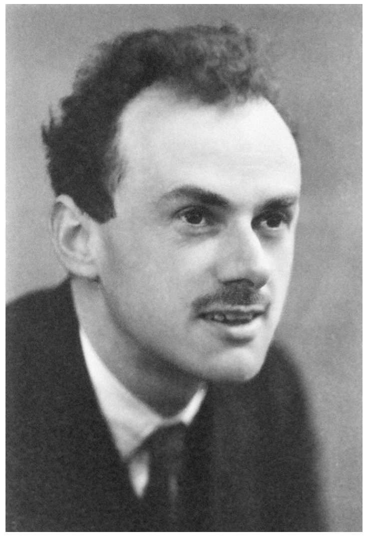


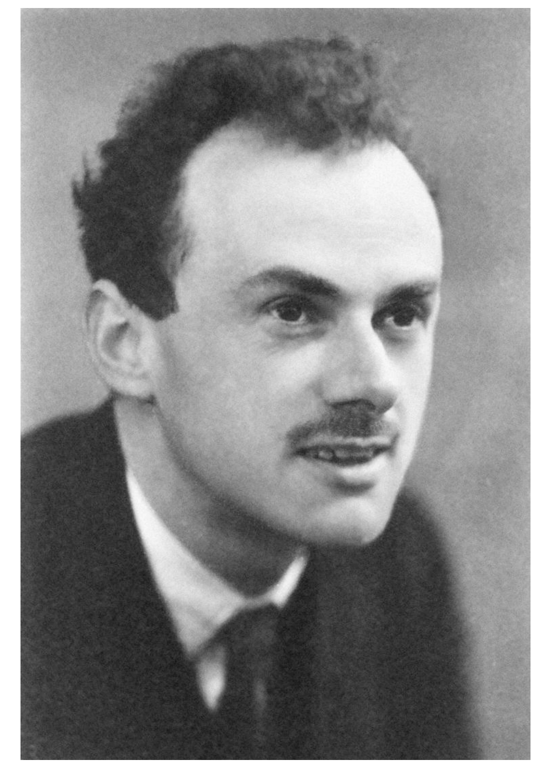
Dirac Gauginos in Supersymmetry

Graham Kribs
University of Oregon

SUSY 2014 Manchester

Tyranny of Majorana
(masses)

Brilliance of Dirac
(masses)



$$\mathcal{L} = \tilde{M}\lambda\lambda + h.c.$$

$$\mathcal{L} = M\lambda\psi + h.c.$$

Fayet (1978)

“In addition to the gluinos we have already considered, now to be called orthogluinos, λ, we introduce a second color-octet of spinorial particles which we call paragluinos, ζ, with opposite R-transformation properties. Both λ and ζ are octets of Majorana spinors. The construction of a massive Dirac gluino field from λ and ζ is compatible with R-invariance.”

Polchinski-Susskind (1982)

“ One interesting operator, which can occur if there is a light field $\hat{L}^a$ in the adjoint representation of G, is $(\hat{W}^{\alpha'}\hat{W}^a_\alpha\hat{L}^a)_F$,

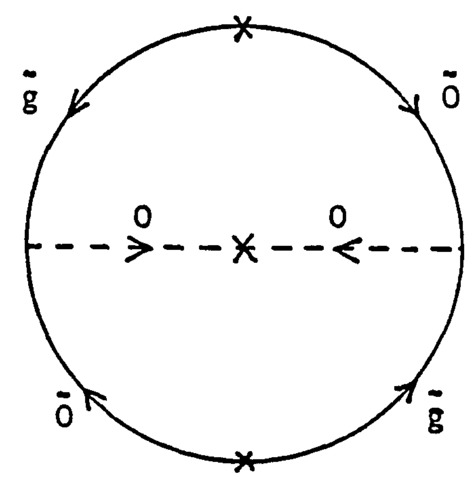
$$(\theta^\alpha \hat{W}^a_\alpha \hat{L}^a)_F = \frac{i}{\sqrt{2}}\lambda^a\psi^a_L + D^a L^a \,. \qquad \text{(B8)}$$

It gives a Dirac mass, mixing the light gauge and matter fermions, plus a mixing between matter scalar and gauge auxiliary fields. ”

Hall-Randall (1990)

Proposed $U(1)_R$-symmetric supersymmetric model -- no SUSY breaking for EW gauginos; gluino acquires Dirac mass.

Recognized CP properties superior to MSSM -- leading contribution to neutron EDM from two-loop contribution to Weinberg operator:



[fermionic partner to gluino]

“The necessity of adding this field is the least attractive feature of this model, but we feel that it is easily outweighed by the advantages.”

Since 2002, substantial literature
on Dirac gauginos has been developed
by many groups worldwide

Dirac gaugino model building

"Supersoft" [Fox, Nelson, Weiner; 0206096]
"Localized Supersoft" [Chacko, Fox, Murayama; 0406142]
"AMSB with Dirac Bino" [Carpenter, Fox, Kaplan; 0503093]
"Splitting Extended Supersymmetry"
[Antoniadis, Delgado, Benakli, Quiros, Tuckmantel; 0507192]
"R-symmetric SUSY & Flavor" [Kribs, Poppitz, Weiner; 0712.2039]
"R-symmetric GM" [Amigo, Blechman, Fox, Poppitz; 0809.1112]
"Dirac Gauginos in GGM" [Benakli, Goodsell; 0811.4409; 0909.0017; 1003.4957; 1106.1649;]
"Dirac Gauginos & GM" [Carpenter; 1007.0017]
"Viable Gravity Mediation w/ Dirac Gauginos" [Kribs, Okui, Roy; 1008.1798]
"Easy Dirac Gauginos" [Abel, Goodsell; 1102.0014]
"SUSY 1HDM" [Davies, March-Russell, McCullough; 1103.1647]

Dirac gaugino model building...

"μ and Bμ w/ Dirac" [Benakli, Goodsell, Maier; 1104.2695]
"$U(1)_R$ Lepton Number" [Frugieuele, Gregoire; 1107.4634]
"D-terms, DSB, Mixed Gauginos" [Itoyama, Maru; 1109.2276]
"Dirac gauginos and unification in F-theory" [Davies; 1205.1942]
"Holographic Correlators in GGM" [Argurio et al.; 1205.4709]
"U(1)R as Origin of Leptonic RPV & at LHC"
[Frugiuele, Gregoire, Kumar, Ponton; 1210.0541, 1210.5257]
"R-symmetric High Scale SUSY" [Unwin; 1210.4936]
"Mapping Dirac gaugino masses" [Abel, Busbridge; 1306.6323]
"Dirac Gluinos in the Pyramid Scheme" [Banks; 1311.4410]
"mh=126, D-term triggered DSB" [Itoyama, Maru; 1312.4157]
"Split Dirac Supersymmetry" [Fox, Kribs, Martin; 1405.3692]

Dirac gaugino phenomenology

“Supersoft” [Fox, Nelson, Weiner; 0206096]
“Chargino NLSP” [Kribs, Martin, Roy; 0807.4936]
“Collider topics” [Choi et al.; 0808.2410; 0812.3586; 0911.1951; 1005.0818; 1012.2688]
“Sgluons” [Plehn, Tait; 0810.3919]
“Squark FV at Colliders” [Kribs, Martin, Roy; 0901.4105]
“Light squarks and N=2” [Heikinheimo, Kellerstein, Sanz; 1111.4322]
“Feynrules (for Dirac)” [Fuks; 1202.4769]
“Supersoft SUSY is Supersafe” [Kribs, Martin; 1203.4821]
“Sgluons @ NLO” [Goncalves Netto et al.; 1203.6358]
“Sarah package (for Dirac!)” [Staub; 1207.0906]
“Dirac Gauginos and mh=125” [Benakli, Goodsell, Staub; 1211.0552]
“Mixing stops at LHC” [Agrawal, Frugiuele; 1304.3068]

Dirac gaugino phenomenology...

"Is SUSY Natural?" [Hardy; 1306.1534]
"Mixed Gauginos at LHC" [Kribs, Raj; 1307.7197]
"Natural Higgs Mass from Non-decoupling"
[Lu, Murayama, Ruderman, Tobioka; 1308.0792]
"Vestiges" [Arvanitaki et al.; 1309.3568]
"Higgs, ν mass, keV DM w/ U(1)R" [Chakraborty, Roy; 1309.6538]
"mD - bM versus Dirac" [Csaki, Goodman, Pavesi, Shirman; 1310.4504]
"Fine-tuning in DiracNMSSM"
[Kaminska, Ross, Schmidt-Hoberg, Staub; 1401.1816]
"EW precision vis-a-vis U(1)R" [Beauchesne, Gregoire; 1402.5403]
"Dirac gauginos, R-symm & mh=125"
[Bertuzzo, Frugiuele, Gregoire, Ponton; 1402.5432]
"Constrained Minimal Dirac" [Benakli, Goodsell, Porod, Staub; 1403.5122]

Dirac gaugino / flavor / neutrino phenomenology

"R-symmetric SUSY & Flavor" [Kribs, Poppitz, Weiner; 0712.2039]

"QCD corrections K0-K0bar" [Blechman, Ng; 0812.3811]

"ν mass, sν DM, & LFV" [Kumar, Tucker-Smith, Weiner; 0910.2475]

"μ -> e in R-symm SUSY" [Fok, Kribs; 1004.0556]

"Small ν mass / R-symm / Λ" [Davies, McCullough; 1111.2361]

"μ -> e @ Project X" [Fok; 1208.6558]

"ν mass & p-decay w/ R-symm" [Morita, Nakano, Shimomura; 1212.4304]

"Flavor models with Dirac & Fake Gluinos"
[Dudas, Goodsell, Heurtier, Tziveloglou; 1312.2011]

Dirac / Pseudo-Dirac gaugino dark matter

"Pseudo-Dirac bino DM" [Hsieh; 0708.3970]
"EFT of Dirac DM" [Harnik, Kribs; 0810.5557]
"DM w/ Dirac" [Belanger, Benakli, Goodsell, Moura, Pukhov; 0905.1043]
"Dirac gaugino as leptophillic DM" [Chun, Park, Scopel; 0911.5273]
"Pseudo-Dirac DM leaves a trace" [DeSimone, Sanz, Sato; 1004.1567]
"Leptogenesis origin of Dirac DM" [Chun; 1009.0983]
"Pheno of Dirac Neutralino DM" [Buckley, Hooper, Kumar; 1307.3561]

Dirac / R-symmetric baryo/leptogenesis

"Leptogenesis origin of Dirac DM" [Chun; 1009.0983]
"EW Baryogenesis w/ approx R symm" [Kumar, Ponton; 1107.1719]
"EW Baryogenesis in R-symm model" [Fok, Kribs, Martin, Tsai; 1208.2784]

Dirac Gauginos in Supersymmetry

Fayet (1978)
Polchinski, Susskind (1982)

Given a D-term SUSY breaking spurion

$$W'_\alpha = \theta_\alpha D'$$

Dirac gaugino masses arise from:

$$\int d^2\theta \sqrt{2} \frac{W'_\alpha W_j^\alpha A_j}{\Lambda}$$

A_j: chiral superfields in adjoint rep

Λ: messenger scale

giving

$$\mathcal{L} = M \lambda_j \psi_j + \text{scalar terms}$$

ψ_j: fermion in adjoint rep

λ_j: gaugino for j[th] group

$M = D'/\Lambda$

In this talk, focus mostly of the consequences of the Dirac gaugino mass operator in the low energy effective theory.

Other operators involving D-term spurions (and possibly F-term spurions) can have important consequences, but their existence, and relative size, is UV-dependent.

Plenty of examples in literature of good (and bad) consequences of more (less) interesting UV models.

Dirac Gauginos in MSSM

Require additional superfields:

	[SU(3), SU(2), U(1)]	
$\begin{pmatrix} \psi_a \\ \phi_a \end{pmatrix}$	(8,1,0)	color octet
$\begin{pmatrix} \psi_j \\ \phi_j \end{pmatrix}$	(1,3,0)	weak triplet
$\begin{pmatrix} \psi \\ \phi \end{pmatrix}$	(1,1,0)	pure singlet

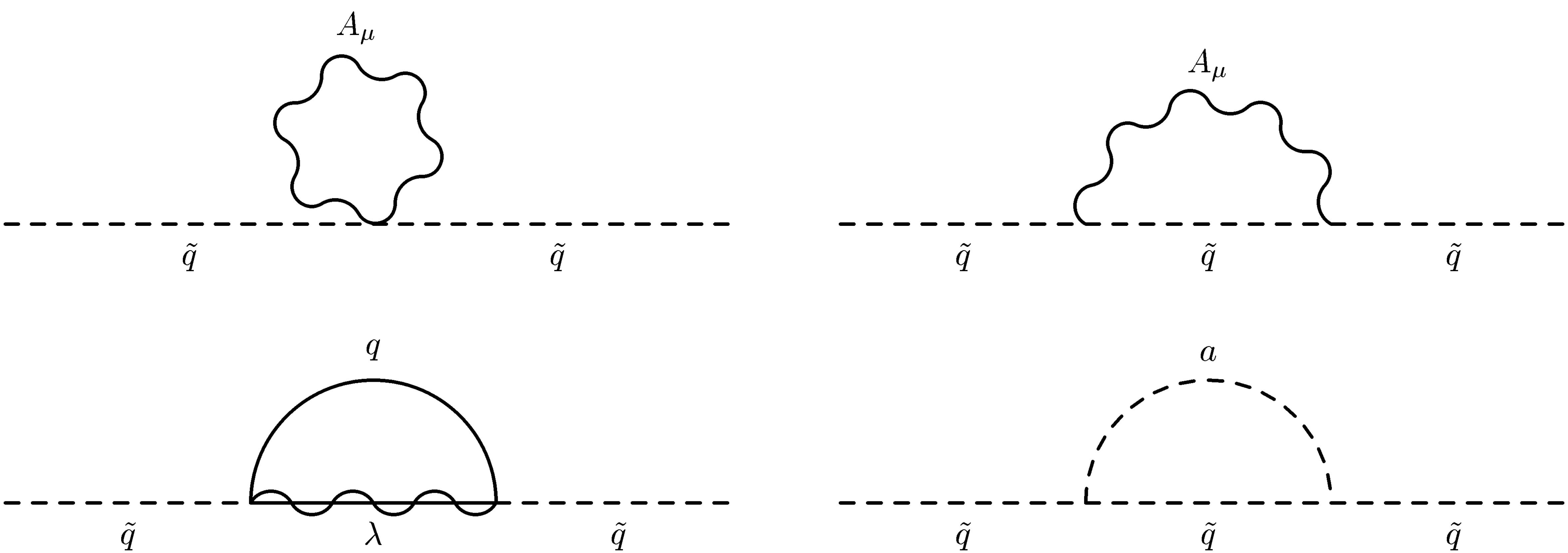
Gauge couplings perturbative but do not unify*

(*when Dirac gauginos at the weak scale and without unifons)

Dirac gauginos induce “supersoft” scalar masses

One-loop contributions:

Fox, Nelson, Weiner (2002)

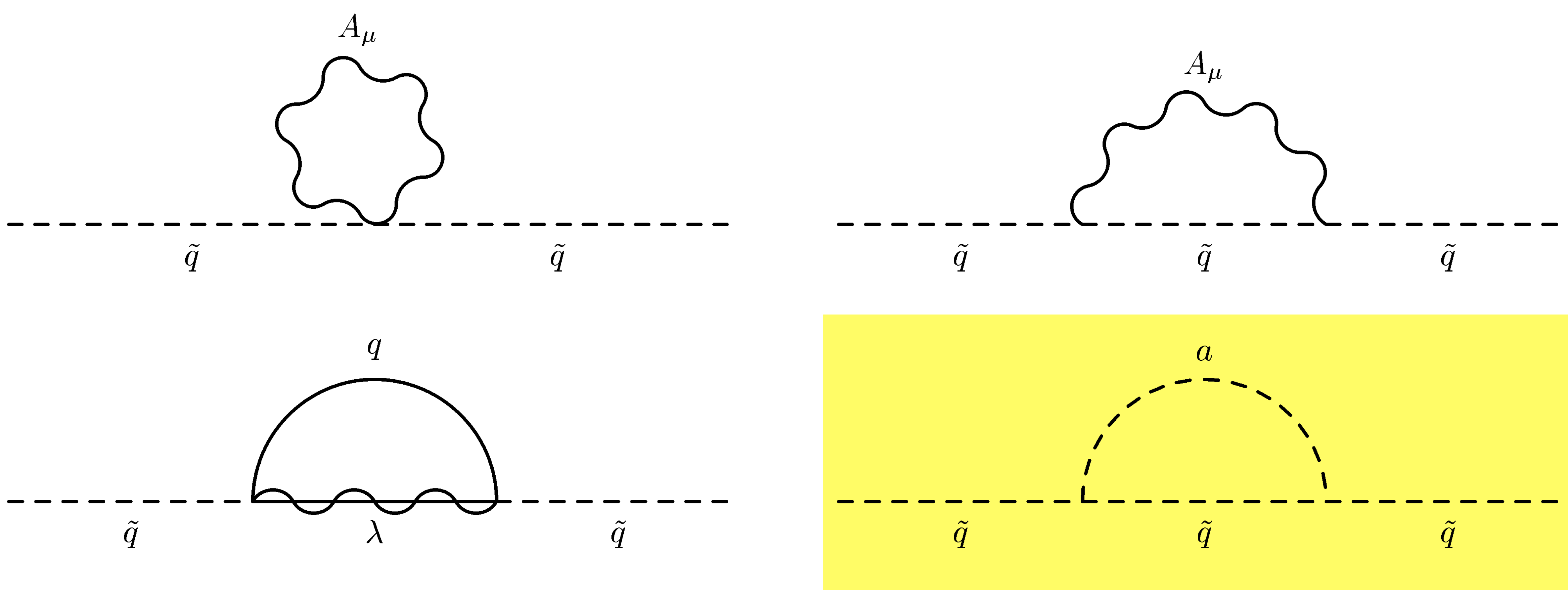


Giving

$$M_{\tilde{f}}^2 = \sum_i \frac{C_i(f)\alpha_i M_i^2}{\pi} \log \frac{\tilde{m}_i^2}{M_i^2}$$

Dirac gauginos induce "supersoft" scalar masses

One-loop contributions:



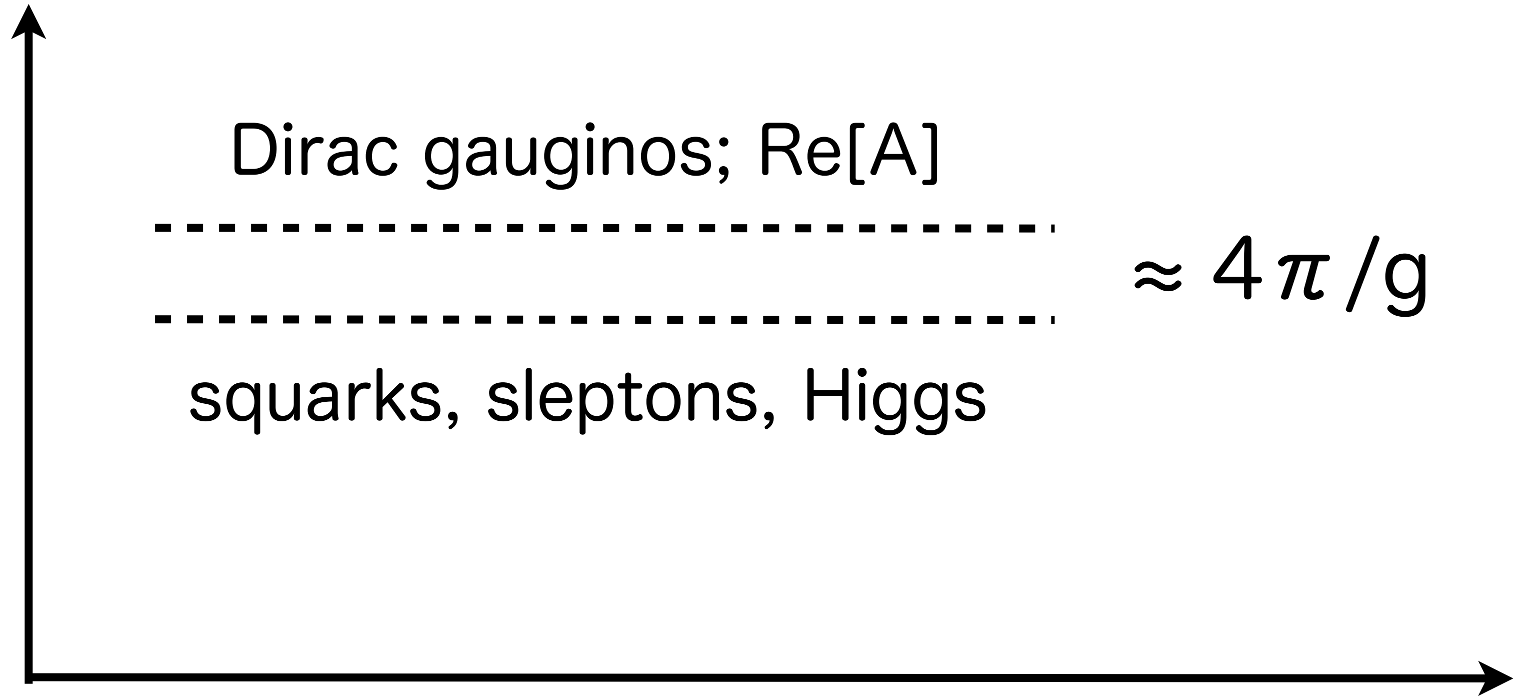
Giving

$$M^2_{\tilde f} = \sum_i \frac{C_i(f)\alpha_i M_i^2}{\pi} \log \frac{\tilde m_i^2}{M_i^2}$$

Would-be log divergence is cutoff by adjoint scalar contribution.

Advantages of Dirac Gauginos

- induce finite (not log divergent) flavor-blind scalar masses
- can be naturally heavier than squark,slepton,Higgs masses



- respect $U(1)_R$-symmetry

Three Applications

1. Naturalness (relax LHC bounds with Dirac gluino)

Kribs, Martin (2012)
[also Heikinheimo, Kellerstein, Sanz (2011)]

2. Flavor (R-symmetric model)

Kribs, Poppitz, Weiner (2007)
Dudas, Goodsell, Heurtier, Tziveloglou (2013)

3. Higgs mass

Benakli, Goodsell, Staub (2012)
Bertuzzo, Frugiuele, Gregoire, Ponton (2014)

(new split "Dirac" supersymmetry model --
lightest sparticles are Higgsinos not gauginos)

Fox, Kribs, Martin (2014)
[also Antoniadis et al. (2005)]

1. Naturalness with a Dirac gluino

Finite Squark Masses from Dirac Gluino

$$M_{\tilde{f}}^2 = \sum_i \frac{C_i(f)\alpha_i M_i^2}{\pi} \log \frac{\tilde{m}_i^2}{M_i^2}$$

Color octet scalar mass (Re[] part)

Plug in numbers:

$$M_{\tilde{q}}^2 \simeq (700\ \mathrm{GeV})^2 \left(\frac{M_3}{5\ \mathrm{TeV}}\right)^2 \frac{\log \tilde{r}_3}{\log 1.5}$$

or

$$M_{\tilde{q}}^2 \simeq (760\ \mathrm{GeV})^2 \left(\frac{M_3}{3\ \mathrm{TeV}}\right)^2 \frac{\log \tilde{r}_3}{\log 4}$$

$$\frac{\text{Dirac gluino}}{\text{squark mass}} \approx 5\text{-}7$$

Naturalness: Majorana versus Dirac Gluino

Majorana mass

one-loop

$$\delta m_{H_u}^2 = -\frac{3\lambda_t^2}{8\pi^2} M_{\tilde{t}}^2 \log \frac{\Lambda^2}{M_{\tilde{t}}^2}$$

two-loop

$$\delta m_{H_u}^2 = -\frac{\lambda_t^2}{2\pi^2}\frac{\alpha_s}{\pi}|\tilde{M}_3|^2 \left(\log \frac{\Lambda^2}{\tilde{M}_3^2}\right)^2$$

evaluate (leading log)

$$\delta m_{H_u}^2|_{\rm MSSM} \simeq -\left(\frac{\tilde{M}_3}{4}\right)^2 \left(\frac{\log \Lambda/\tilde{M}_3}{3}\right)^2$$

Naturalness: Majorana versus Dirac Gluino

Majorana mass

one-loop

$$\delta m_{H_u}^2 = -\frac{3\lambda_t^2}{8\pi^2} M_{\tilde{t}}^2 \log \frac{\Lambda^2}{M_{\tilde{t}}^2}$$

two-loop

$$\delta m_{H_u}^2 = -\frac{\lambda_t^2}{2\pi^2} \frac{\alpha_s}{\pi} |\tilde{M}_3|^2 \left(\log \frac{\Lambda^2}{\tilde{M}_3^2} \right)^2$$

evaluate (leading log)

$$\delta m_{H_u}^2 |_{\mathrm{MSSM}} \simeq - \left(\frac{\tilde{M}_3}{4} \right)^2 \left(\frac{\log \Lambda / \tilde{M}_3}{3} \right)^2$$

Dirac mass

one-loop

$$\delta m_{H_u}^2 = -\frac{3\lambda_t^2}{8\pi^2} M_{\tilde{t}}^2 \log \frac{\tilde{m}_3^2}{M_{\tilde{t}}^2}$$

two-loop

(finite)

evaluate using mstop and:

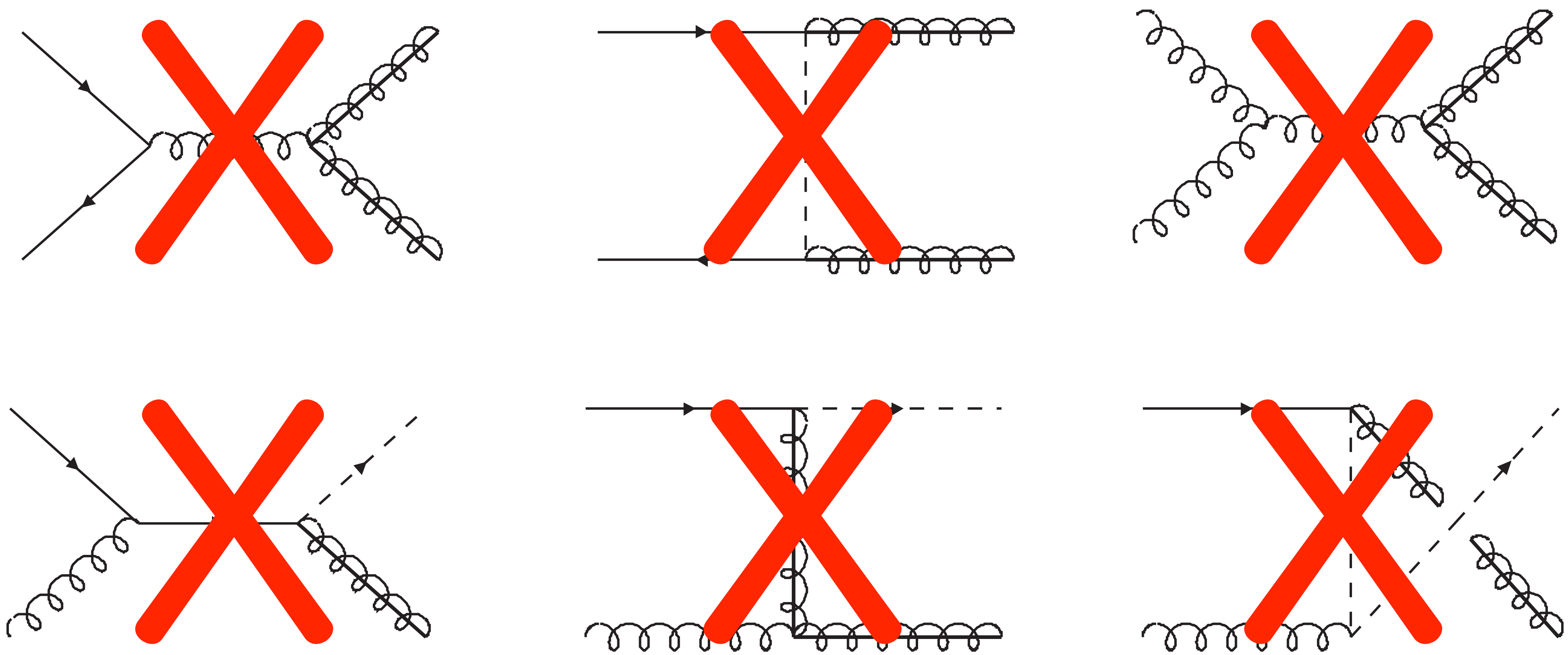
$$M_{\tilde{q}}^2 \simeq (700\ \mathrm{GeV})^2 \left(\frac{M_3}{5\ \mathrm{TeV}} \right)^2 \frac{\log \tilde{r}_3}{\log 1.5} \qquad \log \frac{M_3^2}{M_{\tilde{t}}^2} \simeq \log \frac{3\pi}{4\alpha_s}$$

$$\delta m_{H_u}^2 |_{\mathrm{SSSM}} \simeq - \left(\frac{M_3}{22} \right)^2 \frac{\log \tilde{r}_3}{\log 1.5}$$

Dirac gluino can be substantially heavier than Majorana gluino without fine-tuning penalty (all other things equal)

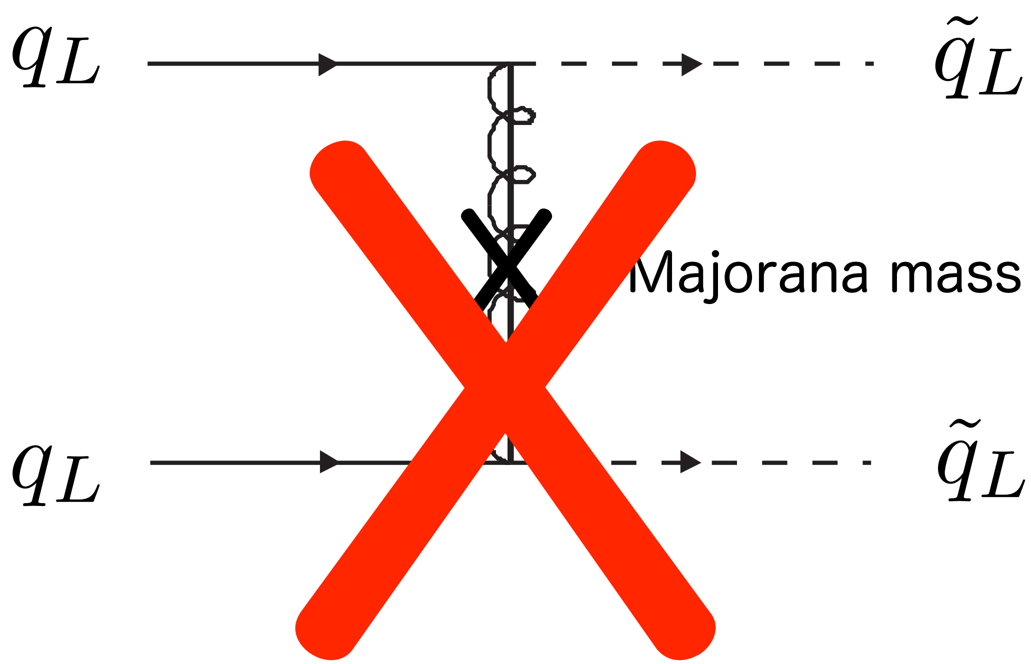
Two Key Implications for LHC

1. Gluino pair/associated production kinematically suppressed.



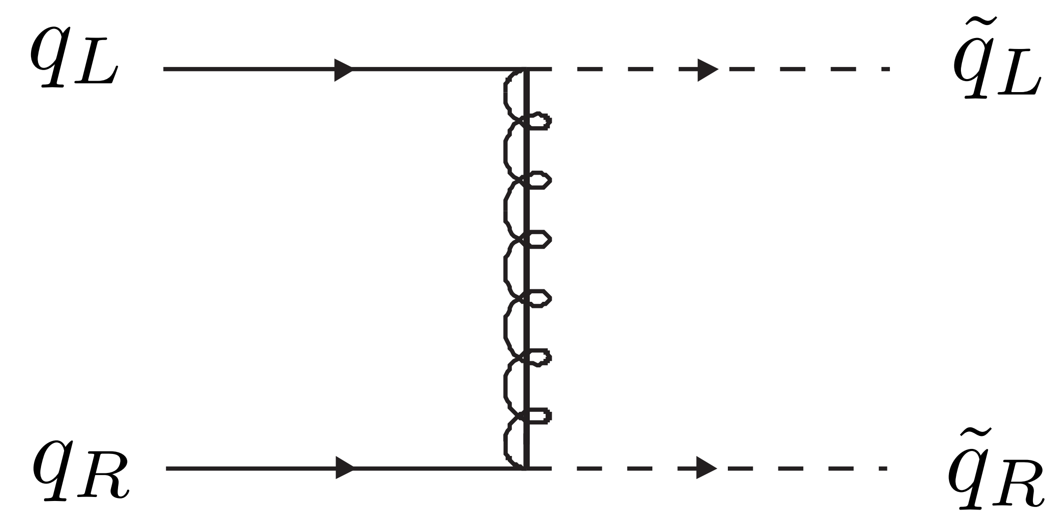
Two Key Implications for LHC

2. Squark production through t-channel gluino exchange suppressed.



scales as $\dfrac{1}{\tilde{M}_{\mathrm{Maj}}}$

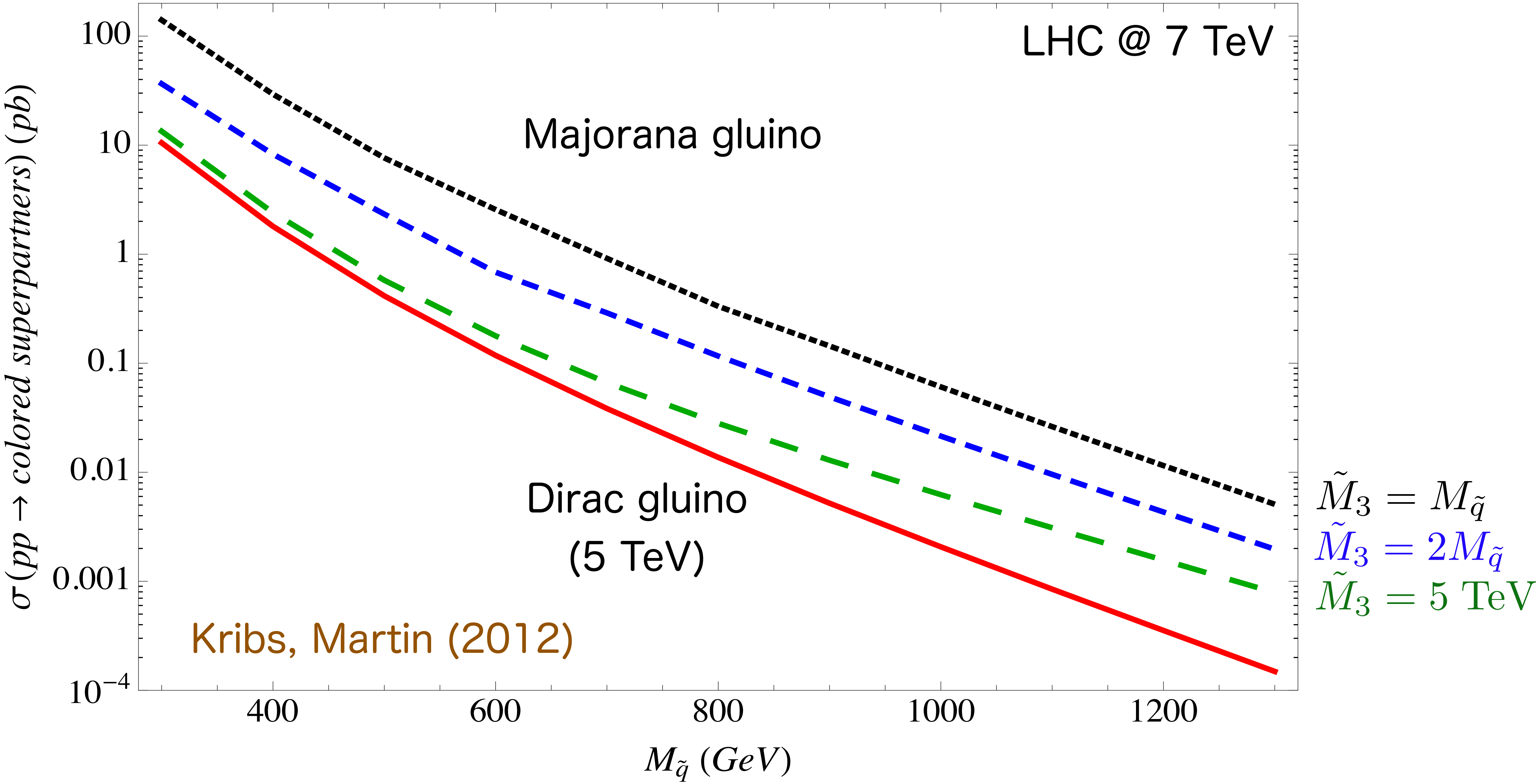
Forbidden



scales as $\dfrac{|p|}{M^2_{\mathrm{Dirac}}}$

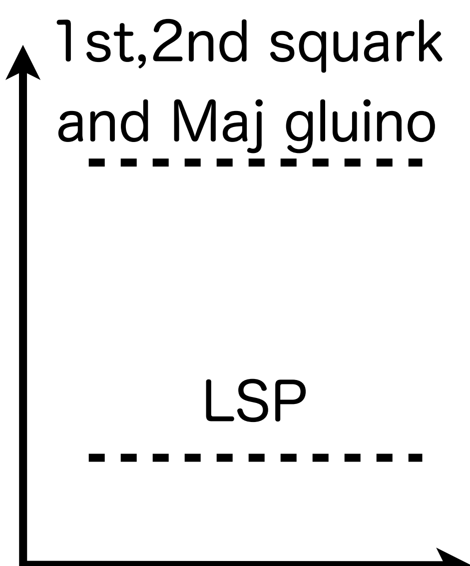
Suppressed

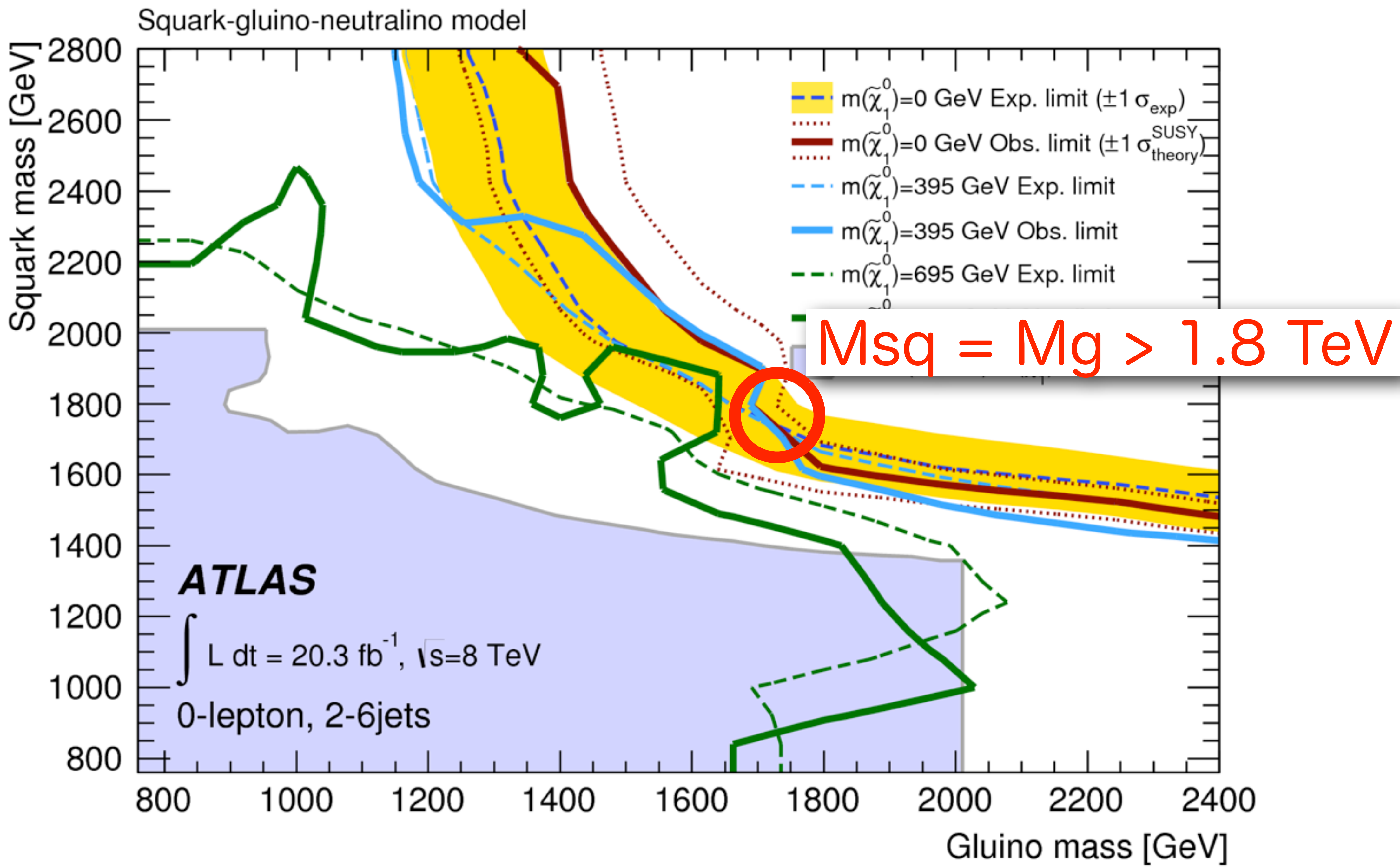
Colored Sparticle Cross Sections



Suppressed by factor of ≈100

ATLAS Bounds on a Squark + Majorana Gluino Simplified Model

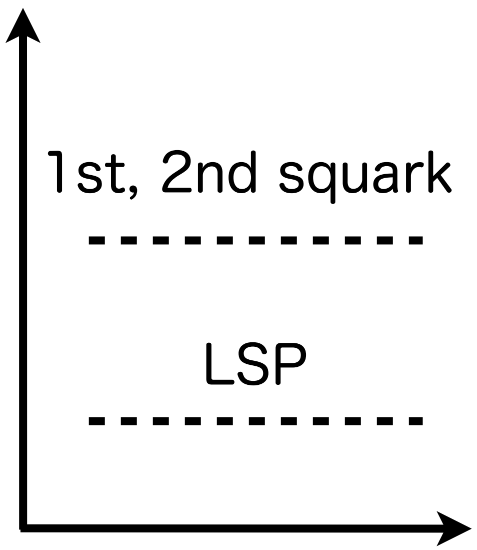


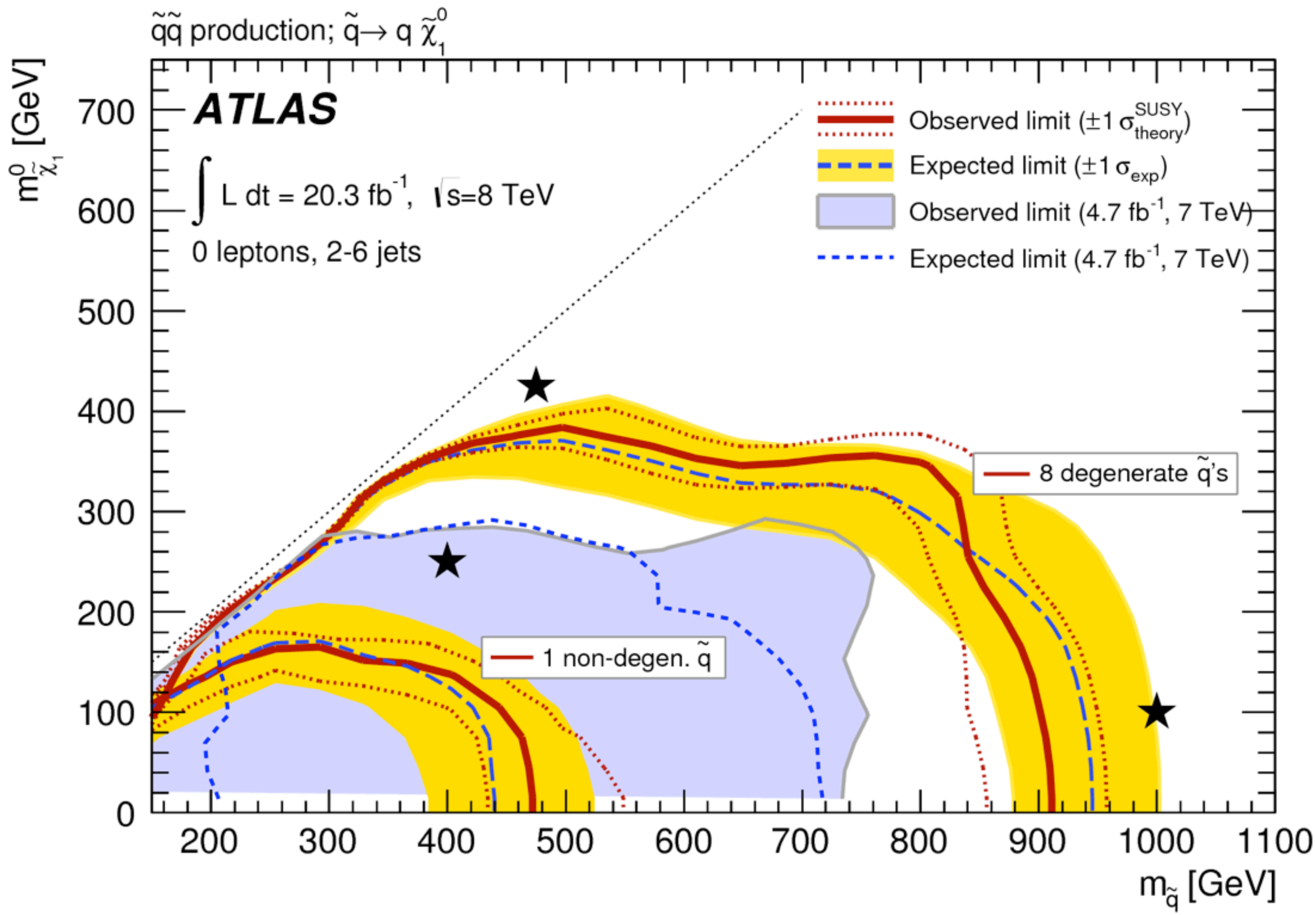


ATLAS 1405.7875

ATLAS Bounds on Squark-LSP Simplified Model

(i.e., masquerading as heavy Dirac gluino model)

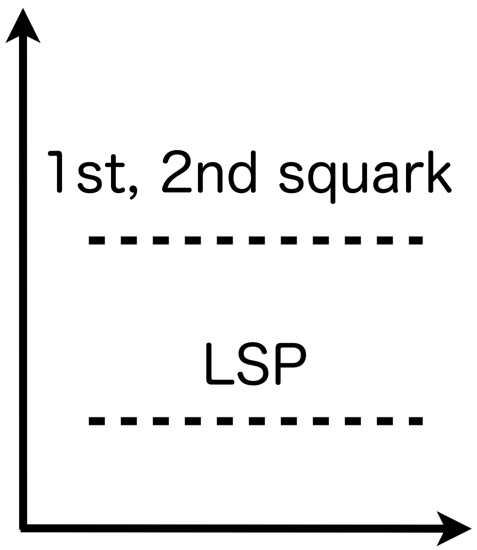


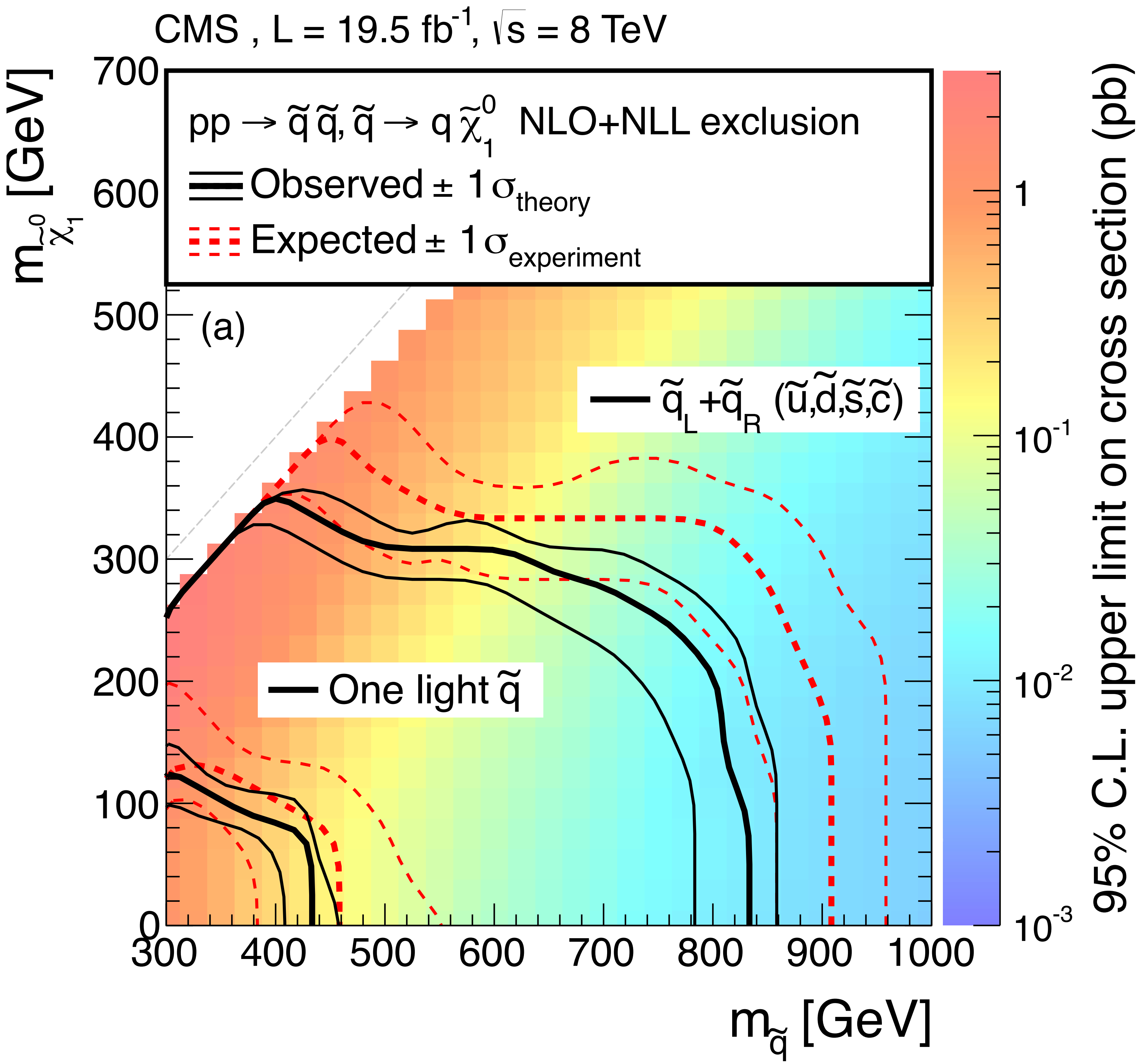


ATLAS 1405.7875

CMS Bounds on Squark-LSP Simplified Model

(i.e., masquerading as heavy Dirac gluino model)





CMS SUS-13-012 (multijets + MET analysis)

If:

heavy Dirac gluino

$+$

LSP $\gtrsim$ 350 GeV

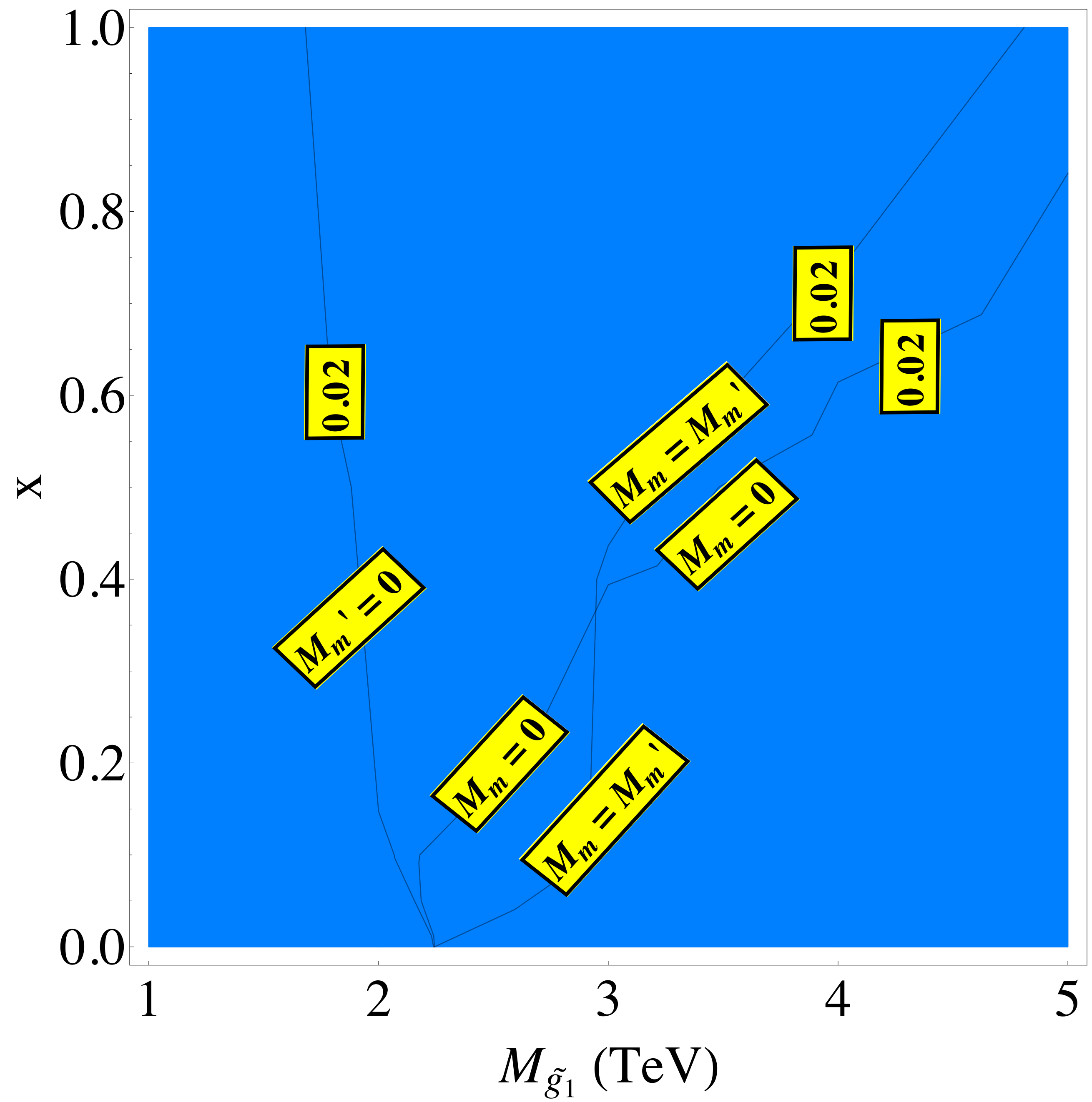
No Bound on 1st,2nd Generation Squarks

(as well as no bound on 3rd generation)

Suppressed Cross Sections Persist with Mixed Gluinos

("mixed": Majorana masses for gaugino and adjoint)

$x = M_m/M_d$ or $x = 2M_m/M_d = 2M'_m/M_d$ or $x' = M'_m/M_d$.



Bound on "Majorananess"
versus
lightest gluino mass

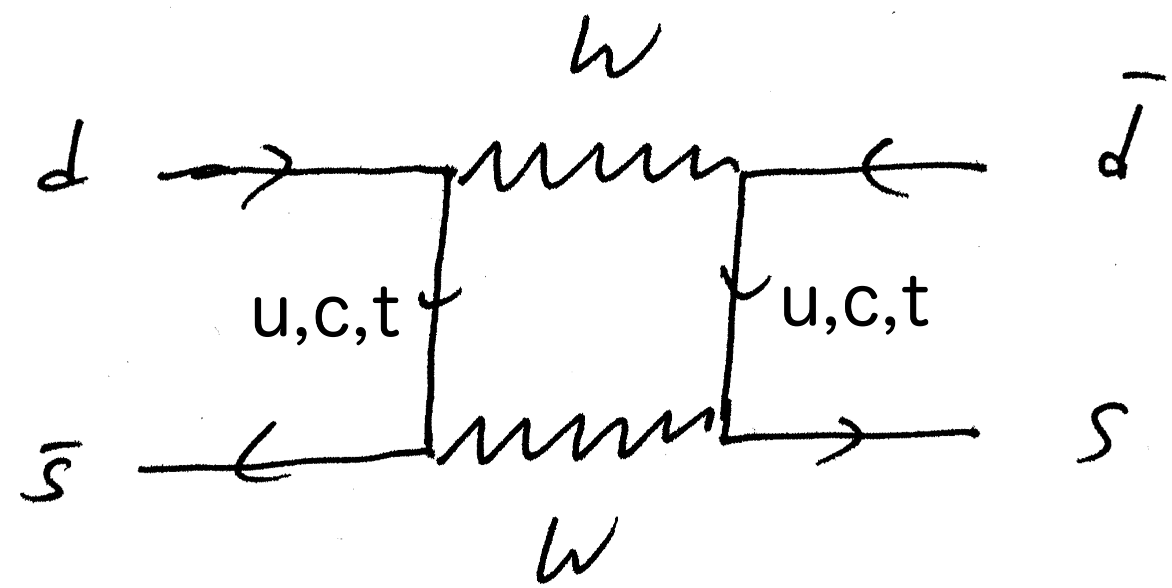
Example:
msquark = 800 GeV;
LSP massless.

Kribs, Raj (2013)

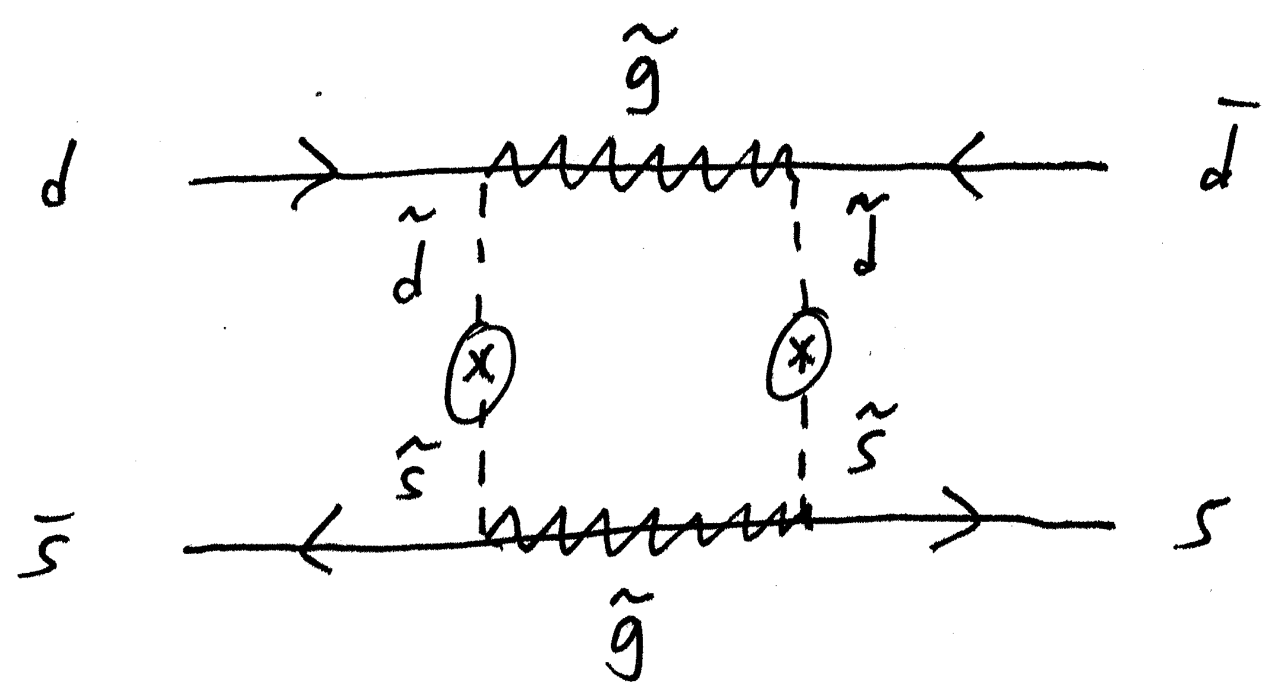
2. Flavor Physics with Dirac gauginos

Supersymmetric Flavor Problem

For example, K^0-$\overline{K}^0$ mixing



Has contributions from superpartner loops



Supersymmetric Flavor/CP Problems

Serious constraints on, e.g.,

- ΔM_K, ε_K [Im(ΔM_K)]
- charged lepton flavor violation ($\mu \to e\gamma$, etc.)
- B mixing; $b \to s\gamma$; other rare b decays
- EDMs
- flavor at large tan β
- proton decay through dim-5
- ...

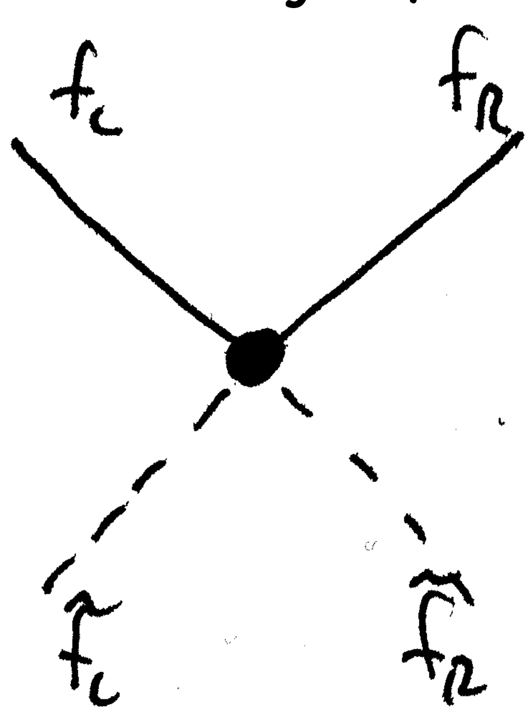
R-symmetric Supersymetry

Kribs, Poppitz, Weiner (2007)

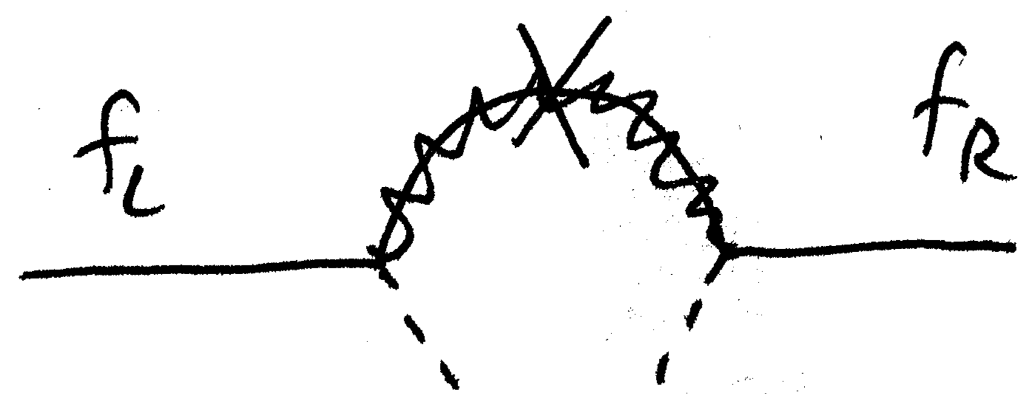
We realized the vast majority of the supersymmetric flavor and CP problems arise from R violating interactions, i.e.:

Majorana masses , A-terms , μ-term

Effective dim-5 operators suppressed by 1/M or 1/μ:



Chirality flip on gauginos or Higgsinos:



R-symmetric Supersymetric Model

Kribs, Poppitz, Weiner (2007)

- MSSM + Dirac gauginos + R-symmetric μ-terms

$$
\begin{aligned}
W \supset\ & \mu_u H_u R_u + \mu_d H_d R_d \\
& + \lambda_{1u} H_u A_1 R_u + \lambda_{1d} H_d A_1 R_d \\
& + \lambda_{3u} H_u A_3^\alpha t^\alpha R_u + \lambda_{3d} H_d A_3^\alpha t^\alpha R_d
\end{aligned}
$$

- Flavor-violating squark/slepton masses not forbidden by R-symmetry. [D-term & F-term contributions.]

(Could arise from gravity mediation with no singlets in hidden sector, e.g., 4-1 model.)

Kribs, Okui, Roy (2010)

Updated K^0-$\bar{K}^0$ mixing with Majorana Gluino

Dudas, Goodsell, Heurtier, Tziveloglou; 1312.2011

$m_{\tilde{q}}$ [GeV]	$\delta^{LL} \neq 0$	$\delta^{LL} = \delta^{RR} \neq 0$	$\delta^{LR} = \delta^{RL} \neq 0$
750	0.211	0.002	0.004
1500	0.180	0.002	0.014
2000	0.157	0.003	0.008

Table 1: Majorana gluino bounds for $M_{\tilde{g}} = 1500\,\text{GeV}$. By δ^{AB} we denote $\sqrt{|\text{Re}\,(\delta_{12}^{AB})^2|}$ and $c\sqrt{|\text{Im}\,(\delta_{12}^{AB})^2|}$.

Updated K^0-$\bar{K}^0$ mixing with Dirac Gluino

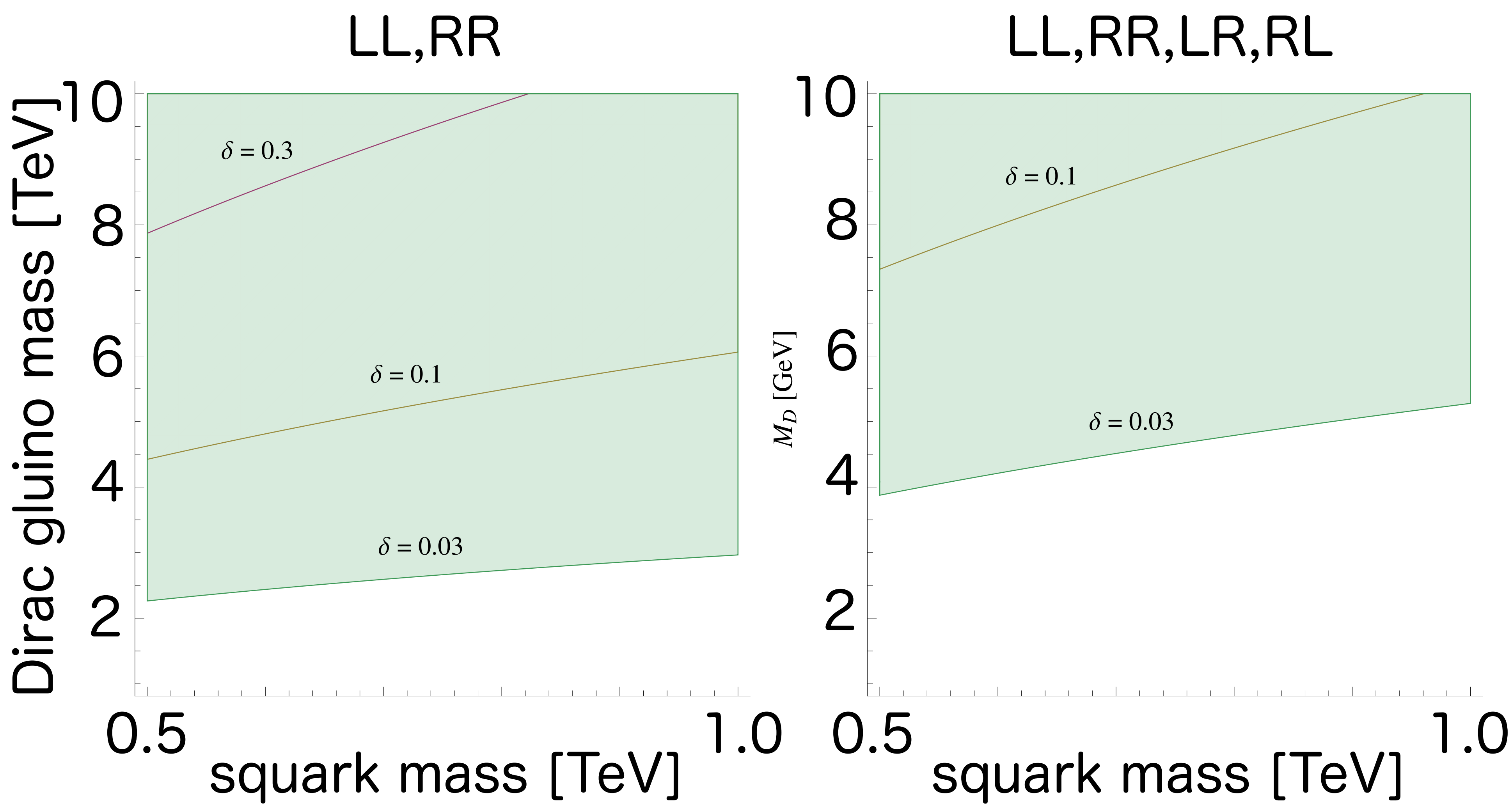


Figure 1: Contour plots in parameter space $m_{\tilde{q}}$ - m_D for purely Dirac gluino ($M = M_\chi = 0$). Left: $\delta^{LL} = \delta^{RR} = \delta$, $\delta^{LR} = \delta^{RL} = 0$. Right: $\delta^{LL} = \delta^{RR} = \delta^{LR} = \delta^{RL} = \delta$. Along the contours $\Delta m_K = \Delta m_K^{\rm exp}$ (for $\delta^{AB} = \sqrt{|{\rm Re}\,(\delta_{12}^{AB})^2|}$) and $\epsilon_K = \epsilon_K^{\rm exp}$ (for $\delta^{AB} = c\sqrt{|{\rm Im}\,(\delta_{12}^{AB})^{\,2}|}$).

Dudas, Goodsell, Heurtier, Tziveloglou; 1312.2011

μ -> e γ

Recently bounds were extracted for several interesting regions of MSSM parameter space (Majorana masses for electroweak gauginos):

$$|\delta_{12}^{LL}| \lesssim (1 \to 6) \times 10^{-5}$$
$$|\delta_{12}^{LR}| \lesssim (1 \to 10) \times 10^{-6}$$
$$|\delta_{12}^{RR}| \lesssim (1 \to 10) \times 10^{-3}$$

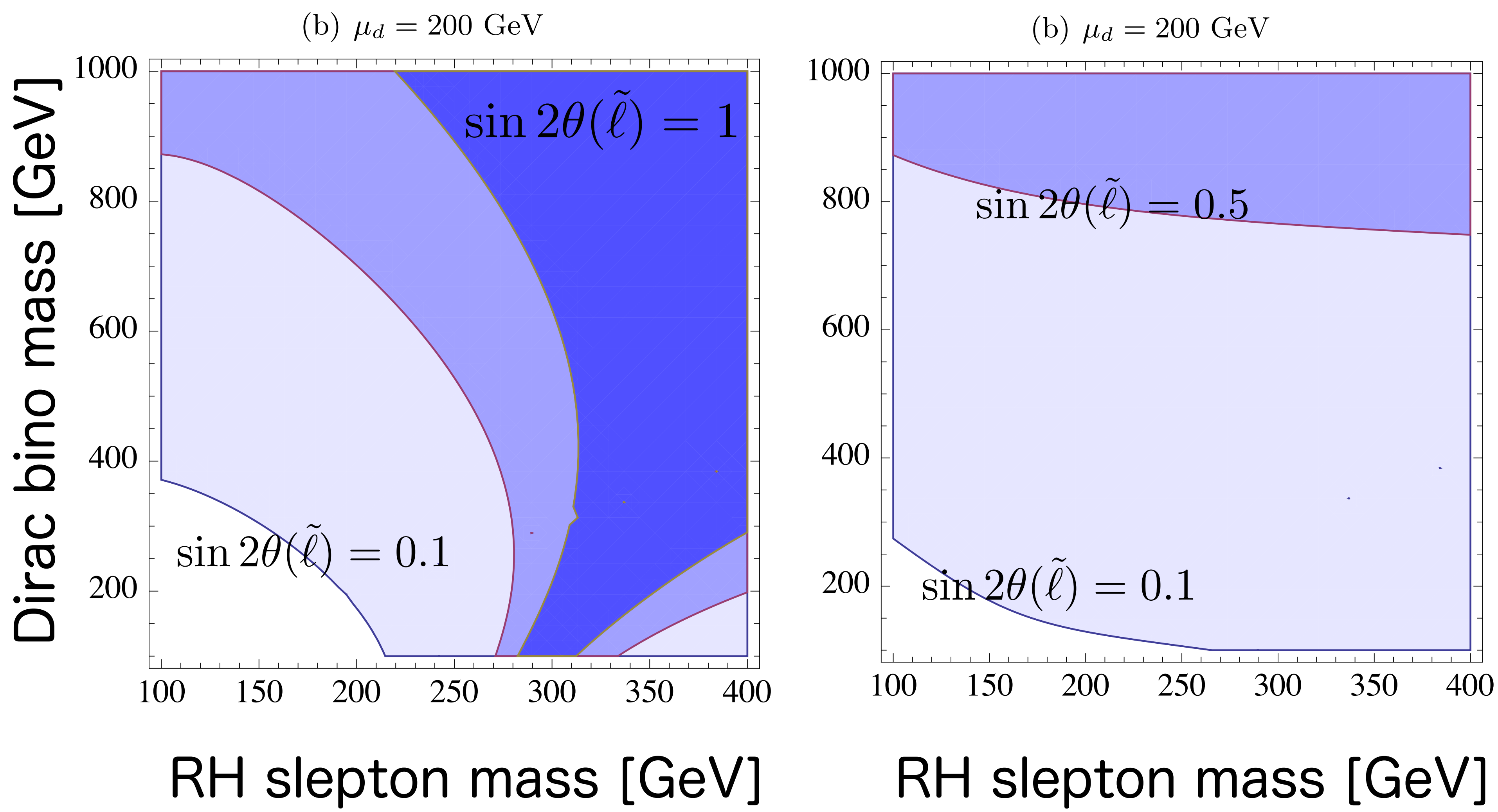
Arana-Catania, Heinemeyer, Herrero; 1303.2783

(under certain assumptions of parameter space; see reference for details)

μ -> e γ ; μ -> e conversion

Fok, Kribs; 1004.0556

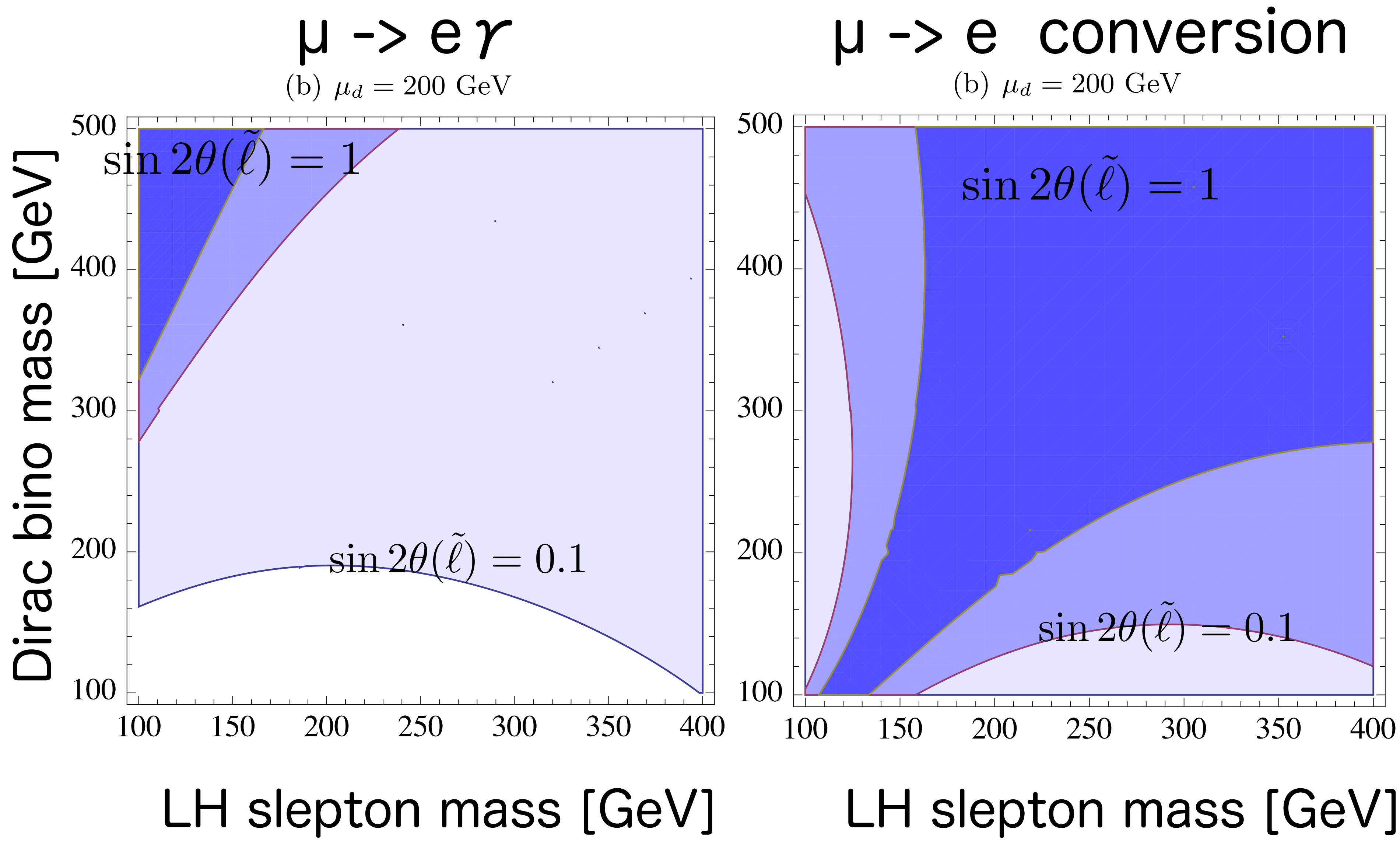
μ -> e γ μ -> e conversion



(under certain assumptions for spectrum)

μ -> eγ ; μ -> e conversion

Fok, Kribs; 1004.0556



(under certain assumptions for spectrum)

Many Other Consequences

- EDMs suppressed
- Negligible same-sign signals
- large $\tan\beta$-induced $\Delta F=1$ processes absent
- ...

3. Higgs Mass

Quartic Coupling with Dirac EW Gauginos

(pure Dirac gauginos; usual μ-term; not R-symmetric)

Dirac electroweak gauginos cause D-term to vanish

$$\mathcal{L} \supset D_a \left(\mathrm{Re}(A_a) + g_a^2 \sum_i \phi_i^* t^a \phi_i \right) + \frac{1}{2}(D_a)^2$$

- $\mathrm{Re}(A_a)$: from Dirac gaugino operator
- $g_a^2 \sum_i \phi_i^* t^a \phi_i$: from scalar kinetic terms
- $\frac{1}{2}(D_a)^2$: from usual kinetic term

Solve for D_a, substitute back into Lagrangian, integrate out masive $\mathrm{Re}(A_a)$, then

usual tree-level quartic vanishes

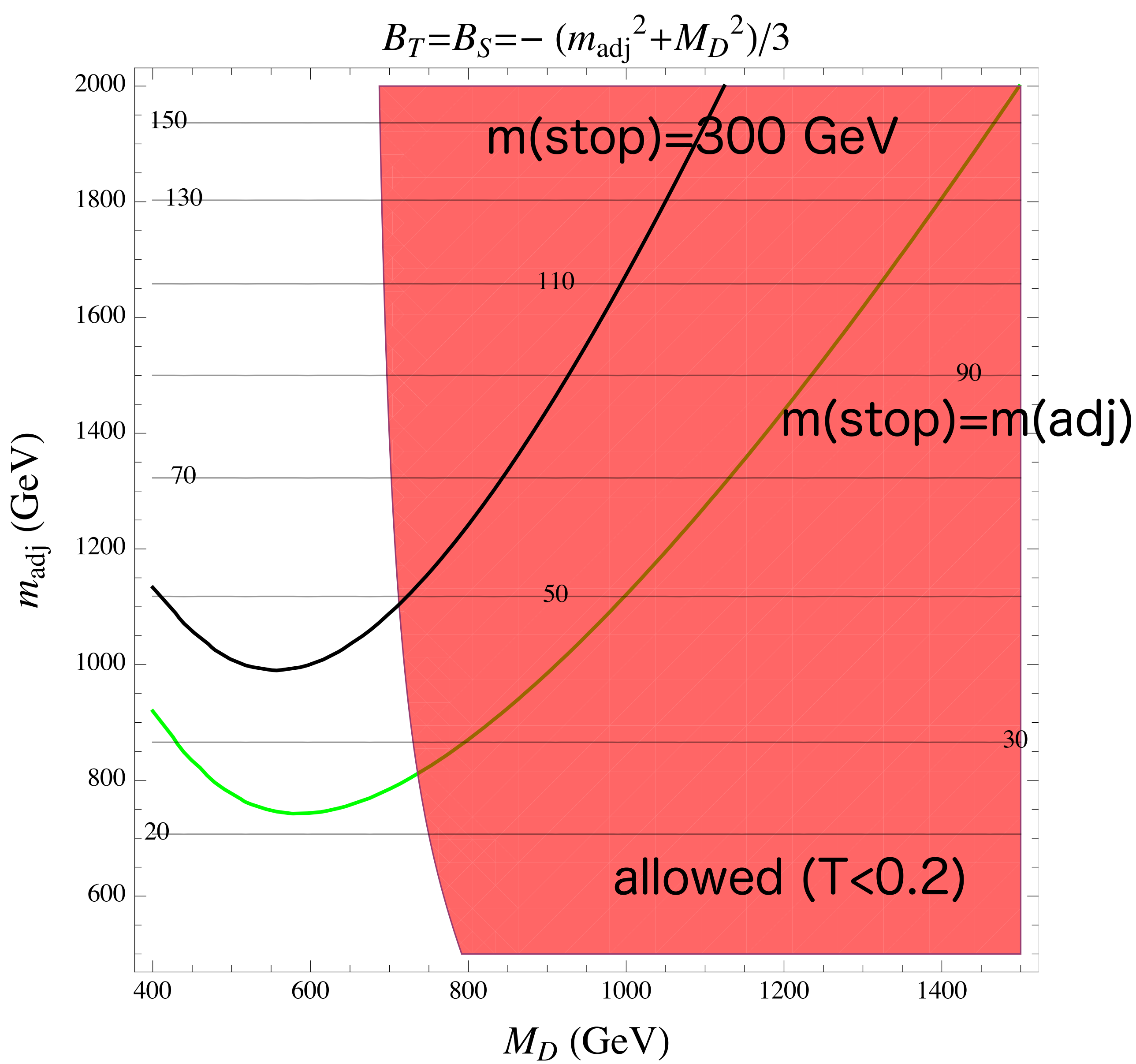
Quartic Coupling in R-Symmetric

Can use λ couplings to get m(h)=125 GeV

Fok, Kribs, Martin, Tsai; 1208.2784

Recent analysis taking into account tree-level and loop effects

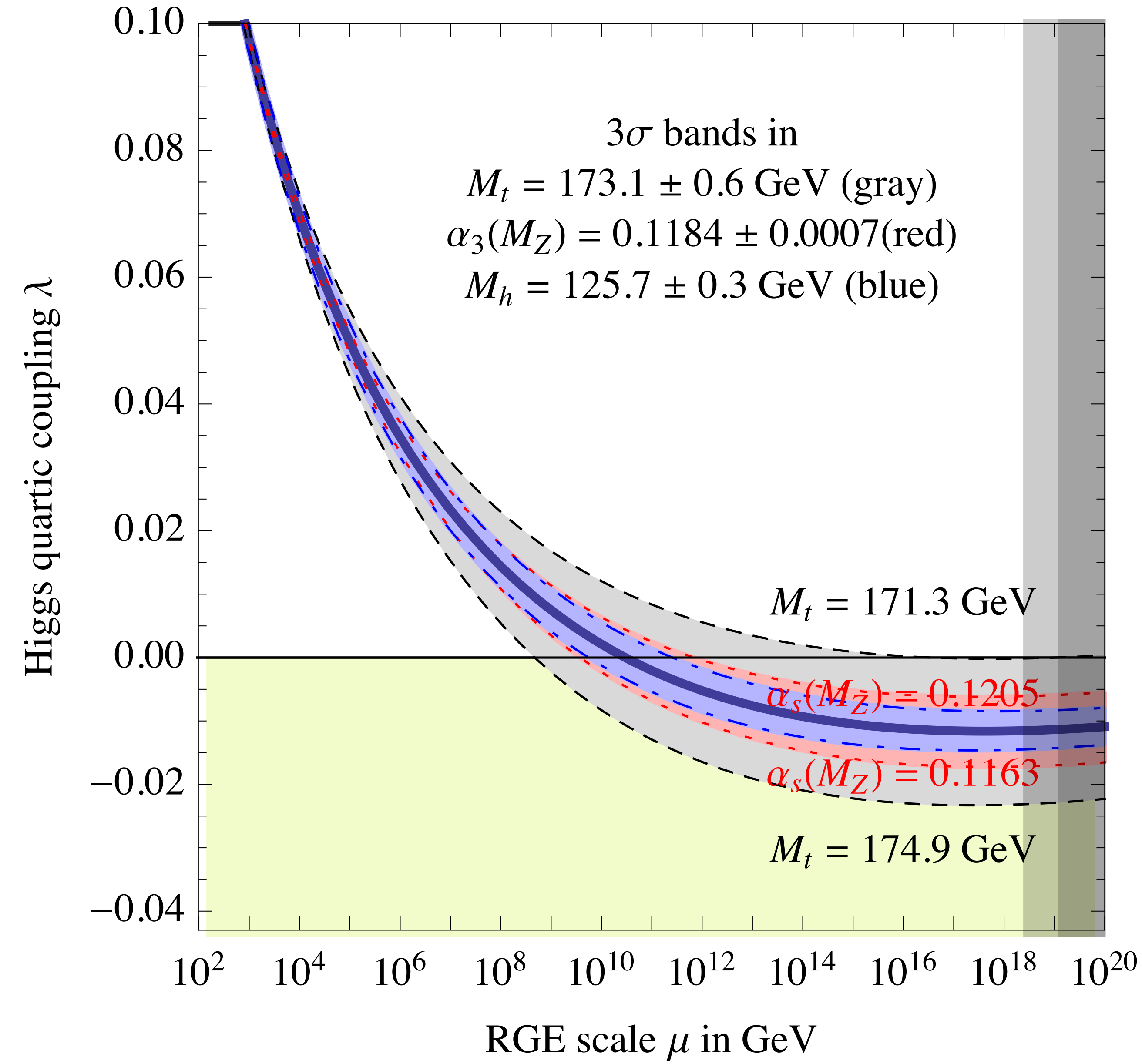
(as well as constraints from EW precision)



Bertuzzo, Frugiuele, Gregoire, Ponton; 1402.5432

Vanishing Quartic Coupling could be a Feature

Quartic coupling passes through zero near $\lambda(10^{11}\ \text{GeV}) \approx 0$



Buttazzo et al, 1307.3536

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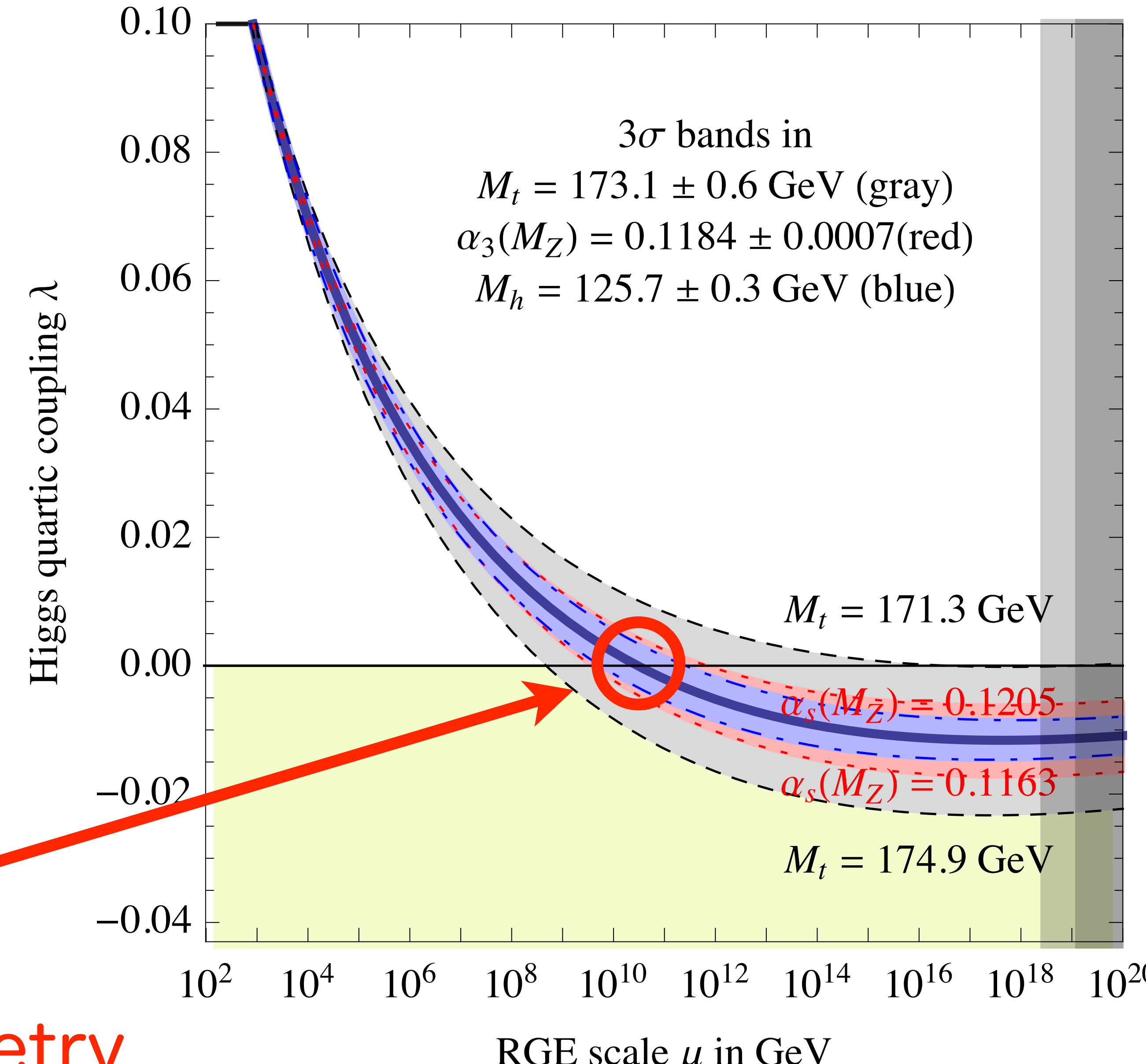
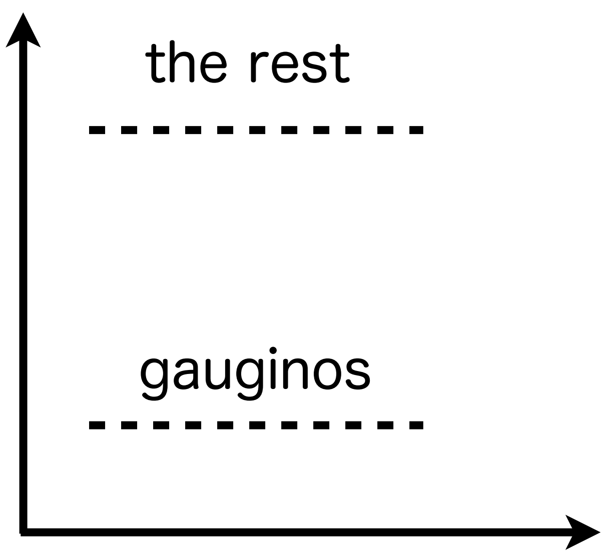


"Split" Supersoft Supersymmetry at an intermediate scale?

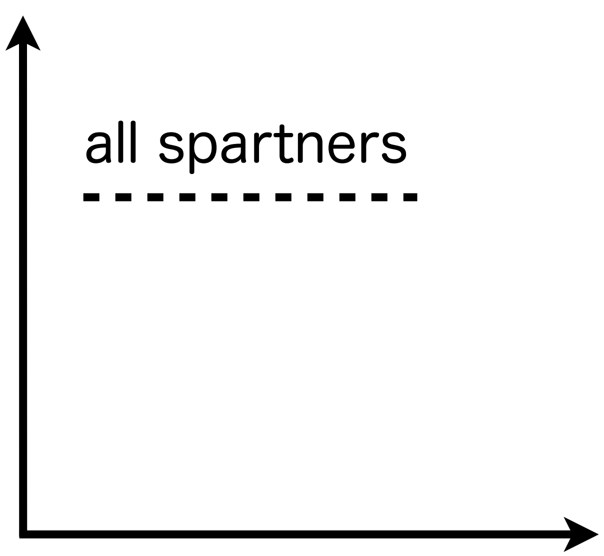
Buttazzo et al, 1307.3536

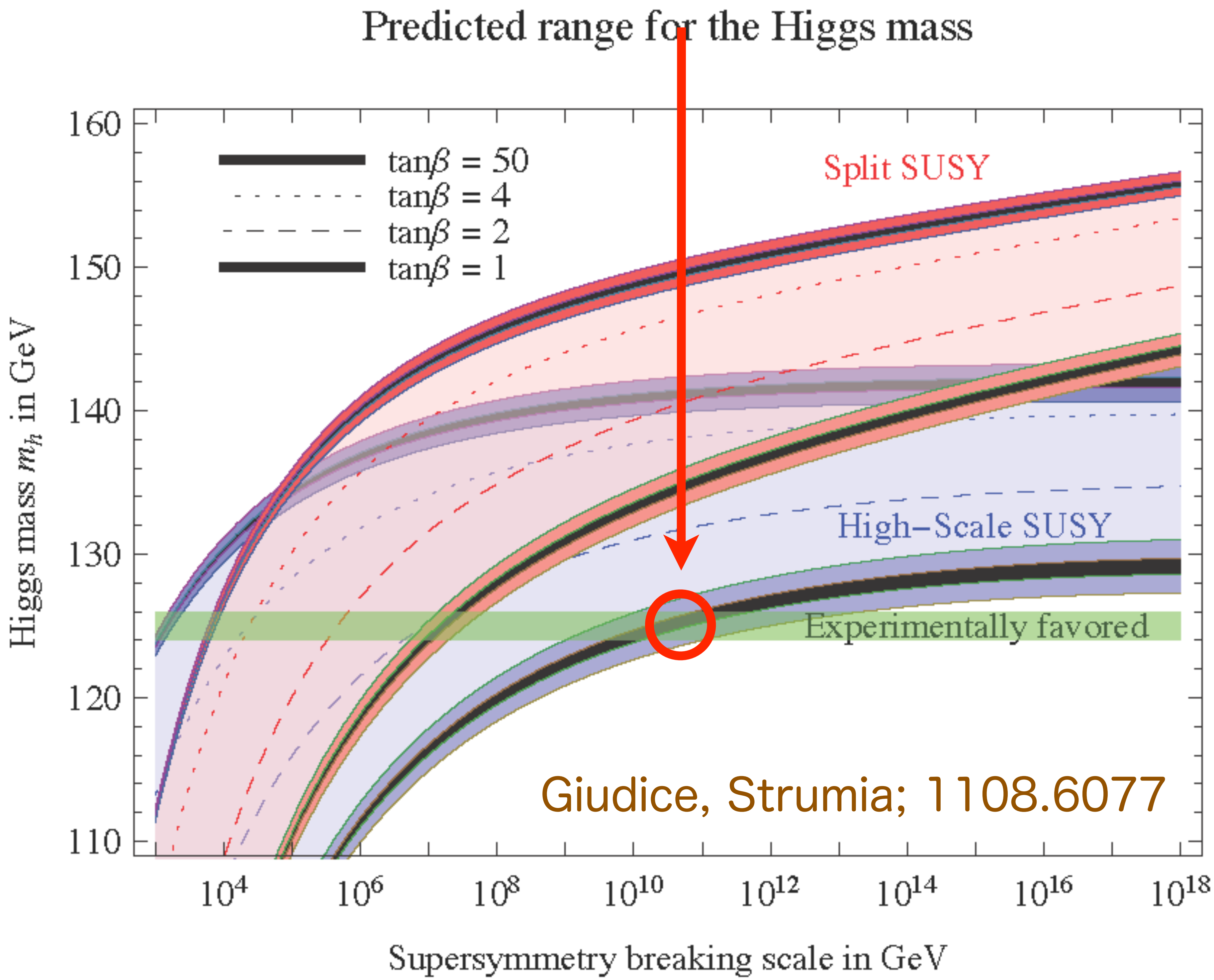
Unlike Split/Mini/High Scale - Sharp (Post)diction

Split SUSY

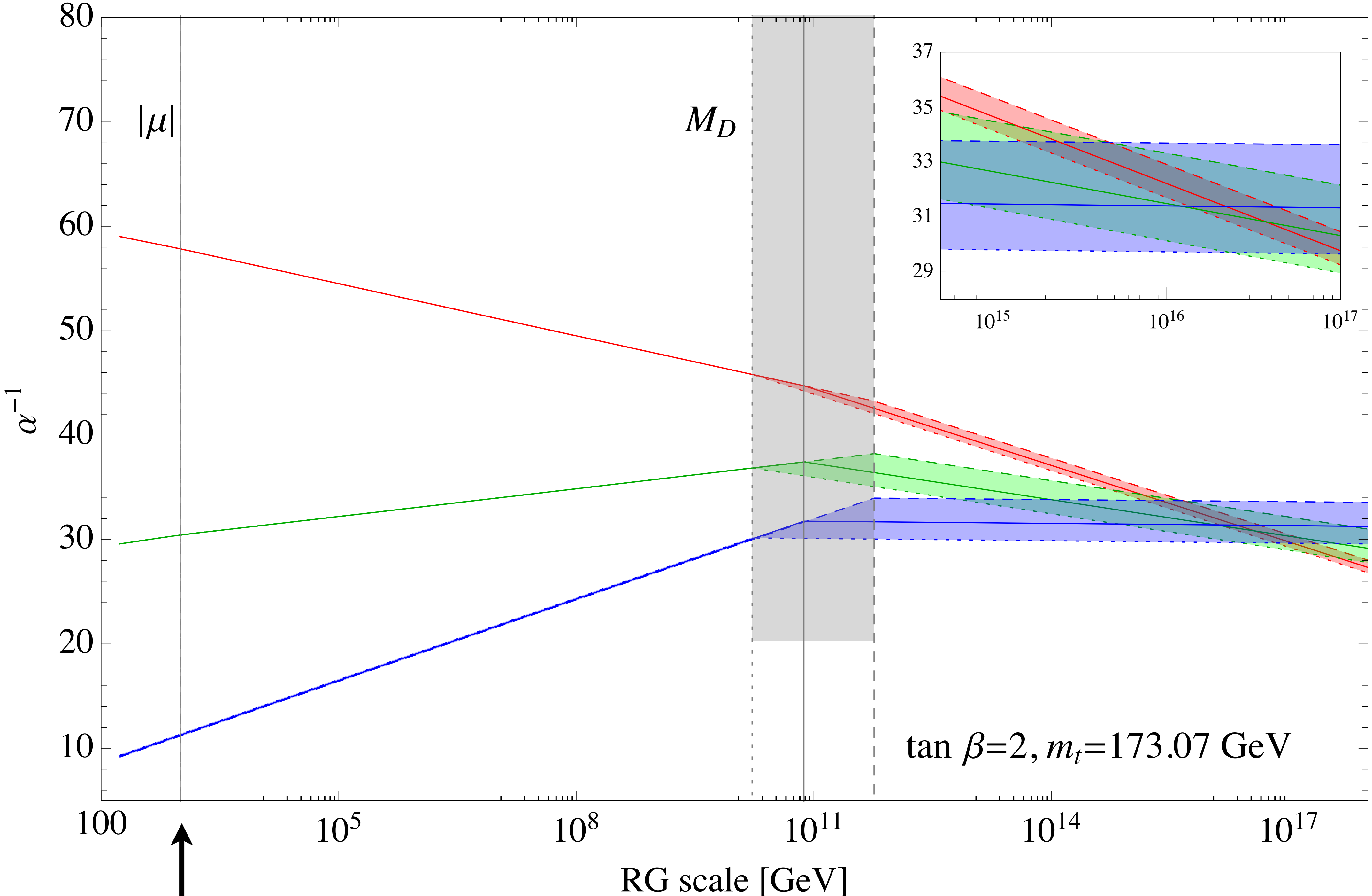


High scale SUSY





With a Feature

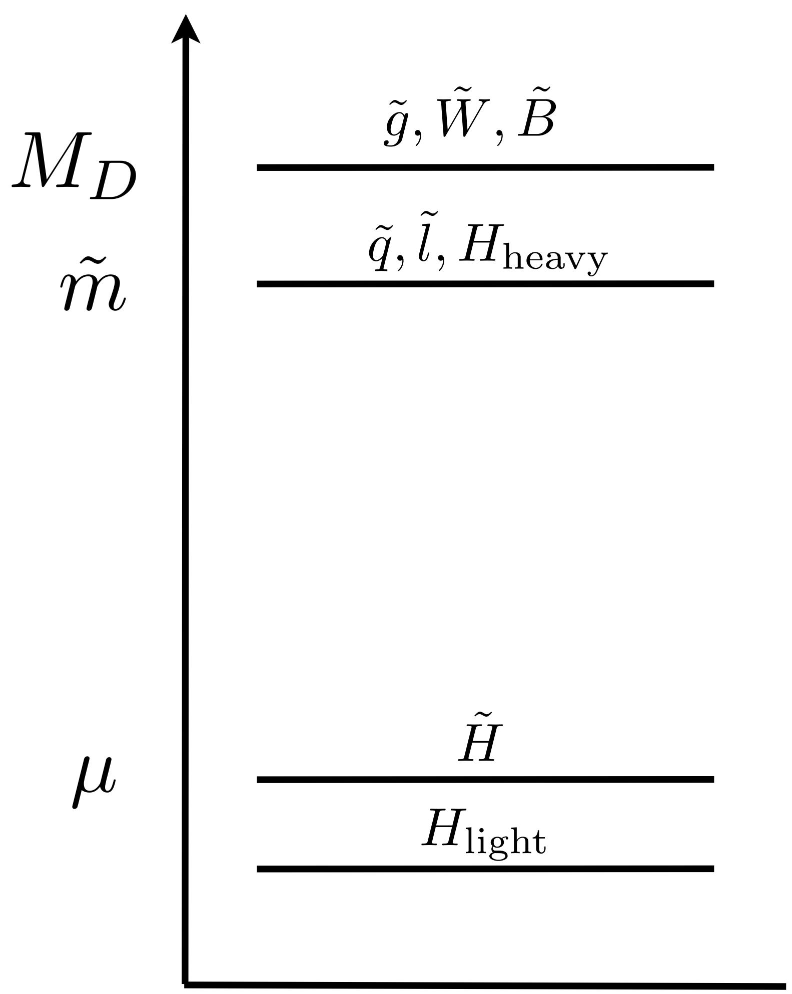


μ induced by higher dimensional operators through SUSY breaking

Fox, Kribs, Martin; 1405.3692

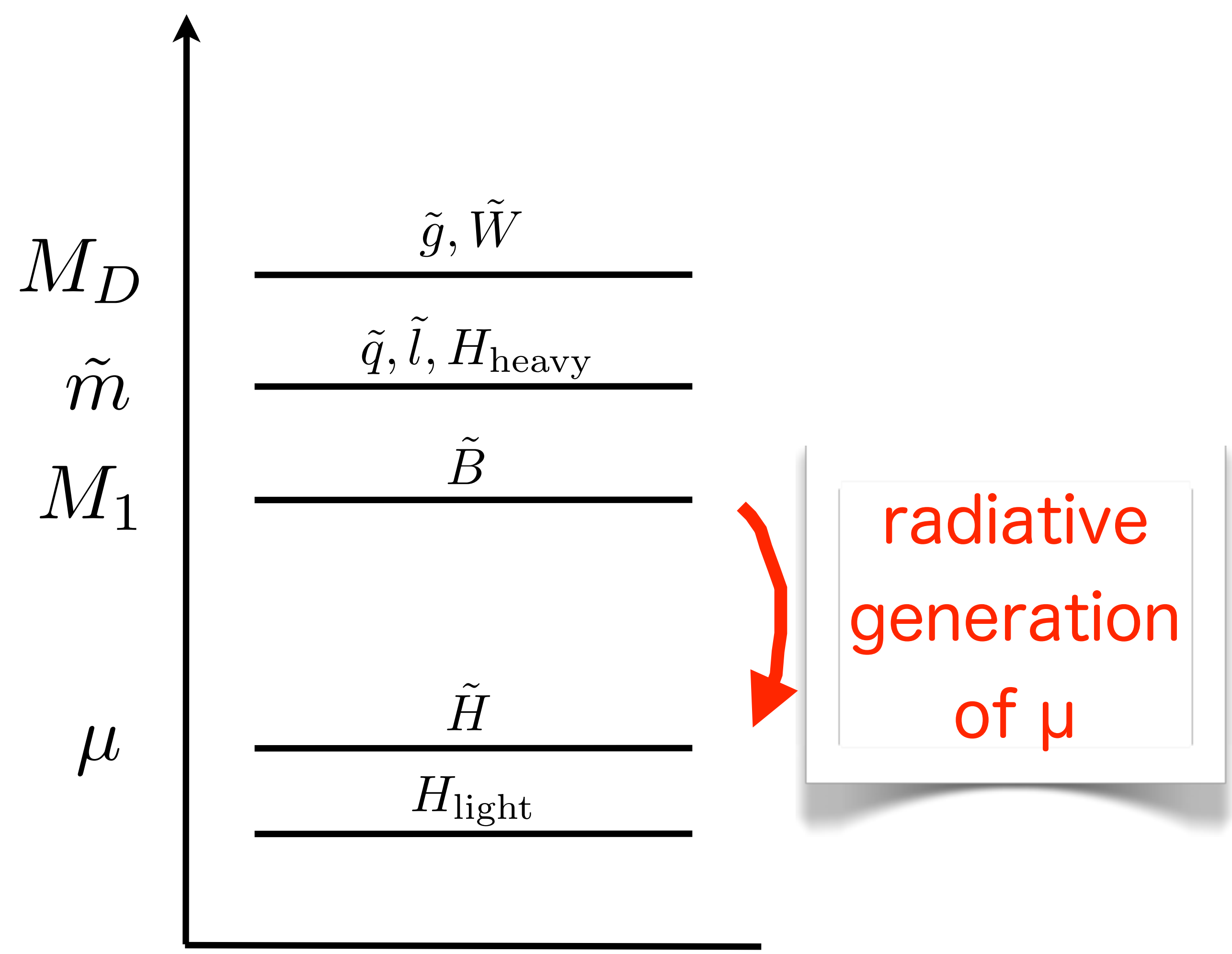
Observables?

Pure Dirac Model



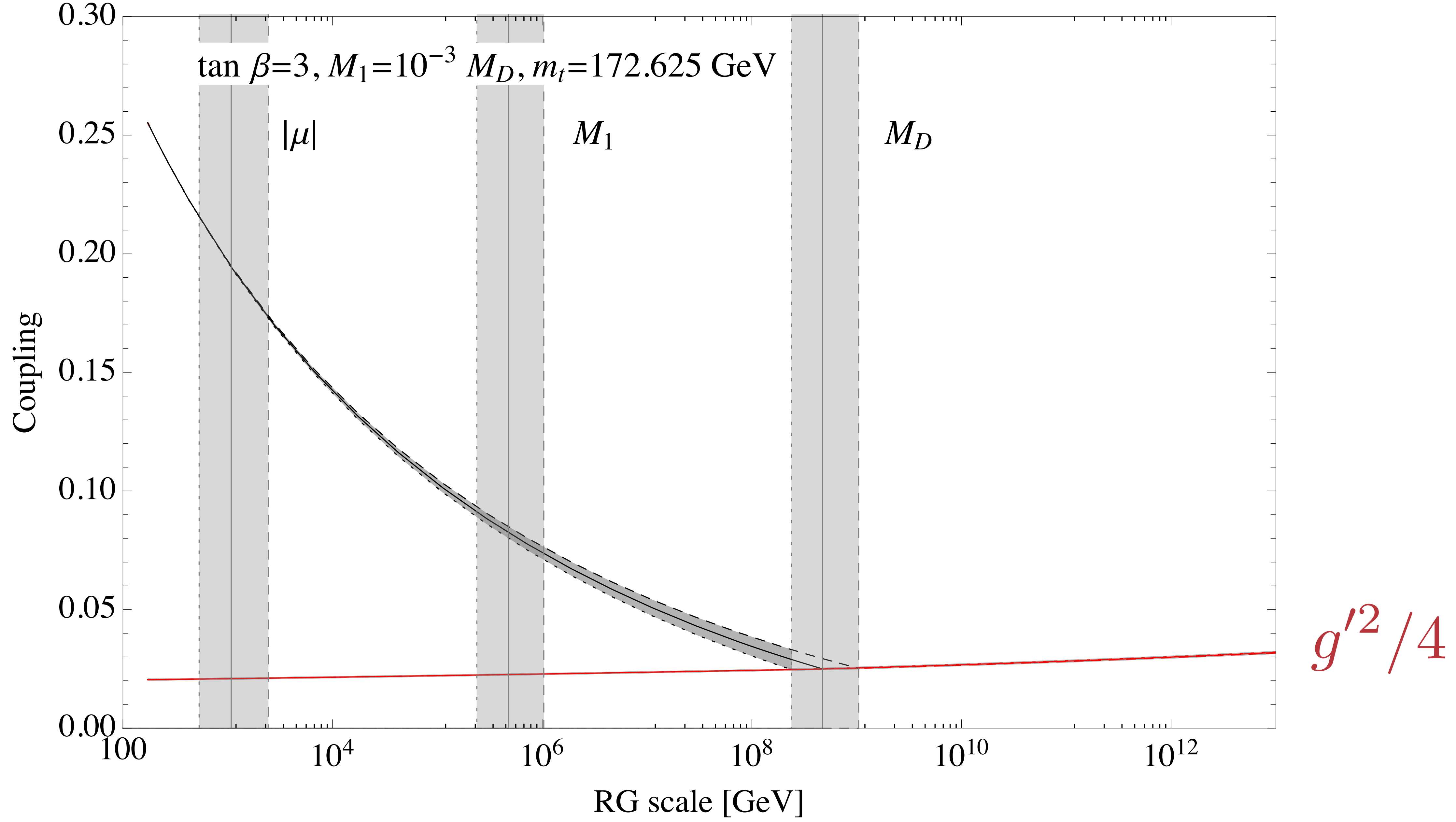
R-parity violating
Higgsino decay

Hypercharge Impure Model



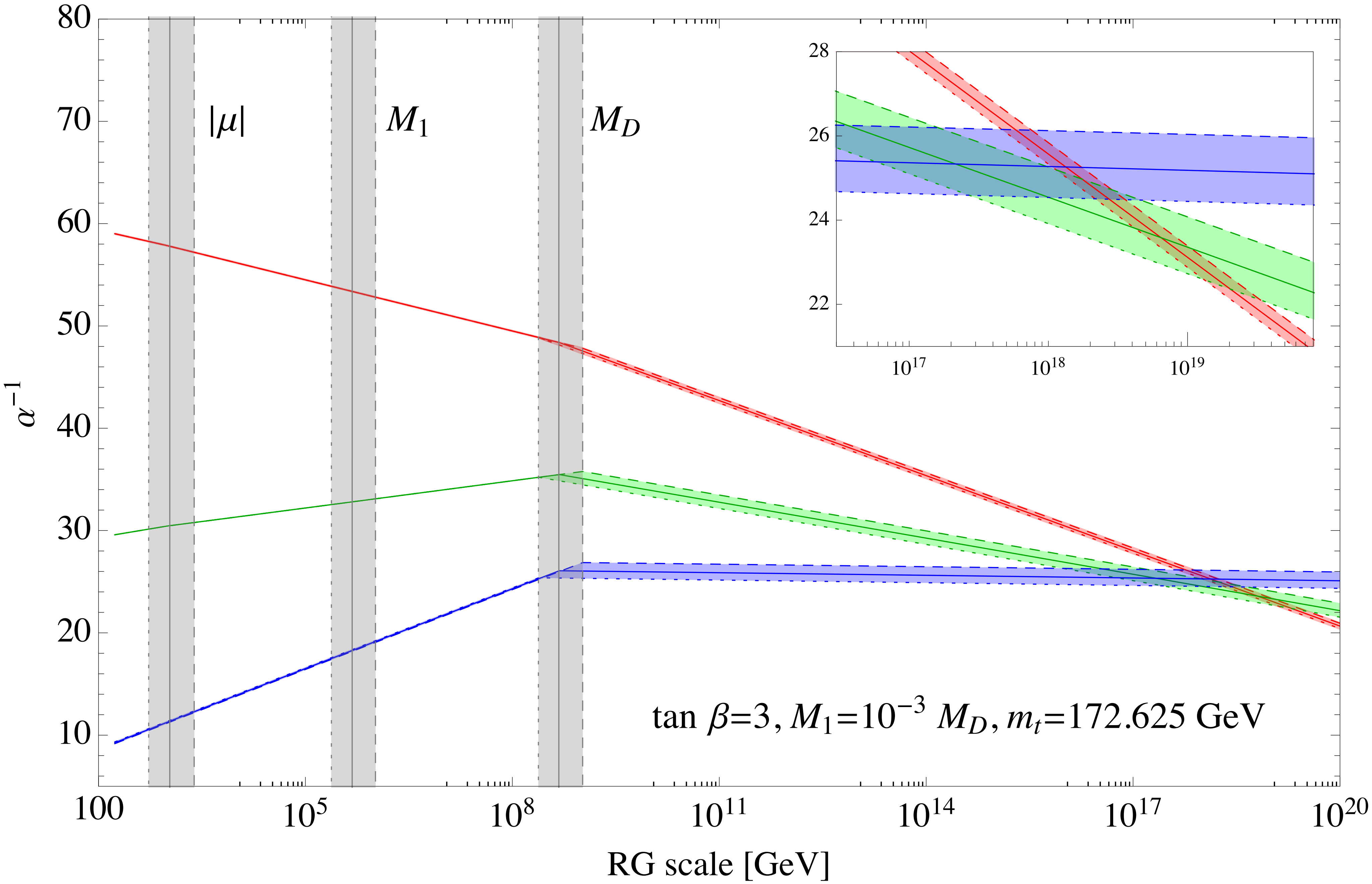
Higgsino dark matter

Split Dirac SUSY with Higgsino Dark Matter



Fox, Kribs, Martin; 1405.3692

Split Dirac SUSY with Higgsino Dark Matter



Fox, Kribs, Martin; 1405.3692

Higgsino Dark Matter

- Higgsino mass generated radiatively from bino mass [U(1)$_R$ breaking] and B_μ term [U(1)$_{PQ}$ breaking]

$$\mu \simeq \frac{\tilde{g}'_u \tilde{g}'_d}{16\pi^2} M_1^* \ln \frac{|B_\mu|^{1/2}}{|M_1|}$$

- Neutral Higgsinos split in mass by bino

$$\Delta \tilde{M}_N = \frac{M_Z^2 \sin^2\theta_W}{M_1} \simeq (200 \text{ keV}) \frac{10^7 \text{ GeV}}{M_1}$$

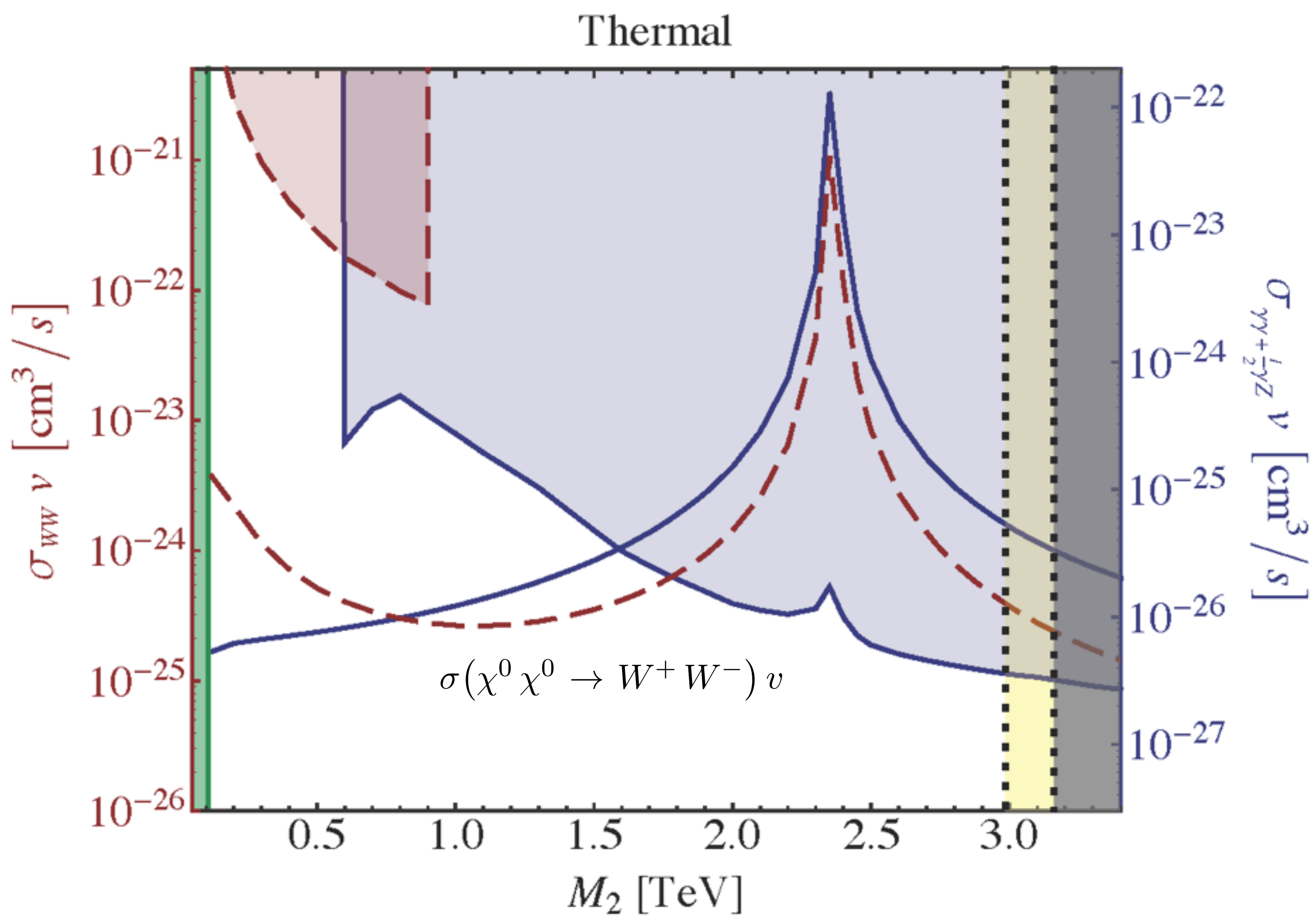
Heavy Bino induces both mass and (inelastic) splitting.
Natural viable DM candidate (μ = 1.1 TeV for thermal abundance)

- Charged Higgsinos split in mass ≈ 340 MeV

(electromagnetic correction -- Cirelli, Fornengo, Strumia; 0512090)

Higgsino Dark Matter

- Unlike winos, does not suffer from galactic center γ-ray constraints



Cohen, Lisanti, Pierce, Slatyer; 1307.4082
also Fan, Reece; 1307.4400

How to discover? Work in progress...

Fox, Kribs, Martin

Summary

Dirac gauginos

- reduced naturalness constraints from gluino
- LHC constraints on squarks weakened
- FCNC constraints significantly weakened
  (can contemplate partly flavor-anarchic
  squark/slepton mass matrices)
- EDM constraints significantly weakened
- new contributions to Higgs mass (R-symmetric)
- new models of split supersymmetry
  (one with Higgsino DM that avoids γ-ray constraints)

Many other Dirac gaugino topics (models, phenomenology) found in references.

We “just” have to find it!