# A (partially) Dirac Gluino versus LHC Bounds on Supersymmetry

Graham Kribs
IAS & U Oregon

mainly: 1203.4821 with Adam Martin (CERN/Notre Dame);
and 1307.xxxx with Nirmal Raj (Oregon)
plus 1208.2784 with Adam Martin, Ricky Fok (York), Yuhsin Tsai (UC Davis)

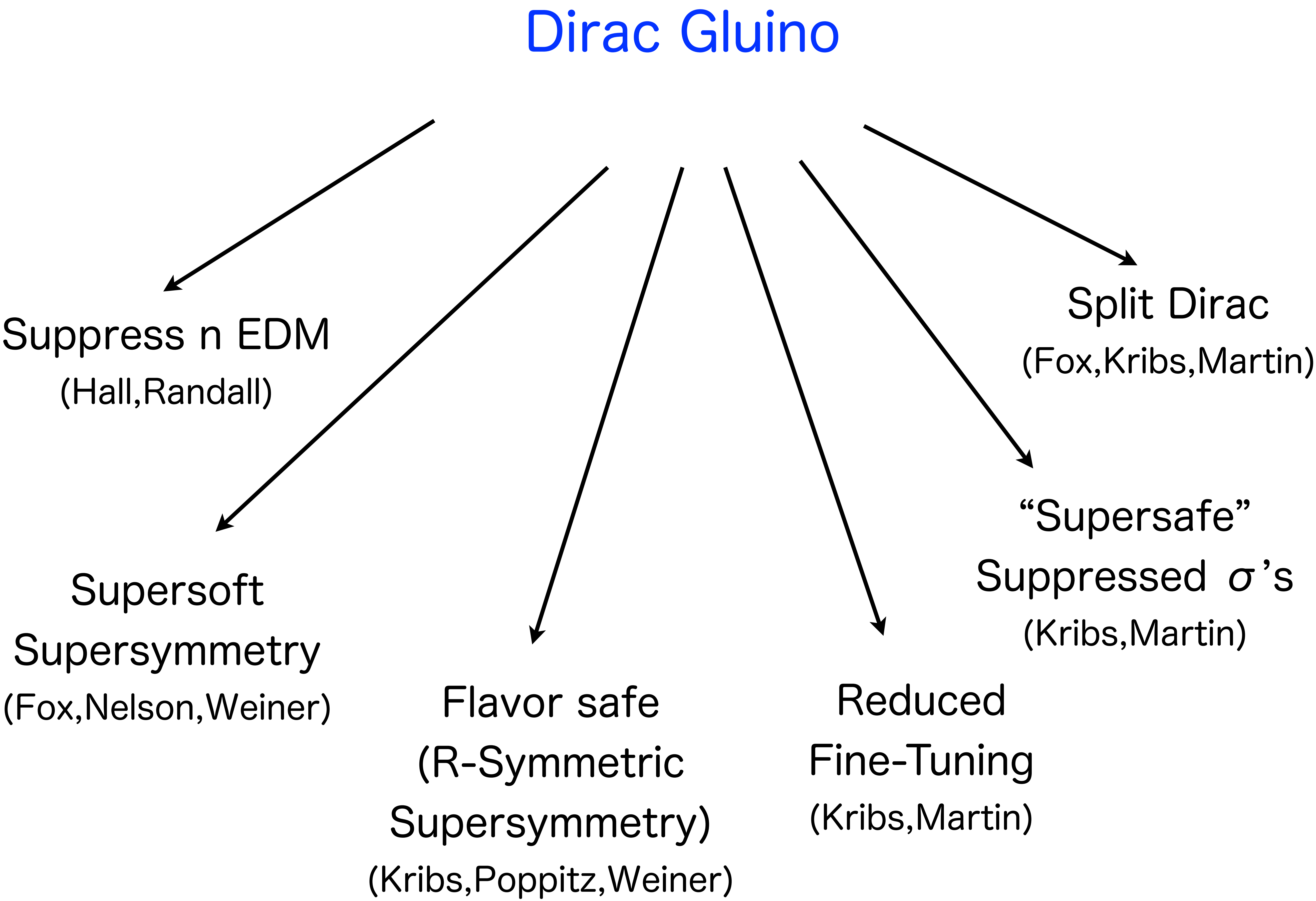
# Take Home Messages

- Gluino could acquire a Dirac mass by pairing up with an fermion in adjoint rep

- An exact or approximately Dirac gluino
  - suppresses gluino-mediated FCNC
  - can be ≈ 5-7 times heavier than Majorana gluino but just as natural w.r.t. EWSB
  - automatically suppresses colored sparticle production

- Dirac + Majorana mass for
  -> gluino slightly lowers squark production
  -> adj ferm slightly increases squark production

- One of the "last chances" for weak scale supersymmetry


Dirac Gluino
Suppress n EDM
(Hall,Randall)
Supersoft
Supersymmetry
(Fox,Nelson,Weiner)
Flavor safe
(R-Symmetric
Supersymmetry)
(Kribs,Poppitz,Weiner)
Reduced
Fine-Tuning
(Kribs,Martin)
“Supersafe”
Suppressed $\sigma$’s
(Kribs,Martin)
Split Dirac
(Fox,Kribs,Martin)

# Dirac Gauginos in Supersymmetry

Polchinski, Susskind (1982)
Hall, Randall (1991)
Fox, Nelson, Weiner (2002)
...

SUSY breaking to gauginos communicated through D-term spurions:

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

Dirac gaugino masses arise from:

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

$M$: messenger scale

giving

$$\mathcal{L} \supset -m_D \lambda_j \tilde{a}_j$$

$\tilde{a}_j$: chiral fermion in adjoint rep

$\lambda_j$: gaugino

$m_D = D'/M$

# Dirac Gauginos in Supersymmetry II

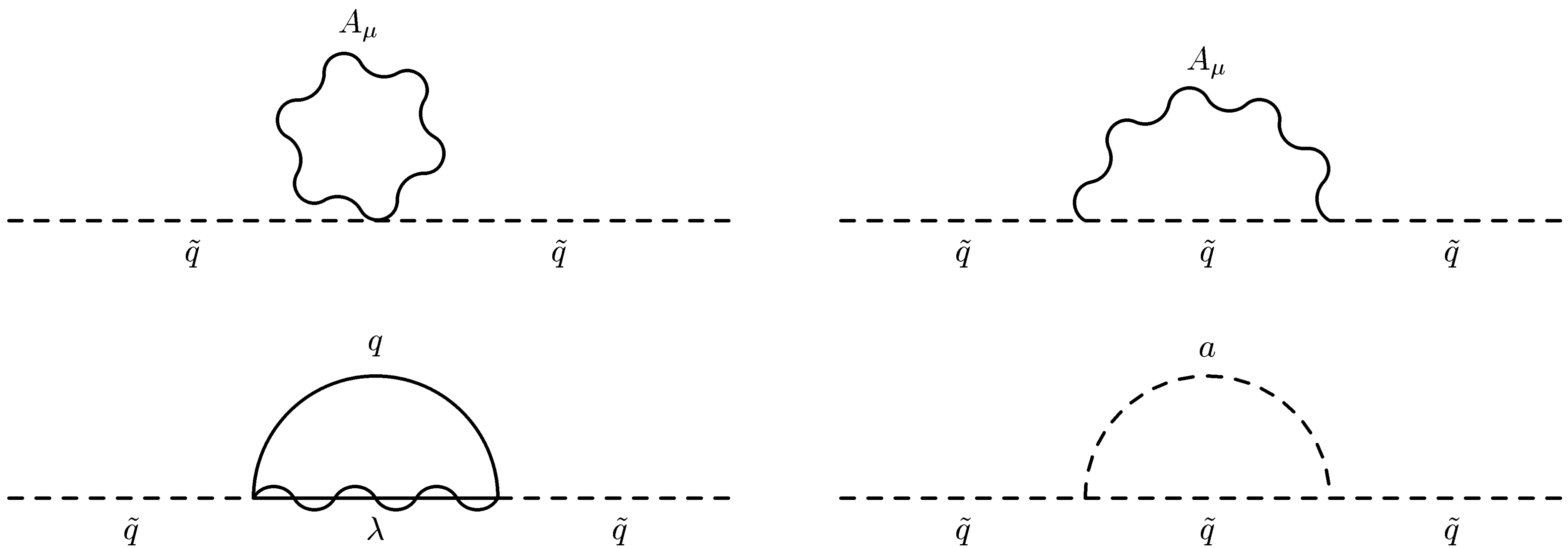
Dirac gaugino masses require extending the MSSM with chiral superfields in adjoint representation:

$$\begin{cases} A_j & j = 1 \ldots 8 \\ A_j & j = 1 \ldots 3 \\ A_j & j = 1 \end{cases}$$

| | | |
|---|---|---|
| $A_j$ | $j = 1 \ldots 8$ | color octet |
| $A_j$ | $j = 1 \ldots 3$ | weak triplet |
| $A_j$ | $j = 1$ | singlet |

# Squark/Slepton Masses

One-loop contributions:

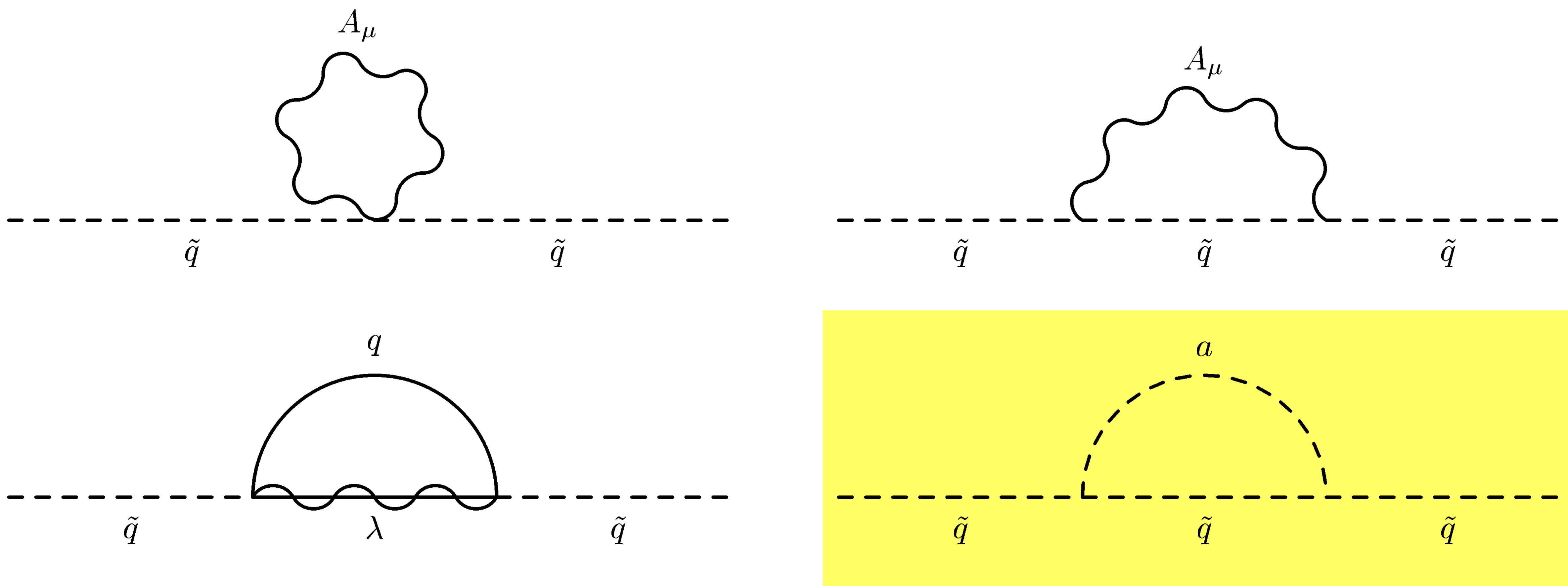



Giving

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

# Squark/Slepton Masses

One-loop contributions:




Giving

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

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

"Supersoft"

Fox, Nelson, Weiner (2002)

# Adjoint Scalar Partners

Gauginos married off with fermionic components of chiral adjoint superfields:

$$A_j = \begin{pmatrix} \tilde{a}_j \\ a_j \end{pmatrix}$$

Also contain scalars in adjoint representation (e.g. “sgluons”).

$$\int d^2\theta \sqrt{2} \frac{W'_\alpha W_j^\alpha A_j}{M} \xrightarrow{\text{also}} \mathcal{L} \supset -m_D^2 (a_j + a_j^*)^2$$

Additional contributions

$$\int d^2\theta \frac{W'_\alpha W'^\alpha}{M^2} A_j^2$$

Masses for Re[$a_j$] and Im[$a_j$] (opposite signs)

# Finite Squark Masses from Dirac Gauginos

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

Plugging in numbers:

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

or

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

Dirac gluino ≈ (5-7) x squark mass

# Naturalness I: Gluino

## MSSM

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

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

# Naturalness I: Gluino

## MSSM

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

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

evaluate

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

## Supersoft

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:

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

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

Dirac gluino can be substantially heavier than Majorana gluino while just as natural.

# Dirac Masses for Electroweak Gauginos?

+

Finiteness maintained by electroweak gauginos.

(Charged) lepton flavor violation suppressed with anarchic sleptons.

Dirac dark matter (Harnik, Kribs; Hooper et al)

Electroweak baryogenesis.

-

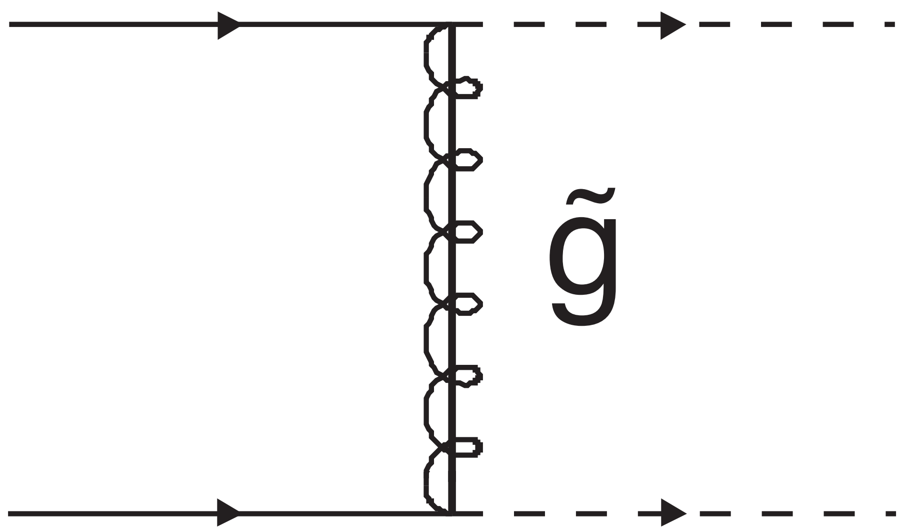
Integrate out massive Re[$a_j$], forces $D_j = 0$, hence tree-level quartic vanishes.

Need new contributions to Higgs mass (for example, "$\lambda$" couplings, see 1208.2784)

# LHC Implications

## Dirac versus Majorana gluino

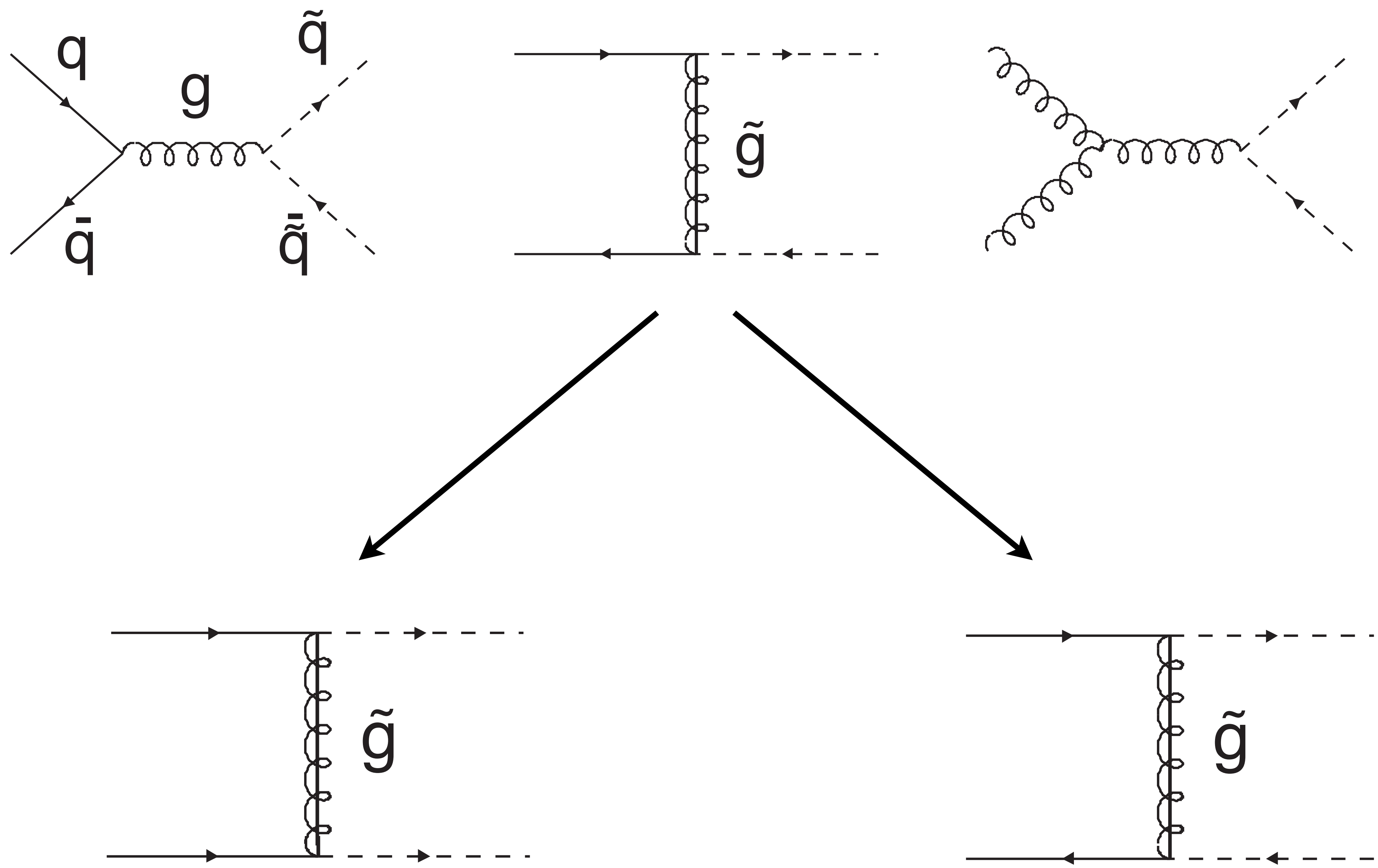
# Squark Production




Gluino exchange diagrams
ought to dominate
LHC production of
(1st generation) squarks

But for heavier gluino (≈ a few TeV)...

# Squark Production with heavier Dirac gluino

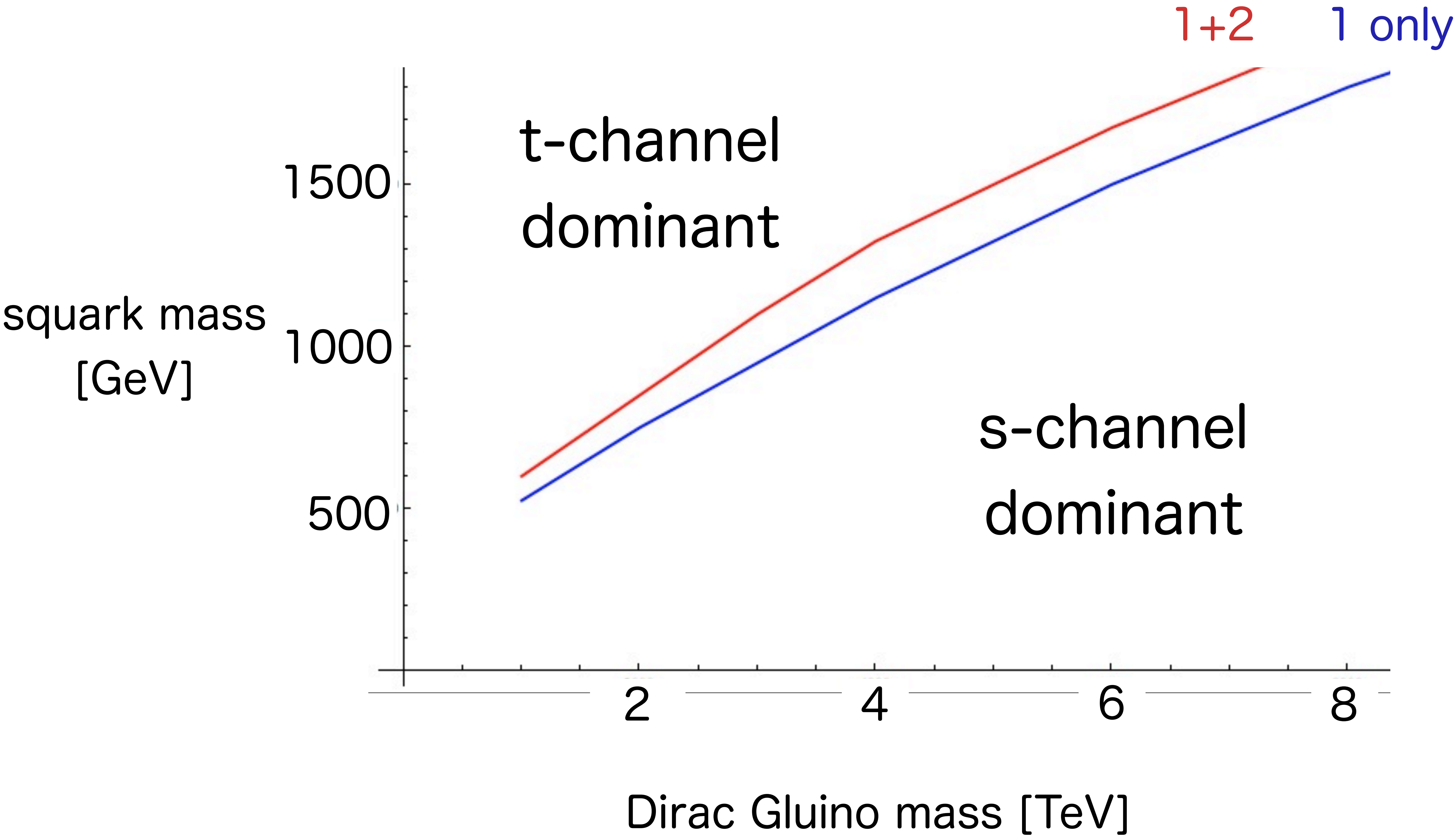



LL, RR absent

LR suppressed $|p|/M^2$

suppressed $|p|/M^2$ & PDFs

# Suppression of t-channel Dirac Gluino

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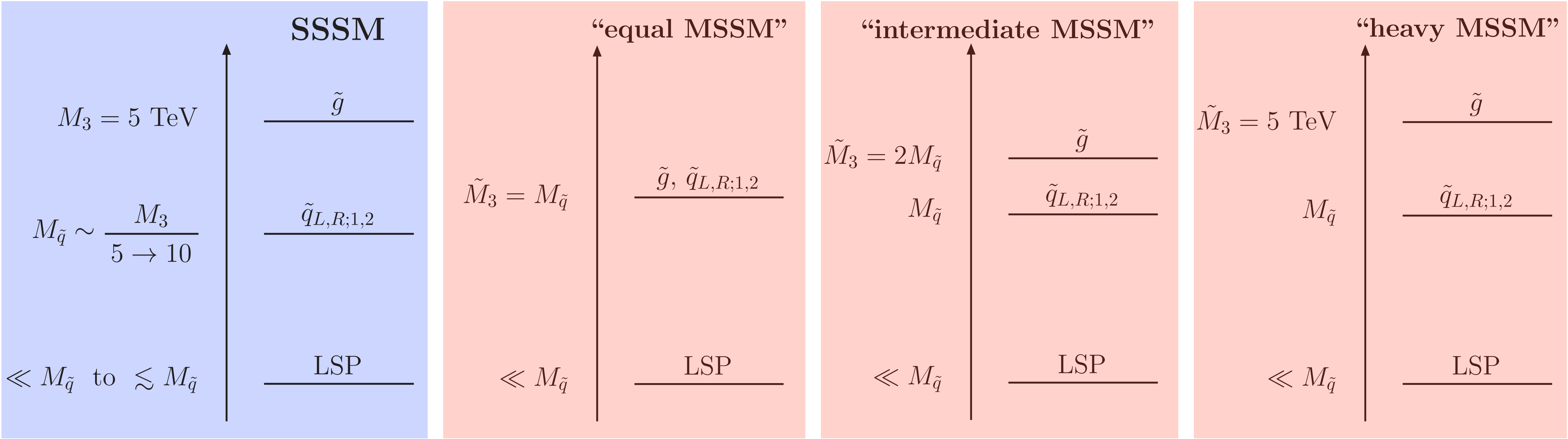
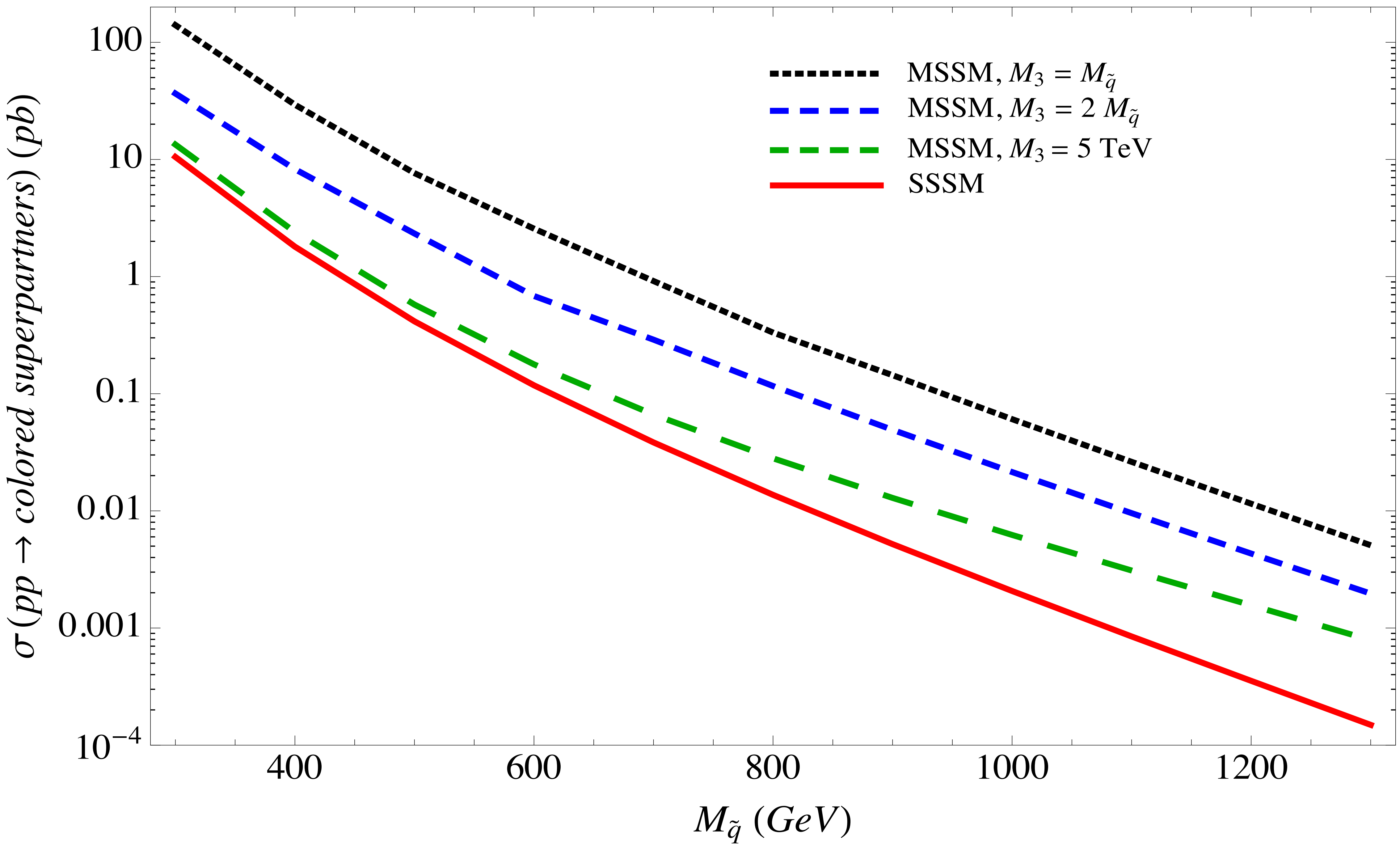
# Simplified Models for Comparisons

Construct a supersoft supersymmetric simplified model (SSSM) and perform apples-for-apples comparison against MSSM.



# Colored Sparticle Cross Sections

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# Simulations

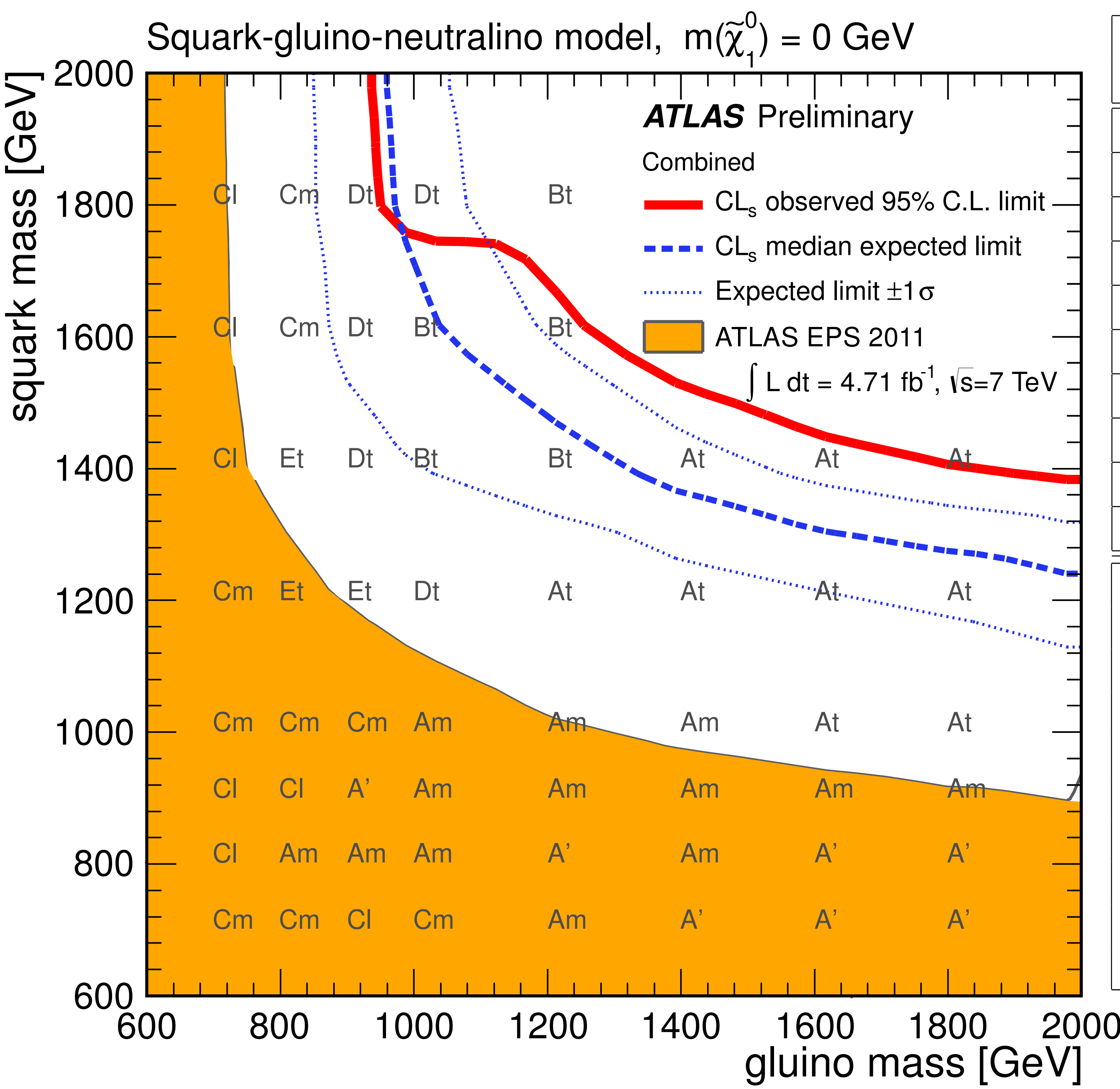
Signal simulation | Depends only on squark mass!

Pythia with NLO K-factors from Prospino
CTEQ6L
DELPHES
jet definitions appropriate to experiments

Backgrounds from ATLAS, CMS analysis notes.

Use simplified models of MSSM as cross checks that we are approximately matching expt analyses limits.

# (old) ATLAS jets + missing search strategy




At Am A' Bt

| Requirement | A | A' | B |
|---|---|---|---|
| $E_T^{miss}$[GeV] > | | | |
| $p_T(j_1)$ [GeV] > | | | |
| $p_T(j_2)$ [GeV] > | | | |
| $p_T(j_3)$ [GeV] > | — | — | 60 |
| $p_T(j_4)$ [GeV] > | — | — | — |
| $p_T(j_5)$ [GeV] > | — | — | — |
| $p_T(j_6)$ [GeV] > | — | — | — |
| $\Delta\phi(\text{jet}, E_T^{miss})_{min}$ > | 0.4 ($i$ = {1, 2, (3)}) | | |
| $E_T^{miss}/m_{eff}(Nj)$ > | 0.3 (2j) | 0.4 (2j) | 0.25 (3j) |
| $m_{eff}$(incl.) [GeV] > | 1900/1400/— | —/1200/— | 1900/—/— |

| | | | | |
|---|---|---|---|---|
| $t\bar{t}$+ Single Top | 0.22 ± 0.35 (0.046) | 7 ± 5 (5.1) | 11 ± 3.4 (10) | 0.21 ± 0.33 (0.066) |
| $Z/\gamma$+jets | 2.9 ± 1.5 (3.1) | 31 ± 9.9 (34) | 64 ± 20 (69) | 2.5 ± 1.4 (1.6) |
| $W$+jets | 2.1 ± 0.99 (1.9) | 19 ± 4.5 (21) | 26 ± 4.6 (30) | 0.97 ± 0.6 (0.84) |
| Multi-jets | 0 ± 0.0024 (0.002) | 0.14 ± 0.24 (0.13) | 0 ± 0.13 (0.38) | 0 ± 0.0034 (0.0032) |
| Di-Bosons | 1.7 ± 0.95 (2) | 7.3 ± 3.7 (7.5) | 15 ± 7.4 (16) | 1.7 ± 0.95 (1.9) |
| Total | 7 ± 0.999 ± 2.26 | 64.8 ± 10.2 ± 6.92 | 115 ± 19 ± 9.69 | 5.39 ± 0.951 ± 2.01 |
| Data | 1 | 59 | 85 | 1 |
| local p-value (Gaus. $\sigma$) | 0.98(-2.1) | 0.65(-0.4) | 0.9(-1.3) | 0.95(-1.7) |
| UL on $N_{BSM}$ | $2.9(6.1^{4.2}_{9})$ | $25(28^{20}_{39})$ | $29(43^{32}_{60})$ | $3.1(5.5^{3.8}_{8.3})$ |
| UL on $\sigma_{BSM}$ /(fb) | $0.62(1.3^{0.89}_{1.9})$ | $5.3(6^{4.3}_{8.2})$ | $6.2(9.2^{6.7}_{13})$ | $0.65(1.2^{0.8}_{1.8})$ |

ATLAS-CONF-2012-033

# ATLAS Search Bounds

| SSSM | MSSM | MSSM | MSSM |
|---|---|---|---|
| M3 = 5 TeV | M3 = Msq | M3 = 2 Msq | M3 = 5 TeV |

1st,2nd generation squark mass

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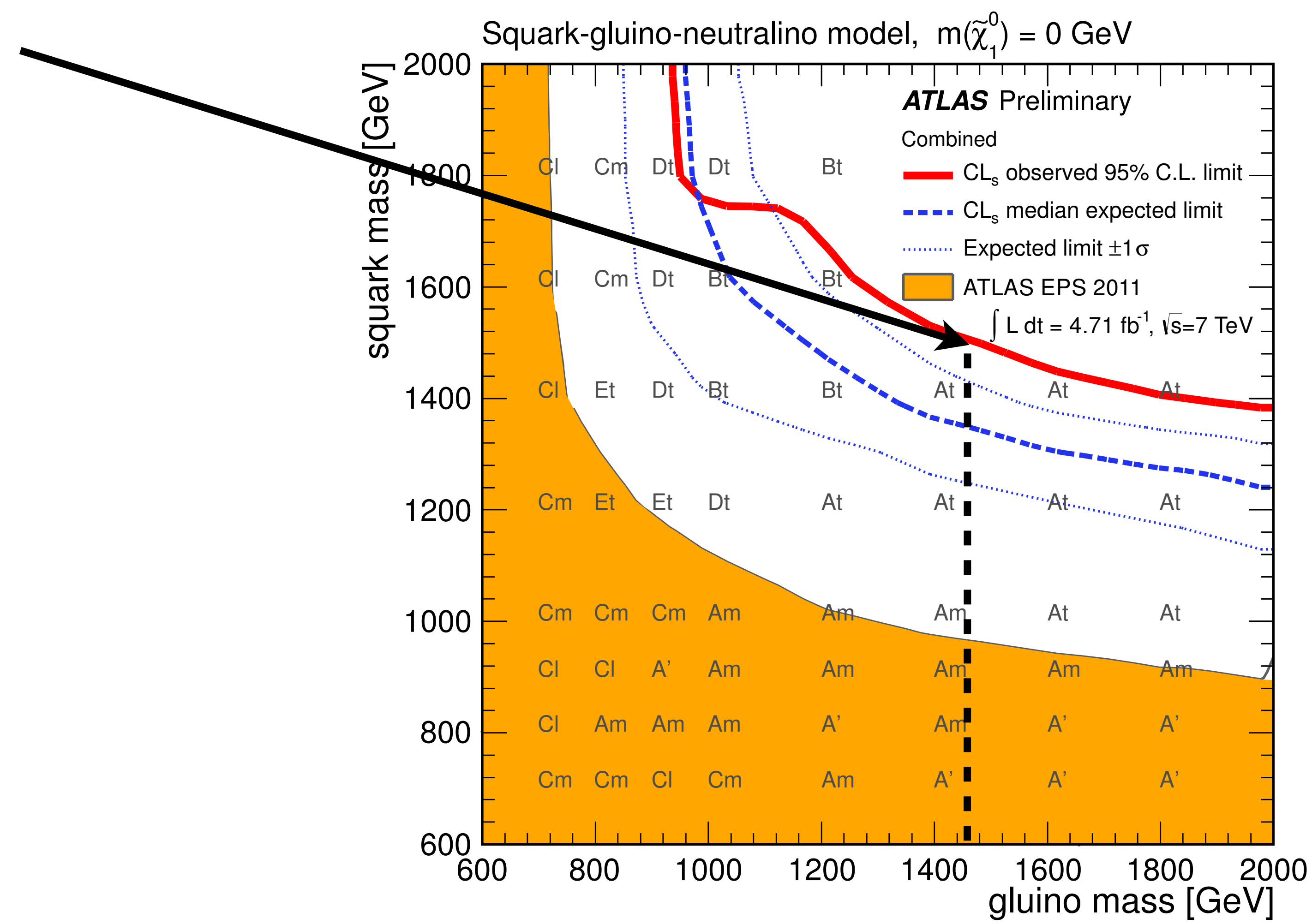
| M3 = 5 TeV | M3 = Msq | M3 = 2 Msq | M3 = 5 TeV |

1st,2nd generation squark mass

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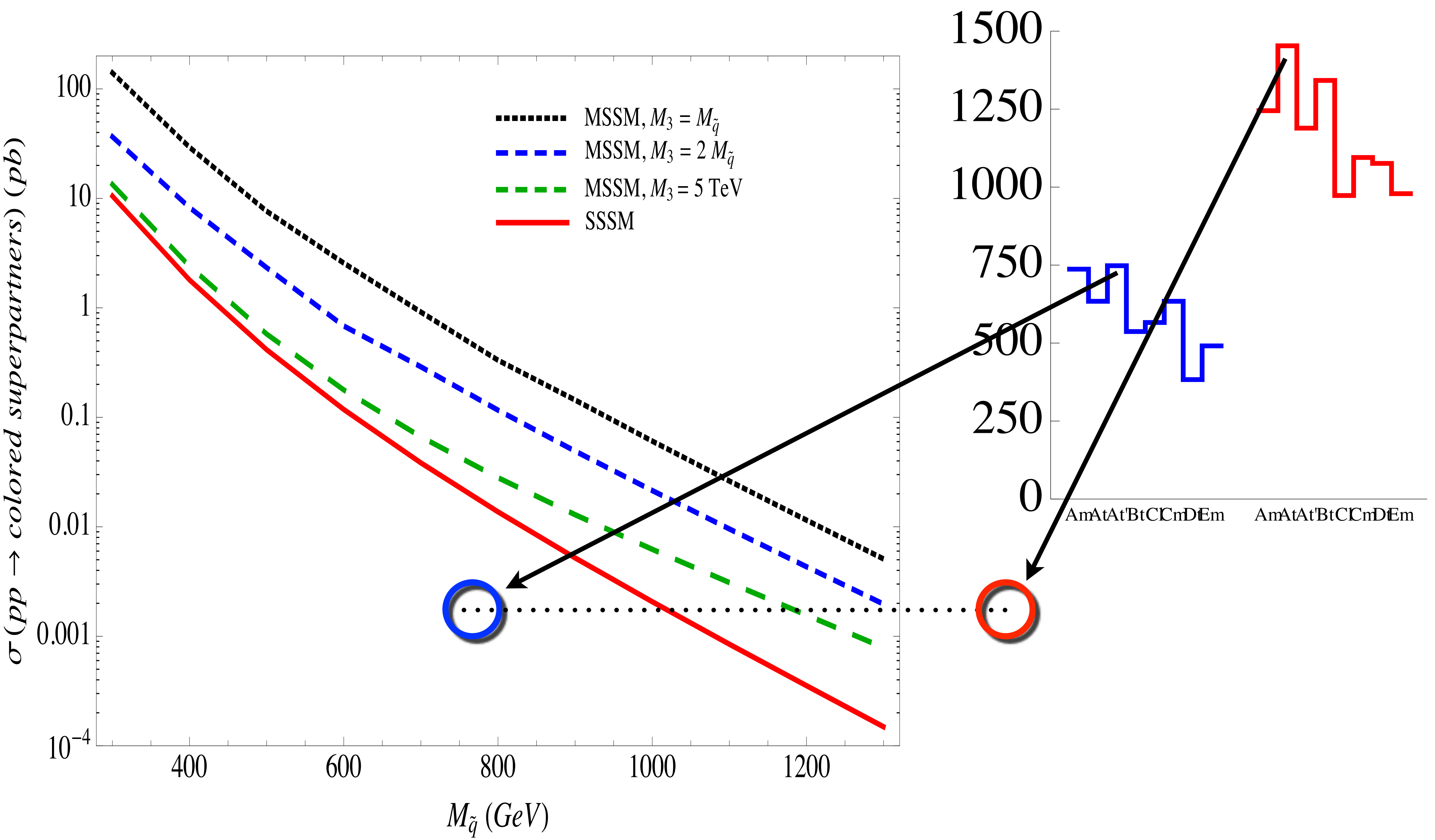
# Effectiveness of ATLAS strategy

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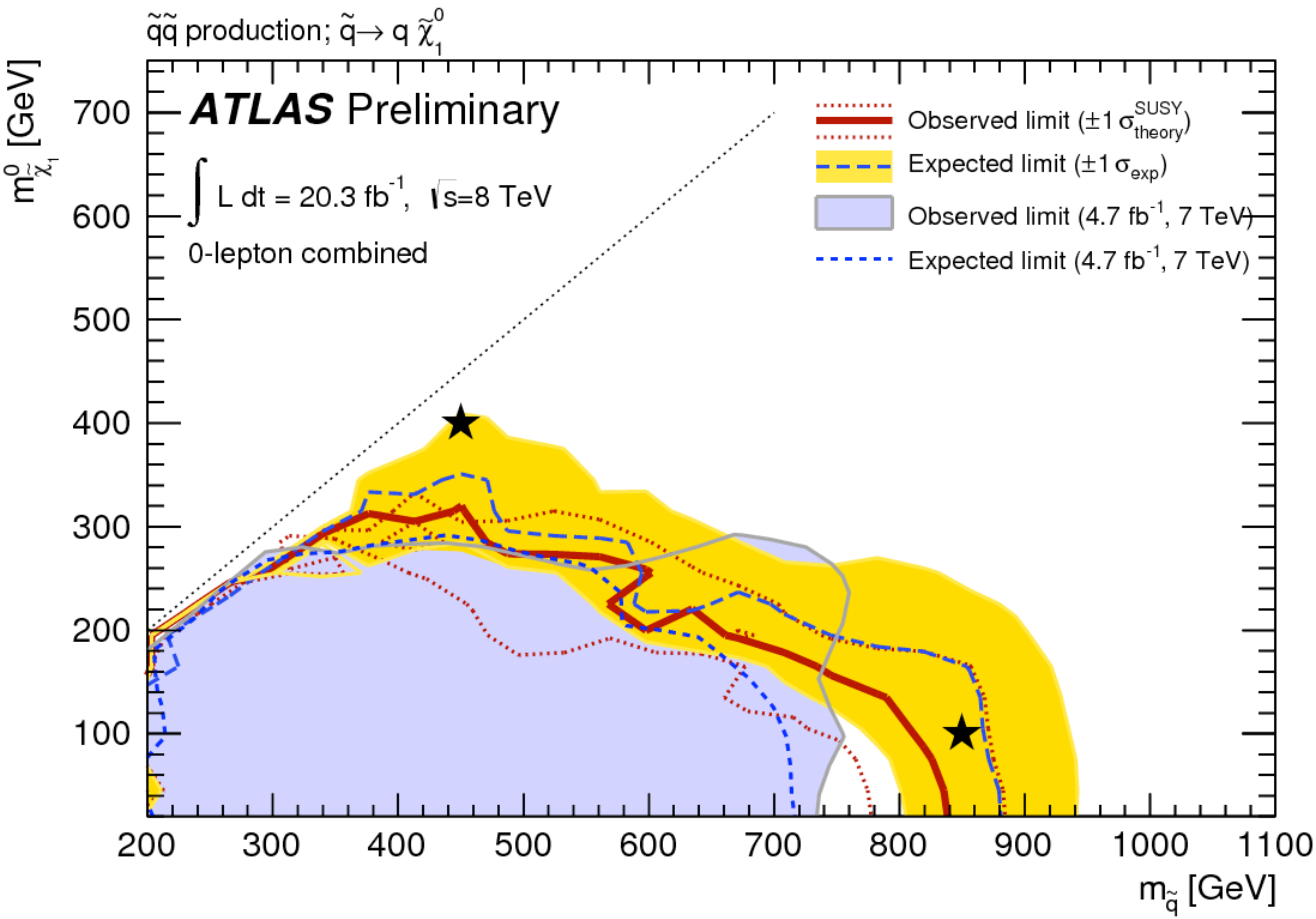
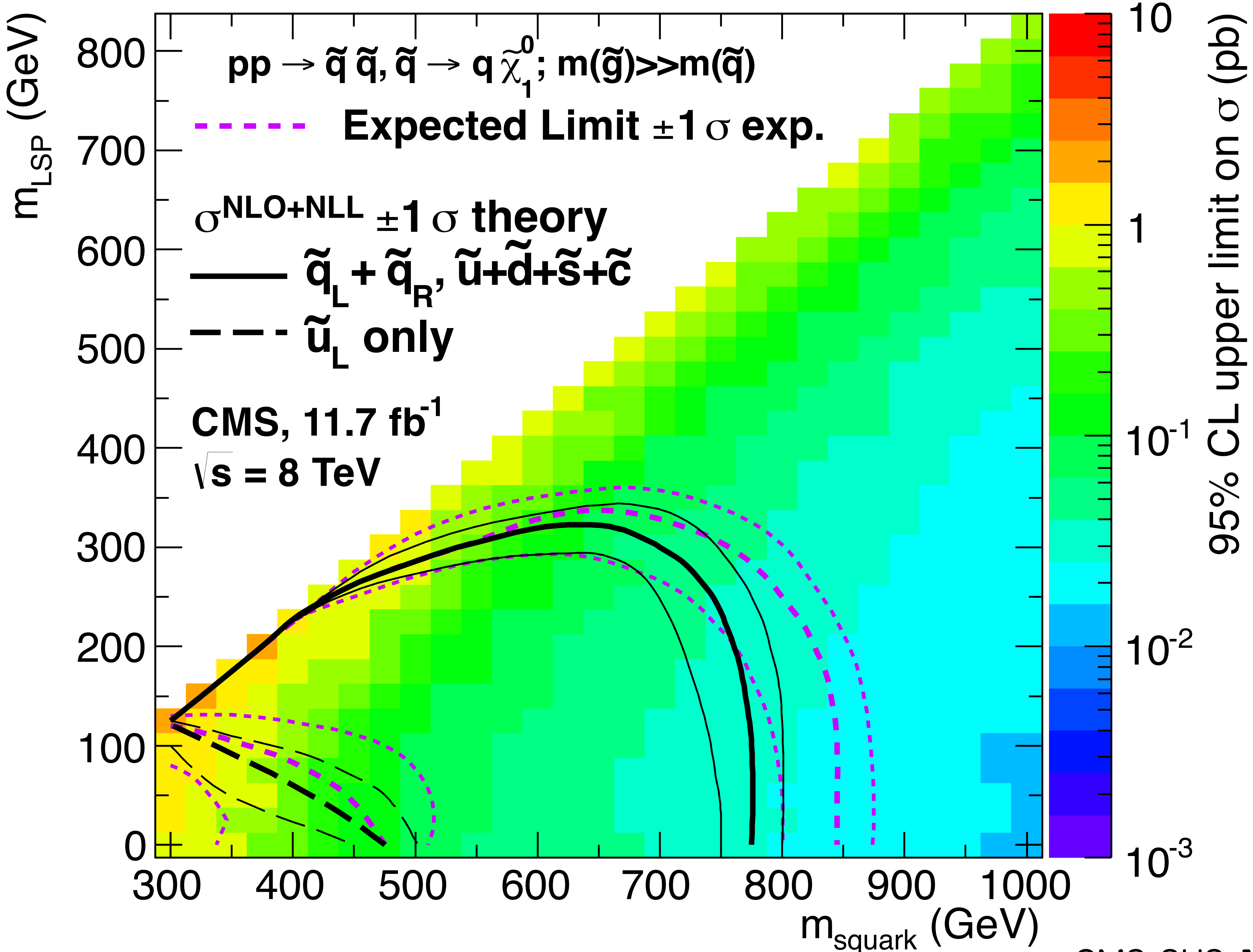
# Current Status: ATLAS (20 fb$^{-1}$)



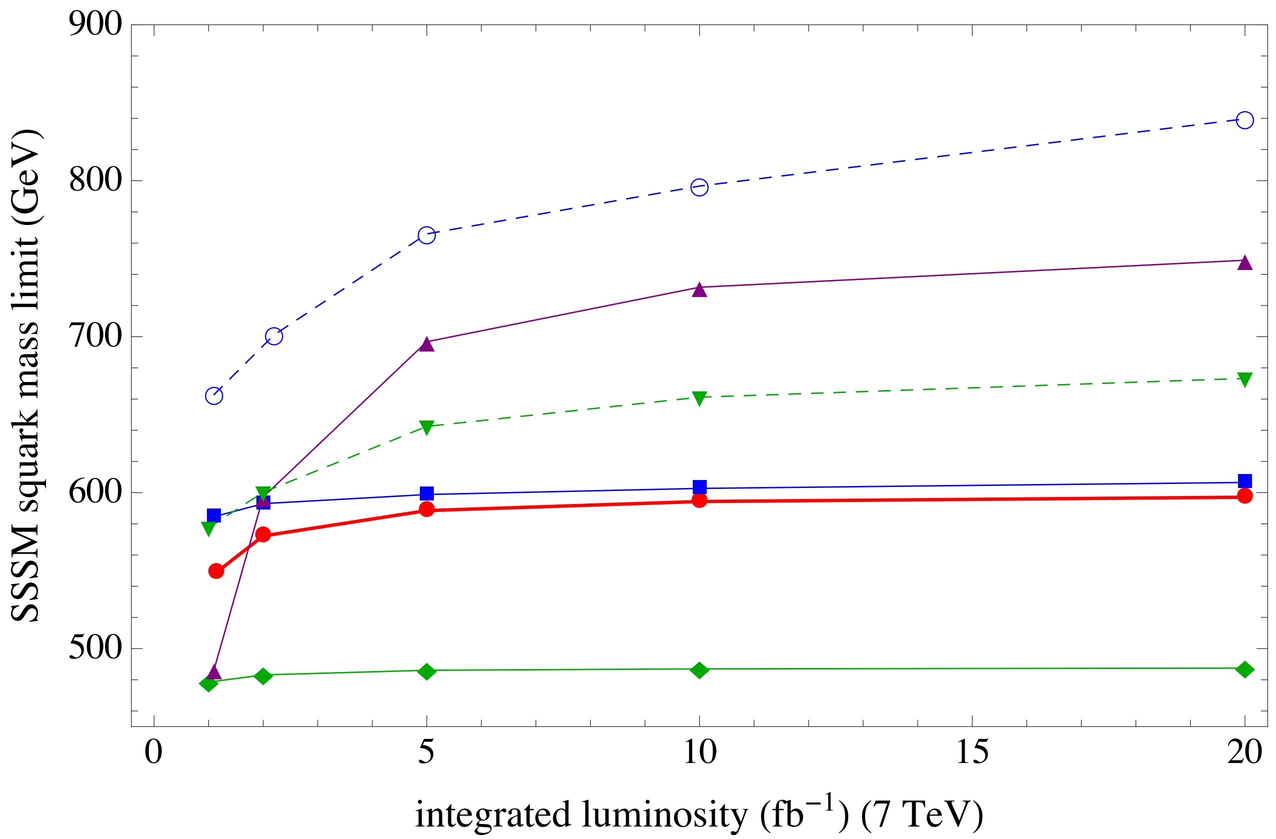

ATLAS-CONF-2013-047

# Current Status: CMS (12 fb$^{-1}$)




CMS-SUS-12-028

# Our prediction...




"The limits asymptote fairly quickly once the analyses become dominated by systematic uncertainties rather than by statistical uncertainties."

Kribs, Martin 1203.4821

# ...appears to be true:

"The expected limits for [decoupled gluino] do not extend substantially beyond those obtained from the previous published ATLAS analysis [17] because the events closely resemble the predominant W/Z + 2-jet background, leading the background uncertainties to be dominated by systematics."

ATLAS-CONF-2013-047

# “Mixed Gauginos”

(Dirac + Majorana masses for gluino and adjoint fermion)

# Mixed Gauginos

Supersymmetry breaking could lead to both Dirac and Majorana masses, e.g. both D-term mediation and F-term mediation. This leads to a mass matrix for the gluino of the form:

$$\mathcal{L}_{\tilde{g}\,\mathrm{mass}} = \begin{pmatrix} g & \psi \end{pmatrix} \begin{pmatrix} M_m & M_d \\ M_d & M'_m \end{pmatrix} \begin{pmatrix} g \\ \psi \end{pmatrix} + \mathrm{h.c.}$$

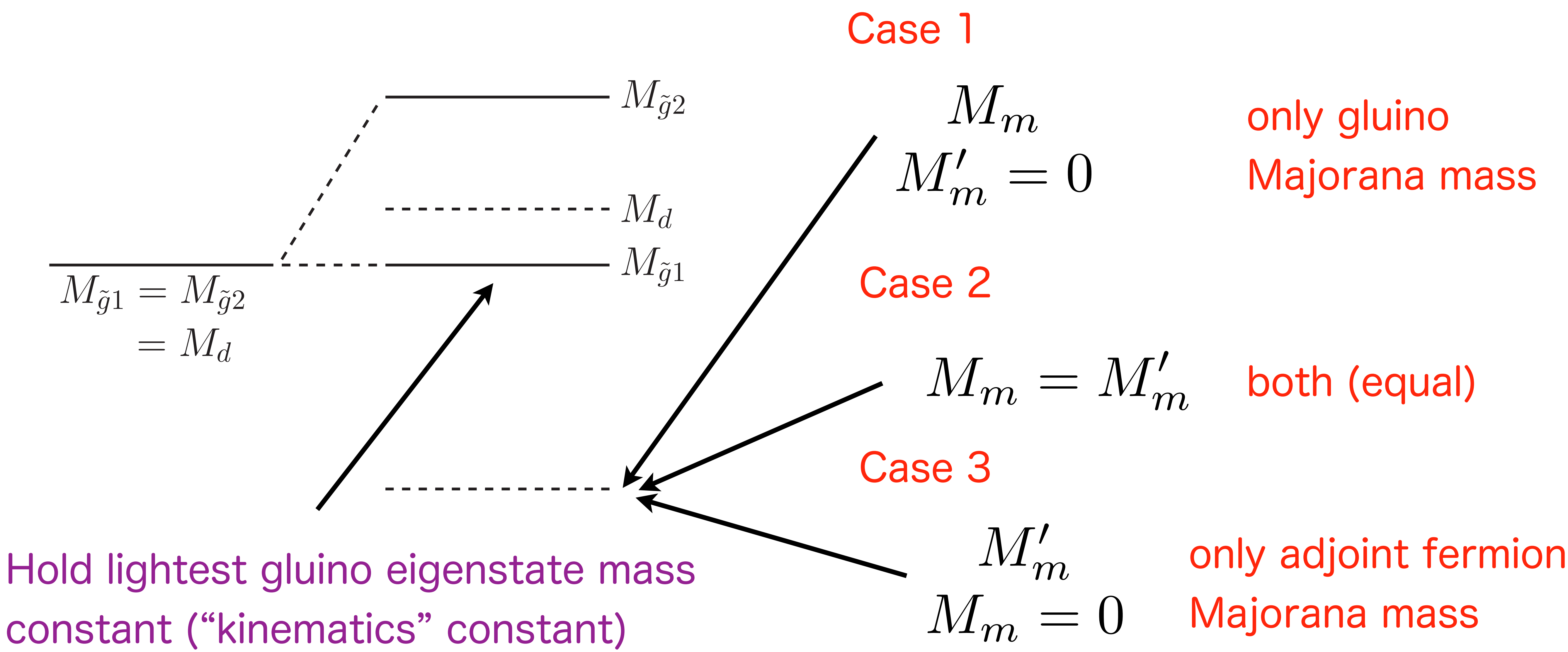
that splits the Dirac gluino into two (pseudo-Dirac) Majorana fermions.

Focus on Mm < Md & Mm' < Md (large Majorana masses re-introduce fine-tuning in electroweak sector)

# Mixed Gaugino Spectrum

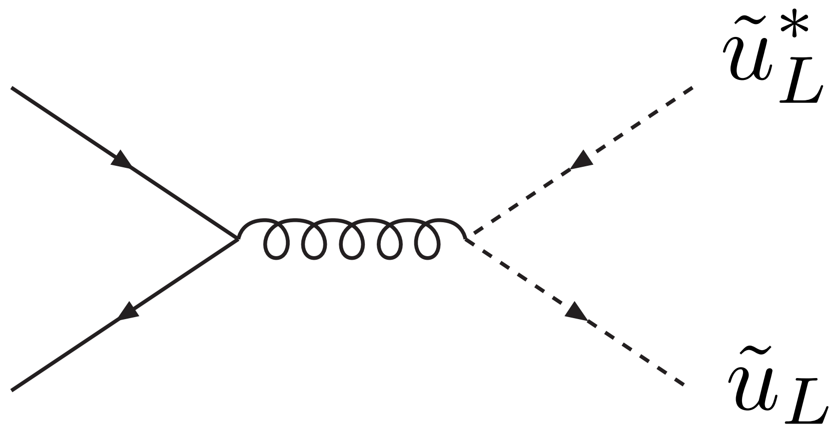
We probed how quickly the suppressed cross-section results for a pure Dirac gluino become more similar to a Majorana gluino as the Majorana masses Mm, Mm’ are introduced.

We considered 3 spectra:

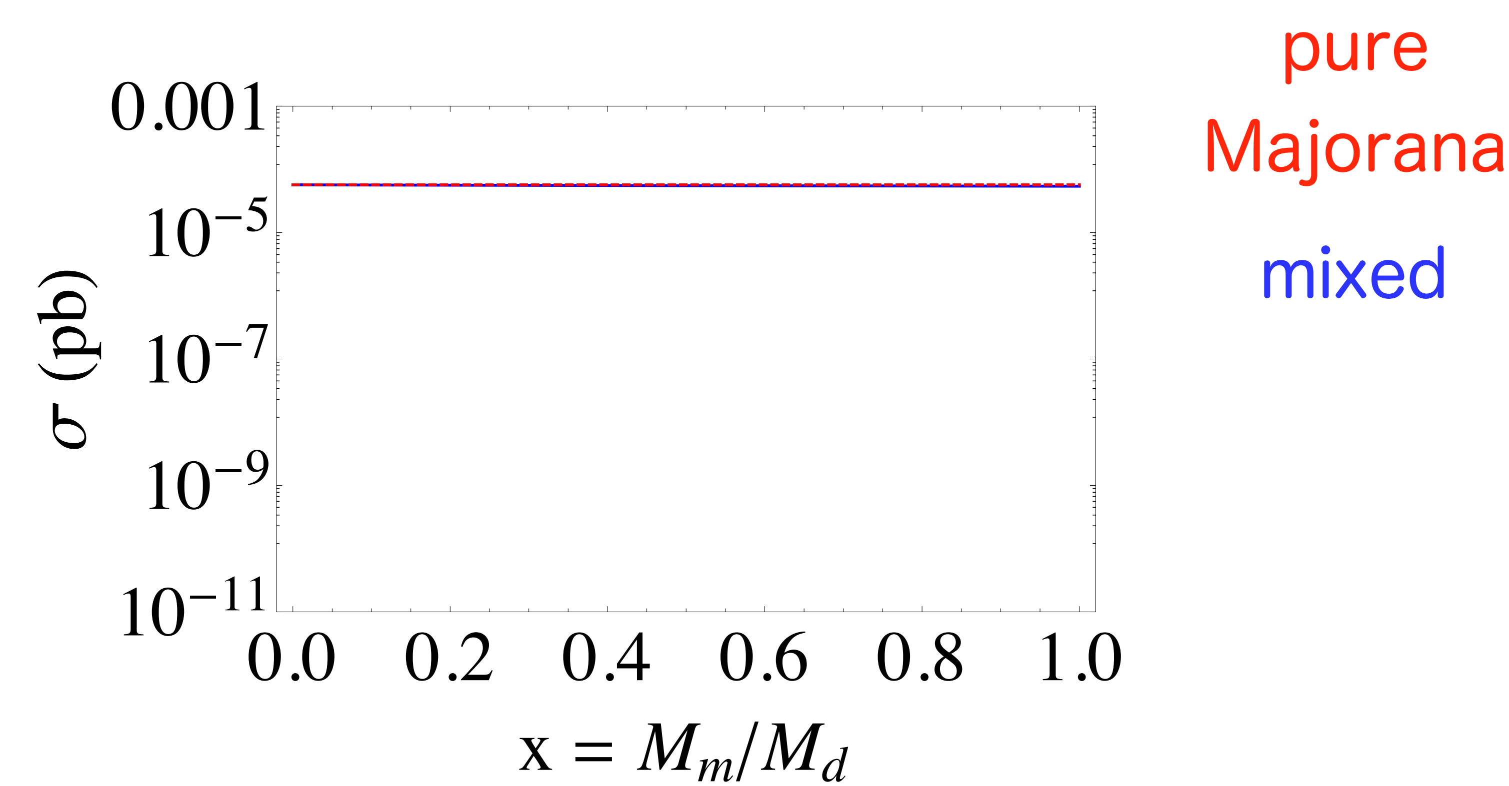


# Case 1: Squark sub-processes

Example: M(g1) = 5 TeV; m(sq) = 1200 GeV




+ other diagrams




(b) $\tilde{u}_L \tilde{u}_L^*$

Independent of Dirac/Majorana (as it should be)

# Case 1: Squark sub-processes

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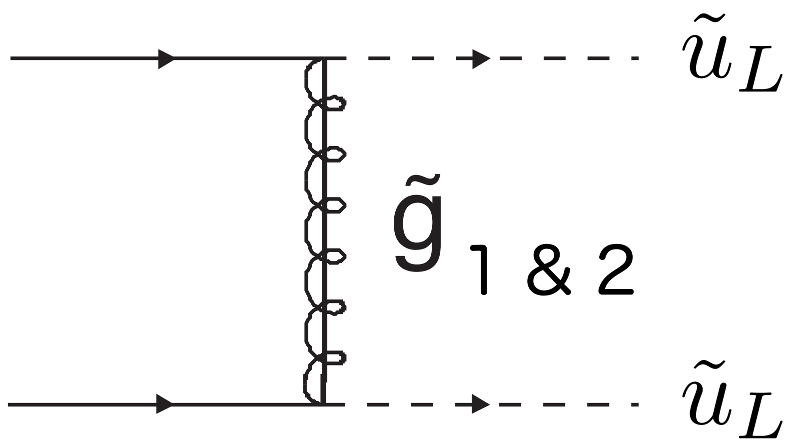
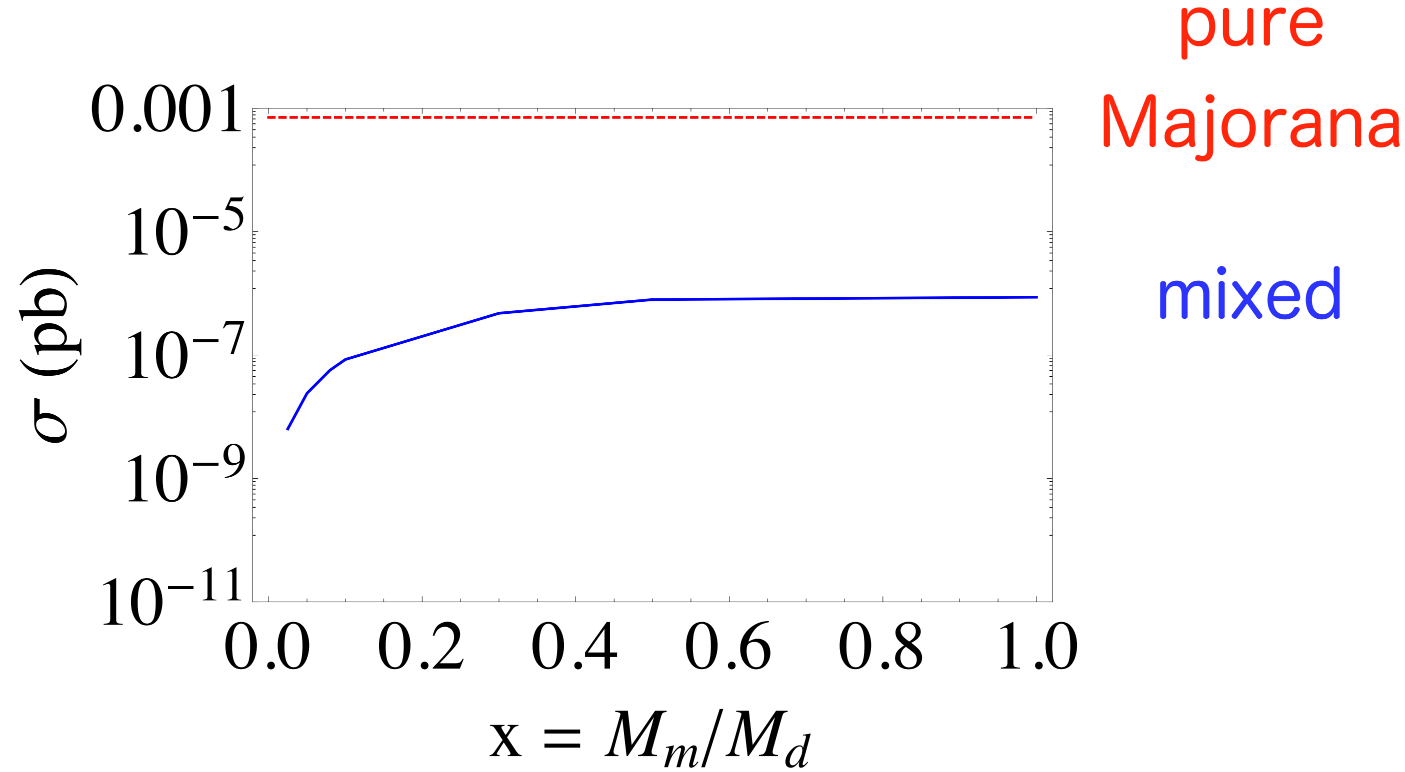



(a) $\tilde{u}_L\tilde{u}_L$

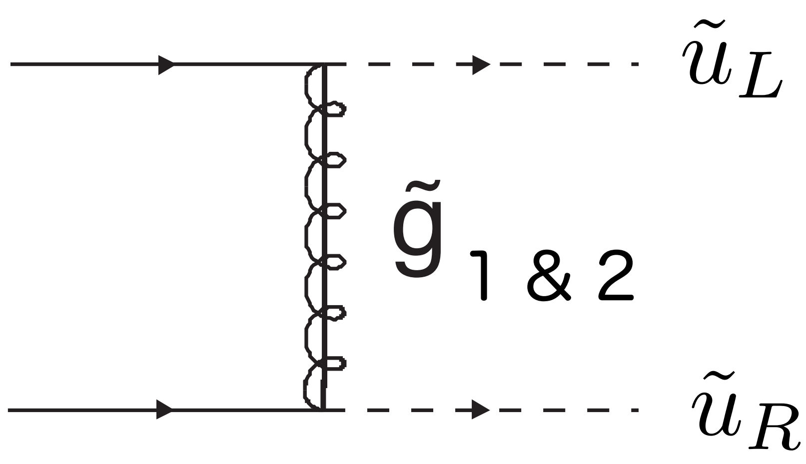
Amplitude proportional to

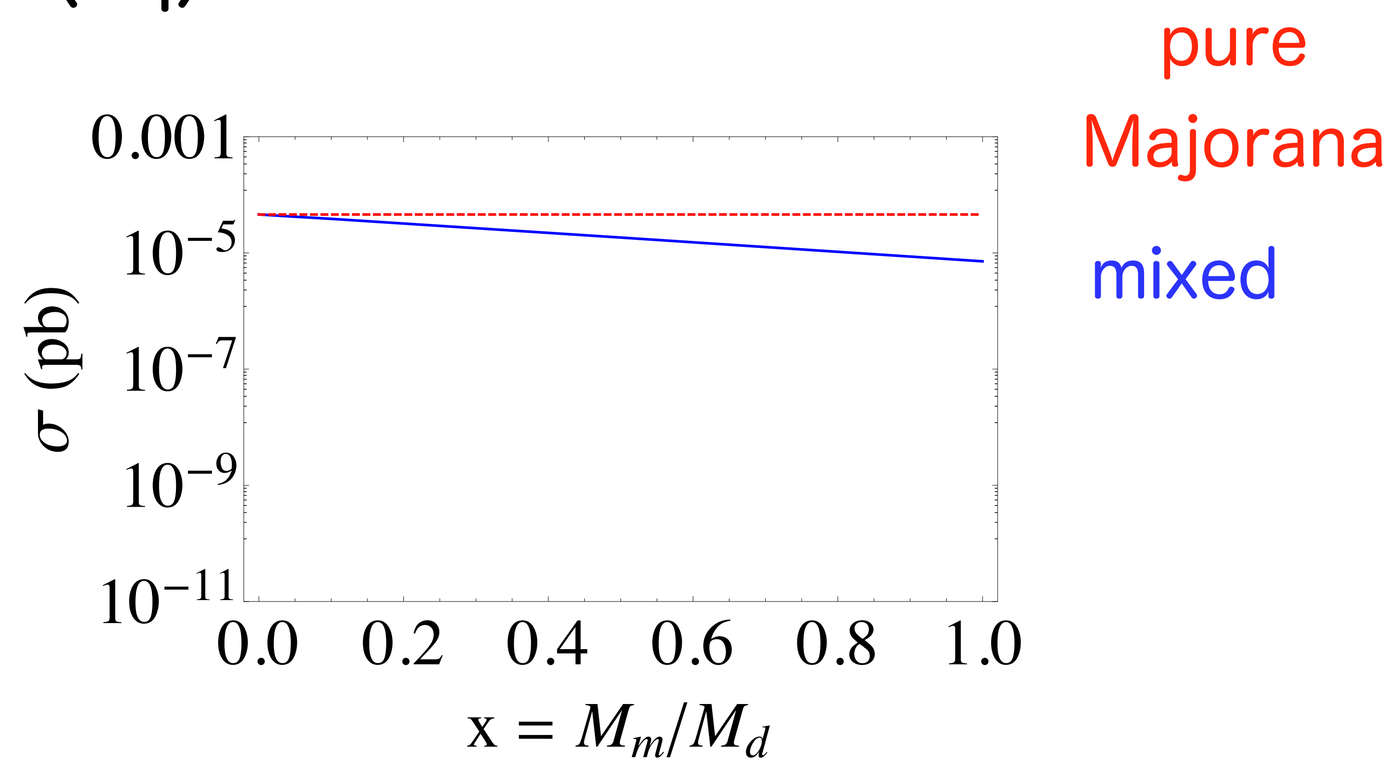
$$\frac{p^2}{M_{\tilde{g}1}^3} x \left(\sqrt{x^2+4} - x\right)^3 + \mathcal{O}(p^4/M_{\tilde{g}1}^4) \quad ($$

Remains suppressed even as Mm ≈ Md!

# Case 1: Squark sub-processes

Example: M(g1) = 5 TeV; m(sq) = 1200 GeV



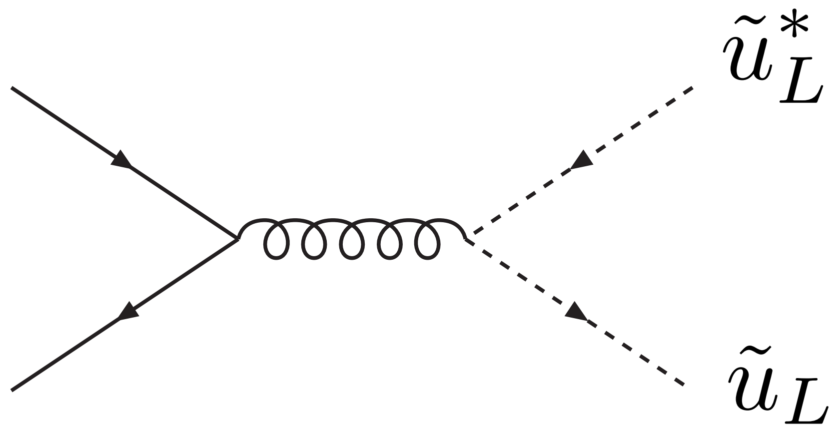

(d) $\tilde{u}_L \tilde{u}_R$

Amplitude proportional to $$\frac{(x-\sqrt{x^2+4})^2}{4M_{\tilde{g}1}^2} + \mathcal{O}(p^2/M_{\tilde{g}1}^2)$$

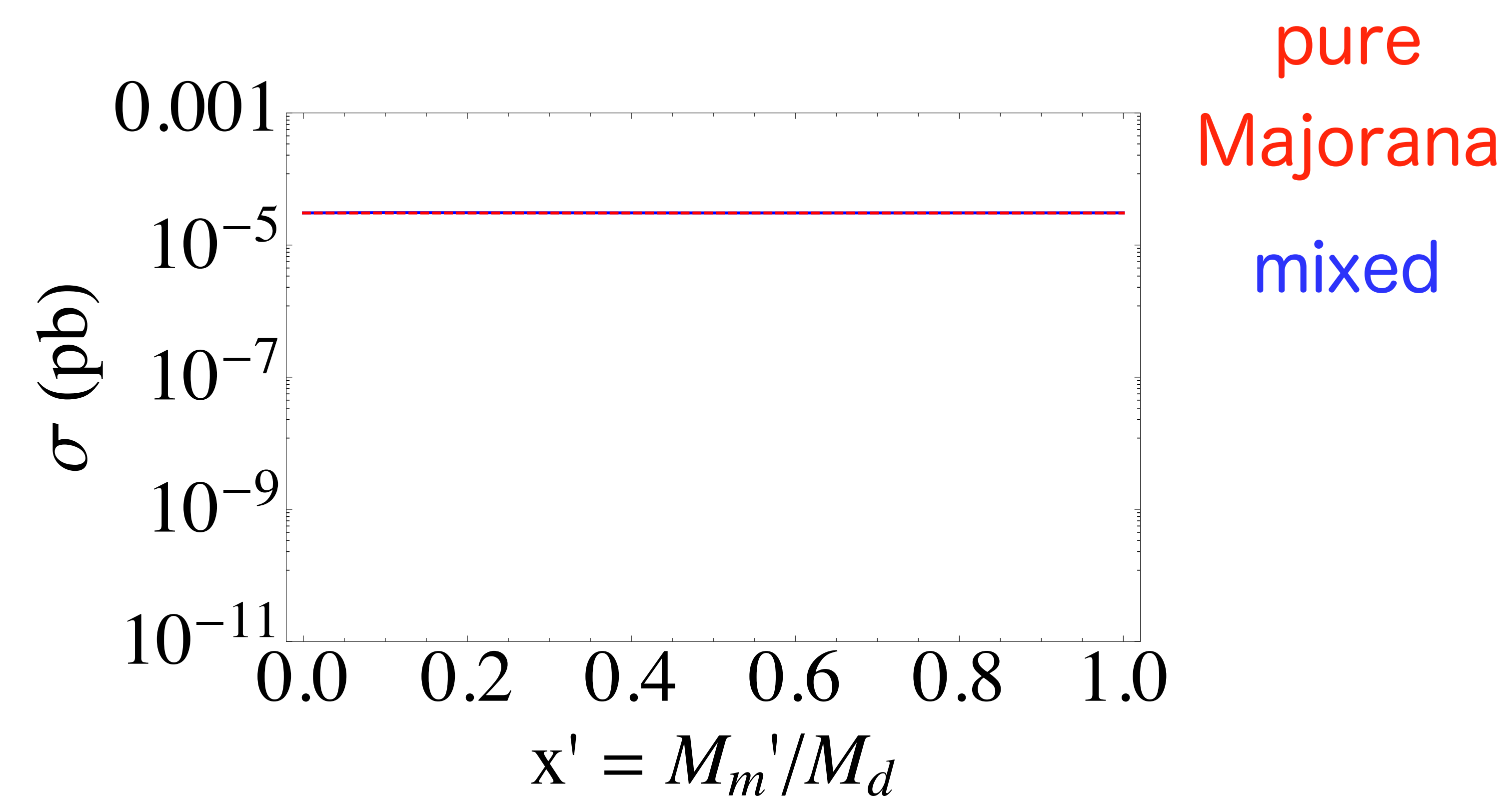
Gradually suppressed as Mm becomes comparable to Md

# Case 3: Squark sub-processes

Example: M(g1) = 5 TeV; m(sq) = 1200 GeV




+ other diagrams

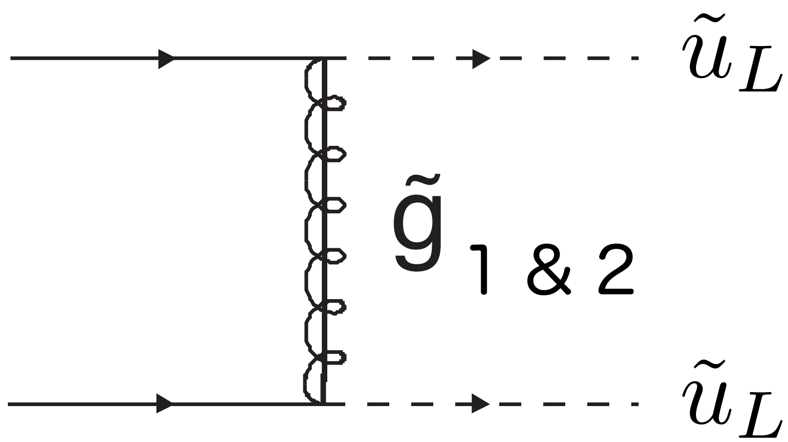


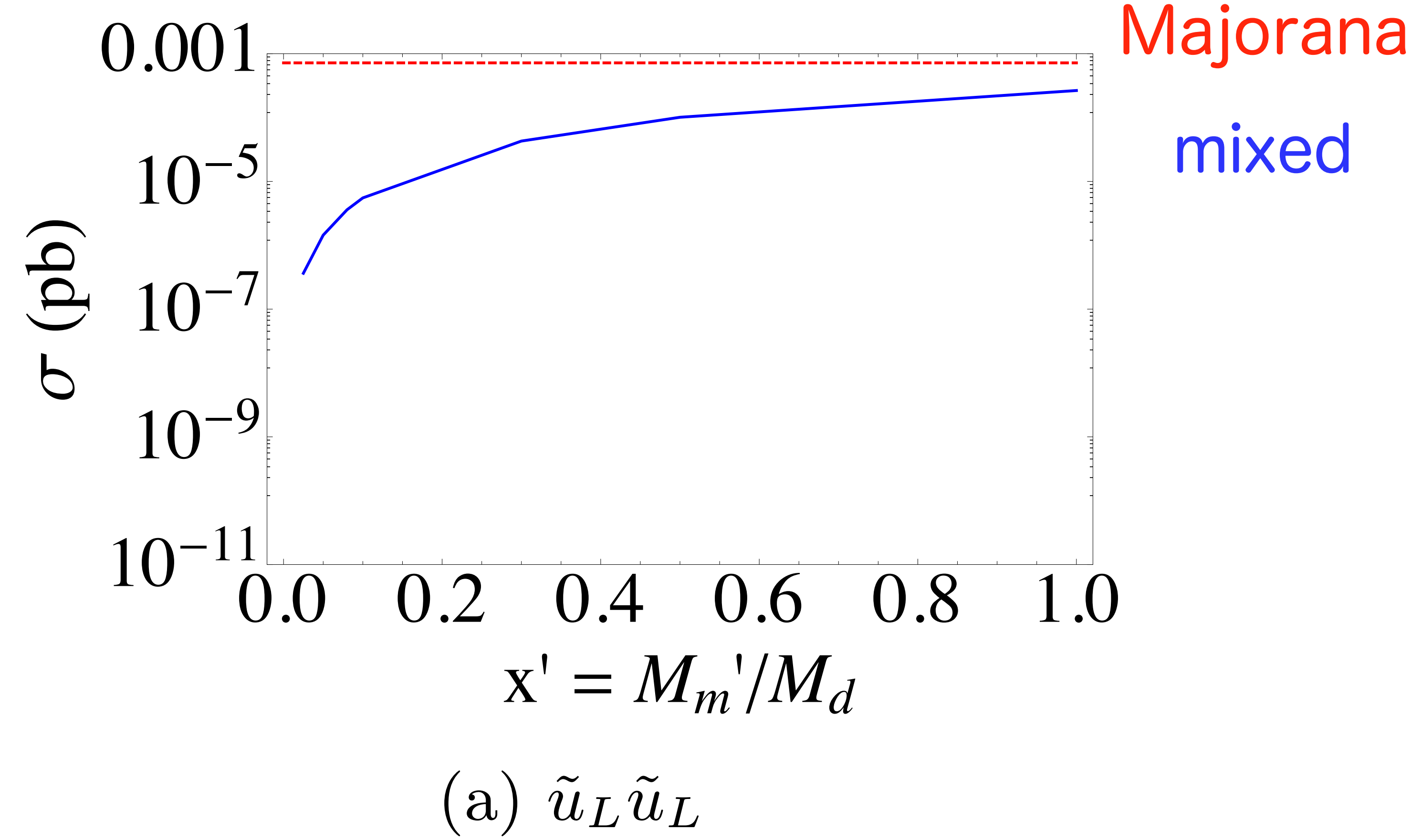

(b) $\tilde{u}_L \tilde{u}_L^*$

Independent of Dirac/Majorana (as it should be)

# Case 3: Squark sub-processes

Example: M(g1) = 5 TeV; m(sq) = 1200 GeV



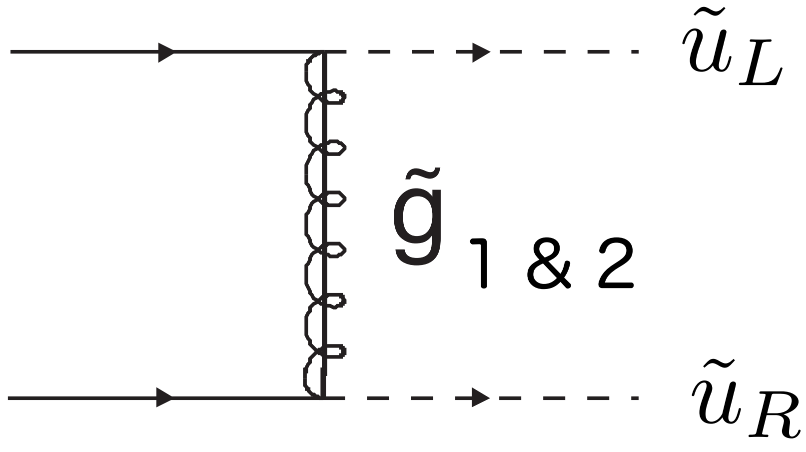

(a) $\tilde{u}_L\tilde{u}_L$

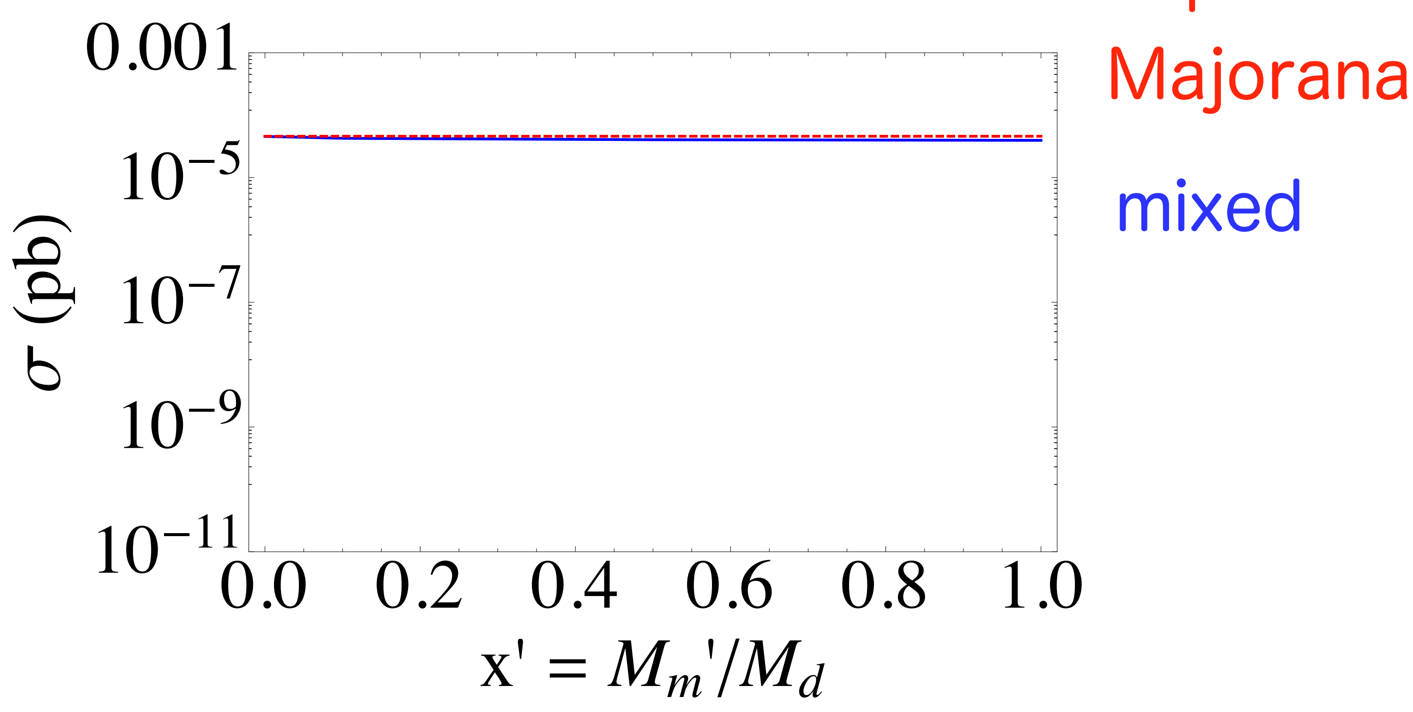
Amplitude proportional to $$\frac{x(x+\sqrt{x^2+4})}{2M_{\tilde{g}1}} + \mathcal{O}(p^2/M_{\tilde{g}1}^2)$$

Approaches pure Majorana for large Mm’ ≈ Md

# Case 3:  Squark sub-processes

Example:  M(g1) = 5 TeV; m(sq) = 1200 GeV



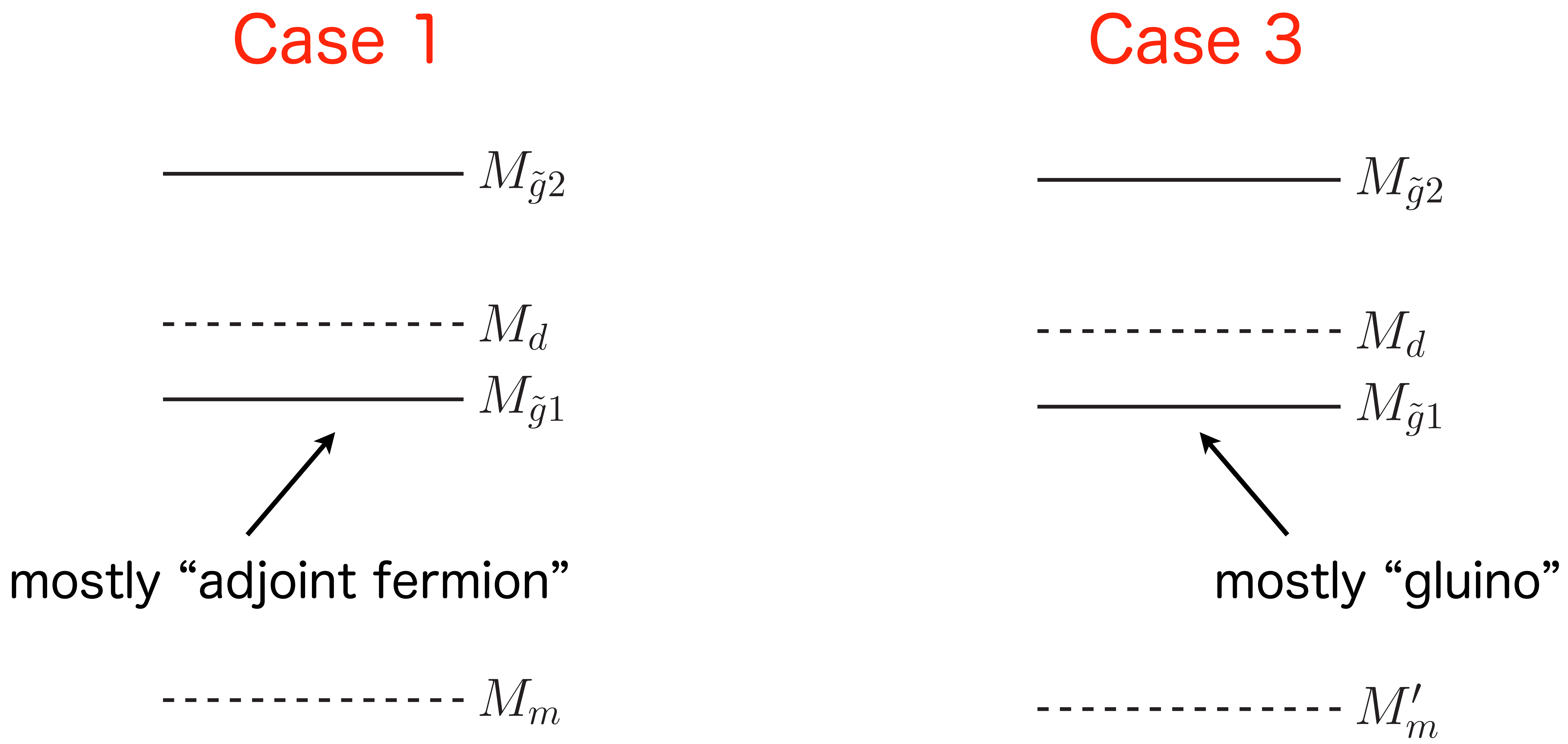




(d) $\tilde{u}_L\tilde{u}_R$

Amplitude proportional to $$\frac{(x^2+1)(x-\sqrt{x^2+4})^2}{4M_{\tilde{g}1}^2} + \mathcal{O}(p^2/M_{\tilde{g}1}^2)$$

Nearly independent of Mm'

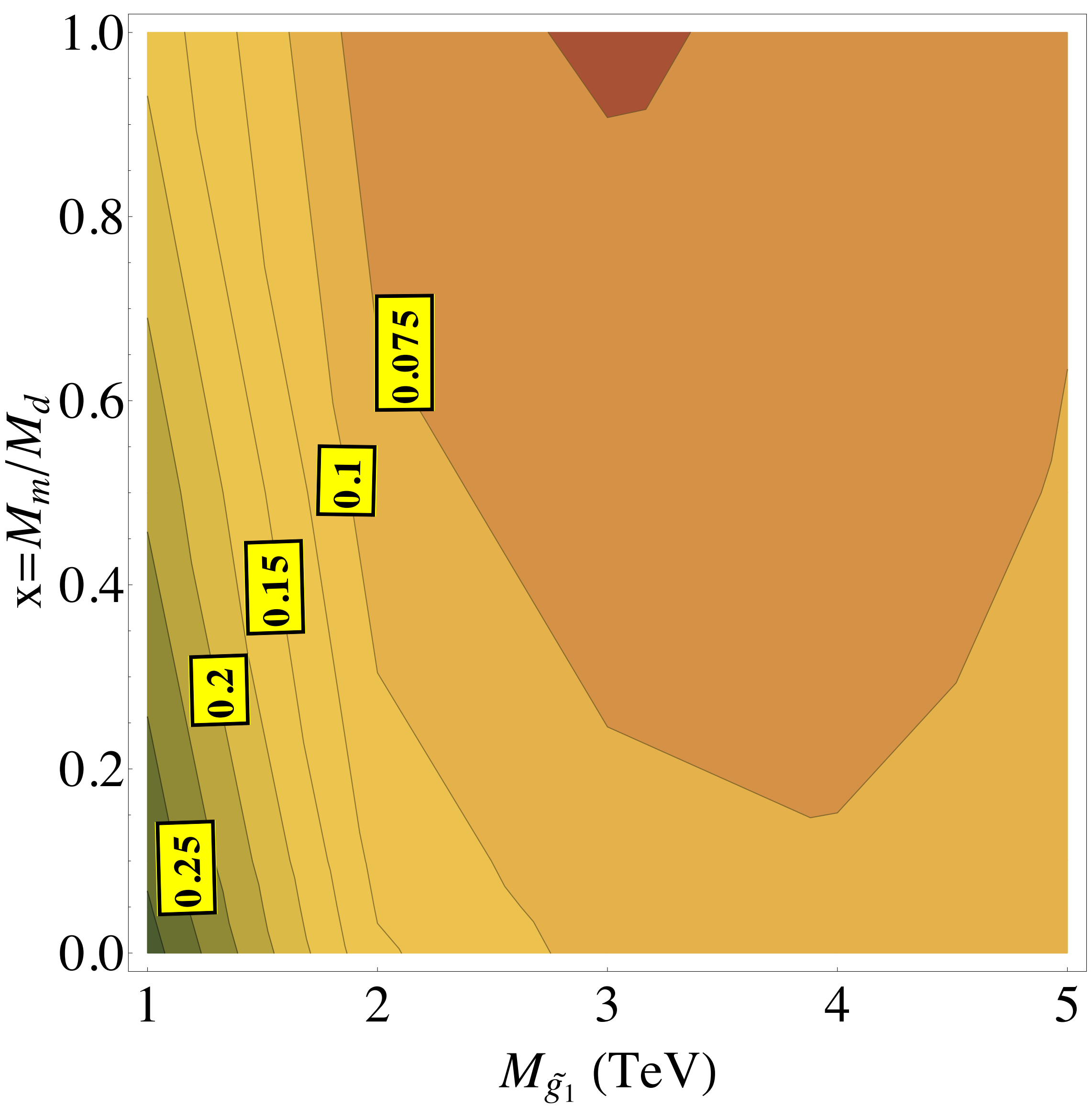
# Not all Majorana masses are created equal!

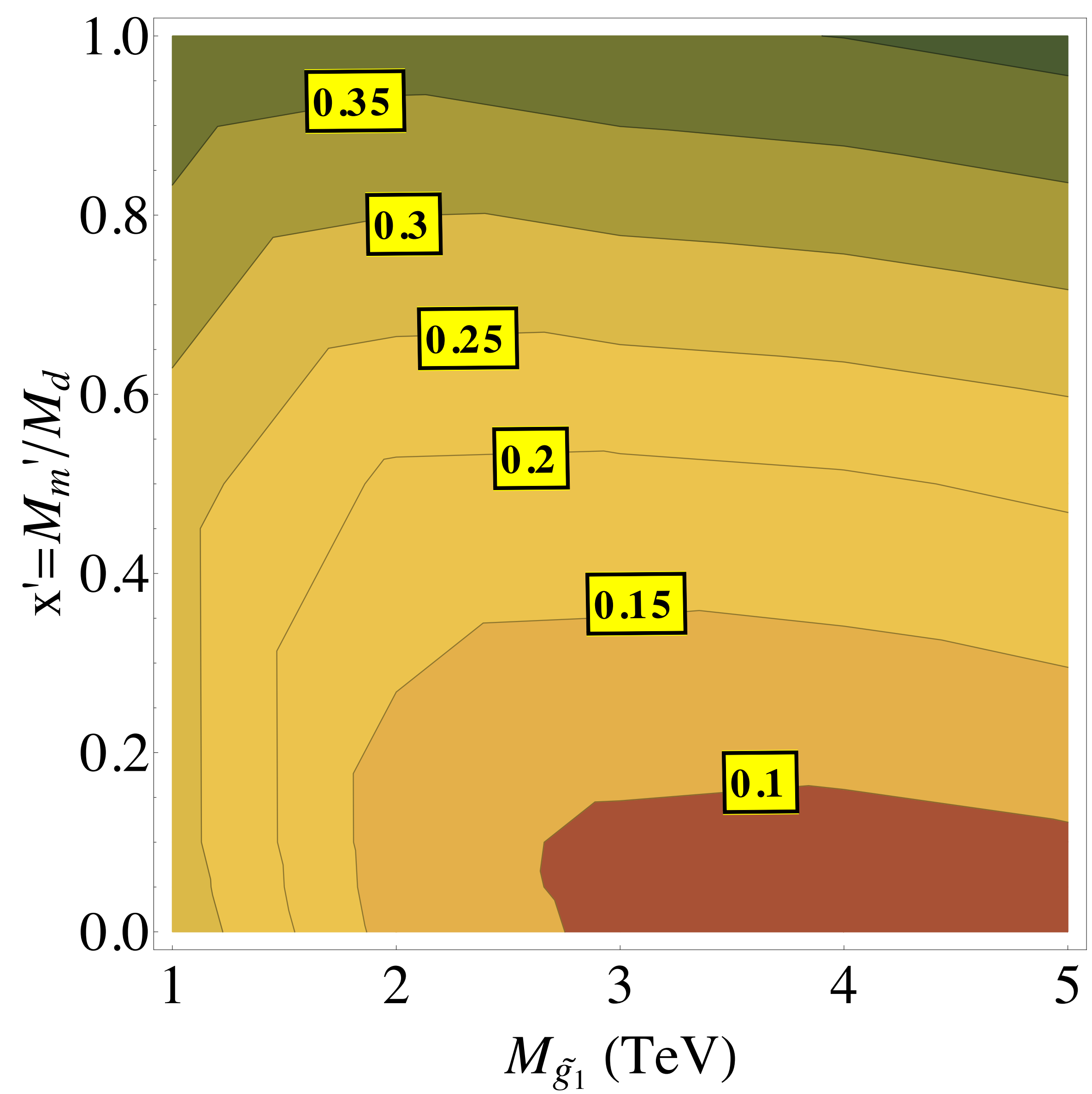


# Case 1       Case 3

Contours of $\sigma$(mixed)/$\sigma$(Majorana)

for 1st,2nd squark production at LHC (8 TeV) with m(sq) = 800 GeV

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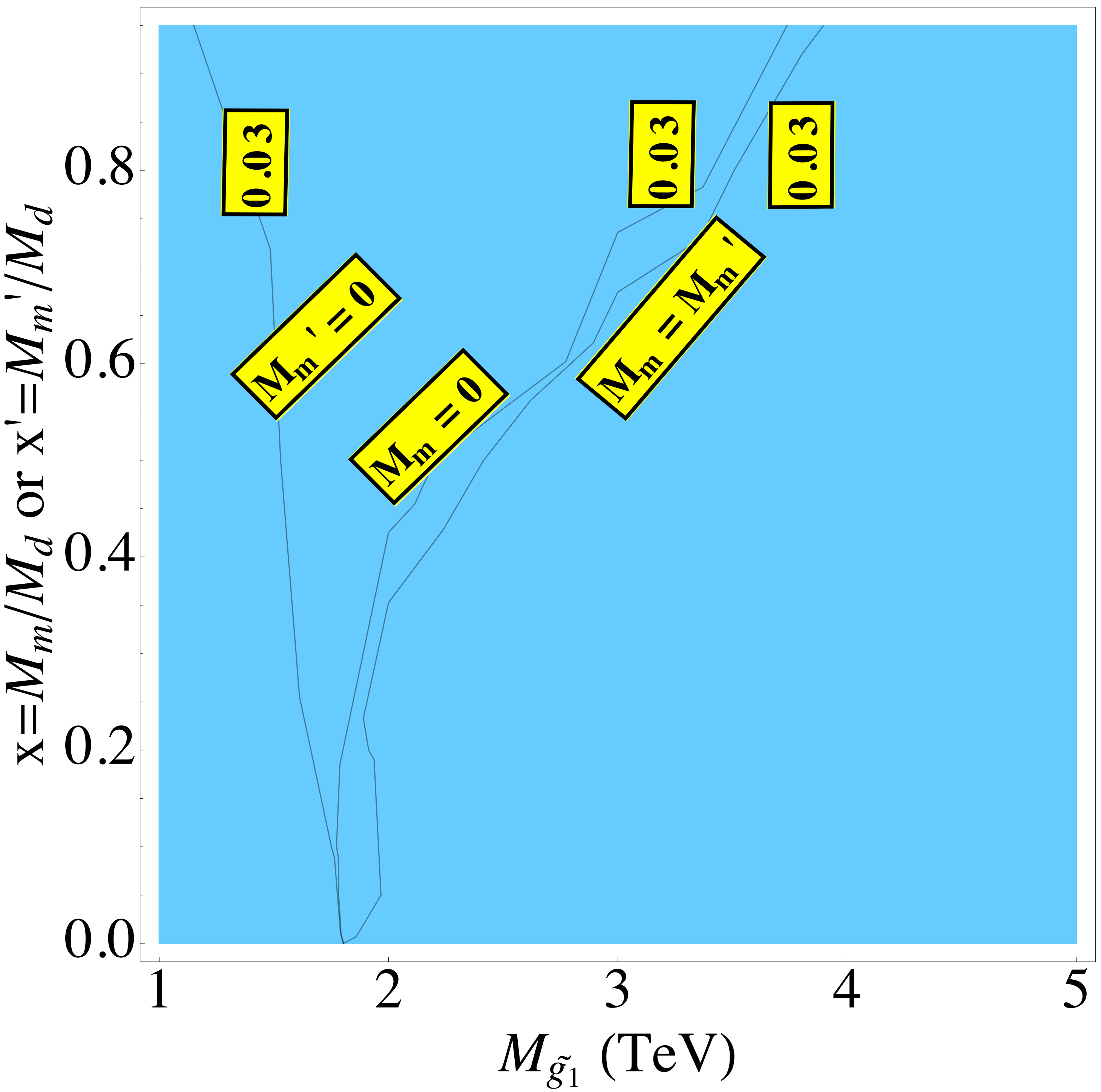
# Extrapolated bounds in (Mg1,x) space:




m(sq) = 800 GeV

m(LSP) = 0

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# Summary

* Heavy Dirac Gluino in “supersoft”, “R-symmetric” naturally suppresses colored sparticle production substantially

* Bounds on 1st,2nd generation squarks up to about 800-840 GeV with current ATLAS & CMS data; now systematics dominanted

* Best search in 2012 was $\alpha_T$ (Mar 2012);
--> optimizing over range of $H_T$ crucial

* Very high mass searches
(e.g. ATLAS Meff > 1400-1900 GeV)
not effective at constraining lighter squarks

* Majorana masses do not substantially change conclusions;
--> Majorana mass for gluino further suppresses $\sigma$(squark)
--> Majorana mass for adj fermion leads to

$$\sigma(\text{Dirac}) < \sigma(\text{Mm}' \neq 0) < \sigma(\text{Majorana})$$