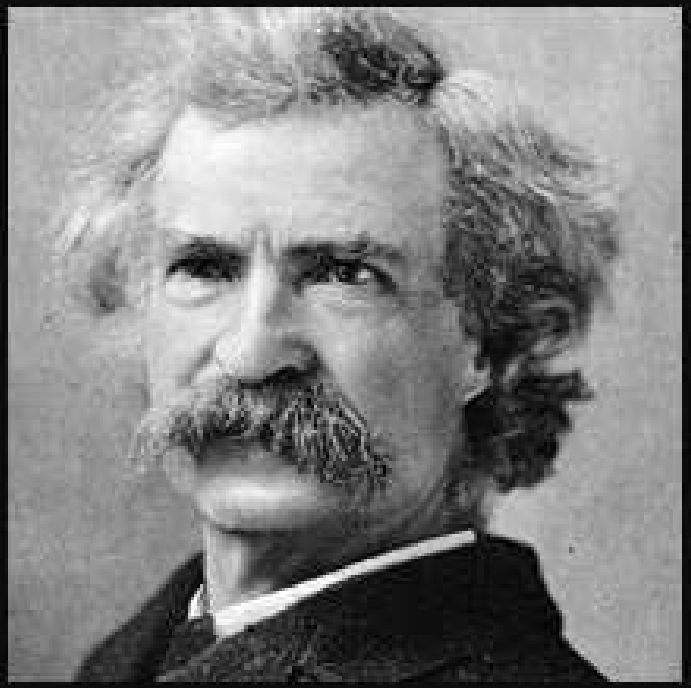
Some original SUSY literature:



The reports of my death have been greatly exaggerated.

~ Mark Twain

EW SUSY production at the ILC and CLIC

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

Arlington, 10/2017

1. Introduction & Motivation
2. Chargino/neutralino production
3. Slepton production
4. Conclusions

1. Introduction & Motivation

Some "recent" measurements:

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

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- top quark mass
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Simple SUSY models predicted correctly:

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

$\Rightarrow$ good motivation to look at SUSY!

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

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

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

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

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

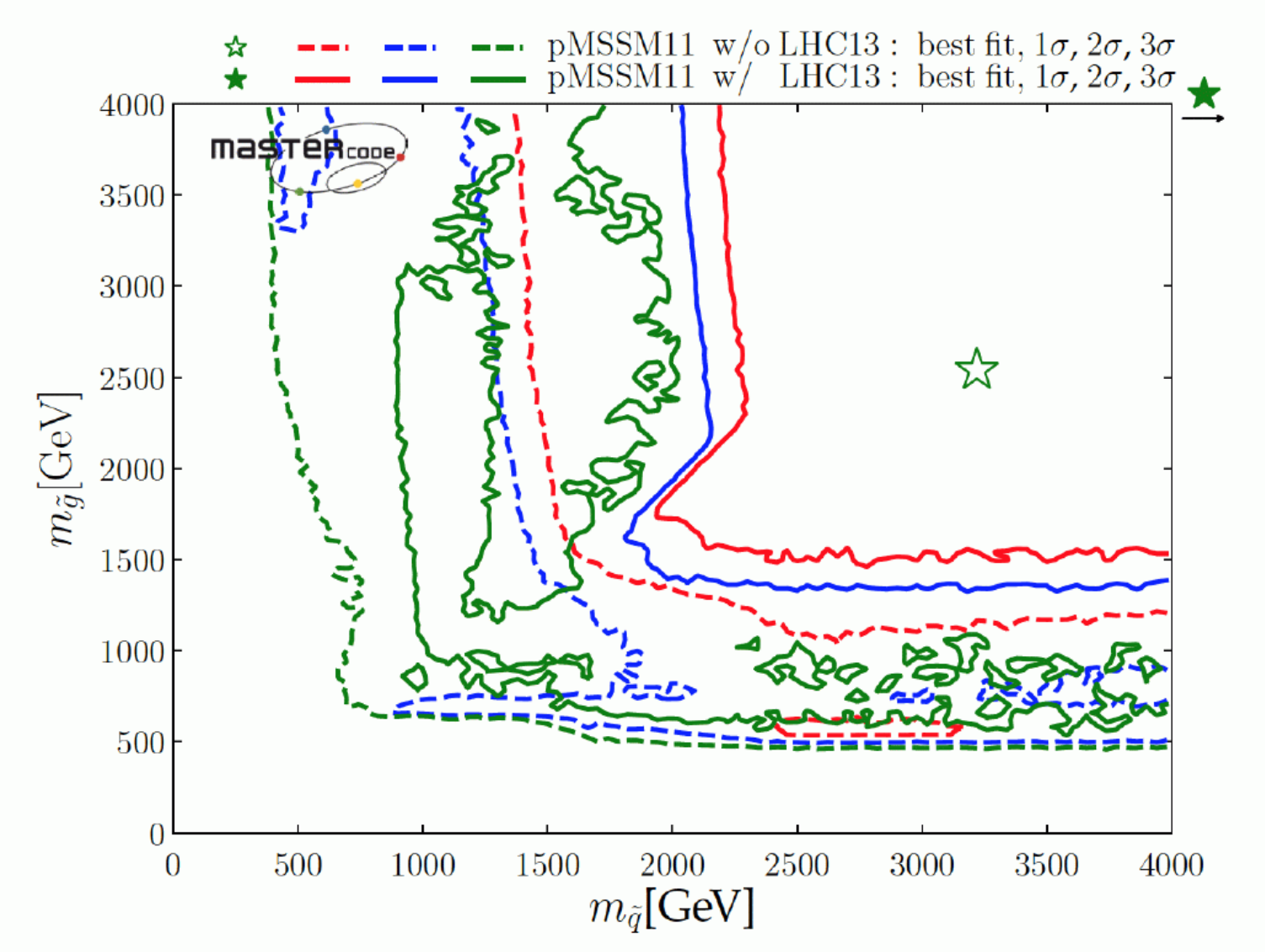
Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: many scales

Problem in the MSSM: complex phases

pMSSM11: Going from 8 TeV to 13 TeV (and adding latest DM limits)

[2017]

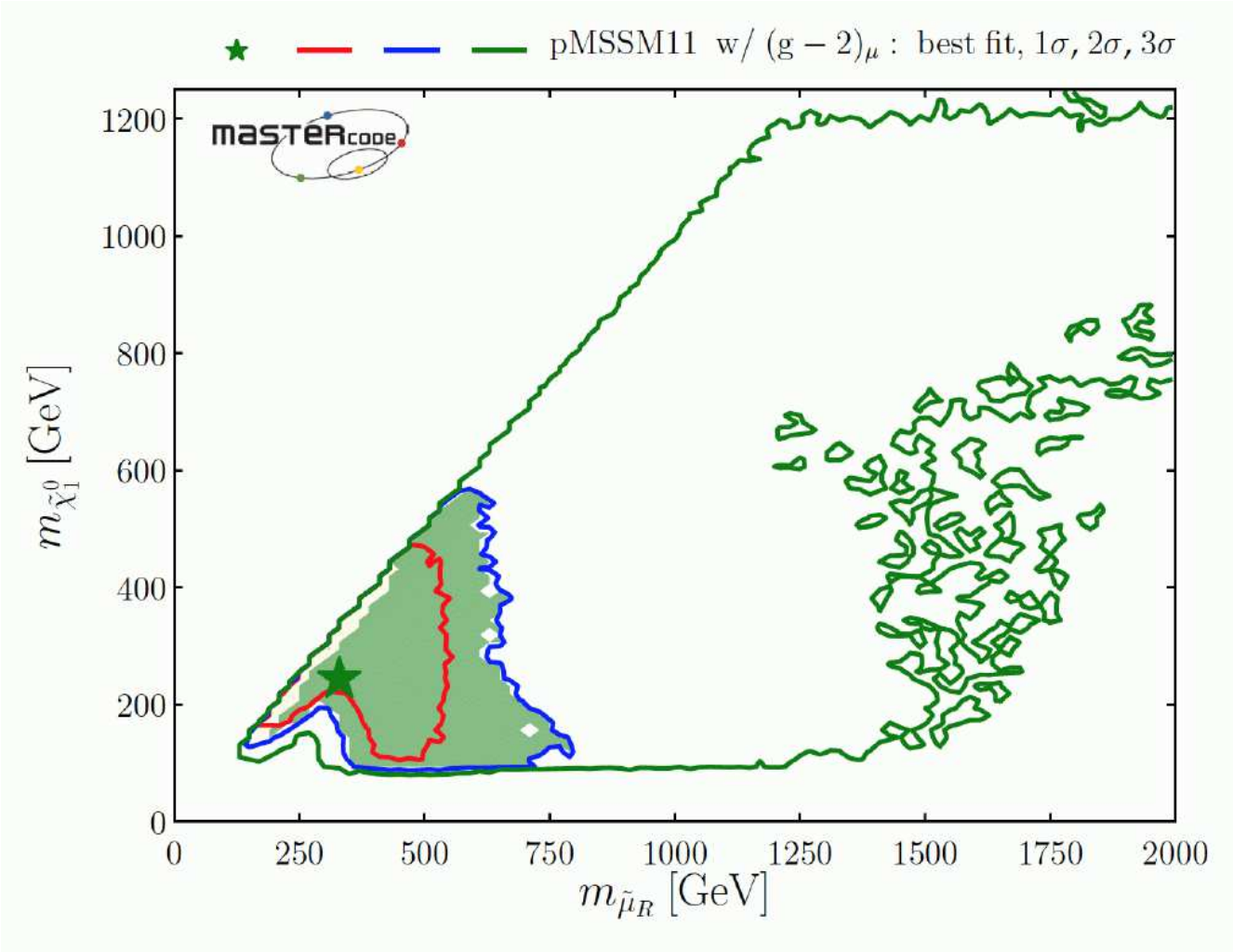


⇒ substantial move to higher masses!

⇒ notice the "nose"!

pMSSM11: $m_{\tilde{\mu}}$–$m_{\tilde{\chi}_1^0}$ plane

[2017]



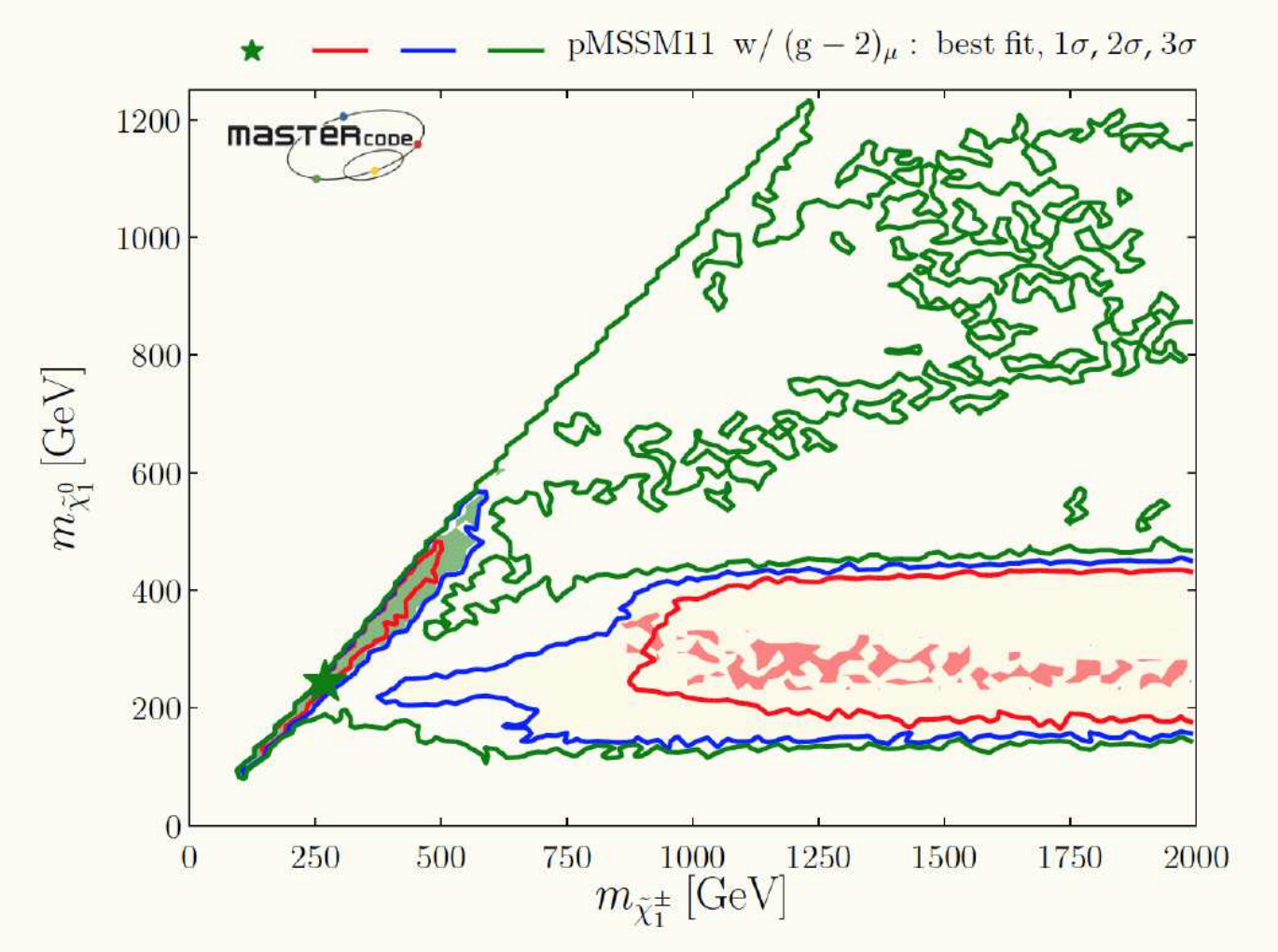
$\tilde{\chi}_1^\pm$ coann. | slep coann. | gluino coann. | stop coann.

A/H funnel | stau coann. | squark coann. | sbot coann.

$\Rightarrow$ all masses low!!

pMSSM11: $m_{\tilde{\chi}_1^\pm}$–$m_{\tilde{\chi}_1^0}$ planbe

[2017]

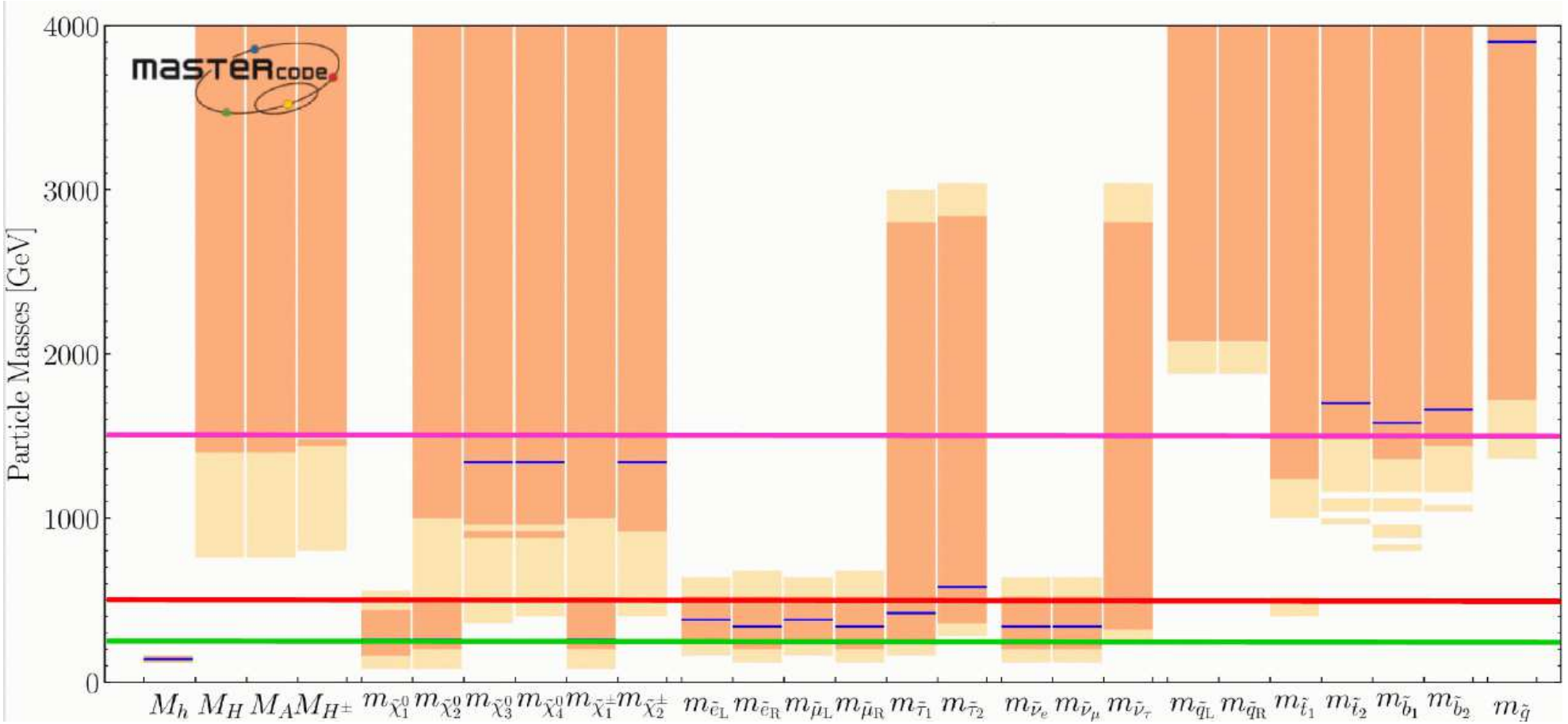


$\tilde{\chi}_1^\pm$ coann. | slep coann. | gluino coann. | stop coann.

A/H funnel | stau coann. | squark coann. | sbot coann.

$\Rightarrow$ chargino co-annihilation $\Rightarrow M_1 \sim M_2$

pMSSM11: prospects for ILC and CLIC [2017]



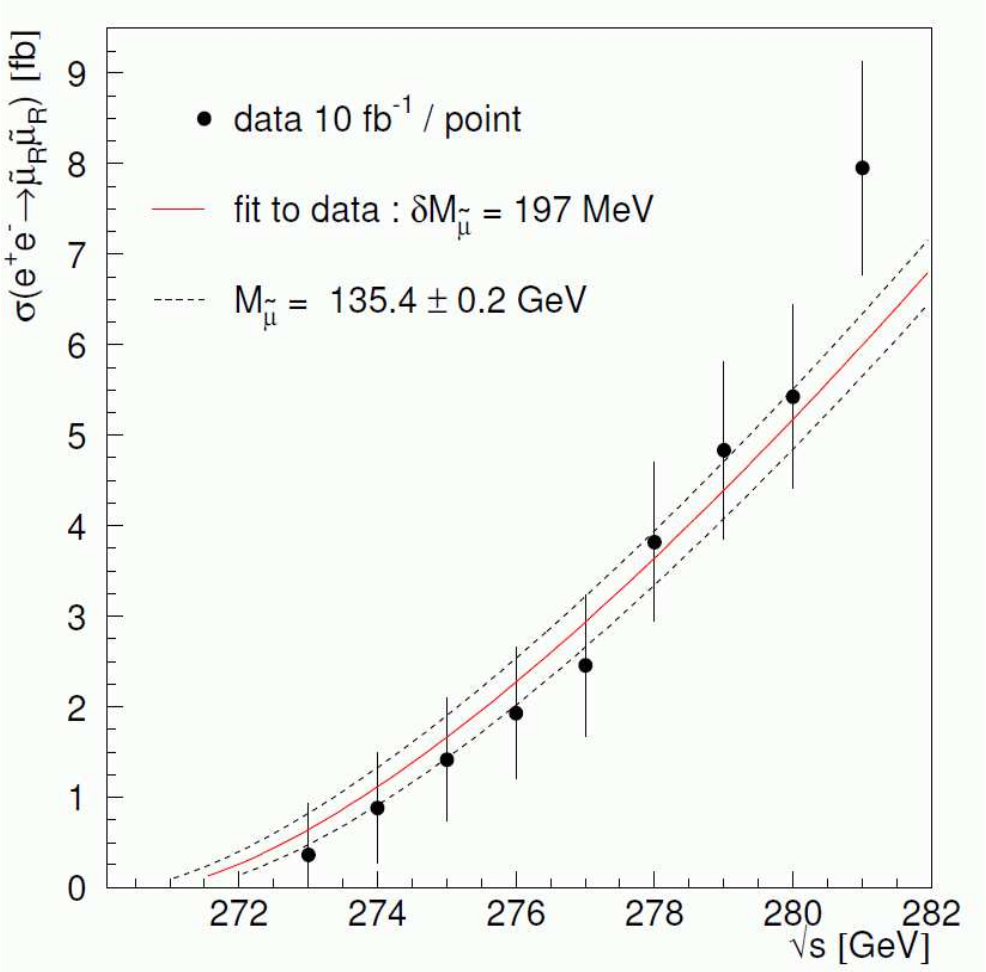
ILC: $\sqrt{s} = 500$ GeV $\Rightarrow$ some particles might be in reach

ILC: $\sqrt{s} = 1000$ GeV $\Rightarrow$ precision analysis of EW particle and DM easy!

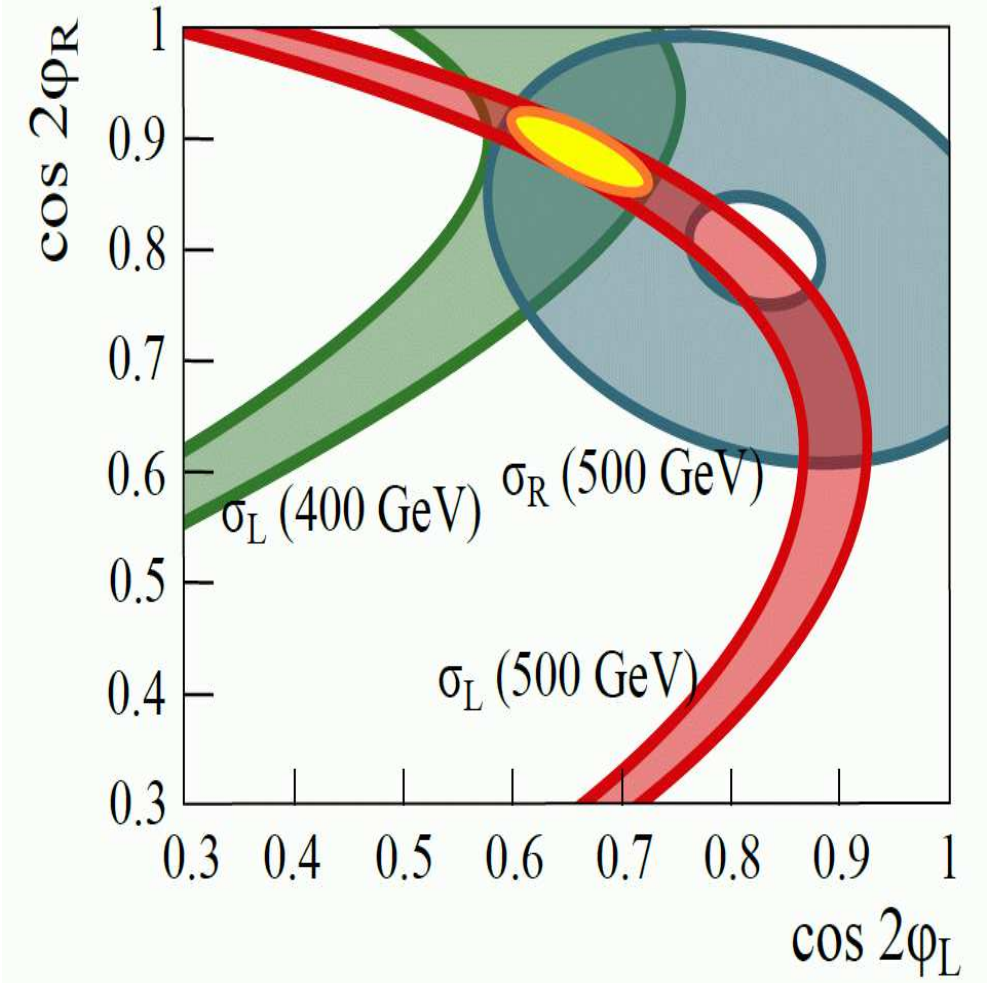
CLIC: $\sqrt{s} = 3000$ GeV $\Rightarrow$ precision analysis of EW particles and DM easy!

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

Some technical/calculational details:

- 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

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⇒ **go and make your prediction!**

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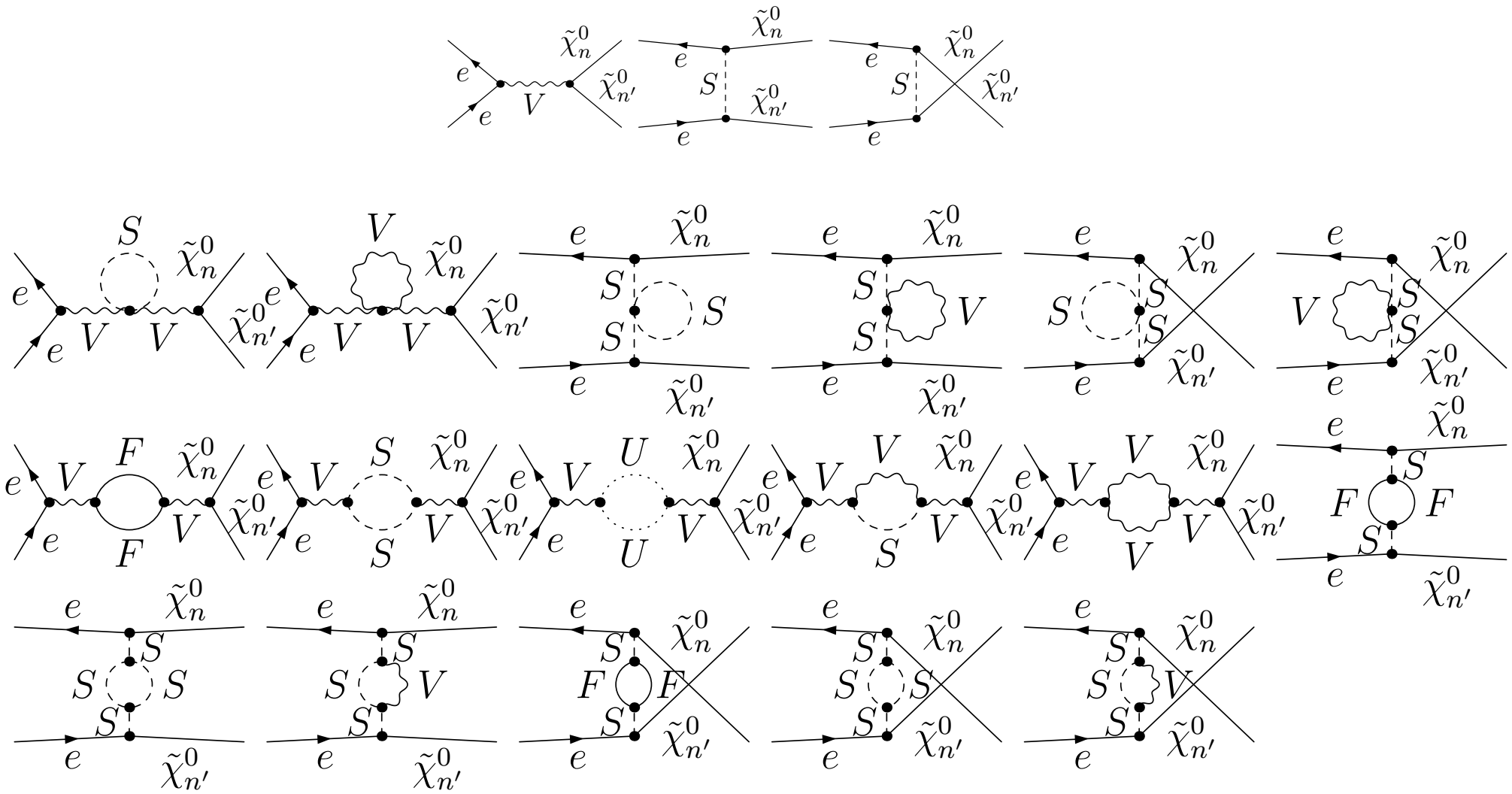
⇒ **go and make your prediction!**

⇒ **and so we did!**

2. Chargino/neutralino production:

$e^+e^- \to \tilde{\chi}^0_n \tilde{\chi}^0_{n'}$ ($e^+e^- \to \tilde{\chi}^\pm_c \tilde{\chi}^\mp_{c'}$ similar):



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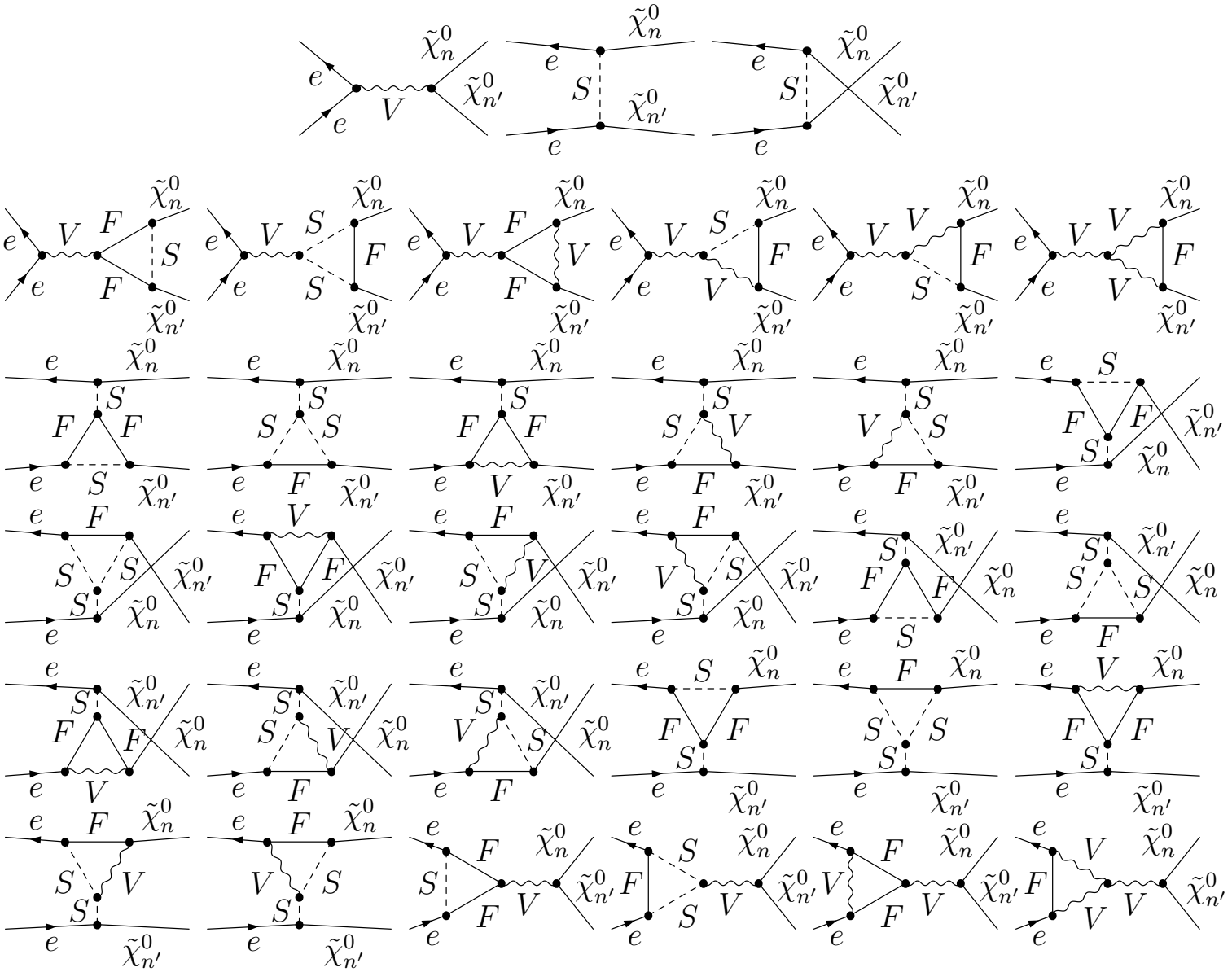

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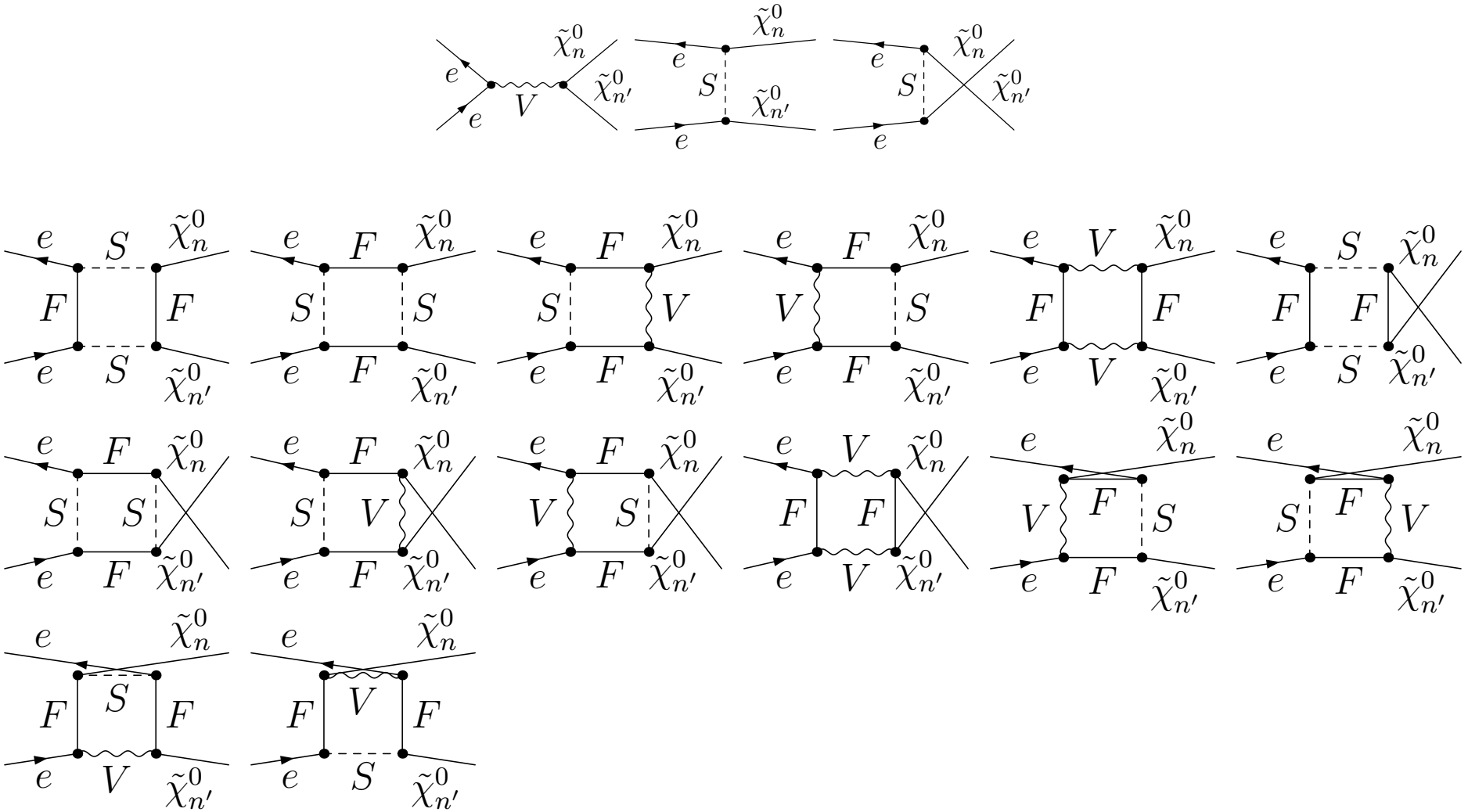

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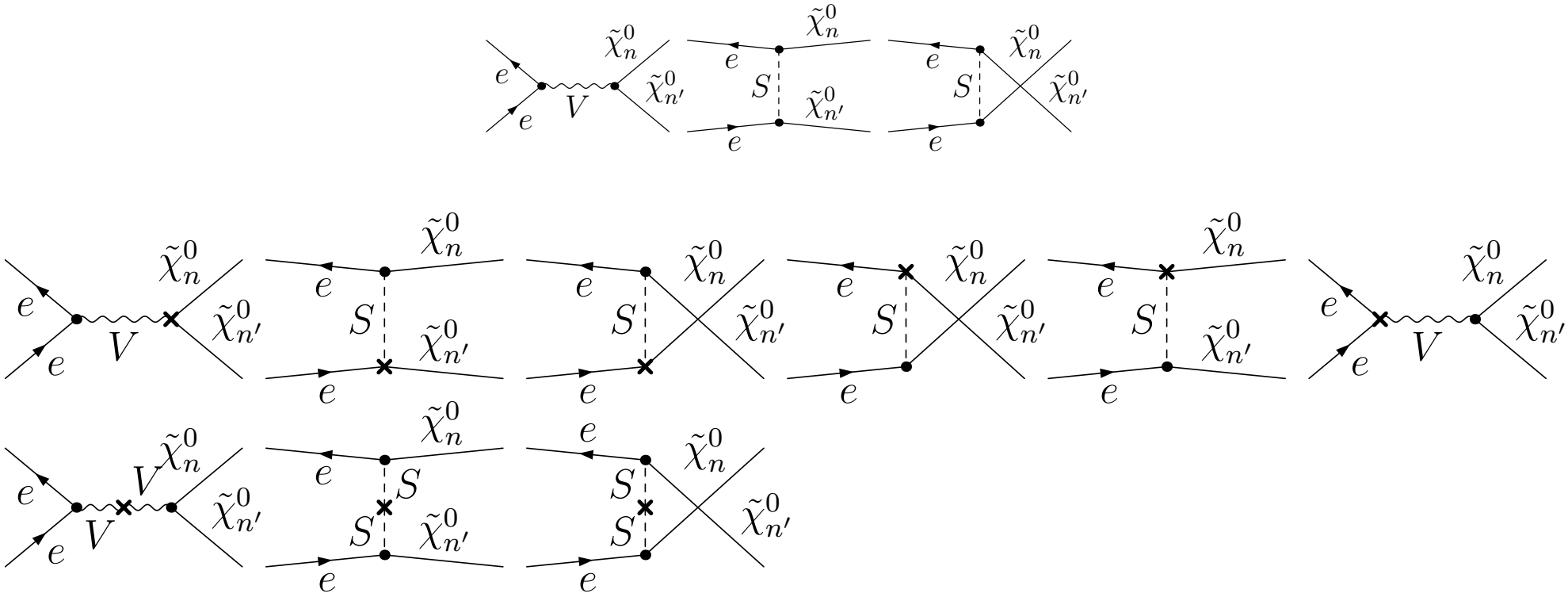


+ soft and hard QED radiation

cMSSM parameters:

Scen.	$\sqrt{s}$	t_β	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
$\mathcal{S}$	1000	10	450	500	1500	1500	2000	$\lvert A_t\rvert$	$M_{\tilde{L}}$	$\mu/4$	$\mu/2$	2000

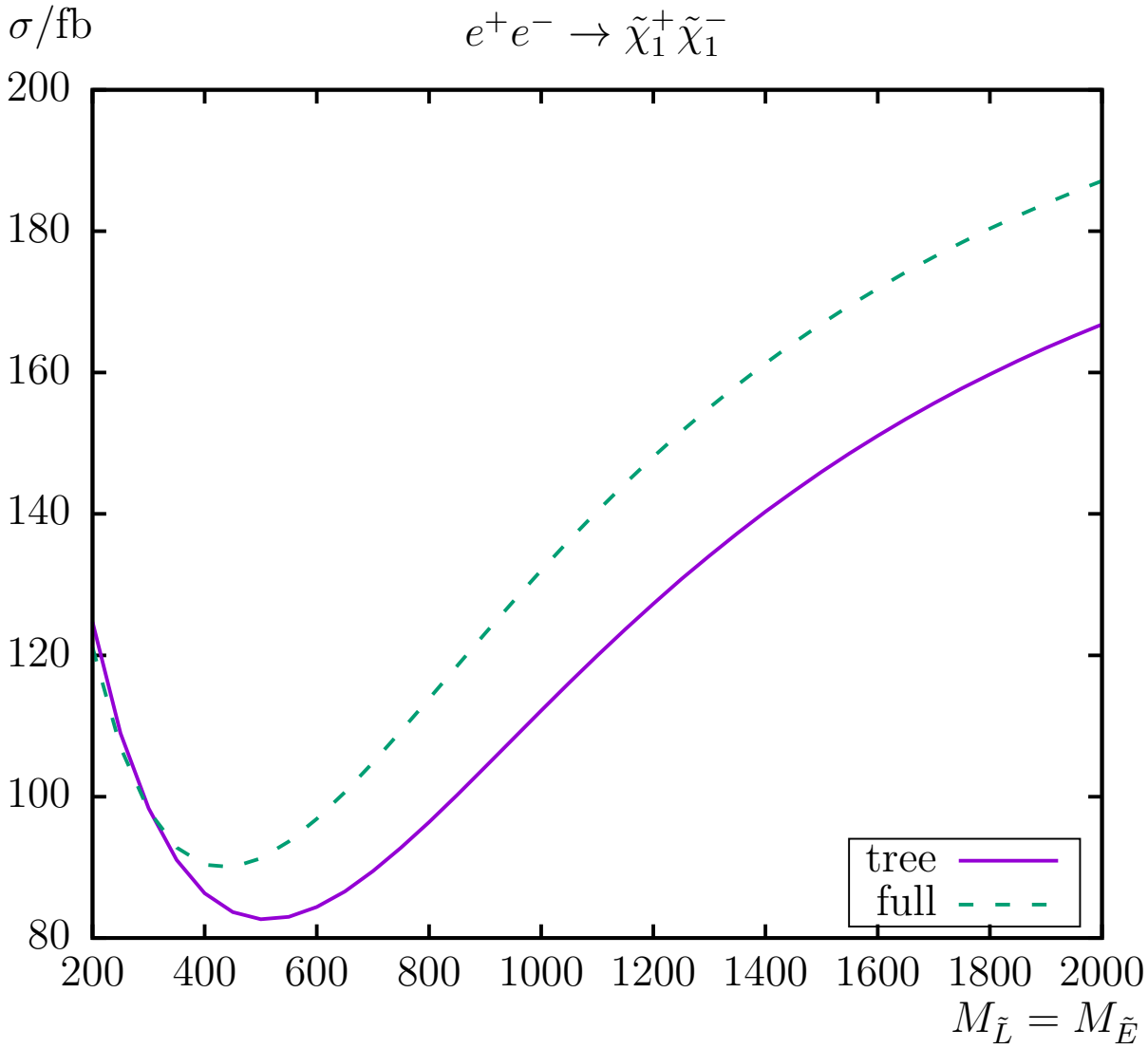
	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\chi}_2^\pm}$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$
trcc	212.760	469.874	110.434	213.002	455.162	469.226
CCN[1]	212.760	469.874	110.434	212.850	455.195	469.560

with $\sqrt{s}$, $M_{H^\pm}$, $\tan\beta$, $M_{\tilde{L}}$, φ_{M_1} varied

– Scenario chosen such that many processes are possible at the same time
– not chosen to maximize loop corrections

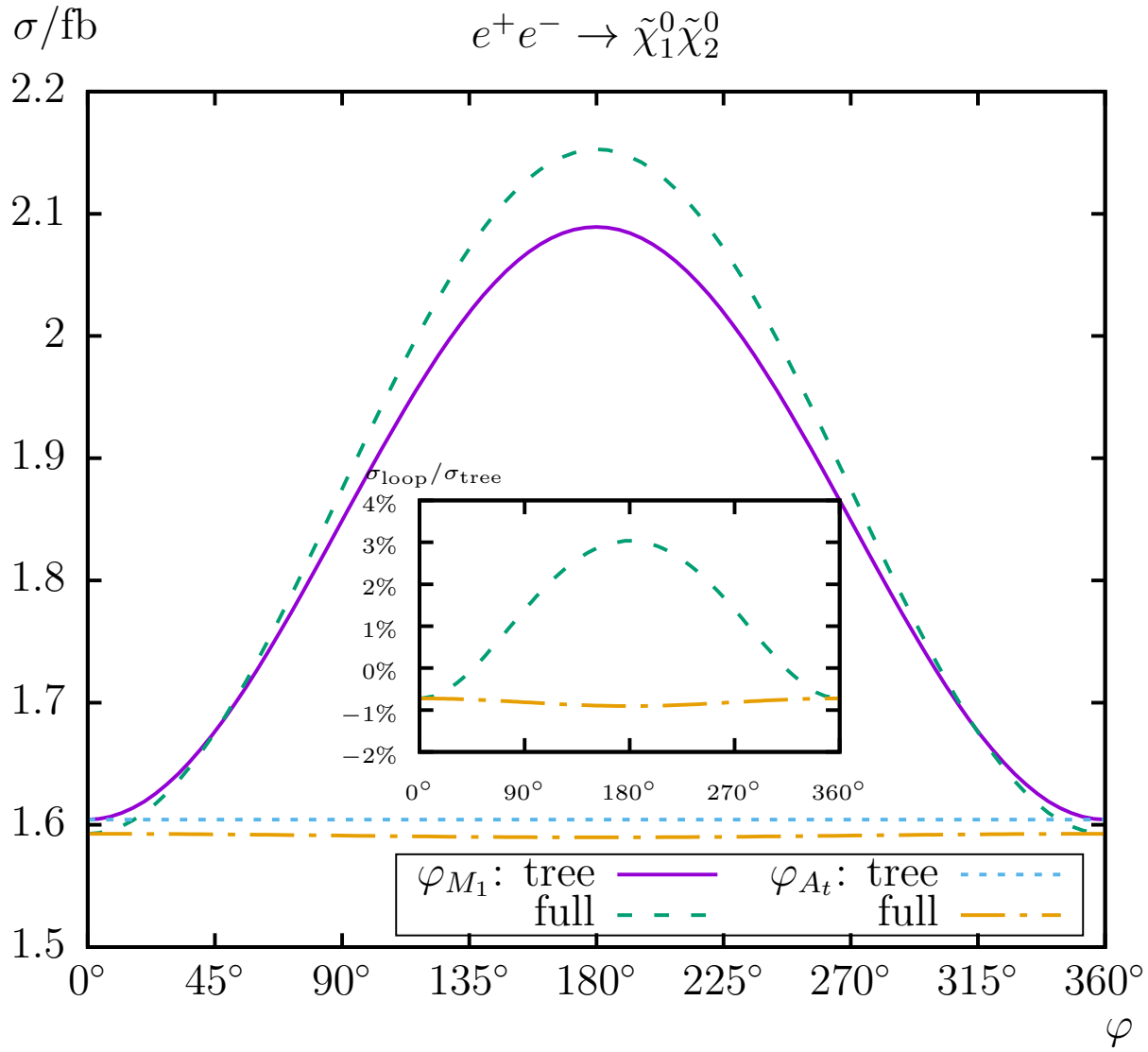
⇒ few example plots

$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$:



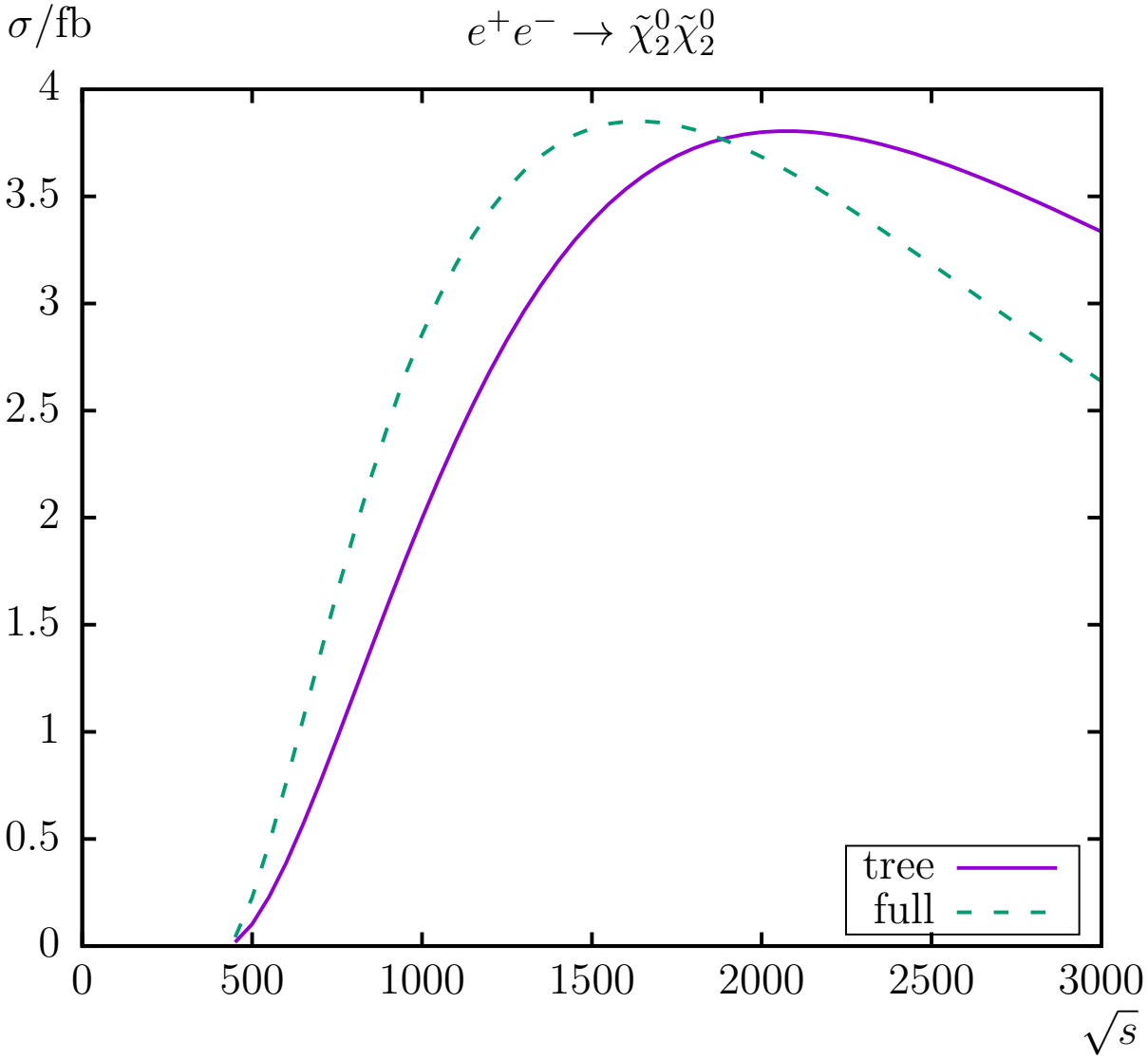
⇒ loop corrections crucial!

$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0$:



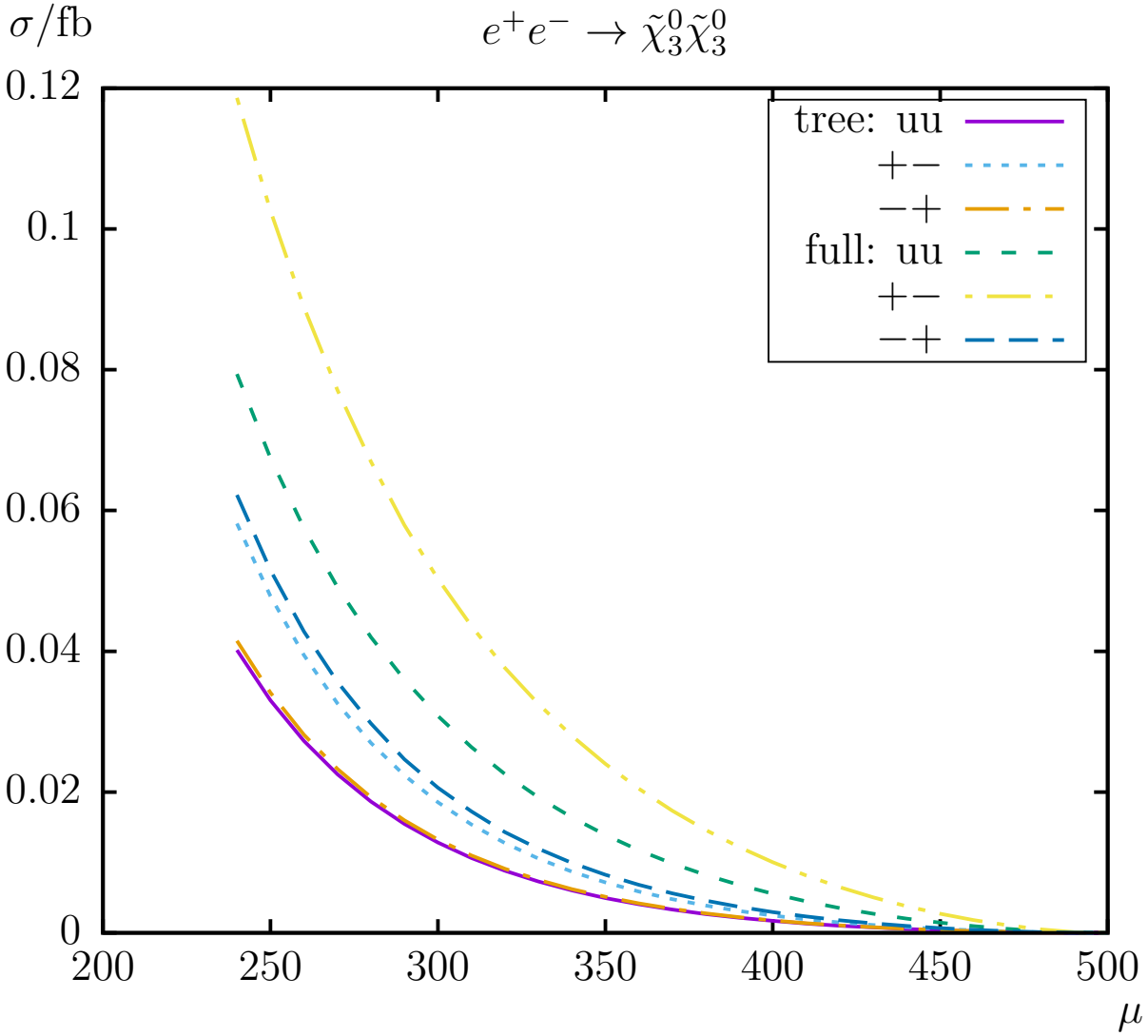
$\Rightarrow M_1$ phase dependence large, loop corrections crucial!

$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_2^0$:



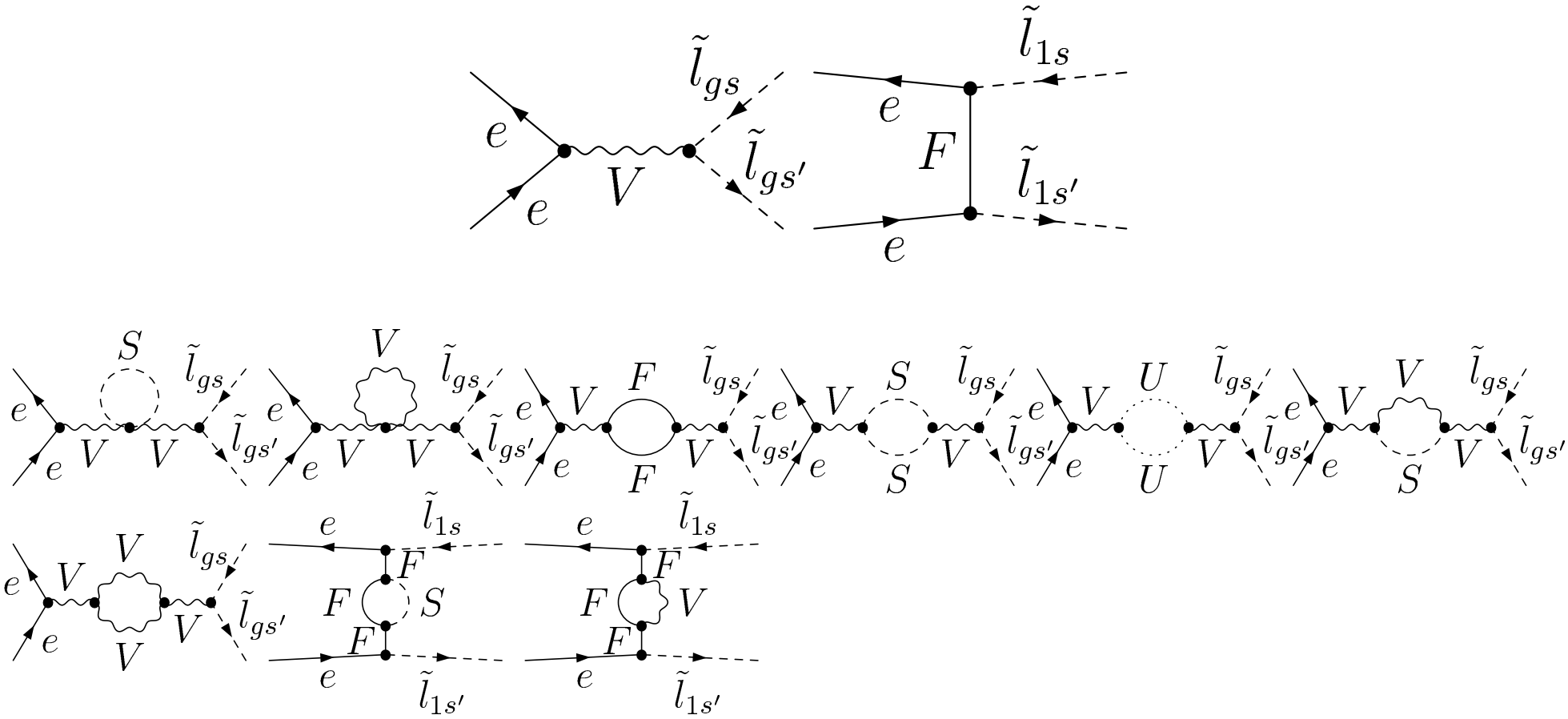
$\Rightarrow$ loop corrections depend strongly on $\sqrt{s}$

$e^+e^- \to \tilde{\chi}_3^0\tilde{\chi}_3^0$:

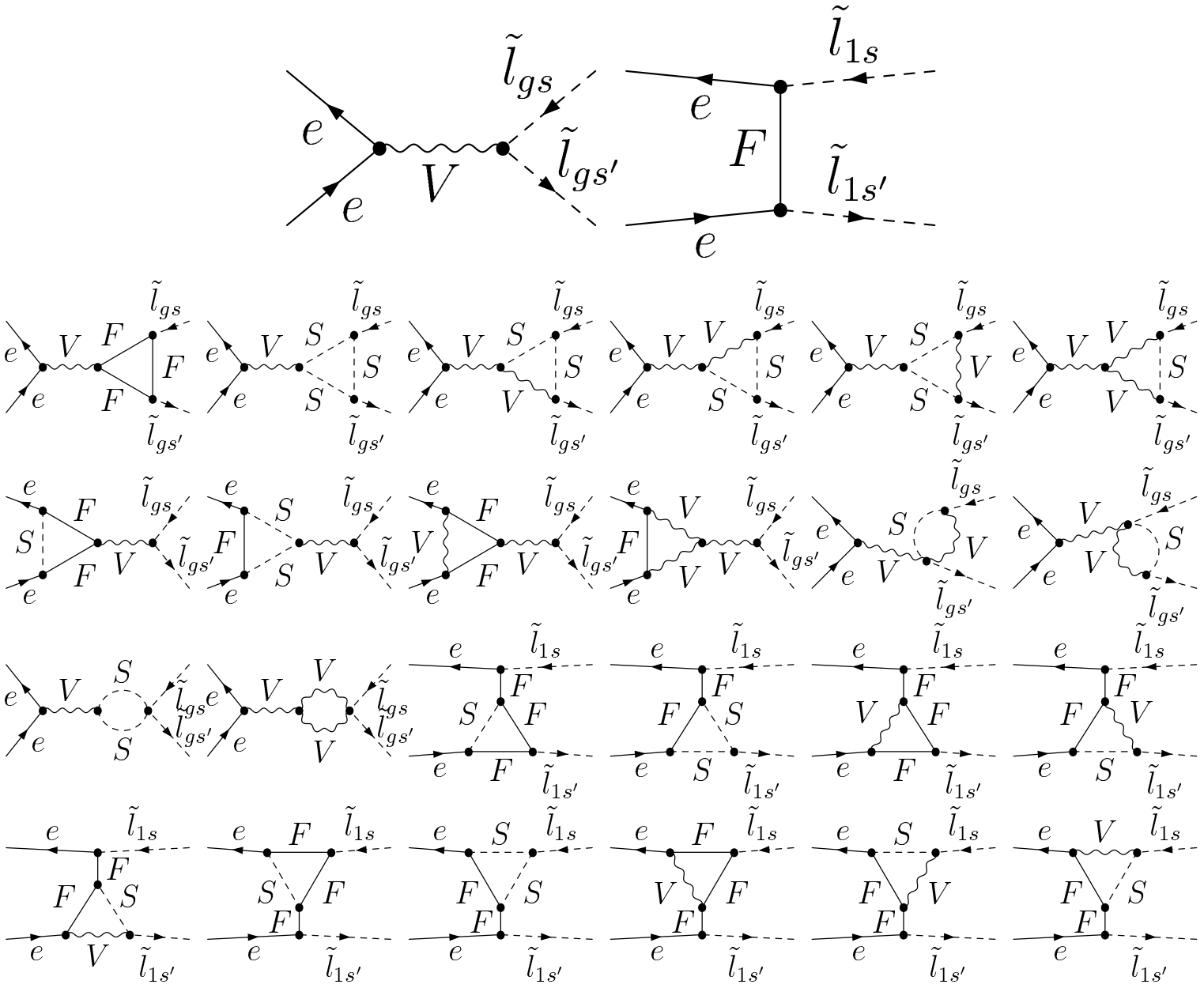


⇒ polarization could be crucial for some processes!

3. Slepton production



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



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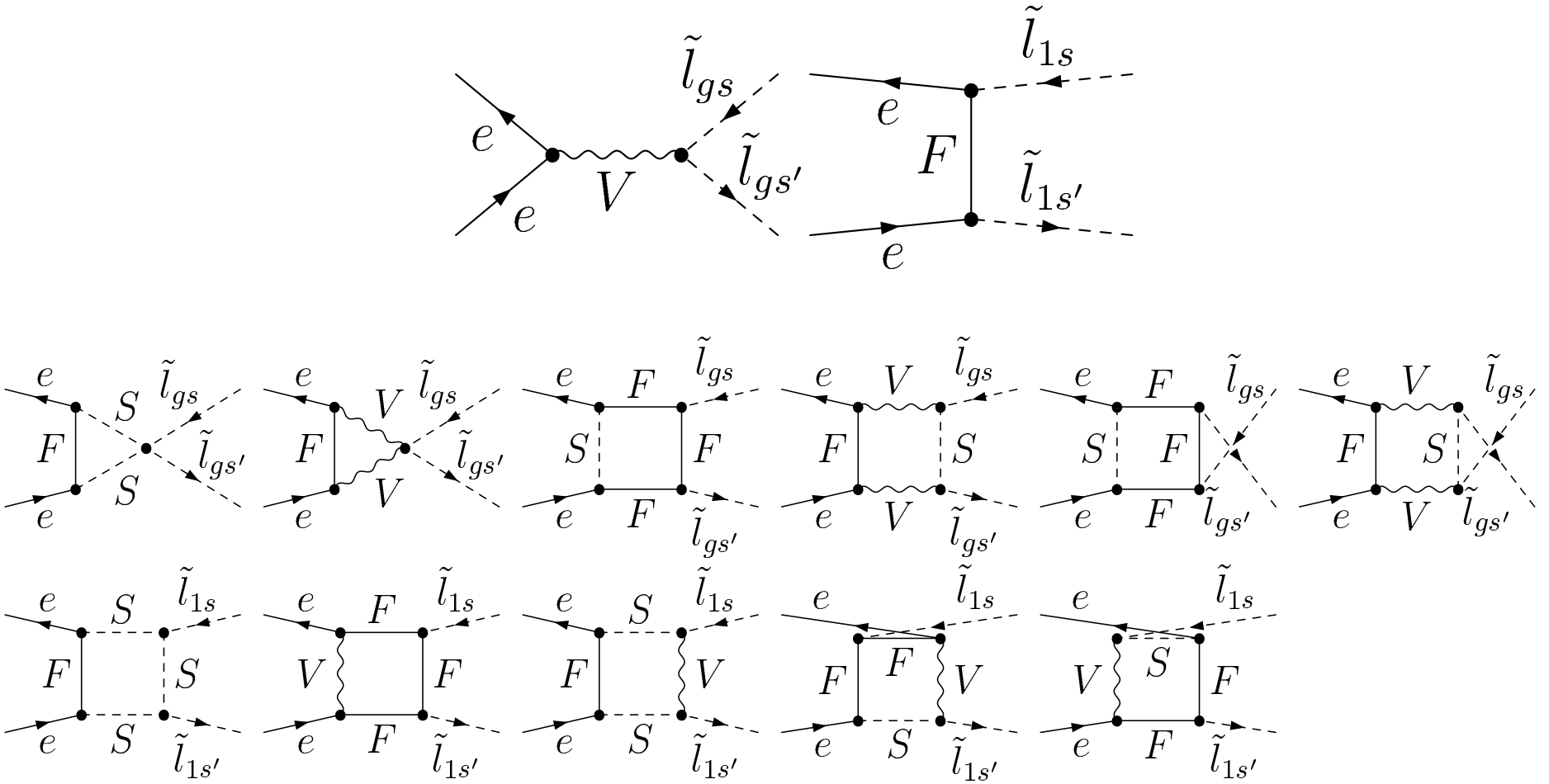

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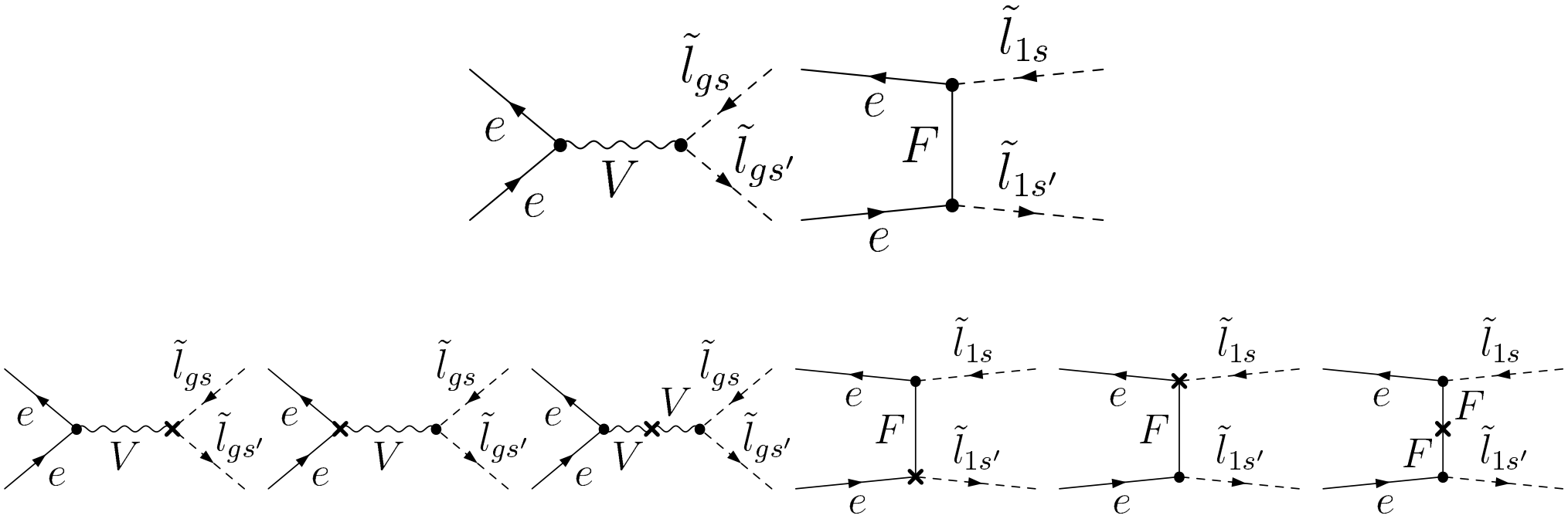


+ soft and hard QED radiation

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

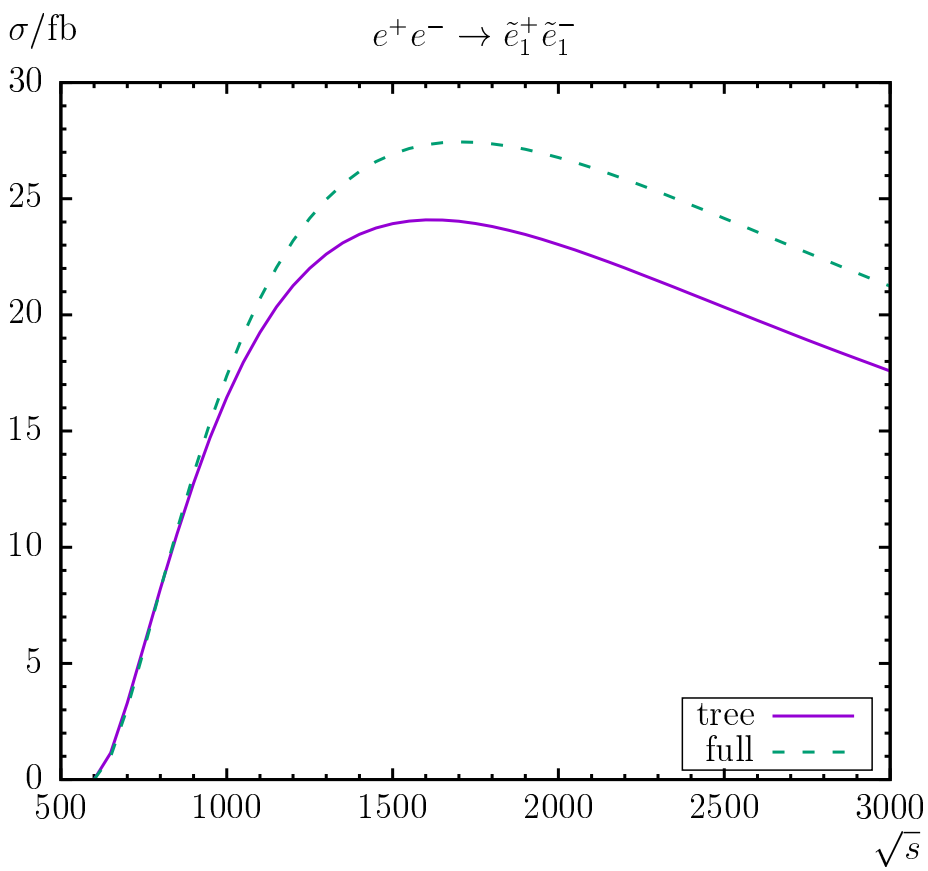
– opens up many (all) production channels

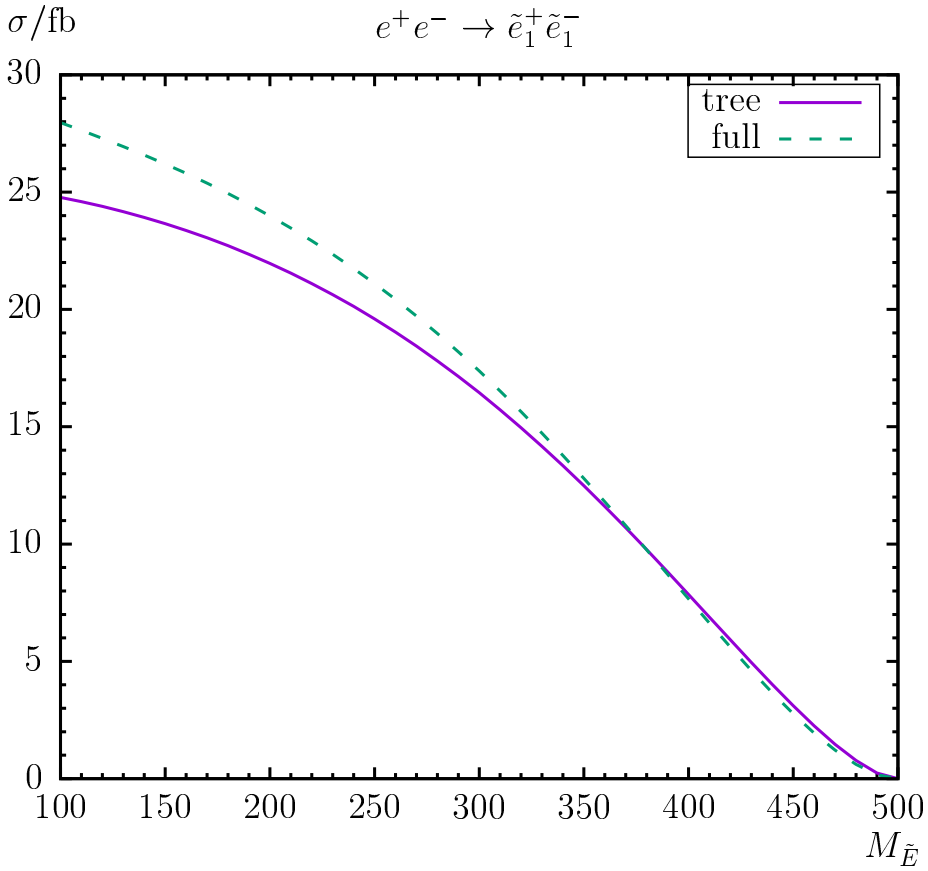
– relevant parameters varied

– ...

⇒ show some relevant examples

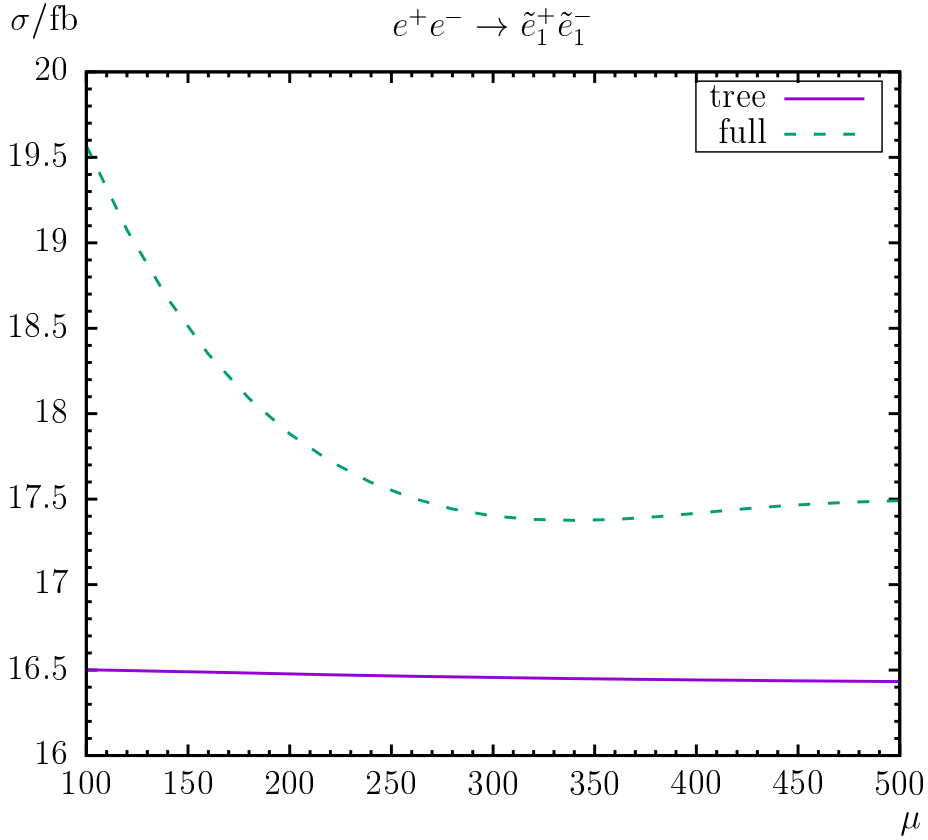
$\tilde{e}_1\tilde{e}_1$ production (I):

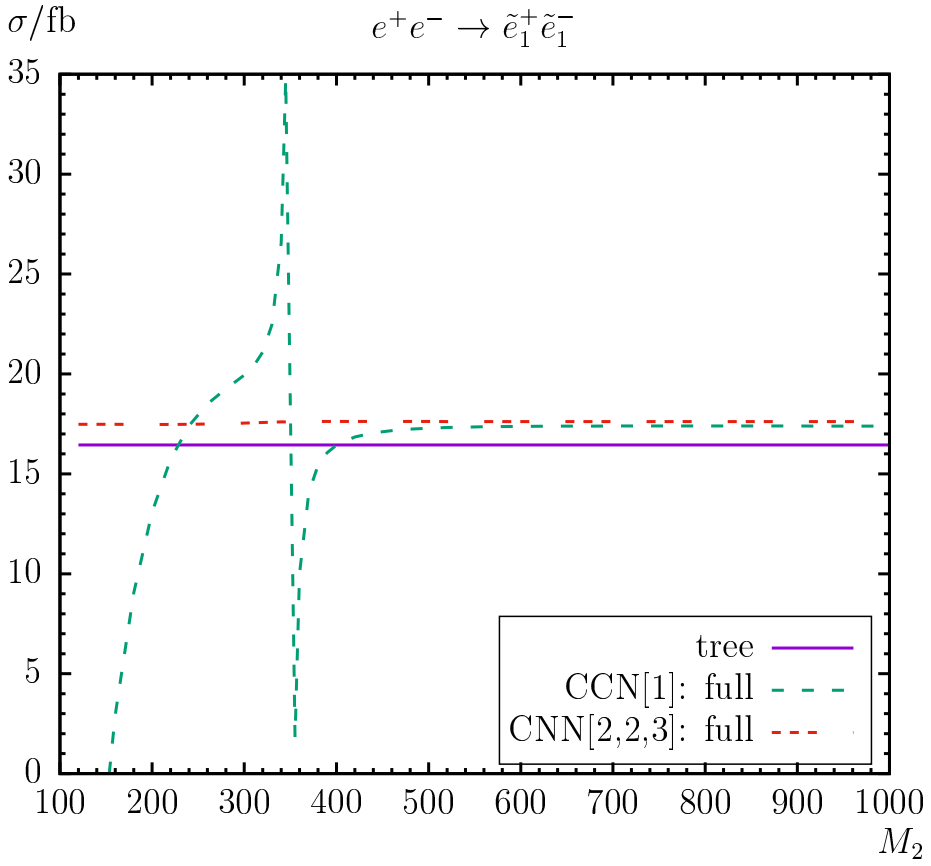




$\Rightarrow$ loop corrections $\sim 20\%$

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



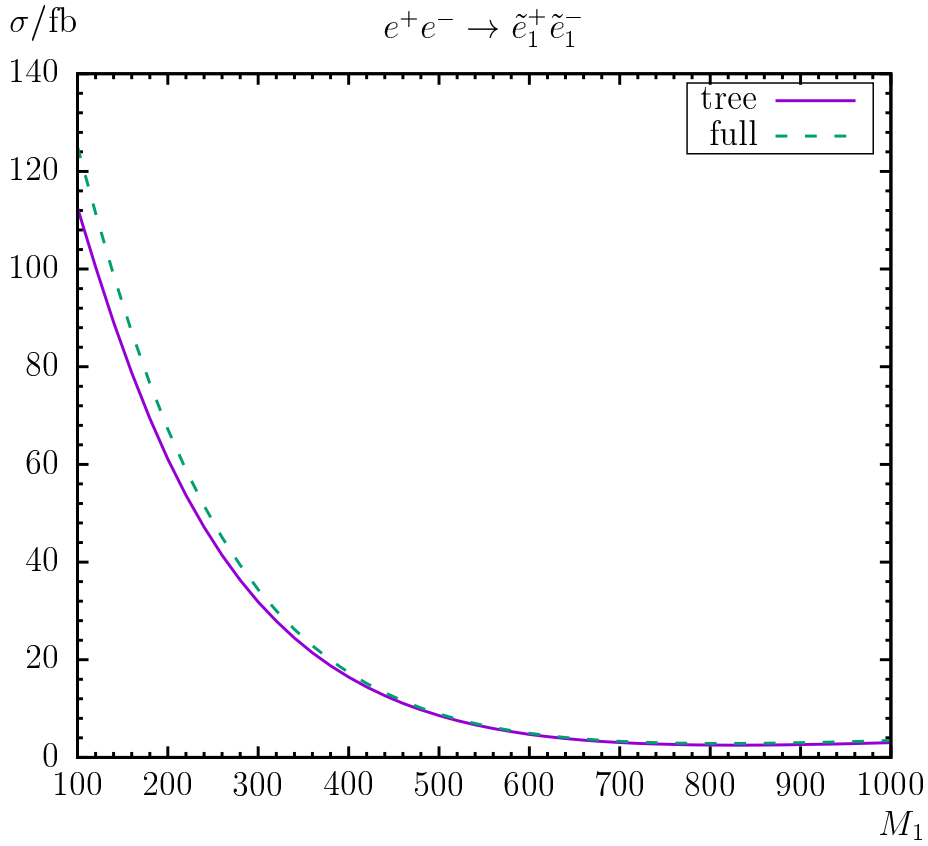


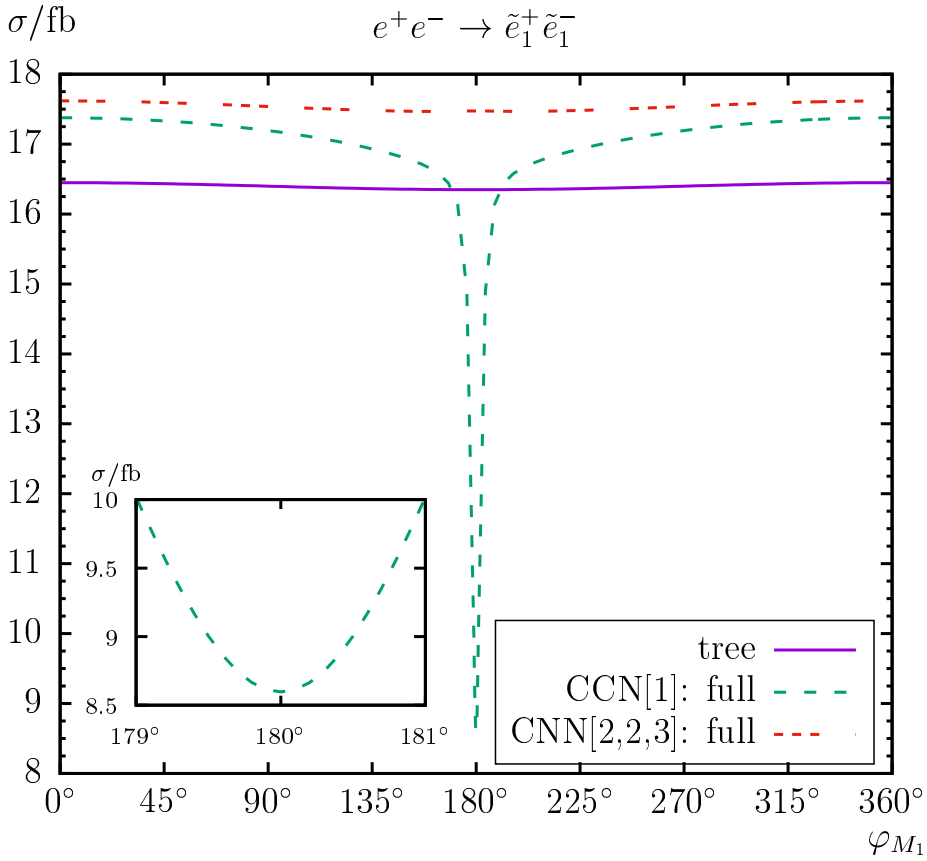
$\Rightarrow$ loop corrections $\sim 20\%$

$\Rightarrow$ strong μ dependance of loop corrections

$\Rightarrow$ CCN1 breaks down at $\mu = M_2$

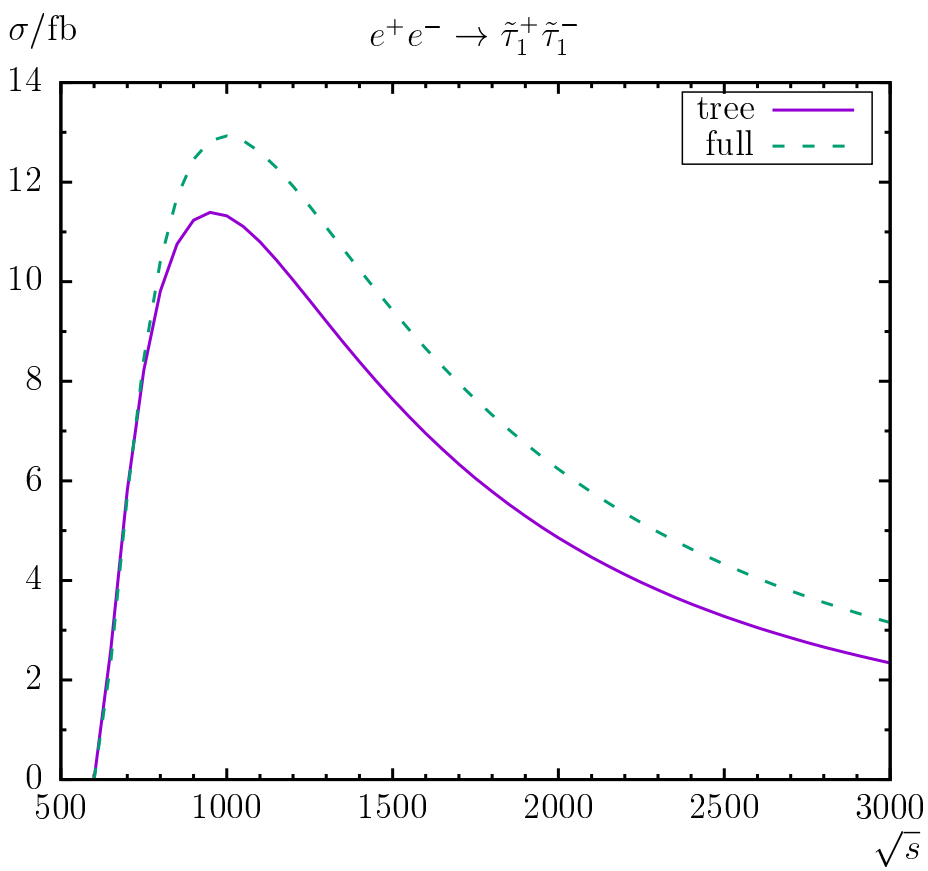
$\tilde{e}_1\tilde{e}_1$ production (III):

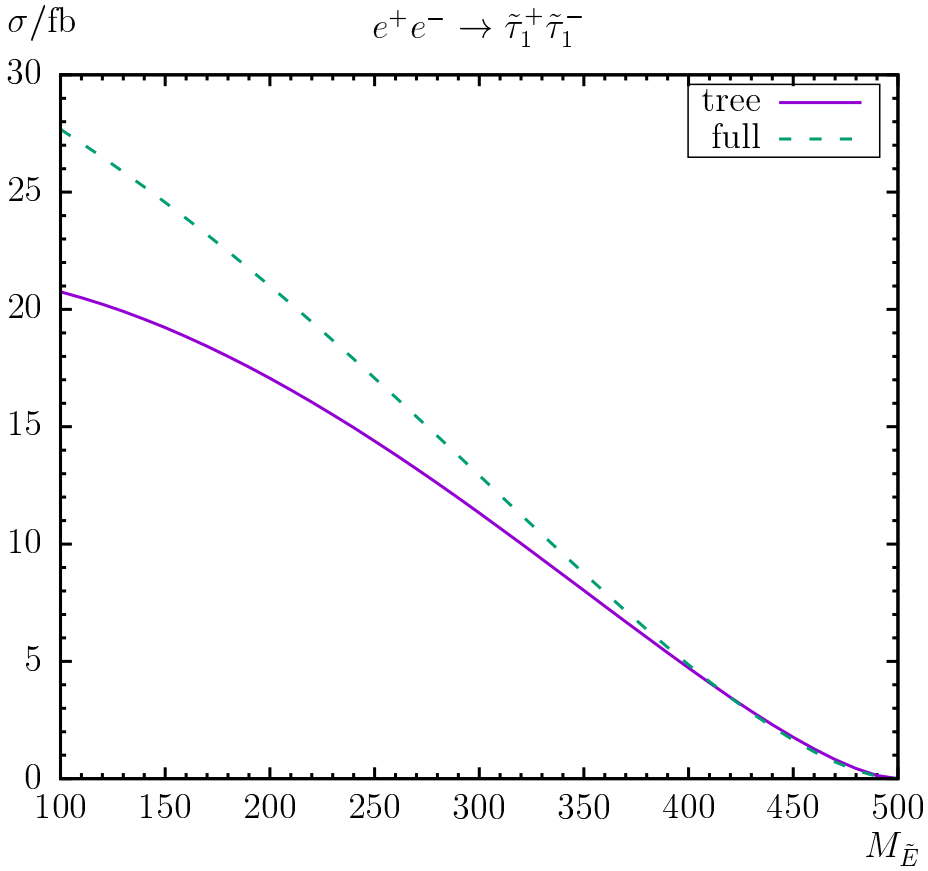




$\Rightarrow$ strong phase dependance of loop corrections

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

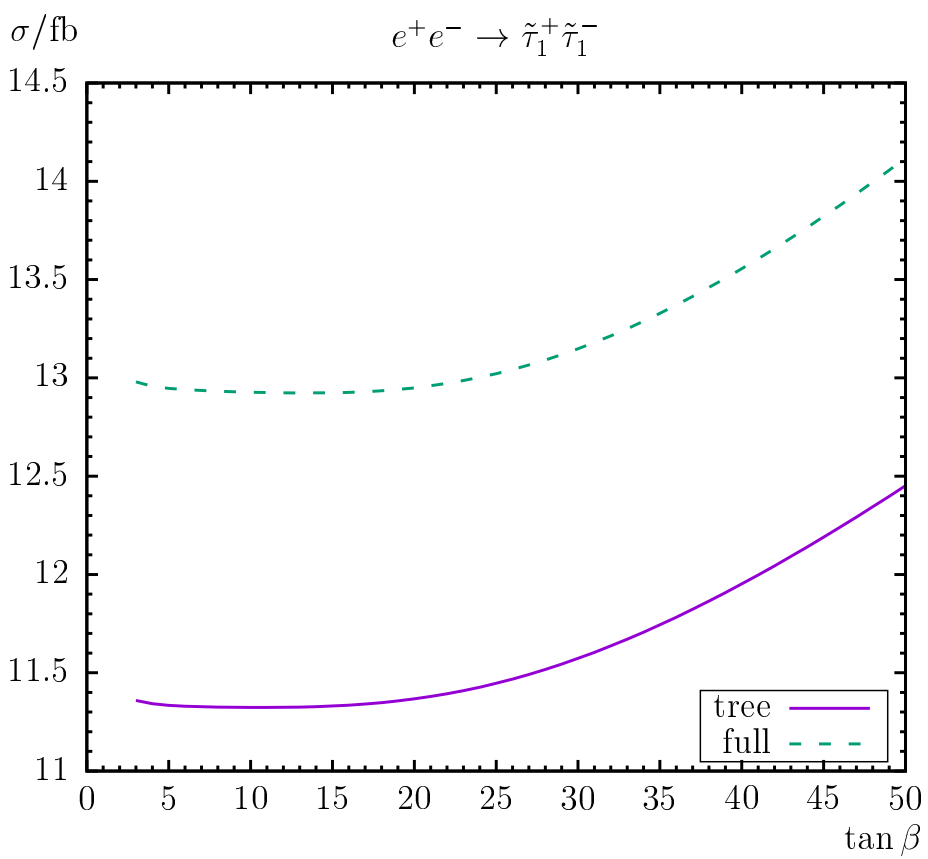


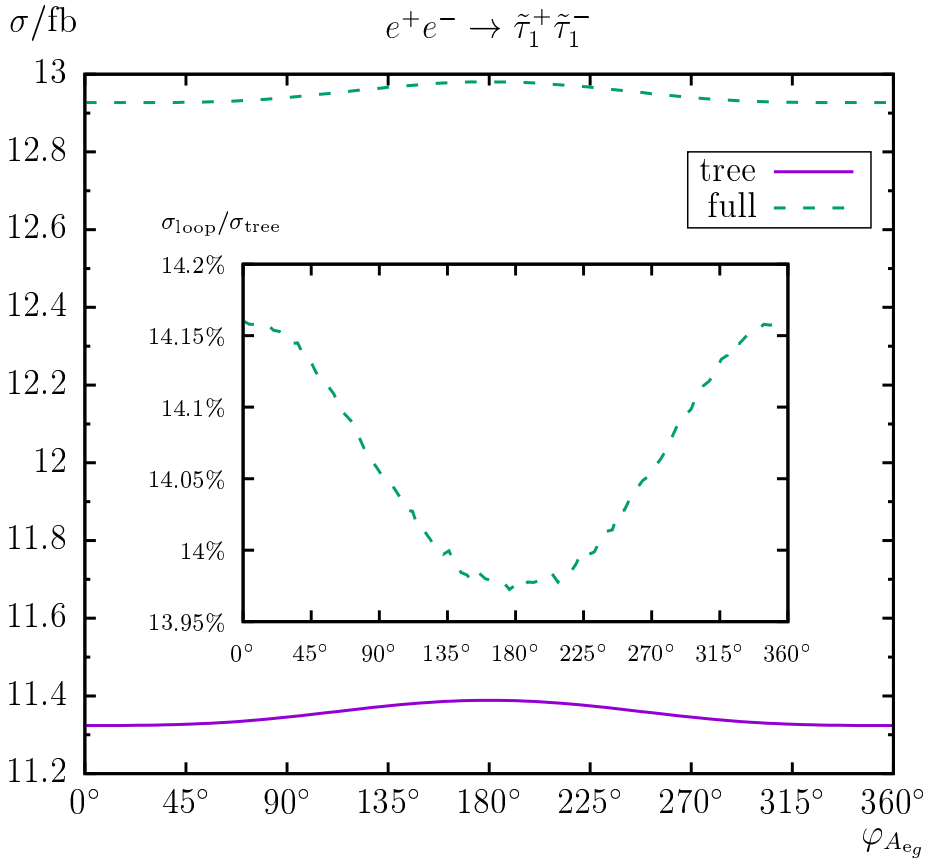


$\Rightarrow$ loop corrections $\sim 20\%$

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

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



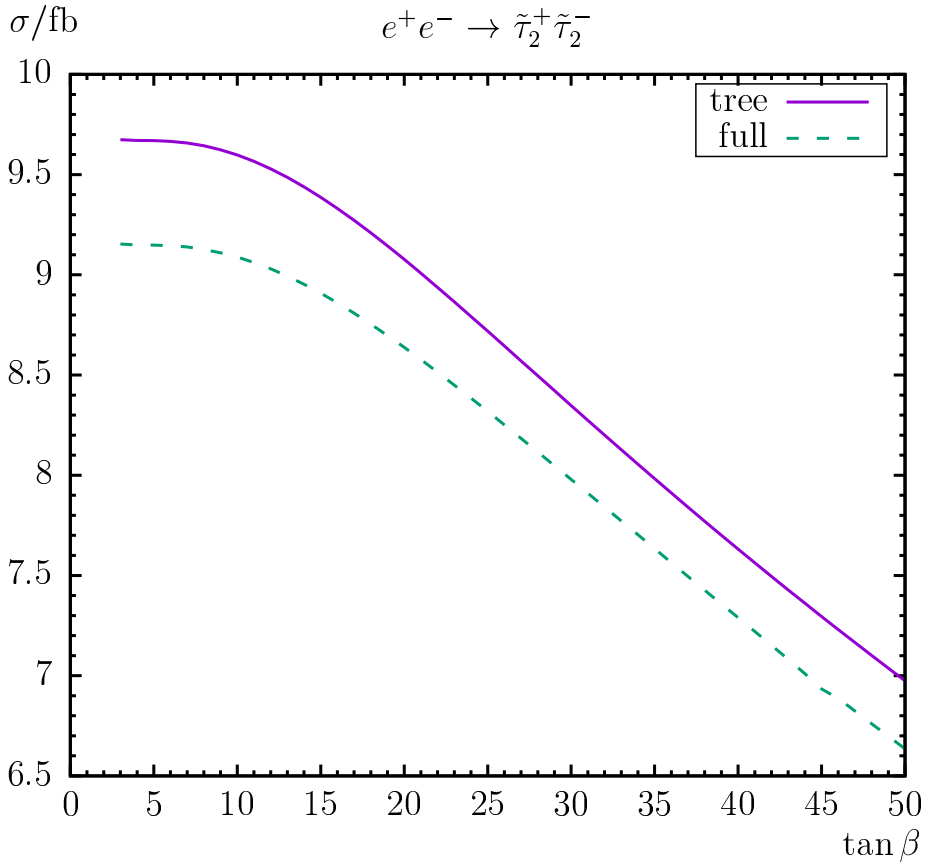


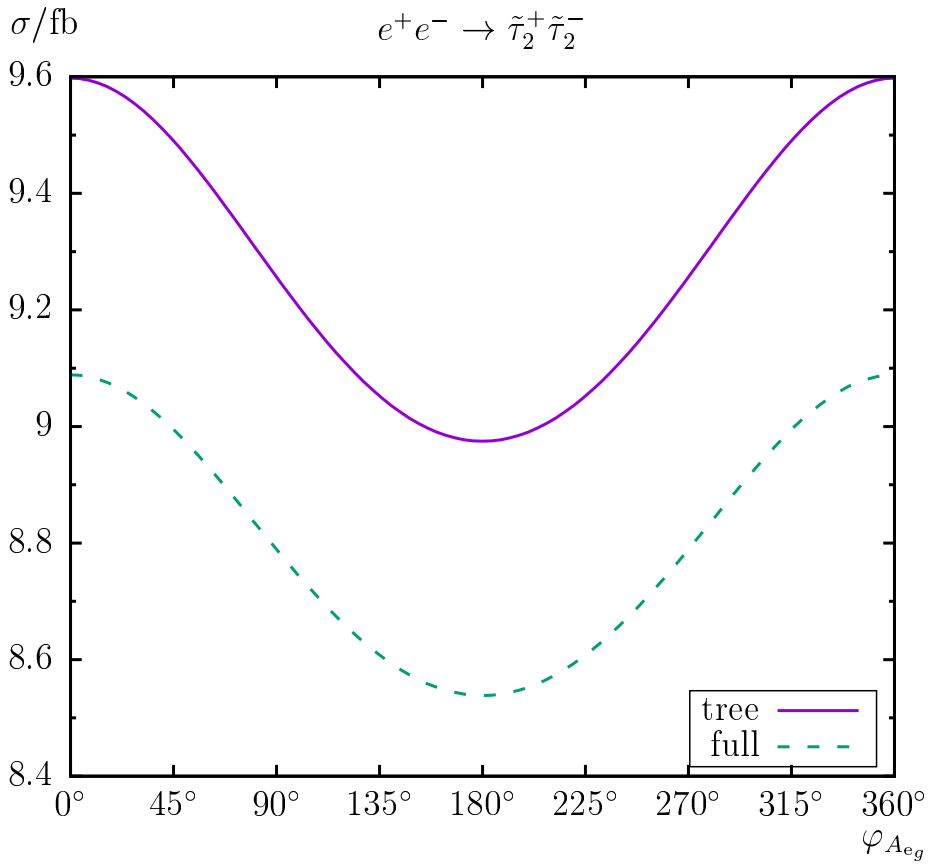
⇒ loop corrections $\sim 15\%$

⇒ 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

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:
    corrections up to $\sim 20\%$, phase dependance relevant


Further Questions?

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!