# Illuminating Scalar Dark Matter Co-Scattering with Mono-photon Signature

Ref: arXiv: 2508.06040 (Accepted in JHEP)

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# Outline



- Motivation
- Singlet Scalar: WIMP
- EFT Model
- Evolution of dark sector particle in early universe
- Co-scattering favored parameter space
- Collider signal and LHC limit
- Summary

# Motivation

## Strong evidence of BSM

**eV scale neutrino mass, Dark Matter, Baryon Asymmetry….**

*Most celebrated DM formation-> Freeze-out of WIMP*

*Extensive astroparticle and collider searches …*

*but no WIMP discovery as of now* 🤔

## Alternate mechanism?

*secluded freeze-out* , *assisted freeze-out* , *DM conversion or co-scattering* , *Forbidden annihilation* , *Freeze-in*

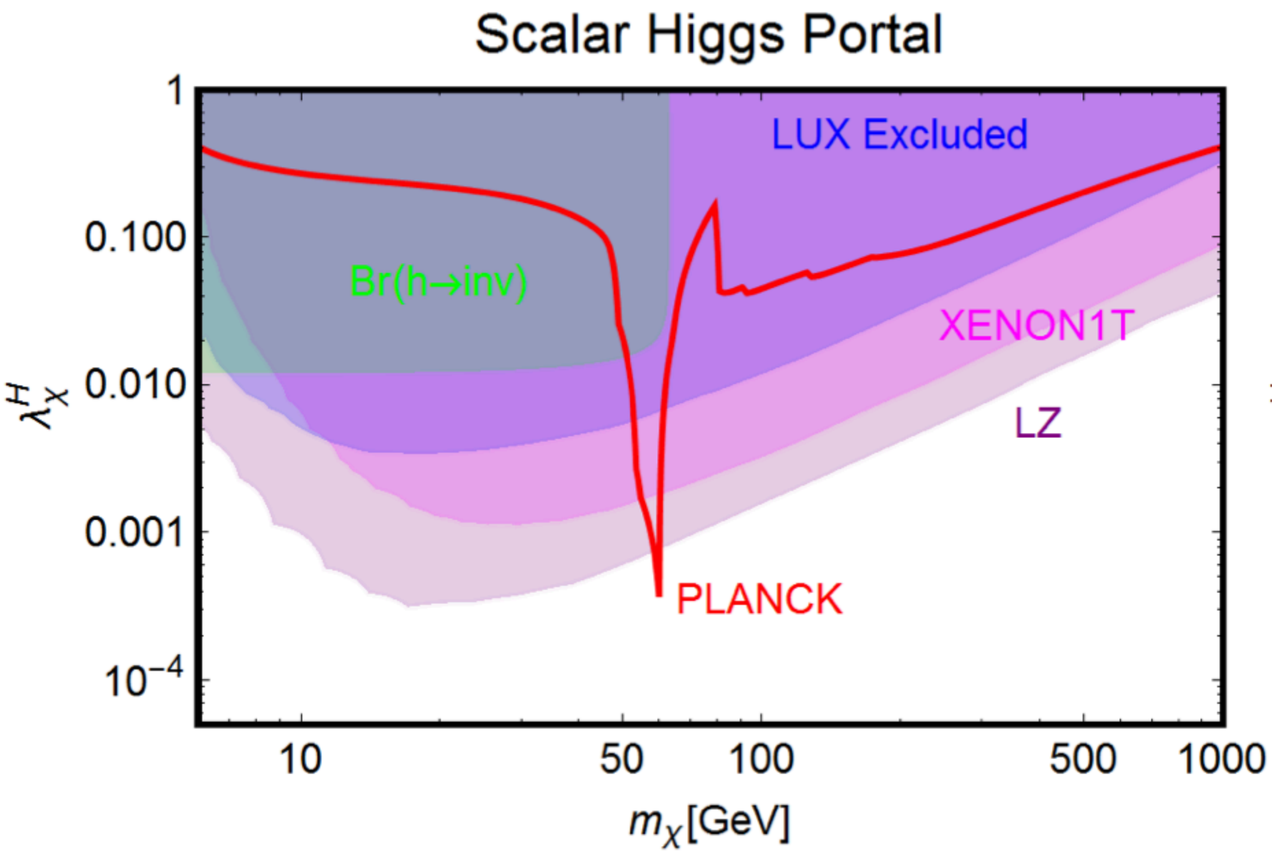
# Singlet Scalar as WIMP: Status

*Arcadi et al.*



$$\lambda_\chi^H \chi^* \chi H^\dagger H$$

- DM phenomenology governed by **Mass and Higgs portal coupling**
- **Stringent limits from direct detection are driving the allowed Higgs-portal coupling to lower values.**
- **Relic Density allowed region almost excluded by Direct Detection**



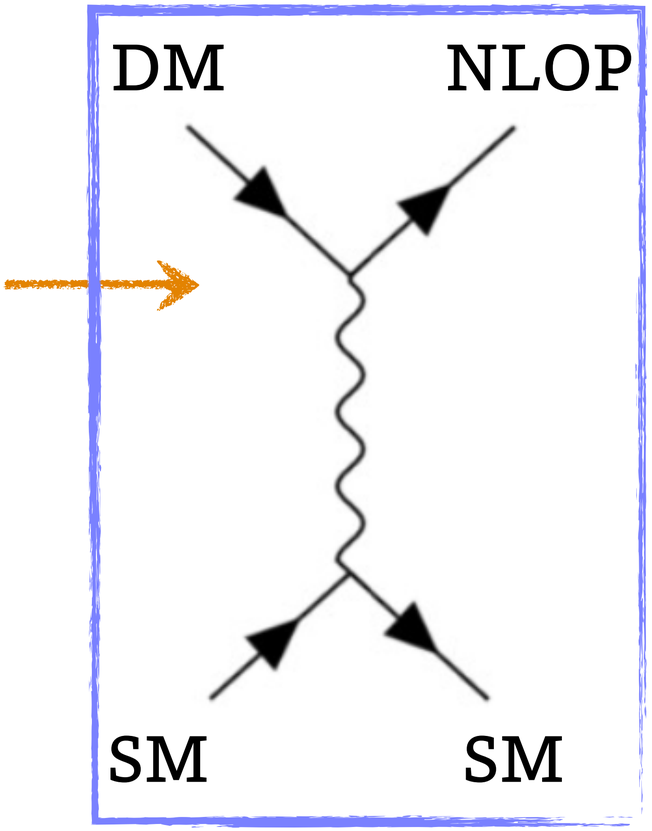

Traditional Freeze-out has no conclusive evidence at DD or LHC yet

**Alternate production mechanism required**

# Co-scattering



- DM is weakly interacting but the WIMP self-annihilation is suppressed
- DM relic abundance is set by inelastic scatterings with SM to NLOP but not by self annihilation.
- Requires small mass splitting between DM and NLOP.
- Opens viable parameter space for while evading direct detection limit
- Motivates novel Collider signature.



# Our EFT Model



*Bélanger et al.*

## Standard Model ($Z_2$-even)

**Fermions, Gauge bosons, Higgs**

## Dark Sector ($Z_2$-odd)

- $\chi \rightarrow$ Real singlet scalar (DM)
- $N_1, N_2 \rightarrow$ Singlet fermions(co-scattering partner )

## d=4 operator

- **Higgs Portal :** $\lambda\ \Phi^\dagger\Phi\chi^2$

**DD strongly constraint**

## d=5 operator

- **Dipole:** $\frac{c_3}{\Lambda}\overline{N^c}\sigma_{\mu\nu}N\ B^{\mu\nu}$ → **c3 anti-symmetric**
- **Yukawa:** $\frac{y}{\Lambda}\bar{L}\tilde{\Phi}N\chi + \frac{c_1}{\Lambda}\overline{N^c}N\chi^2 + \frac{c_2}{\Lambda}\overline{N^c}N\Phi^\dagger\Phi$

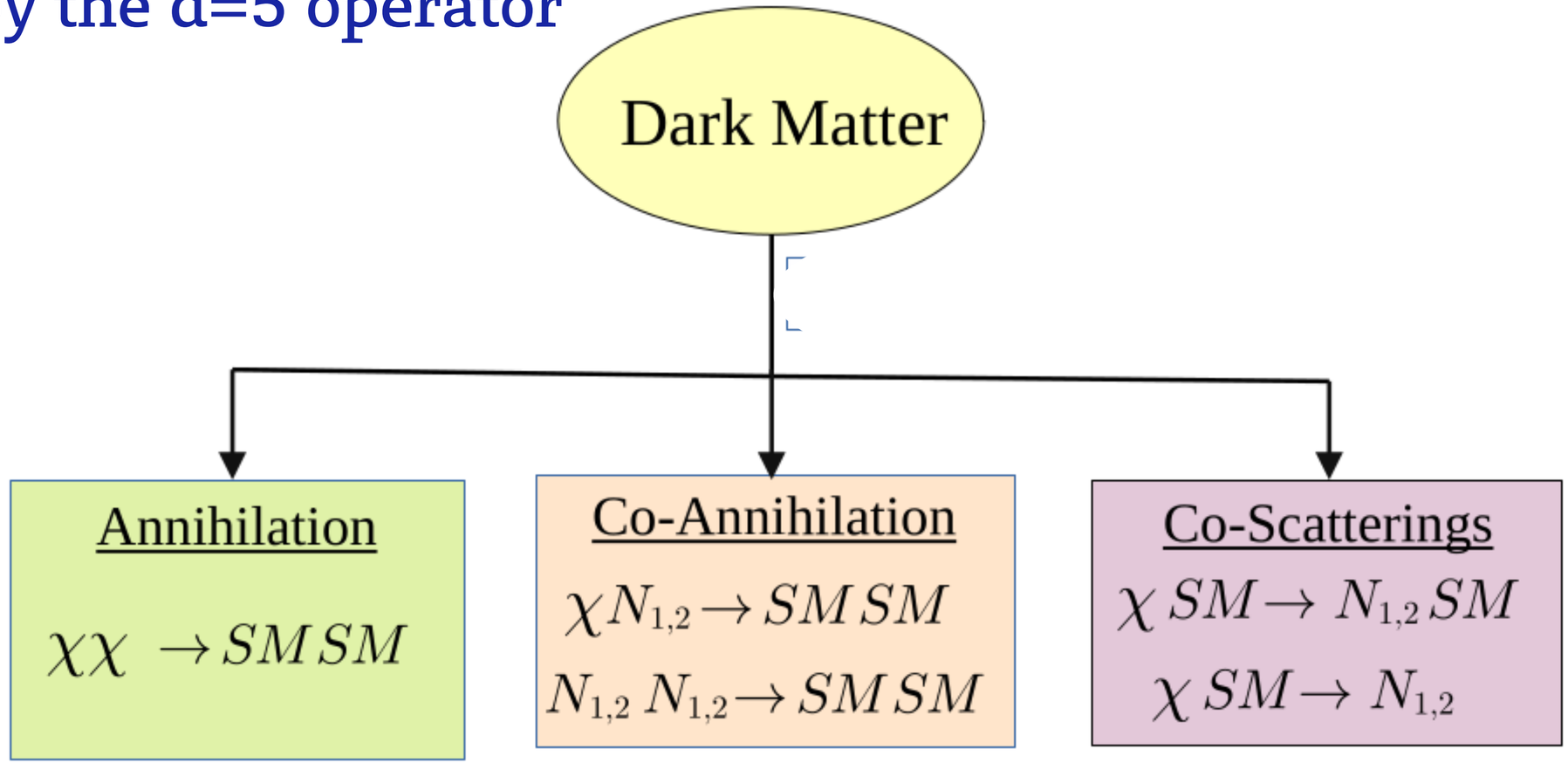
$0$ $0$

$N = [N_1, N_2]^T$

# Dilution of DM



- DM self-annihilation is suppressed
- Relic abundance is set either by co-annihilation or co-scattering mediated by the d=5 operator

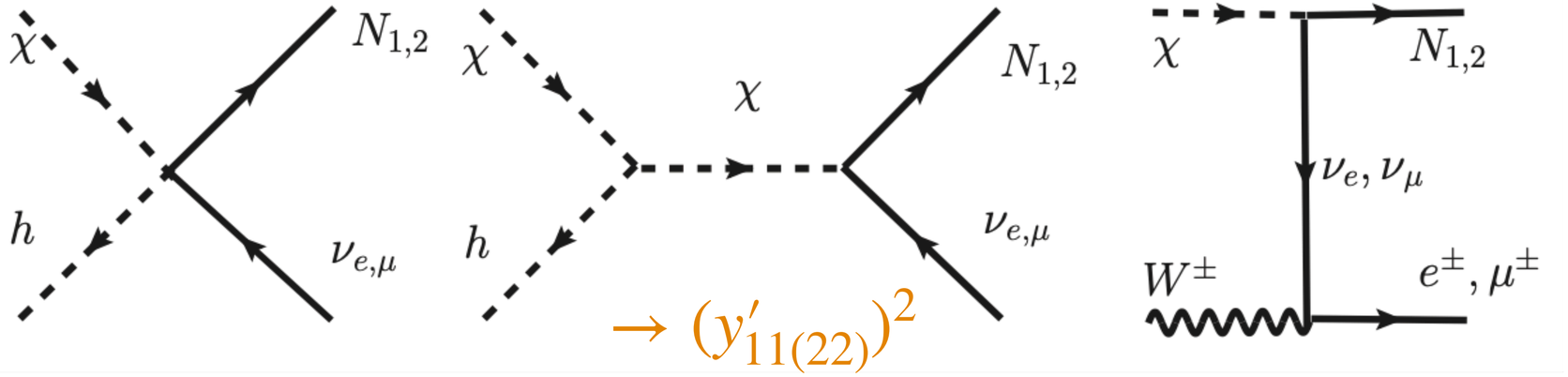


# Dilution of DM

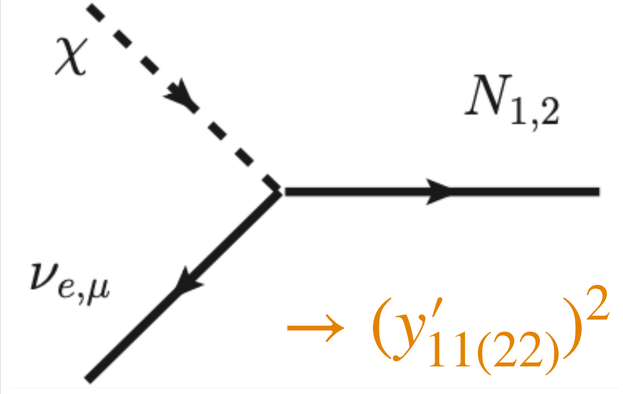
*Relative mass splitting*

$$\delta_1 = \frac{M_{N_1} - M_\chi}{M_\chi}$$

$\delta_1 > 0.5$ : *annihilation* ($\chi\chi \to$ *SM SM*) *dominant*




$\to (y'_{11(22)})^2$




$\to (y'_{11(22)})^2$

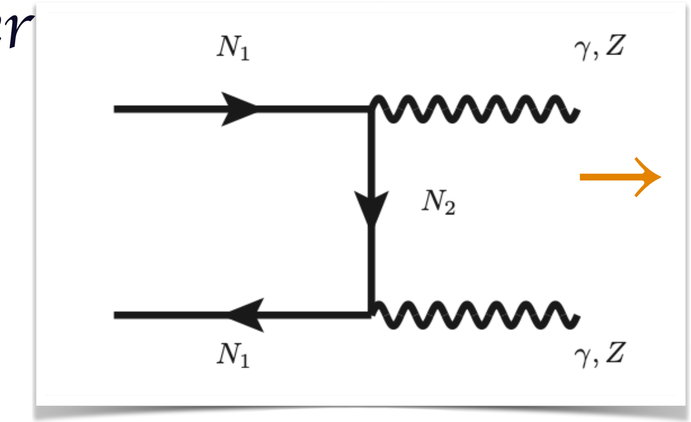
$\delta_1 < 0.5$ : *co-scattering (+decay) or co-annihilation dominant*

Rotating the diagrams anti-clockwise by $90^o$

# Dilution of $N_1$

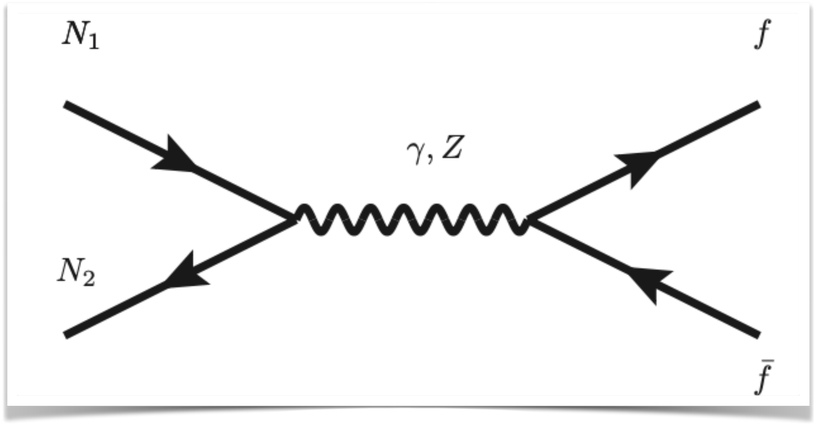
- $M_{N_2} > M_{N_1} > M_\chi$, so $\mathcal{N}2$ decouple much earlier

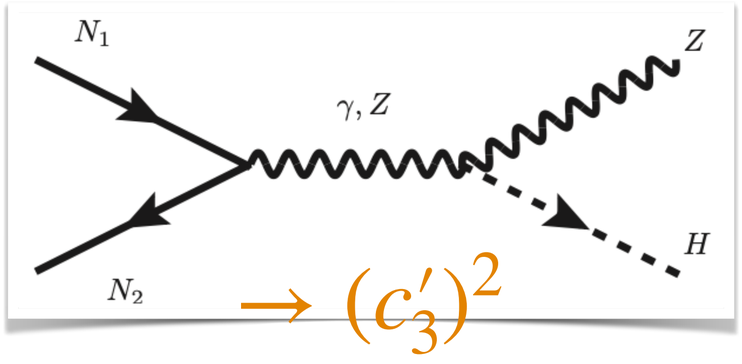
Relative mass splitting $\delta_2 = \dfrac{M_{N_2} - M_{N_1}}{M_{N_1}}$



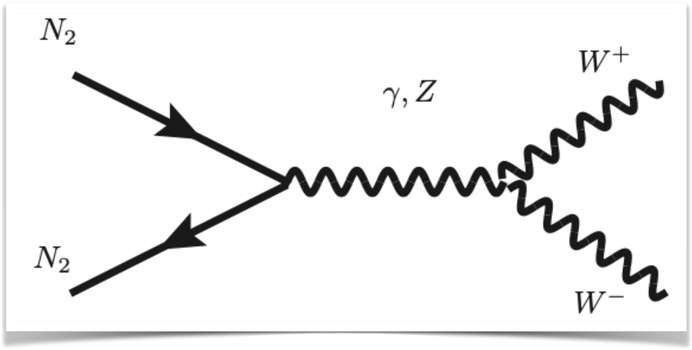

$\rightarrow (c_3')^4$

$\delta_2 > 0.5$ : Pair annihilation dominate




$\rightarrow (c_3')^2$




$\delta_2 < 0.5$ : co-annihilation dominate

# Evolution of DM



$$\Omega_\chi h^2 = 2.742 \times 10^8 (M_{N_1} Y_1 + M_\chi Y_2).$$

$$\frac{dY_1}{dx} = -\frac{1}{x^2}\frac{s(M_\chi)}{\tilde{H}(M_\chi)}\left[\langle\sigma_{1100}v\rangle(Y_1^2 - Y_1^{eq2}) + \langle\sigma_{1122}v\rangle\left(Y_1^2 - Y_2^2\frac{Y_1^{eq2}}{Y_2^{eq2}}\right)\right.$$
$$\left. + \langle\sigma_{1200}v\rangle(Y_1Y_2 - Y_1^{eq}Y_2^{eq}) - \frac{\Gamma_{2\to1}}{s}\left(Y_2 - Y_1\frac{Y_2^{eq}}{Y_1^{eq}}\right)\right],$$

$$\frac{dY_2}{dx} = -\frac{1}{x^2}\frac{s(M_\chi)}{\tilde{H}(M_\chi)}\left[\langle\sigma_{2200}v\rangle(Y_2^2 - Y_2^{eq2}) - \langle\sigma_{1122}v\rangle\left(Y_1^2 - Y_2^2\frac{Y_1^{eq2}}{Y_2^{eq2}}\right)\right.$$
$$\left. + \langle\sigma_{1200}v\rangle(Y_1Y_2 - Y_1^{eq}Y_2^{eq}) + \frac{\Gamma_{2\to1}}{s}\left(Y_2 - Y_1\frac{Y_2^{eq}}{Y_1^{eq}}\right)\right].$$

3 sectors

- $0 \to SM$
- $1 \to N_1, N_2$
- $2 \to \chi$

- For $y' < 10^{-6}$ , DM pair annihilation, co-annihilation, and exchangeProcess becomes negligible

$$\Gamma_{2\to1} = \frac{\sum_{\alpha=1}^{2}\Gamma_{N_\alpha\to\chi,\nu_{e,\mu}}\, g_\alpha M_{N_\alpha}^2 K_1\left(\frac{M_{N_\alpha}}{M_\chi}x\right)}{\sum_{\alpha=1}^{2} g_\alpha M_{N_\alpha}^2 K_2\left(\frac{M_{N_\alpha}}{M_\chi}x\right)} + \langle\sigma_{2010}v\rangle s(M_\chi/x) Y_0^{eq}$$

Conversion term

# Co-scattering Fraction

*fractional difference between relic densities obtained after solving the coupled and single Boltzmann equation*

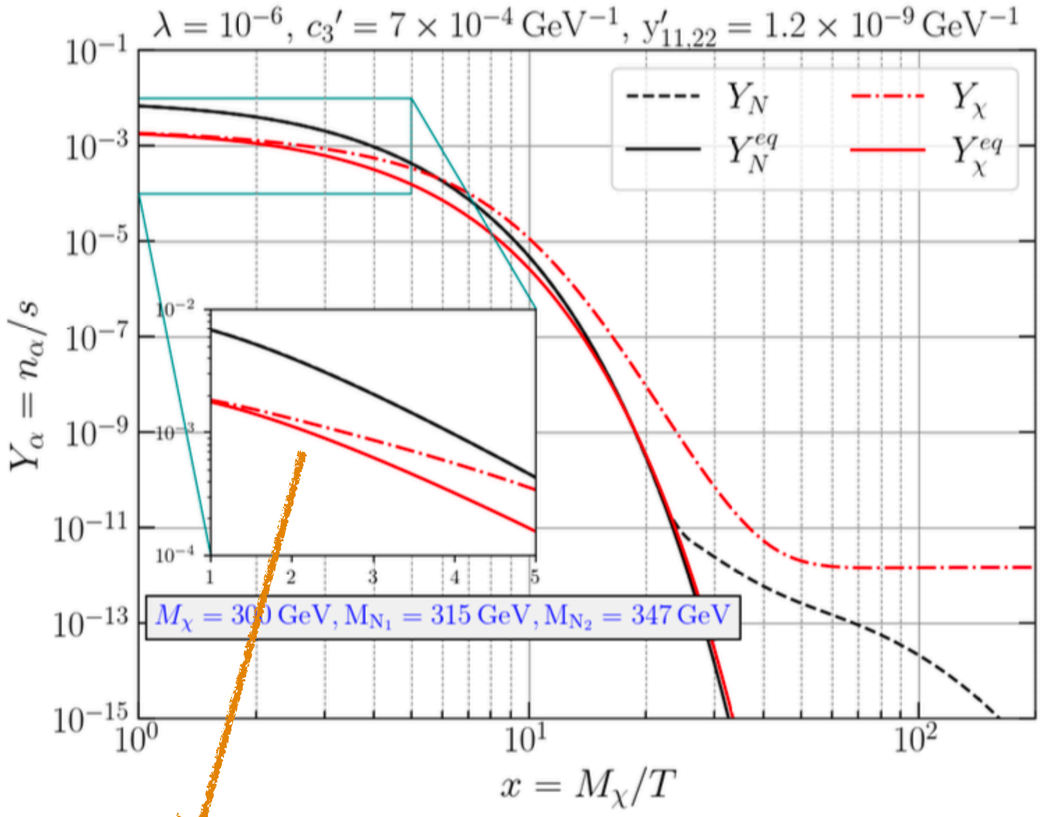
$$\Delta_{\chi}^{1} \equiv 1 - \frac{\Omega h^2(\text{Single})}{\Omega h^2(\text{Coupled})}$$

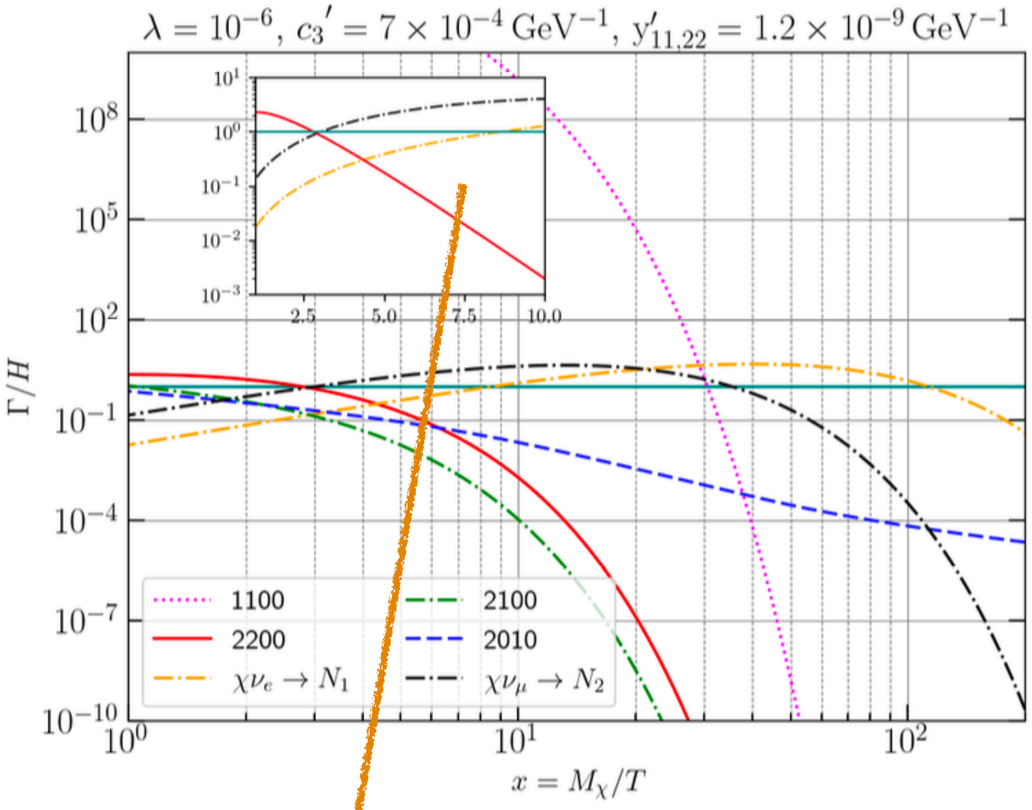
- *Only co-annihilation process*
- *All process*

- $y' < 10^{-7}$ : *co-scattering dominant*
- $y' > 10^{-7}$: *co-annihilation dominant*

# Evolution of DM: co-scattering





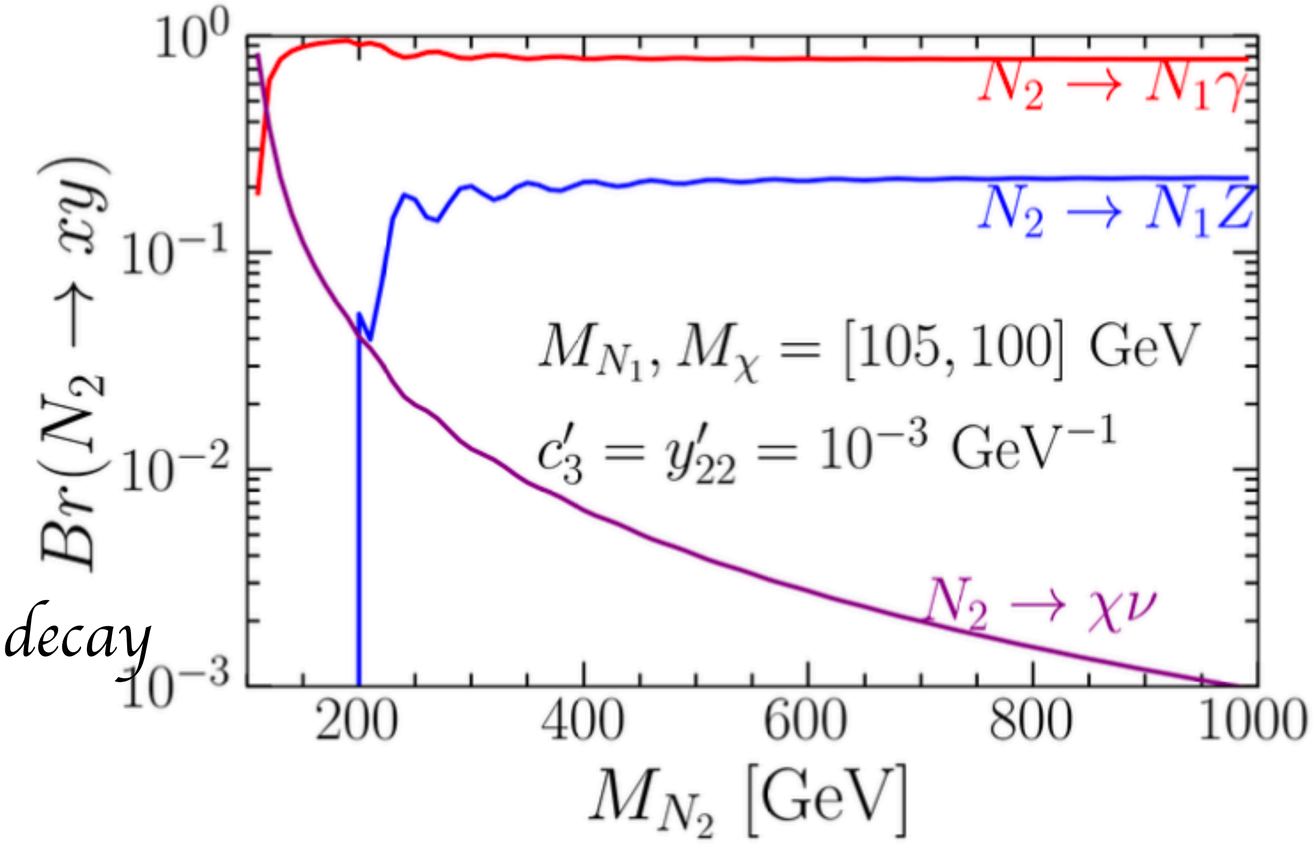

- DM is chemically decoupled at early times x~2
- All $2 \to 2$ process of DM decouple and inverse decay is inefficient to restore chemical equilibrium
- Freeze-out occurs at late times when inverse decay $\chi\nu \to N_1$ stops

# Decay of $N_1$ and $N_2$



$$M_{N_2} > M_{N_1} > M_\chi$$

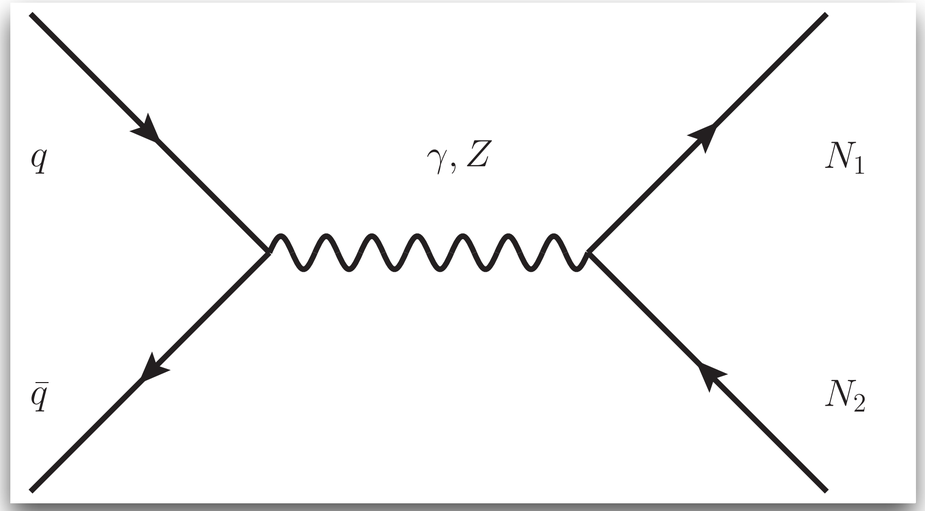
- $N_2 \to N_1\gamma$ , $N_2 \to N_1 Z$ via $c_3' \; \overline{N^c}\sigma_{\mu\nu}N \; B^{\mu\nu}$
- $N_2 \to \chi\nu$ via $y'\bar{L}\tilde{\Phi}N\chi$
- $N_1 \to \chi\nu$ via $y'\bar{L}\tilde{\Phi}N\chi$




- N1 invisible at collider and N2 dominantly decay to photon + MET

# Collider Signal

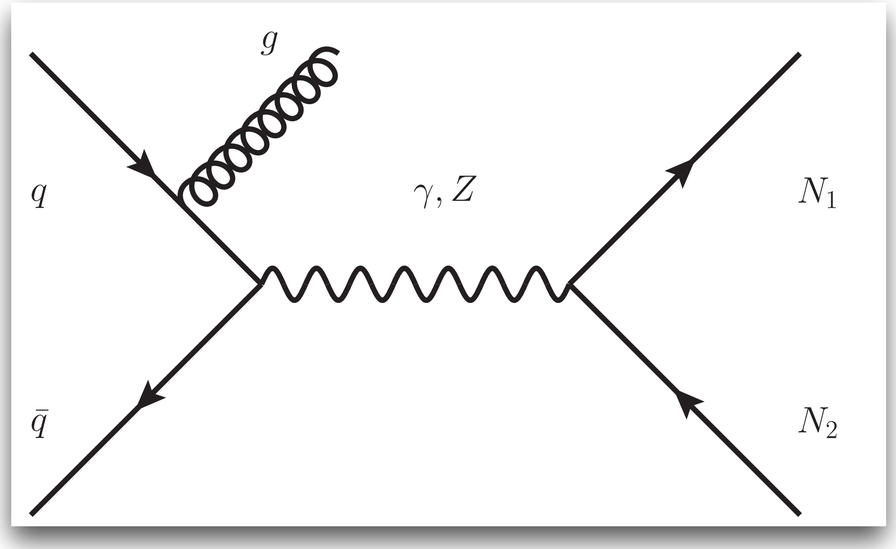
## $\gamma + MET$ (mono-photon)




$$c_3' \, \overline{N^c} \sigma_{\mu\nu} N \, B^{\mu\nu}$$

$M_{N_2} - M_{N_1} > 10\ GeV$

## $jet + MET$ (mono-jet)




$M_{N_2} - M_{N_1} < 10\ GeV$

$$M_{N_2} > M_{N_1} > M_\chi$$

- $N_2 \to N_1 \gamma$ (leading mode), $N_2 \to N_1 Z$, $N_2 \to \chi \nu$
- $N_1 \to \chi\ \nu$ ($\not{E}T$)

- $pp \to h \to \chi\chi\ j$ can also lead to mono-jet but suppressed

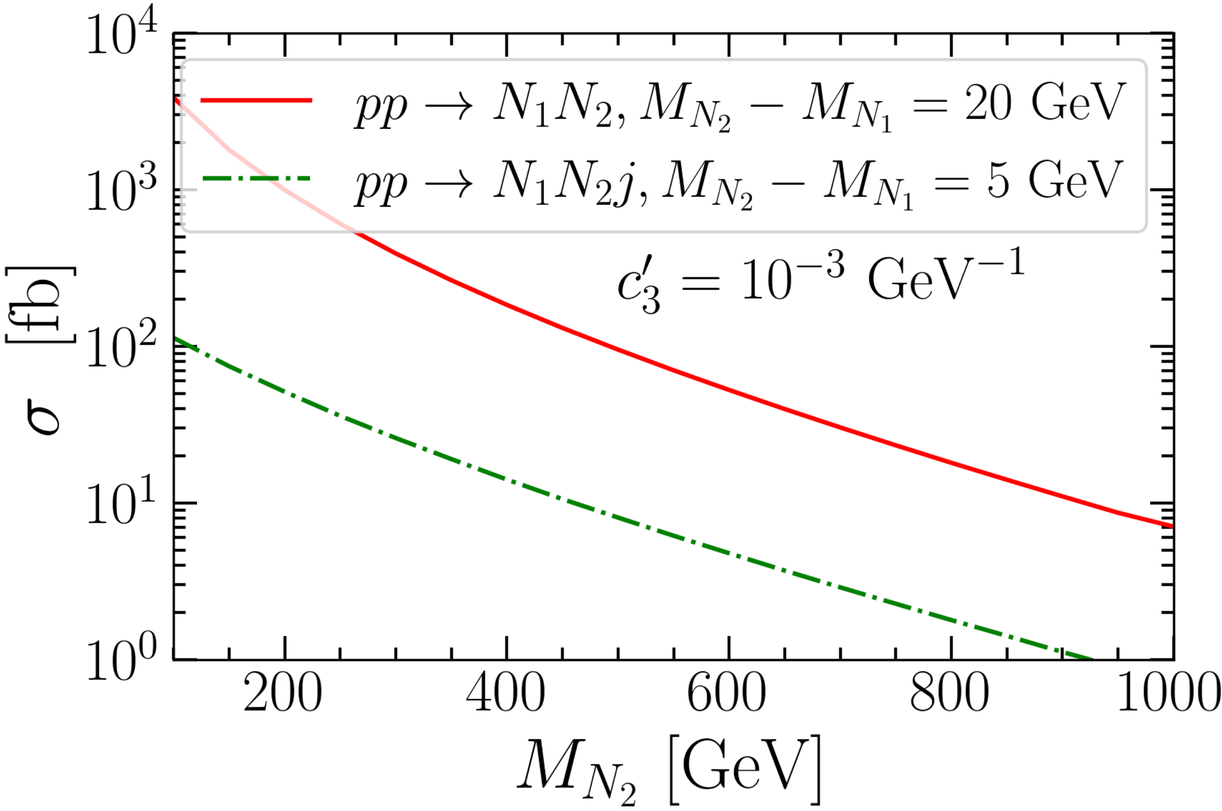
# $N_1N_2$ production at LHC



via the operator: $c_3' \, \overline{N^c} \sigma_{\mu\nu} N \, B^{\mu\nu}$

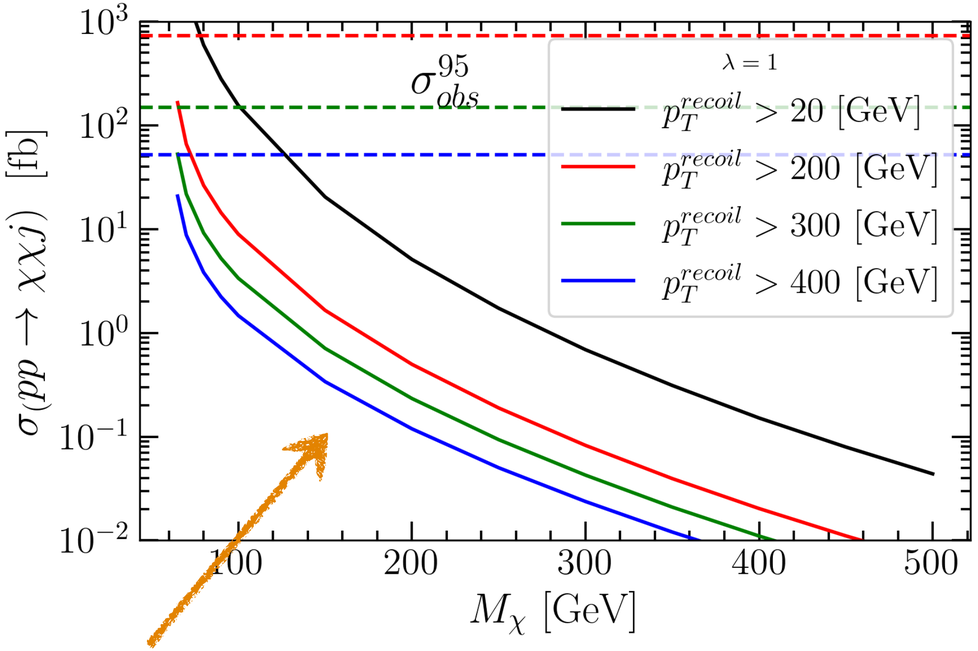
- Cross-section scale as $(c_3')^2$
- Mono-photon via

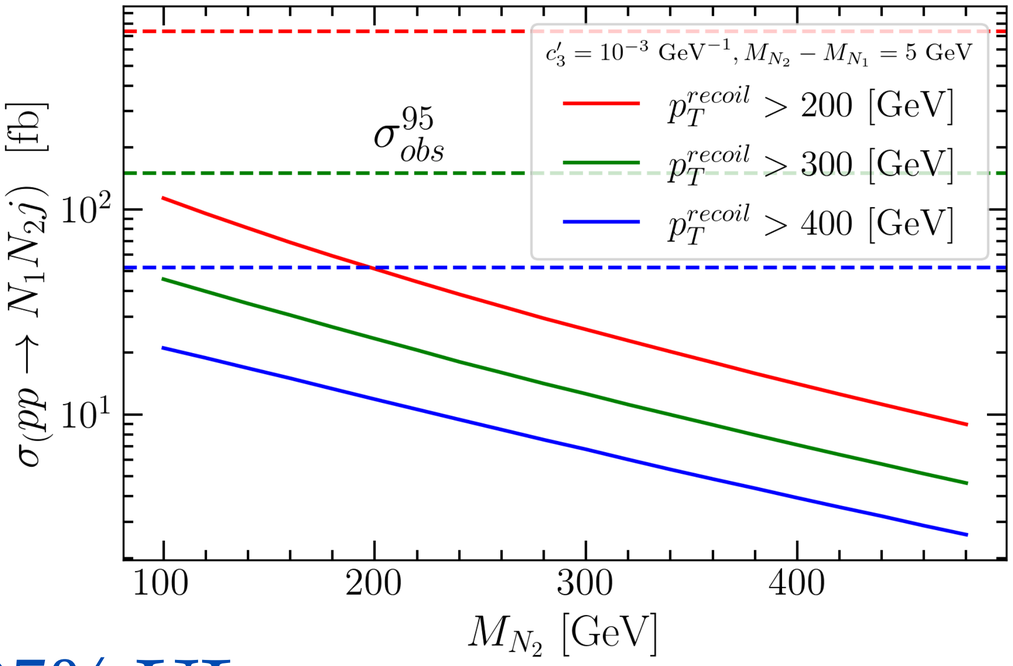
  $pp \to N_1(\to \chi\, \nu)\; N_2(\to N_1\, \gamma)$ is leading channel
- Mono-jet : $pp \to N_1 N_2\; j$ (rates drops for $p_T(j) > 200$ GeV)



# Mono-jet signal

ATLAS mono-jet




- $pp \to h \to \chi\chi\, j$ , *for* $\lambda = 1$. *further suppressed as* $\lambda = 10^{-6}$
- *Not sensitivity to mono-jet*

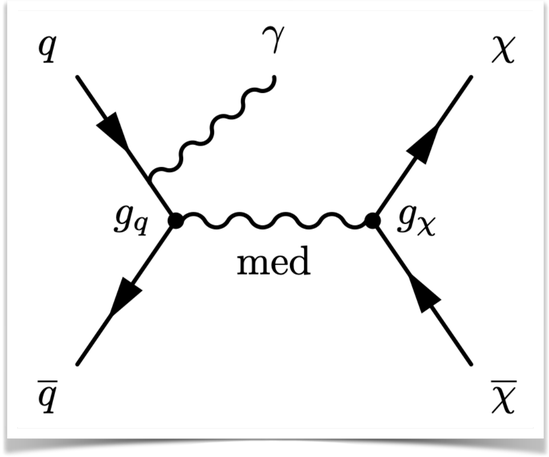
## Observed 95% UL

| **Selection** | $\langle\sigma\rangle^{95}_{\text{obs}}$ [fb] |
|---|---|
| $p_{\text{T}}^{\text{recoil}} > 200\,\text{GeV}$ | 736 |
| $p_{\text{T}}^{\text{recoil}} > 250\,\text{GeV}$ | 296 |
| $p_{\text{T}}^{\text{recoil}} > 300\,\text{GeV}$ | 150 |
| $p_{\text{T}}^{\text{recoil}} > 350\,\text{GeV}$ | 86 |
| $p_{\text{T}}^{\text{recoil}} > 400\,\text{GeV}$ | 52 |

# Mono-photon search

ATLAS mono-photon

$\sqrt{s} = 13$ TeV with 139/fb luminosity




## Selection criteria

| | |
|---|---|
| Leading $\gamma$ | $E_{\mathrm{T}}^{\gamma} > 150$ GeV, $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.37$, tight, isolated, $\lvert\Delta z_{\gamma}\rvert < 250$ mm, $\Delta\phi(\gamma, \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}) > 0.4$ |
| $E_{\mathrm{T}}^{\mathrm{miss}}$ significance | $> 8.5$ |
| Jets | 0 or 1 with $p_{\mathrm{T}} > 30$ GeV, $\lvert\eta\rvert < 4.5$ and $\Delta\phi(\mathrm{jet}, \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}) > 0.4$ |
| Leptons | veto on $e$, $\mu$ and $\tau$ |

| | SRI1 | SRI2 | SRI3 | SRI4 | SRE1 | SRE2 | SRE3 |
|---|---|---|---|---|---|---|---|
| $E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV] | > 200 | > 250 | > 300 | > 375 | 200–250 | 250–300 | 300–375 |

7 Signal regions

| SRs | SRI1 | SRI2 | SRI3 | SRI4 | SRE1 | SRE2 | SRE3 |
|---|---|---|---|---|---|---|---|
| $E_T^{\mathrm{miss}}$ [GeV] | $> 200$ | $> 250$ | $> 300$ | $> 375$ | $200 - 250$ | $250 - 300$ | $300 - 375$ |
| $(\sigma \times A \times \epsilon)_{95}^{\mathrm{obs}}$ [fb] | 2.45 | 1.42 | 0.93 | 0.53 | 1.80 | 1.04 | 0.79 |

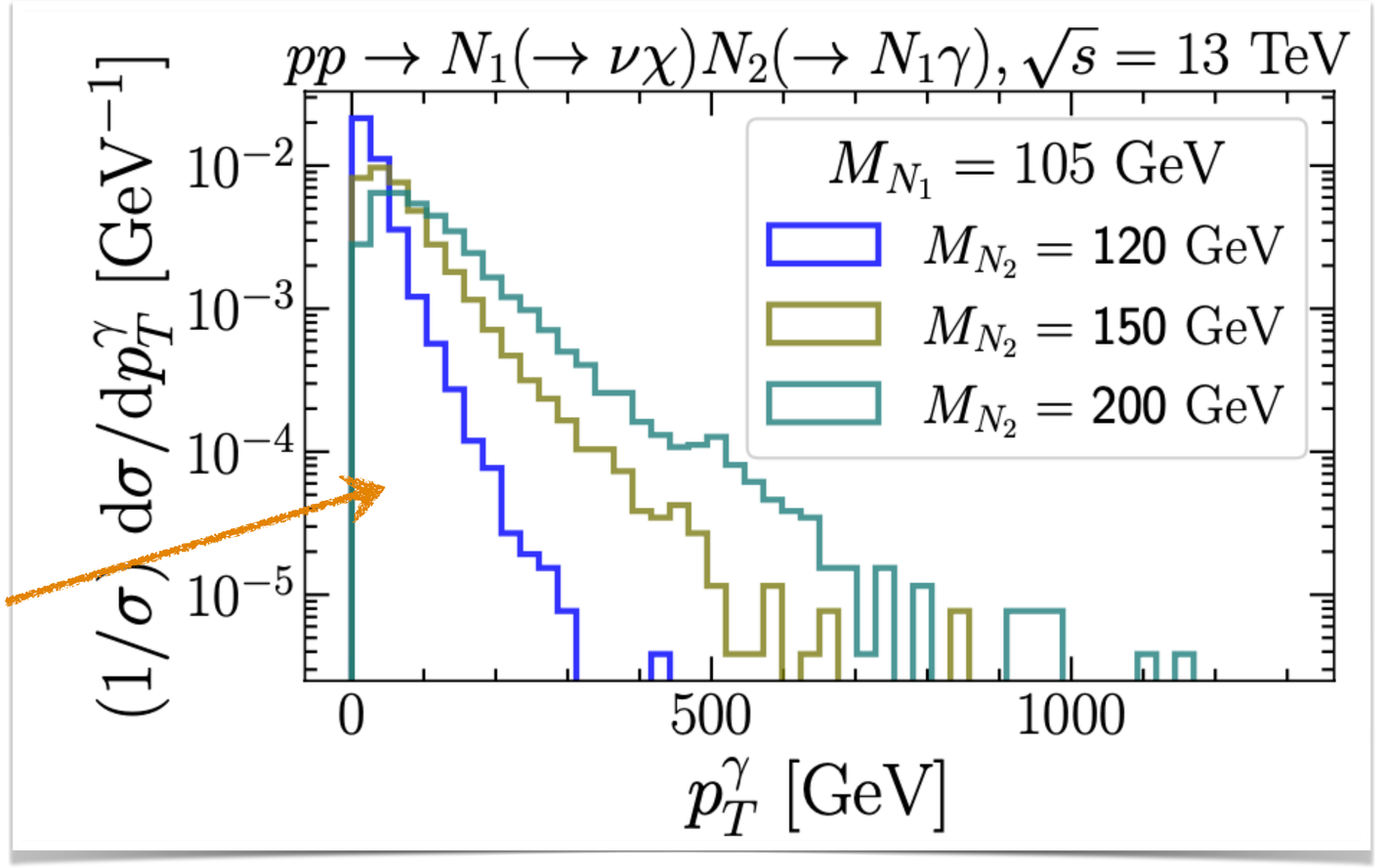
# In Our model

$\gamma + MET$ (mono-photon)

$pp \to N_1(\to \chi\ \nu)\ N_2(\to N_1\ \gamma)$

*Higher Mass splitting*

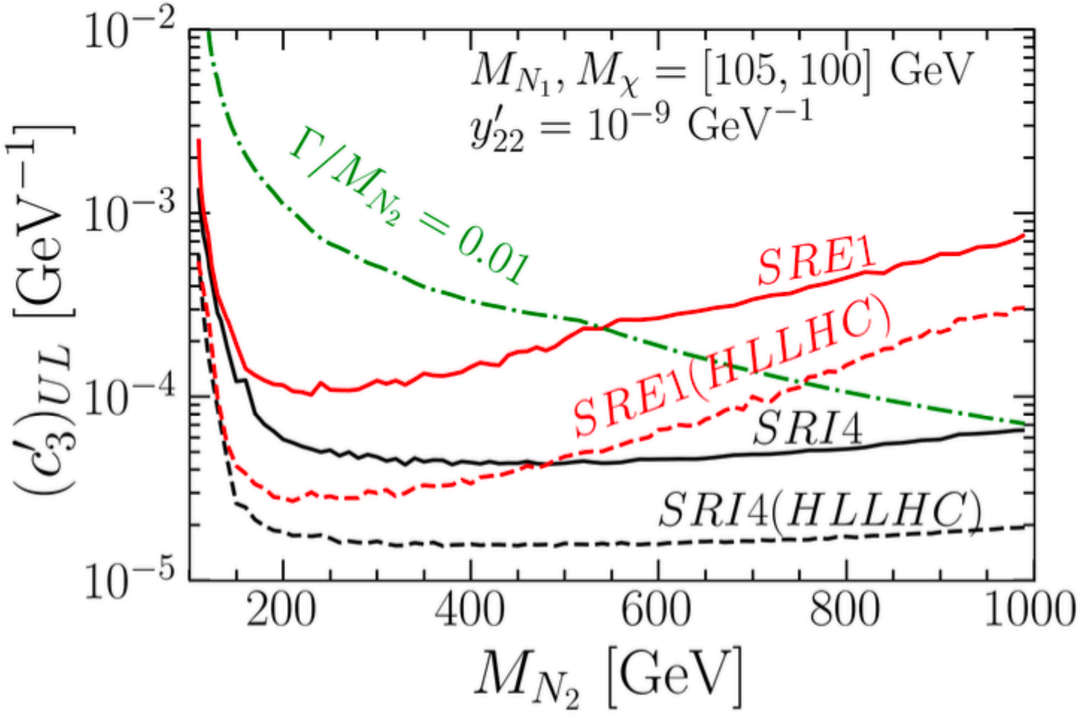
$M_{N_2} - M_{N_1}$ *-> harder photon*

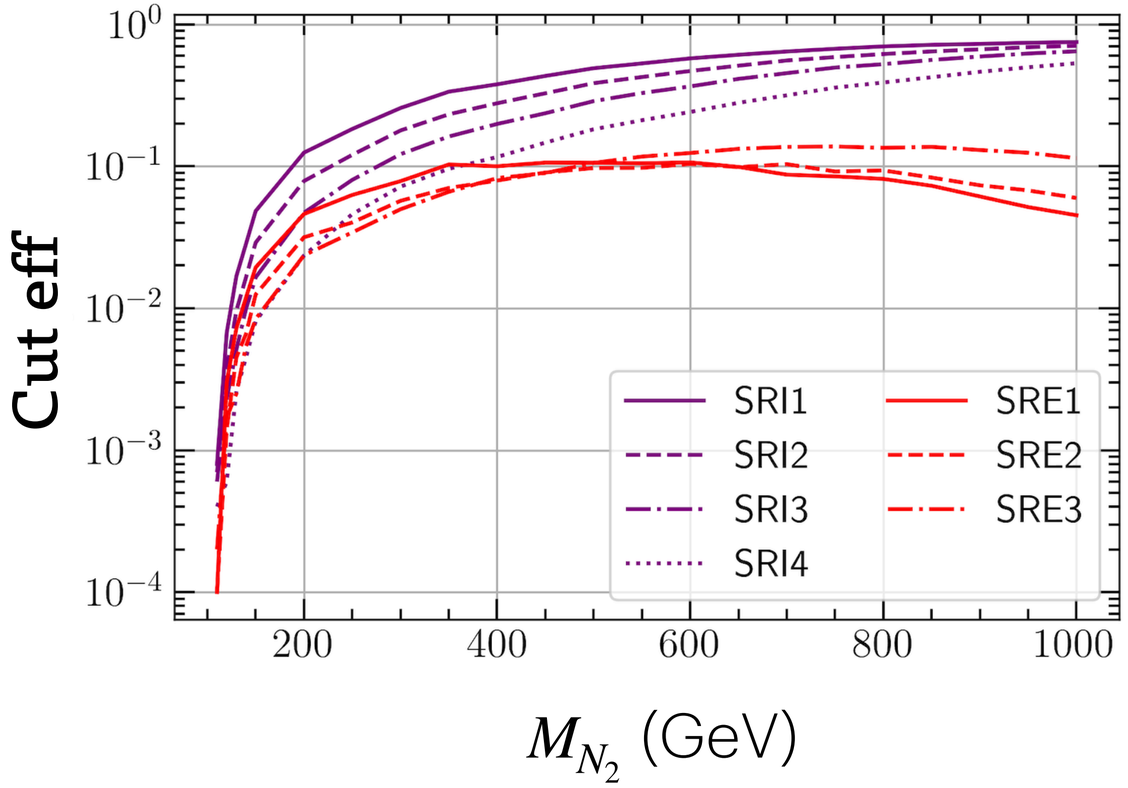



Simulation tools: MADGRAPH5,PYTHIA8, Delphes3.5

# Limit on $c_3'$





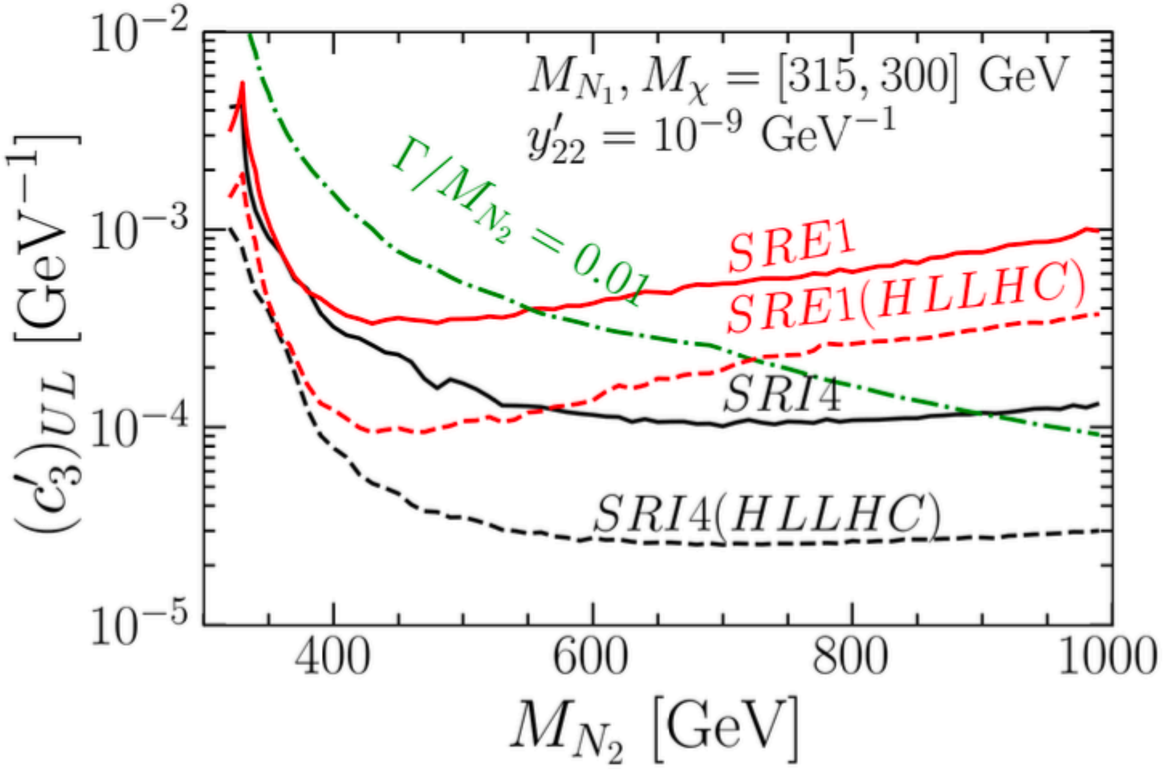



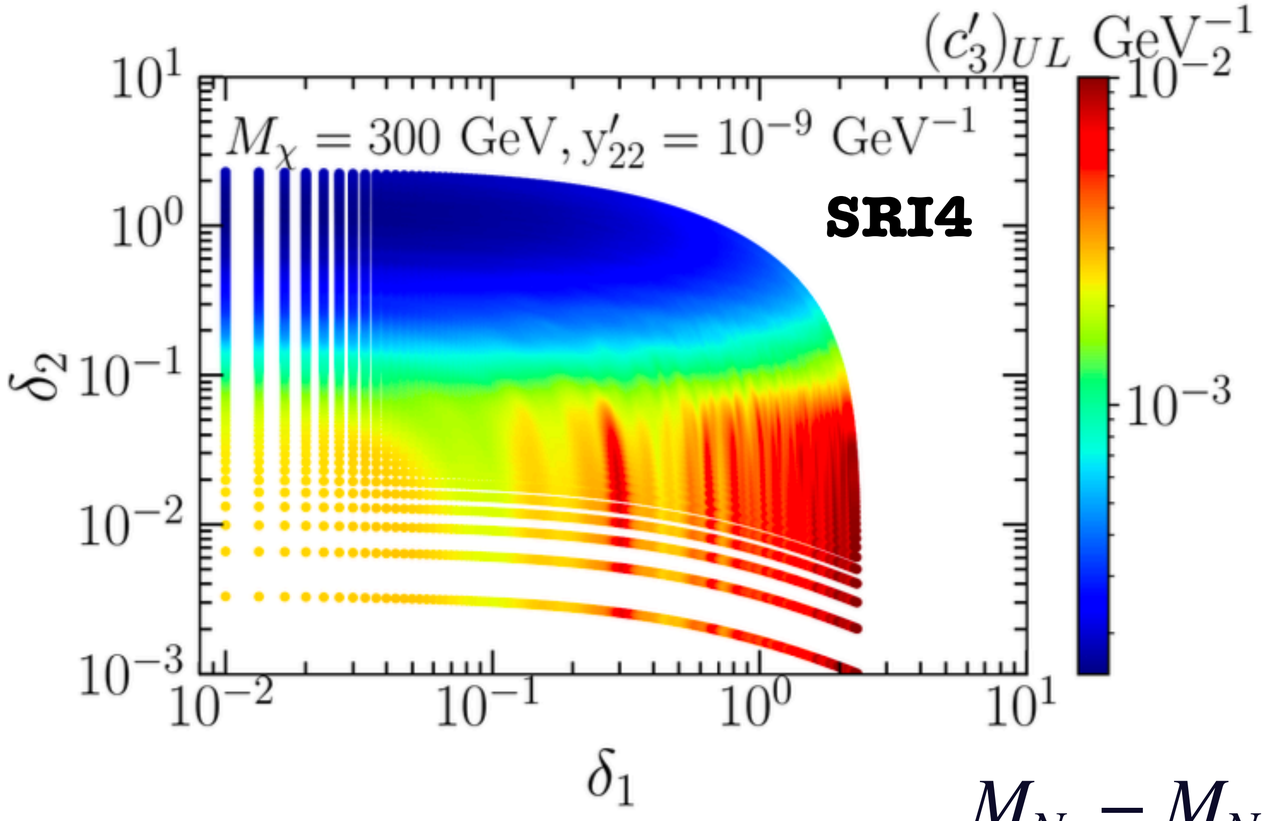

- tightest limit -> SRI4, weakest limit -> SRE1
- For SRI4, cut eff rise and cross section drops wrt $M_{N_2}$ -> almost flat limit on $c_3'$
- For SRE1, variation in cut eff can not balance the decreasing cross -section ->limit weakens wrt $M_{N_2}$
- HL-LHC projection: scale the observed UL on cross-section by $\sqrt{139/3000}$

# Limit on $c_3'$



- *For co-scattering dominant parameter*



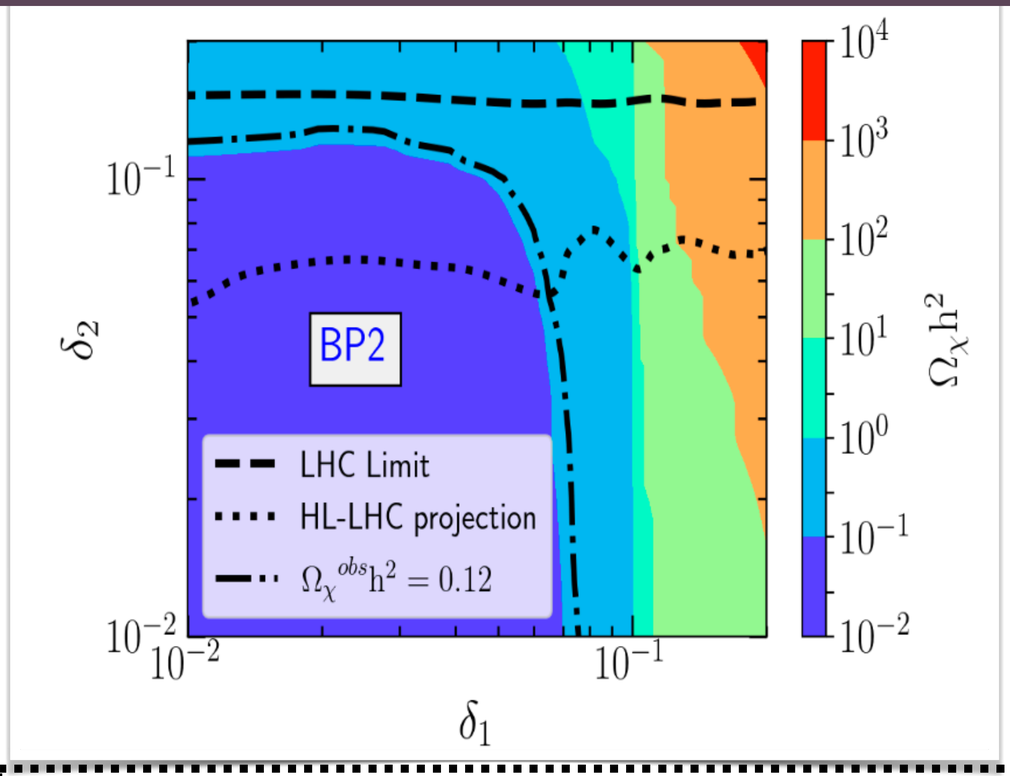



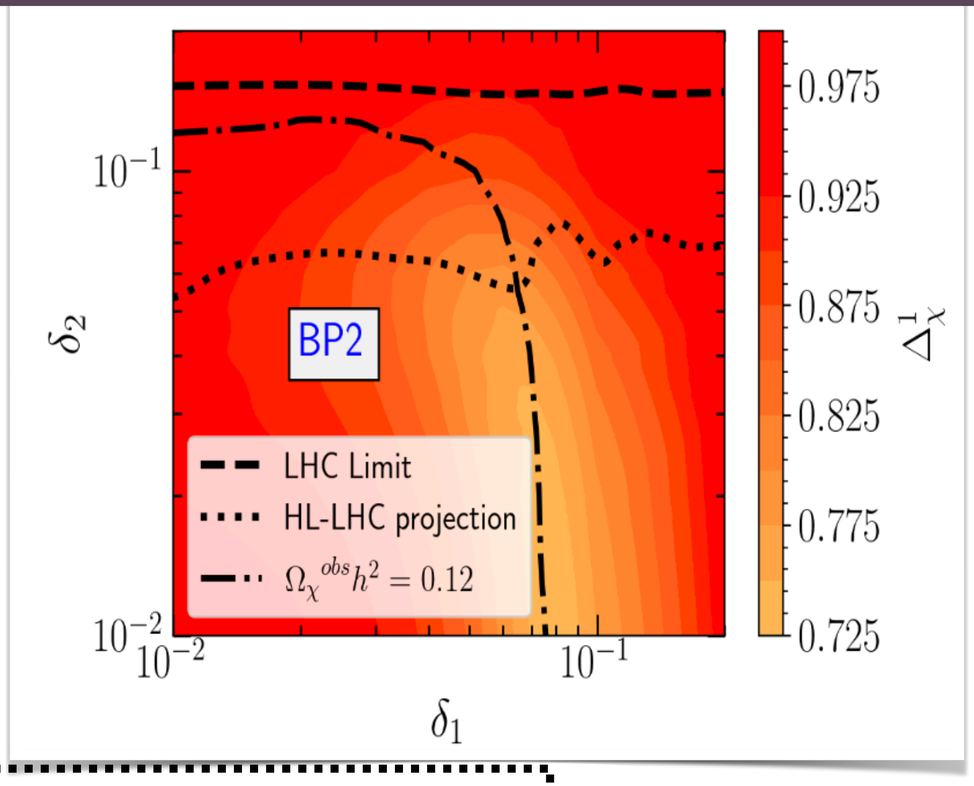

- *Higher $\delta_2$ -> energetic photon -> stronger limit*

$$\delta_2 = \frac{M_{N_2} - M_{N_1}}{M_{N_1}}$$

$$\delta_1 = \frac{M_{N_1} - M_\chi}{M_\chi}$$

# Co-scattering dominant region



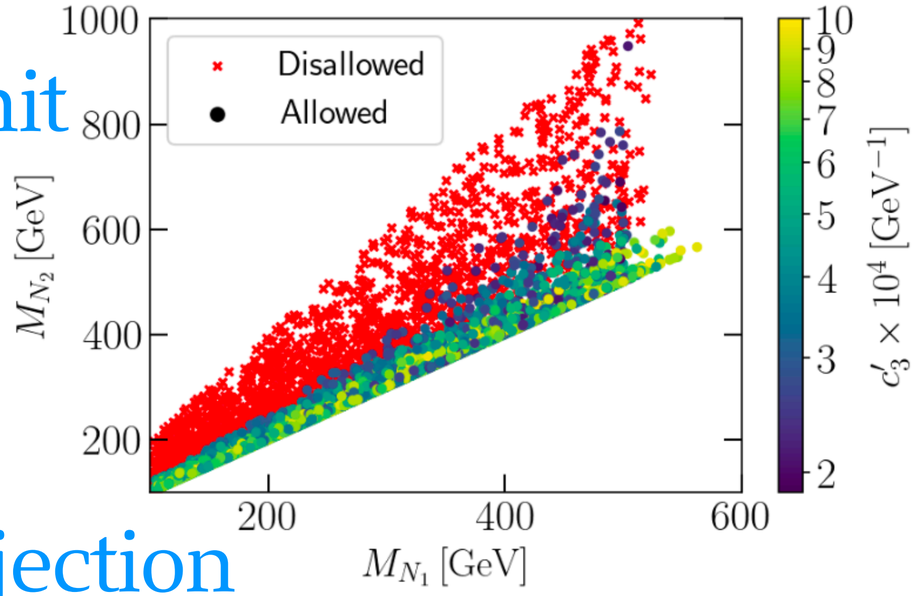

$M_\chi = 300\ GeV, c_3' = 7 \times 10^{-4}\ \ GeV^{-1}, y'_{11,22} = 10^{-9}\ \ GeV^{-1}$

- *Relic density primarily govern by co-scattering*
- *Consistent with mono-photon limit*
- *Can be probed at HL-LHC*

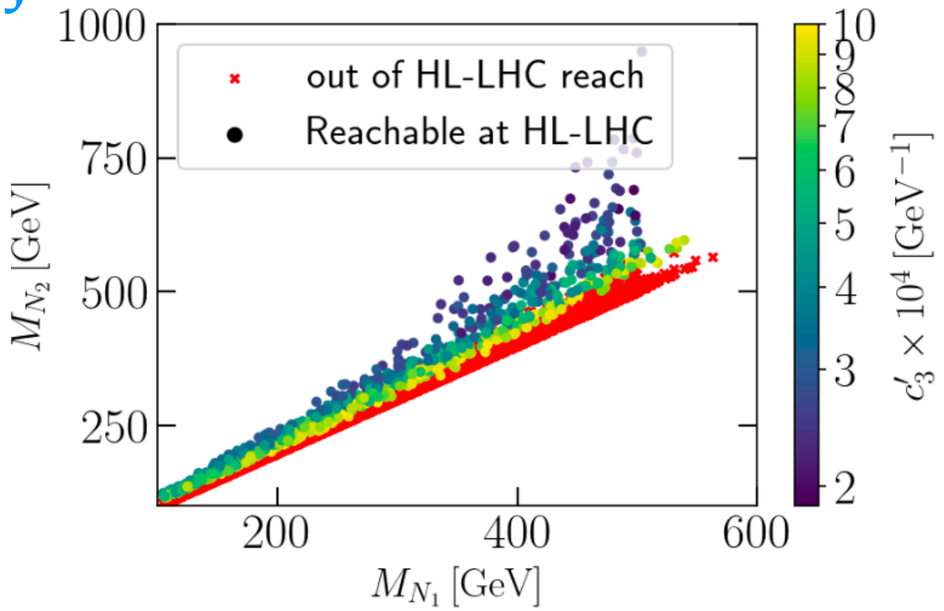
# Parameter Scan

| Parameter | Scanned range |
|---|---|
| $M_\chi$ [GeV] | [100 , 500] |
| $\delta_1(M_{N_1}$ [GeV]) | $[10^{-3}$ , 0.5] ($[\approx M_\chi, 750]$) |
| $\delta_2(M_{N_2}$ [GeV]) | $[10^{-3}$ , 1] ($[\approx M_{N_1}, 1500]$) |
| $y'_{11}$ [GeV$^{-1}$] | $[10^{-11}$ , $10^{-6}]$ |
| $y'_{22}$ [GeV$^{-1}$] | $[10^{-11}$ , $10^{-6}]$ |
| $c'_3$ [GeV$^{-1}$] | $[10^{-6}$ , $10^{-3}]$ |

LHC limit




HL-LHC projection




- *Relic density:* $10^{-4} \leq \Omega_\chi h^2 \leq 0.1224$
- *Mono-photon search constrain larger* $M_{N_2} - M_{N_1}$
- *Parameter space can be probed at HL-LHC*

# Summary

- Co-scattering process via d=5 EFT operator primarily set Relic density
- Singlet scalar (almost excluded by DD) can still be a viable WIMP DM in our EFT model
- Mono-photon search set strong constrain on larger $M_{N_2} - M_{N_1}$
- Parameter space satisfying relic density can be probed at HL-LHC

**Thank You!**