Berkeley week 2024

Precise Estimate of Chargino Decay Rates

Yuhei Nakayama

(ICRR Theory Group)

Based on

JHEP 01(2023)017 (arXiv: 2210.16035)

and JHEP 03(2024)012 (arXiv: 2312.08087)

In Collaboration with

Masahiro Ibe, Masataka Mishima, Satoshi Shirai

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Plan of Talk

1. Introduction
2. Outline of Computation
3. Result & Summary

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Plan of Talk

1. Introduction

✓SUSY Dark Matter

✓Importance of Compressed Region

✓Wino/Higgsino Search in Collider Experiments

Dark Matter in SUSY

- The MSSM provides a few DM candidates:
  Bino, Wino, and Higgsino

$$\psi^0 = \left(\tilde{B}, \tilde{W}^3, \tilde{H}_d^0, \tilde{H}_u^0\right)^T$$

- The EW interactions implement the production mechanism called the thermal freeze-out
  $\to$ TeV-scale Wino or Higgsino

✦ The Bino tends to overclose the Universe
unless there is a sfermion (typically stau) degenerated with the Bino

Difficulties in SUSY

- The weak-scale SUSY faces various difficulties

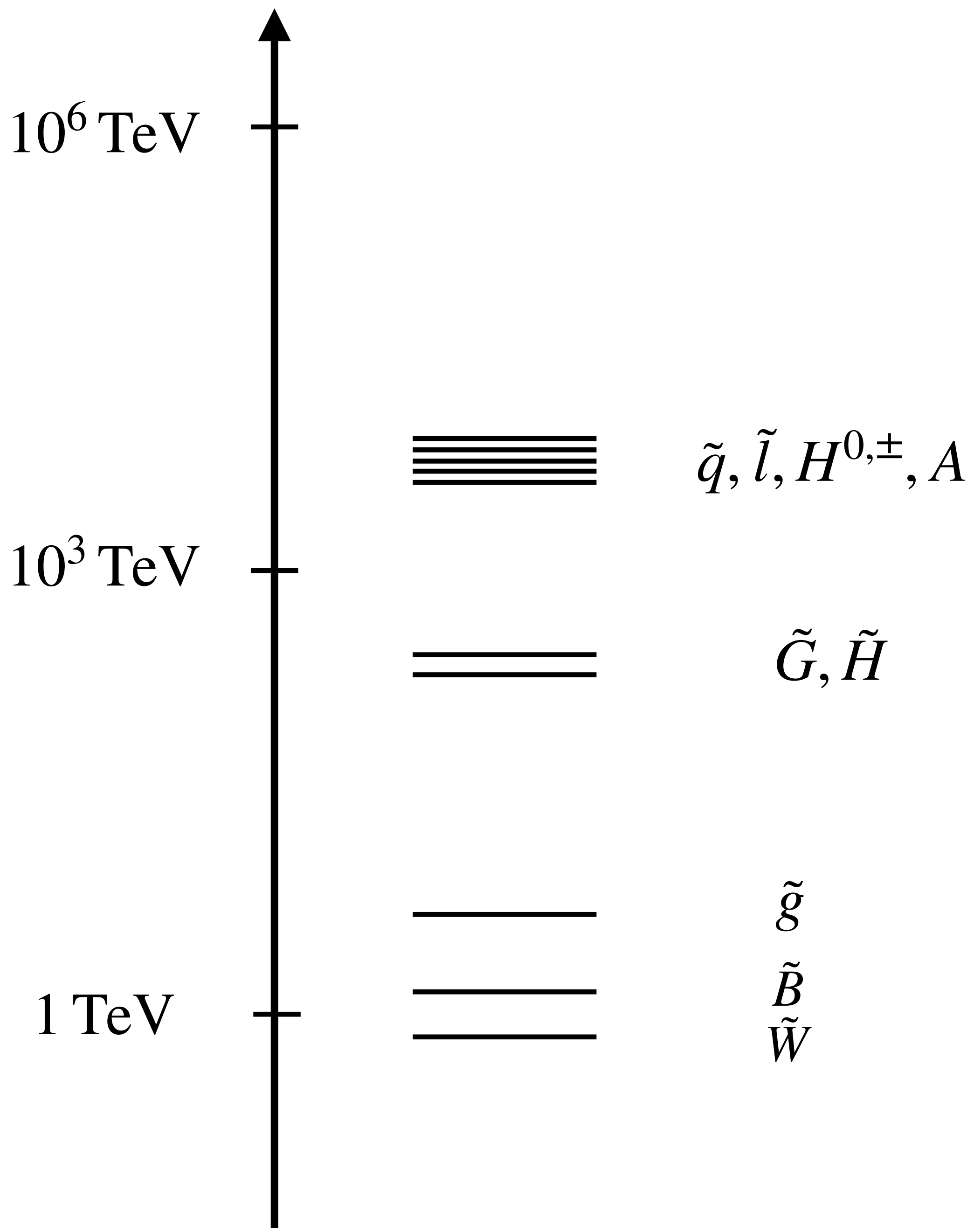
  - No flavor/CP violation in low-energy
  - No sparticles suggested in LHC/LEP
  - The Higgs mass tends to be lighter than 125 GeV

Is SUSY already excluded from experiments/observations?

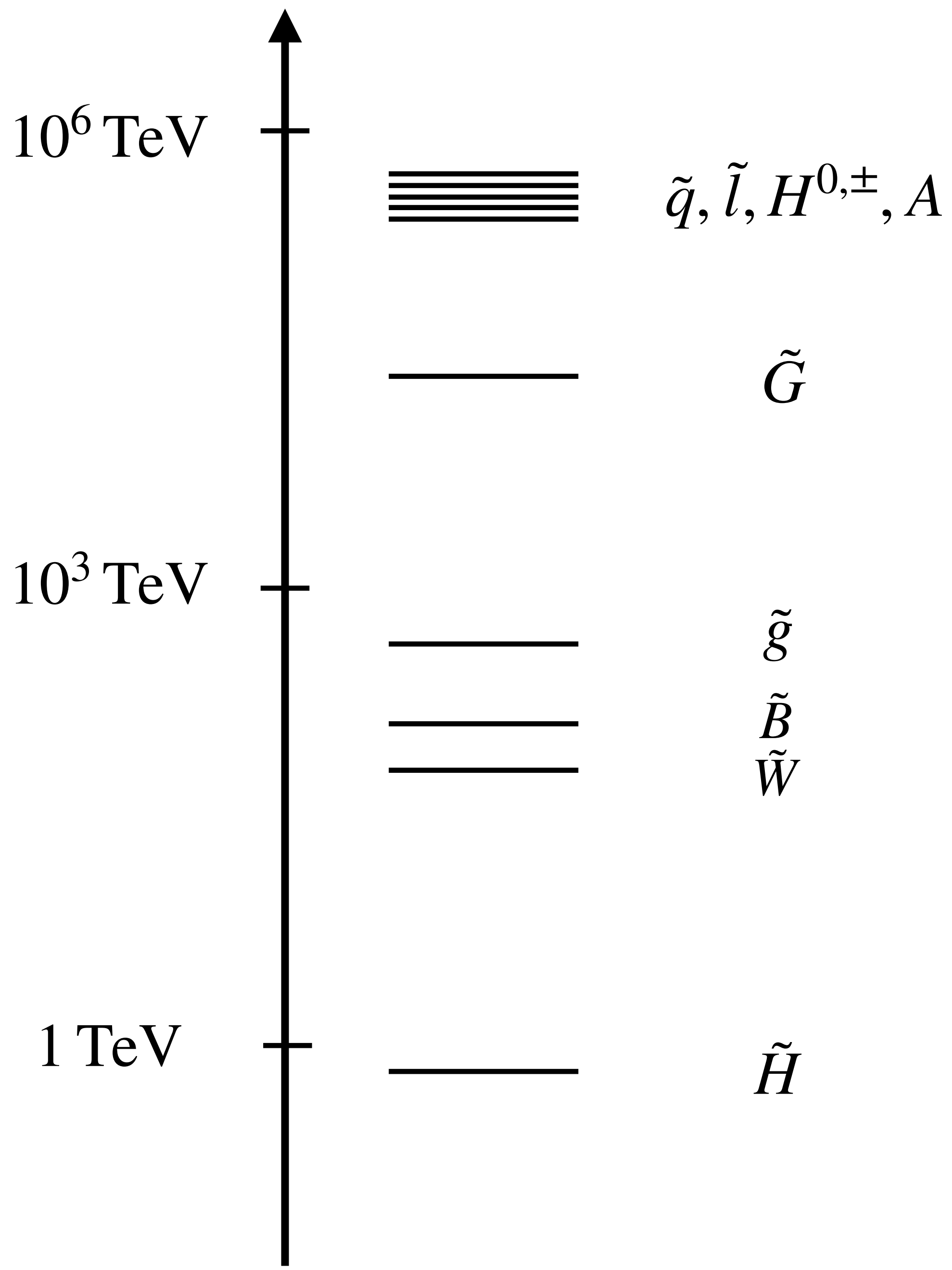
No. SUSY can realize so-called split spectrum:

$$M_{\rm gauginos} \ll M_{\rm sfermions}$$

Mass Spectra in Viable SUSY



Wino-LSP case

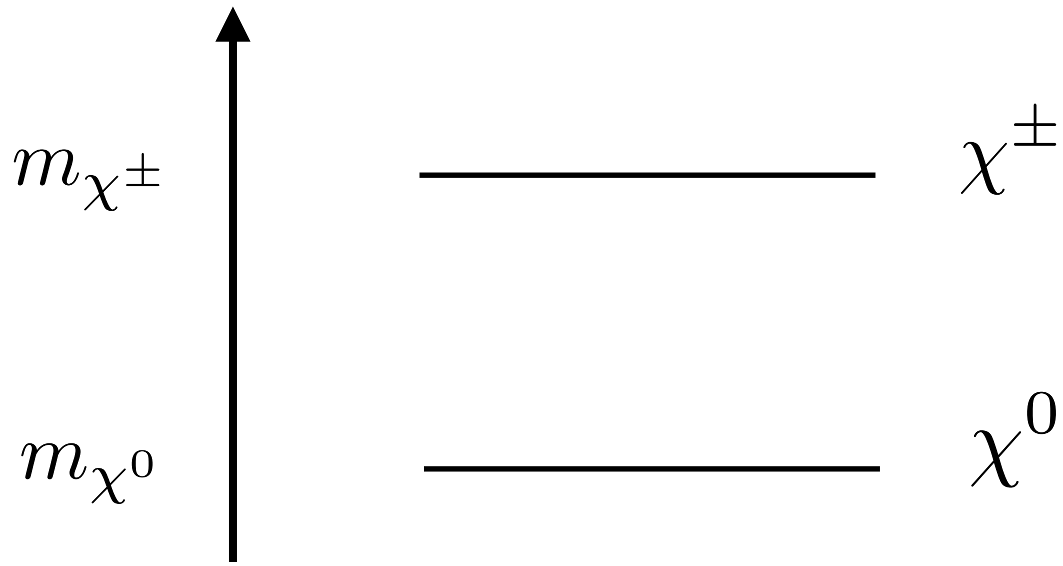


Higgsino-LSP case

EFT of Split SUSY

Additional low-energy parameters in Split SUSY:

- Mass of chargino $m_{\chi^\pm}$
- Mass(es) of neutralino(s) m_{χ^0}



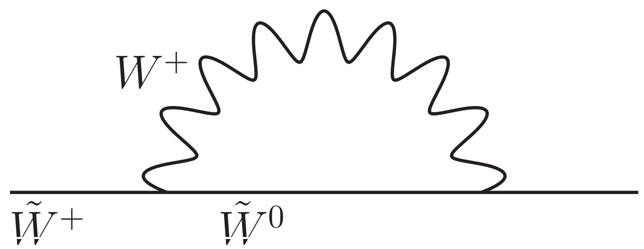
These parameters control phenomenology in low energy

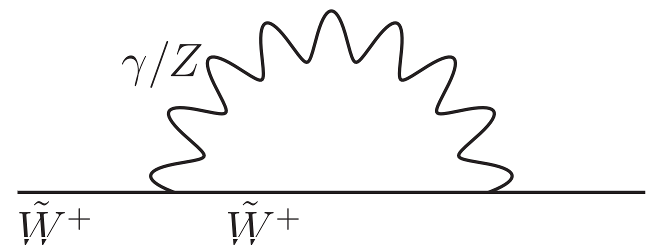
What are the plausible values of the difference between these parameters?

Wino-LSP case

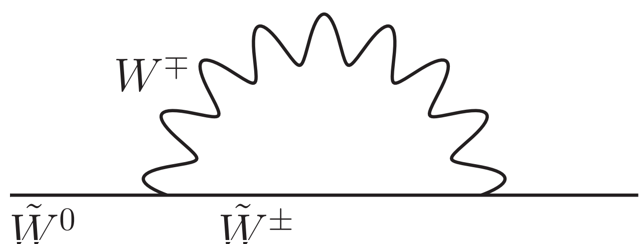
- EW interactions provide mass difference, $\Delta m_{\pm}^{\text{rad}}$

Charged:





Neutral:



- Mixing with other neutralinos (Bino, Higgsinos) also provides a tree-level mass splitting, $\Delta m_{\pm}^{\text{tree}}$ However, this is very small in the Wino-LSP case.

Wino-LSP case

- Hence, the mass difference in the Wino system is determined by the radiative corrections:

$$\begin{aligned} \Delta m_{\pm} &= \Delta m_{\pm}^{\mathrm{rad}}(m_{\chi^{\pm}}) + \Delta m_{\pm}^{\mathrm{tree}} \\ &\simeq \Delta m_{\pm}^{\mathrm{rad}}(m_{\chi^{\pm}}) \end{aligned}$$

$$\Delta m_{\pm} := m_{\chi^{\pm}} - m_{\chi^{0}}$$

- Radiative splitting is known to be around 160 MeV, far smaller than the Wino mass.
Winos are highly compressed!

$$\left| m_{\chi^{\pm}} - m_{\chi^{0}} \right| \ll m_{\chi^{\pm}}, m_{\chi^{0}}$$

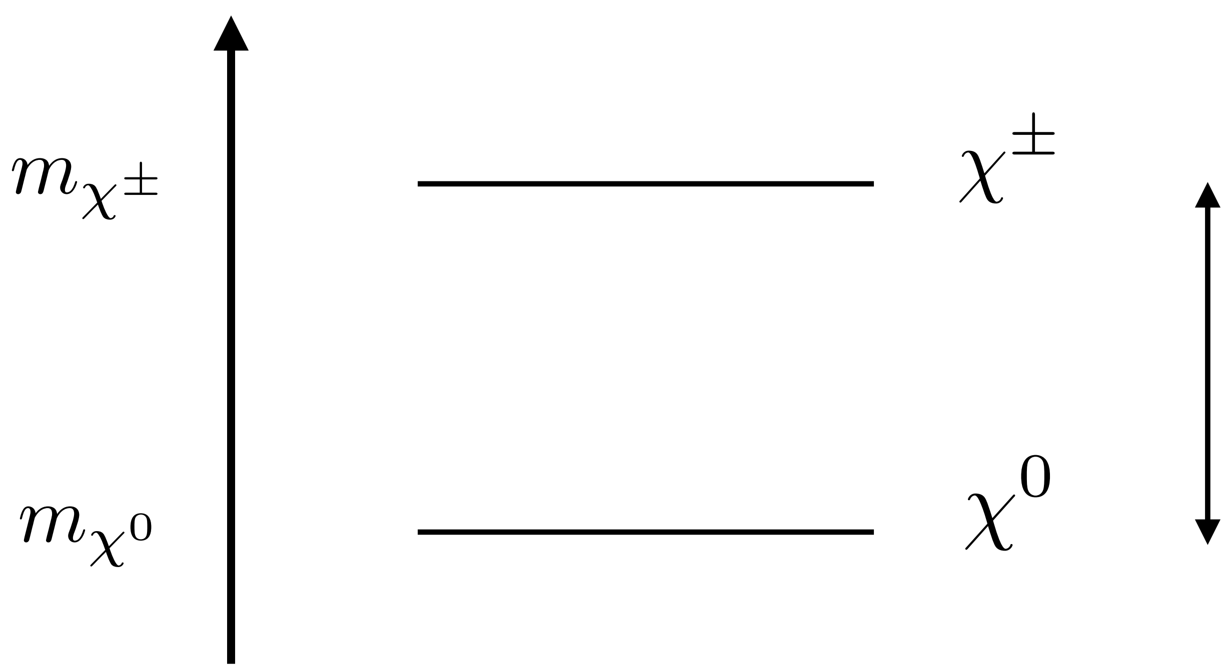
I'll skip the Higgsino-LSP scenario
because it is too complicated!

Even in the Higgsino-LSP case,
the region $\left|m_{\chi^\pm} - m_{\chi^0}\right| \lesssim 1\,\mathrm{GeV}$
is of interest phenomenologically

Point to be remembered:

Compressed region arises in viable SUSY DM models

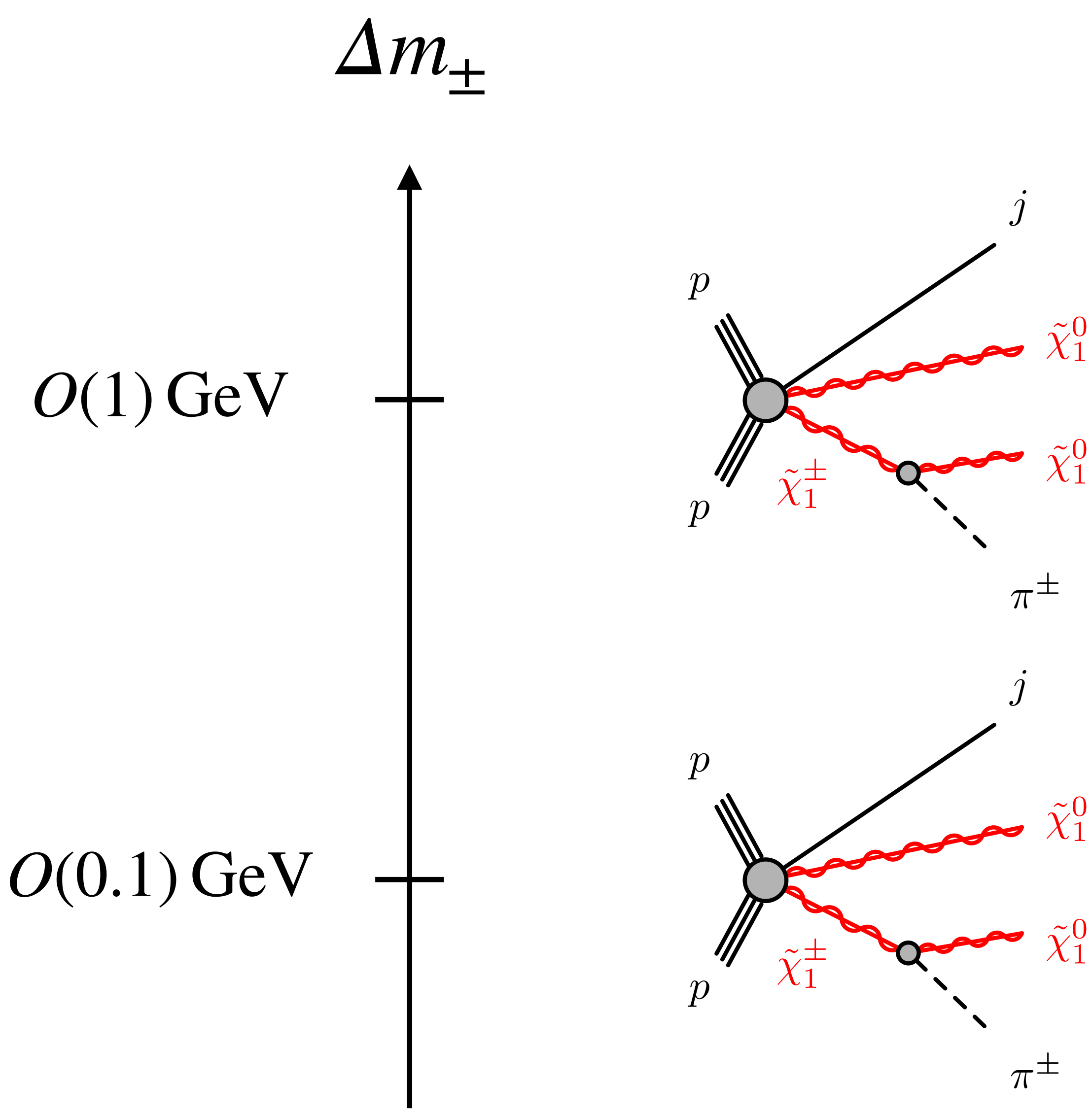
Compressed Region



$$\left|m_{\chi^\pm} - m_{\chi^0}\right| = O(100)\,\mathrm{MeV}$$
$$\ll m_{\chi^\pm}, m_{\chi^0}$$

Collider Constraint

- Mono-jet search cannot establish strong constraint on Wino/Higgsino mass
- Another observable is required to reduce BG

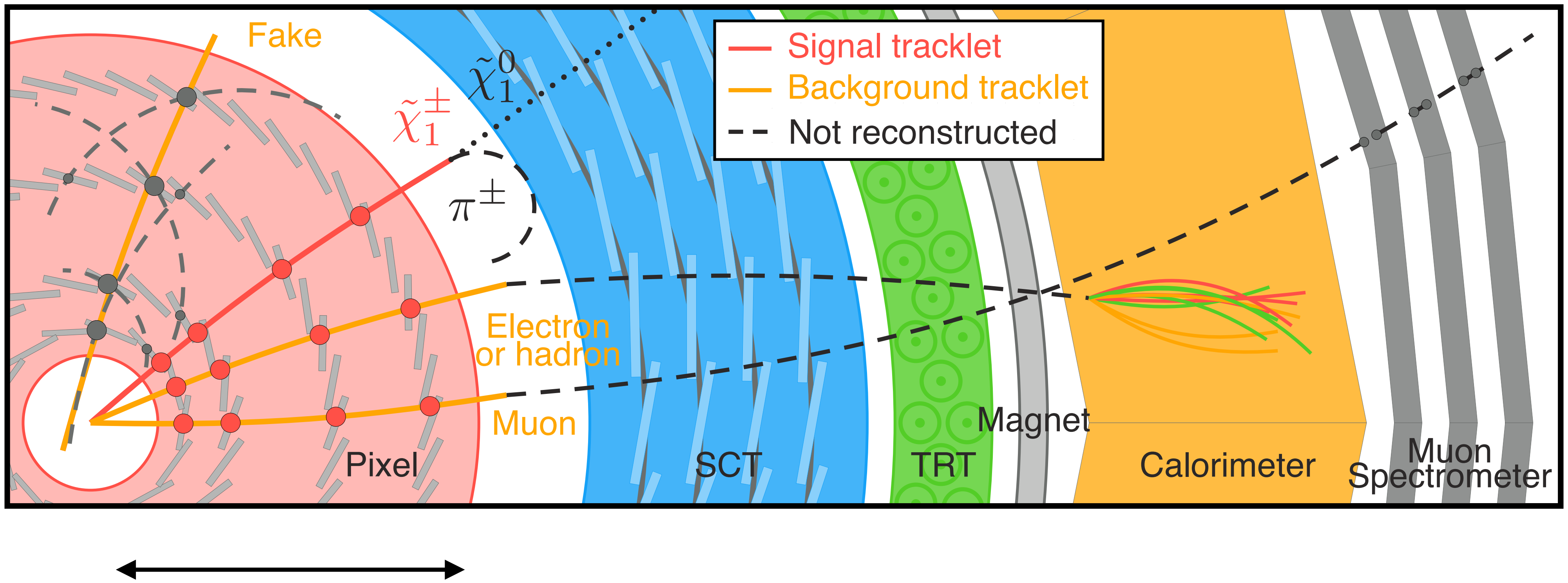


ISR jet + soft pions + MET
(Higgsino)

ISR jet + disappearing track + MET
(Wino/Higgsino)

Disappearing Track

[ATLAS, *Eur.Phys.J.C* 82 (2022) 7, 606]



$L = 12\,\mathrm{cm}$ $> c\tau \sim 7\,\mathrm{cm}$ (the decay length of Wino)

#(expected charged track) $\propto \exp(-L/c\tau)$

10% error in lifetime → 50% error in signals

Crux:

Collider constraint is highly dependent on the prediction of the lifetime

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Necessity of NLO

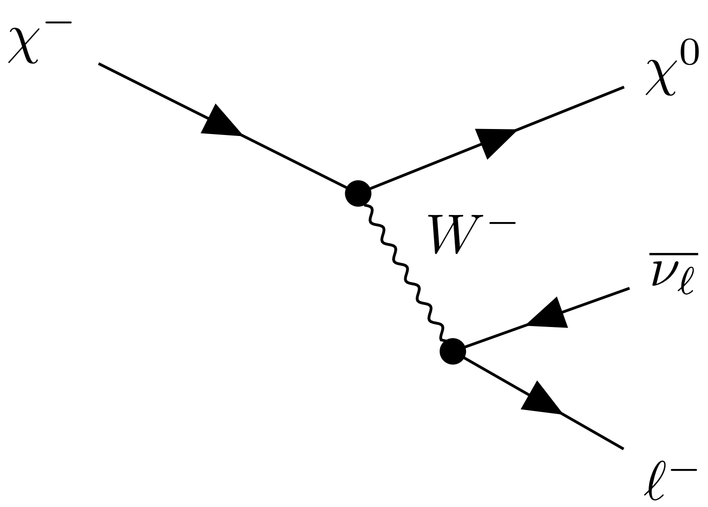
We have learned two important backgrounds in search of SUSY DM models:

1. Compressed region arises in viable SUSY DM models
2. Collider constraint is highly dependent on the prediction of the lifetime

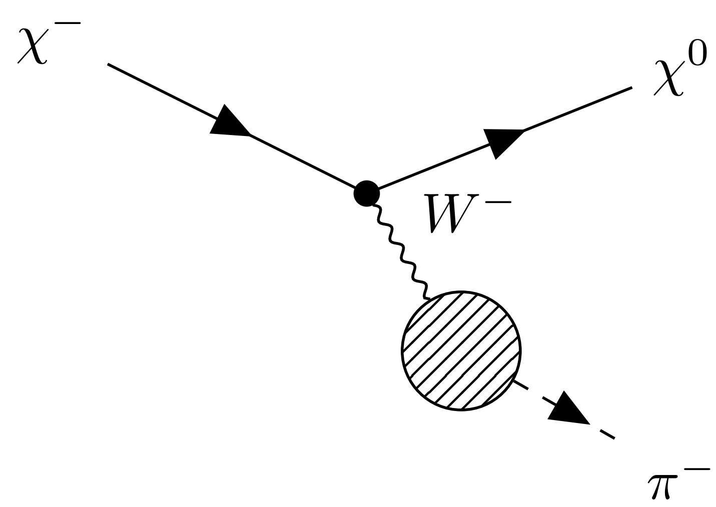
The necessity of NLO decay rates of chargino is a natural consequence of discussions so far.

Decay Modes of Chargino

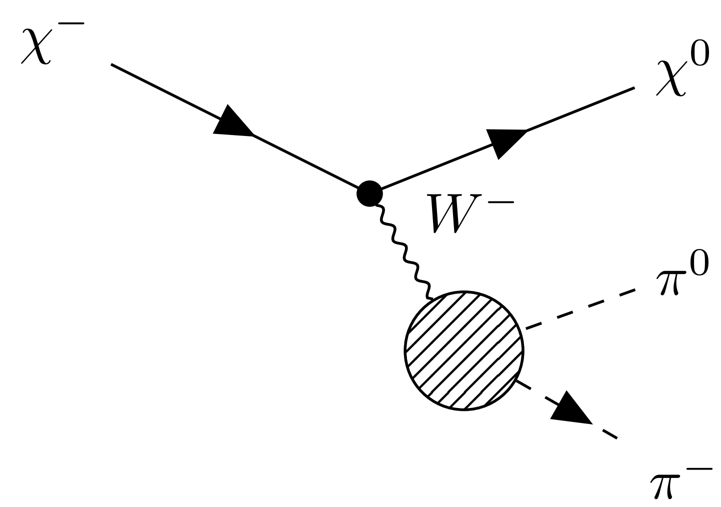
Leptonic mode

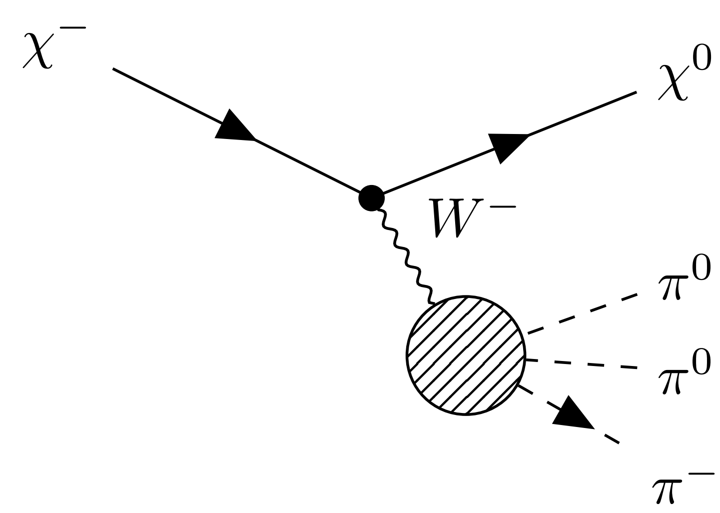


Single pion (Kaon) mode



Multi-meson mode





Outline of Computation

NLO decay rate

$$\Gamma(\chi^- \to \chi^0 + \mathrm{SM}) = \Gamma_{\mathrm{tree}} + \delta\Gamma_{\mathrm{radiative\ corrections}}$$

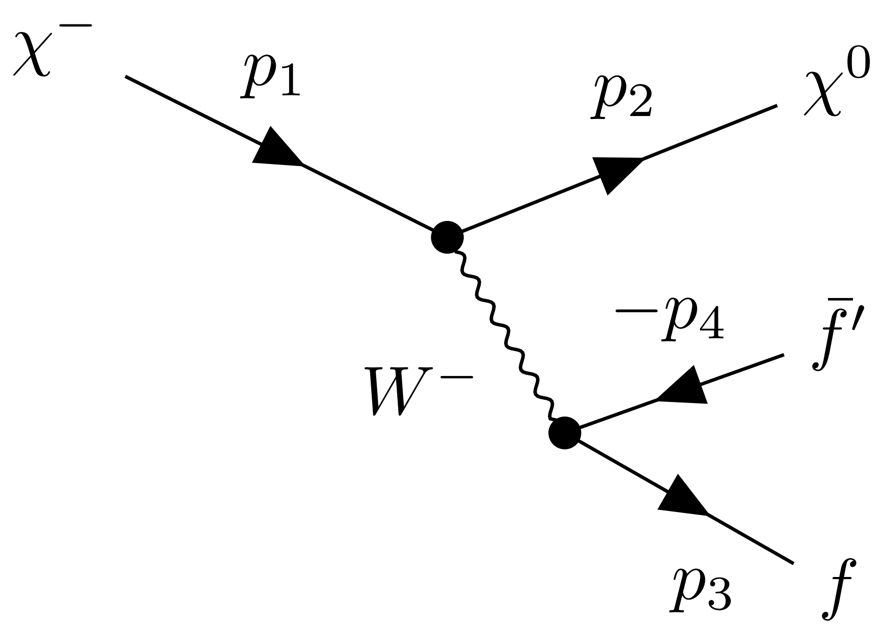
$$\delta\Gamma_{\mathrm{short-distance}} + \delta\Gamma_{\mathrm{long-distance}}$$

- Above QCD scale
- W/Z-boson exchanges
- Calculable with SM+Wino/Higgsino

- Below QCD scale
- Virtual/real photon
- In hadronic mode, strong-coupling effects are significant

Short-distance Correction

On-shell amplitude @ one-loop of EW theory



+

Virtual γ, Z, W-boson loops

- ✓Wavefunctions
- ✓Vertex corrections
- ✓Box diagrams
- ✓W-boson self-energy

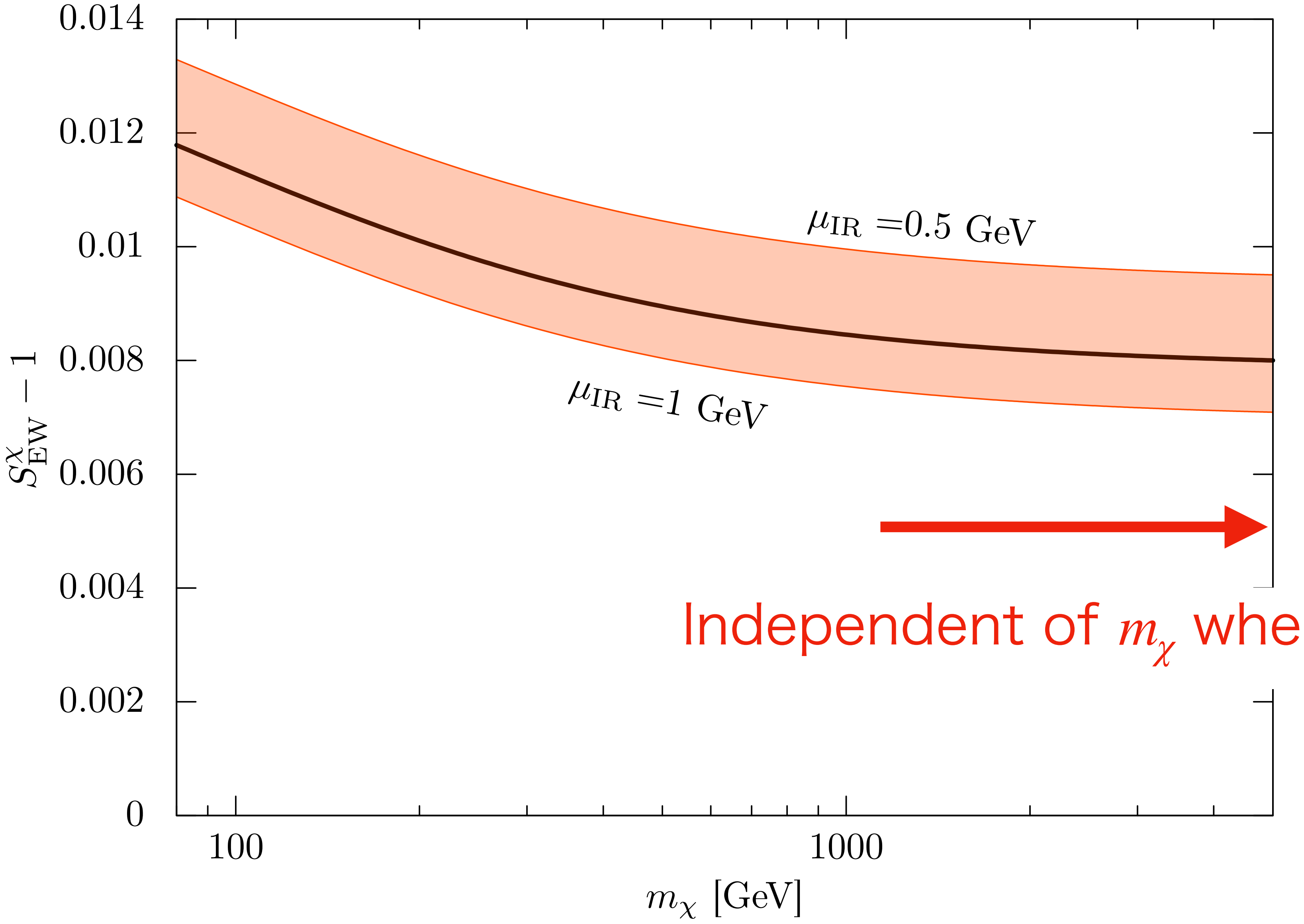
- Masses of SM fermions can be neglected in the matching to low-energy theory: $m_f \simeq 0,\ m_{f'} \simeq 0$
- $\Delta m_\pm \simeq p_1 - p_2$ is far smaller than the chargino mass

$$\alpha \cdot \Delta m_\pm / m_\chi \simeq 0$$

Short-distance Correction

$$\delta\Gamma_{\rm short-distance} = [S^{\chi}_{\rm EW}(\mu_{\rm IR}) - 1] \times \Gamma_{\rm tree}$$

IR cutoff; dependence on it should be disappeared after all of the computation



Independent of m_χ when $m_\chi \to \infty$

Long-distance Corrections

Calculations of long-distance corrections are mode-dependent and very complicated

Basic strategy: method of effective theory (EFT)

$$\delta\Gamma_{\rm long-distance} \supset \delta\Gamma_{\rm loops\ in\ EFT} + \delta\Gamma_{\rm counterterms\ in\ EFT}$$

- Loop diagrams generated by EFT
- EFT is Four-Fermion theory or Chiral Perturbation Theory
- UV divergent

- Contributions to subtract UV divergence in EFT
- Finite parts correspond to input parameter of EFT
- Determined by renormalizable theory or experimental data

Example: Leptonic Mode

EFT for the leptonic mode:

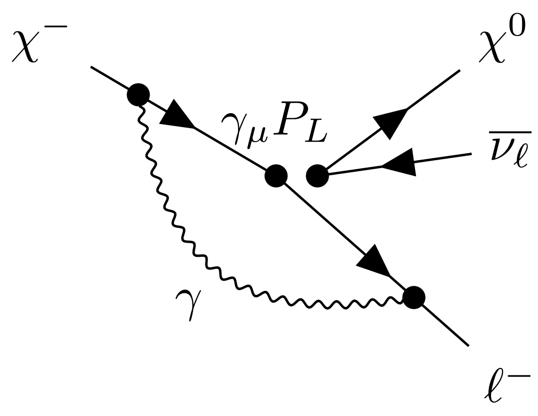
$$\mathcal{L}_{\rm FF}^{\rm lepton} = -2\sqrt{2}G_F\left(\overline{\Psi}_\ell\gamma^\mu P_L\Psi_{\chi^-}\right)\left(\bar{\Psi}_{\chi^0}\gamma_\mu P_L\Psi_{\nu_\ell}\right) + 4\sqrt{2}G_F\left(\overline{\Psi}_\ell P_R\Psi_{\chi^-}\right)\left(\overline{\Psi}_{\chi^0}P_L\Psi_{\nu_\ell}\right)$$

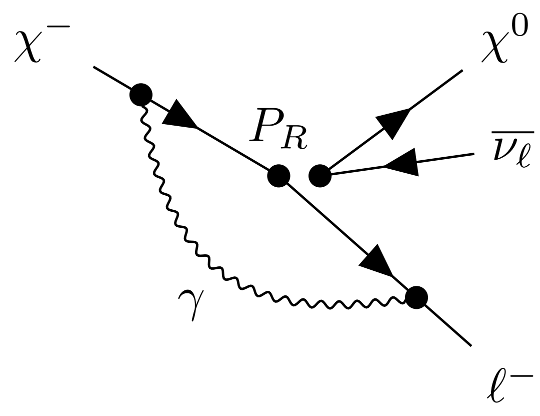
$$\delta\mathcal{L}_{\rm FF}^{\rm lepton} = -2\sqrt{2}G_F\,\delta_V^L\left(\overline{\Psi}_\ell\gamma^\mu P_L\Psi_{\chi^-}\right)\left(\overline{\Psi}_{\chi^0}\gamma_\mu P_L\Psi_{\nu_\ell}\right) + 4\sqrt{2}G_F\,\delta_Y^R\left(\overline{\Psi}_\ell P_R\Psi_{\chi^-}\right)\left(\overline{\Psi}_{\chi^0}P_L\Psi_{\nu_\ell}\right)$$

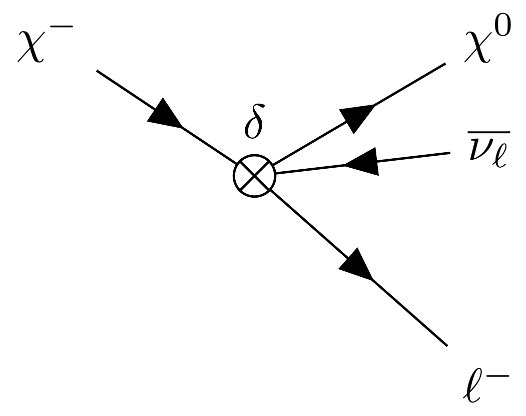
will be chosen to reproduce $\mathcal{M}_{\rm tree}\times\sqrt{S_{\rm EW}^\chi(m_\gamma)}$

Example: Leptonic Mode

Virtual Corrections

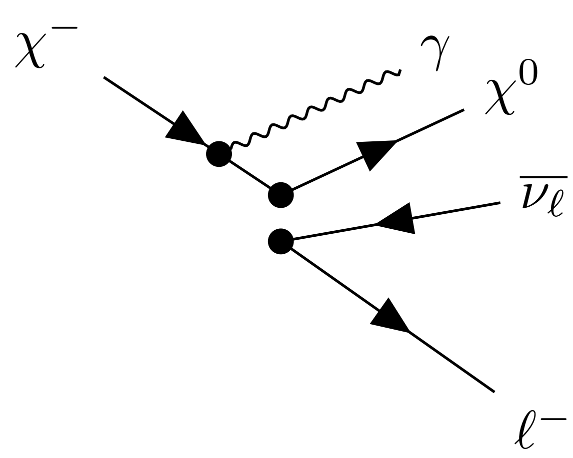


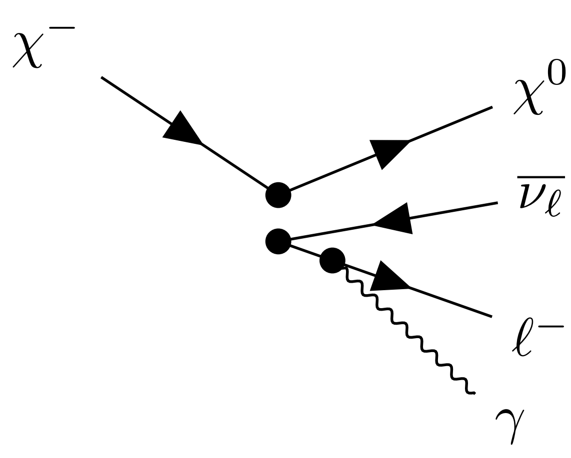




+ Wavefunction

Real photon emissions





Example: Leptonic Mode

Taking the limit $\Delta m_\pm \ll m_\chi$ while keeping $x := m_\ell/\Delta m_\pm$ finite

$$\delta\Gamma_{\chi\to\ell} := \Gamma_{\chi\to\ell} - \Gamma^{\rm tree}_{\chi\to\ell}$$
$$= \left\{\Gamma^{\rm tree}_{\chi\to\ell, m_\ell=0} \times \frac{\alpha}{4\pi}\int_x^1 dw\, \rho_{\rm one-loop}(w) + O(\alpha^2)\right\} + O\left(\frac{\alpha\Delta m}{m_\chi}\right)$$

- No UV/IR divergences
- No collinear divergences (No singularity in $m_\ell \to 0$)
- No $\log m_\chi$ enhancements from long/short-distance corrections

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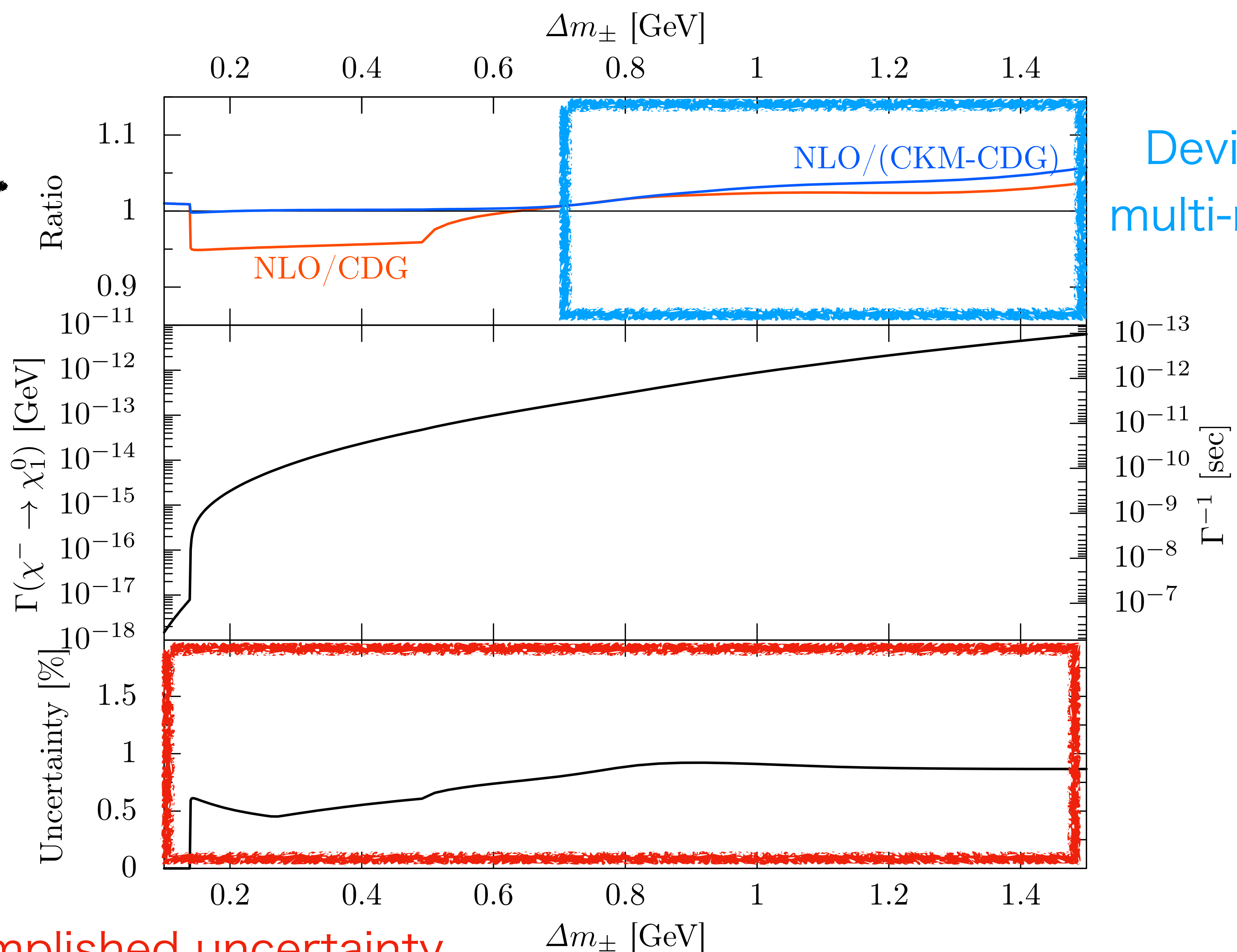
Summary Plots

Comparison with Chen, Drees, and Gunion (CDG) [hep-ph/9607421]



Deviation due to multi-meson modes

Accomplished uncertainty below 1% for mass range of interest

(Errors in each mode is suppressed by its branching fractions)

Summary

- We have computed NLO decay rates in compressed region, where has not been addressed yet in literatures
- We estimated the short- and long-distance correction to the various decay modes
- The error in estimation of decay rate is smaller than 1% for $\Delta m_{\pm} \lesssim 1\,\mathrm{GeV}$