MSSM Phenomenology at the LHC

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Contents

Contents

Contents

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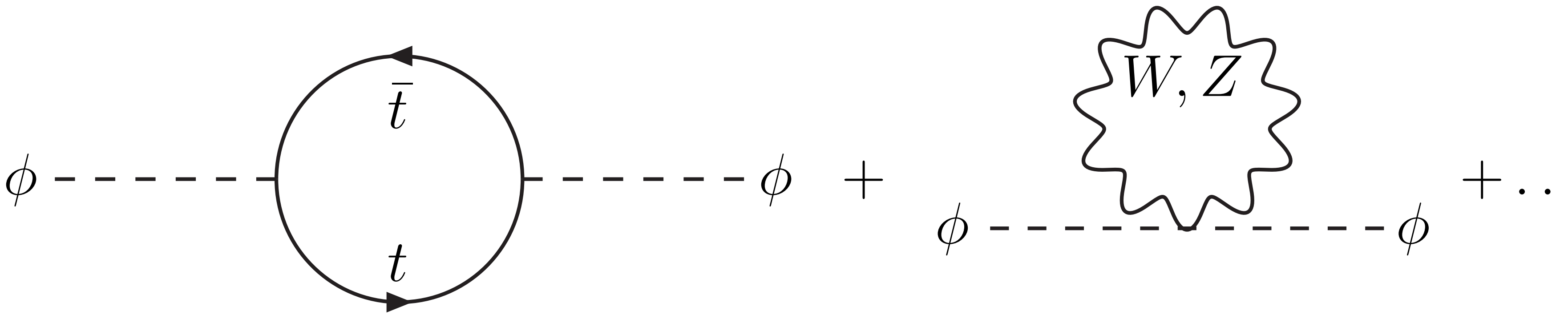
Contents

Introduction: Finetuning Problem

In SM: loop corrections to squared Higgs boson mass diverge quadratically!



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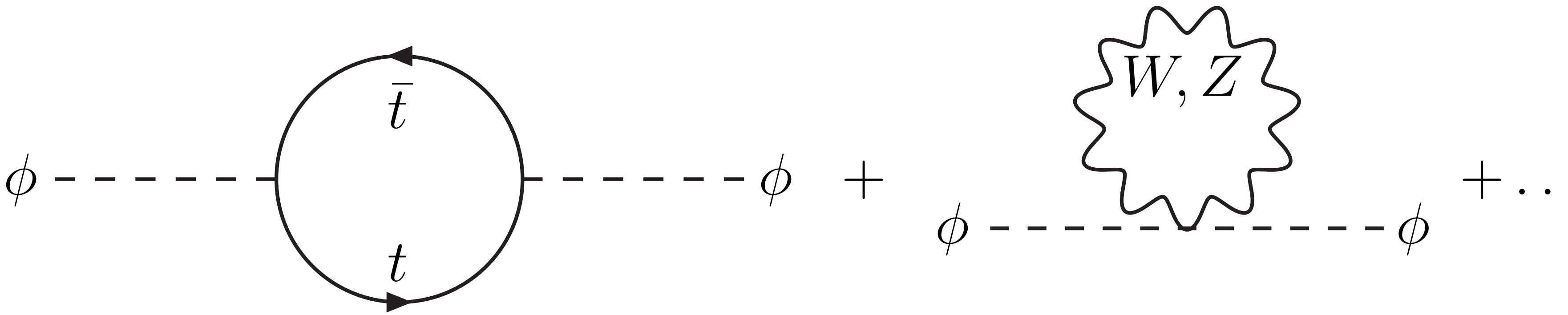

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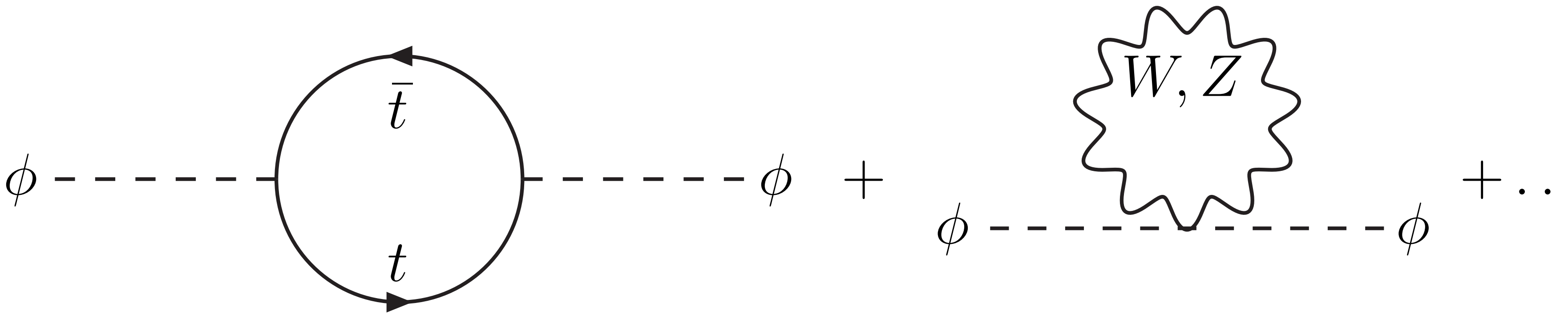

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$\Longrightarrow$ Difficult to keep m_ϕ much below highest energy where SM is applicable!

SUSY to the Rescue!

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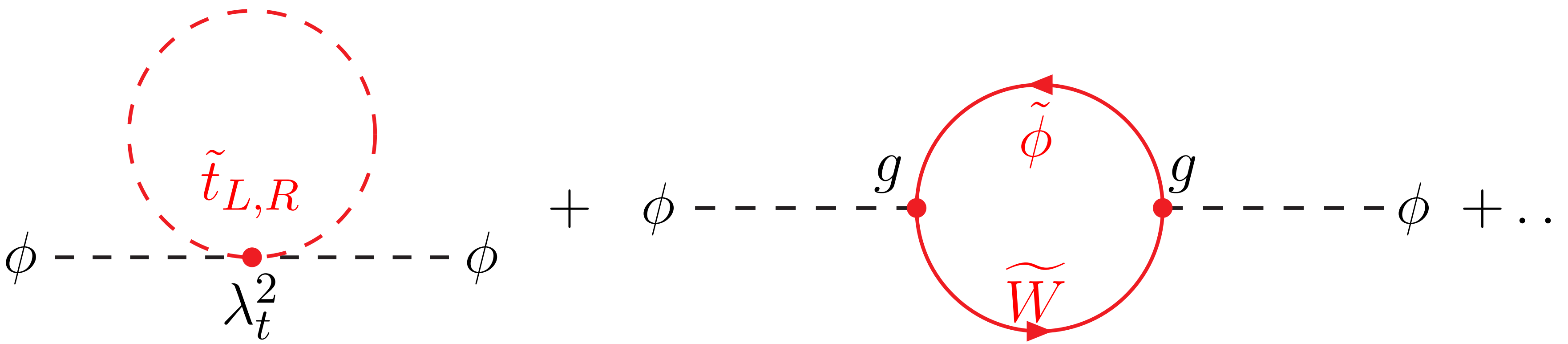

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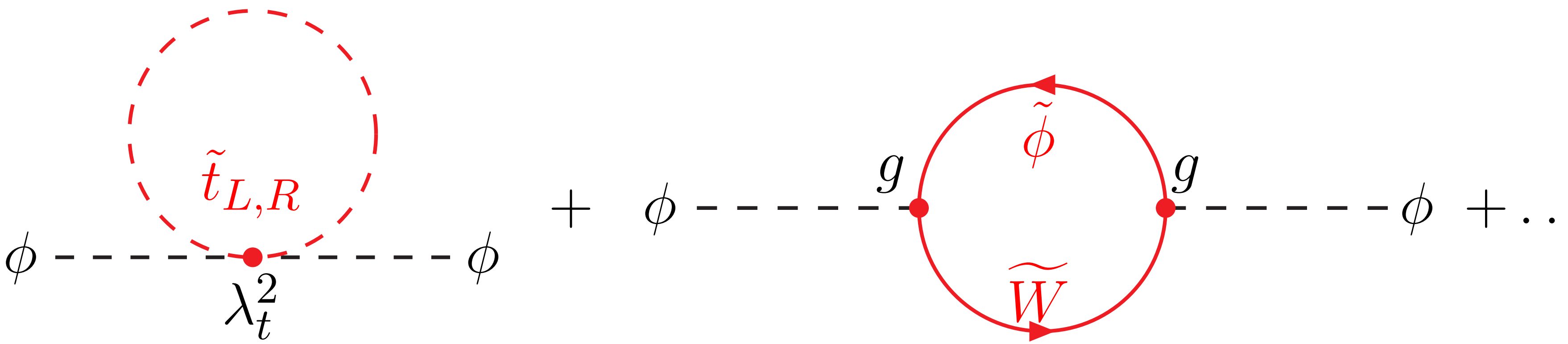

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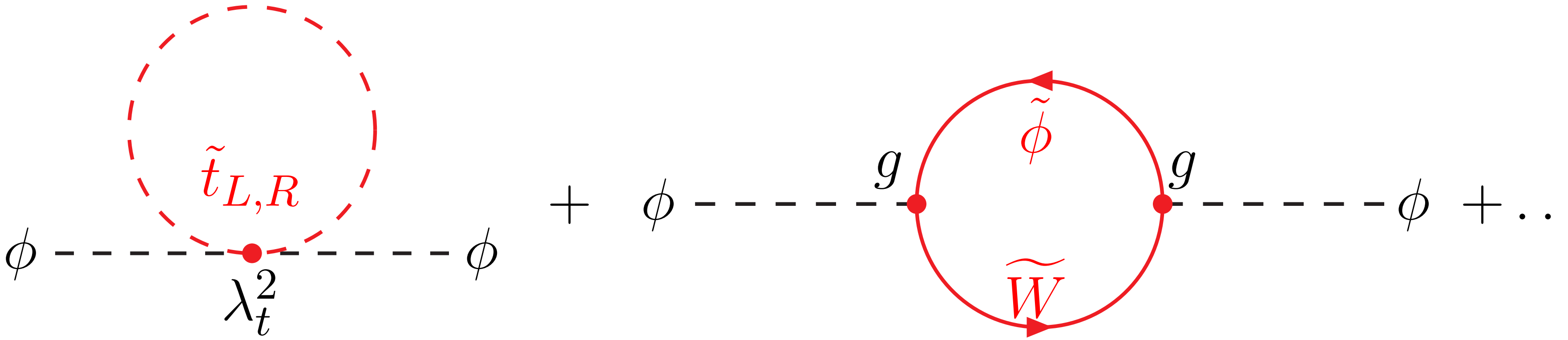

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$$\delta m_\phi^2 \sim \frac{1}{8\pi^2}\left[\lambda_t^2\left(m_{\tilde{t}}^2 - m_t^2\right) + g^2\left(M_{\widetilde{W}}^2 - M_W^2\right) + \dots\right]$$

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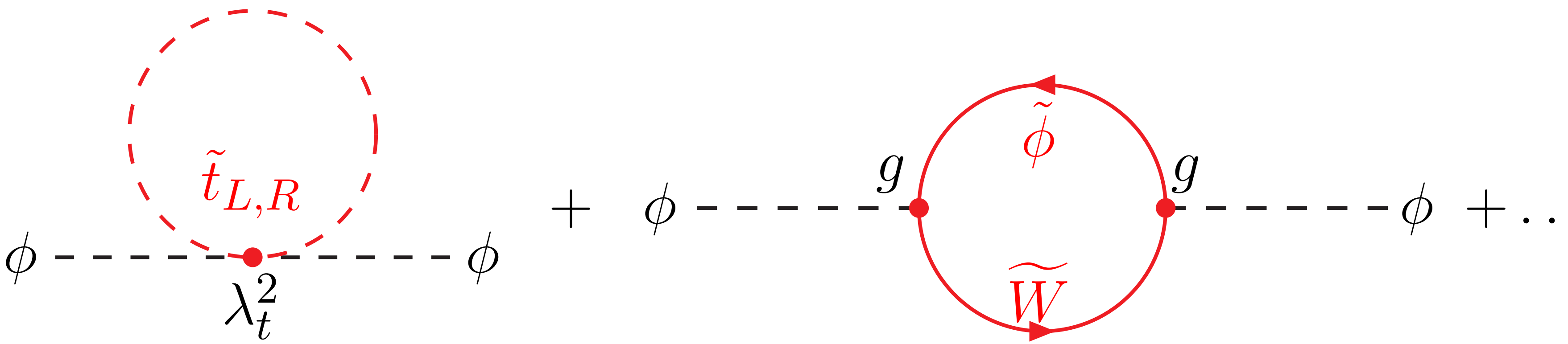

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Want $\delta m_\phi^2 \leq (100\ \mathrm{GeV})^2 \Longrightarrow$ need sparticle masses $\lesssim 1$ TeV!

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- But:
  - $\tilde{g}$ couples strongly to $\tilde{t}$: $m_{\tilde{g}} \gg m_{\tilde{t}_2}$ not possible
  - Get (new) term $\delta m^2_\phi \sim \frac{g_Y^2 Y_\phi}{8\pi^2} \sum_{\tilde{f}} Y_{\tilde{f}} m^2_{\tilde{f}}$
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- Calculation holds for mass in potential, not physical mass.

Other reasons for weak–scale SUSY

- Muon magnetic moment: expt. ~ 3 sigma above SM prediction; can be fixed via "light" $\tilde{\mu}, \tilde{\nu}_\mu$, gauginos.

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- Muon magnetic moment: expt. ~ 3 sigma above SM prediction; can be fixed via "light" $\tilde{\mu}, \tilde{\nu}_\mu$, gauginos.
- Unification of gauge couplings: Logarithmically sensitive to sparticle masses
- Dark Matter: can tolerate $m_{\tilde{\chi}_1^0} > 1$ TeV.

Basics of MSSM Phenomenology

SUSY signals at LHC dominated by production and decay of squarks and gluinos!

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Process	$\hat{\sigma}\ \left[\frac{\pi\alpha_s^2}{\hat{s}}\right]$
$q_i\bar{q}_j \longrightarrow \tilde{q}\bar{\tilde{q}}$	$0.30\delta_{ij} + 0.47$
$gg \longrightarrow \tilde{q}\bar{\tilde{q}}$	0.36
$q_iq_j \longrightarrow \tilde{q}\tilde{q}$	$0.47 - 0.065\delta_{ij}$
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Reminiscent of hierarchy of QCD $2 \rightarrow 2$ cross sections: SUSY at work!

Partonic cross sections (cont'd)

First computed in 1980's. Harrison & Llewellyn–Smith 1983; Dawson, Eichten & Quigg 1985. Refinements:

- NLO QCD corrections Beenakker, Höpker, Spira, Zerwas 1996: "k–factor" $\in [1.0, 1.5]$ for $\tilde{q}$ production, $\in [1.3, 2.5]$ for $\tilde{g}\tilde{g}$.

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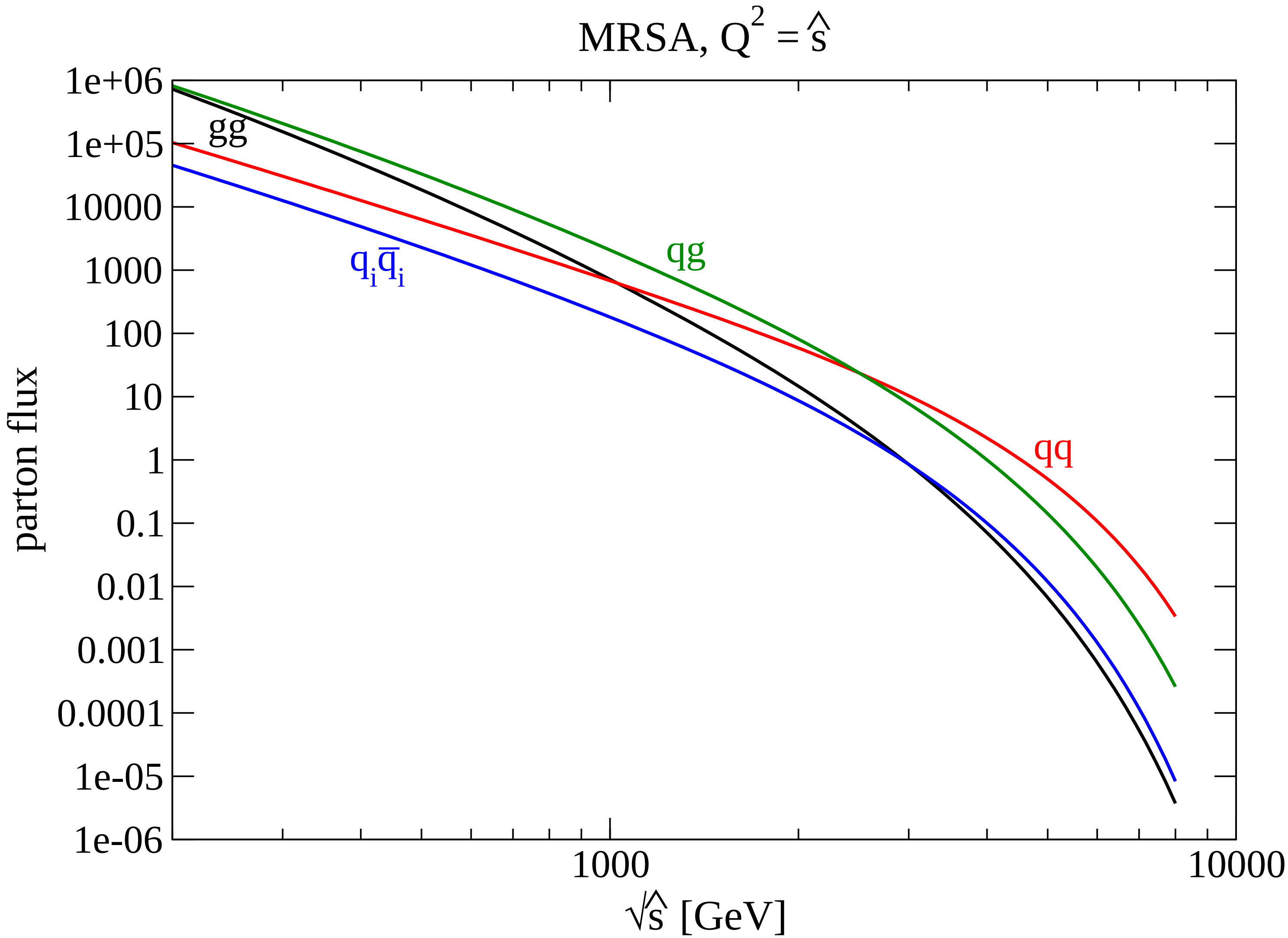
- Flavor effects: See talk by Porod

pp Cross Sections

$$\sigma(pp \to \tilde{S}_1 \tilde{S}_2 X) = \sum_{\text{partons } i,j} \int_{s/s_{\min}}^{1} d\tau \int_{\tau}^{1} \frac{dx}{x} f_{i|p}(x, Q^2) f_{j|p}(\frac{\tau}{x}, Q^2) \cdot \hat{\sigma}(ij \to \tilde{S}_1 \tilde{S}_2)(\hat{s} = \tau s)\,.$$

Orange: partonic flux function; depends on $i, j, \tau,\ (Q^2 = \hat{s})$.

Flux Functions



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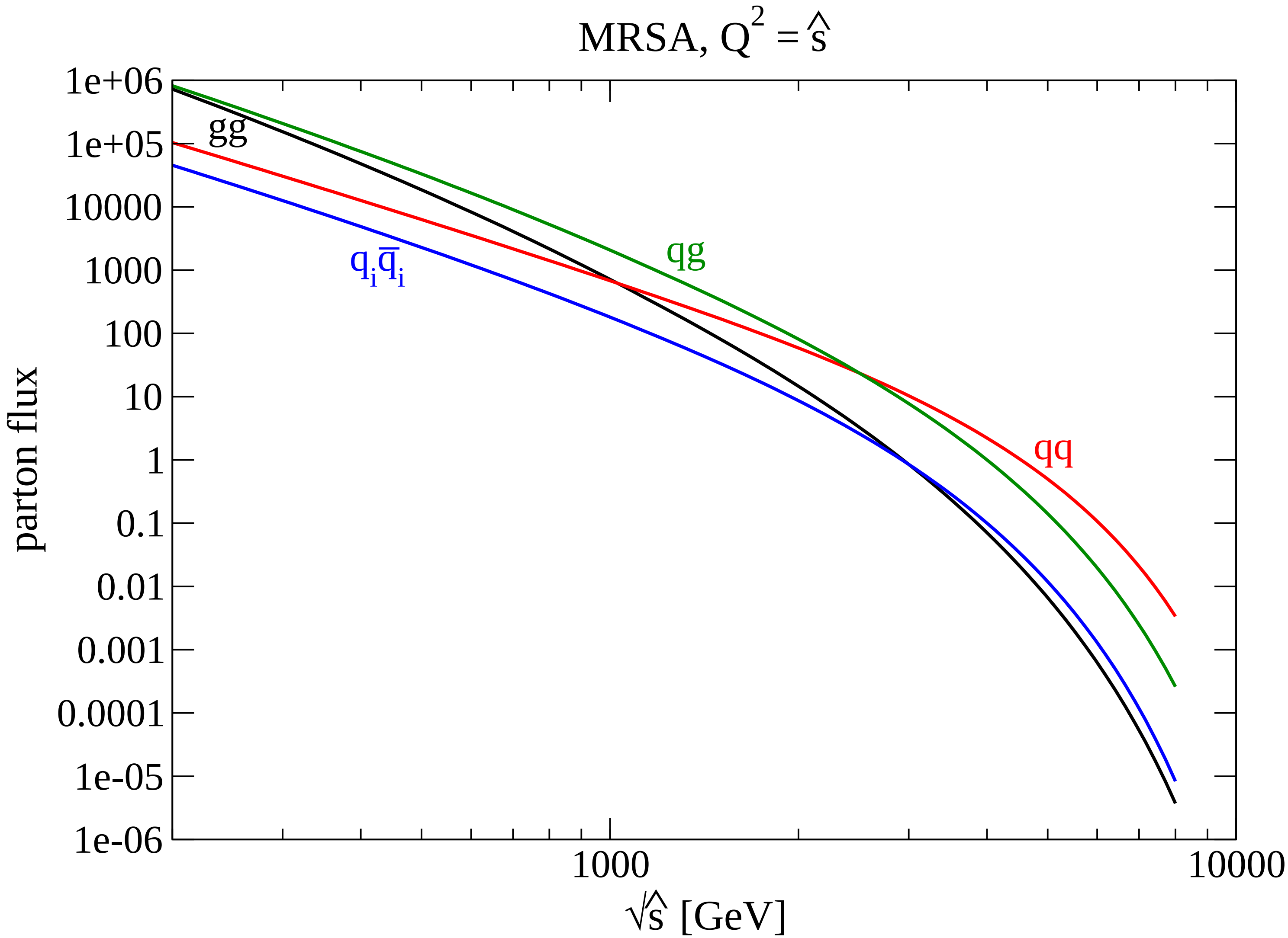
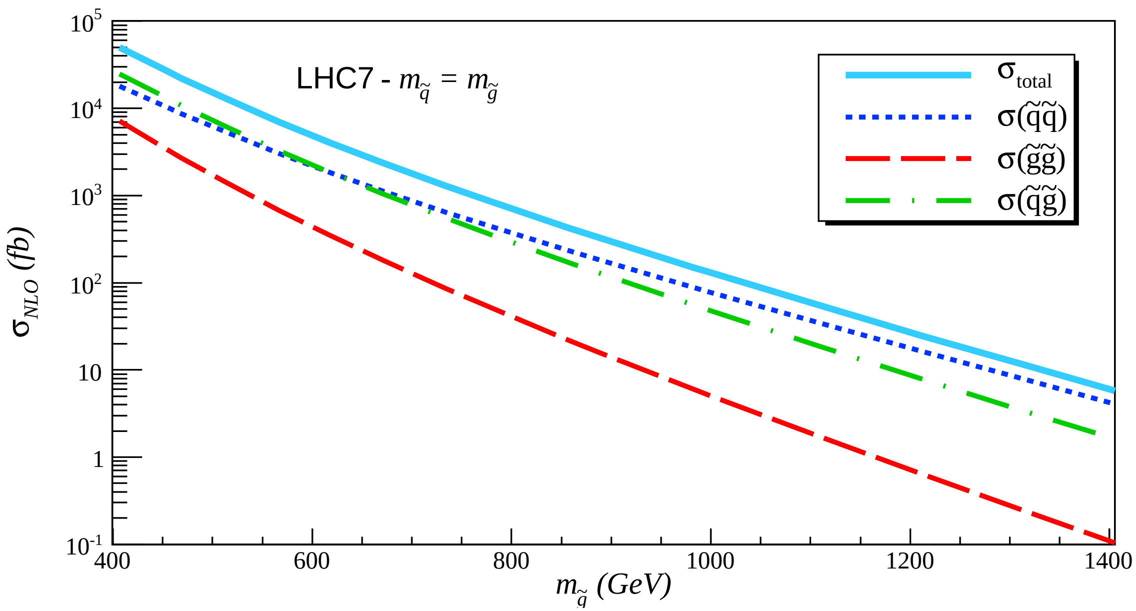
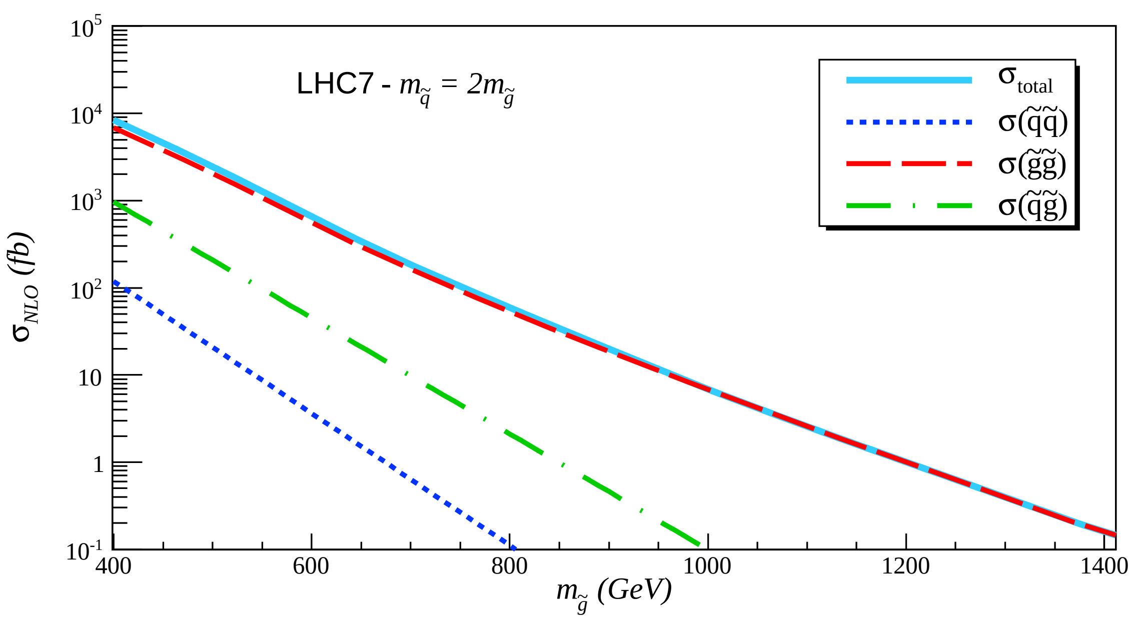


Fluxes drop off faster for $m_{\tilde{g},\tilde{q}} > 0.5 - 1.0$ TeV!

Total NLO $\tilde{q}, \tilde{g}$ cross sections at $\sqrt{s} = 7$ TeV

Baer, Barger, Lessa, Tata 2010





$\tilde{q}, \tilde{g}$ vs ELW Gaugino Production

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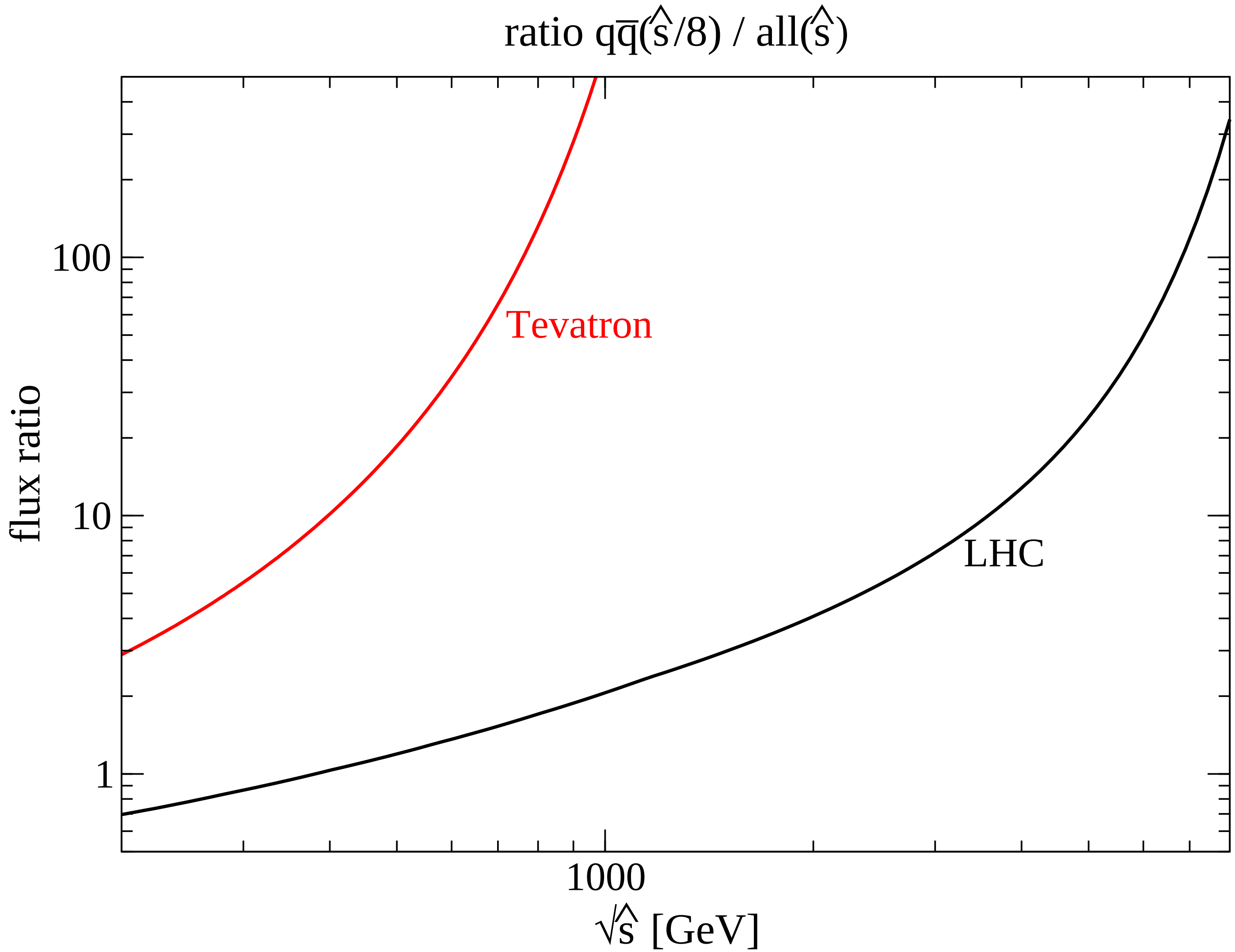
Situation different at Tevatron: $\exists$ pure valence quark contribution to $q\bar{q}$ flux!

Ratio $q\bar{q}$ flux to total flux



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  - $B(\tilde{q} \to \tilde{B} q) \sim \frac{\alpha_Y}{\alpha_s} Y^2_{\tilde{q}}$
- $\tilde{g} \to q\bar{q}\widetilde{W}, \; q\bar{q}\tilde{B}$, with ratio of Brs $\simeq 3\alpha_W/\alpha_Y$ if $m_{\tilde{q}_L} \simeq m_{\tilde{q}_R}$.

If $m_{\tilde{g}} > m_{\tilde{q}}$:

- $\tilde{q}_L \to \widetilde{W} q$ dominant; ratio $\widetilde{W}^{\pm} : \widetilde{W}^0 \simeq 2:1$
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- $\tilde{g} \longrightarrow \tilde{q}_{L,R} q$; about equally into $\tilde{q}_L$ and $\tilde{q}_R$ if $m_{\tilde{q}_L} \simeq m_{\tilde{q}_R}$. But rather close to edge of phase space!

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- $\tilde g \to \tilde q_{L,R} q$; about equally into $\tilde q_L$ and $\tilde q_R$ if $m_{\tilde q_L} \simeq m_{\tilde q_R}$. But rather close to edge of phase space!

Quite often: $m_{\tilde u, \tilde d, \tilde s, \tilde c} > m_{\tilde b, \tilde t}$ (RG effects of b, t Yukawas; $L - R$ mixing)
$\Longrightarrow \tilde g \to \tilde b^{(*)} \bar b, \tilde t^{(*)} \bar t + cc$ often dominant!

If $m_{\widetilde{W}} > m_{\tilde{B}}$ (mSUGRA, mGMSB)

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But: if $m_{\widetilde{W}} > m_{\tilde{\ell}_L}$: $\widetilde{W} \to \tilde{\tau}_1 \tau$ dominates! ($\tilde{\tau}_1$ is lighter, has sizable $\tilde{\tau}_L$ component.)

“Typically” (mGMSB, much of mSUGRA)

Higgsino mass $|\mu| > m_{\widetilde{W}} > m_{\tilde{B}}$

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$\Longrightarrow m_{\tilde{\chi}_3^0} \simeq m_{\tilde{\chi}_4^0} \simeq m_{\tilde{\chi}_2^\pm} \simeq |\mu|$ higgsino–like

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“Typically” (mGMSB, much of mSUGRA)

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But: $|\mu| \simeq m_{\widetilde{W}}$ or $|\mu| \simeq m_{\tilde{B}}$ possible even in mSUGRA: gives more complicated mixing patterns!

Examples of final states (many possibilities!)

- $qq \longrightarrow \tilde{q}_R\tilde{q}_R \longrightarrow (q\tilde{\chi}_1^0)(q\tilde{\chi}_1^0)$
  2 very energetic jets ($E_T \gtrsim m_{\tilde{q}_R}/2$), large missing $\not{E}_T$ ($\gtrsim m_{\tilde{q}_R}/\sqrt{2}$).

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- $ug \to \tilde{u}_L\tilde{g} \to (d\tilde{\chi}_1^+)(\bar{\tilde{t}}_1 t) \to (d\ell^+\nu_\ell\tilde{\chi}_1^0)(\bar{b}s\bar{c}\tilde{\chi}_1^0 b\ell'^+\nu_{\ell'})$
  5 jets (incl. 2 $b-$jets), $\ell^+\ell'^+$ pair and missing E_T.

Classification of events

Standard classifiers are: Number of jets n_j, number of charged leptons n_ℓ ($\ell = e, \mu$)

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In addition, could look for:

- τ candidates, via $\tau \rightarrow \nu_\tau + \mathrm{hadrons}$:
  e.g. from $\tilde{\chi}_1^\pm \rightarrow \tilde{\tau}_1^\pm \nu_\tau \rightarrow \tau^\pm \tilde{\chi}_1^0 \nu_\tau$.
- Z^0 candidates, via $Z^0 \rightarrow \ell^- \ell^+$: e.g. from $\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_{j<i}^0 Z^0$
- top candidates, via "top tagging": e.g. from $\tilde{g} \rightarrow \tilde{t}_1 \bar{t}$
- Higgs candidates, via $h \rightarrow b\bar{b}$: e.g. from $\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_{j<i}^0 h$

mSUGRA≡CMSSM

Most widely studied SUSY framework of SUSY. Defined by:

- Common scalar mass m_0
- Common gaugino mass $m_{1/2}$
- Common trilinear scalar interaction A_0

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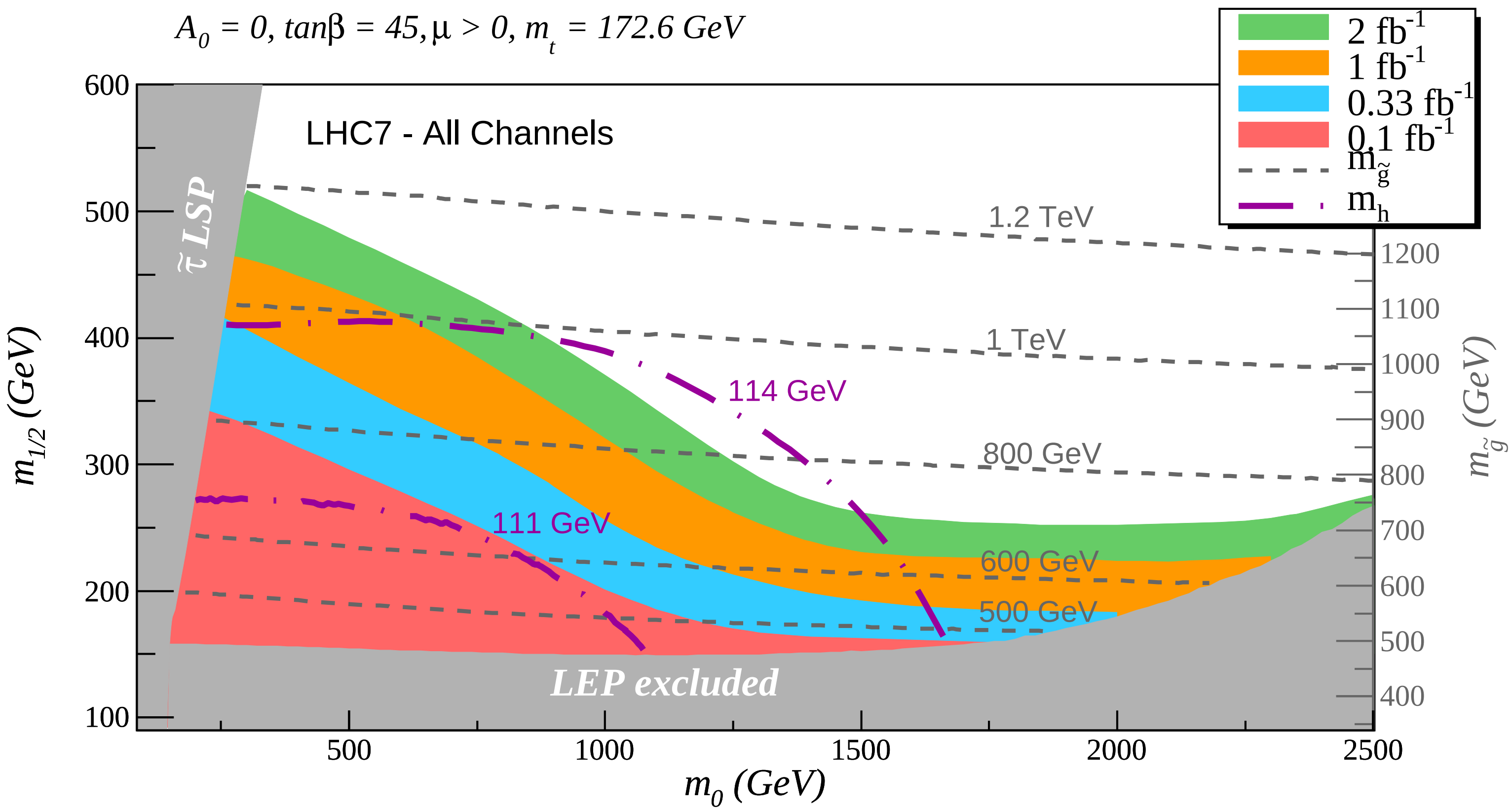
Assume $\tilde{\chi}_1^0$ is stable LSP: DM candidate! (See Dutta's talk.)

LHC reach

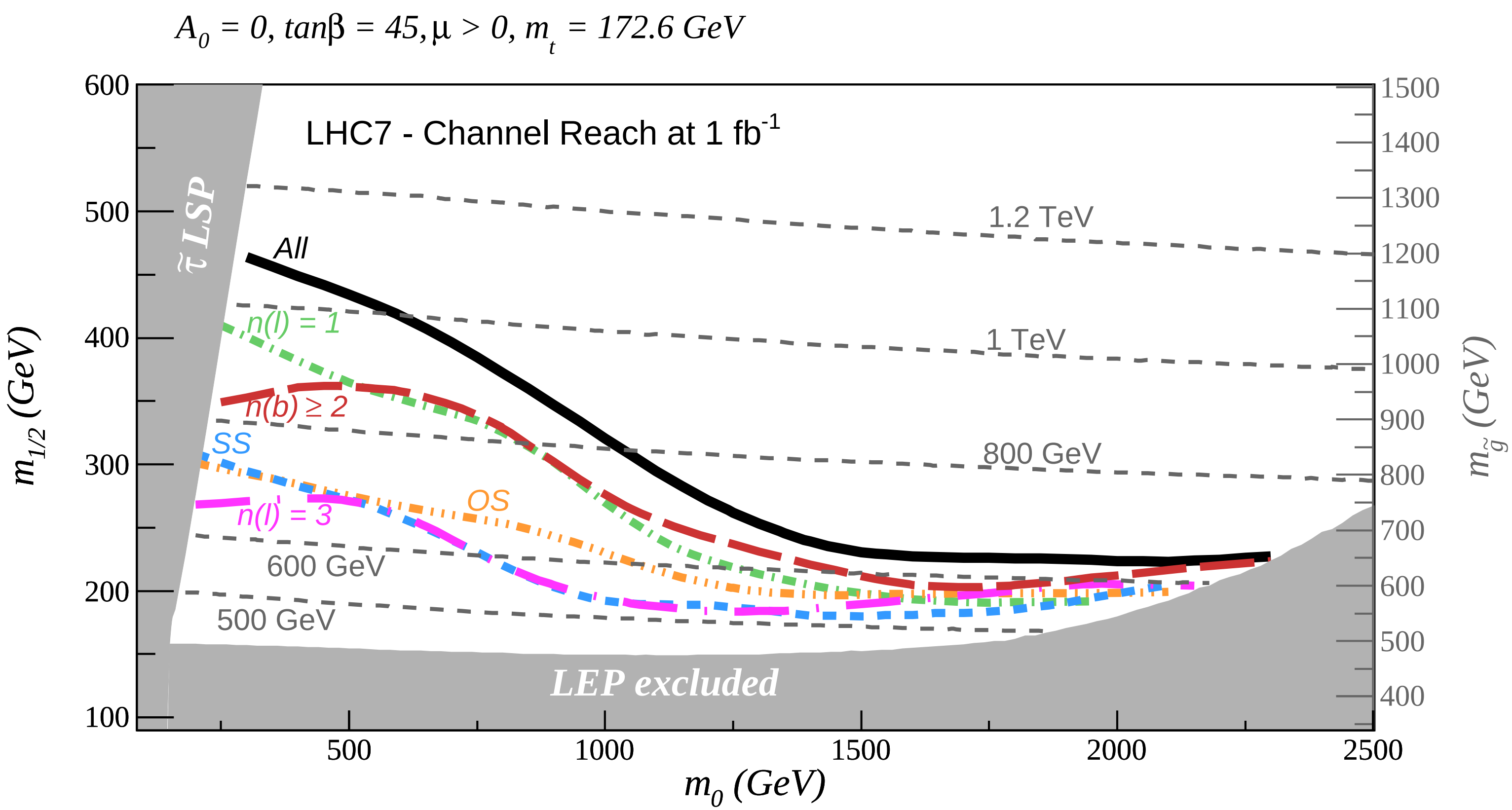
Reach defined by: require $S > 5\sqrt{B},\ S > 0.2B$, at least 5 signal events. Consider many channels, optimize jet and missing $\not\!\!E_T$ cuts within each channel; take best channel. No combination of channels! (Unlike Tevatron SM Higgs search.)

From: Baer, Barger, Lessa & Tata 2009/10

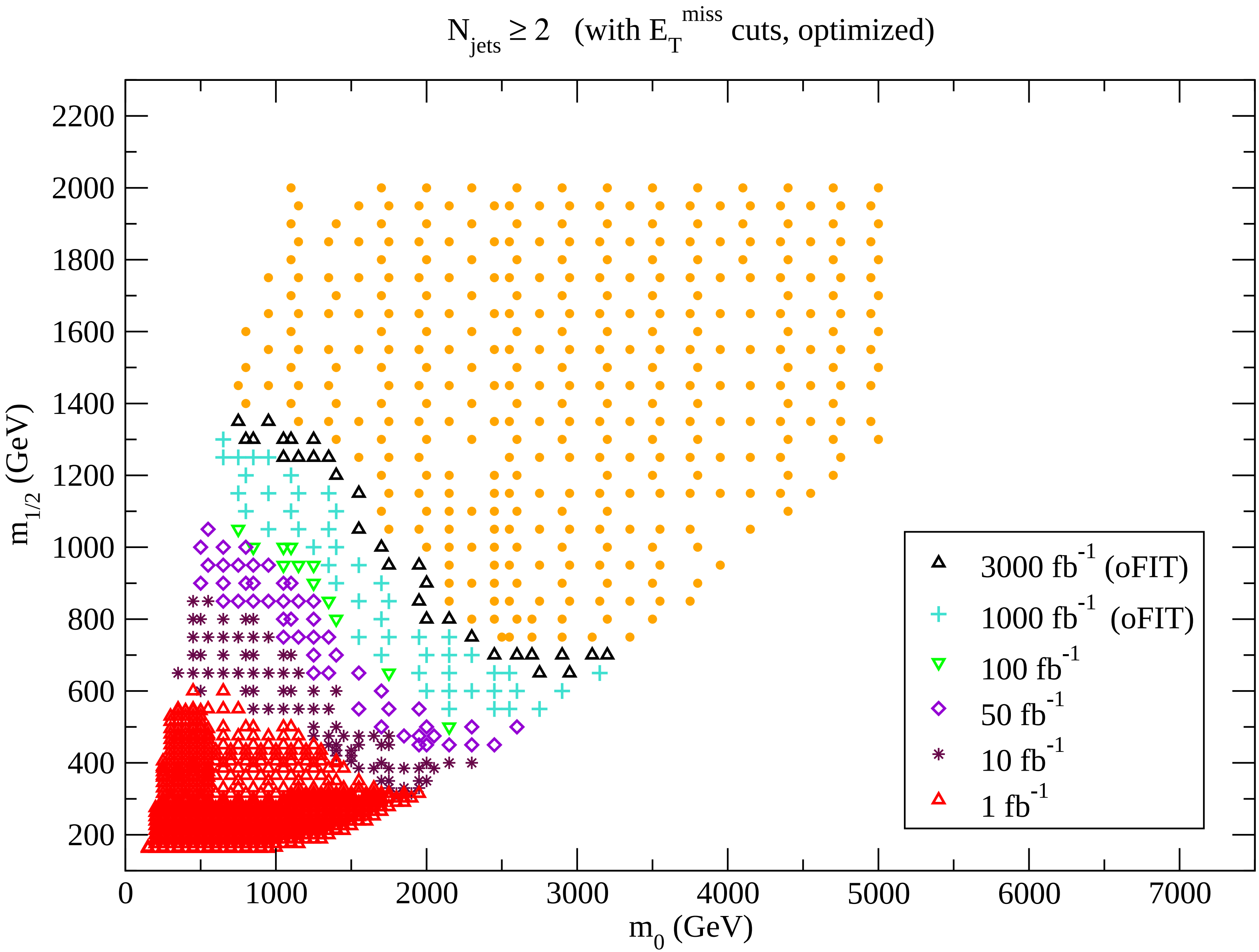
Optimized reach at $\sqrt{s} = 7$ TeV



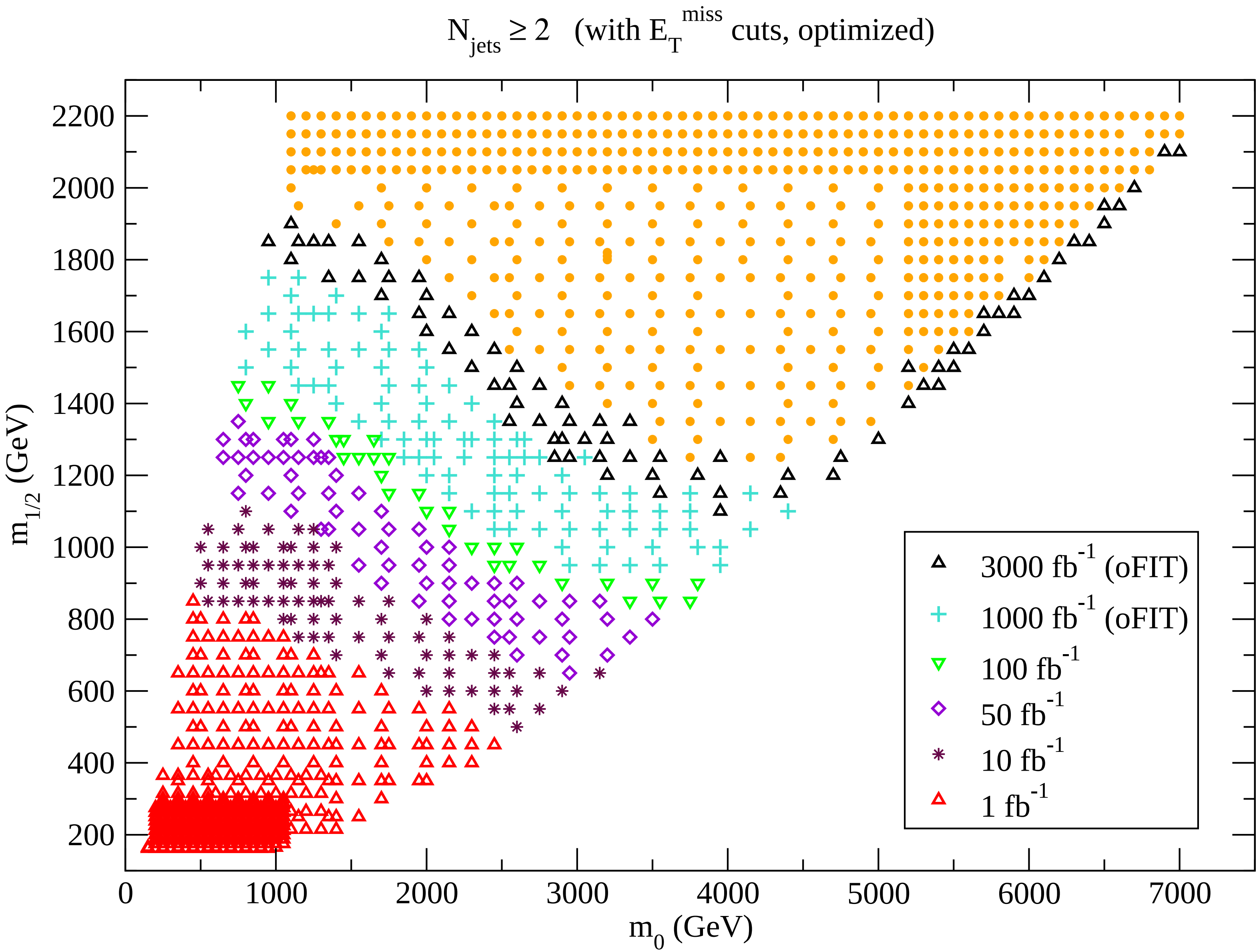
Reach at $\sqrt{s} = 7$ TeV, different channels



Optimized reach at $\sqrt{s} = 10$ TeV



Optimized reach at $\sqrt{s} = 14$ TeV



mSUGRA Reach table: $m_{\tilde{g}}$ reach in TeV

$\sqrt{s}$ [TeV]	$\int \mathcal{L} dt$ [fb^{-1}]	$m_{\tilde{q}} \lesssim m_{\tilde{g}}$	$m_{\tilde{q}} \gg m_{\tilde{g}}$
7	0.1	0.80	0.48
7	1.0	1.1	0.62
7	2.0	1.2	0.70
10	1	1.4	0.8
10	10	1.9	1.0
10	100	2.3	1.3
10	3000	2.9	1.8
14	1	1.9	1.1
14	10	2.4	1.5
14	100	3.1	1.8
14	3000	4.0	2.6 to 4.5 ?

Remarks

- Usually best reach in pure jets plus missing E_T channel. In SM, missing E_T comes from neutrinos, which are frequently produced together with charged leptons ($W+$jets, $t\bar{t}$).

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- Usually best reach in pure jets plus missing $\not\!\!E_T$ channel. In SM, missing $\not\!\!E_T$ comes from neutrinos, which are frequently produced together with charged leptons (W+jets, $t\bar{t}$).
- But: no optimization of leptonic observables attempted!
- For “natural” sparticle masses: expect signals in many channels!

Reach in Other Scenarios

- mGMSB (has gravitino LSP): at least as good, often better (hard, isolated photons or long–lived charged sleptons) Baer, Mercadante, Tata, Wang 2000

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- mAMSB: comparable; better, if long–lived $\tilde{\chi}_1^\pm$ can be detected Baer, Mizukoshi & Tata 2000
- Explicit $R-$parity breaking: Improves reach if $\tilde{\chi}_1^0 \rightarrow \ell^+ \ell'^- \nu$; worse reach for mSUGRA–like searches if $\tilde{\chi}_1^0 \rightarrow udd$ Baer, Chen & Tata 1996. : But: did not consider new single $\tilde{q}$ production channels; new "jet substructure" methods to find "fat jets" from $\tilde{\chi}_1^0$ decay. Butterworth, Ellis, Raklev & Salam 2009.

  Certainly can probe $m_{\tilde{g}} \lesssim 1$ TeV at $\sqrt{s} = 14$ TeV with 10 fb^{-1}.

Example of Model Discrimination

Consider $SO(10)$ model with 2 intermediate scales:
$SO(10) \longrightarrow SU(4) \times SU(2)_L \times SU(2)_R \longrightarrow SU(3)_C \times U(1)_{B-L} \times SU(2)_L \times SU(2)_R \longrightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$ Aulakh, Bajc, Melfo, Rasin & Senjanovic 2000

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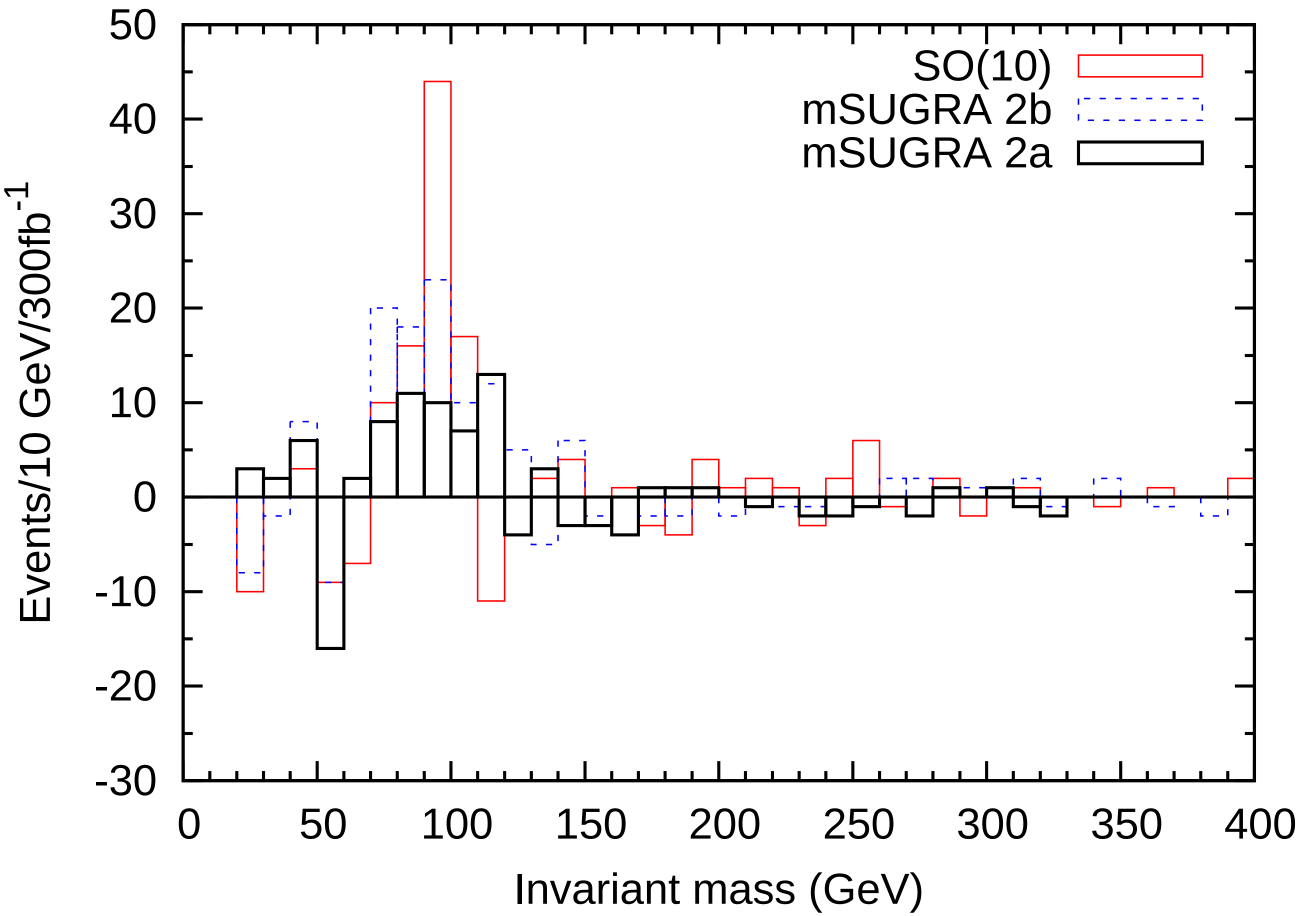
$\Longrightarrow$ significantly increased $B(\tilde{g} \to Z^0 + X)$! (7.6% vs. 4.3% or 5.0%) MD, Kim, Park 2010

Subtracted $M_{\ell^+\ell^-}$ distribution ($m_0 \ll M_{1/2}$)



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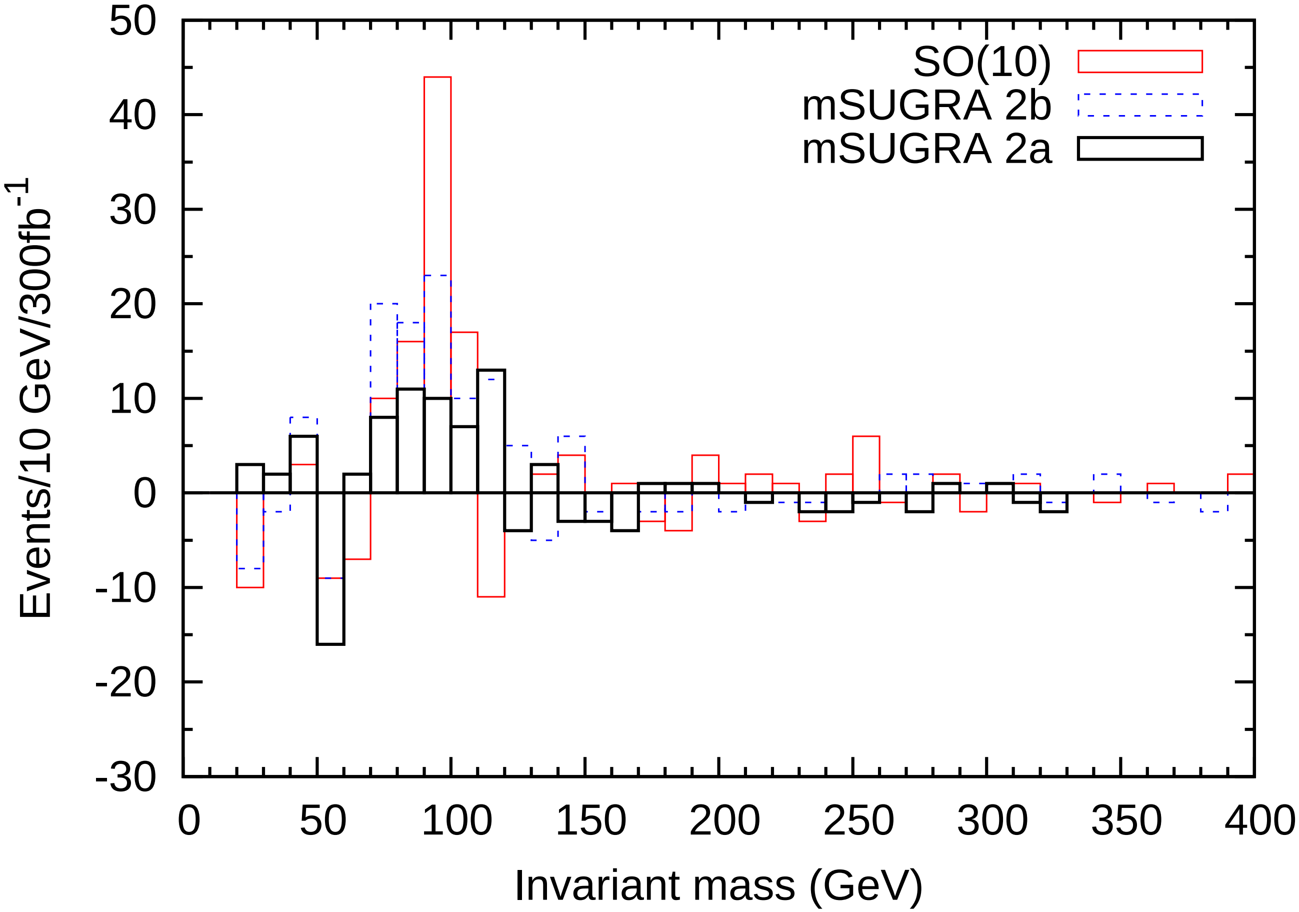

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$SO(10)$ model also has more like–sign di–lepton events: 492 vs. 422 (434).

SUSY and QCD

Bornhauser, MD, Dreiner, Kim 2009

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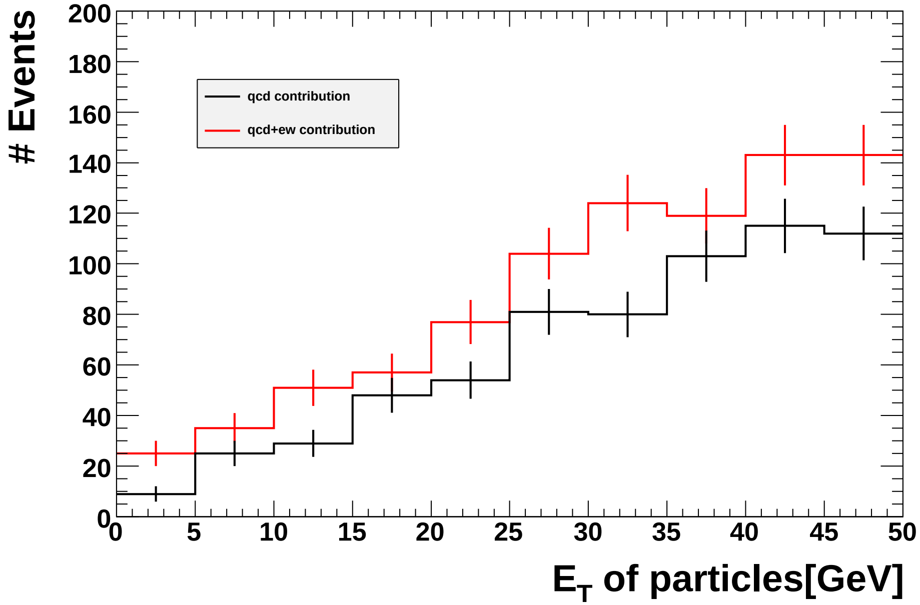
Effect biggest for $\tilde{q}_L\tilde{q}_L$ production ($\widetilde{W}$ exchange)
$\Longrightarrow$ look for events with 2 hard jets, 2 leptons with *same* charge, missing E_T

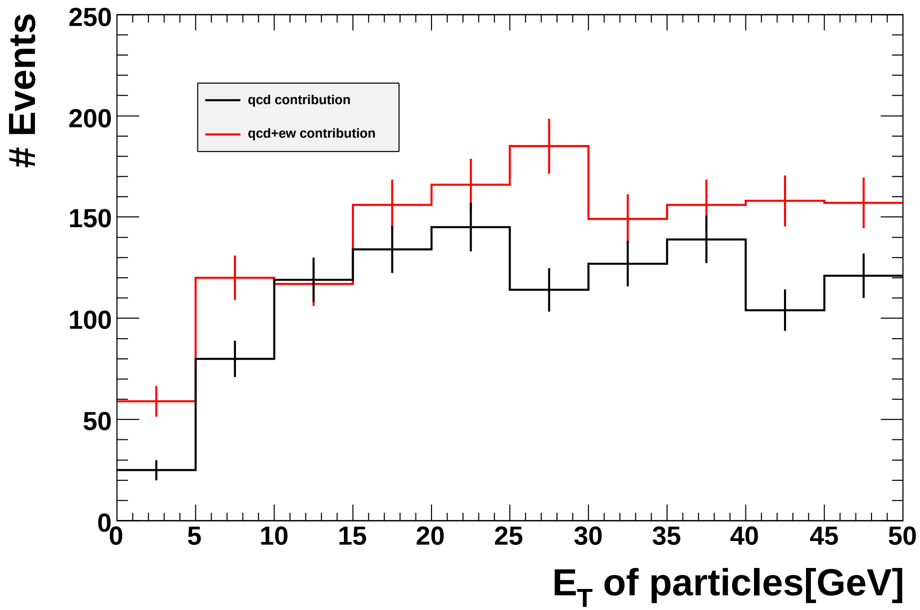
e.g. $uu \to \tilde{u}_L\tilde{u}_L \to (\tilde{\chi}_1^+ d)(\tilde{\chi}_1^+ d) \to (\ell^+ \nu_\ell \tilde{\chi}_1^0 d)(\ell'^+ \nu_{\ell'} \tilde{\chi}_1^0 d)$
Additional leptons allowed.
Require rapidity distance $\delta\eta \geq 3.0$

E_T between the hard jets (SPS1a')

HERWIG:

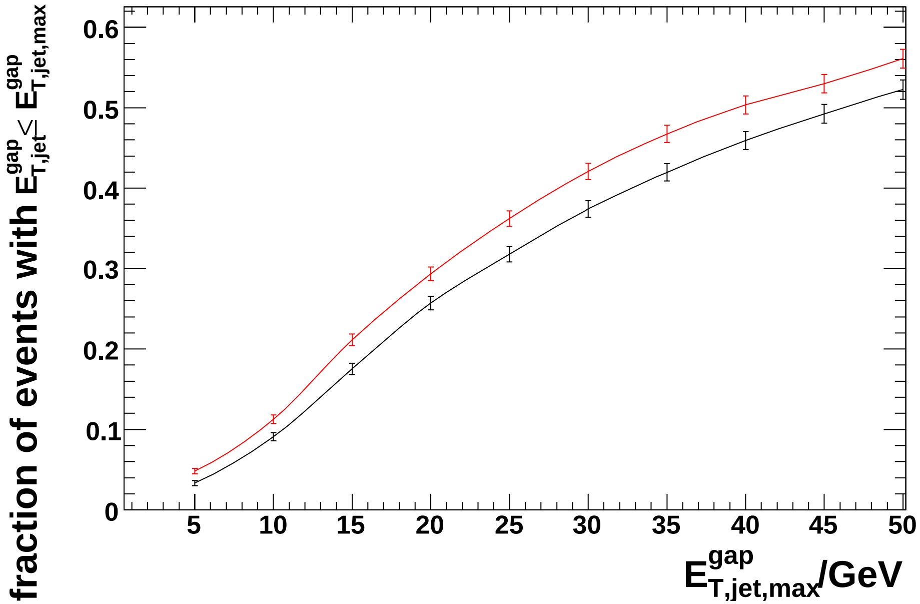


PYTHIA:



Softer jets between the hard jets (SPS1a')

HERWIG:



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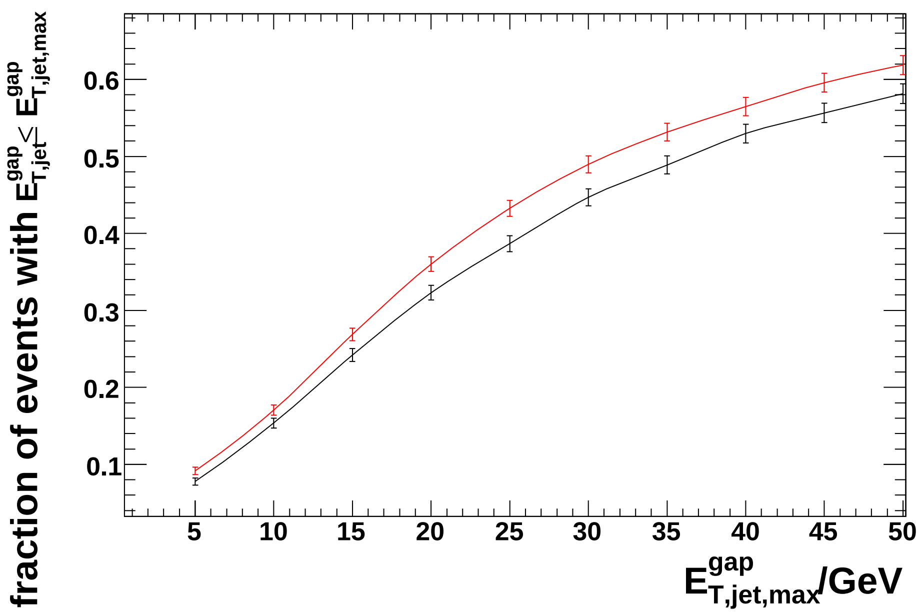

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- Generally will have signals in many different final states: offers many possibilities to distinguish between models by counting events! Can be combined with kinematic methods. (See Dutta’s talk)
- For detailed analyses: sometimes have to worry mundane QCD uncertainties (e.g. HERWIG vs. PYTHIA)