Radiative Corrections to Neutralino Decays

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Outline:

- **Motivation**
- **Numerical Results and Discussions**
- **Summary**

Motivation: Minimal Supersymmetric Standard Model

Supersymmetry (SUSY): **Fermion** $\leftrightarrow$ **Boson**

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Minimal Supersymmetric Standard Model (MSSM)

- add Superpartner to each particle in the SM

  $m_{\text{particle}} = m_{\text{superpartner}}$

  problem: no sparticles have been observed
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- add soft SUSY-breaking terms
- add another Higgs doublet and its superpartner
  - to give masses to u-quarks
  - To cancel the chiral anomaly

Motivation: Minimal Supersymmetric Standard Model

Particle content of the MSSM

Fermions	Bosons
Quarks q_L, q_R	Squarks $\tilde{q}_L, \tilde{q}_R$
Leptons l_L, l_R, ν_l	Sleptons $\tilde{l}_L, \tilde{l}_R, \tilde{\nu}_l$
Higgsinos $\tilde{H}_1, \tilde{H}_2$	Higgses H_1, H_2
Gauginos $\tilde{W}^{\pm}, \tilde{Z}, \tilde{\gamma}$	Gauge Bosons $W^{\pm}, Z, \gamma$
Gluinos $\tilde{g}$	Gluons g

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Squarks $\tilde{q}_R, \tilde{q}_L \rightarrow \tilde{q}_1, \tilde{q}_2$ Sleptons $\tilde{l}_R, \tilde{l}_L \rightarrow \tilde{l}_1, \tilde{l}_2$
Charged higgsinos and gauginos $\rightarrow$ charginos
Neutral higgsinos and gauginos $\rightarrow$ neutralinos

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$\tilde{\chi}_4^0$ $\tilde{\chi}_3^0$ $\tilde{\chi}_2^0$ (next-to-lightest) $\tilde{\chi}_1^0$ (lightest)

Their masses depend on MSSM parameters

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A discrete symmetry: R-parity

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All sparticles $P_R = -1$

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- Lightest sparticle (LSP) is stable

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Assuming lightest neutralino $\tilde{\chi}_1^0$ is LSP
Sparticle $\rightarrow$ lightest neutralino $\tilde{\chi}_1^0$

Phenomenological signature: missing energy

Motivation: Decays of Sparticles at Colliders

Production of Sparticles at Colliders

LHC: gluinos $\tilde{g}$ and squarks $\tilde{q}_s$

ILC: sleptons $\tilde{l}_s$, neutralinos $\tilde{\chi}_i^0$ and charginos $\tilde{\chi}_i^{\pm}$

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Sparticle $\rightarrow$ Lighter one $\rightarrow \cdots \rightarrow \tilde{\chi}_2^0(\tilde{\chi}_1^{\pm}) \rightarrow \tilde{\chi}_1^0 f \bar{f}'$

(f and f' denote lighter SM fermions)

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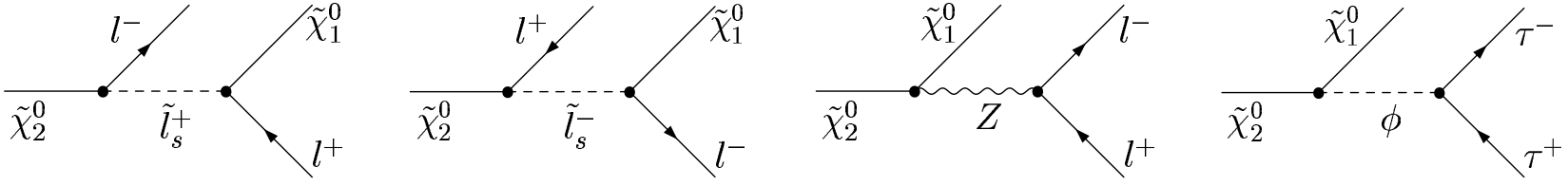
Observable: **dilepton invariant mass** $M_{l^+l^-}(l = e, \mu, \tau)$

Interesting decays $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 l^+ l^-$



$s = 1, 2$ labels the slepton mass eigenstates, $\phi = h^0, H^0$ or A^0

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$\Longrightarrow$ mass relations of sparticles

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Kinematics	Endpoint $M_{l^+l^-}^{\rm Max}$
$\tilde{l}_s^{\mp}$, Z and ϕ are virtual (three-body decays)	$m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$
$\tilde{l}_s^{\mp}$ are real (two-body decays)	$m_{\tilde{\chi}_2^0}\sqrt{1-\frac{m^2_{\tilde{l}_s}}{m^2_{\tilde{\chi}_2^0}}}\sqrt{1-\frac{m^2_{\tilde{\chi}_1^0}}{m^2_{\tilde{l}_s}}}$
$Z(\phi)$ is real (two-body decays)	$m_{Z(\phi)}$

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High precision for the endpoint is expected at LHC and ILC
$\mathcal{O}(0.1\%)$

$\Longrightarrow$ higher-order corrections are necessary !!

Numerical Results

Tree level contribution (diagrams were shown before)

One-Loop Contribution { virtual corrections

real photon bremsstrahlung

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One-Loop Contribution { virtual corrections; real photon bremsstrahlung

$$\Gamma_{1-\mathrm{loop}} = \Gamma_{\mathrm{tree}} + \Gamma_{\mathrm{virtual}} + \Gamma_{\mathrm{real}}$$
$$= \Gamma_{\mathrm{tree}} + \Gamma_{\mathrm{QED}} + \Gamma_{\mathrm{remainder}}$$

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Total χ_2^0 decay width

$\Gamma_{\tilde{\chi}_2^0} = \sum_{f \neq t} \Gamma(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 f \bar{f})$

The branching ratios of charged leptonic decays

$Br(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 l^+ l^-) = \frac{\Gamma(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 l^+ l^-)}{\Gamma_{\tilde{\chi}_2^0}}$

Numerical Results SPS1a parameter set

SPS: Snowmass Points and Slopes

B.C. Allanach et al., *Eur. Phys. J.* **C25**, (2002) 113; G. Weiglein, hep–ph/0301111.

SPS1a: mSUGRA scenario

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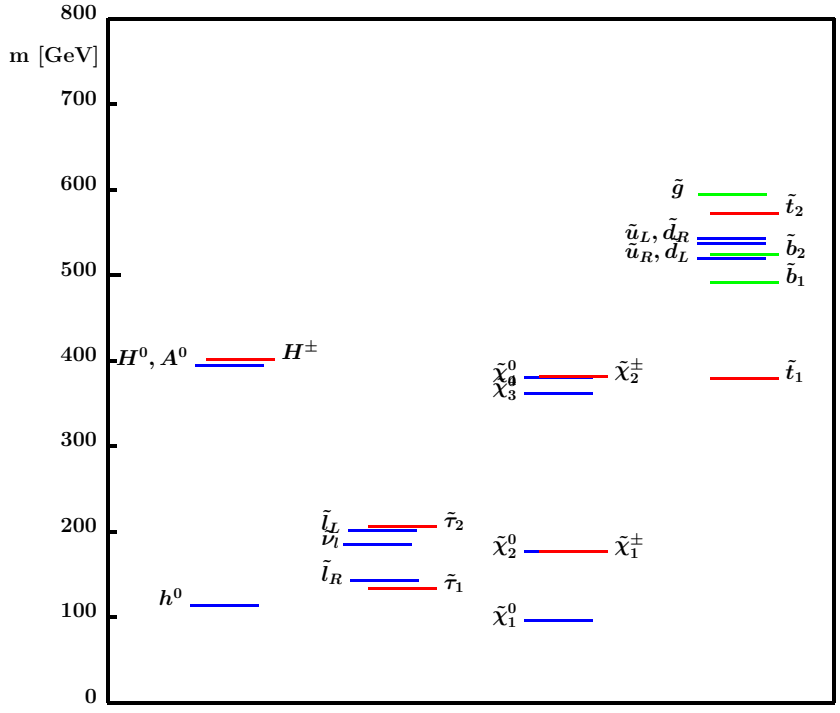
The spectrum corresponding to SPS1a benchmark point

- No slepton mixing:
  $\tilde{l}_R = \tilde{l}_1, \tilde{l}_L = \tilde{l}_2 \; (l = e, \mu)$
- $m_{\tilde{e}_R} = m_{\tilde{\mu}_R}, m_{\tilde{e}_L} = m_{\tilde{\mu}_L}$
- $m_{\tilde{\chi}_1^0} < m_{\tilde{l}_1} < m_{\tilde{\chi}_2^0}$
  $\Longrightarrow \tilde{\chi}_2^0 \to \tilde{l}_1^{\pm} l^{\mp} \to \tilde{\chi}_1^0 l^+ l^-$
  $(l = e, \mu, \tau)$



Numerical Results SPS1a parameter set

$\tilde{\chi}_2^0$ decay mode	tree-level width(MeV), Br	1-loop-level width(MeV), Br
$\tilde{\chi}_1^0 e^- e^+$	1.123, 5.9%	1.297, 6.7%
$\tilde{\chi}_1^0 \mu^- \mu^+$	1.123, 5.9%	1.297, 6.7%
$\tilde{\chi}_1^0 \tau^- \tau^+$	16.870, 88.0%	16.595, 86.2%
$\tilde{\chi}_1^0 \nu_e \bar{\nu}_e$	0.012	0.012
$\tilde{\chi}_1^0 \nu_\mu \bar{\nu}_\mu$	0.012	0.012
$\tilde{\chi}_1^0 \nu_\tau \bar{\nu}_\tau$	0.013	0.013
$q\bar{q}\tilde{\chi}_1^0$	0.015	0.015
total width	19.168	18.915

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- Main decay mode: $\tau^- \tau^+ \tilde{\chi}_1^0$
- Large enhancement at 1-loop level (e, μ): 15.5% (width) 15.0% (Br)

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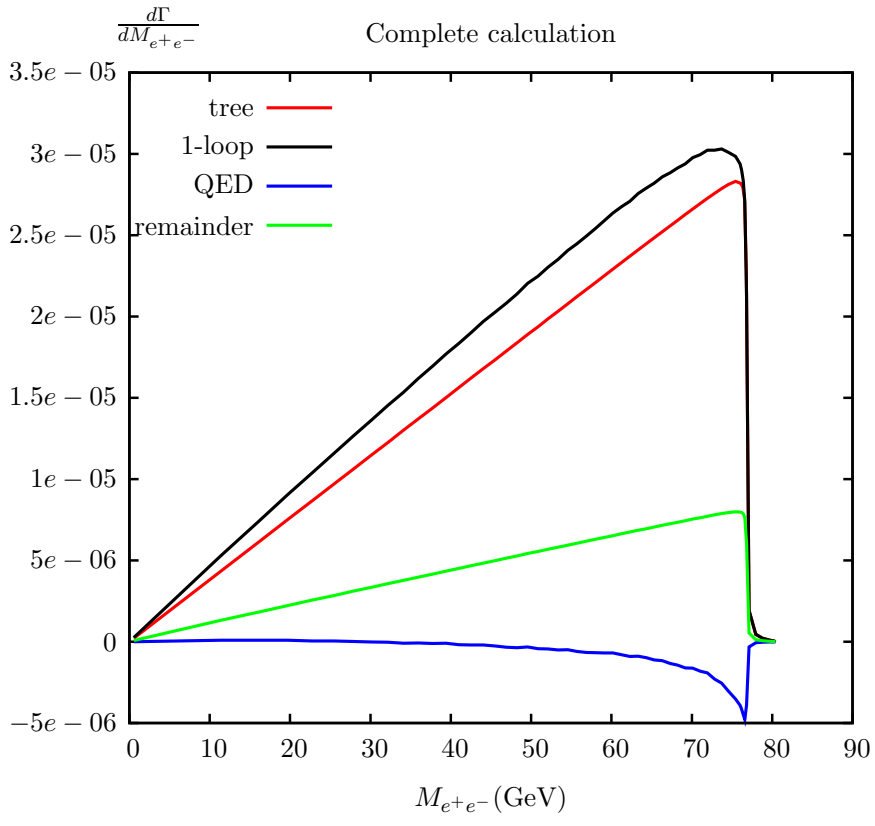

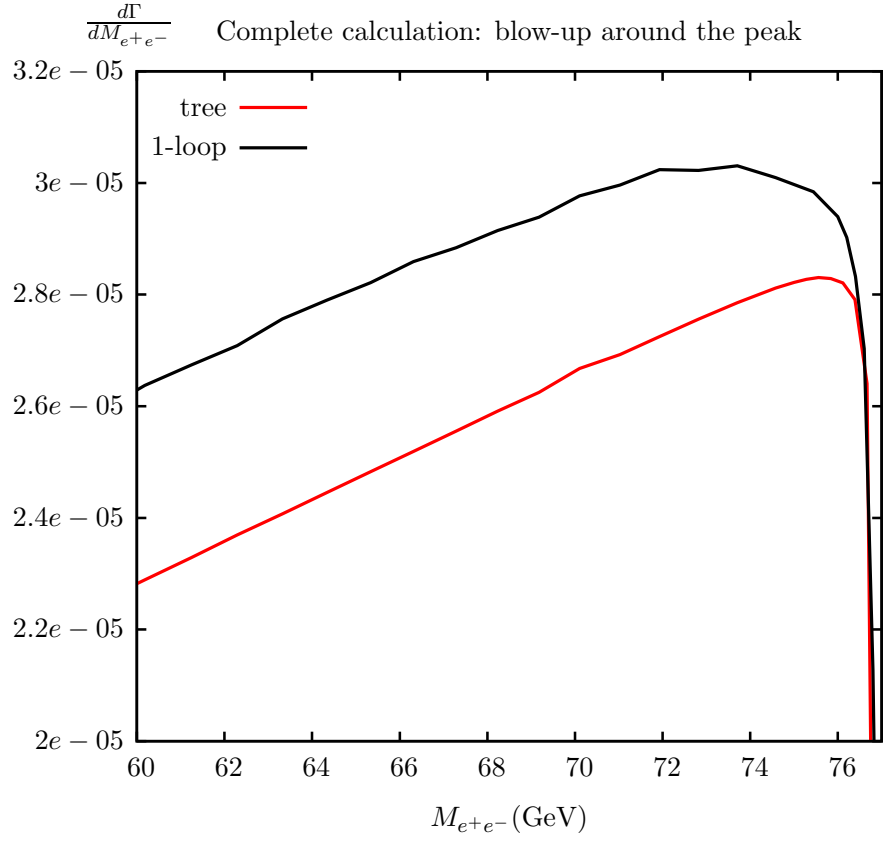

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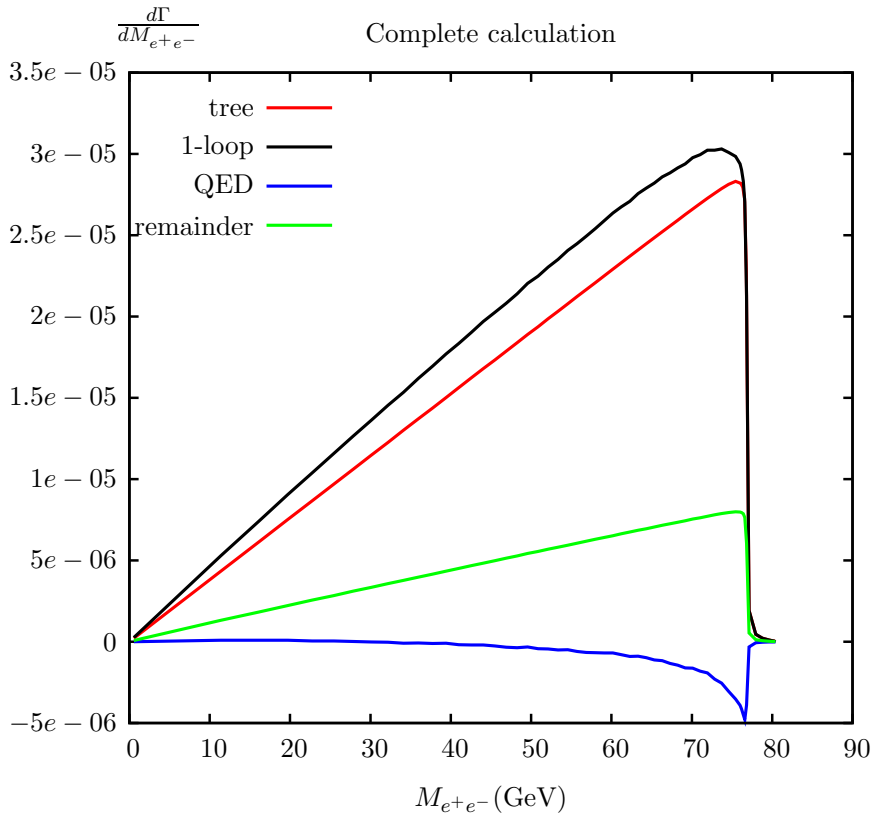

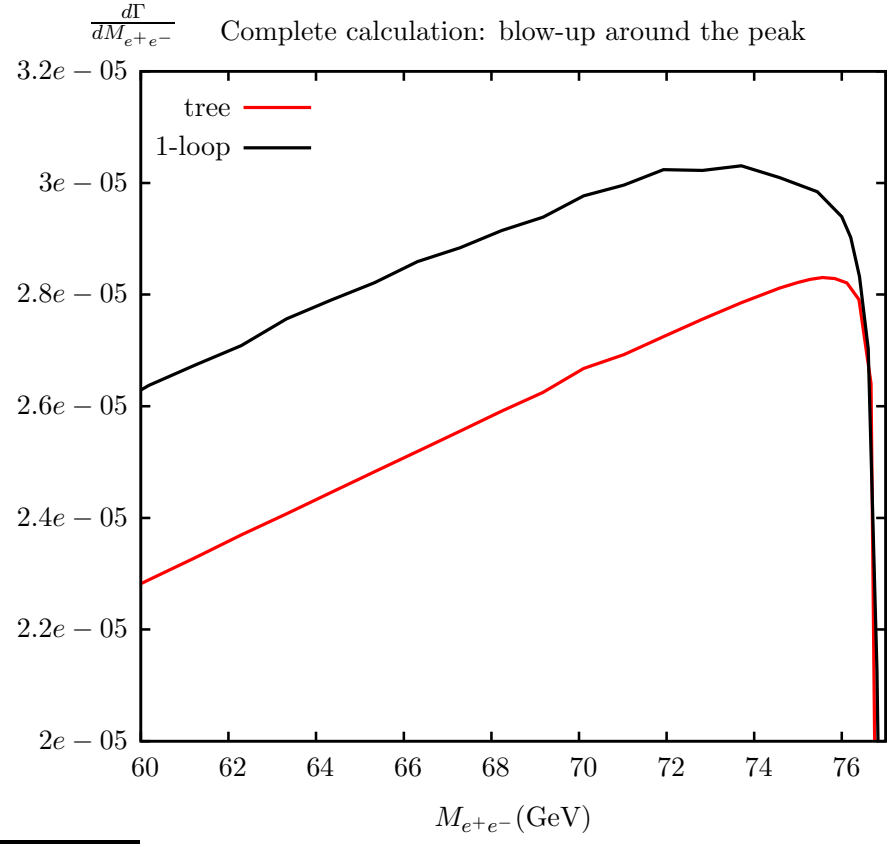

- $M^{\rm Max}_{e^+e^-} = m_{\tilde{\chi}^0_2}\sqrt{1-\frac{m^2_{\tilde{e}^\pm_1}}{m^2_{\tilde{\chi}^0_2}}}\sqrt{1-\frac{m^2_{\tilde{\chi}^0_1}}{m^2_{\tilde{e}^\pm_1}}} \simeq 76.8$ GeV
- Peak is shifted by 4 GeV at 1-loop level

Numerical Results

1.) $m_{\tilde{e}_1} = m_{\tilde{\mu}_1}$, $m_{\tilde{e}_2} = m_{\tilde{\mu}_2}$

2.) $m_l(l = e, \mu) = 0$ except when it appears in one-loop integrals $\Rightarrow \ln m_l$

3.) $\ln m_l$ cancels in 1-loop level **integrated** results

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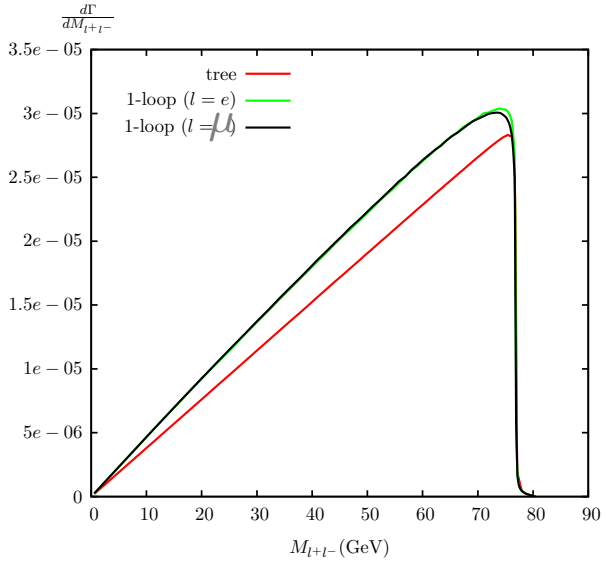
Different treatment of collinear photon radiation:

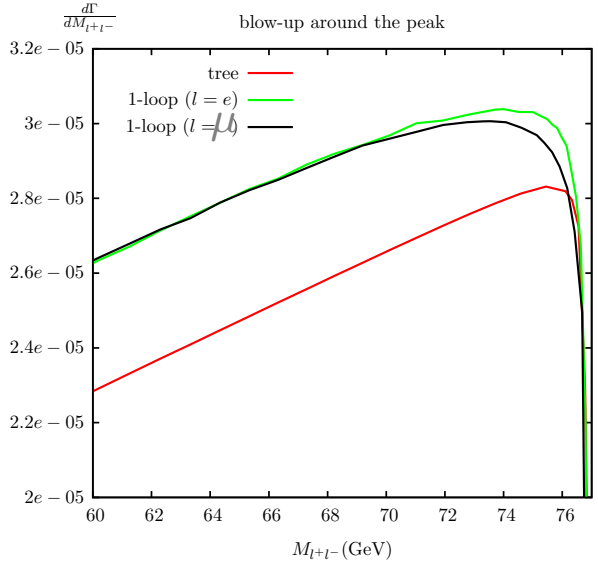
$$\begin{cases} M_{e^+e^-} = \sqrt{(k_{e^+} + k_{e^-} + k_\gamma)^2} & \ln m_e \ \text{cancels} \\ M_{\mu^+\mu^-} = \sqrt{(k_{\mu^+} + k_{\mu^-})^2} & \ln m_\mu \ \text{not cancels} \end{cases}$$

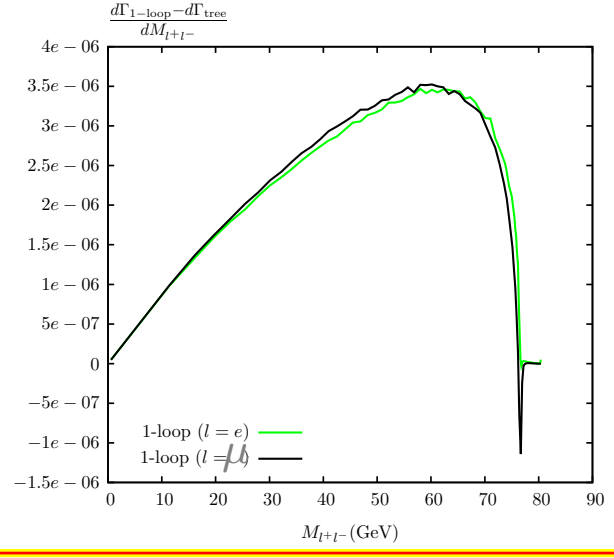
$\Longrightarrow$ 1-loop $M_{l^+ l^-}$ distributions are not identical

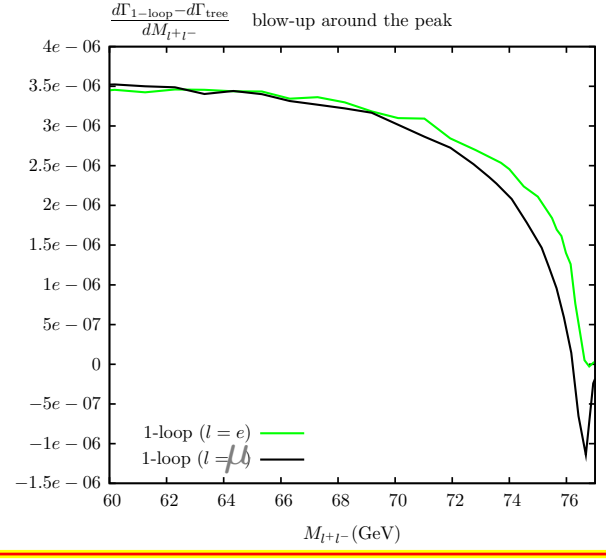
Numerical Results SPS1a parameter set

Comparison of $M_{\mu^+\mu^-}$ and $M_{e^+e^-}$ distributions

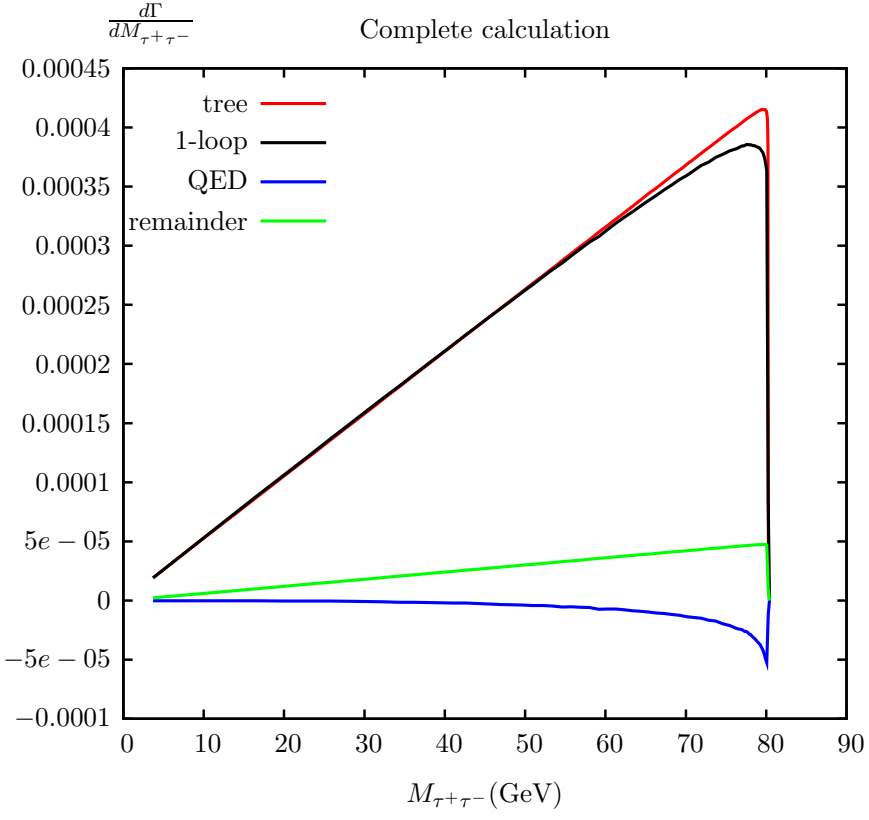


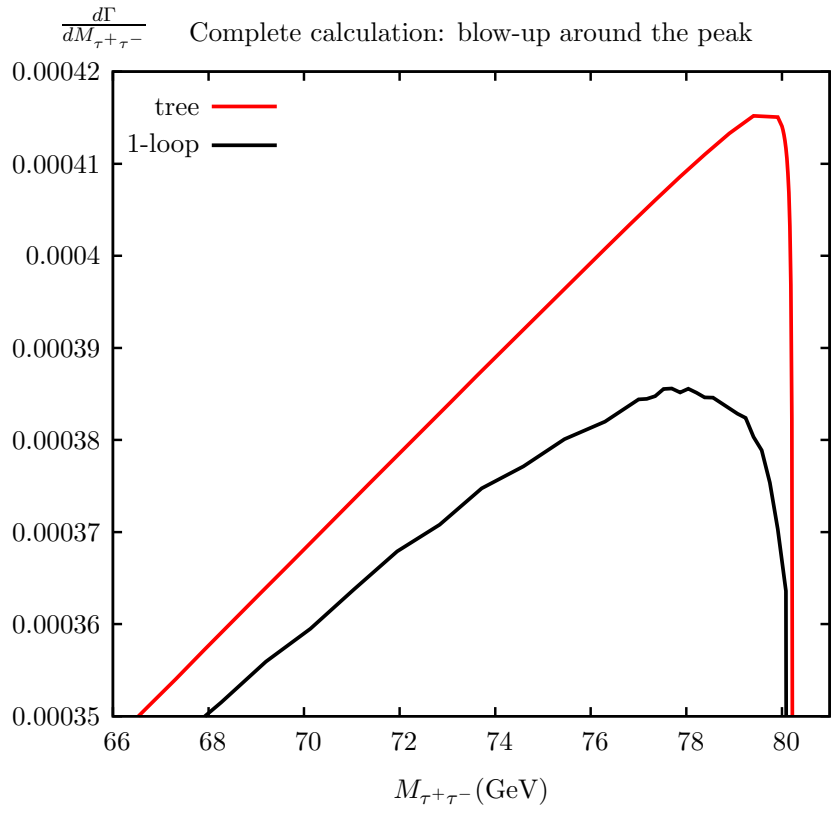






Numerical Results SPS1a parameter set





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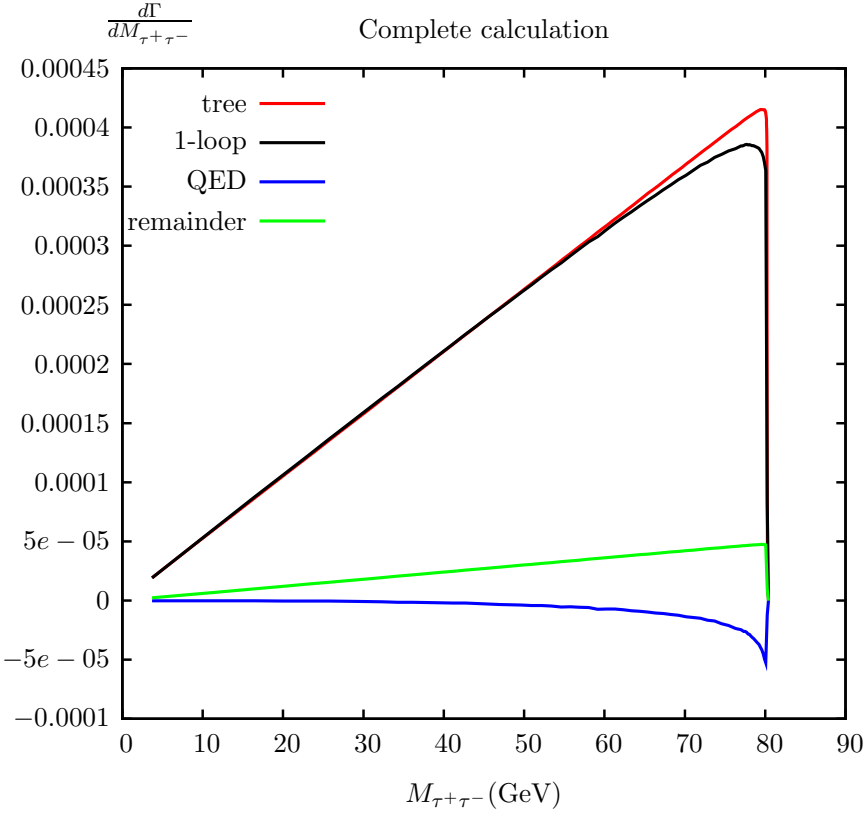

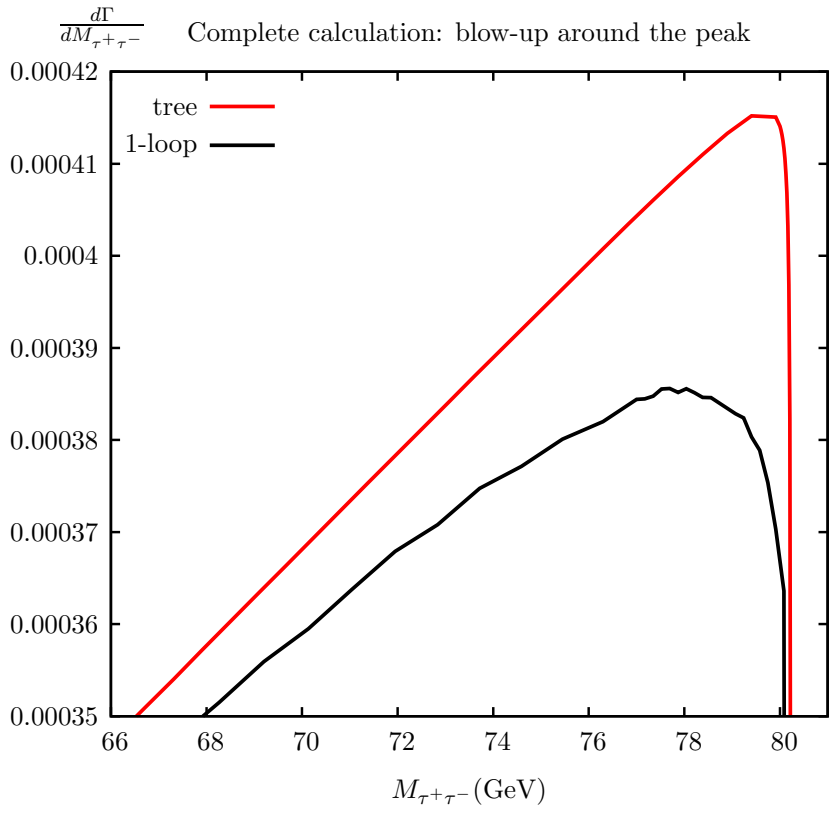

- $m_{\tilde{\tau}_1^\pm} \approx \sqrt{m_{\tilde{\chi}_2^0} m_{\tilde{\chi}_1^0}} \Longrightarrow M^{\rm Max}_{\tau^+\tau^-} = m_{\tilde{\chi}_2^0} \sqrt{1 - \frac{m^2_{\tilde{\tau}_1^\pm}}{m^2_{\tilde{\chi}_2^0}}} \sqrt{1 - \frac{m^2_{\tilde{\chi}_1^0}}{m^2_{\tilde{\tau}_1^\pm}}}$

  $\approx m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \simeq 80.4$ GeV

- Peak is shifted by 2 GeV at 1-loop level

Numerical Results three-body decays

SPS1a parameter set except that the sleptons are heavier

particle	$\tilde{e}_1(\tilde{\mu}_1)$	$\tilde{e}_2(\tilde{\mu}_2)$	$\tilde{\tau}_1$	$\tilde{\tau}_2$	$\tilde{\nu}_l(l = e\,\mu,\tau)$
mass(GeV)	187.9	234.9	182.3	239.2	221.0

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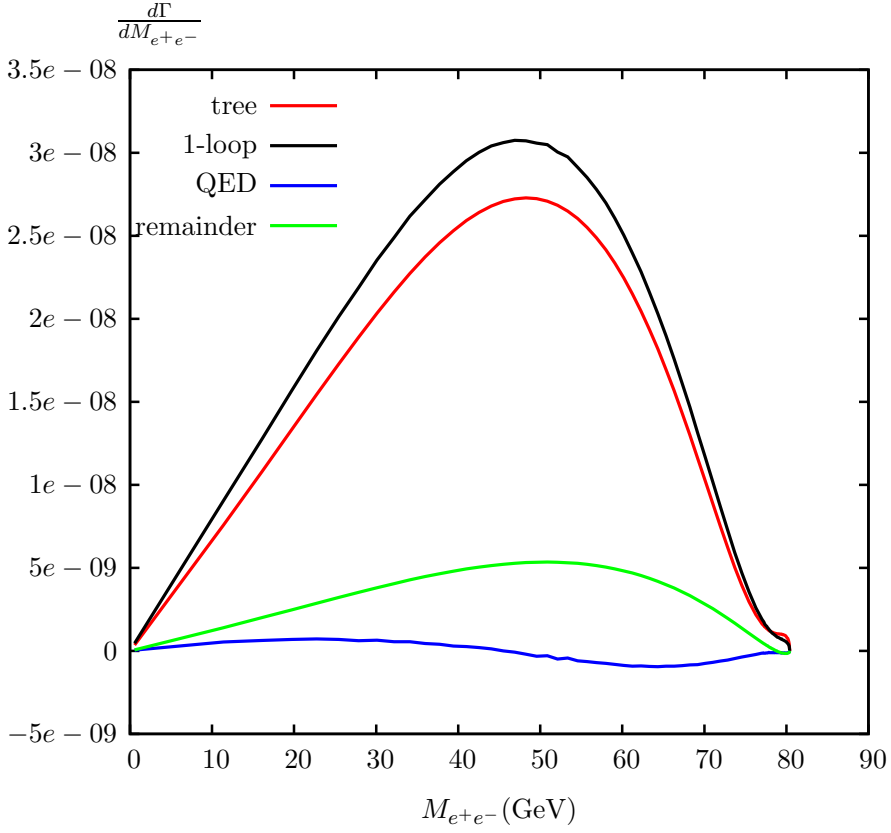
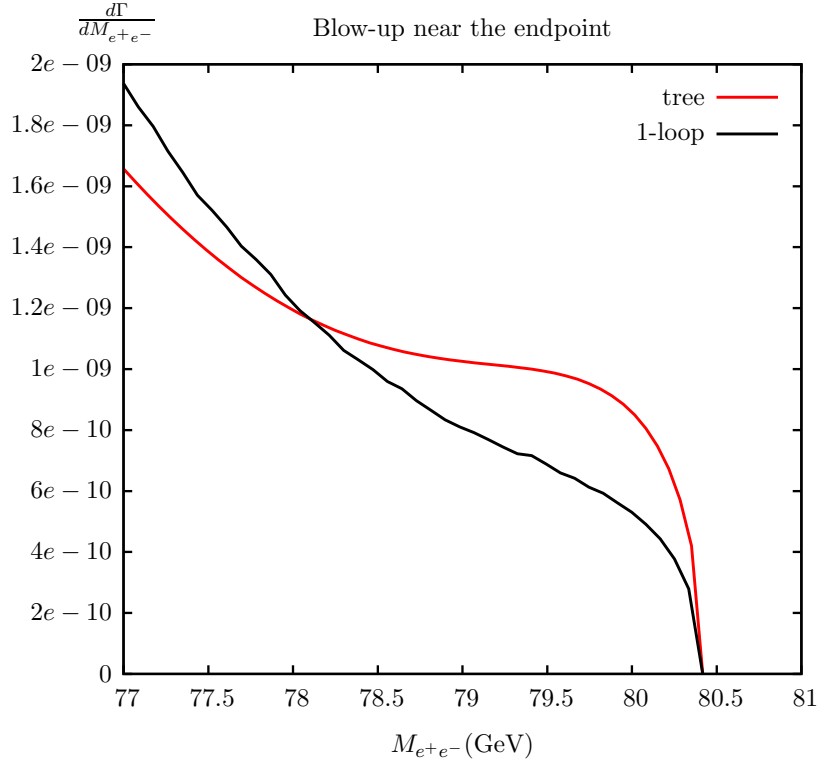
mass(GeV)	187.9	234.9	182.3	239.2	221.0

$\tilde{\chi}_2^0$ decay mode	tree-level width(keV), Br	1-loop-level width(keV), Br
$e^-e^+\tilde{\chi}_1^0$	1.270, 4.4%	1.451, 5.0%
$\mu^-\mu^+\tilde{\chi}_1^0$	1.270, 4.4%	1.451, 5.0%
$\tau^-\tau^+\tilde{\chi}_1^0$	7.209, 25.1%	7.383, 25.4%
$\nu_e\bar{\nu}_e\tilde{\chi}_1^0$	1.273	1.355
$\nu_\mu\bar{\nu}_\mu\tilde{\chi}_1^0$	1.273	1.355
$\nu_\tau\bar{\nu}_\tau\tilde{\chi}_1^0$	1.273	1.354
$q\bar{q}\tilde{\chi}_1^0$	15.210	14.765
total width	28.778	29.114

Numerical Results three-body decays





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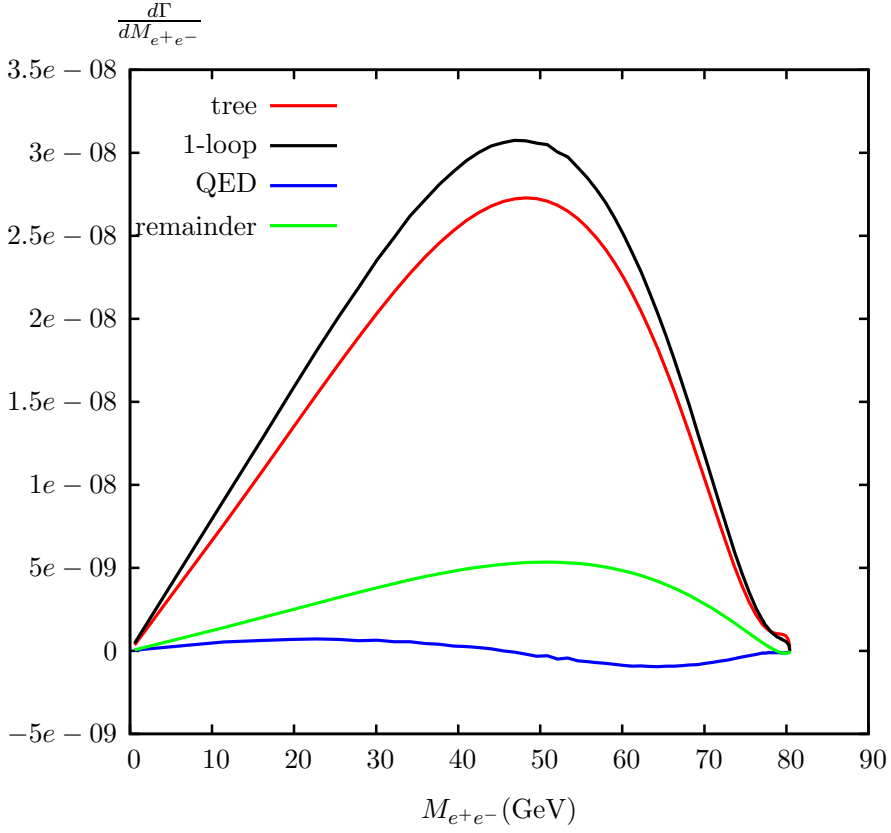
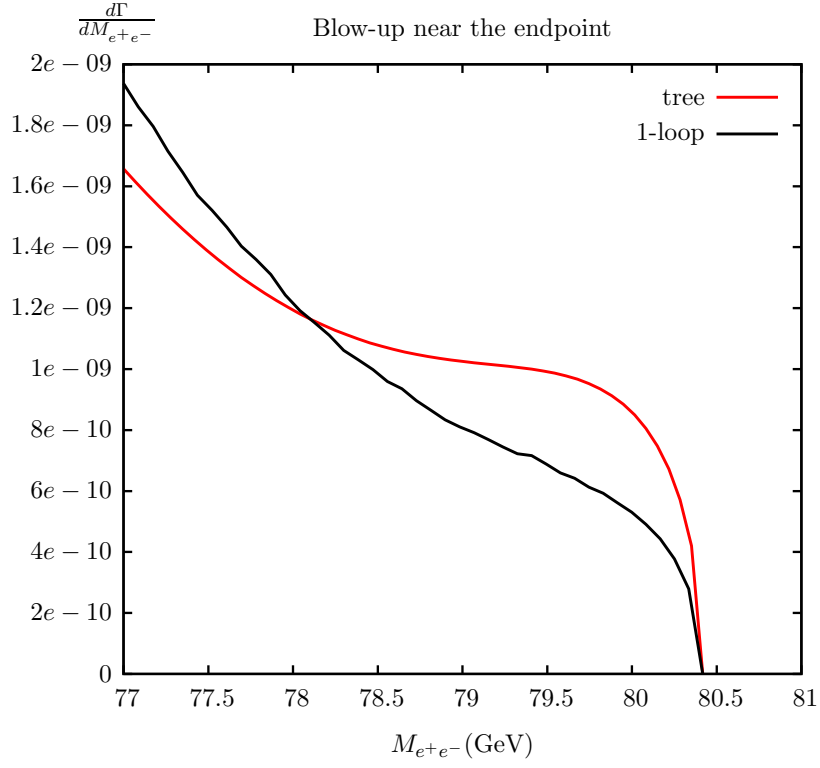
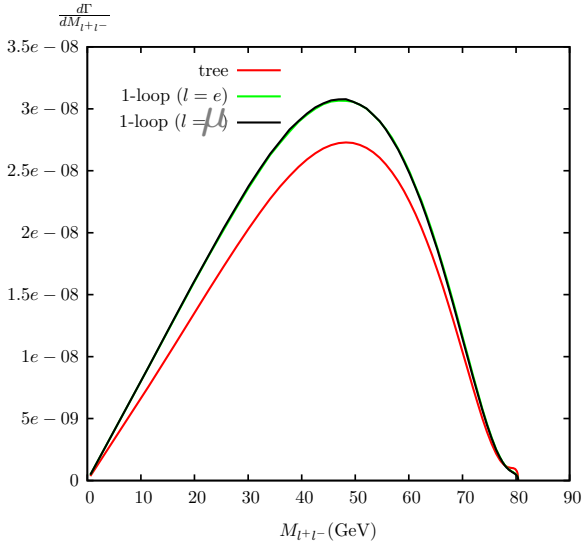


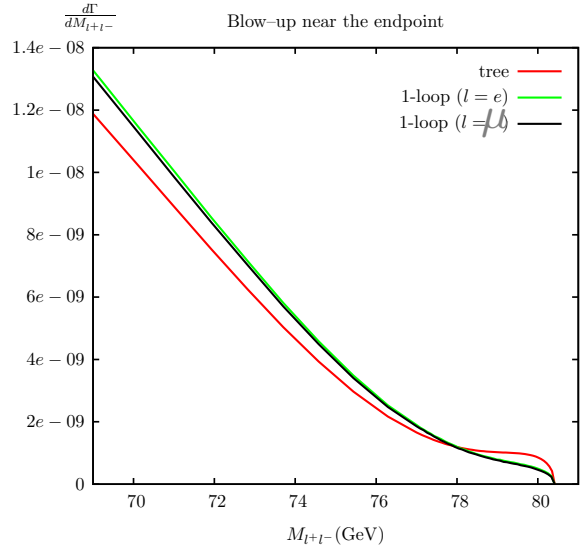


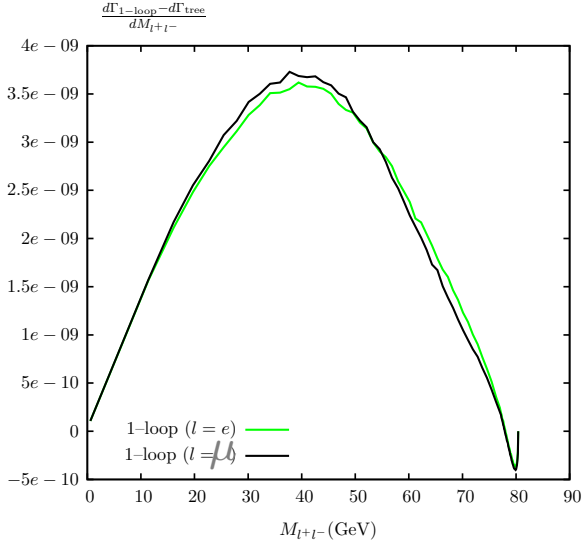
- $M_{e^+e^-}^{\max} = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ three-body kinematics
- Peaks are shifted at 1-loop level, the one near the endpoint comes from the exchange of Z boson

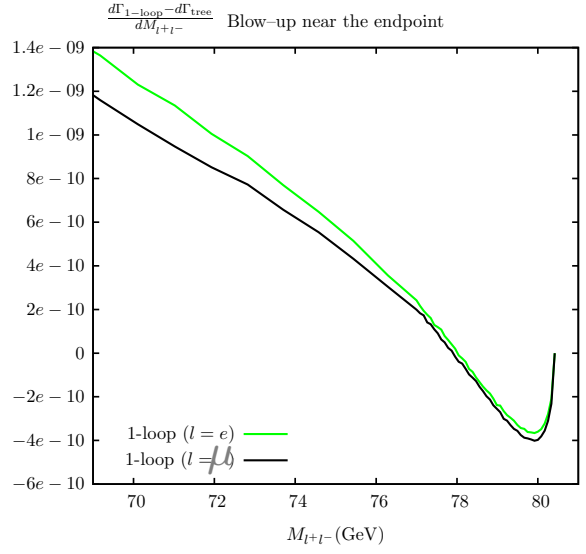
Numerical Results three-body decays

Comparison of $M_{\mu^+\mu^-}$ and $M_{e^+e^-}$ distributions

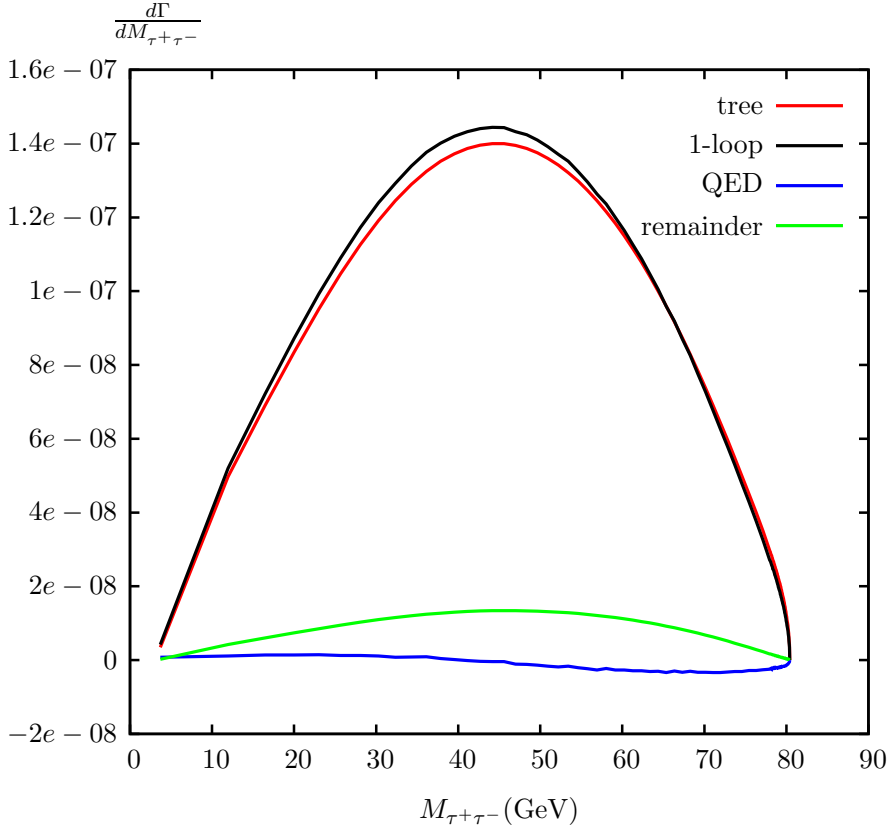


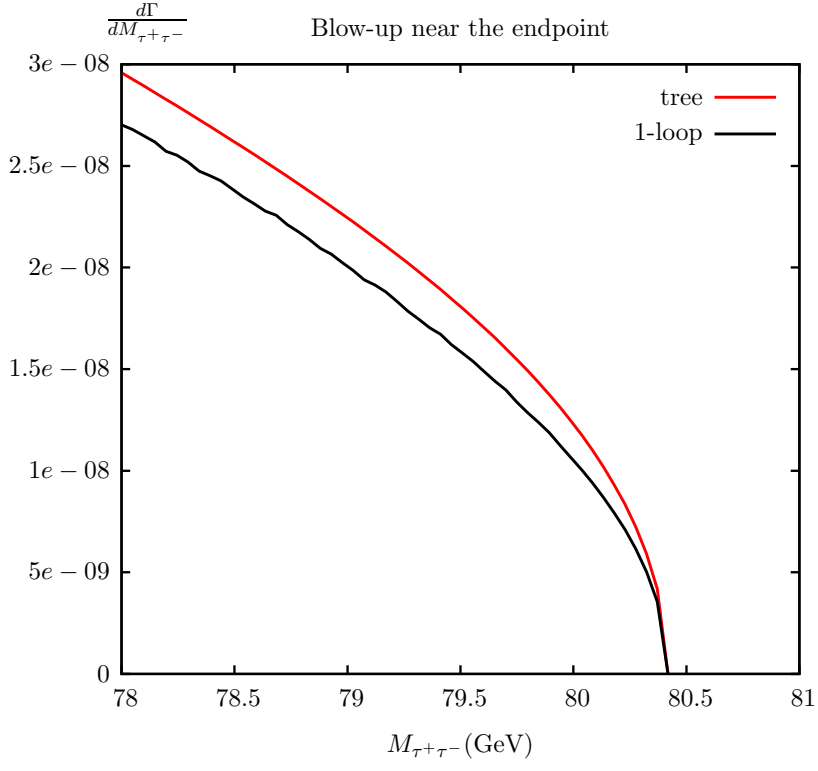






Numerical Results three-body decays





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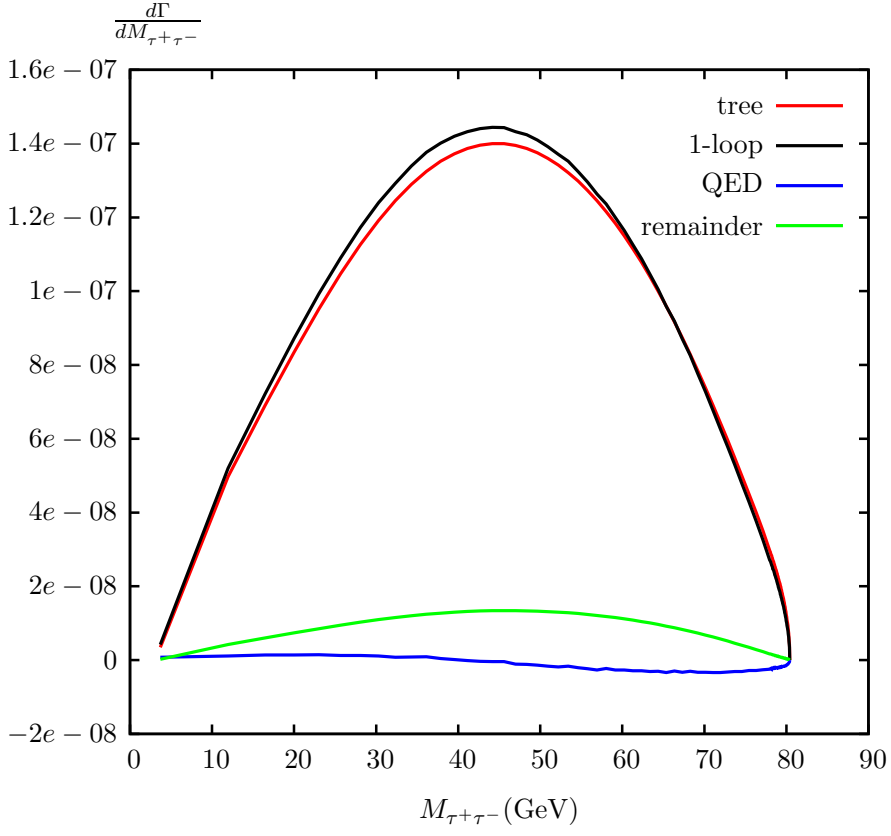

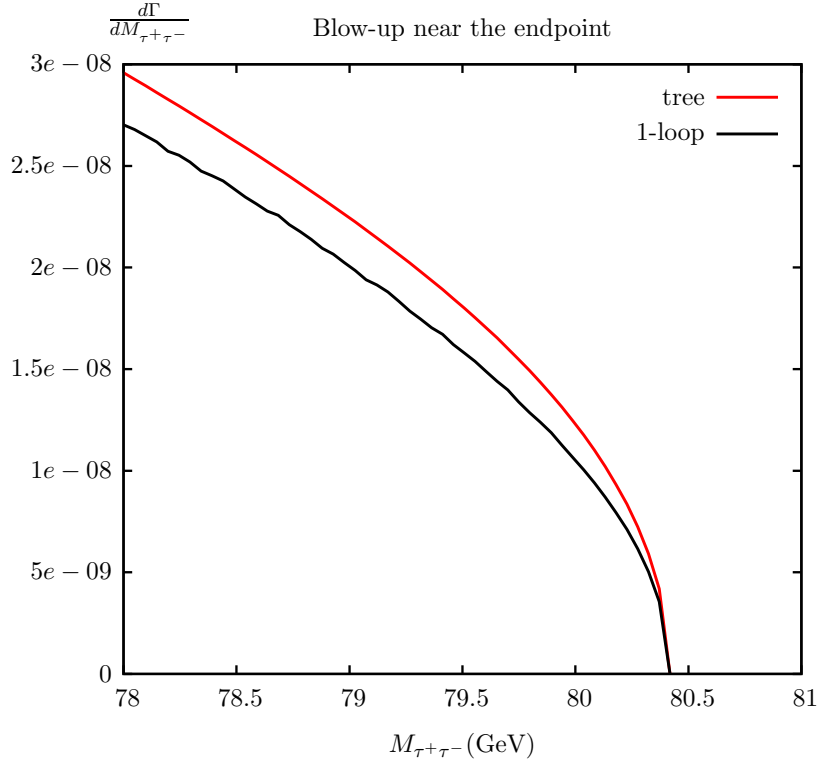

- $M^{\max}_{\tau^+\tau^-} = m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1}$ three-body kinematics
- Peaks are shifted at 1-loop level

Summary

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