Supersoft Supersymmetry at the LHC

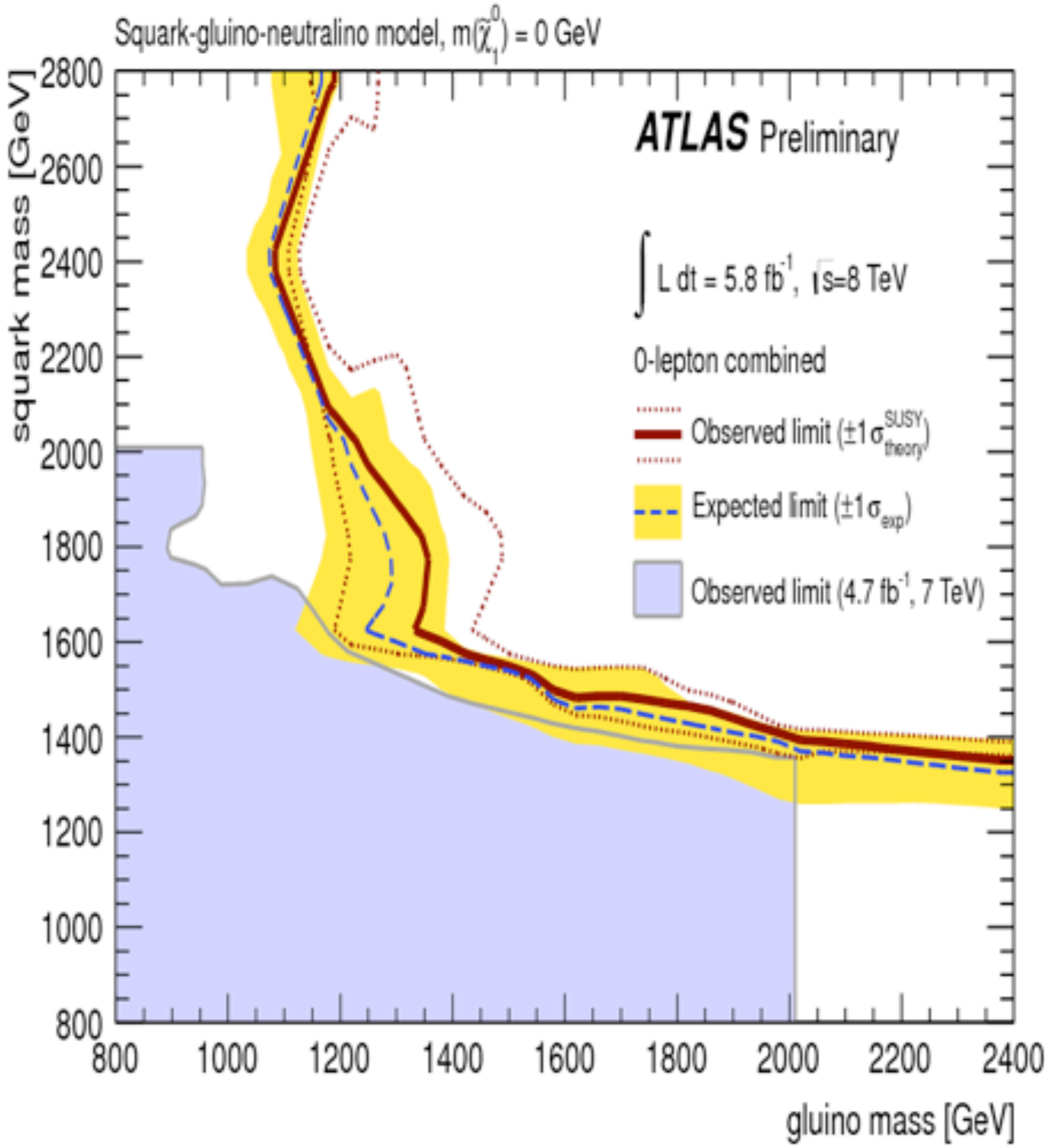
Adam Martin
CERN/Notre Dame
adam.martin@cern.ch

LAPTH Annecy, Nov. 22th, 2012

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

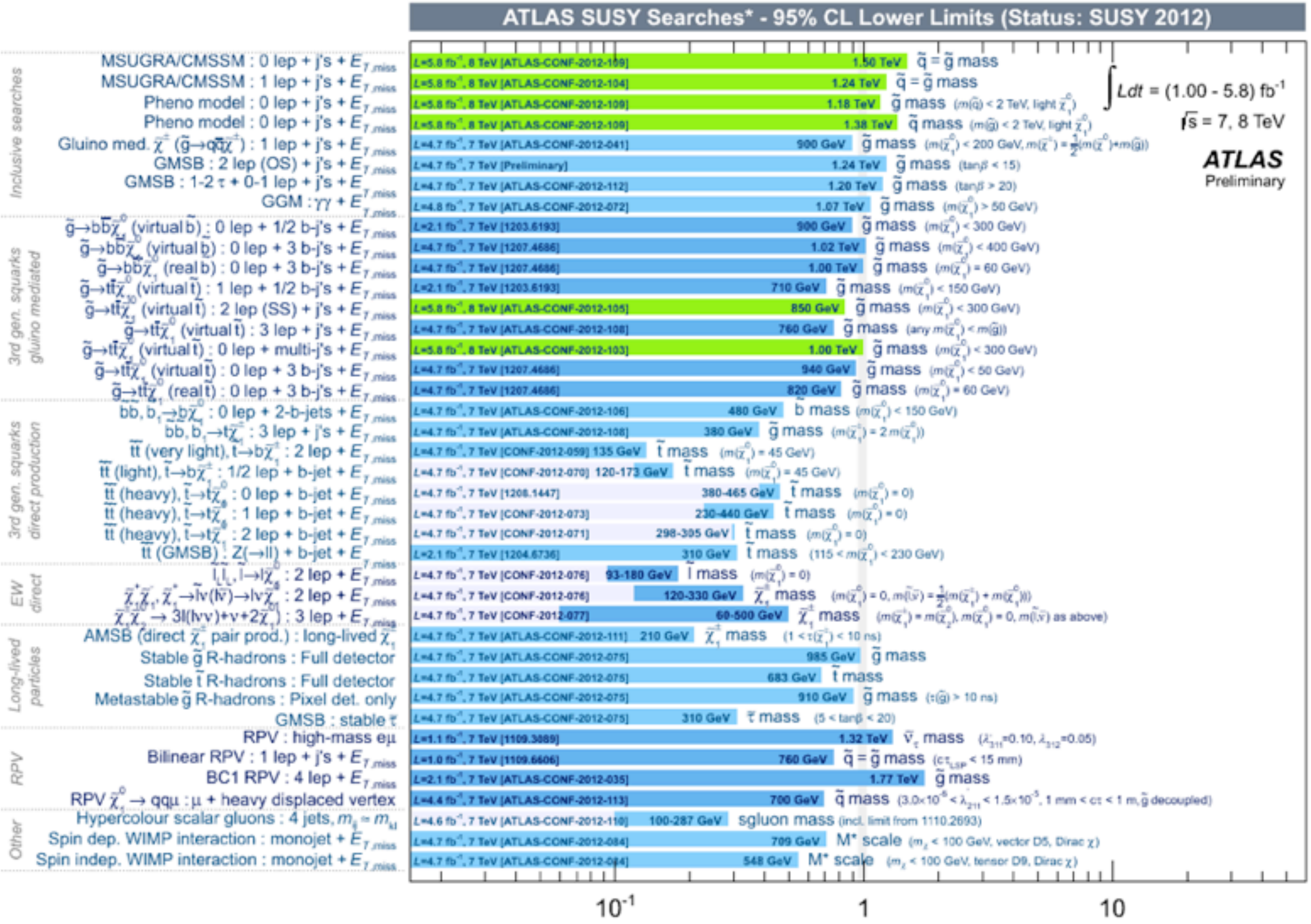
Where's SUSY?



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



*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.

we've seen this for a while

we’ve seen this for a while

time to add this?

we've seen this
for a while

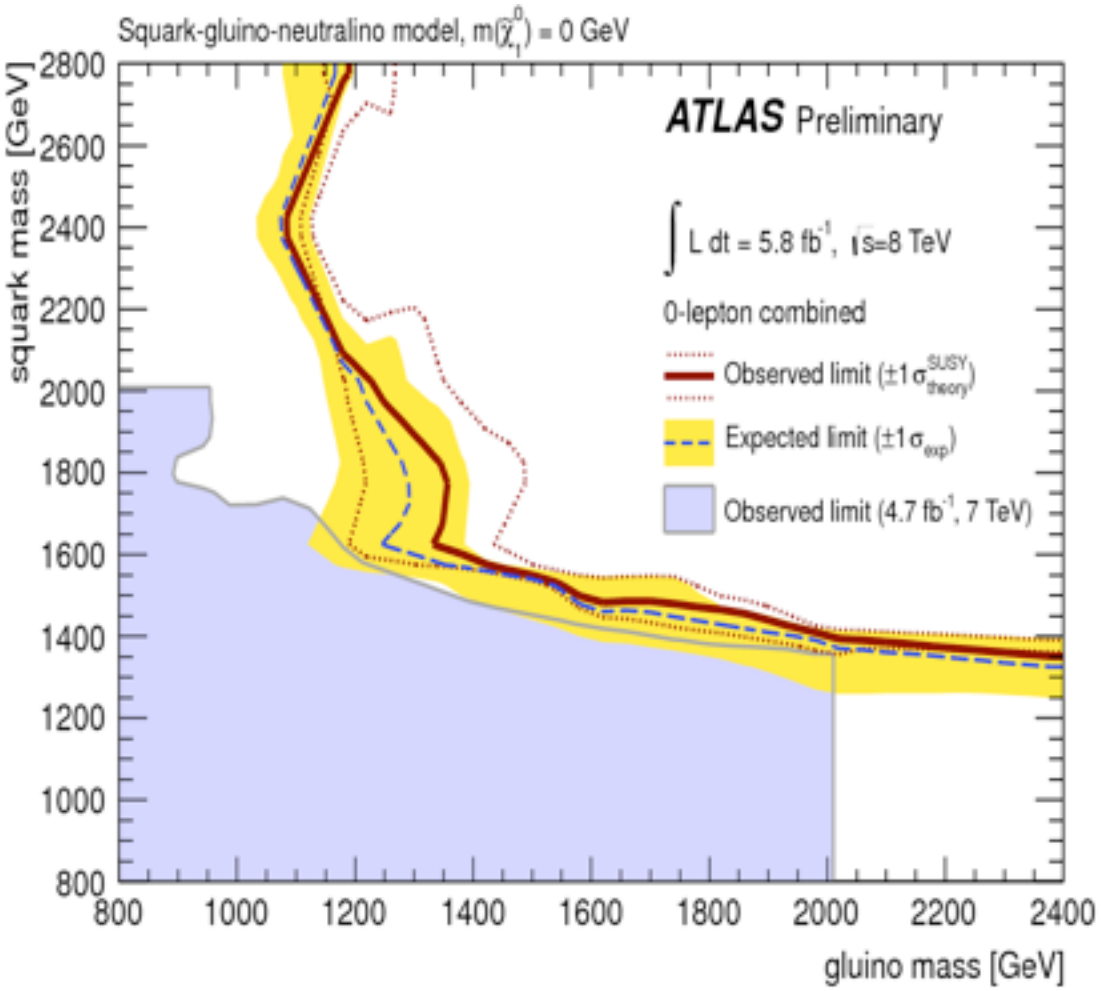
time to add this?

<u>nope</u>: there are still (natural) ways to avoid bounds

"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 = θ²F, etc.), & suppressed by messenger scale

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

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

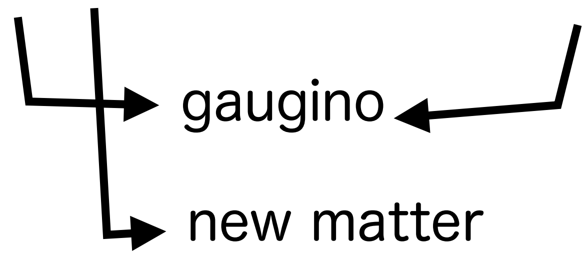
$$\omega_Y \frac{F}{M_{mess}} \lambda_Y \lambda_Y \rightarrow m_{1/2} \lambda_Y \lambda_Y$$

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:

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

Extra matter

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

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

new adjoint scalars

D-term for SM gauge groups

eliminating D_a ...

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

new trilinear interactions

could also add

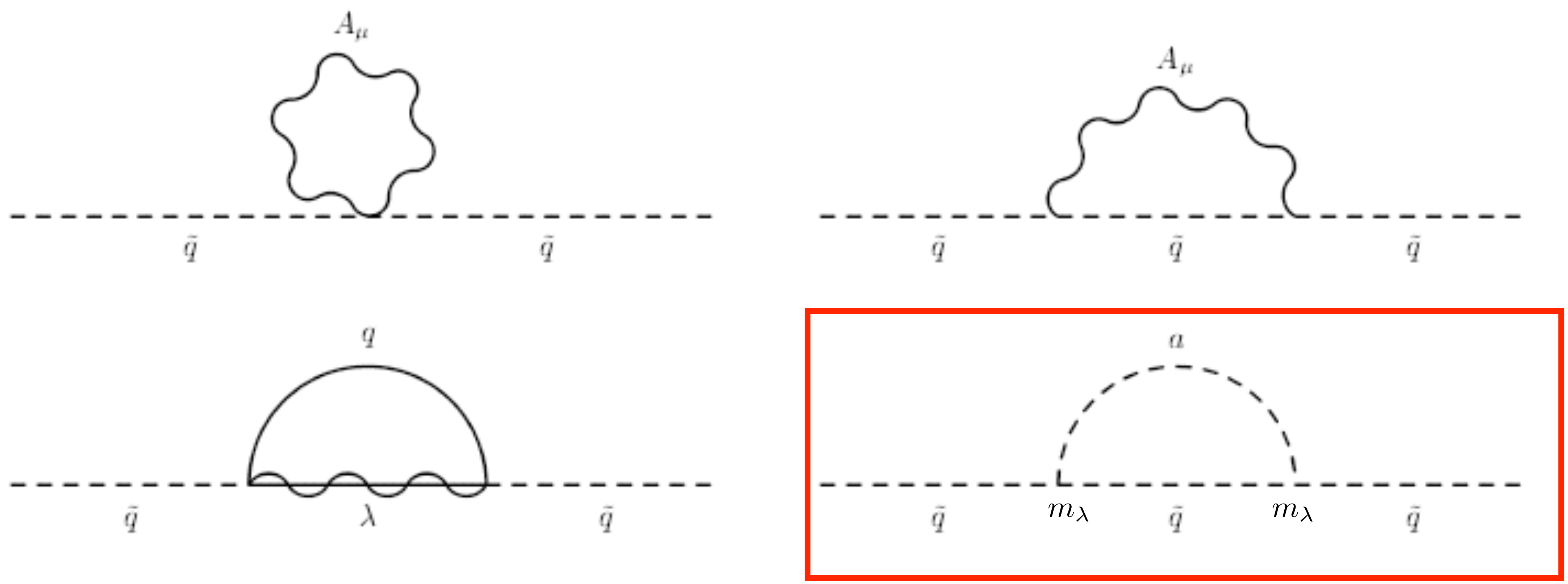
$$\int d^2\theta\, \frac{\mathcal{W}'_\alpha \mathcal{W}'_\alpha \Phi^a \Phi^a}{M_{mess}^2} + \text{h.c.}$$

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}!

Supersoft SUSY

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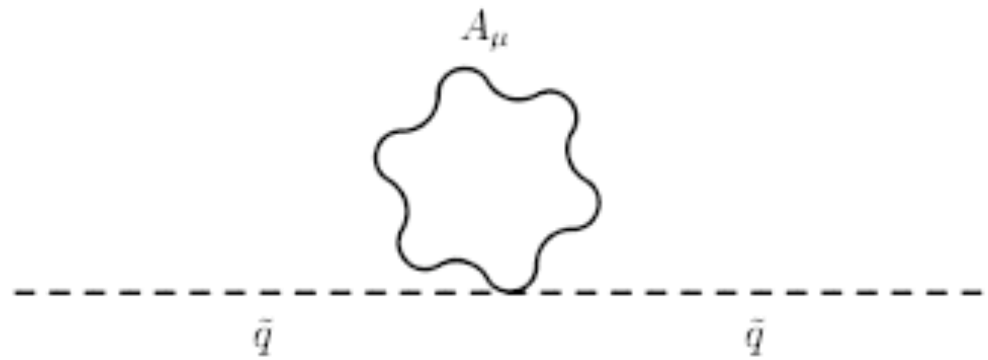

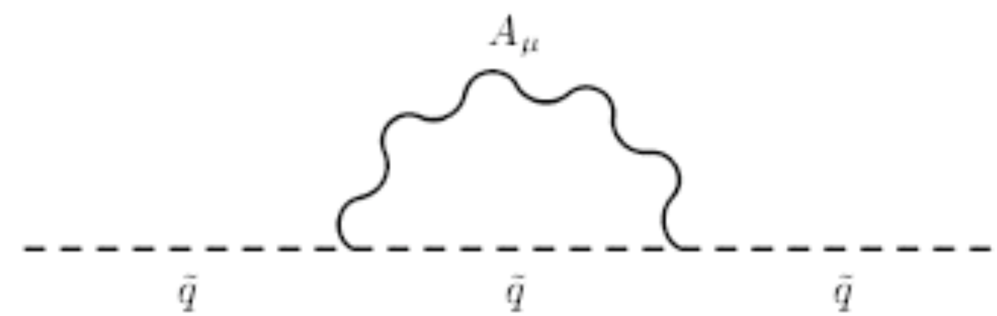

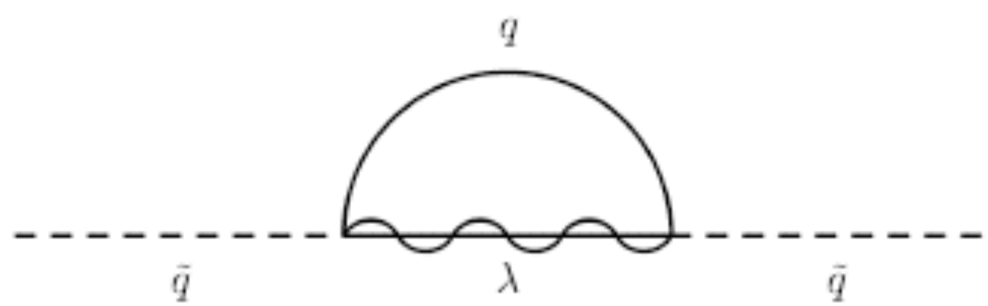

vs. in usual MSSM case

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

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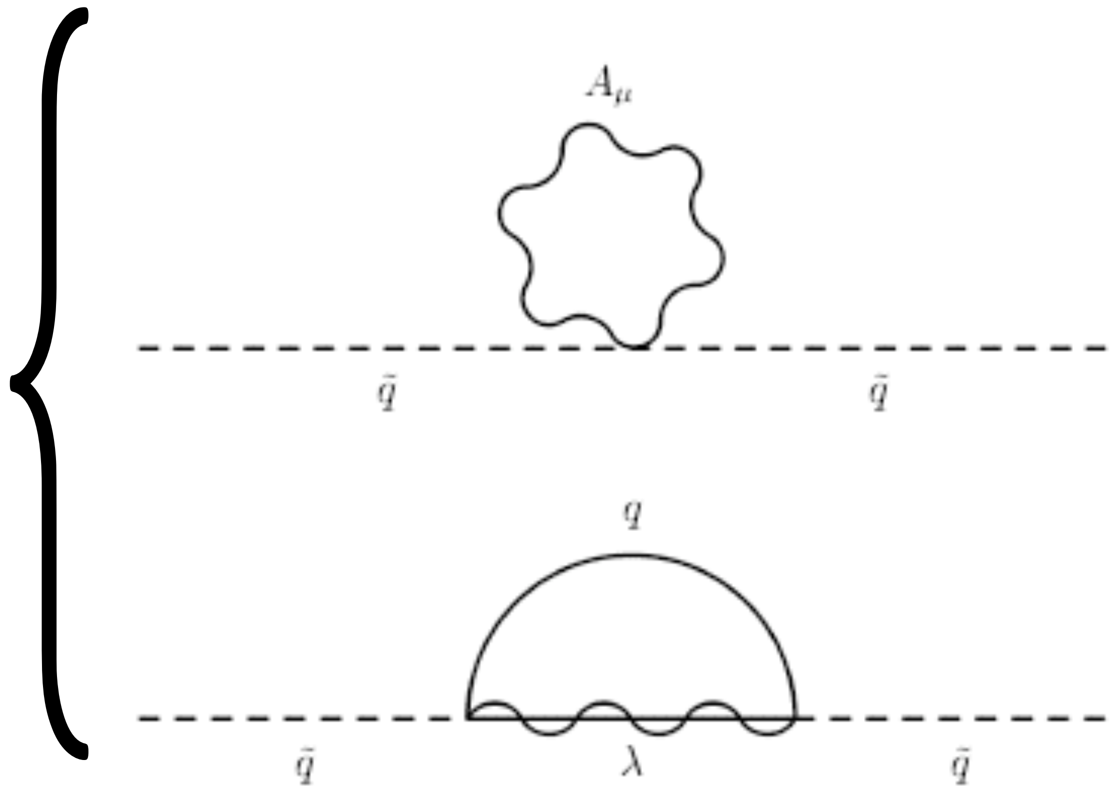

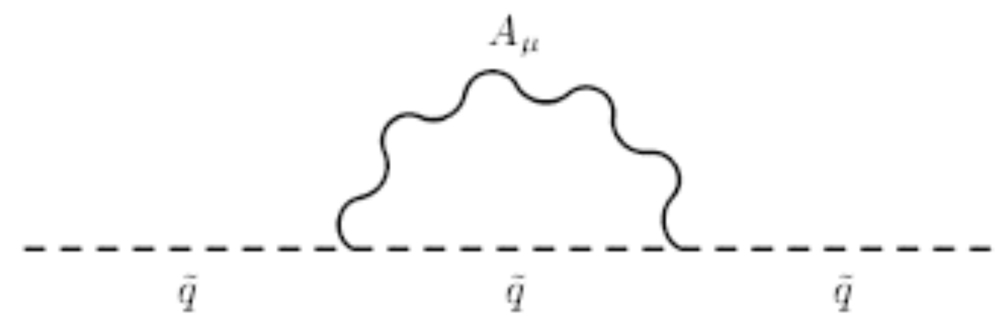

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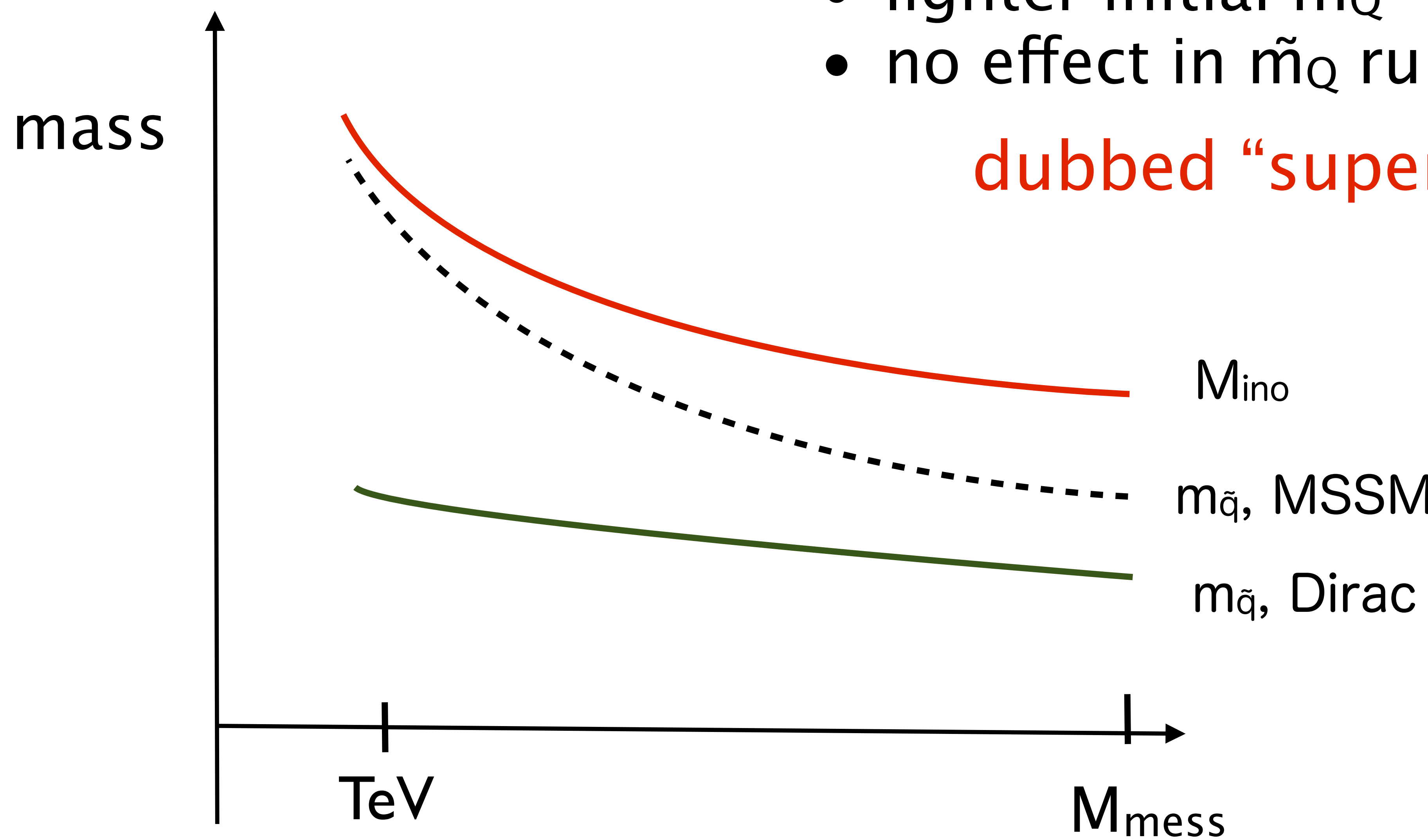
Dirac gauginos:

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

dubbed “supersoft”



$$
\begin{aligned}
16\pi^2 \frac{d}{dt} m^2_{Q_3} &= 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^2_{\bar{u}_3} &= 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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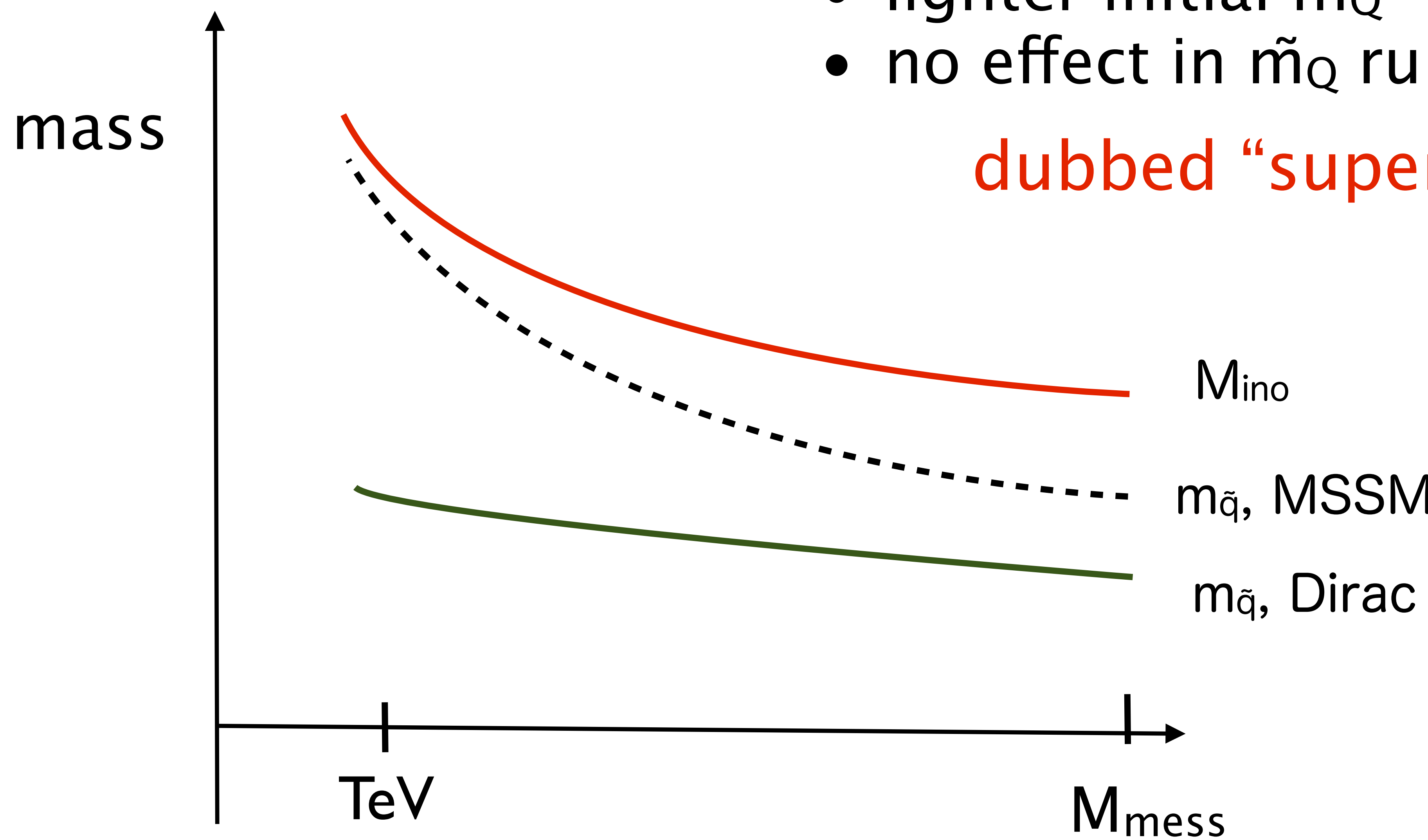

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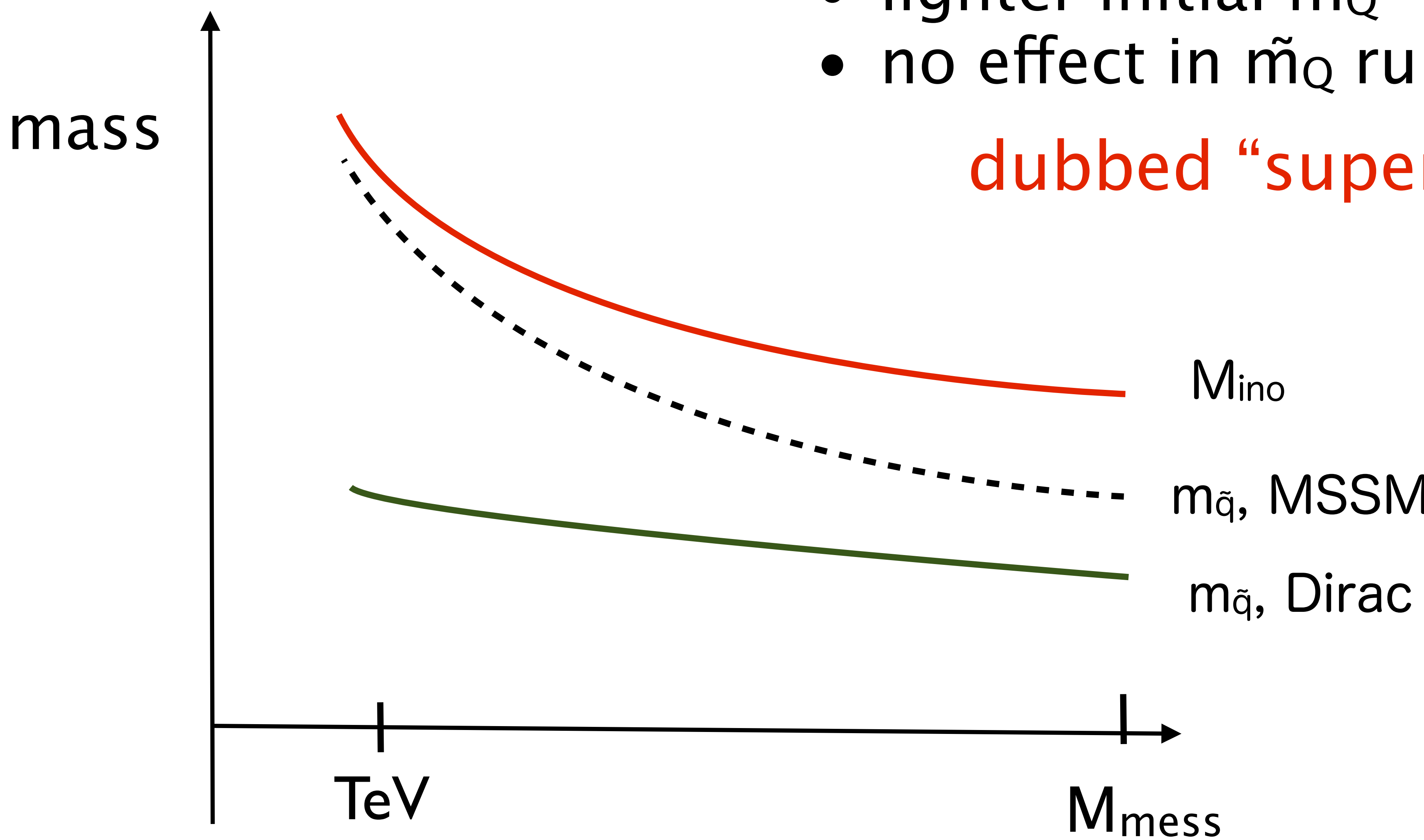

gluinos can easily be several TeV,
while the squarks are ≪ TeV

Supersoft SUSY: naturalness

$\delta m^2{}_H$: 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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$(M_3)_{Dir} = 5.0\,\mathrm{TeV}$

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

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:

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

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

$SU(2)_W$, $U(1)_Y$ 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?

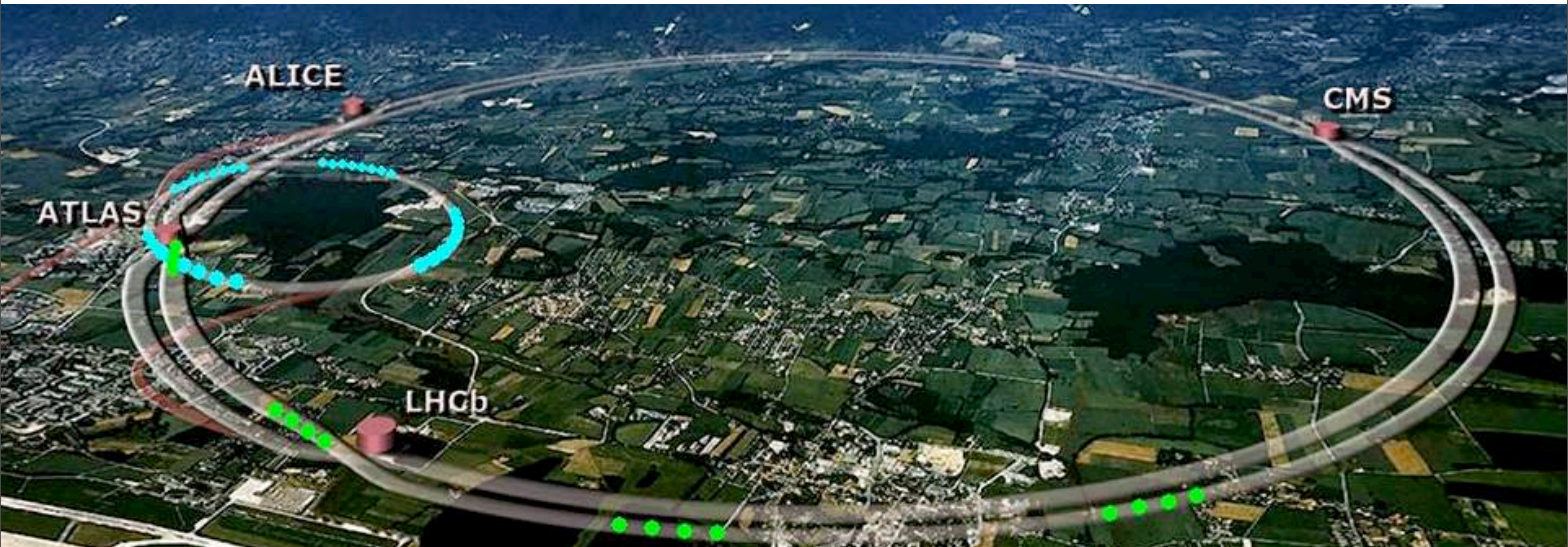
"pure" supersoft won't work. We could...

- 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



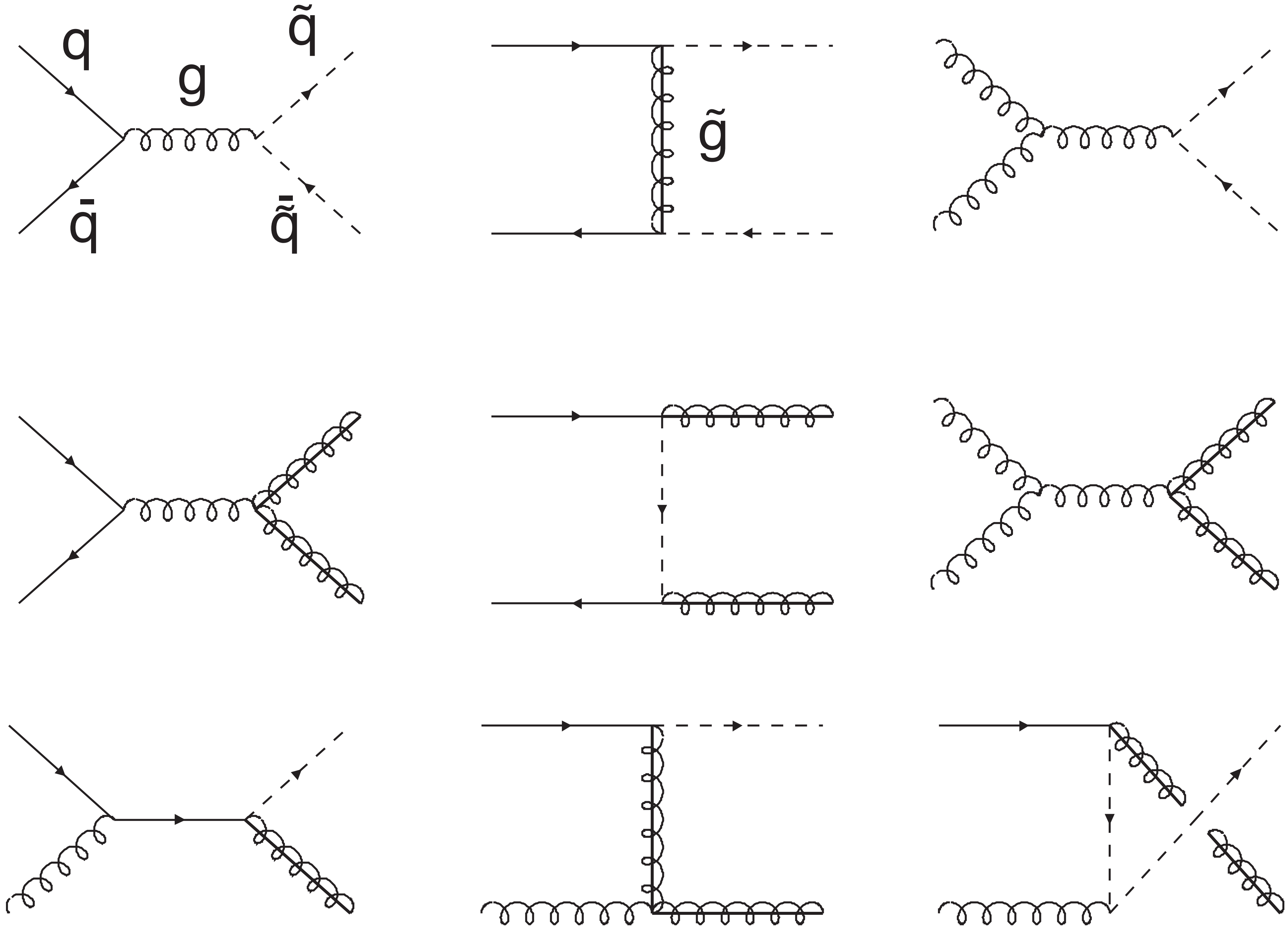
other work on Dirac gauginos @ LHC:

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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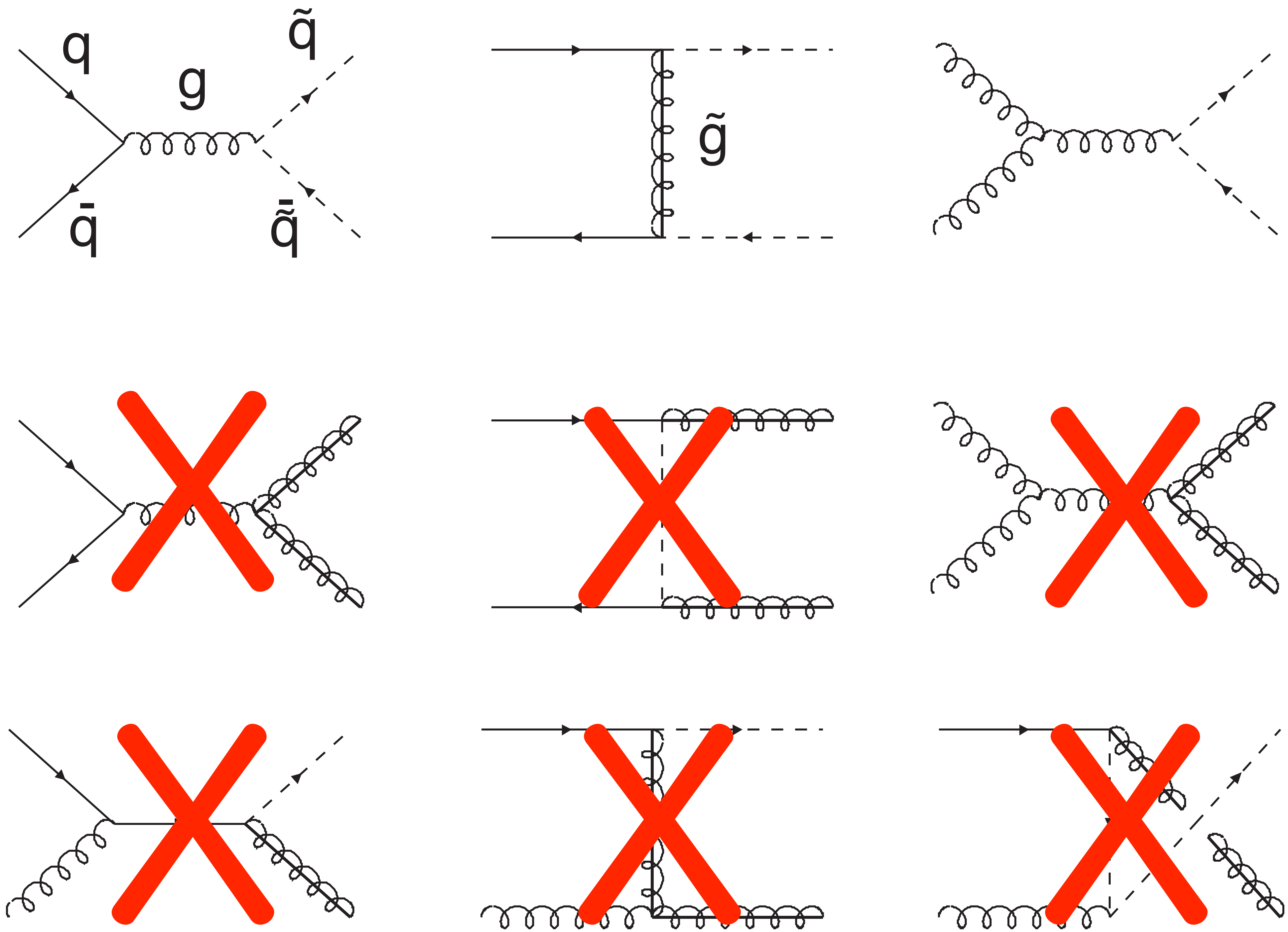


Supersoft at LHC

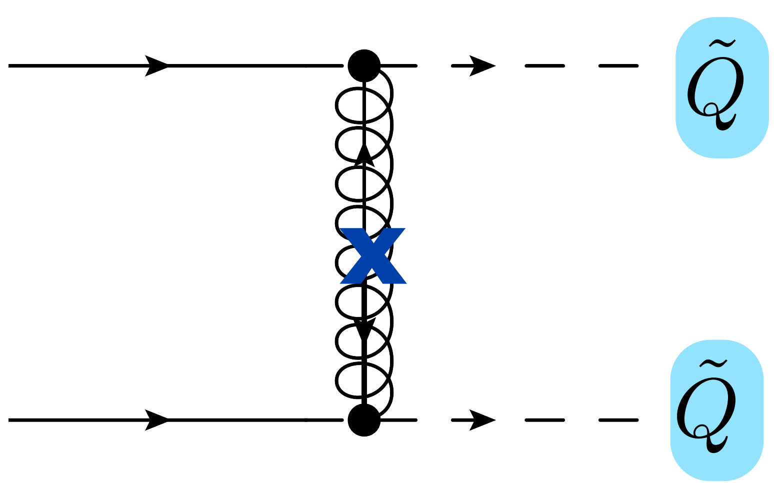
suppression goes beyond kinematics:

SUSY kinetic terms contain a U(1)R symmetry

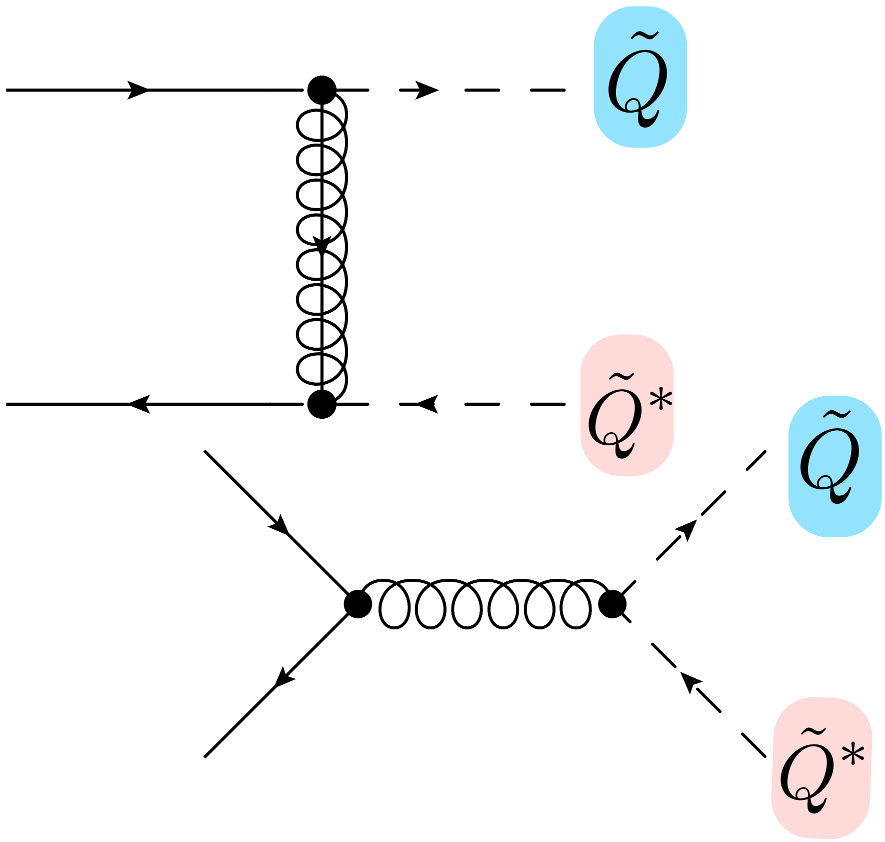
$$R[\lambda] = 1,\ R[q] = R[\tilde{q}]-1$$

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

restricts processes



violate R-symmetry



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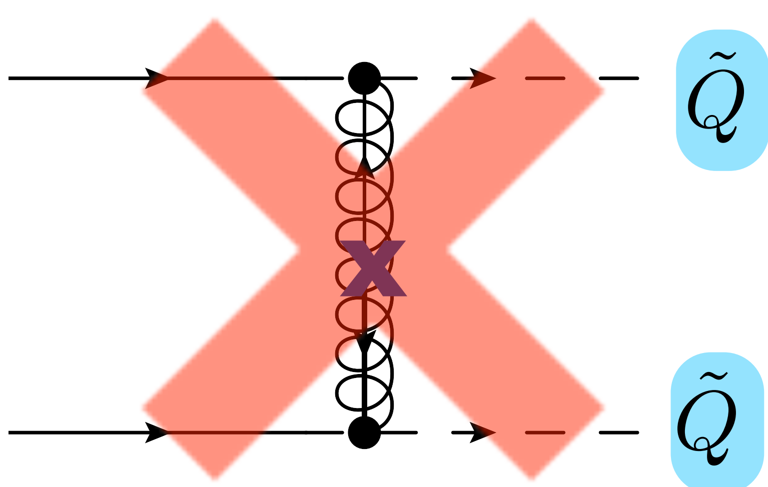

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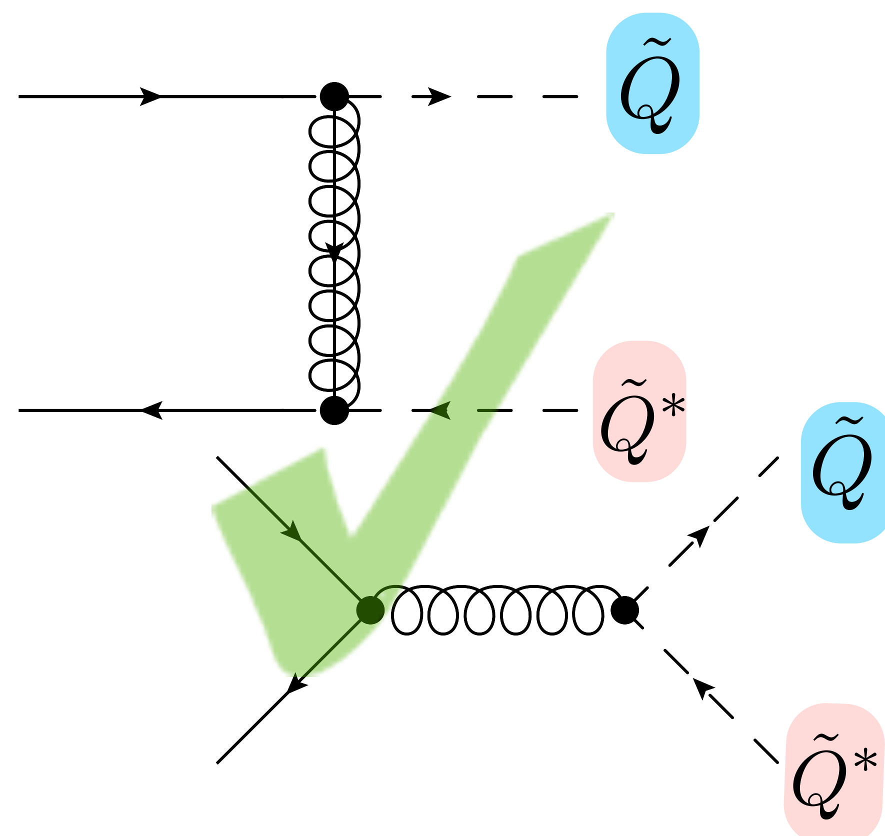

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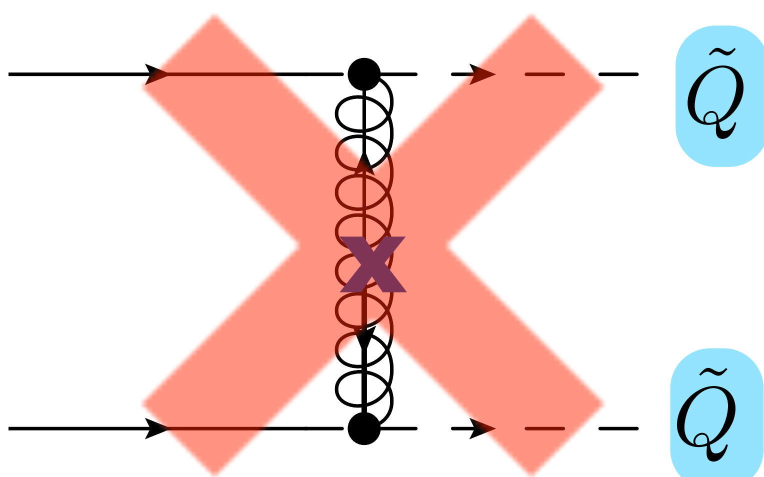

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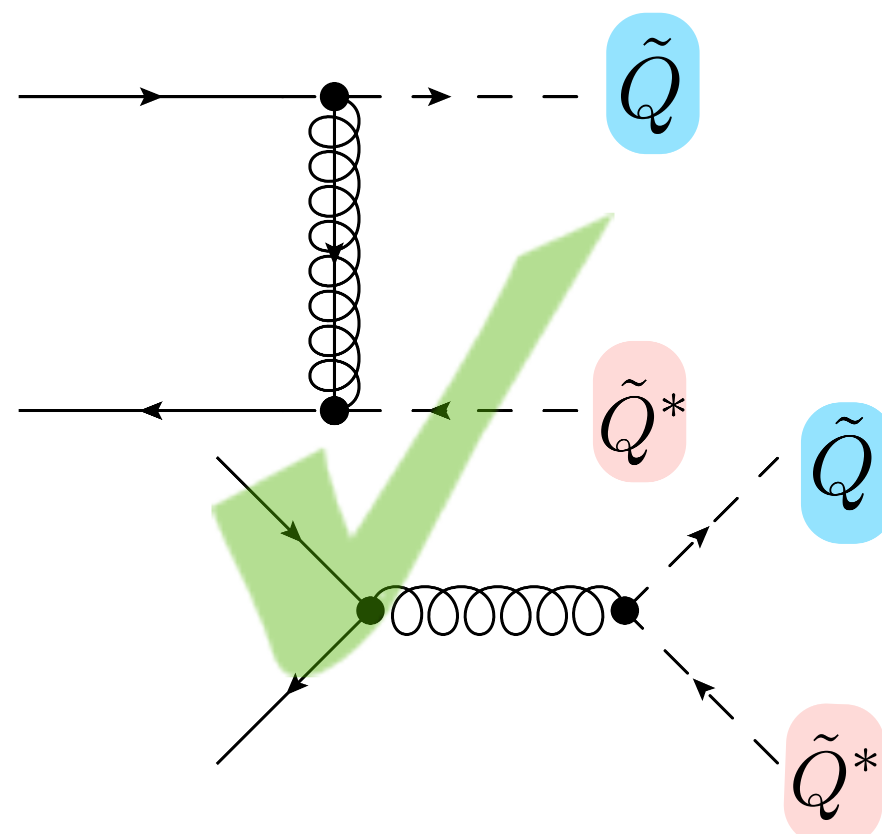
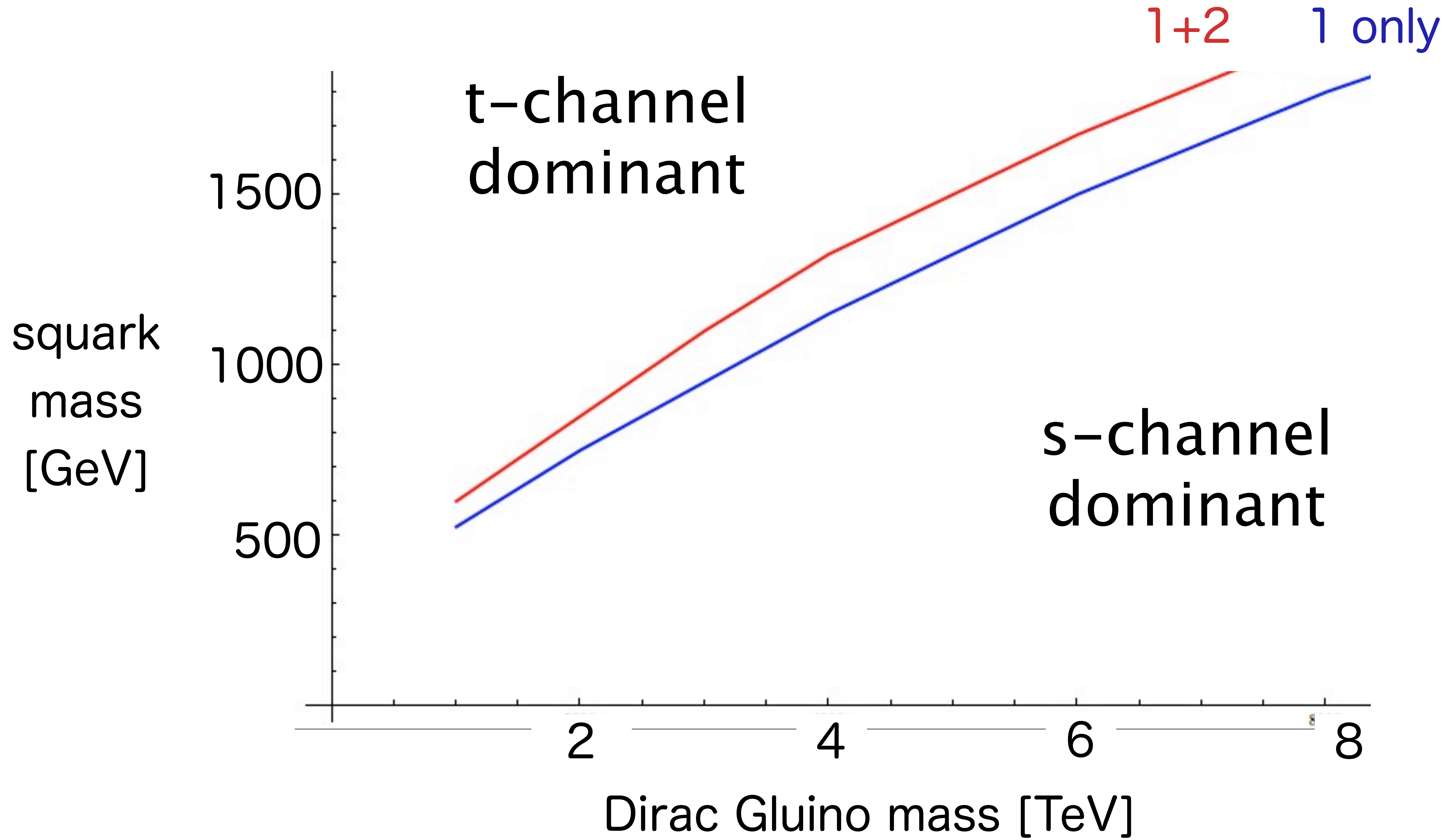


preserve R-symmetry

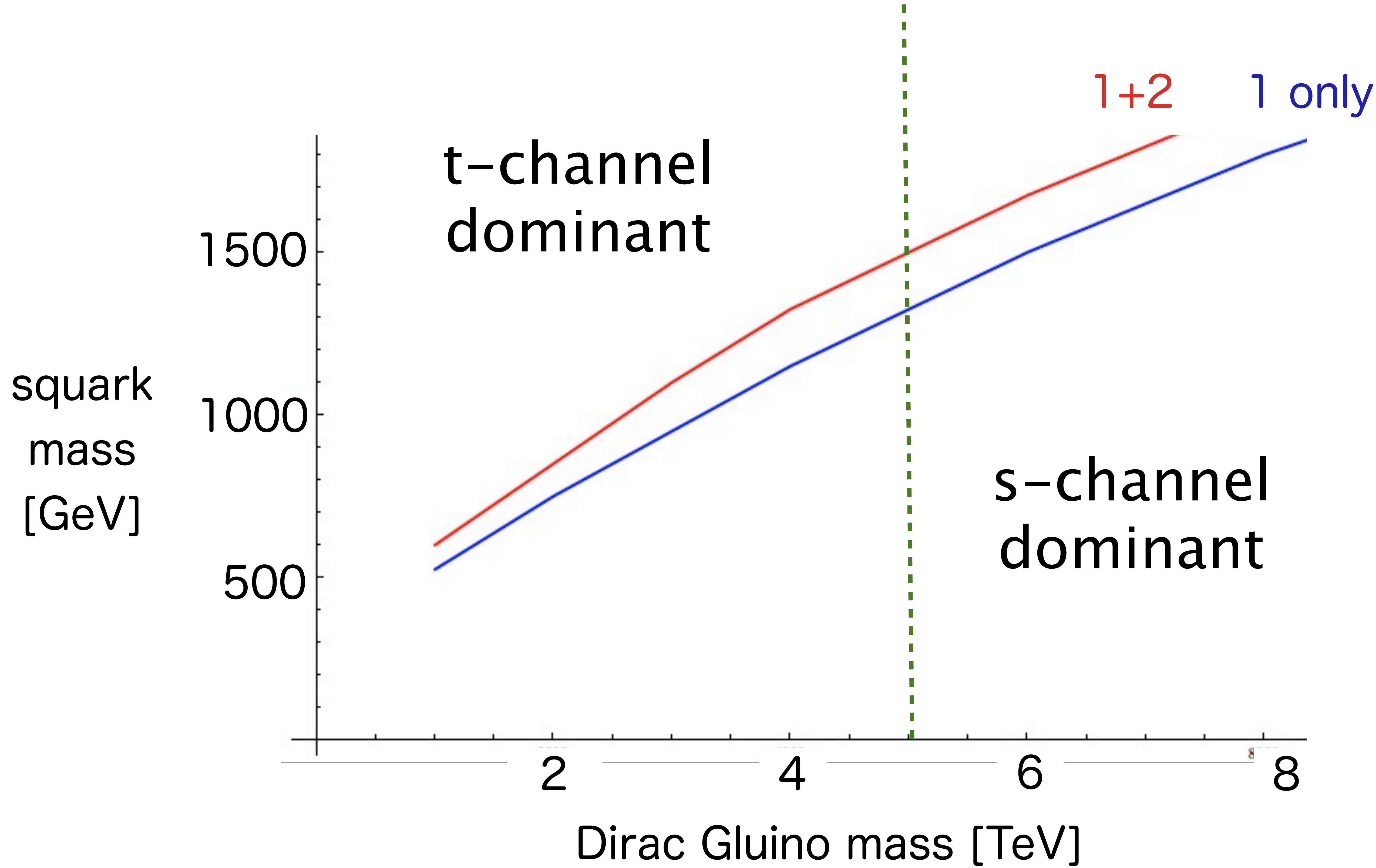
no $\tilde{q}\tilde{q}$, $\tilde{q}^*\tilde{q}^*$, only $\tilde{q}\tilde{q}^*$

Components of supersoft production



[Kribs & Raj]

Components of supersoft production



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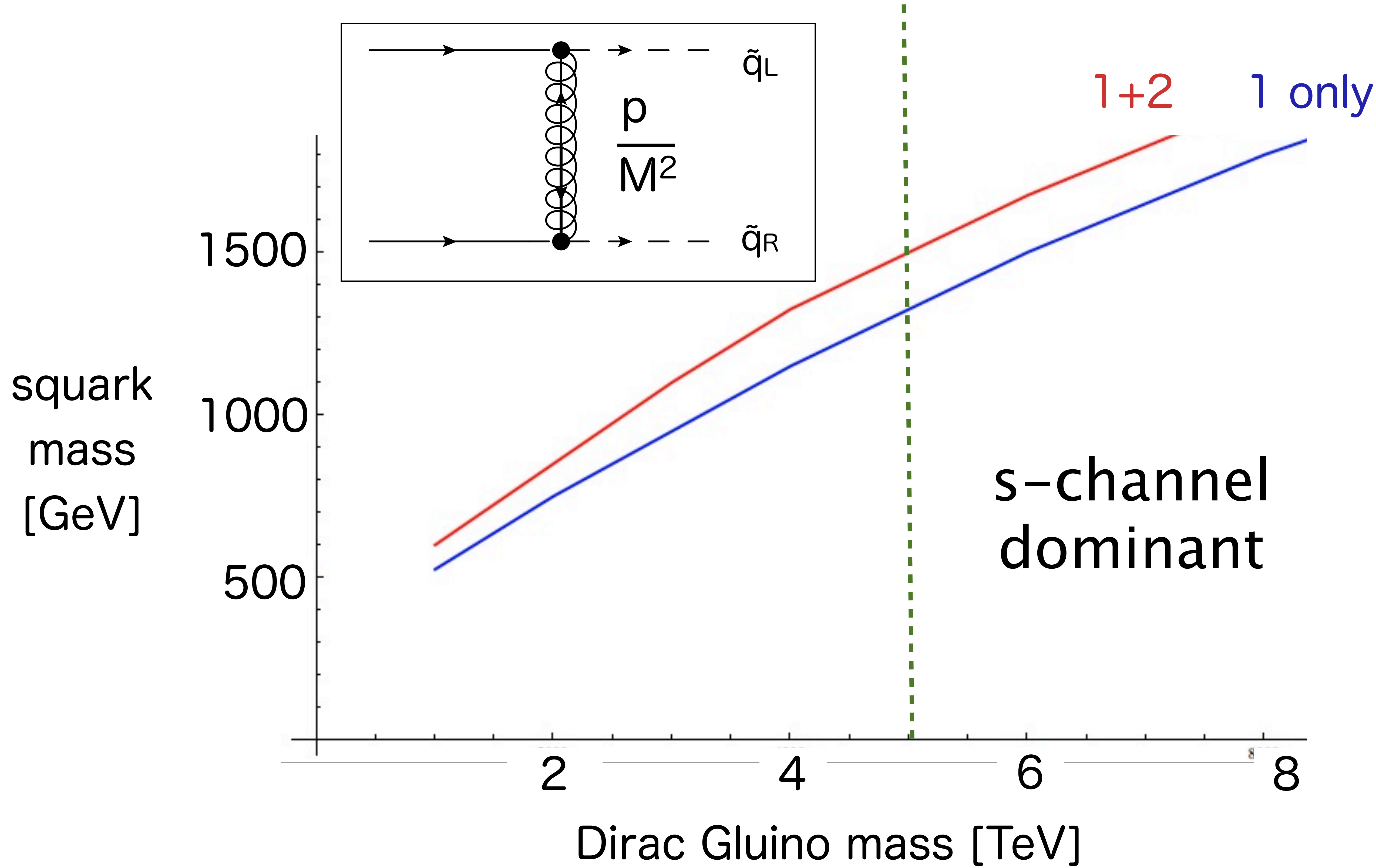

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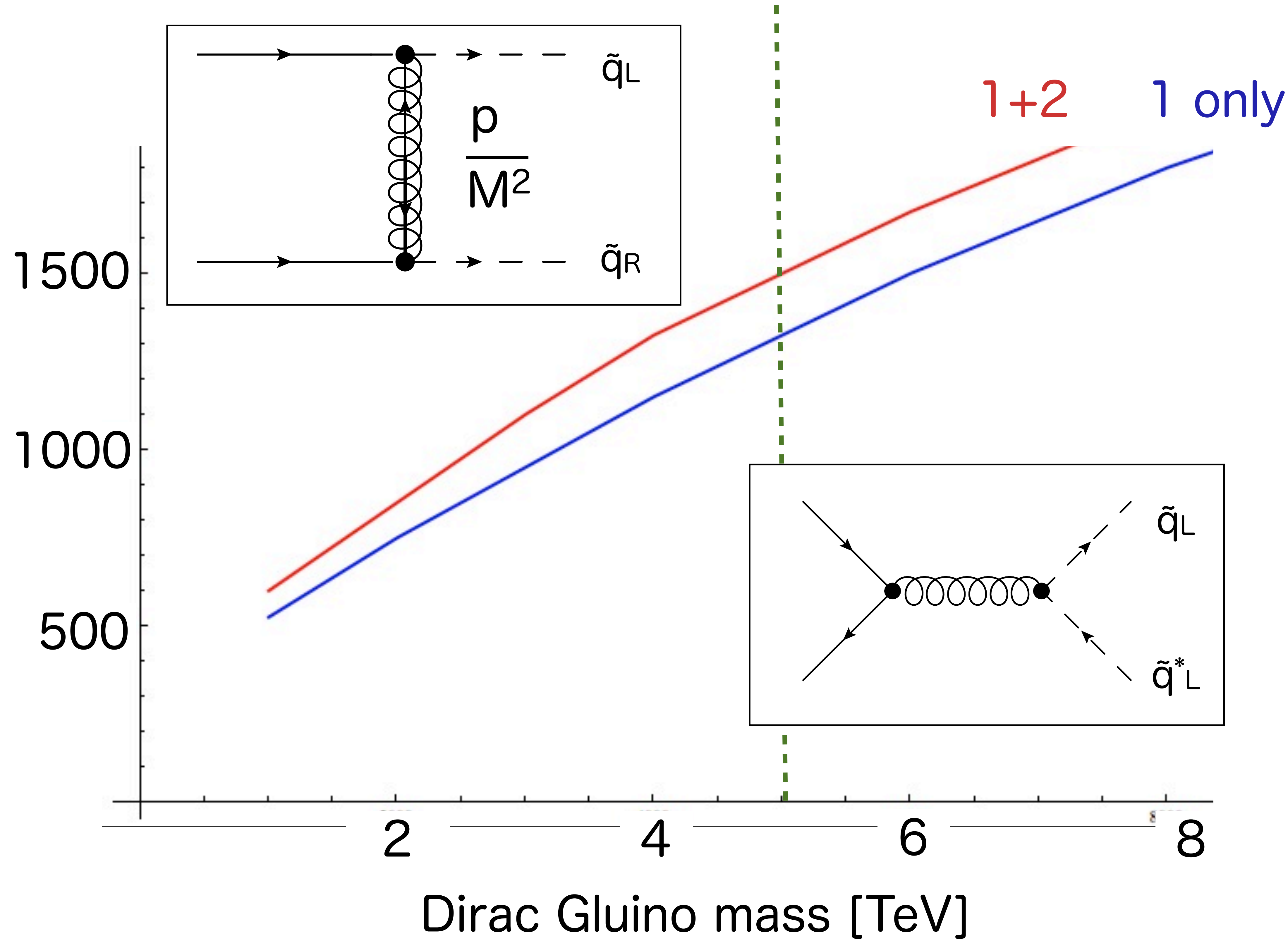

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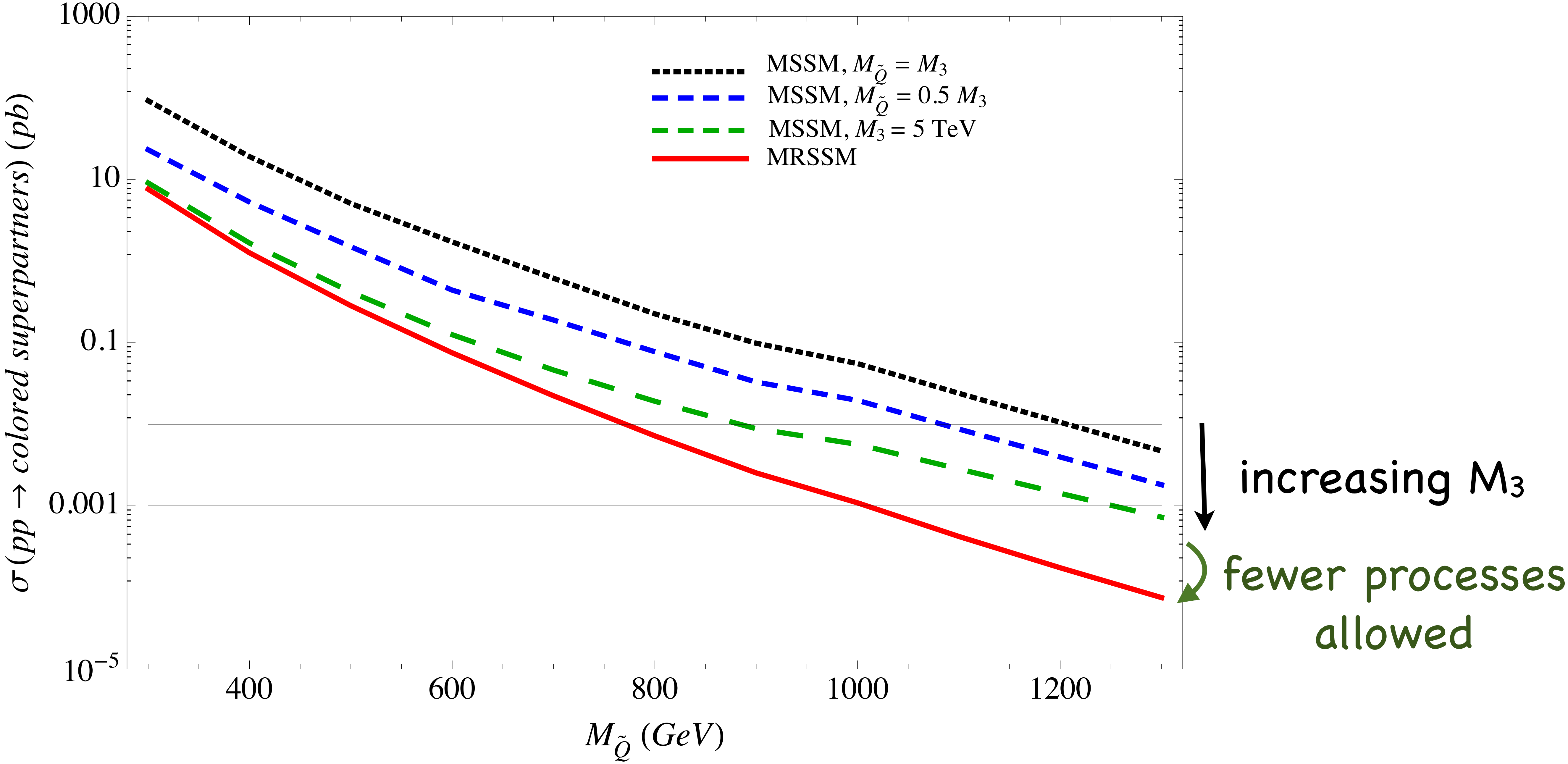
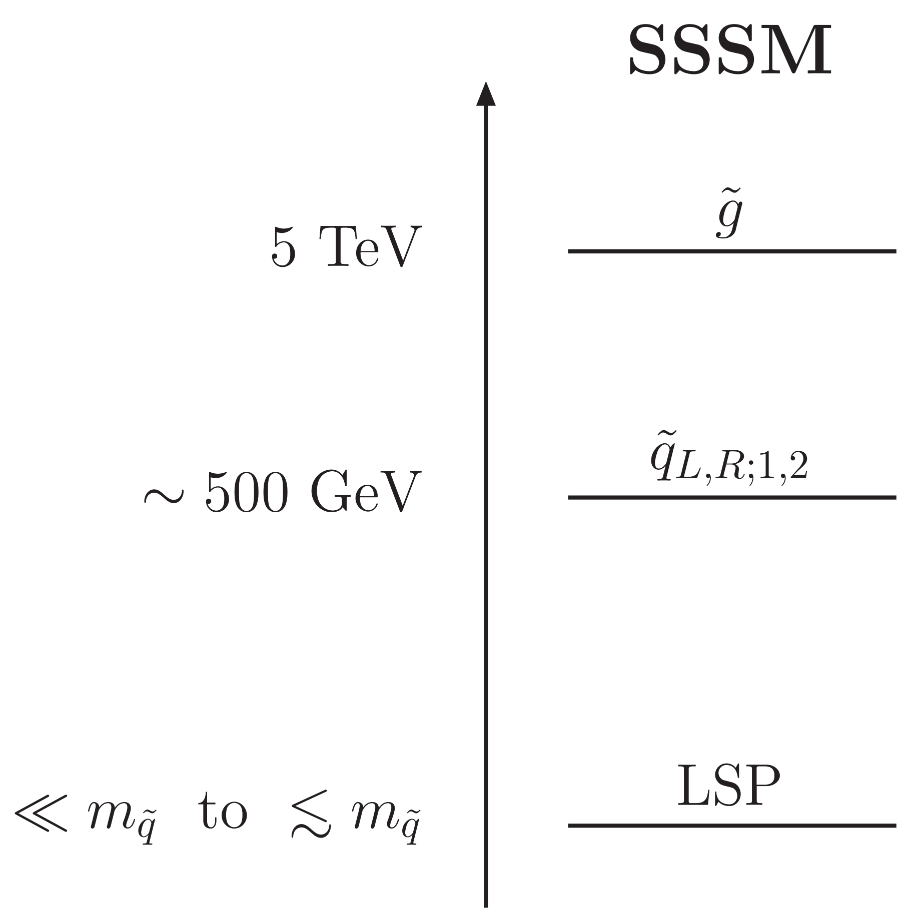


production of colored superstuff with Dirac gluino ≪ traditional MSSM

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

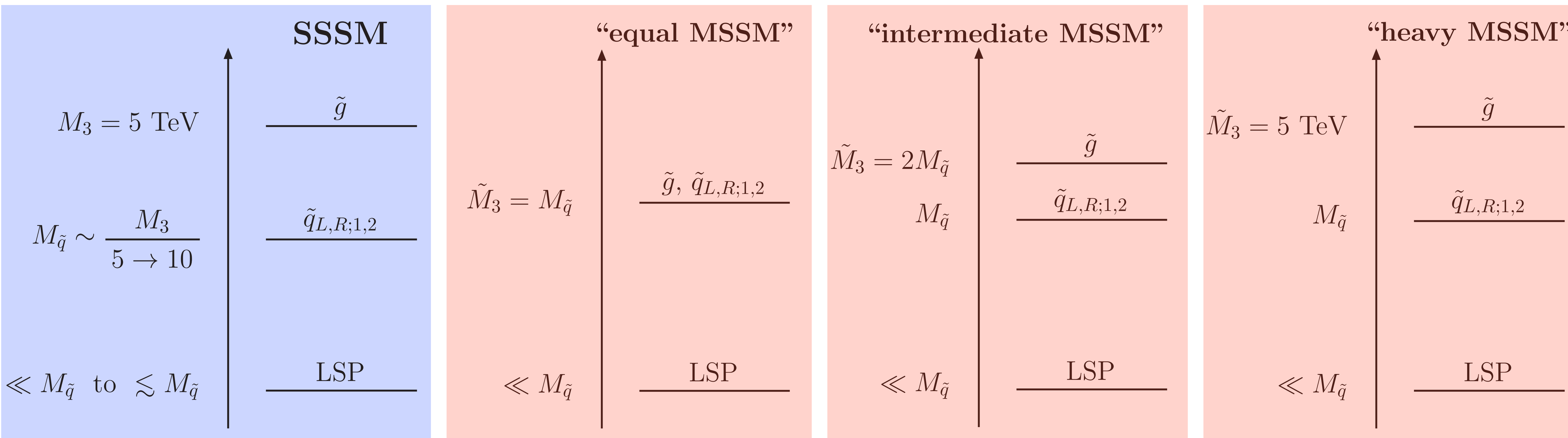
[1109.6752, 1109.2352, CMS-PAS-SUS-11-004, 1107.1279]

signal generated with PYTHIA->Delphes, gets acceptance

PROSPINO for K-factor

Supersoft versus MSSM Simplified Models

then perform apples-for-apples comparison against MSSM.

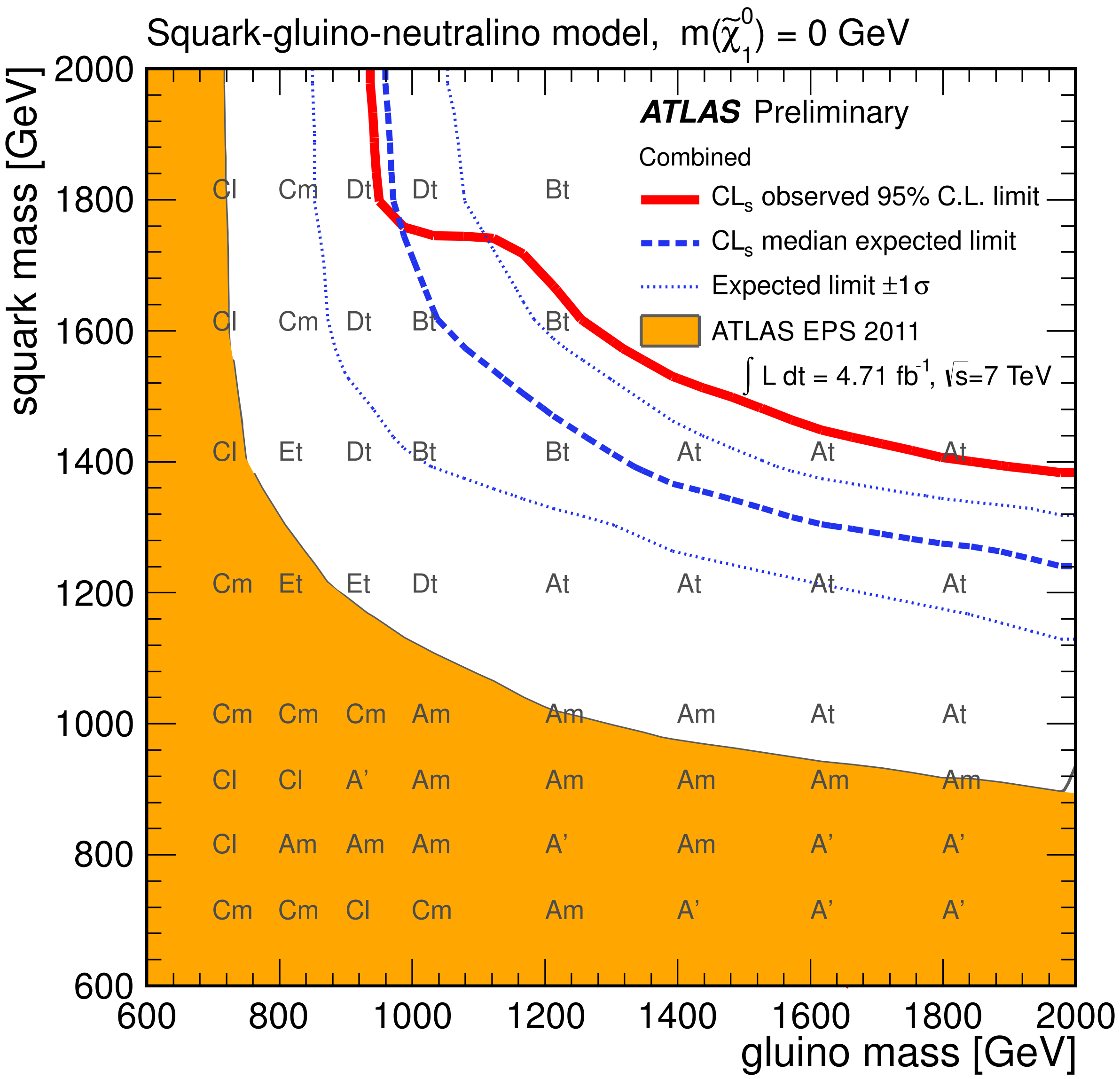


from quoted backgrounds + uncertainly, use calculated cross section (NLO), derived acceptance to bound SUSY parameters

= 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

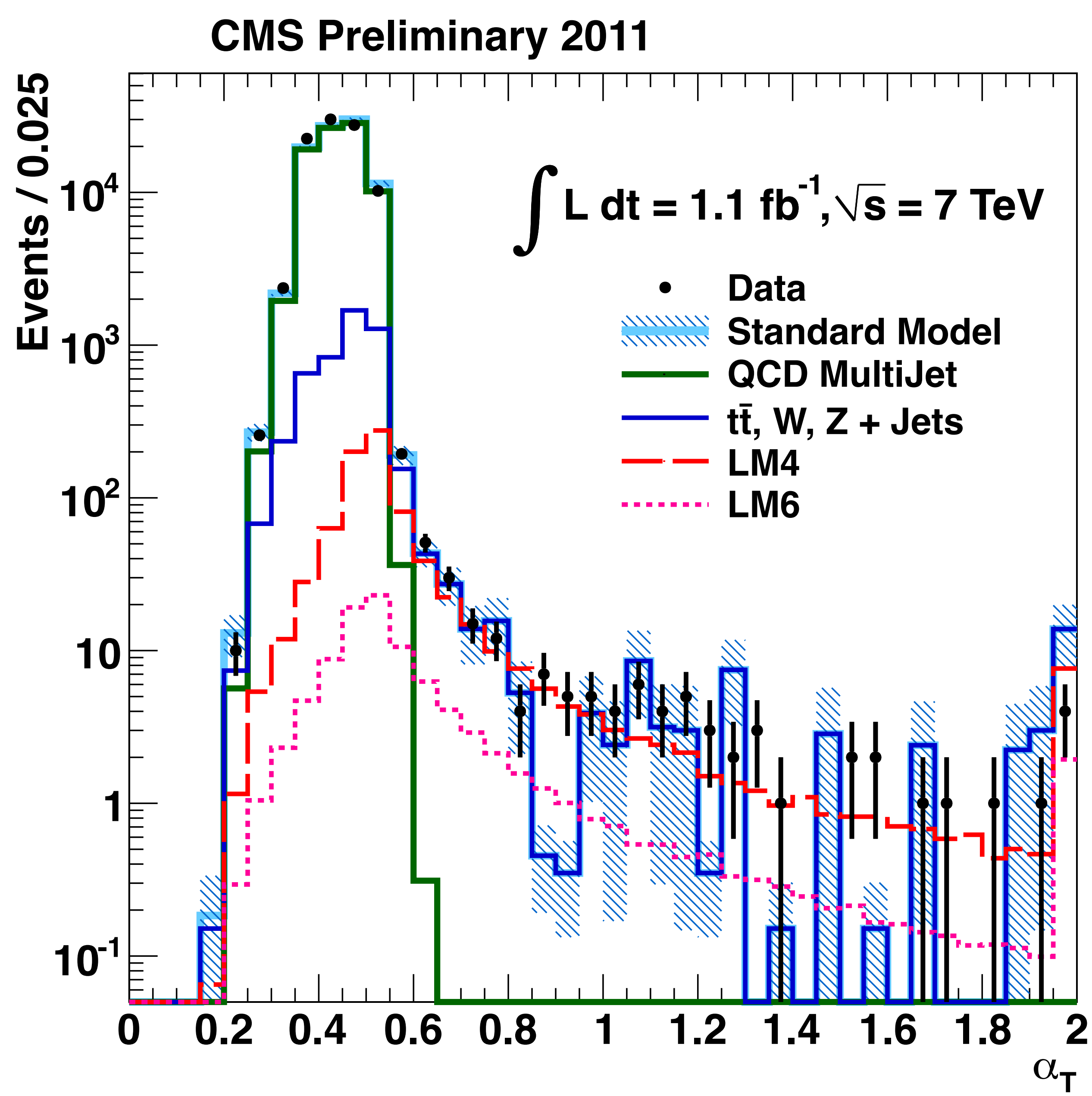
$$H_T = \sum_{i=1}^{n} E_T^{\mathrm{jet}_i}$$

- missing E_T > 100 GeV

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

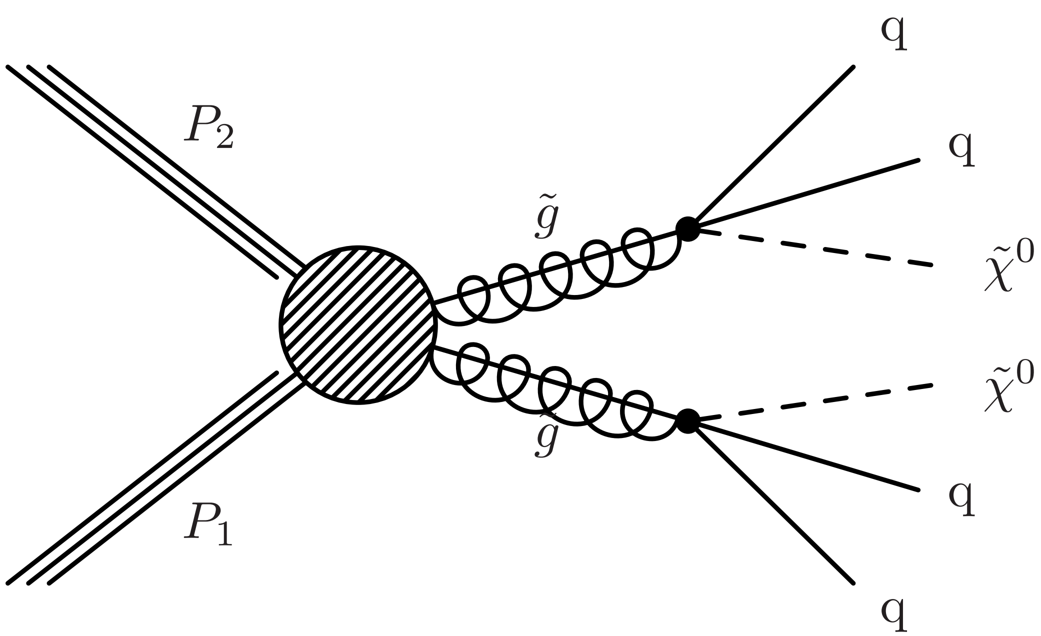
cut on:

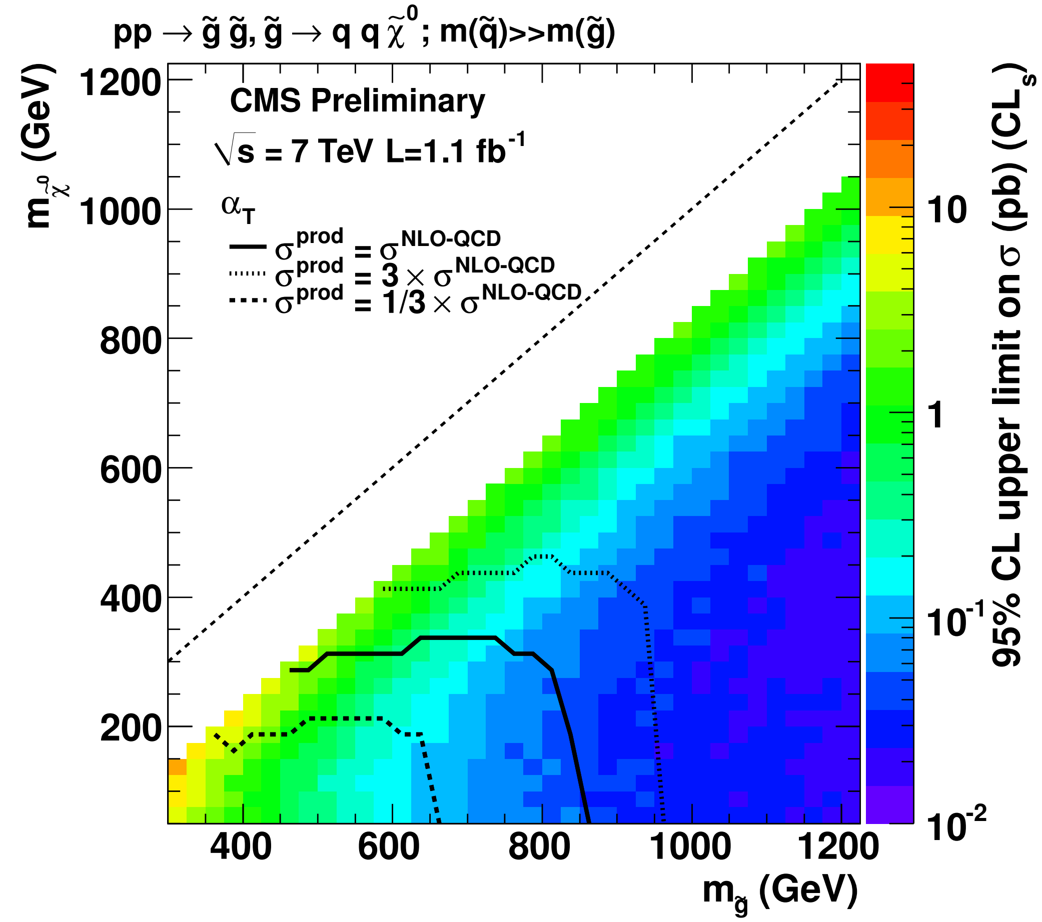
$$\alpha_T = E_{T,jet\#2} / M_{T(j1j2)}$$

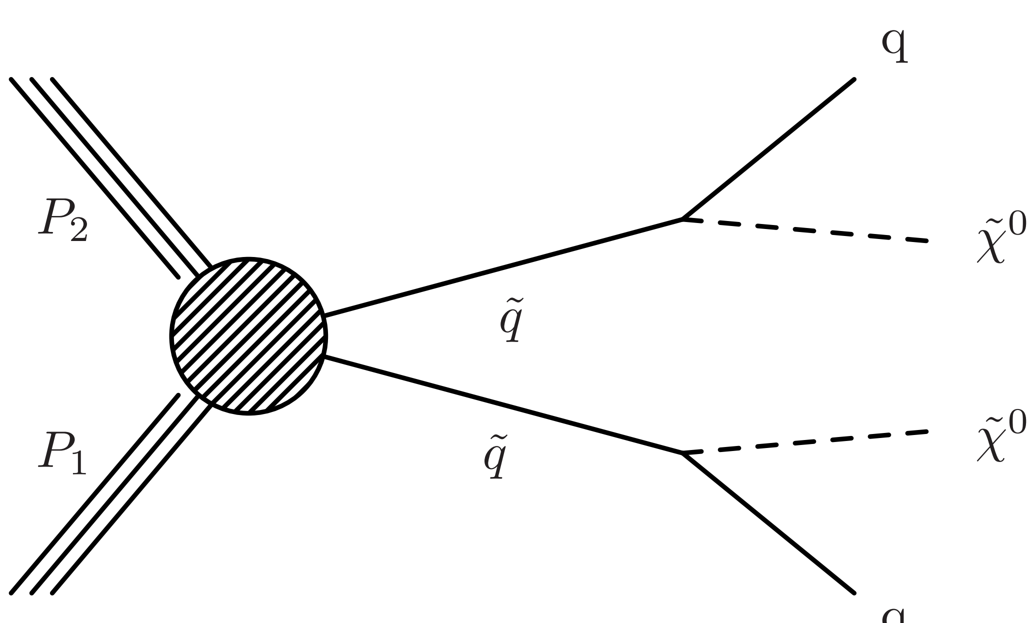


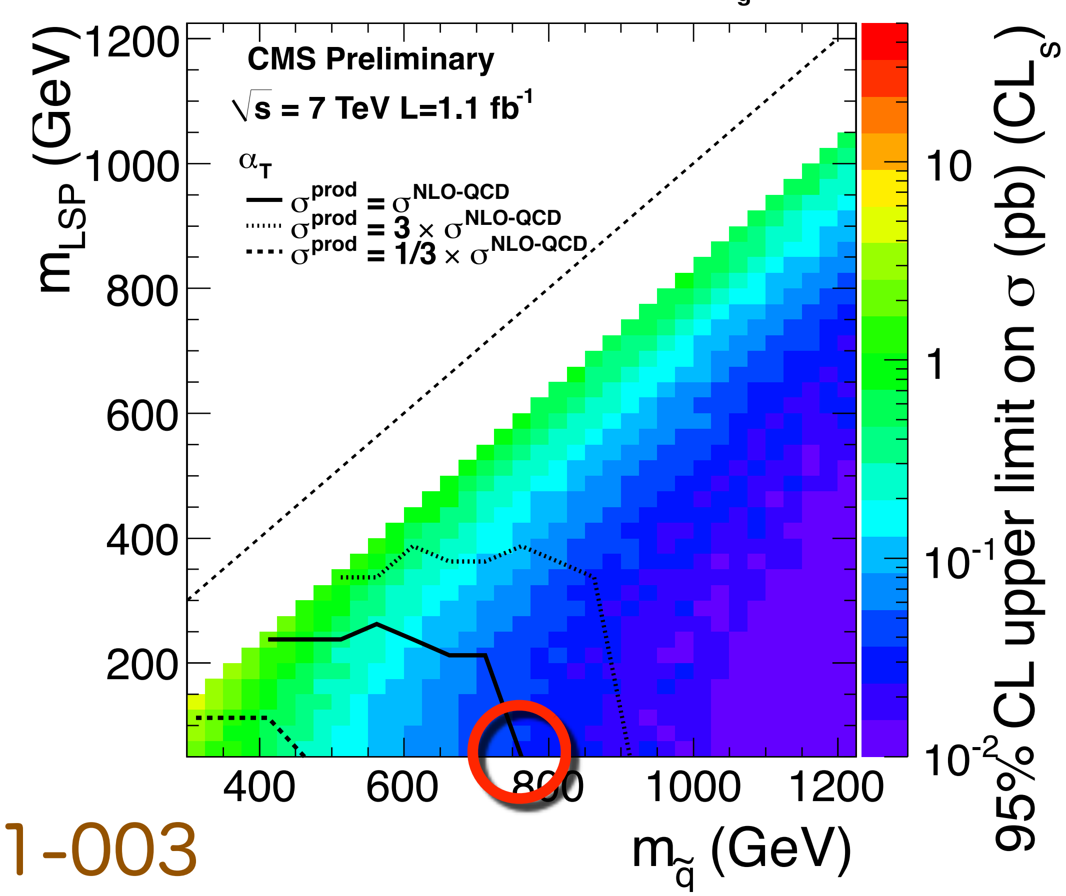
CMS-SUS-11-003

CMS Bounds on Simplified Models









CMS-SUS-11-003

CMS α_T Search Bounds

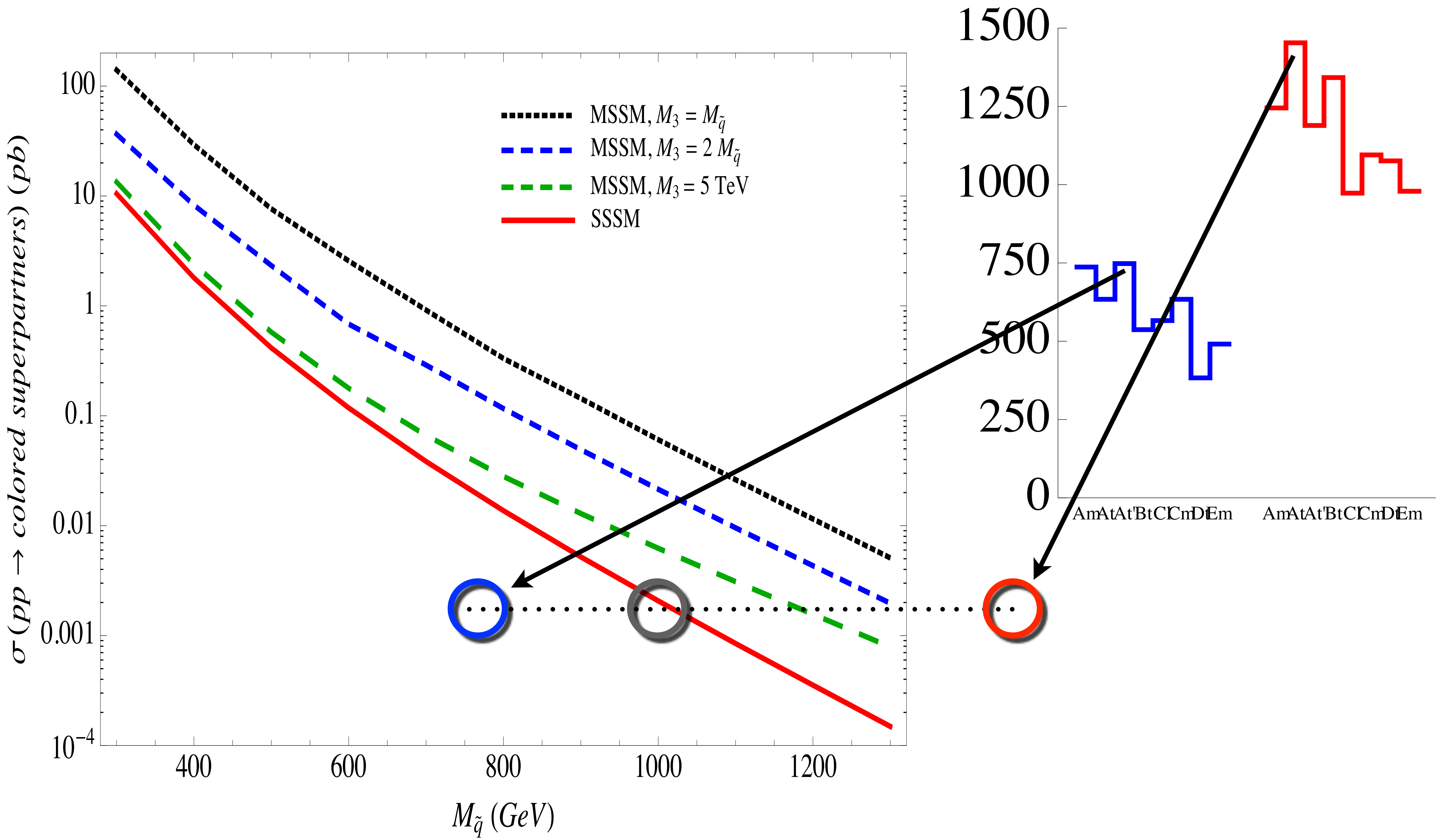
	SSSM	MSSM	MSSM	MSSM
	M3 = 5 TeV	M3 = Msq	M3 = 2 Msq	M3 = 5 TeV

1st,2nd generation squark mass

Kribs & AM

Effectiveness of LHC strategy

difference in limits not just difference in cross-section

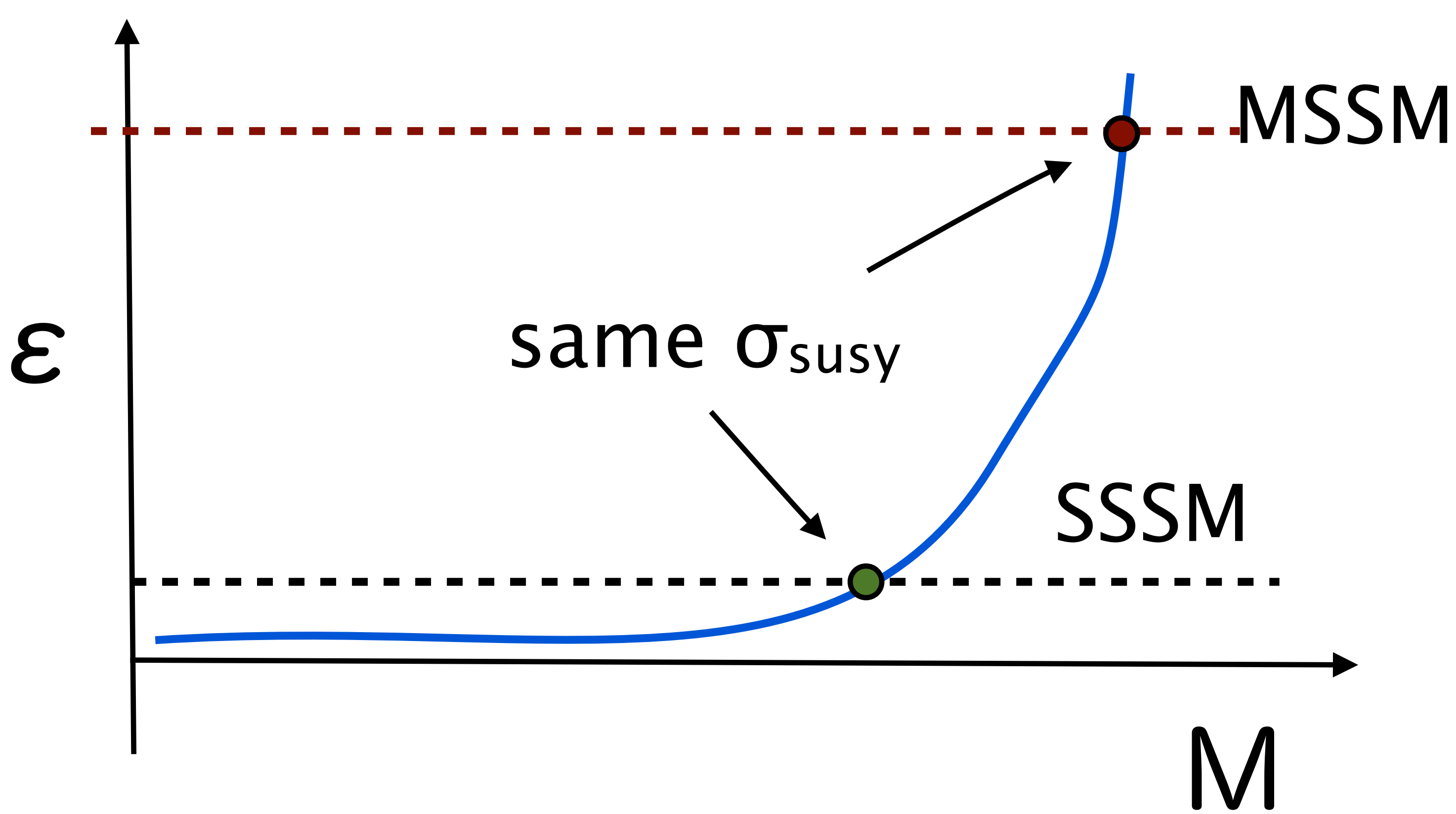


Effectiveness of LHC strategy

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



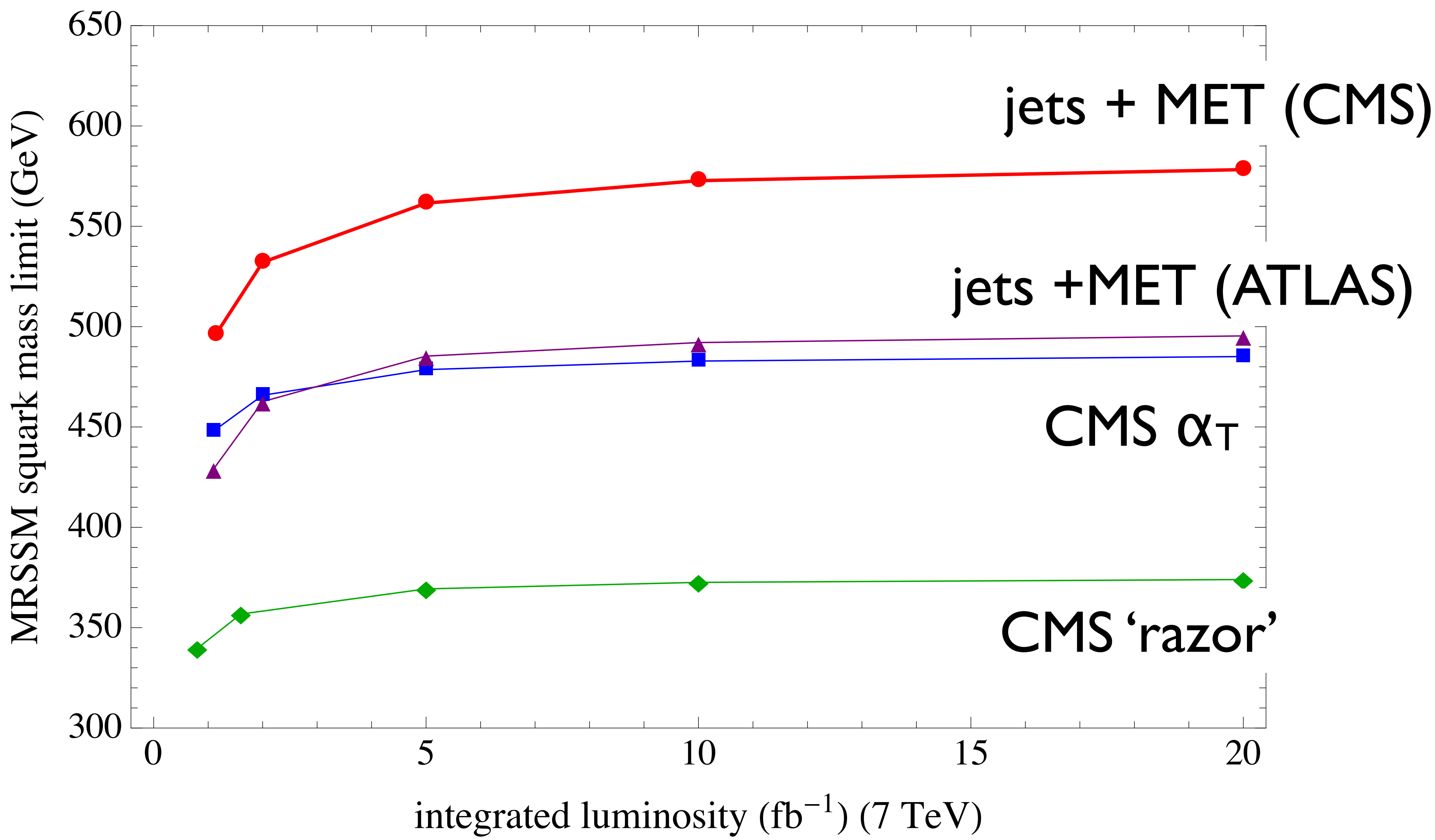
searches with a broader H_T reach would be useful

Supersoft limits

projection to higher luminosity

[Kribs, AM ’12]

expected limit from most stringent **single** channel



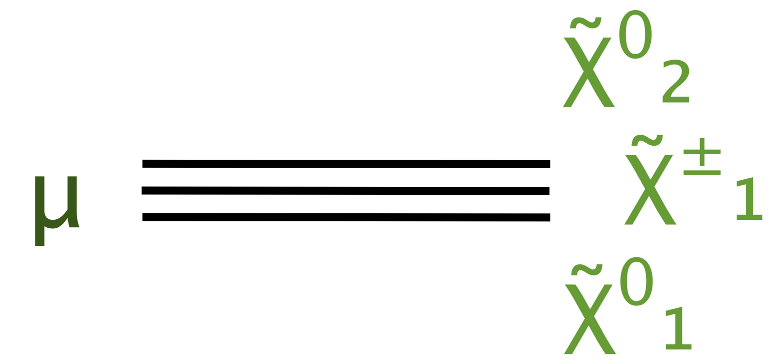
also: limits degrade as M_X gets closer to M_Q

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...

[AM, V. Sanz in progress]

.. About that Higgs mass

... add another source of SUSY breaking:

[Kribs, Okui, Roy '11]

$$\mathbf{X} = \theta^2 \mathbf{F}$$

provided **X** is not a singlet, can't write **X** $W_a W_a$,
gauginos still Dirac

now matter can get mass via: $\dfrac{X^\dagger X\, Q^\dagger Q}{M^2_{mess}}$

mass term: $\dfrac{X^\dagger X\, \Phi_a^\dagger \Phi_a}{M^2_{mess}}$

new adjoints

effects Φ_a EOM, leads to tree-level quartic for Higgs

m_H ~ 125 GeV not a problem

About that Higgs mass

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

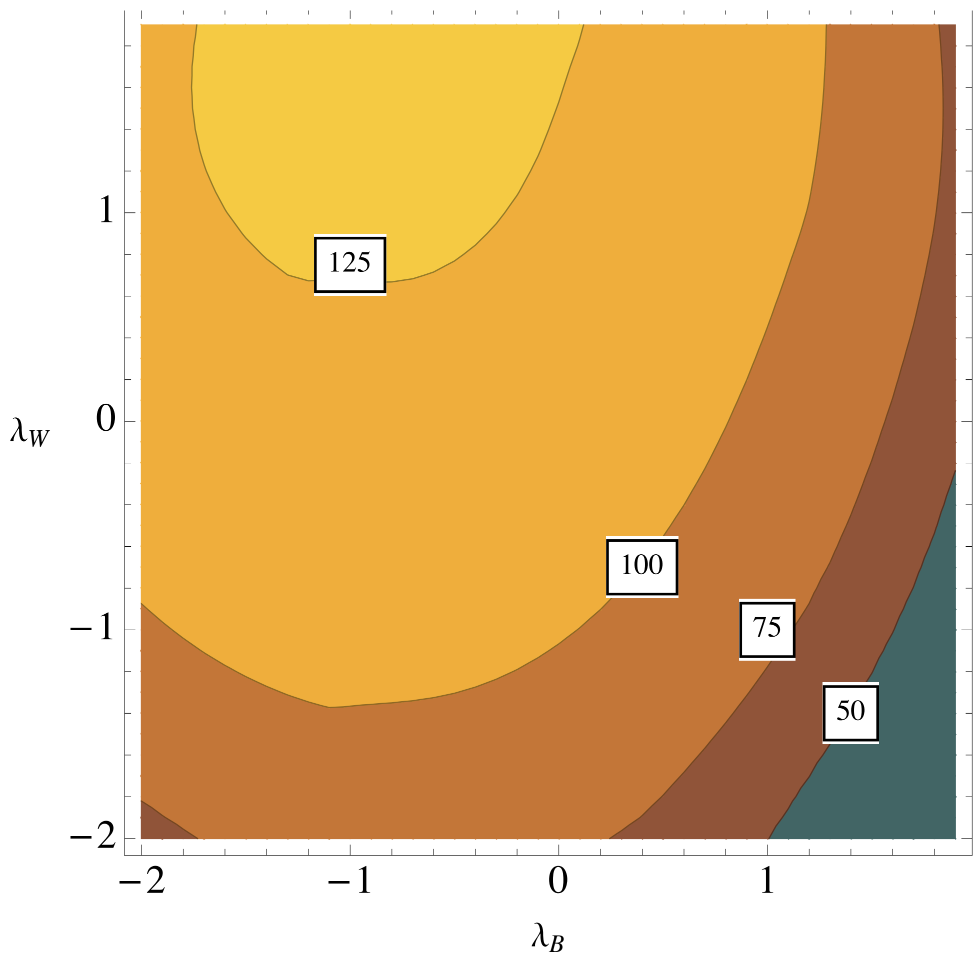
[Kribs, Poppitz, Weiner '07]

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

"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

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

[Fok, Kribs, AM, Tsai '12]

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[Kribs, Poppitz, Weiner '07]

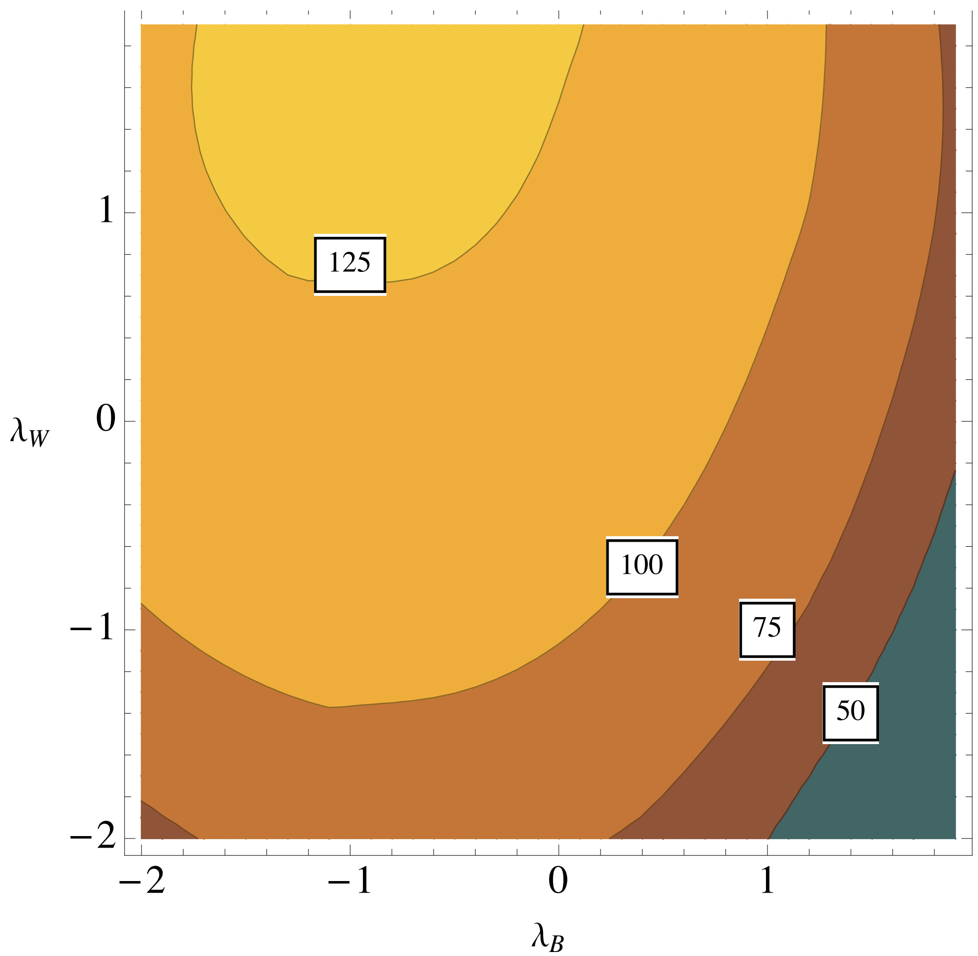
$$W \supset \mu_u\, H_u\, R_u + \mu_d\, R_d\, H_d$$

"μ"-term must be changed

interesting (s)flavor properties!

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

new terms in W



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[Fok, Kribs, AM, Tsai '12]

Conclusions

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

- significantly reduced colored sparticle production

  limits ($\lesssim$ 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

Maj. winos/binos

– many interesting directions to go in from here!

EXTRAS

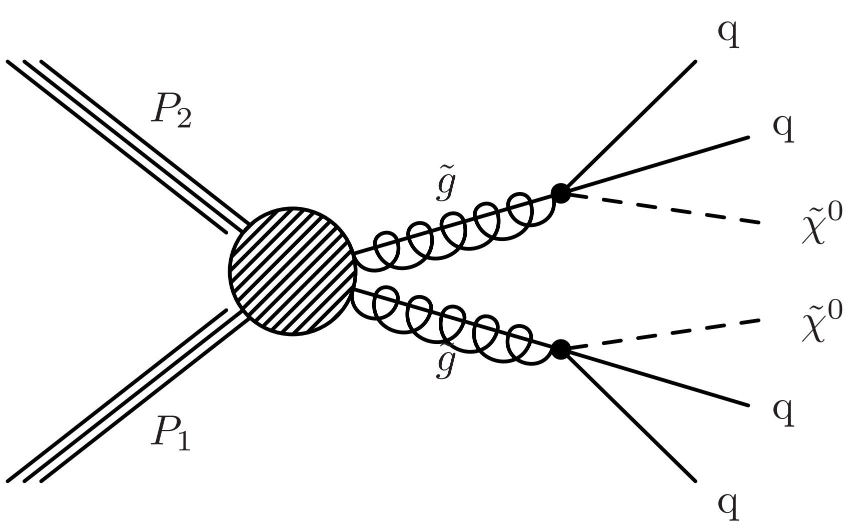
CMS MHT Search Strategy

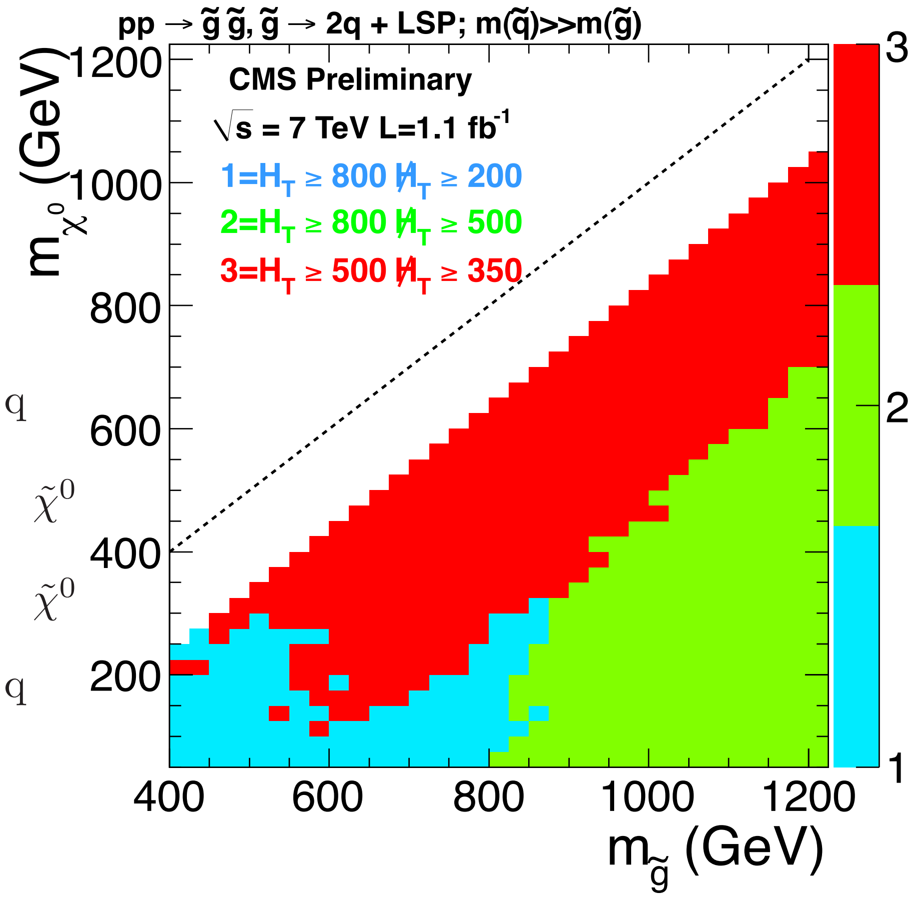
- At least three jets with $p_{\mathrm{T}} > 50\,\mathrm{GeV}$ and $|\eta| < 2.5$.
- $H_{\mathrm{T}} > 350\,\mathrm{GeV}$, with H_{T} defined as the scalar sum of the p_{T}s of all the jets with $p_{\mathrm{T}} > 50\,\mathrm{GeV}$ and $|\eta| < 2.5$.
- $\not{H}_{\mathrm{T}} > 200\,\mathrm{GeV}$, with $\not{H}_{\mathrm{T}}$ defined as the magnitude of the negative vectorial sum of the p_{T}s of the jets having, in this case, $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 5$. The majority of QCD events in the MHT tail are removed with this requirement.
- $|\Delta\phi(J_n, \not{H}_{\mathrm{T}})| > 0.5$ (rad), $n = 1, 2$ and $|\Delta\phi(J_3, \not{H}_{\mathrm{T}})| > 0.3$ (rad), vetoing events in which $\not{H}_{\mathrm{T}}$ is aligned in the transverse plane along one of the three leading jets. This requirement rejects most of the QCD multijet events in which a single mismeasured jet yields a high $\not{H}_{\mathrm{T}}$.
- Veto on isolated muons and electrons.

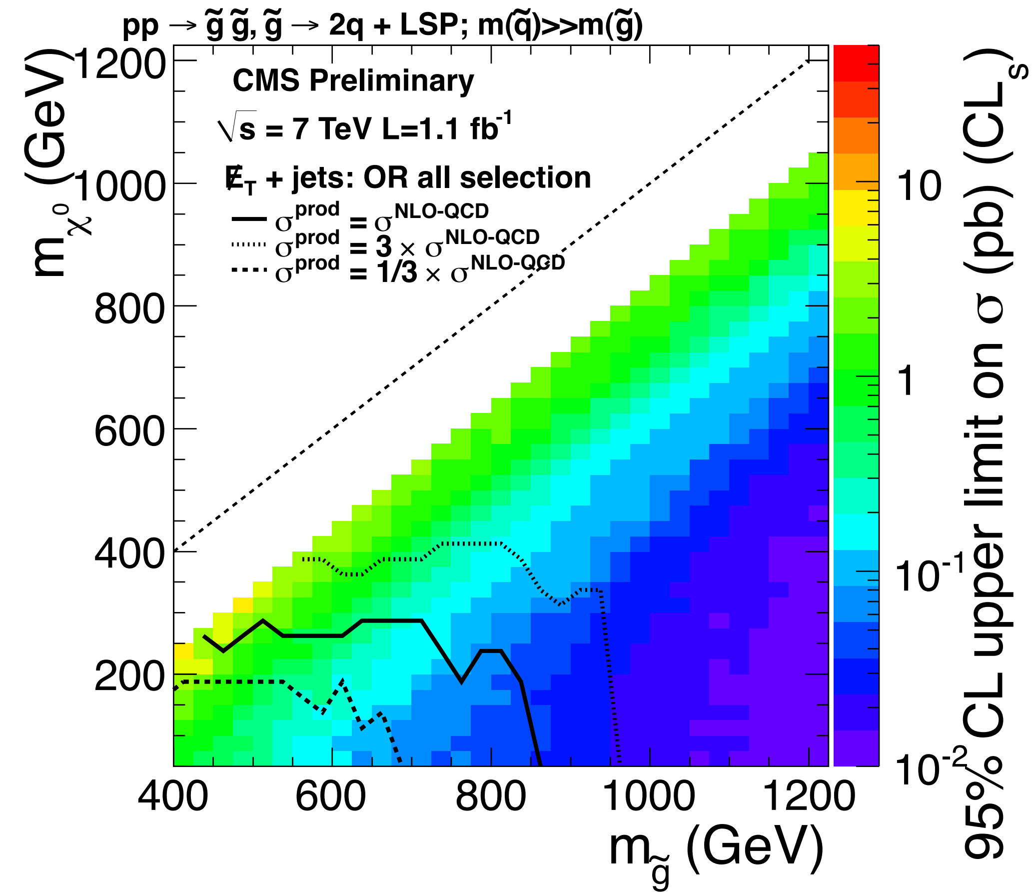
"3"	"1"	"2"
Medium (H_{T} >500 GeV) ($\not{H}_{\mathrm{T}}$ >350 GeV)	High H_{T} (H_{T} >800 GeV) ($\not{H}_{\mathrm{T}}$ >200 GeV)	High $\not{H}_{\mathrm{T}}$ (H_{T} >800 GeV) ($\not{H}_{\mathrm{T}}$ >500 GeV)

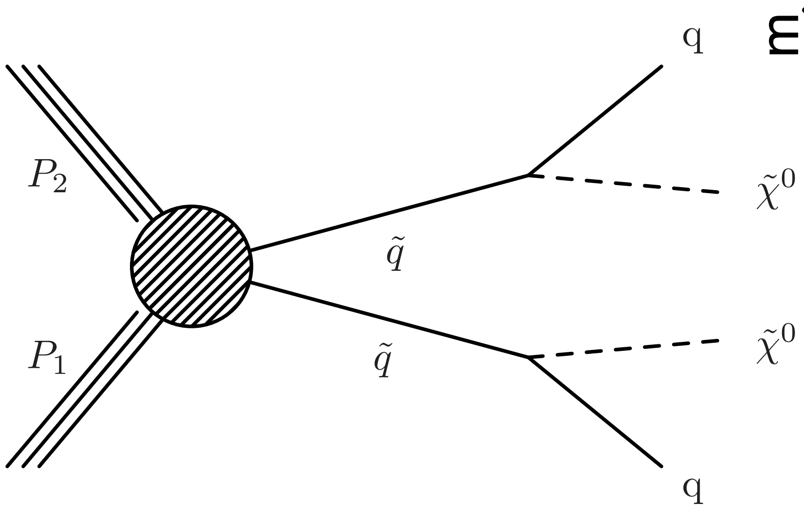
CMS-SUS-11-004

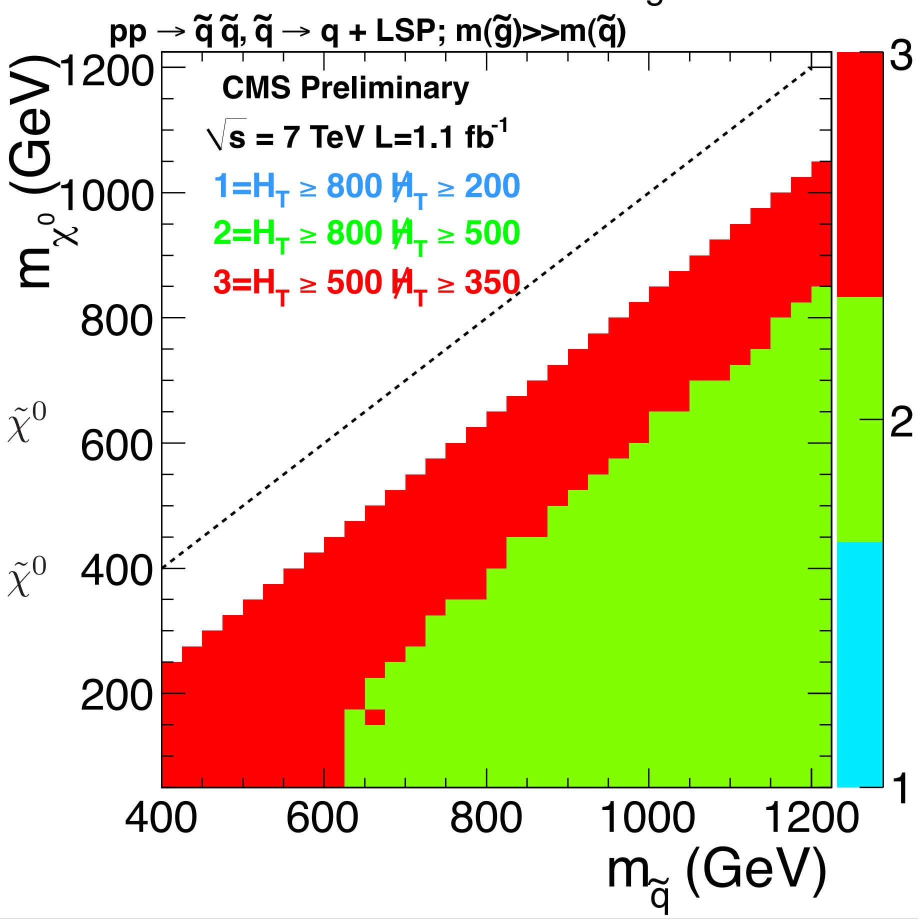
CMS Bounds on Simplified Models

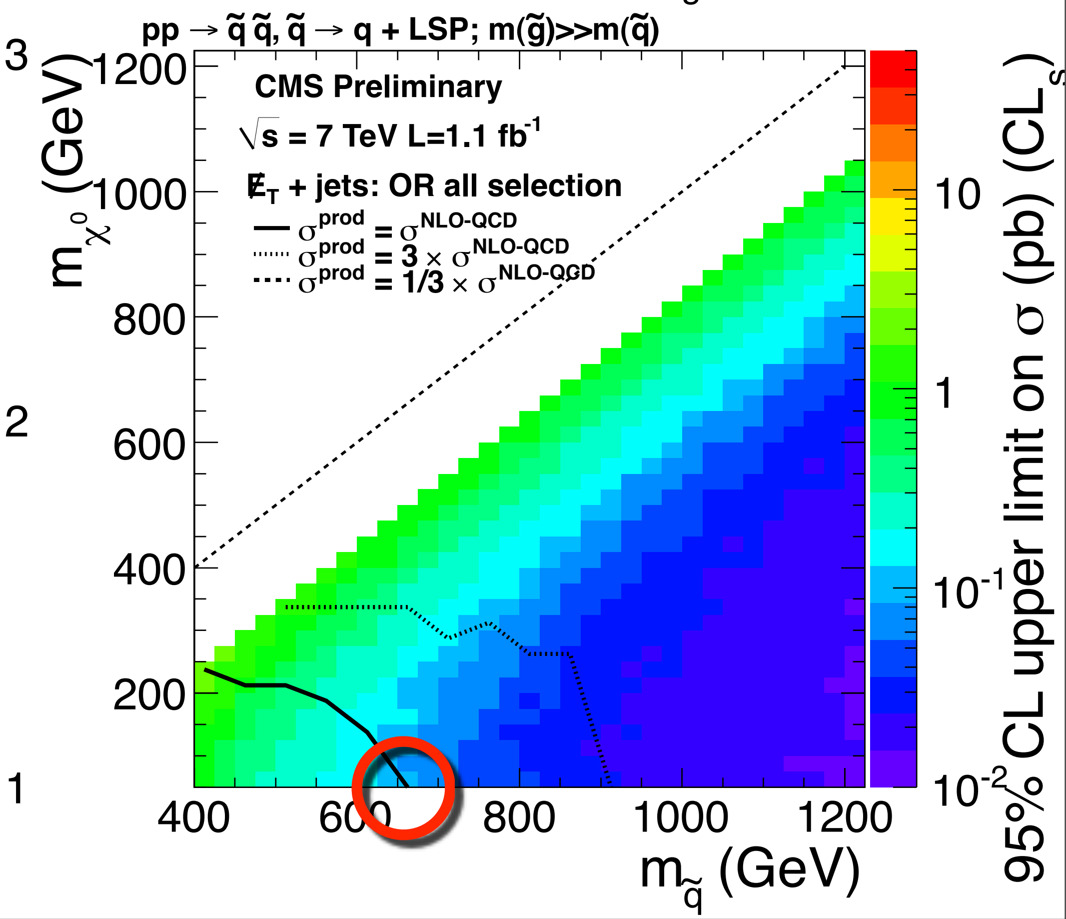












CMS MHT Search Bounds

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

1st,2nd generation squark mass

'3' '1' '2'	'3' '1' '2'	'3' '1' '2'	'3' '1' '2'

"razor" strategy II

Key is to construct two kinematic variables that provide an event-by-event estimator of the underlying scale for a massive particle.

$$M_R \equiv \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

$$M_T^R \equiv \sqrt{\frac{E_T^{miss}(p_T^{j1} + p_T^{j2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{\,j1} + \vec{p}_T^{\,j2})}{2}}$$

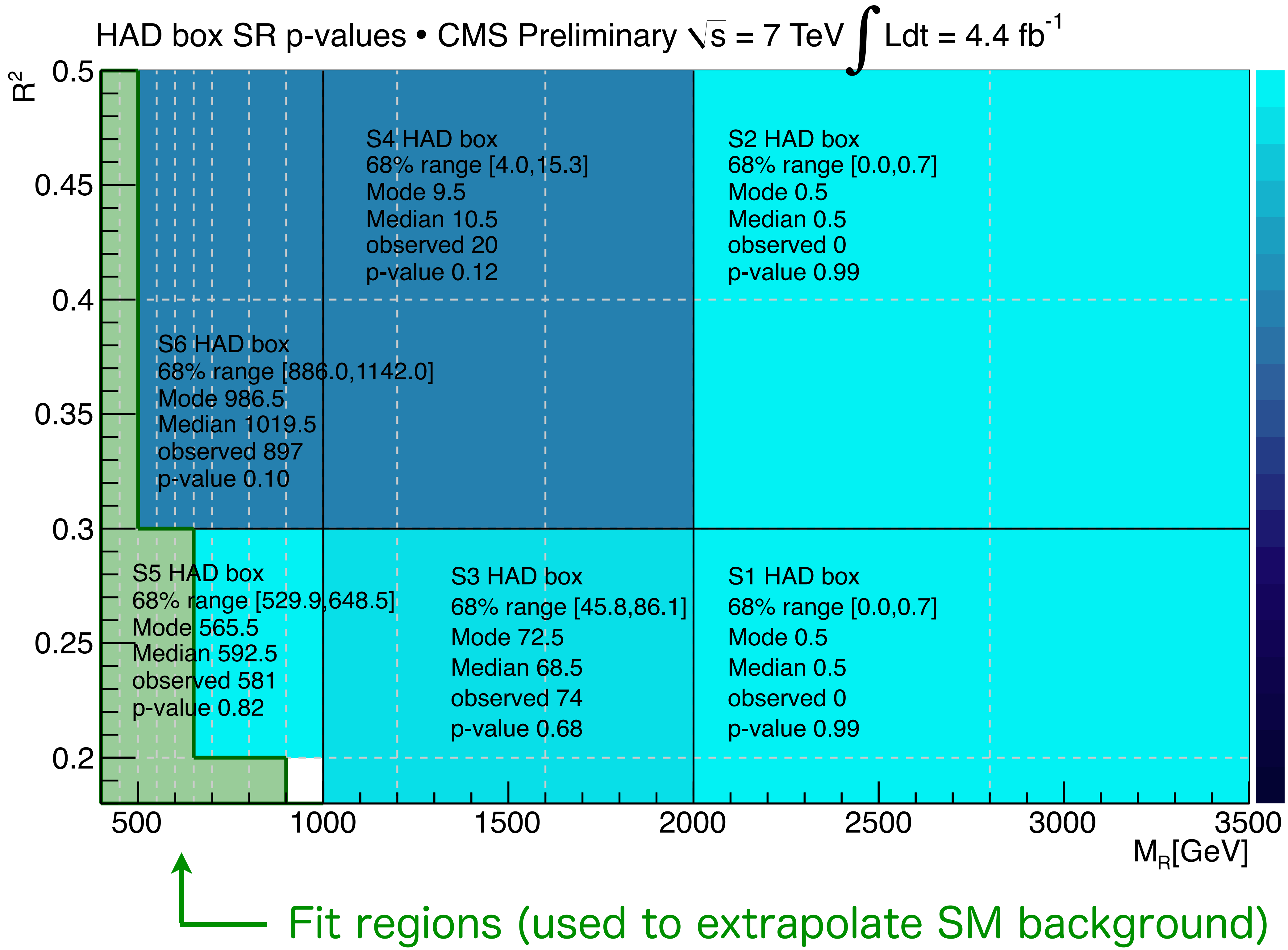
average transverse mass

Cut on the combinations:

$$R \equiv \frac{M_T^R}{M_R} \qquad \text{and} \qquad M_R$$

SM backgrounds have simple exponential (falling) dependence on M_R, R (for $R^2 < 0.5$), while signal peaks $R \approx 0.5$

“razor” signal regions



CMS “razor” Search Bounds

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

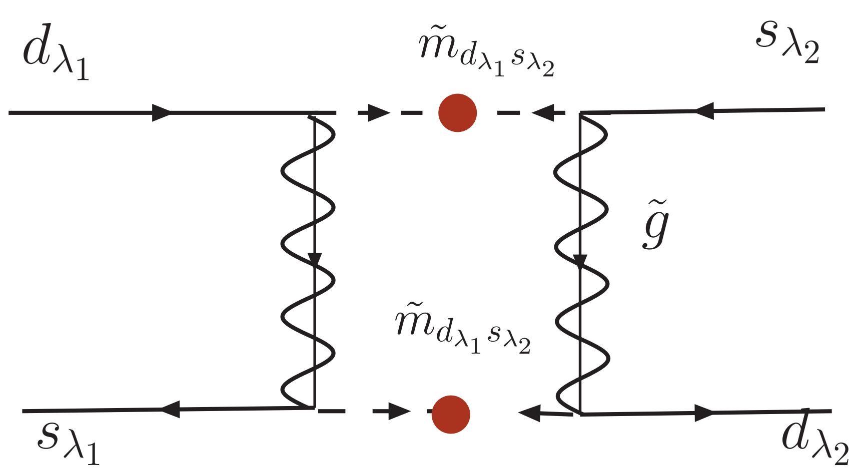
1st,2nd generation squark mass

Kribs & Martin

Flavor & Supersoft

flavor is always a problem for any BSM scenario...

for SUSY, can be phrase the problem as



off-diagonal term

$$\frac{\delta M_{\tilde{Q}}}{M_{\tilde{Q}}} \ll 1$$

generic diagonal sfermion mass element

typically $O(10^{-3})$

usually avoided by working with flavor-blind mediation methods (gauge mediation, etc), often at the expense of introducing new problems

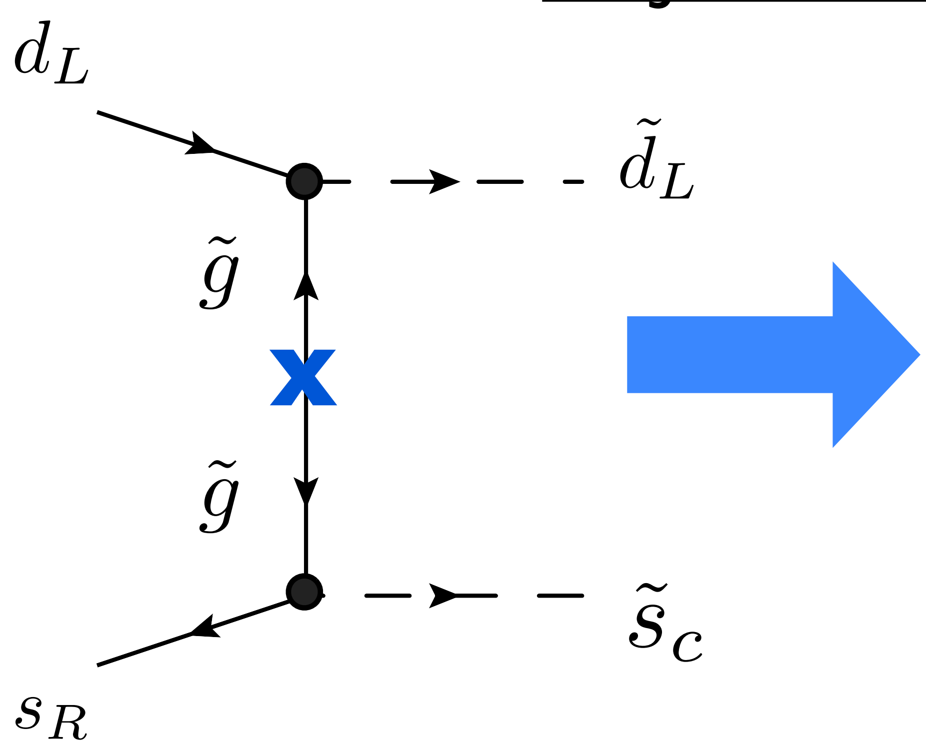
flavor constraints quite different if supersoft

Flavor & Supersoft

we've already seen the gluino is naturally heavy, but there's more

take a box-diagram, integrate out gluino

Majorana case:



$$\frac{(\bar{s}_R\, d_L)\, \tilde{d}_L\, \tilde{s}_c}{M_{\tilde{g}}}$$

Flavor & Supersoft

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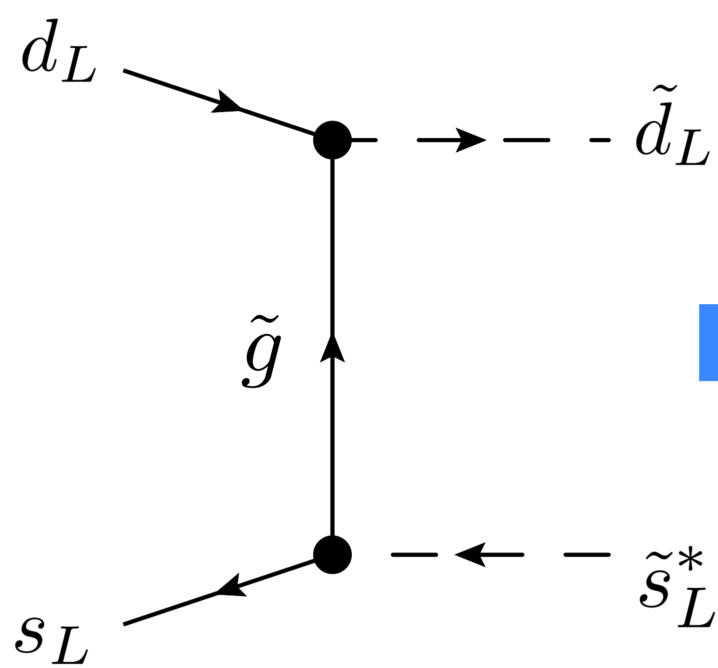
take a box-diagram, integrate out gluino

Dirac case:



$$\frac{\bar{s}_L\, \tilde{s}^*_L \not{\partial}(d_L\, \tilde{d}_L)}{M_D^2}$$

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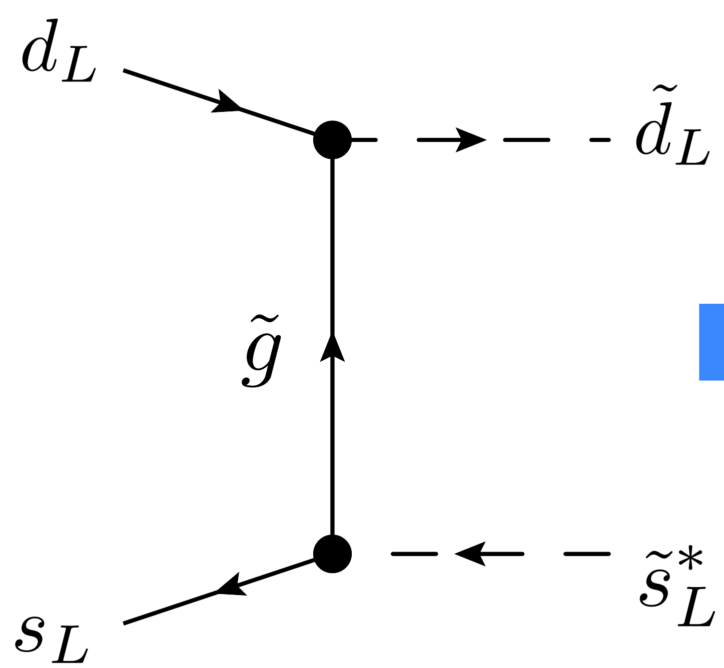

$$\frac{\bar{s}_L\, \tilde{s}^*_L \not{\partial} (d_L\, \tilde{d}_L)}{M_D^2}$$

full box additionally suppressed in Dirac case

$$\left(\frac{m^2_{\tilde{Q}}}{M_D^2}\right) \frac{(\bar{s}\, d)(\bar{s}\, d)}{M_D^2}$$

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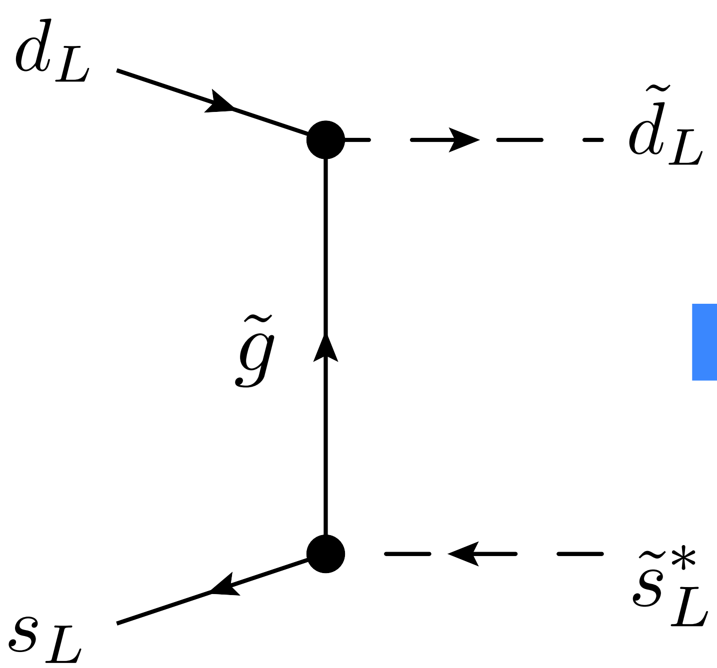


$$\frac{\bar s_L\, \tilde s_L^* \not{\partial} (d_L\, \tilde d_L)}{M_D^2}$$

full box additionally suppressed in Dirac case

$$\left(\frac{m^2_{\tilde Q}}{M_D^2}\right)\frac{(\bar s\, d)(\bar s\, d)}{M_D^2}$$

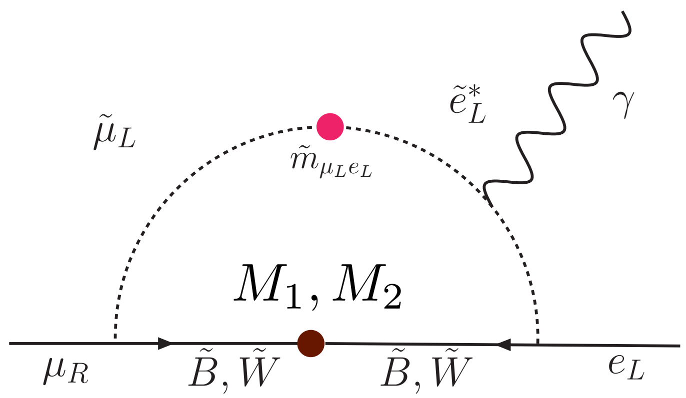
much larger $\frac{\delta M_{\tilde Q}}{M_{\tilde Q}} \sim O(1)$ allowed, low energy observables shielded

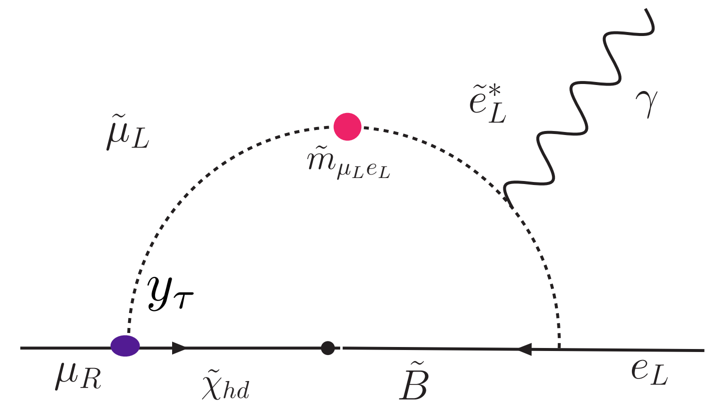
there's more to flavor than just boxes...

in MRSSM:

many flavor problems vanish due to different μ structure, no 'A-terms'

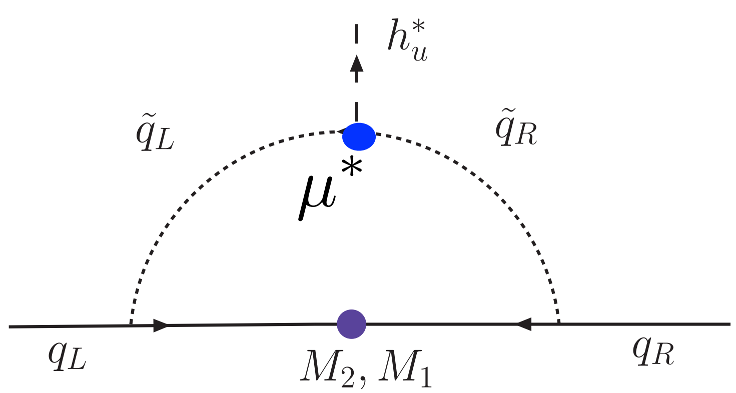
$\mu \to e\gamma$:

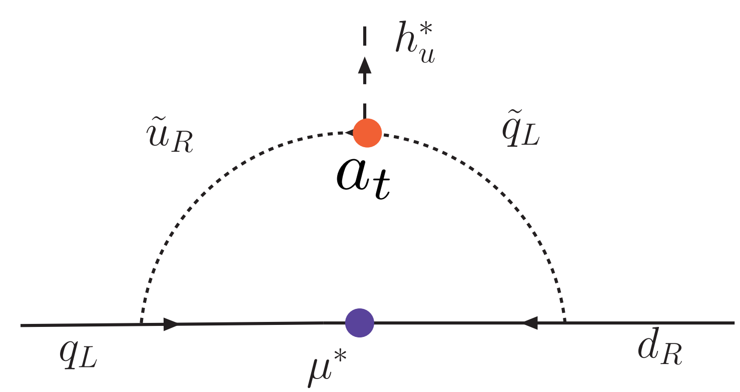




large $\tan\beta$:

$\Delta M_B, \Delta M_K, \cdots$





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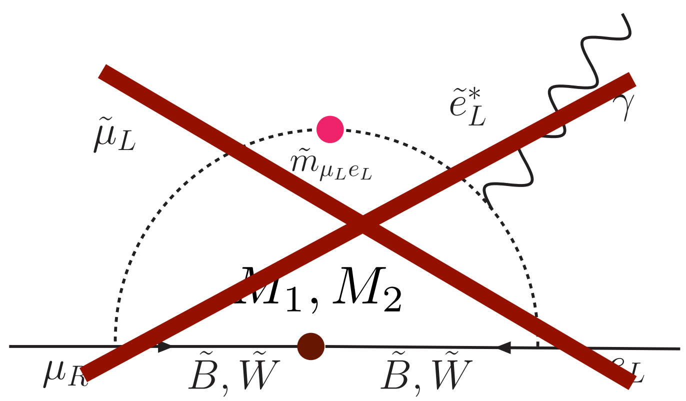

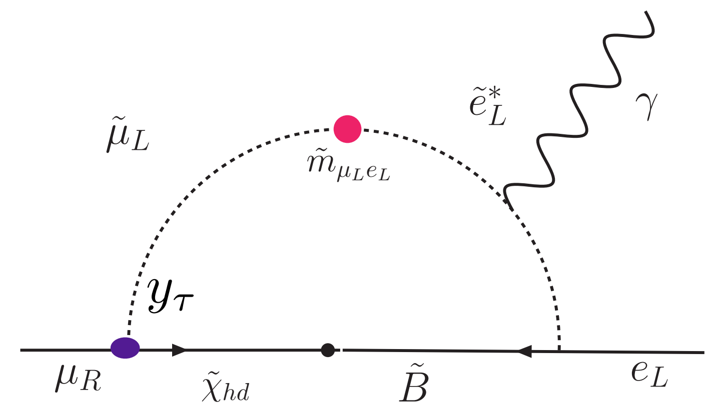

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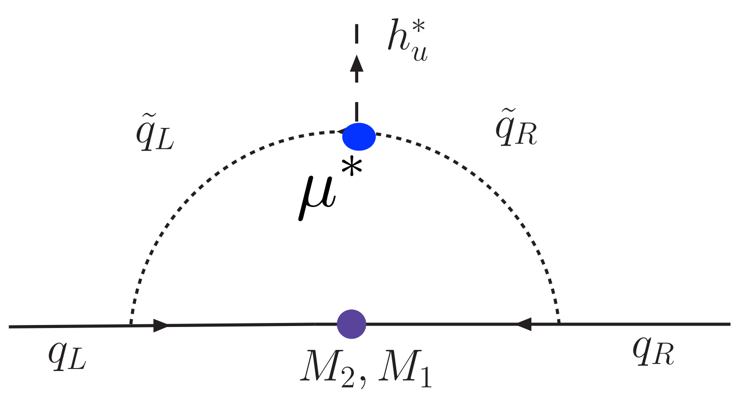
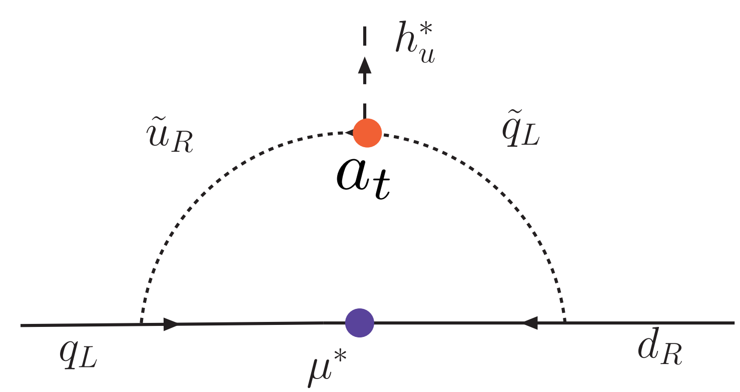
$\Delta M_B, \Delta M_K, \cdots$





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