Sometimes I drive recklessly, just to kill off close copies of me in the multiverse.

$e^+e^- \to$ sleptons and charginos/neutralinos in the cMSSM at the Full One-Loop Level

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

Strasbourg, 10/2017

based on collaboration with *C. Schappacher*

1. The Grand Scheme

2. Chargino/neutralino production

3. Slepton production

4. Conclusions

1. The Grand Scheme

The LHC up and running . . .
→ discovery of BSM physics this year?

ILC(/CLIC?) is still coming . . .
. . . a bit later than anticipated
→ to investigate BSM physics

Worldwide Study of the Physics and Detectors for Future Linear e^+e^- Colliders

⇒ New Physics is certainly around the corner

⇒ Time to get ready for BSM physics

The big question:

Which Lagrangian describes the world?

My guess:

It is a supersymmetric one

$\Rightarrow$ concentrate on the MSSM from now on

(other people $\Rightarrow$ other guesses $\Rightarrow$ other priorities $\Rightarrow$ wrong conference?)

In any case:

$\Rightarrow$ we have to measure as many observables as possible

- masses
- branching ratios
- angular distributions
- cross sections
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⇒ compare with theory calculations at the same level of accuracy

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

$$\left[u, d, c, s, t, b\right]_{L,R} \quad \left[e, \mu, \tau\right]_{L,R} \quad \left[\nu_{e,\mu,\tau}\right]_{L} \qquad \text{Spin } \tfrac{1}{2}$$

$$\left[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\right]_{L,R} \quad \left[\tilde{e}, \tilde{\mu}, \tilde{\tau}\right]_{L,R} \quad \left[\tilde{\nu}_{e,\mu,\tau}\right]_{L} \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^{\pm}, H^{\pm}} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin 1 / Spin 0}$$

$$\tilde{g} \quad \tilde{\chi}^{\pm}_{1,2} \quad \tilde{\chi}^{0}_{1,2,3,4} \qquad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector: Two Higgs doublets

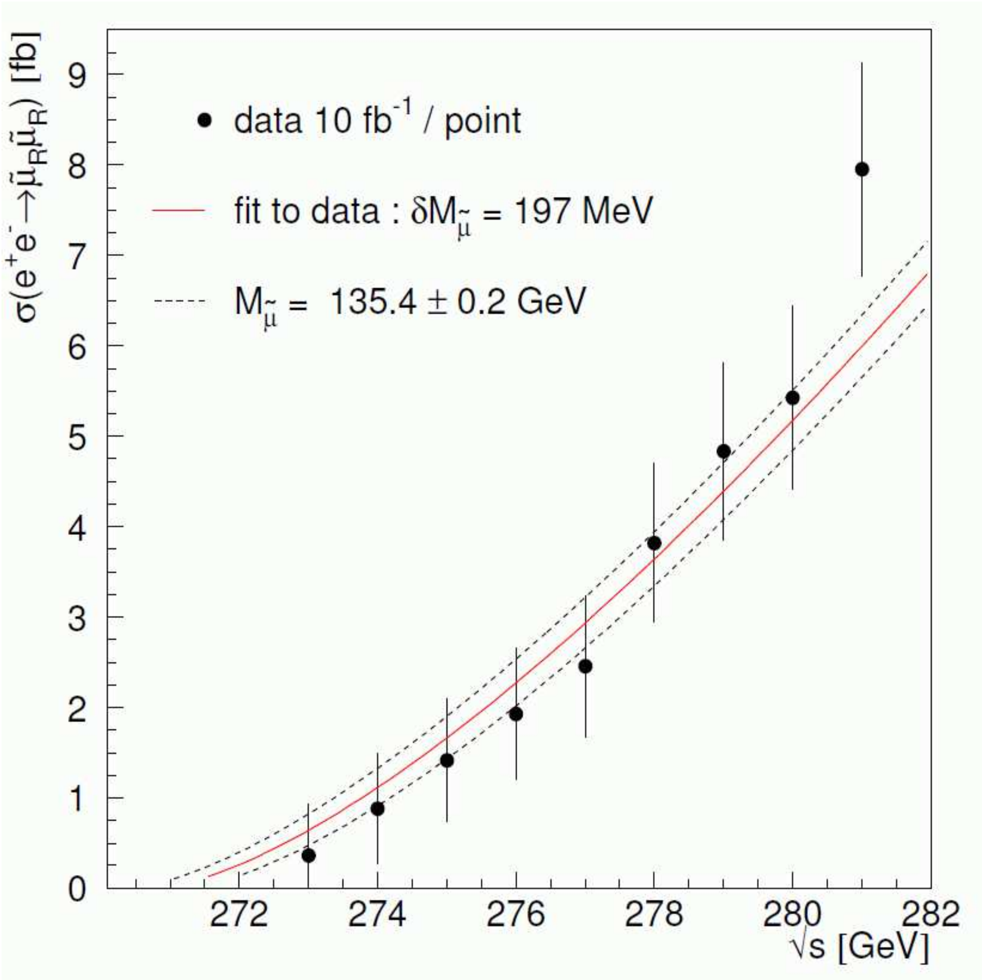
Problem in the MSSM: many scales

Problem in the MSSM: complex phases

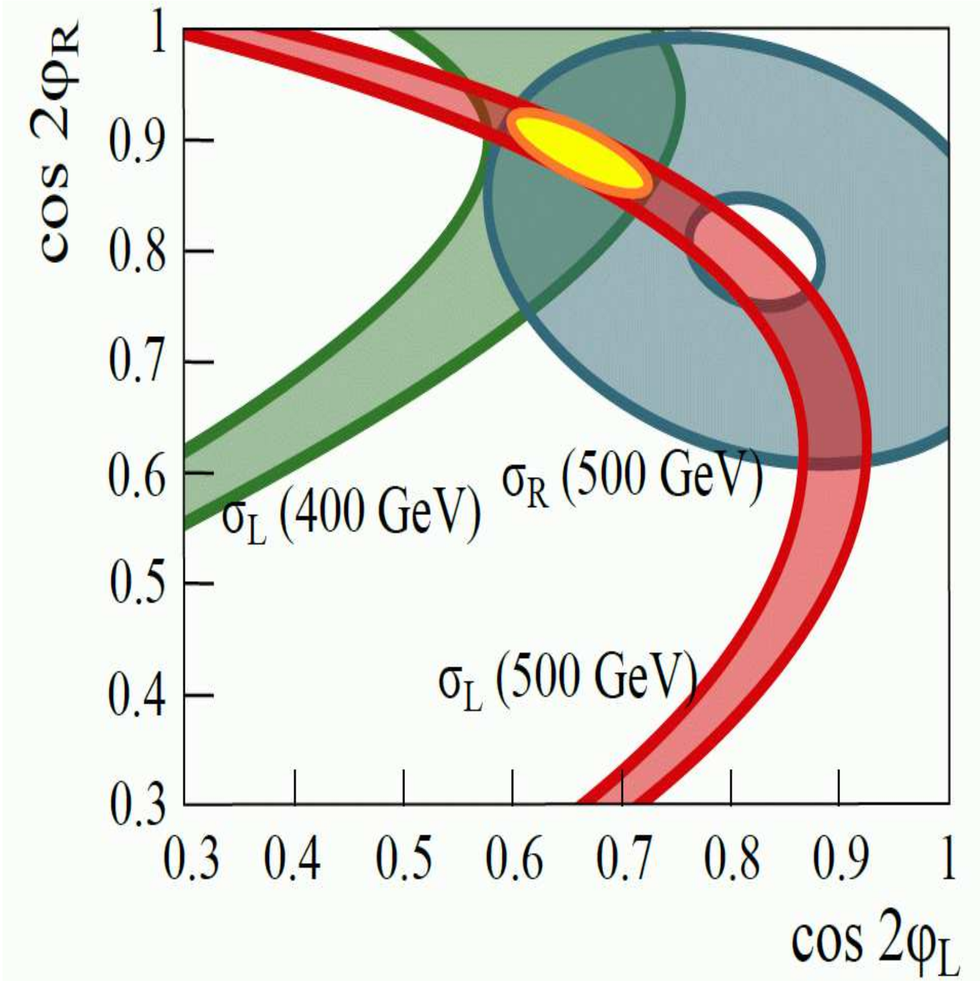
Precision ILC(/CLIC) analyses for SUSY particles:

[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-'17*]

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/PRELIMINARY

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

  ⇒ 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 - '13]

– 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]

– full one-loop calculations possible with FeynArts/FormCalc/LoopTools

– set-up includes full one-loop corrections (hard/soft QED/QCD radiation)

– allows for consistent calculation of production and decay

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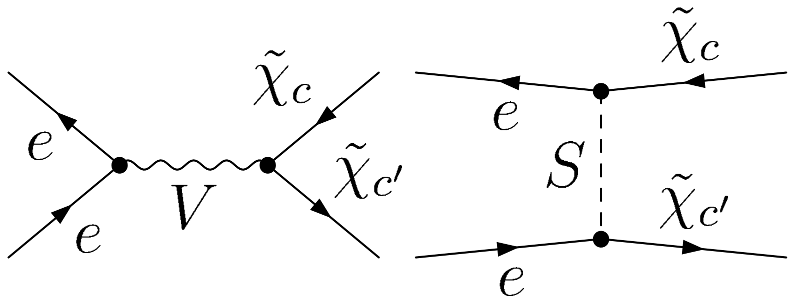
⇒ **and so we did!**

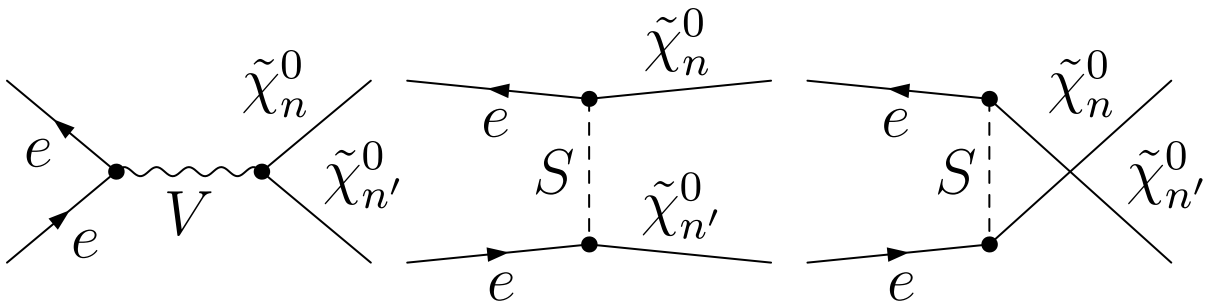
2. Charginos/neutralino production

[*arXiv:1704.07627*]

$$e^+e^- \to \tilde\chi_c^- \tilde\chi_{c'}^+ \qquad (i = 1, 2, 3;\; c, c' = 1, 2)$$

$$e^+e^- \to \tilde\chi_n^0 \tilde\chi_{n'}^0 \qquad (i = 1, 2, 3;\; n, n' = 1, 2, 3, 4)$$





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:

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

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

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

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

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

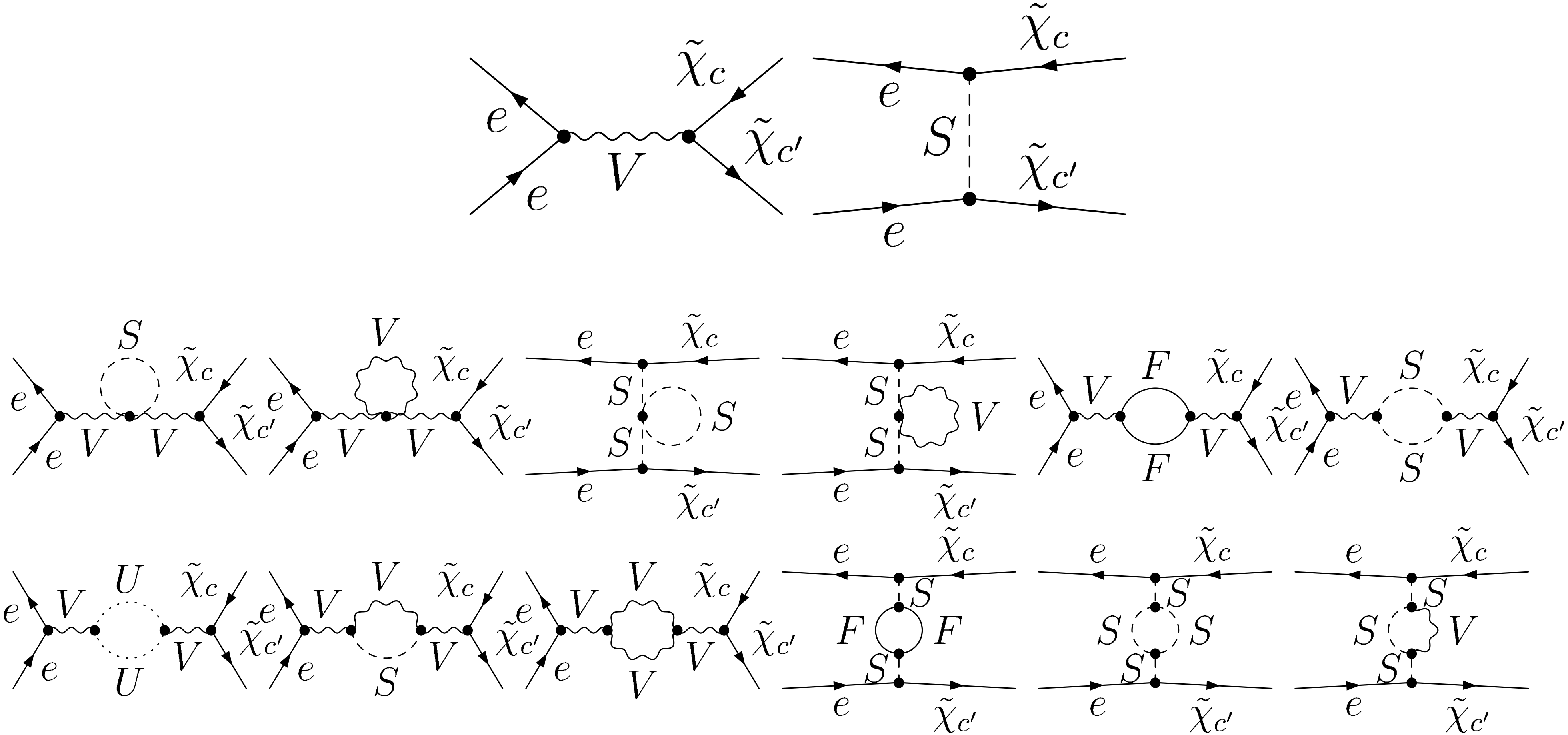
$\Rightarrow$ included into our set-up

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

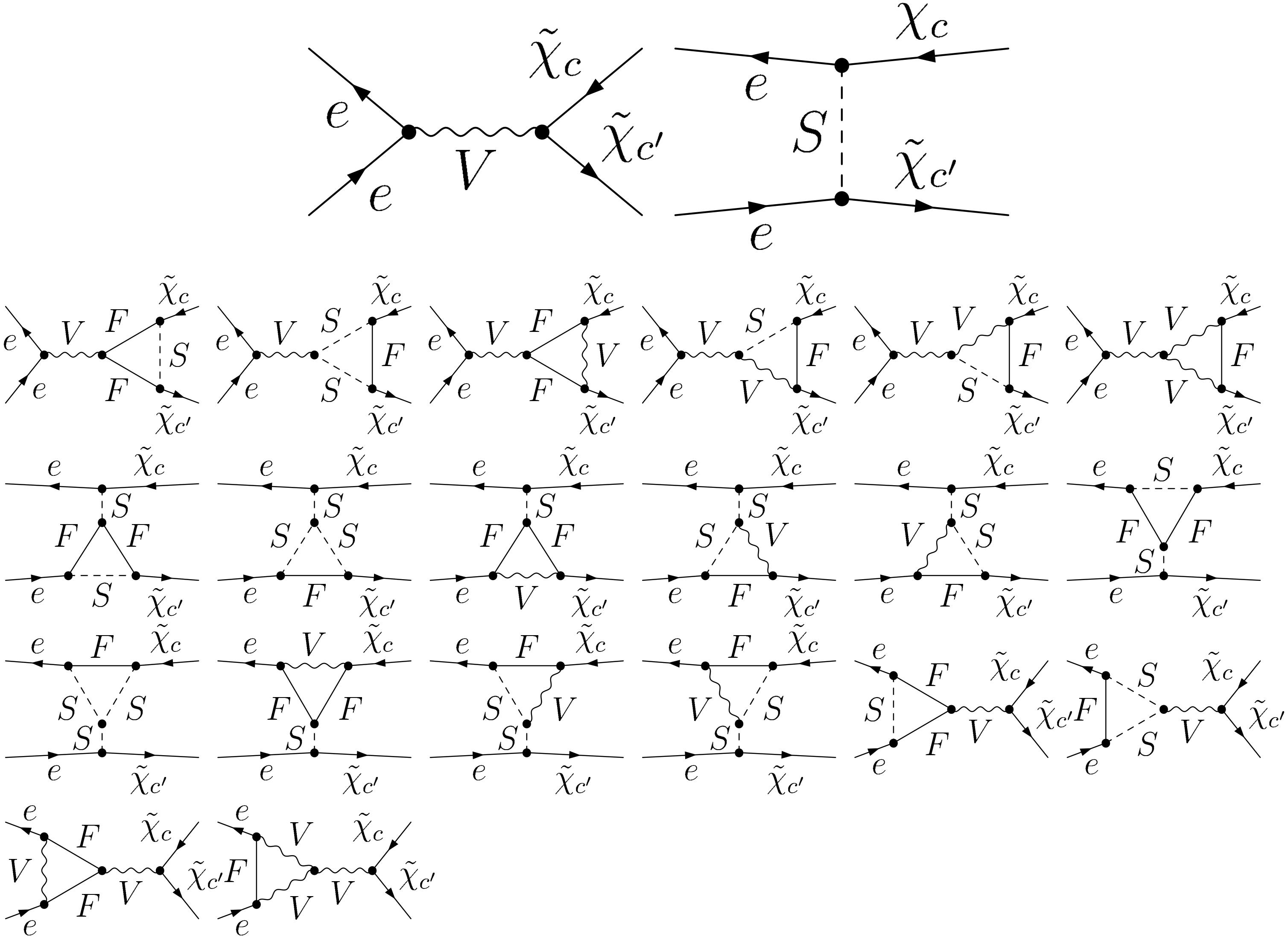
$$\Delta m_{\tilde{\chi}_i^0} = -\frac{1}{2}\text{Re}\Big\{m_{\tilde{\chi}_i^0}\left(\hat{\Sigma}^L_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0}) + \hat{\Sigma}^R_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0})\right) + \hat{\Sigma}^{SL}_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0}) + \hat{\Sigma}^{SR}_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0})\Big\}$$

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

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



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



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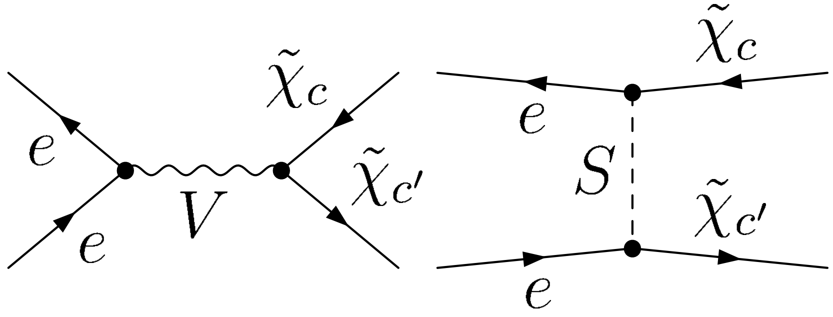
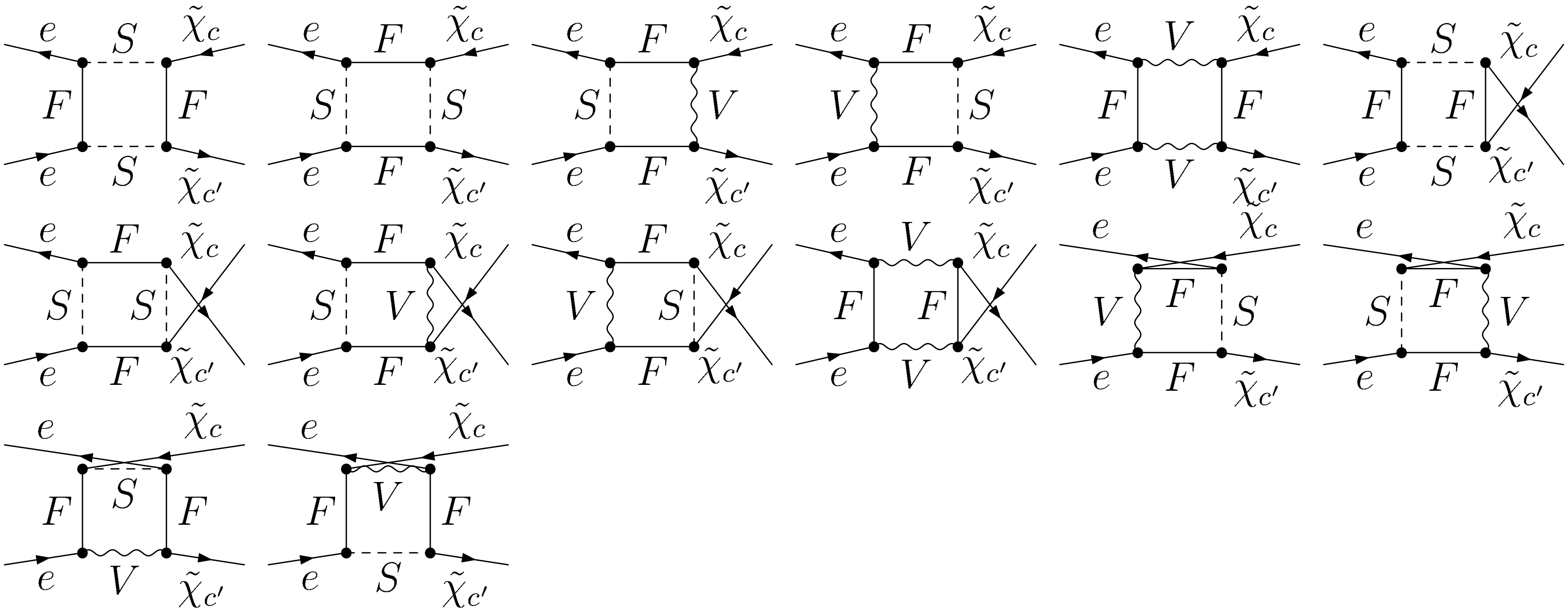
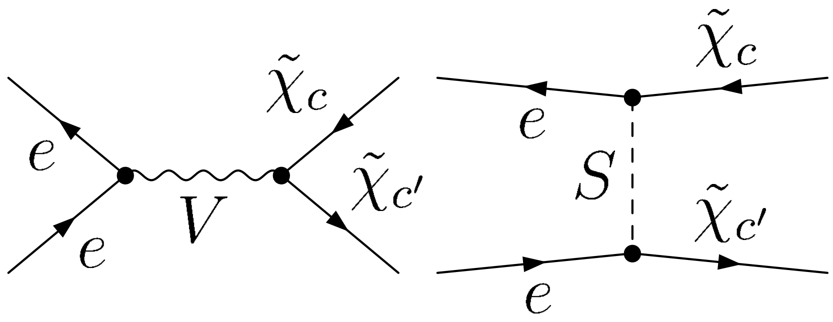
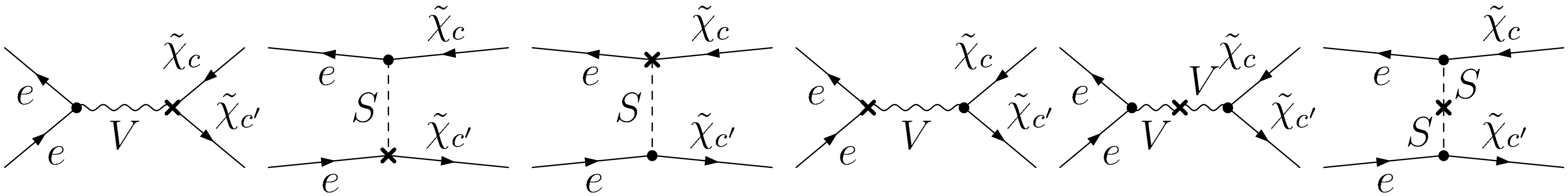




$e^+e^- \to \tilde{\chi}^{\pm}_c \tilde{\chi}^{\mp}_{c'}$:





+ soft and hard QED radiation

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

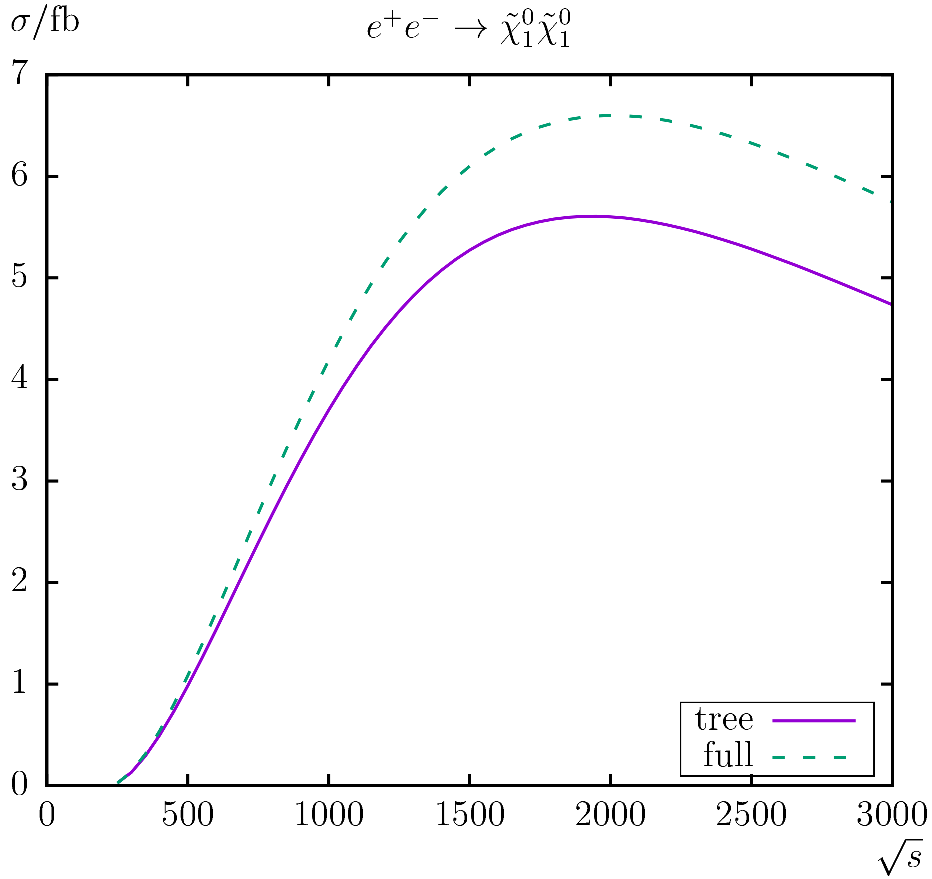
– opens up many (all) production channels

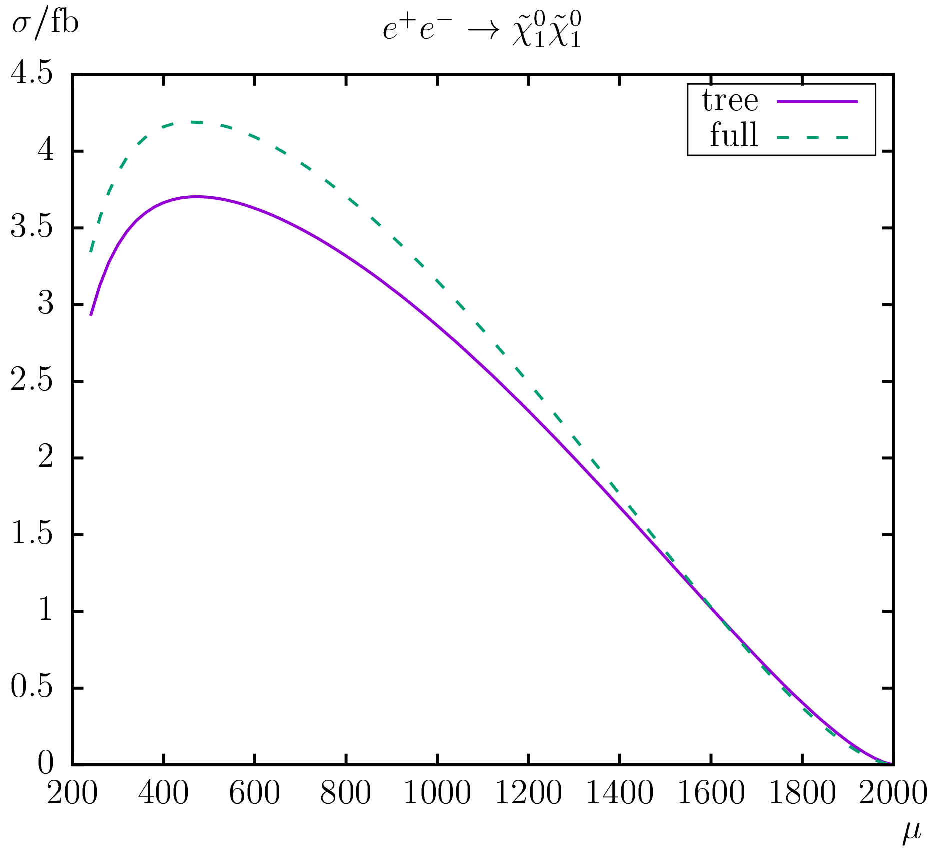
– relevant parameters varied

– . . .

⇒ show some relevant examples

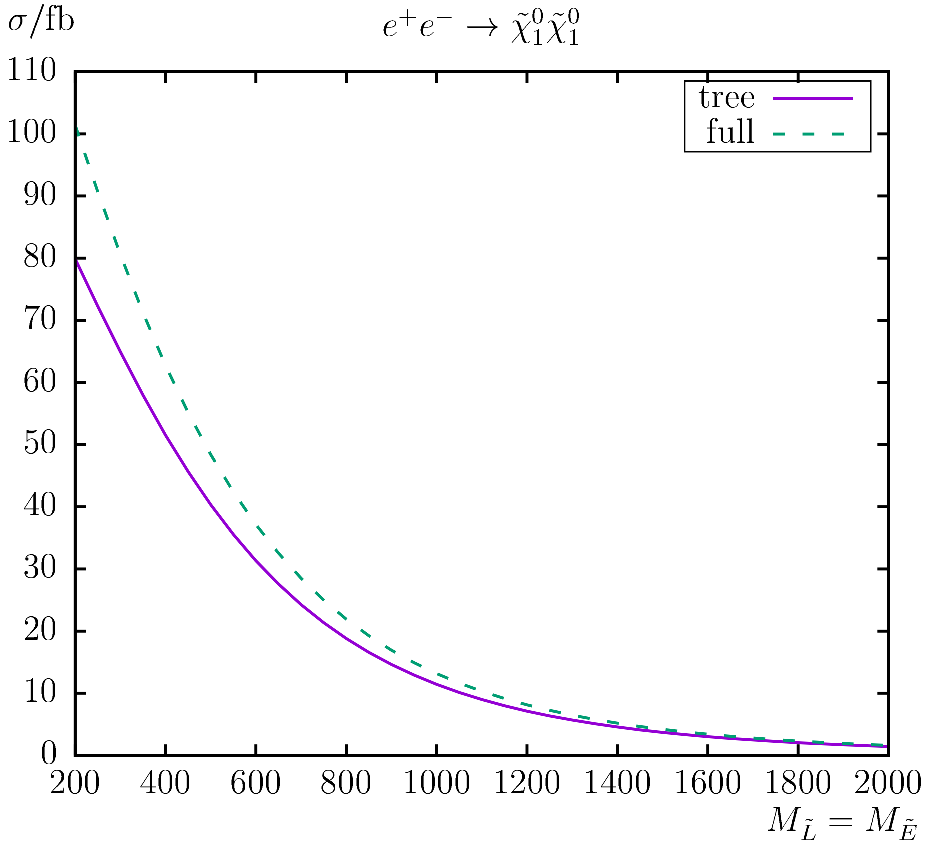
$\tilde{\chi}_1^0\tilde{\chi}_1^0$ production (I):

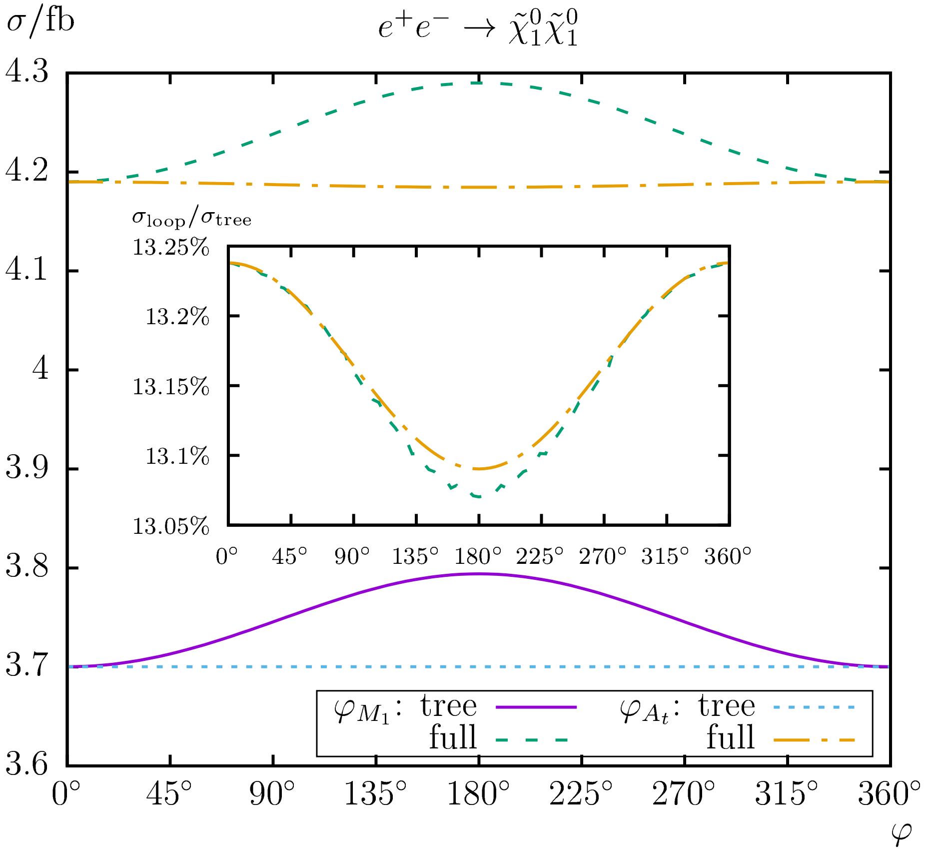




$\Rightarrow$ loop corrections $\sim$ 20%

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



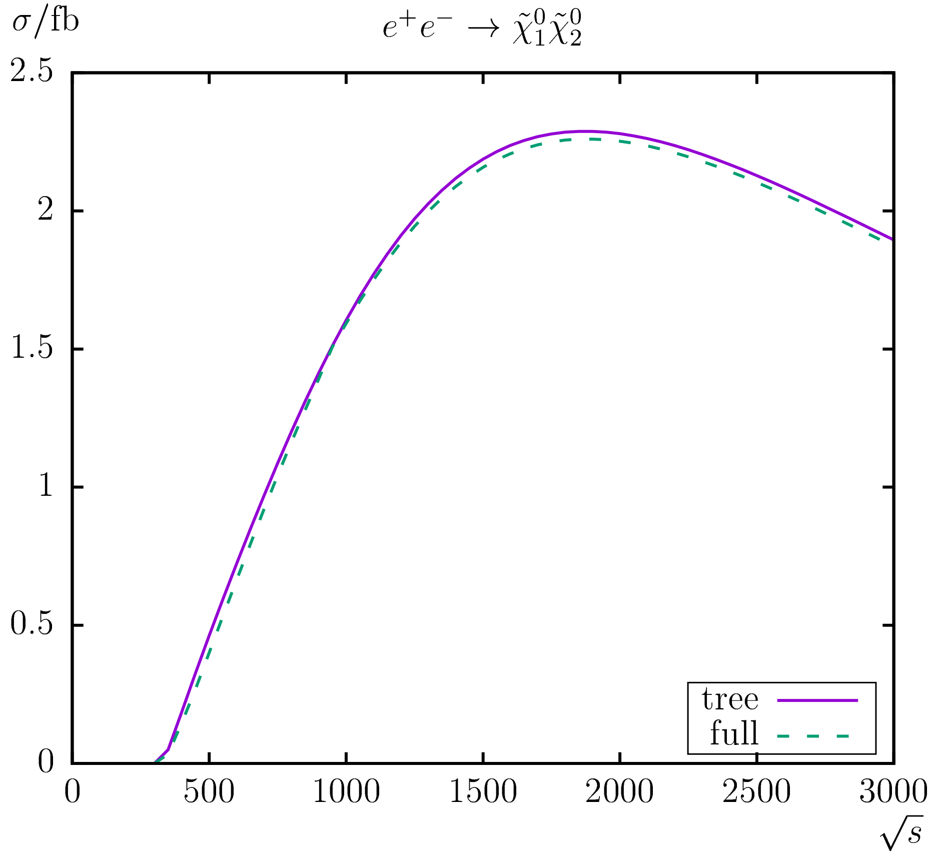


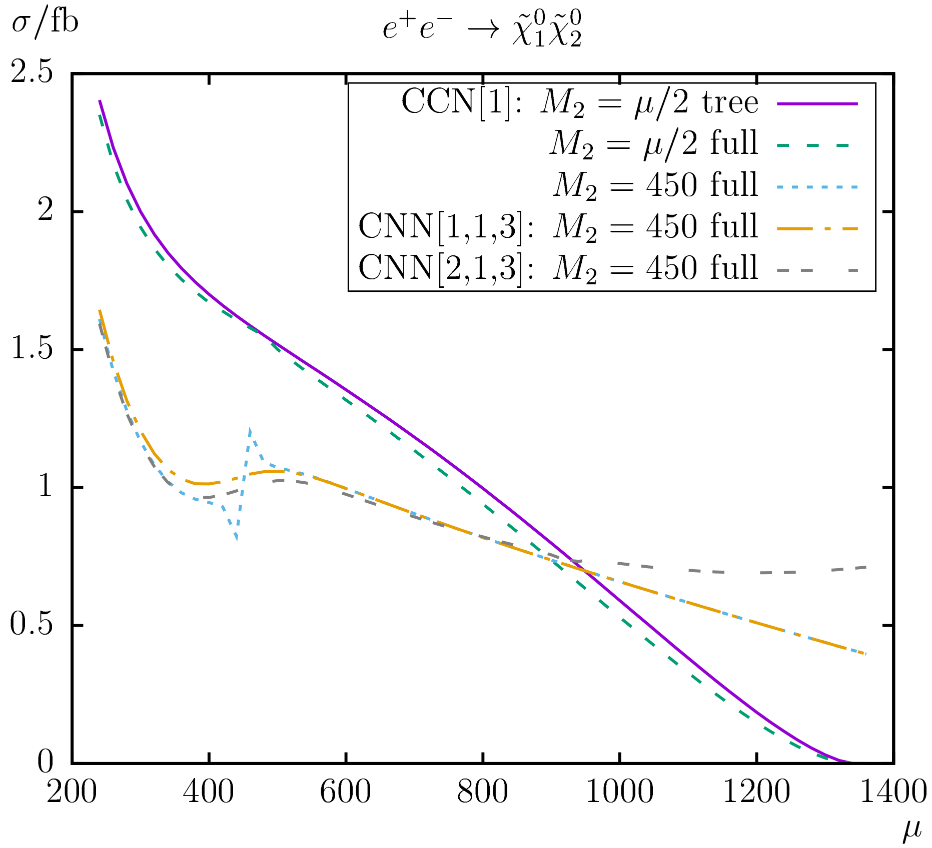
$\Rightarrow$ loop corrections $\sim$ 20%

$\Rightarrow$ strong t-channel dependence

$\Rightarrow$ relevant phase dependance at the tree-level

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

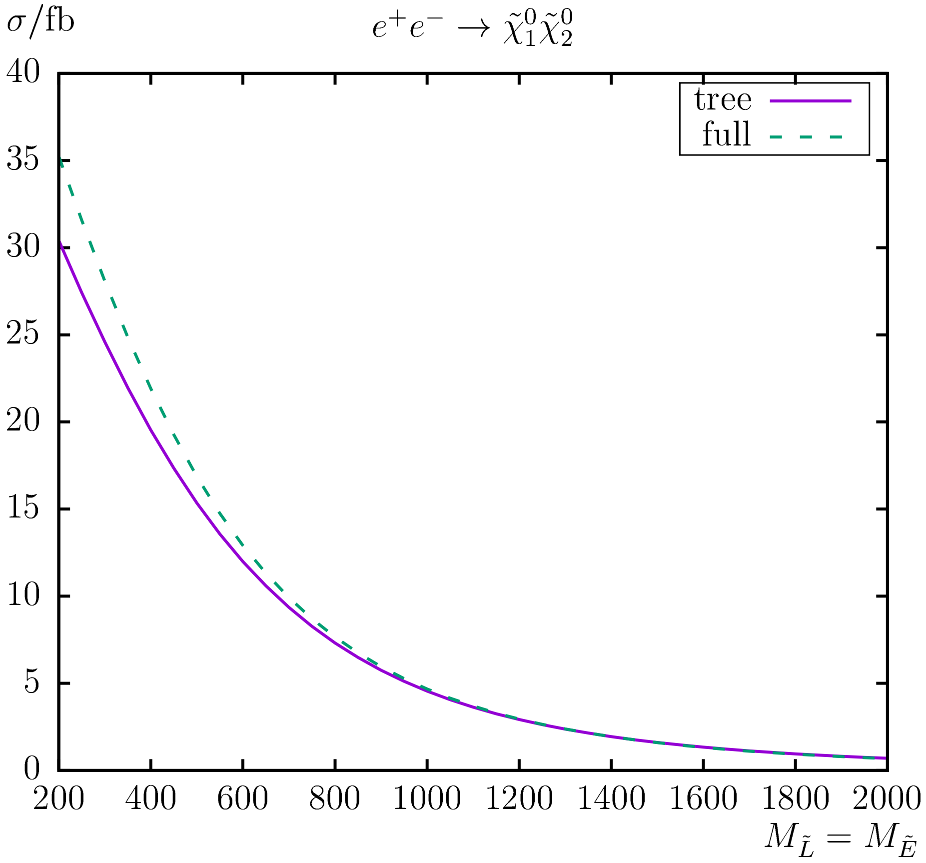


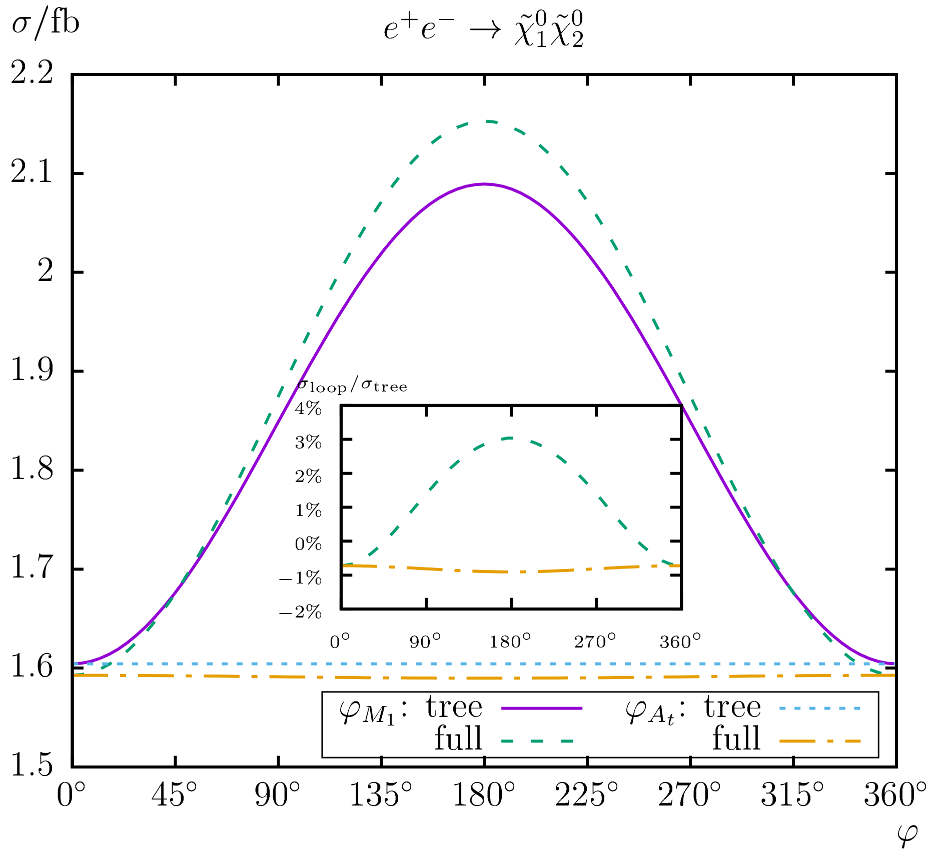


⇒ loop corrections small

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

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



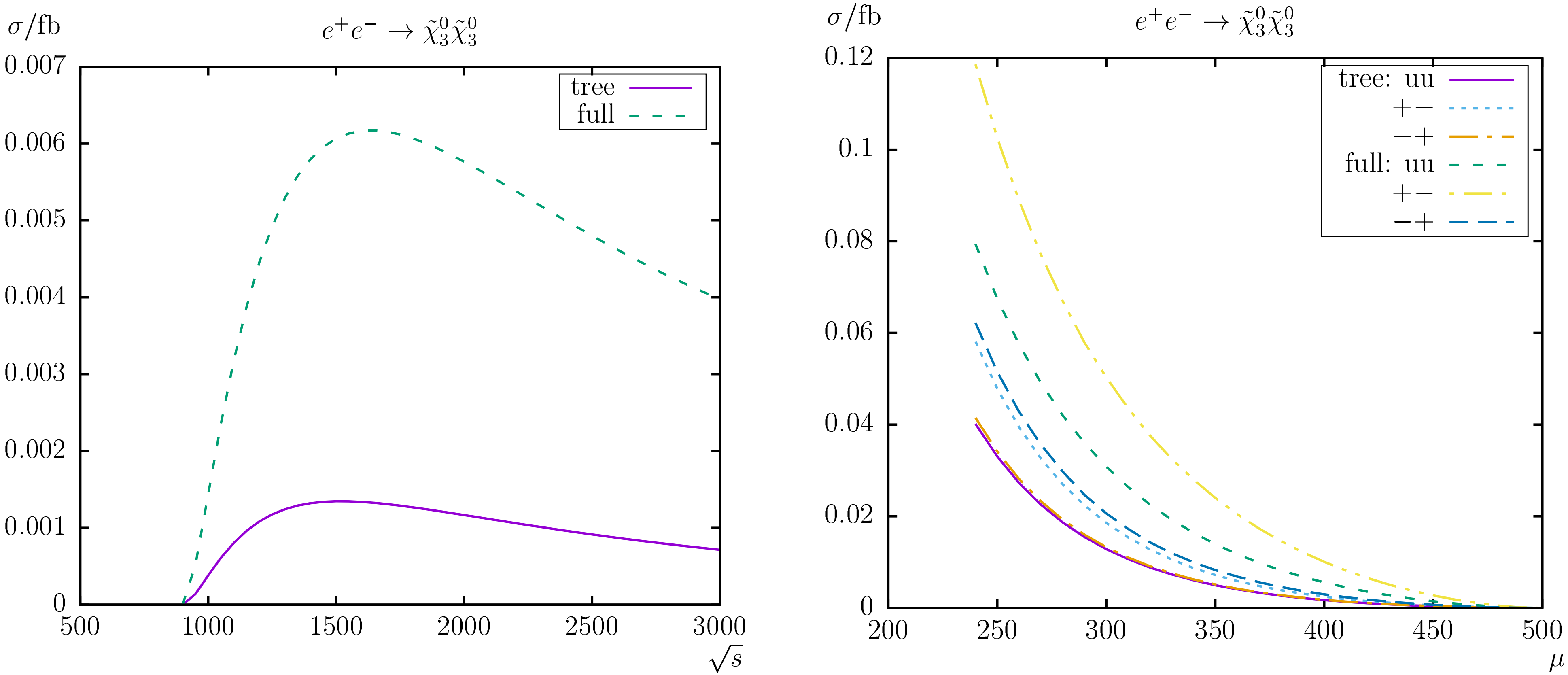


⇒ loop corrections $\lesssim$ 15%

⇒ strong t-channel dependence

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

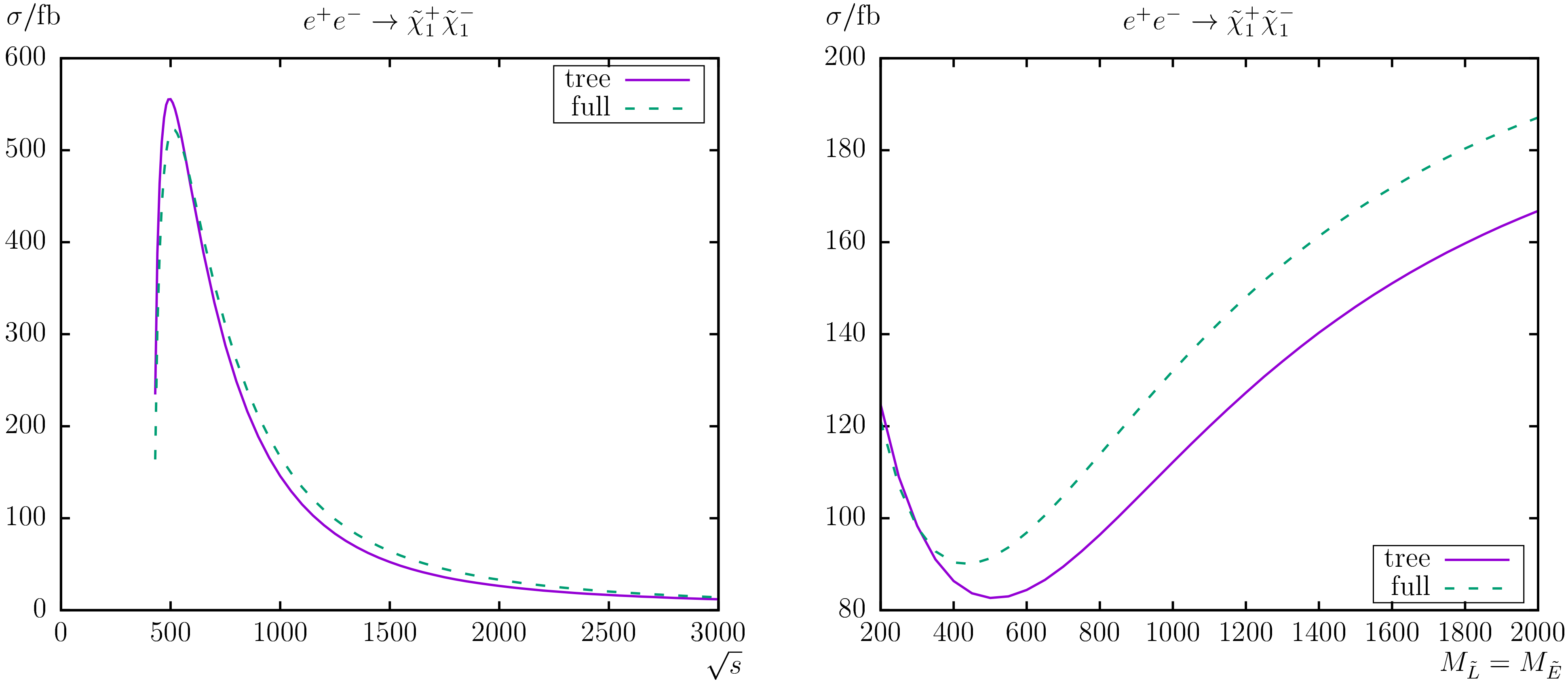
$\tilde{\chi}^0_3\tilde{\chi}^0_3$ production:



$\Rightarrow$ very small tree-level, huge loop corrections

$\Rightarrow$ polarization could be crucial to yield a detectable XS

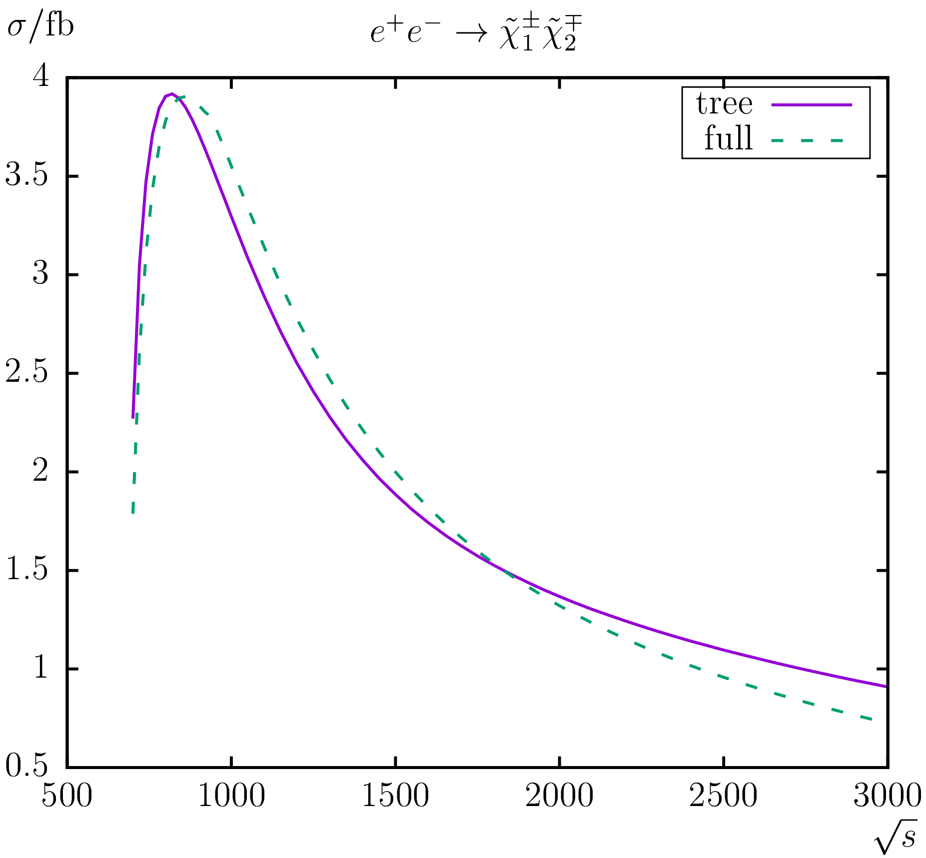
$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ production:

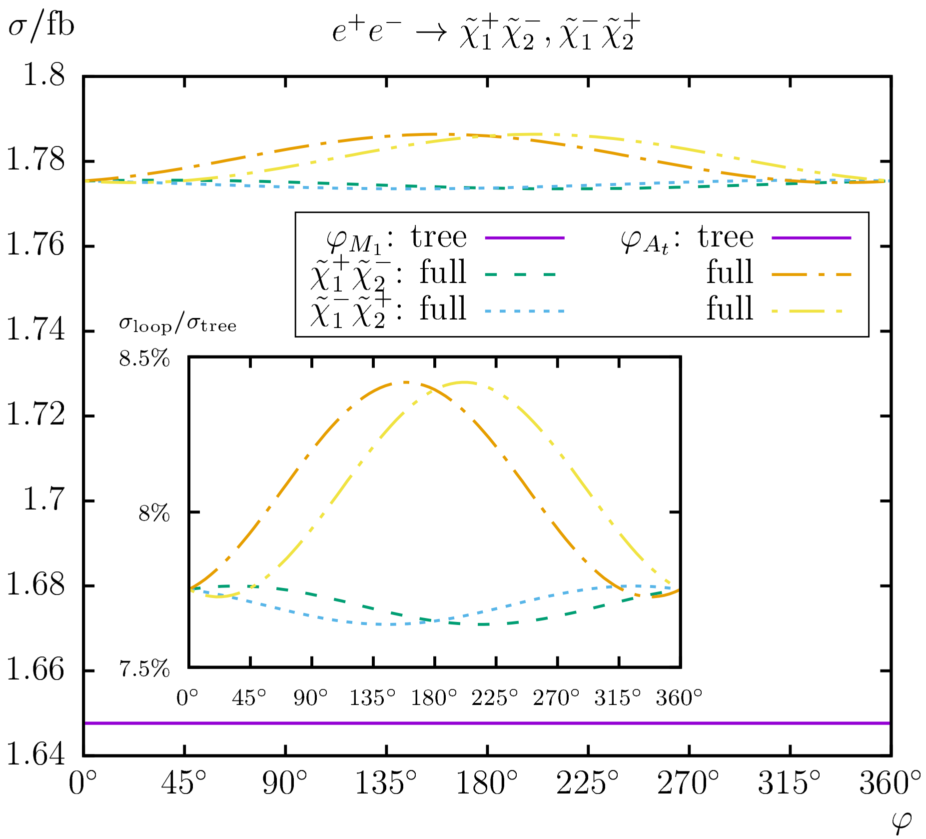


⇒ loop corrections $\sim$ 10%

⇒ strong t-channel dependance

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





⇒ loop corrections $\sim \pm$ 10%

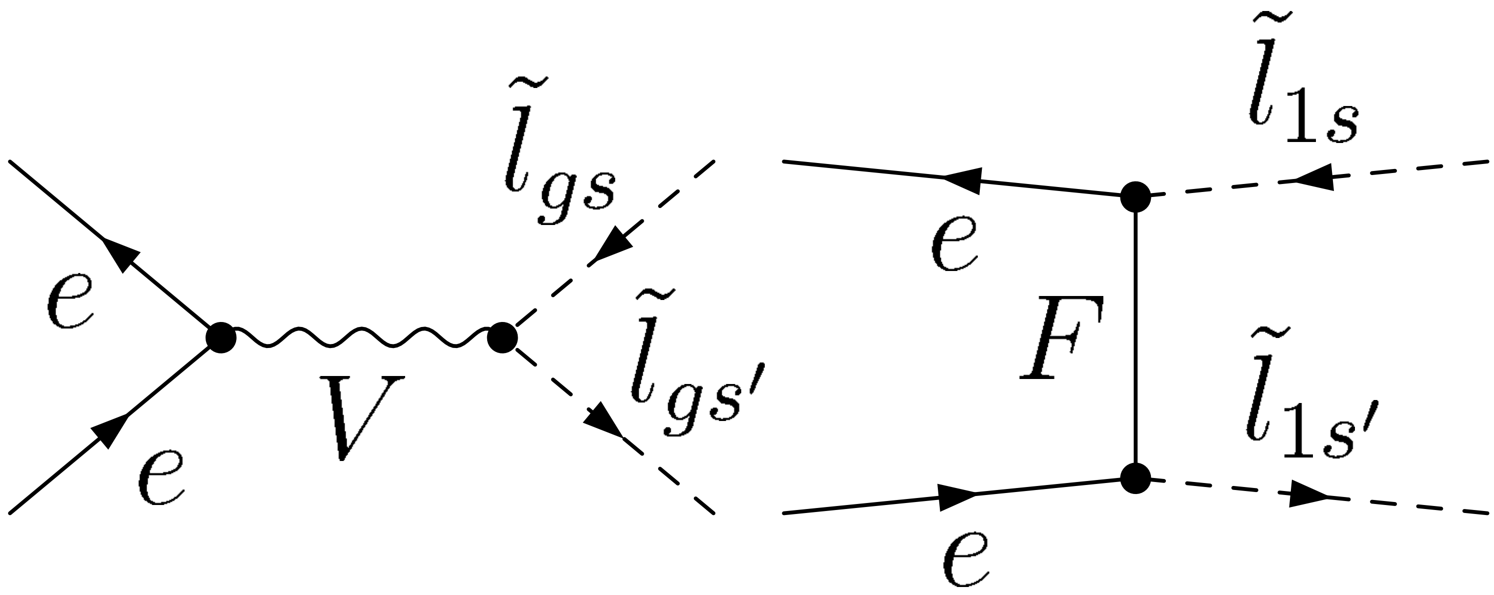
⇒ small $\mathcal{CP}$ assymmetry

3. Slepton production

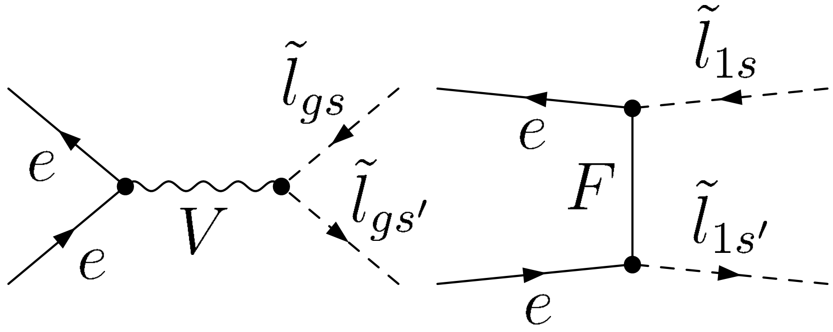
[arXiv:171x.nnnnn – PRELIMINARY]

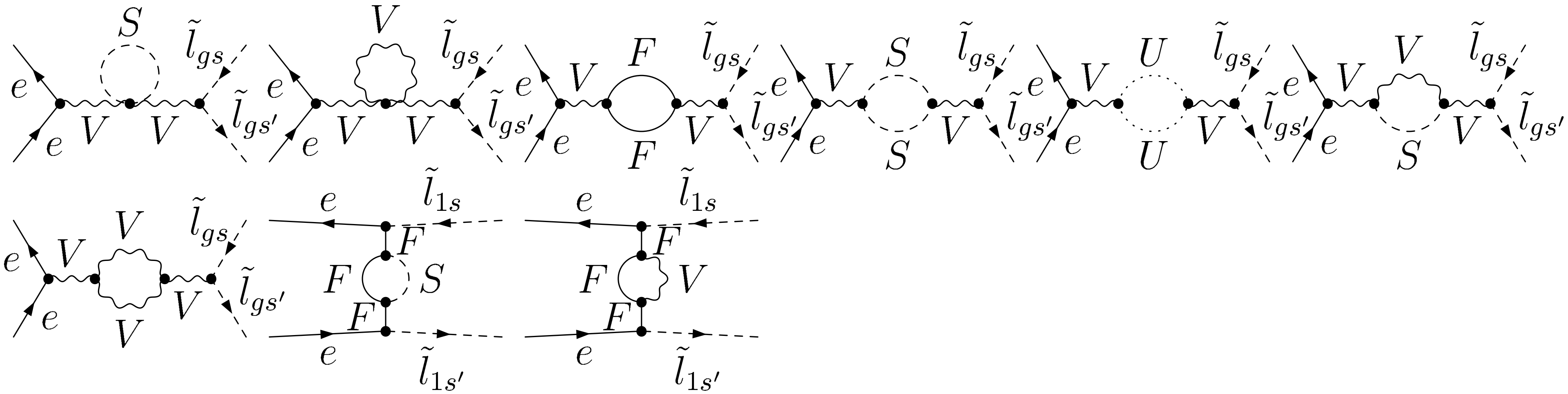
$$\sigma(e^+e^- \to \tilde{e}^{\pm}_{gs}\tilde{e}^{\mp}_{gs'}) \qquad (\tilde{e}_g = \{\tilde{e}, \tilde{\mu}, \tilde{\tau}\}; s, s' = 1, 2)$$

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

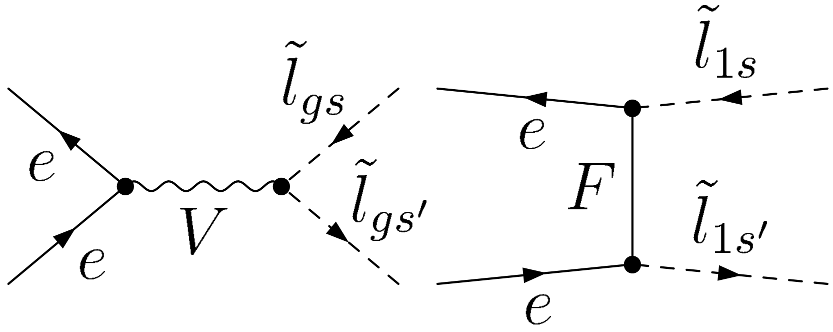


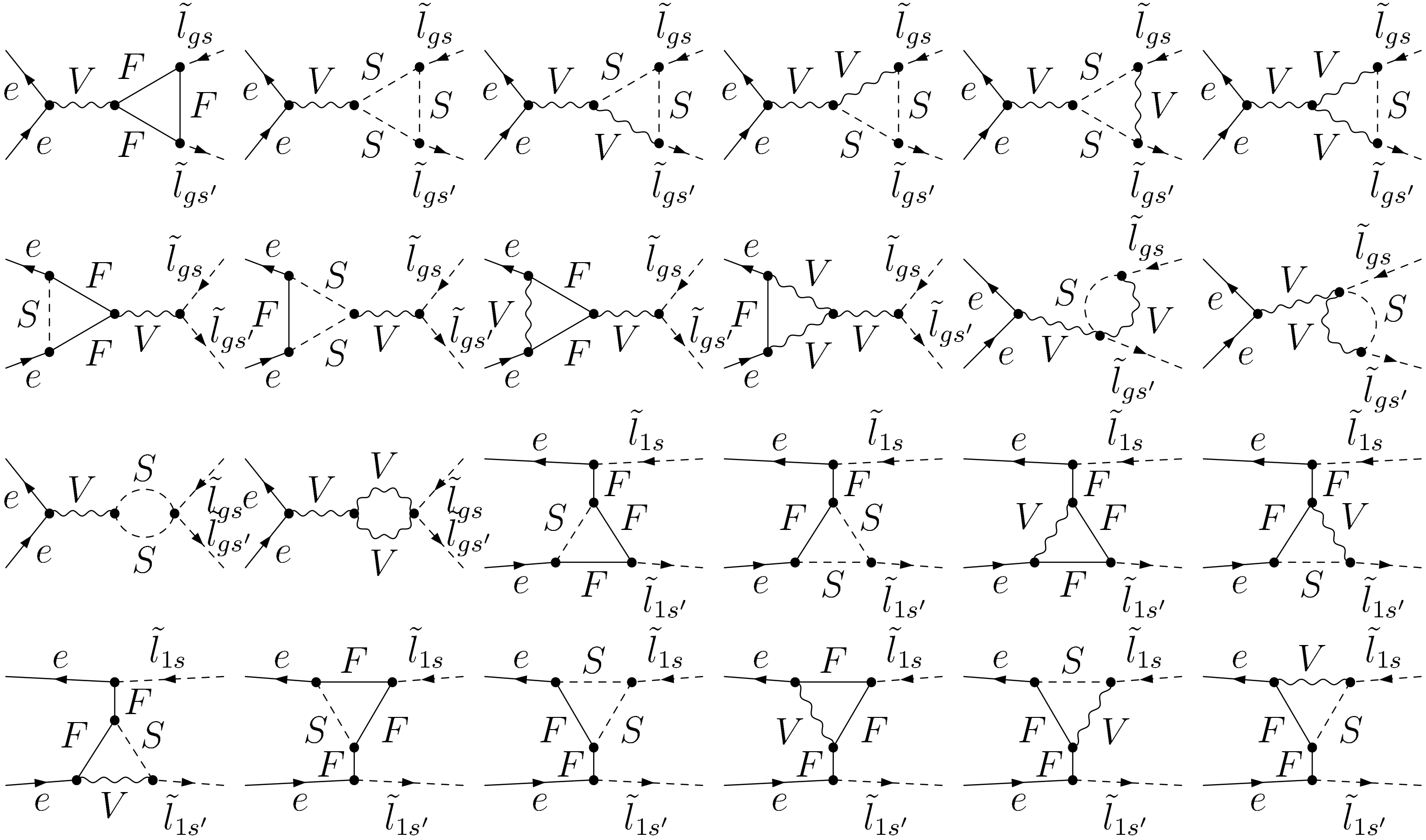
$e^{+}e^{-} \to \tilde{e}^{\pm}_{gs}\tilde{e}^{\mp}_{gs'}$:





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





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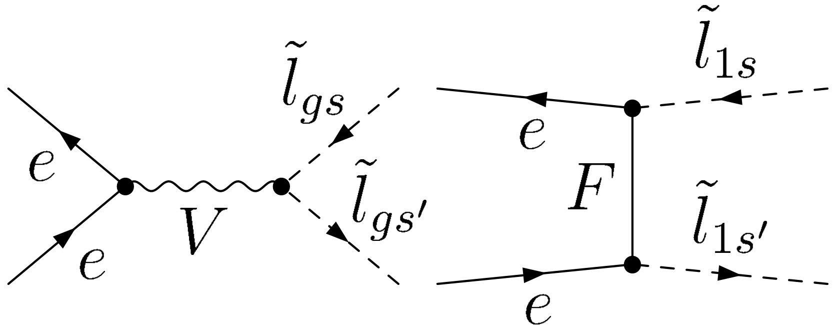

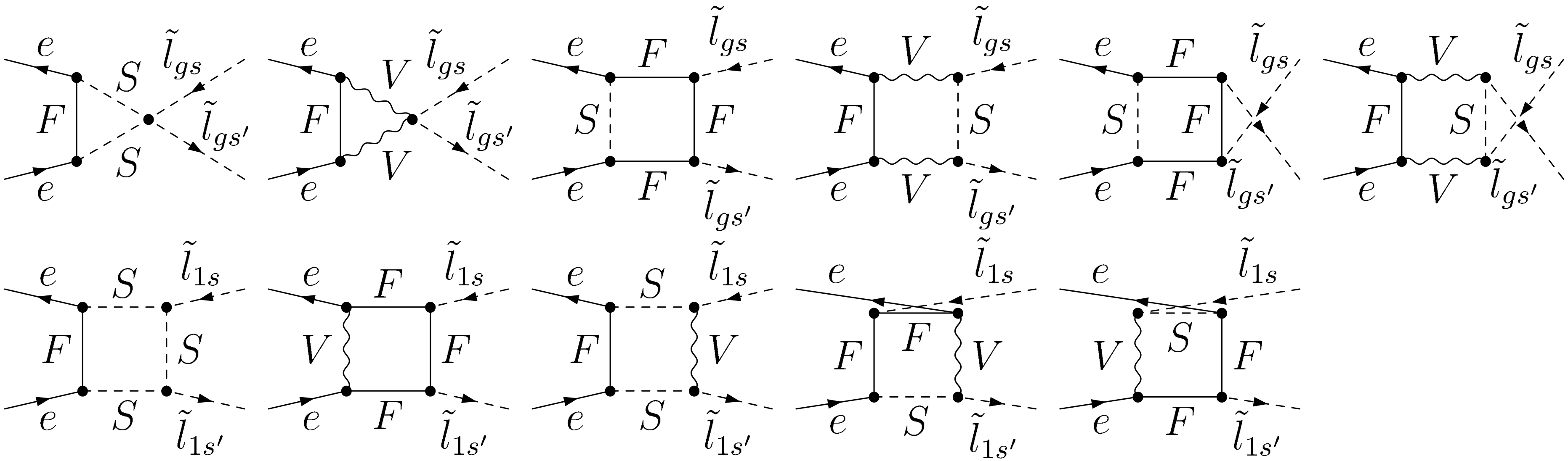

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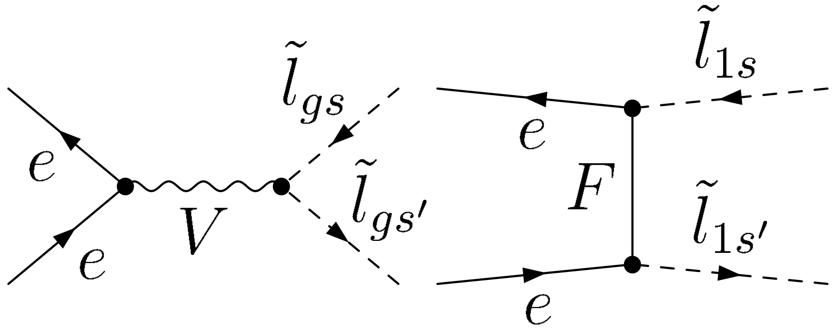
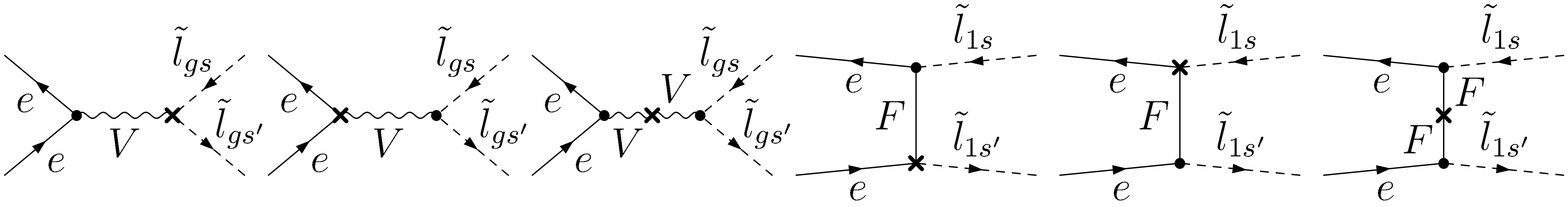




+ soft and hard QED radiation

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

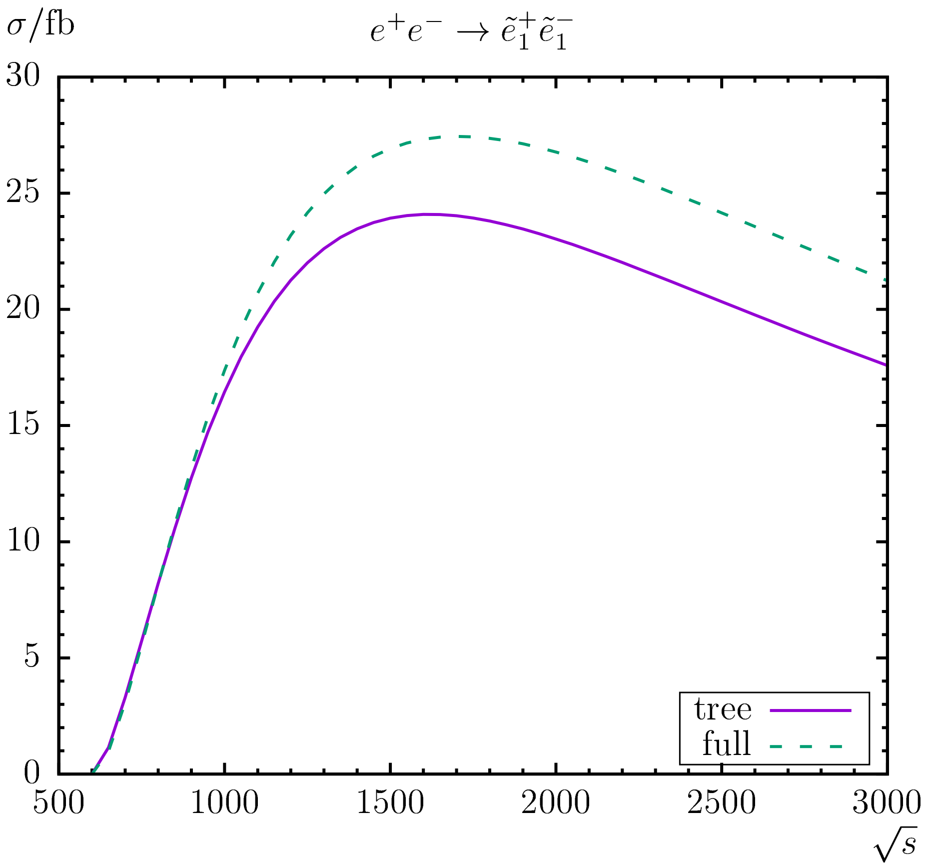
– opens up many (all) production channels

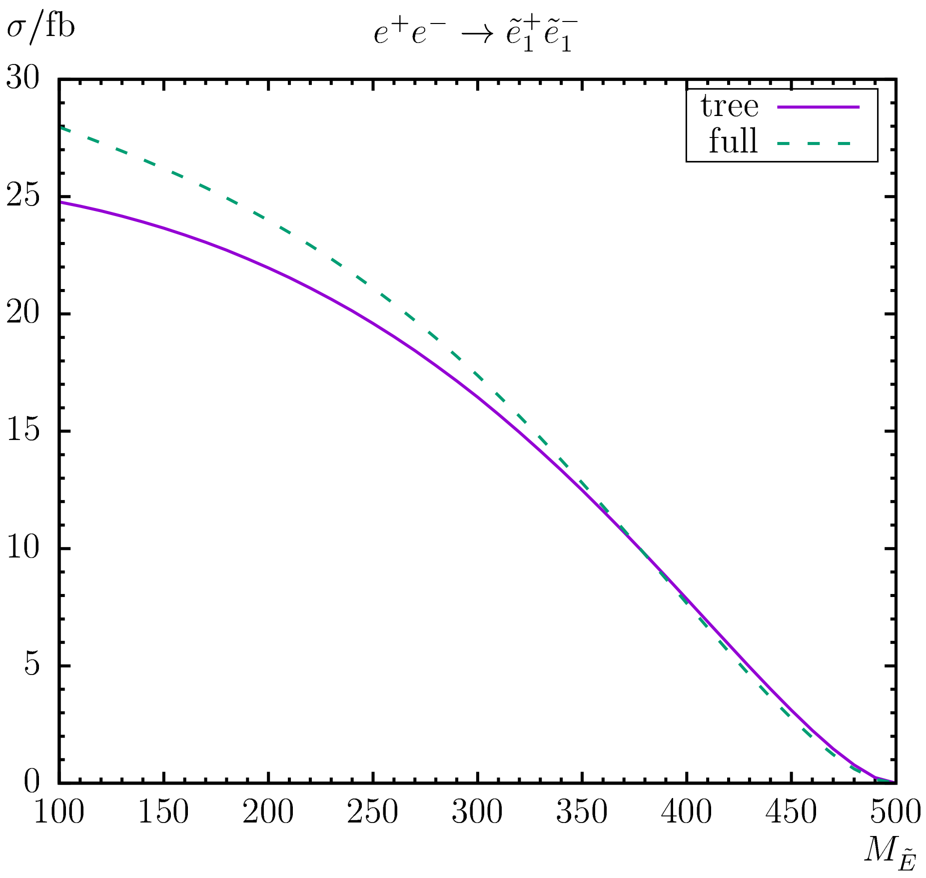
– relevant parameters varied

– . . .

⇒ show some relevant examples

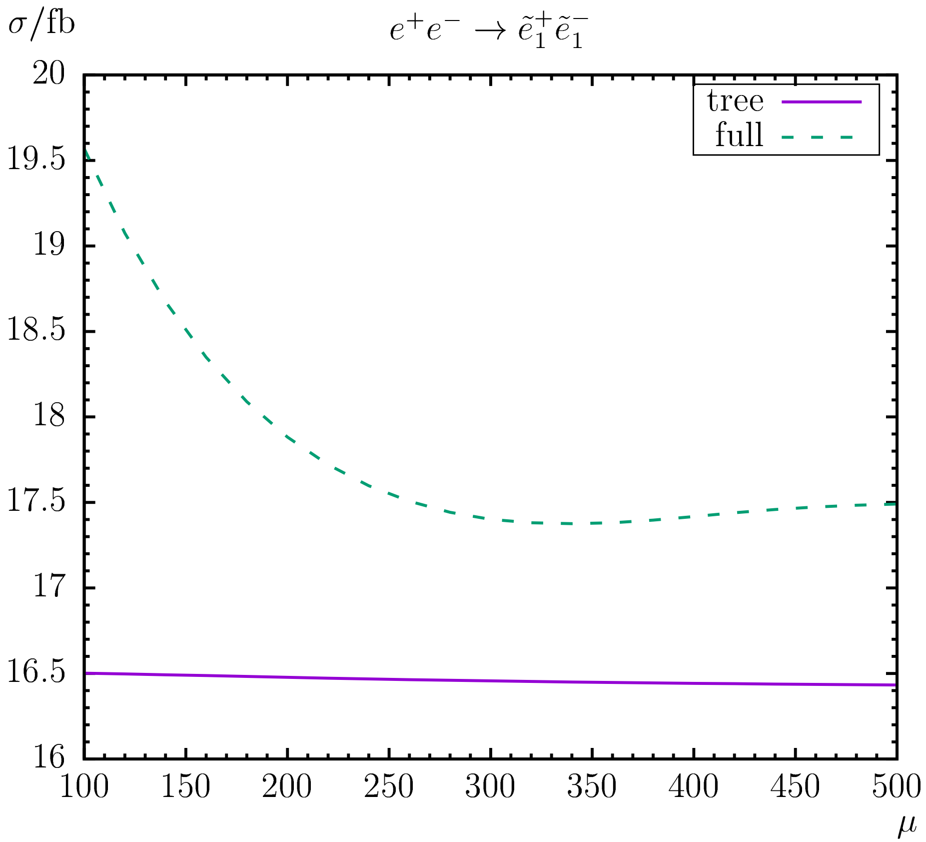
$\tilde{e}_1\tilde{e}_1$ production (I): [PRELIMINARY]

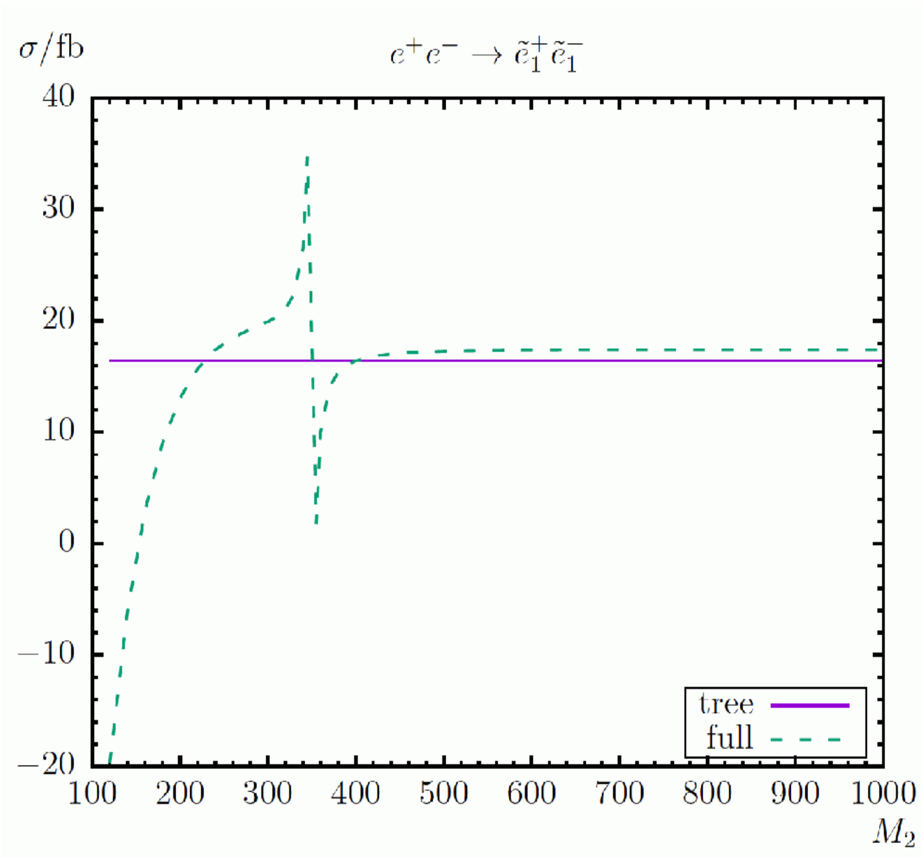




$\Rightarrow$ loop corrections $\sim$ 20%

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



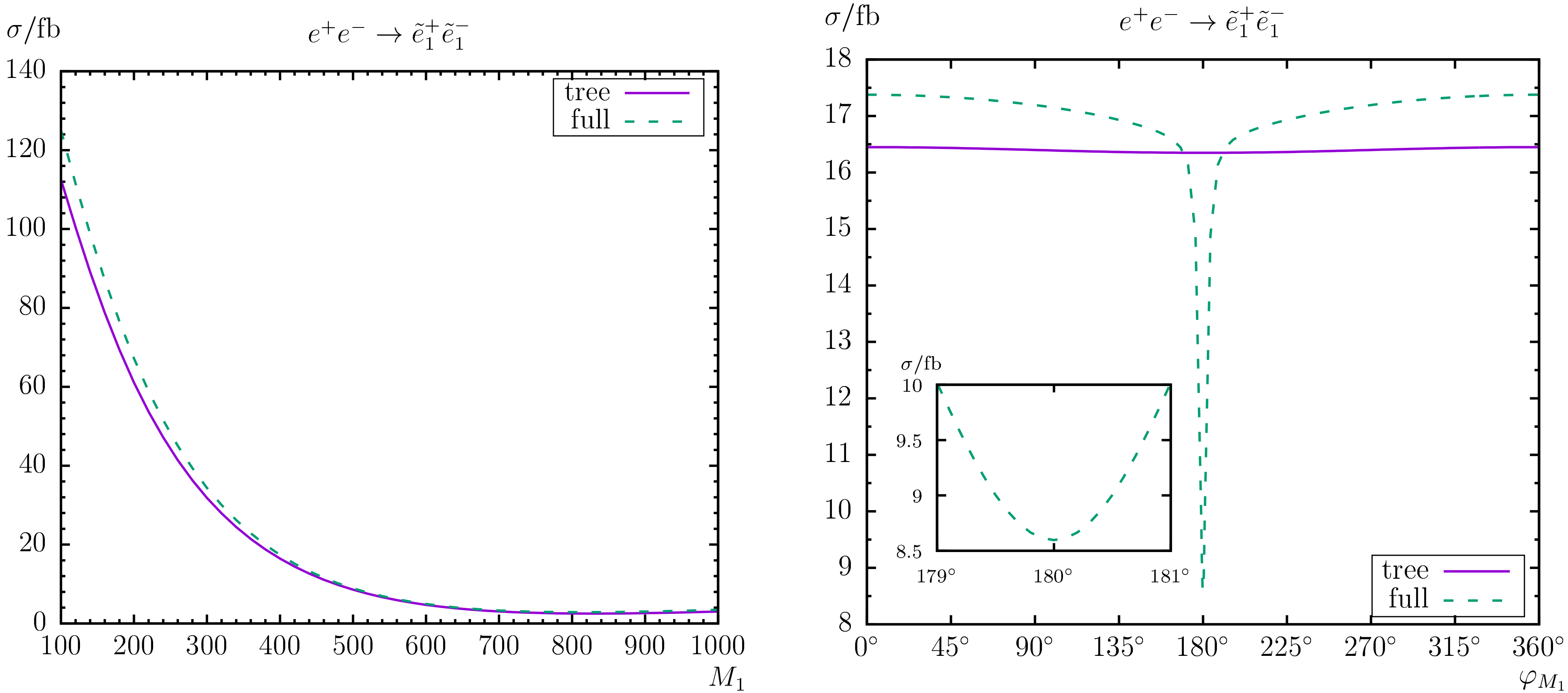


⇒ loop corrections $\sim$ 20%

⇒ strong μ dependance of loop corrections

⇒ CCN1 breaks down at $\mu = M_2$

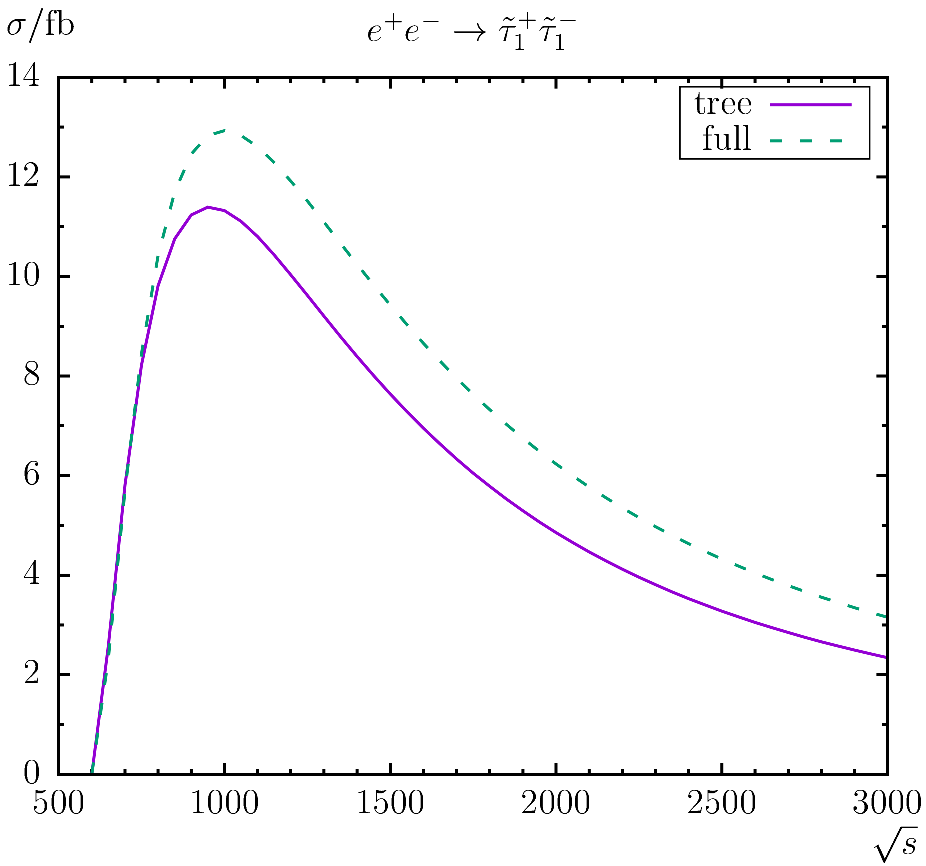
$\tilde{e}_1\tilde{e}_1$ production (III): [PRELIMINARY]

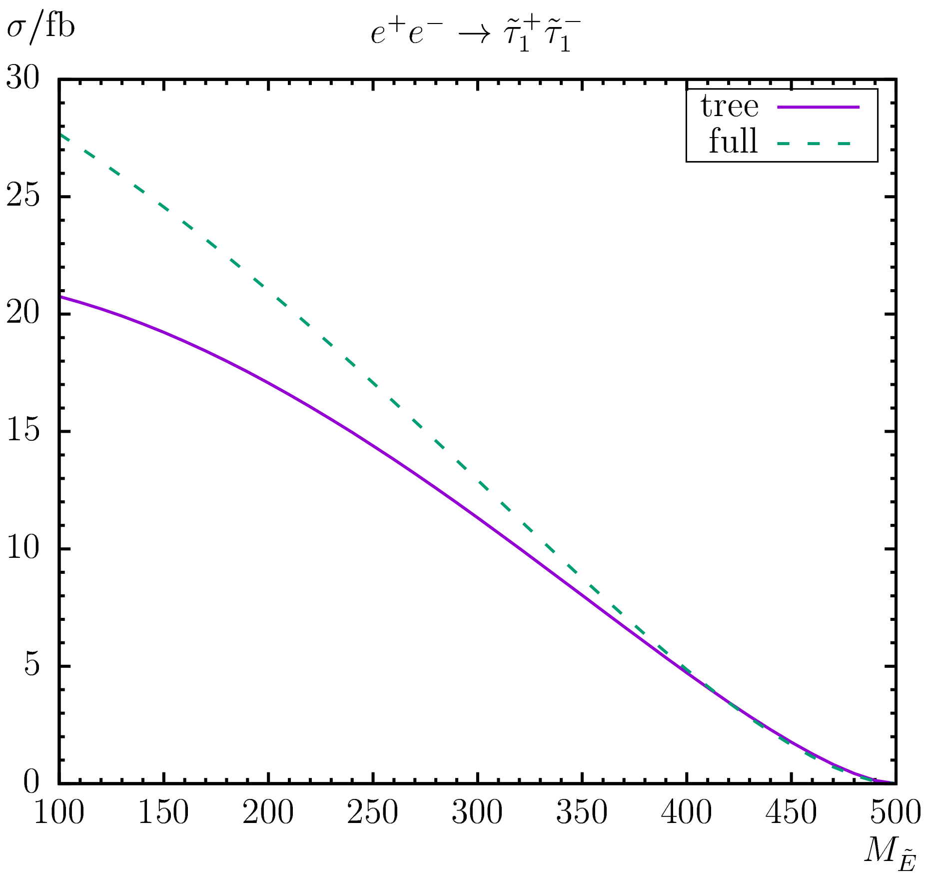


⇒ strong phase dependance of loop corrections

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

[PRELIMINARY]



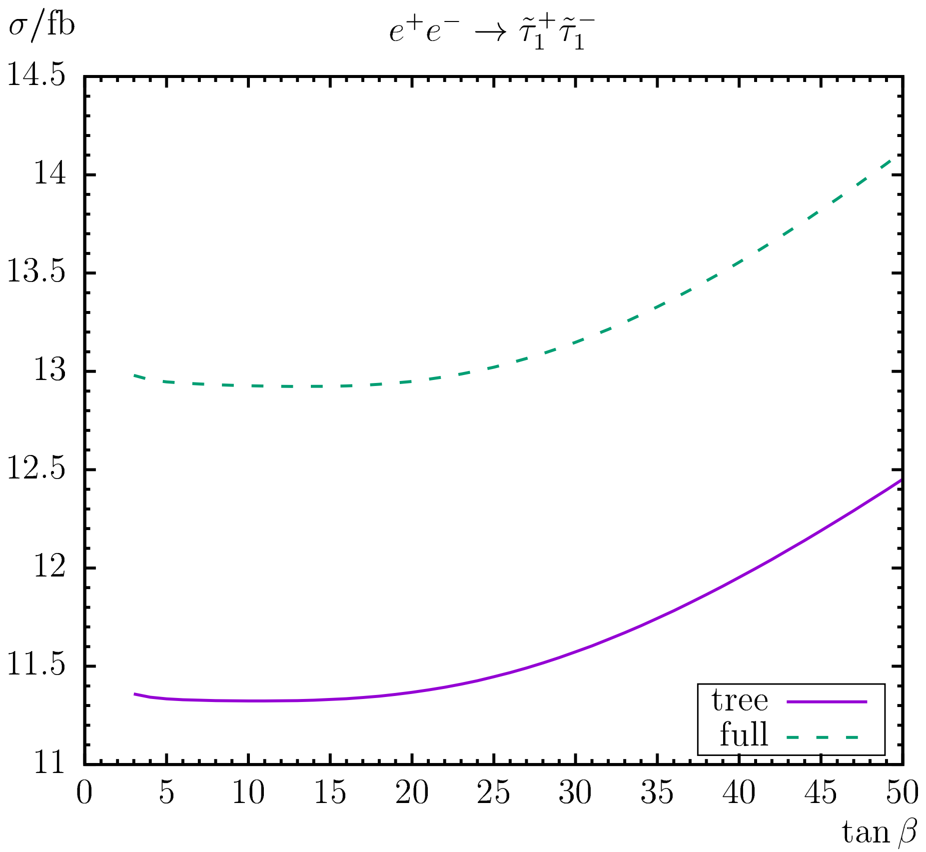


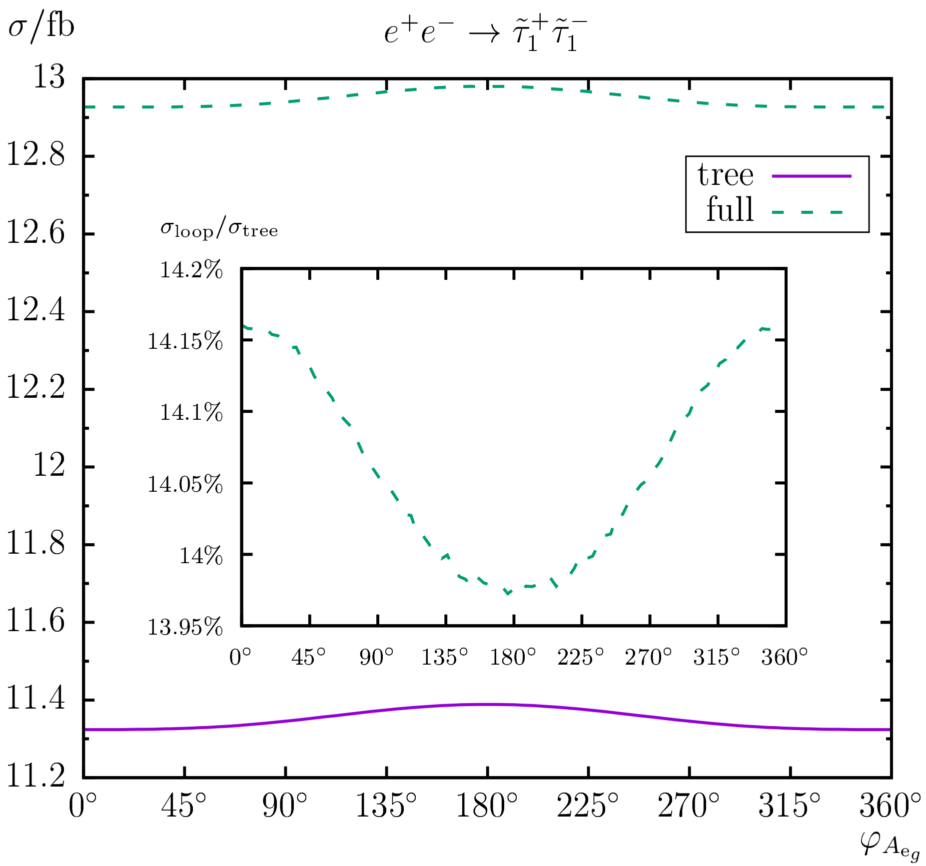
$\Rightarrow$ loop corrections $\sim$ 20%

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

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

[*PRELIMINARY*]





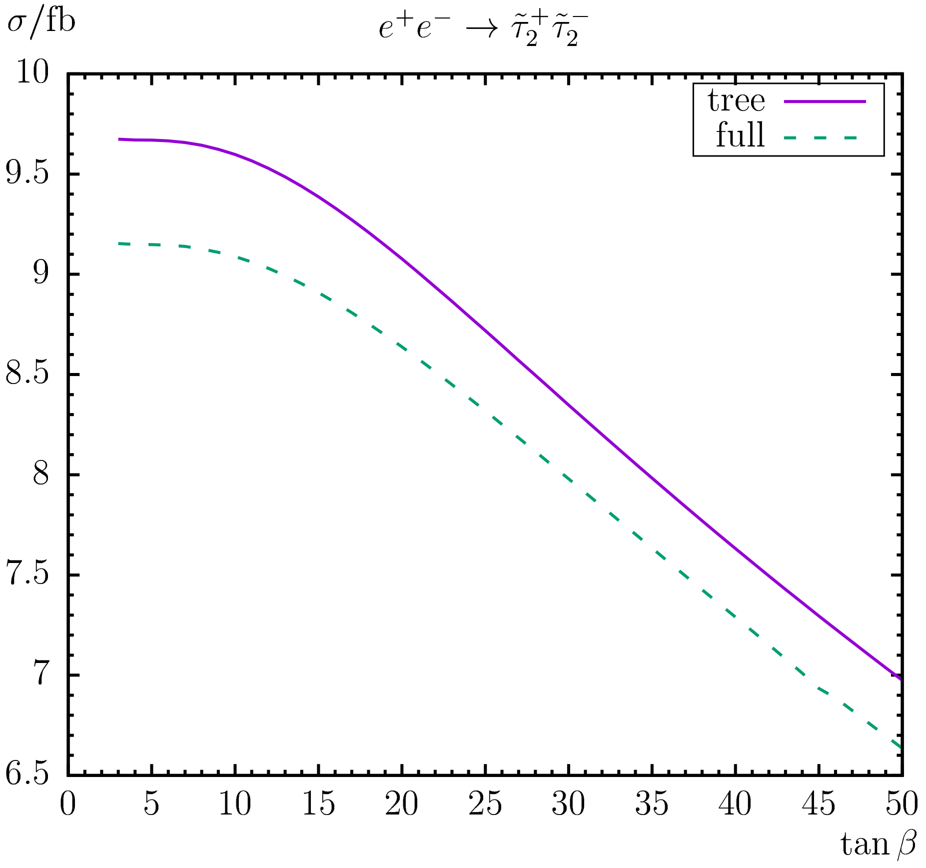
$\Rightarrow$ loop corrections $\sim$ 15%

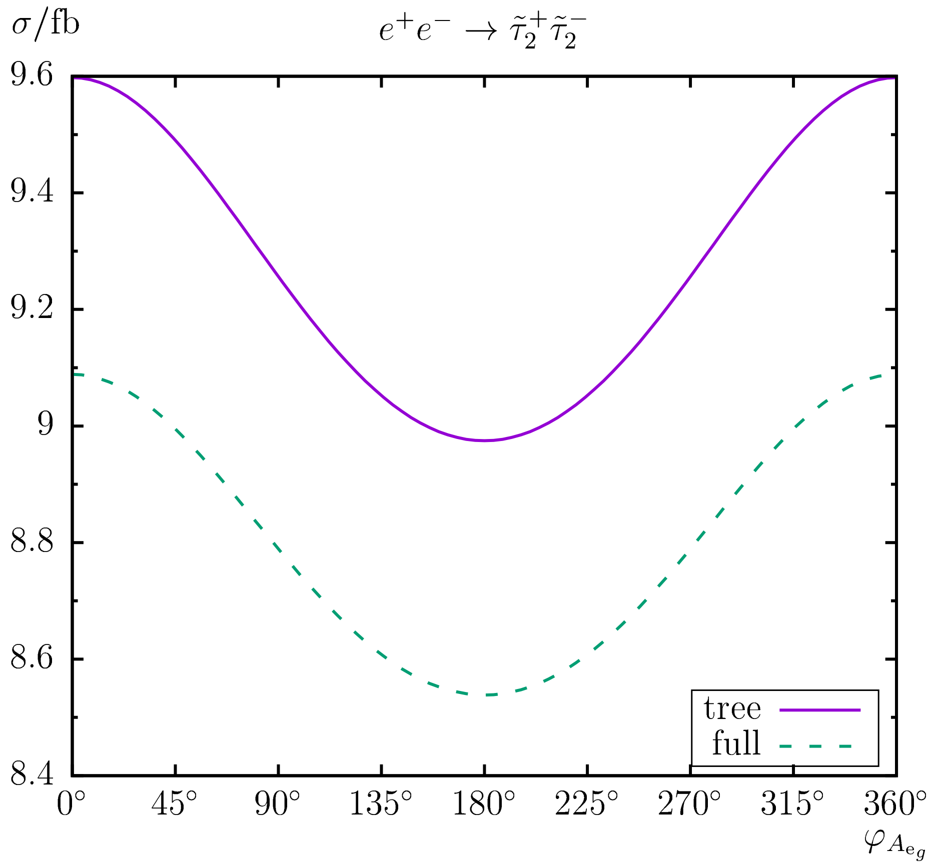
$\Rightarrow$ strong $\tan\beta$ dependance

$\Rightarrow$ weak phase dependance

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

[PRELIMINARY]





⇒ loop corrections $\sim$ 15%

⇒ strong $\tan\beta$ dependance

⇒ strong phase dependance

4. 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: [*PRELIMINARY*]
    corrections up to $\sim 20\%$, phase dependance relevant