Dark Matter Annihilation with Electroweak Bremsstrahlung

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Leptophillic Dark Matter

❖ Consider **"Leptophillic"** models:

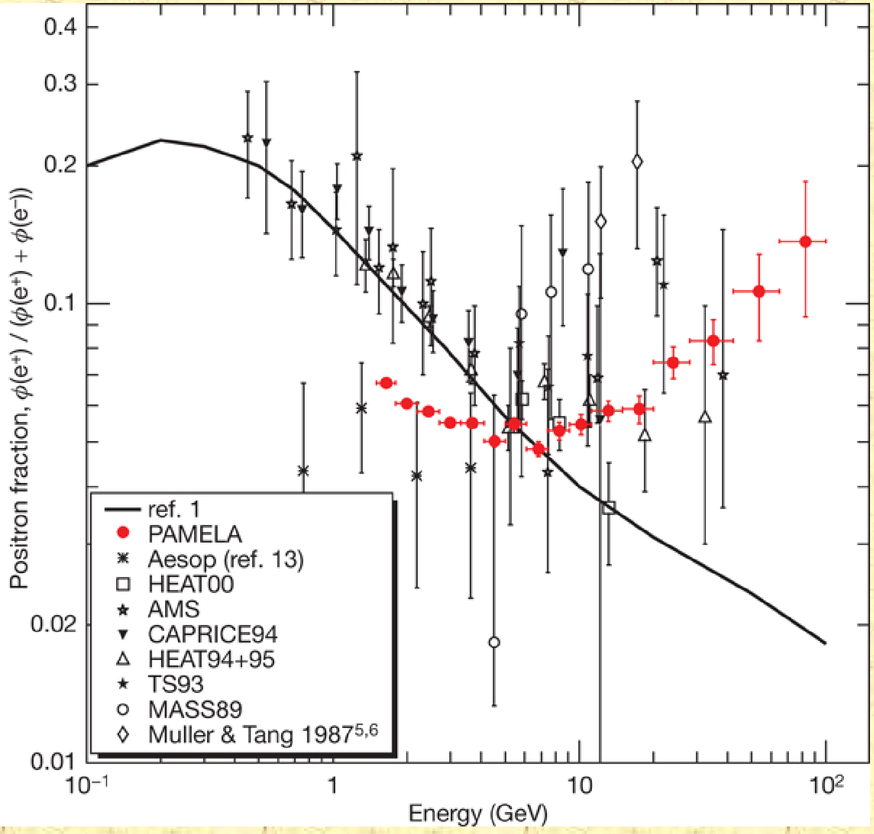
→ dark matter couples only to leptons

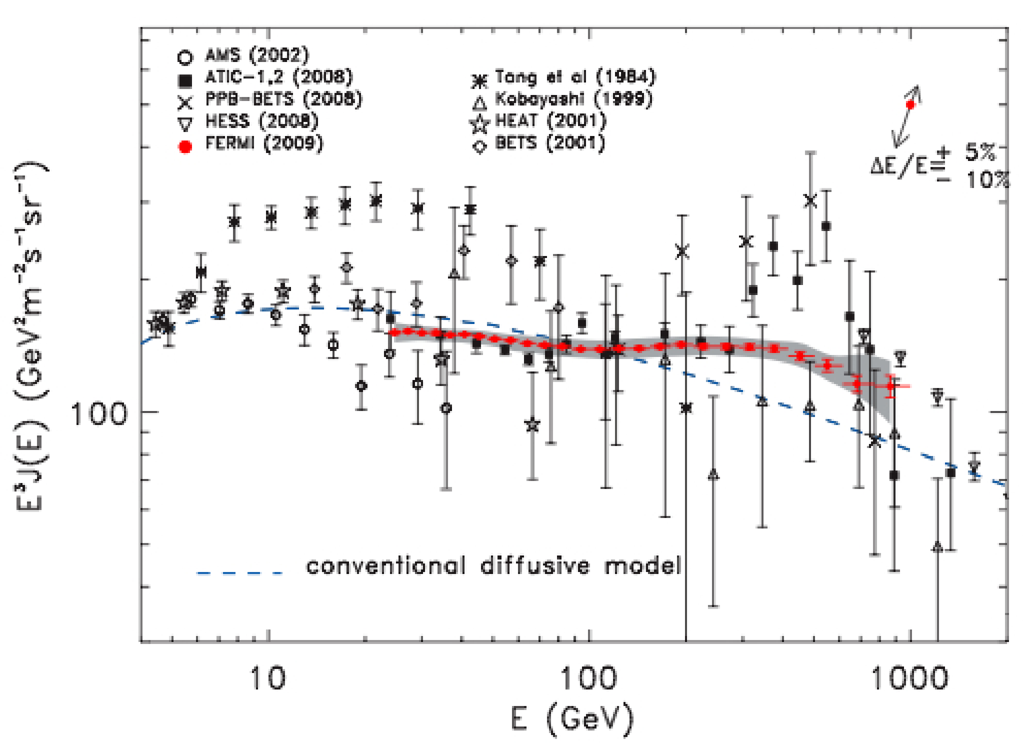
(Note that this can only be true at tree-level. Higher order corrections will inevitably lead to couplings to quarks).

❖ Leptophillic dark matter has been subject of much recent attention due to various observed anomalies in the cosmic ray positrons: PAMELA, ATIC, Fermi…

❖ These observations all suggest more positrons and electrons than can be readily accounted for.

Positrons





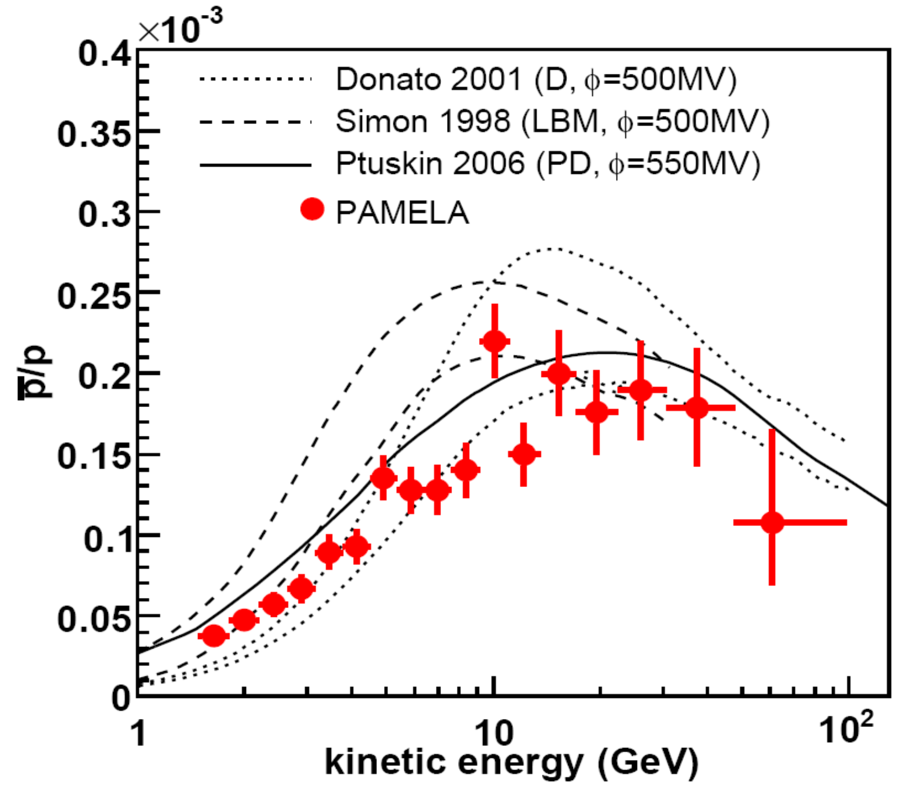
PAMELA e+ excess

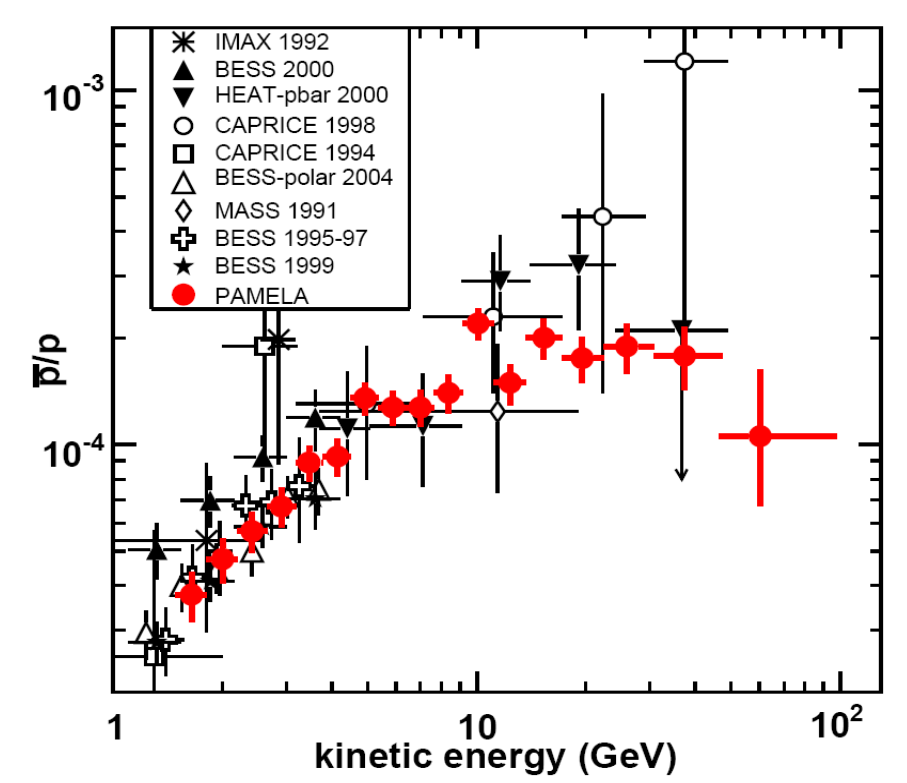
Nature 458, 607-609

Fermi $e^{+}+e^{-}$ excess

Phys. Rev. Lett. 102, 181101 (2009)

Antiprotons





Antiproton data consistent with theory expectation (for secondary production of antiprotons via cosmic ray propagation in the Galaxy).

Solution of positron anomalies

❖ Positrons from astrophysics?

Re-examine the expected positron flux from:

→pulsars

→supernova remnants

→acceleration of secondary e+

→cosmic ray propagation

❖ Positrons from Dark Matter?

→Must produce enough e+e- without overproducing pbar.

→Need big cross sections!

(Boost via DM clumping/substructure or enhanced cross sections→"Sommerfeld", non-thermal DM, …)

→ But annihilation to leptons is often suppressed…...

Annihilation cross section

Parameterize the annihilation cross section as:

$$\langle \sigma v \rangle = a + b v^2 + \ldots$$

a -- from s-wave (L=0) annihilation
b -- both s-wave and p-wave (L=1) contributions

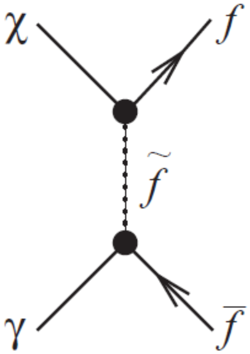
The L^{th} partial wave contribution is suppressed as v^{2L}

In galactic halos, v~ 10^{-3}c, so only the s-wave contribution will be significant.

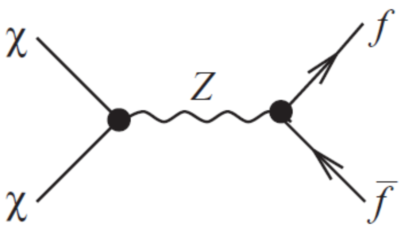
However, in many models, s-wave annihilation to a fermion pair is helicity suppressed by a factor of $\left(m_f / m_{DM}\right)^2$

Example: SUSY

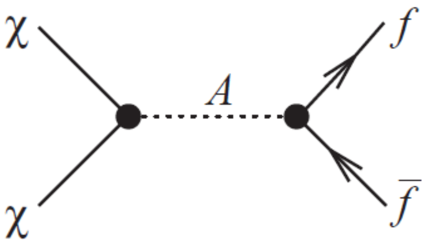
Majorana neutralinos annihilate to a fermion pair via:



- t- and u-channel exchange of sfermions
  → helicity suppressed



- s-channel exchange of Z
  →helicity suppressed

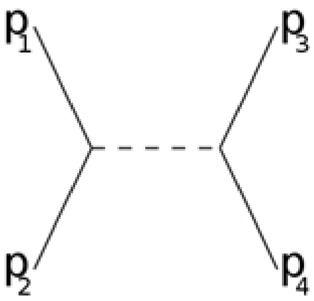


- s-channel exchange of higgs
  → suppressed by yukawa couplings

$$(m_f/\mathrm{vev})^2$$

When is annihilation suppressed?

❖ For s-channel annihilation:

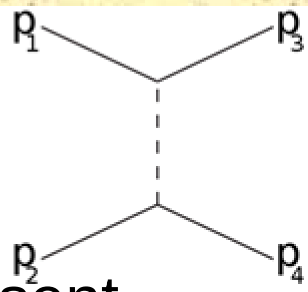


Suppressed: scalar
axial-vector

Non-suppressed: pseudo-scalar
vector (not allowed for Majorana DM)
tensor (not allowed for Majorana DM)

→s-channel exchange of a pseudo-scalar is the sole non-suppressed mode for Majorana DM.

❖What about t- and u-channel annihilation?



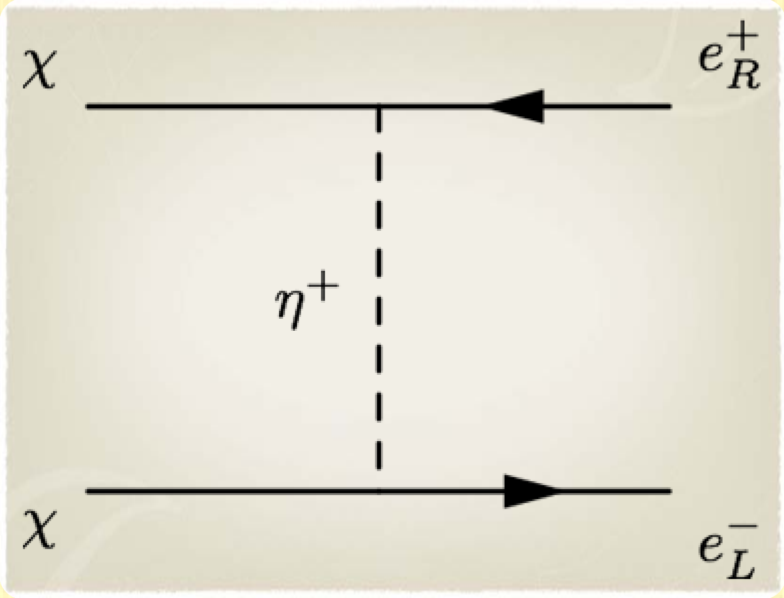
→Fierz transform to s-channel form.
→Non-suppressed only if a pseudo-scalar term present

Example: leptophillic model

❖ Cao, Ma, Shaughnessy, PLB 2009.

Dark matter = gauge-singlet Majorana fermion = χ

$$\mathcal{L} = f(\nu_L \eta^0 - \ell_L \eta^+)\chi + h.c.$$



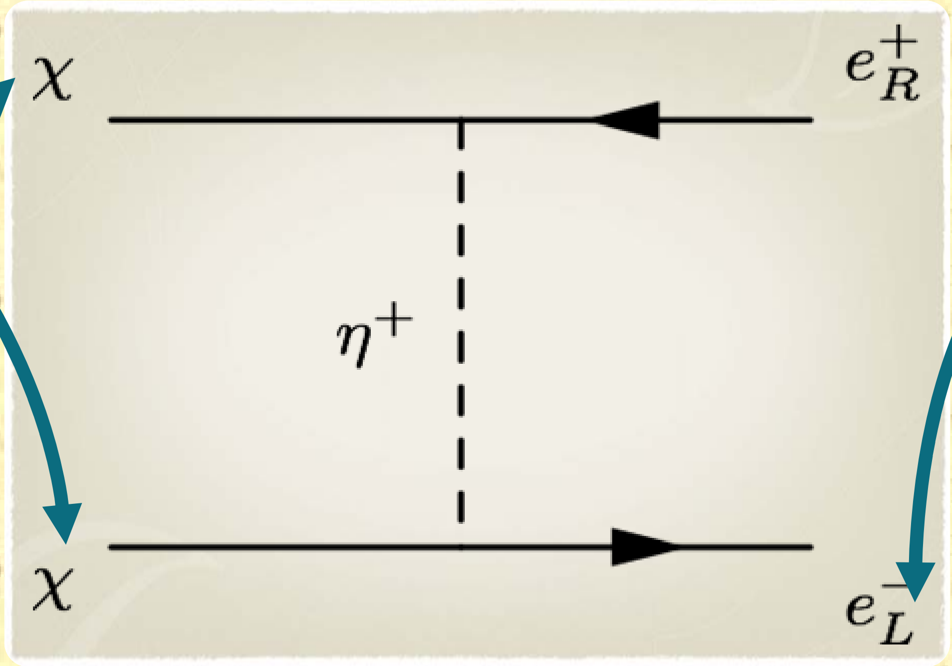
Annihilation to leptons via t- and u-channel exchange of an SU(2) doublet scalar, η.

$$v\,\sigma = \frac{f^4\, M_\chi^2}{16\pi\, M_\eta^4}\left[\frac{m_l^2}{s} + \frac{2}{3}v^2 + \mathcal{O}(v^4)\right]$$

Helicity suppression of s-wave

Majorana

→opposite spins



Opposite Spins

→ in CM frame, same helicity

But, opposite chirality!

In massless limit, helicity = chirality, so

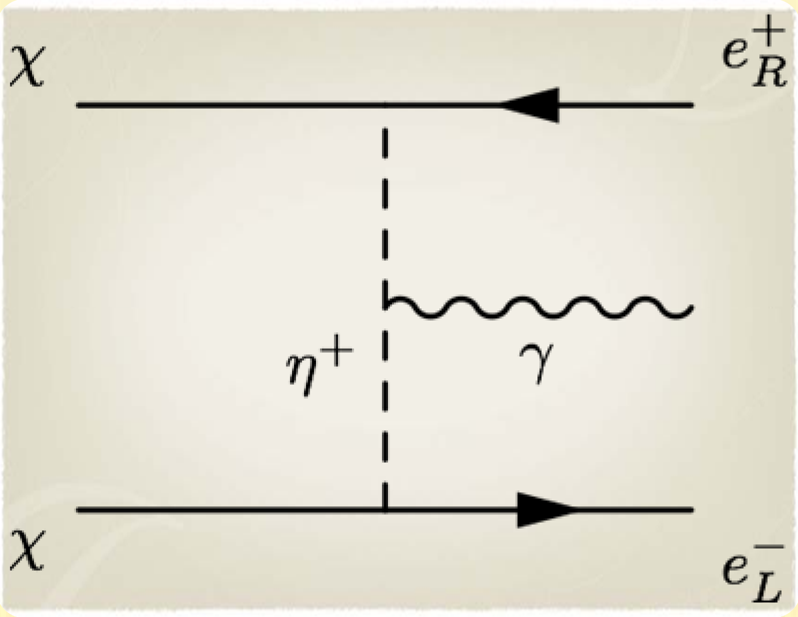
$$\langle \sigma v \rangle = \left(\frac{m_\ell}{E_\ell} \right)^2 a + bv^2$$

Heavily Suppressed!

Lifting the suppression (photons)

Emission of a high energy photon from the propagator can lift this suppression:

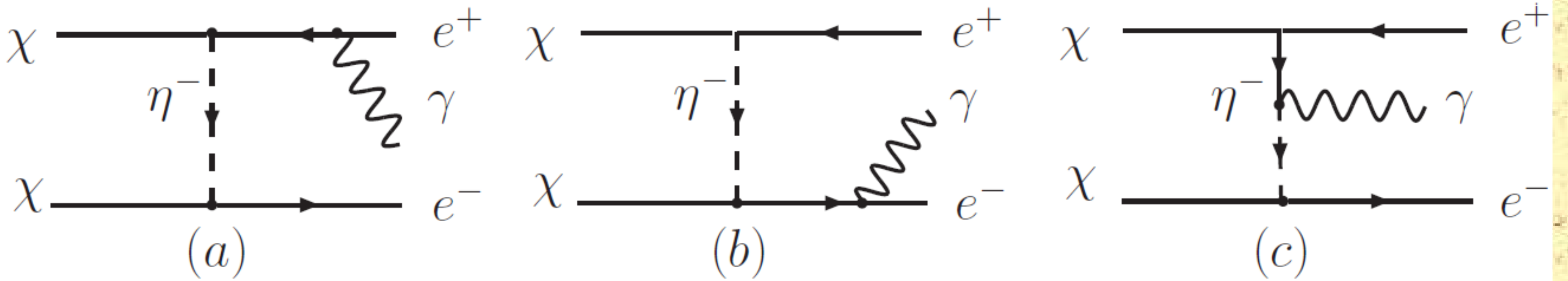
Bergstrom, PLB 225, 372 (1989);
Flores, Olive, Rudaz, PLB 232, 377 (1989);
Bringmann, Bergstrom, Edsjo, 2008);
Barger, Gao, Keung, Marfatia, 2009.



The photon carries away a unit of angular momentum →no longer helicity suppressed.

$$\chi\chi \to f\bar{f}\gamma \gg \chi\chi \to f\bar{f}$$

Lifting the suppression (photons)



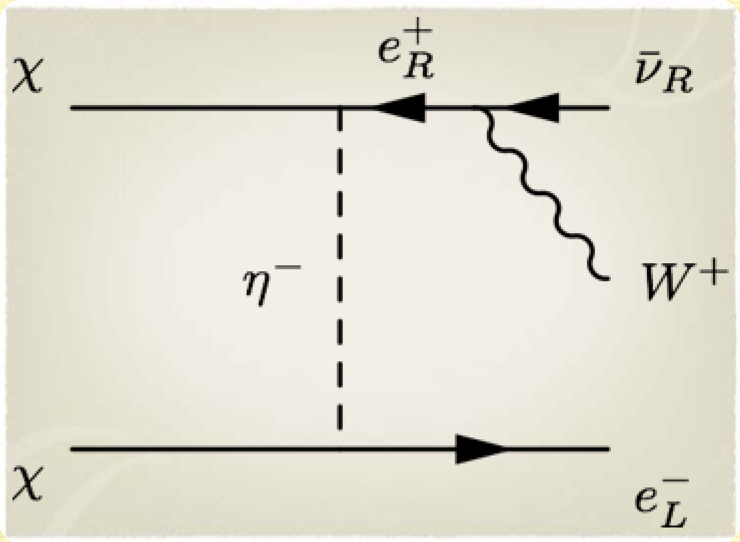
Final state radiation (FSR)

"Virtual internal bremsstrahlung" (VIB)

- FSR not effective in lifting suppression (soft/collinear)
- VIB is effective in lifting suppression, but is suppressed by additional η propagator

→ Large effect only for near-degenerate χ and η masses.

Lifting suppression (electroweak brem.)



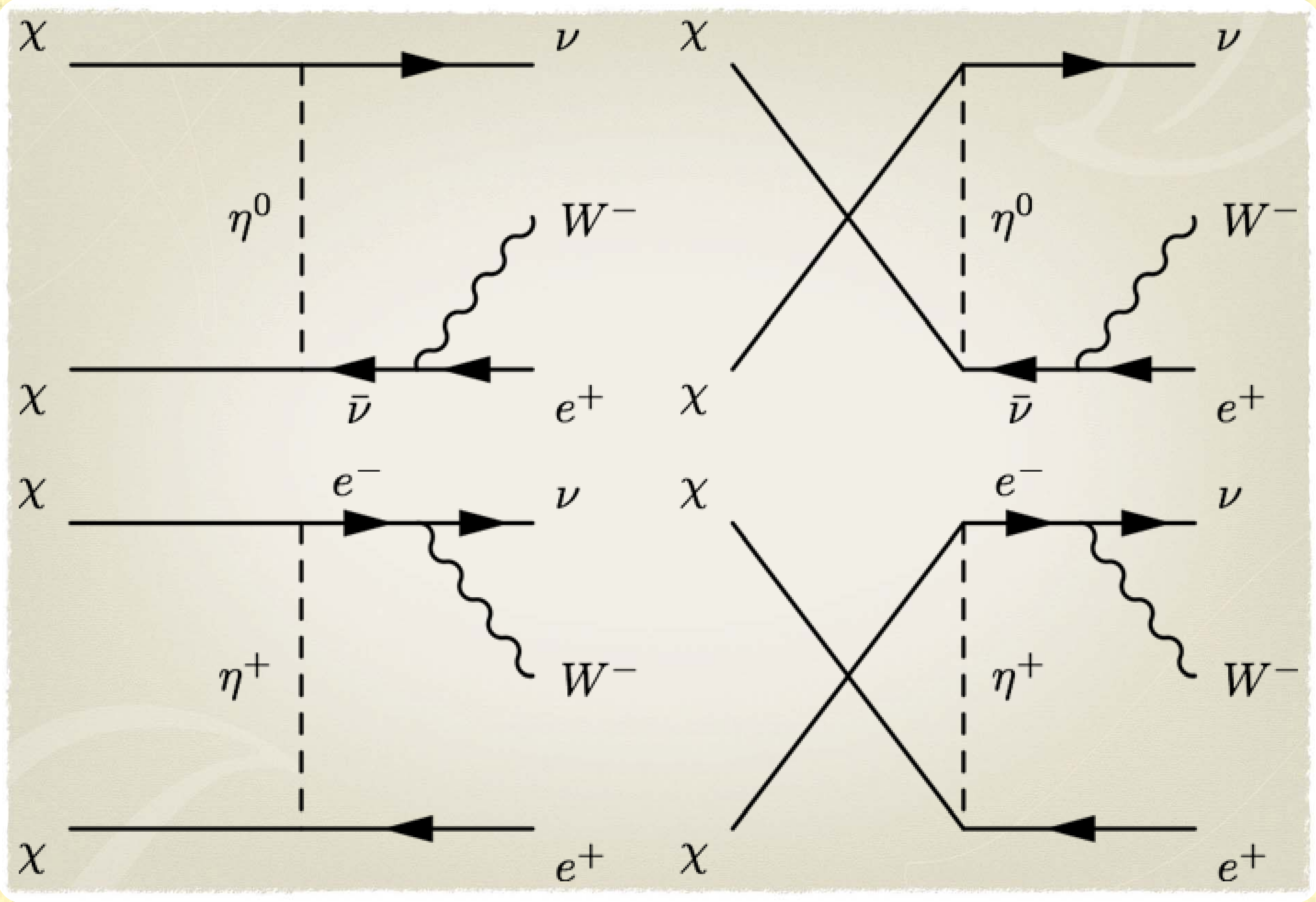
Bell, Dent, Jacques & Weiler

- Radiating a W or Z boson can also lift the suppression
- Radiation from a final state particle is sufficient
  (& radiation from propagator suppressed for heavy η)
- Don't need near-degenerate χ and η masses

- W and Z bosons decay to leptons, gamma, and hadrons

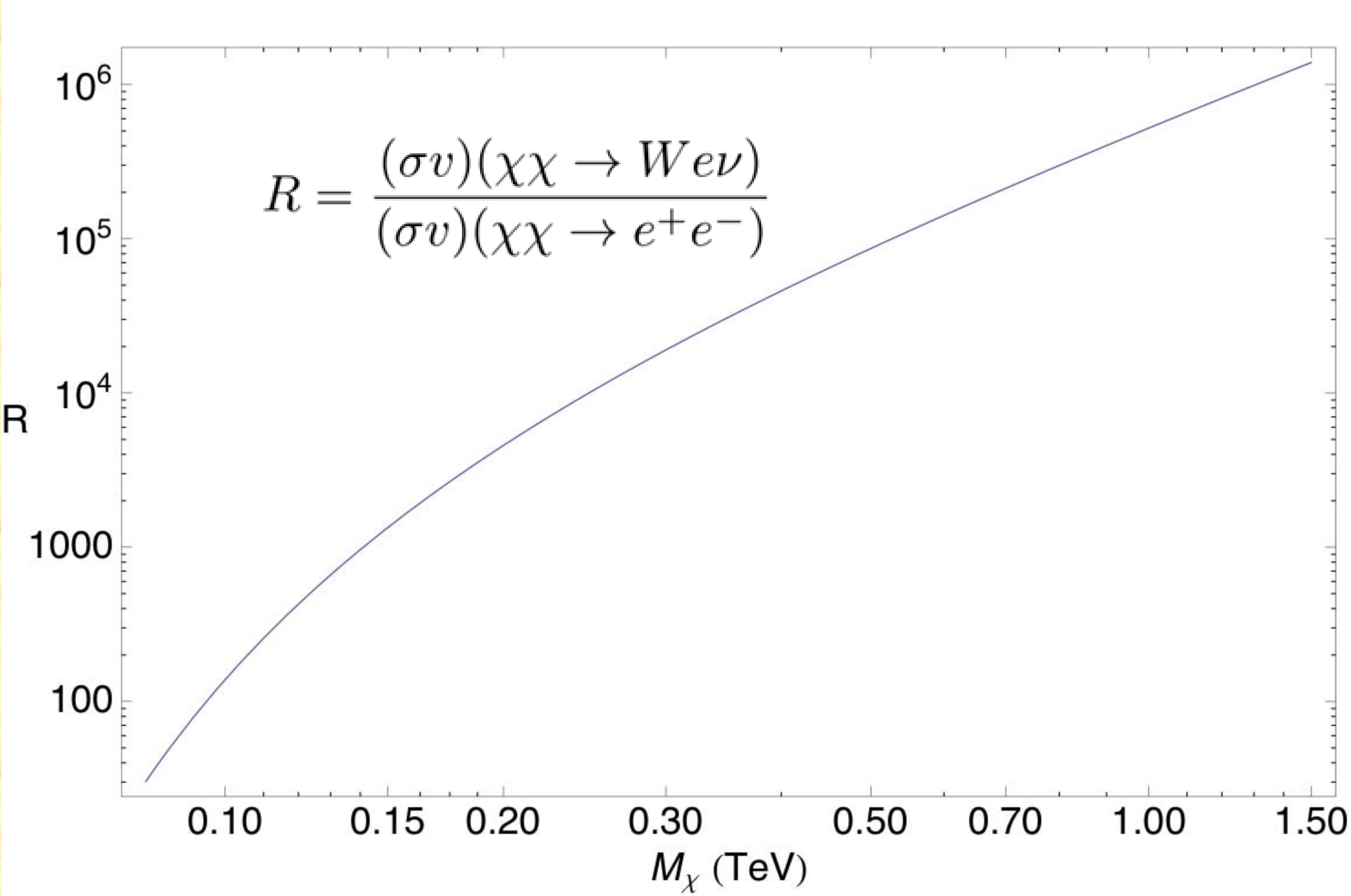
→ hadron production even for leptophillic models

Electroweak brem. diagrams



$\chi\chi \rightarrow e\nu W$

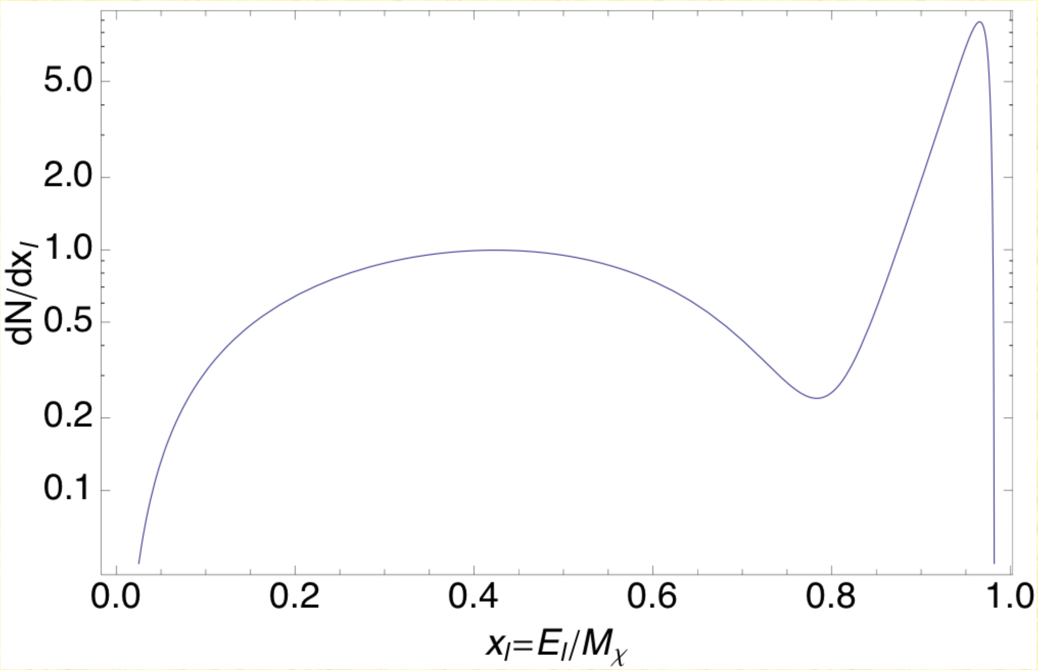
Ratio of eνW and e+e- cross sections



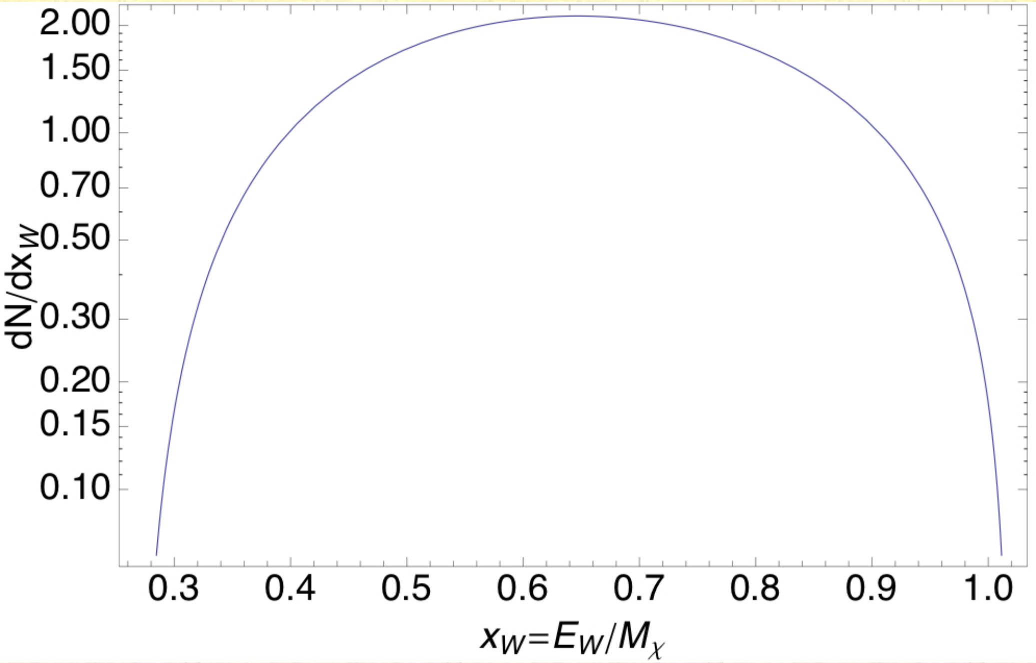
- Annihilation to eνW or e+e-Z dominates over e+e-
- Enhancement by many orders of magnitude!

$\chi\chi \rightarrow e\nu W$

- ❖ lepton energy spectrum



- ❖ W energy spectrum



Including the Z brem

W-brem and Z-brem cross sections related in simple way

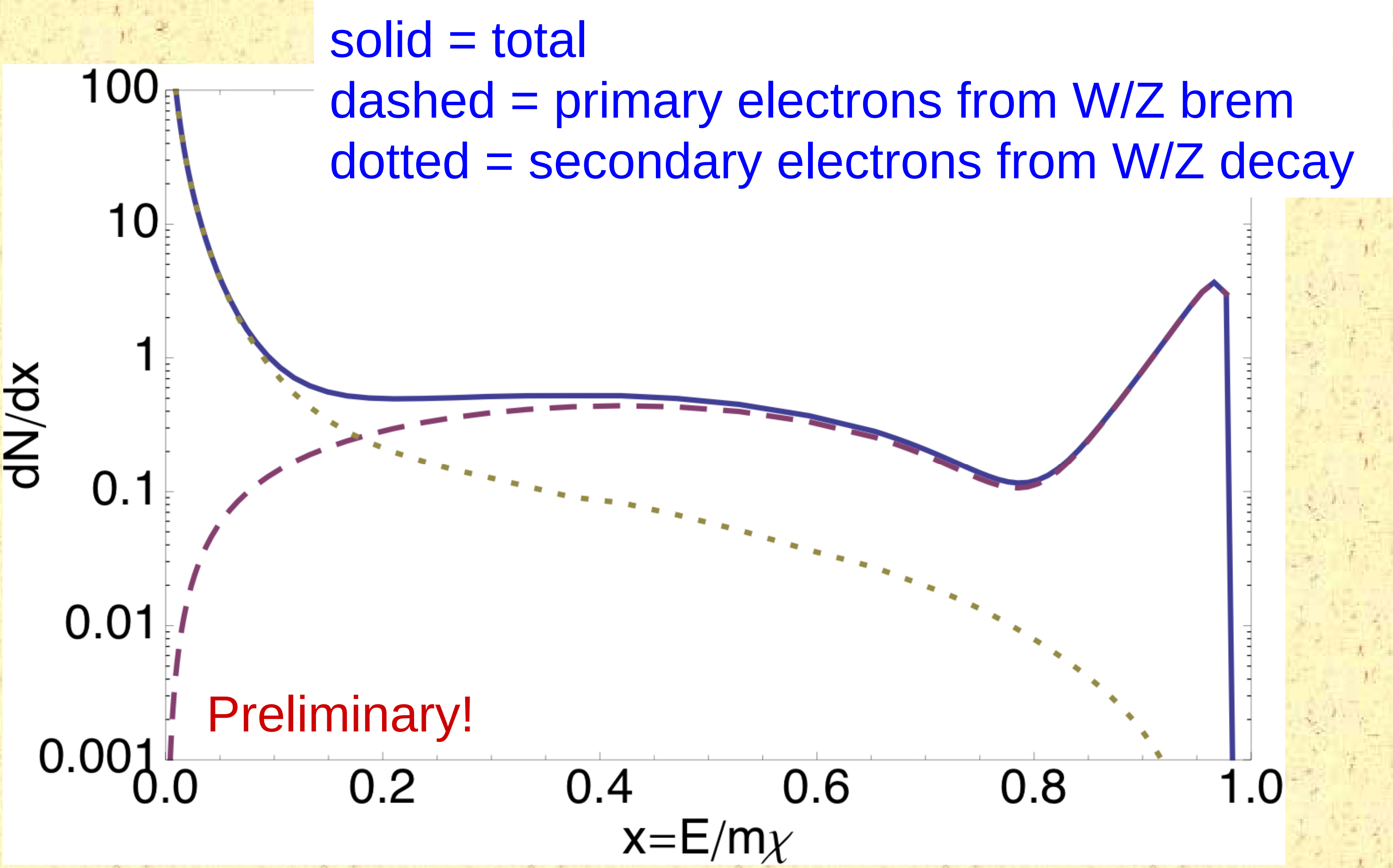
$$\chi\chi \to e^+ \nu W^-$$
$$\chi\chi \to e^- \bar{\nu} W^+$$
$$\chi\chi \to e^+ e^- Z$$
$$\chi\chi \to \nu \bar{\nu} Z$$

$$v\,\sigma_{e^+e^-Z} = \frac{2\left(\sin^2\theta_W - \frac{1}{2}\right)^2}{\cos^2\theta_W} \times v\,\sigma_{e^+\nu W^-}\Big|_{M_W \to M_Z}$$
$$\simeq 0.19 \times\ v\,\sigma_{e^+\nu W^-}\Big|_{M_W \to M_Z}. \qquad ($$

$$v\,\sigma_{\nu\bar{\nu}Z} = \frac{1}{(2\cos^2\theta_W)} \times v\,\sigma_{e^+\nu W^-}\Big|_{M_W \to M_Z}$$
$$\simeq 0.65 \times v\,\sigma_{e^+\nu W^-}\Big|_{M_W \to M_Z}.$$

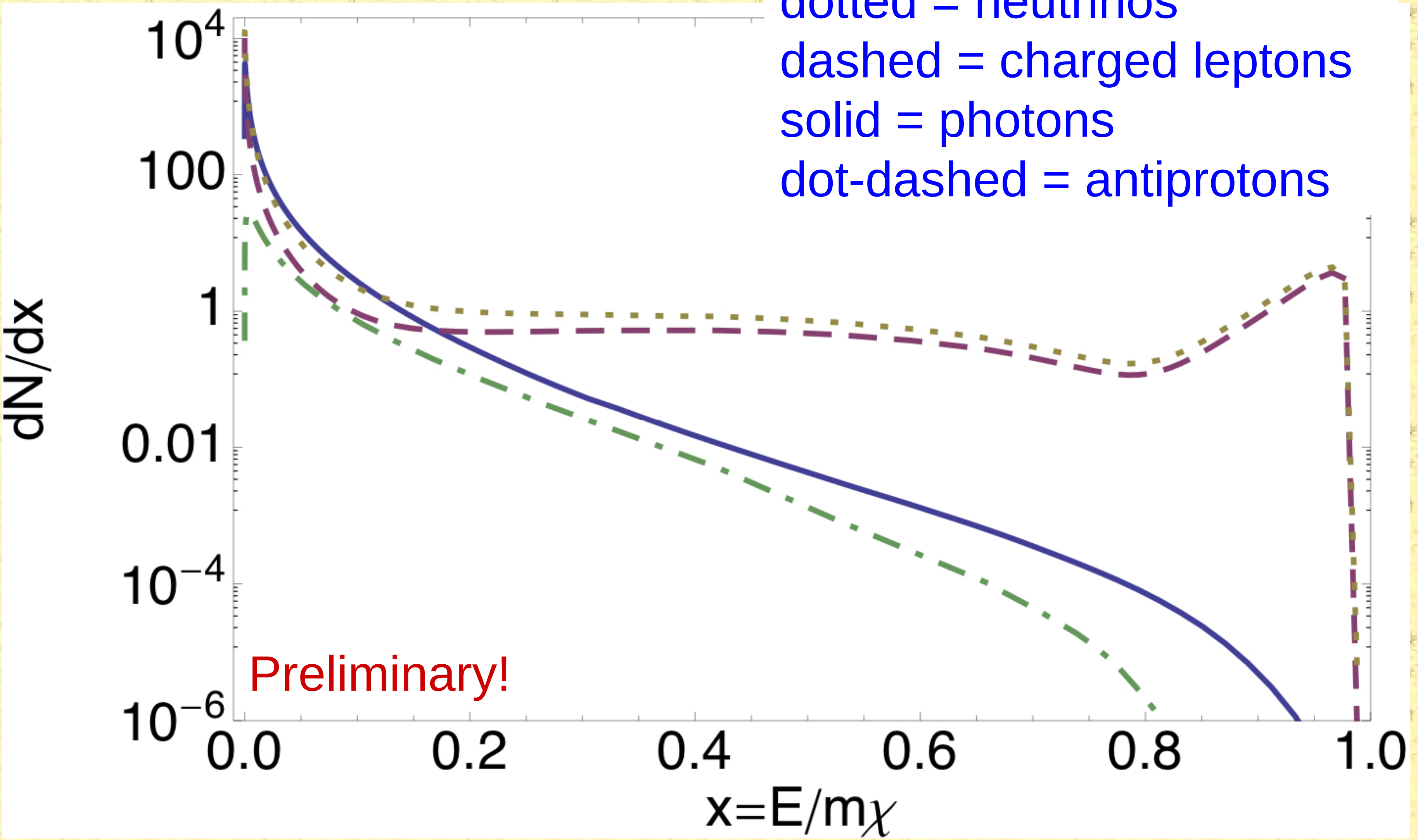
$$\langle \sigma v \rangle_{\rm Brem} = \langle \sigma v \rangle_{e^+\nu W^-} + \langle \sigma v \rangle_{e^-\bar{\nu} W^+} + \langle \sigma v \rangle_{e^+e^-Z} + \langle \sigma v \rangle_{\nu\bar{\nu}Z}$$

Total electron energy spectrum

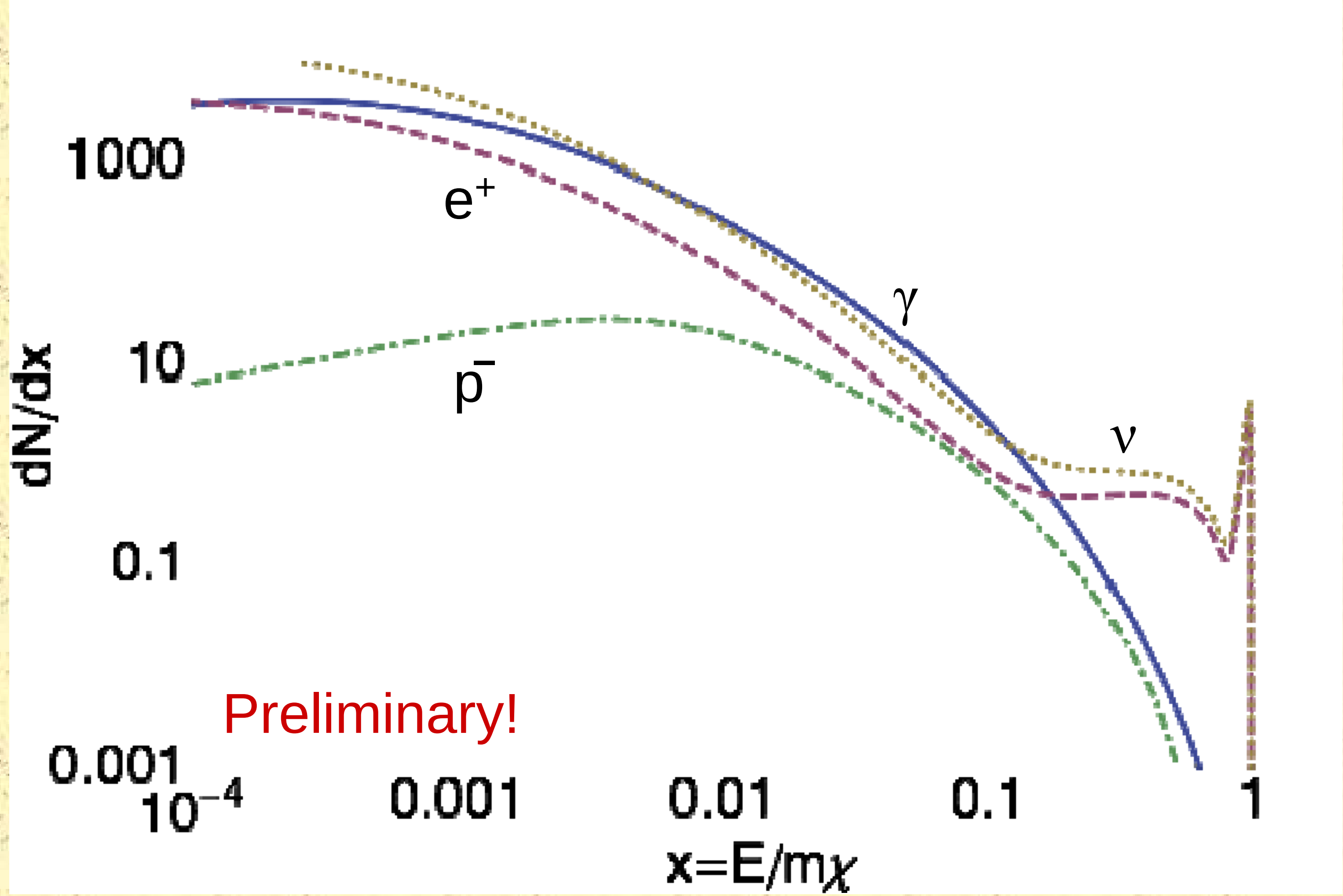


Annihilation spectra

dotted = neutrinos
dashed = charged leptons
solid = photons
dot-dashed = antiprotons

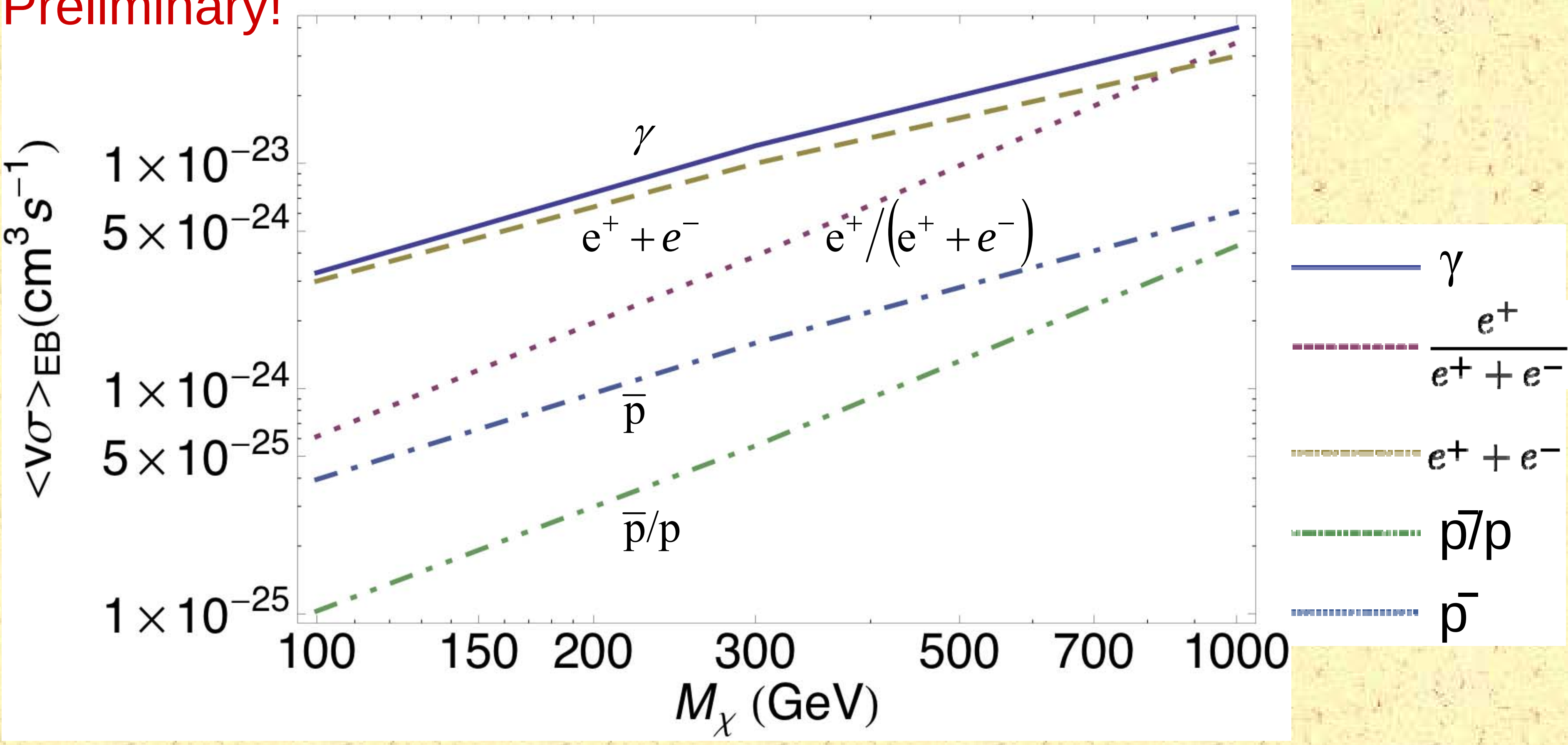


Annihilation spectra



Maximum allowed cross sections

Preliminary!

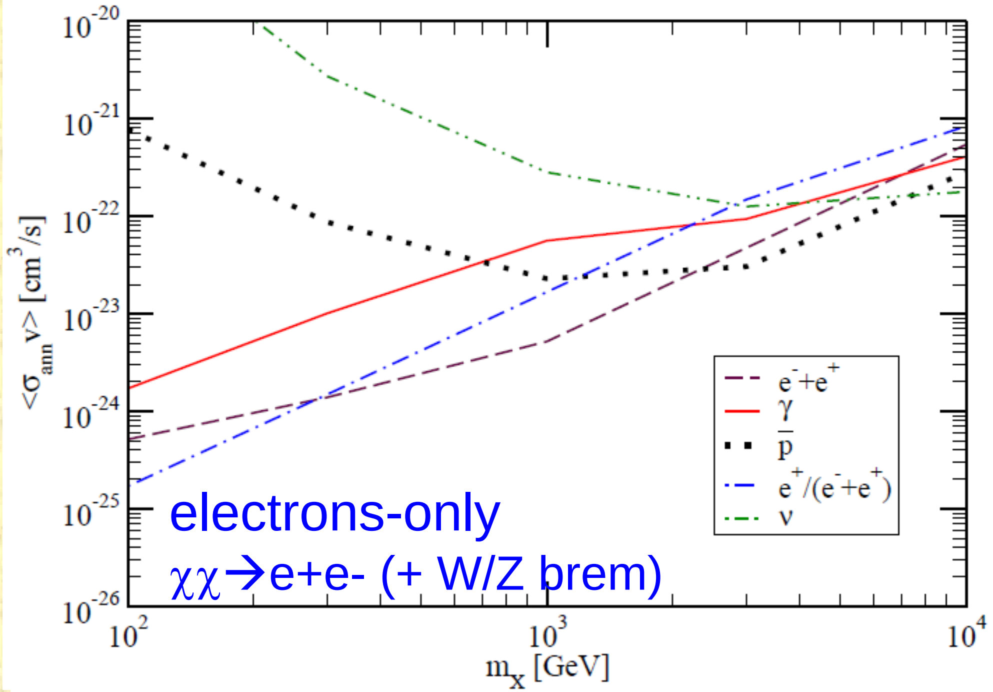


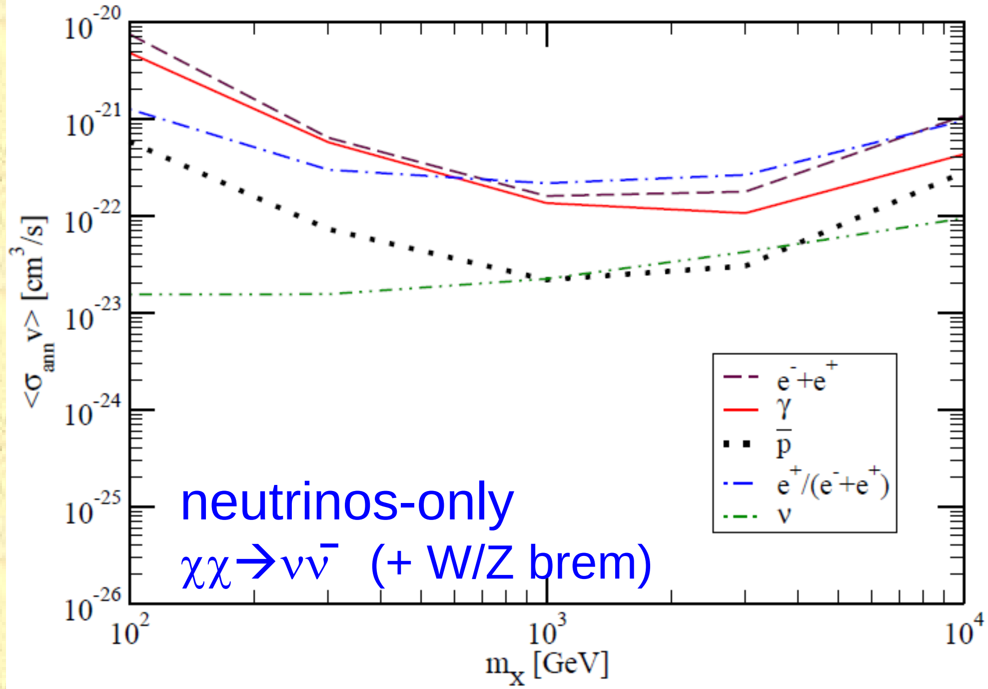
→ Can't make significant contribution to e+ flux, without overproducing pbar!

Models with no helicity suppression

→EW-brem still occurs, but is subdominant

→W/Z decays ensures there is at least a minimal yield of hadrons, photons, charged leptons and neutrinos.





Kachelriess, Serpico and Solberg
arXiv:0911.0001

Conclusions

Electroweak bremsstrahlung lifts helicity suppression → dominant annihilation channel

- e+e-Z and eνW rates dominate over e+e- by several orders of magnitude
- Allows indirect detection of processes that would otherwise be too suppressed to give observable signals
- Unavoidable hadronic component from W/Z decay
- Can't produce significant amount of e+ without overproducing antiprotons.

Even models where the there is no suppression, purely leptonic annihilation products impossible

NFB, J. B. Dent, T. D. Jacques and T. J. Weiler, arXiv:1009.2584
NFB, J. B. Dent, T. D. Jacques and T. J. Weiler, in preparation