

SUPERSYMMETRY AT THE LHC

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- TeV scale supersymmetry
- Inclusive + exclusive signals at LHC
- Measurements at LHC (+ILC)
- LHC pheno at work: split supersymmetry

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 $m_h \rightarrow \Lambda$
- ⇒ solution: counter term for exact cancellation ⇒ **artificial, unmotivated, ugly**
- ⇒ or new physics at TeV scale: **supersymmetry**
extra dimensions
little Higgs (pseudo-Goldstone Higgs)
Higgsless/composite Higgs
YourFavoriteNewPhysics...
- ⇒ all beautiful concepts and symmetries
- ⇒ 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

- 3 running gauge couplings meet — GUT gauge group
- 2 Higgs doublets — radiative symmetry breaking
- R parity — stable proton yields dark matter
- local supersymmetry – including gravity?
- **rich LHC phenomenology** — no nasty surprises [effective theory of everything]

Dark side

- unknown SUSY breaking
 - masses, couplings, phases...
 - e.g. hierarchical spectrum? [Split SUSY]
 - flavor physics and SUSY breaking
 - CKM and lepton flavor?
 - 2 Higgs doublet model
 - μ parameter and SUSY breaking?
- ⇒ **as many as exclusive analyses as possible**

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

TEV SCALE SUPERSYMMETRY: 3

Structures in the SUSY spectrum [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**

$$\begin{pmatrix} m_{\tilde{g}} & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & m_{\tilde{W}} & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ -m_Z s_W c_\beta & m_Z c_W c_\beta & 0 & -\mu \\ m_Z s_W s_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix} \begin{pmatrix} m_{\tilde{W}} & \sqrt{2} m_W s_\beta \\ \sqrt{2} m_W c_\beta & -\mu \end{pmatrix}$$

- stop and sbottom mixing in **MSSM**

$$\begin{pmatrix} m_Q^2 + m_t^2 + \left(\frac{1}{2} - \frac{2}{3} s_W^2\right) m_Z^2 c_{2\beta} & -m_t (A_t + \mu \cot \beta) \\ -m_t (A_t + \mu \cot \beta) & m_U^2 + m_t^2 + \frac{2}{3} s_W^2 m_Z^2 c_{2\beta} \end{pmatrix}$$

- heavy gluinos and squarks through **unification**: $m_{\tilde{B}, \tilde{W}, \tilde{g}}/m_{1/2} \sim 0.4, 0.8, 2.6$
 $m_{\tilde{\ell}, \tilde{q}}/m_{1/2} \sim 0.7, 2.5$ [$m_0 \ll m_{1/2}$]

[mass and coupling unification independent]

Supersymmetric parameter conventions

- comparison of specialized codes crucial [remember: e.g. Comphep–Pythia–Isajet]
- ⇒ fix SUSY conventions once for all
 - soft breaking parameters [e.g. $\pm A_t$]
 - scale dependence of couplings, masses [e.g. $m(q = \text{TeV}, \nu, m_t)$?]
 - definitions of mass matrixes, mixing angles [e.g. $\tilde{t}_{L,R}$ up or down?]

SUSY Les Houches Accord [Allanach, Skands et al.]

- spectrum generators: SoftSusy, SPheno, FeynHiggs,...
- multi-purpose Monte Carlos: Pythia, Herwig, Sherpa
- matrix element generators: Whizard, Smadgraph
- NLO cross sections: Prospino2
- NLO decay rates: Sdecay
- SUSY parameter extraction: Fittino, Sfitter
- dark matter: Micromegas
- ⇒ **fixed parameter convention and read-write format** [list to be extended]

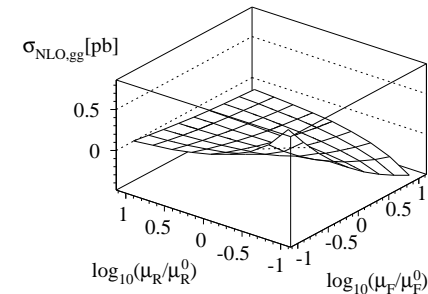
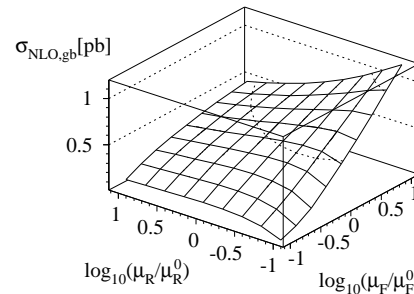
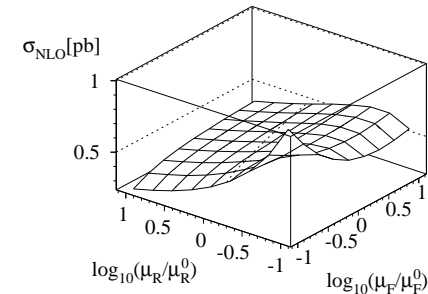
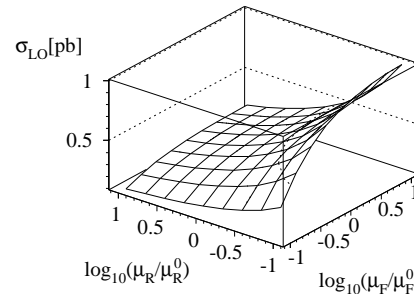
SUSY SIGNALS AT LHC: 1

Supersymmetry at the LHC

- (1) **possible discovery** — signals for new physics, exclusion of parameter space
 - (2) **measurements** — masses, cross sections, decays
 - (3) **parameter studies** — MSSM Lagrangean, SUSY breaking
- ⇒ at least 10% precision to be matched at LHC [theorist's nightmare, yet unsolved]

Hadron collider observables with errors

- ★ masses from σ_{tot}
 - ★ branching fractions from σ_{tot}
 - renormalization scale from $\alpha_s, y_{b,t}$
 - factorization scale from pdf's
 - perturbative series $N_c \alpha_s / \pi \sim 10\%$
 - finite terms [LO-NLO-NNLO: DY, Higgs]
- ⇒ **NLO errors: 15...40 % for SUSY particles**



SUSY SIGNALS AT LHC: 2A

Prospino2: NLO cross sections for LHC

- all two-particle SUSY production channels included
- download from Prospino2 page: <http://pheno.physics.wisc.edu/~plehn>
- extended version beyond Prospino2: $pp \rightarrow SS^*, tH^- \dots$

[thanks to: W. Beenakker, R.Höpker, M. Krämer, M. Spira, P. Zerwas]

SUSY signals included

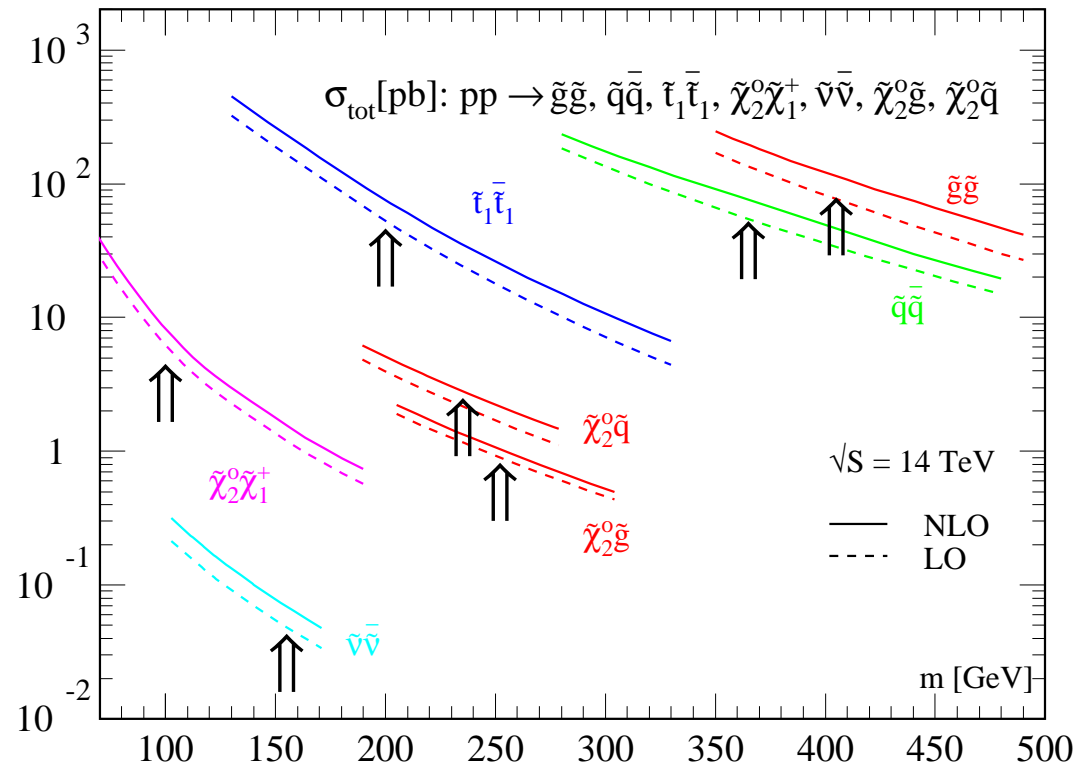
- jets and \cancel{E}_T : $pp \rightarrow \tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$
- funny tops: $pp \rightarrow \tilde{t}_1\tilde{t}_1^*$
- like sign dileptons: $pp \rightarrow \tilde{g}\tilde{g}$

[$\tilde{g} \rightarrow \tilde{u}\tilde{u} \rightarrow \tilde{\chi}_1^+ d\bar{u}$ or c.c.]

- tri-leptons: $pp \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^-$

[$\tilde{\chi}_2^0 \rightarrow \tilde{\ell}\bar{\ell} \rightarrow \tilde{\chi}_1^0\ell\bar{\ell}; \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\ell\bar{\nu}$]

- bottoms and \cancel{E}_T : $pp \rightarrow \tilde{b}_1\tilde{b}_1^*$



SUSY SIGNALS AT LHC: 2B

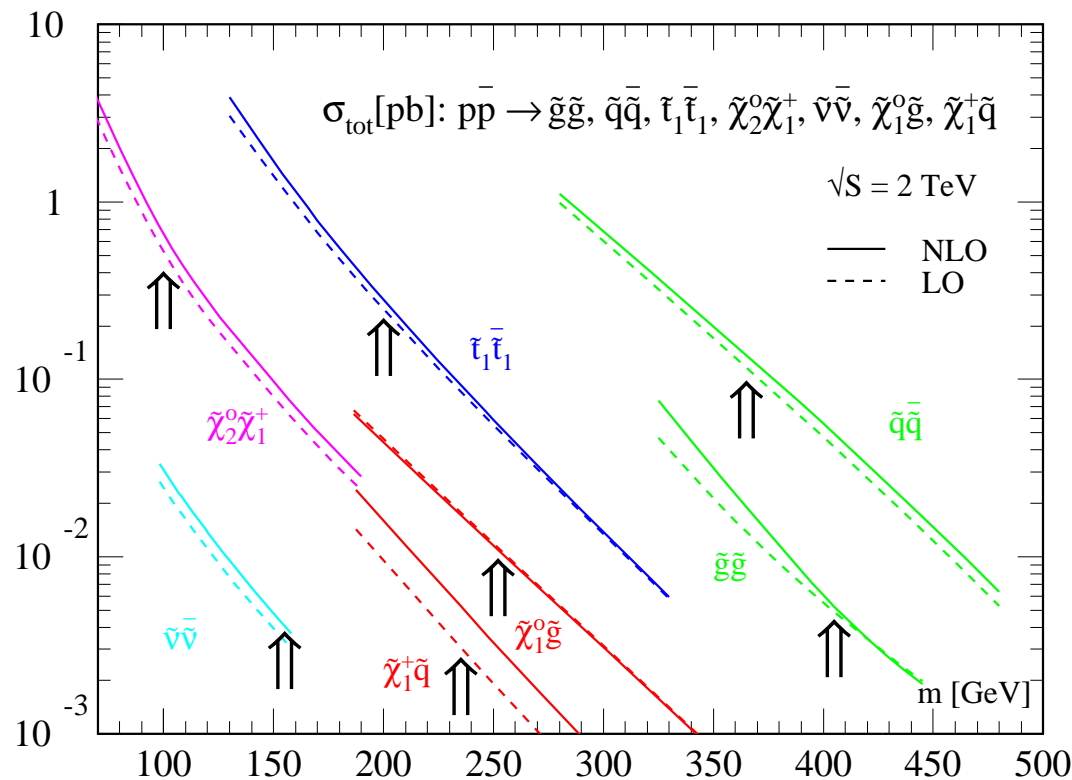
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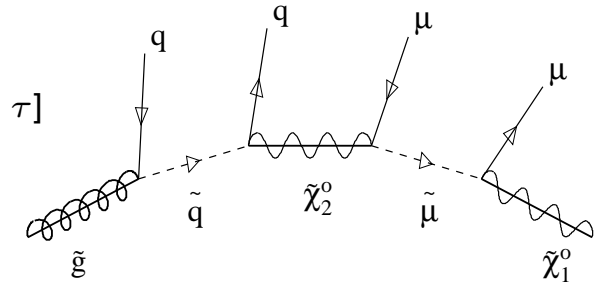
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SUSY MEASUREMENTS AT LHC: 1

SUSY spectra from cascade decays

- decay $\tilde{g} \rightarrow \tilde{q}\bar{q} \rightarrow \tilde{\chi}_2^0 q\bar{q} \rightarrow \mu^+ \mu^- q\bar{q} \tilde{\chi}_1^0$ [better not via Z or to τ]
- cross sections some 100 pb [more than 3×10^5 events]
- thresholds & edges [Hinchliffe, Paige...; Cambridge ex-th]
critical: enough thresholds and edges available?



$$\text{classical } m_{\ell\ell}^2 < (m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\ell}}^2)(m_{\tilde{\ell}}^2 - m_{\tilde{\chi}_1^0}^2)/m_{\tilde{\ell}}^2$$

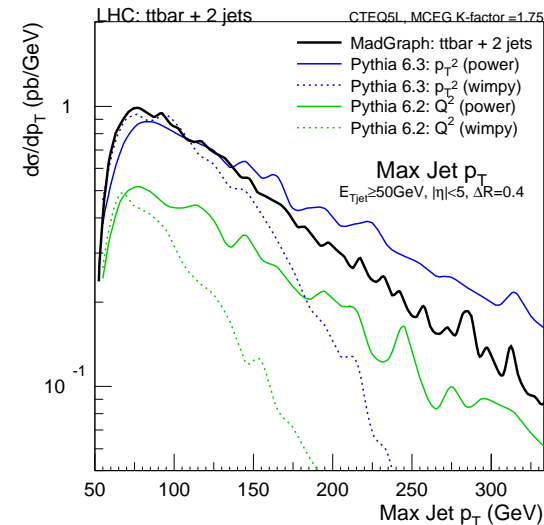
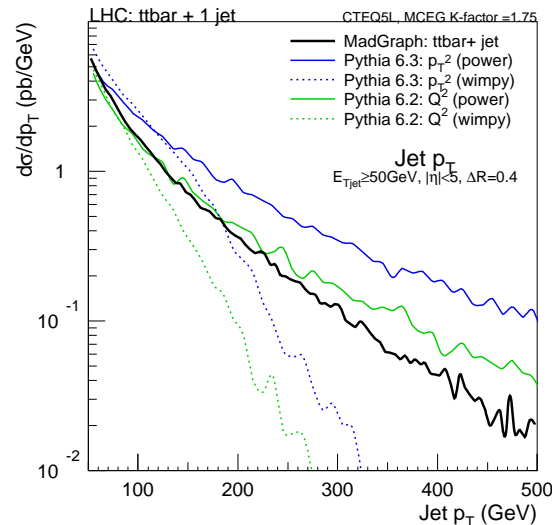
⇒ detector resolution, calibration, systematic errors? [Polesello, Gjelsten, Miller, Osland]

Squarks and gluinos plus jets [TP, Rainwater, Skands]

- **Smadgraph/Smadevent done**
[Hagiwara, Kanzaki, TP, Rainwater, Stelzer]
- compute $\tilde{g}\tilde{g}+2j$ and $\tilde{u}_L\tilde{g}+2j$

σ [pb]	$t\bar{t}_{600}$	$\tilde{g}\tilde{g}$	$\tilde{u}_L\tilde{g}$
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σ_{1j}	0.73	2.89	2.74
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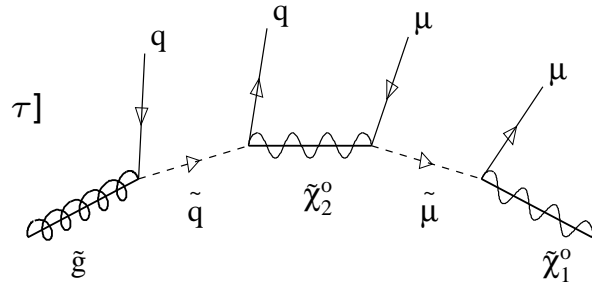
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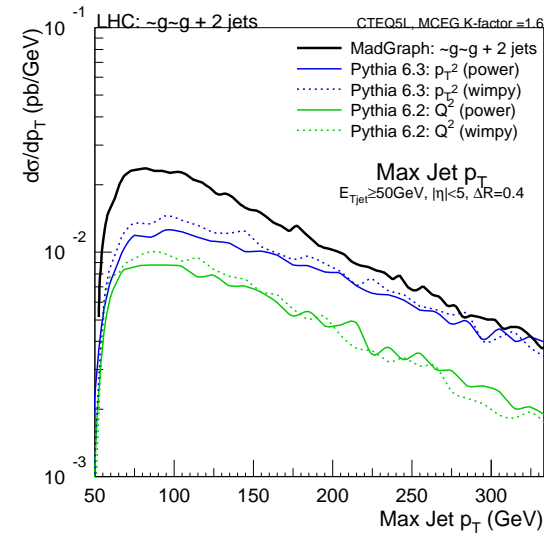
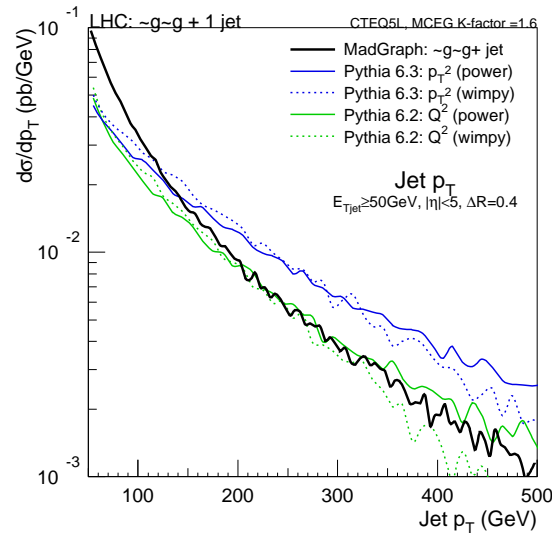
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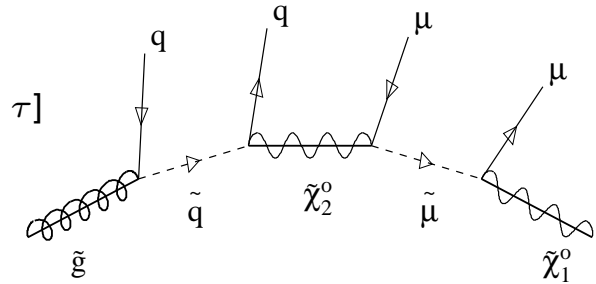
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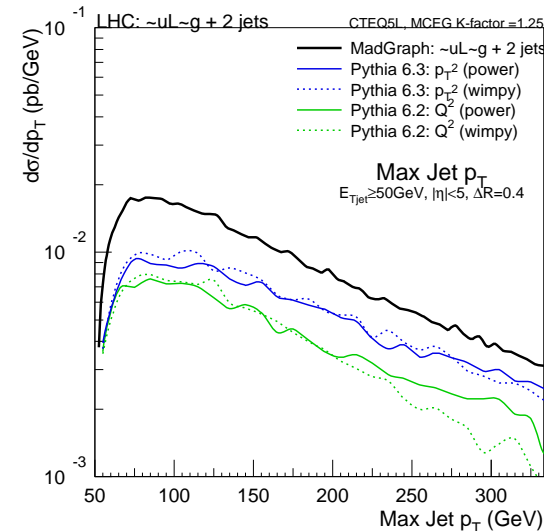
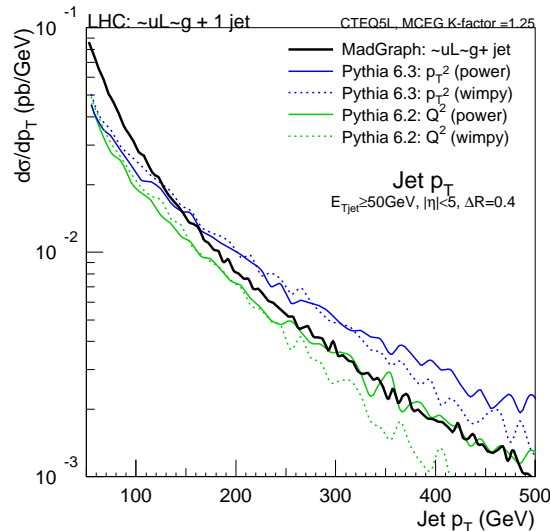
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SUSY MEASUREMENTS AT LHC: 2

Theorist's point of view

- measured masses, cross sections, decays secondary
- parameters in SUSY Lagrangean from measurements
- ⇒ SUSY breaking parameters at TeV (or higher) scale

Warmup: SUGRA top–down fit with errors

- fit including all errors

[Allanach et al; Jack & Jones]

abs. errors	SPS1a	Δ at LHC		Δ at ILC		Δ at LHC+ILC	
		stat	stat+theo	stat	stat+theo	stat	stat+theo
m_0	100	4.0	4.7	0.09	0.6	0.08	0.6
$m_{1/2}$	250	1.8	2.6	0.13	0.6	0.11	0.5
$\tan\beta$	10	1.3	3.5	0.14	0.3	0.14	0.4
A_0	-100	31.8	32.4	4.43	8.5	4.23	12.6

- spectrum from Suspect [Djouadi, Kneur]
- fit Suspect and Softsusy [Allanach]

LHC	Suspect	Δ	Softsusy	Δ
m_0	100.00	4.7	97.9	4.6
$m_{1/2}$	250.00	2.7	252.5	2.9
$\tan\beta$	10.00	3.5	11.6	3.6
A_0	-99.96	32.4	14.7	58.9

LHC+ILC				
m_0	100.0	0.59	98.4	0.7
$m_{1/2}$	249.99	0.49	254.3	0.8
$\tan\beta$	9.99	0.44	7.3	0.3
A_0	-100.1	12.6	902.0	18

- ⇒ looks like fine way to estimate theory errors

SUSY MEASUREMENTS AT LHC: 3

SUSY parameters from observables

- parameters: weak-scale MSSM Lagrangean
- measurements: masses [Suspect, Softsusy, FeynHiggs...]
 branching fractions [MSMlib, Sdecay]
 cross sections [Prospino, MSMlib],...
- errors: general correlation, statistics & systematics & theory
- problem in grid: huge phase space, local minimum?
 problem in fit: domain walls, starting values, global minimum?

SFitter [Lafaye, TP, D. Zerwas, also Fittino]

- (1) grid for closed subset
- (2) fit of remaining parameters
- (3) complete fit

⇒ **LHC+ILC with no assumptions**

	LHC	ILC	LHC+ILC	SPS1a
$\tan\beta$	10.22 ± 9.1	10.26 ± 0.3	10.06 ± 0.2	10
M_1	102.45 ± 5.3	102.32 ± 0.1	102.23 ± 0.1	102.2
M_3	578.67 ± 15	fi x 500	588.05 ± 11	589.4
$M_{\tilde{\tau}_L}$	fi x 500	197.68 ± 1.2	199.25 ± 1.1	197.8
$M_{\tilde{\tau}_R}$	129.03 ± 6.9	135.66 ± 0.3	133.35 ± 0.6	135.5
$M_{\tilde{\mu}_L}$	198.7 ± 5.1	198.7 ± 0.5	198.7 ± 0.5	198.7
$M_{\tilde{q}_{3L}}$	498.3 ± 110	497.6 ± 4.4	521.9 ± 39	501.3
$M_{\tilde{t}_R}$	fi x 500	420 ± 2.1	411.73 ± 12	420.2
$M_{\tilde{b}_R}$	522.26 ± 113	fi x 500	504.35 ± 61	525.6
A_τ	fi x 0	-202.4 ± 89.5	352.1 ± 171	-253.5
A_t	-507.8 ± 91	-501.95 ± 2.7	-505.24 ± 3.3	-504.9
A_b	-784.7 ± 35603	fi x 0	-977 ± 12467	-799.4

SPLIT SUSY AT COLLIDERS: 1

Split Supersymmetry [Dimopoulos, Arkani-Hamed; Giudice, Romanino; Wells; Drees]

- 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]
- ⇒ make all scalars heavy [hope: $\tilde{m} \rightarrow m_{\text{GUT}}$]
- ⇒ protect all gaugino and higgsino masses [$m_{\tilde{\chi}_i}, m_{\tilde{g}} \lesssim \text{TeV}$]

What's new for phenomenology?

- no squarks, sleptons for colliders, astro-particle physics [Giudice, Romanino; Pierce]
- no cascade decays
- stable (hadronizing) gluinos [$\tau \sim \tilde{m}^{-4} \sim 6.5\text{s}$ for $\tilde{m} = 10^9\text{GeV}$]
- heavy hadrons $R_g, R_{q\bar{q}}, R_{qqq}$ [Farrar, Fayet; Baer, Cheung, Gunion; UKQCD; Kraan]
- renormalization group running without scalars [e.g. different in Yukawa couplings by $\lesssim 20\%$]

Collider tests

- (1) Is it supersymmetry?
- (2) Is it split?

SPLIT SUSY AT COLLIDERS: 2

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

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

→ Higgsino mass $\mu \sim m_{\text{weak}}$ by symmetry:

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

→ two solutions:

$$\tan \beta \ll 1 : \quad \tan \beta = \frac{x m_{\text{weak}}}{\tilde{m}} \qquad \tan \beta \gg 1 : \quad \tan \beta = \frac{\tilde{m}}{x m_{\text{weak}}}$$

→ remember Yukawa couplings: $\tan \beta = 1 \dots 100$:

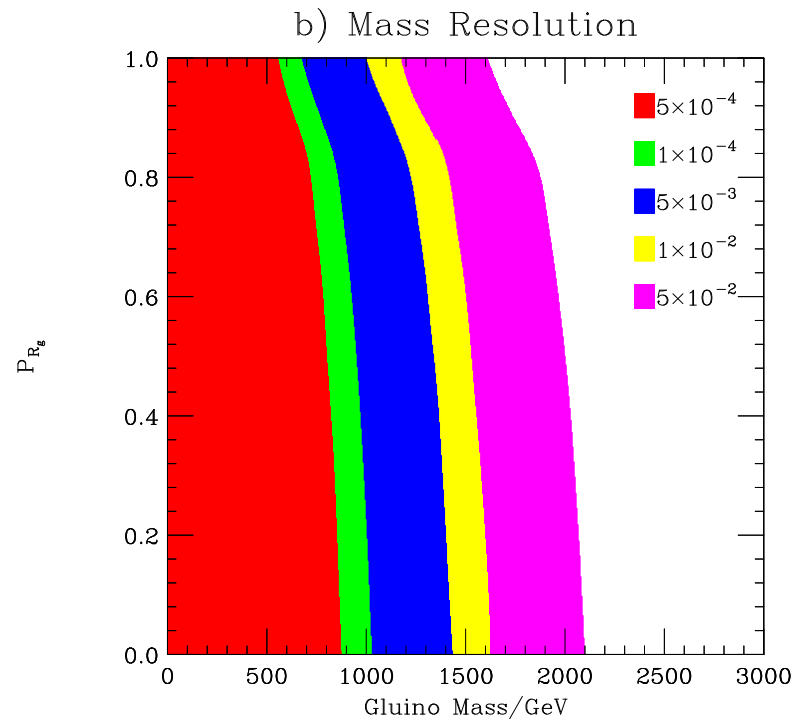
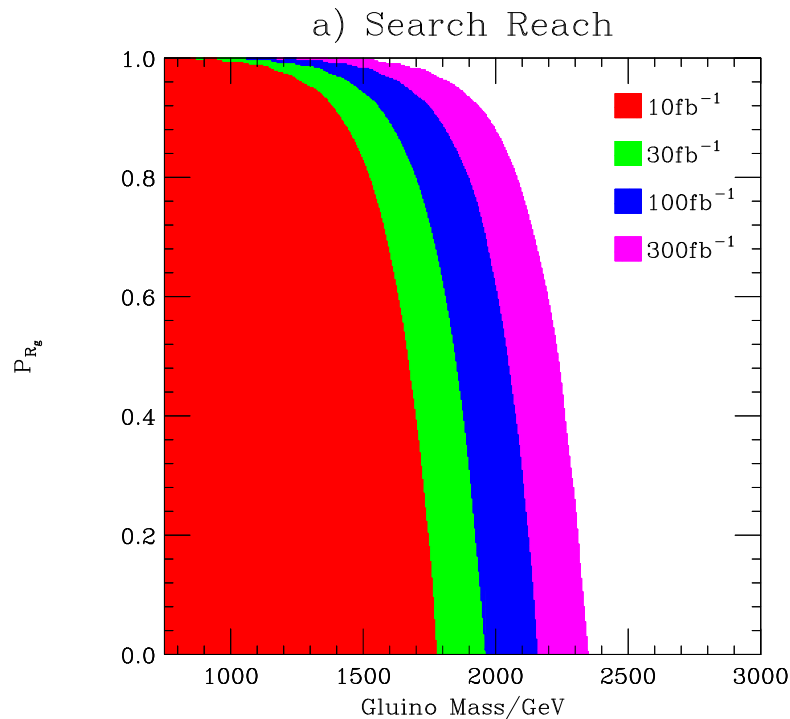
$$\tan \beta < 100 \Rightarrow x > \frac{\tilde{m}}{100 m_{\text{weak}}} \Rightarrow B > \frac{\tilde{m}^2}{100 m_{\text{weak}}}$$

→ **second fine tuning not protected by anything** [and pointing to Planck scale]

SPLIT SUSY AT COLLIDERS: 3

Split SUSY at the LHC [Kilian, TP, Richardson, Schmidt]

- neutralinos, charginos like in MSSM, poor precision
- many gluinos pair-produced [$\sigma \gtrsim 1$ pb, Prospino2]
- gluinonium $\tilde{g}\tilde{g} \rightarrow jj$ [Kühn, Ono; Goldman, Haber; CMS; reach \sim TeV?]
- neutral R hadrons missing \rightarrow missing energy signal
- charged R hadrons in tracker, calorimeter, muon chambers [Cambridge ex-th]
- mass measurement through time of flight tracker–muon chamber



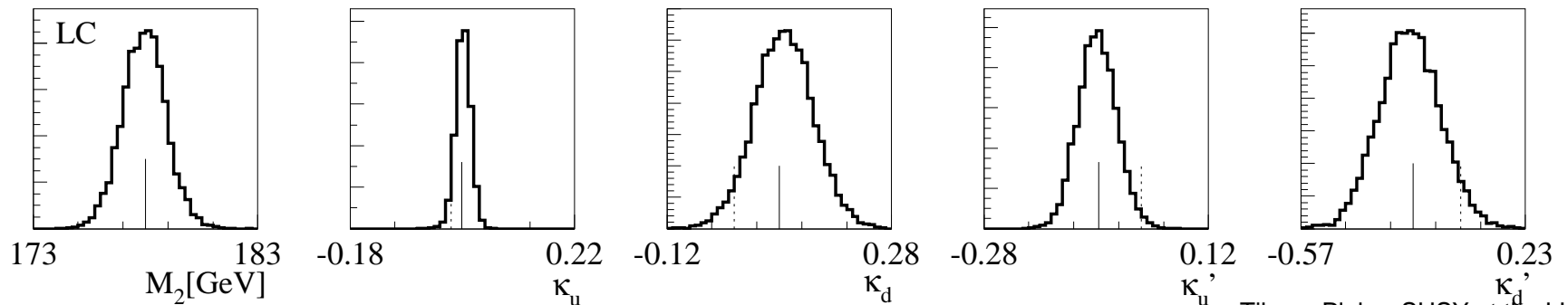
SPLIT SUSY AT COLLIDERS: 4

Split Supersymmetry at the ILC [Kilian, TP, Richardson, Schmidt]

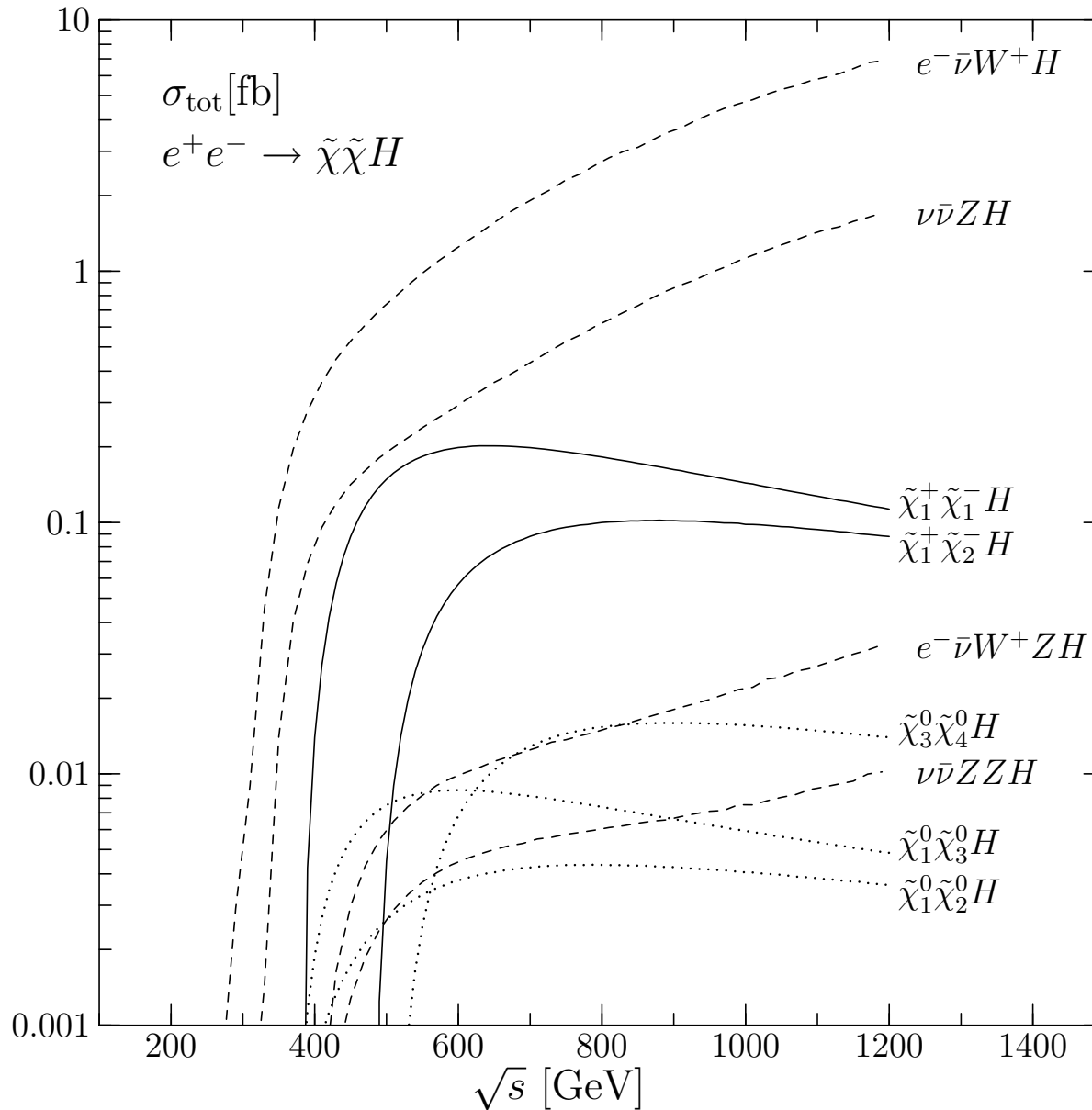
- gluinos not produced because of decoupled squarks
 - neutralino–chargino sector analysis as usual [robust towards decay channels]
 - anomalous Yukawas \equiv off-diagonal mass matrix entries [$g_{s\beta}, g_{c\beta}, g'_{s\beta}, g'_{c\beta}$]
- \Rightarrow (1) direct measurements of $\chi\chi h$ [Whizard, Smadgraph \rightarrow distinctly unpromising]
- (2) indirect determination of mass matrices [poor man's Sfitter]

Indirect determination

- errors crucial [0.5 % error on masses at ILC]
 - 10^4 smeared pseudo-measurements to extract parameters from
- \Rightarrow analytic inversion impossible, fit instead
- \Rightarrow $\mathcal{O}(\text{few}\%)$ errors from distribution of 10^4 best fits



SPLIT SUSY AT COLLIDERS: 4B



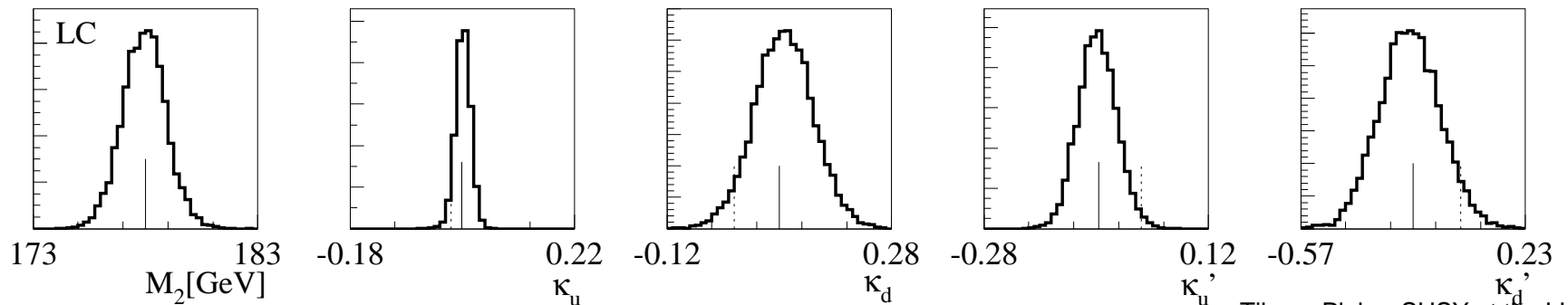
SPLIT SUSY AT COLLIDERS: 4

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OUTLOOK

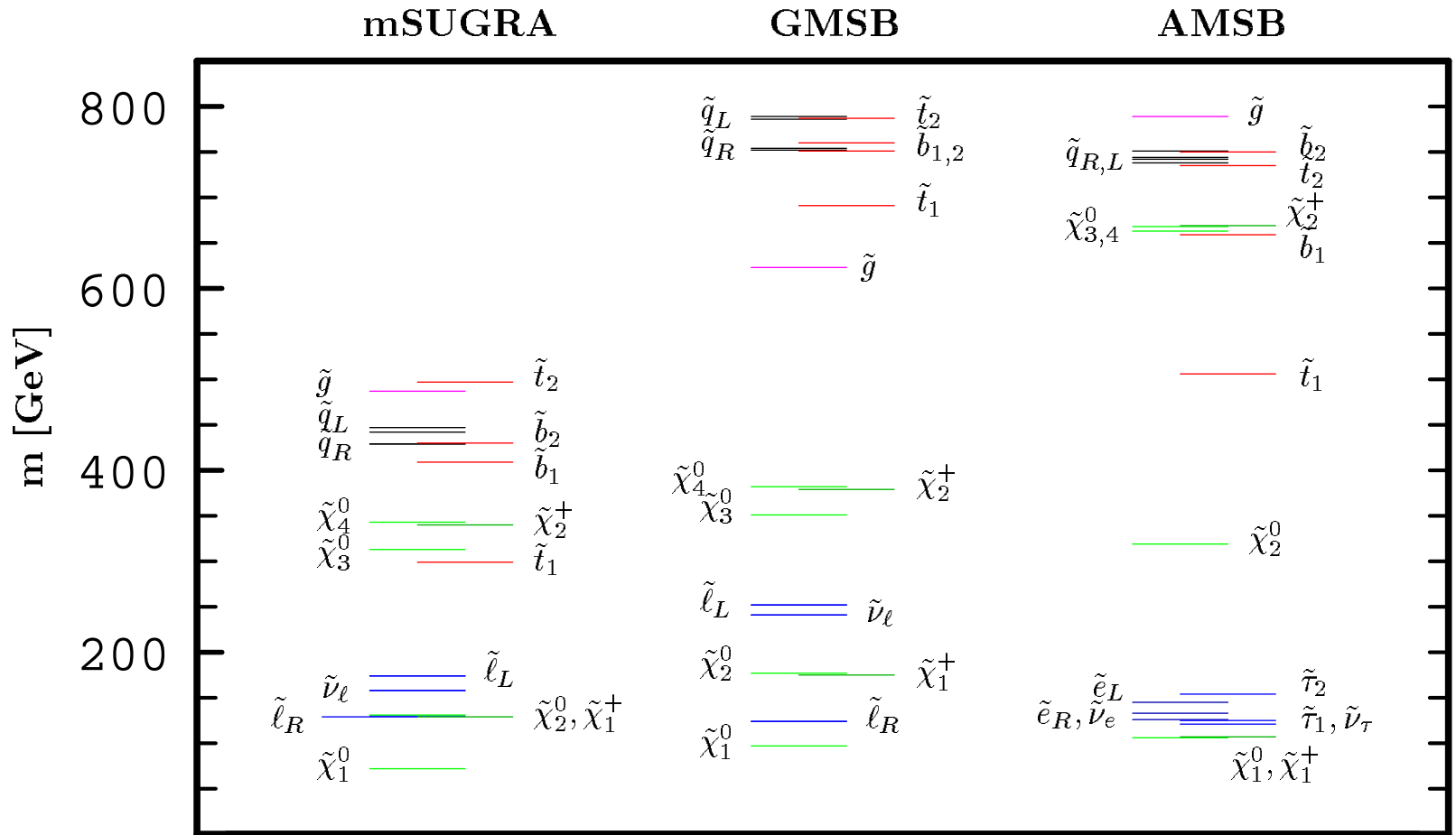
Pheno effort for SUSY@LHC picking up speed

- inclusive searches plus cascade reconstruction with great promise
 - total cross sections available to NLO [Propino2]
 - automatic matrix element generators being tested [Smadgraph, Whizard, Sherpa]
 - parameter extraction tools in use for LHC–ILC studies [Sfitter, Fittino]
- ⇒ errors will be crucial at LHC

Showcase: Split Supersymmetry

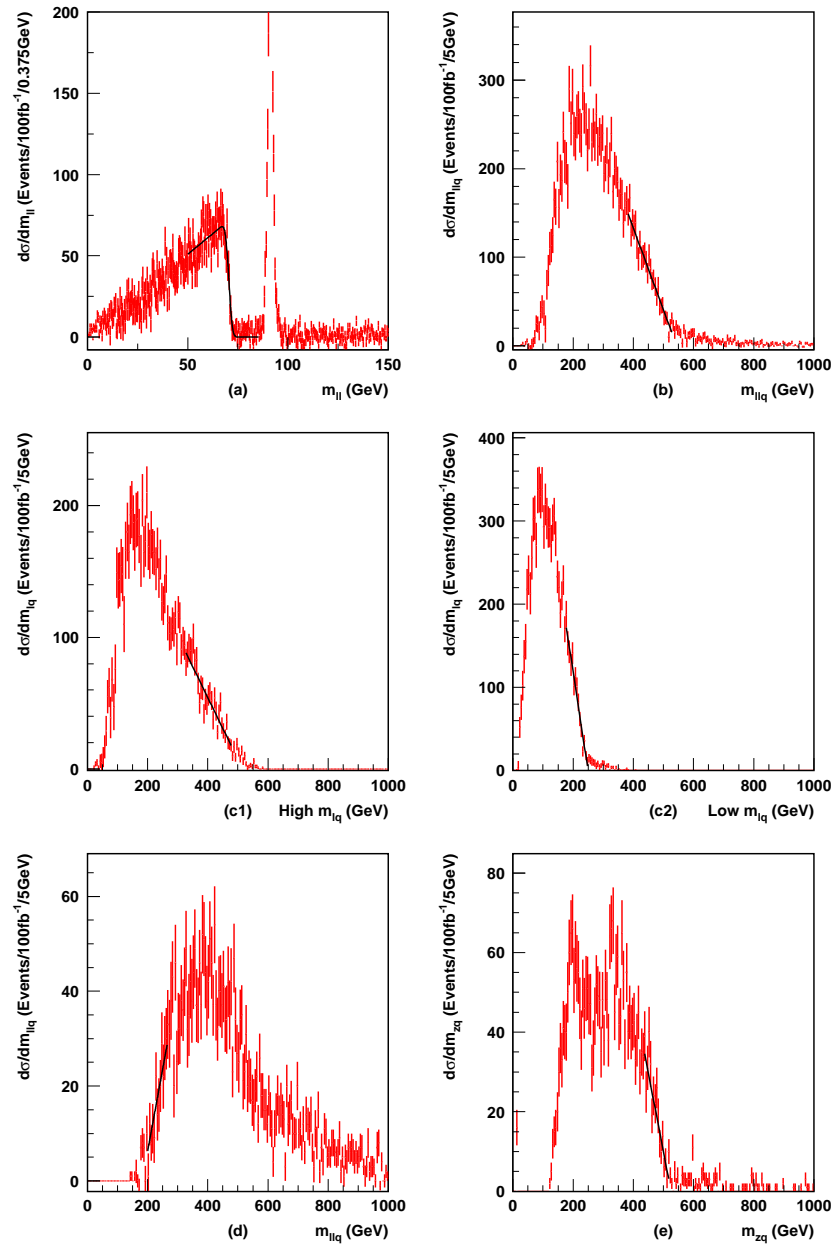
- interesting phenomenology [probably pathetic model]
 - LHC: R hadrons observable with mass measurement
 - ILC: anomalous weak-ino Yukawas accessible
- ⇒ some features always benefit future analyses

APPENDIX

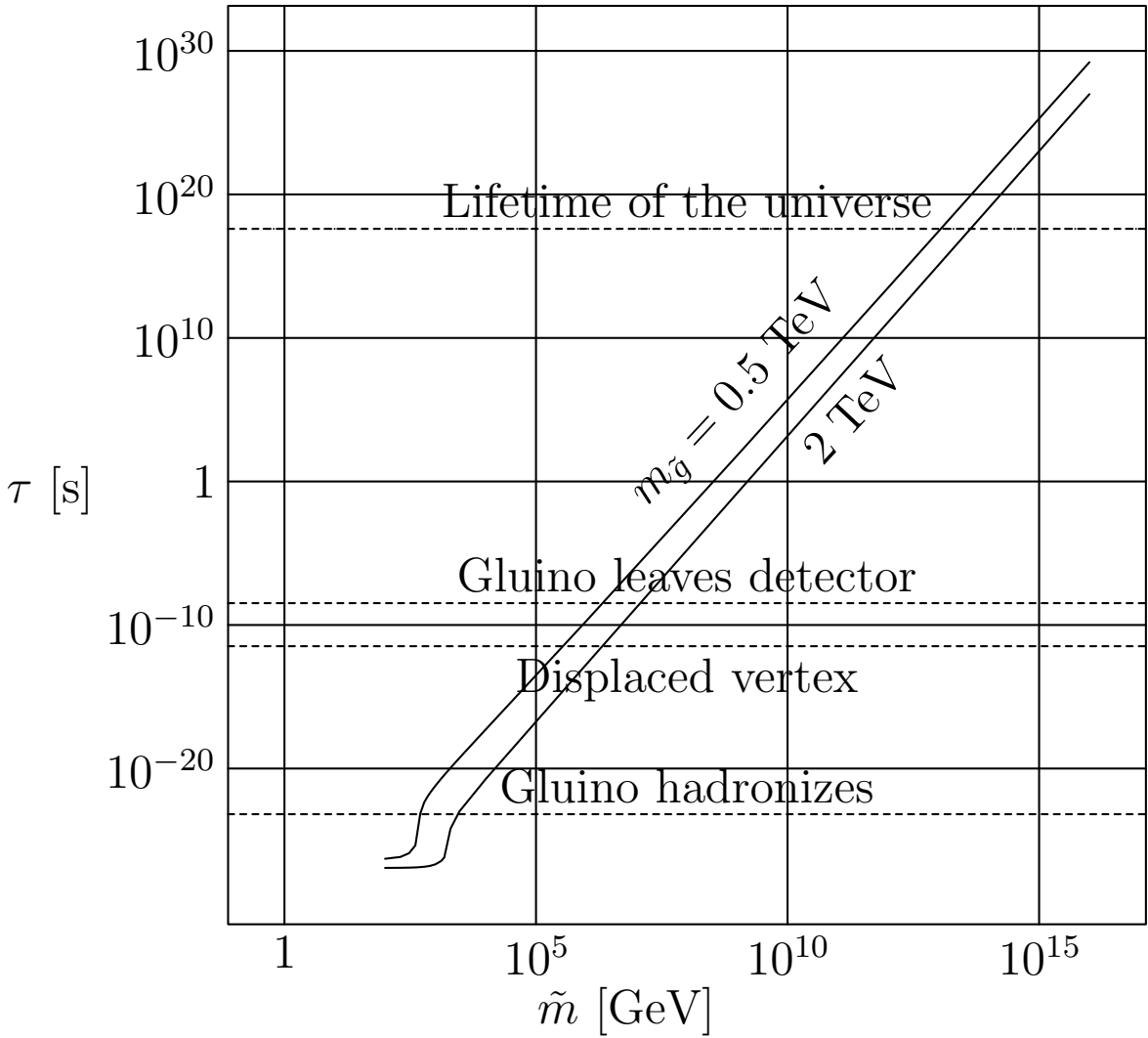


TESLA TDR

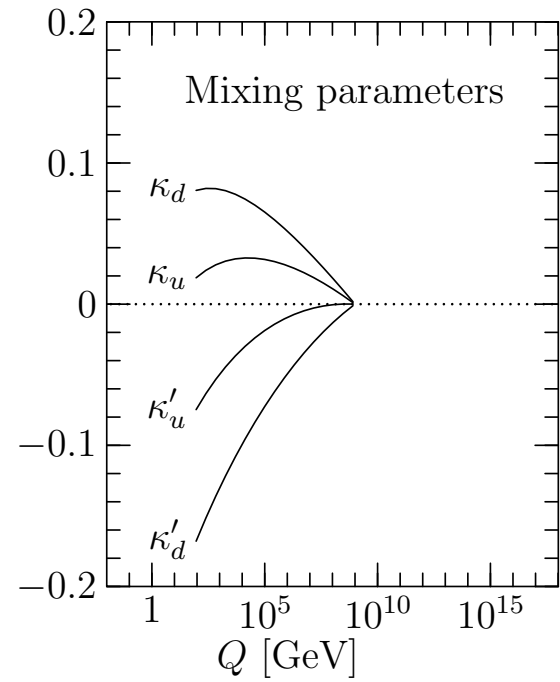
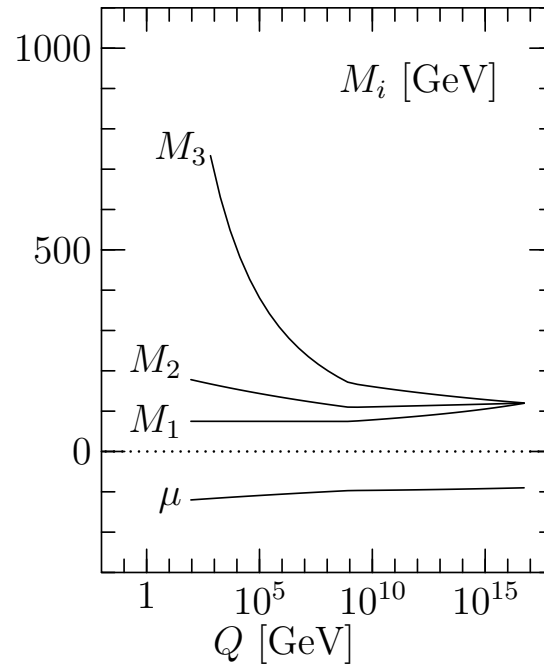
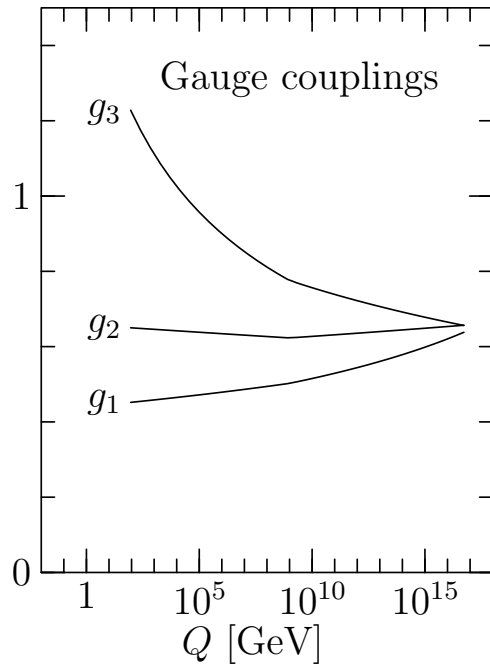
APPENDIX



APPENDIX



APPENDIX



Regularization of supersymmetric theory: $\overline{\text{MS}}$ scheme

- + SUSY-QCD next-to-leading order is mostly QCD [i.e. $\alpha_s, y_b, \text{pdf}, \dots$]
- $\overline{\text{MS}}$ breaks SUSY, but does not violate Ward identities [d.o.f. of gluinos; Jack, Jones]
- correct vertices using additional ‘renormalization’ [Martin, Vaughn]

example: $qqh, \tilde{q}\tilde{q}h, q\tilde{q}\tilde{h}$ vertices in naive $\overline{\text{MS}}$

$$(mg)_{qqh} \equiv m g_{\overline{\text{MS}}} \quad (mg)_{\tilde{q}\tilde{q}h} = (mg)_{qqh} \left(1 + \frac{\alpha_s C_F}{4\pi} \right) \quad (mg)_{q\tilde{q}\tilde{h}} = (mg)_{qqh} \left(1 + \frac{3\alpha_s C_F}{8\pi} \right)$$

- complete set of corrections purely technical complication [Stöckinger]

$\overline{\text{DR}}$ scheme

- + assume gauge invariance not an issue [Siegel]
- + $\overline{\text{DR}}$ scheme explicitly supersymmetric [only shift in space-time dimension]
- inconvenient, missing QCD infrastructure
- additional contribution to collinear factorization with massive final states [Beenakker...; van Neerven, Smith]

APPENDIX

Error on anomalous Yukawa couplings

	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}

Verdict

- LHC: stable R hadrons, charginos and neutralinos
- ILC: anomalous Yukawa couplings
- IceCube: one event per year for low-mass R hadrons [Hewett, Lillie, Mazip, Rizzo]
- Pierre Auger: few events for $\tilde{m} < 10^{11}$ GeV [Anchordoqui, Goldberg, Nunez]
- ⇒ split supersymmetry identifiable at combination of colliders
- ⇒ **what stays:** exotic heavy hadrons visible at LHC
 why did we ever assume MSSM-type ino Yukawas?