Feasibility to probe the dynamical scotogenic model at the LHC

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Neutrino and Dark Matter conference at Institut Henri Poincaré, Paris

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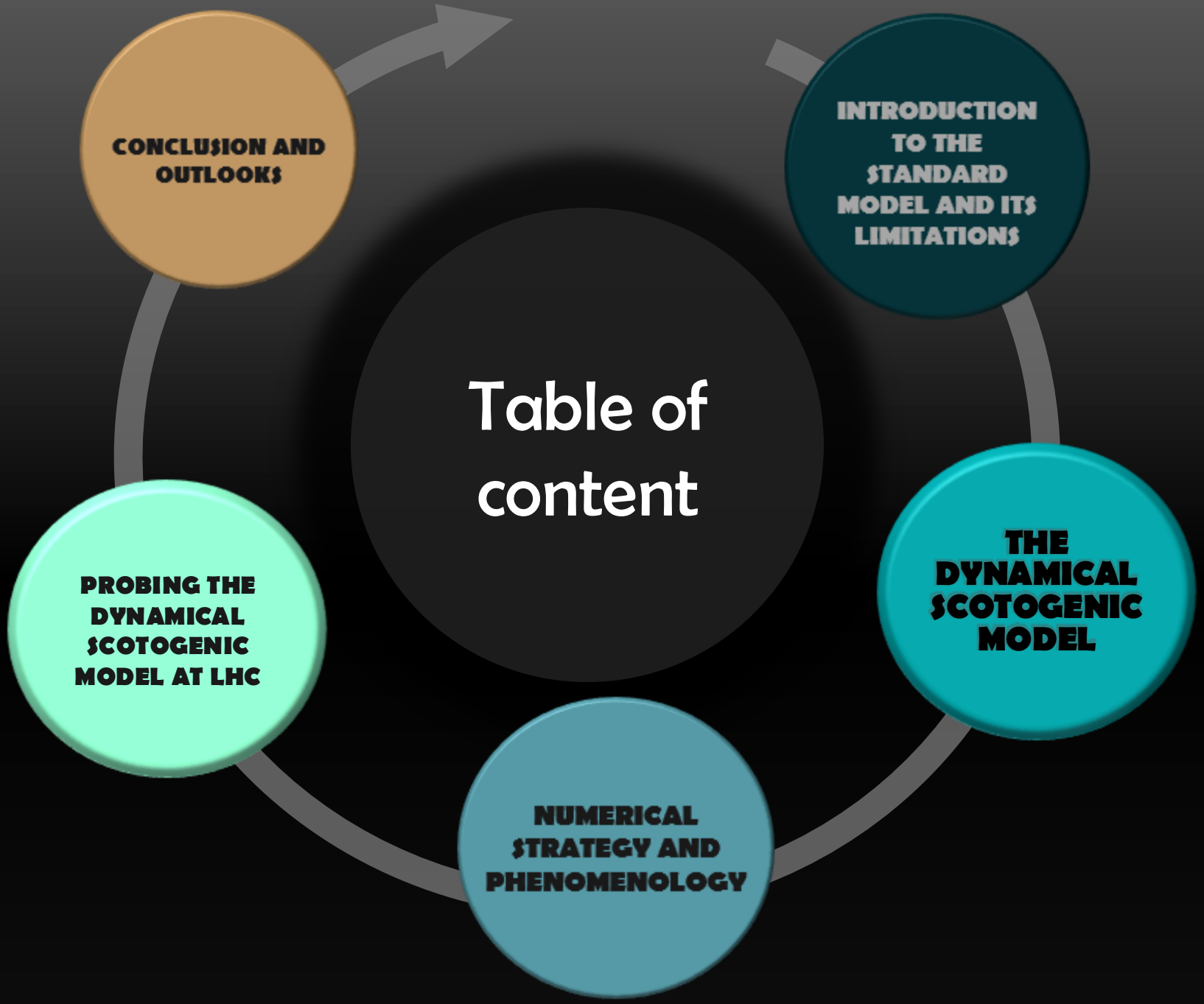


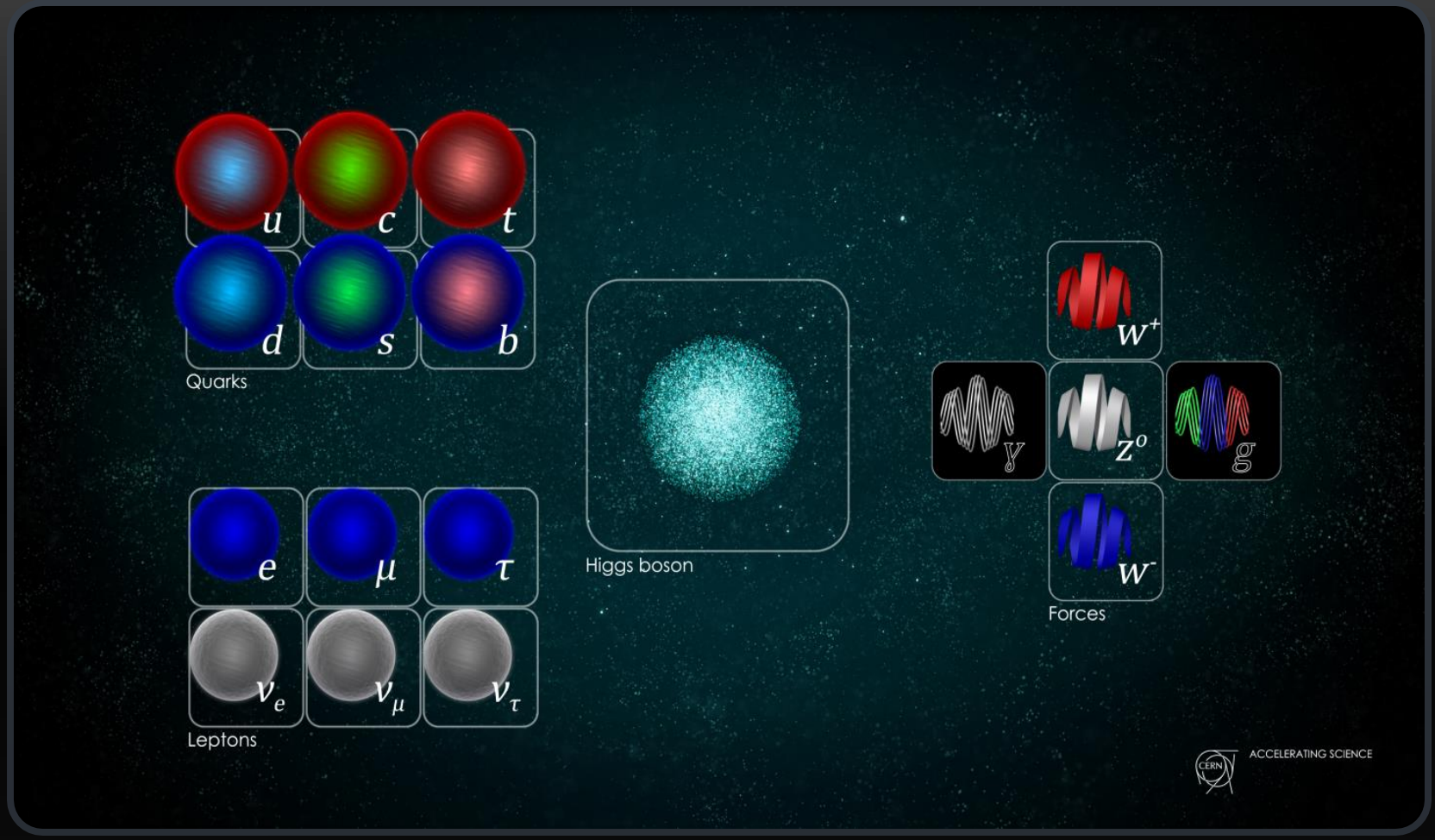
INTRODUCTION TO THE STANDARD MODEL AND ITS LIMITATIONS

INTRODUCTION TO THE STANDARD MODEL AND ITS LIMITATIONS

The SM is a theory that proved itself reliable with the numerous predictions it made.

Indeed, there are still open questions such as:

- Hierarchy problem
- Matter antimatter asymmetry
- Neutrino masses
- Dark matter
- Gravity
- Etc



HOW CAN WE GENERATE NEUTRINO MASSES?

HOW TO PROVIDE A VIABLE CANDIDATE FOR DM?

CAN WE PROBE IT AT THE LHC?

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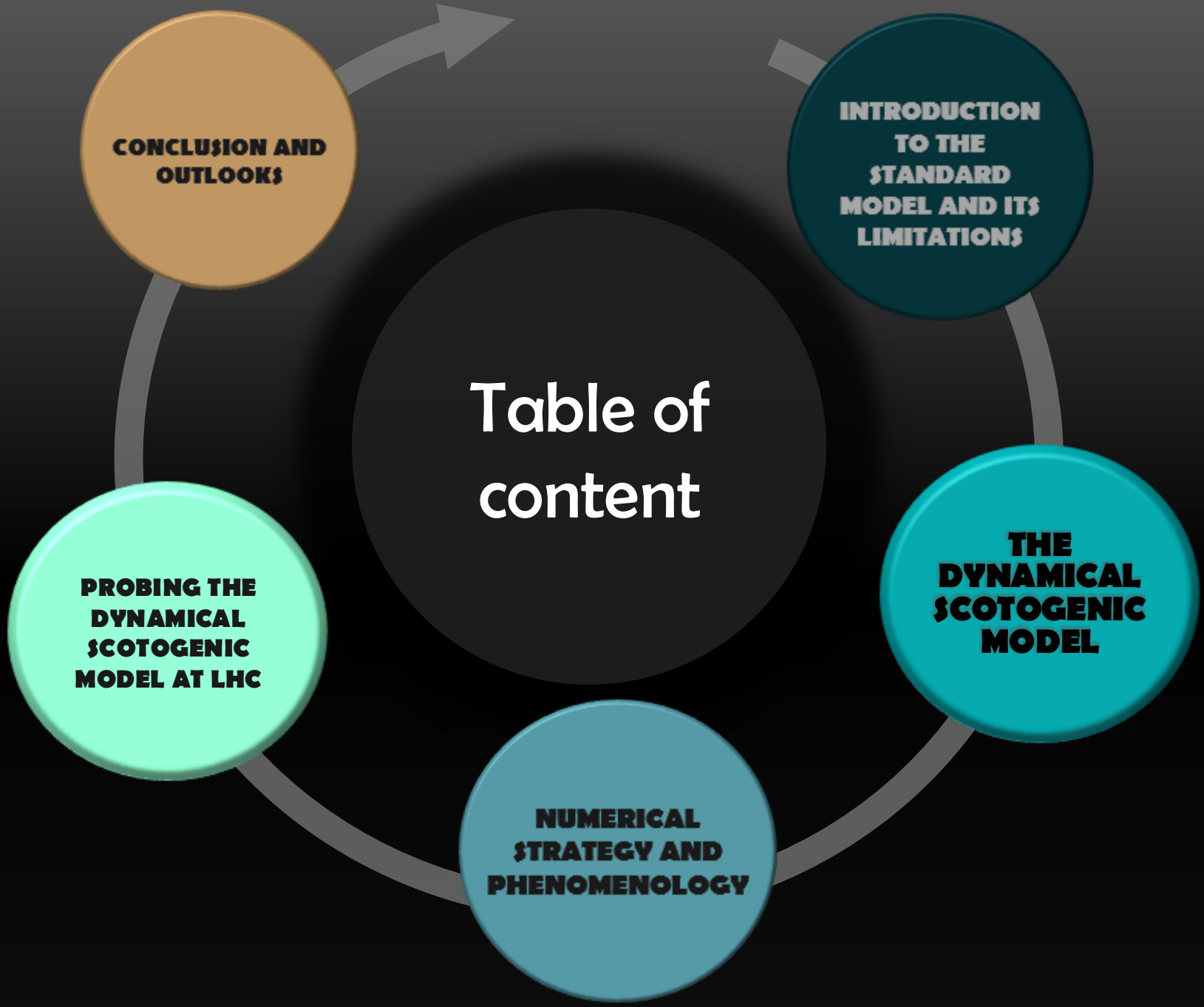


THE DYNAMICAL SCOTOGENIC MODEL

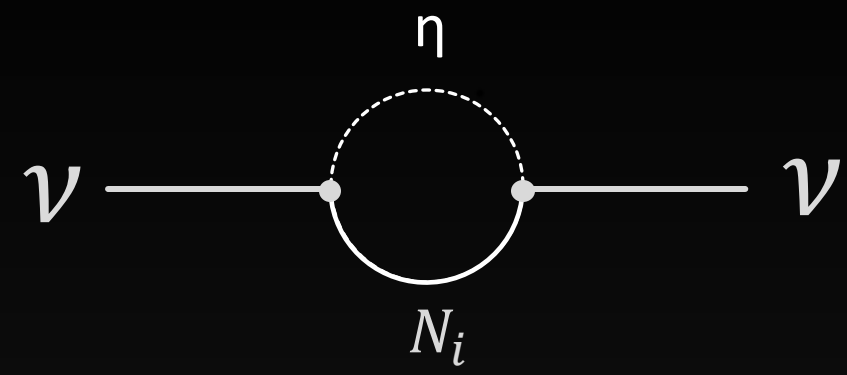
SCOTOGENIC MODELS

MA MODEL

Scotogenic = *scoto* + *genic*

Dark Generate

- The first scotogenic model was developed by Ernest Ma [E.Ma Phys. Rev. D 73 (2006)]
- SM extended by 3 Majorana fermions N_i + 1 scalar field η
- Generate neutrino masses at one loop + provide viable candidate for DM
- A classification of scotogenic models can be found in Restrepo, Zapata and Yaguna paper [JHEP 11 (2013)]



THE DYNAMICAL SCOTOGENIC MODEL

Ref for this model:
[arXiv:1908.04276]
[arXiv:2210.07706]

	ℓ	e_R	N	H	σ	η
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**2**
$U(1)_Y$	$-\frac{1}{2}$	-1	0	$\frac{1}{2}$	0	$\frac{1}{2}$
$U(1)_L$	1	1	1	0	-2	0
$\mathbb{Z}_2$	1	1	-1	1	1	-1

$$H = \begin{pmatrix} H^+ \\ \frac{S_H + iA_h + v}{\sqrt{2}} \end{pmatrix}$$

The $\mathbb{Z}_2$ symmetry is imposed to prevent the DM to decay.

Note that a new $\mathbb{Z}_2$-even scalar is added.

Fermions:

- 3 Majorana fermions N_i

Scalars:

- One doublet η
- One singlet σ

$$\eta = \begin{pmatrix} \eta^+ \\ \frac{\eta_R^0 + i\eta_I^0}{\sqrt{2}} \end{pmatrix}$$

$$\sigma = \frac{1}{\sqrt{2}}(S_\sigma + iA_\sigma + v_\sigma)$$

SCALAR SECTOR

$$\mathcal{V} = m_H^2 H^\dagger H + m_\eta^2 \eta^\dagger \eta + m_\sigma^2 \sigma^\dagger \sigma + \frac{\lambda_1}{2}(H^\dagger H)^2$$
$$+\frac{\lambda_2}{2}(\eta^\dagger \eta)^2 + \frac{\lambda_\sigma}{2}(\sigma^\dagger \sigma)^2 + \lambda_3 (H^\dagger H)(\eta^\dagger \eta) + \lambda_3^{H\sigma}(H^\dagger H)(\sigma^\dagger \sigma)$$
$$+\lambda_3^{\eta\sigma}(\eta^\dagger \eta)(\sigma^\dagger \sigma) + \lambda_4 (H^\dagger \eta)(\eta^\dagger H) + \frac{\lambda_5}{2}[(H^\dagger \eta)^2 + (\eta^\dagger H)^2]$$

$$H = \begin{pmatrix} H^+ \\ \frac{S_H + iA_h + v}{\sqrt{2}} \end{pmatrix} \qquad \eta = \begin{pmatrix} \eta^+ \\ \frac{\eta_R^0 + i\eta_I^0}{\sqrt{2}} \end{pmatrix} \qquad \sigma = \frac{1}{\sqrt{2}}(S_\sigma + iA_\sigma + v_\sigma)$$

SCALAR SECTOR

$$\mathcal{V} = m_H^2 H^\dagger H + m_\eta^2 \eta^\dagger \eta + m_\sigma^2 \sigma^\dagger \sigma + \frac{\lambda_1}{2}(H^\dagger H)^2 + \frac{\lambda_2}{2}(\eta^\dagger \eta)^2 + \frac{\lambda_\sigma}{2}(\sigma^\dagger \sigma)^2 + \lambda_3 (H^\dagger H)(\eta^\dagger \eta) + \lambda_3^{H\sigma}(H^\dagger H)(\sigma^\dagger \sigma)$$
$$+\lambda_3^{\eta\sigma}(\eta^\dagger \eta)(\sigma^\dagger \sigma) + \lambda_4 (H^\dagger \eta)(\eta^\dagger H) + \frac{\lambda_5}{2}[(H^\dagger \eta)^2 + (\eta^\dagger H)^2]$$

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos(\alpha) & \sin(\alpha) \\ -\sin(\alpha) & \cos(\alpha) \end{pmatrix} \begin{pmatrix} S_H \\ S_\sigma \end{pmatrix}$$

$$H = \begin{pmatrix} H^+ \\ \frac{S_H + iA_h + v}{\sqrt{2}} \end{pmatrix} \quad \sigma = \frac{1}{\sqrt{2}}(S_\sigma + iA_\sigma + v_\sigma)$$

A_σ ⟶ Gives a massless Majoron J

A_h ⟶ Contributes to the SM Z boson

The scalar h_1 will be set at 125 GeV and be the SM Higgs boson.
The h_2 mass is fixed at {246, 500} GeV

SCALAR SECTOR

$$\mathcal{V} = m_H^2 H^\dagger H + m_\eta^2 \eta^\dagger \eta + m_\sigma^2 \sigma^\dagger \sigma + \frac{\lambda_1}{2}(H^\dagger H)^2 + \frac{\lambda_2}{2}(\eta^\dagger \eta)^2 + \frac{\lambda_\sigma}{2}(\sigma^\dagger \sigma)^2 + \lambda_3 (H^\dagger H)(\eta^\dagger \eta) + \lambda_3^{H\sigma}(H^\dagger H)(\sigma^\dagger \sigma)$$
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$$H = \begin{pmatrix} H^+ \\ \frac{S_H + iA_h + v}{\sqrt{2}} \end{pmatrix} \quad \sigma = \frac{1}{\sqrt{2}}(S_\sigma + iA_\sigma + v_\sigma)$$

The scalar h_1 will be set at 125 GeV and be the SM Higgs boson

Neutral scalars: $h_1\ , h_2\ , \eta_R^0$

Neutral pseudo scalar: η_I^0

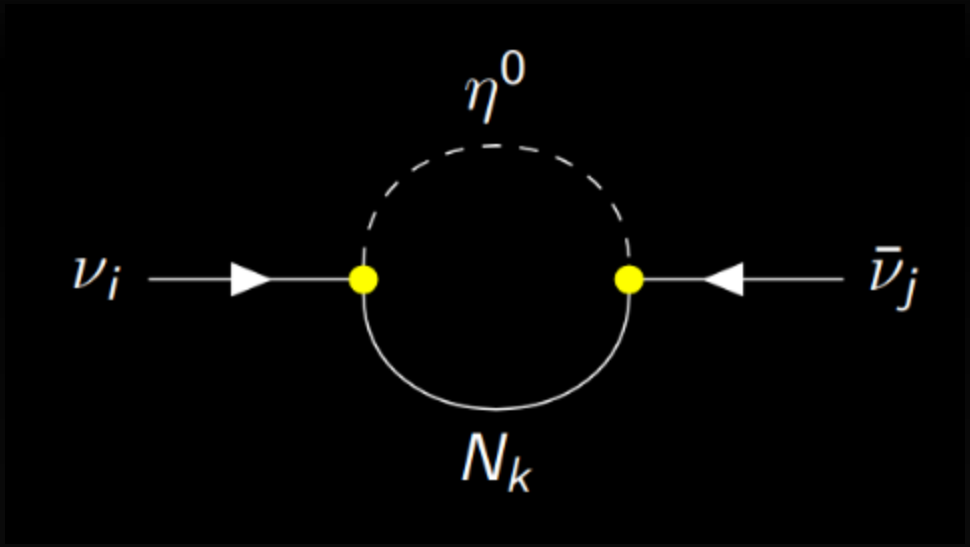
The charged scalar: $\eta^\pm$

Which means 2 possible candidates for DM: η_I^0 N_1

RADIATIVE NEUTRINO MASSES

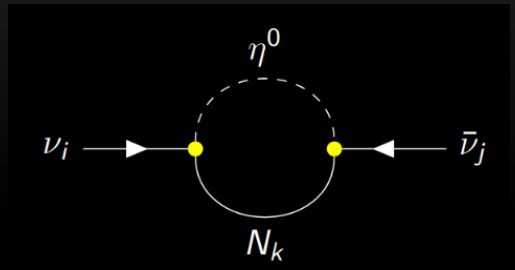
$$\mathcal{L}_F = y_{ik}\bar{\ell}_i \eta N_k + \kappa \overline{N}^c N \sigma + \text{h.c}$$

$$\eta = \begin{pmatrix} \eta^+ \\ \frac{\eta_R^0 + i\eta_I^0}{\sqrt{2}} \end{pmatrix}$$



RADIATIVE NEUTRINO MASSES AND THE CASAS-IBARRA PARAMETRIZATION

$$\mathcal{L}_F = y_{ik}\bar{\ell}_i \eta N_k + \kappa \overline{N}^c N \sigma + \text{h.c}$$



Parameters	Interval in [GeV]
Δm^2_{21}	$[7.0\,;7.84]\,.10^{-23}$
Δm^2_{31}	$[2.47\,;2.57]\,.^{10^{-21}}$

The intervals for neutrino masses are very restrictive

It will be difficult to fit the data with random values of the couplings

$$\mathcal{Y} = U_L D_M^{-1/2} R D_\nu{}^{1/2} U^*_{\text{PMNS}}.$$

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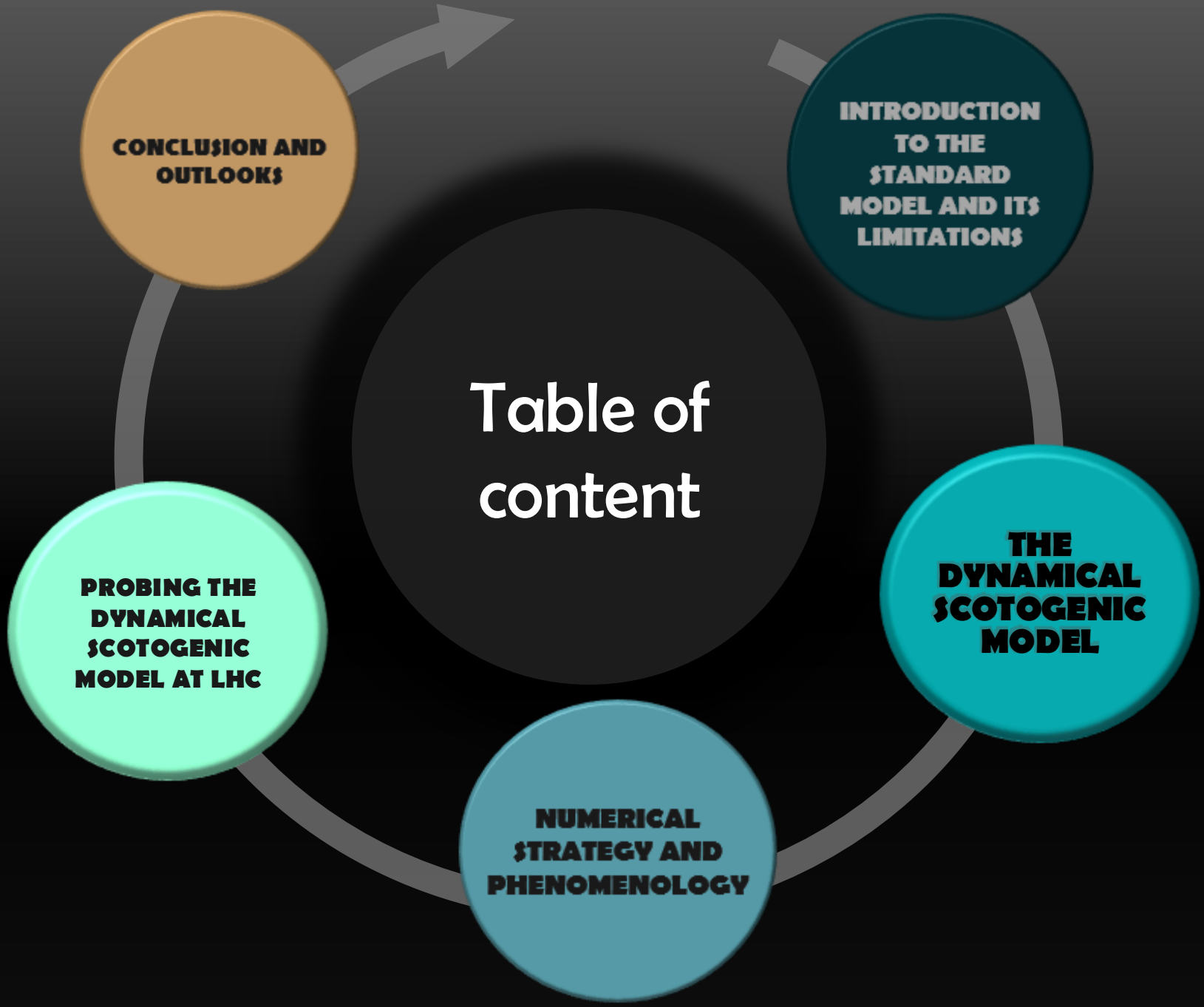


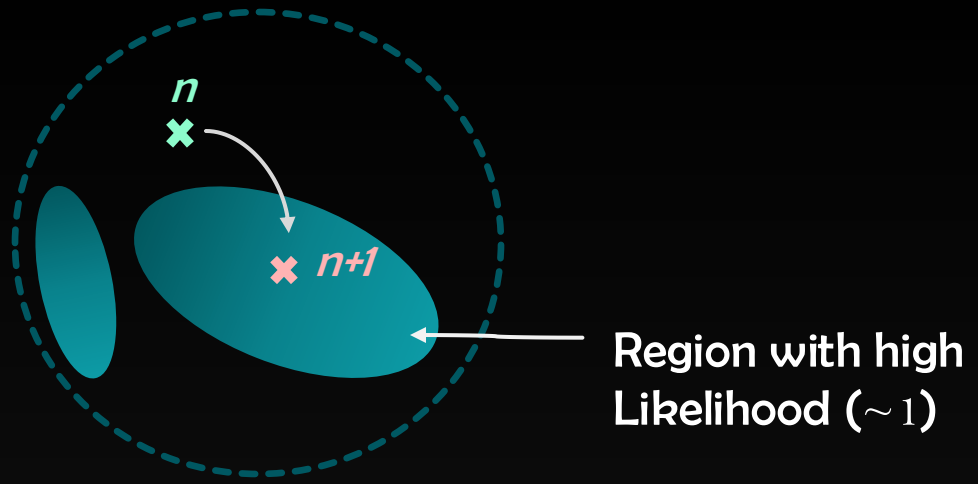
NUMERICAL STRATEGY AND PHENOMENOLOGY

NUMERICAL STRATEGY
PHENOMENOLOGY PART

- Built the model in *SARAH* [arXiv:1309.7223]
- Compute the mass spectrum and observables with *Spheno* [arXiv:1104.1573]
- Implement the model in *micrOMEGAs* [arXiv:1801.0350]
- Use a Markov Chain Monte Carlo technic to scan the viable parameter space of the model [J. Chem. Phys. 21 (1953) 1087-1092]

Likelihood $\mathcal{L}_n = \prod_i \mathcal{L}^i$

$$\log(\mathcal{L}^i) = \frac{-(\theta^i_{\text{obs}} - \theta^i_{\text{exp}})^2}{\sigma^2}$$



THE CONSTRAINTS

To compute the Likelihood we use constraints for experimental data

$$\log(\mathcal{L}^i) = \frac{-(\theta^i_{\text{obs}} - \theta^i_{\text{exp}})^2}{\sigma^2}$$

Observable	Constraint
m_H	125.1 ± 3.0 GeV
$\text{BR}(\mu^- \to e^-\gamma)$	$< 4.2 \cdot 10^{-13}$
$\text{BR}(\tau^- \to e^-\gamma)$	$< 3.3 \cdot 10^{-8}$
$\text{BR}(\tau^- \to \mu^-\gamma)$	$< 4.4 \cdot 10^{-8}$
$\text{BR}(\mu^- \to e^-e^+e^-)$	$< 1.0 \cdot 10^{-12}$
$\text{BR}(\tau^- \to e^-e^+e^-)$	$< 2.7 \cdot 10^{-8}$
$\text{BR}(\tau^- \to \mu^-\mu^+\mu^-)$	$< 2.1 \cdot 10^{-8}$
$\text{BR}(\tau^- \to \mu^+e^-e^-)$	$< 1.5 \cdot 10^{-8}$
$\text{BR}(\tau^- \to \mu^-e^+e^-)$	$< 2.1 \cdot 10^{-8}$
$\text{BR}(\tau^- \to e^+\mu^-\mu^-)$	$< 1.7 \cdot 10^{-8}$
$\text{BR}(\tau^- \to e^-\mu^+\mu^-)$	$< 2.7 \cdot 10^{-8}$
$\text{CR}_{\mu\to e}(\text{Ti})$	$< 4.3 \cdot 10^{-12}$
$\text{CR}_{\mu\to e}(\text{Pb})$	$< 4.6 \cdot 10^{-11}$
$\text{CR}_{\mu\to e}(\text{Au})$	$< 7.0 \cdot 10^{-13}$

Observable	Constraint
$\text{BR}(\tau^- \to e^-\eta\ )$	$< 9.2 \times 10^{-8}$
$\text{BR}(\tau^- \to e^-\eta'\ )$	$< 1.6 \times 10^{-7}$
$\text{BR}(\tau^- \to \mu^-\pi\ )$	$< 1.1 \times 10^{-7}$
$\text{BR}(\tau^- \to \mu^-\eta\ )$	$< 6.5 \times 10^{-8}$
$\text{BR}(\tau^- \to \mu^-\eta'\ )$	$< 1.3 \times 10^{-7}$
$\text{BR}(Z^0 \to e^\pm\mu^\mp\ )$	$< 7.5 \times 10^{-7}$
$\text{BR}(Z^0 \to e^\pm\tau^\mp\ )$	$< 5.0 \times 10^{-6}$
$\text{BR}(Z^0 \to \mu^\pm\tau^\mp\ )$	$< 6.5 \times 10^{-6}$
$\text{BR}(h \to \text{invisible}\ )$	$< 0.19 \times \cos(\alpha)^{-2}$
$\sin(\alpha)$	< 0.3
Direct Detection	LZ
Indirect Detection	Fermi-LAT
$\Omega_{\text{CDM}}h^2$	0.1198 ± 0.0042

FREE AND COMPUTED PARAMETERS

$$\lambda_1 = (m_{h_1}^2 \cos(\alpha)^2 + m_{h_2}^2 \mathrm{csin}(\alpha)^2)/v^2$$

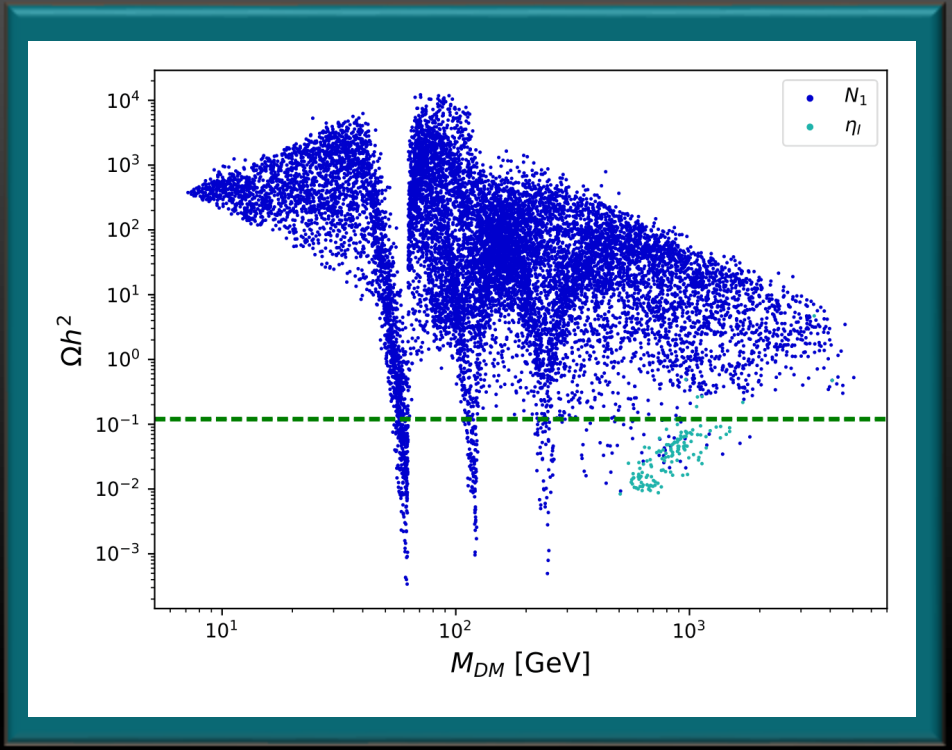
$$\lambda_{H\sigma} = \cos(\alpha)\sin(\alpha)\,(m_{h_1}^2 - m_{h_2}^2)/v\,v_\sigma$$

$$\lambda_{4\sigma} = (m_{h_1}^2 \sin(\alpha)^2 - m_{h_2}^2 \cos(\alpha)^2)/v_\sigma^2$$

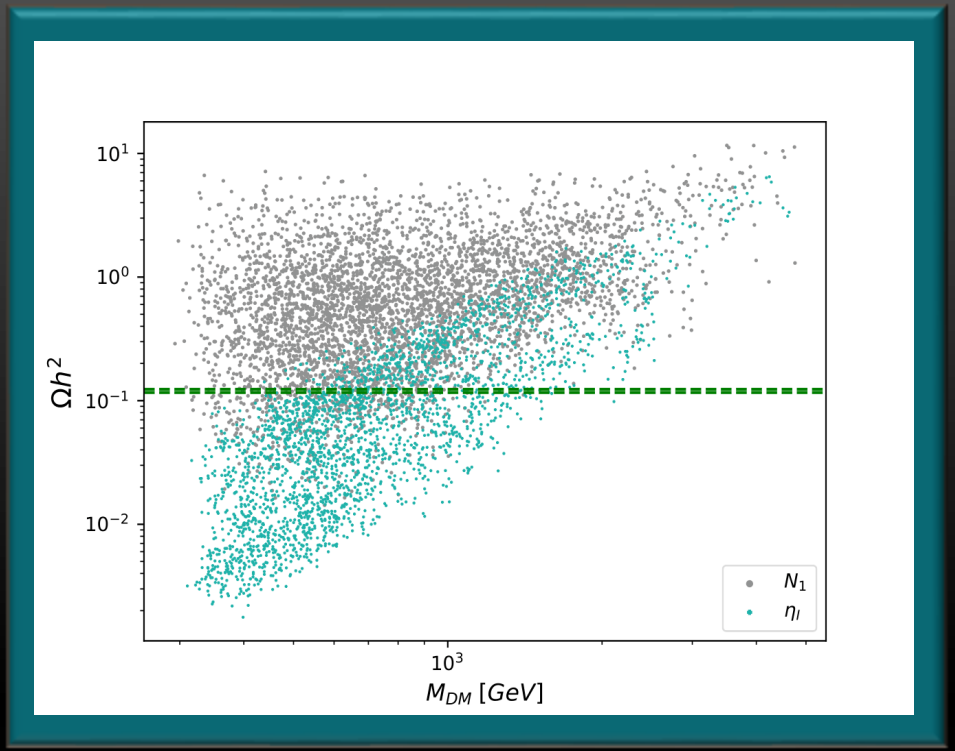
Parameter	Range
λ_2	$[10^{-2}, 1]$
λ_3	$[10^{-2}, 1]$
λ_4	$[10^{-2}, 1]$
λ_5	$[10^{-2}, 1]$
$\lambda_3^{\eta\sigma}$	$[10^{-2}, 1]$
m_η^2	$[9 \times 10^4, 2.5 \times 10^7]$

Parameter	Range
κ_{11}	$[10^{-2}, 0.5]$
κ_{22}	$[10^{-2}, 0.5]$
κ_{33}	$[10^{-2}, 0.5]$
m_{ν_1}	$[10^{-32}, 10^{-10}]$
α	$[-0.3, 0.3]$

DARK MATTER RELIC DENSITY



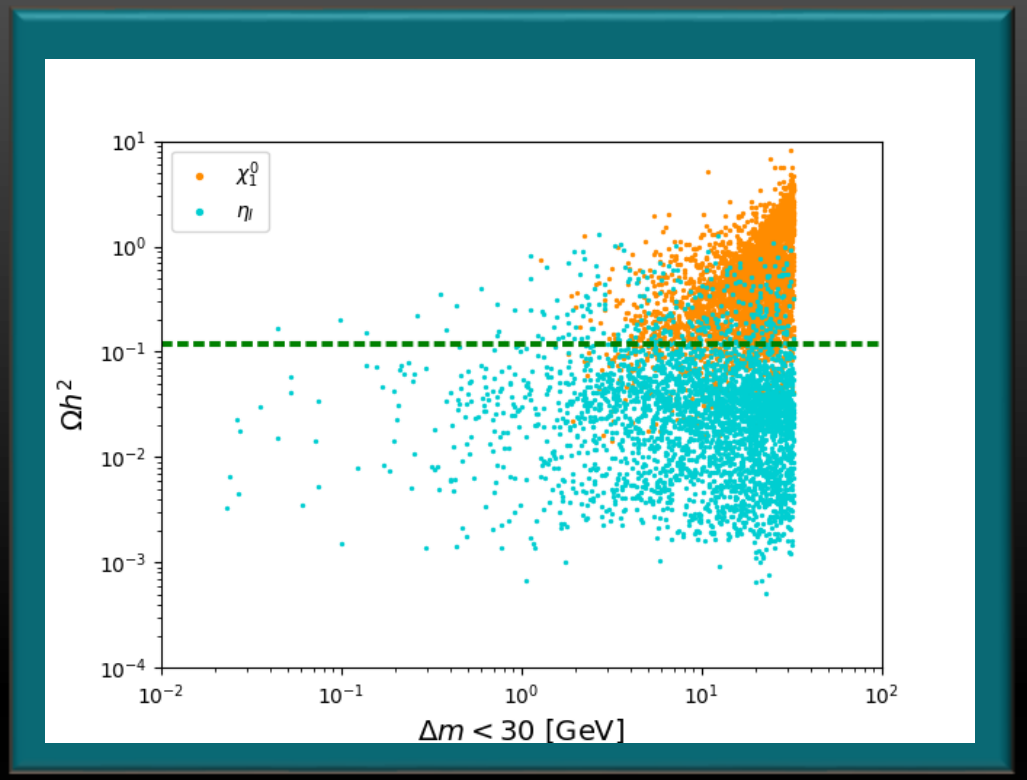
DM relic density vs DM mass
Mass of h1 is fixed at 125 GeV
Mass of h2 is fixed at {246, 500} GeV
New VEV takes value in [1,10] TeV



DM relic density vs DM mass
Mass of h1 is fixed at 125 GeV
Mass of h2 is fixed at 500 GeV in this Fig.
Compress mass spectrum:

$$\Delta m = \left| M_{N_1} - m_{\eta_R^0} \right| < 50 GeV$$

DARK MATTER RELIC DENSITY

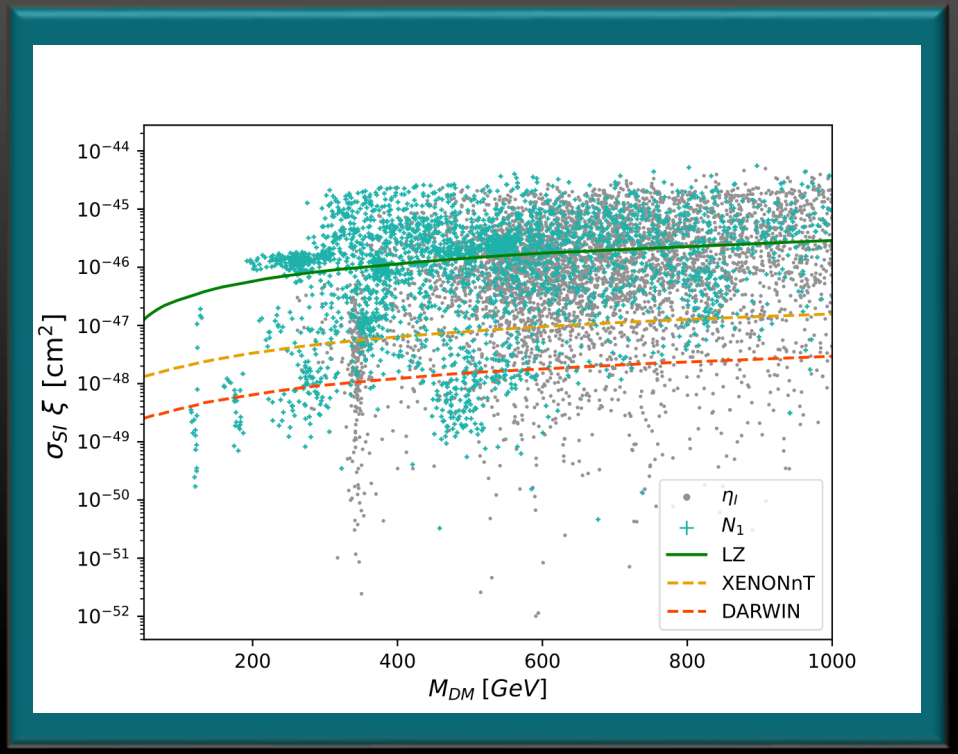


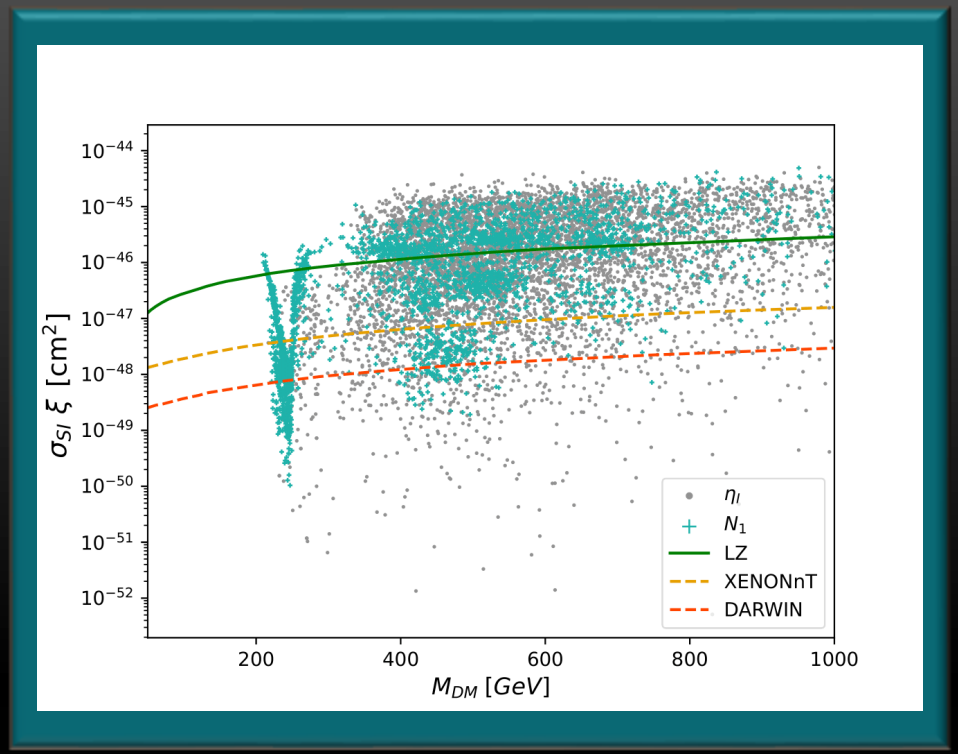
DM relic density vs the difference in mass. Different colors correspond to the DM candidates.

$$\Delta m = |M_{N_1} - m_{\eta_R^0}| < 50GeV$$

Conclusion: explore the compress mass spectrum scenario

DARK MATTER DIRECT DETECTION





DM relic density vs DM mass, Mass of h1 is fixed at 125 GeV
Mass of h2 is fixed at 246 GeV (left), and 500 GeV (right)
New VEV takes value in [1,10] TeV

$$\xi_n = \frac{\Omega^n_{DM}}{\Omega_{Planck}}$$

$$\Delta m < 50\,,30\,\mathrm{GeV}$$

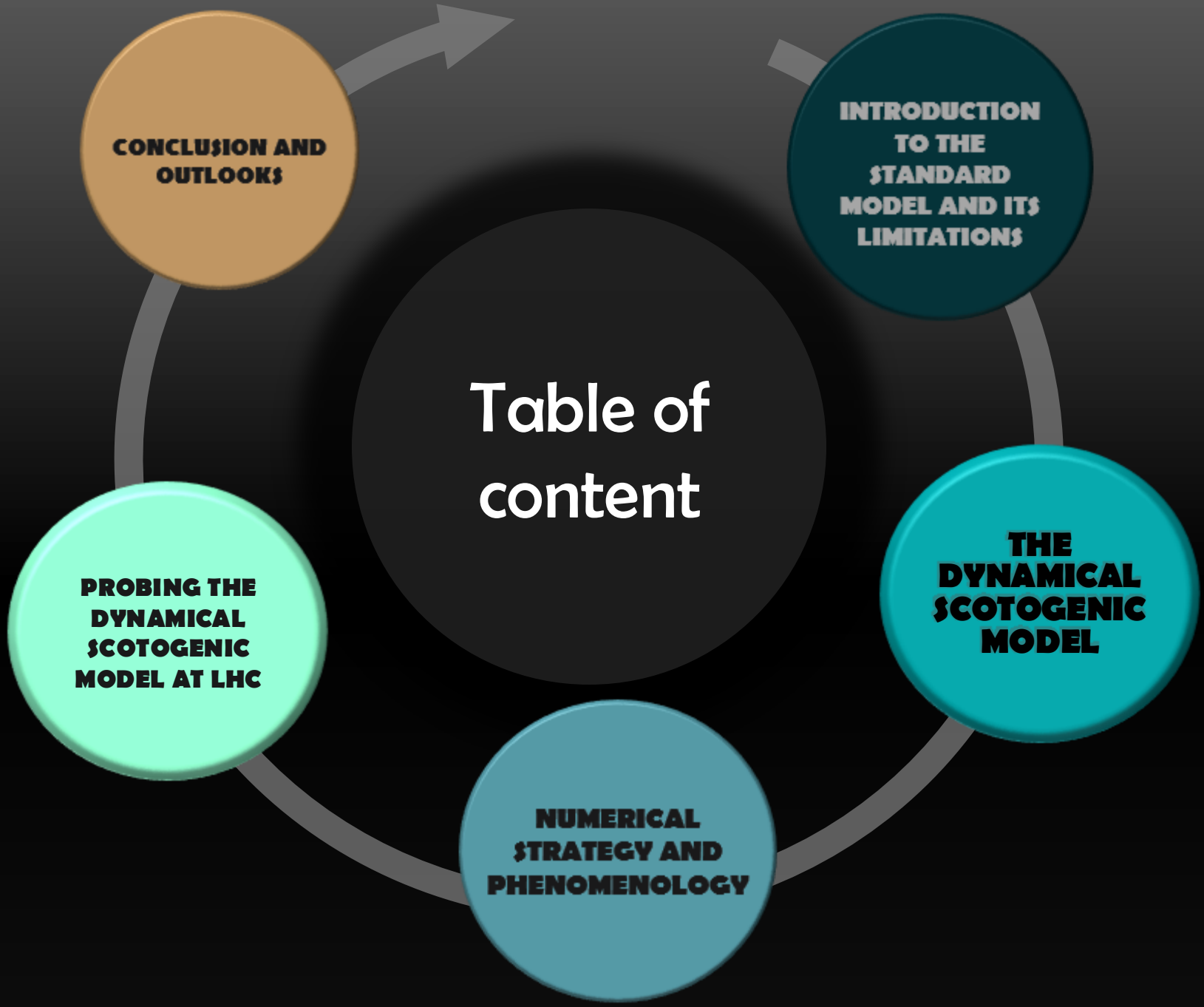
PHENOMENOLOGY IN THE COMPRESS MASS SPECTRUM

Phenomenology of the compress mass spectrum scenario

$$\eta^+\eta^- \to W^+W^- \, , ZZ \, , hh$$

$$\eta_I\eta_I \to W^+W^- \, , ZZ$$

$$\eta_I\eta^\pm \to ZW^\pm \, , \gamma W^\pm$$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PROBING THE DYNAMICAL SCOTOGENIC MODEL AT LHC

THE NUMERICAL STRATEGY

- Implementation of the model in FeynRules
- MadGraph 5 to compute the production cross sections

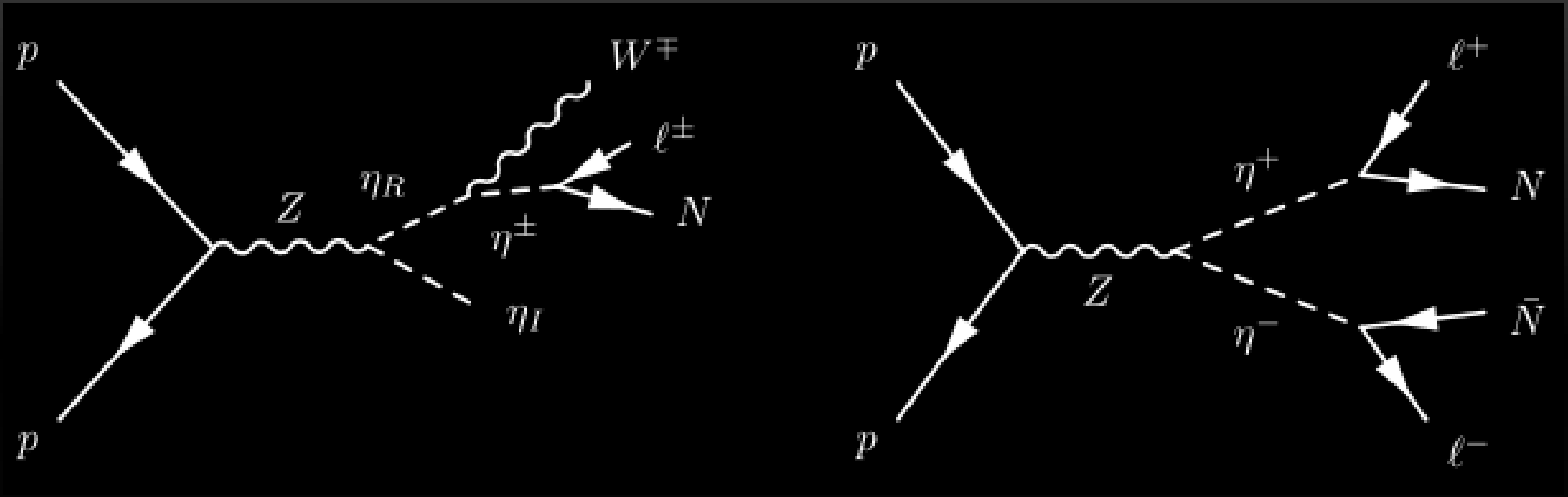
We consider two production mechanism :

- Drell-Yan process
- Vector Boson Fusion process

We considered an optimistic scneario: background is 20% with respect to the signal, 20% systematic uncertanties.

THE PRODCUTION MECHANISMS
DRELL-YAN

Final states include missing energy and charged leptons



For η_I^0 DM

$$\mathrm{p} + \mathrm{p} \rightarrow \eta_I + \eta_R \rightarrow \eta_I + \eta^\pm + \mathrm{W}^\mp$$
$$\rightarrow \eta_I + \ell^\pm + N_i + W^\mp$$

For N_1 DM

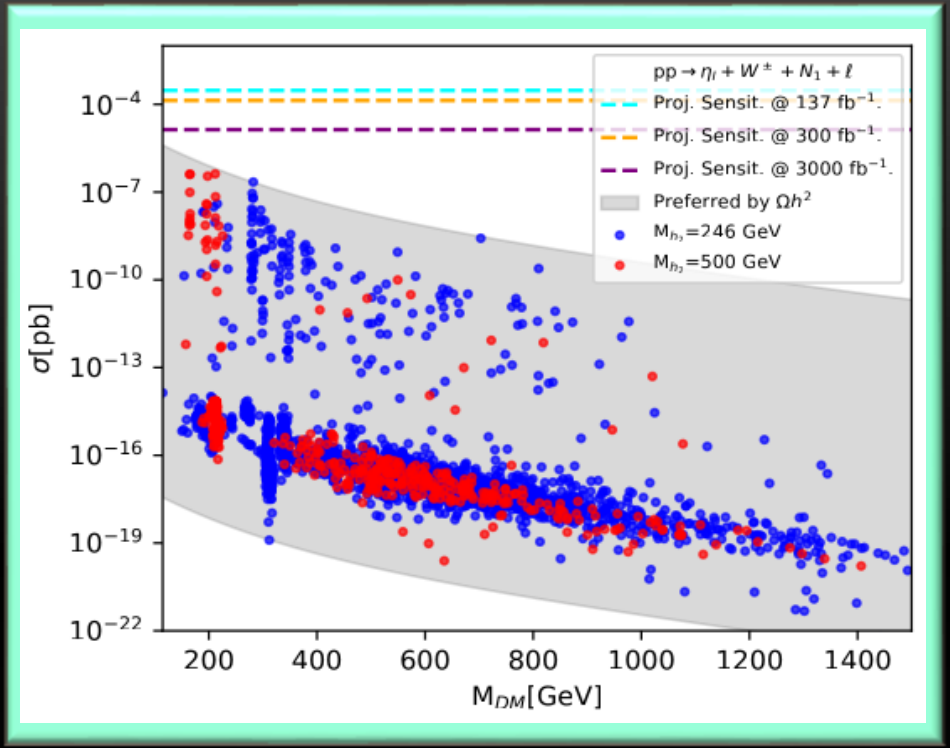
$$\mathrm{p} + \mathrm{p} \rightarrow \eta^\pm + \eta^\mp \rightarrow N_i + \ell^\pm + N_i + \ell^\mp$$

DRELL-YAN

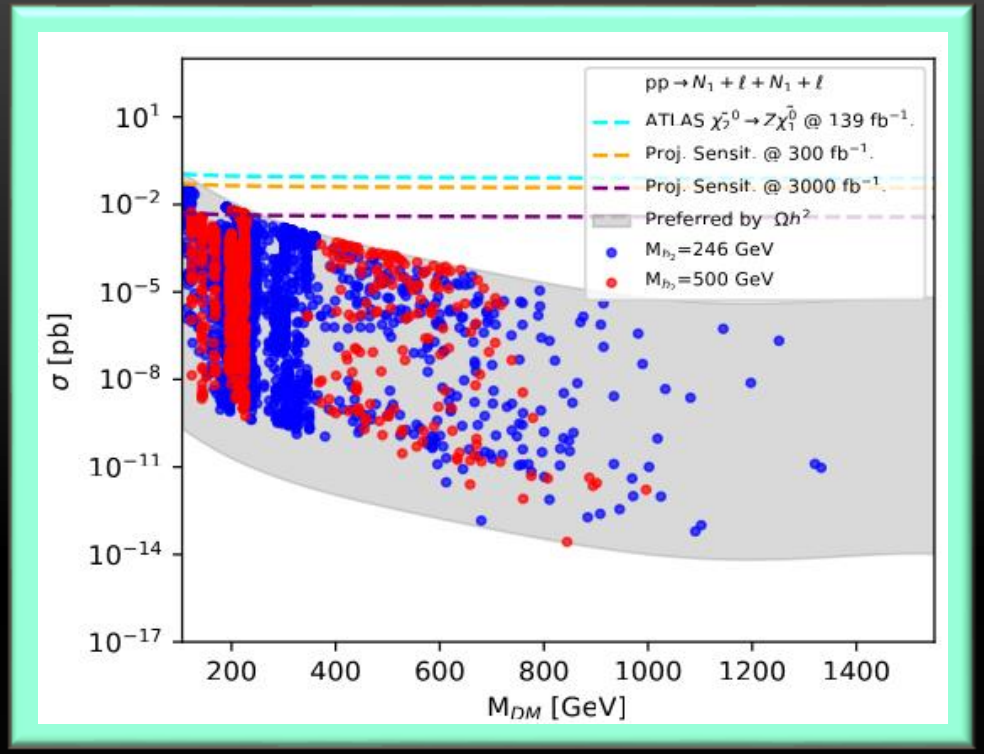
The estimate was performed for three different LHC luminosity scenarios {137, 300, 3000} fb-1 for pseudo-scalar DM

In the case of the fermion DM, we used SUSY analysis for soft leptons, and the formentioned luminosity scenario.

RESULTS ON THE PRODUCTION CROSS-SECTION DRELL-YAN

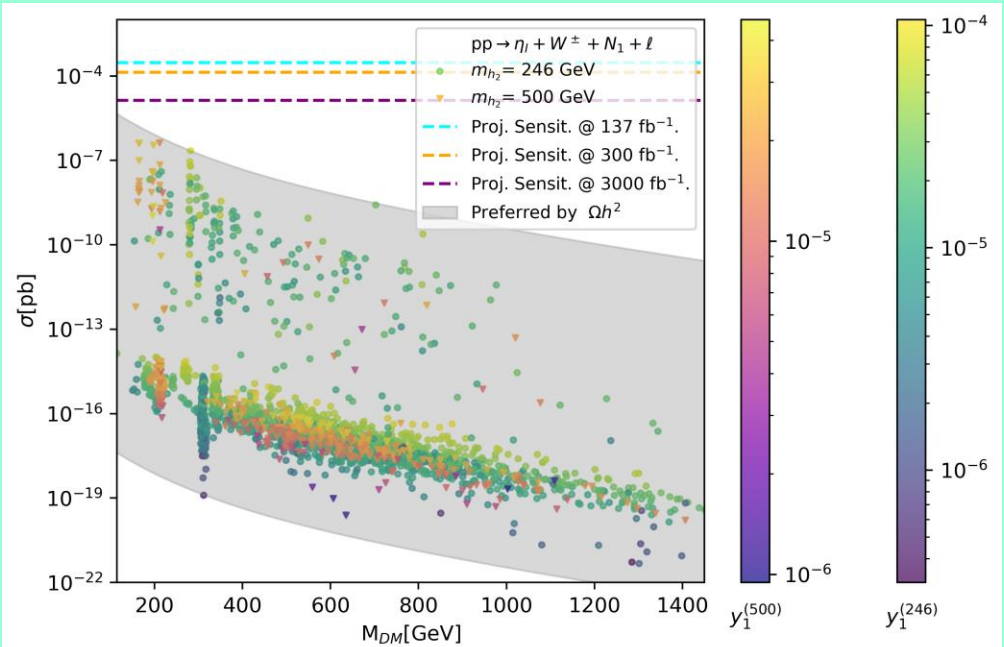


For η_I^0 DM

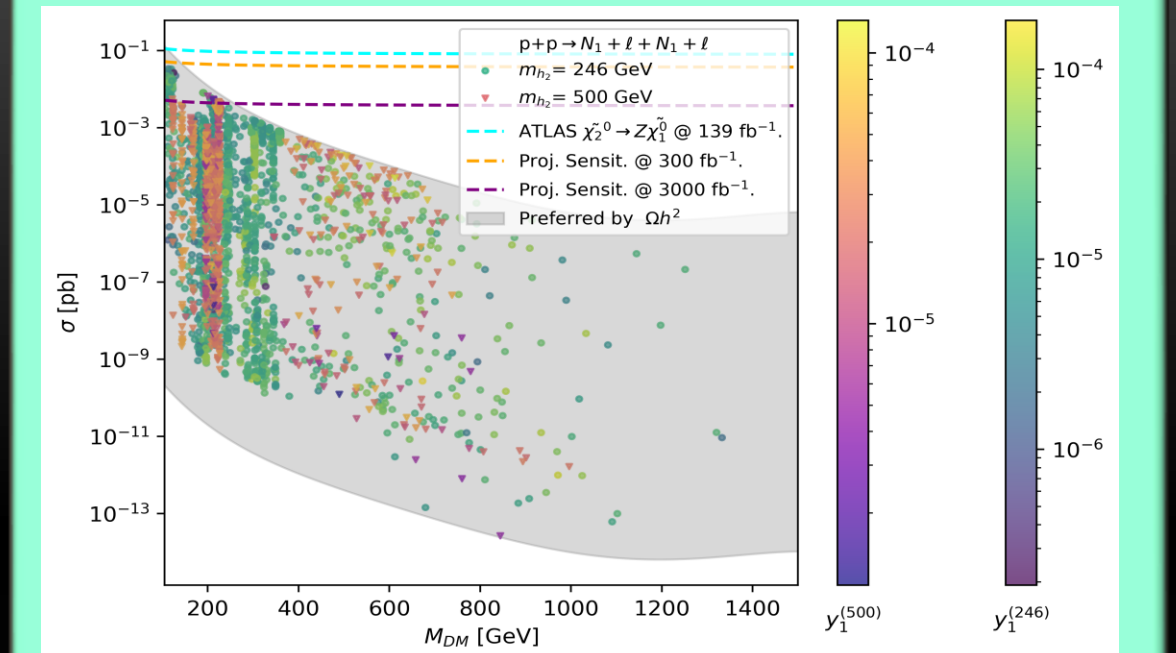


For N_1 DM

RESULTS ON THE PRODUCTION CROSS-SECTION DRELL-YAN

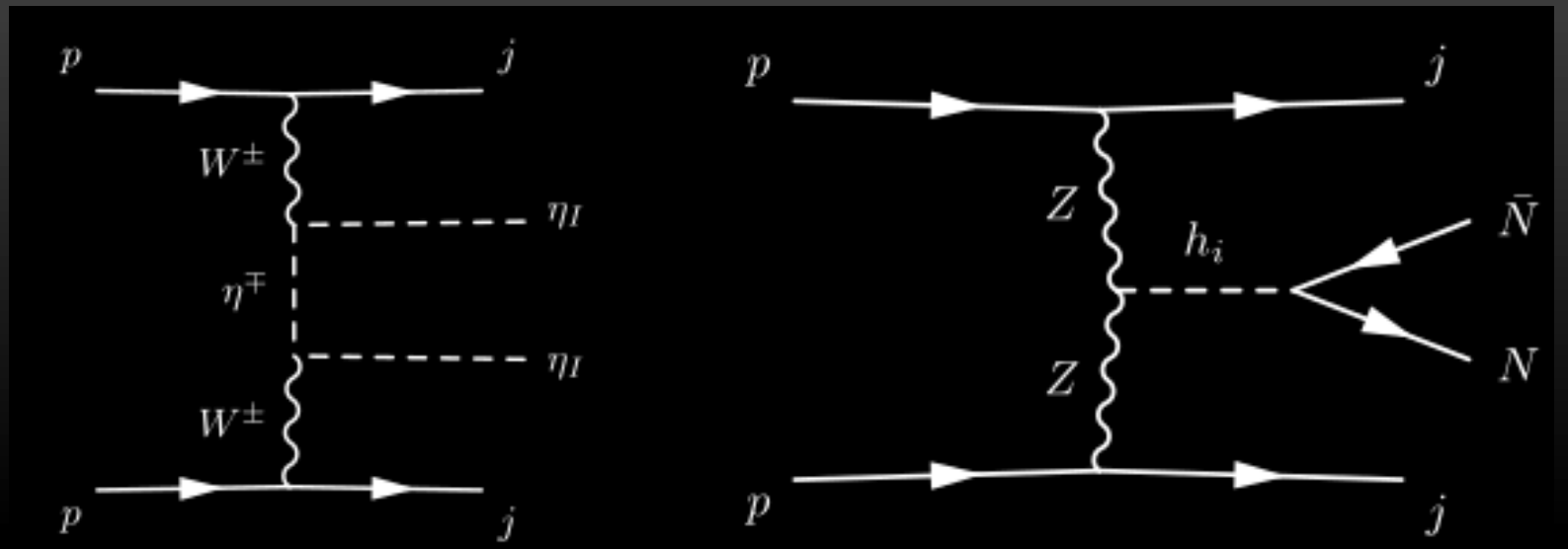


For η_I^0 DM



For N_1 DM

THE PRODCUTION MECHANISMS
VECTOR BOSON FUSION



For η_I^0 DM

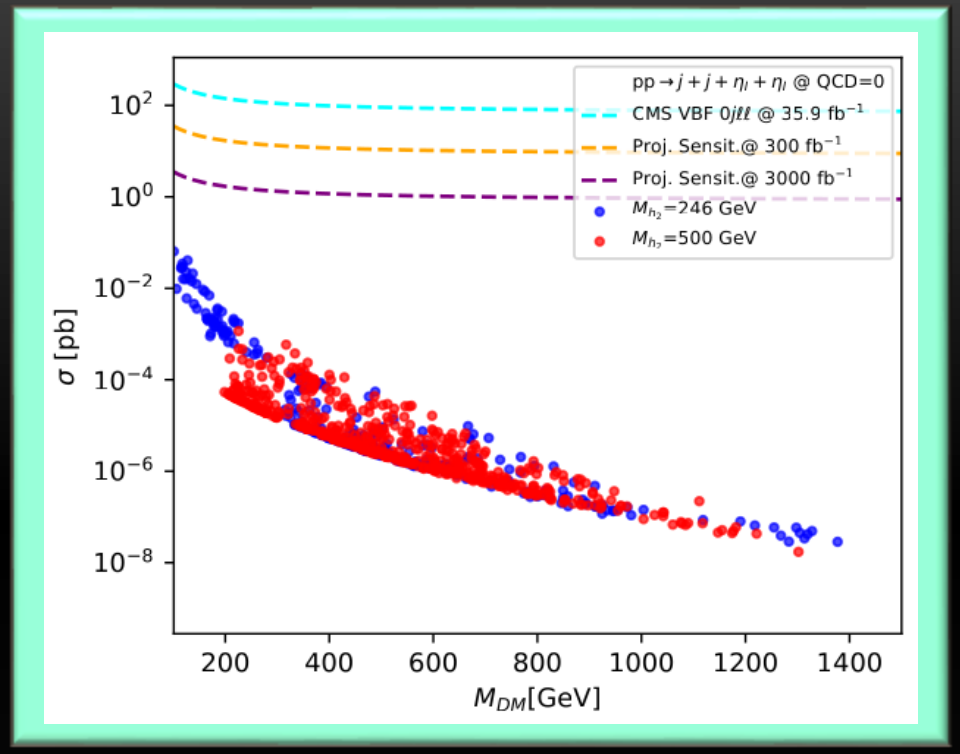
For N_1 DM

$$\mathrm{p} + \mathrm{p} \to 2\eta_I^0 + 2j \qquad \mathrm{p} + \mathrm{p} \to 2N_1 + 2j$$

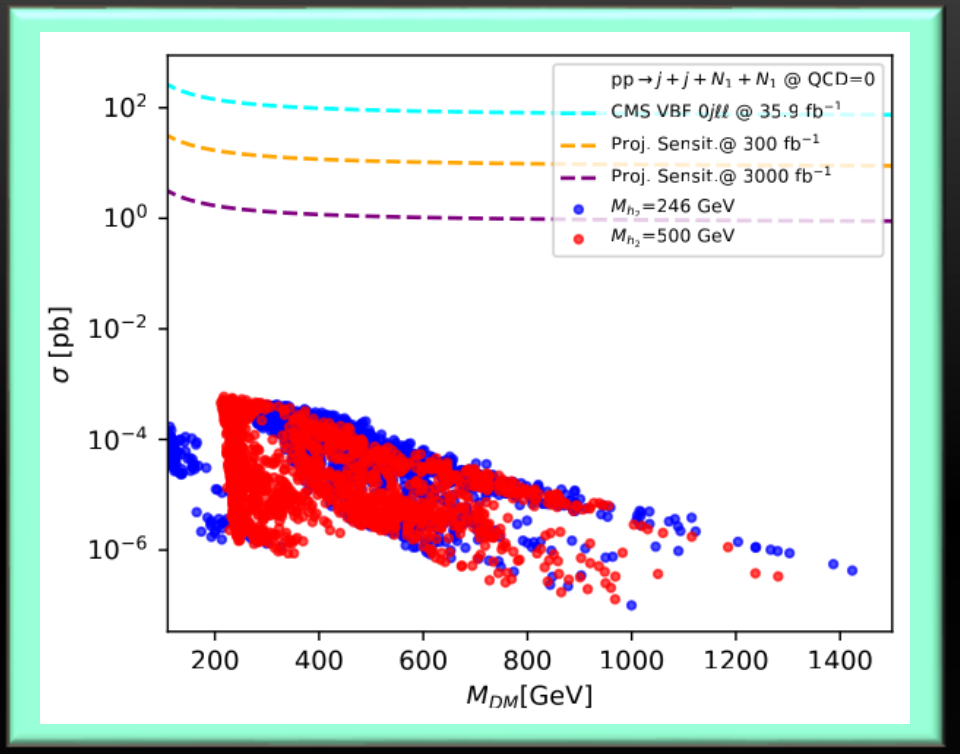
VECTORB BOSON FUSION

These neutral final states are similar to the ones studied in SUSY at CMS. We extrapolate their results, and used the same Luminosity as before.

RESULTS ON THE PRODUCTION CROSS-SECTION VECTOR BOSON FUSION

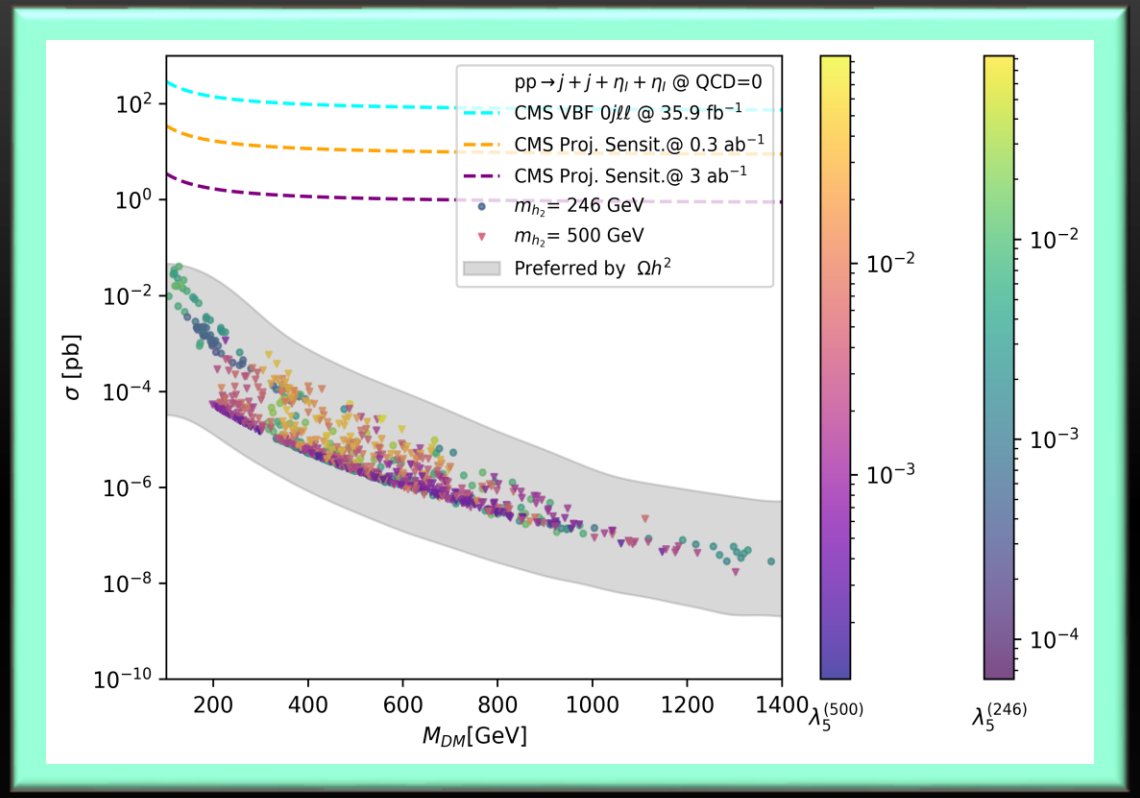


For η_I^0 DM

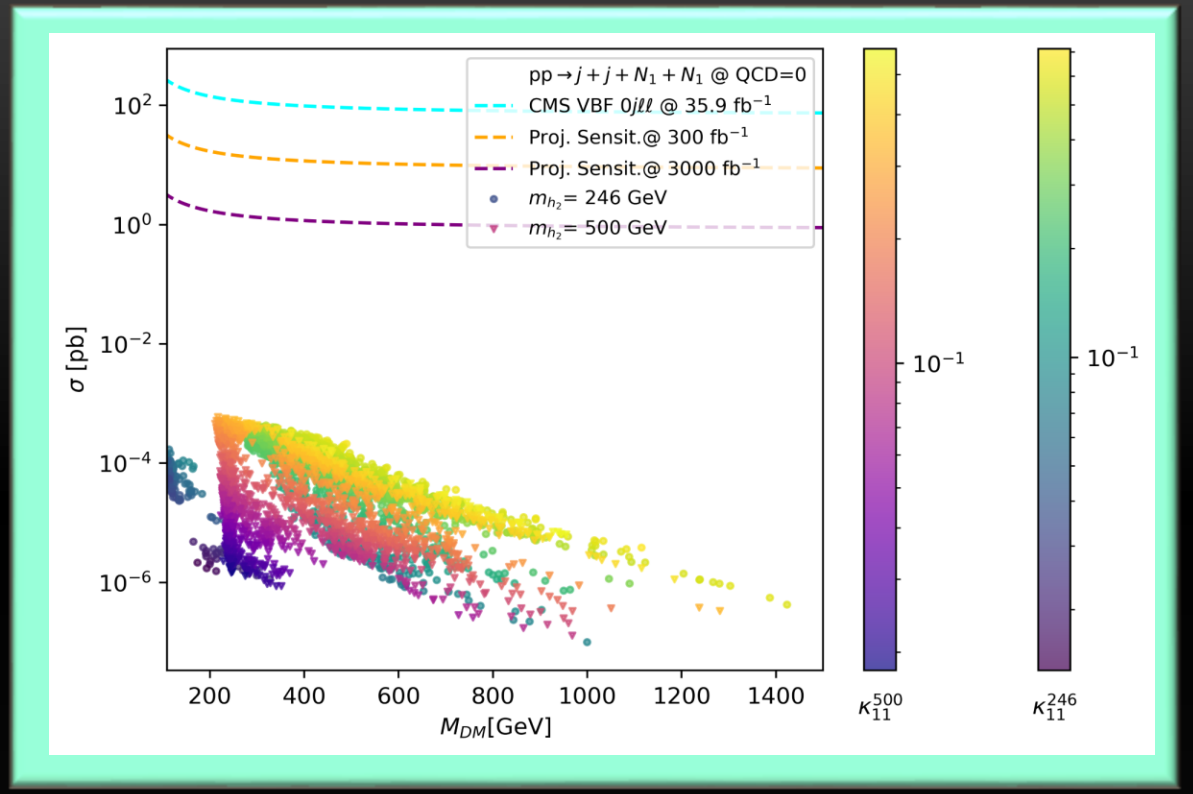


For N_1 DM

RESULTS ON THE PRODUCTION CROSS-SECTION VECTOR BOSON FUSION

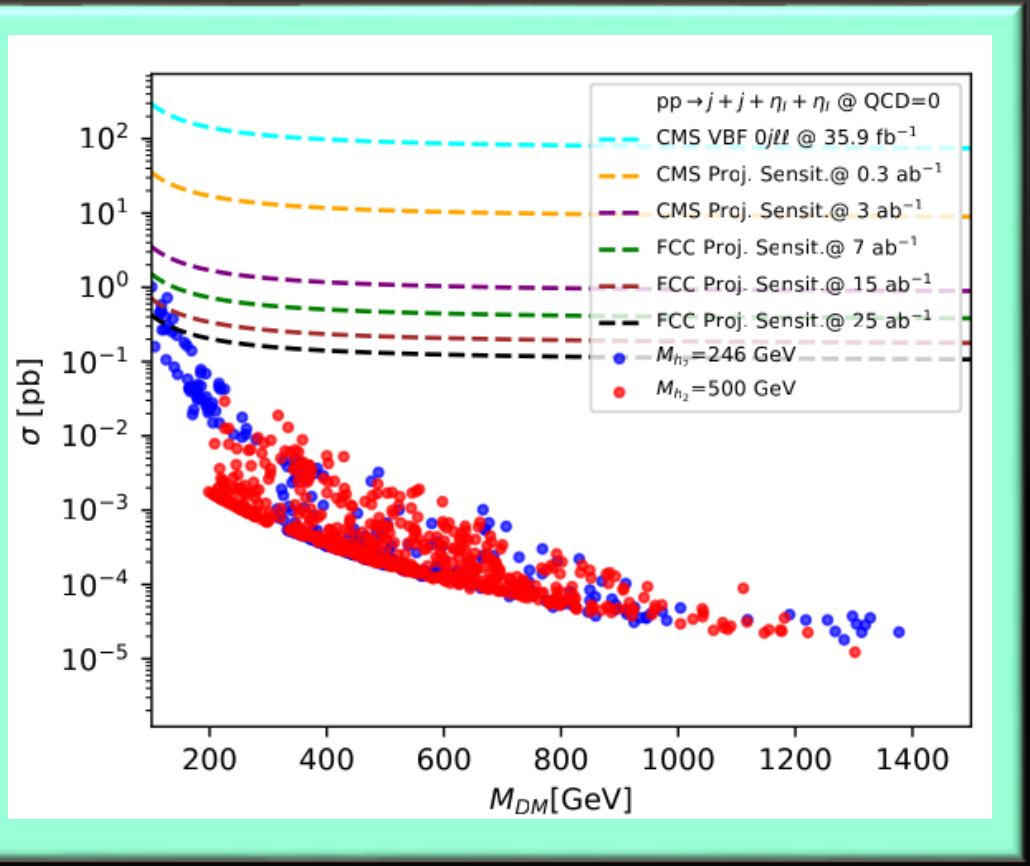


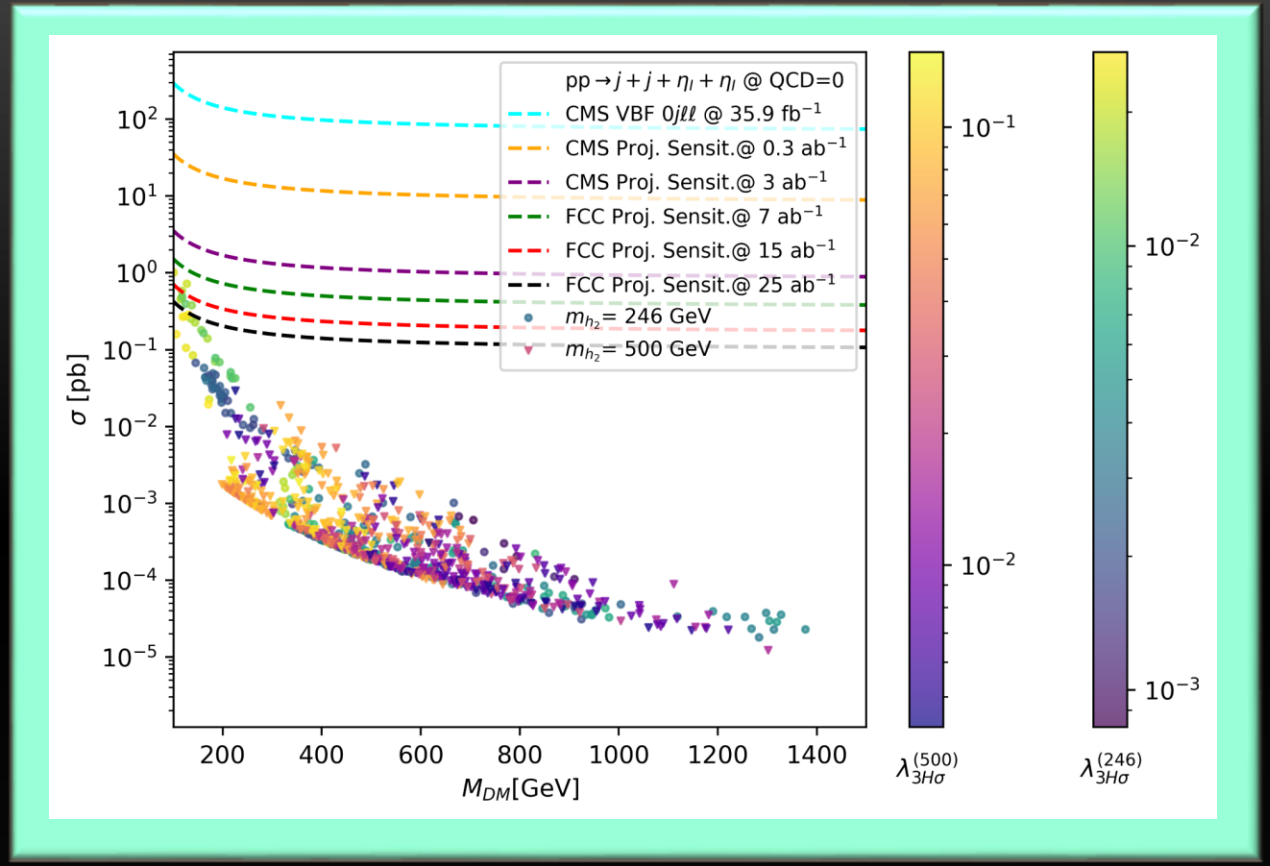
For η_I^0 DM



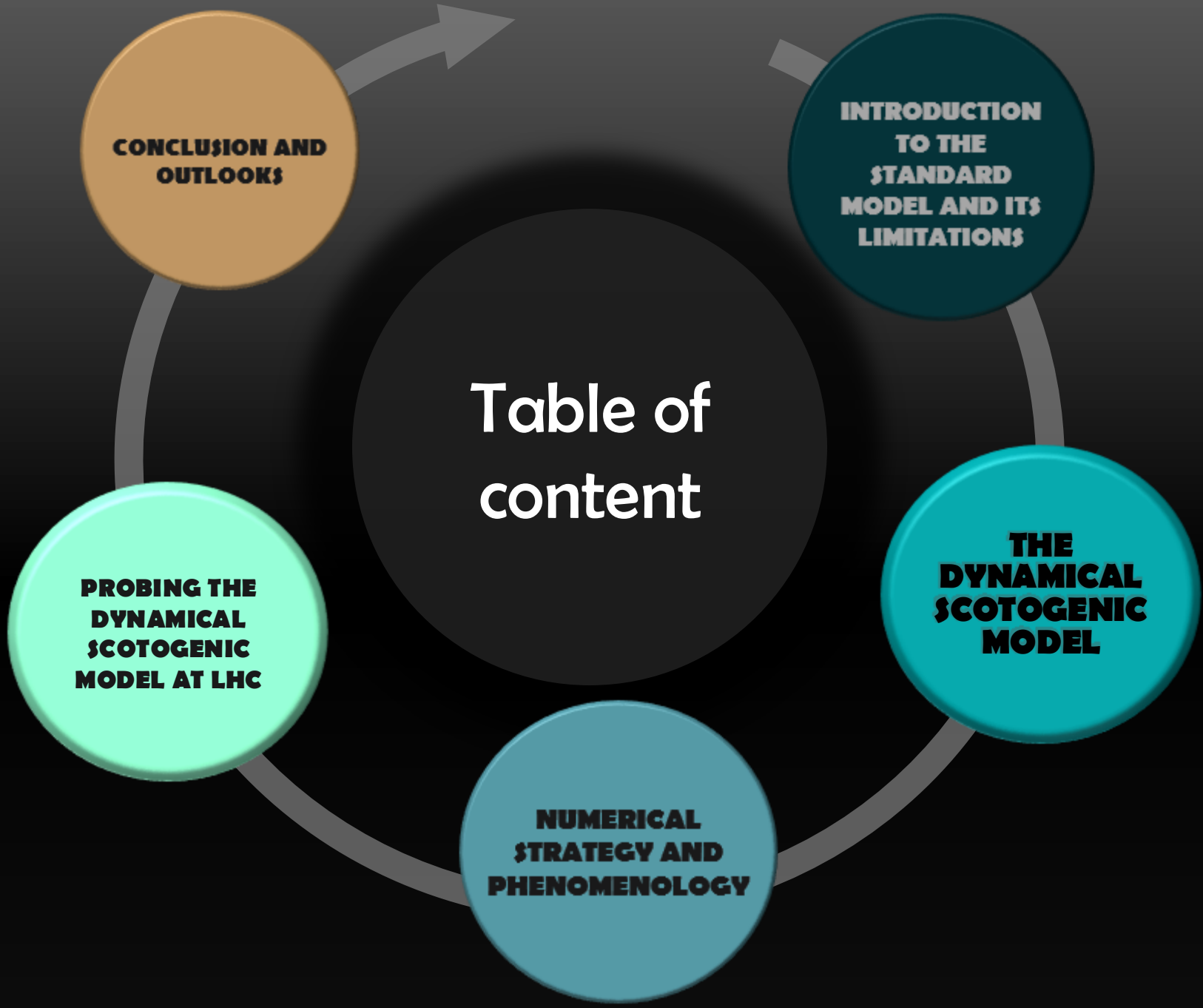
For N_1 DM

RESULTS ON THE PRODUCTION CROSS-SECTION VECTOR BOSON FUSION FCC PREDICTION





For η_I^0 DM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CONCLUSION AND OUTLOOKS

- The dynamical scotogenic model provides 2 viable candidates for DM,
- And three non zero neutrino masses.
- With the DY production, LHC could probe fermion DM with masses between 150 GeV to 220 GeV
- While VBF remains unsuitable for both DM candidates.
- Are those results general or not, in the context of scotogenic models?

"Science is built up of facts, as a house is built of stones; but an accumulation of facts is no more a science than a heap of stones is a house."

- Henri Poincaré

Backup

INDIRECT DETECTION