Supersafe Supersymmetry with a Dirac gluino

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mainly: 1203.4821 with Adam Martin (CERN/Notre Dame);
plus 1208.2784 with Adam Martin, Ricky Fok (York), Yuhsin Tsai (UC Davis)
and work-to-appear with Nirmal Raj (Oregon)

Outline

1. Brief Intro

2. Dirac Gluino and “Supersoft Supersymmetry”

3. Colored Superpartner Production @ LHC

4. Simpified Models

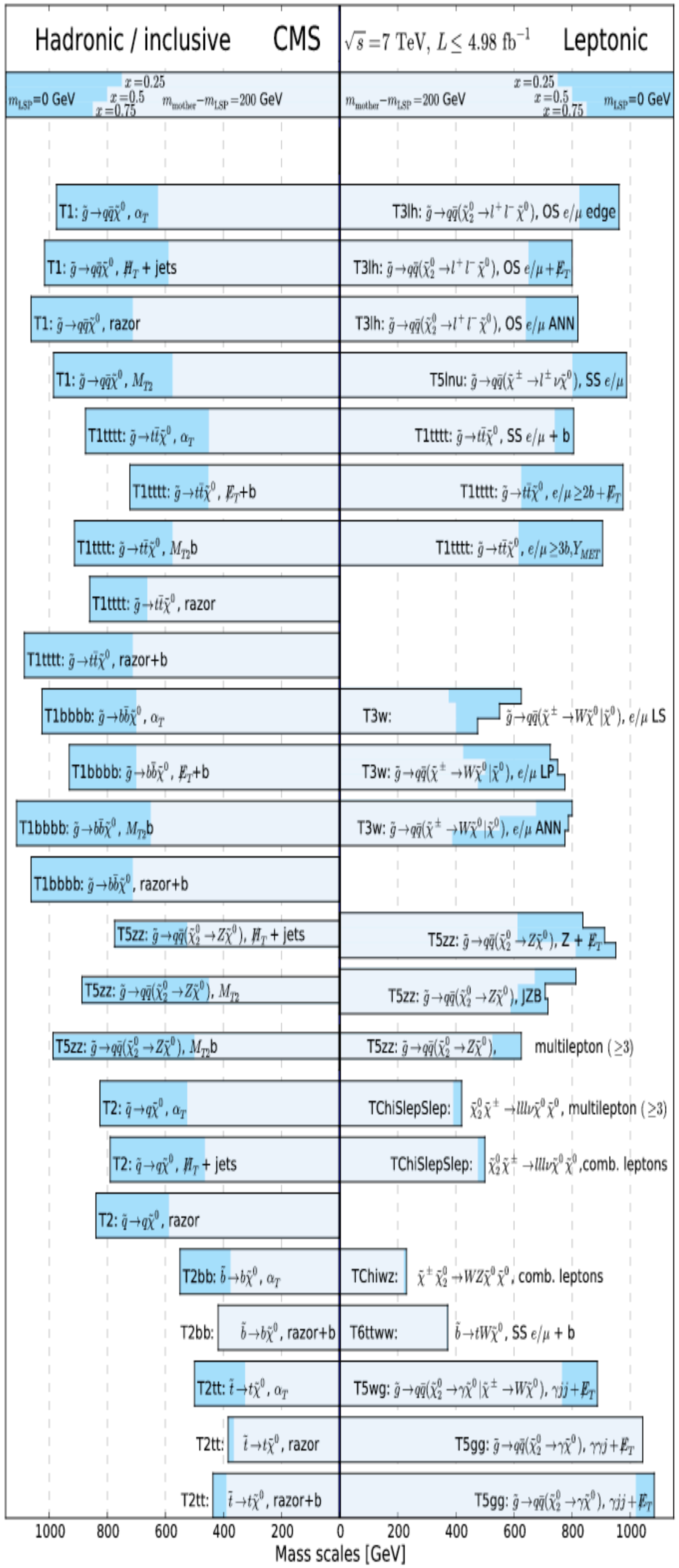
5. Jets + missing searches for supersymmetry @ LHC
   a) ATLAS; CMS α_T; (CMS MHT; CMS “razor”)
   b) Comparisons

6. Generalizations (“mixed gauginos”)

7. Summary

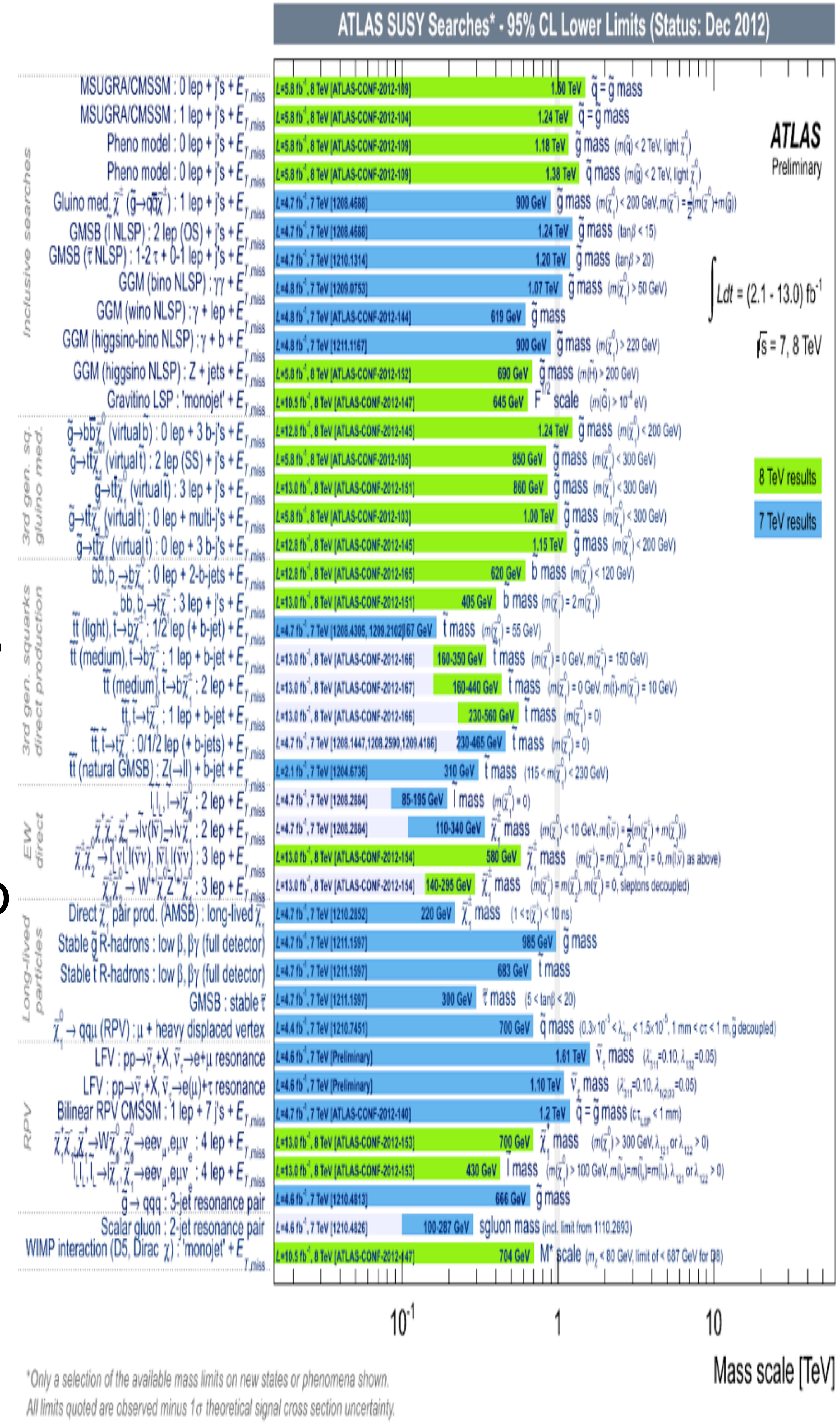
Introduction

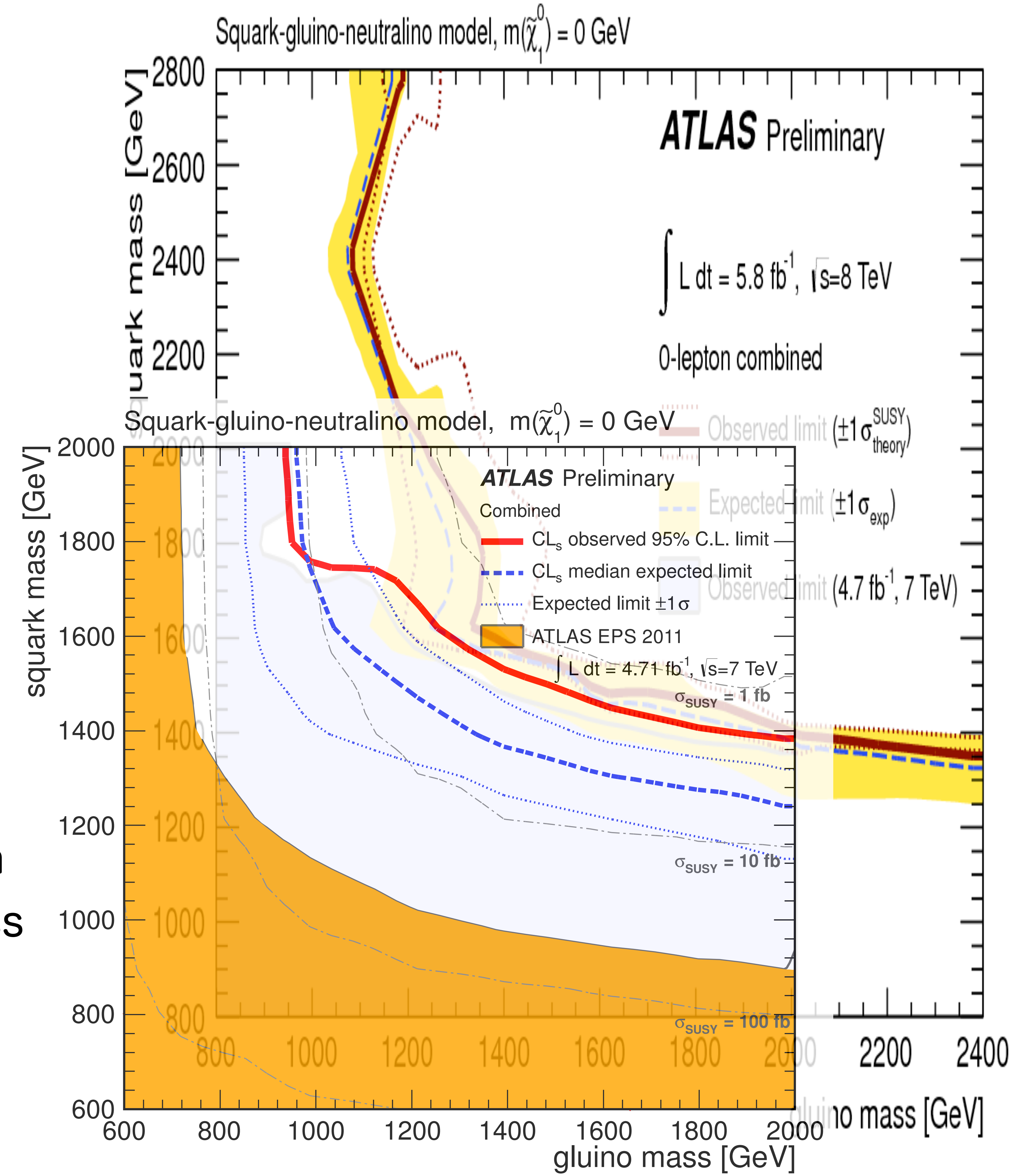
Weak Scale Supersymmetry @ LHC



Many Searches!

In this talk, focus on “jets + MET” that arise from squark and gluino production.



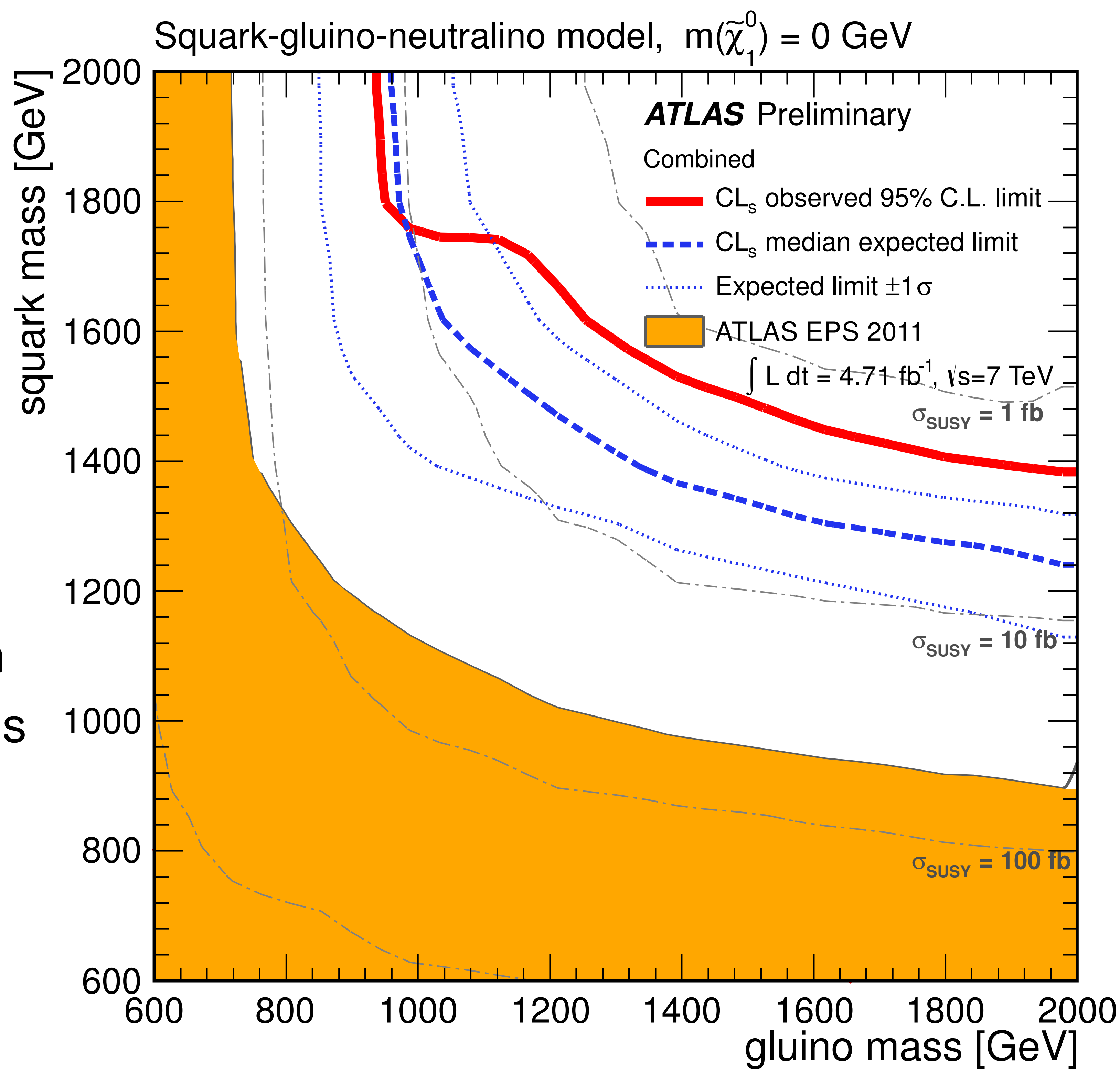


ATLAS
jets + MET
August 2012

ATLAS
jets + MET
March 2011

1st+2nd
generation
squark mass

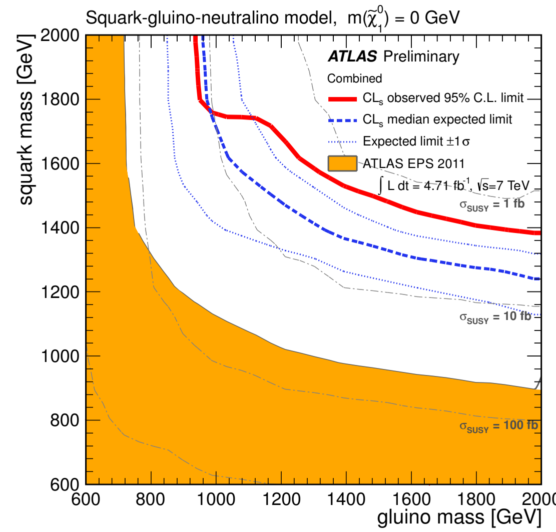
Supersymmetry @ LHC



1st+2nd generation squark mass

ATLAS-CONF-2012-033

If weak scale supersymmetry...



R-parity violation.
LSP decays,
no missing energy.

1st,2nd generation
heavy (> 1.5-2 TeV),
if LSP light
(< 200-300 GeV)

LSP heavier
(at least 300-400 GeV)

Too simplified
a model
(cascades)

Too simplified
a model
(compressed)

Dirac Gluino in Supersymmetry

Dirac Gluino

Solve EDMs
(Hall,Randall)

Supersoft
Supersymmetry
(Fox,Nelson,Weiner)

R-Symmetric
Supersymmetry
-- Flavor safe!
(Kribs,Poppitz,Weiner)

Reduced
Fine-Tuning
(Kribs,Martin)

"Supersafe"
-- Suppressed σ's
(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

λ_j: gaugino

$m_D = D'/M$

Dirac Gauginos in Supersymmetry II

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

$$\begin{cases} A_j & j = 1 \ldots 8 & \text{color octet} \\ A_j & j = 1 \ldots 3 & \text{weak triplet} \\ A_j & j = 1 & \text{singlet} \end{cases}$$

Gauge coupling unification... (for those who still care)

...still perturbative, but requires unifons.

Dirac Gauginos in Supersymmetry III

Scalar masses could arise from:

$$\int d^4\theta \frac{(W'^{\alpha}W'_{\alpha})^{\dagger}W'^{\beta}W'_{\beta}}{M^6}Q^{\dagger}Q$$

which is finite! This is because the only counterterm

$$\int d^4\theta \, \frac{\theta^2\bar{\theta}^2 m_D^4}{M^2}Q^{\dagger}Q$$

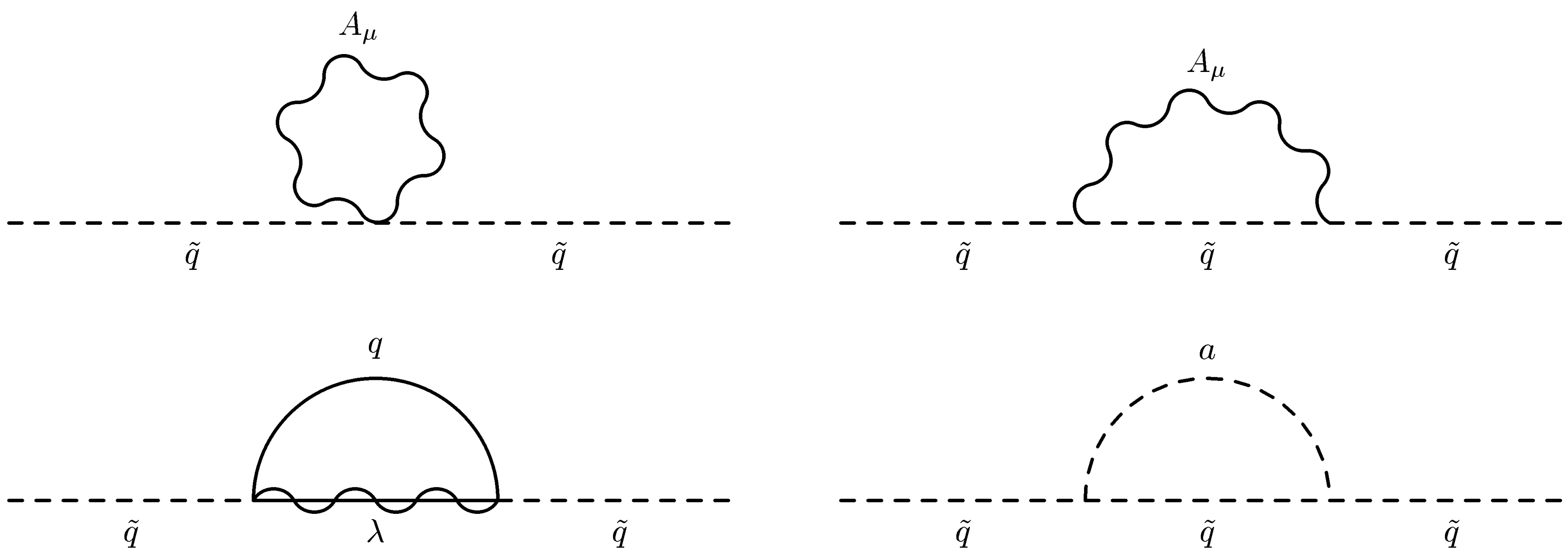
is suppressed by $1/M^2$.

Scalar masses are "supersoft"

Fox, Nelson, Weiner (2002)

Squark/Slepton Masses

One-loop contributions:

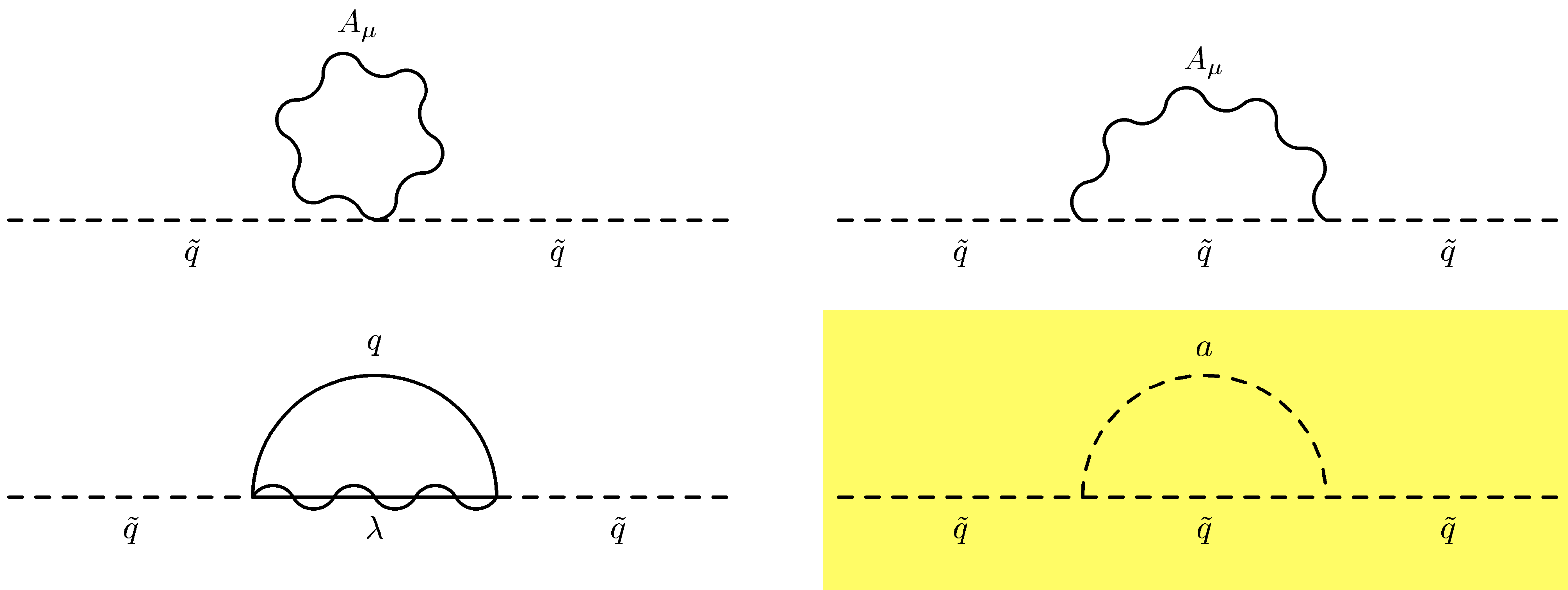


Giving

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

Squark/Slepton Masses

One-loop contributions:



Giving

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

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

"Supersoft" Fox, Nelson, Weiner (2002)

Adjoint Scalars

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

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

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

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

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:

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

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

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

Naturalness II: Dirac Electroweak Gauginos?

With just D-term spurion

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

in components:

$$\mathcal{L} \supset -m_D \lambda_j \tilde{a}_j - \sqrt{2} m_D (a_j + a_j^*) D_j - D_j (\sum_i g_k q_i^* t_j q_i) - \frac{1}{2} D_j^2$$

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

$$m_h^2 = \cancel{m_Z^2 \cos^2 2\beta} + \frac{3}{4\pi^2} \cos^2\alpha \, y_t^2 m_t^2 \ln \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}$$

Naively...a DISASTER! Only stop loop contributions to Higgs mass. (Requires >> 10 TeV mass stops.)

Naturalness II: Higgs Mass

“Pure” Supersoft (Dirac gauginos; D-term & no F-terms) dead.

Need either Majorana winos and binos, or other additional contributions to Higgs mass, e.g.

- NMSSMology
- R-symmetric contributions (λ couplings)
- Composite stops (Csaki, Randall, Terning)
- ...

I’m not directly concerned with Higgs mass. Arguably, the MSSM needs to be extended anyway to minimize EW tuning...

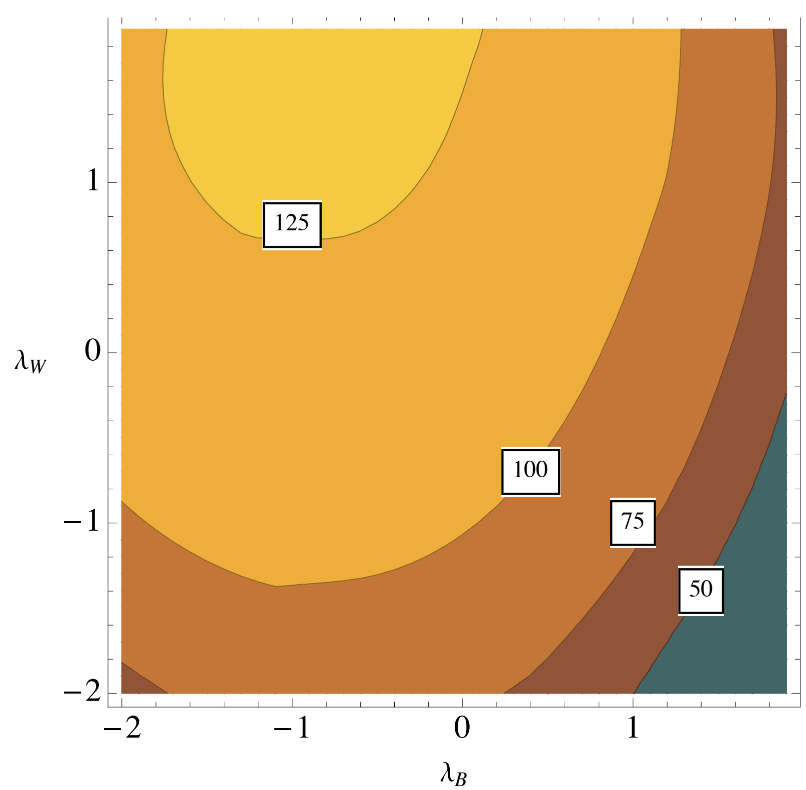
Example: R-Symmetric with λ couplings

In an R-Symmetric model, a tree-level quartic is generated by "mu" terms and "λ" terms:

$$W \supset \mu_u \, H_u \, R_u + \mu_d \, R_d \, H_d$$

$$\begin{aligned} W \;\supset\; & \lambda_B^u \, \Phi_B \, H_u \, R_u + \lambda_B^d \, \Phi_B \, R_d \, H_d \\ & + \lambda_W^u \, \Phi_W^a \, H_u \, \tau^a \, R_u + \lambda_W^d \, \Phi_W^a \, R_d \, \tau^a \, H_d \end{aligned}$$

Example (not optimized for maximal Higgs with minimal stops):



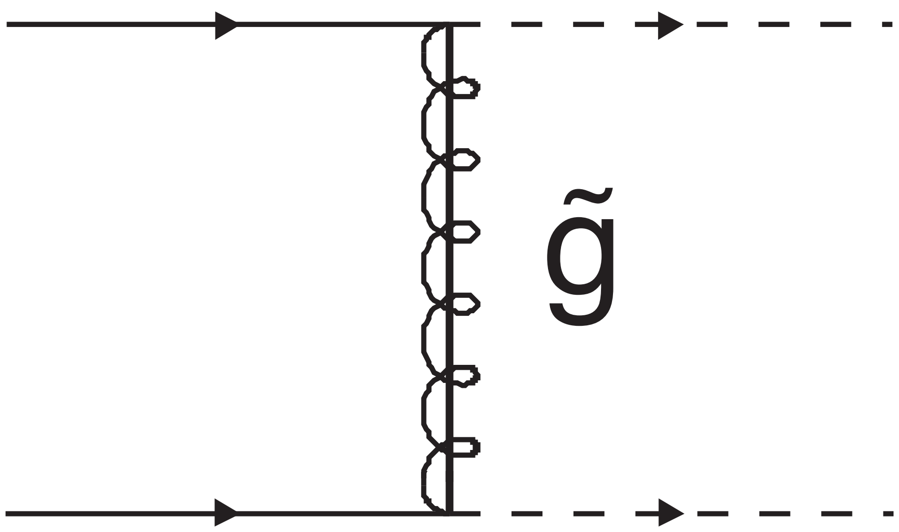
$$M_2 = 1 \text{ TeV}$$
$$\mu_u = \mu_d = 200 \text{ GeV}$$
$$m(\tilde{t}_{L,R}) = 3 \text{ TeV}$$

Fok, Martin, Tsai, GK

LHC Squark & Gluino Production

LHC

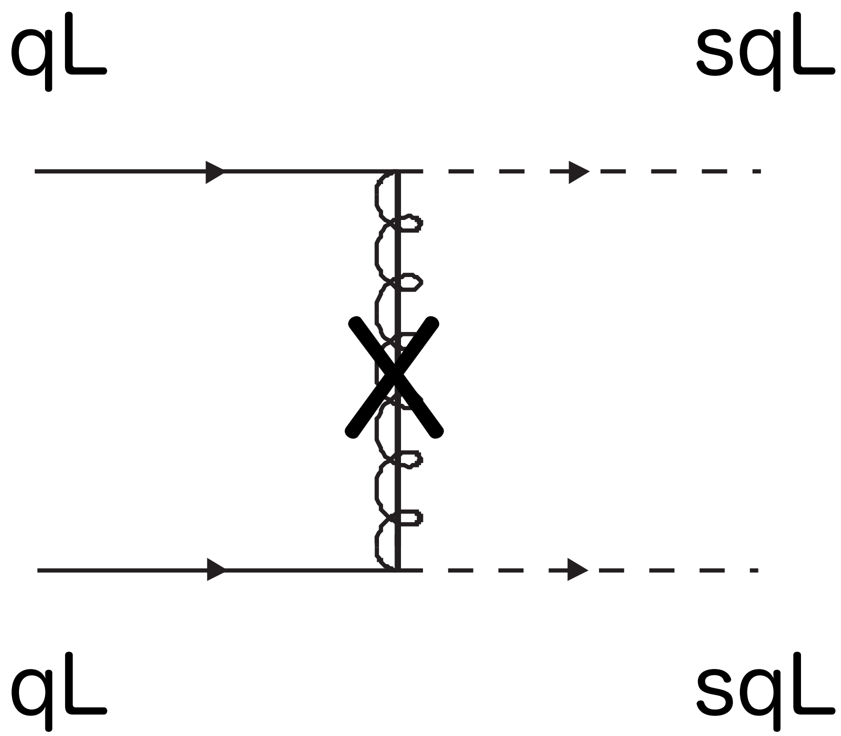
Squark Production

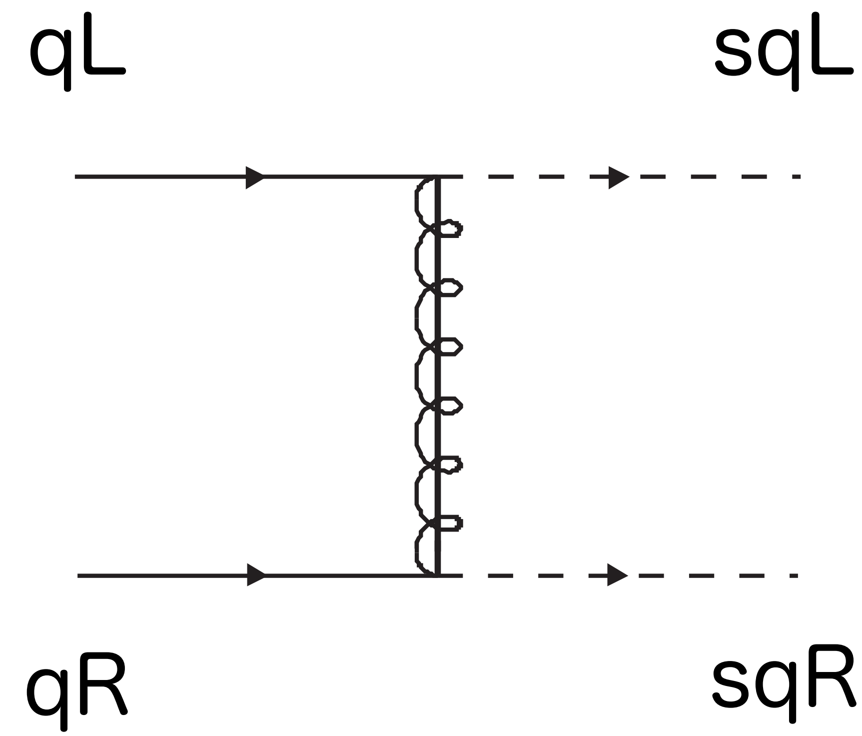


Gluino exchange diagrams ought to dominate LHC production of (1st generation) squarks

But for heavier gluino...

Majorana versus Dirac





Requires Majorana mass insertion. Scales as

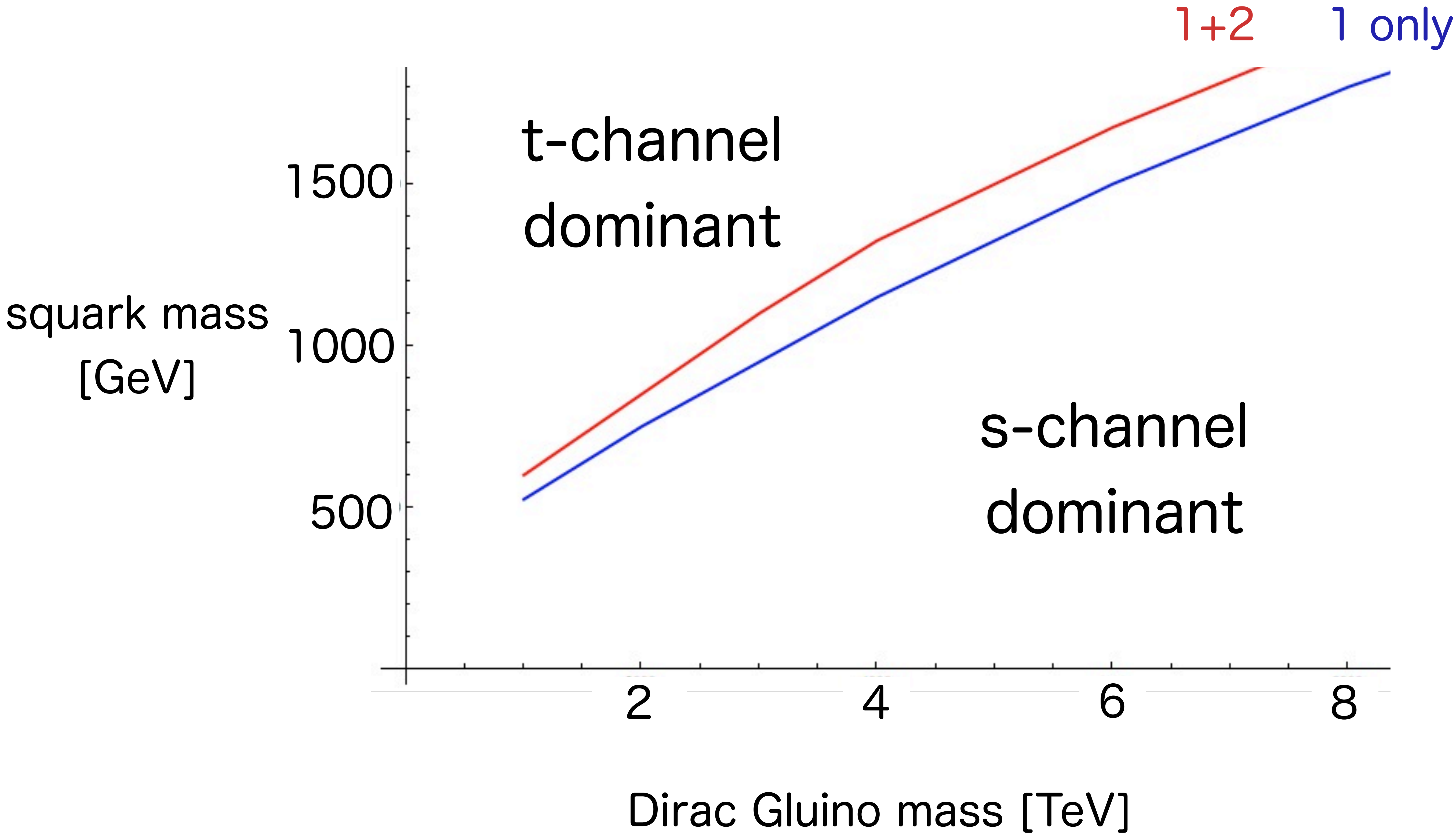
$1/M$

Dirac and Majorana. Scales as

$|p|/M^2$

Suppressed

Suppression of t-channel Dirac Gluino



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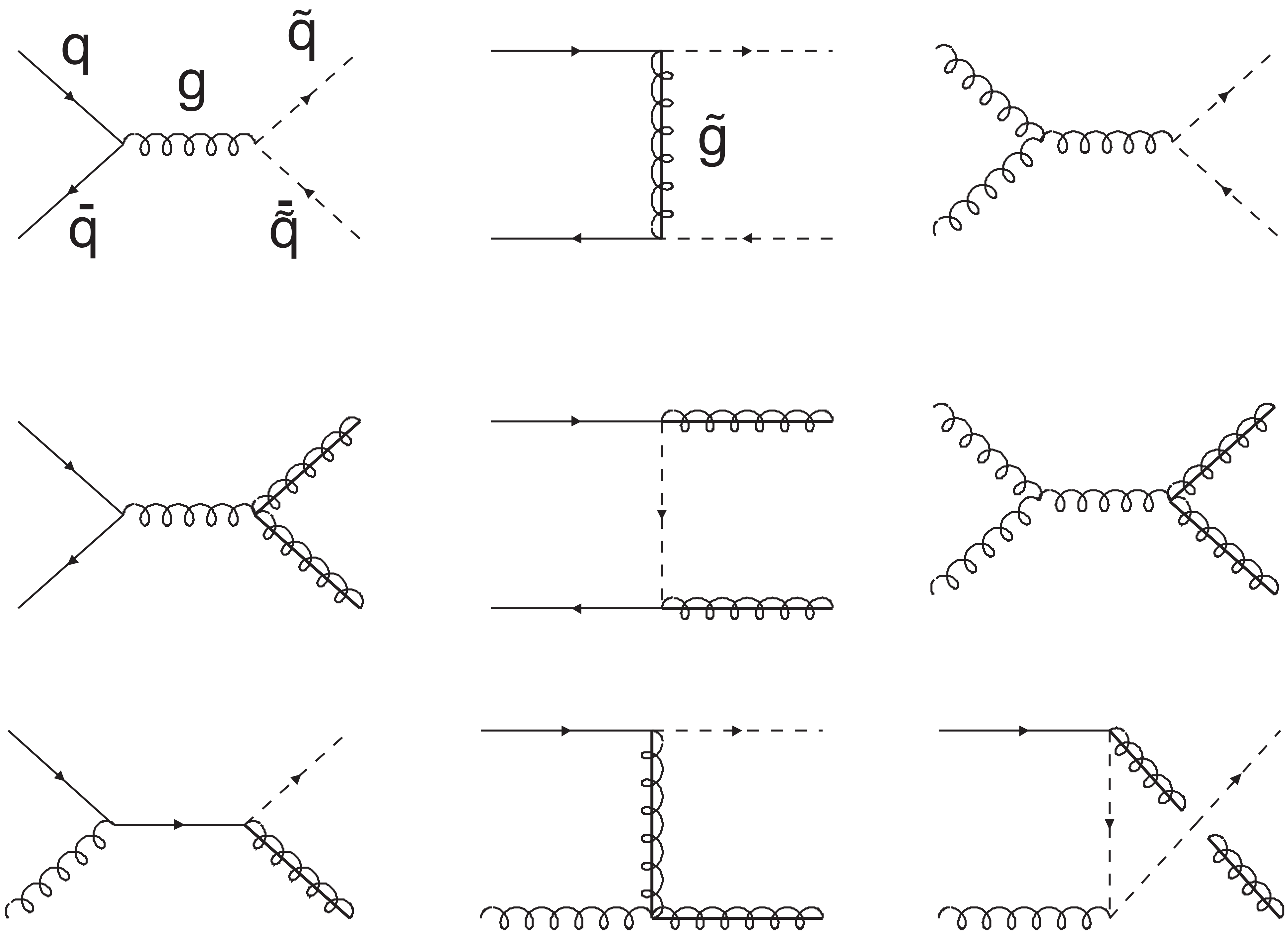
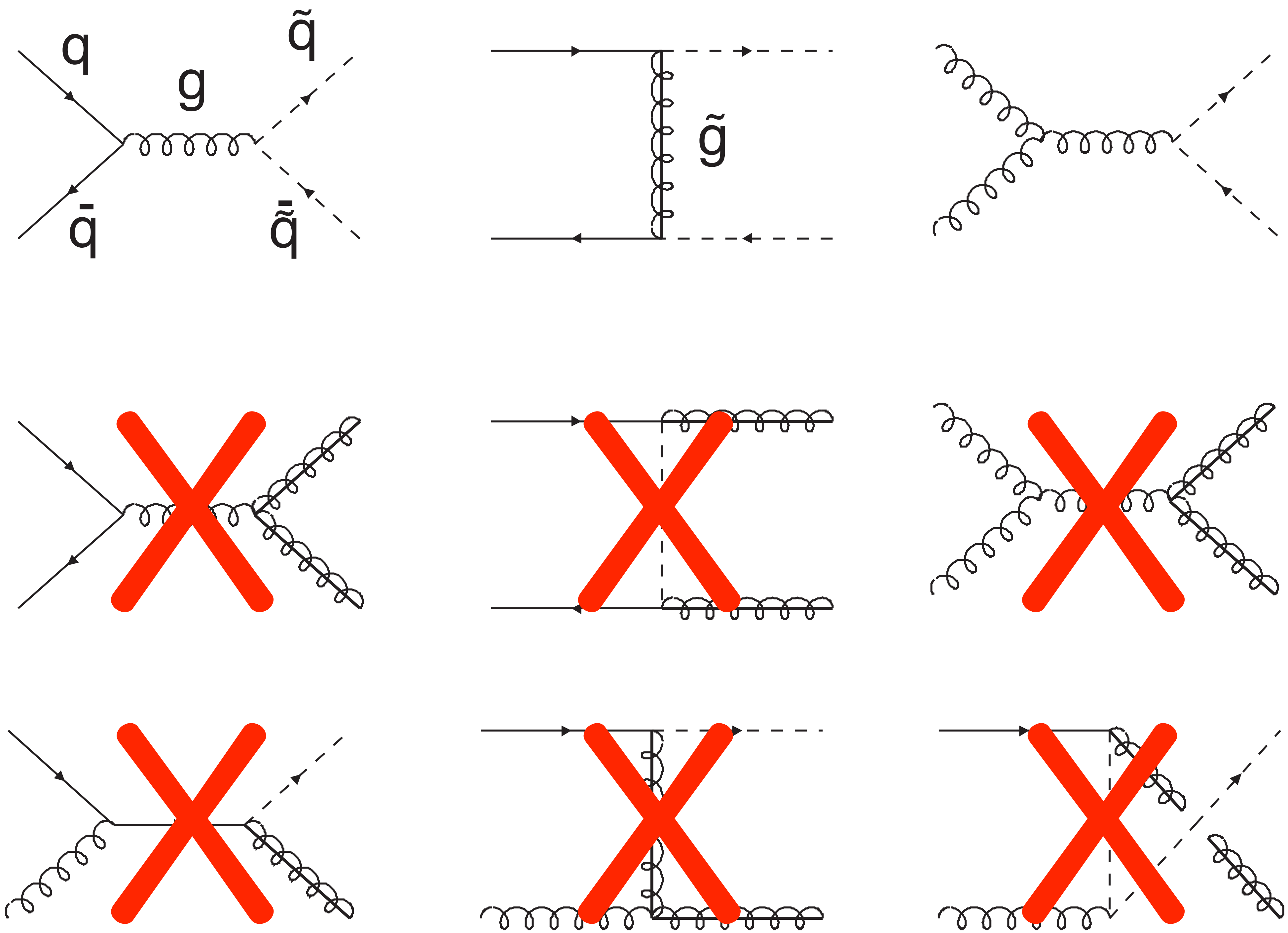
Squark and/or gluino production (LO)

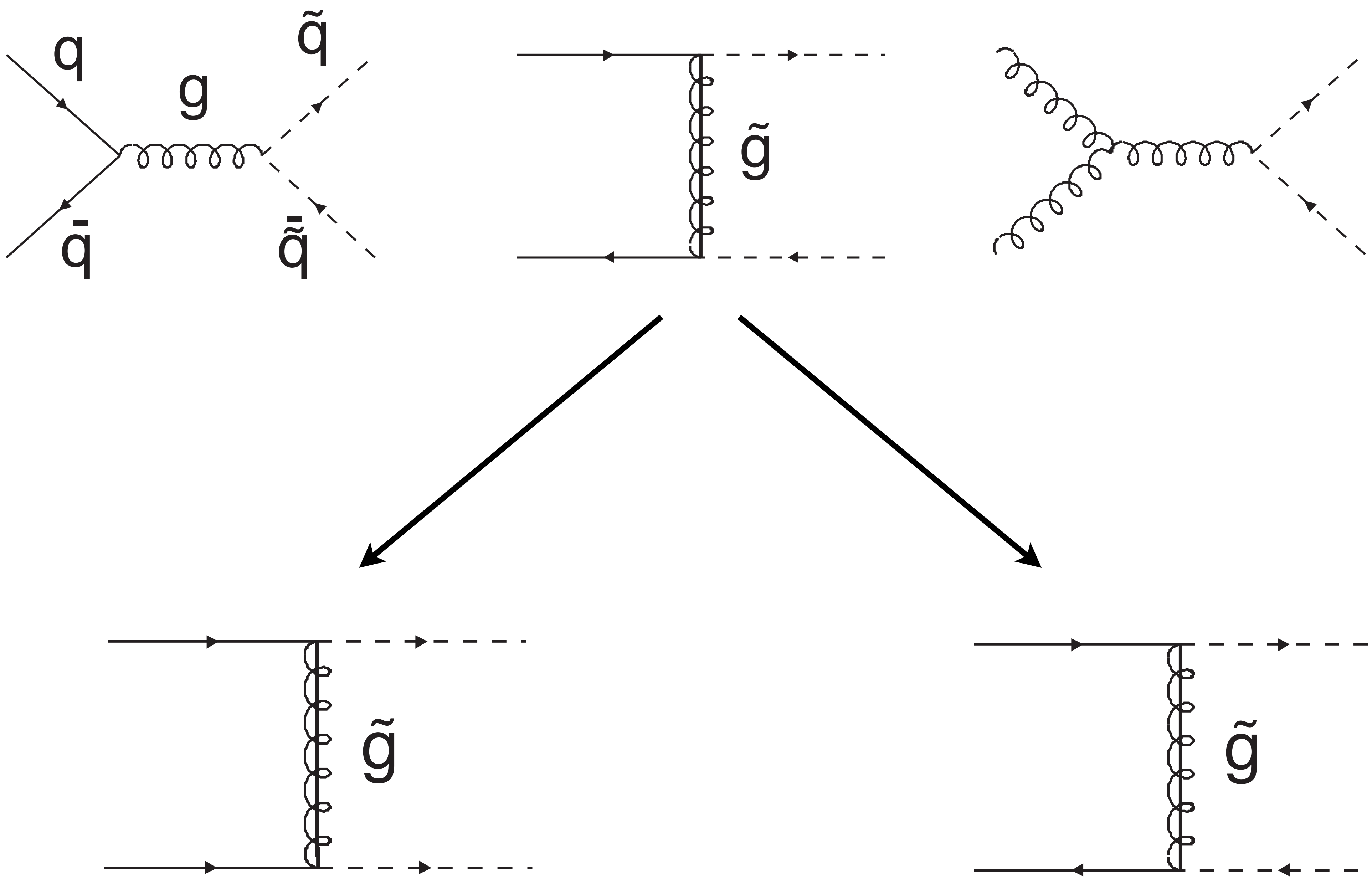


Squark and/or gluino production (LO)

with heavy gluino



Squark production (LO)



LL, RR absent

LR suppressed $1/M^2$

suppressed $1/M^2$ & PDFs

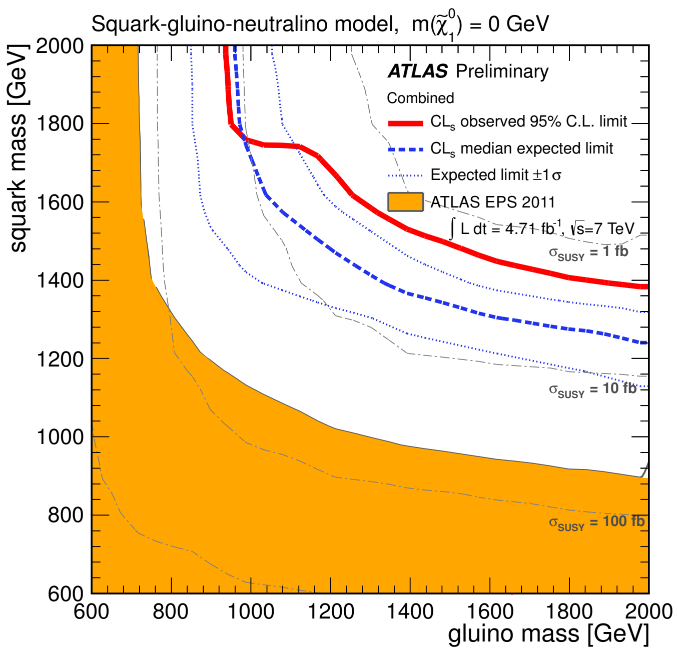
Bottom Line:

Colored Sparticle Production in
Supersoft Supersymmetric Models
Substantially Suppressed at LHC

(numbers in 5 slides)

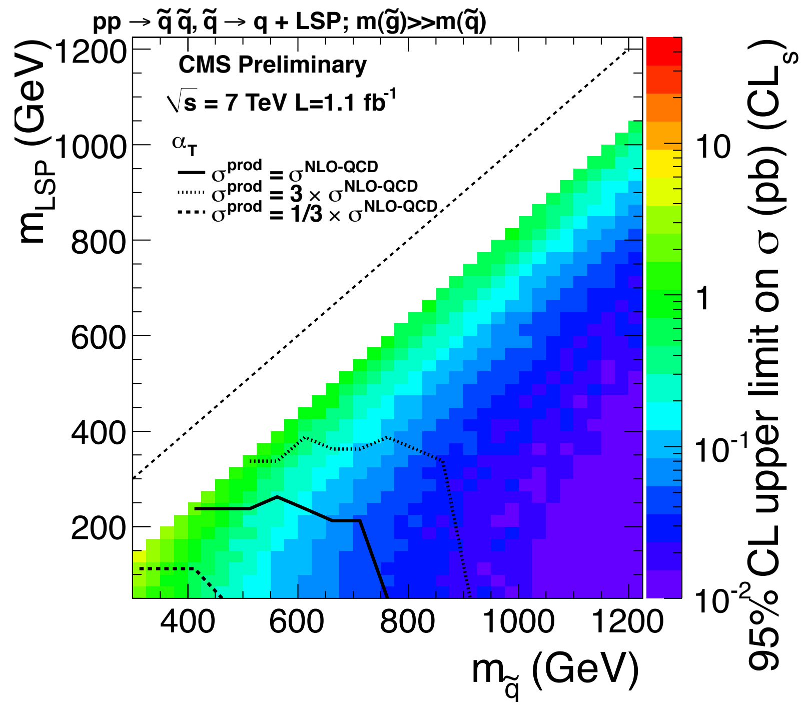
Simplified Models

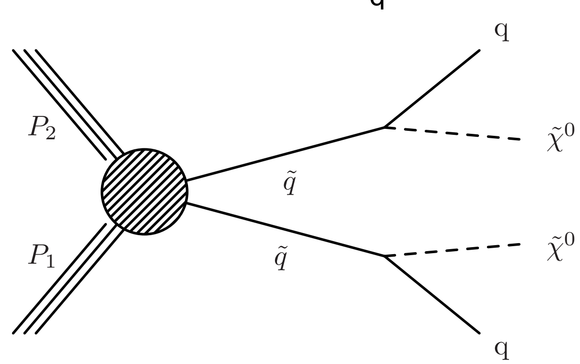
Examples of Simplified Models Bounded @ LHC



- massless LSP

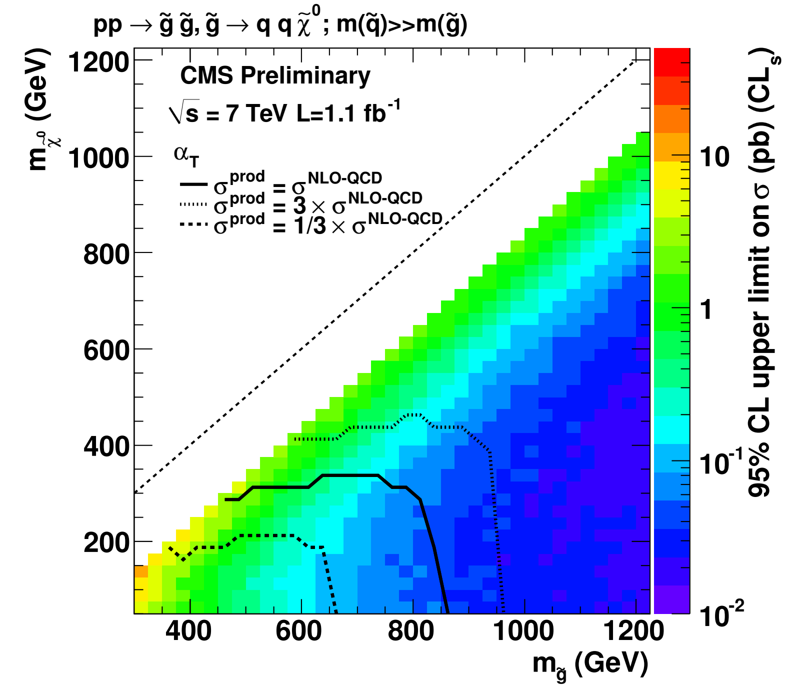
- bounds in (M3, Msq) plane

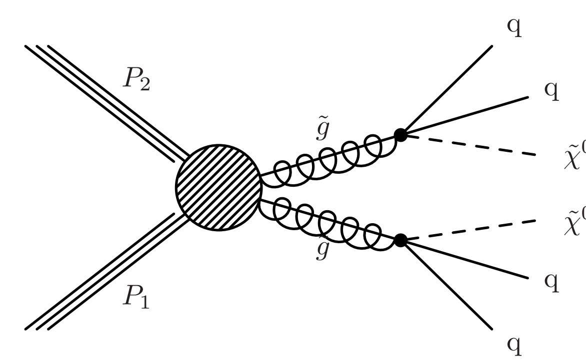




- gluino >> sq

- bounds in (Msq, LSP) plane



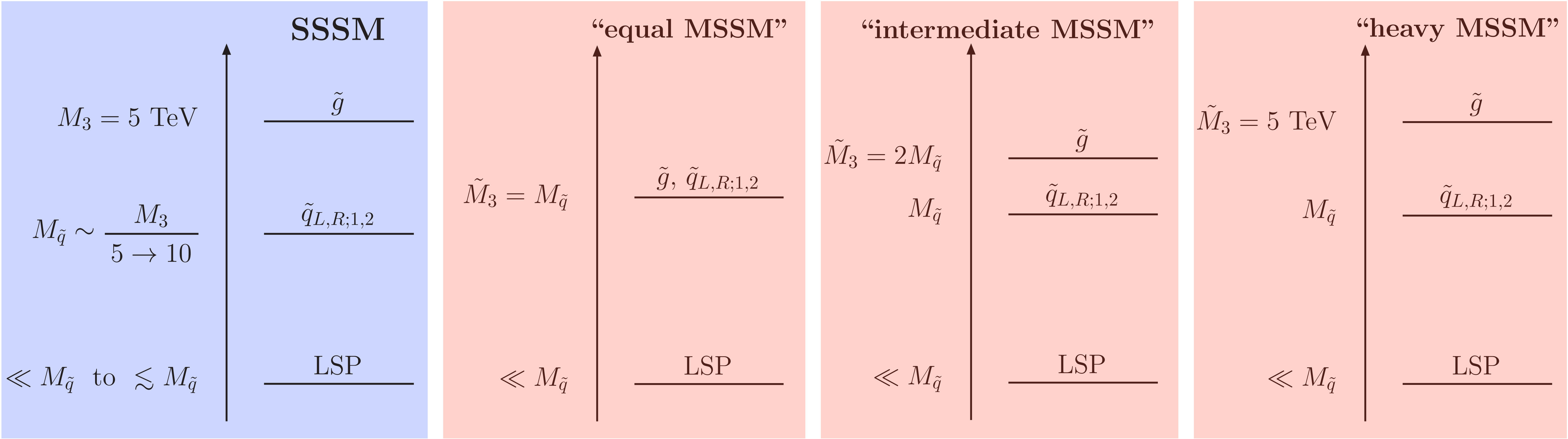


- sq >> gluino

- bounds in (M3, LSP) plane

Dirac versus Majrorana Gluino Simplified Models

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



Simulations

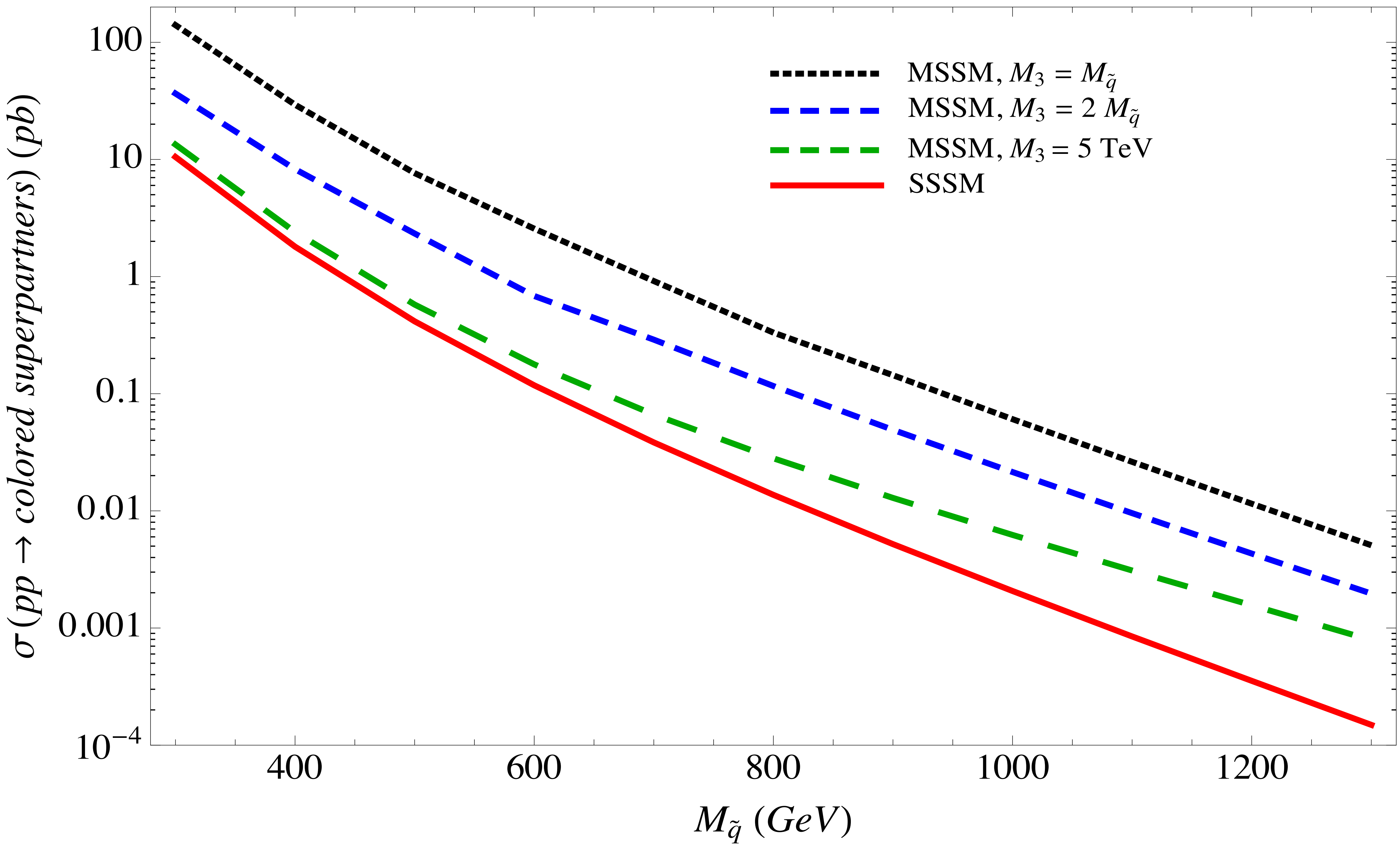
Signal simulation | Depends only on squark mass!

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.

Colored Sparticle Cross Sections

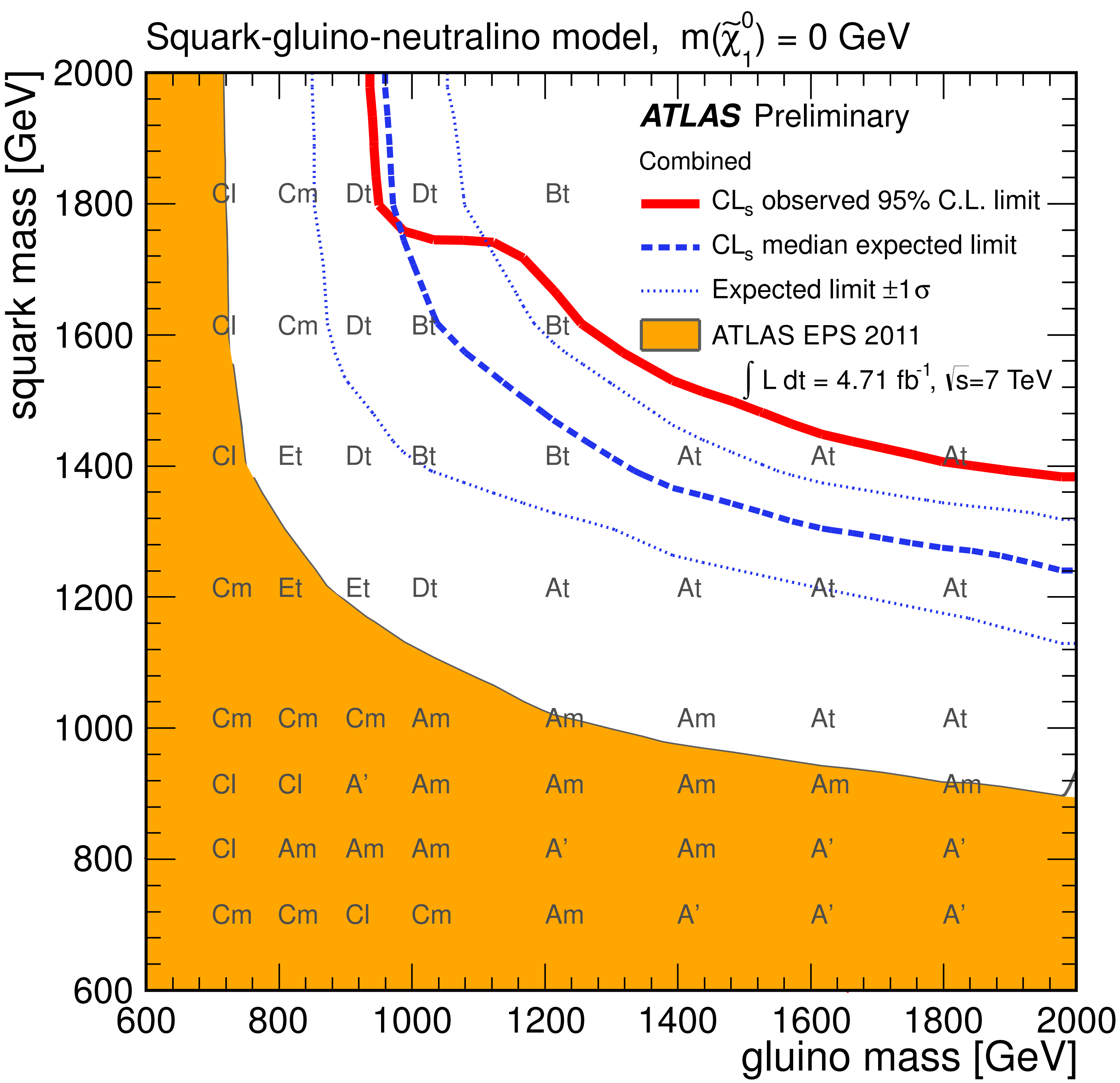


Kribs & Martin

Basic Jets Plus Missing Energy Searches

ATLAS	4.7/fb
CMS	1.1/fb

ATLAS jets + missing search strategy



0 leptons; all jets pT > 40 GeV

Requirement	Channel					
	A	A'	B	C	D	E
E_T^{miss}[GeV] >	160					
$p_T(j_1)$ [GeV] >	130					
$p_T(j_2)$ [GeV] >	60					
$p_T(j_3)$ [GeV] >	–	–	60	60	60	60
$p_T(j_4)$ [GeV] >	–	–	–	60	60	60
$p_T(j_5)$ [GeV] >	–	–	–	–	40	40
$p_T(j_6)$ [GeV] >	–	–	–	–	–	40
$\Delta\phi(\text{jet}, E_T^{miss})_{min}$ >	0.4 (i = {1, 2, (3)})			0.4 (i = {1, 2, 3}), 0.2 (p_T > 40 GeV jets)		
$E_T^{miss}/m_{eff}(Nj)$ >	0.3 (2j)	0.4 (2j)	0.25 (3j)	0.25 (4j)	0.2 (5j)	0.15 (6j)
m_{eff}(incl.) [GeV] >	1900/1400/–	–/1200/–	1900/–/–	1500/1200/900	1500/–/–	1400/1200/900
	tight mid	mid	tight	tight mid loose	tight	tight mid loose

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Meff

This analysis aims to search for the production of heavy SUSY particles decaying into jets and neutralinos, with the latter creating missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$). Because of the high mass scale expected for the SUSY signal, the 'effective mass', m_{eff}, is a powerful discriminant between the signal and most Standard Model backgrounds. For a channel which selects events with N jets, m_{eff} is defined to be the scalar sum of the transverse momenta of the leading N jets together with $E_{\mathrm{T}}^{\mathrm{miss}}$. The final signal selection uses cuts on m_{eff}(incl.) which sums over all jets with $p_{\mathrm{T}} > 40$ GeV.

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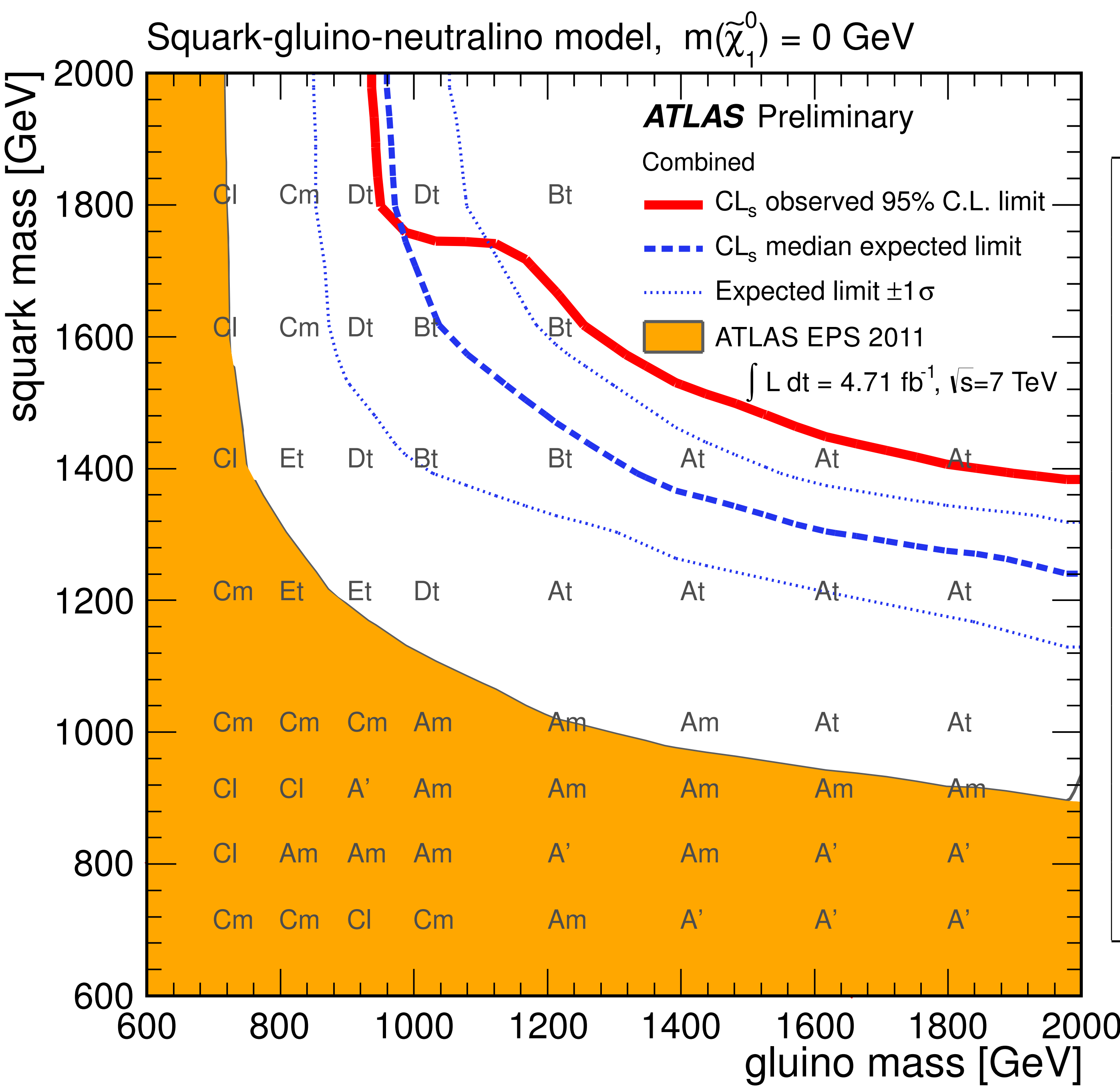
ATLAS jets + missing search strategy



	At	Am	Am’	Bt
$t\bar{t}$+ Single Top	0.22 ± 0.35 (0.046)	7 ± 5 (5.1)	11 ± 3.4 (10)	0.21 ± 0.33 (0.066)
Z/γ+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	$7 \pm 0.999 \pm 2.26$	$64.8 \pm 10.2 \pm 6.92$	$115 \pm 19 \pm 9.69$	$5.39 \pm 0.951 \pm 2.01$
Data	1	59	85	1
local p-value (Gaus. σ)	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 σ_{BSM} /(fb)	$0.62(1.3^{0.89}_{1.9})$	$5.3(6^{4.3}_{8.2})$	$6.2(9.2^{6.7}_{13})$	$0.65(1.2^{0.8}_{1.8})$

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ATLAS Search Bounds

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

1st,2nd generation squark mass

Kribs & Martin

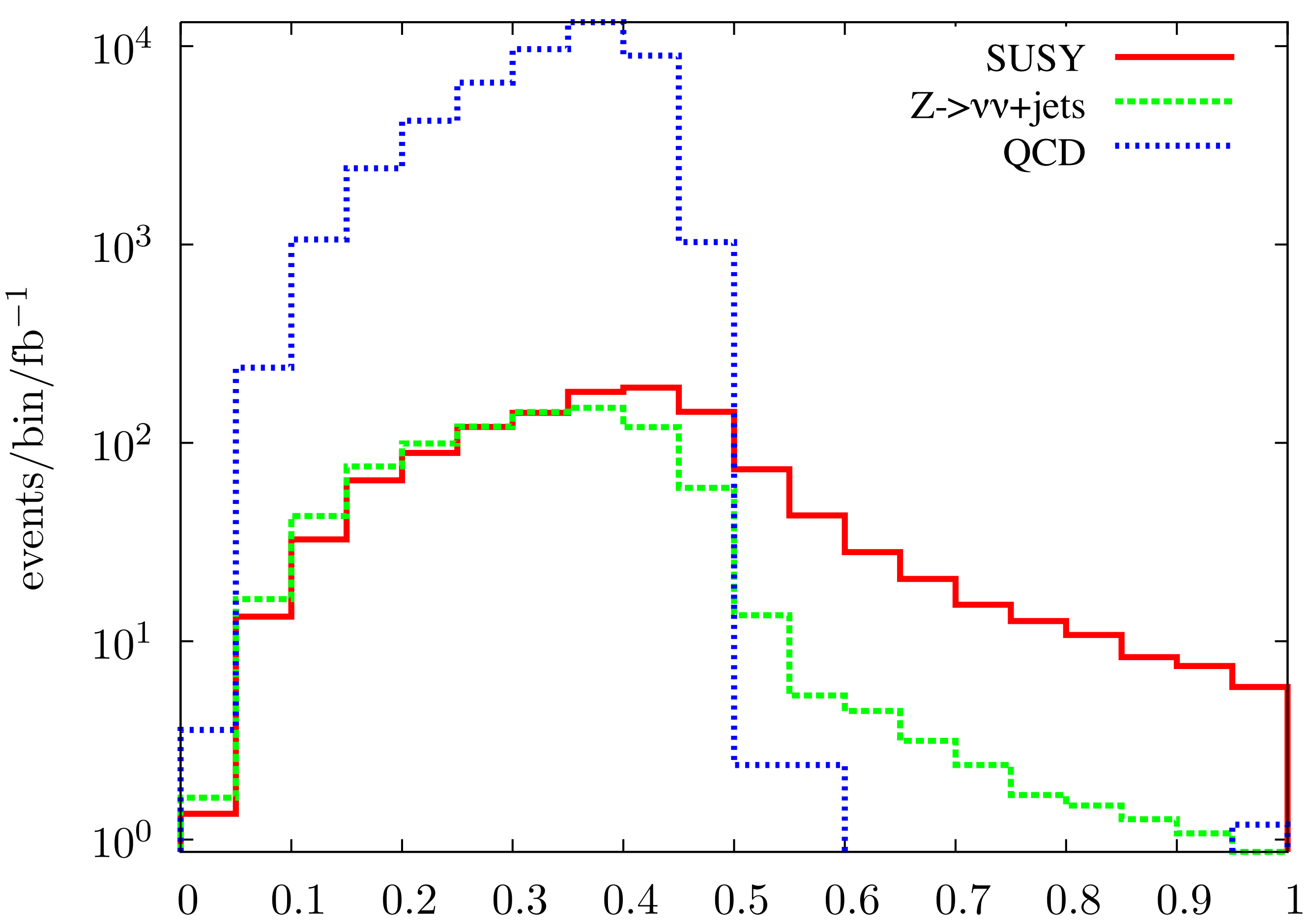
CMS α_T strategy
1.1/fb

α_T strategy

Combine n > 2 jets into 2 “pseudojets”, then calculate:

$$\alpha_T = \frac{E_T^{\text{jet}_2}}{M_T} = \frac{E_T^{\text{jet}_2}}{\sqrt{\left(\sum_{i=1}^{2} E_T^{\text{jet}_i}\right)^2 - \left(\sum_{i=1}^{2} p_x^{\text{jet}_i}\right)^2 - \left(\sum_{i=1}^{2} p_y^{\text{jet}_i}\right)^2}}$$

$$= \frac{\text{ET of 2nd hardest jet}}{\text{invariant mass of hardest 2 jets}}$$



Cut on $\alpha_T \approx 0.5$ highly effective at suppressing QCD background.

Randall & Tucker-Smith 0806.1049

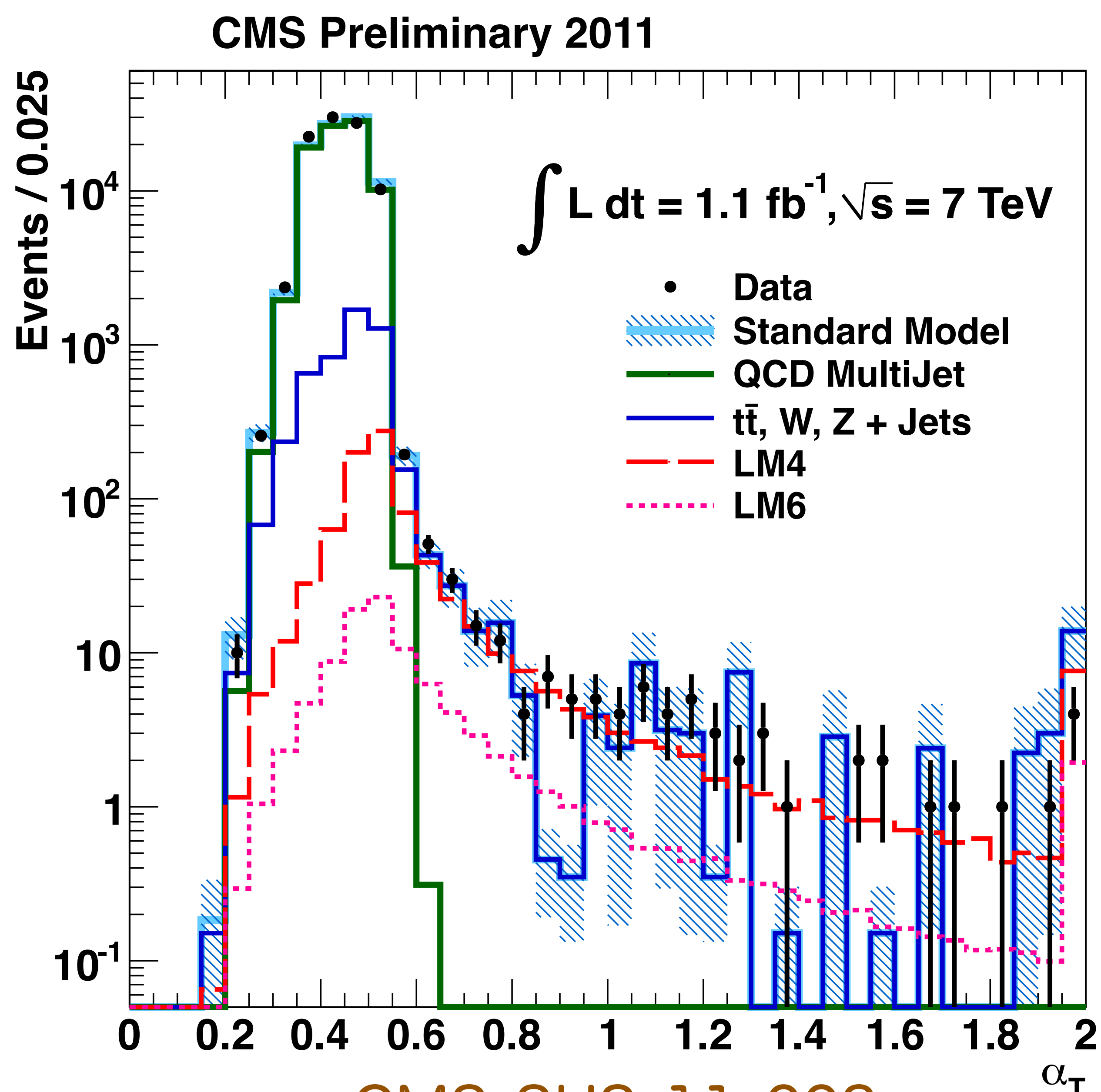
CMS α_T Search Strategy

Triggered >= 2 jets with 0 leptons and 0 photons.

- E_T: all jets > 50 GeV; leading 2 jets > 100 GeV
- Cut and count H_T bins

$$H_T = \sum_{i=1}^{n} E_T^{\text{jet}_i}$$

- missing E_T > 100 GeV
- mild $\Delta\phi$ cut to reduce jet mismeasurement



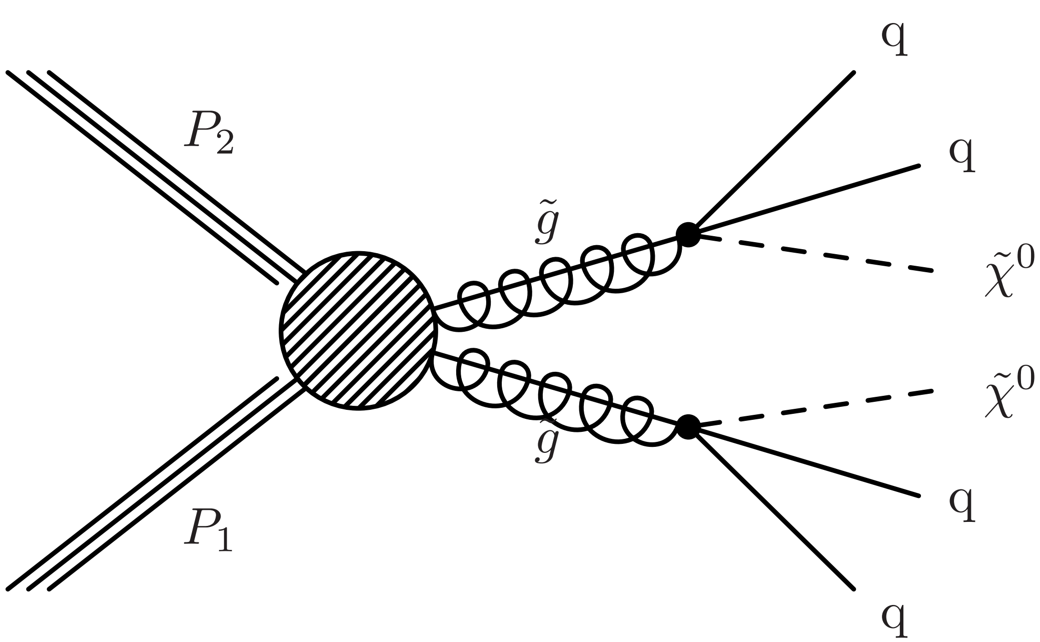
CMS-SUS-11-003

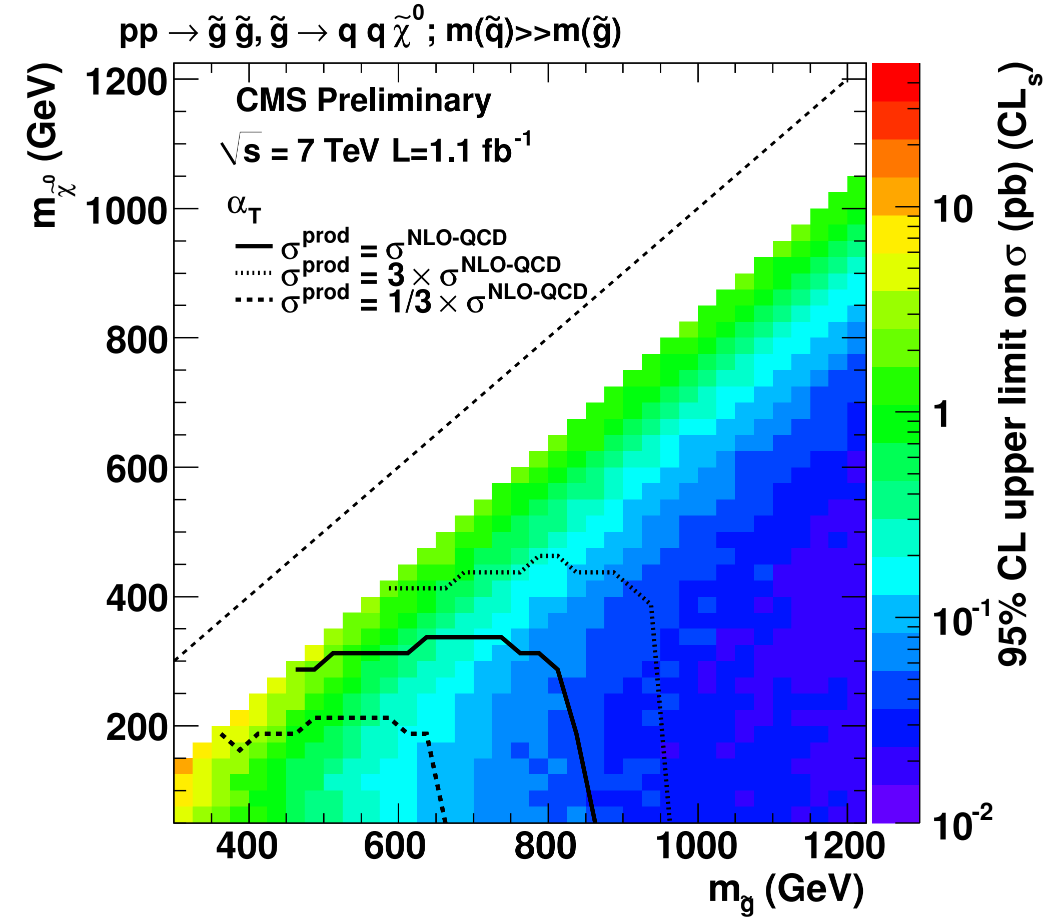
CMS Cuts and Counts

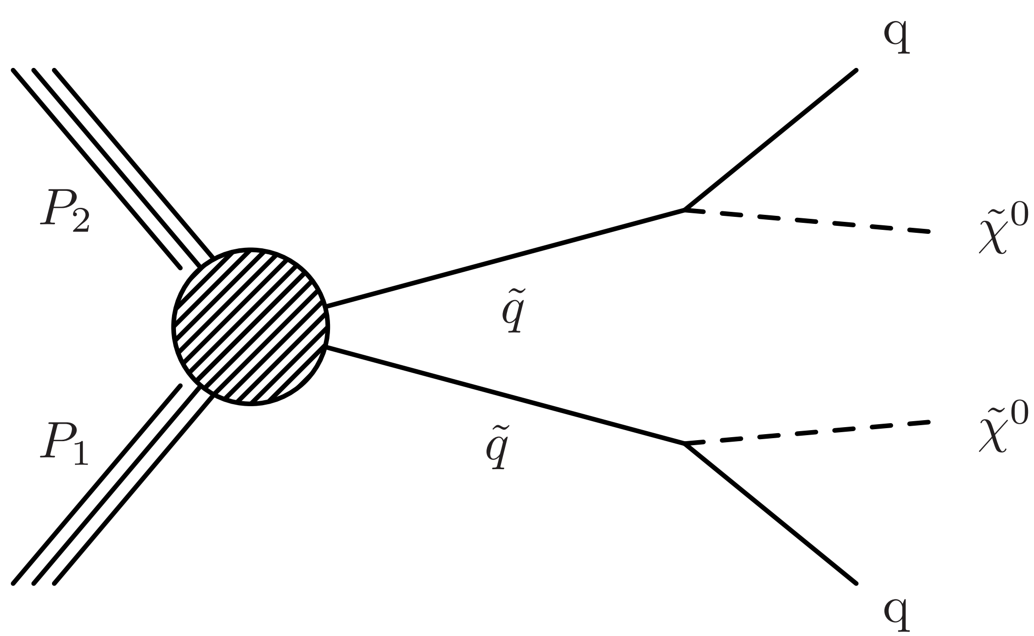
	a	b	c	d	e	f	g	h
H_T Bin (GeV)	275–325	325–375	375–475	475–575	575–675	675–775	775–875	875–∞
p_T^{leading} (GeV)	73	87	100	100	100	100	100	100
p_T^{second} (GeV)	73	87	100	100	100	100	100	100
p_T^{other}(GeV)	37	43	50	50	50	50	50	50
$\alpha_T > 0.55$	782	321	196	62	21	6	3	1
$\alpha_T < 0.55$	$5.73 \cdot 10^7$	$2.36 \cdot 10^7$	$1.62 \cdot 10^7$	$5.12 \cdot 10^6$	$1.78 \cdot 10^6$	$6.89 \cdot 10^5$	$2.90 \cdot 10^5$	$2.60 \cdot 10^5$
$R_{\alpha_T} (10^{-5})$	$1.36 \pm 0.05_{\text{stat}}$	$1.36 \pm 0.08_{\text{stat}}$	$1.21 \pm 0.09_{\text{stat}}$	$1.21 \pm 0.15_{\text{stat}}$	$1.18 \pm 0.26_{\text{stat}}$	$0.87 \pm 0.36_{\text{stat}}$	$1.03 \pm 0.60_{\text{stat}}$	$0.39 \pm 0.52_{\text{stat}}$

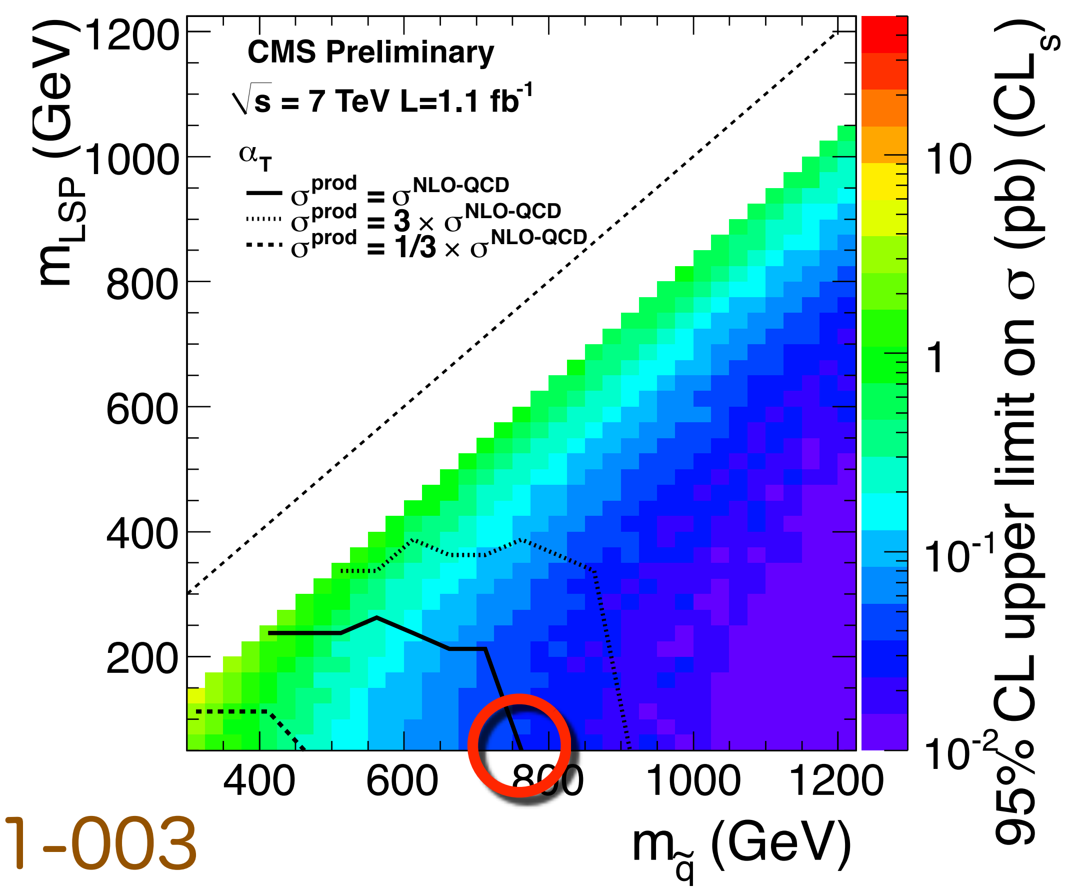
CMS-SUS-11-003

CMS Bounds on Simplified Models









CMS-SUS-11-003

CMS α_T Search Bounds

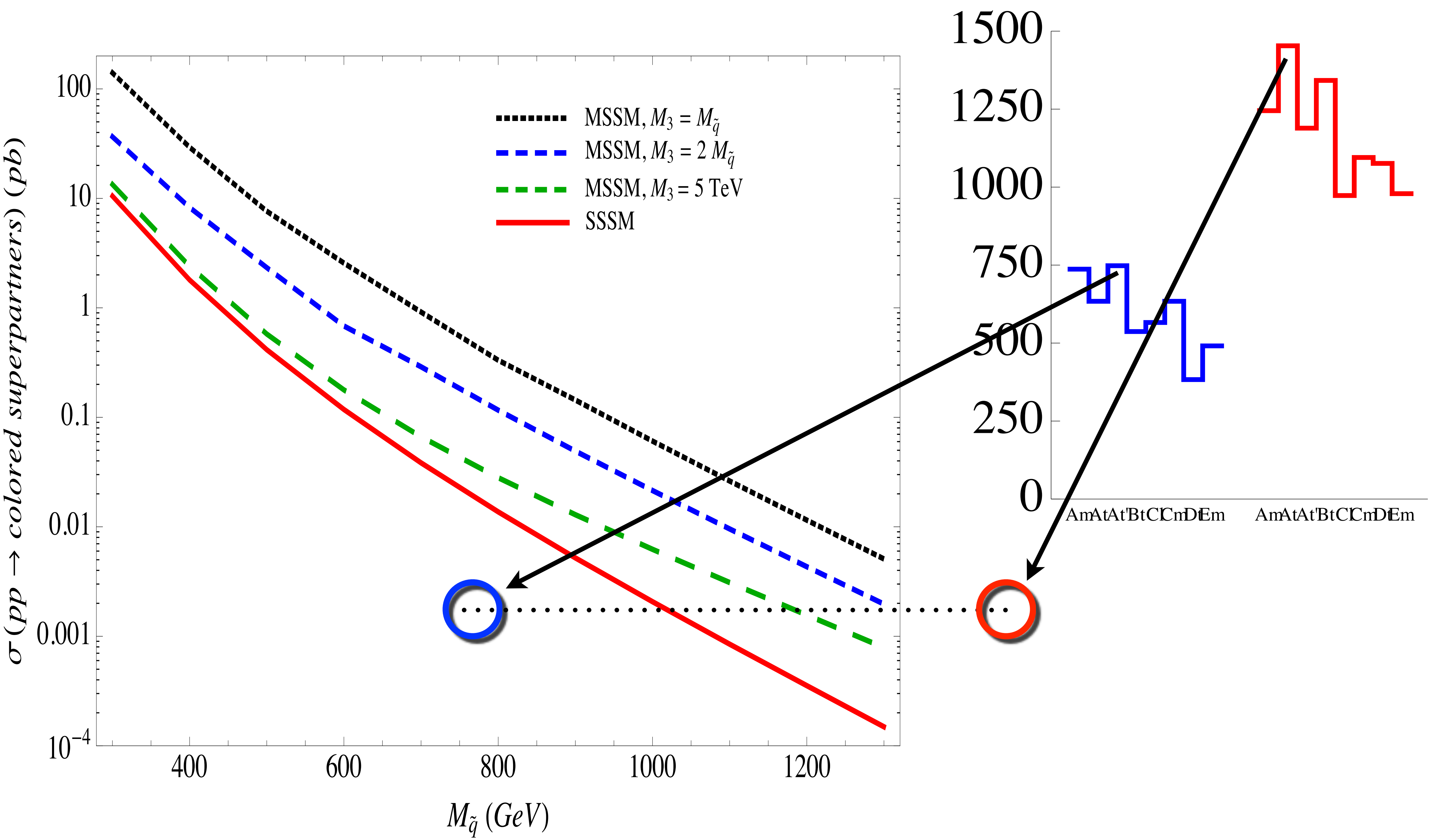
SSSM	MSSM	MSSM	MSSM
M3 = 5 TeV	M3 = Msq	M3 = 2 Msq	M3 = 5 TeV

1st,2nd generation squark mass

Kribs & Martin

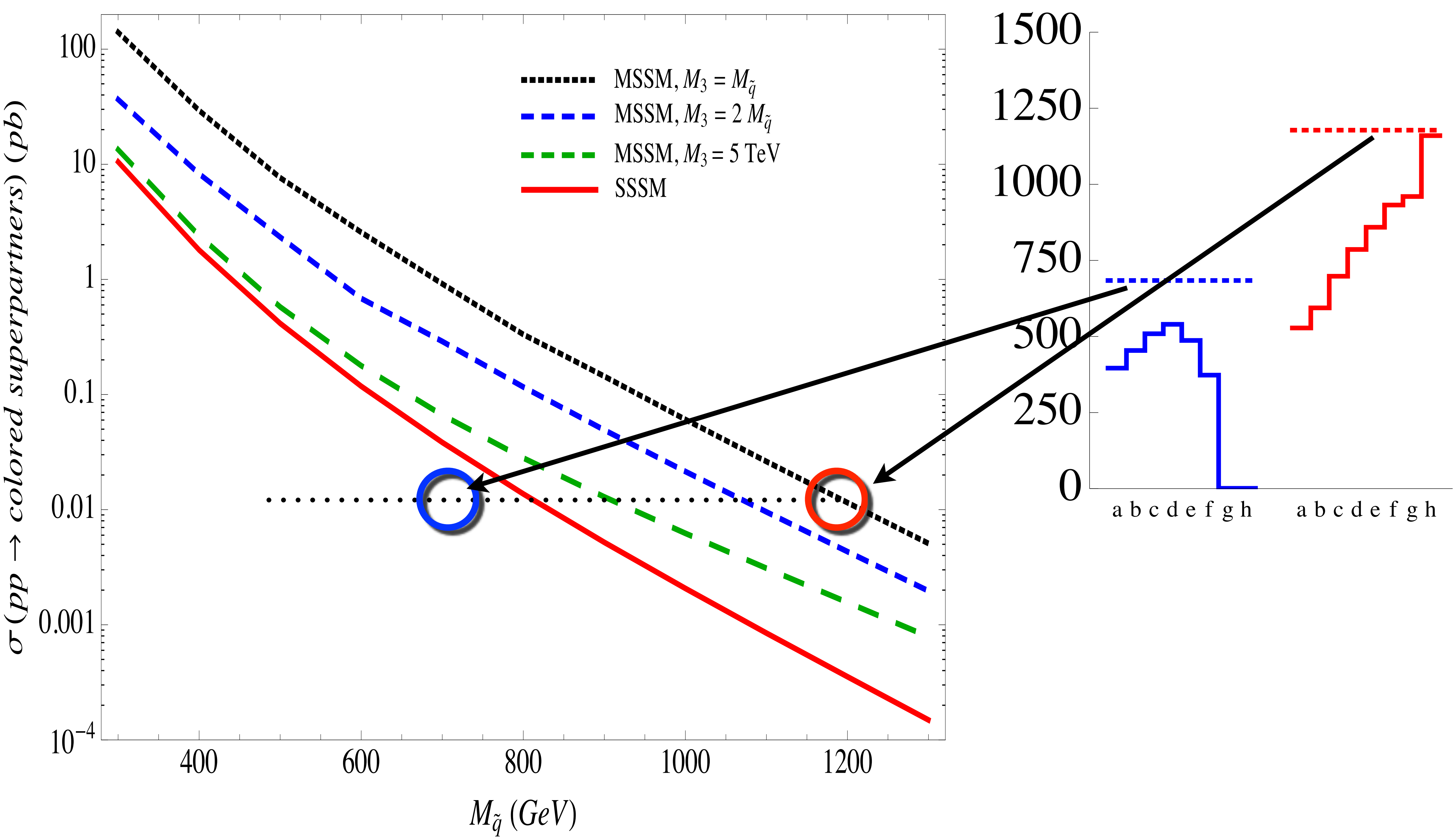
Comparisons

Effectiveness of ATLAS strategy



Kribs & Martin

Effectiveness of CMS α_T strategy



Kribs & Martin

“Mixed Gauginos”

(Dirac gluino and Majorana wino & bino)

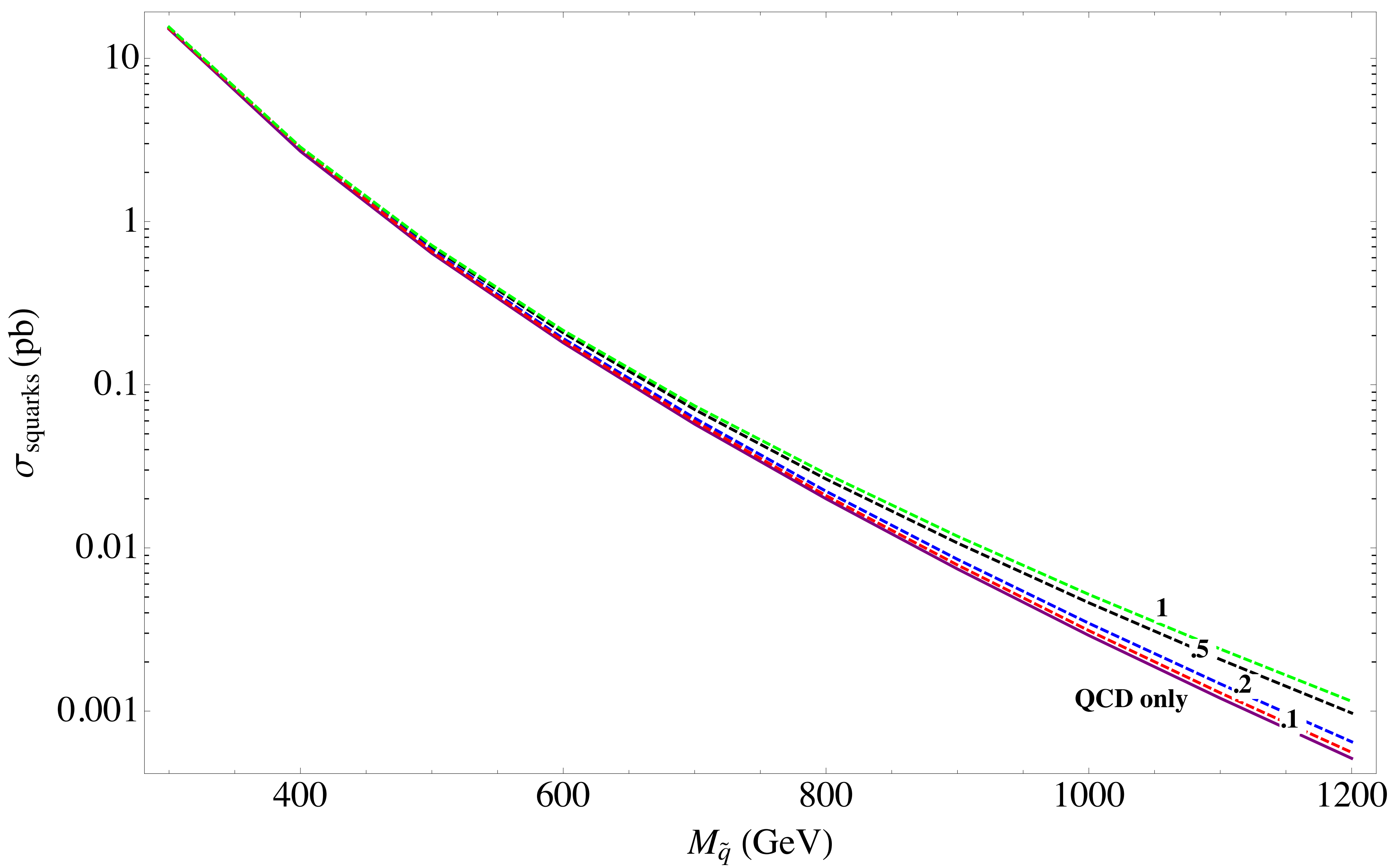
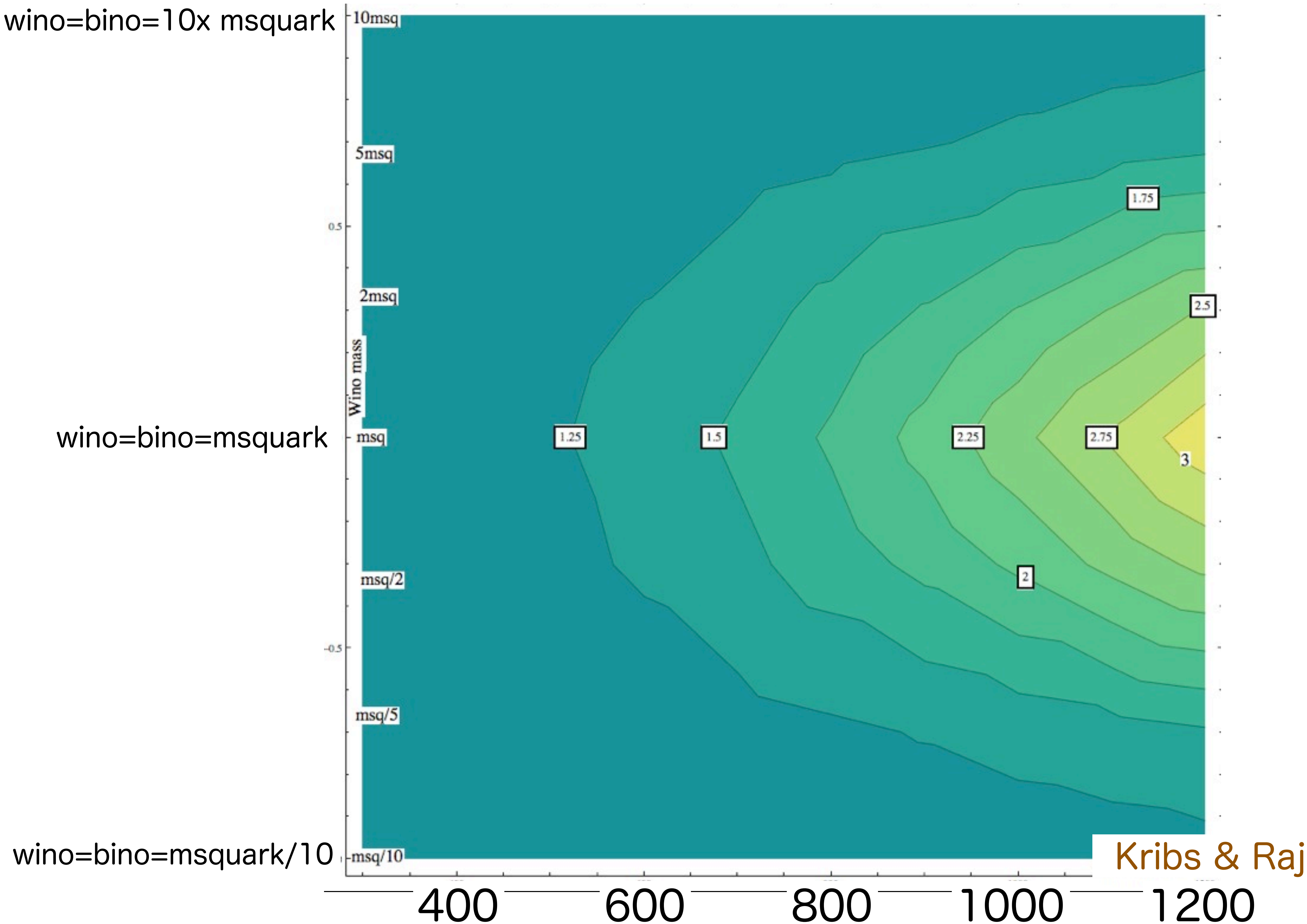


FIG. 8: Impact of turning on electroweak gauginos at different masses, with $M_{\tilde{w}} = M_{\tilde{b}}$. The ratio $M_{\tilde{w}}/M_{\tilde{q}}$ is represented by the different colors; green: 1, black = .5, blue: .2, red = .1. The solid purple line is the QCD-only cross-section provided for comparison.

Fractional Increase in Squark Cross Section



Summary

* Heavy Dirac Gluino in "supersoft", "R-symmetric"
  natural and suppresses colored sparticle production substantially

* Bounds on 1st,2nd generation squarks 680-750 GeV;
  (up to about 800 GeV with 12/fb @ 8 TeV CMS α_T)

* Best search is α_T (Mar 2012); optimize over range of H_T crucial
  (but, "razor" T2 confusion, for off-line...)

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

* SUSY not ruled out yet...even models not tuned to avoid bounds!

* What is "minimally" necessary? (Majorana EW versus Dirac gluino…)