Preparations for CLIC CDR
Chapter 2: Physics Potential

# Supersymmetry

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CERN, 11 Jan 2011

# Introduction

- Supersymmetry is one of the best-motivated BSM theories
  - unified description of fermions and bosons, matter and force particles
  - solution to the hierarchy problem
  - unification of gauge couplings
  - radiative electroweak symmetry breaking
  - light Higgs boson (favoured by EWPO)
  - dark matter candidate
- We expect SUSY at the TeV scale, within the reach of the LHC.
  - discovery and measurement of some states,
    typically gluinos, squarks, light gauginos (light sleptons?)
- To really test SUSY, we need precision measurements.
  - strong point of LC: electroweak states (sleptons and EW-inos)
    but more generally almost anything that is within kinematic reach.

# Need precision

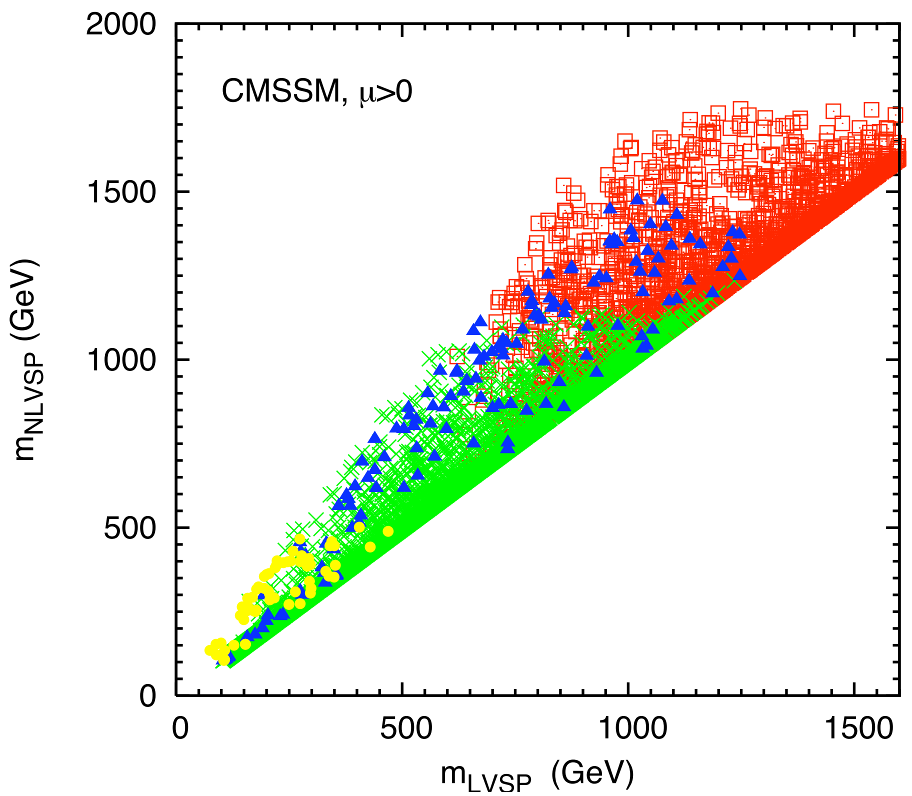
- If weak-scale SUSY is realized, experiments at the LHC will discover some of the sparticles and provide first measurements of their masses and couplings; typical precision O(10%).

- However, to explore the theory fully, we need very accurate measurements of the whole spectrum:
  - test that there is a superpartner to each SM state
    - spin measurements
    - SUSY coupling relations
  - measure in particular the states that are relevant for EWSB
    - gauginos, higgsinos, 3rd generation squarks!
  - determine SUSY breaking parameters in a model-independent way
    - bottom-up reconstruction of the Lagangian

- Need a precision machine: $e^+e^-$ collider

# Need phase space

- To explore the theory fully, we need very accurate measurements of the whole spectrum. $(g-2)_\mu$ prefers light SUSY, but overall SUSY may be O(TeV).




Masses of the lightest visible sparticle (LVSP) and next-to-lightest visible sparticle (NLVSP) in the CMSSM:

red: full model sample,
blue: suitable CDM density,
green: accessible to the LHC,
yellow: amenable to direct DM detection

[Ellis et al., hep-ph/0408118]

- May well need an $e^+e^-$ machine in the multi-TeV regime: CLIC

(NB: 3 TeV may not be enough)

# Need phase space

update, pMSSM?

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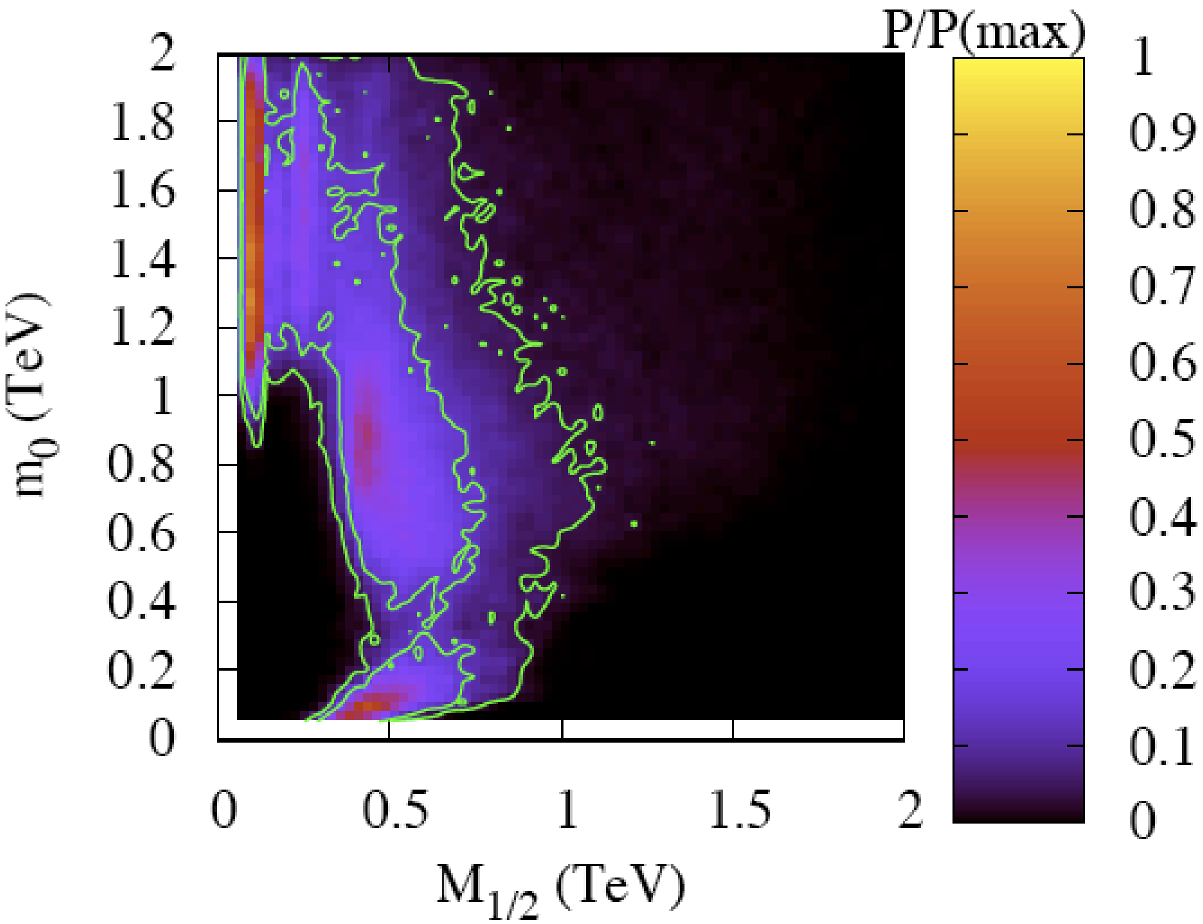



68% and 95% probability contours from Bayesian fit with naturalness prior.

Highest probability in focus point and coannihilation regions

[Allanach, hep-ph/0601089]

- May well need an $e^+e^-$ machine in the multi-TeV regime: CLIC

(NB: 3 TeV may not be enough)

# Sleptons

in progress

- Ex: smuon production and decay to the LSP.

$$e^+e^- \to \tilde{\mu}_L\tilde{\mu}_L \to \mu^+\chi_1^0\mu^-\chi_1^0$$

- If √s is significantly larger than twice the smuon mass, the decay muon energy spectrum has 2 clear endpoints

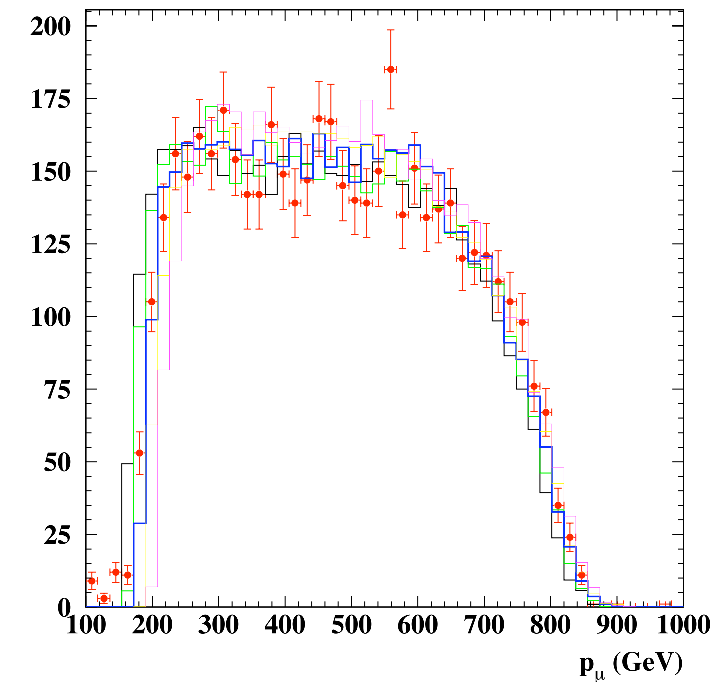
$$E_{\rm max/min} = \frac{M_{\tilde{\mu}}}{2}\left(1 - \frac{M^2_{\chi^0_1}}{M^2_{\tilde{\mu}}}\right) \times \left(1 \pm \sqrt{1 - \frac{M^2_{\tilde{\mu}}}{E^2_{\rm beam}}}\right)$$

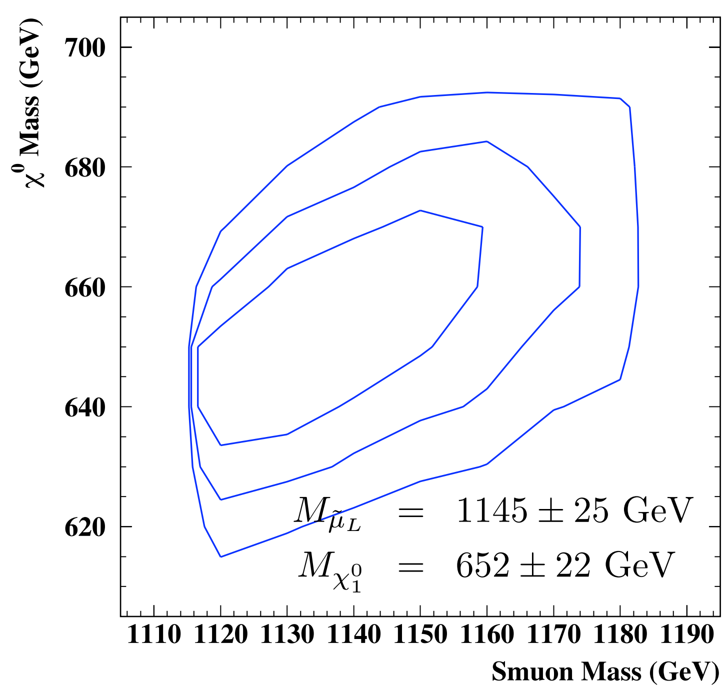
- Main issue is beamstrahlung

Point H: $M_{\tilde{\mu}} = 1150$ GeV, $M_{\chi^0_1} = 660$ GeV.

| $\delta p/p^2$ | Beamstrahlung | Fit result (GeV) |
|---|---|---|
| 0 | none | $1150 \pm 10$ |
| $3.0 \times 10^{-5}$ | none | $1150 \pm 12$ |
| $4.5 \times 10^{-5}$ | none | $1151 \pm 12$ |
| $4.5 \times 10^{-5}$ | standard | $1143 \pm 18$ |

Results of a one-parameter fit to the muon energy distribution for point H, for different assumptions on the $\delta p/p^2$ momentum resolution and the beamstrahlung spectrum. For an integrated luminosity of 1 $ab^{-1}$.




CERN-2004-005

# Sleptons

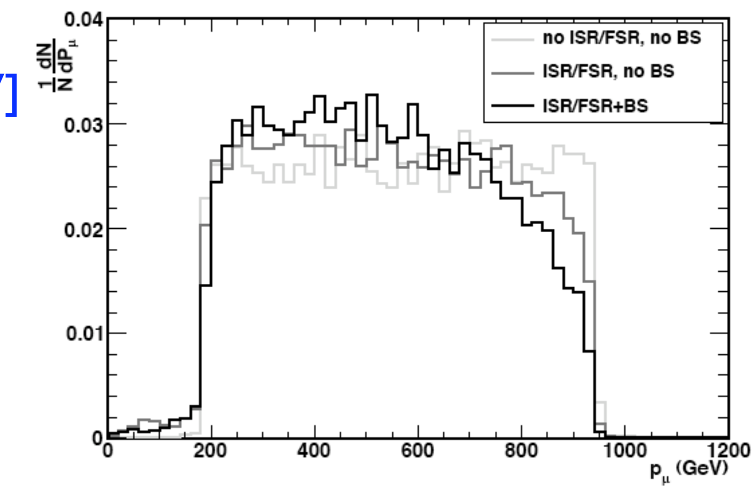
*in progress*

New study by Battaglia and Blaising [arXiv:1006.2547]

$$e^+e^- \to \tilde{\mu}_R\tilde{\mu}_R \to \mu^+\chi_1^0\mu^-\chi_1^0$$

K' (m½=1300, $m_0$=1001, tanβ=46, Sign(μ)<0 )

$$m_{\tilde{\mu}_R} = \mathbf{1108.8}\ \text{GeV},\ m_{\chi_1^0} = \mathbf{554.3}\ \text{GeV}$$




with 2 $ab^{-1}$ int. lumi.

| $\delta p_t/p_t^2$ ($\times 10^{-5}$ GeV$^{-1}$) | $\sqrt{s} >$ (GeV) | Data Set | Pol ($e^-/e^+$) | BX | ($M\pm\sigma_M$) (GeV) $\tilde{\mu}_R^{\pm}$ | $\tilde{\chi}_1^0$ |
|---|---|---|---|---|---|---|
| 0. | 2950 | S | 0/ 0 | 0 | 1106.3± 2.9 | 558.8 ± 1.3 |
| 0. | 2500 | S | 0/ 0 | 0 | 1098.8± 2.6 | 555.4 ± 1.2 |
| 0. | 2500 (ISR only) | S | 0/ 0 | 0 | 1109.2± 3.2 | 555.4 ± 1.2 |
| 0. | 2500 | S (No FSR Cor) | 0/ 0 | 0 | 1095.3± 3.2 | 557.7 ± 1.3 |
| 2. | 2500 | S | 0/ 0 | 0 | 1104.6± 2.9 | 560.0 ± 1.7 |
| 2. | 2500 | S (G4+Reco) | 0/ 0 | 0 | 1107.1± 2.8 | 560.1 ± 1.5 |
| 4. | 2500 | S | 0/ 0 | 0 | 1102.8± 2.9 | 557.2 ± 2.8 |
| 6. | 2500 | S | 0/ 0 | 0 | 1098.8± 3.1 | 559.1 ± 3.6 |
| 8. | 2500 | S | 0/ 0 | 0 | 1101.0± 3.4 | 564.2 ± 4.0 |
| 20. | 2500 | S | 0/ 0 | 0 | 1107.5± 4.2 | 575.7 ± 5.3 |
| 2. | 2500 | S+B (0.8) | 0/ 0 | 0 | 1107.5±15.5 | 542.5 ± 11.3 |
| 2. | 2500 | S+B (0.9) | 0/ 0 | 0 | 1107.5±14.4 | 551.2 ± 12.0 |
| 2. | 2500 | S+B (0.8) | 80/ 0 | 0 | 1107.7± 8.7 | 542.6 ± 4.6 |
| 2. | 2500 | S+B (0.8) | 80/60 | 0 | 1118.5± 6.1 | 551.3 ± 3.0 |
| 2. | 2500 | S+B (0.8) | 80/60 | 5 | 1105.7± 6.3 | 549.4 ± 3.9 |
| 2. | 2500 | S+B (0.8) | 80/60 | 20 | 1113.2± 6.8 | 550.3 ± 3.4 |

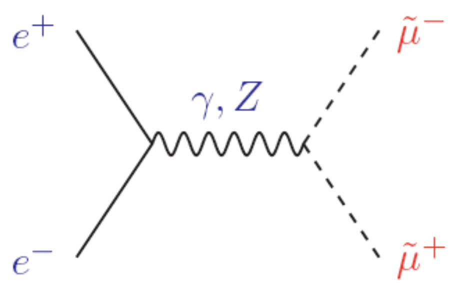
<1%

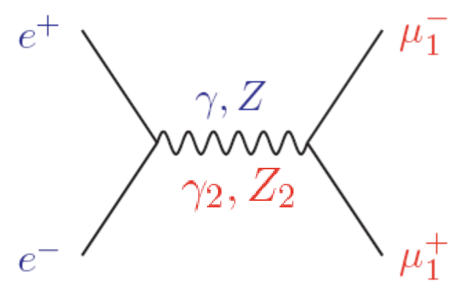
$\gamma\gamma \to$ hadrons per bunch crossing (BX)

# Sleptons

in progress

- Include both left and right smuons $m_{\tilde{\mu}_R} < m_{\tilde{\mu}_L}$ ?
- Consistency check: sneutrino masses $\tilde{\nu}_\mu \to \mu^\pm \tilde{\chi}_1^\mp \to \mu^\pm W^\mp \tilde{\chi}_1^0$
- Scalar or fermionic partner? E.g. distinguish SUSY smuons from KK muons in UED



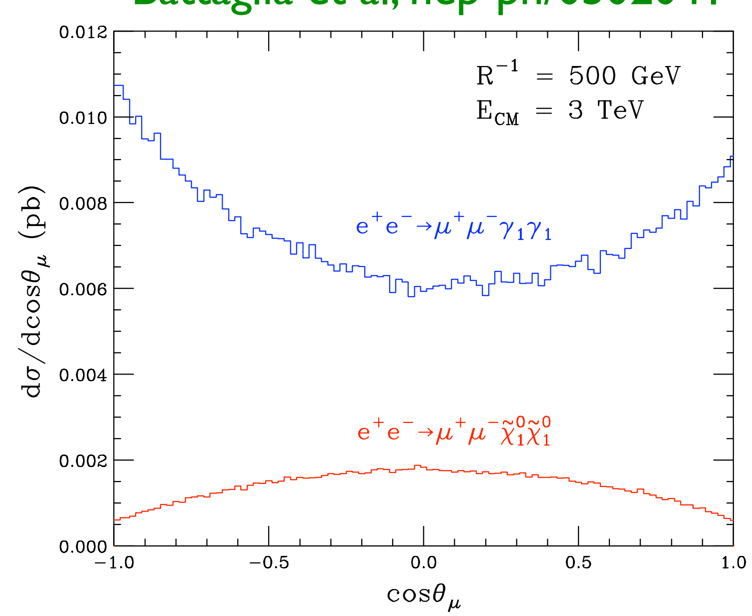

$$\left(\frac{d\sigma}{d\cos\theta}\right)_{SUSY} \sim 1 - \cos^2\theta.$$

$$\left(\frac{d\sigma}{d\cos\theta}\right)_{UED} \sim 1 + \cos^2\theta.$$

- Polarization, threshold curve?
- Same for selectrons?
(check slepton mass universality, SUSY relations: t-channel prod.)

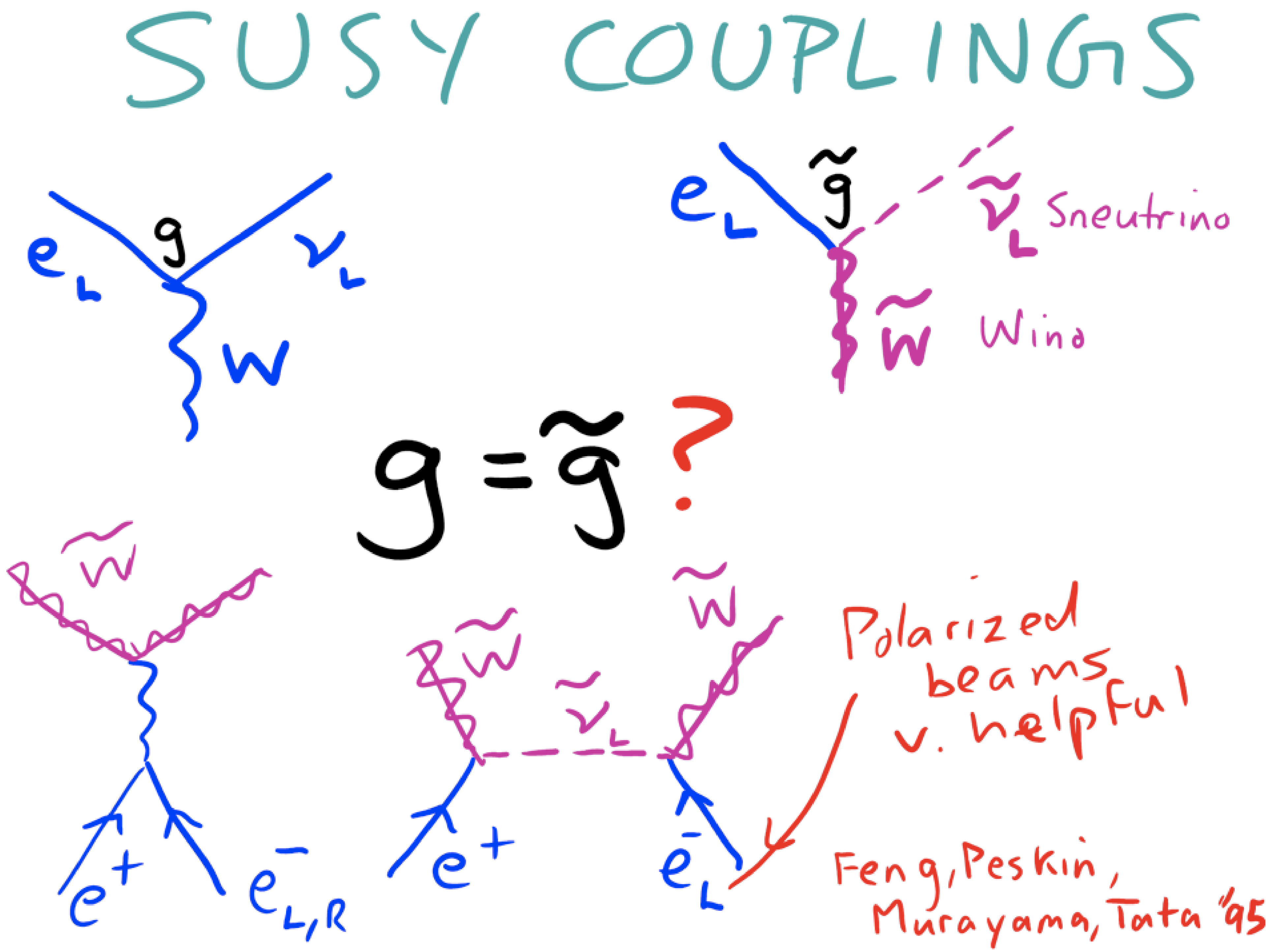
WISHLIST

Battaglia et al, hep-ph/0502041



# Coupling relations

WISHLIST




from R. Sundrum's plenary talk at the LC workshop

# EW-inos (gauginos, higgsinos)

N. Alster and M. Battaglia

in progress

- 2 CMSSM benchmark points

| Parameter | Model I | Model II |
|---|---|---|
| $m_0$ (GeV) | 966 | 1001 |
| $m_{1/2}$ (GeV) | 800 | 1300 |
| $\tan\beta$ | 51 | 46 |
| $A_0$ | 0. | 0. |
| sgn($\mu$) | + | - |
| $m_{top}$ (GeV) | 173.3 | 175 |

| Particle | Mass (GeV) | Width (GeV) | Mass (GeV) | Width (GeV) |
|---|---|---|---|---|
| $\chi_1^0$ | 340.3 | - | 554.3 | - |
| $\chi_2^0$ | 643.2 | 0.02 | 1064.2 | 0.04 |
| $\chi_3^0$ | 905.5 | 4.55 | 1407.2 | 6.75 |
| $\chi_4^0$ | 916.7 | 4.64 | 1413.8 | 6.85 |
| $\chi_1^\pm$ | 643.2 | 0.02 | 1064.3 | 0.04 |
| $\chi_2^\pm$ | 916.7 | 4.63 | 1413.7 | 8.08 |

- Model I: all EW-inos accessible at 3 TeV!

- Decays dominated by W, Z and h bosons

$$\tilde{\chi}_2^0 \rightarrow h^0\tilde{\chi}_1^0 \quad \sim 90\%$$
$$\tilde{\chi}_1^\pm \rightarrow W^\pm\tilde{\chi}_1^0 \quad \sim 100\%$$
$$\tilde{\chi}_{3,4}^0 \rightarrow W^\mp\tilde{\chi}_1^\pm \quad \sim 50\%$$
$$\tilde{\chi}_3^0 \rightarrow Z^0\tilde{\chi}_2^0 \quad \sim 23\%$$
$$\tilde{\chi}_4^0 \rightarrow h^0\tilde{\chi}_2^0 \quad \sim 22\%$$

$$\tilde{\chi}_2^\pm \rightarrow W^\pm\tilde{\chi}_1^0 \quad \sim 12\%$$
$$\rightarrow W^\pm\tilde{\chi}_2^0 \quad \sim 28\%$$
$$\rightarrow Z^0\tilde{\chi}_1^\pm \quad \sim 26\%$$
$$\rightarrow h^0\tilde{\chi}_1^\pm \quad \sim 24\%$$

# EW-inos (gauginos, higgsinos)

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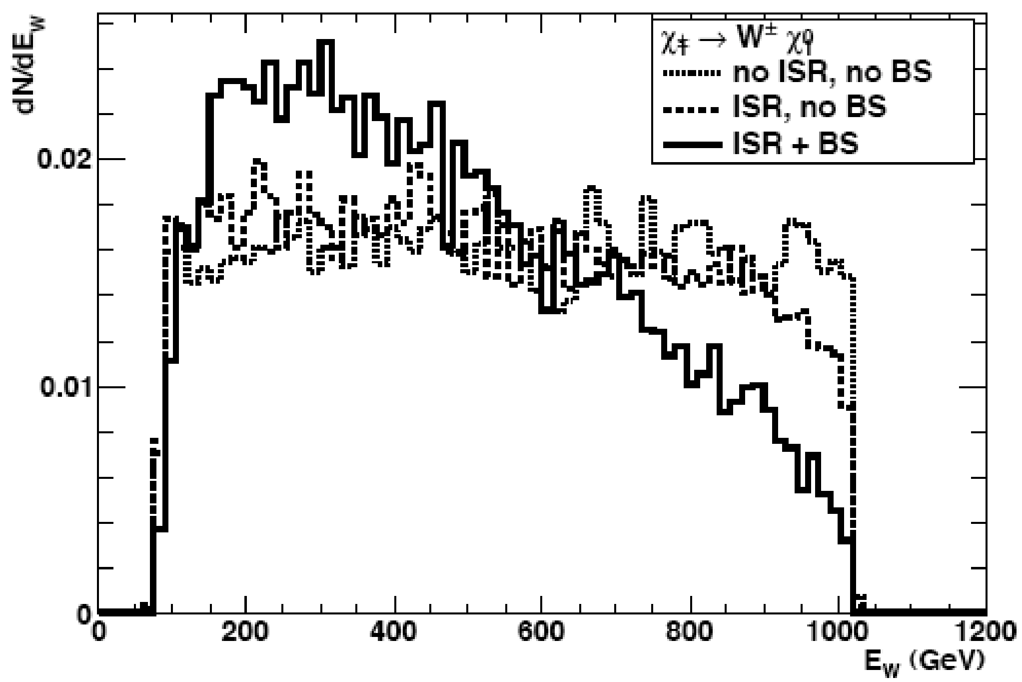



(a) Model I

| Particle | Mass (GeV) | No Rad | ISR | ISR+BS |
|---|---|---|---|---|
| Model I $\chi_1^\pm$ | 643.2 | $\pm$ 0.91 | $\pm$ 1.39 | $\pm$ 2.09 |
| Model II $\chi_1^\pm$ | 1062.2 | $\pm$ 6.10 | $\pm$ 8.25 | $\pm$10.11 |

| Particle | Mass (GeV) | No Rad | ISR | ISR+BS |
|---|---|---|---|---|
| Model I | | | | |
| $\chi_2^0$ | 643.2 | $\pm$ 1.01 | $\pm$ 1.17 | $\pm$ 2.58 |
| Model II | | | | |
| $\chi_2^0$ | 1064.2 | $\pm$10.64 | $\pm$11.12 | $\pm$15.72 |

| Particle | Mass (GeV) | No Rad | ISR | ISR+BS |
|---|---|---|---|---|
| Model I | | | | |
| $\chi_3^0$ | 905.5 | $\pm$ 7.1 | $\pm$ 7.9 | $\pm$12.6 |
| $\chi_4^0$ | 916.7 | $\pm$ 8.7 | $\pm$ 8.9 | $\pm$13.0 |

PRELIMINARY

- Complete reconstruction of neutralino system?
- Improvement if LSP mass known from slepton analysis?
- Effect of beam polarization (and uncertainty on it)?

# Minimal or non-minimal SUSY?

WISHLIST

- An enlarged neutralino sector, as e.g. in the NMSSM, can be distinguished from the minimal case via
  - polarization dependence of the production cross sections
  - sum rules for the couplings

- The latter can be translated into sum rules for the associated cross sections. MSSM, asymptotically:

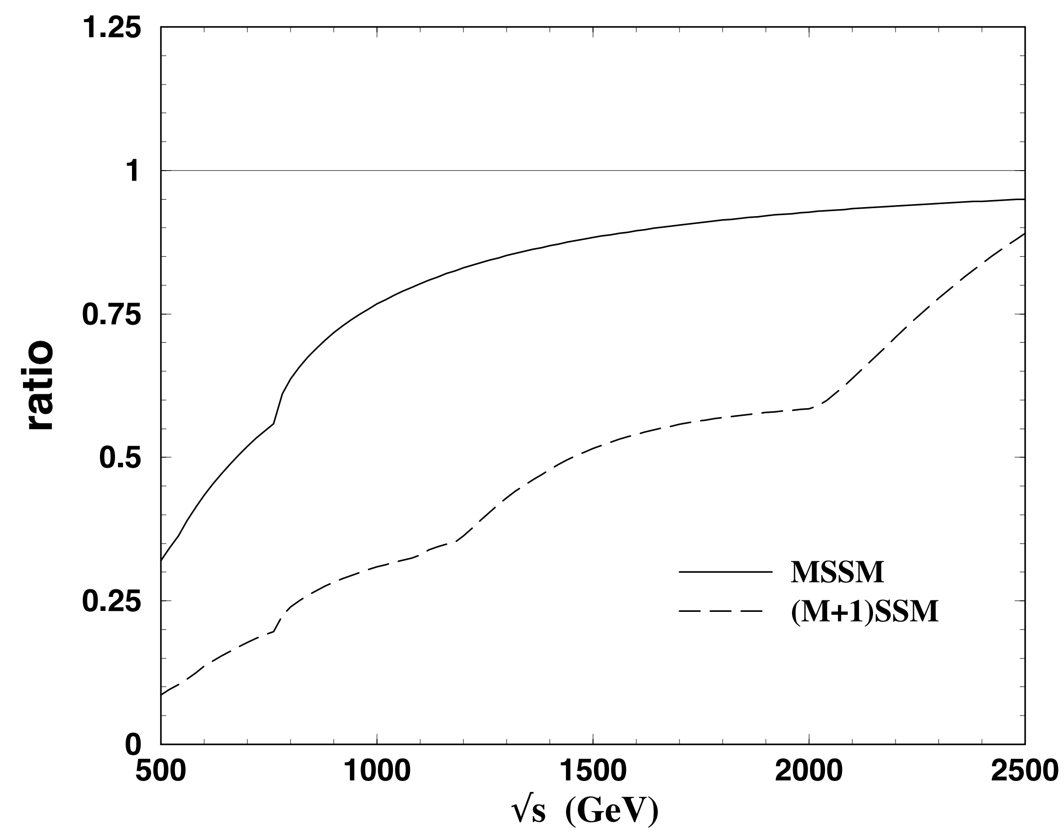
$$\lim_{s\to\infty} s \sum_{i\leq j}^{4} \sigma\{ij\} = \frac{\pi\alpha^2}{48\, c_W^4 s_W^4} \left[64 s_W^4 - 8 s_W^2 + 5\right] .$$

- Beam polarization is important to enhance the prod. rates of neutralino pairs that otherwise have very very low Xsections.

- Need also $\tilde{\chi}_1^0 \tilde{\chi}_1^0$ production from ISR photon spectrum.

- Analogous for charginos; e.g. test of extended gauge groups ...

Choi, Kalinowski, Mortgat-Pick, Zerwas,
hep-ph/0108117, hep-ph/0202039

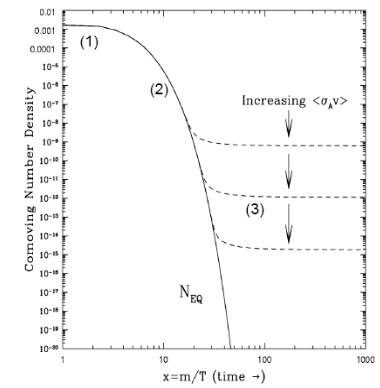



The energy dependence of the sum of all the neutralino-pair production cross sections normalized to the asymptotic form of the summed cross section.

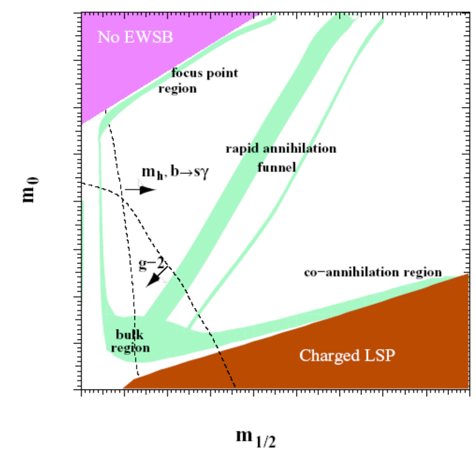
# Dark matter

to do

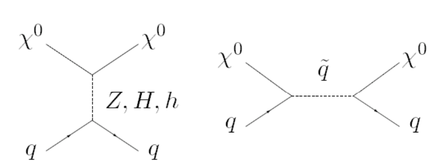
- A neutralino LSP is an excellent candidate for cold dark matter (WIMP!)
  Thermal relic from the Big Bang ... $\Omega h^2 \propto 1/\langle \sigma v \rangle$

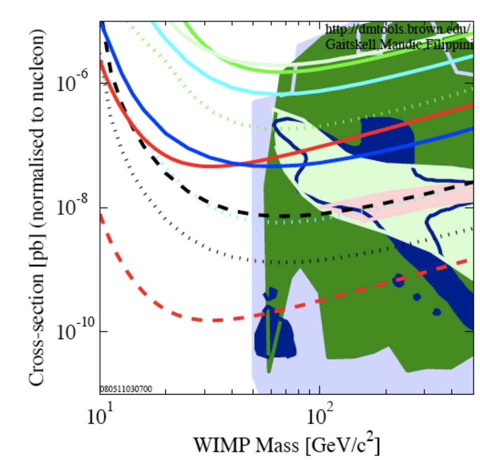



- If we can measure the properties of the SUSY particles precisely enough, we can infer the LSP annihilation cross section:
  - aim: “collider postdiction” of $\Omega h^2$
  - compare with cosmological observations (test cosmological model?)




- We can also predict / compare to direct and indirect detection rates
  - direct detection: $m_\chi$, $\sigma(\chi N)$, local density, velocity dist.
  - indirect det.: $\sigma v$, $m_\chi$, density profile, propagation model



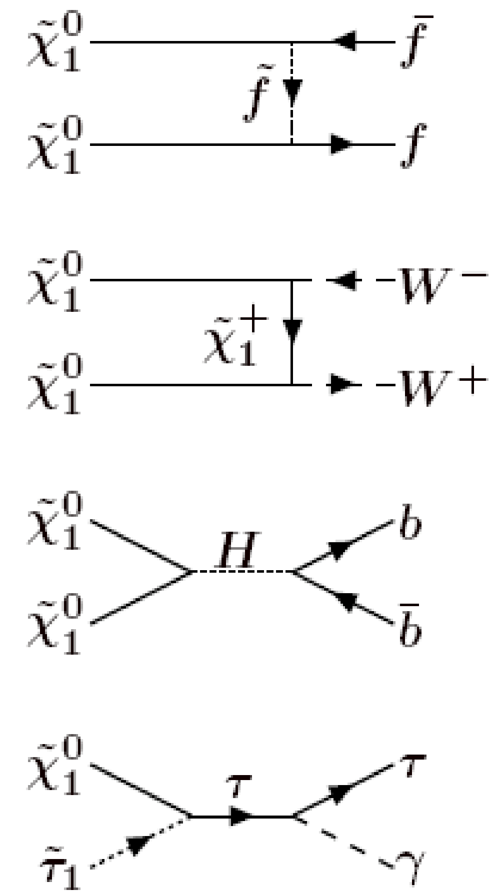




- Alternative SUSY DM candidates: gravitino, axion/axino, mixed sneutrino

# Inferring LSP DM properties

to do

## What do we need to measure?




- ☑ LSP mass and decomposition
  bino, wino, higgsino admixture ($M_1$, $M_2$, $\mu$)
- ☑ Sfermion masses (bulk, coannhilation)
  or at least lower limits on them
- ☑ Higgs masses and widths: h,H,A
- ☑ tan$\beta$ (Yukawa couplings)

Required precisions investigated in, e.g.
Allanach et al., hep-ph/0410091
Baltz et al., hep-ph/0602187

➡ Need (at least) %-level accuracies to match WMAP and evtl. PLANCK.

➡ Pure mass spectroscopy is not sufficient. Need measurements of couplings!
Note also CPV case [Belanger et al., hep-ph/0604150 & 0803.2584]

➡ What can be achieved for CLIC benchmarks?

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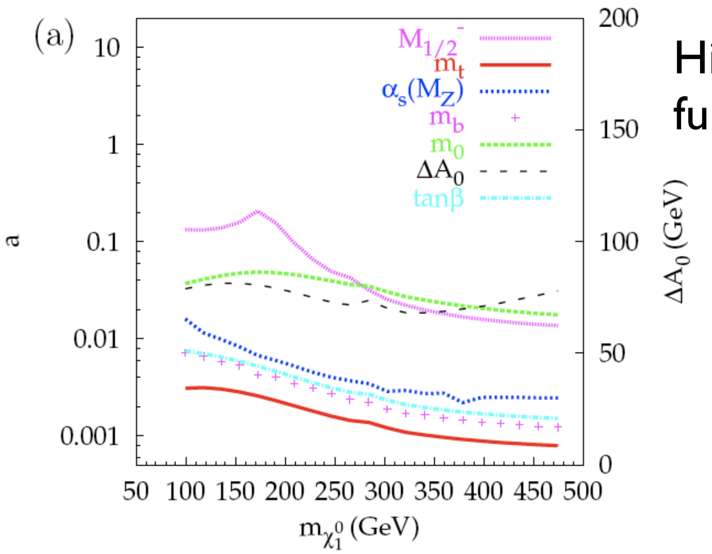
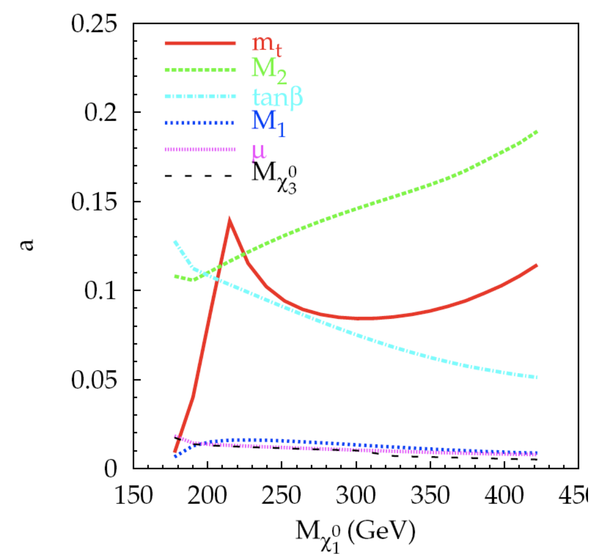



Higgs funnel




Higgsino / focus point region

➡ Need (at least) %-level accuracies to match WMAP and evtl. PLANCK.

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➡ What can be achieved for CLIC benchmarks?

# 3rd generation and trilinear couplings

WISHLIST

- Third generation is particularly interesting for electroweak symmetry breaking.

$$16\pi^2 \frac{d}{dt} m_{H_2}^2 = 6\,|y_t|^2 \,\left(|A_t|^2 + m_{H_2}^2 + m_{Q_3}^2 + m_{U_3}^2\right) - 6\,g_2^2\,|M_2|^2 + \ldots\,,$$

$$16\pi^2 \frac{d}{dt} B_\mu = 6\,\mu\,A_t\,|y_t|^2 + 6\,\mu\,M_2\,g_2^2 + \ldots$$

- Important radiative corrections to the light Higgs mass.

$$m_h^2 \lesssim m_Z^2 + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right] + \ldots\,,$$

$$M_S^2 \equiv \frac{1}{2}\left(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2\right)\,,$$

$$X_t \equiv A_t - \mu\cot\beta\,.$$

- Stop sector may be disentangled by measurement of stop masses and mixing angle. $\Delta A_t \simeq$ few %

- Mixing in the sbottom/stau sector however dominated by $\mu\tan\beta$
  $\tilde{b}_i, \tilde{\tau}_i \Rightarrow \Delta A_b, \Delta A_\tau \simeq$ order of magnitude

  ➡ Need additional information besides masses and mixings

$$e^+e^- \to \tilde{\tau}_i\tilde{\tau}_j A^0 \;\Rightarrow\; |A_\tau \tan\beta|^2$$

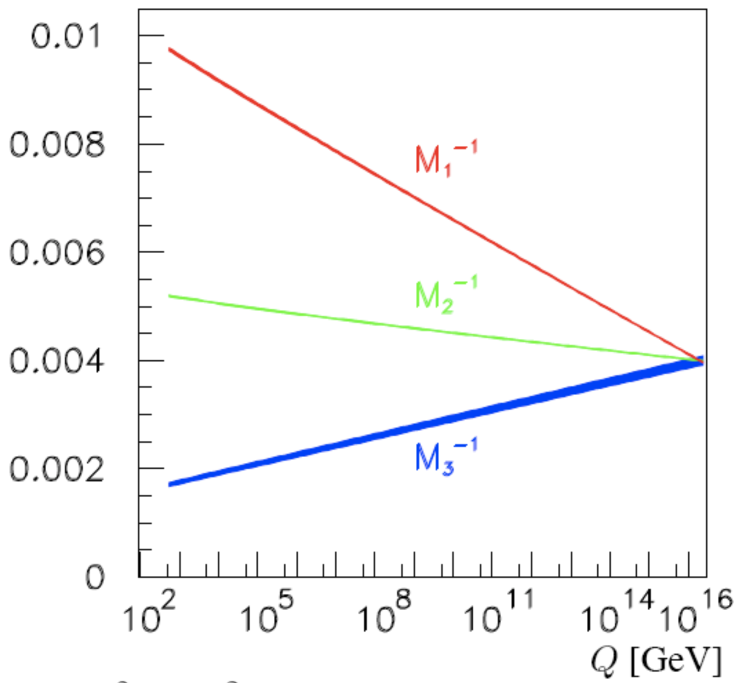
$$\tilde{b}_2 \to \tilde{b}_1 A^0 \;\Rightarrow\; |A_b \tan\beta|^2$$

$$A^0 \to \tilde{b}_2\tilde{b}_1 \;\Rightarrow\; |A_b \tan\beta|^2$$

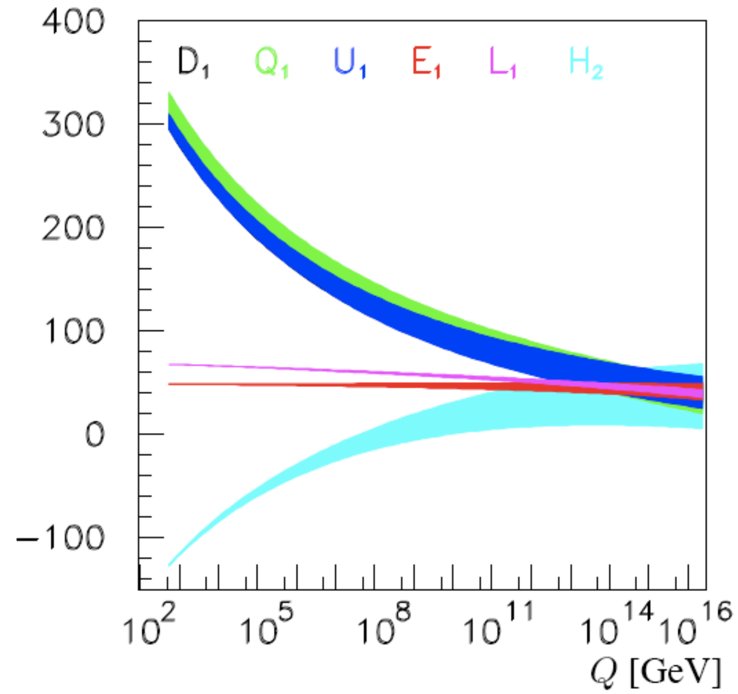
e.g. Datta, Djouadi, Kneur, hep-ph/0101353

# Reconstructing the high-scale theory

a) $1/M_i$ [GeV$^{-1}$]




b) $M_j^2$ [GeV$^2$]



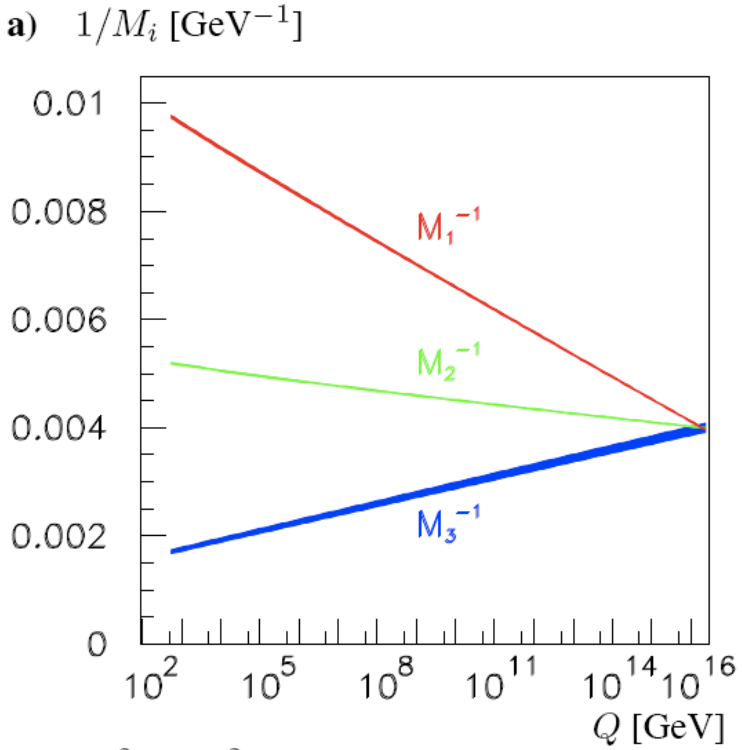

If the measurements of the SUSY masses and couplings are complete and precise enough:

- ➡ determine soft-breaking parameters,
- ➡ perform bottom-up evolution to test the high-scale structure of the theory.

[Blair, Porod, Zerwas]

Figs: Evolution, from low to high scales, of
a) gaugino mass parameters,
b) first-generation sfermion mass parameters and the Higgs mass parameter $m_{H2}$ for mSUGRA point SPS1a.

# Reconstructing the high-scale theory

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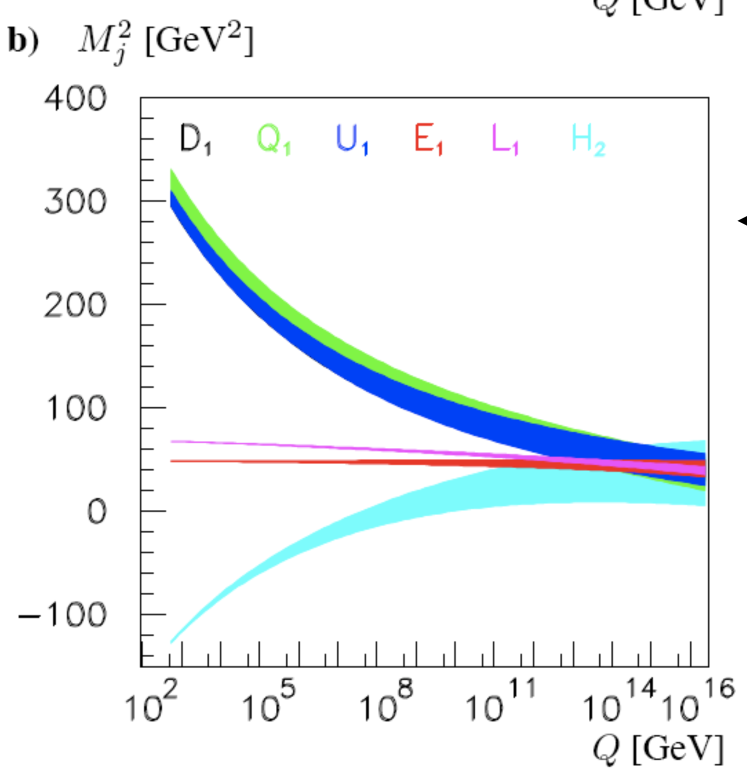
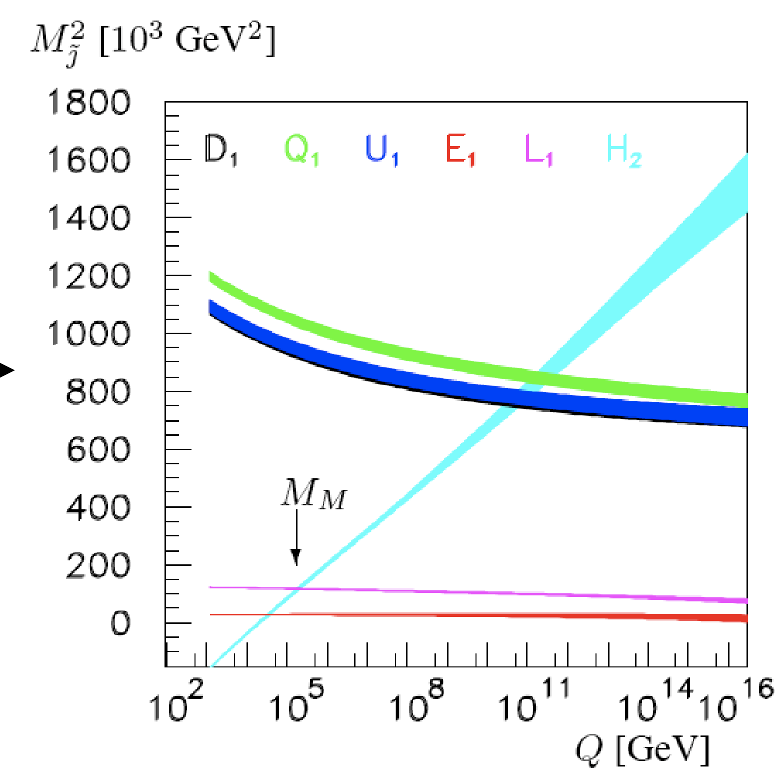


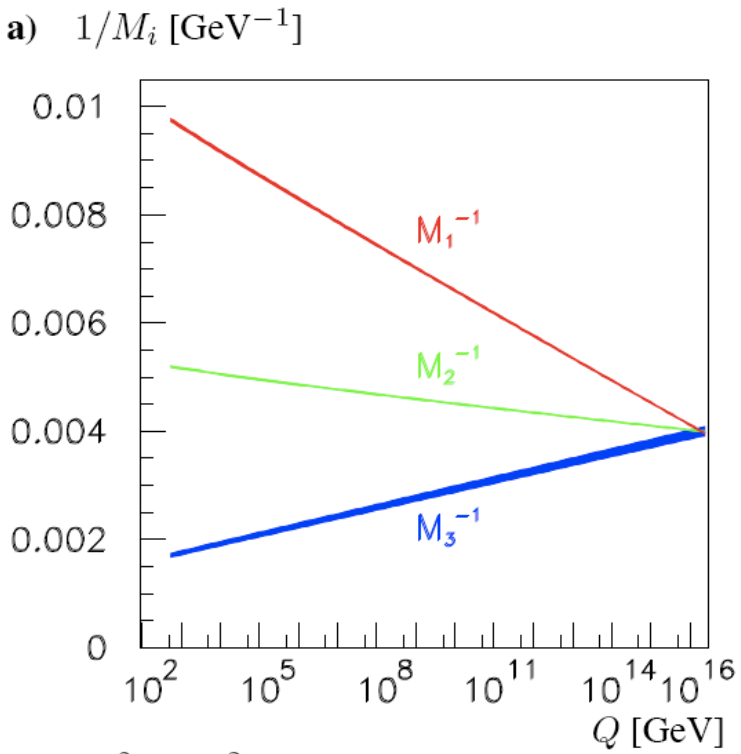

← mSUGRA

versus

mGMSB →



# Reconstructing the high-scale theory

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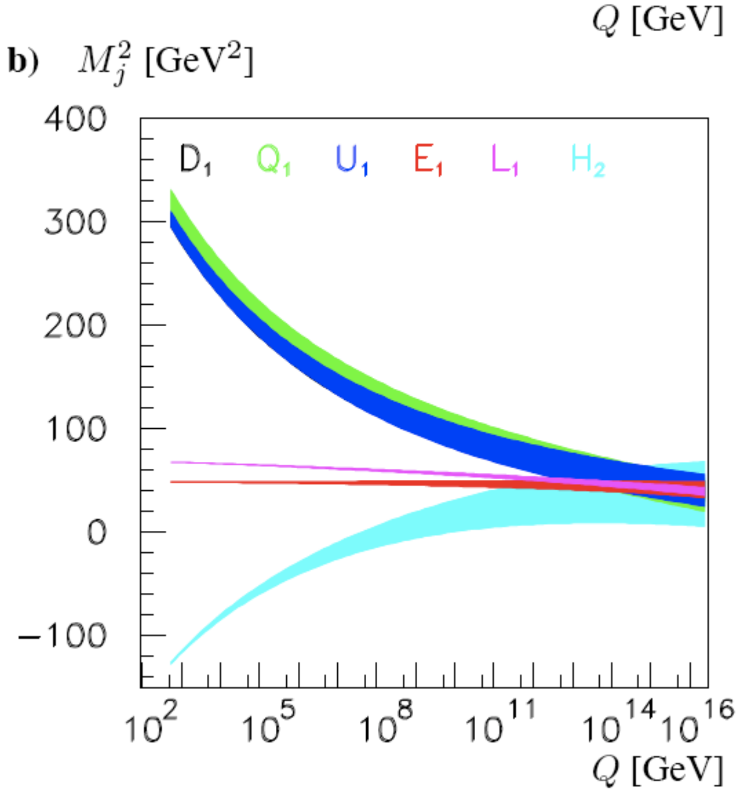
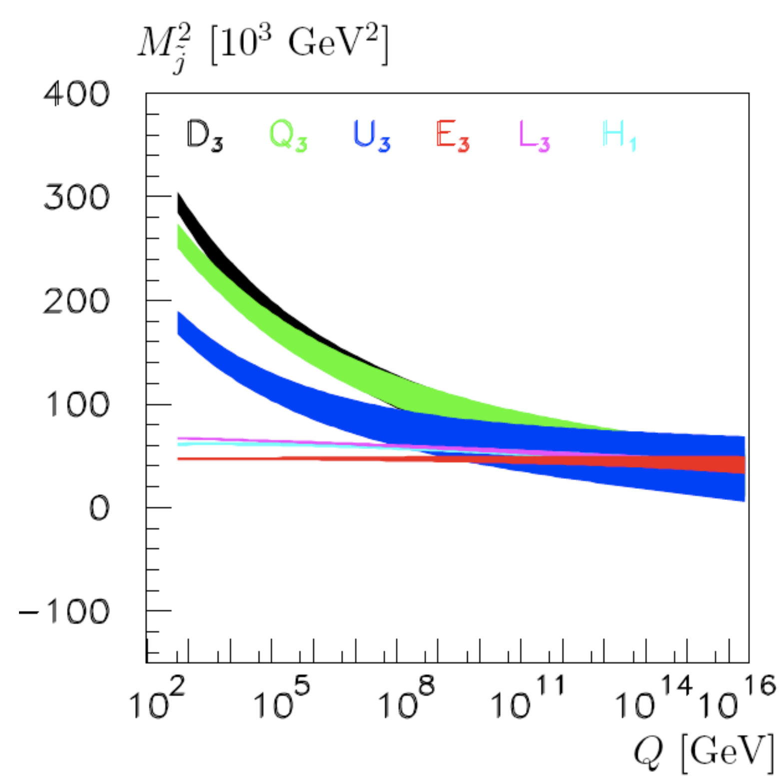


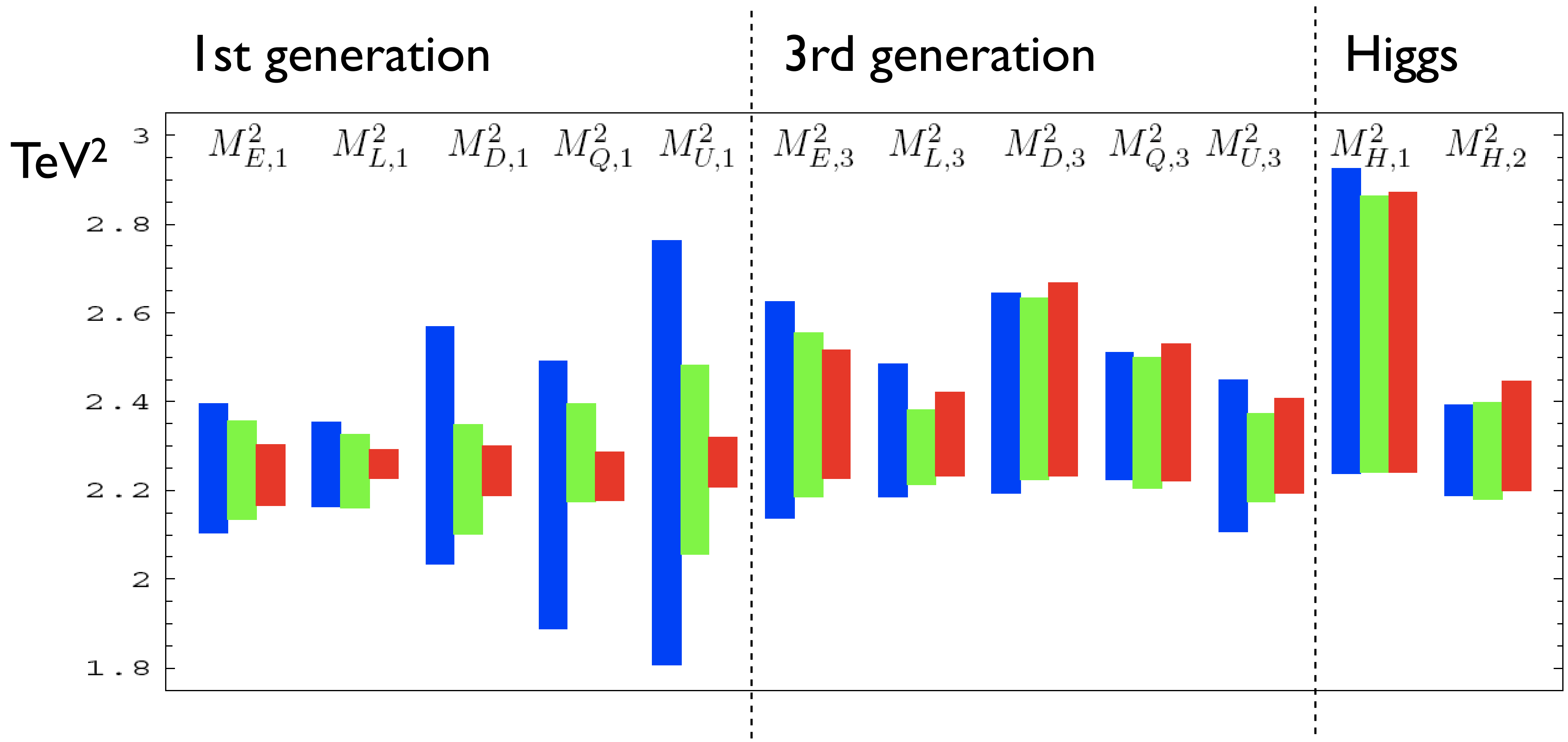

Pb: errors for 3rd gen. and Higgs soft terms much larger than for 1st/2nd generation

A-terms!

# Reconstructing the high-scale theory

update

- knowledge of 3rd gen. and trilinear couplings is essential -




CERN-2004-005

1σ error bars for scalar soft terms (in TeV$^2$) at the GUT scale, assuming ILC precision on chargino/neutralino sector and 3% precision on gluino mass.

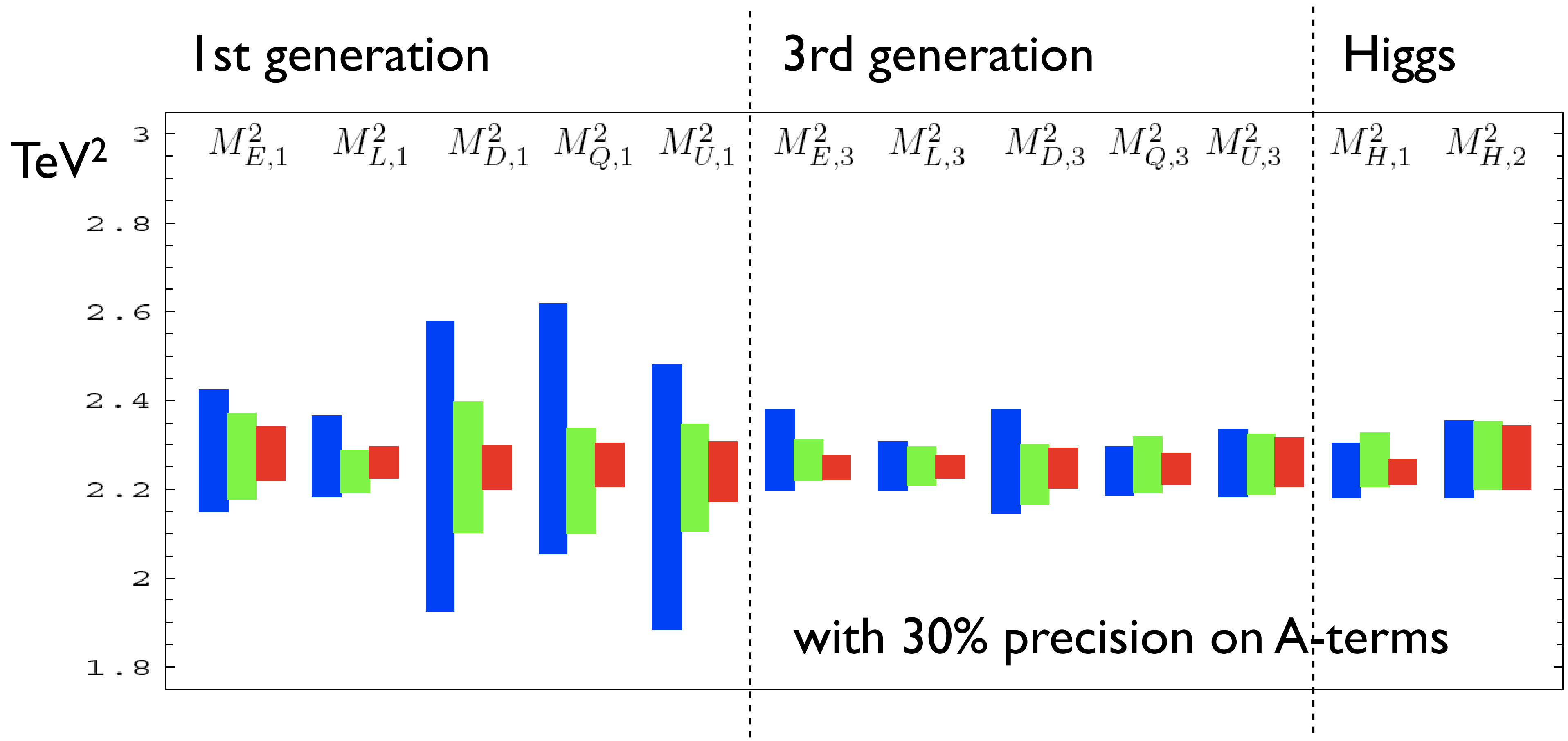
blue: 2% accuracy on slepton masses, 7% for remaining heavy particle masses;
green: 2% accuracy on slepton masses, 3% for remaining heavy particle masses;
red: all masses with 1% accuracy

Point E: $m_{1/2} = 300$ GeV, $m_0 = 1.5$ TeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$.

# Reconstructing the high-scale theory

update

- knowledge of 3rd gen. and trilinear couplings is essential -




CERN-2004-005

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Point E: $m_{1/2} = 300$ GeV, $m_0 = 1.5$ TeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$.

# Stops and bottoms

WISHLIST

- Pb 1: default benchmark point has too heavy stops/sbottoms

$$\tilde{t}_1 : 1393\ \mathrm{GeV}, \qquad \tilde{b}_1 : 1544\ \mathrm{GeV},$$
$$\tilde{t}_2 : 1598\ \mathrm{GeV}, \qquad \tilde{b}_2 : 1610\ \mathrm{GeV}.$$

add new BM

- Pb 2: complicated decay modes, e.g., for model I

$$\begin{aligned}
\tilde{t}_1 \quad &\to t\tilde{\chi}^0_1 &&: 15\% \\
&\to t\tilde{\chi}^0_{3,4} &&: 34\% \\
&\to b\tilde{\chi}^+_1 &&: 14\% \\
&\to b\tilde{\chi}^+_2 &&: 32\% \\
\tilde{t}_2 \quad &\to t\tilde{\chi}^0_2 &&: 10\% \\
&\to t\tilde{\chi}^0_{3,4} &&: 24\% \\
&\to b\tilde{\chi}^+_1 &&: 24\% \\
&\to b\tilde{\chi}^+_2 &&: 22\%
\end{aligned}$$

$$\begin{aligned}
\tilde{b}_1 \quad &\to b\tilde{\chi}^0_2 &&: 18\% \\
&\to b\tilde{\chi}^0_{3,4} &&: 20\% \\
&\to t\tilde{\chi}^-_1 &&: 32\% \\
&\to t\tilde{\chi}^-_2 &&: 24\% \\
\tilde{b}_2 \quad &\to b\tilde{\chi}^0_{3,4} &&: 31\% \\
&\to t\tilde{\chi}^-_2 &&: 47\%
\end{aligned}$$

- multi W, Z, h events with additional b jets

# Conclusions

- Progress: sleptons, neutralinos/charginos
- 2do: polarisation, DM studies, reconstruction of Lagrangian
- It would be important to show that CLIC could resolve a complete SUSY spectrum. The main difficulties here are
  - the number of possible channels and
  - irreducible SUSY-internal background

  That may seem too much for the CDR (aim: show feasibility), but nevertheless it's essential for the physics potential.
- Need to discuss sector-wise reconstruction....
- Open issue: study of 3rd generation
- Please contribute!