OBSERVING SUPERSYMMETRY AT THE LHC

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– TeV scale supersymmetry
– Inclusive + exclusive signals at LHC
– Measurements at LHC (+ILC)
– LHC pheno tools 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 $m_h \to \Lambda$

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

$\Rightarrow$ 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

- 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
  $\longrightarrow$ masses, couplings, phases...
  $\longrightarrow$ e.g. hierarchical spectrum? [Split SUSY]
- flavor physics and SUSY breaking
  $\longrightarrow$ CKM and lepton flavor?
- 2 Higgs doublet model
  $\longrightarrow$ μ parameter and SUSY breaking?

$\Rightarrow$ as many as exclusive analyses as possible

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

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

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

– stop and sbottom mixing in MSSM

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

– 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. $m(q = \text{TeV}, v, m_t)$?]
defi nitions of mass matrixes, mixing angles [e.g.$\tilde{t}_{L,R}$ up or down?]

SUSY Les Houches Accord [P. 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

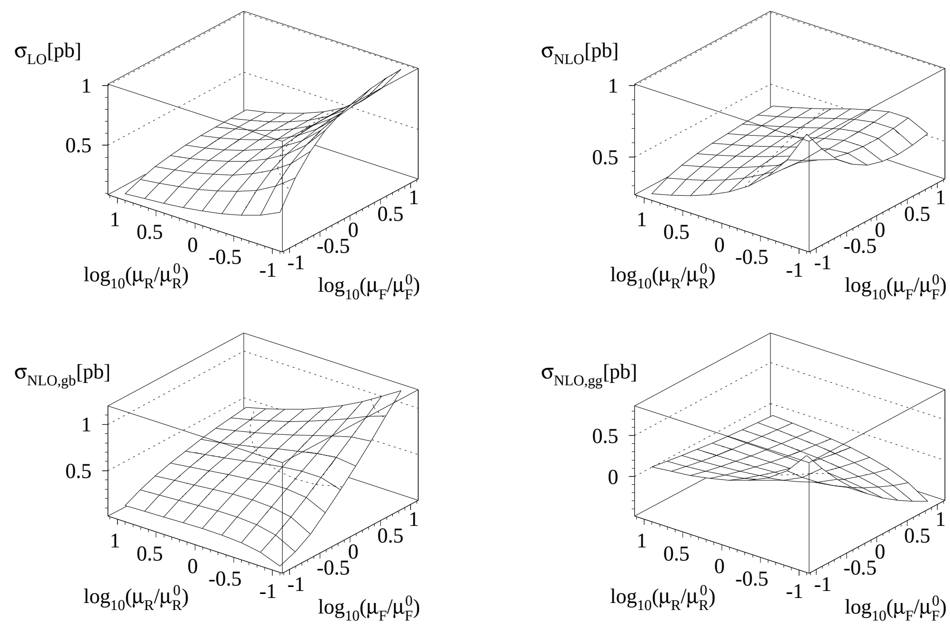
(3) parameter studies — MSSM Lagrangean, SUSY breaking

$\Rightarrow$ at least 10% precision to be matched at LHC [theorist's nightmare, yet unsolved]

Hadron collider observables with errors

- $\star$ masses from σ_{tot}
- $\star$ 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]

$\Rightarrow$ 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: $pp \to SS^*, tH^- ...$

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

SUSY signals included

– jets and $\not{E}_T$: $pp \to \tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$

– funny tops: $pp \to \tilde{t}_1\tilde{t}_1^*$

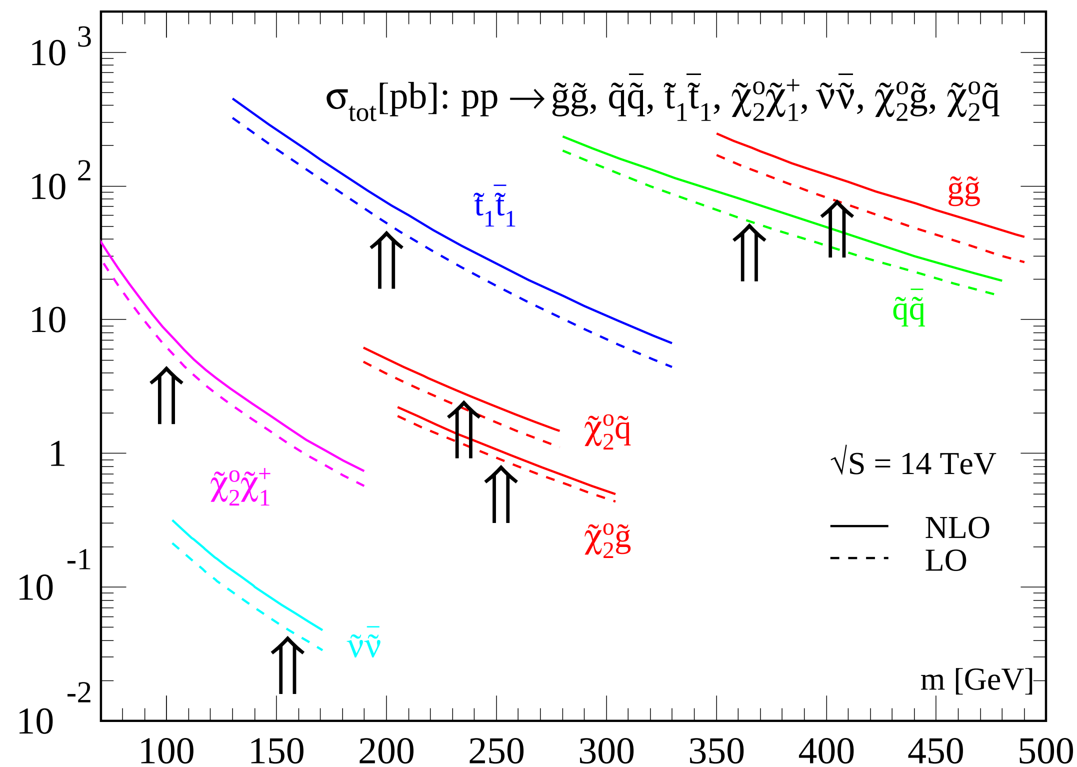
– like sign dileptons: $pp \to \tilde{g}\tilde{g}$

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

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

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

– bottoms and $\not{E}_T$: $pp \to \tilde{b}_1\tilde{b}_1^*$



SUSY SIGNALS AT LHC: 2B

Prospino2: NLO cross sections for Tevatron

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

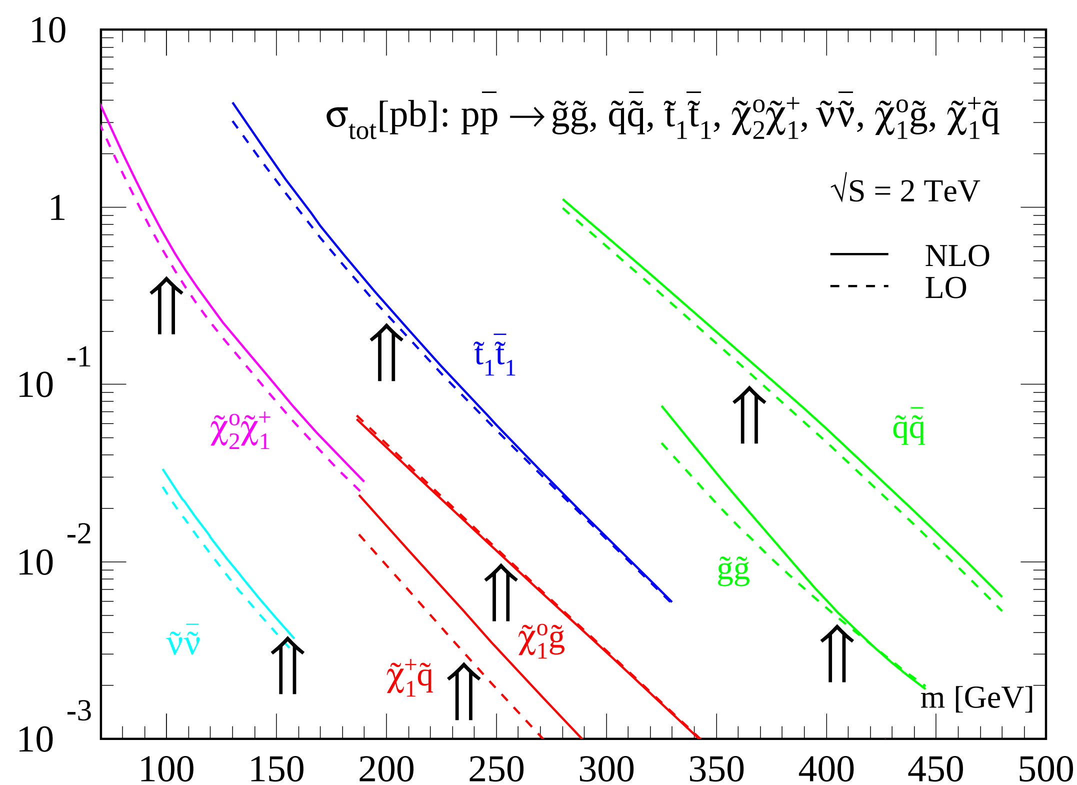
[thanks to: W. Beenakker, R.Höpker, M. Krämer, M. Spira, P. Zerwas]

SUSY signals included

- jets and $\not{E}_T$: $pp \to \tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$
- funny tops: $pp \to \tilde{t}_1\tilde{t}_1^*$
- like sign dileptons: $pp \to \tilde{g}\tilde{g}$

  $[\tilde{g} \to \tilde{u}\bar{u} \to \tilde{\chi}_1^+ d\bar{u}$ or c.c.]
- tri-leptons: $pp \to \tilde{\chi}_2^0\tilde{\chi}_1^-$

  $[\tilde{\chi}_2^0 \to \tilde{\ell}\bar{\ell} \to \tilde{\chi}_1^0\ell\bar{\ell}; \tilde{\chi}_1^- \to \tilde{\chi}_1^0\ell\bar{\nu}]$
- bottoms and $\not{E}_T$: $pp \to \tilde{b}_1\tilde{b}_1^*$

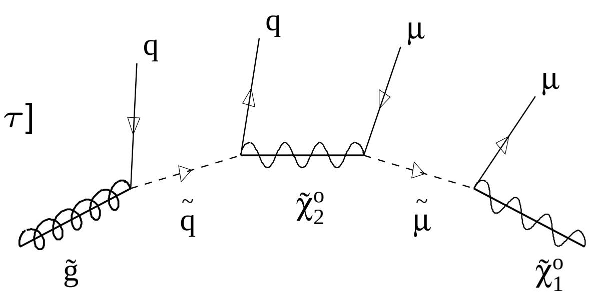


SUSY MEASUREMENTS AT LHC: 1

SUSY spectra from cascade decays

- decay $\tilde{g} \to \tilde{q}\bar{q} \to \tilde{\chi}_2^0 q\bar{q} \to \mu^+\mu^- q\bar{q}\tilde{\chi}_1^0$ [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?

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



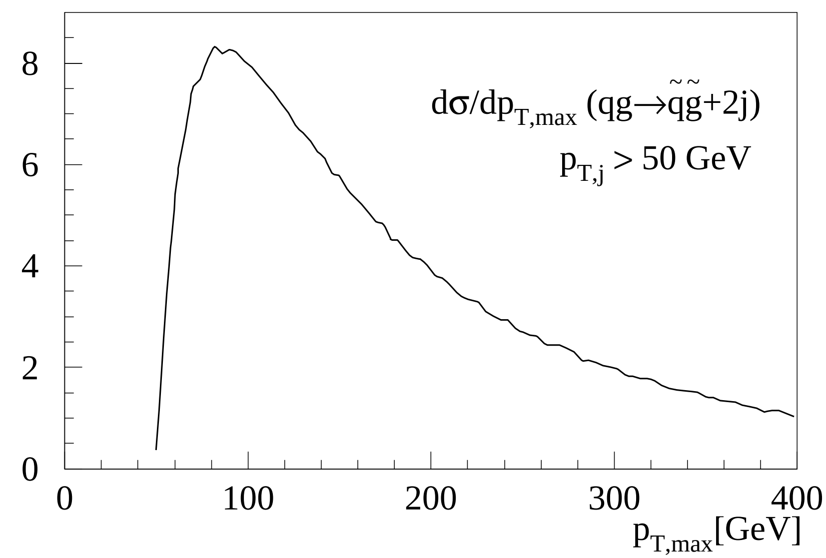
$\Rightarrow$ detector resolution, calibration, systematic errors? [Polesello. Gjelsten, Miller, Osland]

Side remark: problem in decay studies

- typical cuts: $p_{T,j}$>150,100,50,50 GeV
- (a) cuts on $p_{T,j}$ hierarchy?
  (b) combinatorics through jet radiation?

$\Rightarrow$ matrix elements for SUSY + hard jets

$\Rightarrow$ Smadgraph [Hagiwara, Kanzaki, TP, Rainwater, Stelzer]



SUSY Measurements at LHC: 2

Theorist's point of view

– measured masses, cross sections, decays secondary

– parameters in SUSY Lagrangean from measurements

$\Rightarrow$ 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		Δ at LHC		Δ at ILC		Δ at LHC+ILC	
	SPS1a	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

$\Rightarrow$ no one best 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

$\Rightarrow$ LHC+ILC with no assumptions

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

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

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

What's new for phenomenology?

– no squarks, sleptons for colliders, astro-particle physics [Giudice, Romanino; Pierce]

– no cascade decays

– stable (hadronizing) gluinos [$\tau \sim \tilde{m}^{-4} \sim 6.5$s for $\tilde{m} = 10^9$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 ino Yukawa couplings by $\lesssim 20\%$]

Collider tests

(1) Is it supersymmetry?

(2) Is it split?

SPLIT SUSY AT COLLIDERS: 2

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

– neutralinos, charginos like in MSSM, poor precision [Prospino2]

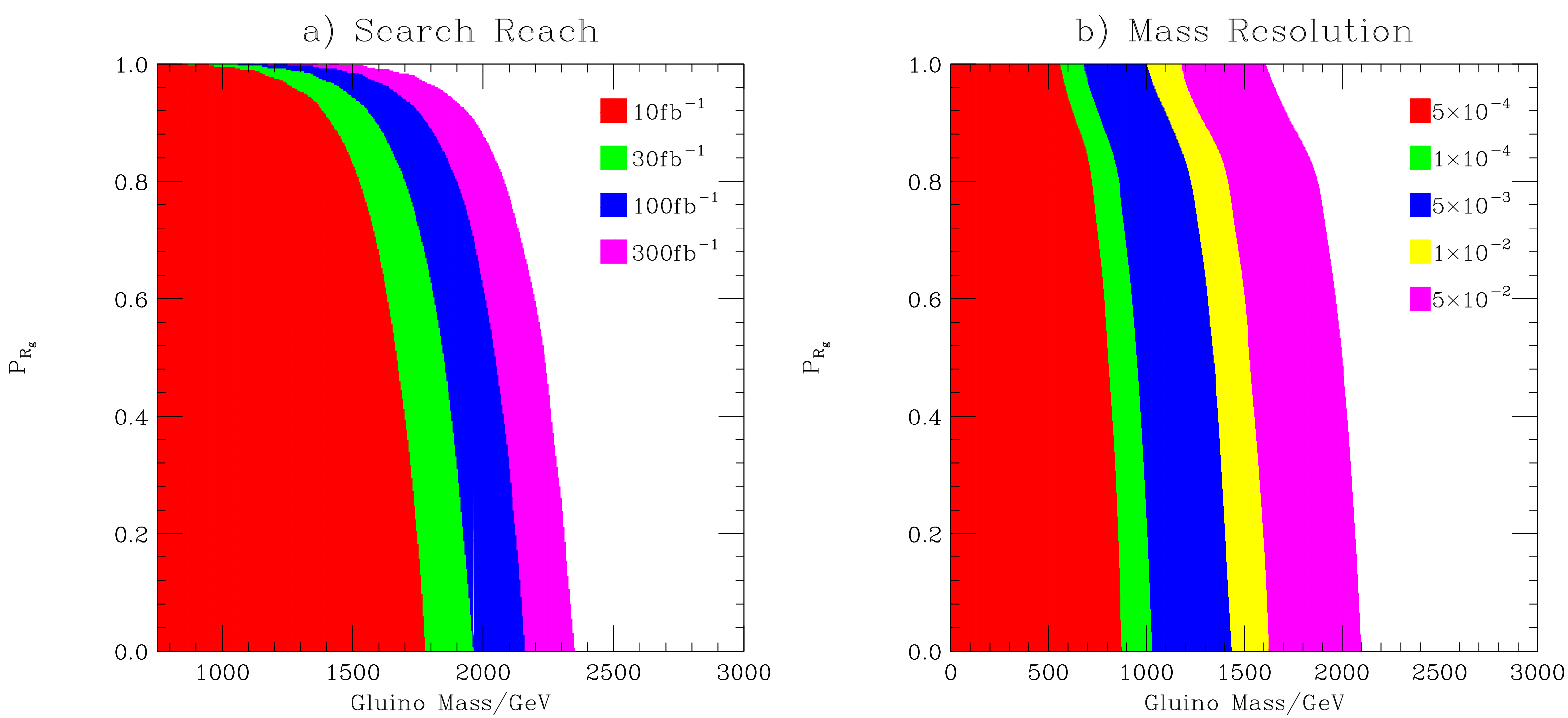
– many gluinos pair-produced [$\sigma \gtrsim$ 1 pb, Prospino2]

– gluinonium $\tilde{g}\tilde{g} \to jj$ [Kühn, Ono; Goldman, Haber; CMS; reach $\sim$ TeV?]

– neutral R hadrons missing $\to$ missing energy signal

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

– mass measurement through time of flight tracker–muon chamber



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 [gs_β, gc_β, $g' s_\beta$, $g' c_\beta$]

$\Rightarrow$ (1) direct measurements of $\chi\chi h$ [Whizard, Smadgraph $\to$ distinctly unpromising]

(2) indirect determination of mass matrices [poor man's Sfitter]

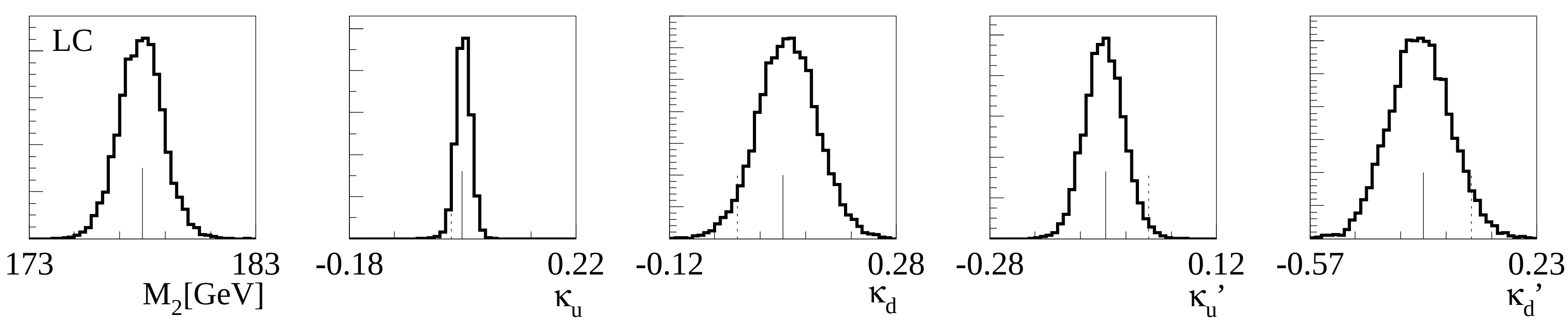
Indirect determination

– errors crucial [0.5 % error on masses at ILC]

– 10^4 smeared pseudo-measurements to extract parameters from

$\Rightarrow$ analytic inversion impossible, fit instead

$\Rightarrow$ errors from distribution of 10^4 best fits



SPLIT SUSY AT COLLIDERS: 4

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 $\widetilde{m} < 10^{11}$ 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?

OUTLOOK

Theory effort for SUSY at the LHC well advanced

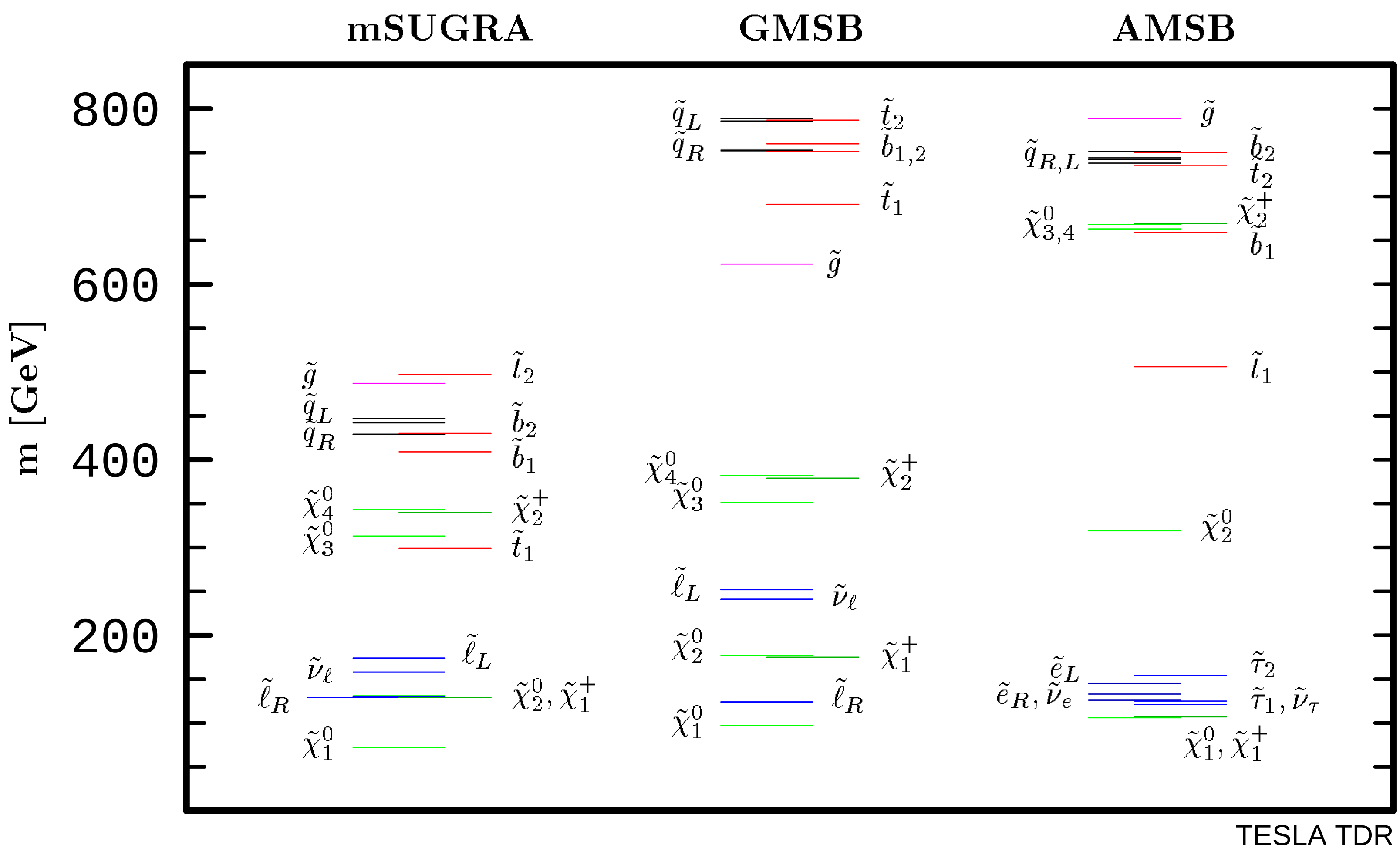
- inclusive searches plus cascade reconstruction with great promise
- total cross sections available to NLO [Propino2]
- automatic matrix element generators being tested [Smadgraph, Whizard, Sherpa]
- parameter extraction tools in use for LHC–ILC studies [Sfi tter, Fittino]

⇒ errors will be crucial at LHC

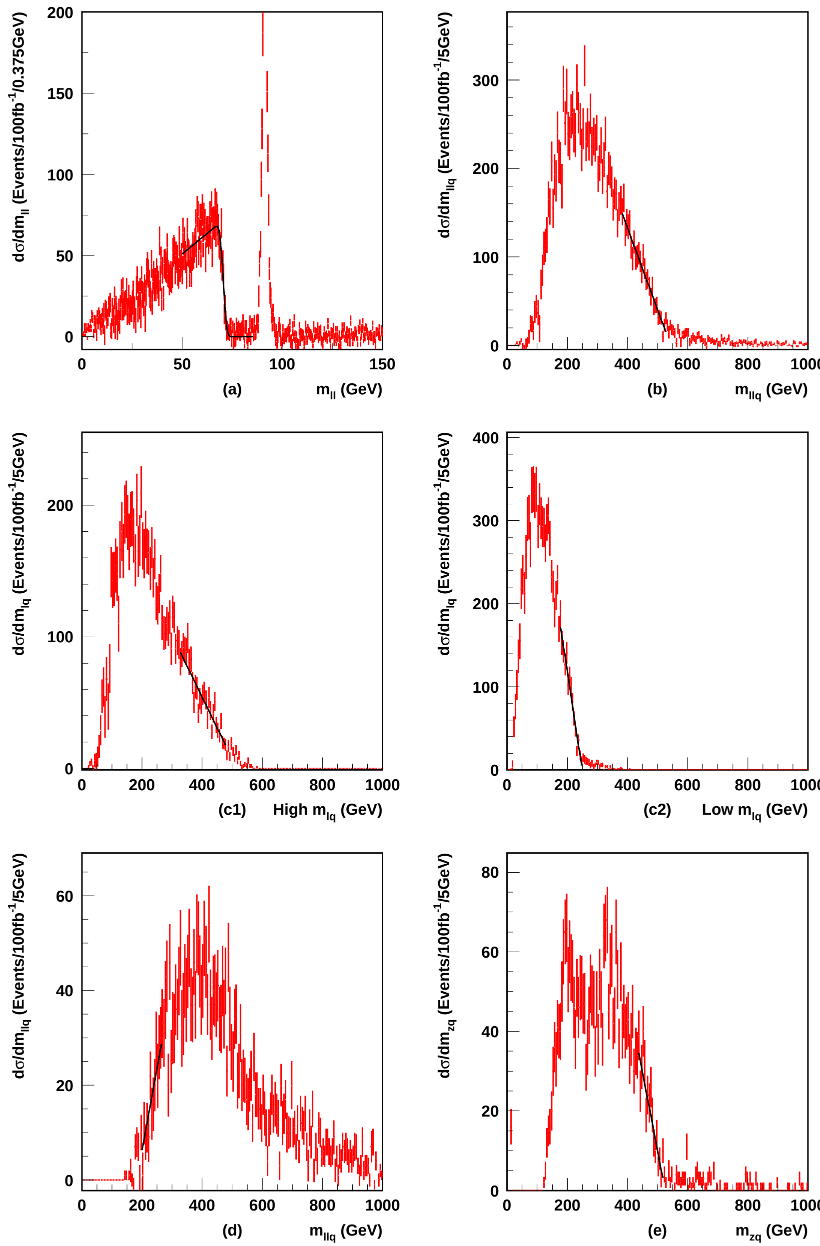
Showcase: Split Supersymmetry

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

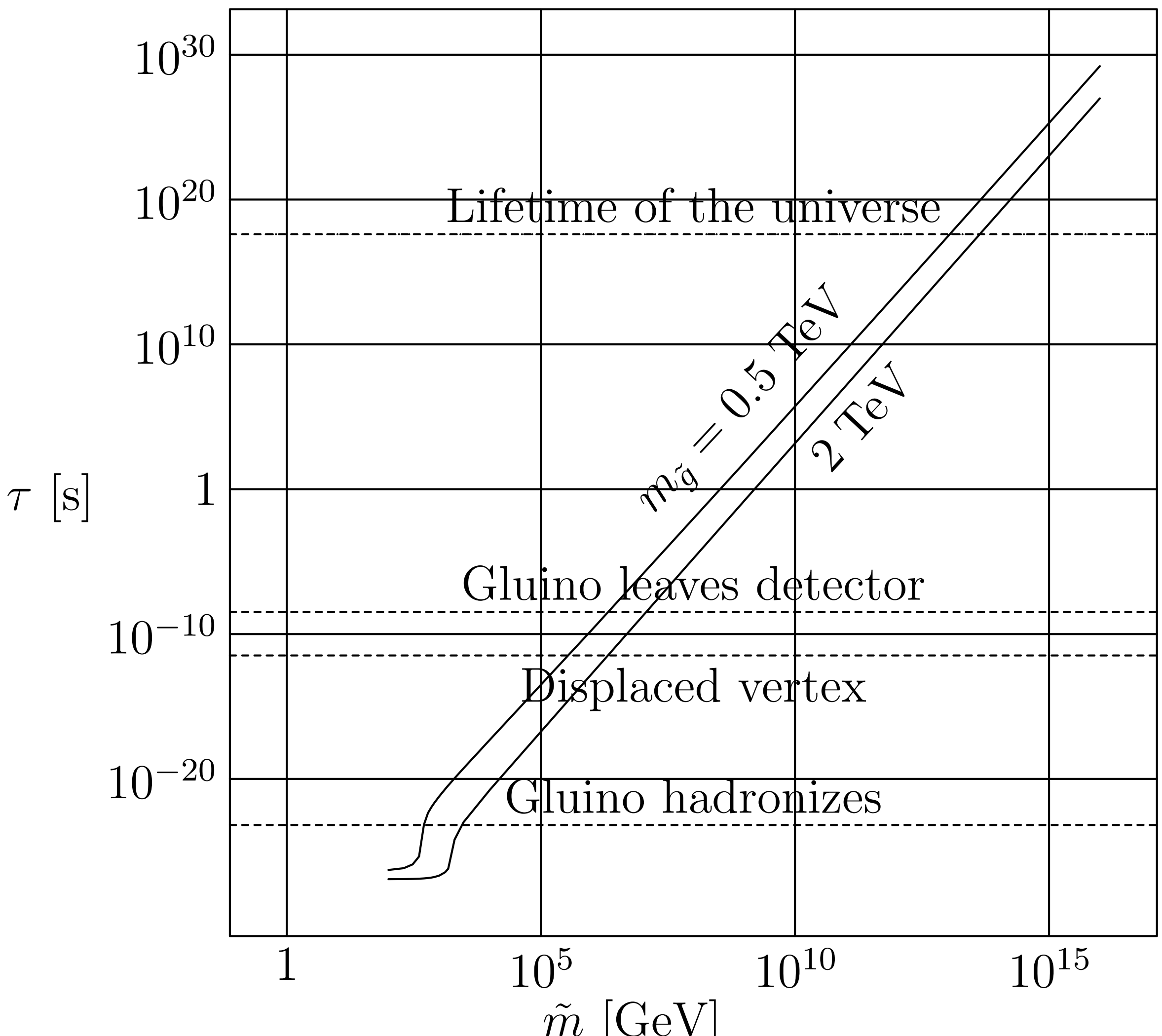
⇒ some features always benefit future analyses


mSUGRA
GMSB
AMSB
m [GeV]
800
600
400
200
TESLA TDR

APPENDIX

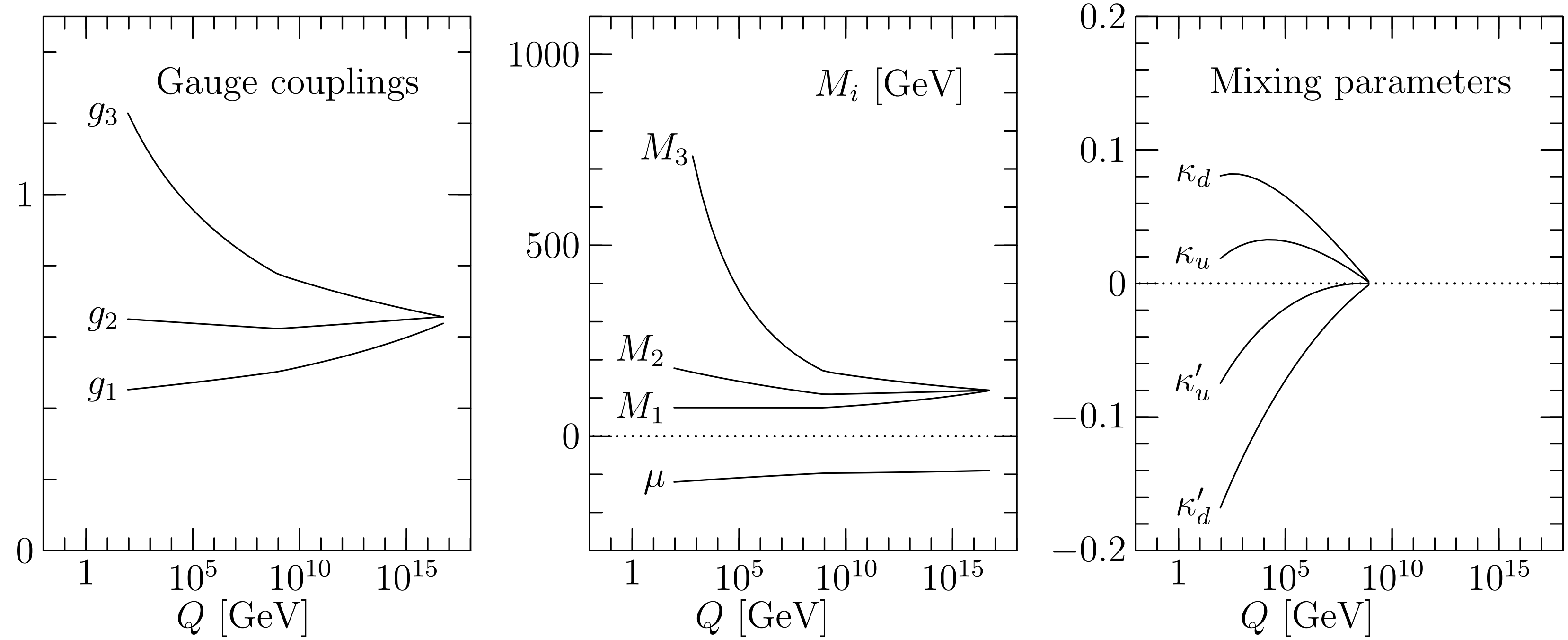


dσ/dm_ll (Events/100fb^-1/0.375GeV)
200
150
100
50
0
0
50
100
150
(a)
m_ll (GeV)
dσ/dm_llq (Events/100fb^-1/5GeV)
300
200
100
0
0
200
400
600
800
1000
(b)
m_llq (GeV)
dσ/dm_lq (Events/100fb^-1/5GeV)
200
100
0
(c1)
High m_lq (GeV)
dσ/dm_lq (Events/100fb^-1/5GeV)
400
300
200
100
0
(c2)
Low m_lq (GeV)
dσ/dm_llq (Events/100fb^-1/5GeV)
60
40
20
0
(d)
m_llq (GeV)
dσ/dm_zq (Events/100fb^-1/5GeV)
80
60
40
20
0
(e)
m_zq (GeV)



10^{30}
10^{20}
10^{10}
1
10^{-10}
10^{-20}
τ [s]
Lifetime of the universe
$m_{\tilde{g}} = 0.5$ TeV
2 TeV
Gluino leaves detector
Displaced vertex
Gluino hadronizes
1
10^{5}
10^{10}
10^{15}
$\tilde{m}$ [GeV]

APPENDIX



Gauge couplings
g_3
g_2
g_1
1
0
1
10^5
10^{10}
10^{15}
Q [GeV]
M_i [GeV]
1000
500
0
M_3
M_2
M_1
μ
1
10^5
10^{10}
10^{15}
Q [GeV]
Mixing parameters
0.2
0.1
0
−0.1
−0.2
κ_d
κ_u
κ'_u
κ'_d
1
10^5
10^{10}
10^{15}
Q [GeV]

APPENDIX

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

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

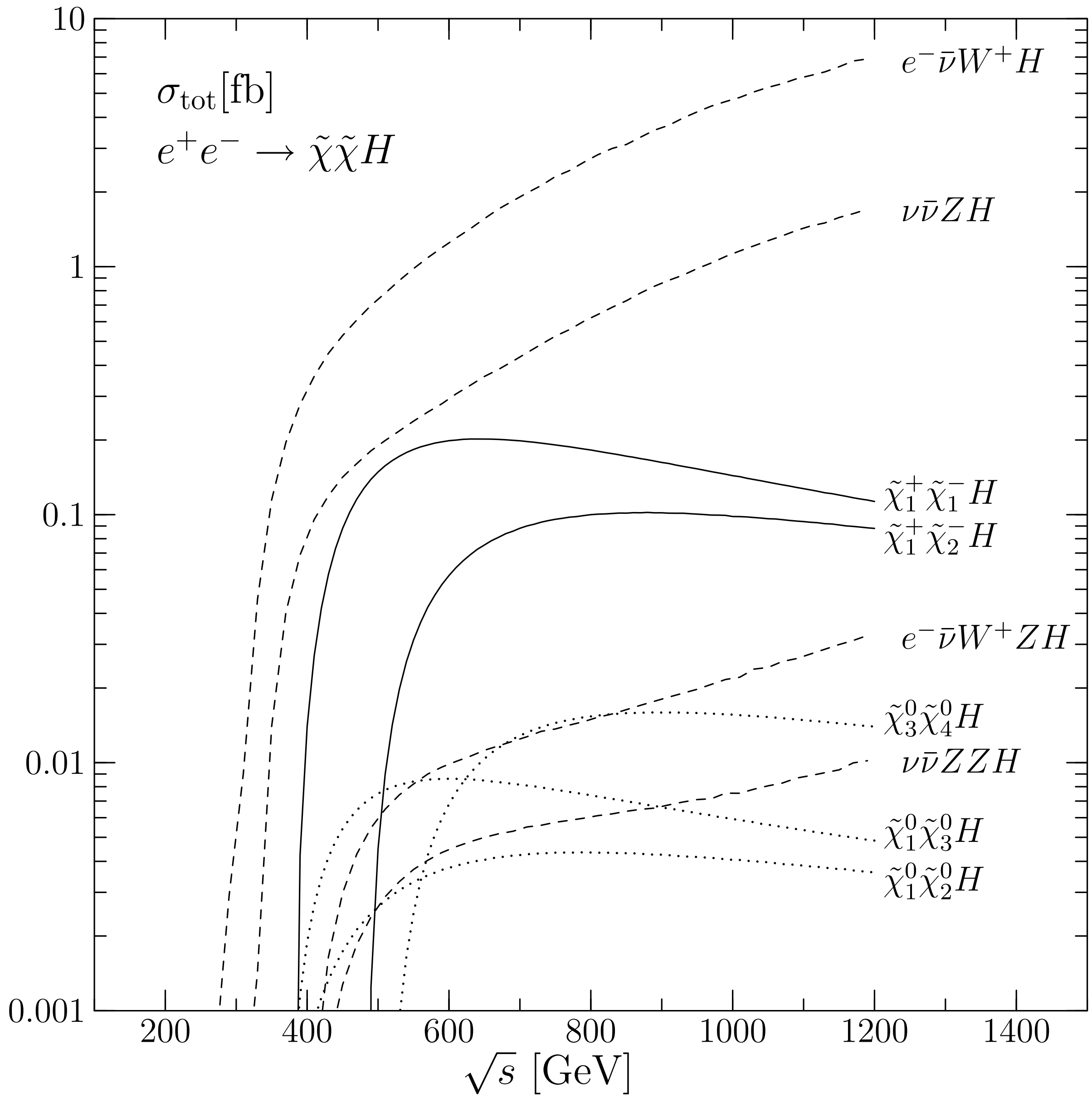
example: qqh, $\tilde{q}\tilde{q}h$, $q\tilde{q}\tilde{h}$ vertices in naive $\overline{\text{MS}}$

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

→ complete set of corrections purely technical complication [Stöckinger]

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

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



$\sigma_{\rm tot}$[fb]
$e^+e^- \to \tilde\chi\tilde\chi H$
$e^-\bar\nu W^+ H$
$\nu\bar\nu ZH$
$\tilde\chi_1^+\tilde\chi_1^- H$
$\tilde\chi_1^+\tilde\chi_2^- H$
$e^-\bar\nu W^+ ZH$
$\tilde\chi_3^0\tilde\chi_4^0 H$
$\nu\bar\nu ZZH$
$\tilde\chi_1^0\tilde\chi_3^0 H$
$\tilde\chi_1^0\tilde\chi_2^0 H$
10
1
0.1
0.01
0.001
200
400
600
800
1000
1200
1400
$\sqrt{s}$ [GeV]