Heavy Dark Matter Annihilation from Effective Field Theory

AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

Grigory Ovanesyan

with T.R. Slatyer, I.W. Stewart (arXiv:1409.8294 accepted to PRL)

related work:

A. Hryczuk, R. Iengo, 1111.2916 (JHEP)

M. Baumgart, I. Rothstein, V. Vaidya, 1409.4415

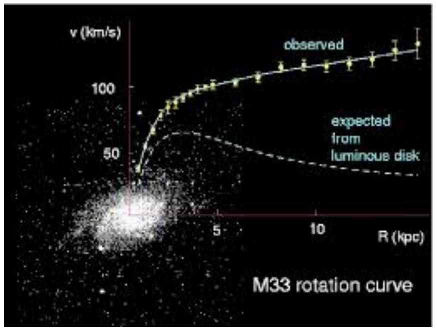
M.Bauer, T.Cohen, R.J.Hill, M.P. Solon, arxiv:1409.7392

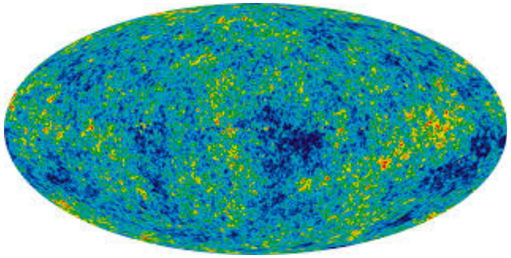
SCET 2015, Santa Fe, NM

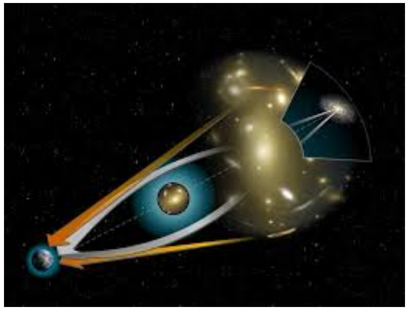
Outline

- Motivation
- Heavy dark matter annihilation to a pair of neutral gauge bosons from SCET
- Results
- Conclusions

Motivation

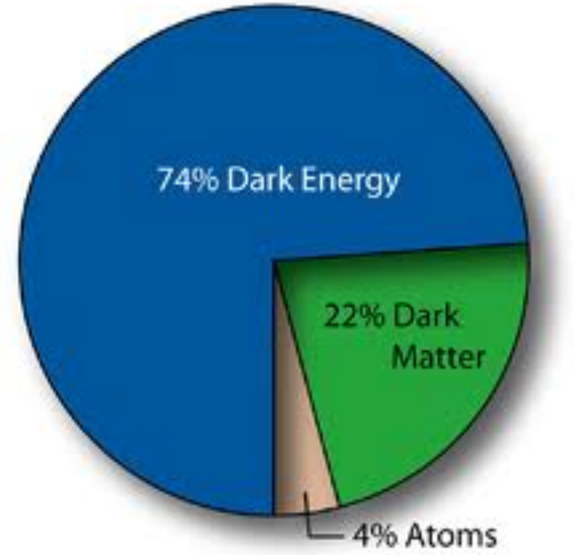


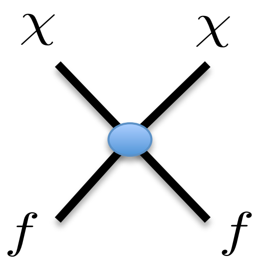




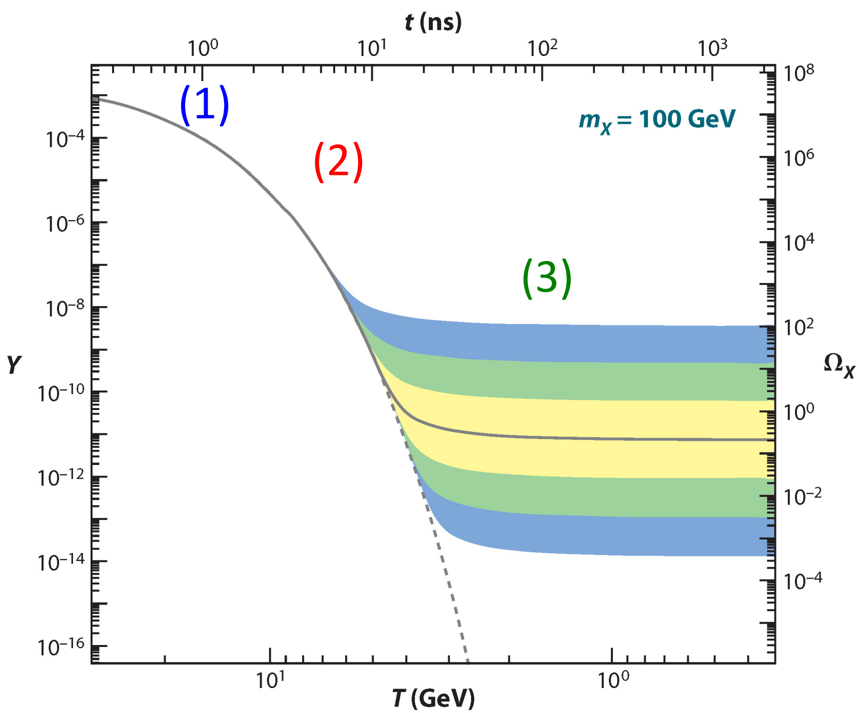
$$\Omega_{\rm DM} \approx 0.22$$

- Overwhelming evidence of dark matter presence in the universe
- All observation based on gravitational interactions only





The "WIMP miracle"



(1) A new heavy particle is in thermal equilibrium

$$\chi\bar{\chi} \leftrightarrow f\bar{f}$$

(2) Universe cools down

$$\chi\bar{\chi} \;\overset{\rightarrow}{\not\leftarrow}\; f\bar{f}$$

(3) Dark matter species freeze out

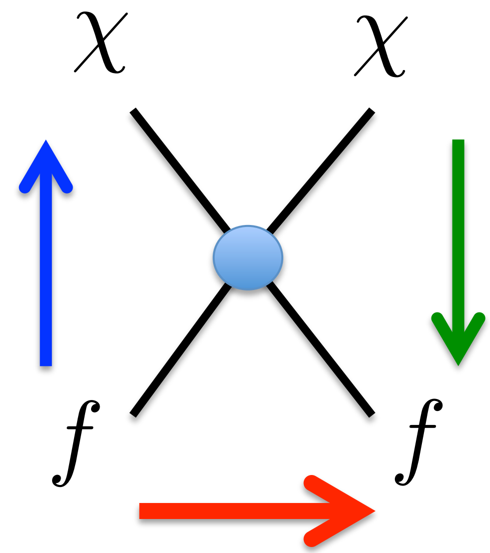
$$\chi\bar{\chi} \;\overset{\not\rightarrow}{\not\leftarrow}\; f\bar{f}$$

$$\Omega_\chi h^2 \sim \frac{3\times 10^{-26}\mathrm{cm}^3/s}{\langle\sigma v\rangle} \sim \mathcal{O}(0.1)$$

(for weak scale interactions)

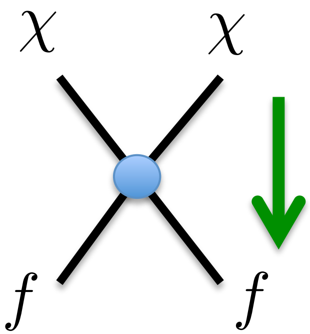
Search for non-gravitational DM interactions

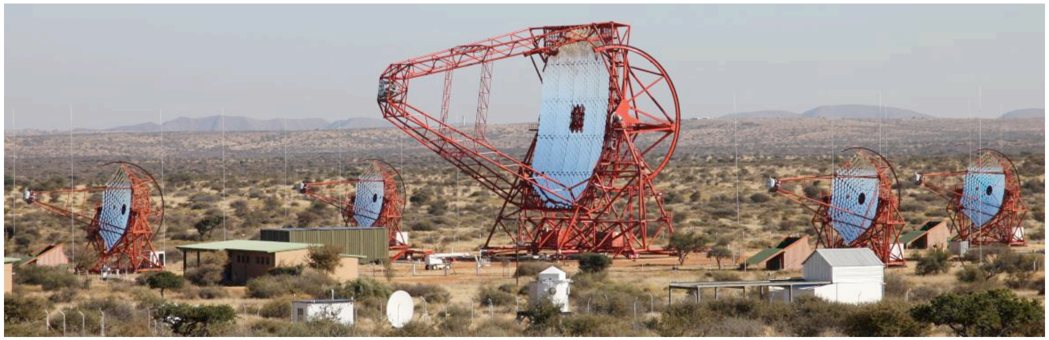
- Produce at LHC
- Indirect detection
- Direct detection



- In this talk we focus on DM annihilation to the pair of SM gauge bosons

Indirect searches





Victor Hess,
nobel laureate who
discovered cosmic rays

- Many different experiments looking for access over the astrophysical backgrounds of photons, neutrinos, positrons, etc. with the goal of observing DM in our galaxy
- **H**igh **E**nergy **S**tereoscopic **S**ystem (H.E.S.S)

Located in Namibia

Cosmic gamma rays in the range ~10 GeV to ~100 TeV

So far only observations consistent with backgrounds. Limits on DM models

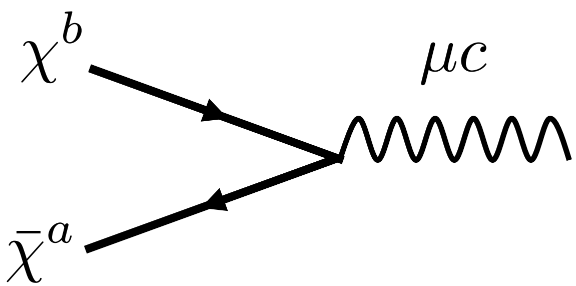
Upcoming more sensitive instrument: CTA (planned for 2020)

The model

Consider Majorana SU(2) triplet $\chi^{1,2,3}$ (wino-like DM)

$$\chi = \begin{pmatrix} \chi_0/\sqrt{2} & \chi^+ \\ \chi^- & -\chi_0/\sqrt{2} \end{pmatrix} \qquad \mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}{\rm Tr}\,\bar{\chi}\, i\not{D}\,\chi - \frac{1}{2}\,{\rm Tr}\,\bar{\chi} M_\chi \chi,$$

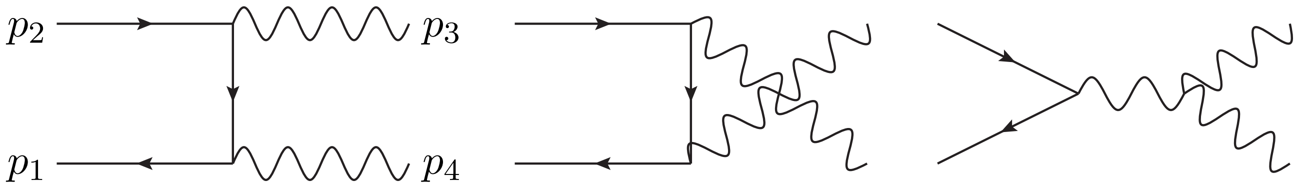
Feynman rule of DM-SU(2) gauge boson interaction:



$$= g\,\epsilon^{abc}\gamma_\mu$$

We are interested in a few TeV DM particles to annihilate to a pair of SM gauge bosons

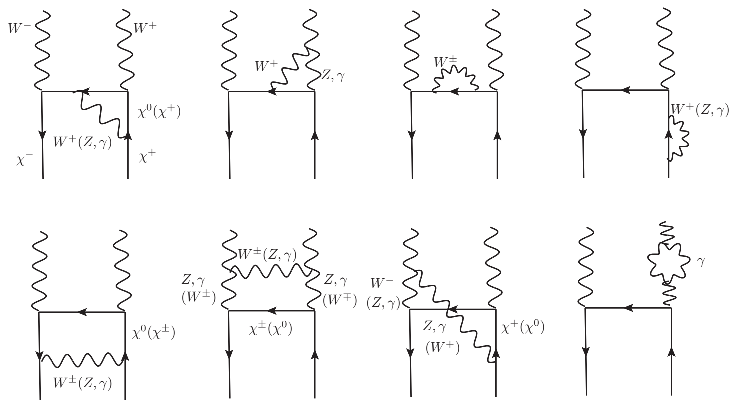
Annihilation at tree level

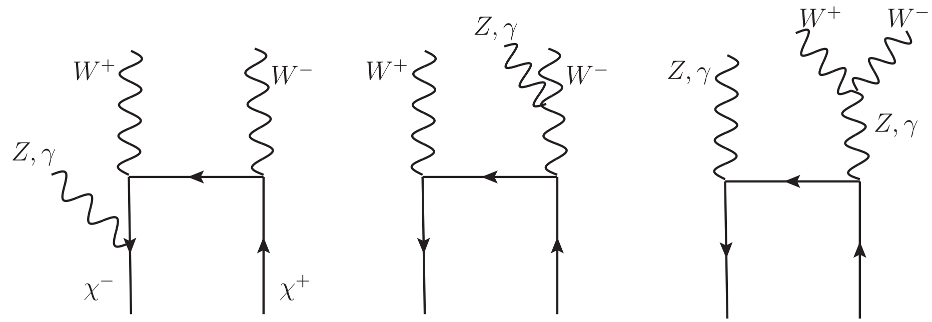


Sum of these graphs gives in the limit $M \gg M_{EW}$ s-wave amplitudes, all proportional to each other depending on the isospin structure

$$\sigma v_{\rm rel}(\chi^0\chi^0 \to W^+W^-) = \frac{2\pi\alpha^2}{m_\chi^2}$$

Why loops are important?

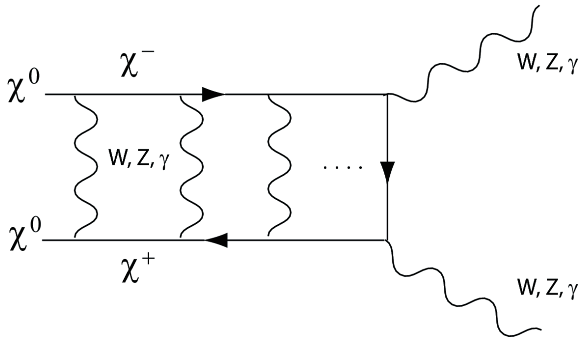




Two reasons:

- Sommerfeld enhancement (initial state)
- Large Sudakov logarithms (final state)

Sommerfeld enhancement



$$\sim \left(\frac{\alpha_2}{v}\right)^n$$

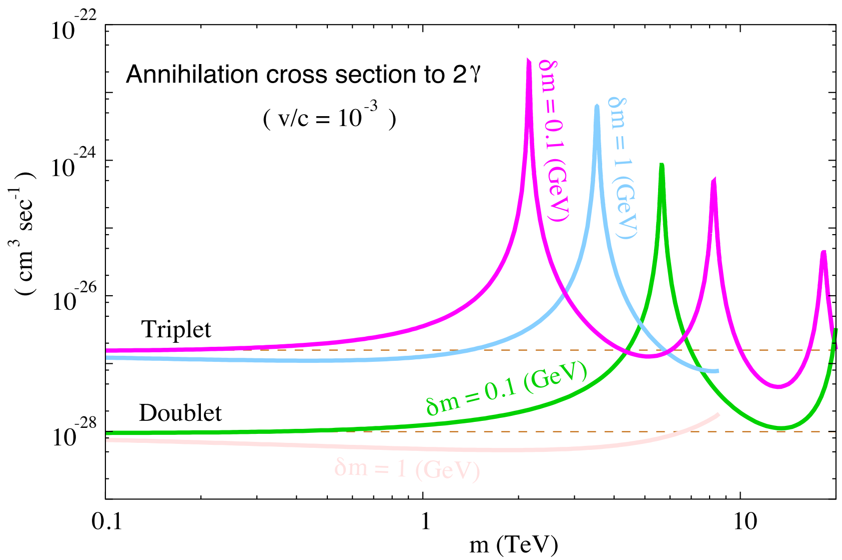
Sommerfeld enhancement is treated via NR Schrodinger equation with a (Yukawa or Coulomb) potential

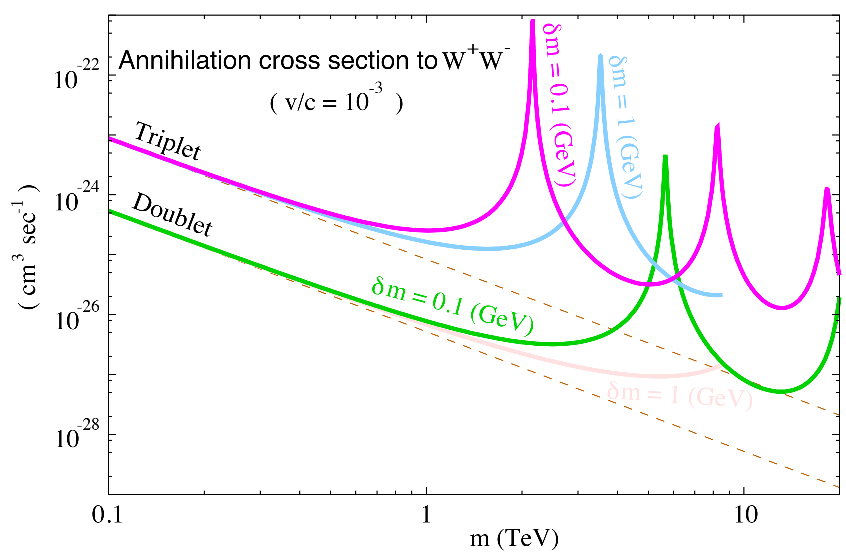
Hisano, Matsumoto, Nojiri, 2003

Hisano, Matsumoto, Nojiri, Saito, 2004

$$\mathcal{L} = \frac{1}{2}\mathbf{\Phi}^T(\mathbf{r})\left(\left(E + \frac{\nabla^2}{m}\right)\mathbf{1} - \mathbf{V}(r) + 2i\mathbf{\Gamma}\delta^3(\mathbf{r})\right)\mathbf{\Phi}(\mathbf{r})$$

$\mathbf{\Phi}(\mathbf{r}) = (\phi_C(\mathbf{r}),\ \phi_N(\mathbf{r}))$ $\quad \phi_N(\mathbf{r})(\simeq 1/2\chi^0\chi^0)$ and $\phi_C(\mathbf{r})(\simeq \chi^-\chi^+)$





Large Sudakov logarithms

Electroweak corrections small?

U(1) $\alpha_1 = \frac{\alpha_{\rm em}}{\cos^2\theta_W} \approx 0.01$

SU(2) $\alpha_2 = \frac{\alpha_{\rm em}}{\sin^2\theta_W} \approx 0.03$

- Naive analysis of loop diagrams with SU(2) and U(1) gauge bosons of SM gives a small result
- However such loop diagrams contain Sudakov double logarithms: $\alpha \ln^2 s/M^2_{W,Z}$

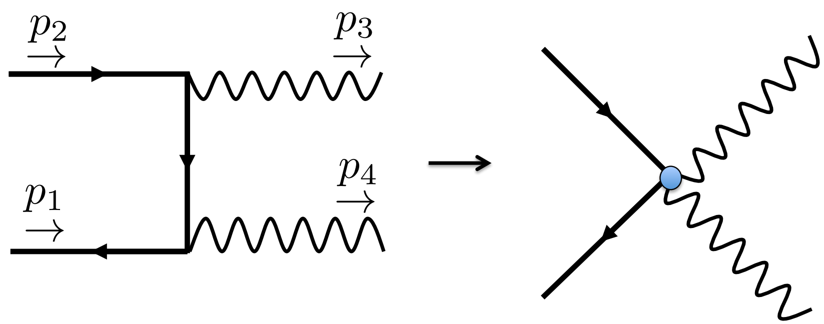
For center of mass energy 1TeV this is an enhancement factor of 21!

$\frac{\alpha_2}{2\pi} \times 21 \approx 0.10$ leads to a sizable effect at TeV scale!

Formalism to resum electroweak Sudakov logarithms using SCET adapted for SU(2) and U(1) gauge bosons ($\mathrm{SCET}_{\mathrm{EW}}$) was developed in Chiu, Golf, Kelley, Manohar, 2007-2010

Is up the order of 40% correction to the LHC cross section for WW production

Our Goal



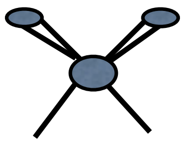
- Factorize and resum electroweak corrections using NRDM/SCET

logarithmic counting: $\alpha L \sim 1$

leading logarithmic order	$1 + \alpha L^2 + \alpha^2 L^4 + \alpha^3 L^6 \ldots,$	LL
next-to-leading logarithmic order	$\alpha L + \alpha^2 L^3 + \alpha^3 L^5 \ldots,$	NLL
next-to-next-to-leading logarithmic order	$\alpha + \alpha^2 L^2 + \alpha^3 L^4 \ldots.$	NNLL

Heavy dark matter annihilation to a pair of neutral gauge bosons from SCET

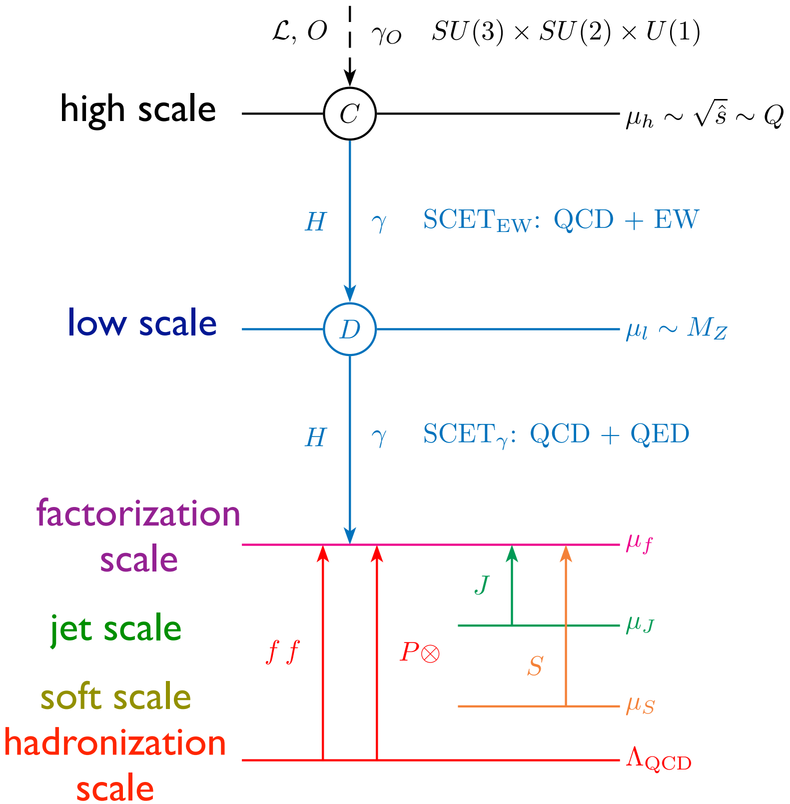
$\mathrm{SCET}_{\mathrm{EW}}$



- Integrate out hard modes at high scale
- Run with anomalous dimension of EFT to the low scale
- Integrate out W and Z bosons at the low scale
- Run to factorization scale

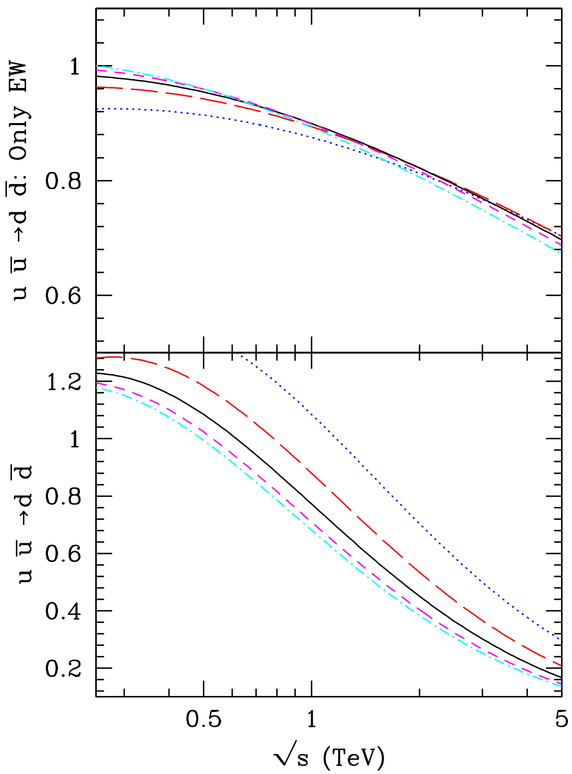
$$\mathcal{M} = \exp\left[\boldsymbol{D}(\alpha(\mu_l))\right] \, P \exp\left(\int_{\mu_h}^{\mu_l} \frac{d\mu}{\mu} \gamma(\alpha(\mu))\right) \times \boldsymbol{c}\left(\alpha(\mu_h), \left\{\ln \frac{p_i \cdot p_j}{\mu_h^2}\right\}\right),$$

Chiu, Golf, Kelley, Manohar (07)

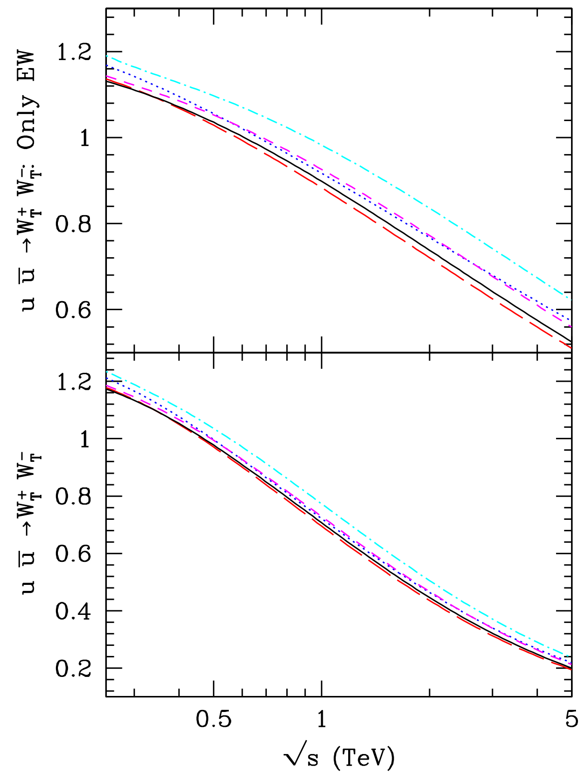


Some results for LHC

- Chiu, Golf, Kelley, Manohar 07-10 (NNLL)



$u\bar{u} \rightarrow d\bar{d}$



$u_L\bar{u}_L \rightarrow W_T^+W_T^-$

Electroweak Sudakov corrections to transverse WW production at 2 TeV suppress cross section by 40%

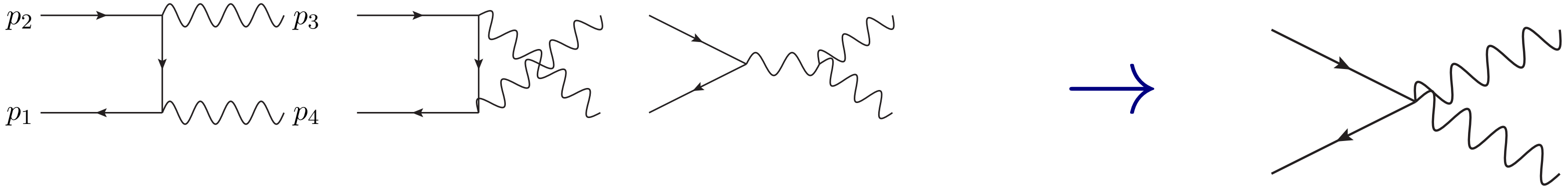
Suppression rate rapidly grows with energy!

What needs to be calculated

- We are after NLL resummation
- Need high scale matching at tree level (our analysis)
- Need the non-cusp anomalous dimension matrix at one loop (our analysis)
- Need the cusp anomalous dimension at 2 loops (known ✓)
- Need the rapidity log part of the one-loop that depends on M_W, M_Z (known ✓)

High Scale Matching

- For NLL resummation tree level matching needed

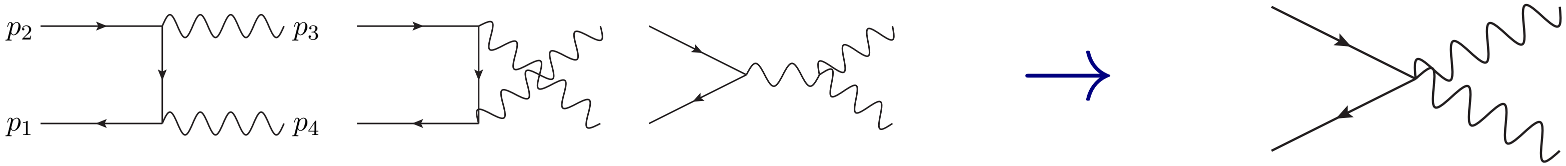


- At the high scale $\mu_h \sim 2m_\chi$ we match on a set of local operators

$$M_1 + M_2 + M_3 = \frac{g^2}{2m_\chi^2} \underbrace{\bar{v}\gamma^\sigma \gamma_5 u}_{\chi\chi \text{ in the spin singlet}} \underbrace{\epsilon_{\alpha\sigma\mu\nu}\, q^\alpha \left(2\delta^{ab}\delta^{cd} - \delta^{ac}\delta^{bd} - \delta^{ad}\delta^{bc}\right) \epsilon^\mu \epsilon^\nu}_{\text{gauge bosons in the spin singlet}}$$

We need to match this amplitude on a tree level matrix elements of gauge invariant SCET operators

Gauge invariant EFT Operators

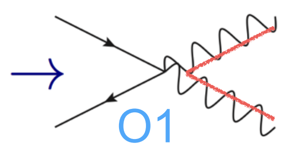


$$\mathcal{L}^{(0)}_{\rm ann} = \sum_{r=1}^{2} C_r(m_\chi, \mu) O_r(m_{W/Z}, v, \mu)$$

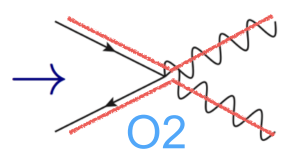
$$O_r = \underbrace{(\chi_v^{aT} i\sigma_2 \chi_v^b)}_{\chi\chi \text{ in the spin singlet}} \underbrace{\left(S_r^{abcd} \mathcal{B}^{ic}_{n\perp} \mathcal{B}^{jd}_{\bar{n}\perp}\right) i\epsilon^{ijk}(n-\bar{n})^k}_{\text{gauge bosons in the spin singlet}}$$

GO, T.Slatyer, I. Stewart, 2014

$$S_1^{abcd} = \delta^{ab}\left(S_n^{ce} S_{\bar{n}}^{de}\right) \rightarrow$$



$$S_2^{abcd} = \left(S_v^{ae} S_n^{ce}\right)\left(S_v^{bf} S_{\bar{n}}^{df}\right) \rightarrow$$



$$C_1(\mu_{m_\chi}) = -C_2(\mu_{m_\chi})$$
$$= -\pi \frac{\alpha_2(\mu_{m_\chi})}{m_\chi}$$

Sudakov-Sommerfeld factorization

$$\mathcal{L}^{(0)}_{\mathrm{NRDM}} = \chi_v^\dagger \left(iv\cdot\partial + \frac{\vec{\nabla}^2}{2m_\chi} \right) \chi_v + \hat{V}\left[\chi_v^{(\dagger)}\right](m_{W,Z})$$

- $\mathcal{L}^{(0)}_{\mathrm{NRDM}}$ contains no interactions with soft of collinear gauge bosons
- The leading SCET Lagrangian $\mathcal{L}^{(0)}_{\mathrm{SCET}}(\xi_n, A_n, A_s)$ contains no interactions with DM fields χ_v

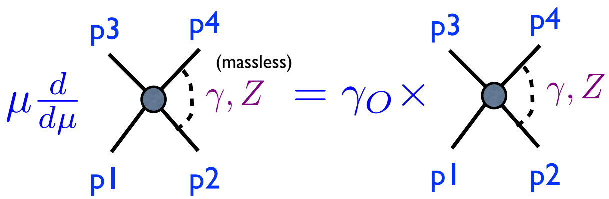
Sudakov piece

$$C_r\langle X|O_r|\chi^0\chi^0\rangle = \left[C_r\, i\epsilon^{ijk}(n-\bar{n})^k\langle X|S_r^{abcd}\,\mathcal{B}^{ic}_{n\perp}\mathcal{B}^{jd}_{\bar{n}\perp})|0\rangle\right]$$

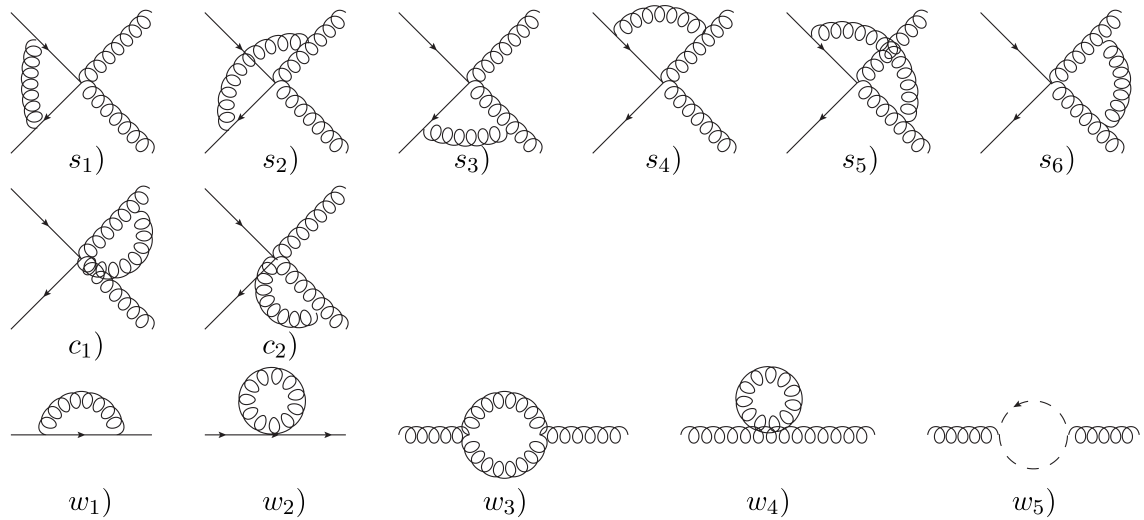
$$\times\,\langle 0|\chi_v^{aT}i\sigma_2\chi_v^b|\chi^0\chi^0\rangle$$

Sommerfeld piece

Anomalous Dimension Matrix



$$\mu\frac{d}{d\mu}C(\mu) = -\gamma_O^T C(\mu)$$



Collinear graphs universal and known (for example see Chiu et al). Soft graphs need to be computed

Previous formalism for resumming EW logs with SCET_{EW} by Chiu et al only considered boosted massive particles (bHQET), we extended their formalism for the un-boosted scenario (HQET).

Used Δ regulator for regularizing the Wilson lines

Chiu, Golf, Kelley, Manohar, 2007-2010

Soft Anomalous dimension

Collinear graphs depend on delta regulators: δ_3, δ_4

Adding the soft graphs cancels this regulator dependence

$$\hat{\gamma} = 2\gamma_{W_T}\mathbb{1} + \hat{\gamma}_S$$

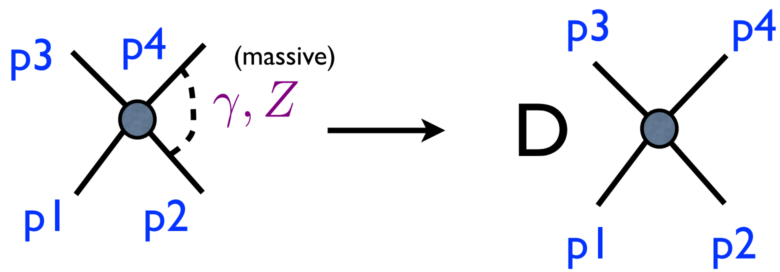
$$\hat{\gamma}_S^{\text{NLL}} = \frac{\alpha_2}{\pi}(1 - i\pi)\begin{pmatrix} 2 & 1 \\ 0 & -1 \end{pmatrix} - \frac{2\alpha_2}{\pi}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

GO, T.Slatyer, I. Stewart, 2014

Low Scale Matching

Chiu, Golf, Kelley, Manohar, 2007-2010

At the low scale $\mu_l = M_Z$ we integrate out the massive gauge bosons



The low scale matching coefficient has been calculated in Manohar et al. up to NNLL order. Keeping NLL order terms we get the result of “low scale matching”

$$W^\dagger W_\perp^\pm = \exp(D_1)\, W_\perp^\pm, \qquad W^\dagger W_\perp^3 = \exp(D_2)\,(Z_\perp \cos\theta_W + A_\perp \sin\theta_W)\ .$$

$$D_1(\mu_l) = \frac{\alpha_2(\mu_l)\ln\frac{s}{\mu_l^2}}{4\pi}\left(\ln\frac{M_W^2}{\mu_l^2} + c_W^2 \ln\frac{M_Z^2}{\mu_l^2}\right), \qquad D_2(\mu_l) = \frac{\alpha_2(\mu_l)\ln\frac{s}{\mu_l^2}}{2\pi}\ln\frac{M_W^2}{\mu_l^2}\ .$$

We now have all ingredients to perform NLL resummation of wino annihilation cross section

Analytical resummed result at NLL

GO, T.Slatyer, I. Stewart, 2014

$$\sigma_{\chi^0\chi^0\to X} = \sigma^{\text{tree}}_{\chi^+\chi^-\to X}\left| s_{00}(\Sigma_1 - \Sigma_2) + \sqrt{2} s_{0\pm}\Sigma_1 \right|^2$$

$$\Sigma_1 = \frac{e^{\Omega+D}}{3}\left(2\, z^{-\frac{4\psi}{b_0}} + z^{\frac{2\psi}{b_0}}\right),$$

$$\Sigma_1 - \Sigma_2 = \frac{2\, e^{\Omega+D}}{3}\left(z^{-\frac{4\psi}{b_0}} - z^{\frac{2\psi}{b_0}}\right),$$

$$\psi = 1 - i\pi$$

$$z = \frac{\alpha_2(\mu_Z)}{\alpha_2(\mu_{m_\chi})}$$

$$\Omega = \frac{-2\pi\Gamma_0^g\,(z\ln z + 1 - z)}{b_0^2\,\alpha_2(\mu_Z)} - \frac{\Gamma_0^g\, b_1\left(\ln z - z - \frac{\ln^2 z}{2} + 1\right)}{2b_0^3}$$

$$-\frac{\ln z}{2b_0}\left[8\left(\ln\frac{4m_\chi^2}{\mu_{m_\chi}^2} - 1\right) - 2b_0\right] - \frac{\Gamma_1^g}{2b_0^2}\,(z - \ln z - 1)$$

$$\Sigma_1^{\text{LL}} = \Sigma_2^{\text{LL}} = \exp\left(-\frac{\alpha_2 \ln^2 \mu_{m_\chi}^2/\mu_{m_Z}^2}{2\pi}\right)$$

Existing literature

Hisano, Matsumoto, Nojiri, 2003

Tree level EW calculation, Sommerfeld enhancement treated to all orders

Hryczuk, Iengo, 2011

One loop fixed order calculation of loops with electroweak gauge bosons

Baumgart, Rothstein, Vaidya, 2014

Wino DM. Resummation of electroweak Sudakov logs to LL order (inclusive)

$$\chi\chi \to \gamma X$$

M.Bauer, T.Cohen, R.J.Hill, M.P. Solon, 2014

Scalar DM. Resummation of Sudakov logs to NLL order (exclusive)

$$\phi\phi \to \gamma\gamma$$

GO, Slatyer, Stewart, 2014

Wino DM. Resummation of electroweak Sudakov logs to NLL order (exclusive)

$$\chi\chi \to \gamma\gamma$$

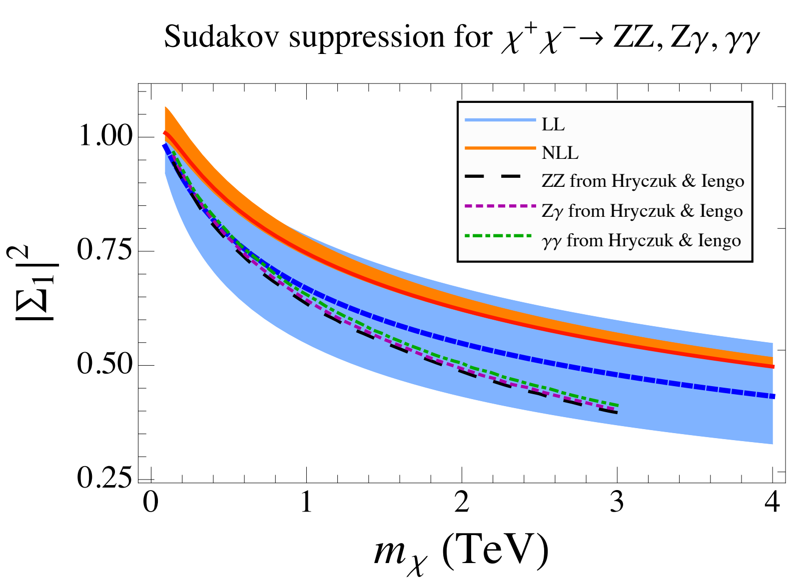
Results

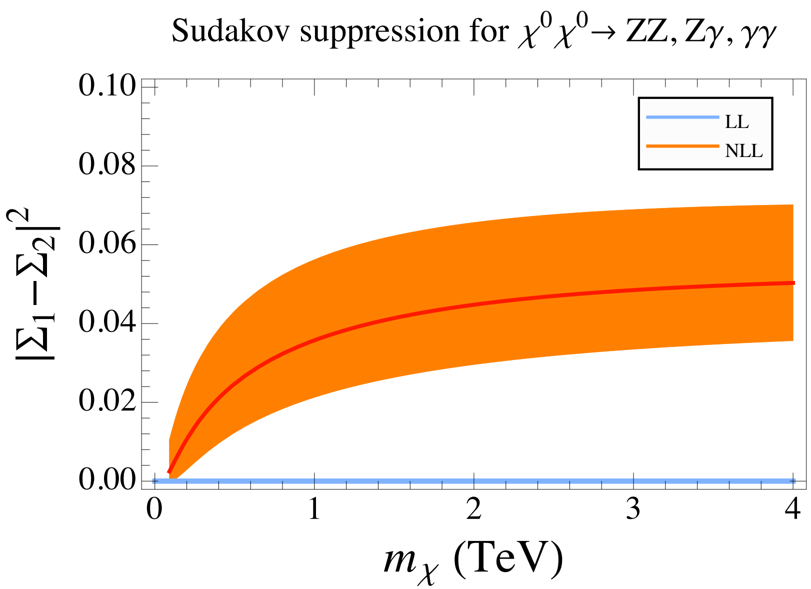
Numerical results for NLL cross section

Electroweak corrections only

(compared to Hryczuk, Iengo, 2011)

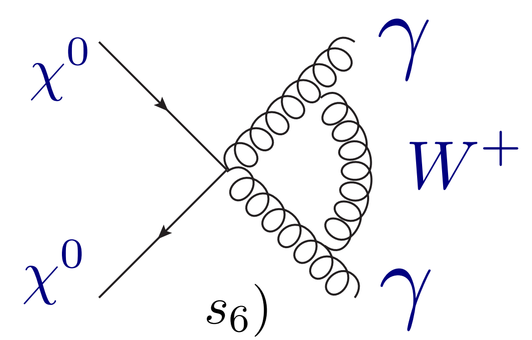
$$\sigma_{\chi^0\chi^0\to X} = \sigma^{\rm tree}_{\chi^+\chi^-\to X}\left|s_{00}(\Sigma_1 - \Sigma_2) + \sqrt{2}s_{0\pm}\Sigma_1\right|^2$$





$$\chi_0\chi_0 \to \gamma\gamma$$

(appears only at the (EW) loop level)

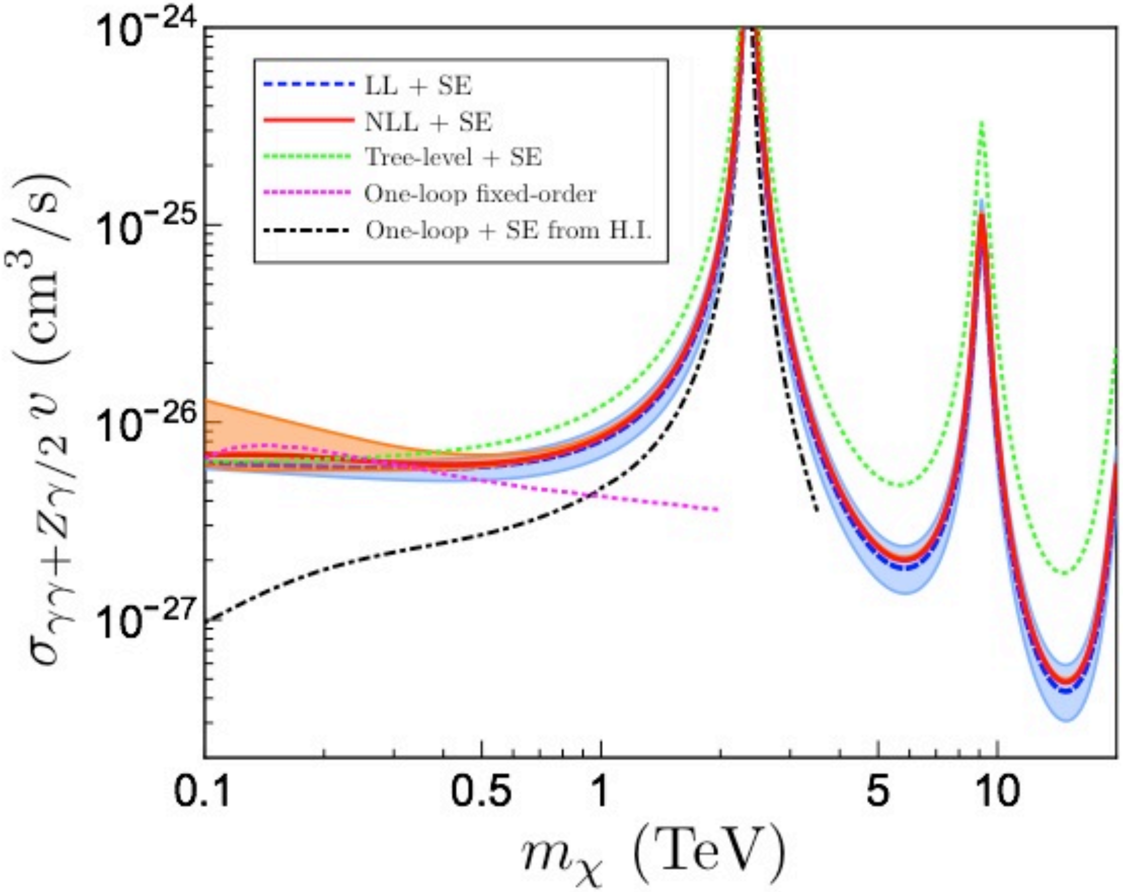


Total annihilation cross section

Electroweak corrections and Sommerfeld enhancement

$$\sigma_{\chi^0\chi^0\to X} = \sigma^{\text{tree}}_{\chi^+\chi^-\to X}\left|s_{00}(\Sigma_1 - \Sigma_2) + \sqrt{2}s_{0\pm}\Sigma_1\right|^2$$

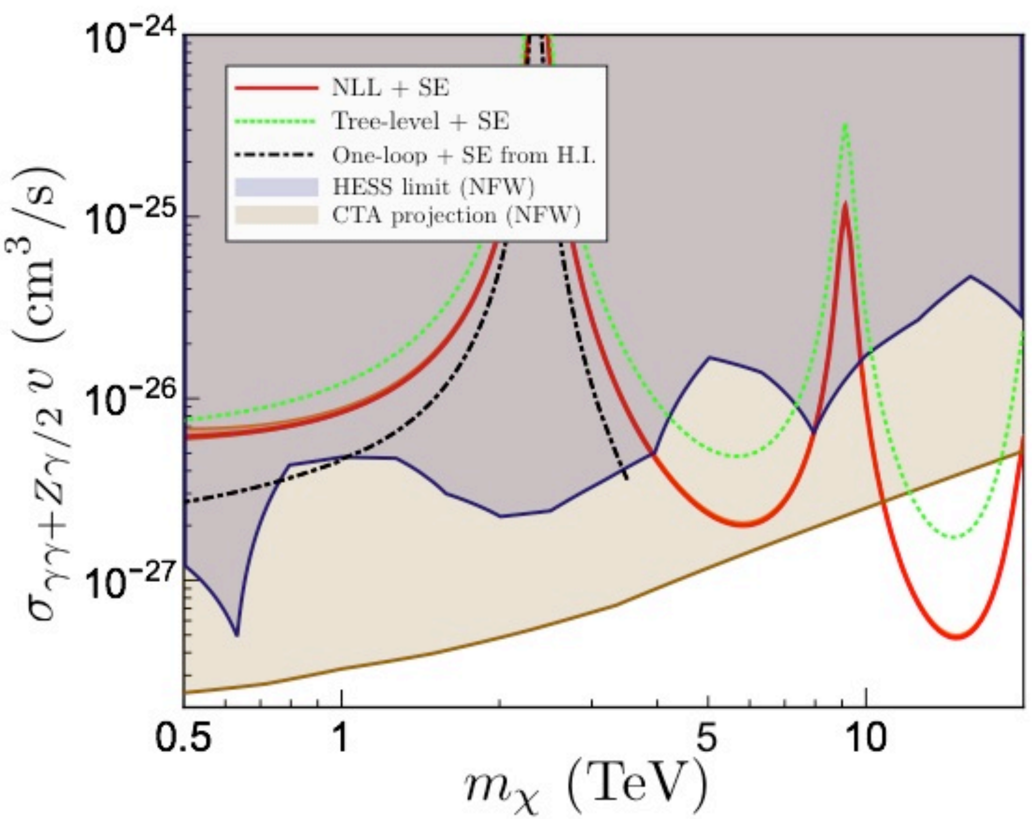
- Good agreement with the fixed order calculation 1 in the low mass region
- Disagreement in the low mass region for SE +fixed order one loop caculation 2 (only valid for large DM mass)
- SM+NLL bound has a 5% perturbative uncertainty



Total annihilation cross section

Bounds from HESS line photons data and projected CTA

- We assume wino constitutes all of DM
- NFW profile



Conclusions

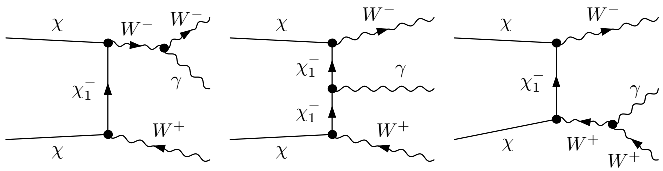
- For heavy DM the annihilation rate suffers from large Sudakov double logarithms
- We resummed these logarithms to NLL order using SCET
- Our results have uncertainty of 5% level and make the DM indirect detection phenomenology robust
- The Sudakov suppression effect is of the order of a factor 2-3 for the DM mass of the order of a few TeV

BACKUP

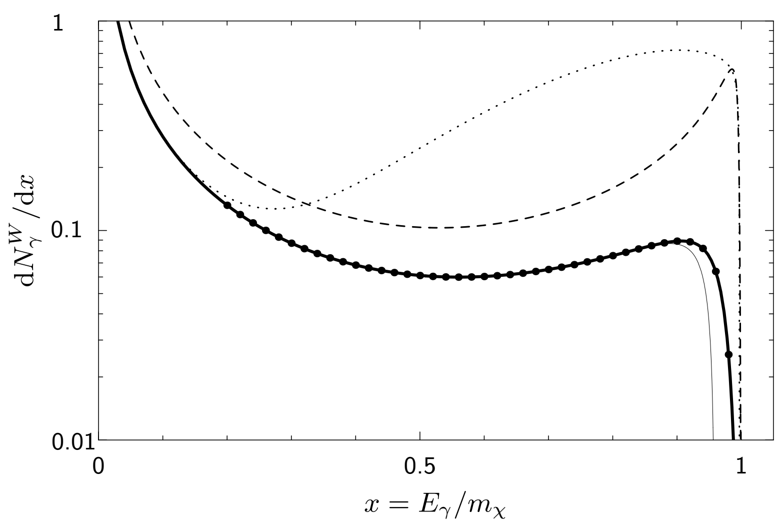
Contribution from $WW\gamma$

Gamma Rays from Heavy Neutralino Dark Matter

Lars Bergström,* Torsten Bringmann,† Martin Eriksson,‡ and Michael Gustafsson§
Department of Physics, Stockholm University, AlbaNova University Center, SE - 106 91 Stockholm, Sweden
(Dated: August 8, 2005)



$$
\begin{aligned}
\frac{\mathrm{d}N_\gamma^W}{\mathrm{d}x} &\equiv \frac{\mathrm{d}(\sigma v)_{WW\gamma}/\mathrm{d}x}{(\sigma v)_{WW}} \\
&\simeq \frac{\alpha_{\mathrm{em}}}{\pi}\left[\frac{4(1-x+x^2)^2\ln(2/\epsilon)}{(1-x)x}\right. \\
&- \frac{2(4-12x+19x^2-22x^3+20x^4-10x^5+2x^6)}{(2-x)^2(1-x)x} \\
&+ \frac{2(8-24x+42x^2-37x^3+16x^4-3x^5)\ln(1-x)}{(2-x)^3(1-x)x} \\
&+ \delta^2\left(\frac{2x(2-(2-x)x)}{(2-x)^2(1-x)} + \frac{8(1-x)\ln(1-x)}{(2-x)^3}\right) \\
&\left. + \delta^4\left(\frac{x(x-1)}{(2-x)^2} + \frac{(x-1)(2-2x+x^2)\ln(1-x)}{(2-x)^3}\right)\right]
\end{aligned}
$$



- The issue of peaking in the signal bin x-->1 is DM mass dependent
- More work is needed to understand precisely the background subtraction procedure of HESS and whether three body final states get subtracted or not