Interplay of inert doublet and vector-like lepton triplet with displaced vertices at the LHC/FCC and MATHUSLA

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Plan

- Hypercharged zero $SU(2)$ triplet fermion: Type-III seesaw
- Unconventional searches: Dispalced decays. Double recoil
- A special case of non-zero hypercharrged $SU(2)$ triplet
- Interplay of Vector like inert triplet lepton and inert doublet
- MATHUSLA detector
- Displaced decay signature of the heavy leptons

Tiny neutrino mass

- Simple extension of SM with a right-handed neutrino (N_R) would solve the problem as

$$\mathscr{L}_{m_\nu} = -\frac{y_\nu v}{\sqrt{2}}\bar{\nu}_L N_R + h.c.$$

- This is a Dirac type mass $m_D = \dfrac{Y_N v}{\sqrt{2}}$
- To have a neutrino mass of $\sim 0.1\,\mathrm{eV}$, one needs $Y_N \sim 10^{-12}$ $\Longrightarrow$ Leads to fine-tuning

- Being charged neutral, a Majorana mass term $M_N \bar{N}_R N_R^c$ is possible
- A popular mechanism called Seesaw explains the small neutrino mass by having heavy Majorana neutrinos mass term

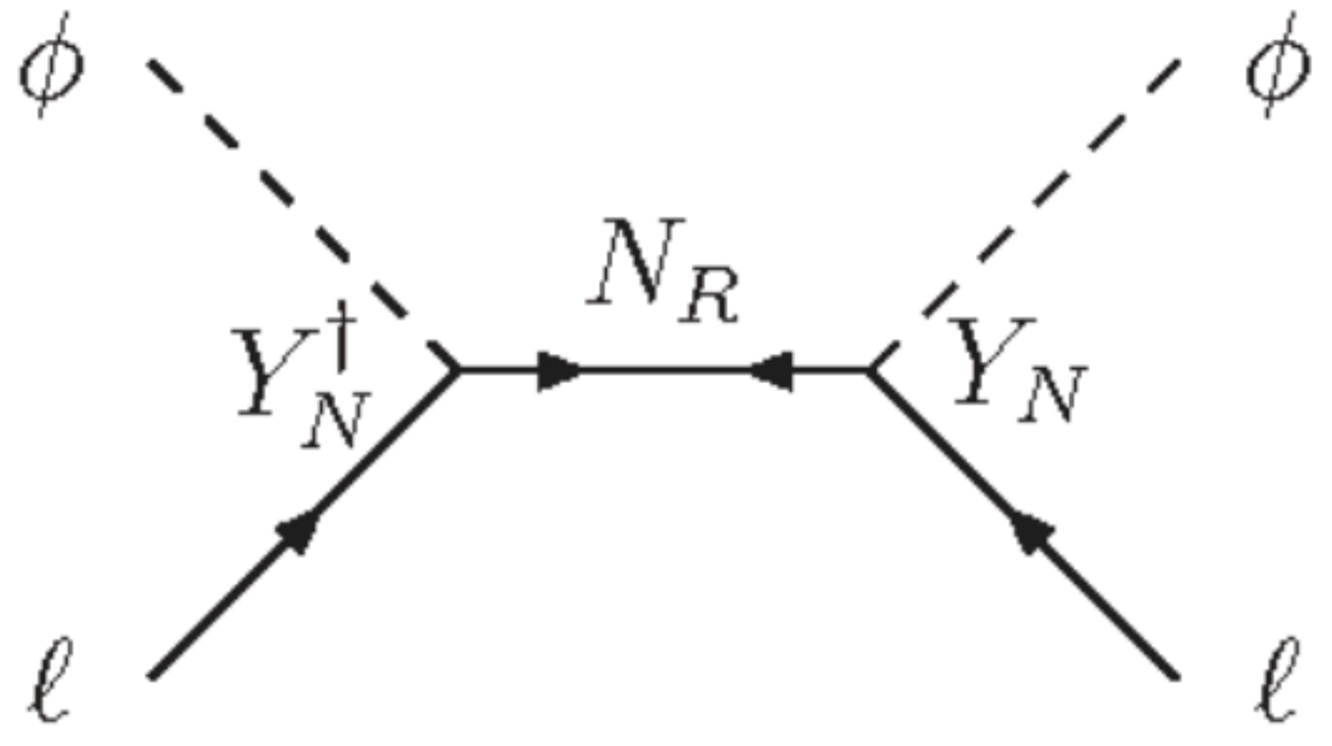
$$m_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

$\Longrightarrow$ existence of heavy Majorana neutrino

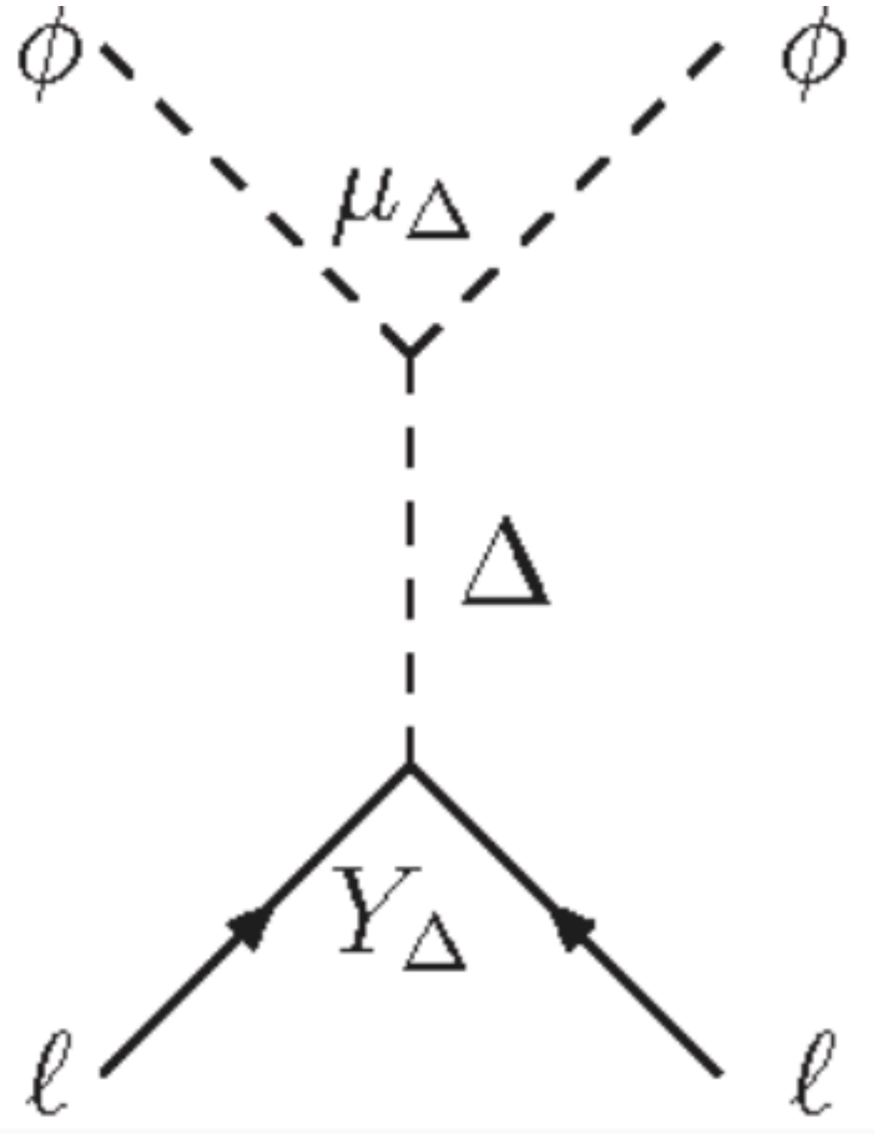
More

Seesaw mechanisms: Most popular senaris

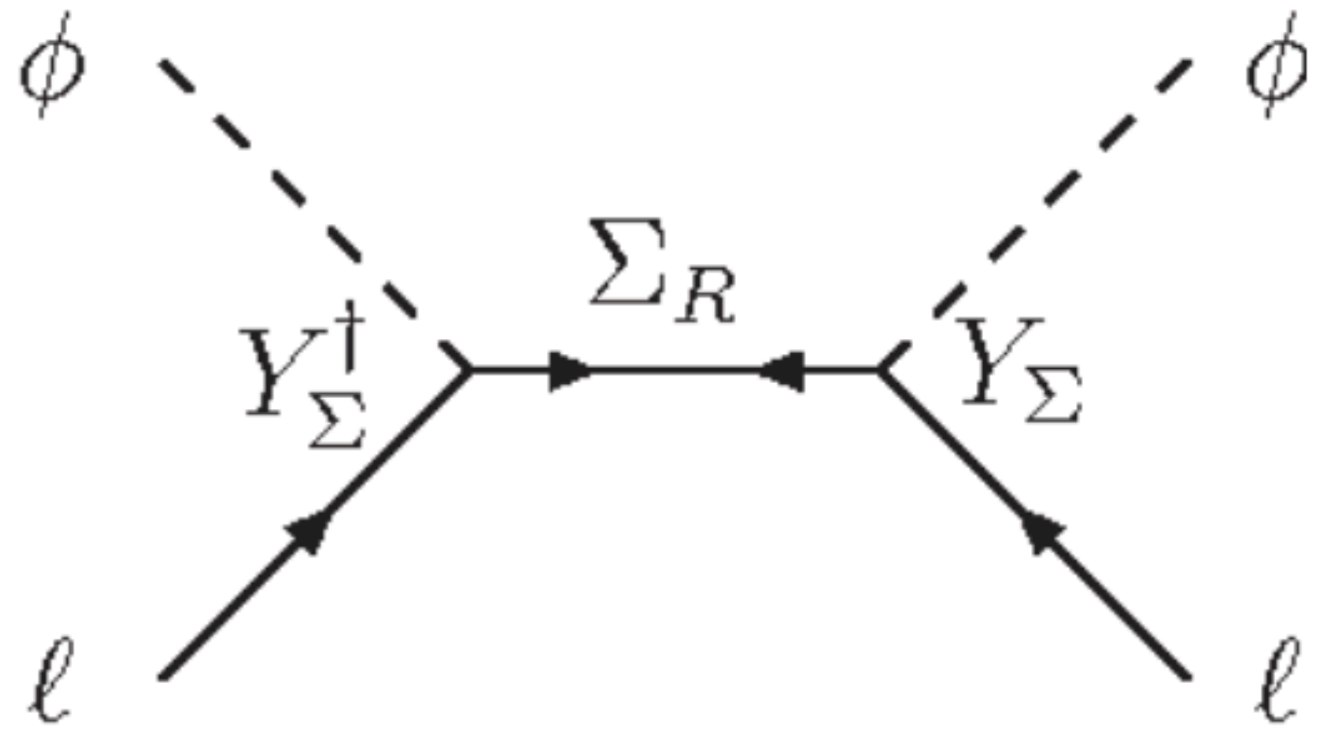
- The most popular variants are Type-I, Type-II and Type-III seesaw
- Type-I and Type-III involve heavy fermions
- Type-II involves heavy scalar



Type-I involves SM gauge singlet heavy neutrino $\nu_R (N_R/N)$



Type-II involves SU(2) triplet scalar Δ



Type-III involves SU(2) triplet fermion $\Sigma(N)$

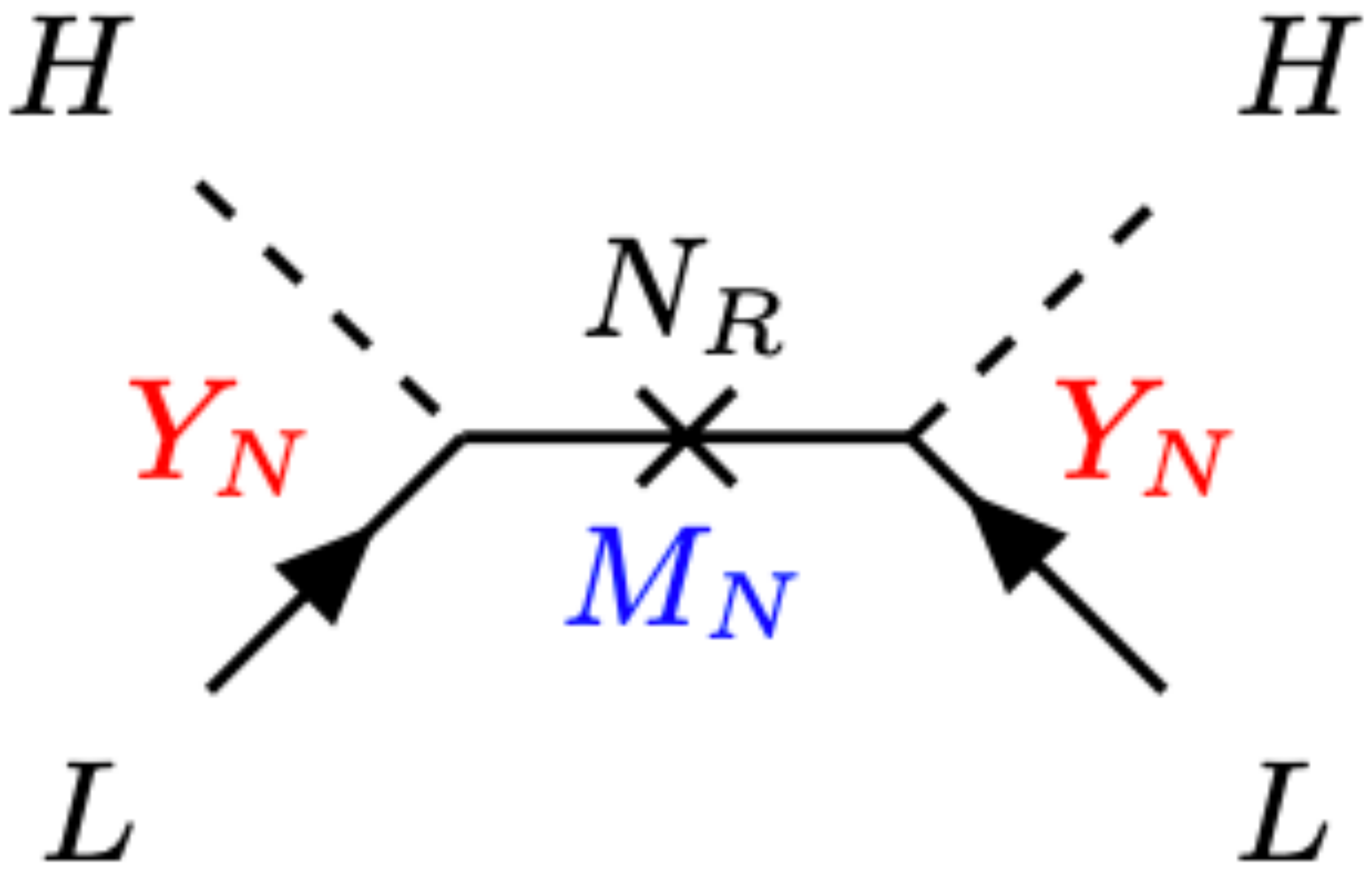
Type-III Seesaw: Extension with zero a hyper (Y=0) charged SU(2) triplet

Type-III Seesaw

- A Y=0, SU(2) triplet fermion can be added which generates tiny neutrino mass

$$\mathscr{L}_N = -\frac{1}{2}Tr[(\overline{N}M_N N) + \overline{N^c}M^*N] - Y_N\bar{L}N\tilde{\phi} + h\,.\,c$$

- A Majorana mass term is possible



The heavy triplet fermions have chared ($N^{\pm}$) and neutral (N^0) part as given by

$$N = \begin{pmatrix} N^0 & \sqrt{2}N^+ \\ \sqrt{2}N^- & -N^0 \end{pmatrix}$$

Foot, Hambye, Struma, Ma, Bajc, He, Senjanovic, Chaubey, Chun, Goswami, Ghosh, Mitra, Rosa,..

Type-III Seesaw

- For Heavy N the decay widths follows:$\Gamma_{N^\pm}^{Z\ell} \simeq \Gamma_{N^\pm}^{Z\ell} \simeq \frac{1}{2}\Gamma_{N^\pm}^{W^\pm\nu} \simeq \frac{Y_N^2 M_N}{32\pi^2}$
- There is another mode modinant for lower Yukawa , i.e. $N^\pm \to N^0\pi^\pm$

with $\Gamma(N^\pm \to N^0\pi^\pm) = \frac{2G_F^2 V_{ud}^2 (\Delta M)^3 f_\pi^2}{\pi}\sqrt{1 - \frac{m_\pi^2}{\Delta M^2}}$

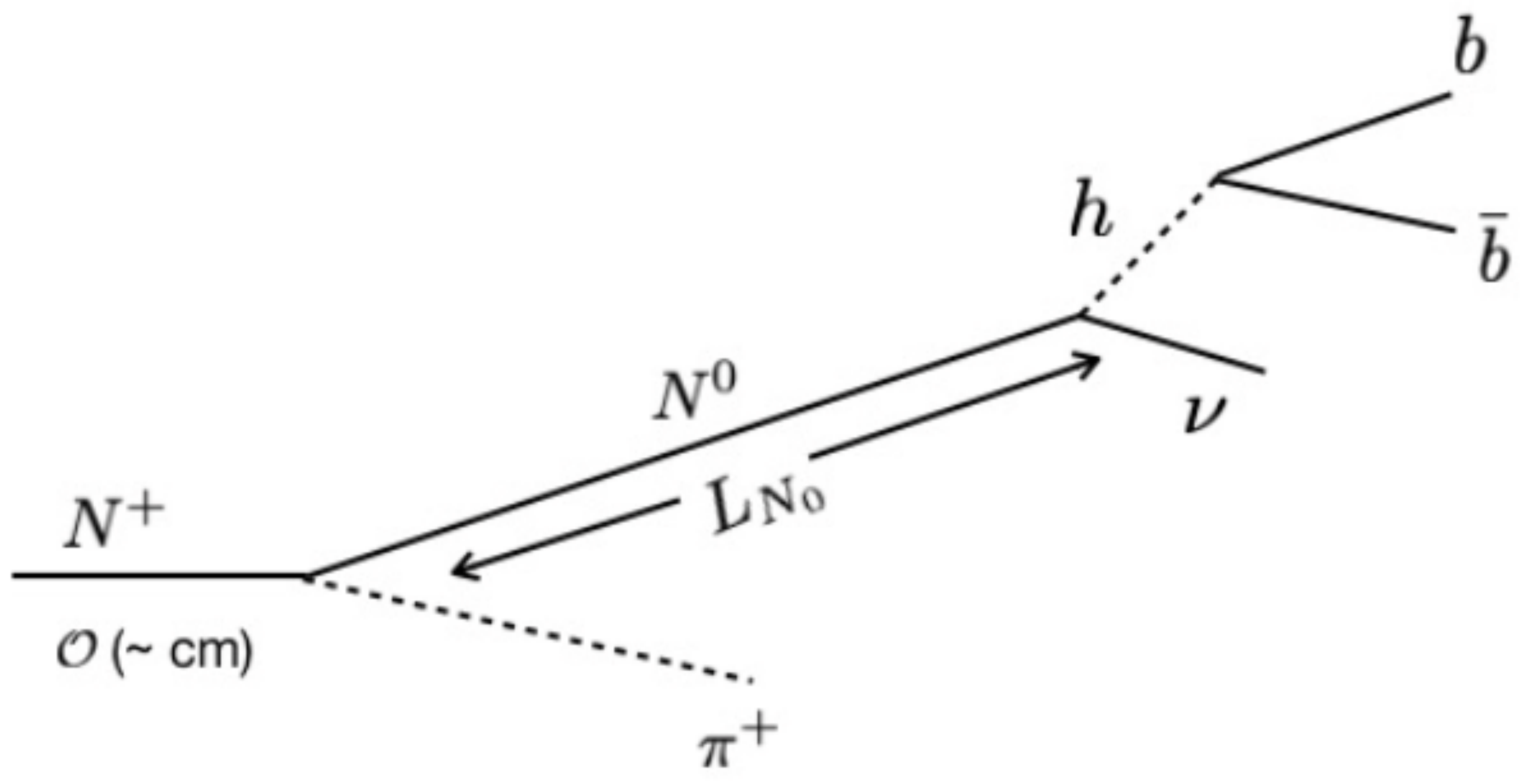
Cirelli et al. :Nucl.Phys.B753:178-194,2006

Where, ΔM is the mass difference between $N^\pm$ and N^0 arising from the quantum corrections which is $\mathcal{O}(166)\,\mathrm{MeV}$

- For $Y_N \sim 5 \times 10^{-7}$, the branching ratio in this mode is less than 1 %
- However, for $Y_N \sim 5 \times 10^{-10}$ the branching fraction is $\sim 97.5\,\%$

More

Displaced Double recoil



- For lower Yukawa, I.e. $Y_N \lesssim 5 \times 10^{-8}$, $N^\pm \to N^0\pi^\pm$ dominates with a decay length of $\mathcal{O}(cm)$
- For similar low values of Yukawa the decay of $N^0 \to h\nu$ can be a few meeter to 100s of meter

- A displaced double recoil is predicted.

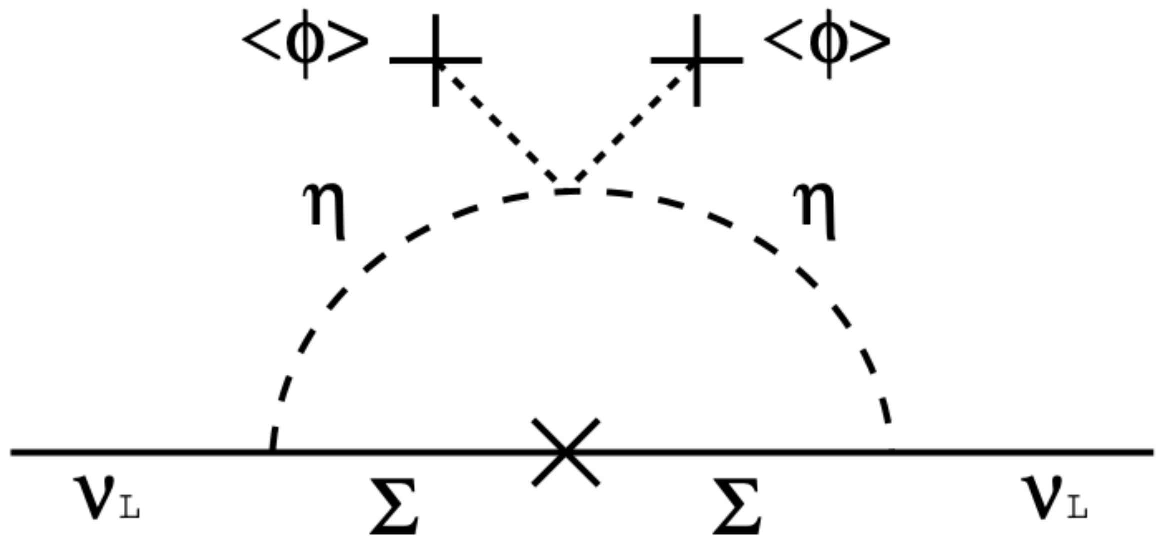
PB, Chandrima Sen, Aleesha KT, Saunak Dutta: Eur.Phys.J.C 82 (2022) 3, 230]

Scotogenic Type-III: Extension with a zero hyper (Y=0) charged Z_2-odd SU(2) triplet

Scotogenic Type-III

- Y=0 triplet fermion (Σ) and inert doublet (η) both are Z_2-odd

$$-\mathcal{L}_\Sigma = \sum_{\alpha=1}^{n_\Sigma}\left(\sum_{i=e,\mu,\tau} h_{i\alpha}\bar{\ell}_{L_i}\Sigma_\alpha\eta + \frac{1}{2}M_\alpha \mathrm{tr}(\bar{\Sigma}_\alpha\Sigma_\alpha^c) + \mathrm{h.c.}\right)$$



- Neutrino mass cannot be generated at the tree-level
- Neutrino mass is generated at one-loop
- A Y=0, SU(2) triplet fermion with Z_2-odd can provide Majorana dark matter
- Due to Y=0, the coupling with Z boson is zero
- It can evade the direct dark matter constraint mediated by Z boson
- For Y=0, a scotogenic Type-III can provide the neutral component of Σ can be a Majorana dark matter

E. Ma, Suematsu: Mod. Phys. Lett. A 24, 583 (2009).

Extension with a non-zero hyper charged SU(2) triplet

Non-zero Hypercharged fermion

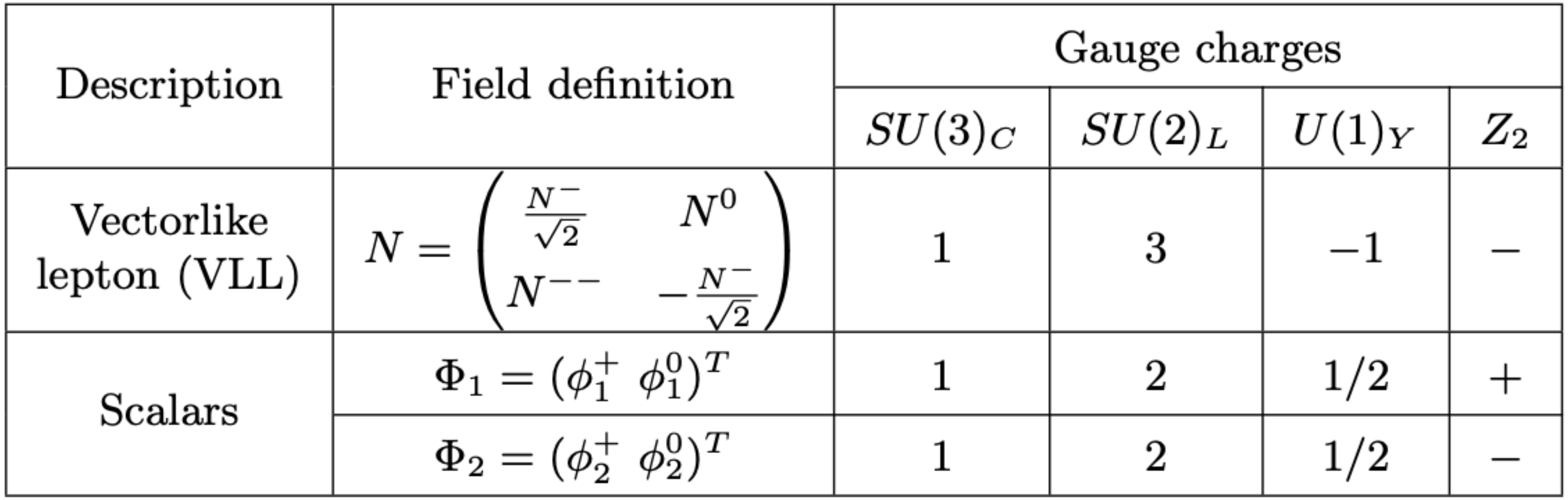
- For $Y \neq 0$, we cannot write a Majorana mass term for $N = \begin{pmatrix} \frac{N^-}{\sqrt{2}} & N^0 \\ N^{--} & \frac{-N^-}{\sqrt{2}} \end{pmatrix}$
- So usual Seesaw will not work
- The gauge invariant Lgrangian also needs a $SU(2)$ doublet scalar $\Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$

$$\mathcal{L}_{VLL} \supset \left[-\frac{M_N}{2} \overline{N_L} N_R + \mathcal{Y}_N \overline{L_L^e} N_R \Phi_2 \right] + h.c.$$

- We make both N, Φ_2 Z_2-odd
- Being Z_2 -odd, in principle, neutral component of both (N^0, ϕ_2^0) can provide the dark matter
- Due to $Y \neq 0$, N^0 couples to Z boson

- For $Y \neq 0$, the possible mass term is Dirac Type, which makes it vector like

SU(2) VLL and IDM



Description	Field definition	Gauge charges			
		$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Z_2
Vectorlike lepton (VLL)	$N = \begin{pmatrix} \frac{N^-}{\sqrt{2}} & N^0 \\ N^{--} & -\frac{N^-}{\sqrt{2}} \end{pmatrix}$	1	3	-1	$-$
Scalars	$\Phi_1 = (\phi_1^+ \; \phi_1^0)^T$	1	2	$1/2$	$+$
	$\Phi_2 = (\phi_2^+ \; \phi_2^0)^T$	1	2	$1/2$	$-$

- The scalar potential can be written as

$$V_{\text{scalar}} = -m_{\Phi_1}^2 \Phi_1^\dagger \Phi_1 - m_{\Phi_2}^2 \Phi_2^\dagger \Phi_2 + \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left[\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + h.c\right]$$

- Being Z_2 odd, Φ_2 does not get vev

SU(2) VLL and IDM

- The physical masses are

$$M_h^2 = 2\lambda_1 v^2$$

$$M_{H^0/A^0}^2 = m_{\Phi_2}^2 + \frac{1}{2}v^2\lambda_{L/S}$$

$$M_{H^\pm}^2 = m_{\Phi_2}^2 + \frac{1}{2}v^2\lambda_3,$$

where, $\lambda_{L/S} = \lambda_3 + \lambda_4 \pm 2\lambda_5$.

- Being Z_2 odd, Φ_2 does not get vev
- Masses of VLLs are all degenerate to M_N at the tree-level
- However, at loop-level their is a mass splitting between the different charged and the neutral components

$$\Delta M_{N^\pm N^0} = \frac{\alpha_2 M_N}{4\pi}\left[(s_W^2+1)\mathcal{G}\left(\frac{M_Z}{M_N}\right) - \mathcal{G}\left(\frac{M_W}{M_N}\right)\right],$$

$$\Delta M_{N^{\pm\pm} N^0} = \frac{\alpha_2 M_N}{4\pi}\left[4\, s_W^2\mathcal{G}\left(\frac{M_Z}{M_N}\right)\right].$$

where, $\mathcal{G}(x) = \frac{x}{2}\left[2x^3\,\ln x - 2x + (x^2+2)\sqrt{x^2-4}\,\ln(\frac{x^2-2-x\sqrt{x^2-4}}{2})\right]$

- For $M_N \geq 400$ GeV, $\Delta M_{N^\pm N^0} \sim 500$ MeV, $\Delta M_{N^{\pm\pm} N^0} \sim 1.5$ GeV

SU(2) VLL and IDM

- Unlike Y=0 Schotogenic Type-III, N^0 can not be dark matter here

- Due to non-Majorana nature, its coupling with Z boson forbids N^0 to be the dark matter, owing to large direct dark matter cross-section

- Whereas, A^0/H^0 due to CP-coonserving lagranngian do not couple to Z boson. The lighter of these two can be a dark matter candidate, which we choose as A^0

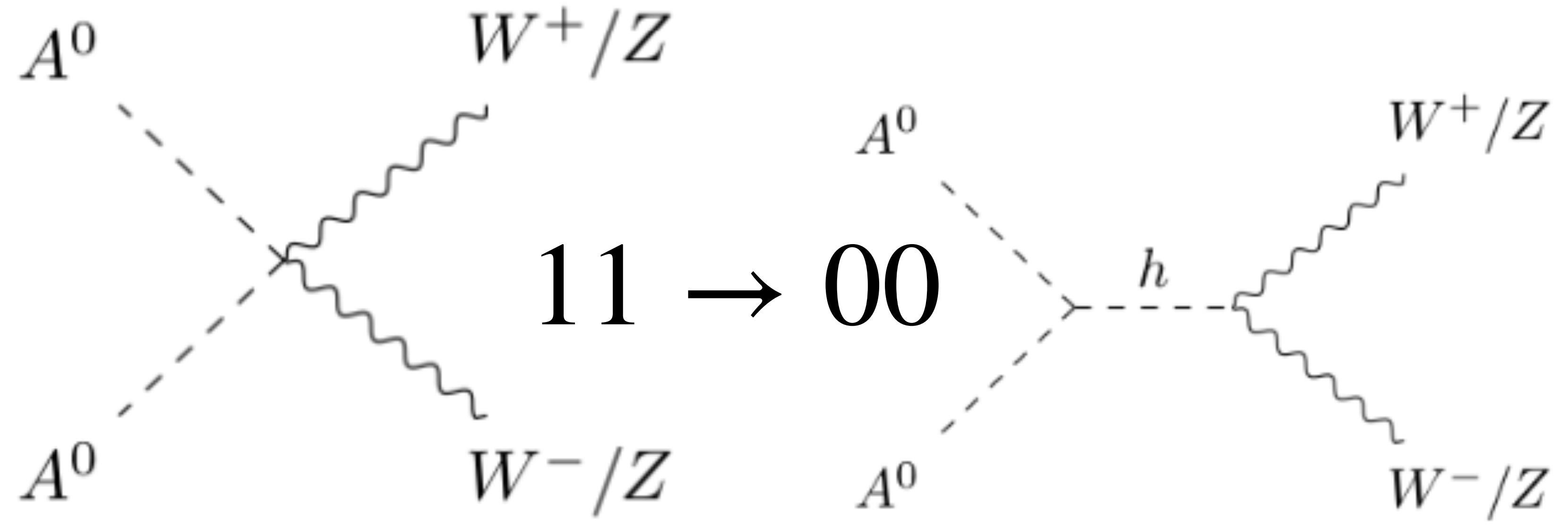
- The direct dark matter constraint even prohibits a multi-component dark matter scenario as well

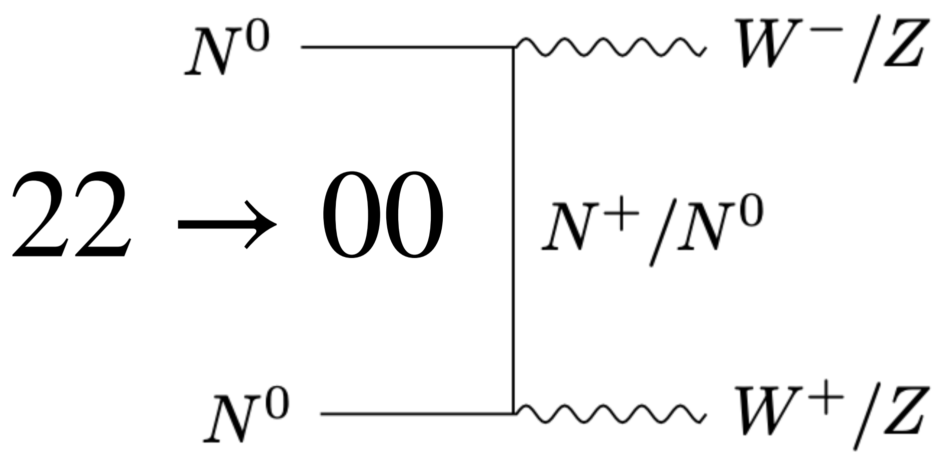
- So for all the practical purpose, this is IDM scenario

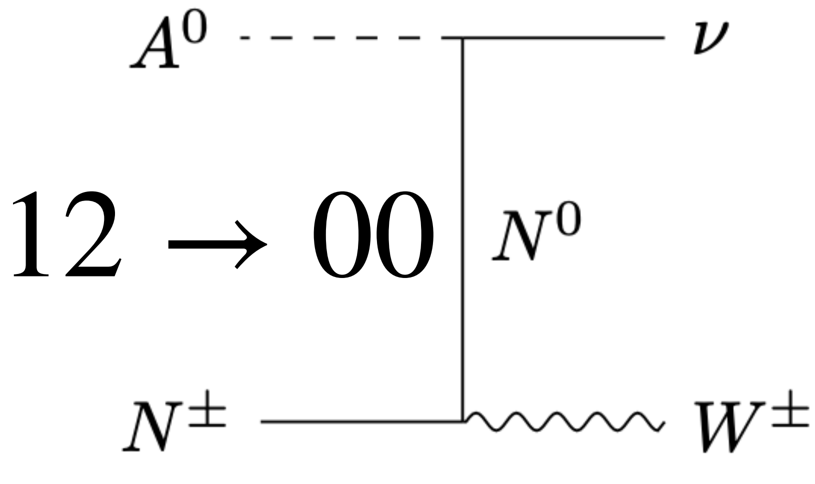
- However, the interplay of N^0 and A^0/H^0 plays an important role in the freeze-out of the dark matter and attaining the correct relic

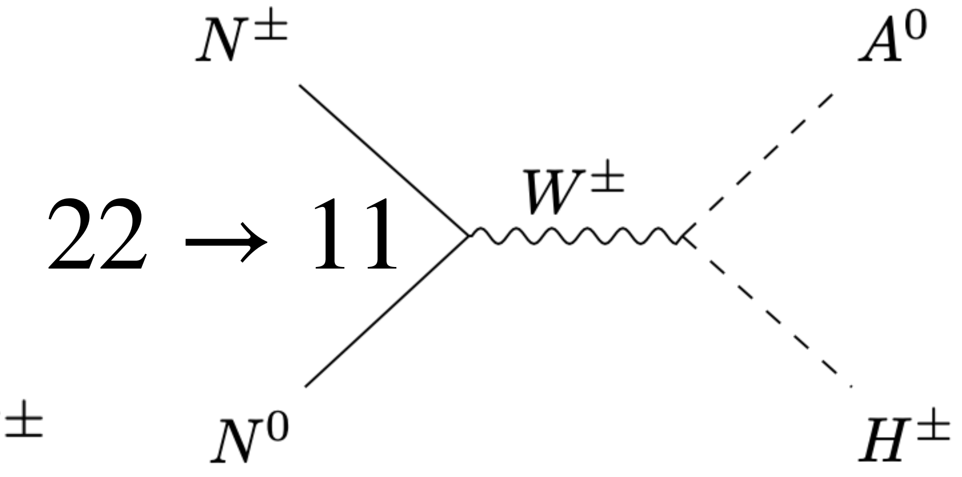
Interplay between IDM and VLL

Convention: **Sector 0: SM particles;** **Sector 1: IDM:** $A^0, H^0, H^\pm$; **Sector 2: VLL:** $N^0, N^\pm, N^{\pm\pm}$







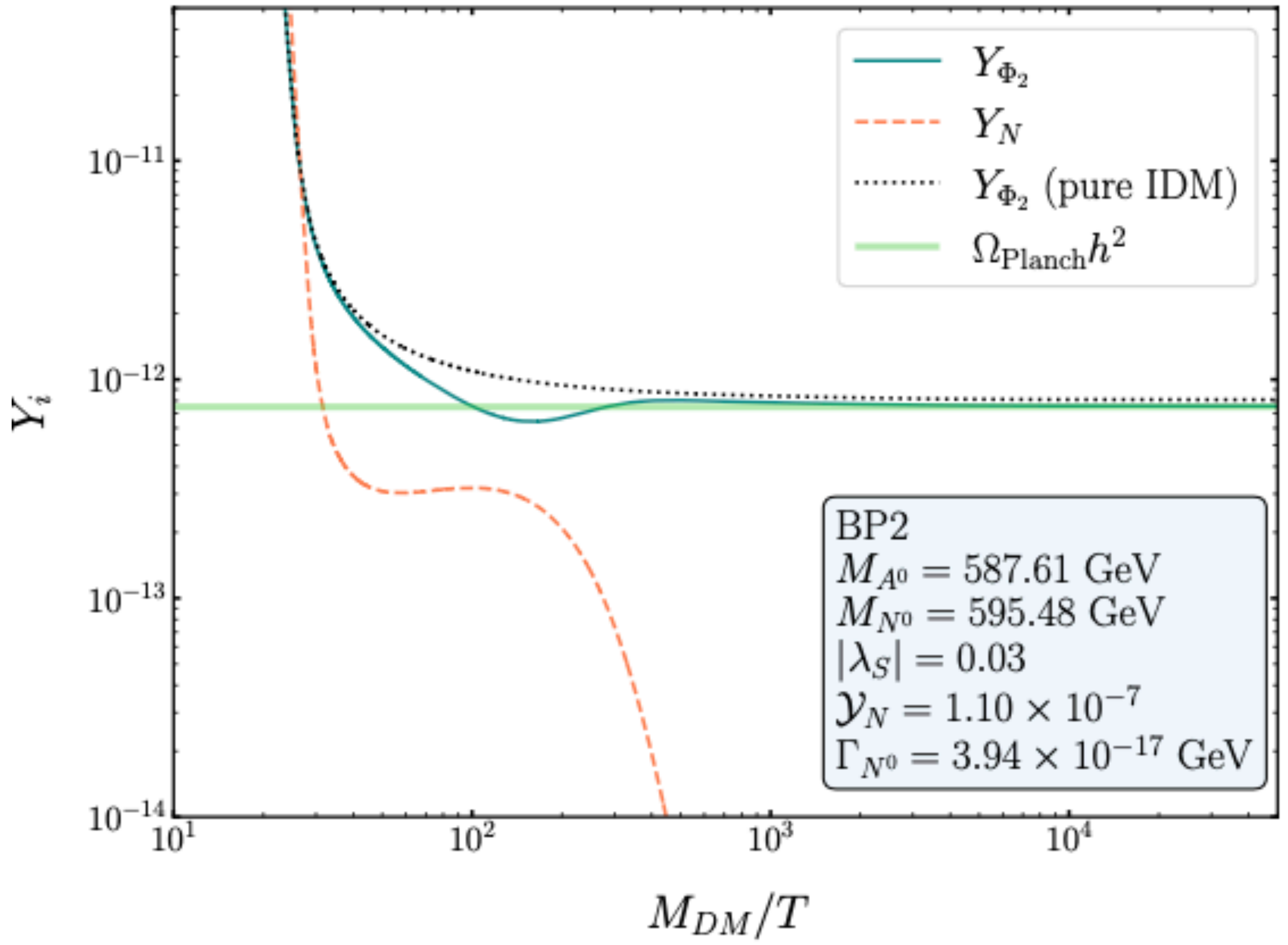


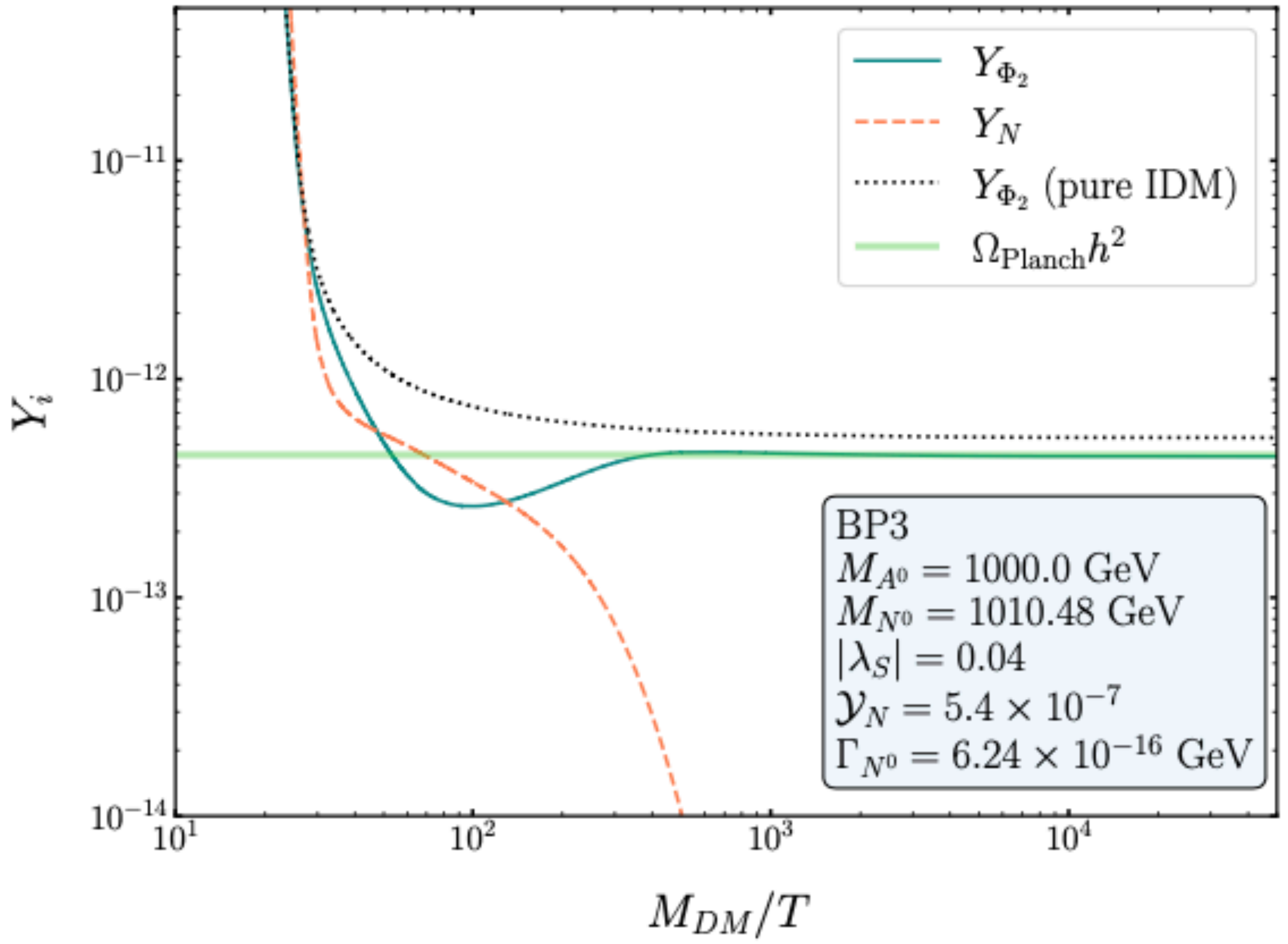
- For $m_{\Phi_2} < M_N$, IDM is the real dark matter
- Pair-annihilation of Z_2 odd particles $\Phi_2\Phi_2 \to \mathrm{SM}\,\mathrm{SM}(11 \to 00)$ and $NN \to \mathrm{SM}\,\mathrm{SM}(22 \to 00)$
- Co-annihilations of Z_2 odd particles $N\Phi_2 \to \mathrm{SM}\,\mathrm{SM}(21 \to 00)$
- Co-scatterring of Z_2 odd particles $\Phi_2\Phi_2 \leftrightarrow N\,N$
- Late decay effect: $N \to \Phi_2\,\mathrm{SM}$

$$\frac{dY_{\Phi_2}}{dx} = -\frac{1}{x^2}\frac{s(M_{A^0})}{H(M_{A^0})}\left[\langle\sigma v\rangle_{1100}\left(Y_{\Phi_2}^2 - (Y_{\Phi_2}^{eq})^2\right) - \langle\sigma v\rangle_{2211}\left(Y_{\Phi_2}^2 - Y_N^2\frac{(Y_{\Phi_2}^{eq})^2}{(Y_N^{eq})^2}\right)\right.$$
$$\left. + \langle\sigma v\rangle_{1200}\left(Y_{\Phi_2}Y_N - Y_{\Phi_2}^{eq}Y_N^{eq}\right)\right] + \frac{x\Gamma_{N\to\Phi_2 X}}{H(M_{A^0})}\left(Y_N - Y_{\Phi_2}\frac{Y_N^{eq}}{Y_{\Phi_2}^{eq}}\right),$$

$$\frac{dY_N}{dx} = -\frac{1}{x^2}\frac{s(M_{A^0})}{H(M_{A^0})}\left[\langle\sigma v\rangle_{2200}\left(Y_N^2 - (Y_N^{eq})^2\right) + \langle\sigma v\rangle_{2211}\left(Y_{\Phi_2}^2 - Y_N^2\frac{(Y_{\Phi_2}^{eq})^2}{(Y_N^{eq})^2}\right)\right.$$
$$\left. + \langle\sigma v\rangle_{1200}\left(Y_{\Phi_2}Y_N - Y_{\Phi_2}^{eq}Y_N^{eq}\right)\right] - \frac{x\Gamma_{N\to\Phi_2 X}}{H(M_{A^0})}\left(Y_N - Y_{\Phi_2}\frac{Y_N^{eq}}{Y_{\Phi_2}^{eq}}\right).$$

Interplay between IDM and VLL





- The A^0 suffers a dip due to co-annihilation due to compresses spectra
- The number density of A^0 increases as N^0 decays completely
- Pure IDM shows over abundant, but due to the inter play with the VLL, the DM relic is back to the allowed
- The situation corresponds to relatively late decay of $N^0, \Gamma_{N^0} \sim 10^{-16} - 10^{-17}\,\mathrm{GeV}$, giving rise to displaced decays N

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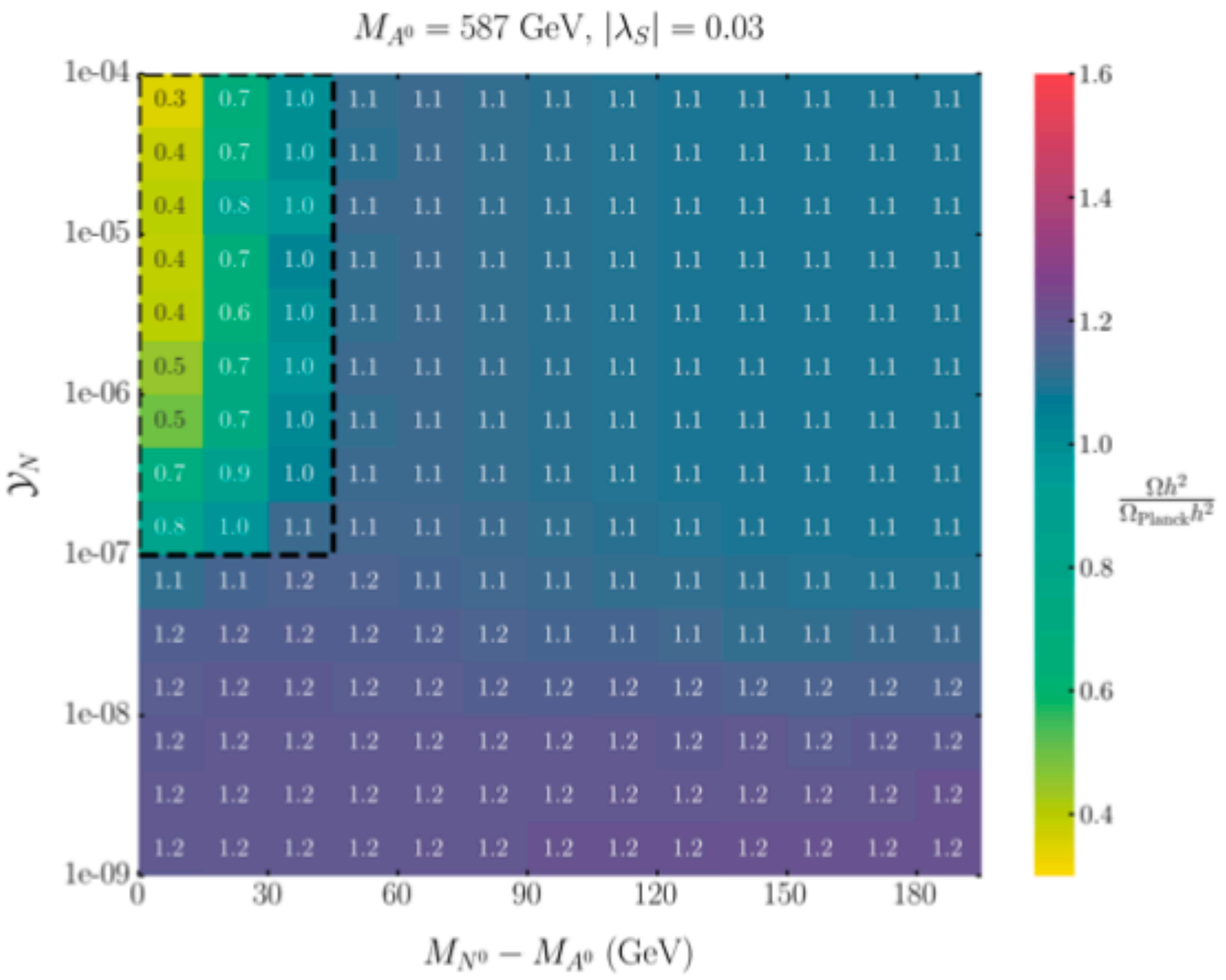
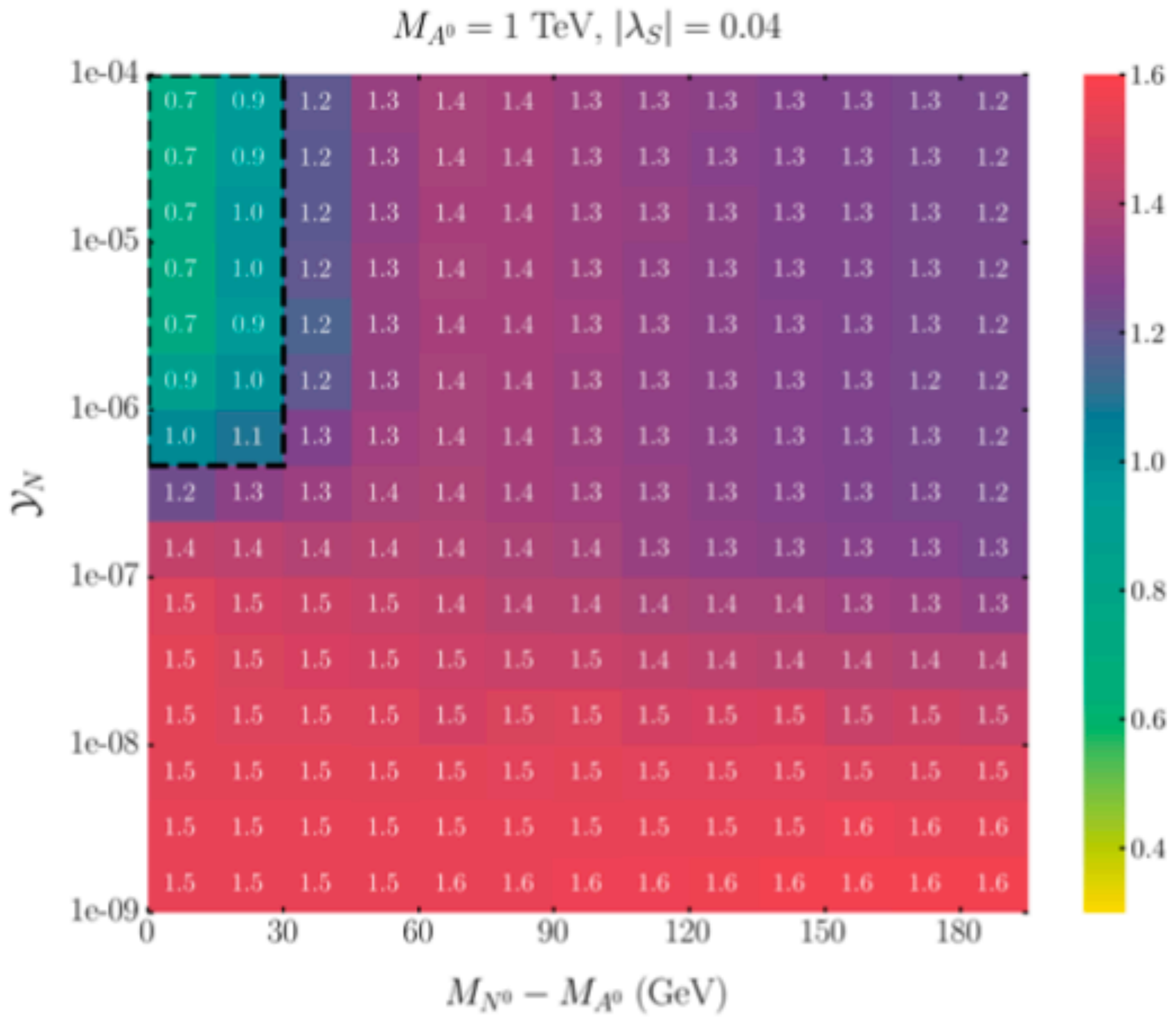
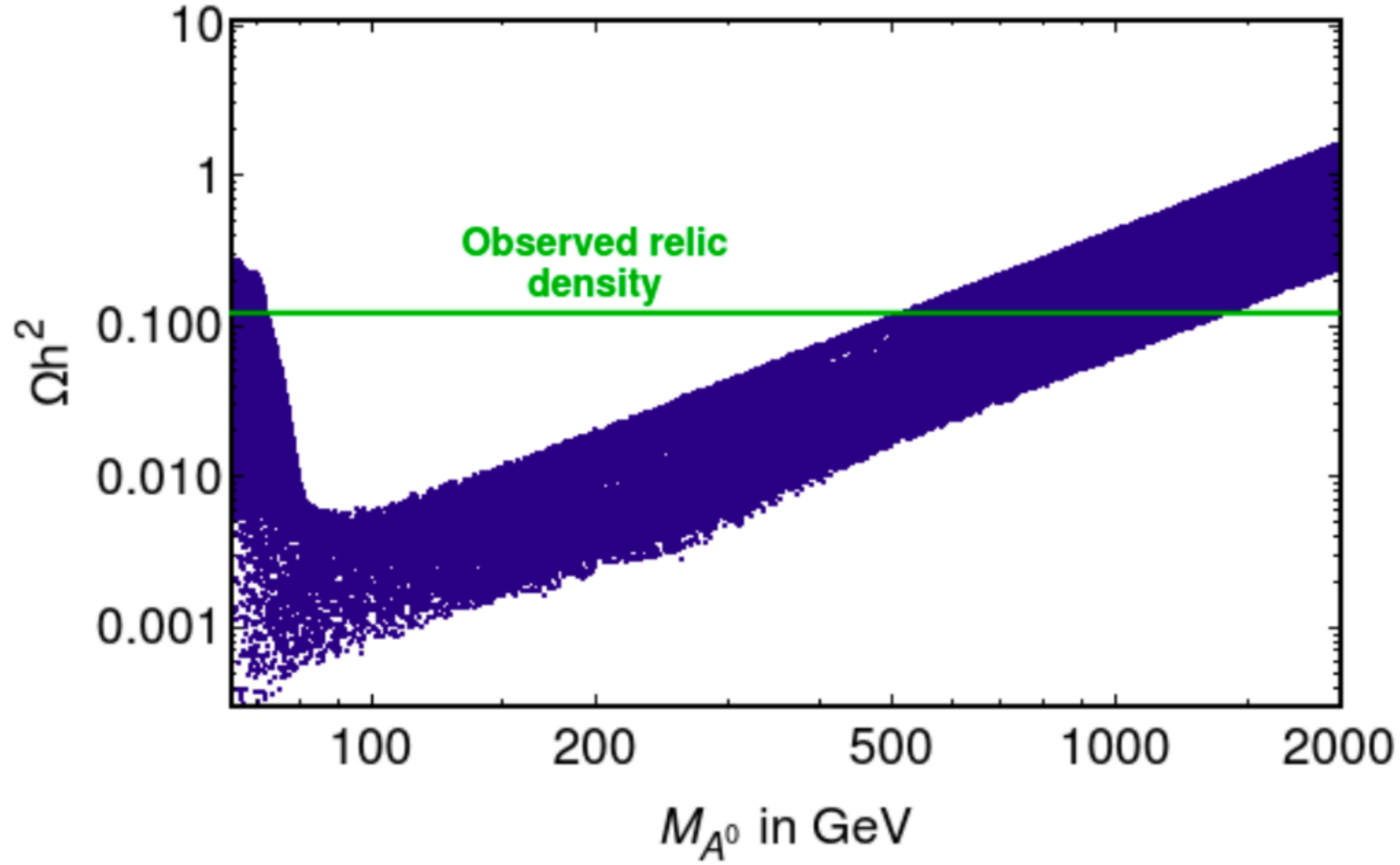
Correlation of mass gap and Yukawa coupling





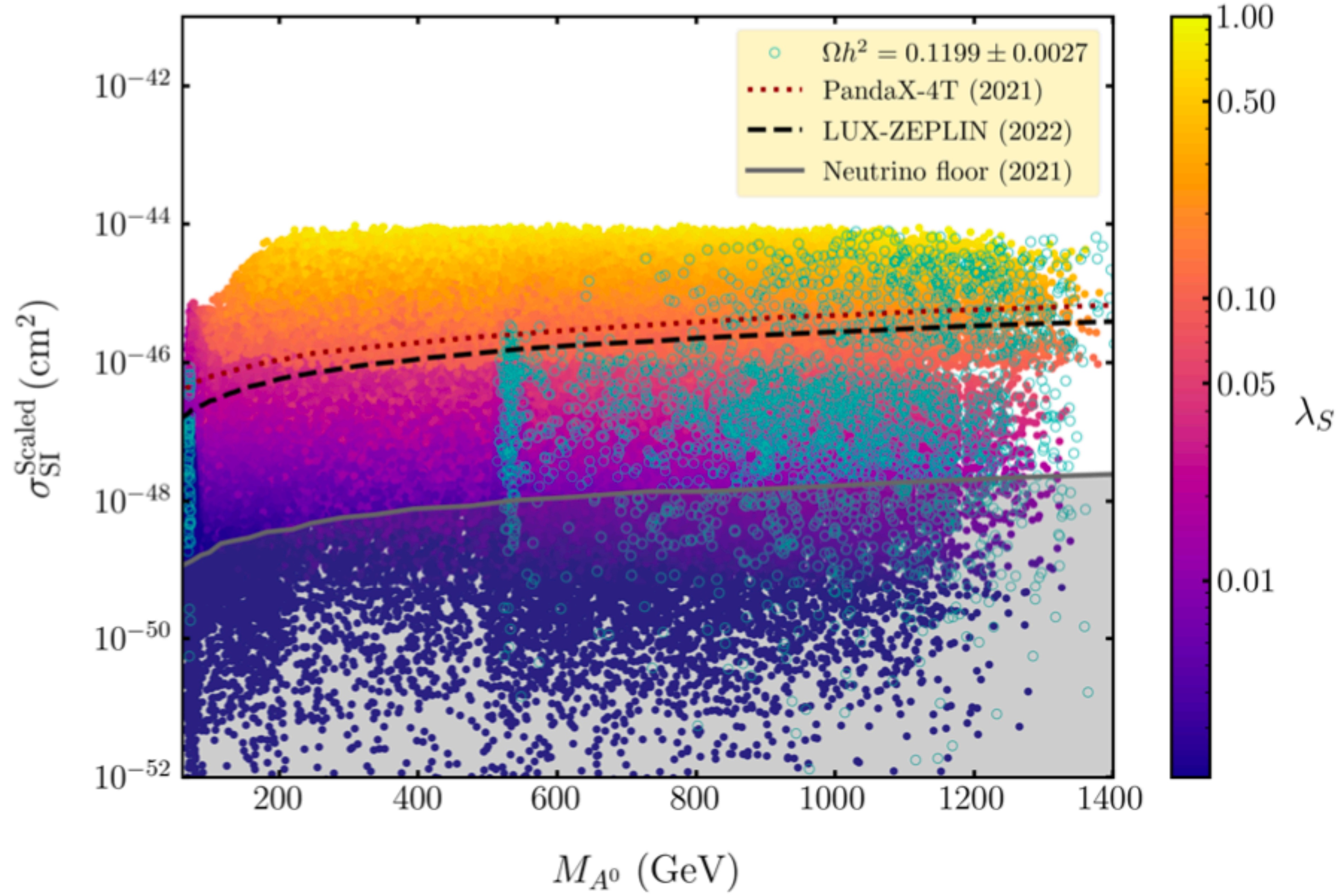
- Lower Yukawa couplings: less co-annihilation and corresponds to very late dacay of N
- Higher mass splitting: Less phase space for co-annihilation, and leads to overabundance of dark matter number density
- Higher dark matter mass: Lesser annihilation of DM, needs more compressed spectrum and larger Yukawa for the correct DM relic

Dark matter relic and the interplay



- The observed relic is $\Omega h^2 = 0.1199 \pm 0.0027$
- The lower region around $M_{A^0} \sim 70\,\mathrm{GeV}$ due to the s-channel annihilation via Higgs boson
- $M_{A^0} > 1.4\,\mathrm{TeV}$ is ruled out due to over abundance

Direct Dark matter Detection



- The direct detection can only happen via the Higgs portal coupling $\lambda_S = \lambda_3 + \lambda_4 - 2\lambda_5$

$$\sigma_{\rm SI} \simeq \frac{\lambda_S^2 f_n^2}{4\pi M_h^4} \frac{M_n^4}{(M_n + M_{A^0})^2},$$

- The most stringent upper bound comes from the LUX-ZEPLIN experiment, which excludes $|\lambda_S| \geq 0.5 \text{ for } M_{A^0} > 500 \text{ GeV}$
- $|\lambda_S| \leq 0.01$ Is excluded from the neutrino floor bound

Dark matter Indirect Detection

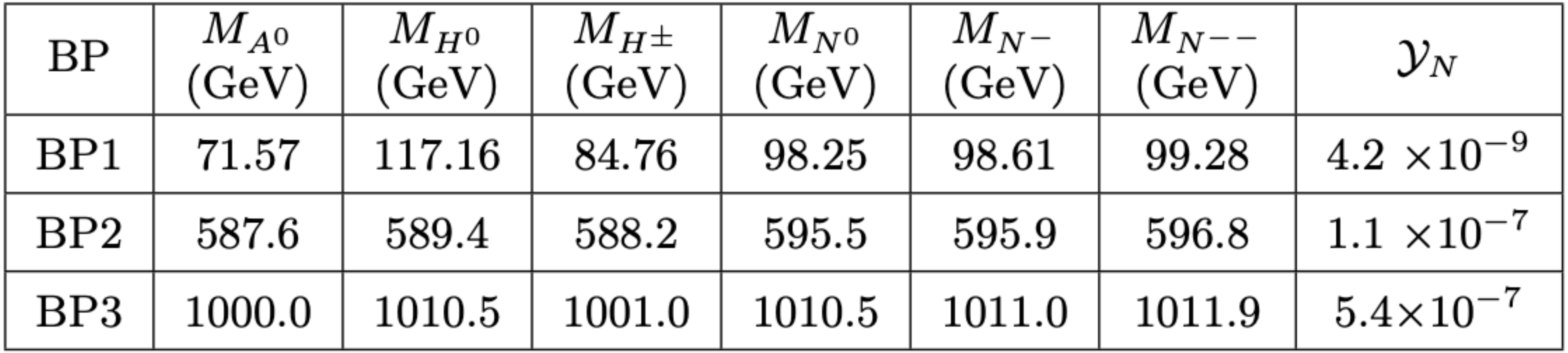
- The dominant annihilation moose of A^0 is $W^{\pm}W^{\mp}, ZZ$

- The Fermi-Lat and HESS detects energetic photons which put bounds won the annihilation cross-section

H.E.S.S. collaboration, Phys. Rev. Lett. 129 (2022) 111101

MAGIC, Fermi-LAT collaboration, JCAP 02 (2016) 039

Benchmark Points



BP	M_{A^0} (GeV)	M_{H^0} (GeV)	$M_{H^\pm}$ (GeV)	M_{N^0} (GeV)	M_{N^-} (GeV)	$M_{N^{--}}$ (GeV)	$\mathcal{Y}_N$
BP1	71.57	117.16	84.76	98.25	98.61	99.28	4.2×10^{-9}
BP2	587.6	589.4	588.2	595.5	595.9	596.8	1.1×10^{-7}
BP3	1000.0	1010.5	1001.0	1010.5	1011.0	1011.9	5.4×10^{-7}

- All the benchmark points satisfy the dark matter relic, direct and indirect bounds
- All the benchmark points have displaced vertex signature.

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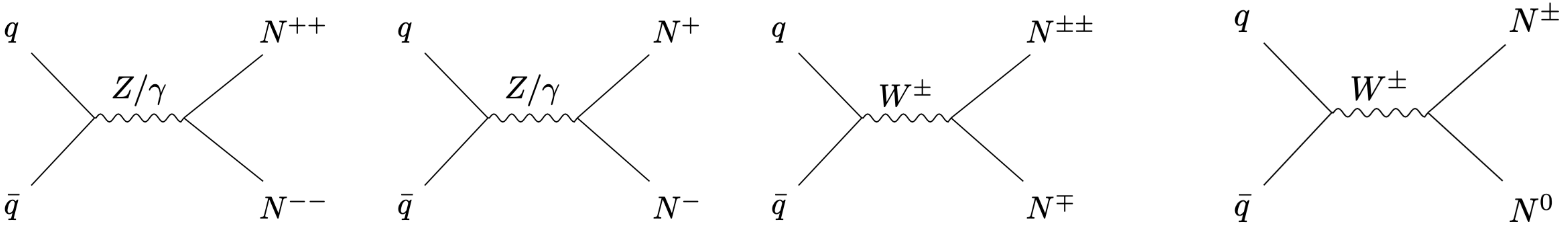
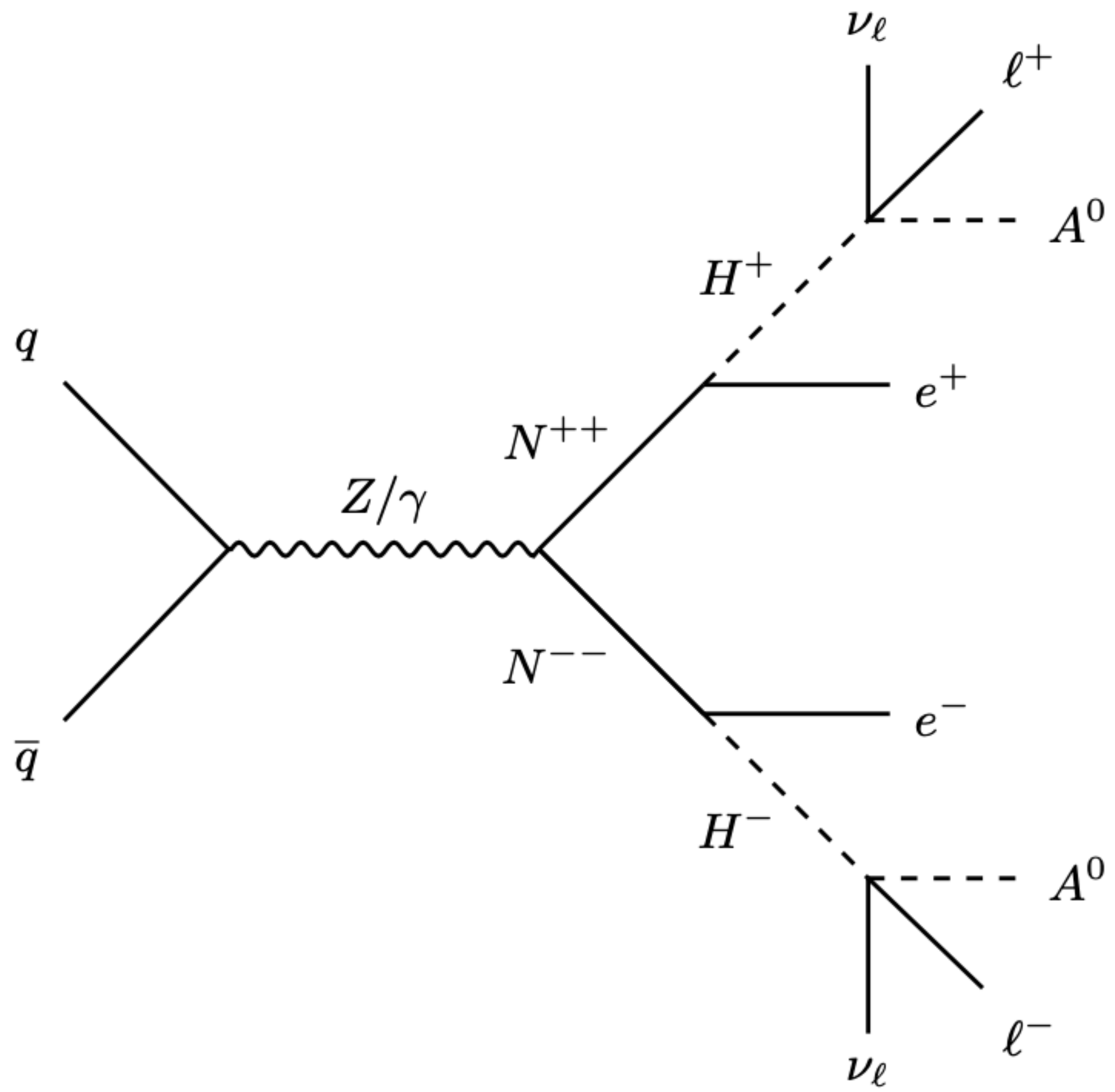
Collider signature

- $pp \to N^{\pm\pm}N^{\mp\mp}, N^{\pm}N^{\mp}, N^{\pm\pm}N^{\mp}, N^{\pm}N^{0}$ are looked into at the LHC and FCC-hh



- Typically hadronically quet displaced multi-leptonic $(1\ell - 6\ell)$ signature can be achieved. However, we present the numbers only till 4ℓ

- Pair production of doubly charged VLL can lead to 4 displaced leptons for small Yukawa couplings and compressed mass spectrum



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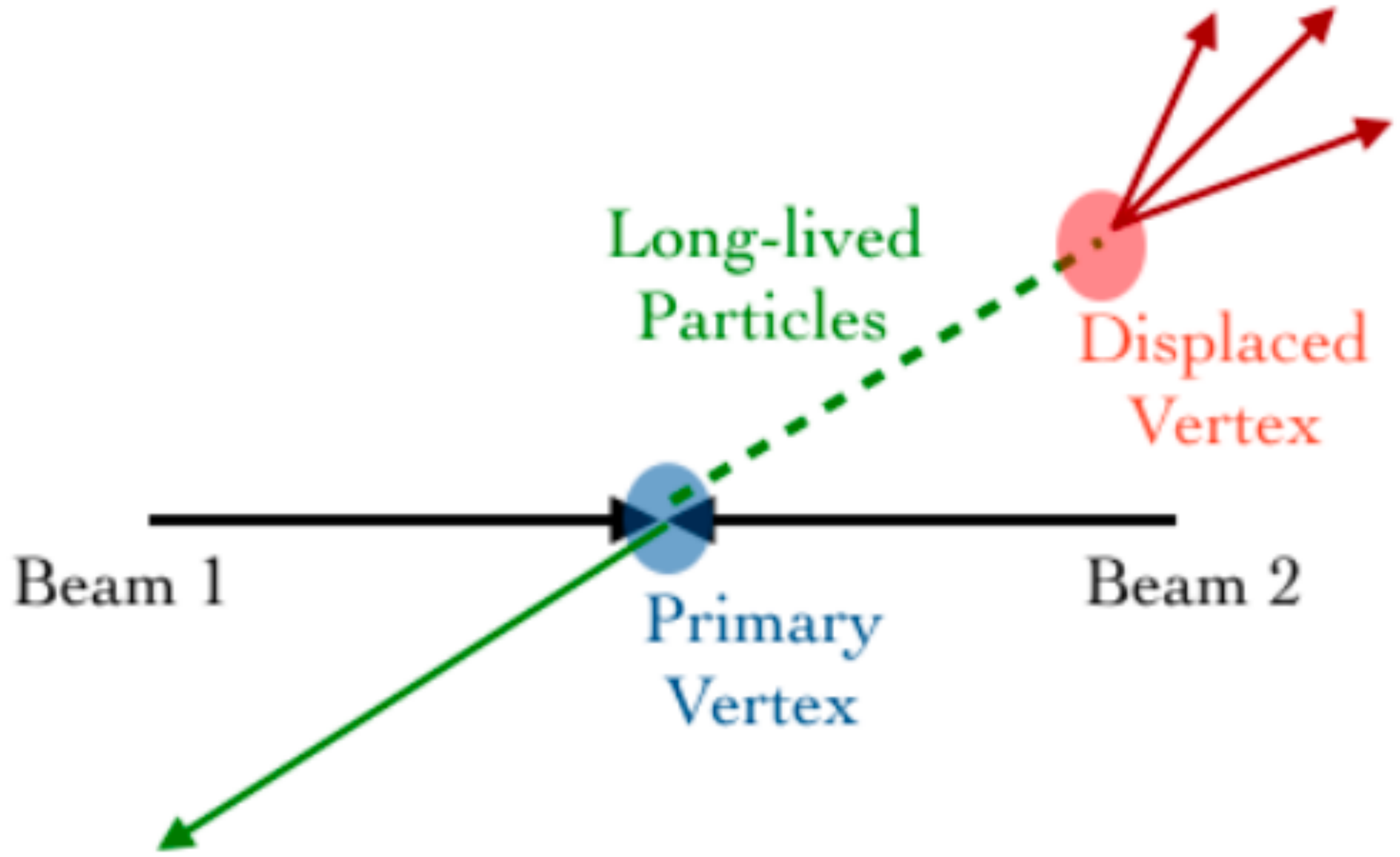
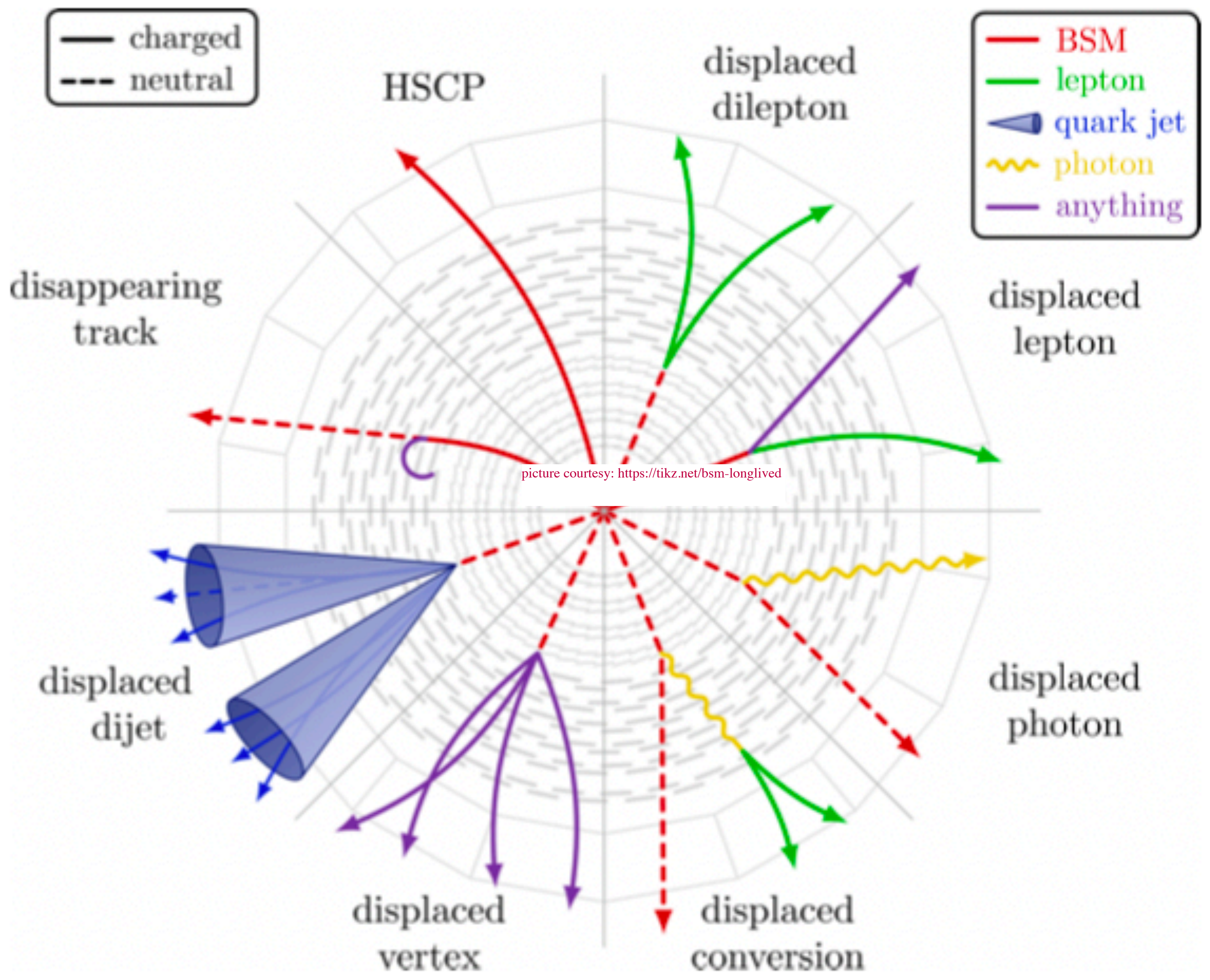
Dispalced decays



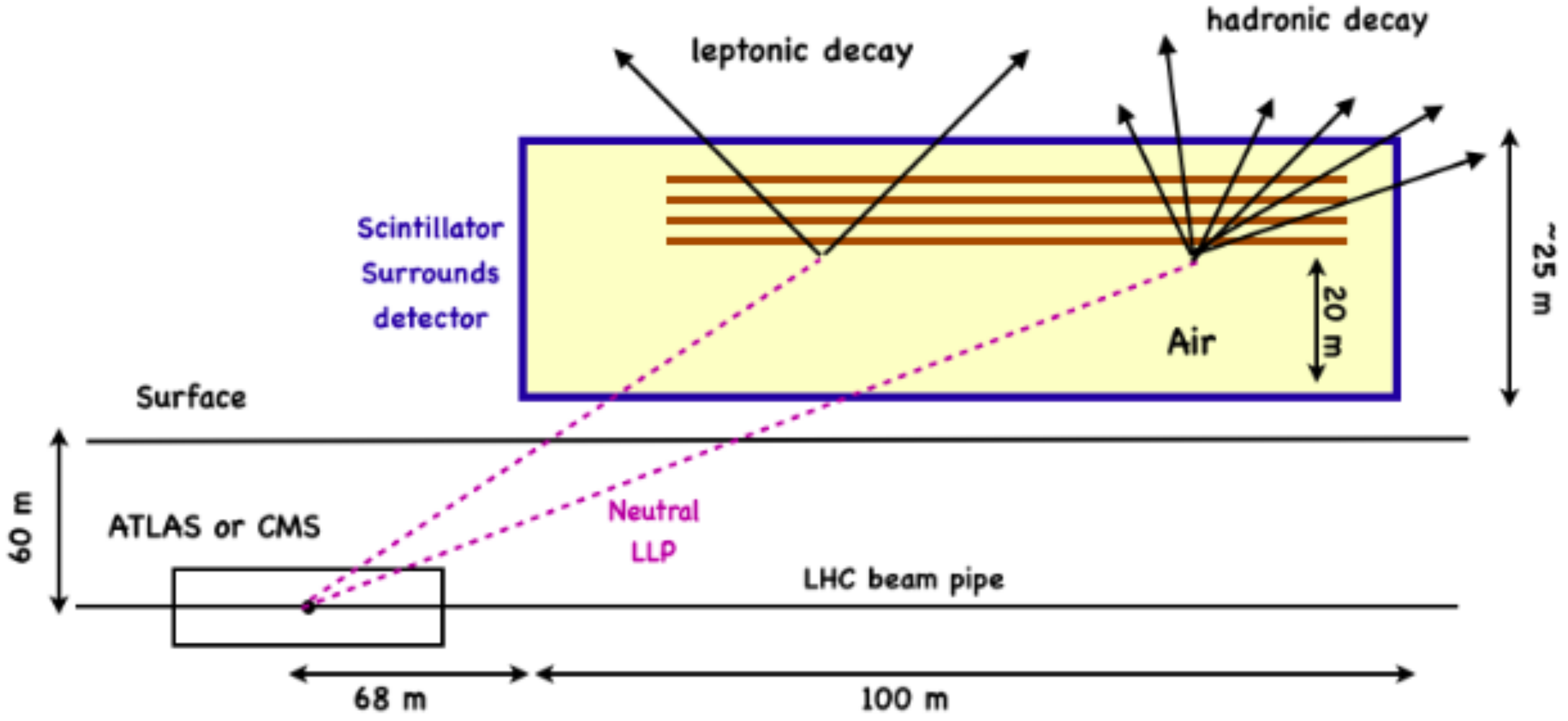


picture courtesy: https://tikz.net/bsm-longlived

- The decay width $\Gamma = \dfrac{1}{\tau} \sim g^2 |\mathscr{M}|^2 \Phi$, which can be small due to

1. Small coupling g
2. Heavy intermediary particle or cancellation in matrix element
3. Llow phase space due to compressed spectrum

MATHUSLA Detecor



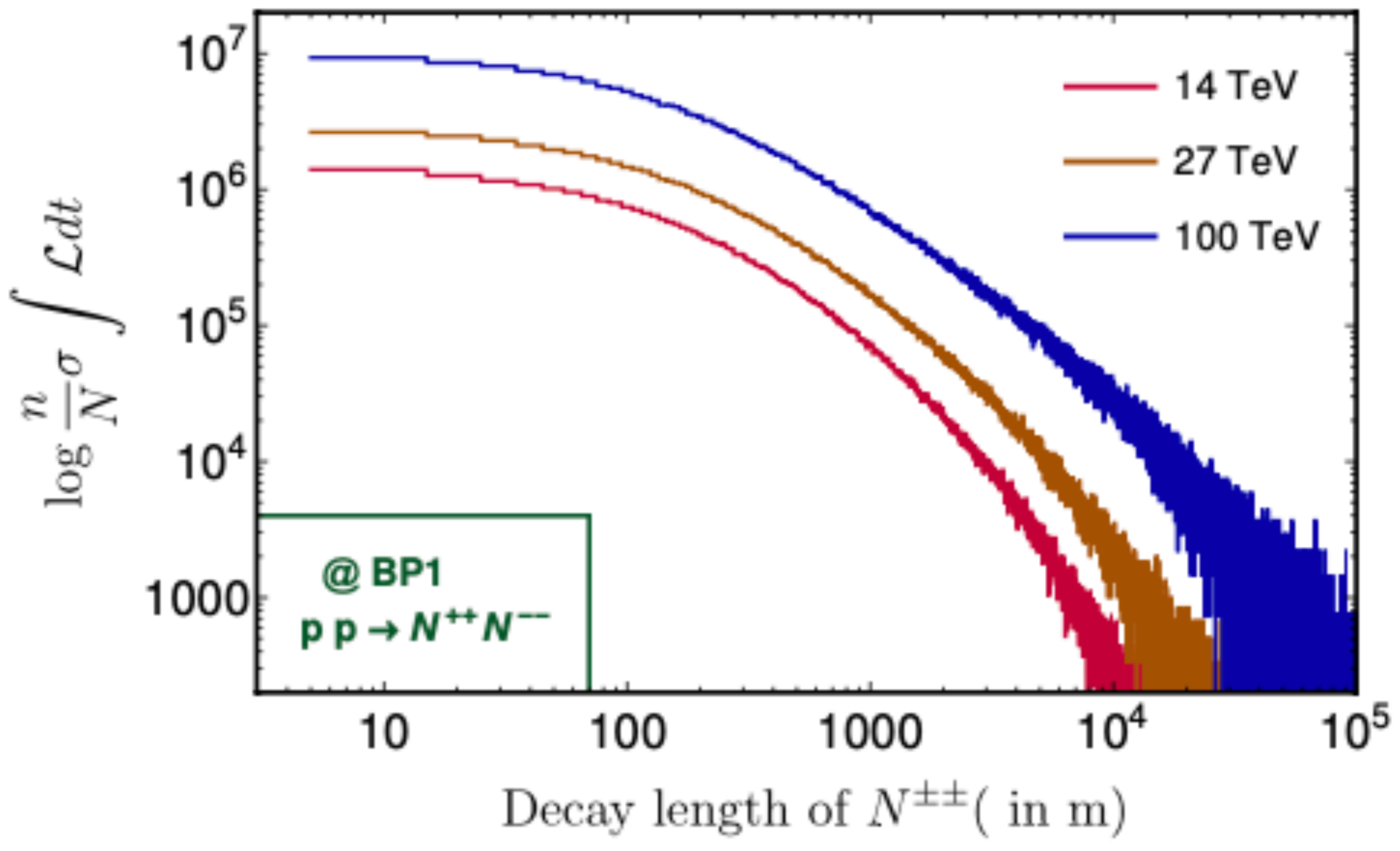
- MATHUSLA is proposed to be built 68 meters from the CMS interaction point in the longitudinal direction, 60 meters in the transverse direction.
- MATHUSLA should be able to search for the long-lived particles with near-zero backgrounds
- MATHUSAL geometry: $25 \times 100 \times 100\,\mathrm{m}^3$

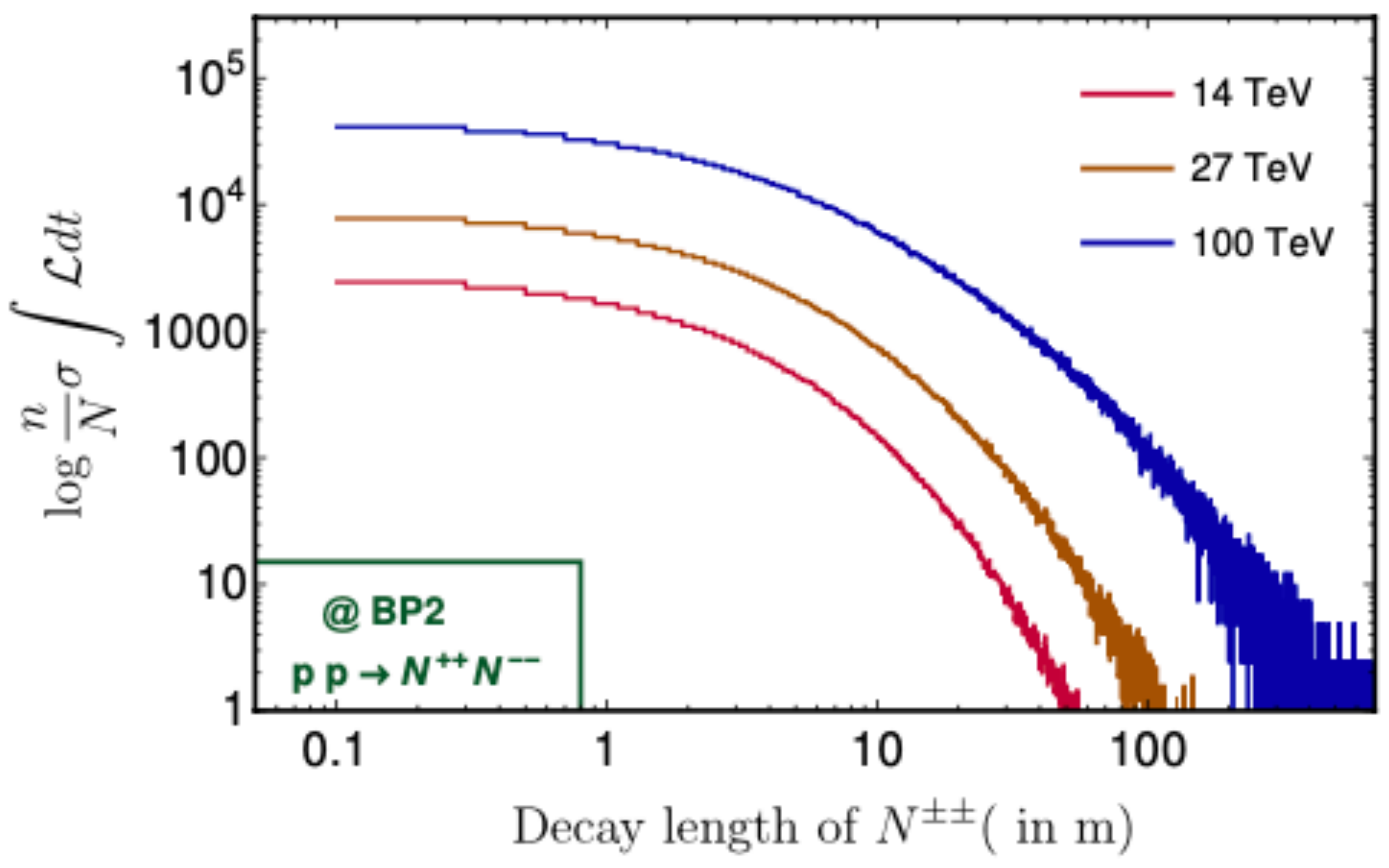
Displaced decay of $N^{\pm\pm}$

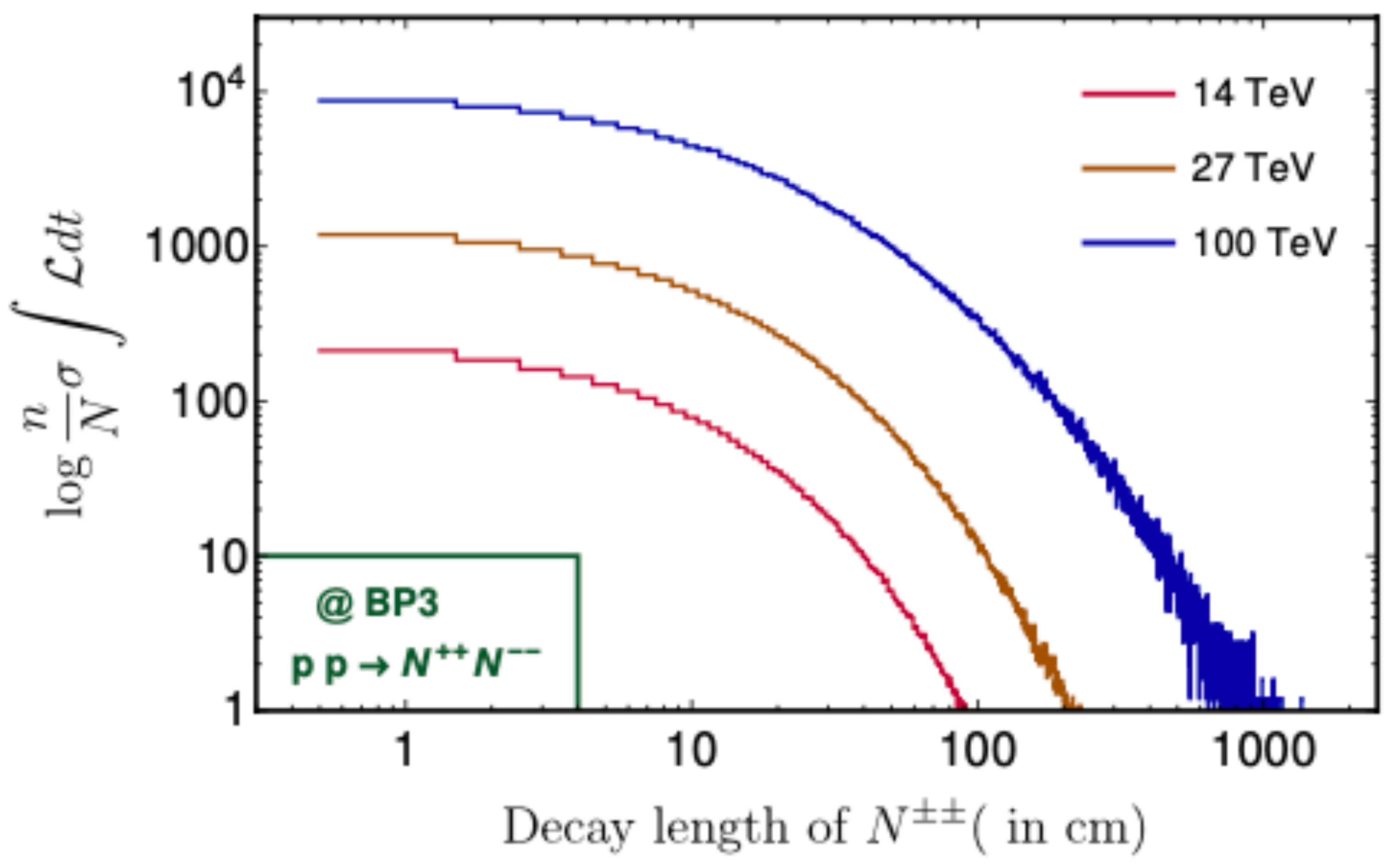
- The decay widths and the rest mass decay lengths of $N^{\pm\pm}$

	BP1 $\mathcal{Y}_N = 4.2 \times 10^{-9}$		BP2 $\mathcal{Y}_N = 1.1 \times 10^{-7}$		BP3 $\mathcal{Y}_N = 5.4 \times 10^{-7}$	
$N^{\pm\pm}$	Γ_{tot} (GeV)	$c\tau_0$ (m)	Γ_{tot} (GeV)	$c\tau_0$ (m)	Γ_{tot} (GeV)	$c\tau_0$ (m)
	1.27×10^{-18}	155.42	5.92×10^{-17}	3.33	1.34×10^{-15}	0.15

- The decay length distributions including the boost effect







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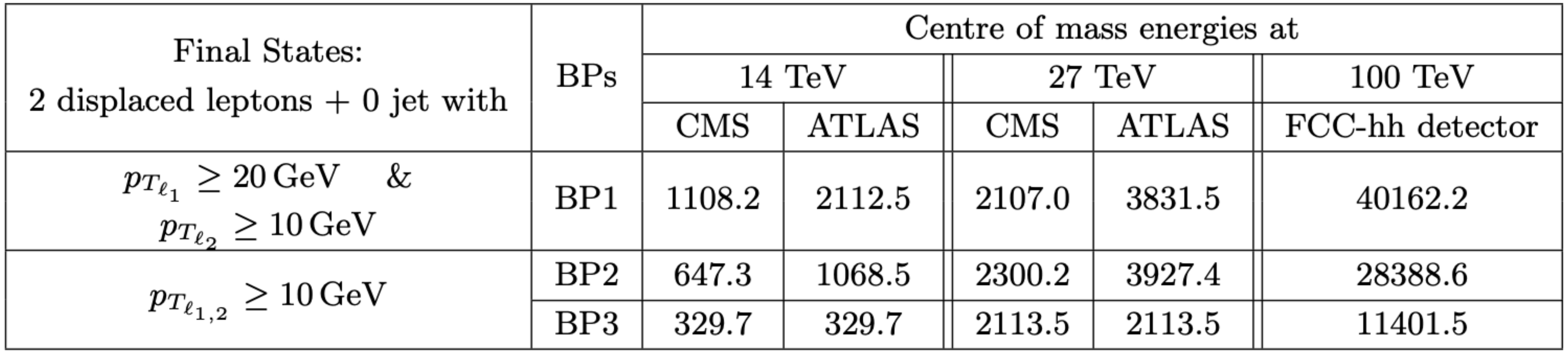
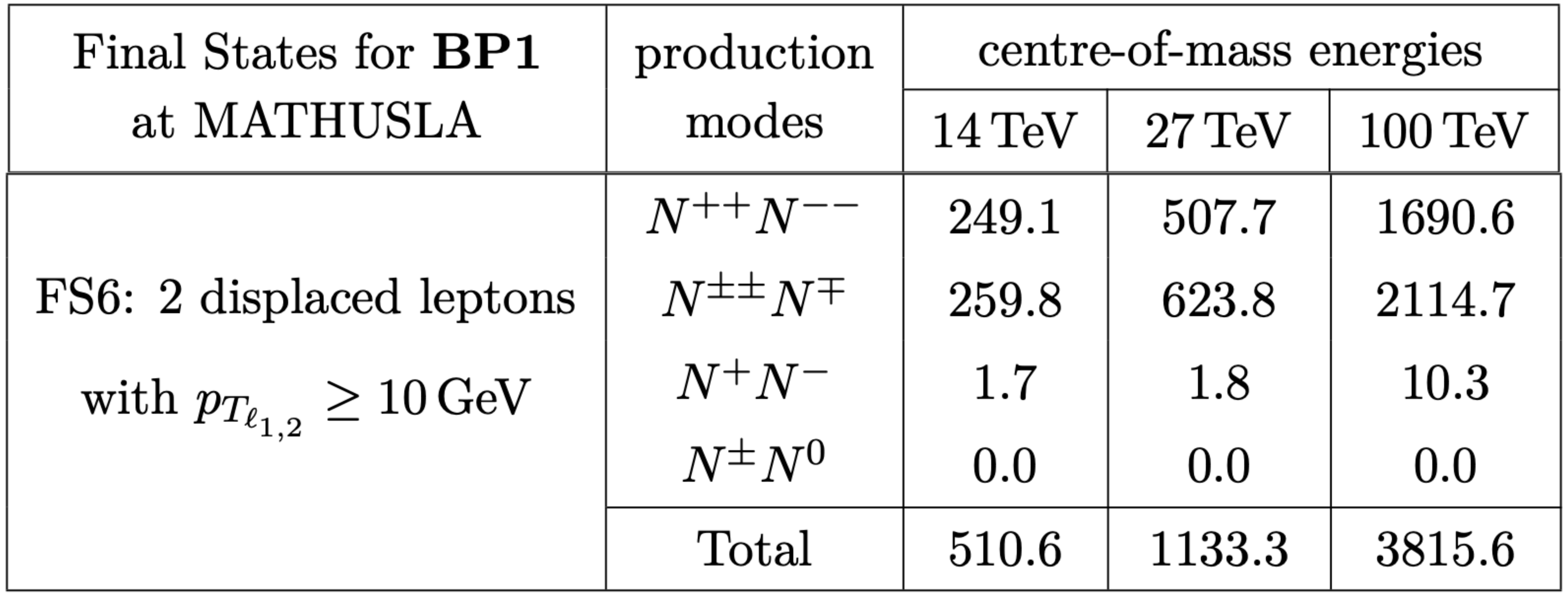
Numbers for 2 displaced leptons

- A typical comparison can be made for the two displaced leptons inside CMS, ATLAS for different centre of mass energies at 300 fb^{-1} luminosity



Final States: 2 displaced leptons + 0 jet with	BPs	Centre of mass energies at				
		14 TeV		27 TeV		100 TeV
		CMS	ATLAS	CMS	ATLAS	FCC-hh detector
$p_{T_{\ell_1}} \geq 20\,\mathrm{GeV}$ & $p_{T_{\ell_2}} \geq 10\,\mathrm{GeV}$	BP1	1108.2	2112.5	2107.0	3831.5	40162.2
$p_{T_{\ell_{1,2}}} \geq 10\,\mathrm{GeV}$	BP2	647.3	1068.5	2300.2	3927.4	28388.6
	BP3	329.7	329.7	2113.5	2113.5	11401.5

- The events inside MATHUSLA is possible only for BP1 and at 300 fb^{-1} luminosity the numbers are



Final States for **BP1** at MATHUSLA	production modes	centre-of-mass energies		
		14 TeV	27 TeV	100 TeV
FS6: 2 displaced leptons with $p_{T_{\ell_{1,2}}} \geq 10\,\mathrm{GeV}$	$N^{++}N^{--}$	249.1	507.7	1690.6
	$N^{\pm\pm}N^{\mp}$	259.8	623.8	2114.7
	$N^{+}N^{-}$	1.7	1.8	10.3
	$N^{\pm}N^{0}$	0.0	0.0	0.0
	Total	510.6	1133.3	3815.6

Conclusions

- Dispalced decays can be used as non-standard searches to probe New physics scenarios
- Dispalce decay of neutral fermions and charged fermions in the case of Type-III or VLL can probe the models for the unexplored territory
- Lower Yukawa coupling and complressed spectrum can alter the DM phenomenology
- $\mathcal{O}(100)$ m decay lengths can be probed inside MATHUSLA detector
- Double recoil: $N^{\pm} \to N^0\pi(\sim \text{cm}) \to h\nu\pi(\sim \text{1-00 m})$ can be probed along with a displaced Higgs production
- A doubly charged displaced lepton charged track and its decay can be searched for


THANK
YOU!