Electroweak corrections to DM annihilations

Michael Kachelrieß

NTNU, Trondheim

Outline of the talk

1. Introduction
   - Motivation
   - Recap: LLO and MLLO corrections in QCD
2. Electroweak bremsstrahlung
3. Phenomenological consequences:
   - Hidden annihilations $XX \to \nu\nu$
   - Limits on leptophilic models $XX \to e^+e^-$
4. Conclusions

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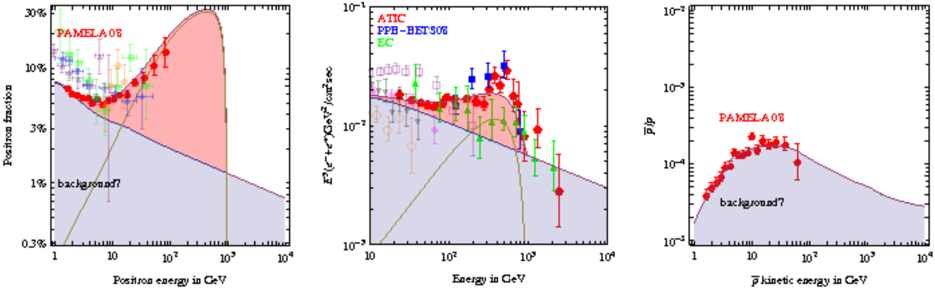
DM annihilations and PAMELA

DM with $M = 1$ TeV that annihilates into $\mu^+\mu^-$



non-standard branching ratios: only leptons

- boost factor 1000 needed
- but minimal γ-ray flux from Bremsstrahlung not seen

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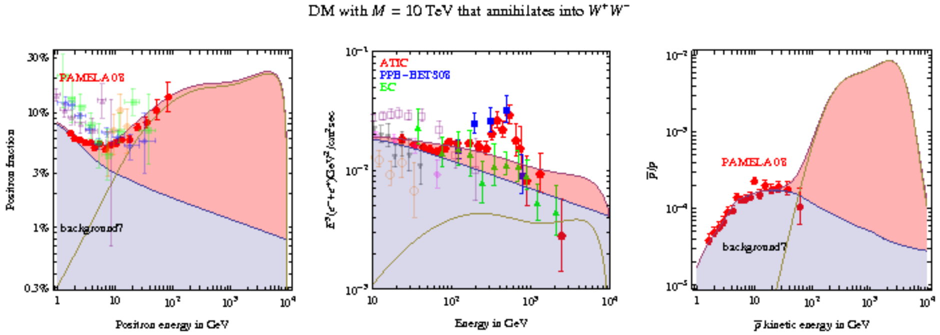

standard branching ratios:

- hide $\bar{p}$ above $E_{\max}$ of Pamela
- happy with $M = 10$ TeV?

WIMPs as thermal relics:

- expansion of universe freezes out annihilation reactions, when

$$\Gamma_{\rm ann} = n\langle\sigma_{\rm ann} v\rangle \approx H$$

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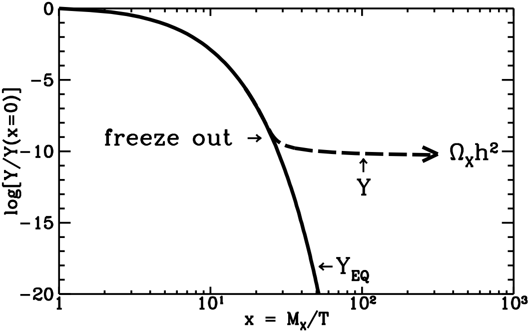

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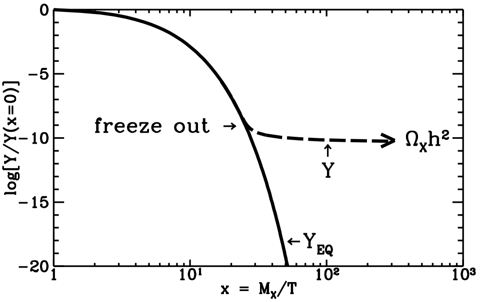

$$\Omega_X h^2 \propto \frac{x_f}{\langle\sigma_{\rm ann} v\rangle} \sim \frac{3\times 10^{-26}{\rm cm}^3/{\rm s}}{\langle\sigma_{\rm ann} v\rangle}$$

⇒ "WIMP miracle:"
suggests weakly interacting DM particle with mass $m \sim m_Z$

Connection of Ω_X and $\langle\sigma_{\rm ann} v\rangle$

- thermally averaged annihilation cross section

$$\langle\sigma_{\rm ann} v\rangle = \sigma_0 + \sigma_1 v^2 + \sigma_2 v^4 + \ldots$$

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- known value of Ω_X fixes σ_0 today

Unitarity induces upper limit on thermal M_X

- Unitarity of S-matrix restricts annihilations into ℓ.th partial wave,

$$\sigma_{\rm ann}^{(\ell)} v_{\rm rel} \leq 4\pi \, \frac{2\ell+1}{v_{\rm rel} M_X^2}$$

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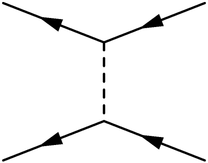
- Multi-TeV DM is interacting pretty strongly

Annihilations of Majorana DM:

- annihilation $XX \to \bar{f}f$ via t exchange of SU(2) scalar



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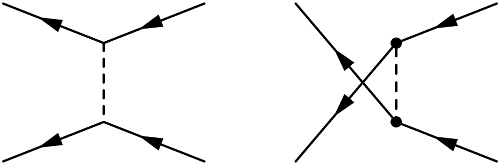

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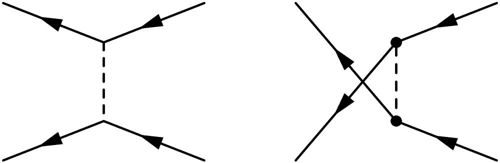

- for $v_{\rm rel} \to 0$, neutralino pair behaves as a pseudoscalar,

$$u_1(P)\bar{v}_2(P) - u_2(P)\bar{v}_1(P) = (m_\chi + \not{P})\gamma_5 \quad , \quad |\rightarrow\rangle|\leftarrow\rangle\,,\; -|\leftarrow\rangle|\rightarrow\rangle,$$
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- for simplicity, $y \equiv M_S^2/M_X^2 \ll 1$, then

$$\mathcal{L}_{\rm eff} = \mathcal{O}_4 + \frac{y^2}{M_X^2}\mathcal{O}_6 + \frac{y^4}{M_X^4}\mathcal{O}_8 + \ldots$$

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$$\mathcal{O}_6 = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar f\gamma^\mu\gamma_5 f)\,.$$

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- $\mathcal{O}_6$ becomes divergence of axial-vector current,

$$\mathcal{O}_6 \to \left[\frac{i}{\sqrt{2}M_X}\bar{\chi}\gamma_5\chi\right]\left[\partial_\mu(\bar{f}\gamma^\mu\gamma_5 f)\right] \propto \frac{m_f}{M_X} \,. \quad (1)$$

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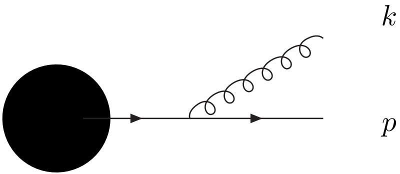
- typical hadronization spectra with
  $\varphi_\nu(E)/2 \sim \varphi_\gamma(E) \sim 3\varphi_e(E) \sim 10\varphi_N(E)$

Bremsstrahlung: soft and collinear log's



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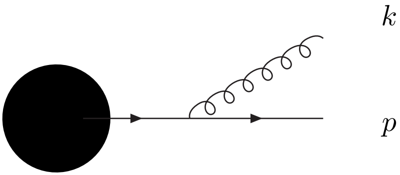

- denominator of the additional fermion propagator is

$$\frac{A(k,p)}{(p-k)^2-m^2}=\frac{A(k,p)}{-2p\cdot k}\approx\frac{A(k,p)}{-2E\omega(1-\cos\vartheta)}$$

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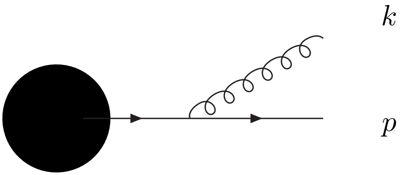

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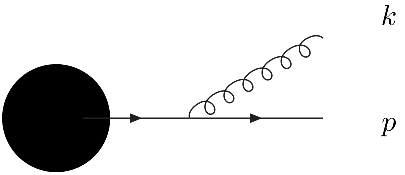

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$\Rightarrow$ compensate the small coupling $\alpha_s(Q^2)/\pi \ll 1$

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$$R = \frac{\Gamma(X \to \bar{\nu}\nu Z)}{\Gamma(X \to \bar{\nu}\nu)} = \frac{\alpha_2}{8\pi c_W^2} \left(\ln^2 \epsilon + 3 \ln \epsilon + \dots \right),$$

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- (modified) DGLAP description possible

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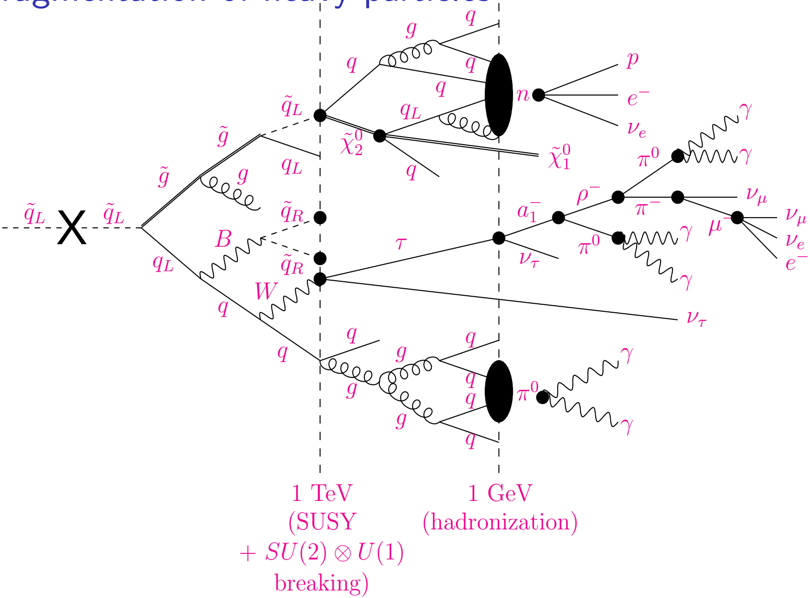
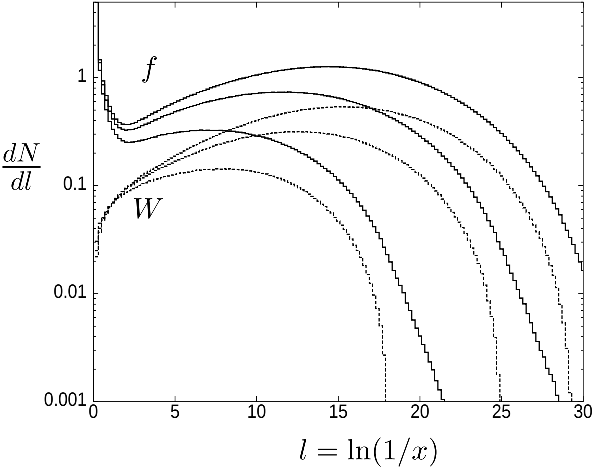


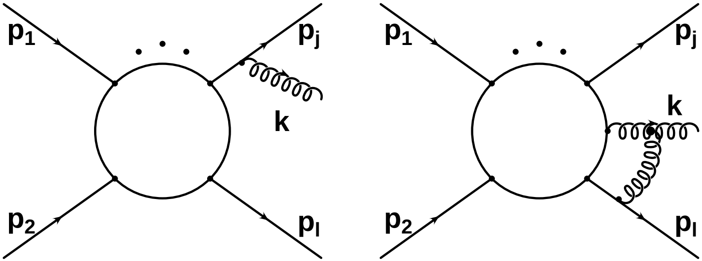
Fragmentation of heavy particles $X \to \nu\nu$



for $m_X = 10^{16}$, 10^{13} and 10^{10} GeV

Electroweak bremsstrahlung: Sudakov form factors

- ≈ 30 works 1998–2005, up to DLLA.



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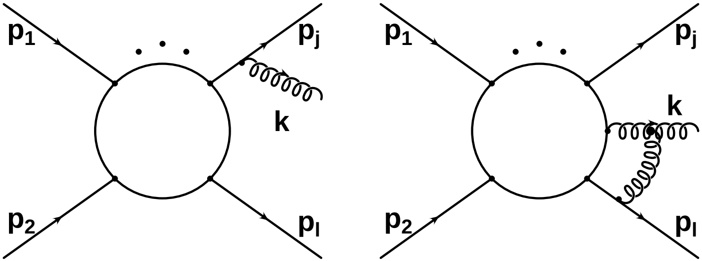

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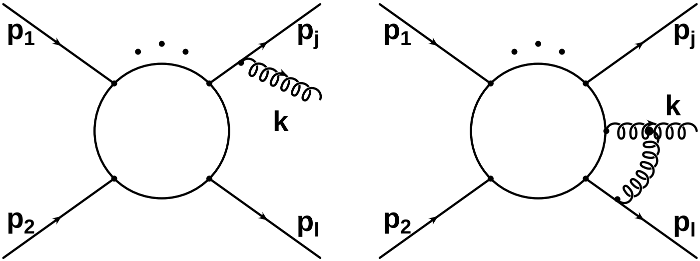

- mass corrections change only subleading log's
- but $\sigma_{\rm NLO}/\sigma_{\rm LO} \sim 50\%$ at LHC: something missed?

TeV DM and electroweak bremsstrahlung

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Perturbative unitarity and multi-TeV masses

- 2 well-known extremes: SM and MSSM
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  - SM: masses $\gtrsim$ TeV break unitarity, e.g. $Z_L \bar{f} f \propto m_f / m_Z$
  - MSSM: decouples for $M_{\rm SUSY} \to \infty$, e.g. $Z_L \chi_1 \chi_1 \propto m_Z / m_\chi$

$$O_{11}^Z \frac{m_\chi}{m_Z} = -\frac{1}{2} O_{11}^G \,,$$

in terms of the neutralino mixings and masses,

$$(N_{14}^2 - N_{13}^2) \frac{m_\chi}{m_Z} = \\ = -(c_W N_{12} - s_W N_{11})(s_\beta N_{14} + c_\beta N_{13})$$

- choose a SUSY inspired simple model

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$$\mathcal{L}_{\rm int}^{\rm scalar} = -\lambda_3(\Phi^\dagger\Phi)(\eta^\dagger\eta) - \lambda_4(\Phi^\dagger\eta)(\eta^\dagger\Phi)\ .$$

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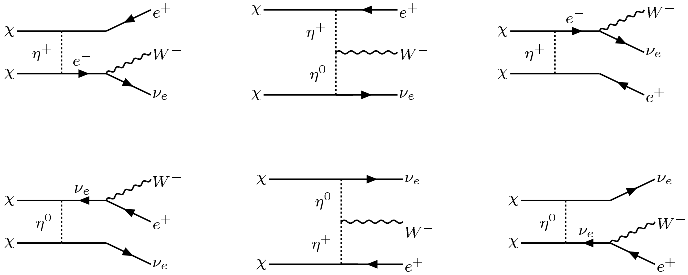

Relative importance of $\mathcal{O}_n$ and FSR/VIB

- effective operator approach

$$\mathcal{L}_{\text{eff}} = \mathcal{O}_4 + \frac{y^2}{M_X^2}\mathcal{O}_6 + \frac{y^4}{M_X^4}\mathcal{O}_8 + \dots$$

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$$\mathcal{M} \sim \frac{\mathcal{O}(v)}{M_\chi}\left[\mathcal{O}\left(y\right)|_{\rm FSR} + \mathcal{O}\left(y^2\right)\big|_{\rm FSR}\right] + \left[\mathcal{O}\left(y^2\right)\big|_{\rm VIB} + \mathcal{O}\left(y^2\right)\big|_{\rm FSR}\right]$$

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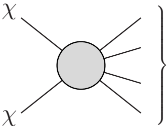
⇒ s-wave appears only at $\mathcal{O}(y^2)$

⇒ cross section

$$v\sigma(\chi\chi \to f\bar{f}Z) \sim \frac{\alpha_W}{M_\chi^2}\left[\mathcal{O}\left(v^2y^2\right) + \mathcal{O}\left(v^2y^3\right) + \mathcal{O}\left(y^4\right)\right] ,$$

Hidden annihilations $XX \to \nu\nu$

- Beacom, Bell, Mack '06: upper Bound on $\langle \sigma_{\rm ann} v \rangle$



All Standard Model final states = "Visible" states: $\gamma\gamma$, $\bar{q}q$, e^+e^-, ... + "Invisible" states: $\bar{\nu}\nu$

Hidden annihilations $XX \to \nu\nu$

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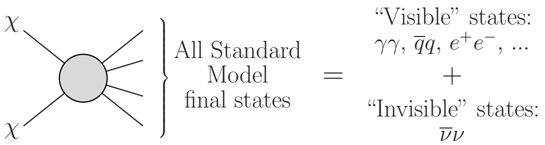
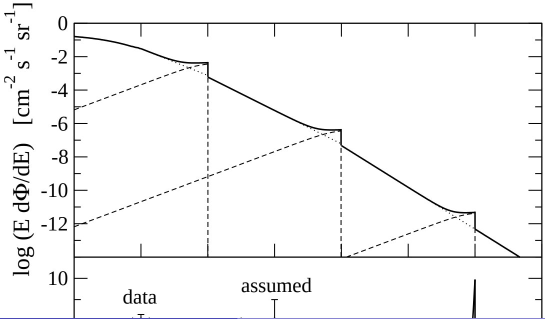




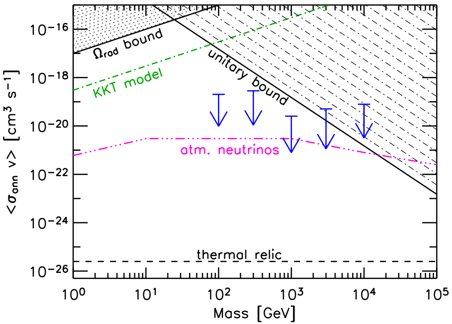
Hidden annihilations $XX \to \nu\nu$

How does electroweak Bremsstrahlung affect the limit?

- peak $\delta(E - m_X)$ becomes smoother
- contribution to diffuse γ-ray background

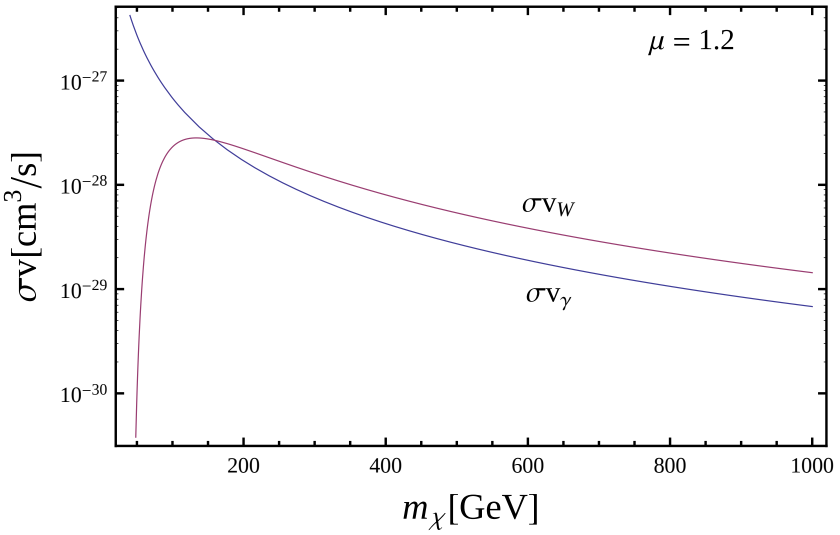
How to handle model-dependence?

- for bound: use only FSR in a model where W_L does not contribute



Toy model $XX \to e^+e^-$

[Bell et al. '11]



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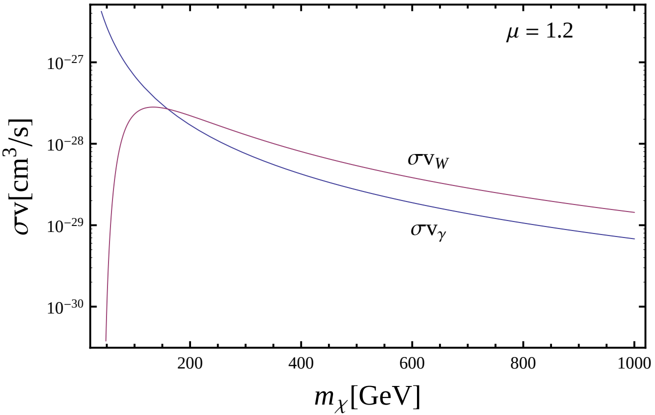
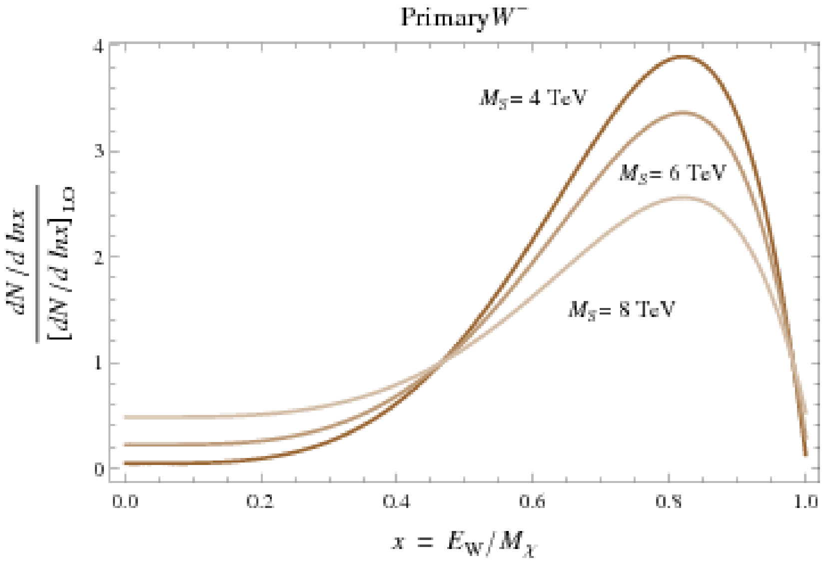


- ratio $\frac{\sigma(e^+\nu_e W^-)}{\sigma(e^+e^-\gamma)} = \frac{1}{2\sin^2\vartheta_W} \sim 2.2$ for $m_X \gg m_W$
- $\sigma(e^+\nu_e W^-) > \sigma(e^+e^-\gamma)$ already for $m_X \gtrsim 200\,\text{GeV}$
- but: γ's from W decay shifted to lower energies

Importance of VIB as function of y:

[Ciafaloni et al. '11]



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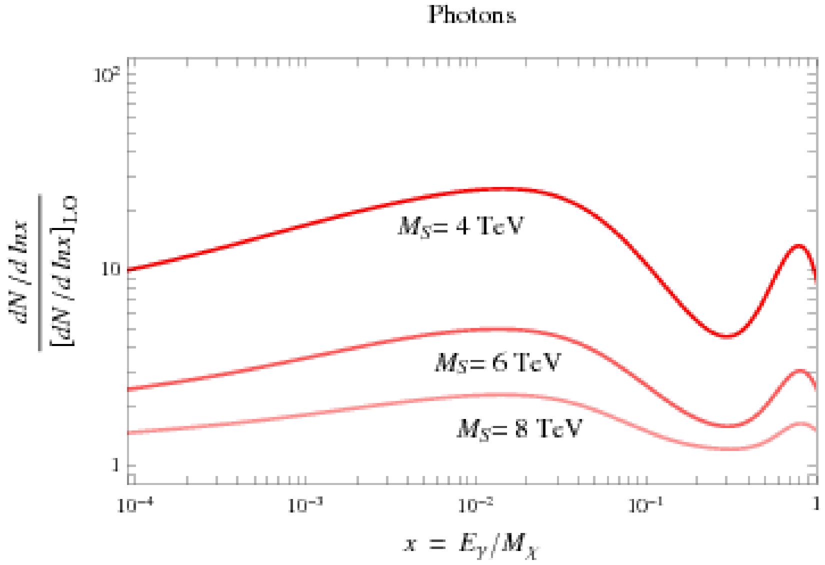
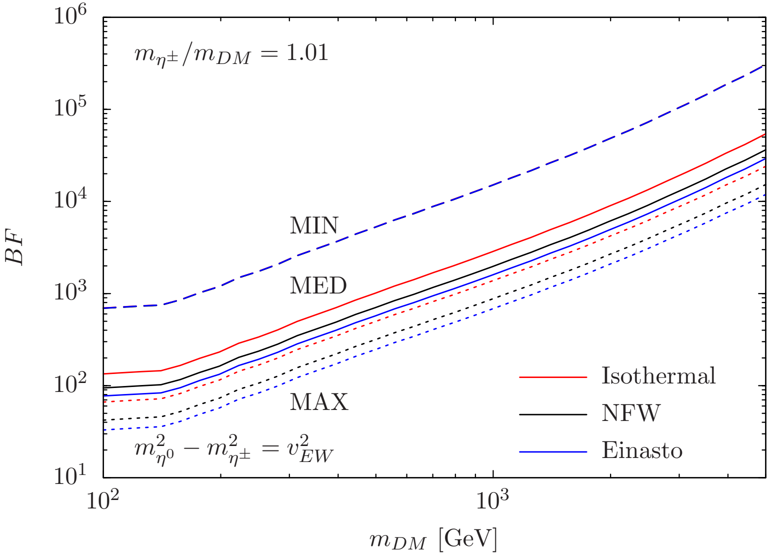


Limit on boost factor from $\bar{p}$:

[Garny, Ibarra, Vogl '11]



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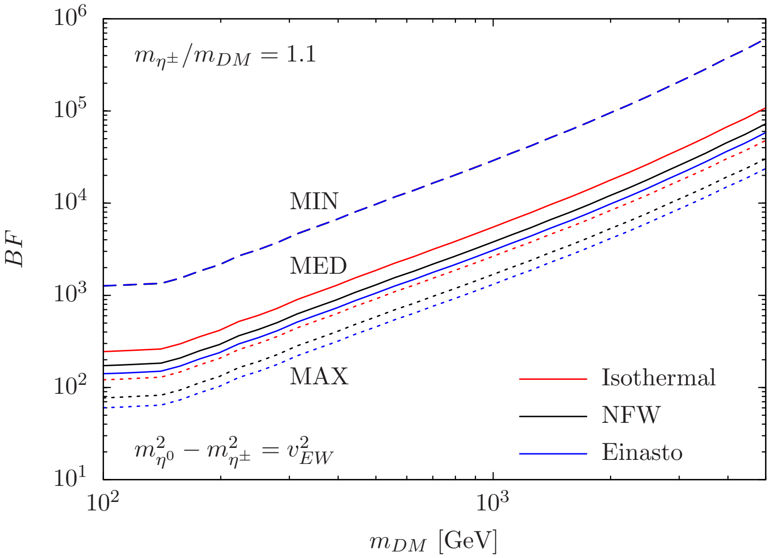

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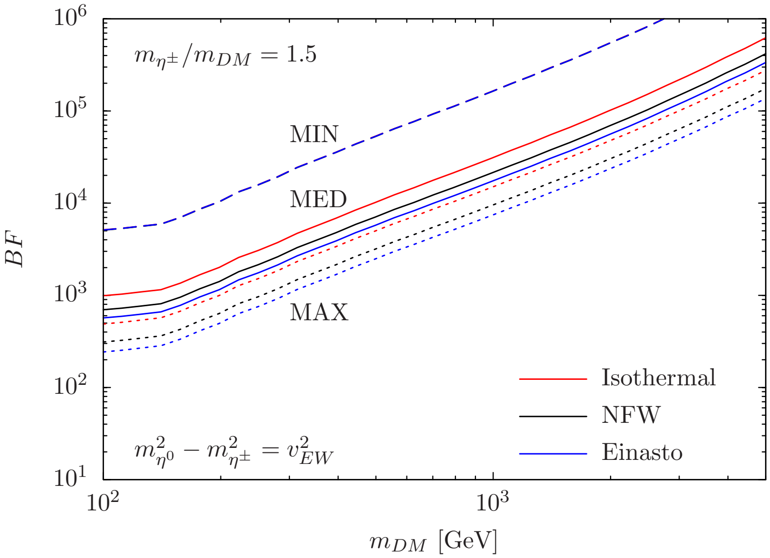

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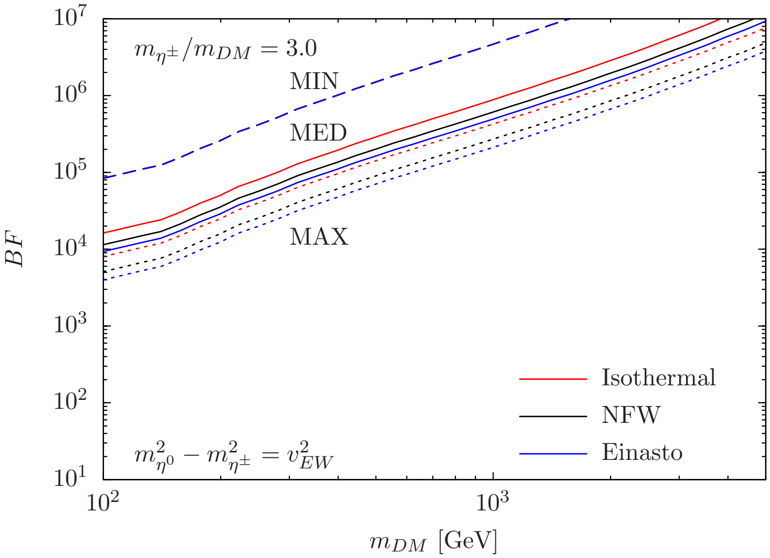

Conclusions

1. At $\mathcal{O}(\alpha)$ only trivial differences between elmag. and elweak. corrections
2. Bremsstrahlung lifts helicity suppression
   - $\bar{p}$ and γ fluxes can give stringent limits on leptophilic models
   - electromagnetic bremsstrahlung features offer DM signature
3. VIB is hard correction
   - no factorization
   - strong model & parameter dependence

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