Split Supersymmetry

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– Split and TeV scale supersymmetry
– Signals at the LHC
– Signals at the ILC
– What stays [W. Kilian, P. Richardson, TP, E. Schmidt: EPC C39]

TeV Scale Supersymmetry: 1

Starting from data...

– ...which seem to indicate a light Higgs

– problem of light Higgs: scalar masses perturbatively unstable
  quadratic divergences $\delta m_h^2 \propto g^2 \Lambda^2$
  all–orders Higgs mass driven to cutoff $m_h \to \Lambda$

$\Rightarrow$ solution: counter term for exact cancellation $\Rightarrow$ artificial, ugly, fine tuned

$\Rightarrow$ or new physics at TeV scale: supersymmetry
  extra dimensions
  little Higgs (pseudo–Goldstone Higgs)
  Higgsless/composite Higgs
  YourFavoriteNewPhysics...

$\Rightarrow$ all beautiful concepts and symmetries

$\Rightarrow$ in general problematic to realize at TeV scale [data seriously in the way]

Idea of supersymmetry: cancellation of divergences through statistics factor (-1)
[scalars vs. SM fermions; fermions vs. SM gauge bosons; fermions vs. SM scalars]

TeV Scale Supersymmetry: 2

Bright side

- light fundamental Higgs by construction [data]
- 3 running gauge couplings meet — GUT gauge group [data]
- R parity — stable proton yields dark matter [data]
- 2 Higgs doublets — radiative symmetry breaking [beauty]
- local supersymmetry – including gravity? [beauty]
- rich LHC phenomenology [effective theory of everything short–lived]

Dark side

- unknown Susy breaking
  $\longrightarrow$ masses, couplings, phases
- flavor physics and Susy breaking
  $\longrightarrow$ CKM and lepton flavor?
- 2 Higgs doublet model
  $\longrightarrow$ μ and Susy breaking? [Giudice, Masiero]

$\Rightarrow$ as many exclusive analyses as possible [never believe us theorists when we say we know...]

		spin	d.o.f.	
gluon	G_μ	1	n-2	
$\longrightarrow$ gluino	$\tilde{g}$	1/2	2	Majorana
gauge bosons	γ, Z	1	2+3	
Higgs bosons	h^0, H^0, A^0	0	3	
$\longrightarrow$ neutralinos	$\tilde{\chi}_i^0$	1/2	$4 \cdot 2$	Majorana
gauge bosons	$W^\pm$	1	$2 \cdot 3$	
Higgs bosons	$H^\pm$	0	2	
$\longrightarrow$ charginos	$\tilde{\chi}_i^\pm$	1/2	$2 \cdot 4$	Dirac
fermion	f_L, f_R	1/2	1+1	
$\longrightarrow$ sfermion	$\tilde{f}_L$, $\tilde{f}_R$	0	1+1	

TeV Scale Supersymmetry: 3

Gauginos and higgsinos in the SUSY spectrum [Dimopoulos; Drees, Martin]

– gauginos–higgsinos mixing: $m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^+}$ or $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^+}$ in MSSM

$$\begin{pmatrix} m_{\tilde{B}} & 0 & -m_Z s_w c_\beta & m_Z s_w s_\beta \\ 0 & m_{\tilde{W}} & m_Z c_w c_\beta & -m_Z c_w s_\beta \\ -m_Z s_w c_\beta & m_Z c_w c_\beta & 0 & -\mu \\ m_Z s_w s_\beta & -m_Z c_w s_\beta & -\mu & 0 \end{pmatrix} \quad \begin{pmatrix} m_{\tilde{W}} & \sqrt{2} m_Z c_w s_\beta \\ \sqrt{2} m_Z c_w c_\beta & -\mu \end{pmatrix}$$

– heavy gluinos through unification: $m_{\tilde{B},\tilde{W},\tilde{g}}/m_{1/2} \sim 0.4, 0.8, 2.6$

[mass and coupling unification independent]

– lightest Susy partner $\tilde{\chi}_1^0, \tilde{\nu}$

$\Rightarrow$ after dark matter data $\tilde{\chi}_1^0 \sim \tilde{B}, \tilde{W}$ [Ellis, Falk, Olive...]

Physics of Split Supersymmetry: 1

Split supersymmetry [Dimopoulos, Arkani-Hamed; Giudice, Romanino]

– forget about fine tuning [Higgs will never be as bad as cosmological constant]

– remember all the good things Susy did for you [dark matter, unification from data]

– notice that scalars are evil [lepton and quark flavor, Higgs mass and LEP2]

– remember simple facts about unification [SU(5) multiplets decouple; Dawson, Georgi 1979]

$\Rightarrow$ make all scalars heavy [hope: $\tilde{m} \to m_{GUT}$?]

$\Rightarrow$ protect all gaugino and higgsino masses [$m_{\tilde{\chi}_i}, m_{\tilde{g}} \lesssim$ TeV]

Fine tuning no excuse for multi–billion dollar experiments [trigger by popular vote of theorists?]

– gluinos and gauginos at the LHC

– gauginos and higgsinos at the ILC

$\Rightarrow$ is it supersymmetry?

$\Rightarrow$ is it split?

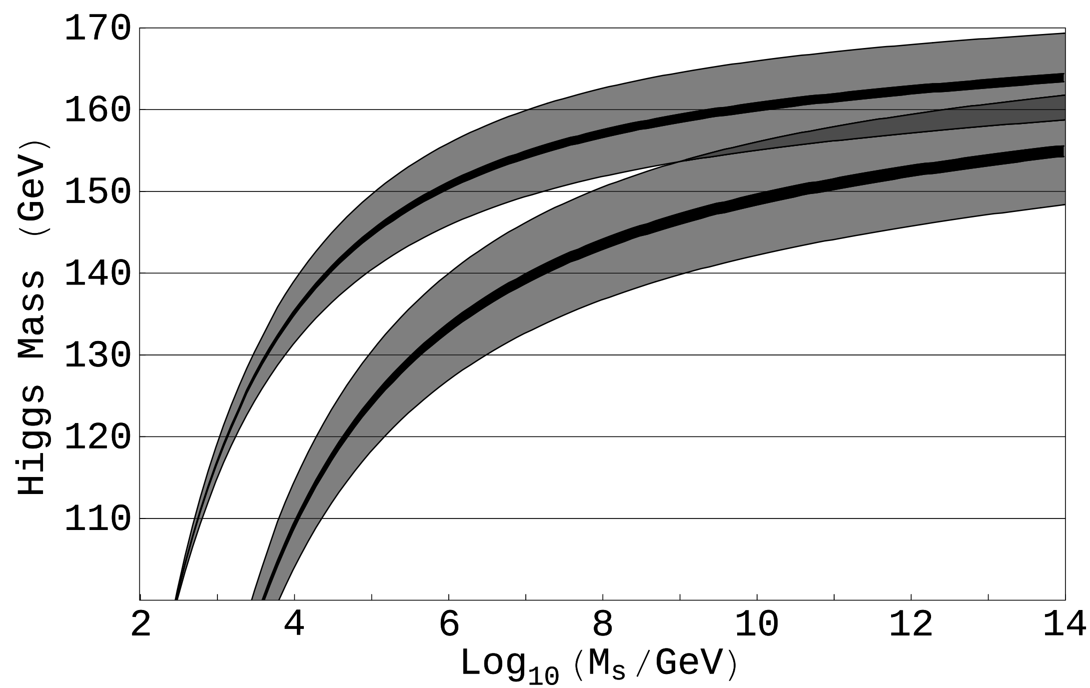
Heavy scalars and the Higgs mass [Giudice, Romanino; Arvantaki, Davis, Graham, Wacker]

– known leading corrections increased: $m_h \sim m_Z + G_F y_t^4 \log(m_{\tilde{t}}^2/m_t^2)$

⇒ large m_h for heavy stops [out of LEP2 reach]

⇒ not a precision observable anymore [large logarithms]

⇒ light Higgs is a SM Higgs boson with $m_h \gtrsim 140$ GeV [other 2HDM heavy]



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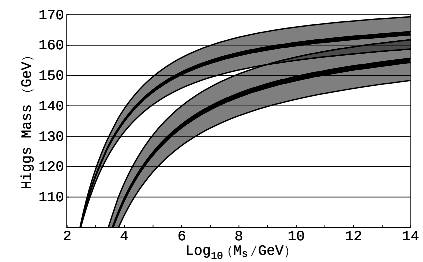


Heavy scalars and the gluino life time [Arkani-Hamed, Dimopoulos; Giudice, Romanino]

– decay through squark $\tau_{\tilde{g}} \sim \tilde{m}^4/m_{\tilde{g}}^5$

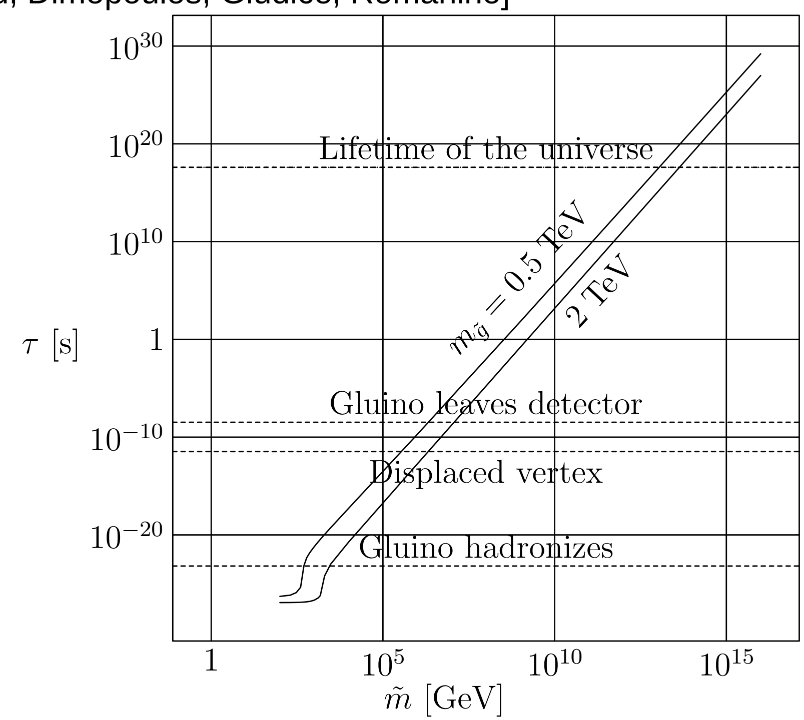
– loop-induced decays? [Toharia, Wells]

– lifetime constrained by nucleosynthesis

– $\tilde{m} \lesssim 10^9\text{GeV} \ll m_{GUT}$ [PeV? Wells]

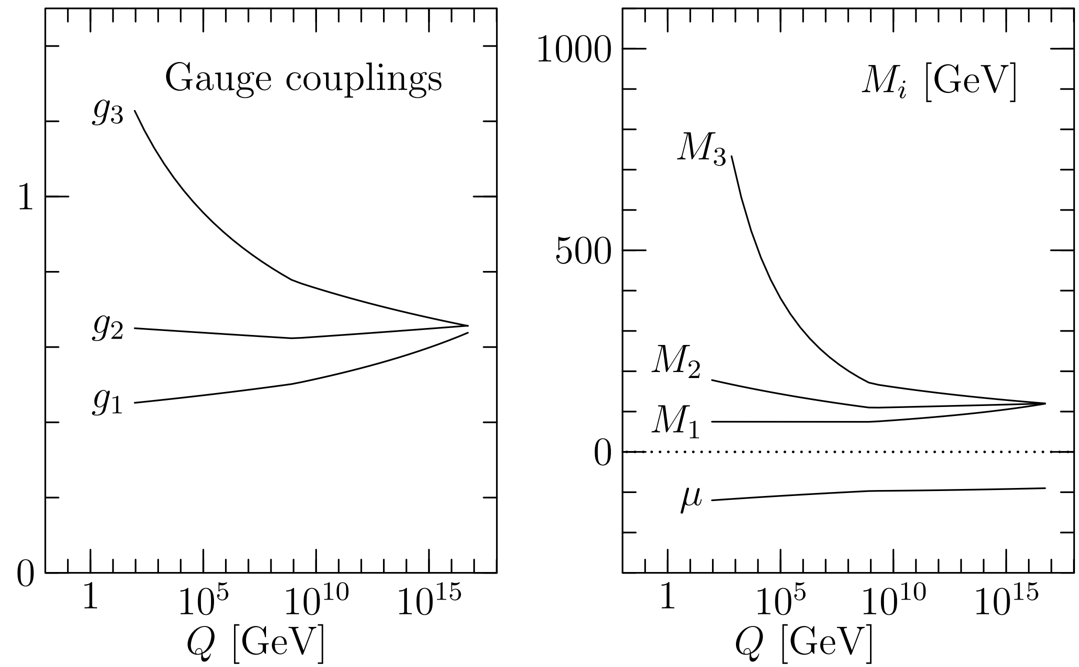
⇒ gluino hadronizes, decays much later

⇒ long-lived gluino collider signature No.1



Renormalization group running

- argued unification, so make Split Susy a GUT
- gauge couplings unify
- gaugino masses as well



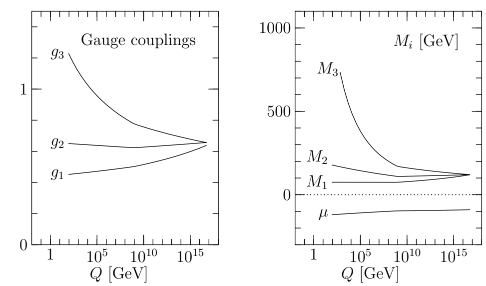
PHYSICS OF SPLIT SUPERSYMMETRY: 3

Renormalization group running

– argued unification, so make Split Susy a GUT

– gauge couplings unify

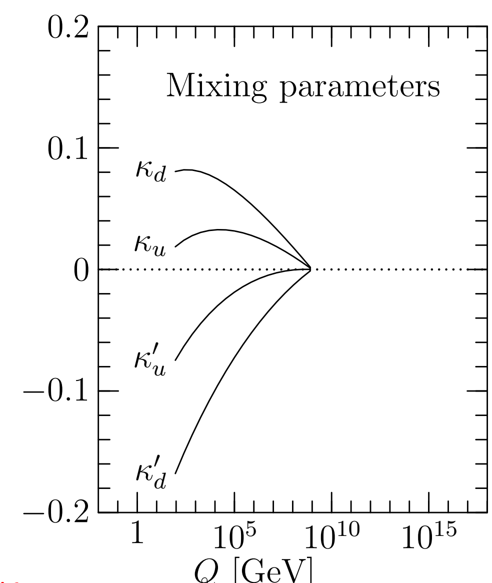
– gaugino masses assumed to unify as well



Anomalous ino Yukawa coupling

– gauginos–higgsinos mixing in MSSM:

$$\begin{pmatrix} m_{\tilde{B}} & 0 & -m_Z s_w c_\beta \equiv -\tilde{g}_d v & m_Z s_w s_\beta \equiv \tilde{g}_u v \\ 0 & m_{\tilde{W}} & m_Z c_w c_\beta \equiv \tilde{g}'_d v & -m_Z c_w s_\beta \equiv -\tilde{g}'_u v \\ -m_Z s_w c_\beta & m_Z c_w c_\beta & 0 & -\mu \\ m_Z s_w s_\beta & -m_Z c_w s_\beta & -\mu & 0 \end{pmatrix}$$



– Yukawas/gaugino–higgsino mixing fixed by Susy

– supersymmetric beta functions broken at $Q = \tilde{m}$

– anomalous Yukawas collider signal No.2: $\tilde{g}/\tilde{g}_{\rm MSSM} = 1 + \kappa$

Manuel's argument [Drees: hep-ph/0501106]

– remember Higgs potential and B parameter [$V \sim -\mu B\, H_u H_d$]

$\longrightarrow$ μ protected by symmetry:

$$\sin 2\beta = 2\,\frac{\tan\beta}{1+\tan^2\beta} = 2\,\frac{B\,\mu}{m^2_{H,u}+m^2_{H,d}} = 2\,\frac{B\,m_{weak}}{\widetilde{m}^2} = 2\,x\,\frac{m_{weak}}{\widetilde{m}} \qquad \text{for} \quad B = x\,\widetilde{m}$$

$\longrightarrow$ two solutions:

$$\tan\beta \ll 1: \qquad \tan\beta = \frac{x\,m_{weak}}{\widetilde{m}} \qquad\qquad \tan\beta \gg 1: \qquad \tan\beta = \frac{\widetilde{m}}{x\,m_{weak}}$$

$\longrightarrow$ remember Yukawa couplings: $\tan\beta = 1...100$:

$$\tan\beta < 100 \quad \Rightarrow \quad x > \frac{\widetilde{m}}{100\,m_{weak}} \quad \Rightarrow \quad B > \frac{\widetilde{m}^2}{100\,m_{weak}}$$

$\longrightarrow$ second fine tuning not protected by anything [and pointing to Planck scale]

Split Susy at the LHC: 1

LHC production of gauginos and higgsinos

– cross sections not small [$M_j(m_{GUT}) = 120$GeV; σ in fb from Prospino2]

$\tilde{g}\tilde{g}$	1710						
$\tilde{\chi}_1^- \tilde{\chi}_1^+$	2910	$\tilde{\chi}_1^- \tilde{\chi}_2^+$	73.7	$\tilde{\chi}_1^+ \tilde{\chi}_2^-$	73.7	$\tilde{\chi}_2^+ \tilde{\chi}_2^-$	604
$\tilde{\chi}_1^0 \tilde{\chi}_1^0$	49.4	$\tilde{\chi}_1^0 \tilde{\chi}_2^0$	49.7	$\tilde{\chi}_1^0 \tilde{\chi}_3^0$	409	$\tilde{\chi}_1^0 \tilde{\chi}_4^0$	0.06
		$\tilde{\chi}_2^0 \tilde{\chi}_2^0$	5.0	$\tilde{\chi}_2^0 \tilde{\chi}_3^0$	876	$\tilde{\chi}_2^0 \tilde{\chi}_4^0$	3.7
				$\tilde{\chi}_3^0 \tilde{\chi}_3^0$	1.4	$\tilde{\chi}_3^0 \tilde{\chi}_4^0$	69.6
						$\tilde{\chi}_4^0 \tilde{\chi}_4^0$	1.0
$\tilde{\chi}_1^- \tilde{\chi}_1^0$	584	$\tilde{\chi}_1^- \tilde{\chi}_2^0$	1780	$\tilde{\chi}_1^- \tilde{\chi}_3^0$	789	$\tilde{\chi}_1^- \tilde{\chi}_4^0$	78.8
$\tilde{\chi}_1^+ \tilde{\chi}_1^0$	914	$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	2870	$\tilde{\chi}_1^+ \tilde{\chi}_3^0$	1310	$\tilde{\chi}_1^+ \tilde{\chi}_4^0$	138
$\tilde{\chi}_2^- \tilde{\chi}_1^0$	2.7	$\tilde{\chi}_2^- \tilde{\chi}_2^0$	55.9	$\tilde{\chi}_2^- \tilde{\chi}_3^0$	66.6	$\tilde{\chi}_2^- \tilde{\chi}_4^0$	430
$\tilde{\chi}_2^+ \tilde{\chi}_1^0$	4.5	$\tilde{\chi}_2^+ \tilde{\chi}_2^0$	97.7	$\tilde{\chi}_2^+ \tilde{\chi}_3^0$	119	$\tilde{\chi}_2^+ \tilde{\chi}_4^0$	798

– but best background rejection $m_{\ell\ell}$ gone with the wind [higgsino searches?]

What's new for LHC phenomenology?

– no squarks, sleptons for cascades [Giudice, Romanino; astro-particle: Pierce]

– stable (hadronizing) gluinos [$\tau \sim \tilde{m}^{-4} \sim 6.5$s for $\tilde{m} = 10^9$GeV, LHC time scale 25 ns]

– heavy hadrons $R_g, R_{q\bar{q}}, R_{qqq}$ [Farrar, Fayet 1978; Baer, Cheung, Gunion 1999; UKQCD 1999]

– gluinonium [Kühn, Ono 1984; Goldman, Haber 1985; Cheung]

Split SUSY at the LHC: 2

Charged R hadrons

– many gluinos pair-produced [$\sigma \gtrsim 1$ pb]

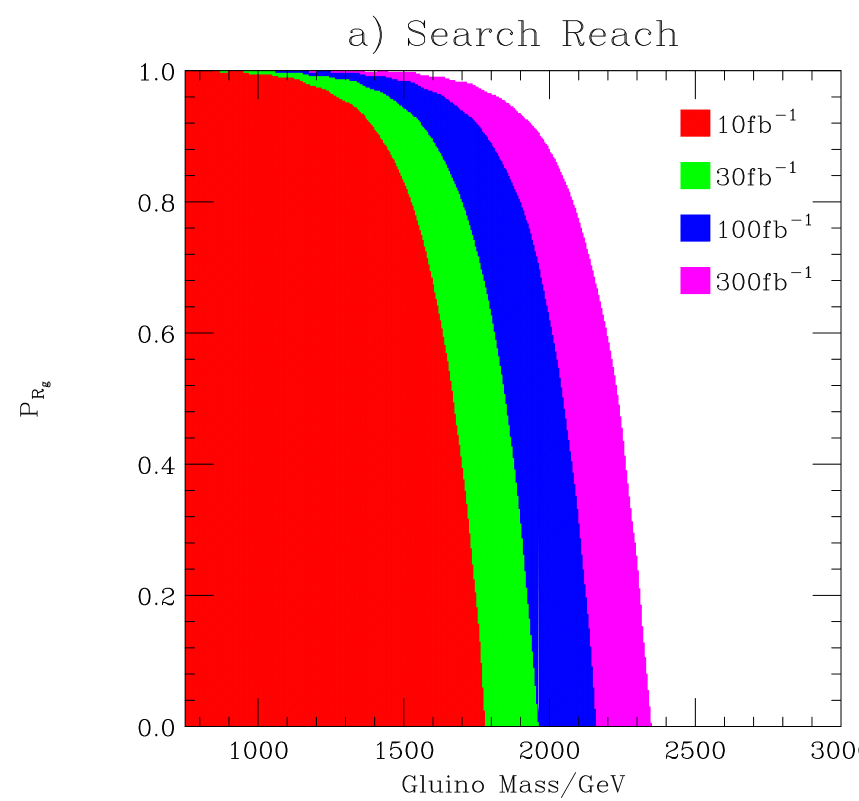
– charged R hadrons in tracker, calorimeter, muon chambers [Cambridge ex-th]

– level-1 trigger without muon chamber? [25...75 ns delay]

– effect of conversion to R baryons because of light pions? [Kraan]

$\Rightarrow$ fraction of charged R hadrons crucial

$\Rightarrow$ effective (not calculable) parameter P_{R_g}



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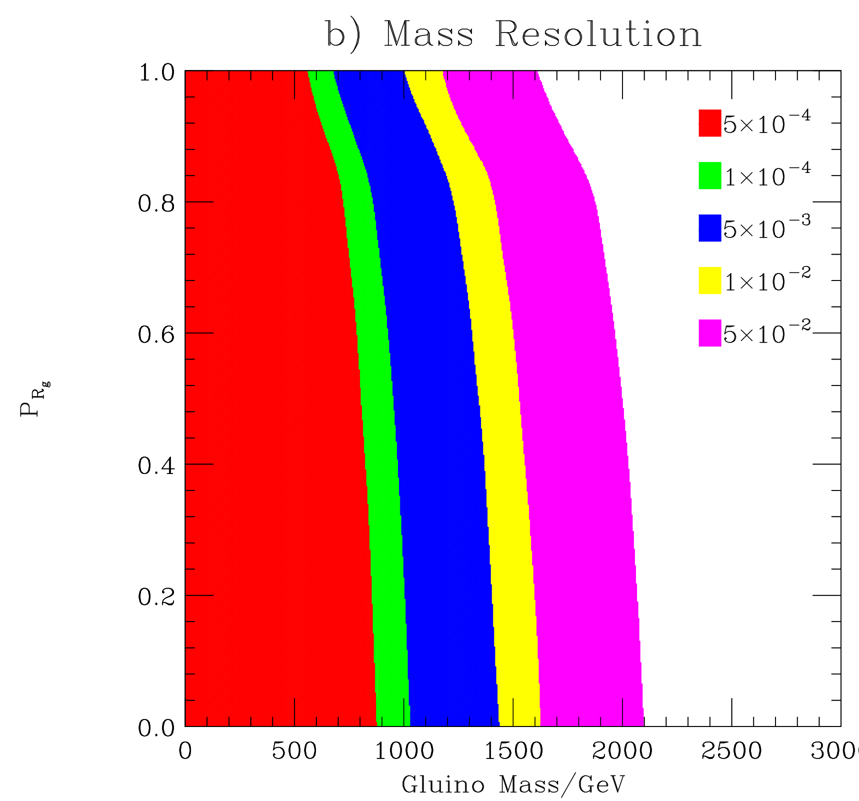


Beyond BSM signal

– mass measurement through time of flight

– charge flipper [Kraan; Hewett, Rizzo,...]

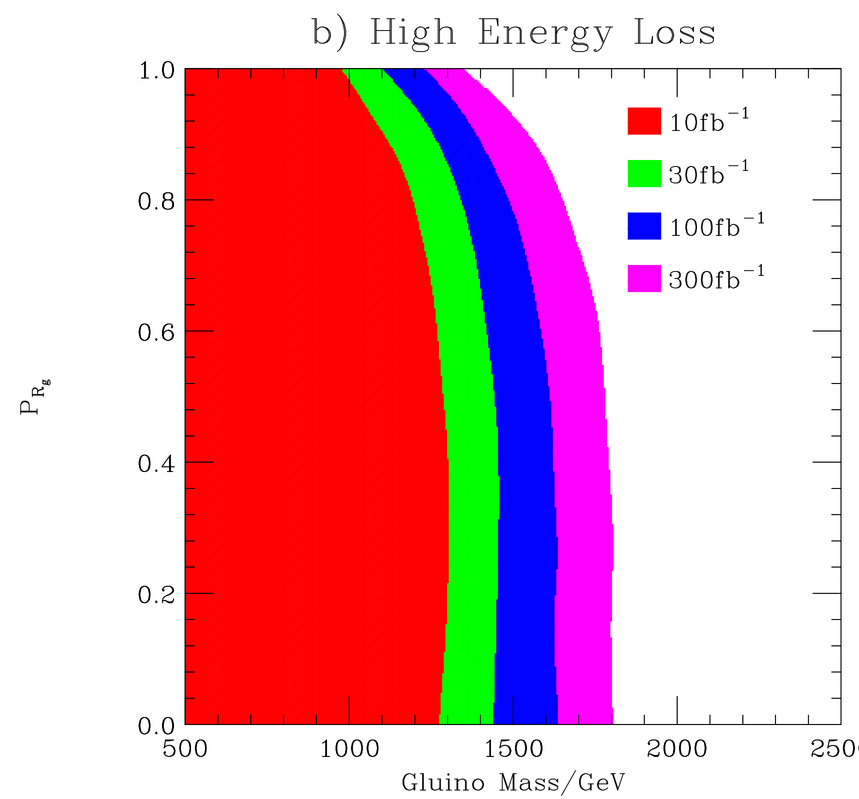
– energy deposition: no heavy lepton

SPLIT SUSY AT THE LHC: 3

Neutral R hadrons

- jets plus missing energy [$\sim 10\%$ energy loss]
- trigger dependent on cross section in calorimeter
- improved in combination with charged R hadron [missing energy trigger]
- mass measurement from gluinonium
- R hadron flavor physics?

$\Rightarrow$ charged R hadrons preferable



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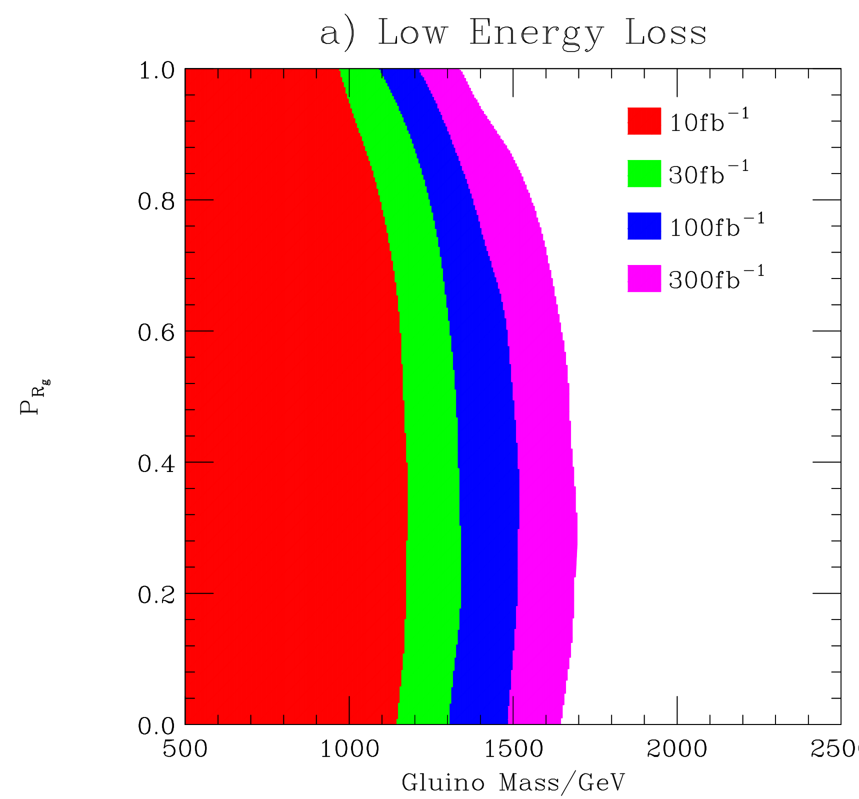


Split Supersymmetry at the ILC: 1

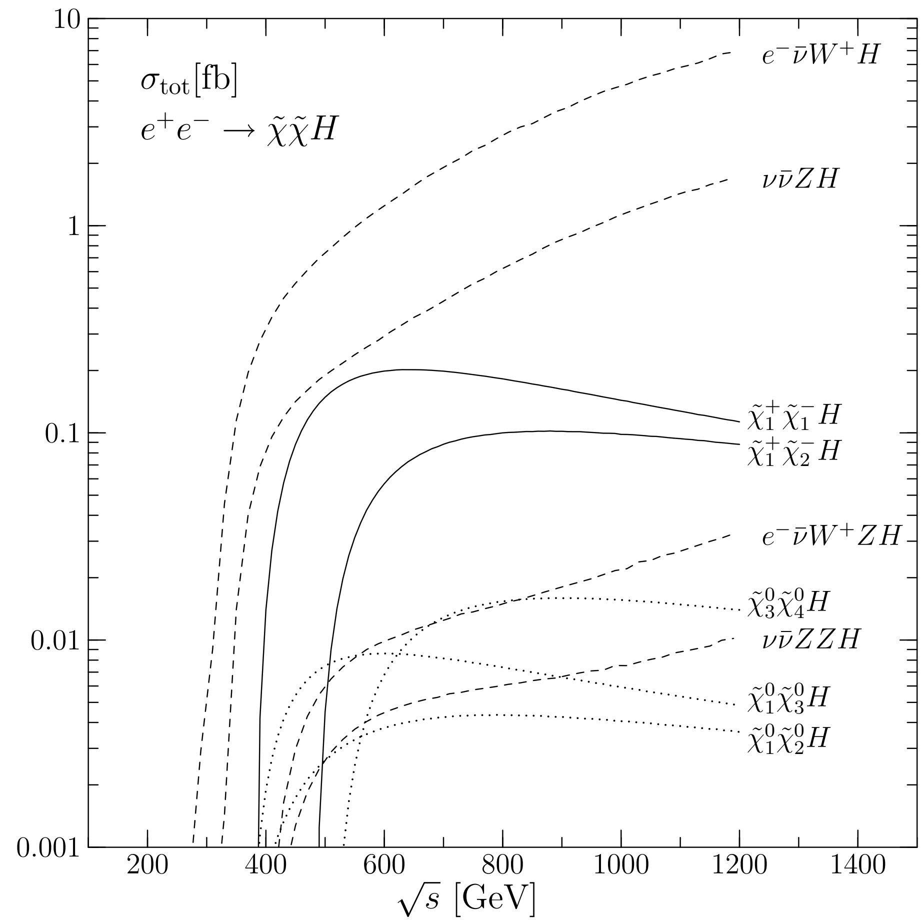
Signals at the ILC

– gluinos not produced because of decoupled squarks

– neutralino–chargino sector analysis as usual [robust with changed decay channels]

– measurement of anomalous Yukawas [$\tilde{g}_u, \tilde{g}_d, \tilde{g}'_u, \tilde{g}'_d$ different by $\sim$ 10%]

⇒ (1) direct measurements of $\chi\chi$H



SPLIT SUPERSYMMETRY AT THE ILC: 1

Signals at the ILC

- gluinos not produced because of decoupled squarks
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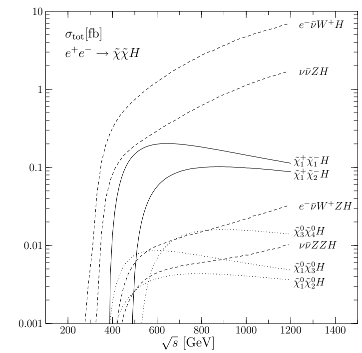
- measurement of anomalous Yukawas $[\tilde{g}_u, \tilde{g}_d, \tilde{g}'_u, \tilde{g}'_d]$

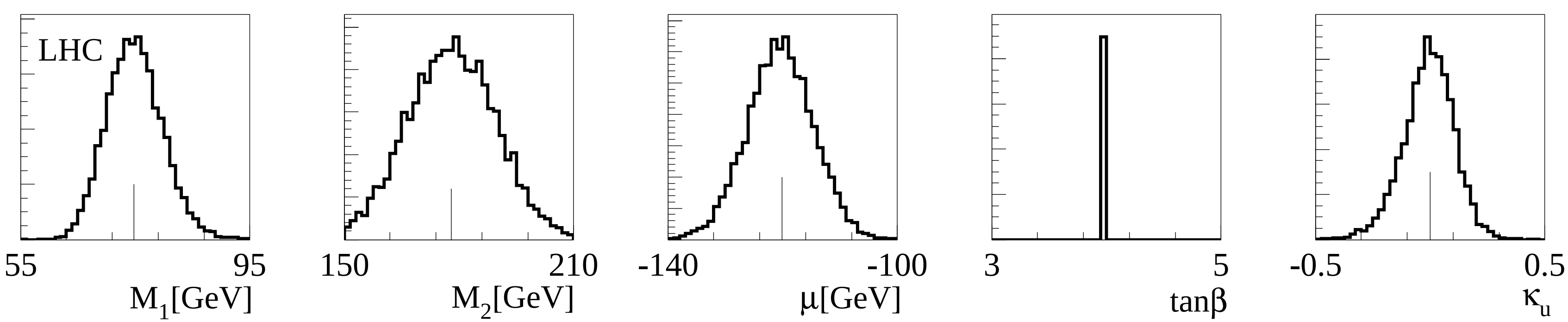
$\Rightarrow$ (1) direct measurements of $\chi\chi H$ [Whizard, Smadgraph; unpromising!]

(2) indirect determination of mass matrices



Extracting parameters from neutralino/chargino sector

- 10^4 smeared measurements of six masses (and cross sections)
- 10^4 fits of M_1, M_2, μ and one or more κ_i
- LHC data alone not promising [masses only, 5% error]

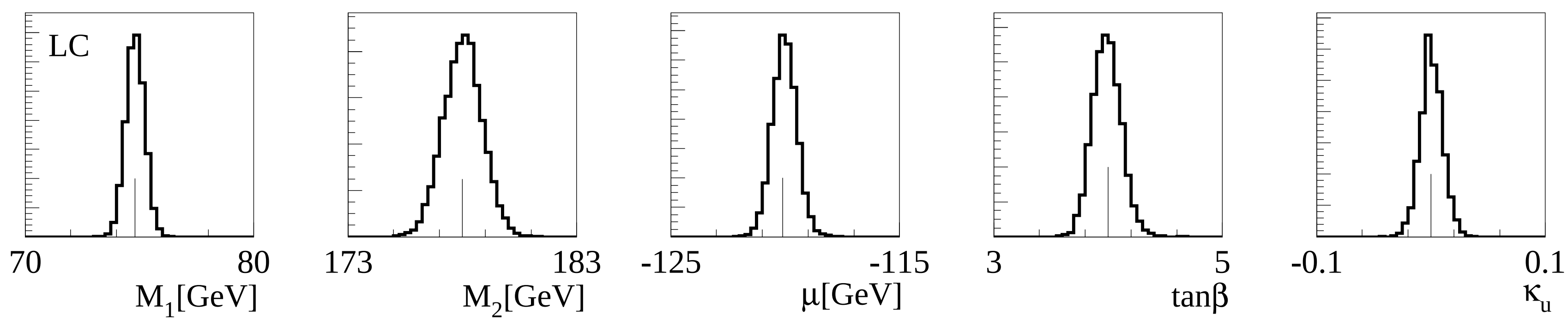


Neutralinos/charginos at the ILC

– mass measurements to 0.5%

– error propagation through 10^4 smeared pseudo-measurements

⇒ one κ at the time to $\lesssim$ 5%

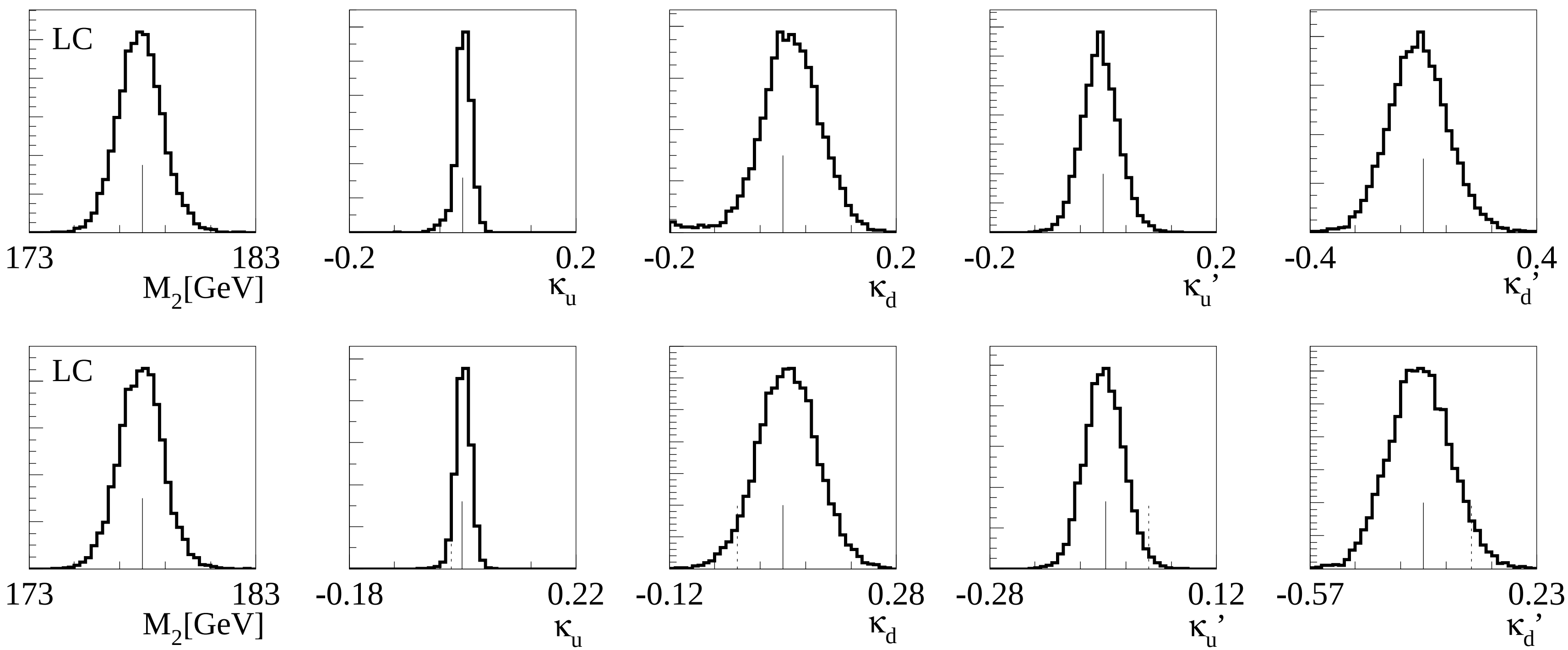


Neutralinos/charginos at the ILC

- mass measurements to 0.5%, cross sections statistical error
- error propagation through 10^4 smeared pseudo-measurements

$\Rightarrow$ one κ at the time to $\lesssim$ 5%

$\Rightarrow$ four κ simultaneously to $\lesssim$ 10%



SPLIT SUPERSYMMETRY AT THE ILC: 2

Neutralinos/charginos at the ILC

- mass measurements to 0.5%, cross sections statistical error
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$\Rightarrow$ four κ simultaneously to $\lesssim$ 10%

So can we tell it is Split Susy?

- mass measurement errors conservative
- only mass and cross section measurements yet [Sfitter-Fittino next step]

	Fit $\tan\beta$	m_i	σ_{ij}	$\Delta\kappa_u$	$\Delta\kappa_d$	$\Delta\kappa'_u$	$\Delta\kappa'_d$
ILC		•	•	0.9×10^{-2}	3×10^{-2}	1.3×10^{-2}	4×10^{-2}
ILC	•	•	•	1.2×10^{-2}	5×10^{-2}	2×10^{-2}	5×10^{-2}
ILC		•		1.1×10^{-2}	5×10^{-2}	3×10^{-2}	8×10^{-2}
ILC	•	•		1.2×10^{-2}	11×10^{-2}	4×10^{-2}	8×10^{-2}
LHC		•		2.2×10^{-1}	6×10^{-1}	2.7×10^{-1}	8×10^{-1}
ILC		•	•	1.4×10^{-2}	5×10^{-2}	3×10^{-2}	10×10^{-2}
ILC*	•	•	•	1.7×10^{-2}	9×10^{-2}	4×10^{-2}	13×10^{-2}
ILC	fix $\tan\beta = 3$	•	•	1.6×10^{-2}	4×10^{-2}	4×10^{-2}	9×10^{-2}
ILC*	$\kappa_i \neq 0$	•	•	1.4×10^{-2}	5×10^{-2}	4×10^{-2}	11×10^{-2}
ILC*	fix $\tan\beta = 5$	•	•	1.6×10^{-2}	7×10^{-2}	4×10^{-2}	14×10^{-2}

$\Rightarrow$ anomalous Yukawas promising at ILC

OUTLOOK

Showcase for state-of-the-art LHC phenomenology: Split Supersymmetry

- interesting phenomenology
- LHC: R hadrons observable with mass measurement
- ILC: anomalous weak-ino Yukawas accessible

What stays

- exotic heavy hadrons visible at LHC [trigger issues]
- why did we aways assume MSSM-type ino Yukawas? [missed Susy test]

SUSY-Madgraph: we are done! [Hagiwara, Kanzaki, TP, Rainwater, Stelzer]

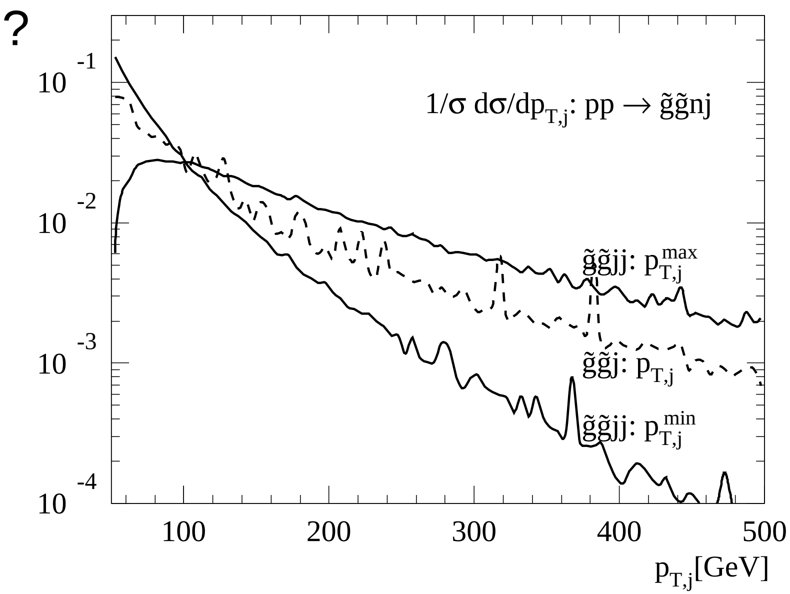
- Majoranas and fermion number violation in Madgraph [Denner, Eck, Hahn, Küblbeck]
- complete set of Feynman rules [300+ processes compared with Whizard and Sherpa]
- beta version upon request, Smadevent in test phase
- first physics project: SUSY pairs in WBF

Using SUSY-Madevent: squarks and gluinos plus jets [TP, Rainwater, Skands]

- cascade studies sensitive to hard jet radiation?
- compute $\tilde{g}\tilde{g}$+2j and $\tilde{u}_L\tilde{g}$+2j [SPS1a, $p_{T,j} > 100$GeV]

σ [pb]	$t\bar{t}_{600}$	$\tilde{g}\tilde{g}$	$\tilde{u}_L\tilde{g}$
σ_{0j}	1.30	4.83	5.65
σ_{1j}	0.73	2.89	2.74
σ_{2j}	0.26	1.09	0.85

- task 1: gluon radiation vs. initial states?
- task 2: comparison with Phythia showers



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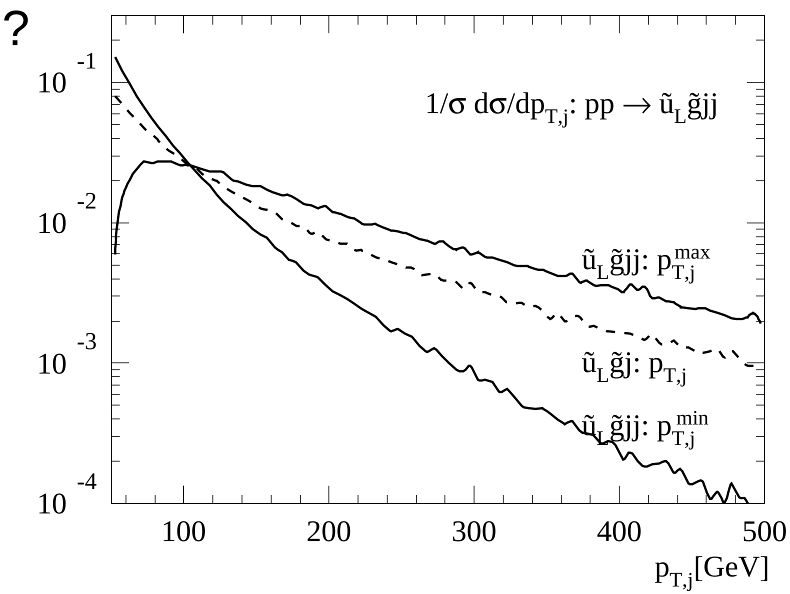

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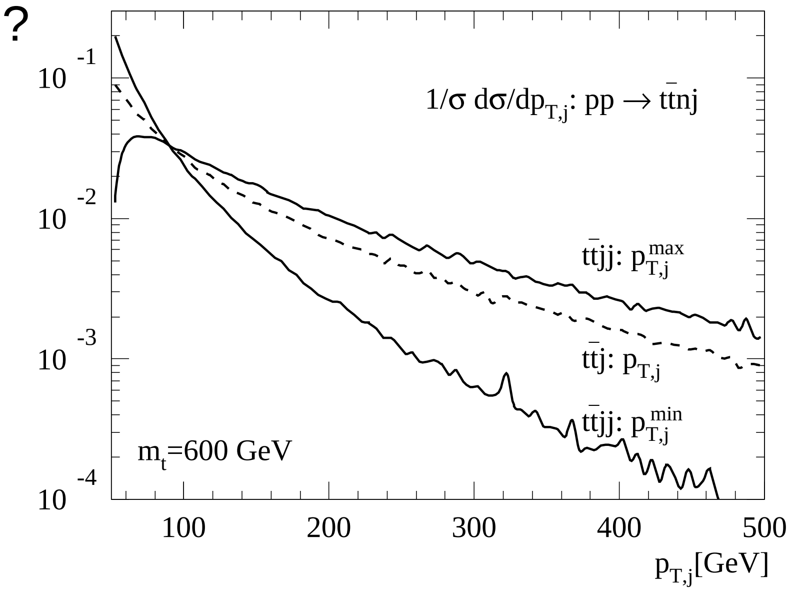

SUSY-MADGRAPH

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