Supersymmetry and the (susy) Higgs at the LHC

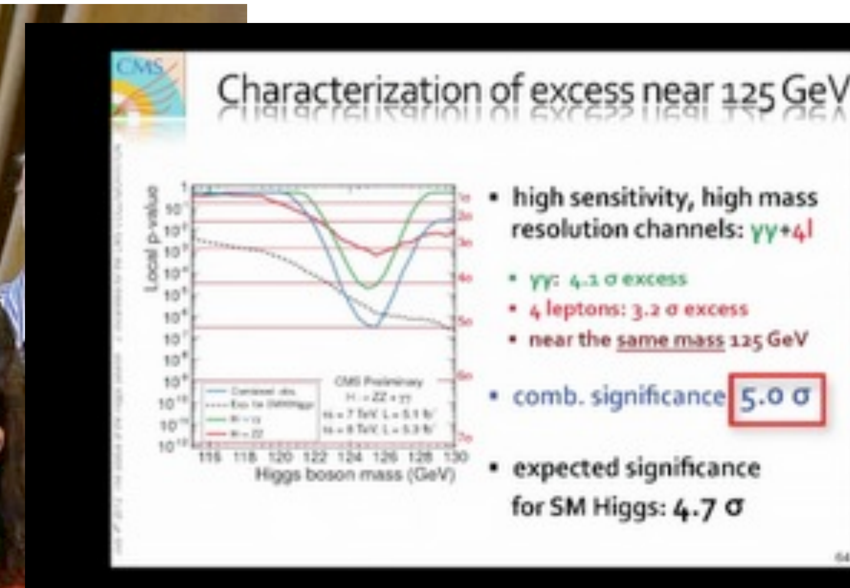
Andreas Weiler
(DESY Theory)

The best of times

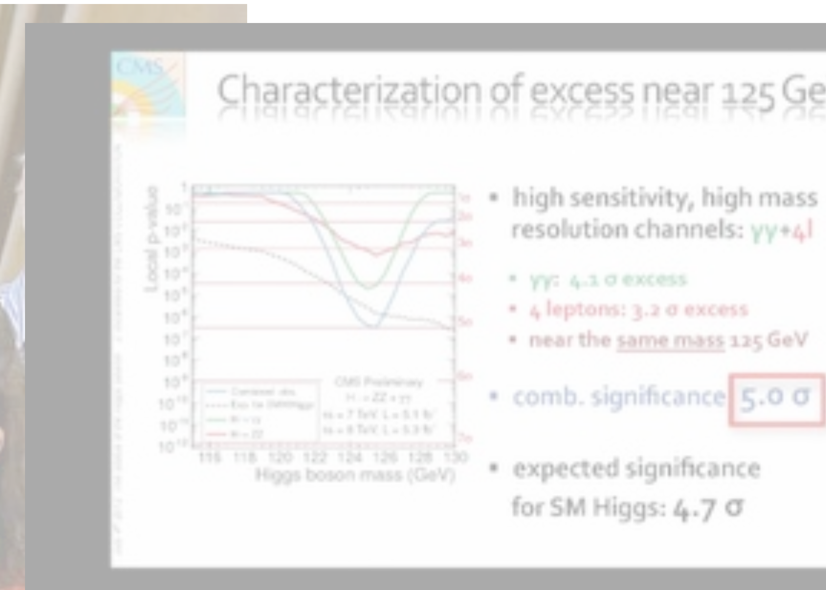
- LHC is exceeding expectations
- SM Higgs like state at $> 5\ \sigma$, 125±1 GeV
- 7 & 8 TeV searches beginning to constrain* most promising models
- Early casualties*: 4th generation, fermiophobic Higgs, techni-color, …

*terms and conditions apply

& Higgs at 125 GeV



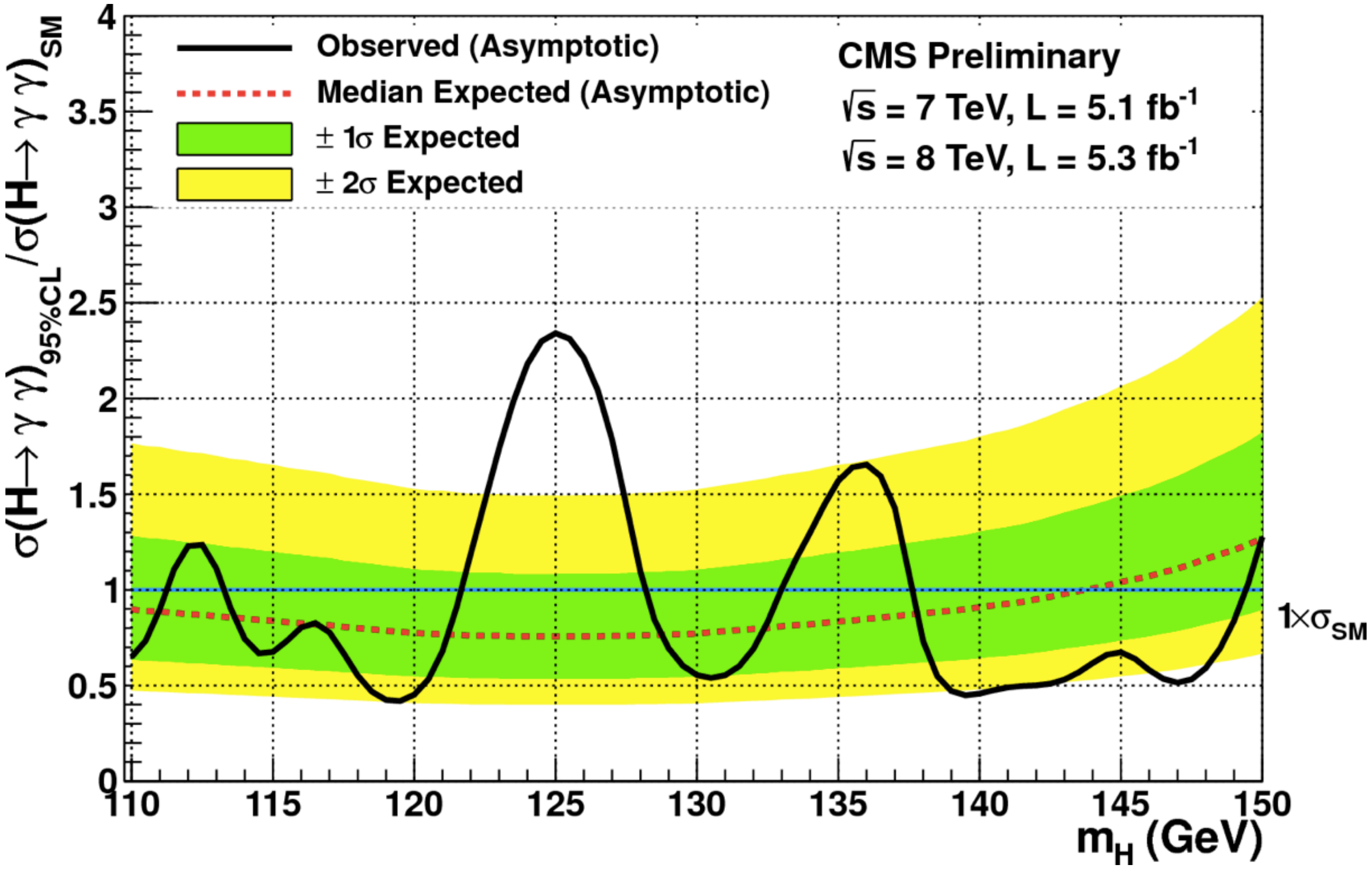
& Higgs at 125 GeV



& Higgs at 125 GeV

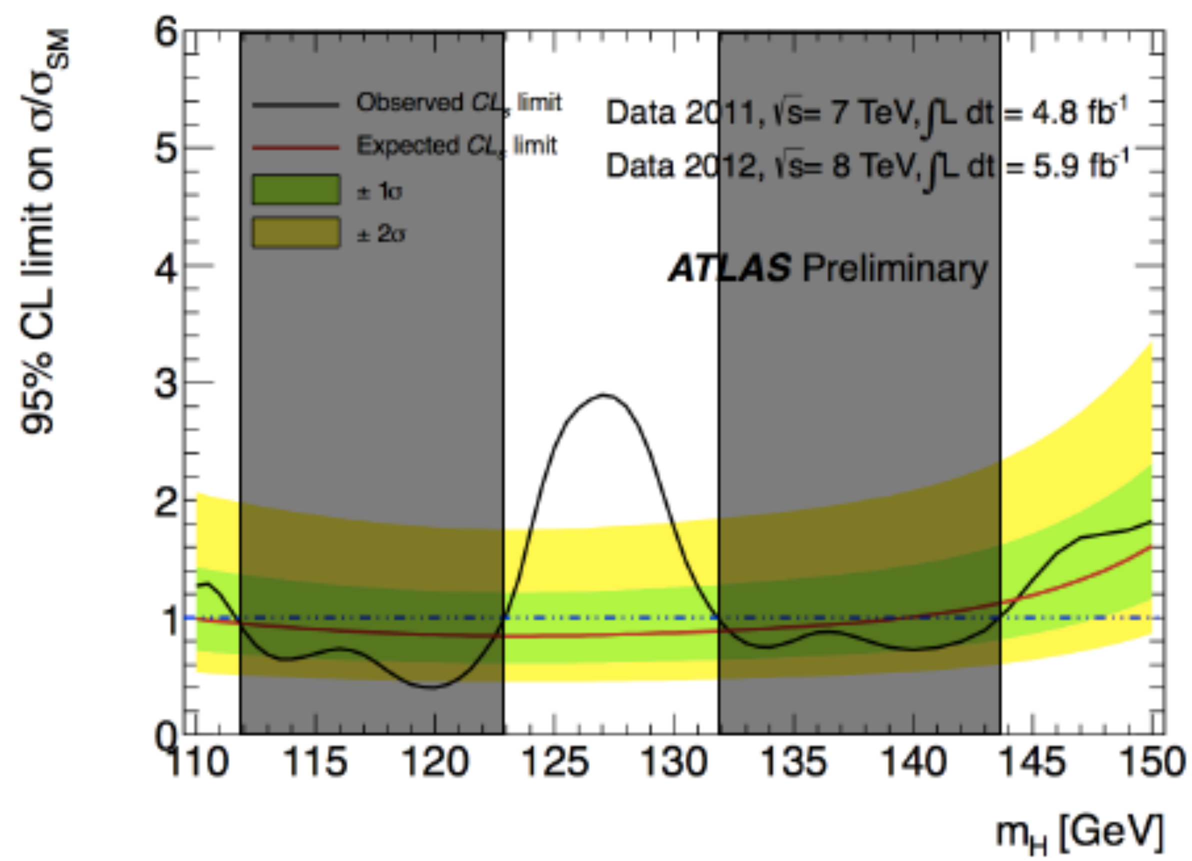
- Next: find new physics!
- Susy predicts a light Higgs (too light for naturalness?)
- Assume NP = susy for this talk. Why? How to find it? Higgs vs. Susy. What's next?

The Higgs at 125 GeV



h → γγ in CMS

h → γγ in ATLAS



A light Higgs is unnatural

$$V(h) = \epsilon \Lambda^2 h^2 + \lambda h^4$$

For $\epsilon = \pm\, \mathcal{O}(1)$

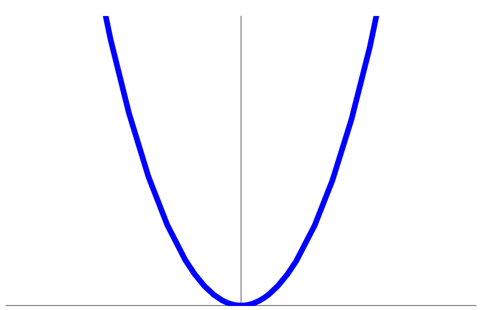
$$\langle h \rangle = 0$$

$$\langle h \rangle = \Lambda$$

Need: $\sqrt{\epsilon} \sim m_W / \Lambda$

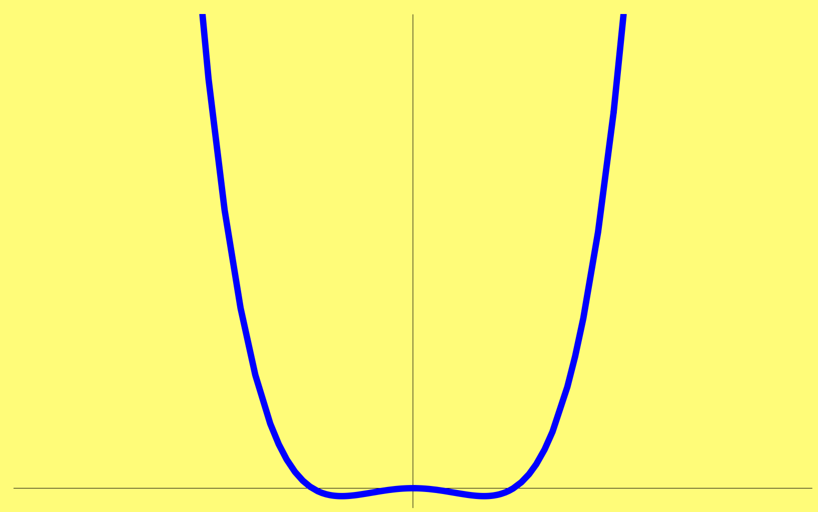
genérically

$\epsilon \sim O(1)$



$< H >= 0$

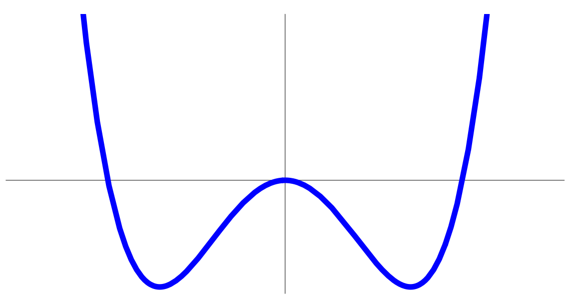
but we need



$\langle H \rangle = \sqrt{\epsilon}\Lambda_{UV}$

$\epsilon \sim 10^{-34}$

$\epsilon \sim -O(1)$



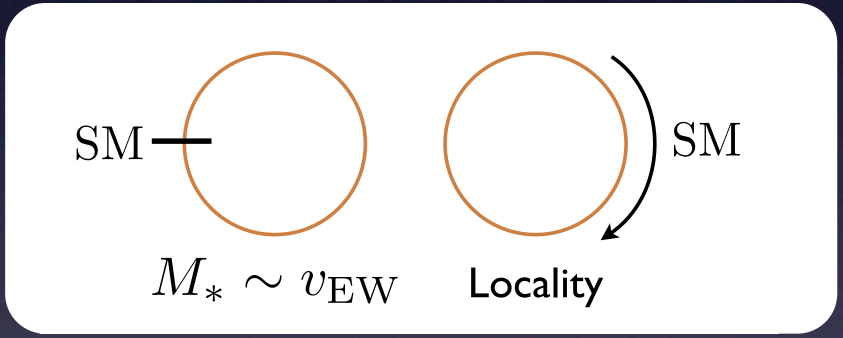
$\langle H \rangle \sim \Lambda_{UV}$

Which principle can stabilize the electro-weak scale?

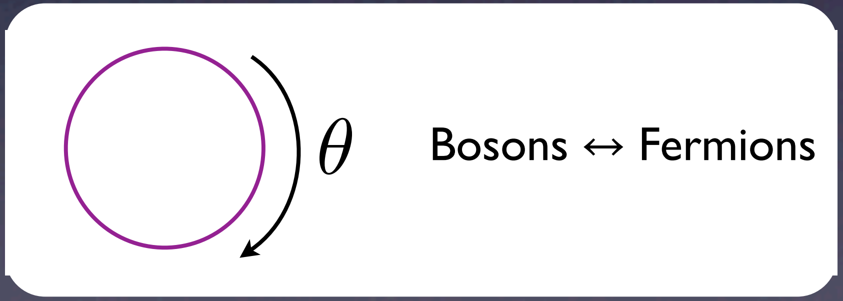
Strong dynamics/ compositeness?

$$\langle \psi \psi^c \rangle \to H \to v_{\rm EW}$$

Higher Dimensions?



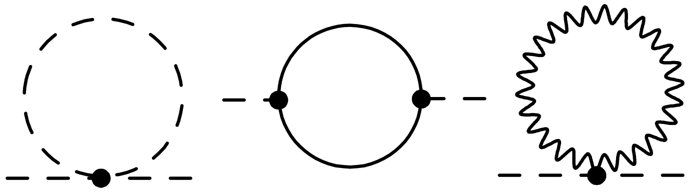
Supersymmetry?



Lack of principles? Anthropic? Non-Wilsonian EFT?

SM UV sensitivity

$$V_{\rm tree} = \frac{1}{2} m_h^2\, h^2 + \frac{m_h^2}{2v} h^3 + \frac{m_h^2}{8v^2} h^4$$
$$\approx (100\,\mathrm{GeV})^2\, h^2 + \ldots$$



? ? ? ?

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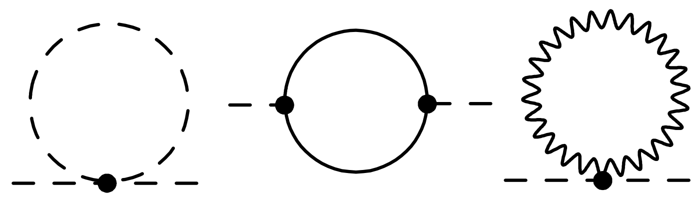
vs. 1-loop



$$V_{\Lambda^2} = \boxed{\;?\quad ?\quad ?\quad ?\;} \; \frac{\Lambda^2}{32\pi^2} \; h^2$$

W,Z, photon   top   higgs

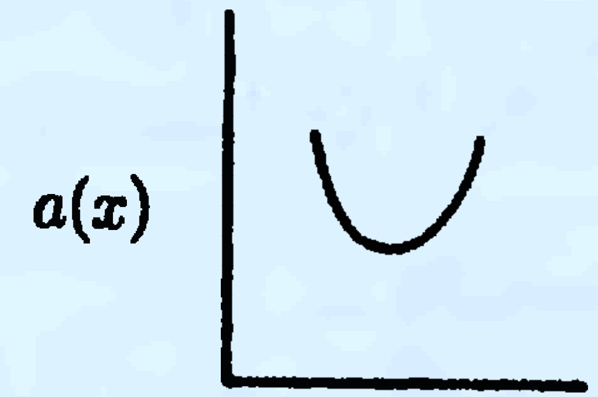
Short-cut calculation

Coleman Weinberg potential

$$V(\phi) = \int \frac{\mathrm{d}^4 k_E}{2(2\pi)^4}\ \mathrm{STr}\ \ln\left(k_E^2 + M^2(\phi)\right)$$

Treat Higgs as a background field
(like a parameter, no derivatives)

3.4 Saddle Point Evaluation of the Path Integral



Integrals of the form

$$I \equiv \int dx\, e^{-a(x)} \quad , \tag{3.4.1}$$

where $a(x)$ is a function of x, can be approximated by expanding $a(x)$ around x_0 where $a(x)$ is stationary:

$$a(x) \simeq a(x_0) + \frac{1}{2}(x - x_0)^2 a''(x_0) + \cdots \quad . \tag{3.4.2}$$

Then

$$I \simeq e^{-a(x_0)} \int dx e^{-\frac{1}{2}(x-x_0)^2 a''(x_0)} \quad , \tag{3.4.3}$$

$$W_E[J] \simeq N_E\, e^{-S_E[\phi_0,J]} \int \mathcal{D}\phi\, \exp\left\{ -\frac{1}{2} \left\langle \phi_1 \frac{\delta^2 S_E}{\delta\phi_1 \delta\phi_2} \phi_2 \right\rangle_{1,2} \right\} \quad . \tag{3.4.10}$$

The Gaussian integral can be done (see Appendix A), with the formal result

$$W_E[J] \simeq N'_E\, e^{-S_E[\phi_0,J]} \left\{ \det\left(\left[-\bar\partial_\mu \bar\partial^\mu + m^2 + V''(\phi_0) \right] \delta_{12} \right) \right\}^{-1/2} \quad . \tag{3.4.11}$$

Clearly this expression needs some getting used to. We can rewrite it in a slightly more suggestive form by using the identity

$$\det \mathrm{M} = e^{\mathrm{Tr}\, \ln \mathrm{M}} \tag{3.4.12}$$

as

$$W_E[J] = N'_E\, e^{-S_E[\phi_0,J] - \frac{1}{2} \mathrm{Tr}\, \ln\left[\left\{ -\bar\partial_\mu \bar\partial^\mu + m^2 + V''(\phi_0) \right\} \delta_{12} \right]} \quad , \tag{3.4.13}$$

Ramond - Field Theory, 2nd ed.

$$V(\phi) = \int \frac{\mathrm{d}^4 k_E}{2(2\pi)^4}\ \mathrm{STr}\ \ln\left(k_E^2 + M^2(\phi)\right)$$

STr = 'super-trace'
(trace of d.o.f with '-' for fermions)

quad. divergent piece

$$V = -\frac{\Lambda^4}{128\pi^2}\ \mathrm{STr}\ 1 \boxed{+\frac{\Lambda^2}{64\pi^2}\ \mathrm{STr}\, M^2(\phi)}$$
$$+\frac{1}{64\pi^2}\ \mathrm{STr}\, M^4(\phi)\ \ln\frac{M^2(\phi)}{\Lambda^2}\ ,$$

H-dependent masses

particles	number of polarizations	off-shell mass
$W^{\pm}$	3×2	$M_W^2 = \frac{1}{4} g^2 H^2$
Z^0	3	$M_Z^2 = \frac{1}{4} (g^2 + g'^2) H^2$
top	4×3	$M_t^2 = \frac{1}{2} y_t^2 H^2$
Higgs	1	$M_H^2 = \lambda (3H^2 - v^2)$
Goldstone	3	$M_G^2 = \lambda (H^2 - v^2)$

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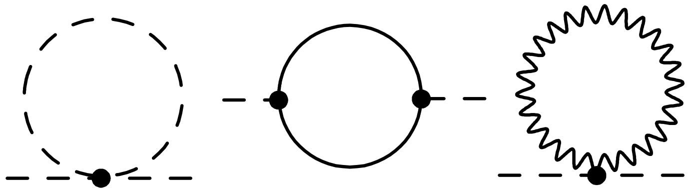

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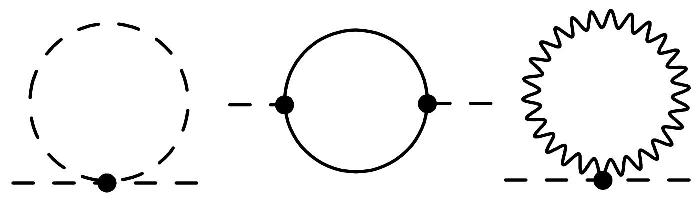

$$V_{\Lambda^2} = \frac{1}{2}\left(\frac{1}{4}(9g^2 + 3g'^2) - 6y_t^2 + 6\lambda\right)\frac{\Lambda^2}{32\pi^2}\, h^2$$

W,Z, photon top higgs

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$$\approx (100\,\text{GeV})^2\, h^2 + \ldots$$

$$V_{\Lambda^2} \approx (\;\; 15 \;\; - 100 \;\; + \;\; 9.5 \;) \cdot (100\,\text{GeV})^2 \;\, h^2$$

SU(2) top higgs

$$\Lambda = 10\,\text{TeV}$$

SM UV sensitivity

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fine-tuning!

$$V_{\Lambda^2} \approx (\;\; 15 \;\; - 100 \;\; + \;\; 9.5 \;\;) \cdot (100 \, \text{GeV})^2 \;\; h^2$$

SU(2) top higgs

$$\Lambda = 10 \, \text{TeV}$$

Why should you care about fine-tuning?

1. Electron self-energy

electrostatic energy: $E \approx \dfrac{\alpha}{r} < m_e c^2 \Rightarrow \Lambda < \dfrac{m_e}{\alpha} \approx 70 \text{ MeV}$

magnetic energy: $E \approx \dfrac{\mu^2}{r^3}, \mu = \dfrac{e\hbar}{2m_e c} < m_e c^2 \Rightarrow \Lambda < \dfrac{m_e}{\alpha^{1/3}} \approx 3 \text{ MeV}$

New physics (positron) at $m_e = 0.5 \text{ MeV}$

2. Pion mass difference

QED contribution: $\dfrac{3\alpha}{4\pi}\Lambda^2 < M_{\pi^+}^2 - M_{\pi^0}^2 \;\Rightarrow\; \Lambda < 850 \text{ MeV}$

New physics (hadrons) at $M_\rho = 770 \text{ MeV}$

3. Neutral kaon mass difference

$$\frac{G_F^2 f_K^2}{6\pi^2}\sin^2\theta_c \Lambda^2 < \frac{M_{K_L^0} - M_{K_S^0}}{M_{K_L^0}} \Rightarrow \Lambda < 2 \text{ GeV}$$

New physics (charm) at $m_c = 1.2$ GeV

The weak scale

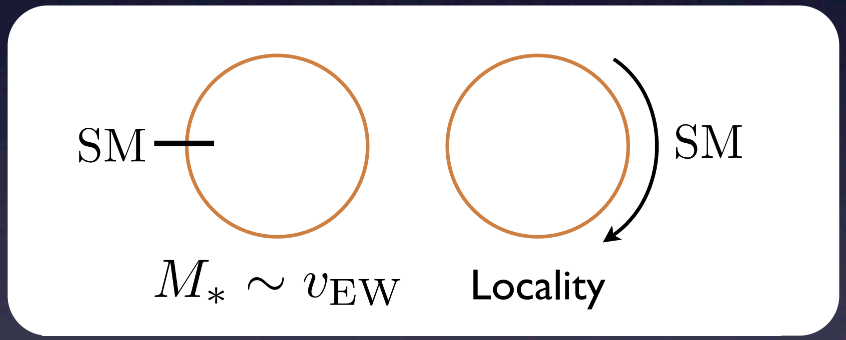
$$\delta m_h^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(4m_t^2 - 2m_W^2 - m_Z^2 - m_h^2\right)\Lambda^2 < m_h^2 \Rightarrow \Lambda < 500 \text{ GeV}$$

Which principle can stabilize the electro-weak scale?

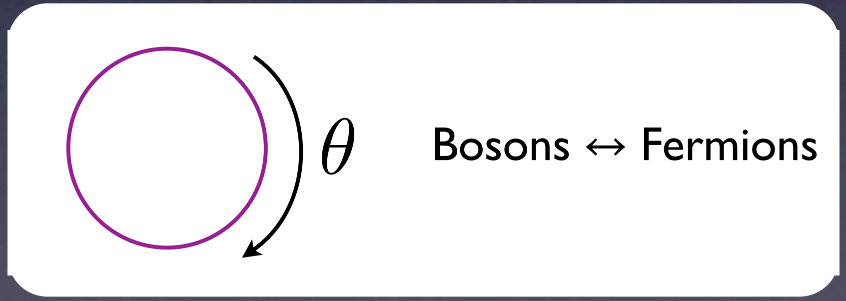
Strong dynamics/ compositeness?

$$\langle \psi \psi^c \rangle \to H \to v_{\mathrm{EW}}$$

Higher Dimensions?

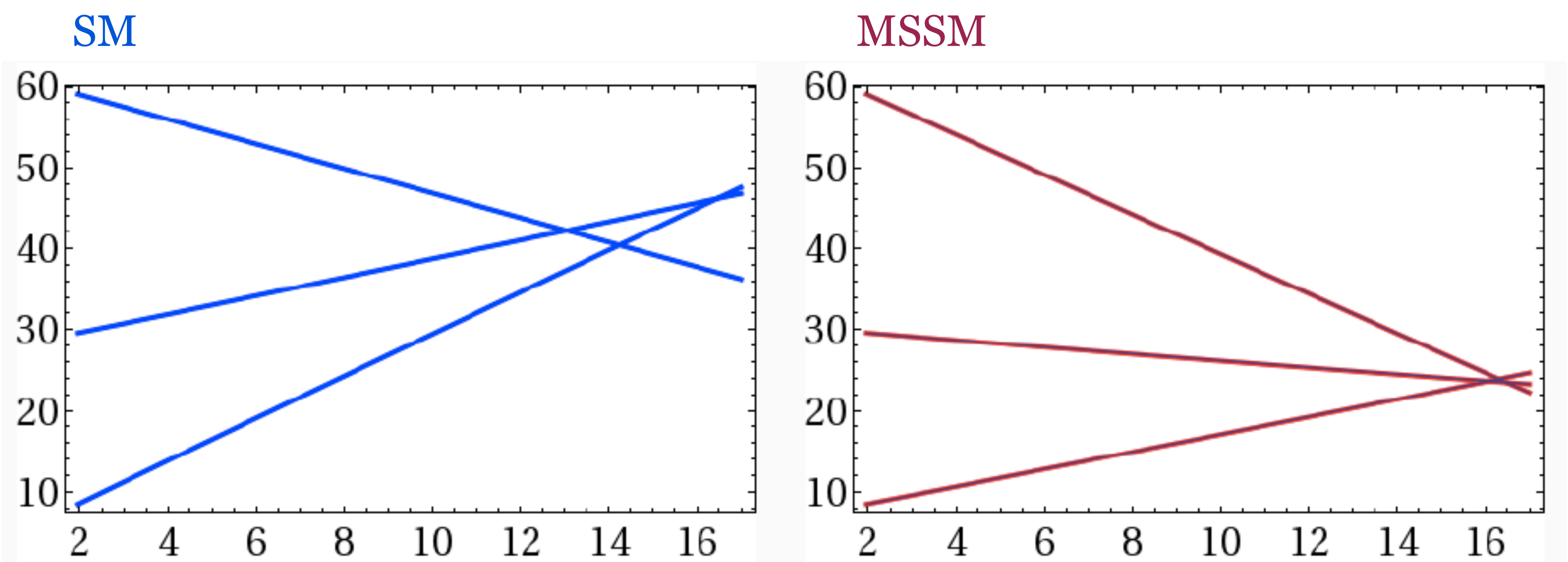


Supersymmetry?



Lack of principles? Anthropic? Non-Wilsonian EFT?

A hint?

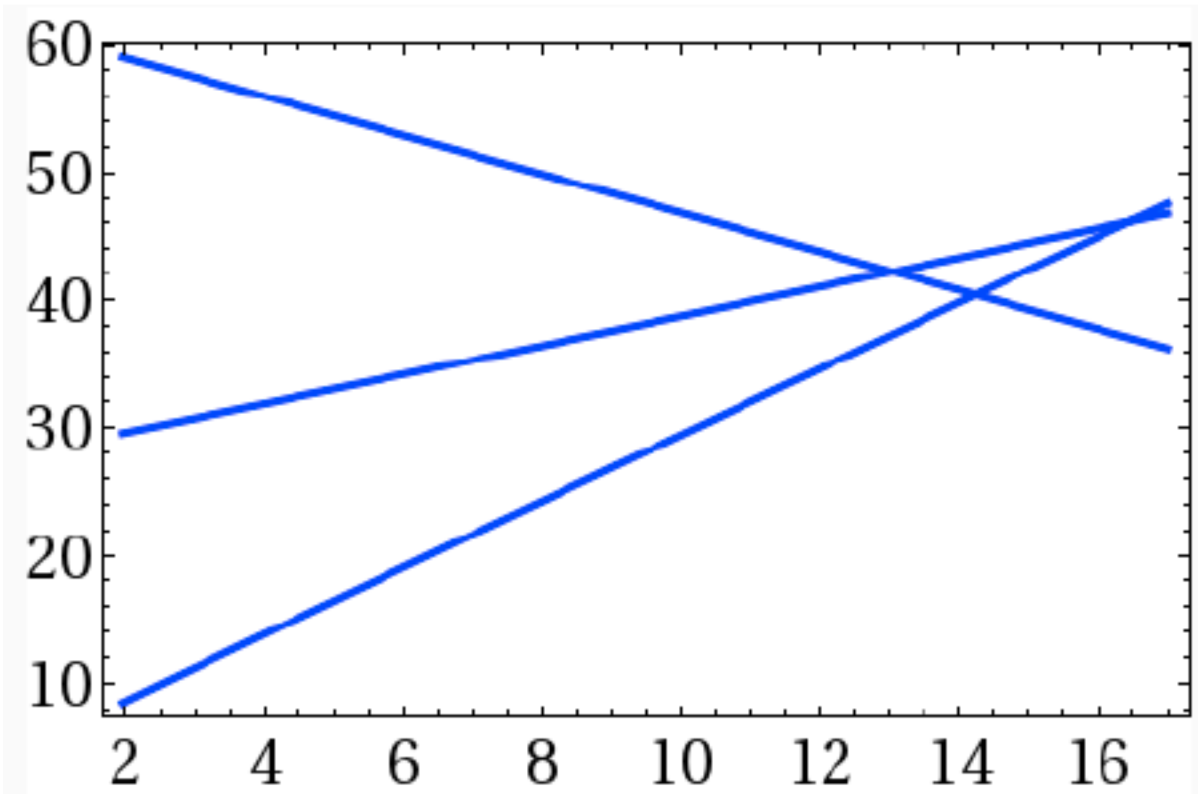


Gauge Coupling running at two loops

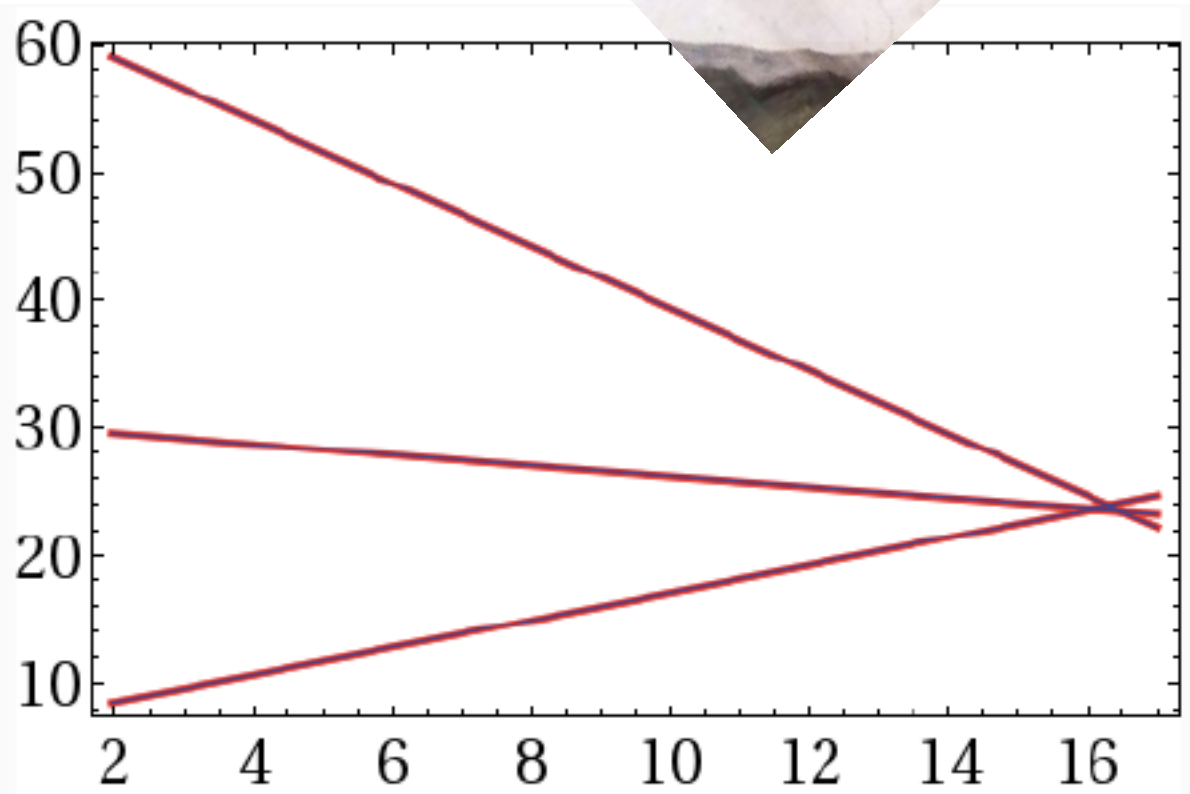
Note, still works with M_{SUSY} = 100 TeV.

A hint?

SM



MSSM



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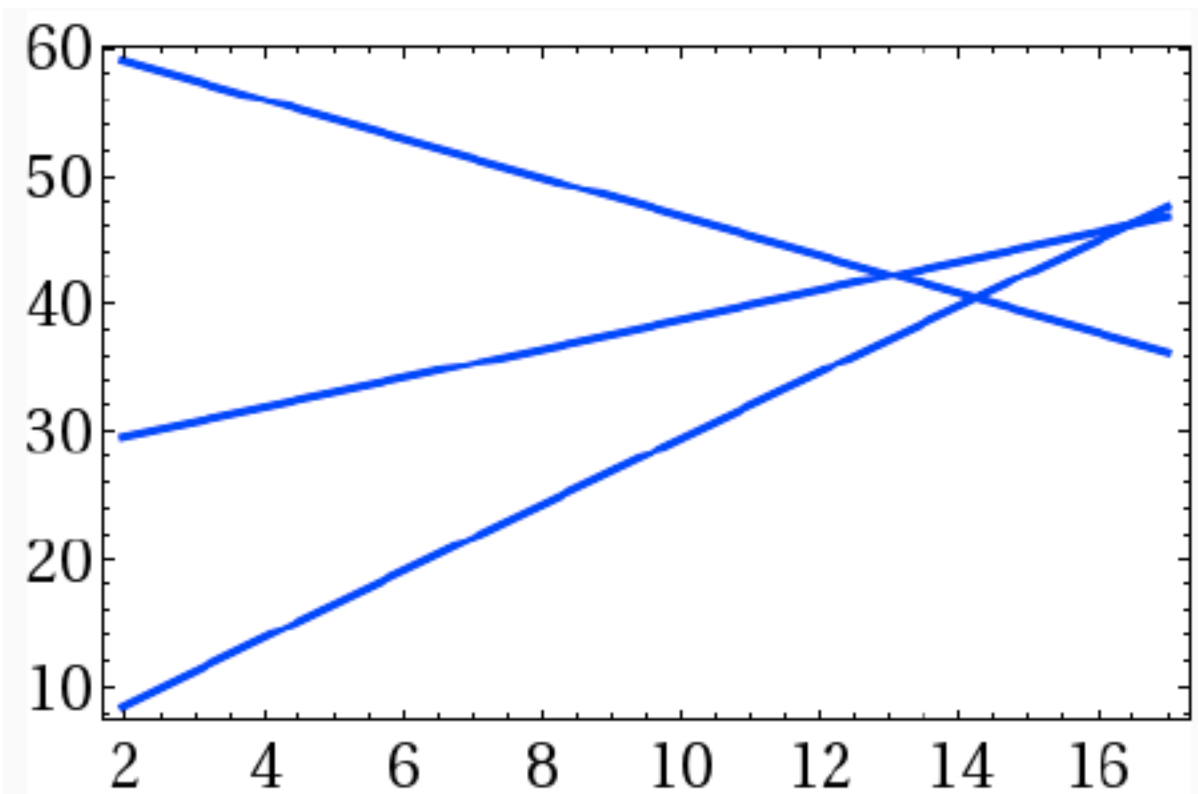

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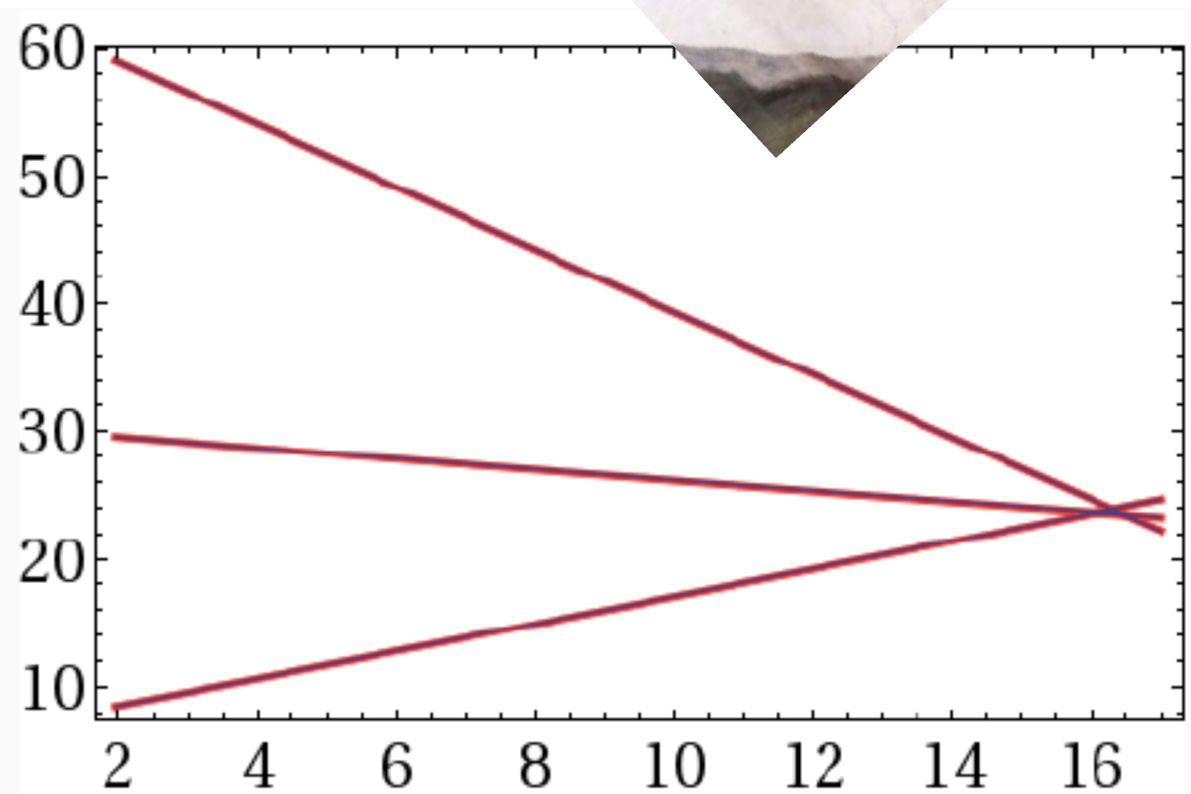
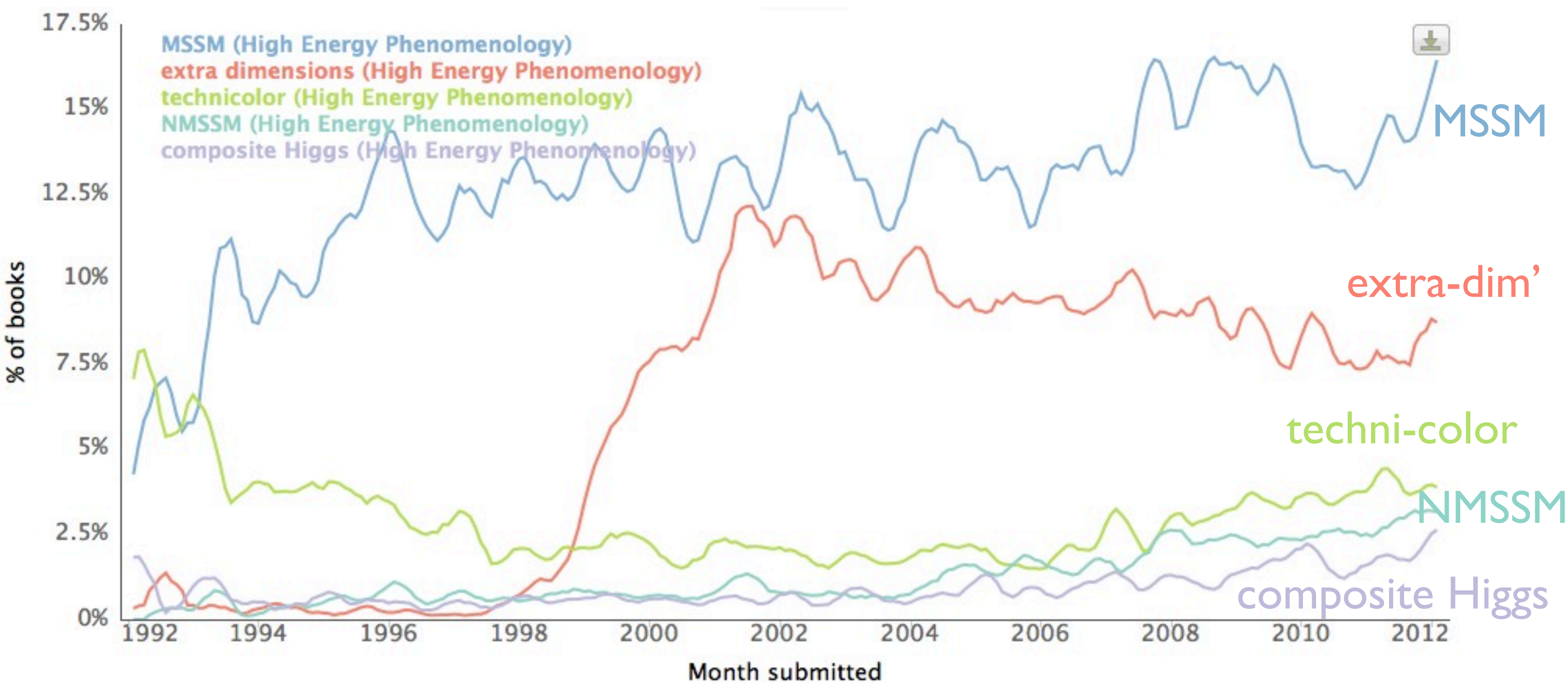


Gauge Coupling running at two loops

Note, still works with M_{SUSY} = 100 TeV.

Let's look at the data

Data pre-LHC



arXiv [hep-ph] mentions

http://arxiv.culturomics.org

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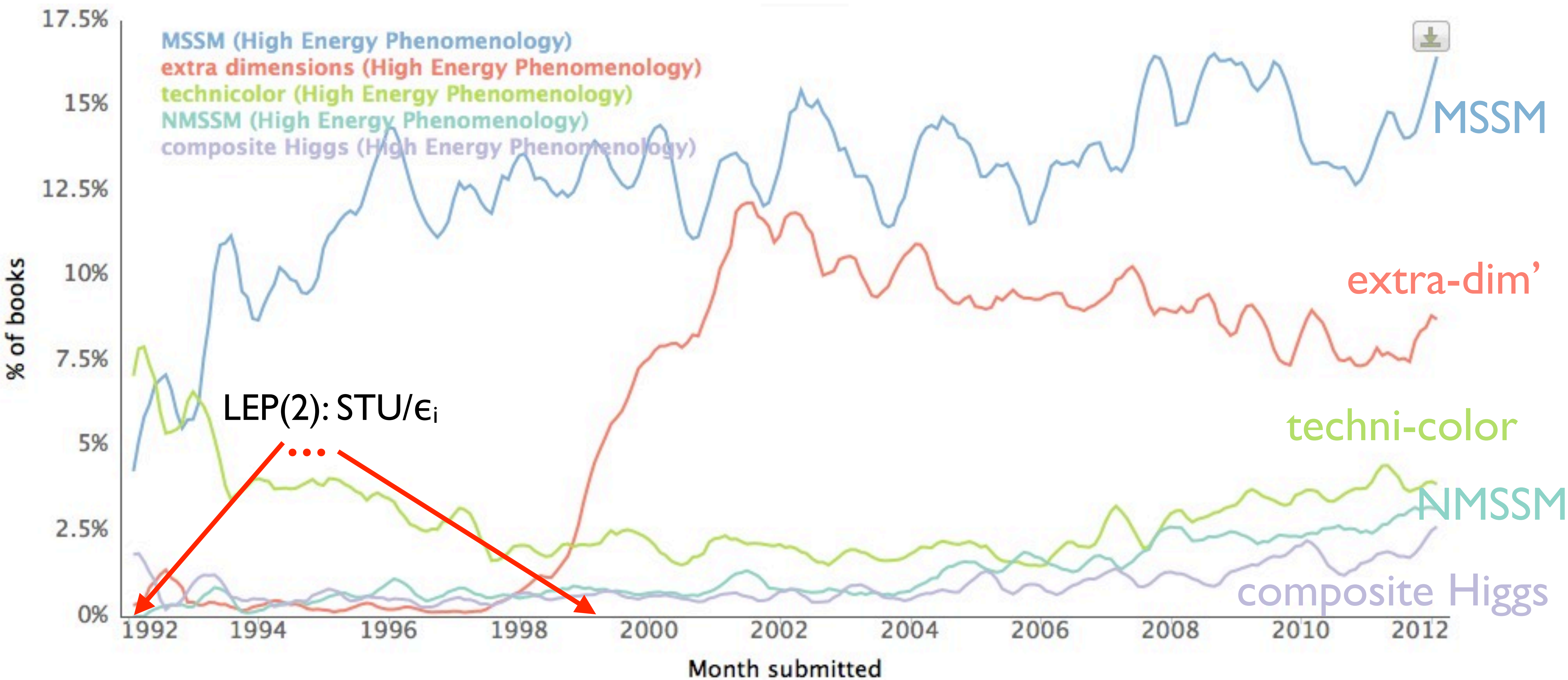

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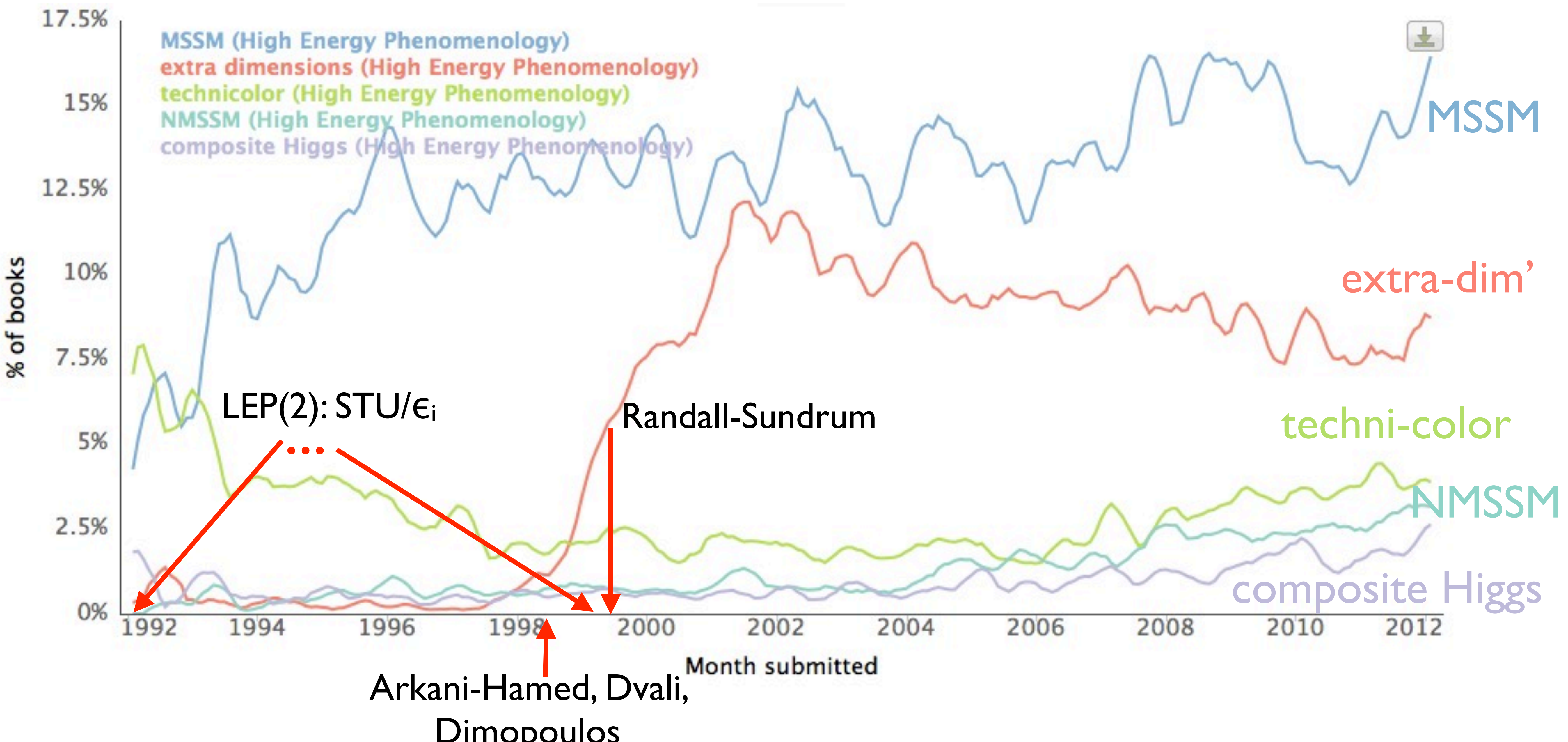

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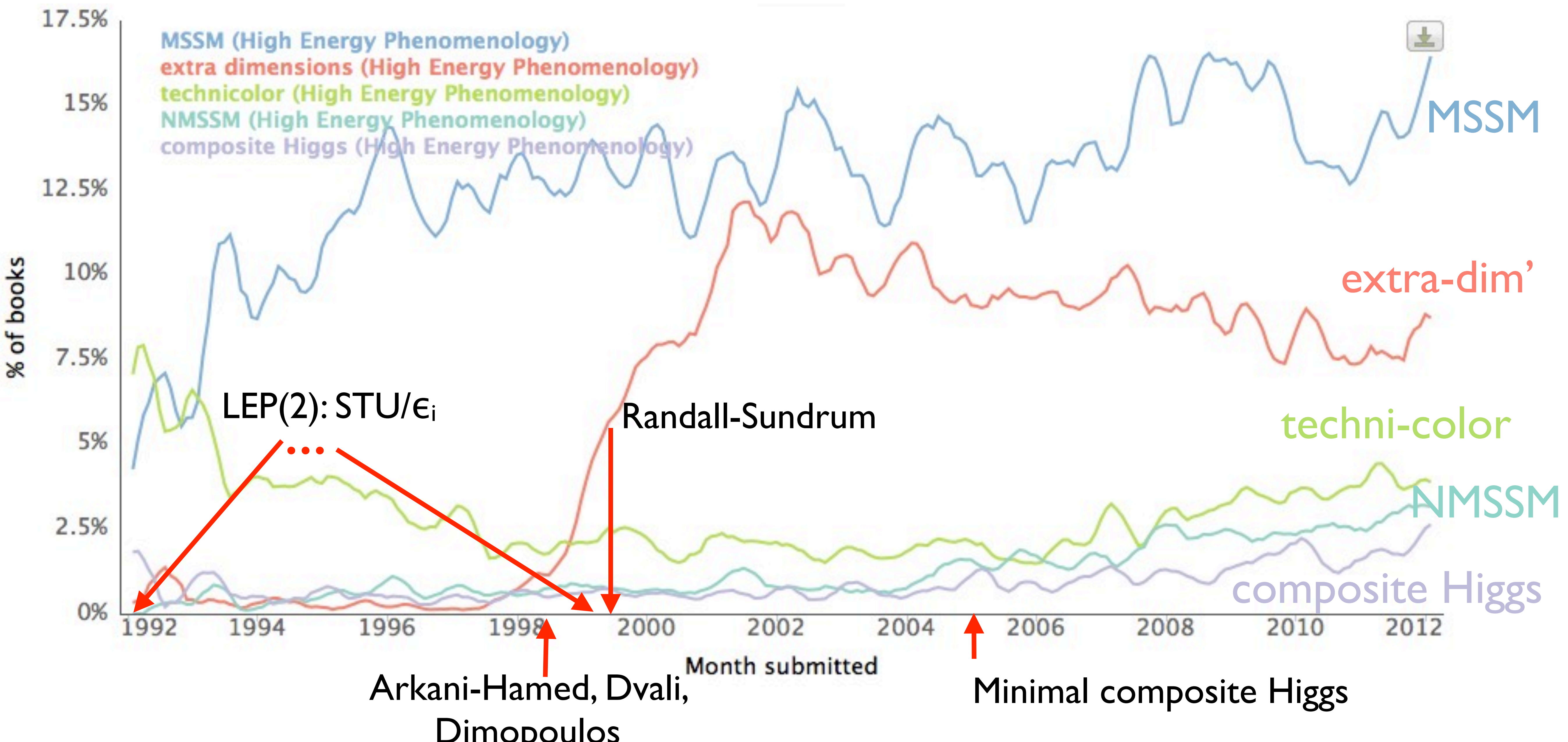

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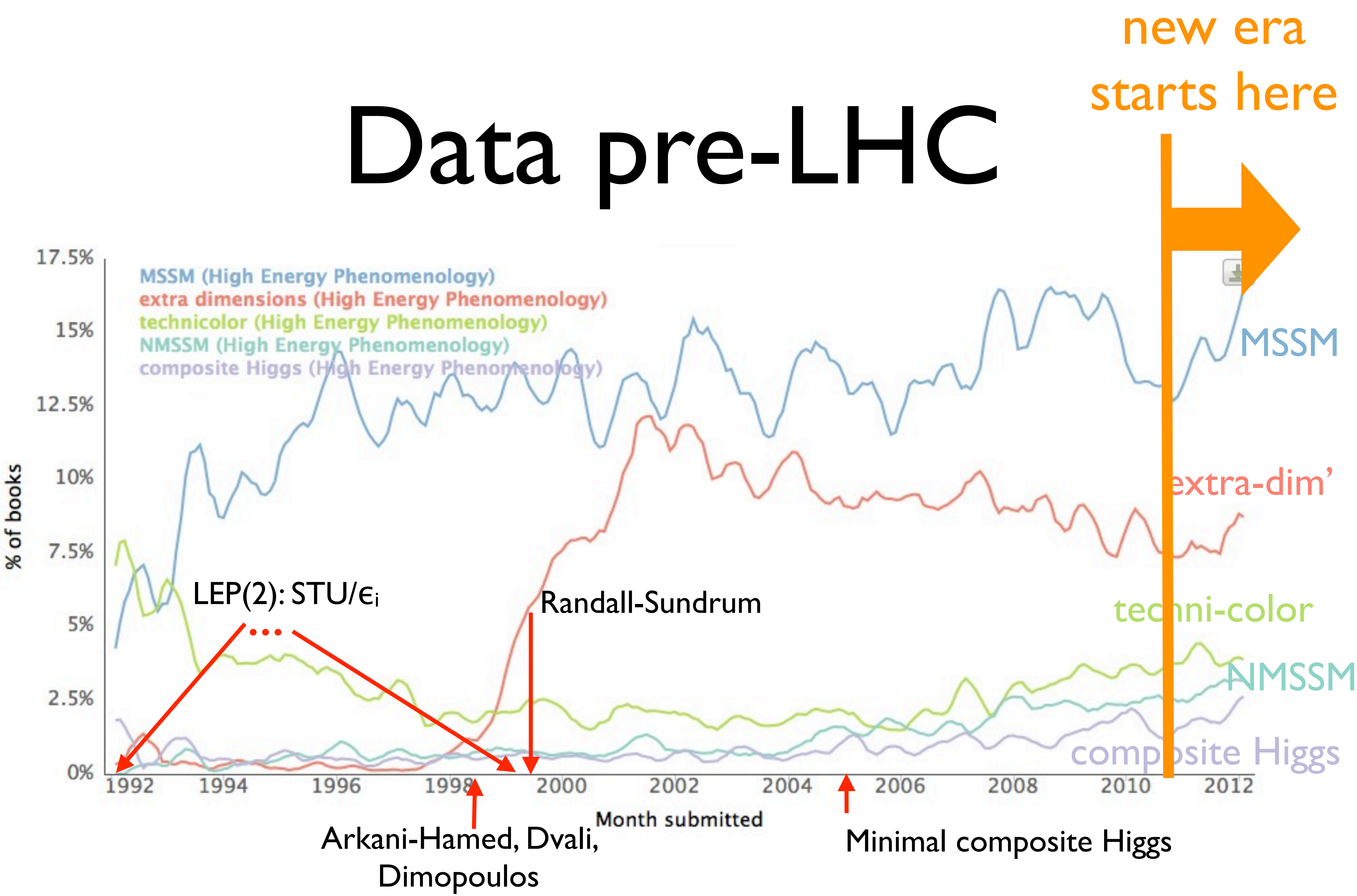

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Will get to
LHC impact shortly

MSSM

	bosons	fermions	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Q_i	$(\widetilde{u}_L, \widetilde{d}_L)_i$	$(u_L, d_L)_i$	$\square$	$\square$	$\frac{1}{6}$
$\overline{u}_i$	$\widetilde{u}^*_{Ri}$	$\overline{u}_i = u^\dagger_{Ri}$	$\overline{\square}$	$\mathbf{1}$	$-\frac{2}{3}$
$\overline{d}_i$	$\widetilde{d}^*_{Ri}$	$\overline{d}_i = d^\dagger_{Ri}$	$\overline{\square}$	$\mathbf{1}$	$\frac{1}{3}$
L_i	$(\widetilde{\nu}, \widetilde{e}_L)_i$	$(\nu, e_L)_i$	$\mathbf{1}$	$\square$	$-\frac{1}{2}$
$\overline{e}_i$	$\widetilde{e}^*_{Ri}$	$\overline{e}_i = e^\dagger_{Ri}$	$\mathbf{1}$	$\mathbf{1}$	1
H_u	(H_u^+, H_u^0)	$(\widetilde{H}_u^+, \widetilde{H}_u^0)$	$\mathbf{1}$	$\square$	$\frac{1}{2}$
H_d	(H_d^0, H_d^-)	$(\widetilde{H}_d^0, \widetilde{H}_d^-)$	$\mathbf{1}$	$\square$	$-\frac{1}{2}$
G	G^a_μ	$\widetilde{G}^a$	$\mathbf{Ad}$	$\mathbf{1}$	0
W	$W^3_\mu, W^\pm_\mu$	$\widetilde{W}^3, \widetilde{W}^\pm$	$\mathbf{1}$	$\mathbf{Ad}$	0
B	B_μ	$\widetilde{B}$	$\mathbf{1}$	$\mathbf{1}$	0

MSSM

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H_d	(H_d^0, H_d^-)	$(\widetilde{H}_d^0, \widetilde{H}_d^-)$	$\mathbf{1}$	$\square$	$-\frac{1}{2}$
G	G^a_μ	$\widetilde{G}^a$	$\mathbf{Ad}$	$\mathbf{1}$	0
W	$W^3_\mu,\, W^\pm_\mu$	$\widetilde{W}^3,\, \widetilde{W}^\pm$	$\mathbf{1}$	$\mathbf{Ad}$	0
B	B_μ	$\widetilde{B}$	$\mathbf{1}$	$\mathbf{1}$	0

same quantum # !

MSSM

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B	B_μ	$\widetilde{B}$	$\mathbf{1}$	$\mathbf{1}$	0

two Higgs doublets

Two Higgs Doublets

Two Higgs doublets with opposite hypercharges are needed to cancel the $U(1)_Y^3$ and $U(1)_Y SU(2)_L^2$ anomalies from higgsinos
even number of fermion doublets to avoid the Witten anomaly for $SU(2)_L$.

The superpotential for the Higgs :

$$W_{\text{Higgs}} = \overline{u}\mathbf{Y_u}QH_u - \overline{d}\mathbf{Y_d}QH_d - \overline{e}\,\mathbf{Y_e}LH_d + \mu H_u H_d \ .$$

+ holomorphy of the super-potential (in SM: H and H*)

Higgs mass terms

$$\mathcal{L}_{\mu,\text{quadratic}} = -\mu(\widetilde{H}_u^+\widetilde{H}_d^- - \widetilde{H}_u^0\widetilde{H}_d^0) + h.c. \\ -|\mu|^2(|H_u^0|^2 + |H_u^+|^2 + |H_d^0|^2 + |H_d^-|^2).$$

The D-term potential adds quartic terms with positive curvature, so there is a stable minimum at the origin with $\langle H_u \rangle = \langle H_d \rangle = 0$.

EWSB requires soft SUSY breaking terms.

without unnatural cancellations we will need $\mu \sim \mathcal{O}(m_{\text{soft}}) \sim \mathcal{O}(M_W)$

cubic scalar

After integrating out auxiliary fields,

$$\begin{aligned}\mathcal{L}_{\mu,\mathrm{cubic}} &= \mu^* \Big(\widetilde{u}_R^* \mathbf{Y_u} \widetilde{u}_L H_d^{0*} + \widetilde{d}_R^* \mathbf{Y_d} \widetilde{d}_L H_u^{0*} + \widetilde{e}_R^* \mathbf{Y_e} \widetilde{e}_L H_u^{0*} \\ &\quad + \widetilde{u}_R^* \mathbf{Y_u} \widetilde{d}_L H_d^{-*} + \widetilde{d}_R^* \mathbf{Y_d} \widetilde{u}_L H_u^{+*} + \widetilde{e}_R^* \mathbf{Y_e} \widetilde{\nu}_L H_u^{+*} \Big) + h.c.\end{aligned}$$

The quartic scalar interactions are obtained in a similar fashion.

other holomorphic renormalizable terms :

$$W_{\mathrm{disaster}} = \alpha^{ijk} Q_i L_j \overline{d}_k + \beta^{ijk} L_i L_j \overline{e}_k + \gamma^i L^i H_u + \delta^{ijk} \overline{d}_i \overline{d}_j \overline{u}_k \ ,$$

W_{disaster} violates lepton and baryon number!

R-Parity

invent a new discrete symmetry called R-parity:

$$\begin{aligned} (\text{observed particle}) &\quad\longrightarrow\quad (\text{observed particle})\ , \\ (\text{superpartner}) &\quad\longrightarrow\quad -(\text{superpartner})\ . \end{aligned}$$

Imposing this discrete R-parity forbids $W_{\rm disaster}$
R-parity $\equiv$ to imposing a discrete subgroup of $B-L$
("matter parity") $P_M = (-1)^{3(B-L)}$ since

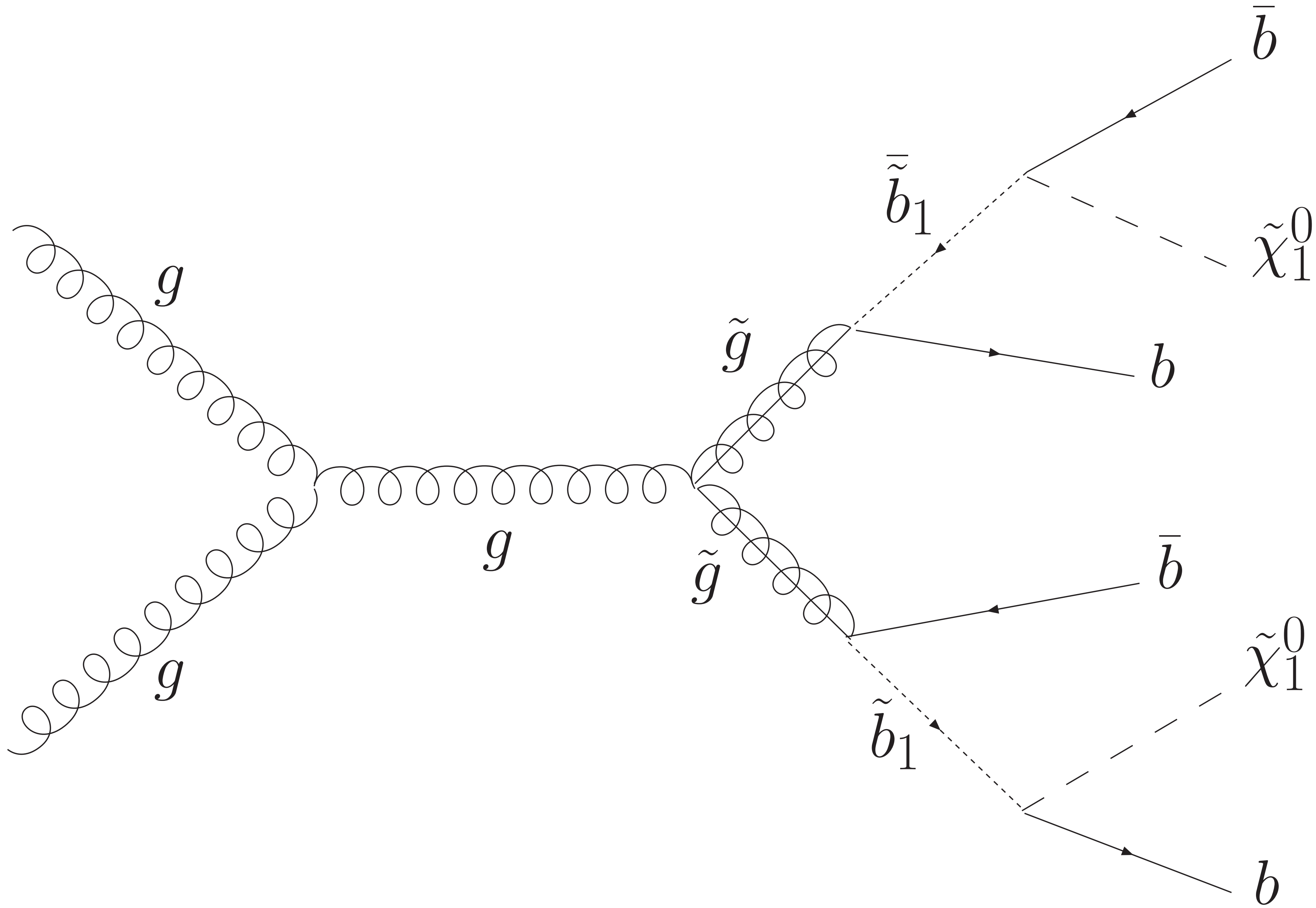
$$R = (-1)^{3(B-L)+F}$$

R-parity is part of the definition of the MSSM

R-Parity

R-parity has important consequences:

- at colliders superpartners are produced in pairs;
- the lightest superpartner (LSP) is stable, and thus (if it is neutral) can be a dark matter candidate;
- each sparticle (besides the LSP) eventually decays into an odd number of LSPs.



g
g
g
$\tilde{g}$
$\tilde{g}$
$\bar{\tilde{b}}_1$
$\tilde{b}_1$
$\bar{b}$
$\tilde{\chi}_1^0$
b
$\bar{b}$
$\tilde{\chi}_1^0$
b

We want to break SUSY such that Higgs – top squark quartic coupling $\lambda = |y_t|^2$. If not we reintroduce a Λ^2 divergence in the Higgs mass:

$$\delta m_h^2 \propto (\lambda - |y_t|^2)\Lambda^2$$

We know: Conserved Susy does not lead to power-divergencies.

How to avoid re-introducing power-divergencies when breaking susy?

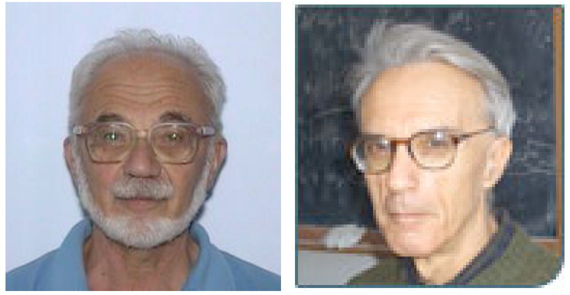
Count powers in diagrams!

If we only introduce **dimensionful couplings** will always **lower** the power of divergence.

We want an *effective theory* of broken SUSY with only soft breaking terms (operators with dimension < 4). Girardello and Grisaru found:

$$\begin{aligned}\mathcal{L}_{\text{soft}} &= -\tfrac{1}{2}(M_\lambda \lambda^a \lambda^a + h.c.) - (m^2)^i_j \phi^{*j}\phi_i \\ &\quad -(\tfrac{1}{2} b^{ij}\phi_i\phi_j + \tfrac{1}{6} a^{ijk}\phi_i\phi_j\phi_k + h.c.) \\ &\quad -\tfrac{1}{2} c_i^{jk}\phi^{i*}\phi_j\phi_k + e^i\phi_i + h.c.\end{aligned}$$

Grisaru, Girardello



means couplings are dimensionful!

Soft SUSY Breaking

$$
\begin{aligned}
\mathcal{L}_{\mathrm{soft}}^{\mathrm{MSSM}} \quad = \quad & -\tfrac{1}{2}\left(M_3 \widetilde{G}\widetilde{G} + M_2 \widetilde{W}\widetilde{W} + M_1 \widetilde{B}\widetilde{B}\right) + h.c. \\
& - \left(\widetilde{\overline{u}}\,\mathbf{A_u}\,\widetilde{Q} H_u - \widetilde{\overline{d}}\,\mathbf{A_d}\,\widetilde{Q} H_d - \widetilde{\overline{e}}\,\mathbf{A_e}\,\widetilde{L} H_d\right) + h.c. \\
& - \widetilde{Q}^* \mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^* \mathbf{m^2_L}\,\widetilde{L} - \widetilde{\overline{u}}^* \mathbf{m^2_{\overline{u}}}\,\widetilde{\overline{u}} - \widetilde{\overline{d}}^* \mathbf{m^2_{\overline{d}}}\,\widetilde{\overline{d}} - \widetilde{\overline{e}}^* \mathbf{m^2_{\overline{e}}}\,\widetilde{\overline{e}} \\
& - m^2_{H_u} H_u^* H_u - m^2_{H_d} H_d^* H_d - (b H_u H_d + h.c.)\,.
\end{aligned}
$$

to $m_{\mathrm{soft}} \approx 1$ TeV in order to solve the hierarchy problem by canceling quadratic divergences:

$$
M_i, \mathbf{A_f} \sim m_{\mathrm{soft}}\ , \quad \mathbf{m^2_f}, b \sim m^2_{\mathrm{soft}}\ .
$$

105 more parameters than the SM!

Higgs potential

$$
\begin{aligned}
V_H = {} & (\mu^2 + m_{H_u}^2)\,|H_u|^2 + (\mu^2 + m_{H_d}^2)\,|H_d|^2 \\
& - B_\mu\, H_u \cdot H_d + h.c. \boxed{+ \tfrac{1}{2} g^2 \,|H_u^\dagger H_d|^2} \\
& \boxed{+ \tfrac{1}{8} (g^2 + g'^2) \left(|H_u|^2 - |H_d|^2 \right)^2}
\end{aligned}
$$

Neutral Higgs potential

$$V = (|\mu|^2 + m_{H_u}^2)\,|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)\,|H_d^0|^2 - B_\mu\,(H_u^0 H_d^0 + h.c.) \boxed{+ \frac{1}{8}(g^2 + g'^2)\left(|H_u^0|^2 - |H_d^0|^2\right)^2}$$

quartic fixed by gauge interactions!

short digression →

Super YM

So full Lagrangian:

gauge trace

$$\mathcal{L} = -\frac{1}{4g^2} \mathrm{Tr}\left(W^\alpha W_\alpha \big|_{\theta^2} + \bar{W}_{\dot\alpha} \bar{W}^{\dot\alpha} \big|_{\bar\theta^2} \right)$$

$$+ \Phi^\dagger e^V \Phi \big|_{\theta^2 \bar\theta^2} + W(\Phi)\big|_{\theta^2} + h.c.$$

Super YM

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gauge trace

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$$+ \Phi^\dagger e^V \Phi\big|_{\theta^2\bar\theta^2} + W(\Phi)\big|_{\theta^2} + h.c.$$

$$\mathcal{L} = \frac{1}{4g^2}\left(W^{a\alpha}W^a_\alpha\big|_{\theta^2} + \bar{W}^a_{\dot\alpha}\bar{W}^{a\dot\alpha}\big|_{\bar\theta^2}\right)$$

$$= -\frac{1}{4} F^a_{\mu\nu}F^{a\mu\nu} + i\bar\lambda^a D_\mu \bar\sigma^\mu \lambda^a + \frac{1}{2} D^a D^a$$

Super YM

So full Lagrangian:

gauge trace

$$\mathcal{L} = -\frac{1}{4g^2}\,\mathrm{Tr}\left(W^\alpha W_\alpha\big|_{\theta^2} + \bar{W}_{\dot\alpha}\bar{W}^{\dot\alpha}\big|_{\bar\theta^2}\right)$$

$$+\,\Phi^\dagger e^V \Phi\big|_{\theta^2\bar\theta^2} + W(\Phi)\big|_{\theta^2} + h.c.$$

$$\mathcal{L} = \frac{1}{4g^2}\left(W^{a\alpha}W^a_\alpha\big|_{\theta^2} + \bar{W}^a_{\dot\alpha}\bar{W}^{a\dot\alpha}\big|_{\bar\theta^2}\right)$$

$$= -\tfrac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar\lambda^a D_\mu\bar\sigma^\mu\lambda^a + \frac{1}{2}D^aD^a$$

$$\Phi^\dagger e^V \Phi\big|_{\theta^2\bar\theta^2} = |D_\mu\varphi|^2$$

$$+\,i\bar\Psi D_\mu\bar\sigma^\mu\Psi + F^*F$$

$$+\,i\sqrt{2}\left(\varphi^* T^a\lambda^a\Psi + h.c.\right)$$

$$+\,\varphi^* T^a D^a\varphi$$

Need to integrate out D^a $\downarrow$ new source for scalar potential.

Full scalar potential

$$V_D = \frac{1}{2} g^2 \sum_a \left| \sum_\varphi \varphi_i^* T^a \varphi_i \right|^2$$

$$V_F = \sum_i \left| \frac{\partial W}{\partial \varphi_i} \right|^2$$

$V(\varphi) \geq 0$ as expected...

Neutral Higgs potential

$$V = \left(|\mu|^2 + m_{H_u}^2\right)|H_u^0|^2 + \left(|\mu|^2 + m_{H_d}^2\right)|H_d^0|^2 - B_\mu\left(H_u^0 H_d^0 + h.c.\right) \boxed{+\frac{1}{8}\left(g^2+g'^2\right)\left(|H_u^0|^2 - |H_d^0|^2\right)^2}$$

quartic fixed by gauge interactions!

Higgs spectrum

$$V(H_u^0, H_d^0) = (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_d^0|^2 - (b\, H_u^0 H_d^0 + h.c.) + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2.$$

- Supersymmetry: gauge interactions always come with quartic scalar interactions (*D*-term potential)

$$\frac{1}{8}\left(g^2 + g'^2\right)\left(\left|H_u^0\right|^2 - \left|H_d^0\right|^2\right)^2$$

- Implication: Higgs quartic related to gauge couplings, which also determine *W*, *Z* masses: tree-level bound

$$m_h \leq m_Z \cos(2\beta)$$

Higgs spectrum

$$
\begin{aligned}
V(H_u^0, H_d^0) \quad &= \quad (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_d^0|^2 - (b\, H_u^0 H_d^0 + h.c.) \\
&\quad + \tfrac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2.
\end{aligned}
$$

- Supersymmetry: gauge interactions always come with quartic scalar interactions (*D*-term potential)

$$
\frac{1}{8}\left(g^2 + g'^2\right)\left(\left|H_u^0\right|^2 - \left|H_d^0\right|^2\right)^2
$$

- Implication: Higgs
also determine *W*,

Higgs mass maximized at *large* tan beta.

$$
m_h \leq m_Z \cos(2\beta)
$$

Susy

$$V = -\frac{\Lambda^4}{128\pi^2}\,\mathrm{STr}\,1 + \cancel{\frac{\Lambda^2}{64\pi^2}\,\mathrm{STr}\,M^2(\phi)}$$

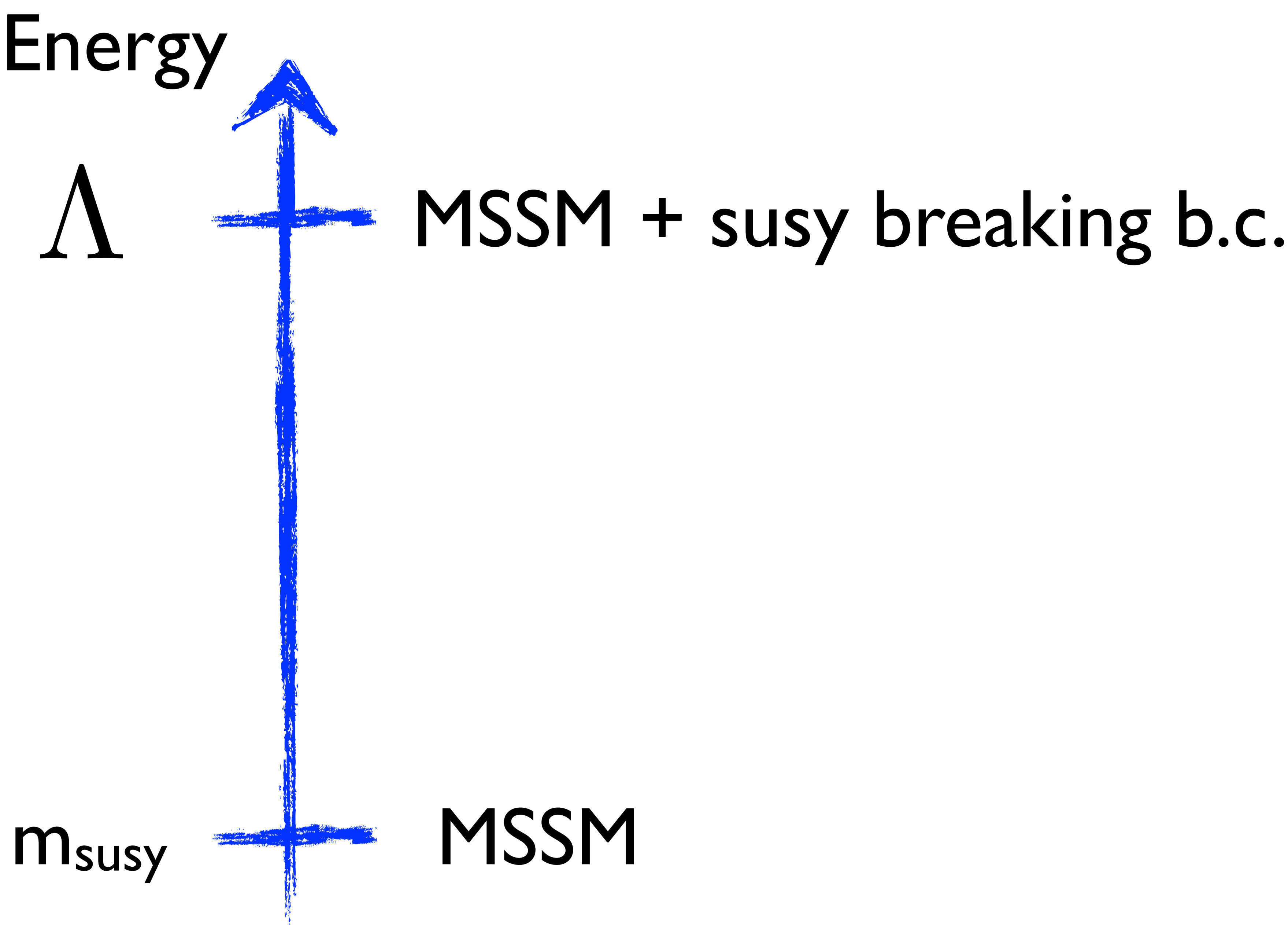
$$+\boxed{\frac{1}{64\pi^2}\,\mathrm{STr}\,M^4(\phi)\,\ln\frac{M^2(\phi)}{\Lambda^2}},$$

top $\qquad M(\phi) = y_{top}\,\phi$

stop $\qquad M(\phi)^2 \approx (y_{top}\,\phi)^2 + M^2_{susy}$

Exercise: 1) Show the cancellation using the top and stop mass matrices.
2) Calculate the stop contribution to the quartic.

Susy: log enhanced



SM

Susy

$$\frac{1}{16\pi^2}\,\Lambda^2 \longrightarrow \frac{1}{16\pi^2}\,m_{susy}^2 \log\left(\frac{\Lambda}{m_{susy}}\right)$$

≈ 30 for $\Lambda = M_{\mathrm{GUT}}$

Tuning very acute for high scale super symmetry breaking

Susy and the 125 GeV Higgs

$\tilde{t}$ $\tilde{t}$

MSSM:

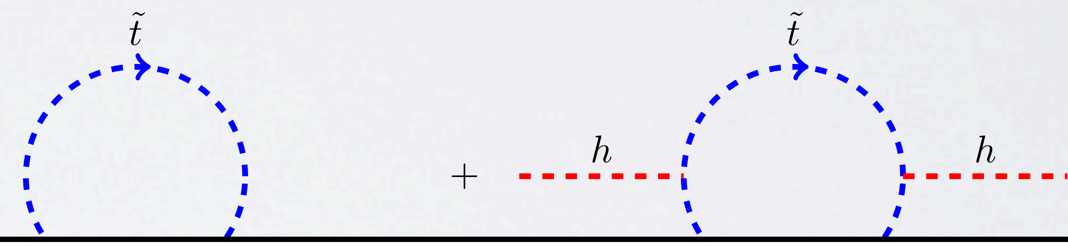
tree-level bound < *M_Z*

$$m_h^2 = \boxed{m_Z^2 c_{2\beta}^2} + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

Haber, Hempfling '91

Susy and the 125 GeV Higgs

MSSM:



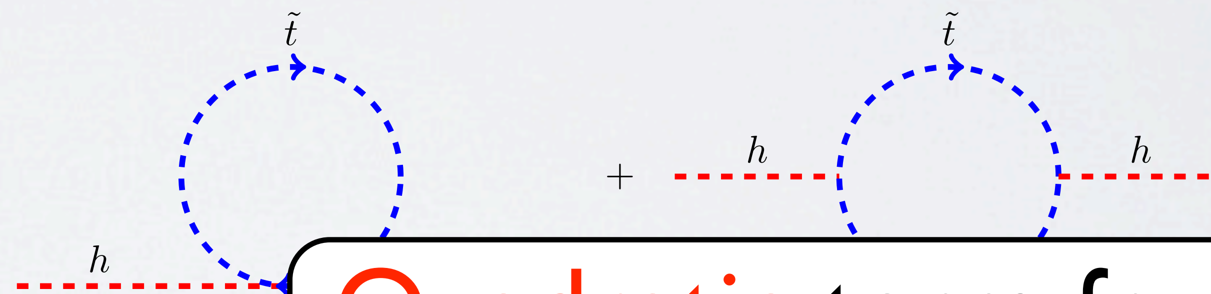
Logarithmic growth with M_{SUSY}

$$m_h^2 = m_Z^2 c_{2\beta}^2$$

$$+\frac{3m_t^4}{4\pi^2 v^2}\left(\boxed{\log\left(\frac{M_S^2}{m_t^2}\right)}+\frac{X_t^2}{M_S^2}\left(1-\frac{X_t^2}{12M_S^2}\right)\right)$$

Susy and the 125 GeV Higgs

MSSM:

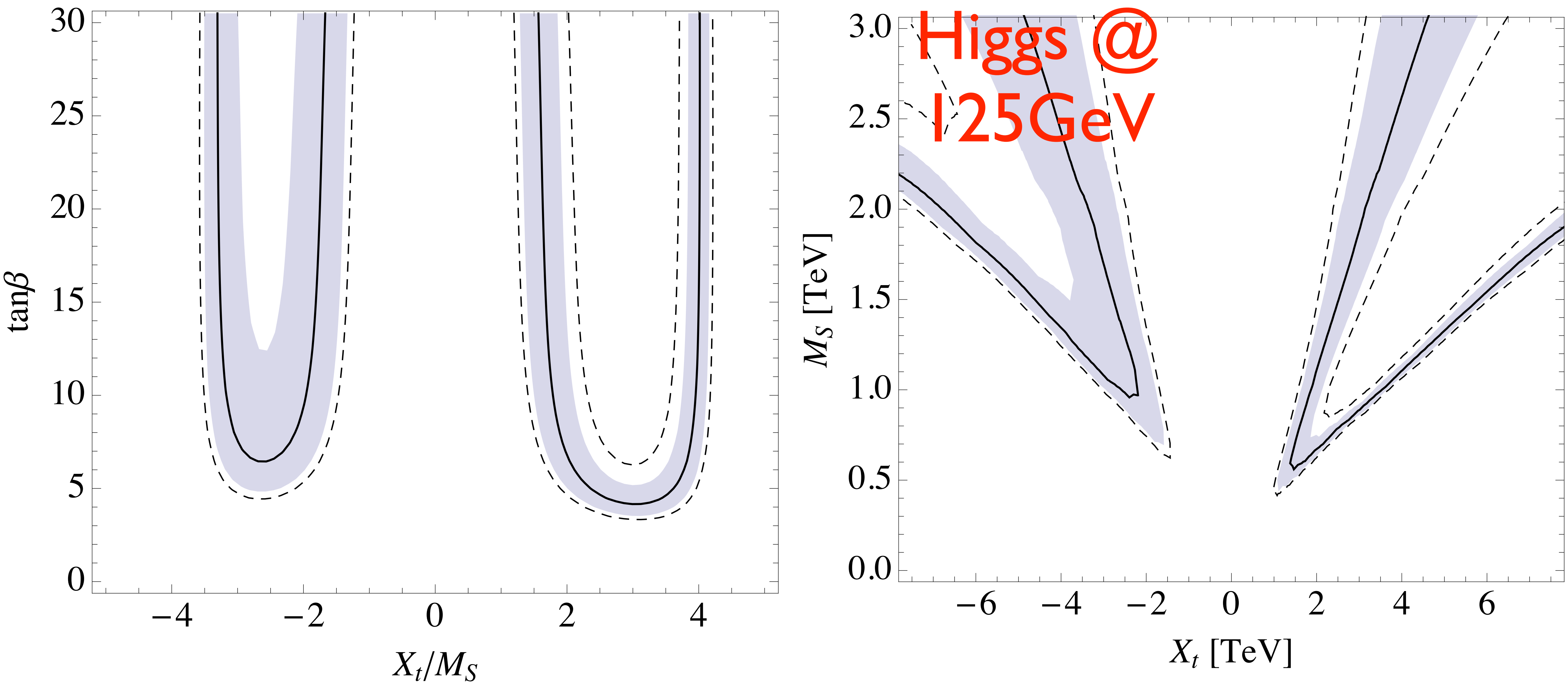


Quadratic term from stop mixing

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \boxed{\frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)}\right)$$

more: Haber, Hempfling, Hoang, Ellis, Ridolfi, Zwirner, Casas, Espinosa, Quiros, Riotto, Carena, Wagner, Degrassi, Heinemeyer, Hollik, Slavich, Weiglein

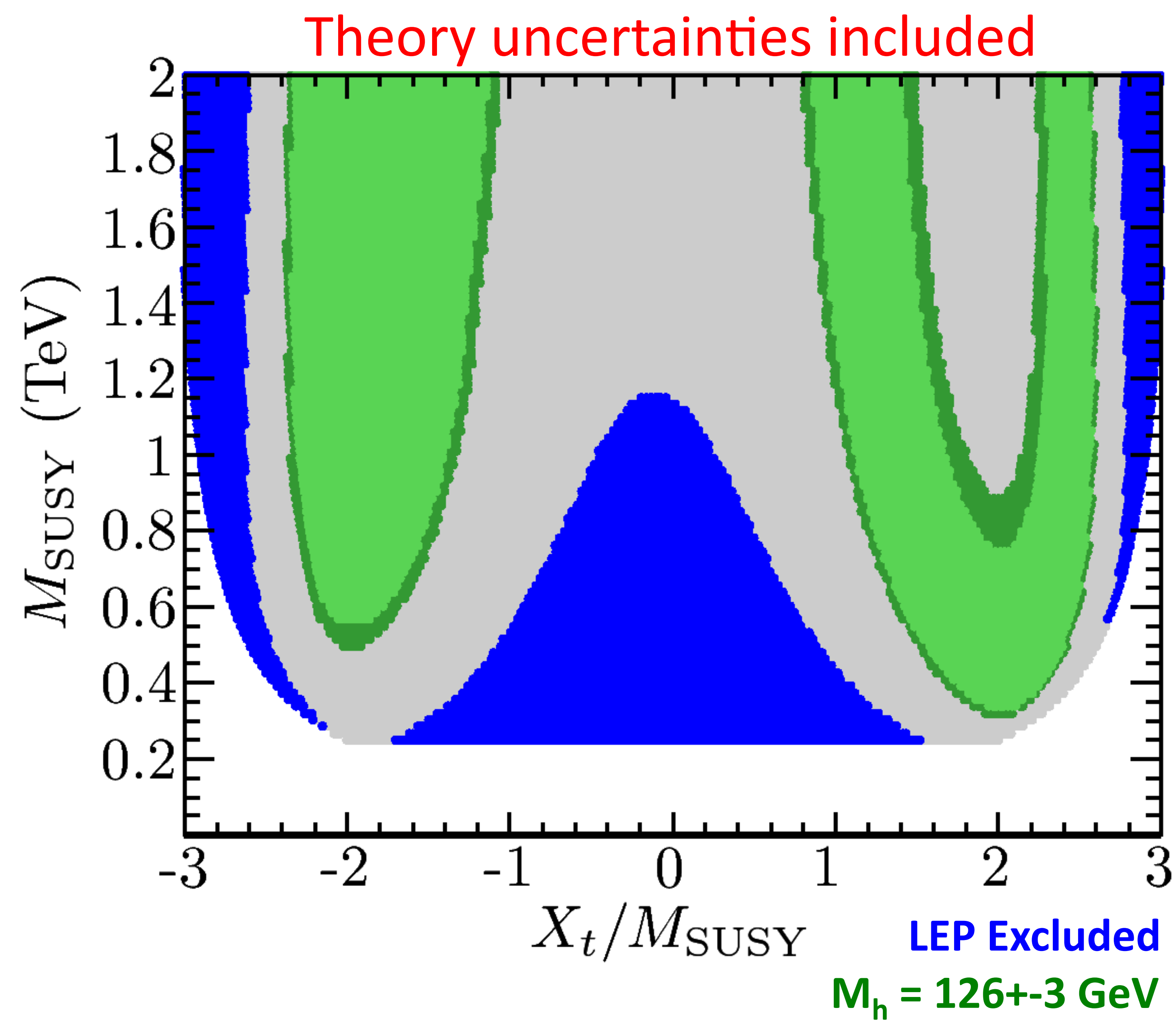
Susy and the Higgs at 125 GeV



$$\tan\beta \gtrsim 3.5 \qquad \frac{X_t}{M_S} \approx -3,\ \ -1.7,\ \ 1.5,\ \ \text{or}\ \ 3.5 \qquad M_S \gtrsim 500\ \text{GeV}$$

More conservative error bars on theory calculation (added linearly)

Heinemeyer et al'12

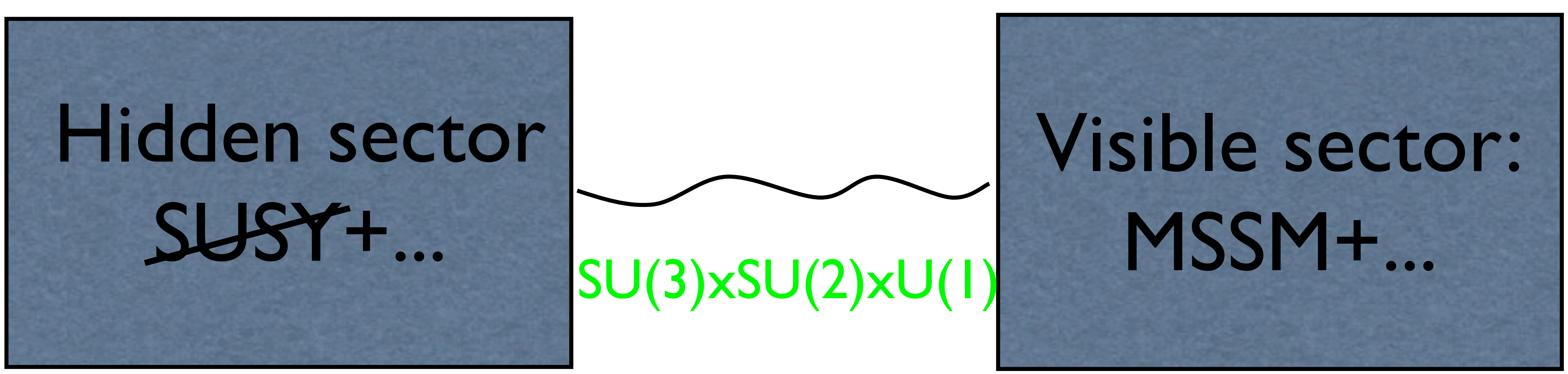


$$M_{\mathrm{SUSY}} > 350\ \mathrm{GeV}, \quad m_{\tilde{t}_1} \gtrsim 150\ \mathrm{GeV}$$

Consequences for Susy breaking scenarios

Consequences for Susy breaking scenarios

- Gauge mediation predicts: negligible A-terms (stop mixing) at messenger scale

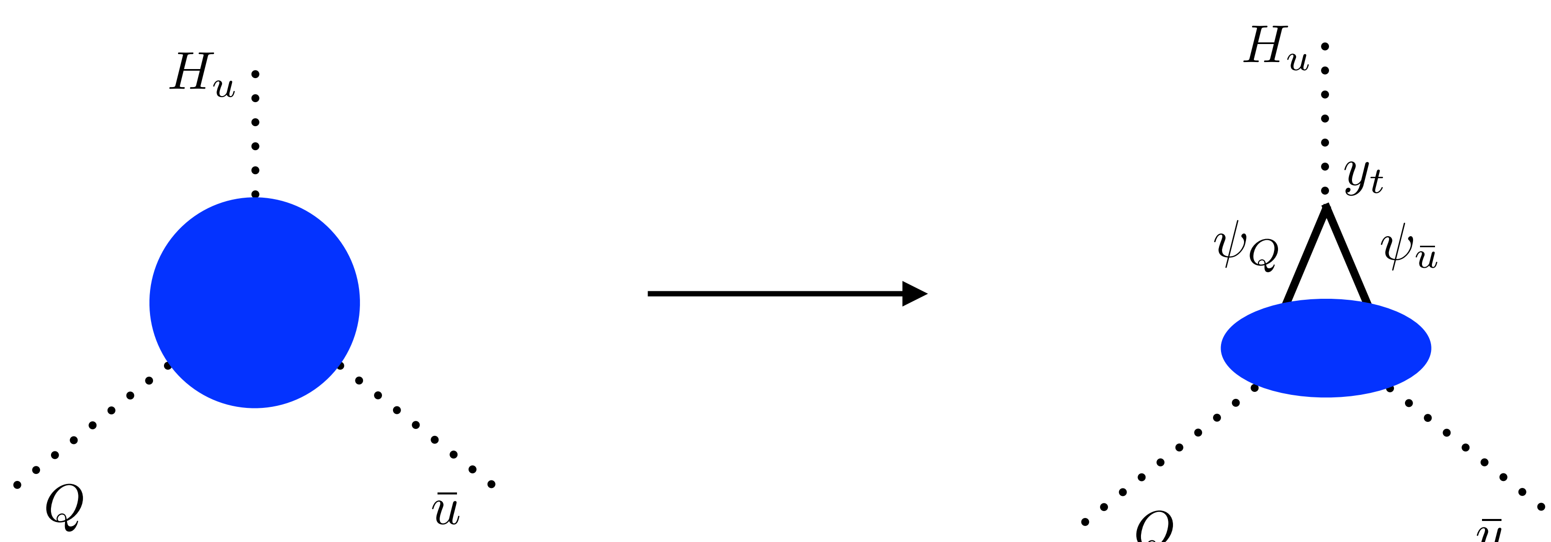


A terms in gauge mediation

$$\mathcal{L} \supset A_t Q \bar{u} H_u + c.c.$$

Like Yukawa couplings, break chiral (flavor) symmetries

Can not be induced by gauge interactions alone (those leave chiral symmetries intact)→



A terms in gauge mediation

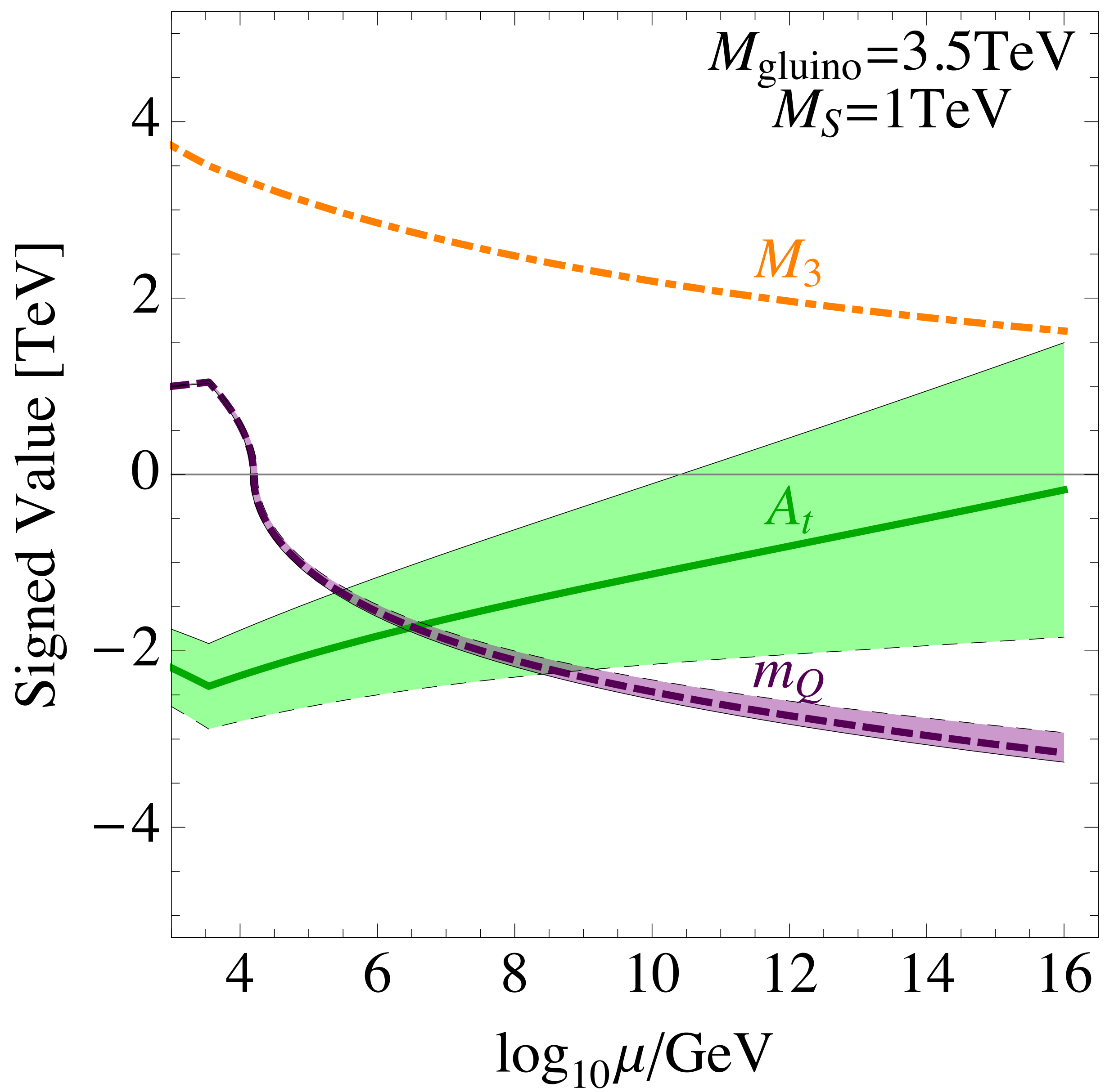
$$\mathcal{L} \supset A_t Q \bar{u} H_u + c.c.$$

Leading order effect comes at two-loops…

For high-scale breaking: can induce by RGE:

⇒ Run the A-terms up using MSSM RGEs to infer the messenger scale!

$$\frac{dA_t}{dt} \sim y_t^2 A_t + g_3^2 M_3$$



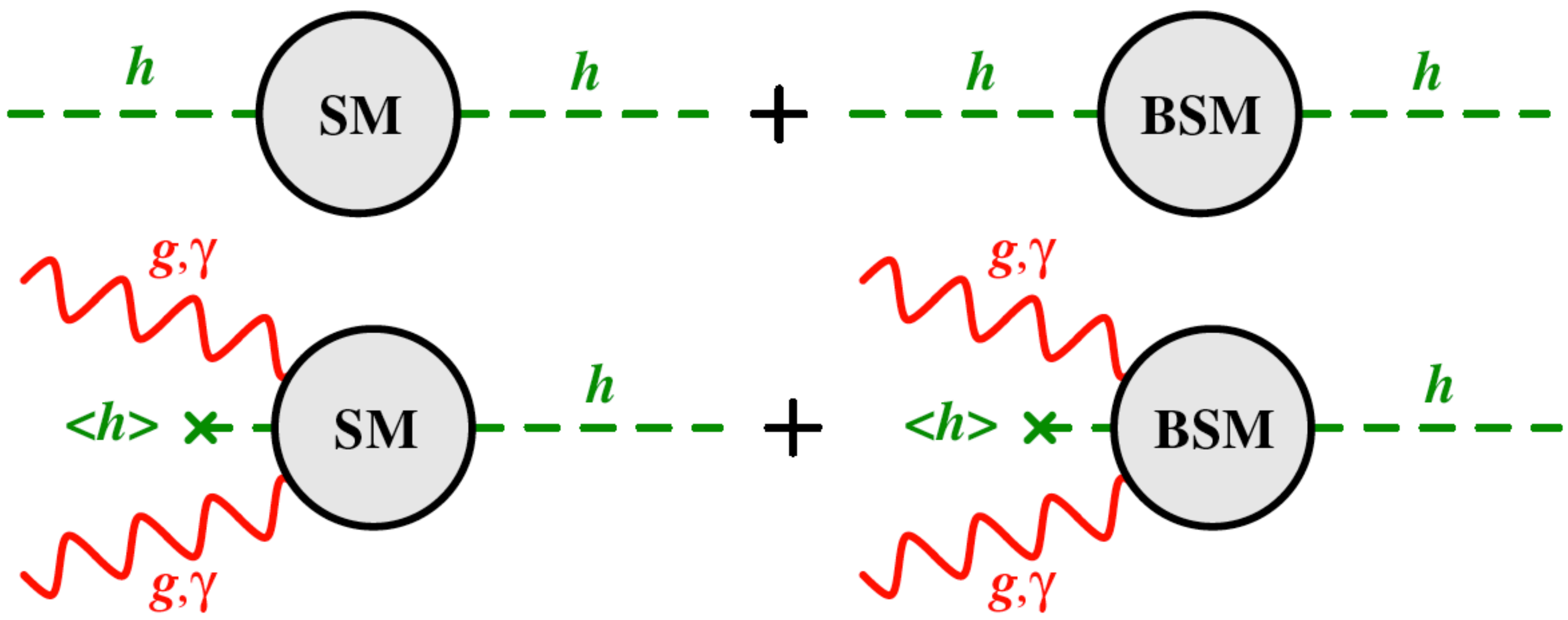
Higgs beyond the MSSM

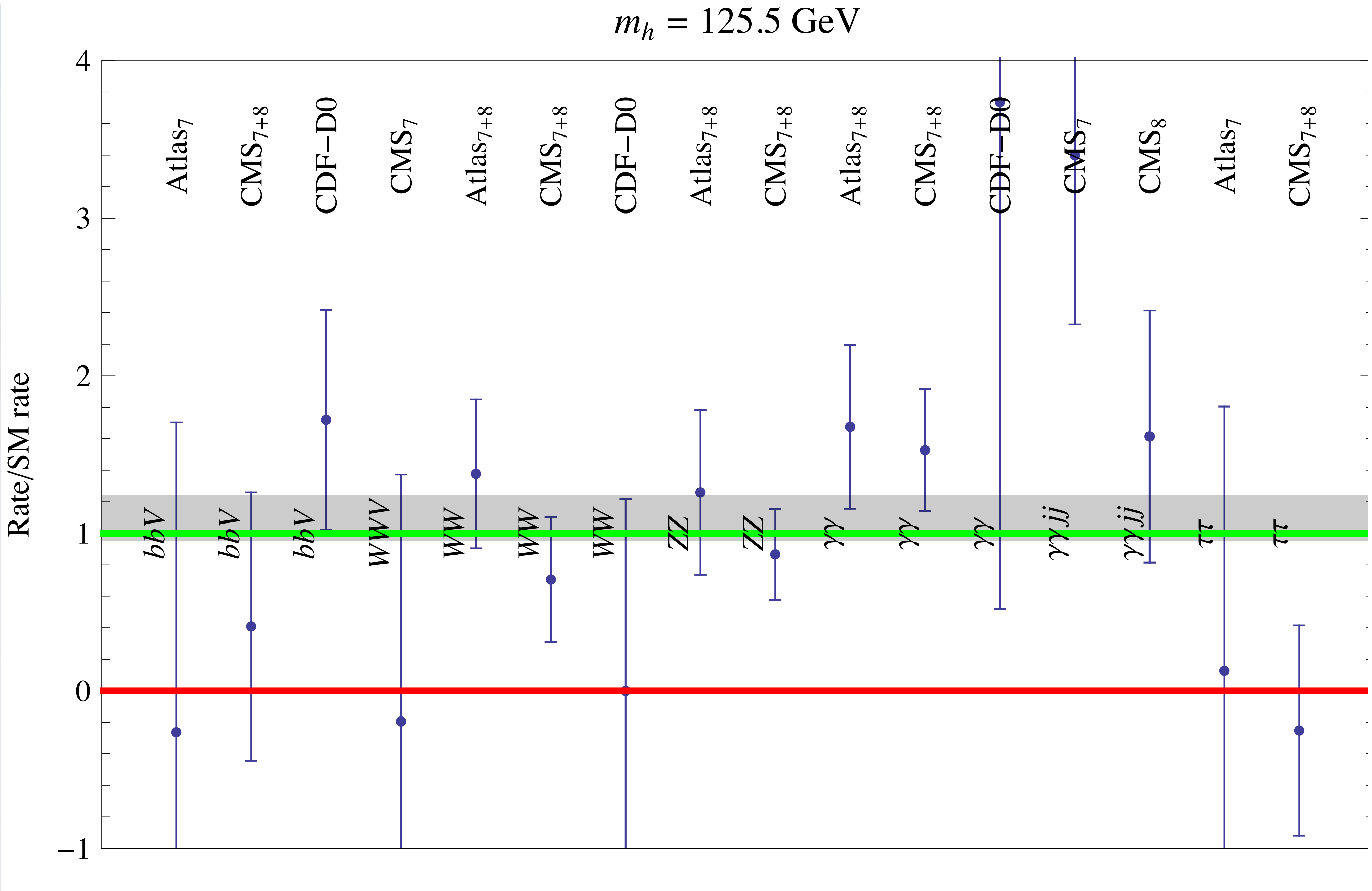
$$W \supset \lambda S H_u H_d + \ldots$$

- In NMSSM, can have m_{higgs} = 125 GeV without requiring large A-terms.

- NMSSM+GMSB has even more problems:
  - A-terms for singlet are small for the same reasons as before.
  - Need these A-terms together with negative singlet mass-squared for successful EWSB and extended Higgs spectrum. Generally near-impossible to achieve. (Dine & Nelson '93; de Gouvea, Friedland, Murayama '97; Morrissey & Pierce '08;....)

Higgs precision properties

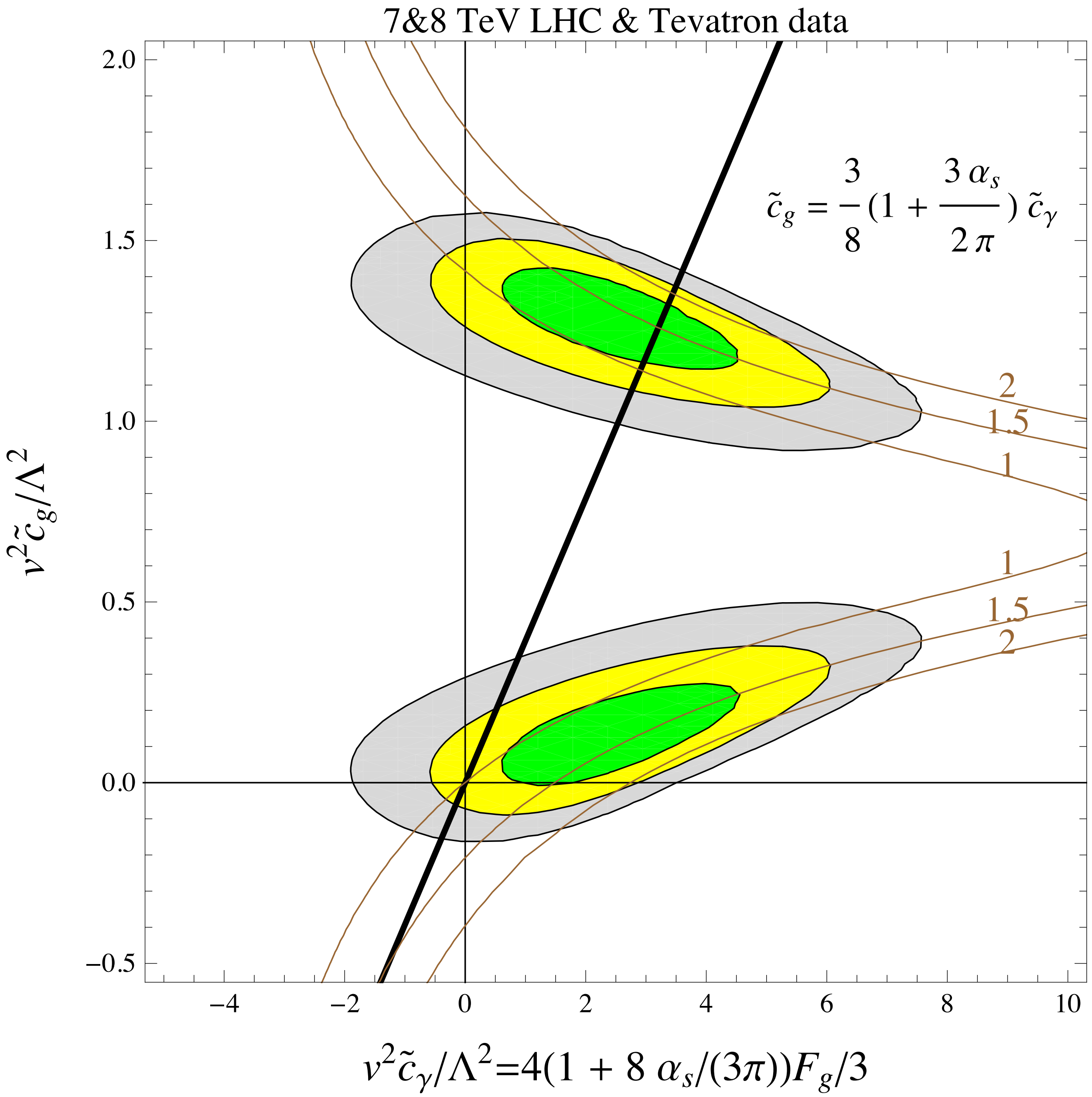




Giardino et al

Photons are high, taus are low, WW/ZZ just about right.
Error bars still sizable. More data is coming in quickly

$$\mathcal{L}_{HD} = -\frac{c_g\, g_3^2}{2\,\Lambda}\, h\, G^A_{\mu\nu} G^{A\,\mu\nu} - \frac{c_\gamma\,(2\,\pi\,\alpha)}{\Lambda}\, h\, F_{\mu\nu} F^{\mu\nu}$$



$$\frac{\tilde{c}_g}{\tilde{c}_\gamma} = \frac{1}{2N_c Q^2_{\tilde{t}}} \frac{C_g(\alpha_s)}{C_\gamma(\alpha_s)} = \frac{3}{8}\left(1 + \frac{3\,\alpha_s}{2\,\pi}\right)$$

Higgs low-energy theorems

J. R. Ellis, M. K. Gaillard and D. V. Nanopoulos, Nucl. Phys. B **106**, 292 (1976).
M. A. Shifman, A. I. Vainshtein, M. B. Voloshin and V. I. Zakharov, Sov. J. Nucl. Phys. **30**,

Integrate out new physics: $\mu < M(h)$

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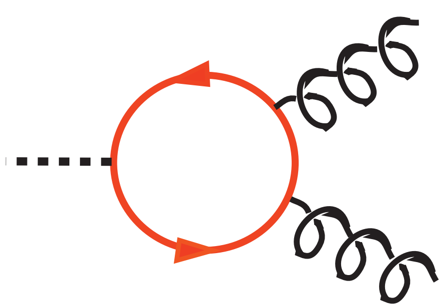
By gauge invariance: $f(h)G^a_{\mu\nu}G^{a\,\mu\nu}$



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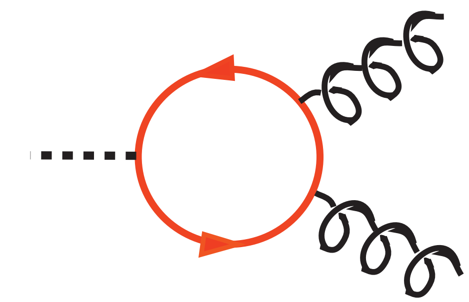


Matching at threshold M(h):

$$\mathcal{L}_{eff} = -\frac{1}{4}\frac{1}{g^2_{eff}(\mu,h)}G^a_{\mu\nu}G^{a\,\mu\nu} = -\frac{1}{4}\left(\frac{1}{g^2_s(\mu)} - b\frac{t_r}{4\pi^2}\log\frac{M(h)}{\mu}\right)G^a_{\mu\nu}G^{a\,\mu\nu}$$

t_R : Dynkin index (1/2 for fundamental),
b: 2/3 for Dirac fermion, 1/6 for complex scalar

$$\frac{g_s^2}{16\pi^2}\left(\frac{2}{3}\sum_{r_F} t_{r_F}\log m_{r_F}(h)+\frac{1}{6}\sum_{r_S} t_{r_S}\log m_{r_S}(h)\right)G_{\mu\nu}G^{\mu\nu}$$

fermion **scalar**

$$\frac{g_s^2}{16\pi^2}\left(\frac{2}{3}\sum_{r_F} t_{r_F}\log m_{r_F}(h)+\frac{1}{6}\sum_{r_S} t_{r_S}\log m_{r_S}(h)\right)G_{\mu\nu}G^{\mu\nu}$$

fermion **scalar**

OS- contribution: $h \to v + h$

$$\mathcal{L}_{hgg}=\frac{g_s^2}{48\pi^2}\frac{h}{v}\left(2\sum_{r_F} t_{r_F}\frac{\partial\log m_{r_F}(v)}{\partial\log v}+\frac{1}{2}\sum_{r_S} t_{r_S}\frac{\partial\log m_{r_S}(v)}{\partial\log v}\right)G^a_{\mu\nu}G^{a\,\mu\nu}$$

$$\frac{g_s^2}{16\pi^2}\left(\frac{2}{3}\sum_{r_F} t_{r_F}\log m_{r_F}(h) + \frac{1}{6}\sum_{r_S} t_{r_S}\log m_{r_S}(h)\right) G_{\mu\nu}G^{\mu\nu}$$

fermion scalar

OS- contribution: $h \to v + h$

$$\mathcal{L}_{hgg} = \frac{g_s^2}{48\pi^2}\frac{h}{v}\left(2\sum_{r_F} t_{r_F}\frac{\partial \log m_{r_F}(v)}{\partial \log v} + \frac{1}{2}\sum_{r_S} t_{r_S}\frac{\partial \log m_{r_S}(v)}{\partial \log v}\right) G^a_{\mu\nu}G^{a\,\mu\nu}$$

… and analogously for $h\, F_{\mu\,\nu}F^{\mu\,\nu}$

Susy

$$\mathcal{L}_{eff} = -\frac{1}{4}\left(\frac{1}{g_s^2(\mu)} - \frac{2}{3}\times\frac{1}{8\pi^2}\log\frac{m_t(h)}{\mu} - \frac{1}{12}\times\frac{1}{8\pi^2}\log\frac{\mathcal{M}_{\tilde{t}}^\dagger\mathcal{M}_{\tilde{t}}}{\mu^2}\right)G^a_{\mu\nu}G^{a\,\mu\nu}$$

warm up: A terms → 0

$$\mathcal{M}_{\tilde{t}}^\dagger\mathcal{M}_{\tilde{t}} = \begin{pmatrix} \tilde{m}_L^2 + (\lambda_t h)^2/2 & 0 \\ 0 & \tilde{m}_R^2 + (\lambda_t h)^2/2 \end{pmatrix}$$

hgg coupling: indirect limit on stops

$$\frac{\partial}{\partial \log h} \log \frac{m_t(h)}{\mu}\bigg|_{h=v} + \frac{1}{8}\,\frac{\partial}{\partial \log h} \log \frac{\det \mathcal{M}_{\tilde{t}}^{\dagger}\mathcal{M}_{\tilde{t}}}{\mu^2}\bigg|_{h=v}$$

$$= 1 + \frac{1}{4}\left(\frac{m_t^2}{2\tilde{m}_L^2 + m_t^2/2} + \frac{m_t^2}{2\tilde{m}_R^2 + m_t^2/2}\right),$$

10% measurement of hgg,

… approximately 450 GeV reach for mstop

LHC projection

Implications of LHC results for TeV-scale physics: signals of electroweak symmetry breaking

Submitted to the Open Symposium of the European Strategy Preparatory Group.

Editors: S. Heinemeyer, M. Kado, C. Mariotti, G.Weiglein, A.Weiler,

Decay	Prod	$10\,\mathrm{fb}^{-1}$ 7 - 8 TeV	$60\,\mathrm{fb}^{-1}$ 8 TeV	$300\,\mathrm{fb}^{-1}$ 14 TeV
$H \to b\bar{b}$	VH	70%	30%	10 %
$H \to b\bar{b}$	$t\bar{t}H$	-	60%	10 %
$H \to \tau\tau$	ggH	64%	40%	10 %
$H \to \tau\tau$	qqH		40%	10 %
$H \to \gamma\gamma$	ggH	38%	20%	6 %
$H \to \gamma\gamma$	qqH		40%	10 %
$H \to WW^*$	ggH	42%	16%	5 %
$H \to WW^*$	qqH	-	60%	16 %
$H \to ZZ^*$	ggH	40%	16%	5 %
c_V	-	10%	-	2%
c_F	-	25%	-	5%

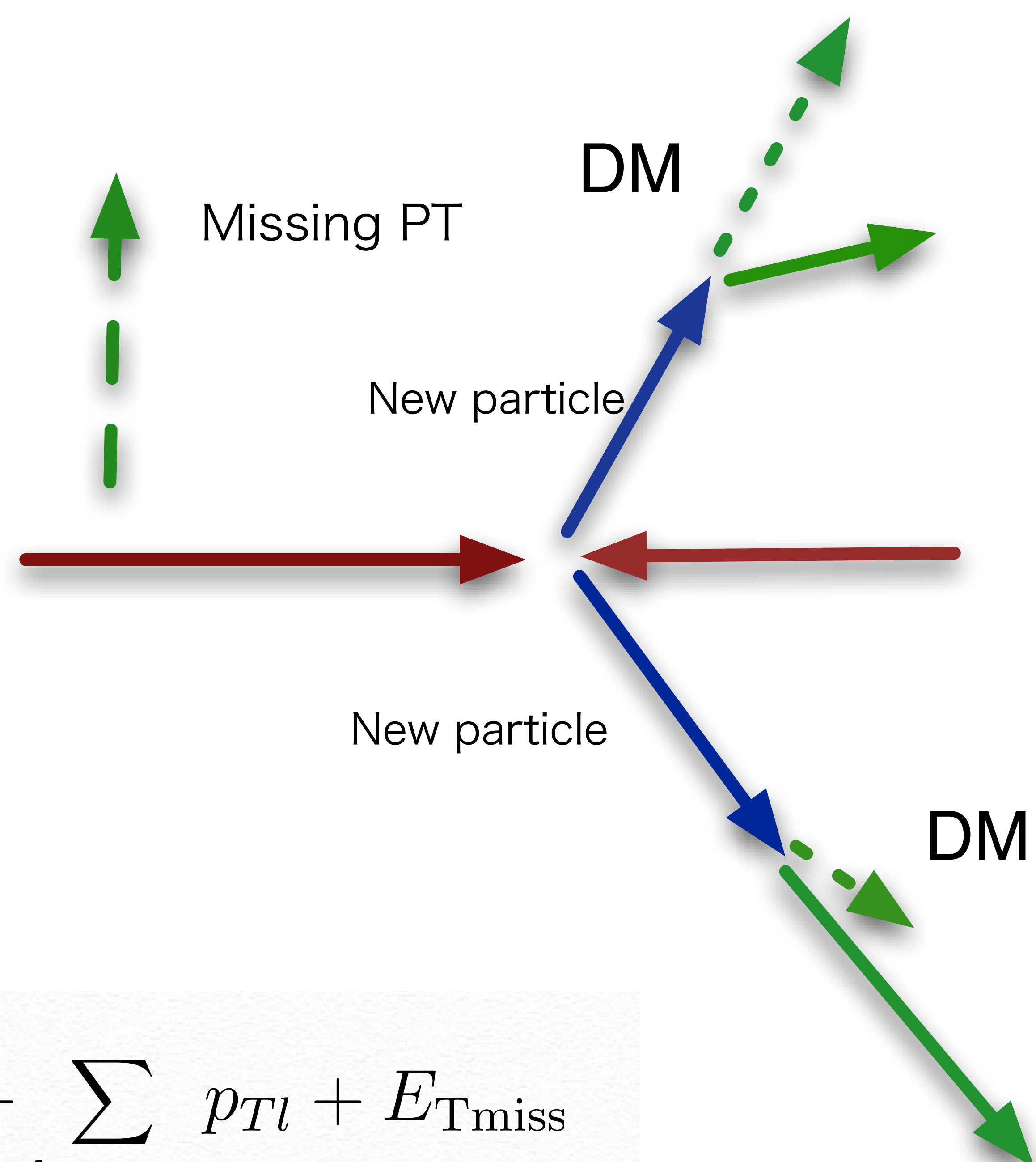
Linear collider

Table 3: Examples of the precision of couplings, g_{Hxx}, and branching ratios, $\mathrm{BR}(H \to xx)$, for a SM-like Higgs at a $\sqrt{s} = 500\ \mathrm{GeV}$ LC assuming a Higgs boson mass of $125\ \mathrm{GeV}$. The branching ratio into invisible final states is denoted as "BR(invis.)". The results are based on the ILC set-up for an integrated luminosity of $\mathcal{L}^{\mathrm{int}} = 500\,\mathrm{fb}^{-1}$.

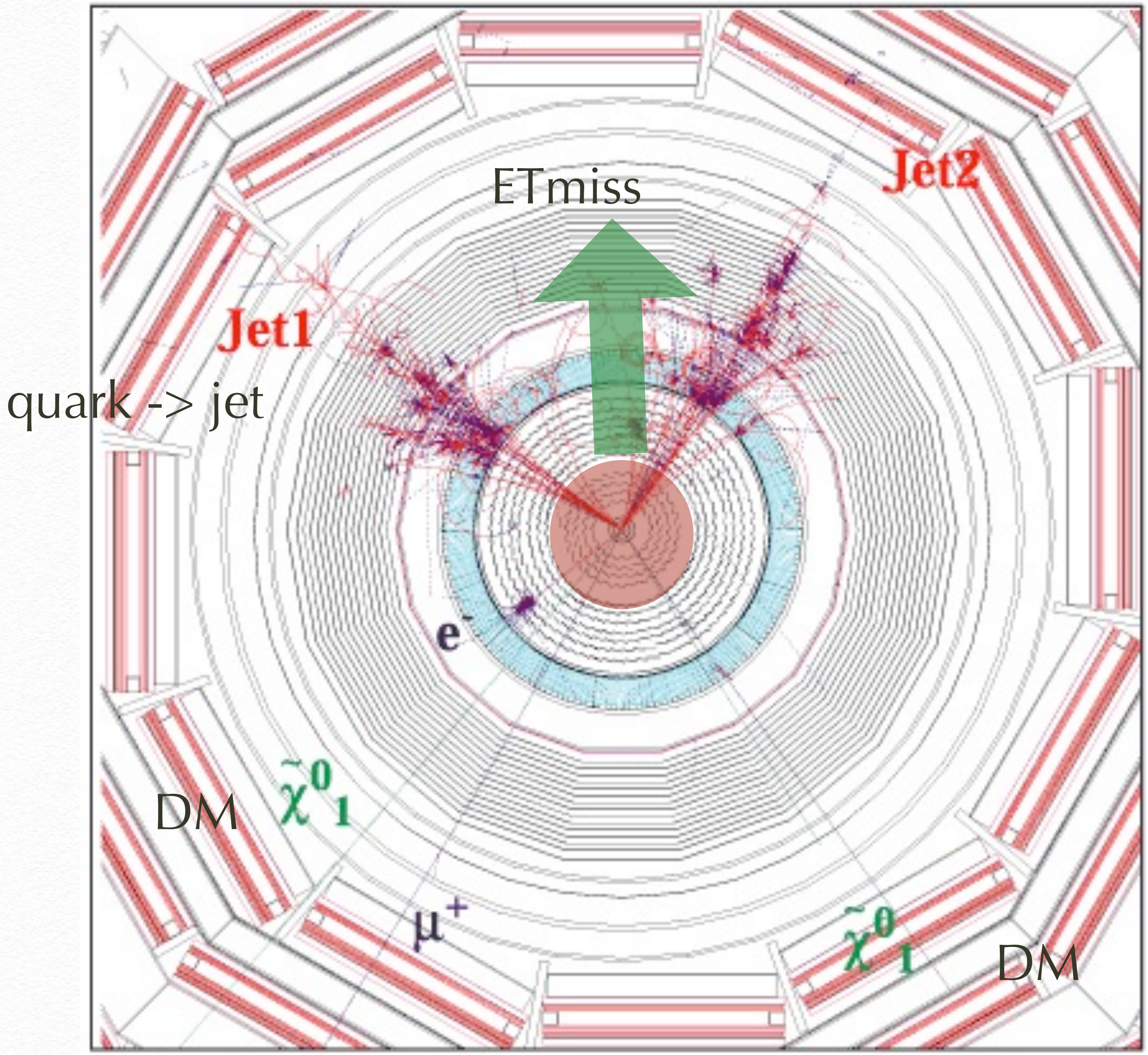
g / BR	g_{HWW}	g_{HZZ}	g_{Hbb}	g_{Hcc}	$g_{H\tau\tau}$	g_{Htt}	g_{HHH}	$\mathrm{BR}(\gamma\gamma)$	$\mathrm{BR}(gg)$	BR(invis.)
Precision	1.4 %	1.4 %	1.4 %	2.0 %	2.5 %	15 %	40 %	15 %	5 %	0.5 %

Direct Searches for Supersymmetry

Basic idea

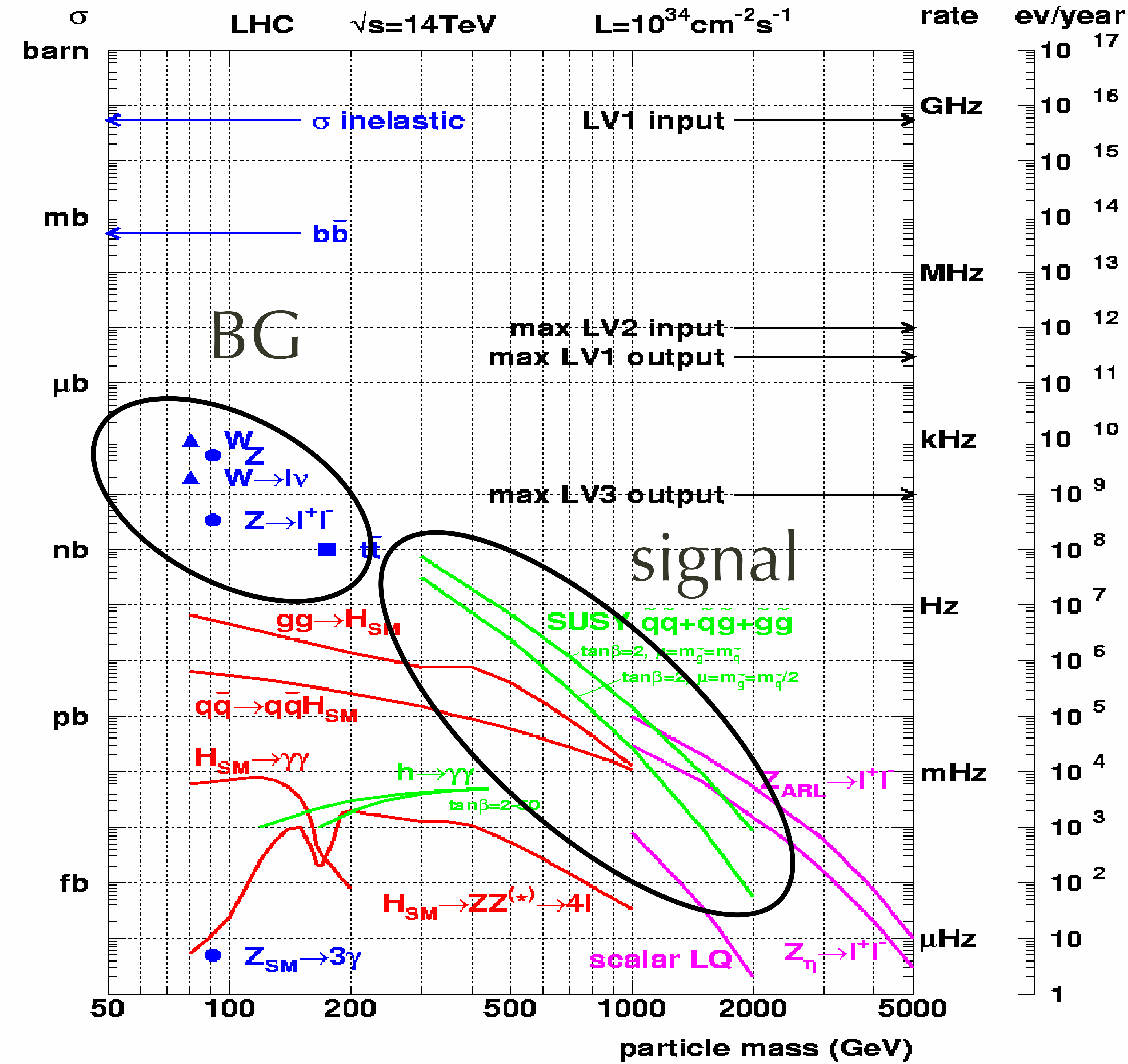


$$M_{\text{eff}} \equiv \sum_{i=1,\ldots 4} p_{Ti} + \sum_{\text{leptons}} p_{Tl} + E_{\text{Tmiss}}$$

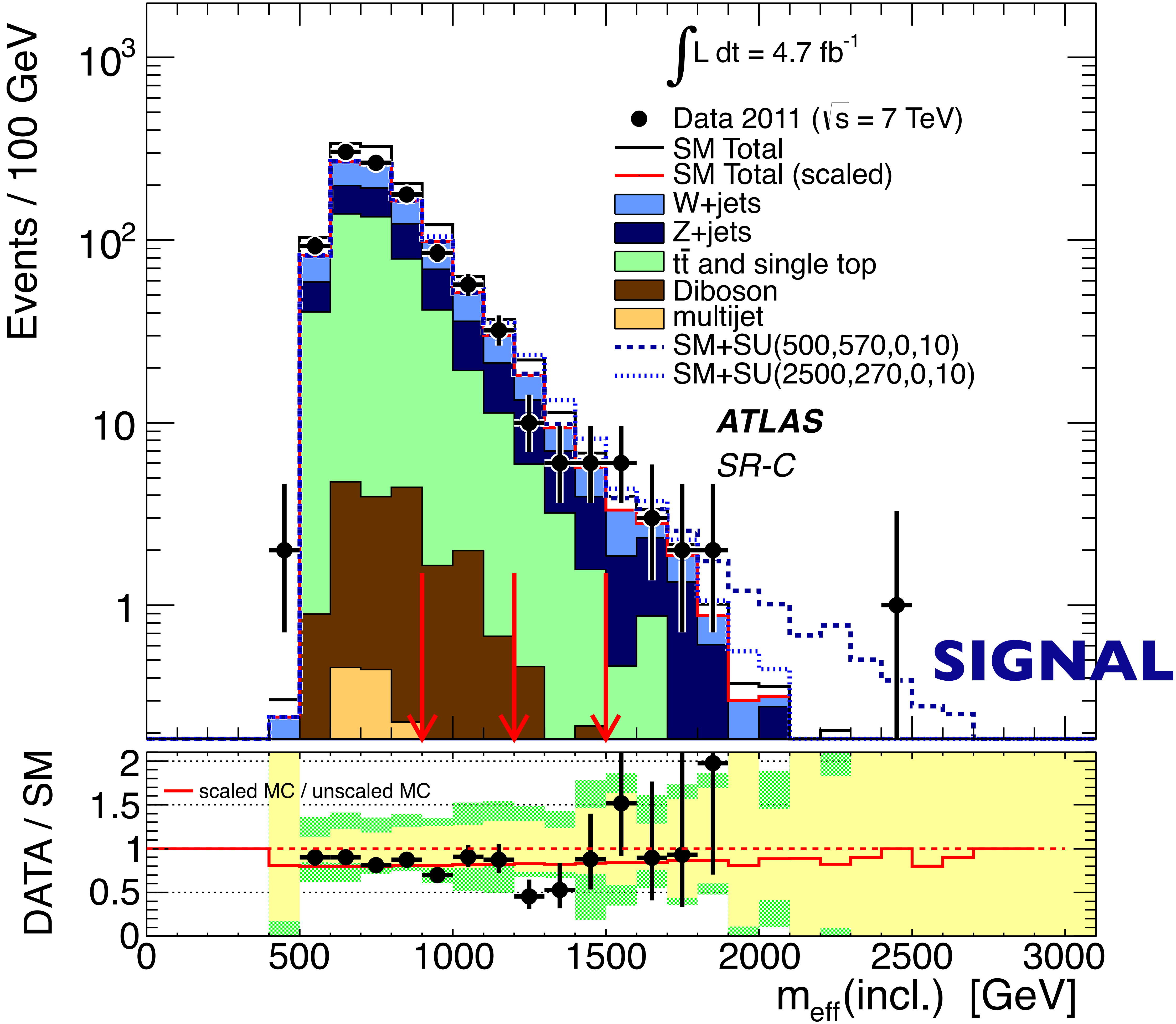

ETmiss
Jet2
Jet1
quark -> jet
e⁻
DM
$\tilde{\chi}^0_1$
μ^+
$\tilde{\chi}^0_1$
DM

Backgrounds

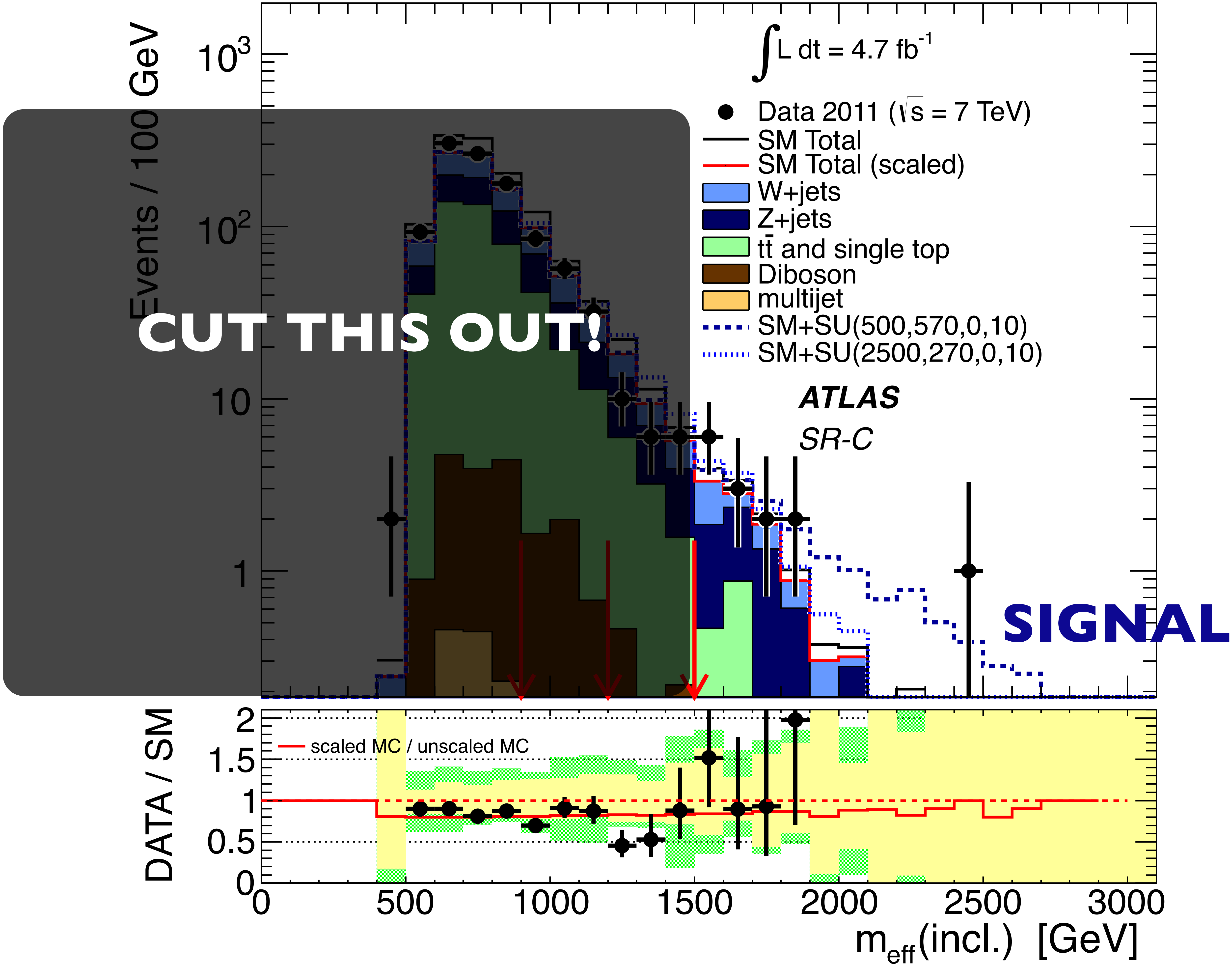
The typical number of SUSY events are 10^5 for 10 fb^{-1}, while BG rate is 10^{9-8} for W, Z and ttbar productions. 10^{-4} rejection of SM process is required.



σ
barn
LHC √s=14TeV L=10^34 cm^-2 s^-1
rate
ev/year
σ inelastic
LV1 input
GHz
mb
bb̄
MHz
BG
max LV2 input
max LV1 output
μb
kHz
W
Z
W→lν
Z→l+l-
max LV3 output
nb
tt̄
signal
gg→H_SM
SUSY q̃q̃+q̃g̃+g̃g̃
tanβ=2, μ=m_g̃=m_q̃
tanβ=2, μ=m_g̃=m_q̃/2
Hz
qq̄→qq̄H_SM
pb
H_SM→γγ
h→γγ
tanβ=2-50
Z_ARL→l+l-
mHz
fb
H_SM→ZZ(*)→4l
Z_SM→3γ
scalar LQ
Z_η→l+l-
μHz
50
100
200
500
1000
2000
5000
particle mass (GeV)



Events / 100 GeV
$\int L\,dt = 4.7\ fb^{-1}$
Data 2011 ($\sqrt{s}$ = 7 TeV)
SM Total
SM Total (scaled)
W+jets
Z+jets
$t\bar{t}$ and single top
Diboson
multijet
SM+SU(500,570,0,10)
SM+SU(2500,270,0,10)
ATLAS
SR-C
SIGNAL
DATA / SM
scaled MC / unscaled MC
m_{eff}(incl.) [GeV]



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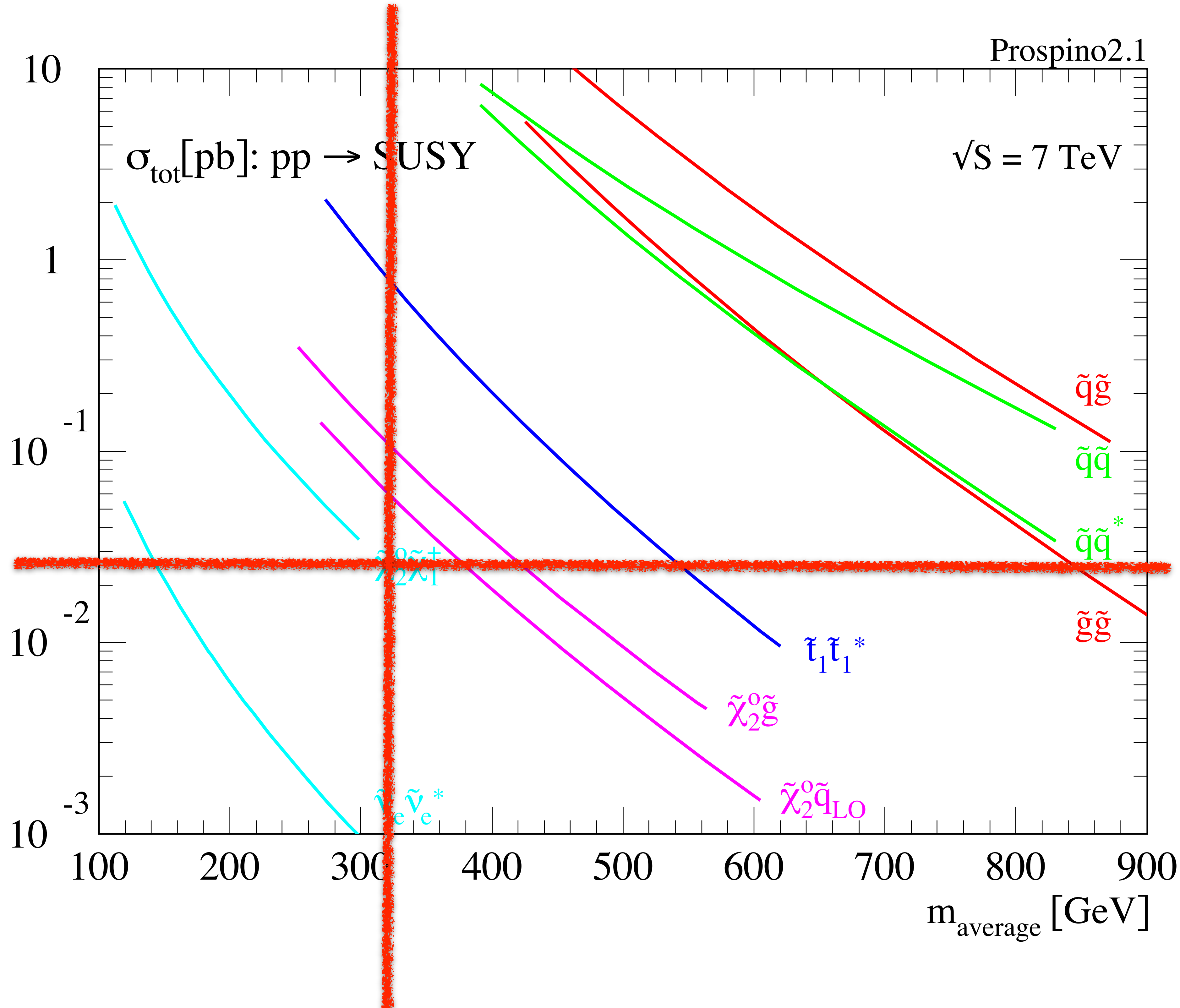
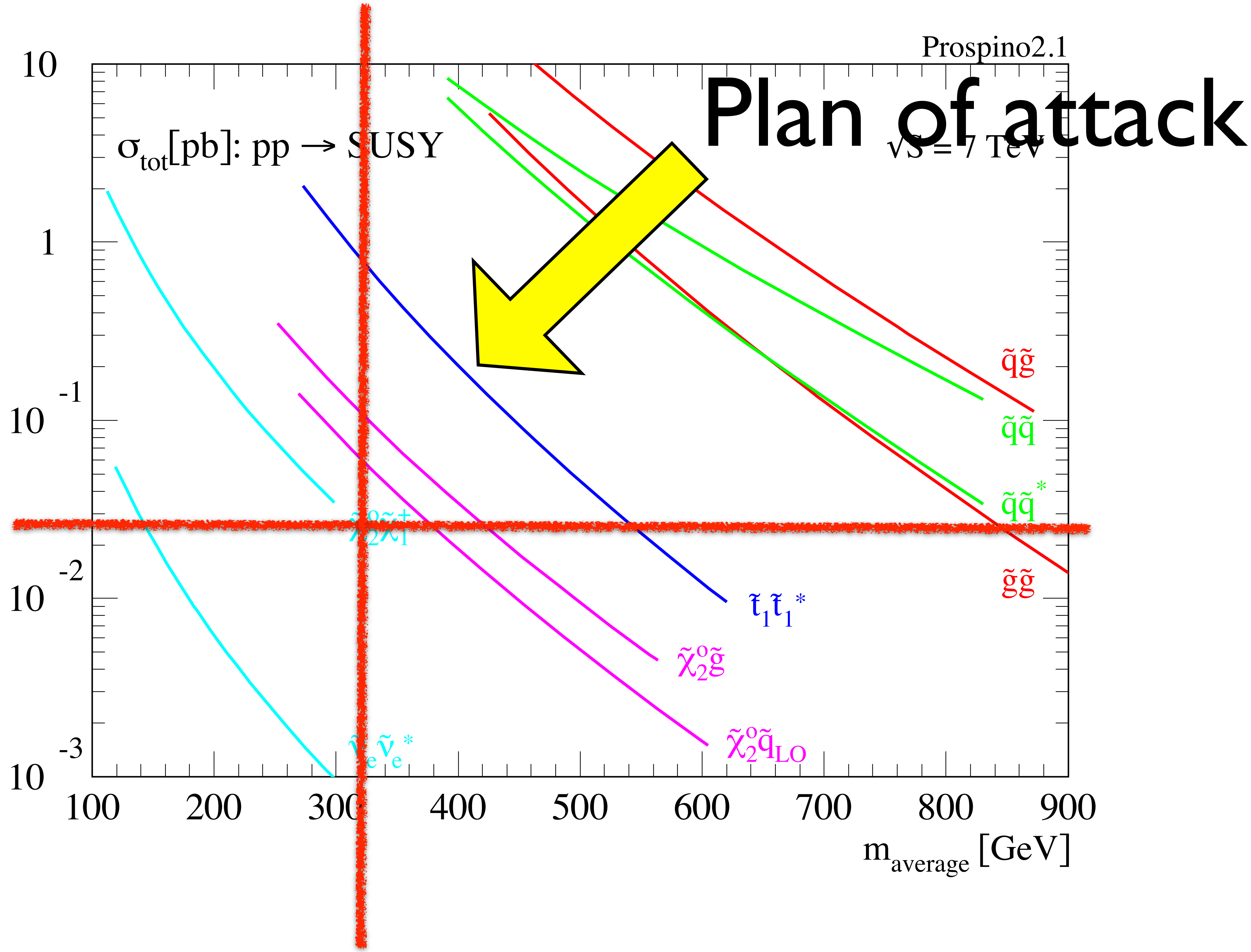
Diboson
multijet
SM+SU(500,570,0,10)
SM+SU(2500,270,0,10)
ATLAS
SR-C
CUT THIS OUT!
SIGNAL
Events / 100 GeV
10^3
10^2
10
1
DATA / SM
scaled MC / unscaled MC
2
1.5
1
0.5
0
0
500
1000
1500
2000
2500
3000
m_{eff}(incl.) [GeV]

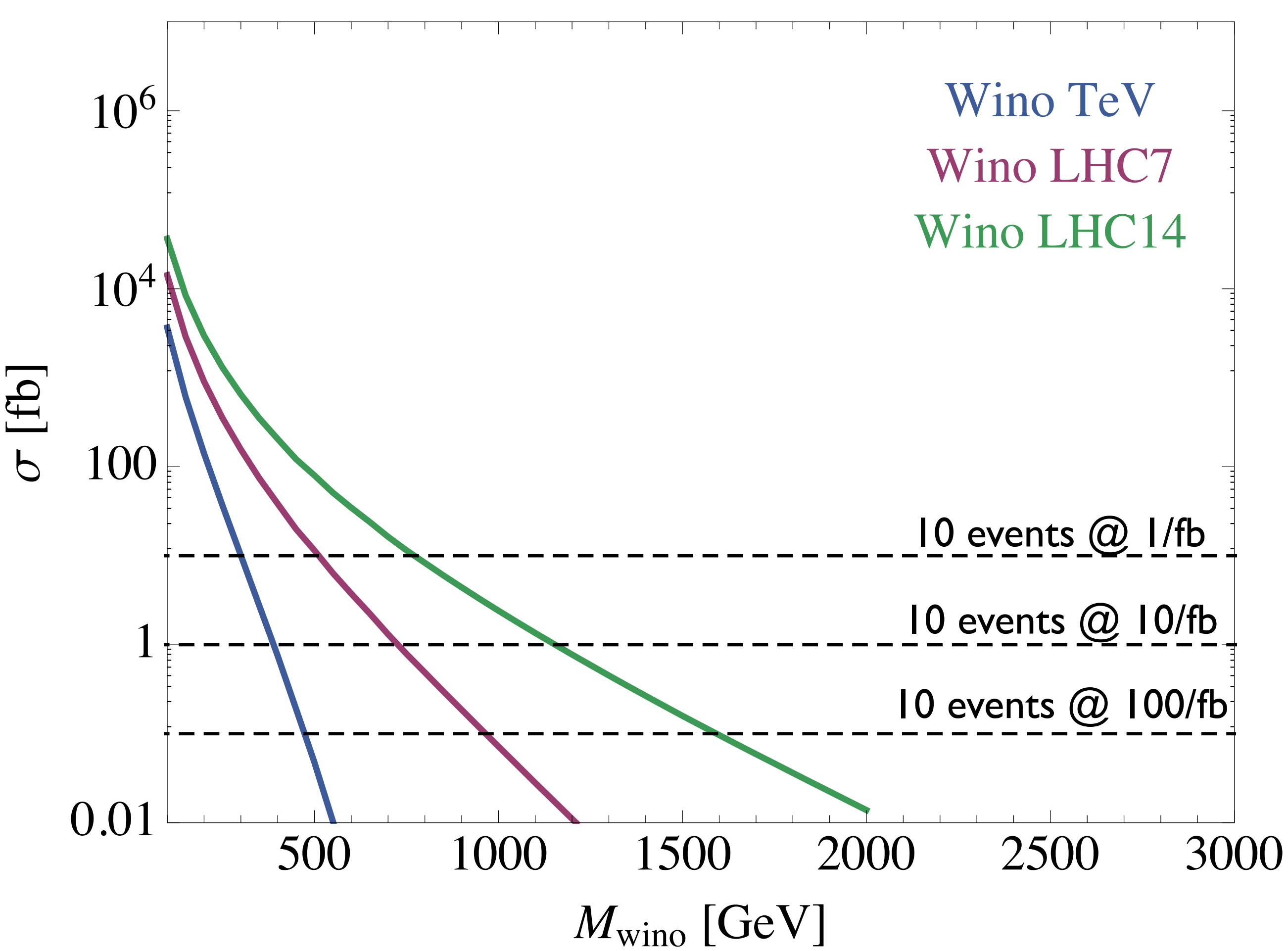
Looking for susy

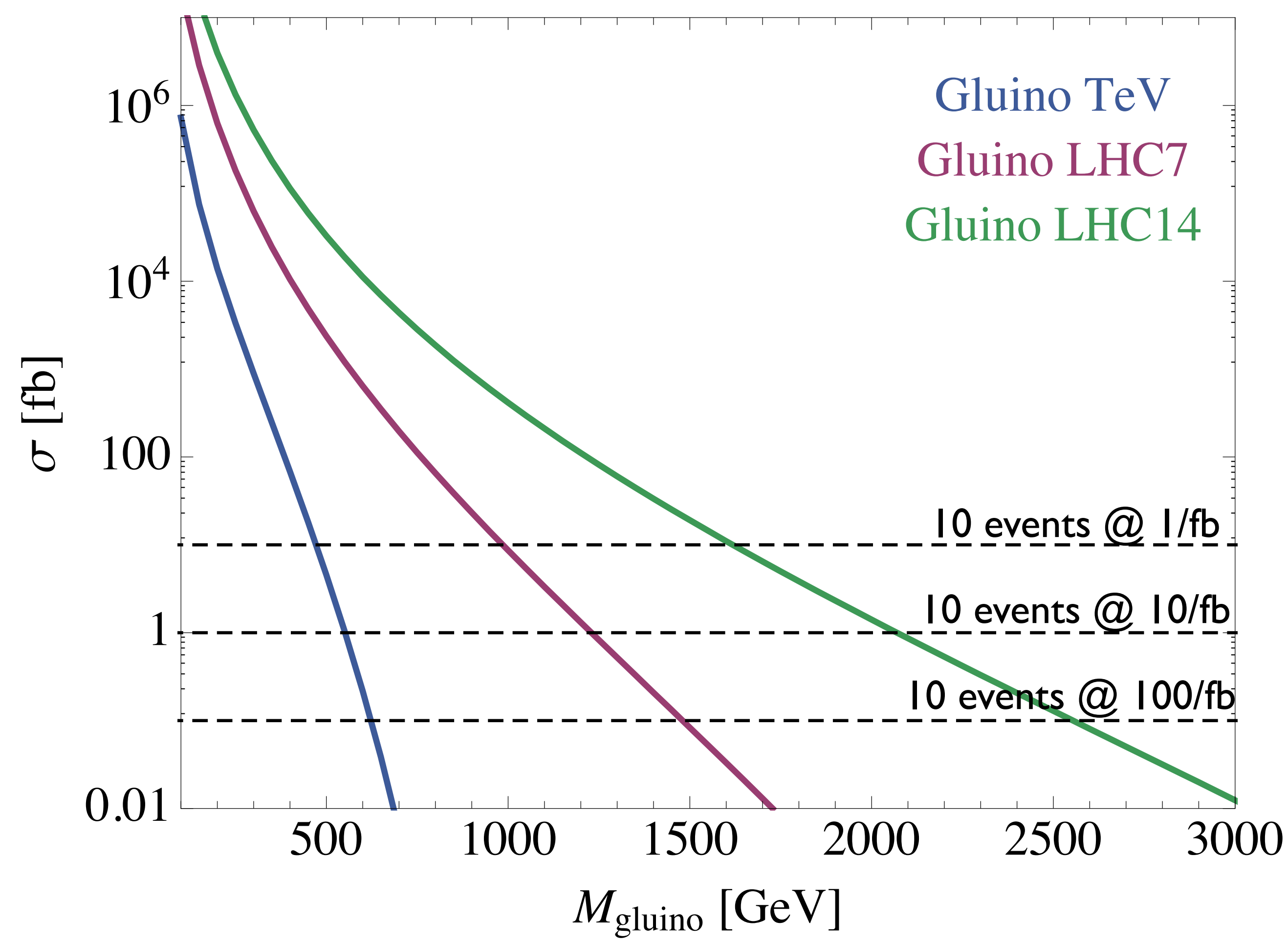


Looking for susy



SUSY production at the LHC





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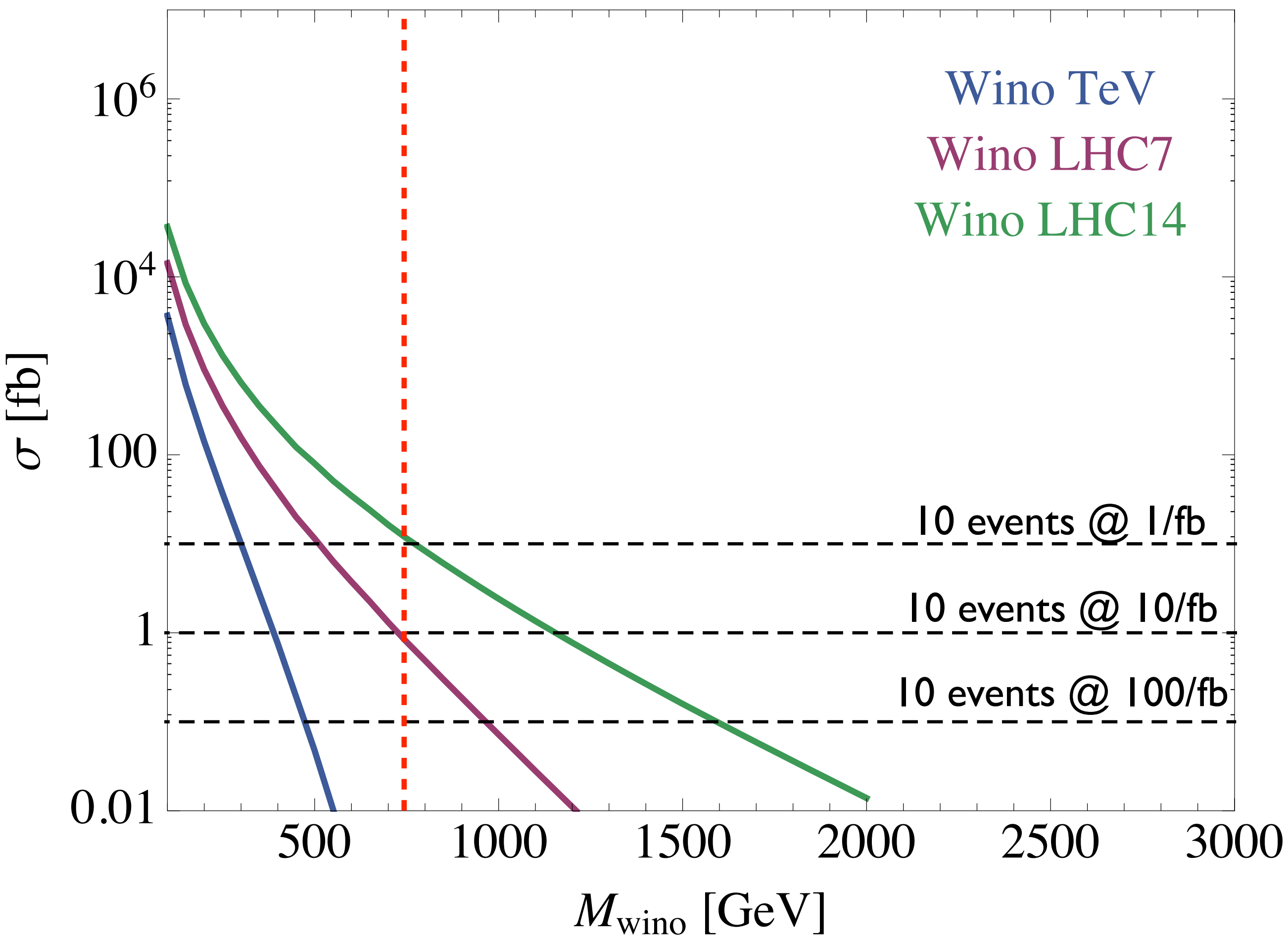
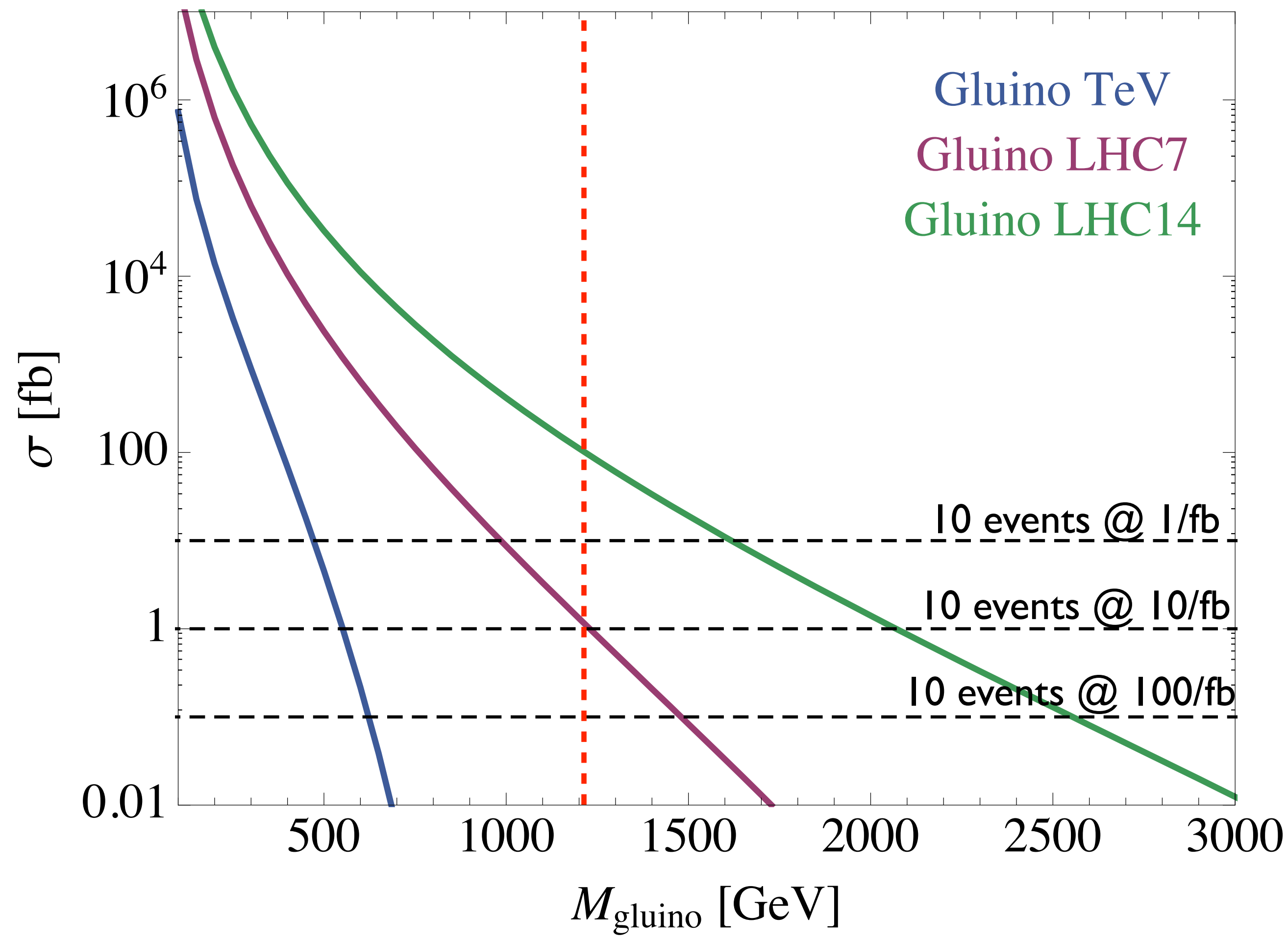
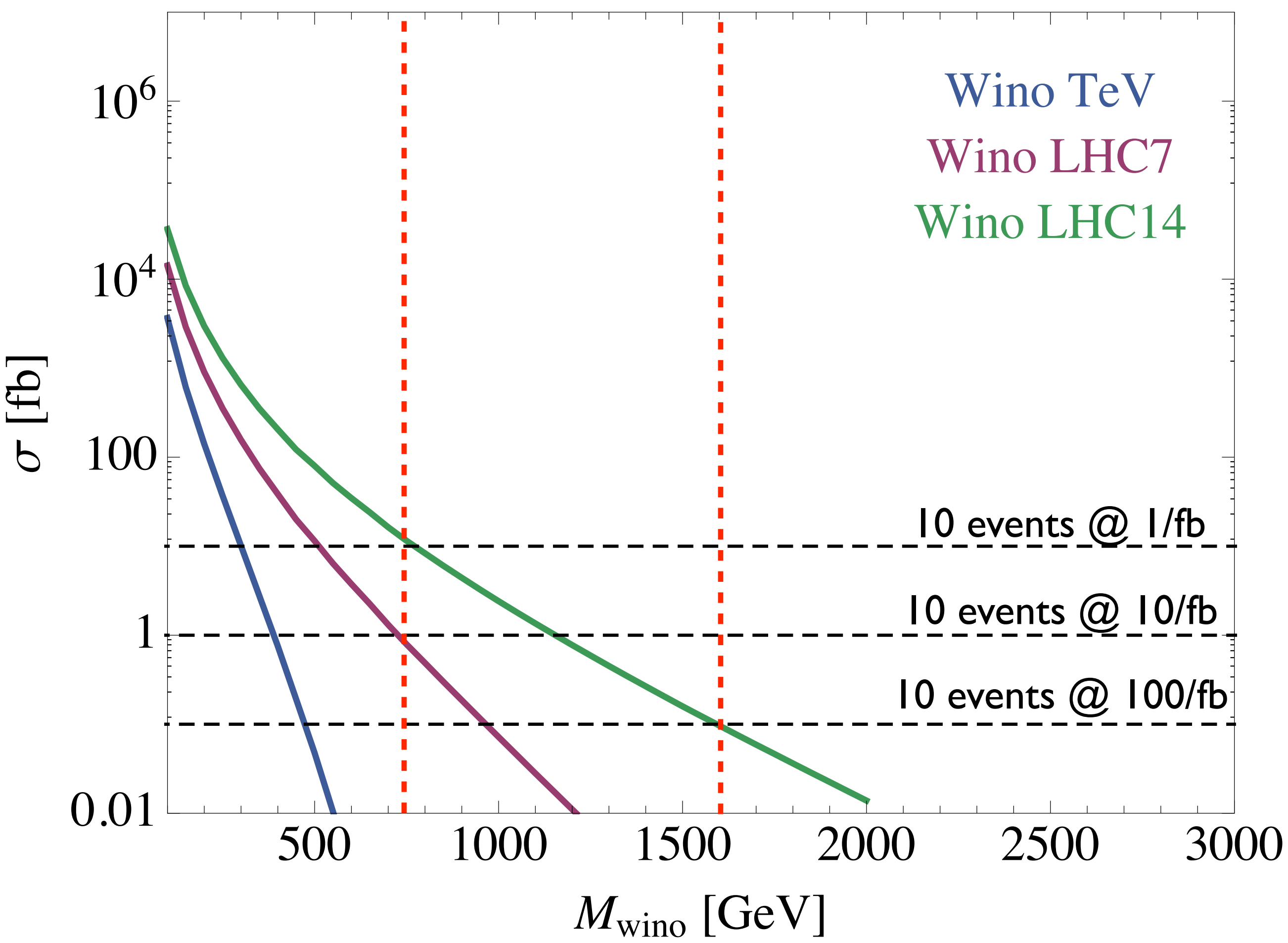


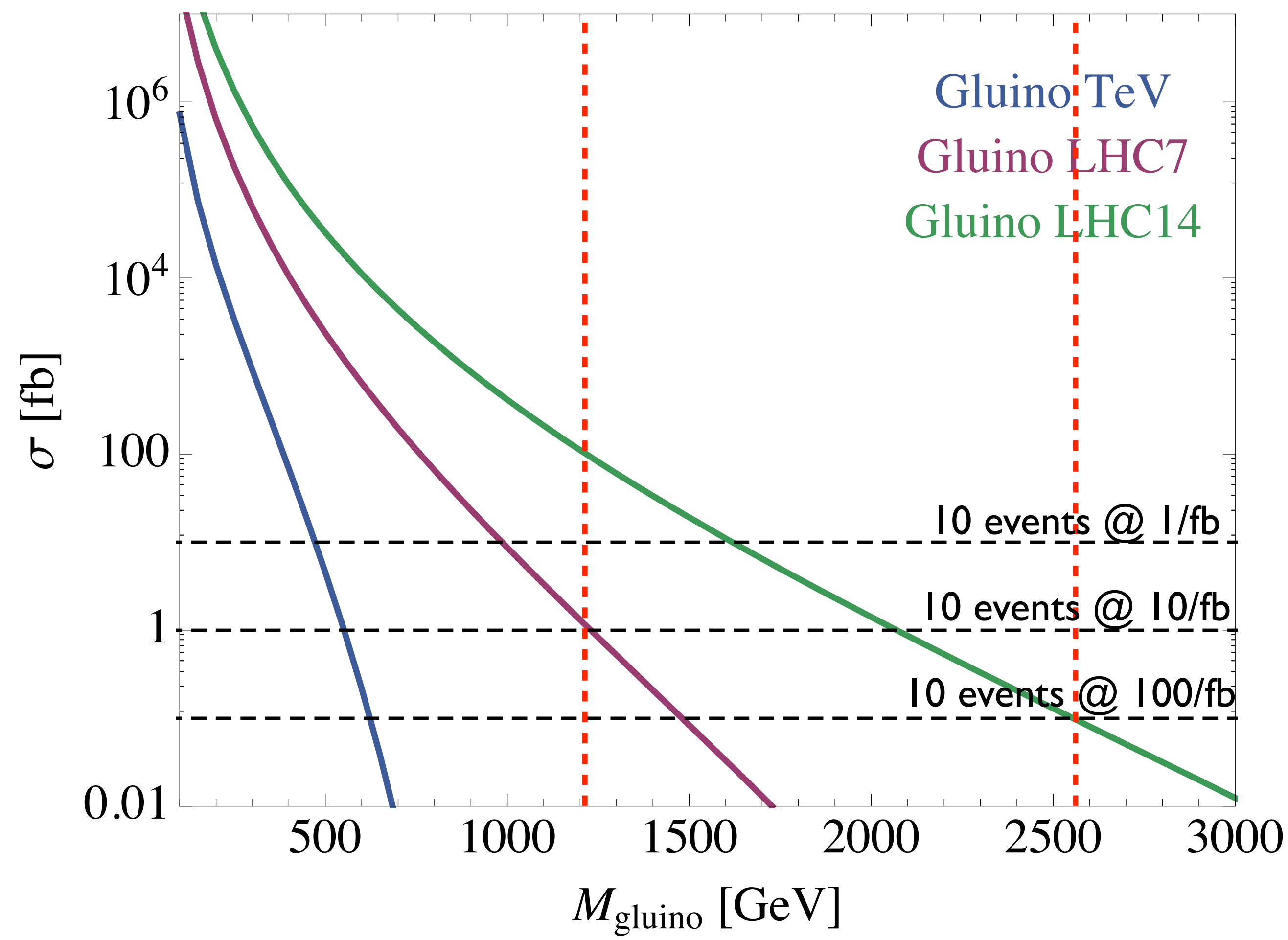


"Kinematic reach" of LHC7: $M_{\mathrm{wino}} \sim 700$ GeV $M_{\mathrm{gluino}} \sim 1200$ GeV

10 events @ 10/fb

SUSY production at the LHC





"Kinematic reach" of LHC7: $M_{\mathrm{wino}} \sim 700$ GeV $M_{\mathrm{gluino}} \sim 1200$ GeV

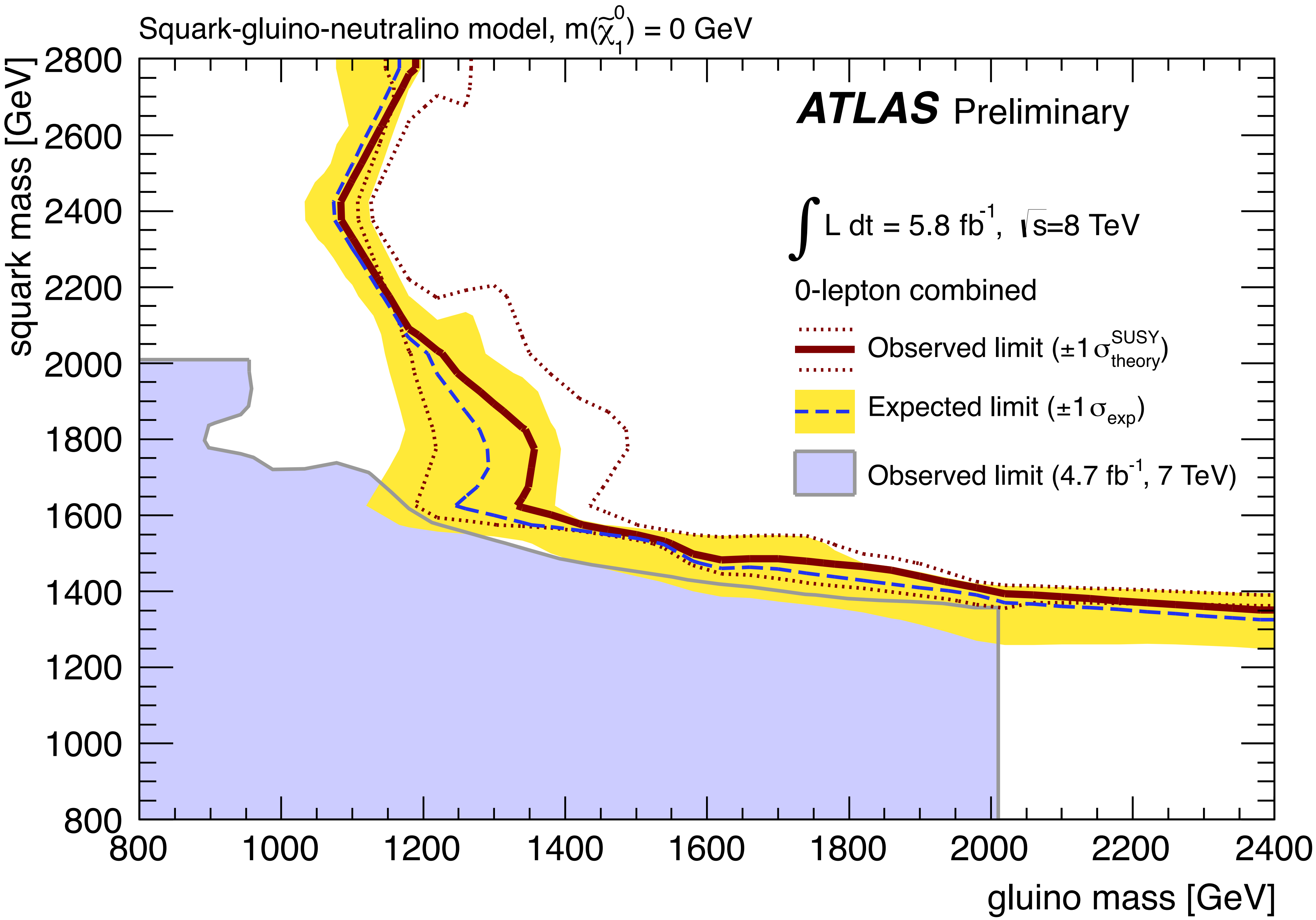
10 events @ 10/fb

"Kinematic reach" of LHC14: $M_{\mathrm{wino}} \sim 1600$ GeV $M_{\mathrm{gluino}} \sim 2500$ GeV

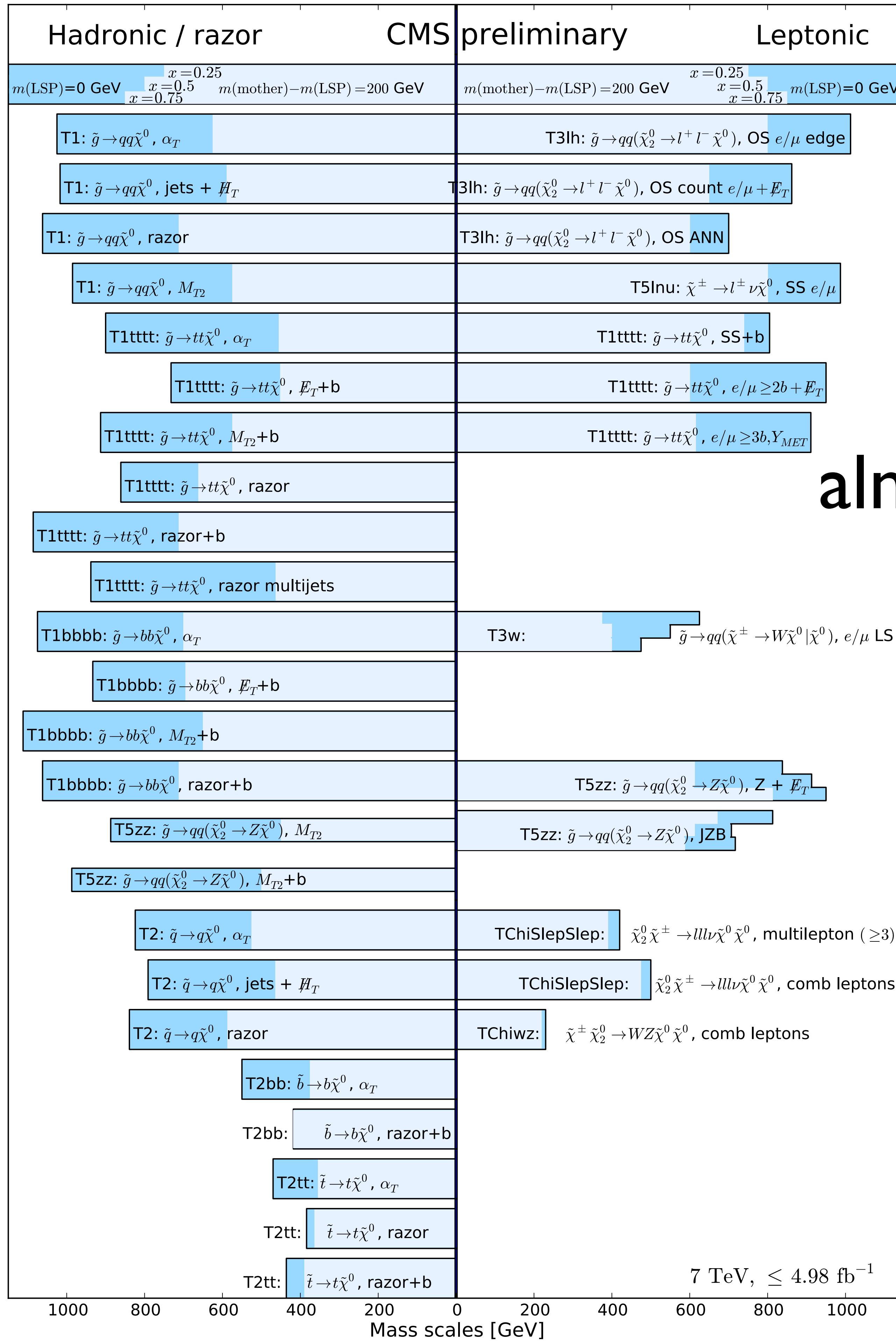
10 events @ 100/fb

Measures where we are.

ATLAS gluino-squark-LSP (8 TeV, 5.8 fb^{-1})

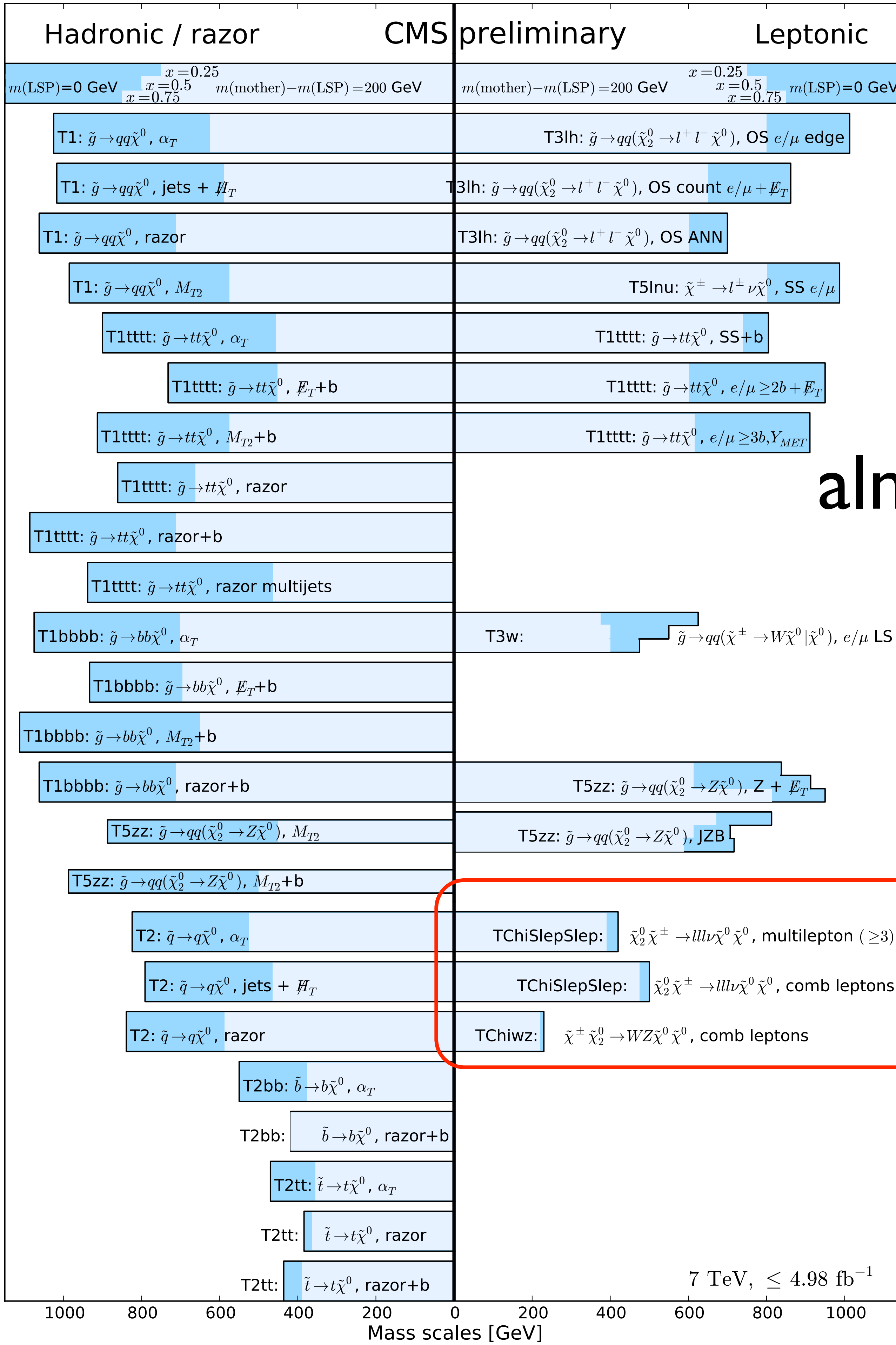


CMS



almost all colored objects

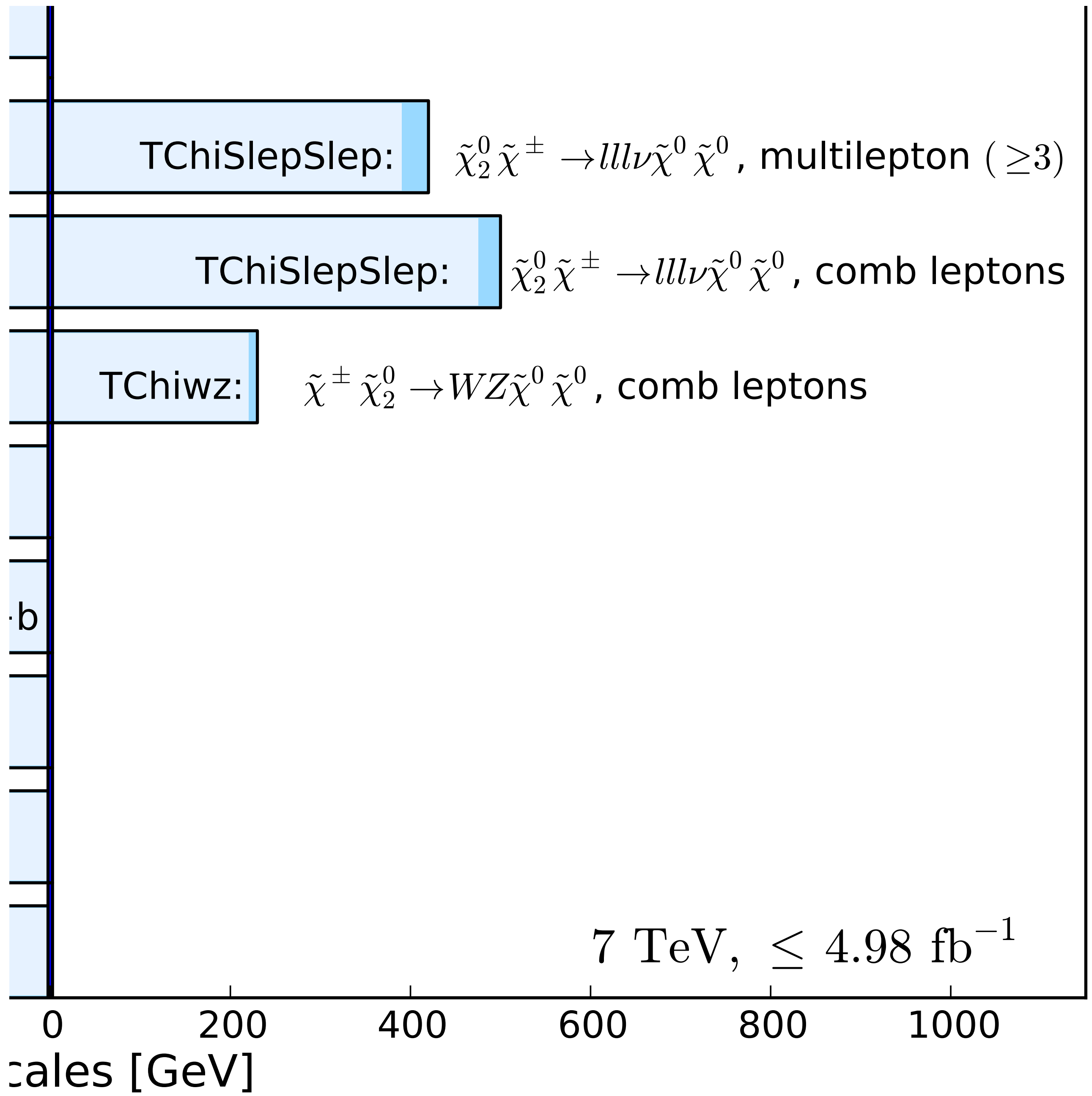
CMS



almost all colored objects

EWinos

CMS



EWino limits

Susy searches

What have we learned about the susy spectrum after 5 1/fb ?

- 1st & 2nd generation squarks need to be heavy > 1 TeV from jets+MET searches
- gluino limits above ~1200 GeV (also from various other channels)

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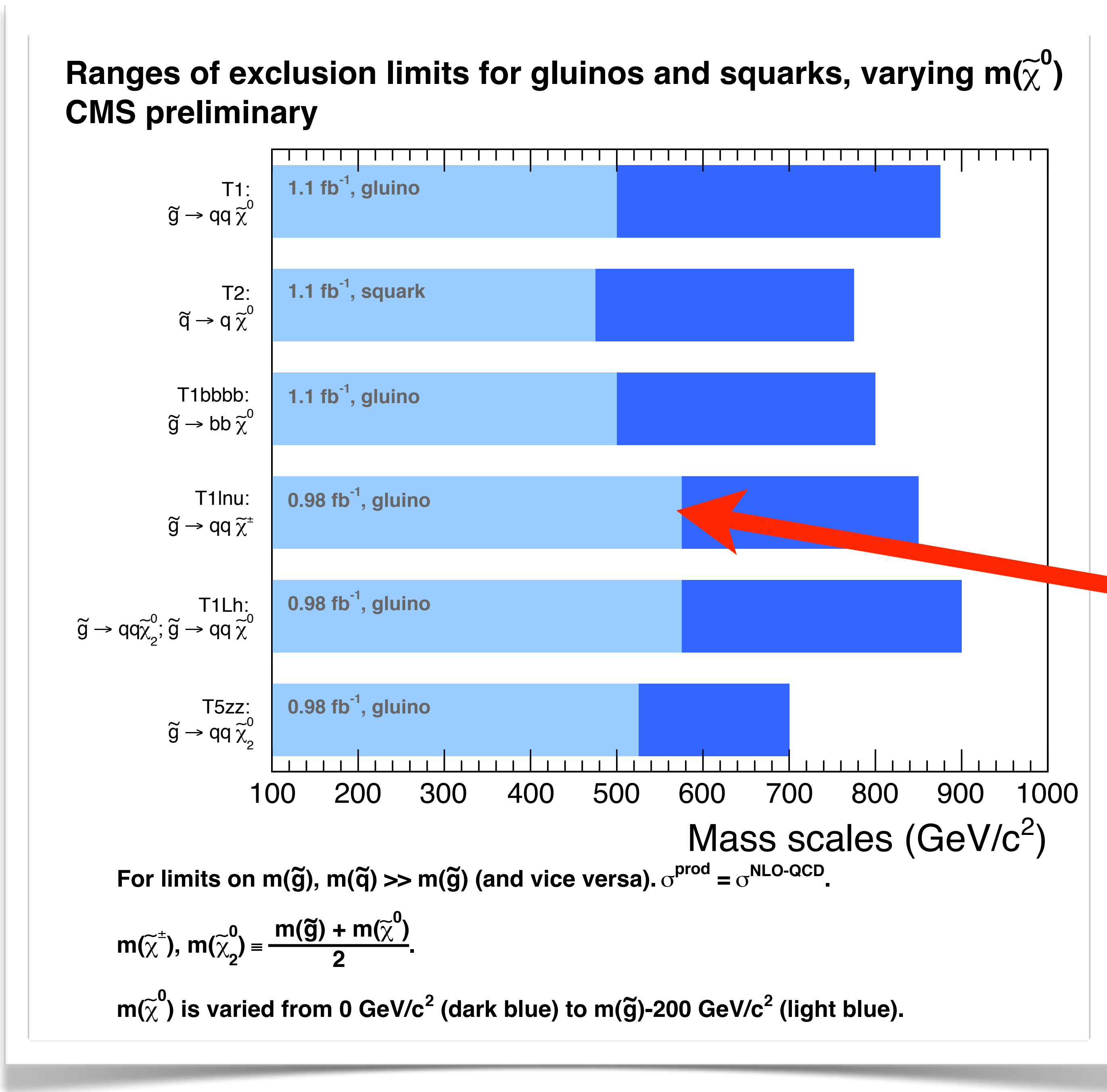
Caveats?

Impact of LSP mass

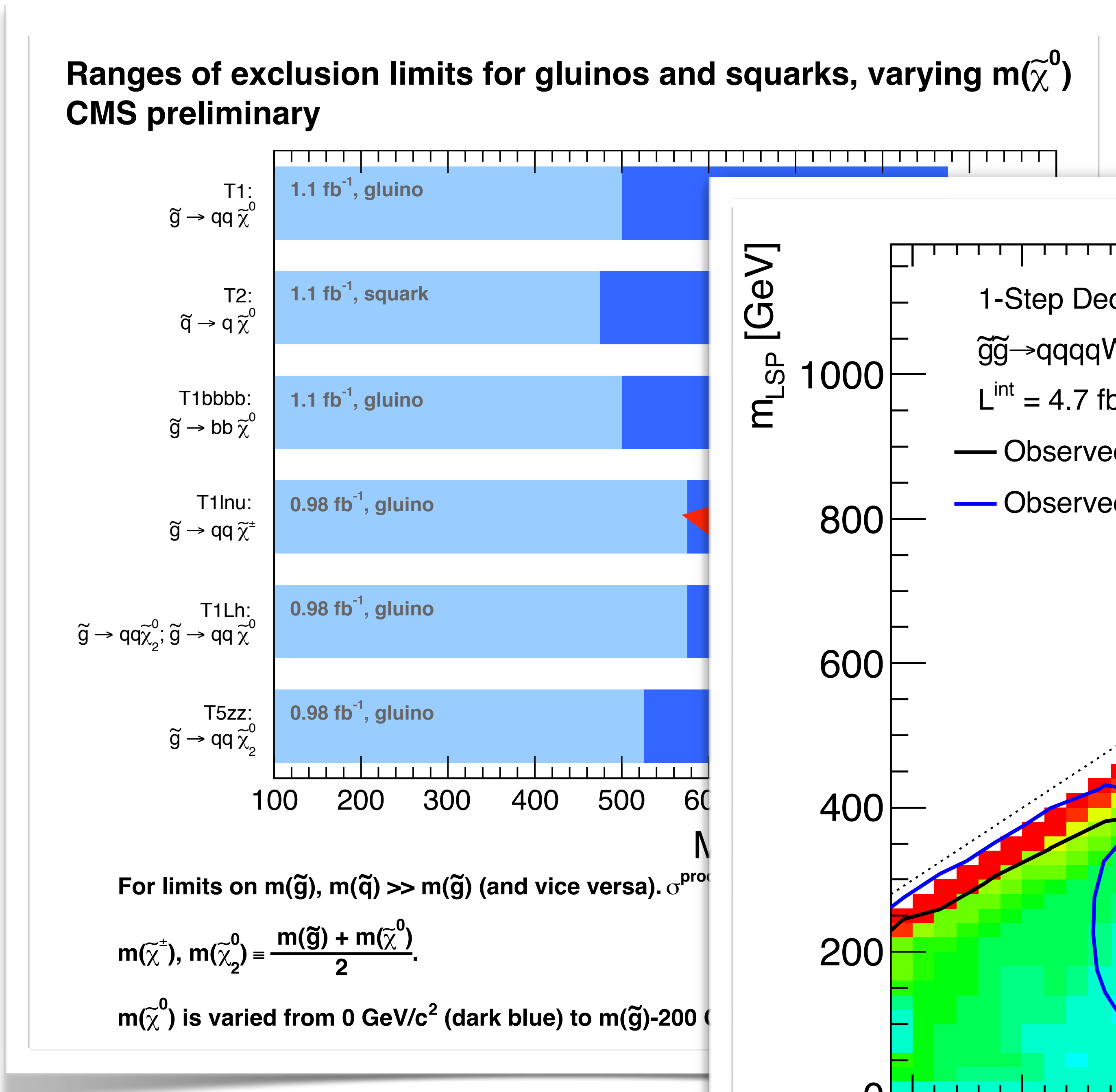


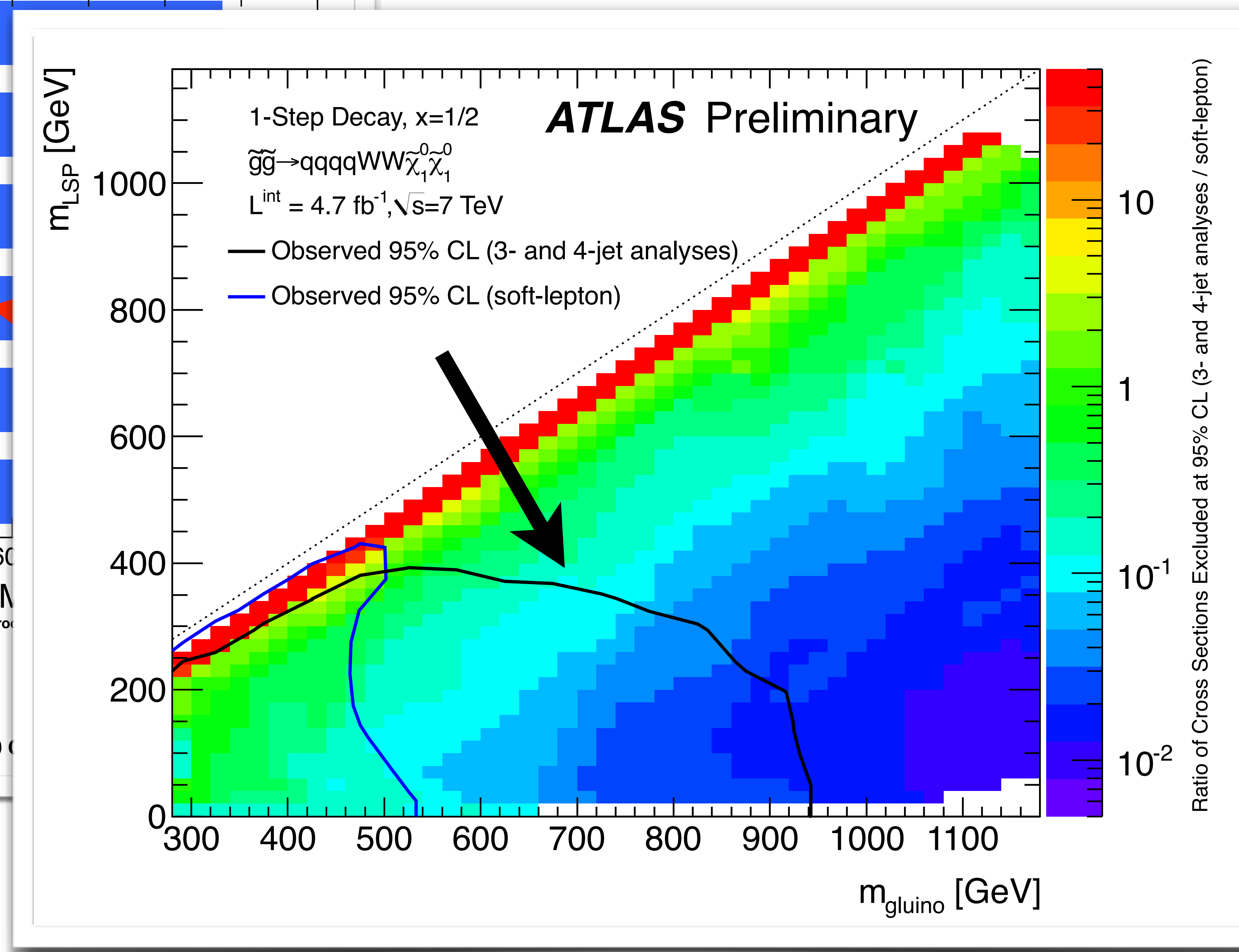
Compressed spectrum alleviates bounds

$m_{gluino} - m_{LSP} = 200$ GeV

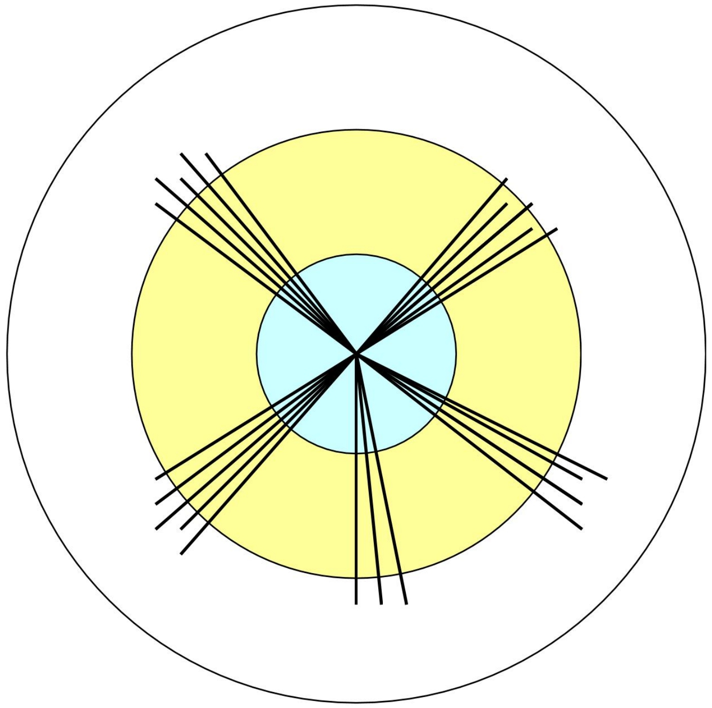
Impact of LSP mass

Compressed spectrum alleviates bounds



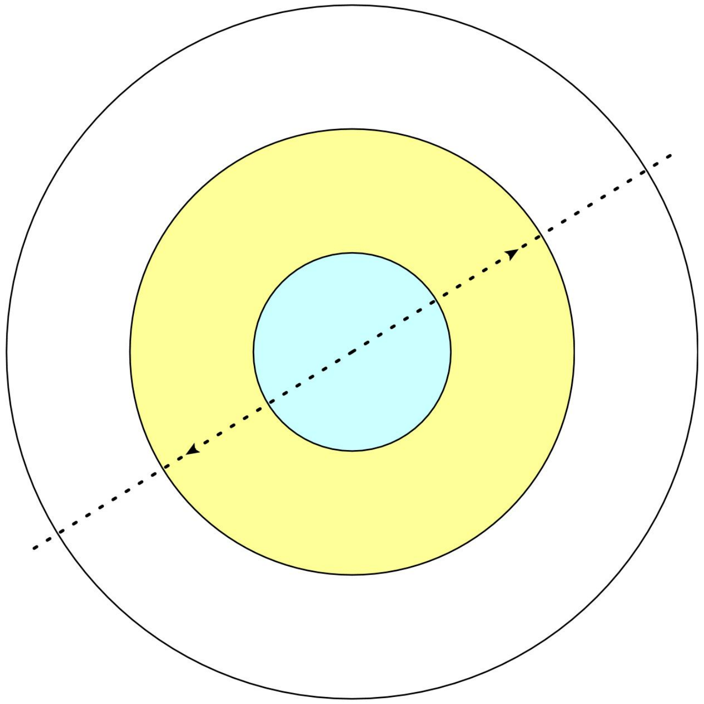


No missing energy in the event



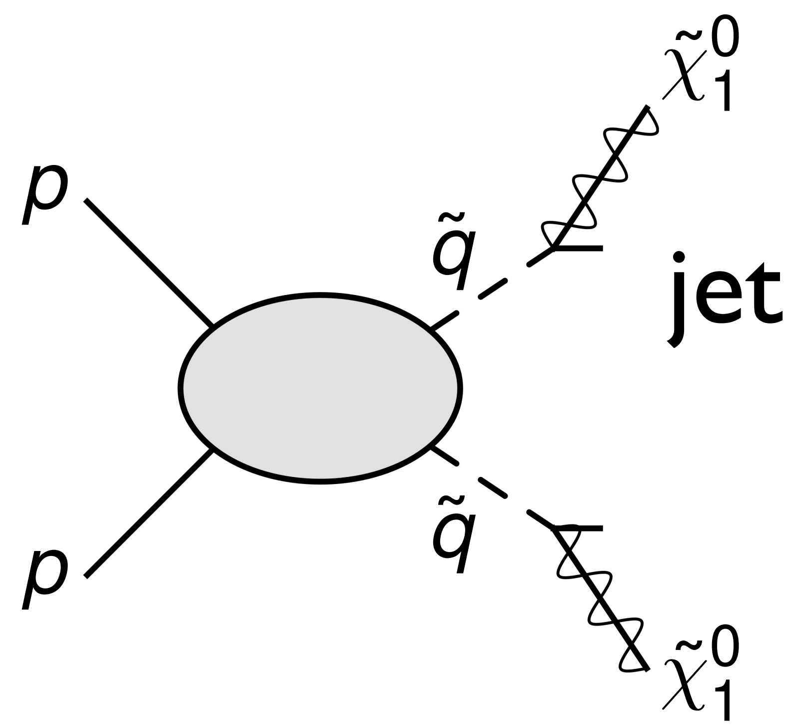
How to discriminate against QCD?

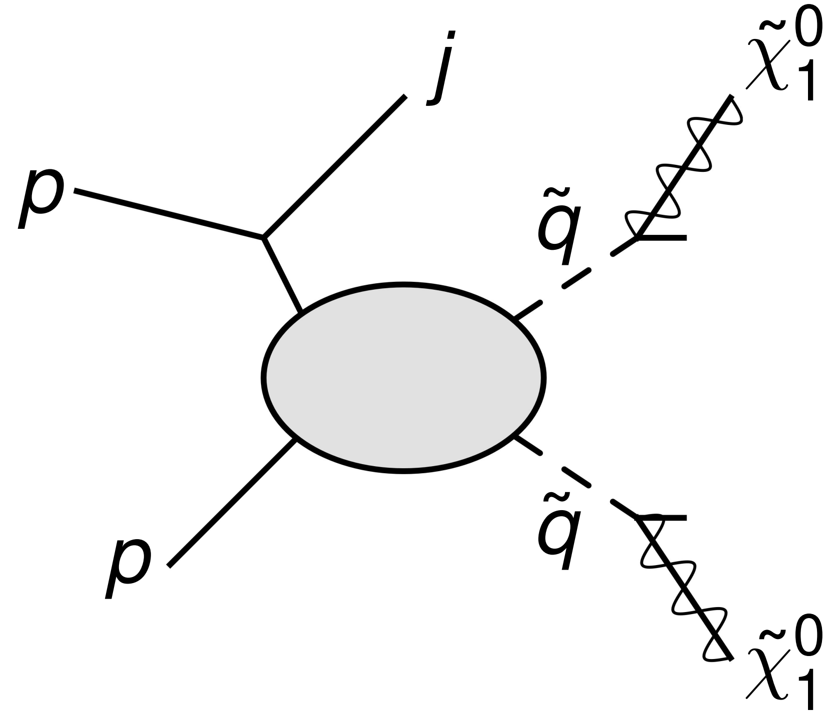
Only missing energy



Invisible to the detector

Spectrum compressed: all momentum is carried by the LSP.

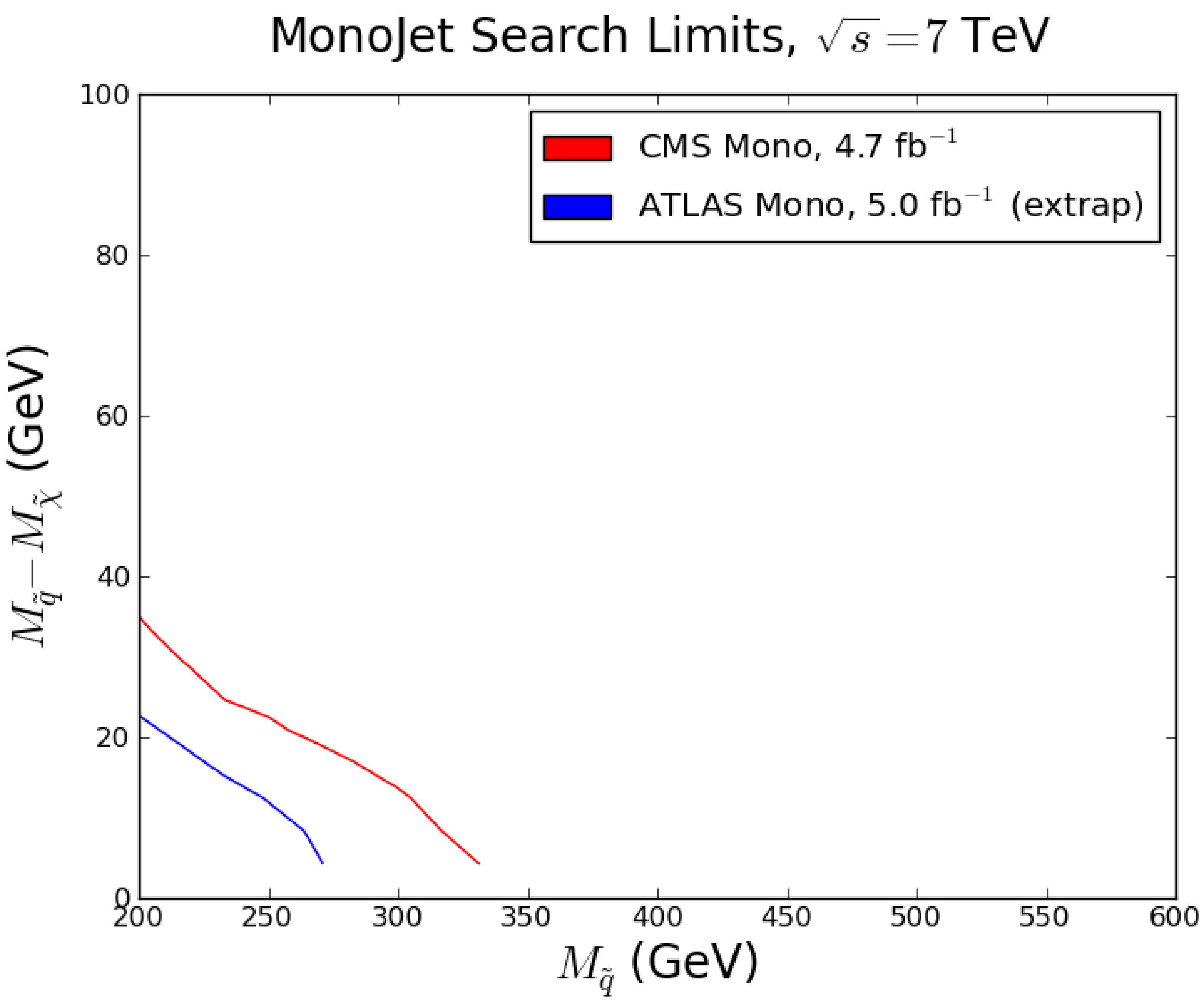


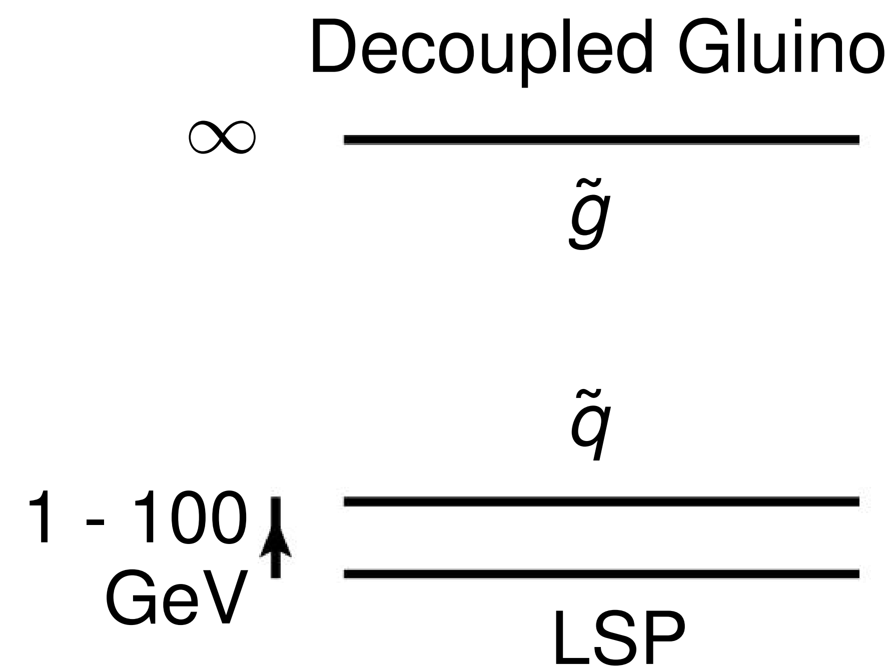


Hard ISR jets are a reasonable price to pay

Process, $m_{\tilde{q}_i}$ = 500 GeV $p_T(j) > 100$ GeV	Xsec (fb)
$pp \to \tilde{q}\tilde{q}$	24
$pp \to \tilde{q}\tilde{q}\ j$	6.6
$pp \to \tilde{q}\tilde{q}\ j\ j$	1.1

Squark limits for compressed spectra





Tattersall, talk @ LHC2TSP, July 2012

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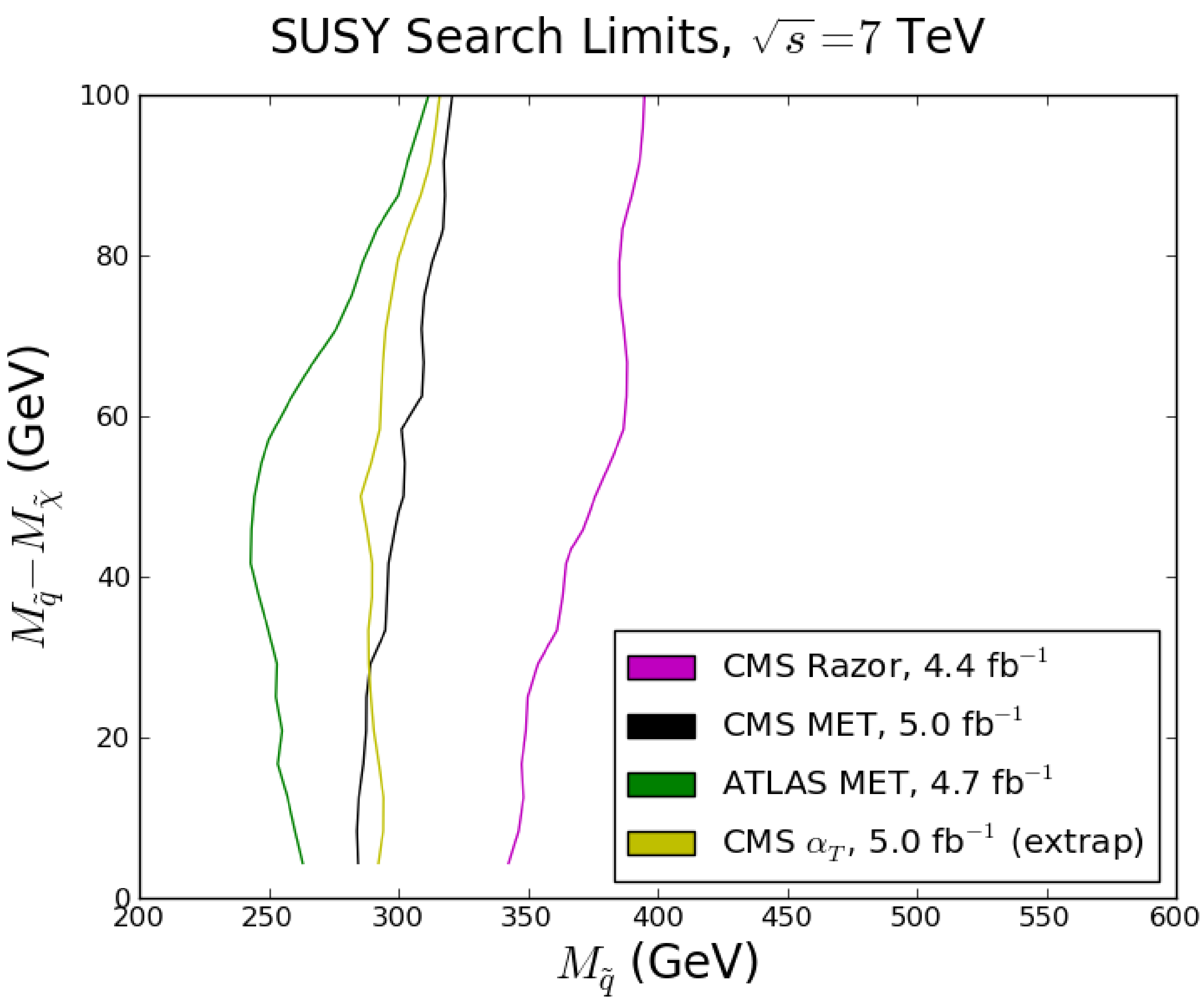

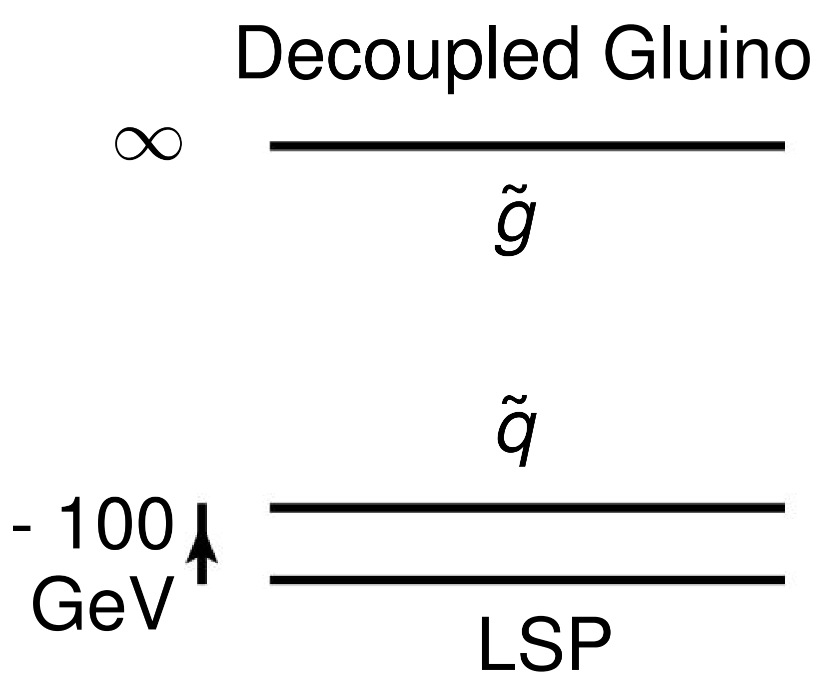

Tattersall, talk @
LHC2TSP, July 2012

While limits are pushed we need to make sure that no stone is left unturned:

- Globally scan SUSY parameter space (e.g. Hewett et al., or Aubrey et al.)
- Focus on theoretically-motivated models first (this talk)

What is the LHC telling you about your favorite Model?

DYI limits

CERN-PH-EP-2011-145

Search for squarks and gluinos using final states with jets and missing transverse momentum with the ATLAS detector in $\sqrt{s} = 7$ TeV proton-proton collisions

The ATLAS Collaboration

Example: jets+ MET

DYI limits

CERN-PH-EP-2011-145

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The ATLAS Collaboration

Example: jets+ MET

Signal Region	$\geq$ 2-jet	$\geq$ 3-jet	$\geq$ 4-jet	High mass
E_T^{miss}	> 130	> 130	> 130	> 130
Leading jet p_T	> 130	> 130	> 130	> 130
Second jet p_T	> 40	> 40	> 40	> 80
Third jet p_T	–	> 40	> 40	> 80
Fourth jet p_T	–	–	> 40	> 80
$\Delta\phi(\text{jet}, \vec{P}_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
E_T^{miss}/m_{eff}	> 0.3	> 0.25	> 0.25	> 0.2
m_{eff}	> 1000	> 1000	$> 500/1000$	> 1100

signal bins

Bgd's are left to the experimentalists…
stay out of control regions!

Process	Signal Region				
	$\geq$ 2-jet	$\geq$ 3-jet	$\geq$ 4-jet, $m_{\mathrm{eff}} > 500$ GeV	$\geq$ 4-jet, $m_{\mathrm{eff}} > 1000$ GeV	High mass
Z/γ+jets	$32.3 \pm 2.6 \pm 6.9$	$25.5 \pm 2.6 \pm 4.9$	$209 \pm 9 \pm 38$	$16.2 \pm 2.2 \pm 3.7$	$3.3 \pm 1.0 \pm 1.3$
W+jets	$26.4 \pm 4.0 \pm 6.7$	$22.6 \pm 3.5 \pm 5.6$	$349 \pm 30 \pm 122$	$13.0 \pm 2.2 \pm 4.7$	$2.1 \pm 0.8 \pm 1.1$
$t\bar{t}$+ single top	$3.4 \pm 1.6 \pm 1.6$	$5.9 \pm 2.0 \pm 2.2$	$425 \pm 39 \pm 84$	$4.0 \pm 1.3 \pm 2.0$	$5.7 \pm 1.8 \pm 1.9$
QCD multi-jet	$0.22 \pm 0.06 \pm 0.24$	$0.92 \pm 0.12 \pm 0.46$	$34 \pm 2 \pm 29$	$0.73 \pm 0.14 \pm 0.50$	$2.10 \pm 0.37 \pm 0.82$
Total	$62.4 \pm 4.4 \pm 9.3$	$54.9 \pm 3.9 \pm 7.1$	$1015 \pm 41 \pm 144$	$33.9 \pm 2.9 \pm 6.2$	$13.1 \pm 1.9 \pm 2.5$
Data	58	59	1118	40	18

Table 2: Fitted background components in each SR, compared with the number of events observed in data. The Z/γ+jets background is constrained with co regions CR1a and CR1b, the QCD multi-jet, W and top quark backgrounds by control regions CR2, CR3 and CR4, respectively. In each case the first (sec quoted uncertainty is statistical (systematic). Background components are partially correlated and hence the uncertainties (statistical and systematic) on the background estimates do not equal the quadrature sums of the uncertainties on the components.

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[5] has improved the ATLAS reach at large m_0. The five signal regions are used to set limits on $\sigma_{new} = \sigma A \epsilon$, for non-SM cross-sections (σ) for which ATLAS has an acceptance A and a detection efficiency of ϵ [44]. The excluded values of σ_{new} are 22 fb, 25 fb, 429 fb, 27 fb and 17 fb, respectively, at the 95% confidence level.

upper bound on signal xsec

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LIMIT!

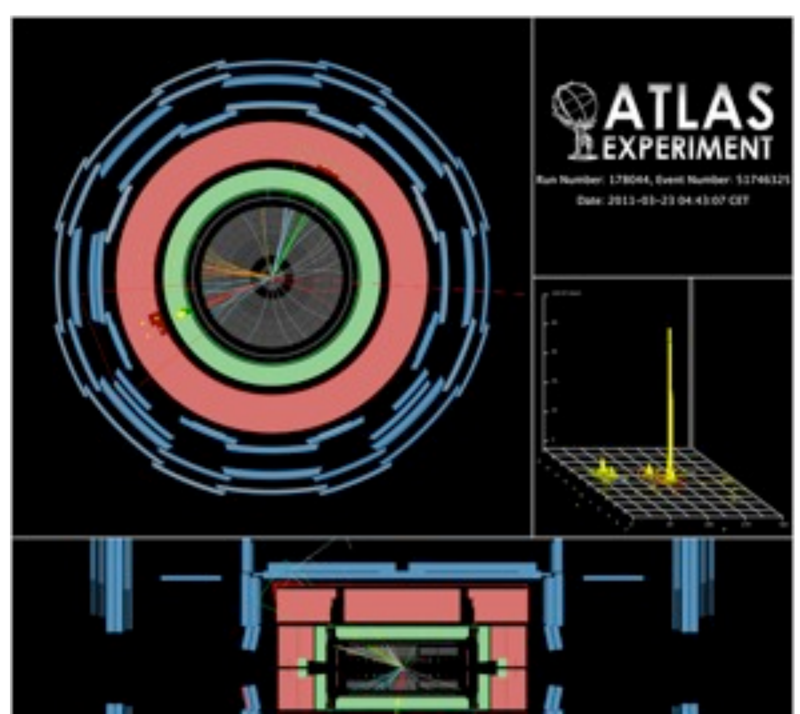
The problem

New Model

?

✓ Viable

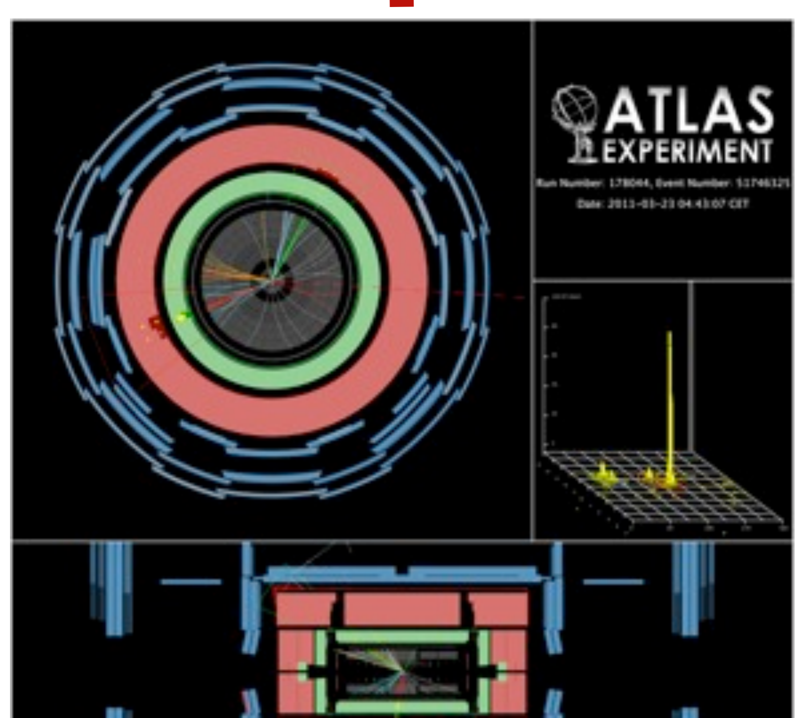
✶ Ruled Out



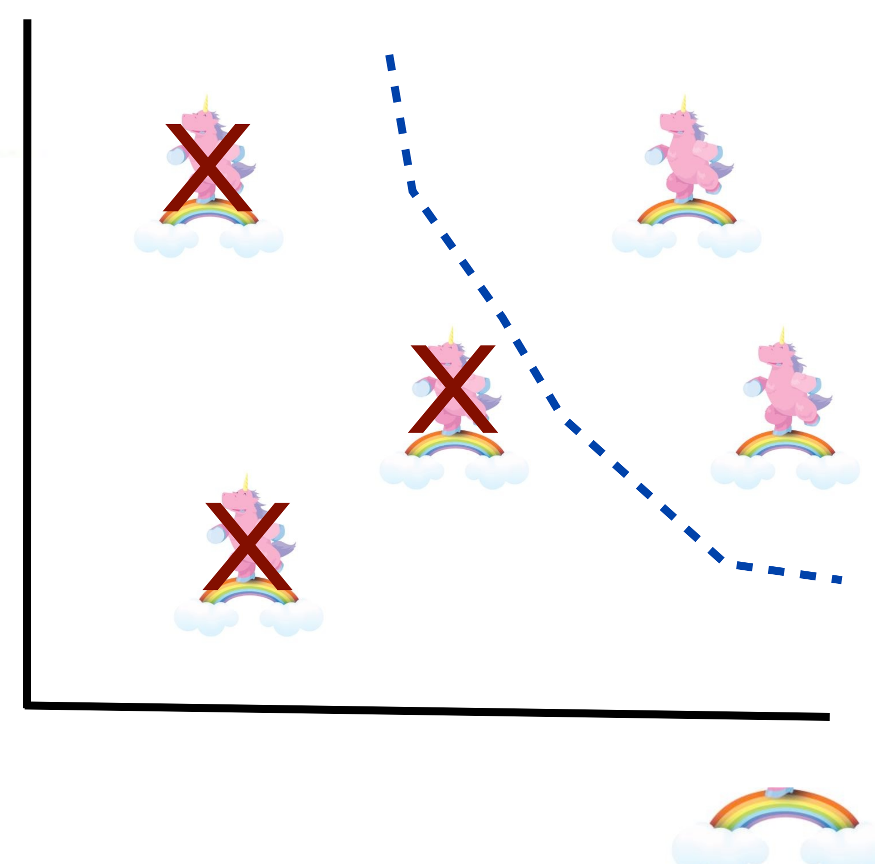
The problem

New Model
($\{c_i\}$)

?



Exclusion
plots in $\{c_i\}$



ATOM

an **A**utomated **T**ester **O**f **M**odels

Public Tool developed by

QCD/Jets: C. Vermillion (Berkeley)

BSM: M. Papucci (Berkeley),
T. Volansky (Tel Aviv), A. Weiler (DESY)

ATOM

pythia / herwig / etc

↓

fastjet

↓

truth leptons / photons /b's

- l/gamma iso
- parameterized efficiencies

+fast-sim

User provides truth level MC events

Atom tells if current analyses exclude model

Checks sensitivity of cut & leakage in control region

Statistics module based on RooFit/RooStats

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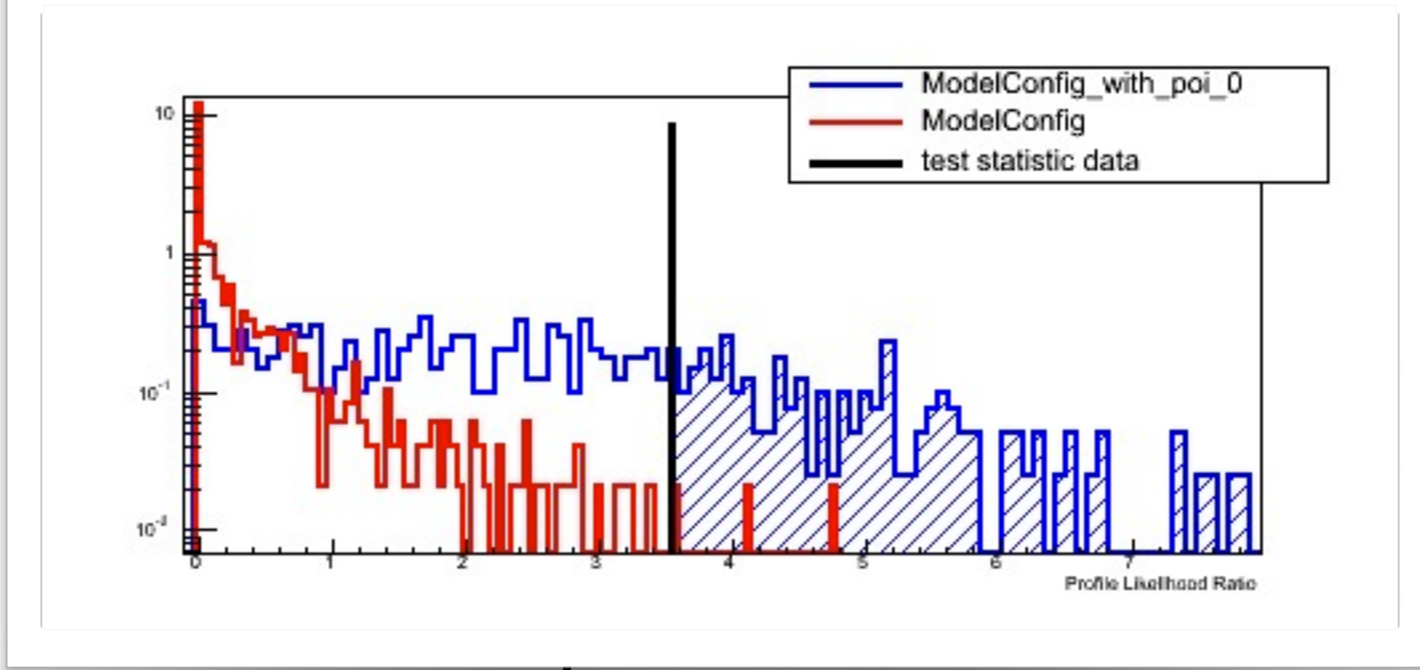

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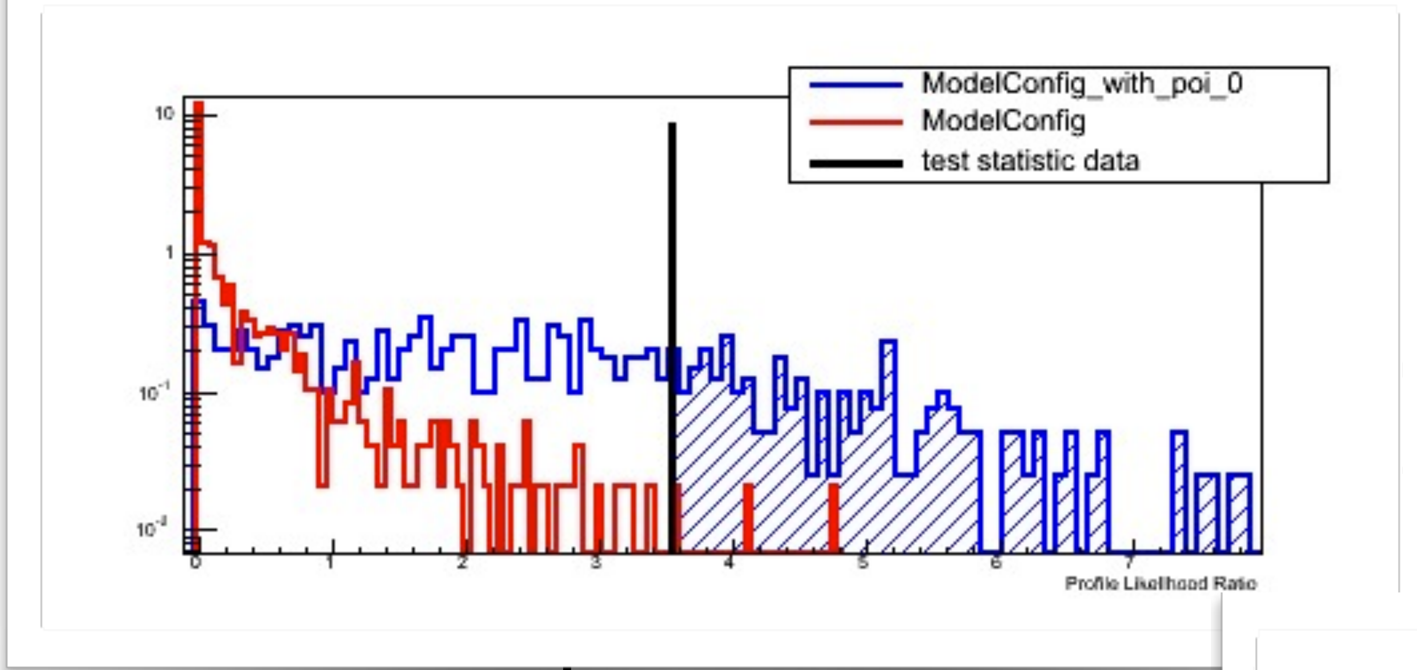

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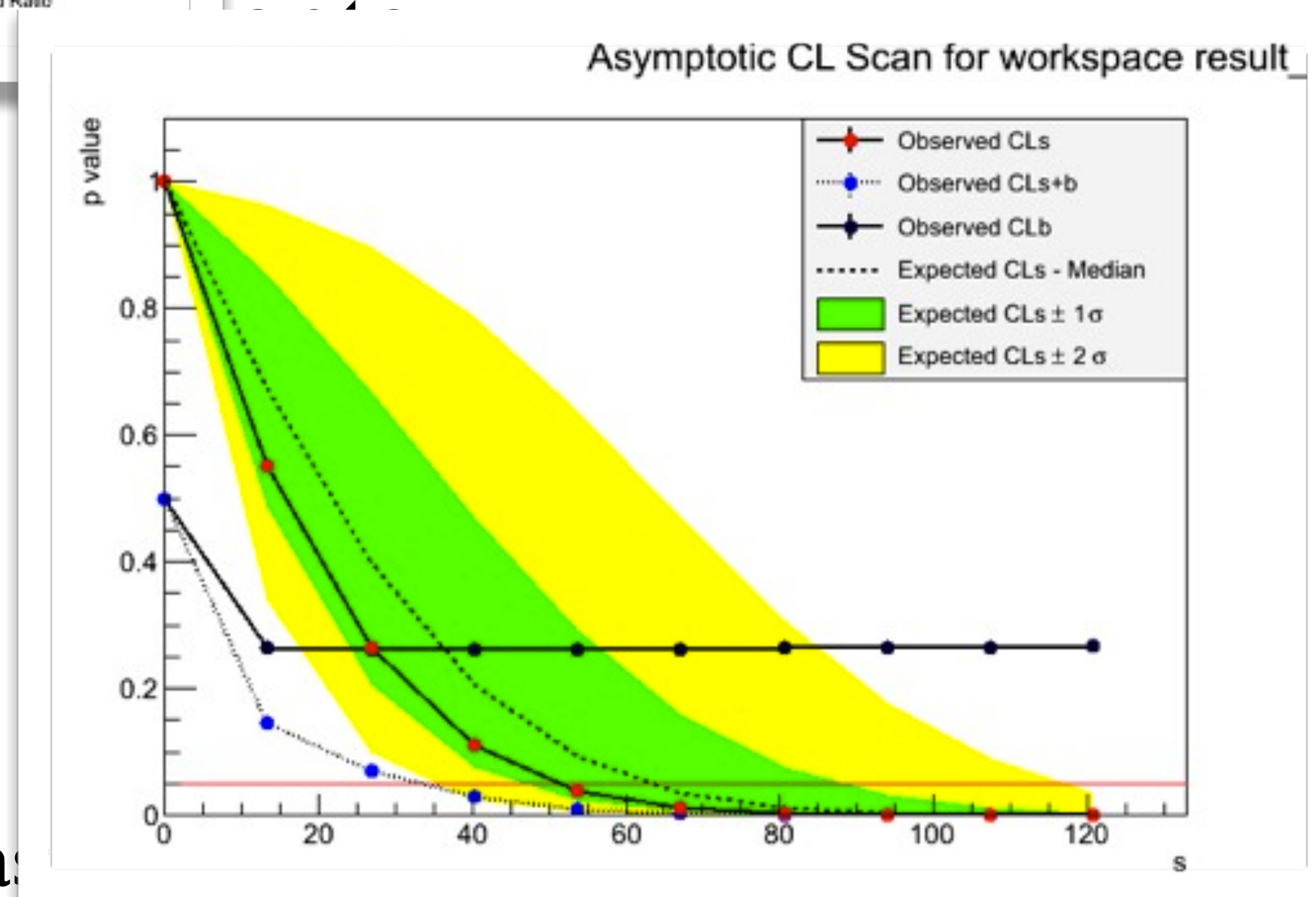


Checks sensitivity of cut & leakage in control region

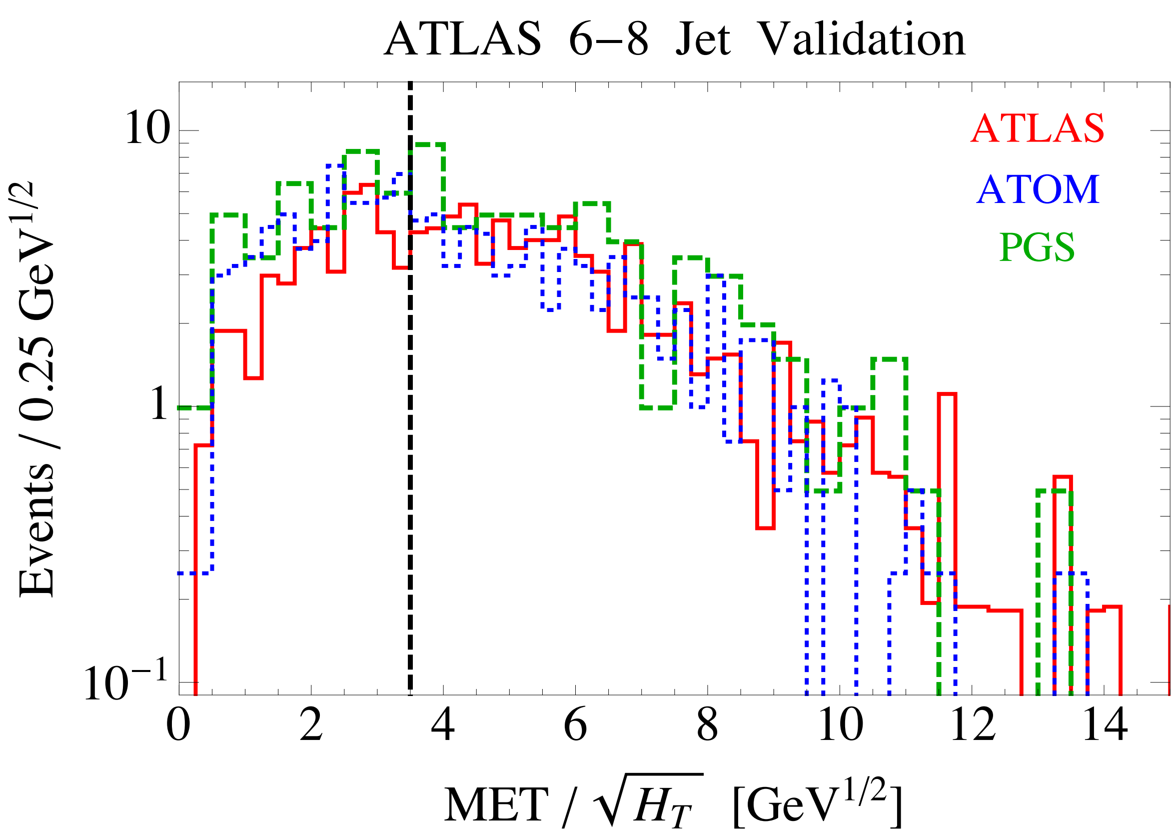
Statistics module based on RooFit/RooStats

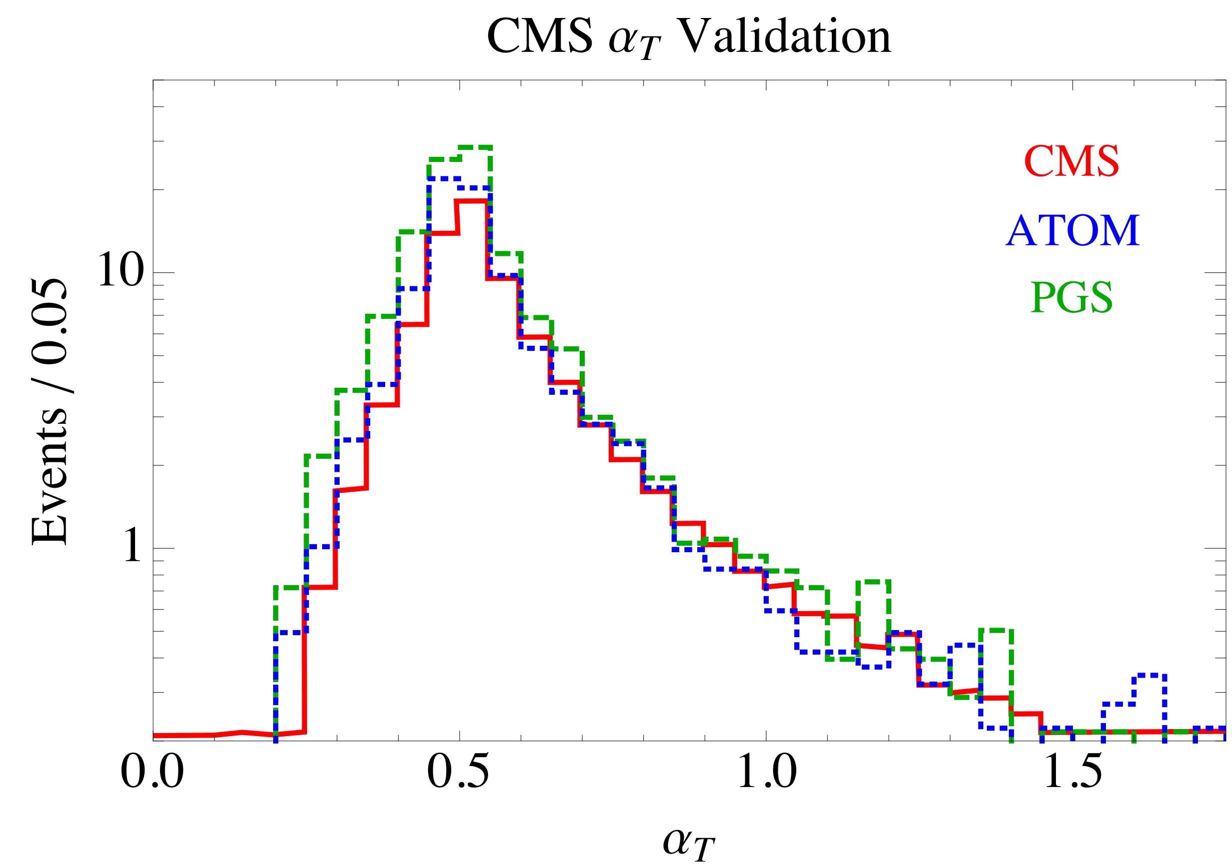
Calibration

"theorist limits"

To calibrate compare:

1) key kinematical distributions
2) limits





Check:

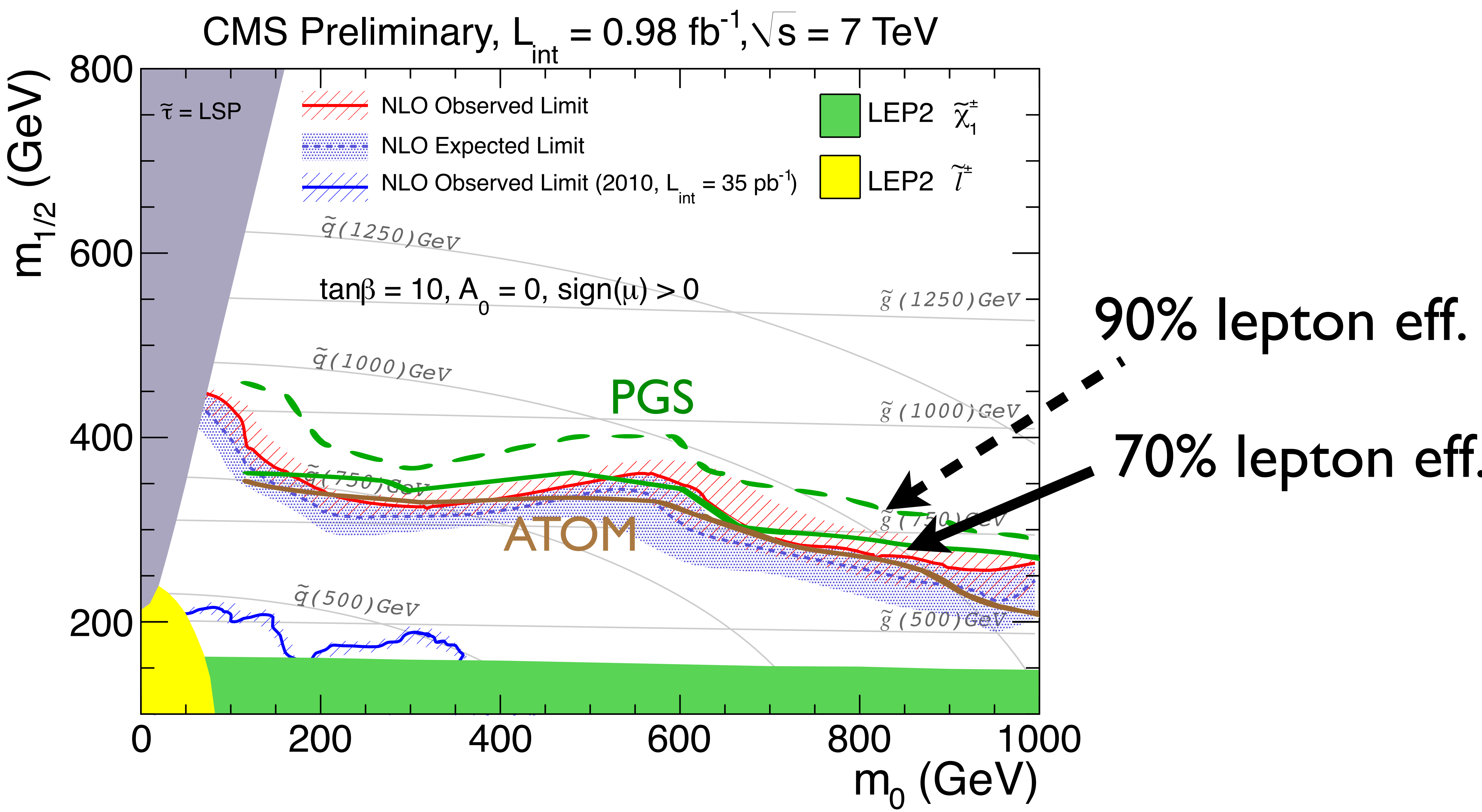
- kinematic distortions (shape)
- signal $\epsilon \times \mathcal{A}$ (normalization)

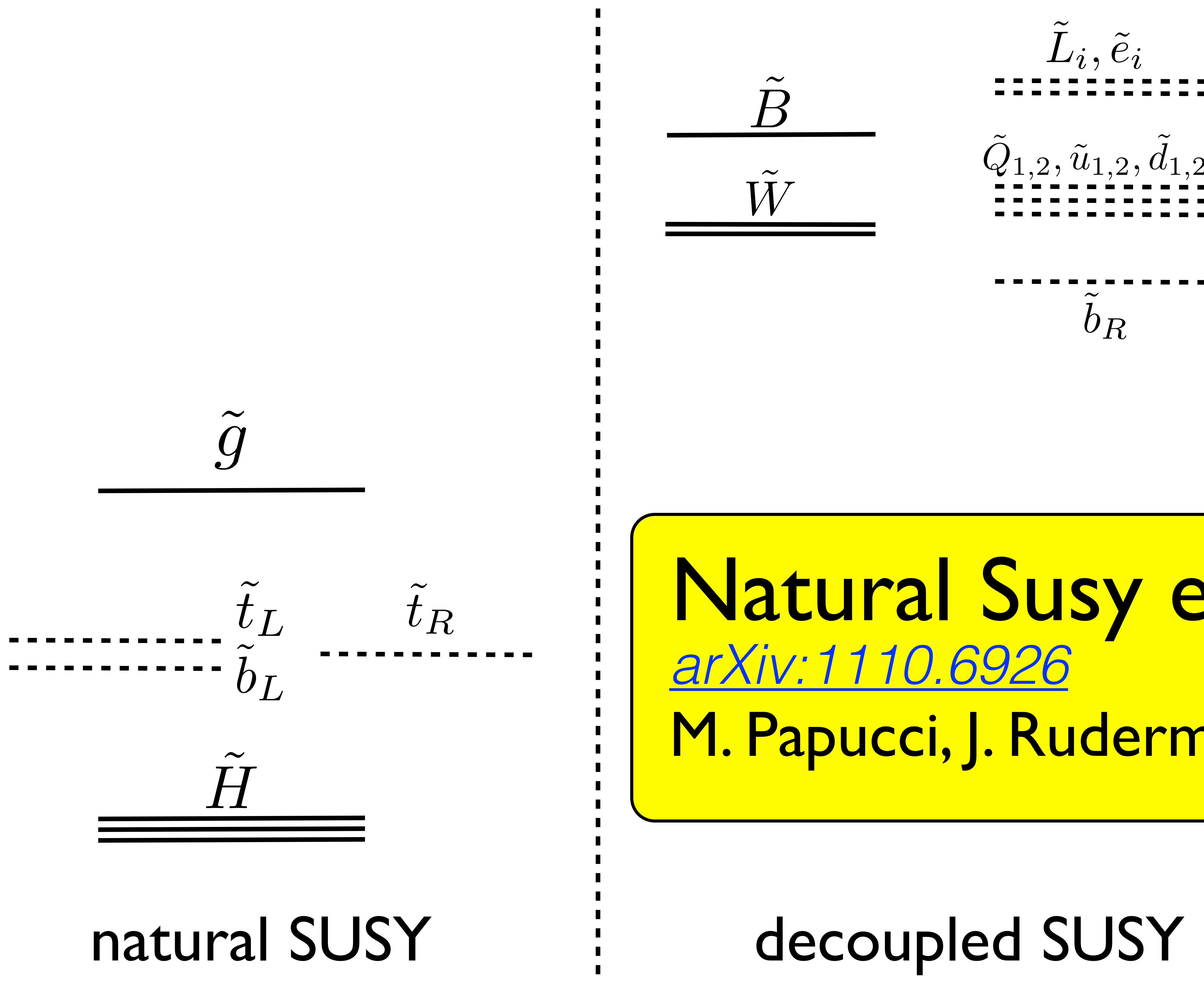
\+ compare to all available limit plots…

~ 50 GeV accuracy (usually better)

Compare limits

Example: Same-Sign dilepton by CMS





Natural Susy endures

arXiv:1110.6926

M. Papucci, J. Ruderman, AW

Natural EWSB & SUSY *

* valid for MSSM,NMSSM, …

Do not want tuning in (Higgs mass)^2

$$\frac{m^2_{Higgs}}{2} = -|\mu|^2 + \ldots + \delta m^2_H$$

Dimopoulos,
Giudice/

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$$\frac{m^2_{Higgs}}{2} = -\boxed{|\mu|^2} + \ldots + \boxed{\delta m^2_H}$$

Higgsinos

1loop $\boxed{\delta m^2_H|_{stop}} = -\frac{3}{8\pi^2} y_t^2 \left(\underline{m^2_{U_3} + m^2_{Q_3} + |A_t|^2}\right) \log\left(\frac{\Lambda}{\text{TeV}}\right)$

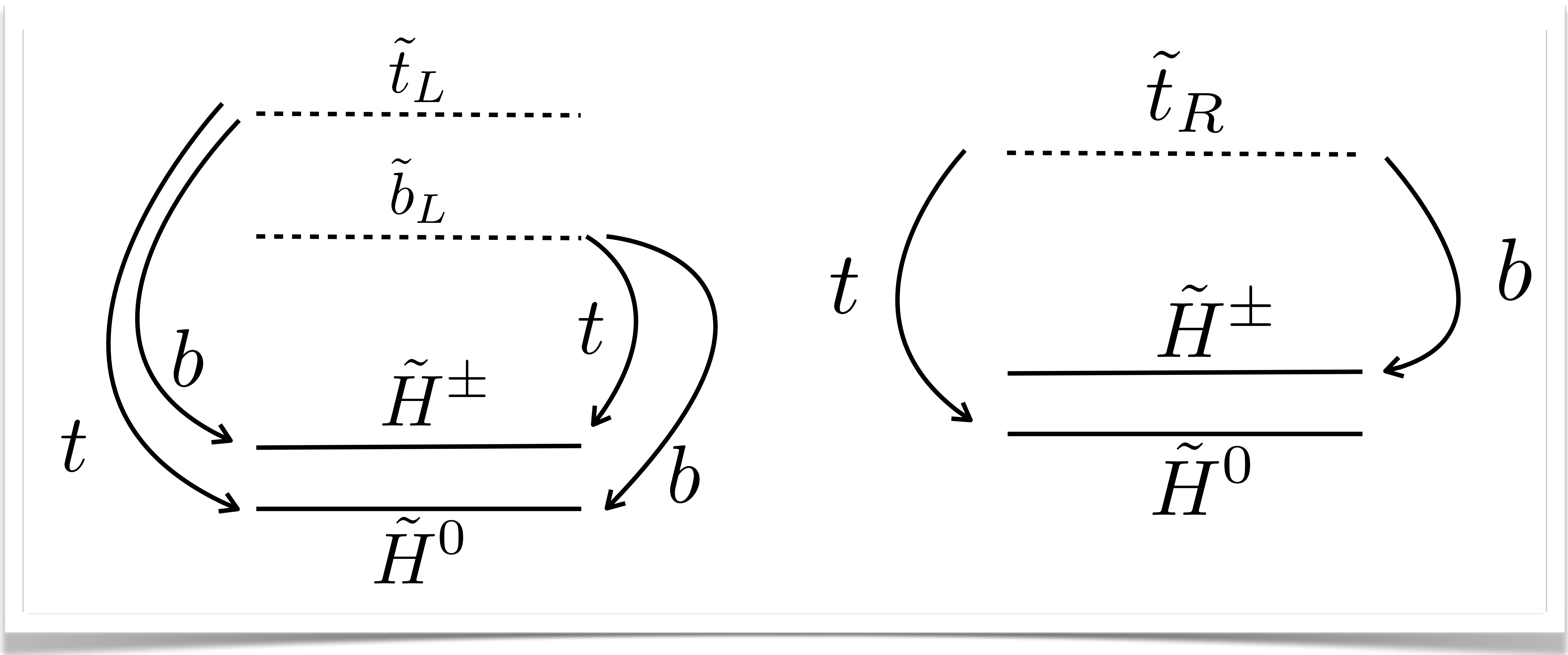
stops, sbottom$_L$

2loop $\boxed{\delta m^2_H|_{gluino}} = -\frac{2}{\pi^2} y_t^2 \left(\frac{\alpha_s}{\pi}\right) \underline{|M_3|^2} \log^2\left(\frac{\Lambda}{\text{TeV}}\right)$

gluino

Dimopoulos, Giudice/

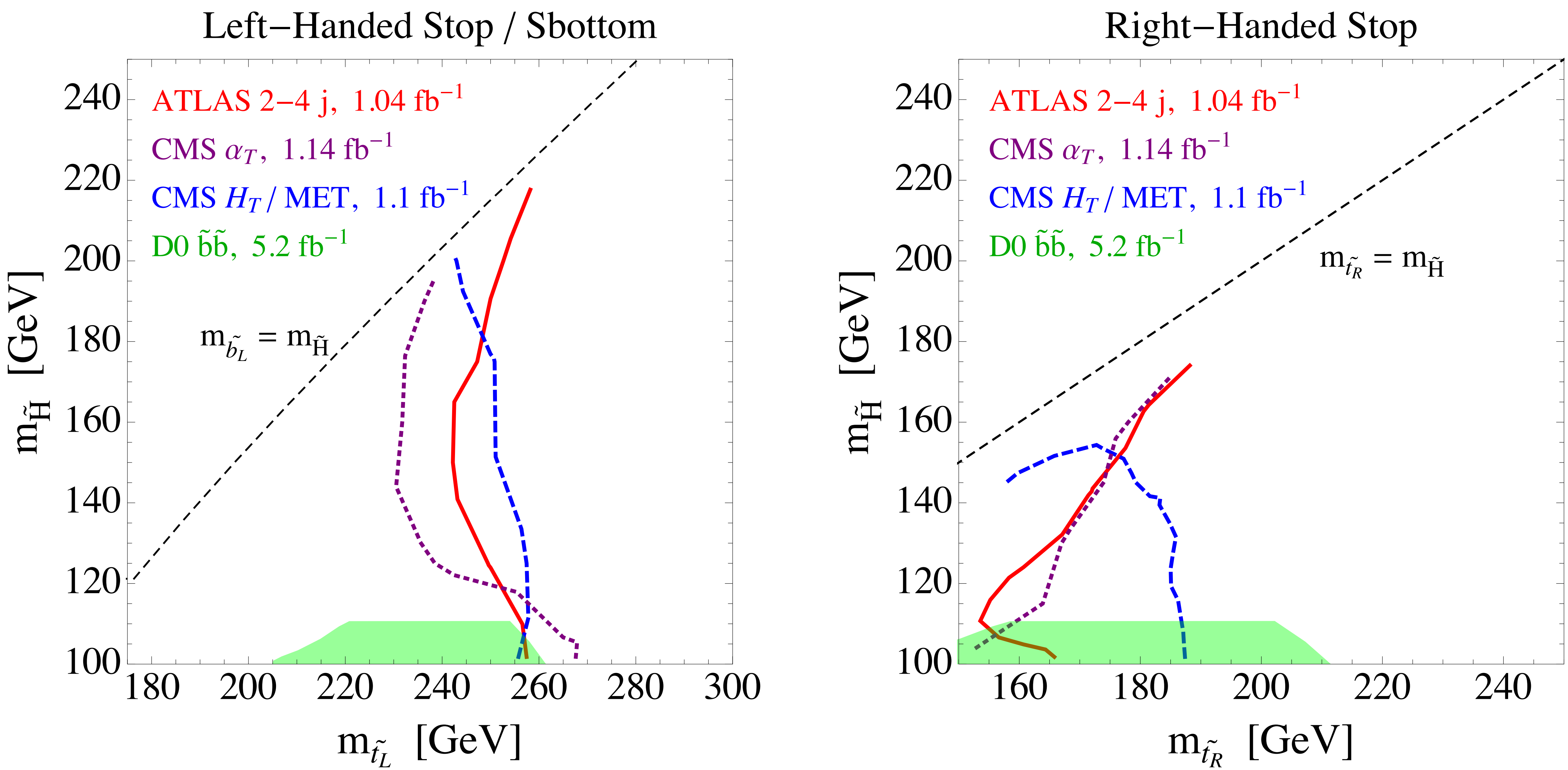
Stops (sbottom) + Higgsinos



Stops can act as "sbottom" (bjet+χ) !

Chargino-neutralino splitting irrelevant for present searches

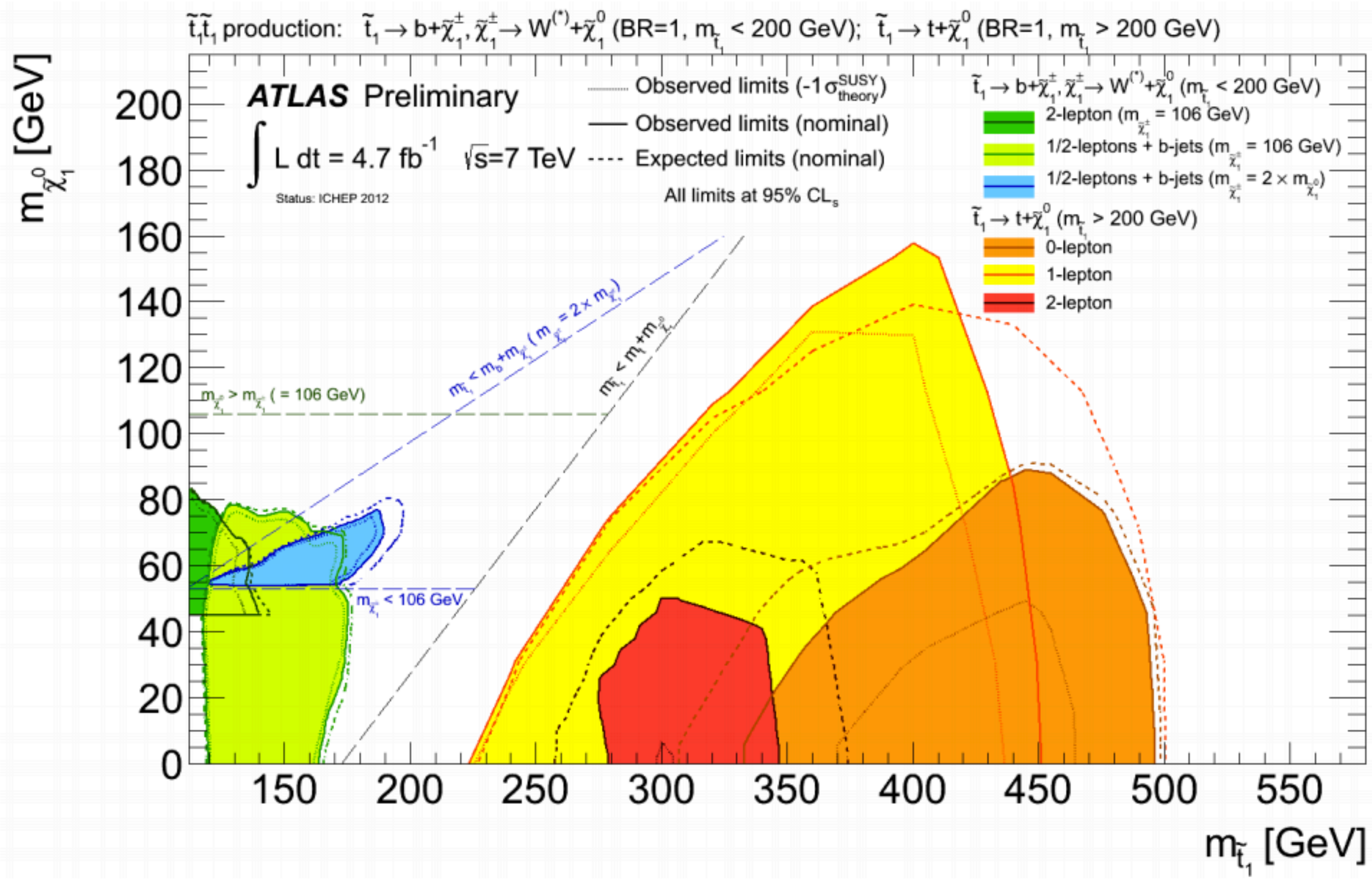
Stops (sbottom) + Higgsinos



LHC surpasses Tevatron:

Strongest bounds from jets + MET

First Results for Direct Stop Production



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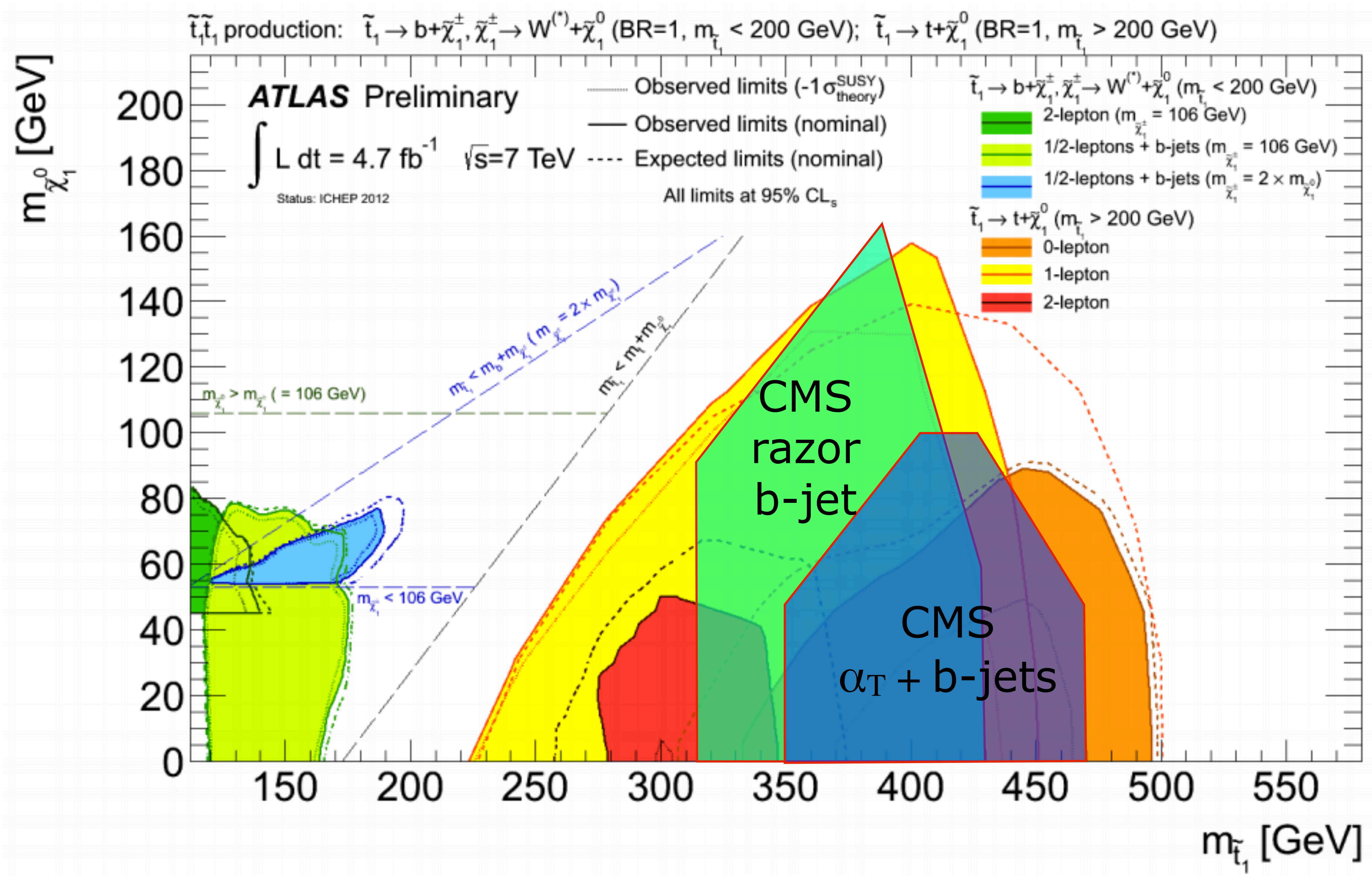


Any caveats beyond that?

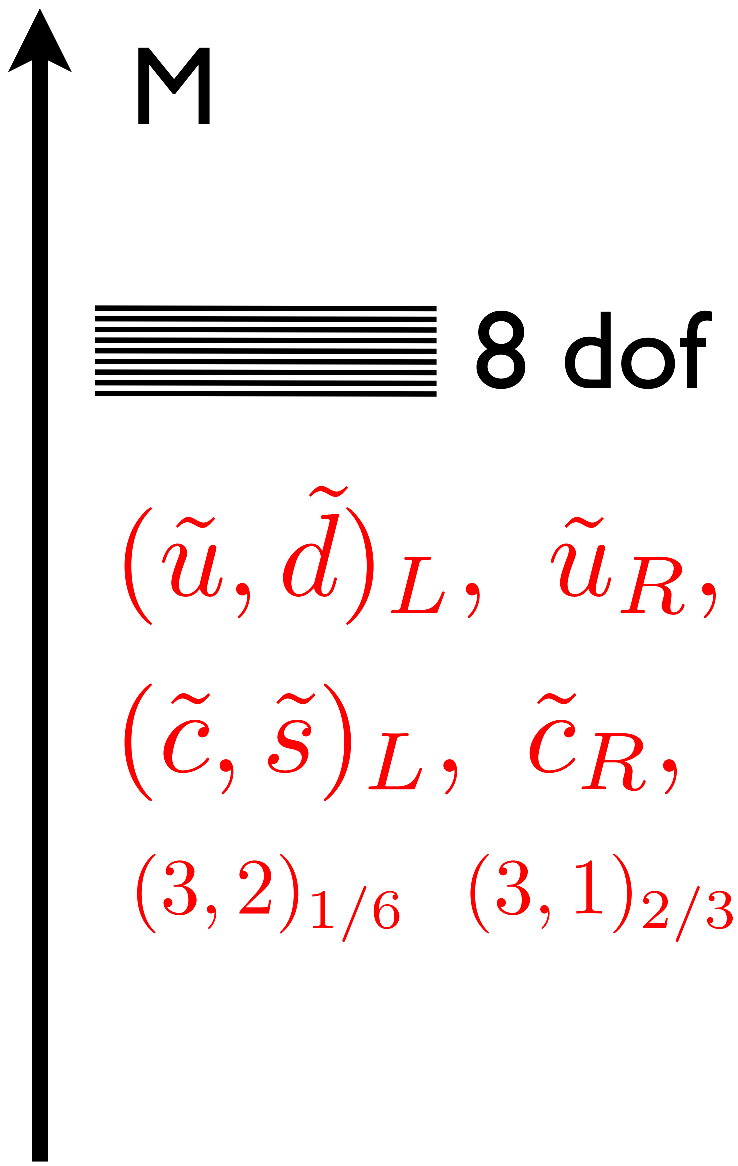
We have already seen that a 1-2 vs. 3 splitting (natural susy) leads to weaker constraints:

- What if there is a splitting in 1-2 sector?
- Not covered even in most exhaustive scans: pMSSM assumes 1-2 degeneracy, all of the constrained MSSMs (CMSSM, …) obviously assume 1-2 degeneracy

Degenerate squarks?

work in progress with
Michele Papucci, Josh Ruderman *(LBL Berkely)*
Gilad Perez, Rakhi Mahbubani *(CERN)*

Do the 1st & 2nd gen' squarks have to be degenerate?



$$(\tilde{u}, \tilde{d})_L, \ \tilde{u}_R, \ \tilde{d}_R,$$

$$(\tilde{c}, \tilde{s})_L, \ \tilde{c}_R, \ \tilde{s}_R$$

$$(3,2)_{1/6} \quad (3,1)_{2/3} \ (3,1)_{-1/3}$$

- Because of flavor constraints? Not really.

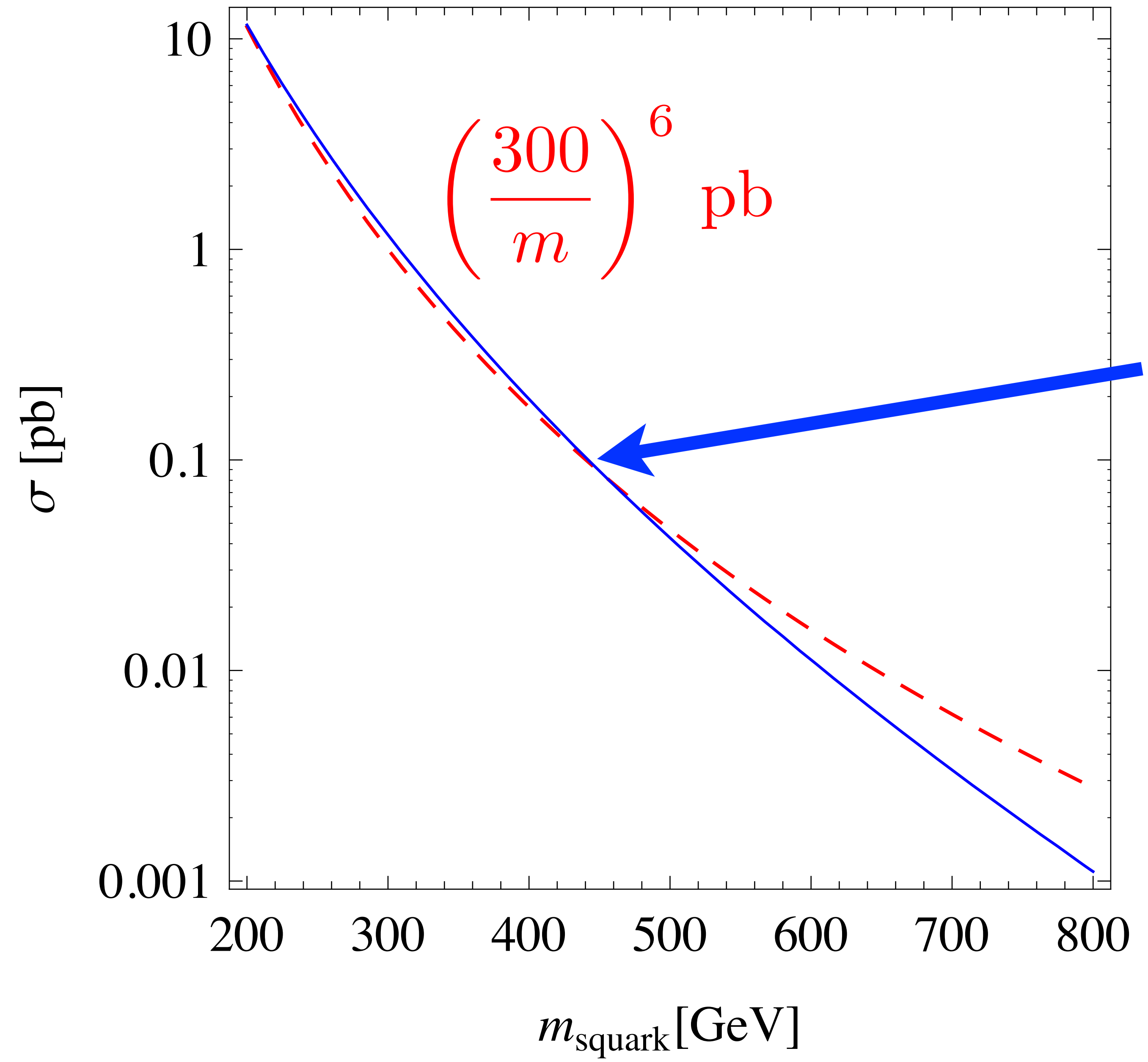
Assumed spectrum in ATLAS/CMS plots

Does it matter if we relax the degeneracy assumption?

Naive answer: not so much.

Cross-sections vs. mass

$$\sigma(pp \to \tilde{u}_R \tilde{u}_R^*) \propto \frac{1}{m^6}$$ (roughly)



NLO xsec (Prospino)

(gluino decoupled)

Back of the envelope estimate

Cross-sections roughly scale like ~1/m^6.

Example: 8 light squarks → 2 light squarks

Shift limit only by $\sim 4^{1/6} - 1 \approx 25\%$

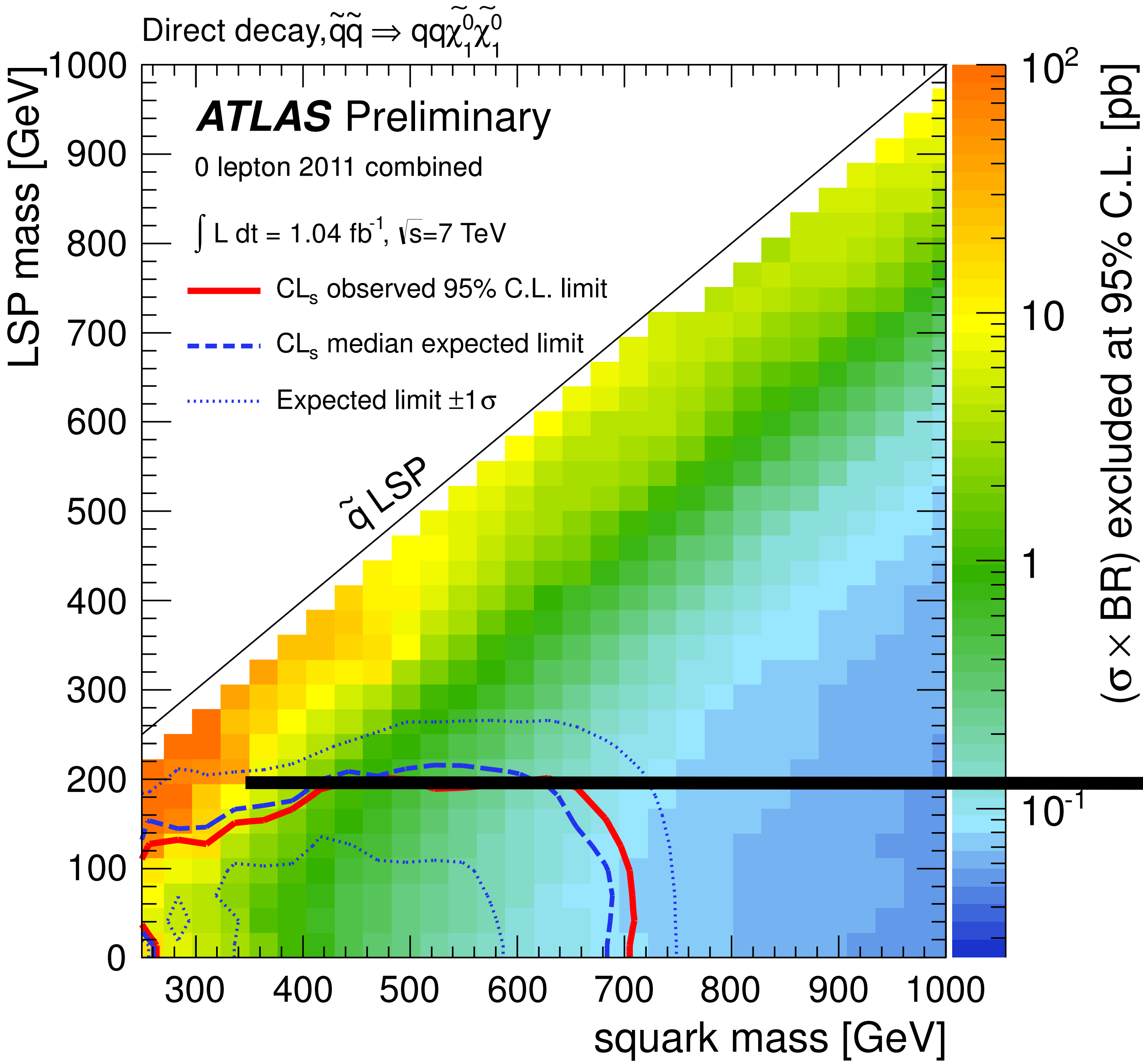
→ **too naive!**

Dedicated study needed

- Production cross-section can be flavor dependent if gluino is not fully decoupled through p.d.f's (u vs. d, sea vs. valence)
- Experimental efficiencies for light squarks efficiencies have thresholds and current limits are on the thresholds

Efficiencies

Searches might become inefficient for light squarks

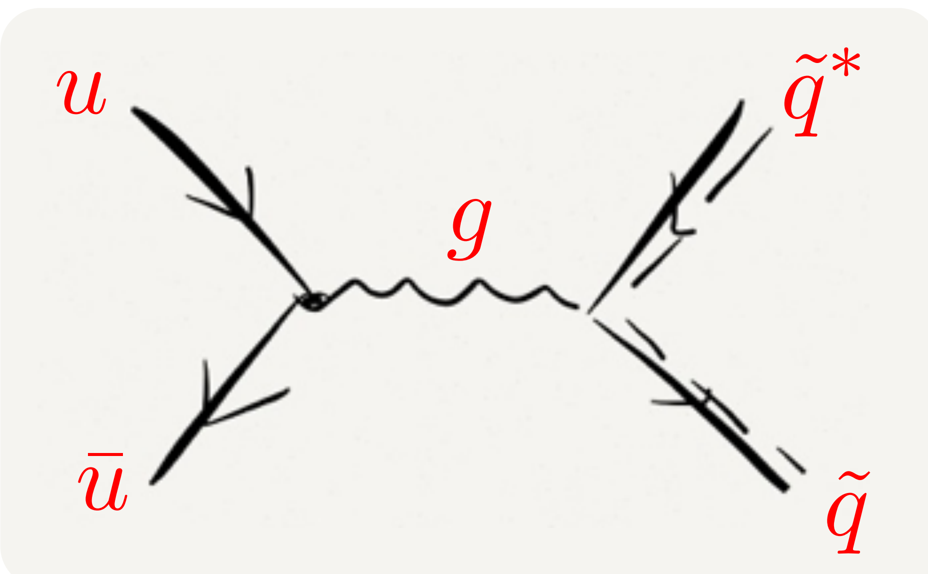


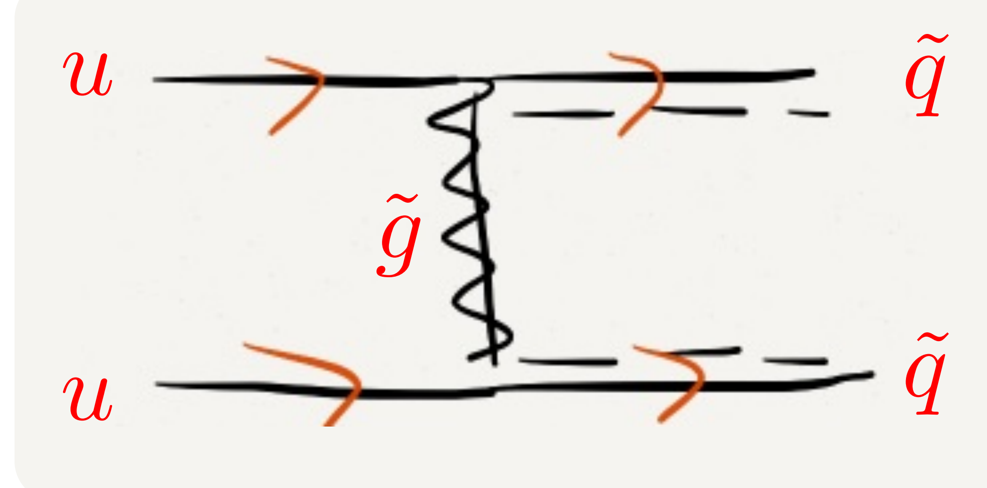
$$\sigma \times A \times \epsilon \approx const.$$

What is driving the strong ATLAS/CMS limit?

Squark - Squark production:

Majorana nature of gluino allows **u u** initial state!





Independent of squark flavor (and gluino mass)

$$\frac{1}{m_{\tilde{g}}}\tilde{q}\tilde{q}\,u_R u_R$$ dim5 op.

$$\rightarrow \quad \sigma \sim 1/m_{\tilde{g}}^2$$

Simple d.o.f rescaling

slow decoupling

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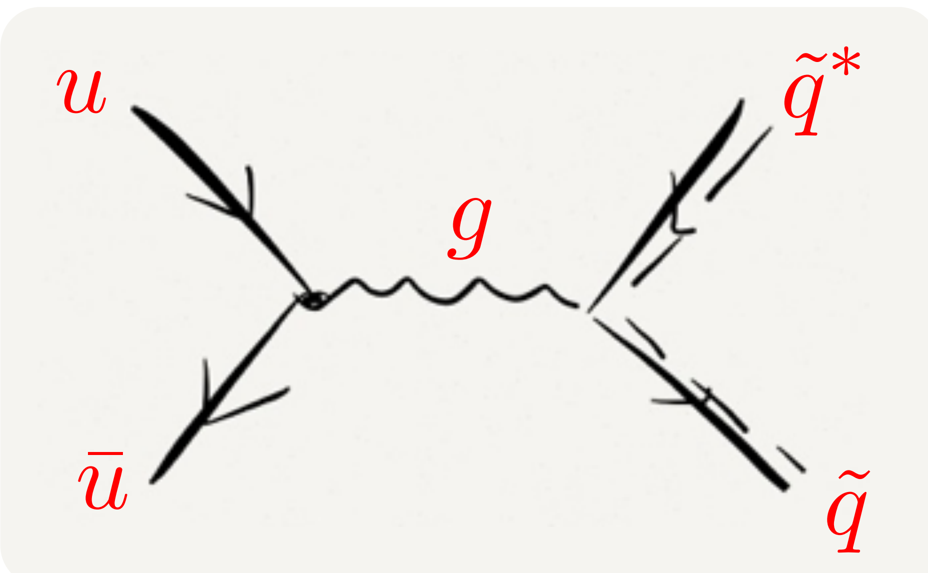

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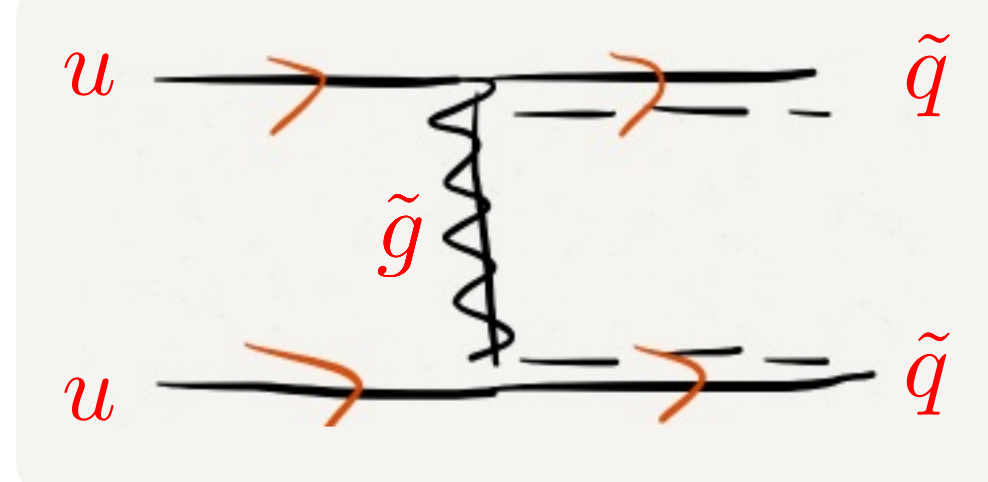

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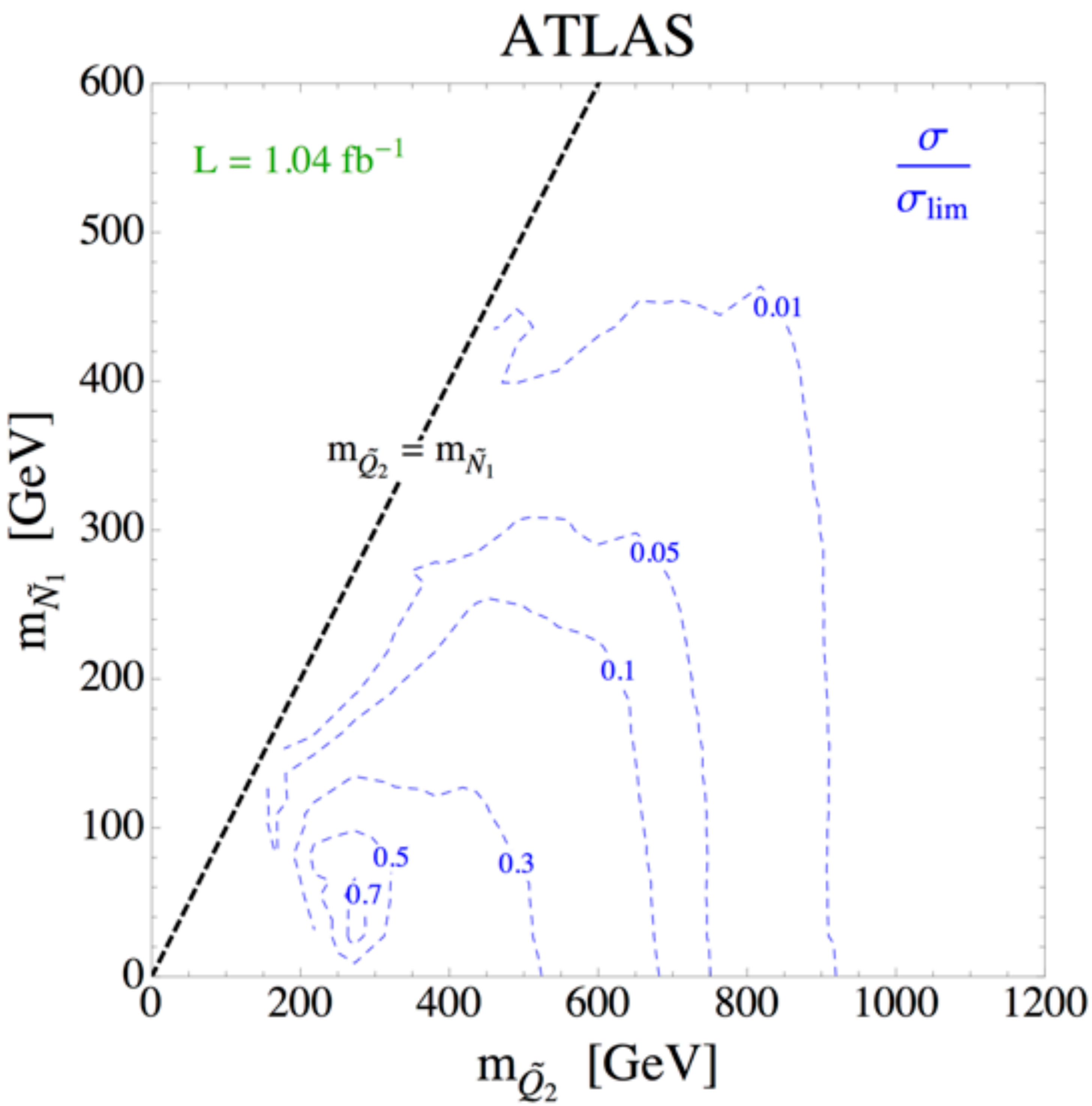
slow decoupling

Aligned sea squark

$$
\begin{array}{llll}
 & \tilde{Q}_1 & \tilde{Q}_2 & \tilde{Q}_3 \\
\text{Squarks} & \begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix} & \boxed{\begin{pmatrix} \tilde{c}_L \\ \tilde{s}_L \end{pmatrix}} & \begin{pmatrix} \tilde{t}_L \\ \tilde{b}_L \end{pmatrix} \\
 & \tilde{u}_R & \tilde{c}_R & \tilde{t}_R \\
 & \tilde{d}_R & \tilde{s}_R & \tilde{b}_R
\end{array}
$$

2 d.o.f

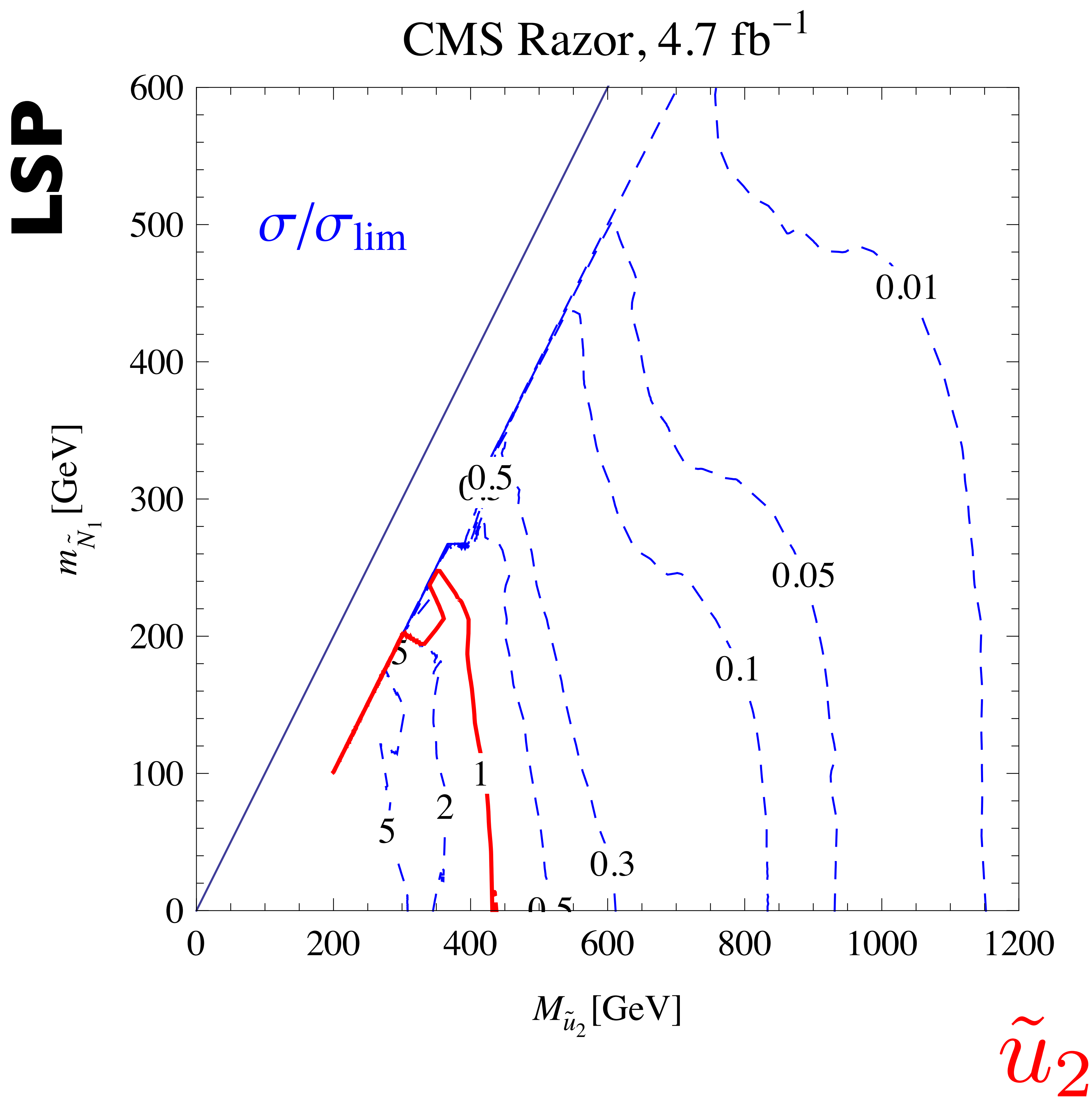
No limit on LH 2nd gen' squark*



* Pre-ICHEP

No bounds for Q_2 in 1/fb of data
(decoupled gluinos at 3TeV)

Post-ICHEP limit on sea squark



Outlook

- The 125 GeV Higgs is a challenge and a great opportunity for supersymmetry
- Precision Higgs physics might reveal hints for new physics
- 'Vanilla susy' pushed beyond TeV scale
- Natural susy evades stringent bounds, will go to m_{stop} ~ 500 GeV at the end of this run, gluino limits becoming worrisome
- Leave no stone unturned: The LHC won't tell us if don't ask the right questions.