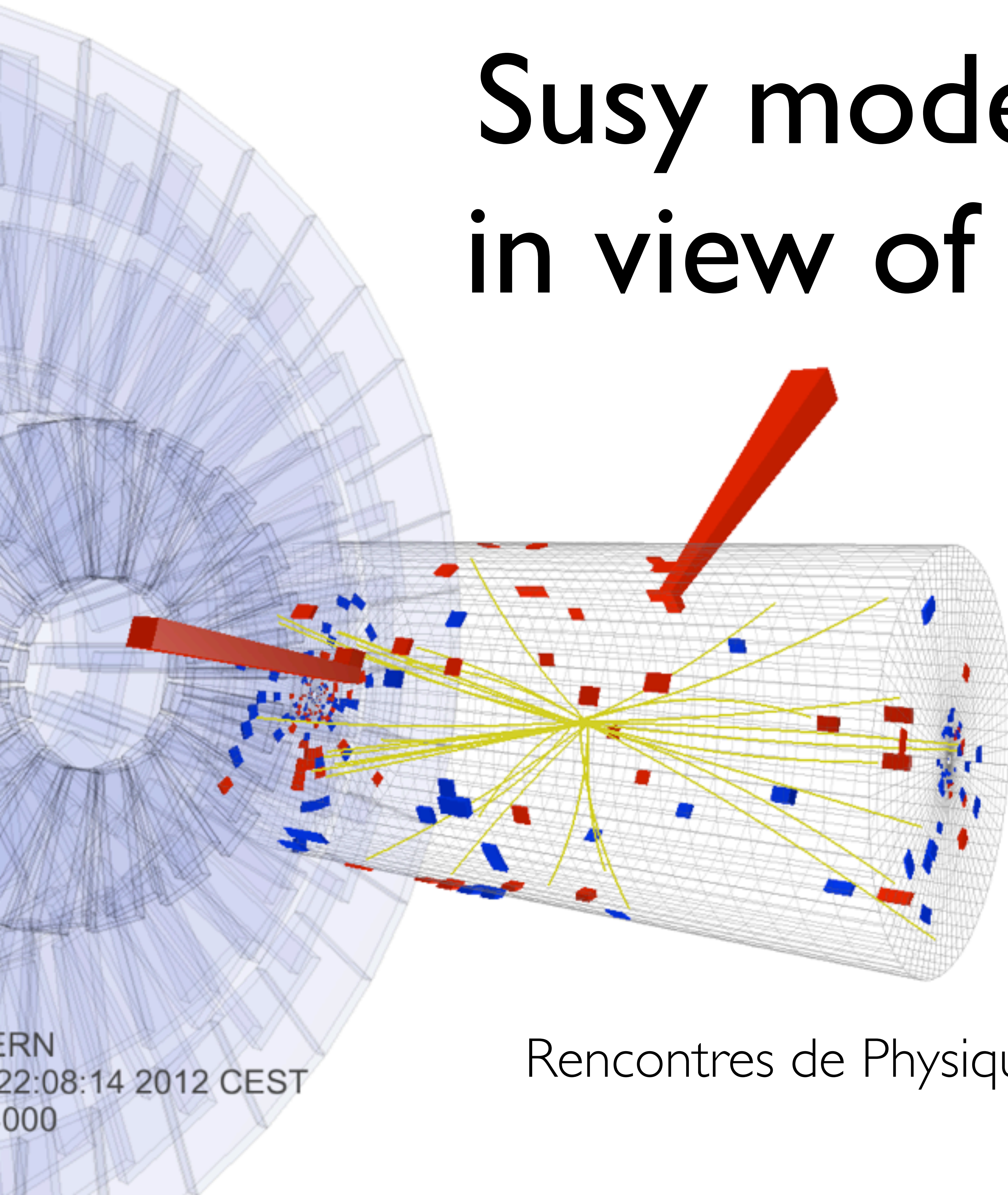
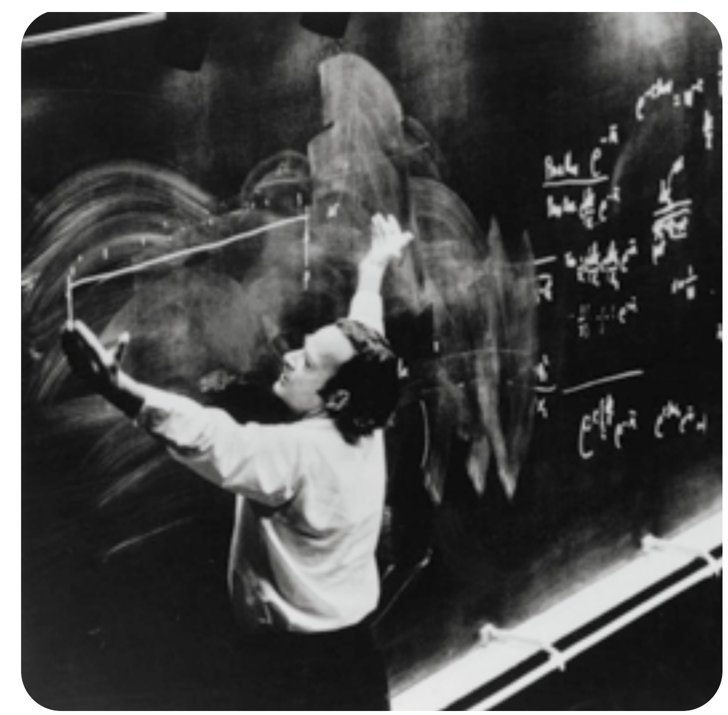
Susy model-building in view of LHC data

Andreas Weiler
(DESY)

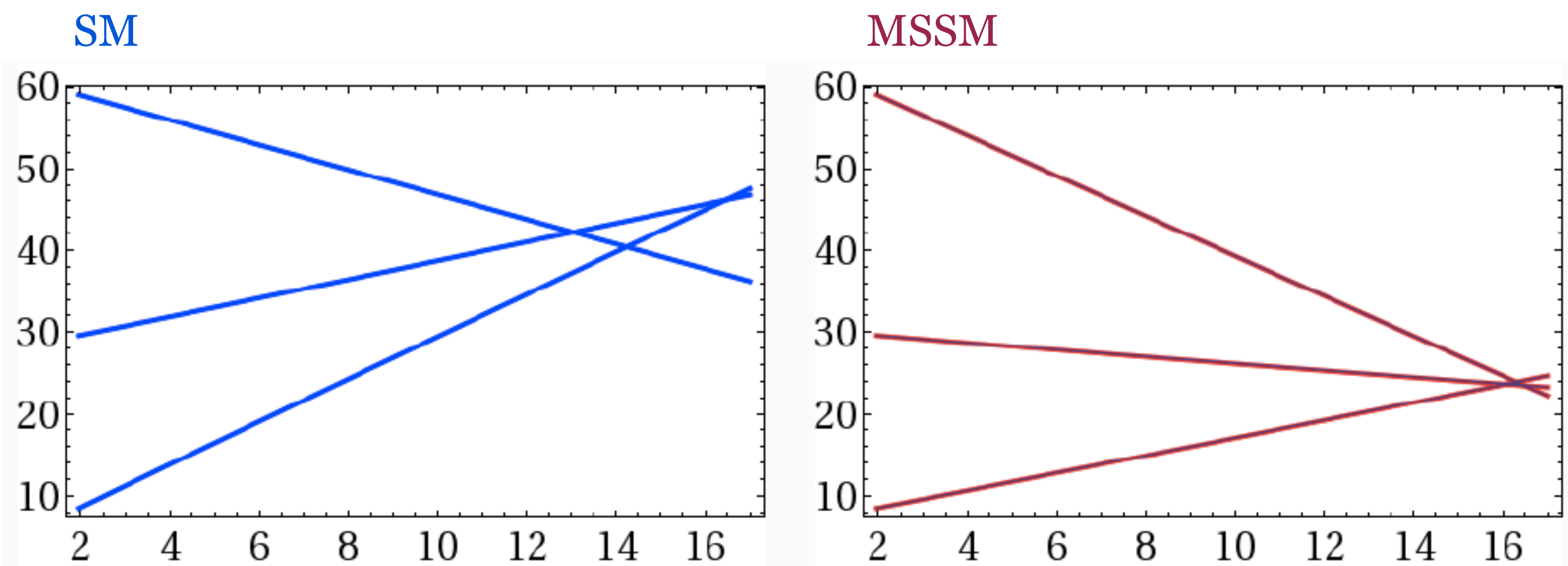




Rencontres de Physique de la Vallée d'Aoste
2013-3-1

A hint?

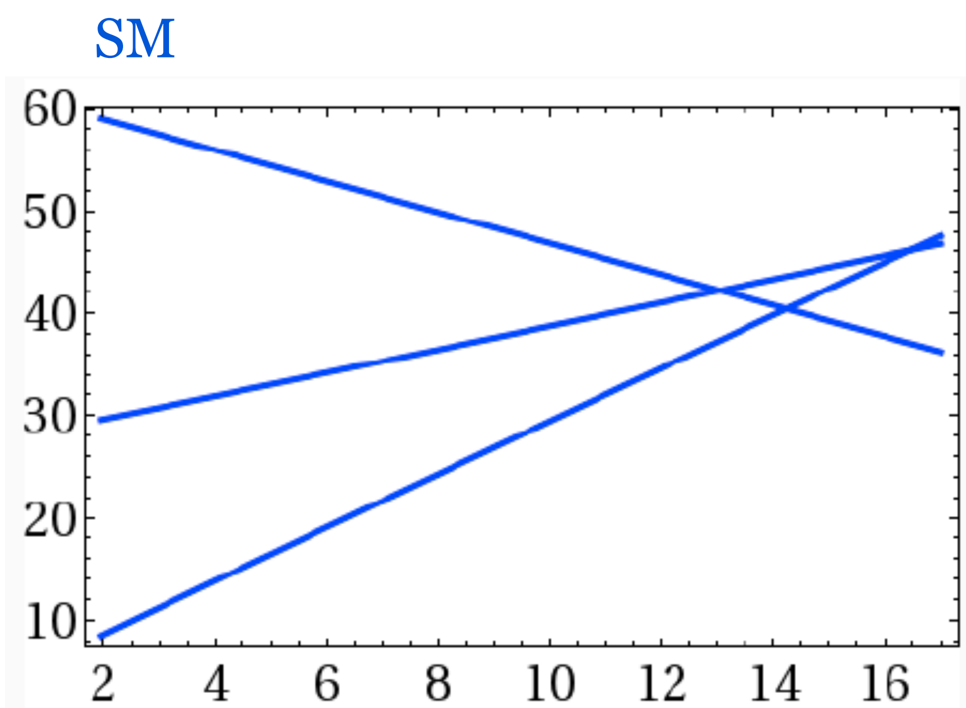
gauge coupling running at 2 loops

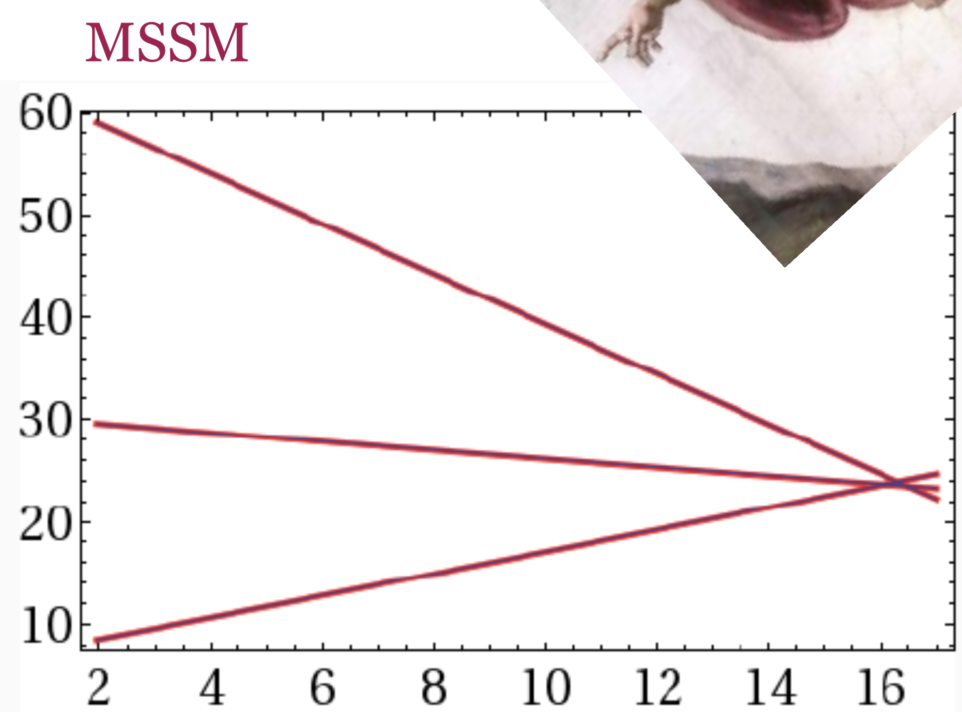


Unification below Planck scale,
high enough for proton stability

A hint?

gauge coupling running at 2 loops





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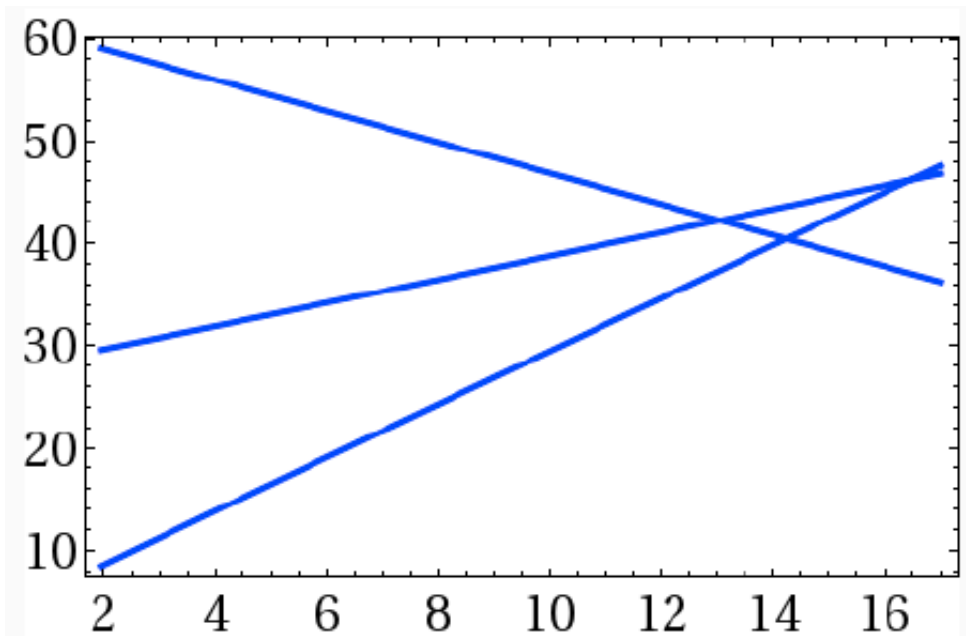
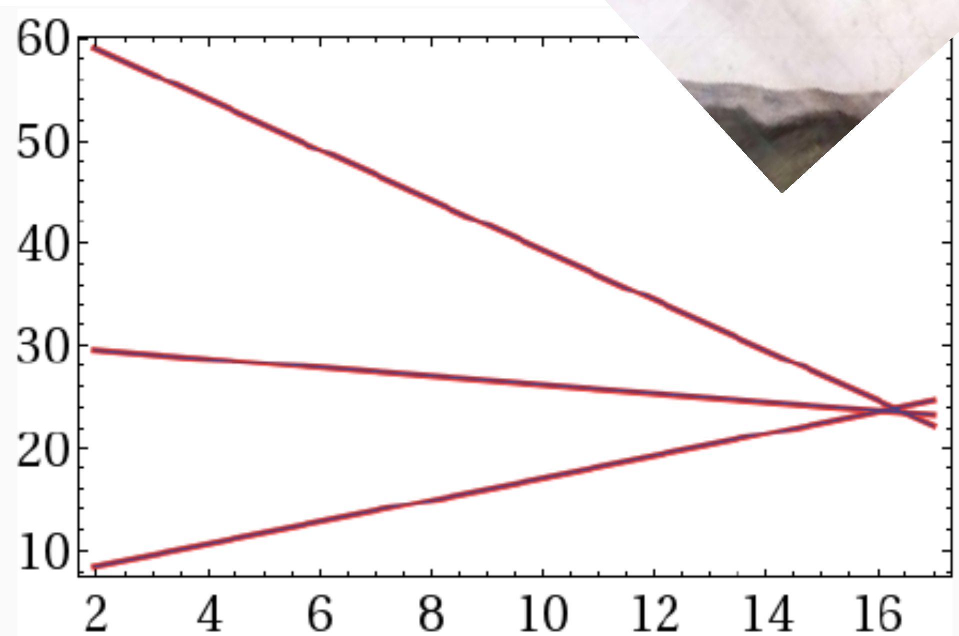
SM



MSSM



Unification below Planck scale,
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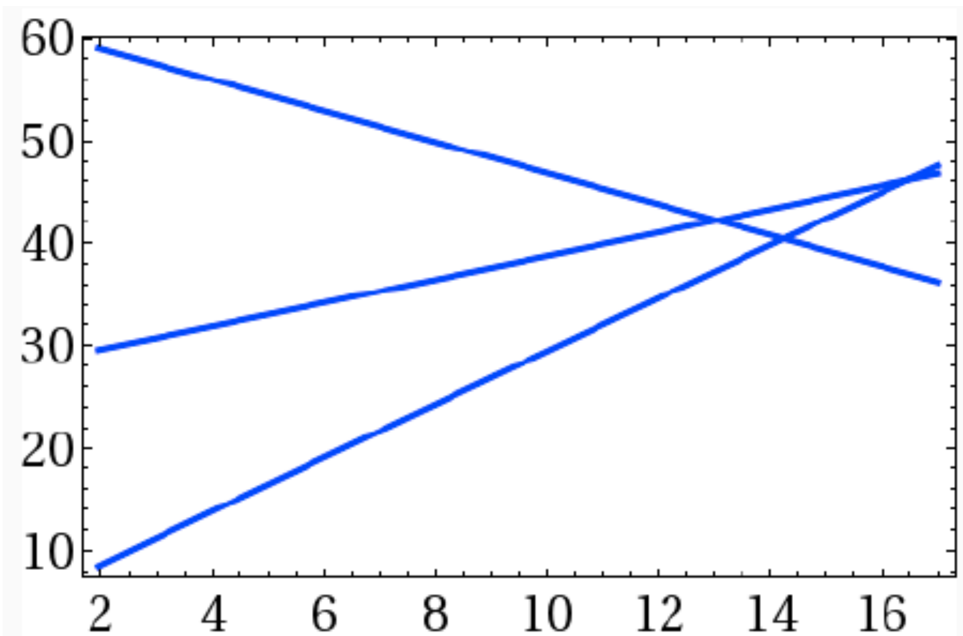
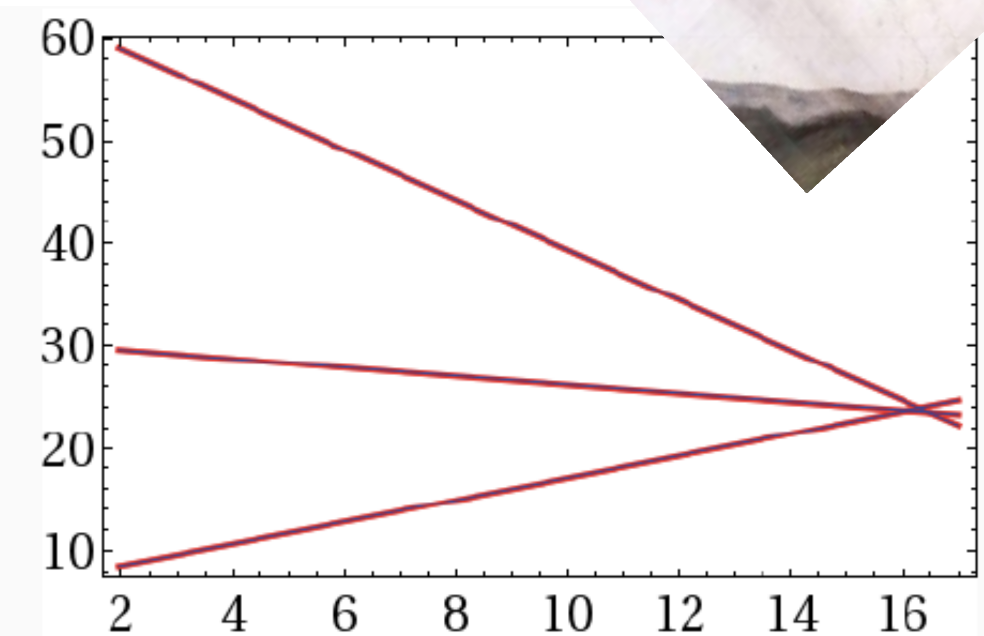


MSSM

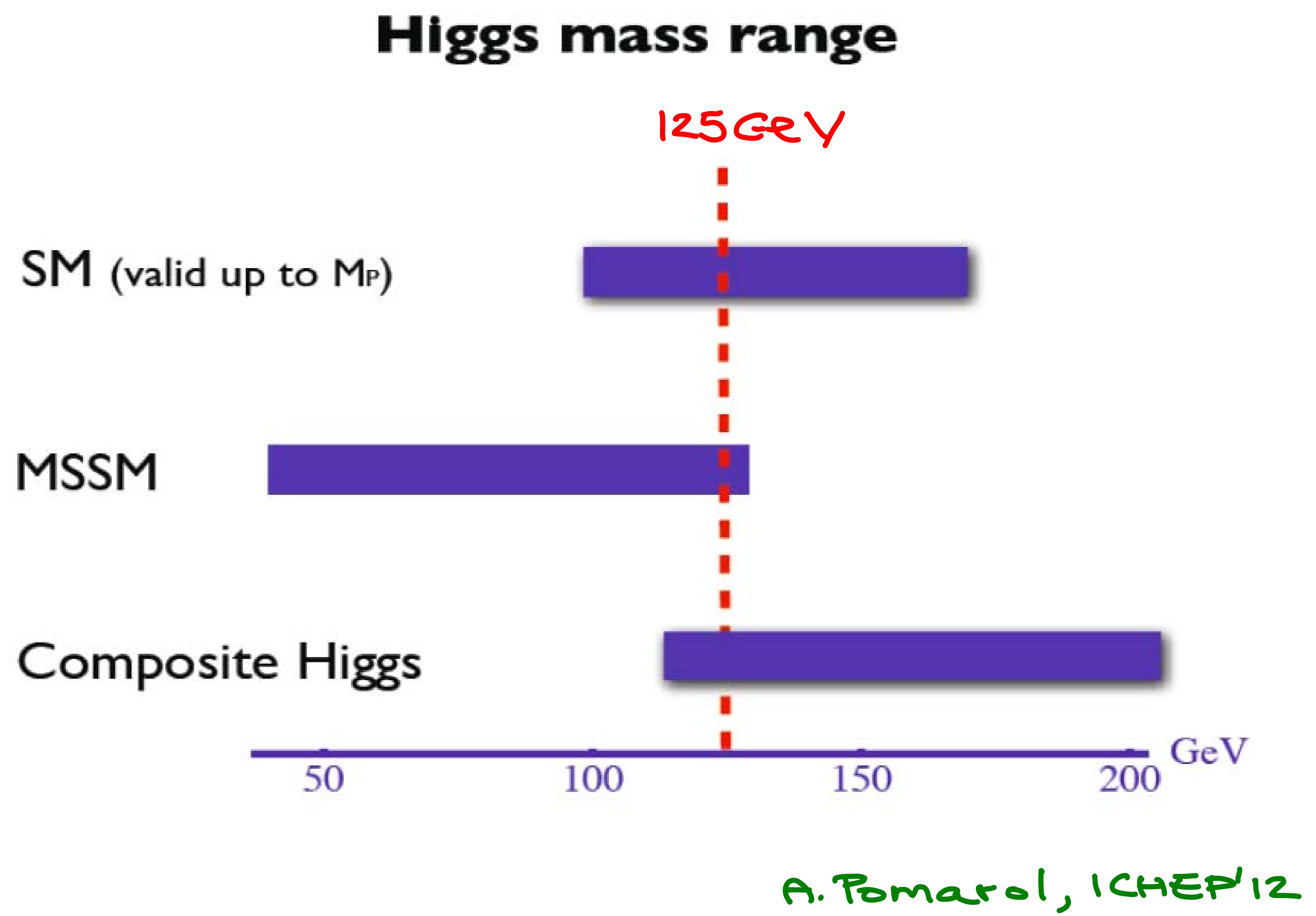


Unification below Planck scale, high enough for proton stability

Elegance

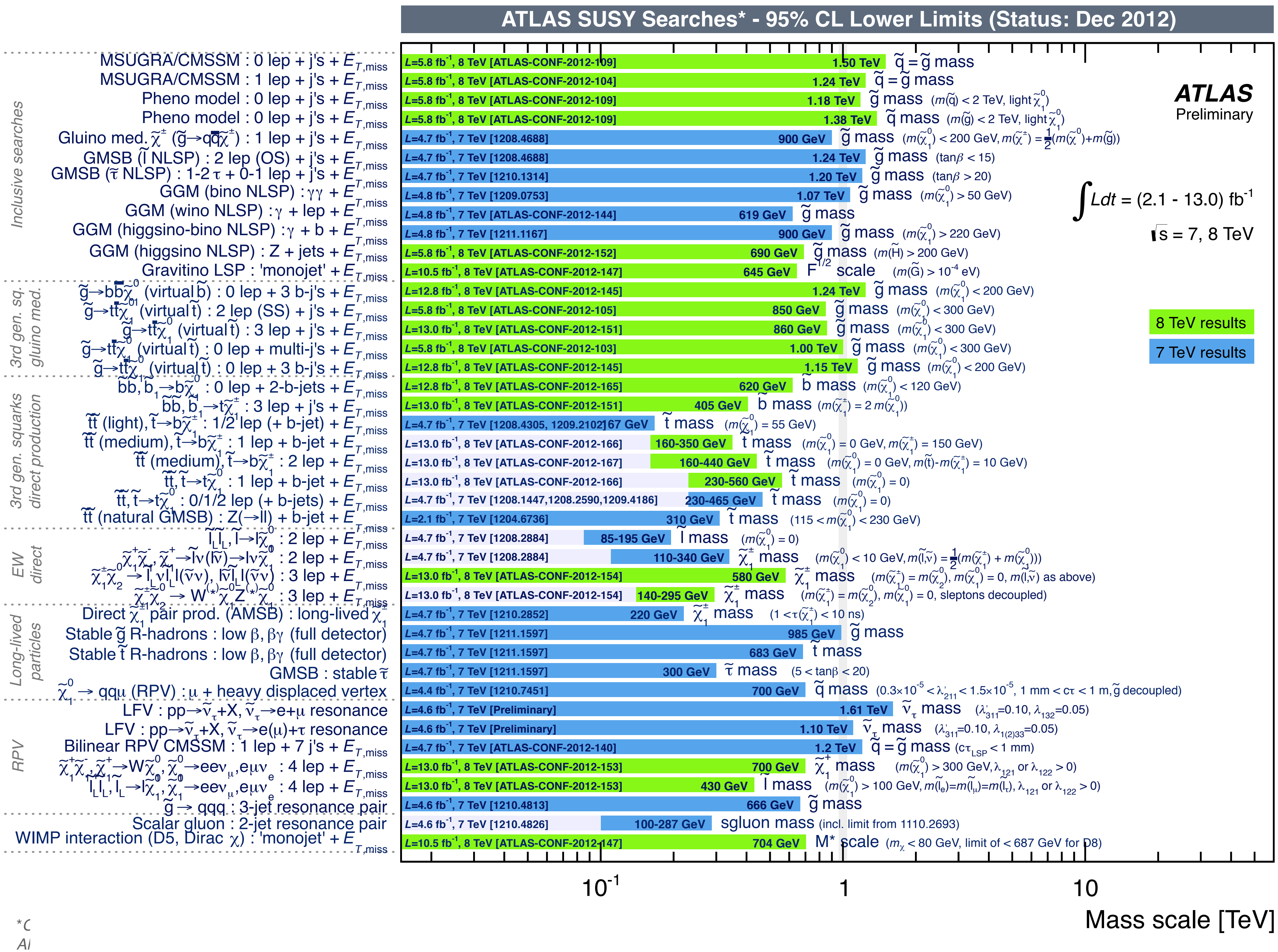
$$S = \int \mathrm{d}^4x \left(\mathrm{d}^2\theta \mathrm{d}^2\bar{\theta}\, \Phi_i^* \exp\left(2g_A T_A^a V_A^a\right) \Phi_i + \left\{ \mathrm{d}^2\theta \left[\mathcal{W}(\{\Phi_i\}) + \frac{1}{4} W_A^a W_A^a \right] + \mathrm{h.c.} \right\} \right)$$

MH AS MODEL DISCRIMINATOR



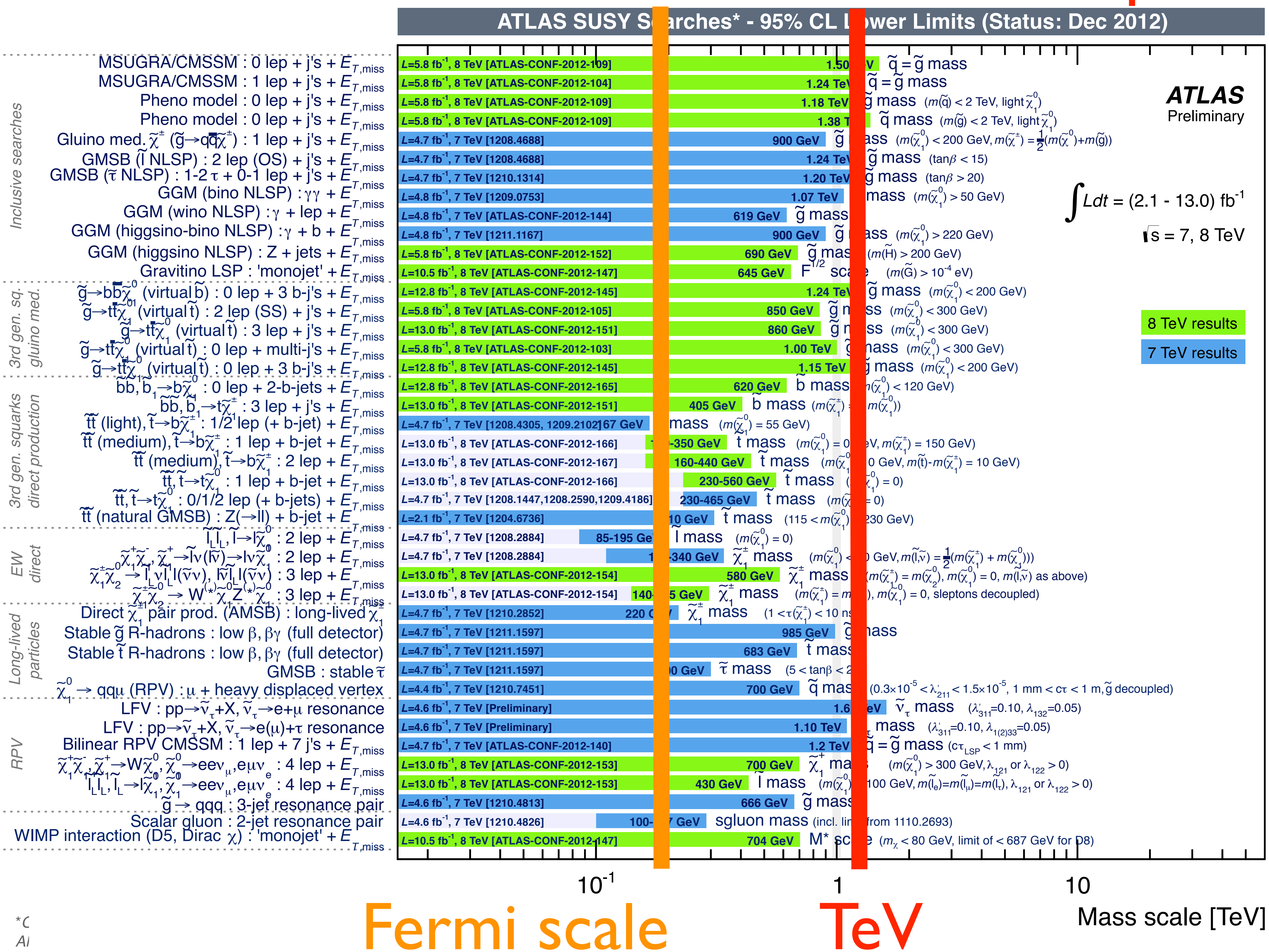
José Ramón Espinosa's talk

An anti-hint?


ATLAS SUSY Searches* - 95% CL Lower Limits (Status: Dec 2012)
ATLAS Preliminary
∫Ldt = (2.1 - 13.0) fb^-1
√s = 7, 8 TeV
8 TeV results
7 TeV results
Inclusive searches
3rd gen. sq. gluino med.
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
MSUGRA/CMSSM : 0 lep + j's + E_T,miss — L=5.8 fb^-1, 8 TeV [ATLAS-CONF-2012-109] — 1.50 TeV q̃ = g̃ mass
MSUGRA/CMSSM : 1 lep + j's + E_T,miss — L=5.8 fb^-1, 8 TeV [ATLAS-CONF-2012-104] — 1.24 TeV q̃ = g̃ mass
Pheno model : 0 lep + j's + E_T,miss — L=5.8 fb^-1, 8 TeV [ATLAS-CONF-2012-109] — 1.18 TeV g̃ mass (m(q̃) < 2 TeV, light χ̃₁⁰)
Pheno model : 0 lep + j's + E_T,miss — L=5.8 fb^-1, 8 TeV [ATLAS-CONF-2012-109] — 1.38 TeV q̃ mass (m(g̃) < 2 TeV, light χ̃₁⁰)
Gluino med. χ̃± (g̃→qq̄χ̃±) : 1 lep + j's + E_T,miss — L=4.7 fb^-1, 7 TeV [1208.4688] — 900 GeV g̃ mass (m(χ̃₁⁰) < 200 GeV, m(χ̃±) = ½(m(χ̃⁰)+m(g̃)))
GMSB (l̃ NLSP) : 2 lep (OS) + j's + E_T,miss — L=4.7 fb^-1, 7 TeV [1208.4688] — 1.24 TeV g̃ mass (tanβ < 15)
GMSB (τ̃ NLSP) : 1-2 τ + 0-1 lep + j's + E_T,miss — L=4.7 fb^-1, 7 TeV [1210.1314] — 1.20 TeV g̃ mass (tanβ > 20)
GGM (bino NLSP) : γγ + E_T,miss — L=4.8 fb^-1, 7 TeV [1209.0753] — 1.07 TeV g̃ mass (m(χ̃₁⁰) > 50 GeV)
GGM (wino NLSP) : γ + lep + E_T,miss — L=4.8 fb^-1, 7 TeV [ATLAS-CONF-2012-144] — 619 GeV g̃ mass
GGM (higgsino-bino NLSP) : γ + b + E_T,miss — L=4.8 fb^-1, 7 TeV [1211.1167] — 900 GeV g̃ mass (m(χ̃₁⁰) > 220 GeV)
GGM (higgsino NLSP) : Z + jets + E_T,miss — L=5.8 fb^-1, 8 TeV [ATLAS-CONF-2012-152] — 690 GeV g̃ mass (m(H̃) > 200 GeV)
Gravitino LSP : 'monojet' + E_T,miss — L=10.5 fb^-1, 8 TeV [ATLAS-CONF-2012-147] — 645 GeV F^1/2 scale (m(G̃) > 10^-4 eV)
g̃→bb̄χ̃₁⁰ (virtual b̃) : 0 lep + 3 b-j's + E_T,miss — L=12.8 fb^-1, 8 TeV [ATLAS-CONF-2012-145] — 1.24 TeV g̃ mass (m(χ̃₁⁰) < 200 GeV)
g̃→tt̄χ̃₁⁰ (virtual t̃) : 2 lep (SS) + j's + E_T,miss — L=5.8 fb^-1, 8 TeV [ATLAS-CONF-2012-105] — 850 GeV g̃ mass (m(χ̃₁⁰) < 300 GeV)
g̃→tt̄χ̃₁⁰ (virtual t̃) : 3 lep + j's + E_T,miss — L=13.0 fb^-1, 8 TeV [ATLAS-CONF-2012-151] — 860 GeV g̃ mass (m(χ̃₁⁰) < 300 GeV)
g̃→tt̄χ̃₁⁰ (virtual t̃) : 0 lep + multi-j's + E_T,miss — L=5.8 fb^-1, 8 TeV [ATLAS-CONF-2012-103] — 1.00 TeV g̃ mass (m(χ̃₁⁰) < 300 GeV)
g̃→tt̄χ̃₁⁰ (virtual t̃) : 0 lep + 3 b-j's + E_T,miss — L=12.8 fb^-1, 8 TeV [ATLAS-CONF-2012-145] — 1.15 TeV g̃ mass (m(χ̃₁⁰) < 200 GeV)
b̃b̃, b̃₁→bχ̃₁⁰ : 0 lep + 2-b-jets + E_T,miss — L=12.8 fb^-1, 8 TeV [ATLAS-CONF-2012-165] — 620 GeV b̃ mass (m(χ̃₁⁰) < 120 GeV)
b̃b̃, b̃₁→tχ̃₁± : 3 lep + j's + E_T,miss — L=13.0 fb^-1, 8 TeV [ATLAS-CONF-2012-151] — 405 GeV b̃ mass (m(χ̃₁±) = 2 m(χ̃₁⁰))
t̃t̃ (light), t̃→bχ̃₁± : 1/2 lep (+ b-jet) + E_T,miss — L=4.7 fb^-1, 7 TeV [1208.4305, 1209.2102] — 167 GeV t̃ mass (m(χ̃₁⁰) = 55 GeV)
t̃t̃ (medium), t̃→bχ̃₁± : 1 lep + b-jet + E_T,miss — L=13.0 fb^-1, 8 TeV [ATLAS-CONF-2012-166] — 160-350 GeV t̃ mass (m(χ̃₁⁰) = 0 GeV, m(χ̃₁±) = 150 GeV)
t̃t̃ (medium), t̃→bχ̃₁± : 2 lep + E_T,miss — L=13.0 fb^-1, 8 TeV [ATLAS-CONF-2012-167] — 160-440 GeV t̃ mass (m(χ̃₁⁰) = 0 GeV, m(t̃)-m(χ̃₁±) = 10 GeV)
t̃t̃, t̃→tχ̃₁⁰ : 1 lep + b-jet + E_T,miss — L=13.0 fb^-1, 8 TeV [ATLAS-CONF-2012-166] — 230-560 GeV t̃ mass (m(χ̃₁⁰) = 0)
t̃t̃, t̃→tχ̃₁⁰ : 0/1/2 lep (+ b-jets) + E_T,miss — L=4.7 fb^-1, 7 TeV [1208.1447,1208.2590,1209.4186] — 230-465 GeV t̃ mass (m(χ̃₁⁰) = 0)
t̃t̃ (natural GMSB) : Z(→ll) + b-jet + E_T,miss — L=2.1 fb^-1, 7 TeV [1204.6736] — 310 GeV t̃ mass (115 < m(χ̃₁⁰) < 230 GeV)
l̃_L l̃_L, l̃→lχ̃₁⁰ : 2 lep + E_T,miss — L=4.7 fb^-1, 7 TeV [1208.2884] — 85-195 GeV l̃ mass (m(χ̃₁⁰) = 0)
χ̃₁⁺χ̃₁⁻, χ̃₁⁺→l̃ν(lν̃)→lνχ̃₁⁰ : 2 lep + E_T,miss — L=4.7 fb^-1, 7 TeV [1208.2884] — 110-340 GeV χ̃₁± mass (m(χ̃₁⁰) < 10 GeV, m(l̃,ν̃) = ½(m(χ̃₁±) + m(χ̃₁⁰)))
χ̃₁±χ̃₂⁰→l̃_L ν l̃_L l(ν̃ν), lν̃ l̃_L l(ν̃ν) : 3 lep + E_T,miss — L=13.0 fb^-1, 8 TeV [ATLAS-CONF-2012-154] — 580 GeV χ̃₁± mass (m(χ̃₁±) = m(χ̃₂⁰), m(χ̃₁⁰) = 0, m(l̃,ν̃) as above)
χ̃₁±χ̃₂⁰ → W^(*)χ̃₁⁰Z^(*)χ̃₁⁰ : 3 lep + E_T,miss — L=13.0 fb^-1, 8 TeV [ATLAS-CONF-2012-154] — 140-295 GeV χ̃₁± mass (m(χ̃₁±) = m(χ̃₂⁰), m(χ̃₁⁰) = 0, sleptons decoupled)
Direct χ̃₁± pair prod. (AMSB) : long-lived χ̃₁± — L=4.7 fb^-1, 7 TeV [1210.2852] — 220 GeV χ̃₁± mass (1 < τ(χ̃₁±) < 10 ns)
Stable g̃ R-hadrons : low β, βγ (full detector) — L=4.7 fb^-1, 7 TeV [1211.1597] — 985 GeV g̃ mass
Stable t̃ R-hadrons : low β, βγ (full detector) — L=4.7 fb^-1, 7 TeV [1211.1597] — 683 GeV t̃ mass
GMSB : stable τ̃ — L=4.7 fb^-1, 7 TeV [1211.1597] — 300 GeV τ̃ mass (5 < tanβ < 20)
χ̃₁⁰ → qqμ (RPV) : μ + heavy displaced vertex — L=4.4 fb^-1, 7 TeV [1210.7451] — 700 GeV q̃ mass (0.3×10^-5 < λ'₂₁₁ < 1.5×10^-5, 1 mm < cτ < 1 m, g̃ decoupled)
LFV : pp→ν̃_τ+X, ν̃_τ→e+μ resonance — L=4.6 fb^-1, 7 TeV [Preliminary] — 1.61 TeV ν̃_τ mass (λ'₃₁₁=0.10, λ₁₃₂=0.05)
LFV : pp→ν̃_τ+X, ν̃_τ→e(μ)+τ resonance — L=4.6 fb^-1, 7 TeV [Preliminary] — 1.10 TeV ν̃_τ mass (λ'₃₁₁=0.10, λ₁(2)33=0.05)
Bilinear RPV CMSSM : 1 lep + 7 j's + E_T,miss — L=4.7 fb^-1, 7 TeV [ATLAS-CONF-2012-140] — 1.2 TeV q̃ = g̃ mass (cτ_LSP < 1 mm)
χ̃₁⁺χ̃₁⁻, χ̃₁⁺→Wχ̃₁⁰, χ̃₁⁰→eeν_μ, eμν_e : 4 lep + E_T,miss — L=13.0 fb^-1, 8 TeV [ATLAS-CONF-2012-153] — 700 GeV χ̃₁⁺ mass (m(χ̃₁⁰) > 300 GeV, λ₁₂₁ or λ₁₂₂ > 0)
l̃_L l̃_L, l̃_L→lχ̃₁⁰, χ̃₁⁰→eeν_μ, eμν_e : 4 lep + E_T,miss — L=13.0 fb^-1, 8 TeV [ATLAS-CONF-2012-153] — 430 GeV l̃ mass (m(χ̃₁⁰) > 100 GeV, m(l̃_e)=m(l̃_μ)=m(l̃_τ), λ₁₂₁ or λ₁₂₂ > 0)
g̃ → qqq : 3-jet resonance pair — L=4.6 fb^-1, 7 TeV [1210.4813] — 666 GeV g̃ mass
Scalar gluon : 2-jet resonance pair — L=4.6 fb^-1, 7 TeV [1210.4826] — 100-287 GeV sgluon mass (incl. limit from 1110.2693)
WIMP interaction (D5, Dirac χ) : 'monojet' + E_T,miss — L=10.5 fb^-1, 8 TeV [ATLAS-CONF-2012-147] — 704 GeV M* scale (m_χ < 80 GeV, limit of < 687 GeV for D8)
10^-1
1
10
Mass scale [TeV]

Colored susy > TeV ?

colored sparticles

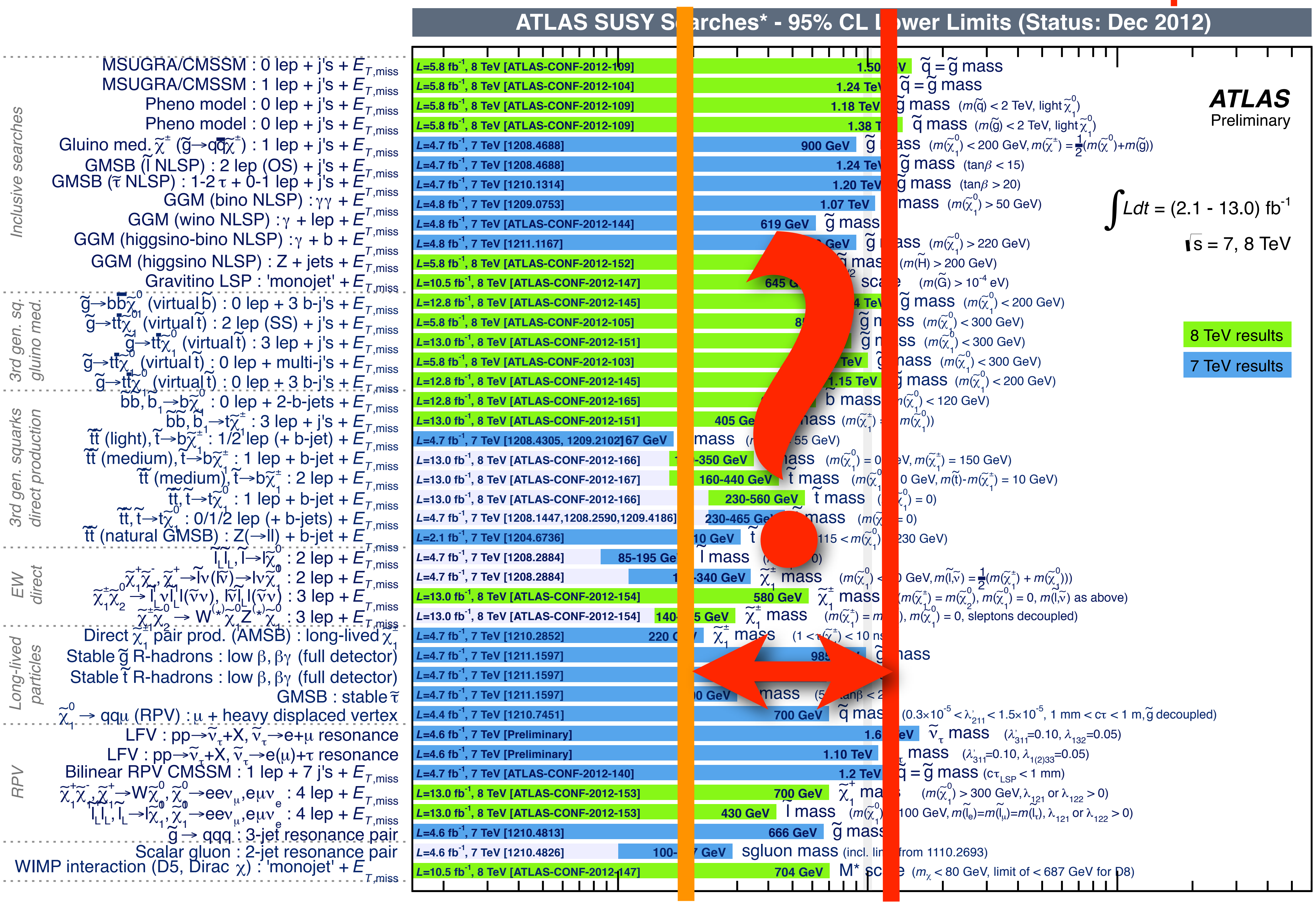


Fermi scale

TeV

Colored susy > TeV ?

colored sparticles



Fermi scale

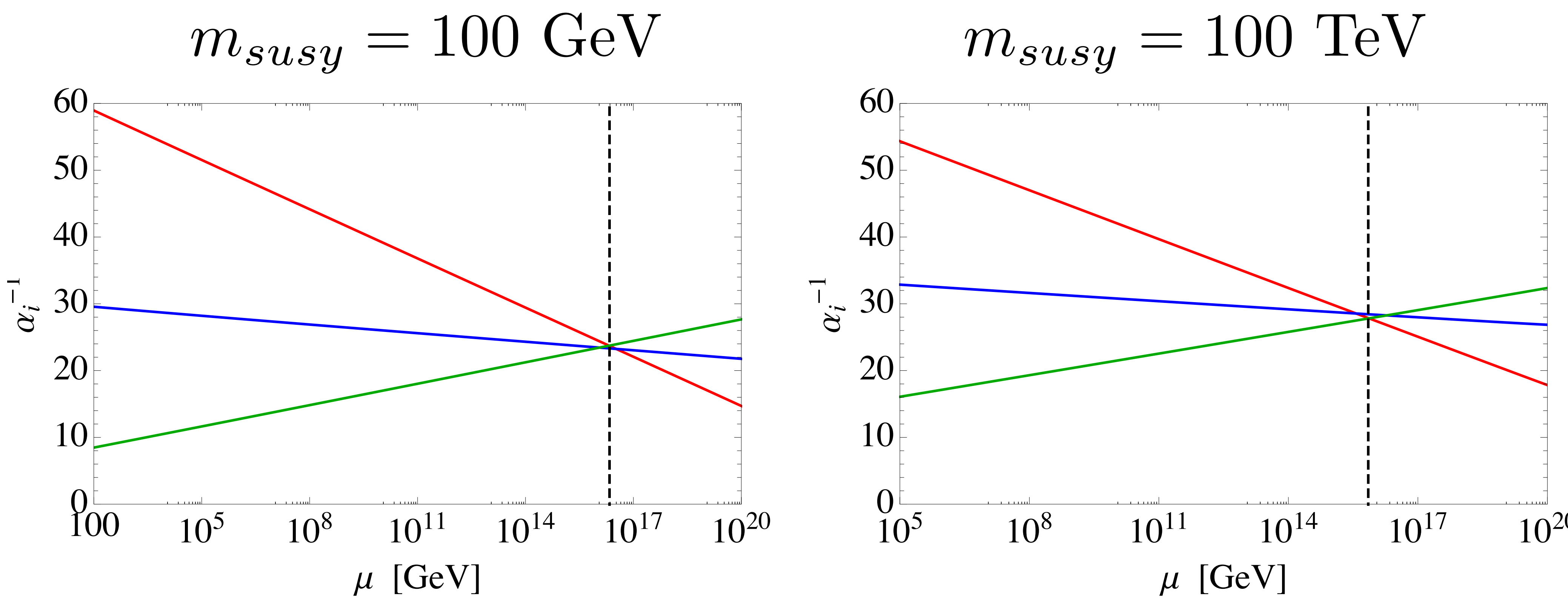
TeV

Why expect susy to be light?

- Gauge coupling unification? ✘
- Dark matter? ✘
- Higgs mass? ✘
- Naturalness? ✓

Gauge coupling unification

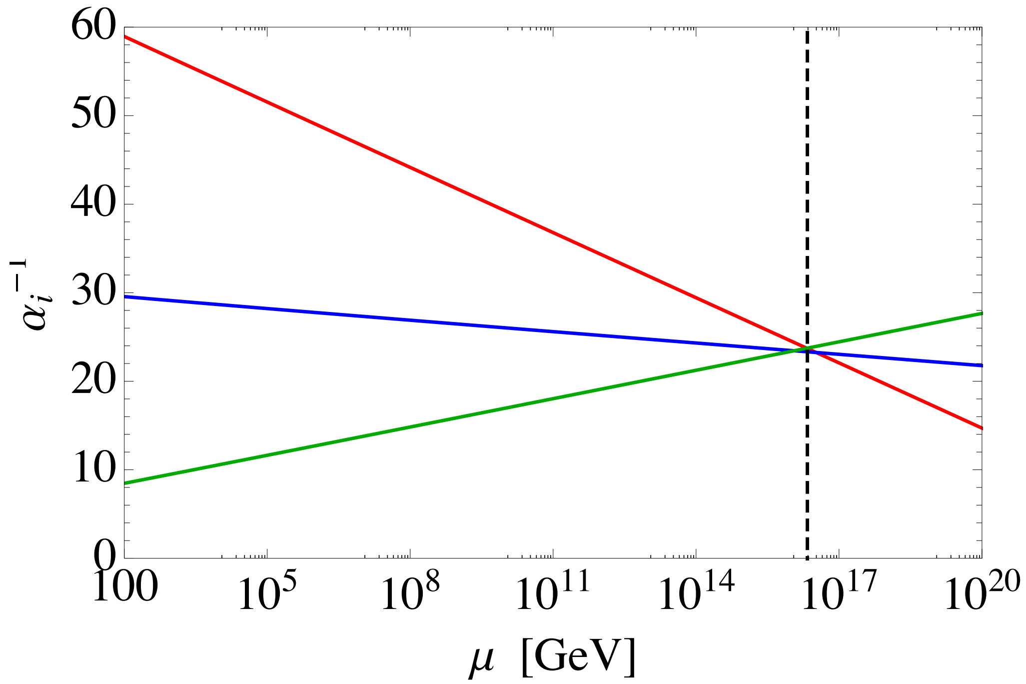
Hall et al.



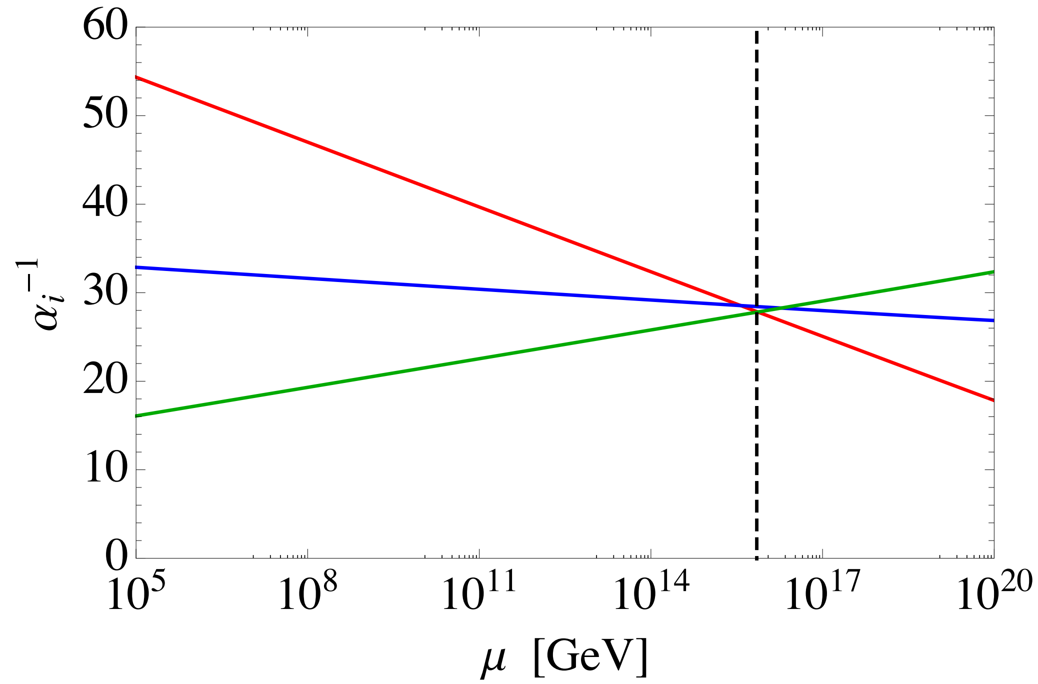
Gauge coupling unification

Hall et al.

$m_{susy} = 100$ GeV



$m_{susy} = 100$ TeV



Required threshold correction at GUT scale

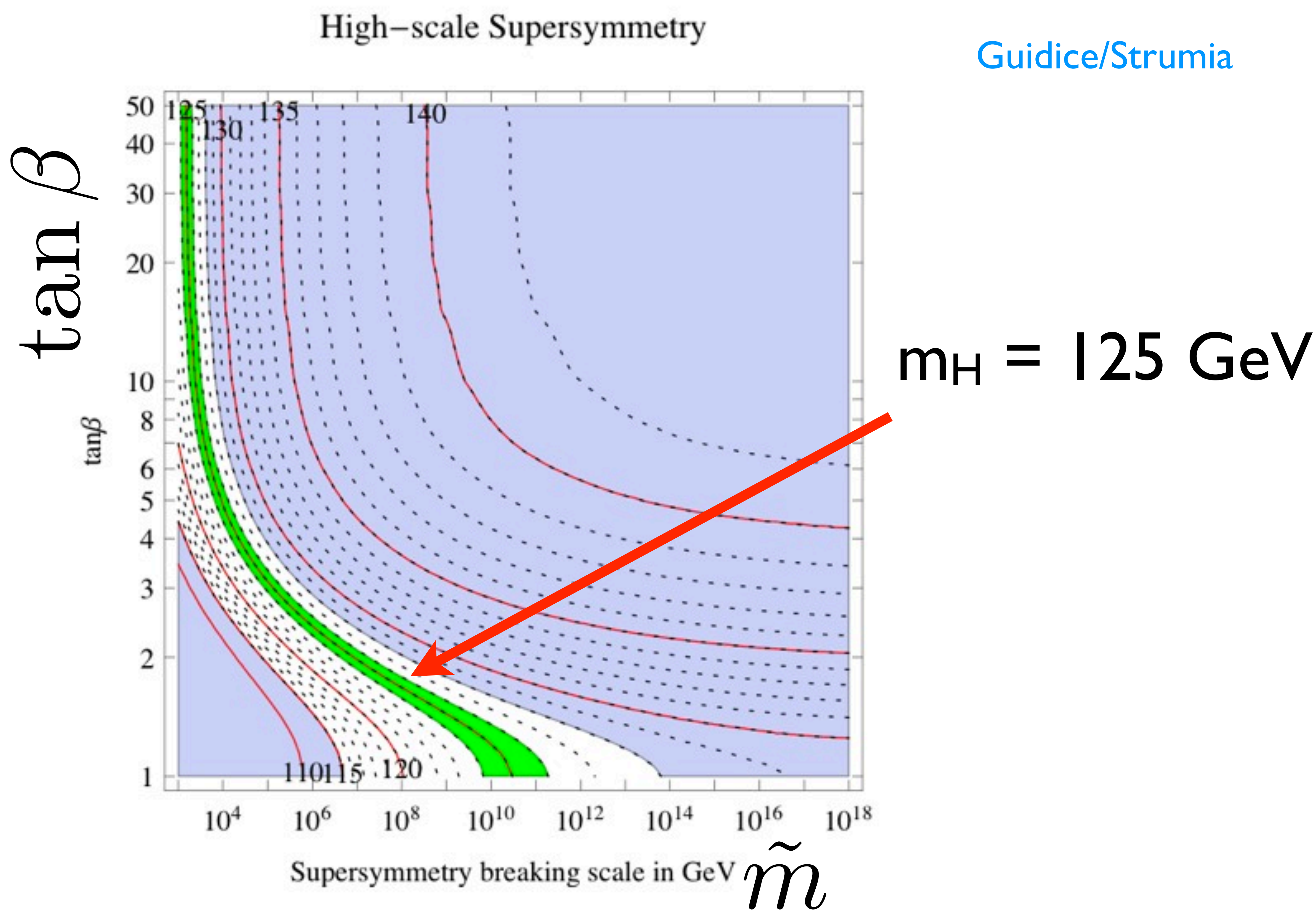
$$\epsilon_g = 0.014 \quad \Rightarrow \quad \epsilon_g = 0.017$$

$$\frac{1}{\bar{g}^2(M_U)} = \frac{1}{g_a^2(M_U)}(1 + \epsilon_a)$$

Compare to $\epsilon_g^{\mathrm{SM}} = 0.12$

Higgs mass vs. susy scale

Guidice/Strumia



Natural susy

~~Natural~~ Ascetic susy

Natural EWSB in times of austerity

Barbieri/Guidice

MSSM,NMSSM, ...

Fine-tuning of (Higgs mass)^2

$$\frac{m_{Higgs}^2}{2} = -|\mu|^2 + \ldots + \delta m_H^2$$

Natural EWSB in times of austerity

Barbieri/Guidice

MSSM,NMSSM, ...

Fine-tuning of (Higgs mass)^2

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

Higgsinos

Natural EWSB in times of austerity

Barbieri/Guidice

MSSM,NMSSM, ...

Fine-tuning of (Higgs mass)^2

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

Higgsinos

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

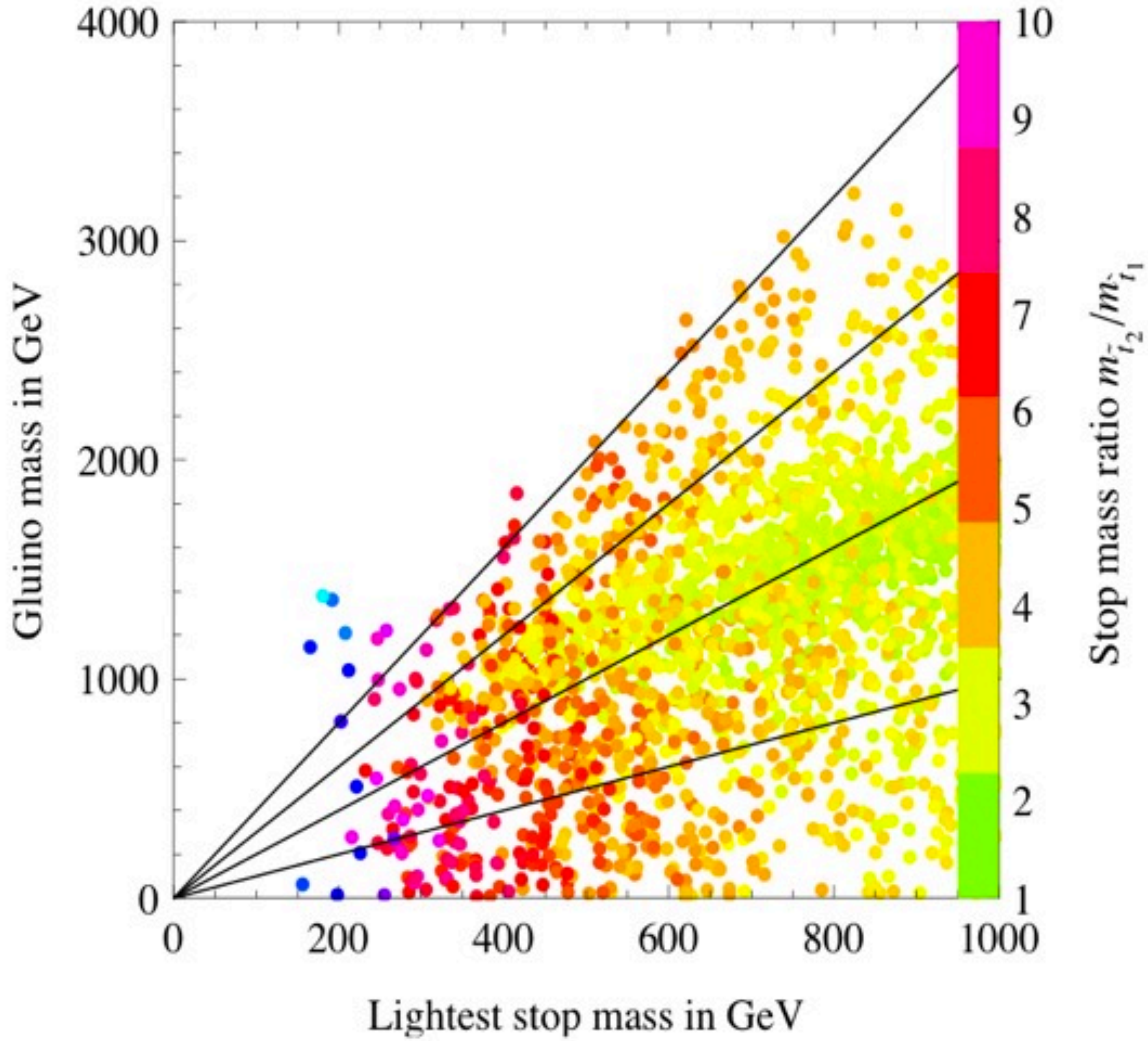
stops, sbottom$_L$

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

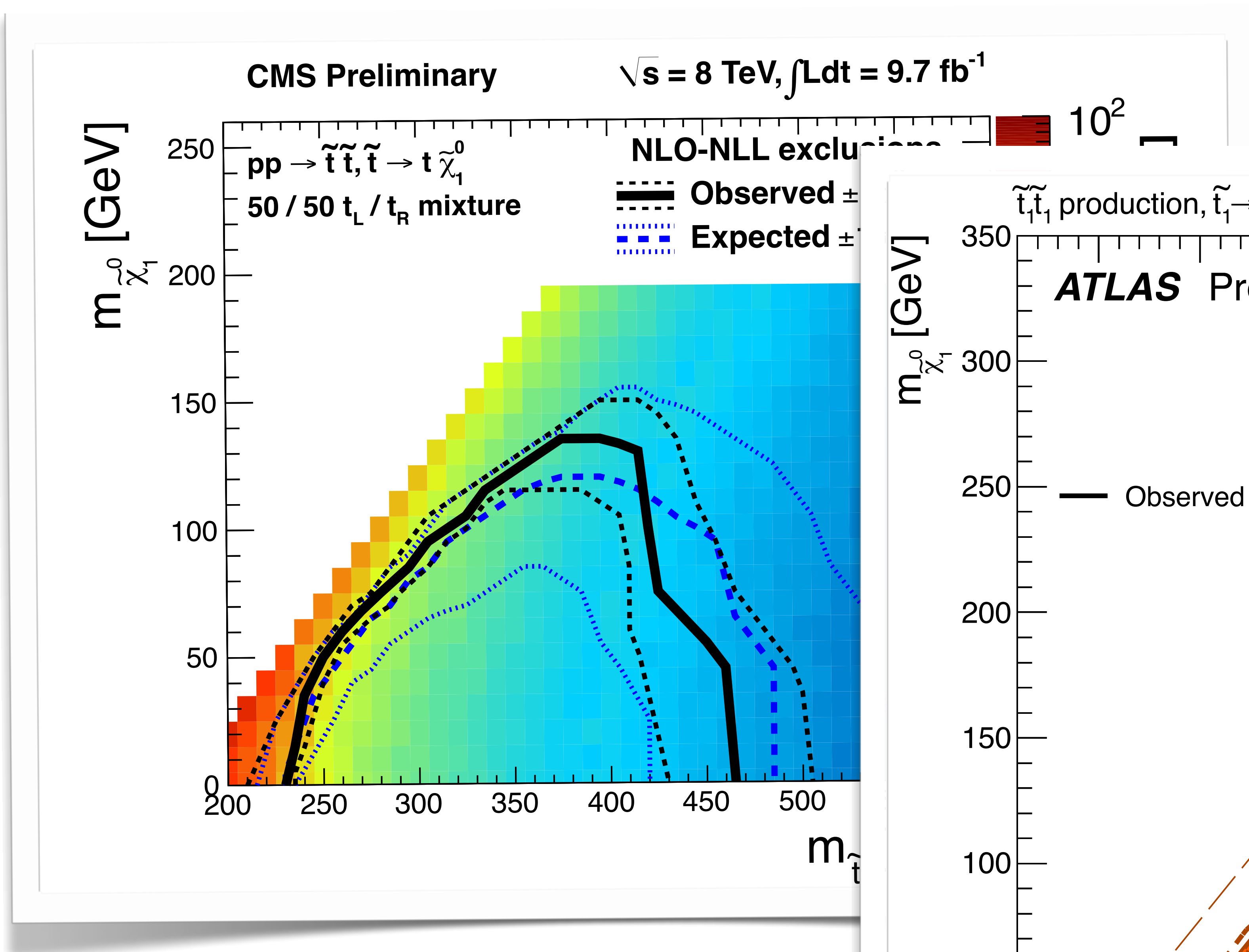
gluino

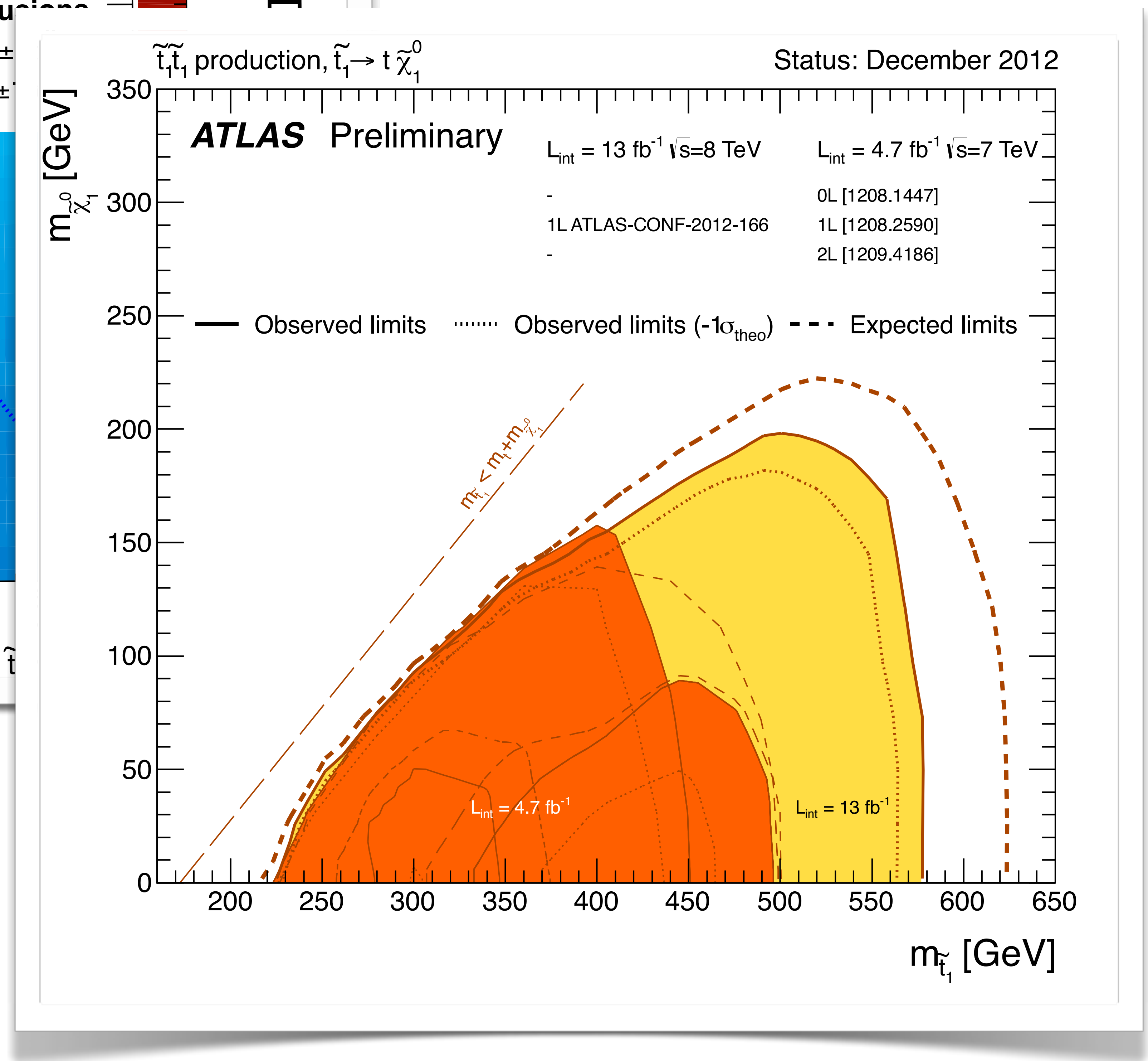
MSSM stops vs. mH

Delgado, Isidori et al.



Direct stop searches



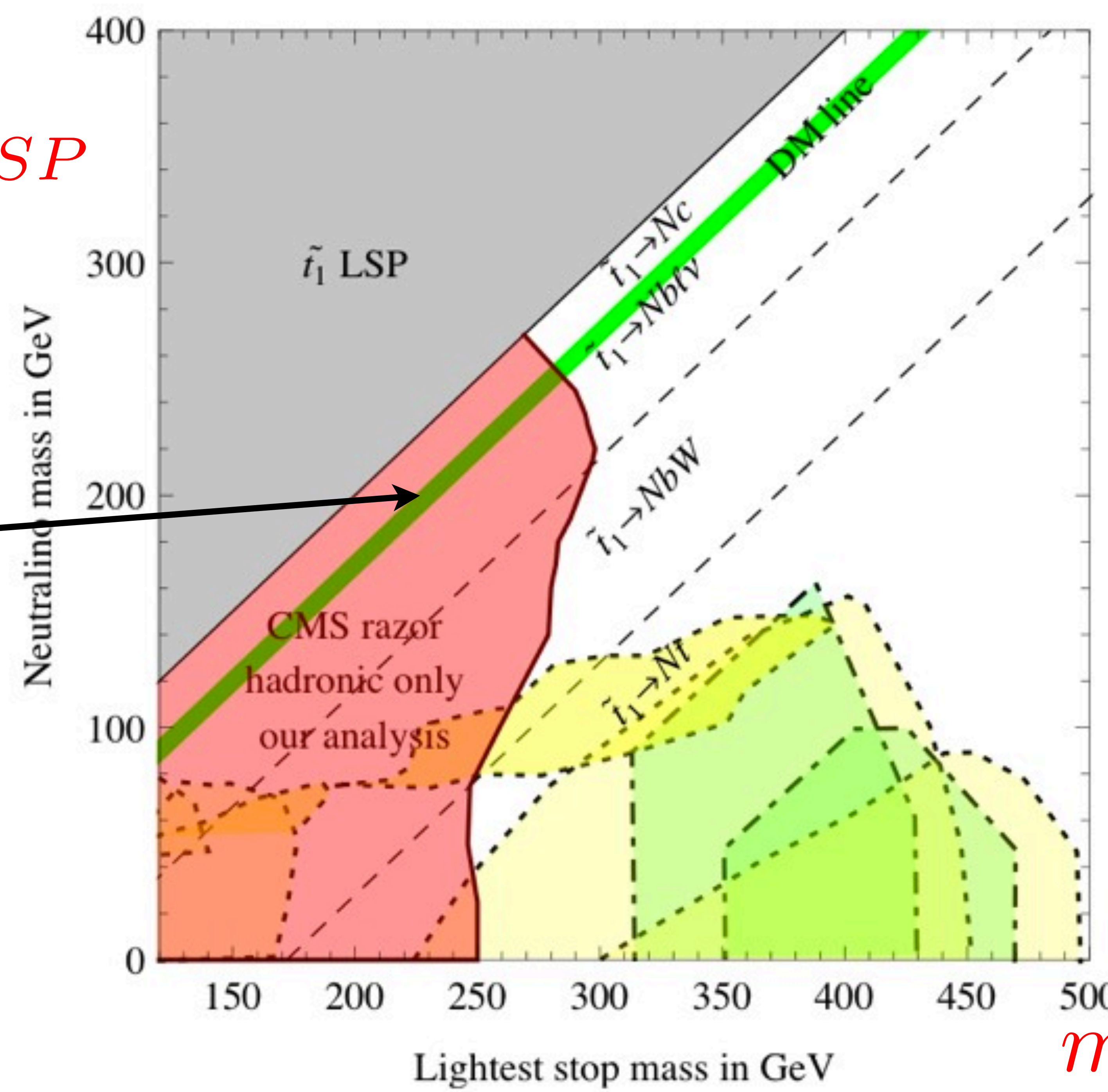


$$(m_{\tilde{t}_1} - m_{LSP}) < 30 - 40\,\mathrm{GeV}$$

Delgado, Isidori et al.

Leads to
the right
relic abundance

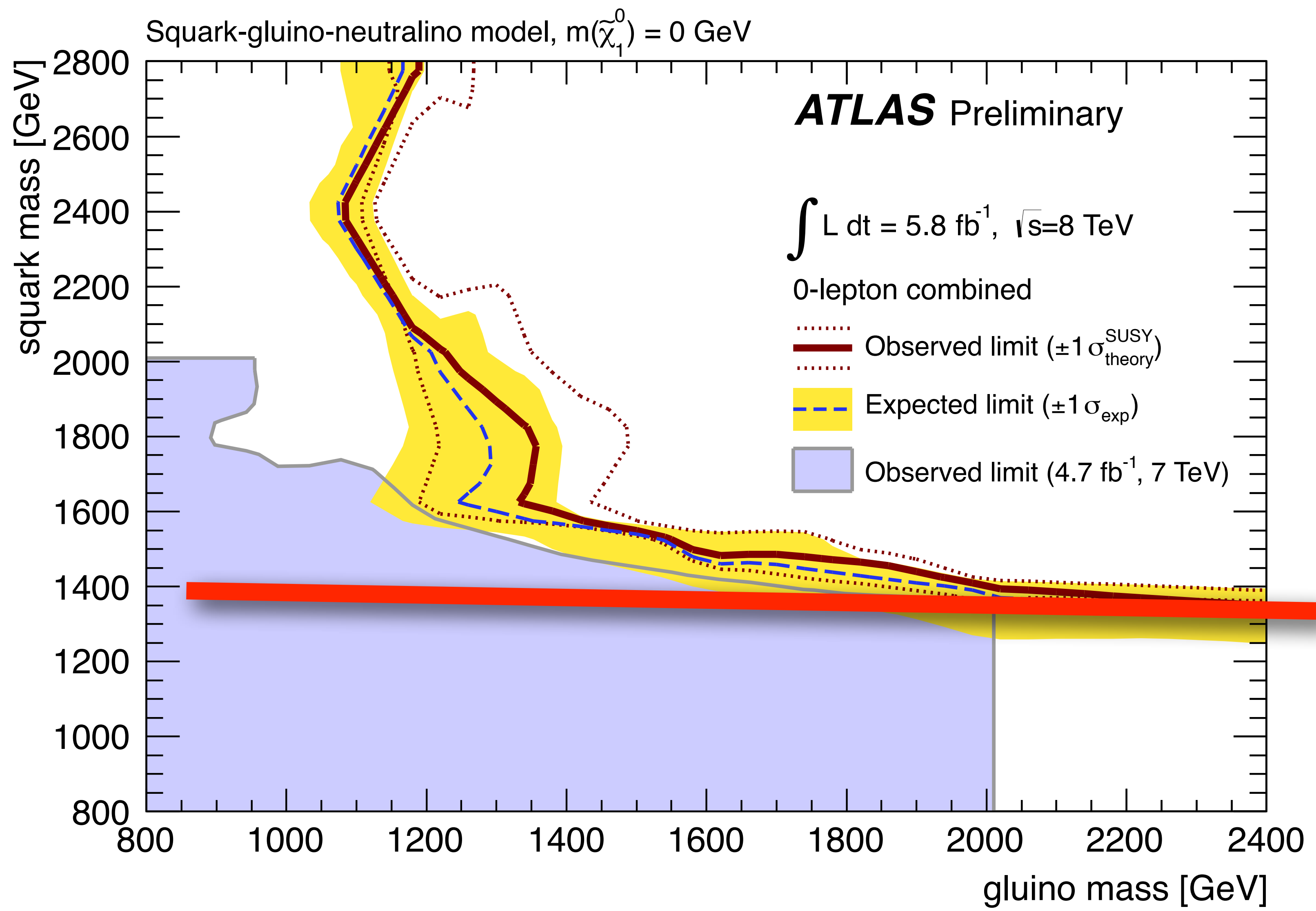
m_{LSP}



$m_{\tilde{t}_1}$

Limit on squarks

squarks

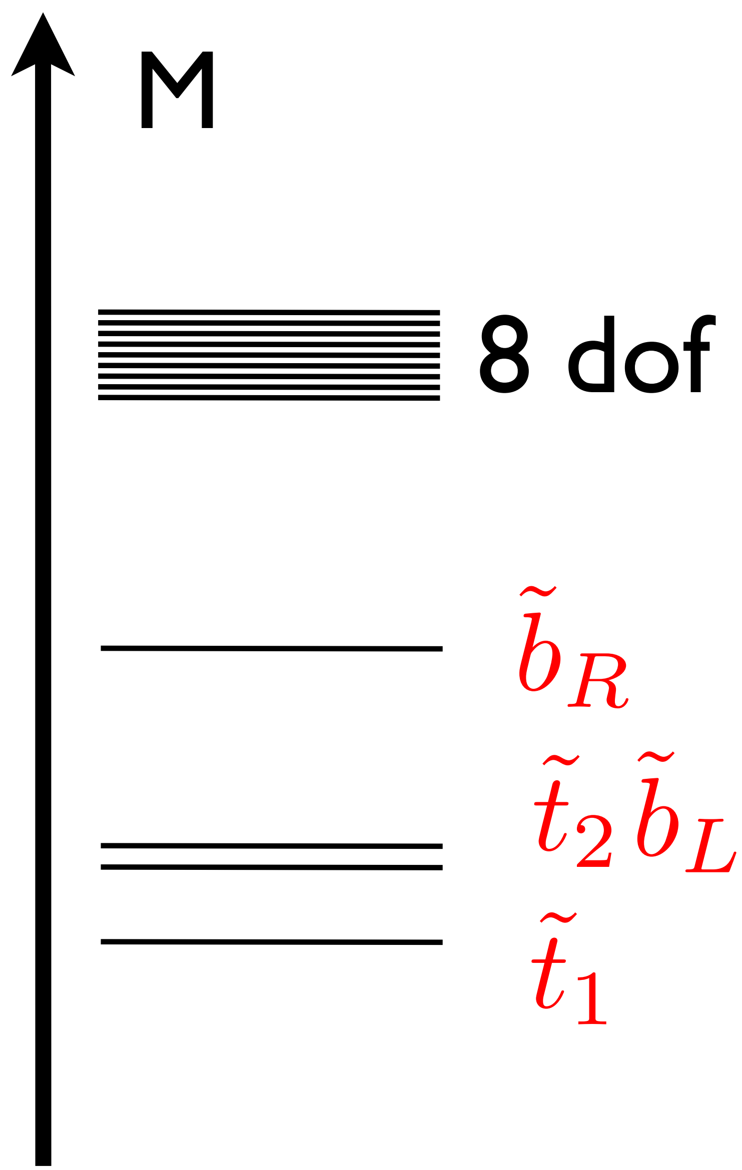


> 1.4 TeV

udcs-squarks

gluino

Naturalness requires split squarks



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

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

Splitting via RGE?

Papucci, Ruderman, AW '11

Splitting via renormalization group does not help

$$\delta m_H^2 \simeq 3\left(m_{Q_3}^2 - m_{Q_{1,2}}^2\right) \simeq \frac{3}{2}\left(m_{U_3}^2 - m_{U_{1,2}}^2\right)$$

1-loop, LLog,
tanß moderate

Higgs fine-tuning = RGE mass splitting

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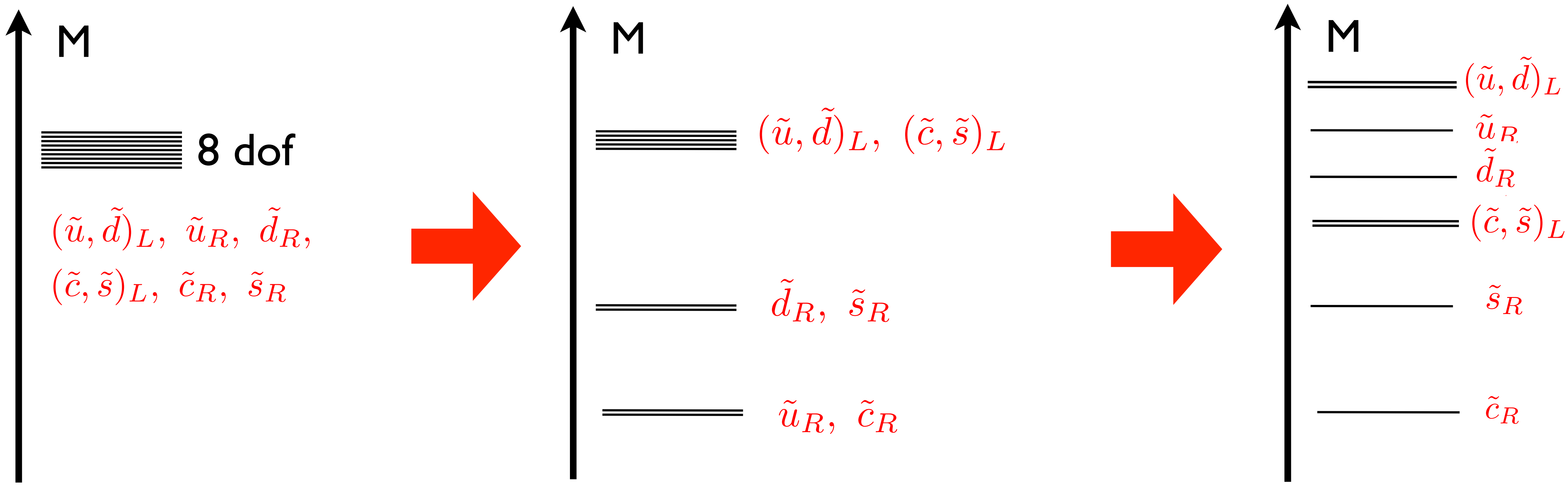
1-loop, LLog,
tanß moderate

Higgs fine-tuning = RGE mass splitting

→ Flavor non-trivial susy breaking!



Degenerate

Minimal Flavor

Anarchy!

mSugra, CMSSM,
pMSSM, ...

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!

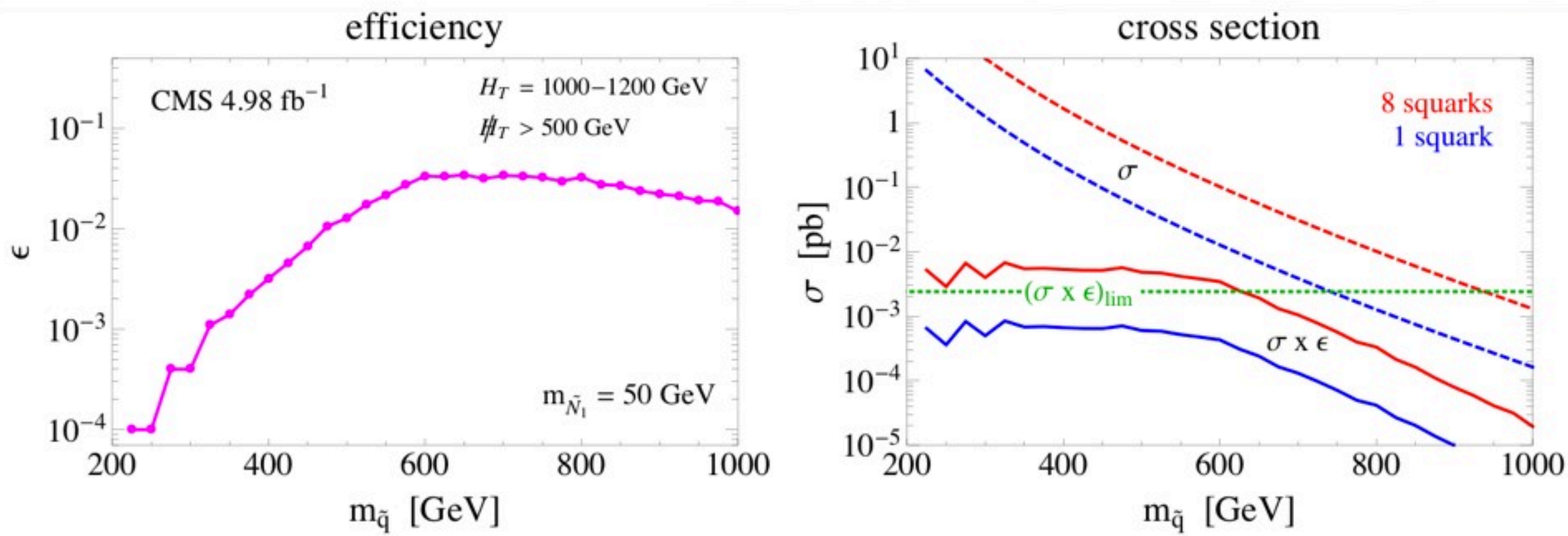
Dedicated study needed

- Production cross-section can be flavor dependent through p.d.f's (u vs. d, sea vs. valence)
- Experimental efficiencies have thresholds and current limits are on the thresholds

Squark searches

M. Papucci, J. Ruderman
G. Perez, R. Mahbubani, AW

Effect of the efficiency threshold:

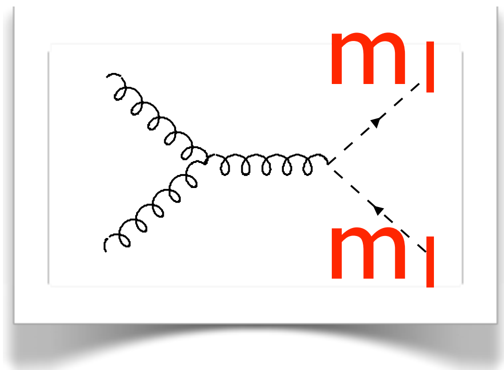


Pythia/MadEvent

+Prospino/NLLfast
+checks with MLM matched sample

simplified Model

available → CMS



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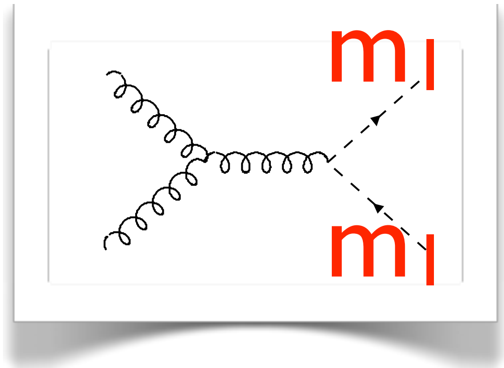
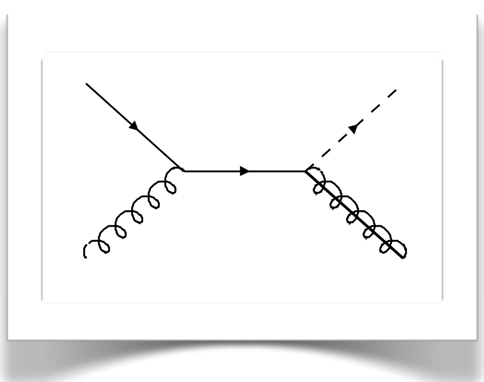
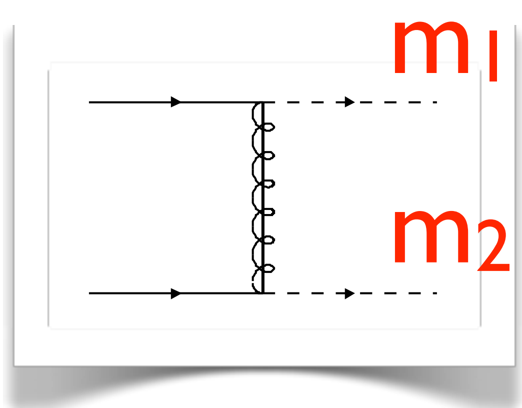


Pythia/MadEvent

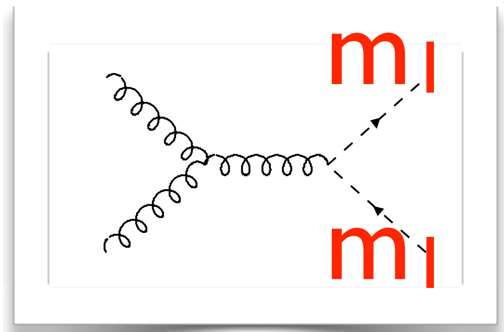
+Prospino/NLLfast
+checks with MLM matched sample

Atom recast





simplified Model available → CMS



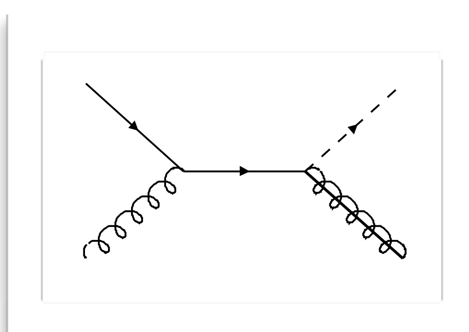
Signal regions

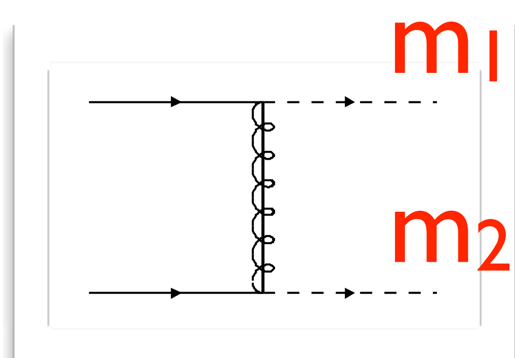
$H_T, \not{H}_T$
$H_T, \not{H}_T$
...
$H_T, \not{H}_T$
$H_T, \not{H}_T$
$H_T, \not{H}_T$

Pythia/MadEvent

+Prospino/NLLfast
+checks with MLM matched sample

Atom recast





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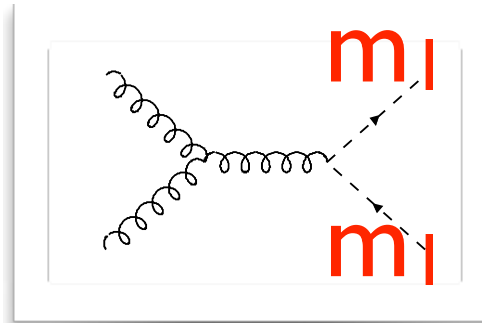

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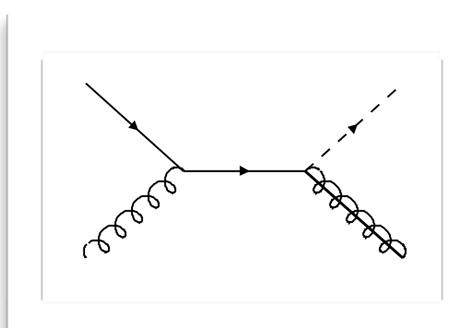
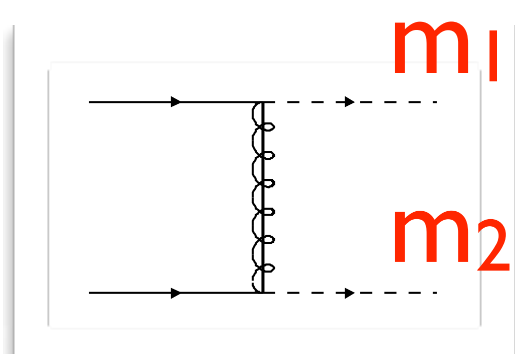
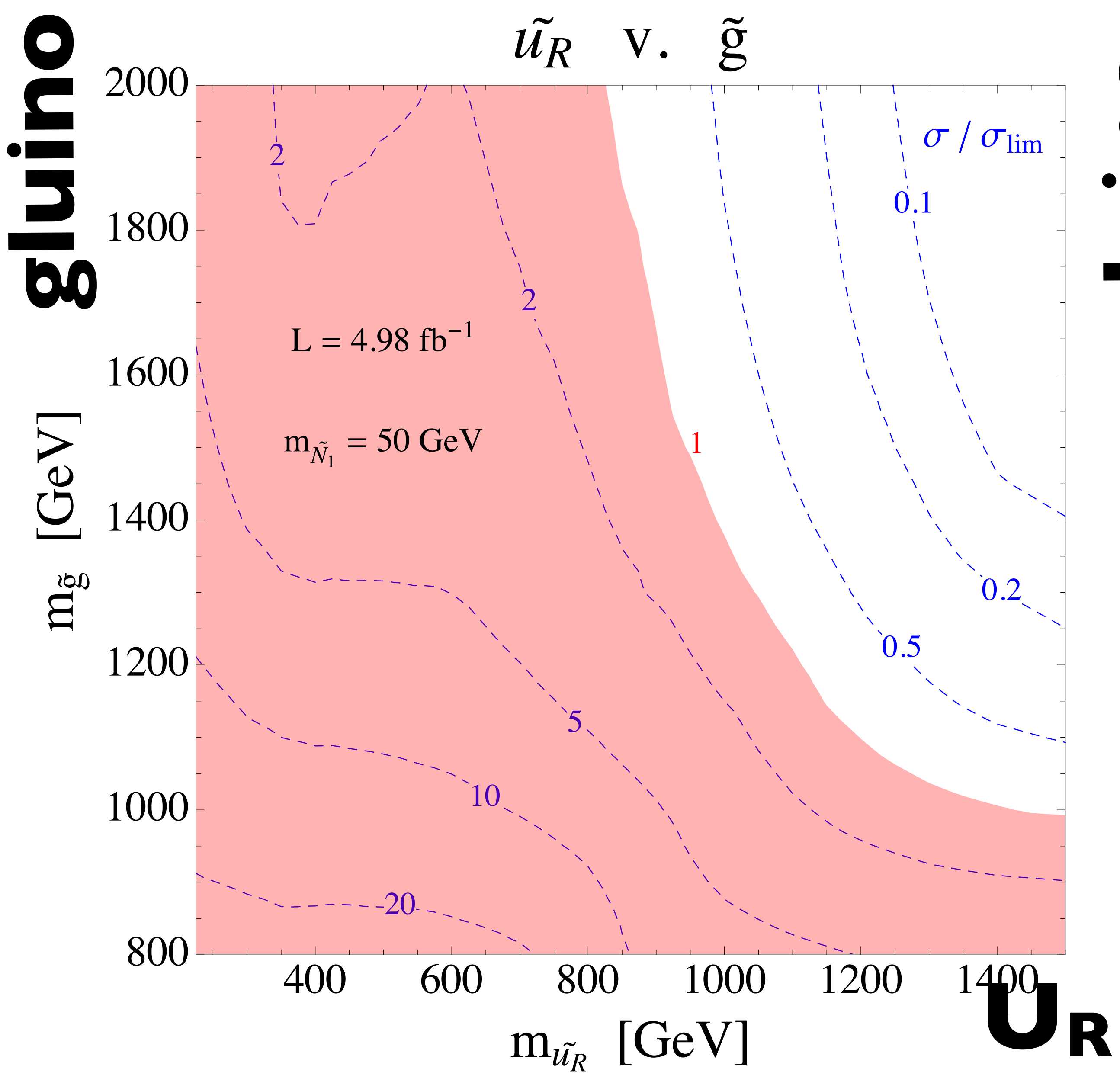
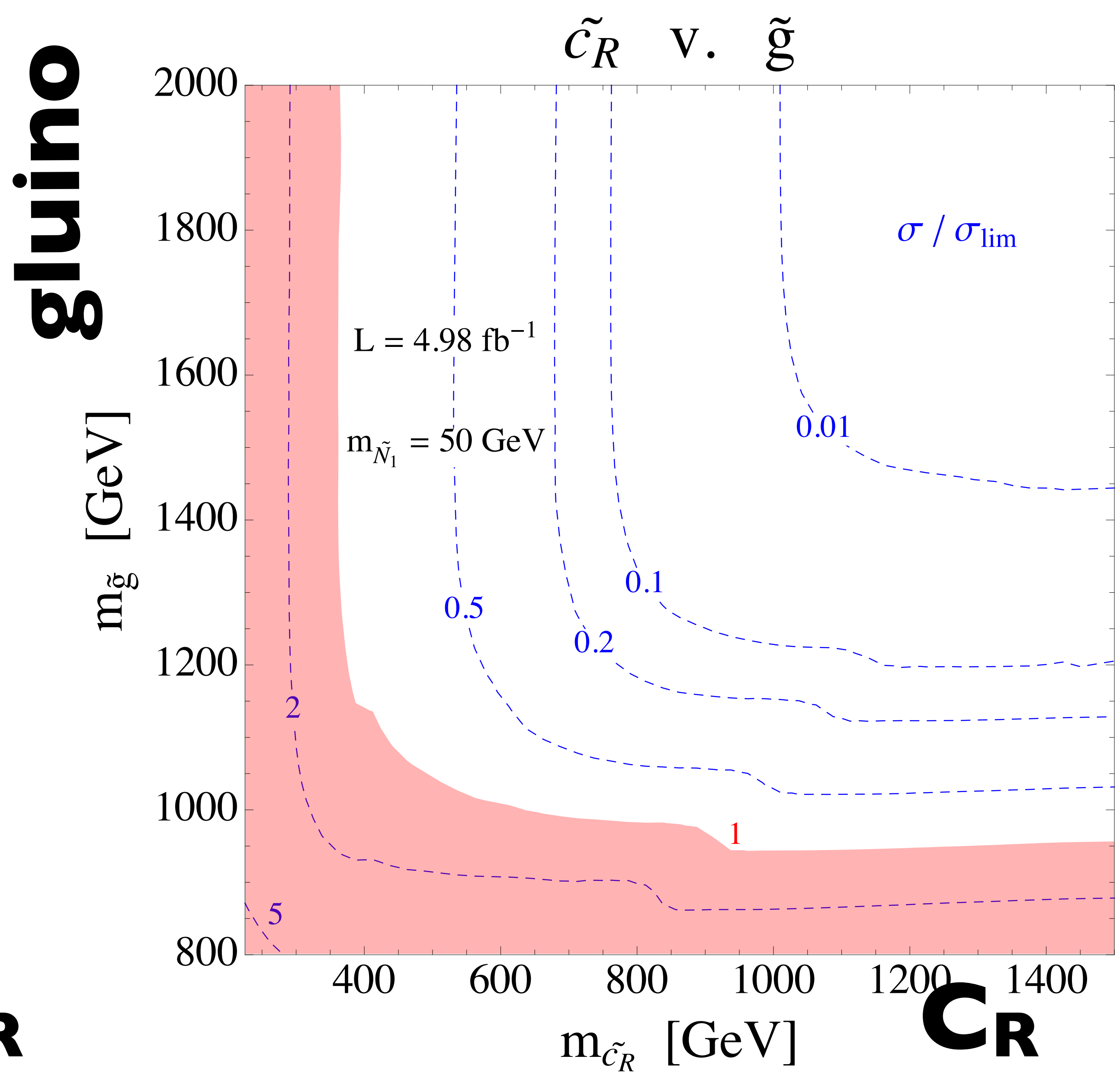


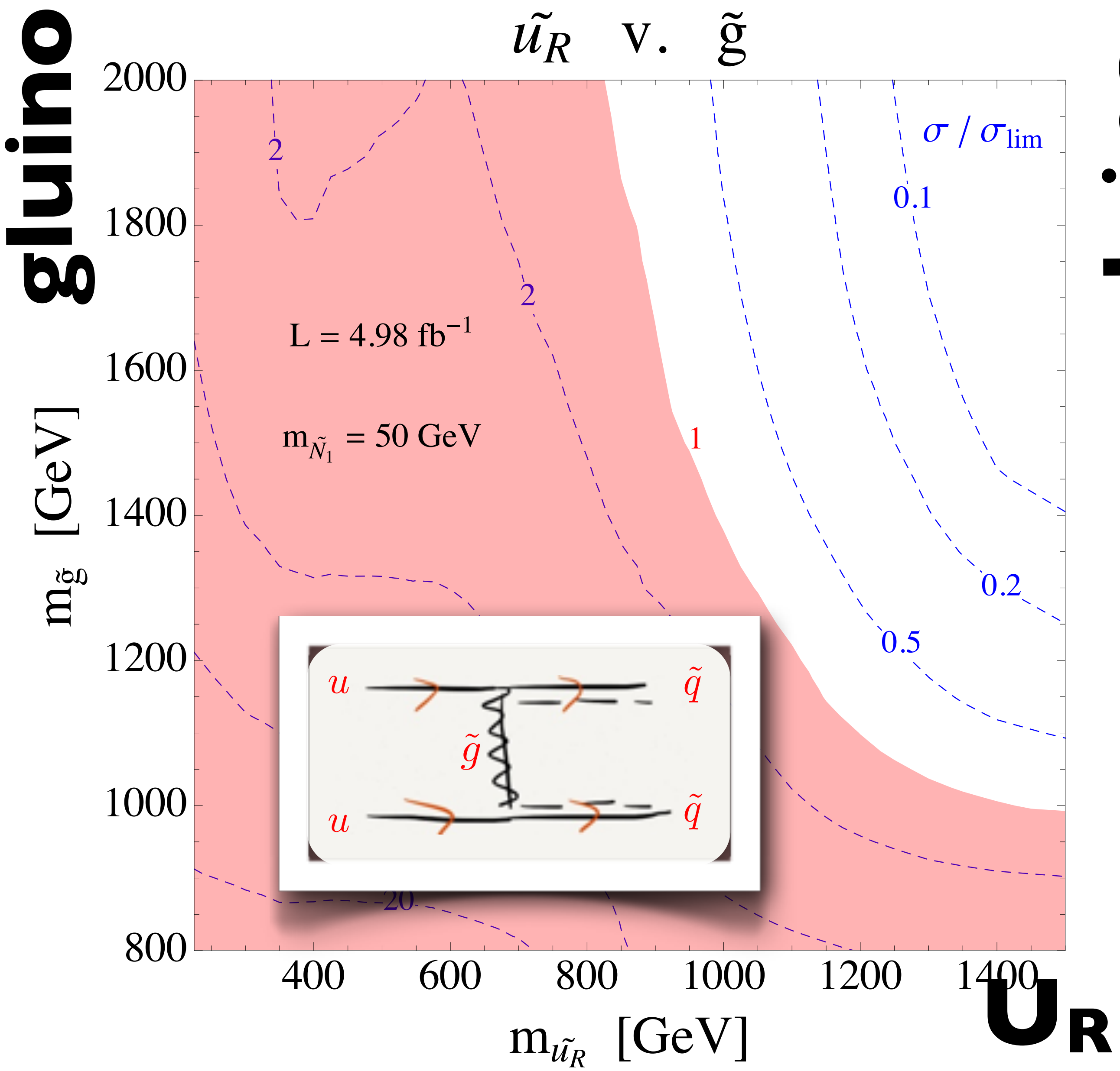


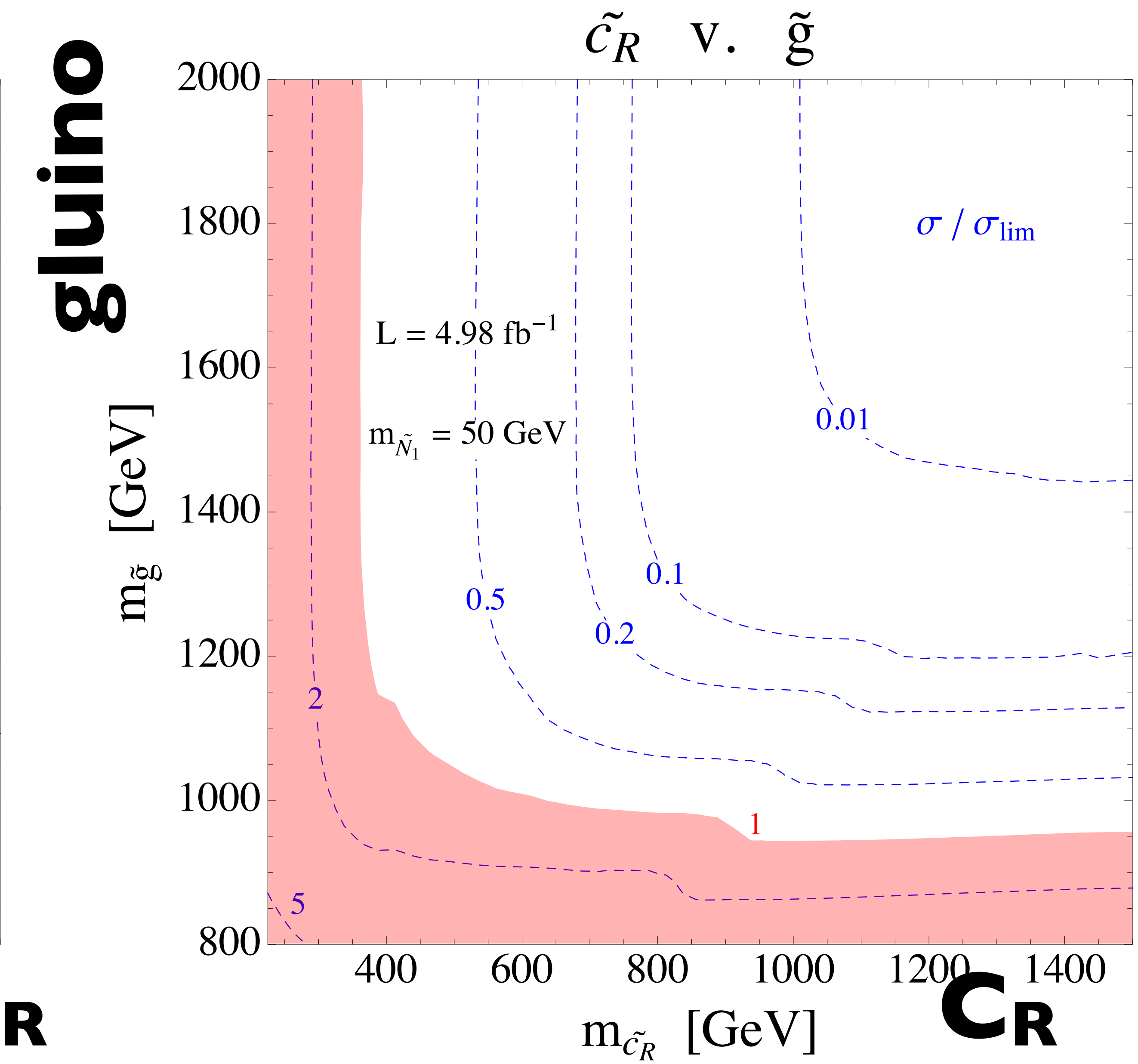
$$\Pi_i \mathrm{poiss}(s_i + b_i \delta b_i)\, \mathrm{gauss}(\delta b_i) \to CL_s$$





M. Papucci, J. Ruderman
G. Perez, R. Mahbubani, AW



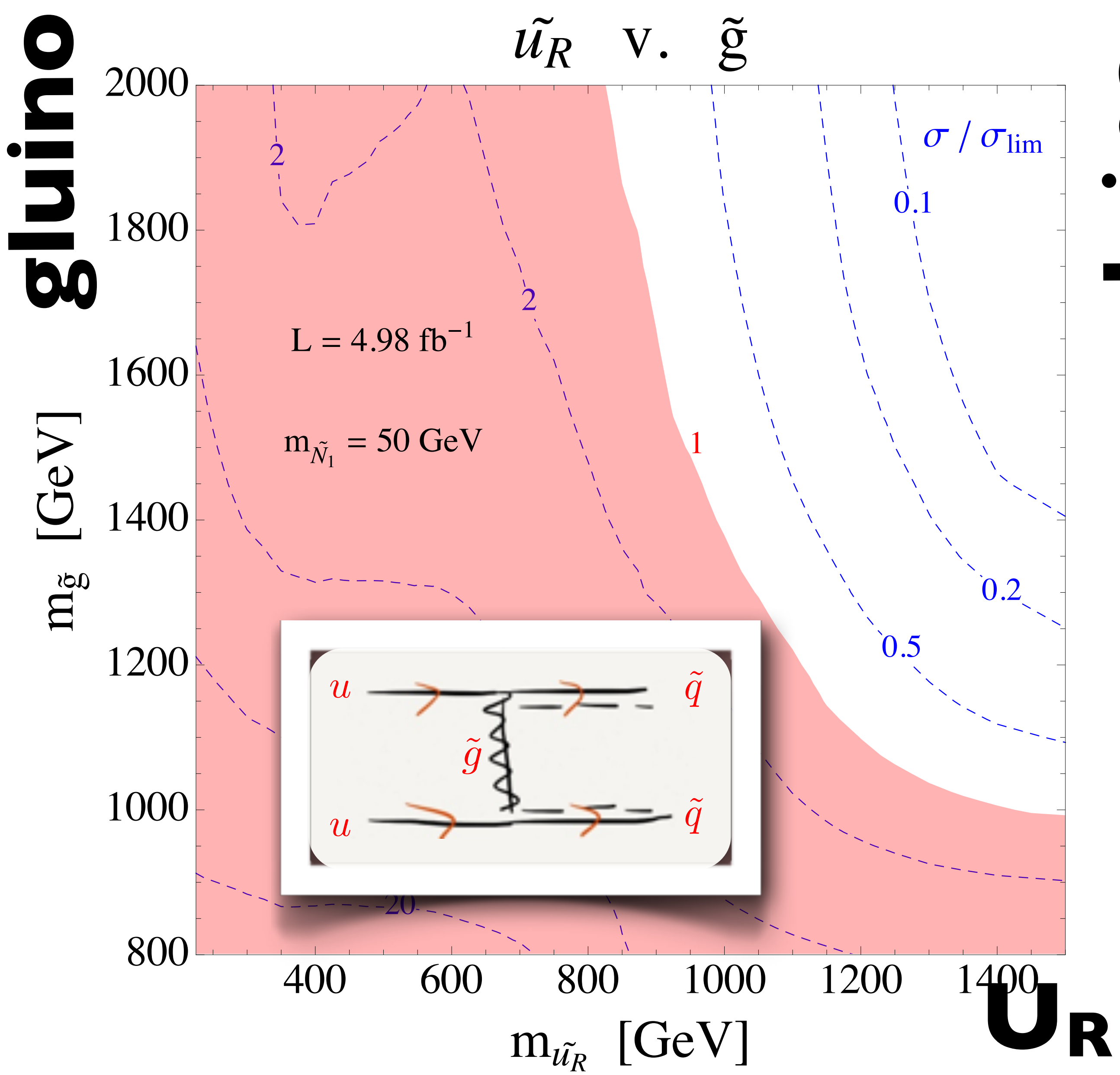


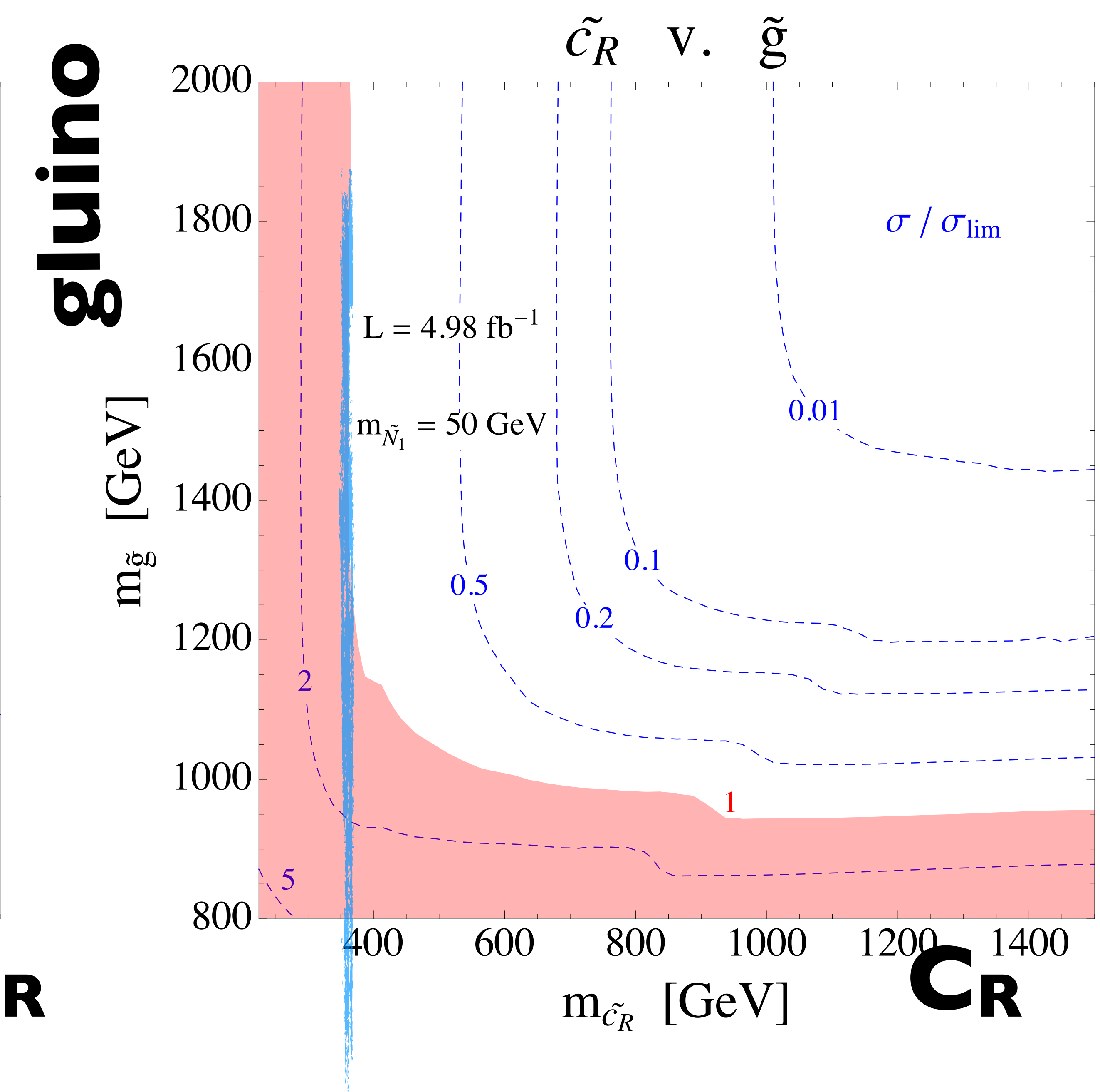
$\frac{1}{m_{\tilde{g}}}\tilde{q}\tilde{q}\, u_R u_R$ dim5-operator

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

slow decoupling

M. Papucci, J. Ruderman
G. Perez, R. Mahbubani, AW





$$\frac{1}{m_{\tilde{g}}}\tilde{q}\tilde{q}\,u_R u_R$$ dim5-operator

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

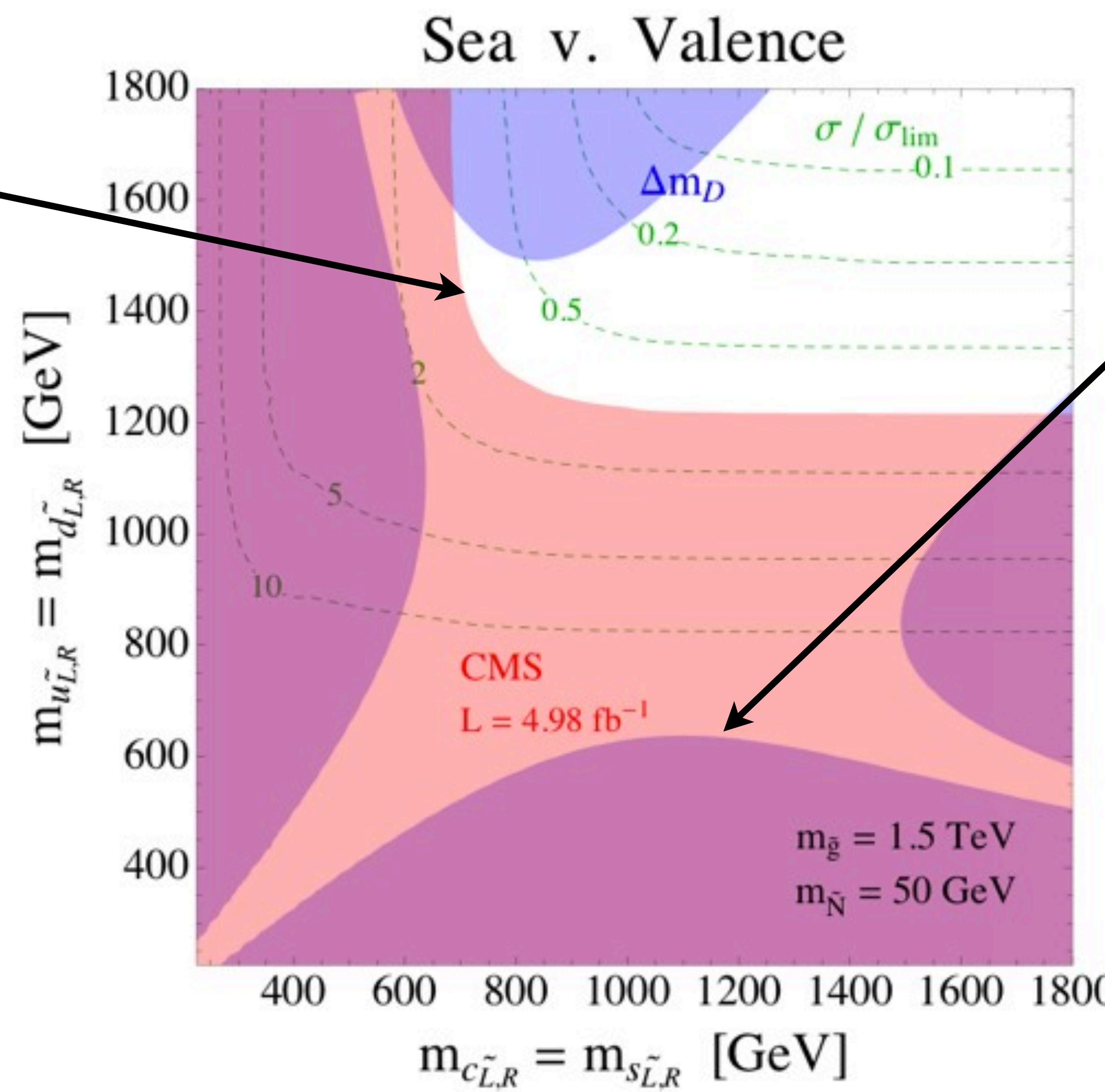
slow decoupling

Sea squarks can still be < 350 GeV

M. Papucci, J. Ruderman
G. Perez, R. Mahbubani, AW

Collider vs. Flavor for sea & valence squarks

Collider constraint (CMS recast)



ΔM_D Flavor limit

$$H_{\text{eff}} = C_1\ (\overline{u}^i \gamma_\mu P_L\, c^i)\,(\overline{u}^j \gamma^\mu P_L\, c^j)\ , \qquad x_D \simeq 2.6 \times 10^{10}\ \text{Re}\ C_1$$

Assuming full down alignment, calculated w/o MIA


Come to where the flavor is...

Gauge Mediation

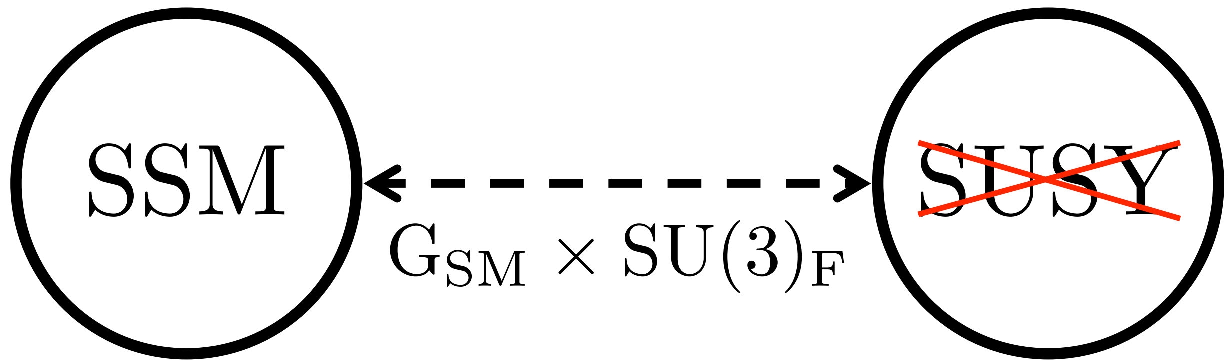
see e.g. Giudice/Rattazzi

$$\text{SSM} \xleftrightarrow[G_{\text{SM}}]{} \cancel{\text{SUSY}}$$

$$G_{\text{SM}} = SU(3) \times SU(2) \times U(1)$$

Flavor Gauge Mediation

U(1): Kaplan, Kribs '99; Craig, McCullough, Thaler '12



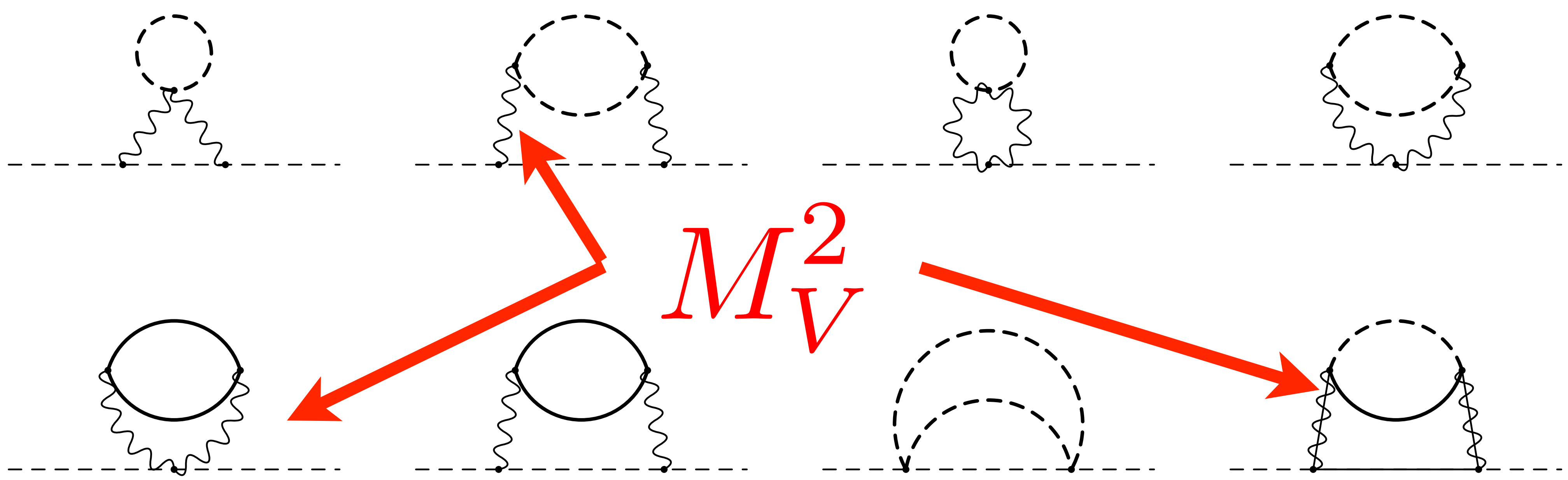
$$W = \frac{1}{M_{S_u}} \boldsymbol{S_u H_u Q U^c} + \frac{1}{M_{S_d}} \boldsymbol{S_d H_d Q D^c}$$

$$\langle \boldsymbol{S_u} \rangle = \begin{pmatrix} v_{u1} & 0 & 0 \\ 0 & v_{u2} & 0 \\ 0 & 0 & v_{u3} \end{pmatrix}, \qquad \langle \boldsymbol{S_d} \rangle = V_{\mathrm{CKM}} \begin{pmatrix} v_{d1} & 0 & 0 \\ 0 & v_{d2} & 0 \\ 0 & 0 & v_{d3} \end{pmatrix} V_{\mathrm{CKM}}^T$$

$$\propto Y_U \qquad\qquad \propto Y_D$$

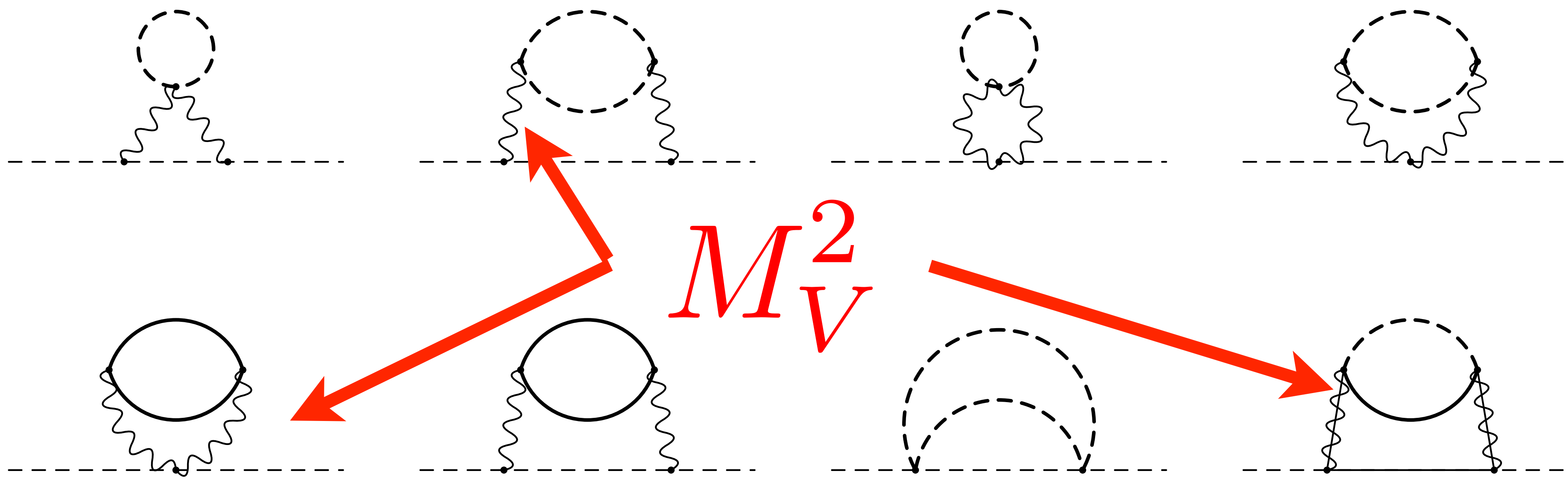
2-loop soft masses

Craig, McCullough, Thaler '12

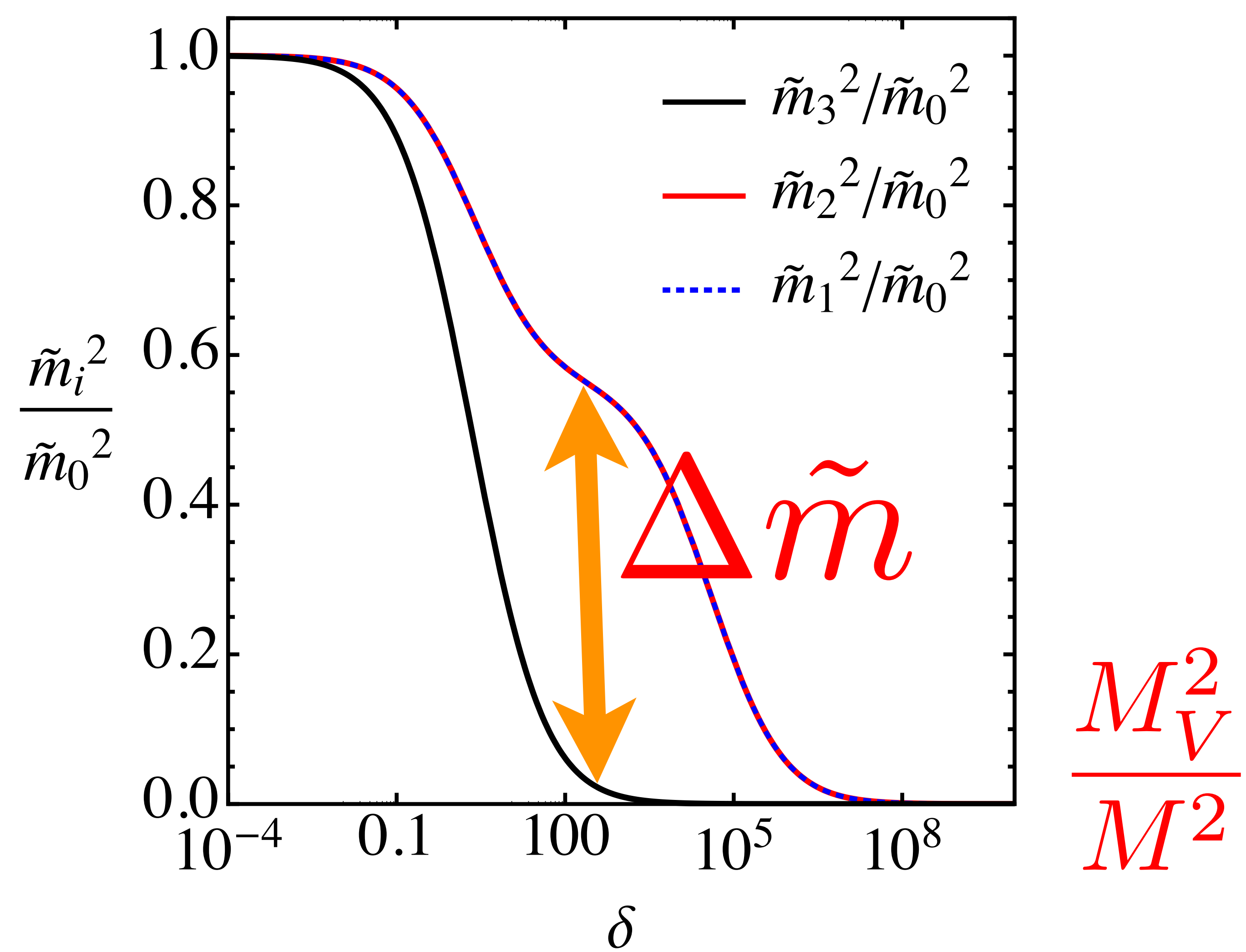


2-loop soft masses

Craig, McCullough, Thaler '12



3rd gen' flavor gauge bosons are heaviest
=> smallest soft-masses
→ natural stops



The missing missing energy

RPV SUSY

- R parity violated: LSP can decay
- Typically also the proton decays…

MFV RPV SUSY

Csaki, Grossman, Heidenreich '11 (see also C. Smith '08)

- R parity violated: LSP can decay
- Typically also the proton decays…
- If minimal flavor violating, only one holomorphic RPV term:

$$W_{\rm BNV} = \frac{1}{2}\, w''(Y_u\, \bar{u})(Y_d\, \bar{d})(Y_d\, \bar{d})$$

Tiny baryon number violation, e.g. $\lambda''_{uds} \sim \lambda^3 t_\beta^2 \frac{m_d m_s m_u}{2\, m_t^3}$

MFV RPV II

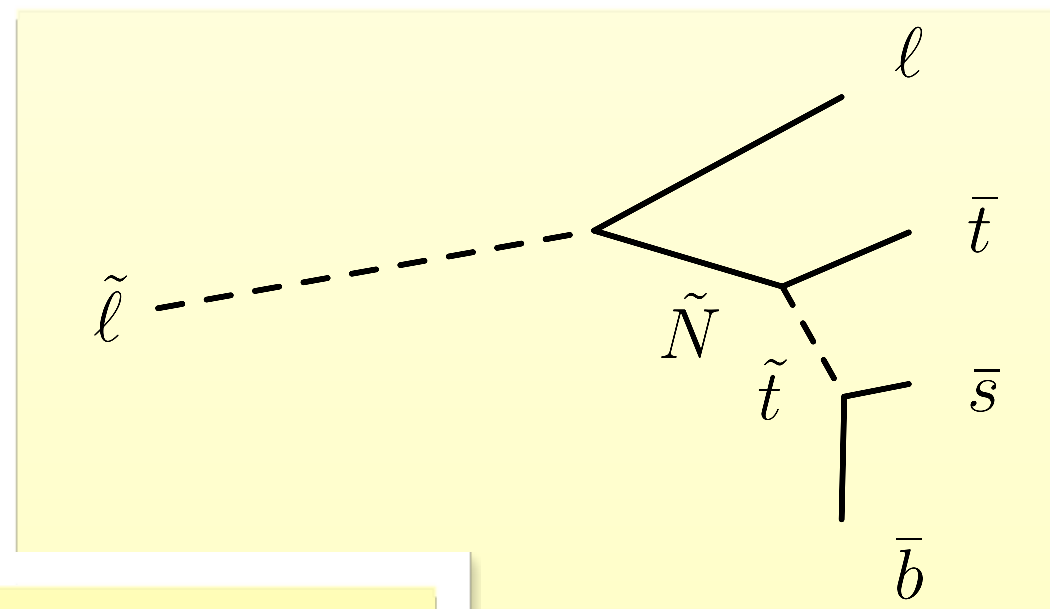
Berger, Csaki, Heidenreich, Grossman

Search for colored resonances/no MET…

Depending on LSP, interesting phenomenology

e.g. Slepton LSP:

4 body, displaced vertex

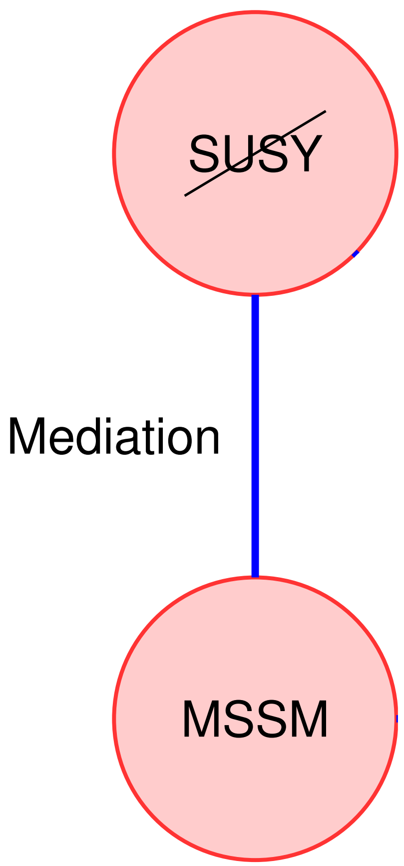


$$\tau_{\tilde{\tau}} \sim (44\ \mu\mathrm{m}) \left(\frac{45}{\tan\beta}\right)^4 \left(\frac{500\ \mathrm{GeV}}{m_{\tilde{\tau}}}\right)$$

Small missing energy without RPV

Stealth Susy

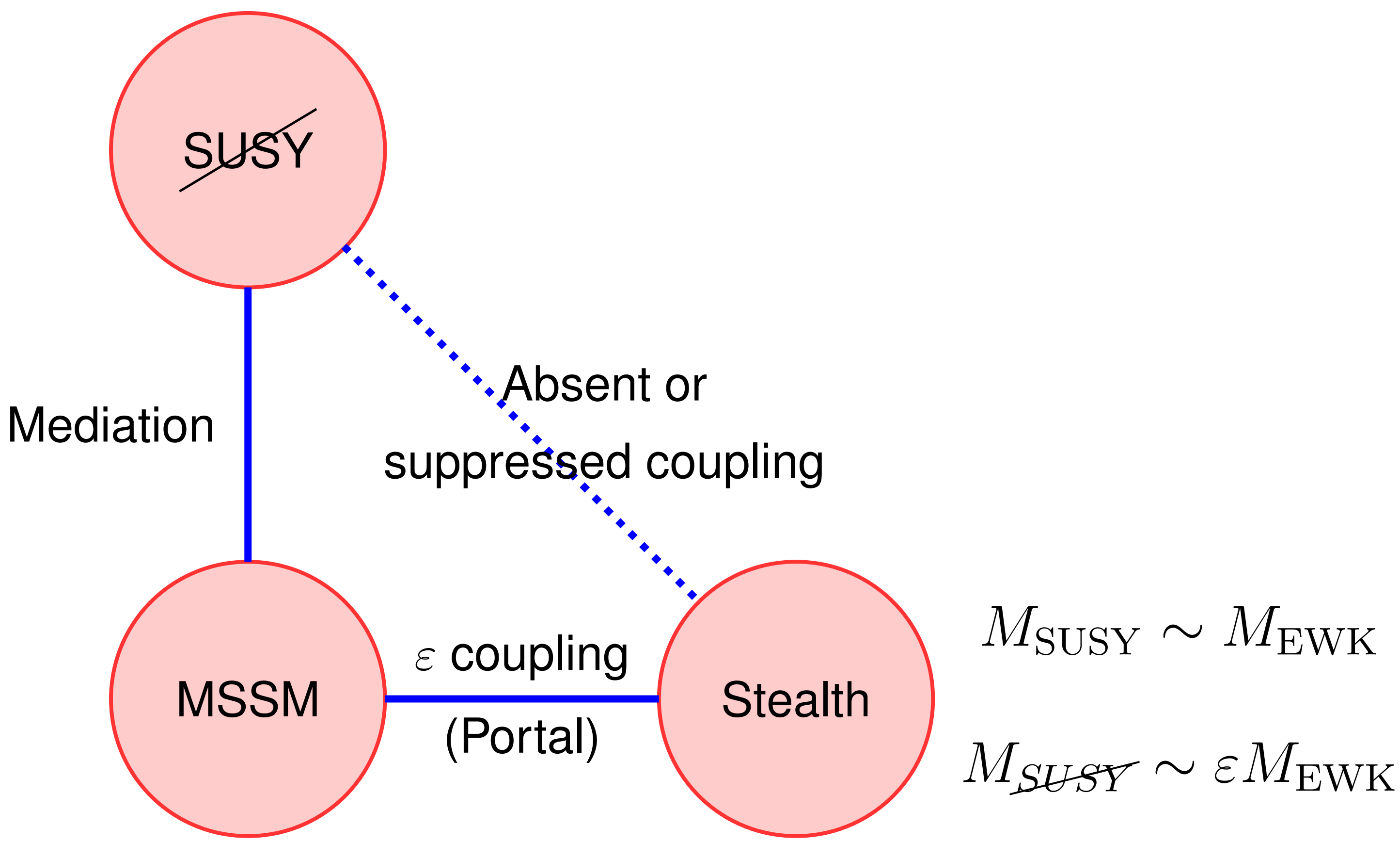
Fan, Reece, Ruderman '11



Standard picture

Stealth Susy

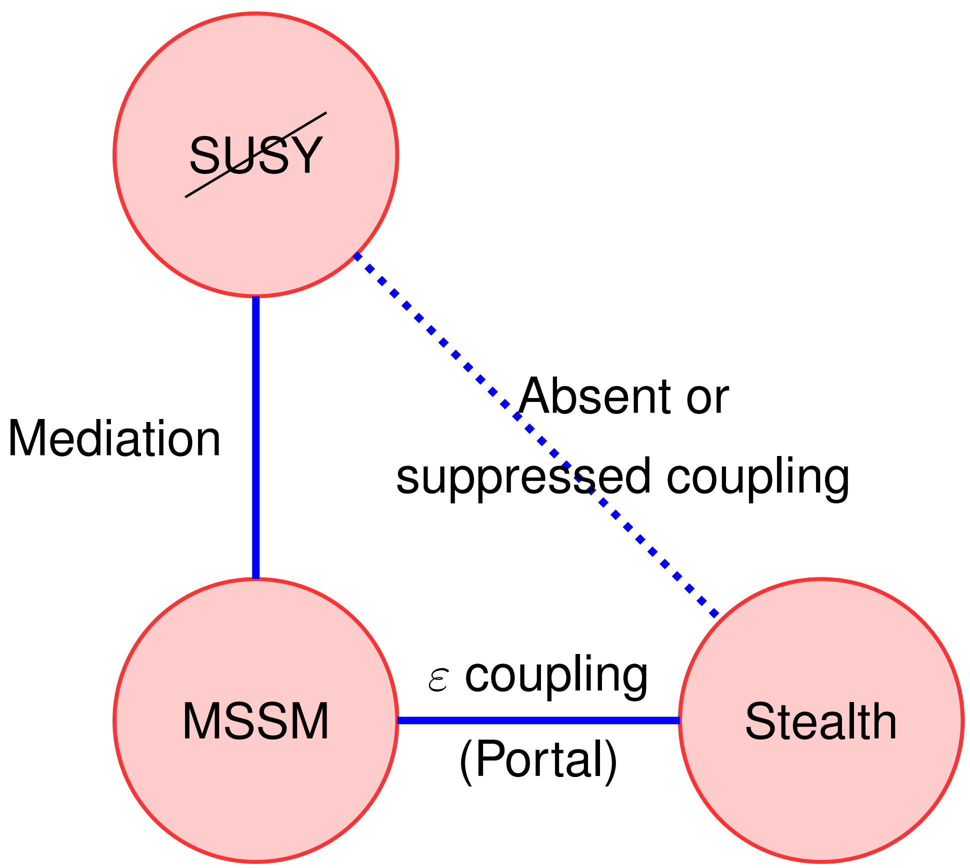
Fan, Reece, Ruderman '11



New sector with
small susy breaking

Stealth Susy

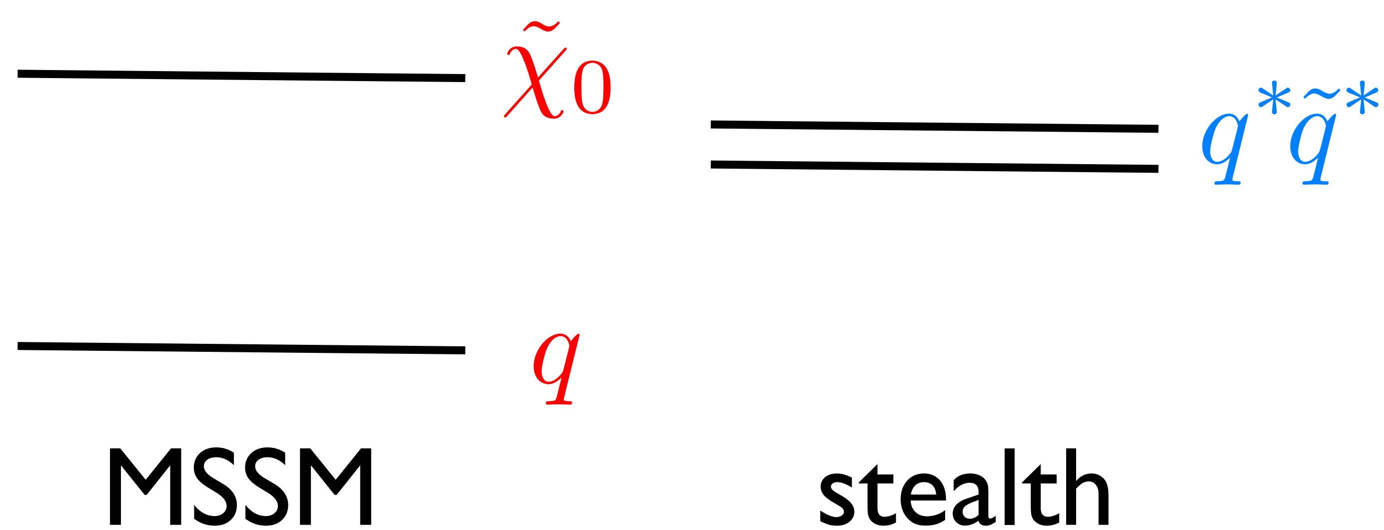
Fan, Reece, Ruderman '11



$M_{\rm SUSY} \sim M_{\rm EWK}$

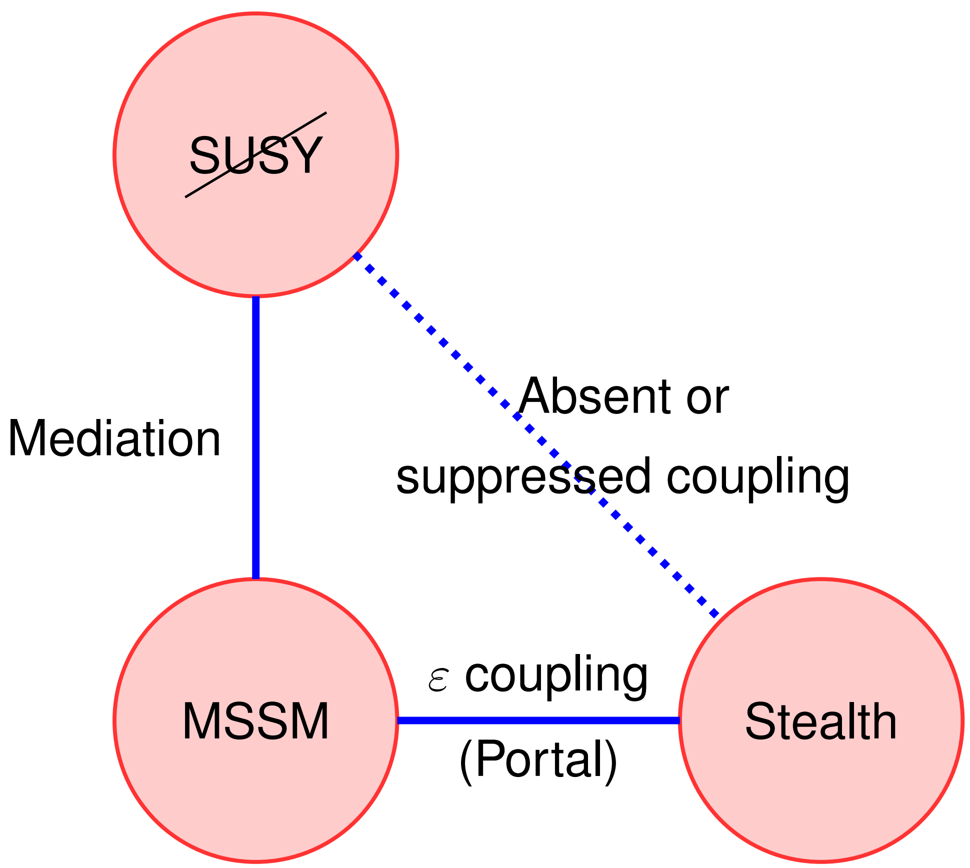
$M_{\cancel{SUSY}} \sim \varepsilon M_{\rm EWK}$

New sector with small susy breaking



Stealth Susy

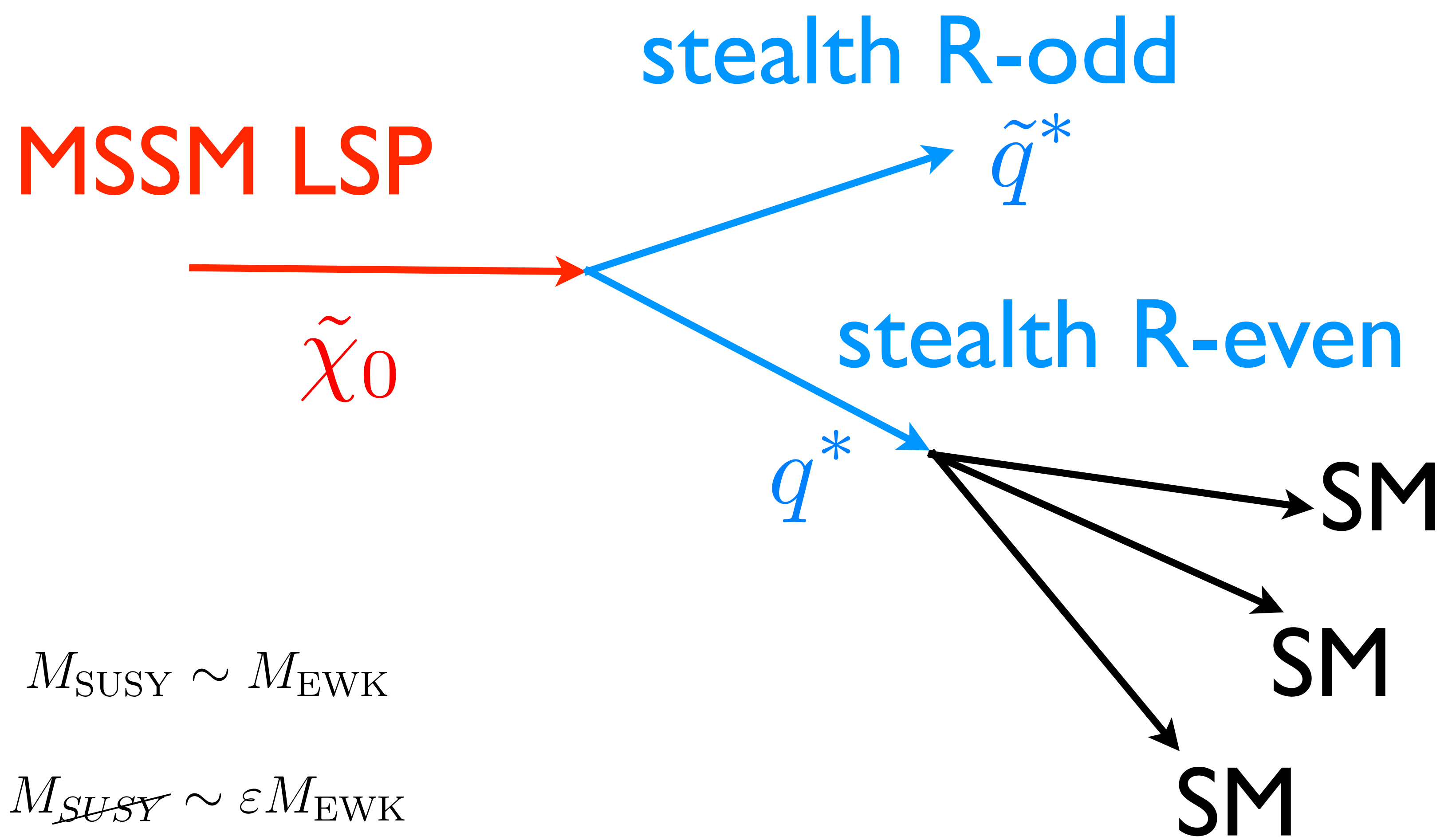
Fan, Reece, Ruderman '11



$M_{\text{SUSY}} \sim M_{\text{EWK}}$

$M_{\cancel{SUSY}} \sim \varepsilon M_{\text{EWK}}$

very little MET!



New sector with
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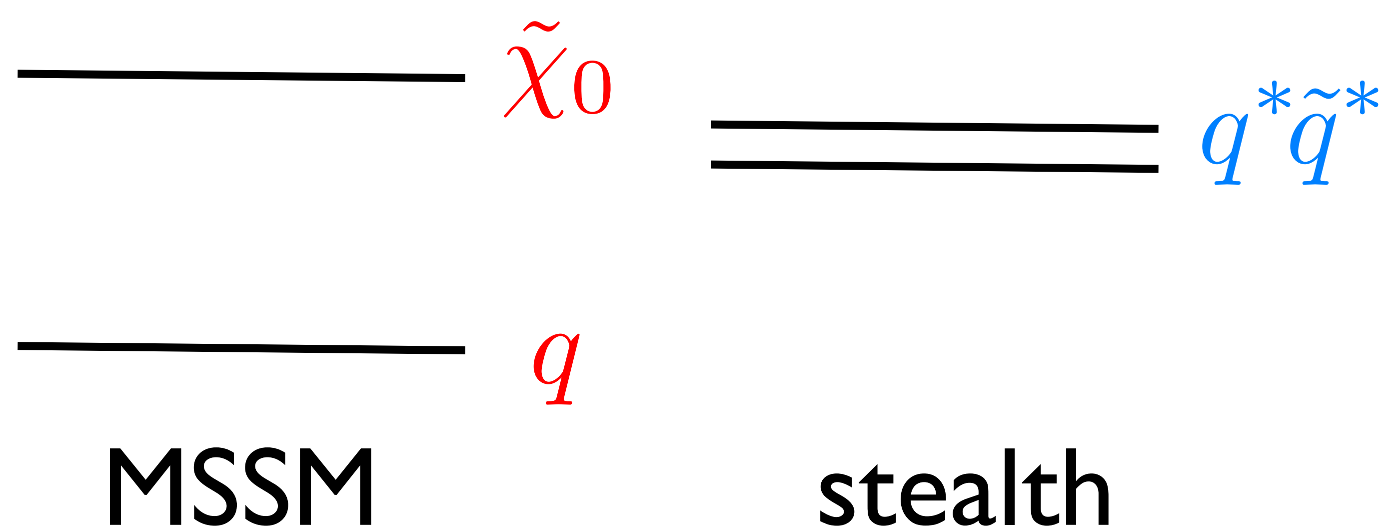
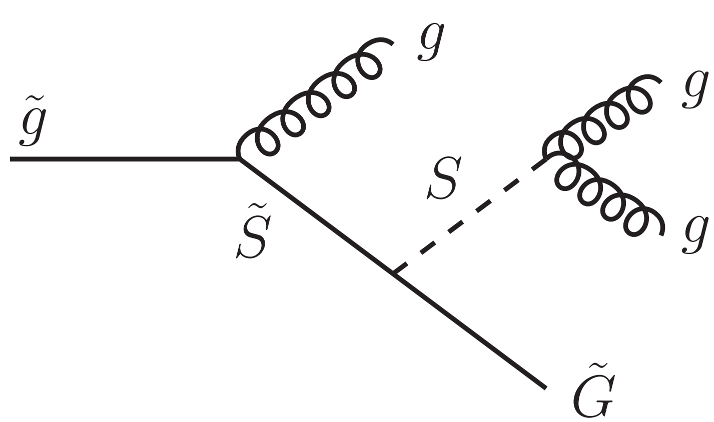
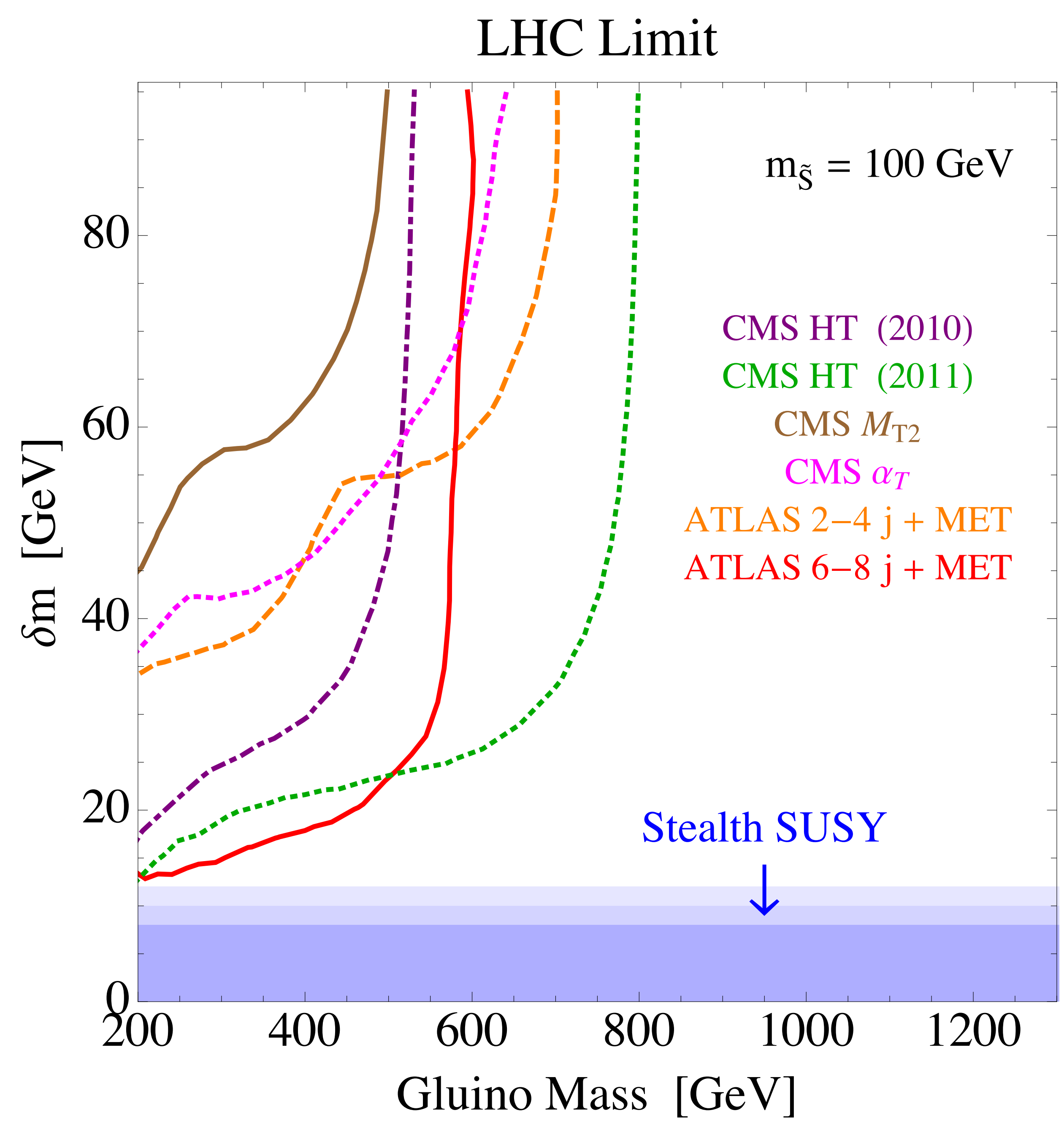


Stealth limits

Fan, Reece, Ruderman '11





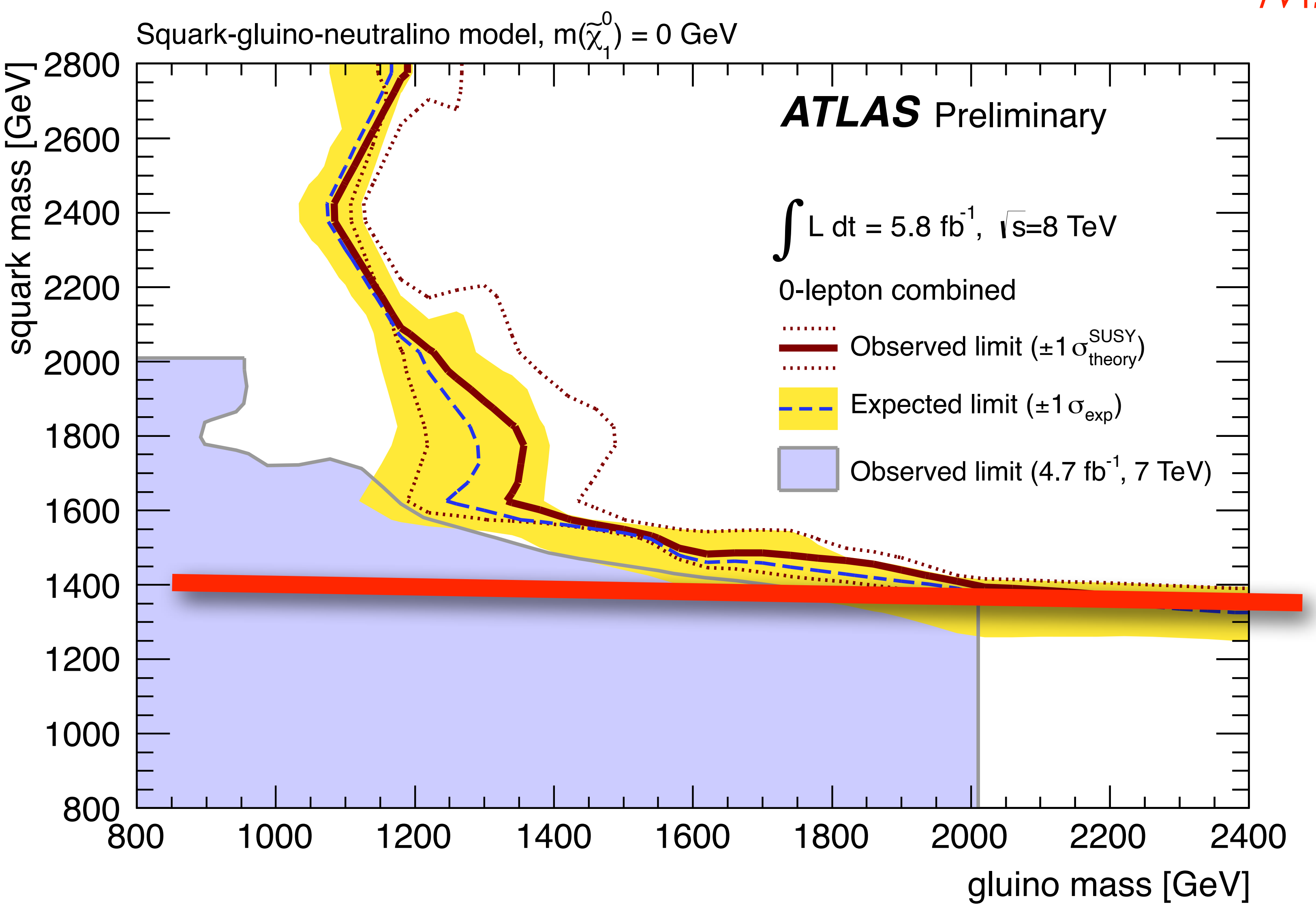
Conclusions

- Vanilla susy models pushed to high scales
- If supersymmetry is realized, could well be beyond MSSM
- Light squarks might be buried, stealthy, RPV, natural
- Intensify non-standard susy searches
- Still hoping for surprises!

Light non-degenerate squarks at the LHC

squarks

M. Papucci, J. Ruderman (LBL Berkely)
G. Perez, R. Mahbubani (CERN)



> 1.4 TeV

gluino

arXiv:1212.3328

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

M

8 dof

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

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

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

- Because of flavor constraints?

Not really.

Assumed spectrum in ATLAS/CMS plots

The SM flavor puzzle

$$Y_D \approx \mathrm{diag}\left(2\cdot 10^{-5} \quad 0.0005 \quad 0.02\right)$$

$$Y_U \approx \begin{pmatrix} 6\cdot 10^{-6} & -0.001 & 0.008+0.004i \\ 1\cdot 10^{-6} & 0.004 & -0.04+0.001 \\ 8\cdot 10^{-9}+2\cdot 10^{-8}i & 0.0002 & 0.98 \end{pmatrix}$$

Other dimensionless parameters of the SM:

$g_s \approx 1$, $g \approx 0.6$, $g' \approx 0.3$, $\lambda_{Higgs} \approx 1$, $|\theta| < 10^{-9}$

Operator	Bounds on Λ in TeV ($c_{ij}=1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

UTfit 08, Isidori, Perez, Nir '10

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Very strong suppression! New flavor violation must either approximately (exactly?) follow SM structure…

UTfit 08, Isidori, Perez, Nir '10

Operator	Bounds on Λ in TeV ($c_{ij}=1$) Re	Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	Im	Observables
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Very strong suppression! New flavor violation must either approximately (exactly?) follow SM structure…

… or exist only at very high scales (*10^2 - 10^5* TeV)

UTfit 08, Isidori, Perez, Nir '10

SUSY & Flavor

Flavor Bounds (K, D, B, Bs mixing, …) controlled by

$$(\delta^q_{ij})_{MM} = \frac{1}{\tilde{m}_q^2} \sum_\alpha (K^q_M)_{i\alpha} (K^q_M)^*_{j\alpha} \Delta \tilde{m}^2_{q_\alpha}$$

SUSY & Flavor

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mixing matrices

SUSY & Flavor

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mixing matrices   mass splitting

SUSY & Flavor

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mixing matrices mass splitting

(m=1TeV)

q	ij	$(\delta^q_{ij})_{MM}$	$\langle\delta^q_{ij}\rangle$
d	12	0.03	0.002
d	13	0.2	0.07
d	23	0.6	0.2
u	12	0.1	0.008

SUSY & Flavor

Flavor Bounds (K, D, B, Bs mixing, ...) controlled by

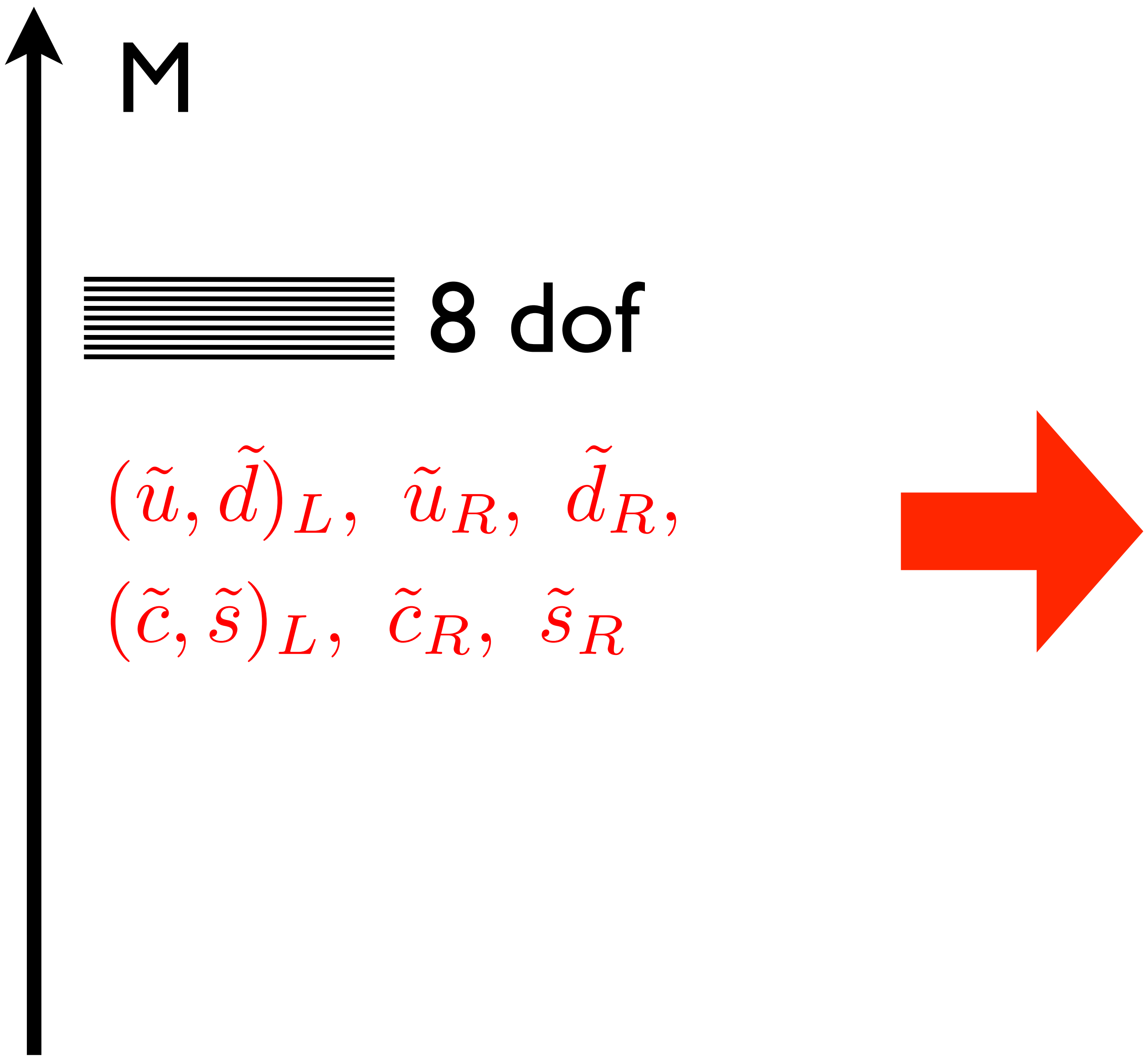
$$(\delta^q_{ij})_{MM} = \frac{1}{\tilde{m}^2_q} \sum_\alpha \boxed{(K^q_M)_{i\alpha}(K^q_M)^*_{j\alpha}} \boxed{\Delta\tilde{m}^2_{q_\alpha}}$$

mixing matrices mass splitting

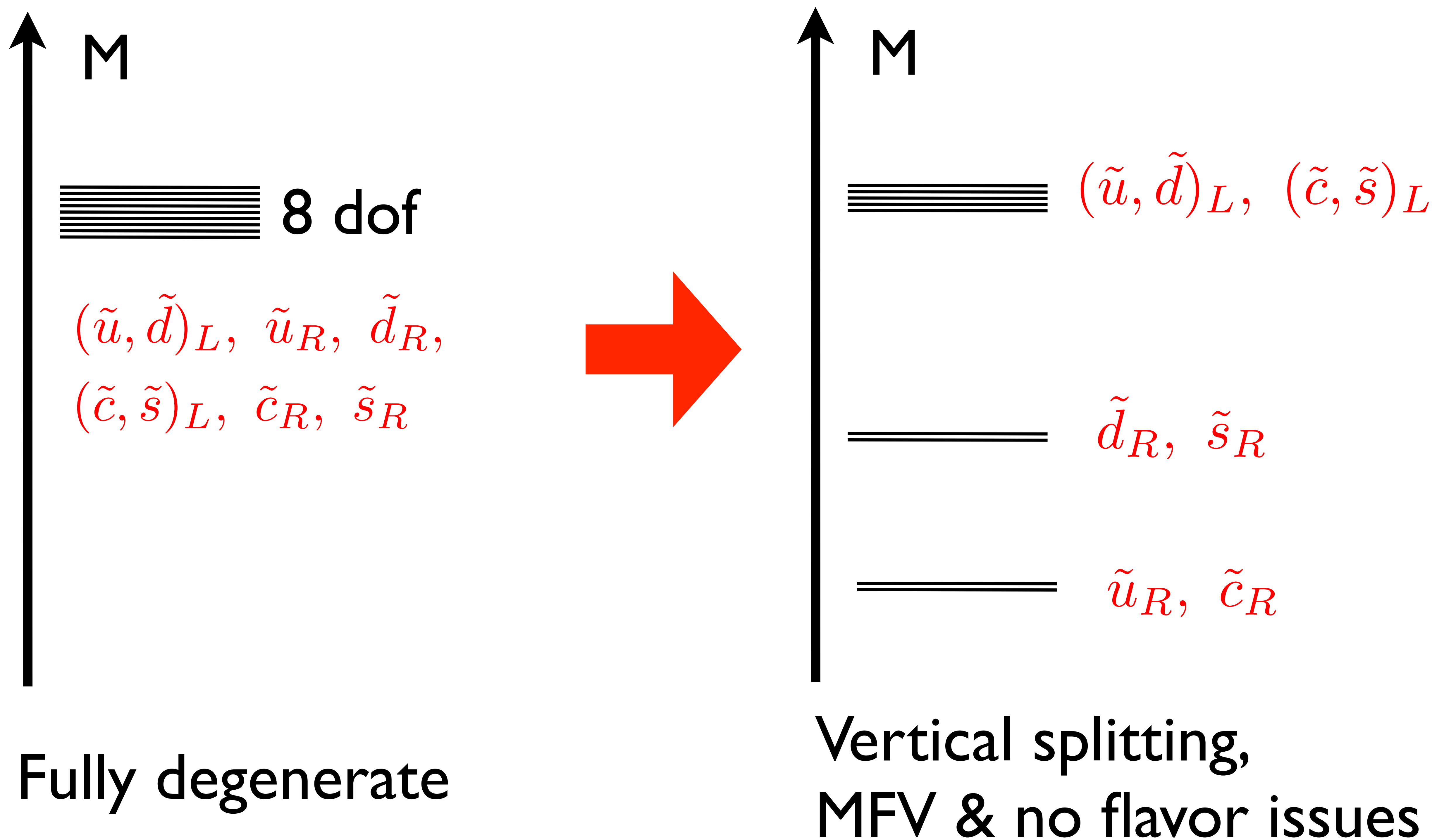
(m=1TeV)

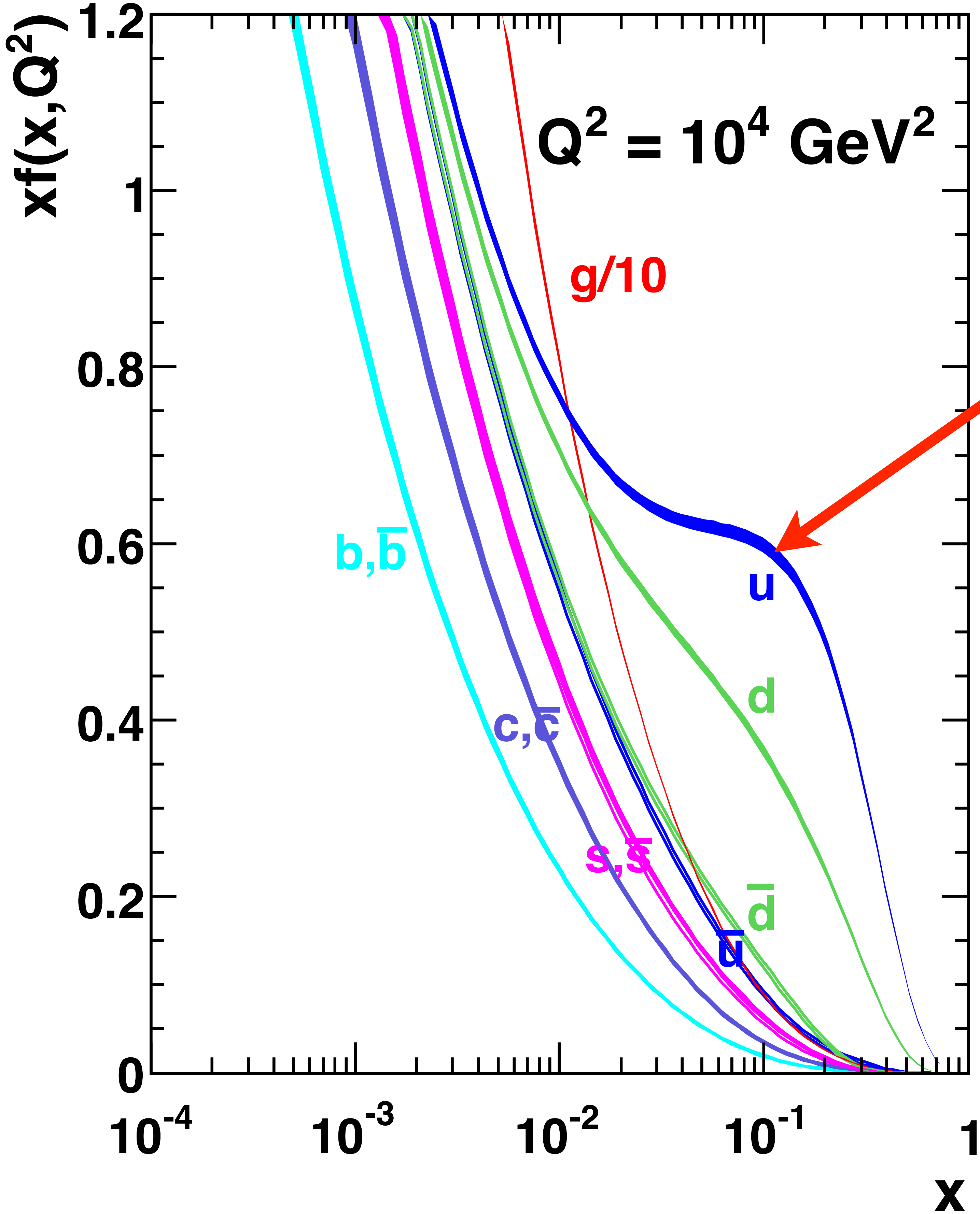
q	ij	$(\delta^q_{ij})_{MM}$	$\langle\delta^q_{ij}\rangle$
d	12	0.03	0.002
d	13	0.2	0.07
d	23	0.6	0.2
u	12	0.1	0.008

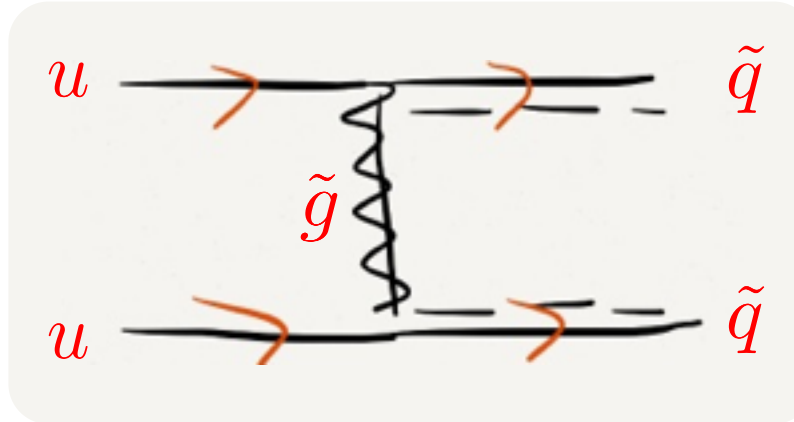
large mixing
means splitting
must be << 1



Fully degenerate


M
8 dof
$(\tilde{u},\tilde{d})_L,\ \tilde{u}_R,\ \tilde{d}_R,$
$(\tilde{c},\tilde{s})_L,\ \tilde{c}_R,\ \tilde{s}_R$
Fully degenerate
M
$(\tilde{u},\tilde{d})_L,\ (\tilde{c},\tilde{s})_L$
$\tilde{d}_R,\ \tilde{s}_R$
$\tilde{u}_R,\ \tilde{c}_R$
Vertical splitting,
MFV & no flavor issues



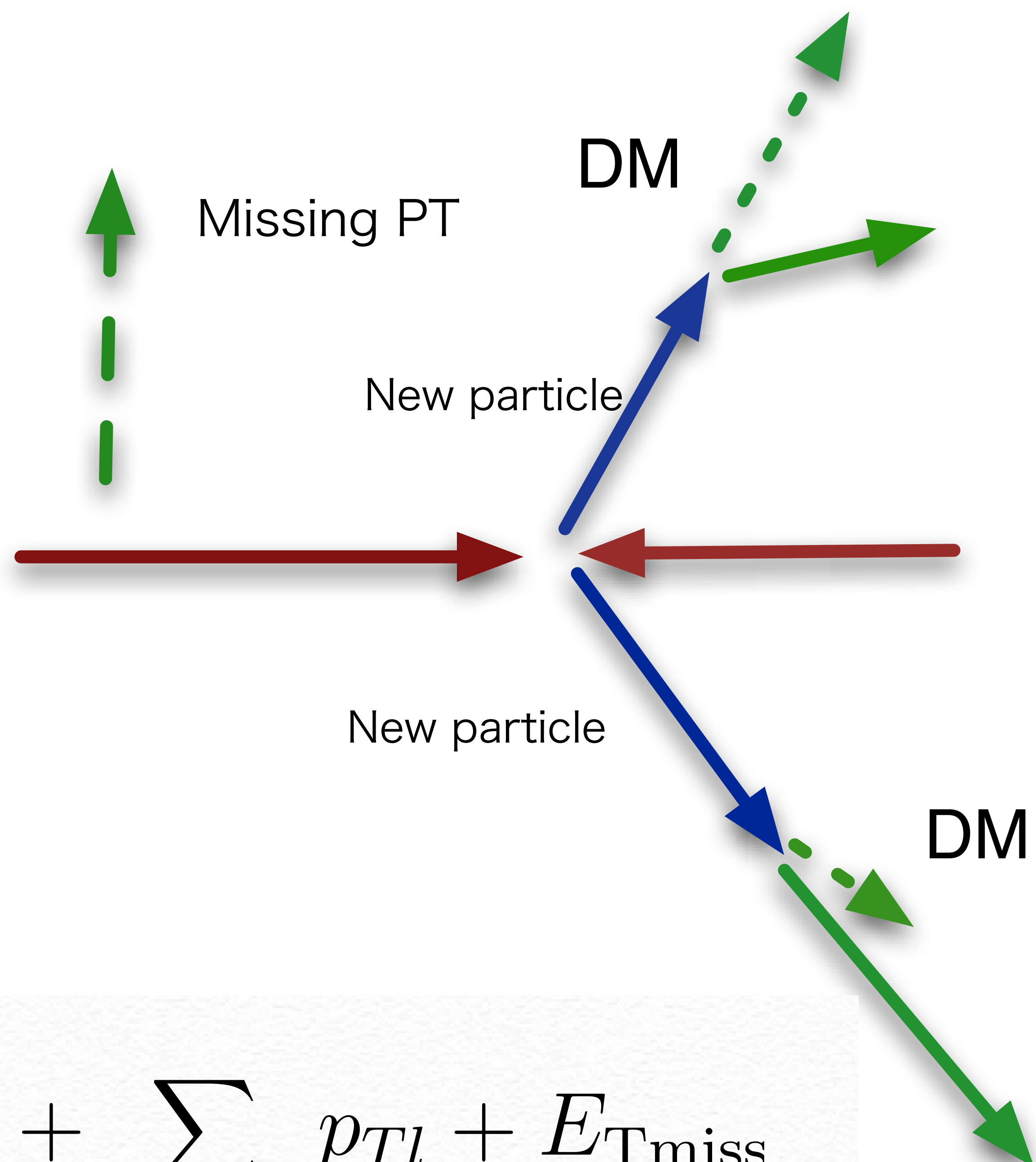


access to large up quark pdf

$$E \approx x \cdot 7\,\mathrm{TeV}$$

What has the LHC done to your favorite Model?

Basic idea



E_{Tmiss}

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

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, 1ifb

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, 1ifb

Signal Region	$\geq$ 2-jet	$\geq$ 3-jet	$\geq$ 4-jet	High mass
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 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
$\Delta\phi(\mathrm{jet}, \vec{P}_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}}$	> 0.4	> 0.4	> 0.4	> 0.4
$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$	> 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, $m_{\text{eff}} > 500$ GeV	$\geq$ 4-jet, $m_{\text{eff}} > 1000$ 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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upper bound on signal xsec

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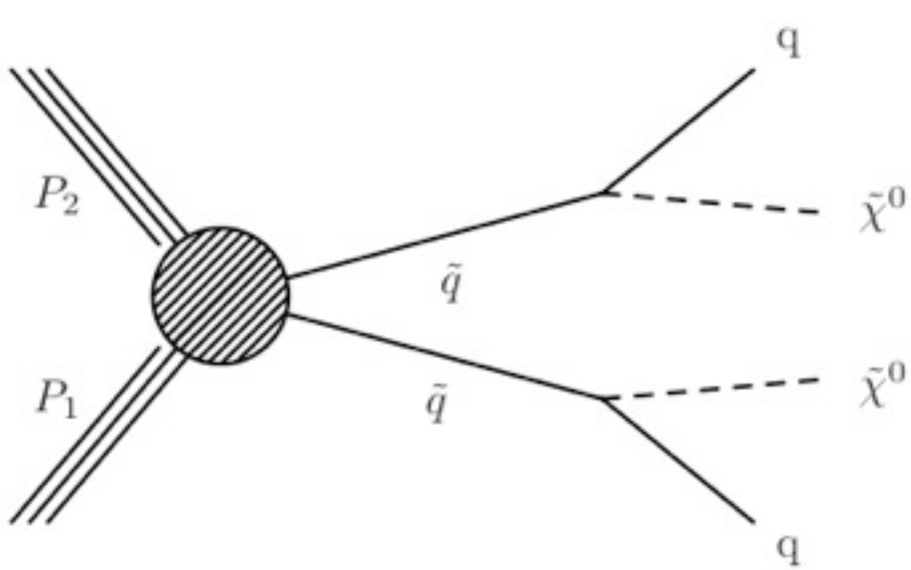
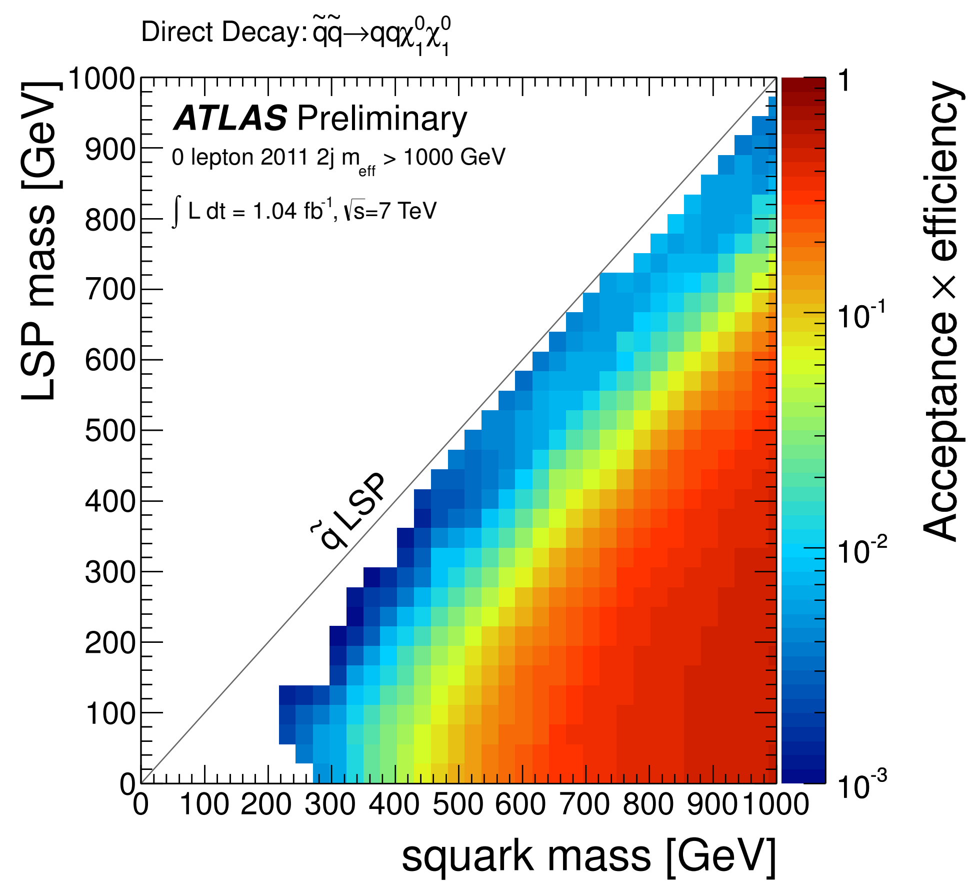
LIMIT!

Simplified Models

- ATLAS and CMS provide efficiencies for a small set of simplified models

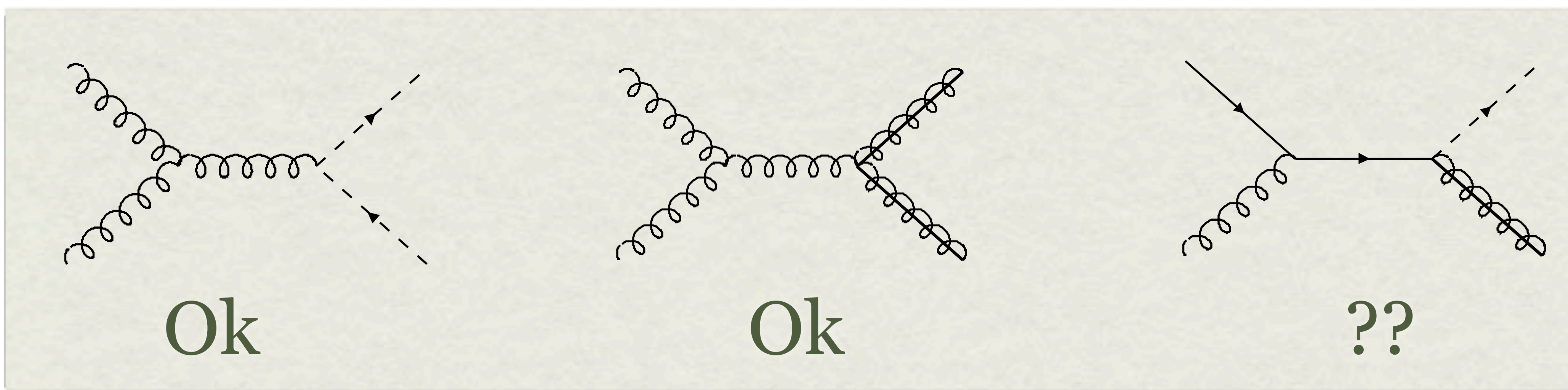




simplified topology

Unfortunately, simplified models are usually not sufficient.

Susy example: jets + MET



Simplified models do not cover associate production, pair produced non-degenerate squarks, …

Unreasonable to produce simplified models for every conceivable case* (especially for only setting limits)

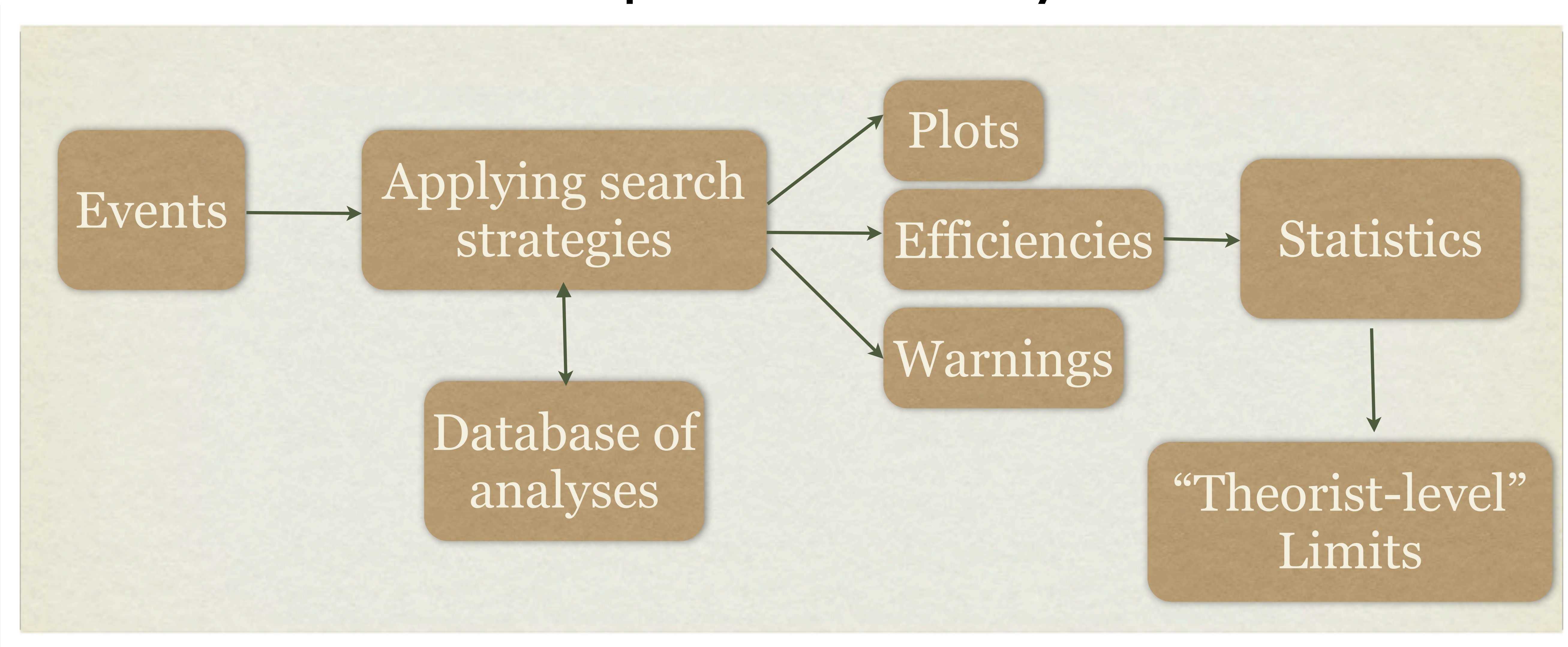
One needs to do something else...

Have to extract ε*A ourselves
(and compare with information provided)

* see e.g. http://www.lhcnewphysics.org for an attempt at an exhaustive list

ATOM: automatic test of models

A fast, local way to (approximately) “re-interpret” LHC analyses



w/ M. Papucci (LBL), D. Neuenfeld

Analyses (12k lines), Atom Core (~25k lines)

Two options:

1) "Truth level" (within 20-30% right answer)

- o lepton isolation (projection) according to various requirements of ATLAS and CMS
- o b and τ tagging done by looking in jet for a b or τ progenitor and applying efficiency factor/fake factor
- o residual (20%) efficiency correction: compare with available data

Extract efficiency corrections by comparing with available data

2) Apply efficiencies and smearing defined per object per experiment per year, pT and η- dependent

```
% atom --list-analyses
```

```
ATLAS_2010_CONF_2010_049    Cross-section of and fragmentation function in anti-kt track jets
ATLAS_2010_S8591806         Charged particles at 900 GeV in ATLAS
ATLAS_2010_S8755477         $Dijet mass distriubtion$
ATLAS_2010_S8814007         Dijet Angular distributions at 7 TeV with $3.1pb^{-1}$.
ATLAS_2010_S8817804         Inclusive jet cross section and di-jet mass and chi spectra at 7 TeV in ATLAS
ATLAS_2010_S8894728         Track-based underlying event at 900 GeV and 7 TeV in ATLAS
ATLAS_2010_S8914249         Diphoton+MET search
ATLAS_2010_S8914702         Inclusive isolated prompt photon analysis
ATLAS_2010_S8918562         Track-based minimum bias at 900 GeV and 2.36 and 7 TeV in ATLAS
ATLAS_2010_S8919674         W+jets jet multiplicities and pT
ATLAS_2011_CONF_2011_036    Anomalous MET in ttbar Events at the LHC 7TeV with $35pb^{-1}$.
ATLAS_2011_CONF_2011_039    Trileptons search at 7 TeV with $35pb^{-1}$.
ATLAS_2011_CONF_2011_086    Jets+MET at 7 TeV with $165pb^{-1}$.
ATLAS_2011_CONF_2011_090    1lepton+jets+MET at 7 TeV with $165pb^{-1}$.
ATLAS_2011_CONF_2011_096    <Insert short ATLAS_2011_CONF_2011_096 description>
ATLAS_2011_CONF_2011_098    bjets+MET+0L at 7 TeV with $830pb^{-1}$.
ATLAS_2011_CONF_2011_123    <Insert short ATLAS_2011_CONF_2011_123 description>
ATLAS_2011_CONF_2011_126    Search for Anomalous Production of Prompt Like-sign Muon Pairs with 1.6 $fb^{-1}$.
ATLAS_2011_CONF_2011_130    bjets+1lept+jets+MET SUSY search at 7TeV with $1fb^{-1}$
ATLAS_2011_CONF_2011_144    <Insert short ATLAS_2011_CONF_2011_144 description>
ATLAS_2011_I919017          Measurement of ATLAS track jet properties at 7 TeV
ATLAS_2011_I925932          Measurement of the W pT with electrons and muons at 7 TeV
ATLAS_2011_I926145          Measurement of electron and muon differential cross-section from heavy-flavour decays
ATLAS_2011_I944826          KS0 and Lambda production at 0.9 and 7 TeV with ATLAS
ATLAS_2011_I945498          Z+jets in pp at 7TeV
ATLAS_2011_S8924791         Jet shapes at 7 TeV in ATLAS
ATLAS_2011_S8970084         1lepton+jets+MET at 7 TeV with $35pb^{-1}$.
ATLAS_2011_S8971293         Dijet azimuthal decorrelations
ATLAS_2011_S8983313         Jets+MET at 7 TeV with $35pb^{-1}$.
ATLAS_2011_S8994773         Calo-based underlying event at 900 GeV and 7 TeV in ATLAS
ATLAS_2011_S8996709         <Insert short ATLAS_2011_S8996709 description>
ATLAS_2011_S9002537         Muon charge asymmetry in W events at 7 TeV in ATLAS
ATLAS_2011_S9011218         bjets+MET at 7 TeV with $35pb^{-1}$.
ATLAS_2011_S9019553         SF lepton pairs SUSY search  at 7 TeV with $35pb^{-1}$.
ATLAS_2011_S9019561         2leptons+MET at 7TeV with $35pb^{-1}$.
ATLAS_2011_S9108483         <Insert short ATLAS_2011_S9108483 description>
ATLAS_2011_S9120726         Diphoton+MET at 7TeV with $36 pb^{-1}$
ATLAS_2011_S9120807         Inclusive isolated diphoton analysis
ATLAS_2011_S9126244         Measurement of dijet production with a veto on additional central jet activity
ATLAS_2011_S9128077         Measurement of multi-jet cross sections
ATLAS_2011_S9131140         Measurement of the Z pT with electrons and muons at 7 TeV
ATLAS_2011_S9203559         <Insert short ATLAS_2011_S9203559 description>
ATLAS_2011_S9225137         multijet SUSY search at 7TeV
ATLAS_2012_CONF_2012_033    2-6 jets + MET SUSY search at 7TeV
ATLAS_2012_I1082009         $D^{*\pm}$ production in jets
ATLAS_2012_I1082936         Inclusive jet and dijet cross sections at 7 TeV
ATLAS_2012_I1083318         W+jets production at 7 TeV
ATLAS_2012_I1084540         Rapidity gap cross sections measured with the ATLAS detector in pp collisions at sqrt(
ATLAS_2012_I1091481         Azimuthal ordering of charged hadrons
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CMS_2011_S8950903            Dijet azimuthal decorrelations in $pp$ collisions at $\sqrt{s} = 7$ TeV
CMS_2011_S8957746            Event shapes
CMS_2011_S8968497            Measurement of dijet angular distributions and search for quark compositeness in $pp$ collisions at $\
CMS_2011_S8973270            B/anti-B angular correlations based on secondary vertex reconstruction in pp collisions
CMS_2011_S8978280            Kshort, Lambda, and Cascade- transverse momentum and rapidity spectra from proton-proton collisions at
CMS_2011_S8990433            Diphoton+MET at 7 TeV with $35pb^{-1}$.
CMS_2011_S8991847            OS dileptons at 7TeV with $35pb^{-1}$
CMS_2011_S9036504            Same Sign dileptons at 7TeV in $35pb^{-1}$
CMS_2011_S9086218            Measurement of the inclusive jet cross-section in $pp$ collisions at $\sqrt{s} = 7$ TeV
CMS_2011_S9088458            Measurement of ratio of the 3-jet over 2-jet cross section in pp collisions at sqrt(s) = 7 TeV
CMS_2011_S9120041            Traditional leading jet UE measurement at $\sqrt(s)=0.9$ and 7 TeV
CMS_2011_S9215166            Forward energy flow in MB and dijet events at 0.9 and 7 TeV
CMS_PAS_EXO_11_017           Search for quark compositeness in dijet angular distributions from $pp$ collisions at $\sqrt{s} = 7$ T
CMS_PAS_EXO_11_036           <Insert short CMS_PAS_EXO_11_036 description>
CMS_PAS_EXO_11_050           <Insert short CMS_PAS_EXO_11_050 description>
CMS_PAS_EXO_11_051           Search for pair production of a fourth-generation t' quark in the lepton-plus-jets channel with the CM
CMS_PAS_SUS_10_005           HT,MHT susy search in jets+MET at 7 TeV with $35pb^{-1}$.
CMS_PAS_SUS_10_009           razor analysis on jets+MET and 1lepton+jets+MET at  7 TeV with $35pb^{-1}$.
CMS_PAS_SUS_10_011           $\alpha_T$ analysis on b jets+MET at 7 TeV with $35pb^{-1}$.
CMS_PAS_SUS_11_003           Jets+MET with $\alpha_T$ variable with $1.1 fb^{-1}$
CMS_PAS_SUS_11_004           <Insert short CMS_PAS_SUS_11_004 description>
CMS_PAS_SUS_11_005           <Insert short CMS_PAS_SUS_11_005 description>
CMS_PAS_SUS_11_006           <Insert short CMS_PAS_SUS_11_006 description>
CMS_PAS_SUS_11_010           <Insert short CMS_PAS_SUS_11_010 description>
CMS_PAS_SUS_11_011           <Insert short CMS_PAS_SUS_11_011 description>
CMS_PAS_SUS_11_015           <Insert short CMS_PAS_SUS_11_015 description>
CMS_PAS_SUS_11_017           Search for New Physics in Events with a Z Boson and Missing Transverse Energy
CMS_PAS_SUS_11_028           <Insert short CMS_PAS_SUS_11_028 description>
CMS_PAS_SUS_12_011           <Insert short CMS_PAS_SUS_12_011 description>
CMS_QCD_10_024               Pseudorapidity distributions of charged particles at sqrt(s)=0.9 and 7 TeV
D0_2000_S4480767             Transverse momentum of the W boson
D0_2001_S4674421             Tevatron Run I differential W/Z boson cross-section analysis
D0_2004_S5992206             Run II jet azimuthal decorrelation analysis
D0_2006_S6438750             Inclusive isolated photon cross-section, differential in pT(gamma)
D0_2007_S7075677             $Z/\gamma^* + X$ cross-section shape, differential in $y(Z)$
D0_2008_S6879055             Measurement of the ratio sigma($Z/\gamma^*$ + $n$ jets)/sigma($Z/\gamma^*$)
D0_2008_S7554427             $Z/\gamma^* + X$ cross-section shape, differential in $pT(Z)$
D0_2008_S7662670             Measurement of D0 Run II differential jet cross sections
D0_2008_S7719523             Isolated $\gamma$ + jet cross-sections, differential in pT($\gamma$) for various $y$ bins
D0_2008_S7837160             Measurement of W charge asymmetry from D0 Run II
D0_2008_S7863608             Measurement of differential $Z/\gamma^*$ + jet + $X$ cross sections
D0_2009_S8202443             $Z/\gamma^*$ + jet + $X$ cross sections differential in pT(jet 1,2,3)
D0_2009_S8320160             Dijet angular distributions
D0_2009_S8349509             Z+jets angular distributions
D0_2010_S8566488             Dijet invariant mass
D0_2010_S8570965             Direct photon pair production
D0_2010_S8671338             Measurement of differential $Z/\gamma^*$ pT
D0_2010_S8821313             Precise study of Z pT using novel technique
D0_2011_I895662              3-jet invariant mass
DELPHI_1995_S3137023         Strange baryon production in $Z$ hadronic decays at Delphi
DELPHI_1996_S3430090         Delphi MC tuning on event shapes and identified particles.
```
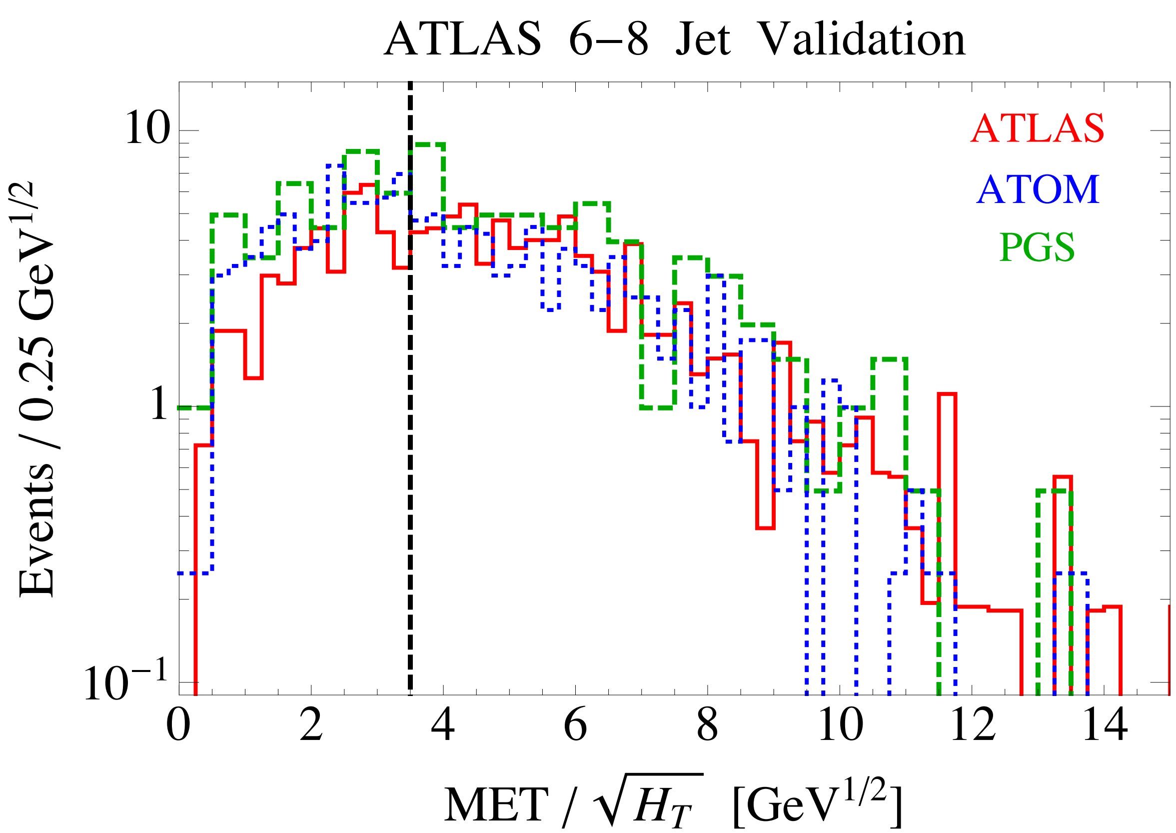
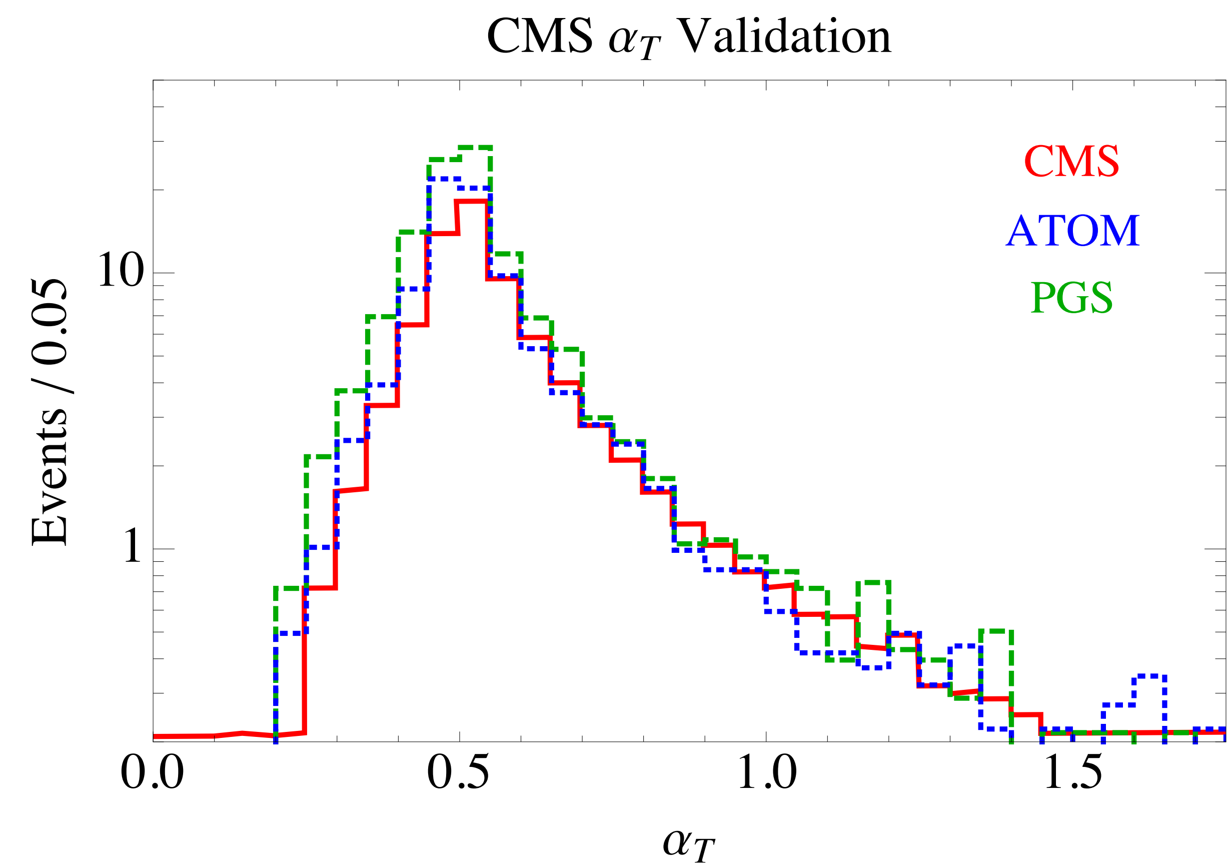

- Cut flow efficiencies, and final efficiencies per subprocess

Cuts (click to collapse)

Cut Flow	Description	Efficiency	Derivative
Ht	description of Ht cut	20.00%	-0.767
....MHt		11.72%	-1.089
........dphiJ1	description of dphiJ1 cut	11.53%	0.000
............dphiJ2		10.54%	-0.164
................dphiJ3		9.78%	0.000
....................lowHt		1.15%	0.382
........................lowHt1		0.61%	0.714
............................lowHt2		0.54%	0.000
................................lowHt3		0.00%	0.000
....................................lowHt4		0.00%	0.000
........................medHt		1.73%	0.000
............................high1Ht		1.71%	0.000
................................high1Ht1		0.65%	0.000
....................................high1Ht2		0.79%	1.894
....high1Ht3		0.28%	-5.356
................................high2Ht		1.83%	0.240
....................................high2Ht1		0.80%	0.000
....high2Ht2		1.03%	-1.862
....................................high3Ht		3.36%	-4.281
....high3Ht3		3.36%	-1.299
............................medHt1		0.20%	2.246
................................medHt2		1.15%	0.383
....................................medHt3		0.19%	0.000
....medHt4		0.19%	0.000





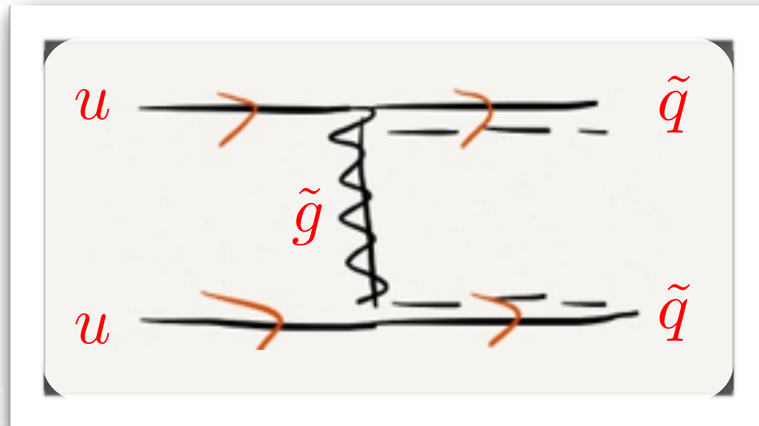
Check:

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

\+ compare to all available limit plots…

~ 50 GeV accuracy (usually better)

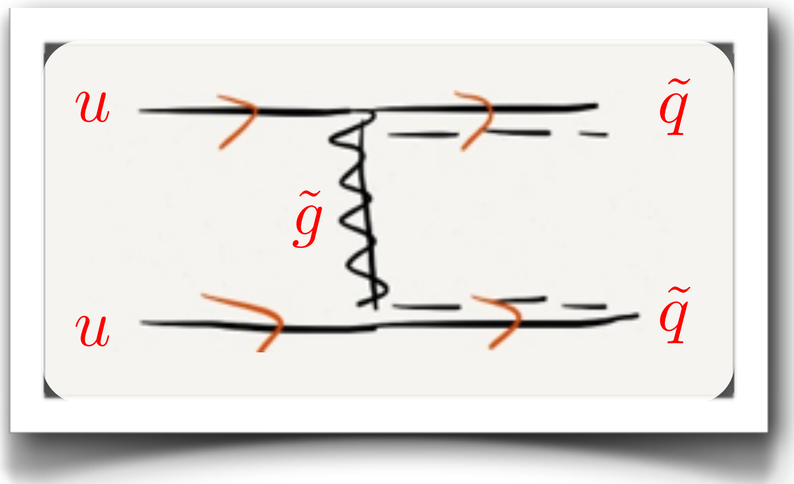
Remark on prospino



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

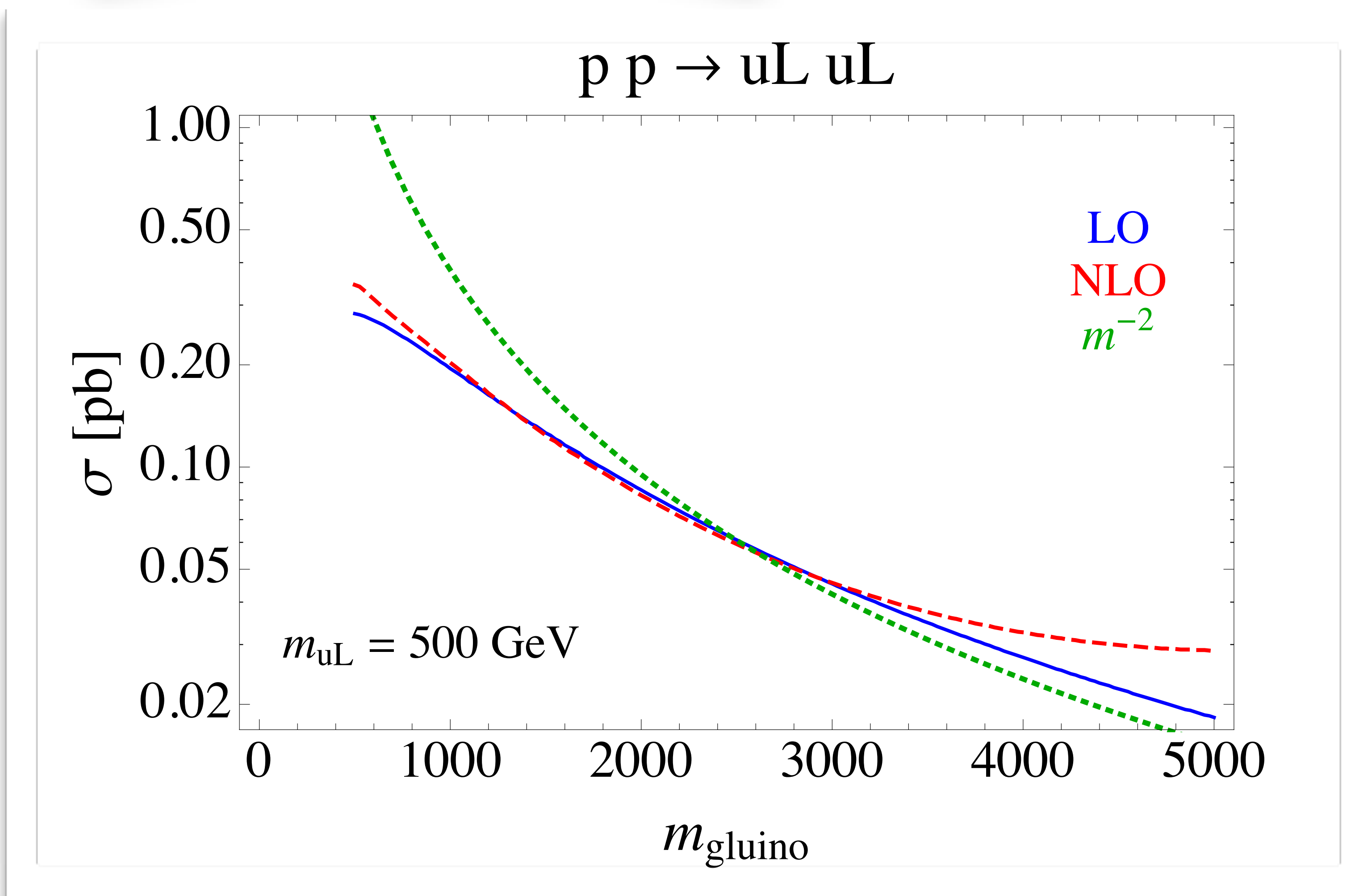
$$\rightarrow \quad \sigma \sim 1/m_{\tilde{g}}^2$$

Remark on prospino

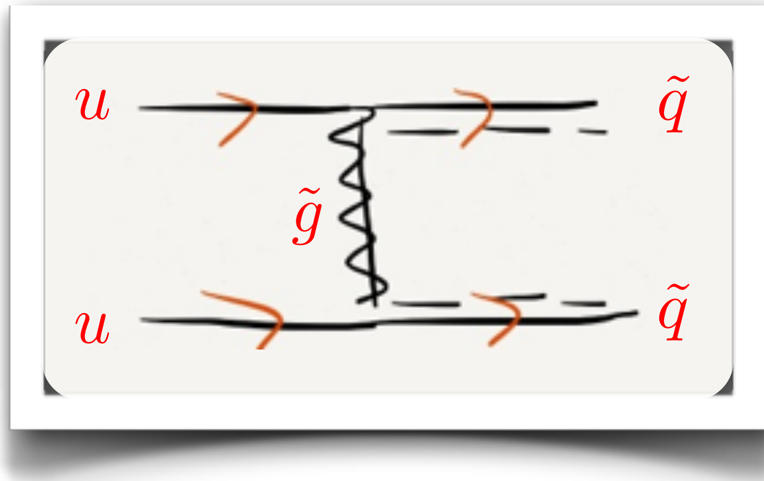


$$\frac{1}{m_{\tilde{g}}}\tilde{q}\tilde{q}\,u_R u_R$$ dim5 operator

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

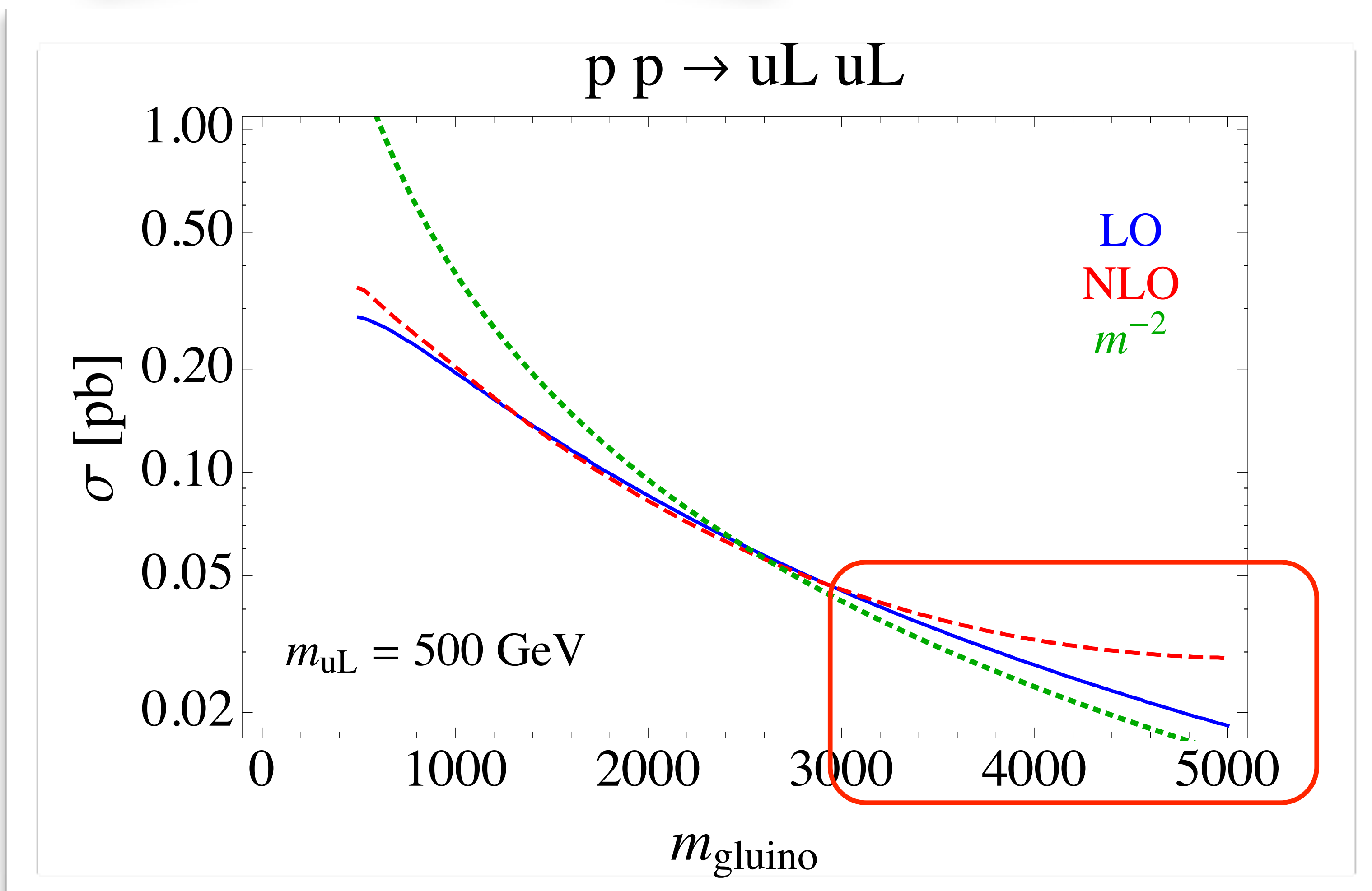


Remark on prospino



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

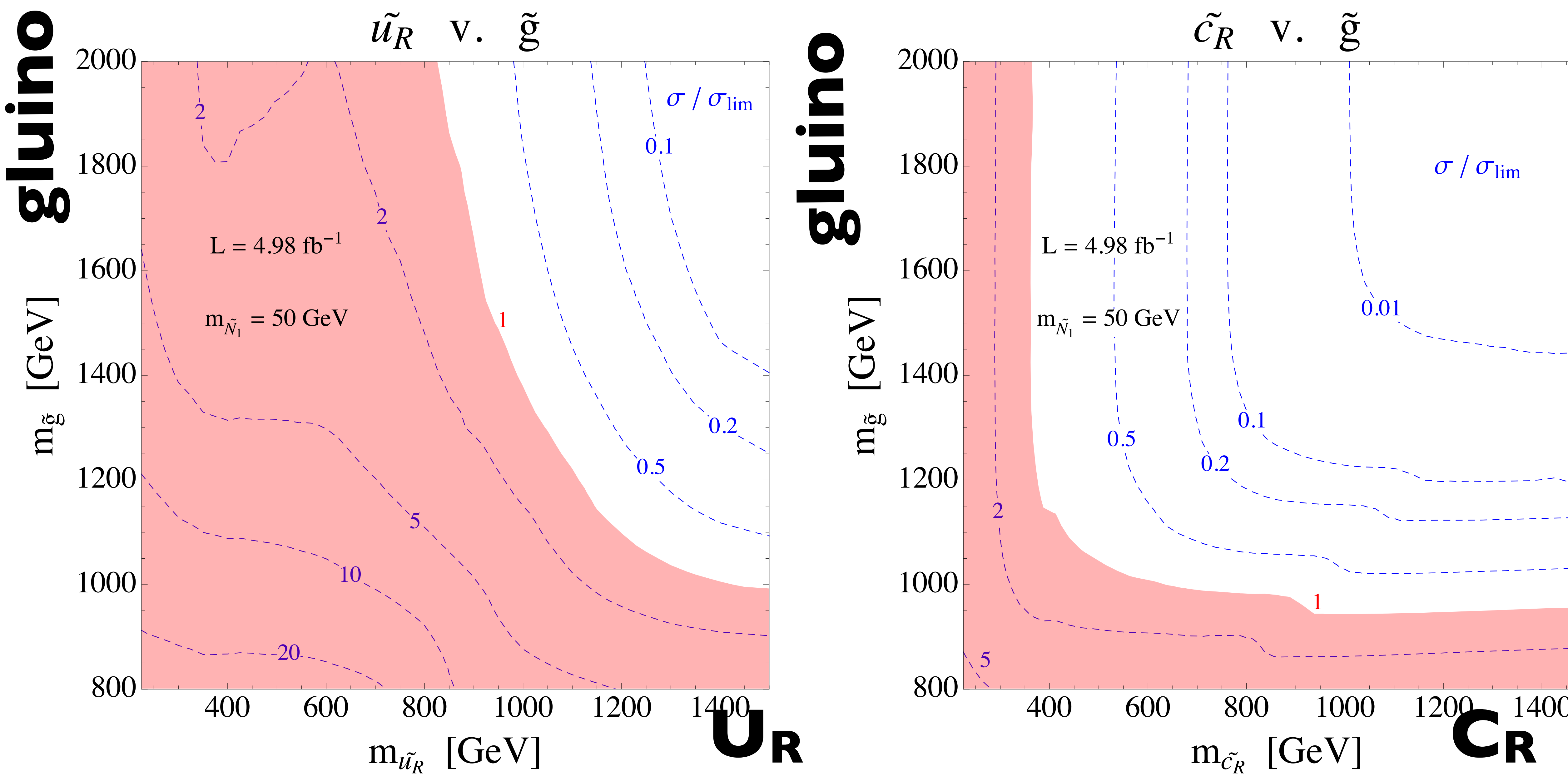
$$\rightarrow \quad \sigma \sim 1/m_{\tilde{g}}^2$$



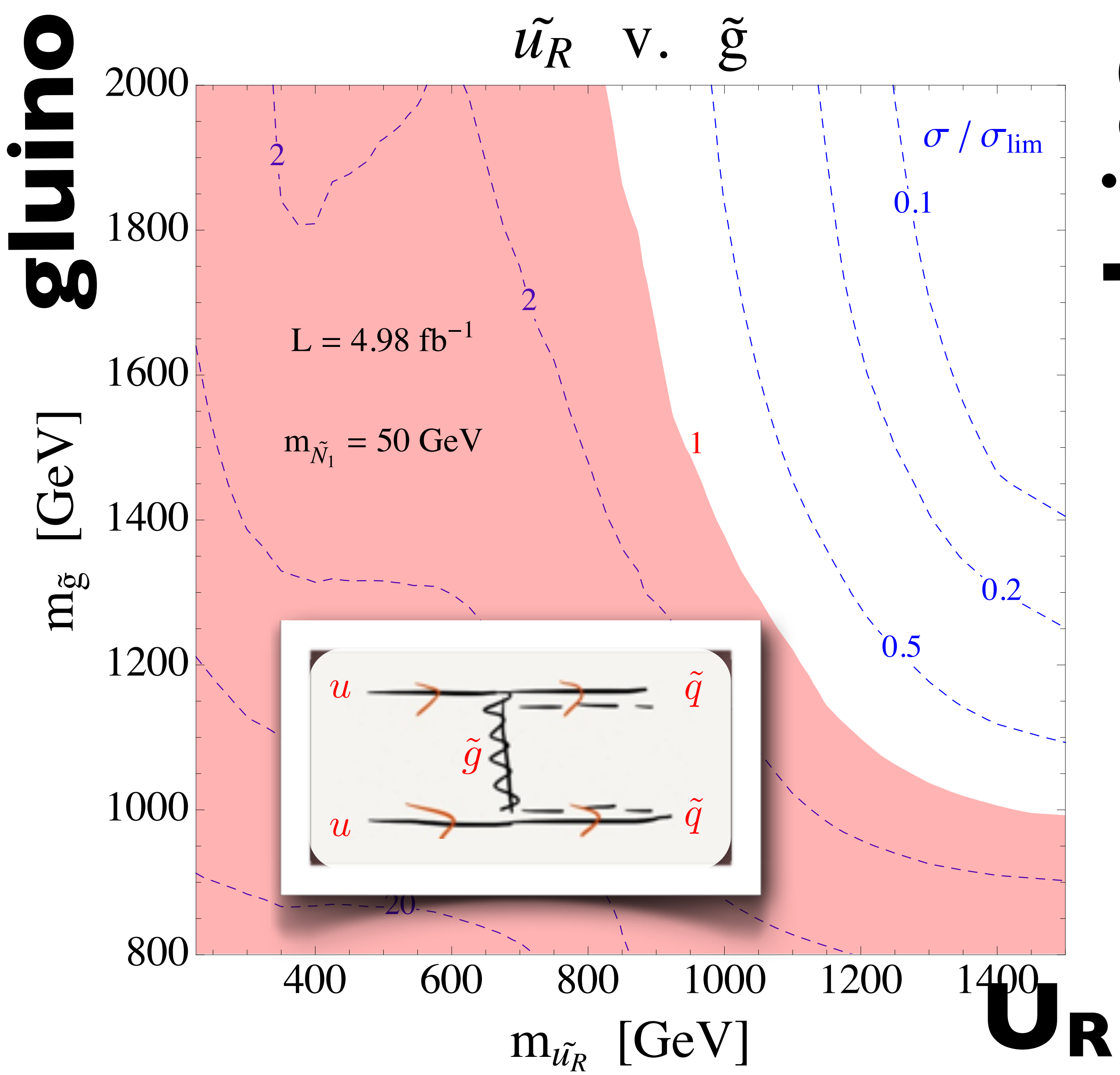
With heavy gluinos prospino fails at reproducing the decoupling behavior

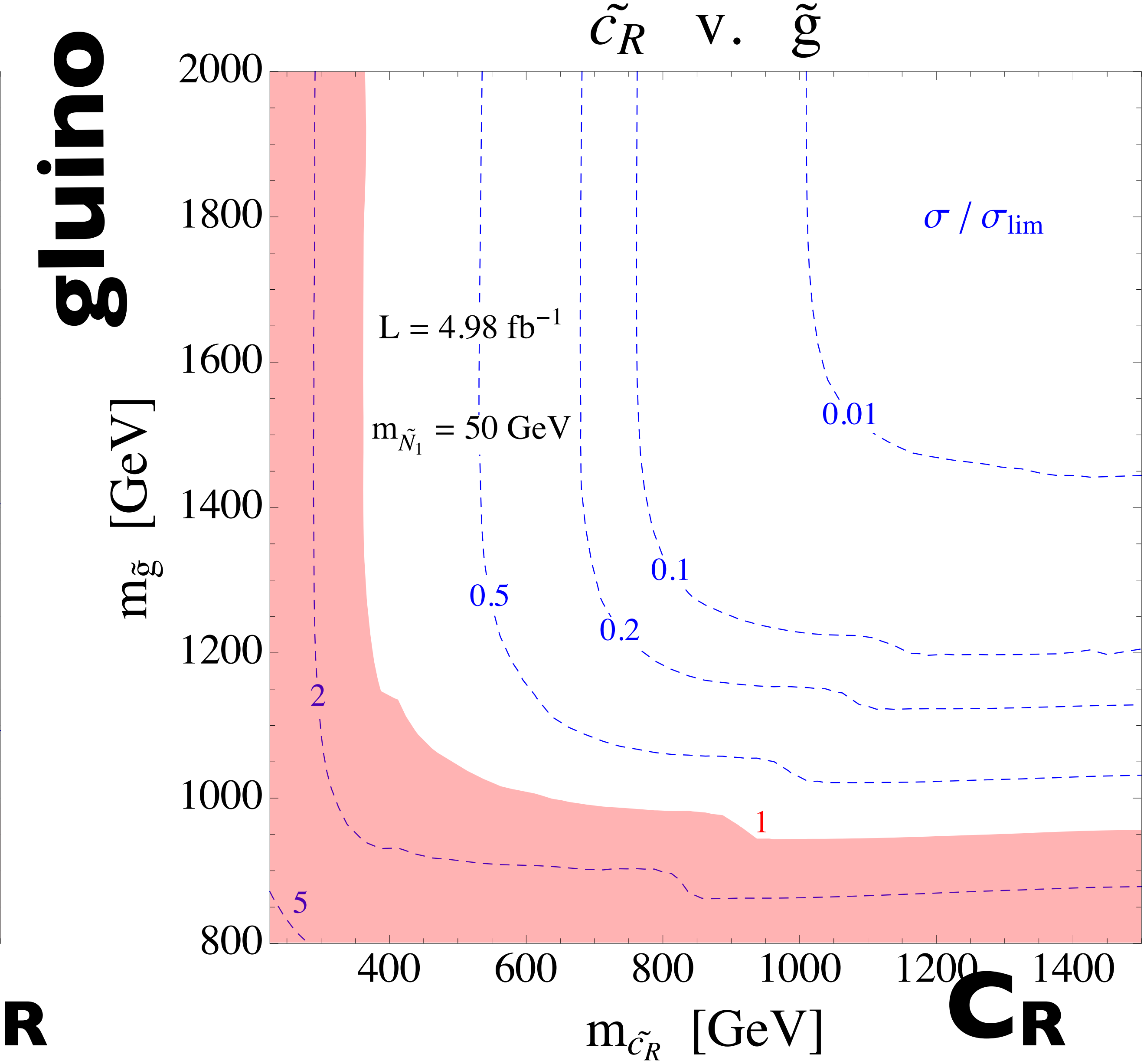
One light squark vs.
gluino mass

sea vs. valence squark



gluino
$\tilde{u_R}$ v. $\tilde{g}$
$\sigma / \sigma_{\rm lim}$
L = 4.98 fb^{-1}
$m_{\tilde{N}_1}$ = 50 GeV
$m_{\tilde{g}}$ [GeV]
$m_{\tilde{u_R}}$ [GeV]
U$_R$
gluino
$\tilde{c_R}$ v. $\tilde{g}$
$\sigma / \sigma_{\rm lim}$
L = 4.98 fb^{-1}
$m_{\tilde{N}_1}$ = 50 GeV
$m_{\tilde{g}}$ [GeV]
$m_{\tilde{c_R}}$ [GeV]
C$_R$

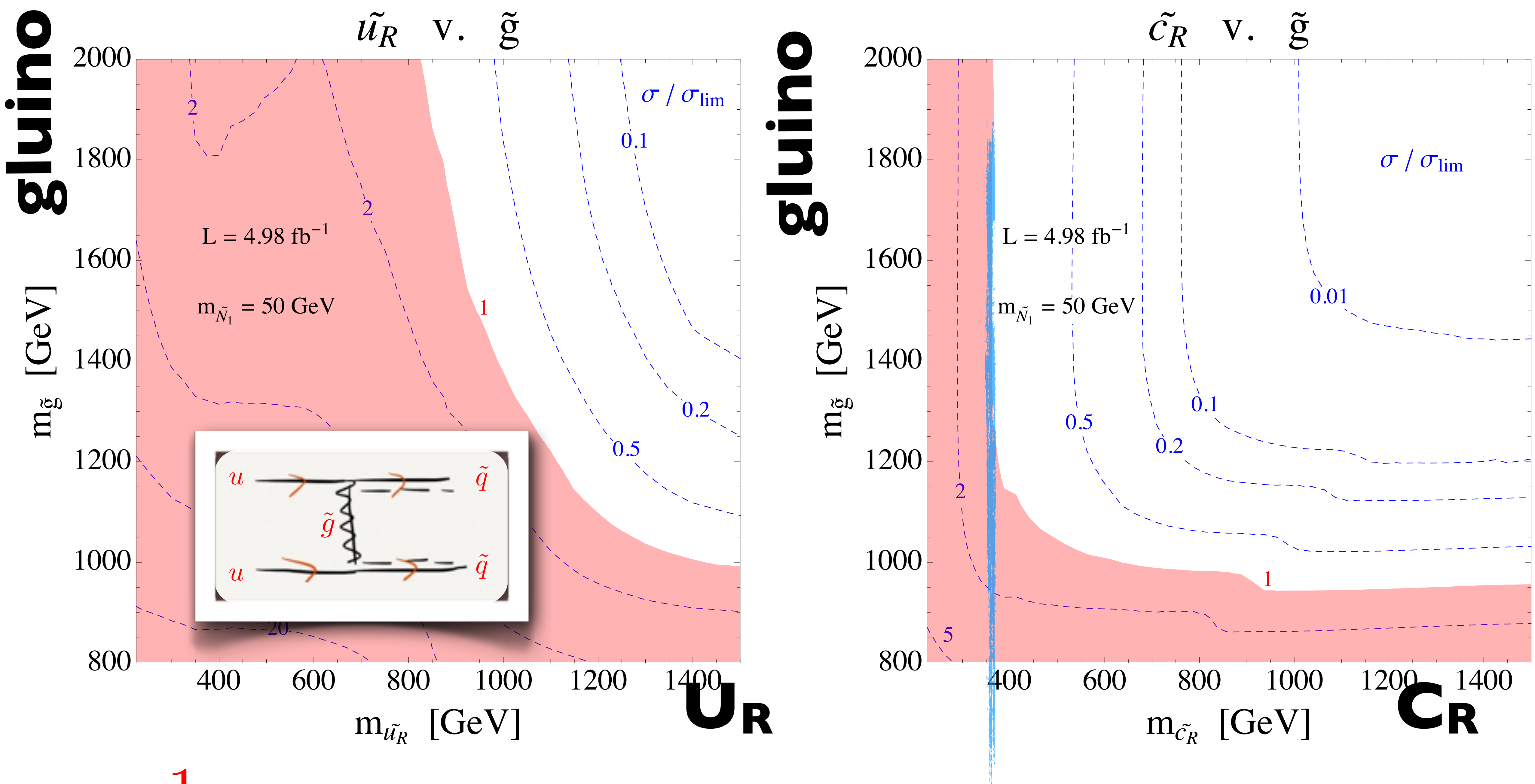




$\dfrac{1}{m_{\tilde g}}\tilde q \tilde q\, u_R u_R$ dim5 operator

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

slow decoupling



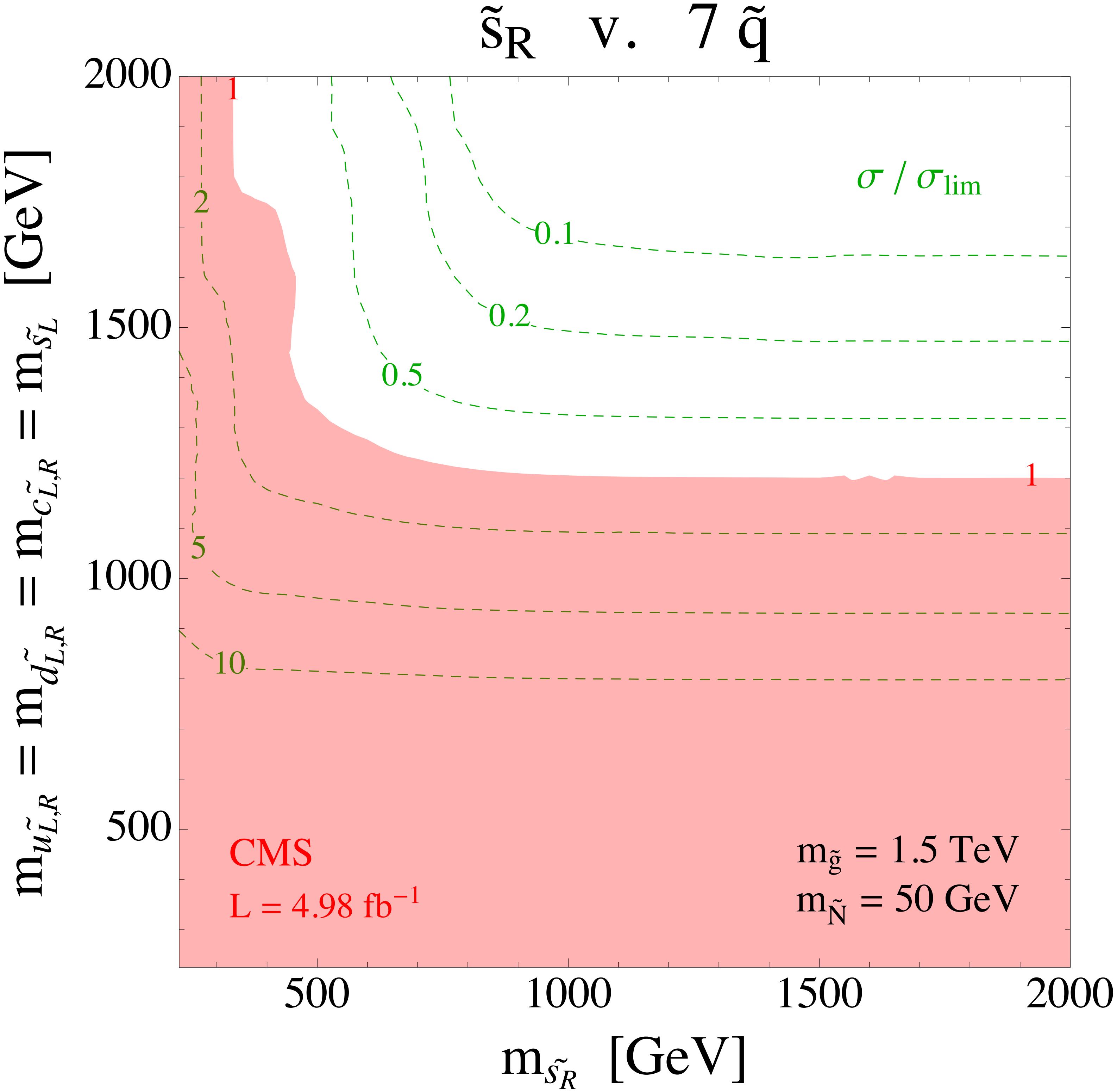
$$\frac{1}{m_{\tilde{g}}}\tilde{q}\tilde{q}\,u_R u_R$$ dim5 operator

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

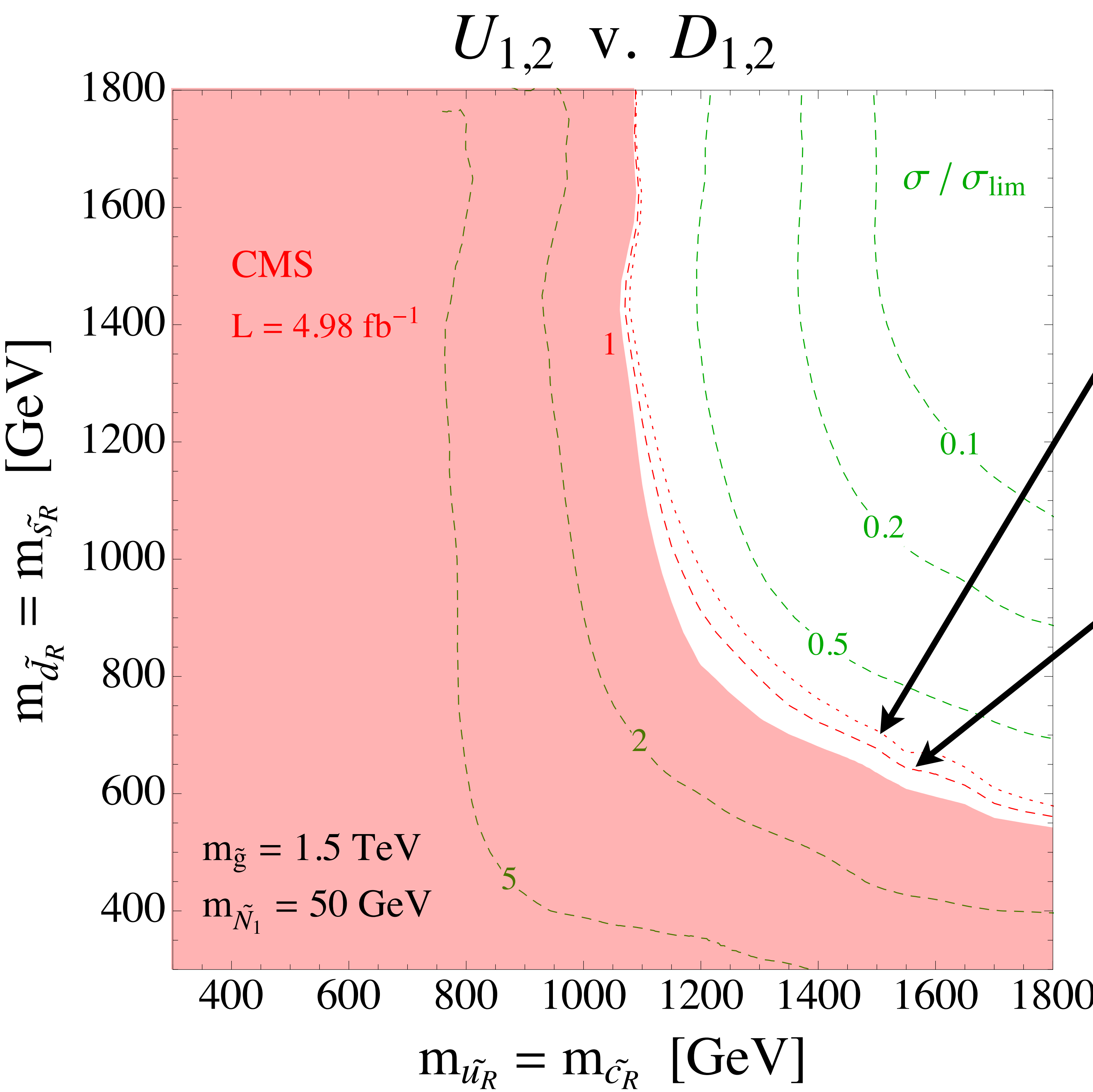
slow decoupling

Sea squarks
can still be < 350 GeV

One light squark & 7 heavy: how fast is the decoupling?



MFV splitting - flavor trivial light squarks

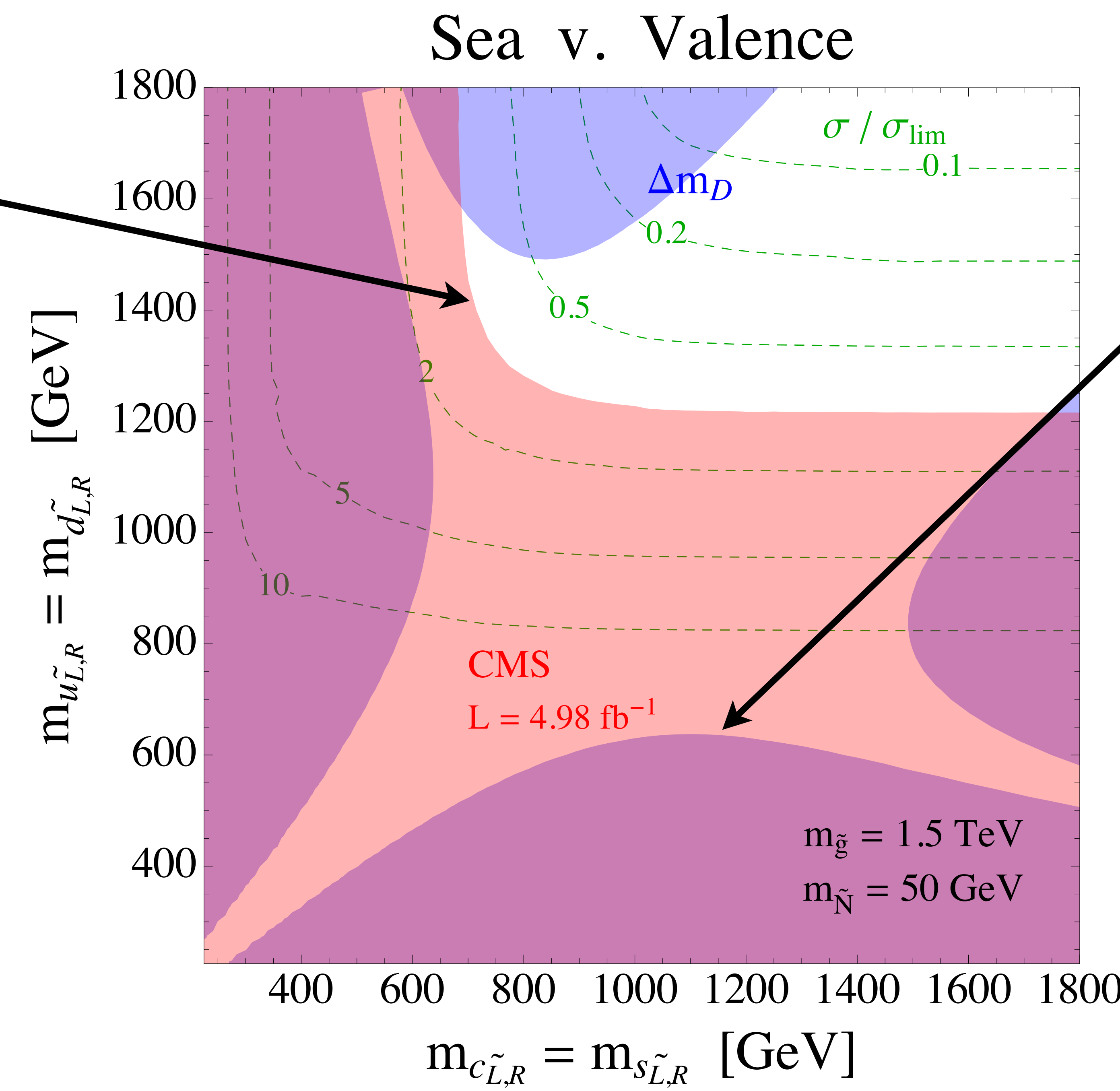


effect of unknown NLO (K=1.5,2)

compared to MadGolem, usually corrections are smaller

Collider vs. Flavor for sea & valence squarks

Collider constraint (CMS recast)



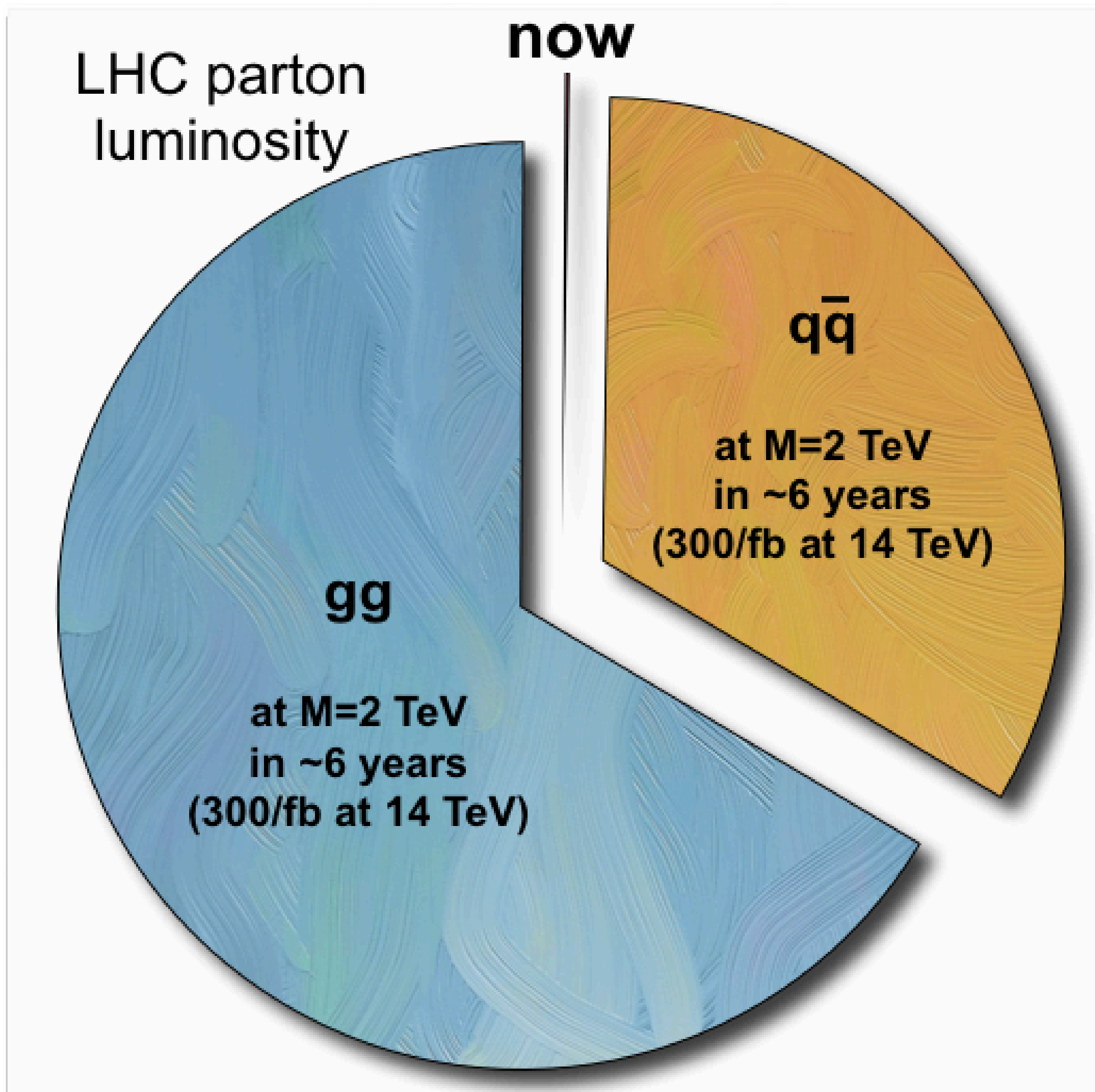
ΔM_D

Flavor limit

$$H_{\rm eff} = C_1 \, (\overline{u}^i \gamma_\mu P_L \, c^i) \, (\overline{u}^j \gamma^\mu P_L \, c^j) \; , \qquad x_D \simeq 2.6 \times 10^{10} \; {\rm Re} \; C_1$$

Assuming full down alignment, calculated w/o MIA

Outlook



G. Rolandi, private comm.