

Behind!
~~Beyond~~ the
Standard Model

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DaMeSyFla



Plan of the lecture

1. **The SUSY Higgs**
2. **Sparticles Searches** (“Naturally” ordered)
3. **Top Partners**
4. **Heavy Vector Triplets** (I wish I had time, but I don't)

The SUSY Higgs

In SUSY, fields are promoted to **SuperFields**.

One would thus naively expect:

SM Higgs field

$$H \in \mathbf{2}_{1/2}$$



SUSY Higgs SF

$$\Phi \in \mathbf{2}_{1/2}$$

Instead, **we need two:** $\Phi_u \in \mathbf{2}_{1/2}$, $\Phi_d \in \mathbf{2}_{-1/2}$

In **SM** we can freely use **conjugate** H : $H^c = i\sigma_2 H^*$

$$\mathcal{L}_Y^u = y_u q_L H u_R^c$$

$$\mathbf{2}_{1/6} \otimes \mathbf{2}_{1/2} \otimes \mathbf{1}_{-2/3} \supset \mathbf{1}_0$$

$$\mathcal{L}_Y^d = y_d q_L H^c d_R^c$$

$$\mathbf{2}_{1/6} \otimes \mathbf{2}_{-1/2} \otimes \mathbf{1}_{1/3} \supset \mathbf{1}_0$$

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$$\mathcal{L}_Y^u = y_u q_L H u_R^c$$

$$\mathcal{L}_Y^d = y_d q_L H^c d_R^c$$

In **SUSY** instead we use **Superpotential** $W[\Phi, \Phi^*]$

$$W_Y^u = y_u \Phi_{q_L} \Phi_u \Phi_{u_R^c}$$

$$W_Y^d = y_d \Phi_{q_L} \Phi_d \Phi_{d_R^c}$$



$$\mathcal{L}_Y^u = y_u q_L H_u u_R^c$$



$$\mathcal{L}_Y^d = y_d q_L H_d d_R^c$$

The SUSY Higgs

The SUSY Higgses scalar potential:

F-Term ($|\partial W/\partial\Phi|^2$)
from
 $W = \mu\Phi_u\Phi_d$

D-Term ($\sim g^2|\phi|^4$)
from
EW int. + SUSY

$$V[H_u, H_d] = \mu^2 [|H_u|^2 + |H_d|^2]$$

$$+ \frac{g^2 + g'^2}{8} [|H_u|^2 - |H_d|^2]^2 + \frac{g^2}{2} |H_u^\dagger H_d|^2$$

$$+ m_u^2 |H_u|^2 + m_d^2 |H_d|^2 + B [H_u H_d + H_u^* H_d^*]$$

Soft terms:
only masses can
break SUSY

Particular case of generic 2 Higgs doublet model

The SUSY Higgs

Four implications of the SUSY Higgs sector structure.

Implication #0: (actually 5 impl.) vacuum is **viable**
(no e.m., color, L and B breaking)

The SUSY Higgs

Four implications of the SUSY Higgs sector structure.

Implication #1: both Higgses take VEV

$$\langle |H_u|^2 \rangle = \frac{v_u^2}{2} \qquad \langle |H_d|^2 \rangle = \frac{v_d^2}{2}$$

2 sources of EWSB $\longrightarrow v_u^2 + v_d^2 = v^2 = (246\text{GeV})^2$

define: $v_u/v_d = \tan \beta$ \longrightarrow $\begin{cases} v_u = v \sin \beta \\ v_d = v \cos \beta \end{cases}$

Abbreviations:
 $s_\beta = \sin \beta$ $t_\beta = \frac{s_\beta}{c_\beta}$
 $c_\beta = \cos \beta$

Both Higgses **must** take VEV, for u and d-type masses:

$$\begin{aligned} \mathcal{L}_Y^u &= y_u q_L H_u u_R^c \\ \mathcal{L}_Y^d &= y_d q_L H_d d_R^c \end{aligned} \longrightarrow \begin{cases} m_u = y_u v_u / \sqrt{2} \\ m_d = y_d v_d / \sqrt{2} \end{cases}$$

For $y_{u,d} < 4\pi$ (perturbative): $0.08 \simeq \frac{y_{\text{top}}^{\text{SM}}}{4\pi} \lesssim t_\beta \lesssim \frac{4\pi}{y_{\text{bot}}^{\text{SM}}} \simeq 500$

The SUSY Higgs

Four implications of the SUSY Higgs sector structure.

Implication #2: **many scalars** around

In Unitary Gauge

$$H_u = \begin{bmatrix} 0 \\ \frac{v_u + h_u}{\sqrt{2}} \end{bmatrix} + \begin{bmatrix} c_\beta H_+ \\ c_\beta \frac{iA}{\sqrt{2}} \end{bmatrix} \quad H_d = \begin{bmatrix} \frac{v_d + h_d}{\sqrt{2}} \\ 0 \end{bmatrix} + \begin{bmatrix} s_\beta \frac{iA}{\sqrt{2}} \\ s_\beta H_- \end{bmatrix}$$

$H_+ = (H_-)^*$: one **charged** scalar

A : one **neutral** pseudo-scalar (CP-odd)

$h_{u,d}$: two **neutral** scalars

$$\begin{bmatrix} h_u \\ h_d \end{bmatrix} = \begin{bmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{bmatrix} \begin{bmatrix} h \\ H \end{bmatrix}$$

The Higgs we saw
 $m_h = 125 \text{ GeV}$

The Other Higgs
(maybe heavier)

The SUSY Higgs

Four implications of the SUSY Higgs sector structure.

Implication #3: modified Higgs couplings

$$\kappa_u = \frac{g_{h_{uu}}}{g_{h_{uu}}^{\text{SM}}} = \frac{\sin(\alpha + \pi/2)}{\sin \beta}$$

$$\kappa_d = \frac{g_{h_{dd}}}{g_{h_{dd}}^{\text{SM}}} = \frac{\cos(\alpha + \pi/2)}{\cos \beta}$$

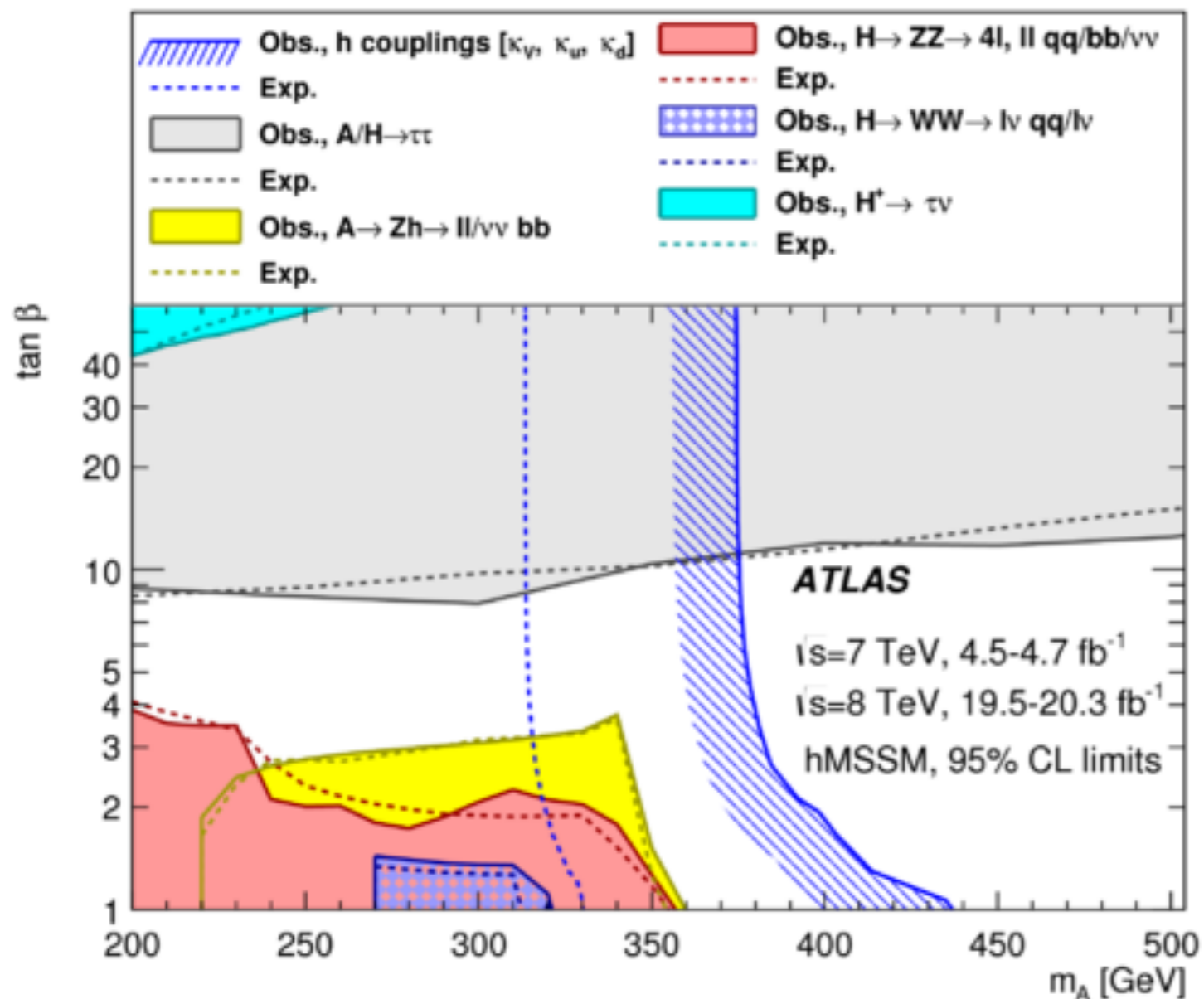
$$\kappa_V = \frac{g_{h_{VV}}}{g_{h_{VV}}^{\text{SM}}} = \sin(\beta - \alpha)$$

The form of the potential allows us to express α in terms of β and of the pseudo-scalar A mass:

$$\tan \alpha = \frac{(m_A^2 + m_Z^2)t_\beta}{m_h^2(1 + t_\beta^2) - m_Z^2 - m_A^2 t_\beta^2}$$

The SUSY Higgs

Four implications of the SUSY Higgs sector structure.
Implication #3: modified Higgs couplings



ATLAS arXiv:1509.00672

Direct scalar searches play an important role in this plane.

The SUSY Higgs

Four implications of the SUSY Higgs sector structure.

Implication #3: modified Higgs couplings

$$\kappa_u = \frac{g_{h_{uu}}}{g_{h_{uu}}^{\text{SM}}} = \frac{\sin(\alpha + \pi/2)}{\sin \beta}$$

$$\kappa_d = \frac{g_{h_{dd}}}{g_{h_{dd}}^{\text{SM}}} = \frac{\cos(\alpha + \pi/2)}{\cos \beta}$$

$$\kappa_V = \frac{g_{h_{VV}}}{g_{h_{VV}}^{\text{SM}}} = \sin(\beta - \alpha)$$

The form of the potential allows us to express α in terms of β and of the pseudo-scalar A mass:

$$\tan \alpha = \frac{(m_A^2 + m_Z^2)t_\beta}{m_h^2(1 + t_\beta^2) - m_Z^2 - m_A^2 t_\beta^2}$$

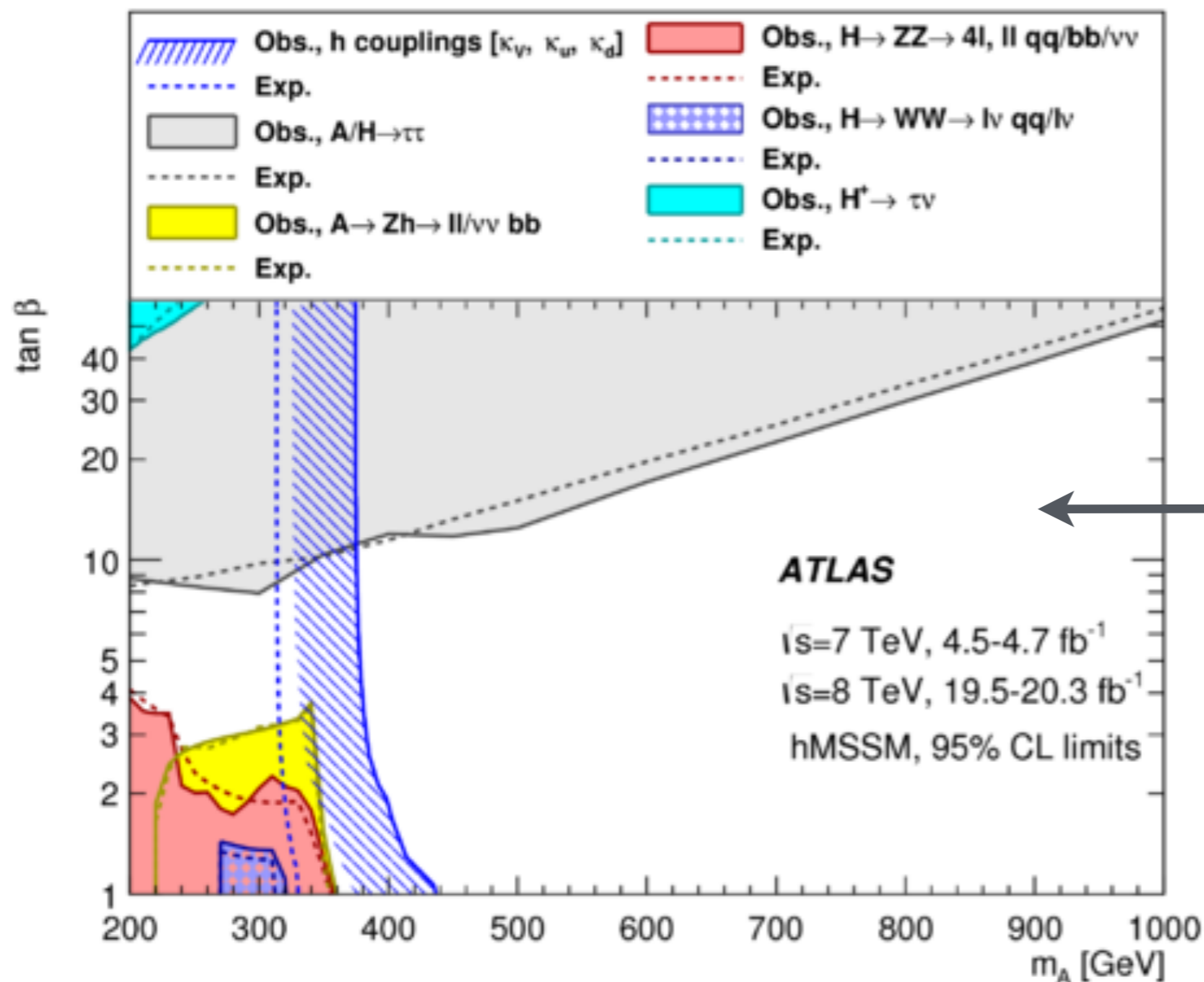
Decoupling limit: $m_d^2 \rightarrow \infty$ (technically natural)

$$m_A^2 = m_d^2 + \dots \rightarrow \infty \rightarrow \tan \alpha \simeq -\frac{1}{t_\beta} \rightarrow \alpha \simeq \beta - \pi/2 \rightarrow \text{SM Higgs}$$

In the limit we also have: $\sin 2\beta \stackrel{||}{=} \frac{2B}{m_A^2} \Rightarrow t_\beta \simeq \frac{m_A^2}{B} \rightarrow \infty$

The SUSY Higgs

Four implications of the SUSY Higgs sector structure.
Implication #3: modified Higgs couplings



ATLAS arXiv:1509.00672

Huge decoupling limit region is **technically natural**.

The SUSY Higgs

Four implications of the SUSY Higgs sector structure.

Implication #4: **wrong Higgs mass !!**

In the decoupling limit, H_d can be **ignored** (set to zero)

$$V[H_u, H_d] \rightarrow V_{\text{SM}} = \mu_{\text{SM}}^2 |H_u|^2 + \lambda |H_u|^4$$

Habitual SM formula gives:

$$m_H = \sqrt{2\lambda}v = \sqrt{g^2 + g'^2}v/2 = m_Z$$

$$\mu_{\text{SM}}^2 = \mu^2 + m_u^2$$
$$\lambda = \frac{g^2 + g'^2}{8}$$

Beyond decoupling limit: $m_H \leq |\cos 2\beta| m_Z$. Even worse

Problem: λ is too small.

Solution: increase λ .

$$\lambda \rightarrow \lambda + \delta\lambda \quad \delta\lambda = \frac{m_H^2 - m_Z^2}{2v^2} \simeq 0.06$$

The SUSY Higgs

Two ways to increase λ :

First way: **rely on large loop corrections** (only way in MSSM)

$$\delta\lambda = \text{[top loop]} + \text{[stau loop]} \sim \frac{3y_t^4}{8\pi^2} \log \frac{M_{\tilde{t}}}{m_t}$$

The diagram shows two Feynman diagrams representing loop corrections to the Higgs quartic coupling. The first diagram is a top quark loop (solid lines with arrows) forming a square loop. The second diagram is a stau loop (dashed lines with arrows) forming a circle loop. The external lines are dashed, representing Higgs bosons.

Need **exponentially heavy stops** ... (use $y_t \simeq 0.94$)

$$M_{\tilde{t}} \sim m_t e^{\frac{8\pi^2 \delta\lambda}{3y_t^2}} \sim 1.3 \text{ TeV}$$

... which is **exponentially bad for tuning:**

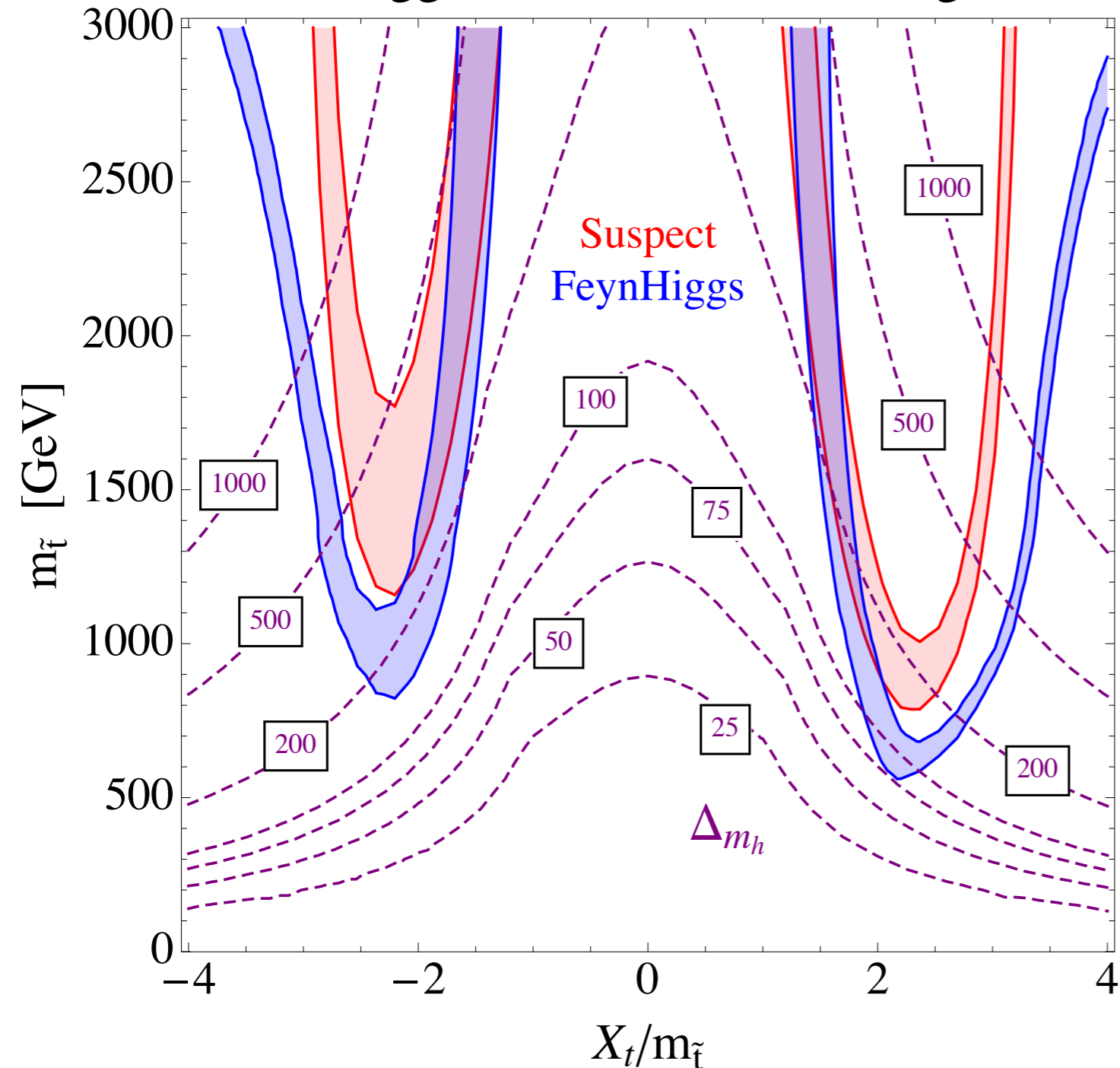
$$\Delta \geq \left(\frac{M_{\text{soft}}}{500 \text{ GeV}} \right)^2 \log(\Lambda_{\text{SUSY}} / M_{\text{EW}})$$

\downarrow \downarrow \downarrow
 14 ~ 7 ~ 5

low $\Lambda_{\text{SUSY}} = 10 \text{ TeV}$

The SUSY Higgs

Higgs Mass vs. Fine Tuning



from arXiv:1112.2703

$$\Delta \gtrsim 100$$



The MSSM is **not anymore** (after Higgs discovery) a **Natural** theory.

moreover ...

LHC discovery not expected (heavy spart.) even if true.



look for SUSY **beyond MSSM !**

The SUSY Higgs

Second way to make m_H right:

Add an extra singlet SF. (NMSSM or λ SUSY)

$$W_S = \lambda_S \Phi_S \Phi_u \Phi_d \quad \longrightarrow \quad V_S = \lambda_S^2 |H_u H_d|^2$$

Mechanism works at **moderate** t_β (H_d is involved)



No (obvious) decoupling limit.



Interesting to study **Higgs couplings** and **extra scalars** in this framework.

Caveat: needed values of $\lambda_S \sim 1$ give **~ 10 TeV cutoff.**

Sparticles searches

Direct searches: look for sparticles production and decay.

Results:

presented as a pointless higher-excluded-mass race.

Let's try to put some order in this mess.

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: July 2015

ATLAS Preliminary

$\sqrt{s} = 7, 8 \text{ TeV}$

Model	e, μ, τ, γ	Jets	E_T^{miss}	$f(\mathcal{L}, \mathcal{B}, \dots)$	Mass limit		Reference	
					$\sqrt{s} = 7 \text{ TeV}$	$\sqrt{s} = 8 \text{ TeV}$		
Inclusive Searches	MSUGRA/CMSSM	0-3 e, μ / 1-2 τ	2-10 jets/3 b	Yes	20.3	850 GeV	1507.05525	
	$\tilde{q}\tilde{q} \rightarrow q\bar{q}\tilde{g}$	0	2-6 jets	Yes	20.3	1.8 TeV	1405.7675	
	$\tilde{q}\tilde{q} \rightarrow q\bar{q}\tilde{g}$ (compressed)	mono-jet	1-3 jets	Yes	20.3	100-440 GeV	1507.05525	
	$\tilde{q}\tilde{q} \rightarrow q\bar{q}\tilde{g}/\tilde{g}\tilde{g}\tilde{g}$	2 e, μ (off-Z)	2 jets	Yes	20.3	760 GeV	1503.03290	
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{g}$	0	2-6 jets	Yes	20.3	1.33 TeV	1405.7675	
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{g}$	0-1 e, μ	2-6 jets	Yes	20	1.26 TeV	1507.05525	
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{g}/\tilde{g}\tilde{g}\tilde{g}$	2 e, μ	0-3 jets	-	20	1.32 TeV	1501.03555	
	GMSB (\tilde{g} NLSP)	1-2 $e + 0-1 \tau$	0-2 jets	Yes	20.3	1.6 TeV	1407.0603	
	GGM (bino NLSP)	2 γ	-	Yes	20.3	1.29 TeV	1507.05493	
	GGM (higgsino-bino NLSP)	7	1 b	Yes	20.3	1.3 TeV	1507.05493	
$\tilde{\nu}^j$ gen. \tilde{g} mod.	$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{g}$	0	3 b	Yes	20.1	1.25 TeV	1407.0600	
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{g}$	0	7-10 jets	Yes	20.3	1.1 TeV	1306.1841	
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{g}$	0-1 e, μ	3 b	Yes	20.1	1.34 TeV	1407.0600	
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{g}$	0-1 e, μ	3 b	Yes	20.1	1.3 TeV	1407.0600	
$\tilde{\nu}^j$ gen. squarks direct production	$\tilde{t}_1\tilde{t}_1 \rightarrow t\bar{t}\tilde{g}$	0	2 b	Yes	20.1	100-620 GeV	1306.2631	
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\bar{t}\tilde{g}$	2 e, μ (SS)	0-3 b	Yes	20.3	275-440 GeV	1404.2500	
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\bar{t}\tilde{g}$	1-2 e, μ	1-2 b	Yes	4.7/20.3	110-167 GeV	1209.2102, 1407.0583	
	$\tilde{t}_1\tilde{t}_1 \rightarrow W\tilde{b}\tilde{g}$ or $\tilde{t}_1\tilde{t}_1 \rightarrow t\bar{t}\tilde{g}$	0-2 e, μ	0-2 jets/1-2 b	Yes	20.3	90-191 GeV	1506.08616	
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\bar{t}\tilde{g}$	0	mono-jet/1-tag	Yes	20.3	90-240 GeV	1407.0608	
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	150-580 GeV	1403.5222	
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\bar{t}\tilde{g} + Z$	3 e, μ (Z)	1 b	Yes	20.3	290-600 GeV	1403.5222	
EW direct	$\tilde{t}_1\tilde{t}_1 \rightarrow t\bar{t}\tilde{g}$	2 e, μ	0	Yes	20.3	90-325 GeV	1403.5294	
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\bar{t}\tilde{g}$	2 e, μ	0	Yes	20.3	140-603 GeV	1403.5294	
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\bar{t}\tilde{g}$	2 τ	-	Yes	20.3	100-350 GeV	1407.0350	
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\bar{t}\tilde{g}/\tilde{g}\tilde{g}\tilde{g}$	3 e, μ	0	Yes	20.3	700 GeV	1402.7029	
	$\tilde{t}_1\tilde{t}_1 \rightarrow W\tilde{b}\tilde{g}$	2-3 e, μ	0-2 jets	Yes	20.3	420 GeV	1403.5294, 1402.7029	
	$\tilde{t}_1\tilde{t}_1 \rightarrow W\tilde{b}\tilde{g}$	4 e, μ, γ	0-2 b	Yes	20.3	250 GeV	1501.07110	
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\bar{t}\tilde{g}$	4 e, μ	0	Yes	20.3	620 GeV	1405.5086	
	GGM (wino NLSP) weak prod.	1 $e, \mu + \gamma$	-	Yes	20.3	124-361 GeV	1507.05493	
	Direct $\tilde{t}_1\tilde{t}_1$ prod. long-lived \tilde{t}_1^0	Disapp. trk	1 jet	Yes	20.3	270 GeV	1310.2675	
	Direct $\tilde{t}_1\tilde{t}_1$ prod. long-lived \tilde{t}_1^0	dE/dx trk	-	Yes	18.4	482 GeV	1506.05332	
Long-lived particles	Stable, stopped \tilde{g} R-hadron	0	1-5 jets	Yes	27.9	632 GeV	1310.6584	
	Stable \tilde{g} R-hadron	trk	-	-	19.1	1.27 TeV	1411.6795	
	GMSB, stable $\tilde{t}_1, \tilde{t}_1^0 \rightarrow T\tilde{t}_1, \tilde{t}_1^0 \rightarrow \tau(e, \mu)$	1-2 μ	-	-	19.1	537 GeV	1411.6795	
	GMSB, $\tilde{t}_1^0 \rightarrow \gamma\tilde{t}_1$, long-lived \tilde{t}_1^0	2 γ	-	Yes	20.3	435 GeV	1409.5542	
	$\tilde{g}\tilde{g} \rightarrow \nu\bar{\nu}\tilde{g}/\tilde{g}\tilde{g}\tilde{g}$	displ. $\nu\bar{\nu}/\tilde{g}\tilde{g}$	-	-	20.3	1.0 TeV	1504.05162	
	GGM $\tilde{g}\tilde{g} \rightarrow Z\tilde{g}$	displ. vtx + jets	-	-	20.3	1.0 TeV	1504.05162	
	RPV	LFV $\tilde{g}\tilde{g} \rightarrow \nu\bar{\nu} + X, \tilde{g}\tilde{g} \rightarrow \nu\bar{\nu}/\tilde{g}\tilde{g}$	$\nu\bar{\nu}/\tilde{g}\tilde{g}$	-	-	20.3	1.7 TeV	1503.04430
		Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	1.35 TeV	1404.2500
$\tilde{t}_1\tilde{t}_1 \rightarrow t\bar{t}\tilde{g}$		4 e, μ	-	Yes	20.3	750 GeV	1405.5086	
$\tilde{t}_1\tilde{t}_1 \rightarrow t\bar{t}\tilde{g}$		3 $e, \mu + \tau$	-	Yes	20.3	450 GeV	1405.5086	
$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{g}$		0	6-7 jets	-	20.3	917 GeV	1502.05686	
$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{g}$		0	6-7 jets	-	20.3	870 GeV	1502.05686	
$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{g}$		2 e, μ (SS)	0-3 b	Yes	20.3	850 GeV	1404.2500	
Other	Scalar charm, $\tilde{c} \rightarrow c\tilde{c}^0$	0	2 c	Yes	20.3	100-300 GeV	ATLAS CONF-2015-026	
						490 GeV	ATLAS CONF-2015-015	

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 σ theoretical signal cross section uncertainty.

Sparticles searches

Direct searches: look for sparticles production and decay.

We can order sparticles by their “Naturalness Cost”: the price in terms of Naturalness of not finding them light.

Working again in the decoupling limit, we saw that

$$\mu^2 + m_u^2 = \mu_{\text{SM}}^2 = m_H^2/2 \simeq (88 \text{ GeV})^2$$

Naturalness argument associates to μ a tuning of

$$\Delta = 2 \frac{\mu^2}{m_H^2} \simeq \left(\frac{\mu}{100 \text{ GeV}} \right)^2$$

Higgsinos (of mass $\sim \mu$) are the most “expensive” sparticles.
Because **contribute at tree-level.**

remember:

$$W = \mu \Phi_u \Phi_d$$

$$\frac{\partial^2 W}{\partial \Phi \partial \Phi} |_{\phi \psi \psi} = \mu \psi_u \psi_d$$

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Next come the **stops**, that contribute to m_u^2 at one loop:

$$\Delta = \left(\frac{M_{\tilde{t}}}{500 \text{ GeV}} \right)^2 \log(\Lambda_{\text{SUSY}}/M_{\text{EW}})$$

Then **gauginos**: one loop but proportional to g_W^2 ...

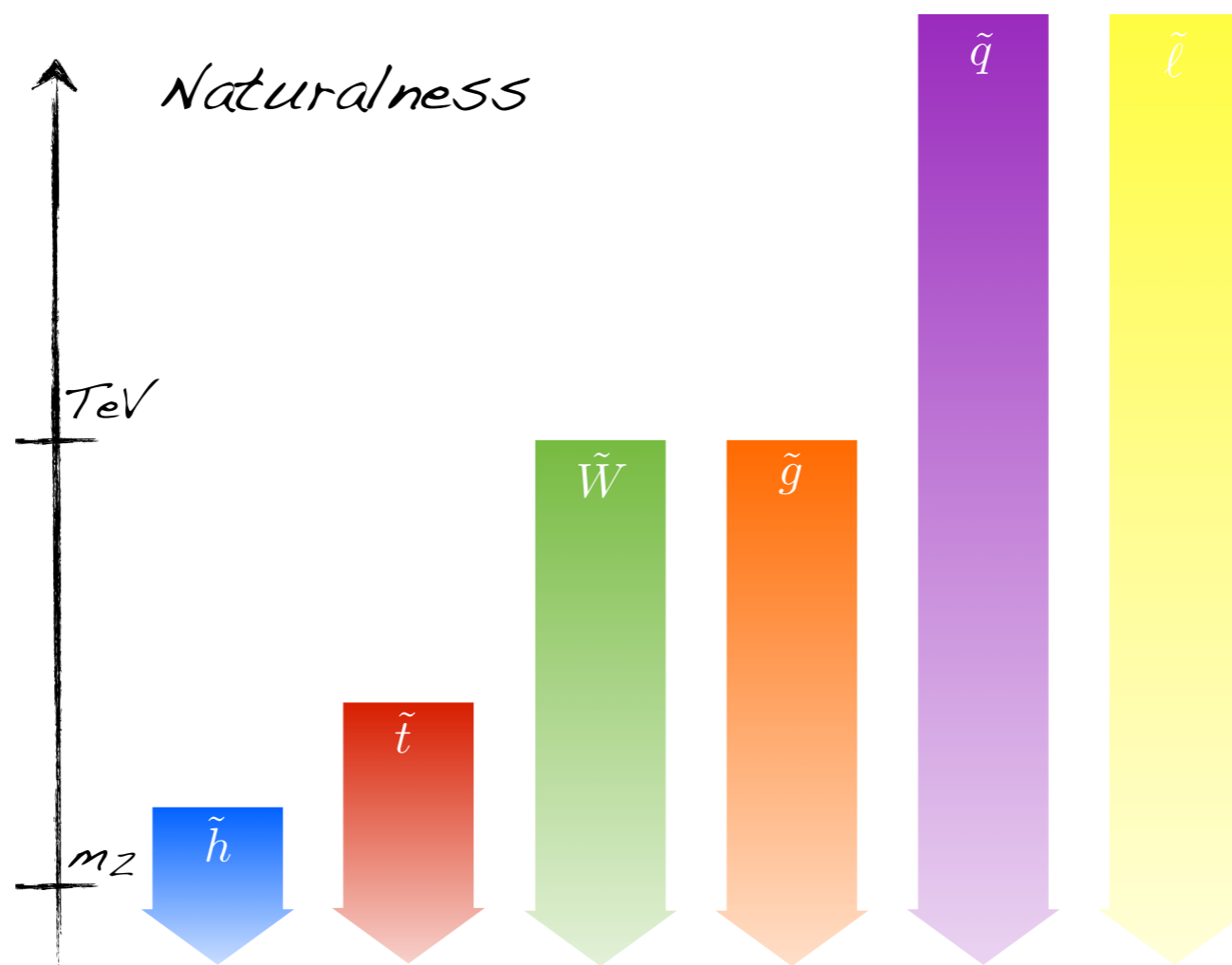
... and **gluinos**: two loops through stops coupling.

Squarks and sleptons are the cheapest: small H coupling

Sparticles searches

Direct searches: look for sparticles production and decay.

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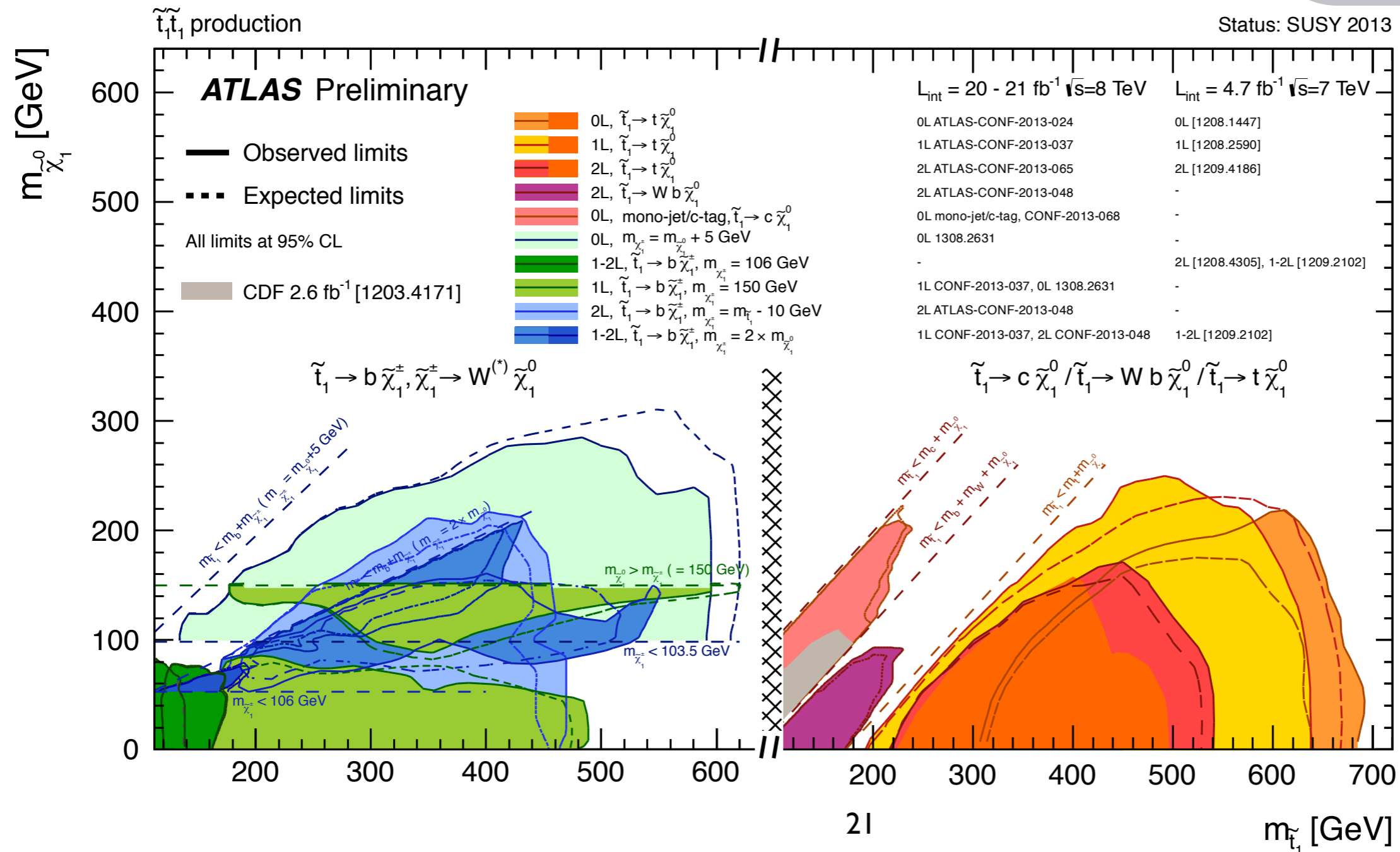
from arXiv:1309.0528

Sparticles searches

Stop: QCD pair produced and decaying in:

$$\tilde{t} \rightarrow t\chi_1^0 \text{ or } \tilde{t} \rightarrow b\chi^\pm \rightarrow bW^\pm\chi_0^1$$

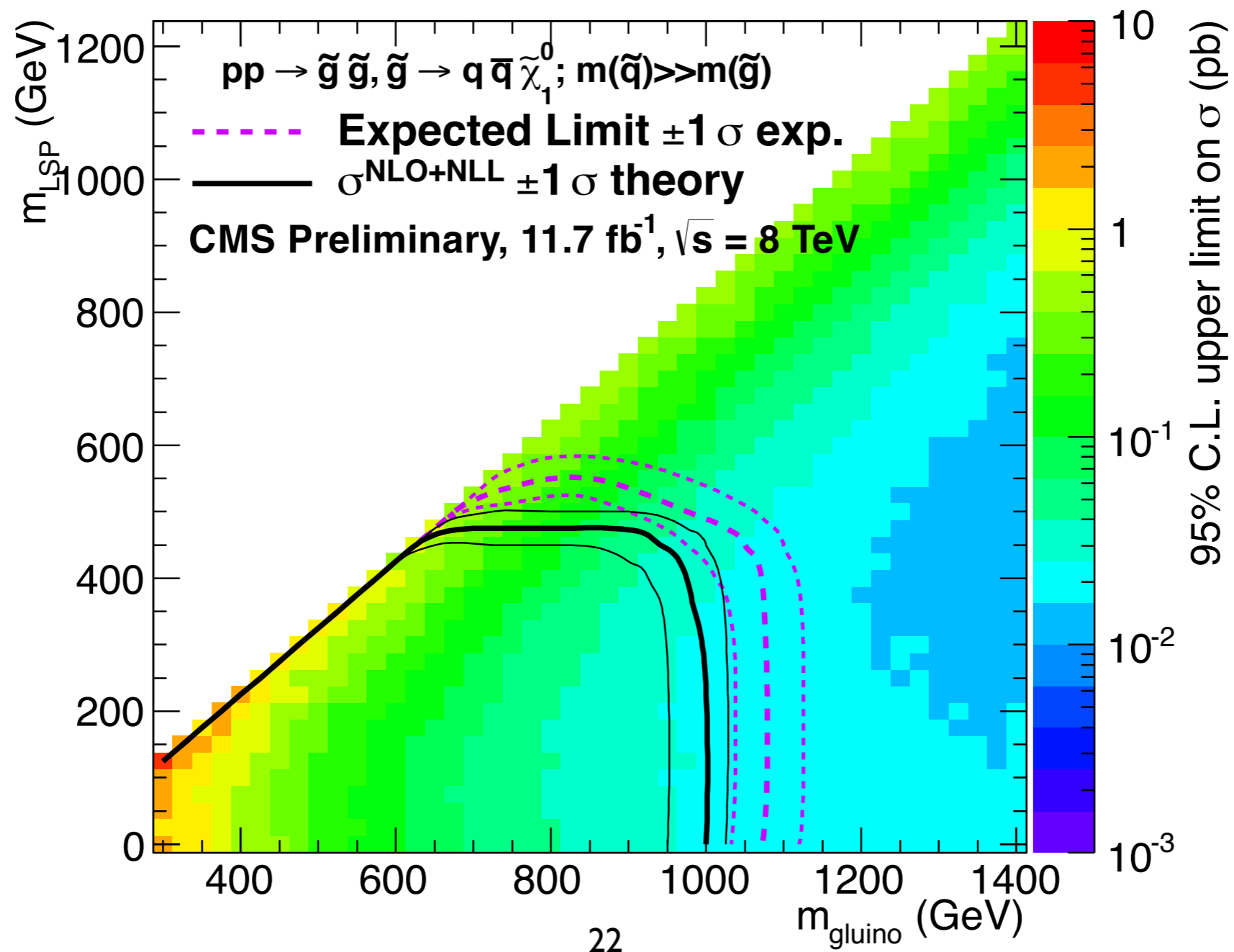
LSP (χ_0) is at the end of the decay chain. Gives MET



Sparticles searches

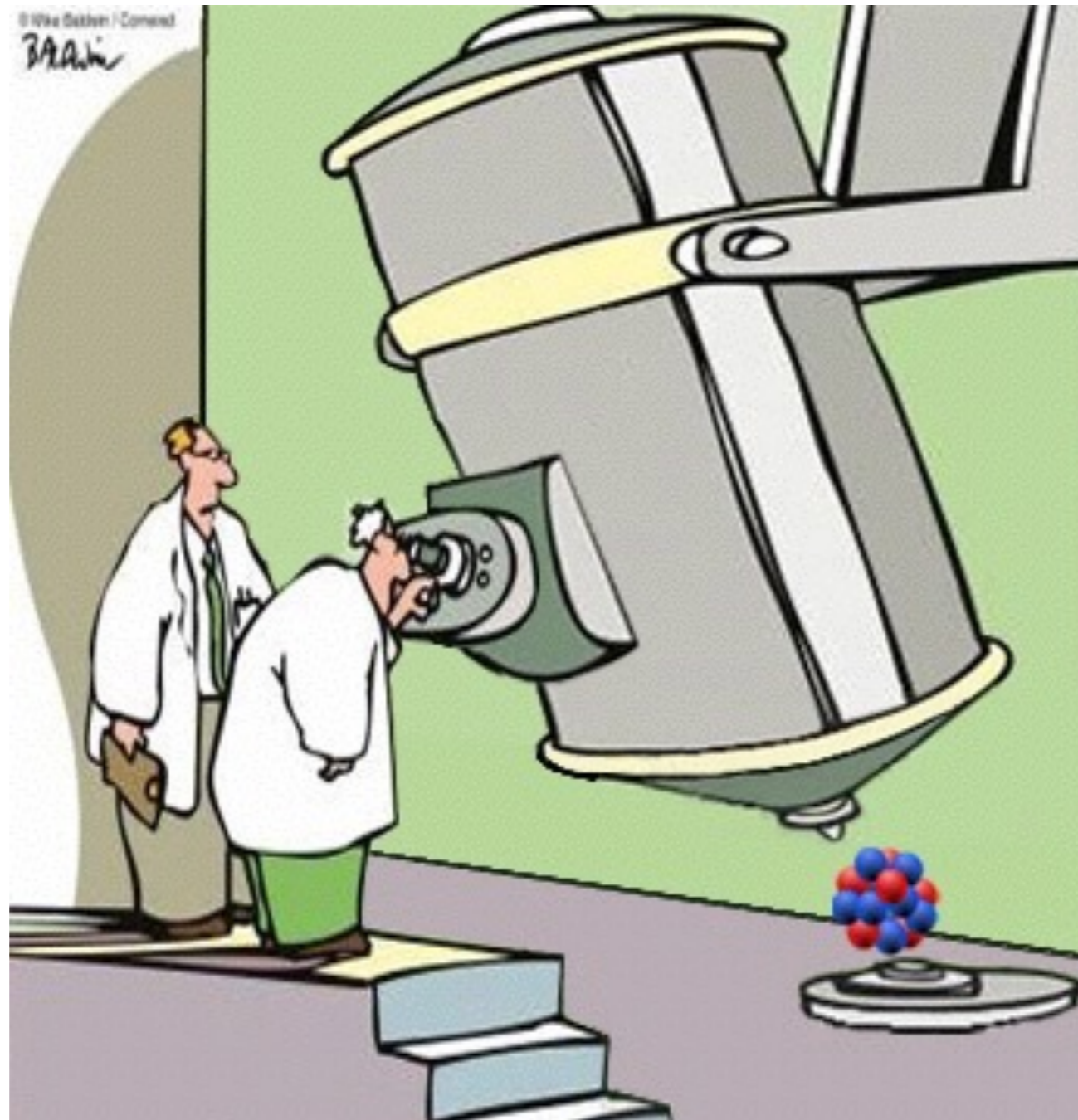
Gluginos: QCD pair produced (huge rate) and decaying in:

$$\tilde{g} \rightarrow q\bar{q}\chi_1^0$$



Top Partners

Composite Higgs: Direct resonance searches



Top Partners

Back to the **Partial Compositeness** formula:

$$\mathcal{L}_{\text{int}}^f = \lambda_R \bar{T}_R^I \mathcal{O}_L^I + \lambda_L \bar{Q}_L^I \mathcal{O}_R^I$$

after confinement, operators produce particles ...

$$\langle 0 | \mathcal{O} | \text{TP} \rangle \neq 0 \quad \mathcal{O} \leftrightarrow \text{TP}$$

... with the same quantum numbers of the operator.

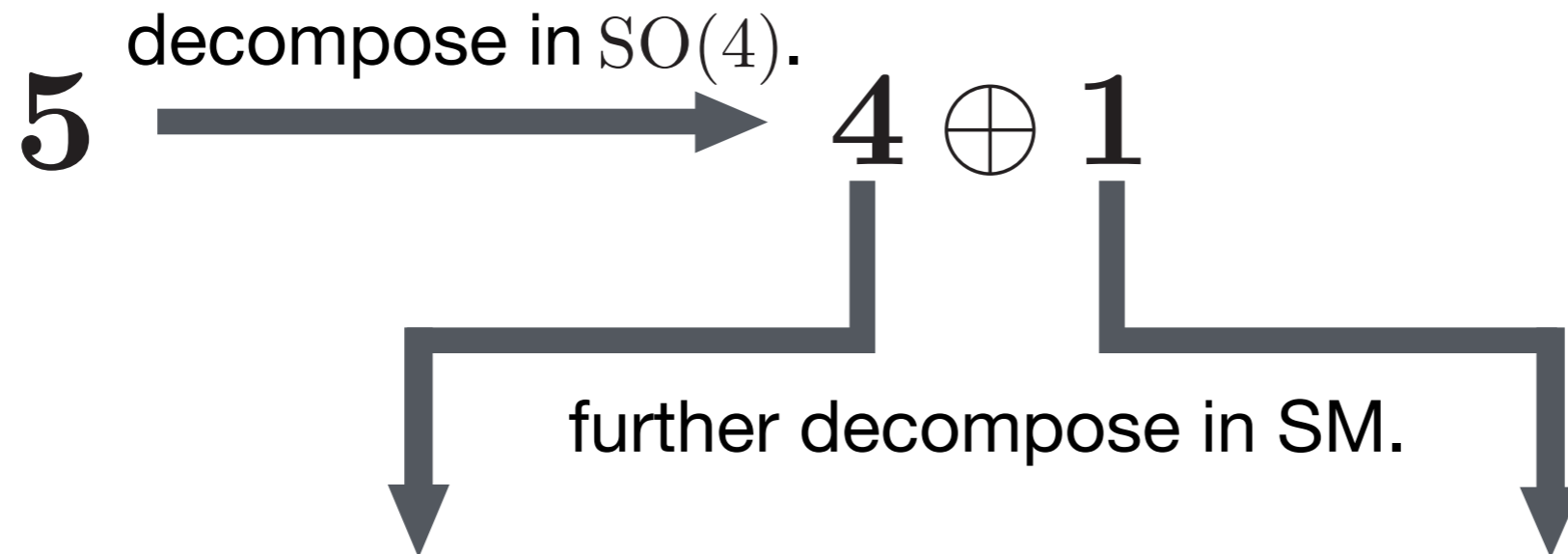
Therefore the **Top Partners** (TP) are:

1. **Dirac Fermions**, with mass $M_{\text{TP}} \sim m_*$ (like other resonances)
2. **QCD colour triplets** (like quarks)
3. **EW-charged**, in multiplets dictated by the representation of \mathcal{O} .

Top Partners

If $\mathcal{O} \in 5$, TP are:

(the $U(1)_X$ caveat also applies here)



Two SM doublets:

$$\left[\begin{array}{c} \left(\begin{array}{c} T \\ B \end{array} \right) \\ \left(\begin{array}{c} X_{5/3} \\ X_{2/3} \end{array} \right) \end{array} \right]$$

Nearly mass-degenerate,
since part of fourplet.

One SM singlet:

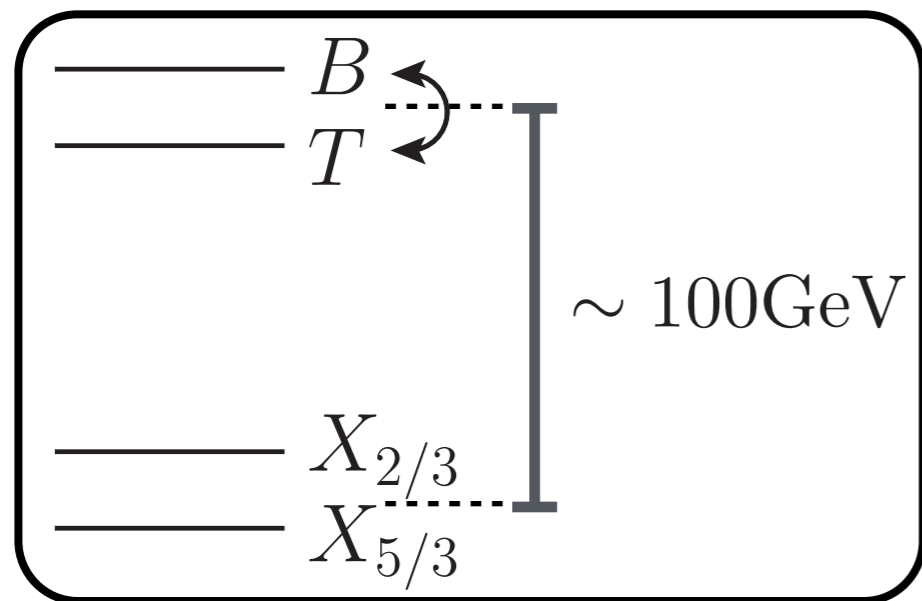
$$\tilde{T}$$

only one charge-2/3 state

Fourplet plus singlet always there in viable models.
But other multiplets might appear. (e.g. triplets)

Top Partners

Typical TP **spectrum:**
(the \tilde{T} can be everywhere)



Typical Top Partners
Branching Ratios:

\tilde{T}	Wb	Zt	ht
$X_{5/3}$	Wt		
$\tilde{X}_{2/3}$	Zt	ht	
T	Zt	ht	
B	Wt		

From **QCD** pair-production, current mass limits $\sim 700\text{ GeV}$

Top Partners

The strength of TP **couplings** can be estimated (specific numbers in specific models) as follows:

We introduced **two scales** to characterise the CS

$$m_*$$

= Confinement scale

= typical **CS mass**

$$f$$

= Spont. breaking scale

$$SO(5) \xrightarrow{f} SO(4)$$

Different, but related: $g_* = \frac{m_*}{f}$ = typical **CS coupling**
(expected **large**, even $= 4\pi$)

Concrete rule:

$$\mathcal{L} \sim \frac{m_*^4}{g_*^2} \widehat{\mathcal{L}} \left[\frac{\partial}{m_*}, \frac{g_* \Pi}{m_*}, \frac{g_* \Psi}{m_*^{3/2}} \right]$$

applies to all CS fields. Including Higgs and Top Partners. Only difference is energy dim. of fields (1 for bosons, 3/2 for fermions)

Top Partners

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= Spont. breaking scale

$$SO(5) \xrightarrow{f} SO(4)$$

Different, but related: $g_* = \frac{m_*}{f}$ = typical **CS coupling**
(expected **large**, even $= 4\pi$)

Concrete rule:

$$\mathcal{L} \sim \frac{m_*^4}{g_*^2} \widehat{\mathcal{L}} \left[\frac{\partial}{m_*}, \frac{g_* \Pi}{m_*}, \frac{g_* \Psi}{m_*^{3/2}} \right]$$

same as Π/f factors in U .

Top Partners

The strength of TP **couplings** can be estimated (specific numbers in specific models) as follows:

We introduced **two scales** to characterise the CS

$$m_*$$

= Confinement scale

= typical **CS mass**

$$f$$

= Spont. breaking scale

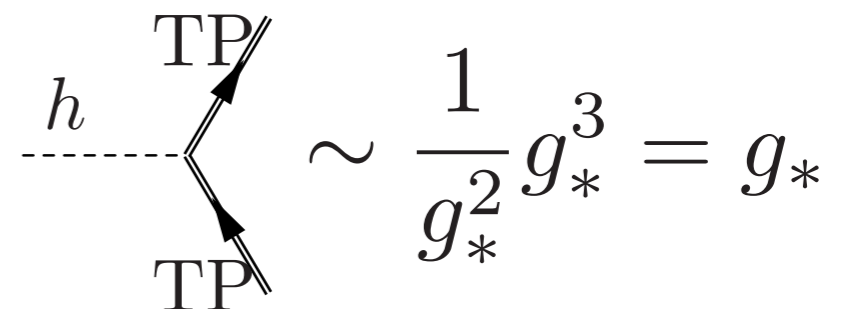
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Concrete rule:

example:

$$\mathcal{L} \sim \frac{m_*^4}{g_*^2} \widehat{\mathcal{L}} \left[\frac{\partial}{m_*}, \frac{g_* \Pi}{m_*}, \frac{g_* \Psi}{m_*^{3/2}} \right]$$



$$\sim \frac{1}{g_*^2} g_*^3 = g_*$$

Top Partners

Elementary fields are not part of the CS. Thus they have their own **(smaller)** couplings. For instance:

$$\mathcal{L}_{\text{int}}^f = \lambda_R \bar{t}_R \mathcal{O}_L + \lambda_L \bar{q}_L \mathcal{O}_R$$

General rule: $\mathcal{L} \sim \frac{m_*^4}{g_*^2} \hat{\mathcal{L}} \left[\frac{\partial}{m_*}, \frac{g_* \Pi}{m_*}, \frac{g_* \Psi}{m_*^{3/2}}, \frac{\lambda_R t_R}{m_*^{3/2}}, \frac{\lambda_L q_L}{m_*^{3/2}} \right]$

example: fermion-fermion partner **mixing**

$$m_* \frac{\lambda_R}{g_*} \bar{t}_R T_L + m_* \frac{\lambda_L}{g_*} \bar{q}_L Q_R$$

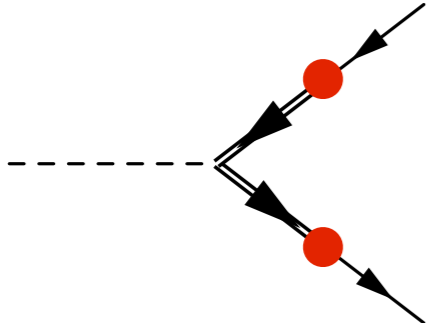
diagonalising the mass matrix ($\sim m_*$ mass term for TP)

$$\begin{aligned} |q_L\rangle &= \cos \phi_L |q_L^{\text{elem.}}\rangle + \sin \phi_L |Q_L^{\text{comp.}}\rangle \\ |t_R\rangle &= \cos \phi_R |t_R^{\text{elem.}}\rangle + \sin \phi_R |T_R^{\text{comp.}}\rangle \end{aligned} \quad \sin \phi_{L,R} \simeq \frac{\lambda_{L,R}}{g_*} \ll 1$$

Top Partners

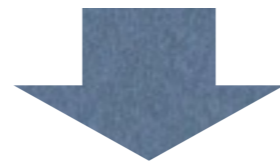
$$\begin{aligned} |q_L\rangle &= \cos \phi_L |q_L^{\text{elem.}}\rangle + \sin \phi_L |Q_L^{\text{comp.}}\rangle \\ |t_R\rangle &= \cos \phi_R |t_R^{\text{elem.}}\rangle + \sin \phi_R |T_R^{\text{comp.}}\rangle \end{aligned} \quad \sin \phi_{L,R} \simeq \frac{\lambda_{L,R}}{g_*} \ll 1$$

Partial Compositeness generates Yukawa couplings


$$y = \sin \phi_L \sin \phi_R g_* \simeq \frac{y_L y_R}{g_*}$$

Top quark is **slightly composite**, has large Yukawa

Light quarks and leptons have **small compositeness fraction**.

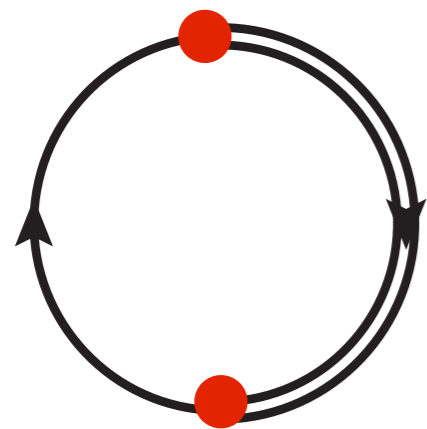


They couple less strongly with the CS resonances.

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$$\begin{aligned}
 |q_L\rangle &= \cos \phi_L |q_L^{\text{elem.}}\rangle + \sin \phi_L |Q_L^{\text{comp.}}\rangle \\
 |t_R\rangle &= \cos \phi_R |t_R^{\text{elem.}}\rangle + \sin \phi_R |T_R^{\text{comp.}}\rangle
 \end{aligned}
 \quad \sin \phi_{L,R} \simeq \frac{\lambda_{L,R}}{g_*} \ll 1$$

Partial Compositeness also generates Higgs potential.
 Top-Top Partner loops dominate (large compositeness)



$$\longrightarrow V \sim \frac{\lambda_{L,R}^2}{16\pi^2} M_{\text{TP}}^2 H^2 + \dots$$

$$\delta m_H^2 \sim \frac{\lambda_{L,R}^2}{8\pi^2} M_{\text{TP}}^2 = \lambda_{L,R}^2 \left(\frac{M_{\text{TP}}}{500 \text{ GeV}} \right)^2 m_H^2$$

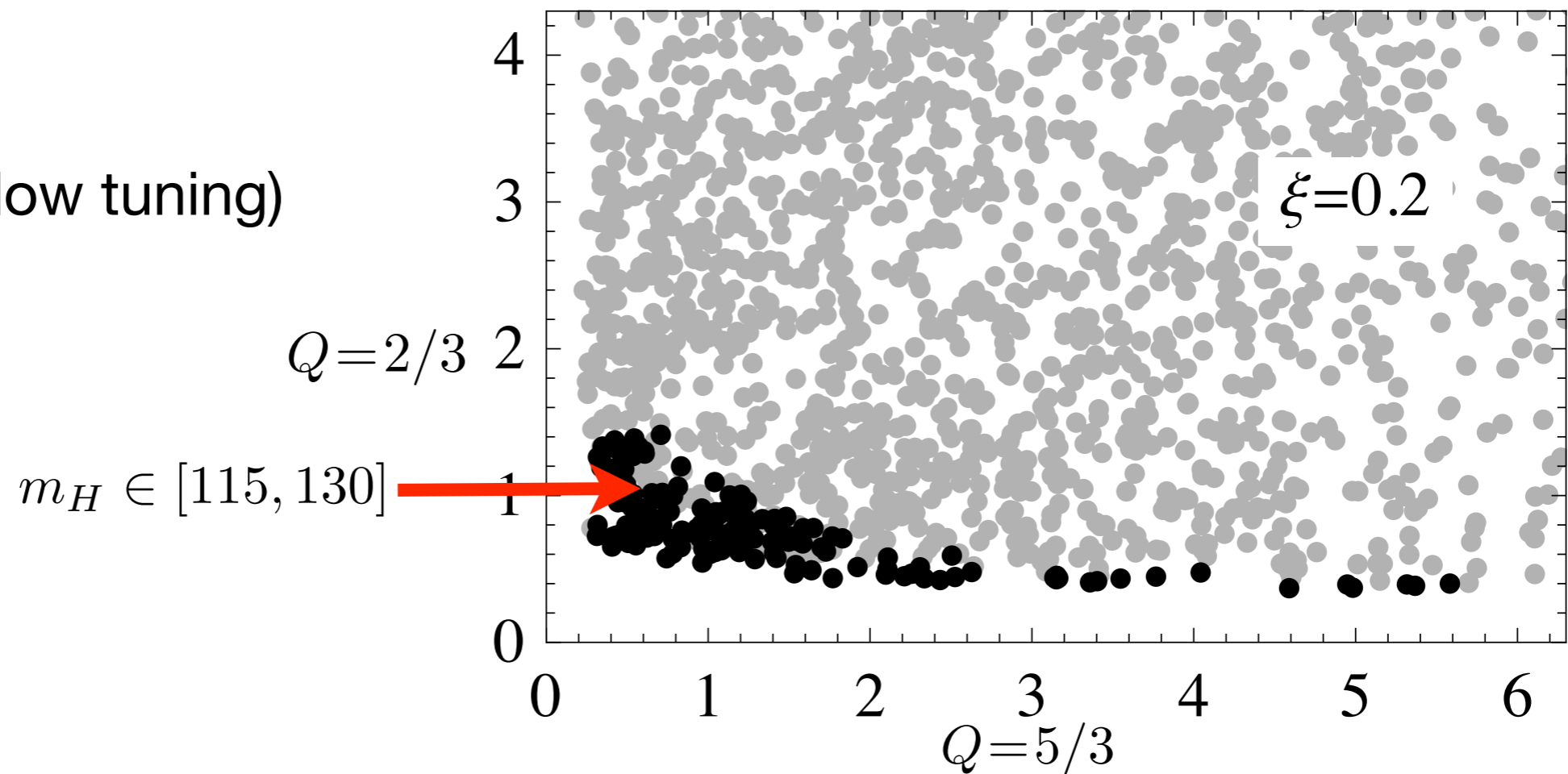
Top Partners have to be light in order to get m_H right without fine-tuning. Somewhat like the stops in SUSY

Top Partners

Light Top Partners for a light Composite Higgs

A pragmatic illustration:

$\xi = 0.2$: (low tuning)

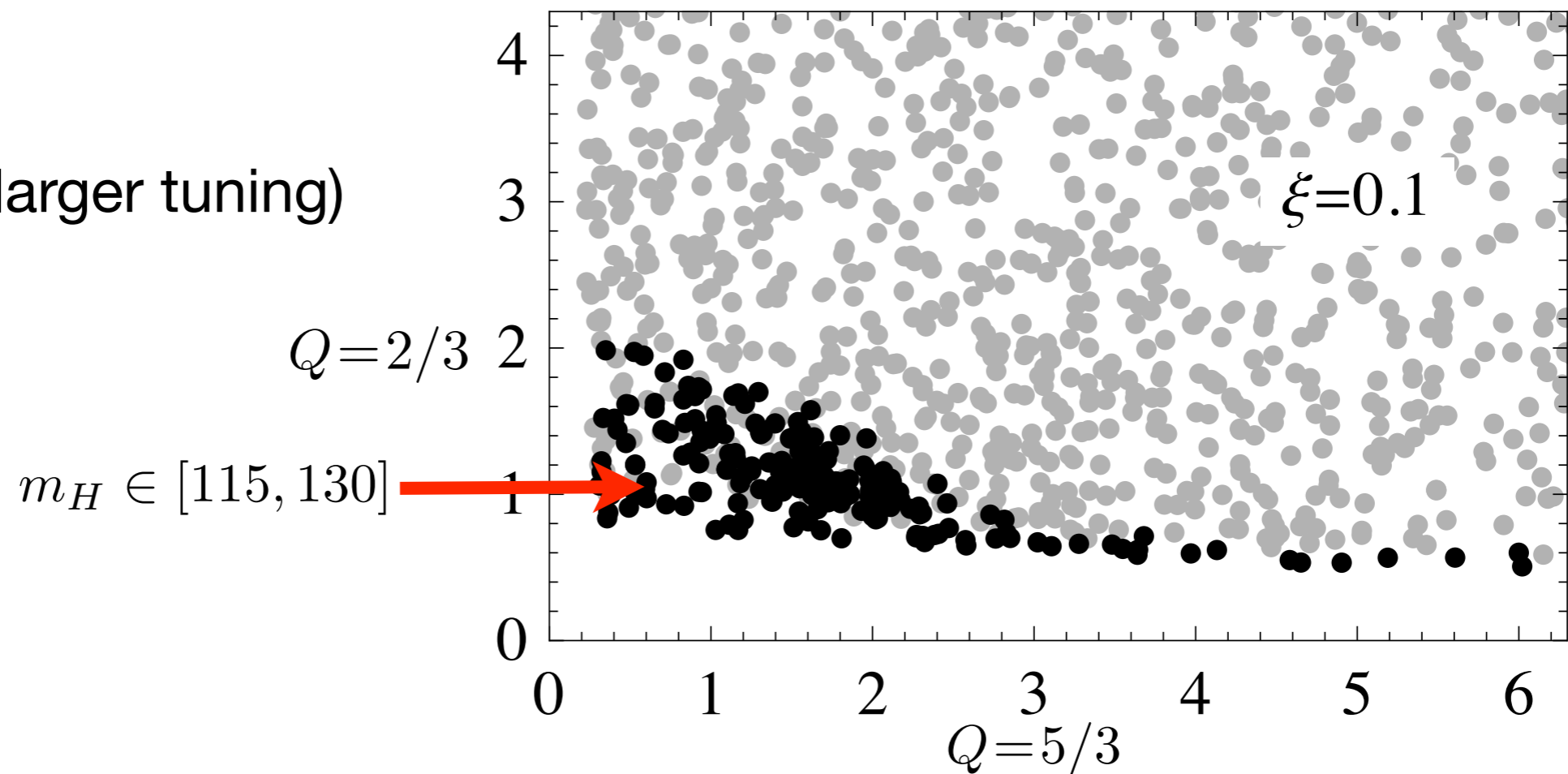


Top Partners

Light Top Partners for a light Composite Higgs

A pragmatic illustration:

$\xi = 0.1$: (larger tuning)

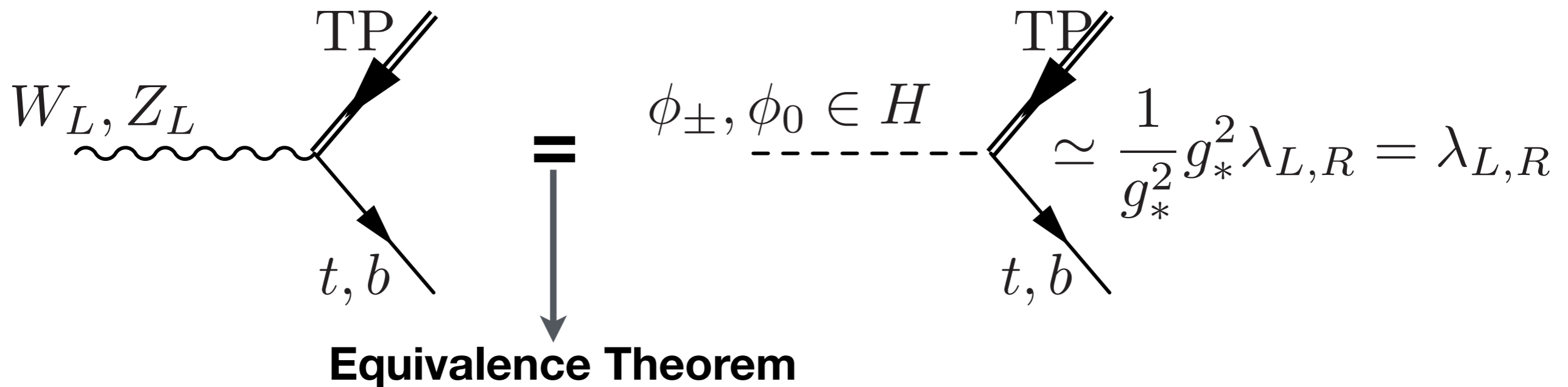


Run-2 reach: ~ 1.5 TeV from QCD prod. only.

Top Partners

We might push the reach up by **single production**:

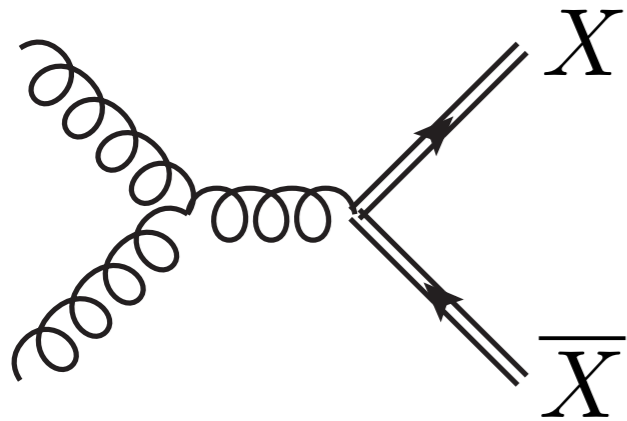
General rule: $\mathcal{L} \sim \frac{m_*^4}{g_*^2} \widehat{\mathcal{L}} \left[\frac{\partial}{m_*}, \frac{g_* \Pi}{m_*}, \frac{g_* \Psi}{m_*^{3/2}}, \frac{\lambda_R t_R}{m_*^{3/2}}, \frac{\lambda_L q_L}{m_*^{3/2}} \right]$



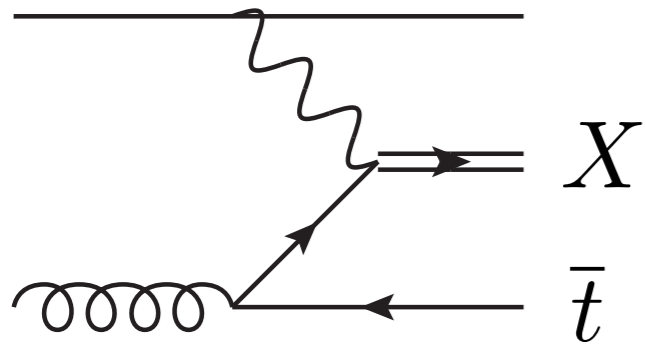
Typically large V –TP–third family quarks coupling.

Top Partners

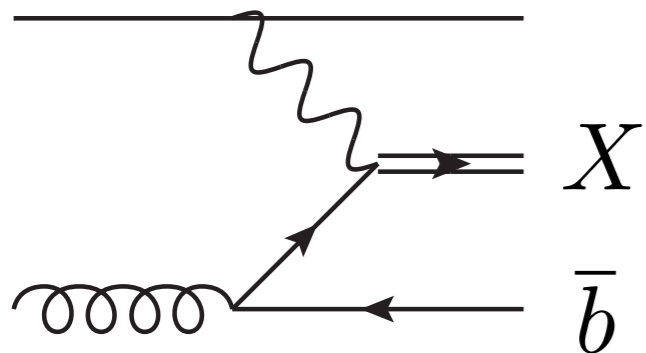
Top Partners production mechanisms



QCD pair prod.
model indep.,
relevant at low mass



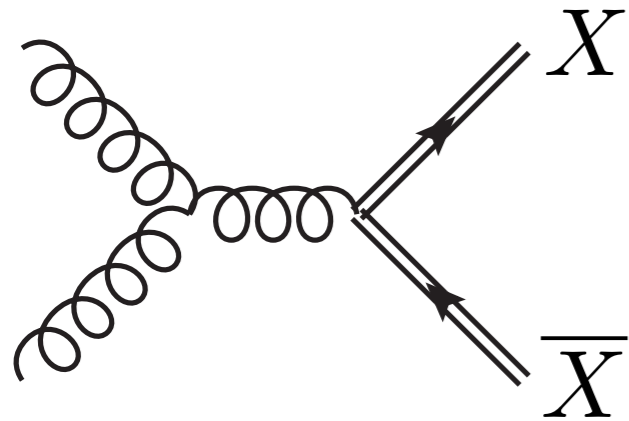
single prod. with t
model dep. coupling
pdf-favoured at high mass



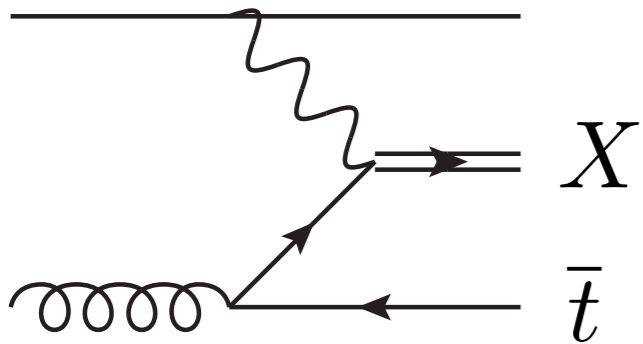
single prod. with b
favoured by small b mass
dominant when allowed

Top Partners

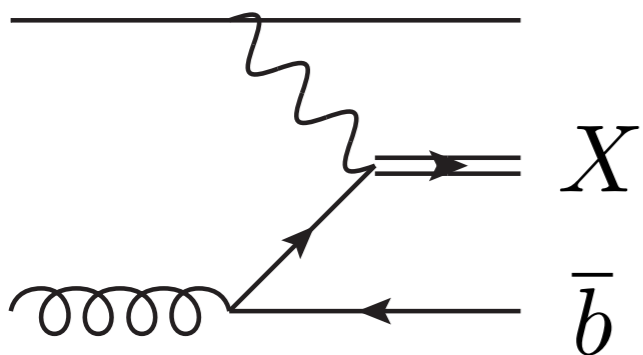
Top Partners production mechanisms



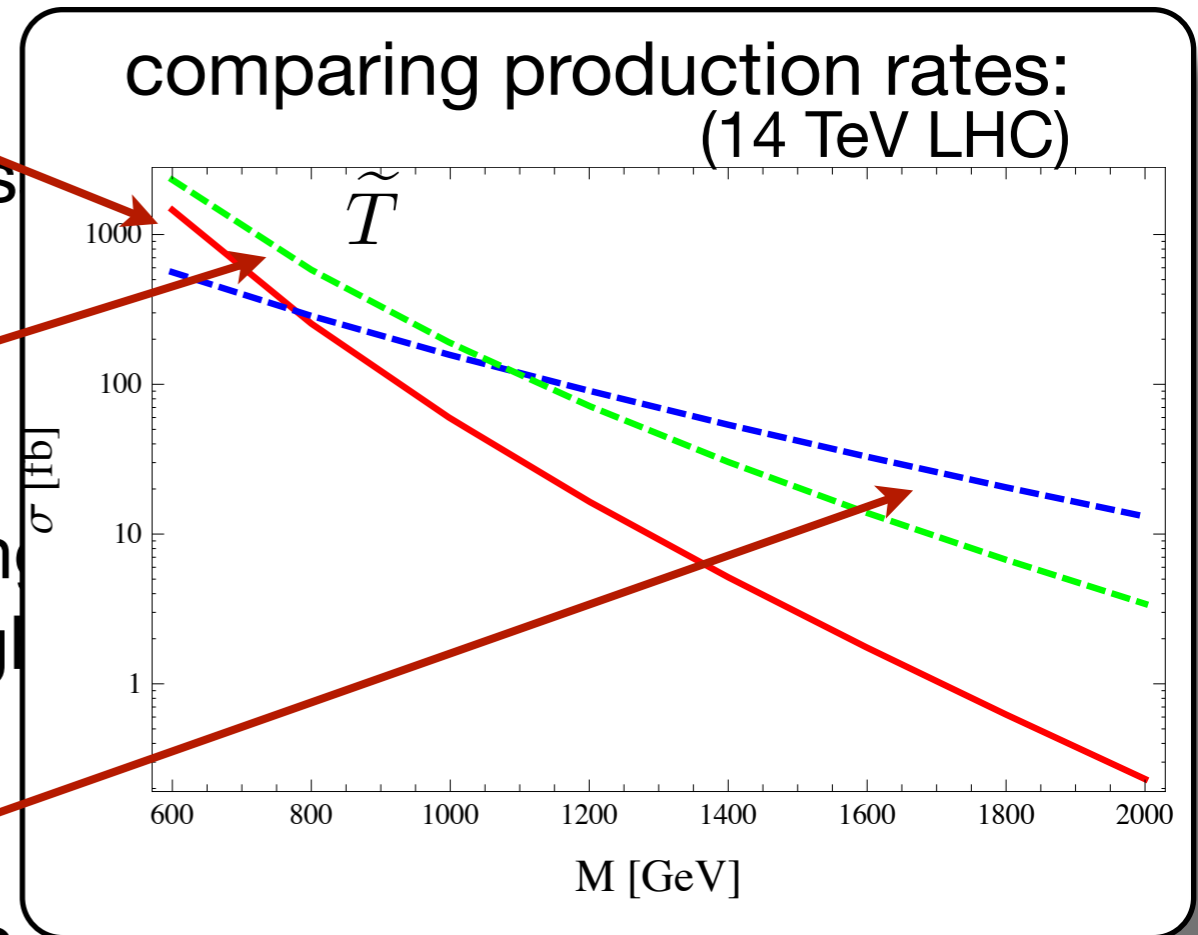
QCD pair prod.
model indep.,
relevant at low mas



single prod. with t
model dep. couplin
pdf-favoured at high



single prod. with b
favoured by small b mass
dominant when allowed



Challenge for run-2: **reach 2 TeV**, i.e. $\xi \sim 0.05$.

Final Thoughts

After the Higgs discovery, no no-loose theorem is left.
No new guaranteed discovery in any research field.

BSM is not (must not be) a collection of models.

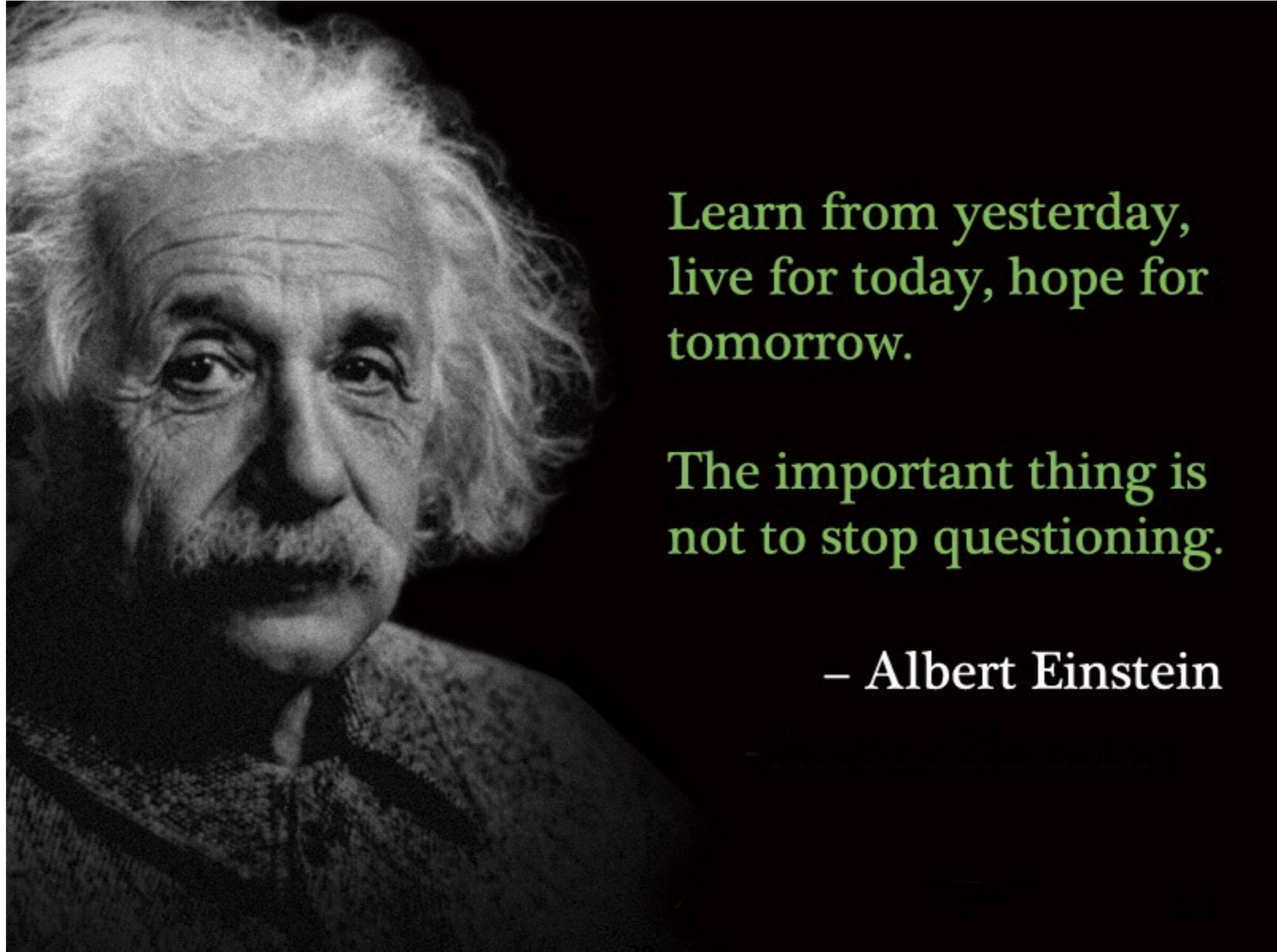
It a set of questions and possible answers about
fundamental physics, to be checked with data.

Naturalness is one of those questions, not the only one.

Experimentalists should not **blindly trust** theorists.

They should **critically listen** to theorists. And get
convinced (or not). Nobody has the truth.

Final Thoughts



Learn from yesterday,
live for today, hope for
tomorrow.

The important thing is
not to stop questioning.

– Albert Einstein