MITP Workshop "Cosmic Rays and Photons from Dark Matter Annihilation: Theoretical issues"

Enhancement of Neutralino Dark Matter Annihilation from Electroweak Corrections

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

Neutralino DM Annihilation

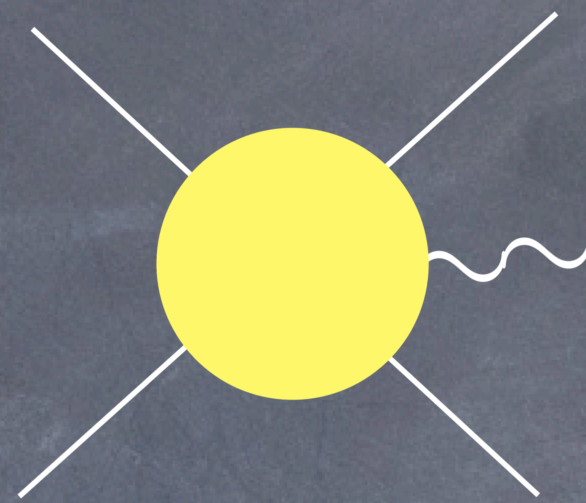
$$\langle \sigma_{ann} v \rangle = a + b v^2 + O(v^4)$$

- Velocity suppression: if present the S-wave dominates the cross section
- Helicity suppression: for a fermionic Majorana DM candidate the S-wave annihilation into light fermion-antifermion pairs is $\propto m_f^2/m_\chi^2$

The lifting of the helicity suppression via radiative corrections is possible

Radiative corrections

$$\chi\chi \to f\bar{F}V$$



$$V = \gamma,\ Z, W^{\pm}$$

- Electromagnetic Corrections:
  - emission of an additional photon
  - FSR: logarithmic enhancement of collinear photons
  - VIB: spectral features at high energies from di-boson and co-annihilation channel

  Bringmann et al., 2008

- Electroweak Corrections:
  - emission of W, Z
  - more stable particles in the low-energy tail of the spectrum; multi-messenger signal
  - lifting of the helicity suppression from VIB and ISR; FSR logarithmic enhancement

EW Radiative Corrections

- Motivation: relevance of EW corrections in modeling the predicted DM fluxes

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- Current literature:
  - specific models corresponding to some MSSM neutralino limit (i.e. bino, wino, higgsino)

Kachelrieß et al., 2009
Bell et al., 2011
Garny et al., 2011, 1012

EW Radiative Corrections

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- Current literature:
  - specific models corresponding to some MSSM neutralino limit (i.e. bino, wino, higgsino)
  - rather model-independent approach (effective field theory operators)

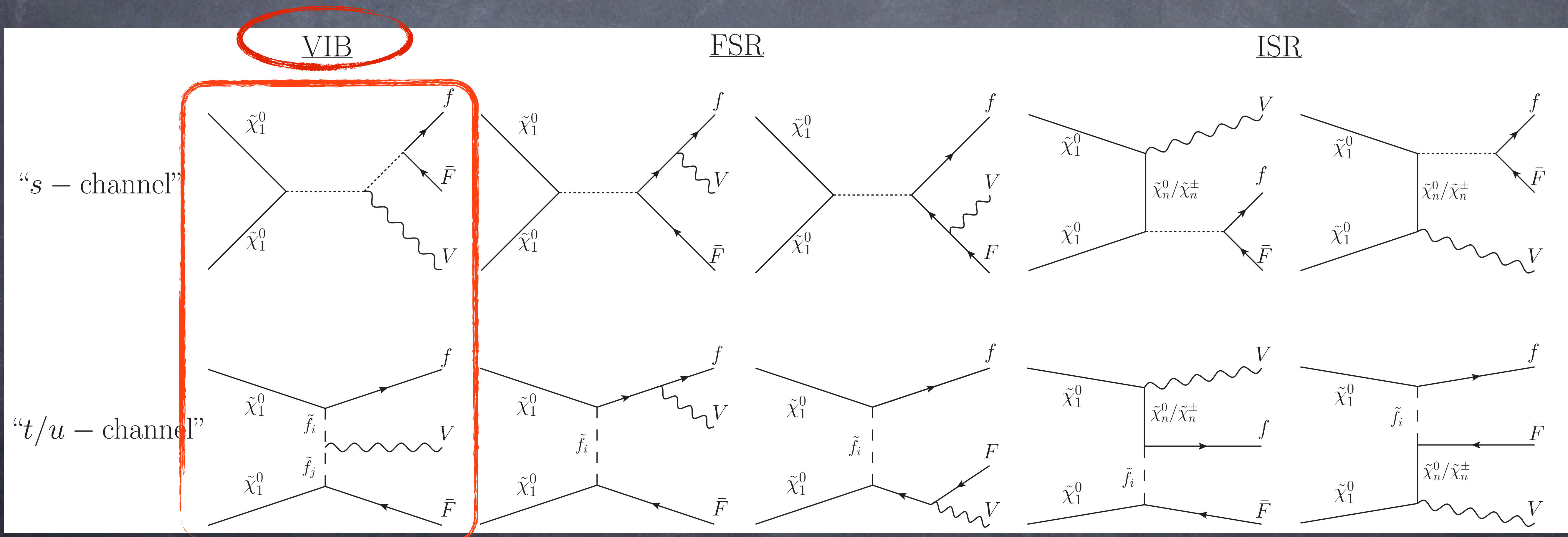
Ciafaloni et al., 2010, 2011, 2012
PPPC4DMID

EW Radiative Corrections

- Motivation: relevance of EW corrections in modeling the predicted DM fluxes
- Current literature:
  - specific models corresponding to some MSSM neutralino limit (i.e. bino, wino, higgsino)
  - rather model-independent approach (effective field theory operators)
- Novelty of this work: first fully general calculation for MSSM neutralino DM, keeping
  - all relevant diagrams
  - the full mass dependence of fermions, gauge bosons and other involved particles.

The Method

- generation of diagrams (46) with FeynArts for the process: $\chi\chi \to f\bar{F}V$



Virtual Internal Bremsstrahlung

The Method

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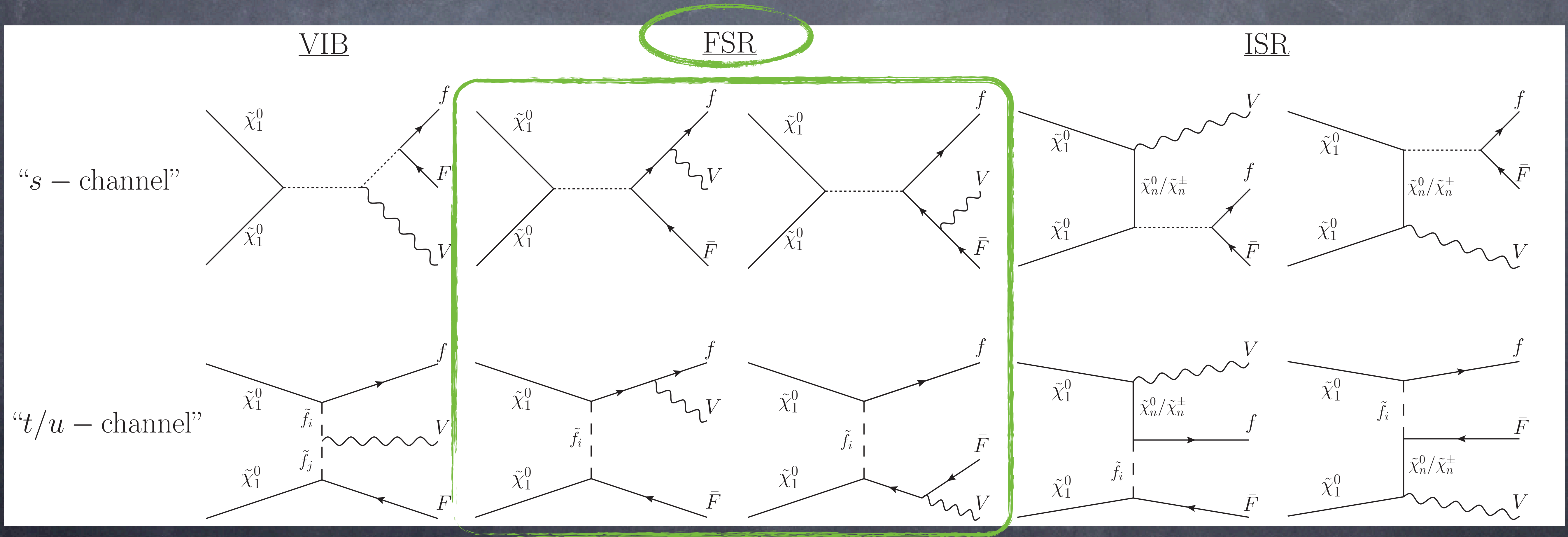
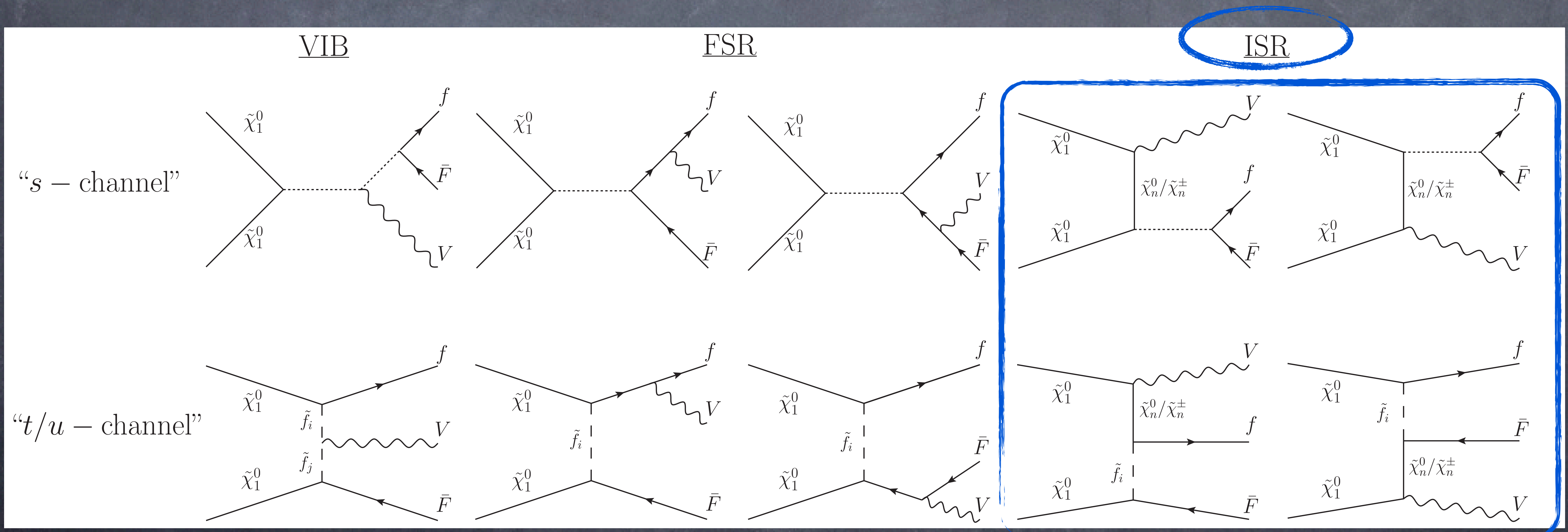


Final State Radiation

The Method

- *generation of diagrams (46) with* FeynArts *for the process:* $\chi\chi \to f\bar{F}V$



Initial State Radiation

The Method

- generation of diagrams with FeynArts
- computation of the total squared matrix element in the limit $v \to 0$
    - $^1P_0$ S-wave projector
    - kinematics: only two independent variables
    - "helicity amplitudes method" extended to three-body final state

Edsjo&Gondolo,1997

S-Wave Initial State Projector

DM Majorana fermion annihilating in the zero-velocity limit acts as a pseudo-scalar decaying particle

Initial State S-Wave projector: only the pseudo-scalar current and the temporal component of the vector current lead to non-vanishing contributions

$$(P_{^1S_0})_0 = \frac{\gamma_5 \, m_\chi (1 - \gamma_0)}{\sqrt{2}}$$

in the CM system

$$P_{^1S_0} = S(\Lambda)(P_{^1S_0})_0 S^{-1}(\Lambda) = \frac{\gamma_5 \, (m_\chi - (p^0\gamma_0 - p^i\gamma_i)/2)}{\sqrt{2}}$$

Lorentz invariant expression

"Helicity amplitudes method"

$$\chi(p_1)\chi(p_2) \to f(k_1)\bar{F}(k_2)V(k_3)$$

typical s-channel matrix element structure

$$M \propto \bar{v}_i(p_2)\,(\Gamma_{\text{initial}})_{ij}\,u_j(p_1)\,\bar{u}_m(k_1)\,(\Gamma_{\text{final}})_{mn}\,v_n(k_2)\,\epsilon^*_\mu(k_3)$$

$^1P_0$ initial state projector — fermionic final chain — polarization vector

$$(\bar{u}\,\Gamma^{\mu\ldots\nu}\,v)_{(s,\lambda)} = \sum_{\alpha\ldots\beta}\left(\left(C^{\alpha\ldots\beta}_{\mu\ldots\nu}\right)_{(s',\lambda')}\,e'^{\mu}_{\alpha}\ldots e'^{\nu}_{\beta}\right)\,\delta^{s',\lambda'}_{s,\lambda}$$

Total Squared Matrix

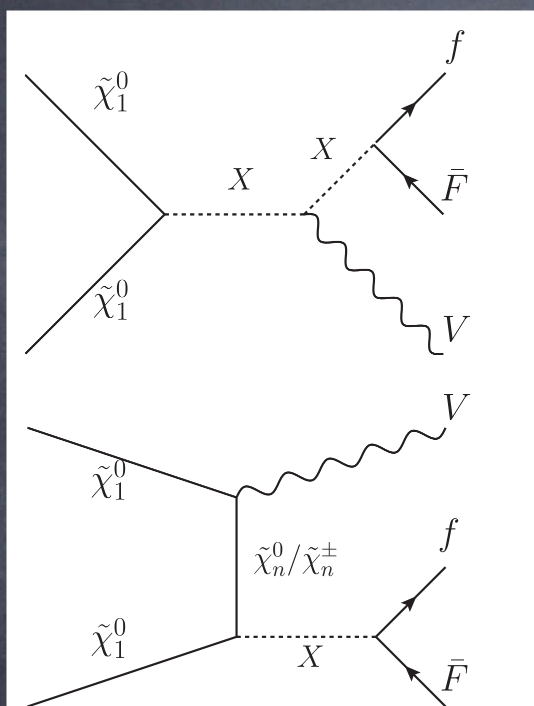
$$\frac{1}{4}\sum_{r,s,r',s',\lambda}\left|\mathcal{M}_{\chi\chi\to f\bar{F}V}\right|^2 \equiv \frac{1}{4}\sum_{h,\lambda}\left|\sum_{\text{diag.}}\mathcal{M}_{\chi\chi\to f\bar{F}V}\right|^2$$

The Method

- generation of diagrams with FeynArts
- computation of the total squared matrix element in the limit $v \to 0$
- numerical implementation in DarkSUSY:
    - squared matrix element
    - differential cross section
    - spectra of final state particles
    - spectra of final stable particles

The importance of s-channel resonances

s-channel VIB/ISR

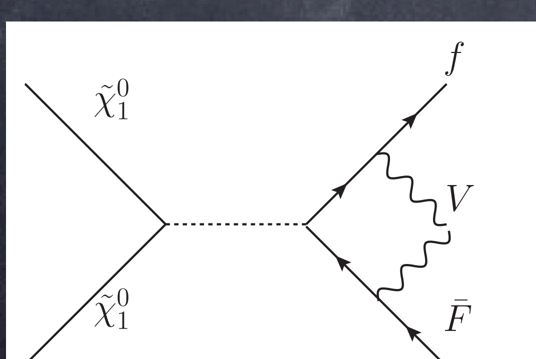


$$D_X(q) \quad \propto \quad ((p-k_V)^2 - m_X^2)^{-1}$$
$$\simeq \quad (4m_\chi^2 + m_V^2 - 4m_\chi E_V - m_X^2)^{-1}$$

$$\rightarrow \quad E_V^{res} \simeq m_\chi \left(1 + \frac{m_V^2 - m_X^2}{4m_\chi^2}\right)$$

$$X = h, H, A, H^\pm, Z, W^\pm$$

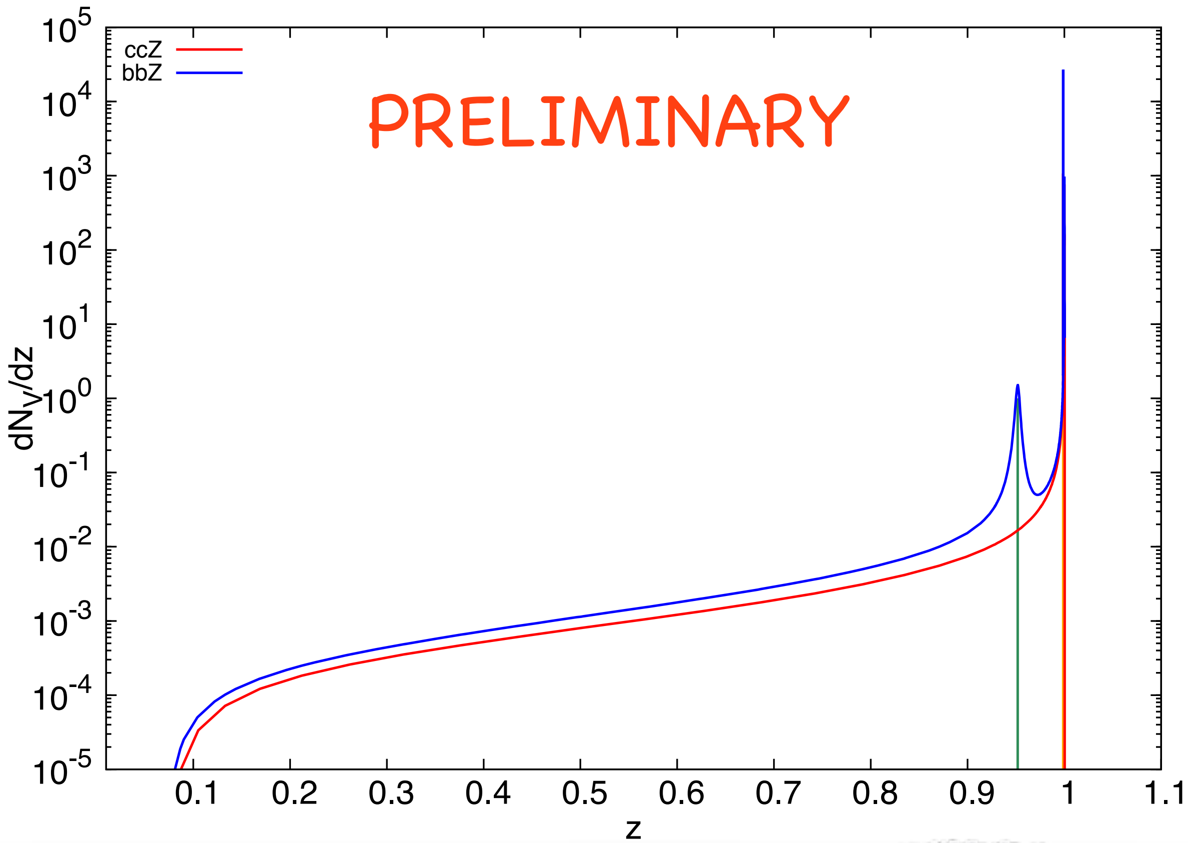
s- and t-channel FSR



$$D_{f_i}(q) \quad \propto \quad ((p-k_i)^2 - m_{f_i}^2)^{-1}$$
$$\simeq \quad (4m_\chi^2 - 4m_\chi E_i)^{-1}$$

$$\rightarrow \quad E_i^{res} \simeq m_\chi$$

Results: final state particles spectra



An MSSM example

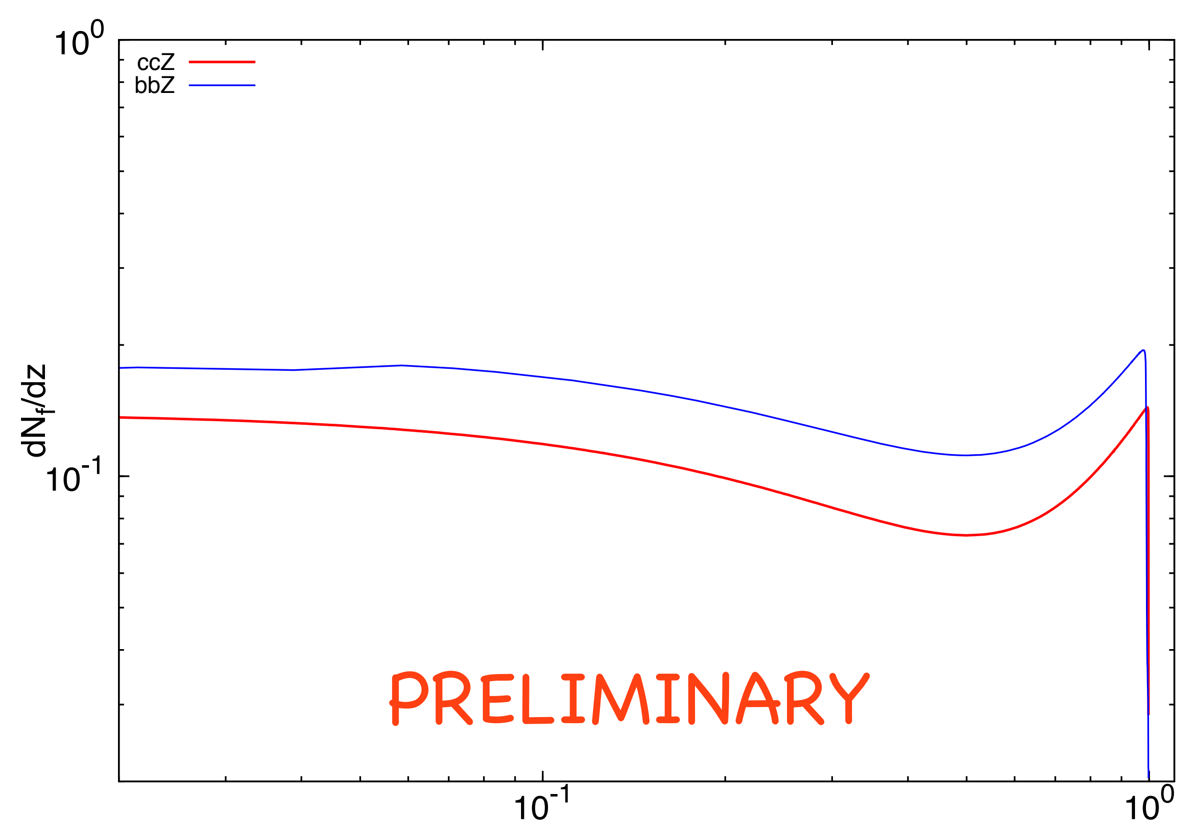
$$m_\chi = 1210.8\,\mathrm{GeV}$$
$$Z_g = 3.55 \cdot 10^{-4}$$
$$m_h = 124.4\,\mathrm{GeV}$$
$$m_H = 532.2\,\mathrm{GeV}$$

s-channel resonances

$$z_{res} \equiv \frac{E_{res}}{m_\chi} = 1 + \frac{m_V^2 - m_\chi^2}{4m_\chi^2}$$

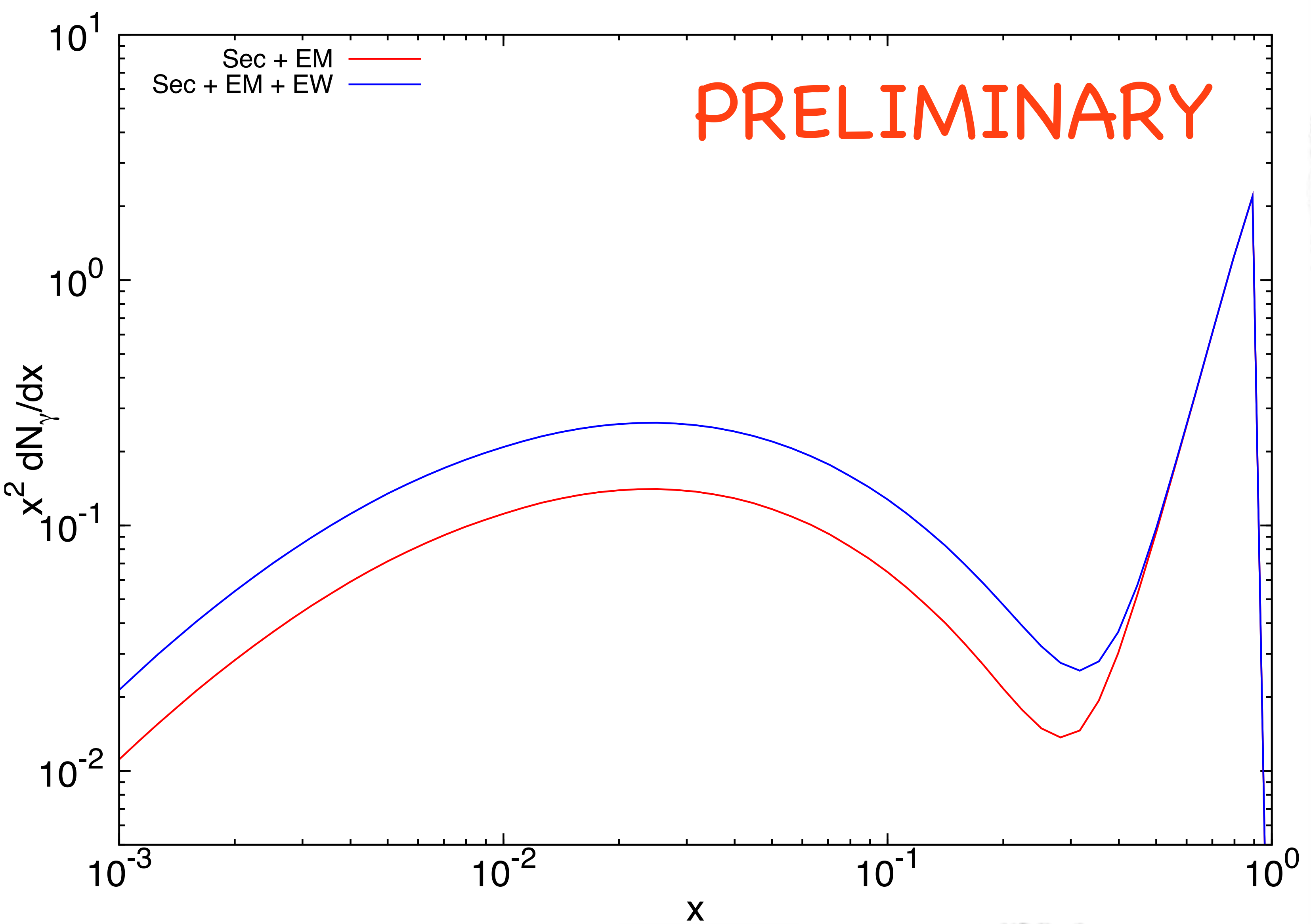
$$z_{res}^H = 0.952$$

$$z_{res}^h = 0.998 \qquad z_{res}^Z = 1$$



Results: total photon yield

$$\frac{dN_\gamma^{tot}}{dE} = \frac{dN_\gamma^{sec}}{dE} + \frac{dN_\gamma^{IB}}{dE} + \frac{dN_\gamma^{line}}{dE}$$



__A cMSSM example__

$$m_\chi = 233.3\,\mathrm{GeV}$$

$$m_{\tilde{\tau}} = 238.9\,\mathrm{GeV}$$

$$Z_g/(1-Z_g) = 220$$

$$\frac{dN}{dx} = m_\chi \frac{dN}{dE};\ x = \frac{E_\gamma}{m_\chi}$$

Conclusions and Outlook

- first fully general computation of EW corrections for MSSM neutralino
- all the diagrams are included (s-, t- and u- channel)
- implementation in DarkSUSY
- enhancement in co-annihilation region due to the lifting of the helicity suppression
- importance of resonances in the s-channel diagrams
- an extended scan over cMSSM and MSSM models is running and almost complete
    - enhancement mechanisms ?
    - relevance for the low-energy spectra ?
    - Viable models as new benchmark for ID DM ?
- not only gamma-rays...

Backup slides

DM Majorana fermion annihilating in the zero-velocity limit acts as a pseudo-scalar decaying particle

$$
\begin{aligned}
P &= (-1)^{L+1} = -1 \\
C &= +1
\end{aligned}
$$

Definition of helicity states in terms of 4-component spinors with helicity +/-:

$$(\bar{u}\,\Gamma\,v)_{(0,0)} = \frac{(\bar{u}_+\,\Gamma\,v_+ - \bar{u}_-\,\Gamma\,v_-)}{\sqrt{2}} \quad (1)$$

$$(\bar{u}\,\Gamma\,v)_{(1,-1)} = \bar{u}_-\,\Gamma\,v_+ \quad (2)$$

$$(\bar{u}\,\Gamma\,v)_{(1,0)} = \frac{(\bar{u}_+\,\Gamma\,v_+ + \bar{u}_-\,\Gamma v_-)}{\sqrt{2}} \quad (3)$$

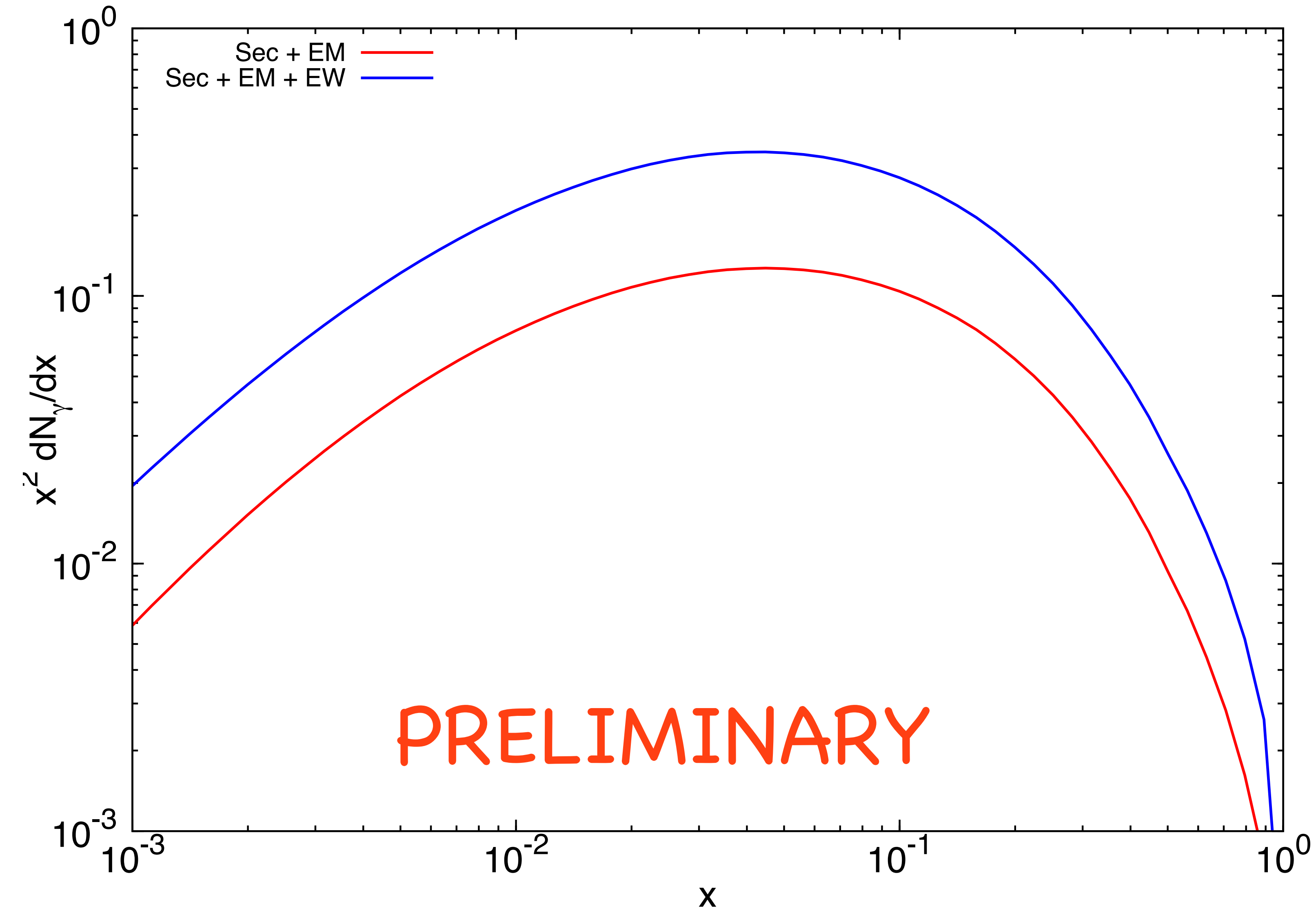
$$(\bar{u}\,\Gamma\,v)_{(1,1)} = \bar{u}_+\,\Gamma\,v_- \quad (4)$$

Where $\Gamma \equiv \Gamma^{\mu\ldots\nu}$

Kinematical boundaries

$$
\begin{aligned}
x_1^{min} &= \frac{m_1}{m_\chi} \\
x_1^{max} &= (4 + \frac{m_1^2}{m_\chi^2} - \frac{(m_V + m_2)^2}{m_\chi^2})/4 \\
x_V^{min} &= \frac{m_V}{m_\chi} \\
x_V^{max} &= (4 + \frac{m_V^2}{m_\chi^2} - \frac{(m_1 + m_2)^2}{m_\chi^2})/4
\end{aligned}
$$

Results: total photon yield (II)



MSSM example

***** MODEL A *****

Neutralino mass: 1210.8; Gaugino Fraction: $3.55 \cdot 10^{-4}$

$\sigma v^0_{2-body} = 8.08 \cdot 10^{-27}$ $\sigma v^0_{3-body} = 1.50 \cdot 10^{-26}$

$2.04 \cdot 10^{-27}$ $4.71 \cdot 10^{-27}$ $1.53 \cdot 10^{-29}$

$2.60 \cdot 10^{-27}$ $5.25 \cdot 10^{-27}$ $4.13 \cdot 10^{-28}$

$1.27 \cdot 10^{-29}$ $3.6 \cdot 10^{-32}$

***** MODEL B *****

Neutralino mass: 233.26; Gaugino Fraction: 0.995

$\sigma v^0_{2-body} = 8.50 \cdot 10^{-29}$ $\sigma v^0_{3-body} = 2.43 \cdot 10^{-28}$

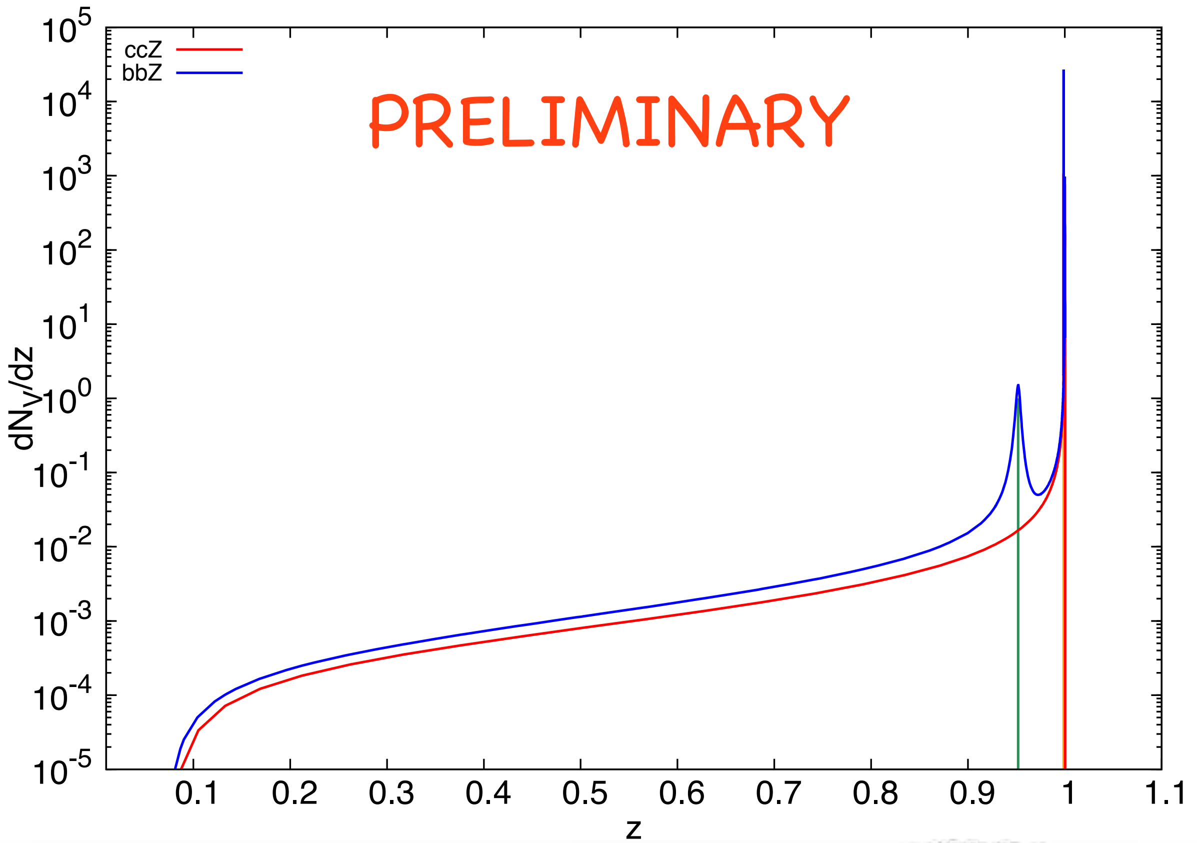
$1.69 \cdot 10^{-29}$ $5.13 \cdot 10^{-31}$ $1.89 \cdot 10^{-34}$

$1.23 \cdot 10^{-30}$ $1.12 \cdot 10^{-28}$ $1.12 \cdot 10^{-28}$

$6.32 \cdot 10^{-29}$ $1.04 \cdot 10^{-32}$

[units of $\mathrm{cm}^3\mathrm{s}^{-1}$]

Results: final state particles spectra



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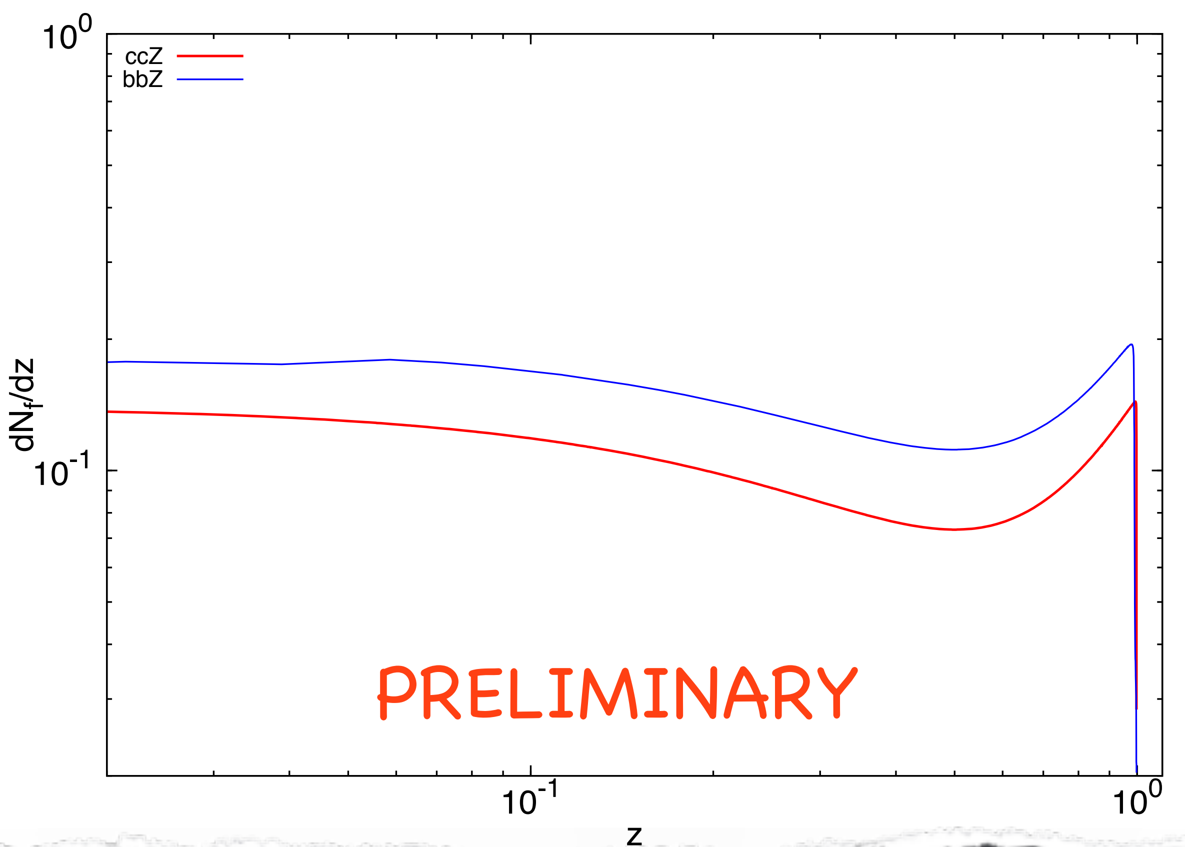
s-channel resonances

$$z_{res} \equiv \frac{E_{res}}{m_\chi} = 1 + \frac{m_V^2 - m_X^2}{4m_\chi^2}$$

$$z_{res}^{H} = 0.952 \qquad z_{res}^{H^\pm} = 0.949$$

$$z_{res}^{h} = 0.998 \qquad z_{res}^{Z/W} = 1$$



The Method

Squared matrix element

$$|M|^2$$

$$\frac{d(\sigma v)}{dE_1 dE_2} = \frac{1}{16\, m_\chi^2} \frac{1}{(2\pi)^3} \overline{|\mathcal{M}|}^2$$

$$\frac{dN_p^{\bar{F}fV}}{dE_p} = \frac{1}{\sigma v_0^{tree}} \int_{E_{p'}^{\min}(E_p)}^{E_{p'}^{\max}(E_p)} \frac{d(\sigma v)}{dE_p dE_{p'}} dE_{p'}$$

$$\frac{dN_P^{\bar{F}fV}}{dE_P} = \sum_{p=F,f,V} \int_{E_p^{\min}}^{E_p^{\max}} \frac{1}{2} \frac{dN_P^{\bar{p}p\to P+X}}{dE_P} \frac{dN_p^{\bar{F}fV}}{dE_p}\, dE_p$$

The Method

Differential cross section

$$|M|^2$$

$$\frac{d(\sigma v)}{dE_1 dE_2} = \frac{1}{16\, m_\chi^2}\, \frac{1}{(2\pi)^3} \overline{|\mathcal{M}|}^2$$

$$\frac{dN_p^{\bar{F}fV}}{dE_p} = \frac{1}{\sigma v_0^{tree}} \int_{E_{p'}^{\min}(E_p)}^{E_{p'}^{\max}(E_p)} \frac{d(\sigma v)}{dE_p dE_{p'}} dE_{p'}$$

$$\frac{dN_P^{\bar{F}fV}}{dE_P} = \sum_{p=F,f,V} \int_{E_p^{\min}}^{E_p^{\max}} \frac{1}{2} \frac{dN_P^{\bar{p}p \to P+X}}{dE_P} \frac{dN_p^{\bar{F}fV}}{dE_p}\, dE_p$$

The Method

Spectra of final state particles

$$|M|^2$$

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The Method

Spectra of final stable particles

$$|M|^2$$

$$\frac{d(\sigma v)}{dE_1 dE_2} = \frac{1}{16\, m_\chi^2} \frac{1}{(2\pi)^3} \overline{|\mathcal{M}|}^2$$

$$\frac{dN_p^{\bar{F}fV}}{dE_p} = \frac{1}{\sigma v_0^{tree}} \int_{E_{p'}^{\min}(E_p)}^{E_{p'}^{\max}(E_p)} \frac{d(\sigma v)}{dE_p dE_{p'}} dE_{p'}$$

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