

# MEASURING THE MSSM LAGRANGEAN

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- TeV scale supersymmetry
- Inclusive + exclusive signals at LHC: Prospino2, Smadgraph
- Measurements at LHC (+ILC): Sfitter
- 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  $m_h \rightarrow \Lambda$
- ⇒ 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
    - $\mu$  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	$G_\mu$	1	n-2	
→ gluino	$\tilde{g}$	1/2	2	Majorana
gauge bosons	$\gamma, Z$	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**:  $m_{\tilde{g}, \tilde{W}, \tilde{g}}/m_{1/2} \sim 0.4, 0.8, 2.6$   
 $m_{\tilde{\ell}, \tilde{q}}/m_{1/2} \sim 0.7, 2.5$  [ $m_0 \ll m_{1/2}$ ]

[mass and coupling unification independent]

# TeV SCALE SUPERSYMMETRY: 4

## 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 [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]

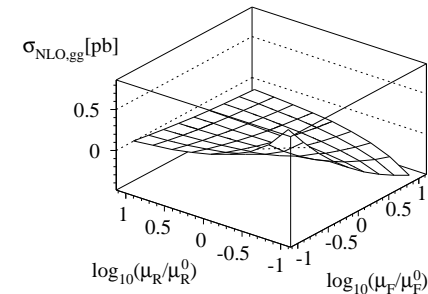
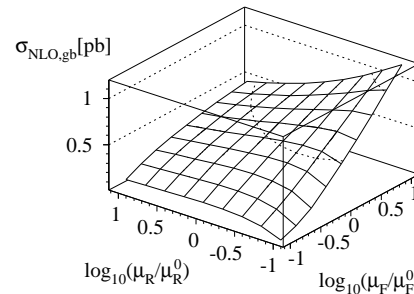
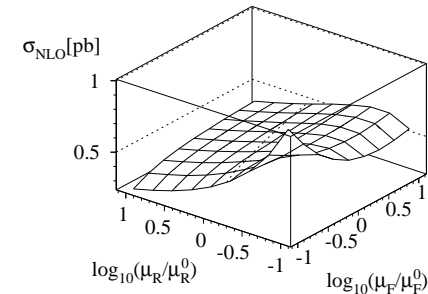
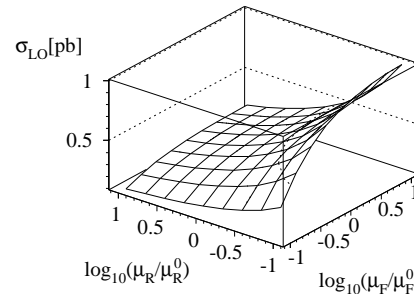
# SUSY SIGNALS AT LHC: 1

## 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
- ⇒ at least 10% precision to be matched at LHC [theorist's nightmare, yet unsolved]

## Hadron collider observables with errors

- ★ masses from  $\sigma_{\text{tot}}$
  - ★ branching fractions from  $\sigma_{\text{tot}}$
  - 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: 2

## Prospino2: NLO cross sections for Tevatron and 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

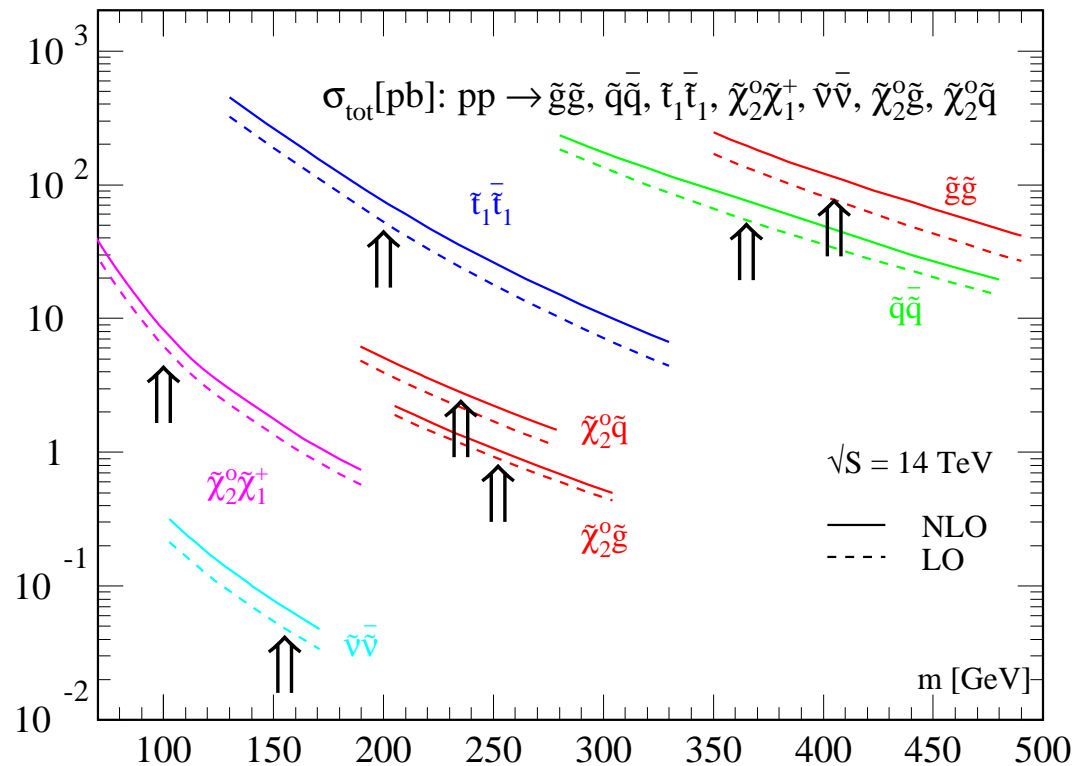
- jets and  $\cancel{E}_T$ :  $pp \rightarrow \tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$
- funny tops:  $pp \rightarrow \tilde{t}_1\tilde{t}_1^*$
- like sign dileptons:  $pp \rightarrow \tilde{g}\tilde{g}$

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

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

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

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



# SUSY SIGNALS AT LHC: 3

## 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

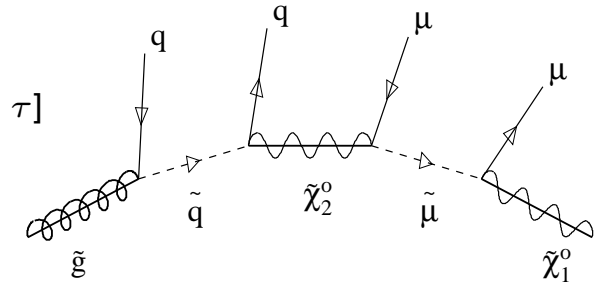
- + assume gauge invariance not an issue [Siegel]
- +  $\overline{\text{DR}}$  scheme explicitly supersymmetric [only shift in space-time dimension]
- inconvenient, missing QCD infrastructure
- additional contribution to collinear factorization with massive final states [Beenakker...; van Neerven, Smith]



# 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  $\tau$ ]
- cross sections some 100 pb [more than  $3 \times 10^5$  events]
- thresholds & edges [Hinchliffe, Paige...; Cambridge ex-th]  
critical: enough thresholds and edges available?



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

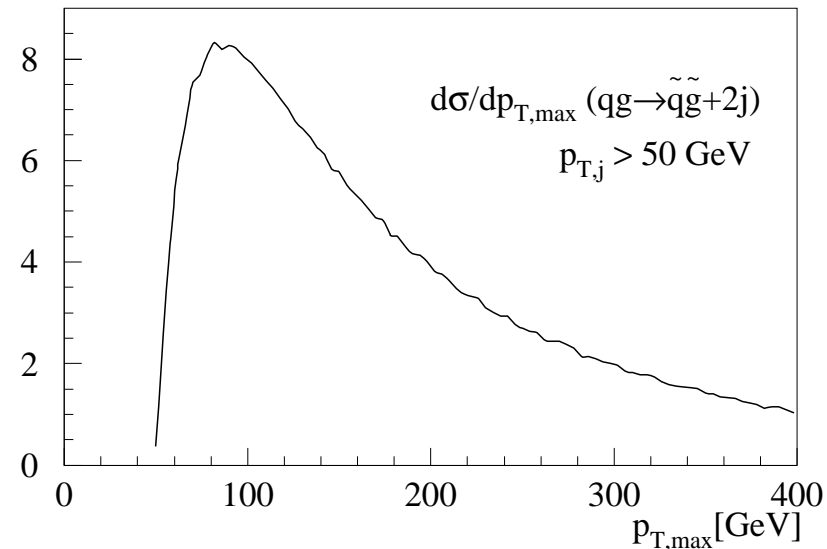
⇒ detector resolution, calibration, systematic errors? [Polesello, Gjelsten, Miller, Osland]

## 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?

⇒ matrix elements for SUSY + hard jets

⇒ **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
- ⇒ 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	$\Delta$ at LHC		$\Delta$ at ILC		$\Delta$ 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	$\Delta$	Softsusy	$\Delta$
$m_0$	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

- ⇒ no one best way to estimate theory errors

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

# 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
$\tan\beta$	$10.22\pm 9.1$	$10.26\pm 0.3$	$10.06\pm 0.2$	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
$M_{\tilde{q}_{3L}}$	$498.3\pm 110$	$497.6\pm 4.4$	$521.9\pm 39$	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
$A_\tau$	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, 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  $\lesssim 20\%$ ]

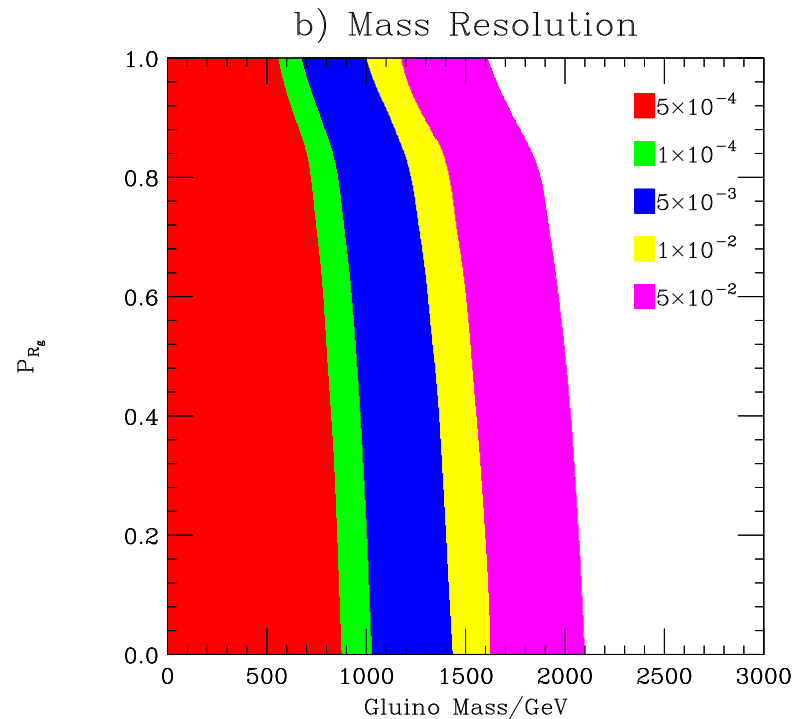
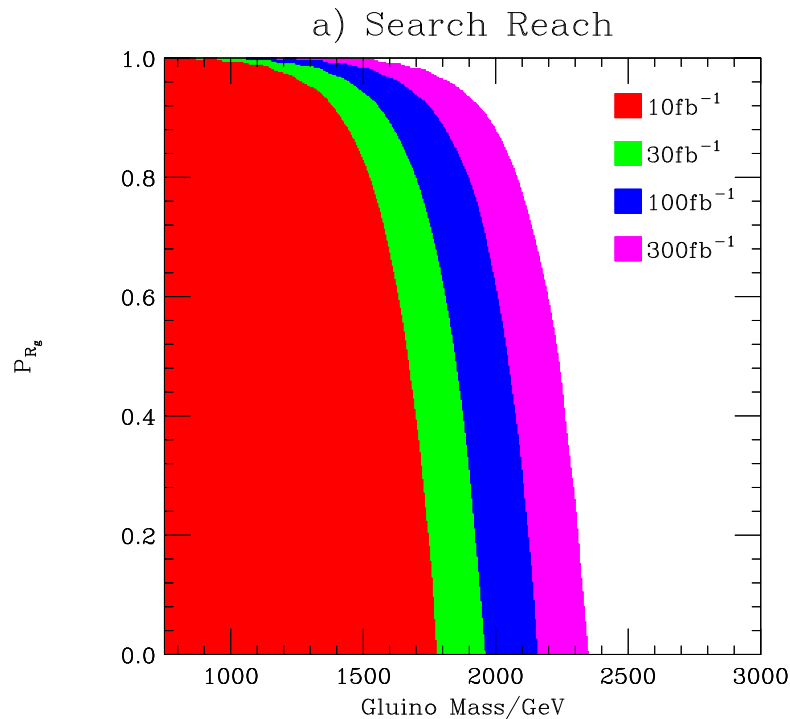
## Collider tests

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

# SPLIT SUSY AT COLLIDERS: 2

## 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  $\tilde{g}\tilde{g} \rightarrow jj$  [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



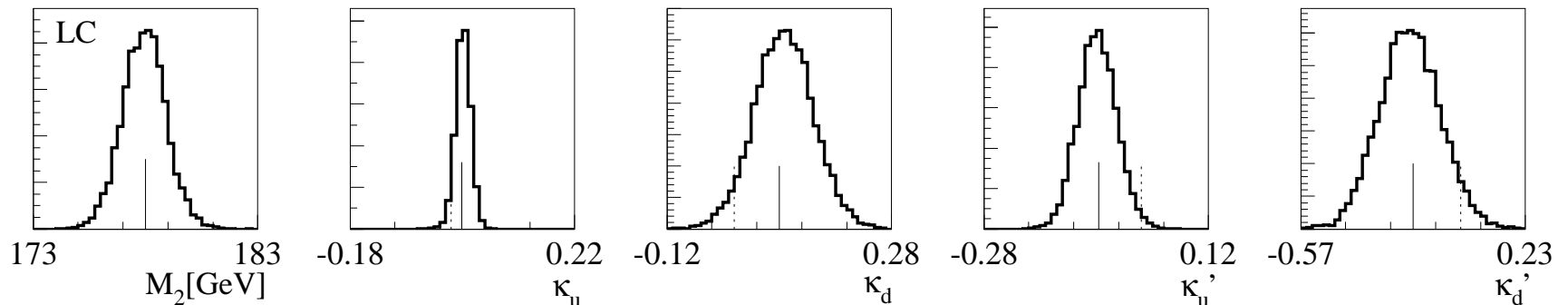
# SPLIT SUSY AT COLLIDERS: 3

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

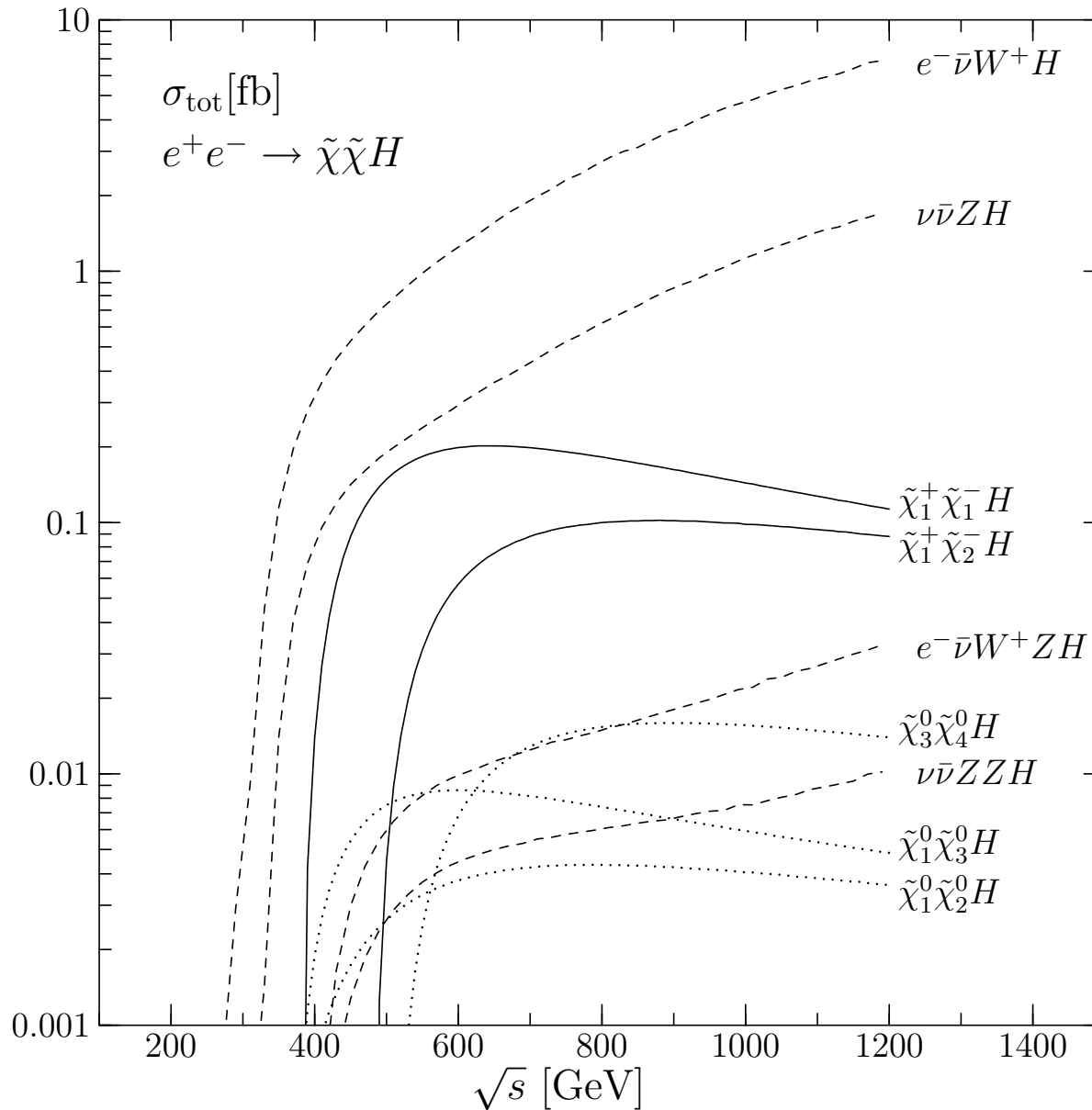
- gluinos not produced because of decoupled squarks
  - neutralino–chargino sector analysis as usual [robust towards decay channels]
  - anomalous Yukawas  $\equiv$  off-diagonal mass matrix entries [ $g_{s\beta}, g_{c\beta}, g'_{s\beta}, g'_{c\beta}$ ]
- $\Rightarrow$  (1) direct measurements of  $\chi\chi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

## 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: 3B



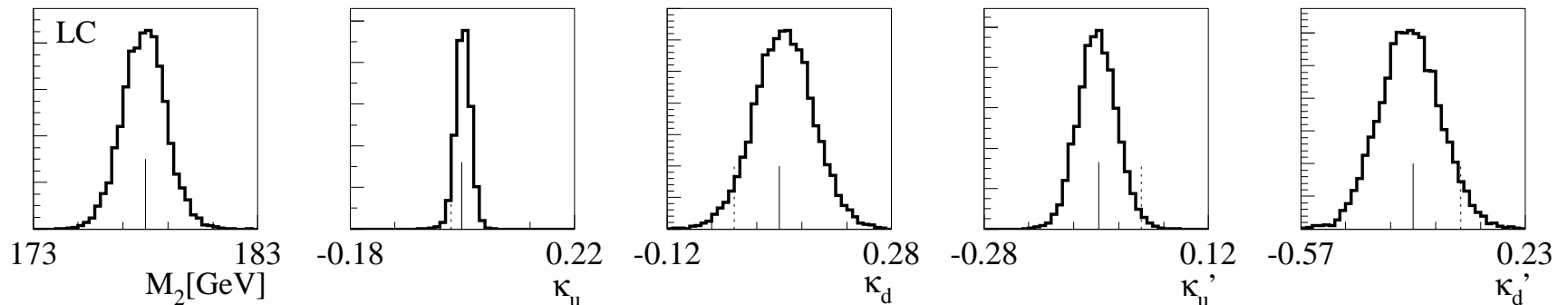
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# SPLIT SUSY AT COLLIDERS: 4

## Error on anomalous Yukawa couplings

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

## 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?

# OUTLOOK

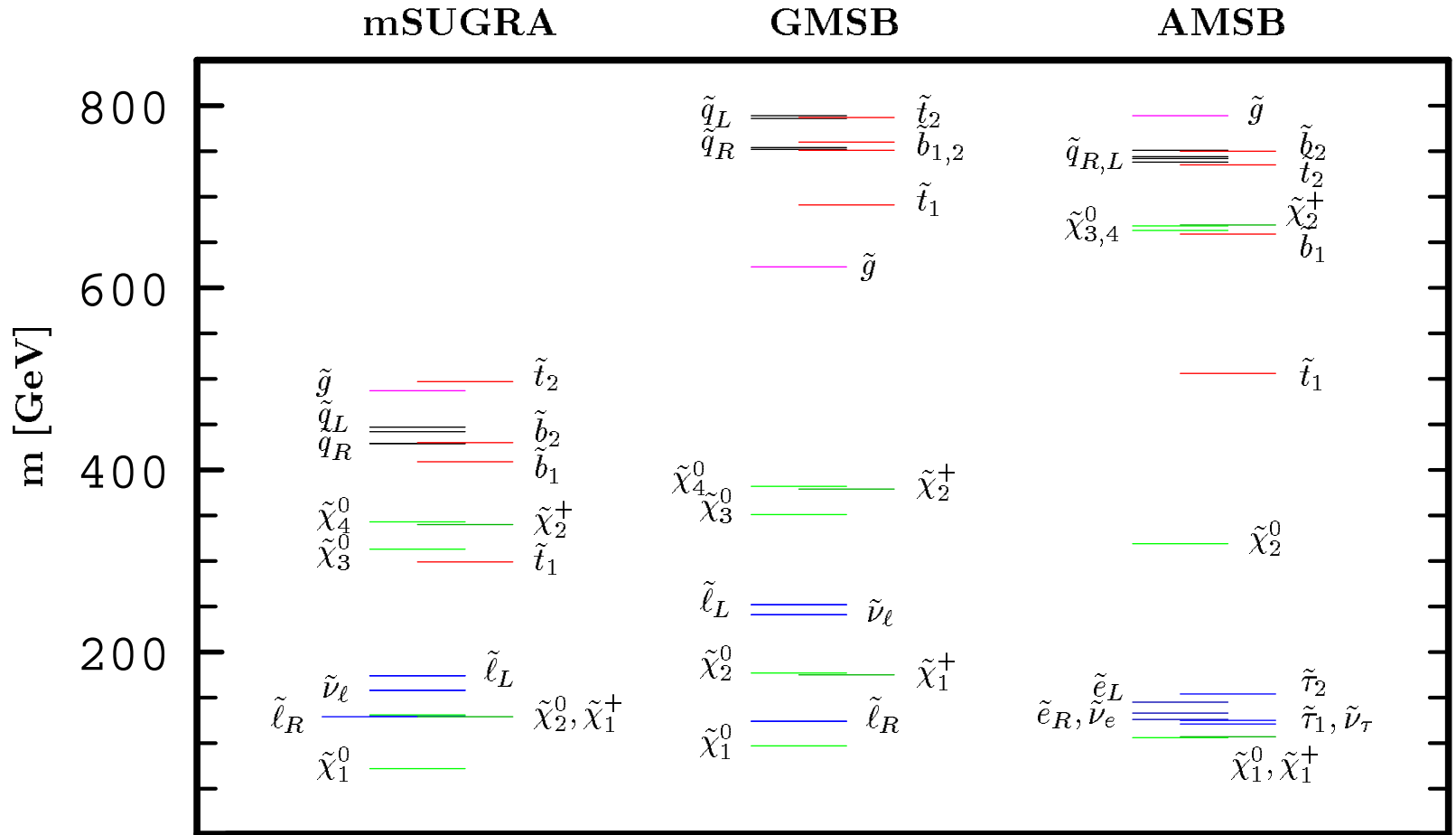
## Theory effort for SUSY at the LHC well advanced

- 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 [Sfitter, Fittino]
- ⇒ errors will be crucial at LHC

## Showcase: Split Supersymmetry

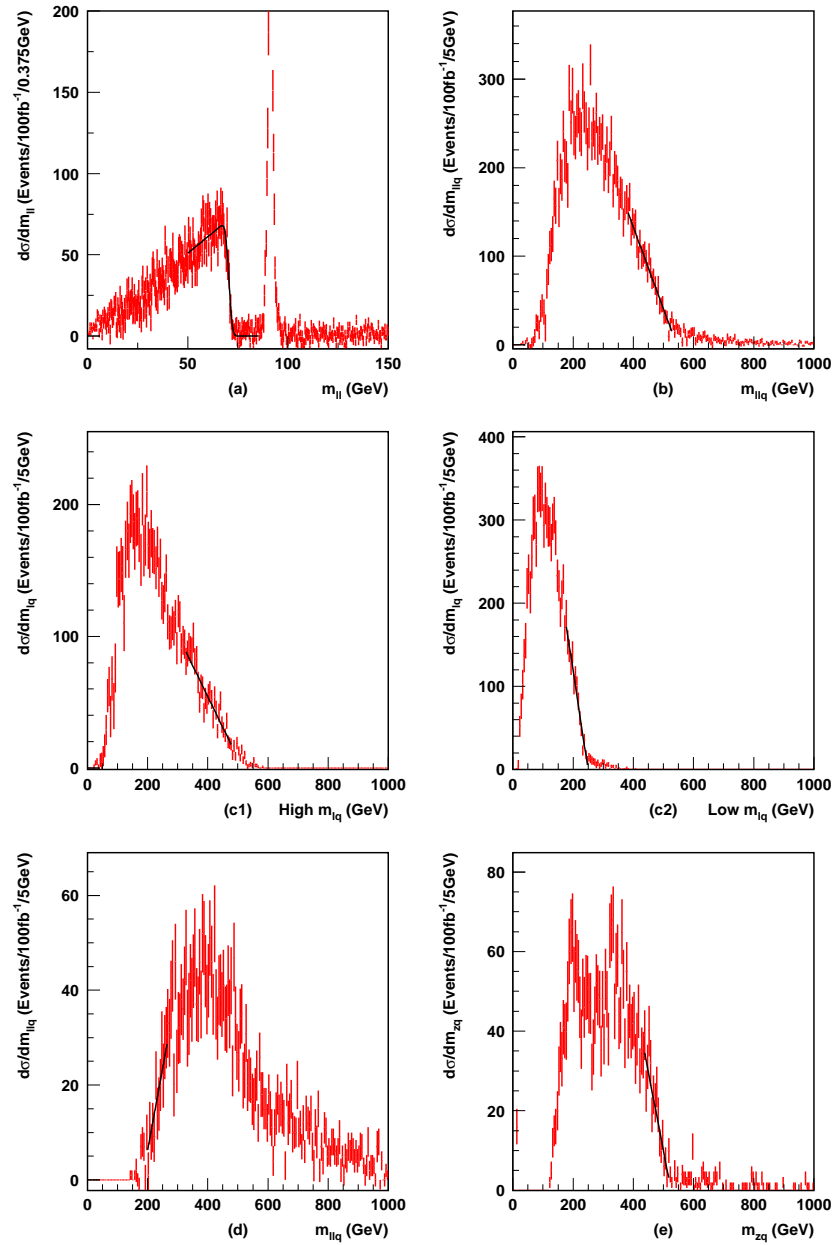
- interesting phenomenology
  - LHC: R hadrons observable with mass measurement
  - ILC: anomalous weak-ino Yukawas accessible
- ⇒ some features always benefit future analyses

# APPENDIX: 1

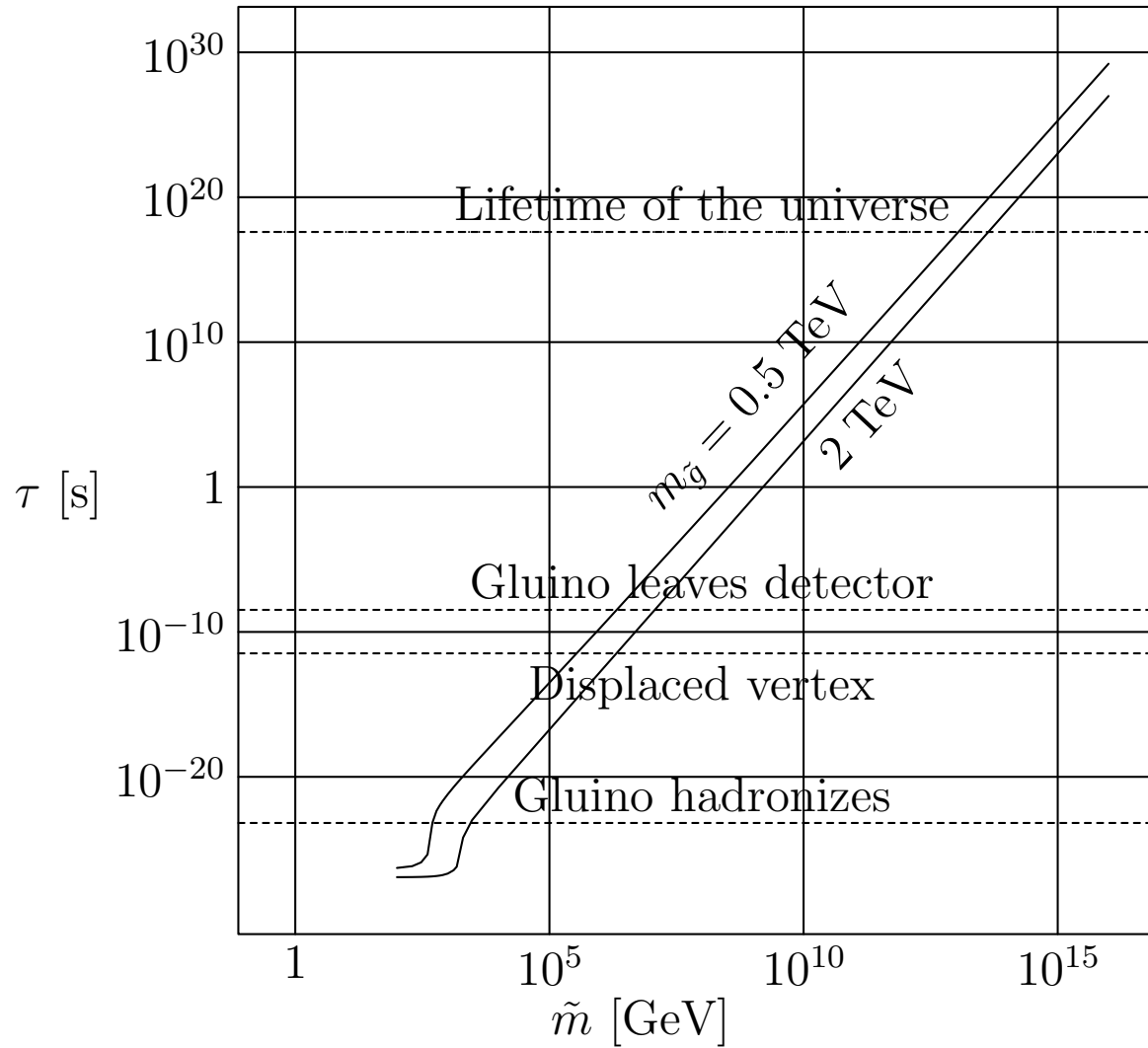


TESLA TDR

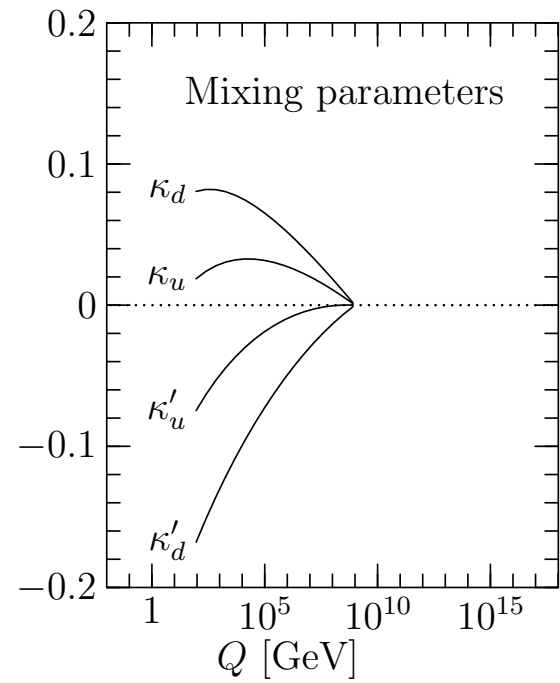
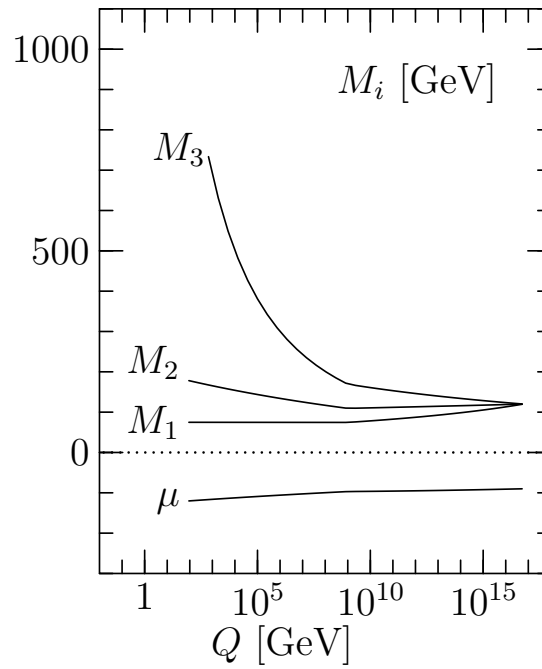
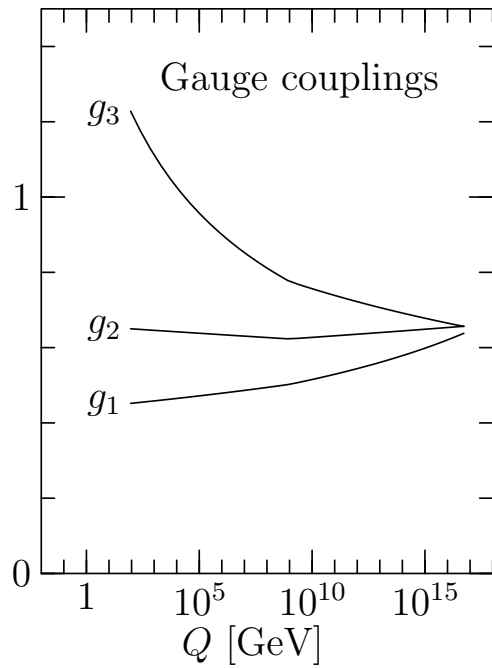
# APPENDIX: 2



# APPENDIX: 3



# APPENDIX: 4



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## SUSY signals included

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- funny tops:  $pp \rightarrow \tilde{t}_1\tilde{t}_1^*$
- like sign dileptons:  $pp \rightarrow \tilde{g}\tilde{g}$   
 $[\tilde{g} \rightarrow \tilde{u}\tilde{u} \rightarrow \tilde{\chi}_1^+ d\tilde{u} \text{ or c.c.}]$
- tri-leptons:  $pp \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^-$   
 $[\tilde{\chi}_2^0 \rightarrow \tilde{\ell}\tilde{\ell} \rightarrow \tilde{\chi}_1^0\tilde{\ell}\tilde{\ell}; \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\tilde{\ell}\tilde{\nu}]$
- bottoms and  $E_T$ :  $pp \rightarrow \tilde{b}_1\tilde{b}_1^*$

