Behind!

~~Beyond~~ the Standard Model

Andrea Wulzer

UNIVERSITÀ
DEGLI STUDI
DI PADOVA

INFN
Istituto Nazionale
di Fisica Nucleare

European Research Council
DaMeSyFla
erc

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 $\longrightarrow$ **SUSY Higgs SF**

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

Instead, **we need two:** $\Phi_{\mathrm{u}} \in \mathbf{2}_{\mathbf{1/2}}$, $\Phi_{\mathrm{d}} \in \mathbf{2}_{\mathbf{-1/2}}$

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

$$\mathcal{L}_{\mathrm{Y}}^{\mathrm{u}} = y_{\mathrm{u}} q_L H u_R^c \qquad \mathcal{L}_{\mathrm{Y}}^{\mathrm{d}} = y_{\mathrm{d}} q_L H^c d_R^c$$

$$\mathbf{2}_{\mathbf{1/6}} \otimes \mathbf{2}_{\mathbf{1/2}} \otimes \mathbf{1}_{\mathbf{-2/3}} \supset \mathbf{1}_{\mathbf{0}} \qquad \mathbf{2}_{\mathbf{1/6}} \otimes \mathbf{2}_{\mathbf{-1/2}} \otimes \mathbf{1}_{\mathbf{1/3}} \supset \mathbf{1}_{\mathbf{0}}$$

The SUSY Higgs

In SUSY, fields are promoted to **SuperFields.**
One would thus naively expect:

SM Higgs field → **SUSY Higgs SF**

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

Instead, **we need two:** $\Phi_{\mathrm{u}} \in \mathbf{2}_{\mathbf{1/2}},\ \Phi_{\mathrm{d}} \in \mathbf{2}_{\mathbf{-1/2}}$

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

$$\mathcal{L}_{\mathrm{Y}}^{\mathrm{u}} = y_{\mathrm{u}} q_L H u_R^c \qquad \mathcal{L}_{\mathrm{Y}}^{\mathrm{d}} = y_{\mathrm{d}} q_L H^c d_R^c$$

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

$$W_{\mathrm{Y}}^{\mathrm{u}} = y_{\mathrm{u}} \Phi_{q_L} \Phi_{\mathrm{u}} \Phi_{u_R^c} \qquad W_{\mathrm{Y}}^{\mathrm{d}} = y_{\mathrm{d}} \Phi_{q_L} \Phi_{\mathrm{d}} \Phi_{d_R^c}$$

$$\Downarrow \qquad\qquad\qquad \Downarrow$$

$$\mathcal{L}_{\mathrm{Y}}^{\mathrm{u}} = y_{\mathrm{u}} q_L H_{\mathrm{u}} u_R^c \qquad \mathcal{L}_{\mathrm{Y}}^{\mathrm{d}} = y_{\mathrm{d}} q_L H_{\mathrm{d}} d_R^c$$

The SUSY Higgs

The SUSY Higg**ses** scalar potential:

F-Term ($|\partial W/\partial\Phi|^2$)
from
$W = \mu\Phi_{\rm u}\Phi_{\rm d}$

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

$$V[H_{\rm u},H_{\rm d}] = \mu^2\left[|H_{\rm u}|^2+|H_{\rm d}|^2\right]$$

$$+\frac{g^2+g'^2}{8}\left[|H_{\rm u}|^2-|H_{\rm d}|^2\right]^2+\frac{g^2}{2}|H_{\rm u}^\dagger H_{\rm d}|^2$$

$$+m_{\rm u}^2|H_{\rm u}|^2+m_{\rm d}^2|H_{\rm d}|^2+B\left[H_{\rm u}H_{\rm d}+H_{\rm u}^*H_{\rm d}^*\right]$$

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

$$\langle |H_\mathrm{u}|^2 \rangle = \frac{v_\mathrm{u}^2}{2} \qquad \langle |H_\mathrm{d}|^2 \rangle = \frac{v_\mathrm{d}^2}{2}$$

2 sources of EWSB $\Longrightarrow$ $v_\mathrm{u}^2 + v_\mathrm{d}^2 = v^2 = (246\mathrm{GeV})^2$

define: $v_\mathrm{u}/v_\mathrm{d} = \tan\beta$ $\Longrightarrow$ $\begin{cases} v_\mathrm{u} = v \sin\beta \\ v_\mathrm{d} = v \cos\beta \end{cases}$

Abbreviations:

$s_\beta = \sin\beta \quad t_\beta = \frac{s_\beta}{c_\beta}$

$c_\beta = \cos\beta$

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

$$\begin{aligned} \mathcal{L}_\mathrm{Y}^\mathrm{u} &= y_\mathrm{u} q_L H_\mathrm{u} u_R^c \\ \mathcal{L}_\mathrm{Y}^\mathrm{d} &= y_\mathrm{d} q_L H_\mathrm{d} d_R^c \end{aligned} \Longrightarrow \begin{cases} m_\mathrm{u} = y_\mathrm{u} v_\mathrm{u}/\sqrt{2} \\ m_\mathrm{d} = y_\mathrm{d} v_\mathrm{d}/\sqrt{2} \end{cases}$$

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

The SUSY Higgs

Four implications of the SUSY Higgs sector structure.

Implication #2: **many scalars** around

In Unitary Gauge

$$H_{\mathrm{u}}=\begin{bmatrix} 0 \\ \frac{v_{\mathrm{u}}+h_{\mathrm{u}}}{\sqrt{2}} \end{bmatrix}+\begin{bmatrix} c_\beta H_+ \\ c_\beta \frac{iA}{\sqrt{2}} \end{bmatrix} \qquad H_{\mathrm{d}}=\begin{bmatrix} \frac{v_{\mathrm{d}}+h_{\mathrm{d}}}{\sqrt{2}} \\ 0 \end{bmatrix}+\begin{bmatrix} s_\beta \frac{iA}{\sqrt{2}} \\ s_\beta H_- \end{bmatrix}$$

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

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

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

$$\begin{bmatrix} h_{\mathrm{u}} \\ h_{\mathrm{d}} \end{bmatrix}=\begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix}\begin{bmatrix} h \\ H \end{bmatrix}$$

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

The Other Higgs
(maybe heavier)

The SUSY Higgs

Four implications of the SUSY Higgs sector structure.

Implication #3: **modified Higgs couplings**

$$\kappa_{\mathrm{u}} = \frac{g_{h\mathrm{uu}}}{g_{h\mathrm{uu}}^{\mathrm{SM}}} = \frac{\sin(\alpha + \pi/2)}{\sin\beta}$$

$$\kappa_{\mathrm{d}} = \frac{g_{h\mathrm{dd}}}{g_{h\mathrm{dd}}^{\mathrm{SM}}} = \frac{\cos(\alpha + \pi/2)}{\cos\beta}$$

$$\kappa_{V} = \frac{g_{hVV}}{g_{hVV}^{\mathrm{SM}}} = \sin(\beta - \alpha)$$

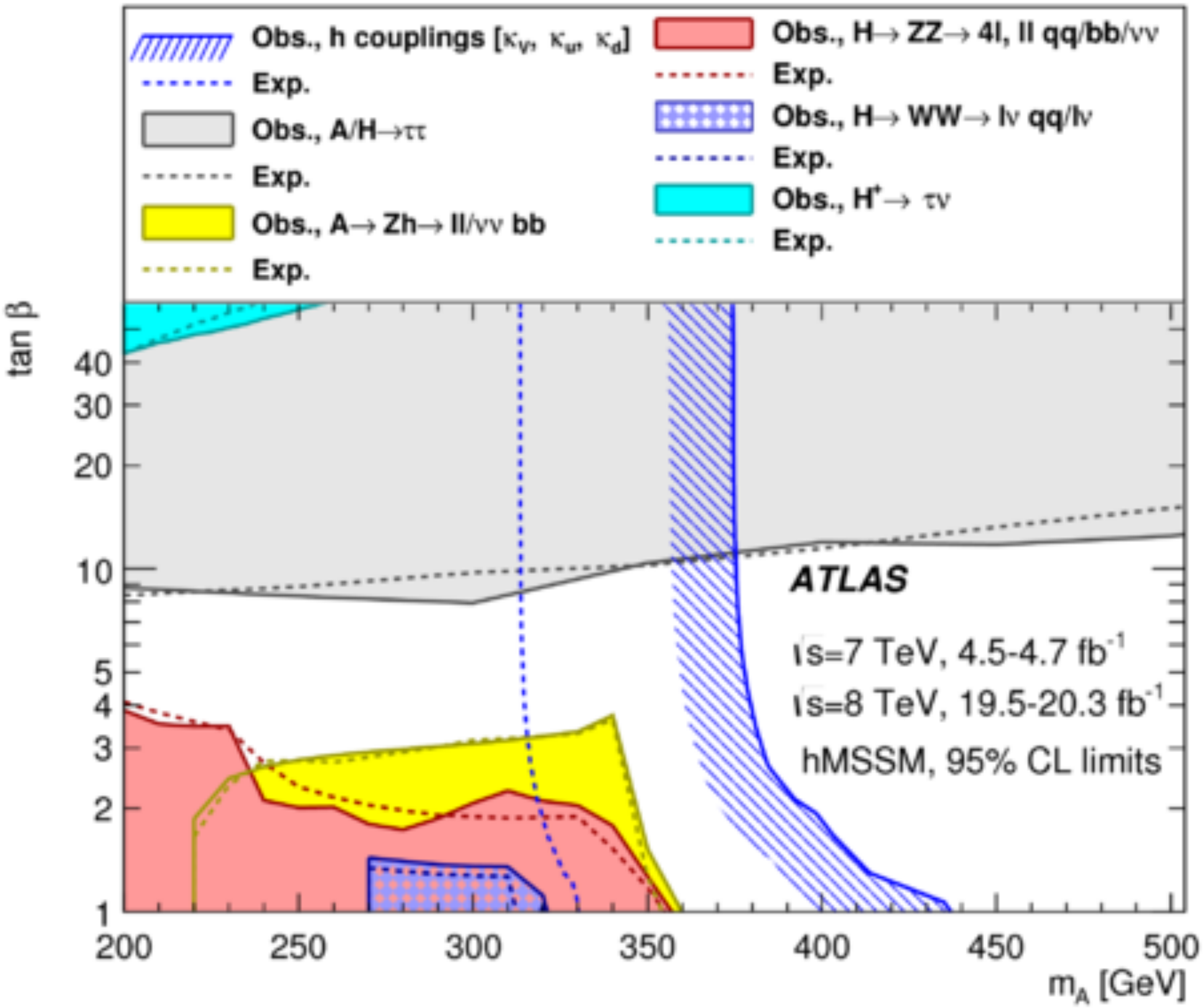
The form of the potential allows us to express α in terms of β and of the pseudo-scalar A mass:

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

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**

$$\kappa_{\mathrm{u}} = \frac{g_{h\mathrm{uu}}}{g^{\mathrm{SM}}_{h\mathrm{uu}}} = \frac{\sin(\alpha + \pi/2)}{\sin\beta}$$

$$\kappa_{\mathrm{d}} = \frac{g_{h\mathrm{dd}}}{g^{\mathrm{SM}}_{h\mathrm{dd}}} = \frac{\cos(\alpha + \pi/2)}{\cos\beta}$$

$$\kappa_V = \frac{g_{hVV}}{g^{\mathrm{SM}}_{hVV}} = \sin(\beta - \alpha)$$

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: $m_{\mathrm{d}}^2 \to \infty$ (technically natural)

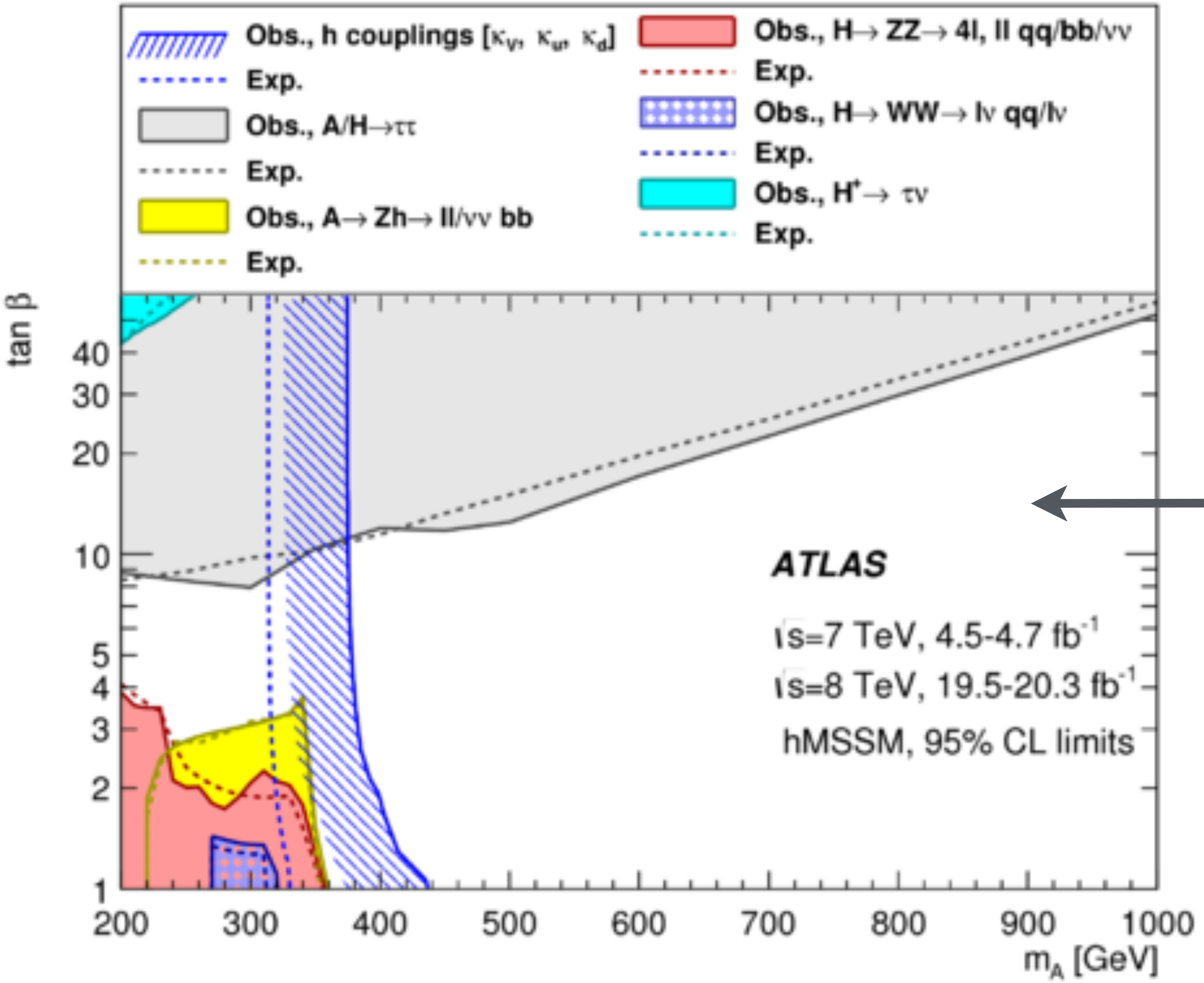
$m_A^2 = m_{\mathrm{d}}^2 + \ldots \to \infty$ ➡ $\tan\alpha \simeq -\dfrac{1}{t_\beta}$ ➡ $\alpha \simeq \beta - \pi/2$ ➡ **SM Higgs**

In the limit we also have: $\sin 2\beta \underset{||}{=} \dfrac{2B}{m_A^2} \Rightarrow t_\beta \simeq \dfrac{m_A^2}{B} \to \infty$

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)

$$V[H_\mathrm{u}, H_\mathrm{d}] \Rightarrow V_\mathrm{SM} = \mu^2_\mathrm{SM}|H_\mathrm{u}|^2 + \lambda|H_\mathrm{u}|^4$$

$$\mu^2_\mathrm{SM} = \mu^2 + m^2_\mathrm{u}$$

$$\lambda = \frac{g^2 + g'^2}{8}$$

Habitual SM formula gives:

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

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

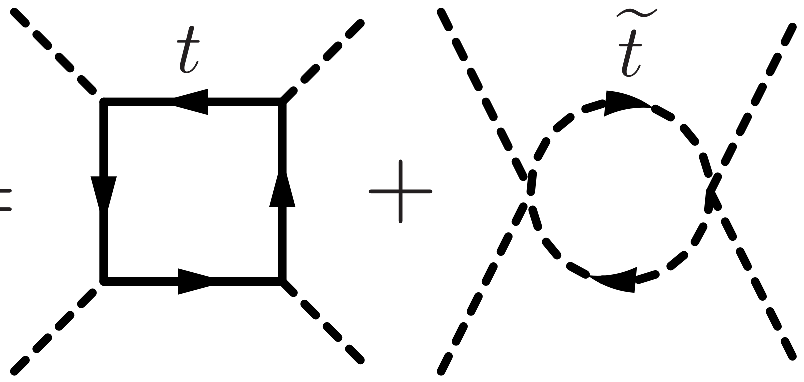
Problem: λ is too small. **Solution:** increase λ.

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

The SUSY Higgs

Two ways to increase λ :

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



$$\delta\lambda = \square + \bigcirc \sim \frac{3y_t^4}{8\pi^2}\log\frac{M_{\tilde{t}}}{m_t}$$

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

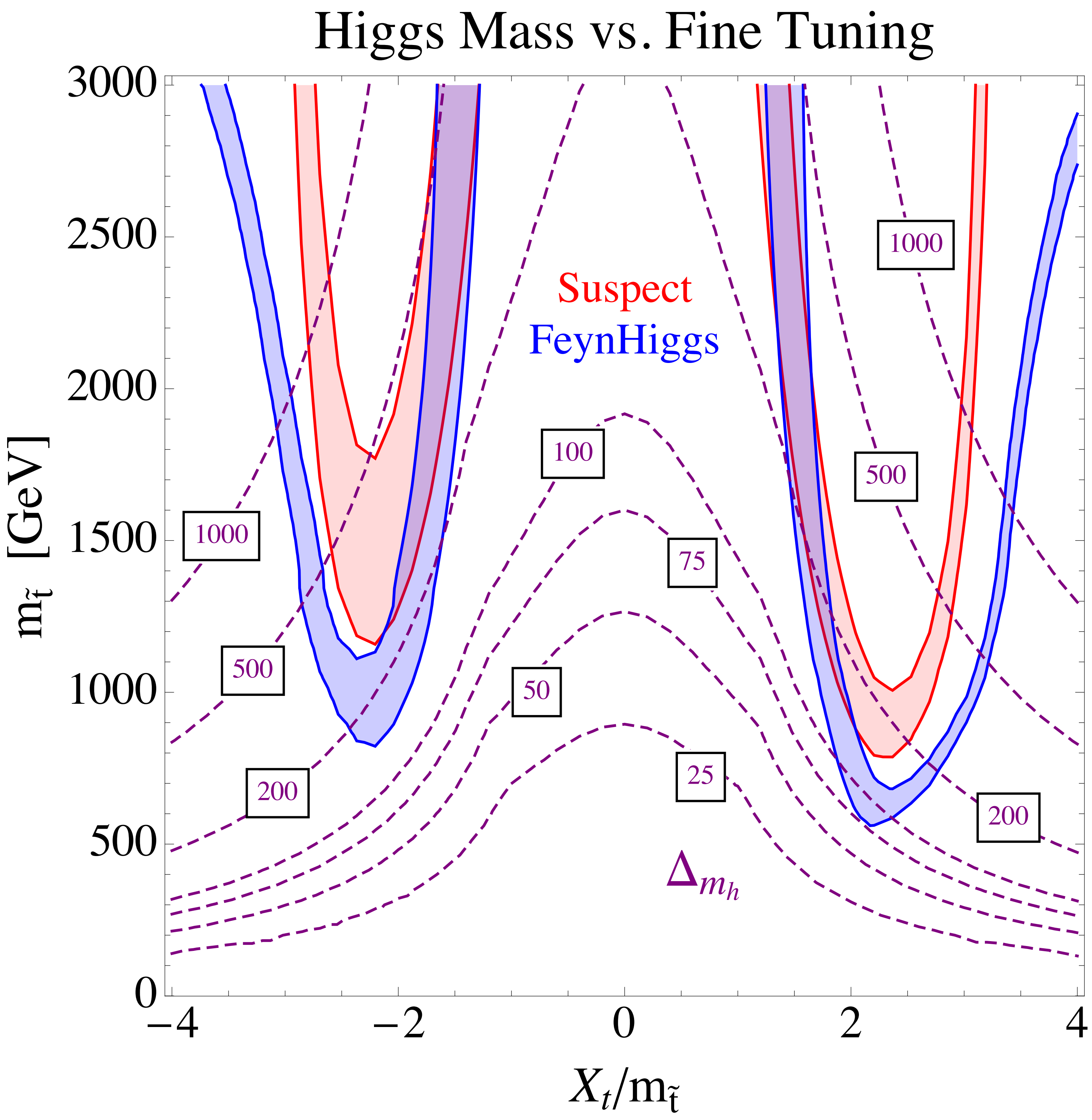
$$M_{\tilde{t}} \sim m_t e^{\frac{8\pi^2\delta\lambda}{3y_t^2}} \sim 1.3\ \text{TeV}$$

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

$$\Delta \geq \underset{\downarrow \atop \sim 7}{\left(\frac{M_{\text{soft}}}{500\ \text{GeV}}\right)^2}\ \underset{\downarrow \atop \sim 5}{\log(\Lambda_{\cancel{\text{SUSY}}}/M_{\text{EW}})}$$

low $\Lambda_{\cancel{\text{SUSY}}}$ = 10 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 $\lambda\mathrm{SUSY}$)

$$W_S = \lambda_S \Phi_S \Phi_\mathrm{u} \Phi_\mathrm{d} \quad \longrightarrow \quad V_S = \lambda_S^2 |H_\mathrm{u} H_\mathrm{d}|^2$$

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

$$\Downarrow$$

No (obvious) **decoupling limit.**

$$\Downarrow$$

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.

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

$$\mu^2 + m_{\rm u}^2 = \mu_{\rm SM}^2 = m_H^2/2 \simeq (88\ \mathrm{GeV})^2$$

Naturalness argument associates to μ a tuning of

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

Higgsinos (of mass ~ μ) are the most “expensive” sparticles. Because **contribute at tree-level.**

remember:

$$W = \mu\Phi_{\rm u}\Phi_{\rm d}$$

$$\frac{\partial^2 W}{\partial\Phi\partial\Phi}|_\phi \psi\psi = \mu\psi_{\rm u}\psi_{\rm d}$$

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

$$\mu^2 + m_{\mathrm{u}}^2 = \mu_{\mathrm{SM}}^2 = m_H^2/2 \simeq (88\ \mathrm{GeV})^2$$

Next come the **stops**, that contribute to m_{u}^2 at one loop:

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

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

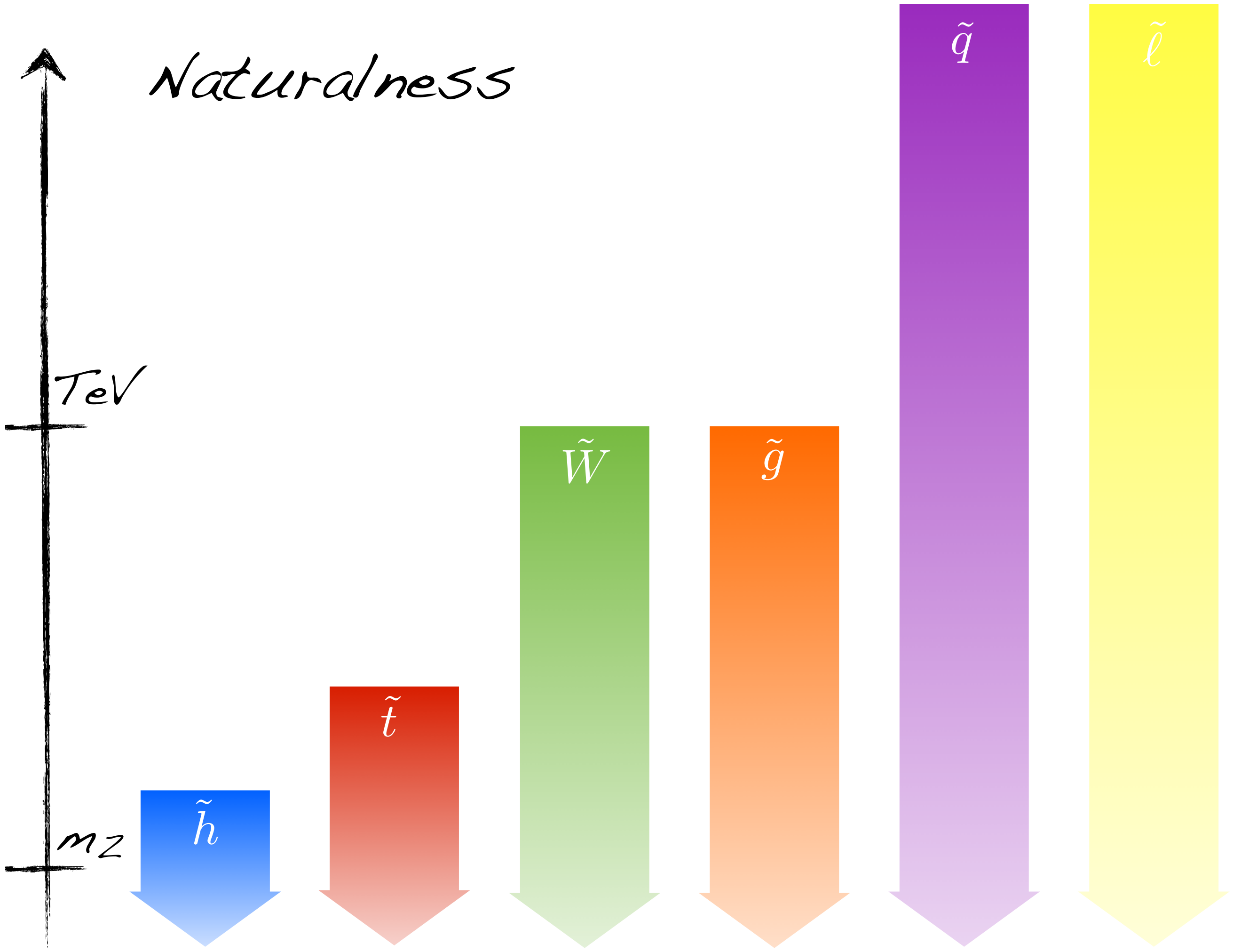
… and **gluinos:** two loops through stops coupling.

Squarks and sleptons are the cheapest: small H coupling

Sparticles searches

Direct searches: look for sparticles production and decay.

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



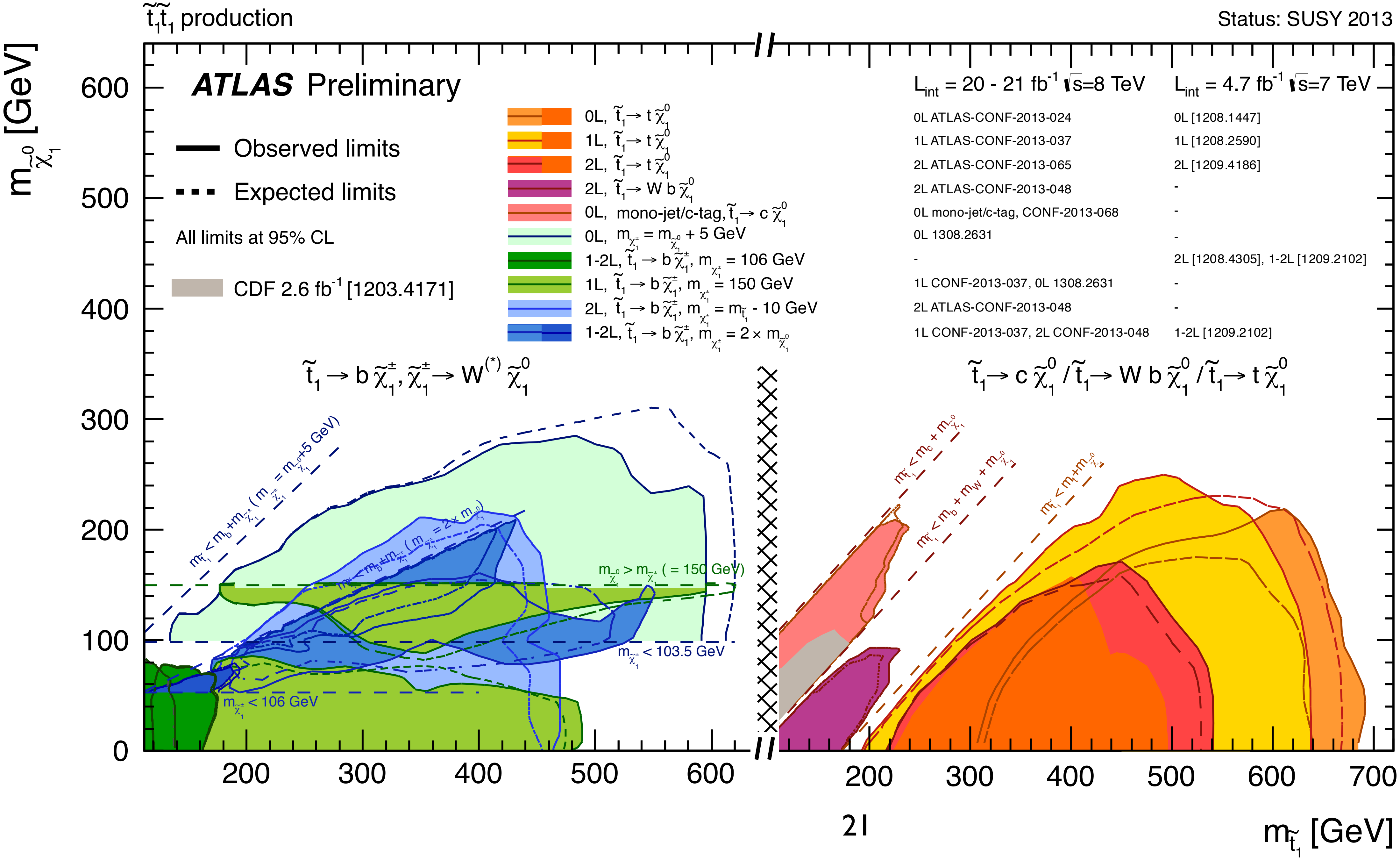
from arXiv:1309.0528

Sparticles searches

Stop: QCD pair produced and decaying in:

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

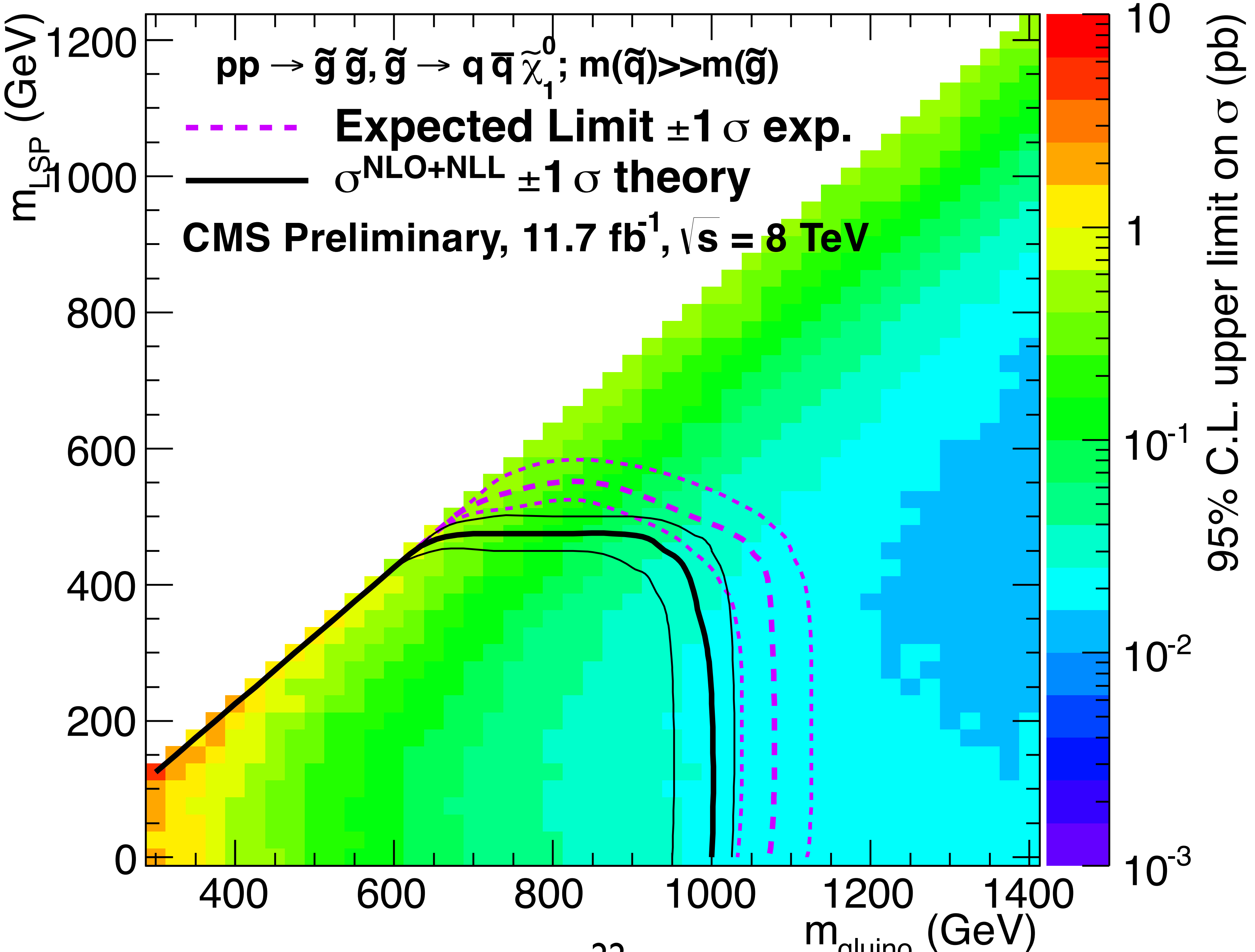
LSP (χ_0) is at the end of the decay chain. Gives MET



Sparticles searches

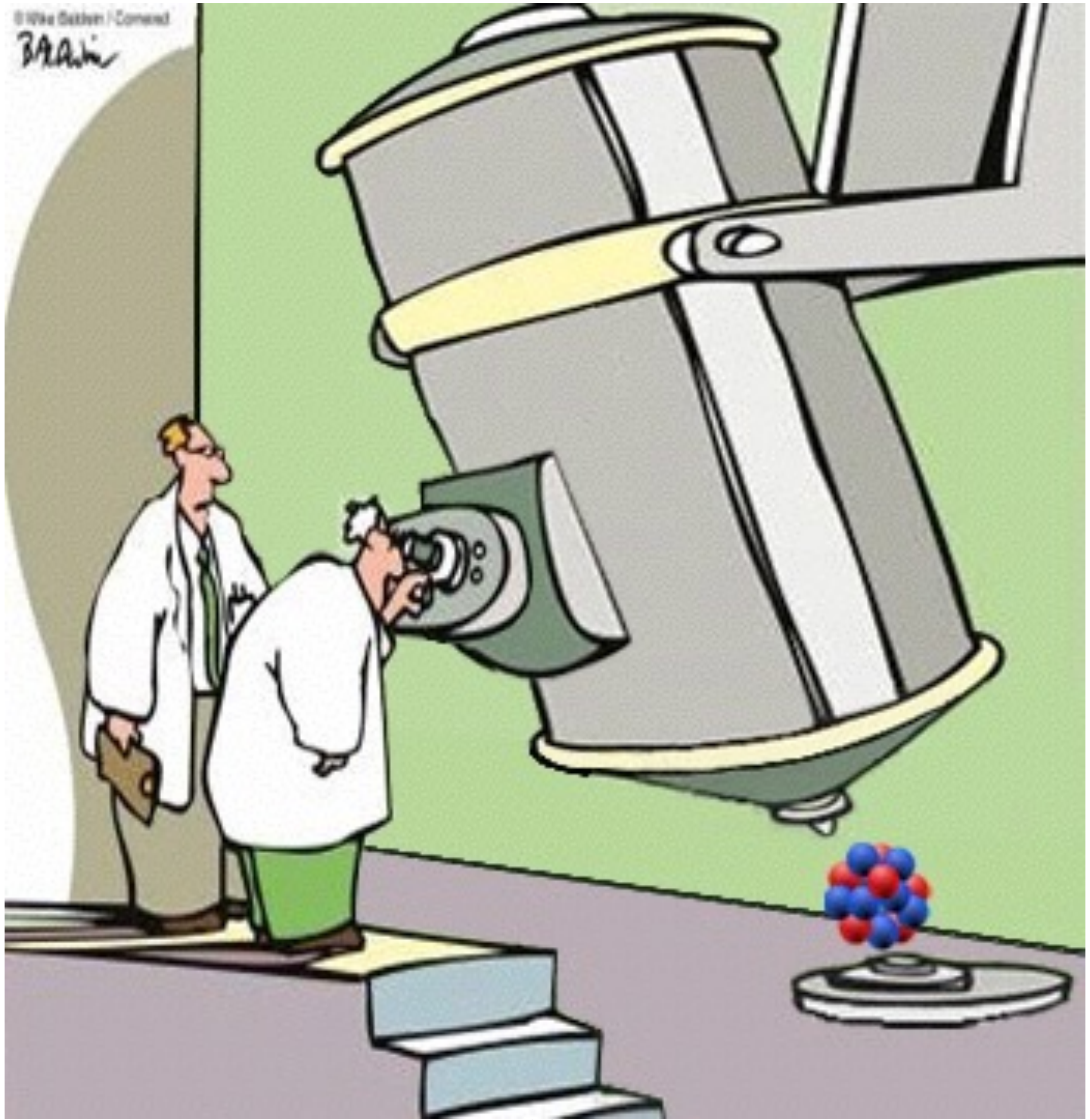
Gluinos: QCD pair produced (huge rate) and decaying in:

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



Top Partners

Composite Higgs: Direct resonance searches



Top Partners

Back to the **Partial Compositeness** formula:

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

after confinement, operators produce particles …

$$\langle 0|\mathcal{O}|\mathrm{TP}\rangle \neq 0 \qquad \mathcal{O} \leftrightarrow \mathrm{TP}$$

… with the same quantum numbers of the operator.

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

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

Top Partners

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

(the $\mathrm{U}(1)_X$ caveat also applies here)

$$\mathbf{5} \xrightarrow{\text{decompose in } \mathrm{SO}(4).} \mathbf{4} \oplus \mathbf{1}$$

further decompose in SM.

Two SM doublets:

$$\left[\begin{pmatrix} T \\ B \end{pmatrix} \begin{pmatrix} X_{5/3} \\ X_{2/3} \end{pmatrix}\right]$$

Nearly mass-degenerate,
since part of fourplet.

One SM singlet:

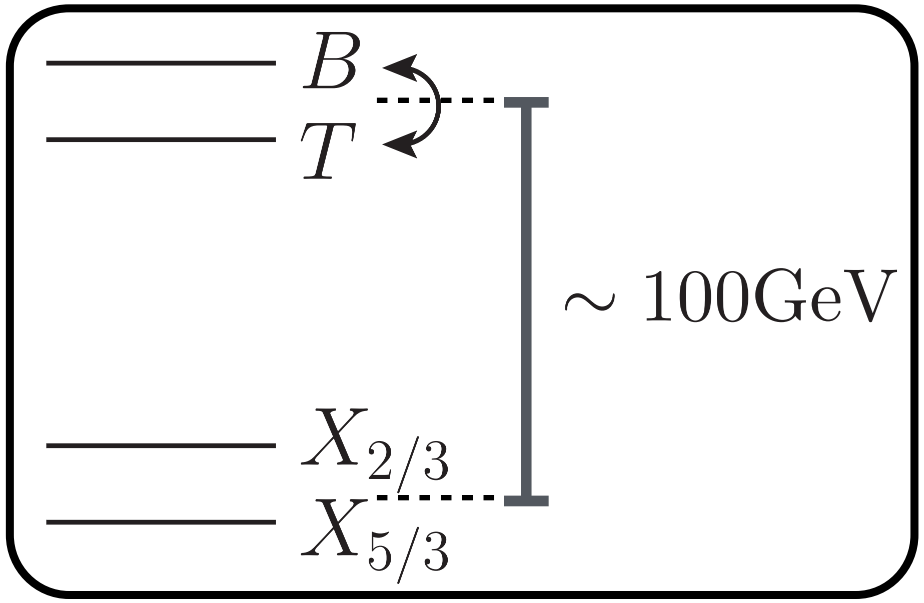
$$\widetilde{T}$$

only one charge-2/3 state

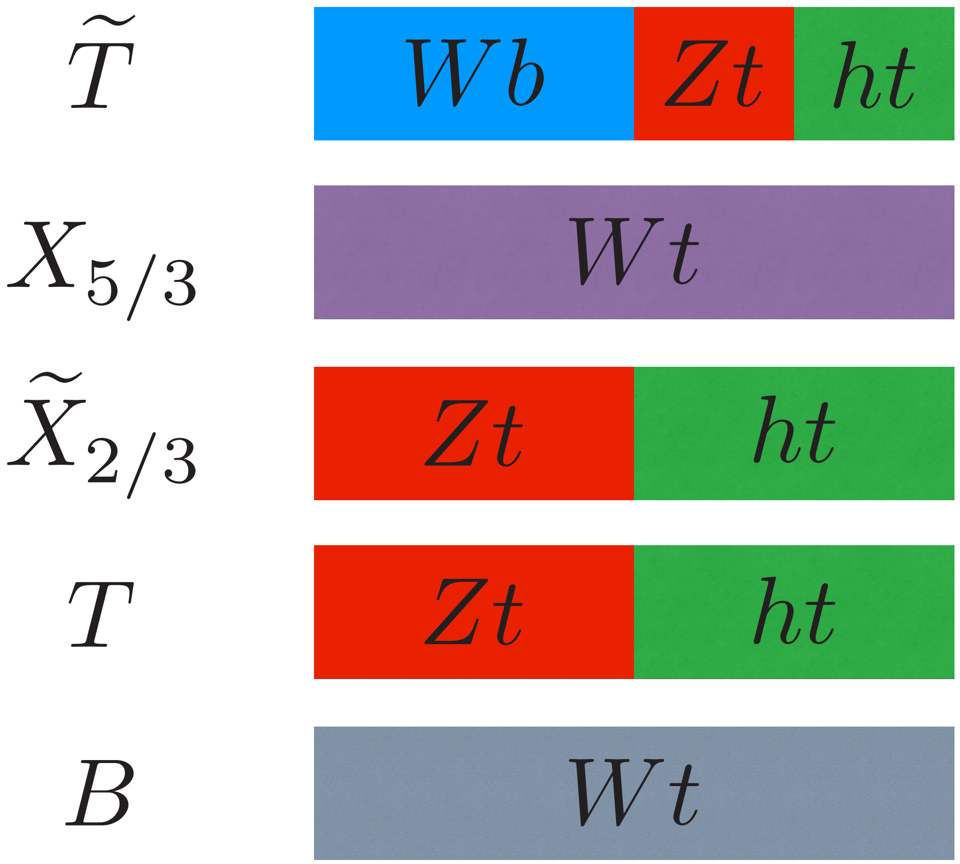
Fourplet plus singlet always there in viable models.
But other multiplets might appear. (e.g. triplets)

Top Partners

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



Typical Top Partners
Branching Ratios:



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

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

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

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

Different, but related: $g_* = \dfrac{m_*}{f}$ = 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

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
$\mathrm{SO}(5) \overset{f}{\to} \mathrm{SO}(4)$

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

Concrete rule:

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

$g_* \Pi$ → 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

$$\mathrm{SO}(5) \overset{f}{\to} \mathrm{SO}(4)$$

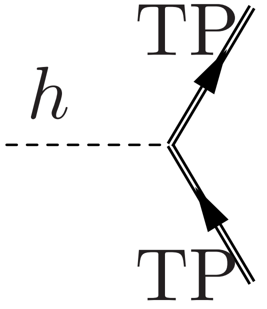
Different, but related: $g_* = \dfrac{m_*}{f}$ = typical **CS coupling**

(expected **large**, even =4π)

Concrete rule:

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

example:



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

Top Partners

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

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

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

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 (~ m_* mass term for TP)

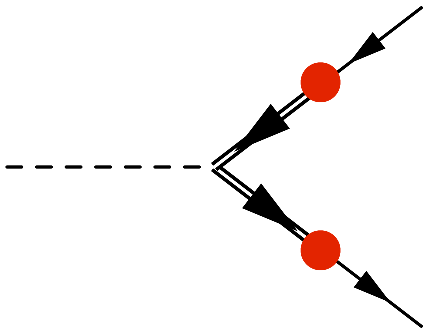
$$\begin{aligned} |q_L\rangle &= \cos\phi_L |q_L^{\text{elem.}}\rangle + \sin\phi_L |Q_L^{\text{comp.}}\rangle \\ |t_R\rangle &= \cos\phi_R |t_R^{\text{elem.}}\rangle + \sin\phi_R |T_R^{\text{comp.}}\rangle \end{aligned} \qquad \sin\phi_{L,R} \simeq \frac{\lambda_{L,R}}{g_*} \ll 1$$

Top Partners

$$|q_L\rangle = \cos\phi_L |q_L^{\text{elem.}}\rangle + \sin\phi_L |Q_L^{\text{comp.}}\rangle$$
$$|t_R\rangle = \cos\phi_R |t_R^{\text{elem.}}\rangle + \sin\phi_R |T_R^{\text{comp.}}\rangle$$

$$\sin\phi_{L,R} \simeq \frac{\lambda_{L,R}}{g_*} \ll 1$$

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

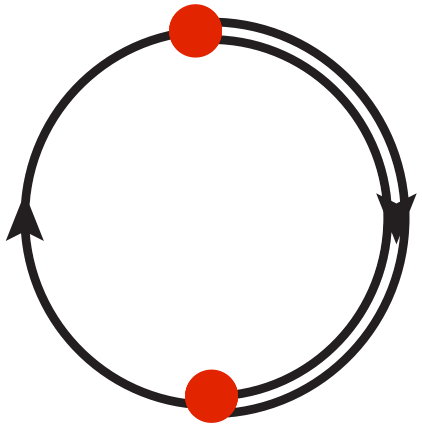
Light quarks and leptons have **small compositeness fraction.**

They couple less strongly with the CS resonances.

Top Partners

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

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



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

$$\Big\downarrow$$

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

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

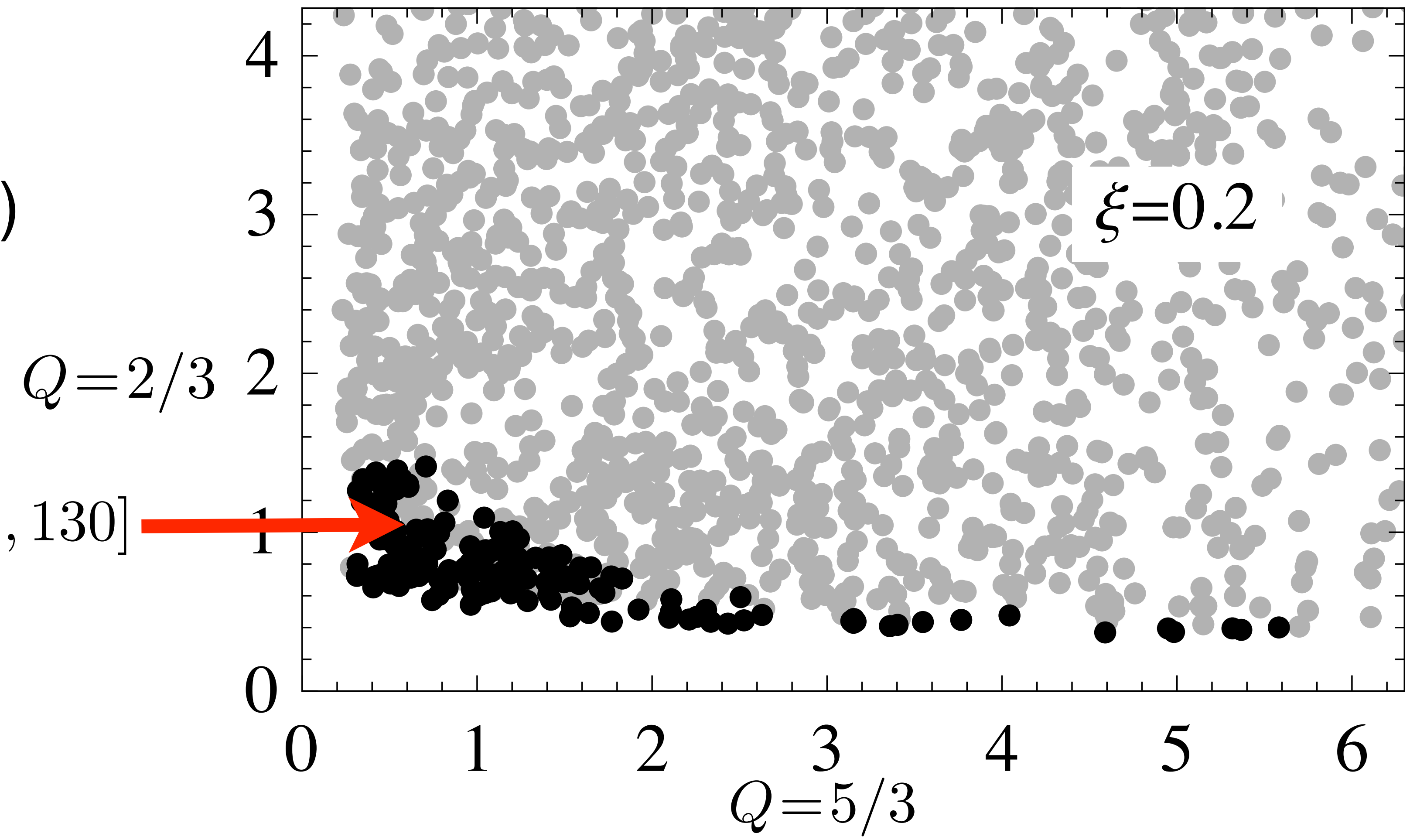
Top Partners

Light Top Partners for a light Composite Higgs

A pragmatic illustration:

$\xi = 0.2:$ (low tuning)

$m_H \in [115, 130]$



Top Partners

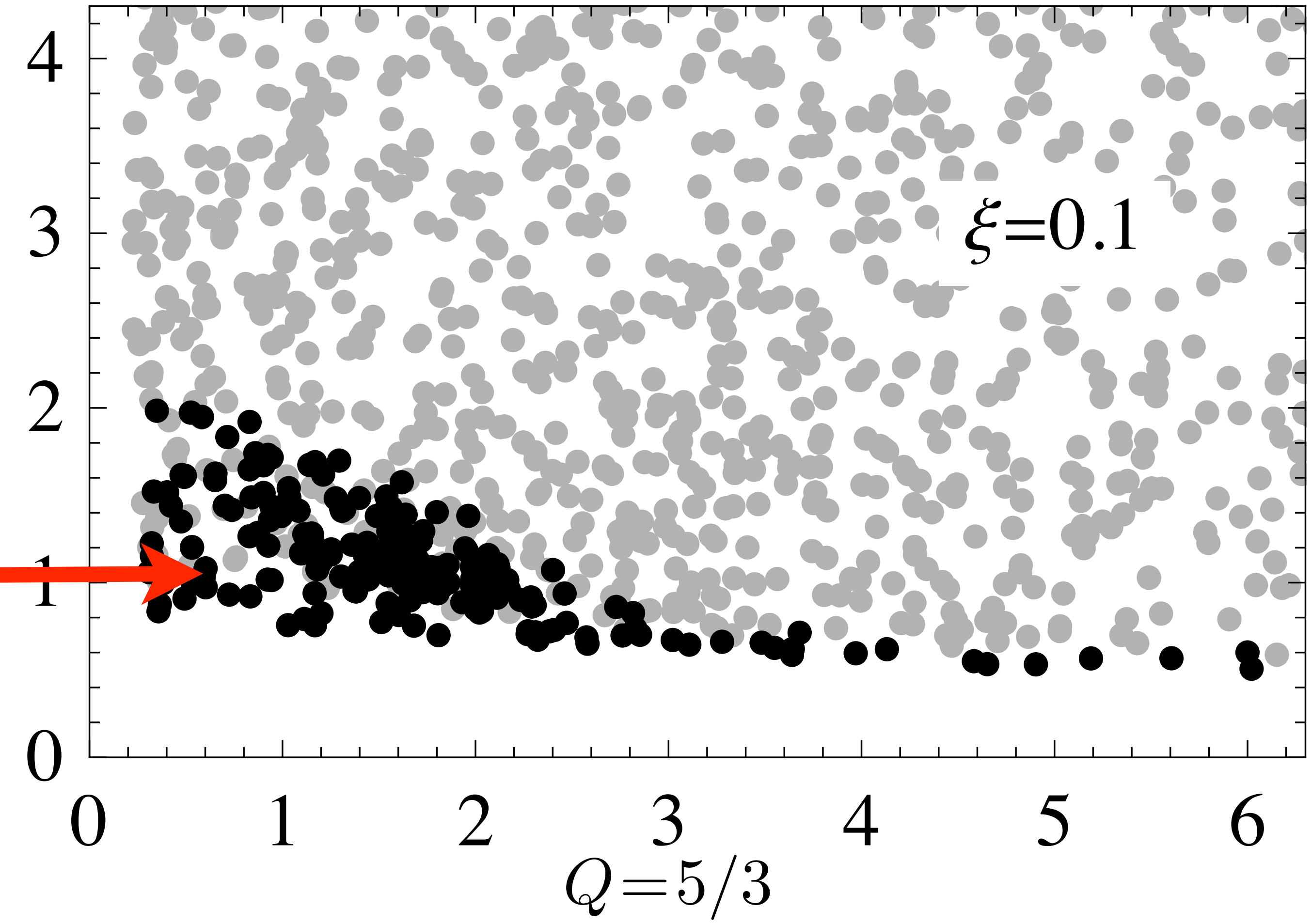
Light Top Partners for a light Composite Higgs

A pragmatic illustration:

$\xi = 0.1:$ (larger tuning)

$Q = 2/3$

$m_H \in [115, 130]$

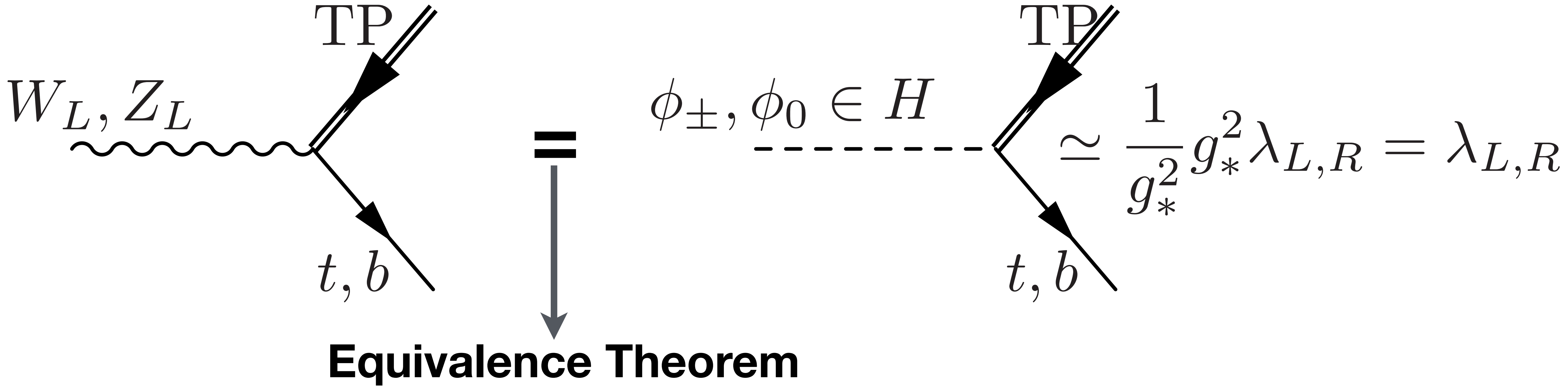


Run-2 reach: ~ 1.5 TeV from QCD prod. only.

Top Partners

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

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

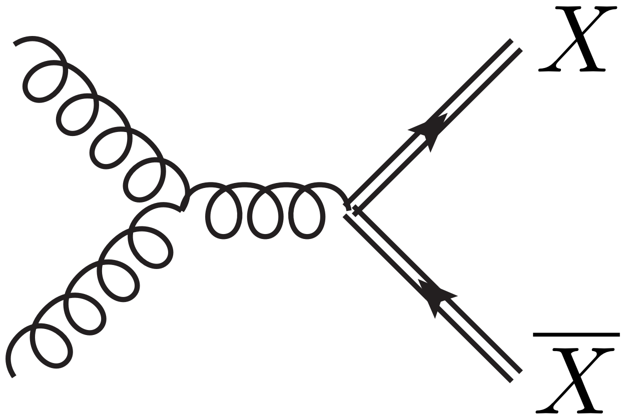


$$\simeq \frac{1}{g_*^2} g_*^2 \lambda_{L,R} = \lambda_{L,R}$$

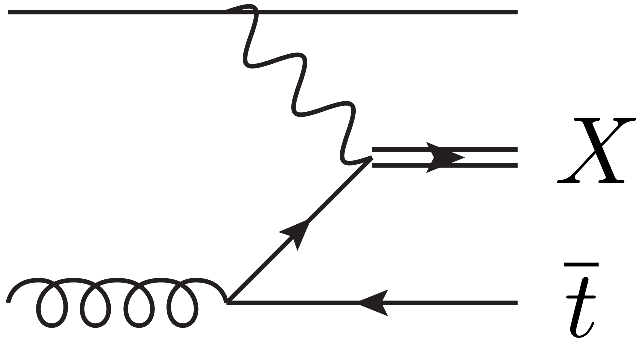
Typically large V—TP—third family quarks coupling.

Top Partners

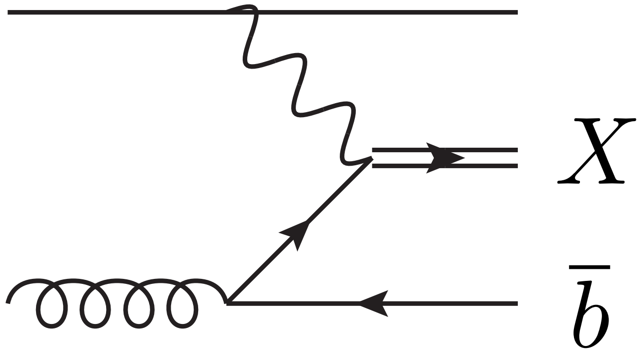
Top Partners production mechanisms



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



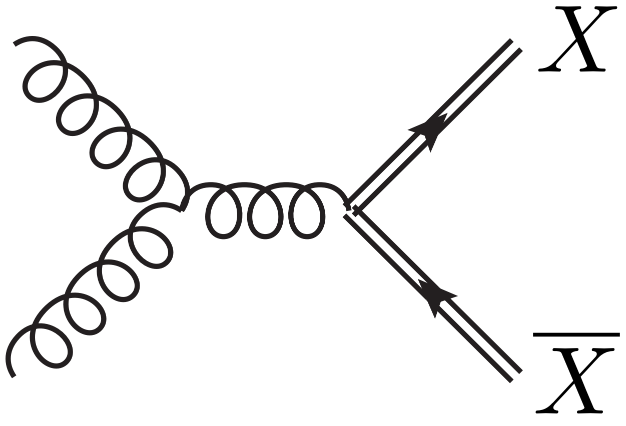
single prod. with **t**
model dep. coupling
pdf-favoured at high mass



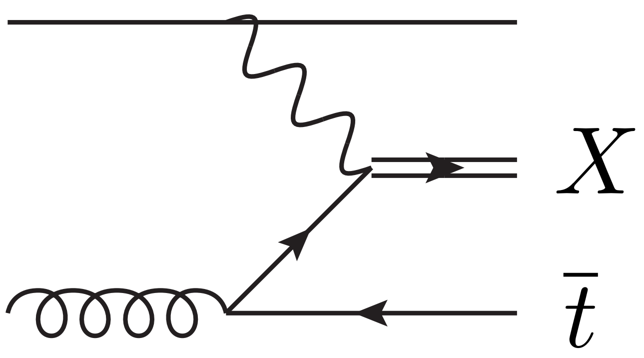
single prod. with **b**
favoured by small b mass
dominant when allowed

Top Partners

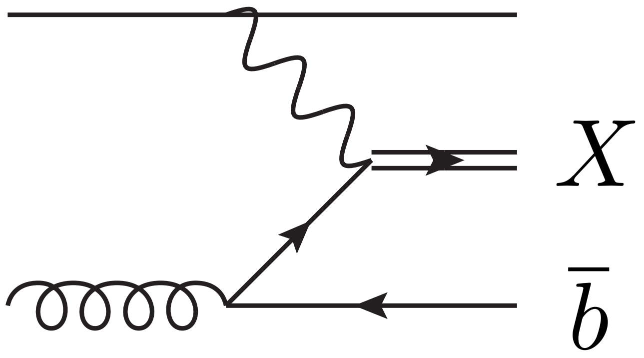
Top Partners production mechanisms



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

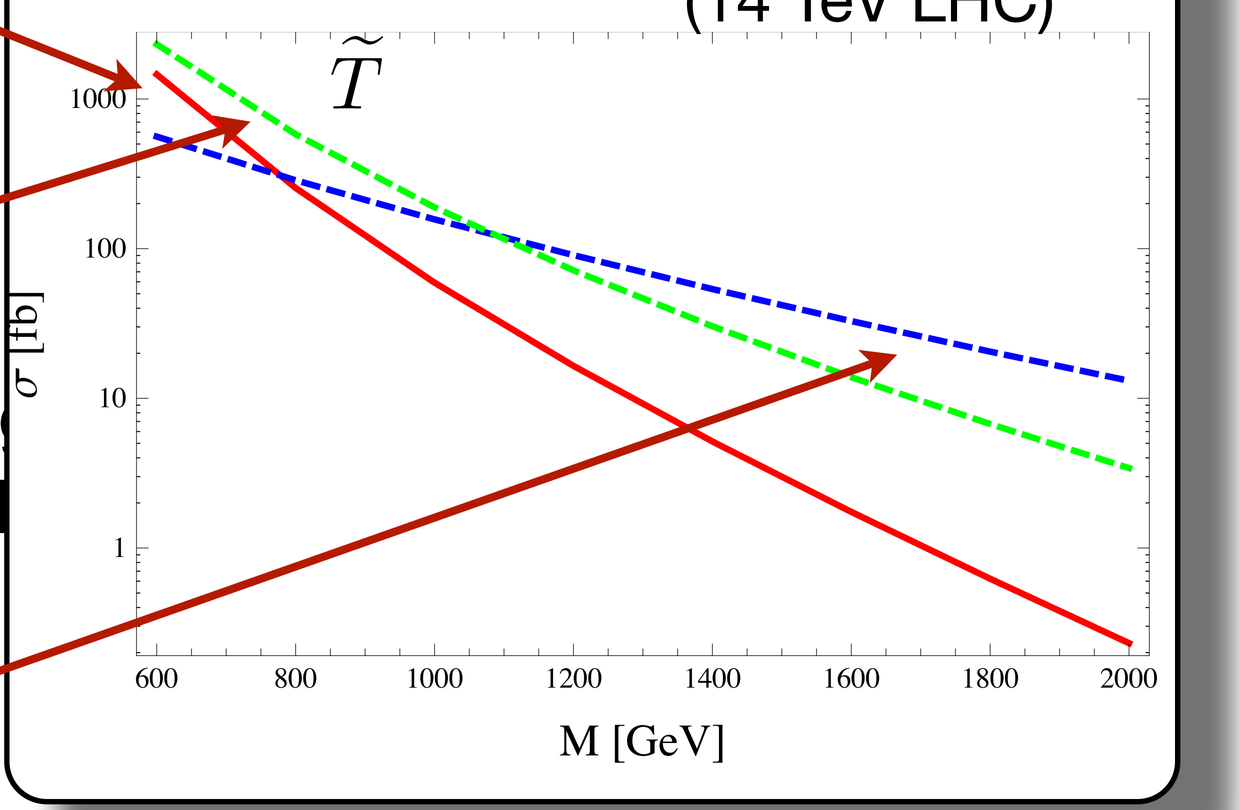


single prod. with **t**
model dep. couplin
pdf-favoured at hig



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

comparing production rates:
(14 TeV LHC)



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.

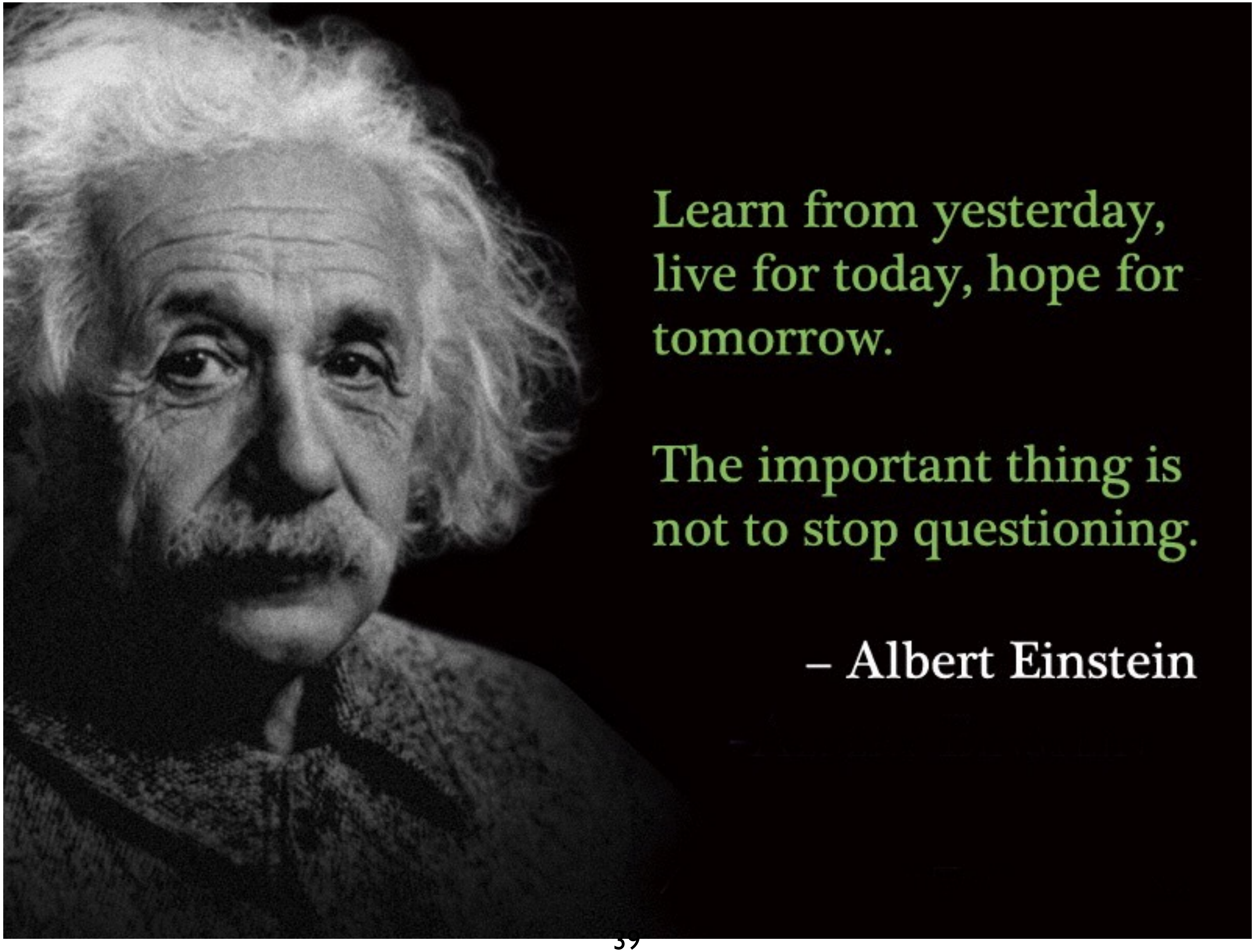
It a set of questions and possible answers about fundamental physics, to be checked with data.

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