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# Precise predictions for slepton pair production

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- Introduction
- Mass measurements in threshold scans
- Determination of SUSY couplings
- NLO results for selectron and smuon pair production
- Conclusions

Production of smuons  $\tilde{\mu}$  and selectrons  $\tilde{e}$  is very interesting for precision physics at LC

→ accurate test of SUSY relations

→ reconstruction of breaking mechanism

$$e^+ e^- \rightarrow \tilde{l}_{L/R}^+ \tilde{l}_{L/R}^-$$

$$\tilde{l}_R^\pm \rightarrow l^\pm \tilde{\chi}_1^0$$

$$\tilde{l}_L^\pm \rightarrow l^\pm \tilde{\chi}_2^0$$

$$\quad \quad \quad \searrow \tau^+ \tau^- \tilde{\chi}_1^0$$

Clean signature:

e.g.  $l^+ l^- + \cancel{E}$  for R-sleptons

Values for SPS1 scenario:

	Decay	BR	$m$ [GeV]	$\Gamma$ [MeV]
$\tilde{\mu}_R^\pm$	$\mu^\pm \tilde{\chi}_1^0$	100%	143	$\sim 200$
$\tilde{e}_R^\pm$	$e^\pm \tilde{\chi}_1^0$	100%	143	$\sim 200$
$\tilde{e}_L^\pm$	$e^\pm \tilde{\chi}_1^0$	$\sim 49\%$	202	$\sim 240$
	$e^\pm \tilde{\chi}_2^0$	$\sim 18\%$		
	$\nu_e \tilde{\chi}_1^\pm$	$\sim 33\%$		

Scan of cross-section near threshold allows measurement of mass with **high accuracy** and in **model-independent** way.

$$e^+e^- \rightarrow \tilde{\mu}_R^+ \tilde{\mu}_R^- \quad [\gamma, Z] \quad \propto \beta^3 \text{ (P-wave)}$$

$$e^+e^- \rightarrow \tilde{e}_R^+ \tilde{e}_R^- \quad [\gamma, Z, \tilde{\chi}^0] \quad \propto \beta^3 \text{ (P-wave)}$$

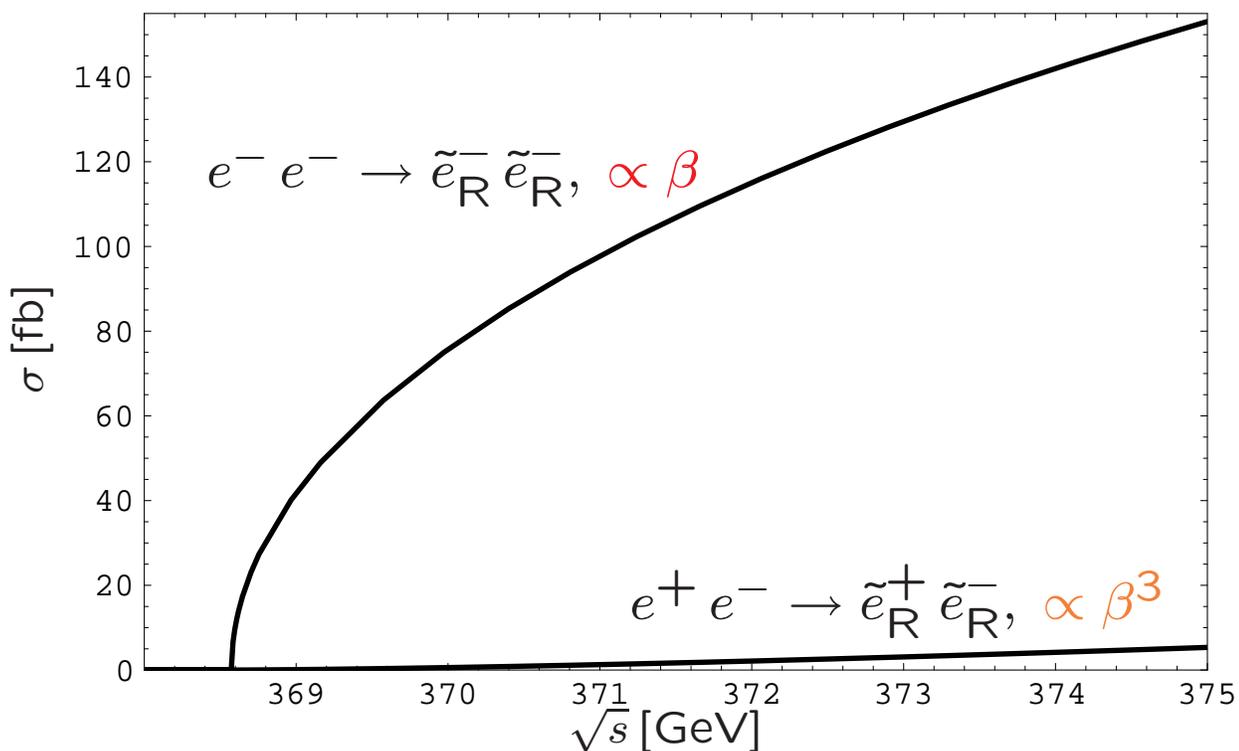
$$e^+e^- \rightarrow \tilde{e}_R^+ \tilde{e}_L^- \quad [\tilde{\chi}^0] \quad \propto \beta \text{ (S-wave)}$$

$$e^+e^- \rightarrow \tilde{e}_L^+ \tilde{e}_L^- \quad [\gamma, Z, \tilde{\chi}^0] \quad \propto \beta^3 \text{ (P-wave)}$$

$$e^-e^- \rightarrow \tilde{e}_R^- \tilde{e}_R^- \quad [\tilde{\chi}^0] \quad \propto \beta \text{ (S-wave)}$$

$$e^-e^- \rightarrow \tilde{e}_R^- \tilde{e}_L^- \quad [\tilde{\chi}^0] \quad \propto \beta^3 \text{ (P-wave)}$$

$$e^-e^- \rightarrow \tilde{e}_L^- \tilde{e}_L^- \quad [\tilde{\chi}^0] \quad \propto \beta \text{ (S-wave)}$$



section requires

1. Inclusion of finite widths in gauge-invariant way
2. Treatment of coulomb rescattering effects
3. ISR (leading-log approximation),  
beamstrahlung (program *Circe* [Ohl '97] )
4. Simulation and reduction of SUSY and SM background  
e. g. for R-selectrons

$$e^+ e^- \rightarrow (\tilde{e}_R^+ \tilde{e}_R^-) \rightarrow e^+ e^- \tilde{\chi}_1^0 \tilde{\chi}_1^0:$$

$$\text{all contributions } e^+ e^- \rightarrow e^+ e^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

$$\text{and } e^+ e^- \rightarrow e^+ e^- \nu \bar{\nu}$$

[A.F., D.J. Miller, P.M. Zerwas '01]

$e^+e^- \rightarrow (\tilde{e}_R^+ \tilde{e}_R^-)$ $\rightarrow e^+e^- \cancel{E}$	$m_{\tilde{e}_R} = 143.0^{+0.21}_{-0.19} \text{ GeV}$ $\Gamma_{\tilde{e}_R} = 150^{+300}_{-250} \text{ MeV}$
$e^-e^- \rightarrow (\tilde{e}_R^- \tilde{e}_R^-)$ $\rightarrow e^-e^- \cancel{E}$	$m_{\tilde{e}_R} = 143.0^{+0.048}_{-0.053} \text{ GeV}$ $\Gamma_{\tilde{e}_R} = 200^{+50}_{-40} \text{ MeV}$
$e^+e^- \rightarrow (\tilde{e}_R^\pm \tilde{e}_L^\mp)$ $\rightarrow e^+e^- \tau\tau \cancel{E}$	$m_{\tilde{e}_L} = 202.2^{+0.37}_{-0.33} \text{ GeV}$ $\Gamma_{\tilde{e}_L} = 240^{+20}_{-20} \text{ MeV}$
$e^-e^- \rightarrow (\tilde{e}_L^- \tilde{e}_L^-)$ $\rightarrow e^+e^- 4\tau \cancel{E}$	$m_{\tilde{e}_L} = 202.2^{+0.62}_{-0.44} \text{ GeV}$ $\Gamma_{\tilde{e}_L} = 240^{+500}_{-240} \text{ MeV}$
$\mu^+\mu^- \rightarrow (\tilde{\mu}_R^+ \tilde{\mu}_R^-)$ $\rightarrow \mu^+\mu^- \cancel{E}$	$m_{\tilde{\mu}_R} = 143.0^{+0.42}_{-0.38} \text{ GeV}$ $\Gamma_{\tilde{e}_R} = 350^{+400}_{-400} \text{ MeV}$

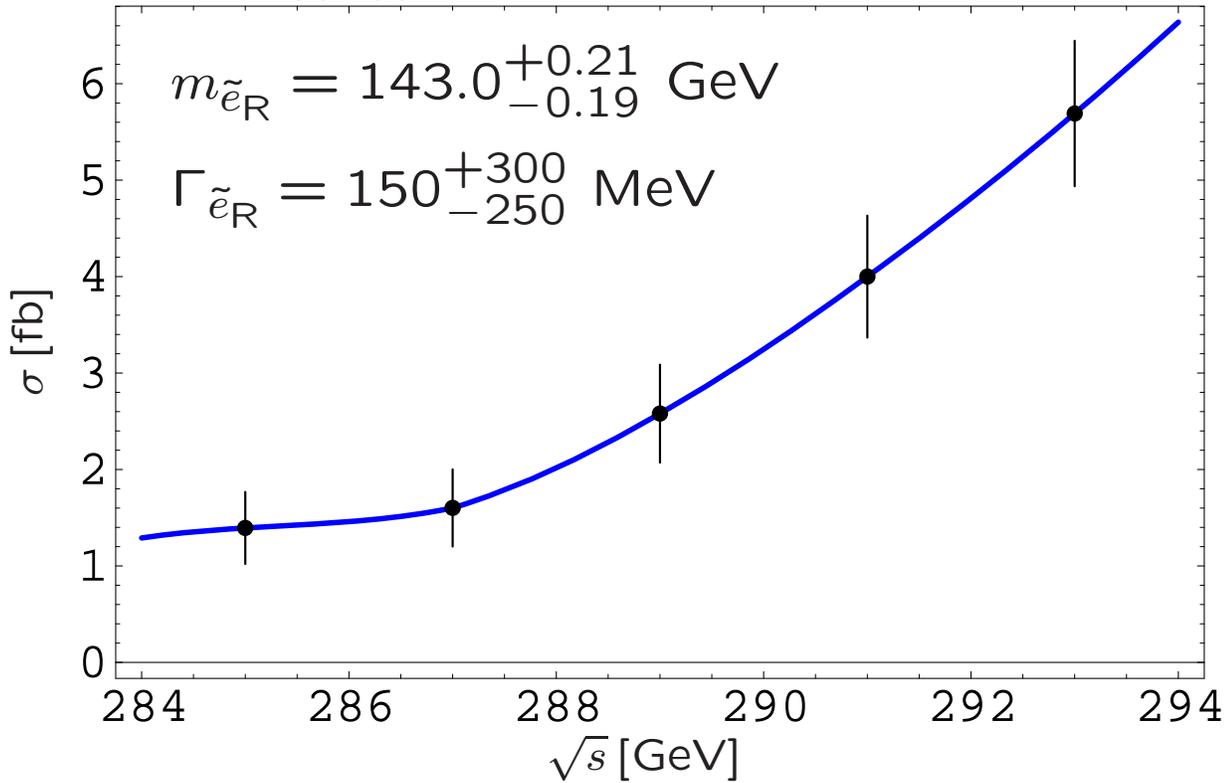
Polarization: 80%  $e^-$   
50%  $e^+$

Use five equidistant points

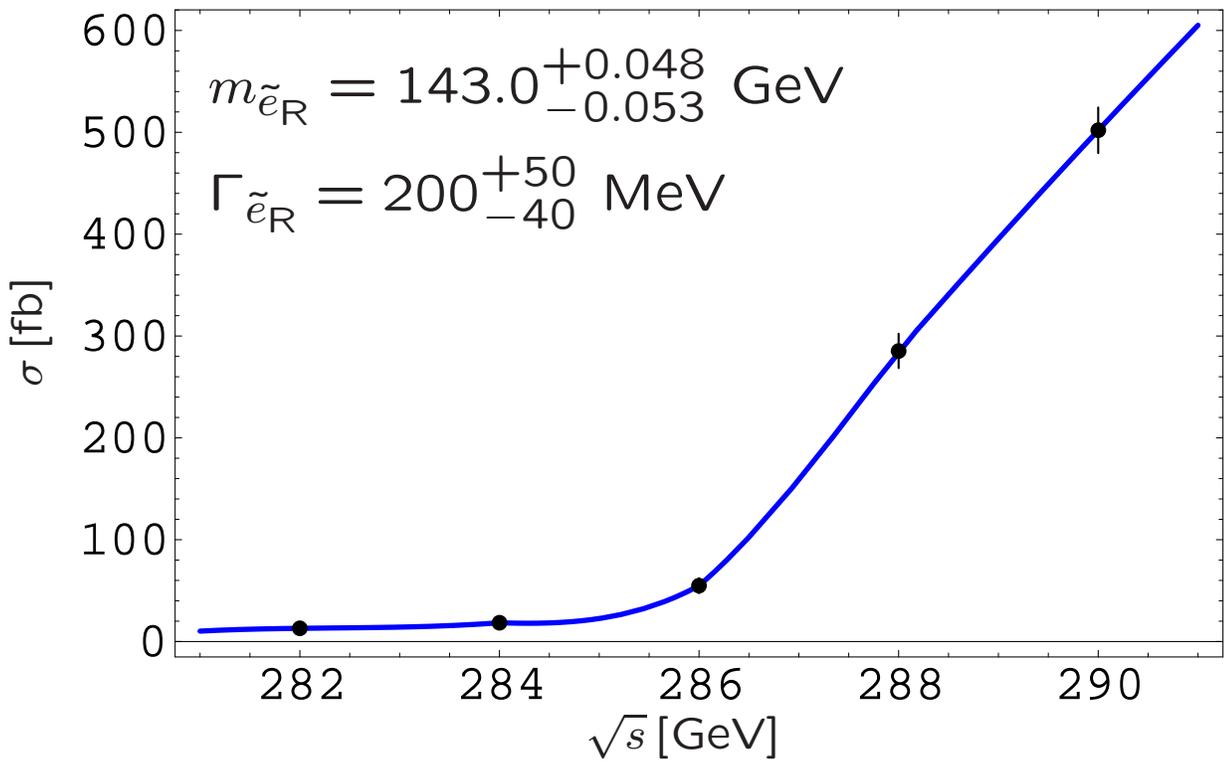
10  $\text{fb}^{-1}$  each for  $e^+e^-$

1  $\text{fb}^{-1}$  each for  $e^-e^-$

$e^+e^- \rightarrow (\tilde{e}_R^+ \tilde{e}_R^-) \rightarrow e^+e^- \cancel{E}$ : 10 fb<sup>-1</sup> per point



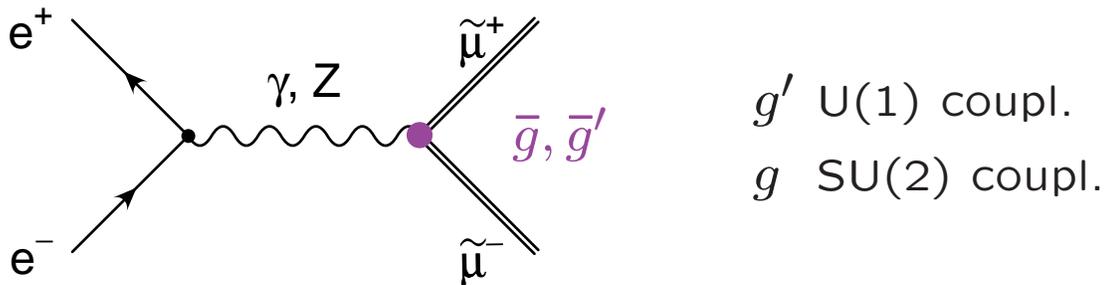
$e^-e^- \rightarrow (\tilde{e}_R^- \tilde{e}_R^-) \rightarrow e^-e^- \cancel{E}$ : 1 fb<sup>-1</sup> per point



- One of the fundamental relations in SUSY:

$$\begin{aligned}
 & V f f \quad \text{gauge coupling } g \\
 & \underline{\underline{!}} V \tilde{f} \tilde{f} \quad \text{gauge coupling } \bar{g} \\
 & \underline{\underline{!}} \tilde{V} f \tilde{f} \quad \text{Yukawa coupling } \hat{g}
 \end{aligned}$$

- Measurement of  $e^+e^- \rightarrow \tilde{\mu}^+\tilde{\mu}^-$  allows extraction of slepton gauge coupling



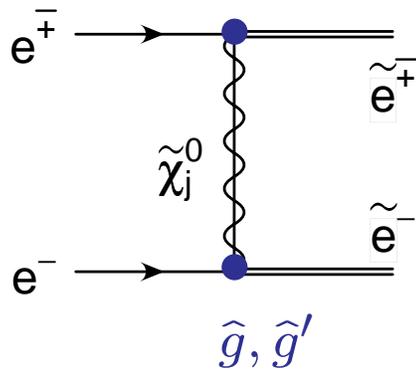
→ Test of equivalence of gauge couplings  $g = \bar{g}$

Extraction of  $\delta\bar{g}'$  from  $e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^-$ :

$$\frac{\delta\bar{g}'}{\bar{g}'} \approx 1\% \quad \text{with } 500 \text{ fb}^{-1}$$

Error sources:  $\delta m_{\tilde{\mu}_R}$ , polarization

# extraction of SUSY Yukawa couplings



$g'$  U(1) coupl.  
 $g$  SU(2) coupl.

→ Test of equivalence  
 gauge coupling  $g$  = Yukawa coupling  $\hat{g}$

$e^+e^- \rightarrow \tilde{e}_R^+\tilde{e}_R^-$ $\rightarrow e^+e^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$	500 fb <sup>-1</sup>	$\delta\hat{g}'/\hat{g}' \approx 0.2\%$
$e^+e^- \rightarrow \tilde{e}_R^\pm\tilde{e}_L^\mp$ $\rightarrow e^+e^- \tilde{\chi}_1^0 \tilde{\chi}_2^0$ $\rightarrow e^+e^- \tau\tau \tilde{\chi}_1^0 \tilde{\chi}_1^0$		$\delta\hat{g}/\hat{g} \approx 0.7\%$
$e^-e^- \rightarrow \tilde{e}_R^-\tilde{e}_R^-$ $\rightarrow e^-e^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$	50 fb <sup>-1</sup>	$\delta\hat{g}'/\hat{g}' \approx 0.2\%$
$e^-e^- \rightarrow \tilde{e}_L^-\tilde{e}_L^-$ $\rightarrow e^+e^- \tilde{\chi}_2^0 \tilde{\chi}_2^0$ $\rightarrow e^+e^- 4\tau \tilde{\chi}_1^0 \tilde{\chi}_1^0$		$\delta\hat{g}/\hat{g} \approx 0.8\%$

[values for SPS1 scenario]

Error sources:  $\delta m_{\tilde{e}}$ , polarization,  
 neutralino sector

## pair production

→ Clearly the inclusion of radiative corrections is necessary

Width effects less important for slepton production in *continuum*

⇒ S sleptons treated on-shell as first step

- $\mathcal{O}(\alpha)$  Sfermion decay  $\tilde{f} \rightarrow f \tilde{\chi}_i^0, \tilde{f} \rightarrow f' \tilde{\chi}^j$   
[→ talk of J. Guasch]

- This presentation:

$\mathcal{O}(\alpha)$  corrections to R-smuon production

$$e^+ e^- \rightarrow \tilde{\mu}_R^+ \tilde{\mu}_R^-$$

and R-selectron production

$$e^+ e^- \rightarrow \tilde{e}_R^+ \tilde{e}_R^-, e^- e^- \rightarrow \tilde{e}_R^- \tilde{e}_R^-$$

→ large number of particles and parameters  
 $\mathcal{O}(1000)$  diagrams

Use of computer algebra tools:

- Generation of diagrams and amplitudes with *FeynArts* [Küblbeck, Böhm, Denner '90]  
[Hahn '00]
- Dirac algebra and tensor integral reduction with *FeynCalc* [R. Mertig, M. Böhm, A. Denner '91]
- General  $R_\xi$  gauge  
→ check gauge-parameter independence algebraically
- Numerical evaluation of the scalar one-loop integrals with *LoopTools* [G. 't Hooft, M. Veltman '79]  
[G.J. v. Oldenborgh, J.A.M. Vermaseren '90]  
[T. Hahn '98]
- Virtual corrections are combined with real bremsstrahlung contributions

- Renormalization of  $M_Z, s_W, \dots$  as in SM
- Renormalization of neutralinos depends on  $M_1, M_2, \mu$ 
  - fix by on-shell conditions for e.g.  $\tilde{\chi}_1^-, \tilde{\chi}_2^-, \tilde{\chi}_1^0$
  - ⇒  $\mathcal{O}(\alpha)$  relations for masses of  $\tilde{\chi}_{2,3,4}^0$ 
    - [D.Pierce, A.Papadopoulos '94]
    - [H.Eberl, M.Kinzel, W.Majerotto, Y.Yamada '01]
    - [T.Fritzsche, W.Hollik '02]

- No standard procedure for  $\tan \beta$ 
  - $\tan \beta$  is no physical observable
    - [→ talk of D.Stöckinger in Higgs session]

$\overline{\text{DR}}$  renormalization for  $\tan \beta$

practically convenient, but gauge-dependent

[→ talk of Y.Yamada in Higgs session]

(*alternative:*

define  $\tan \beta$  via decay  $A^0 \rightarrow \tau\tau$ )

**Goal:** Renormalize  $\tan \beta$  in the Higgs sector,  
gauge-invariant,  
stable in higher orders

[A. F., D. Stöckinger '02]

1.  $A^0 Z$  unmixing

$$\frac{\delta \tan \beta}{\tan \beta} = \frac{1}{M_Z \sin 2\beta} \Sigma_{A^0 Z}(M_A^2)$$

→ gauge dependent,  
higher orders?

2. Requiring SUSY breaking parameter  $m_3$  to  
be gauge-independent

$$V_{\text{Higgs}} \supset m_3^2 H_1^0 H_2^0 + \text{h.c.}$$

Diagonalization of mass matrices yields

$$M_A^2 = \sin^2 \beta \frac{t_1}{\sqrt{2} v_1} + \cos^2 \beta \frac{t_2}{\sqrt{2} v_2} \\ - m_3^2 (\tan \beta + 1/\tan \beta)$$

→  $\tan \beta$  gauge-independent,  
but large loop corrections,  
large scale dependence

combination of quantities of the Higgs sector (self-energies, tadpoles, residues)

3.  $\overline{MS}$  Renormalization for  $\tan \beta$

→ small scale dependence

independent on  $R_\xi$  gauge at 1-loop,

but gauge dependent in general

4. Define  $\tan \beta$  via physical process,

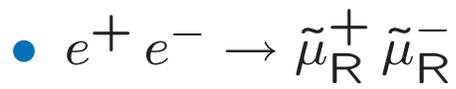
e. g.  $A^0 \rightarrow \tau\tau$

→ process-dependent,

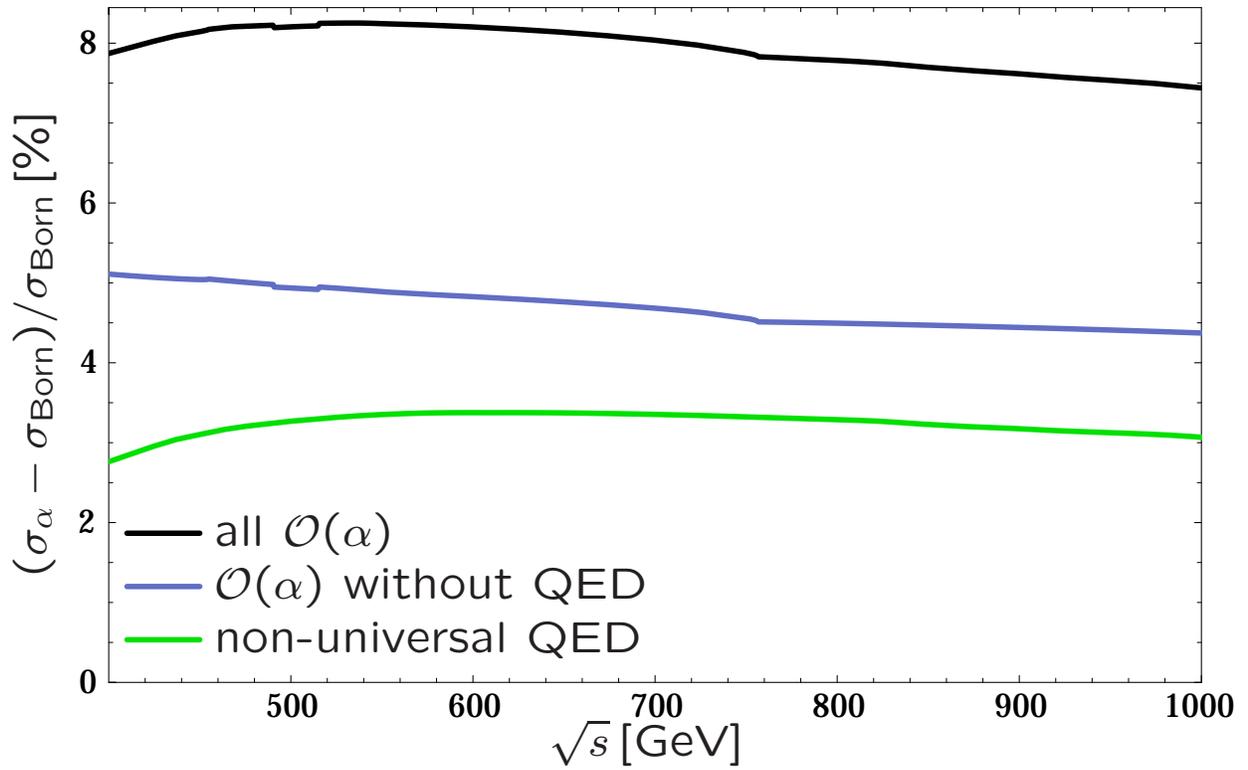
requires 3-point functions

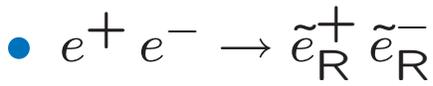
(problem beyond 1-loop)

→ No scheme meets all requirements

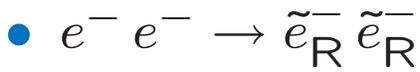
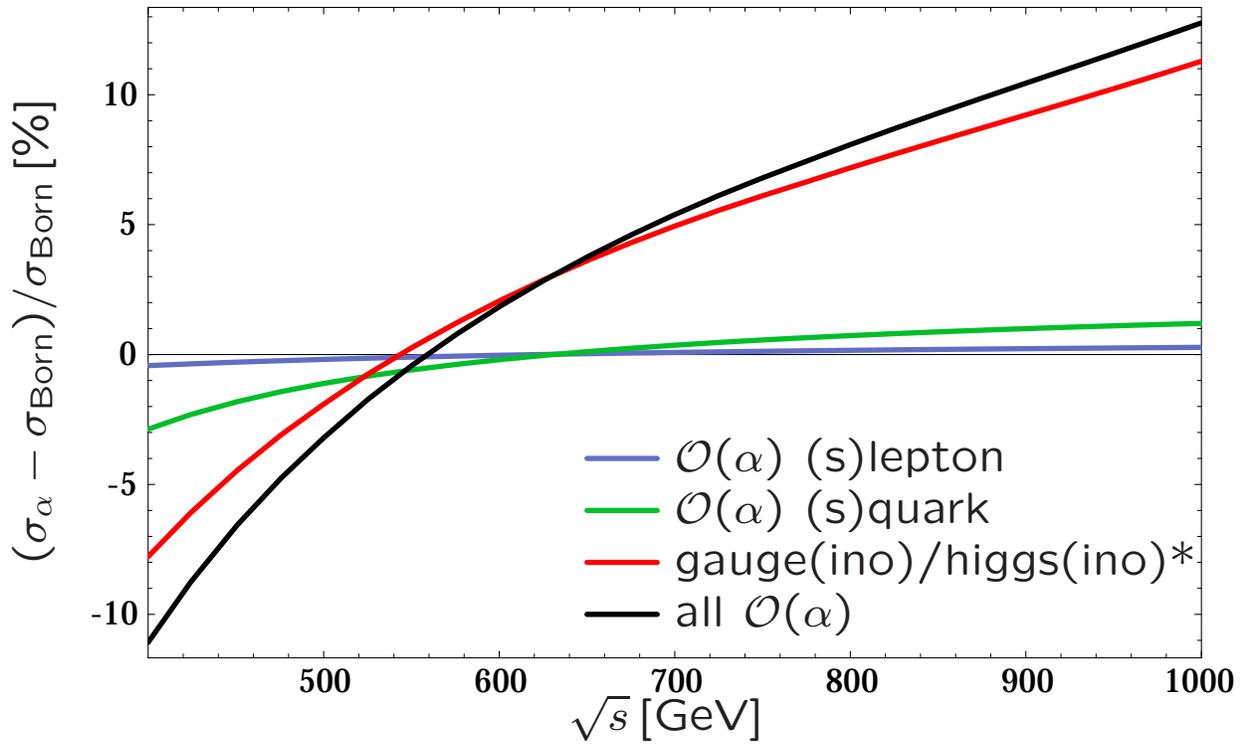


[SPS1 scenario]

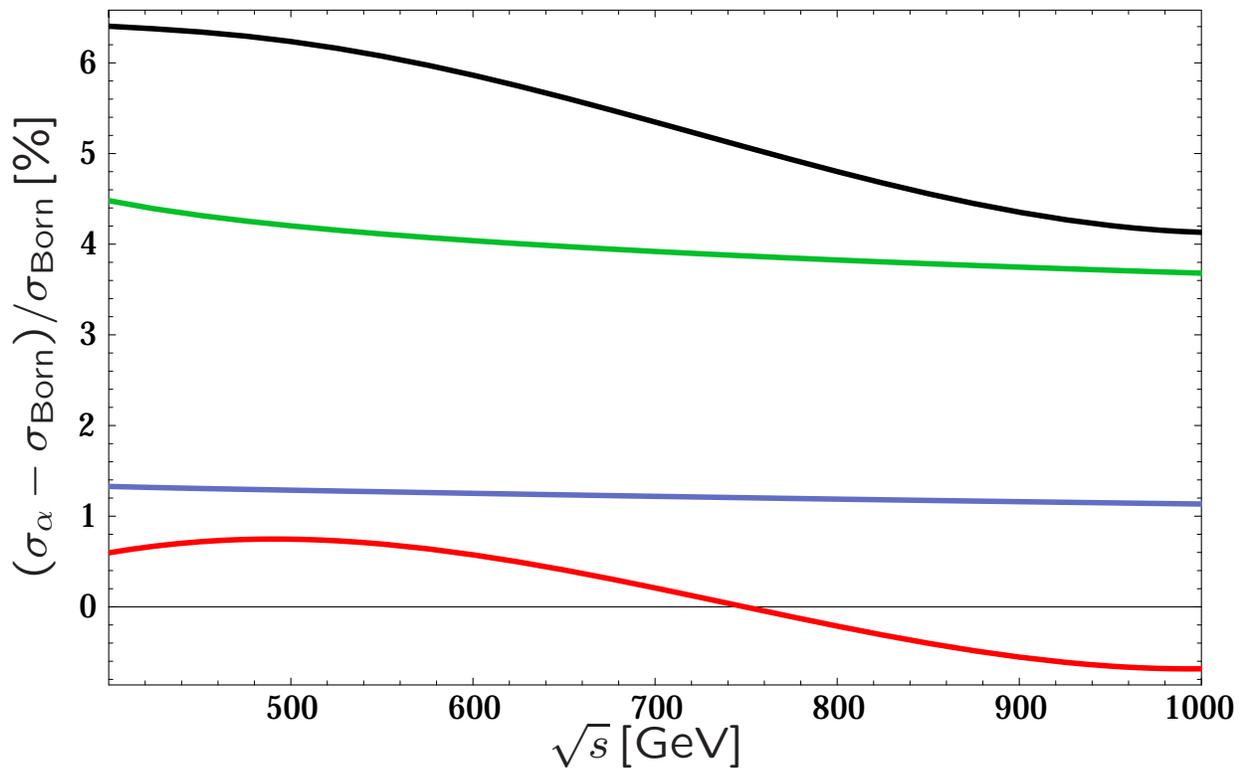




[SPS1 scenario]

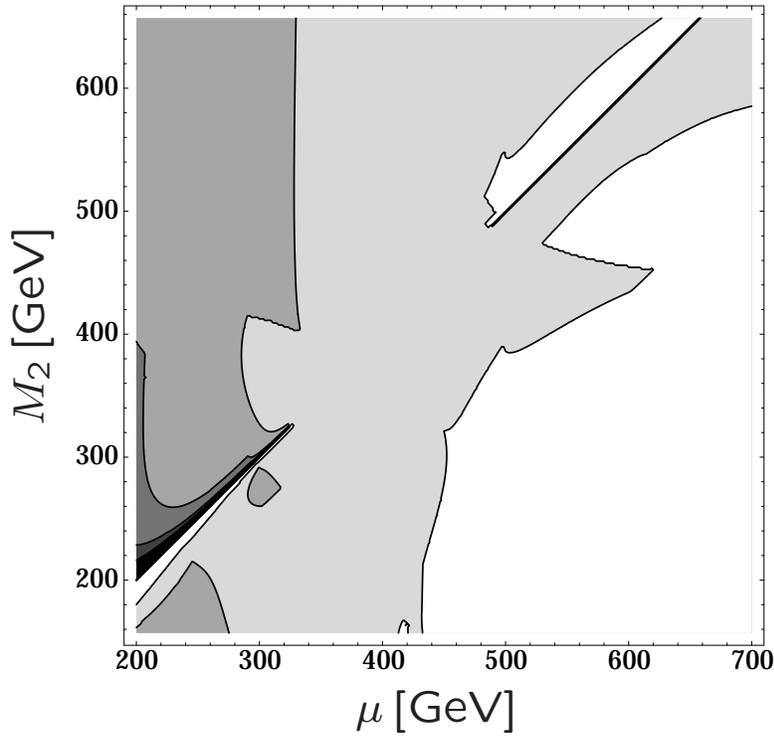


(\* incl. QED)

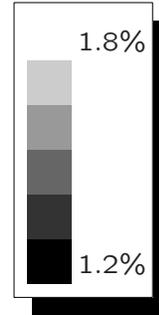


- $e^+ e^- \rightarrow \tilde{e}_R^+ \tilde{e}_R^-$

$$\sqrt{s} = 600 \text{ GeV}$$

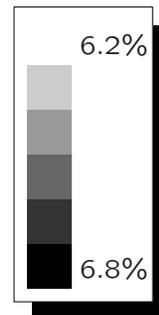
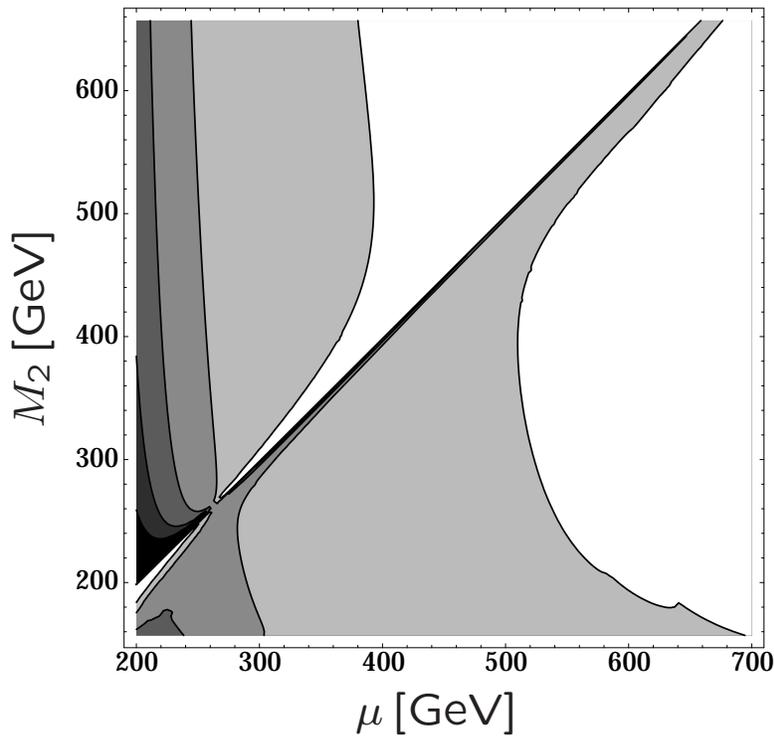


$$\frac{\sigma_\alpha - \sigma_{\text{Born}}}{\sigma_{\text{Born}}} [\%]$$



- $e^- e^- \rightarrow \tilde{e}_R^- \tilde{e}_R^-$

$$\sqrt{s} = 400 \text{ GeV}$$

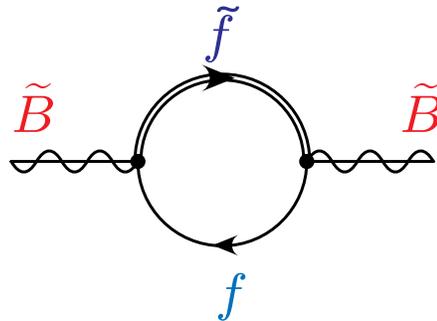


Non-decoupling corrections from fermion/sfermion loops,

$$\propto \log \frac{m_{\tilde{f}}}{m_{\text{weak}}}$$

in neutralino loop corrections

e. g. for U(1):



→ Equivalence of effective gauge and Yukawa couplings

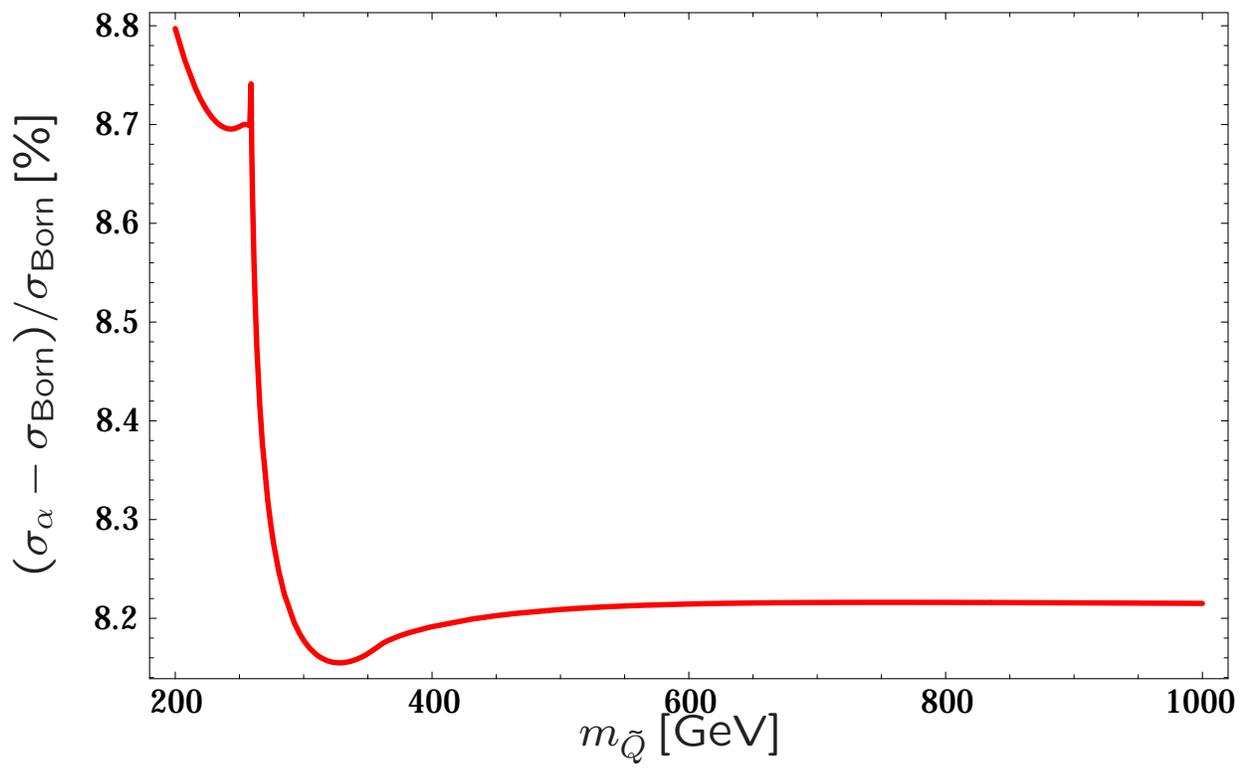
$$g_{\text{gauge}} = \hat{g}_{\text{Yuk}}$$

modified at higher orders:

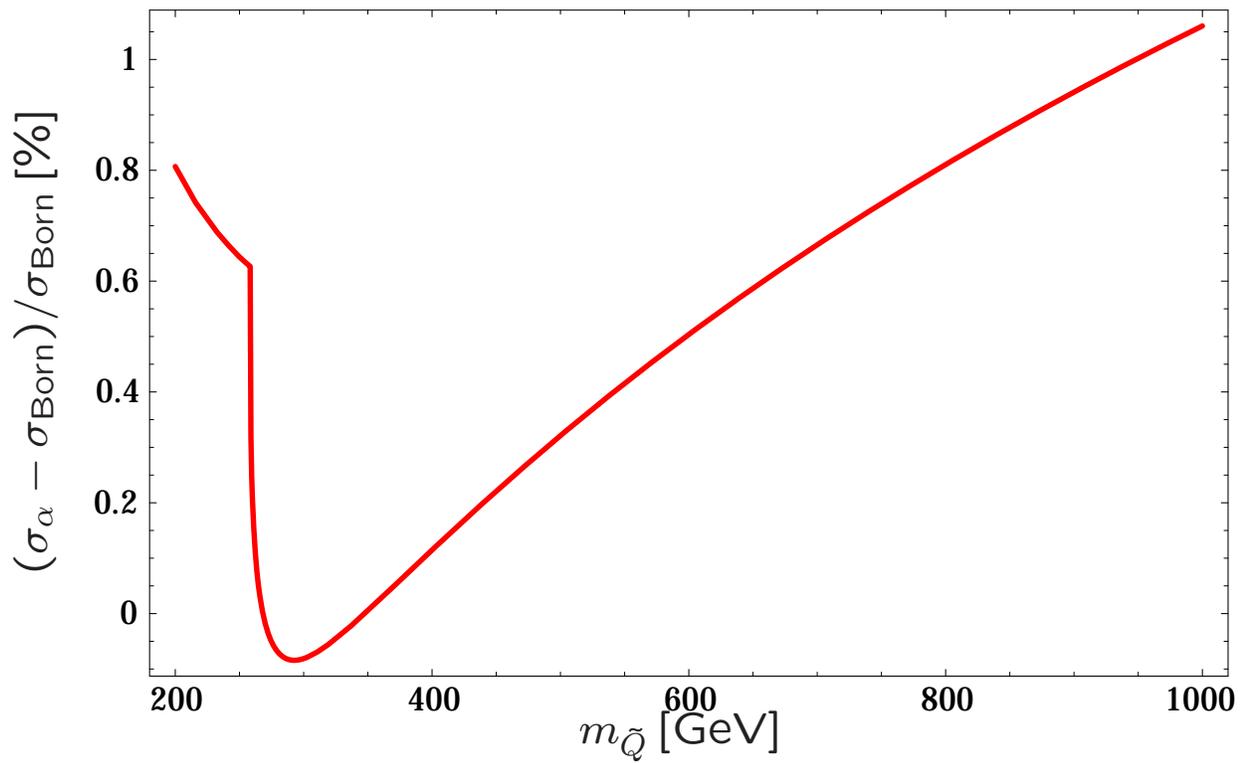
$$g_{\text{gauge,eff}} \neq \hat{g}_{\text{Yuk,eff}}$$

Additional corrections  $\propto \log \frac{m_{\tilde{f}}}{m_{\text{weak}}}$  from neutralino mass relations.

→ Large log corrections are in general non-universal



- $e^- e^- \rightarrow \tilde{e}_R^- \tilde{e}_R^-$



- Precision studies of  $\tilde{\mu}$  and  $\tilde{e}$  pair production possible at future LC
  - Important for test of SUSY and reconstruction of breaking mechanism
- Determination of
  - masses
  - couplingsat **per-cent** or even **per-mille** level
- Accurate theoretical prediction necessary
- Complete radiative  $\mathcal{O}(\alpha)$  corrections to on-shell  $\tilde{\mu}$  and  $\tilde{e}$  production
  - Corrections to cross-section of 5–10%
  - Sizeable effects from sparticles in loops