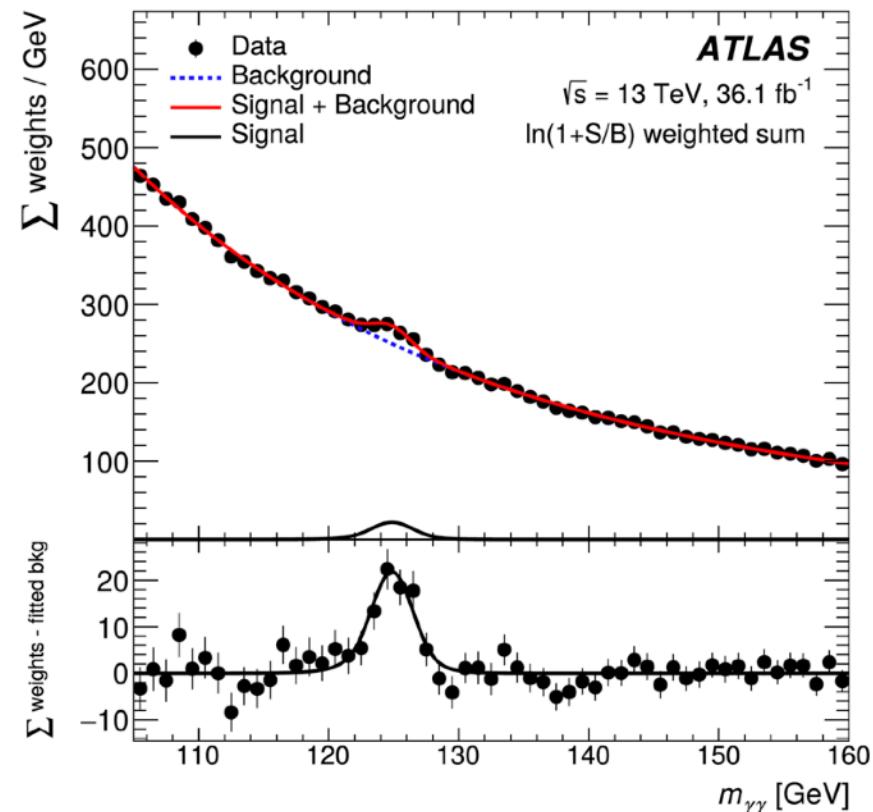
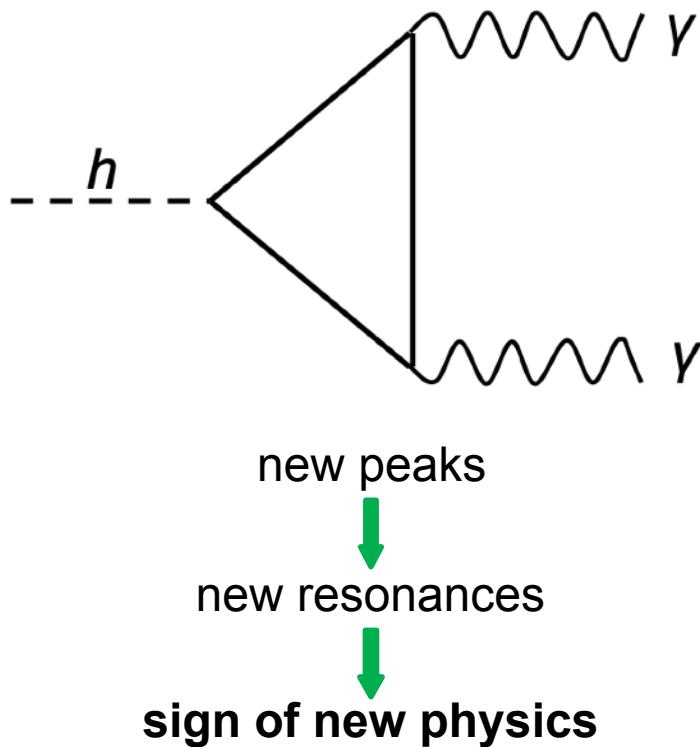
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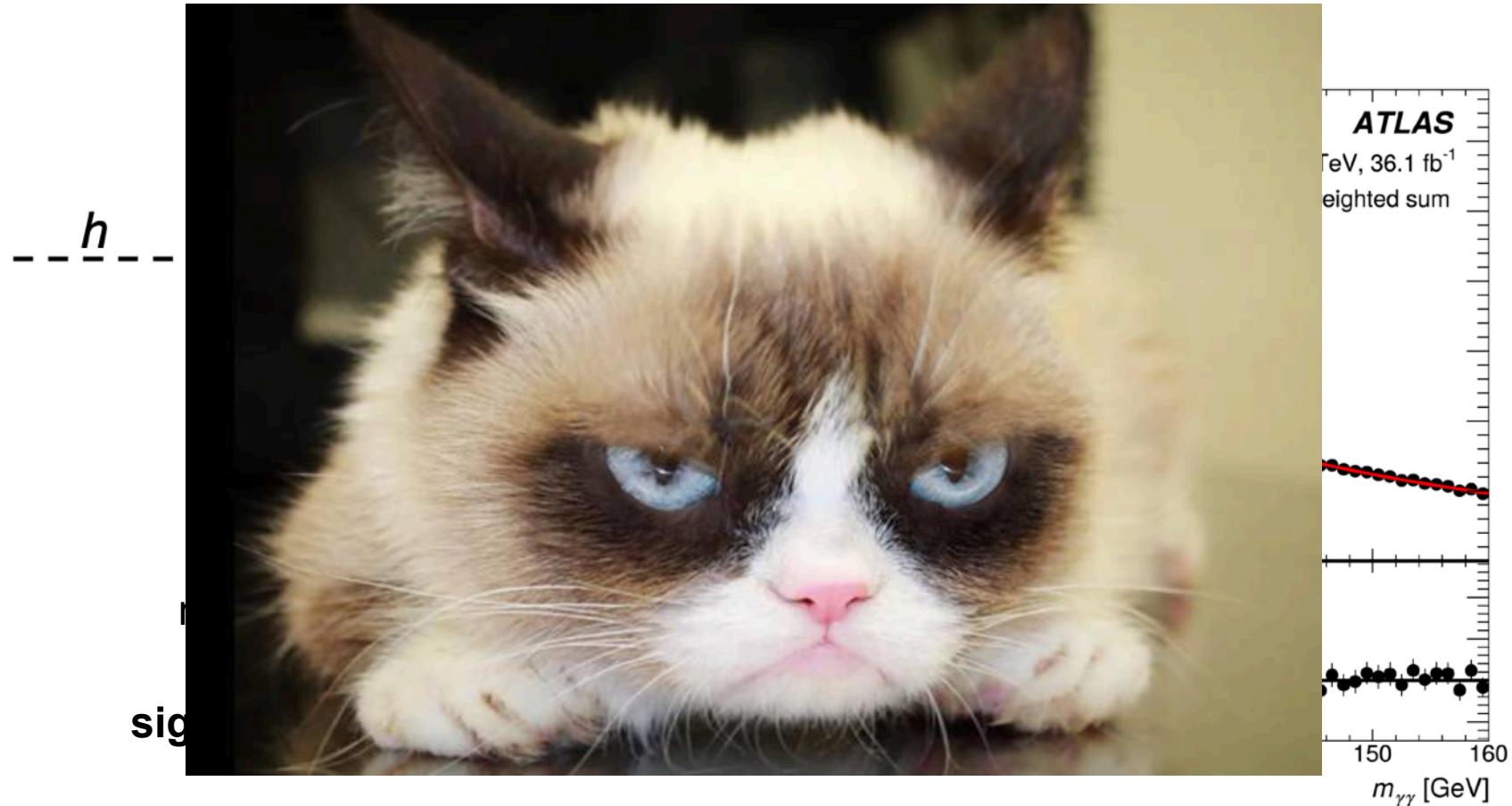
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[Statistical break]

[Statistical break]



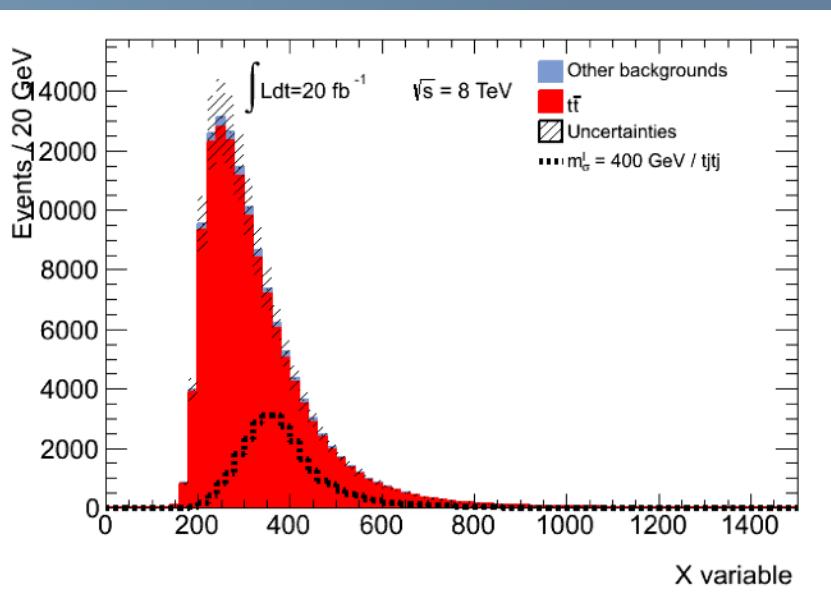
KEEP
CALM
AND
DON'T
PANIC

[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**

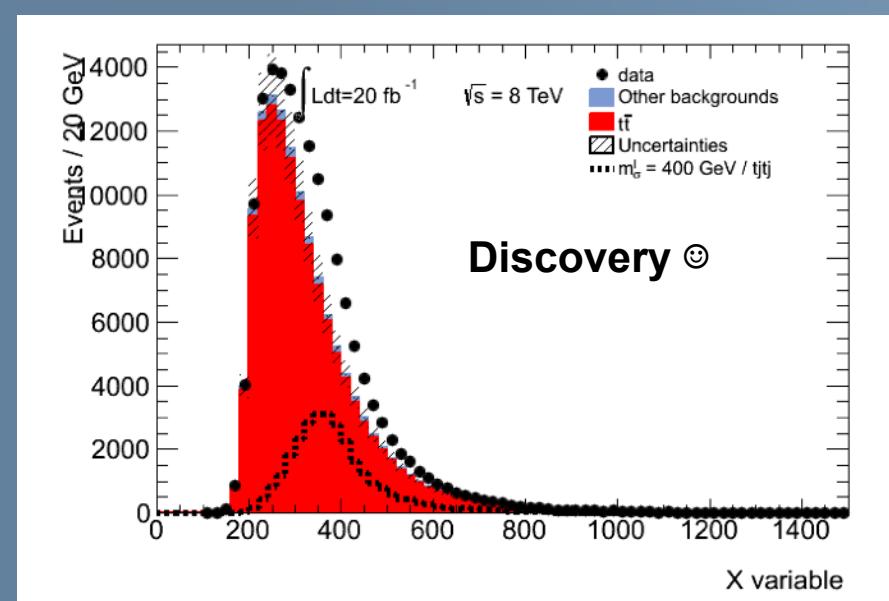
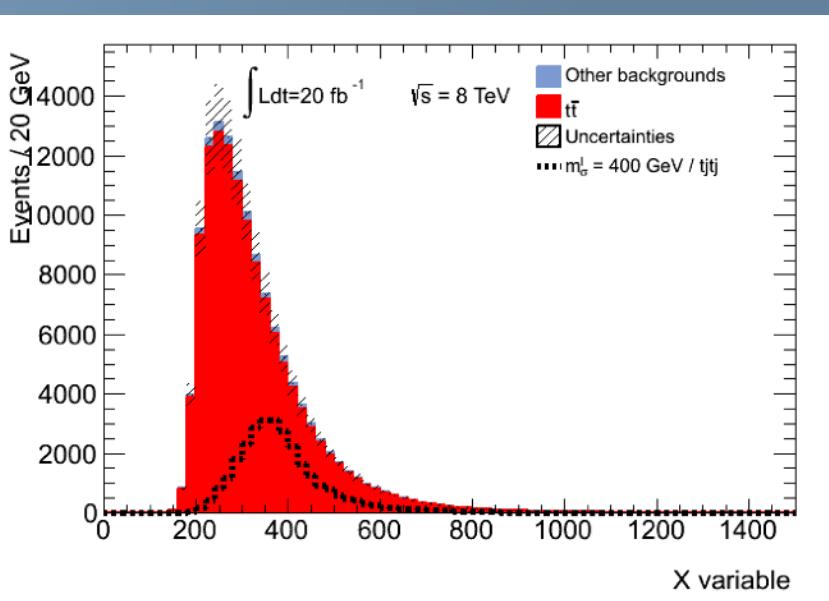
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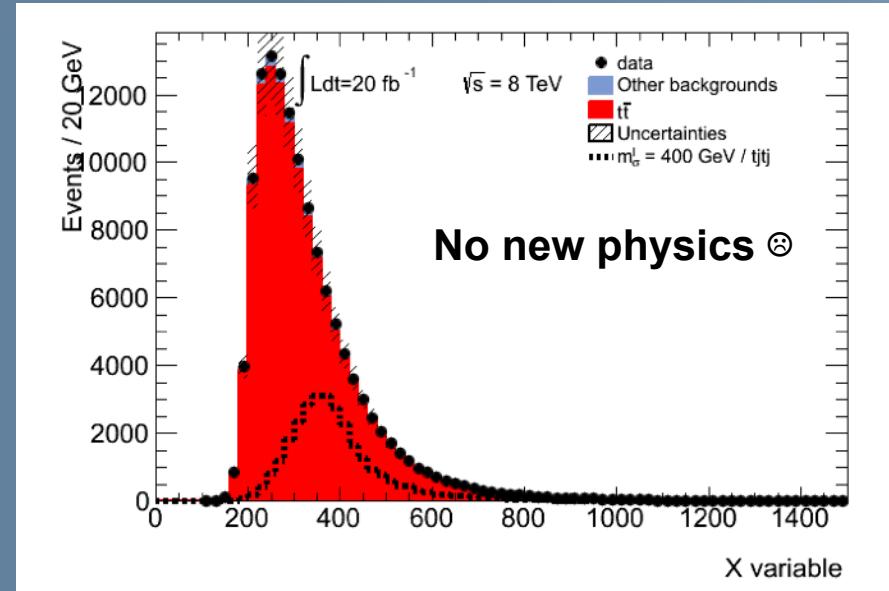
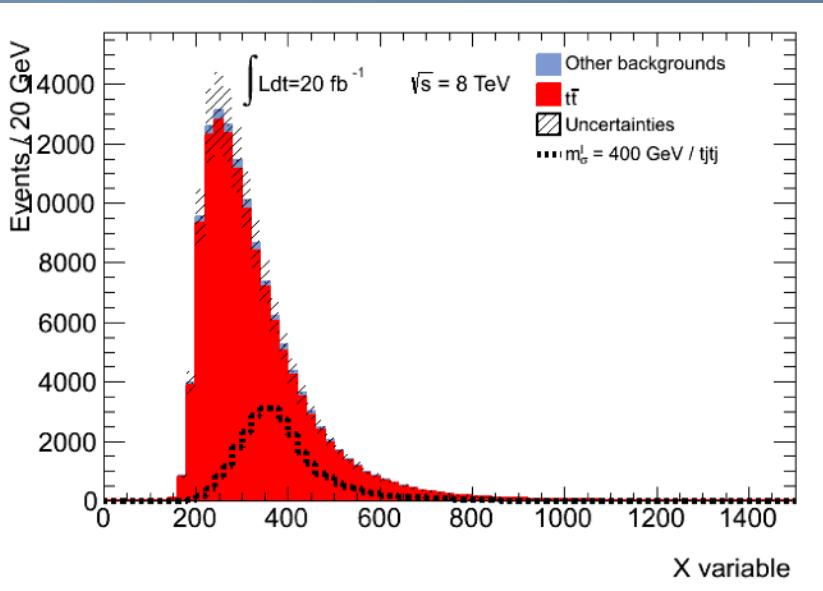
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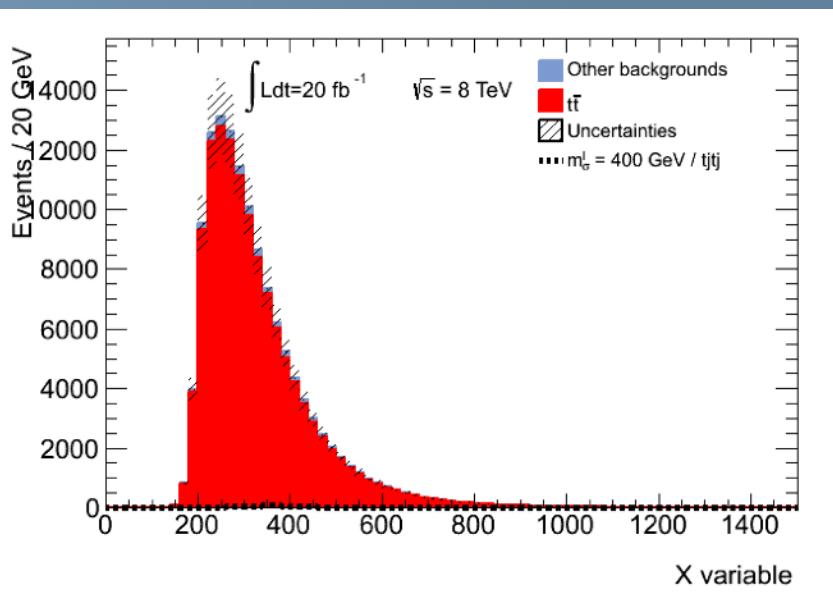
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- If this signal existed ... we would have seen it !
- **If we don't see anything → signal likely doesn't exist**
 - This signal (at this rate) is **excluded**

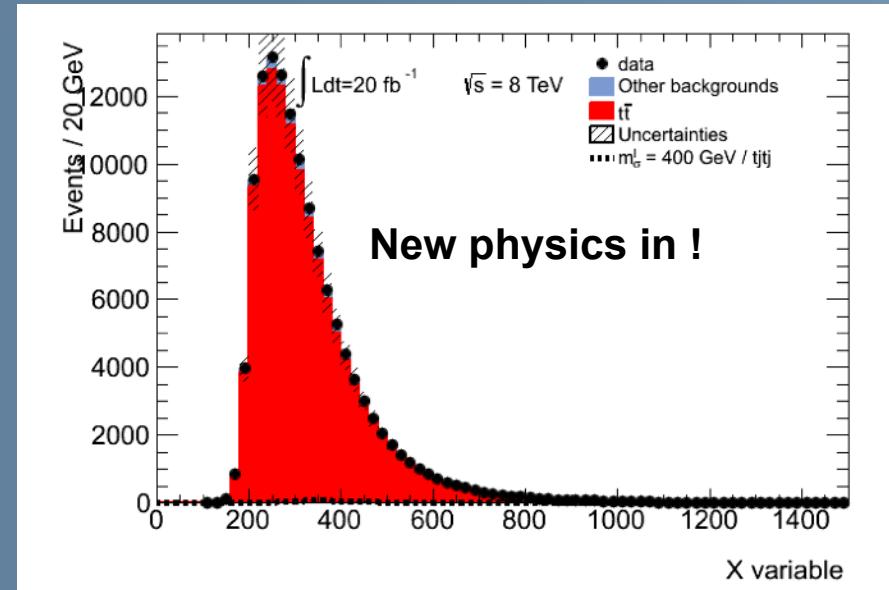
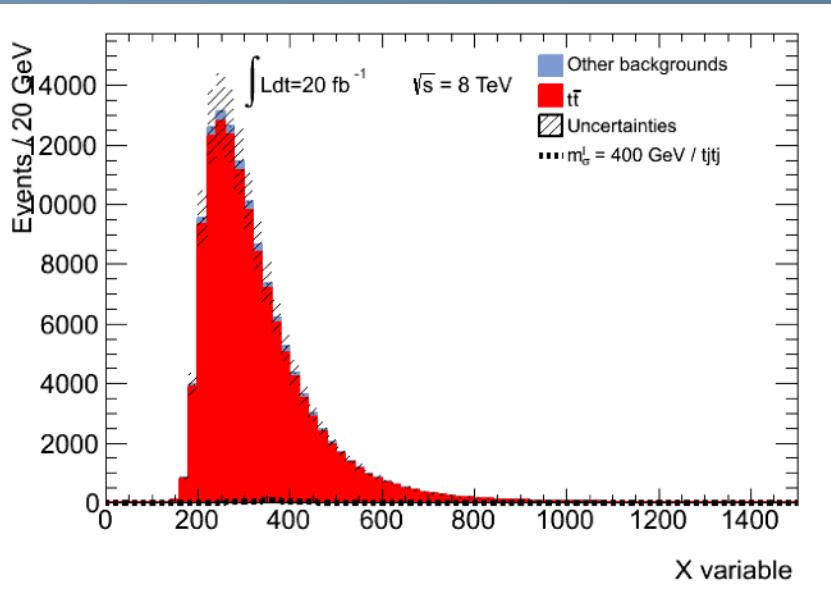
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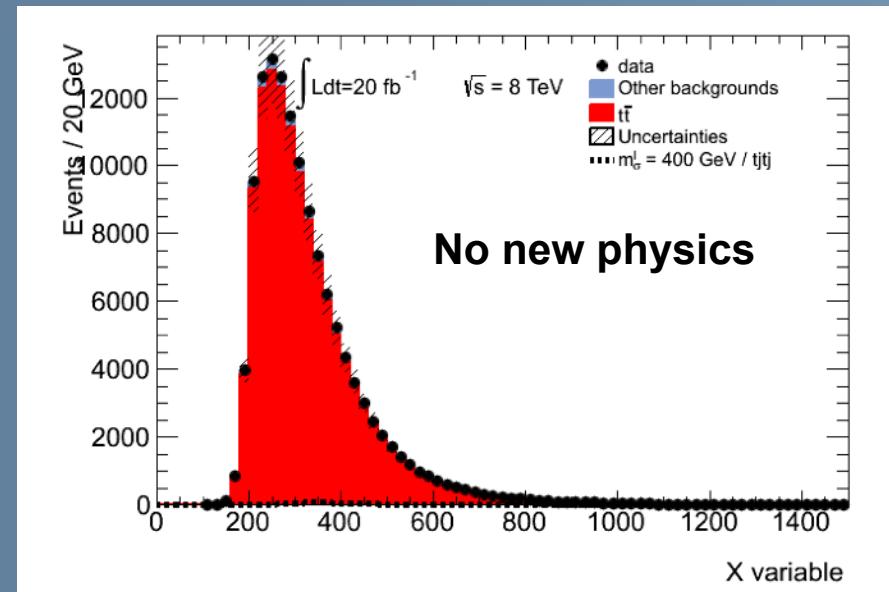
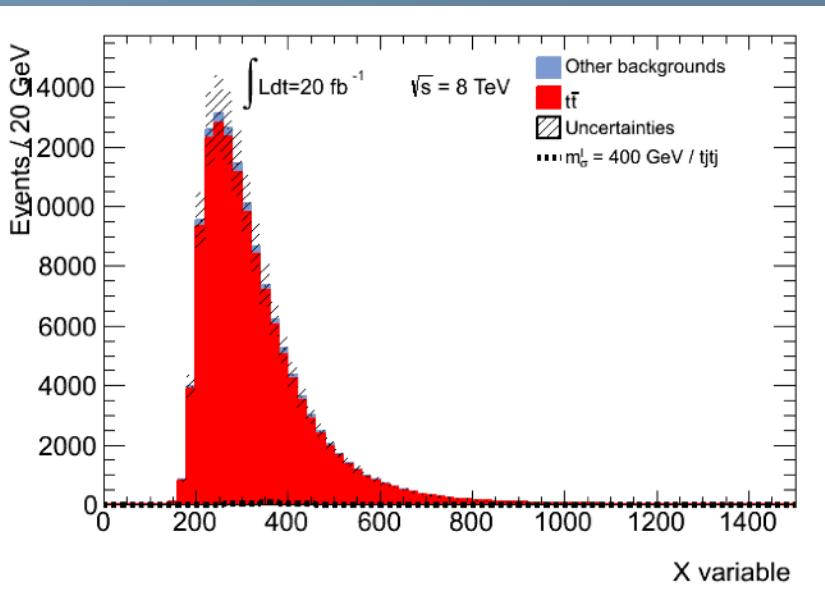
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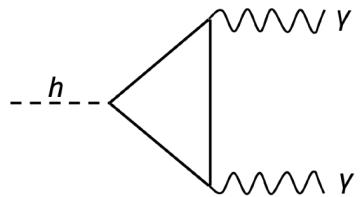
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- Let's assume that our signal has a **tiny production rate**

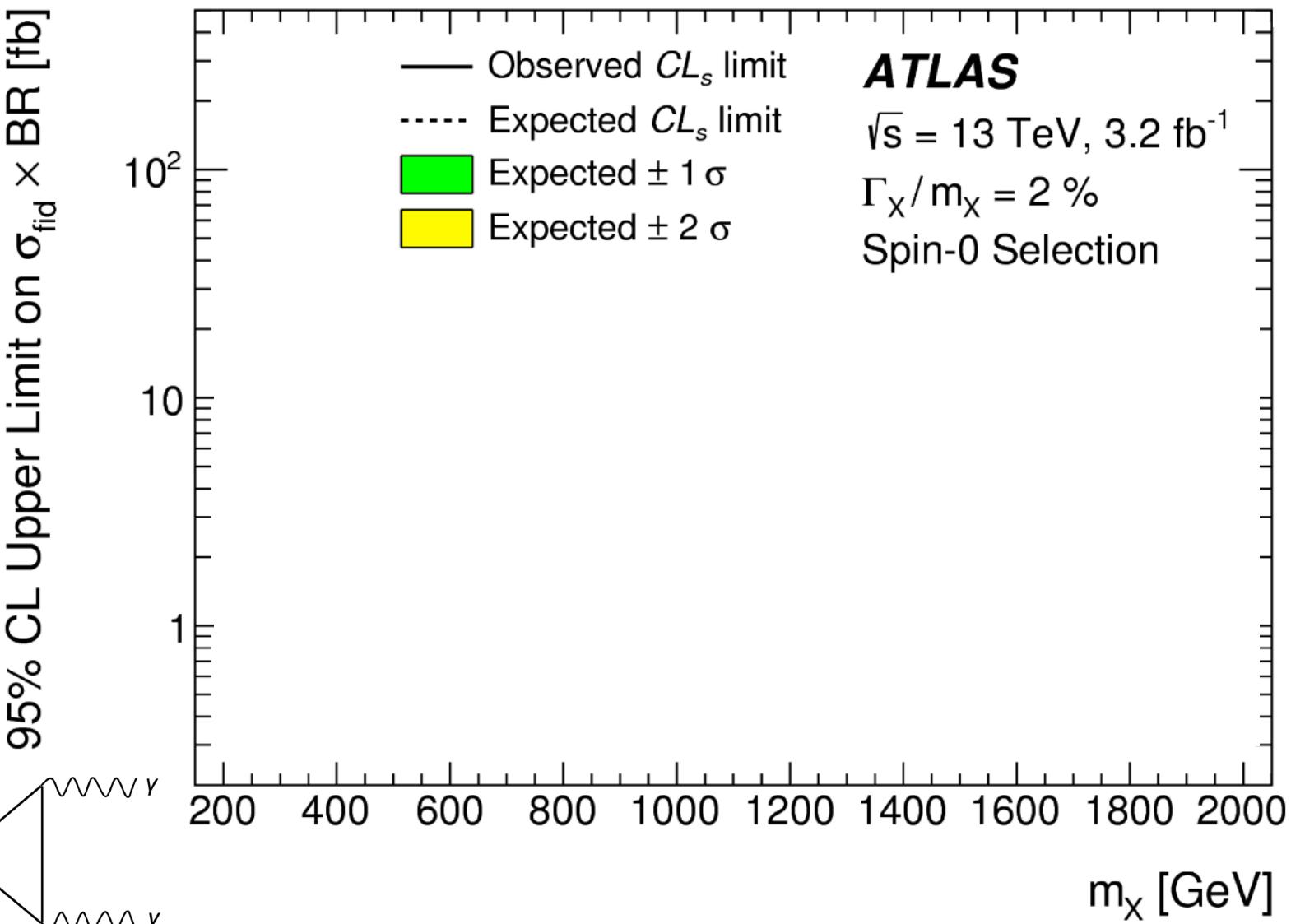


- Even if this signal existed ... we couldn't have seen it !
- **No sensitivity** for this signal (at this rate)

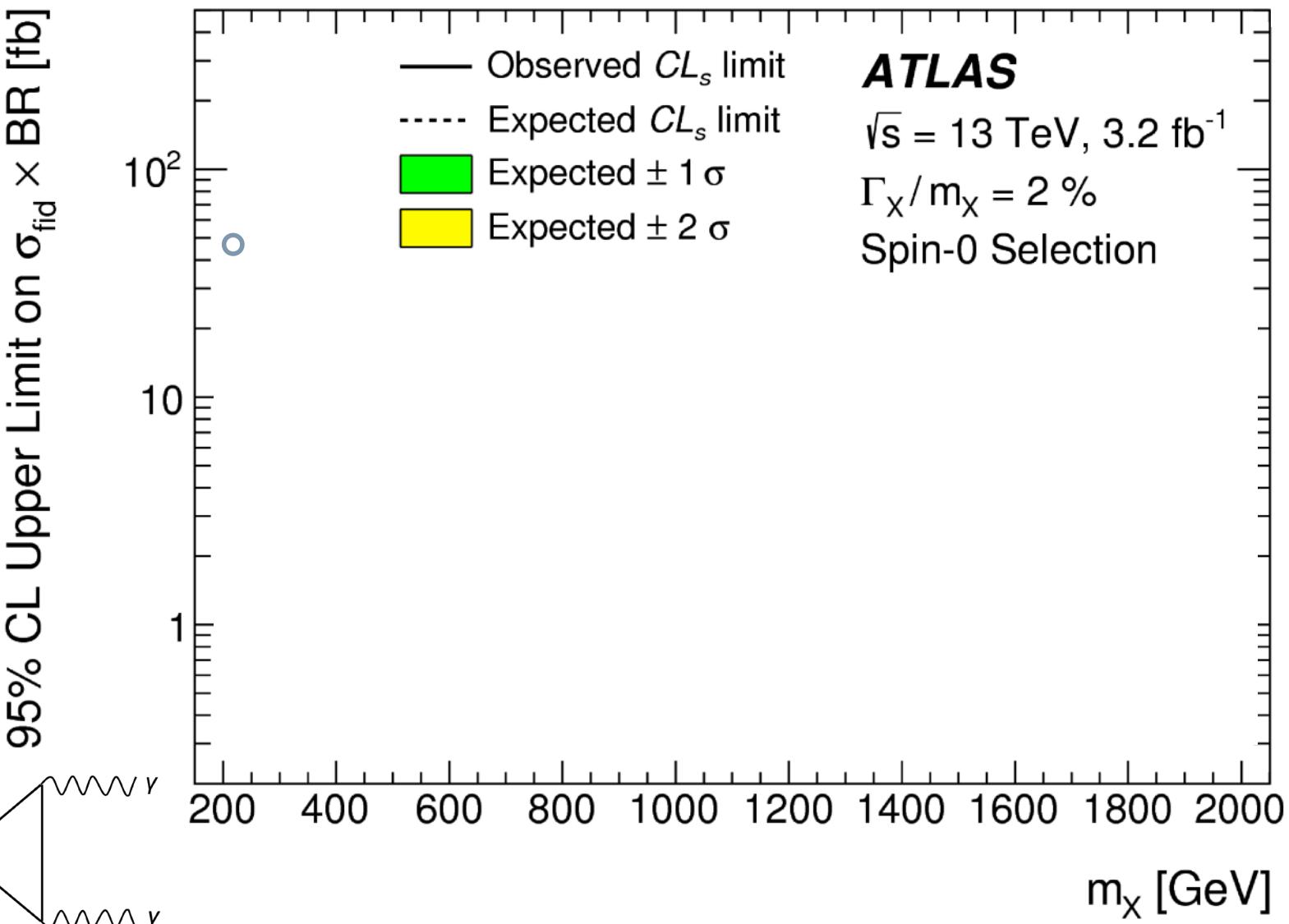
Direct search



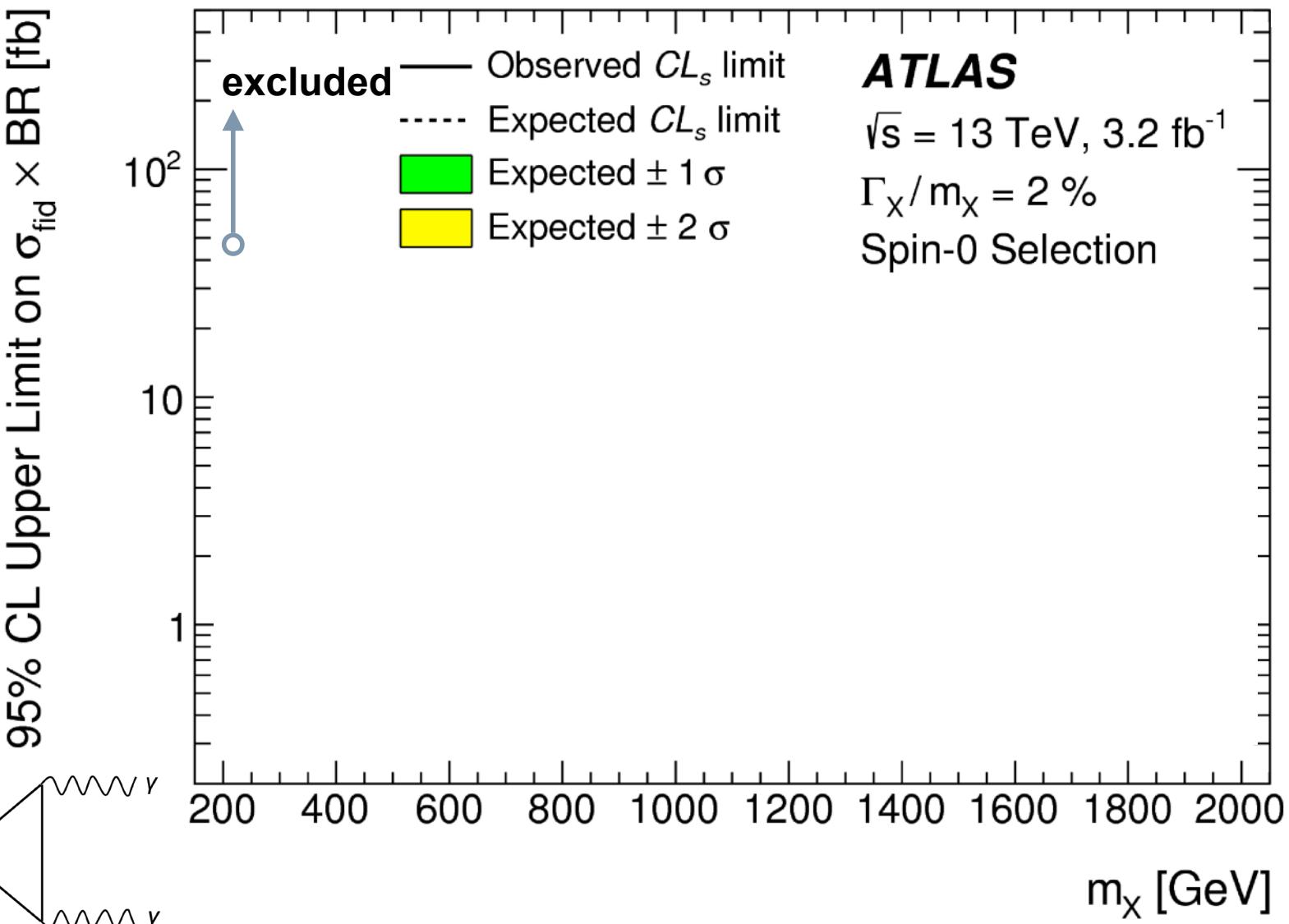
Direct search



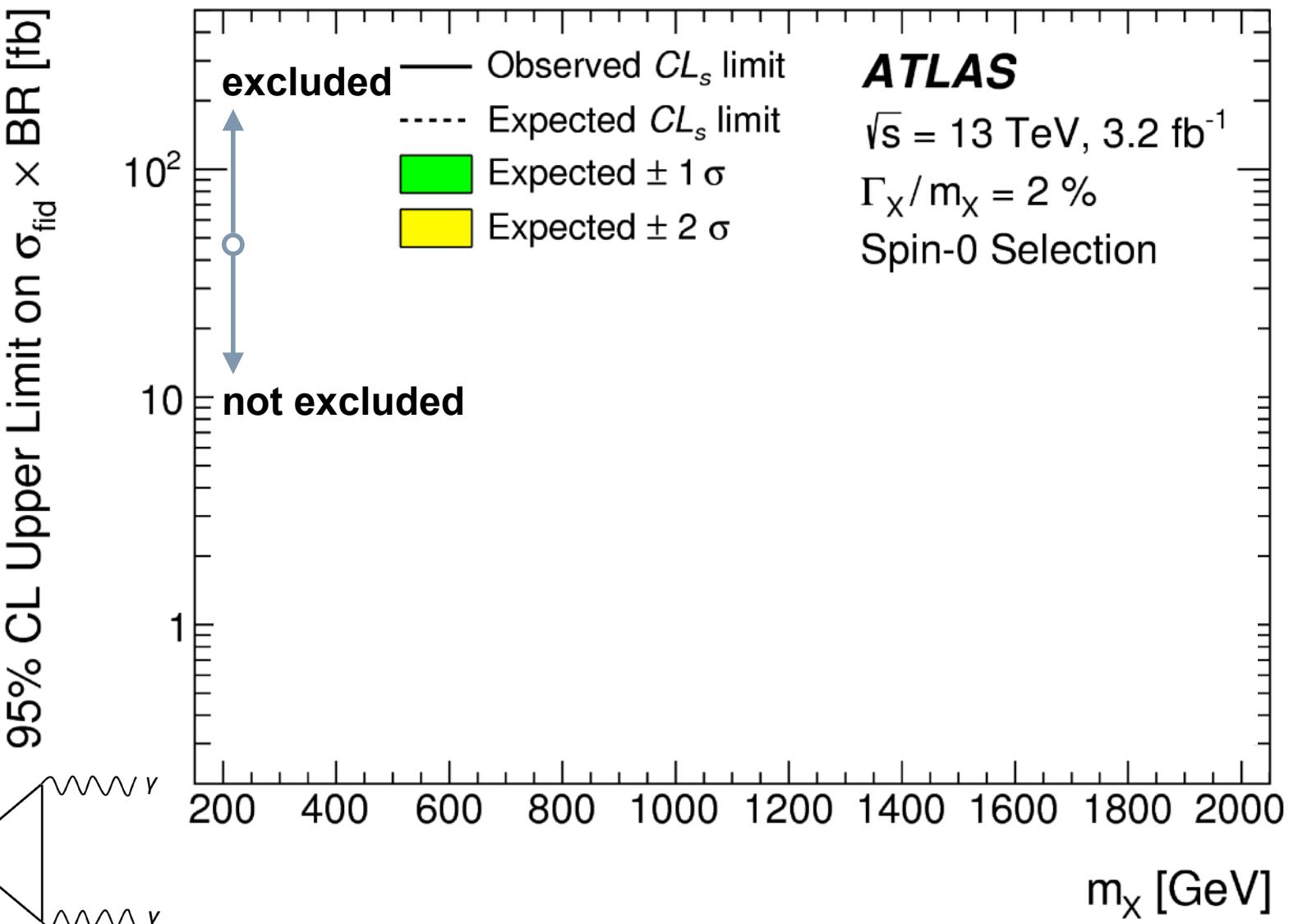
Direct search



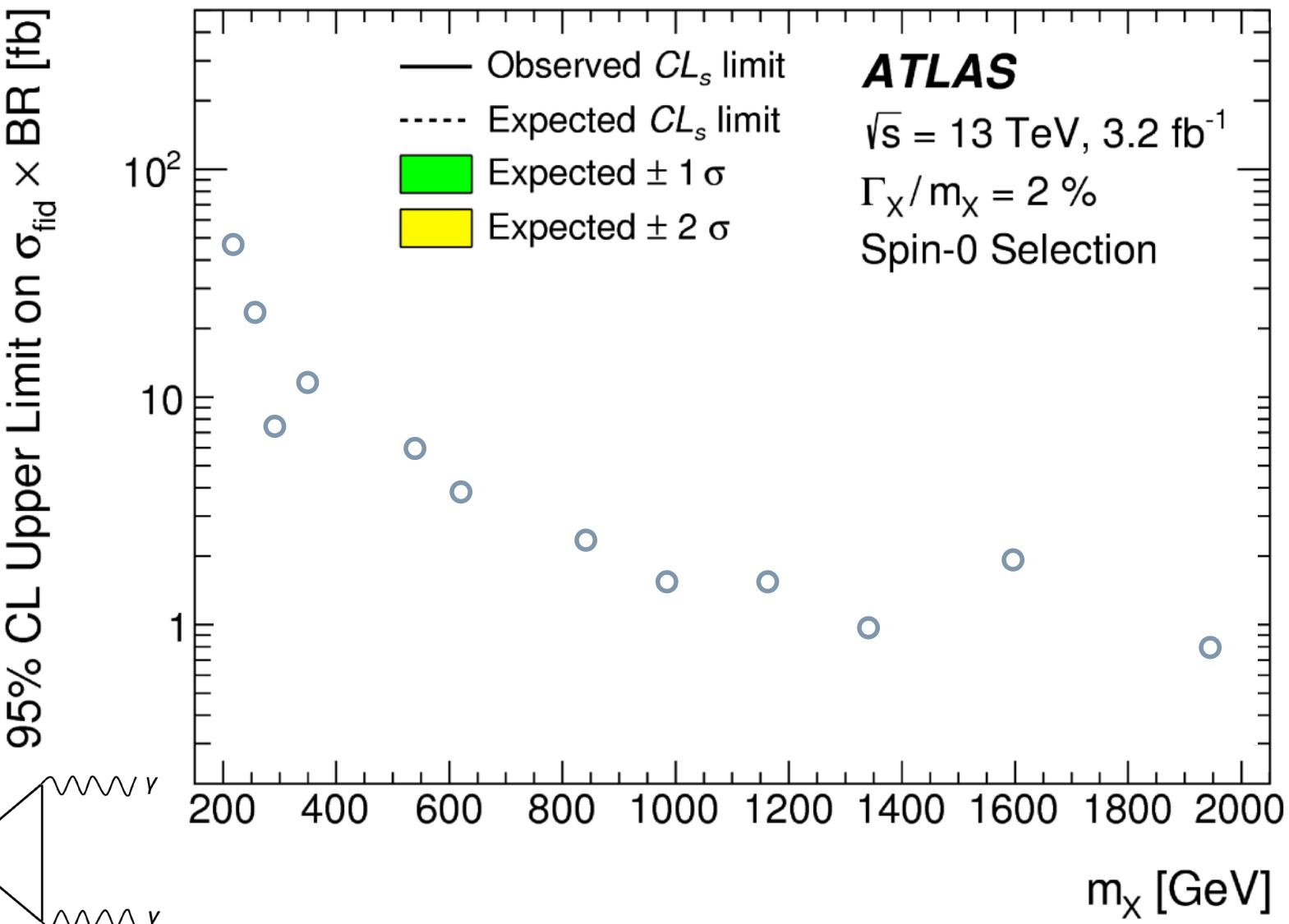
Direct search



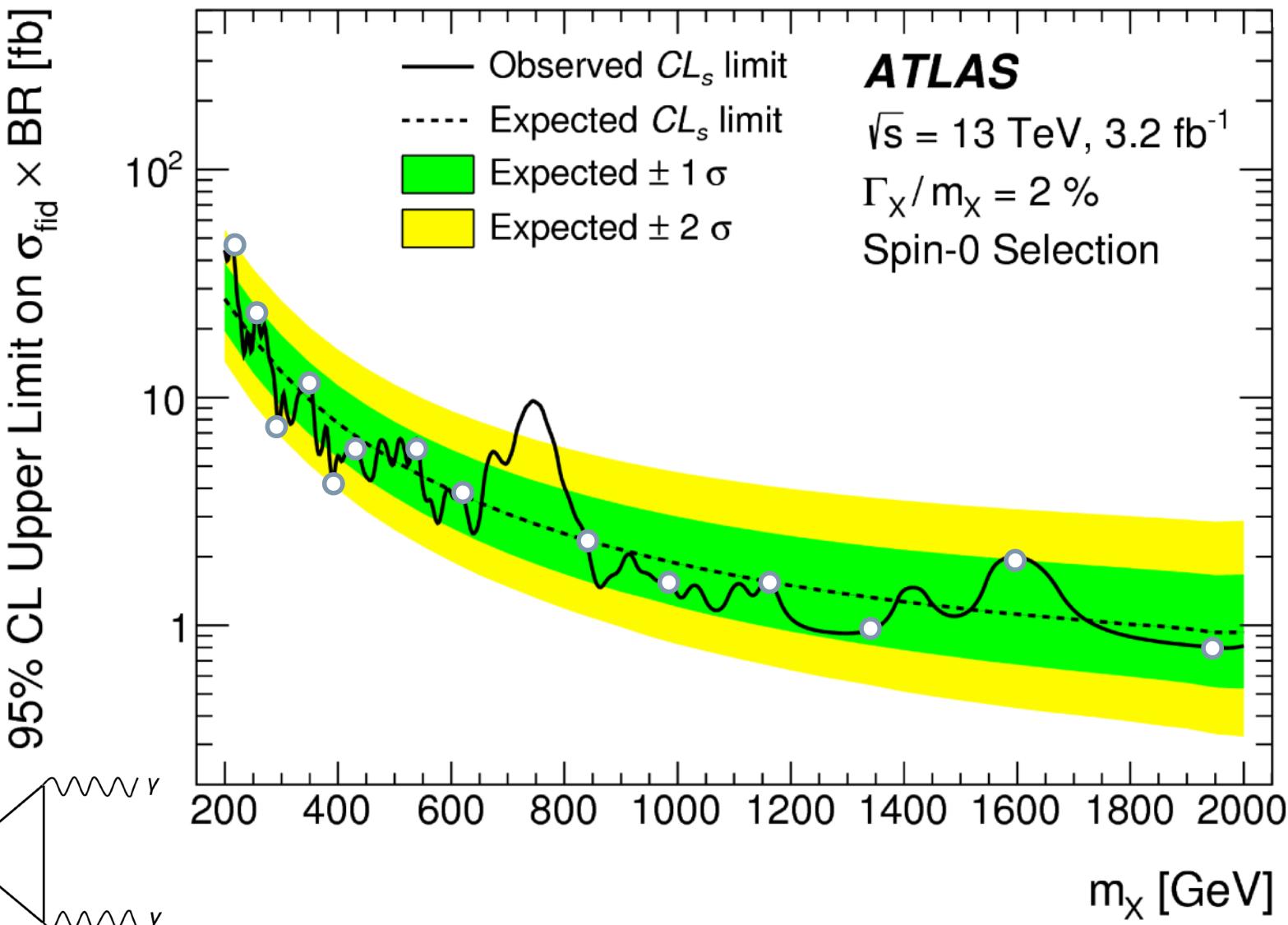
Direct search



Direct search



Direct search

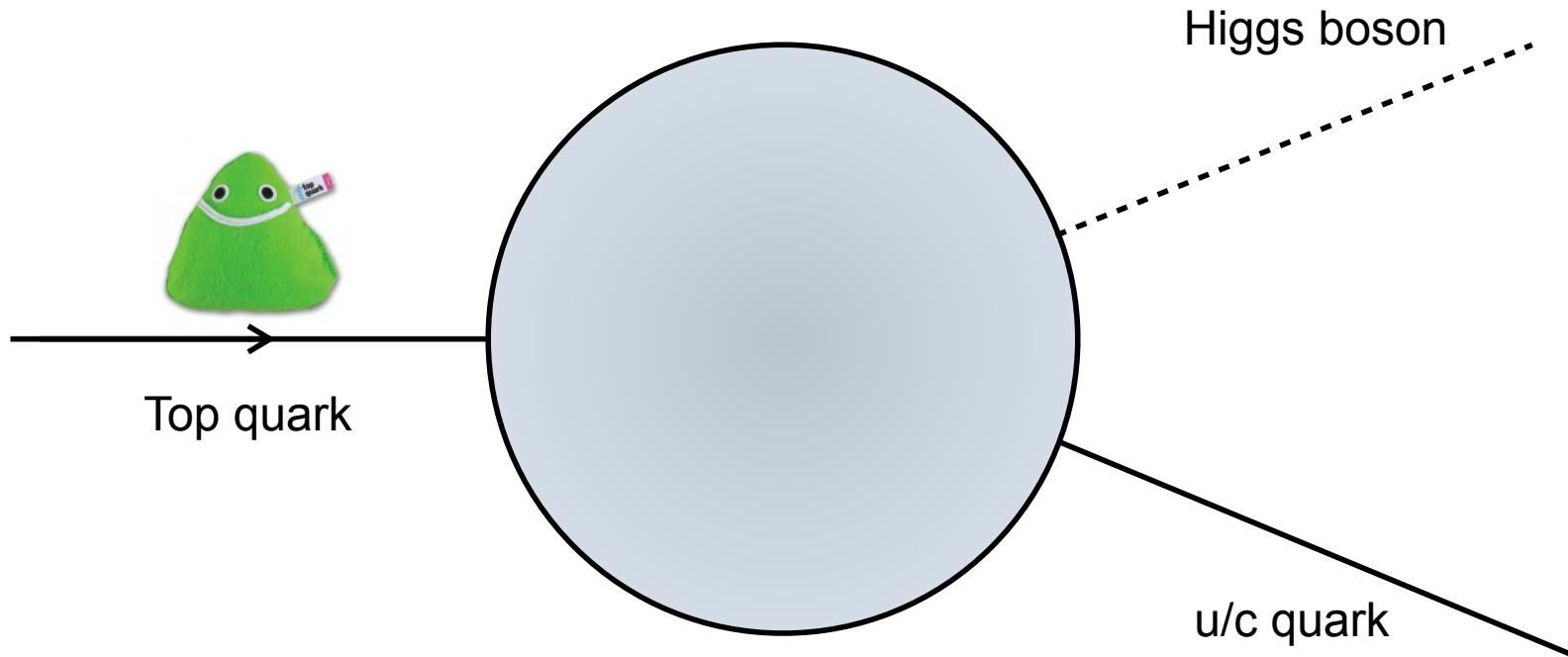




Indirect search

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

$$t \rightarrow Hc$$



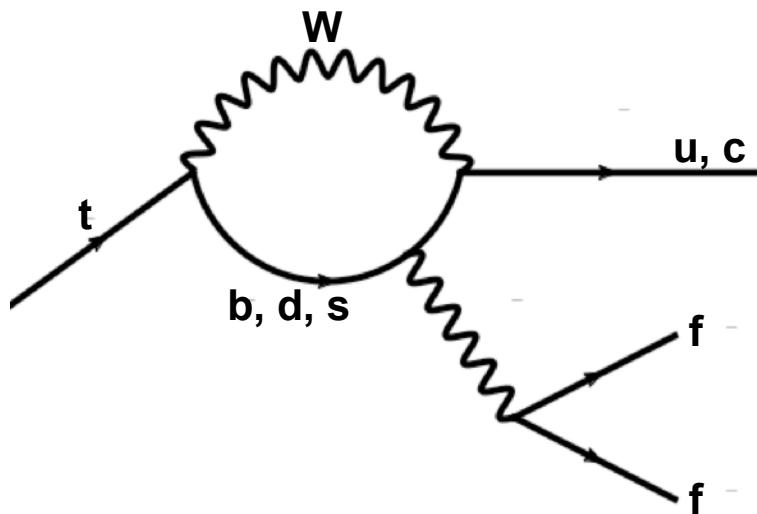


Indirect search

In total, about $2 \cdot 10^8$ top quarks produced at LHC since 2011

SM

$t \rightarrow H u, H c, \dots$ X (at tree level)



$$\mathcal{P}(t \rightarrow H u) \approx 10^{-15}$$

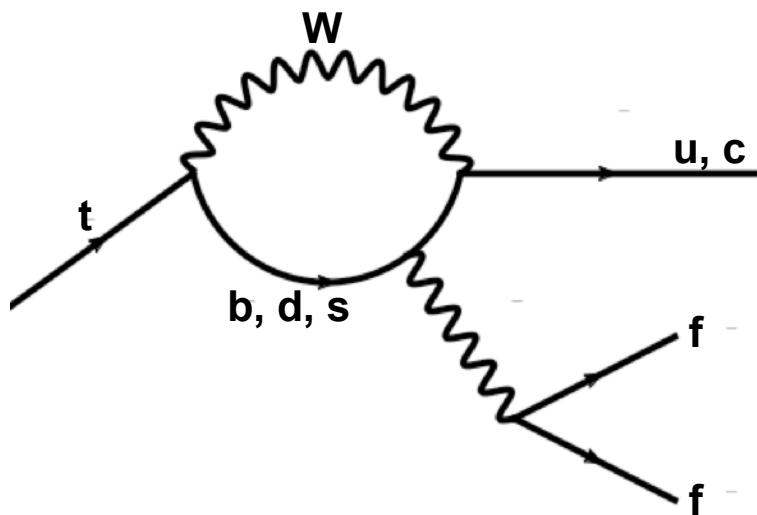


Indirect search

In total, about $2 \cdot 10^8$ top quarks produced at LHC since 2011

SM

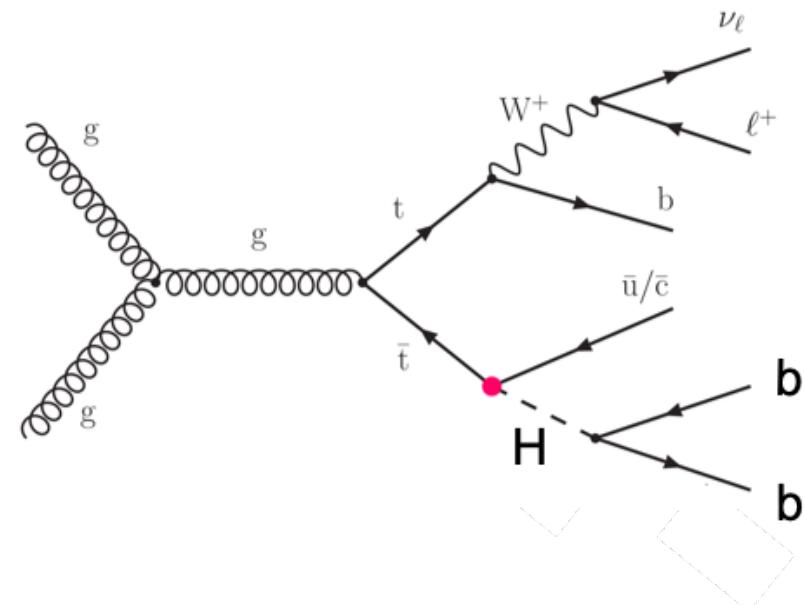
$t \rightarrow Hu, Hc, \dots$  (at tree level)



$$\mathcal{P}(t \rightarrow Hu) \approx 10^{-15}$$

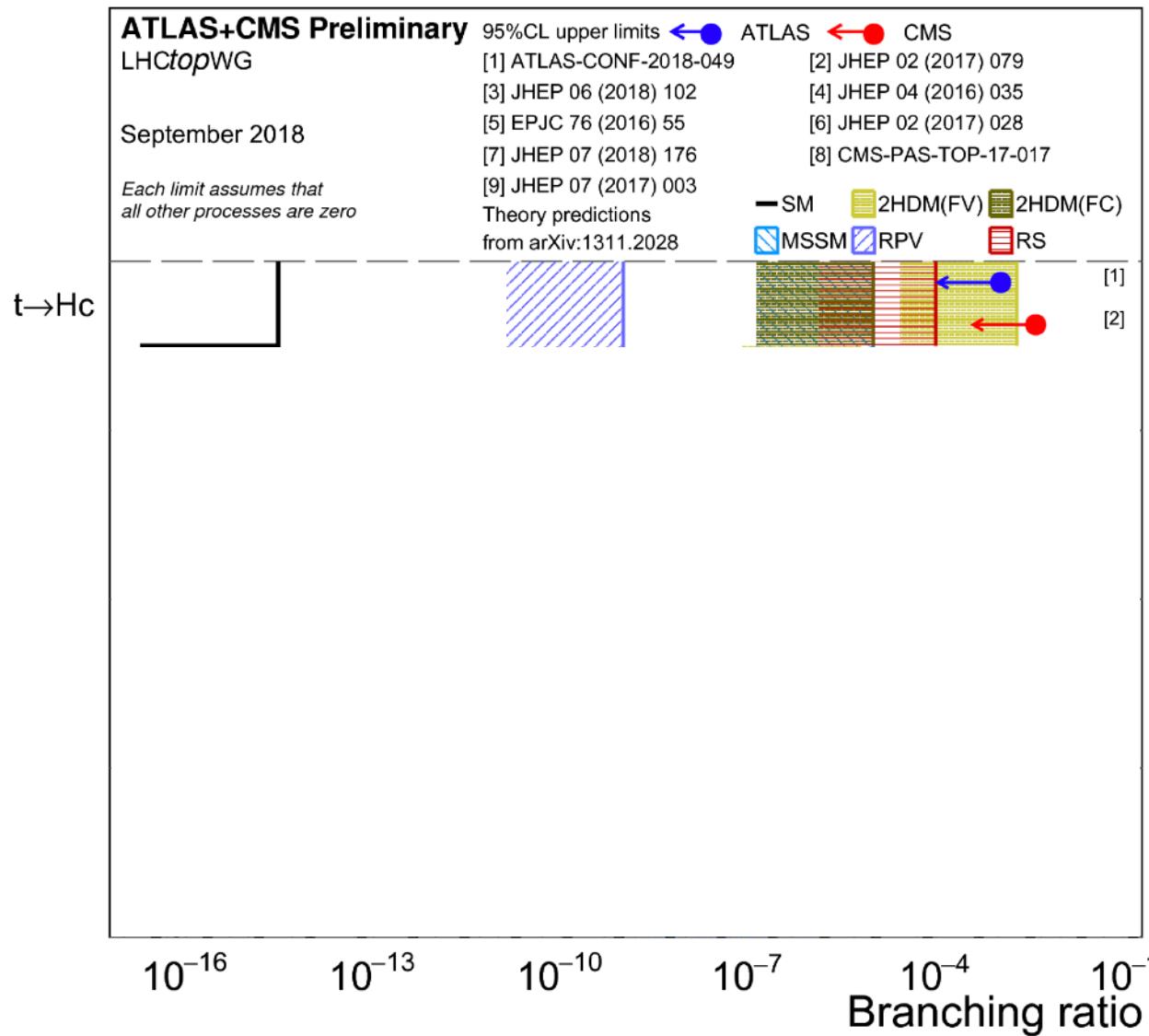
BSM

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

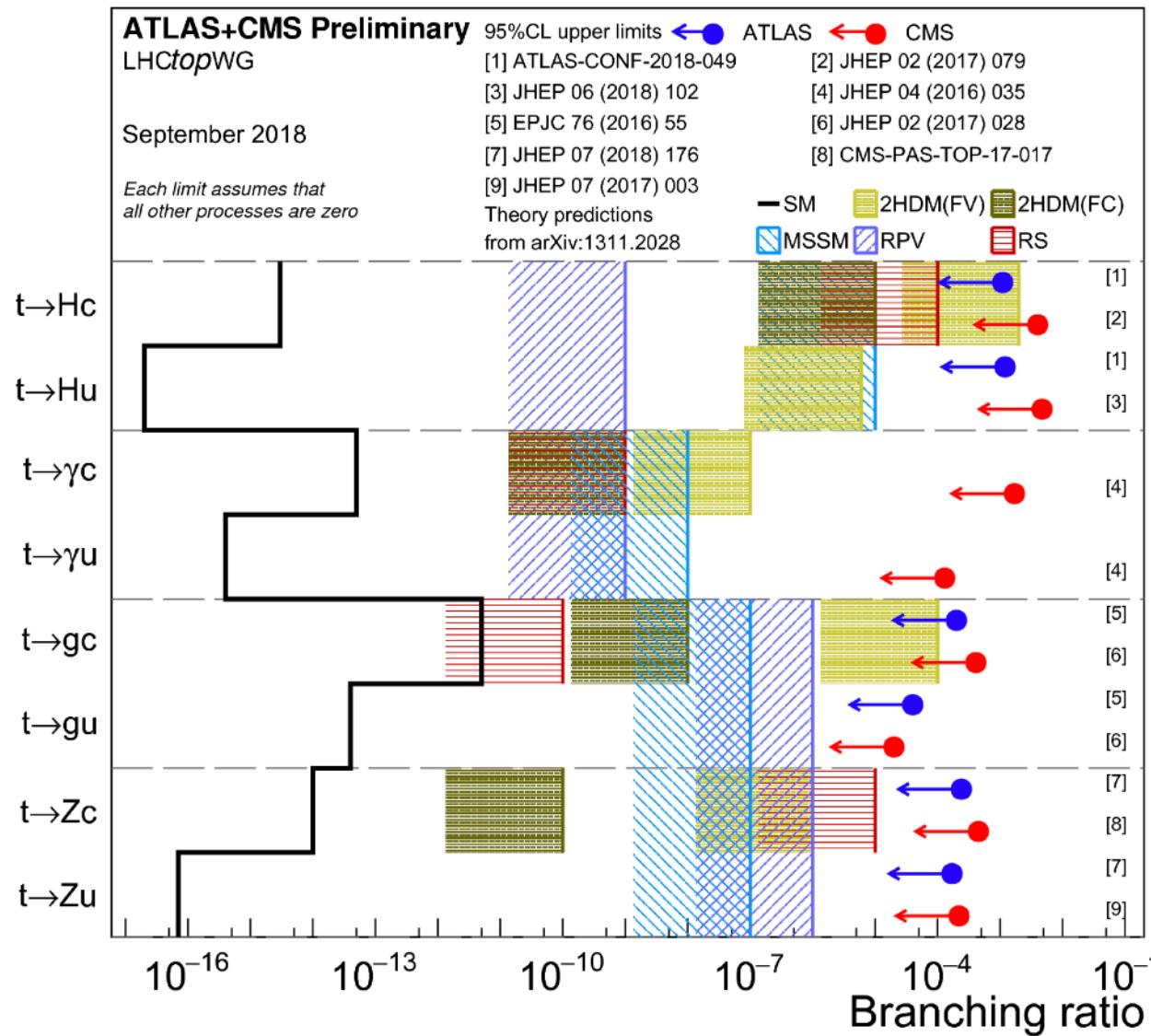


$$\mathcal{P}(t \rightarrow Hu) \leq 10^{-5}$$

Indirect search



Indirect search



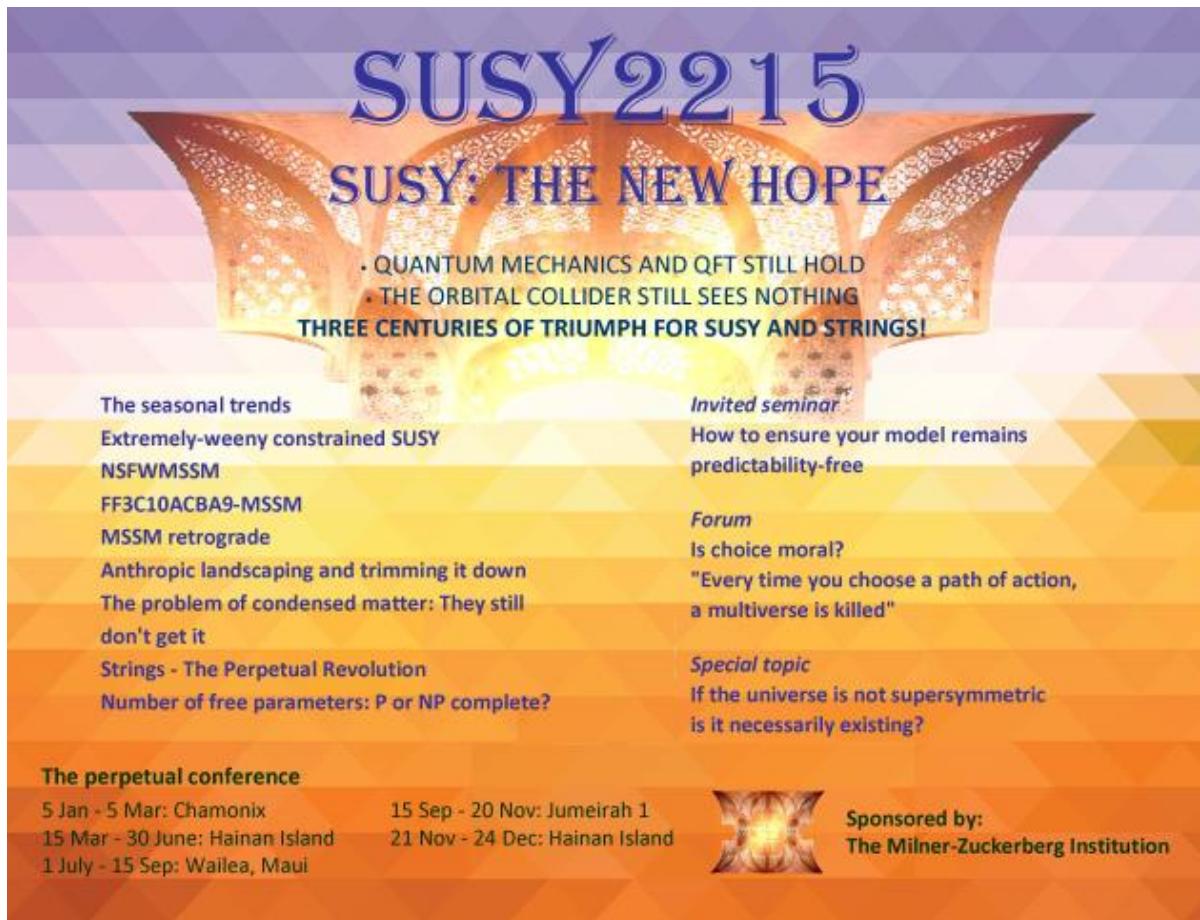
Summary

- **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 ☹



The poster features a purple and orange background with a central graphic of three stylized, glowing wings or petals. The title "SUSY2215" is at the top 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 across the middle reads "THREE CENTURIES OF TRIUMPH FOR SUSY AND STRINGS!". The left side lists various topics under "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", and "Number of free parameters: P or NP complete?". The right side lists topics under "Invited seminar": "How to ensure your model remains predictability-free", "Forum": "Is choice moral?", "Special topic": "If the universe is not supersymmetric is it necessarily existing?", and "The perpetual conference" with dates and locations: "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". At the bottom right is a logo for "The Milner-Zuckerberg Institution" and the text "Sponsored by: The Milner-Zuckerberg Institution".

SUSY2215

SUSY: THE NEW HOPE

- QUANTUM MECHANICS AND QFT STILL HOLD
- THE ORBITAL COLLIDER STILL SEES NOTHING

THREE CENTURIES OF TRIUMPH FOR SUSY AND STRINGS!

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 Sep - 20 Nov: Jumeirah 1
15 Mar - 30 June: Hainan Island	21 Nov - 24 Dec: Hainan Island
1 July - 15 Sep: Wailea, Maui	

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