Resummed photon spectra from dark matter annihilation for intermediate and narrow energy resolution

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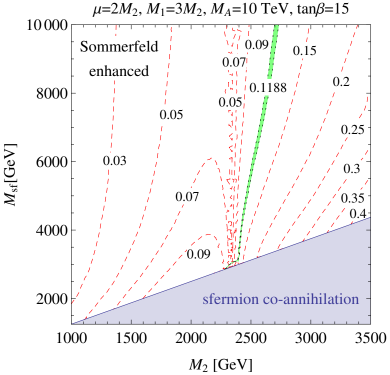
based on
arXiv:1805.07367/1903.08702
with M. Beneke, A. Broggio,
C. Hasner and M. Vollmann

SFB 1258 Neutrinos Dark Matter Messengers

Motivation

Weakly interacting massive particles (WIMPs) - wino

- "WIMP" miracle: TeV-scale particle with weak scale cross section $\xrightarrow{\text{freeze-out}}$ observed DM relic abundance $\Omega h^2 \sim 0.1\,\frac{3\cdot 10^{26}\text{cm}^3\text{s}^{-1}}{\langle\sigma v\rangle} \sim 0.1\,\frac{\pi\alpha_2^2/m_\chi^2}{\langle\sigma v\rangle}$
- In this talk wino dark matter $SU(2)_L$ triplet $\delta\mathcal{L} = \frac{1}{2}\bar{\chi}\left(i\gamma^\mu D_\mu - m_\chi\right)\chi$
- Splits into neutralino χ^0 and charginos $\chi^\pm$ (mass difference $\delta m \approx 165\,\text{MeV}$)
- Thermal wino $m_\chi \approx 2.7 - 3\,\text{TeV}$
- Results and framework also applicable to other models (higgsino, MSSM ...)
- Direct detection: around neutrino floor
- LHC: too heavy to be seen
- Indirect detection: wino will be testable



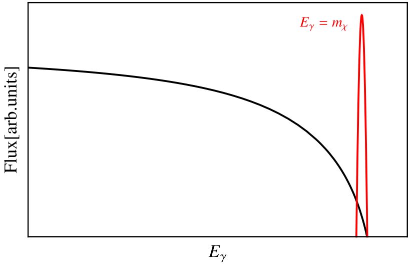
[Beneke et al. '16]

Motivation

Line signal

- Wino 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

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

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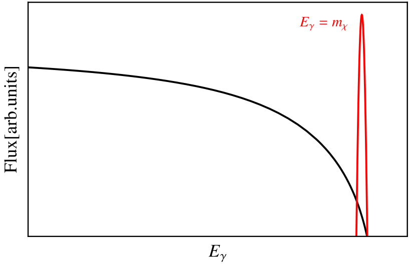

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differential cross section

(particle physics only)

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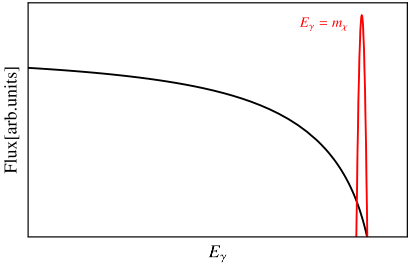

Line signal count rate in experiment

Detector resolution function

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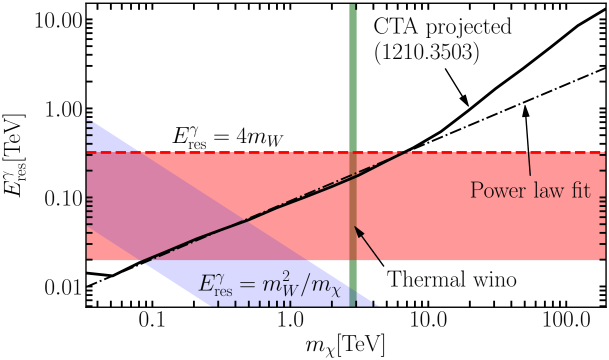
differential cross section (particle physics only)

Motivation

Indirect detection $\chi\chi \to \gamma + X$

- Telescope experiments such as HESS/CTA/... look for high energy γ-rays from dark matter annihilation
- Finite energy resolution E^γ_{res} (leads to different EFT setups)
  $\Rightarrow$ observable not $\chi\chi \to \gamma\gamma/\gamma Z$, but $\chi\chi \to \gamma + X$
  - narrow resolution - $E^\gamma_{\text{res}} \sim m_W^2/m_\chi$ [this work]
  - intermediate resolution - $E^\gamma_{\text{res}} \sim m_W$ [this work]
  - wide resolution - $E^\gamma_{\text{res}} \gg m_W$ [Baumgart et al. '17/'18]



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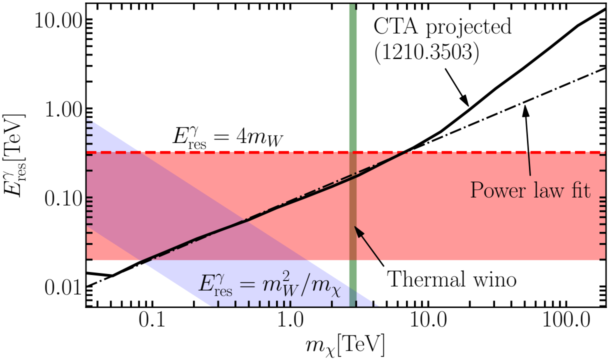
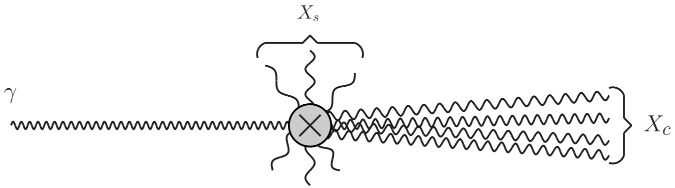


Motivation

$\chi\chi \to \gamma + X$ - Multiscale problem



Want to deal with large (Sudakov double) log's $\alpha_2^n \ln^{2n}$ of the ratios

- m_W/m_χ
- $E^\gamma_{\text{res}}/m_\chi$
- $m_W/E^\gamma_{\text{res}}$

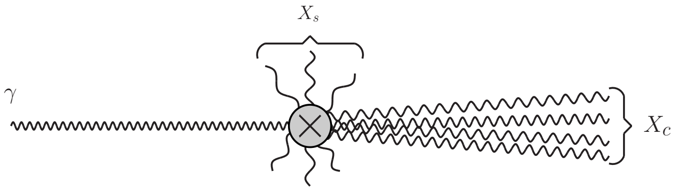
to all orders in perturbation theory (e.g. $\alpha_2/\pi \ln^2(4m_\chi^2/m_W^2) \overset{m_\chi=3\text{ TeV}}{\approx} 0.83$)

In this talk choose $E^\gamma_{\text{res}} \sim m_W$ (intermediate energy resolution) as an example

Also need to include non-perturbative effect due to ladder diagrams of order $\alpha_2 m_\chi/m_W$ (Sommerfeld effect) [Hisano et al. 2004]

Motivation

$\chi\chi \to \gamma + X$ - Multiscale problem



Several modes $\lambda = m_W/m_\chi$ - modes of same virtuality (rapidity divergencies):

- Anti-collinear modes $(k_+, k_-, k_\perp) \sim m_\chi\,(\lambda^2, 1, \lambda)$
- Soft modes $(k_+, k_-, k_\perp) \sim m_\chi\,(\lambda, \lambda, \lambda)$

$\Longrightarrow$ Factorization breaking logarithms

Solution: rapidity regulator (further factorization - mixed $\mathrm{SCET_I}$ / $\mathrm{SCET_{II}}$ problem)

Solve problem in PNRDM$\otimes$SCET

Factorization for $\chi\chi \to \gamma + X$

Factorization formula - Example intermediate resolution case

$$\frac{d(\sigma v_{\rm rel})}{dE_\gamma} = \sum_{I,J} S_{IJ}\;\Gamma_{IJ}(E_\gamma) \qquad \text{with} \quad I,J = (00),(+-)$$

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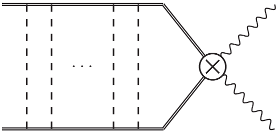

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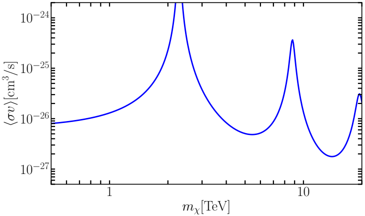
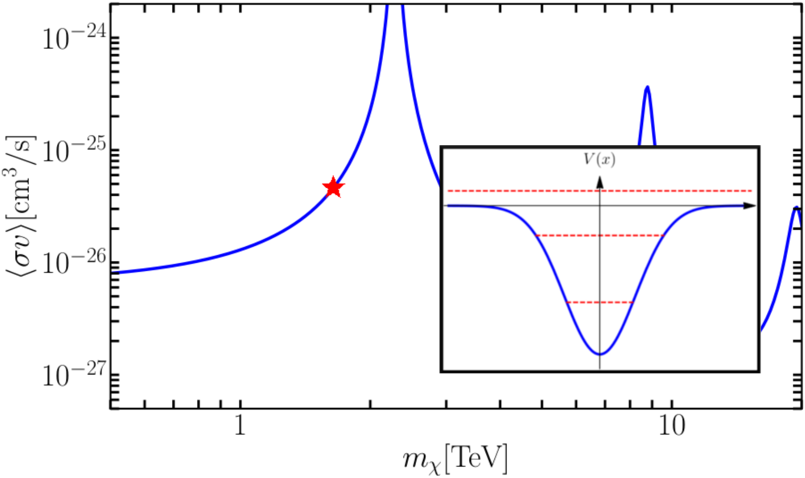


Sommerfeld effect - potential modes $(k_0 \sim m_\chi \lambda^2, \mathbf{k} \sim m_\chi \lambda)$

Yukawa/Coulomb potentials $V(r) \sim -\dfrac{\alpha_2 \exp(-m_W r)}{r}$ [Hisano et al. 2004]

Factorization for $\chi\chi \to \gamma + X$

Sommerfeld enhancement



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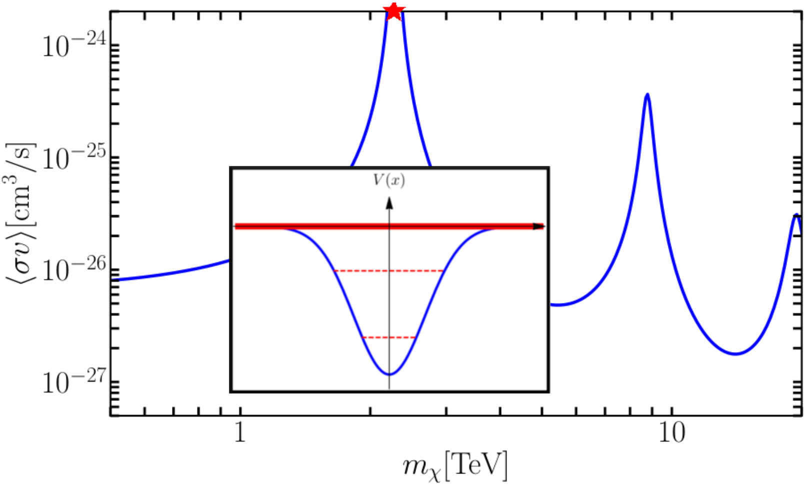

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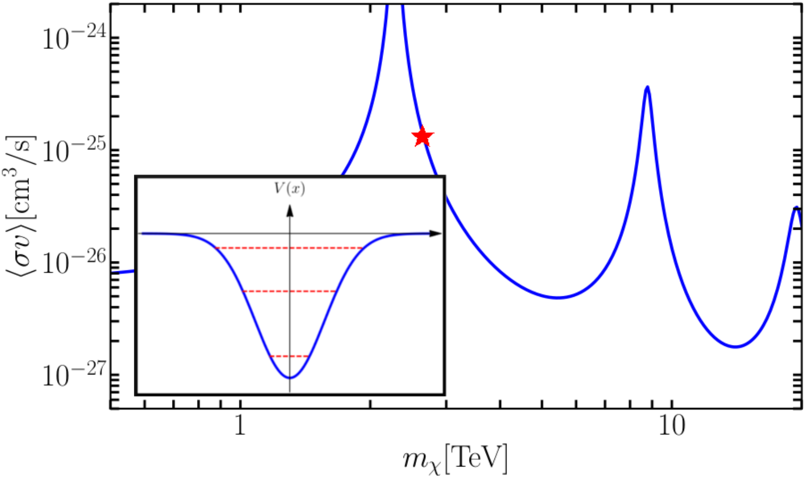

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$$\Gamma_{IJ} \sim \sum_{i,j} C_i(\mu) C_j^*(\mu)\, Z_\gamma^{33}(\mu,\nu)$$
$$\times \int d\omega\, J_{\rm int}(4m_\chi(m_\chi - E_\gamma - \omega/2),\mu)\, W_{IJ}^{ij}(\omega,\mu,\nu)$$

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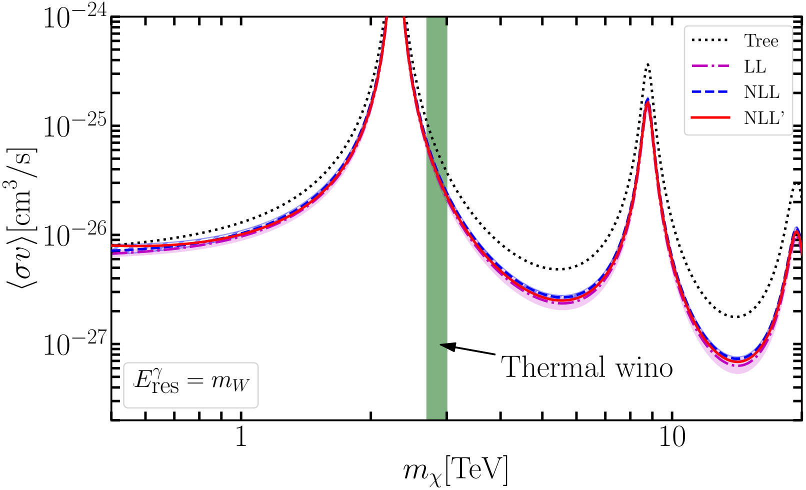
Resum all functions to

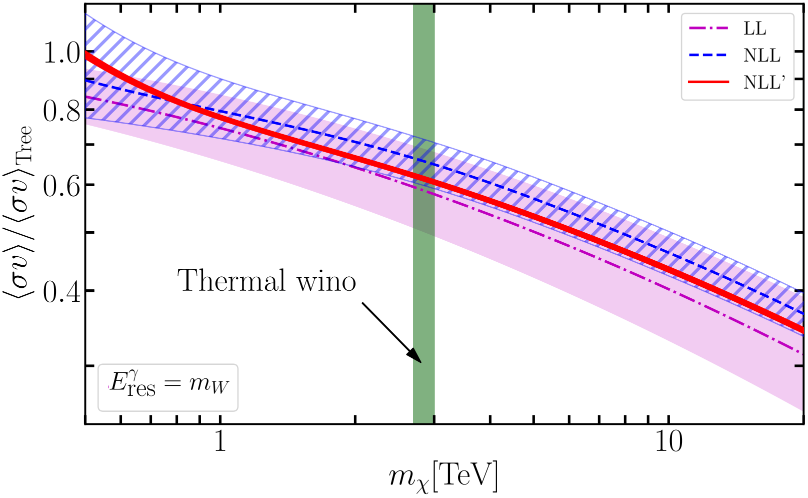
- Leading log (LL) $\exp(\#\ln^2(\#)) \cdot (\text{TL})$
- Next-to-Leading log (NLL) $\exp(\#\ln^2(\#) + \#\ln(\#)) \cdot (\text{TL})$
- NLL' $\exp(\#\ln^2(\#) + \#\ln(\#)) \cdot (\text{TL} + \text{NLO})$

achieve NLL' for both intermediate and narrow resolution case ($E^\gamma_{\rm res} \sim \frac{m_W^2}{m_\chi}$ - different factorization formula)

Predicted cross section



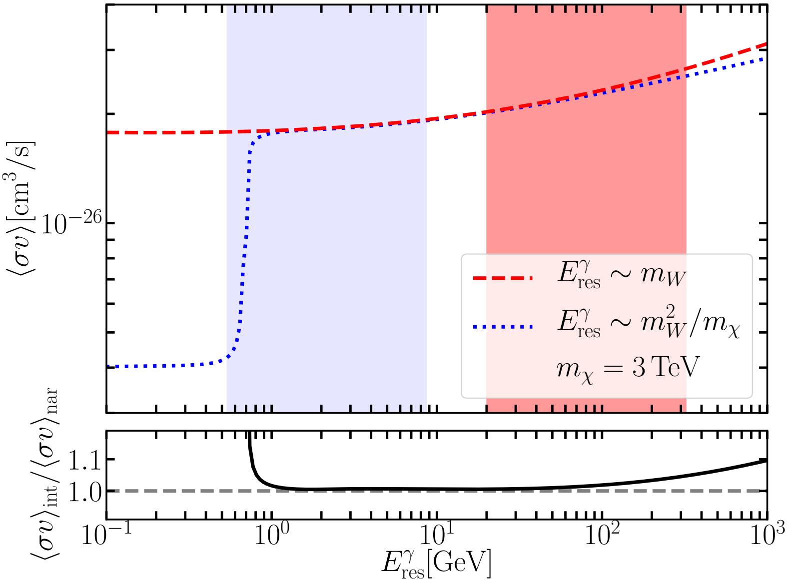
Corrections due to resummation of EW Sudakov logs



Scale uncertainty of NLL' result of order $\lesssim 1\%$!

($\langle \sigma v \rangle_i$ include Sommerfeld factors)

Matching of different EFT descriptions

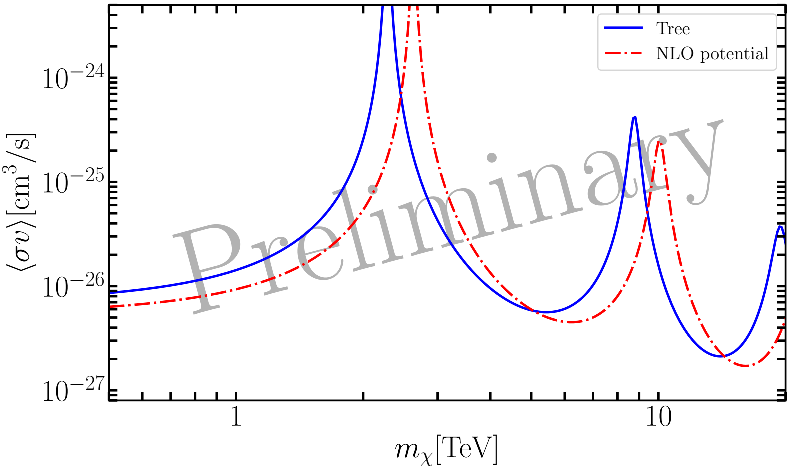


Summary

- Radiative corrections relevant for indirect DM detection of TeV-WIMPs sizeable
  - Sommerfeld enhancement
  - Electroweak Sudakov logarithms $\alpha_2^n \ln^{2n}(m_W/m_\chi)$
- Factorization approach within EFT framework
  - Achieved NLL' accuracy for wino model for resolutions from line signal to $E^\gamma_{\rm res} \approx 4m_W$
  - Suppression of the cross section of $\sim 35\%$ (int. res.) and $\sim 50\%$ (narrow res.) for the thermal wino
- Framework allows similar treatment for wide class of WIMP models $m_\chi \sim \mathcal{O}(\text{TeV})$ and other models with corresponding scales (mediator mass $\ll$ DM mass)

Outlook

Corrections to the potential



[Work in preparation with M. Beneke and R. Szafron]

Summary

- Radiative corrections relevant for indirect DM detection of TeV-WIMPs sizeable
  - Sommerfeld enhancement
  - Electroweak Sudakov logarithms $\alpha_2^n \ln^{2n}(m_W/m_\chi)$
- Factorization approach within EFT framework
  - Treatment of rapidity divergences and resummation of rapidity logs possible
  - Achieved NLL' accuracy for wino model for resolutions from line signal to $E^\gamma_{\text{res}} \approx 4m_W$
  - Theoretical uncertainties from electroweak corrections reduced to $\lesssim 1\%$ for wide range of possible detector resolutions
- Framework allows similar treatment for wide class of WIMP models $m_\chi \sim \mathcal{O}(\text{TeV})$ and other models with corresponding scales (mediator mass $\ll$ DM mass)

Thank you for your attention!

Backup

Operator basis

For the case of the wino find three operators

$$
\begin{aligned}
\mathcal{O}_1 &= \chi_v^{c\dagger}\Gamma^{\mu\nu}\chi_v\,\mathcal{A}^B_{\perp c,\mu}(sn_+)\mathcal{A}^B_{\perp\bar{c},\nu}(tn_-)\,,\\
\mathcal{O}_2 &= \frac{1}{2}\,\chi_v^{c\dagger}\Gamma^{\mu\nu}\{T^A,T^B\}\chi_v\,\mathcal{A}^A_{\perp c,\mu}(sn_+)\mathcal{A}^B_{\perp\bar{c},\nu}(tn_-)\,,\\
\mathcal{O}_3 &= \chi_v^{c\dagger}\sigma^\rho(n_{-\rho}-n_{+\rho})T^C\chi_v\,\epsilon^{CAB}\mathcal{A}^A_{\perp c,\mu}(sn_+)\mathcal{A}^{B,\mu}_{\perp\bar{c}}(tn_-)\,,
\end{aligned}
$$

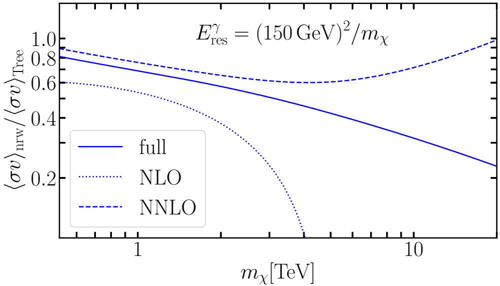
with

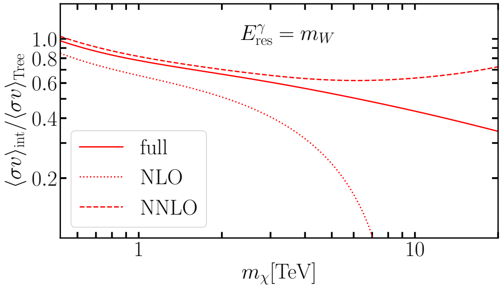
$$
\Gamma^{\mu\nu} = \frac{i}{4}\,[\sigma^\mu,\sigma^\nu]\,\sigma^\alpha(n_{-\alpha}-n_{+\alpha})\,.
$$

For indirect detection only $\mathcal{O}_1$ and $\mathcal{O}_2$ relevant.

Backup

Fixed order expanded results





- Fixed order result breaks down for $m_\chi \sim$ few TeV!
- Resummation of the logs to all orders necessary

$\langle\sigma v\rangle_i$ includes Sommerfeld factors

Backup

Wino potentials - Sommerfeld factors

Wino potential

$$V(r) = \begin{pmatrix} 0 & -\sqrt{2}\alpha_2 \frac{\exp(-m_W r)}{r} \\ -\sqrt{2}\alpha_2 \frac{\exp(-m_W r)}{r} & 2\delta m - \frac{\alpha}{r} - \alpha_2 c_W^2 \frac{\exp(-m_Z r)}{r} \end{pmatrix}$$

with the mass difference $\delta m = 164.1\,\mathrm{MeV}$ for our input parameters [Yamada et al. '09 , Ibe et al. '12]

Solve Schrödinger equation

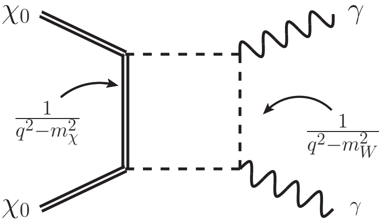
$$\left(\left[-\frac{\nabla^2}{2\mu_I} - E \right] \delta_{IK} + V_{IK}(r) \right) [\psi_E(\mathbf{r})]_{K,ij} = 0$$

to get the necessary Sommerfeld factors

$$S_{IJ} = \left[\psi_{J,00}^{(0,S)} \right]^* \psi_{I,00}^{(0,S)} .$$

Backup

Sudakov logarithms - EFT regions



$$\mathcal{M} \sim g_2^4 \ln^2 \frac{4m_\chi^2}{m_W^2} \gtrsim g_2^2$$

method of regions analysis (int. resolution) for this and similar diagrams $\lambda = m_W/m_\chi$:

- hard modes
  $(k_+, k_-, k_\perp) \sim m_\chi\,(1, 1, 1)$
- hard-collinear modes
  $(k_+, k_-, k_\perp) \sim m_\chi\,(1, \lambda, \lambda^{1/2})$
- anti-collinear modes
  $(k_+, k_-, k_\perp) \sim m_\chi\,(\lambda^2, 1, \lambda)$
- soft modes
  $(k_+, k_-, k_\perp) \sim m_\chi\,(\lambda, \lambda, \lambda)$
- potential modes
  $(k_0, \mathbf{k}) \sim m_\chi(\lambda^2, \lambda)$
- ultrasoft modes
  $(k_+, k_-, k_\perp) \sim m_\chi\,(\lambda^2, \lambda^2, \lambda^2)$

similar for narrow resolution

(hard-collinear $\rightarrow$ collinear)

Backup

Factorization formula

Factorization formula - Example intermediate resolution case

$$\frac{d(\sigma v_{\rm rel})}{dE_\gamma} = \sum_{I,J} S_{IJ}\;\Gamma_{IJ}(E_\gamma) \qquad \text{with} \quad I,J = (00),(+-)$$

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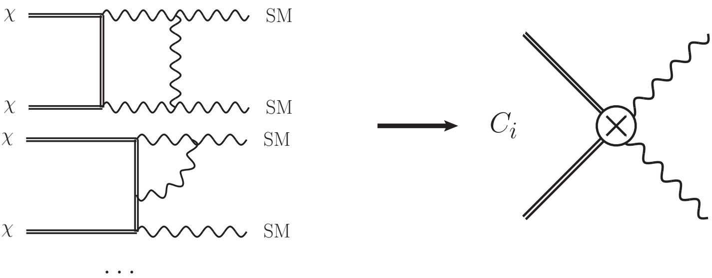

Hard Wilson coefficients - hard modes $(k_+, k_-, k_\perp) \sim m_\chi\,(1,1,1)$

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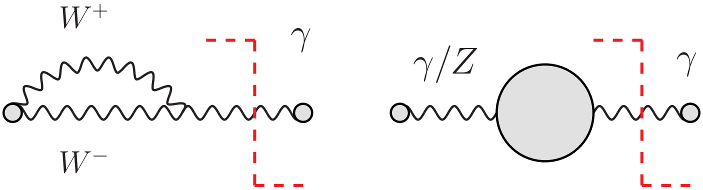

Photon jet function - anti-collinear modes $(k_+, k_-, k_\perp) \sim m_\chi(1, \lambda^2, \lambda)$

like a generalized on-shell Z-factor

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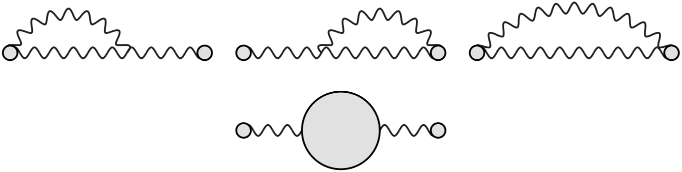

Unobserved jet function - hard-collinear modes $(k_+, k_-, k_\perp) \sim m_\chi\,(\lambda, 1, \sqrt{\lambda})$

virtuality $k^2 \sim m_\chi^2 \lambda \sim 2 m_\chi m_W \gg m_W^2$ - object in the unbroken theory

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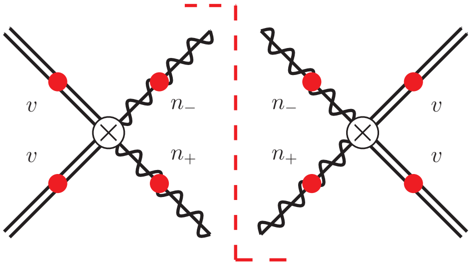

Soft function - soft modes $(k_+, k_-, k_\perp) \sim m_\chi\,(\lambda,\lambda,\lambda)$