SUSY Conference 2023

Precise Estimate of Chargino Decay

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Based on

JHEP 01 (2023) 017 (arXiv: 2210.16035)

and work in progress

In Collaboration with

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July 19th, 2023, University of Southampton

Plan of Talk

1. Introduction
2. Wino Decay and Mass Difference
3. EW Corrections in Single Pion Mode
4. Results and Summary

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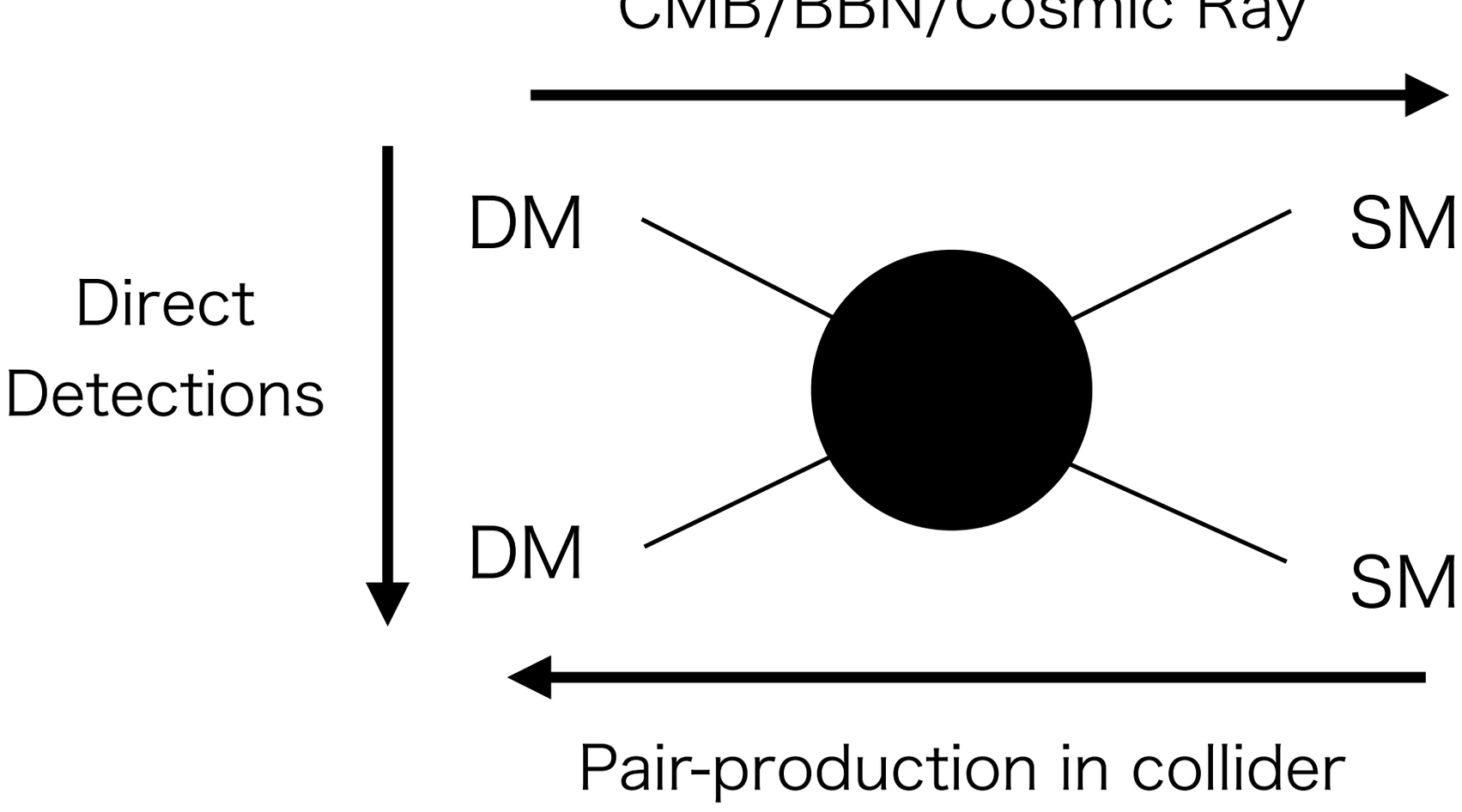
Dark Matter in SUSY

- The MSSM contains an attractive candidate of freeze-out DM
- The supersymmetric DM can be tested with experiments in various way



Wino and Higgsino

Wino

- $\mathrm{SU}(2)_L$ triplet
- Zero hypercharge
- One charged Dirac
  + One neutral Majorana

Higgsino

- $\mathrm{SU}(2)_L$ doublet
- $Y = \pm 1/2$
- One charged Dirac
  + Two neutral Majorana

Today's discussion

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1. Introduction

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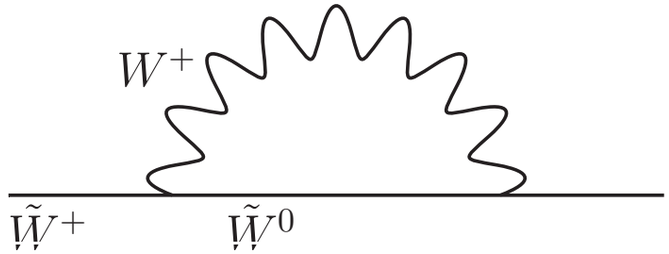
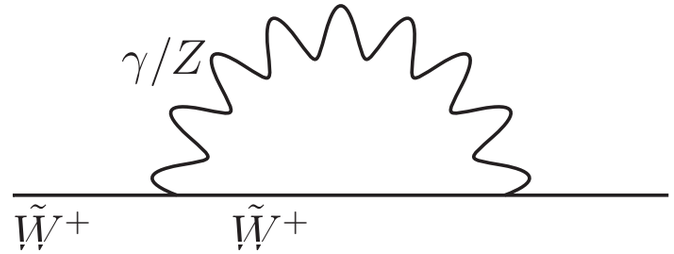
Mass Splitting and Decay

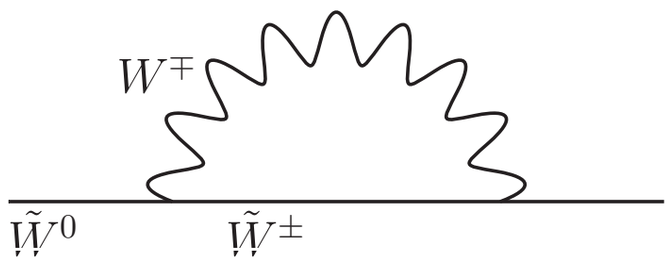
- The charged Wino becomes heavier than the neutral one because of EW radiative corrections
- At one-loop level,

Charged Wino



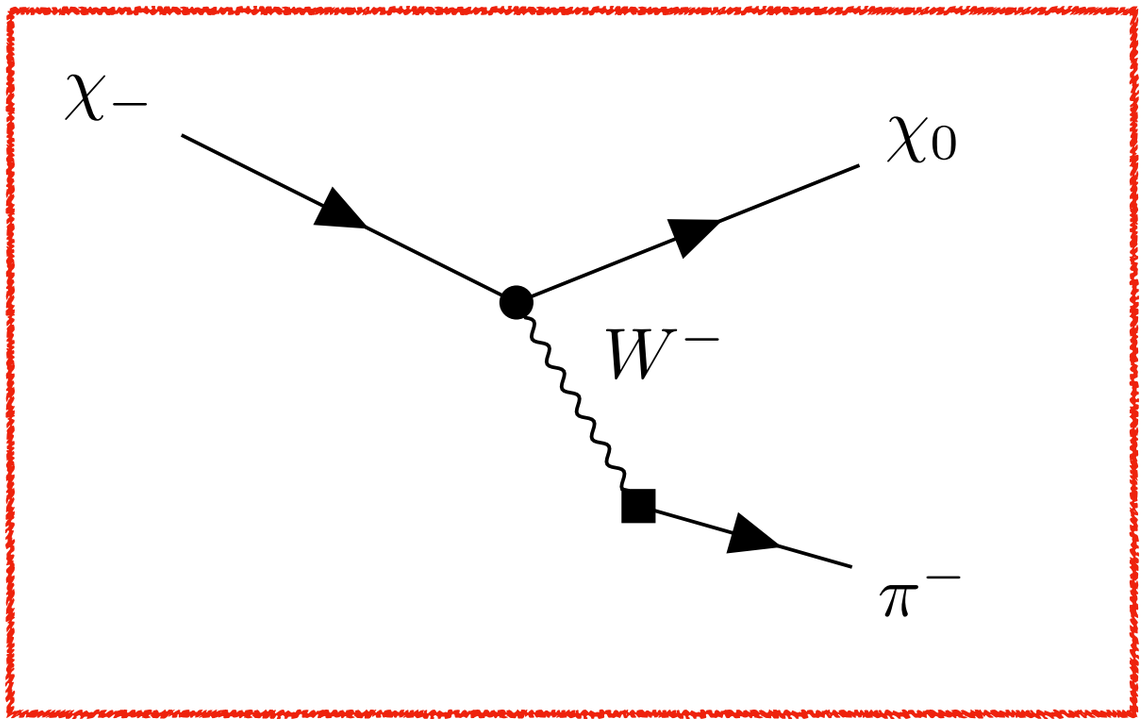


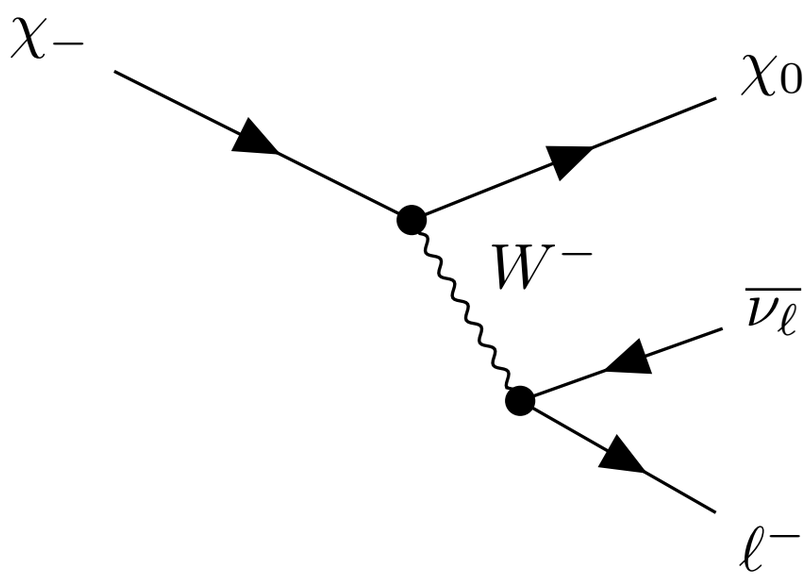
Neutral Wino



Mass Splitting and Decay

- The charged Wino can decay into the lighter neutral Wino through weak interaction

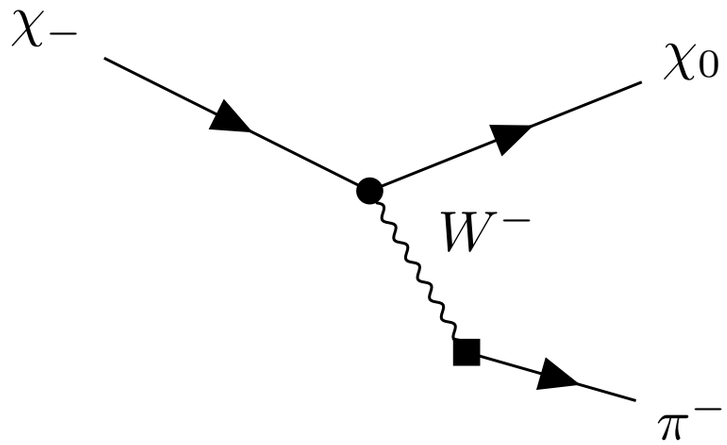




Dominant for $\Delta m \sim 160\,\mathrm{MeV}$

Mass Splitting and Decay

- The theoretical prediction of the charged Wino decay rate is very sensitive to the mass difference

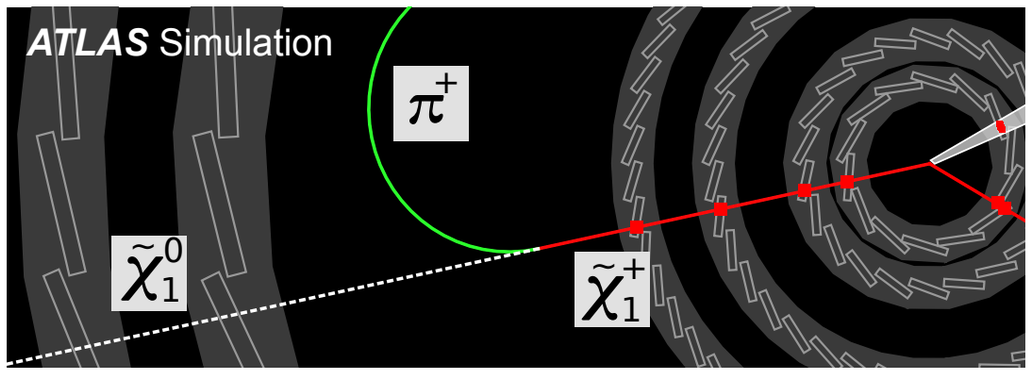


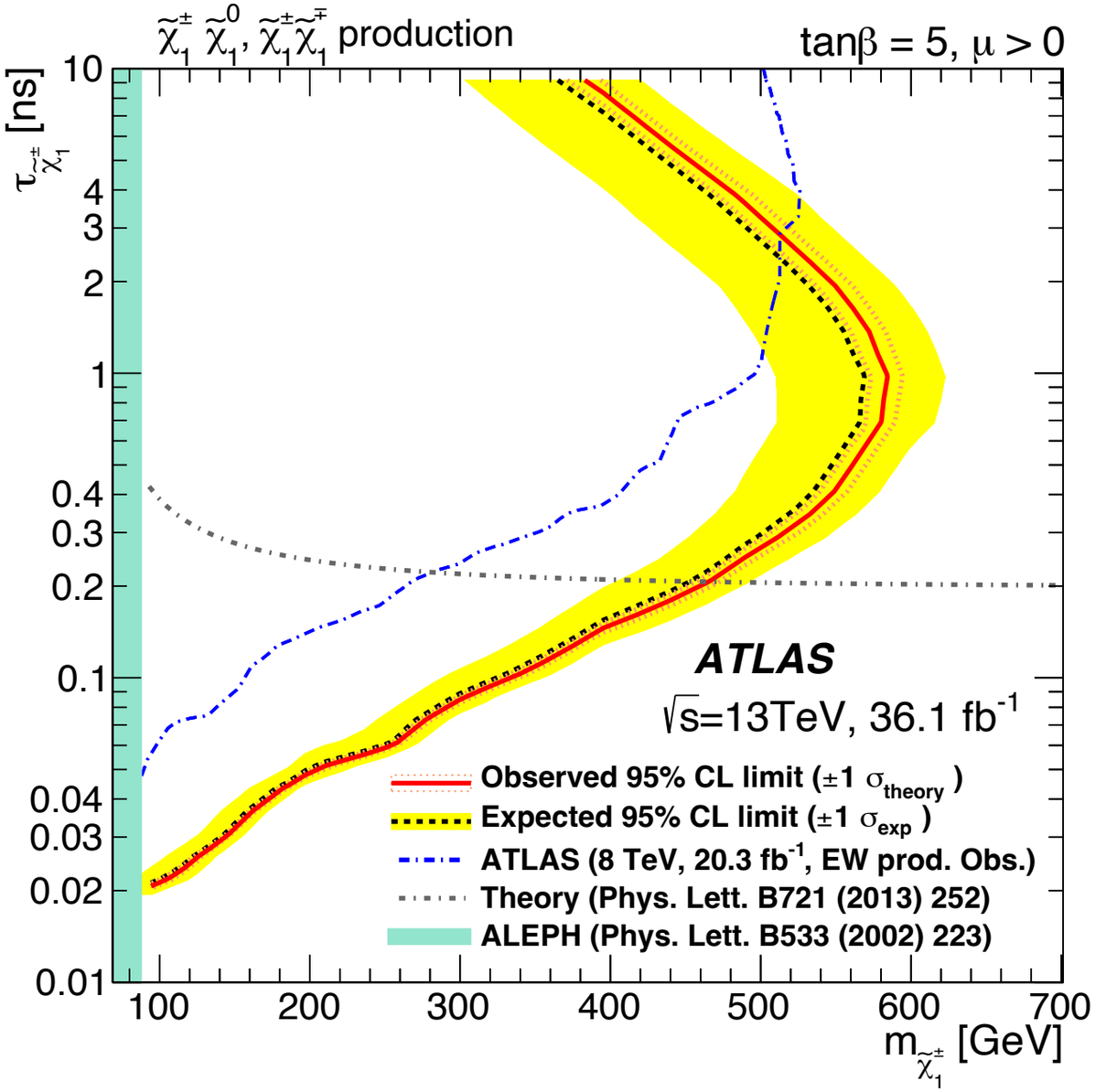
$$\Gamma_{\mathrm{tree}}(\chi^- \to \pi^- + \chi^0) \simeq \frac{4}{\pi} F_\pi^2 (G_\pi^0)^2 \Delta m^3 \left(1 - \frac{m_\pi^2}{\Delta m^2}\right)^{1/2}$$

2% error in $\Delta m \rightarrow$ about $3 \times 2\,\% \simeq 6\,\%$ in the decay rate

Experimental Constraint

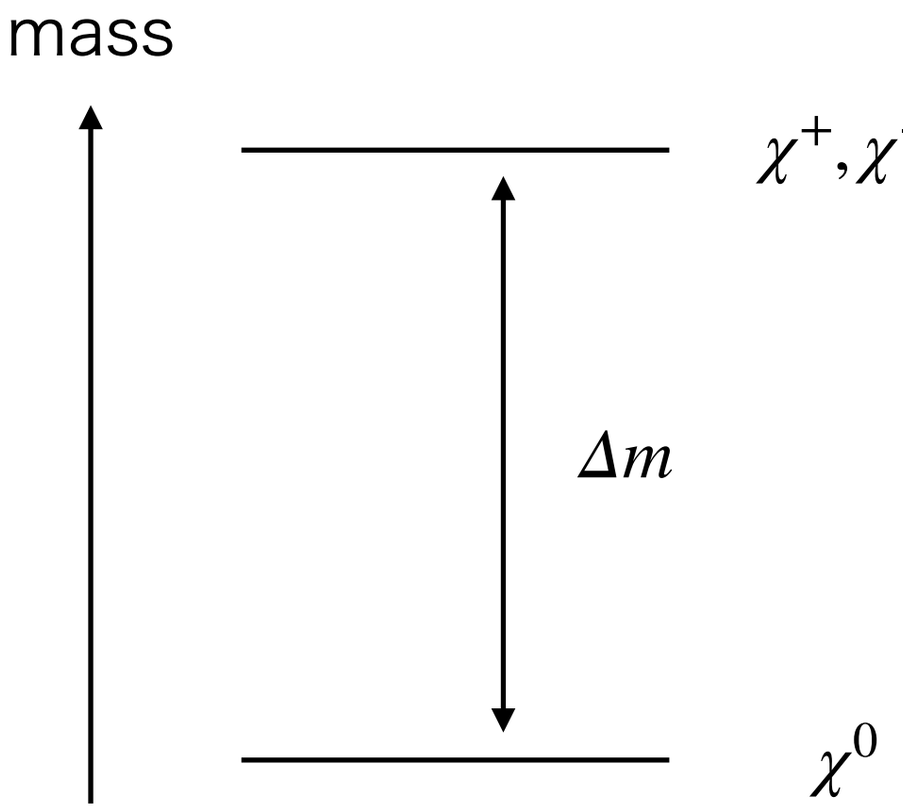
- Collider constraint on the Wino mass strongly depends on the rate of the single pion mode

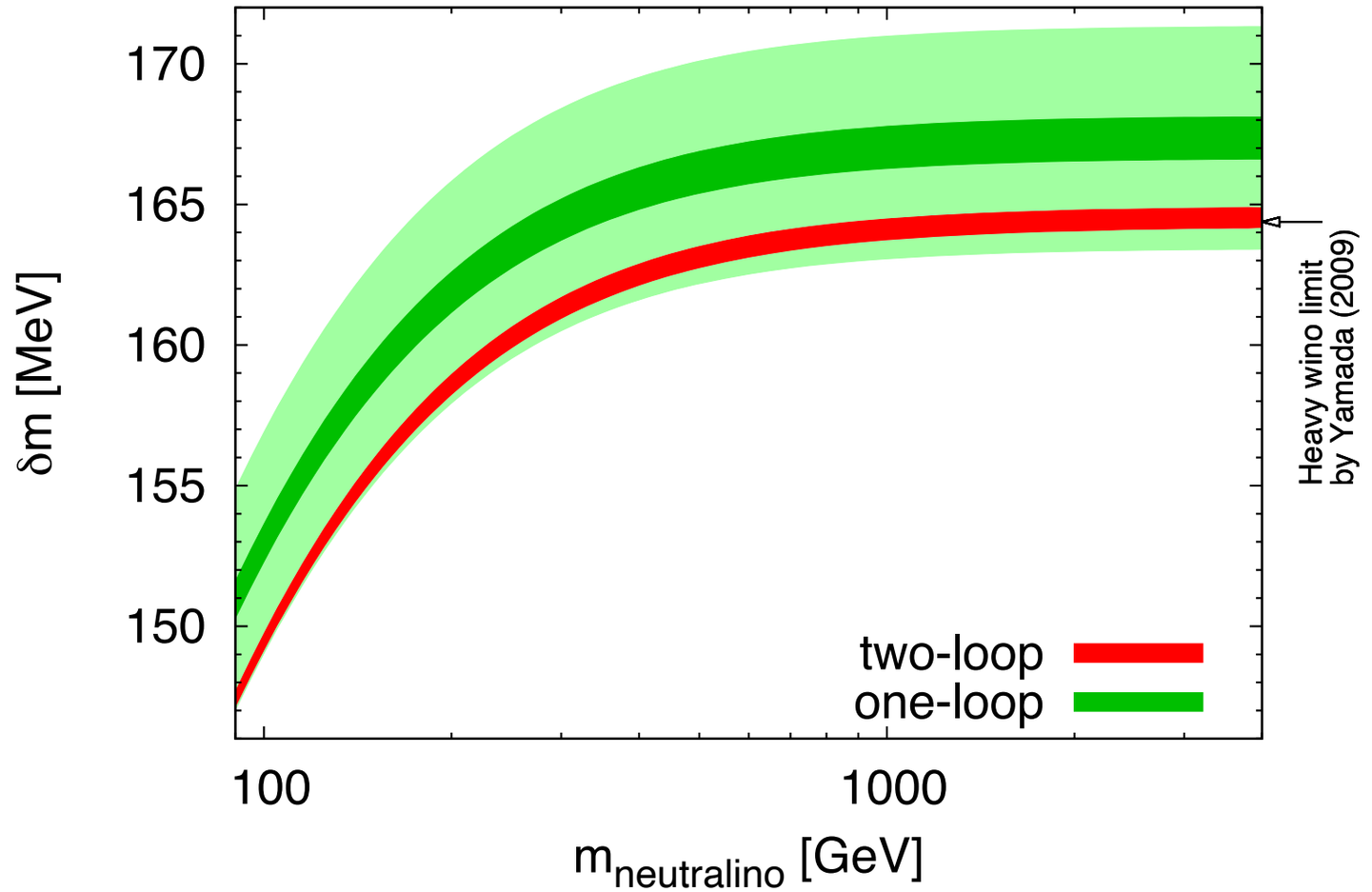




NNLO Wino Mass Difference

- Actually in literature the mass difference of SU(2) triplet has already been computed in two-loop level!





[M. Ibe, R. Sato, S. Matsumoto, Phys. Lett. B 721 (2013) 252-260]

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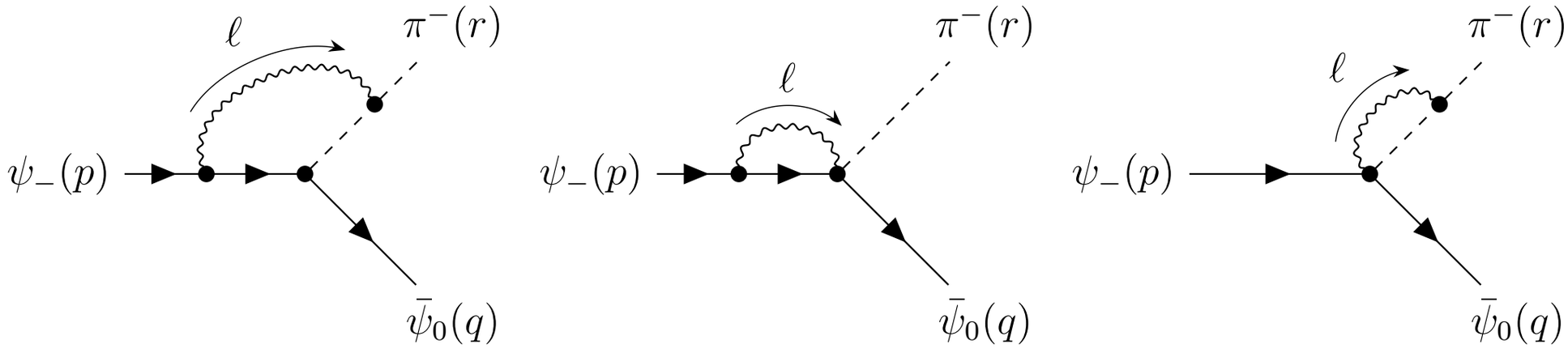
Remaining Corrections

How about EW corrections to the decay process itself?



Scales of the problem

$$m_\chi \gg m_W \gg \Delta m \gtrsim m_\pi$$

Question

Is there large contribution such as $\log(m_\chi/m_\pi)$?

How are experimental constraint changed?

Violation of Shift Symmetry

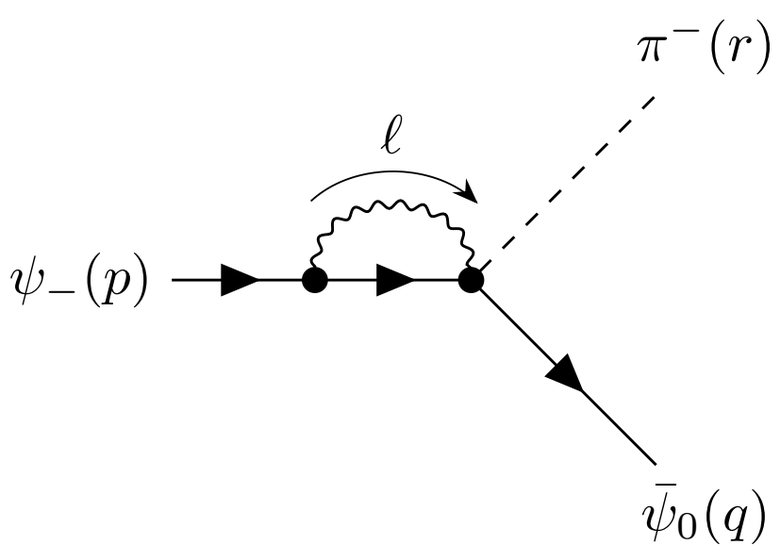
Pion's shift symmetry ensures that the decay amplitude is suppressed by Δm

$$\mathcal{L}_{\mathrm{Wino-Pion}} = -2\sqrt{2} f_\pi G_\pi^0 (\partial_\mu \pi^-) \times (\bar{\psi}_- \gamma^\mu \psi_0) + \mathrm{h.c.}$$

$$p \sim \Delta m$$

But QED corrections break the symmetry:

$$\partial_\mu \to D_\mu = \partial_\mu - ieA_\mu$$



mass correction to the Wino

$m_\chi/\Delta m$ enhancement???

→ Cured by appropriate determination of CTs

Computational Scheme

Matching procedure à la Descotes-Genon and Moussallam

[S. Descotes-Genon and B. Moussallam, Eur. Phys. J. C 42, 403 (2005)]

EW theory w/ Wino

$$\mathscr{L} = \mathscr{L}_{\mathrm{EW}} + \mathscr{L}_{\mathrm{Wino}}$$

Match free-quark decay rate

$\Gamma(\chi^- \to \chi^0 + \bar{u} + d)$ @ 1-loop

Four-Fermi theory w/ Wino

$$\mathscr{L} = \mathscr{L}_{\mathrm{Four-Fermi}} + \mathscr{L}_{\mathrm{Wino}} + \mathscr{L}_{\mathrm{CT}}$$

ChPT w/ Wino

$$\mathscr{L} = \mathscr{L}_{\mathrm{ChPT}} + \mathscr{L}_{\mathrm{Wino}} + \mathscr{L}_{\mathrm{CT}}$$

Match the “current correlator”
@ 1-loop

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Single Pion Mode (pure-Wino)

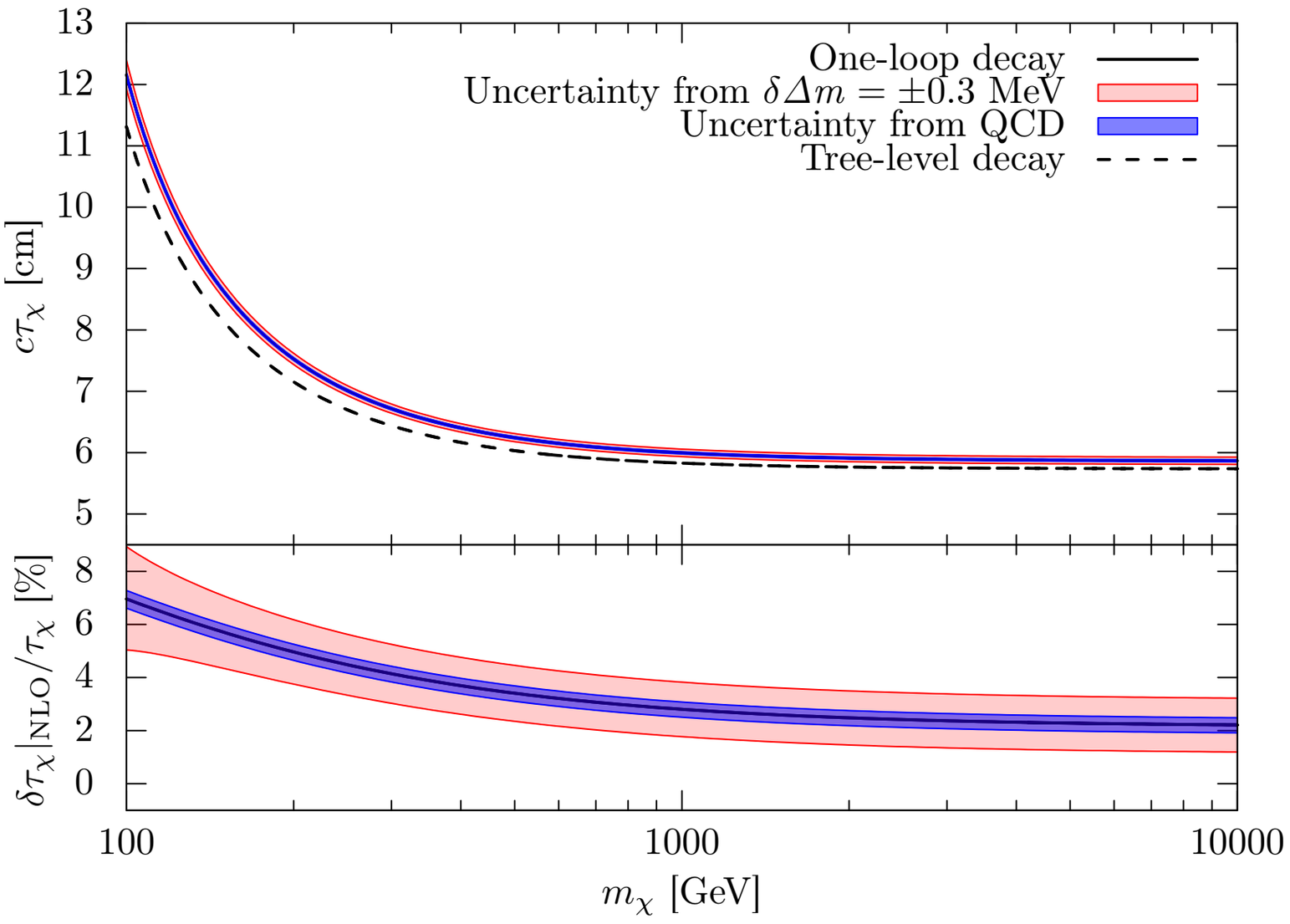
In total, ~ 0.03

$$\Gamma = \Gamma_{\rm tree}\left\{1 + \frac{\alpha}{4\pi}\left[\sum_{n<0} c^{(n)}\left(\frac{\Delta m}{m_\chi}\right)^n + c^{(\log)}\log\left(\frac{m_\chi}{\Delta m}\right) + \sum_{n=0}^{\infty} c^{(n)}\left(\frac{\Delta m}{m_\chi}\right)^n\right]\right\}$$

Exactly canceled by CT

Canceled between
various contributions

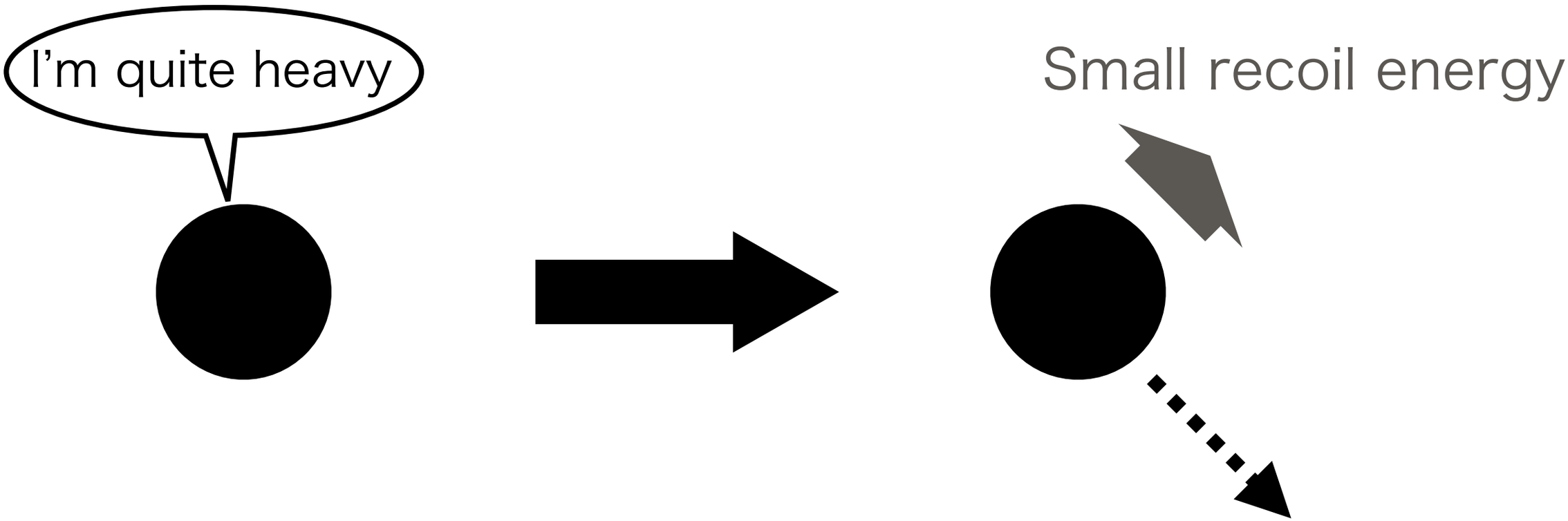
Single Pion Mode (pure-Wino)



- Apart from uncertainties, Wino decay length become around 2-7% longer, depending on m_χ
- Radiative correction tends to be a constant as $m_\chi \to \infty$
- The 3-loop effect on Δm dominates the uncertainty

$$\delta\tau_\chi|_{\rm NLO} \equiv \tau_\chi|_{\rm NLO} - \tau_\chi|_{\rm LO}$$

A New Theorem?

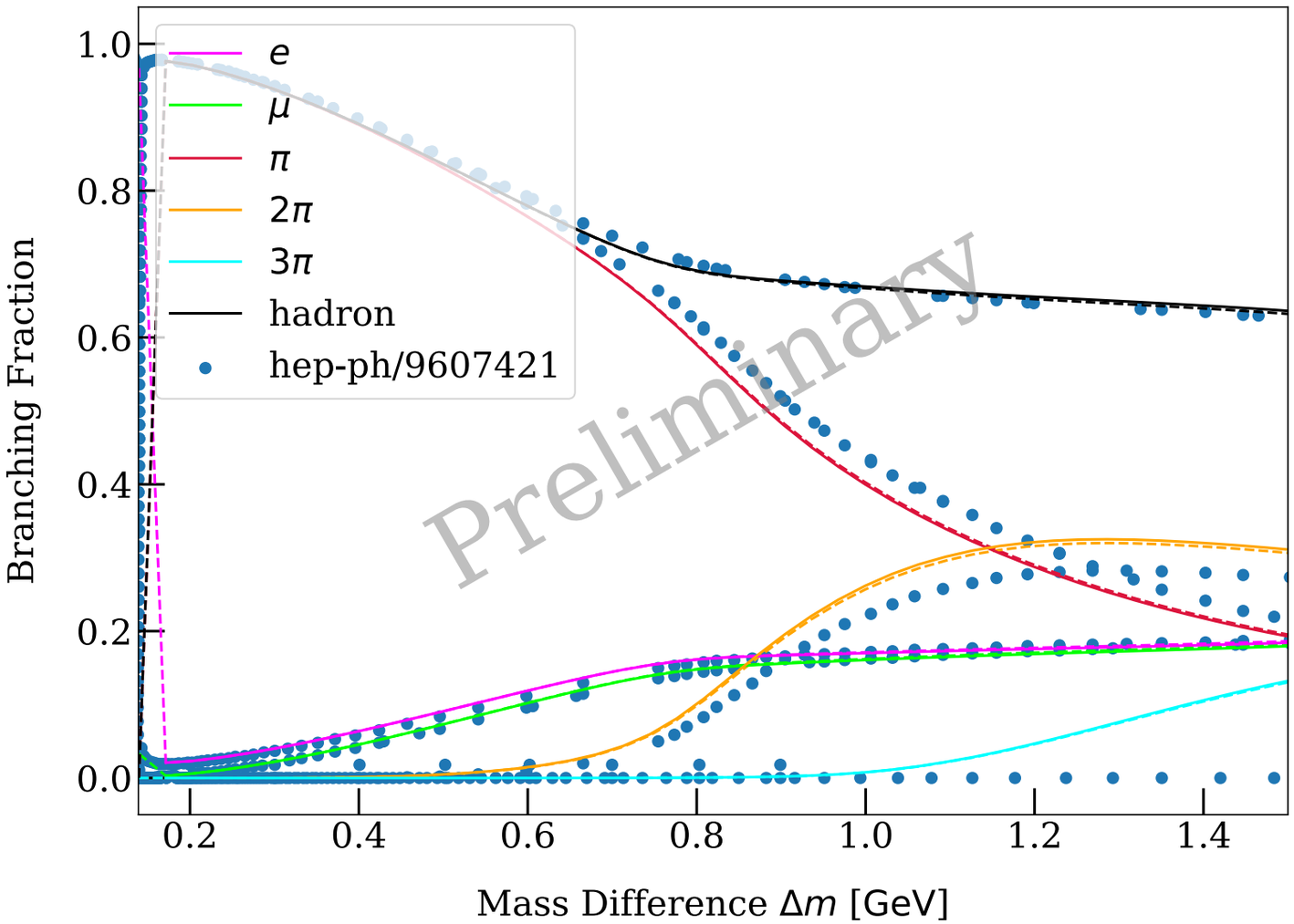


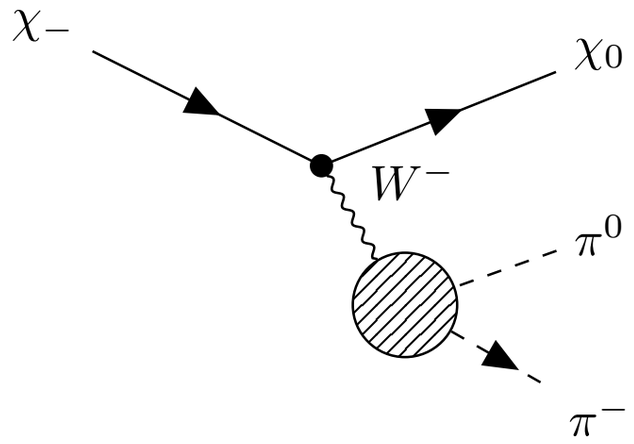
$$\Gamma = \sum_{n<0} \left(\frac{\Delta m}{m_\chi}\right)^n \Gamma^{(n)} + \log\left(\frac{m_\chi}{\Delta m}\right)\Gamma^{(\log)} + \sum_{n=0}^{\infty} \left(\frac{\Delta m}{m_\chi}\right)^n \Gamma^{(n)}$$

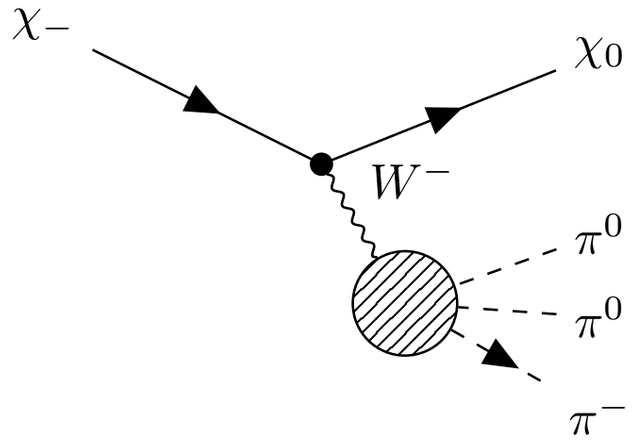
should be zero at all order of α

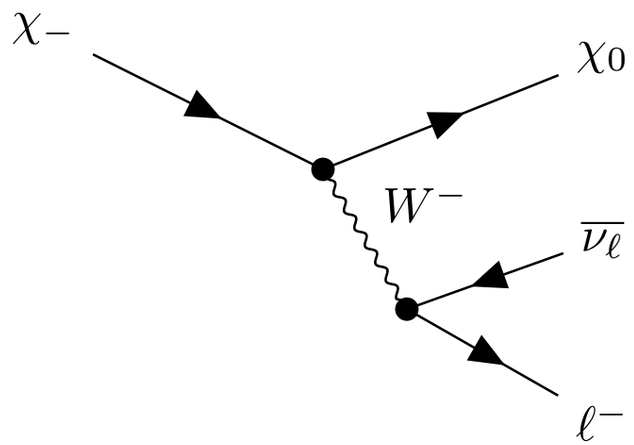
Comment on Higgsino Case

Higgsino has larger mass difference,
so various modes should be considered
Updating the previous work in progress









Summary

- We computed the single pion mode at EW one-loop;
  and obtained O(1)% correction with 0.5% th. error

- No $m_\chi/\Delta m$ or $\log m_\chi$ enhancement at one-loop level;

  We conjecture that heavy external particles decouple
  from physical quantities at any order,
  although it has not been proofed rigorously

- Higgsino can decay into heavier state due to
  the larger mass difference.
  Stay tuned for our numerical estimate of Higgsino decay!

Back up

Mass Splitting

Chargino-neutralino mass matrices

$$M_{\tilde{N}} = \begin{pmatrix} M_1 & 0 & g_1\langle H_d^0\rangle/\sqrt{2} & -g_1\langle H_u^0\rangle/\sqrt{2} \\ 0 & M_2 & -g_2\langle H_d^0\rangle/\sqrt{2} & g_2\langle H_u^0\rangle/\sqrt{2} \\ g_2\langle H_d^0\rangle/\sqrt{2} & -g_2\langle H_d^0\rangle/\sqrt{2} & 0 & \mu \\ -g_2\langle H_u^0\rangle/\sqrt{2} & g_2\langle H_u^0\rangle/\sqrt{2} & \mu & 0 \end{pmatrix}$$

$$X = \begin{pmatrix} M_2 & -g_2\langle H_u^0\rangle \\ -g_2\langle H_d^0\rangle & -\mu \end{pmatrix}$$

induce tree-level mixing and mass splittings:

$$\mathcal{L}_{\mathrm{MSSM}} \supset g_2 W_\mu^- \left(\bar{\Psi}_\chi^-\right)_i \gamma^\mu \left(O_{ij}^L P_L + O_{ij}^R P_R\right) \left(\Psi_\chi^0\right)_j$$

$$m_{\tilde{N}_1} < m_{\tilde{N}_2} < m_{\tilde{N}_3} < m_{\tilde{N}_4}, \;\; m_{\tilde{C}_1} < m_{\tilde{C}_2}$$

Computational Scheme

The counterterm contribution to the Wino decay rate

Cancels the Δm enhancement

$$\left.\frac{\delta\Gamma_\chi}{\Gamma_\chi}\right|_{K,Y} = e^2\left[\frac{8}{3}(K_1+K_2)+\frac{20}{9}(K_5+K_6)+4K_{12}\right.$$
$$\left.-\hat{Y}_6-\frac{4}{3}(Y_1+\hat{Y}_1)-4\left(Y_2+\hat{Y}_2-\frac{m_\chi}{\Delta m}Y_3\right)\right]$$

Matching with the FF theory

(Pole of ChPT) + (Finite part of the FF theory's CT)

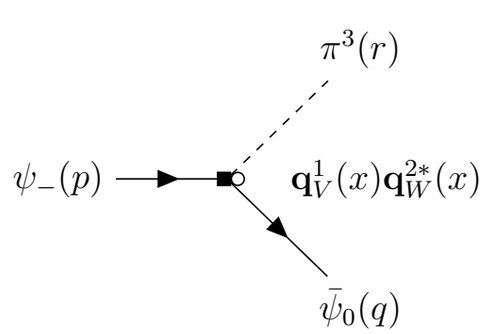
Matching with the EW theory

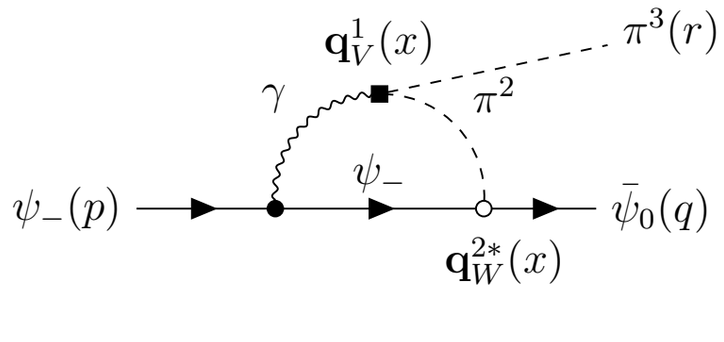
(Pole of ChPT) + (The EW theory's input parameters)

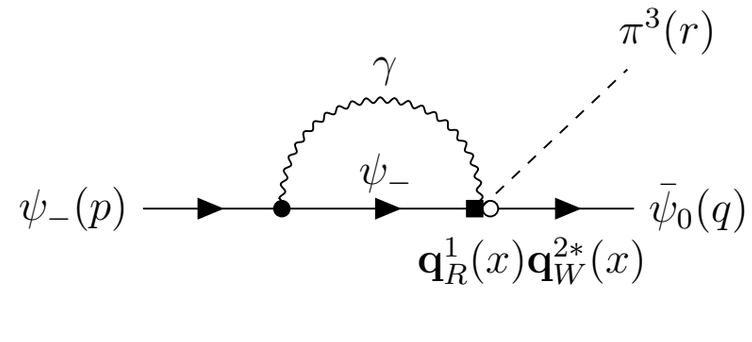
FF-ChPT Matching

Matching example $\langle 0|T\psi_-(x)\bar{\psi}_0(y)\pi^3(x)|0\rangle$

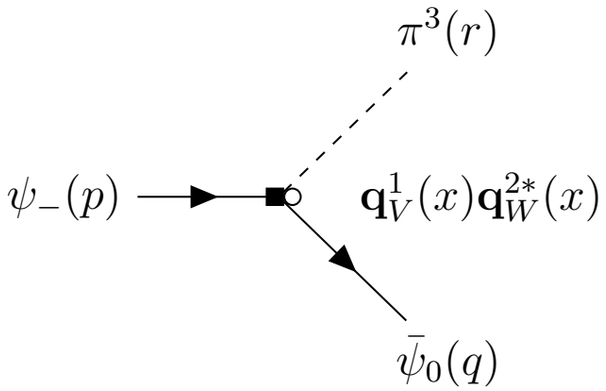
- In the ChPT w/ Wino:

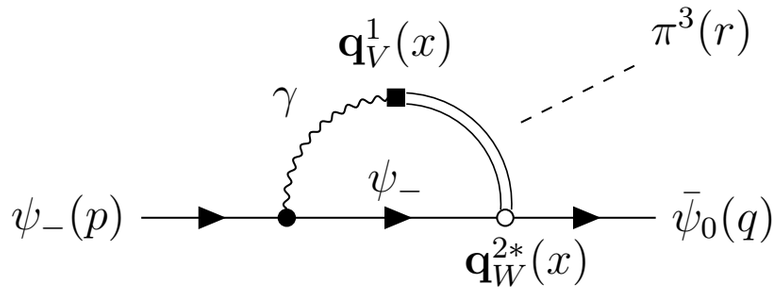






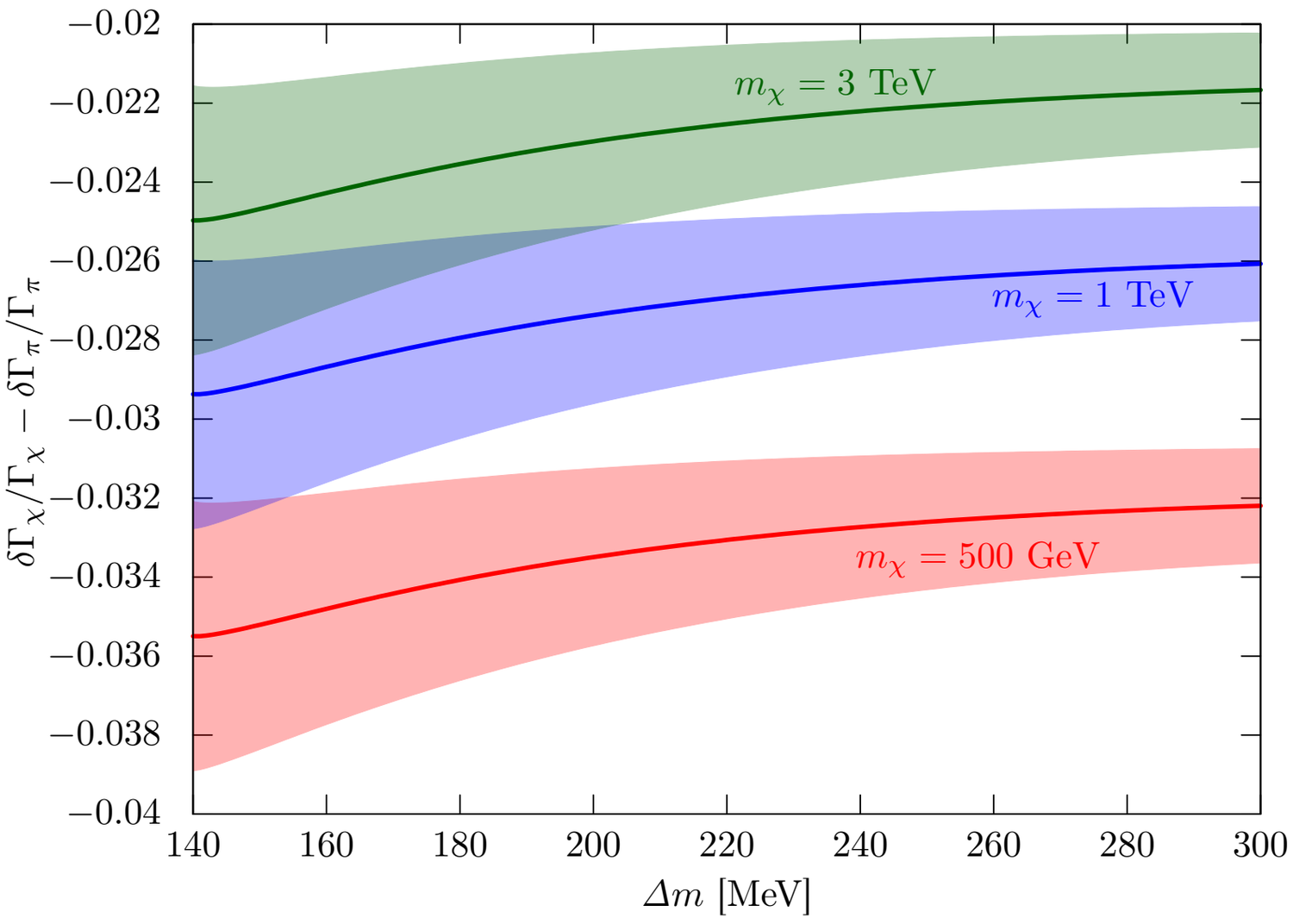
- In the FF theory w/ Wino:





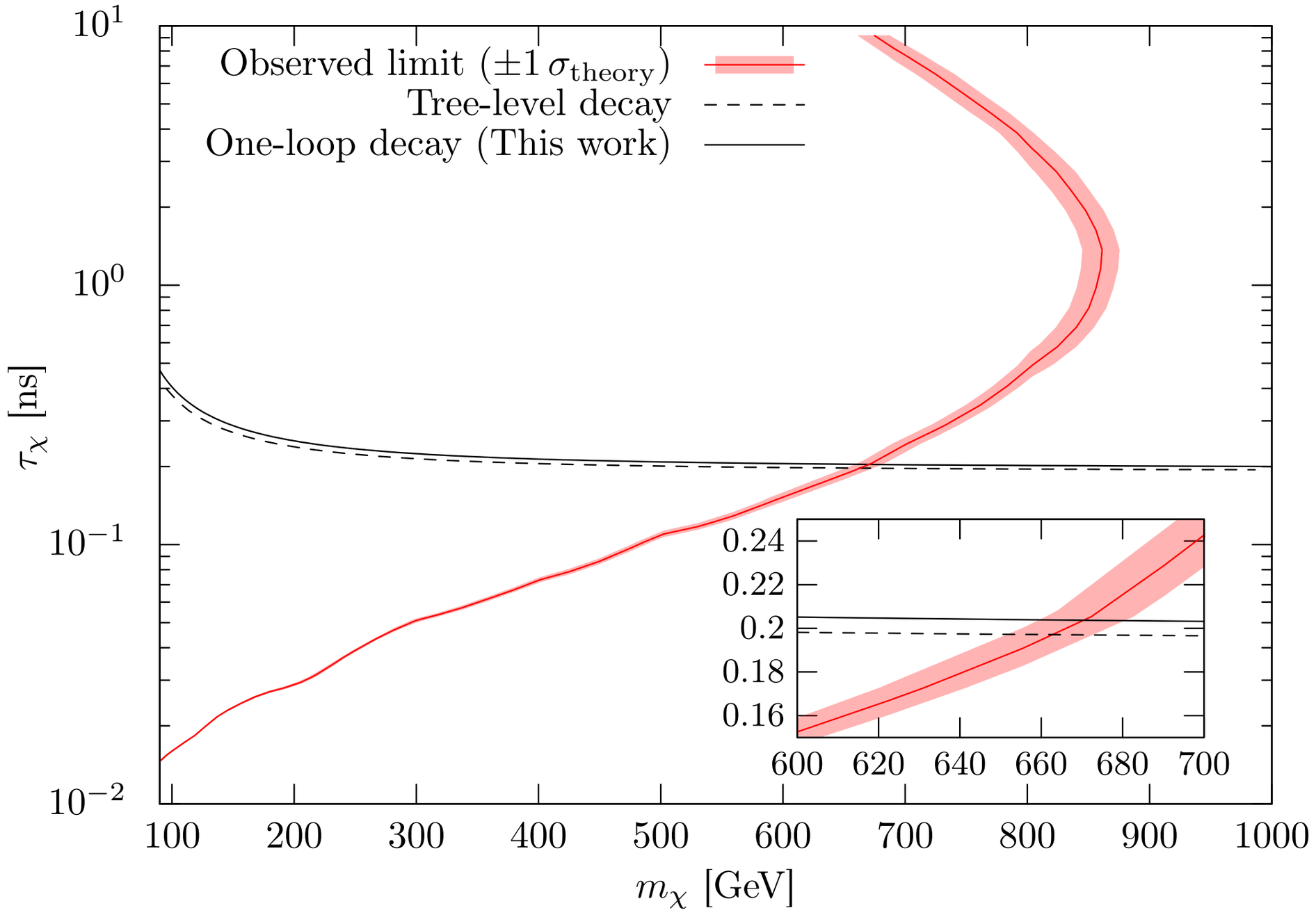
requires $\langle \pi^a(r)|TJ_V^{b\mu}(x)J_A^{c\nu}(0)|0\rangle$

Theory Error



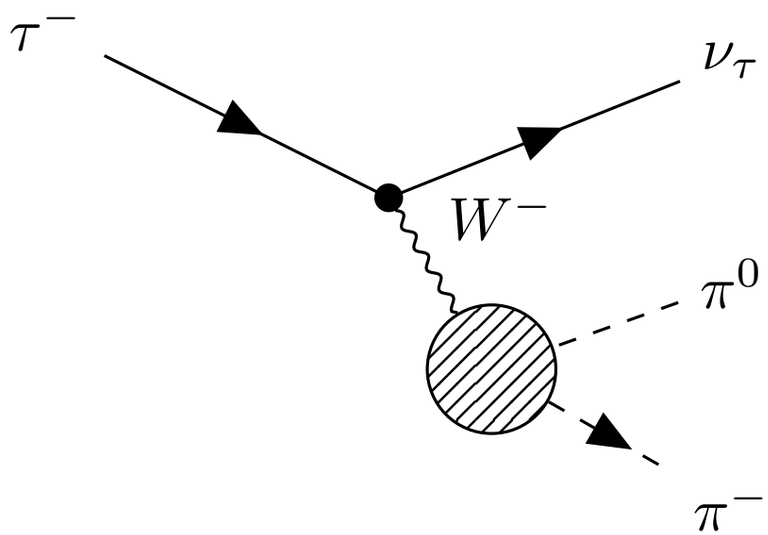
- Each band represents uncertainty from the minimal resonance model
- In the pure Wino theory, $\Delta m \sim 163 - 165\,\mathrm{MeV}$ for $m_\chi > 600\,\mathrm{MeV}$
- For this mass difference, one-loop contribution reduces Γ_χ/Γ_π about 2-4%

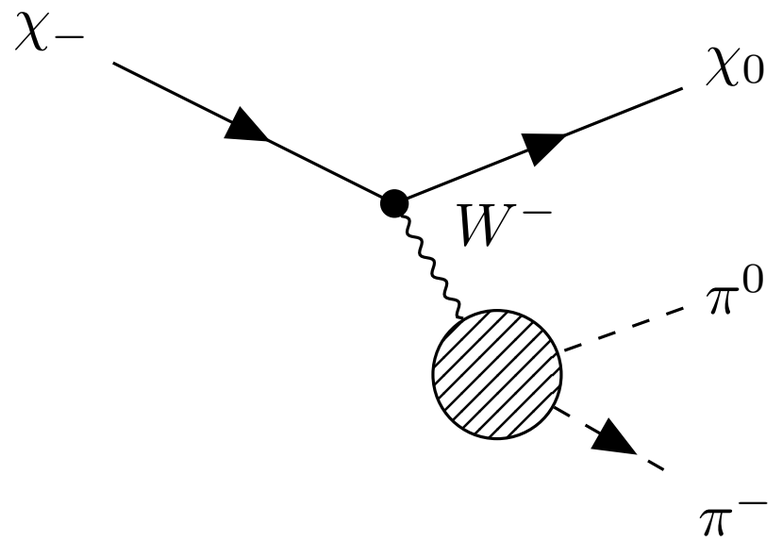
Updated ATLAS Constraint



Treatment of Hadronization

We have very similar decay process; tau decay





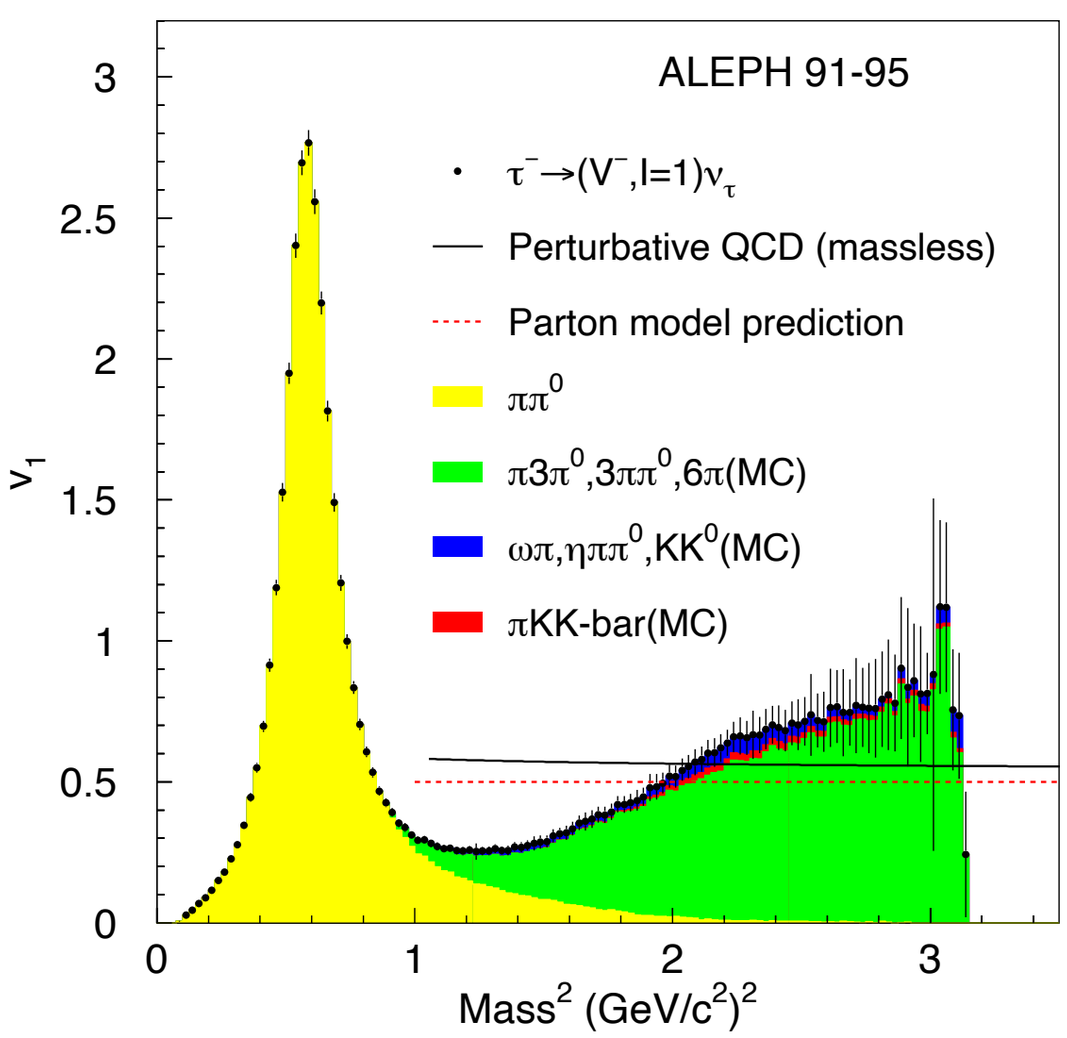
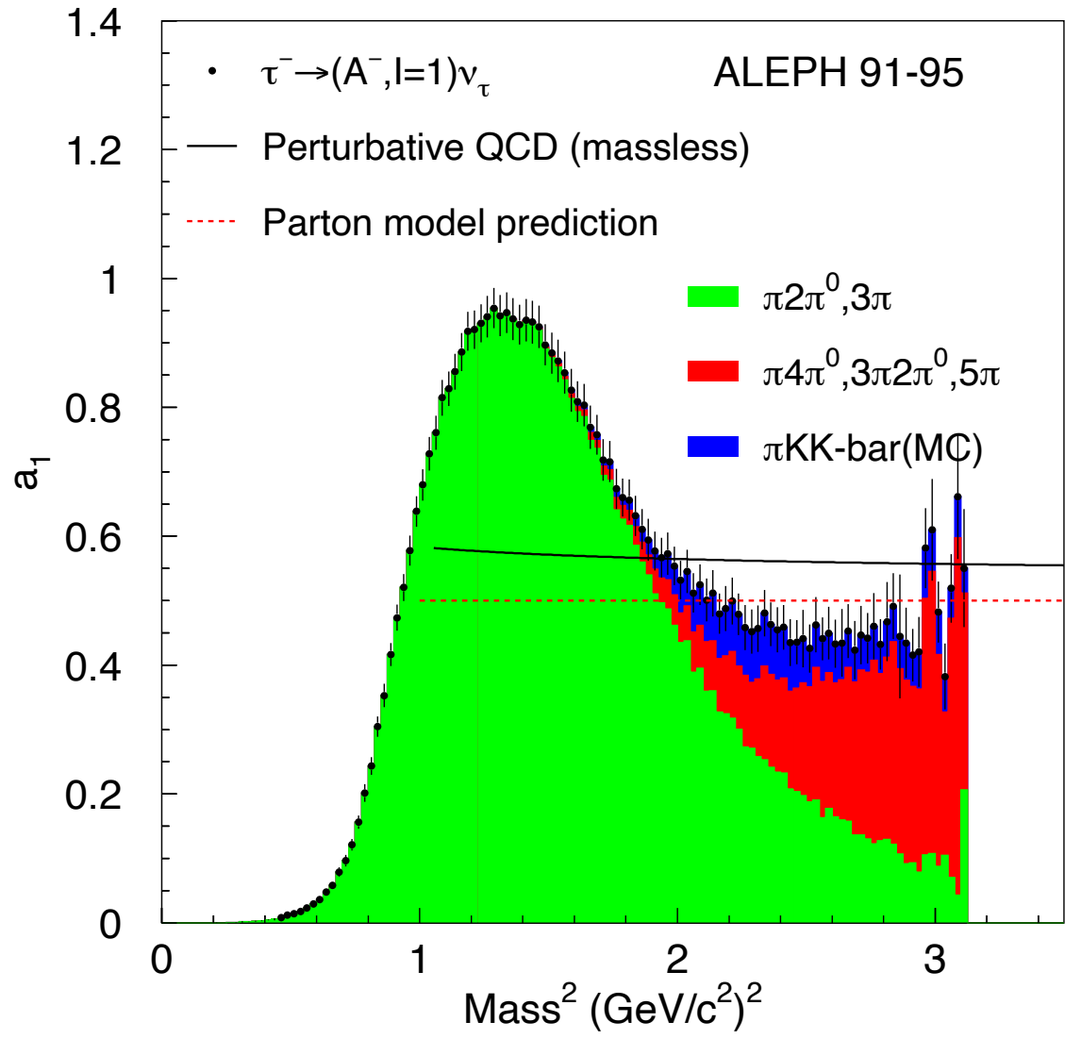
Extract
mass distributions

$$\langle \pi^- \pi^0 | \bar{d} \gamma^\mu u | 0 \rangle$$

Interpolate
or
parametrize
data

Nonperturbative QCD encoded

Data of Mass Distributions

Experimental data of non-strange spectral functions is available up to tau lepton mass squared

[ALEPH Collaboration, Phys. Rept. 421(2005) 191]