Matching resummed endpoint and continuum γ-ray spectra from dark-matter annihilation

Kai Urban

Technical University Munich

Planck 2022, Paris
May 30, 2022

based on
arXiv:2203.01692
with M. Beneke and M. Vollmann

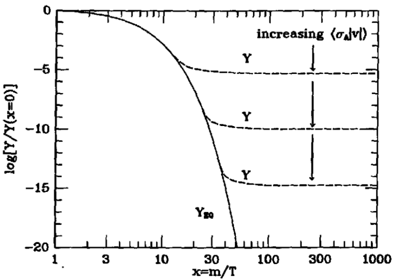
also see earlier works
1903.08702/1912.02034 – Sudakov logs
1909.04584/2108.07285 – NLO potentials

SFB 1258 Neutrinos Dark Matter Messengers

Motivation

TeV-scale electroweak WIMPs

- "WIMP" miracle: TeV-scale particle with weak scale cross section $\overset{\text{freeze-out}}{\rightarrow}$ observed DM relic abundance $\Omega h^2 \sim 0.1 \frac{3\times 10^{26}\text{cm}^3\text{s}^{-1}}{\langle\sigma v\rangle} \sim 0.1 \frac{\pi\alpha_2^2/m_\chi^2}{\langle\sigma v\rangle}$
- two main minimal DM scenarios:
  - $\text{SU}(2)_L$-triplet (wino) thermal mass $m_\chi \approx (2.7-3)\,\text{TeV}$
  - $\text{SU}(2)_L$-doublet w. hypercharge (higgsino) thermal mass $m_\chi \approx 1\,\text{TeV}$
- Results and framework also applicable to broader class of models (e.g. MSSM, ...)
- Direct detection: around neutrino floor
- LHC: too heavy to be seen
- Indirect detection: higgsino/wino testable



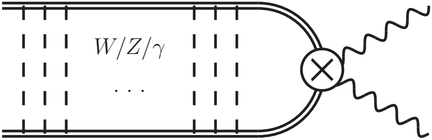
[Kolb, Turner '90]

Motivation

Sommerfeld effect

Non-relativistic DM particles exchange EW gauge bosons (freeze-out $v \sim 0.1$ / indirect detection $v \sim 10^{-3}$)

[Hisano et al. '04/'06]



each ladder rung suppressed by (potential region)

$$\alpha_2 \frac{m_\chi}{m_W} \quad \text{or} \quad \frac{\alpha_2}{v} \quad \sim \mathcal{O}(1)$$

results in static force in form of Yukawa/Coulomb potentials

$$V(r) \sim -\alpha_2 \frac{e^{-m_{W/Z} r}}{r} \quad \text{or} \quad -\frac{\alpha}{r}$$

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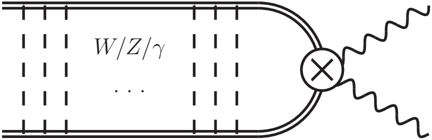

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Example: Tree-level wino potential - neutral sector ${}^1S_0$

$$V_{\rm LO}(r) = \begin{pmatrix} 0 & -\sqrt{2}\,\alpha_2 \dfrac{e^{-m_W r}}{r} \\ -\sqrt{2}\,\alpha_2 \dfrac{e^{-m_W r}}{r} & 2\delta m - \dfrac{\alpha}{r} - \alpha_2\, c_W^2 \dfrac{e^{-m_Z r}}{r} \end{pmatrix} \qquad \begin{matrix} (00) \\ (+-) \end{matrix}$$

Solve Schrödinger equation $\Rightarrow$ cross-section enhancement

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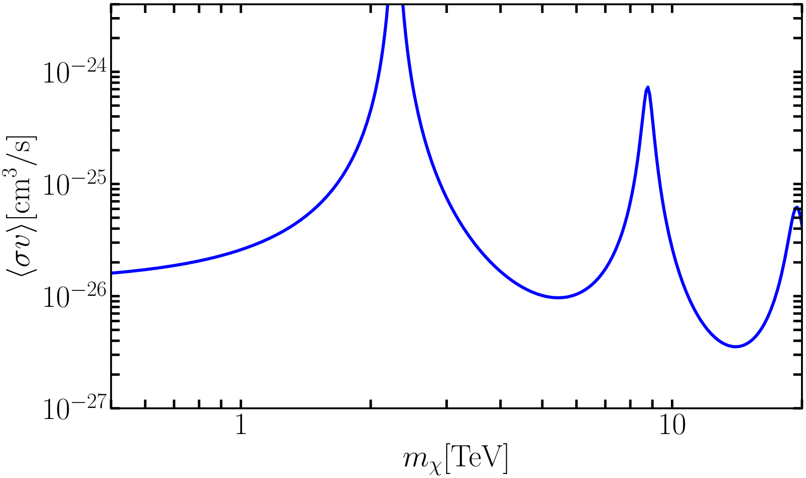

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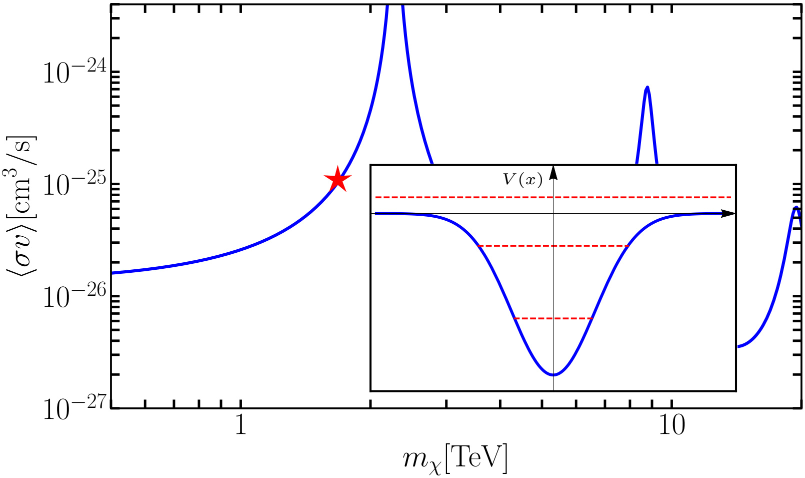

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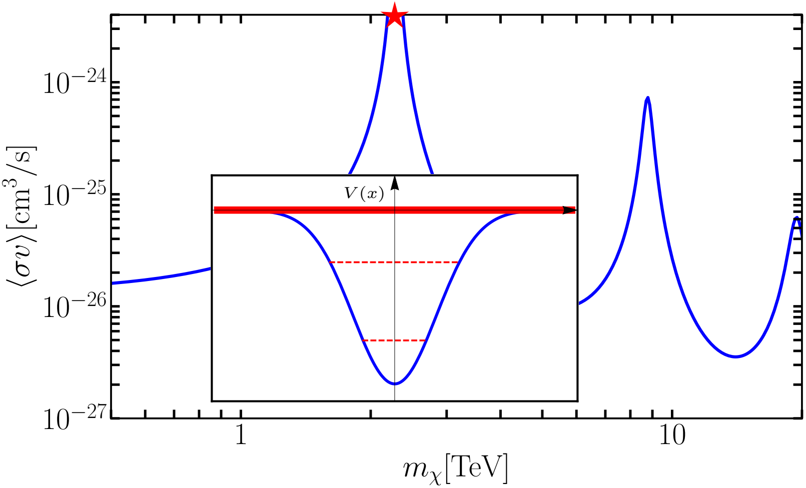

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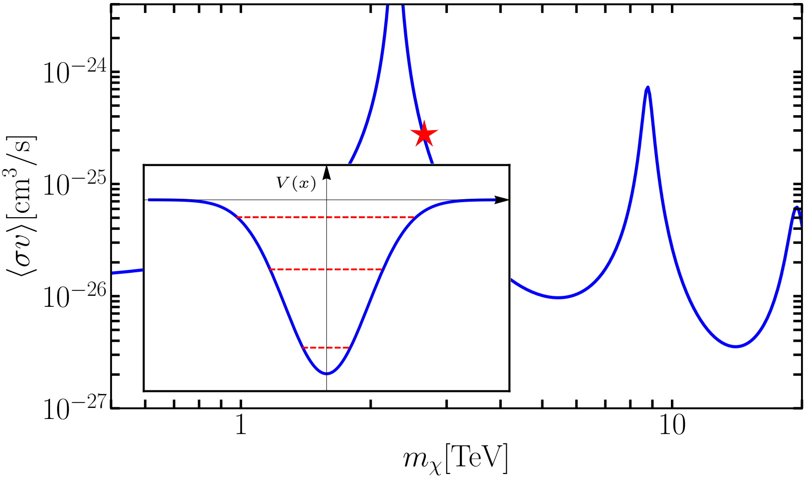
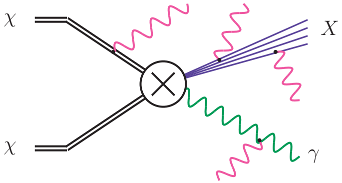
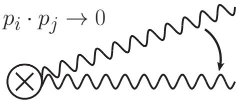


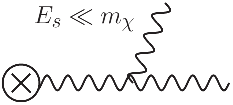
Motivation

Sudakov logarithms



Kinematics force soft/collinear limits for the soft radiation





IR divergencies cause large Sudakov double logs at all orders in perturbation theory

$$\frac{\alpha_2}{\pi} \log^2 \frac{4m_\chi^2}{m_W^2} \overset{m_\chi = 3\,\text{TeV}}{\approx} 0.83$$

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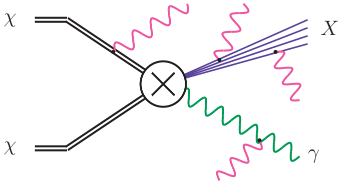

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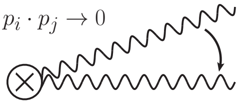

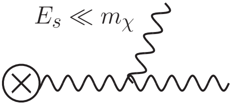

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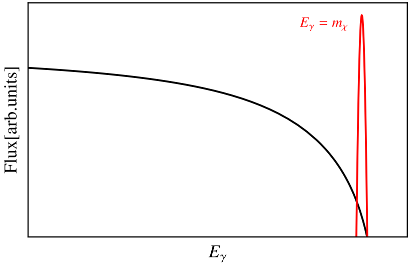
⇒ Employ full QFT/EFT machinery (NRDM ⊗ SCET)
(full NLO, factorization, resummation, ...)

Motivation

Line signal

- Heavy WIMP non-relativistic today ($v \sim 10^{-3}$)

  $\Rightarrow$ annihilation at threshold / photon energies $E_\gamma \approx m_\chi$
- large corrections in exclusive case [Bauer et al. '15, Ovanesyan et al. '15/'17] and semi-inclusive case [Baumgart et al. '15/'16]



Line signal count rate in experiment

$$N_{jk}^S = T \frac{1}{8\pi m_\chi^2} J_k \int_{\Delta E_k} dE \int dE' A_{\text{eff}}(E')\, G(E', E)\, \frac{d\langle \sigma v \rangle}{dE}$$

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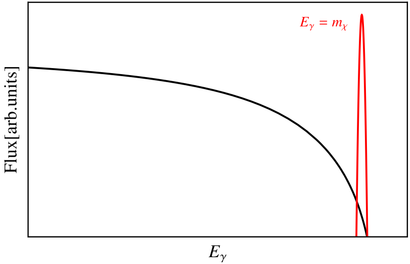

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differential cross section (particle physics only)

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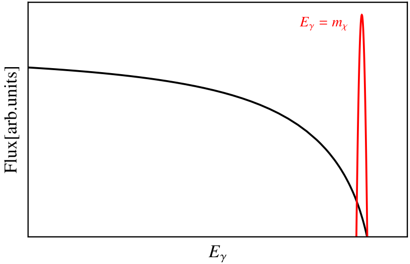

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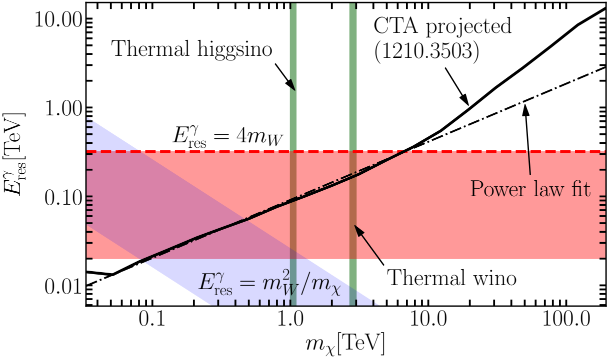
Detector resolution function

differential cross section (particle physics only)

Finite energy resolution - $\chi^0\chi^0 \to \gamma + X$

- Finite energy resolution of detector E^γ_{res} (leads to different EFT setups)
  - line signal - $E^\gamma_{\text{res}} \sim 0$
    [Bauer et al. '14, Ovanesyan et al. '14/'16, Baumgart et al. '14]
  - narrow resolution - $E^\gamma_{\text{res}} \sim m_W^2/m_\chi$ [Beneke et al. '18]
  - intermediate resolution - $E^\gamma_{\text{res}} \sim m_W$
    [Beneke, Hasner, KU, Vollmann, 1912.02034 + Broggio, 1903.08702]
  - wide resolution - $E^\gamma_{\text{res}} \gg m_W$ [Baumgart et al. '17/'18]



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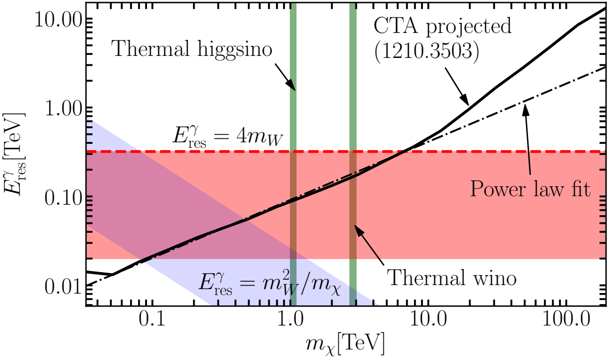
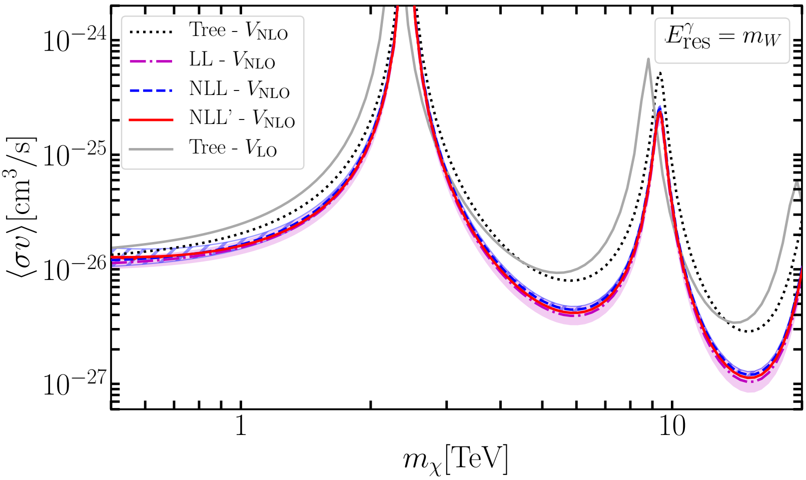


Wino indirect detection – $\chi^0\chi^0 \to \gamma + X$

[1903.08702/1912.02034]



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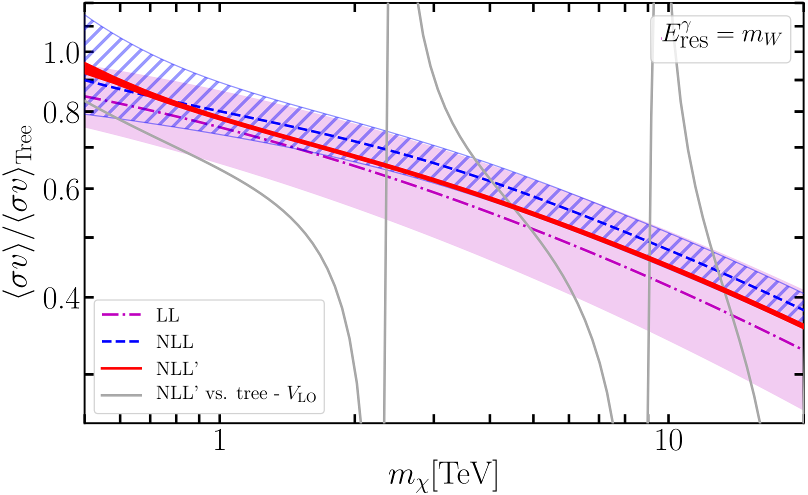

Extending energy spectrum beyond the endpoint

- For real experimental analysis, and thorough estimate of impact on theoretical predictions need differential spectrum also beyond kinematic endpoint.
- Two small parameters in the problem:

$$\epsilon = \frac{m_W}{2m_\chi}\,, \qquad 1-x = 1-\frac{E_\gamma}{m_\chi}$$

- Away from endpoint, i.e., $1-x \sim \mathcal{O}(1)$, regime of parton showers (in this talk PPPC4 DM ID [Cirelli et al. '10])
- Logarithmic discussion independent of specific parton shower used.

Compare splitting functions:

$$\frac{dN^{IJ}_{WW}}{dx} \equiv m_\chi \left.\frac{\Gamma^{\rm res}_{IJ}}{\hat{\Gamma}^{WW}_{IJ,\rm tree}}\right|_{\mathcal{O}(\hat{\alpha}_2)} + \mathcal{O}(\hat{\alpha}_2^2) \qquad (x<1)$$

Splittings wino $\chi^0\chi^0 \to W^+W^-\gamma$

intermediate resolution $(1-x \sim \epsilon \ll \mathcal{O}(1))$

$$\frac{dN_{WW}}{dx}\bigg|^{\text{int.}}_{\chi^0\chi^0\to WW\gamma} = \frac{2\alpha_{\text{em}}}{\pi}\left[\frac{1}{1-x}\ln\left(1+\frac{(1-x)^2}{\epsilon^2}\right) - \frac{1-x}{\epsilon^2+(1-x)^2}\right]$$

collinear approximation – PPPC4DM $(\epsilon \ll 1-x \sim \mathcal{O}(1))$

$$\frac{dN_{WW}}{dx}\bigg|_{\text{PPPC4DM}} = \frac{2\alpha_{\text{em}}}{\pi}\left[\frac{x}{1-x}\ln\frac{(1-x)^2}{\epsilon^2} - \left(\frac{1-x}{x}+x(1-x)\right)\ln\epsilon^2\right]$$

one-loop fixed order expanded for small ϵ, and $\delta m_\chi = m_{\chi^+} - m_{\chi^0}$
$(1-x \gg \epsilon$ and $x \gg \epsilon)$

$$\frac{dN_{WW}}{dx}\bigg|^{\text{f.o.}}_{\chi^0\chi^0\to WW\gamma} = \frac{2\alpha_{\text{em}}}{\pi}\left[\frac{(1-x+x^2)^2}{(1-x)x}\ln\frac{1}{\epsilon^2} - \frac{(4-12x+19x^2-22x^3+20x^4-10x^5+2x^6)}{(2-x)^2(1-x)x} + \frac{8-24x+42x^2-37x^3+16x^4-3x^5}{(2-x)^3(1-x)x}\ln(1-x)\right]$$

Splittings wino $\chi^0\chi^0 \to W^+W^-\gamma$

Leading $1/\epsilon$ term

$$\frac{dN_{WW}}{dx} = \frac{2\alpha_{\rm em}}{\pi}\,\frac{1}{\epsilon}\left\{\begin{array}{cc} \frac{\ln(1+\beta^2)}{\beta} - \frac{\beta}{1+\beta^2} & \text{int. res.} \\ \frac{\ln\beta^2}{\beta} & \text{PPPC4DM} \\ \frac{\ln\beta^2-1}{\beta} & \text{full fixed order} \end{array}\right\} + \mathcal{O}(\epsilon^0)\,.$$

with $1 - x = \beta\epsilon$.

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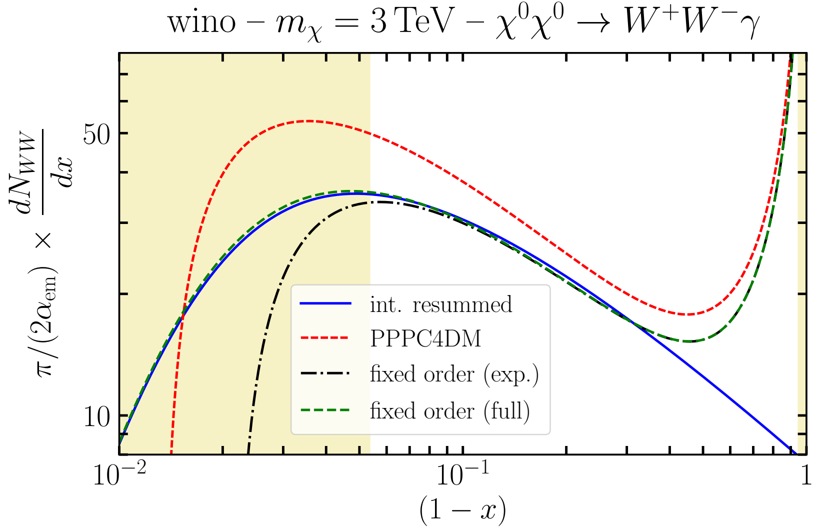
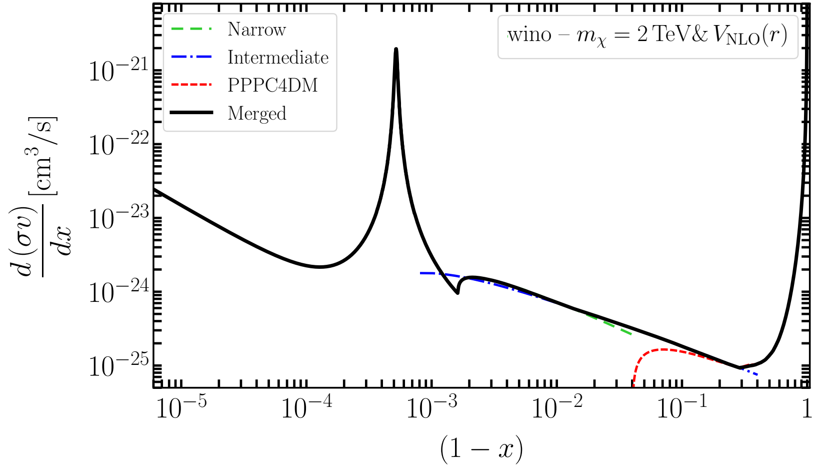


Wino differential spectrum – $\chi^0\chi^0 \to \gamma + X$



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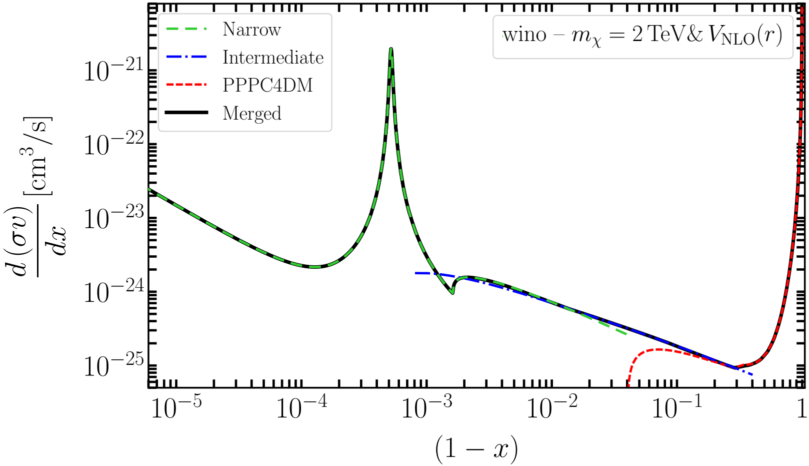

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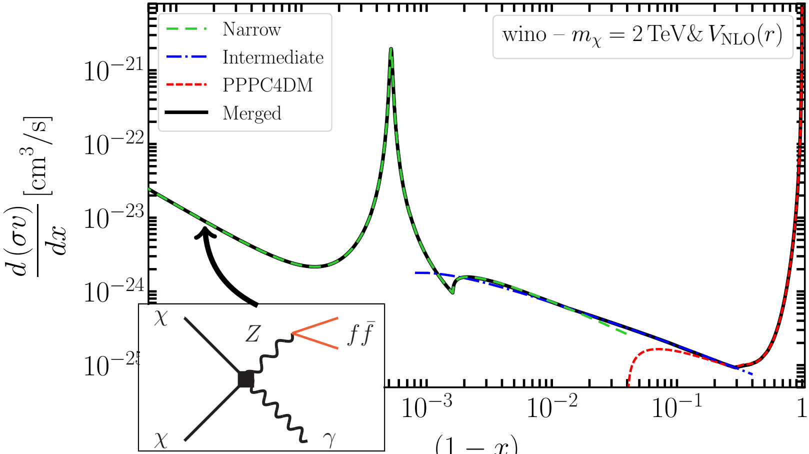

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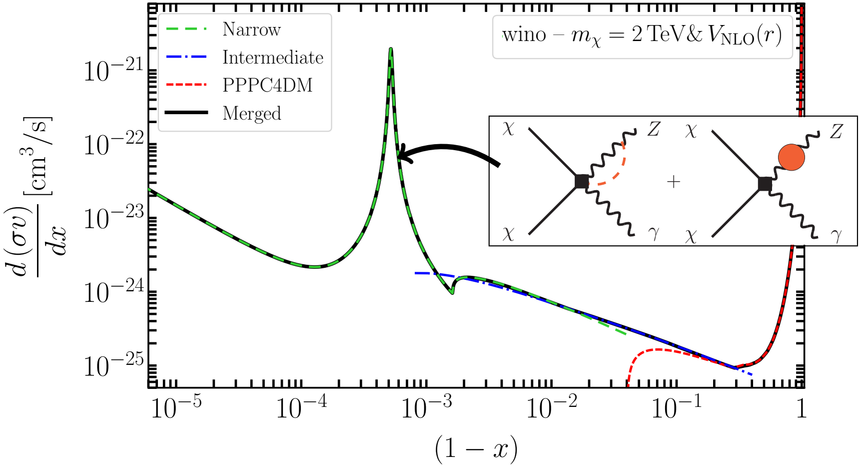

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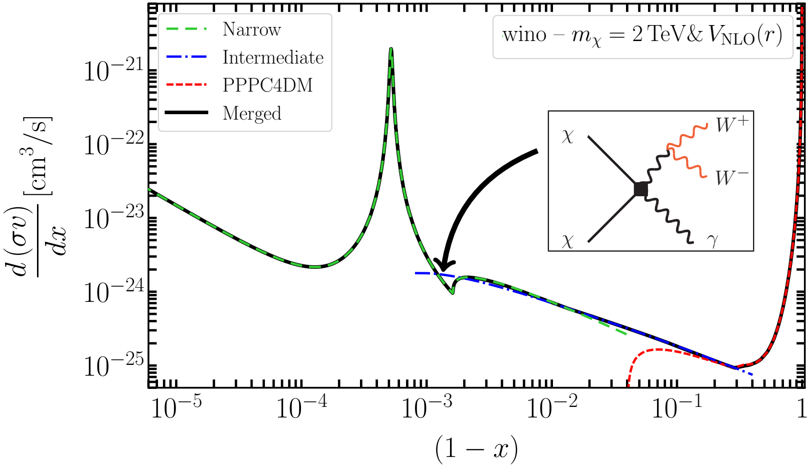

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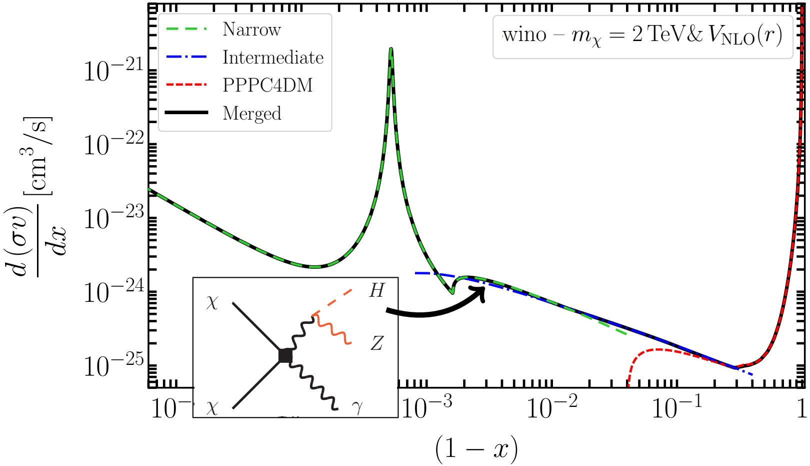

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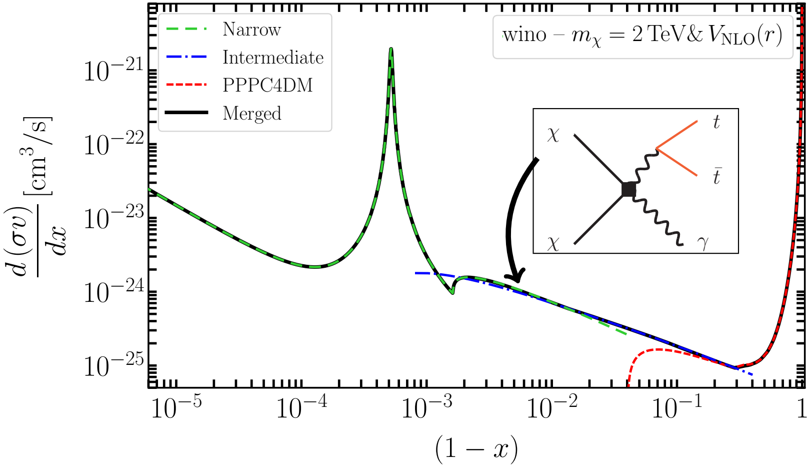

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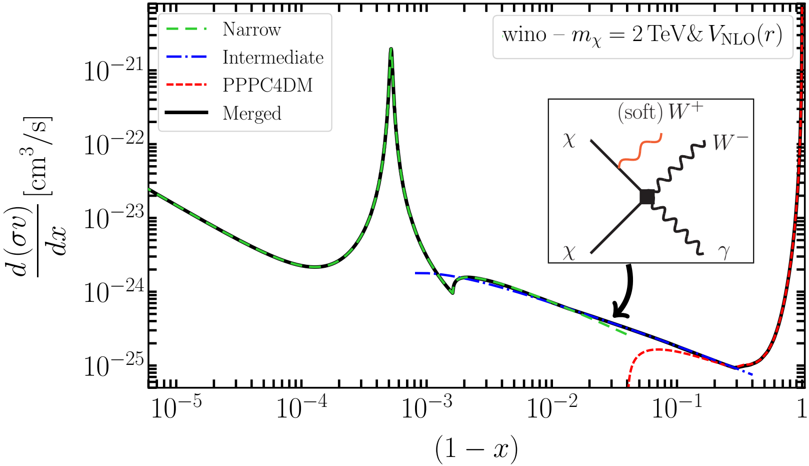
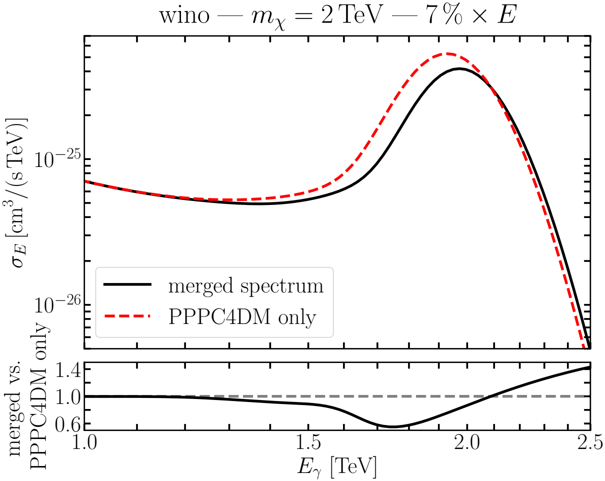


Estimated effect in experiment

Folding with Gaussian resolution

$$7\% \times E \;\widehat{=}\; \int_0^{m_\chi} dE'_\gamma \, \frac{d(\sigma v)}{dE'_\gamma} \, \frac{1}{\sqrt{2\pi}\cdot(7\%)\cdot E_\gamma} e^{-\frac{(E_\gamma - E'_\gamma)^2}{2\cdot(7\%)^2\cdot E_\gamma^2}}$$



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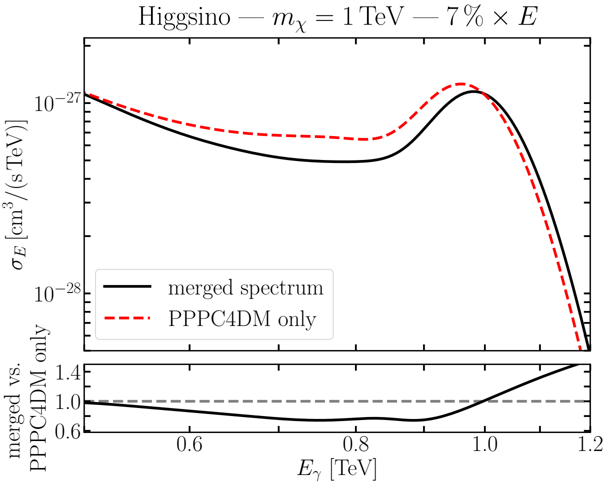

Summary and Outlook

Main results:

- Achieved merging between endpoint resummed (NLL') and parton shower calculation
- Effect several 10's % suppression around nominal endpoint w.r.t. naive line prediction.
- Accurate predictions over entire possible range of photon energies including NLO Sommerfeld results for wino and Higgsino DM
- Code available `DM`γ`spec`, check out `dmyspec.hepforge.org`

In future:

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