ElectroWeakDarkMatter: SRT effect vs indirect detections

Based on 1210.6104 with J.C. Park and S. Scopel
& work in progress with J.C.Park

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Outline

- Introduction to general EWDM:

  - Arbitrary $(m_{DM}, \ \delta m)$ with $\Omega_{DM} = 0.2$ assumed.
- Non-perturbative correction to annihilation:

  - Sommerfeld-Ramsauer-Towsend effect.
- Direct detection of inelastic EWDM (with nonzero Y).
- Constraints from indirect detections: anti-protons at AMS2, & gamma lines at Fermi-LAT & HESS

  – Higgsino-like, Wino-like, Hypercharged triplet
- Conclusion.

Electro-Weak Dark Matter

- A simplistic dark matter candidate: $SU(2)_L$ multiplet with Q=0 component.
- No Yukawa coupling allowed for the stability: automatic (minimal), or imposed by hand.
- Gauge coupling, mass & mass gaps determines all the properties.

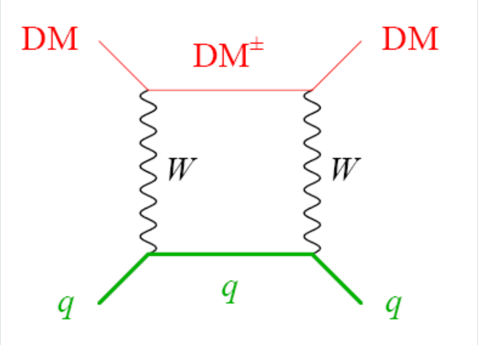
EWDM: basics

- A large gauge annihilation rate: multi-TeV mass for the thermal freeze-out relic density.
- Nucleonic scattering at one-loop: $\sigma_{SI} \sim 10^{-45}$ cm^2.
- Radiative mass splitting between the charged and neutral components

  ~ 0.1 GeV.
- Disappearing (multi-) charged tracks at LHC.

$$\langle \sigma_A v \rangle \approx \frac{4\pi\alpha_2^2}{m_{DM}^2}$$

$$\Omega_{\rm DM} h^2 \sim 0.1 \left(\frac{2{\rm TeV}}{m_{DM}} \right)^2$$



$$\mathrm{DM}^{\pm} \to \mathrm{DM}^0 \pi^{\pm}$$

$$\mathrm{DM}^{++} \to \mathrm{DM}^{+} \pi^{+}$$

EWDM: basics

Quantum numbers $SU(2)_L$	$U(1)_Y$	Spin	DM can decay into	DM mass in TeV	$m_{DM^\pm} - m_{DM}$ in MeV	Events at LHC $\int \mathcal{L}\,dt = 100/\text{fb}$	σ_{SI} in $10^{-45}\,\text{cm}^2$
2	1/2	0	EL	0.54 ± 0.01	350	$320 \div 510$	0.2
2	1/2	1/2	EH	1.1 ± 0.03	341	$160 \div 330$	0.2
3	0	0	HH^*	2.0 ± 0.05	166	$0.2 \div 1.0$	1.3
3	0	1/2	LH	2.4 ± 0.06	166	$0.8 \div 4.0$	1.3
3	1	0	HH, LL	1.6 ± 0.04	540	$3.0 \div 10$	1.7
3	1	1/2	LH	1.8 ± 0.05	525	$27 \div 90$	1.7
4	1/2	0	HHH^*	2.4 ± 0.06	353	$0.10 \div 0.6$	1.6
4	1/2	1/2	(LHH^*)	2.4 ± 0.06	347	$5.3 \div 25$	1.6
4	3/2	0	HHH	2.9 ± 0.07	729	$0.01 \div 0.10$	7.5
4	3/2	1/2	(LHH)	2.6 ± 0.07	712	$1.7 \div 9.5$	7.5
5	0	0	(HHH^*H^*)	5.0 ± 0.1	166	$\ll 1$	12
5	0	1/2	–	4.4 ± 0.1	166	$\ll 1$	12
7	0	0	–	8.5 ± 0.2	166	$\ll 1$	46

Cirelli, et.al., 0512090

Three examples

- Vector-like doublet with Y= +- ½ (Higgsino)

$$\chi_u = (\chi_u^+, \chi_u^0)\,,\ \chi_d = (\chi_d^0, \chi_d^-) \quad \Rightarrow \chi_{0,1}^0 (\text{Majorana})$$

$$m_\chi \chi_u \chi_d, \quad \frac{1}{\Lambda}(H_u \chi_d)^2,\ \frac{1}{\Lambda}(H_d \chi_u)^2,\ \frac{1}{\Lambda}(H_u \chi_d)(H_d \chi_u)$$

Dirac mass   Mass splitting → Majorana masses

- Majorana triplet with Y=0 (wino)

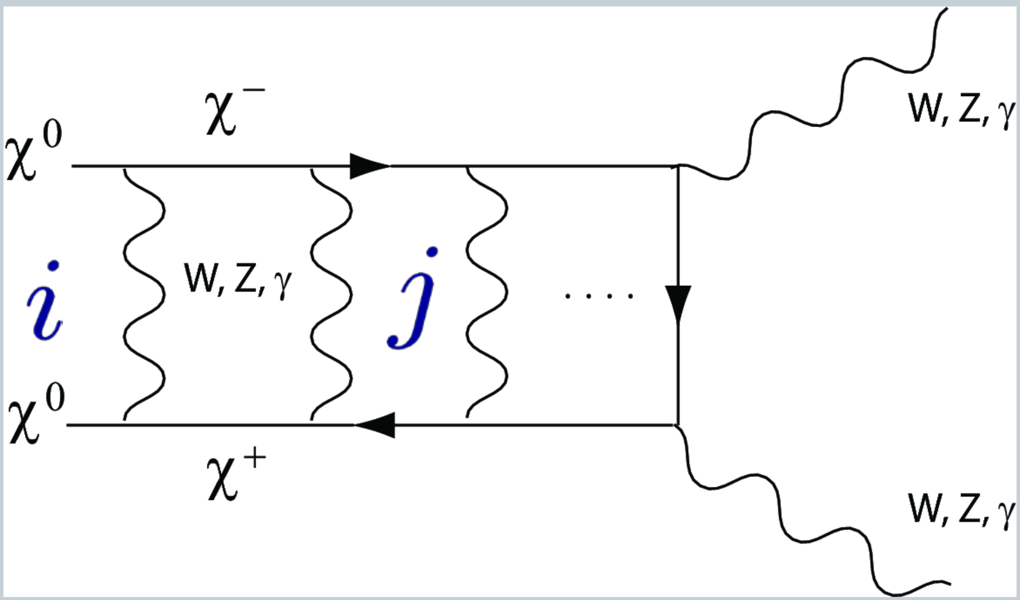
$$\chi = (\chi^+, \chi^0, \chi^-)$$

- Vector-like triplet with Y=+-1 (hyper-charged)

$$\chi_u = (\chi_u^{++}, \chi_u^+, \chi_u^0)\,,\ \chi_d = (\chi_d^0, \chi_d^-, \chi_d^{--})$$

Non-perturbative effect

- In non-relativistic limit, pair annihilations can be strongly modified by two-body bound state effect.



Hisano, et.al., 0412403
Cirelli, et.al., 0706.4071

Non-perturbative effect

- Two-body wave functions are governed by Shroedinger eq. with EW potential:

$$-\frac{1}{m_{DM}}\frac{\partial^2 g_{ij}(r)}{\partial r^2}+V_{ik}(r)g_{kj}(r)=K g_{ij}(r)$$

$$K = m_{DM}\beta^2$$

$$g_{ij}(0)=\delta_{ij}$$

$$\partial g_{ij}(\infty)/\partial r = i\sqrt{m_{DM}(K-V_{ii}(\infty))}g_{ij}(\infty)$$

$$V_{ij}(r)=2\,\delta m_{i0}\,\delta_{ij}-\alpha_2 N_i N_j\sum_A [T^A_{ij}]^2\frac{e^{-m_A r}}{r}$$

N_i is 1 or $\sqrt{2}$ for the Dirac (charged) or Majorana (neutral)

Non-perturbative effect

- Annihilation with non-perturbative corrections:

$$\sigma v(\chi_0^0\chi_0^0 \to AB) = 2 d_{0i} d_{0j}^* \Gamma_{ij}^{AB}$$

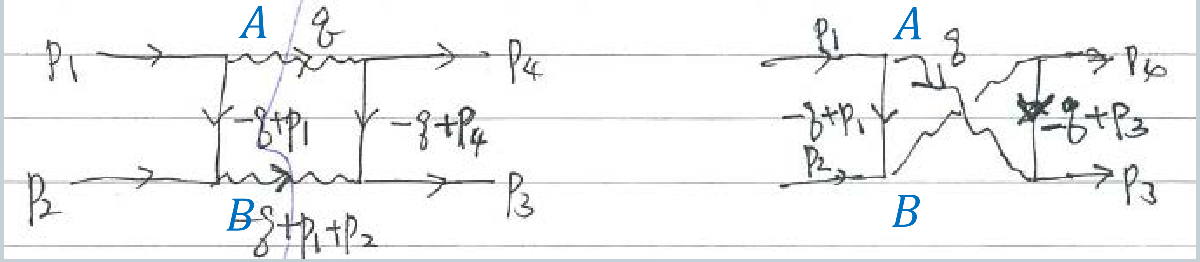
$$d_{0j} = g_{0j}(\infty) \qquad v = 2\beta$$

$$AB = (W^+W^-, ZZ, \gamma Z, \gamma\gamma)$$

$$\Gamma_{ij}^{AB} = \frac{\pi\alpha_2^2}{2(1+\delta_{AB})m_{DM}^2} f(x_A, x_B) N_i N_j \{T^A, T^B\}_{ii} \{T^A, T^B\}_{jj}$$

$$f(x_A, x_B) \equiv \frac{\left(1 - \frac{x_A + x_B}{2}\right)}{\left(1 - \frac{x_A+x_B}{4}\right)^2} \sqrt{1 - \frac{x_A + x_B}{2} + \frac{(x_A - x_B)^2}{16}} \qquad x_A = \frac{m_A^2}{m_{DM}^2}$$

- σv = Im(T)/2m^2



Potential matrix for wino-like EWDM

Two states: $(\chi^+\chi^-)$, $(\chi^0\chi^0)$

$$V := \begin{bmatrix} 2\,\delta m - \frac{sw^2\,\alpha 2^2}{r} - \frac{cw^2\,\alpha 2^2\,e^{-mZ\,r}}{r} & -\frac{\alpha 2^2\,e^{-mW\,r}\sqrt{2}}{r} \\ -\frac{\alpha 2^2\,e^{-mW\,r}\sqrt{2}}{r} & 0 \end{bmatrix}$$

Scattering matrix for wino-like EWDM

$$\Gamma(WW) := \begin{bmatrix} \frac{1}{2} & \frac{1}{2}\sqrt{2} \\ \frac{1}{2}\sqrt{2} & 1 \end{bmatrix} \times \frac{\pi\alpha_2^2}{m^2}$$

$$\Gamma(ZZ) := \begin{bmatrix} cw^4 & 0 \\ 0 & 0 \end{bmatrix}$$

$$\Gamma(AZ) := \begin{bmatrix} 2\, cw^2\, sw^2 & 0 \\ 0 & 0 \end{bmatrix}$$

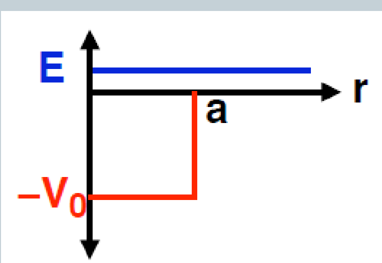
$$\Gamma(AA) := \begin{bmatrix} sw^4 & 0 \\ 0 & 0 \end{bmatrix}$$

Sommerfeld-Ramsauer-Townsend

- Three important factors: mass, mass gaps, velocity.
- Consider the simplest case of wino-like DM having two bound states, one mass gap.

$$(\chi^+\chi^- \text{ and } \chi^0\chi^0) \qquad \delta m_+ \equiv m_{\chi^+} - m_{\chi^0}$$

- Sommerfeld effect: 1931
- RT effect: 1921 electron diffraction in a noble gas.



$$\sigma = \frac{4\pi \sin^2 \delta_0}{k^2} \qquad \tan \delta_0 = \frac{k\left(\frac{1}{\alpha} - \frac{\tan ka}{k}\right)}{1 + \frac{k}{a} \tan ka}$$

$$\frac{1}{\alpha} = \frac{\tan ka}{k} \Rightarrow \boxed{\frac{\tan k_1 a}{k_1} = \frac{\tan ka}{k}}$$

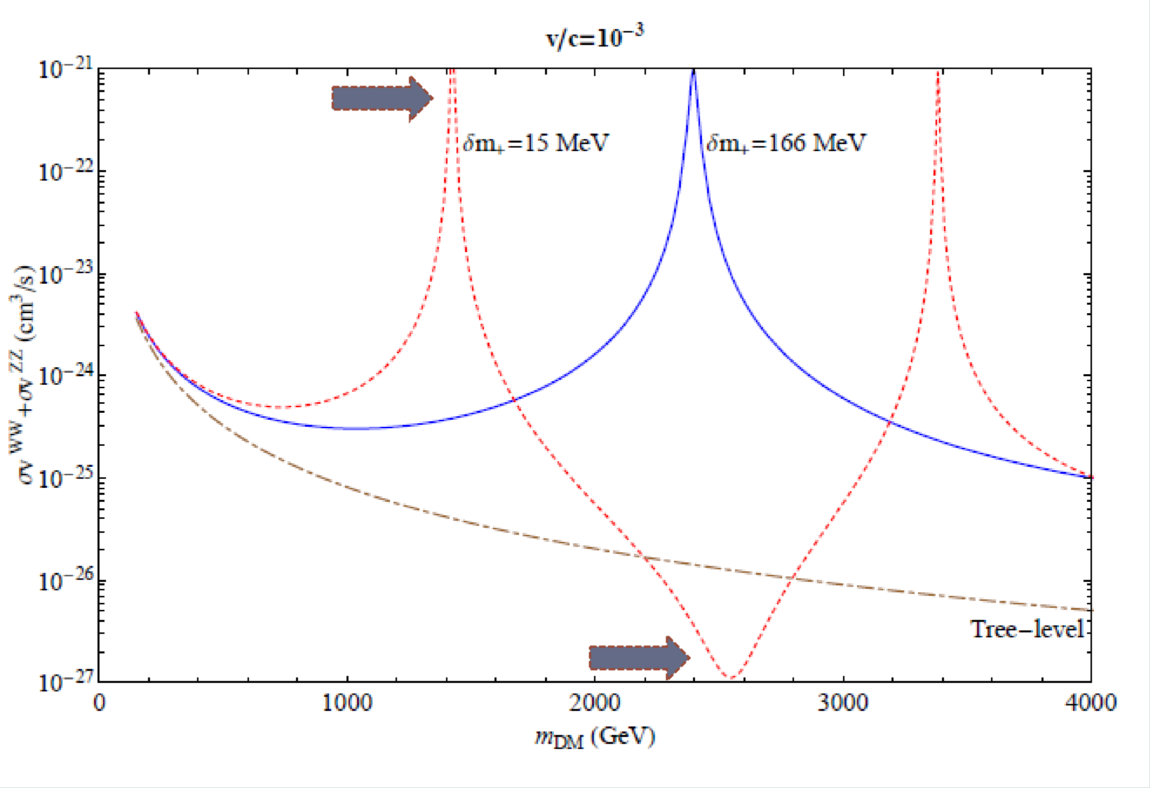
Dependence on the mass gap

- Smaller mass gap → easier transition of the DM state to the charged state which has a long-range Coulomb force (EM).

$$\delta m_+ \equiv m_{\chi^+} - m_{\chi^0}$$

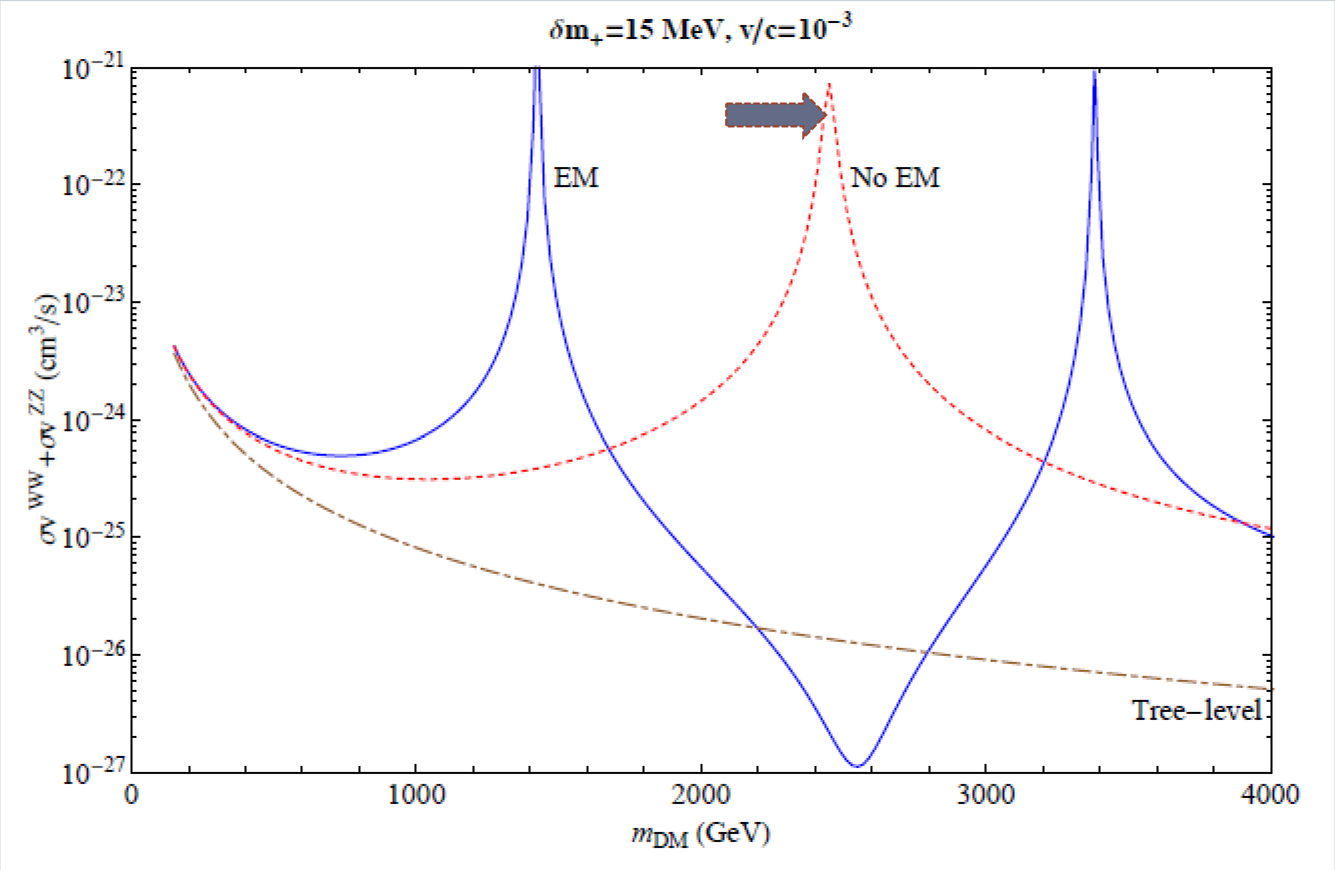
$$K = m_{DM}\beta^2$$

Smaller mass gap → earlier S peak & RT dip with smaller m_{DM} or K.



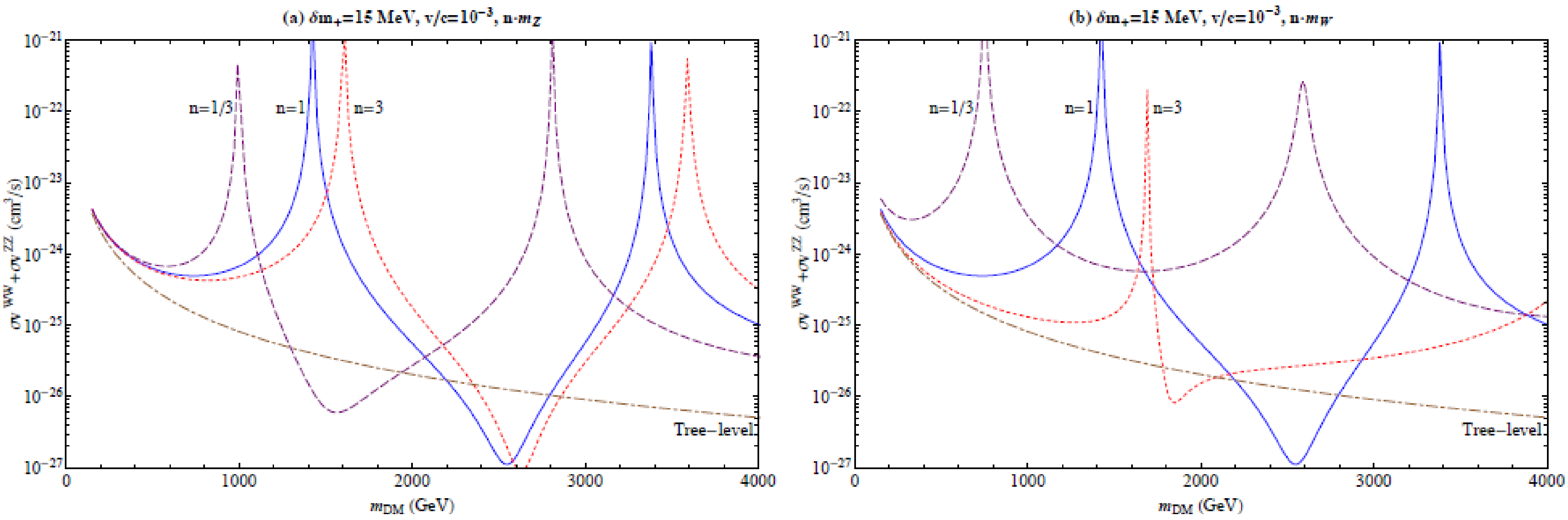
Dependence on the EW strength

- No EM → SRT effect insensitive to the mass gap.



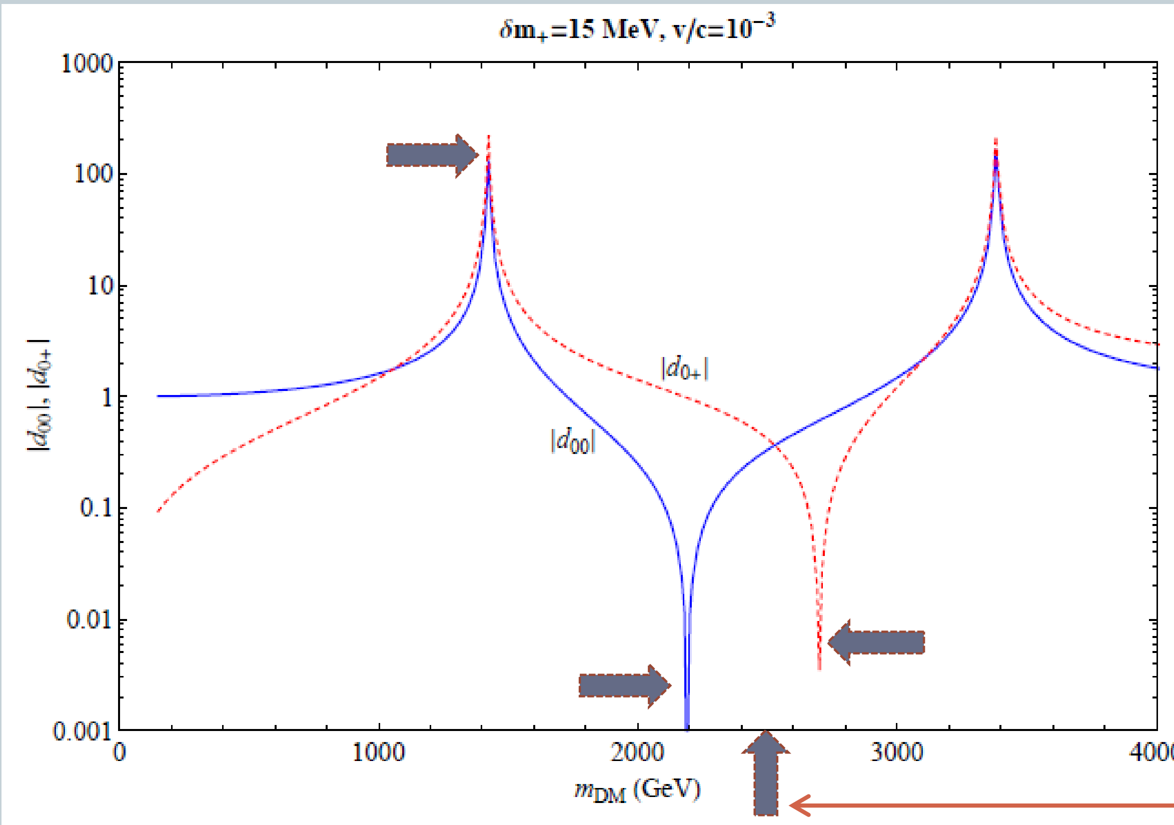
Dependence on the EW strength

- SRT effect more sensitive to W interaction.



Behavior of the amplitudes

- Shows constructive (S) and destructive (RT) resonances.
- S peaks coincides but RT dips not.

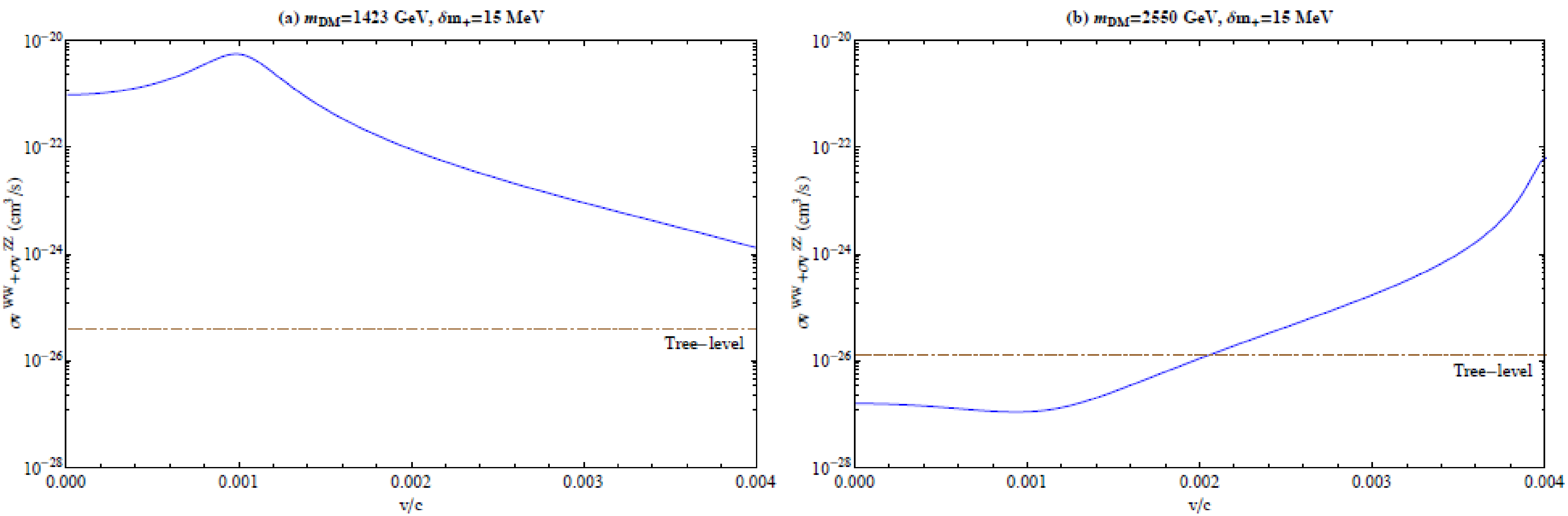


RT dip in σv
due to cancelation btw
two RT resonances.

Dependence on the velocity

$$\langle \sigma v \rangle = N(v_{esc}) \int_0^{2v_{esc}} [\sigma v(v)] v^2 exp\left[-\frac{3}{4}\left(\frac{v}{v_{rms}}\right)^2\right] dv$$

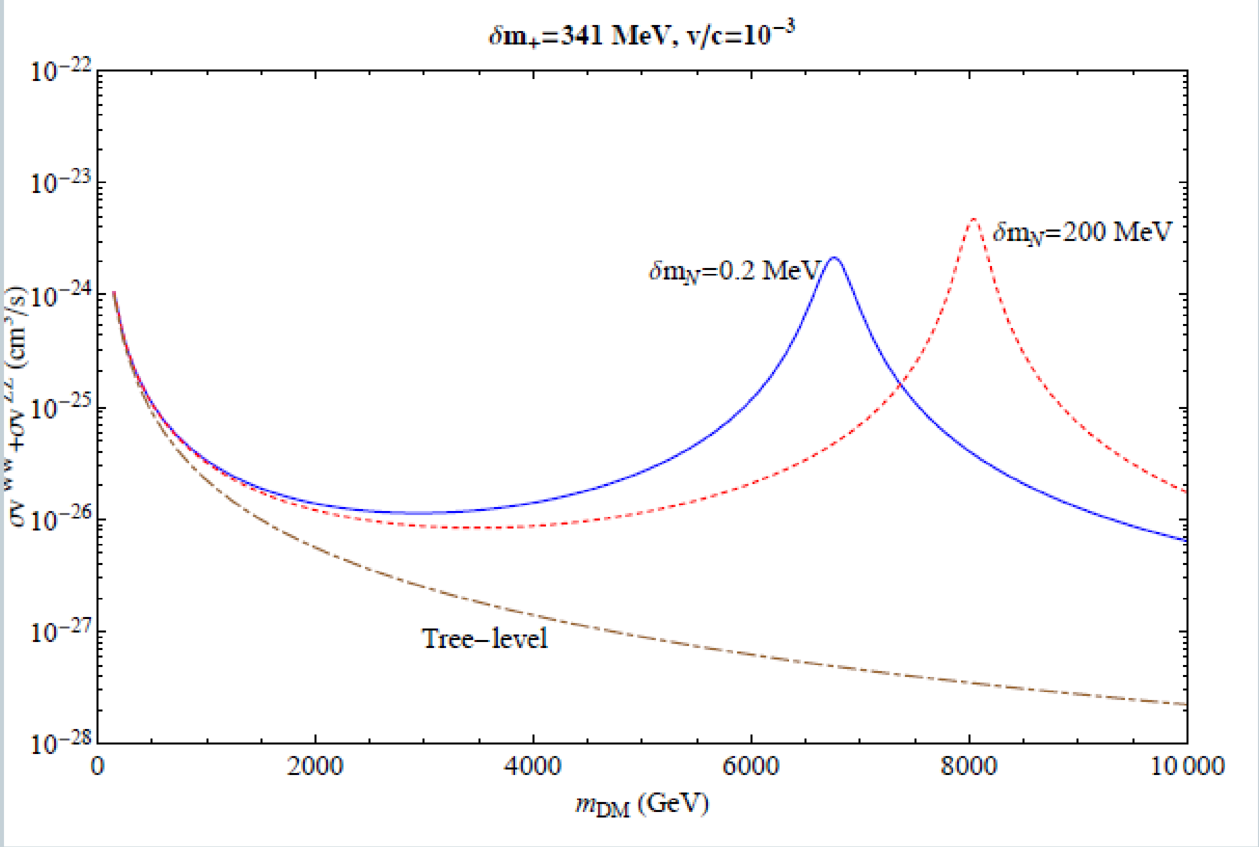
v_{rms}=270 km/s, v_{esc}=550 km/s



Dependence on the neutral mass gap

- In the Higgsino-like DM:

$$\delta m_N \equiv m_{\chi_1^0} - m_{\chi_0^0}$$



Direct detection

- Inelastic EWDM with nonzero Y.
- Minimum velocity to allow the transition.

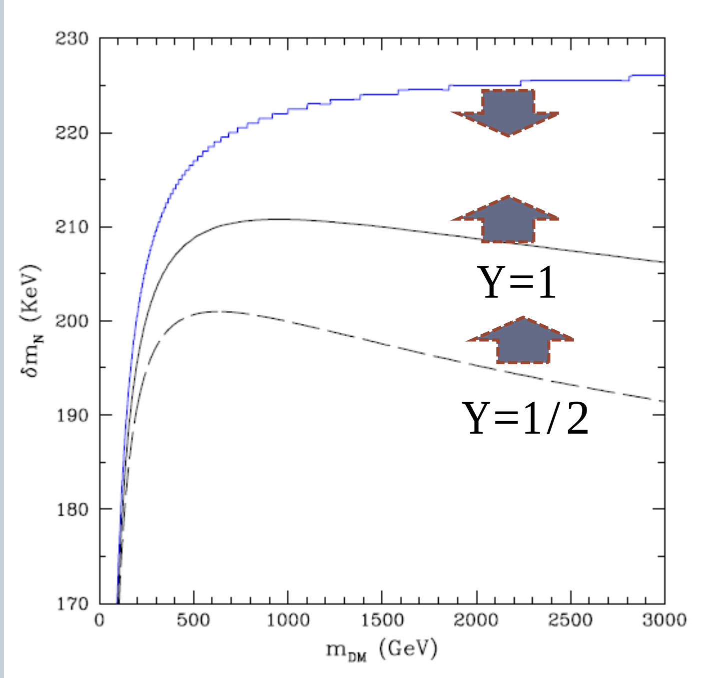
$$\beta_{min} = \sqrt{\frac{1}{2M_N E_R}}\left(\frac{M_N E_R}{\mu} + \delta m_N\right)$$

$$c\beta_{min} > v_{max} = v_{esc} + v_{earth}$$

- Cross-section with no mass gap:

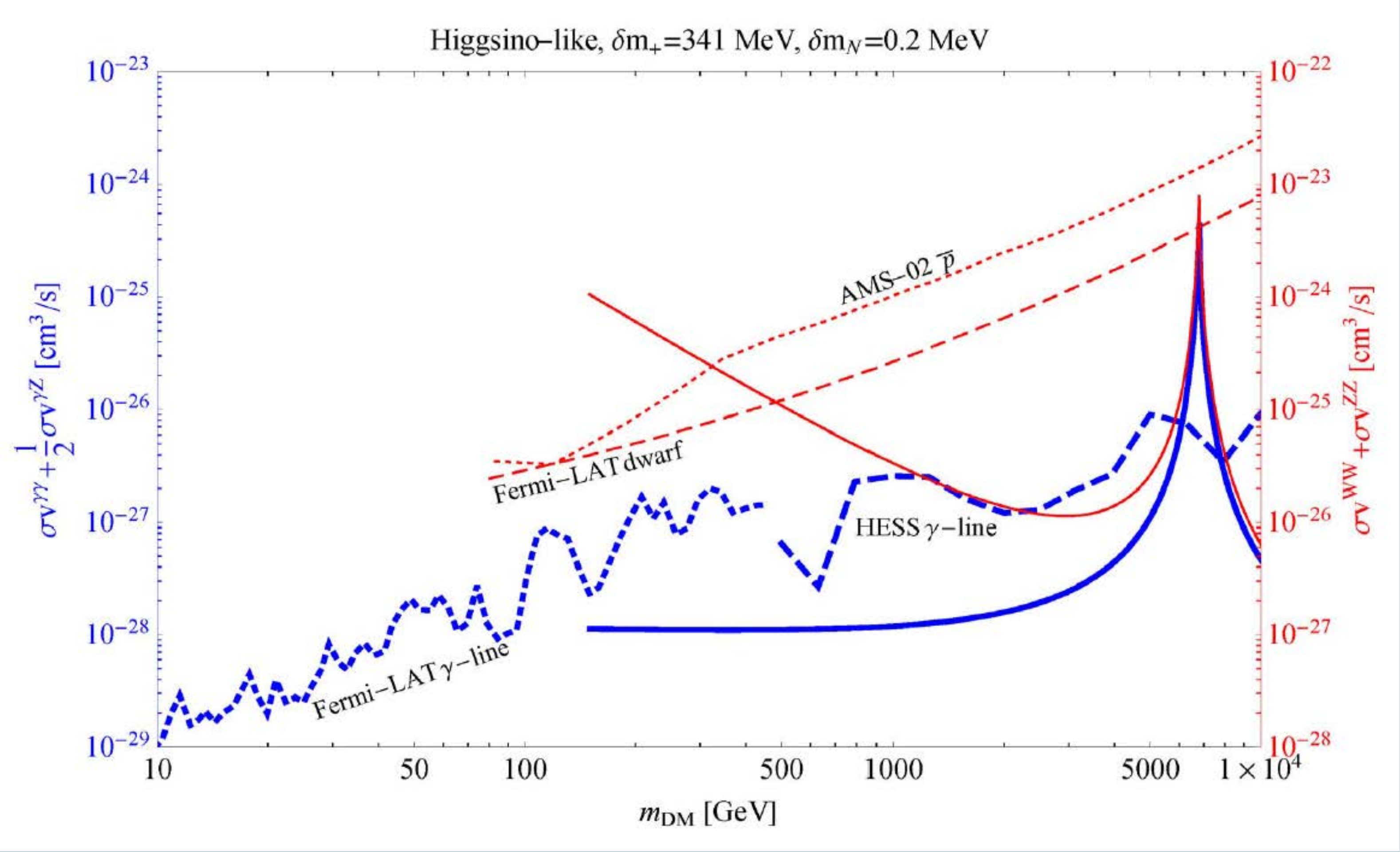
$$c\frac{G_F^2 M_N^2}{2\pi} Y^2 (N - (1 - 4s_W^2)Z)^2$$

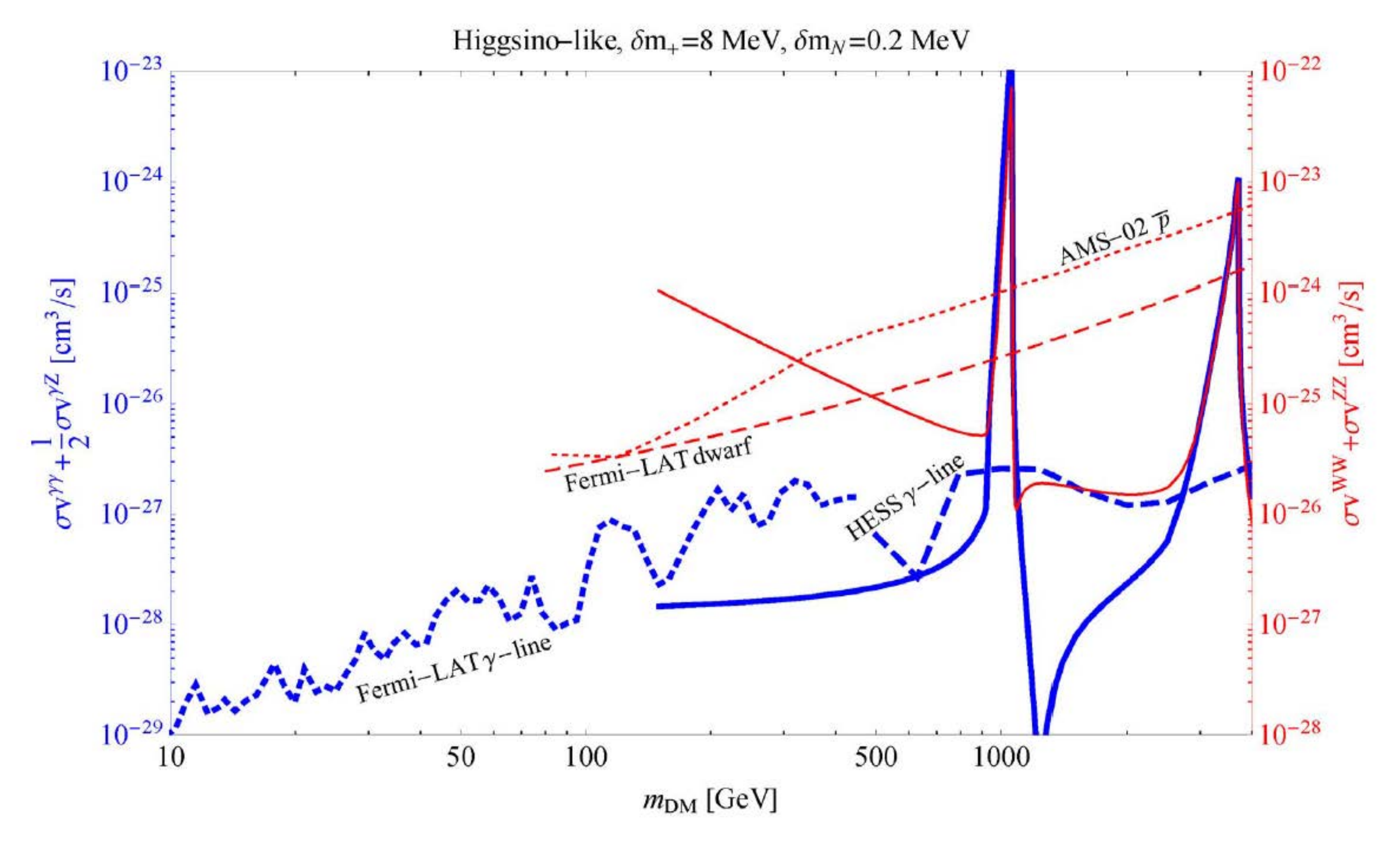
$$\delta m_N \equiv m_{\chi_1^0} - m_{\chi_0^0}$$



Observable I-EWDM

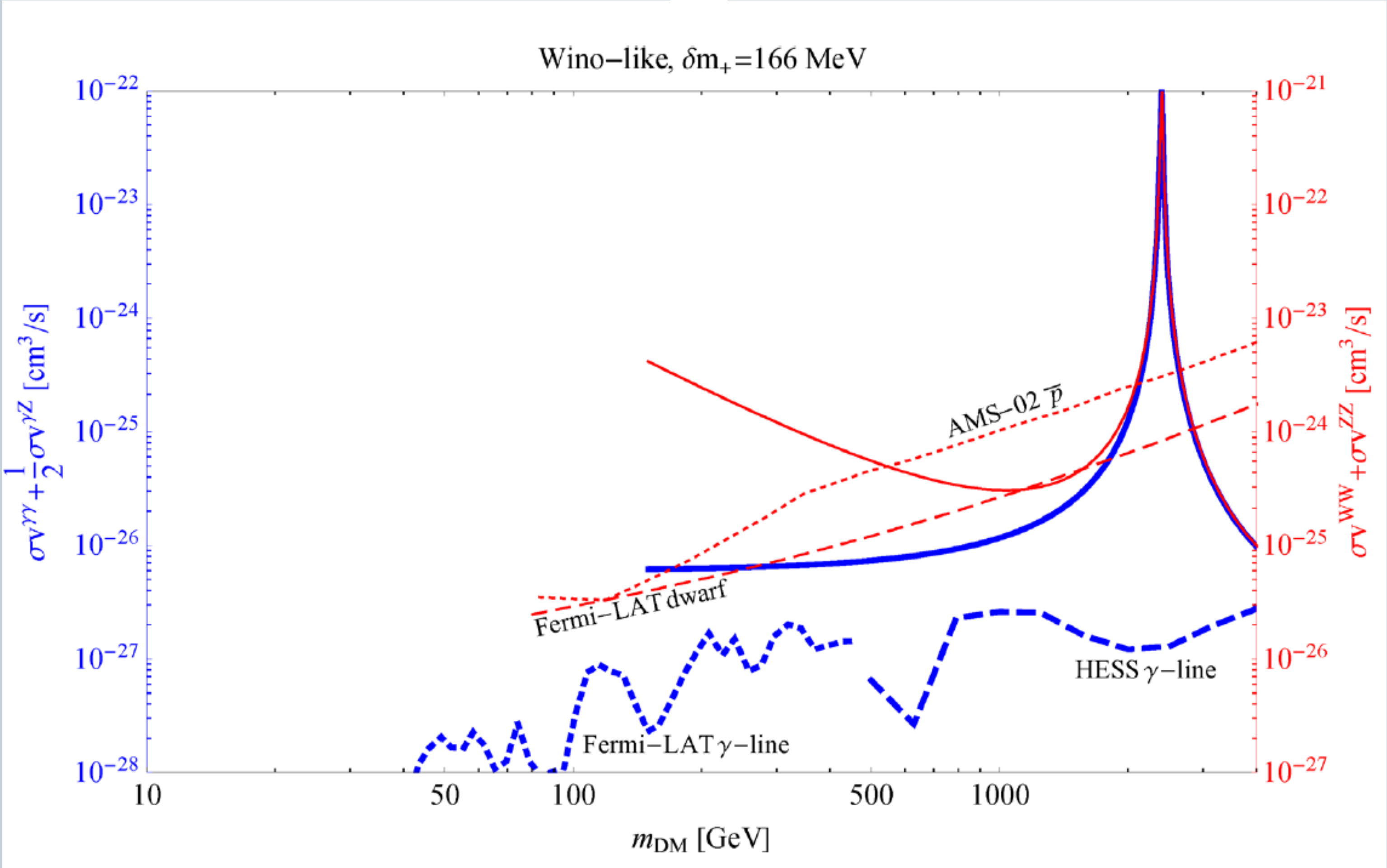
Indirect detection: Higgsino-like

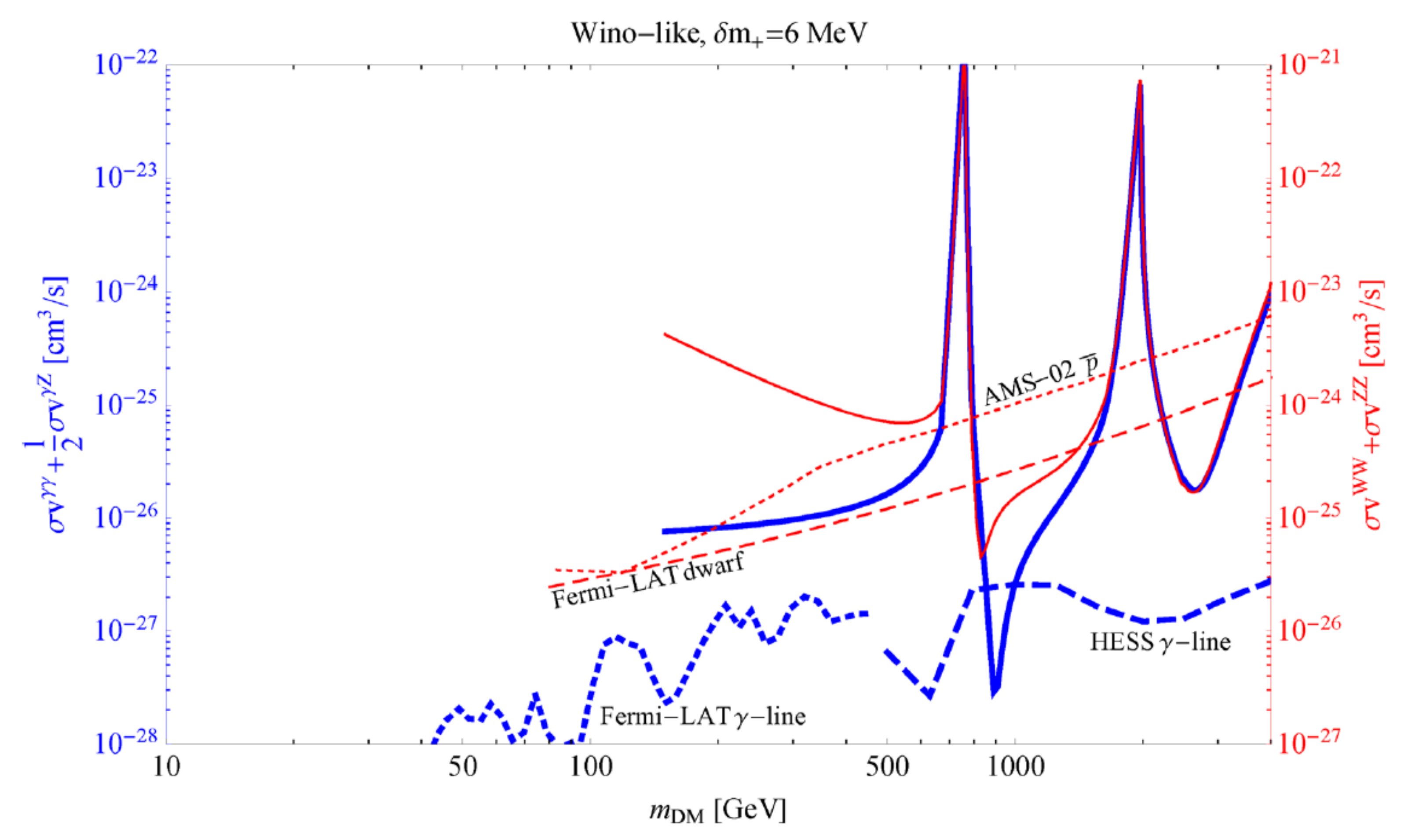




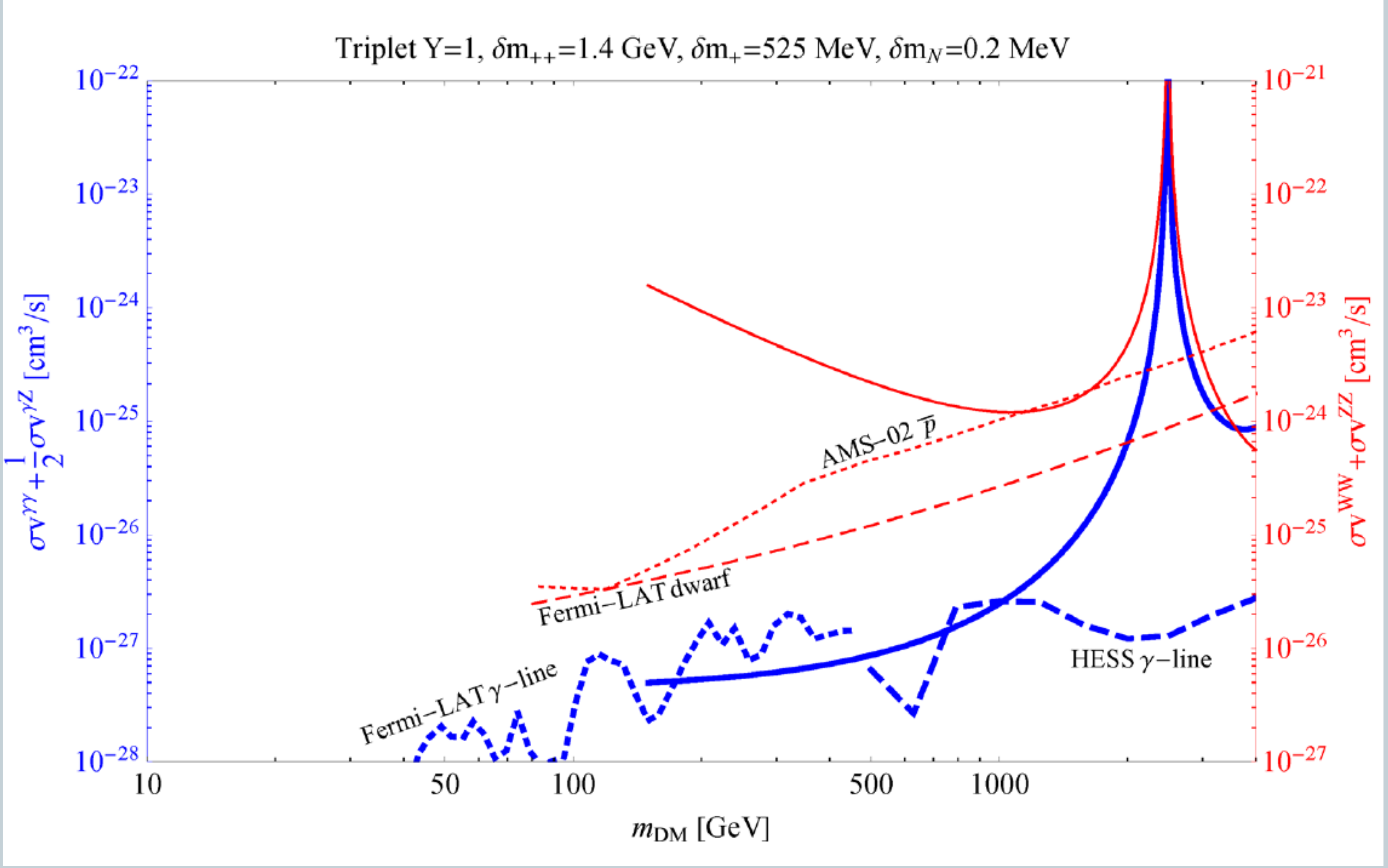
Higgsino–like, δm_+=8 MeV, δm_N=0.2 MeV
$\sigma v^{\gamma\gamma} + \frac{1}{2}\sigma v^{\gamma Z}$ [cm^3/s]
$\sigma v^{WW} + \sigma v^{ZZ}$ [cm^3/s]
m_{DM} [GeV]
AMS–02 $\bar{p}$
Fermi–LAT dwarf
HESS γ–line
Fermi–LAT γ–line
10
50
100
500
1000
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}

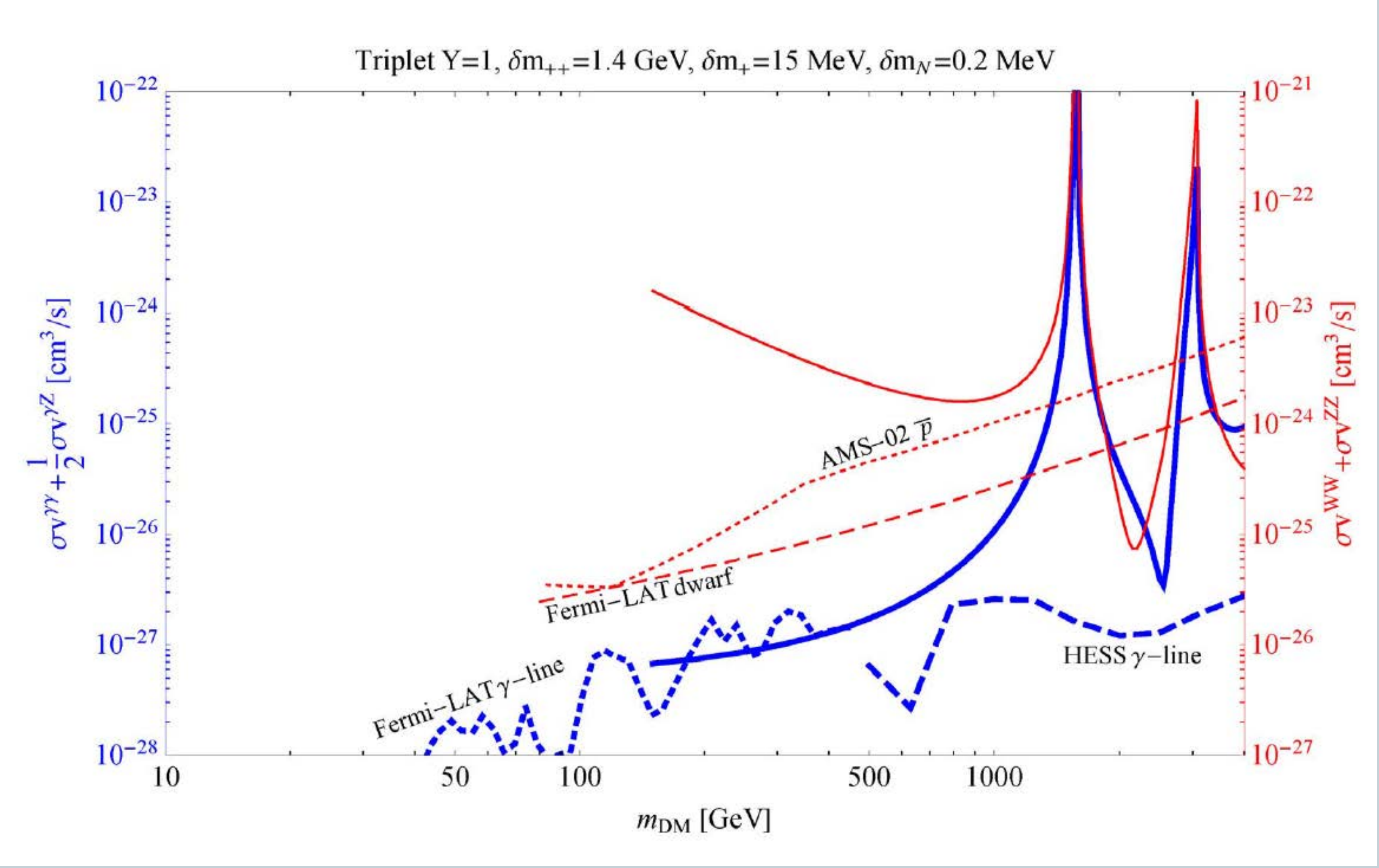
Indirect detection: Wino-like




Wino–like, δm_+=6 MeV
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
$\sigma v^{\gamma\gamma}+\frac{1}{2}\sigma v^{\gamma Z}$ [cm^3/s]
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
$\sigma v^{WW}+\sigma v^{ZZ}$ [cm^3/s]
AMS–02 $\overline{p}$
Fermi–LAT dwarf
HESS γ–line
Fermi–LAT γ–line
10
50
100
500
1000
m_{DM} [GeV]

Indirect detection: Hypercharged triplet




Triplet Y=1, δm++=1.4 GeV, δm+=15 MeV, δmN=0.2 MeV
AMS−02 p̄
Fermi−LAT dwarf
Fermi−LAT γ−line
HESS γ−line
mDM [GeV]
σvγγ + 1/2 σvγZ [cm3/s]
σvWW + σvZZ [cm3/s]
10
50
100
500
1000

Conclusion

- EWDM: a minimal candidate.
- A general study on the non-perturbative effect on non-relativisitic annihilation depending on the DM mass, mass gaps, velocity.
- Appearance of constructive and destructive resonances → Sommerfeld peaks and Ramauser-Townsend dips.
- Strong indirect detection limit from anti-proton, gamma ray and line searches: escape by RT dips?
- Direct detection of inelastic EWDM in the future?