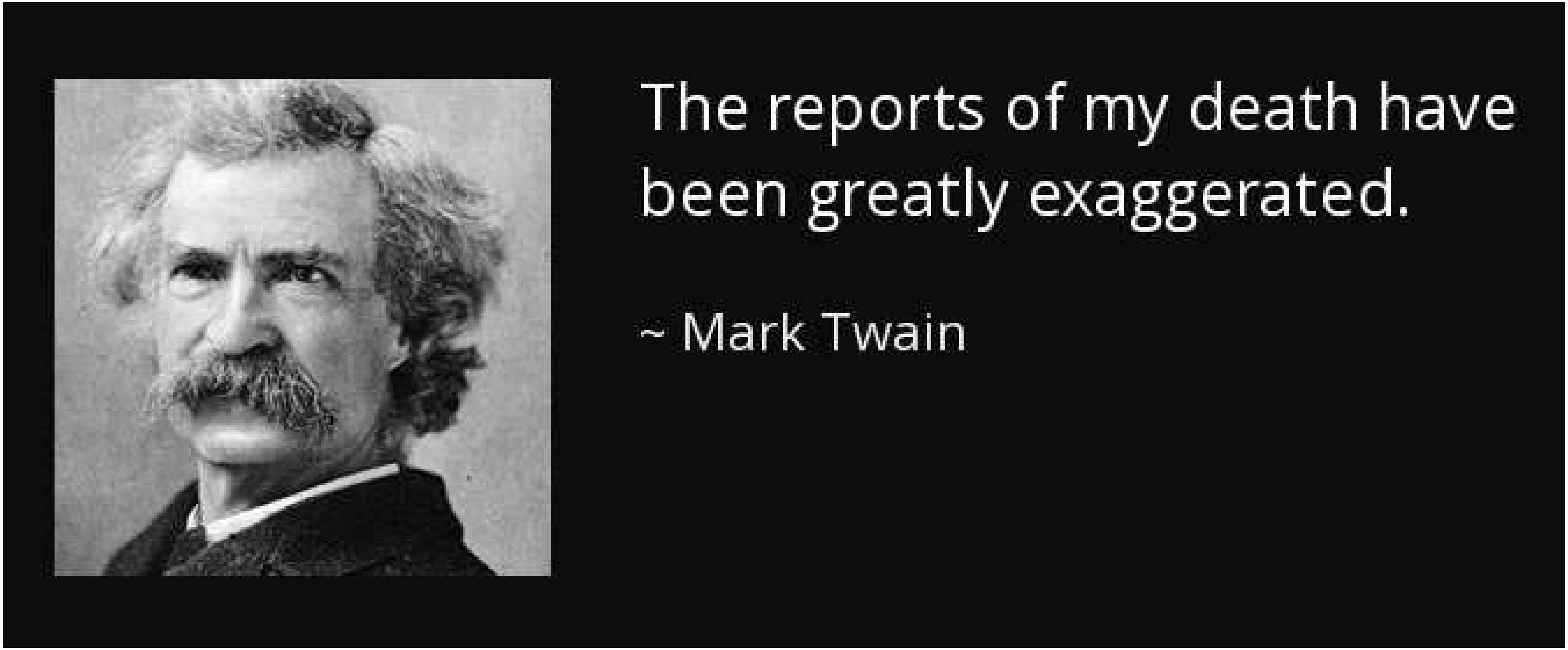
Some original SUSY literature:



Automated High-Precision SUSY Production Cross Sections

Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)

St. Goar, 05/2018

based on collaboration with *C. Schappacher*

- Motivation
- Automated calculation of SUSY production cross sections
- Electroweakino production
- Slepton production
- Conclusions

1. Motivation

Fact:

The SM cannot be the ultimate theory!

1. gravity is not included

2. the hierarchy problem

3. Dark Matter is not included

4. neutrino masses are not included

5. anomalous magnetic moment of the muon shows a $\sim 4\,\sigma$ discrepancy

$\Rightarrow$ Time to get ready for BSM physics

Which model should we focus on?

Some "recent" measurements:

– top quark mass
– Higgs boson mass
– Higgs boson "couplings"
– Dark Matter (properties)

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- Higgs boson mass
- Higgs boson "couplings"
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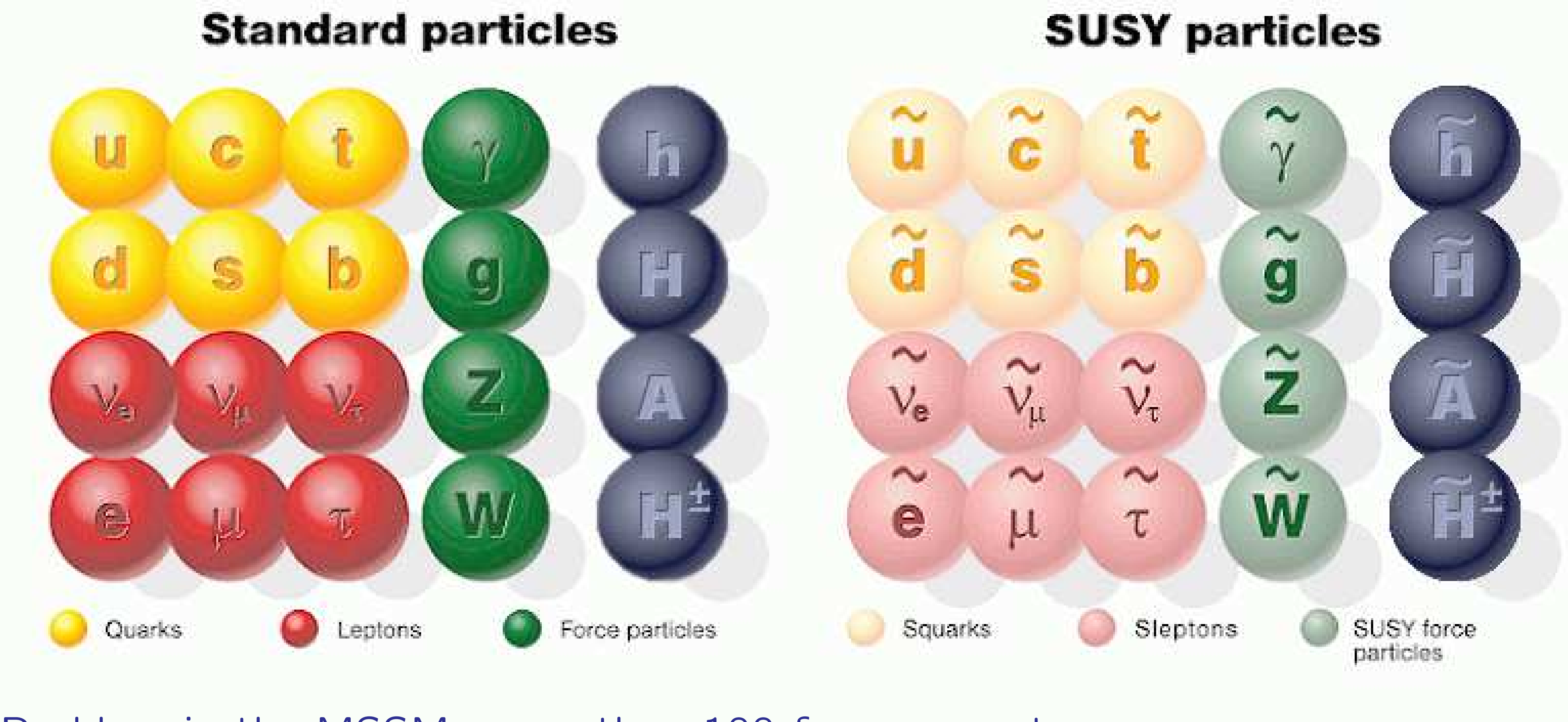
$\Rightarrow$ **good motivation to look at SUSY! :-)**

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles



Problem in the MSSM: more than 100 free parameters

⇒ makes theory calculations intrinsicly complicated

GUT based models? Does not help from the calculation point of view . . .

Current at future collider experiments:

LHC (Large Hadron Collider): running

pp collisions at 13 TeV

HL-LHC final high-luminosity phase: approved

HE-LHC new magnets $\Rightarrow$ 27 TeV possible?

ILC (International Linear Collider) decision 2018 in Japan

e^+e^- collisions at 250 GeV (final stage 1000 GeV)

CLIC (Compact LInear Collider)

e^+e^- collisions at 380 GeV (final stage 3000 GeV)

FCC-hh (Future Circular Collider)

pp collisions at 100 TeV

FCC-ee/CEPC (Future Circular Collider - CERN/China)

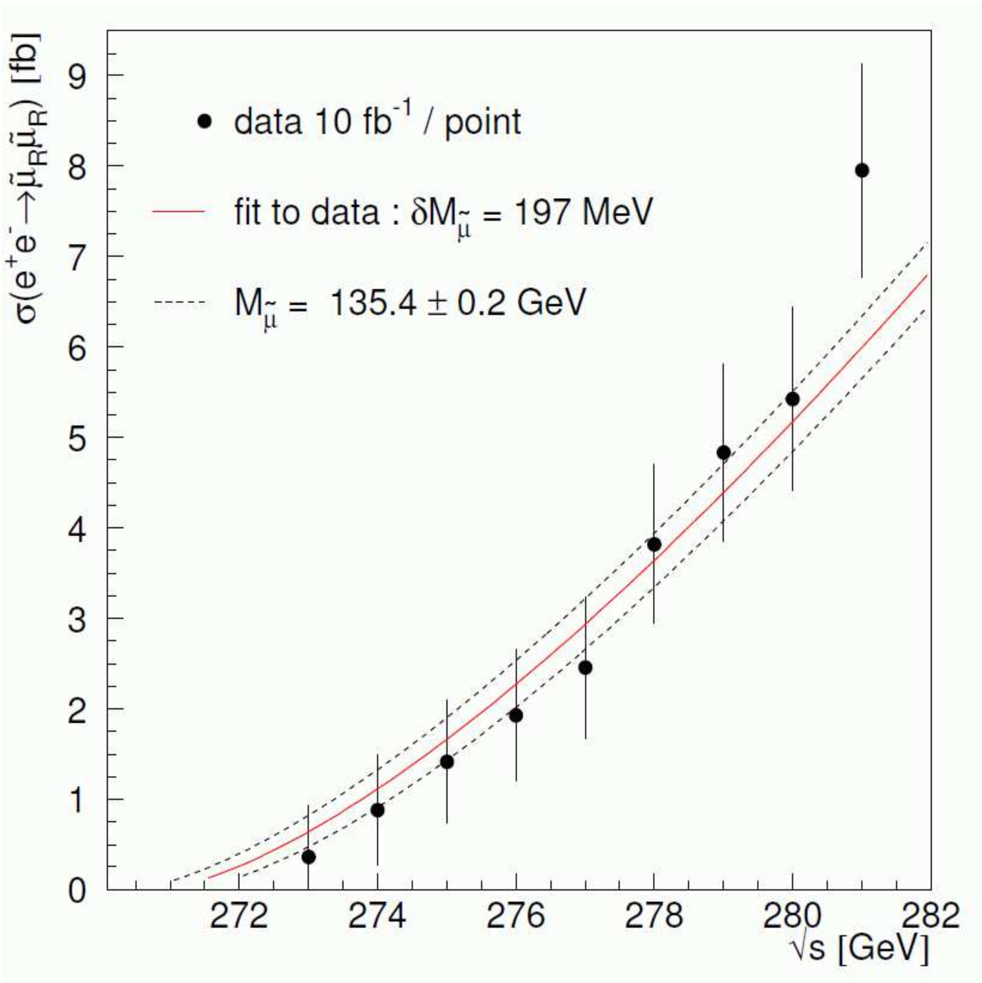
e^+e^- collisions at $\lesssim$ 350/250 GeV

$\Rightarrow$ Precision calculations particularly needed for e^+e^- colliders

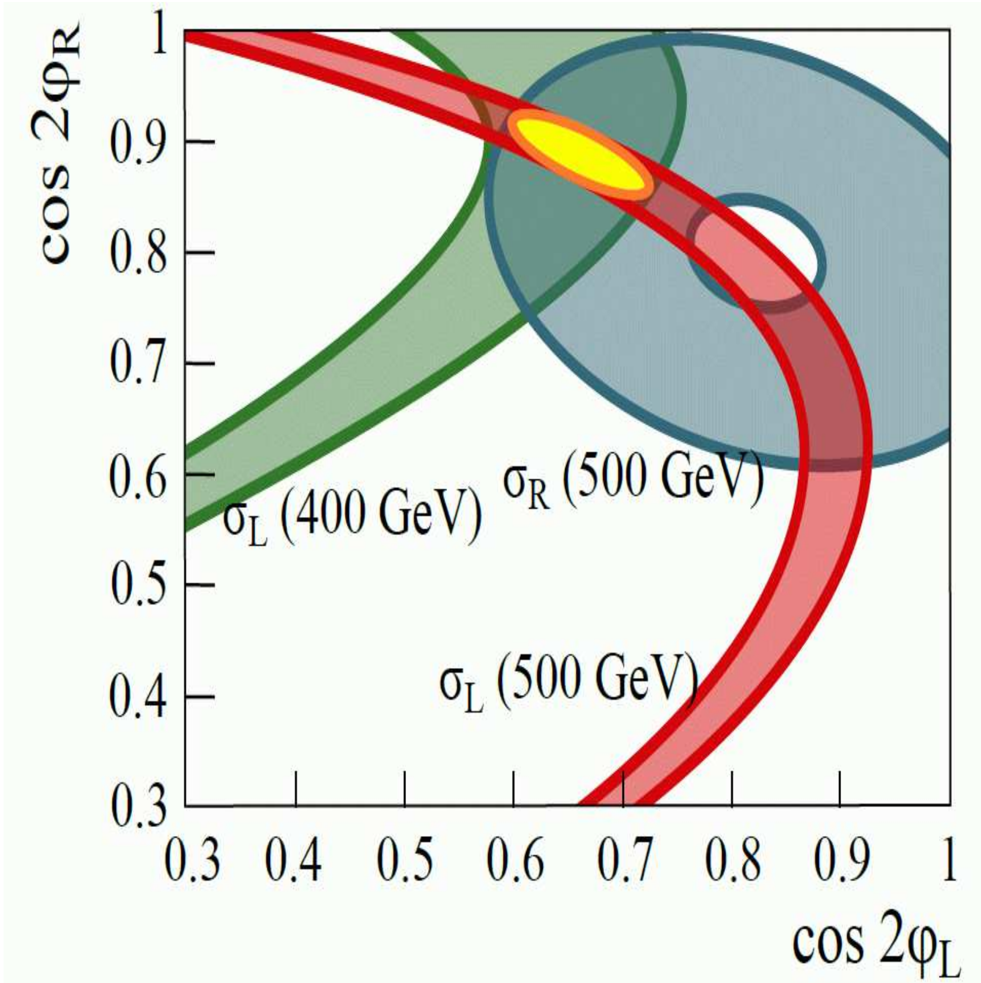
Precision ILC(/CLIC) analyses for SUSY particles:

[ILC TDR '13]

smuon mass



chargino parameter



⇒ (sub)per-cent precision possible at the ILC

⇒ Theory predictions at the same level of accuracy crucial!

Where are we for SUSY production/decay?

Over the last years several processes have been evaluated consistently at the full one-loop level in the cMSSM

[*S.H., C. Schappacher et al. (A. Bharucha, F. v.d. Pahlen, H.Rzehak) '10-'18*]

1. Higgs decays to SUSY
2. Sfermion decays
3. Gluino decays
4. Chargino/neutralino decays
5. Neutral/charged Higgs production (e^+e^-, $2 \to 2$)
6. Chargino/neutralino production (e^+e^-) $\Leftarrow$ NEW
7. Slepton production (e^+e^-) $\Leftarrow$ NEW

2. Automated calculation of SUSY production cross sections

Generic problems for SUSY loop calculations:

- SUSY has to be preserved in the calculation
- Many different mass scales
- Many more mass scales than free parameters
- Even more parameters: mixing angles, complex phases
- Renormalization is much more involved than in the SM
  - much less explored than in the SM
  - has to preserve/respect mass relations
  - depend on mass scales realized in Nature
  - sometimes no really good solution exist (e.g. $\tan\beta$)
  - many sectors enter at the same time

  $\Rightarrow$ this is (was!) the biggest issue!

Renormalization summary:

- LHC/LC precision requires all calculations at the per-cent level
- full complex MSSM renormalized

  [*A. Bharucha, T. Fritzsche, T. Hahn, S.H., F.v.d. Pahlen, H. Rzehak, C. Schappacher '11 - '14*]
- stable and well behaved results over nearly complete parameter space
- available as FeynArts model file

  [*T. Fritzsche, T. Hahn, S.H., F.v.d. Pahlen, H. Rzehak, C. Schappacher '13*]
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$\Rightarrow$ **go and make your prediction!**

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– still missing: automated choice of Renormalization Scheme

$\Rightarrow$ **go and make your prediction!**

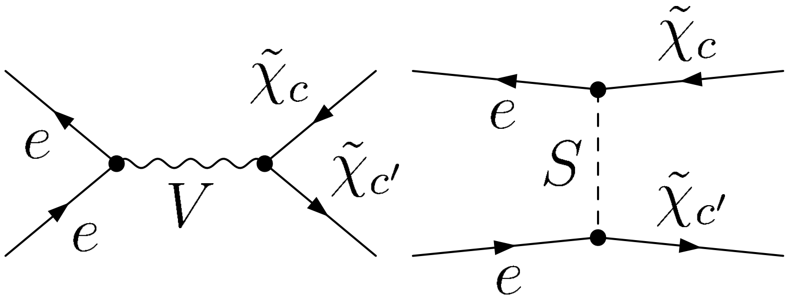
$\Rightarrow$ **and so we did!**

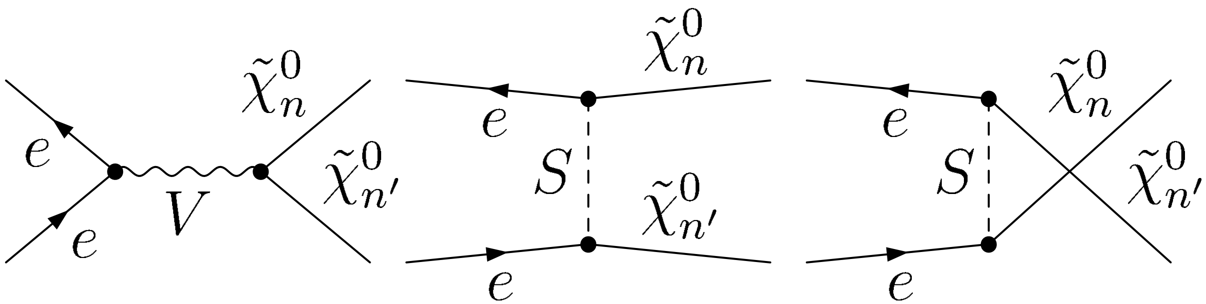
3. Charginos/neutralino production

[arXiv:1704.07627]

$$e^+e^- \to \tilde{\chi}_c^- \tilde{\chi}_{c'}^+ \quad (i = 1, 2, 3;\; c, c' = 1, 2)$$

$$e^+e^- \to \tilde{\chi}_n^0 \tilde{\chi}_{n'}^0 \quad (i = 1, 2, 3;\; n, n' = 1, 2, 3, 4)$$





Some comments on the chargino/neutralino renormalization:

4+2 masses, but only 3 free parameters: M_1, M_2, μ

$\Rightarrow$ OS renormalization for 3 masses:

CCN1: $$\left(\left[\widetilde{\text{Re}}\hat{\Sigma}_{\tilde{\chi}^-}(p)\right]_{ii}\tilde{\chi}_i^-(p)\right)\Big|_{p^2=m^2_{\tilde{\chi}_i^\pm}} = 0 \qquad (i = 1, 2)\ ,$$

$$\left(\left[\widetilde{\text{Re}}\hat{\Sigma}_{\tilde{\chi}^0}(p)\right]_{11}\tilde{\chi}_1^0(p)\right)\Big|_{p^2=m^2_{\tilde{\chi}_1^0}} = 0$$

$\Rightarrow$ Scheme can easily be extended to other variants, e.g.

CCNi $(i = 1, 2, 3, 4)$ or CNNijk $(i = 1, 2; j, k = 1, 2, 3, 4)$

$\to$ relevant for $|\mu| \approx M_2$ (see also: [*Drees et al. '11*])

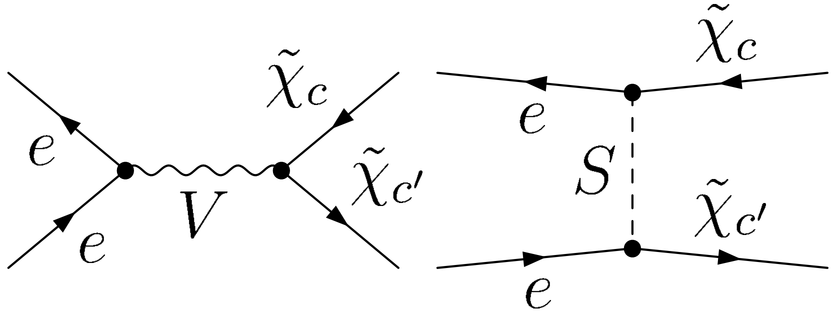
$\Rightarrow$ included into our set-up

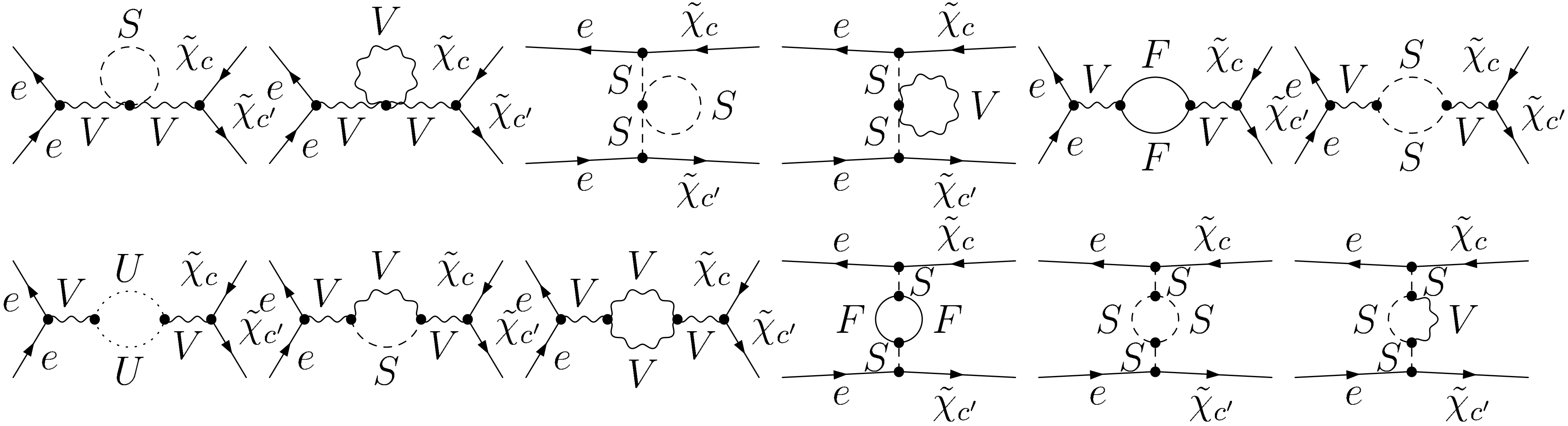
$\Rightarrow$ Scheme requires a shift of three (neutralino) masses to their OS value:

$$\Delta m_{\tilde{\chi}_i^0} = -\frac{1}{2}\text{Re}\Big\{m_{\tilde{\chi}_i^0}\left(\hat{\Sigma}^L_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0}) + \hat{\Sigma}^R_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0})\right) + \hat{\Sigma}^{SL}_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0}) + \hat{\Sigma}^{SR}_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0})\Big\}$$

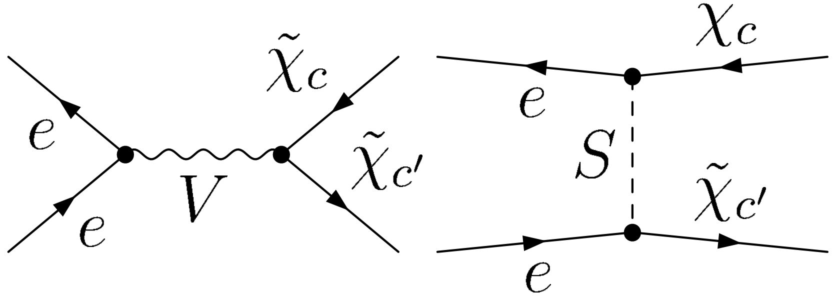
$$m^{\text{OS}}_{\tilde{\chi}_i^0} = m_{\tilde{\chi}_i^0} + \Delta m_{\tilde{\chi}_i^0}$$

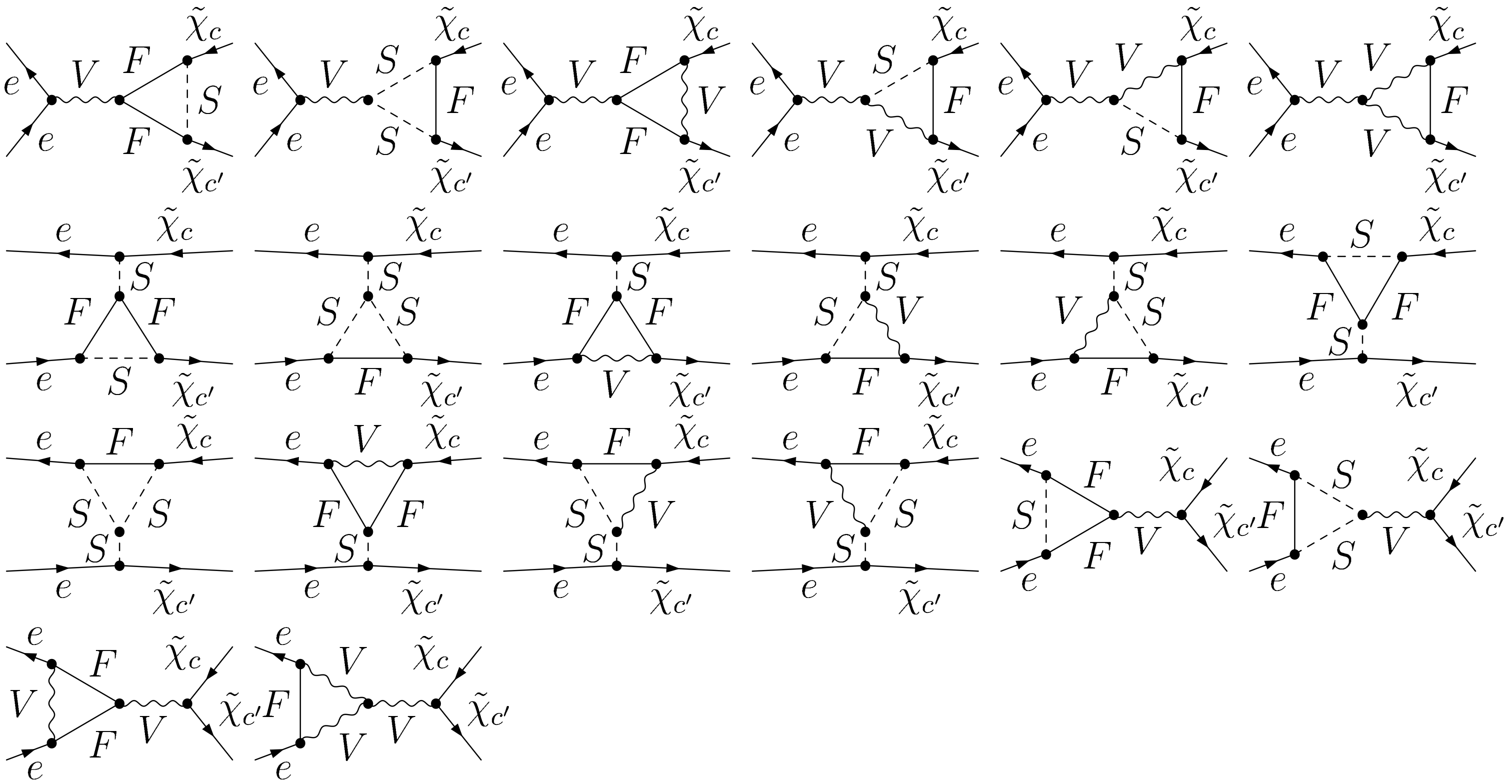
$e^+e^- \to \tilde{\chi}_c^{\pm}\tilde{\chi}_{c'}^{\mp}$:



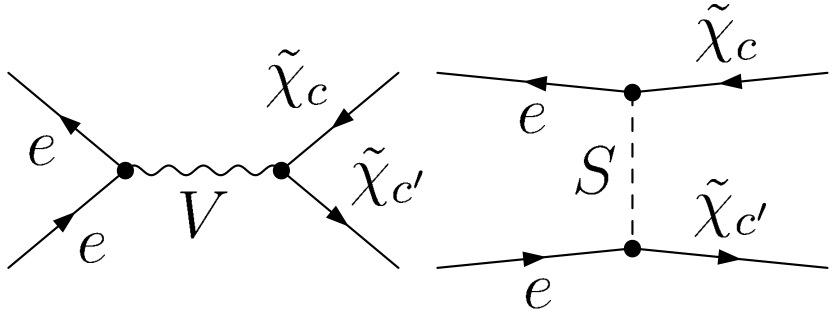


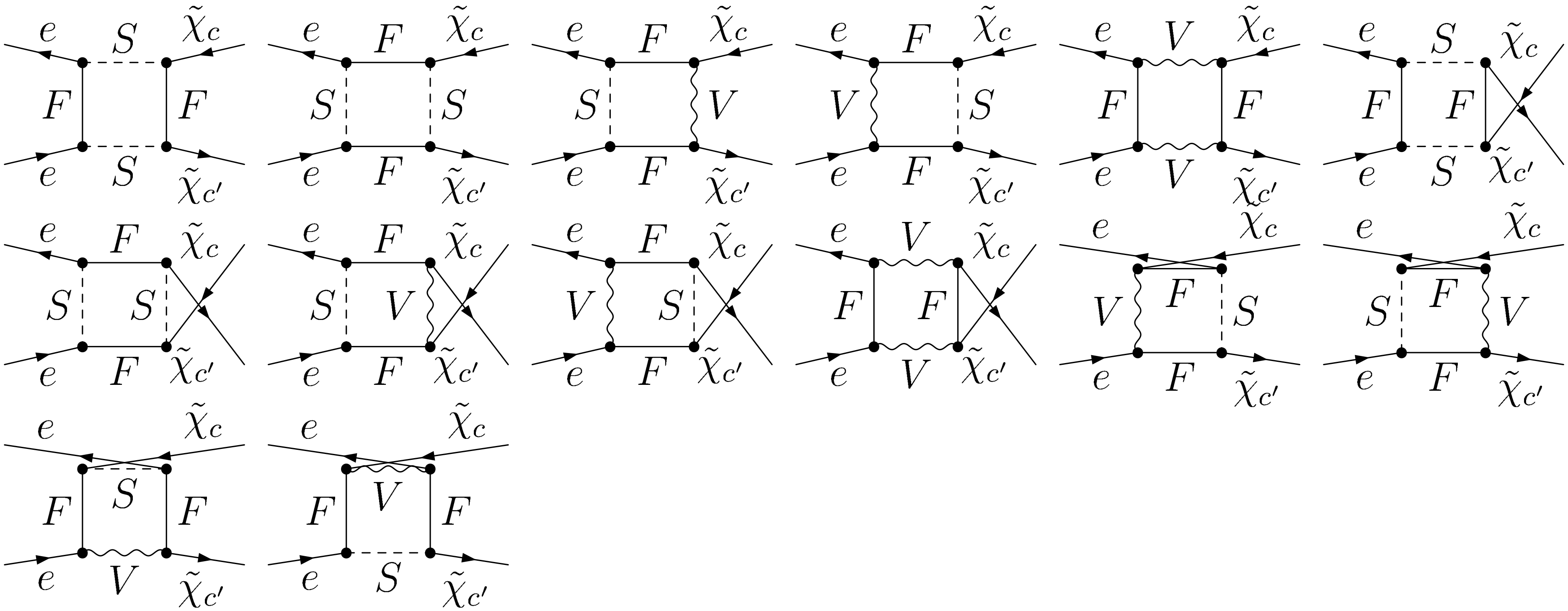
$e^+e^- \to \tilde{\chi}^\pm_c \tilde{\chi}^\mp_{c'}$:



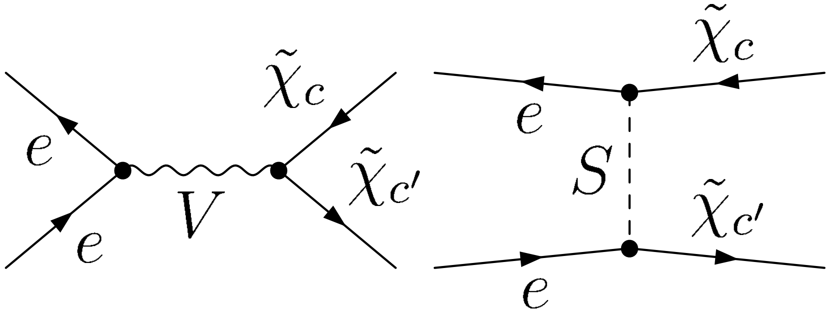


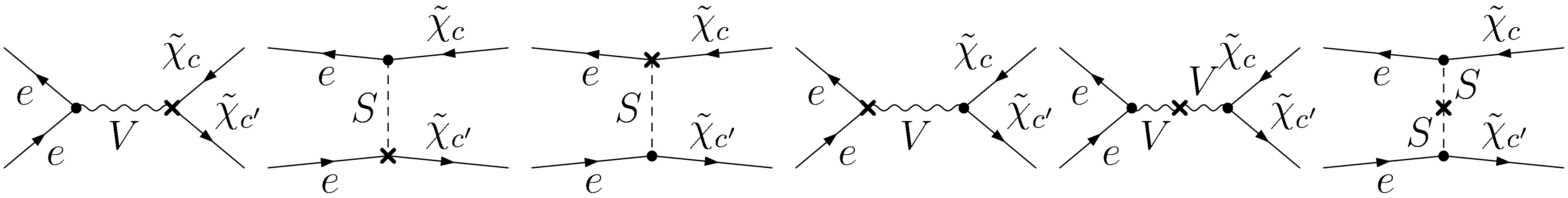
$e^+e^- \to \tilde{\chi}_c^{\pm}\tilde{\chi}_{c'}^{\mp}$:





$e^+e^- \to \tilde{\chi}_c^{\pm}\tilde{\chi}_{c'}^{\mp}$:





+ soft and hard QED radiation

Comparison with the literature (mostly rMSSM, 1-loop)

⇒ many papers give too few details to make a comparison possible . . .

[S. Kiyoura et al. '98] : $e^+e^- \to \tilde{\chi}_c^\pm \tilde{\chi}_{c'}^\mp$ $(q/\tilde{q})$: good agreement

[T. Blank, W. Hollik '00] : $e^+e^- \to \tilde{\chi}_n^0 \tilde{\chi}_{n'}^0$, $e^+e^- \to \tilde{\chi}_c^\pm \tilde{\chi}_{c'}^\mp$: bad/good agreement for for small/large M_{SUSY} ("too different" RS?)

[M. Diaz, D. Ross '02] : $e^+e^- \to \tilde{\chi}_c^\pm \tilde{\chi}_{c'}^\mp$: bad agreement

[W. Kilian, J. Reuter, T. Robens '06] : $e^+e^- \to \tilde{\chi}_c^\pm \tilde{\chi}_{c'}^\mp$: good ageement

[T. Fritzsche '04] : $e^+e^- \to \tilde{\chi}_n^0 \tilde{\chi}_{n'}^0$, $e^+e^- \to \tilde{\chi}_c^\pm \tilde{\chi}_{c'}^\mp$: good agreement

[W. Oller, H. Eberl, W. Majerotto '05] : $e^+e^- \to \tilde{\chi}_n^0 \tilde{\chi}_{n'}^0$, $e^+e^- \to \tilde{\chi}_c^\pm \tilde{\chi}_{c'}^\mp$: bad numerical agreement ("bad" RS?!)

[K. Rolbiecki, P. Osland, A. Vereshagin '07] : $A_{12}(e^+e^- \to \tilde{\chi}_c^\pm \tilde{\chi}_{c'}^\mp)$ (cMSSM) : good agreement

[A. Bharucha, A. Fowler, G. Moortgat-Pick, G. Weiglein '12] : $e^+e^- \to \tilde{\chi}_c^\pm \tilde{\chi}_{c'}^\mp$: significant differences, ok "after re-calculation"

[A. Bharucha et al. '12] : $e^+e^- \to \tilde{\chi}_c^\pm \tilde{\chi}_{c'}^\mp$, cMSSM : significant differences, ok "after re-calculation"

Numerical example scenario:

$\sqrt{s}$	$\tan\beta$	μ	$M_{H^\pm}$	$M_{\tilde{Q},\tilde{U},\tilde{D}}$	$M_{\tilde{L},\tilde{E}}$	$\lvert A_t\rvert$	A_b	A_τ	$\lvert M_1\rvert$	M_2	M_3
1000	10	450	500	1500	1500	2000	$\lvert A_t\rvert$	$M_{\tilde{L}}$	$\mu/4$	$\mu/2$	2000

	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\chi}_2^\pm}$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$
tree	212.760	469.874	110.434	213.002	455.162	469.226
CCN1	212.760	469.874	110.434	212.850	455.195	469.560

Parameters varied: $\sqrt{s}$, μ, $M_{\tilde{L},\tilde{E}}$, $\tan\beta$, φ_{M_1}, ϕ_{A_t}

– in agreement with exp. data

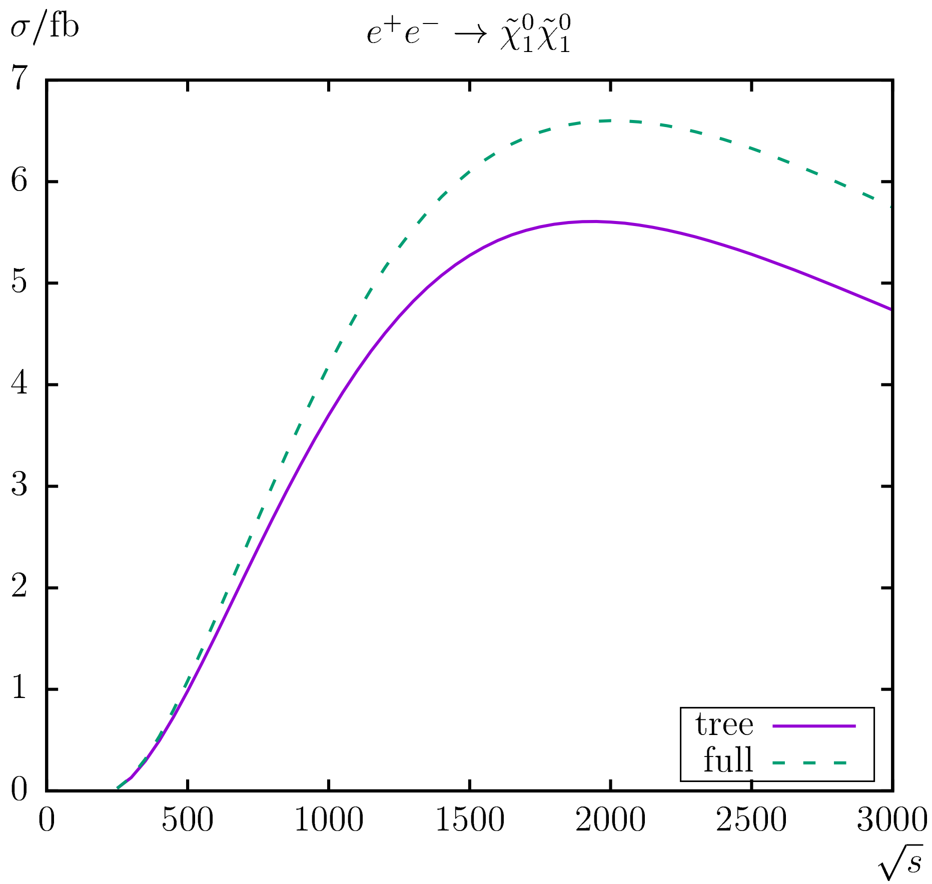
– opens up many (all) production channels

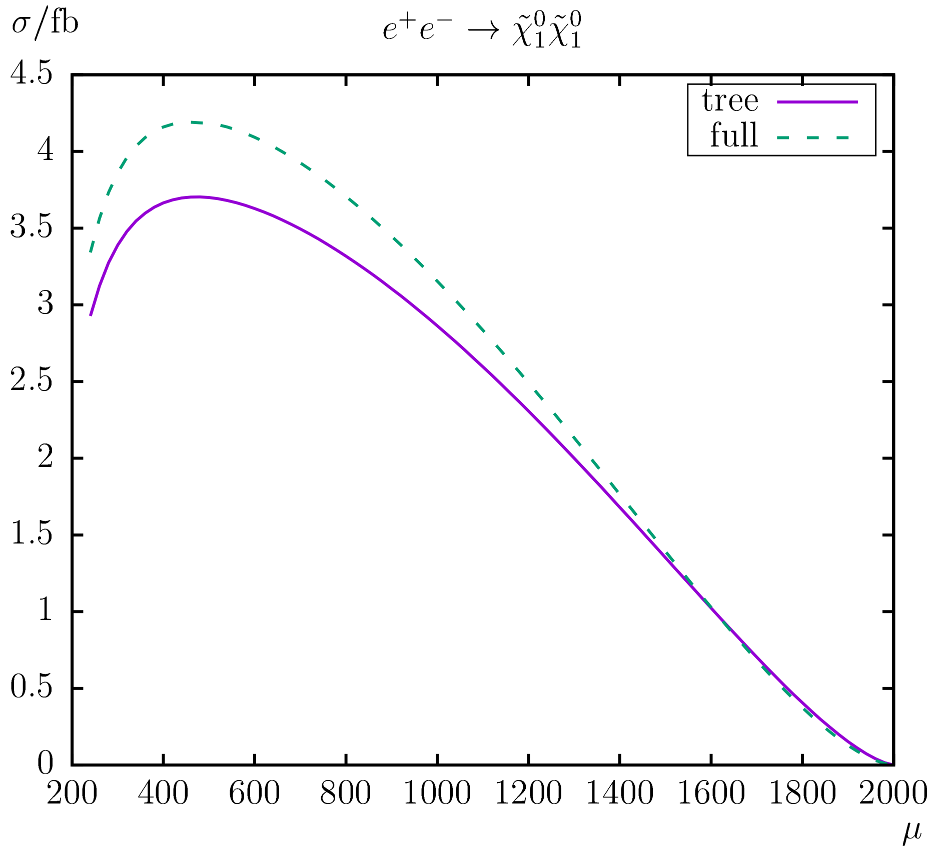
– relevant parameters varied

– ...

$\Rightarrow$ show some relevant examples

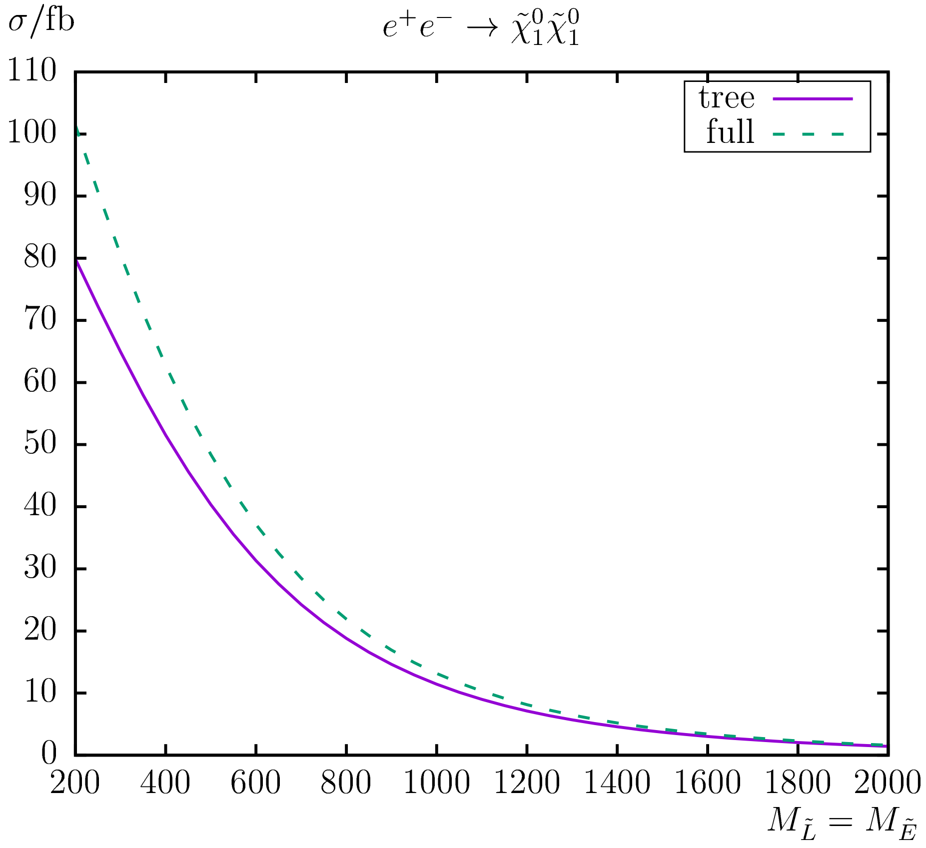
$\tilde{\chi}_1^0\tilde{\chi}_1^0$ production (I):

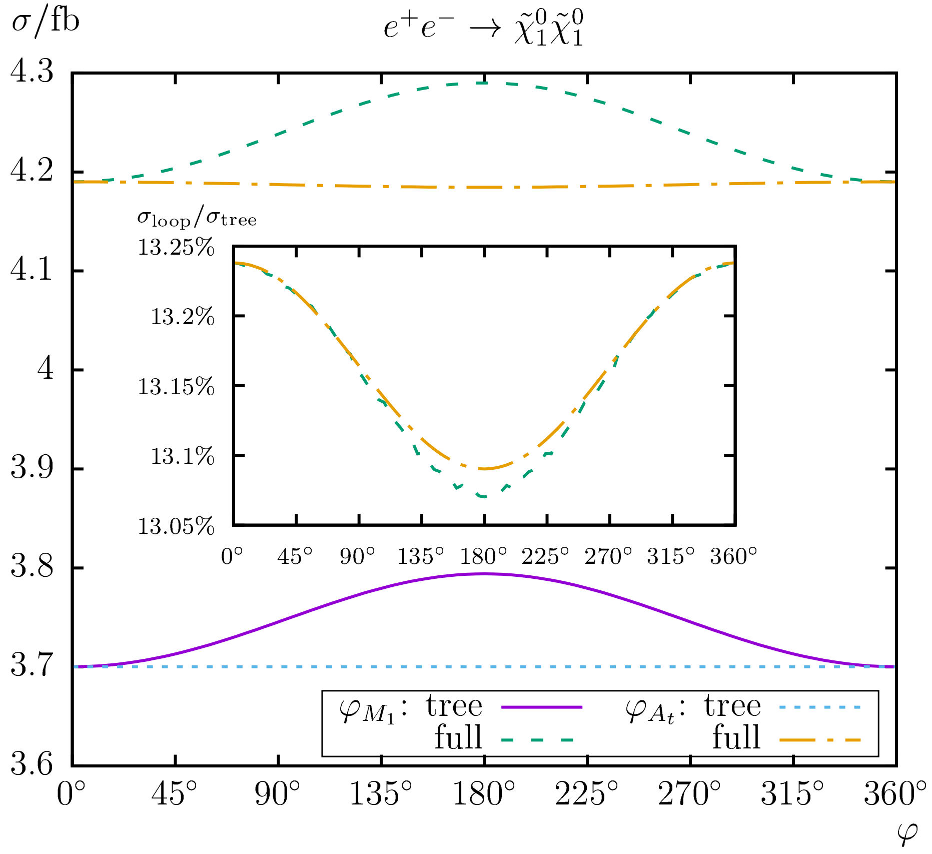




$\Rightarrow$ loop corrections $\sim$ 20%

$\tilde{\chi}_1^0\tilde{\chi}_1^0$ production (II):



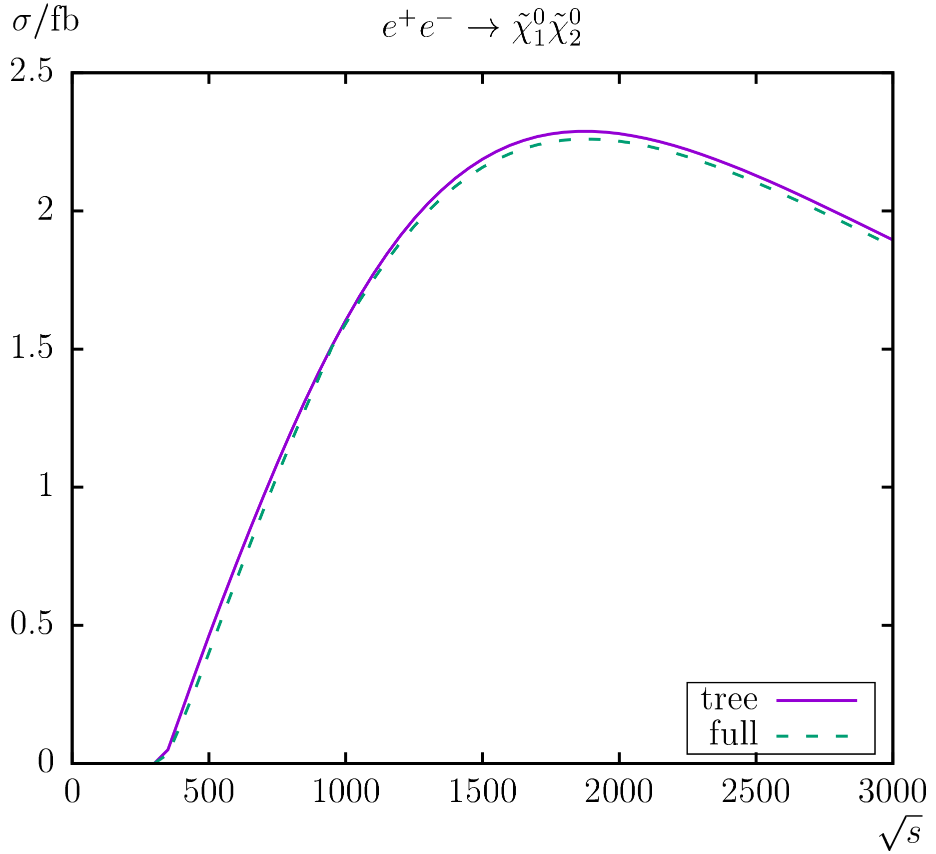


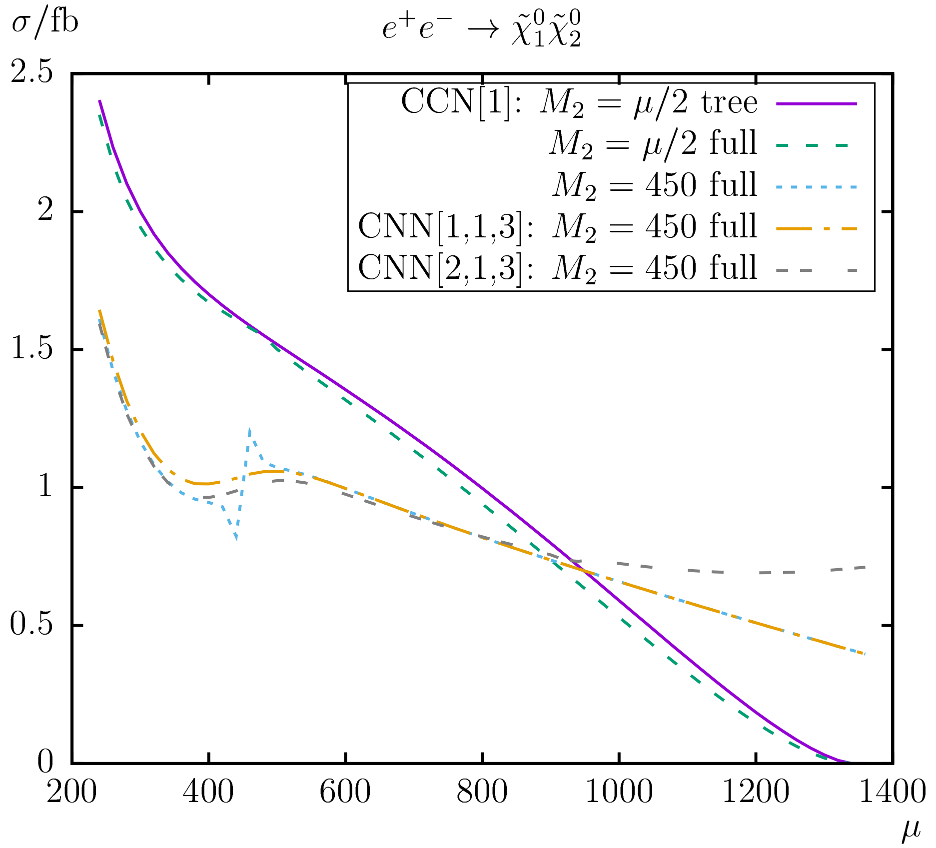
⇒ loop corrections $\sim$ 20%

⇒ strong t-channel dependence

⇒ relevant phase dependance at the tree-level

$\tilde{\chi}^0_1\tilde{\chi}^0_2$ production (I):

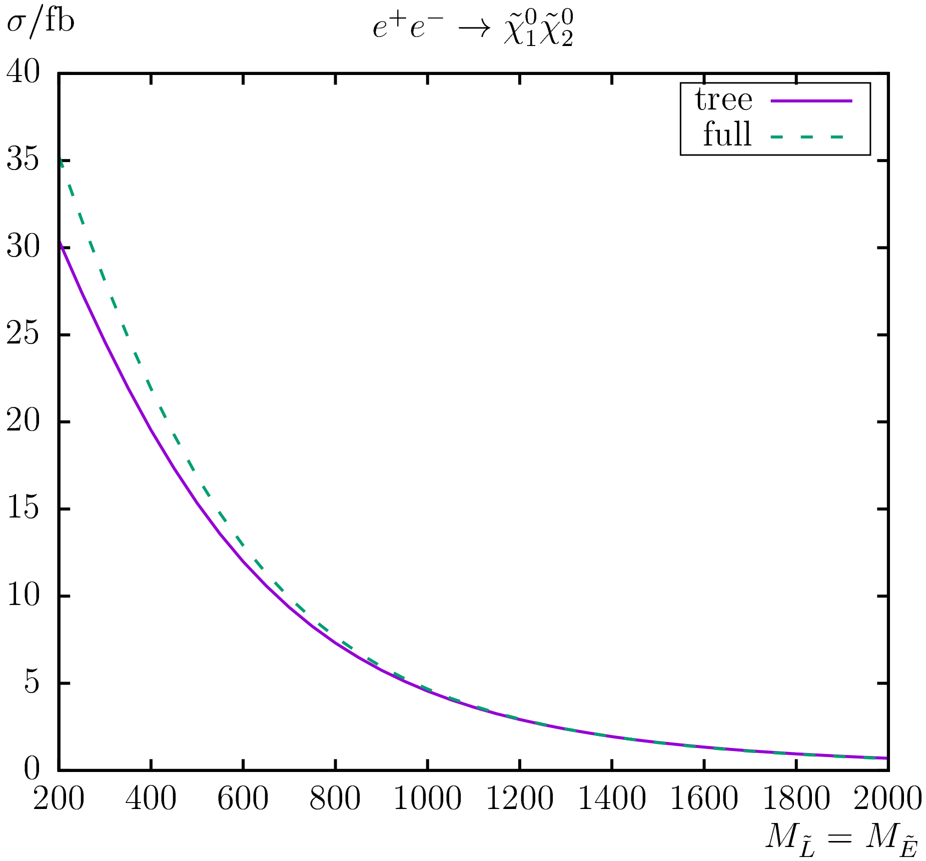


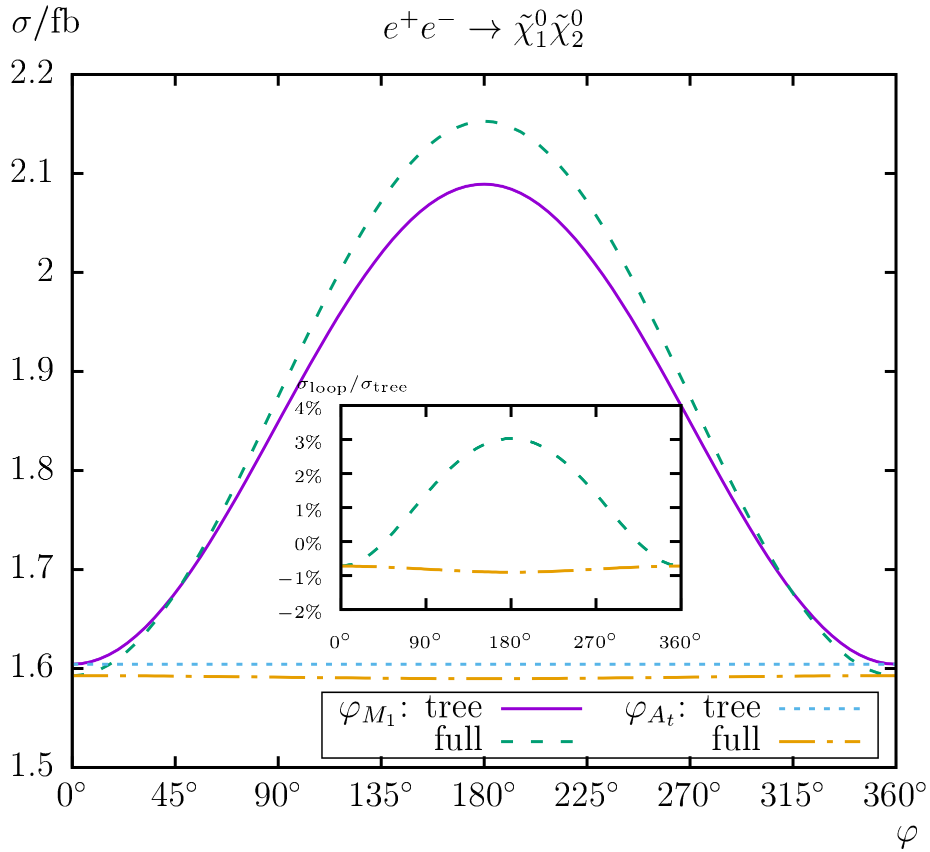


⇒ loop corrections small

⇒ CCN1 breaks down for $\mu = M_2$ ⇒ other schemes!

$\tilde{\chi}^0_1\tilde{\chi}^0_2$ production (II):



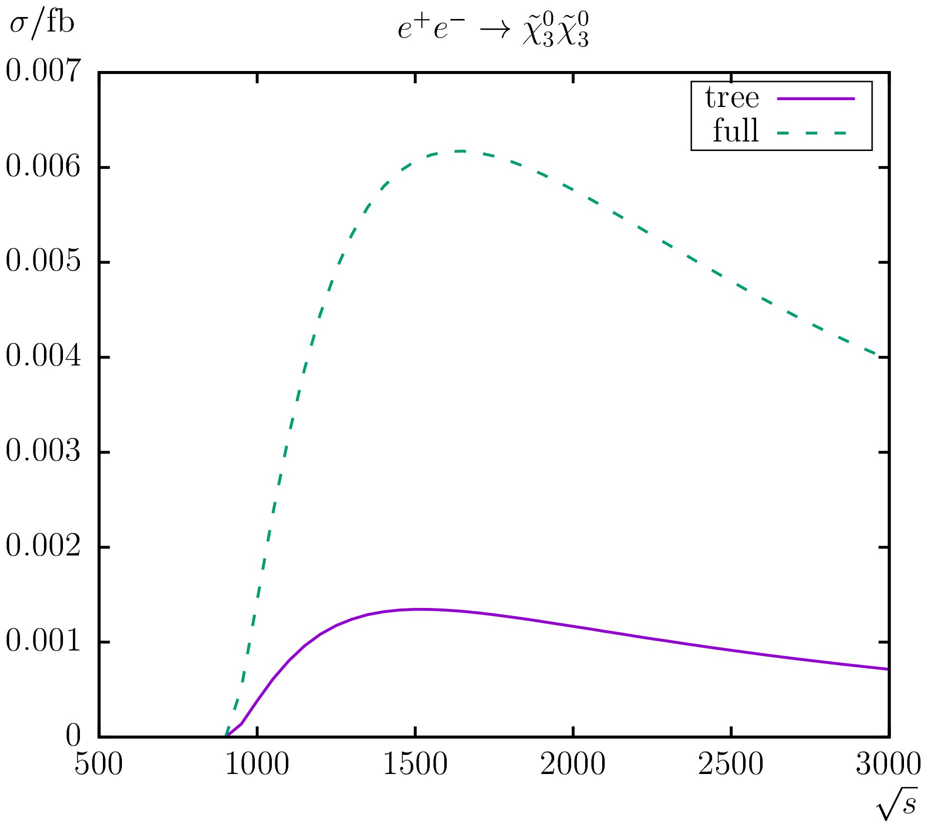


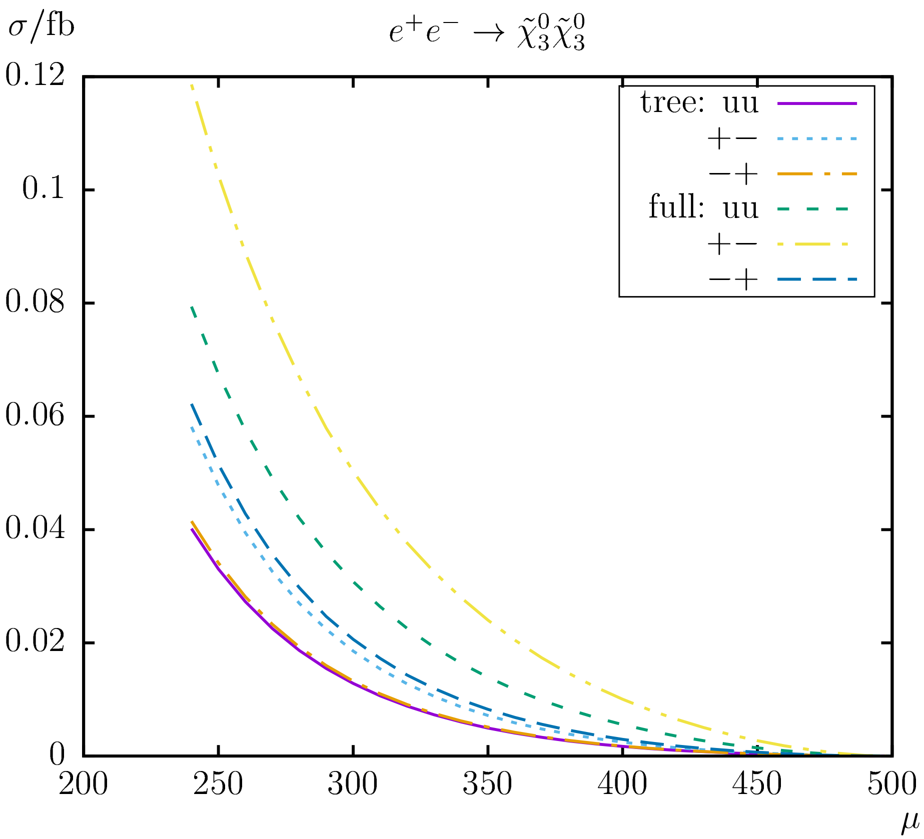
⇒ loop corrections $\lesssim$ 15%

⇒ strong t-channel dependence

⇒ relevant phase dependance at the tree- and loop-level

$\tilde{\chi}_3^0 \tilde{\chi}_3^0$ production:

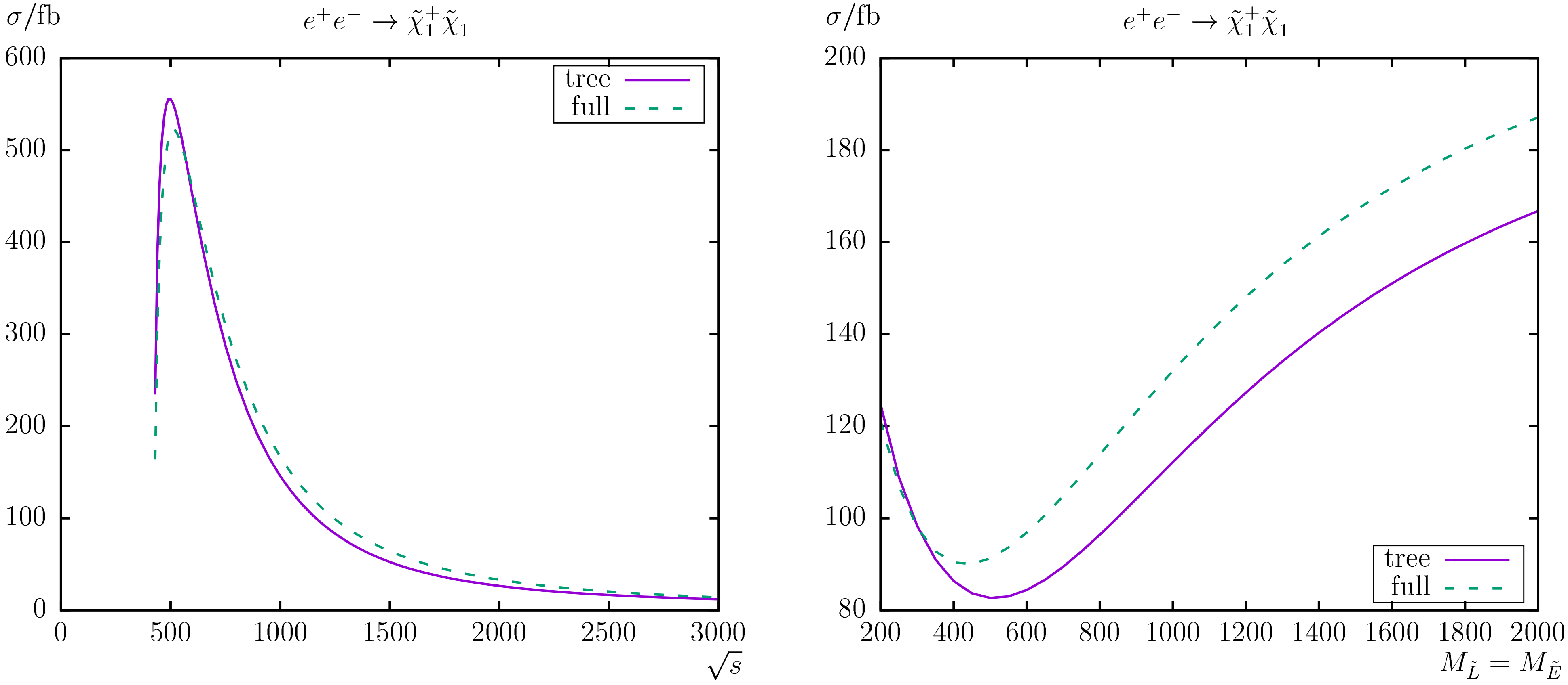




⇒ very small tree-level, huge loop corrections

⇒ polarization could be crucial to yield a detectable XS

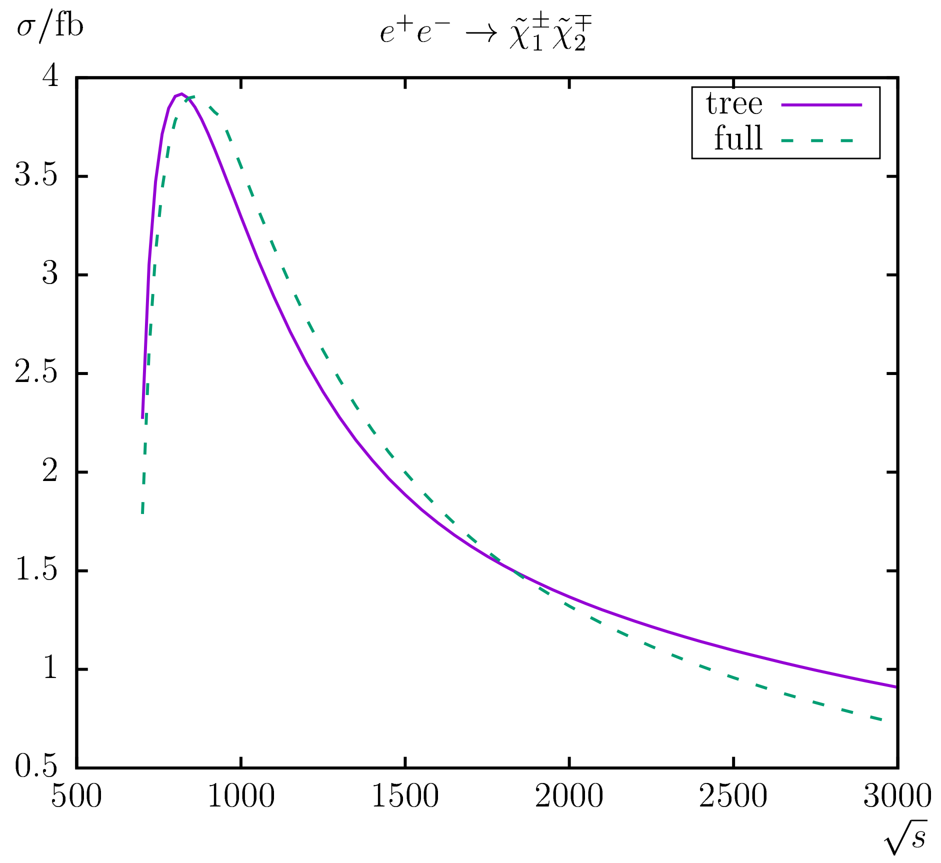
$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ production:

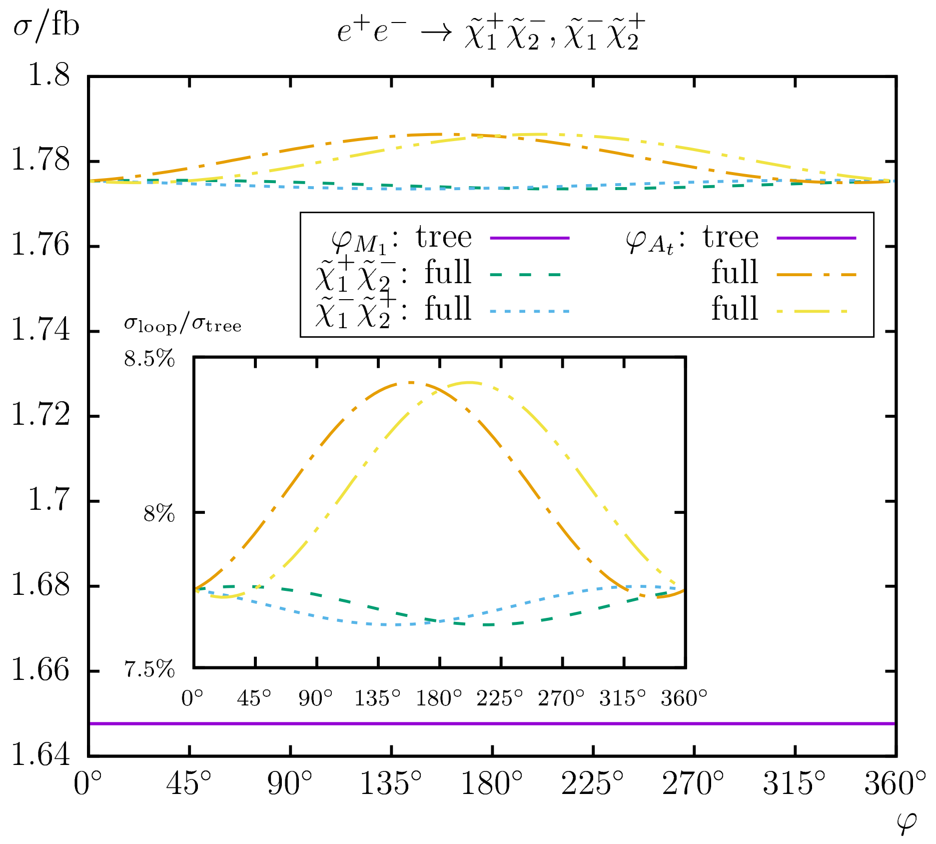


⇒ loop corrections $\sim$ 10%

⇒ strong t-channel dependance

$\tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$ production:





⇒ loop corrections $\sim \pm$ 10%

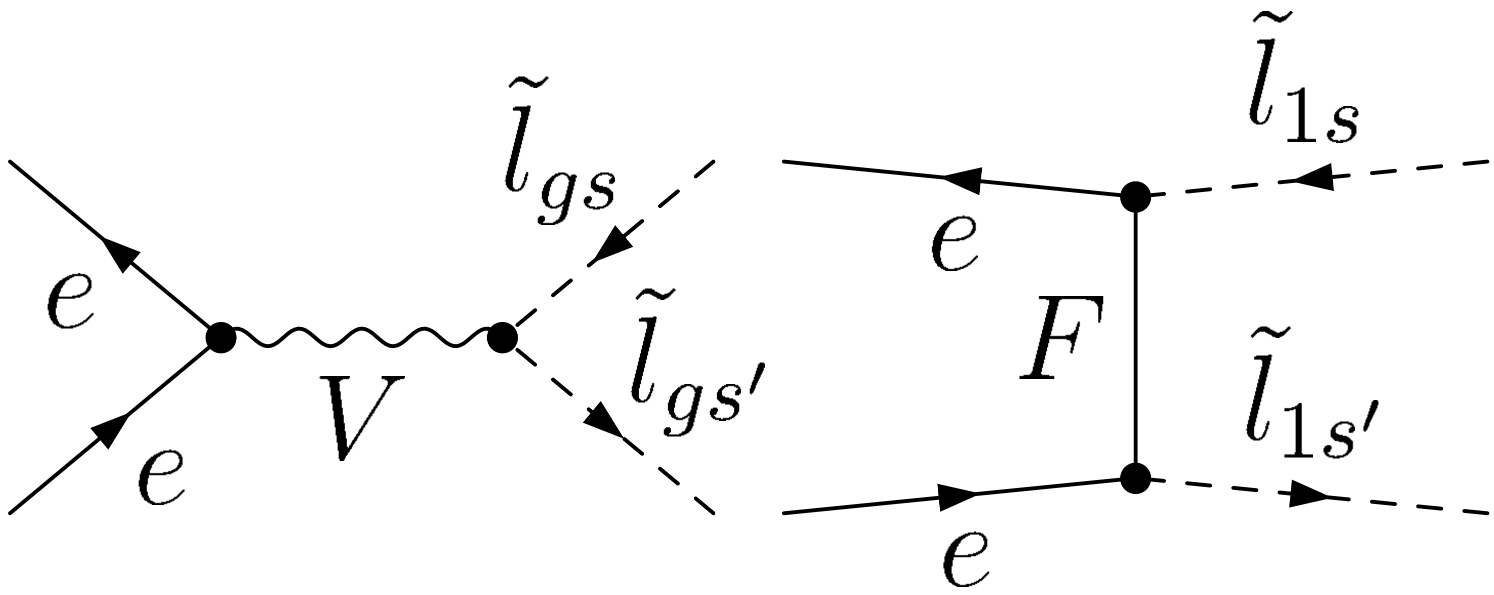
⇒ small $\mathcal{CP}$ assymmetry

4. Slepton production

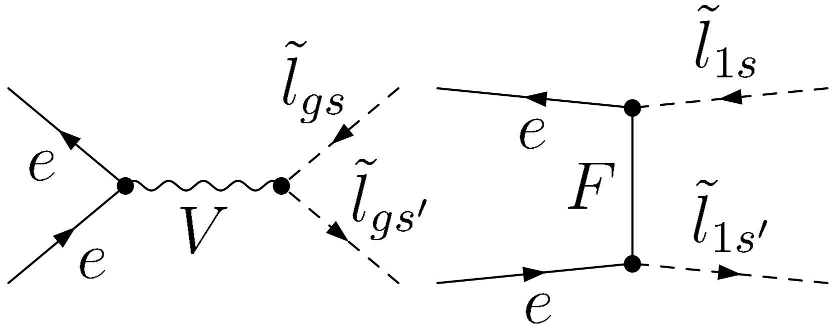
[arXiv:1803.10645]

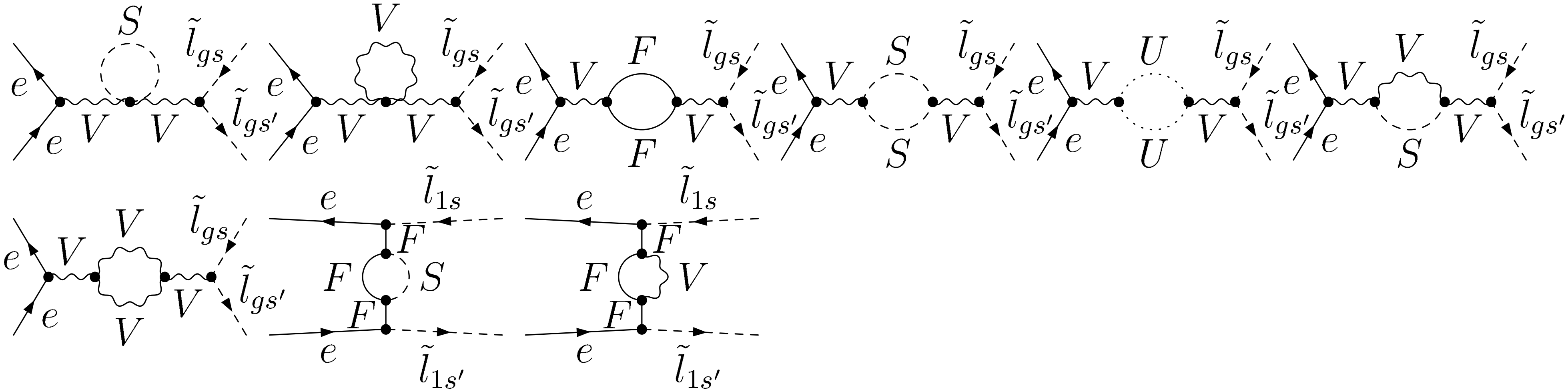
$$\sigma(e^+e^- \to \tilde{e}^{\pm}_{gs}\tilde{e}^{\mp}_{gs'}) \qquad (\tilde{e}_g = \{\tilde{e}, \tilde{\mu}, \tilde{\tau}\}; s, s' = 1, 2)$$

$$\sigma(e^+e^- \to \tilde{\nu}_g\tilde{\nu}_g) \qquad (\tilde{\nu}_g = \{\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau\}, g = 1, 2, 3)$$



$e^+e^- \to \tilde{e}^{\pm}_{gs}\tilde{e}^{\mp}_{gs'}$:





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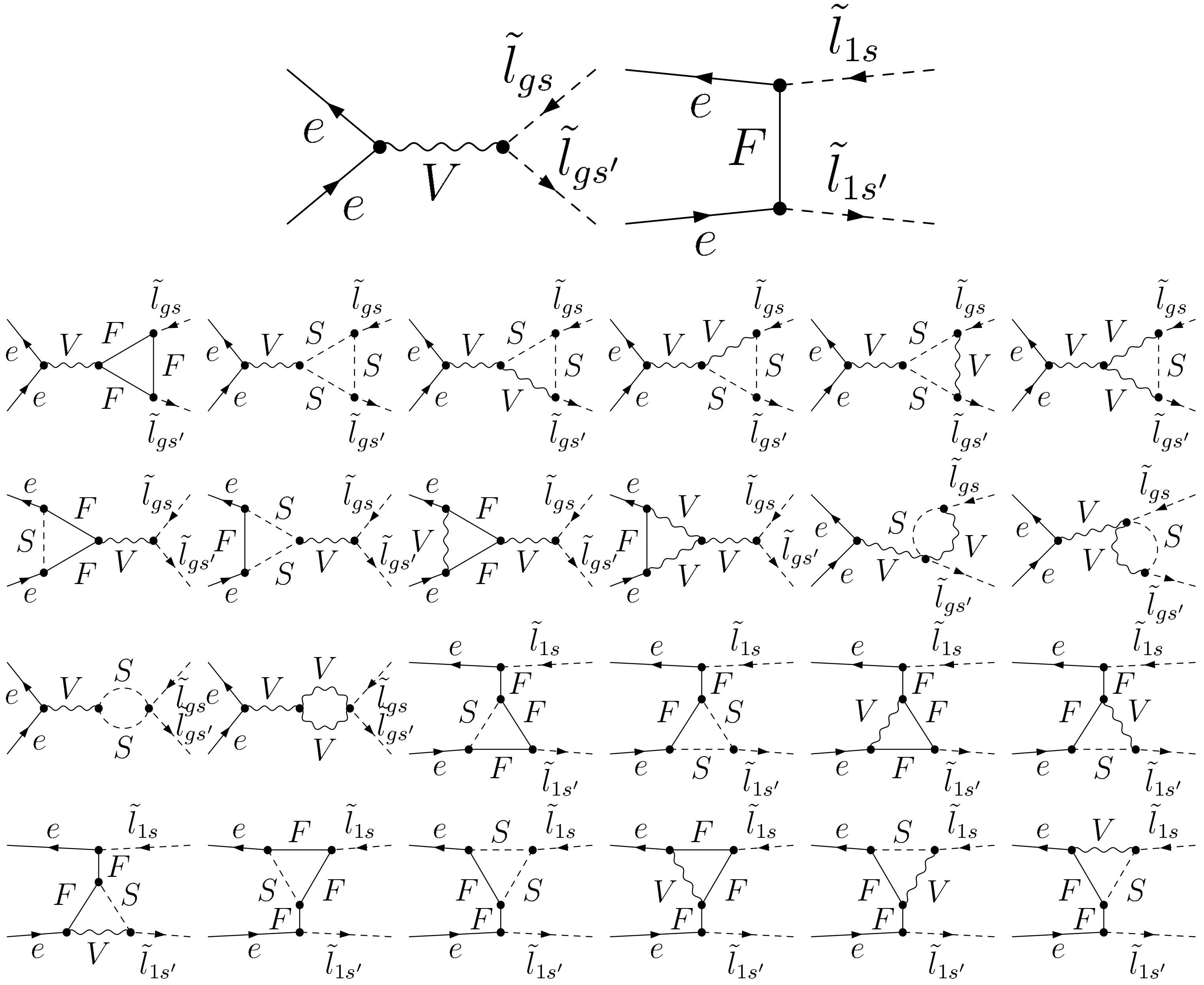

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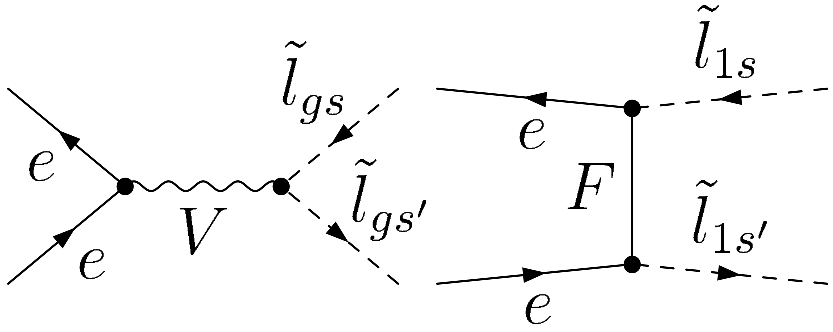
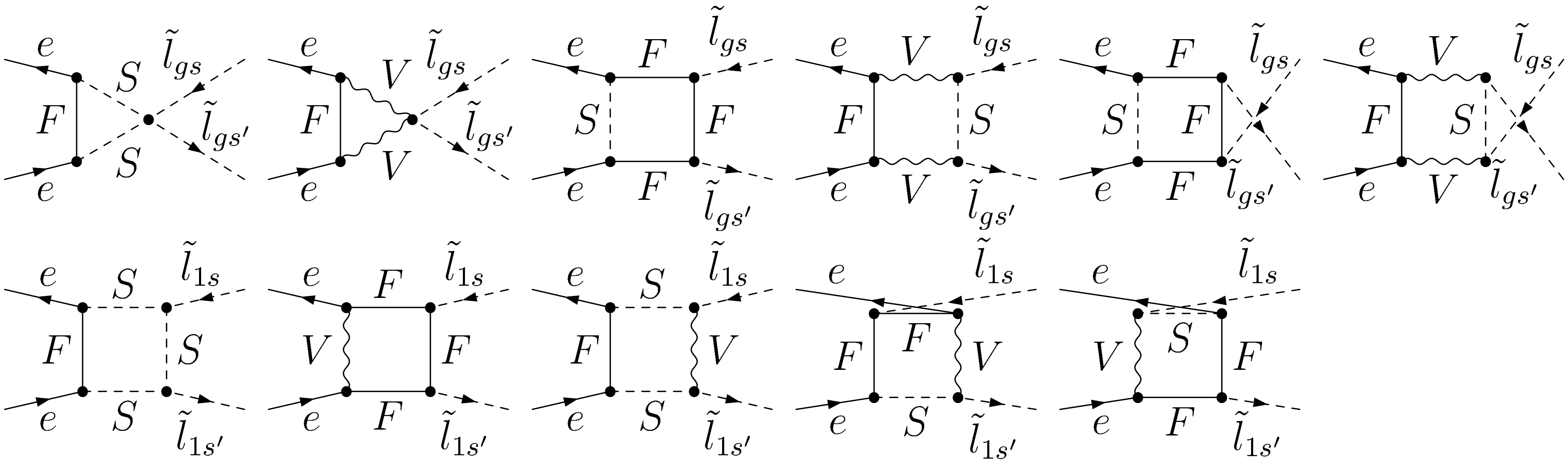
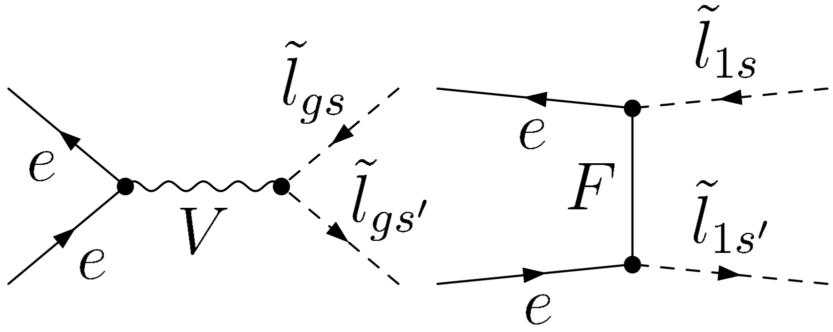
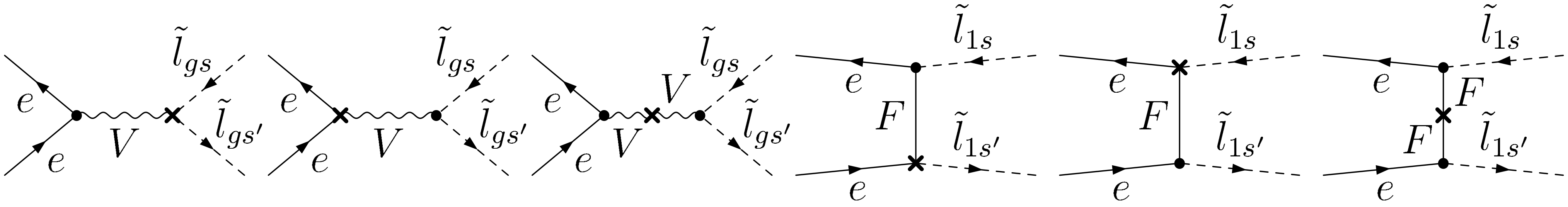




$e^+e^- \to \tilde{e}^{\pm}_{gs}\tilde{e}^{\mp}_{gs'}$:





+ soft and hard QED radiation

Comparison with the literature (all rMSSM, 1-loop)

⇒ many papers give too few details to make a comparison possible . . .

[*A. Freitas, A. v. Manteuffel, P. Zerwas '03*] : selectron/smuon : good agreement (no photon resum.)

[*A. Freitas, A. v. Manteuffel, P. Zerwas '04*] : sneutrinos : $\tilde{\nu}_\mu$, $\tilde{\nu}_\tau$ ok; $\tilde{\nu}_e$ not ok

[*A. Arhrib, W. Hollik '03*] : squarks/staus : good agreement

[*K. Kovarik, C. Weber, H. Eberl, W. Majerotto '04*] : 3rd gen. sfermions : good agreement

[*K. Kovarik, C. Weber, H. Eberl, W. Majerotto '05*] : 3rd gen. sfermions : $\tilde{\tau}_1\tilde{\tau}_2$, $\tilde{\tau}_2\tilde{\tau}_2$ ok at 1L, $\tilde{\tau}_1\tilde{\tau}_1$, $\tilde{\nu}_\tau\tilde{\nu}_\tau$ bad at tree-level already

Numerical example scenario:

$\sqrt{s}$	$\tan\beta$	μ	$M_{H^\pm}$	$M_{\tilde{Q},\tilde{U},\tilde{D}}$	$M_{\tilde{L}} = M_{\tilde{E}} + 50$	A_{u_g}	A_{d_g}	$\lvert A_{e_g}\rvert$	$\lvert M_1\rvert$	M_2	M_3
1000	10	350	1200	2000	300	2600	2000	2000	400	600	2000

Parameters varied: $\sqrt{s}$, μ, $M_{\tilde{L}}$, $\tan\beta$, M_1, M_2, φ_{M_1}, $\varphi_{A_{eg}}$

– in agreement with exp. data

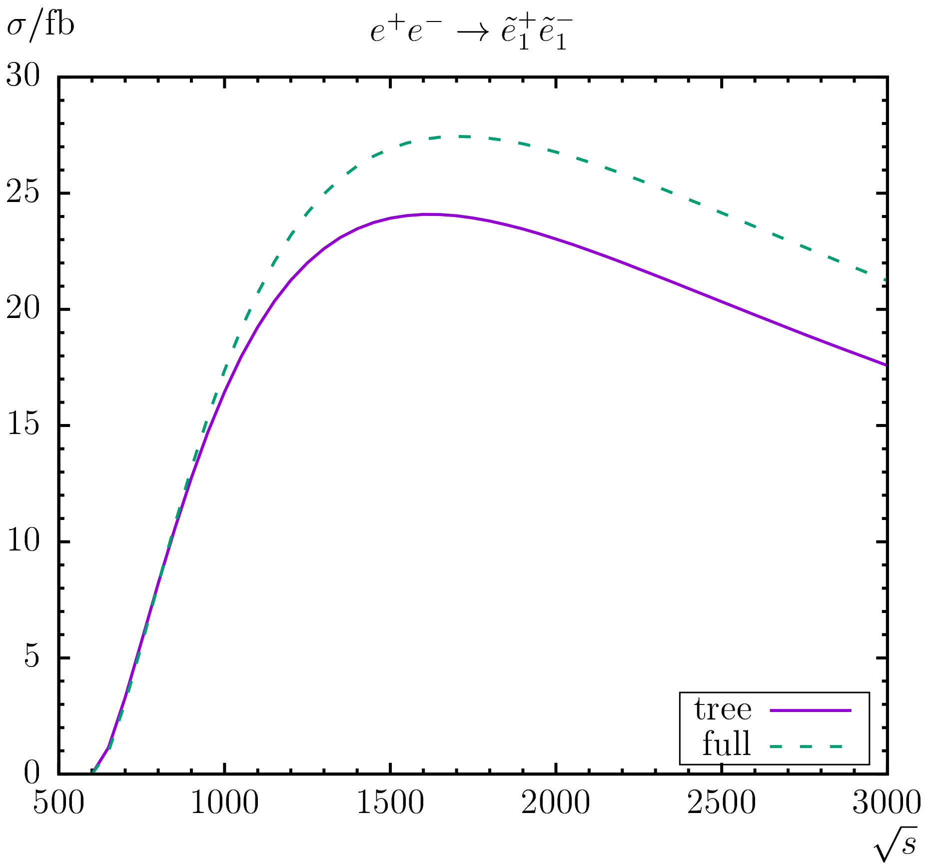
– opens up many (all) production channels

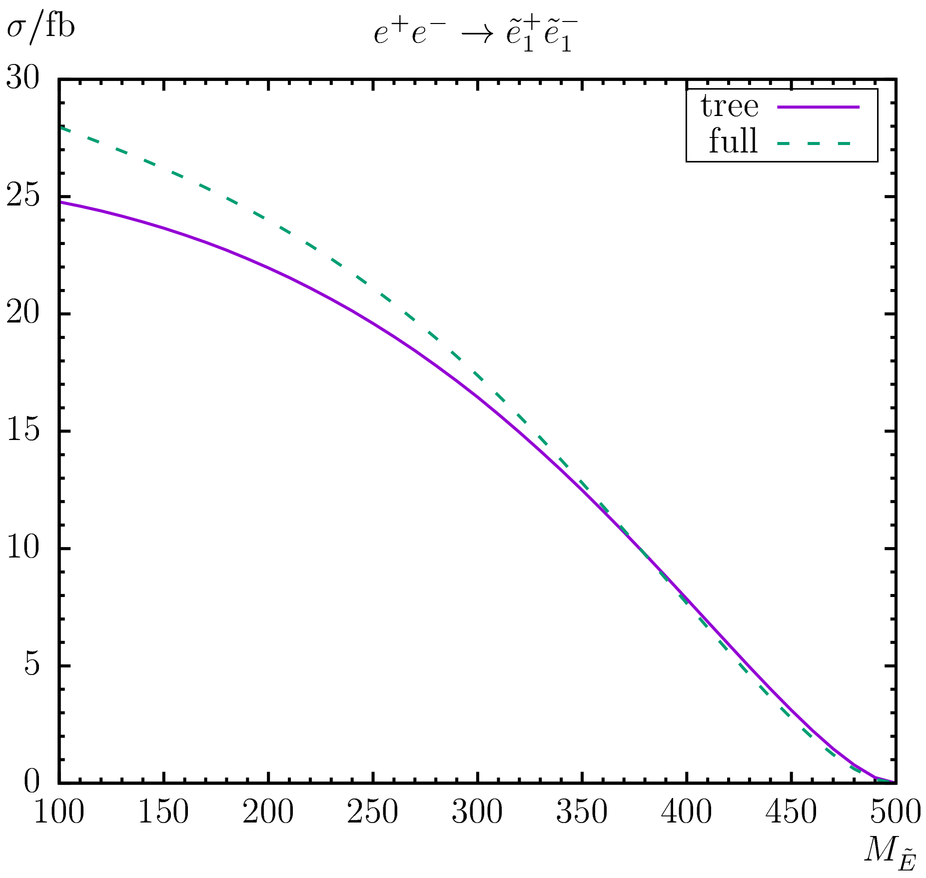
– relevant parameters varied

– . . .

⇒ show some relevant examples

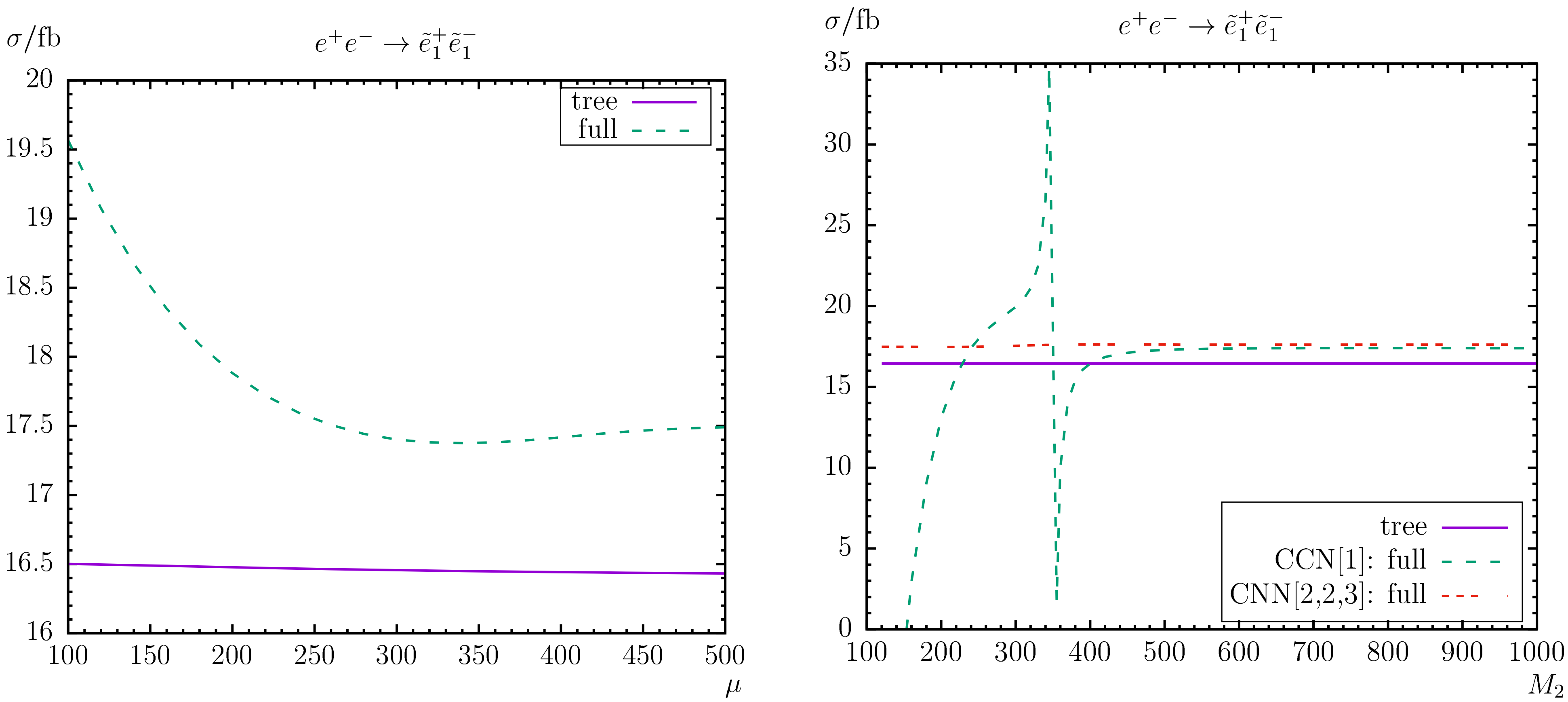
$\tilde{e}_1\tilde{e}_1$ production (I):





$\Rightarrow$ loop corrections $\sim$ 20%

$\tilde{e}_1\tilde{e}_1$ production (II):

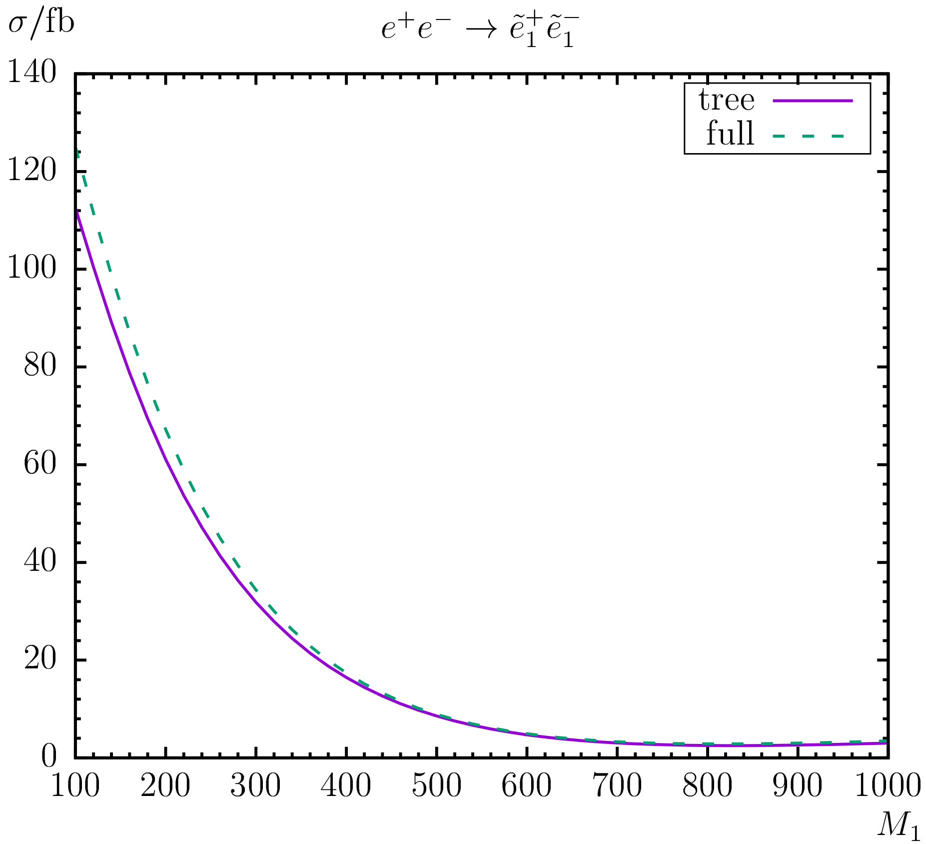


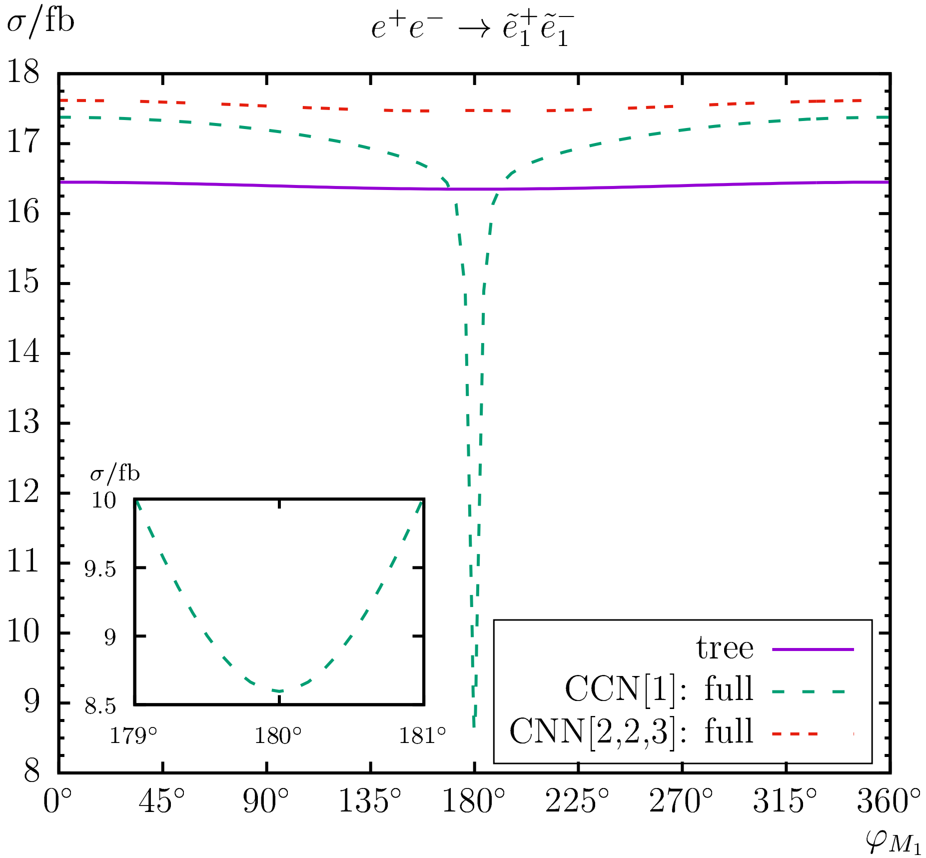
⇒ loop corrections $\sim 20\%$

⇒ strong μ dependance of loop corrections

⇒ CCN1 breaks down at $\mu = M_2$

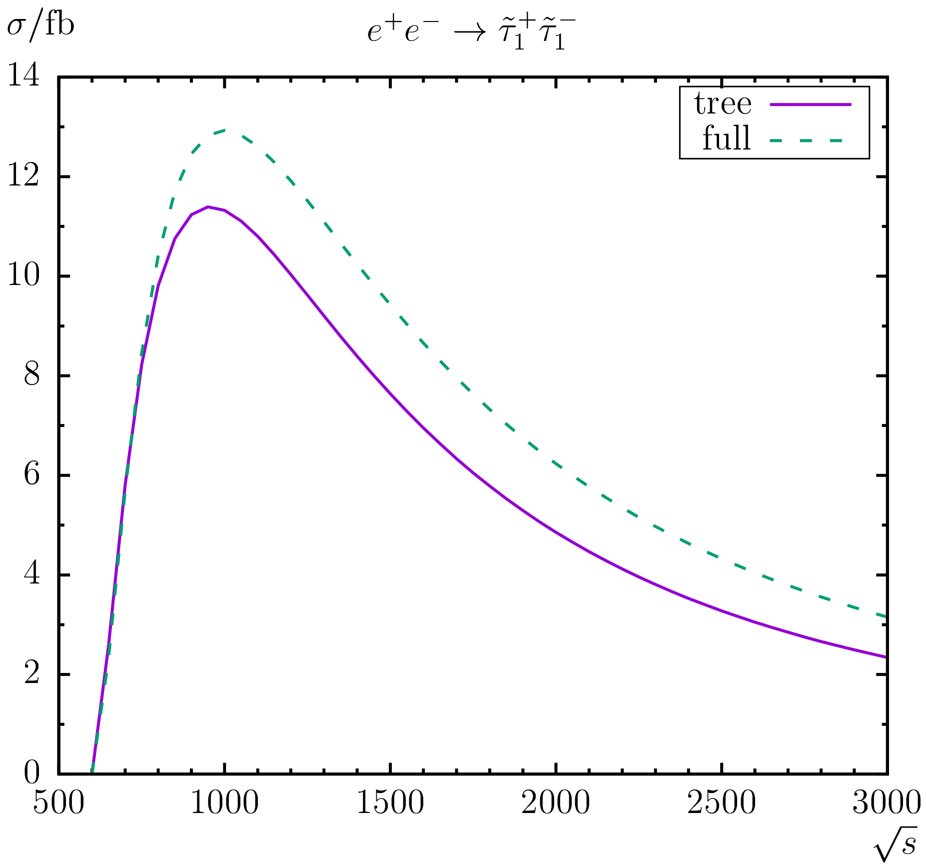
$\tilde{e}_1\tilde{e}_1$ production (III):

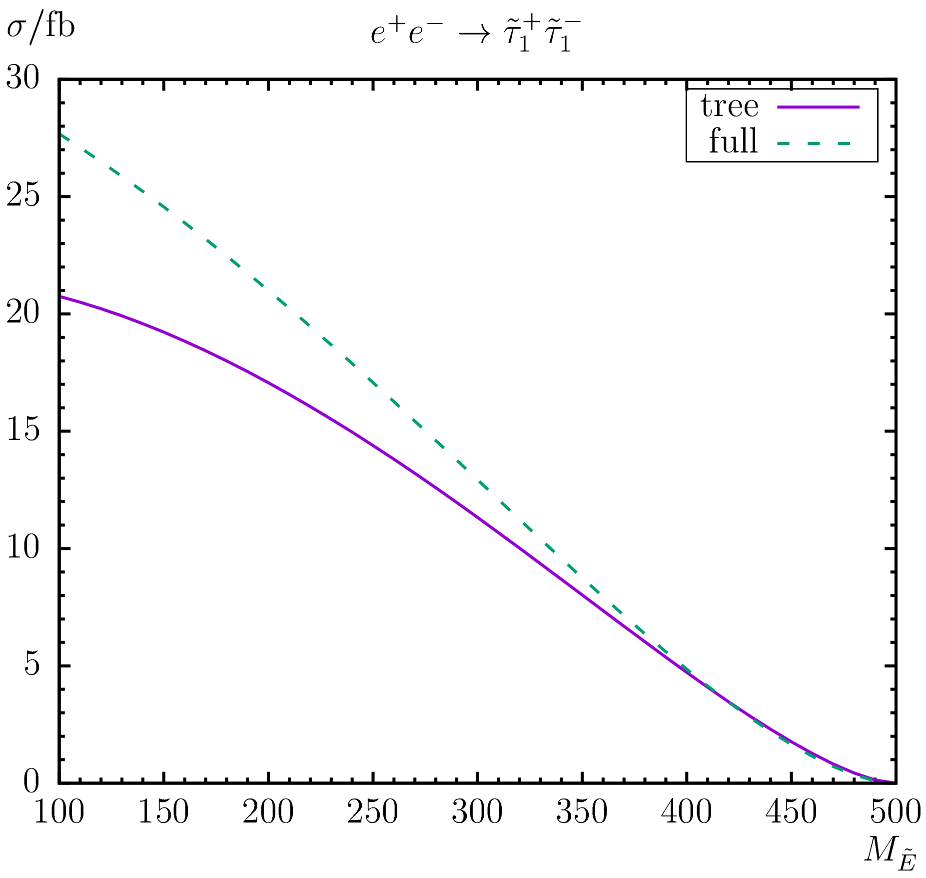




⇒ strong phase dependance of loop corrections

$\tilde{\tau}_1\tilde{\tau}_1$ production (I):

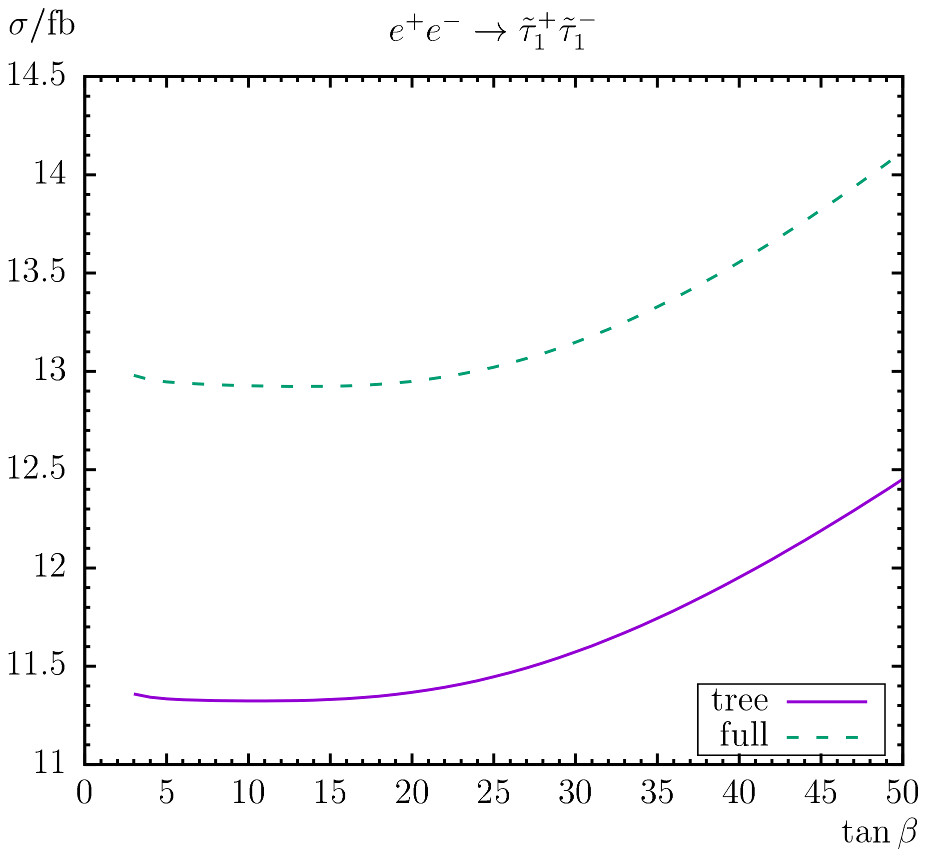


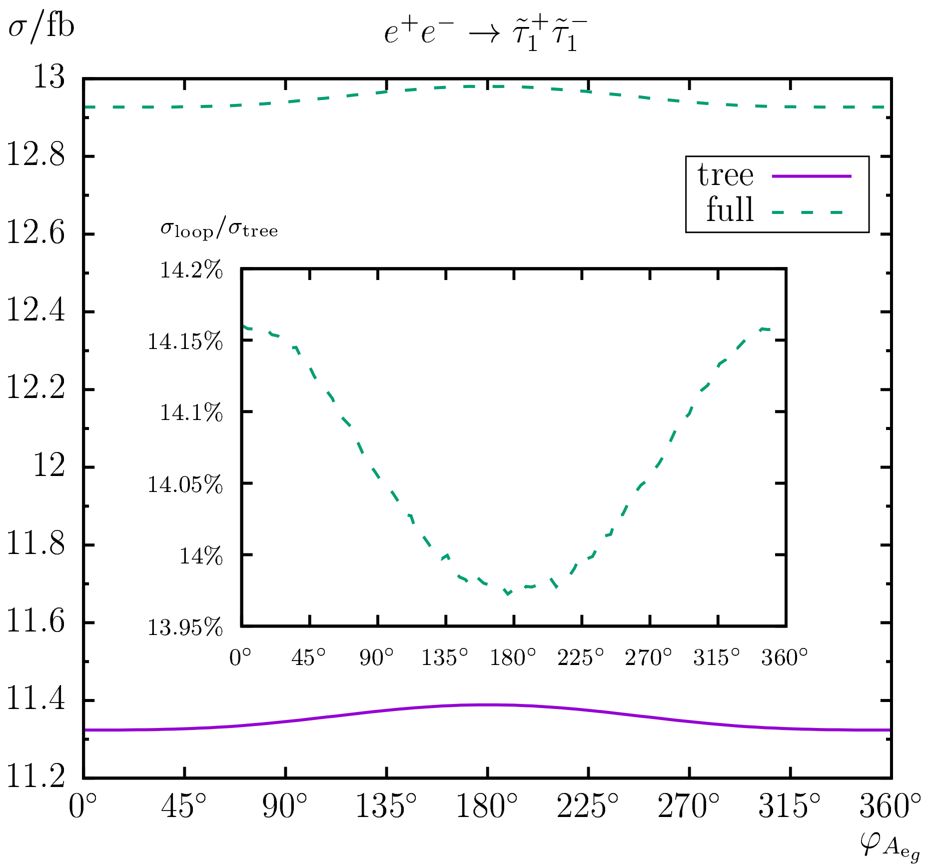


⇒ loop corrections $\sim$ 20%

⇒ but negligible for $\sqrt{s} \lesssim$ 700 GeV

$\tilde{\tau}_1\tilde{\tau}_1$ production (II):



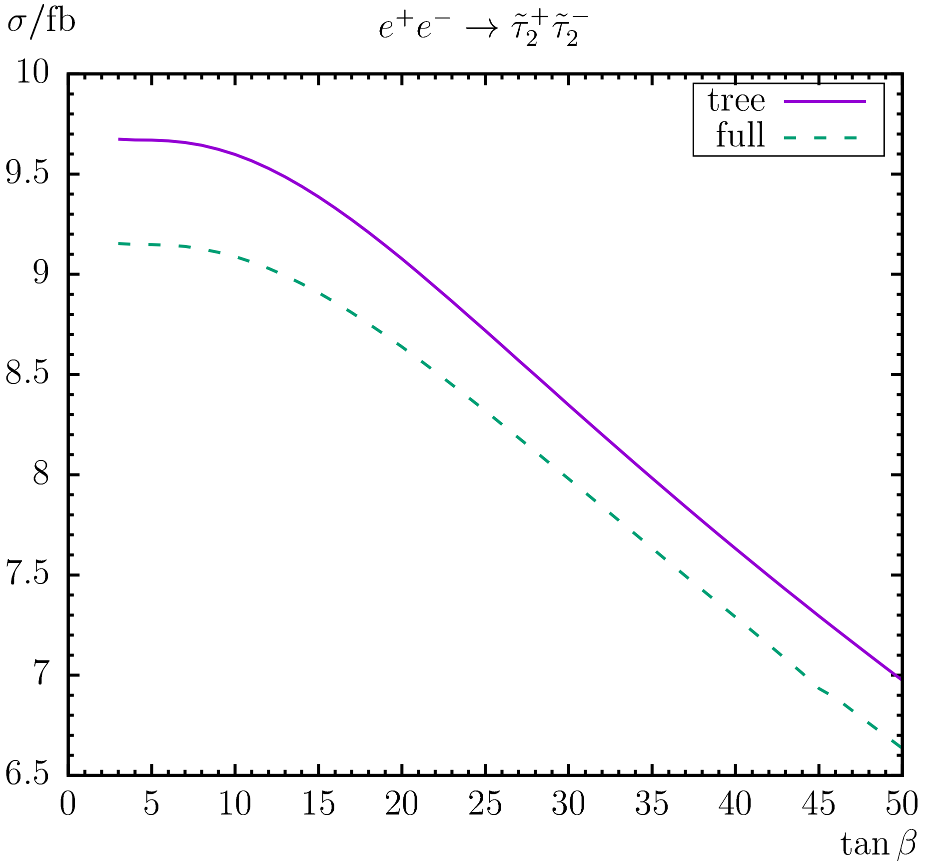


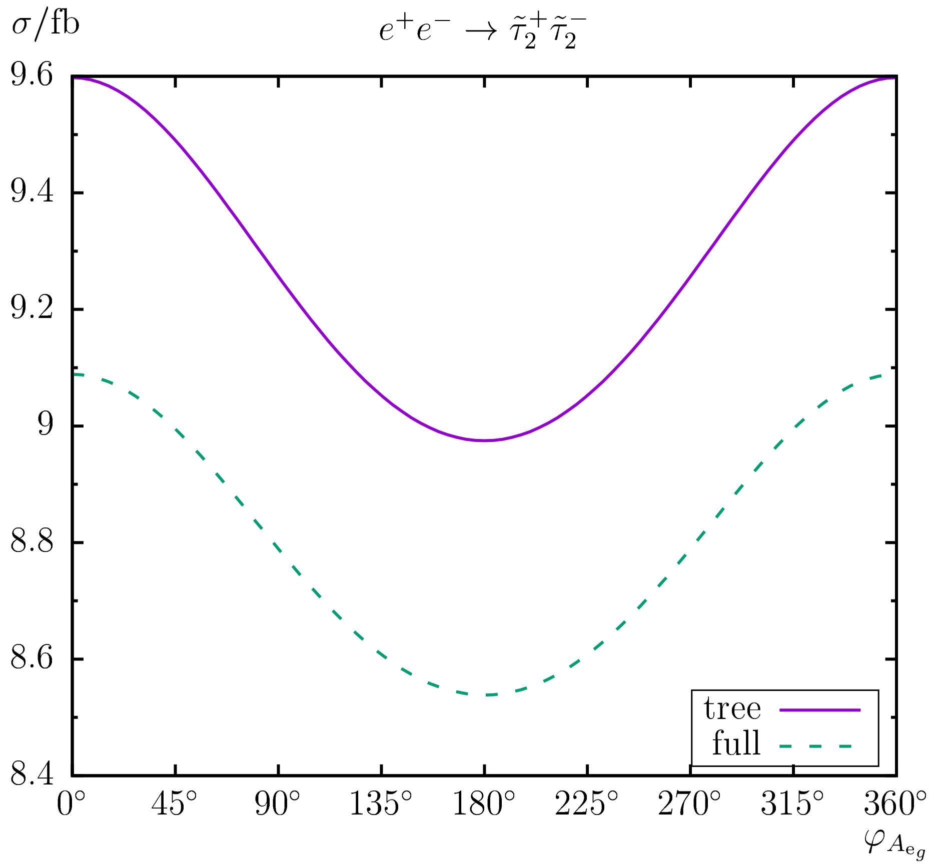
⇒ loop corrections ∼ 15%

⇒ strong $\tan\beta$ dependance

⇒ weak phase dependance

$\tilde{\tau}_2\tilde{\tau}_2$ production:





$\Rightarrow$ loop corrections $\sim$ 15%

$\Rightarrow$ strong $\tan\beta$ dependance

$\Rightarrow$ strong phase dependance

5. Conclusinos

- Loop corrections in BSM models are clearly important now
- MSSM: renormalization was the biggest issue
- FeynArts, FormCalc: model file incl. complex renormalization ready (one-loop, thoroughly tested!)
  Can be used consistently for production and decay
- New calculation: $e^+e^- \to$ neutralinos, charginos, sleptons
- Examples shown:
  - Neutralino production:
    correction up to $\sim 20\%$, phase dependance relevant, polarization?!
  - Chargino production:
    correction up to $\sim \pm 10\%$, t-channel dependance
  - Slepton production:
    corrections up to $\sim 20\%$, phase dependance relevant


Further Questions?

Renormalization schemes in the stop/sbottom sector

("analogously" in the slepton sector!)

Generic parameter and field renormalization for scalar quarks:

$$\mathbf{D}_{\tilde{q}} = \mathbf{U}_{\tilde{q}} \mathbf{M}_{\tilde{q}} \mathbf{U}_{\tilde{q}}^{\dagger} \quad (\tilde{q} = \tilde{t}, \tilde{b})$$

$$\mathbf{U}_{\tilde{q}} \mathbf{M}_{\tilde{q}} \mathbf{U}_{\tilde{q}}^{\dagger} \to \mathbf{U}_{\tilde{q}} \mathbf{M}_{\tilde{q}} \mathbf{U}_{\tilde{q}}^{\dagger} + \mathbf{U}_{\tilde{q}} \, \delta\mathbf{M}_{\tilde{q}} \, \mathbf{U}_{\tilde{q}}^{\dagger} = \begin{pmatrix} m_{\tilde{q}_1}^2 & Y_q \\ Y_q^* & m_{\tilde{q}_2}^2 \end{pmatrix} + \begin{pmatrix} \delta m_{\tilde{q}_1}^2 & \delta Y_q \\ \delta Y_q^* & \delta m_{\tilde{q}_2}^2 \end{pmatrix}$$

$$\delta\mathbf{M}_{\tilde{q}12} = U_{\tilde{q}11}^* U_{\tilde{q}12} (\delta m_{\tilde{q}_1}^2 - \delta m_{\tilde{q}_2}^2) + U_{\tilde{q}11}^* U_{\tilde{q}22} \delta Y_q + U_{\tilde{q}12} U_{\tilde{q}21}^* \delta Y_q^*$$

$$\begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \end{pmatrix} \to \left(\mathbb{1} + \frac{1}{2} \delta\mathbf{Z}_{\tilde{q}} \right) \begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \end{pmatrix} \quad \text{with} \quad \delta\mathbf{Z}_{\tilde{q}} = \begin{pmatrix} \delta Z_{\tilde{q}_{11}} & \delta Z_{\tilde{q}_{12}} \\ \delta Z_{\tilde{q}_{21}} & \delta Z_{\tilde{q}_{22}} \end{pmatrix}$$

Renormalization of the $t/\tilde{t}$ sector

→ employ the widely used on-shell renormalization

$$\delta m_t = \frac{1}{2}\widetilde{\mathrm{Re}}\left\{m_t\left[\Sigma_t^L(m_t^2) + \Sigma_t^R(m_t^2)\right] + \left[\Sigma_t^{SL}(m_t^2) + \Sigma_t^{SR}(m_t^2)\right]\right\}$$

$$\delta m_{\tilde{t}_i}^2 = \widetilde{\mathrm{Re}}\Sigma_{\tilde{t}_{ii}}(m_{\tilde{t}_i}^2) \qquad (i = 1, 2)$$

$$\delta Y_t = \frac{1}{2}\widetilde{\mathrm{Re}}\left\{\Sigma_{\tilde{t}_{12}}(m_{\tilde{t}_1}^2) + \Sigma_{\tilde{t}_{12}}(m_{\tilde{t}_2}^2)\right\}$$

[W. Hollik, H. Rzehak '03]

This defines the counter term for A_t:

$$\delta A_t = \frac{1}{m_t}\Big[U_{\tilde{t}_{11}}U^*_{\tilde{t}_{12}}(\delta m_{\tilde{t}_1}^2 - \delta m_{\tilde{t}_2}^2) + U_{\tilde{t}_{11}}U^*_{\tilde{t}_{22}}\delta Y_t^* + U^*_{\tilde{t}_{12}}U_{\tilde{t}_{21}}\delta Y_t \\ - (A_t - \mu^* \cot\beta)\,\delta m_t\Big] + (\delta\mu^* \cot\beta - \mu^* \cot^2\beta\,\delta\tan\beta)$$

(with $\delta\mu$ from chargino/neutralino sector, $\delta\tan\beta$ from Higgs sector)

Field renormalization for on-shell squarks ($\tilde{t}$, $\tilde{b}$, ...):

Diagonal Z factors:

the real part of the residua of propagators is set to unity:

$$\widetilde{\text{Re}} \frac{\partial \hat{\Sigma}_{\tilde{q}_{ii}}(k^2)}{\partial k^2}\Big|_{k^2=m^2_{\tilde{q}_i}} = 0 \qquad (i = 1, 2)$$

yielding

$$\text{Re}\delta Z_{\tilde{q}_{ii}} = -\widetilde{\text{Re}} \frac{\partial \Sigma_{\tilde{q}_{ii}}(k^2)}{\partial k^2}\Big|_{k^2=m^2_{\tilde{q}_i}} \qquad \text{Im}\,\delta Z_{\tilde{q}_{ii}} = 0 \qquad (i = 1, 2)$$

Off-diagonal Z factors:

no transition from one squark to the other occurs:

$$\widetilde{\text{Re}}\hat{\Sigma}_{\tilde{q}_{12}}(m^2_{\tilde{q}_1}) = 0 \qquad \widetilde{\text{Re}}\hat{\Sigma}_{\tilde{q}_{12}}(m^2_{\tilde{q}_2}) = 0$$

yielding

$$\delta Z_{\tilde{q}_{12}} = +2 \frac{\widetilde{\text{Re}}\Sigma_{\tilde{q}_{12}}(m^2_{\tilde{q}_2}) - \delta Y_q}{(m^2_{\tilde{q}_1} - m^2_{\tilde{q}_2})} \qquad \delta Z_{\tilde{q}_{21}} = -2 \frac{\widetilde{\text{Re}}\Sigma_{\tilde{q}_{21}}(m^2_{\tilde{q}_1}) - \delta Y_q^*}{(m^2_{\tilde{q}_1} - m^2_{\tilde{q}_2})}$$

$SU(2)$ relation $\Rightarrow M_{\tilde{t}_L} = M_{\tilde{b}_L}$

"LL" soft SUSY-breaking term for $\tilde{q} = \{\tilde{t}, \tilde{b}\}$:

$$M^2_{\tilde{Q}_L}(\tilde{q}) = |U_{\tilde{q}11}|^2 m^2_{\tilde{q}_1} + |U_{\tilde{q}12}|^2 m^2_{\tilde{q}_2} - M_Z^2 c_{2\beta}(T_q^3 - Q_q s_W^2) - m_q^2$$

Keeping $SU(2)$ relation at the one-loop level leads to a shift in the soft SUSY-breaking parameters

[A. Bartl, H. Eberl, K. Hidaka, S. Kraml, W. Majerotto, W. Porod, Y. Yamada '97, '98]

[A. Djouadi, P. Gambino, S.H., W. Hollik, C. Jünger, G. Weiglein '98]

$$M^2_{\tilde{Q}_L}(\tilde{b}) = M^2_{\tilde{Q}_L}(\tilde{t}) + \delta M^2_{\tilde{Q}_L}(\tilde{t}) - \delta M^2_{\tilde{Q}_L}(\tilde{b})$$

with

$$\delta M^2_{\tilde{Q}_L}(\tilde{q}) = |U_{\tilde{q}11}|^2 \delta m^2_{\tilde{q}_1} + |U_{\tilde{q}12}|^2 \delta m^2_{\tilde{q}_2} - U_{\tilde{q}22} U^*_{\tilde{q}12} \delta Y_q - U_{\tilde{q}12} U^*_{\tilde{q}22} \delta Y_q^* - 2 m_q \delta m_q \\ + M_Z^2\, c_{2\beta}\, Q_q\, \delta s_W^2 - (T_q^3 - Q_q s_W^2)(c_{2\beta}\, \delta M_Z^2 + M_Z^2\, \delta c_{2\beta})$$

$\to$ under control

Complex renormalization in $t/\tilde{t}$ sector:

1) A_t complex

$\Rightarrow$ renormalization of $|A_t|$ and ϕ_{A_t}: $\delta A_t = e^{i\,\phi_{A_t}} \delta|A_t| \; + \; i\,A_t\,\delta\phi_{A_t}$

$\Rightarrow$ $\overline{\text{DR}}$ renormalization

2) alternatively $\theta_{\tilde{t}}$ complex

$\Rightarrow$ renormalization of $|\theta_{\tilde{t}}|$ and $\phi_{\tilde{t}}$:

$\Rightarrow$ On-shell renormalization via

$$\widetilde{\text{Re}}\hat{\Sigma}_{\tilde{t}_{12}}(m^2_{\tilde{t}_1}) + \widetilde{\text{Re}}\hat{\Sigma}_{\tilde{t}_{12}}(m^2_{\tilde{t}_2}) \stackrel{!}{=} 0$$

$$\Rightarrow \widetilde{\text{Re}}\Sigma_{\tilde{t}_{12}}(m^2_{\tilde{t}_1}) + \widetilde{\text{Re}}\Sigma_{\tilde{t}_{12}}(m^2_{\tilde{t}_2}) = e^{i\phi_{\tilde{t}}}(m^2_{\tilde{t}_1} - m^2_{\tilde{t}_2}) \times (\delta\theta_{\tilde{t}} + i\,s_{\tilde{t}}\,c_{\tilde{t}}\,\delta\phi_{\tilde{t}})$$

$\Rightarrow$ evaluate $\delta|A_t|$ and $\delta\phi_{A_t}$ as dependent parameters

$\Rightarrow$ preferred scheme

Renormalizations of the $b/\tilde{b}$ sector in the complex MSSM:

scheme	$m_{\tilde{b}_{1,2}}$	m_b	A_b	Y_b	name
analogous to the $t/\tilde{t}$ sector: "OS"	OS	OS	—	OS	RS1
"m_b, A_b $\overline{\text{DR}}$"	OS	$\overline{\text{DR}}$	$\overline{\text{DR}}$	—	RS2
"m_b, Y_b $\overline{\text{DR}}$"	OS	$\overline{\text{DR}}$	—	$\overline{\text{DR}}$	RS3
"m_b $\overline{\text{DR}}$, Y_b OS"	OS	$\overline{\text{DR}}$	—	OS	RS4
"A_b $\overline{\text{DR}}$, ReY_b OS"	OS	—	$\overline{\text{DR}}$	ReY_b: OS	RS5
"A_b vertex, ReY_b OS"	OS	—	vertex	ReY_b: OS	RS6

"— " = dependent parameter

⇒ often very involved analytical dependences

→ more combinations possible

. . . also tested

. . . upcoming results remain unchanged

Renormalization of the sbottom masses:

OS renormalization:

$$\delta m^2_{\tilde{b}_i} = \widetilde{\text{Re}}\Sigma_{\tilde{b}_{ii}}(m^2_{\tilde{b}_i}) \qquad (i = 1, 2)$$

Renormalization of the bottom mass:

OS renormalization:

$$\delta m_b = \frac{1}{2}\widetilde{\text{Re}}\left\{m_b\left[\Sigma_b^L(m_b^2) + \Sigma_b^R(m_b^2)\right] + \left[\Sigma_b^{SL}(m_b^2) + \Sigma_b^{SL}(m_b^2)\right]\right\}$$

$\overline{\text{DR}}$ renormalization:

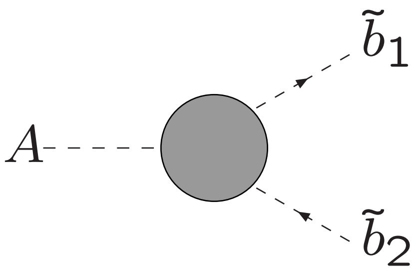
$$\delta m_b = \frac{1}{2}\widetilde{\text{Re}}\left\{m_b\left[\Sigma_b^L(m_b^2) + \Sigma_b^R(m_b^2)\right]_{\text{div}} + \left[\Sigma_b^{SL}(m_b^2) + \Sigma_b^{SL}(m_b^2)\right]_{\text{div}}\right\}$$

Renormalization of A_b:

$\overline{\text{DR}}$ renormalization: analogous to A_t:

$$\delta A_b = \frac{1}{m_b}\Big[U_{\tilde{b}_{11}} U^*_{\tilde{b}_{12}} \left(\widetilde{\text{Re}}\Sigma_{\tilde{b}_{11}}(m^2_{\tilde{b}_1})|_{\text{div}} - \widetilde{\text{Re}}\Sigma_{\tilde{b}_{22}}(m^2_{\tilde{b}_2})|_{\text{div}}\right)$$
$$+ \frac{1}{2} U^*_{\tilde{b}_{12}} U_{\tilde{b}_{21}} \left(\widetilde{\text{Re}}\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_1})|_{\text{div}} + \widetilde{\text{Re}}\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_2})|_{\text{div}}\right)$$
$$+ \frac{1}{2} U_{\tilde{b}_{11}} U^*_{\tilde{b}_{22}} \left(\widetilde{\text{Re}}\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_1})|_{\text{div}} + \widetilde{\text{Re}}\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_2})|_{\text{div}}\right)^*$$
$$- \frac{1}{2}(A_b - \mu^* \tan\beta)\, \widetilde{\text{Re}}\Big\{m_b \left[\Sigma^L_b(m^2_b) + \Sigma^R_b(m^2_b)\right]_{\text{div}}$$
$$+ \left[\Sigma^{SL}_b(m^2_b) + \Sigma^{SR}_b(m^2_b)\right]_{\text{div}}\Big\}\Big] + \delta\mu^*|_{\text{div}} \tan\beta + \mu^*\, \delta\tan\beta$$

Vertex renormalization:



$\widehat{=} \quad i\,\hat{\Lambda}(p^2_A, p^2_{\tilde{b}_1}, p^2_{\tilde{b}_2})$

$$\text{via} \quad \widetilde{\text{Re}}\hat{\Lambda}(0, m^2_{\tilde{b}_1}, m^2_{\tilde{b}_1}) + \widetilde{\text{Re}}\hat{\Lambda}(0, m^2_{\tilde{b}_2}, m^2_{\tilde{b}_2}) \stackrel{!}{=} 0$$

Renormalization of Y_b:

OS renormalization:

$$\delta Y_b = \frac{1}{2}\widetilde{\text{Re}}\left\{\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_1}) + \Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_2})\right\}$$

$\overline{\text{DR}}$ renormalization:

$$\delta Y_b = \frac{1}{2}\widetilde{\text{Re}}\left\{\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_1})|_{\text{div}} + \Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_2})|_{\text{div}}\right\}$$

ReY_b OS renormalization

$$\text{Re}\delta Y_b = \frac{1}{2}\text{Re}\left\{\widetilde{\text{Re}}\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_1}) + \widetilde{\text{Re}}\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_2})\right\}$$

What is the "preferred" renormalization scheme?

one counterterm is a "dependent" quantity

$\Rightarrow$ no scheme can be identified that shows "good" behavior over the full cMSSM parameter space

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Most "robust" behavior:

– RS2: "m_b, A_b $\overline{\text{DR}}$"
  $\Rightarrow$ problems only for maximal sbottom mixing
– RS6: "A_b vertex, ReY_b OS"
  $\Rightarrow$ problems depending on ϕ_{A_b}

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⇒ we choose RS2: "m_b, A_b $\overline{\mathrm{DR}}$" as our "preferred" scheme

Renormalization in the chargino/neutralino sector

⇒ Two "OS" schemes:

1. **Scheme I:**

   [T. Fritzsche, S.H., H. Rzehak, C. Schappacher '11][S.H., F. v.d. Pahlen, C. Schappacher '12]

$$\left(\left[\widetilde{\mathbf{Re}} \hat{\Sigma}_{\tilde{\chi}^-}(p) \right]_{ii} \tilde{\chi}_i^-(p) \right) \Big|_{p^2 = m^2_{\tilde{\chi}_i^\pm}} = 0 \qquad (i = 1, 2) \ ,$$

$$\left(\left[\widetilde{\mathbf{Re}} \hat{\Sigma}_{\tilde{\chi}^0}(p) \right]_{11} \tilde{\chi}_1^0(p) \right) \Big|_{p^2 = m^2_{\tilde{\chi}_1^0}} = 0$$

2. **Scheme II:**

   [A. Fowler, G. Weiglein '09]

$$\left(\left[\mathbf{Re} \hat{\Sigma}_{\tilde{\chi}^-}(p) \right]_{ii} \tilde{\chi}_i^-(p) \right) \Big|_{p^2 = m^2_{\tilde{\chi}_i^\pm}} = 0 \qquad (i = 1, 2) \ ,$$

$$\left(\left[\mathbf{Re} \hat{\Sigma}_{\tilde{\chi}^0}(p) \right]_{11} \tilde{\chi}_1^0(p) \right) \Big|_{p^2 = m^2_{\tilde{\chi}_1^0}} = 0$$

Some comments:

– Scheme I and Scheme II agree for real parameters

– Both schemes can easily be extended to other variants, e.g.

CCN_i $(i = 1, 2, 3, 4)$ or CNN_{ijk} $(i = 1, 2; j, k = 1, 2, 3, 4)$

→ relevant for $|\mu| \approx M_2$ (see also: [Drees et al. '11])

⇒ included into our set-up

– Both schemes require a shift of three (neutralino) masses to their on-shell value:

$$\Delta m_{\tilde{\chi}_i^0} = -\frac{1}{2}\text{Re}\Big\{ m_{\tilde{\chi}_i^0} \Big(\hat{\Sigma}^L_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0}) + \hat{\Sigma}^R_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0}) \Big) + \hat{\Sigma}^{SL}_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0}) + \hat{\Sigma}^{SR}_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0}) \Big\}$$

$$m^{\text{OS}}_{\tilde{\chi}_i^0} = m_{\tilde{\chi}_i^0} + \Delta m_{\tilde{\chi}_i^0}$$