Precise Estimation of Charged Higgsino/Wino Decay Rates

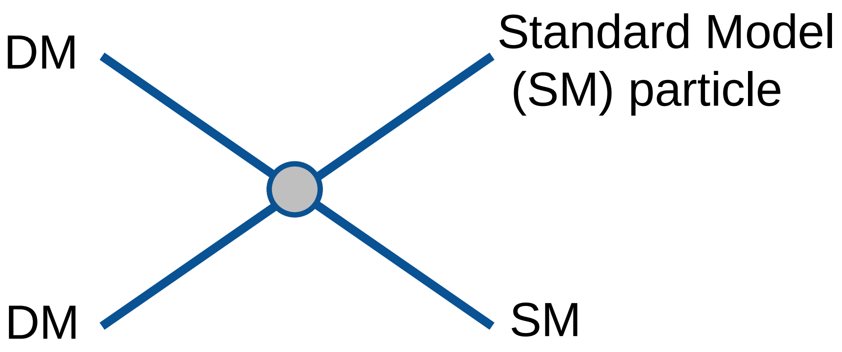
Satoshi Shirai (Kavli IPMU)

Based on arXiv:2210.16035 and 2312.08087 with

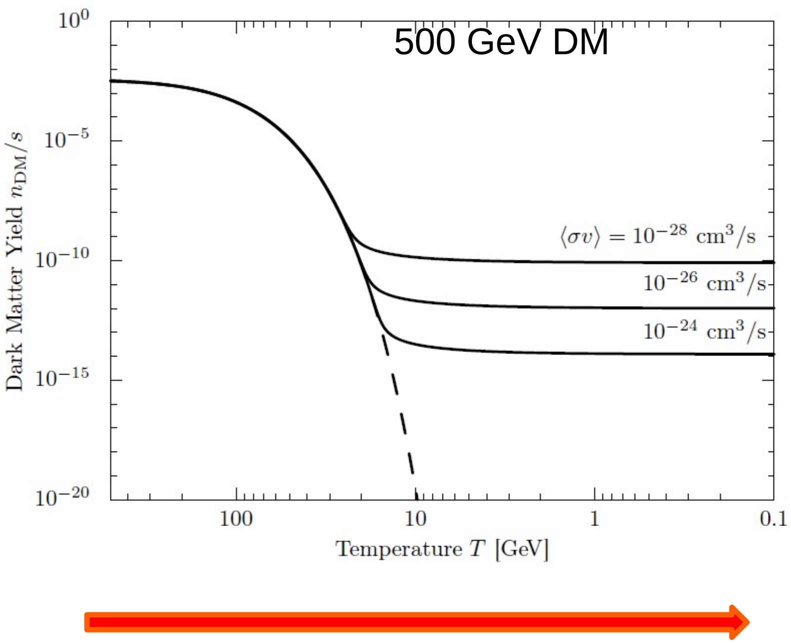
Masahiro Ibe, Masataka Mishima, and Yuhei Nakayama

WIMP Dark Matter

Weakly Interacting Massive Particle



DM abundance



Time

Minimal WIMP Model

Gauge Portal dark matter

- DM charged weak interaction.
- Annihilation via electroweak interaction.
- Wino or Higgsino in SUSY model with R-parity.
- 5plet fermion.

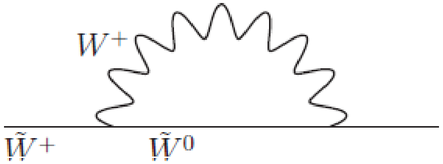
Example: Wino

- Majorana fermion $\widetilde{W}$

- Hypercharge Y=0

- $SU(2)_L$ triplet $\begin{pmatrix} \widetilde{W}^+ \\ \widetilde{W}^0 \\ \widetilde{W}^- \end{pmatrix}$

Wino Spectrum



$\widetilde{W}^{\pm}$

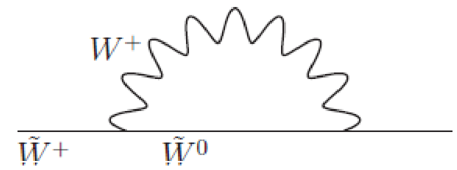
Radiative correction

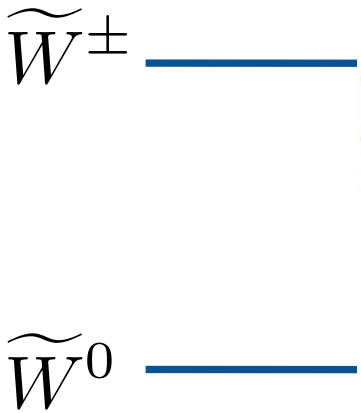
$$\Delta m \simeq 160\ \mathrm{MeV}$$

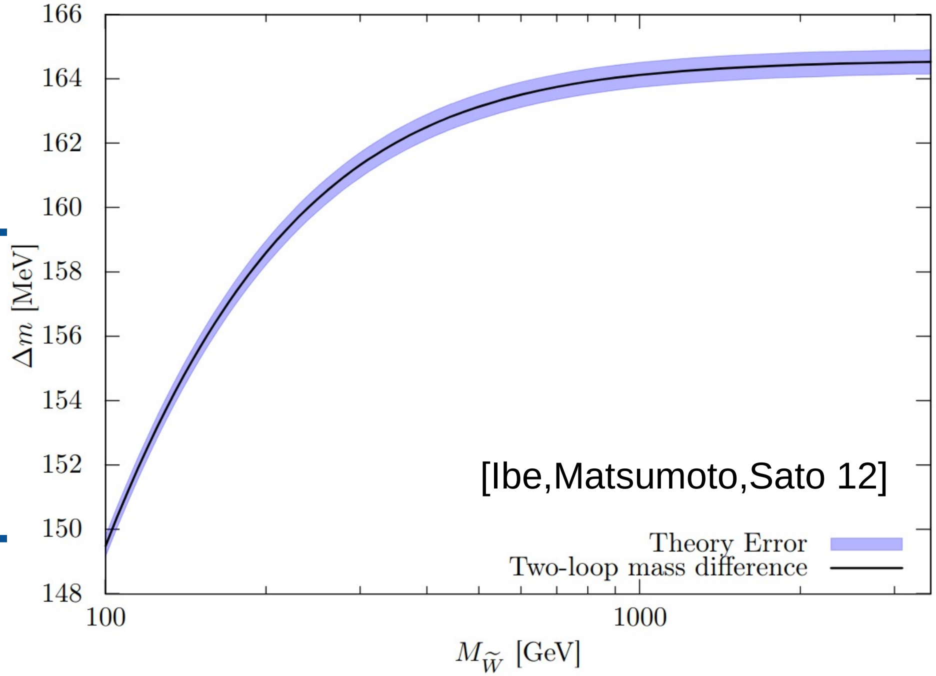
$$\mathcal{O}\left(\frac{\alpha}{4\pi} m_Z\right)$$

$\widetilde{W}^{0}$

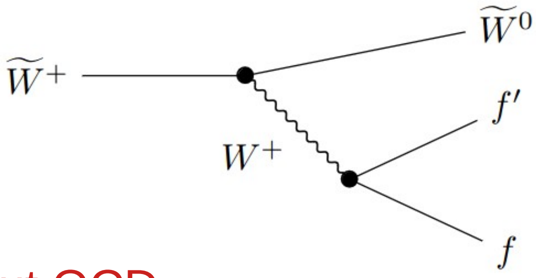
Wino Spectrum







Charged Wino Decay

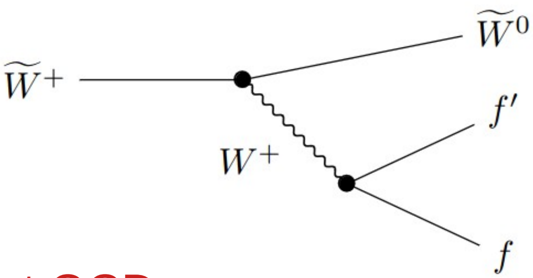


$$\Gamma = \frac{2(G_F)^2 \Delta m^5}{15\pi^3}$$

$$\longrightarrow \quad c\tau \simeq 1\ \mathrm{m} \left(\frac{\Delta m}{160\ \mathrm{MeV}} \right)^{-5}$$

Without QCD

Charged Wino Decay



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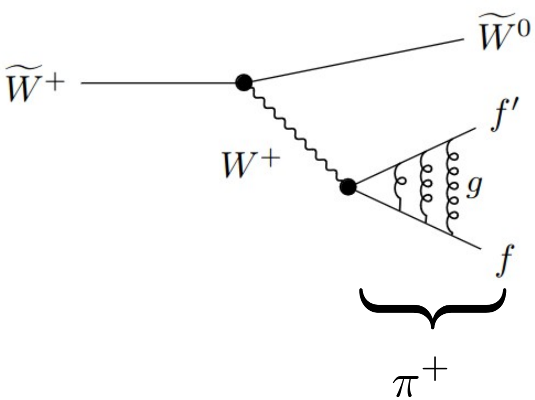
Without QCD

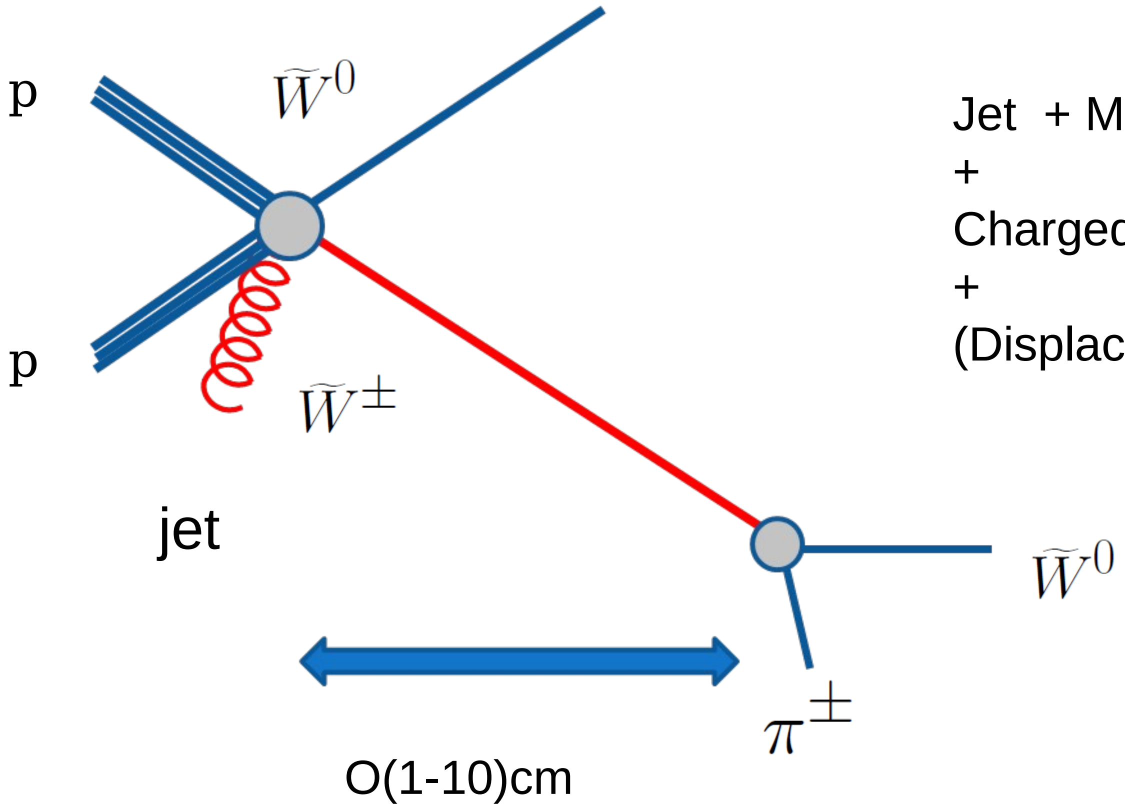
With QCD



$$\Gamma = \frac{4}{\pi} F_\pi^2 (G_F)^2 \Delta m^3 \left(1 - \frac{m_\pi^2}{\Delta m^2}\right)^{1/2}$$

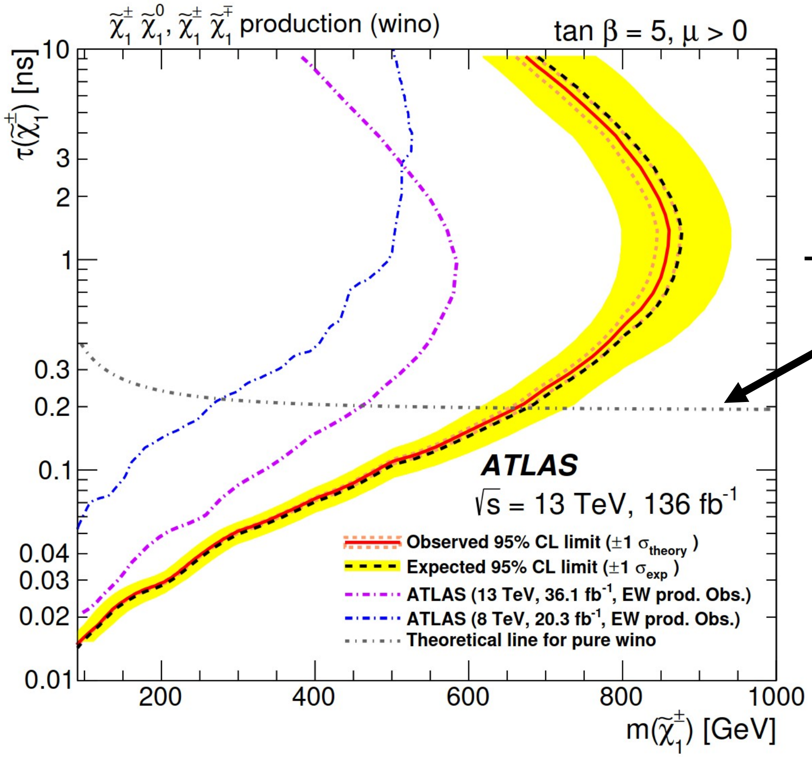
$$\longrightarrow \quad c\tau \simeq 5 \text{ cm} \left(\frac{\Delta m}{160 \text{ MeV}}\right)^{-3}$$

Direct LHC Signals



Jet + Missing energy
+
Charged track
+
(Displaced)Soft pion

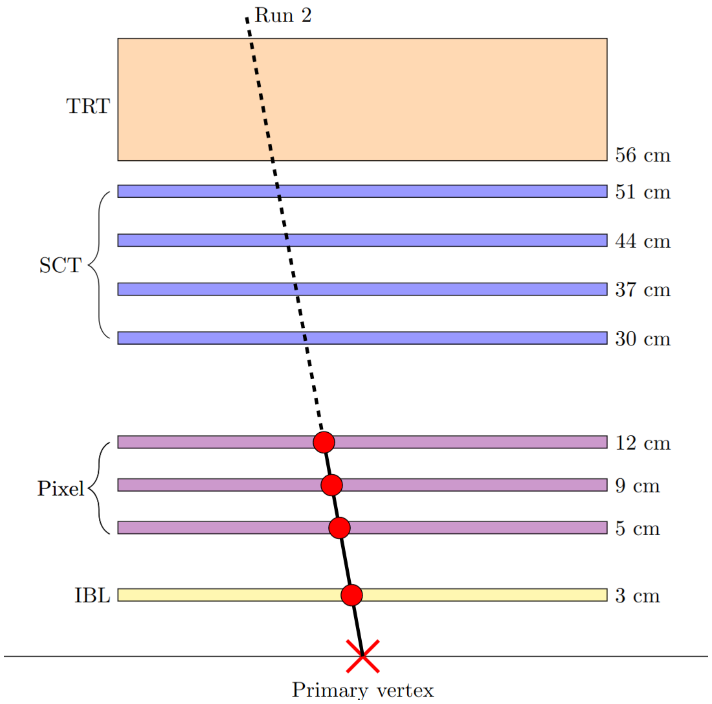
LHC Search



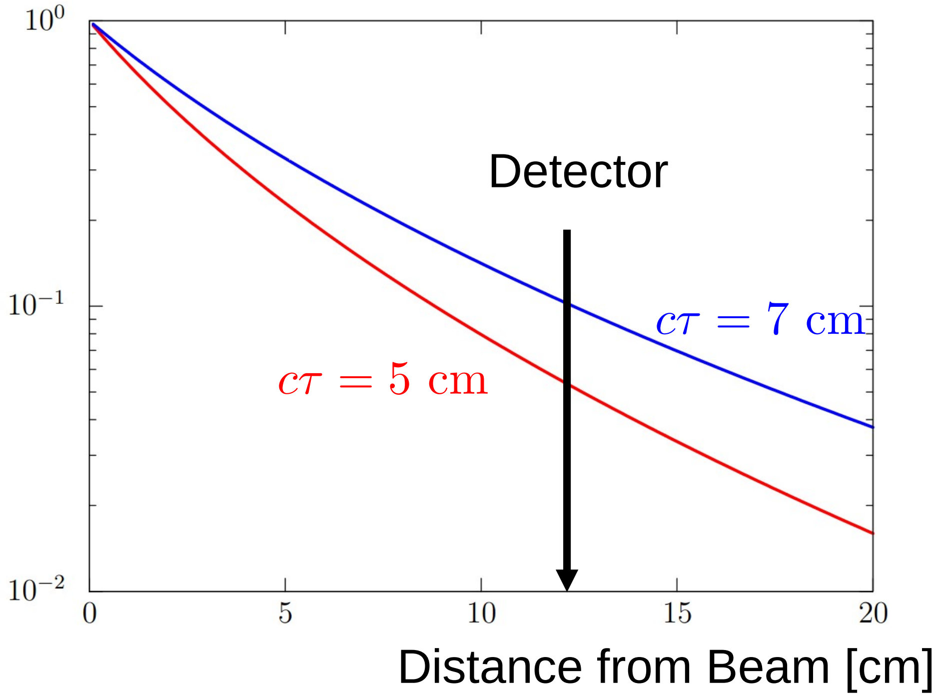
Theory prediction

Decay Rate and Signals

ATLAS detector

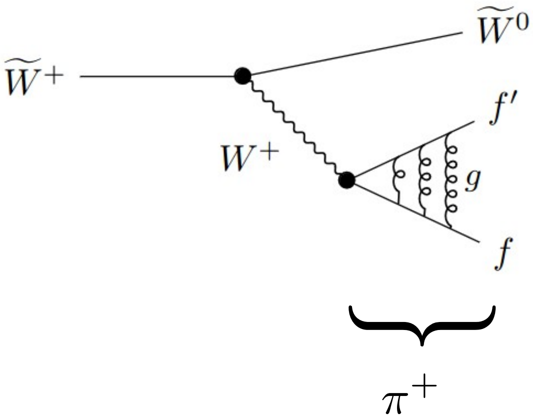


Survival Probability



10% error of lifetime → 50% error of signal.

Tree-level Wino Decay



$$\Gamma = \frac{4}{\pi} F_\pi^2 (G_F)^2 \Delta m^3 \left(1 - \frac{m_\pi^2}{\Delta m^2}\right)^{1/2}$$

$$G_F = \frac{\sqrt{2}}{8} \frac{g^2}{m_W^2}$$

Multi scale problem: $m_{\widetilde{W}} \gg m_W \gg \Lambda_{\rm QCD} \sim \Delta m$

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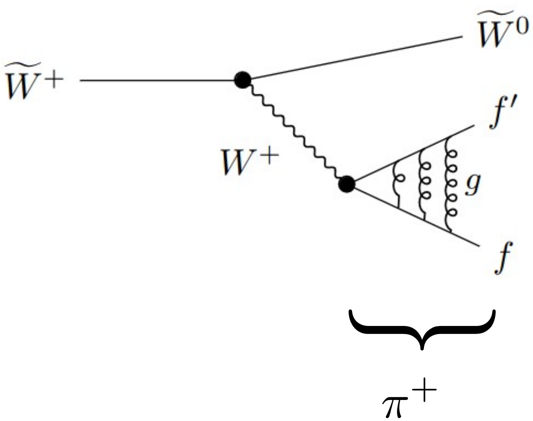

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Multi scale problem: $m_{\widetilde{W}} \gg m_W \gg \Lambda_{\rm QCD} \sim \Delta m$

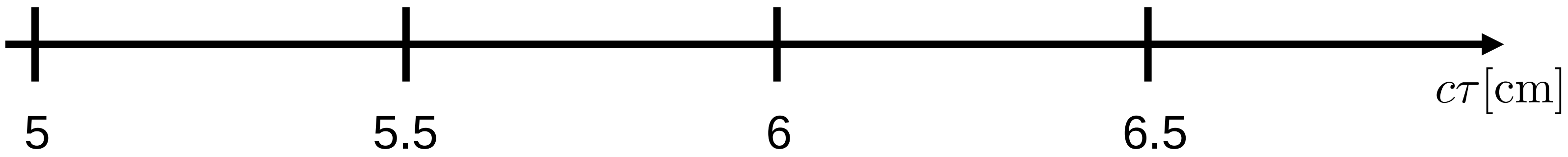
Which gauge coupling should be used?

$g(\mu = m_{\tilde{W}})$, $g(\mu = m_W)$, $g(\mu = \Delta m)$?

Tree-level Wino Decay

1 TeV Wino, Δm = 164.11 MeV

$$G_F \simeq \frac{\sqrt{2}}{8}\frac{g^2}{m_W^2} \simeq \frac{e^2}{4\sqrt{2}s_W^2 m_W^2} \simeq \frac{e^2}{4\sqrt{2}m_W^2}\left(1-\frac{m_W^2}{m_Z^2}\right)^{-1}$$



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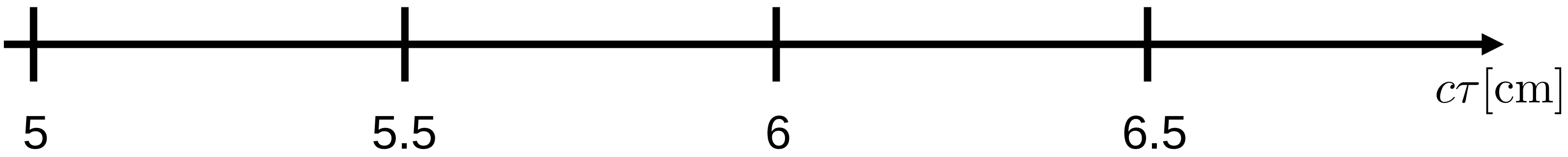
1.166×10^{-5} GeV^{-2} (PDG)

1.211×10^{-5} GeV^{-2} $\alpha(m_Z)=1/128$

1.126×10^{-5} GeV^{-2} $\alpha=1/137$



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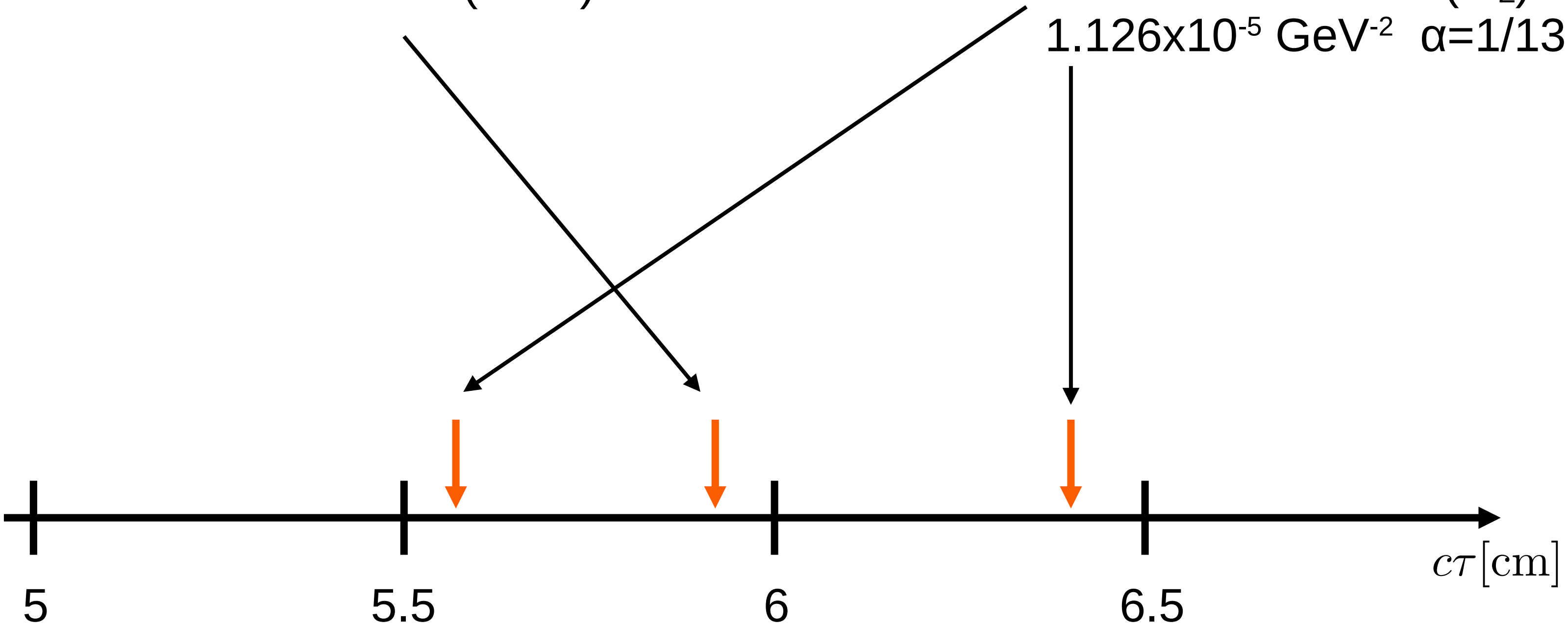

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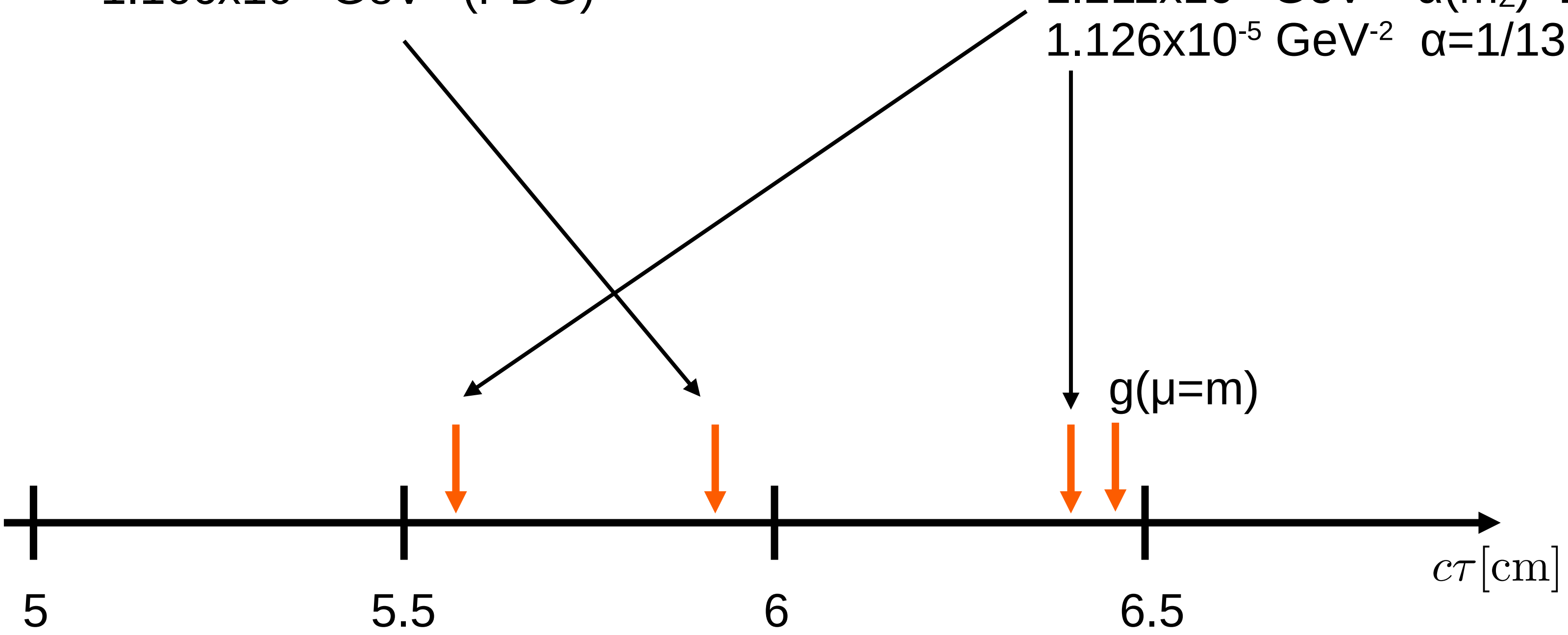

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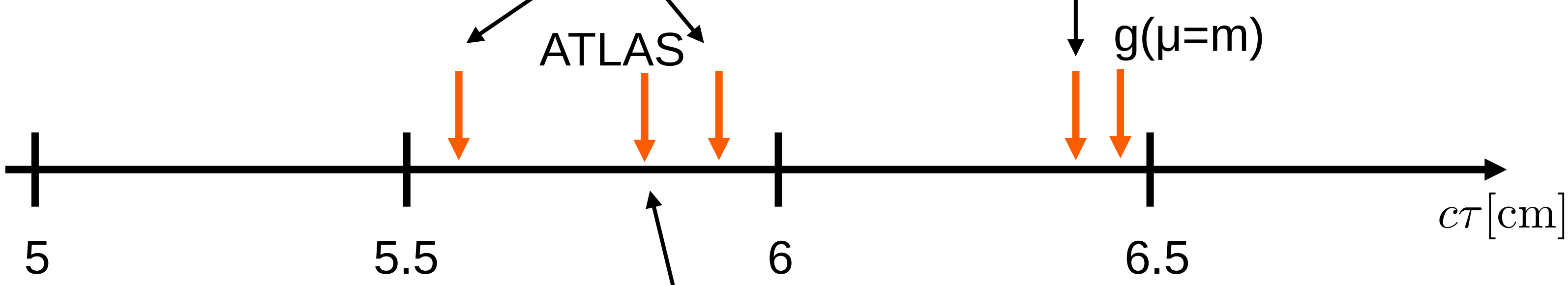
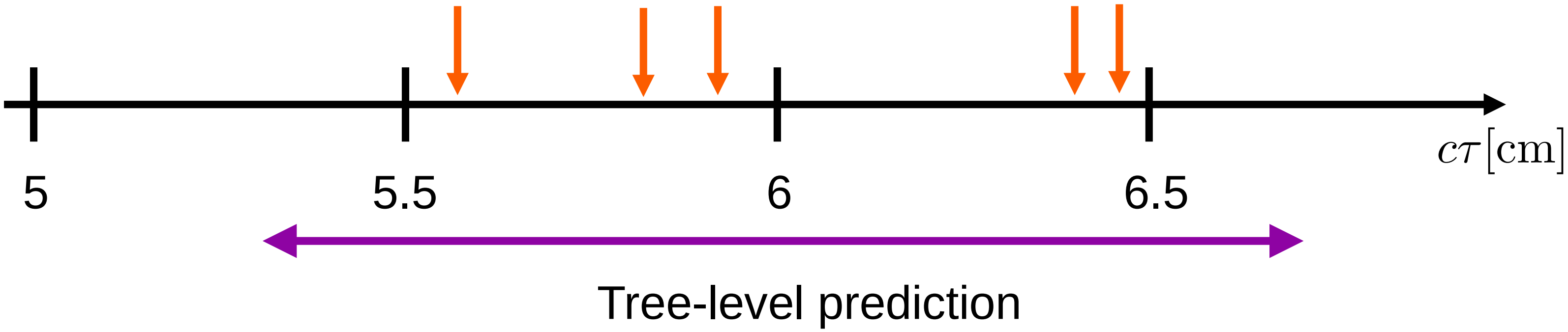


$$\Gamma \simeq \Gamma(\pi^- \to \mu^- + \overline{\nu_\mu}) \times \frac{4\Delta m^3}{m_\pi m_\mu^2}\left(1-\frac{m_\pi^2}{\Delta m^2}\right)^{1/2}\left(1-\frac{m_\mu^2}{m_{\pi^\pm}^2}\right)^{-2} .$$

Tree-level Wino Decay

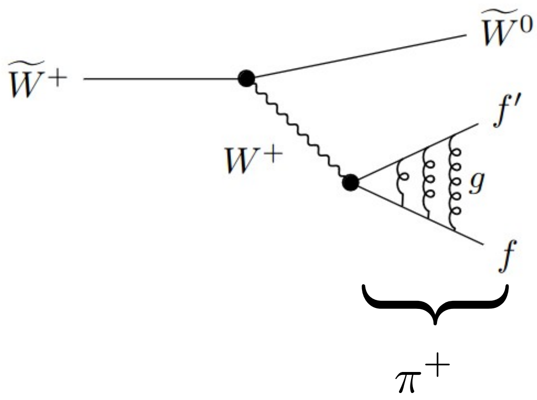


All the values are correct as far as we consider tree level.

Need of next-to-leading order calculation!

Charged Wino Decay at NLO

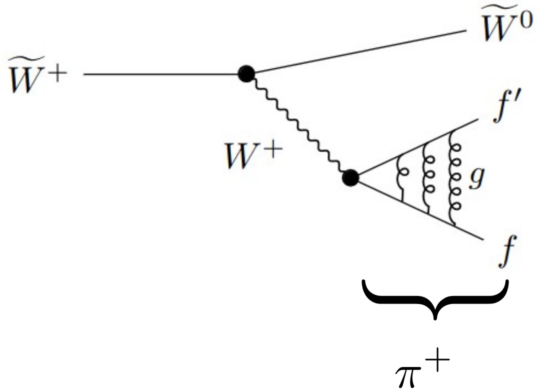
Charged Wino Decay



$$m_{\widetilde{W}} \gg m_W \gg \Lambda_{\rm QCD} \sim \Delta m$$

EW correction includes multi-scale physics.

Charged Wino Decay



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Large logarithm? e.g., $\frac{\alpha}{4\pi} \log\left(\frac{m_{\widetilde{W}}}{\Lambda_{\rm QCD}}\right)$?

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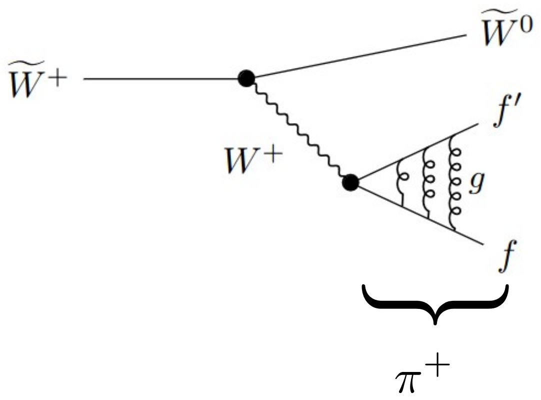

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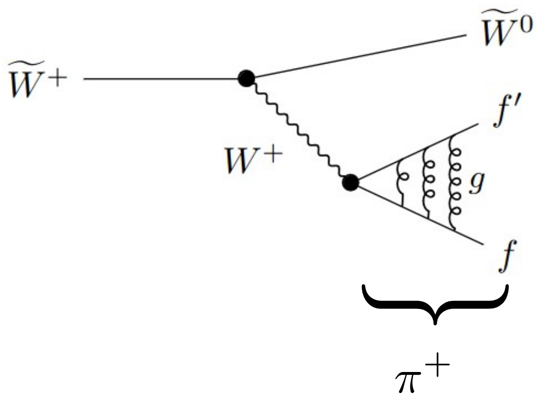
Which energy scale parameter? $\alpha(m_{\widetilde{W}})$? $\alpha(m_W)$? $\alpha(\Lambda_{\rm QCD})$?

Charged Wino Decay



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EW next-to-leading order calculation.

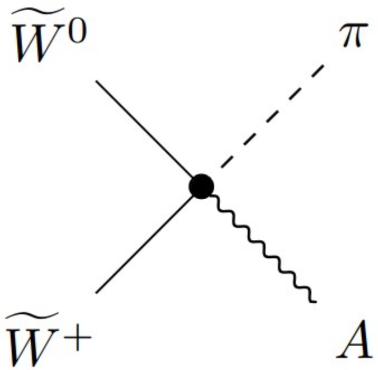
Inclusion of QED in Pion

Coupling Wino and pion

covariant derivative

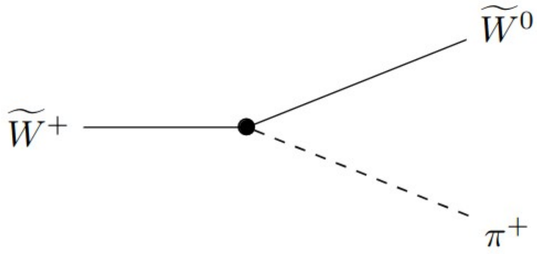
$$2\sqrt{2}F_\pi G_F(\partial_\mu \pi^-) \times (\bar{\psi}_\pm \gamma^\mu \psi_0) \quad \Rightarrow \quad 2\sqrt{2}F_\pi G_F(D_\mu \pi^-) \times (\bar{\psi}_\pm \gamma^\mu \psi_0)$$

$$D_\mu = \partial_\mu + ieA_\mu$$



$$2\sqrt{2}eF_\pi G_F$$

Photon Loop Example

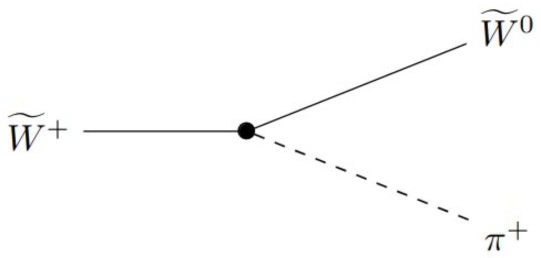


$$\mathcal{M}_{\text{tree}} \simeq F_\pi G_F m_{\widetilde{W}} \Delta m$$

c.f., $\Delta m \sim \frac{\alpha}{4\pi} m_Z$

Photon Loop Example

$$2\sqrt{2}F_\pi G_F(\partial_\mu \pi^-)\times(\bar{\psi}_\pm\gamma^\mu\psi_0)$$



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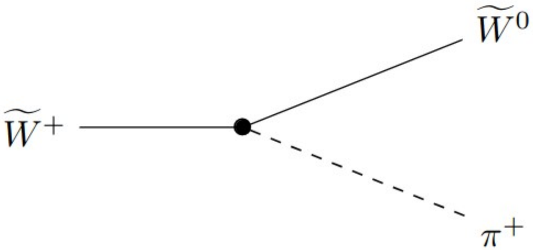

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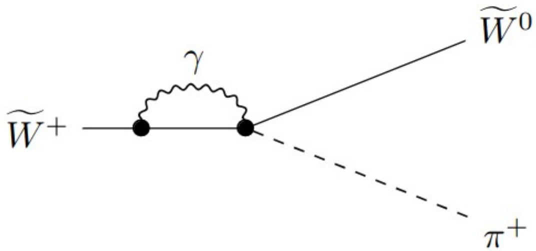
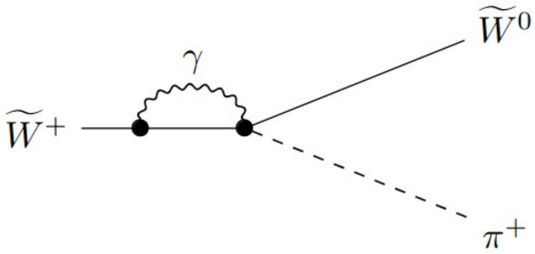


$$\mathcal{M}_{\rm loop} \simeq F_\pi G_F m_{\widetilde{W}}^2 \times \frac{\alpha}{4\pi}\left(\frac{1}{\bar{\epsilon}} - 2\log\frac{m_{\widetilde{W}}}{\mu} + \frac{4}{3}\right)$$

Loop is much larger than tree?

To get observable effect



$$\mathcal{M}_{\rm loop} \simeq F_\pi G_F m_{\widetilde{W}}^2 \times \frac{\alpha}{4\pi}\left(\frac{1}{\epsilon} - 2\log\frac{m_{\widetilde{W}}}{\mu} + \frac{4}{3}\right)$$

UV divergent

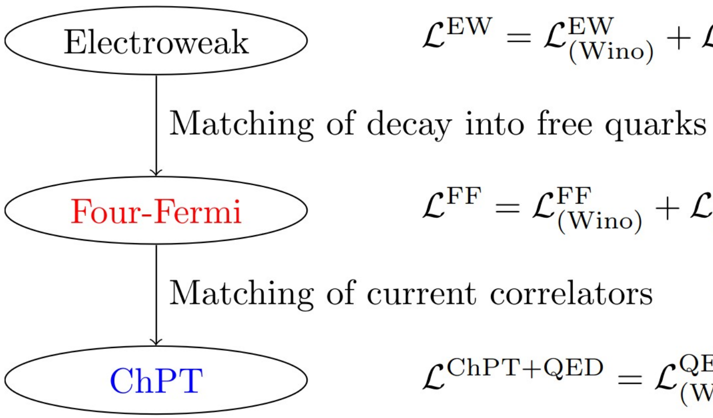
We need specify counter-terms relevant for Wino decay.

Matching with electroweak theory and chiral perturbation (ChPT)

Matching procedure

Strategy is similar to precision of pion decay calculation in SM.

[Descotes-Genon & Moussallam 2005]



$$\mathcal{L}^{\rm EW} = \mathcal{L}^{\rm EW}_{\rm (Wino)} + \mathcal{L}^{\rm EW}_{\rm (SM)} + \mathcal{L}^{\rm EW}_{\rm CT}$$

$$\mathcal{L}^{\rm FF} = \mathcal{L}^{\rm FF}_{\rm (Wino)} + \mathcal{L}^{\rm FF}_{\rm (SM)} + \mathcal{L}^{\rm FF}_{\rm CT}$$

$$\mathcal{L}^{\rm ChPT+QED} = \mathcal{L}^{\rm QED}_{({\rm Wino}+\pi)} + \mathcal{L}^{\rm ChPT}_{({\rm Wino}+\pi)} + \mathcal{L}^{\rm ChPT+QED}_{\rm CT}$$

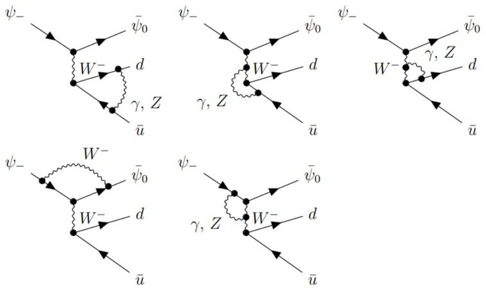
Compute both Wino decay and pion decay with EW/QCD corrections.

Relating

$$\Gamma_{\rm loop}(\pi^+ \to \mu^+ \nu(\gamma)) \Longleftrightarrow \Gamma_{\rm loop}(\widetilde{W}^+ \to \widetilde{W}^0 \pi^+(\gamma))$$

Computing...

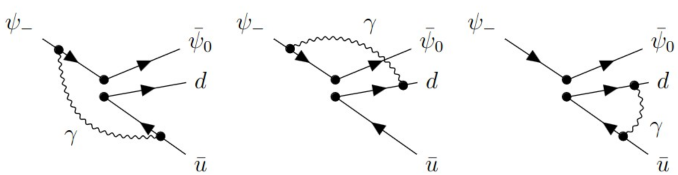
$$\frac{\mathcal{M}^{\rm WF,Box,Vertex(EW)}}{\mathcal{M}^{\rm quark}_{\rm tree}} = \frac{\alpha}{4\pi}\left[\frac{3}{2}\log\frac{M_Z^2}{m_\gamma^2} - \left(\frac{1}{s_W^2}-\frac{4}{s_W^4}\right)\log c_W + \frac{3}{s_W^2}\right] - \frac{\alpha(4+6c_W+c_W^2)}{4(1+c_W)s_W^2}\frac{M_W}{m_\chi} + \mathcal{O}(M_W^2/m_\chi^2)\,.$$



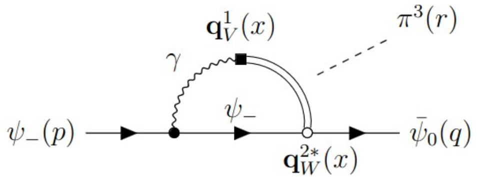
$$\hat{\mathcal{M}}^{\rm quark}_{\rm tree}\times\frac{\alpha}{8\pi}\left[-Q_\chi^2\left(\frac{1}{\bar\epsilon_{\rm FF}}+\log\frac{\mu_{\rm FF}^2}{m_\chi^2}+2\log\frac{m_\gamma^2}{m_\chi^2}+4\right)-(Q_d^2+Q_{\bar u}^2)\left(\frac{1}{\bar\epsilon_{\rm FF}}+\log\frac{\mu_{\rm FF}^2}{m_\gamma^2}-\frac{1}{2}\right)\right]$$

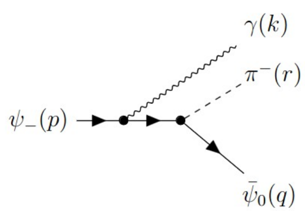
$$\begin{aligned}F_{VW}^{(\rm loop,FF)} = \frac{\alpha}{16\pi\sqrt{2}}F_0G_F\Bigg[&\frac{5}{\bar\epsilon_{\rm ChPT}} + 5\log\frac{\mu_{\rm FF}^2}{m_\chi^2} + \log\frac{m_\chi^2}{m_\gamma^2} + \log\frac{m_\chi^2}{M_V^2}\\ &- \frac{5\pi^2}{3} - 4\log\frac{m_\gamma^2}{M_V^2} - \log^2\frac{m_\gamma^2}{4\Delta m^2}\\ &+ \frac{6M_A^2-9M_V^2}{M_A^2-M_V^2} + 3\frac{M_V^4}{(M_A^2-M_V^2)^2}\log\frac{M_A^2}{M_V^2}\\ &- \frac{4}{\Delta m}\frac{\pi M_A M_V}{M_A+M_V}\Bigg]\times\bar u_0(q)\not{r}u_-(p)\,.\end{aligned}$$

$$\begin{aligned}\mathcal{L}_K = e^2F_0^2\Big\{&\frac{1}{2}K_1\,\langle(\mathcal{Q}_L)^2+(\mathcal{Q}_R)^2\rangle\langle u_\mu u^\mu\rangle + K_2\,\langle\mathcal{Q}_L\mathcal{Q}_R\rangle\langle u_\mu u^\mu\rangle\\ &- K_3\,[\langle\mathcal{Q}_L u_\mu\rangle\langle\mathcal{Q}_L u^\mu\rangle + \langle\mathcal{Q}_R u_\mu\rangle\langle\mathcal{Q}_R u^\mu\rangle] + K_4\,\langle\mathcal{Q}_L u_\mu\rangle\,\langle\mathcal{Q}_R u^\mu\rangle\\ &+ K_5\,\langle[(\mathcal{Q}_L)^2+(\mathcal{Q}_R)^2]u_\mu u^\mu\rangle + K_6\,\langle(\mathcal{Q}_L\mathcal{Q}_R+\mathcal{Q}_R\mathcal{Q}_L)u_\mu u^\mu\rangle\\ &+ \frac{1}{2}K_7\,\langle(\mathcal{Q}_L)^2+(\mathcal{Q}_R)^2\rangle\,\langle\chi_+^{(\rm sp)}\rangle + K_8\,\langle\mathcal{Q}_L\mathcal{Q}_R\rangle\,\langle\chi_+^{(\rm sp)}\rangle\\ &+ K_9\,\langle[(\mathcal{Q}_L)^2+(\mathcal{Q}_R)^2]\chi_+^{(\rm sp)}\rangle + K_{10}\,\langle(\mathcal{Q}_L\mathcal{Q}_R+\mathcal{Q}_R\mathcal{Q}_L)\chi_+^{(\rm sp)}\rangle\\ &- K_{11}\,\langle(\mathcal{Q}_L\mathcal{Q}_R-\mathcal{Q}_R\mathcal{Q}_L)\chi_-^{(\rm sp)}\rangle\\ &- iK_{12}\,\langle[(\mathcal{Q}_{L\mu}\mathcal{Q}_L-\mathcal{Q}_L\mathcal{Q}_{L\mu})-(\mathcal{Q}_{R\mu}\mathcal{Q}_R-\mathcal{Q}_R\mathcal{Q}_{R\mu})]u^\mu\rangle\\ &+ K_{13}\,\langle\mathcal{Q}_{L\mu}\mathcal{Q}_R^\mu\rangle + K_{14}\,\langle(\mathcal{Q}_{L\mu}\mathcal{Q}_L^\mu)+(\mathcal{Q}_{R\mu}\mathcal{Q}_R^\mu)\rangle\Big\}\,.\end{aligned}$$



$$\begin{aligned}\mathcal{L}_Y = e^2\Big\{\sqrt{2}F_0^2G_F\Big[&Y_1\bar\psi_-\gamma_\mu\psi_0\langle u^\mu\{\mathcal{Q}_R,\mathcal{Q}_W\}\rangle + Y_1\psi_-\gamma_\mu\psi_0\langle u^\mu\{\mathcal{Q}_L,\mathcal{Q}_W\}\rangle\\ &+ Y_2\bar\psi_-\gamma_\mu\psi_0\langle u^\mu[\mathcal{Q}_R,\mathcal{Q}_W]\rangle + \hat{Y}_2\bar\psi_-\gamma_\mu\psi_0\langle u^\mu[\mathcal{Q}_L,\mathcal{Q}_W]\rangle\\ &+ Y_3 m_\chi\bar\psi_-\psi_0\langle\mathcal{Q}_R\mathcal{Q}_W\rangle\\ &+ iY_4\bar\psi_-\gamma_\mu\psi_0\langle\mathcal{Q}_L^\mu\mathcal{Q}_W\rangle + iY_5\bar\psi_-\gamma_\mu\psi_0\langle\mathcal{Q}_R^\mu\mathcal{Q}_W\rangle + h.c.\Big]\\ &+ \hat{Y}_6\bar\psi_-(i\not{\partial}-e\not{A})\psi_- + \hat{Y}_7 m_\chi\bar\psi_-\psi_-\Big\}\,.\end{aligned}$$





$$\begin{aligned}\frac{\delta\Gamma_\chi}{\Gamma_\chi} = &-\frac{\alpha M_A M_V}{\Delta m(M_A+M_V)} + \frac{\alpha}{16\pi}g_\chi\left(\frac{M_V}{M_A},\frac{\Delta m}{M_A}\right) + \frac{\alpha}{\pi}f_\chi\left(\frac{m_\pi}{\Delta m}\right)\\ &+ e^2(2f^r_{\chi\chi}(\mu_{\rm FF}) + f^r_{\chi d}(\mu_{\rm FF}) - f^r_{\chi\bar u}(\mu_{\rm FF}) + 2f^r_{d\bar u}(\mu_{\rm FF}))\\ &+ \frac{8}{3}e^2(K_1^r(\mu_{\rm ChPT})+K_2) + \frac{20}{9}e^2(K_5^r(\mu_{\rm ChPT})+K_6)\\ &+ \frac{3\alpha}{8\pi}\log\frac{\mu_{\rm ChPT}^2}{M_V^2} + \frac{3\alpha}{4\pi}\log\frac{\mu_{\rm FF}^2}{\mu_{\rm ChPT}^2} + \frac{\alpha}{4\pi}\log\left(\frac{\Delta m^2M_V^4}{m_\pi^6}\right) + \frac{2\alpha}{\pi}\log 2\end{aligned}$$

Final Result

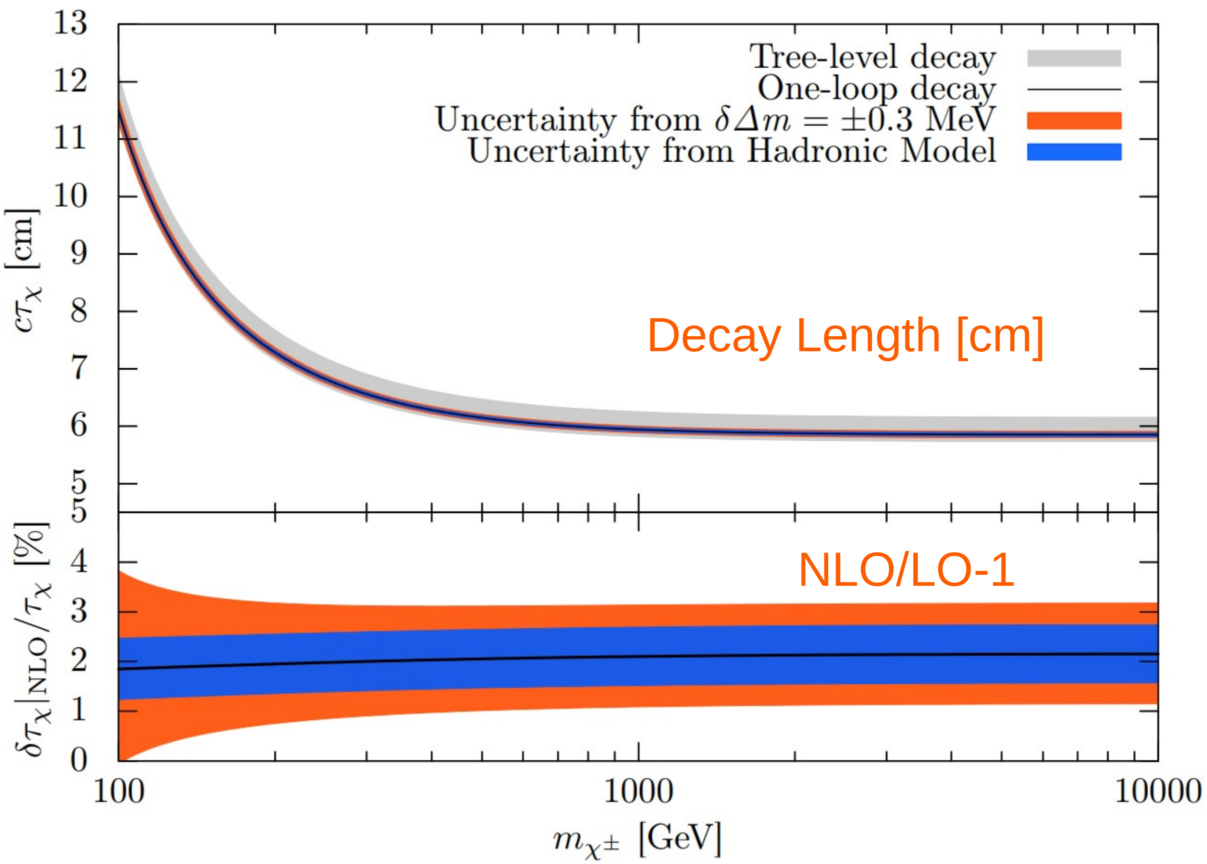
$$\Gamma^{\text{loop}}_{\widetilde{W}^\pm} = \Gamma^{\text{tree}}_{\widetilde{W}^\pm} \left\{ 1 + \frac{\alpha}{4\pi} \left[c_{-2} \left(\frac{m_{\widetilde{W}}}{\Delta m} \right)^2 + c_{-1} \left(\frac{m_{\widetilde{W}}}{\Delta m} \right) + c_{\log} \log \left(\frac{m_{\widetilde{W}}}{\Delta m} \right) + c_0 + \cdots \right] \right\}$$

Final Result

$$\Gamma^{\text{loop}}_{\widetilde{W}^\pm} = \Gamma^{\text{tree}}_{\widetilde{W}^\pm} \left\{ 1 + \frac{\alpha}{4\pi} \left[\underbrace{ \underset{=0}{c_{-2} \left(\frac{m_{\widetilde{W}}}{\Delta m} \right)^2} + \underset{=0}{c_{-1} \left(\frac{m_{\widetilde{W}}}{\Delta m} \right)} + \underset{=0}{c_{\log} \log \left(\frac{m_{\widetilde{W}}}{\Delta m} \right)} + c_0 + \cdots }_{\sim -0.02} \right] \right\}$$

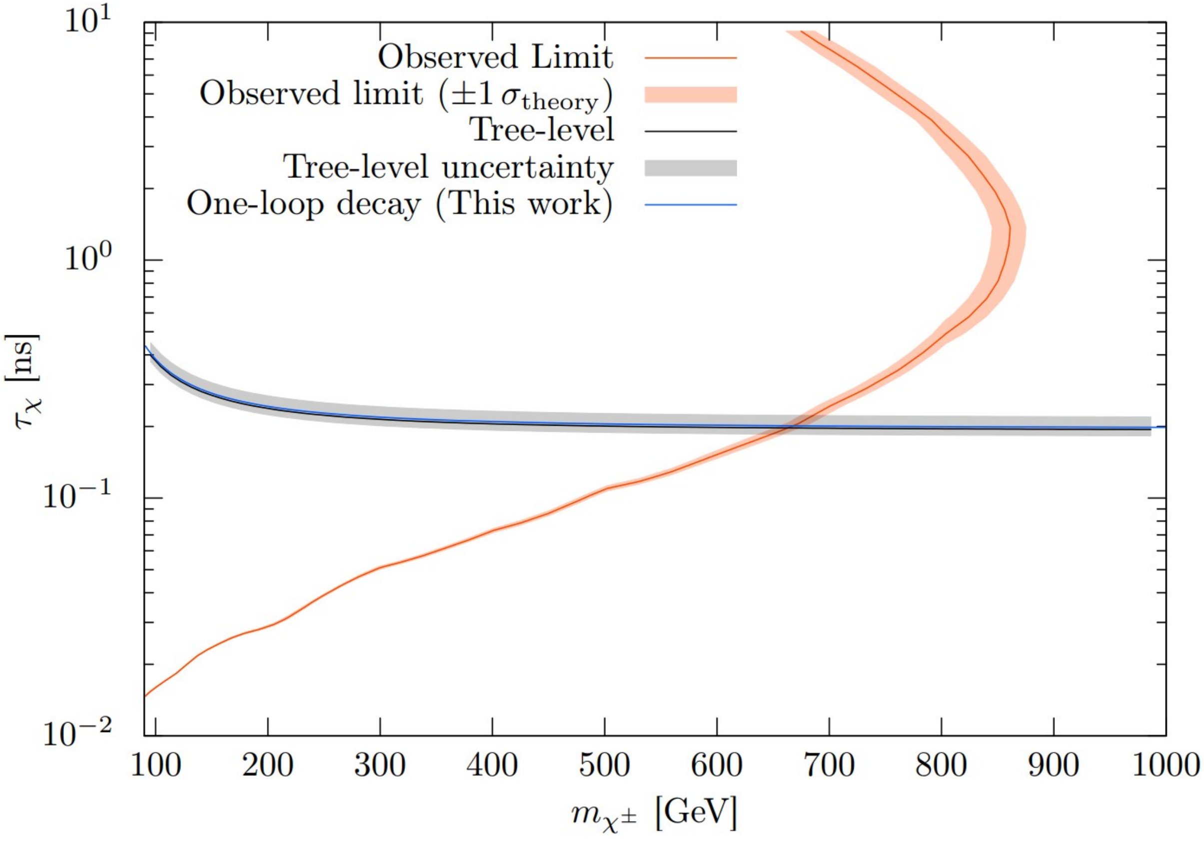
No Wino mass enhancement effect is found!

Final Result

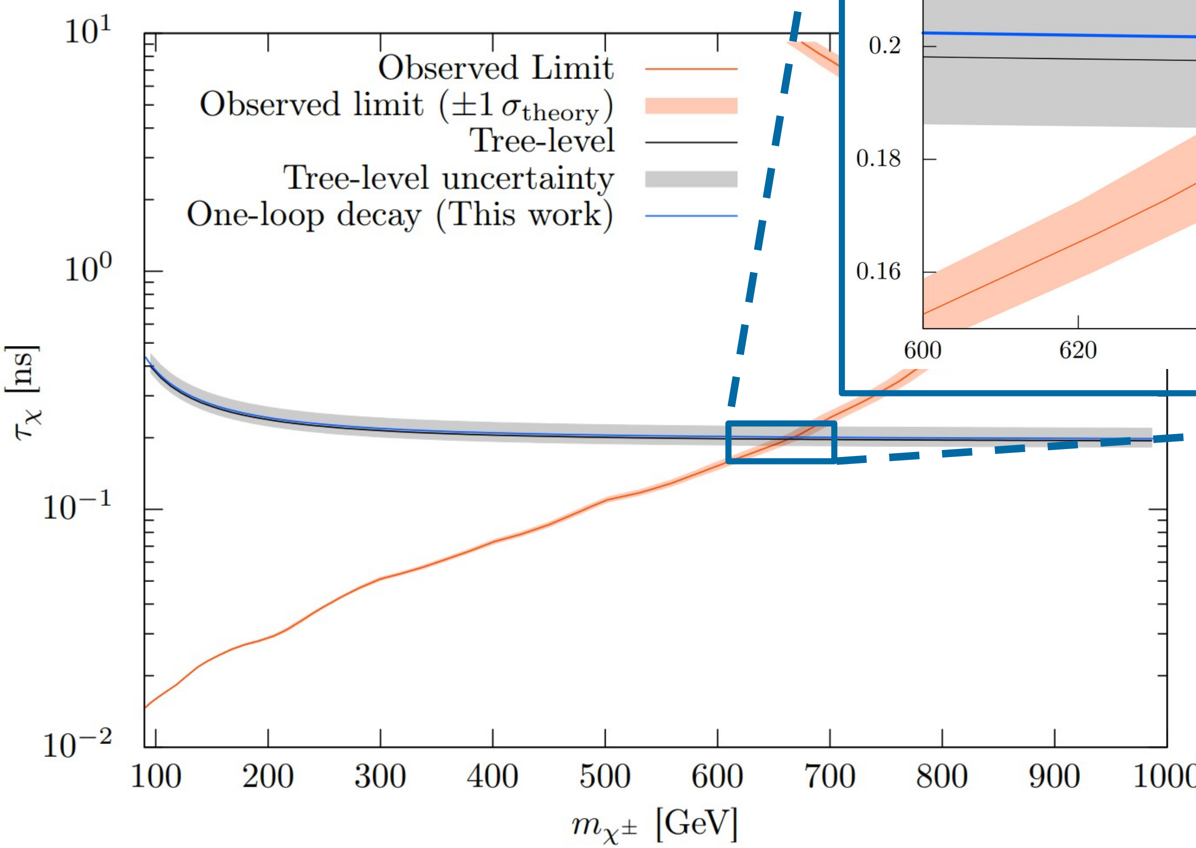


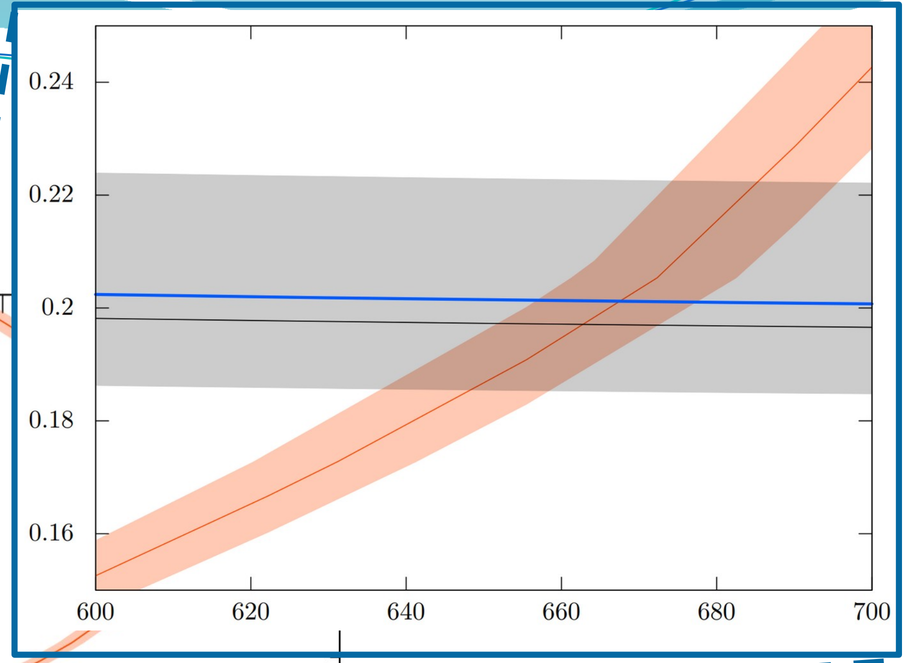
Main theory errors from unknown piece of three-loop mass difference $\Delta_{3-\mathrm{loop}} m$

Impact on LHC Search



Impact on LHC

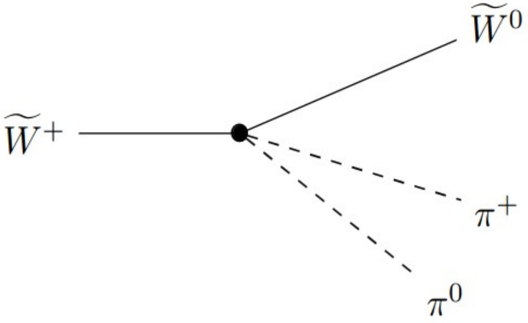




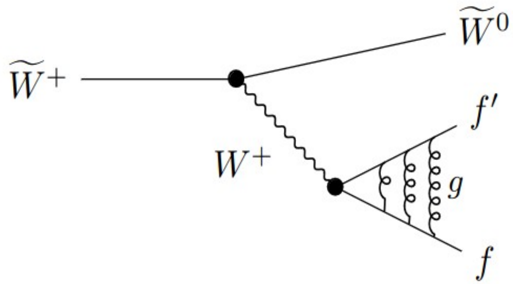
General Mass Difference

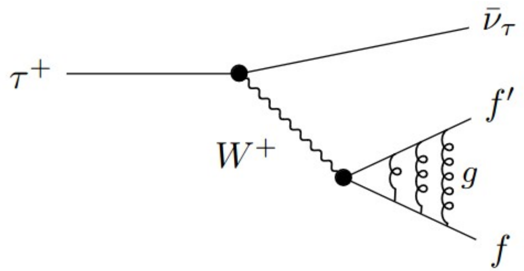
	Δm
Pure Wino DM	~160 MeV
Higgsino-like DM	~300 MeV – 2 GeV from gaugino mixing
5-plet DM	~160 MeV and ~500 MeV

For larger mass difference, lepton and multi-meson decay modes are dominant.



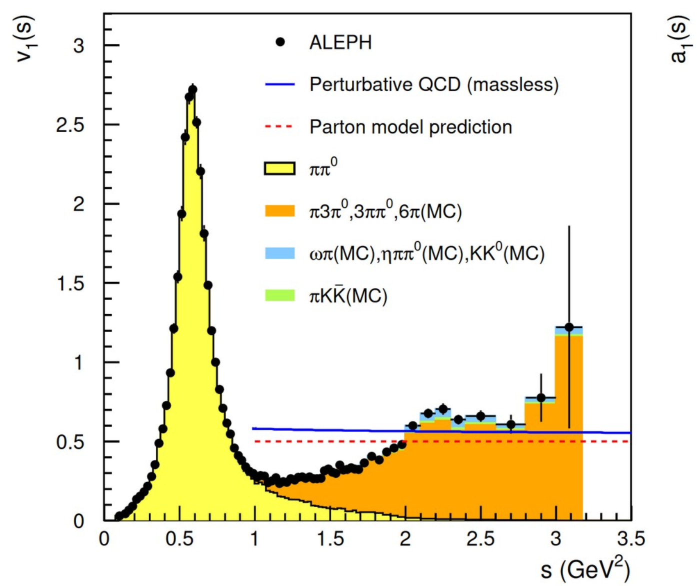
Tau Decay





Tau decay has similar structure.
Hadron data for tau decay is available for BSM particle decay.

[Chen, Drees & Gunion, 96]

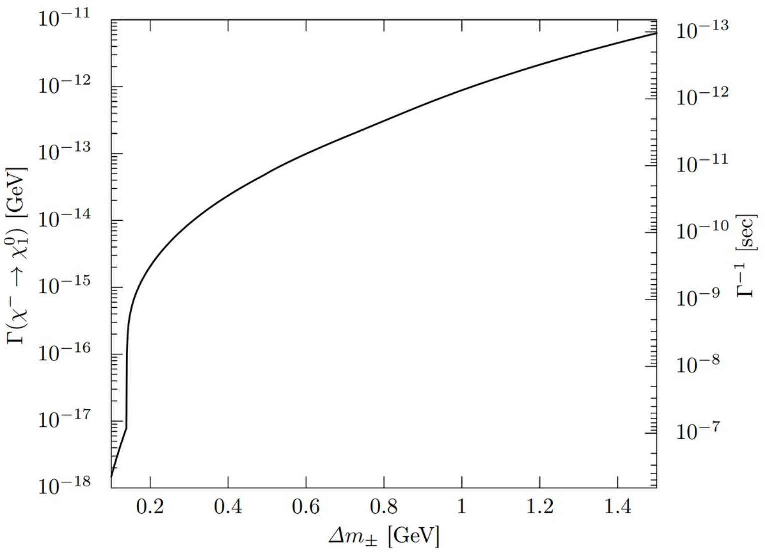


Higgsino Decay

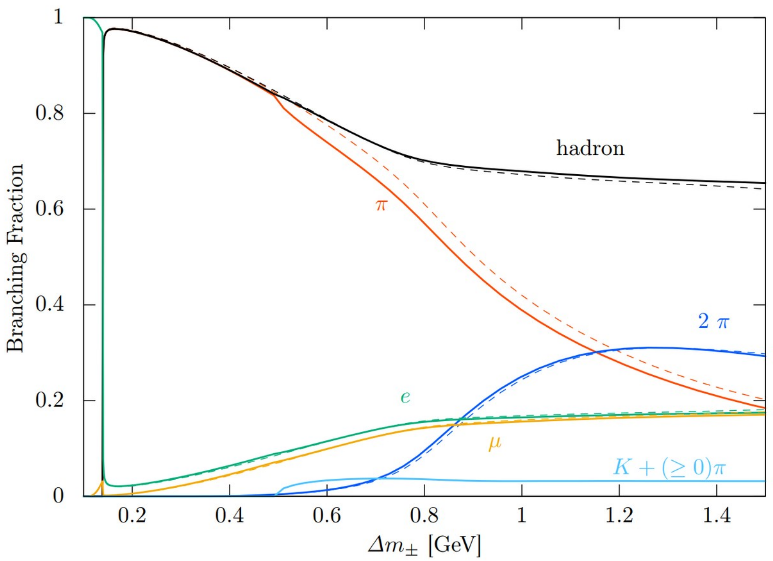
Single meson:	EW corrections.
Lepton:	EW corrections.
Multi-meson:	EW + leading QED+ Latest hadron data (Belle and Aleph)

Charged Higgsino Decay

Decay Rate



Branching Fraction



Dashed line: previous work

5-10% change from work by Chen, Drees & Gunion.

Summary

- Precise estimation of EW charged fermion is crucial for LHC search.
- All the large enhancements from heavy DM are completely canceled.
  - Non-relativistic version of Appelquist-Carazzone's decoupling theorem.
- EW correction to lepton and pion mode, achieving O(0.1)% precision.
- Leading EW correction + latest hadron rate for multi-meson mode.
- Data is available: https://member.ipmu.jp/satoshi.shirai/Chargino_Decay/