Supersoft Supersymmetry at the LHC

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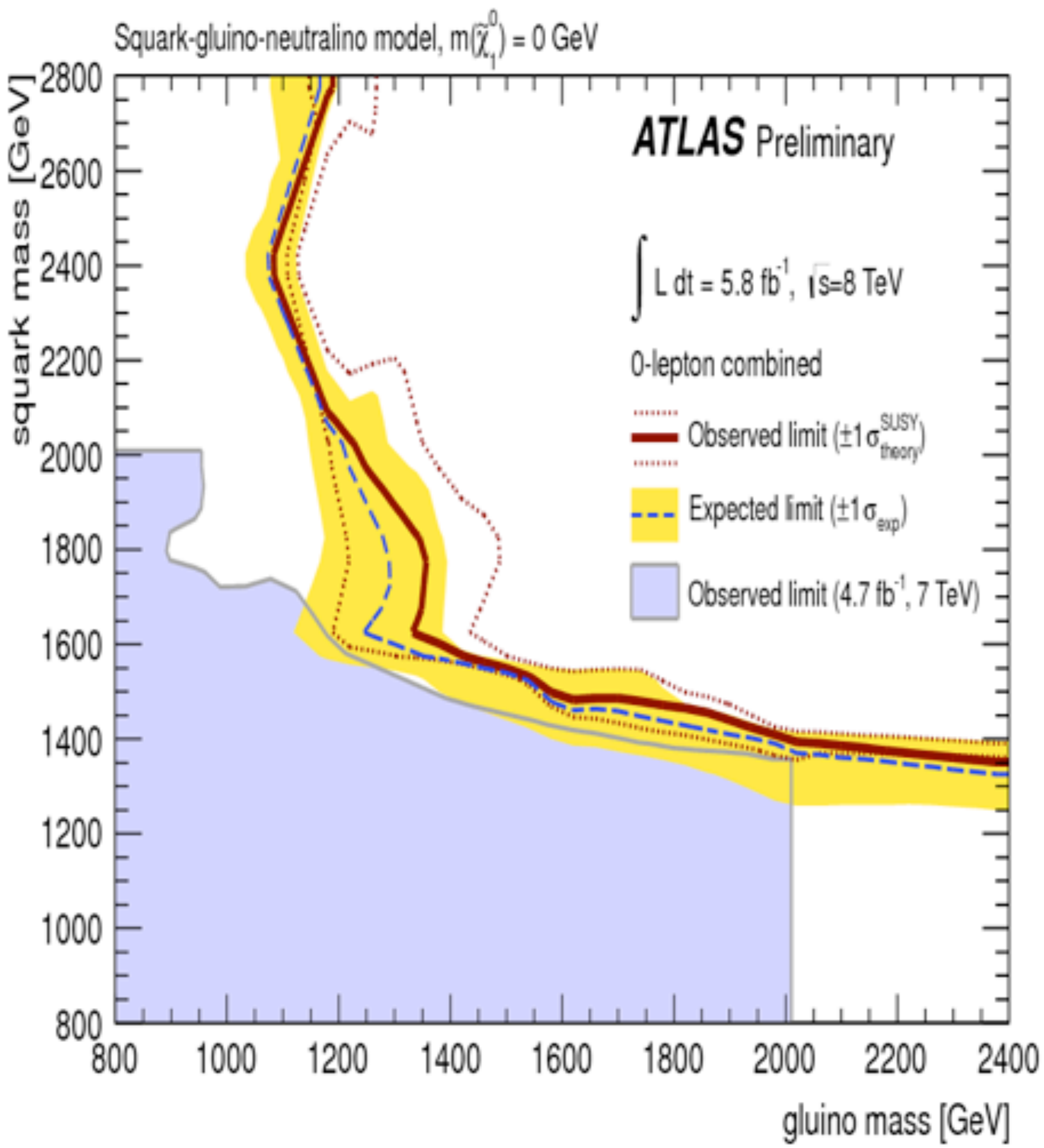
Outline

1. Brief Intro
2. Dirac Gauginos and "Supersoft Supersymmetry"
3. Colored Superpartner Production @ LHC
4. Jets + missing searches for supersymmetry @ LHC
   ex.) ATLAS; CMS α_T;
5. Further extensions, directions
6. Conclusions

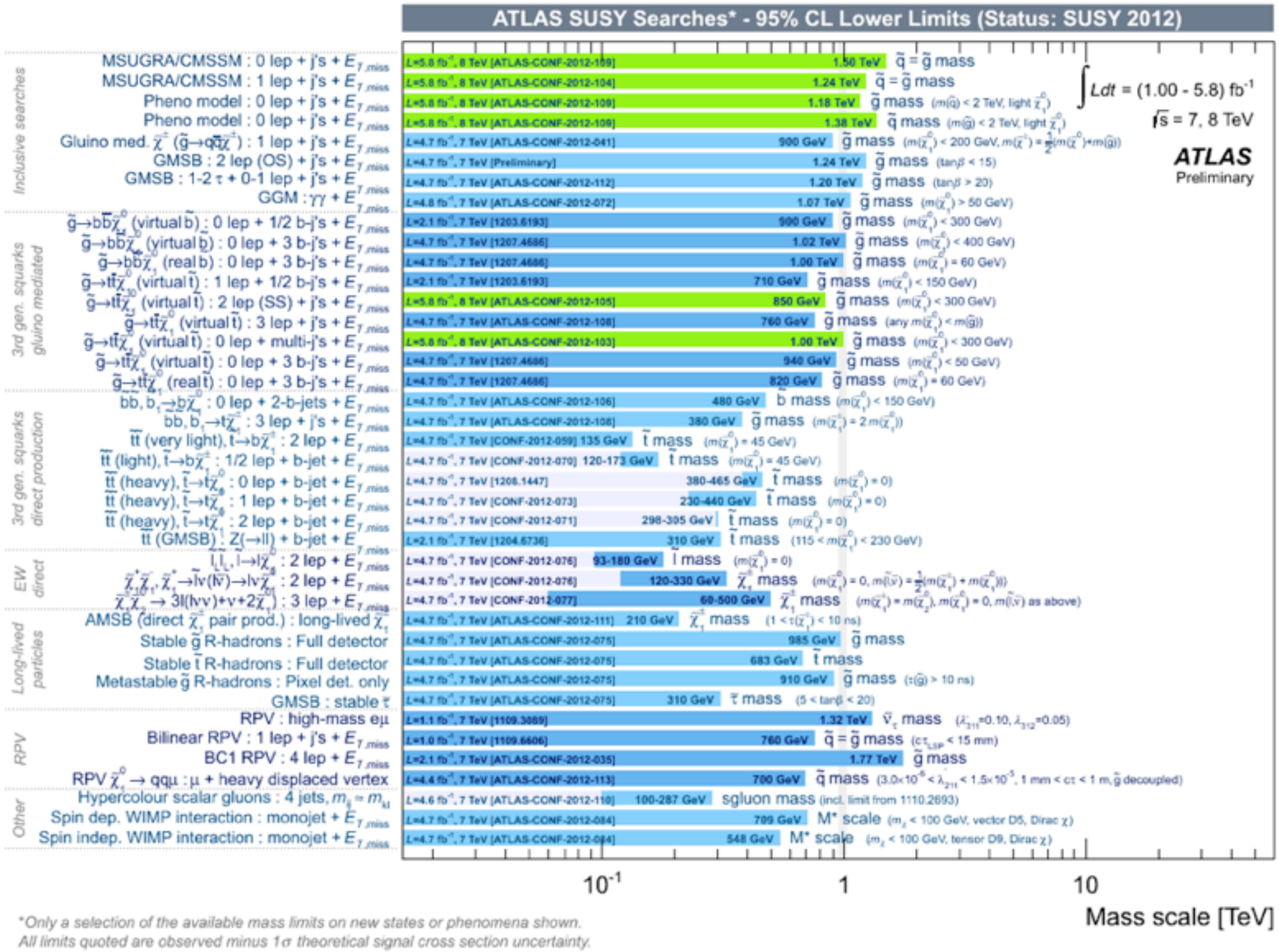
Where's SUSY?



ATLAS
jets + MET
August 2012

in simplified, yet generic cases, limits on MSSM colored sparticles are pushed to ~**1.5 TeV**...

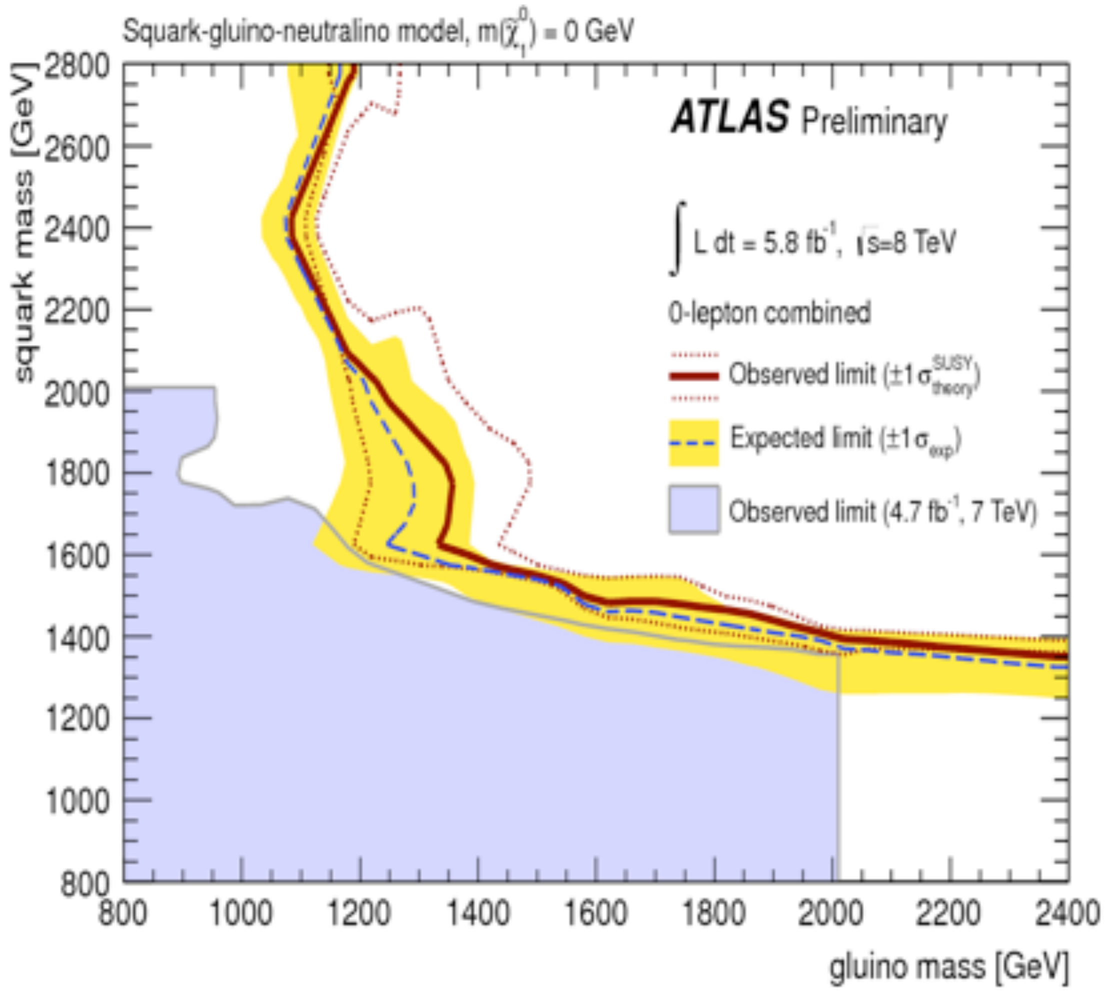
limits are driven by jet + ME T channels, though many other searches


ATLAS SUSY Searches* - 95% CL Lower Limits (Status: SUSY 2012)
ATLAS
Preliminary
∫Ldt = (1.00 - 5.8) fb⁻¹
√s = 7, 8 TeV
Inclusive searches
MSUGRA/CMSSM : 0 lep + j's + E_T,miss
MSUGRA/CMSSM : 1 lep + j's + E_T,miss
Pheno model : 0 lep + j's + E_T,miss
Pheno model : 0 lep + j's + E_T,miss
GMSB : 2 lep (OS) + j's + E_T,miss
GMSB : 1-2 τ + 0-1 lep + j's + E_T,miss
GGM : γγ + E_T,miss
3rd gen. squarks gluino mediated
3rd gen. squarks direct production
EW direct
AMSB (direct χ̃₁± pair prod.) : long-lived χ̃₁±
Stable g̃ R-hadrons : Full detector
Stable t̃ R-hadrons : Full detector
Metastable g̃ R-hadrons : Pixel det. only
GMSB : stable τ̃
Long-lived particles
RPV : high-mass eμ
Bilinear RPV : 1 lep + j's + E_T,miss
BC1 RPV : 4 lep + E_T,miss
RPV
Hypercolour scalar gluons : 4 jets
Spin dep. WIMP interaction : monojet + E_T,miss
Spin indep. WIMP interaction : monojet + E_T,miss
Other
1.50 TeV q̃ = g̃ mass
1.24 TeV q̃ = g̃ mass
1.18 TeV g̃ mass
1.38 TeV q̃ mass
900 GeV g̃ mass
1.24 TeV g̃ mass
1.20 TeV g̃ mass
1.07 TeV g̃ mass
900 GeV g̃ mass
1.02 TeV g̃ mass
1.00 TeV g̃ mass
710 GeV g̃ mass
850 GeV g̃ mass
760 GeV g̃ mass
1.00 TeV g̃ mass
940 GeV g̃ mass
820 GeV g̃ mass
480 GeV b̃ mass
380 GeV g̃ mass
135 GeV t̃ mass
120-173 GeV t̃ mass
380-465 GeV t̃ mass
230-440 GeV t̃ mass
298-305 GeV t̃ mass
310 GeV t̃ mass
93-180 GeV l̃ mass
120-330 GeV χ̃₁± mass
60-500 GeV χ̃₁± mass
210 GeV χ̃₁± mass
985 GeV g̃ mass
683 GeV t̃ mass
910 GeV g̃ mass
310 GeV τ̃ mass
1.32 TeV ν̃_τ mass
760 GeV q̃ = g̃ mass
1.77 TeV g̃ mass
700 GeV q̃ mass
100-287 GeV sgluon mass
709 GeV M* scale
548 GeV M* scale
10⁻¹
1
10
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

"Data are coming! Data are coming!"

[from J. Lykken]

Escape routes?



- make it unnatural:

  heavy squarks (especially 1st, 2nd generation), though 3rd gen. limits are catching up

- deplete MET:

  R-parity violation

- deplete visible energy:

  compressed spectra, long/complicated cascades

- **go Dirac/supersoft**

A little reminder

- ~~SUSY~~ in hidden sector, communicated to MSSM via messengers at scale M_{mess}
- ~~SUSY~~ parameterized by soft-masses

describe soft masses with higher-dim. operators involving **spurions** ($X = \theta^2 F$, etc.), & suppressed by messenger scale

$$\mathcal{L} \supset \int d^4\theta \kappa \frac{QQ^\dagger X_i X_i^\dagger}{M_{mess}^2} \cdots , \quad \int d^2\theta \; \omega_Y \frac{X}{M_{mess}} \mathcal{W}_Y \mathcal{W}_Y \; \cdots$$ etc.

$$\kappa \frac{|F|^2}{M_{mess}^2} \tilde{Q}\tilde{Q}^* \to m_Q^2 \tilde{Q}\tilde{Q}^*$$

$$\omega_Y \frac{F}{M_{mess}} \lambda_Y \lambda_Y \to m_{1/2} \lambda_Y \lambda_Y$$

- RG run operators from M_{mess} to EW scale

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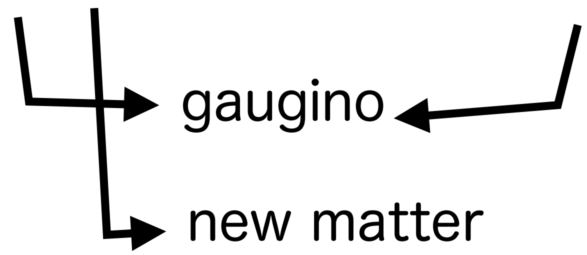
Majorana gaugino masses

- RG run operators from M_{mess} to EW scale

What about Dirac masses?

$M_3\, \lambda\Psi$ vs. $M_3\, \lambda\lambda$



simple change has big implications

requires communicating SUSY breaking to gauginos through **D-term** spurions:

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

$$\mathcal{W}'_\alpha = \theta_\alpha D$$

Dirac gaugino masses arise from:

$$\int d^2\theta \sqrt{2}\, \frac{\mathcal{W}'_\alpha \mathcal{W}^\alpha_a \Phi^a}{M_{mess}} \quad \text{+h.c.} \;\longrightarrow\; \frac{D}{M_{mess}} \lambda_a \psi^a + \cdots \;\longrightarrow\; M_D\, \lambda_a \psi^a + \cdots$$

Extra matter

we have to give up minimality to get Dirac masses
.. added new adjoint superfields Φ_a for each gauge group

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

new adjoint scalars

D-term for SM gauge groups

eliminating D_a ...

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

new trilinear interactions

could also add

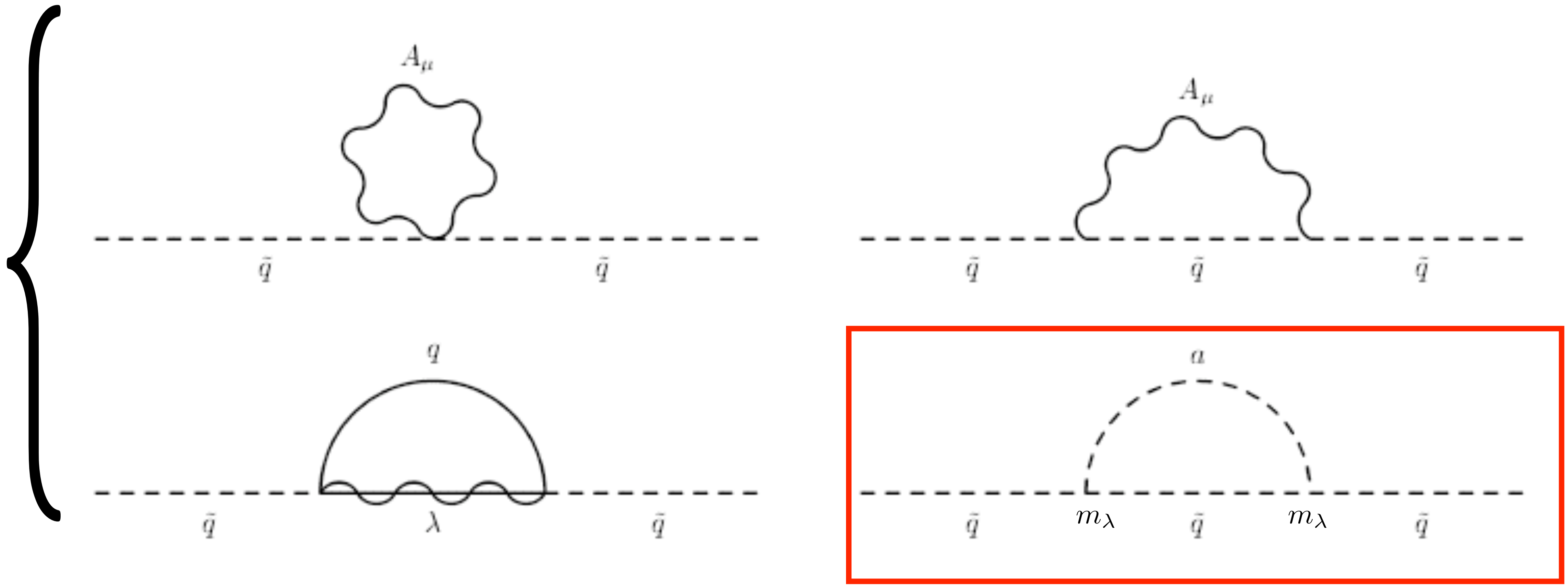
$$\int d^2\theta \frac{\mathcal{W}'_\alpha \mathcal{W}'_\alpha \Phi^a \Phi^a}{M_{mess}^2} + \text{h.c.}$$

opposite sign mass terms for Re[A_a], Im[A_a]

Supersoft SUSY

squark/slepton masses generated at loop level

$\delta\tilde{m}_Q^2$



from new trilinear interactions

$$\tilde{m}_Q^2 = 4\, g_i^2\, C_i(\phi) \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2} - \frac{1}{k^2 - M_D^2} + \frac{M_D^2}{k^2(k^2 - m_{adj}^2)} \propto M_D^2 \log\left(\frac{m_{adj}^2}{M_D^2}\right)$$

masses are independent of M_{mess}!

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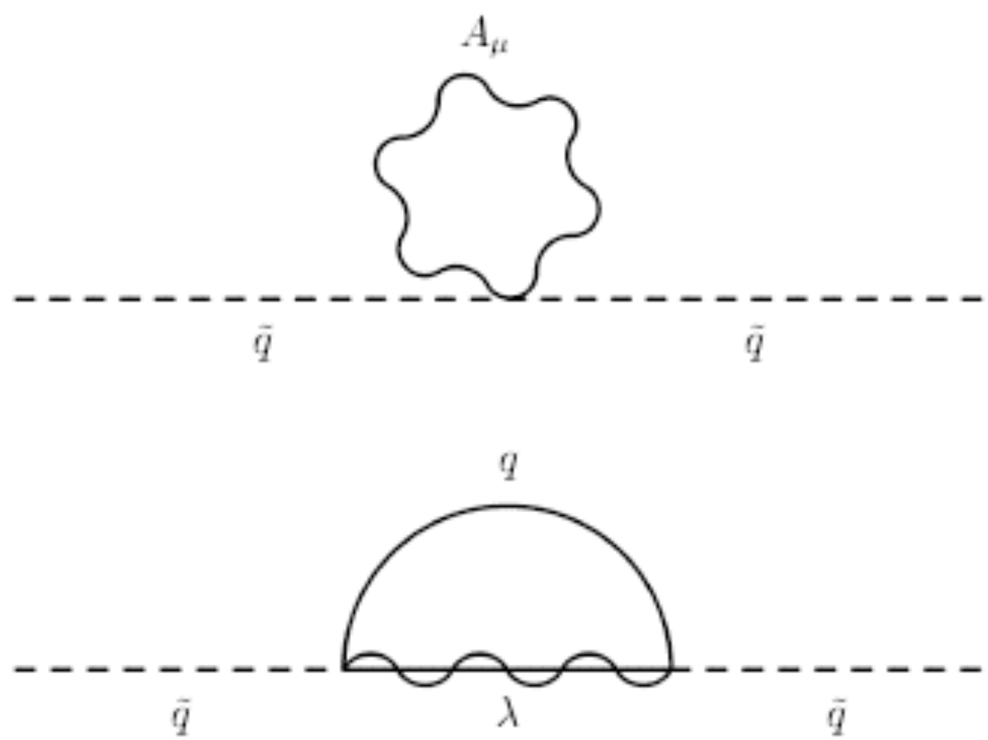

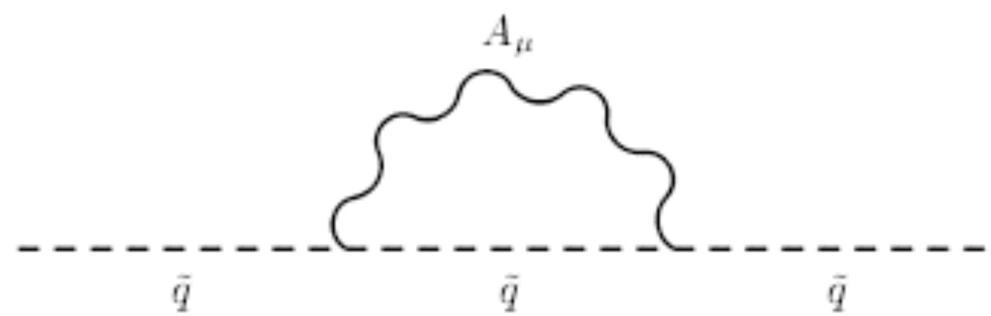

vs. in usual MSSM case

$$\tilde{m}_Q^2 = 4\,g_i^2\,C_i(\phi)\int\frac{d^4k}{(2\pi)^4}\frac{1}{k^2}-\frac{1}{k^2-M_D^2}\qquad\propto\; M_D^2\log\left(\frac{\Lambda^2}{M_D^2}\right)$$

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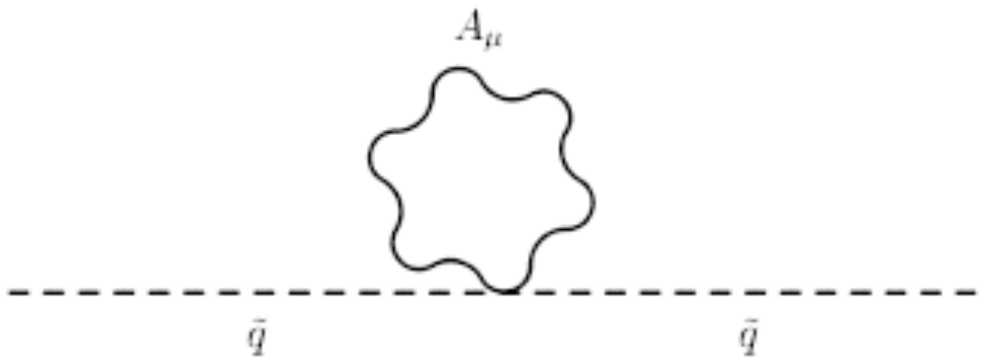

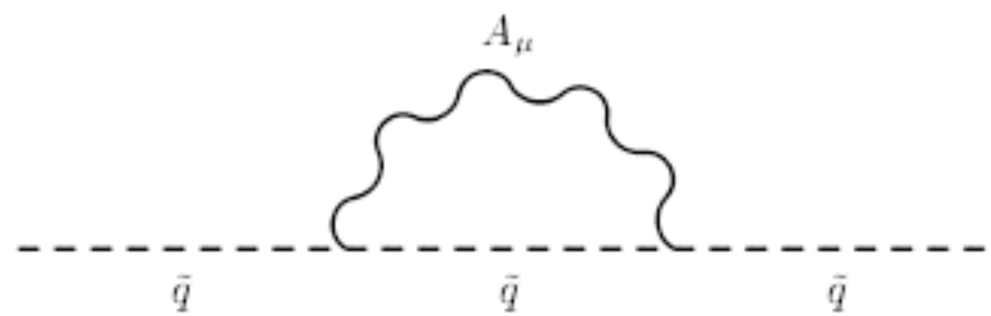

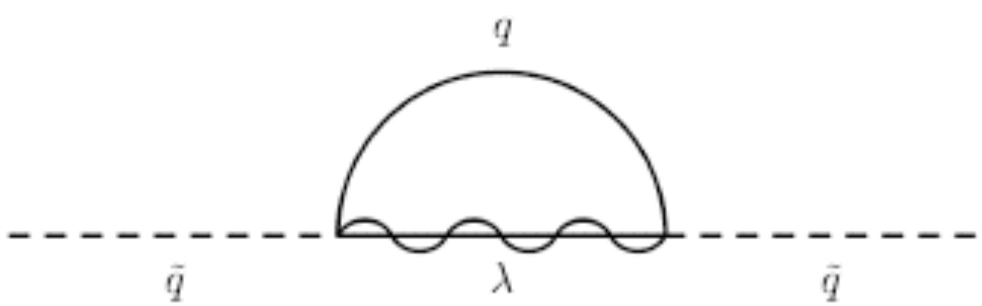

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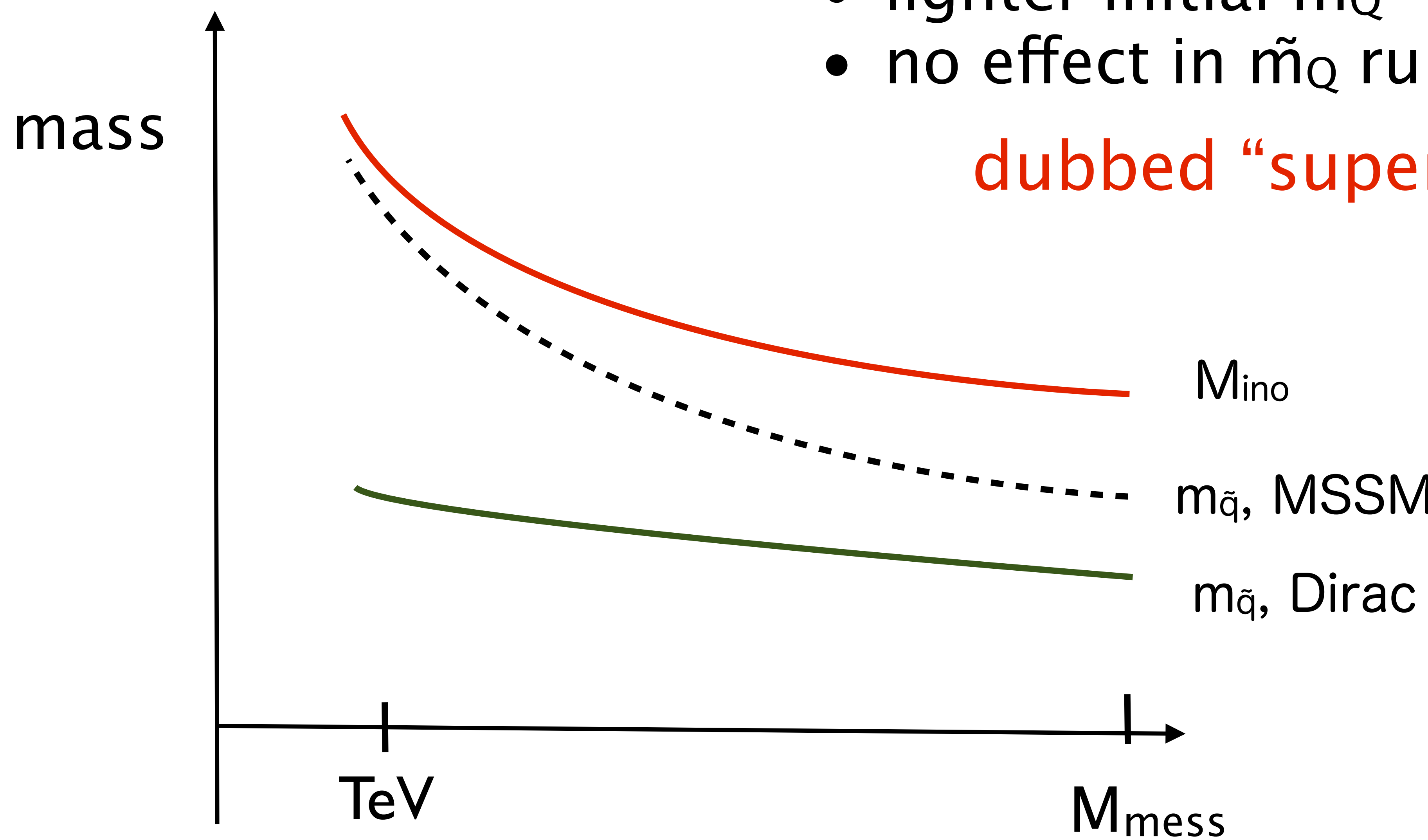
Supersoft SUSY

Dirac gauginos:

- lighter initial $\tilde{m}_Q$
- no effect in $\tilde{m}_Q$ running

dubbed "supersoft"



$$16\pi^2 \frac{d}{dt} m_{Q_3}^2 = X_t + X_b - \frac{32}{3} g_3^2 |M_3|^2 - 6 g_2^2 |M_2|^2 - \frac{2}{15} g_1^2 |M_1|^2 + \frac{1}{5} g_1^2 S,$$

$$16\pi^2 \frac{d}{dt} m_{\bar{u}_3}^2 = 2X_t - \frac{32}{3} g_3^2 |M_3|^2 - \frac{32}{15} g_1^2 |M_1|^2 - \frac{4}{5} g_1^2 S,$$

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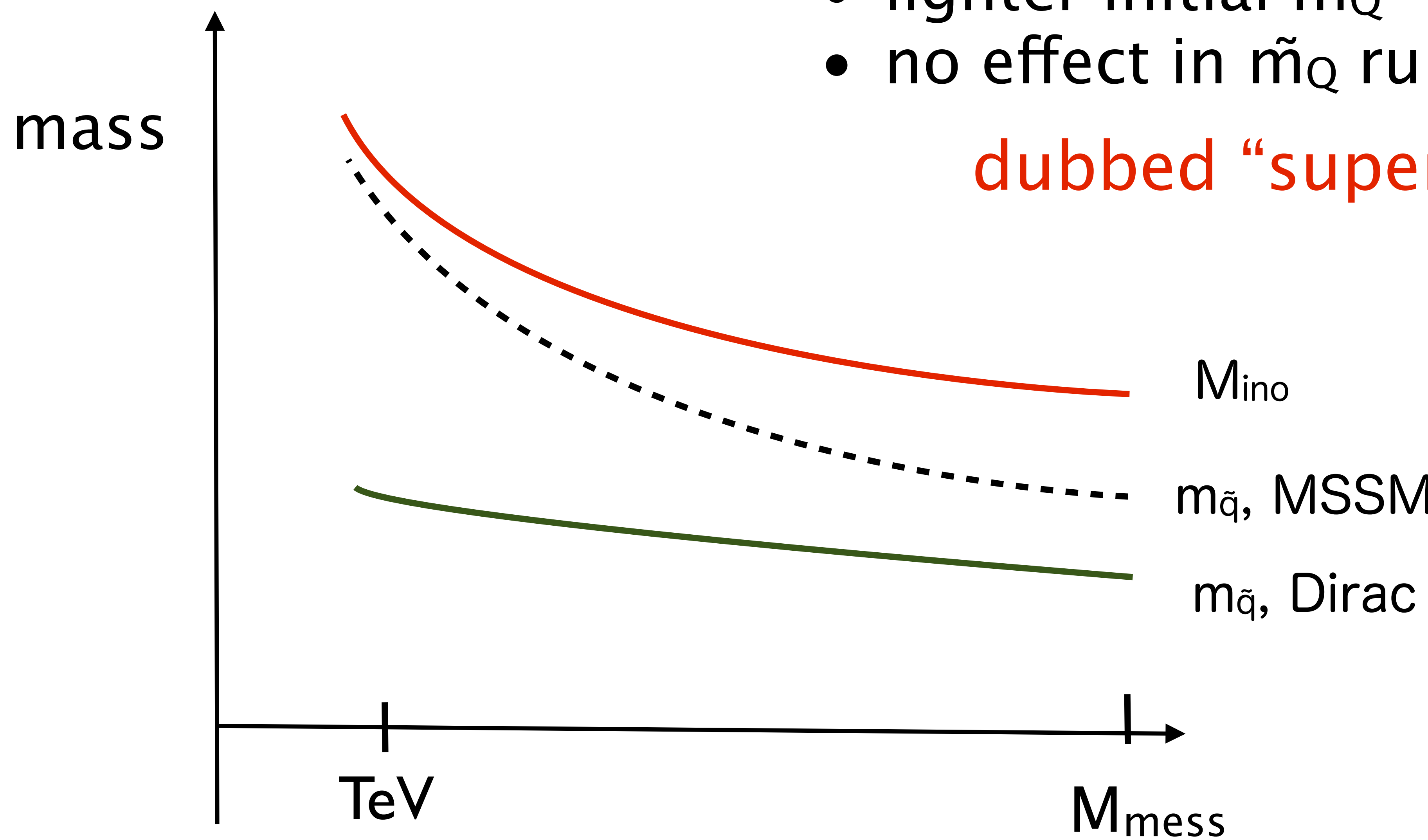

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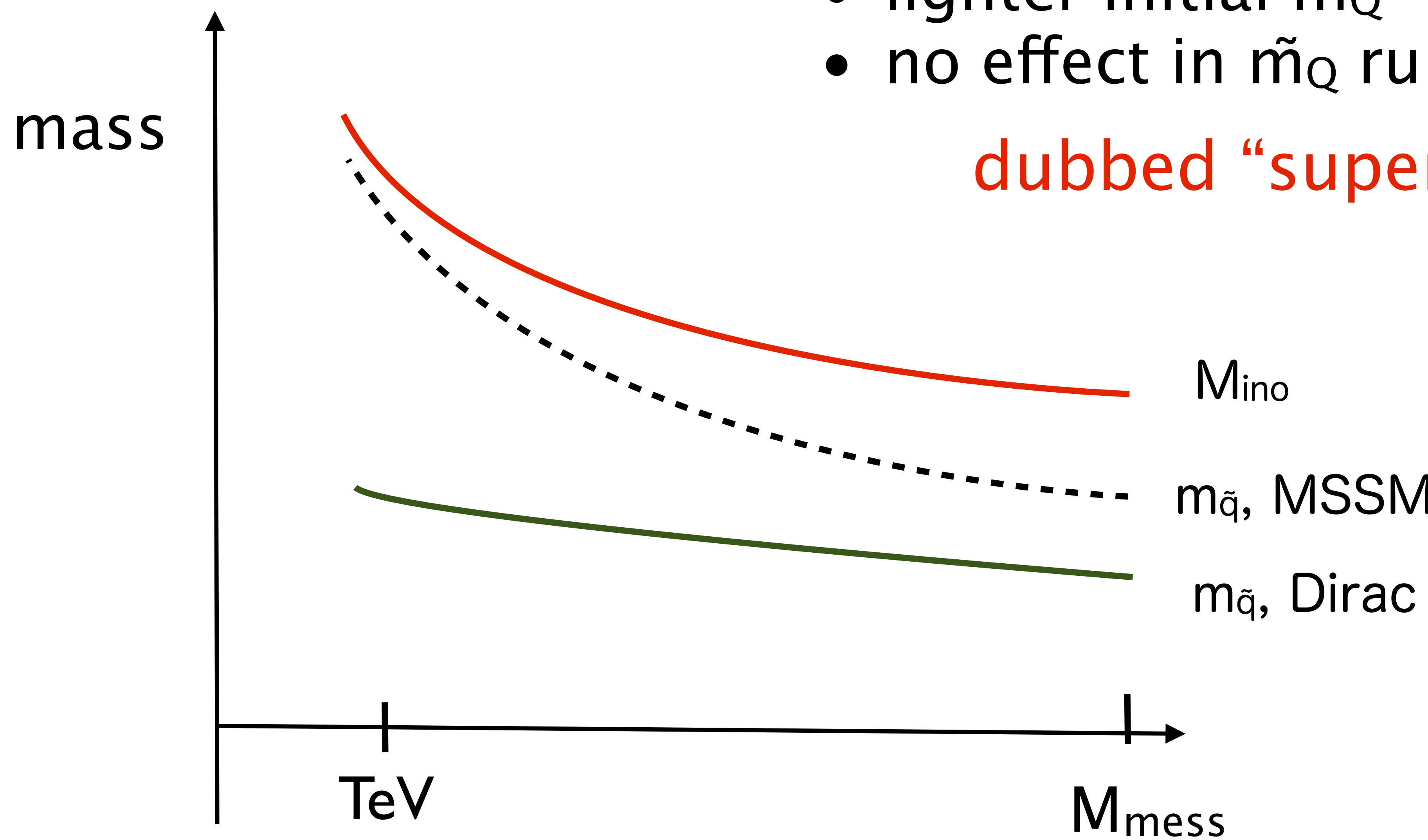

gluinos can easily be several TeV,
while the squarks are ≪ TeV

Supersoft SUSY: naturalness

δm^2_H : compare the MSSM and supersoft

MSSM

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

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

plug in numbers:

$$\Lambda = 20\, M_3$$

tuning for: $(M_3)_{Maj} = 900\,\mathrm{GeV}$

supersoft

$$\delta m^2_{H_u} = -\frac{3\lambda_t^2}{8\pi^2} M^2_{\tilde{t}} \log \frac{M_3^2}{M^2_{\tilde{t}}}$$

(finite)

$$\log \frac{m^2_{adj}}{M_3^2} = 1.5$$

$$M^2_{\tilde{t}} = \frac{3\alpha_s}{4\pi} M_3^2$$

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2-loop:	$\delta m^2_{H_u} = -\frac{\lambda_t^2}{2\pi^2} \frac{\alpha_s}{\pi} \lvert\tilde{M}_3\rvert^2 \left(\log \frac{\Lambda^2}{\tilde{M}_3^2}\right)^2$	(finite)
plug in numbers:	$\Lambda = 20\, M_3$	$\log \frac{m^2_{adj}}{M_3^2} = 1.5$ $M^2_{\tilde{t}} = \frac{3\alpha_s}{4\pi} M_3^2$
tuning for:	$(M_3)_{Maj} = 900\,\mathrm{GeV}$	$(M_3)_{Dir} = 5.0\,\mathrm{TeV}$

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$(M_3)_{Dir} = 5.0\,\text{TeV}$

substantially heavier gluino **just as natural** in supersoft

Why not supersoft?

sounds great so far, as we can have heavier sparticles and stay natural

BUT, recall:

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

EOM for Re[A_a]: $\dfrac{\partial \mathcal{L}}{\partial Re(A^a)} \cong D_a = 0$

$SU(2)_W$, $U(1)_Y$ D-terms = Higgs quartic -> tree level Higgs mass

so if EW gauginos are Dirac then m_h = 0 at tree level!

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

Why not supersoft?

"pure" supersoft won't work. We could...

- keep winos, binos Majorana
- make stops very heavy (>10 TeV)
- NMSSM-ology
- add other sources of SUSY
- ...

production of squarks/gluinos basically independent of how we repair EW/Higgs sector

so: focus on collider ramifications for now, return to m_H issue later

LHC limits on supersoft

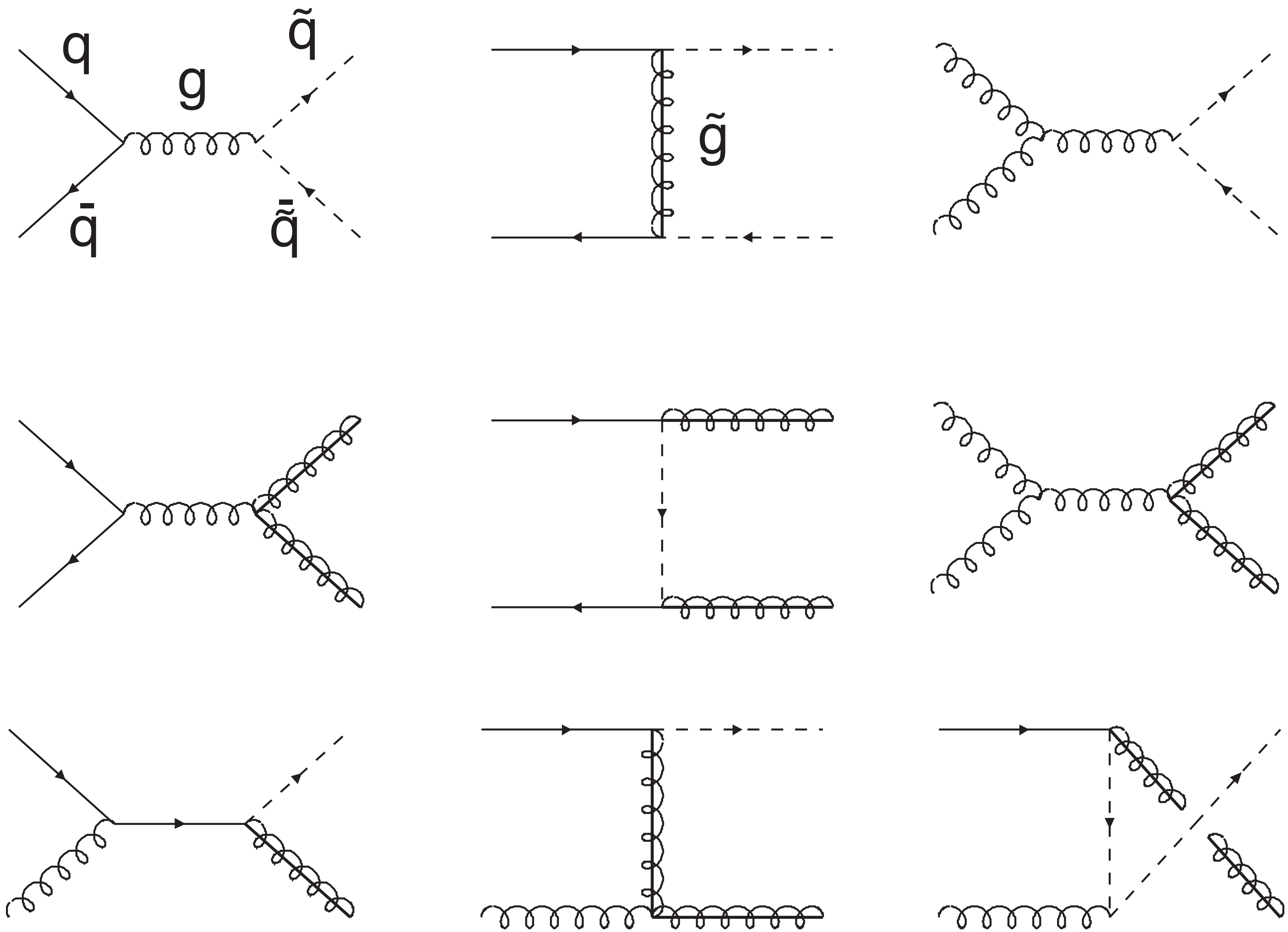
other work on Dirac gauginos @ LHC:

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

differ in treatment of EW sector

Supersoft at the LHC

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



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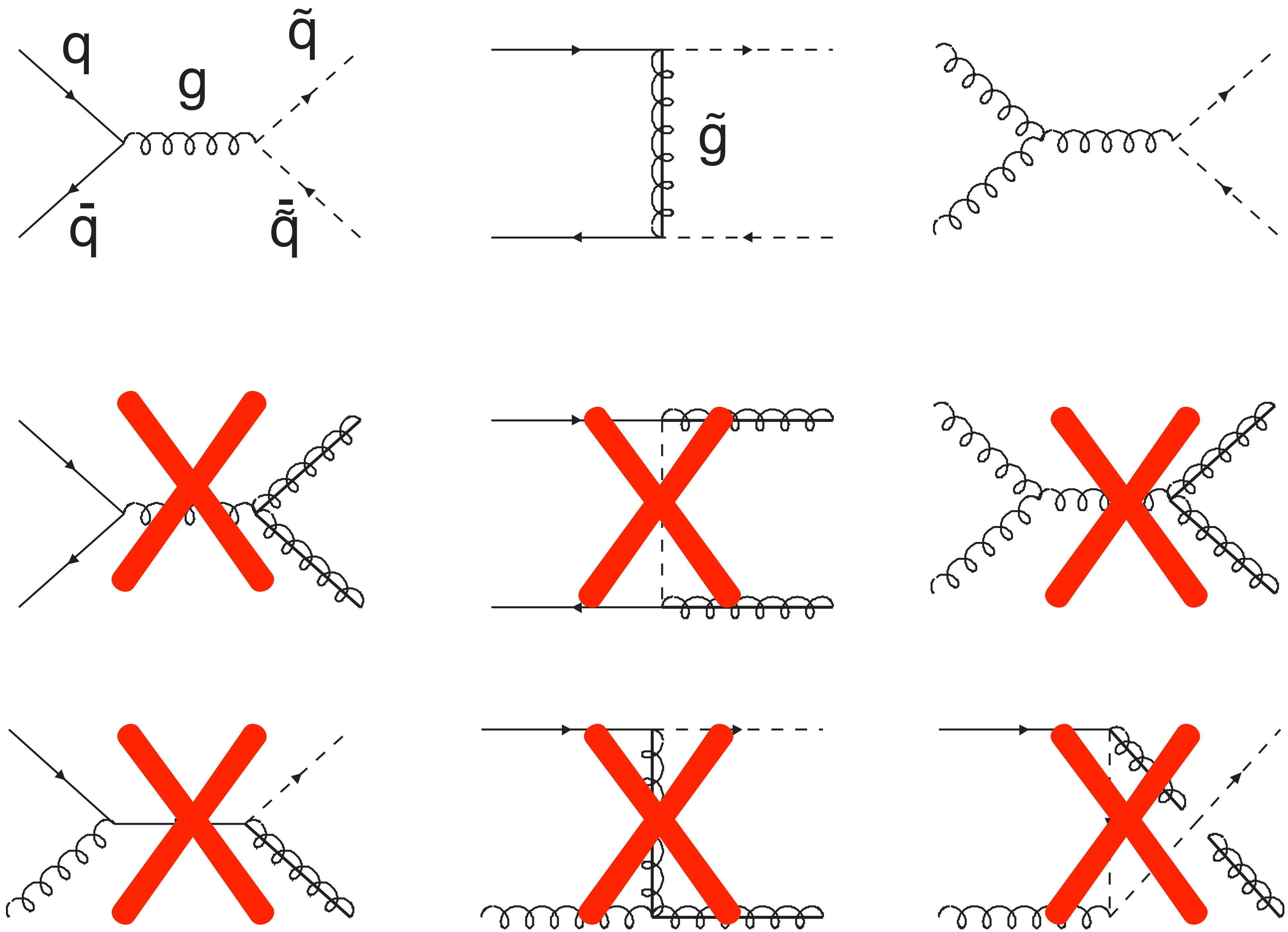


Supersoft at LHC

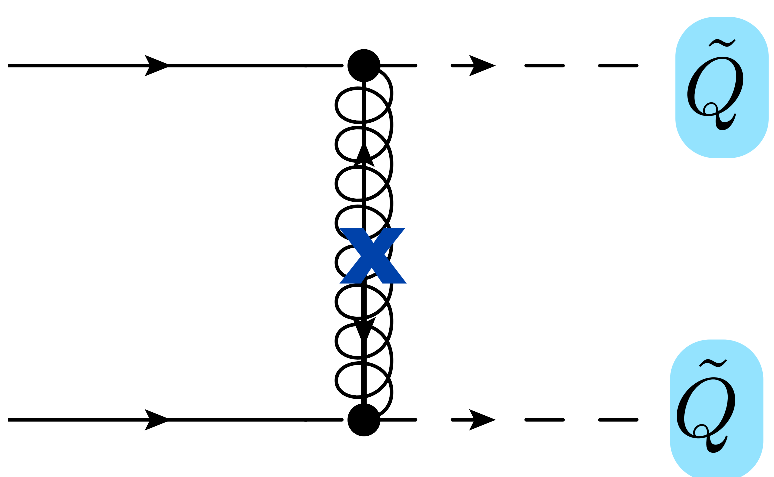
suppression goes beyond kinematics:

SUSY kinetic terms contain a U(1)R symmetry

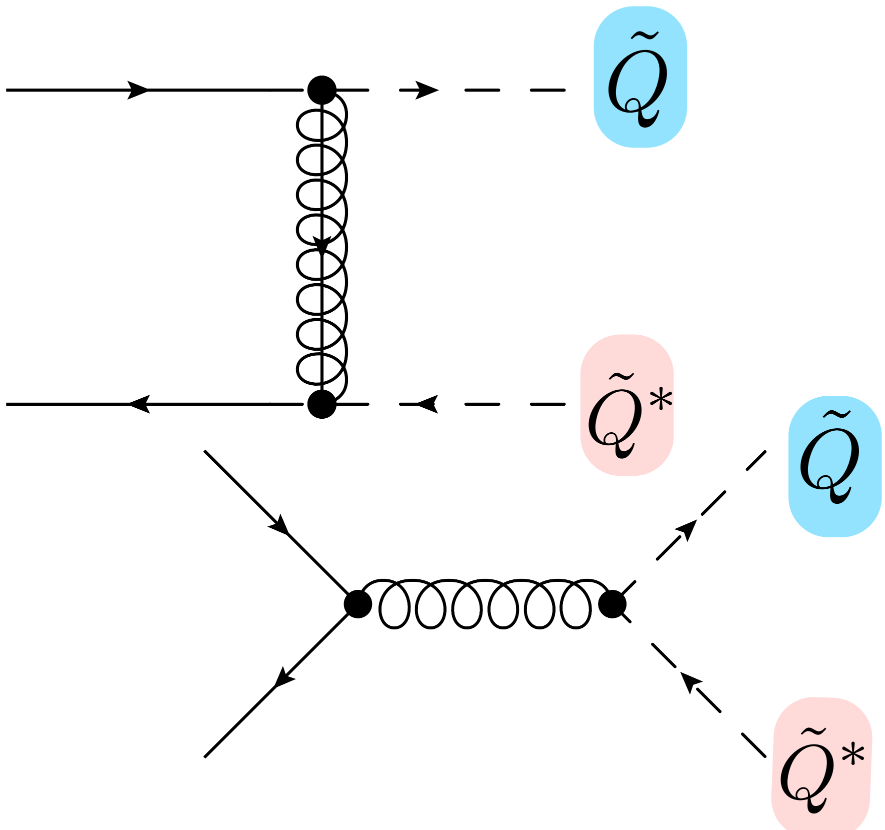
$$R[\lambda] = 1, \; R[q] = R[\tilde{q}]-1$$

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

restricts processes



violate R-symmetry



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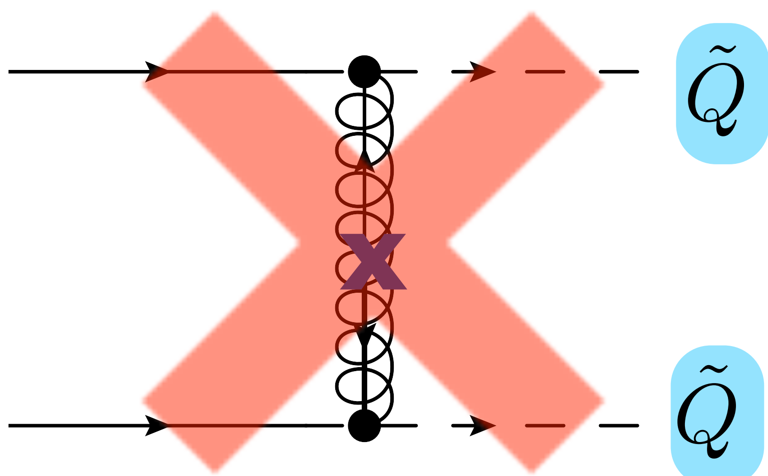

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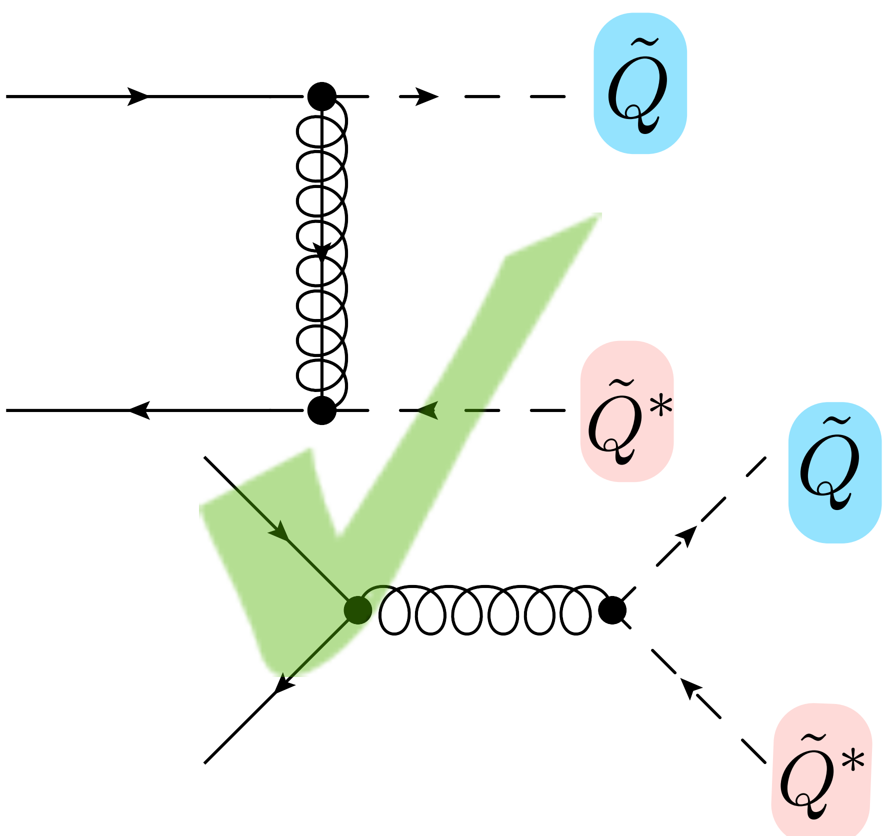

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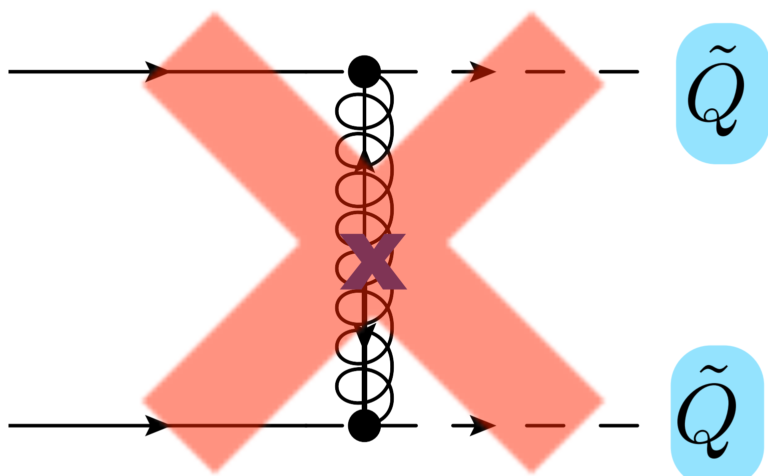

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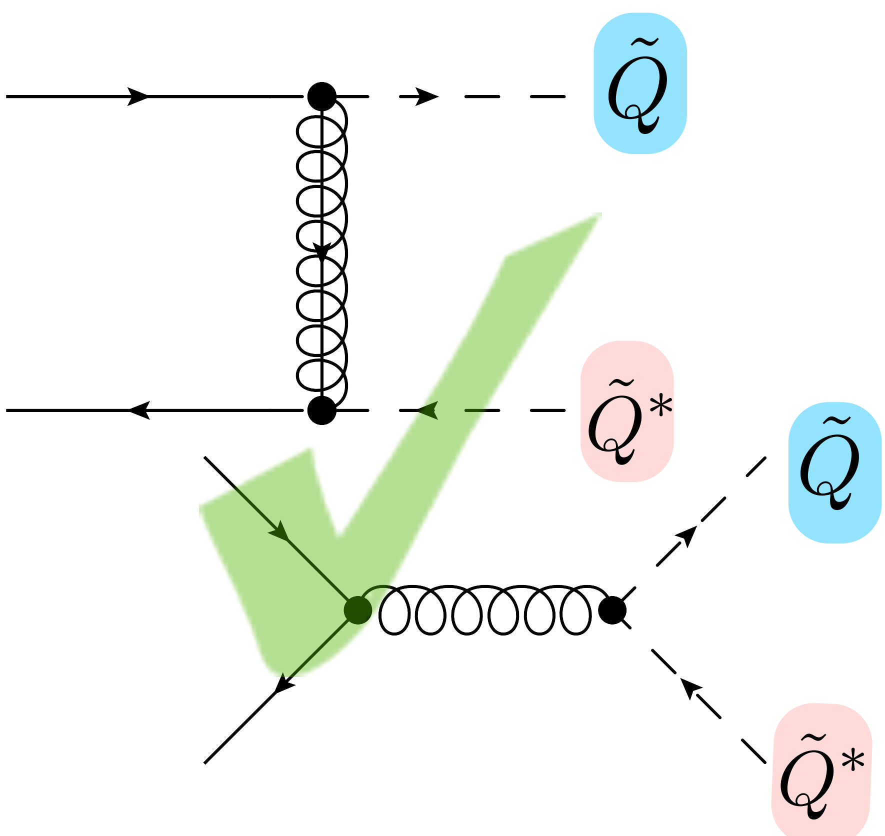
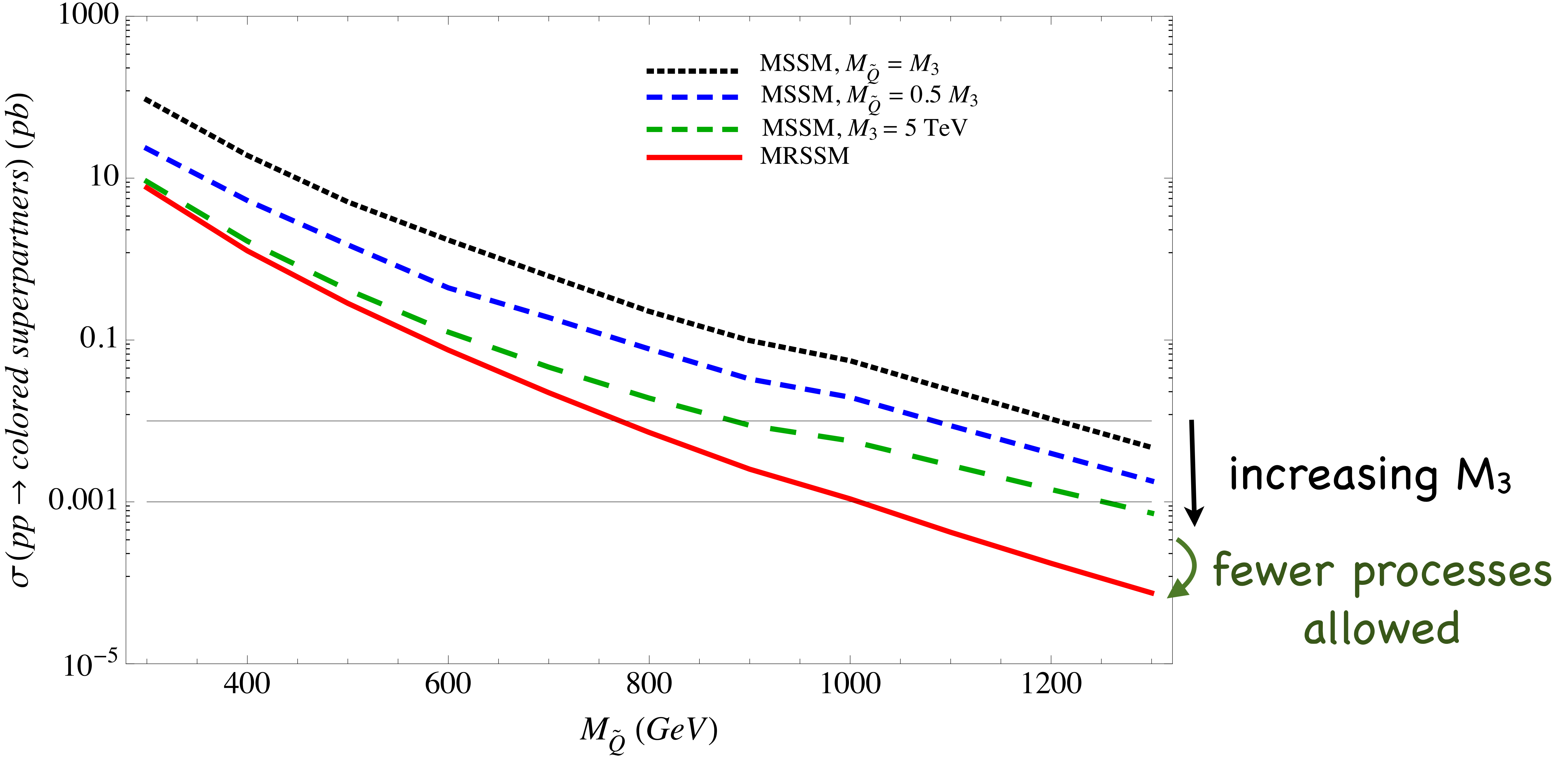


preserve R-symmetry

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

Supersoft production

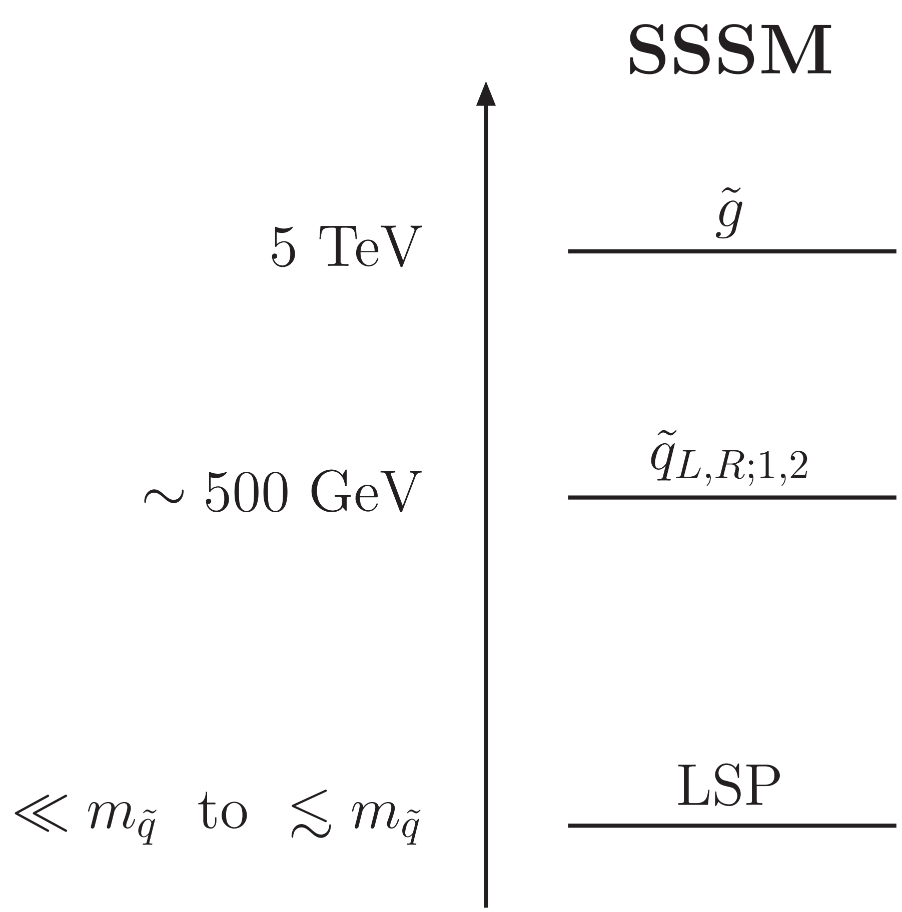


production of colored superstuff with Dirac gluino ≪ traditional MSSM

Supersoft limits

form a 'simplified supersoft model' [Kribs, AM '12]

heavy gluino, degenerate 1^{st}, 2^{nd} gen. squarks (L,R), massless LSP



and repeat (1-5fb^{-1}) jets + MET analyses from ATLAS/CMS

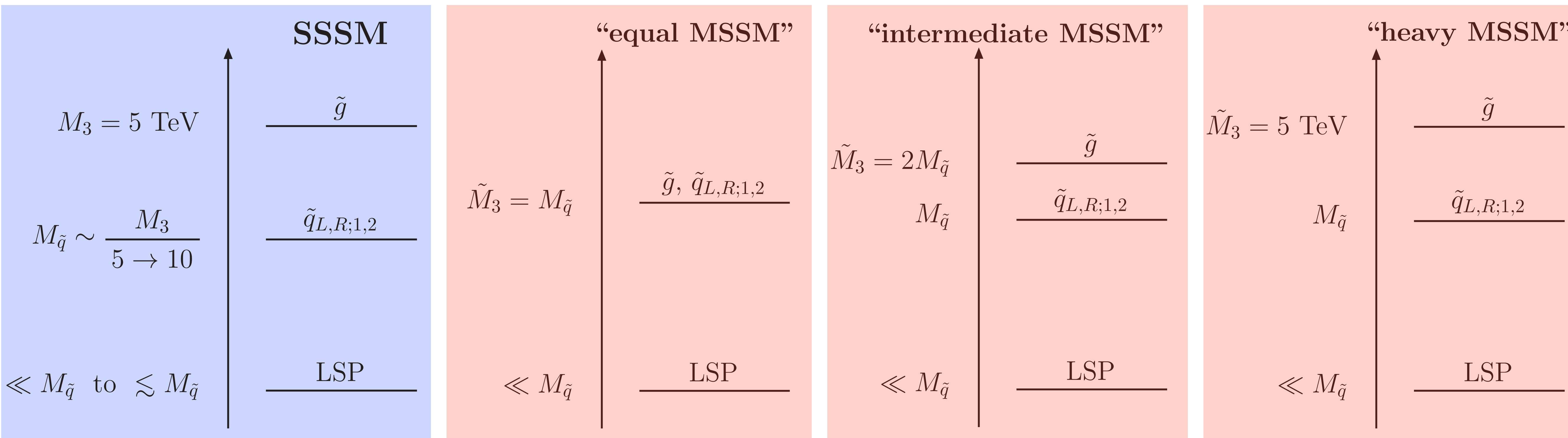
[1109.6752, 1109.2352, CMS-PAS-SUS-11-004, 1107.1279]

signal generated with PYTHIA->Delphes, gets acceptance

PROSPINO for K-factor

Supersoft versus MSSM Simplified Models

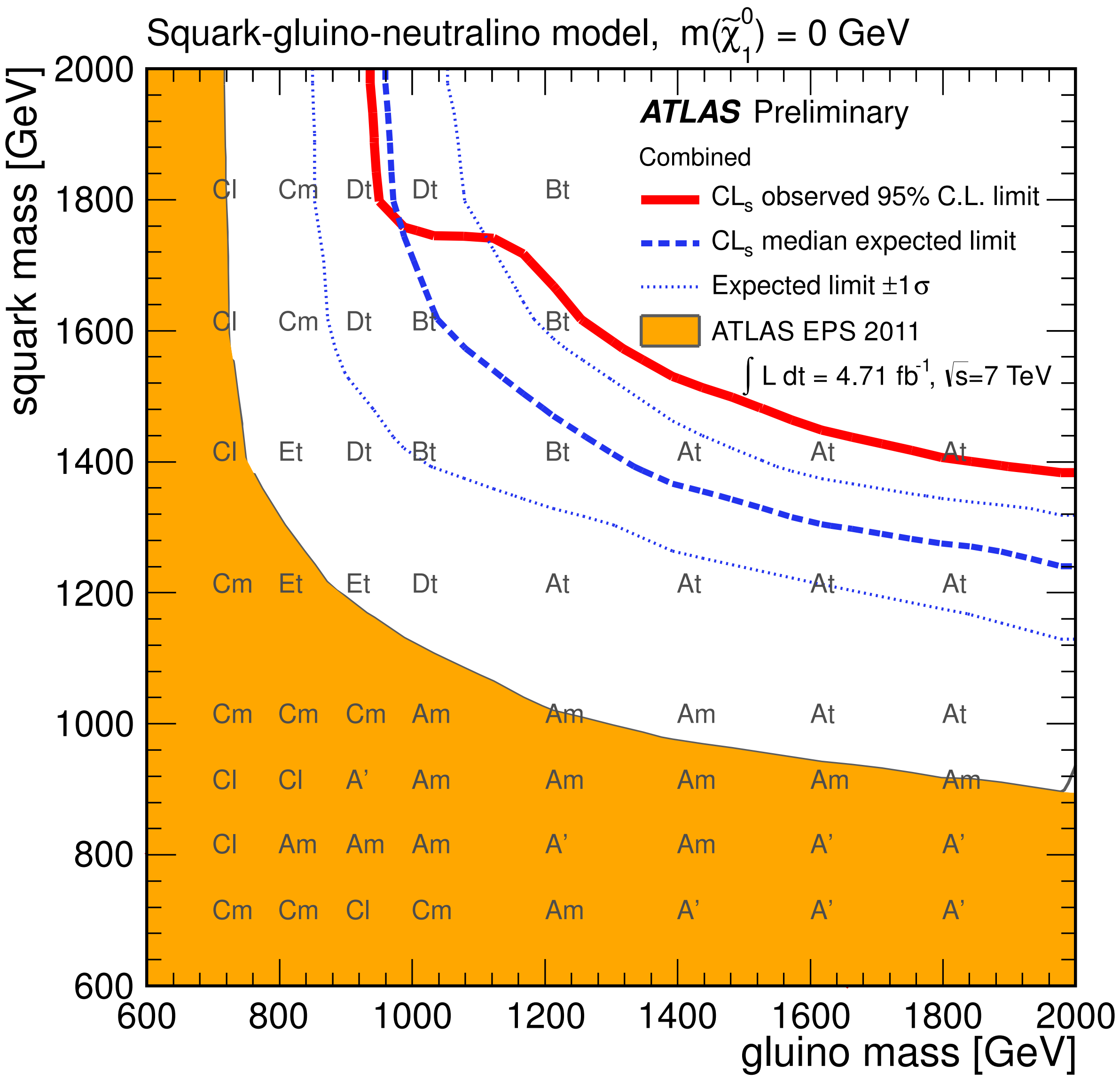
then perform apples-for-apples comparison against MSSM.



from quoted backgrounds + uncertainly, use calculated cross section (NLO), derived acceptance to bound SUSY parameters = M_Q

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

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

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

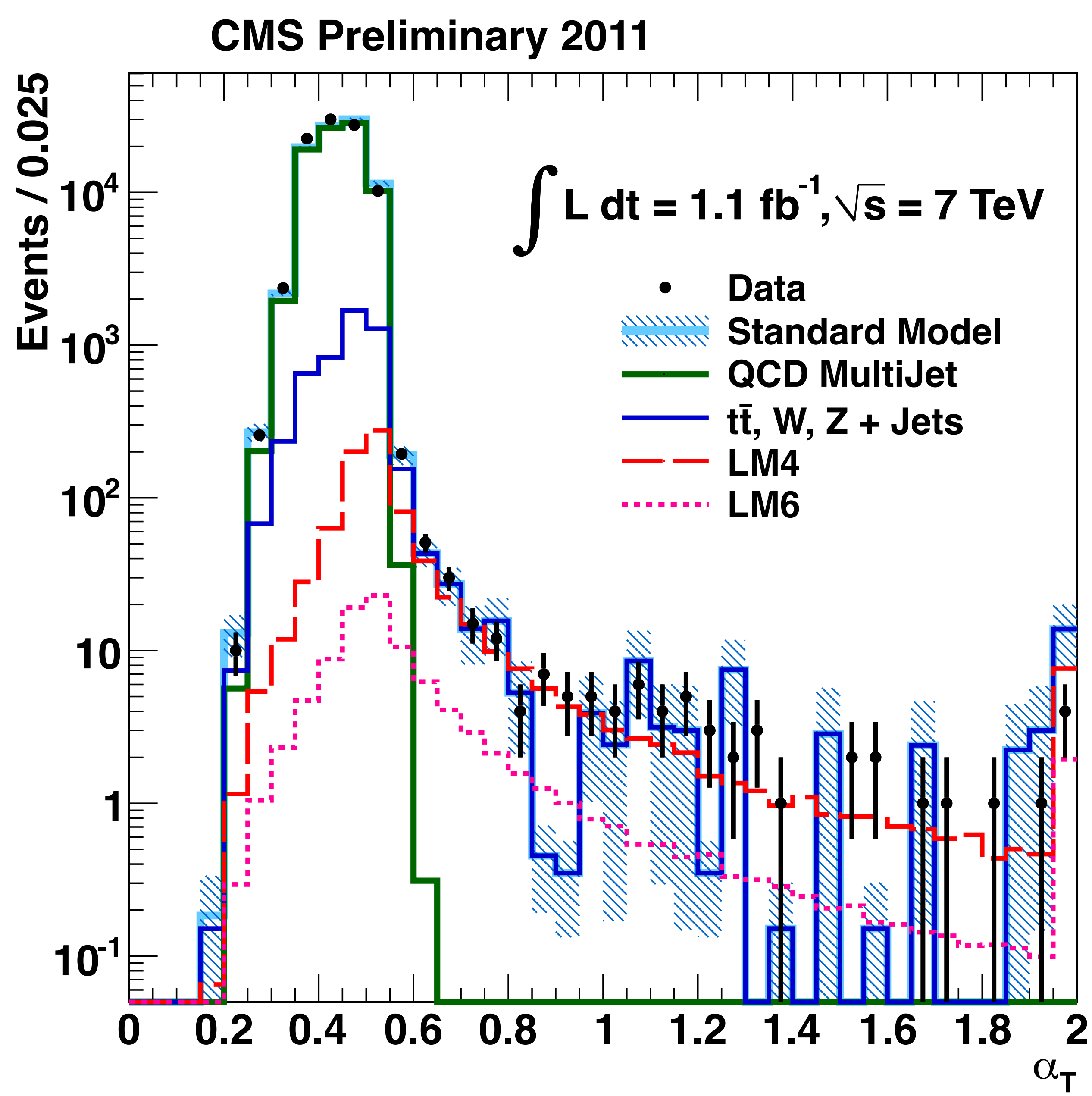
$$H_T = \sum_{i=1}^{n} E_T^{\mathrm{jet}_i}$$

- missing E_T > 100 GeV

- mild $\Delta\varphi$ cut to reduce jet mismeasurement

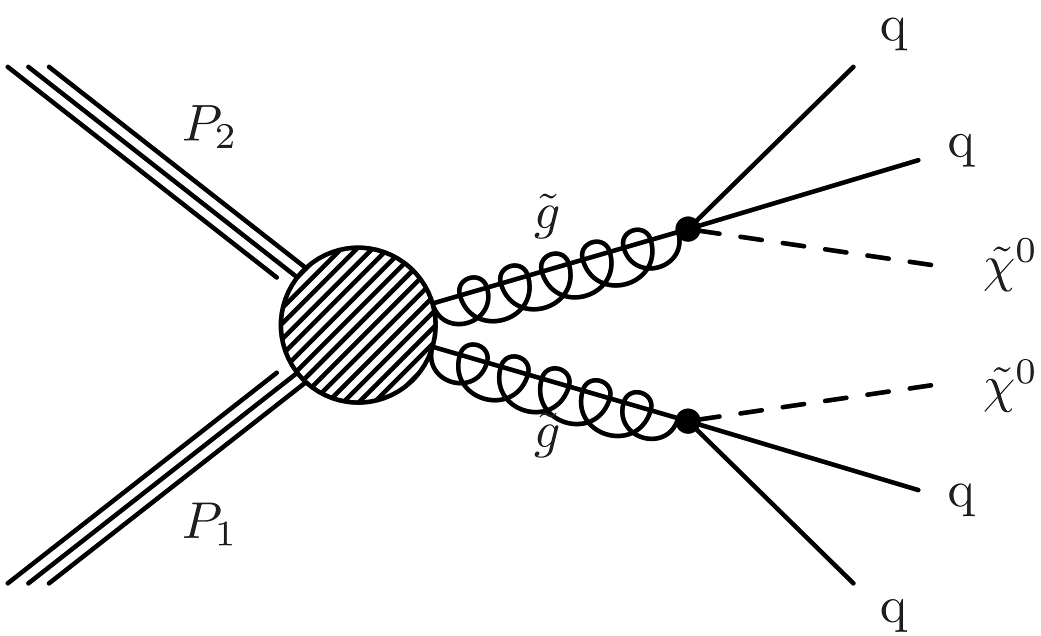
cut on:

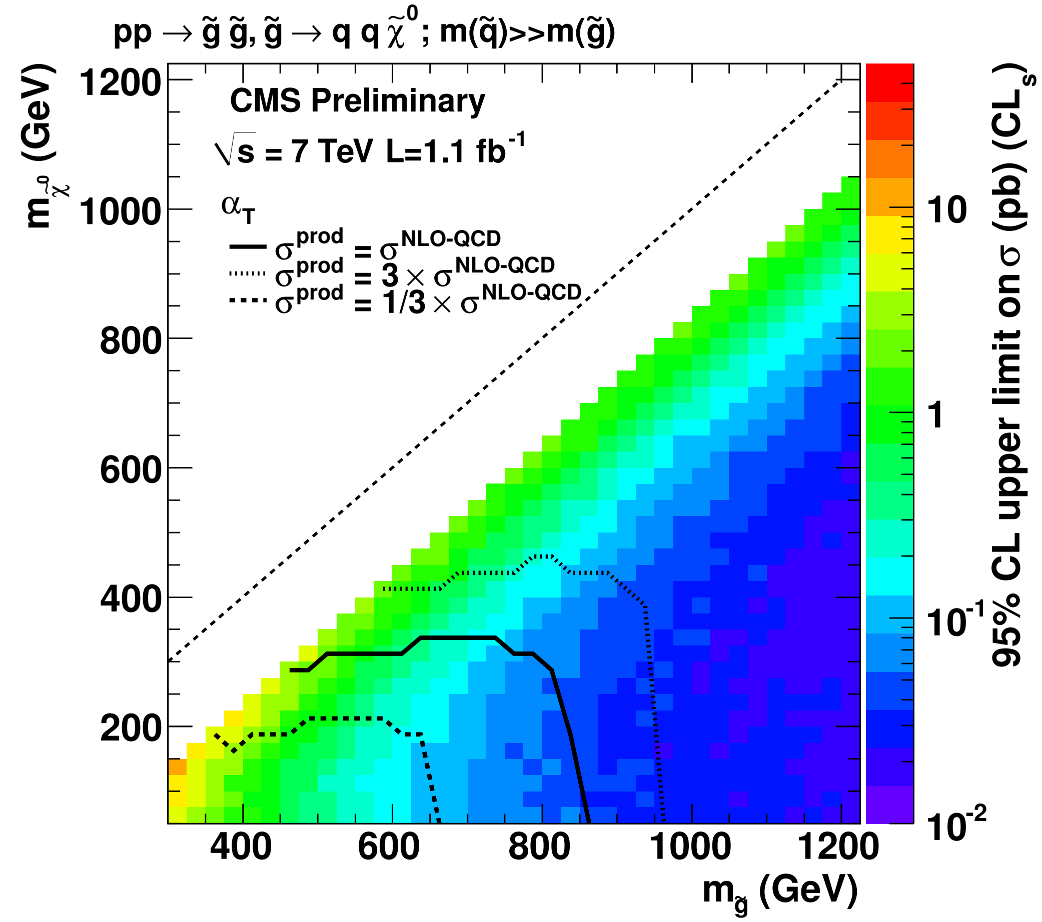
$$\alpha_T = E_{T,\mathrm{jet\#2}} / M_{T(j1j2)}$$

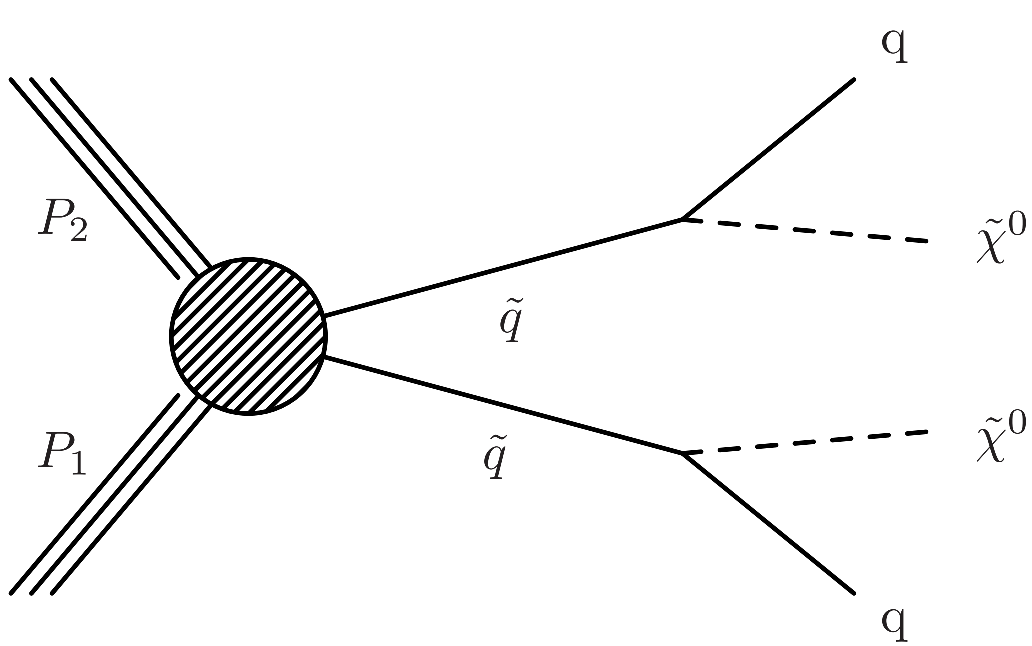


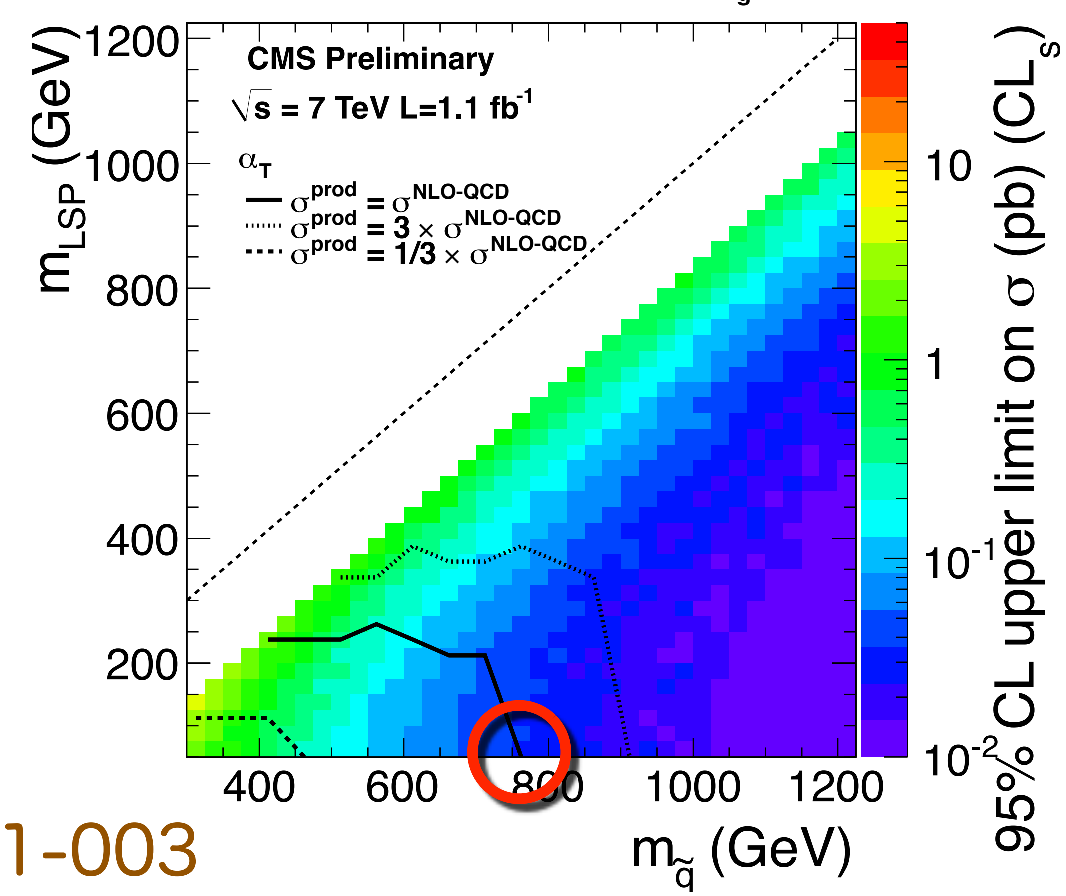
CMS-SUS-11-003

CMS Bounds on Simplified Models









CMS-SUS-11-003

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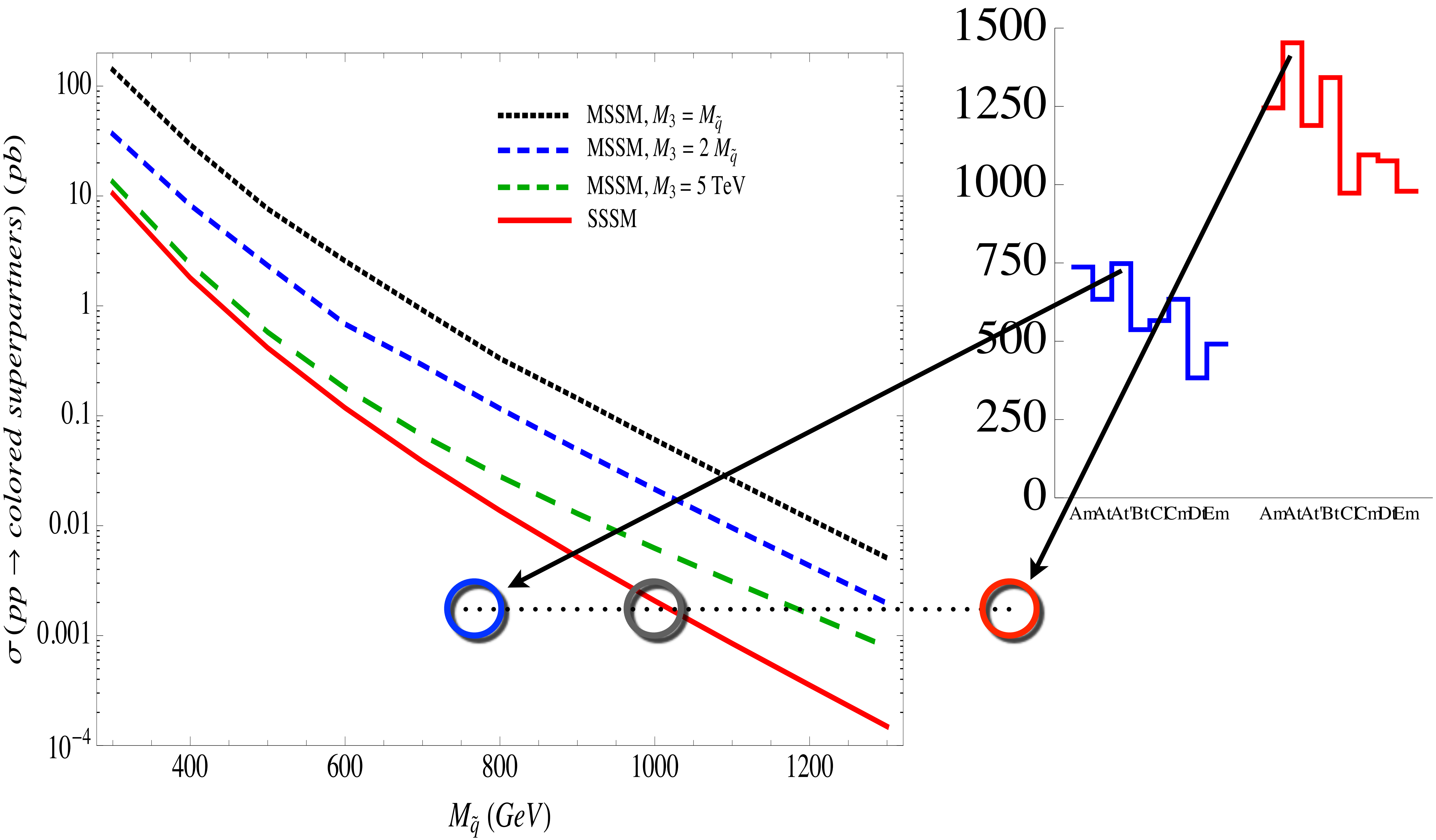
1st,2nd generation squark mass

Kribs & AM

Effectiveness of LHC strategy

difference in limits not just difference in cross-section

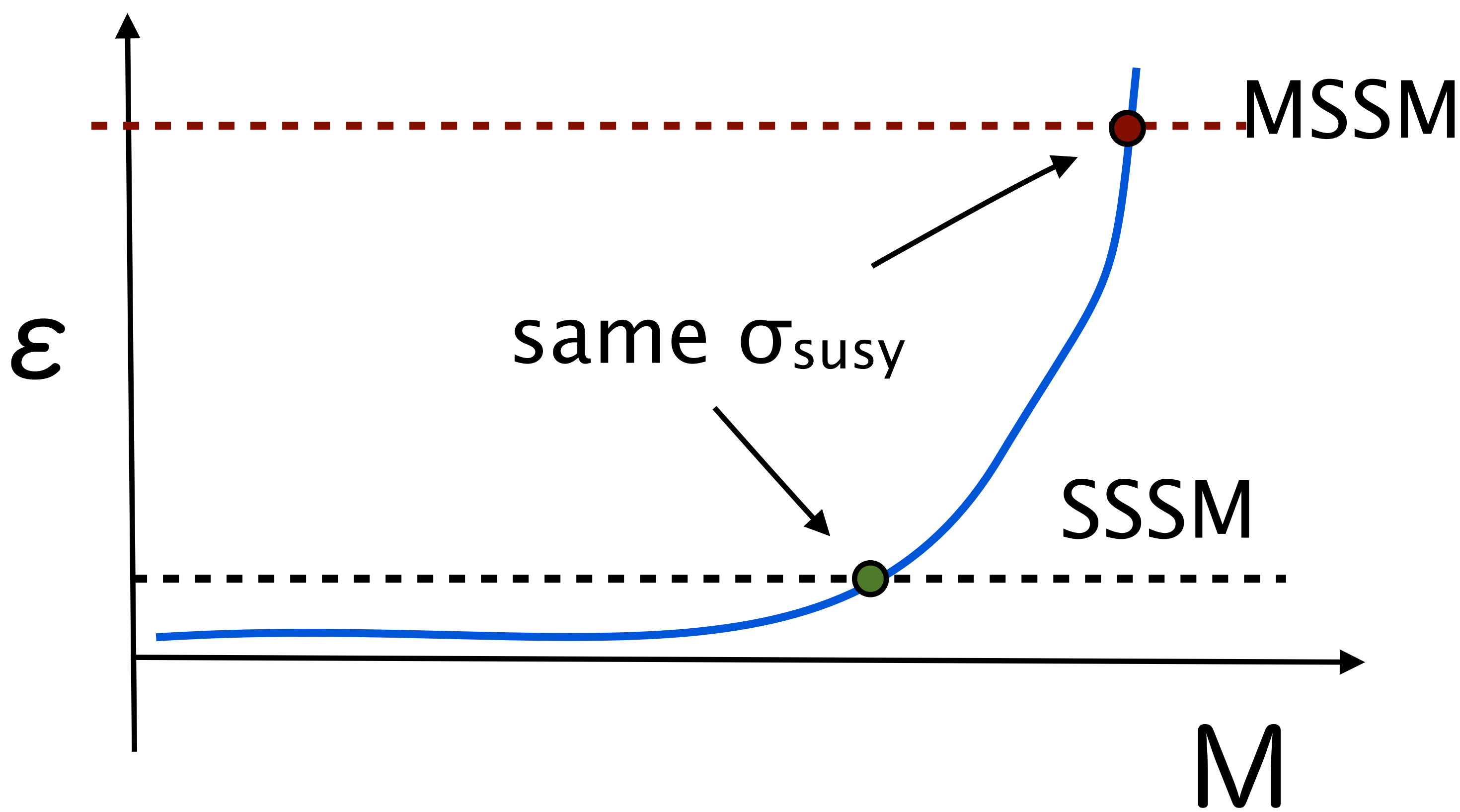


Effectiveness of LHC strategy

strongest limits on MSSM points come from **highest** M_{eff}/H_T cuts

[showed α_T, ATLAS jets + MET, also true for CMS MHT, razor searches...]

at lower squark mass, where SSSM has comparable cross section, high cuts are very inefficient



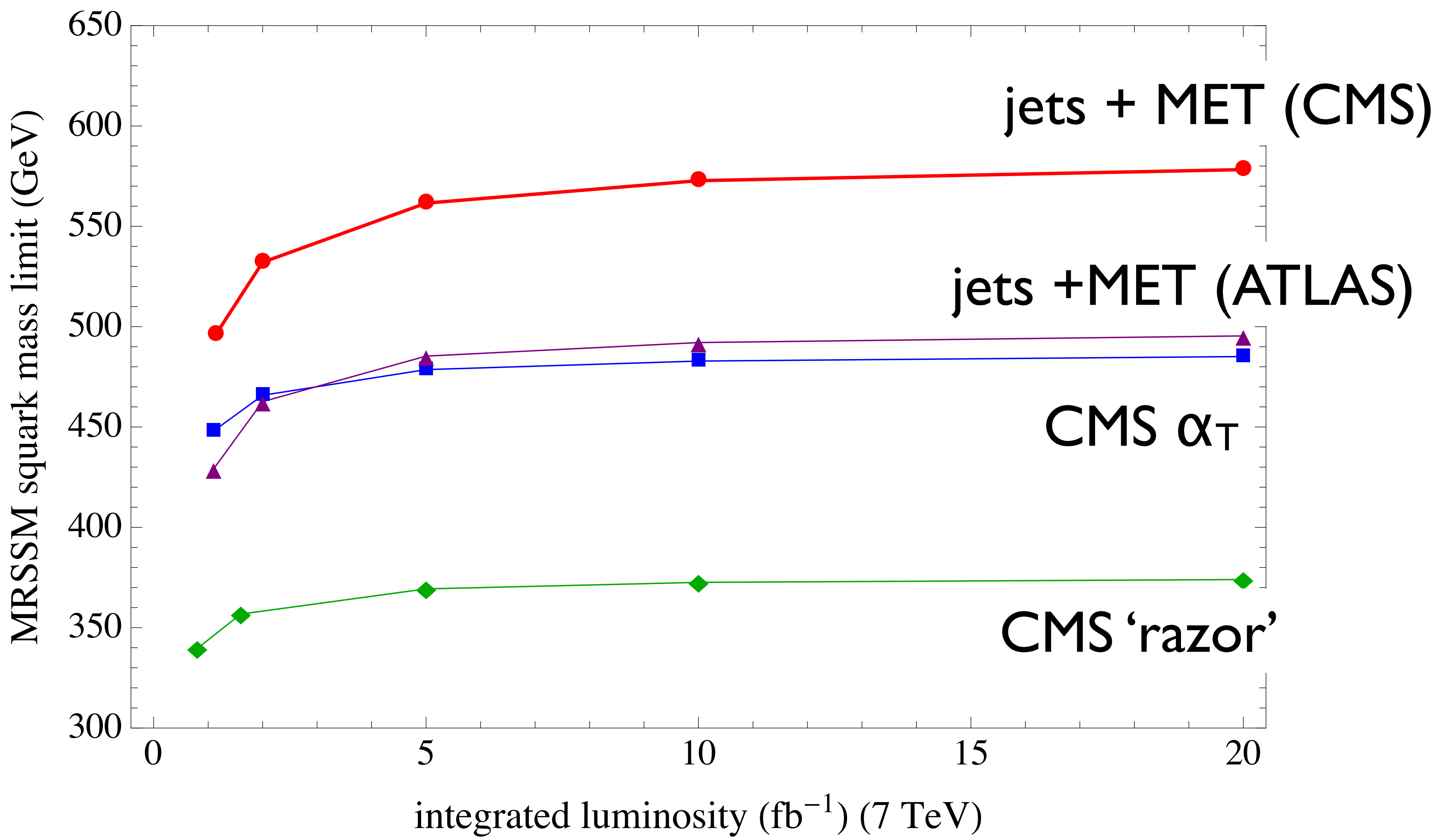
searches with a broader H_T reach would be useful

Supersoft limits

projection to higher luminosity

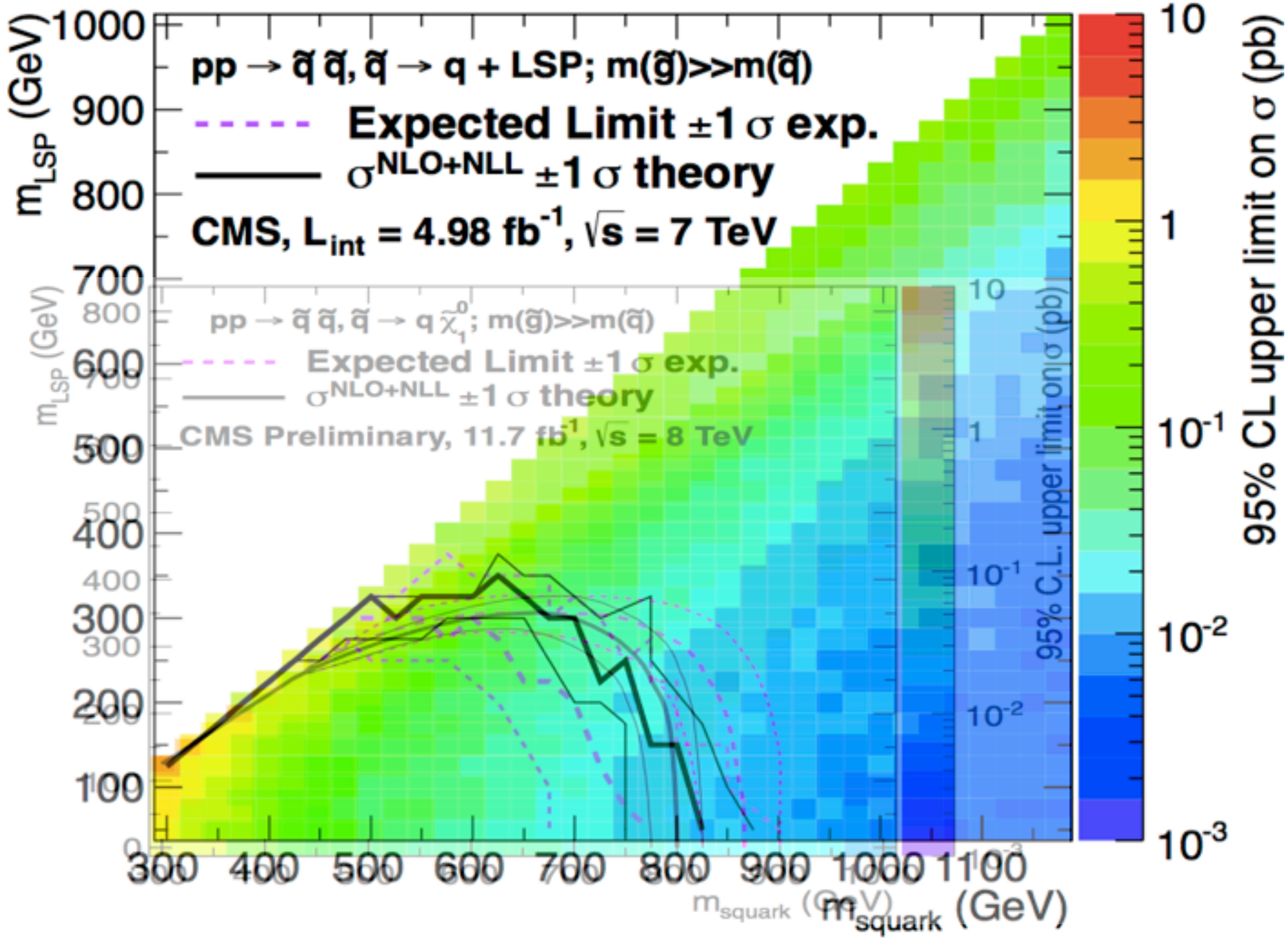
[Kribs, AM '12]

expected limit from most stringent **single** channel



also: limits degrade as M_X gets closer to M_Q

Keynote physics

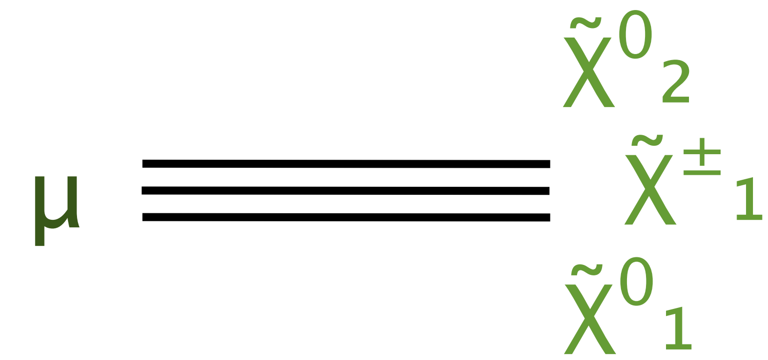


Implications on other LHC searches

- R-symmetry prevents same-sign lepton channel

- for natural μ, large M_2, M_1 (Dirac):

  lighest charginos/neutralinos are
  Higginos, are very degenerate



if neutralino is LSP:
little phase space for

$$\tilde{\chi}^{\pm}_1 \rightarrow \tilde{\chi}^0_1 + W^{\pm}$$
$$\tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1 + Z^0$$

if gravitino is LSP:
often have

$$\tilde{\chi}^0_i \rightarrow \tilde{G} + h^0$$

will effect tri-lepton limits...

Implications on other LHC searches

3rd generation searches:

most dedicated stop searches rely on leptons, assume 100% BR to one mode

$\tilde{t} \rightarrow b\, \chi^{\pm}$

↳ $W\, \chi^0$

$\tilde{t} \rightarrow t\, \chi^0$

↳ $b\, W$

$\mu \ll M_1, M_2$ = degenerate chargino/neutralino + mixture of stop BR → much looser bounds

strongest bound from sbottom searches (b-jets + MET)

[Kribs, AM, Menon in progress]

Implications on other LHC searches

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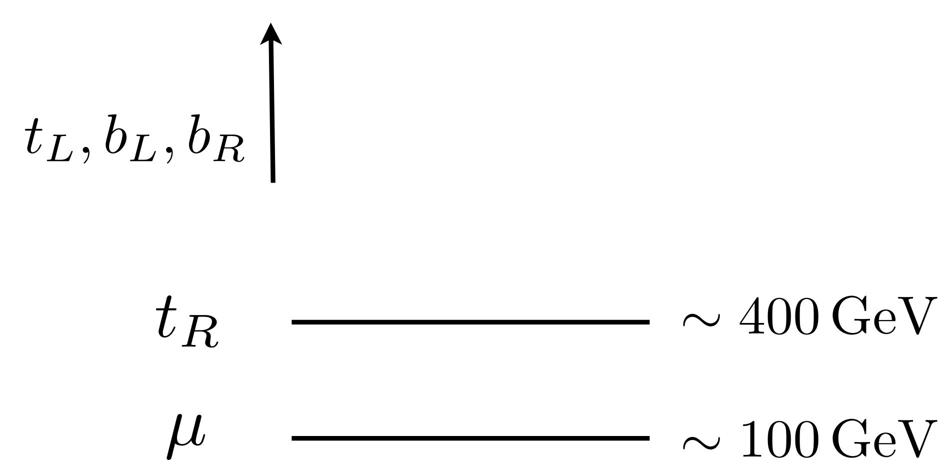
region with light stops still allowed, a 'supernatural' setup



[Kribs, AM, Menon in progress]

Implications on other LHC searches

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

YES: extra states, the scalars in $\Phi_i = A_i$

$Re[A_i]$ are heavy, mass ~ M_D, $Im[A_i]$ can be light

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

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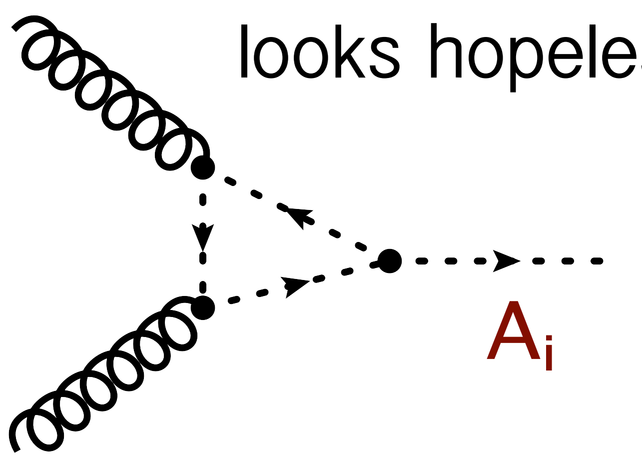

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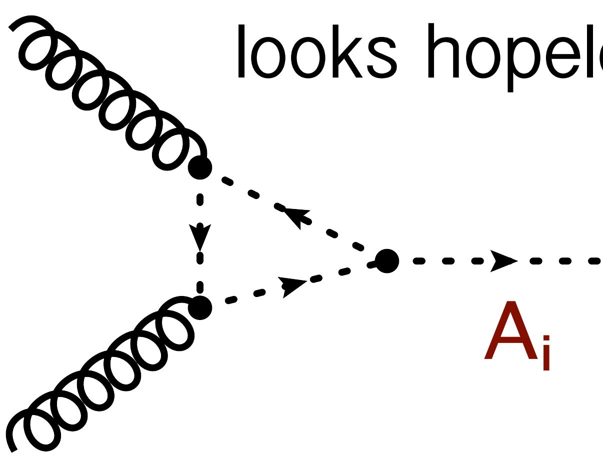
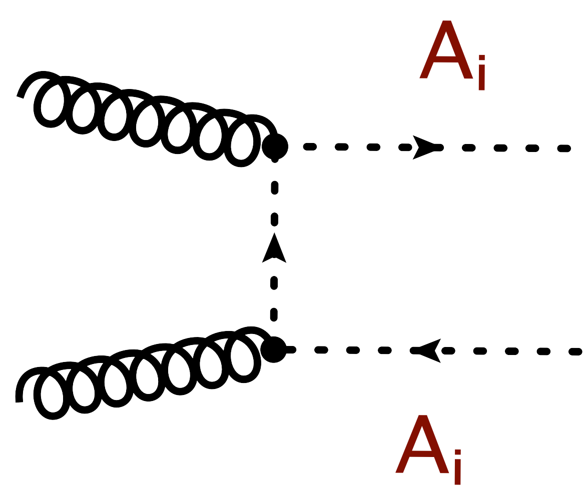


pair production better:



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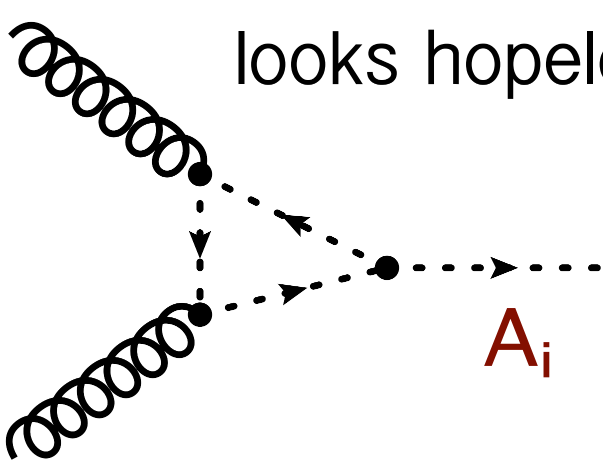

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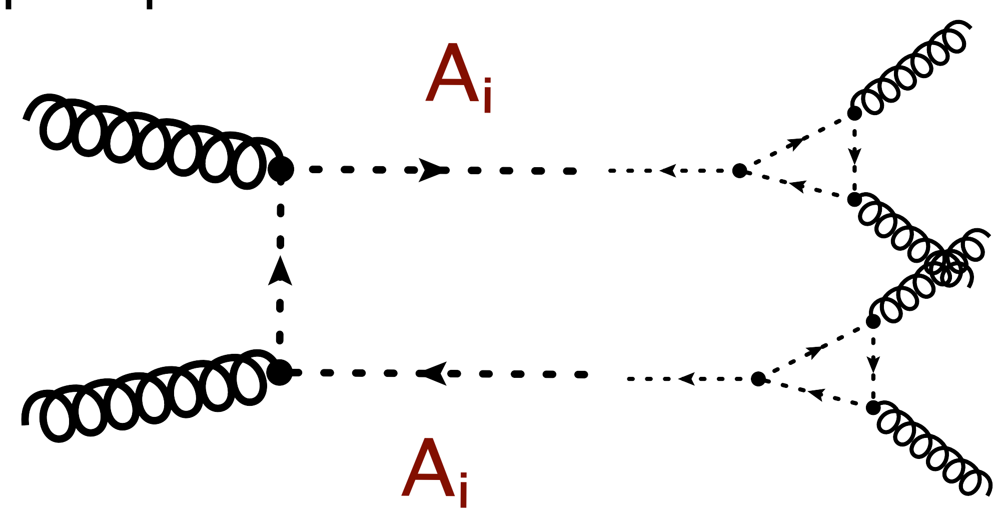

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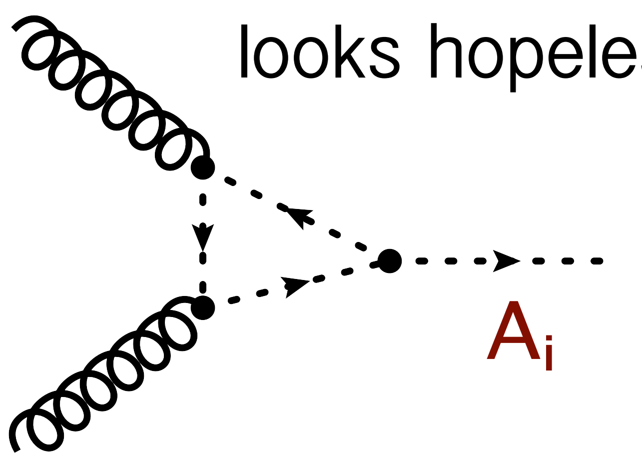

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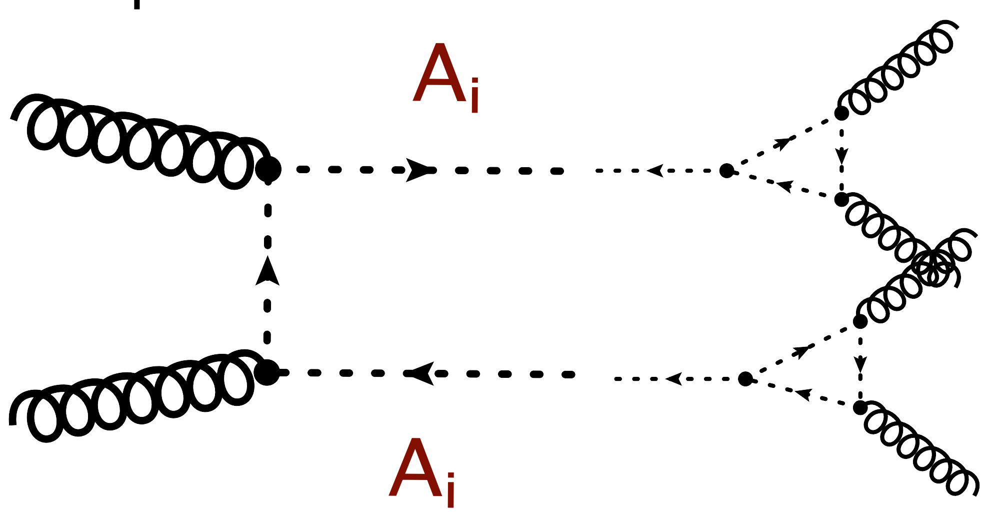

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see Plehn, Tait '08, also CMS-EXO-11-016, ATLAS 1110.2693

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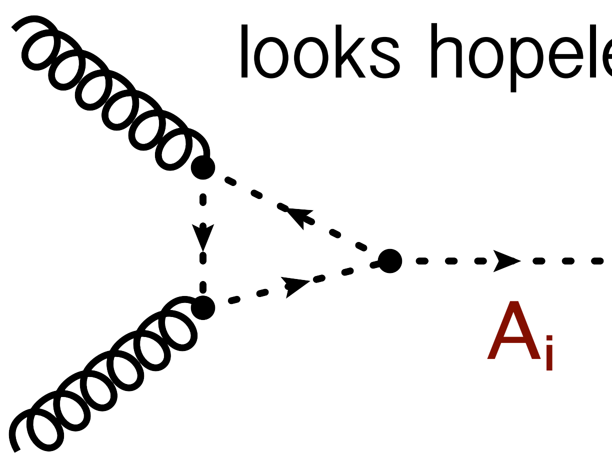

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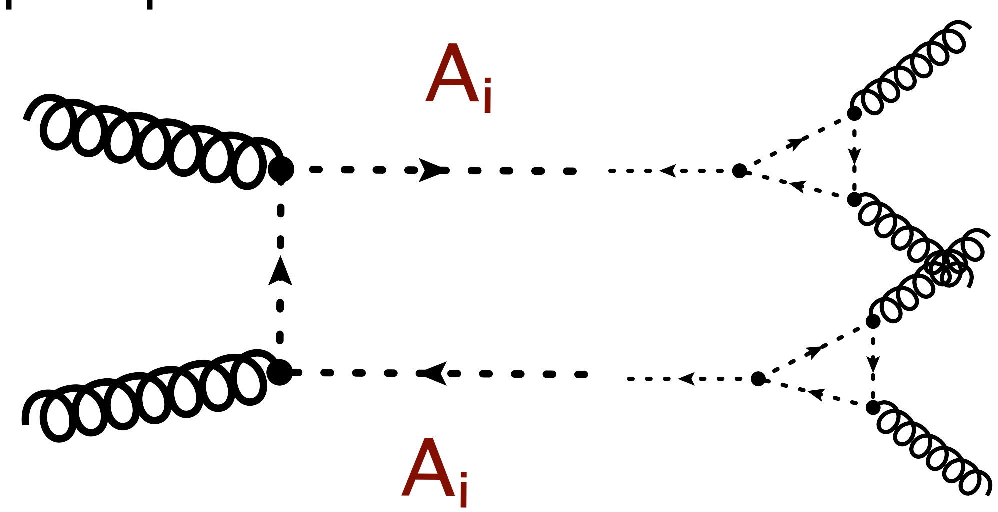

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EW A_i production unexplored

.. About that Higgs mass

some example fixes for $\lambda_{h,tree} = 0$

1.) extend the EW-sector (nMSSMology):

ex.) add in $R_u = (1,2)_{-1/2}$, $R_d = (1,2)_{+1/2}$ $R[R_u] = R[R_d] = 2$

allows: $W \supset \kappa\, H_u\, \Phi_B\, R_u + u \leftrightarrow d$

implies (schematically)

$$V(h) = \frac{m_0^2}{2} h^2 + \frac{1}{2}\left(2\, M_D\, a - \frac{g}{2} h^2\right)^2 + \kappa\, \mu\, h^2\, a + \cdots$$

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$$a \sim \frac{g\,h^2}{4\,M_D}$$

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becomes effective quartic

.. About that Higgs mass

1.) mass term for Φ_i: $$\delta V(h) = m_a^2\, a^2$$

requires a second SUSY-breaking spurion: $\mathbf{X} = \theta^2\mathbf{F}$

provided **X** is not a singlet, can't write **X** $W_\alpha W^\alpha$,
gauginos still Dirac

[Kribs, Okui, Roy '11]

but matter can get mass via: $$\frac{\mathbf{X}^\dagger\mathbf{X}\,\Phi_B^\dagger\Phi_B}{M^2_{mess}}$$ ← new adjoints

generates quartic $$\sim \frac{g^2\, m_a^2}{32\, M_D^2}$$

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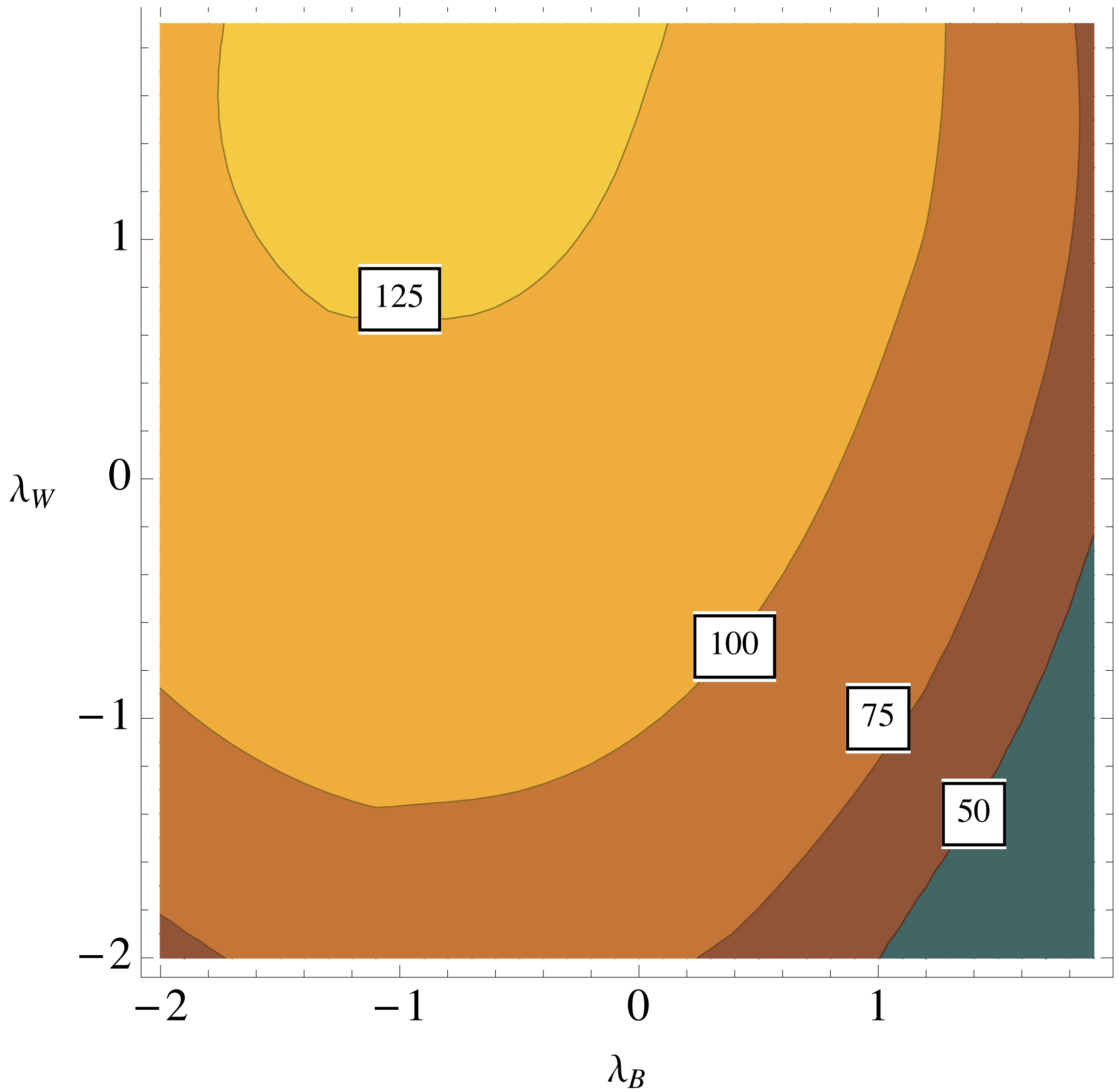
1+2.) charge **X** under $U(1)_R$ preserved by SUSY kinetic terms, R [X] = 2. add matter to enforce R-symm throughout = M**R**SSM

[Kribs, Poppitz, Weiner '07]

mRSSM

$$W \supset \mu_u H_u R_u + \mu_d R_d H_d$$ "μ"-term must be changed

$$W \supset \lambda_B^u \Phi_B H_u R_u + \lambda_B^d \Phi_B R_d H_d + \lambda_W^u \Phi_W^a H_u \tau^a R_u + \lambda_W^d \Phi_W^a R_d \tau^a H_d$$ new terms in W



can get m_H~125 GeV and strong EWPT

$$M_2 = 1 \text{ TeV}$$
$$\mu_u = \mu_d = 200 \text{ GeV}$$
$$m(\tilde{t}_{L,R}) = 3 \text{ TeV}$$
$$m_a = 0$$

[Fok, Kribs, AM, Tsai '12]

mRSSM

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

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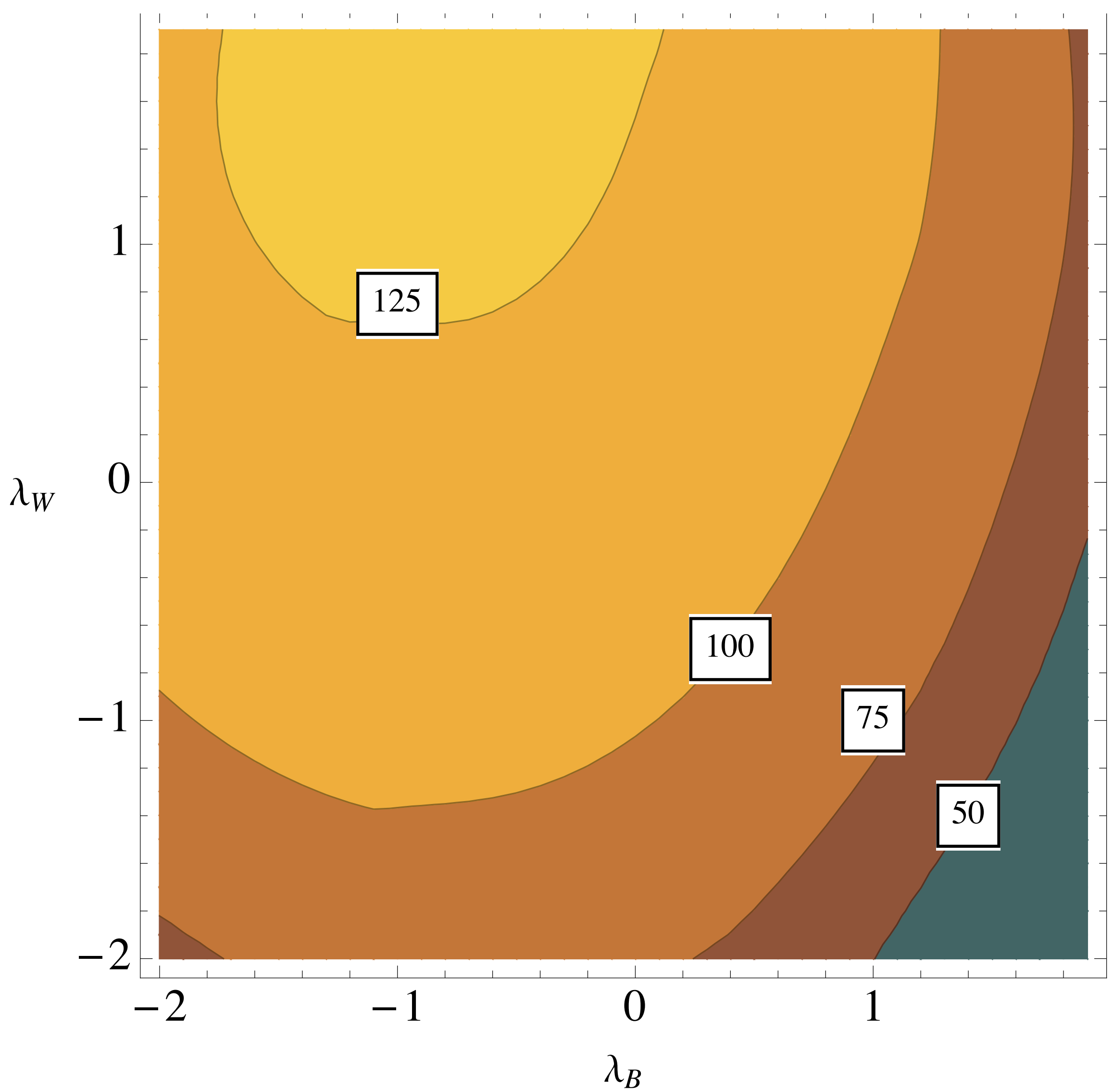
$$W \supset \lambda_B^u\, \Phi_B\, H_u\, R_u + \lambda_B^d\, \Phi_B\, R_d\, H_d + \lambda_W^u\, \Phi_W^a\, H_u\, \tau^a R_u + \lambda_W^d\, \Phi_W^a\, R_d\, \tau^a H_d$$

new terms in W

interesting (s)flavor properties!



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$$m_a = 0$$

[Fok, Kribs, AM, Tsai '12]

Conclusions

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

- significantly reduced colored sparticle production

  limits (≲ 5 fb−1, 8 TeV data): ~ **680−750 GeV**

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

  - analysis optimized for high H_T do poorly

limits ~ independent of EW sector, which cannot be pure supersoft & achieve m_H ~125 GeV

extra **X** spurion, interactions

Maj. winos/binos

- many interesting directions to go in from here!