Supersoft Supersymmetry and Effective Dark Matter At The LHC

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Trajectory

Standard Model Lore

Supersymmetry Review

Supersoft Supersymmetry Breaking

Mixed Gauginos; LHC Signals

Thermal Dark Matter Review

Effective Model and Phenomenology

The Standard Model

- Effective Theory
  - Renormalizable = four-dimensional

- Simplest available quantum description for physics up to weak scale
  - All known interactions minus gravity
  - All observed degrees of freedom

- Consistent with nearly all empirical observations

The Standard Model

Empirical Problems

- Gravity
- Dark energy
- Neutrino masses
- Flavour puzzle
- Baryon asymmetry
- Cosmic inflation
- Dark matter

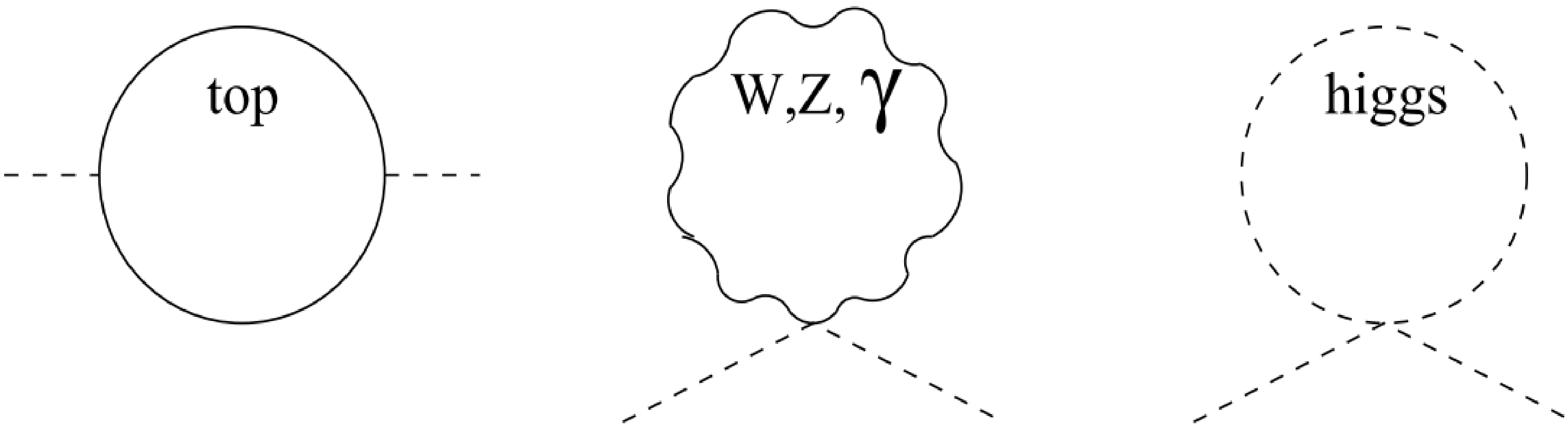
Aesthetical Problems

- Gauge hierarchy
- Neutrino masses
- Strong CP

The Standard Model

Empirical Problems	Aesthetical Problems
* Gravity	* Gauge hierarchy
* Dark energy	* Neutrino masses
* Neutrino masses	* Strong CP
* Flavour puzzle	
* Baryon asymmetry	
* Cosmic inflation	
* Dark matter	

Hierarchy Problem and Fine–Tuning



Higgs mass unprotected by symmetries

unlike photon or electron mass

Instability of electroweak scale

quadratically sensitive to new physics scale

Supersymmetry

Principal incentive for the phenomenologist:

Provides the symmetry that cures the fine-tuning problem

And

- Dark matter candidate (in models with R-parity)
- Facilitates gauge coupling unification
- You name it

Supersymmetry
What is it?

A continuous spacetime symmetry that exchanges bosons with fermions

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle$$

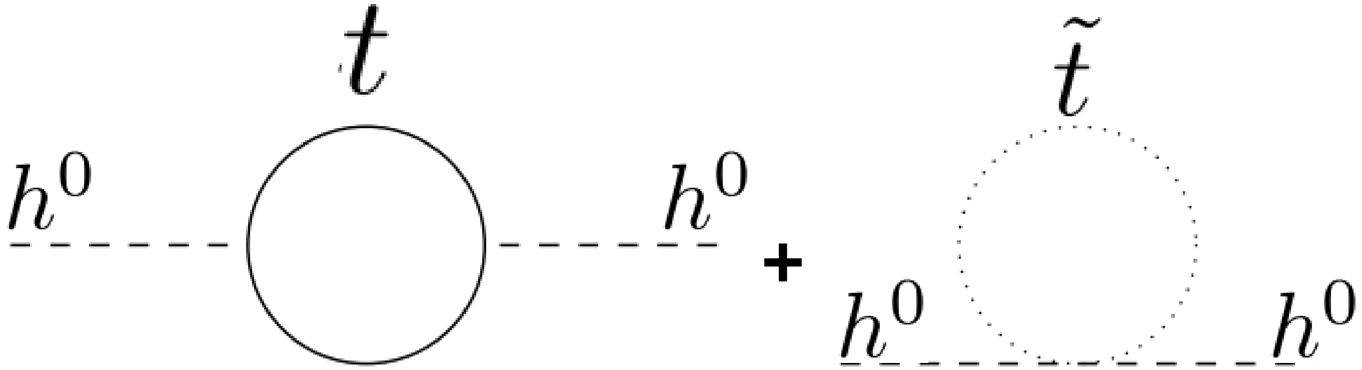
$$Q|\text{Fermion}\rangle = |\text{Boson}\rangle$$

Simple example

$$\mathcal{L} = -\partial^\mu \phi^* \partial_\mu \phi + i\psi^\dagger \overline{\sigma}^\mu \partial_\mu \psi$$

$$\left.\begin{array}{l} \delta\phi = \epsilon\psi, \;\; \delta\phi^* = \epsilon^\dagger\psi^\dagger \\ \delta\psi_\alpha = -i(\sigma^\mu\epsilon^\dagger)_\alpha\, \partial_\mu\phi, \;\; \delta\psi^\dagger_{\dot\alpha} = i(\epsilon\sigma^\mu)_{\dot\alpha}\, \partial_\mu\phi^* \end{array}\right\} \delta S = 0$$

Supersymmetry
What could it do?



Kills the quadratic divergence

Nonrenormalization theorem: $d\mu/dt \propto \mu$

Insures removal of q.d. at all orders

Supersymmetry
What else is it?

(Super)algebra

$$\{Q, Q^\dagger\} = P^\mu, \qquad [J_i, J_j] = i\hbar\varepsilon_{ijk}J_k \ ,$$

$$\{Q, Q\} = \{Q^\dagger, Q^\dagger\} = 0 \qquad [J_i, K_j] = i\hbar\varepsilon_{ijk}K_k \ ,$$

$$[P^\mu, Q] = [P^\mu, Q^\dagger] = 0 \qquad [K_i, K_j] = -i\hbar\varepsilon_{ijk}J_k \ .$$

P^2 commutes with Q, J, K

– a state and its superpartner have the same mass!

Supersymmetry
What else is it?

P^2 commutes with Q, J, K
- a state and its superpartner have the same mass
- not true of the world we see

Supersymmetry, if realized in nature, must be a broken symmetry
- We've then only observed "half" of the broken whole (if the number of supercharges N=1)
- SUSY-breaking terms must be 'soft'
  = no new quadratic divergences

Broken Supersymmetry

Some permissible soft SUSY-breaking terms

(1) Scalar masses $(m^2)^i_j \phi^{j*} \phi_i$

(2) Trilinear interactions $\frac{1}{6} a^{ijk} \phi_i \phi_j \phi_k$

(3) Gaugino masses $\frac{1}{2} M_a \lambda^a \lambda^a$

Supersoft* Supersymmetry Breaking

Gaugino Masses

* no log-div. contribs. to soft params.!

MSSM

$$c_m \int d^2\theta \frac{X}{M} W^\alpha W_\alpha$$

Chiral N = 1
Adjoint N = 1
F-term breaking

S(upersoft)SSM

Fox, Nelson, Weiner
JHEP 0208 (2002) 035

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

Chiral N = 1
Adjoint N = 2
D-term breaking
R-symmetric

Supersoft Supersymmetry Breaking

Gaugino Masses

MSSM

$$\boxed{\mathcal{L} \supset \frac{1}{2} M_m g_a g_a}$$

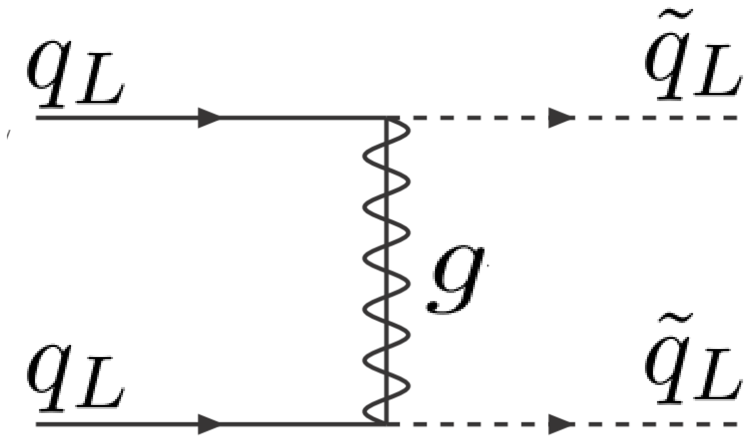
Chiral N = 1
Adjoint N = 1
F-term breaking

SSSM

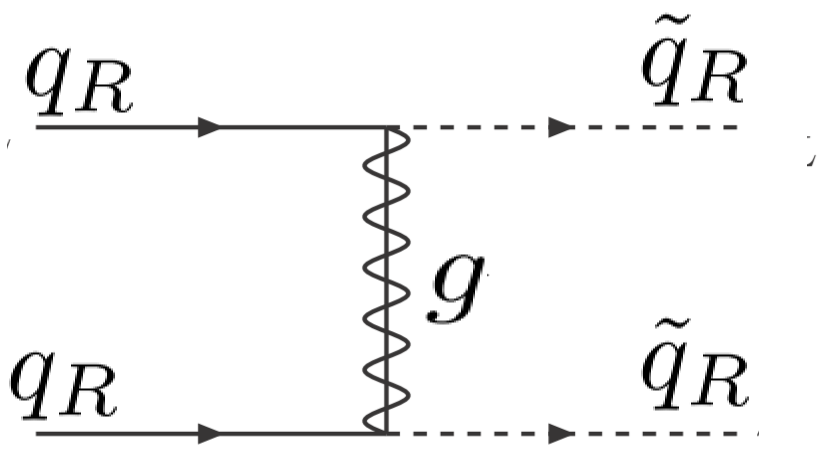
$$\boxed{\mathcal{L} \supset M_d g_a \psi_a}$$

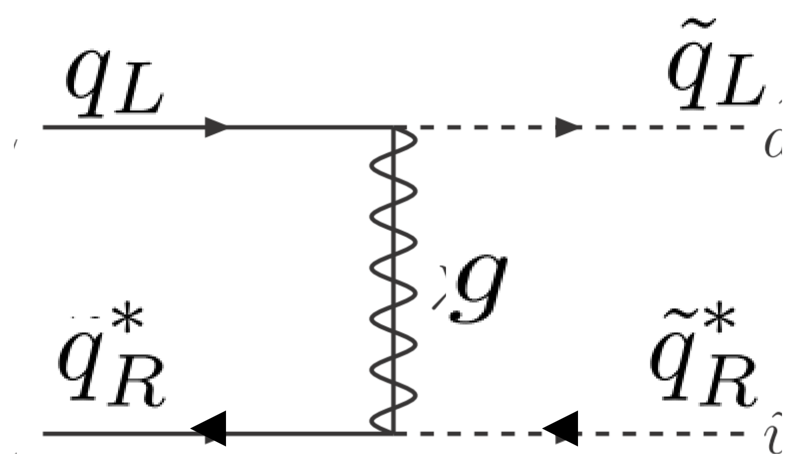
Chiral N = 1
Adjoint N = 2
D-term breaking
R-symmetric

MSSM v SSSM Phenomenology



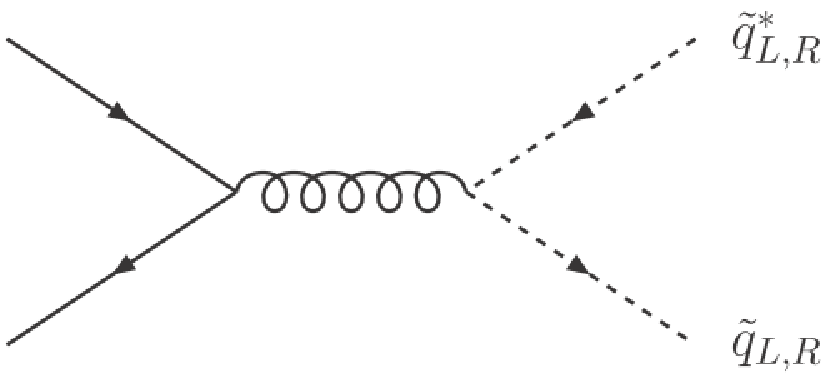
In SSSM,
same-handed
t-channel
squark pair production
absent.



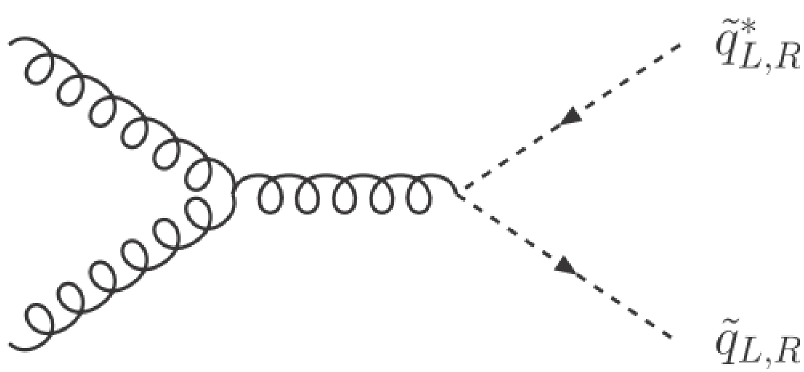


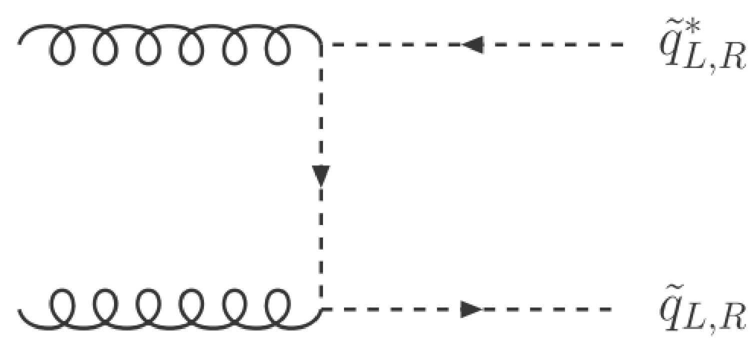
G D Kribs, A Martin, Phys.Rev. D85 (2012) 115014

MSSM v SSSM Phenomenology



SSSM dominant diagrams

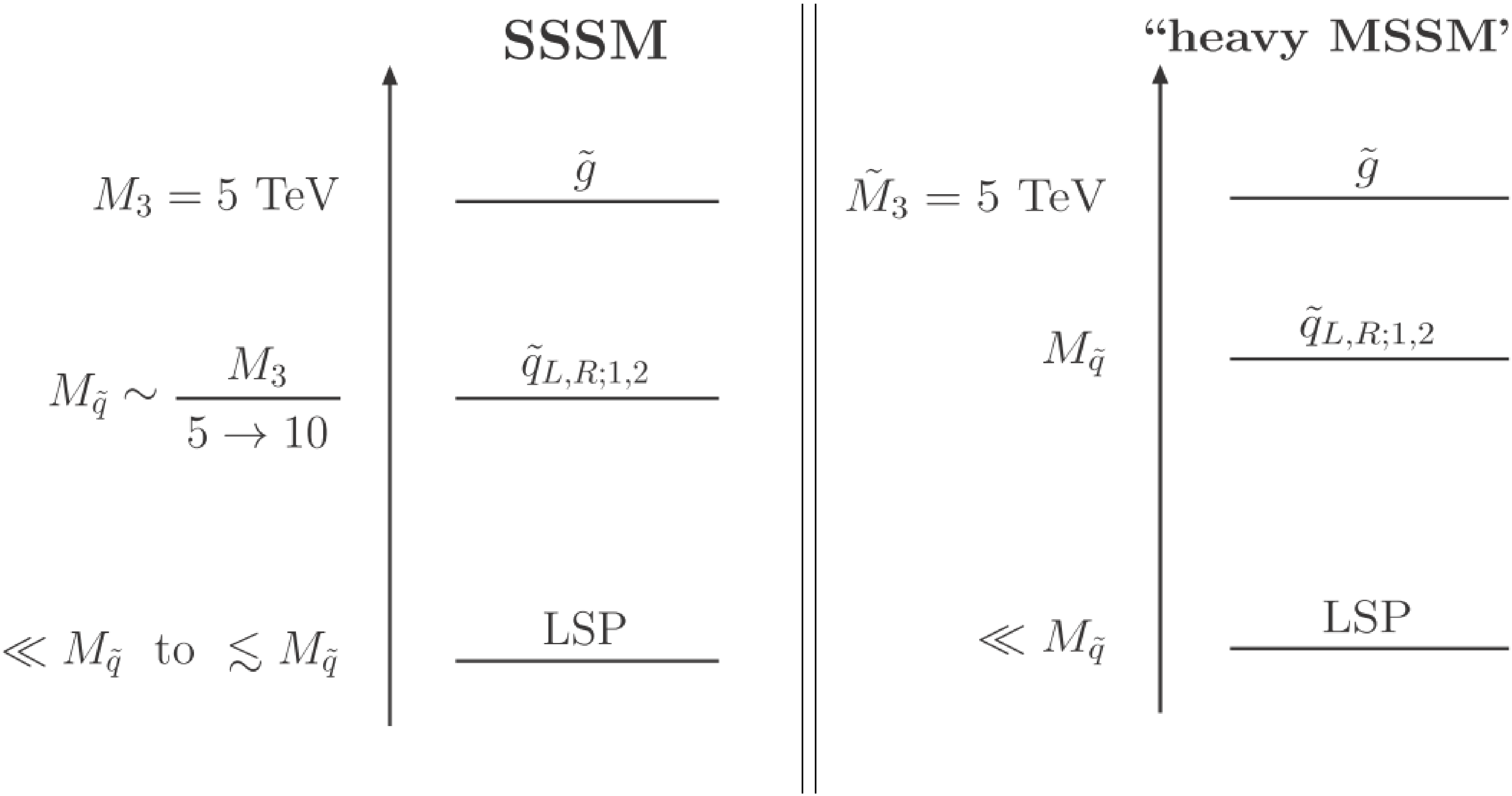




G D Kribs, A Martin, Phys.Rev. D85 (2012) 115014

MSSM v SSSM Phenomenology

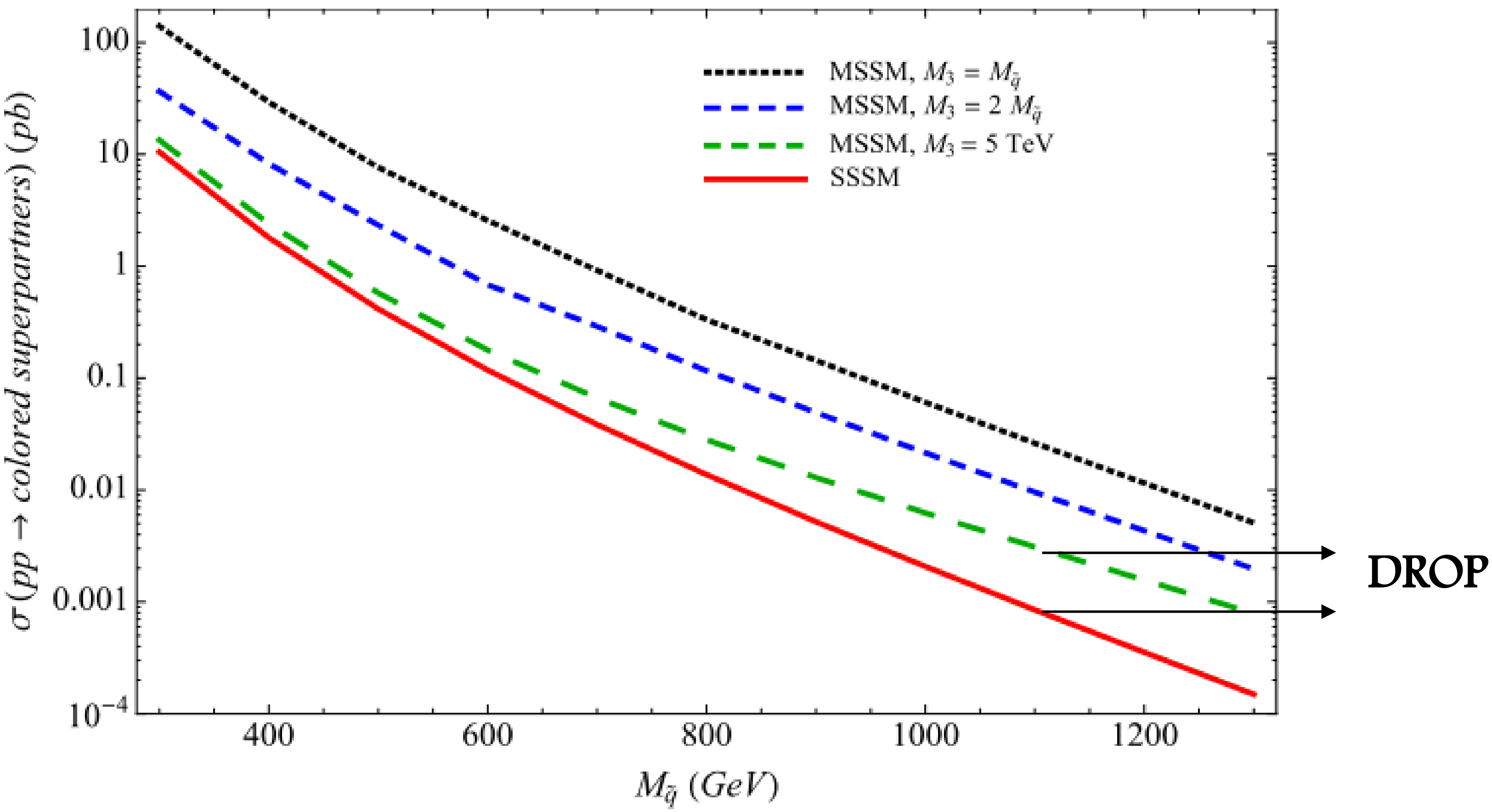
Comparison with a "simplified model"



G D Kribs, A Martin

MSSM v SSSM Phenomenology

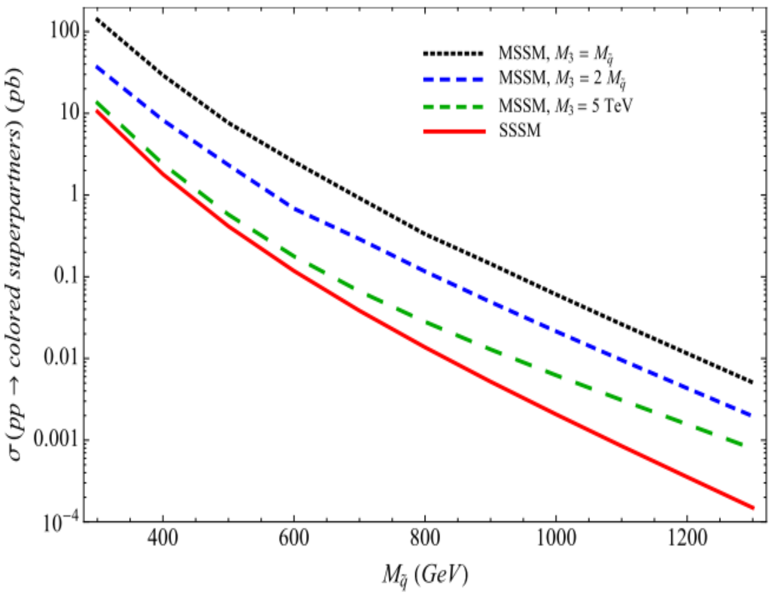
Comparison with a "simplified model"



G D Kribs, A Martin

MSSM v SSSM Phenomenology

Comparison with a "simplified model"



Most conservative theoretical bound:
Squark mass > 750 GeV

Most stringent experimental (ATLAS) bound
[from "Heavy MSSM"]:
Squark mass > 1040 GeV

{Today, > 1.4 TeV}

G D Kribs, A Martin

Inadequacies of Supersoft

(1) F-terms much smaller than D-terms
– not natural

(2) Vanishing Higgs quartic coupling
unless electroweakinos
are Majorana

For a realistic theory, gauginos must have both Dirac and Majorana masses

Mixed Gauginos

$$\boxed{c_m \int d^2\theta \frac{X}{M} W^\alpha W_\alpha}$$

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

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

$$\boxed{c_{m'} \int d^4\theta \frac{1}{2} \frac{X^\dagger}{M} \mathrm{tr} A_j A_j + \mathrm{h.c.}}$$

$$\begin{pmatrix} g_1 \\ g_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{g}} & \sin\theta_{\tilde{g}} \\ -\sin\theta_{\tilde{g}} & \cos\theta_{\tilde{g}} \end{pmatrix} \begin{pmatrix} \psi \\ g \end{pmatrix}$$

G D Kribs, N Raj hep-ph/1307.7197

Interaction with quarks and squarks

$$\begin{aligned}\mathcal{L}_{int} \ = \\ - \sqrt{2} g_s \Big(\tilde{u}^*_{L,i} \ t^a \ g_a \ u_{L,i} + \tilde{d}^*_{L,i} \ t^a \ g_a \ d_{L,i} \\ - \tilde{u}^*_{R,i} \ t^a \ g_a u_{R,i} - \tilde{d}^*_{R,i} \ t^a \ g_a \ d_{R,i} \Big) + \text{h.c.}\end{aligned}$$

Interaction with quarks and squarks

$$\begin{aligned}\mathcal{L}_{int} \;=\;& \\ & -\sqrt{2}g_s\Big(\tilde{u}^*_{L,i}\; t^a\; g_a\; u_{L,i} + \tilde{d}^*_{L,i}\; t^a\; g_a\; d_{L,i} \\ & -\tilde{u}^*_{R,i}\; t^a\; g_a u_{R,i} - \tilde{d}^*_{R,i}\; t^a\; g_a\; d_{R,i}\Big) + \text{h.c.}\end{aligned}$$

$$\begin{aligned}-\mathcal{L}_{int}/\sqrt{2}g_s \;=\;& \\ & +\tilde{u}^*_{L,i}\; t^a\; g_1\cos\theta_{\tilde{g}}\; u_{L,i} + \tilde{u}^*_{L,i}\; t^a\; g_2\sin\theta_{\tilde{g}}\; u_{L,i} \\ & +\tilde{d}^*_{L,i}\; t^a\; g_1\cos\theta_{\tilde{g}}\; d_{L,i} + \tilde{d}^*_{L,i}\; t^a\; g_2\sin\theta_{\tilde{g}}\; d_{L,i} \\ & -\tilde{u}^*_{R,i}\; t^a\; g_1\cos\theta_{\tilde{g}}\; u_{R,i} - \tilde{u}^*_{R,i}\; t^a\; g_2\sin\theta_{\tilde{g}}\; u_{R,i} \\ & -\tilde{d}^*_{R,i}\; t^a\; g_1\cos\theta_{\tilde{g}}\; d_{R,i} - \tilde{d}^*_{R,i}\; t^a\; g_2\sin\theta_{\tilde{g}}\; d_{R,i} \\ & +\;\text{h.c.}\end{aligned}$$

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

Perturbations to Dirac mass: swaths to cover

- $M'_m/M_d \neq 0 \qquad M_m = 0$
- $M_m/M_d \neq 0 \qquad M_m = M'_m$
- $M_m/M_d \neq 0 \qquad M'_m = 0$

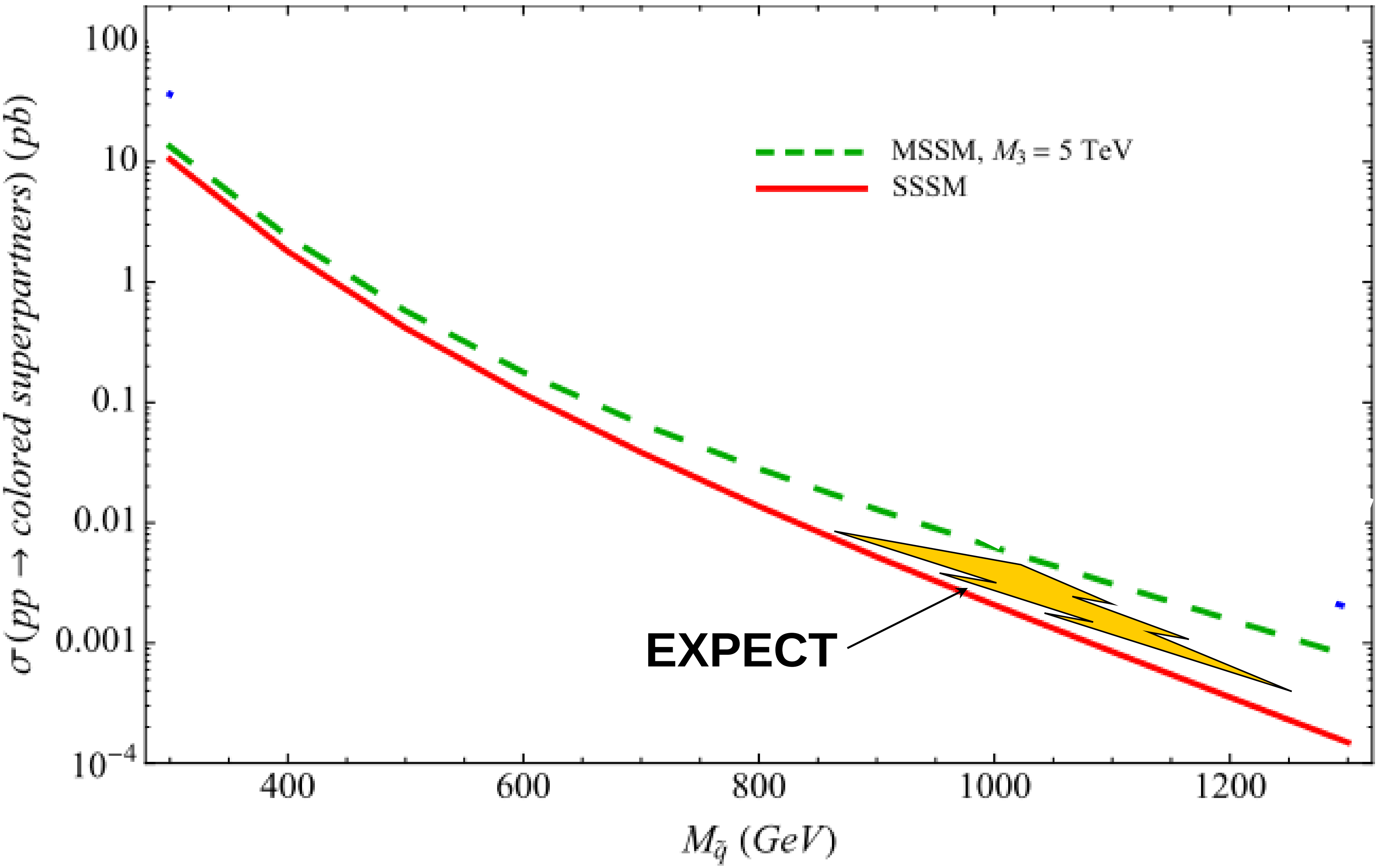
$$\mathcal{L}_{\tilde{g}\,\mathrm{mass}} = \begin{pmatrix} g_a & \psi_a \end{pmatrix} \begin{pmatrix} M_m & M_d \\ M_d & \end{pmatrix} \begin{pmatrix} g_a \\ \psi_a \end{pmatrix} + \mathrm{h.c.}$$

Perturbations to Dirac mass: swaths to cover

This talk

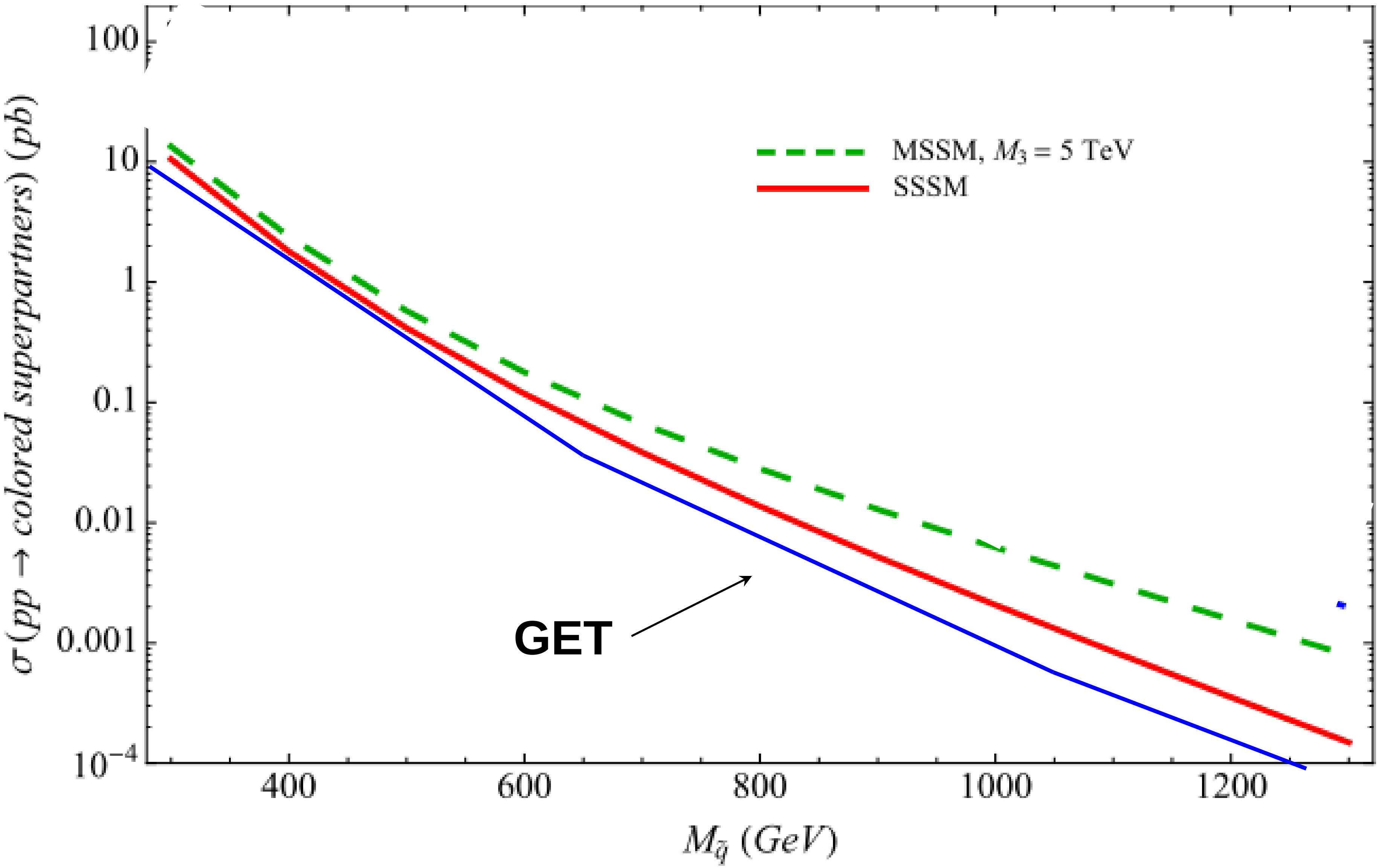
- $M_m/M_d \neq 0 \quad M'_m = 0$

Spoiler



MSSM, M_3 = 5 TeV
SSSM
EXPECT
100
10
1
0.1
0.01
0.001
10^{-4}
400
600
800
1000
1200
$\sigma(pp \to colored\ superpartners)\ (pb)$
$M_{\tilde{q}}\ (GeV)$

Spoiler


100
10
1
0.1
0.01
0.001
10^{-4}
$\sigma(pp \to colored\ superpartners)\ (pb)$
MSSM, $M_3 = 5$ TeV
SSSM
GET
400
600
800
1000
1200
$M_{\tilde{q}}\ (GeV)$

Assumptions

- R–parity valid
- LSP = Massless gravitino or light bino
- Decay prompt, 100% BR
- Squarks degenerate, don’t mix
- ‘Squarks’ = first two generations
- LO; will explain why if time permits
- CTEQ6L1 PDF’s

"Pure" mass terms

$$\mathcal{L}_{\tilde{g}\,\mathrm{mass}} = \begin{pmatrix} g_a & \psi_a \end{pmatrix} \begin{pmatrix} M_m & \\ & \end{pmatrix} \begin{pmatrix} g_a \\ \psi_a \end{pmatrix} + \mathrm{h.c.}$$

$$\mathcal{L}_{\tilde{g}\,\mathrm{mass}} = \begin{pmatrix} g_a & \psi_a \end{pmatrix} \begin{pmatrix} & M_d \\ M_d & \end{pmatrix} \begin{pmatrix} g_a \\ \psi_a \end{pmatrix} + \mathrm{h.c.}$$

“Pure” mass terms

$$\mathcal{L}_{\tilde{g}\,\mathrm{mass}} = \begin{pmatrix} g_a & \psi_a \end{pmatrix} \begin{pmatrix} M_m & \\ & \end{pmatrix} \begin{pmatrix} g_a \\ \psi_a \end{pmatrix} + \mathrm{h.c.}$$

$$\begin{pmatrix} g_1 \\ g_2 \end{pmatrix} = \begin{pmatrix} \mathbf{1} & \mathbf{0} \\ \mathbf{0} & \mathbf{1} \end{pmatrix} \begin{pmatrix} \psi \\ g \end{pmatrix}$$

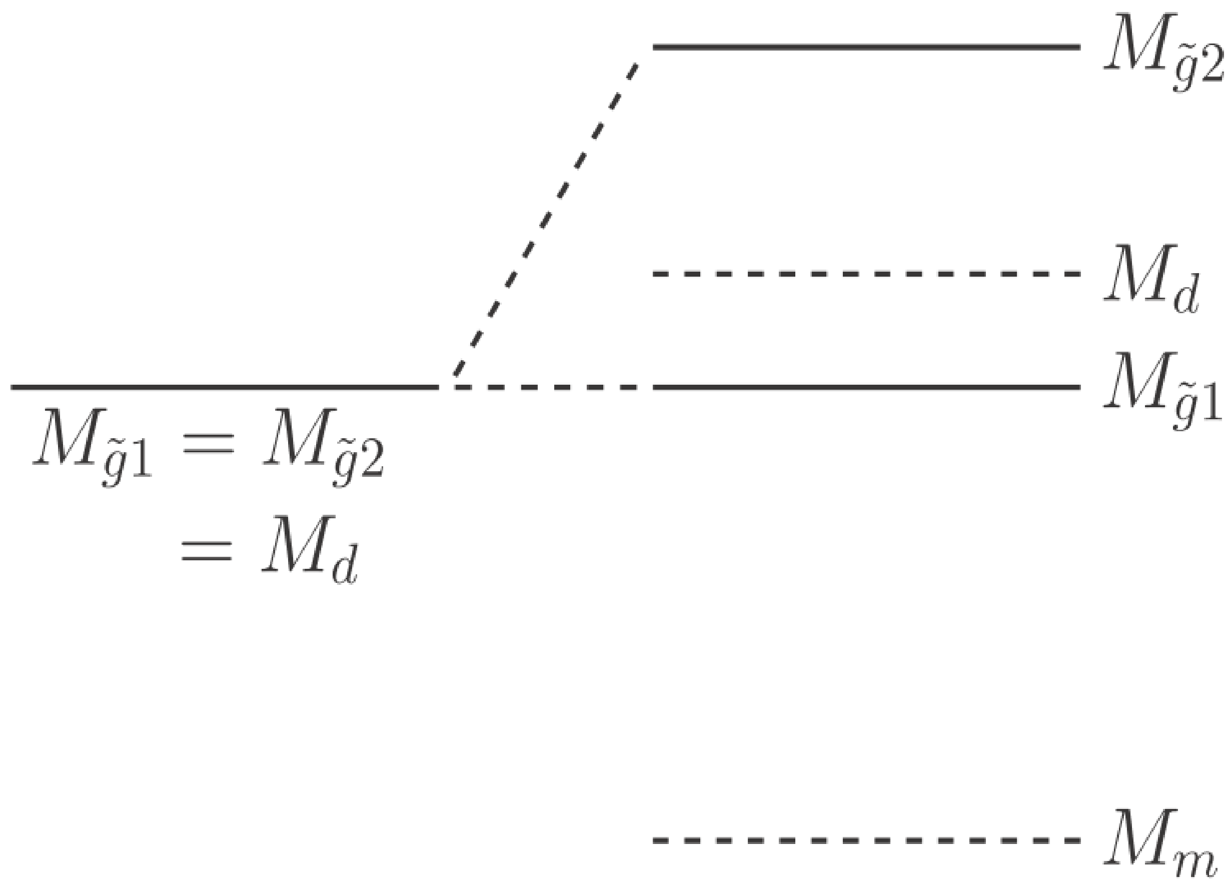
$$\mathcal{L}_{\tilde{g}\,\mathrm{mass}} = \begin{pmatrix} g_a & \psi_a \end{pmatrix} \begin{pmatrix} & M_d \\ M_d & \end{pmatrix} \begin{pmatrix} g_a \\ \psi_a \end{pmatrix} + \mathrm{h.c.}$$

$$\begin{pmatrix} g_1 \\ g_2 \end{pmatrix} = \begin{pmatrix} \mathbf{.707} & \mathbf{.707} \\ \mathbf{-.707} & \mathbf{.707} \end{pmatrix} \begin{pmatrix} \psi \\ g \end{pmatrix}$$

Mixed mass terms

$$\mathcal{L}_{\tilde{g}\,\mathrm{mass}} = \begin{pmatrix} g_a & \psi_a \end{pmatrix} \begin{pmatrix} M_m & M_d \\ M_d & \end{pmatrix} \begin{pmatrix} g_a \\ \psi_a \end{pmatrix} + \mathrm{h.c.}$$

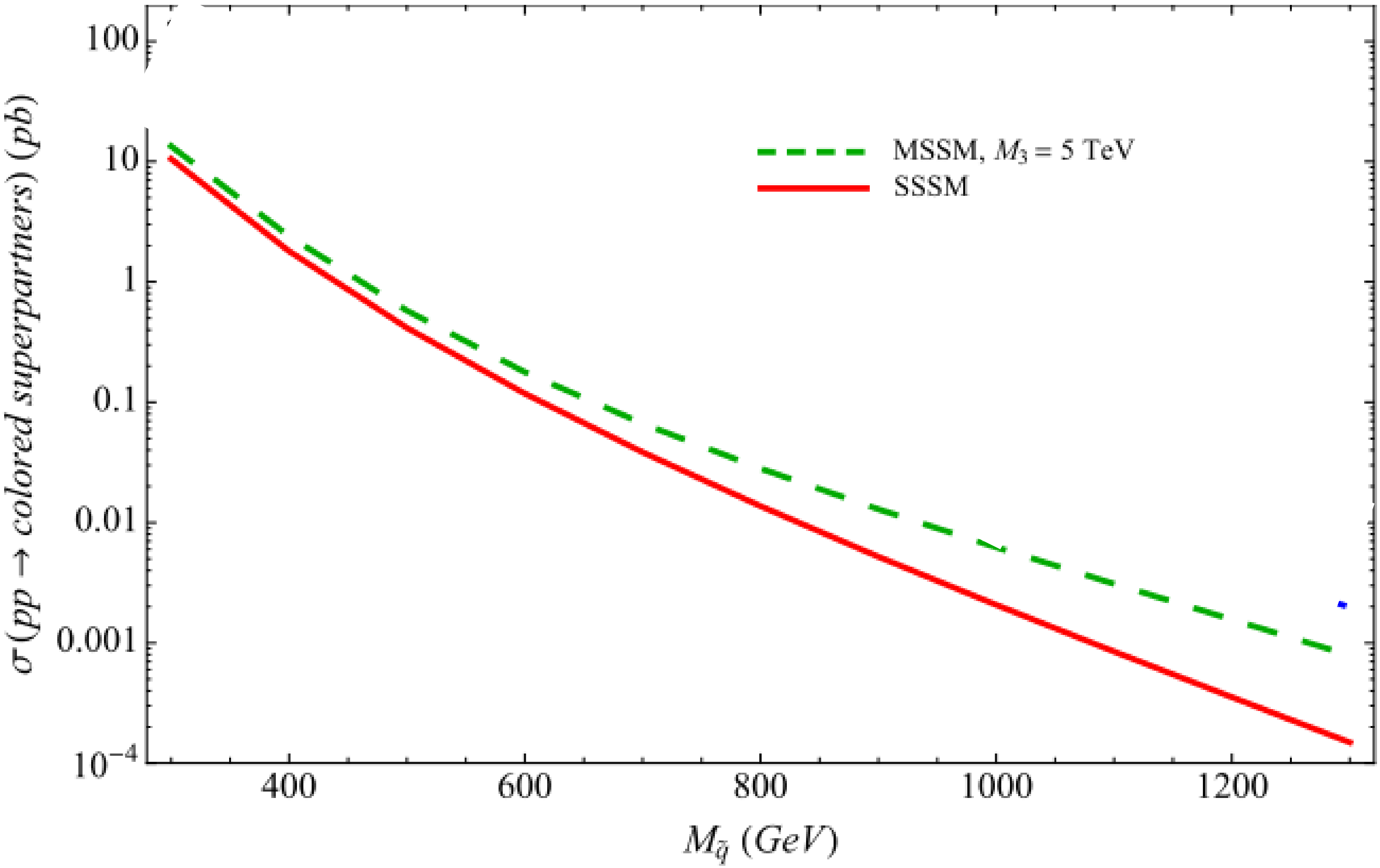
Meaning of M_m/M_d



$M_m, M'_m = 0$
Dirac

$M_m/M_d \neq 0$
Mixed, $M'_m = 0$

Revisit and reinterpretation



Mixed mass terms

$$\mathcal{L}_{\tilde{g}\,\mathrm{mass}} = \begin{pmatrix} g_a & \psi_a \end{pmatrix} \begin{pmatrix} M_m & M_d \\ M_d & \end{pmatrix} \begin{pmatrix} g_a \\ \psi_a \end{pmatrix} + \mathrm{h.c.}$$

M_m/M_d raised => increases decreases

$$\begin{pmatrix} g_1 \\ g_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{g}} & \sin\theta_{\tilde{g}} \\ -\sin\theta_{\tilde{g}} & \cos\theta_{\tilde{g}} \end{pmatrix} \begin{pmatrix} \psi \\ g \end{pmatrix}$$

The interaction

$$\mathcal{L}_{int} \;=$$

$$-\sqrt{2} g_s \big(\tilde{u}^*_{L,i}\; t^a\; g_a\; u_{L,i} + \tilde{d}^*_{L,i}\; t^a\; g_a\; d_{L,i}$$

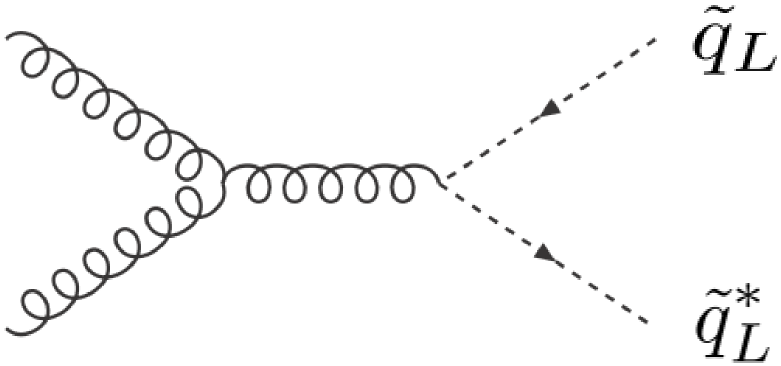
$$- \tilde{u}^*_{R,i}\; t^a\; g_a u_{R,i} - \tilde{d}^*_{R,i}\; t^a\; g_a\; d_{R,i} \big) + \text{h.c.}$$

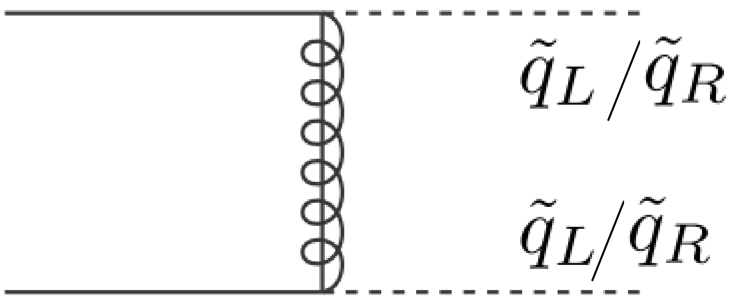
$$\mathcal{L}_{\tilde{g}\,\text{mass}} \;=\; \begin{pmatrix} g_a & \psi_a \end{pmatrix} \begin{pmatrix} M_m & M_d \\ M_d & \end{pmatrix} \begin{pmatrix} g_a \\ \psi_a \end{pmatrix} + \text{h.c.}$$

M_m/M_d raised => increases decreases

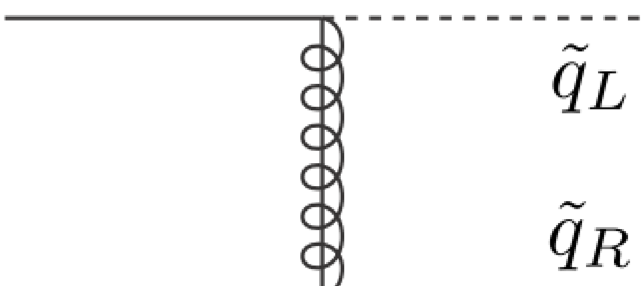
$$\begin{pmatrix} g_1 \\ g_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{g}} & \sin\theta_{\tilde{g}} \\ -\sin\theta_{\tilde{g}} & \cos\theta_{\tilde{g}} \end{pmatrix} \begin{pmatrix} \psi \\ g \end{pmatrix}$$

Individual Modes



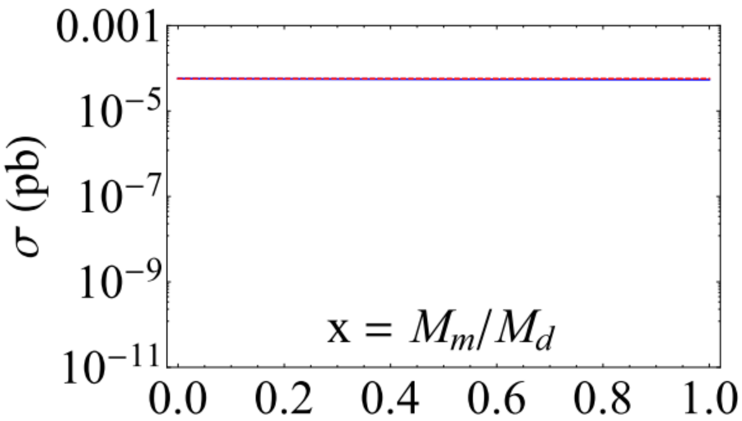


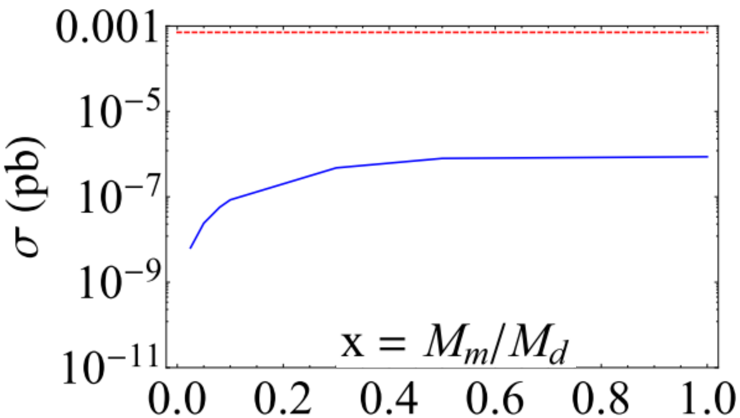
$$\frac{c^2_{\theta_{\tilde{g}}} M_{\tilde{g}2}}{p^2 + M^2_{\tilde{g}2}} - \frac{s^2_{\theta_{\tilde{g}}} M_{\tilde{g}1}}{p^2 + M^2_{\tilde{g}1}} = \frac{p^2}{M^3_{\tilde{g}1}} x \left(\sqrt{x^2+4} - x\right)^3 + \mathcal{O}(p^4/M^4_{\tilde{g}1})$$



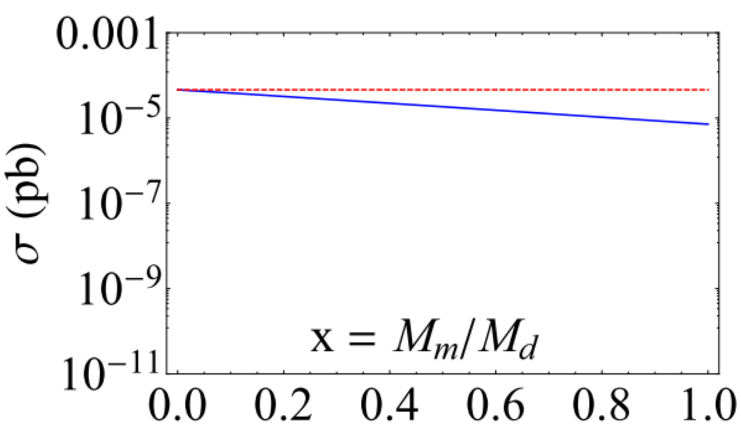
$$\frac{c^2_{\theta_{\tilde{g}}}}{p^2 + M^2_{\tilde{g}2}} + \frac{s^2_{\theta_{\tilde{g}}}}{p^2 + M^2_{\tilde{g}1}} = \frac{(x - \sqrt{x^2+4})^2}{4M^2_{\tilde{g}1}} + \mathcal{O}(p^2/M^2_{\tilde{g}1})$$

Individual Modes





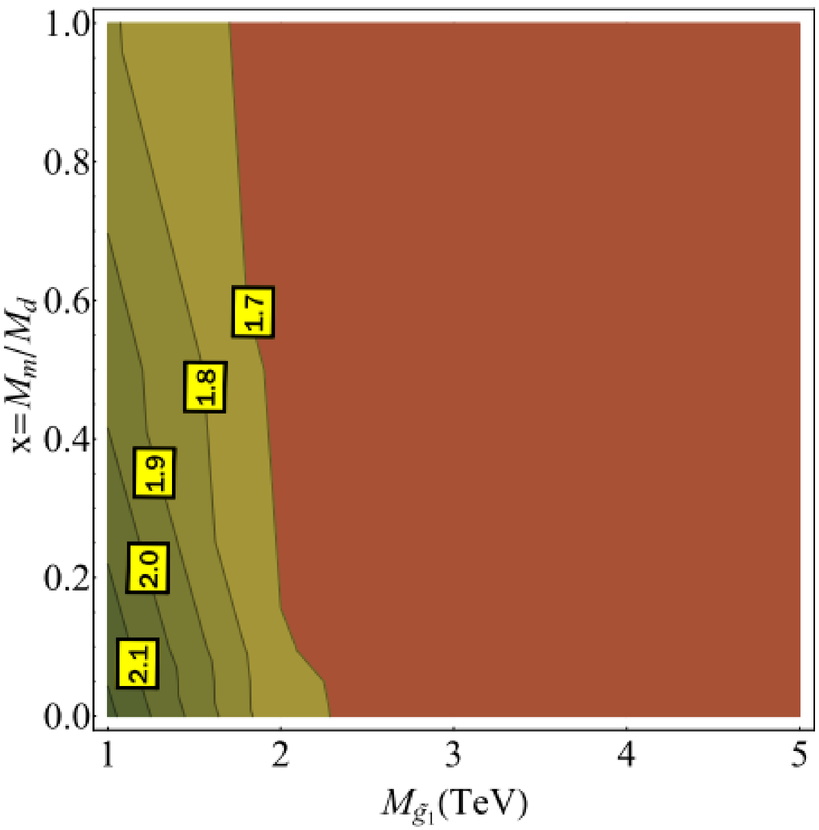
$$\frac{c^2_{\theta_{\tilde{g}}} M_{\tilde{g}2}}{p^2 + M^2_{\tilde{g}2}} - \frac{s^2_{\theta_{\tilde{g}}} M_{\tilde{g}1}}{p^2 + M^2_{\tilde{g}1}} = \frac{p^2}{M^3_{\tilde{g}1}} x \left(\sqrt{x^2+4} - x\right)^3 + \mathcal{O}(p^4/M^4_{\tilde{g}1})$$



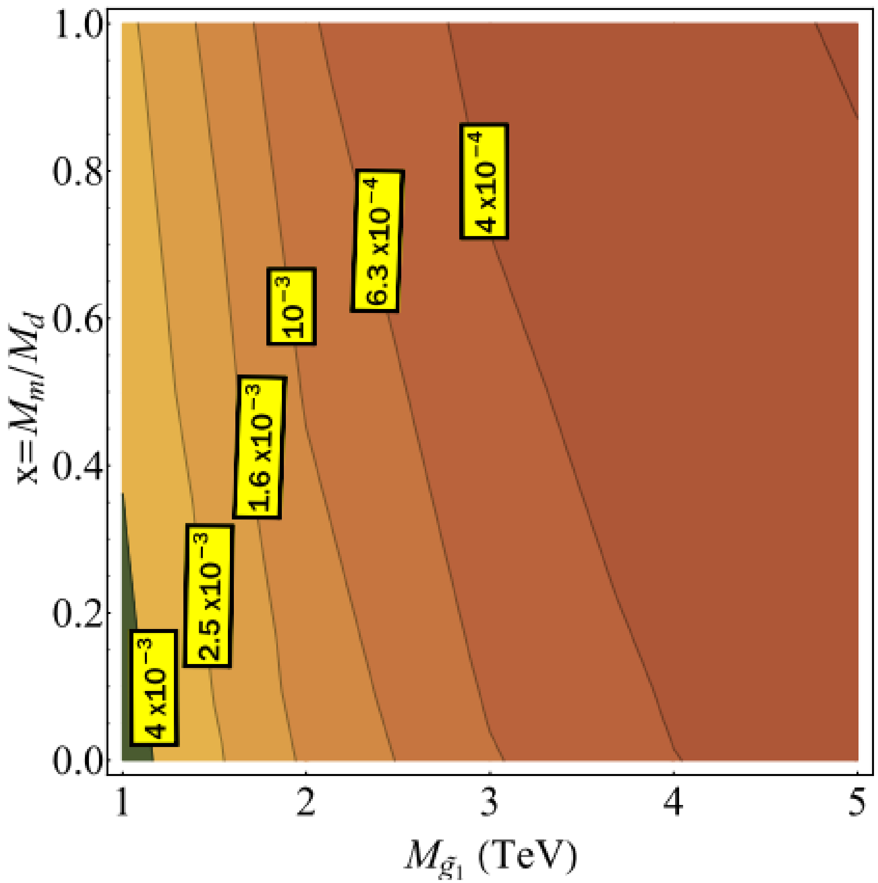
$$\frac{c^2_{\theta_{\tilde{g}}}}{p^2 + M^2_{\tilde{g}2}} + \frac{s^2_{\theta_{\tilde{g}}}}{p^2 + M^2_{\tilde{g}1}} = \frac{(x - \sqrt{x^2+4})^2}{4M^2_{\tilde{g}1}} + \mathcal{O}(p^2/M^2_{\tilde{g}1})$$

XS↓ in vertical direction

$M_{\tilde{q}} = 400$ GeV: cross-sections



$M_{\tilde{q}} = 1200$ GeV: cross-sections



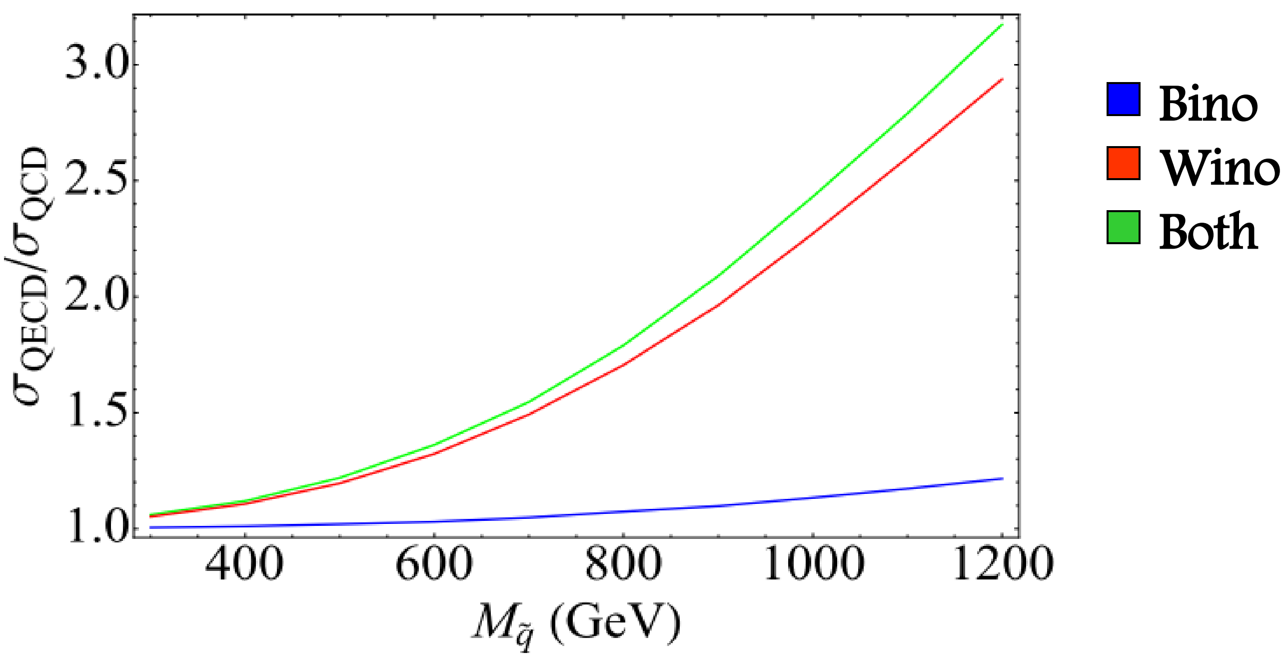
Role of Electroweakinos

	wino	bino
$u_{i,L};\tilde{u}_{i,L}$	$g/\sqrt{2}$	$g'/3\sqrt{2}$
$d_{i,L};\tilde{d}_{i,L}$	$-g/\sqrt{2}$	$g'/3\sqrt{2}$
$u_{i,R};\tilde{u}_{i,R}$	0	$-4g'/3\sqrt{2}$
$d_{i,R};\tilde{d}_{i,R}$	0	$2g'/3\sqrt{2}$

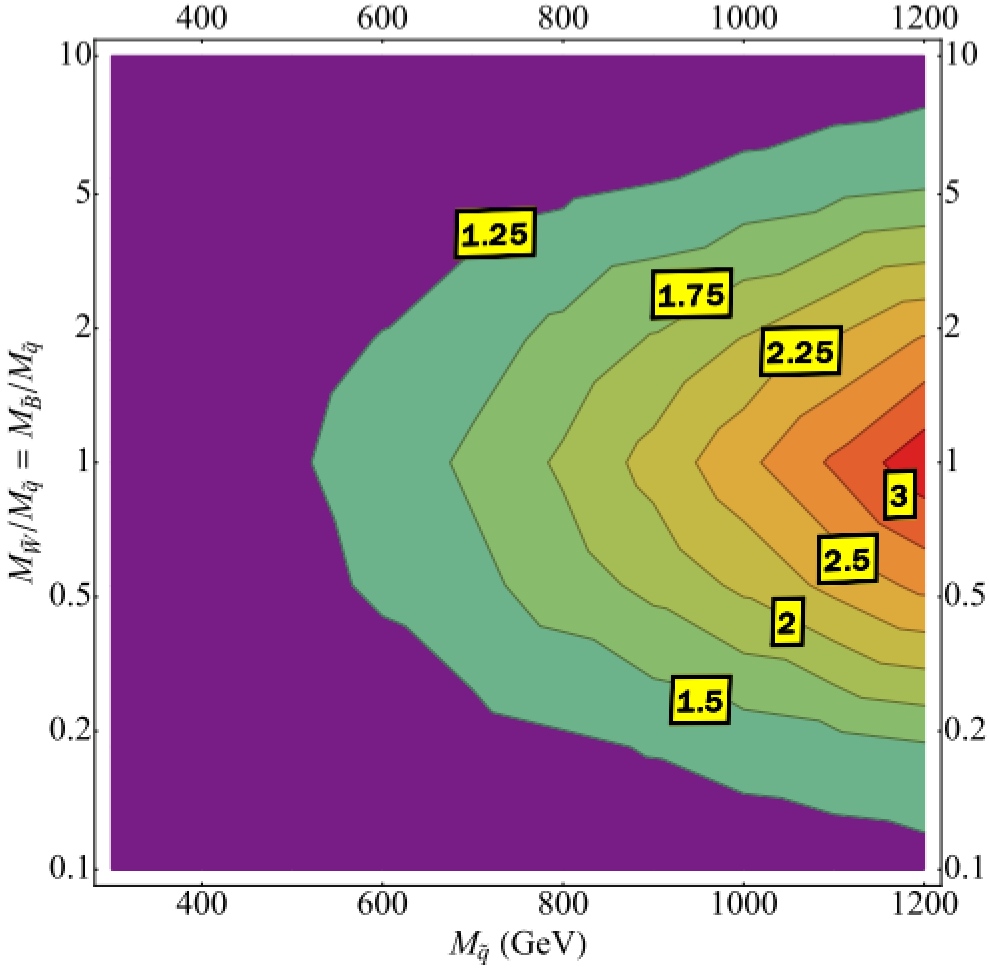
$$\tilde{q}_L, \tilde{q}_L:\quad g_f^2 \frac{M_f}{t - M_f^2}$$

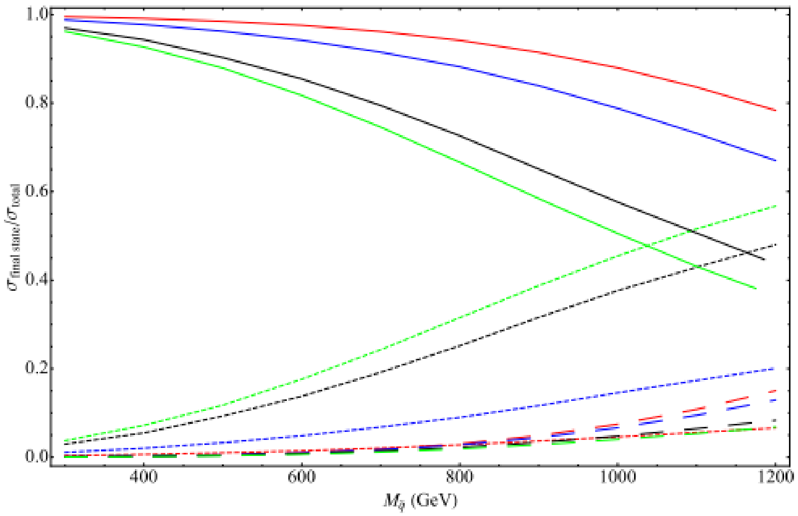
$$\tilde{q}_L, \tilde{q}_R:\quad g_f^2 \frac{p \cdot \sigma}{t - M_f^2}$$

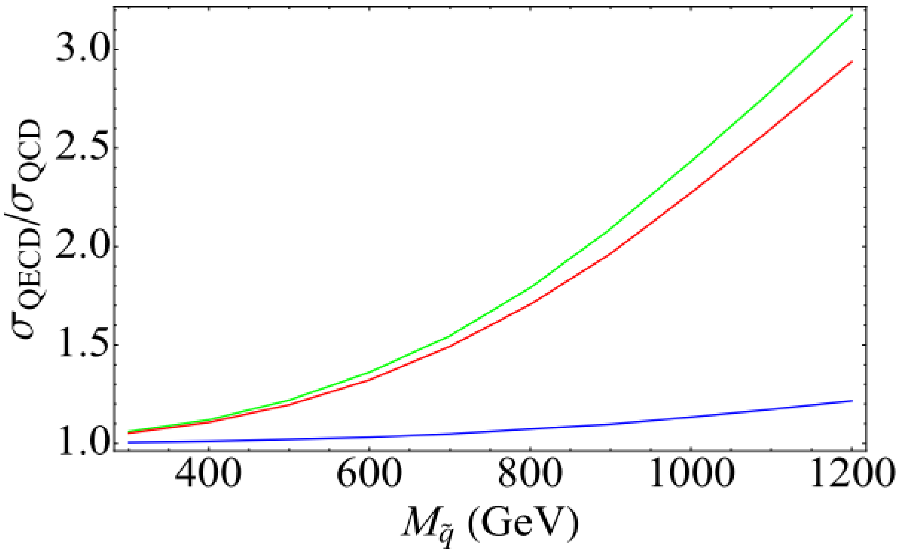
Maximal Electroweakino Impact (MEI)



MEI


1.25
1.75
2.25
3
2.5
2
1.5
$M_{\tilde{W}}/M_{\tilde{q}} = M_{\tilde{B}}/M_{\tilde{q}}$
$M_{\tilde{q}}$ (GeV)


$\sigma_{\text{final state}}/\sigma_{\text{total}}$
$M_{\tilde{q}}$ (GeV)

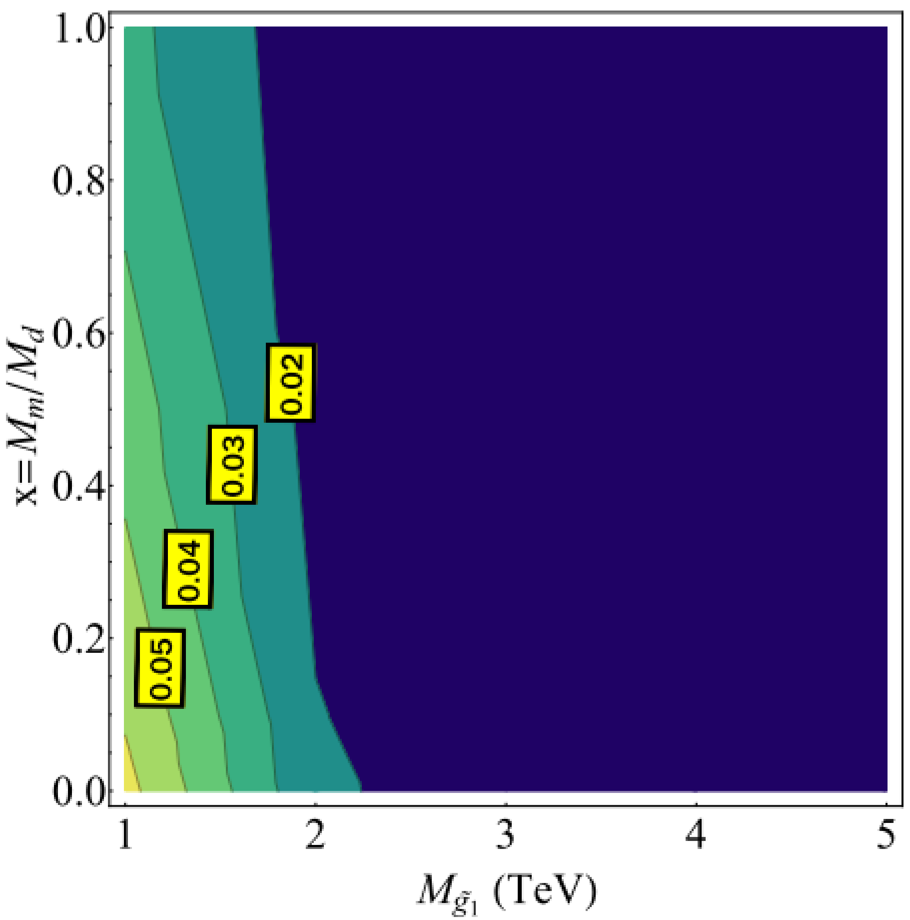

$\sigma_{\text{QECD}}/\sigma_{\text{QCD}}$
$M_{\tilde{q}}$ (GeV)

CMS Bound

Search strategy:

$\not\!\!E_T$ and 0, 1, 2, 3, or ≥ 4 b-jets at $\sqrt{s} = 8$ TeV and $\mathcal{L} = 11.7$/fb

$M_{\tilde{q}} = 800$ GeV: cross-sections

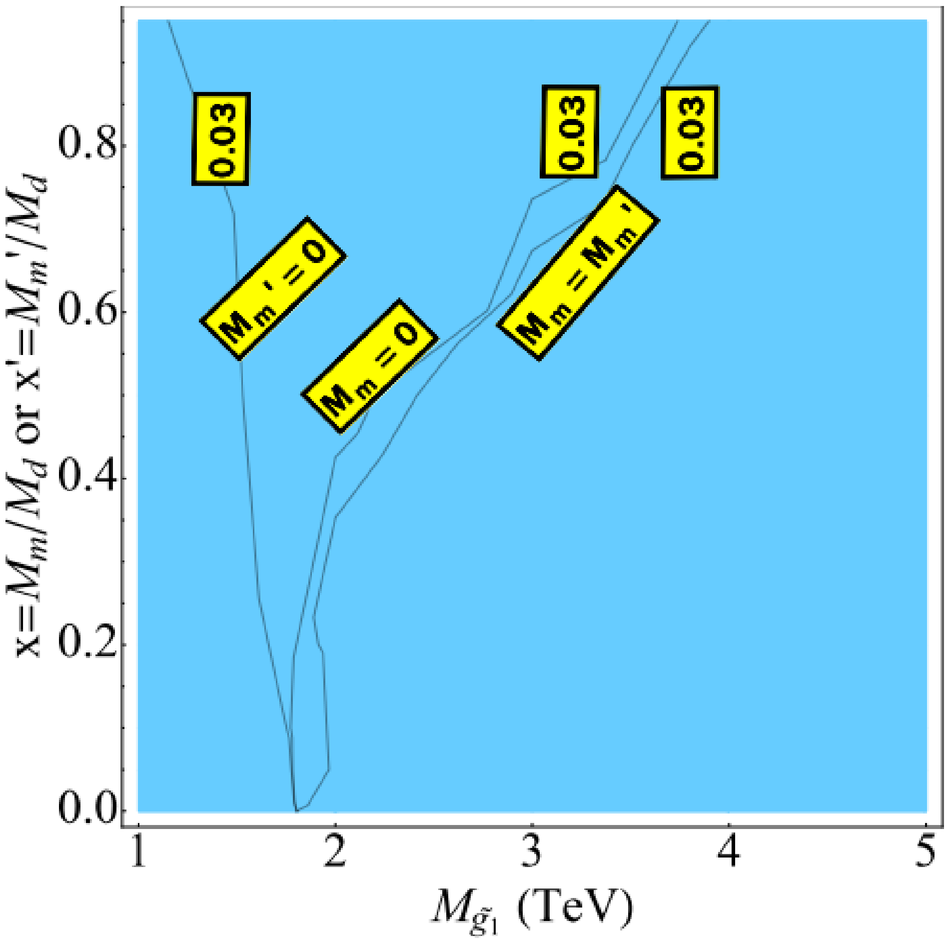


CMS Bound

Search strategy:

$\not{E}_T$ and 0, 1, 2, 3, or ≥ 4 b-jets at $\sqrt{s} = 8$ TeV and $\mathcal{L} = 11.7/\text{fb}$

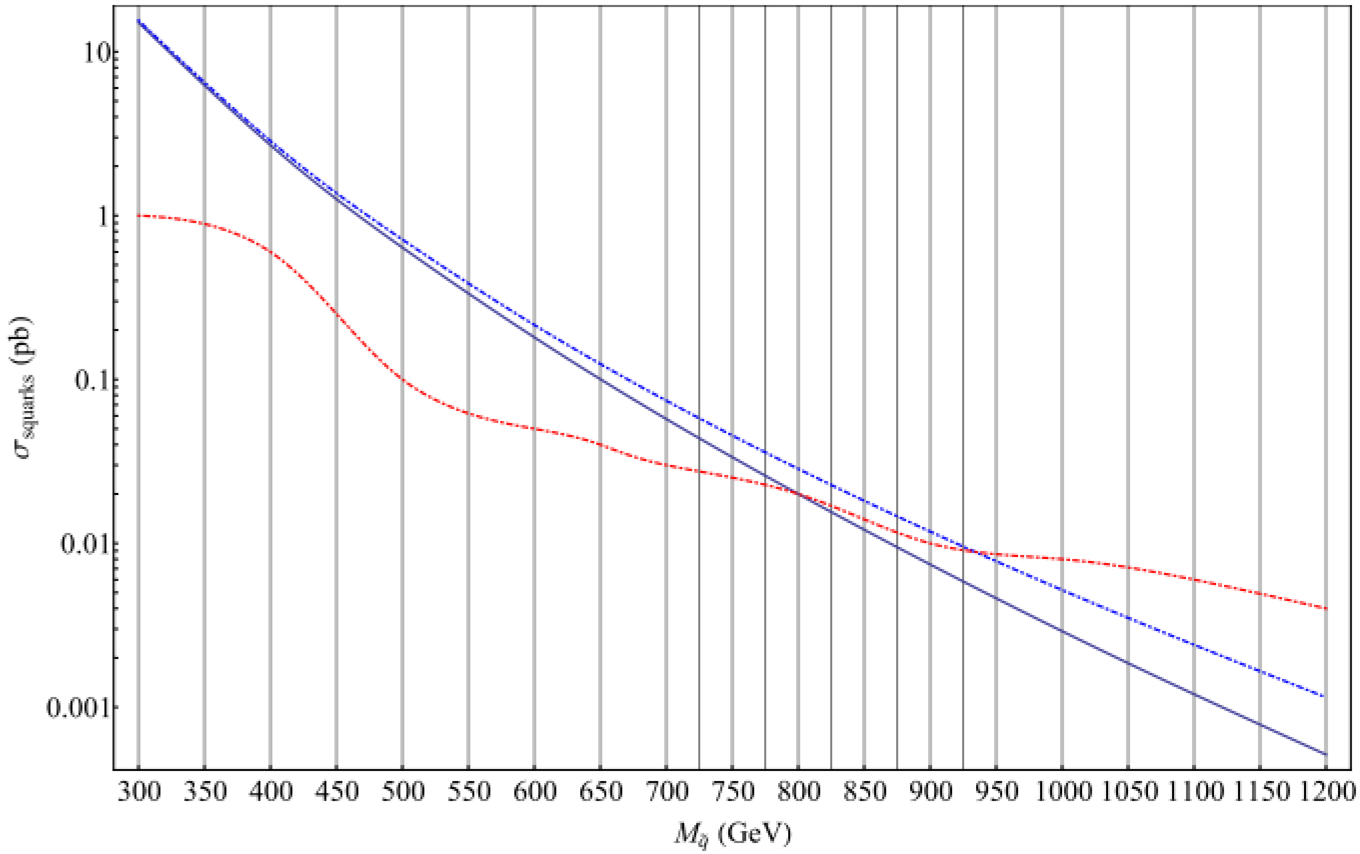
$M_{\tilde{q}} = 800$ GeV: cross-sections



CMS Bound

Search strategy:

$\not{E}_T$ and 0, 1, 2, 3, or $\geq$ 4 b-jets at $\sqrt{s} = 8$ TeV and $\mathcal{L} = 11.7/\text{fb}$



Pure Dirac: $M_{\tilde{q}} \geq 800$ GeV

MEI: $M_{\tilde{q}} \geq 925$ GeV

Recommended New Simplified Models

1) **Dirac gluino, several choices of LSP mass**: Cross section bounds in $M_{\tilde{q}} - M_D$ plane; $M_{\rm LSP} = 0, 200, 400$ GeV.

2) **Dirac gluino, several choices of gluino mass**: Cross section bounds in $M_{\tilde{q}} - M_{\rm LSP}$ plane $M_D = 1$-3 TeV in steps of 0.5 TeV.

3) **Mixed gluino, several choices of squark mass**: Cross section bounds in $M_{\tilde{g}1} - x$ plane for Cases I,II,III; $M_{\tilde{q}} =$ 500-1000 GeV in steps of 100-250 GeV, with a massless LSP.

4) **Mixed gluino, several choices of LSP mass**: Cross section bounds in $M_{\tilde{g}1} - x$ plane for Cases I,II,III; $M_{\tilde{q}} = 500$, $M_{\rm LSP} = 0, 200, 400$ GeV.

5) **Dirac gluino with Majorana electroweakinos, several choices of LSP mass**: Cross section bounds in $M_{\tilde{q}} - M_{\tilde{W},\tilde{B}}/M_{\tilde{q}}$ plane; take $M_{\tilde{W}} = M_{\tilde{B}}$ and $M_{\tilde{W}} = 2M_{\tilde{B}}$; $M_{\rm LSP} = 0, 200, 400$ GeV.

Conclusions

~ Supersoft and F-term breaking leading to and $M_m/M_d \neq 0$ is *less* constrained at the LHC than a pure Dirac gluino

~ All other cases of mixed gluinos more constrained

~ Electroweakino interference makes little difference except at MEI values; even there, not much

~ Proliferation of parameter space warrants new simplified models for LHC collaborations to comb

Dark Matter

In the know:

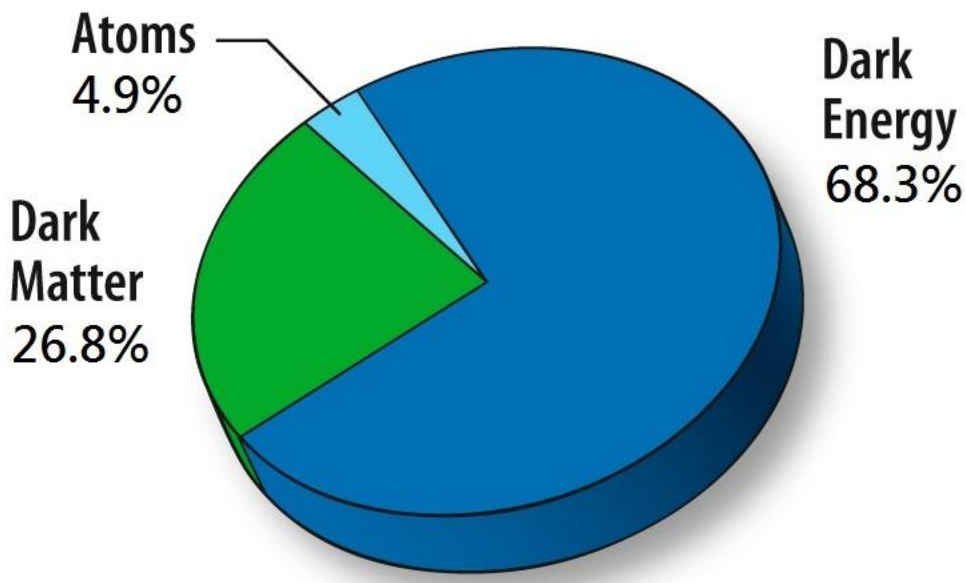
+ Feels gravity (rotation curves, lensing)

+ Undetectably tiny/ no EM interaction

[hence the name]

+ Non–baryonic (Bullet Cluster)

+ "Cold": $v \sim 10^{-2}$



A Classification

- Non-thermal

  E.g. Asymmetric dark matter, axions

- Thermal

  - Relic of freeze-out in early universe
  - Lightest state of a hidden sector (like SUSY) distinguished from visible sector via some parity
  - Could be Weakly Interacting Massive Particles (WIMP's)

WIMP's

Weak scale mass (~1 TeV) + weak coupling

↓

Annihilation $\langle\sigma v\rangle = 3.0\times10^{-26}\ \mathrm{cm^3/s}$

↓

Correct relic abundance $\Omega h^2 = 0.11$

⇓

"WIMP Miracle"

Natural candidate: Lightest Supersymmetric Particle (LSP) in Weak Scale SUSY

LSP's

Gravitino $\tilde{G}$

Sneutrino $\tilde{\nu}$

Neutralino $\tilde{\chi}_1^0$

- Wino-like $\tilde{W}$
- Bino-like $\tilde{B}$
- Higgsino-like $\tilde{H}^0$

Each its own merits and sicknesses; SUSY model-dependent

Must explore effective theories with pheno ~ SUSY

An Effective Model [Phenomenologically Motivated]

- Hidden sector odd under a Z_2 parity
- Three low-lying (=LHC-accessible) states:

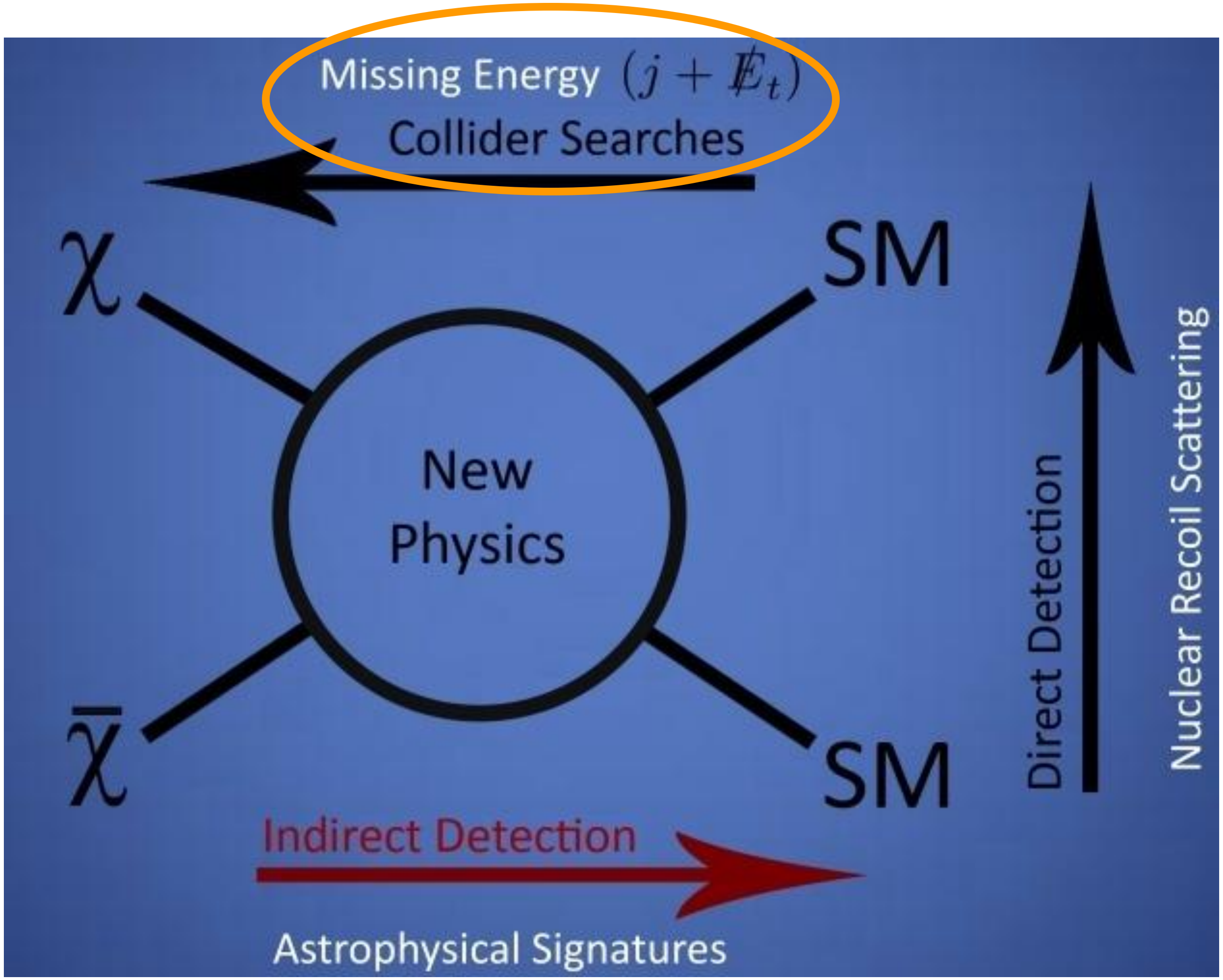
$$\tilde{q}\ (3, 1, \tfrac{2}{3}\ \text{or} - \tfrac{1}{3}), \tilde{l}\ (1, 1, -1), \chi\ (1, 1, 0)$$

scalar | scalar | fermion, DM

- Inspired by SUSY, but couplings to visible sector undetermined
- Non-minimal scenarios can have $SU(2)_W$ doublets $\tilde{q}\ (3, 2, \frac{1}{6}), \tilde{l}\ (1, 1, -\frac{1}{2})$ as well

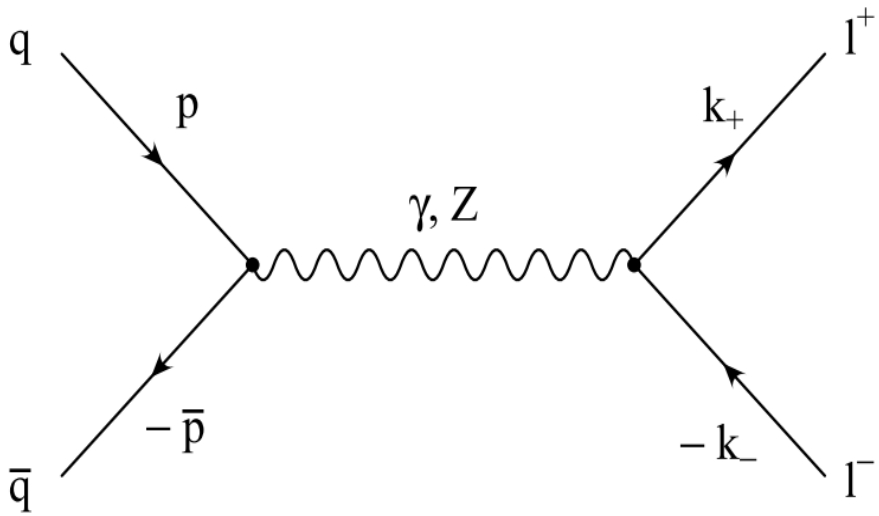
Altmannshofer, Fox, Harnik, Kribs, Raj

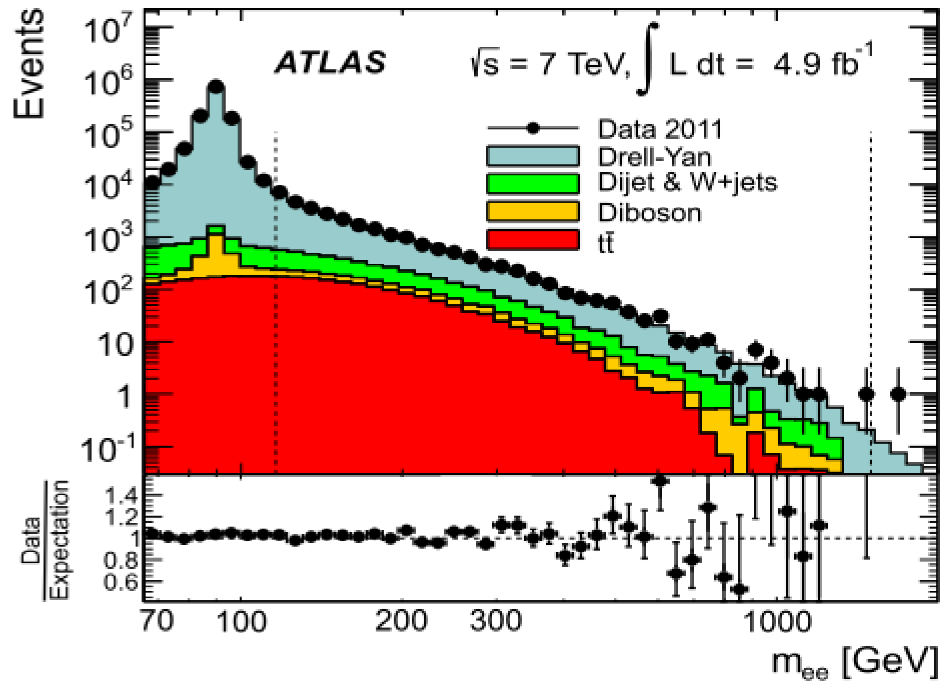
Non-gravitational Evidence

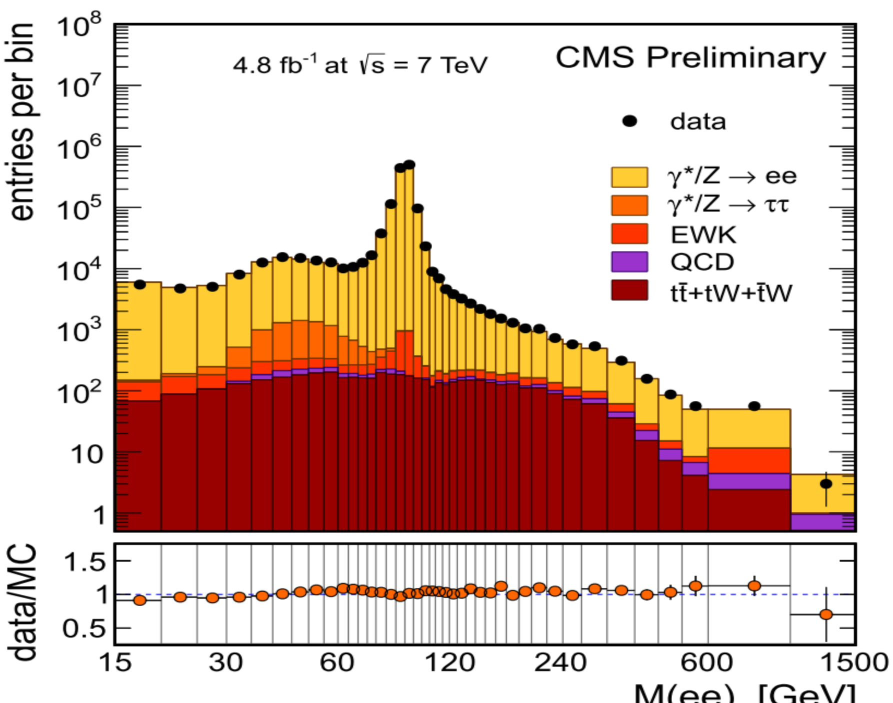


Eric Carlson, TASI 2013

Collider Search with a Twist





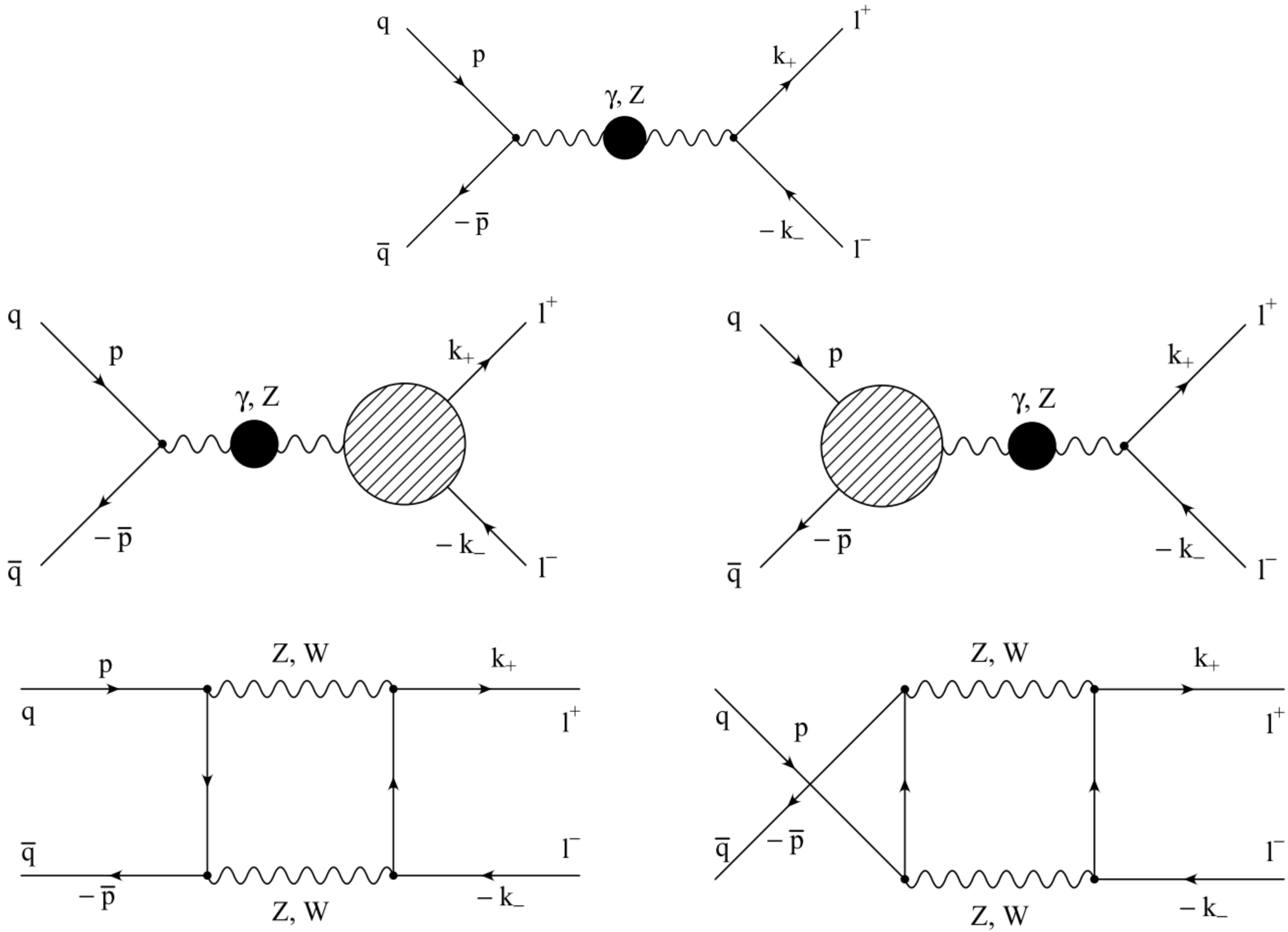


Neutral Current Drell-Yan

Historically, discovery of Z, W's, J/ψ, ϒ, Oops-Leon, …

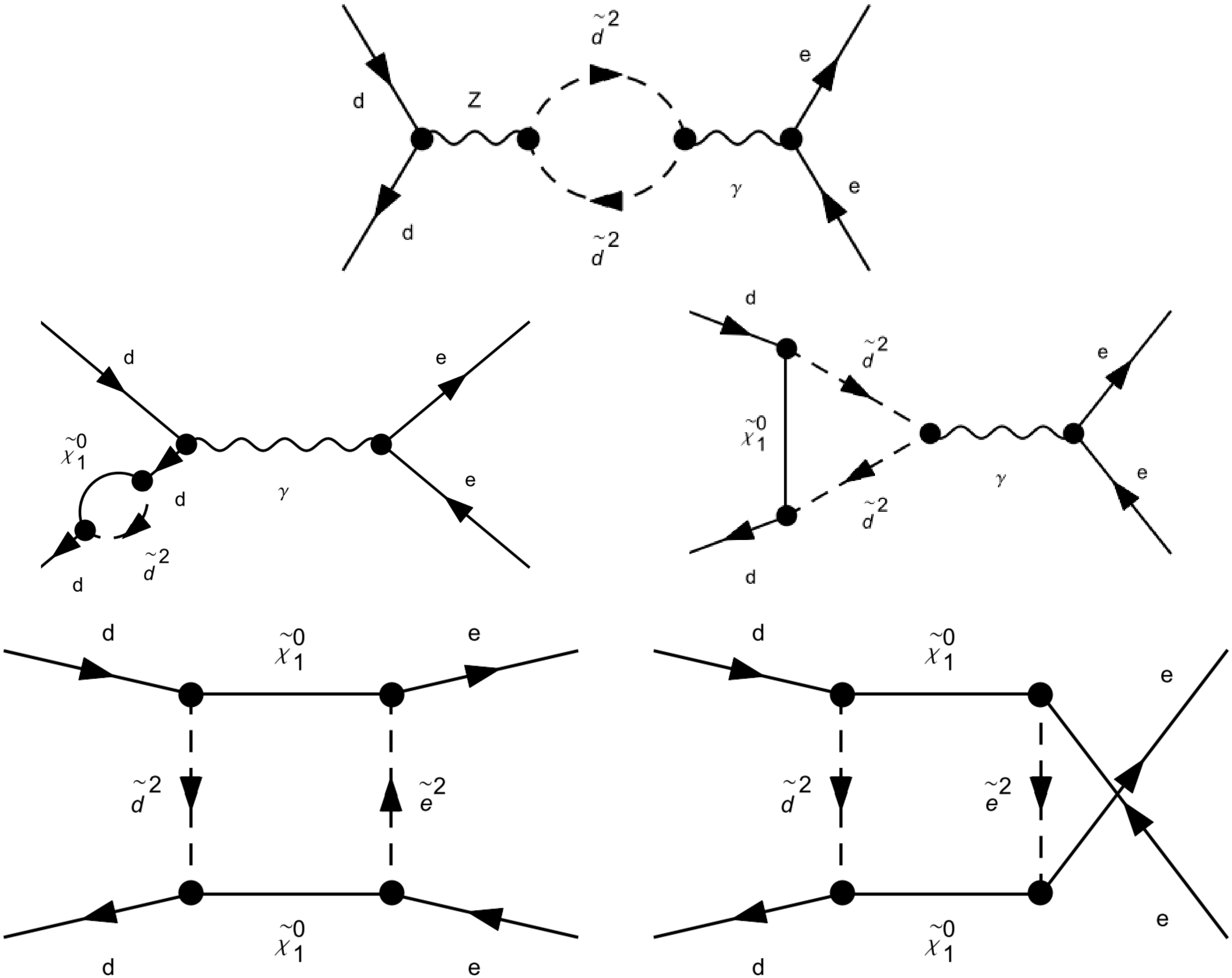
Good old-fashioned
New Physics portal

SM Drell–Yan at NLO



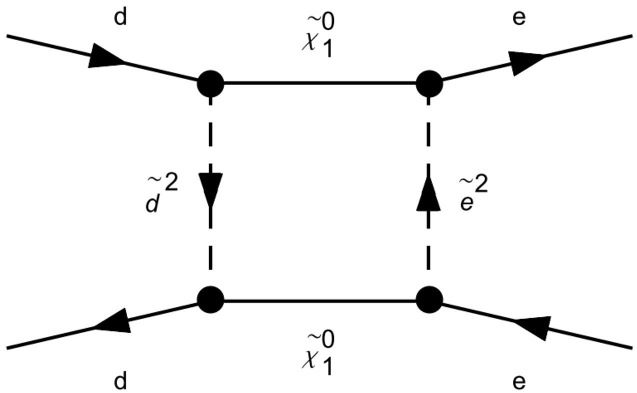
Drell–Yan: Effects of Our Model

N.B.: Inexhaustive set of diagrams shown

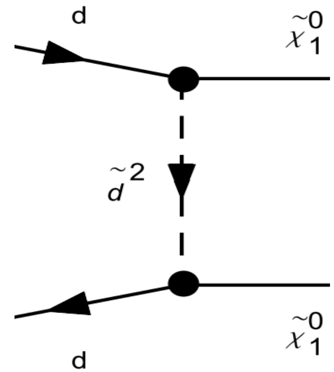


Optical Theorem

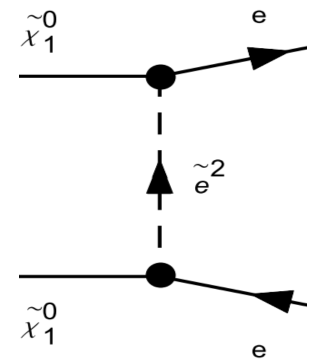
Im



~



x



when $\sqrt{s} > 2M_\chi$

$$2\ \mathrm{Im}\ \mathcal{M}(a \to b) \;=\; \sum_F \int d\Pi_F \mathcal{M}^*(b \to F)\mathcal{M}(a \to F)$$

$$|A_{\text{tree}} + A_{\text{box}}|^2 \Rightarrow |A_{\text{tree}} + A^{\text{real}}_{\text{box}} + iA^{\text{imag}}_{\text{box}}|^2$$

$$\sigma_{\text{tree}} + \sigma_{\text{int}} + \sigma_{\text{box}}$$

$$\Rightarrow \quad \sigma_{\text{tree}} + \sigma^{\text{re}}_{\text{int}} + \sigma^{\text{im}}_{\text{int}} + \sigma^{\text{real}}_{\text{box}} + \sigma^{\text{imag}}_{\text{box}} + \sigma^{\text{re-im}}_{\text{box}}$$

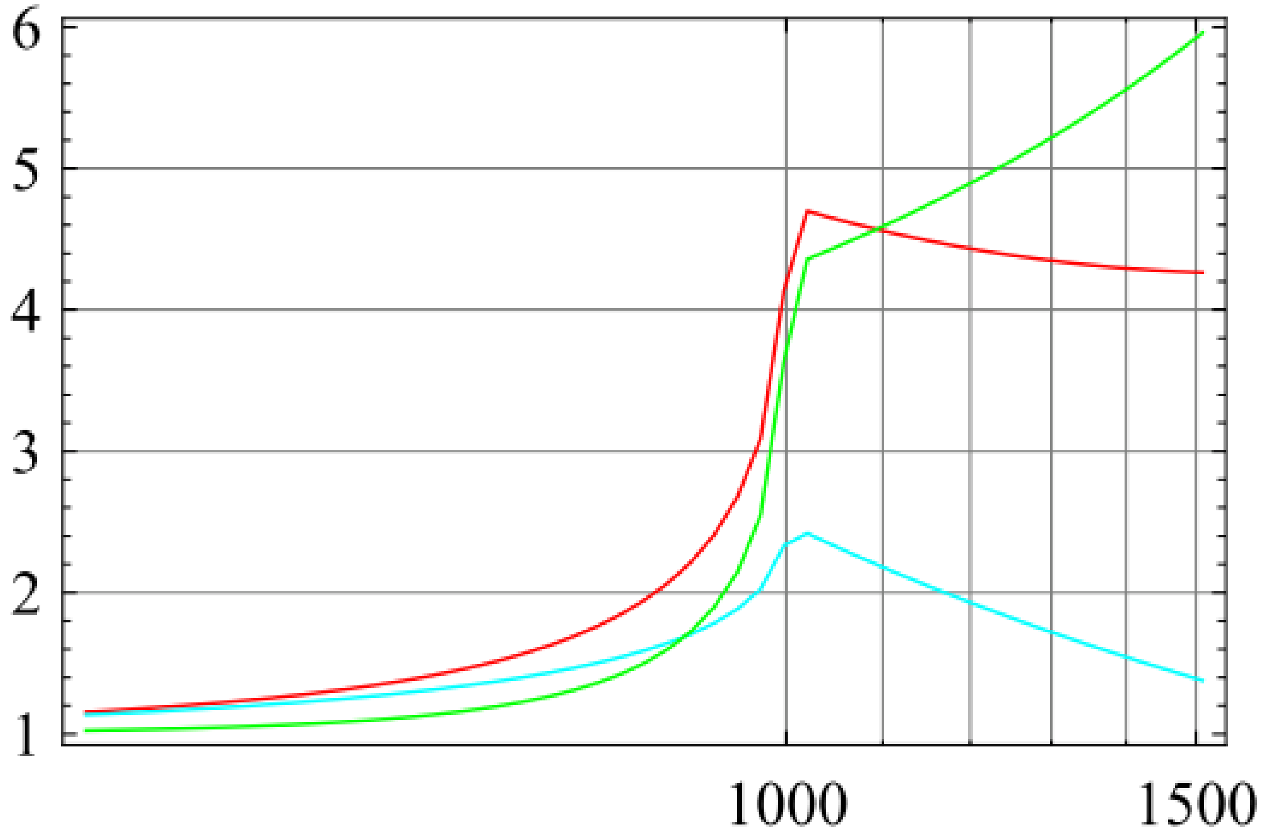
Affects both $d\sigma/dm_{ll}$ **and** $d\sigma/d\cos\theta$

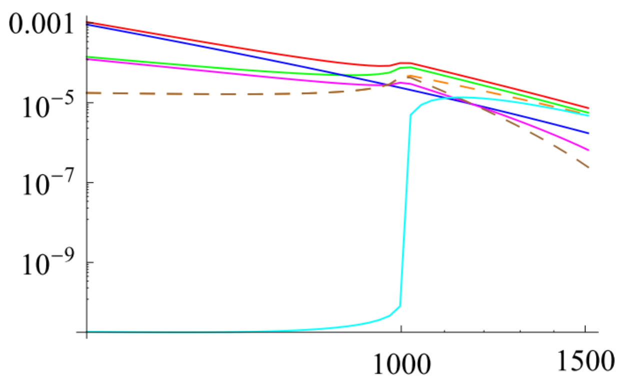
$$(d\sigma/dc_\theta) \propto \frac{3}{8}(1 + c_\theta^2) + A_{FB}\, c_\theta$$

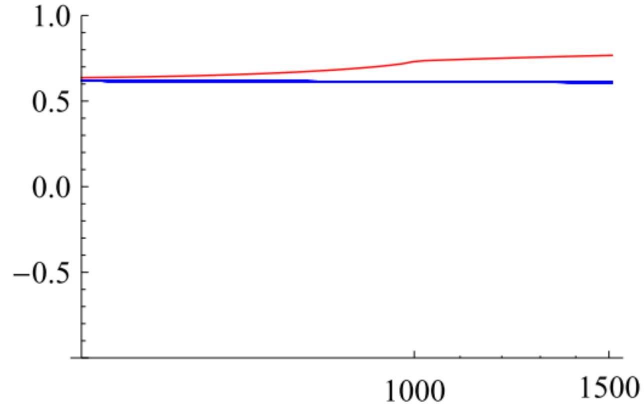
$$\frac{\int_0^1 dc_\theta (d\sigma/dc_\theta) - \int_{-1}^0 dc_\theta (d\sigma/dc_\theta)}{\int_{-1}^1 dc_\theta (d\sigma/dc_\theta)}$$

New Physics Signals

$\lambda_u = 1.8, M_\chi = M_\phi = 500$ GeV







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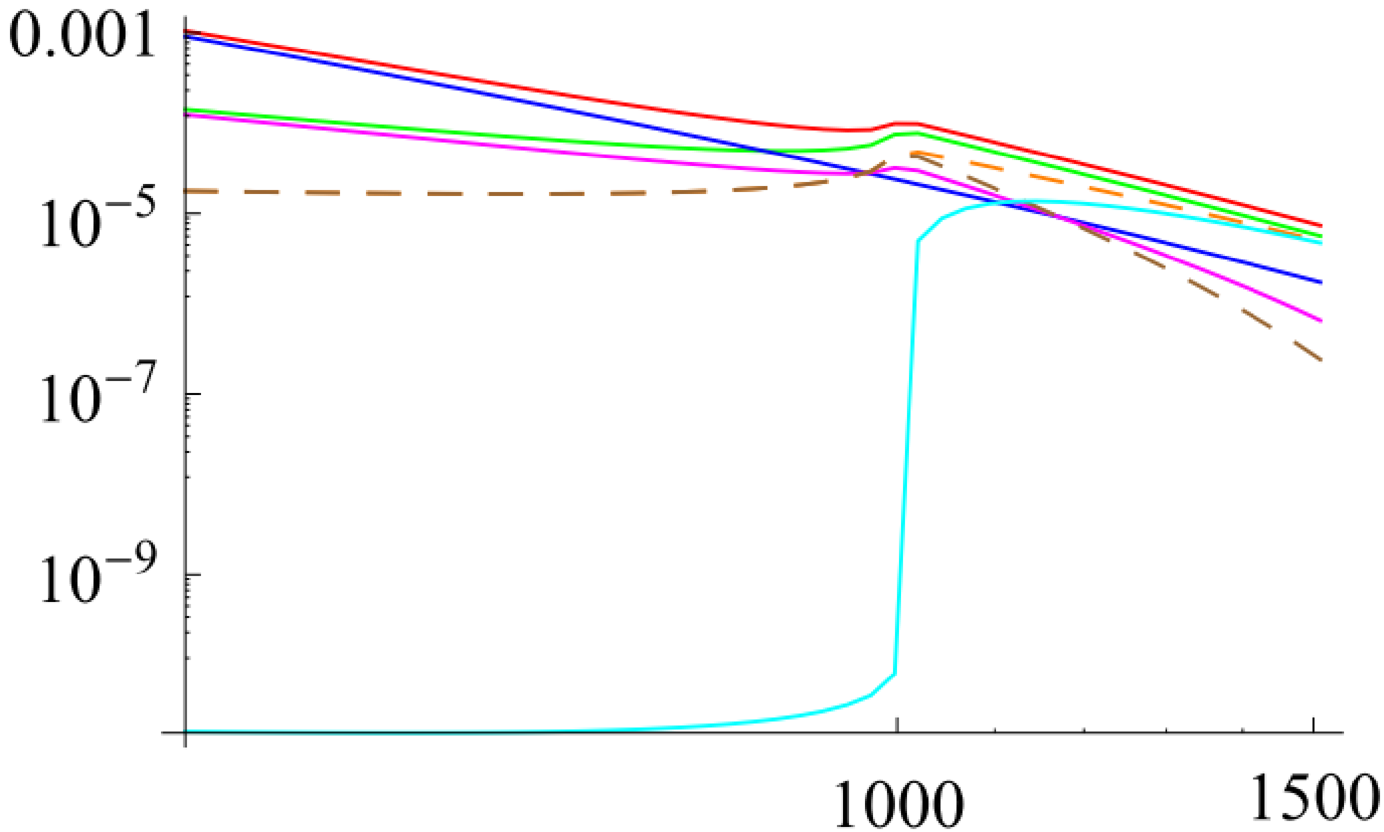

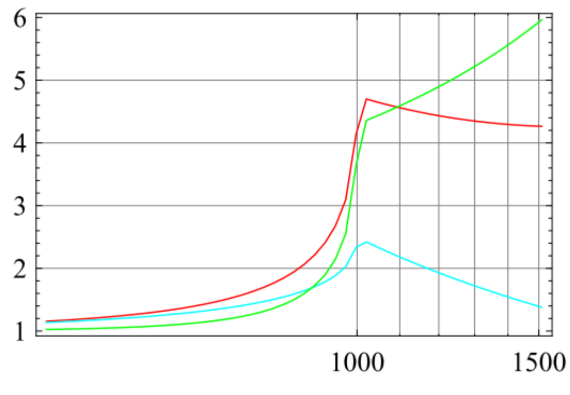

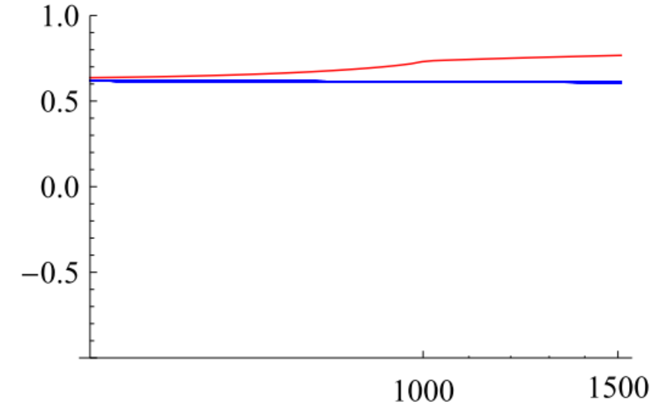

New Physics Signals

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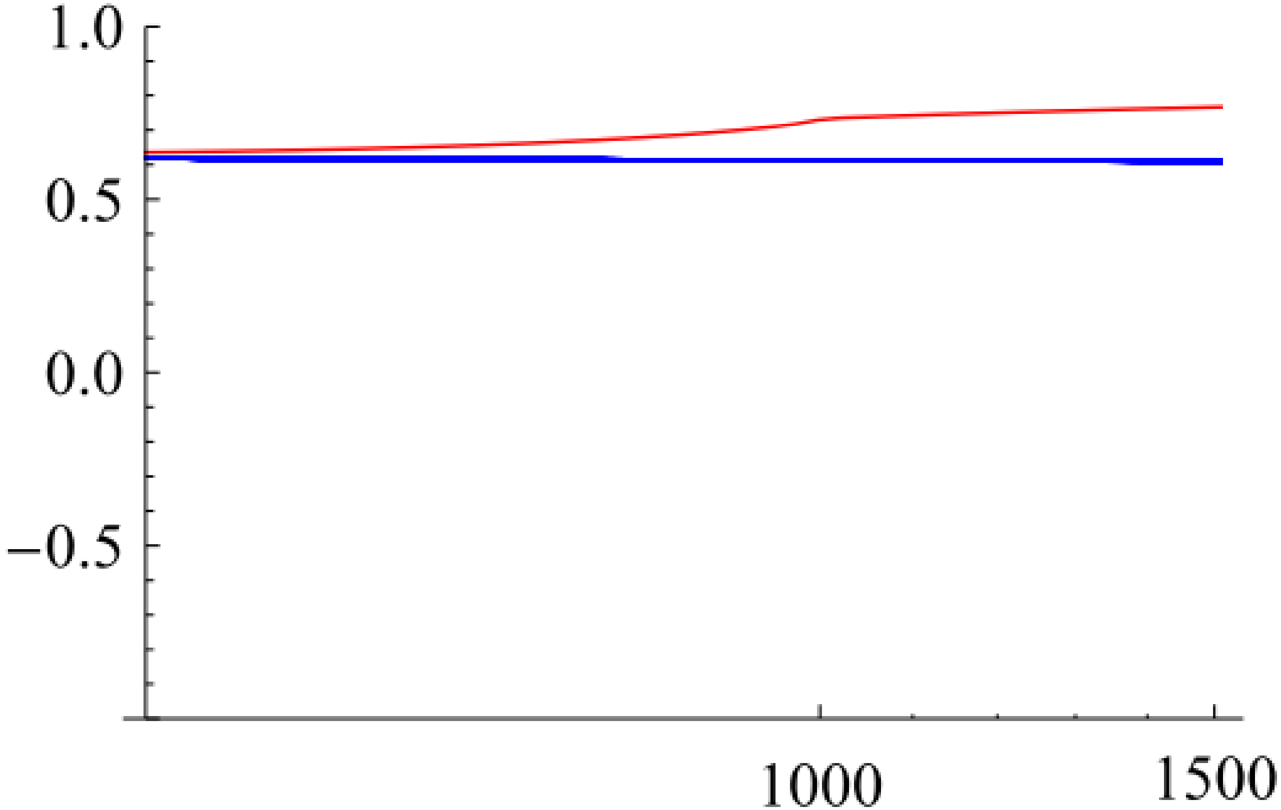
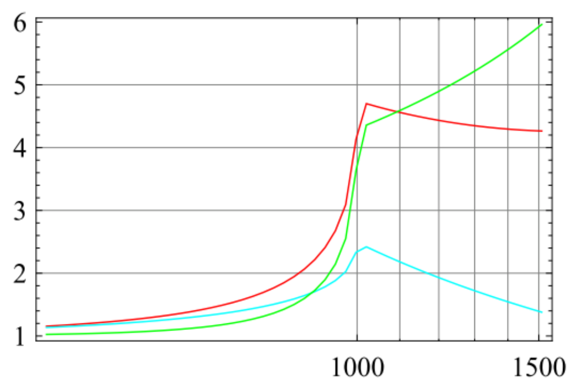
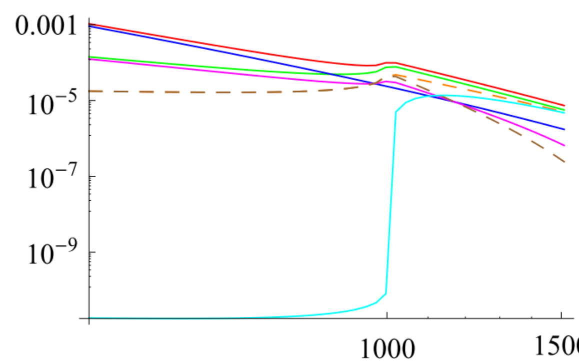
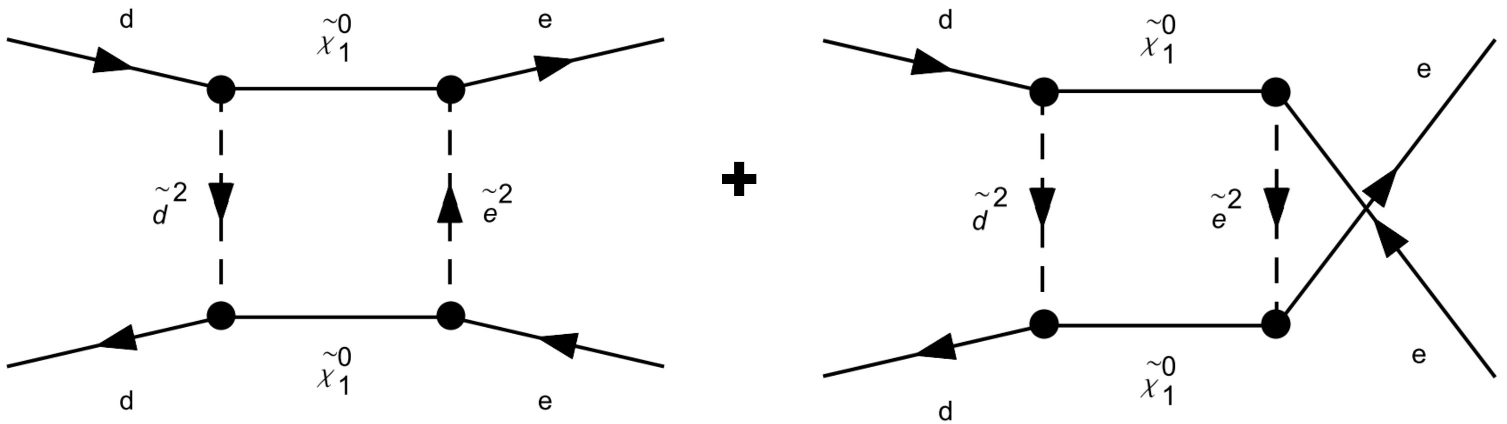






Emergent Realizations

- Better have Majorana DM
  - Dirac dislikes direct detection limits
  - Majorana => crossed boxes => three more terms



- Phase-independent – predictive!
- Electroweak Sudakov corrections unimportant
- Tevatron's t-tbar A_{FB} wrong tree to bark up

In the pipeline

- Relic abundance constraints
  - Parameter space permissible
  - Effects of co-annihilation
- Direct detection limits
- UV issues
  - RG flows of couplings, masses; Landau poles
- Translation to Experimentalese
  - Poisson events prediction
  - Likelihood fits

Conclusions

+ Effective model within LHC reach considered

  – SUSY–inspired

  – Obeys relic abundance constraints well

  – Minimal: only three states introduced

+ Dispersion relations =>

  unusual Drell–Yan signals

  – Must write tools to hunt down bumps and deficiencies, not just resonance peaks

  – XS and AFB to be analyzed together

Articles

- ***A Supersymmetry Primer***
  S Martin – **hep-ph/9709356**

- ***Dirac Gaugino Masses and Supersoft Supersymmetry Breaking***
  Fox, Nelson, Weiner – **JHEP 0208 (2002) 035**

- ***Supersoft Supersymmetry is Supersafe***
  Kribs, Martin **– Phys.Rev. D85 (2012) 115014**

- ***Mixed Gauginos Sending Mixed Signals to the LHC***
  Kribs, Raj – **hep-ph/1307.7197**

- ***Effective WIMP's***
  Chang, Edezhath, Hutchinson, Luty – **hep-ph/1307.8120**

- **ATLAS and CMS results**
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ and https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

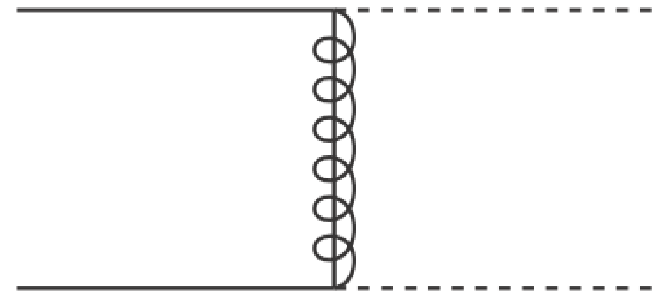
THANK YOU

Confession: My first seminar

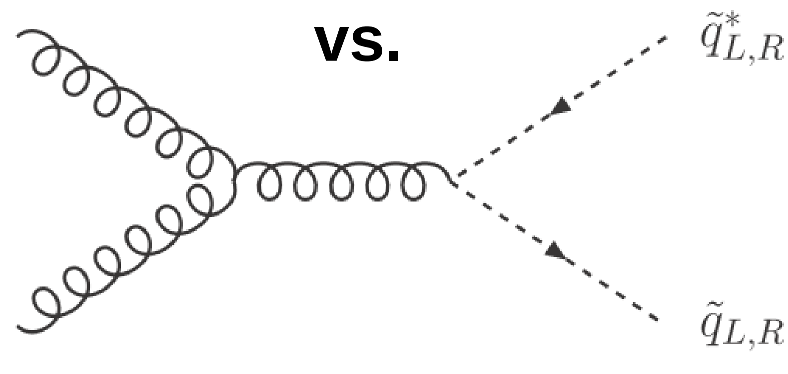
Supplementary Slides

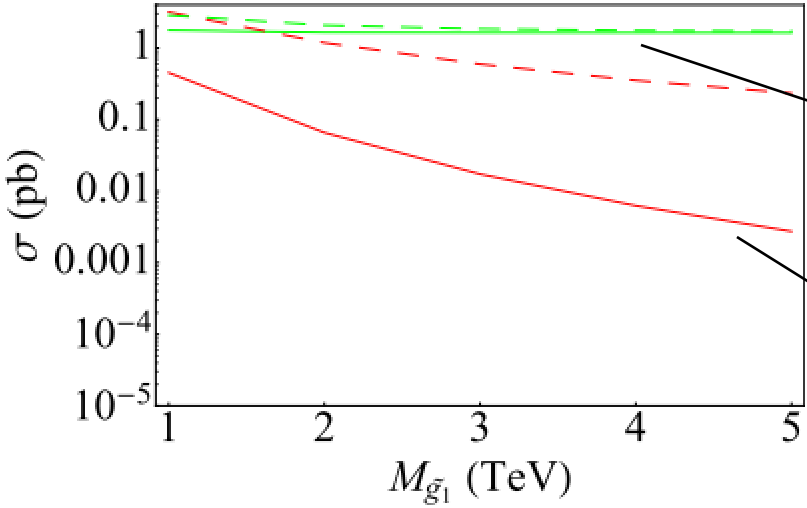
NO SEESAW

Horizontal properties of the contour plots



vs.

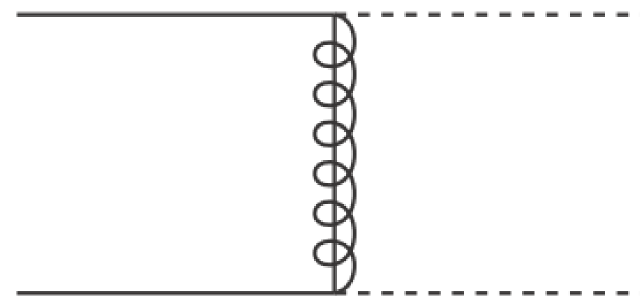




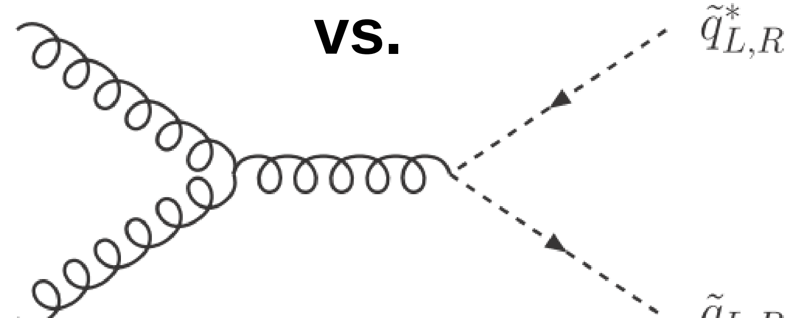
(a) $M_{\tilde{q}} = 400$ GeV

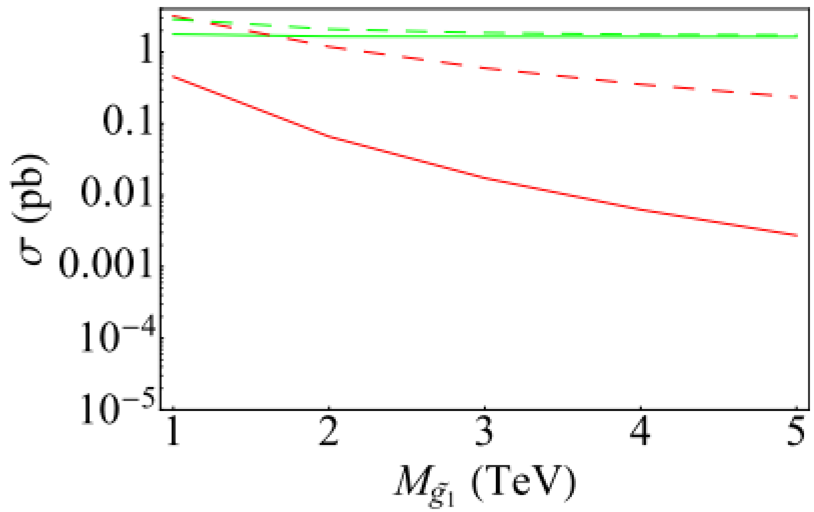
Squark-antisquark

Squark-squark

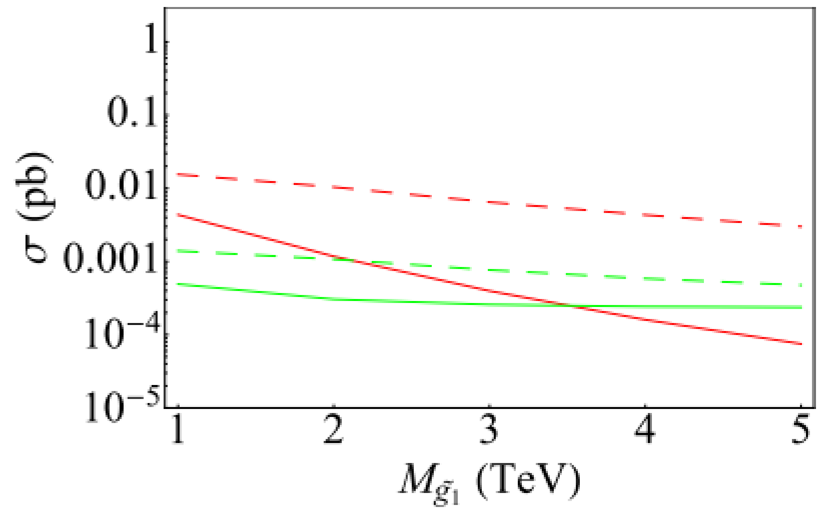


vs.

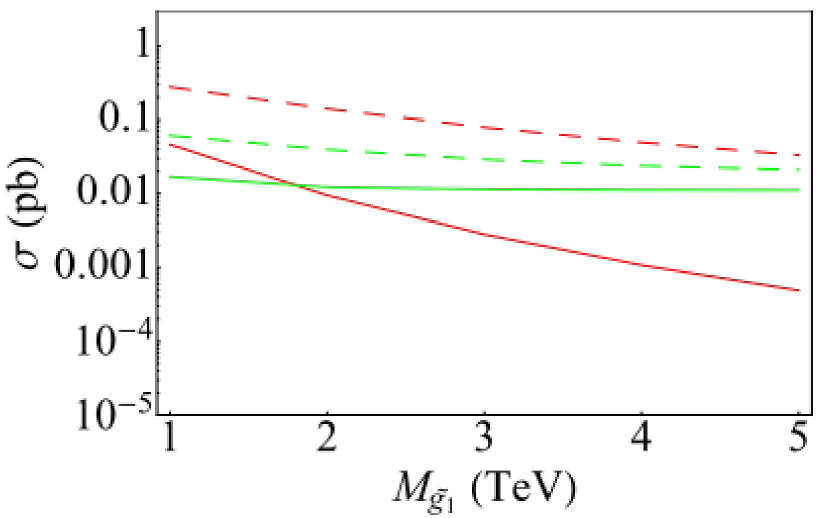




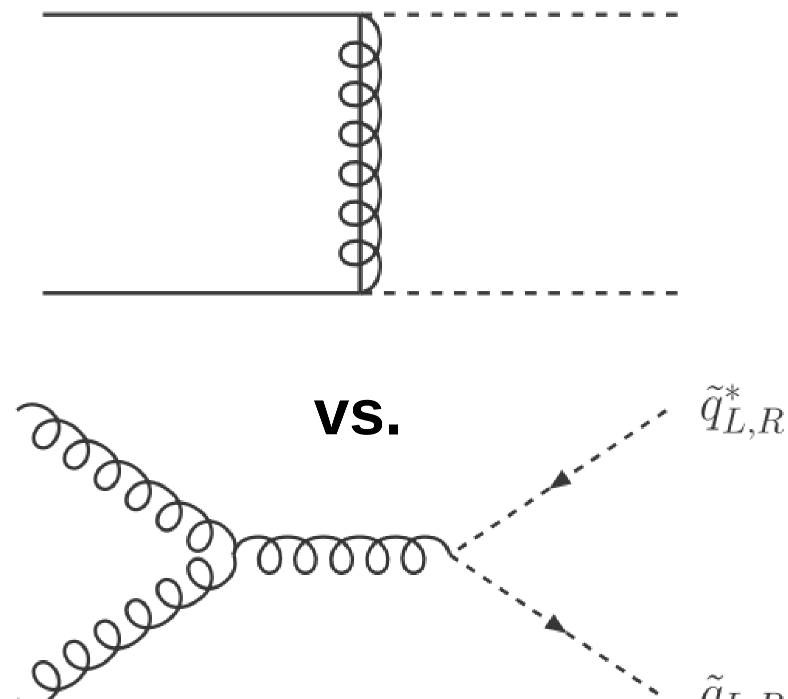
(a) $M_{\tilde{q}} = 400$ GeV

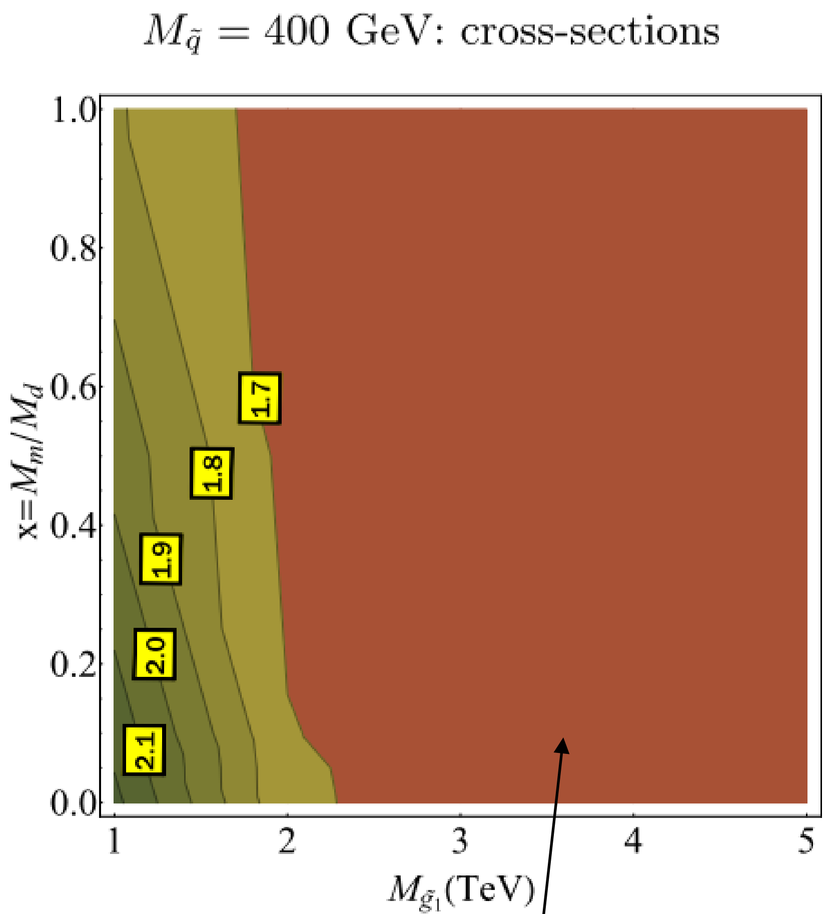


(c) $M_{\tilde{q}} = 1200$ GeV

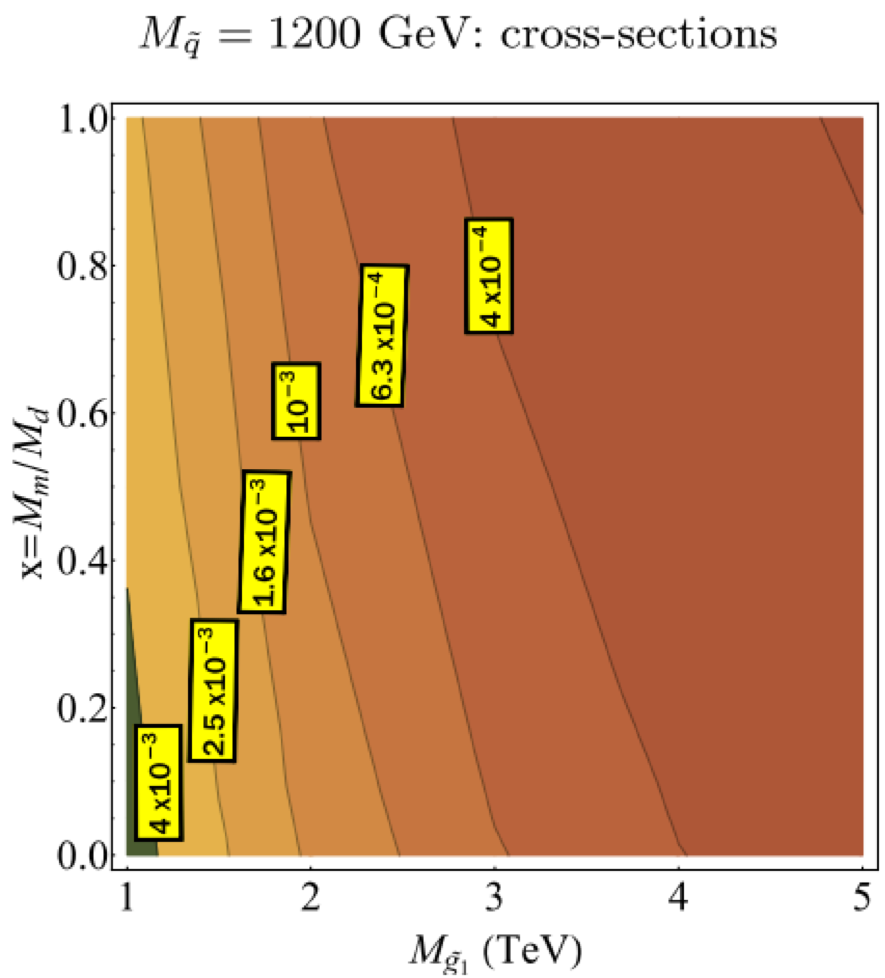


(b) $M_{\tilde{q}} = 800$ GeV





XS↓ in vertical direction



XS flattens in horizontal direction for light squarks