Dirac Gauginos & friends at the LHC

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Gauginos (gluinos/winos/binos) are Majorana particles

$$M_3\,\tilde{g}_A\,\tilde{g}_A$$

at least in the MSSM

not the only option... could be Dirac fermions

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- requires adding new matter
- invariant under U(1) symmetry (R-symmetry)

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$M_3\,\tilde{g}_A\,\tilde{\lambda}_A$ i.e. new color adjoint

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How do you get Dirac?

Fayet (1978)
Polchinski, Susskind (1982)
Hall, Randall (1991)
Fox, Nelson, Weiner (2002)
...

usually (Majorana gaugino masses):

$$\int d^2\theta \, \frac{\mathbf{X}\, \mathcal{W}_A^\alpha \mathcal{W}_\alpha^A}{\Lambda_{mess}} \longrightarrow \frac{F}{\Lambda_{mess}} \tilde{g}_A \, \tilde{g}_A \longrightarrow M_3 \, \tilde{g}_A \, \tilde{g}_A$$

instead, use $\mathcal{W}'_\alpha = \theta_\alpha \mathbf{D}$ D-term spurion

$$\int d^2\theta \frac{\mathcal{W}'_\alpha \, \mathcal{W}_A^\alpha \, \Phi^A}{\Lambda_{mess}} \longrightarrow \frac{\mathbf{D}}{\Lambda_{mess}} \tilde{g}_A \, \tilde{\lambda}^A \longrightarrow M_D \, \tilde{g}_A \, \tilde{\lambda}^A$$

+ ...

have to give up minimality

in order for all gauginos to be Dirac, we must add:

$\Phi_A, \quad A = 1..8$ color octet

$\Phi_i, \quad i = 1..3$ weak triplet

Φ singlet

the Φ are chiral superfields = (complex scalar, fermion) not just fermions

mix and match: could have Dirac gluino, Majorana wino, etc...

$\Phi_A = (A_A, \lambda_A)$ contain new adjoint scalars

= i.e. ‘sgluons’

$$\int d^2\theta \, \sqrt{2} \, \frac{\mathcal{W}'_\alpha \, \mathcal{W}^\alpha_a \, \Phi^a}{M_{mess}} \quad \supset \quad M_D \left(A^a + A^{*a} \right) D_a$$

new adjoint scalars

D-term for SM gauge groups

eliminating D_a ...

$$-\frac{M_D^2}{2} \left(A^a + A^{*a} \right)^2 - M_D \left(A^a + A^{*a} \right) \left(\sum_i g_a \phi_i^* \tau_a \phi_i \right)$$

mass for Re[A_a]

new trilinear interactions

could also add

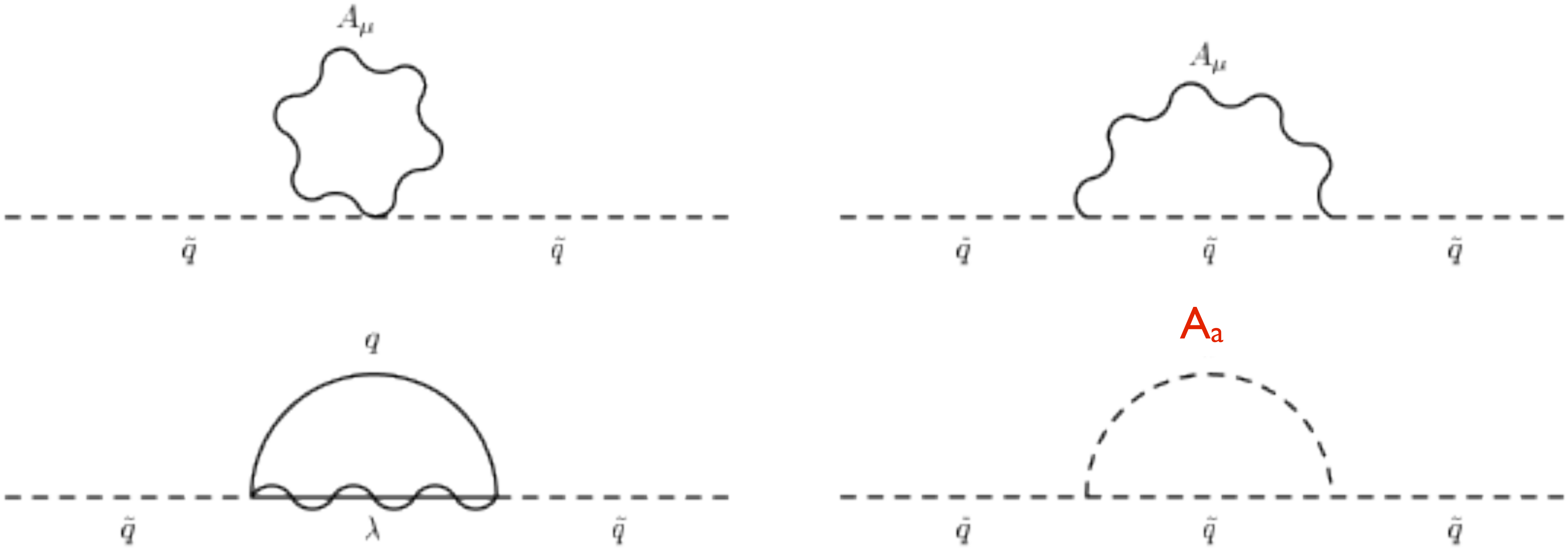
$$\int d^2\theta \, \frac{\mathcal{W}'_\alpha \mathcal{W}'_\alpha \Phi^a \Phi^a}{M_{mess}^2} + \text{h.c.}$$

opposite sign mass terms for

Re[A_a], Im[A_a]

squark/slepton masses

generated at 1-loop level:



from new trilinear interactions

$$m_{\tilde{f}}^2 = \sum_i \frac{\alpha_i C_i(f)\, M_{D,i}^2}{\pi} \log \frac{m_{adj,i}^2}{M_{D,i}^2}$$

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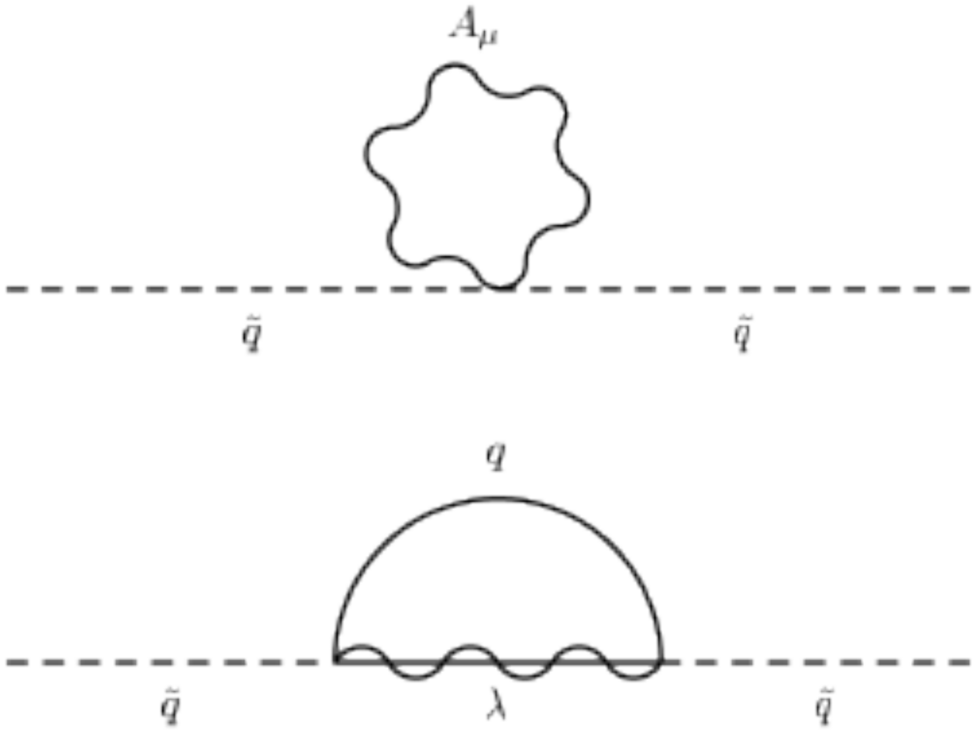
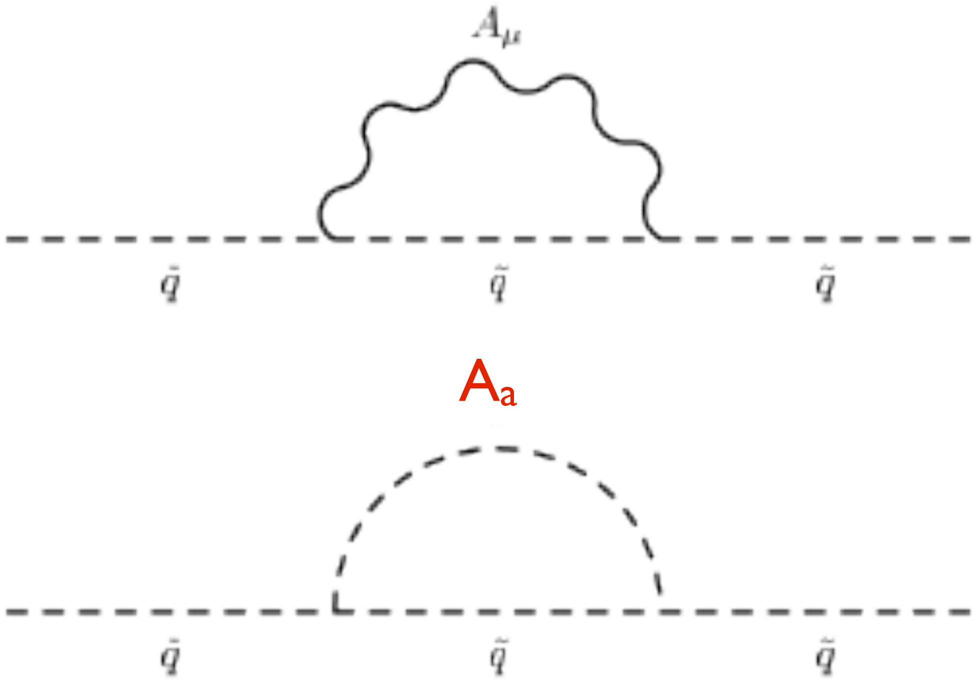
Im[A$_a$] mass as well!





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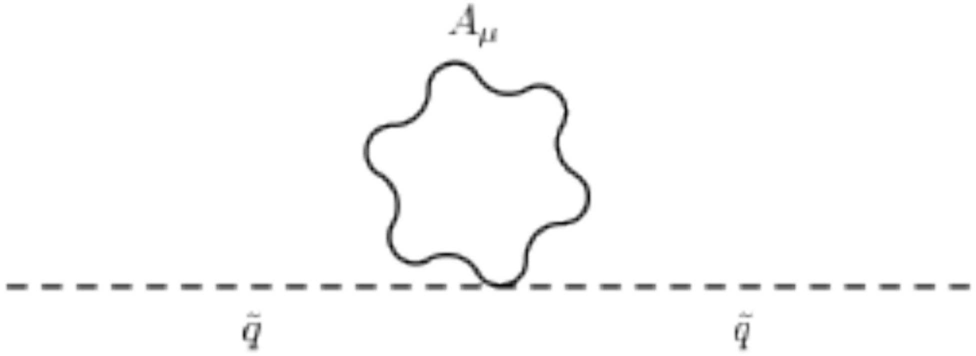

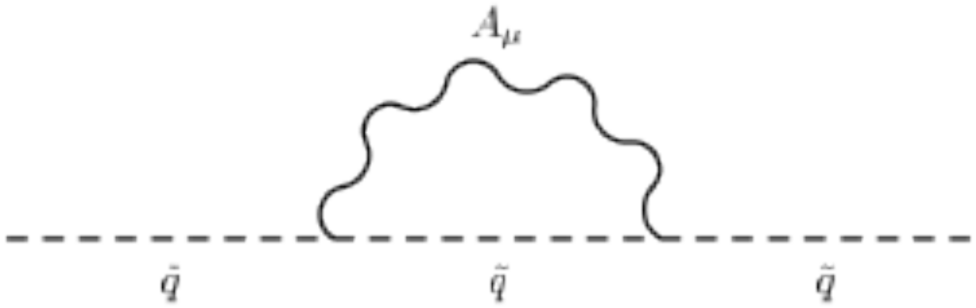

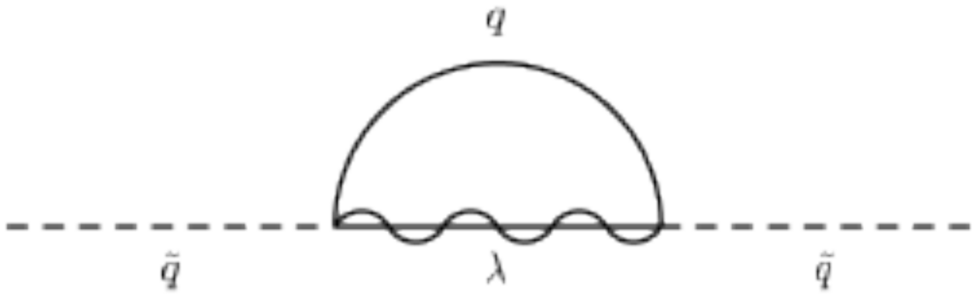

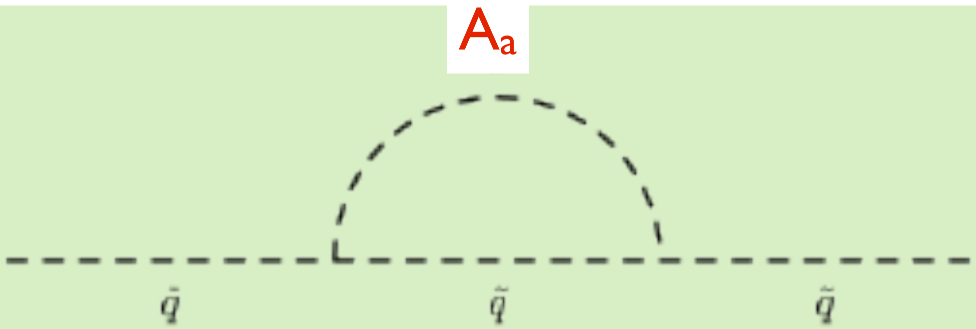

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$$m^2_{\tilde{f}} = \sum_i \frac{\alpha_i C_i(f)\, M^2_{D,i}}{\pi} \log \frac{m^2_{adj,i}}{M^2_{D,i}}$$

insensitive to Λ_{mess} !

integral cut off by m_{adj}

“Supersoft”

Fox, Nelson, Weiner (2002)

squark/slepton masses

$$m_{\tilde{f}}^2 = \sum_i \frac{\alpha_i C_i(f)\, M_{D,i}^2}{\pi} \log \frac{m_{adj,i}^2}{M_{D,i}^2}$$

plug in some numbers

$$m_{\tilde{Q}}^2 \simeq (700\,\mathrm{GeV})^2 \left(\frac{M_3}{5\,\mathrm{TeV}}\right)^2 \frac{\log r_3}{\log 1.5}$$

or

$$m_{\tilde{Q}}^2 \simeq (760\,\mathrm{GeV})^2 \left(\frac{M_3}{3\,\mathrm{TeV}}\right)^2 \frac{\log r_3}{\log 4}$$

Dirac gluino ≈ (5-7) x squark mass for $m_{adj} \gtrsim M_D$

Dirac inos and naturalness

δm^2_H : compare the MSSM and Dirac

MSSM

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

$$\sim \alpha_s M_3^2 \log \frac{\Lambda^2}{M_3^2}$$

Dirac (Supersoft)

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M_3 = 900 GeV

Λ_{mess}= 20 TeV

same tuning as

M_D = 5 TeV

m_{adj} = 2 M_D

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substantially heavier gluino quite natural in supersoft

Dirac inos and naturalness

no free lunch: can be hidden tuning (= non-Higgs related) in m_{adj}

recall:

[Benakli & Goodsell ’08, Arvanitaki et al ’13]

$$\kappa \int d^2\theta \, \frac{\mathcal{W}'_\alpha \mathcal{W}'_\alpha \Phi^a \Phi^a}{M^2_{mess}} + \text{h.c.} \quad = \kappa \, M_D^2 \left(Re(A_a)^2 - Im(A_a)^2 \right)$$

if this term ≫ original Dirac term, can lead to:

- tachyonic A_a pieces
- big m_{adj}/MD hierarchy → $m_{\tilde{q}}$ too big or too small

UV model dependent: simple counterexamples

[Kribs, Okui, Roy ’10, Csaki et al ’13]

nice features in Higgs tuning motivate more model-building

Dirac EW-inos?

for naturalness and LHC pheno, gluino is by far the most important gaugino. If wino, bino are Dirac as well:

- finiteness of $m_{\tilde{q}}$, smaller tuning also from EW stuff
- nice flavor properties, interesting DM, baryogenesis possibilities

[Kribs, Poppitz, Weiner ’07], [Harnik, Kribs ’08], [Fok, Kribs, AM, Tsai ’12]

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BUT:

SU(2), U(1) D-term

$$\int d^2\theta\, \sqrt{2}\, \frac{\mathcal{W}'_\alpha\, \mathcal{W}^\alpha_a\, \Phi^a}{M_{mess}} \quad \supset \quad M_D \left(A^a + A^{*a}\right) D_a$$

integrate out heavy $\mathrm{Re}[A_i] \to D_i = 0$

tree-level Higgs quartic vanishes

new contributions needed to get m_H = 126 GeV:

nMSSM-ology, “λ” couplings of KPW

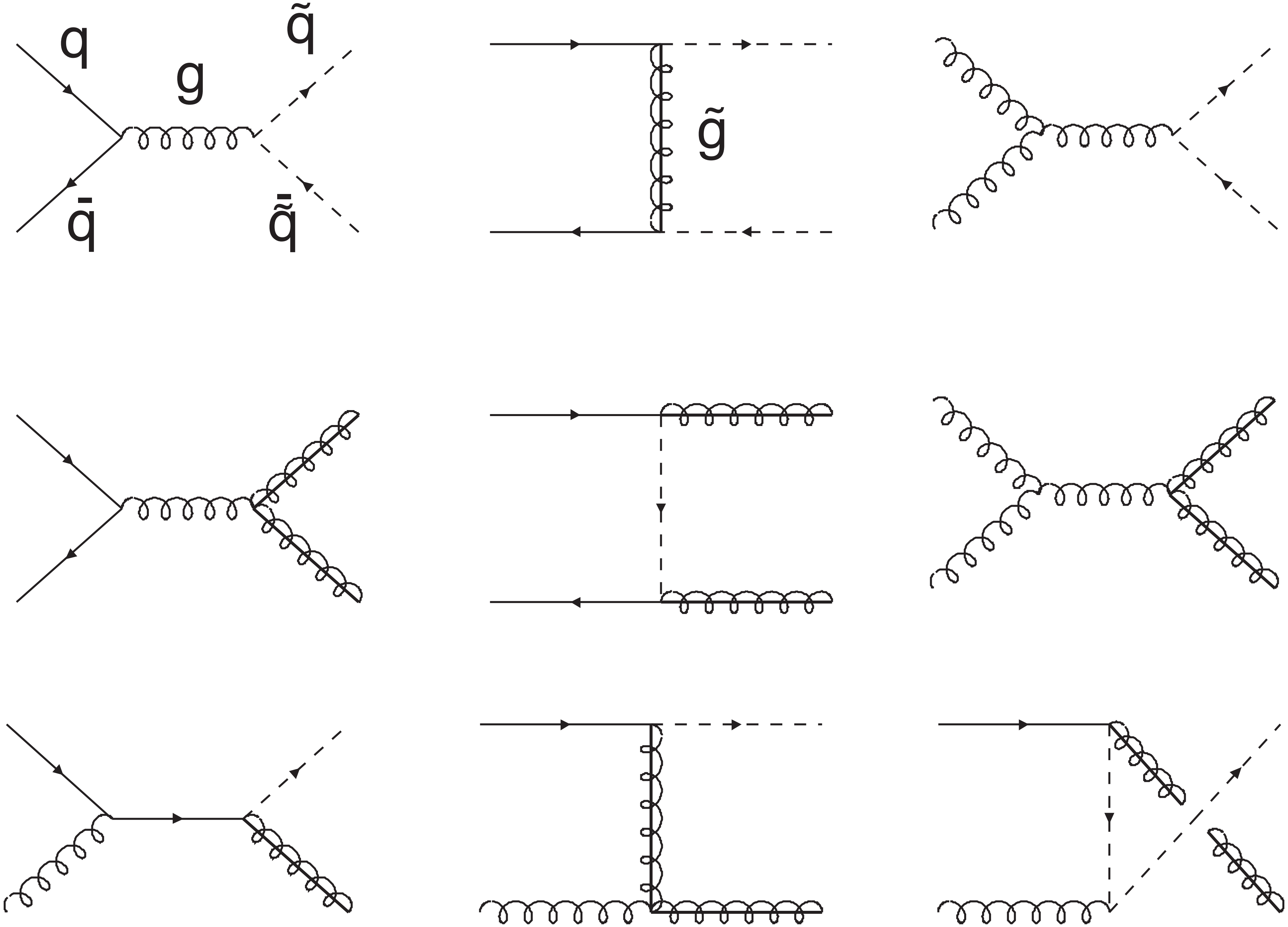
Dirac vs. Majorana gluinos at LHC

other work on Dirac gauginos @ LHC:

Choi, Drees et al ’08
Benakli, Goodsell ’08, ’09, ’11
Frugiuele, Gregoire et al ’11,’12

differ in treatment of EW sector

heavy Dirac gluino means several colored sparticle production channels are suppressed by kinematics alone



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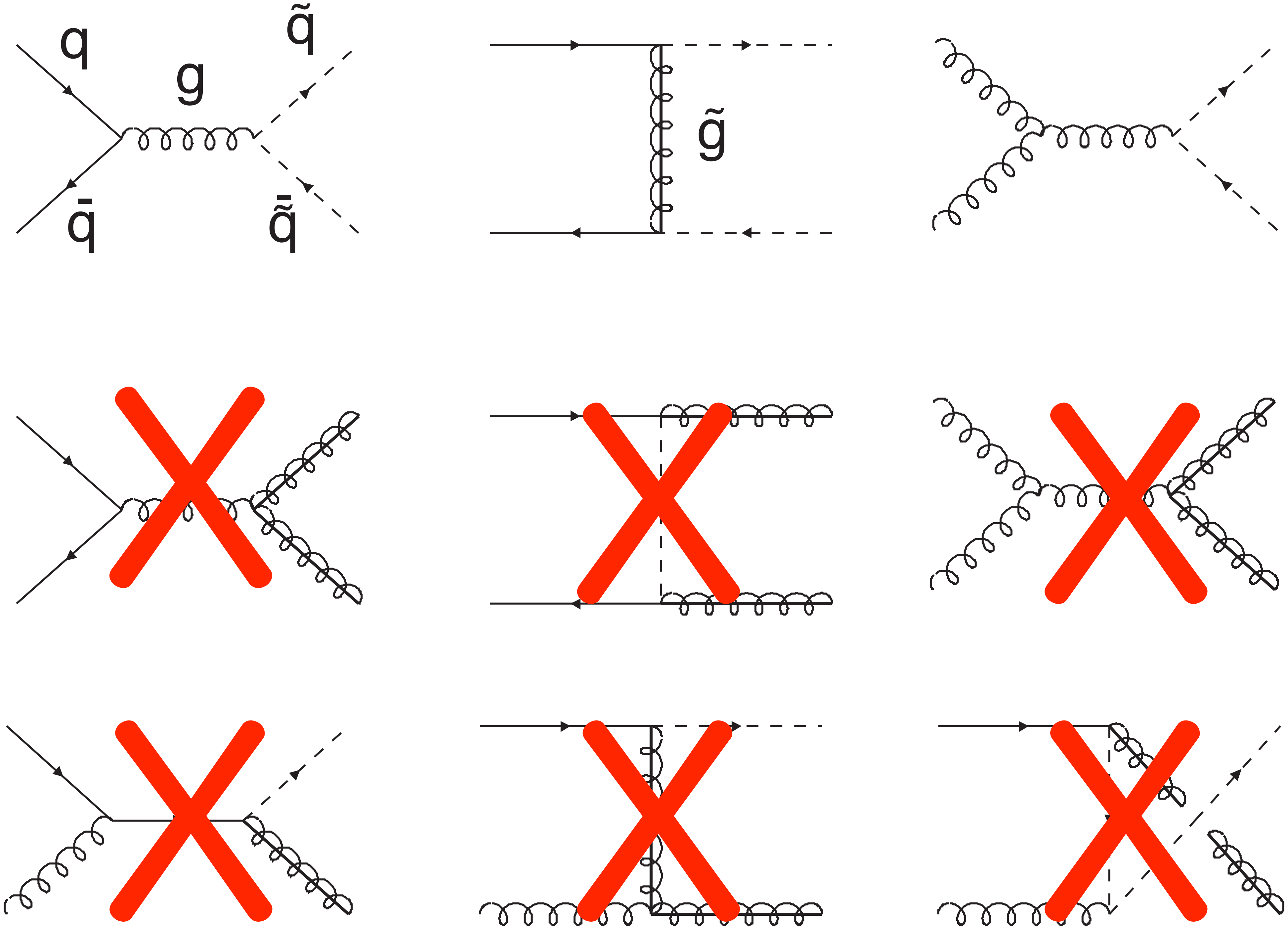


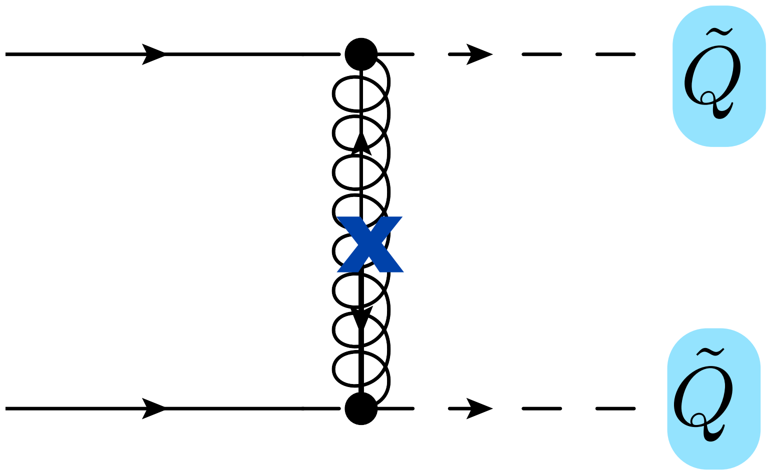
suppression goes beyond kinematics:

SUSY kinetic terms contain a $U(1)_R$ symmetry

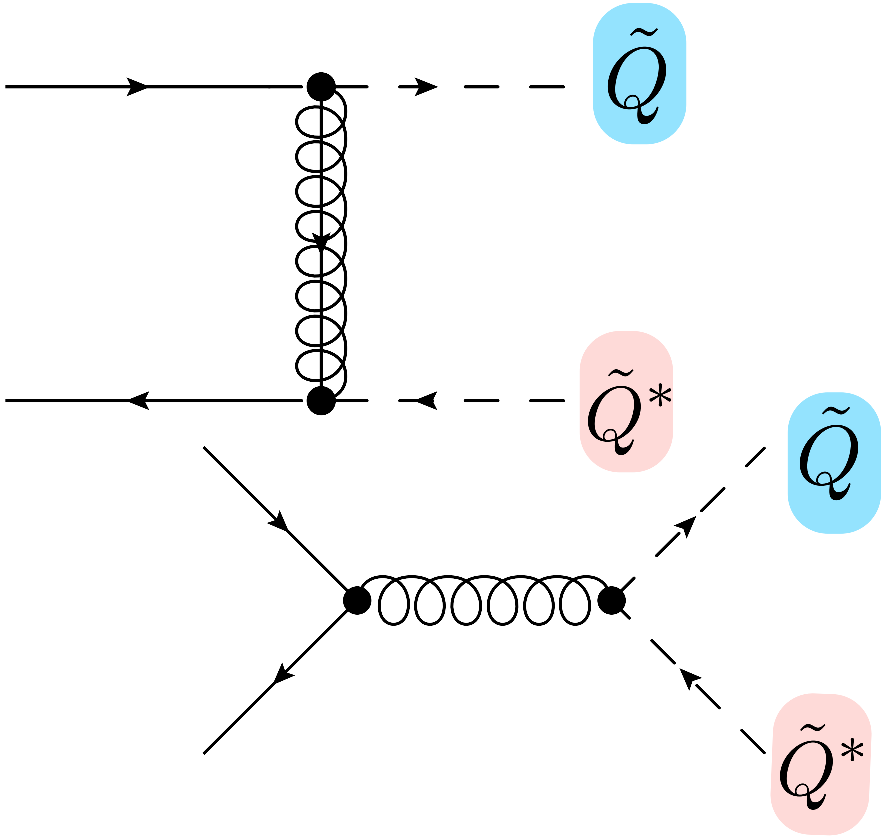
$R[\lambda] = 1$, $R[q] = R[\tilde{q}]-1$

preserved by Dirac masses, $R[\psi] = -1$

restricts processes



violate R-symmetry



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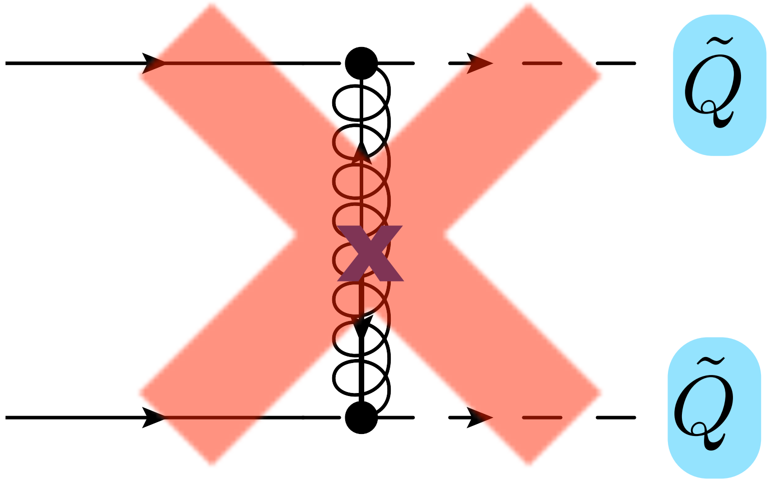

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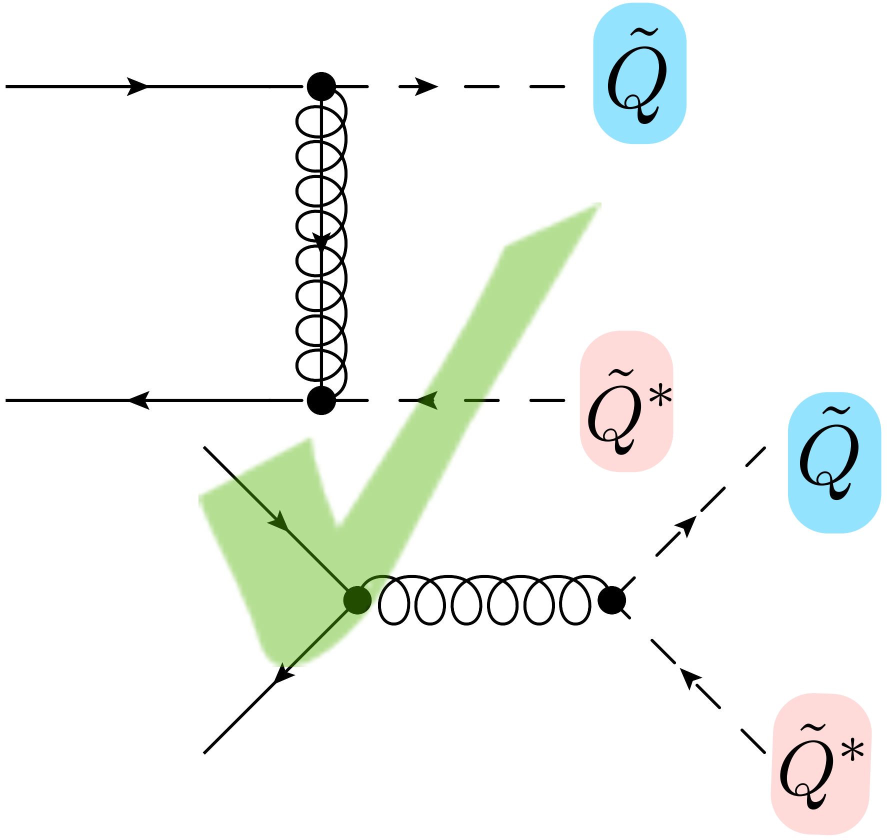

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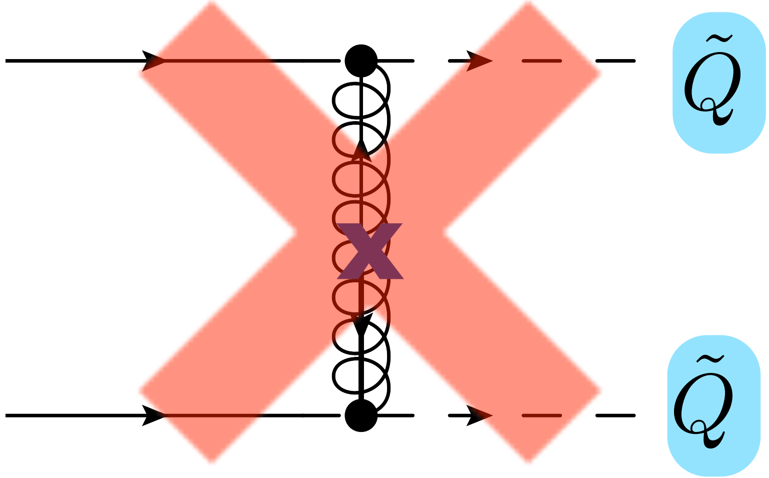
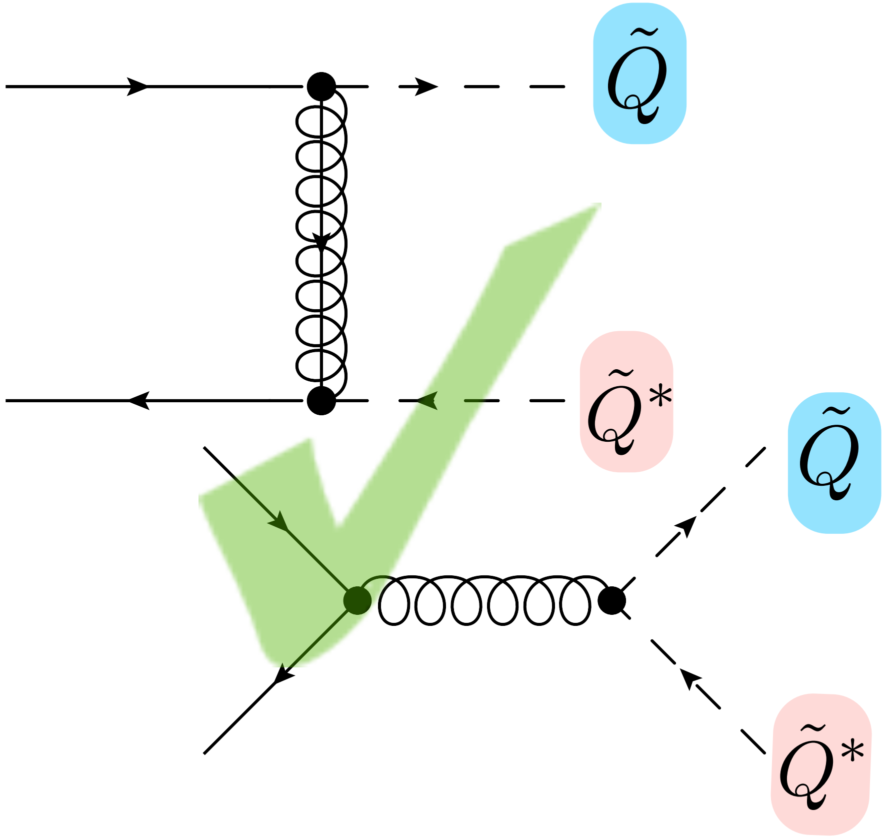


violate R-symmetry

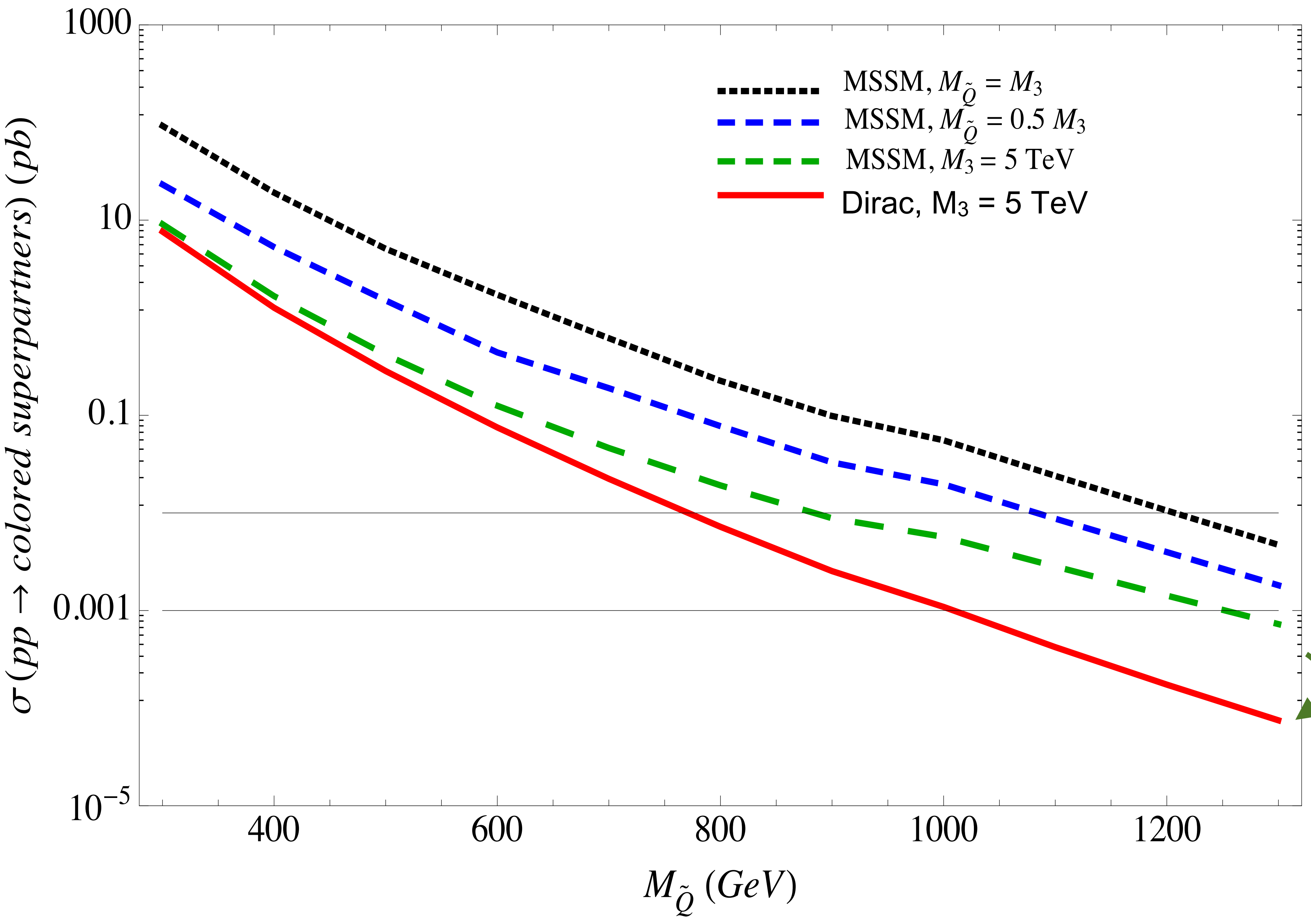
no $\tilde{q}\tilde{q}$, $\tilde{q}^*\tilde{q}^*$, only $\tilde{q}\tilde{q}^*$



preserve R-symmetry

colored sparticle cross section

[Kribs, AM ’12]

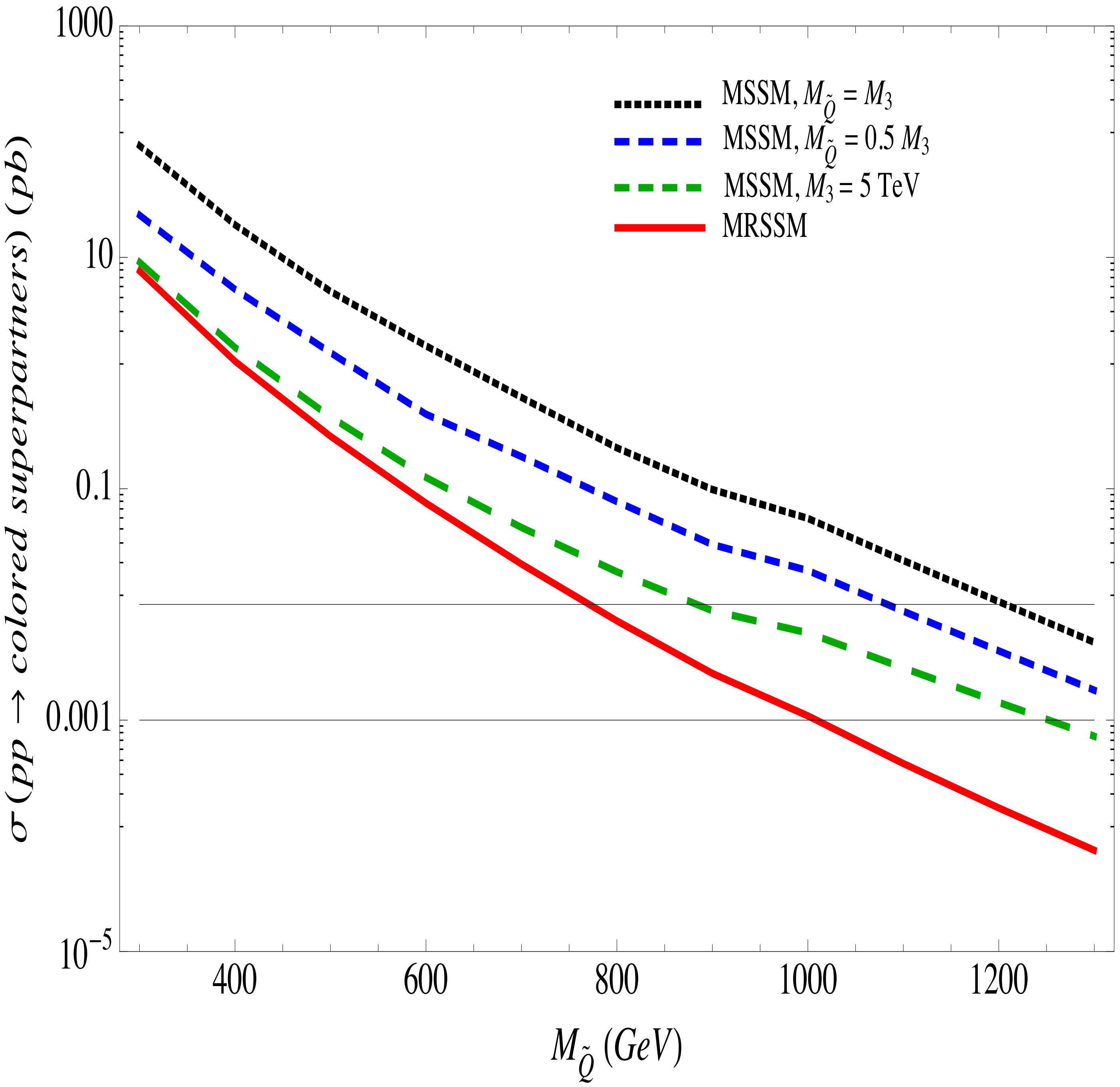


increasing M_3

fewer processes allowed

recall: PDFs make qq → $\tilde{q}\tilde{q}$ the dominant subprocess at large $m_{\tilde{q}}$

production of colored superstuff with Dirac gluino ≪ traditional MSSM



to get same σ_{SUSY}, squarks need to be much lighter

$\sigma_{\text{MSSM}}\ (m_{\tilde{q}} = 1.2\ \text{TeV}) =$
$\sigma_{\text{Dirac}}\ (m_{\tilde{q}} = 750\ \text{GeV})$

lighter squarks →
less energy
dumped in detector

cuts designed to capture ~ TeV squarks may miss/be inefficient for lighter q̃ !

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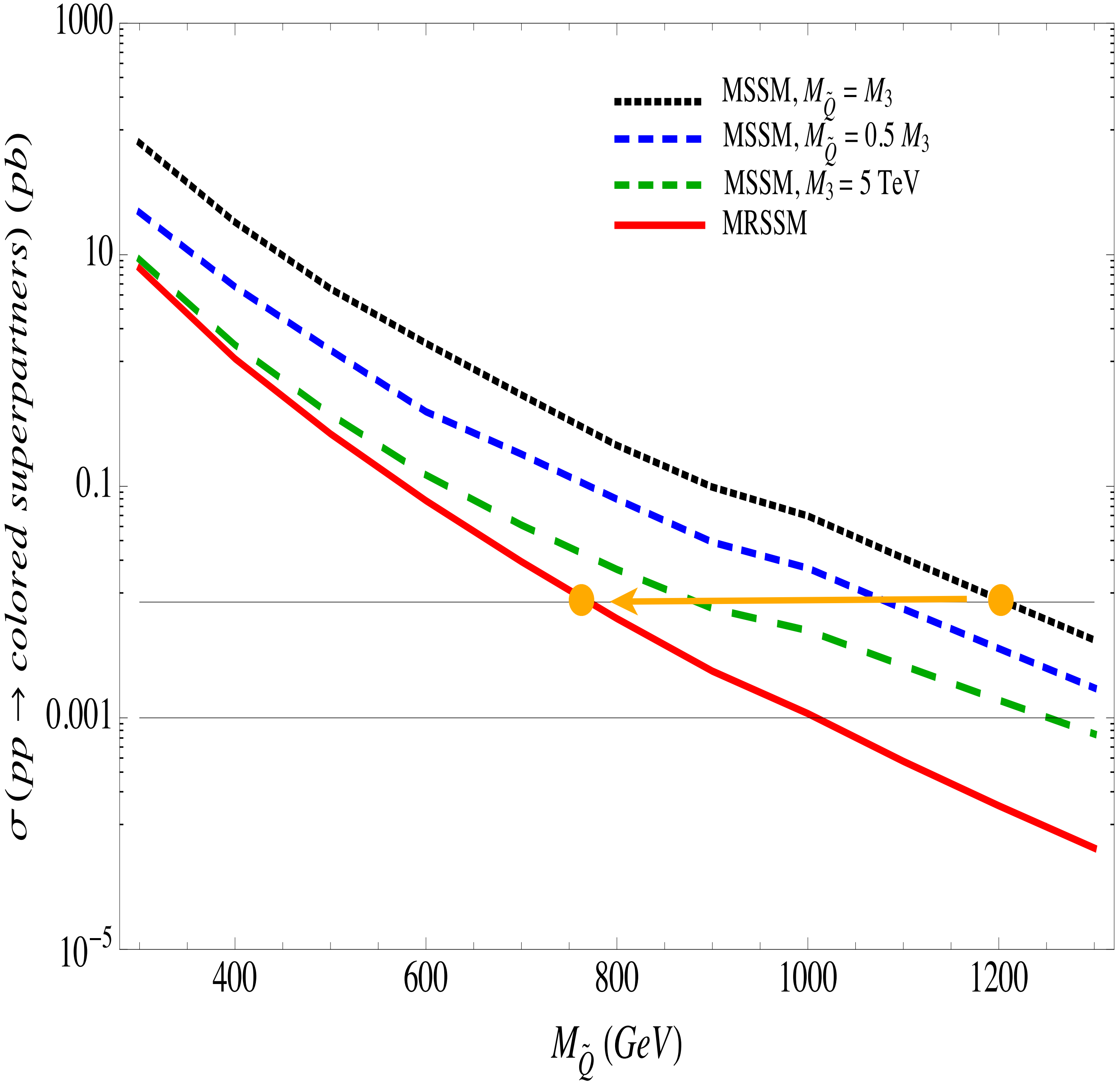

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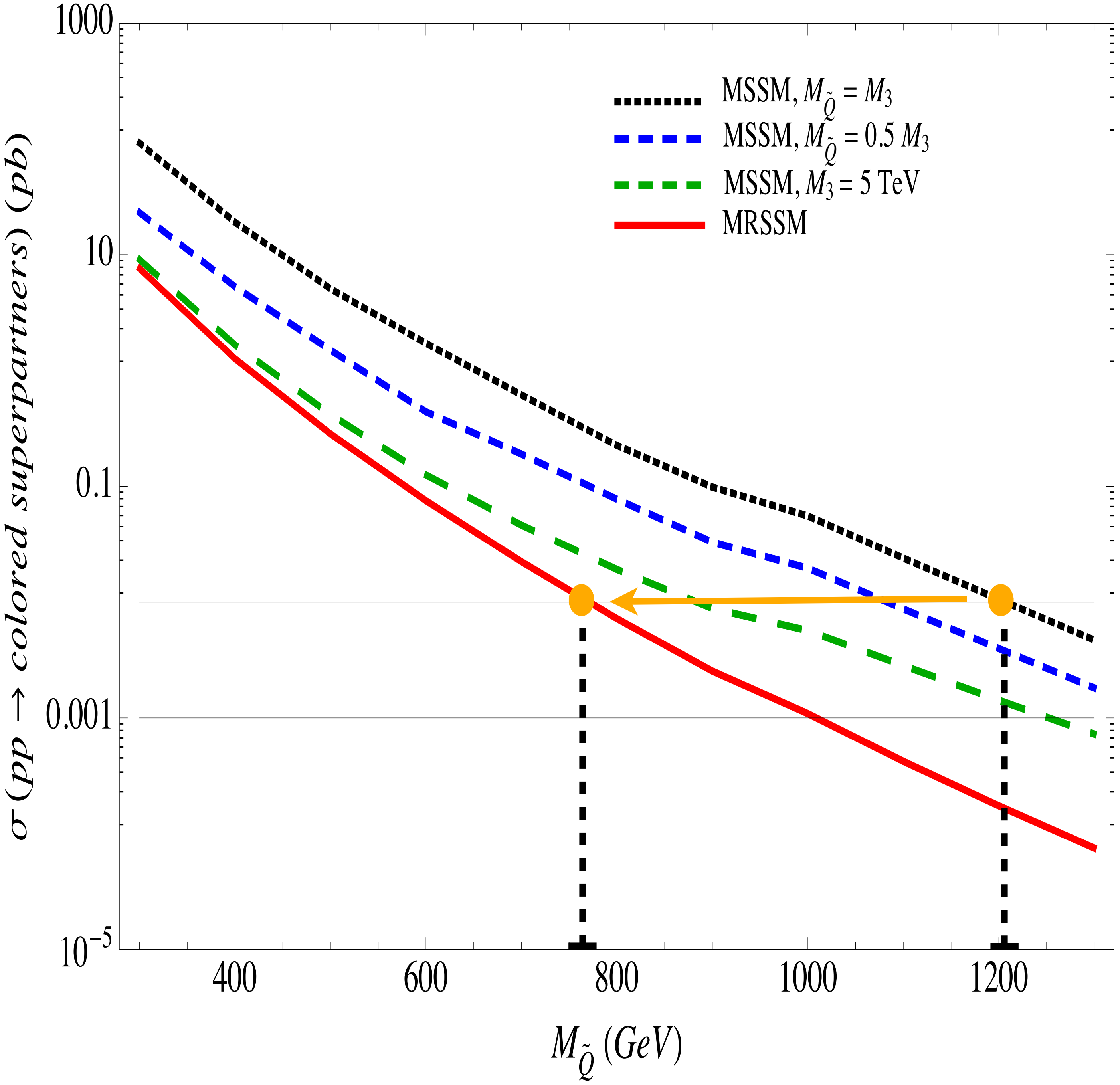

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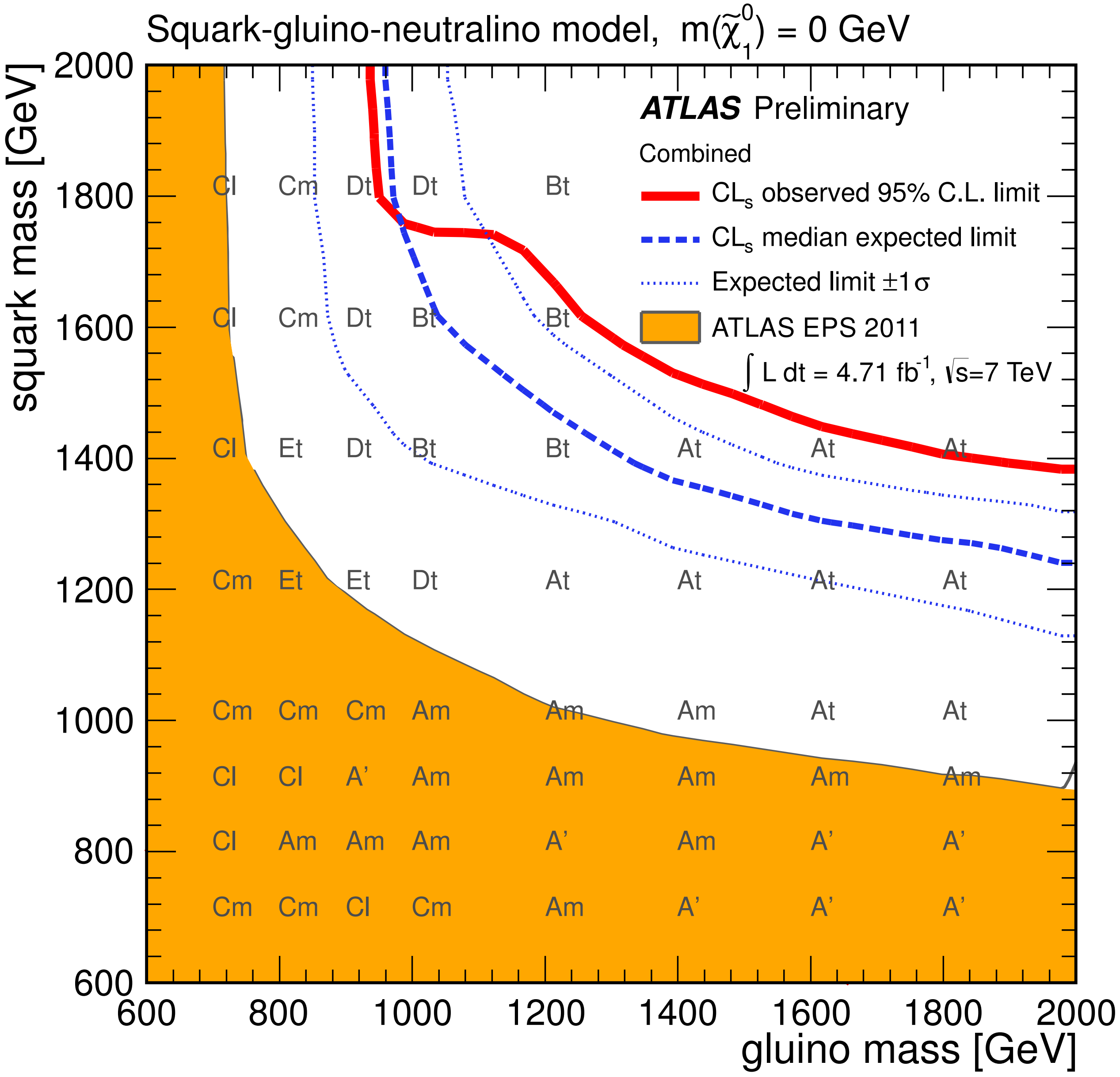
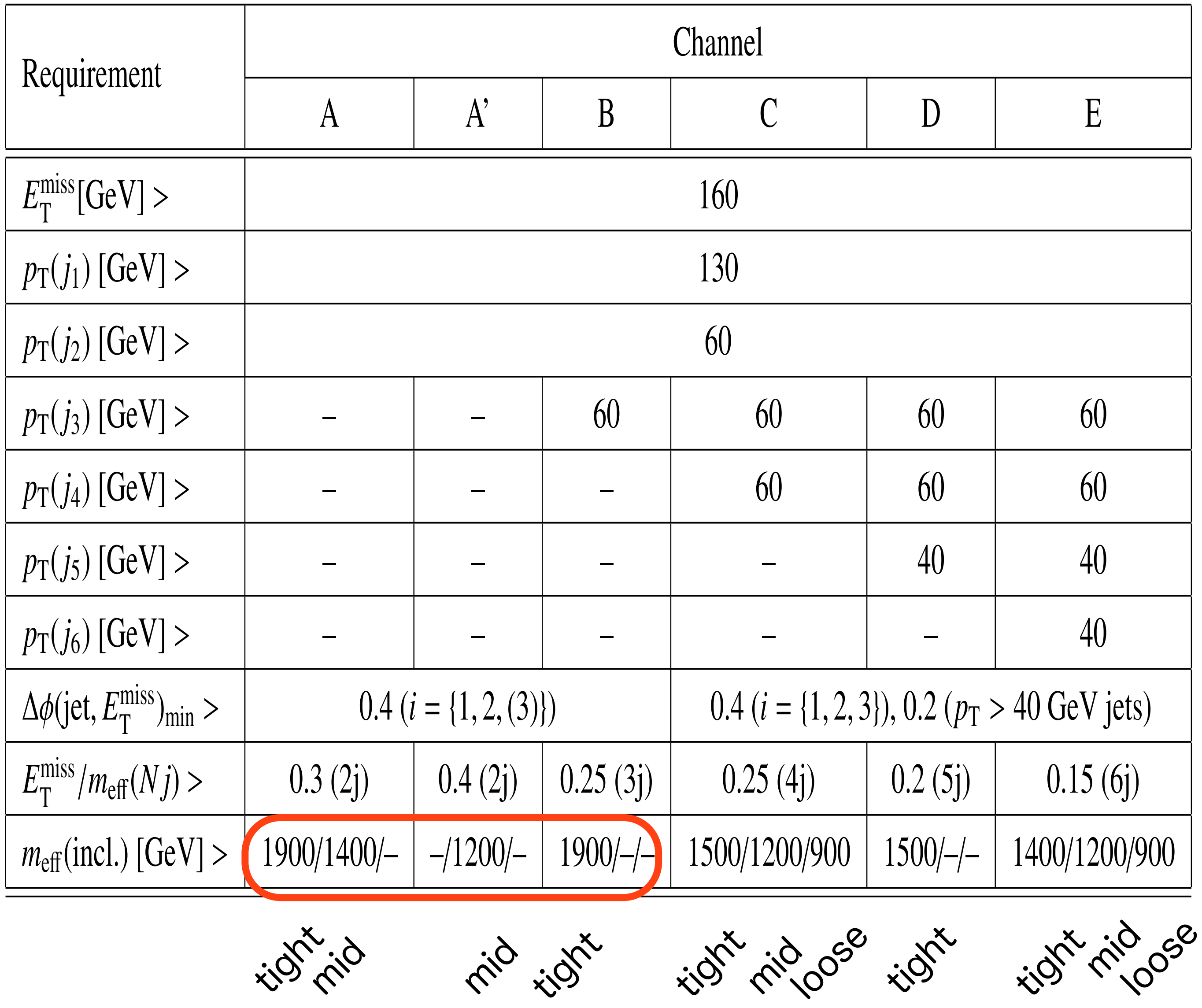
Dirac gluinos in action: old ATLAS jet + MET search

0 leptons; all jets pT > 40 GeV





Requirement	Channel					
	A	A'	B	C	D	E
$E_{\mathrm{T}}^{\mathrm{miss}}$[GeV] >	160					
$p_{\mathrm{T}}(j_1)$ [GeV] >	130					
$p_{\mathrm{T}}(j_2)$ [GeV] >	60					
$p_{\mathrm{T}}(j_3)$ [GeV] >	–	–	60	60	60	60
$p_{\mathrm{T}}(j_4)$ [GeV] >	–	–	–	60	60	60
$p_{\mathrm{T}}(j_5)$ [GeV] >	–	–	–	–	40	40
$p_{\mathrm{T}}(j_6)$ [GeV] >	–	–	–	–	–	40
$\Delta\phi(\mathrm{jet}, E_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}}$ >	0.4 ($i = \{1, 2, (3)\}$)			0.4 ($i = \{1, 2, 3\}$), 0.2 ($p_{\mathrm{T}} > 40$ GeV jets)		
$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}(Nj)$ >	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

ATLAS-CONF-2012-033

for $m_{\tilde{q}} \lesssim$ Mgluino, sensitivity from SR with high HT cuts

ATLAS Search Bounds

[Kribs, AM ’12]

Dirac
M3 = 5 TeV

MSSM
M3 = Msq

MSSM
M3 = 2 Msq

MSSM
M3 = 5 TeV

1st,2nd generation squark mass

all setups:

- degenerate 1st, 2nd gen squarks, massless LSP
- PYTHIA (+PROSPINO) → DELPHES
- limits derived using quoted BR, uncertainty

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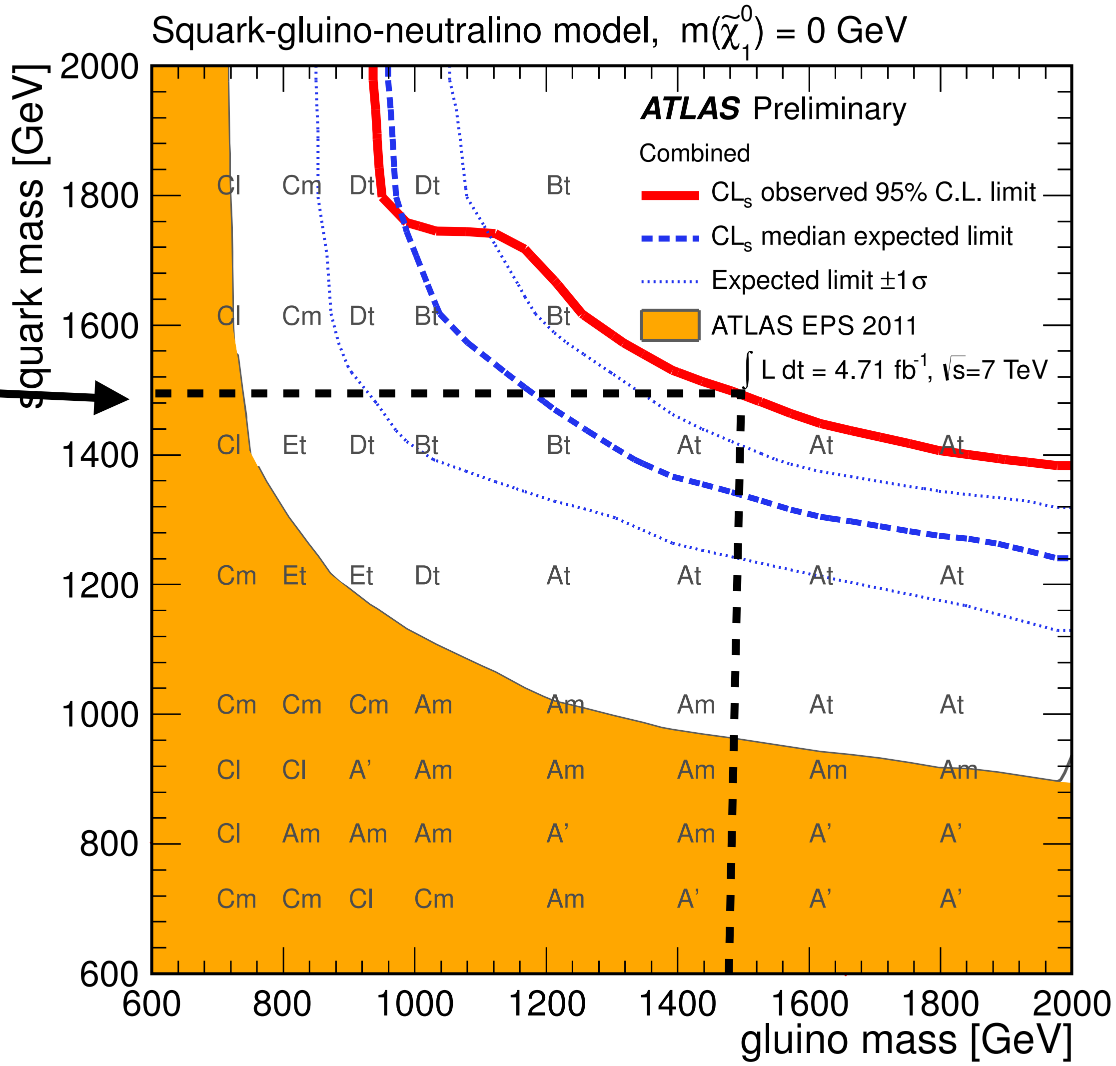

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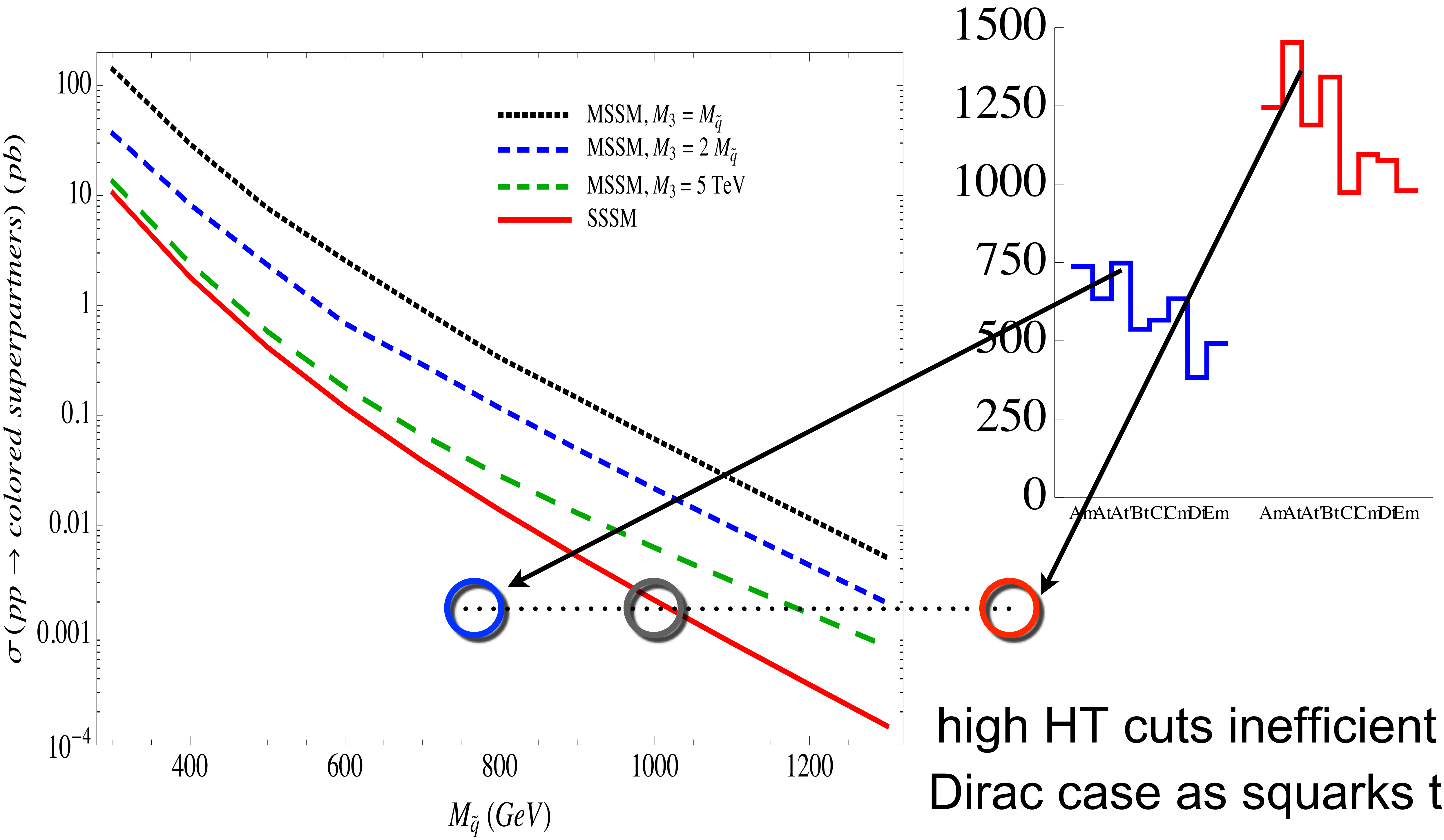
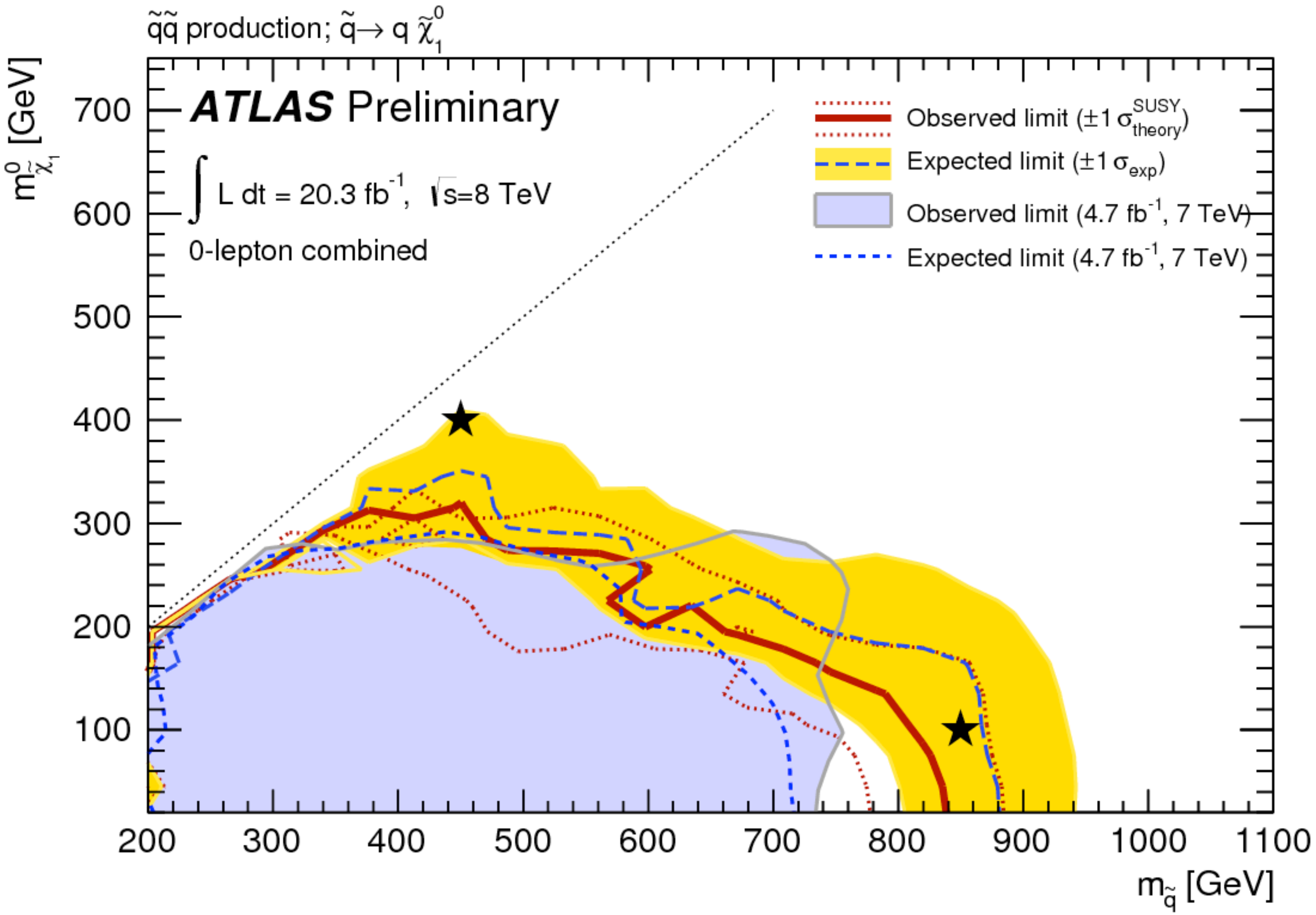


high HT cuts inefficient in Dirac case as squarks too light

∴ limit is even lower, larger σ compensates low efficiency

Searches with broader HT range are better

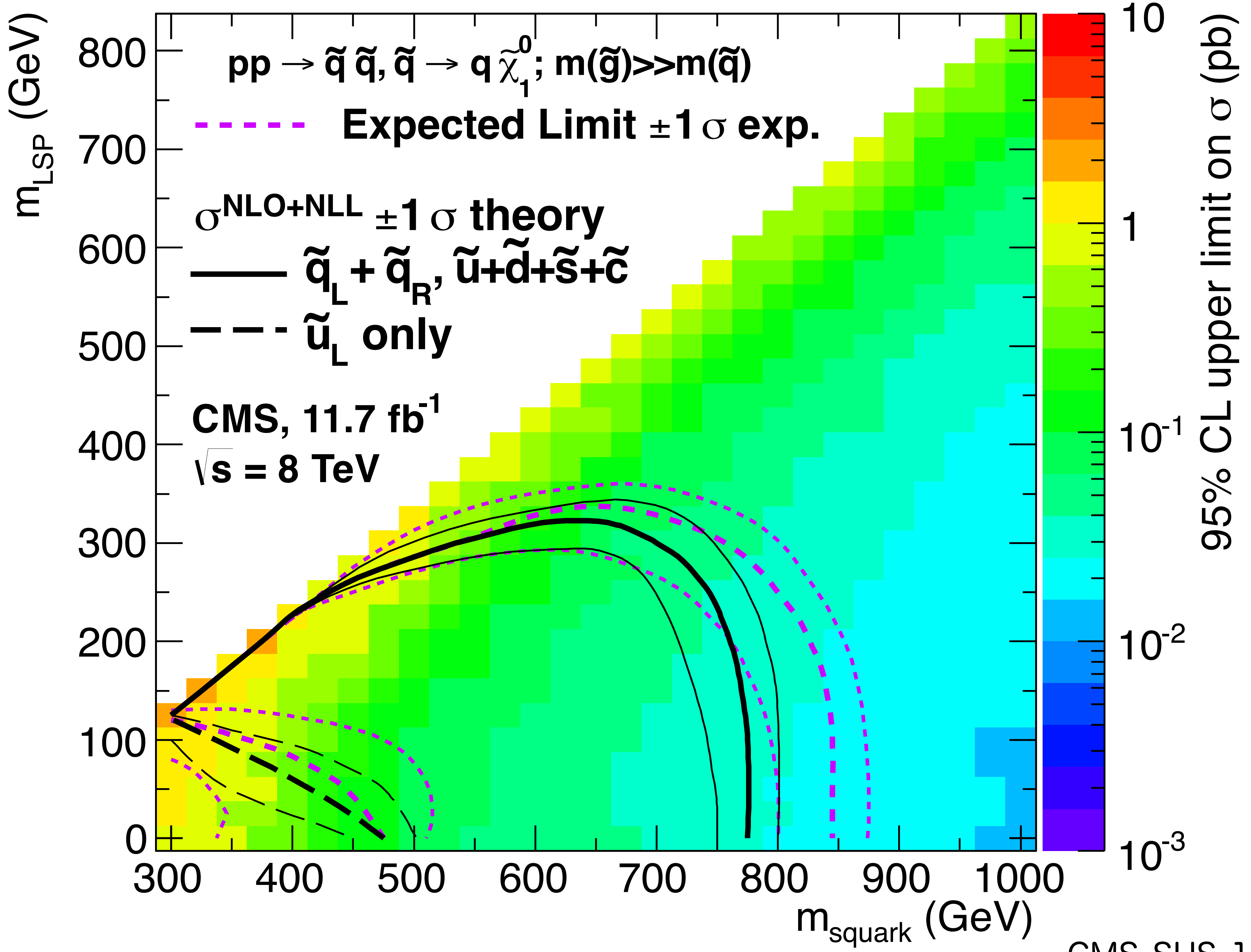
ATLAS 'decoupled gluino' search: 20 fb^{-1}, 8 TeV



ATLAS-CONF-2013-047

Searches with broader HT range are better

CMS α_T, T2 model: 12 fb^{-1}, 8 TeV



CMS-SUS-12-028

Comments

Dirac gluino setup naturally realizes ‘decoupled gluino’ simplified model

current limits: $m_{\tilde{q}} \gtrsim 850$ GeV for massless LSP,
~zero limit if $m_{LSP} > 300$ GeV

limits ~unchanged from 5 fb^{-1}, 7TeV

background (W/Z + jets) uncertainties dominated by systematics...

opportunity for new strategies?

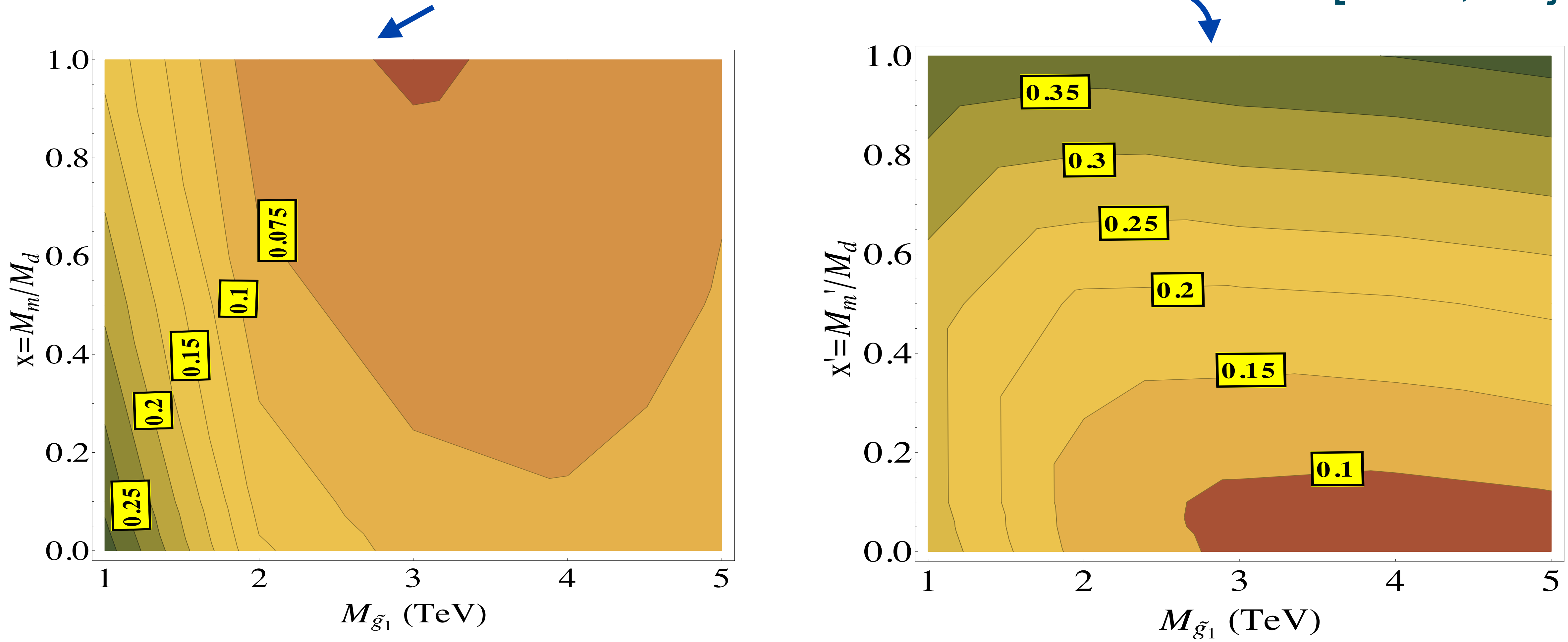
Comments

pseudo-Dirac gluino (both Dirac and Majorana mass): roughly same conclusions

effect on σ_{SUSY} depends on whether we add

$M_m\, \tilde{g}_A \tilde{g}_A$ or $M'_m\, \tilde{\lambda}_A \tilde{\lambda}_A$

[Kribs, Raj ’13]



σ(mixed)/σ(Majorana), 800 GeV squarks (1st, 2nd gen), 8 TeV

Dirac ino friends?

is there a ‘smoking - gun’ signal for the dirac setup?

YES: extra states, the scalars in $\Phi_a = A_a$

Re[A_a] are heavy, mass ~ $2M_D$, but Im[A_a] can be light (~$m_{\tilde{q}}$)

A_i are R-parity even → they can be singly produced, though only tree-level interactions involve gauge fields..

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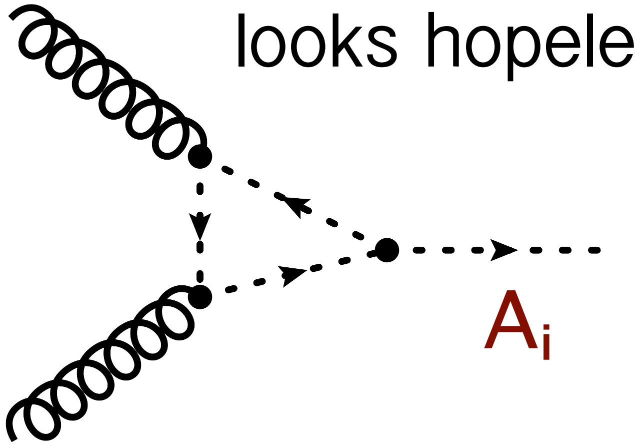

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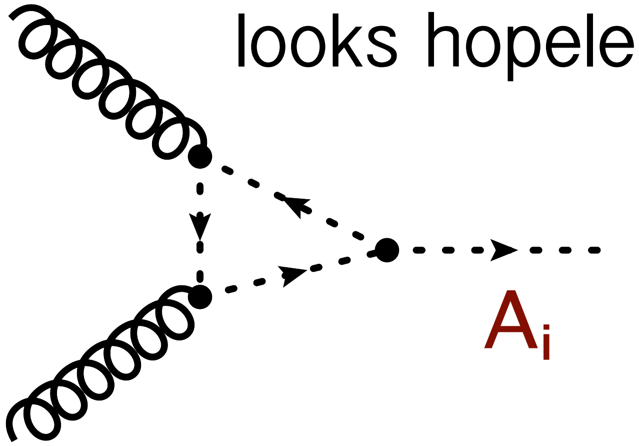
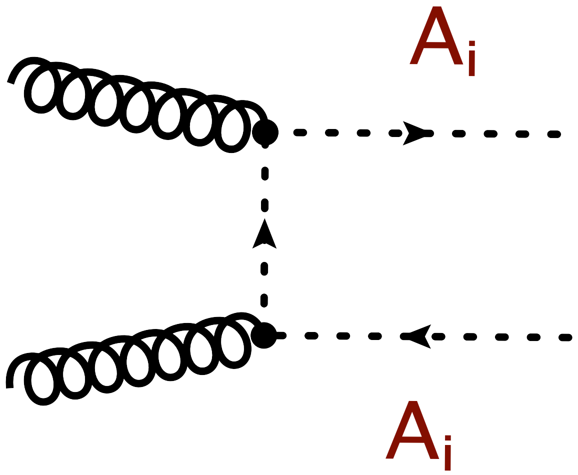


pair production better:



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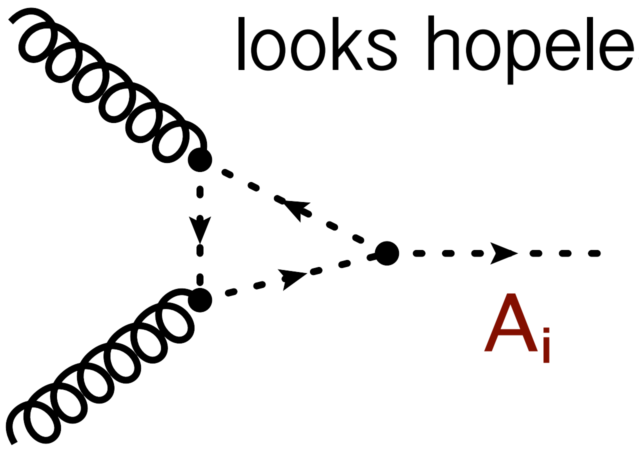
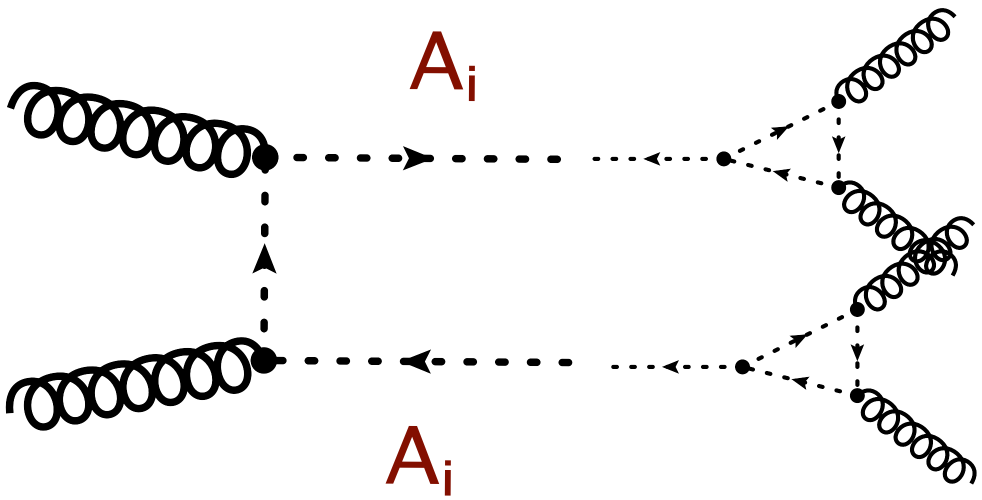


pair production better:



pp → equal mass di-jet resonances

Dirac ino friends?

is there a ‘smoking - gun’ signal for the dirac setup?

YES: extra states, the scalars in $\Phi_a = A_a$

$\mathrm{Re}[A_a]$ are heavy, mass ~ $2M_D$, but $\mathrm{Im}[A_a]$ can be light ($\sim m_{\tilde{q}}$)

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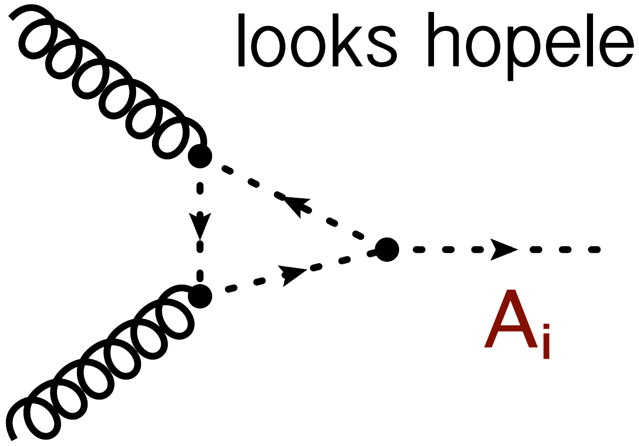

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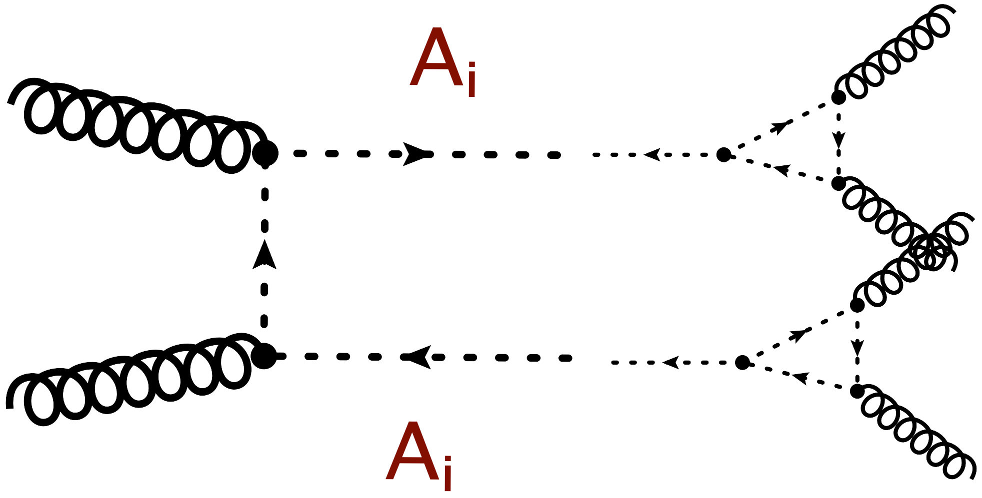

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see Plehn, Tait ’08, also CMS-EXO-11-016, ATLAS 1110.2693

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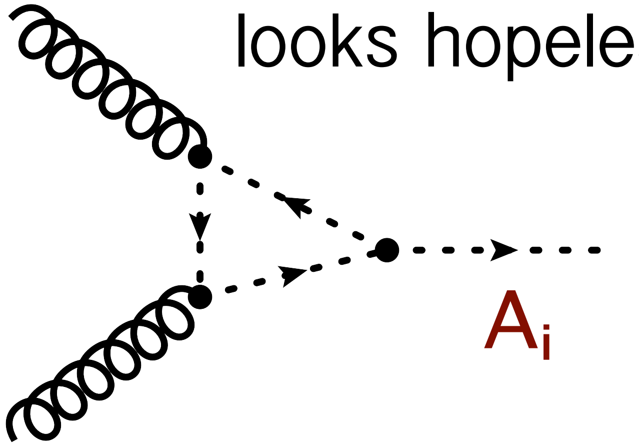

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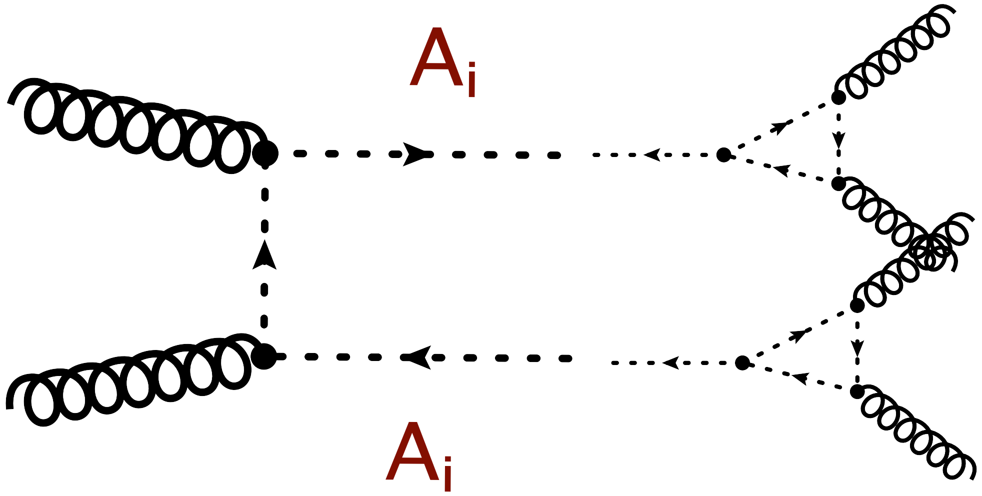

A_i ($SU(2)_w$ triplet scalars) unexplored

pp → equal mass di-jet resonances

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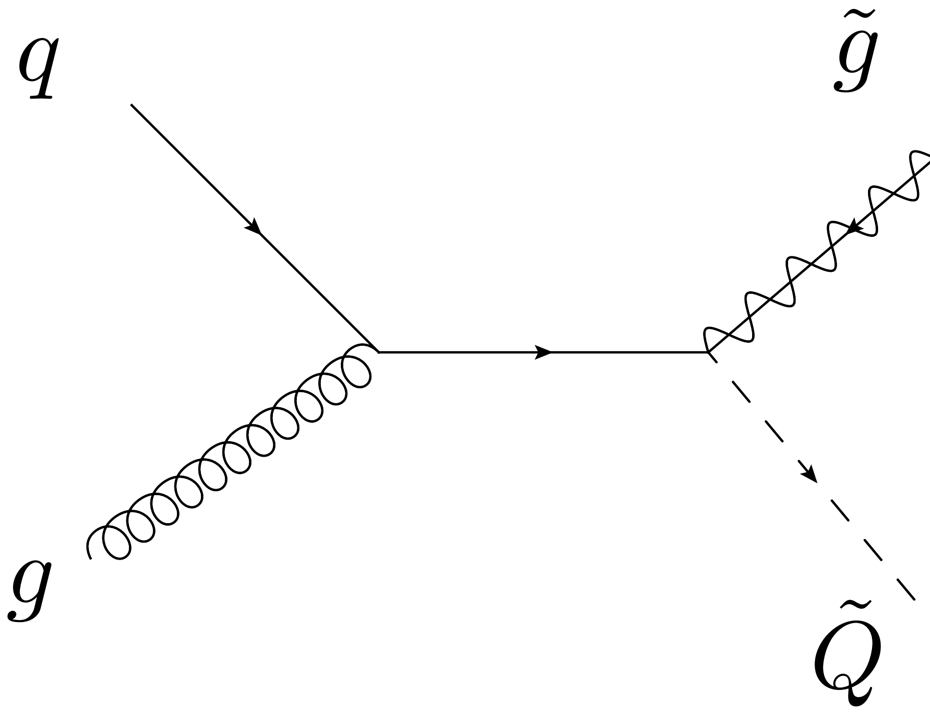
future signals

Dirac setup: looks like ‘decoupled gluino’ but gluino is there in spectrum at ~few TeV

so, if signal seen in ‘decoupled gluino’...

Dirac gluinos are a target for future high-energy/ high-luminosity machines



for 5 TeV gluino, 1 TeV squark:

$$\sigma(\tilde{q}+\tilde{g}) \sim 0.015\ \text{fb} \qquad \sqrt{s} = 14\ \text{TeV}$$
$$\sigma(\tilde{q}+\tilde{g}) \sim 12\ \text{fb} \qquad \sqrt{s} = 33\ \text{TeV}$$

Conclusions

- Dirac gauginos (supersoft SUSY): naturally very heavy, $U(1)_R$ preserved

- significantly reduced colored sparticle production

  limits: ~ **800−850 GeV**, systematics dominated

  degenerate 1st, 2nd gen. squarks, massless LSP

  \- analysis optimized for high H_T do poorly

- pseudo-Dirac gluinos, treatment of EW sector doesn't change result

- additional distinct signals (scalar adjoints, squark + Dirac gluino) at LHC14 & beyond

many interesting directions to go in from here!