Non relativistic effect on indirect probe of EWIMP at LHC

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(work in progress)

Contents

- EWIMP and our model
- Indirect probe
- Relativistic calculation and over view
- NR calculation
- Result and conclusion

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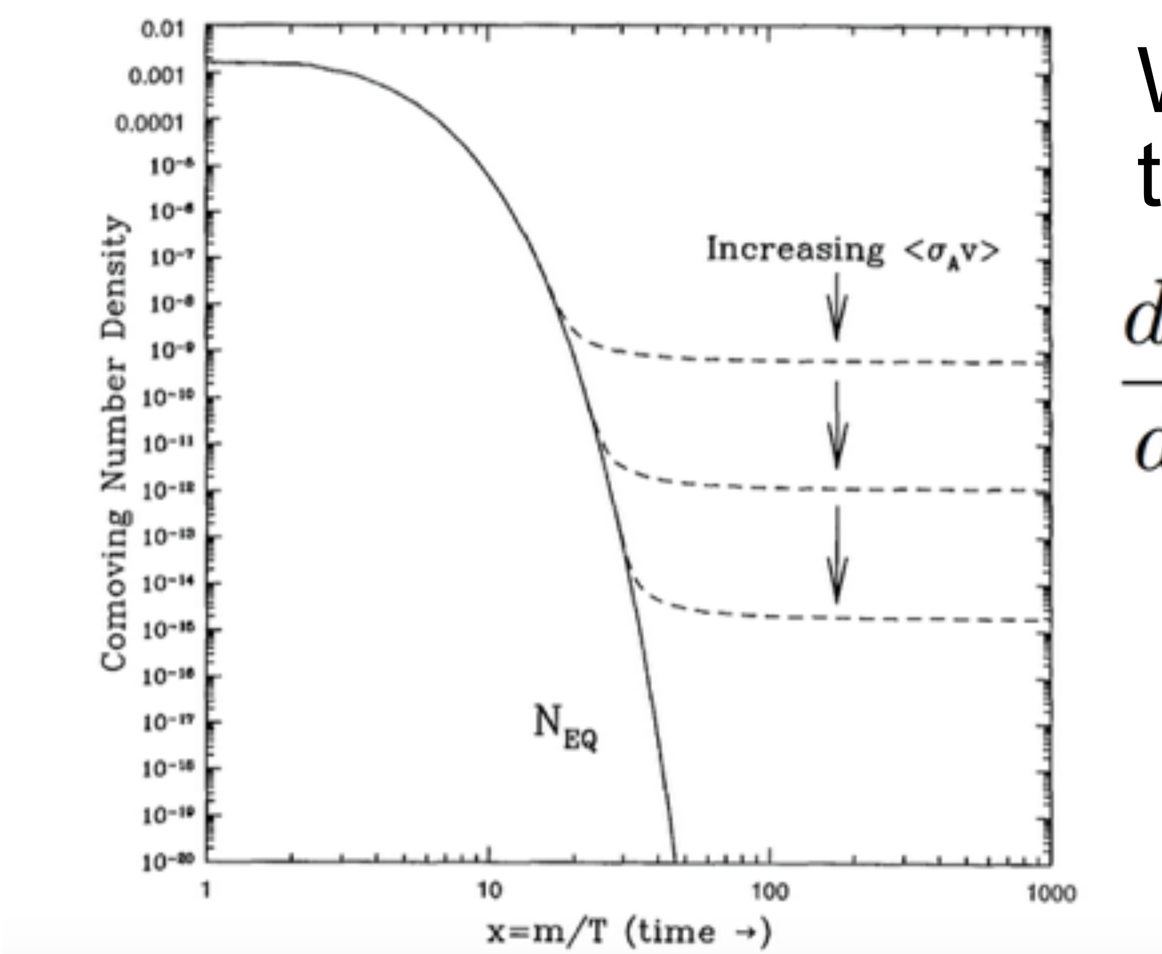
EWIMP

- ElectroWeakly Interacting Massive Particle
- Wino or Higgsino in SUSY
- (E)WIMP is good candidate of dark matter



We can estimate relic density through Boltzmann equation.

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{eq}^2)$$

n is number density of WIMP
σ is cross section of
DM + DM → SM + SM

Our model

- Consider Majorana fermonic EWIMP
- SU(2) (2n+1)-plet, U(1) hypercharge is 0
- Parameter is only m_χ (Majorana mass)

$$\mathcal{L} \;=\; \mathcal{L}_{\rm sm} + \frac{i}{2}\bar{\chi}\gamma^\mu D_\mu \chi - \frac{1}{2} m_\chi \bar{\chi}\chi$$

$$\chi = \begin{pmatrix} \begin{pmatrix} \eta_n^c \\ \eta_n \end{pmatrix} \\ \vdots \\ \begin{pmatrix} \eta_0^c \\ \eta_0 \end{pmatrix} \\ \vdots \\ \begin{pmatrix} \eta_{-n}^c \\ \eta_{-n} \end{pmatrix} \end{pmatrix}$$

$$\eta_k^c = (-1)^k(-i\sigma_2)\eta_{-k}^*$$

- 3-plet case: wino
- 5-plet case: MDM

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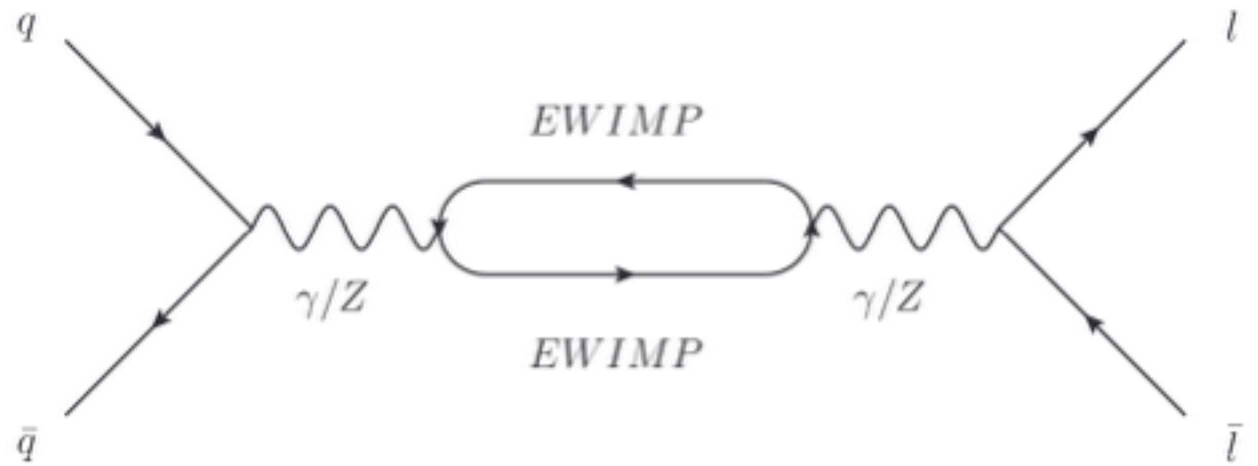
Indirect probe

- Look at the radiative correction by EWIMP



- Running of gauge coupling constant
- At proton collider, we can scan center mass energy ($\sqrt{\hat{s}}$)
- $\sqrt{\hat{s}}$ can be identified by invariant mass of final particles

Radiative correction

$$\mathcal{L} = \mathcal{L}_{\rm sm} + \frac{i}{2}\bar{\chi}\gamma^\mu D_\mu \chi - \frac{1}{2}m_\chi \bar{\chi}\chi$$

$$D_\mu = \partial_\mu - igT_a W^a$$

integrating out dark matter field

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{g^2 C_{WW}}{2} W^a_{\mu\nu}\Pi(-D^2/m_\chi^2)W^{a\mu\nu}$$

$$C_{WW} \equiv (n^3 - n)/6$$

$-D^2$ inside of π can be considered as "$\hat{s}$" (square of CME)

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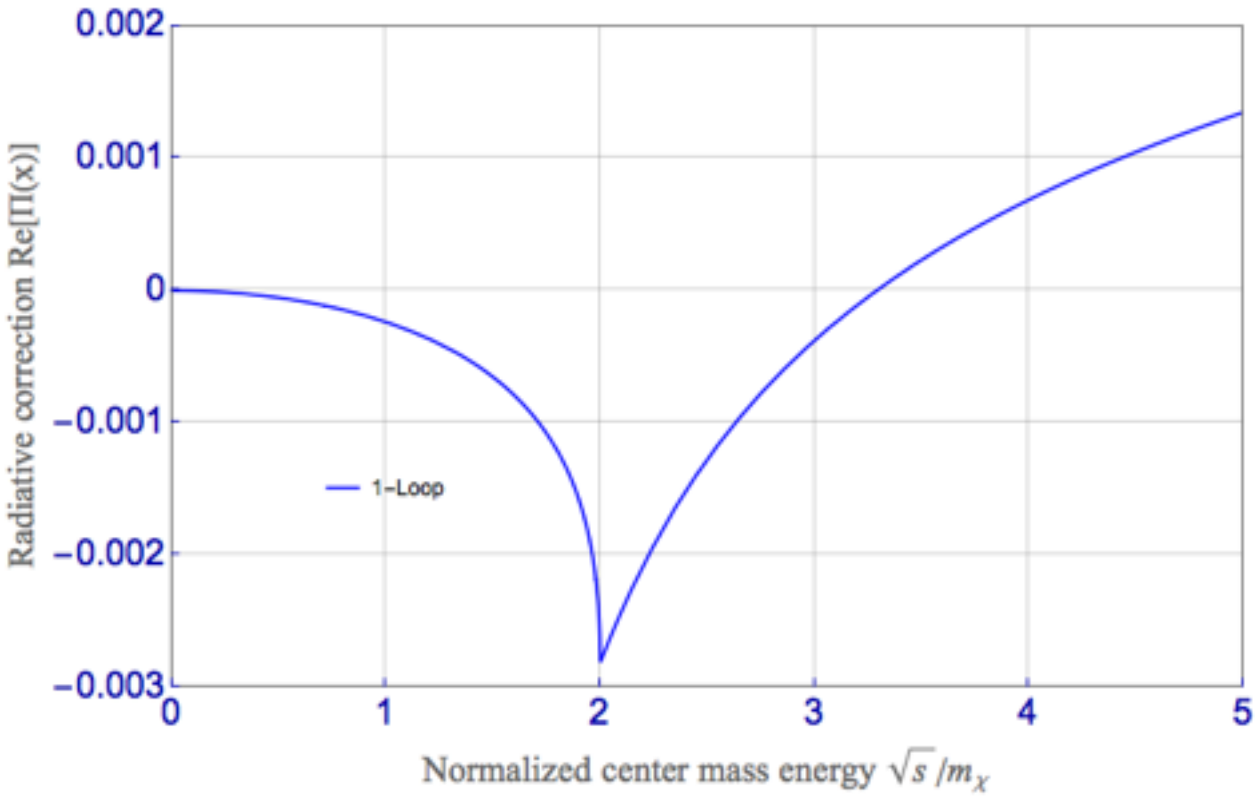
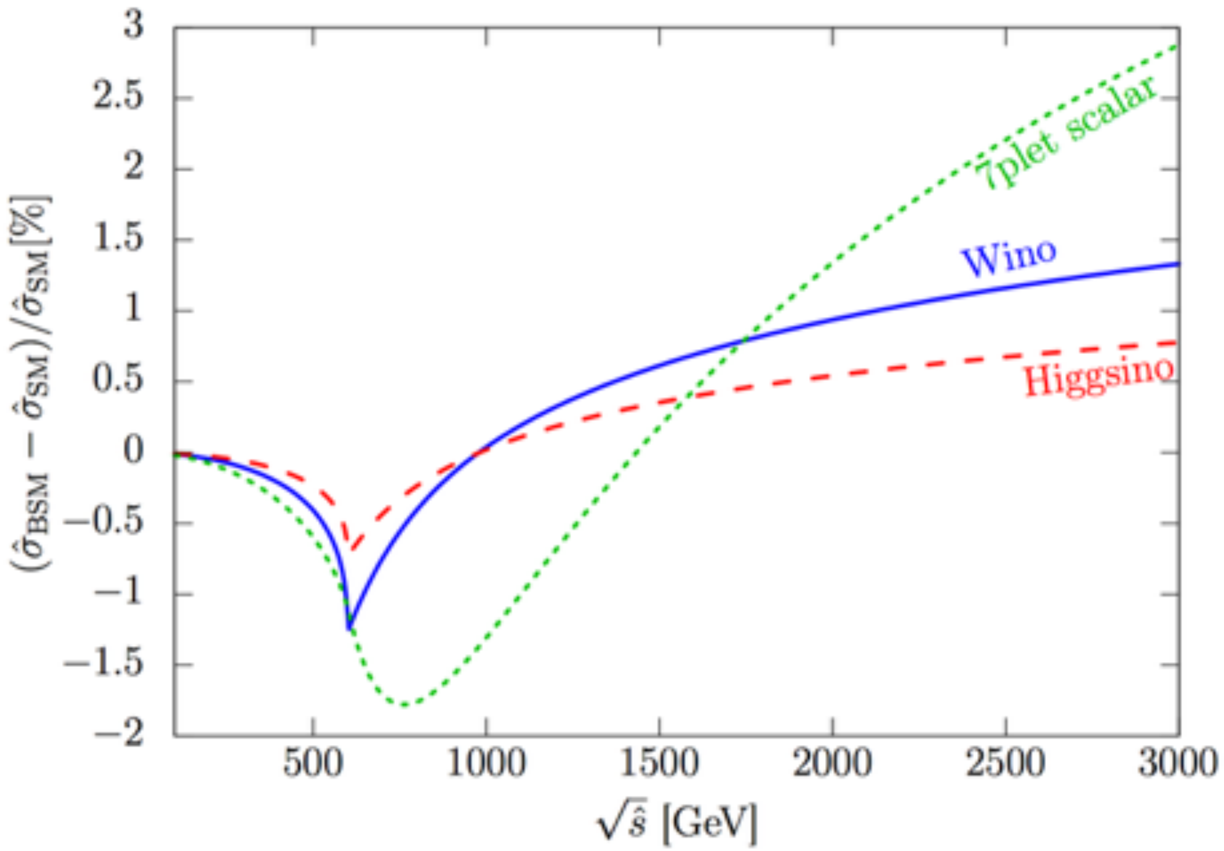
1-loop calculation

$$\Pi(x) = \frac{1}{16\pi^2}\int_0^1 dy\, y(1-y)\ln[1-y(1-y)x - i0^+]$$





[2019, Shigeki Matsumoto, Satoshi Shirai and Michihisa Takeuchi]

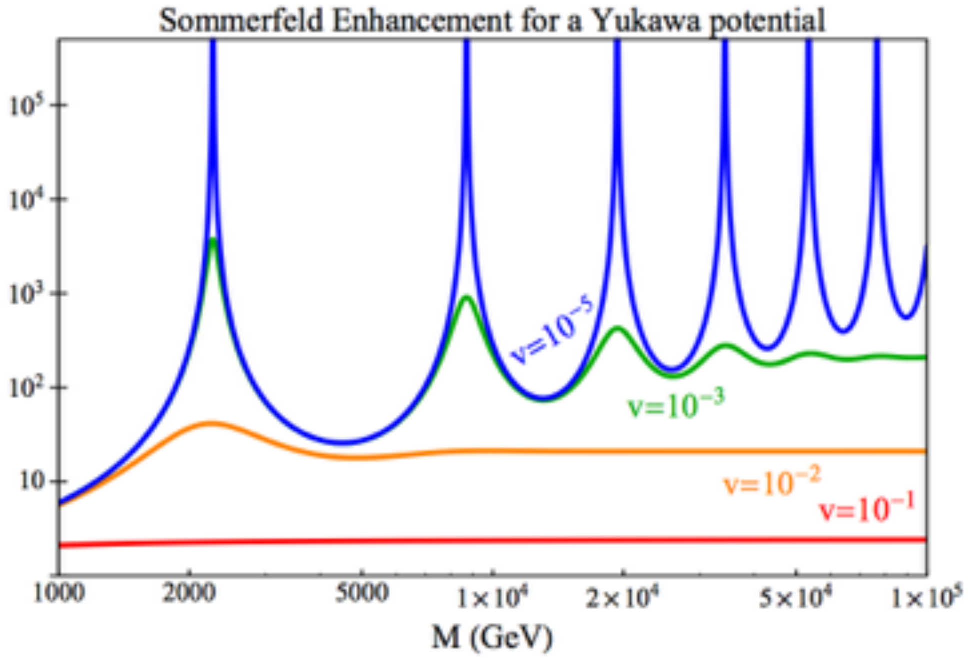
Is 1-loop enough?

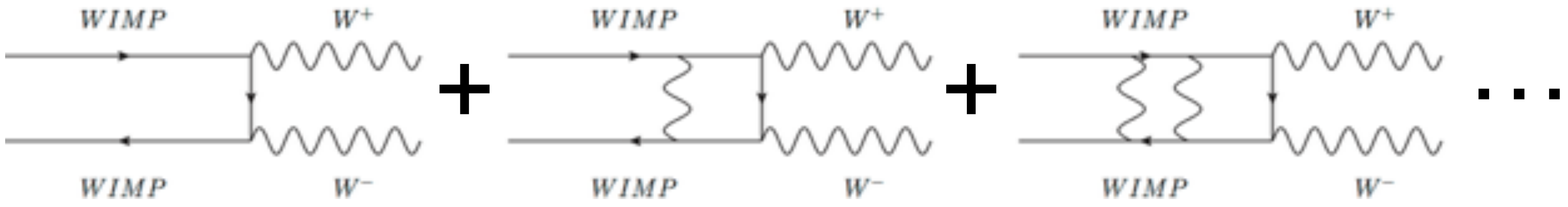
Partially not !!

- For non relativistic EWIMP, there might be enhancement
- cf. Sommerfeld enhancement of annihilation cross section for non relativistic WIMP

(2004, Junji Hisano, Shigeki Matsumoto and Mihoko Nojiri)

- We need sum up all orders of diagrams!





(Picuture from Phys.Rev.D88 (2013) 083506 Brando Bellazzini et al.)

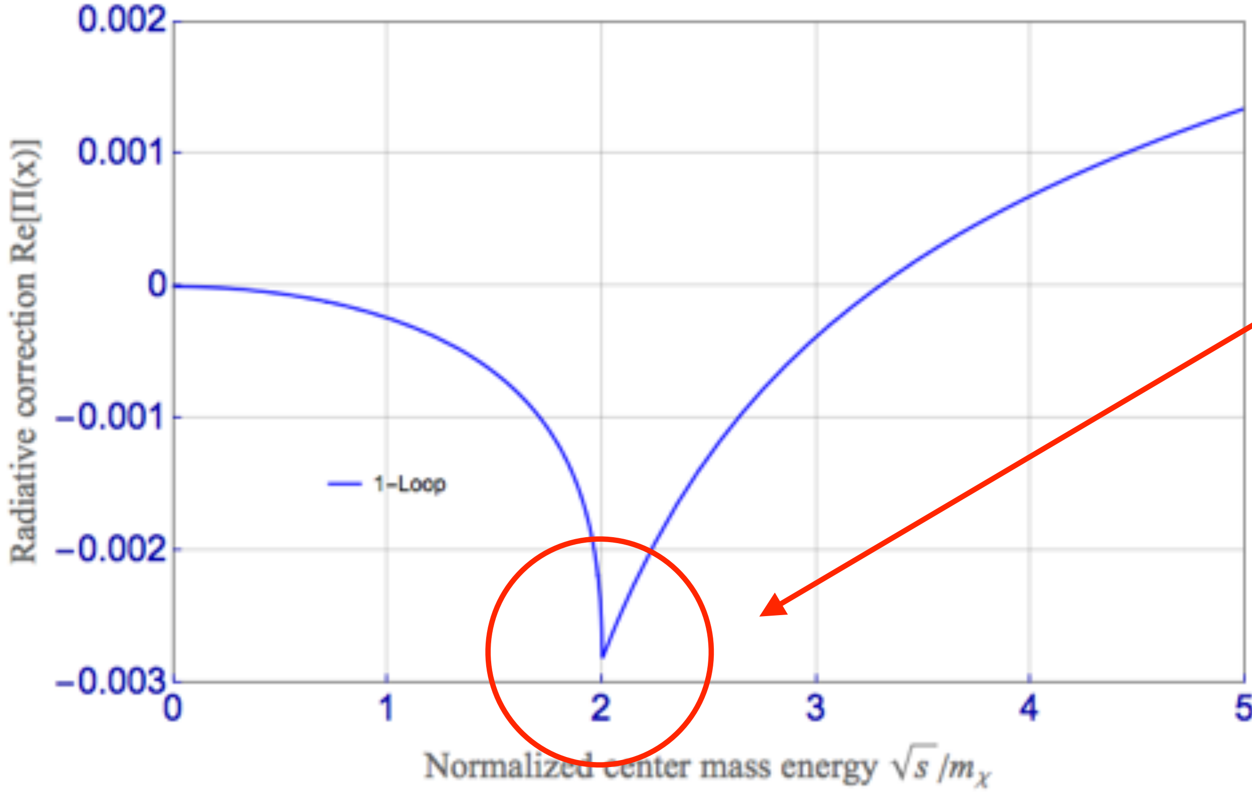
Easy view (of sommerfeld enhancement)

- Suppose EWIMP is much heavier than weak scale
- Exchange of massive gauge boson act like long range force.
- For non relativistic EWIMP, loop expansion does not work well

  →It works as (α/v) expansion, (v is relative velocity) and if $(\alpha/v)>1$, higher loop diagram diverge.

- Use non relativistic Schrodinger equation to solve this

Our case



EWIMPs are non relativistic here

There may be the enhancement for the already extremum region!!

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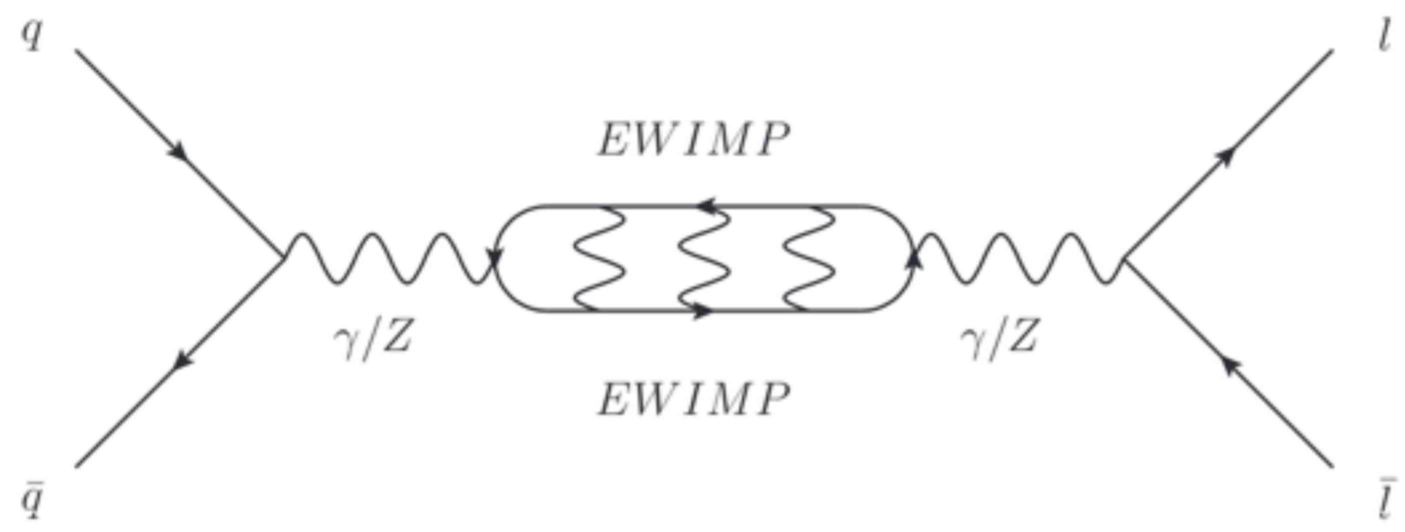
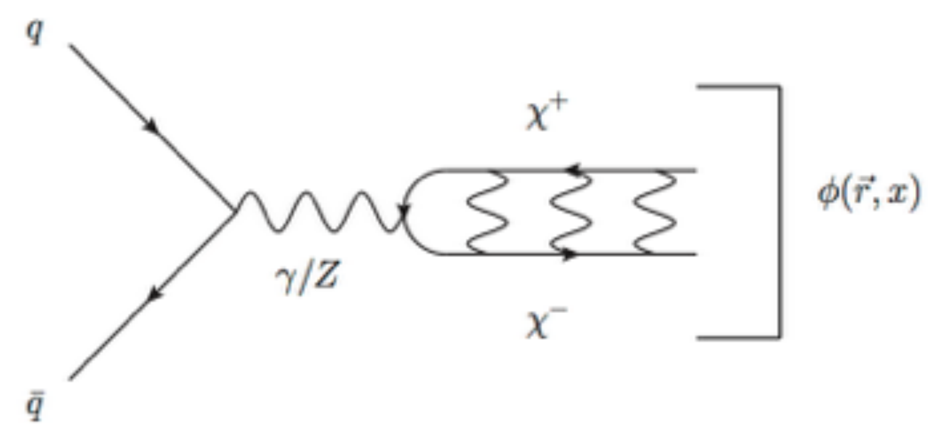
Calculation

Let's calculate such diagrams at non relativistic region



1. Introduce 2-body state φ(r,x)
   r is relative coordinate of EWIMPs
   x is barycenter coordinate of EWIMPs



Calculation

2. Write the lagrangian with 2-body state φ(r,x)

$$\mathcal{L}_{2-\mathrm{body}} = -\Big[gd\phi_+^{a\dagger}(\vec{0},x)2\sqrt{2}e^{2imt}W_a^+(x) + gd\phi_-^{a\dagger}(\vec{0},x)2\sqrt{2}e^{2imt}W_a^-(x)$$
$$+gQ\phi_0^{a\dagger}(\vec{0},x)2\sqrt{2}e^{2imt}W_a^3(x) + h.c\Big] + \int \mathrm{d}^3\mathrm{r} \sum_{i=0,+,-} \phi_i^{a\dagger}(\vec{r},x)\mathcal{D}_i^{\mathrm{NR}}(\vec{r},x)\phi_i^a(\vec{r},x)$$
$$\mathcal{D}_i^{\mathrm{NR}} = i\partial_0 + \nabla_x^2/4m + \nabla_r^2/m - V_i(|\vec{r}|)$$

Behavior at the origin (r=0) is important

3. Integrate out 2-body state φ(r,x) and get the result

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{g^2 C_{WW}}{2} W_{\mu\nu}^a \Pi(-D^2/m_\chi^2) W^{a\mu\nu}$$

NR radiative correction

After these calculation, we get

$$\Pi(x) \quad = \quad -\frac{3}{8\pi}\frac{1}{n^3-n}Q\left(\lim_{y\to 0}\frac{dg_0(y;x)}{dy}\right)Q$$

Here, $g_0(y;x)$ is the solution of this Schrodinger eq.

$$\left[-\frac{d^2}{dy^2}+V_0(y)\right]g_0(y;x) \quad = \quad (E+i\epsilon^+)g_0(y;x)$$

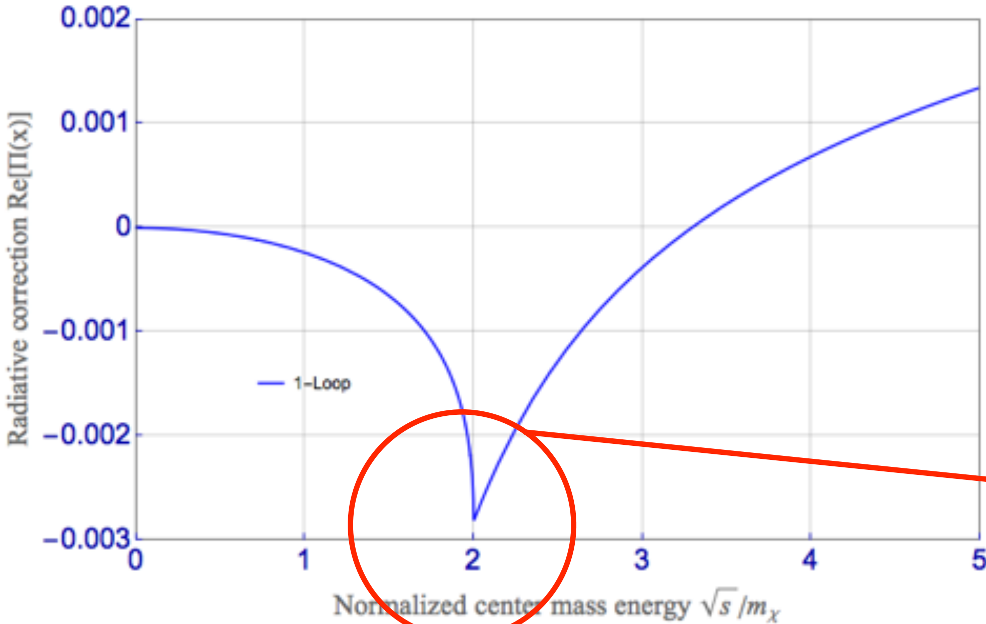
Potential term

$$V_0(y) \quad = \quad -\frac{\alpha}{y}-\frac{\alpha_z}{y}\exp\left(-\frac{m_z}{m_\chi}y\right)$$

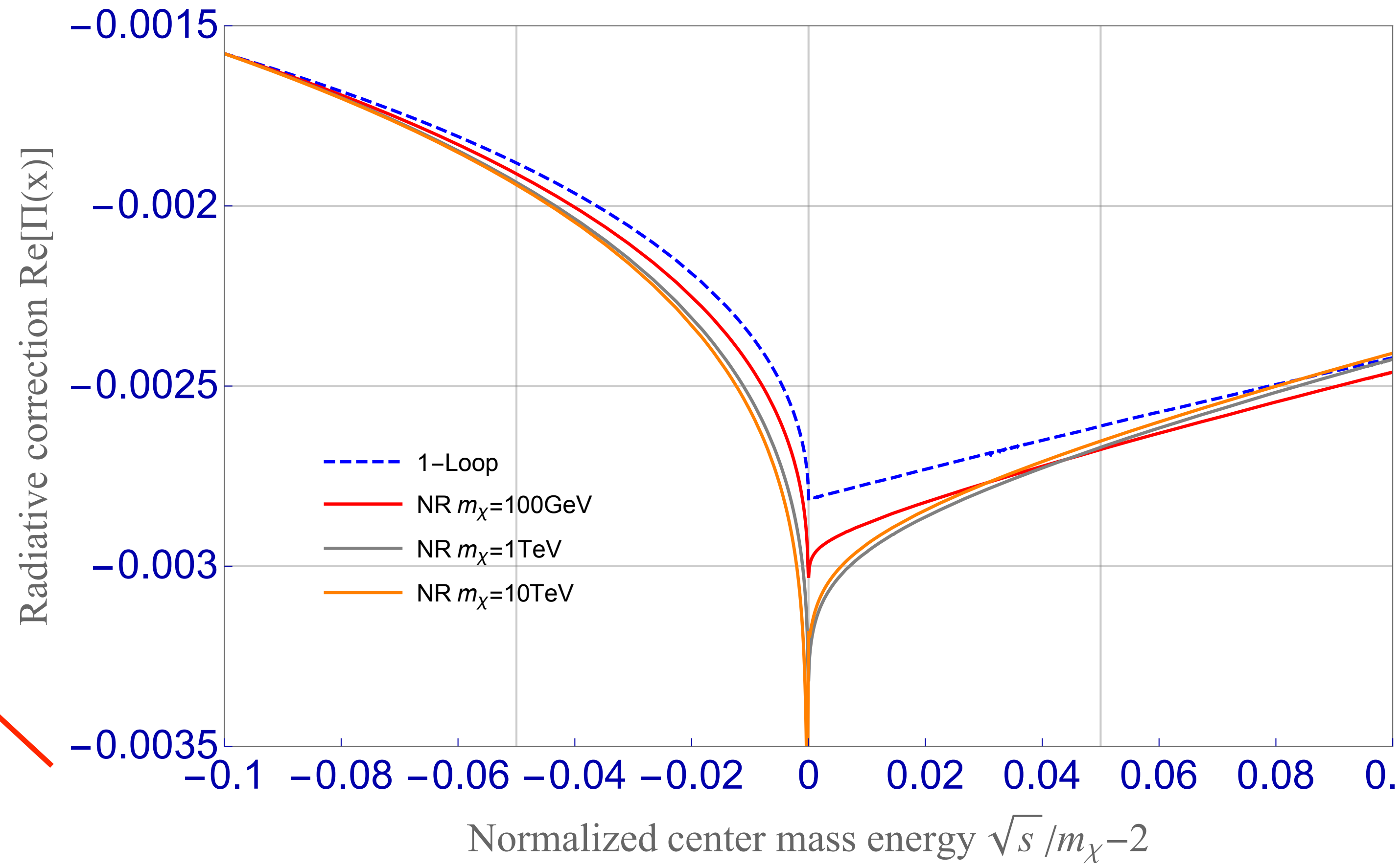
Kinetic energy of EWIMPs

$$E = \sqrt{x}-2$$

Numerical calculation



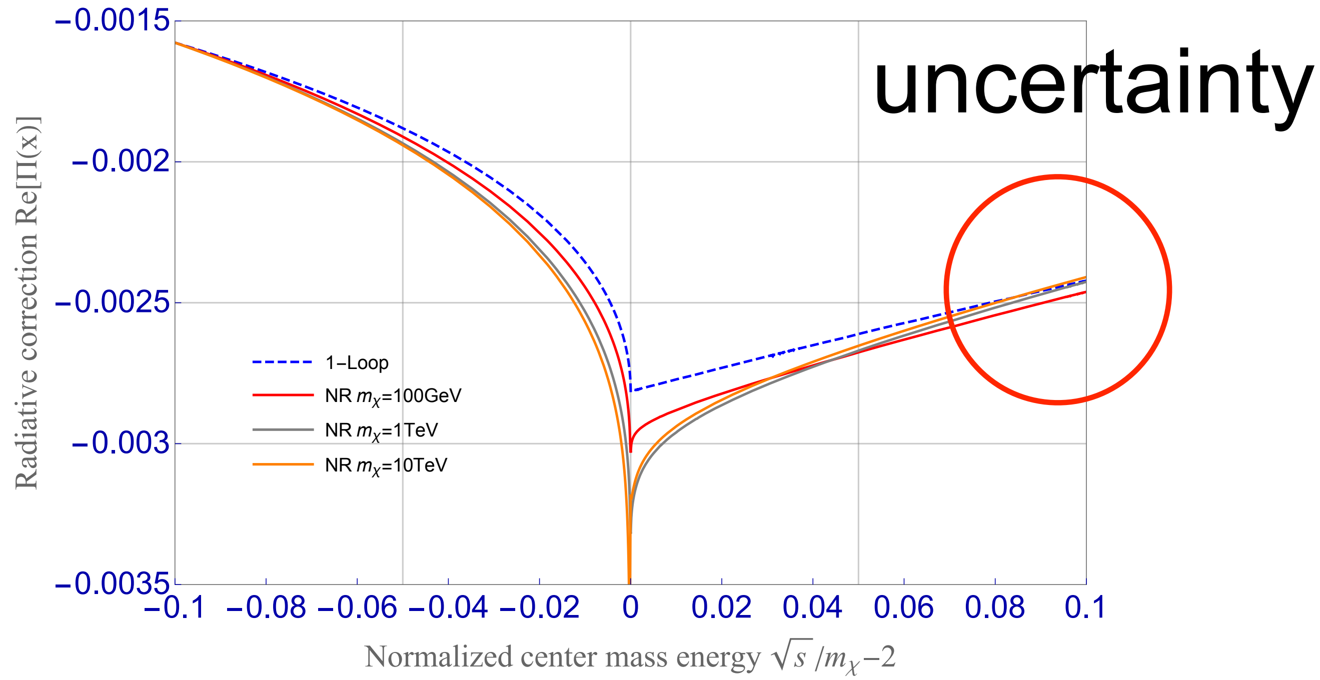
Because there is uncertainty of renormalization constant for $W_{\mu\nu}W^{\mu\nu}$, we need to match 1-loop calculation and NR calculation by hand.



Matching at √s/m=1.9

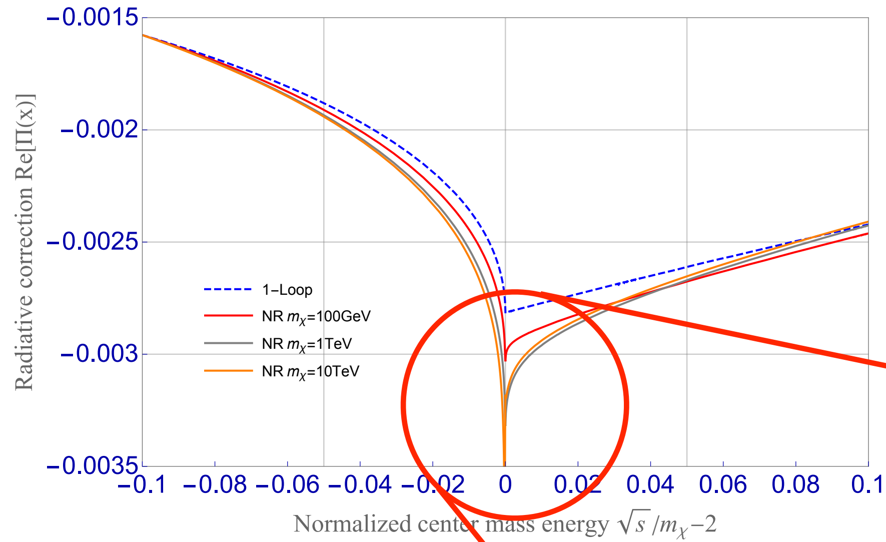
Why √s/m=1.9?

- 1-loop calculation is valid at $v \gg \alpha$. (v is relative velocity)
- NR calculation is valid at $1 \gg v$.
- Choose somewhere at $1 \gg v \gg \alpha$ for matching.
- Still uncertainty of $O(\alpha^2)$ remains.

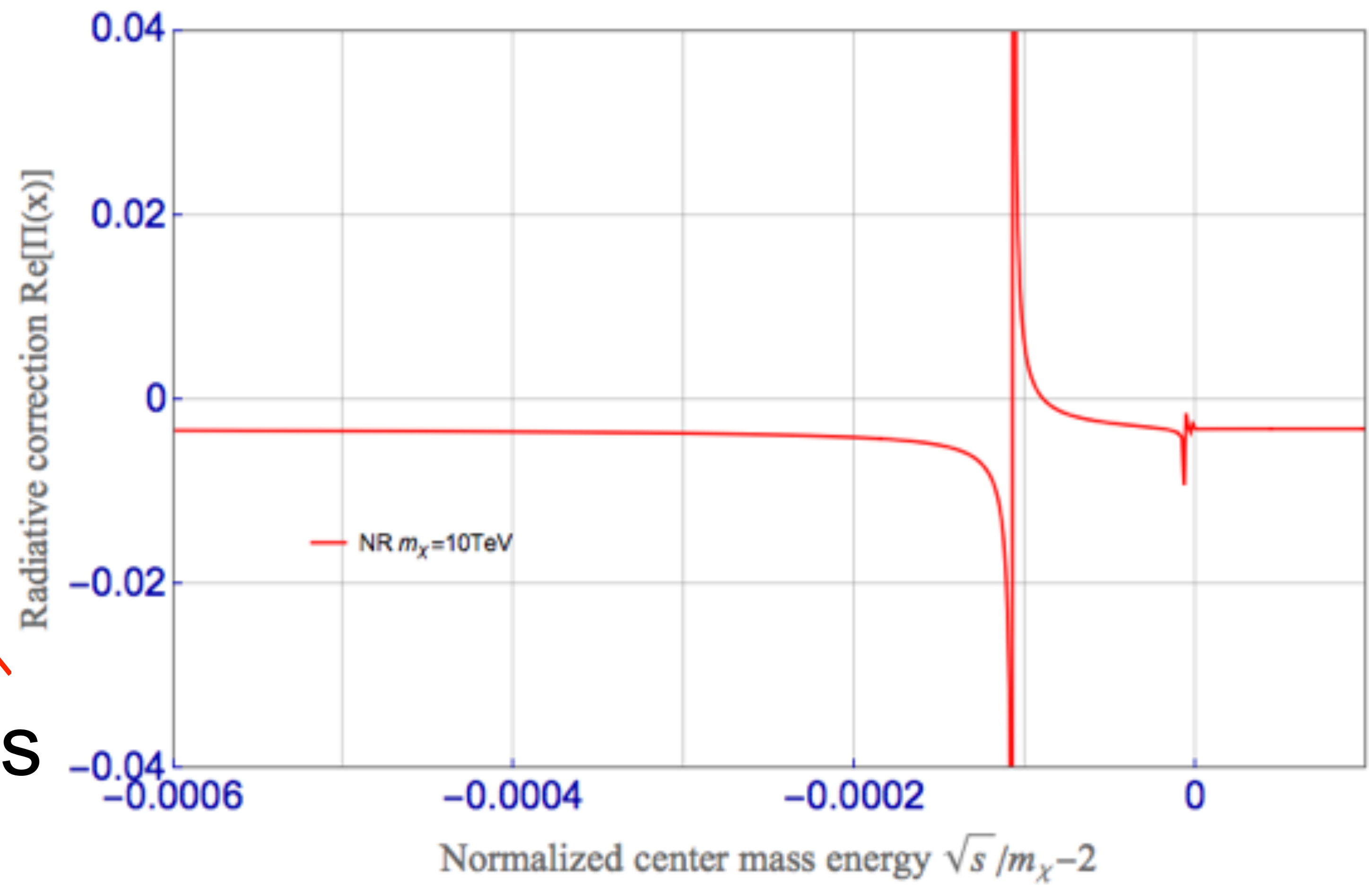


These arguments are based on [1997, A,H,Hoang]

Bound state



- Divergence from bound state
- Very close to the threshold
- Difficult to see with the resolution of LHC



We neglect this, because this contribute higher order of correction.

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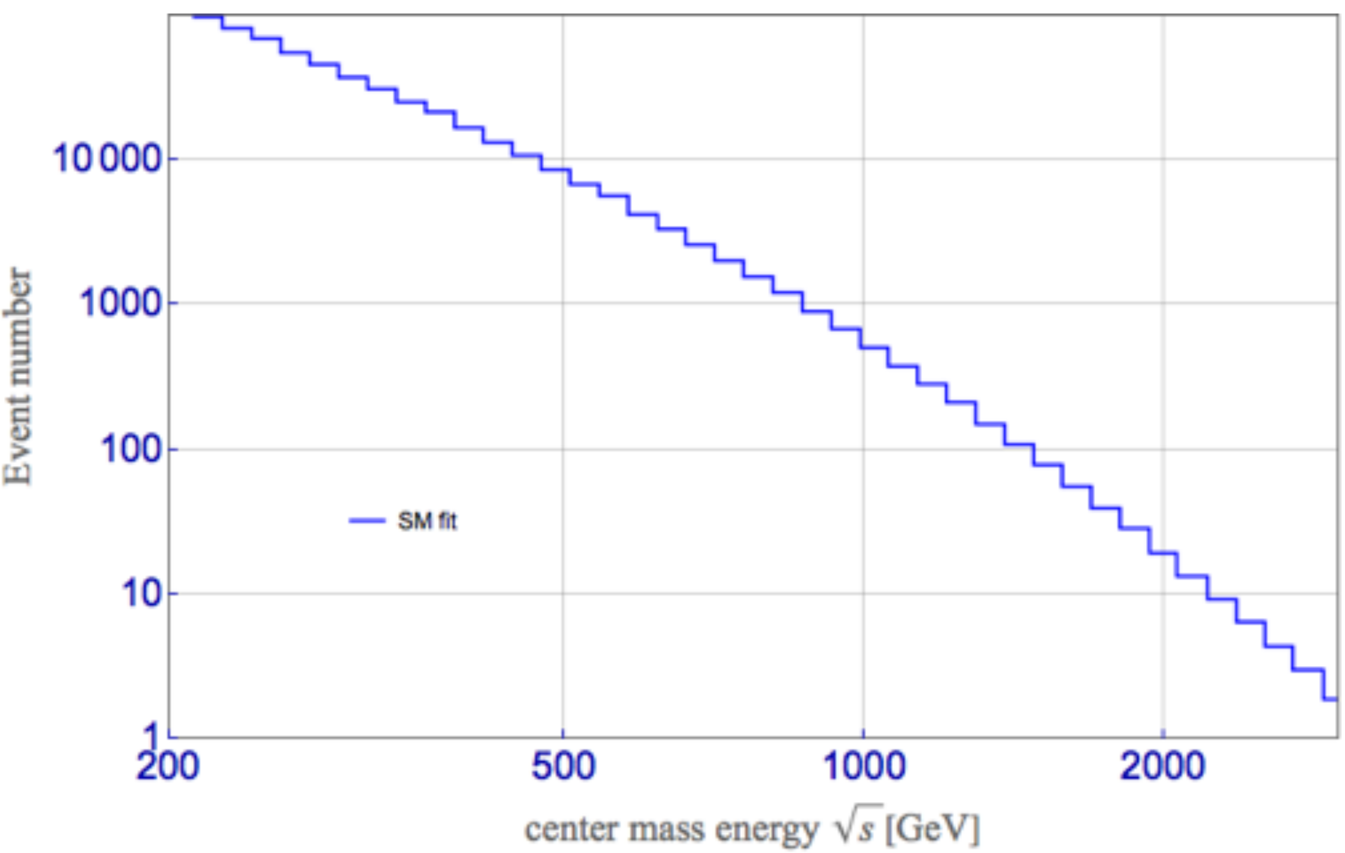
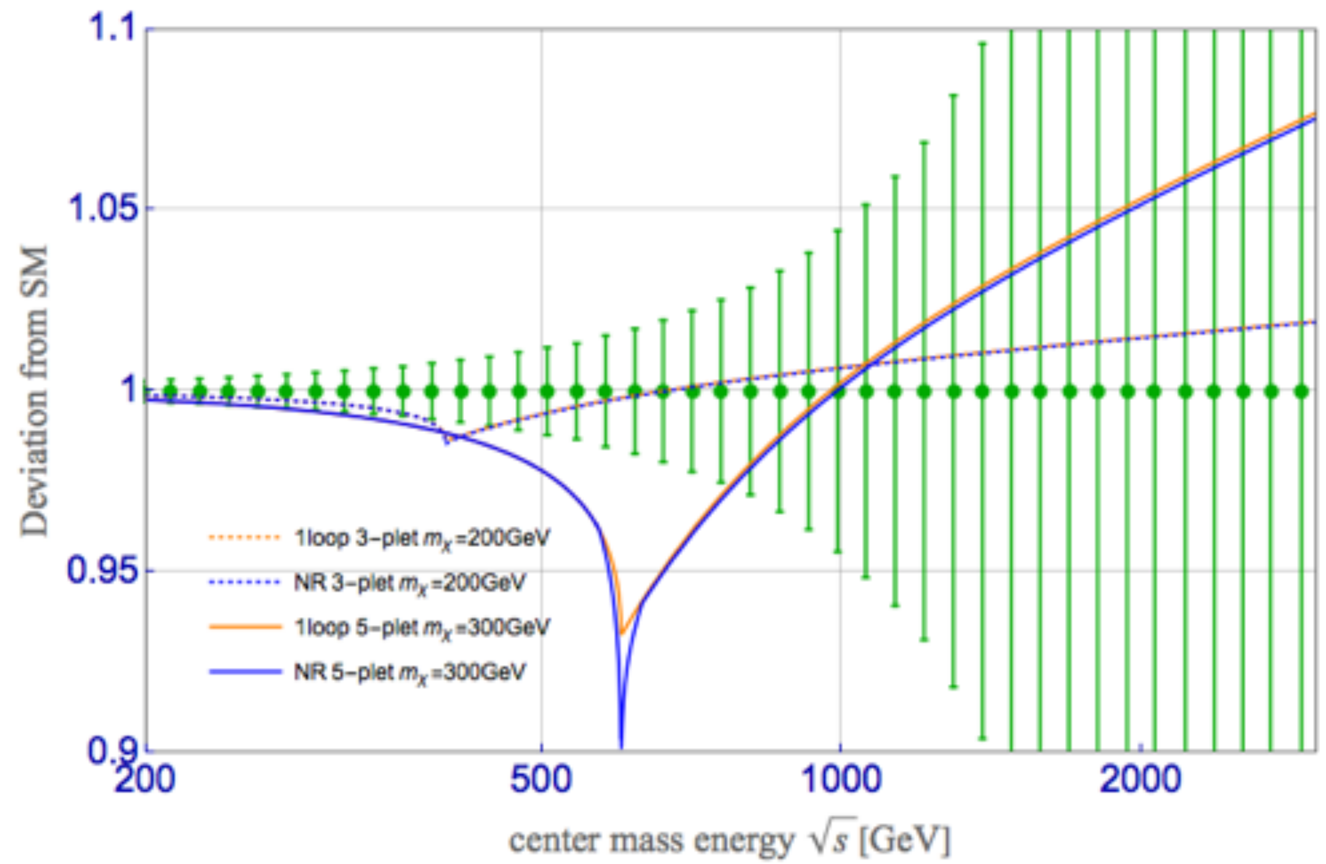
Result

Event number (SM)
PP → e^+e^- at $300fb^{-1}$



Deviation from SM
3-plet and 5-plet case



Conclusion

- Indirect probe is useful for the test of EWIMP
- NR effect is non negligible for SU(2) multiplet EWIMP
- The resolution of the detector is also important for indirect probe