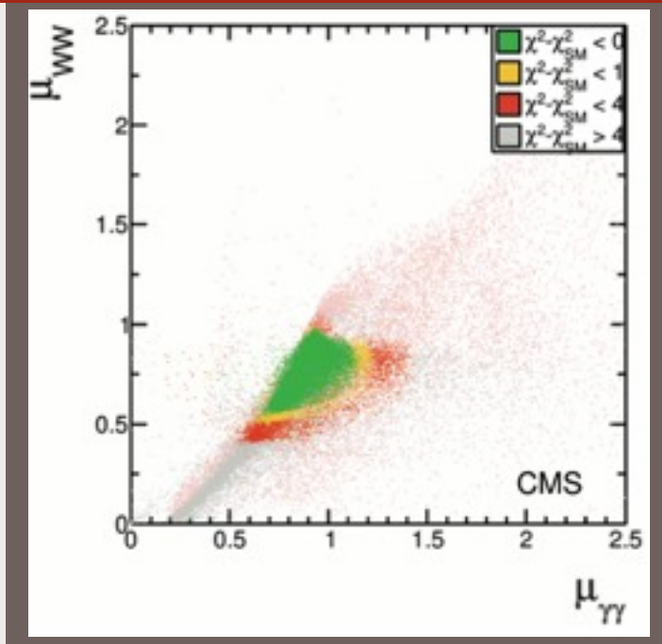
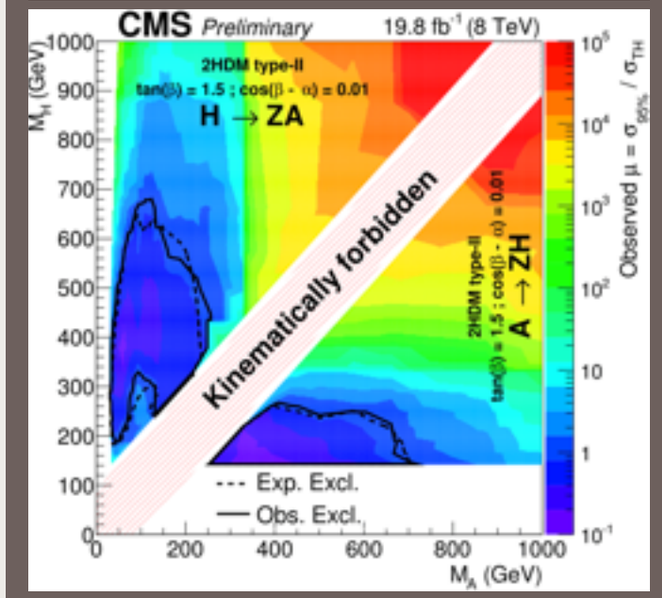
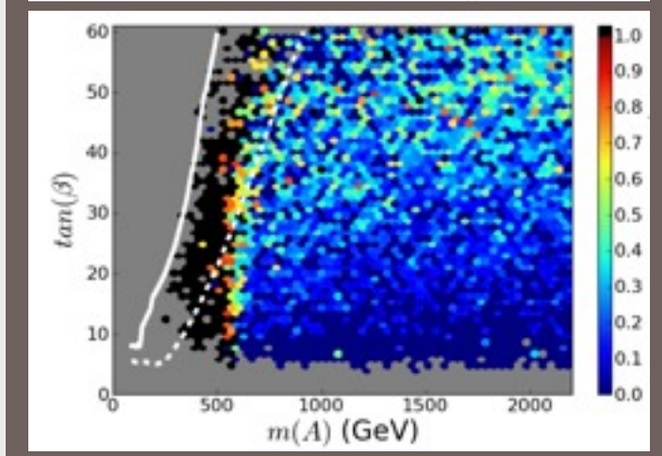
Before and After - Consequences of the Higgs Discovery

Travis Martin, TRIUMF

CAP Congress 2015
Edmonton, Alberta



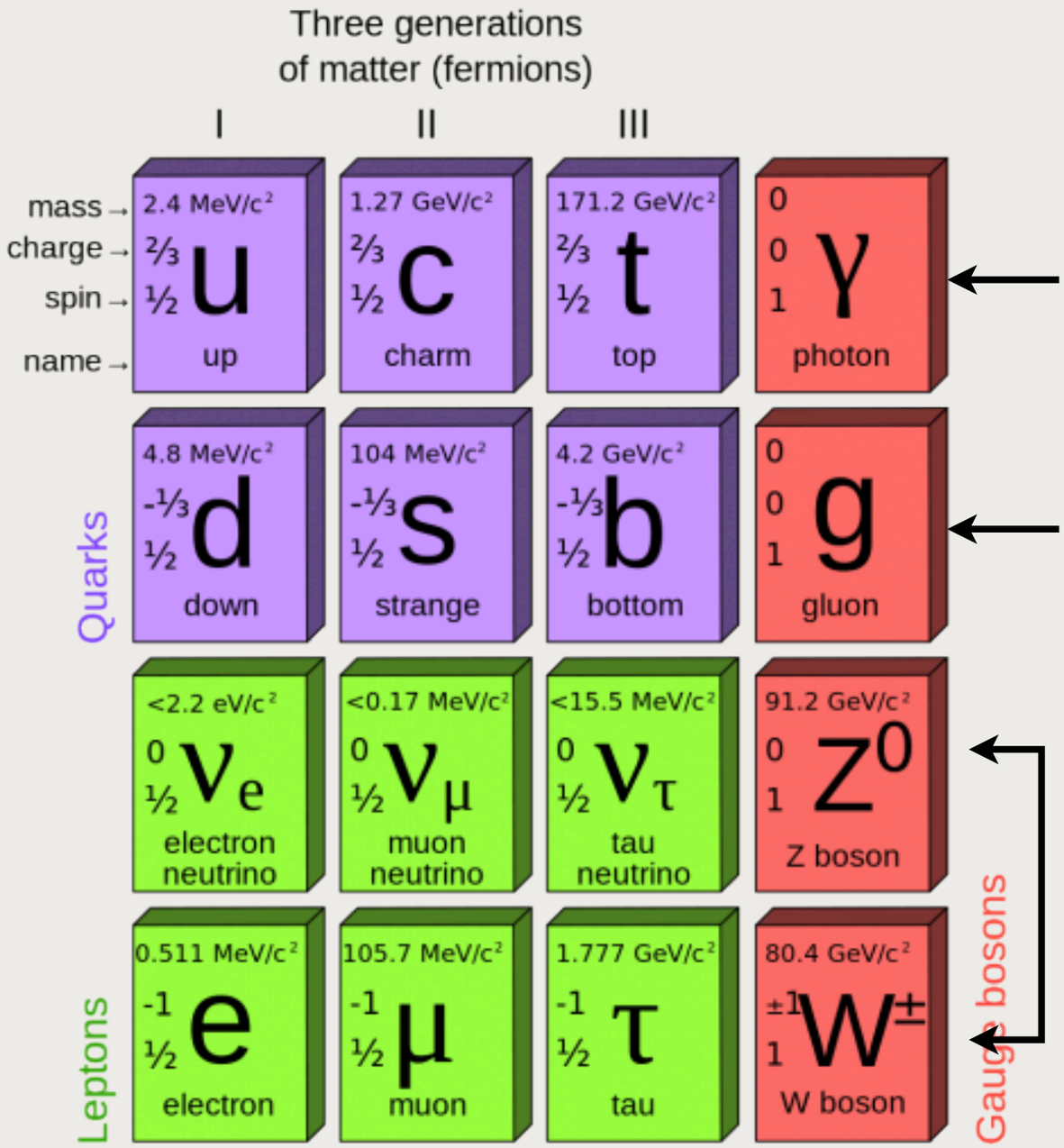




Overview

- On the necessity for a Higgs boson
- Confirming “a Higgs boson”
- State of theory after the discovery
  - Little Higgs
  - Supersymmetry
- What this all means for the future of particle physics

Standard Model



$U(1)_{em}$

Light
Electromagnetism
Chemical Binding
Substance/Structure

$SU(3)_C$

Nucleus Binding
Quark Binding

$SU(2)_W$

Beta Decay
Neutrino recoil

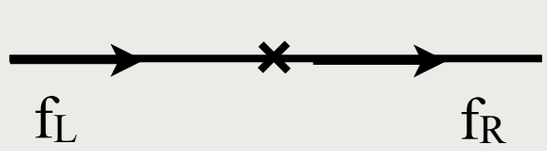
Developed in the 1960s

Forbidden Mass

- Mass in nucleons, matter: mostly binding energy

- Fundamental mass terms forbidden for standard model fermions/gauge bosons

- Mass terms for fermions/gauge bosons violate the fundamental conservation laws/symmetries upon which the standard model is based

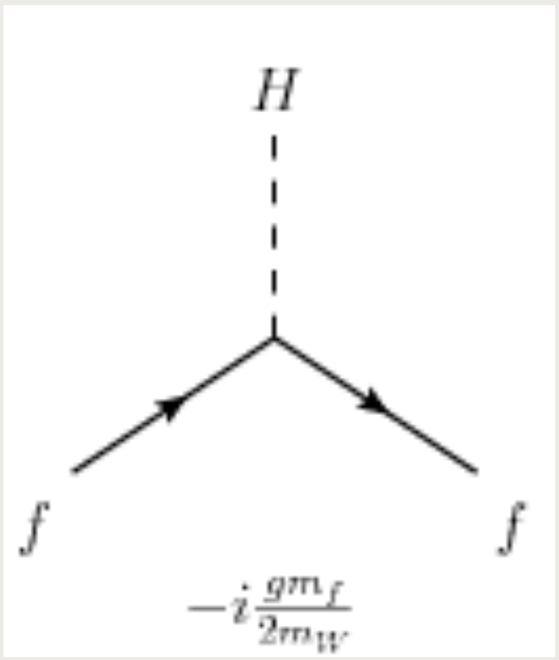


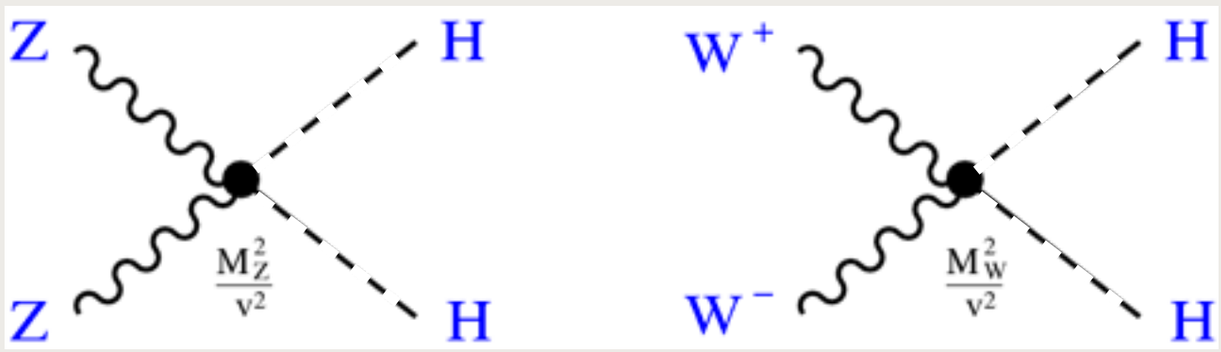
Not Forbidden: Scalar

- Scalar fundamental mass, self coupling not forbidden

$$V \supset \mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

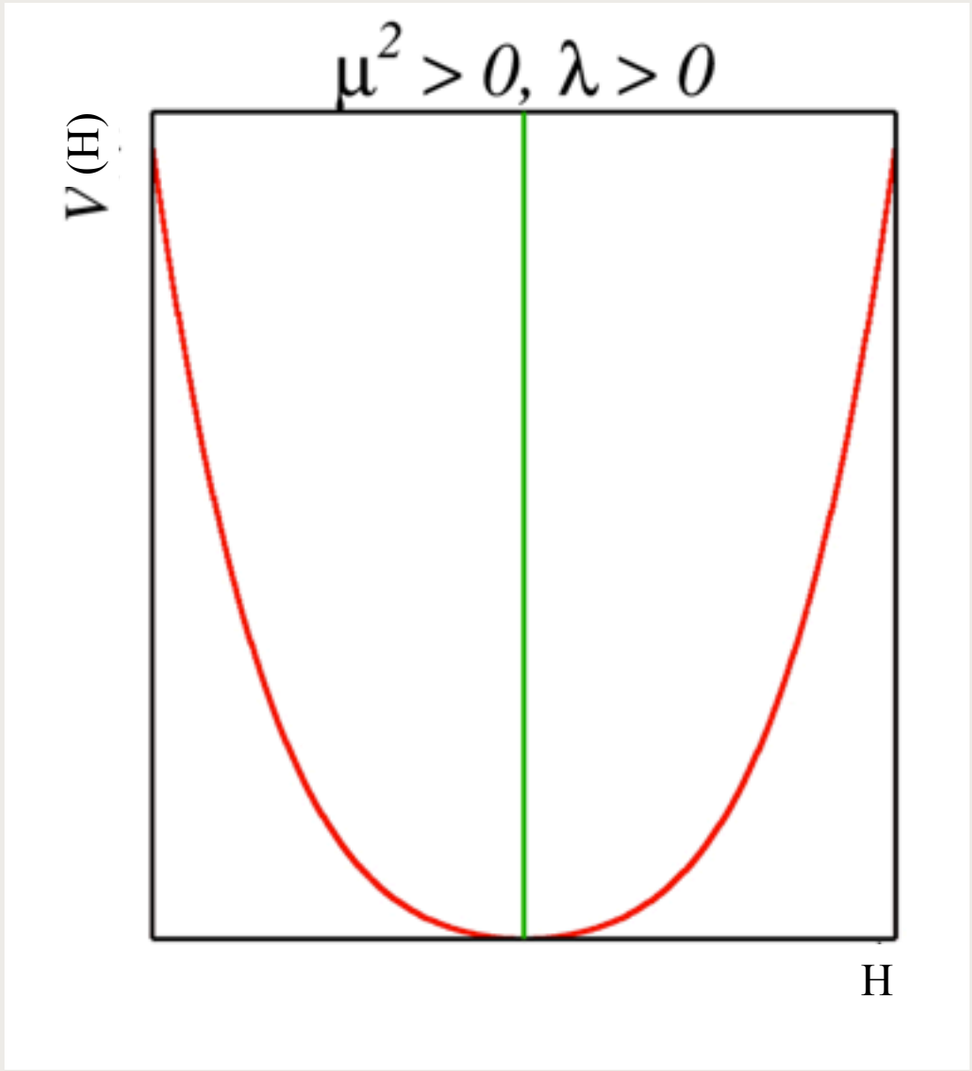
- Can include interactions between scalars & fermions/gauge bosons





Spontaneous Symmetry Breaking

$$V \supset \mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$



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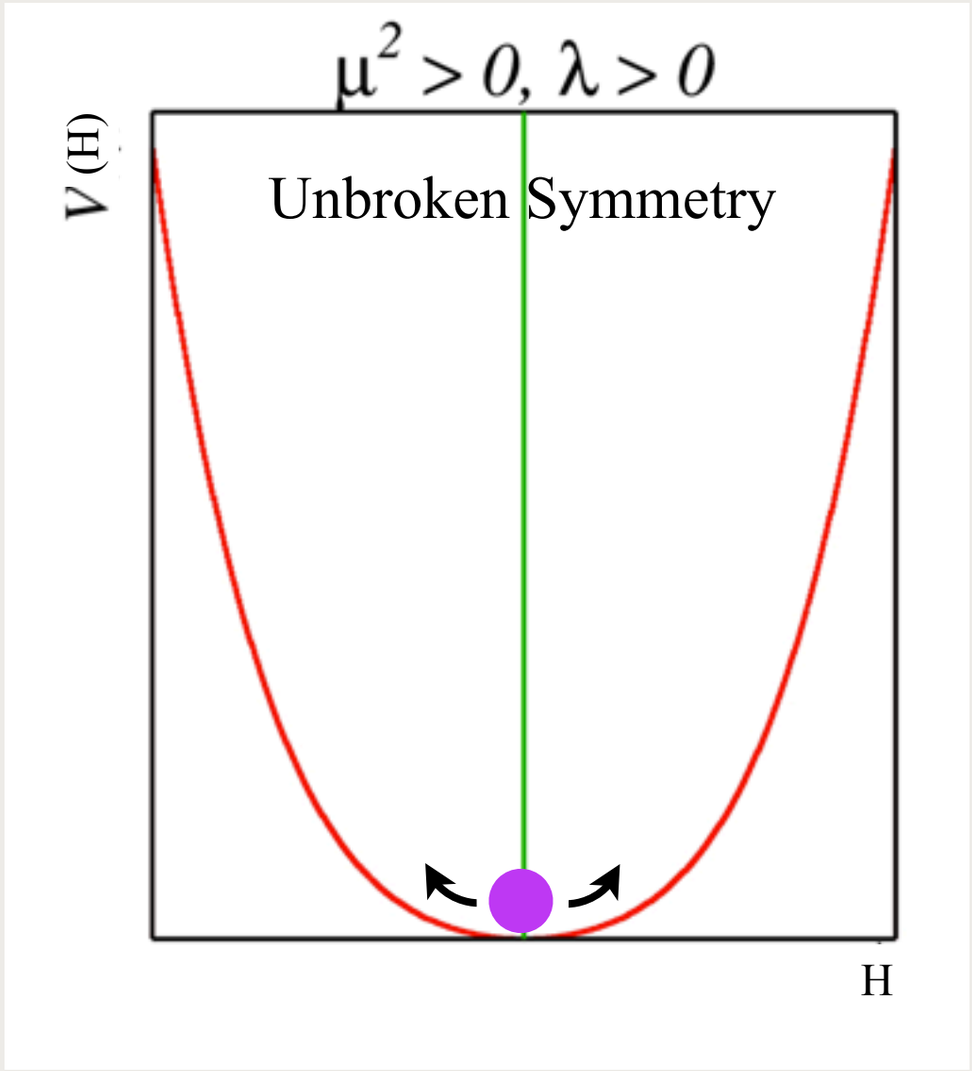

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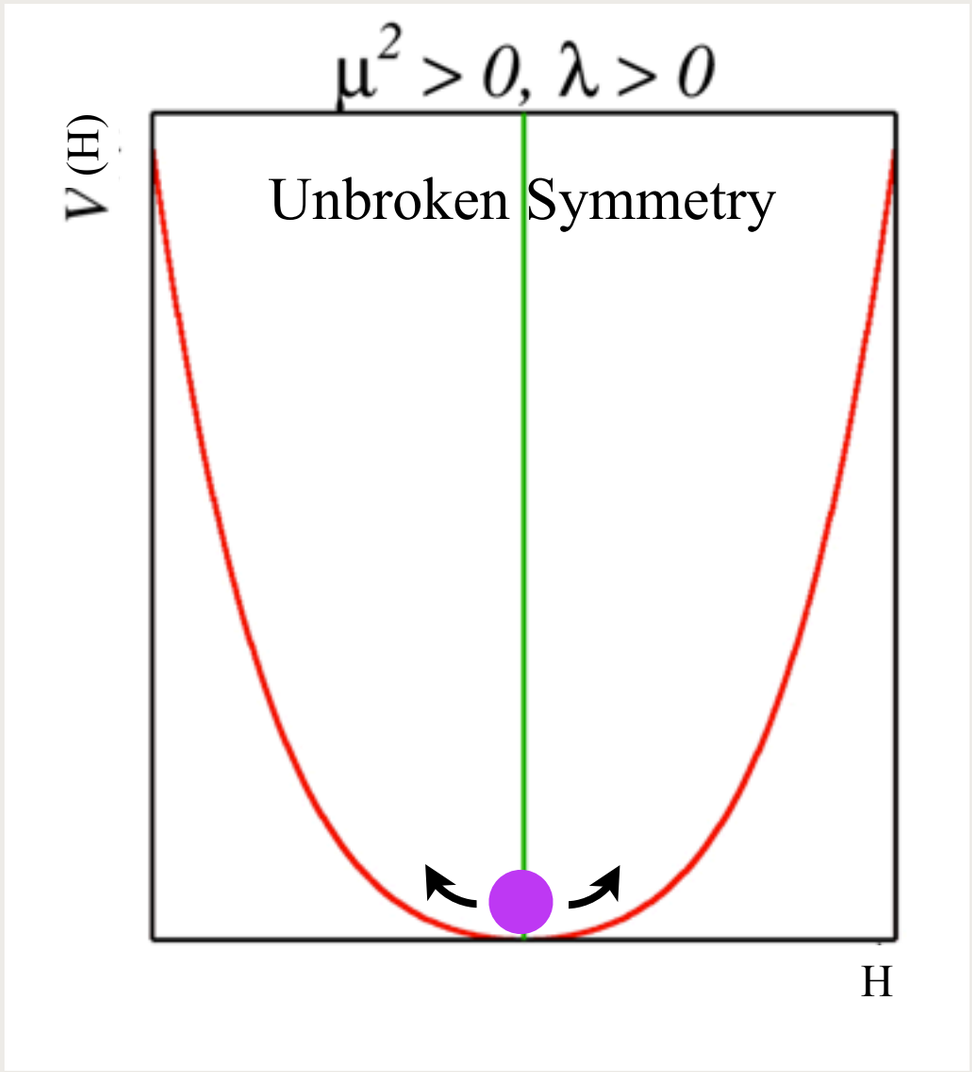

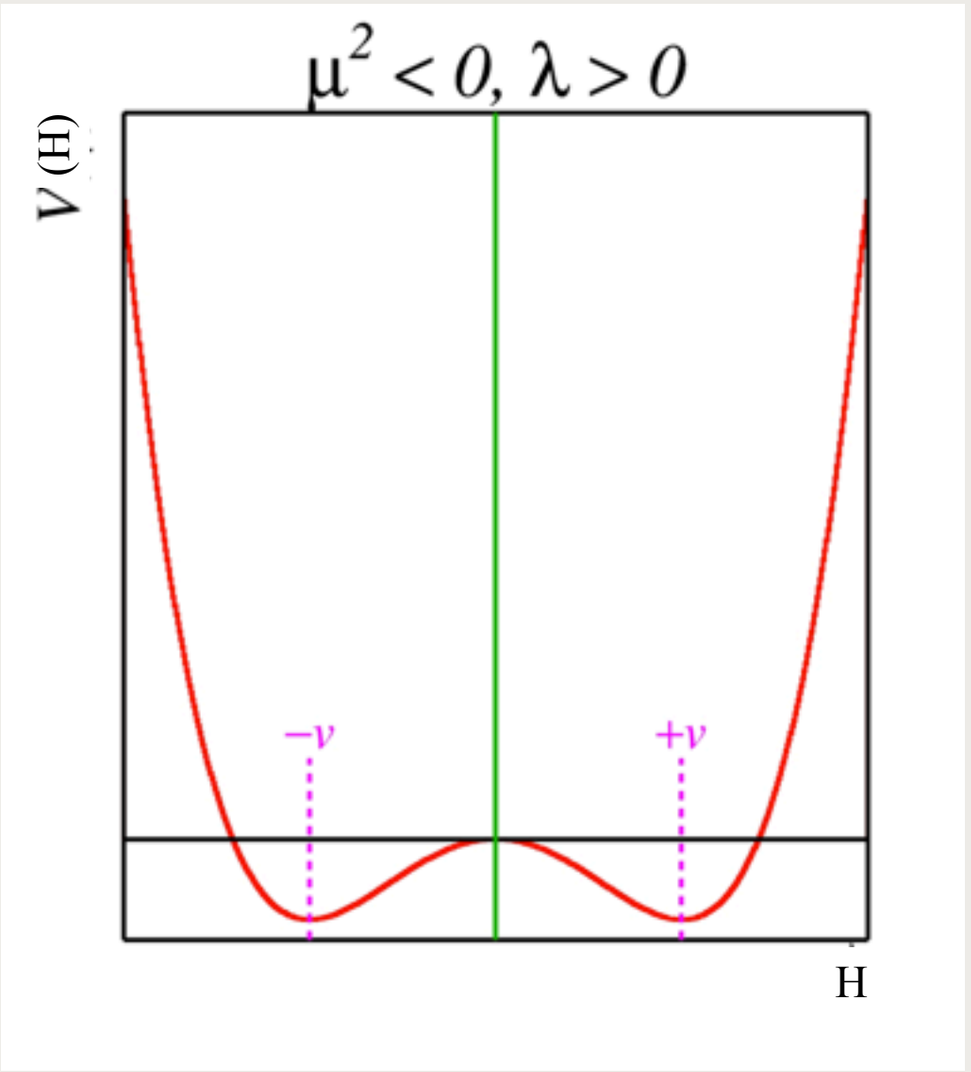

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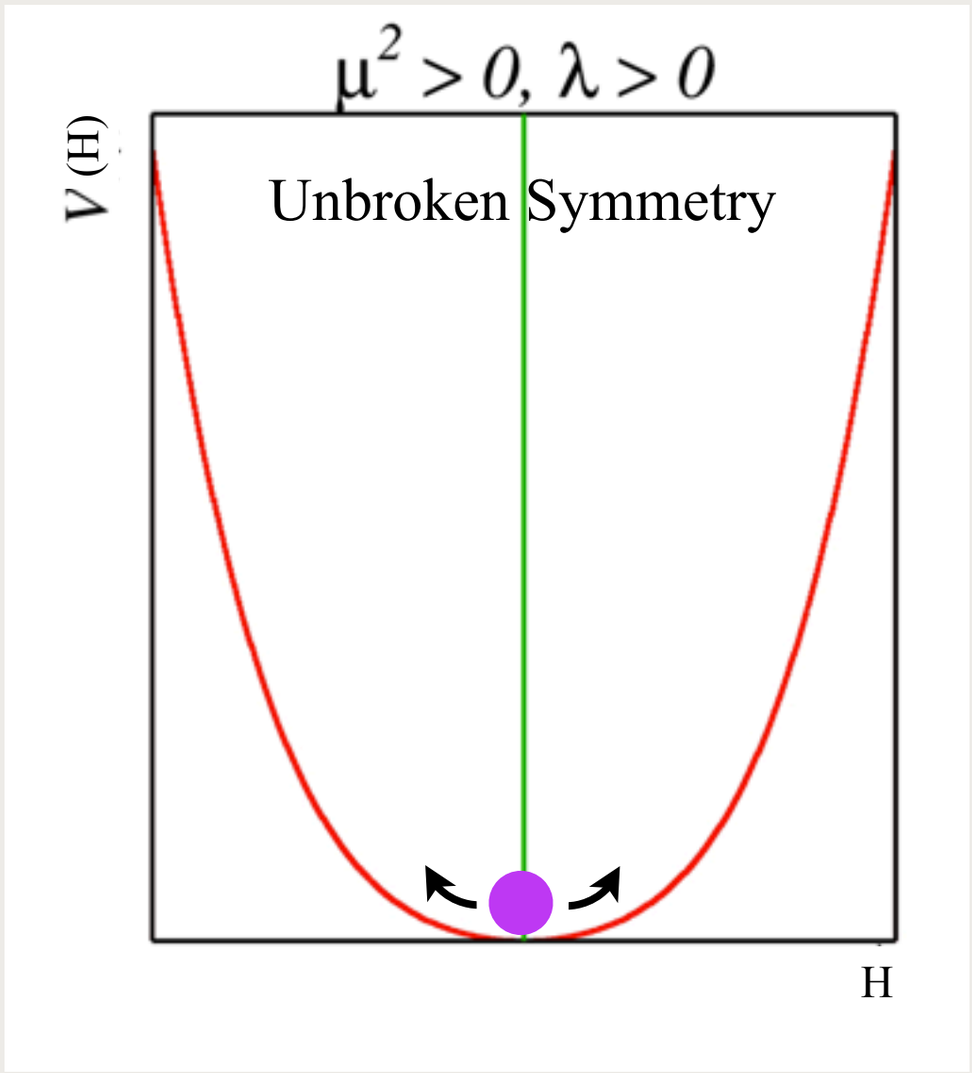
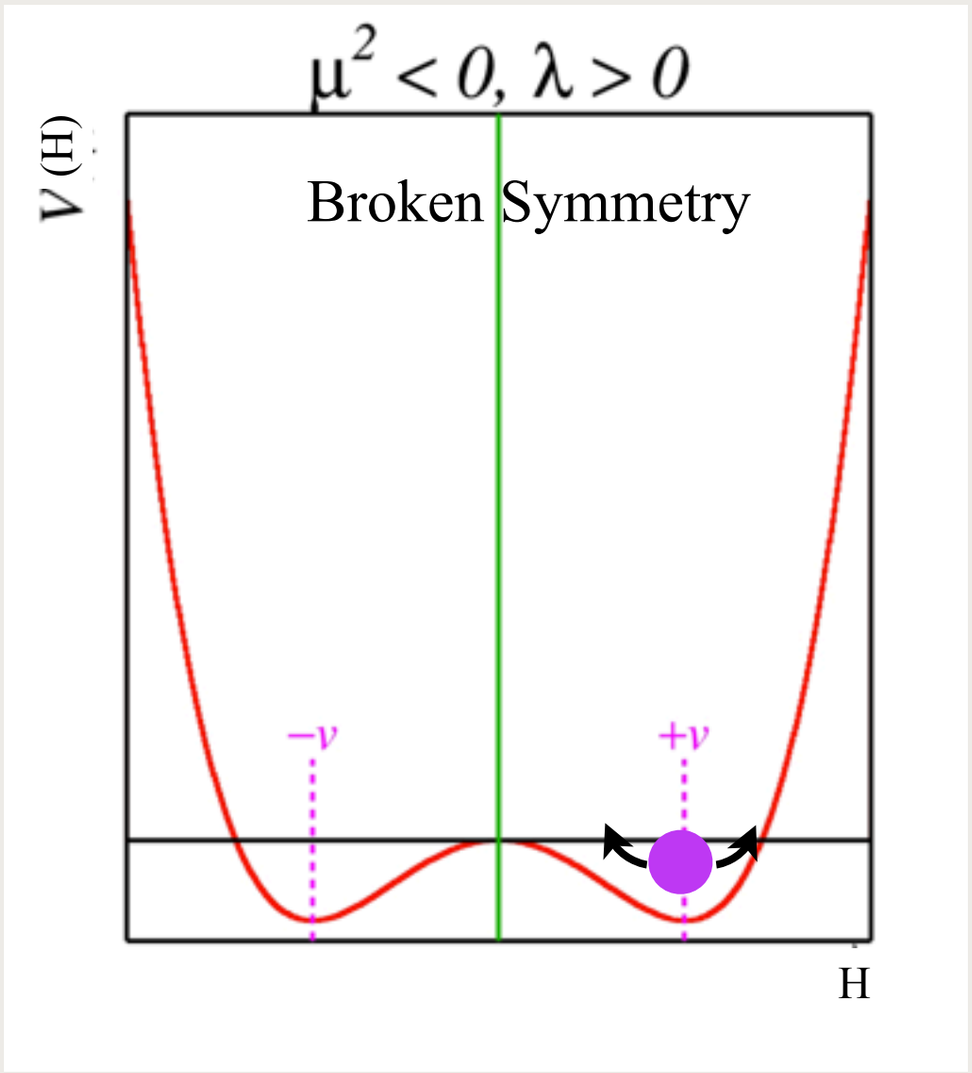
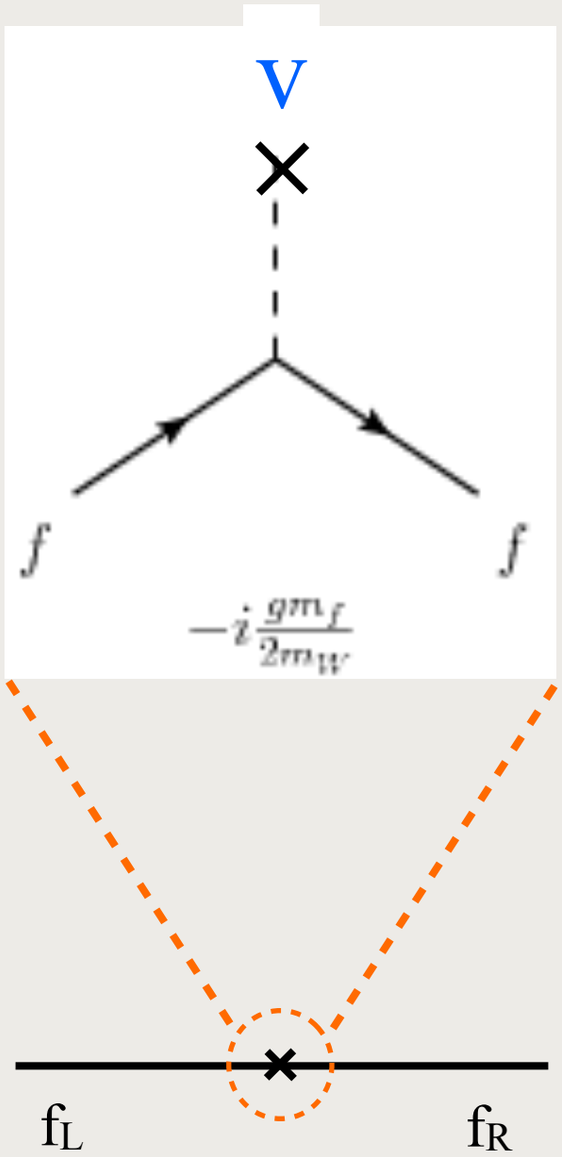
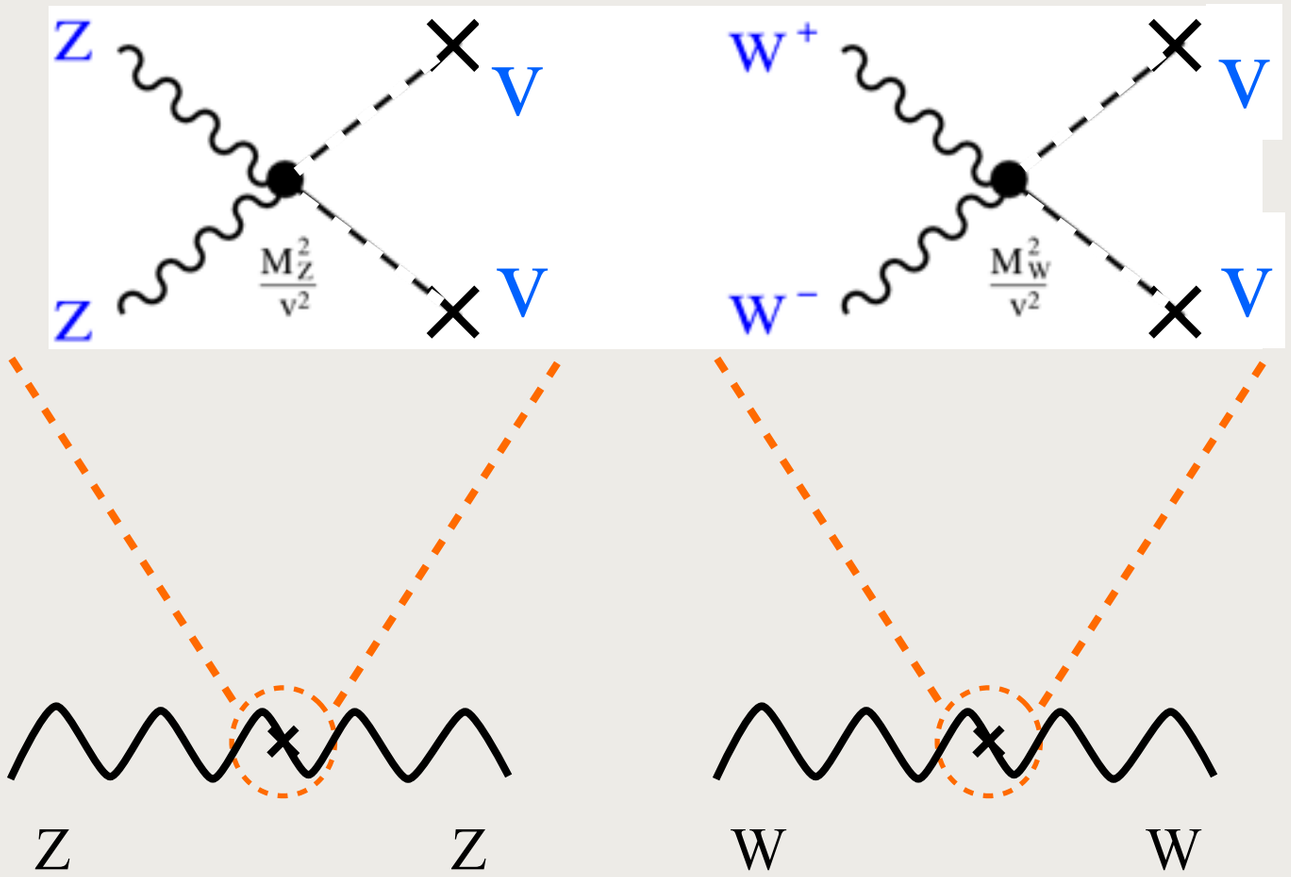




$$H \rightarrow h + v$$

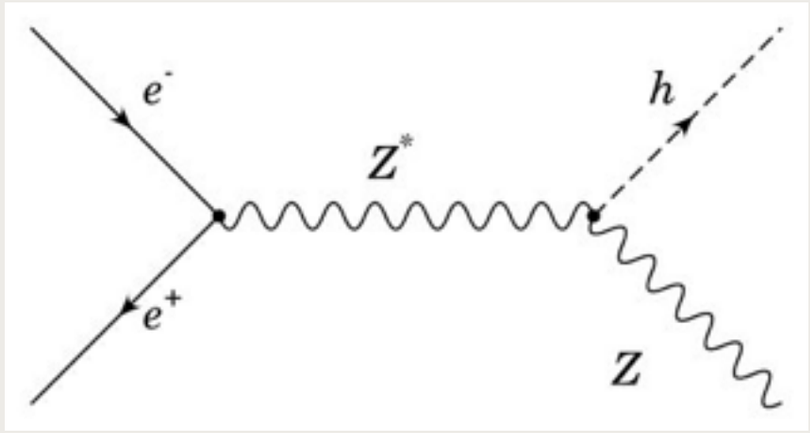
Mass terms





$H \rightarrow h + v$

Previous Searches



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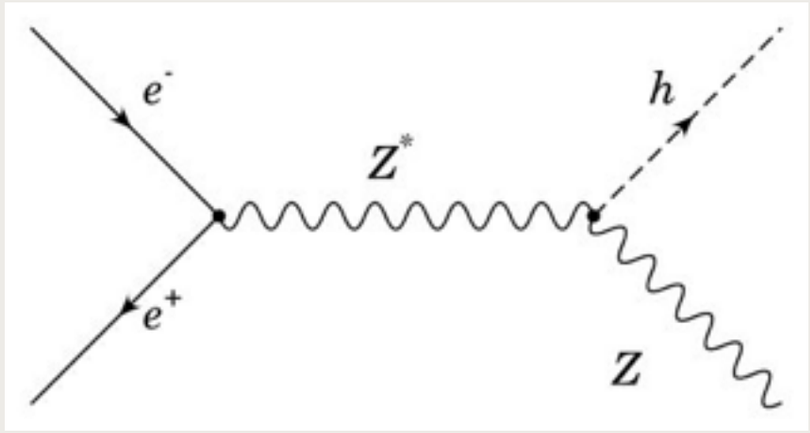
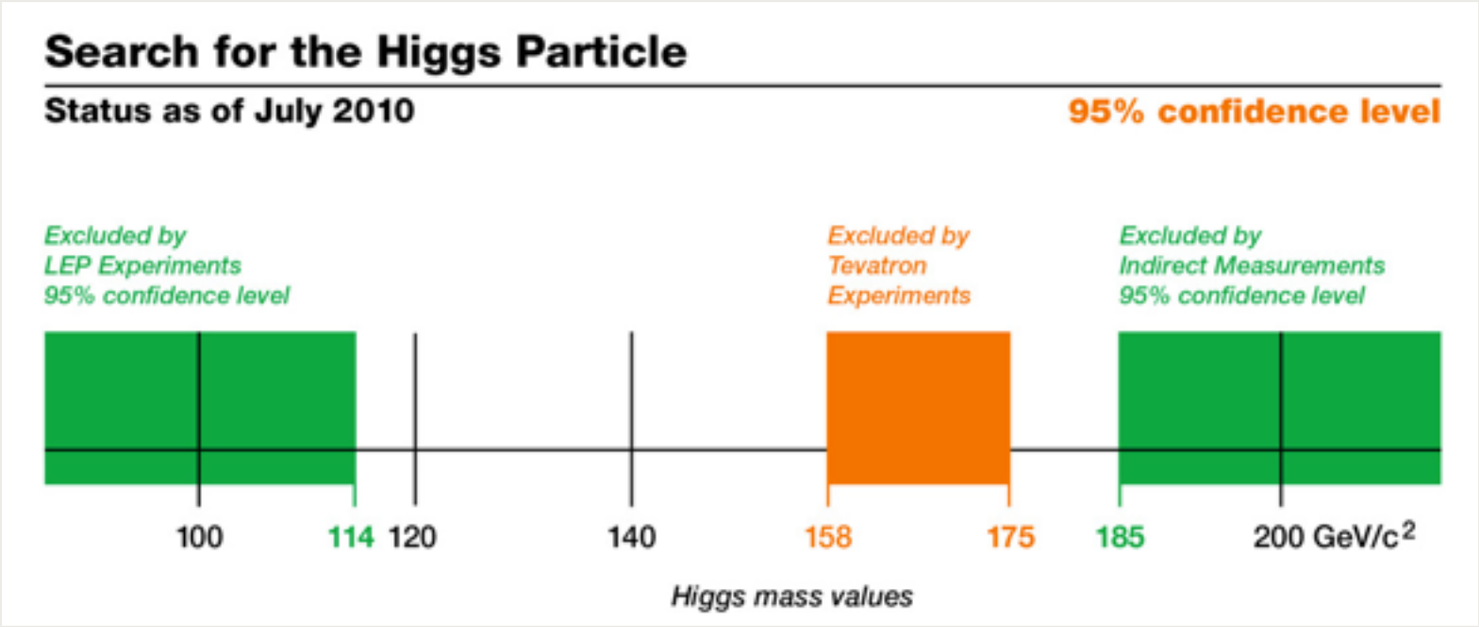
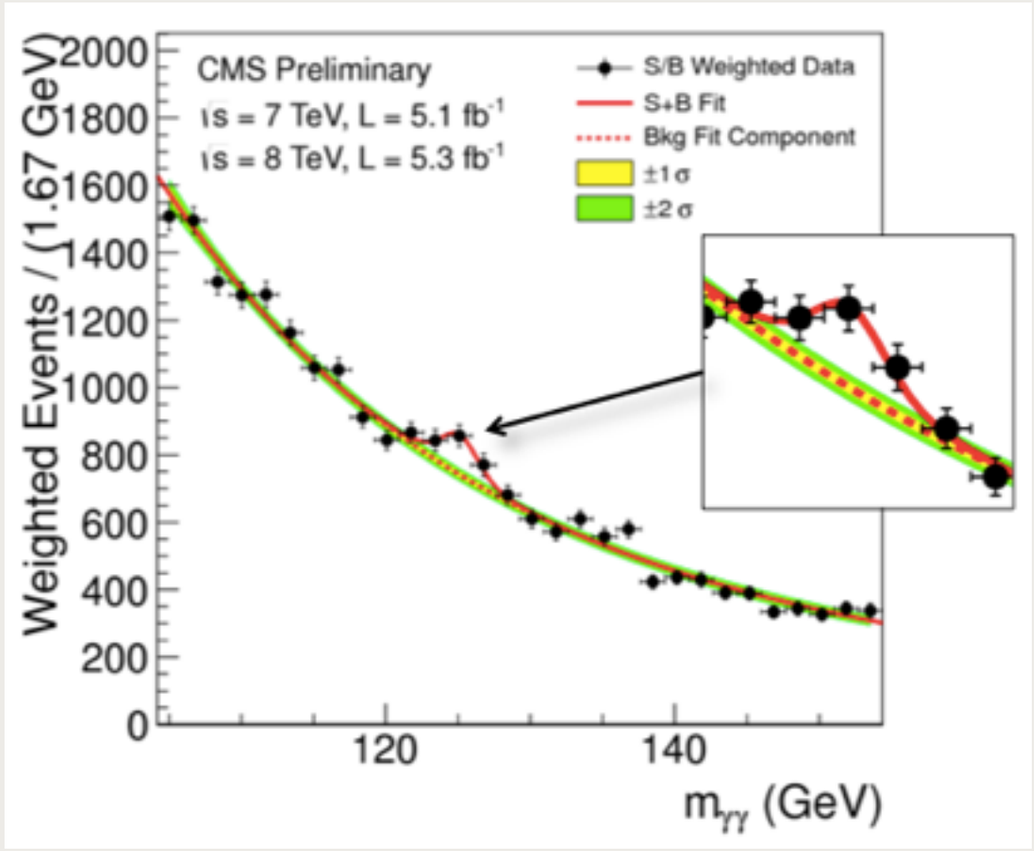
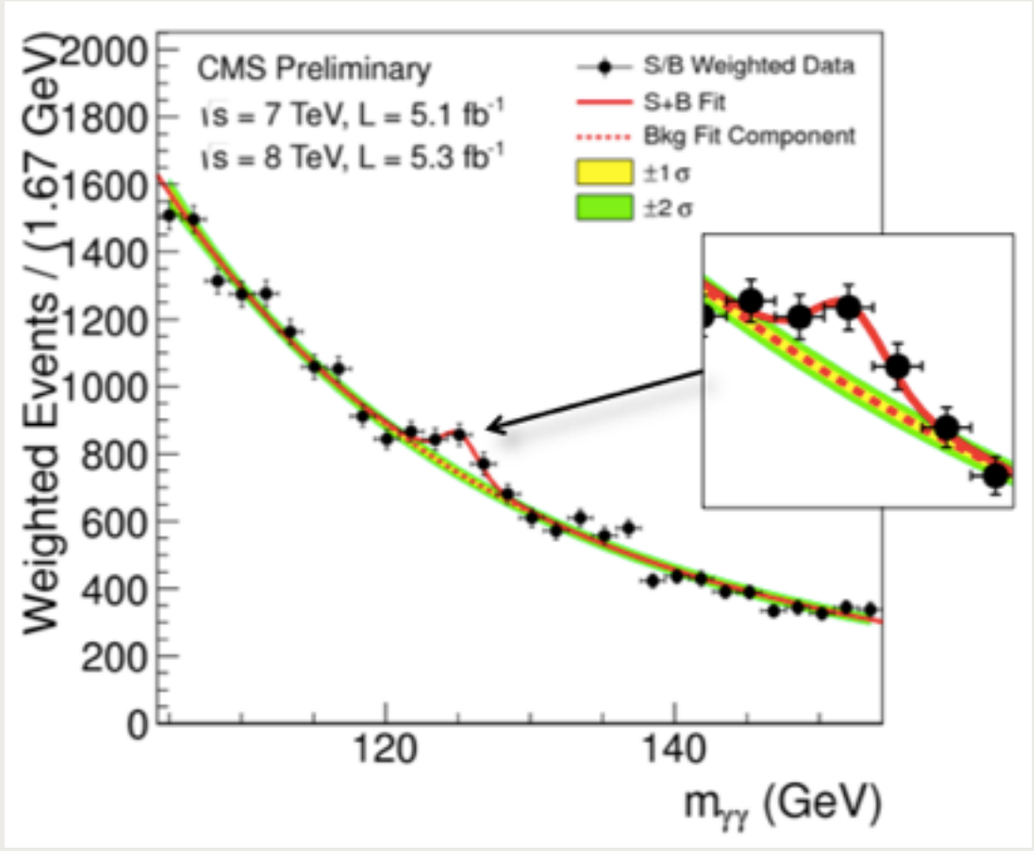
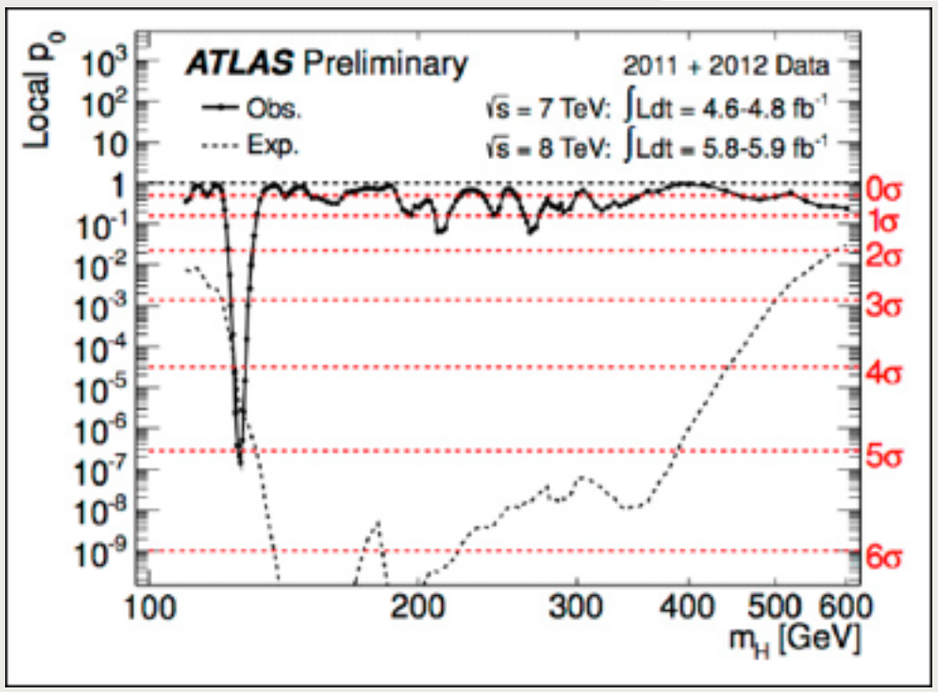


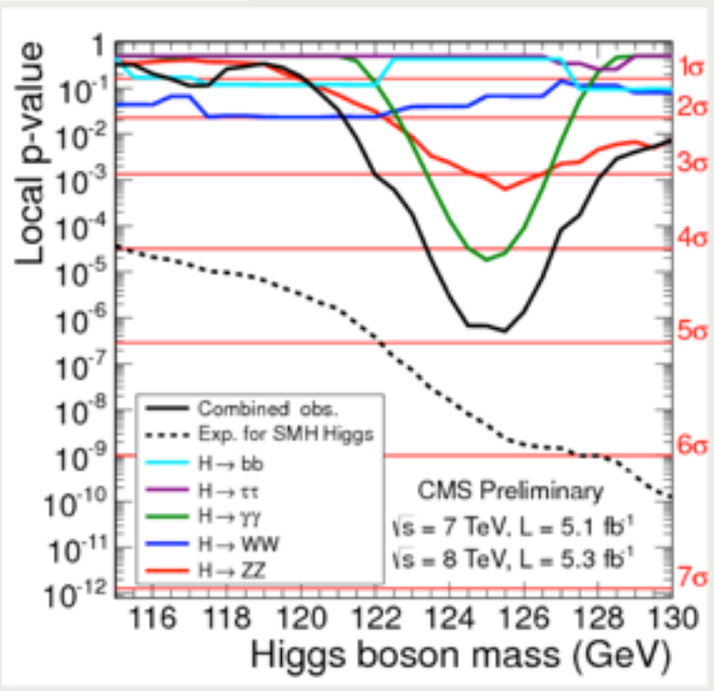



CMS Preliminary
√s = 7 TeV, L = 5.1 fb-1
√s = 8 TeV, L = 5.3 fb-1
S/B Weighted Data
S+B Fit
Bkg Fit Component
±1σ
±2σ
Weighted Events / (1.67 GeV)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
120
140
mγγ (GeV)

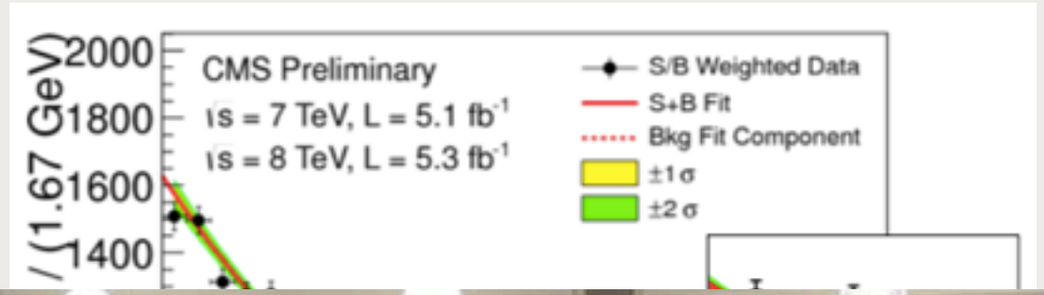
“Discovery”, July 4, 2012

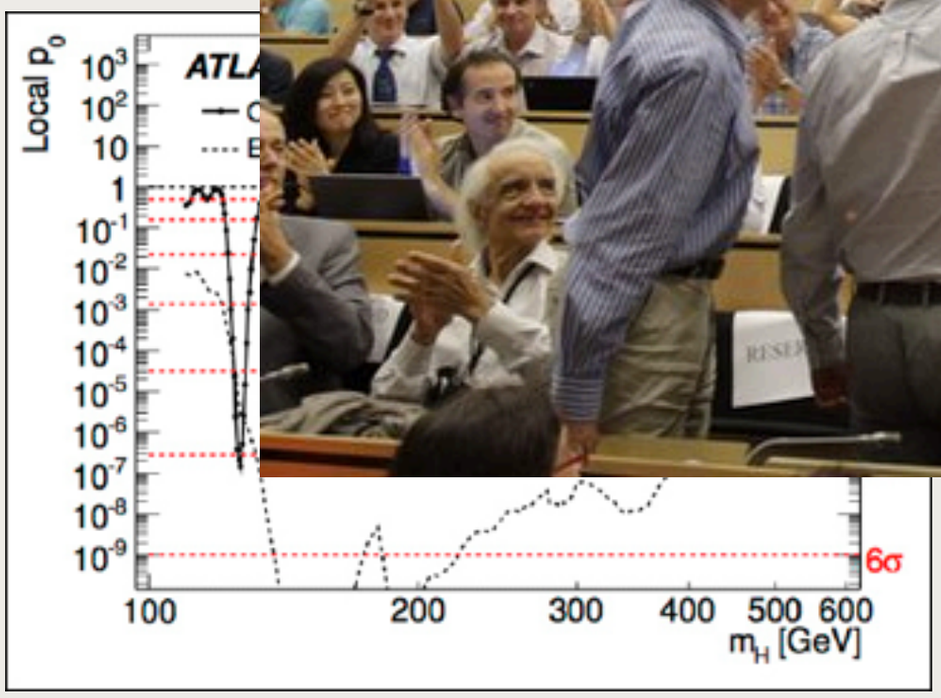




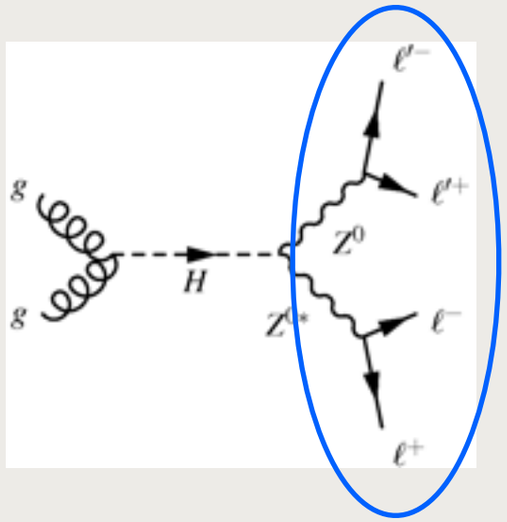


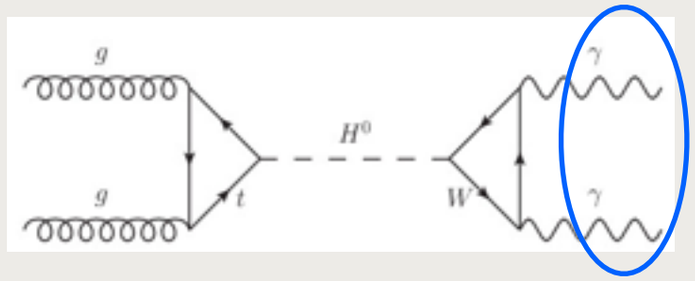
“Discovery”, July 4, 2012

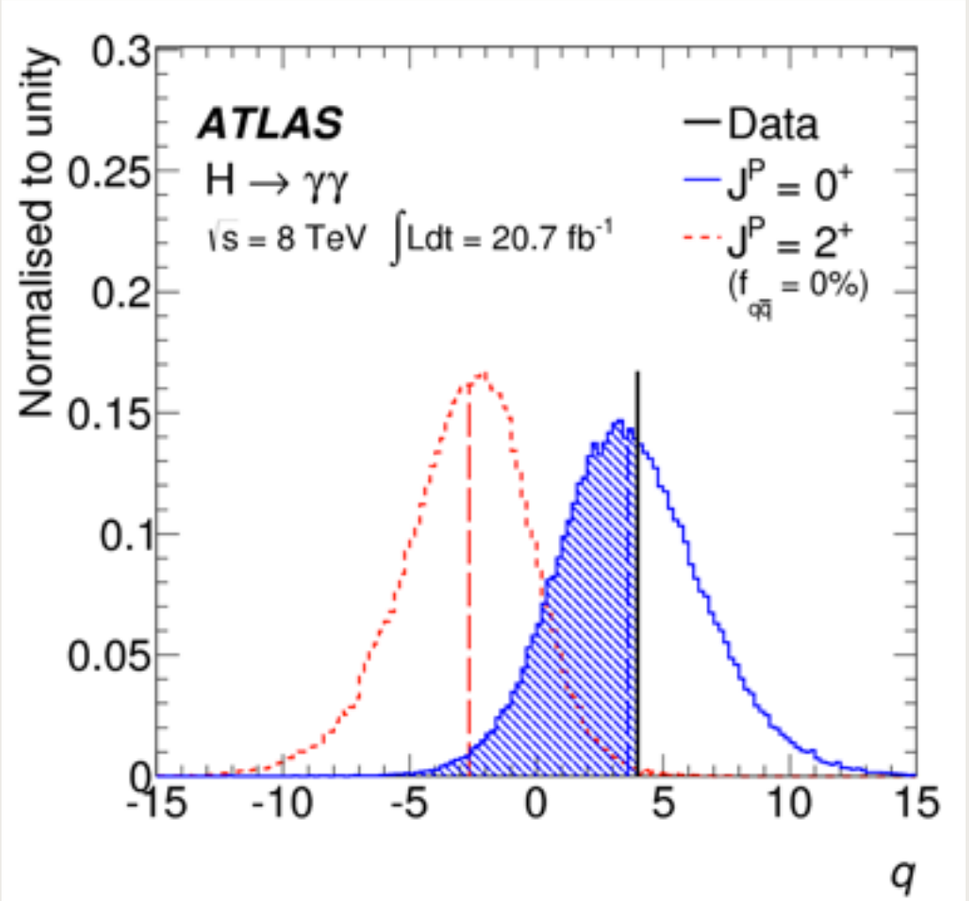




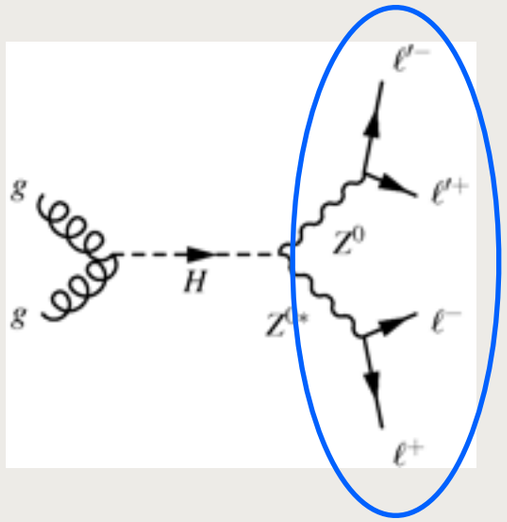
Spin

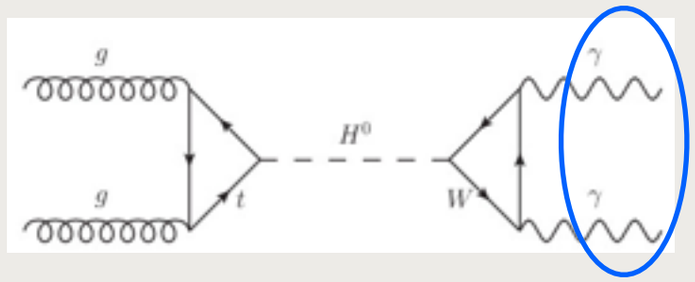

g
g
H
Z⁰
Z*
ℓ'⁻
ℓ'⁺
ℓ⁻
ℓ⁺

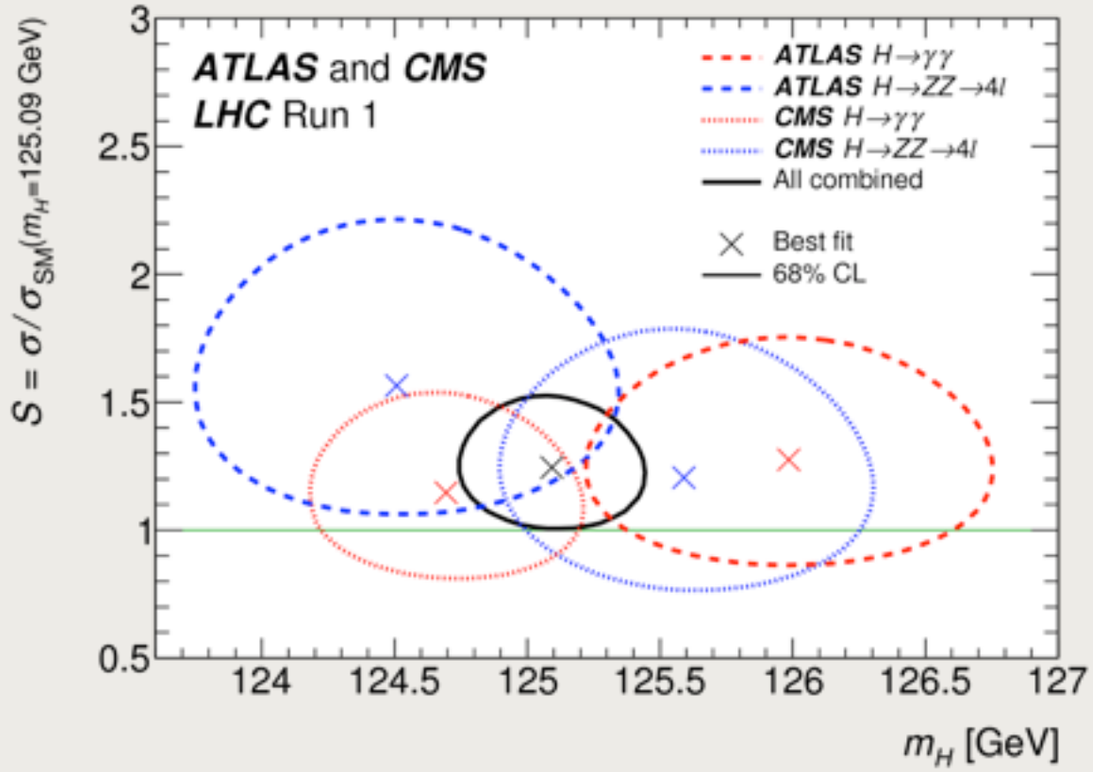

g
g
t
H⁰
W*
γ
γ


Normalised to unity
0.3
0.25
0.2
0.15
0.1
0.05
0
ATLAS
H → γγ
√s = 8 TeV ∫Ldt = 20.7 fb⁻¹
Data
J^P = 0⁺
J^P = 2⁺
(f_qq̄ = 0%)
-15
-10
-5
0
5
10
15
q

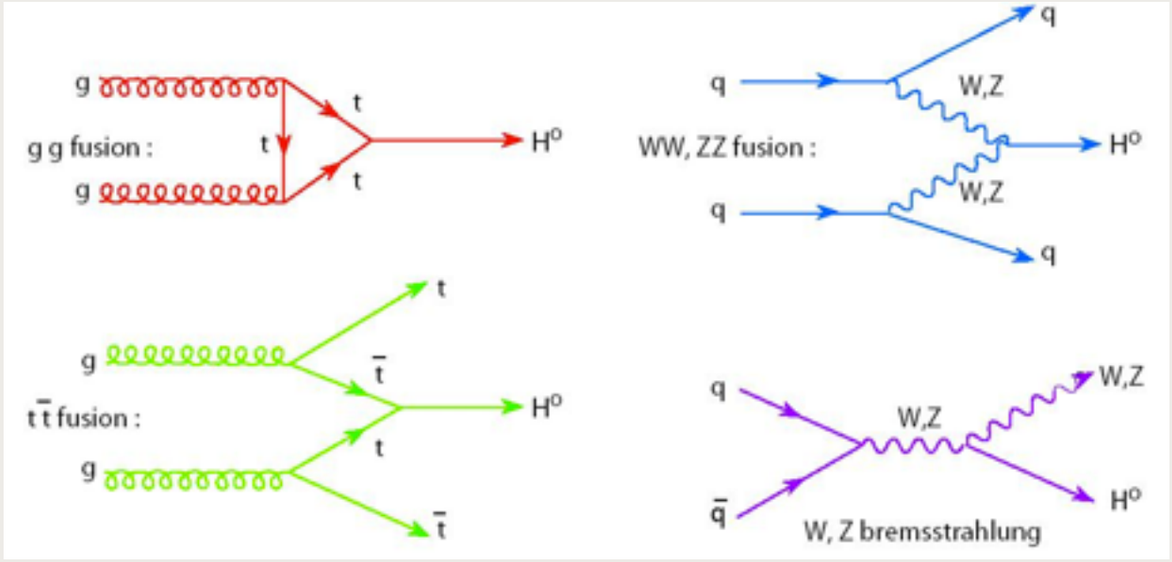
Mass

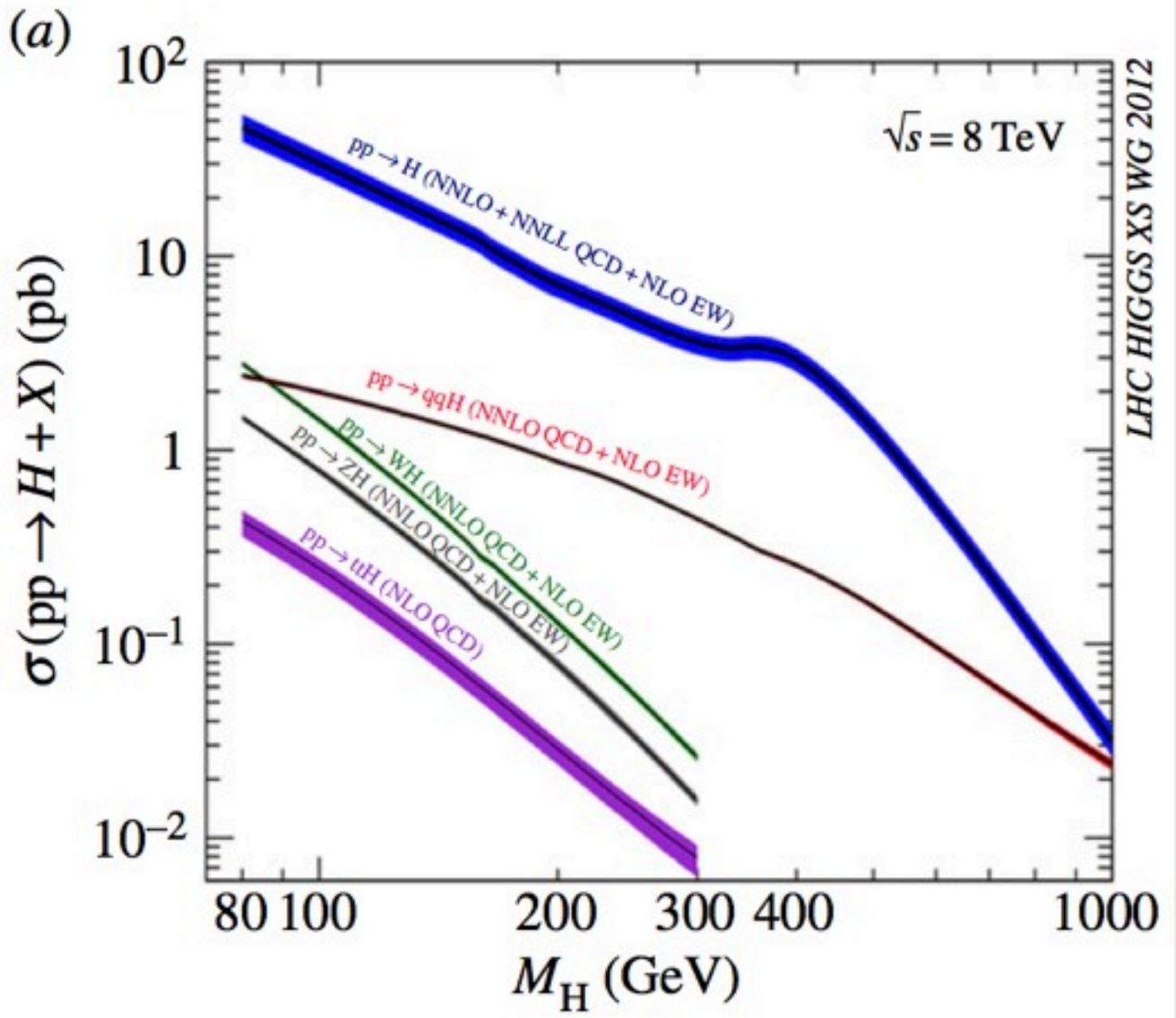

g
g
H
Z⁰
Z*
ℓ⁻
ℓ⁺
ℓ⁻
ℓ⁺


g
g
t
H⁰
W
γ
γ

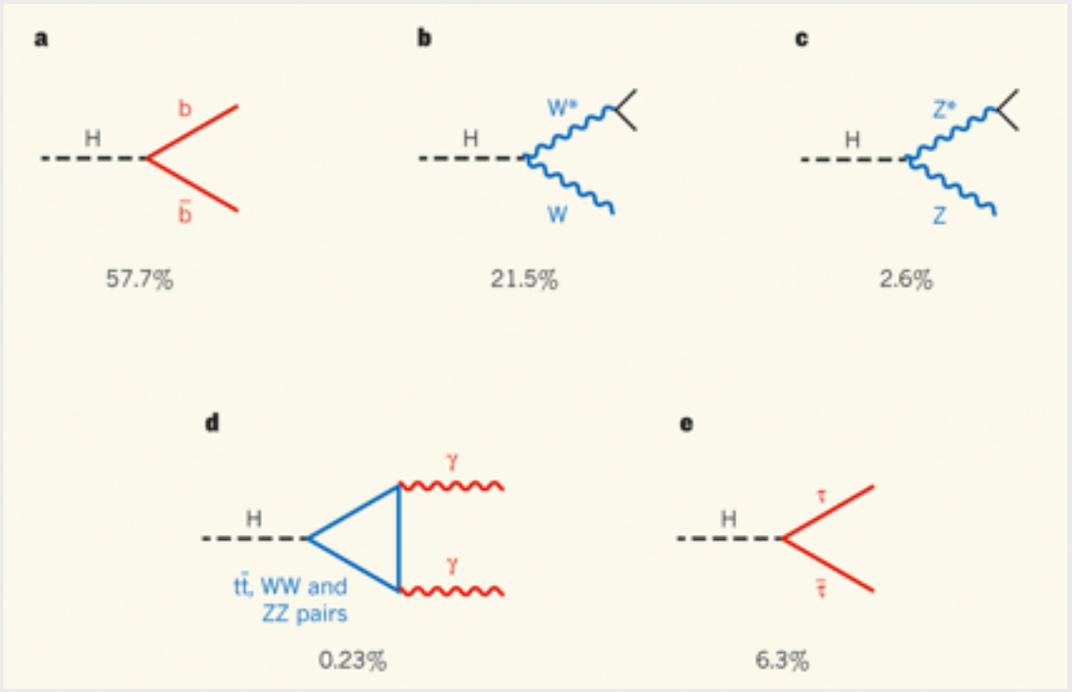

ATLAS and CMS
LHC Run 1
ATLAS H→γγ
ATLAS H→ZZ→4l
CMS H→γγ
CMS H→ZZ→4l
All combined
Best fit
68% CL
S = σ/σSM(mH=125.09 GeV)
mH [GeV]
0.5
1
1.5
2
2.5
3
124
124.5
125
125.5
126
126.5
127

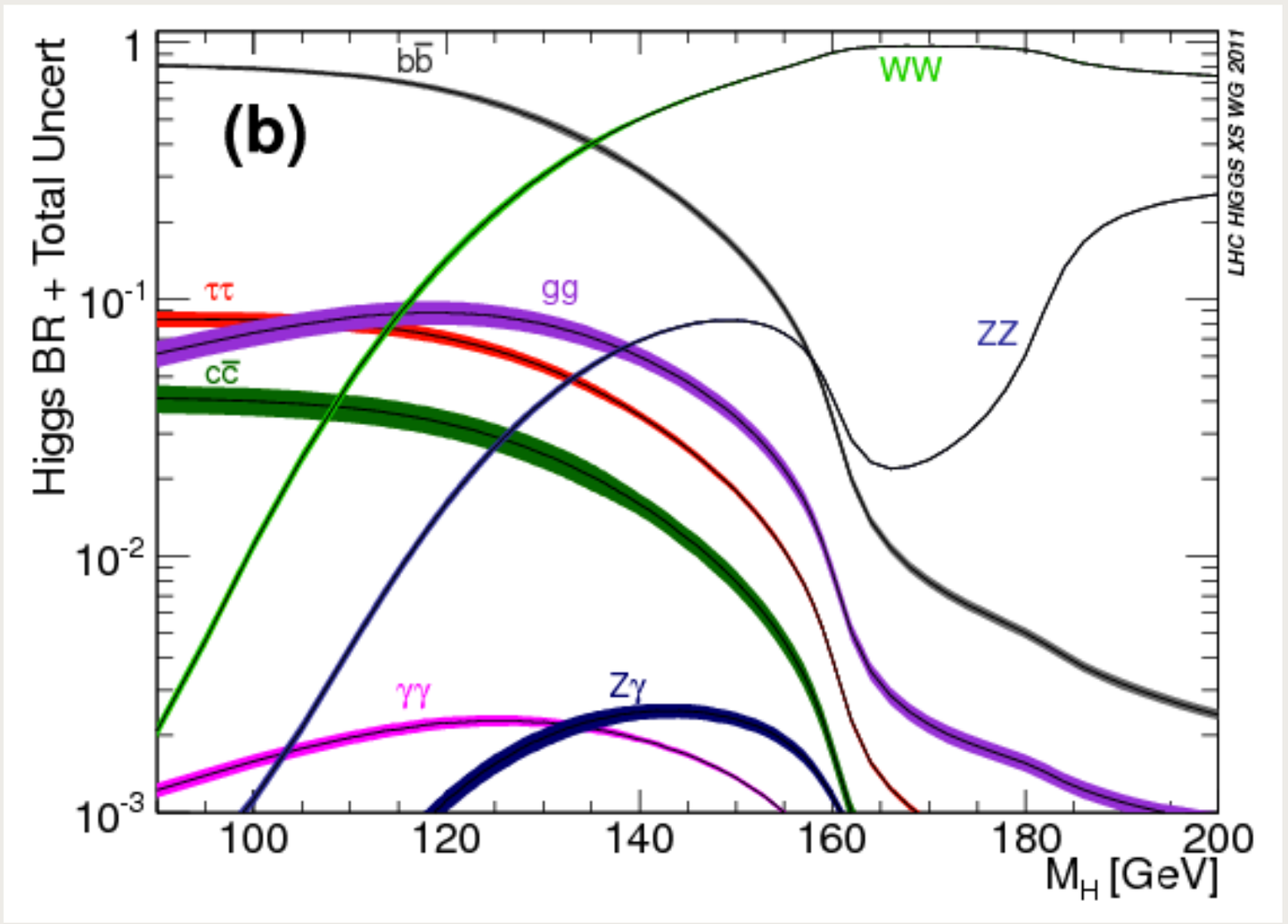
Production


g
g g fusion :
g
t
t
t
H°
q
q
W,Z
WW, ZZ fusion :
W,Z
q
q
H°
g
t t fusion :
g
t
t
t
t
H°
q
q
W,Z
W,Z
H°
W, Z bremsstrahlung

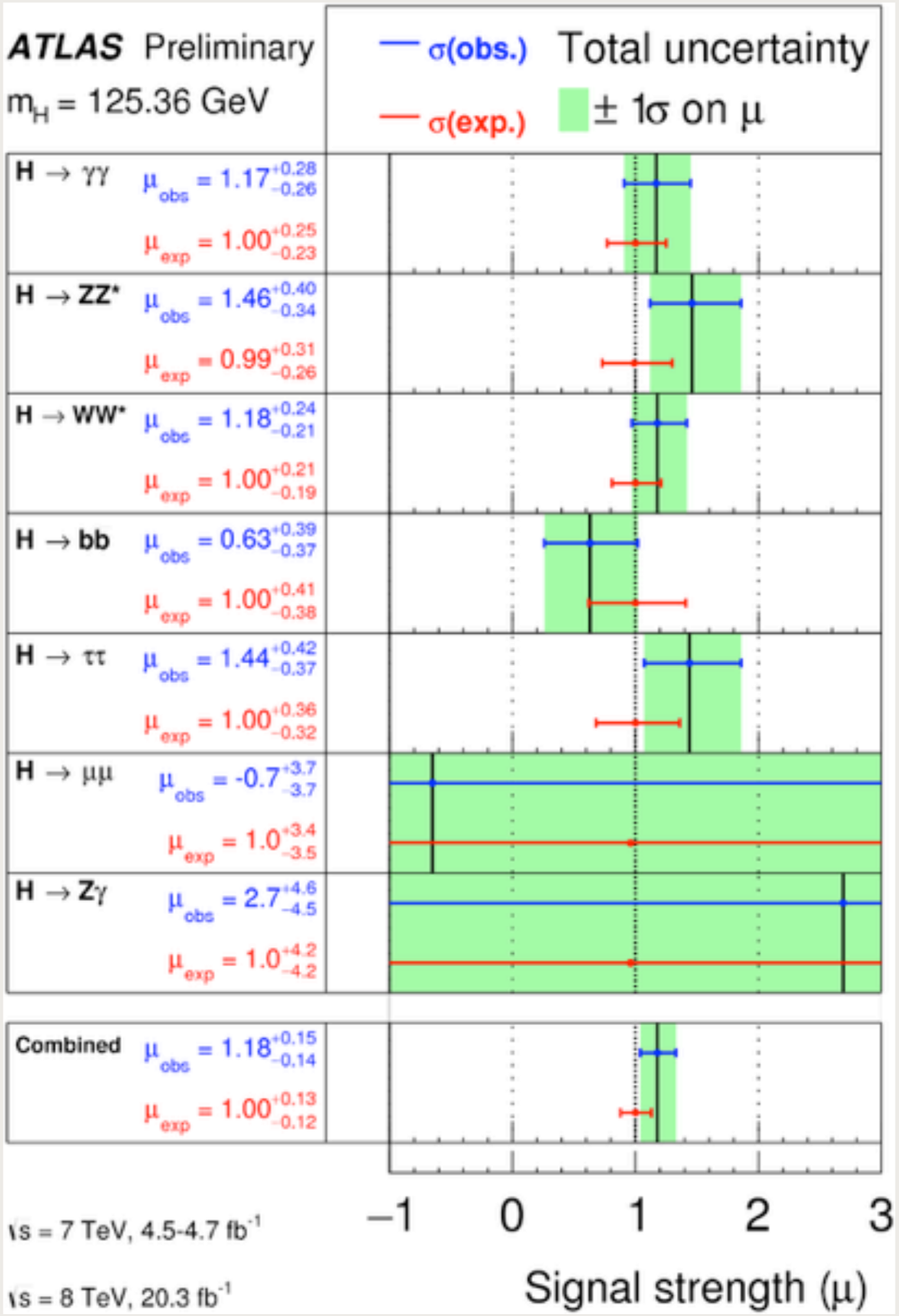

(a)
10^2
10
1
10^{-1}
10^{-2}
$\sqrt{s} = 8$ TeV
$pp \to H$ (NNLO + NNLL QCD + NLO EW)
$pp \to qqH$ (NNLO QCD + NLO EW)
$pp \to WH$ (NNLO QCD + NLO EW)
$pp \to ZH$ (NNLO QCD + NLO EW)
$pp \to ttH$ (NLO QCD)
$\sigma(pp \to H + X)$ (pb)
80 100
200
300 400
1000
M_H (GeV)
LHC HIGGS XS WG 2012

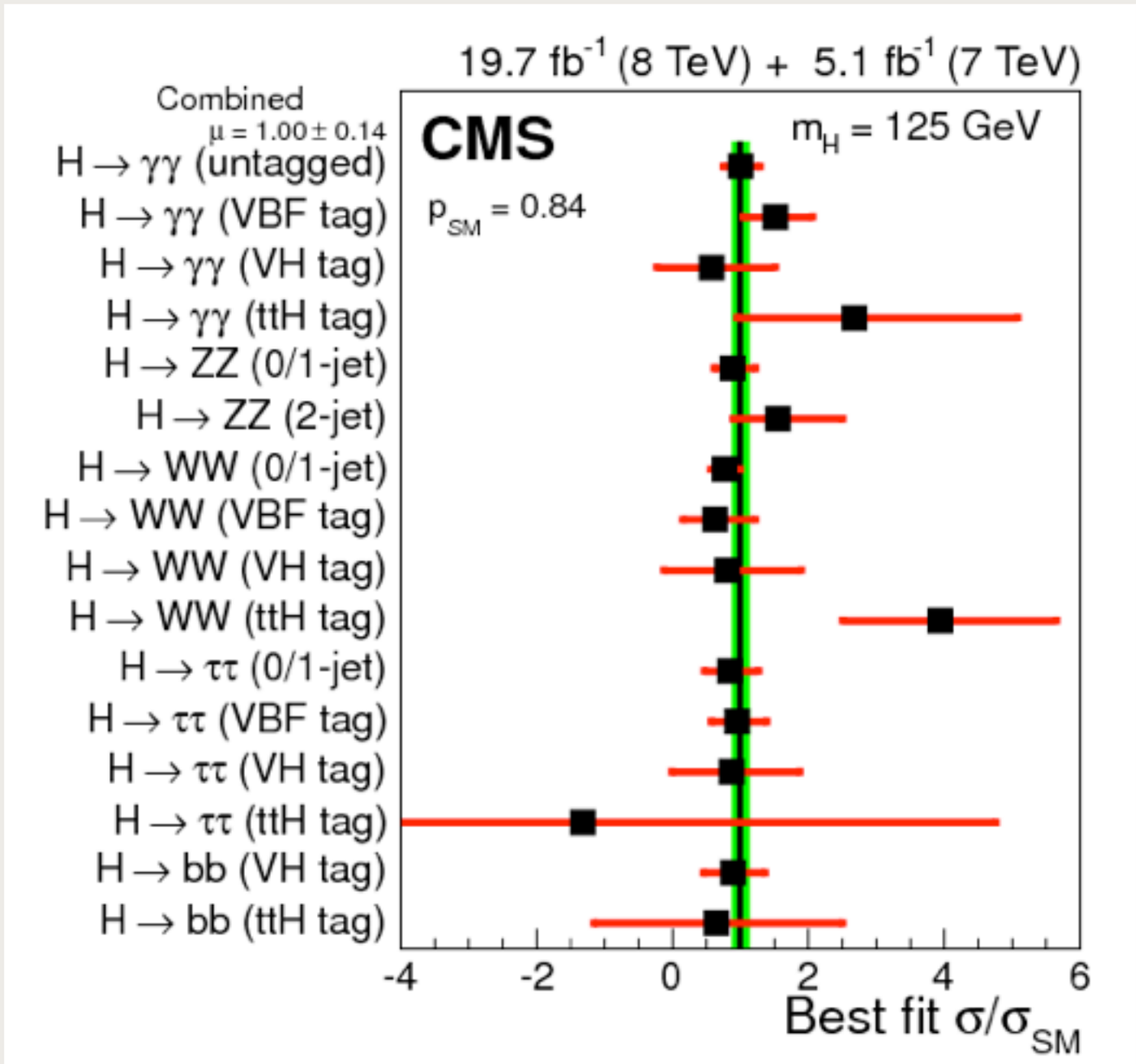
Decays


a
H
b
b̄
57.7%
b
H
W*
W
21.5%
c
H
Z*
Z
2.6%
d
H
γ
γ
tt̄, WW and
ZZ pairs
0.23%
e
H
τ
τ̄
6.3%

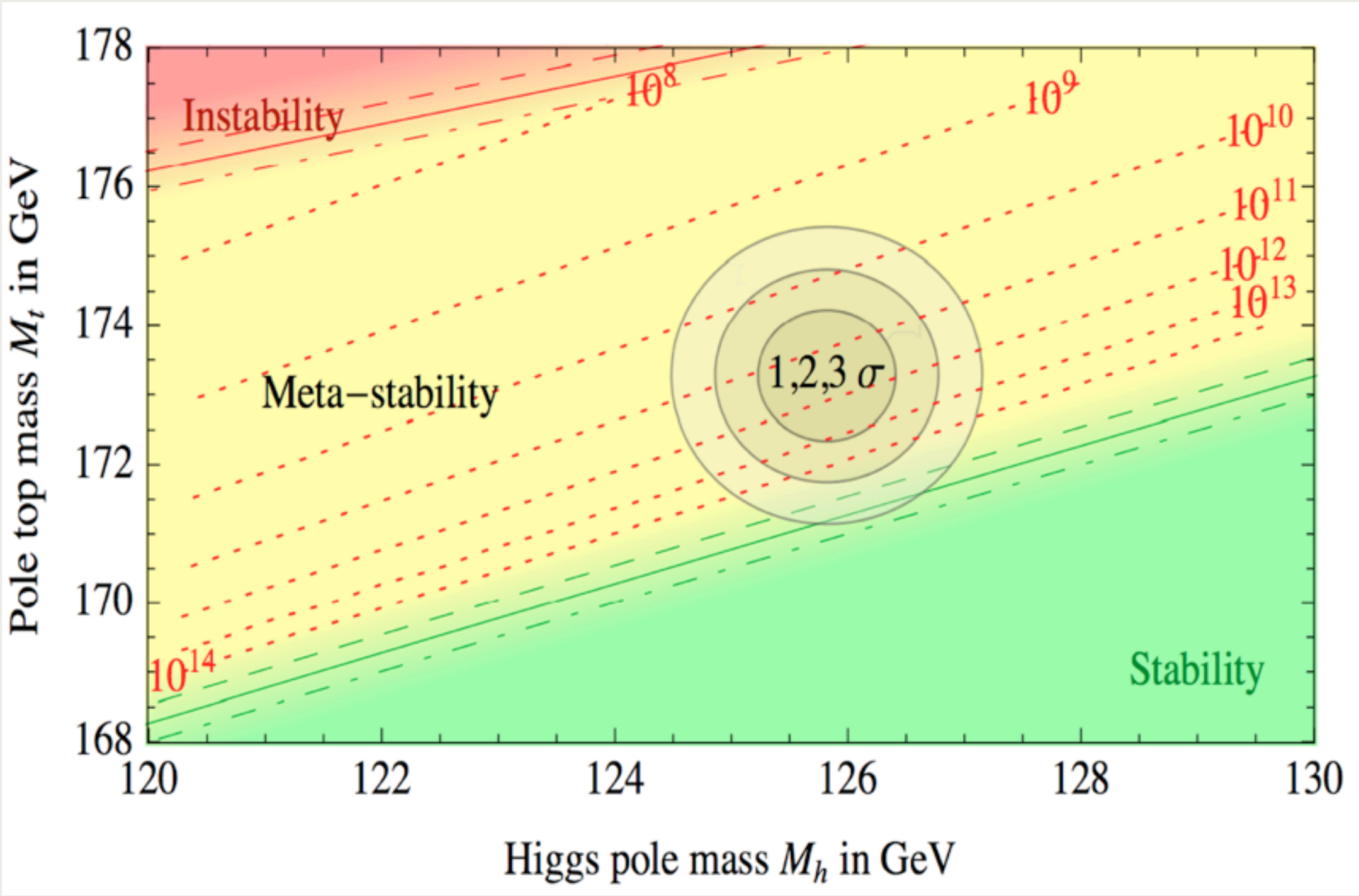

(b)
Higgs BR + Total Uncert
1
10⁻¹
10⁻²
10⁻³
bb̄
WW
ZZ
ττ
gg
cc̄
γγ
Zγ
100
120
140
160
180
200
M_H [GeV]
LHC HIGGS XS WG 2011

Measurements



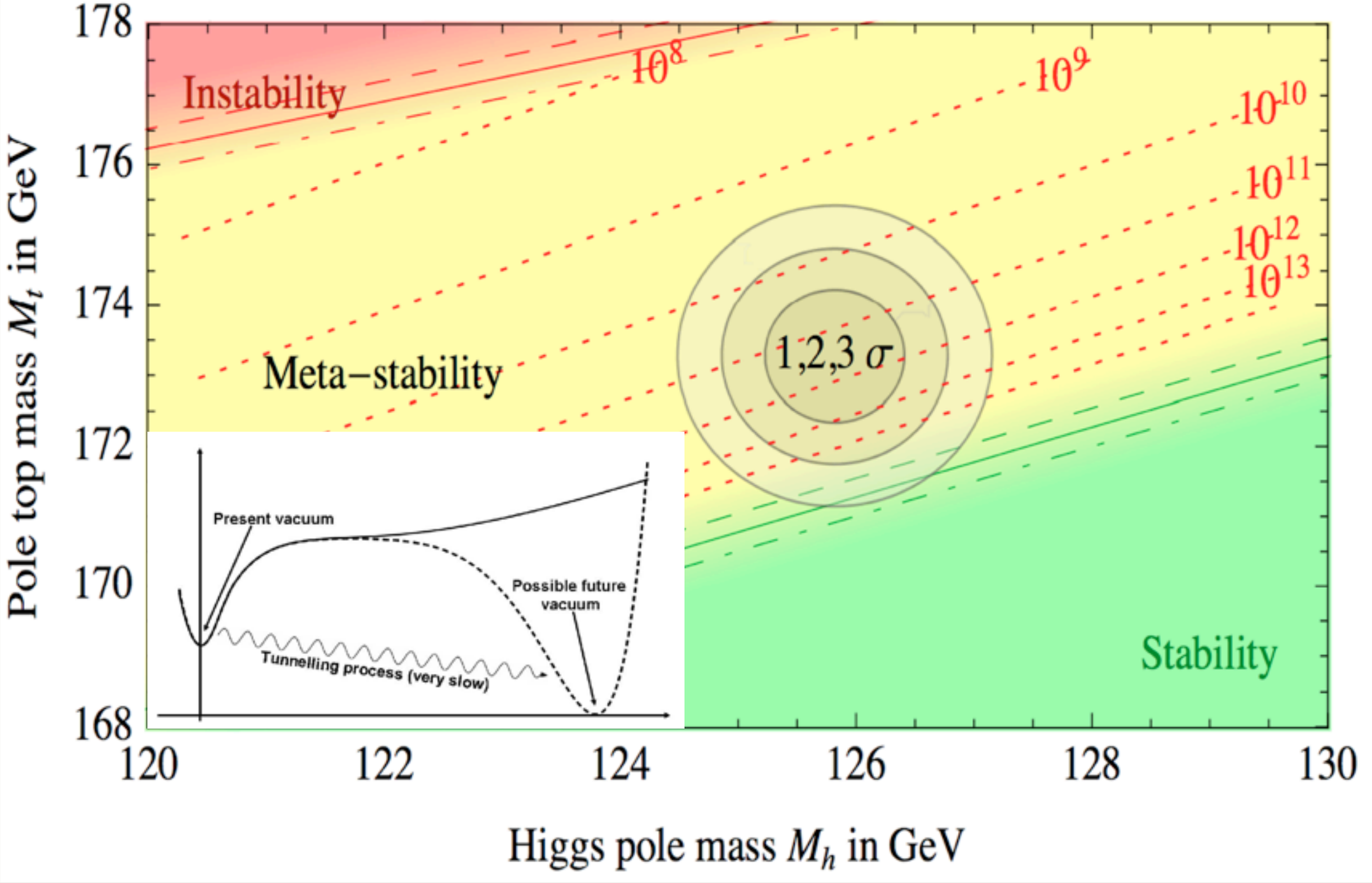


Stability



Degrassi et al. arXiv:1205.6497

Stability



Degrassi et al. arXiv:1205.6497

Fine Tuning/Hierarchy

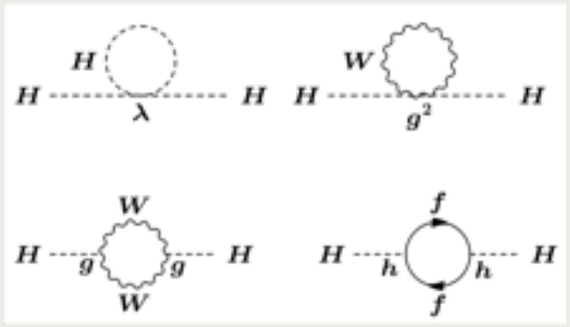
$$m_h^2 = m_0^2 + \delta m^2$$

Bare mass:

H ------- × ------- H

m_0^2

1 loop correction:



$$\delta m^2 = \frac{3}{64\pi^2}(3g^2 + g'^2 + 8\lambda - 8\lambda_t^2)\Lambda^2$$

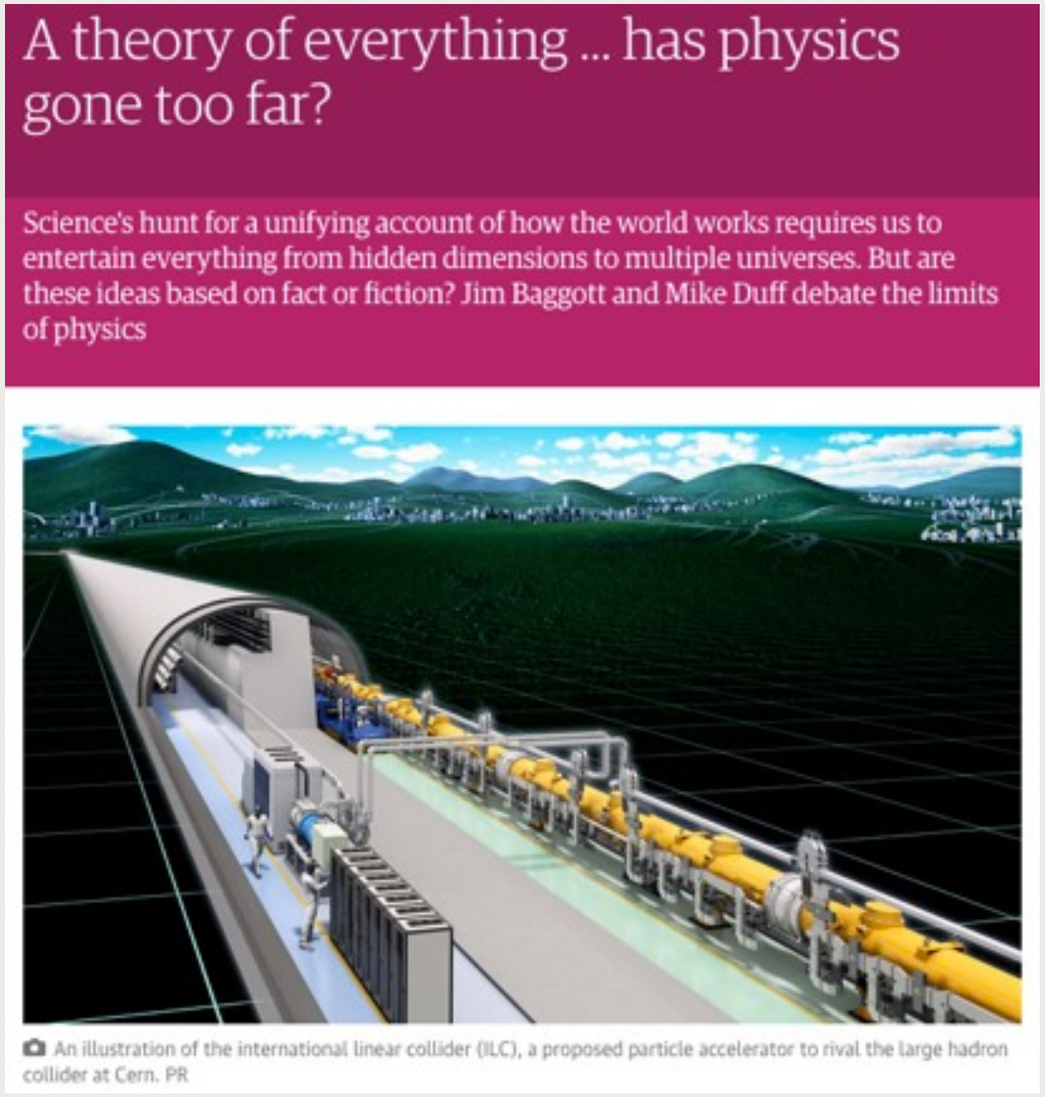
Λ = Scale of New Physics (Gravity?)

$\Lambda >> m_h \rightarrow$ Hierarchy Problem

Solutions

- Introduce new particles, new symmetries

- Possibilities:
  - Little Higgs
  - Supersymmetry
  - Extra Dimensions
  - *many more*



A theory of everything ... has physics gone too far?

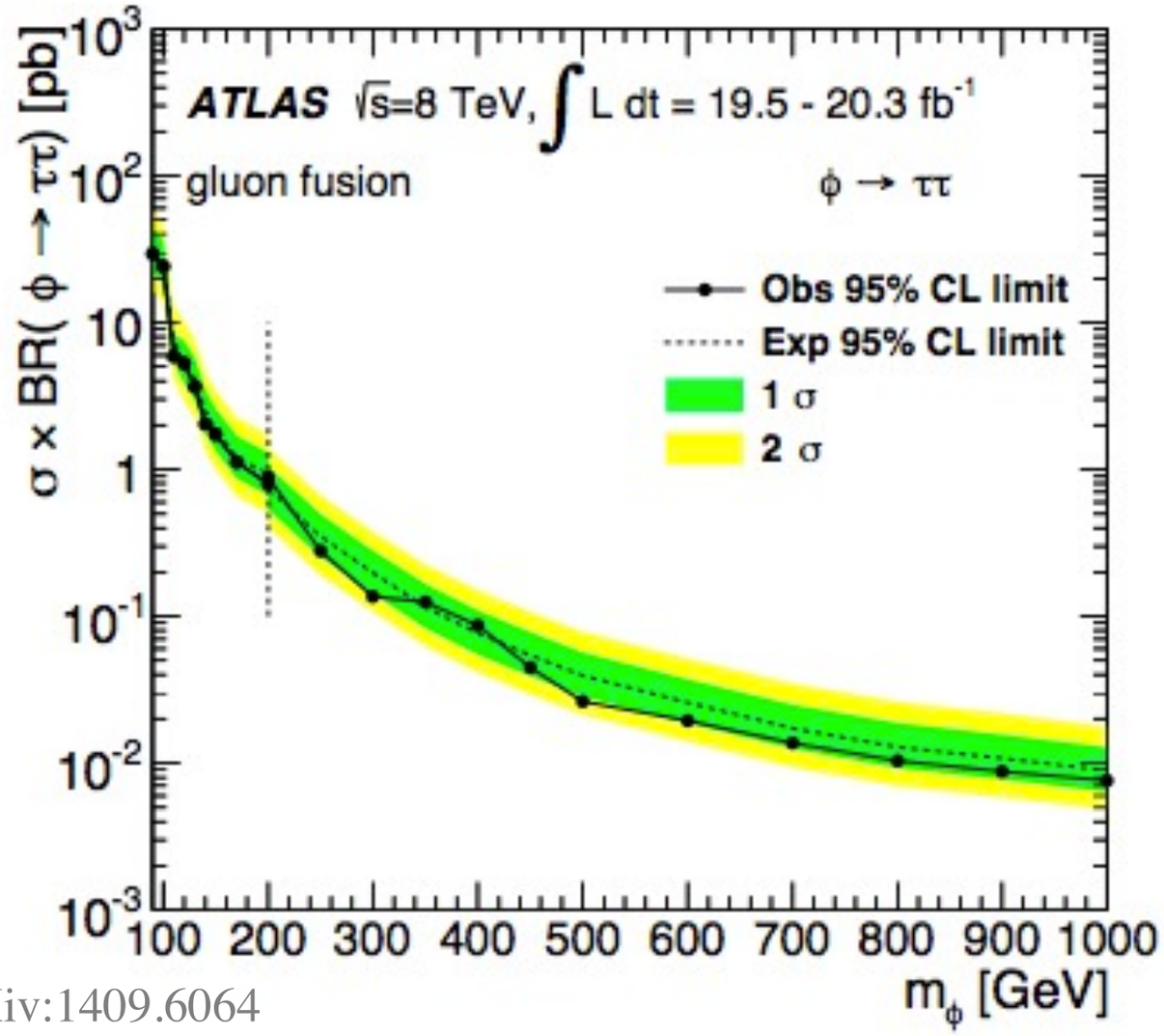
Science's hunt for a unifying account of how the world works requires us to entertain everything from hidden dimensions to multiple universes. But are these ideas based on fact or fiction? Jim Baggott and Mike Duff debate the limits of physics

An illustration of the international linear collider (ILC), a proposed particle accelerator to rival the large hadron collider at Cern. PR

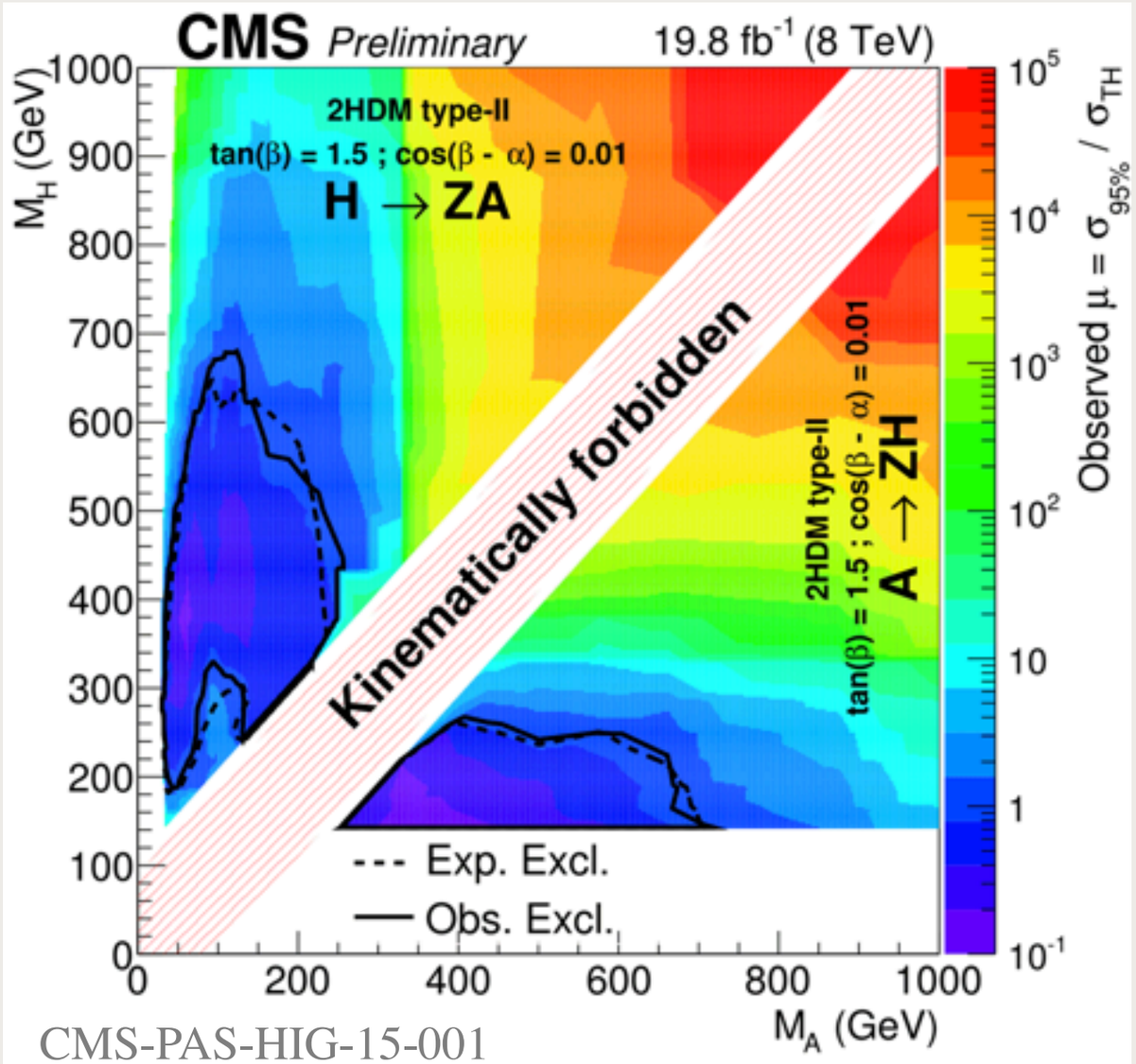
http://www.theguardian.com/science/2013/jun/16/has-physics-gone-too-far

Two-Higgs Doublets

- 2HDM: H_1 for up-type, H_2 for down-type
- Search for heavy Higgs bosons (h, H, A, $H^{\pm}$)



arXiv:1409.6064

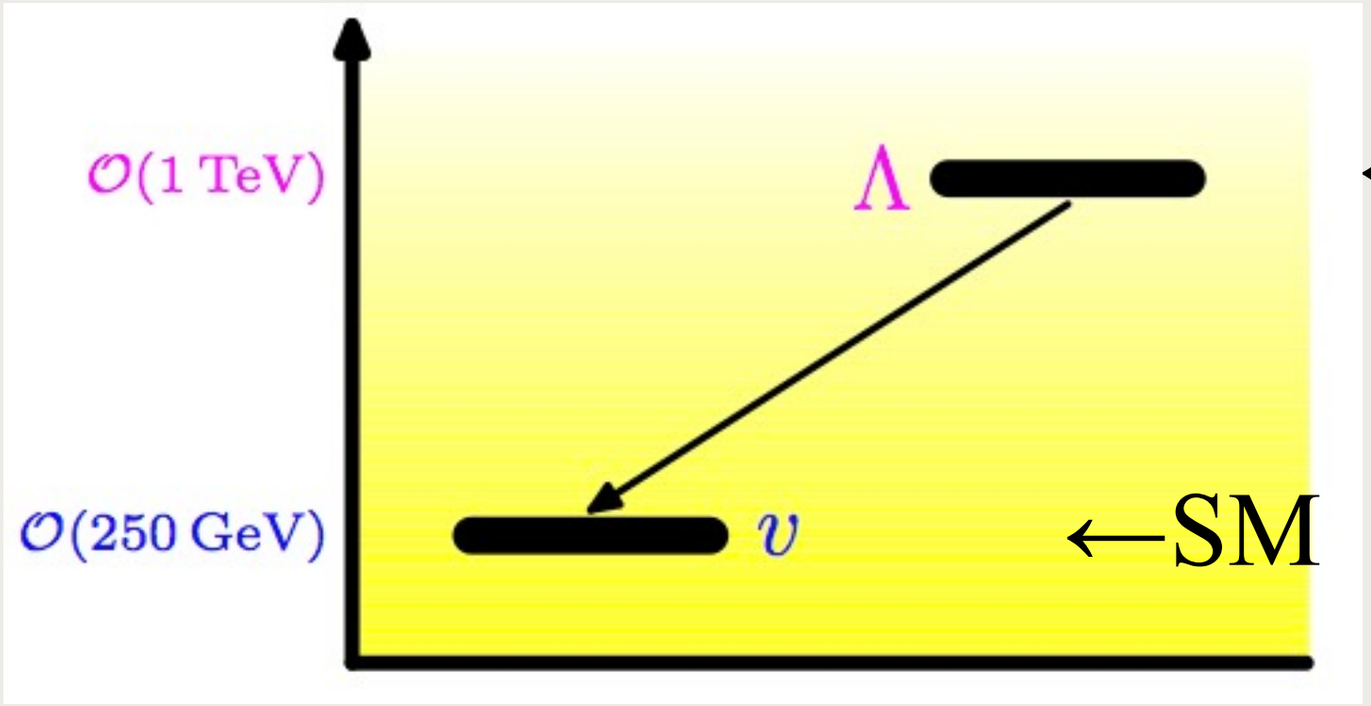


CMS-PAS-HIG-15-001

Little Higgs

- New gauge symmetries, vector-like particles

- Collective cancellation of Higgs divergence



←BSM

←SM

Λ = scale of new physics
f = vev of BSM model
$\Lambda \sim 4\pi$ f

Bestest Little Higgs

SO(6)xSO(6)

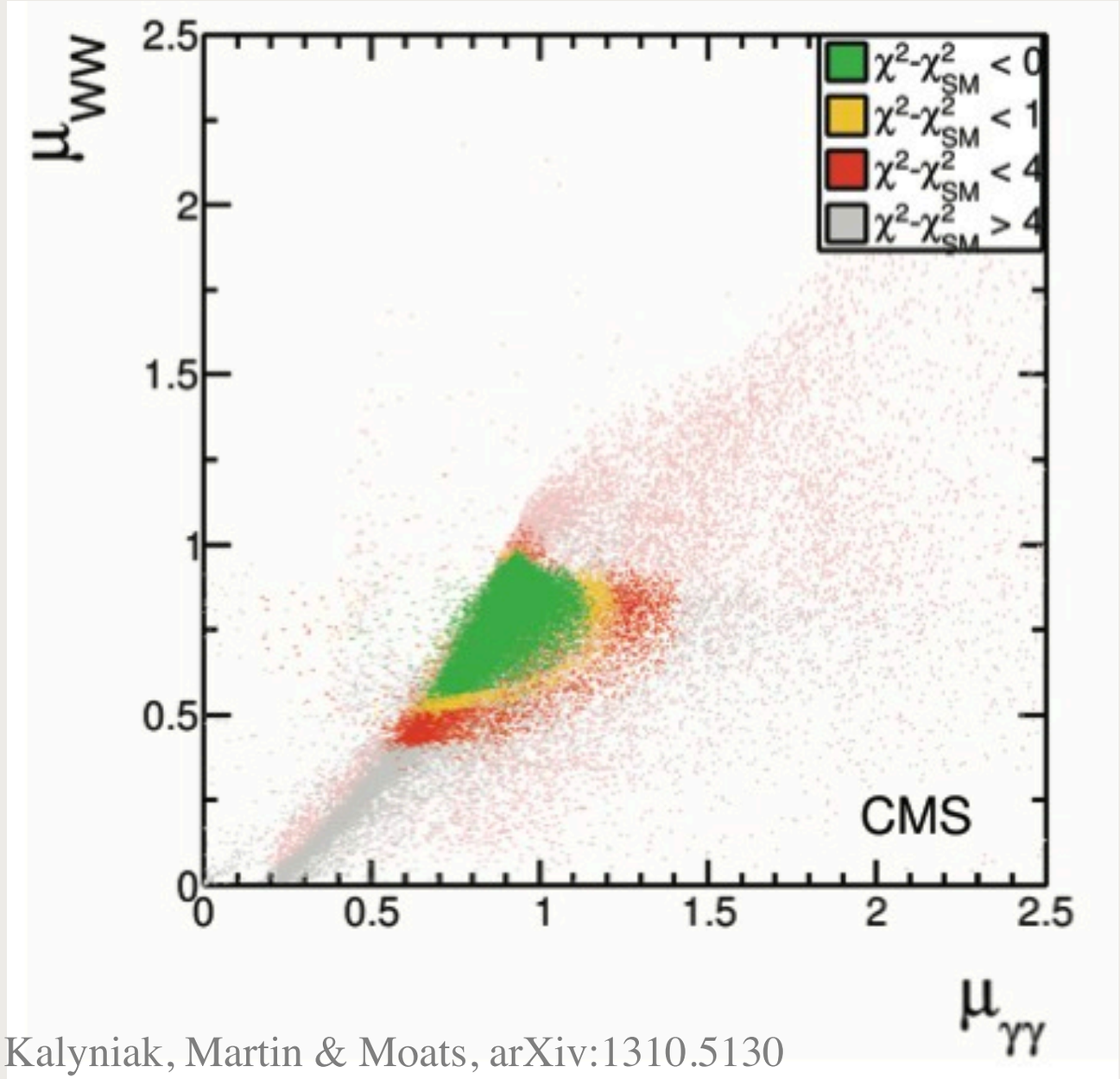
New:

6 fermions

3 gauge bosons

20 scalars

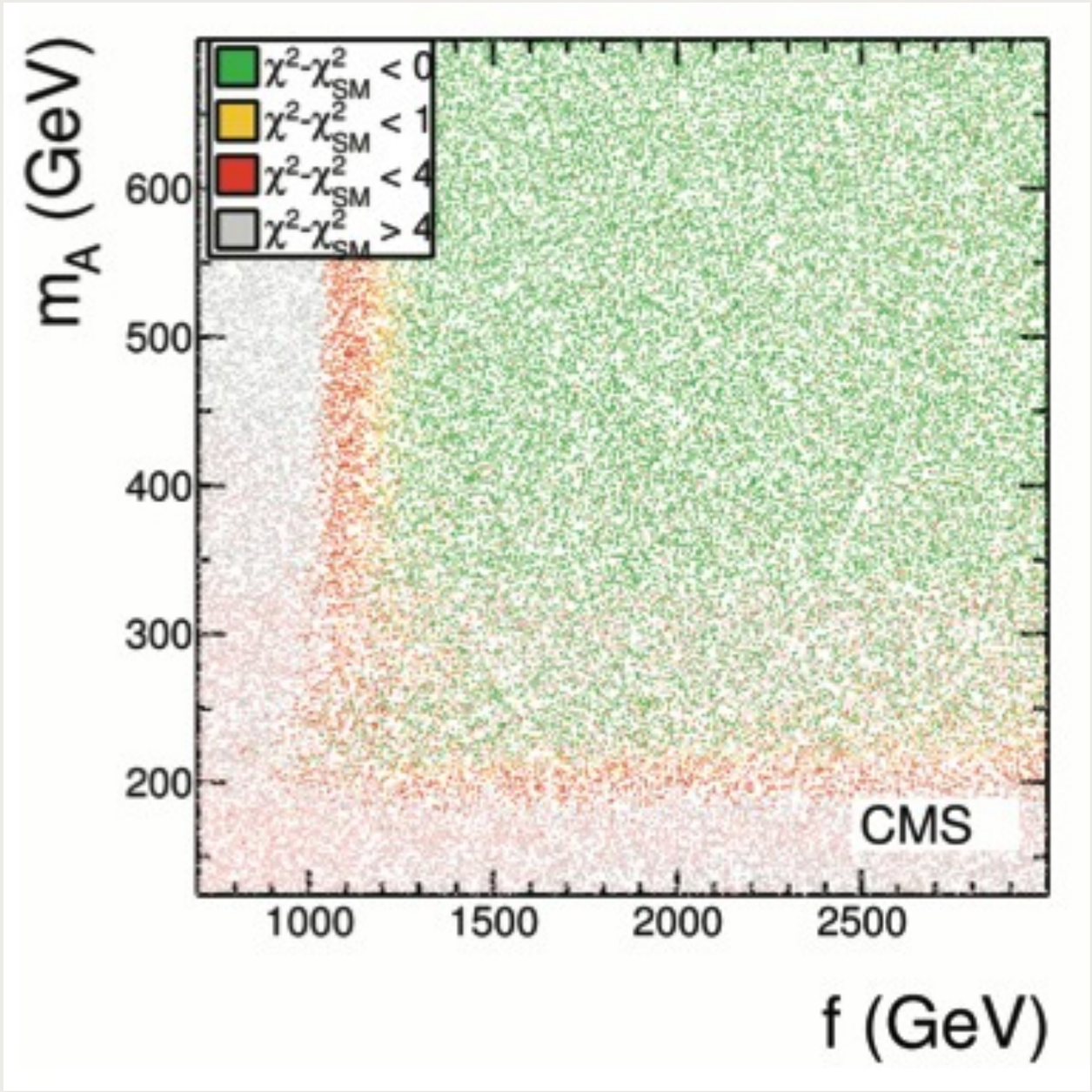
2 Higgs Doublets (h, H, A, $H^{\pm}$)



Kalyniak, Martin & Moats, arXiv:1310.5130

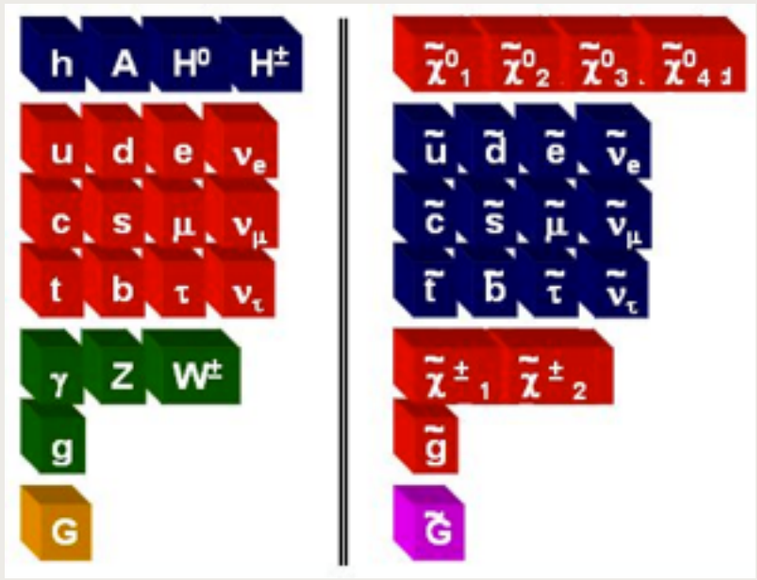
Bestest Little Higgs

$$f \gtrsim 4\ v$$



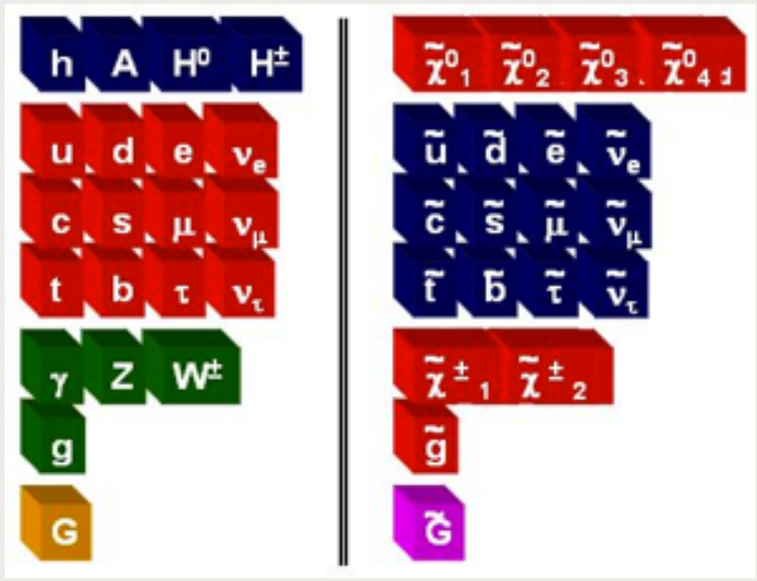
Supersymmetry

- Boson - Fermion symmetry



Supersymmetry

- Boson - Fermion symmetry



Starts With a **BANG!**

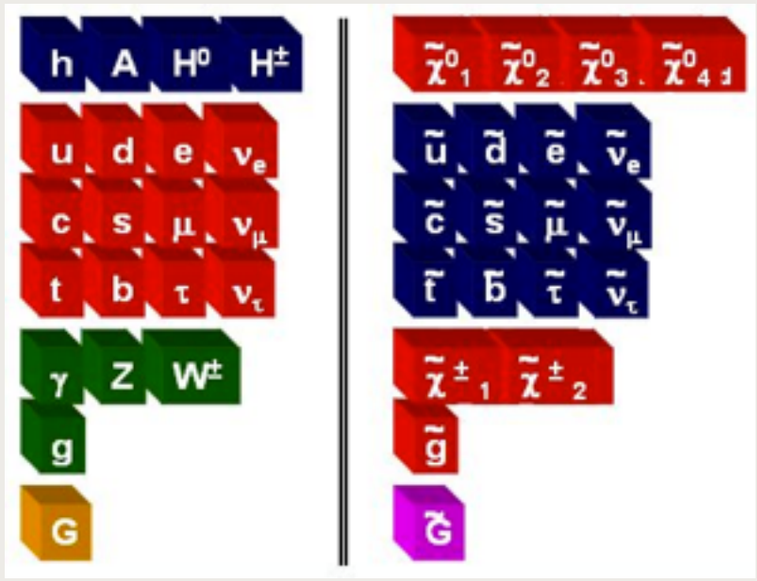
with ETHAN SIEGEL

The Rise and Fall of Supersymmetry

Posted by **Ethan** on May 15, 2013

Supersymmetry

- Boson - Fermion symmetry



Starts With a **BANG!**

with ETHAN SIEGEL

The Rise and Fall of Supersymmetry

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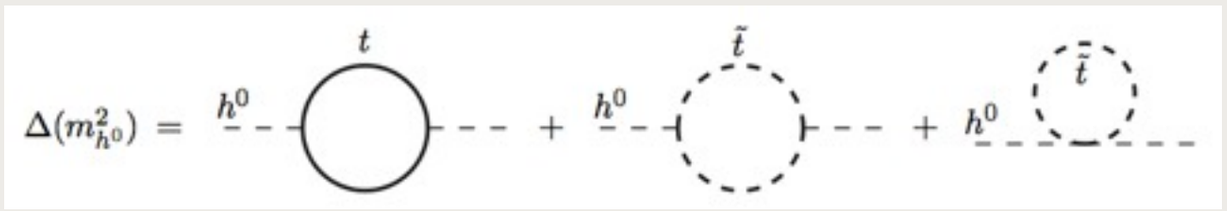
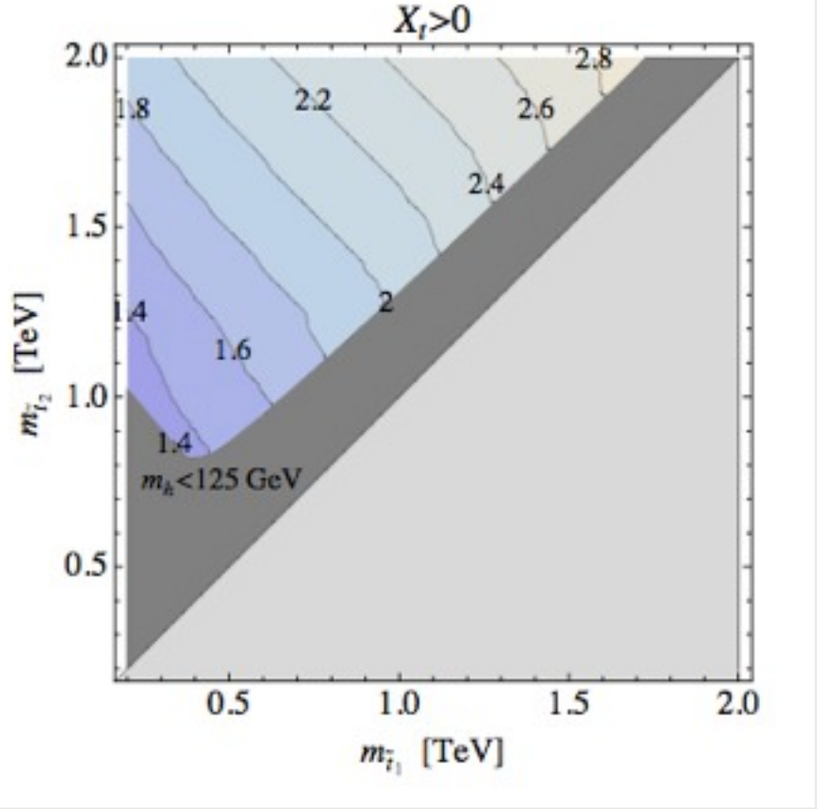
$$m_{h^0} < m_Z |\cos(2\beta)|$$



$$\Delta(m_{h^0}^2) = \frac{3}{4\pi^2}\cos^2\alpha\ y_t^2 m_t^2 \ln\left(m_{\tilde{t}_1} m_{\tilde{t}_2}/m_t^2\right).$$



Draper et al. arXiv:1112.3068

Minimal Supersymmetry

- MSSM not ruled out!

Minimal Supersymmetry

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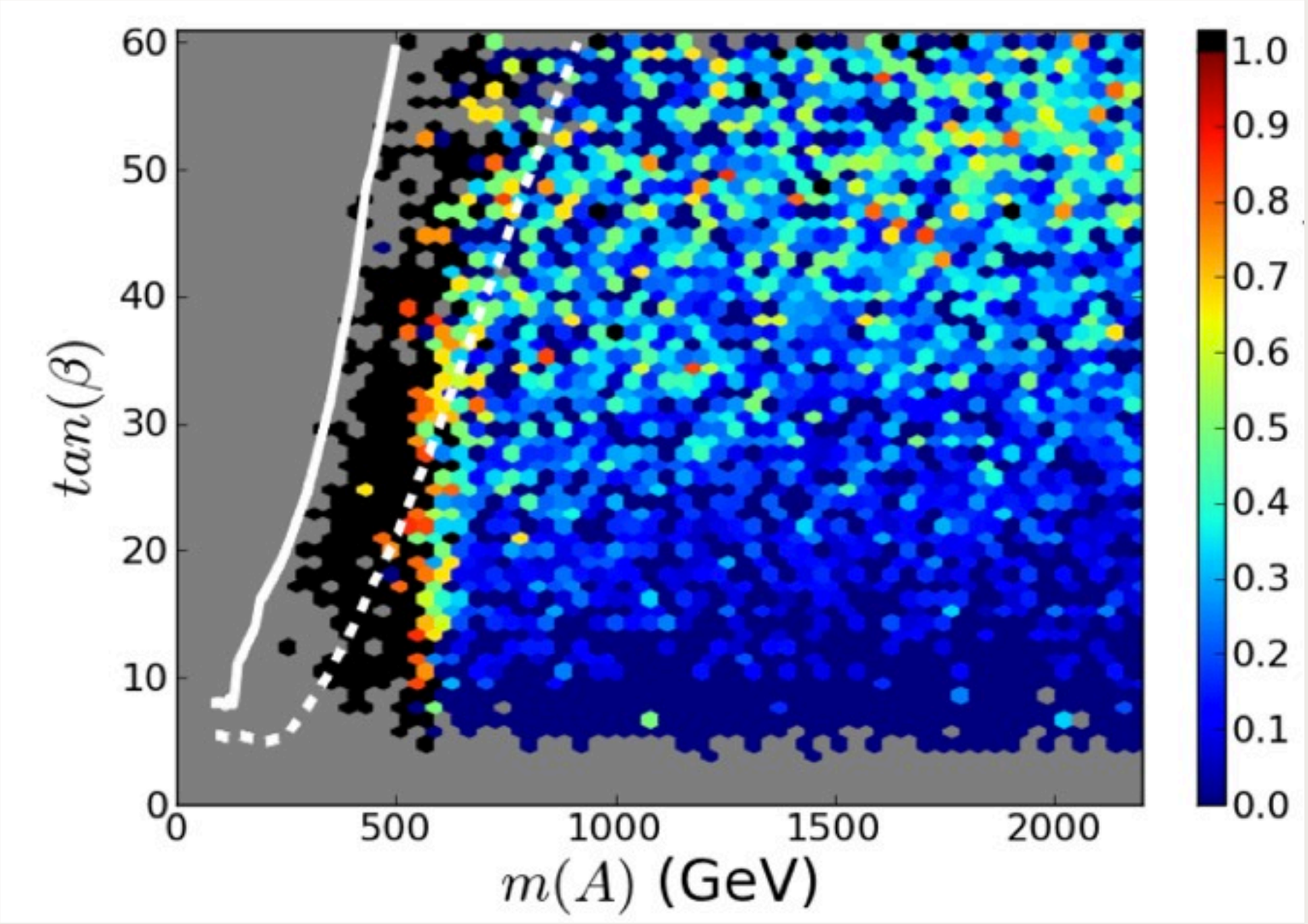
Minimal Supersymmetry

- MSSM not ruled out!



Cahill-Rowley et al. arXiv:1407.7021

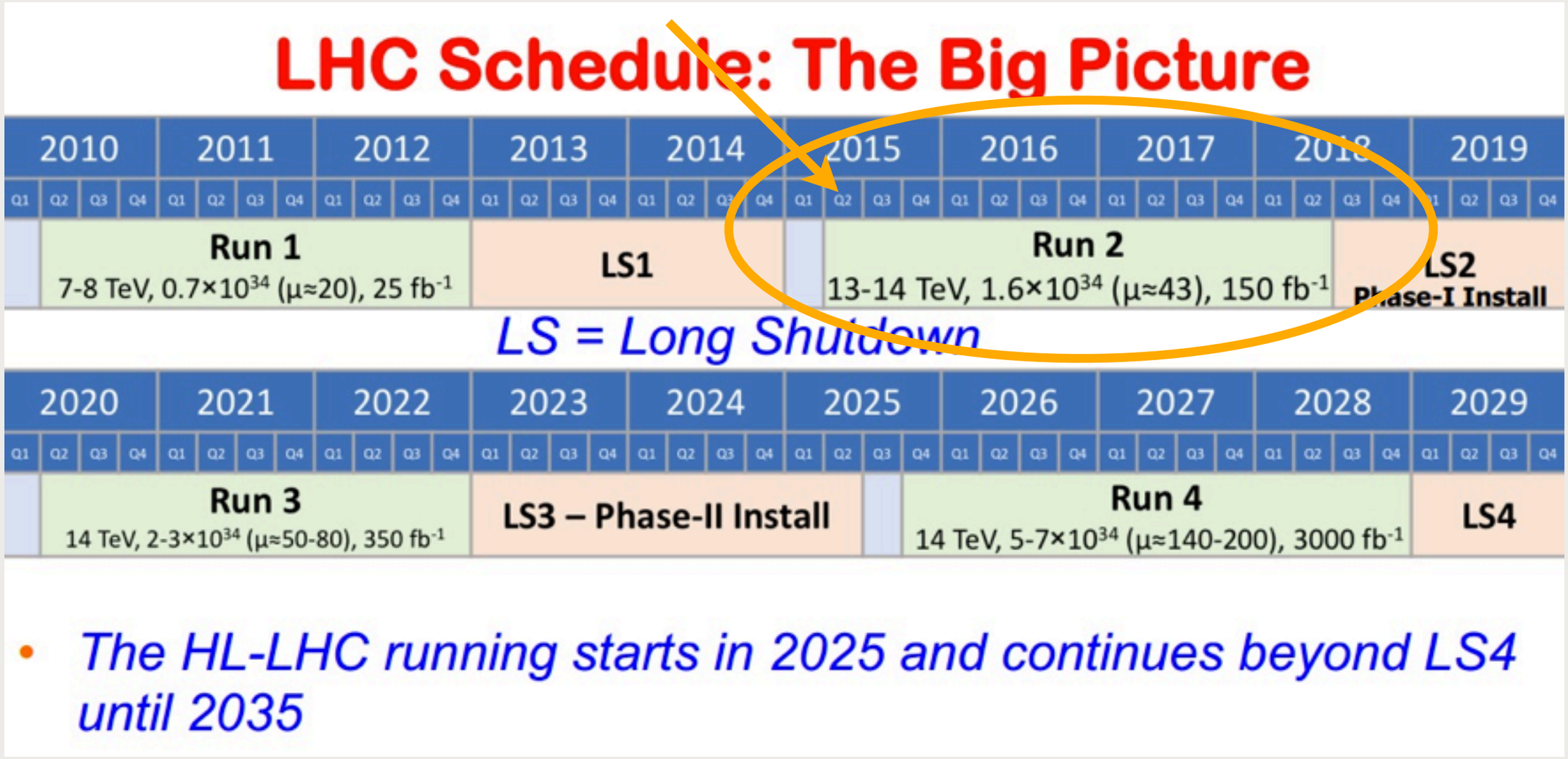
Outlook

- Holding our breath for Run II of the LHC!

- *The HL-LHC running starts in 2025 and continues beyond LS4 until 2035*

Outlook

- Holding our breath for Run II of the LHC!



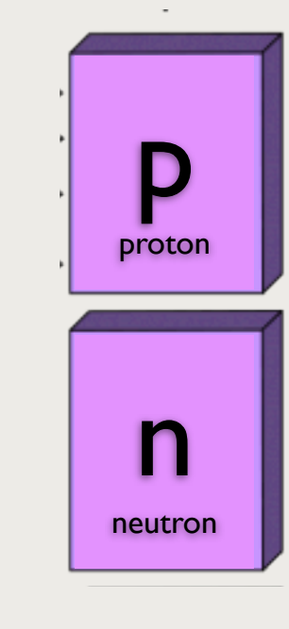
- *The HL-LHC running starts in 2025 and continues beyond LS4 until 2035*

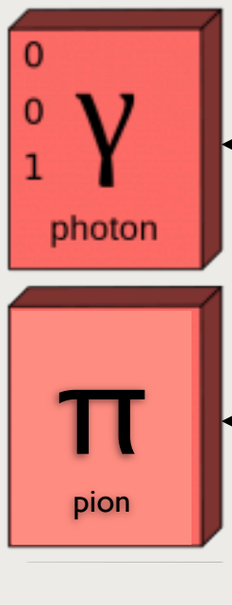
Conclusions?

- Higgs discovered - YAY!
- Looks like the SM Higgs - Yay?
- Fine tuning not resolved - Umm...
- Meta stable Higgs - Uh oh...
- BSM models not ruled out - YAY!

Questions?

Standard Model



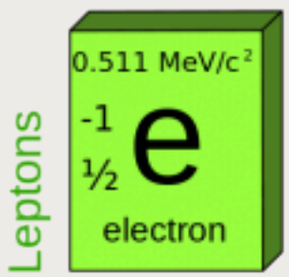


$U(1)_{em}$

$SU(2)_F$

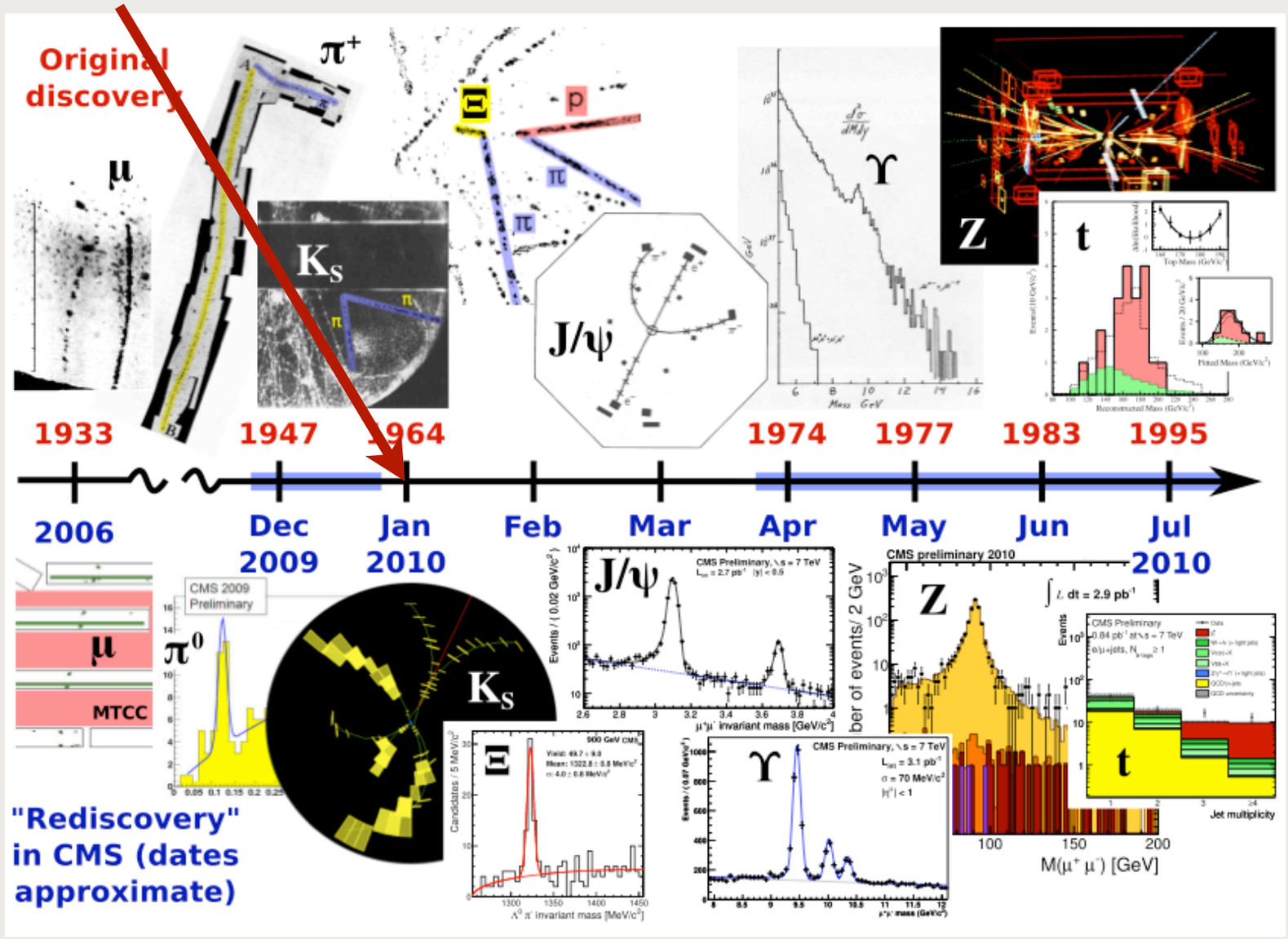
Light
Electromagnetism
Chemical Binding
Substance/Structure

Nucleon Binding



Origin of the SM

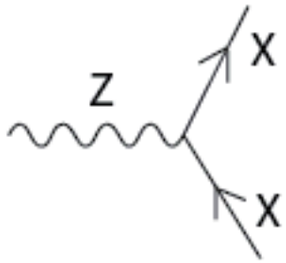
Quark model proposed
Higgs Mechanism proposed
Electroweak theory proposed



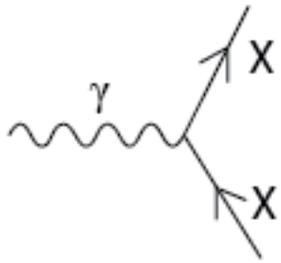
LHC Era

Allowed Interactions

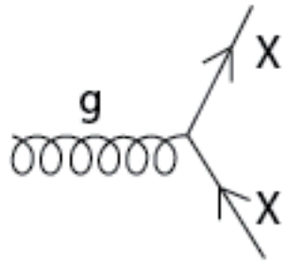
Standard Model Interactions
(Forces Mediated by Gauge Bosons)



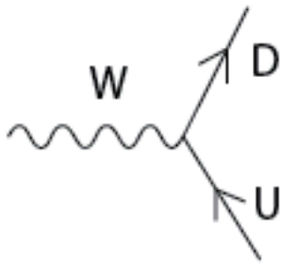
X is any fermion in the Standard Model.



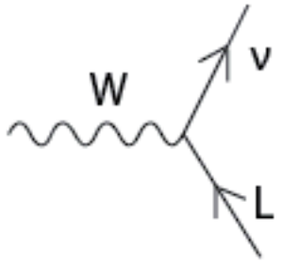
X is electrically charged.



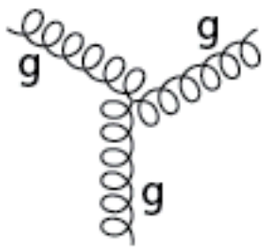
X is any quark.

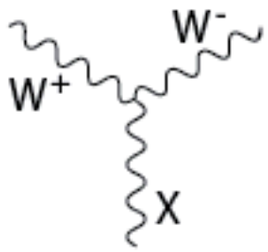


U is a up-type quark;
D is a down-type quark.

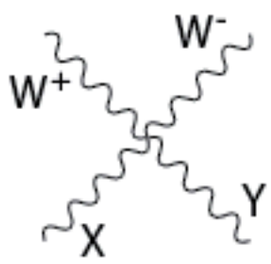


L is a lepton and ν is the corresponding neutrino.

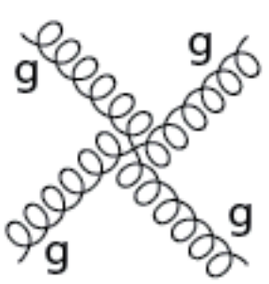




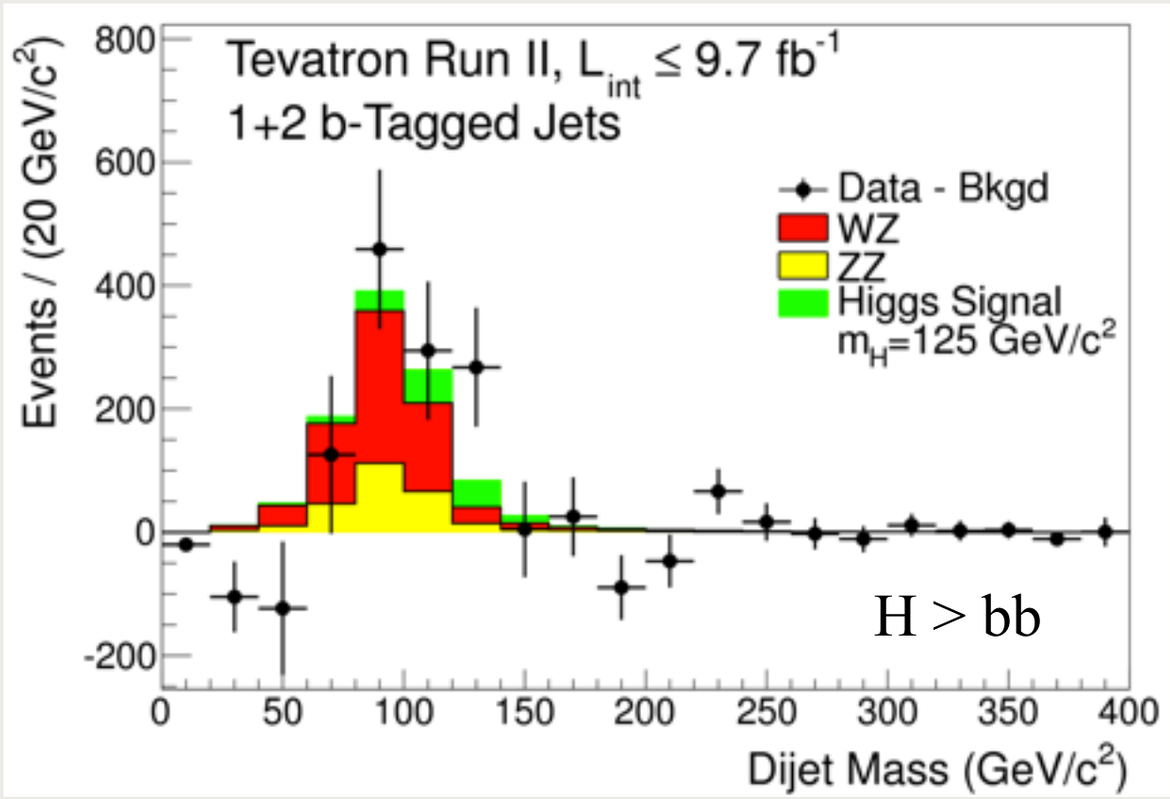
X is a photon or Z-boson.

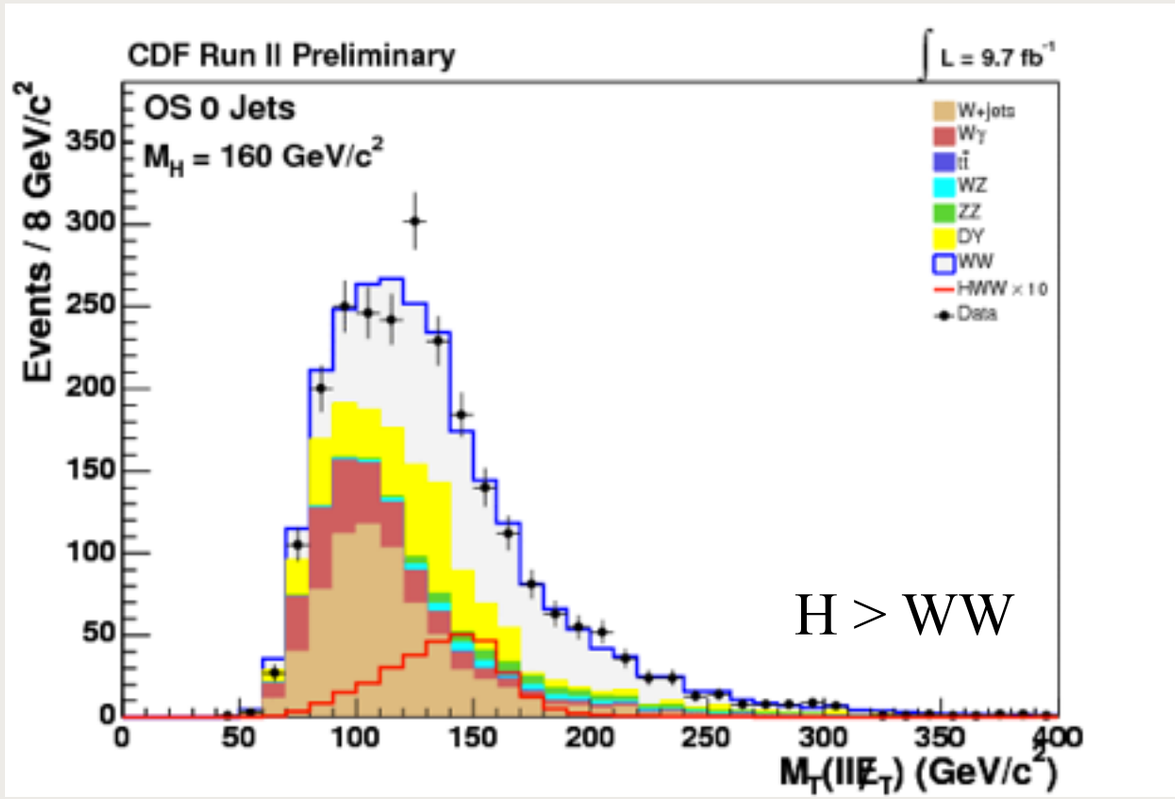


X and Y are any two electroweak bosons such that charge is conserved.



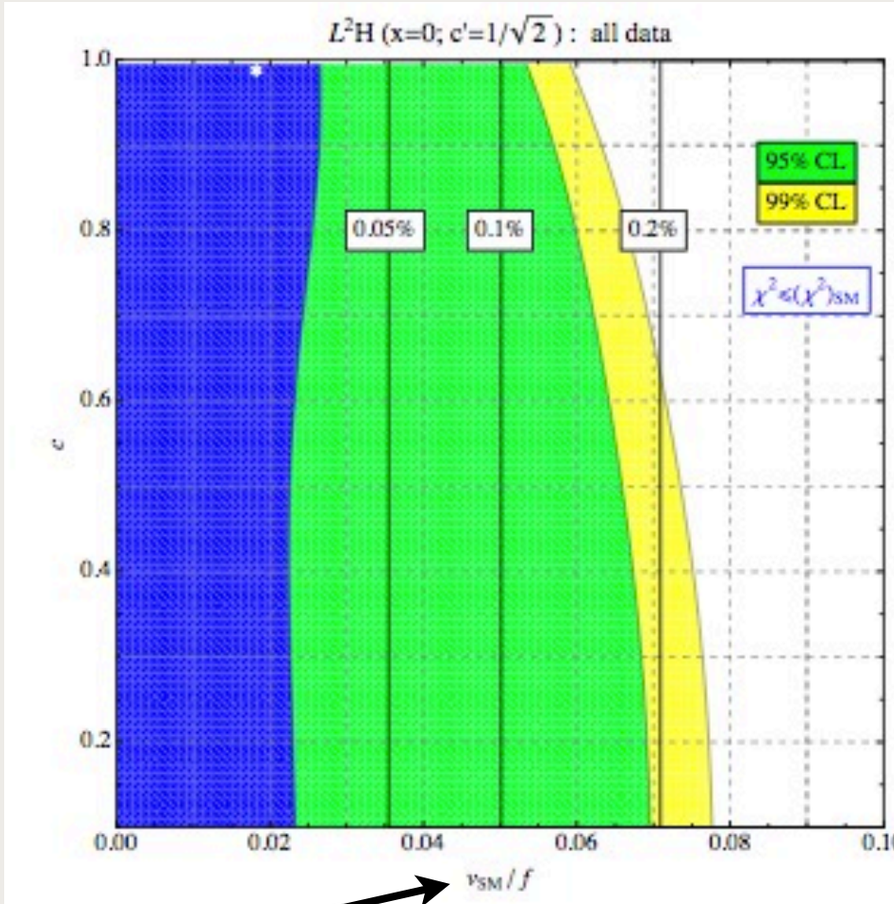
Previous Searches



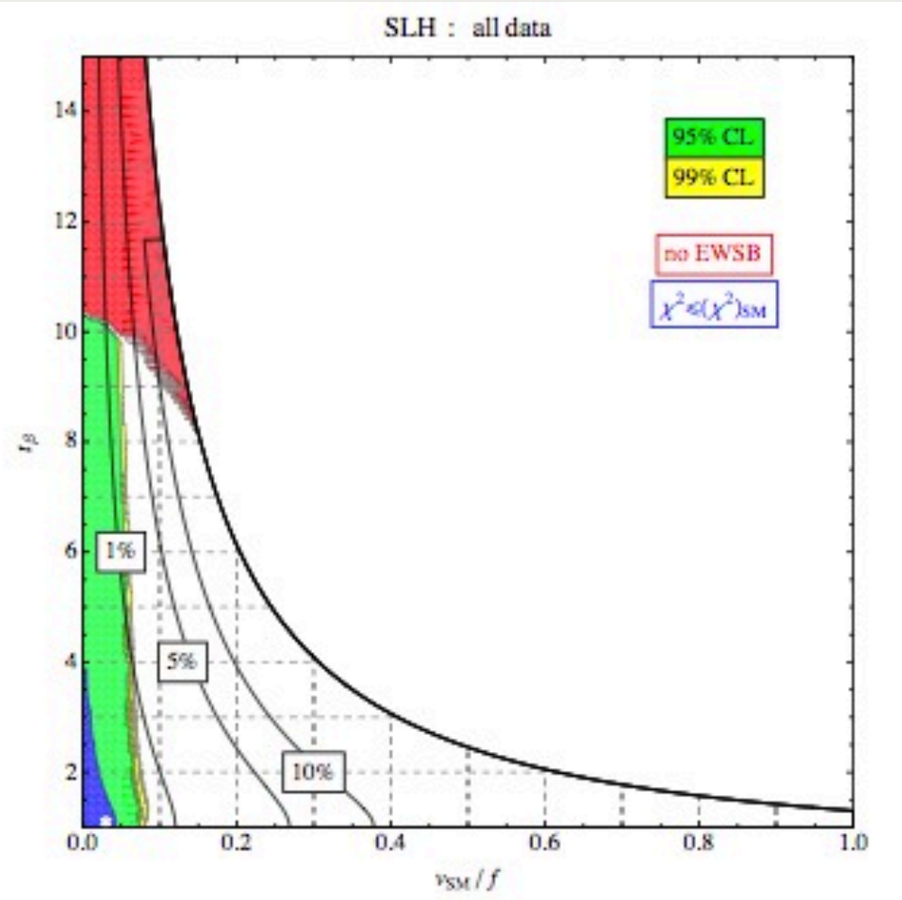


Little Higgs

f ≳ 50 v



Littlest Higgs



Simplest Little Higgs

f ≳ 25 v

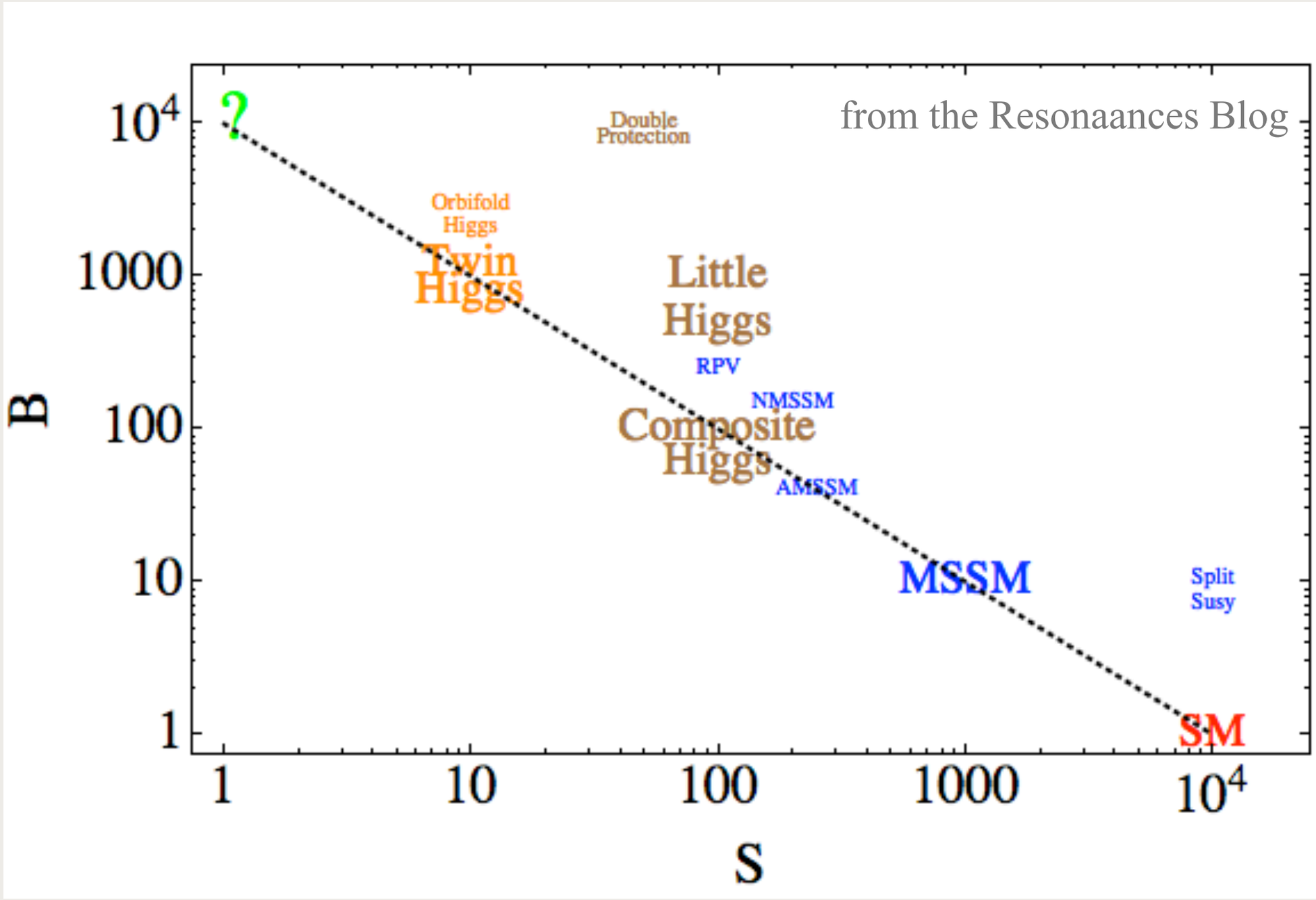
v/f

Reuter & Tonini, arXiv:1212.5930

Λ = scale of new physics
f = vev of BSM model
$\Lambda \sim 4\pi$ f

Trade-offs

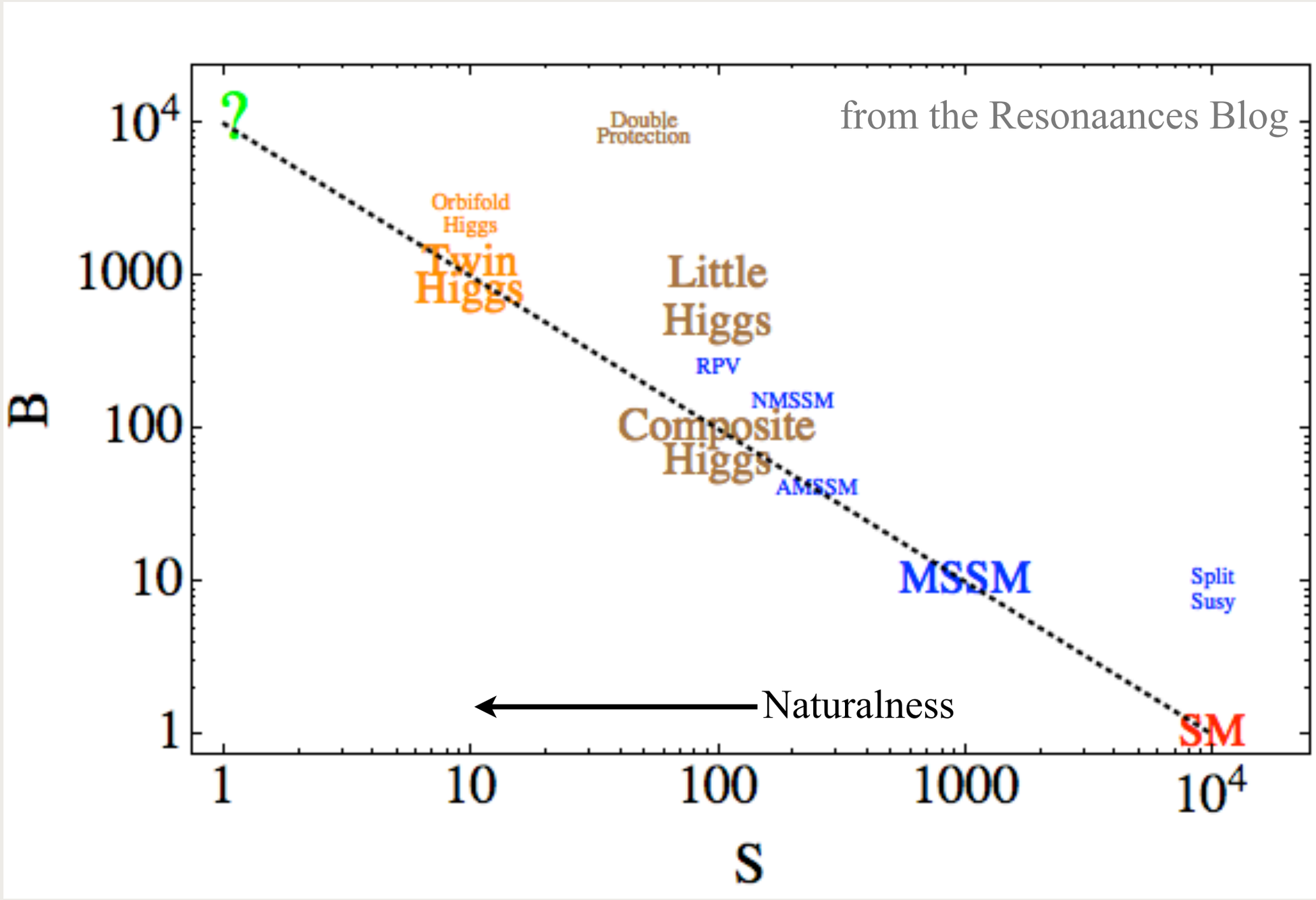
Baroque-ness: measure of model complexity



Strangeness: measure of fine-tuning

Trade-offs

Baroque-ness: measure of model complexity



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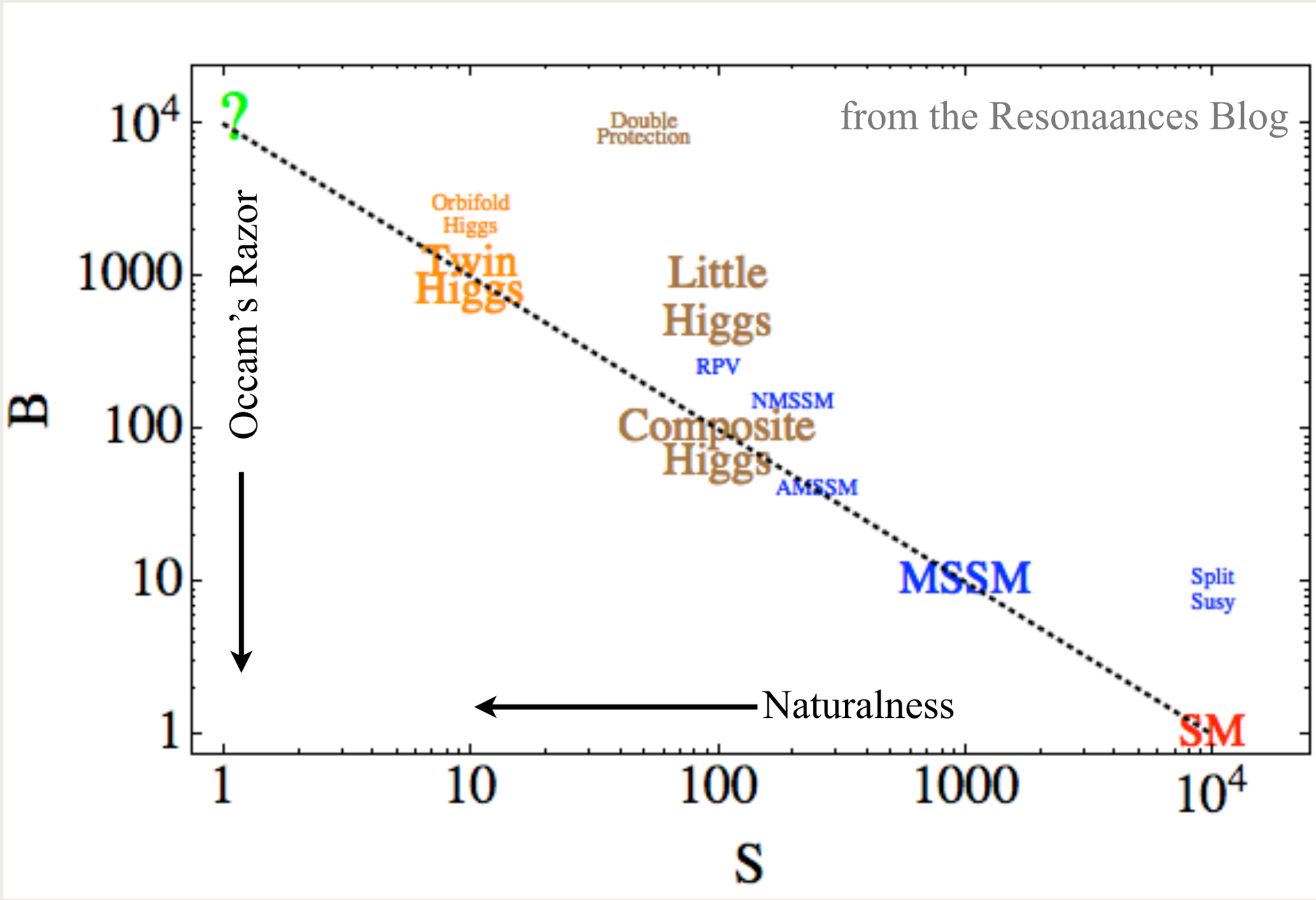

Strangeness: measure of fine-tuning