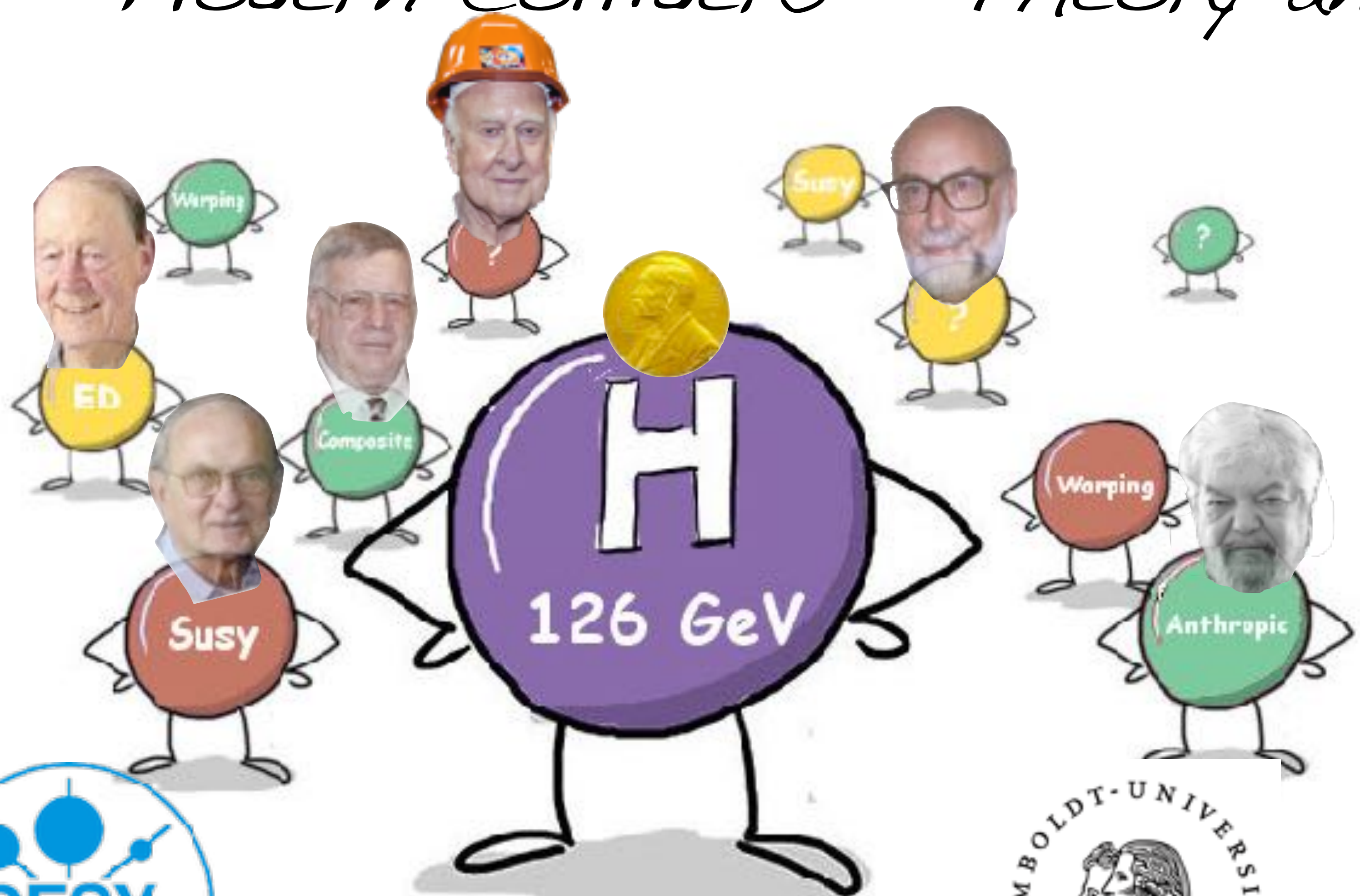
Beyond the Standard Model

Helmholtz International School

" Modern Colliders - Theory and Experiment 2018 "



Lecture 1/3

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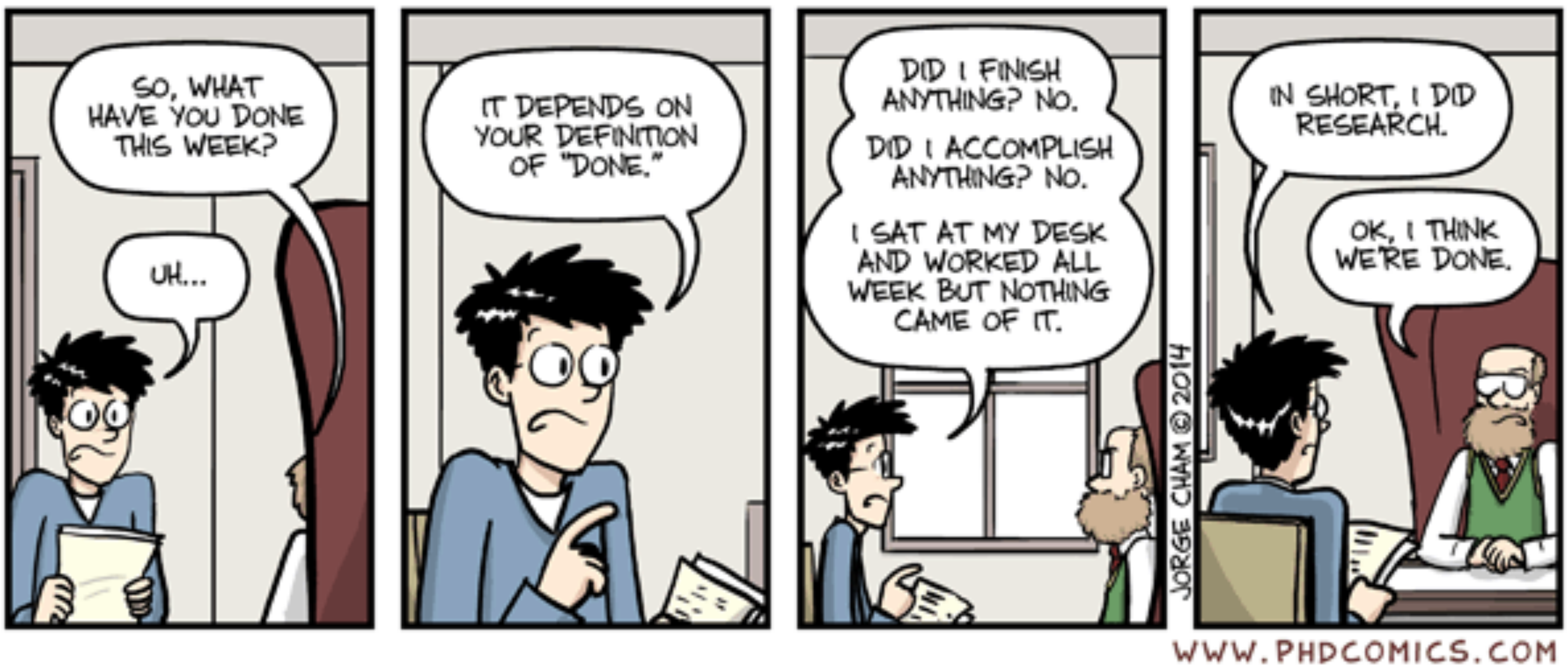
Outline

- Lecture #1
  - General introduction
  - Higgs physics as a door to BSM
  - Naturalness and the weak scale hierarchy problem
  - Supersymmetry
- Lecture #2
  - Composite Higgs
  - Extra dimensions
  - Cosmological relaxation: a concrete example of different energy frontier
  - NNaturalness
- Lecture #3
  - Beyond colliders searches for new physics
    - Gravitational waves
    - AMO: isotope spectroscopy
    - Electric dipole moment
    - Neutron-antineutron oscillations
    - Primordial black holes
  - Weak gravity conjecture and the swampland

Ask questions!

Your work, as students, is to question all what you are listening during the lectures...



What is physics beyond the Standard Model?

?

I don't know. Nobody knows

If it were known, it would be part of the SM!

You won't learn during these lectures what BSM is.

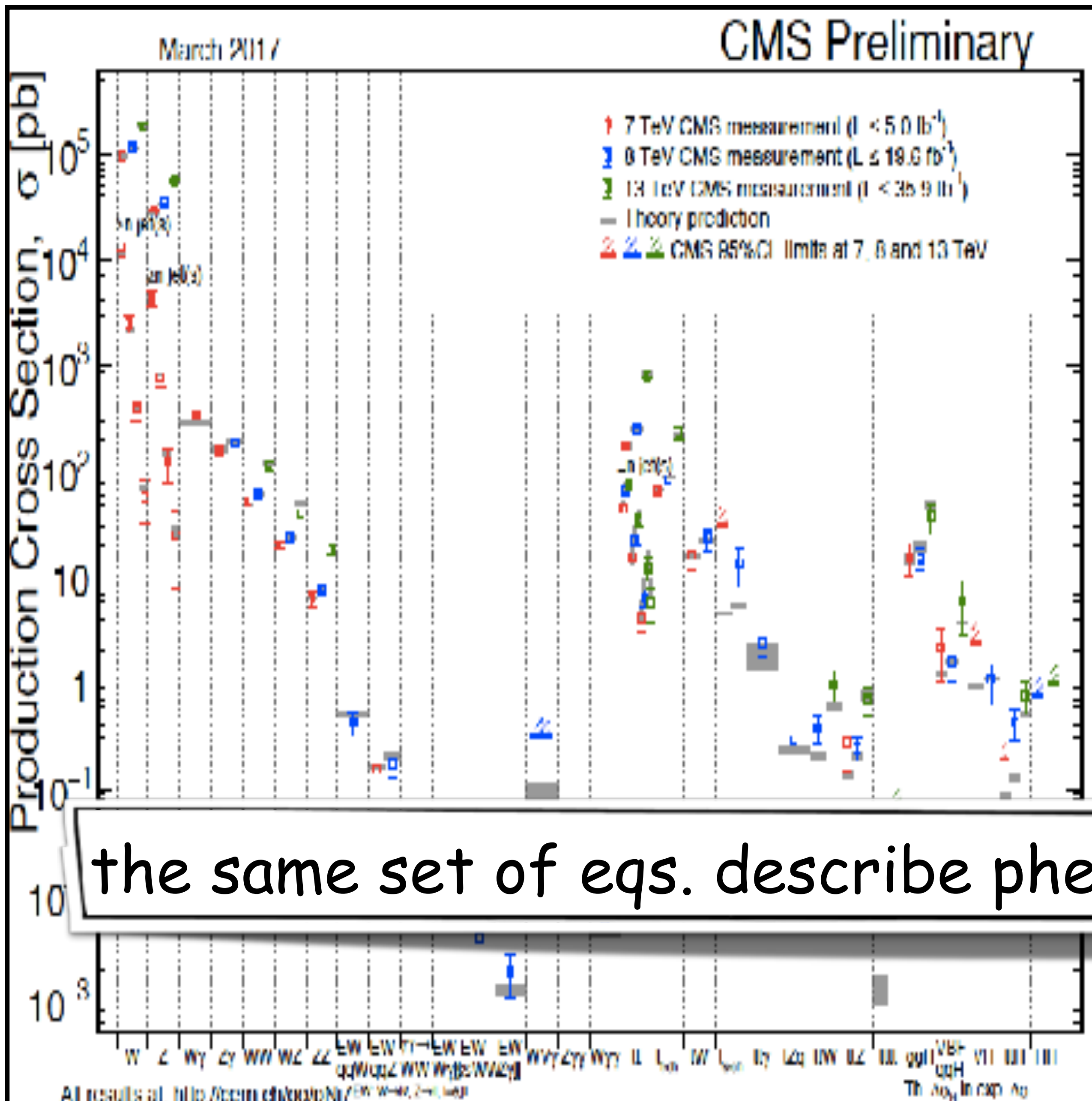
You'll learn (maybe) what BSM could be.

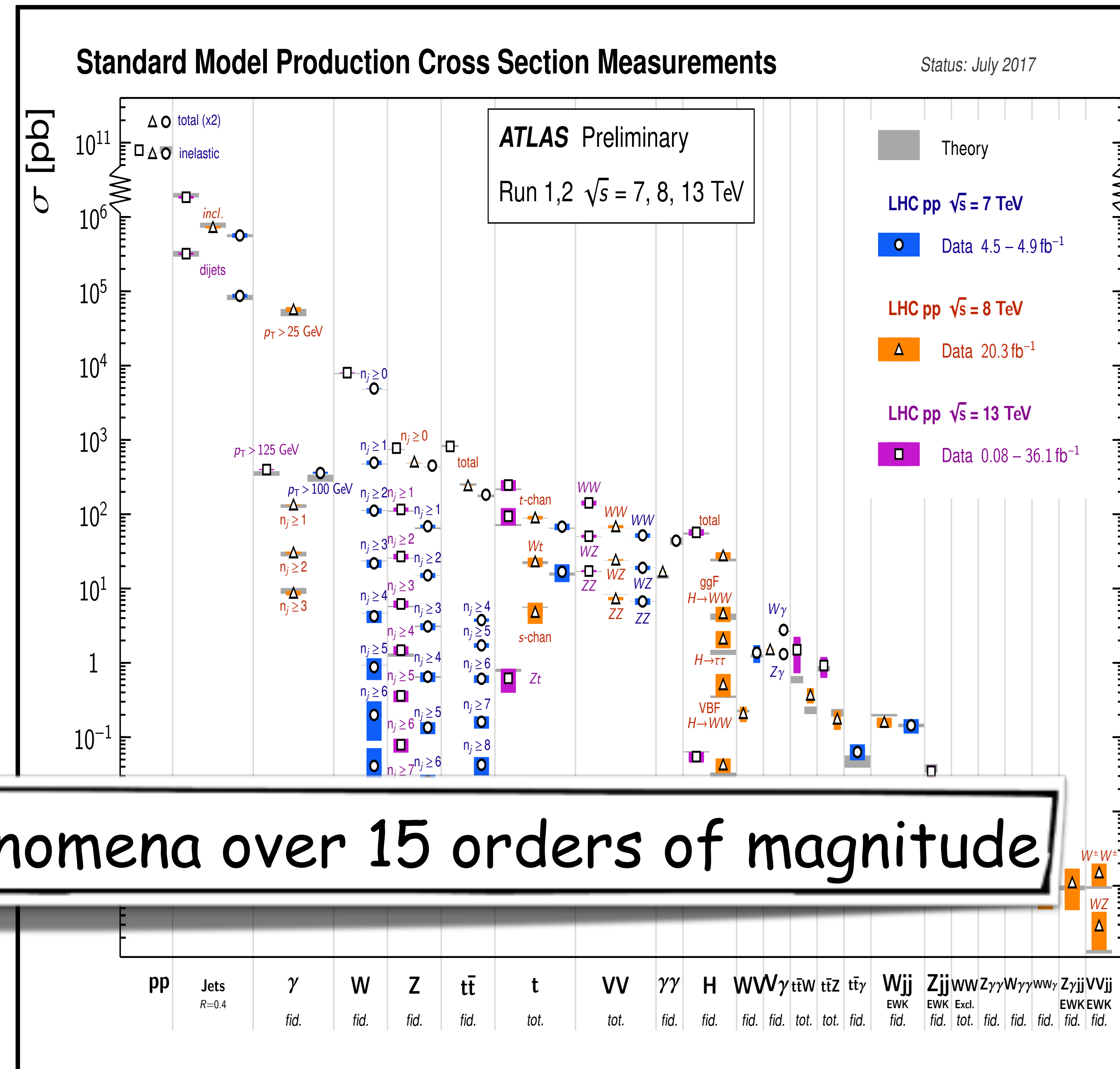
" Looking and not finding is different than not looking"

We'll study the limitations/defaults of the SM as a guide towards BSM.

We want to learn from our failures

The SM and... the LHC data so far





the same set of eqs. describe phenomena over 15 orders of magnitude

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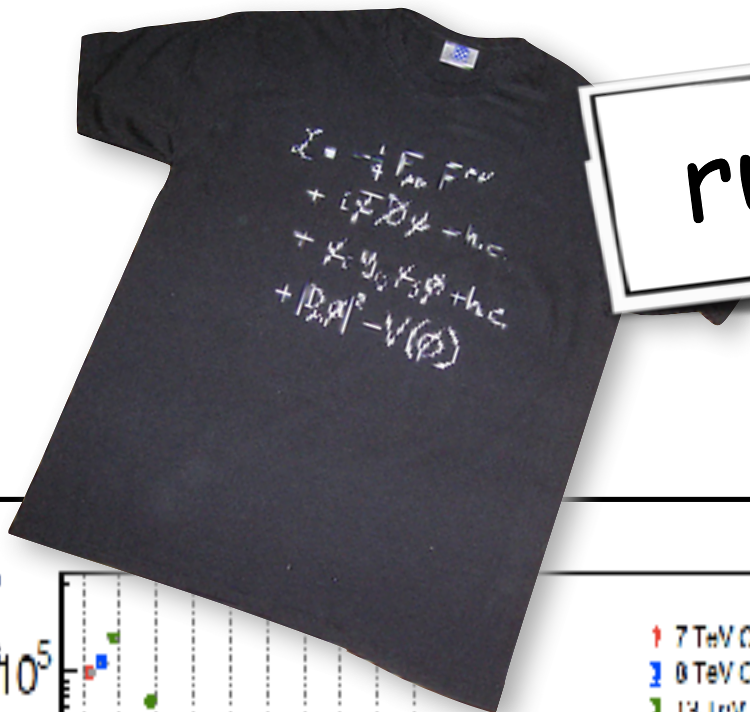
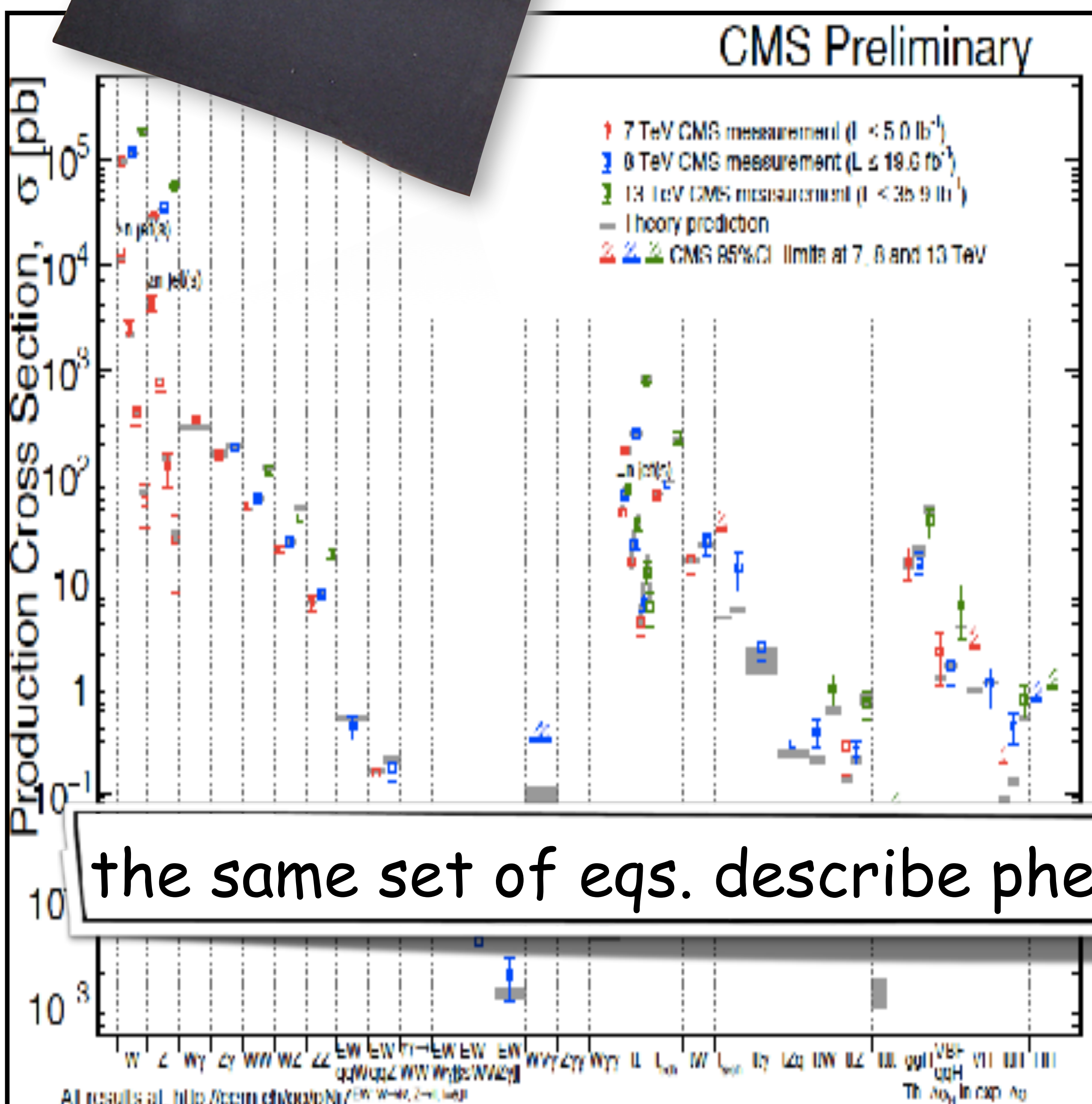
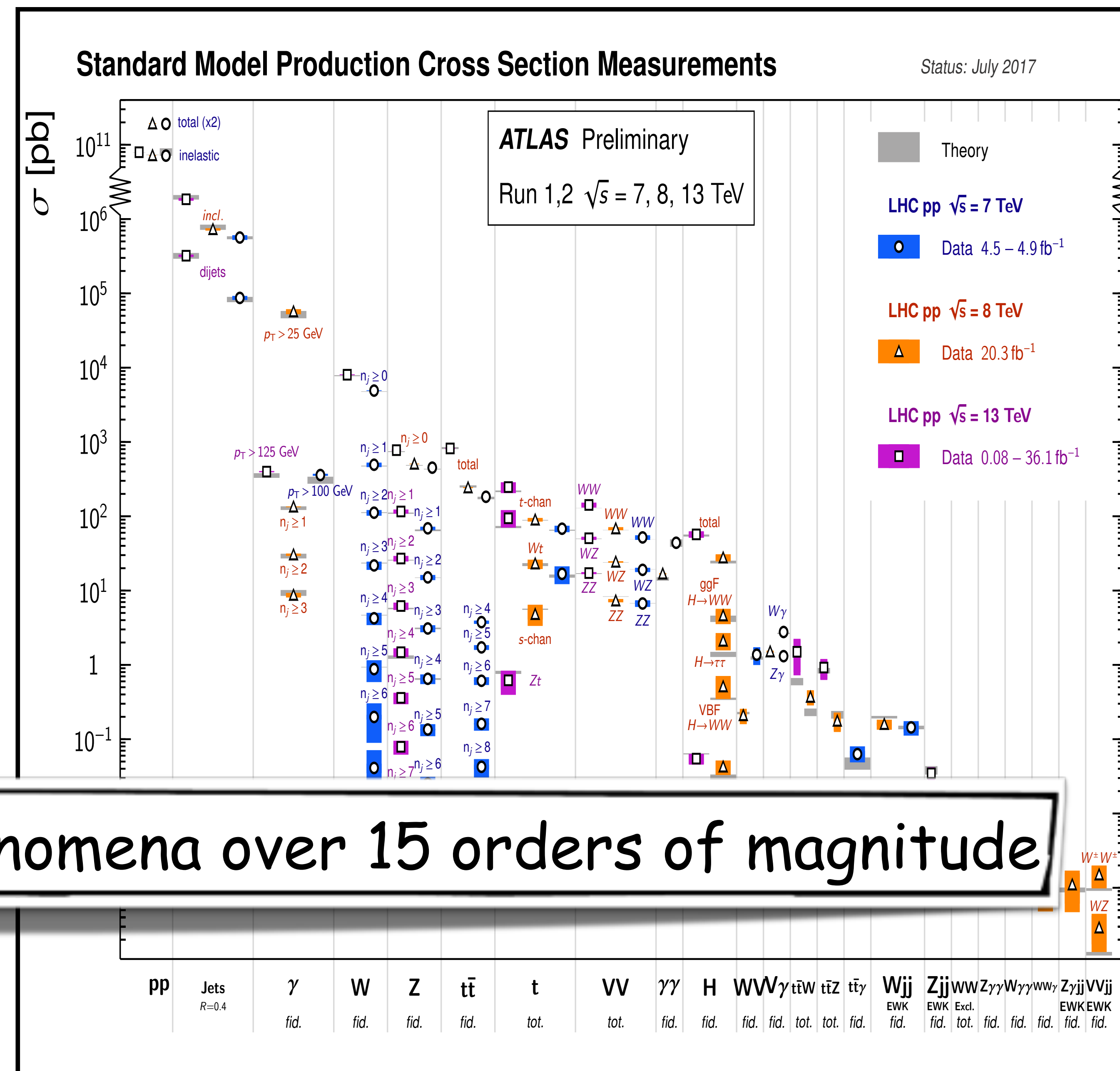


rules the world!





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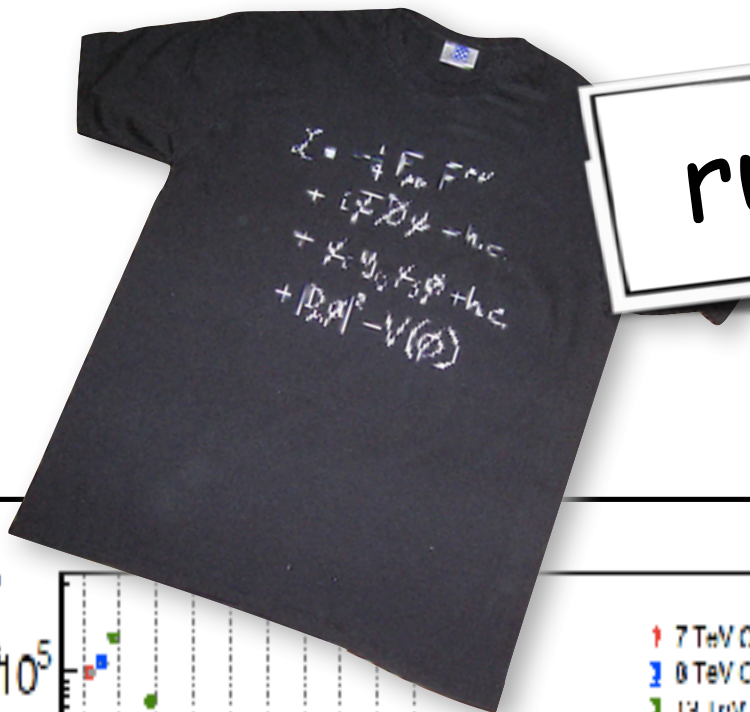
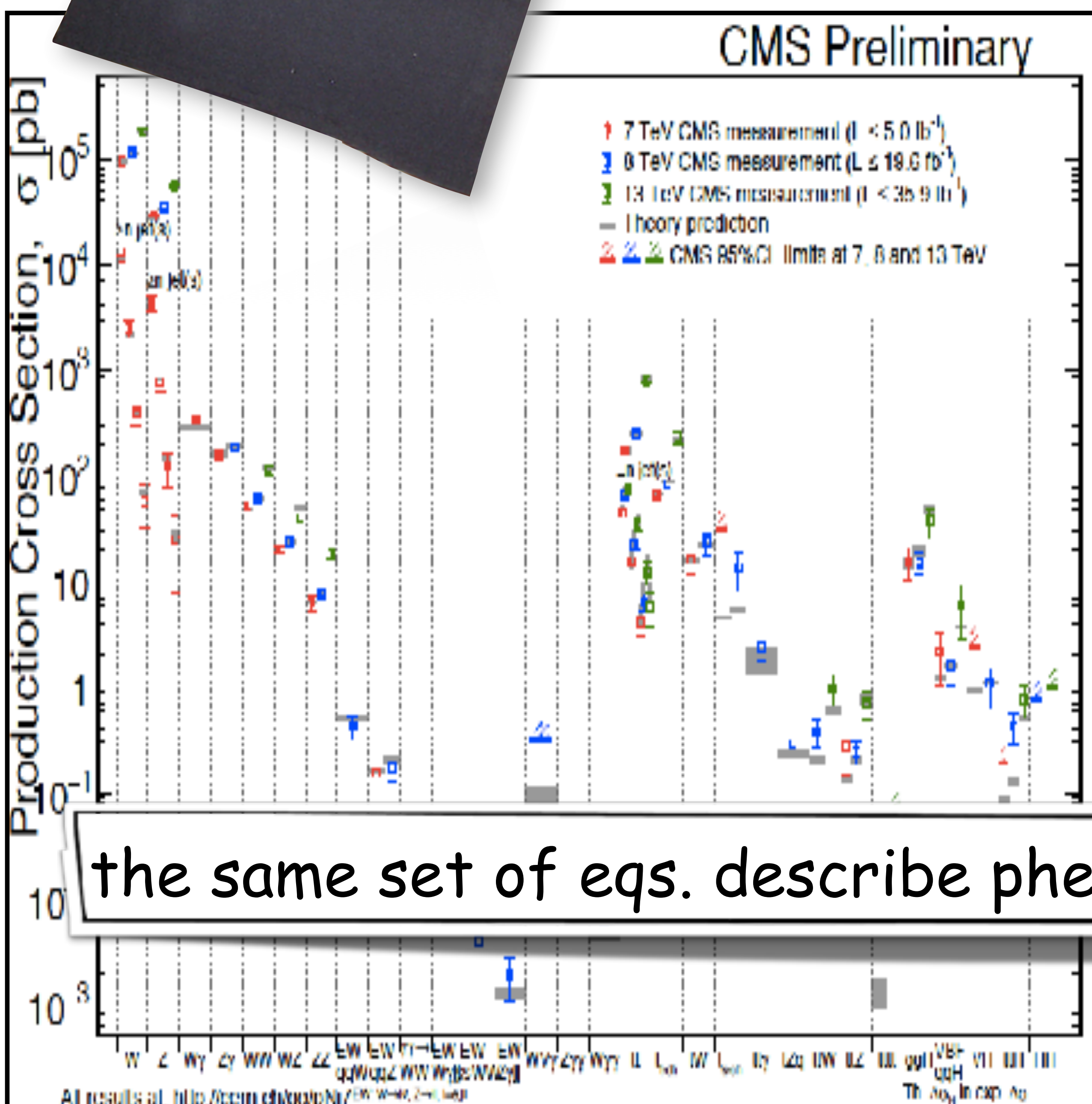
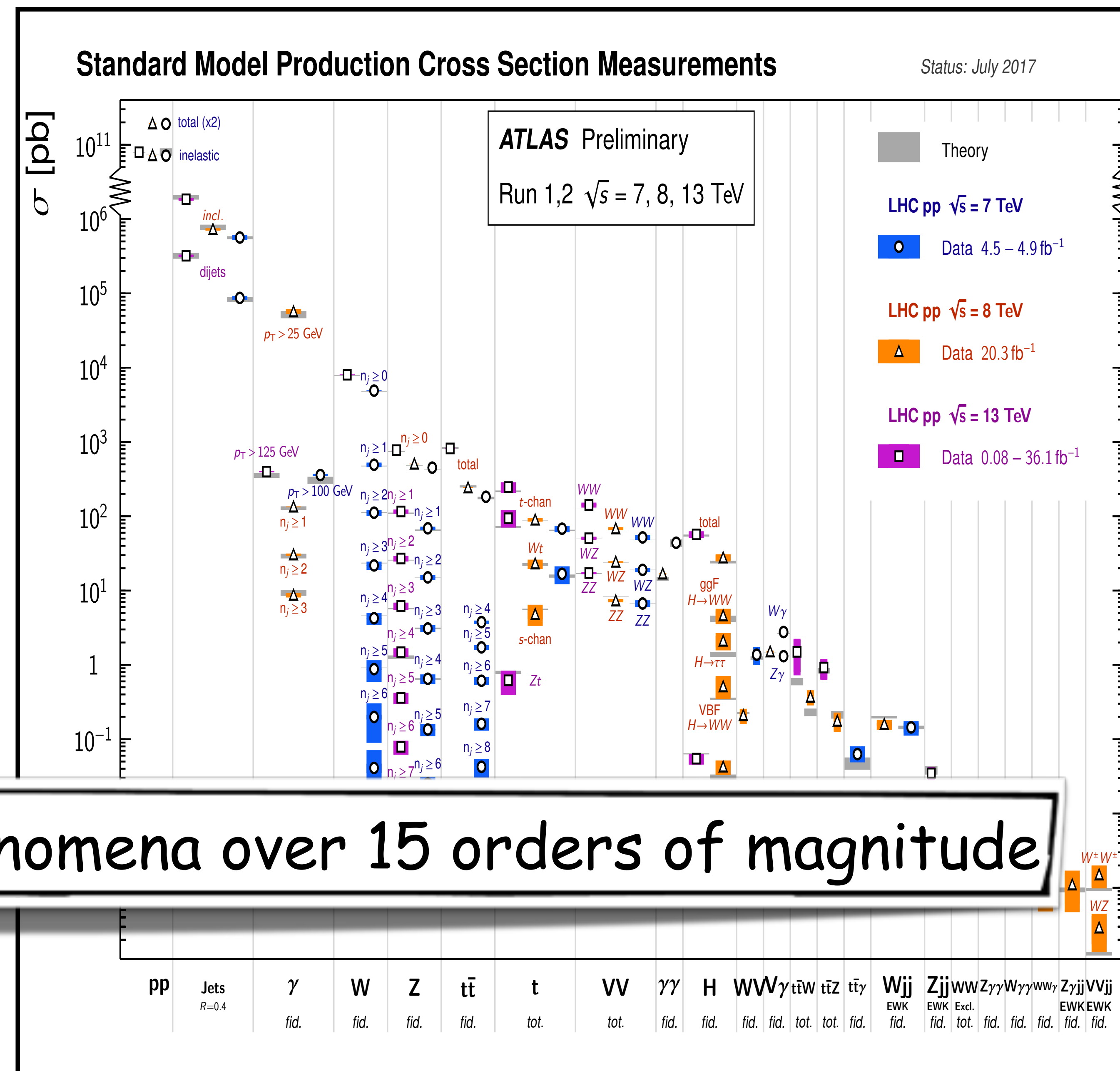


rules the world!

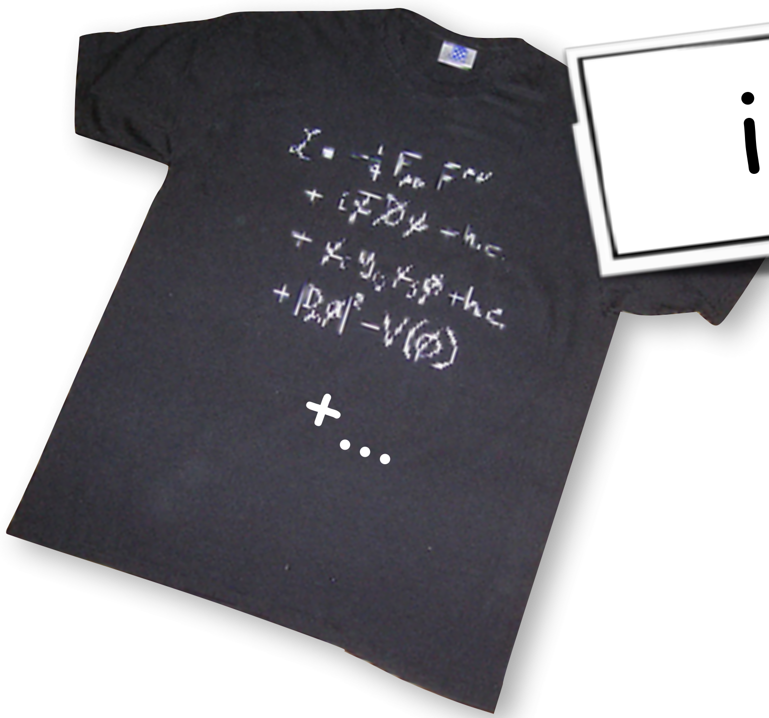
[and we, HEP practitioners, are all entitled for some royalties!]





the same set of eqs. describe phenomena over 15 orders of magnitude

The SM and... the rest of the Universe



is not enough

[and we all have to return our royalties!]

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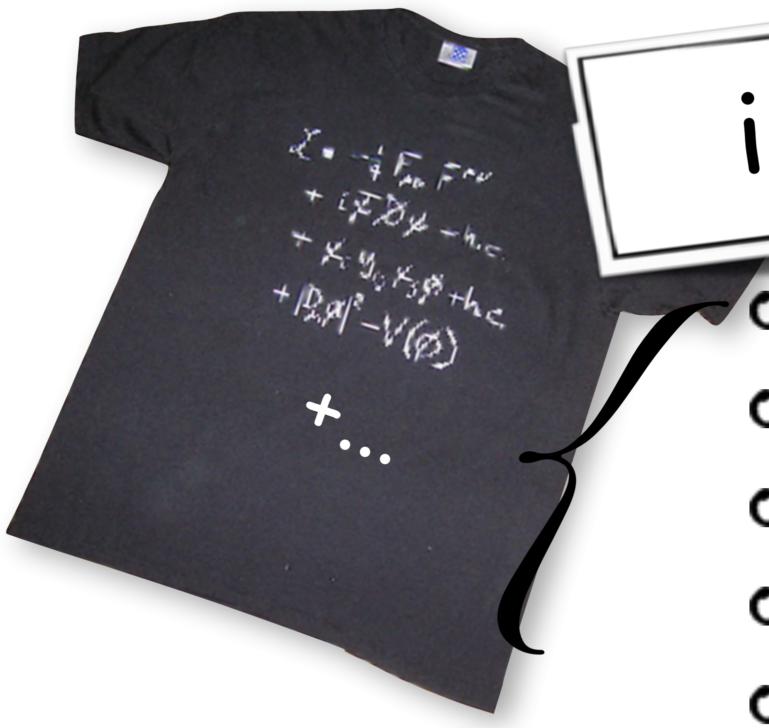
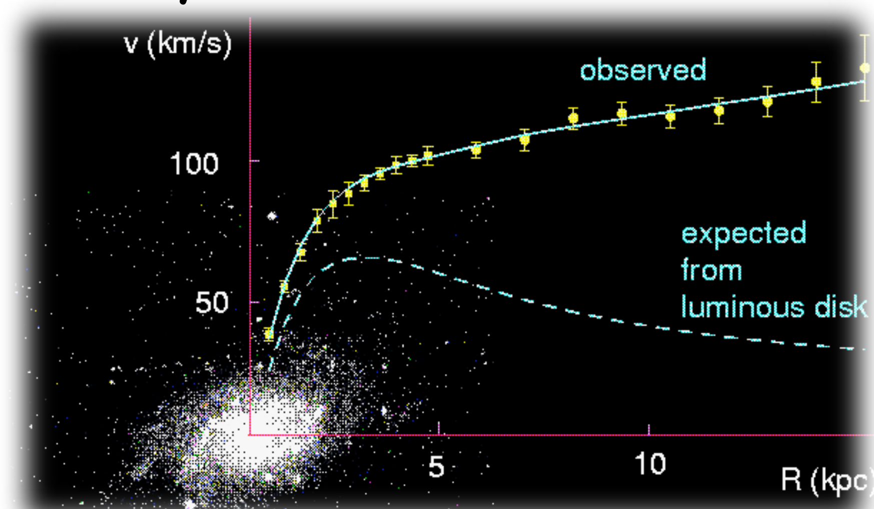
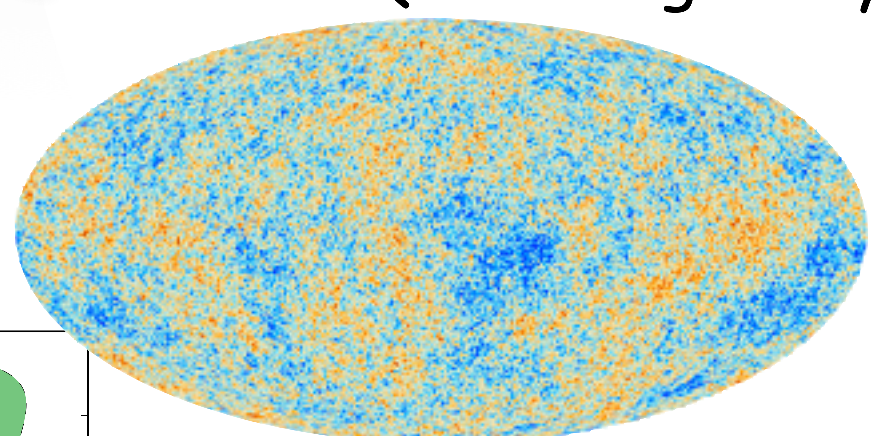
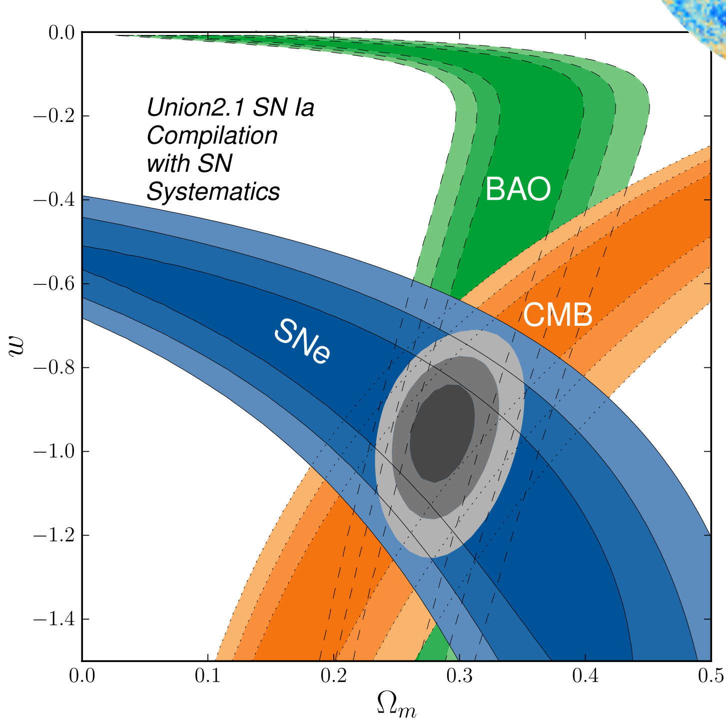
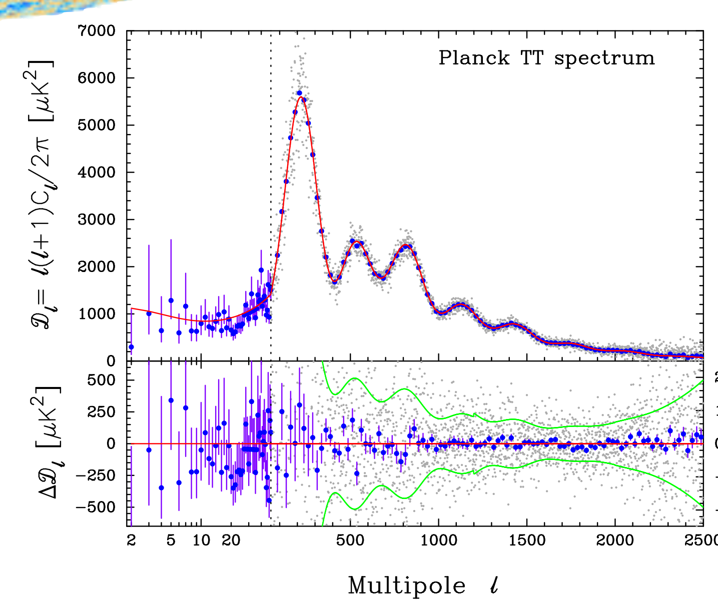


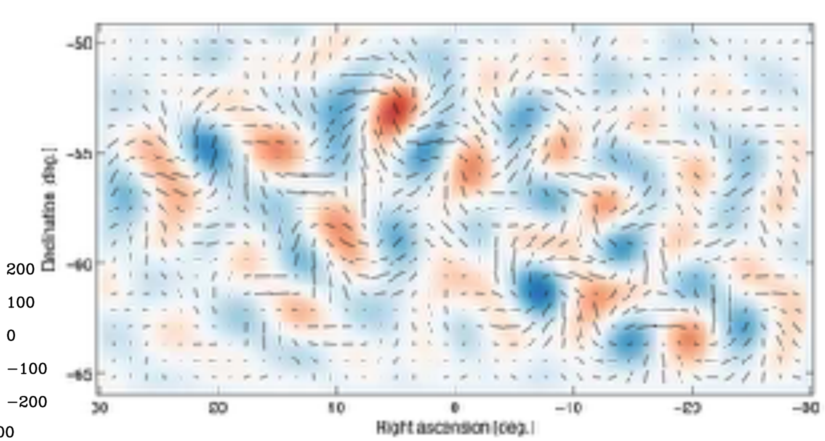
- neutrino masses
- matter-antimatter aymmetry
- Dark Matter
- Dark Energy
- Quantum gravity





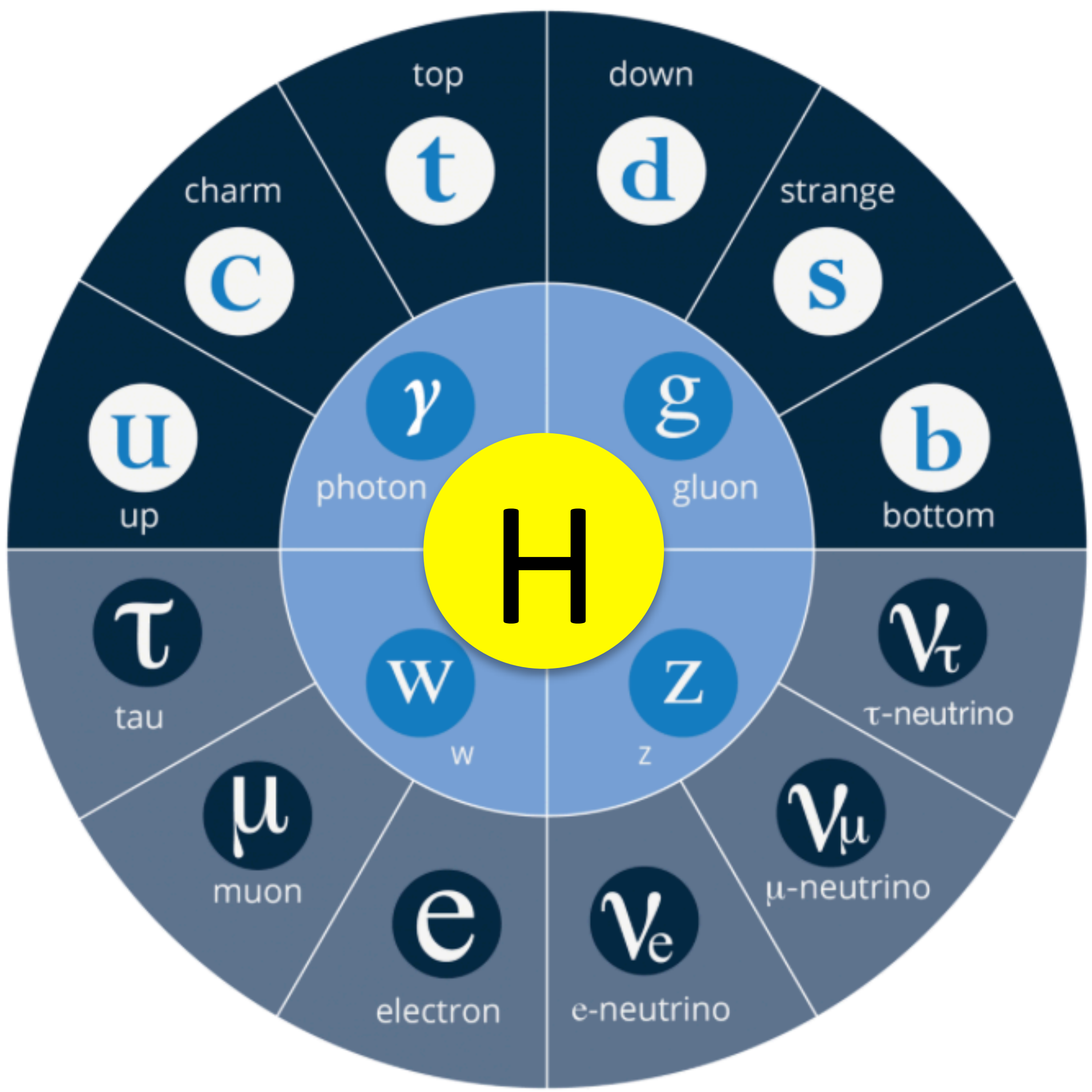


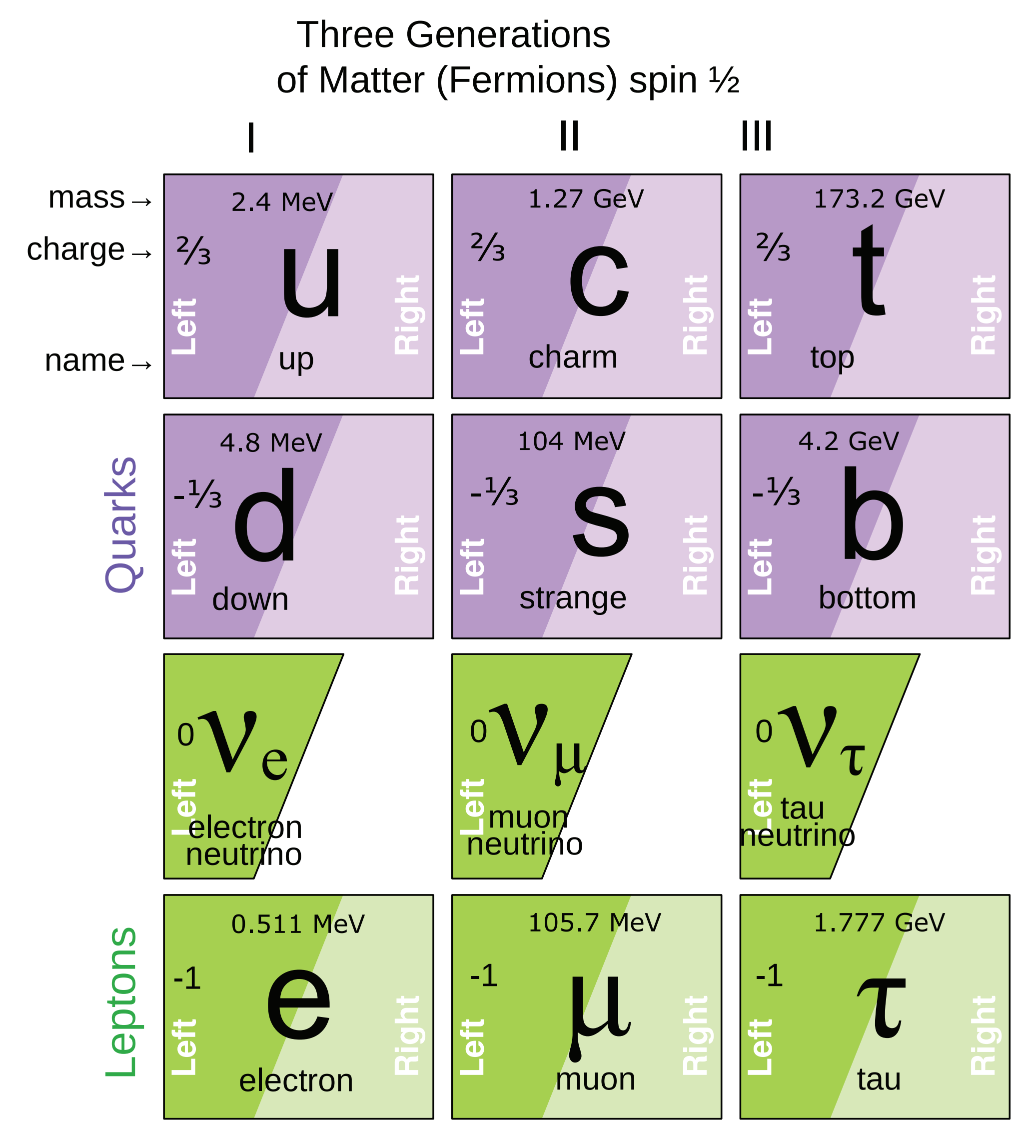




The Standard Model: Matter

~~How many quarks and leptons?~~





The Standard Model: Matter

~~How many quarks and leptons?~~

$6+6=12$?

$6\times 3+6=24$?

shouldn't we count different color states?

$6\times 3\times 2+3\times 2+3=45$?

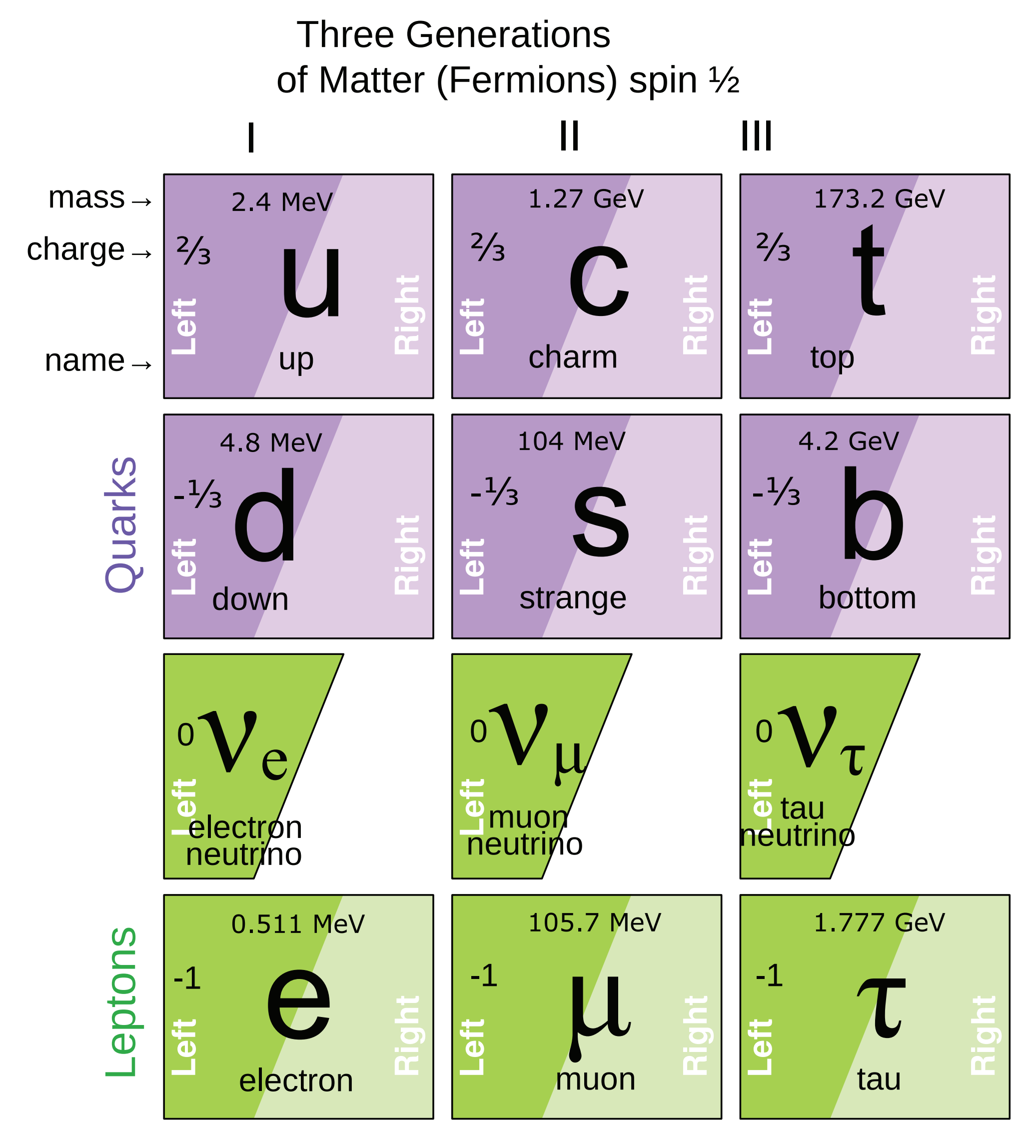
it is an accident that $e_L \sim e_R$ for QED

SM is a chiral theory: $e_L \neq e_R$

$6\times 3\times 2+6\times 2=48$?

are there ν_R?

are they part of the SM?



The Standard Model: Matter

~~How many quarks and leptons?~~

~~Is the SM theoretically consistent?~~

SM = theory based on (chiral) gauge symmetries
a symmetry is consistent with QM
iff the "sum" of the charges of the different fermions vanishes

$$Q = T_L^3 - Y$$

Particles	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$L_L^i = \begin{cases} N^i = (\nu^i, \tilde{\nu}^i) \\ E_L^i = (l_L^i, \tilde{l}_L^i) \end{cases}$	1	2	1/2
$E^i = (CP(l_R^i), CP(\tilde{l}_R^i))$	1	1	-1
$Q_L^i = \begin{cases} U_L^i = (u_L^i, \tilde{u}_L^i) \\ D_L^i = (d_L^i, \tilde{d}_L^i) \end{cases}$	3	2	$-1/6$
$U_R^i = (CP(u_R^i), CP(\tilde{u}_R^i))$	$\bar{3}$	1	2/3
$D_R^i = (CP(d_R^i), CP(\tilde{d}_R^i))$	$\bar{3}$	1	$-1/3$

Exercise 1: within the SM, check that
(1) $Tr_L Y - Tr_R Y = 0$
(2) $Tr_L Y^3 - Tr_R Y^3 = 0$
note that this was a priori no-guarantee to find a solution to this system of non-linear equations.
It works because EM is a vector-like theory

Exercise 2: Within the SM, the anomaly cancelation fixes the relative electric charges of the leptons and quarks. Show that with the addition of a right-handed neutrino, this ratio of electric charges is free. Still the cancelation of the anomaly imposes that the proton is electrically neutral

The Standard Model: Matter

~~The particles seen in a detector~~

Absolutely stable particles	Collider stable particles	Sort of stable particles	Displaced vertex particles
γ (m=0)	n (m=940MeV, ct=10^{14}mm)	Ξ, Λ, Σ, Ω	B, D
(G (m=0))	μ (m=940MeV, ct=10^{6}mm)	(m=1-2GeV, ct=10-100mm)	$\Xi_{c,b}$, $\Lambda_{c,b}$
(ν (m~0))	K_L (m=500MeV, ct=10^{4}mm)	K_S	(m=2-5GeV,
e^- (m=511keV)	$\pi^\pm$ (m=140MeV, ct=10^{4}mm)	(m=500MeV, ct=30mm)	ct=0.1-0.5mm)
p (m=938MeV)	$K^\pm$ (m=500MeV, ct=10^{3}mm)		

You don’t “see” most of the SM particles!
You have to infer their existence

Test: have you ever seen dinosaurs? You “reconstruct” them from their decay products

Physics probed at Colliders

Colliders are best places to search for

Heavy objects
With short lifetime
That are rarely produced
That have a direct coupling to quarks/gluons or electrons

Are we sure that BSM falls in this category?
No, and actually, we only have evidence that BSM has gravitational interactions
Nonetheless there are compelling arguments that BSM can be seen at colliders

What is the scale of New Physics?

High Scale Wishes

small FCNC: $\dfrac{gF_{\mu\nu}\bar{\psi}H\sigma^{\mu\nu}\psi}{M_{\rm NP}^2}$

tiny neutrino masses: $\dfrac{(LH)^2}{M_{\rm NP}}$

slow proton decay: $\dfrac{UUDE}{M_{\rm NP}^2}$

Low Scale Wishes

small EDMs: $\mathrm{argdetY} \leq 10^{-10}$

↪ axion?

tiny vacuum energy: $\Lambda \approx M_{\rm NP}^4 \gg \left(10^{-3}\mathrm{eV}\right)^4$

↪ ?

light Higgs boson: $m_H^2 \approx M_{\rm NP}^2 \gg (125\mathrm{GeV})^2$

↪ light susy?

Where is everyone?

even new physics at few hundreds of GeV might be difficult to see and could escape our detection

- **compressed spectra**
- **displaced vertices**
- **no MET, soft decay products, long decay chains**
- **uncoloured new physics**

$\not{R}$-susy

Neutral naturalness
(twin Higgs, folded susy)

Relaxion

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↻ light susy?

Two approaches to make progress:

⊙ Theoretically motivated: UV gives constraints on IR (string, GUT, naturalness…)

⊙ Data driven: infer UV completions from IR data

Best objects at our disposal: Higgs, top, heavy mesons???

▹ **no MET, soft decay products, long decay chains**

▹ **uncoloured new physics**

Relaxion ◃

HEP with a Higgs boson

The Higgs discovery has been an important milestone for HEP
but it hasn't taught us much about **BSM** yet

typical Higgs coupling deformation: $\frac{\delta g_h}{g_h} \sim \frac{v^2}{f^2} = \frac{g_*^2 \, v^2}{\Lambda_{\rm BSM}^2}$

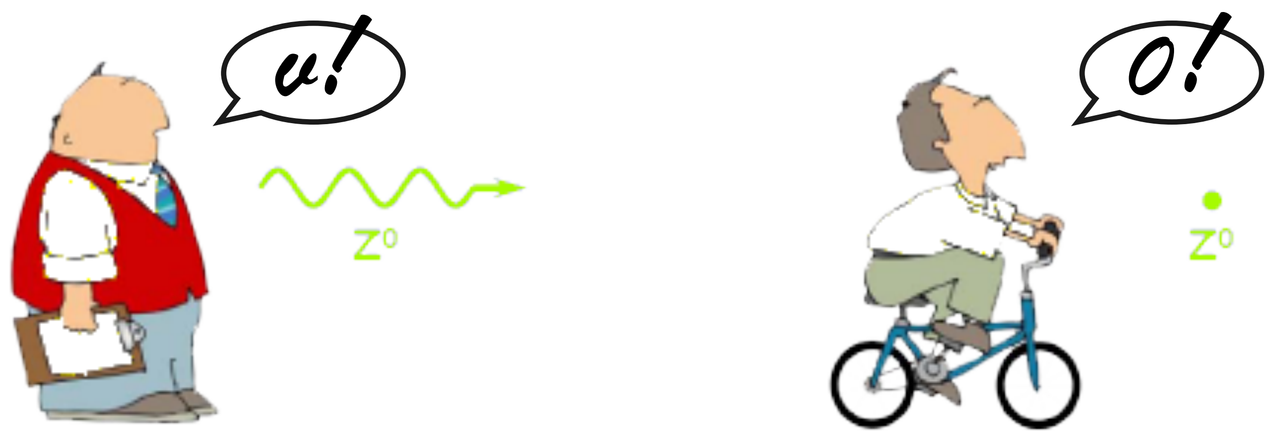
current (and future) LHC sensitivity
O(10-20)% ⇔ $\Lambda_{\rm BSM}$ > 500(g_*/g_{SM}) GeV

not doing better than direct searches unless in the case of strongly coupled new physics
(notable exceptions: New Physics breaks some structural features of the SM
e.g. flavor number violation as in h→$\mu\tau$)

Higgs precision program is very much wanted
to probe BSM physics

The longitudinal polarization of massive W, Z

a massless particle is never at rest: always possible to distinguish (and eliminate!) the longitudinal polarization



the longitudinal polarization is physical for a massive spin-1 particle

(pictures: courtesy of G. Giudice)

symmetry breaking: new phase with more degrees of freedom

$$\epsilon_{\|} = \left(\frac{|\vec{p}|}{M}, \frac{E}{M} \frac{\vec{p}}{|\vec{p}|} \right)$$ polarization vector grows with the energy

The longitudinal polarization of massive W, Z

a massless particle is never at rest: [redacted] distinguish (and [redacted]

3=2+1

Guralnik et al '64

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(pictures: courtesy of G. Giudice)

symmetry breaking: new phase with more degrees of freedom

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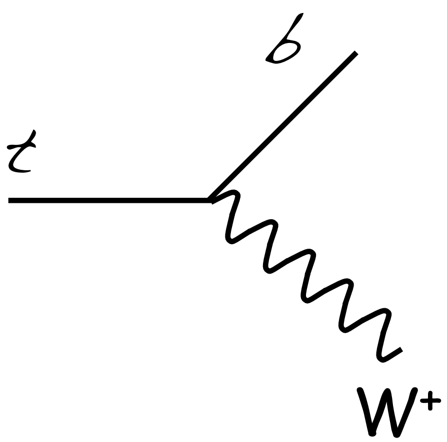
The BEH mechanism: “V_L=Goldstone bosons”

At high energy, the physics of the gauge bosons becomes simple



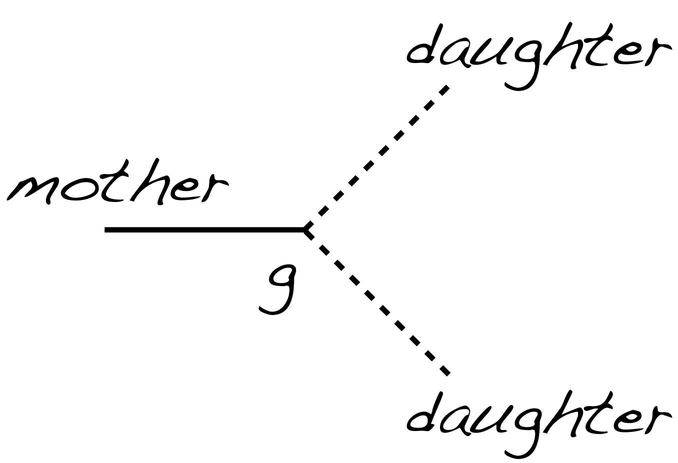
$$\Gamma(t \to bW_L) = \frac{g^2}{64\pi} \frac{m_t^2}{m_W^2} \frac{(m_t^2 - m_W^2)^2}{m_t^3}$$

$$\Gamma(t \to bW_T) = \frac{g^2}{64\pi} \frac{2(m_t^2 - m_W^2)^2}{m_t^3}$$

- at threshold ($m_t \sim m_W$) democratic decay
- at high energy ($m_t \gg m_W$) W_L dominates the decay

At high energy, the dominant degrees of freedom are W_L

~~ why you should be stunned by this result: ~~



we expect: (dimensional analysis) $\Gamma \sim g^2\, m_{\rm mother}$

instead $\Gamma \propto m^3_{\rm mother}$ means $g \propto m$ like the Higgs couplings!

very efficient way to get energy from the mother particle $\tau \ll \tau_{\rm naive}$

This is the physics that was understood at LEP
The pending question was then: is there something else?
That was the job of the LHC

The BEH mechanism: "V_L=Goldstone bosons"

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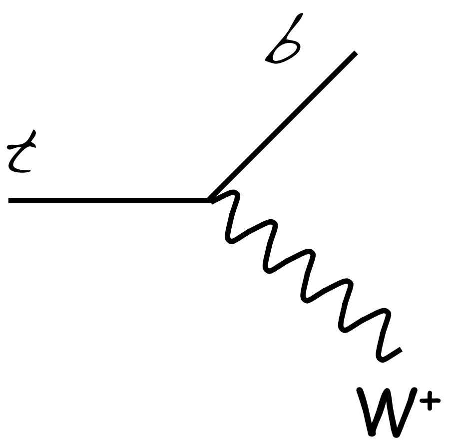

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- at threshold (m...
- ...dominates the decay

Goldstone equivalence theorem

$W^{\pm}_L, Z_L \approx SO(4)/SO(3)$

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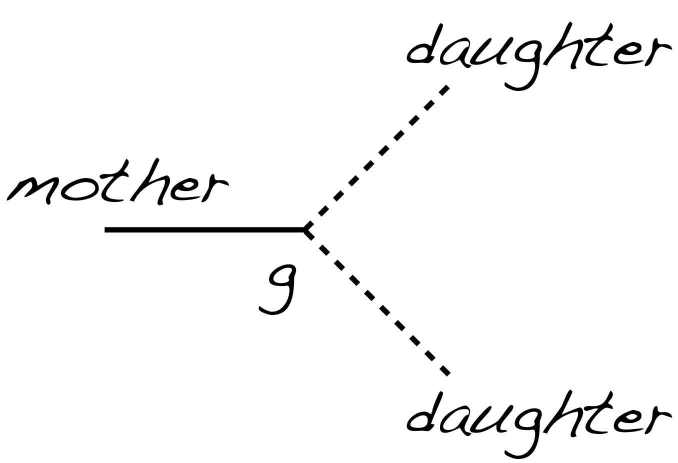

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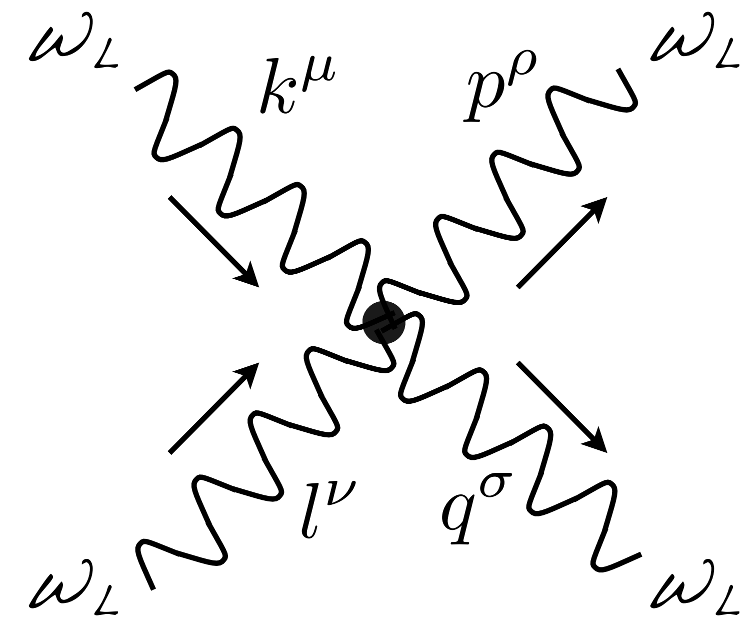
That was the job of the LHC

Call for extra degrees of freedom

NO LOSE THEOREM

Bad high-energy behaviour for the scattering of the longitudinal polarizations



$$\mathcal{A} = \epsilon_{\|}^{\mu}(k)\epsilon_{\|}^{\nu}(l)g^2\left(2\eta_{\mu\rho}\eta_{\nu\sigma} - \eta_{\mu\nu}\eta_{\rho\sigma} - \eta_{\mu\sigma}\eta_{\nu\rho}\right)\epsilon_{\|}^{\rho}(p)\epsilon_{\|}^{\sigma}(q)$$

$$\boxed{\mathcal{A} = g^2 \frac{E^4}{4M_W^4}}$$

violations of perturbative unitarity around E ~ M/√g (actually M/g)

Extra degrees of freedom are needed to have a good description of the W and Z masses at higher energies

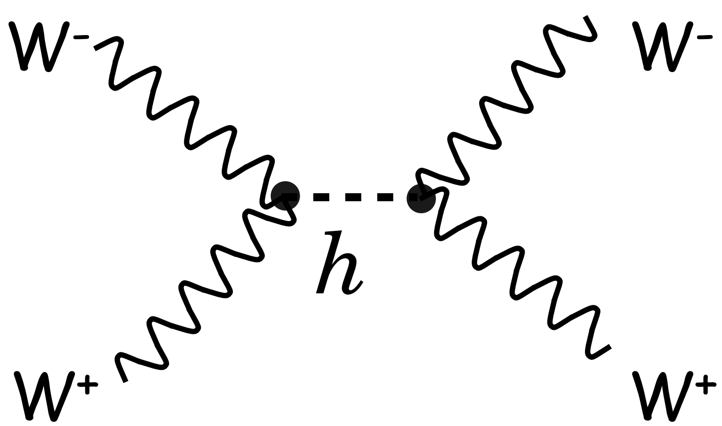
numerically: E ~ 3 TeV ⬅ the LHC was sure to discover something!

What is the SM Higgs?

A single scalar degree of freedom that couples to the mass of the particles

$$\mathcal{L}_{\mathrm{EWSB}} = m_W^2 W_\mu^+ W_\mu^+ \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - m_\psi \bar{\psi}_L \psi_R \left(1 + c\frac{h}{v}\right)$$

'a', 'b' and 'c' are arbitrary free couplings



$$\mathcal{A} = \frac{1}{v^2}\left(s - \frac{a^2 s^2}{s - m_h^2}\right)$$

growth cancelled for
a = 1
restoration of
perturbative unitarity

What is the Higgs the name of?

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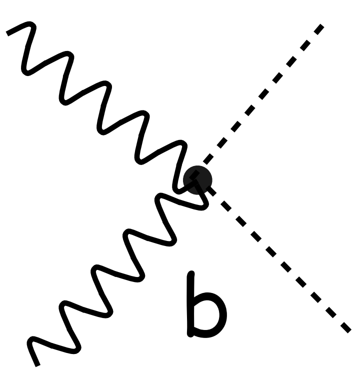
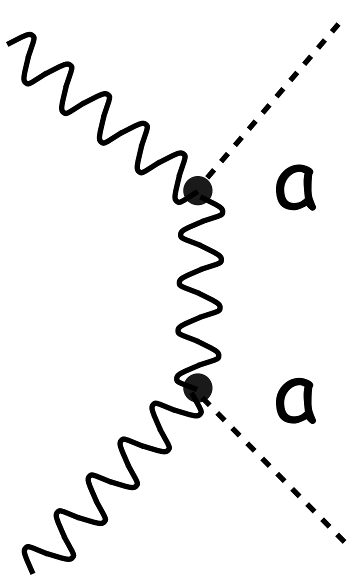
For a=1: perturbative unitarity in elastic channels WW $\to$ WW

For b = a²: perturbative unitarity in inelastic channels WW $\to$ hh

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10





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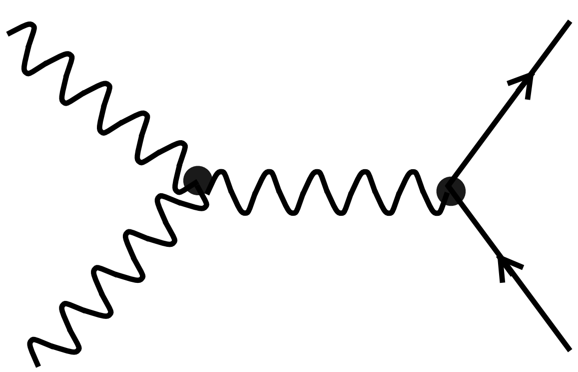

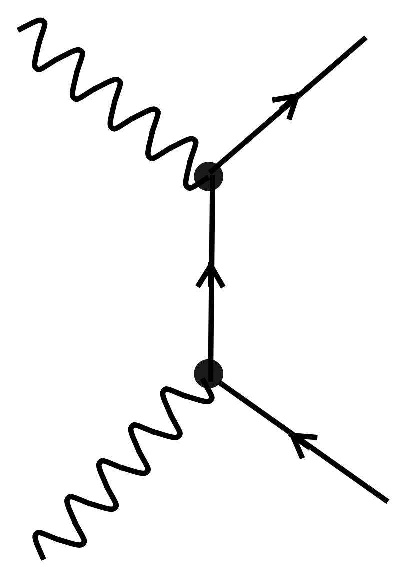

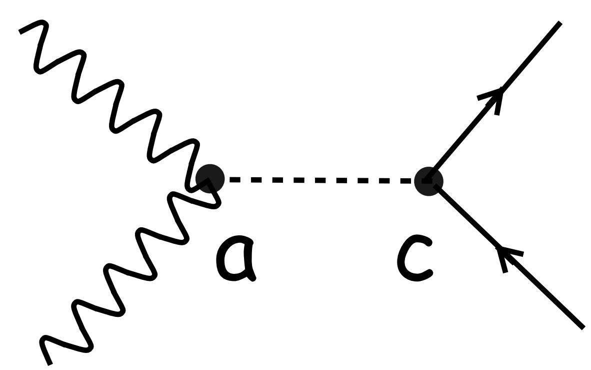

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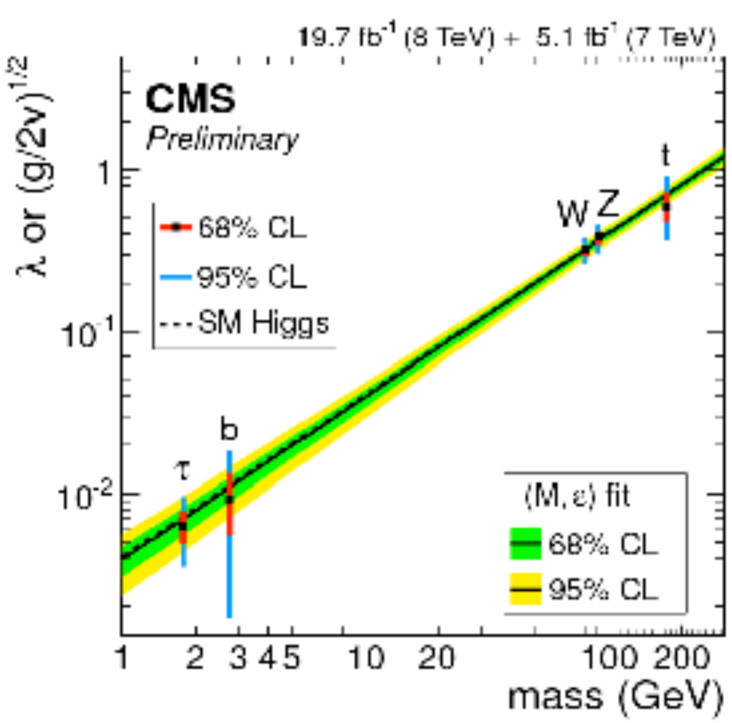


CMS PAS-HIG-14-009

Higgs couplings
are proportional
to the masses of the particles

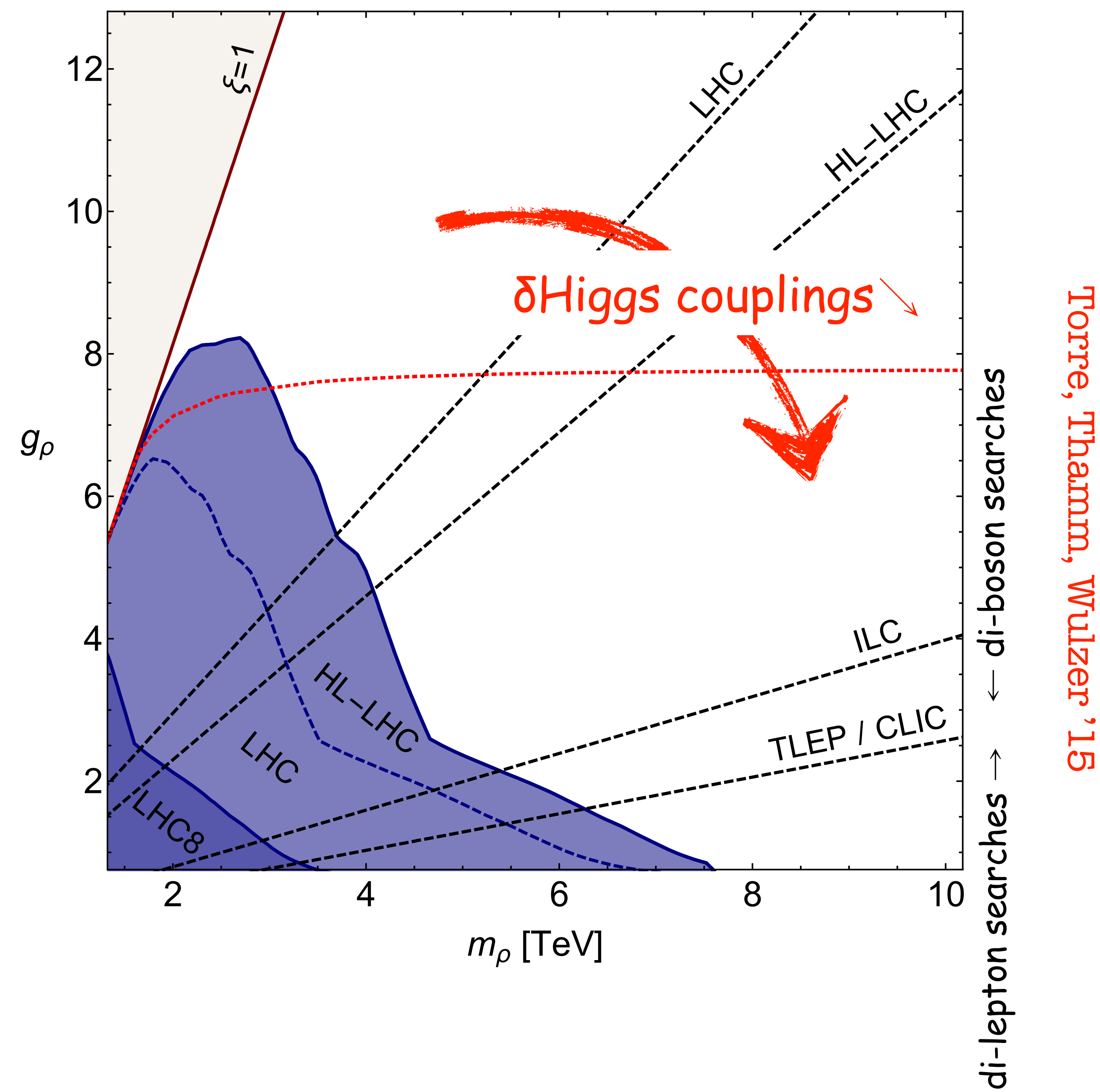
$$\lambda_\psi \propto \frac{m_\psi}{v}, \qquad \lambda_V^2 \equiv \frac{g_{VVh}}{2v} \propto \frac{m_V^2}{v^2}$$

Higgs couplings = door to BSM

heavy new physics induce deformation of the Higgs couplings
(in the same way that W exchange mediate muon decay and β decay)

DY production xs of resonances decreases as $1/g_\rho^2$

$$\frac{\delta g}{g} \sim \frac{g_*^2 v^2}{\Lambda_{\rm BSM}^2} \sim \left(\frac{g_*}{0.3}\right)^2 \left(\frac{1\text{TeV}}{\Lambda}\right)^2 0.5\%$$



Higgs coupling precision measurements
are an indirect way to probe
heavy (strongly coupled) new physics
that cannot be observed directly

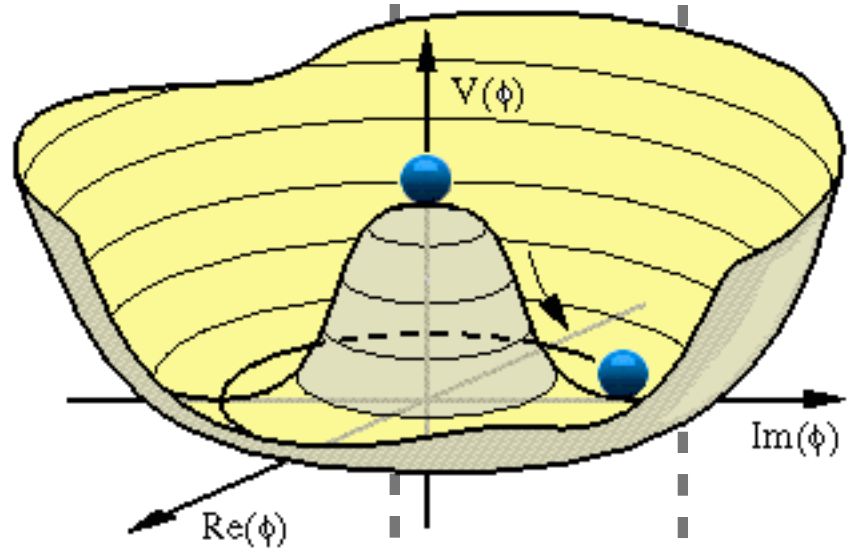
Higgs Mechanism

Symmetry of the Lagrangian

$$SU(2)_L \times U(1)_Y$$

Higgs Doublet

$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$



Symmetry of the Vacuum

$$U(1)_{e.m.}$$

Vacuum Expectation Value

$$\langle H \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \quad \text{with} \quad v \approx 246 \text{ GeV}$$

$$D_\mu H = \partial_\mu H - \frac{i}{2} \begin{pmatrix} g W^3_\mu + g' B_\mu & \sqrt{2} g W^+_\mu \\ \sqrt{2} g W^-_\mu & -g W^3_\mu + g' B_\mu \end{pmatrix} H \quad \text{with} \quad \mathrm{W}^\pm_\mu = \frac{1}{\sqrt{2}} \left(\mathrm{W}^1_\mu \mp \mathrm{W}^2_\mu \right)$$

$$|D_\mu H|^2 = \frac{1}{4}\, g^2 v^2\, W^+_\mu W^{-\,\mu} + \frac{1}{8} \left(W^3_\mu \; B_\mu \right) \begin{pmatrix} g^2 v^2 & -g g' v^2 \\ -g g' v^2 & g'^2 v^2 \end{pmatrix} \begin{pmatrix} W^{3\,\mu} \\ B^\mu \end{pmatrix}$$

- Gauge boson spectrum
  - electrically charged bosons $M_W^2 = \frac{1}{4} g^2 v^2$
  - electrically neutral bosons $Z_\mu = c W^3_\mu - s B_\mu$, $\gamma_\mu = s W^3_\mu + c B_\mu$

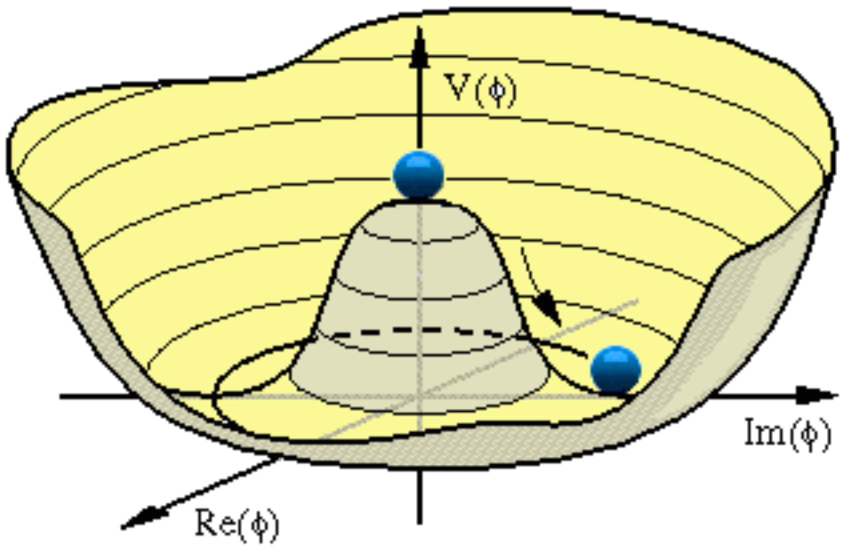
Weak mixing angle

$$c = \frac{g}{\sqrt{g^2 + g'^2}} \qquad s = \frac{g'}{\sqrt{g^2 + g'^2}}$$

$$M_Z^2 = \frac{1}{4}(g^2 + g'^2) v^2$$

$$M_\gamma = 0$$

Higgs and EW vacuum Stability



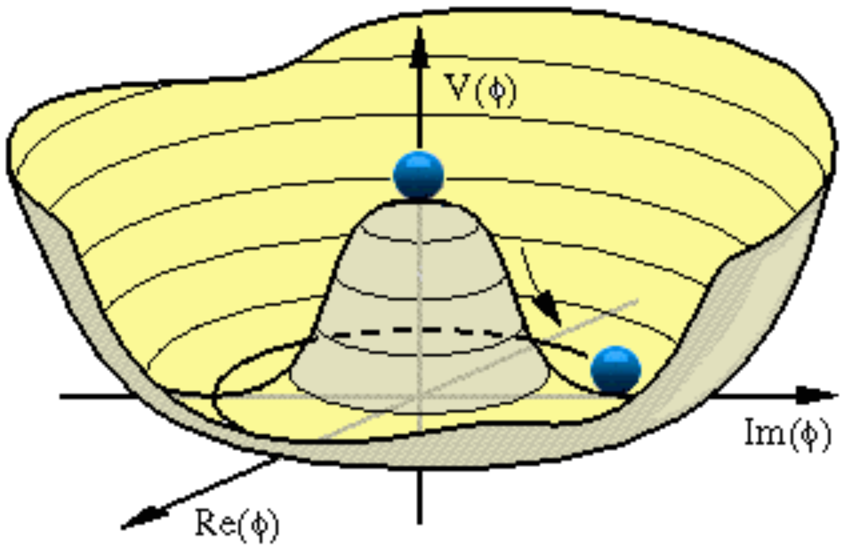
$$\boxed{V(h) = -\frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4}$$

vev: $v^2 = \mu^2/\lambda$ mass: $m_H^2 = 2\lambda v^2$

the vacuum is not empty even classically $(\hbar \to 0)$

How is Quantum Mechanics changing the picture?

Higgs and EW vacuum Stability



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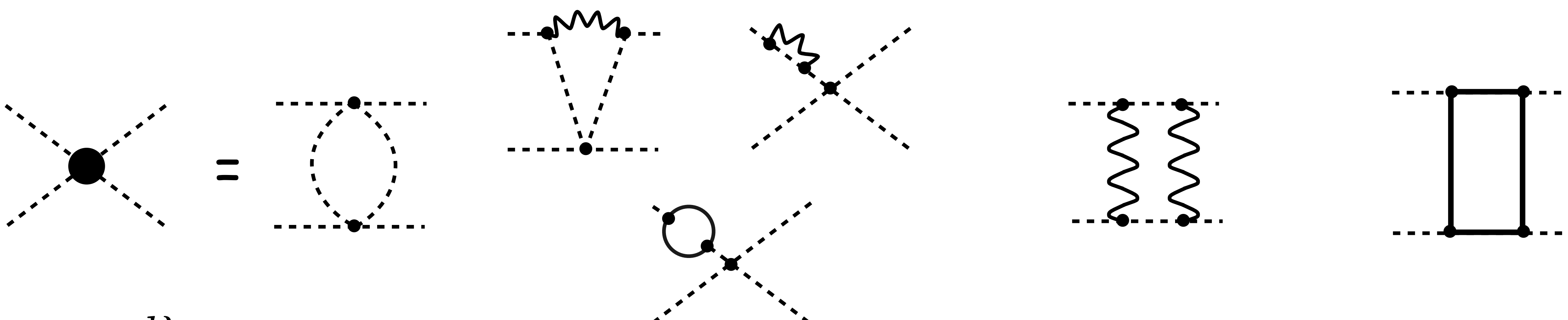


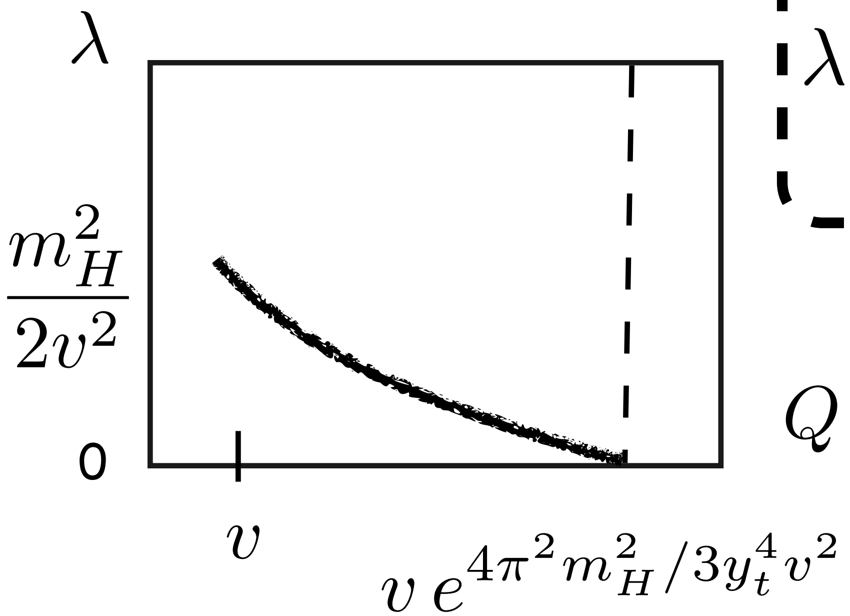
$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \tfrac{3}{8}g'^4 + \tfrac{3}{4}g'^2 g^2 + \tfrac{9}{8}g^4 - 6y_t^4 +$$ Higher loops Small Yukawa

Higgs and EW vacuum Stability

Small mass (y_t dominated RGE)

$$\lambda(Q) = \lambda_0 - \frac{\frac{3}{8\pi^2} y_0^4 \ln \frac{Q}{Q_0}}{1 - \frac{9}{16\pi^2} y_0^2 \ln \frac{Q}{Q_0}}$$

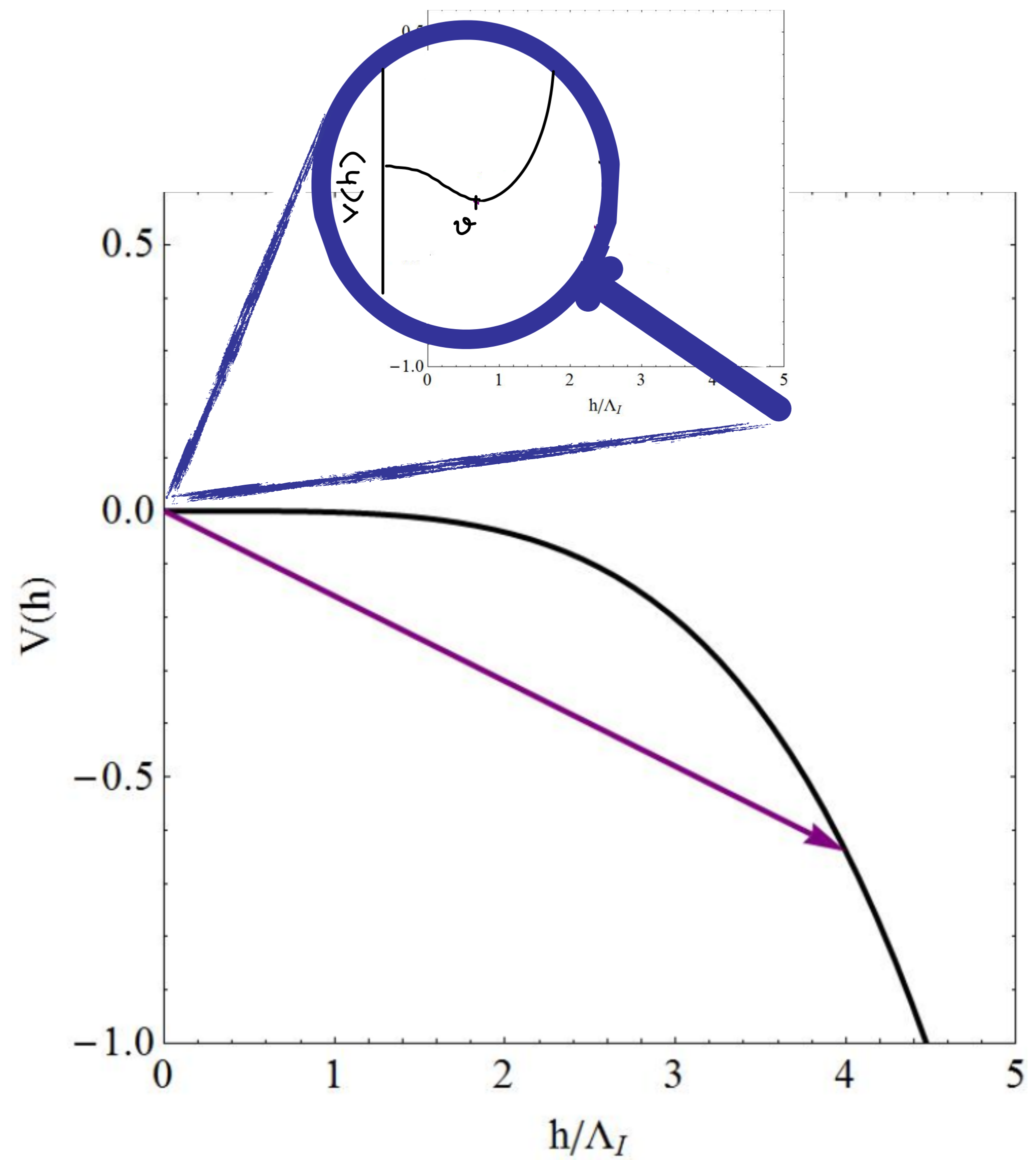
Linde '76, '80
Weinberg '76
Maini et al '78, '79
Politzer, Wolfram '79
Lindner '86
+...



$\lambda < 0 \;\; \Rrightarrow$ potential unbounded from below

$$\Lambda \leq v\, e^{4\pi^2 m_H^2/3y_t^4 v^2}$$

New physics should appear before that point to restore stability



Higgs and EW vacuum Stability

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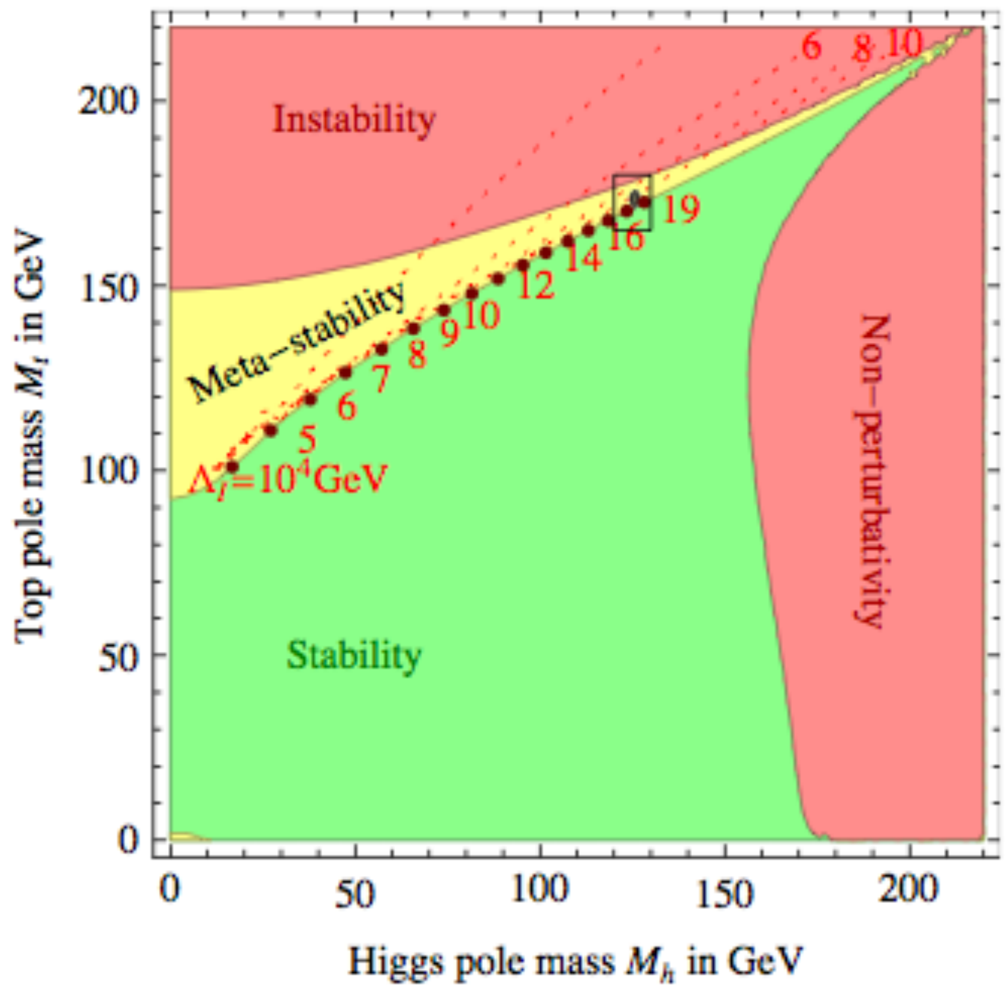
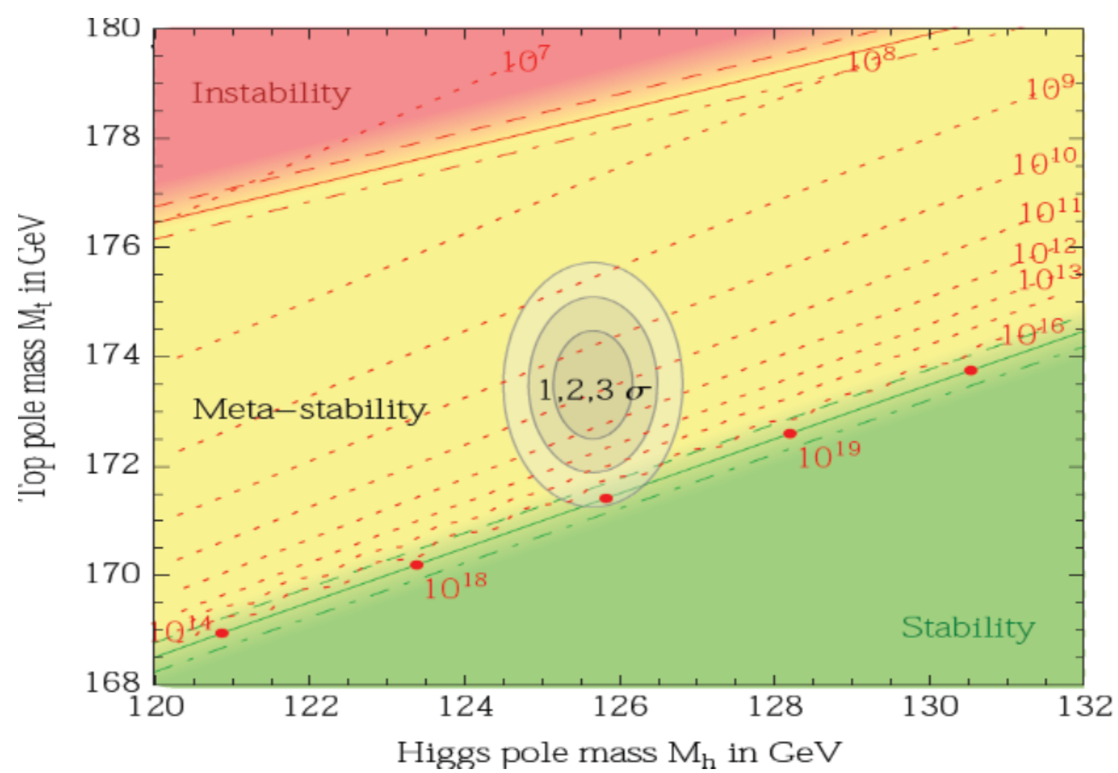
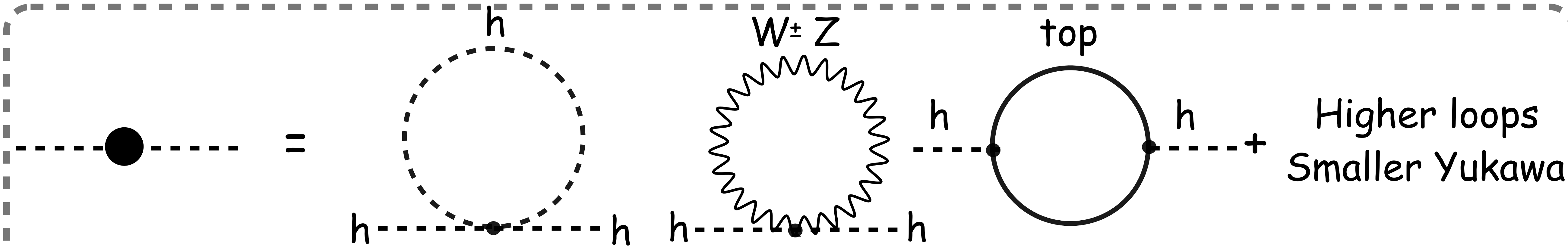




Buttazzo et al '13

Quantum Instability of the Higgs Mass

so far we looked only at the RG evolution of the Higgs quartic coupling (dimensionless parameter). The Higgs mass has a totally different behavior: it is highly dependent on the UV physics, which leads to the so called hierarchy problem



$$\int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2-m^2} \propto \Lambda^2 \qquad \int \frac{d^4k}{(2\pi)^4}\frac{k^2}{(k^2-m^2)^2} \propto \Lambda^2$$

Weisskopf '39
't hooft '79

$$\delta m_H^2 = \left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right)\frac{3G_F\Lambda^2}{8\sqrt{2}\pi^2}$$

$$m_H^2 \sim m_0^2 - (115\ \mathrm{GeV})^2\left(\frac{\Lambda}{700\ \mathrm{GeV}}\right)^2$$

Naturalness principle @ work

Following the arguments of Wilson, 't Hooft (and others):
only small numbers associated to the breaking of a symmetry survive quantum corrections

Introduce new degrees of freedom to regulate the high-energy behavior

Beautiful examples of naturalness to understand the need of "new" physics

see for instance Giudice '13 (and refs. therein) for an account

- the need of the **positron** to screen the electron self-energy: $\Lambda < m_e/\alpha_{\rm em}$
- the **rho meson** to cutoff the EM contribution to the charged pion mass: $\Lambda < \delta m_\pi^2/\alpha_{\rm em}$
- the kaon mass difference regulated by the **charm** quark: $\Lambda^2 < \dfrac{\delta m_K}{m_K}\dfrac{6\pi^2}{G_F^2 f_K^2 \sin^2\theta_C}$
- the light **Higgs** boson to screen the EW corrections to gauge bosons self-energies
- ...
- **new physics** at the weak scale to cancel the UV sensitivity of the Higgs mass?

The different paths to Higgs naturalness

- Single vacuum

the low Higgs mass is screened from
large quantum corrections by

1. a symmetry (Susy, PQ)
2. a form factor (composite Higgs)
3. a low UV scale (xdim, RS, large N…)
4. a combination of the above

- Multiple vacua

many metastable vacua
with a vast range of values for m_H
Dynamical (or anthropic selection) of $m_H \ll \Lambda$

1. anthropic multiverse
2. NNaturalness with 10^{16} copies of SM
3. relaxion and cosmological scanning
with non-trivial back reaction

How to Stabilize the Higgs Potential

The spin trick

a particle of spin s: 2s+1 polarization states

...with the only exception of a particle moving at the speed of light

... fewer polarization states

Spin 1	Gauge invariance	$\longrightarrow$	no longitudinal polarization	$\searrow$ m=0
Spin 1/2	Chiral symmetry	$\longrightarrow$	only one helicity	$\nearrow$ m=0

If the symmetries are broken, the radiative mass will be set by the scale of symmetry breaking, not the UV/Planck scale

... but the Higgs is a spin 0 particle

Symmetries to Stabilize a Scalar Potential

Supersymmetry

fermion ~ boson

Higher Dimensional Lorentz invariance

$\Lleftarrow$ gauge-Higgs unification models

[Manton '79, Fairlie 79, Hosotani '83 +...]

$$A_\mu \sim A_5$$

4D spin 1

4D spin 0

These symmetries cannot be exact symmetry of the Nature. They have to be broken. We want to look for a soft breaking in order to preserve the stabilization of the weak scale.

Other approaches to the hierarchy problem

the hierarchy problem can be reformulated as:
why the weak scale so much smaller than the Planck scale of quantum gravity?

$$M_{\mathrm{Pl}} = \sqrt{\frac{\hbar c}{G_{\mathrm{N}}}} \sim 10^{19}\,\mathrm{GeV}/c^2$$

✳ **large extra dimensions (~1mm)**: dilute gravitational interactions into large volume not accessible to other forces. Scale of quantum gravity around 1TeV. Black holes could be produced at the LHC.

✳ **many different species**: $M_* = M_{Pl}/\sqrt{N}$. $M_* \sim 1$TeV if $N \sim 10^{32}$

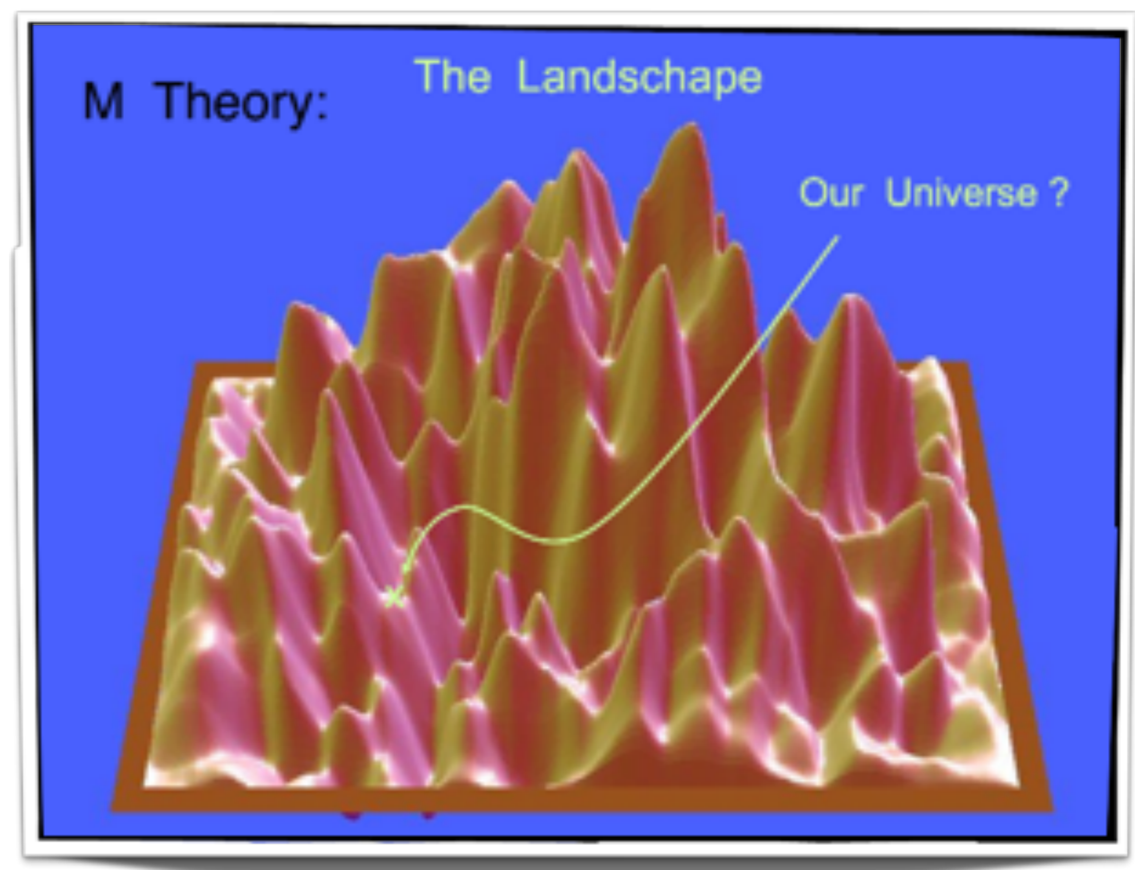
✳ **composite Higgs**: above the scale of compositeness, the Higgs boson dissolves into its fundamental constituents. Momentum-dependent form factors cut off the divergent integrals

✳ ~~break EW symmetry **without a Higgs boson**, aka technicolor models~~. Ruled out by the Higgs boson discovery

Could the EW scale accidentally small?

The Sun and the Moon have the same angular size seen from Earth. Why?

- Dynamical explanation?
- Accident?
- Multiverse... there exist many (exo)planets with moons!
- Anthropic selection (probably not for the Moon, but maybe for the Higgs)

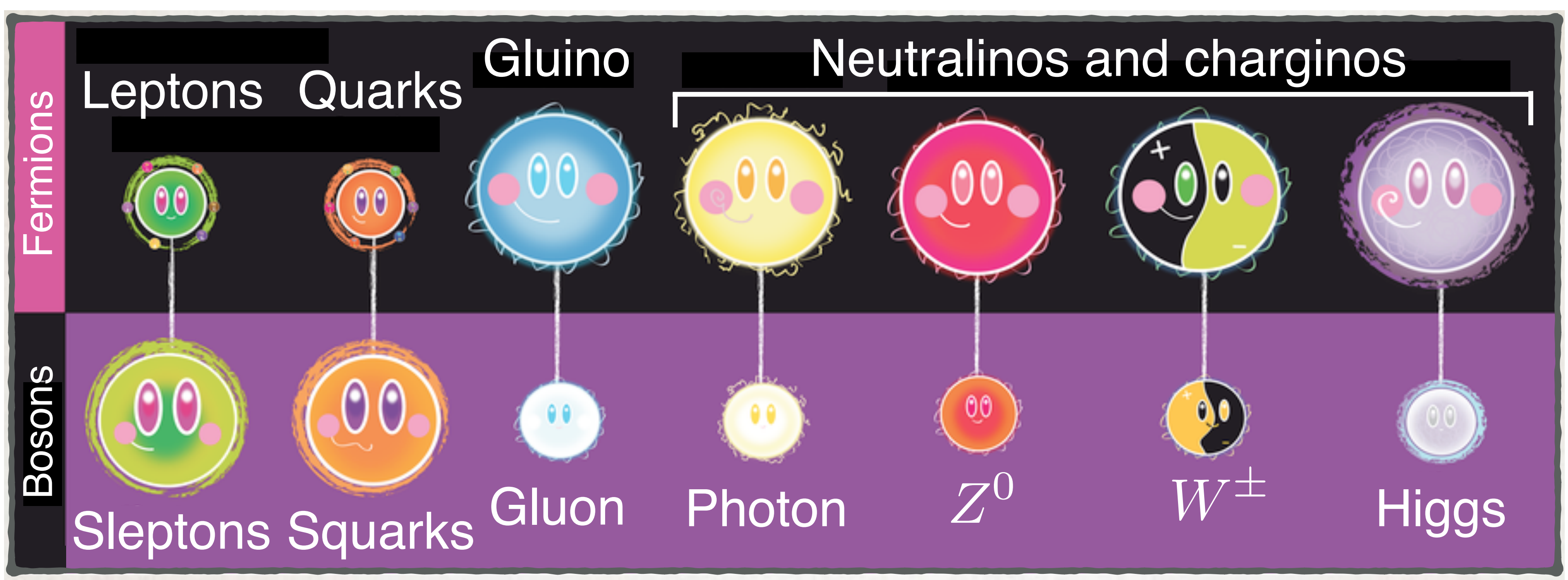


Supersymmetry

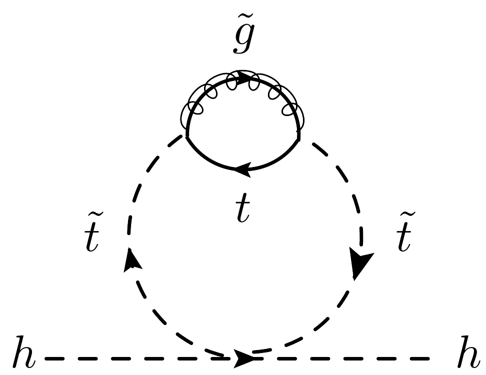
Minimal Supersymmetric SM - Matter Content

	particles				Sparticles		
quarks	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	u_R	d_R	*squarks*	$\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$	$\tilde{u}_R$	$\tilde{d}_R$
leptons	$\begin{pmatrix} e_L \\ \nu_L \end{pmatrix}$	e_R		*sleptons*	$\begin{pmatrix} \tilde{e}_L \\ \tilde{\nu}_L \end{pmatrix}$	$\tilde{e}_R$	
Higgs doublets	H_1 (hypercharge $= -1$) H_2 (hypercharge $= +1$)			*Higgsinos*	$\tilde{H}_1$ $\tilde{H}_2$		
	$W_\mu^\pm, W_\mu^3$			*winos*	$\tilde{\omega}^\pm, \tilde{\omega}^3$		
	B_μ			*bino*	$\tilde{b}$		
	G_μ^A	$A = 1, \ldots, 8$		*gluinos*	$\tilde{g}^A$		

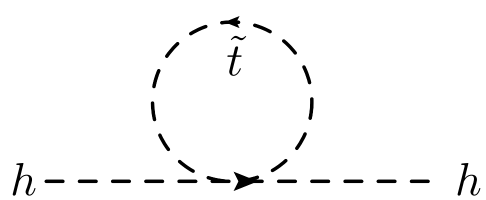
(G. Giudice HCPSS'09)



Probing natural SUSY

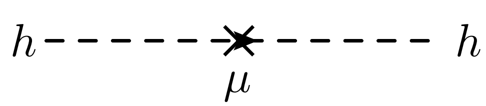


$$\delta m_H^2 \sim -\frac{y_t^2}{\pi^2}\frac{\alpha_s}{\pi} m_{gluino}^2 \left(\log\frac{\Lambda}{m_{gluino}}\right)^2$$



$$\delta m_H^2 \sim -\frac{3}{8\pi^2} y_t^2 m_{stop}^2 \log\frac{\Lambda}{m_{stop}}$$

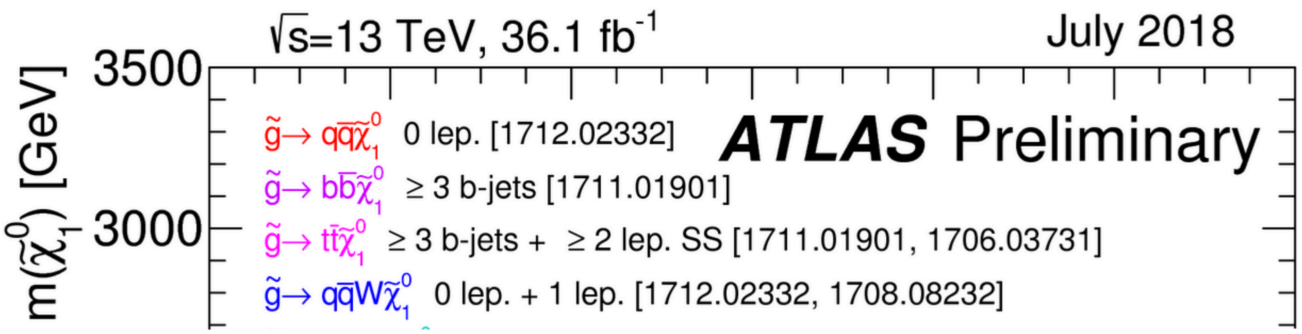
light stops, light gluinos!
well tested @ LHC
but most questionable predictions
(RG effects)

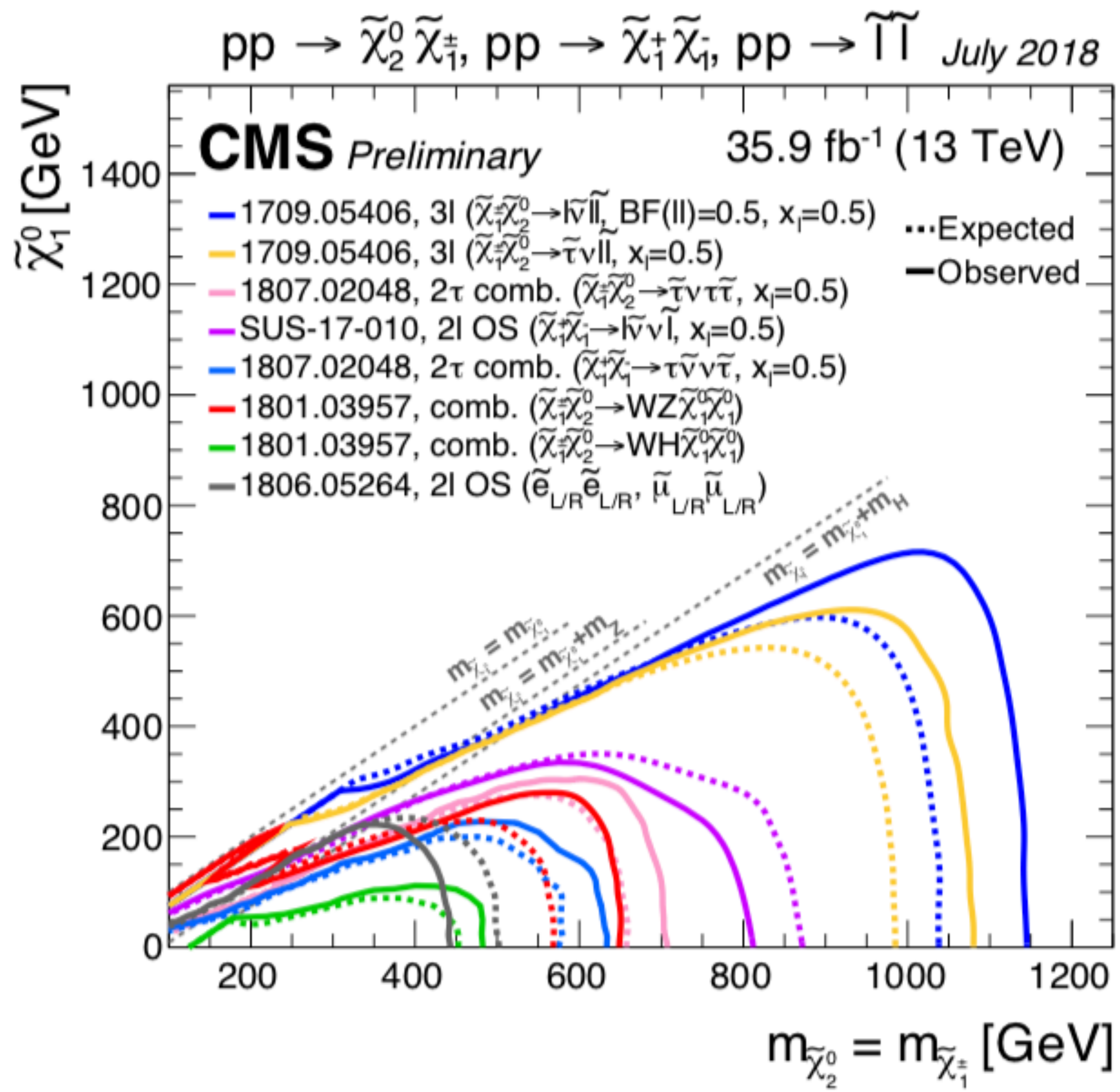


$$\delta m_H^2 \sim |\mu|^2$$

light Higgsinos!
very low sensitivity @ LHC
ILC needed to probe the other side

Probing natural SUSY





Probing natural SUSY

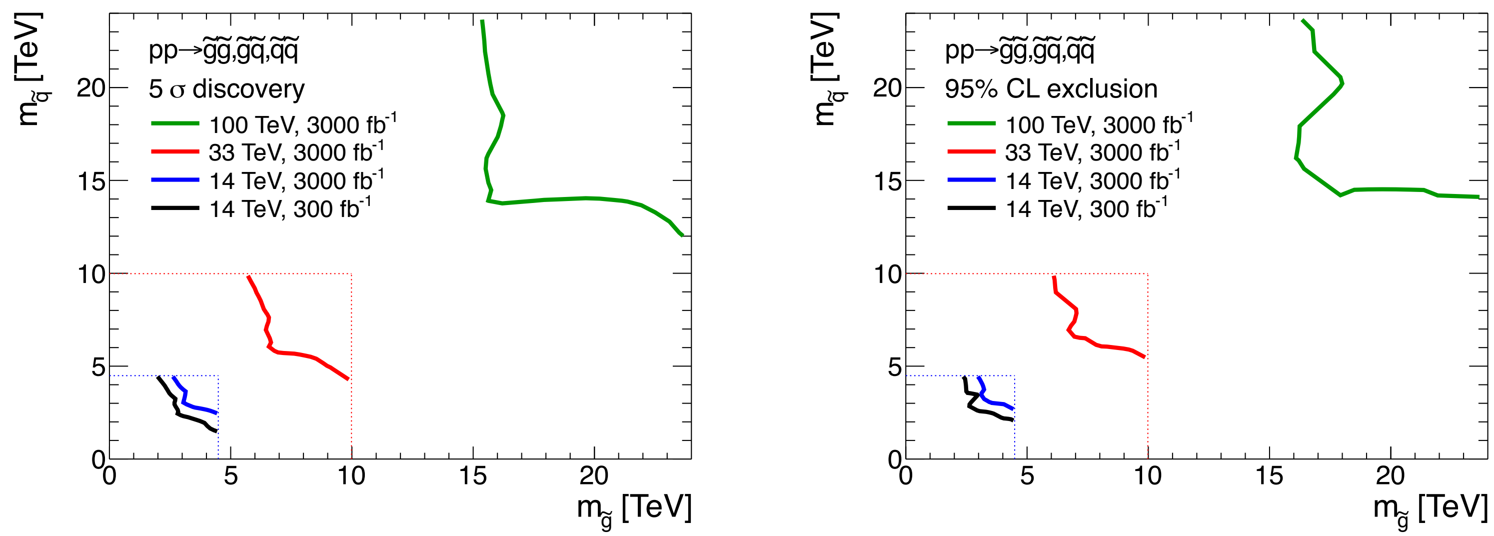
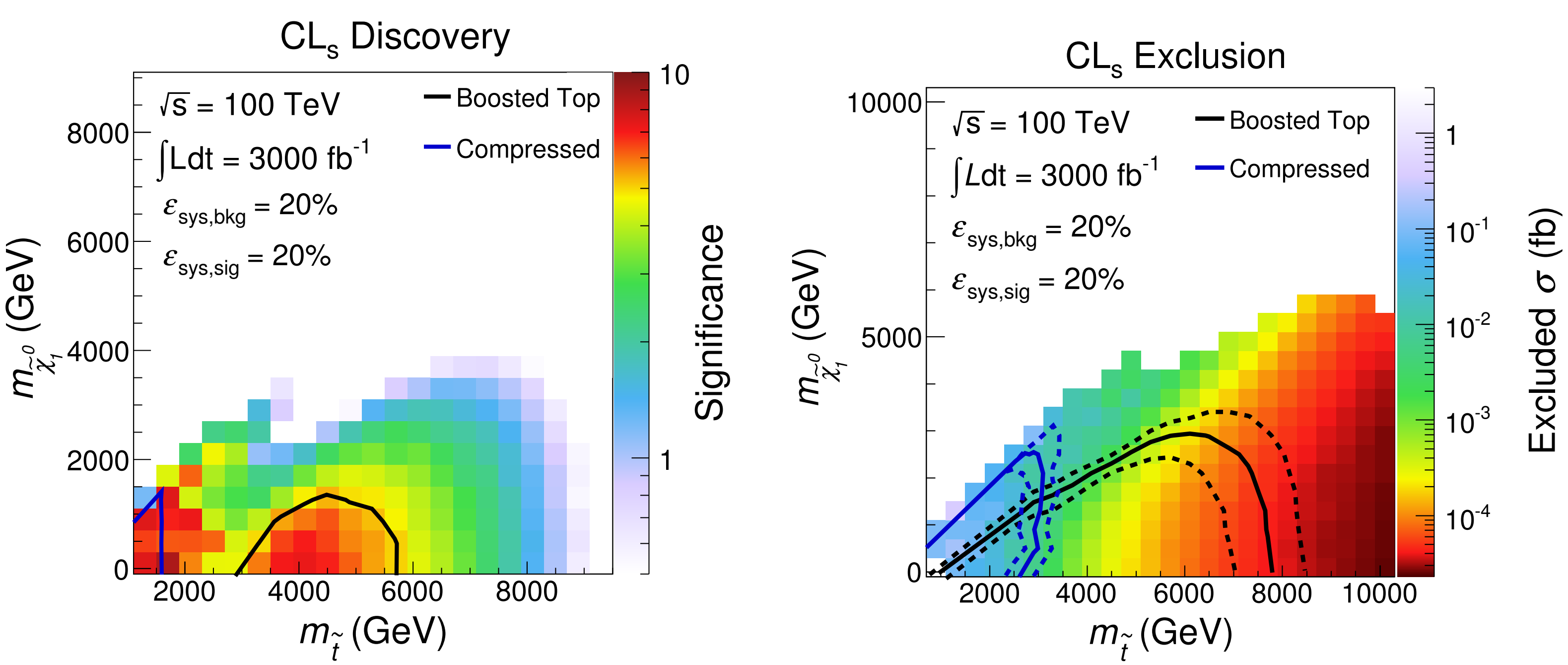


Fig. 16: Results for the gluino-squark-neutralino model. The neutralino mass is taken to be 1 GeV. The left [right] panel shows the $5\,\sigma$ discovery reach [95% CL exclusion] for the four collider scenarios studied here. A 20% systematic uncertainty is assumed and pile-up is not included.



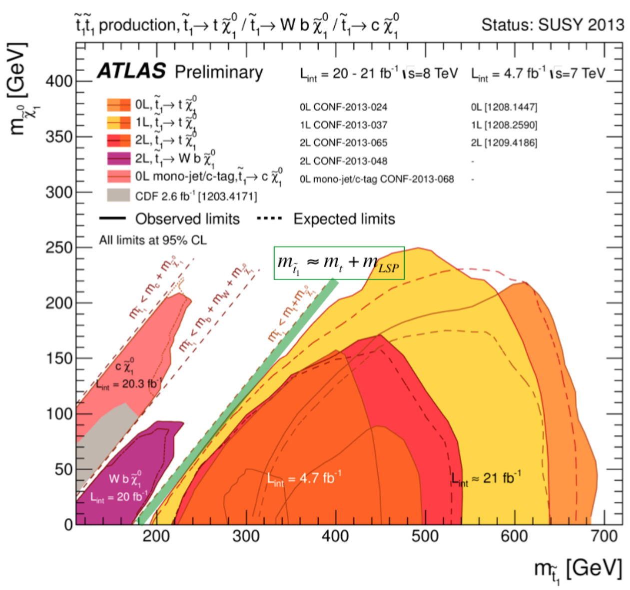
Collider	Energy	Luminosity	Cross Section	Mass
LHC8	8 TeV	20.5 fb^{-1}	10 fb	650 GeV
LHC	14 TeV	300 fb^{-1}	3.5 fb	1.0 TeV
HL LHC	14 TeV	3 ab^{-1}	1.1 fb	1.2 TeV
HE LHC	33 TeV	3 ab^{-1}	91 ab	3.0 TeV
FCC-hh	100 TeV	1 ab^{-1}	200 ab	5.7 TeV

Fig. 12: Left: Discovery potential and Right: Projected exclusion limits for 3000 fb^{-1} of total integrated luminosity at $\sqrt{s} = 100$ TeV. The solid lines show the expected discovery or exclusion obtained from the boosted top (black) and compressed spectra (blue) searches. In the boosted regime we use the $\not\!\!E_T$ cut that gives the strongest exclusion for each point in the plane. The dotted lines in the left panel show the $\pm 1\sigma$ uncertainty band around the expected exclusion.

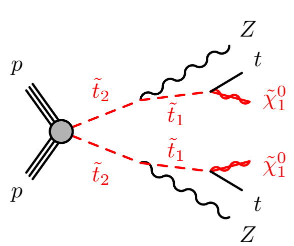
Natural SUSY: beyond standard searches

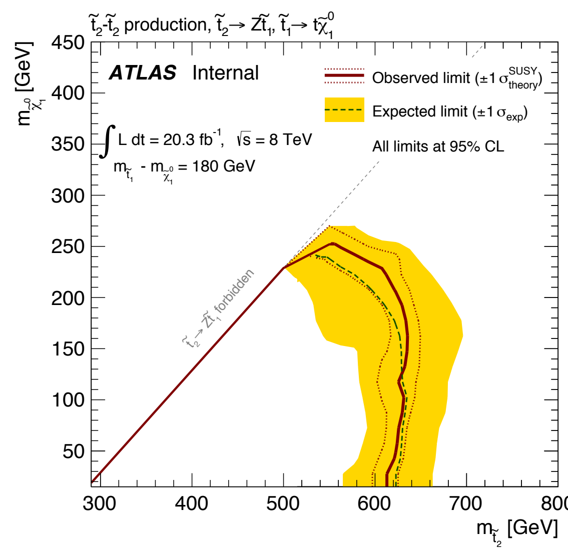
Searching for light stop from heavy stop decay

~ RUN 1 ~



- 2012 (20 fb^{-1}): stops searches based on $\tilde{t}_1\tilde{t}_1$ production, with $\tilde{t}_1 \to t\tilde{\chi}_1^0$ or $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$
- No sensitivity for $\tilde{t}_1 \to t\tilde{\chi}_1^0$ with $m_{\tilde{t}_1} \gtrsim m_{\tilde{\chi}_1^0} + m_t$: very similar to SM $t\bar{t}$
- **[New at the LHC]** Production of the heavier stop mass eigenstate ($\tilde{t}_2$) relying on the $\tilde{t}_2 \to Z\tilde{t}_1$ decay to reduce $t\bar{t}$ → Signature: $Z(\ell^+\ell^-)+\ell+b+E_T^{miss}$
- Eur. Phys. J. C **74** (2014) 2883 (20 fb^{-1})

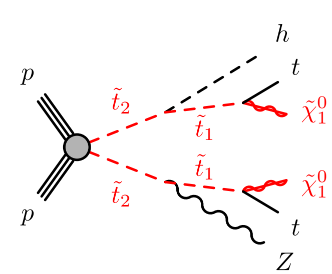


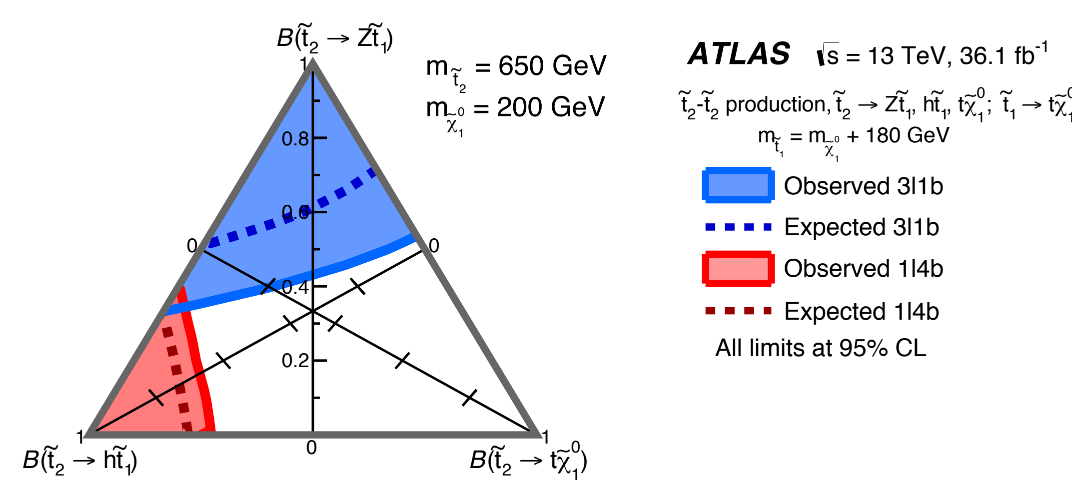


X. Poveda @ DESY'17

~ RUN 2 ~

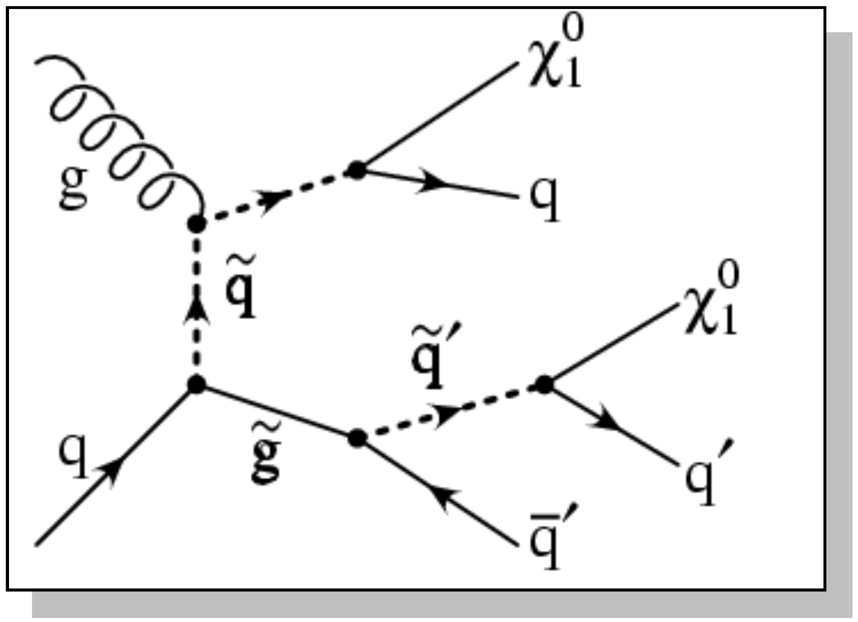
- ATLAS-CONF-2016-038 (13 fb^{-1}): explore $\tilde{t}_2 \to Z\tilde{t}_1$ with $3\ell+b+E_T^{miss}$
- JHEP **1708** (2017) 006 (36 fb^{-1}): analysis extended to $\tilde{t}_2 \to h\tilde{t}_1$ with $1\ell+4b+E_T^{miss}$
- Interpretations for varying BRs in $\tilde{t}_2 \to h\tilde{t}_1/Z\tilde{t}_1$ and also for $\tilde{t}_1 \to t\chi_2^0$, $\chi_2^0 \to h/Z\tilde{\chi}_1^0$

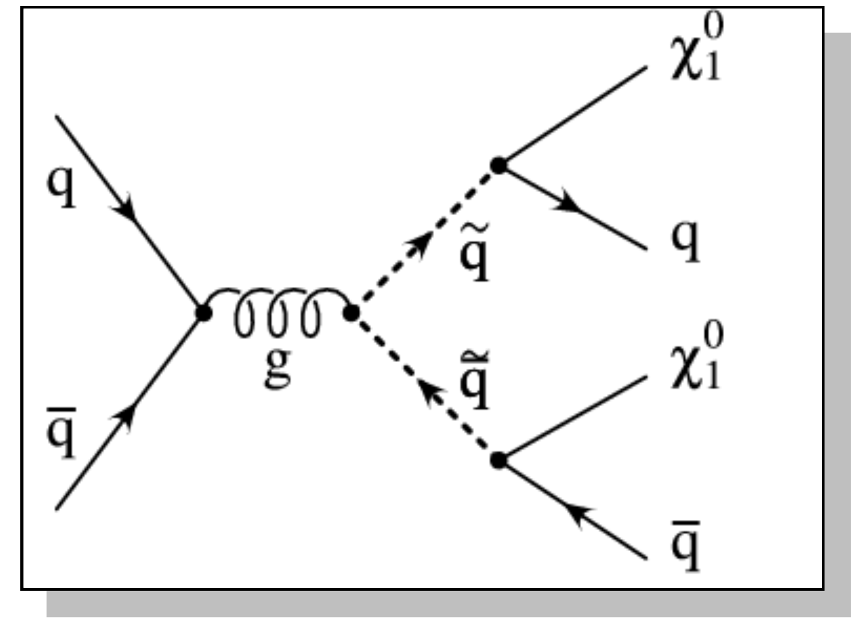




SUSY searches

gluinos and squarks are produced by QCD interactions





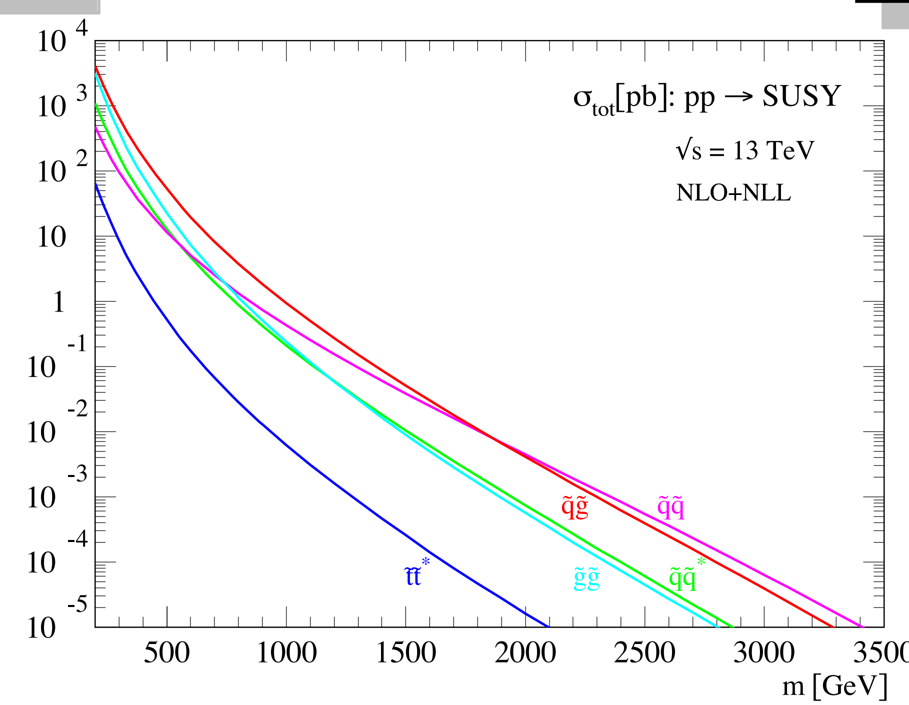
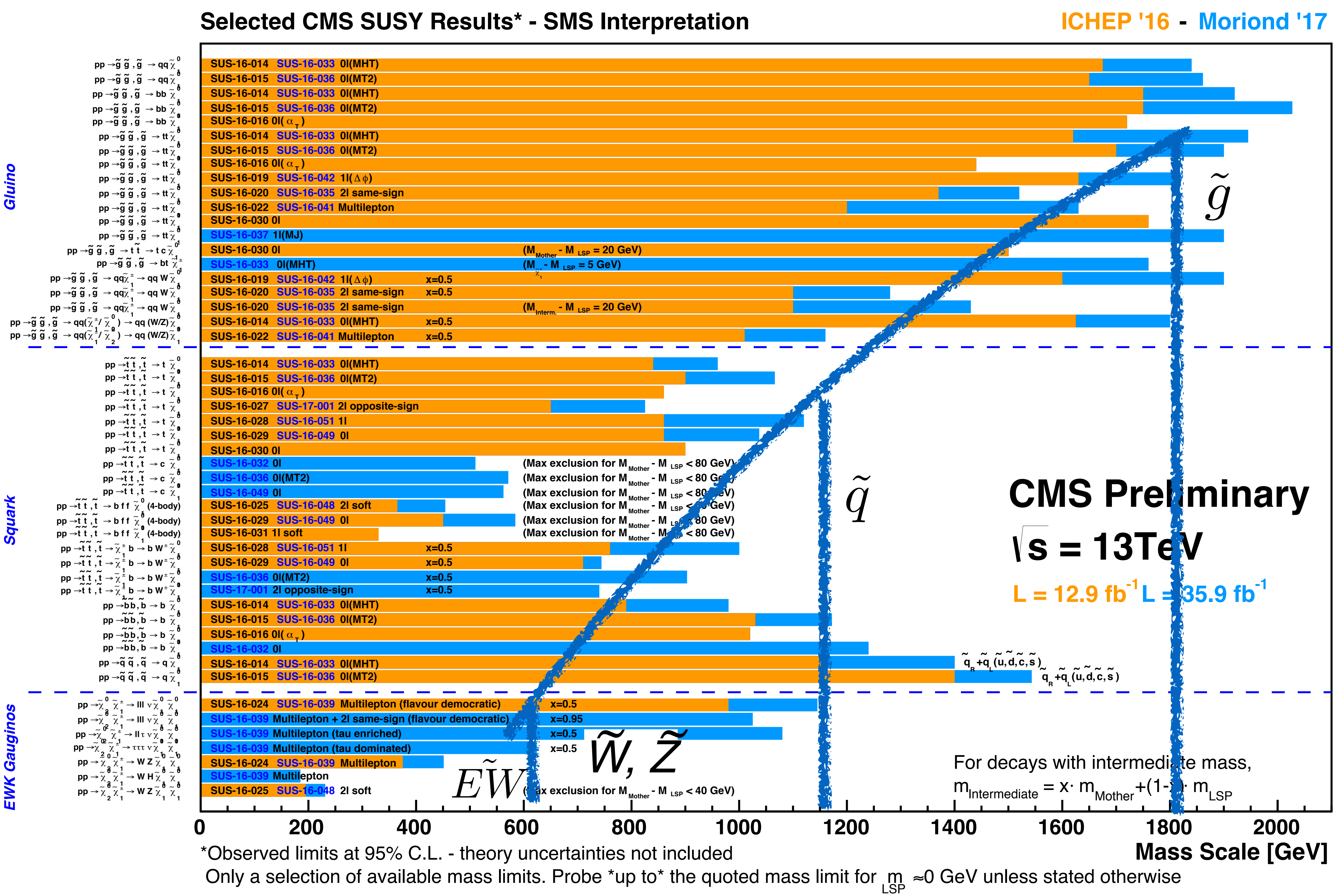


Figure 1: NLO+NLL production cross sections for the case of equal degenerate squark and gluino masses as a function of mass at $\sqrt{s} = 13$ TeV.

LSP (lightest supersymmetric particle) is stable ≈ Missing Energy

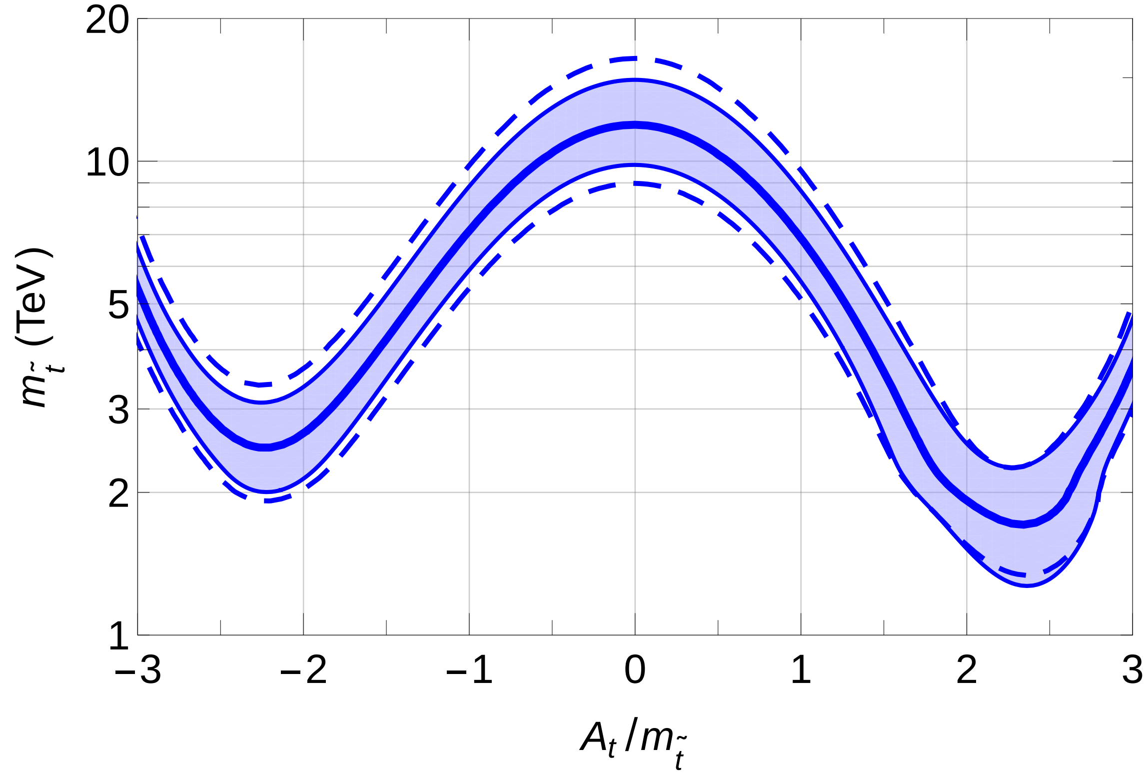
SUSY searches

gluinos and squarks are produced by QCD interactions



LSP (lightest supersymmetric particle) is stable ≈ Missing Energy

The MSSM Higgs mass and stop searches



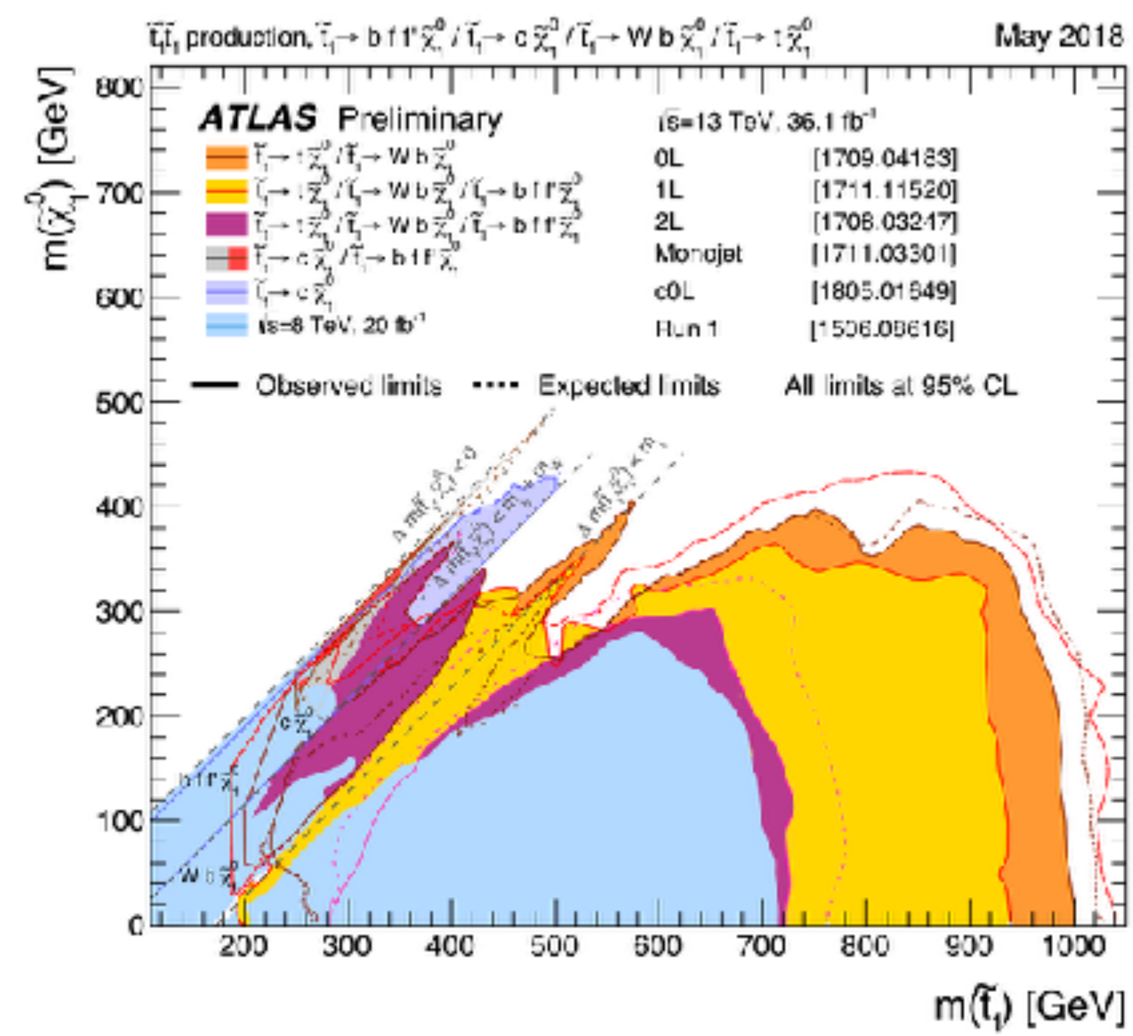
Pardo Vega, Villadoro '15 + many others

One needs heavy stop(s) to obtain a 125GeV Higgs (within the MSSM)

Figure 5: *Allowed values of the OS stop mass reproducing $m_h = 125$ GeV as a function of the stop mixing, with $\tan\beta = 20$, $\mu = 300$ GeV and all the other sparticles at 2 TeV. The band reproduce the theoretical uncertainties while the dashed line the 2σ experimental uncertainty from the top mass. The wiggle around the positive maximal mixing point is due to the physical threshold when $m_{\tilde{t}}$ crosses $M_3 + m_t$.*

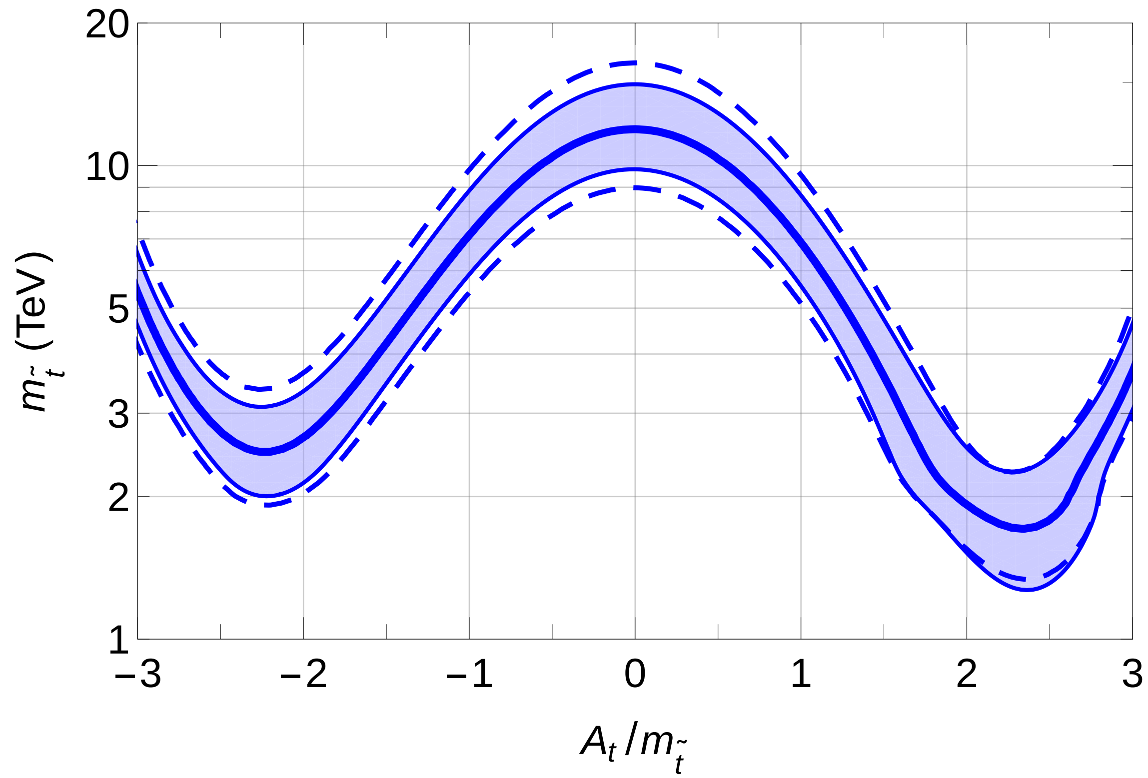
Current and future bounds on stop mass

LHC (2018)



The MSSM Higgs mass and stop searches

Pardo Vega, Villadoro '15 + many others



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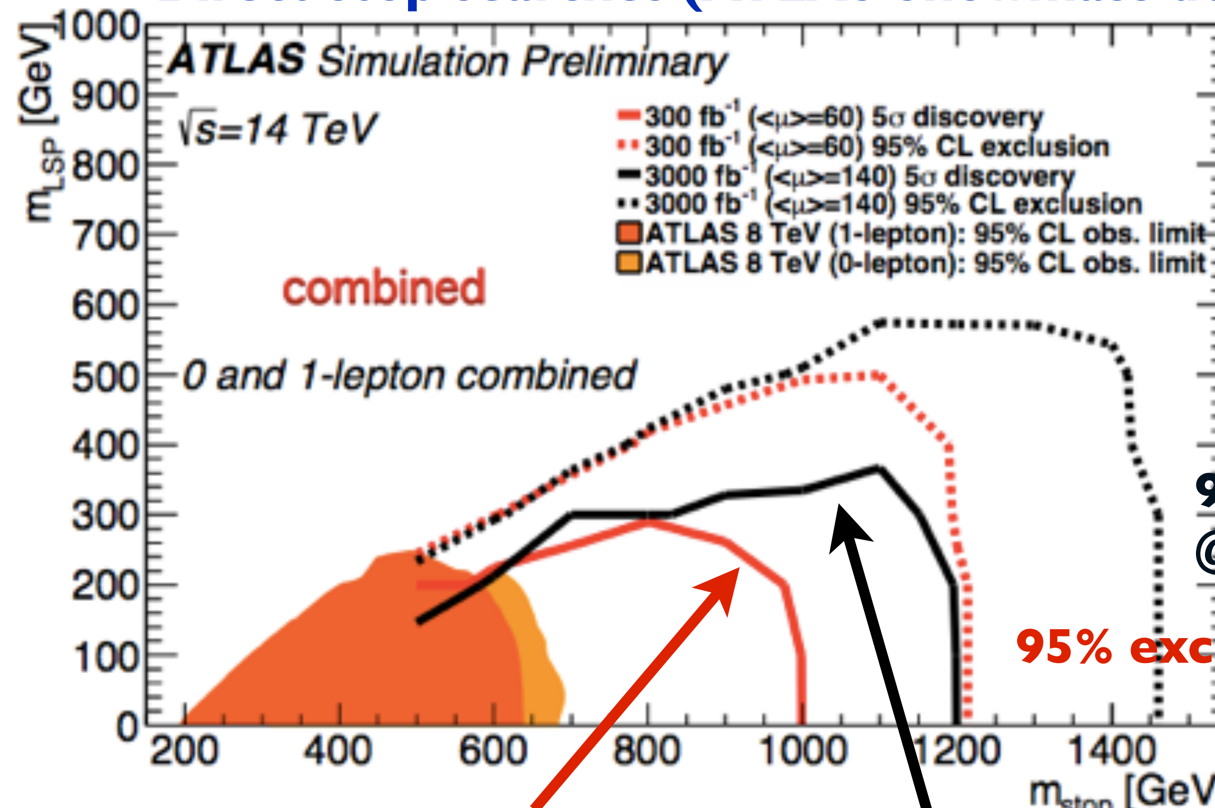
One needs heavy stop(s) to obtain a 125GeV Higgs (within the MSSM)

Direct stop searches (ATLAS Snowmass doc)



95% excl @ 3000/fb

95% excl @ 300/fb

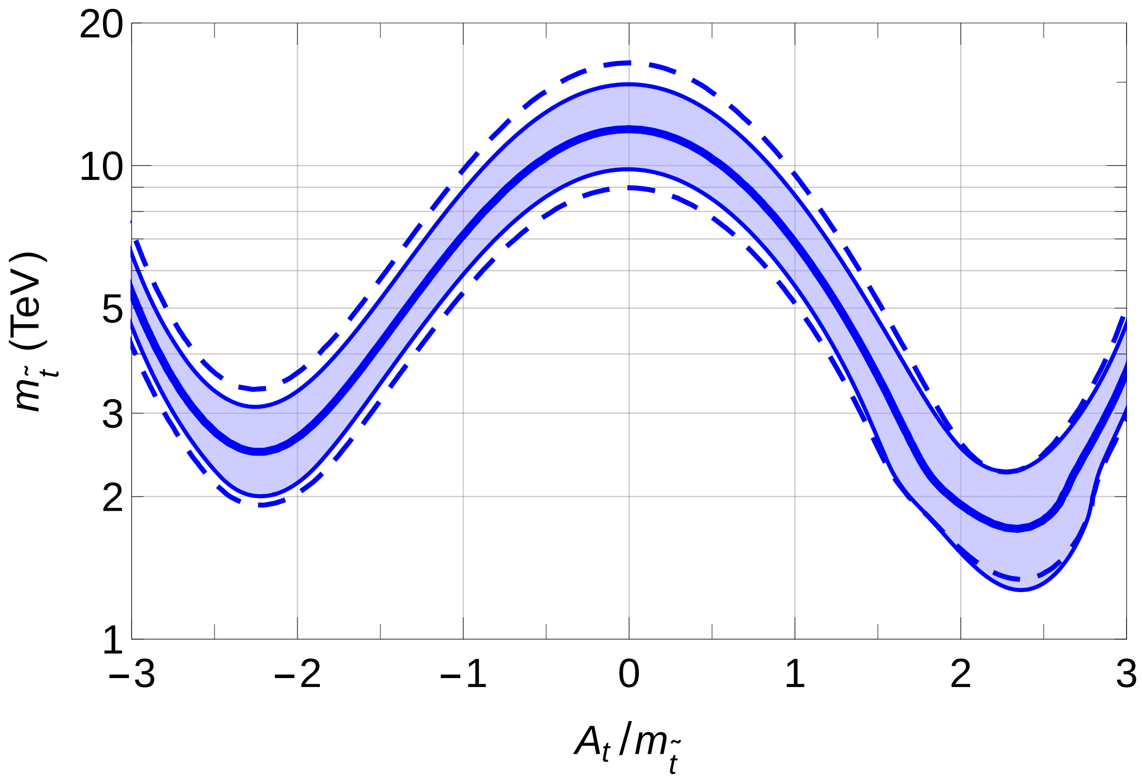
5σ @ 300/fb

5σ @ 3000/fb

Current and future bounds on stop mass

HL-LHC (2030)

The MSSM Higgs mass and stop searches



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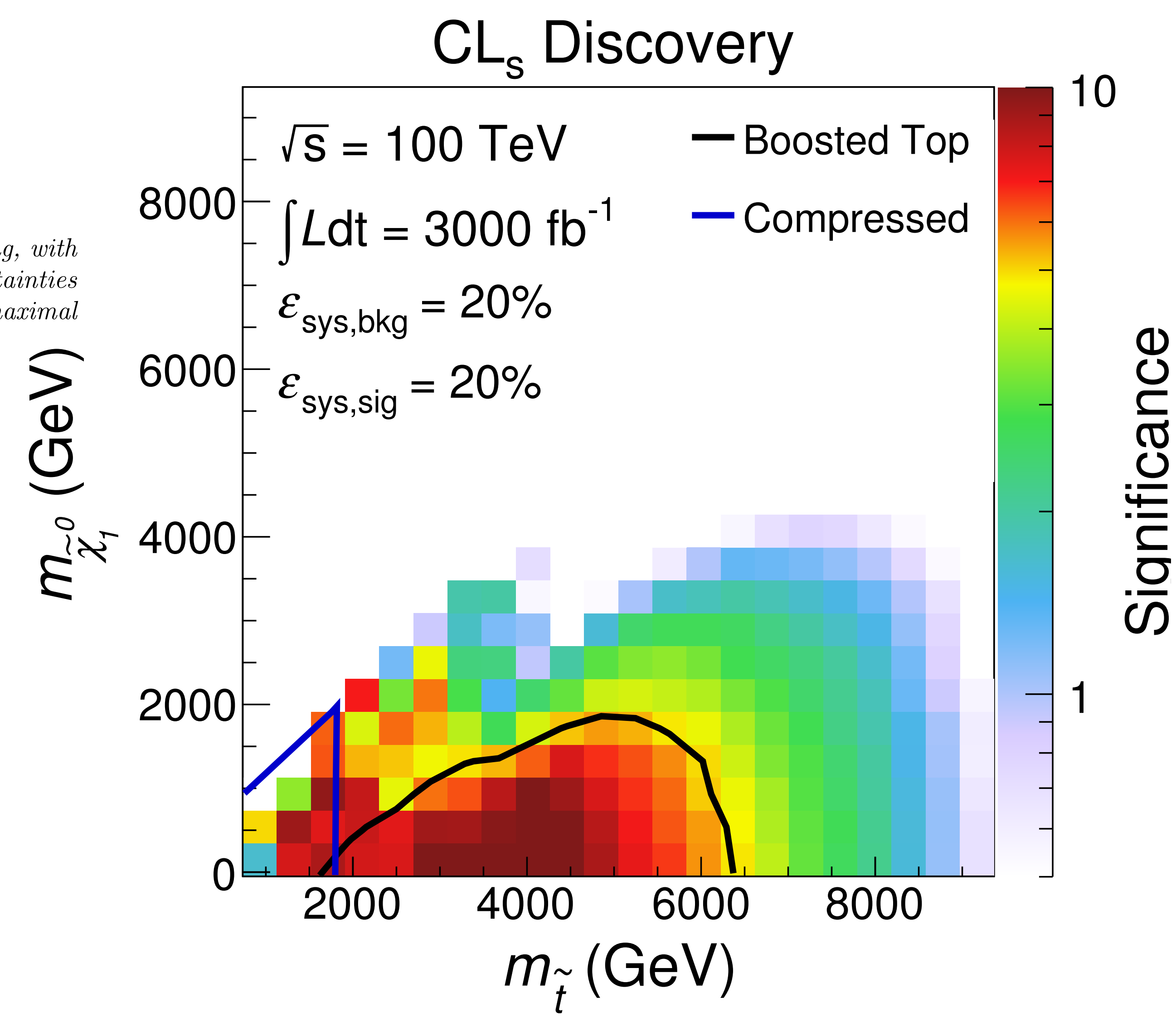
Pardo Vega, Villadoro '15 + many others

One needs heavy stop(s) to obtain a 125GeV Higgs (within the MSSM)

Current and future bounds on stop mass

FCC-hh @ 100TeV (2060)



Saving SUSY

SUSY is Natural
but not plain vanilla

- ~~CMSSM~~
- pMSSM
- NMSSM
- colorless stops ("folded susy")
- Hide SUSY, e.g. smaller phase space
  - reduce production (eg. split families) Mahbubani et al
  - reduce MET (e.g. R-parity, Csaki et al compressed spectrum)
  - dilute MET (decay to invisible particles with more invisible particles)
  - soften MET (stealth susy, stop -top degeneracy) Fan et al

$\text{LHC}_{300(0)\text{fb}^{-1}}$ will tell!

Good coverage of

hidden natural susy

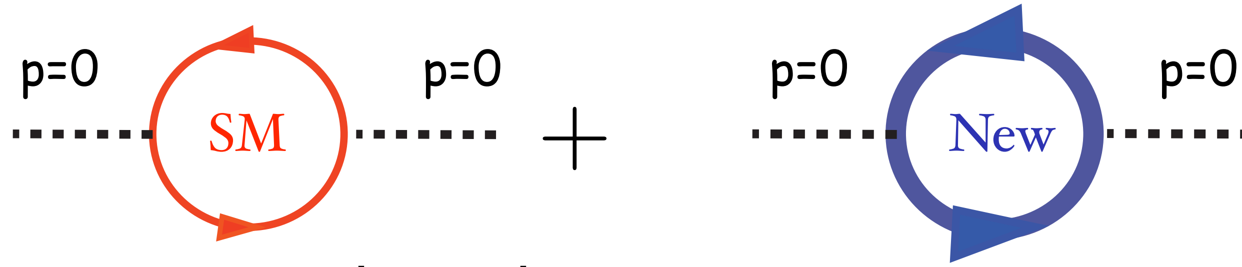
- mono-top searches (DM, flavored naturalness - mixing among different squark flavors-, stop-higgsino mixings)
- mono-jet searches with ISR recoil (compressed spectra)
- precise tt inclusive measurement+ spin correlations
  (stop → top + soft neutralino)
- multi-hard-jets (RPV, hidden valleys, long decay chains)

Neutral naturalness, aka Twin Higgs

Neutral Naturalness

$$-(125\text{ GeV})^2\left(\frac{\Lambda}{600\text{ GeV}}\right)^2 \qquad\qquad \frac{g_*^2}{16\pi^2}\Lambda^2$$

$\delta m_H^2 =$

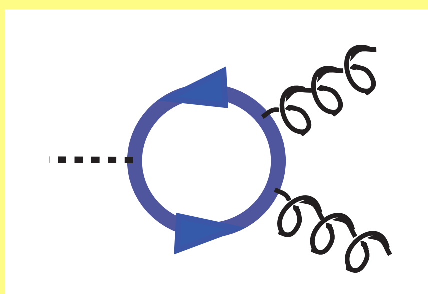


$\sim m_H^2$

charged particles

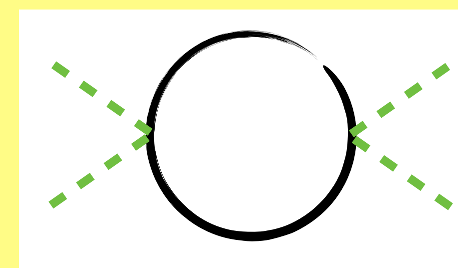
generically

neutral particles



$$\frac{g_s^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 G_{\mu\nu}^2 \qquad \frac{e^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 F_{\mu\nu}^2$$

$$\frac{\Delta BR(h\to\gamma\gamma, Z\gamma, gg)}{\text{SM}} \sim \frac{g_*^2 v^2}{m_*^2}$$



$$\frac{g_*^2}{16\pi^2}\frac{1}{m_*^2}\left(\partial_\mu |H|^2\right)^2$$

$$BR(h\to ii) = BR_{\text{SM}} \qquad \Gamma = \left(1 - \frac{g_*^2 v^2}{16\pi^2 m_*^2}\right)\Gamma_{\text{SM}}$$

$$\delta\sigma_{Zh} = -\frac{g_\star^2}{8\pi^2}\frac{v^2}{m_\star^2}$$

nice to be able to measure Zh & Γ

Colorful naturalness probed @ LHC

Neutral naturalness (invisible?) @ LHC

Twin Higgs

[Chacko, Goh, Harnik '05]

Standard Model $\overset{Z_2}{\longleftrightarrow}$ **Standard Model**

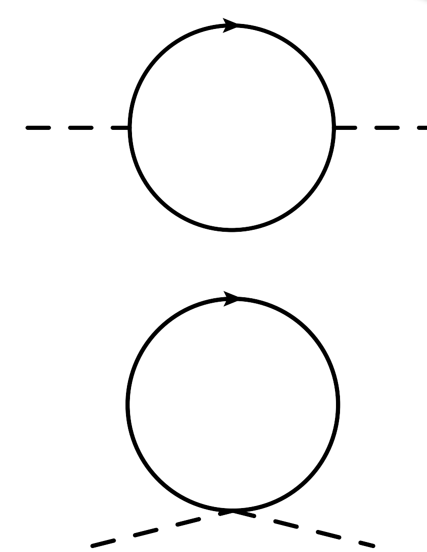
Radiative corrections to the Higgs mass are SU(4) symmetric thanks to Z_2:

$$V(H) \supset \frac{\Lambda^2}{16\pi^2}\left(-6y_t^2 + \frac{9}{4}g^2 + \ldots\right)\left(|H_A|^2 + |H_B|^2\right)$$

(N. Craig @ Paris'18)

Higgs is a PNGB of ~SU(4), but partner states neutral under SM.

$$\mathcal{L} \supset -y_t \underbrace{H_A}_{h+\ldots} Q_3^A \bar{u}_3^A - y_t \underbrace{H_B}_{f - \frac{h^2}{2f} + \ldots} Q_3^B \bar{u}_3^B$$



Neutral Naturalness: new signatures

" Looking and not finding is different than not looking"

giving the null search results, the top partners should either be

- **heavy** (harder to produce because of phase space)
- **stealthy** (easy to produce but hard to distinguish from background, e.g. $m_{stop} \sim m_{top}$)
- **colorless** (hard to produce, unusual decay)

need to go beyond traditional searches

	Scalar Top Partner	Fermion Top Partner
All SM Charges	SUSY '70	pNGB/RS '00
EW Charges	Folded SUSY '05	Quirky Little Higgs '02
No SM Charges	Hyperbolic Higgs '18	Twin Higgs '05

only little corner of theory/model space has been explored so far

(C. Verhaaren@NKPI'16)

require **hidden QCD** with a higher confining scale:

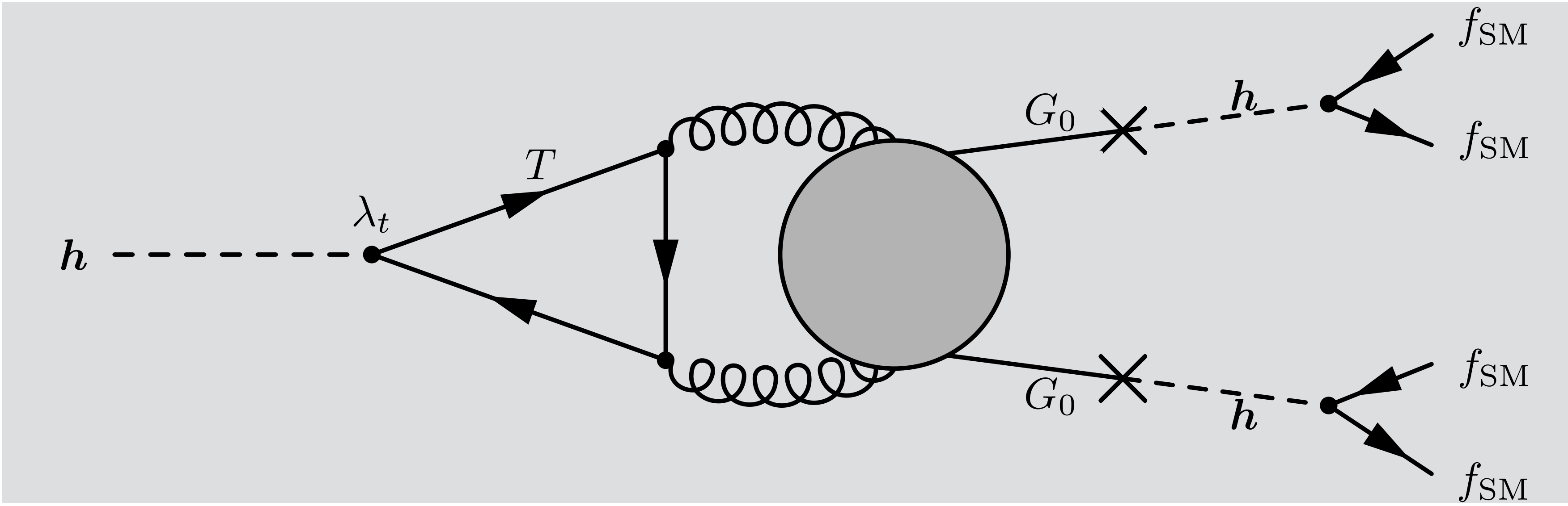
$\Rightarrow$ 1) hidden glueball (0^{++}) that can mix with Higgs $h \to G_0 G_0 \to 4l$ with displaced vertices

Curtin, Verhaaren '1

$\Rightarrow$ 2) emerging jets

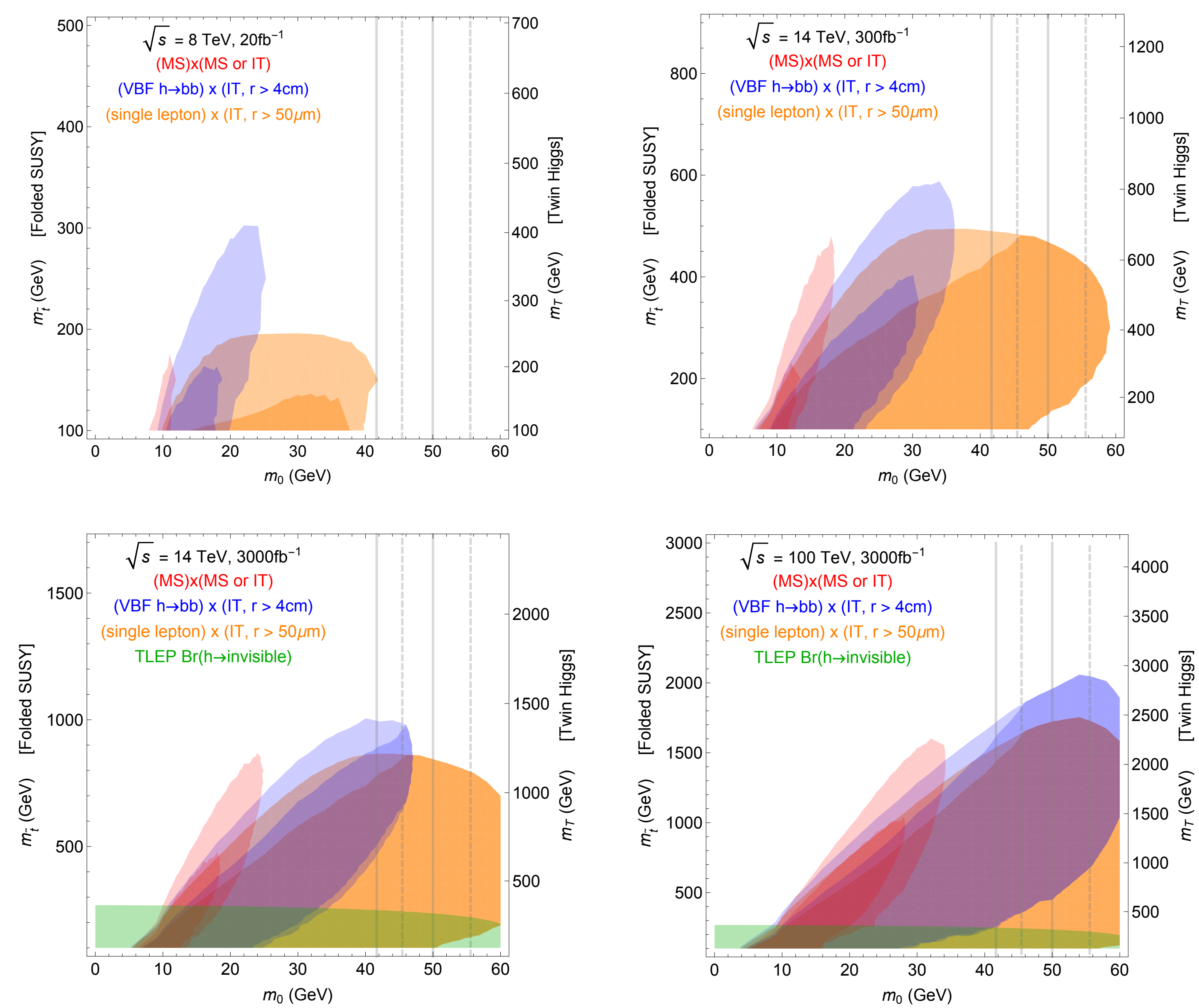
Schwaller, Stolarski, Weiler '15

Neutral Naturalness: new signatures



displaced vertices

Curtin, Verhaaren '15



Higgs couples to QCD' bound states

Produce in rare Higgs decays (BR~10^{-3}-10^{-4})

$$gg \to h \to 0^{++} + 0^{++} + \ldots$$

Decay back to SM via Higgs

$$0^{++} \to h^* \to f\bar{f}$$

Long-lived, length scale ~ LHC detectors