Discovery of the real and complex triplet models at the LHC and future colliders

based on arXiv: 2003.07867,
and JHEP 01(2019)101

Yong Du

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CLHCP2020, November 6, Tsinghua University

Disclaimer: Apologize for missing your work here

The real triplet model

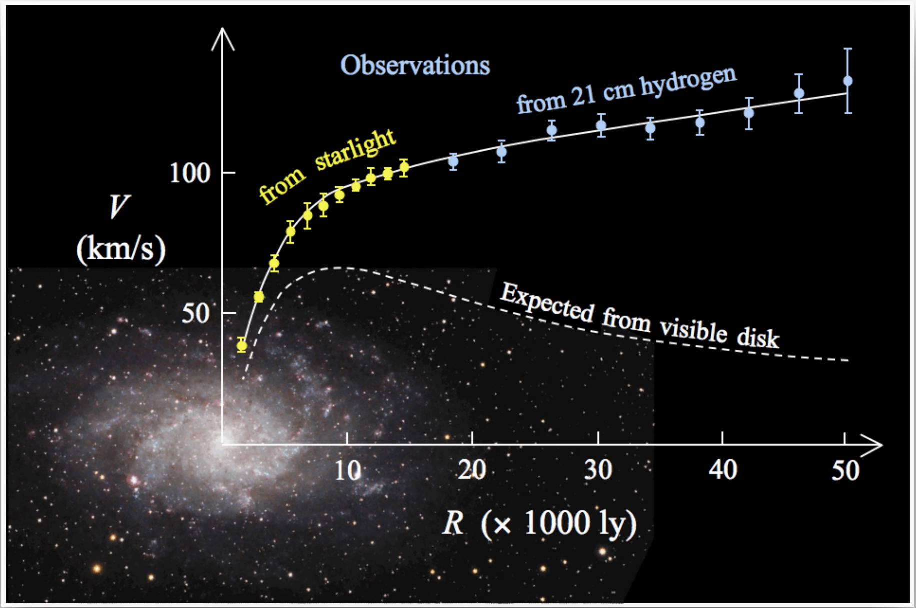
In collaboration with Cheng-Wei Chiang, Giovanna Cottin, Kaori Fuyuto, Michael Ramsey-Musolf

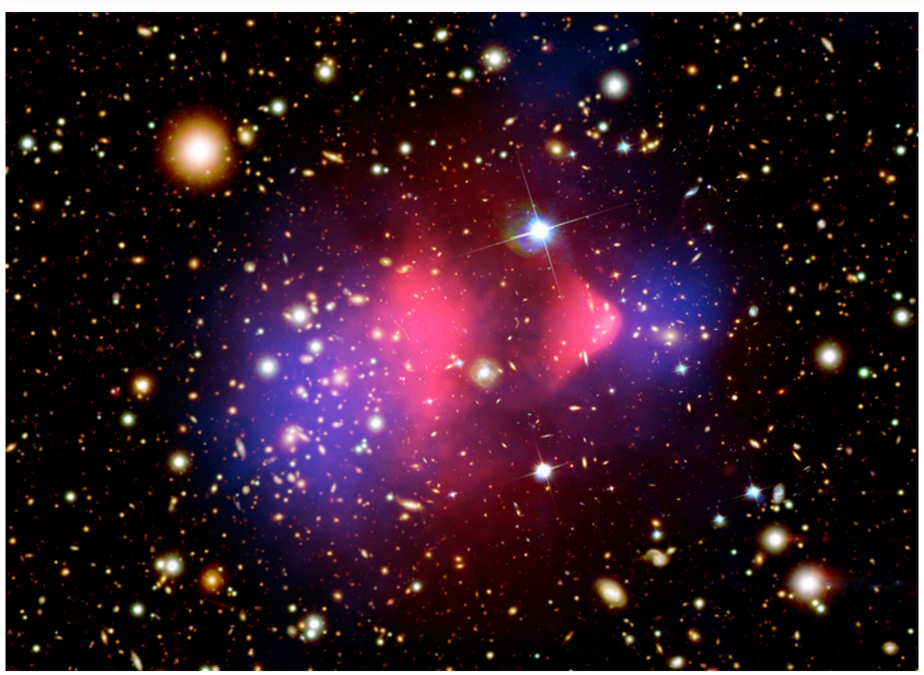
based on arXiv: 2003.07867,

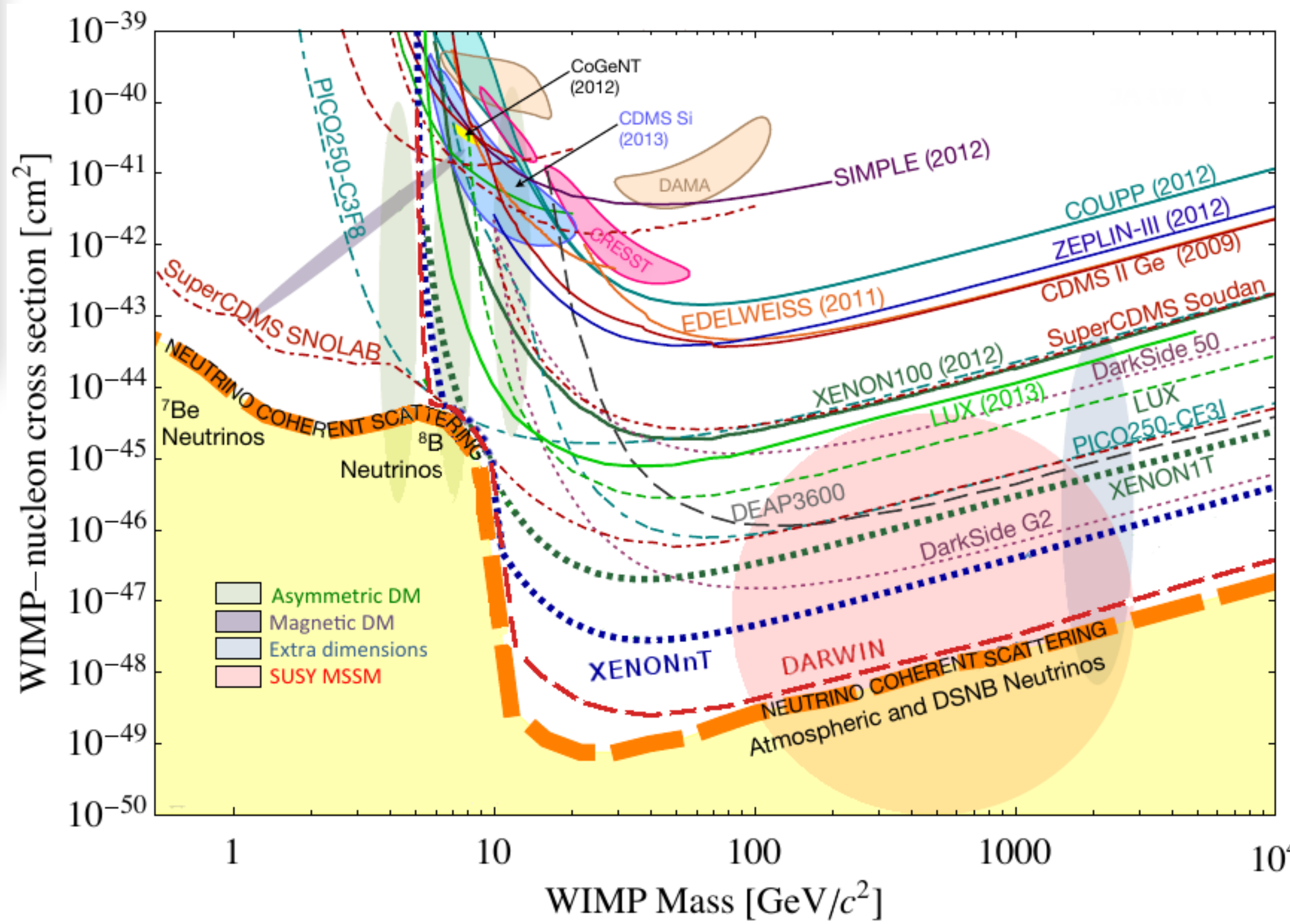
Dark matter: Background

Yong Du, F. Huang, H.L. Li, J.H. Yu, arXiv: 2005.01717

(SIDM from freeze-in)







Klasen et al, arXiv: 1507.03800

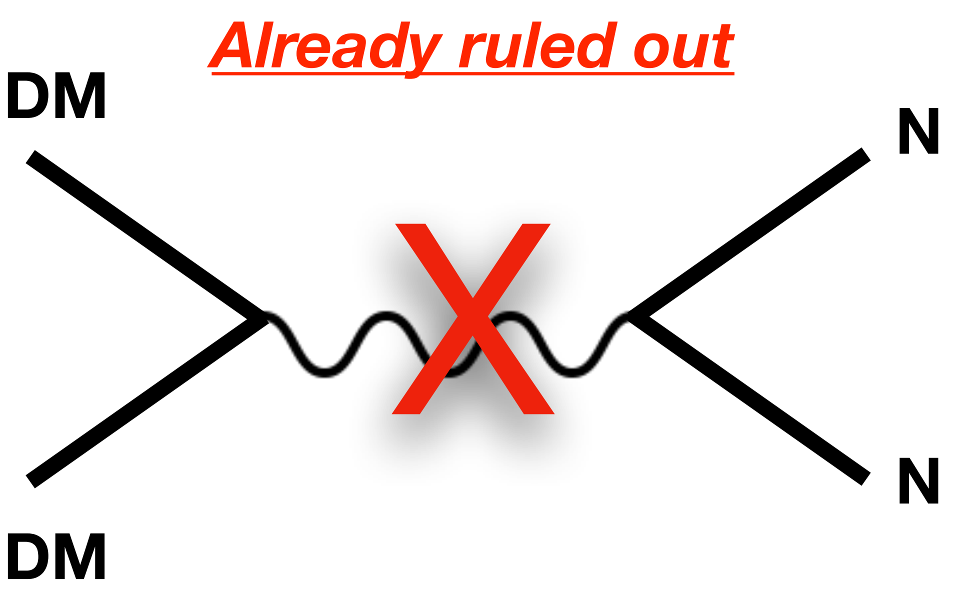
Dark matter: Background

The real triplet model!

Brief model introduction

Σ := Real triplet (1, 3, 0)

$$\Sigma = \frac{1}{2}\begin{pmatrix} \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0 \end{pmatrix}$$



Brief model introduction

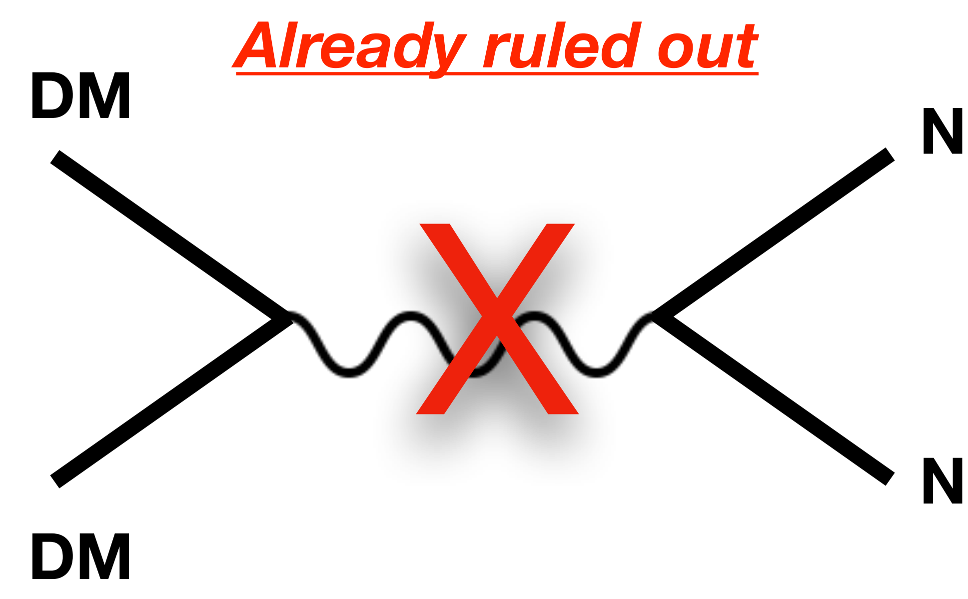
$\boldsymbol{\Sigma}$:= Real triplet (1, 3, 0)

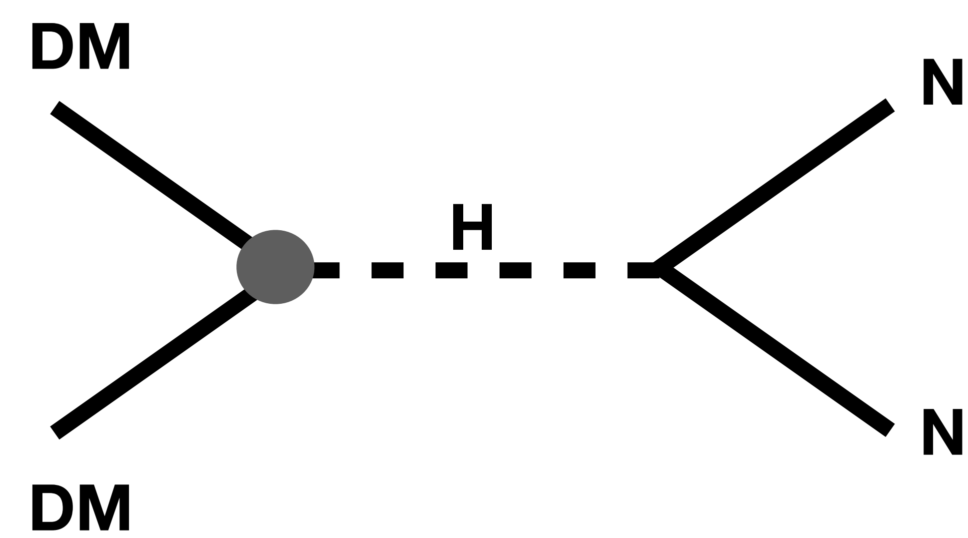
$$\boldsymbol{\Sigma} = \frac{\mathbf{1}}{\mathbf{2}} \begin{pmatrix} \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0 \end{pmatrix}$$

$$\mathbf{V}(\mathbf{H}, \boldsymbol{\Sigma}) = -\mu^2 \mathbf{H}^\dagger \mathbf{H} + \lambda_0 (\mathbf{H}^\dagger \mathbf{H})^2$$

$$- \frac{1}{2} \mathbf{M}_\Sigma^2 \mathbf{F} + \frac{\mathbf{b_4}}{4} \mathbf{F}^2 + \frac{\mathbf{a_2}}{2} \mathbf{H}^\dagger \mathbf{H} \mathbf{F}$$

$$\mathbf{F} = (\boldsymbol{\Sigma}^0)^2 + 2\boldsymbol{\Sigma}^+ \boldsymbol{\Sigma}^-$$





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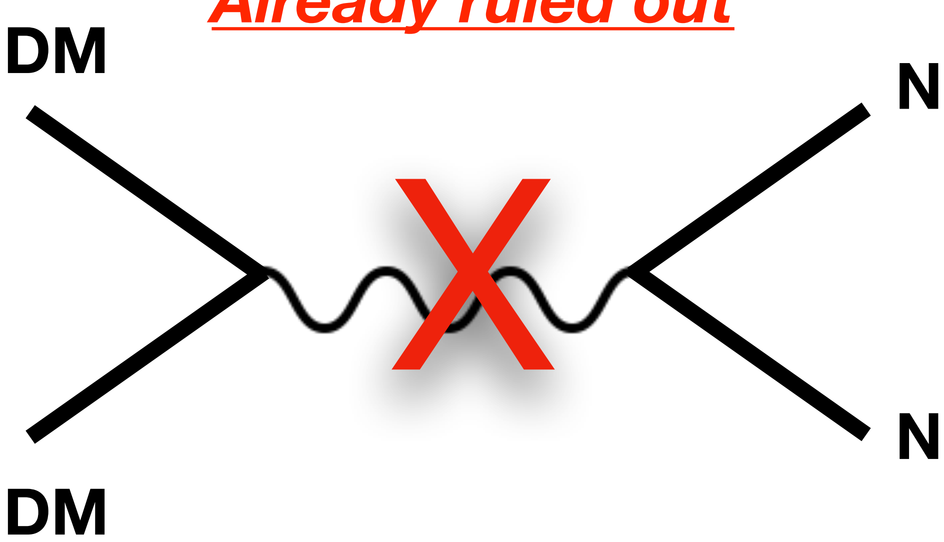
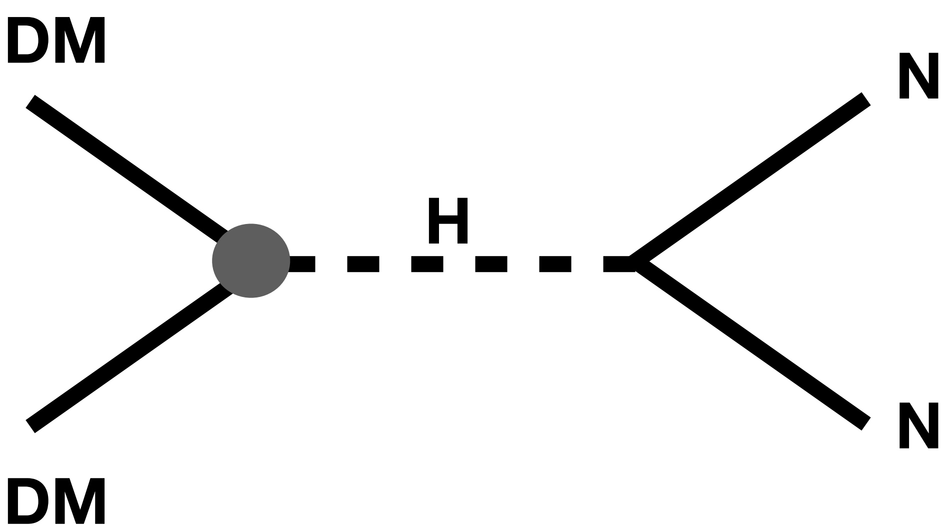
$$-\frac{1}{2}M_\Sigma^2 F + \frac{b_4}{4}F^2 + \frac{a_2}{2}H^\dagger H F$$

$$F = (\Sigma^0)^2 + 2\Sigma^+\Sigma^-$$

Already ruled out

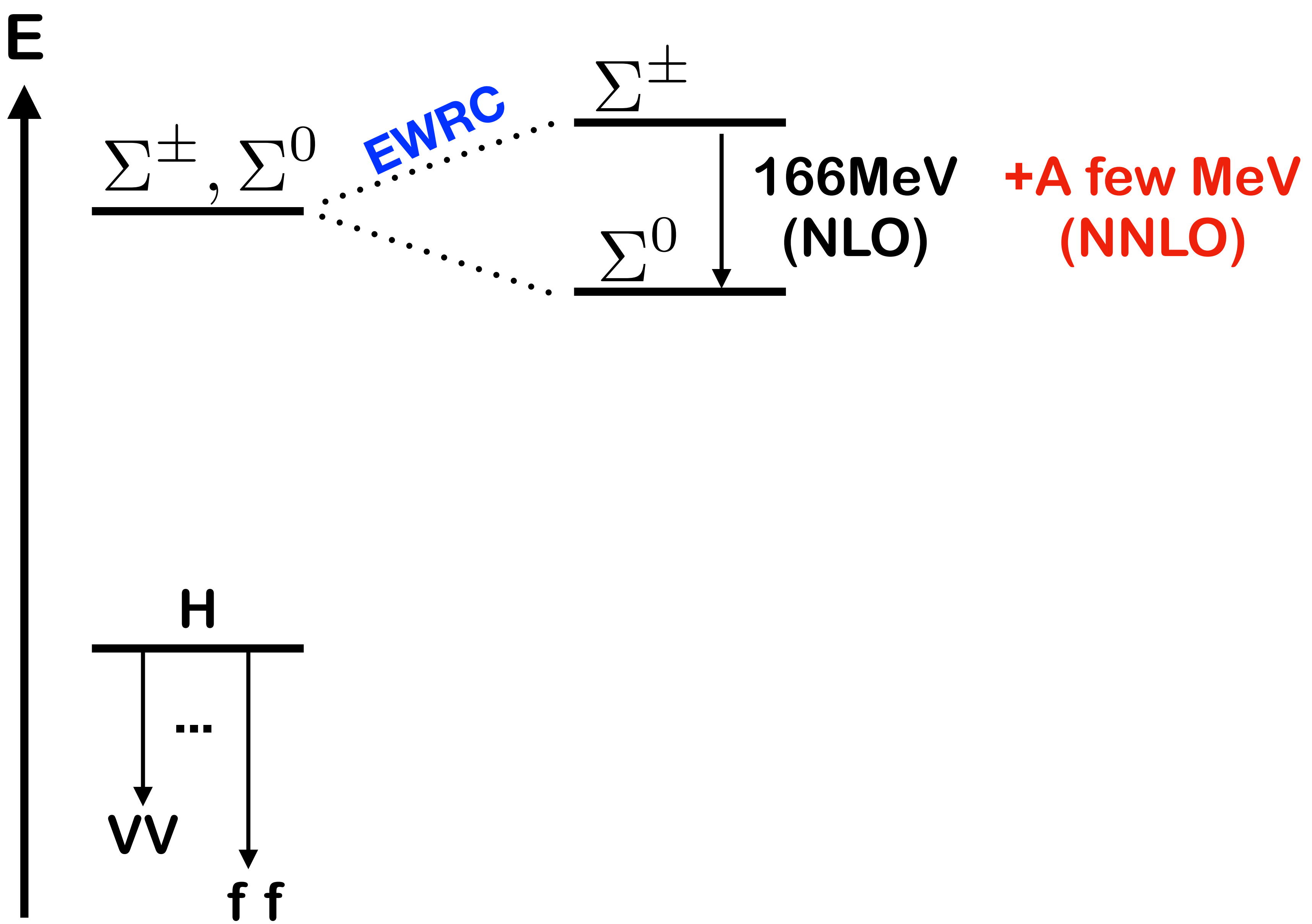




Collider phenomenologies?

Brief model introduction

$$\boldsymbol{\Sigma} = \frac{\mathbf{1}}{\mathbf{2}} \begin{pmatrix} \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0 \end{pmatrix}$$



Brief model introduction

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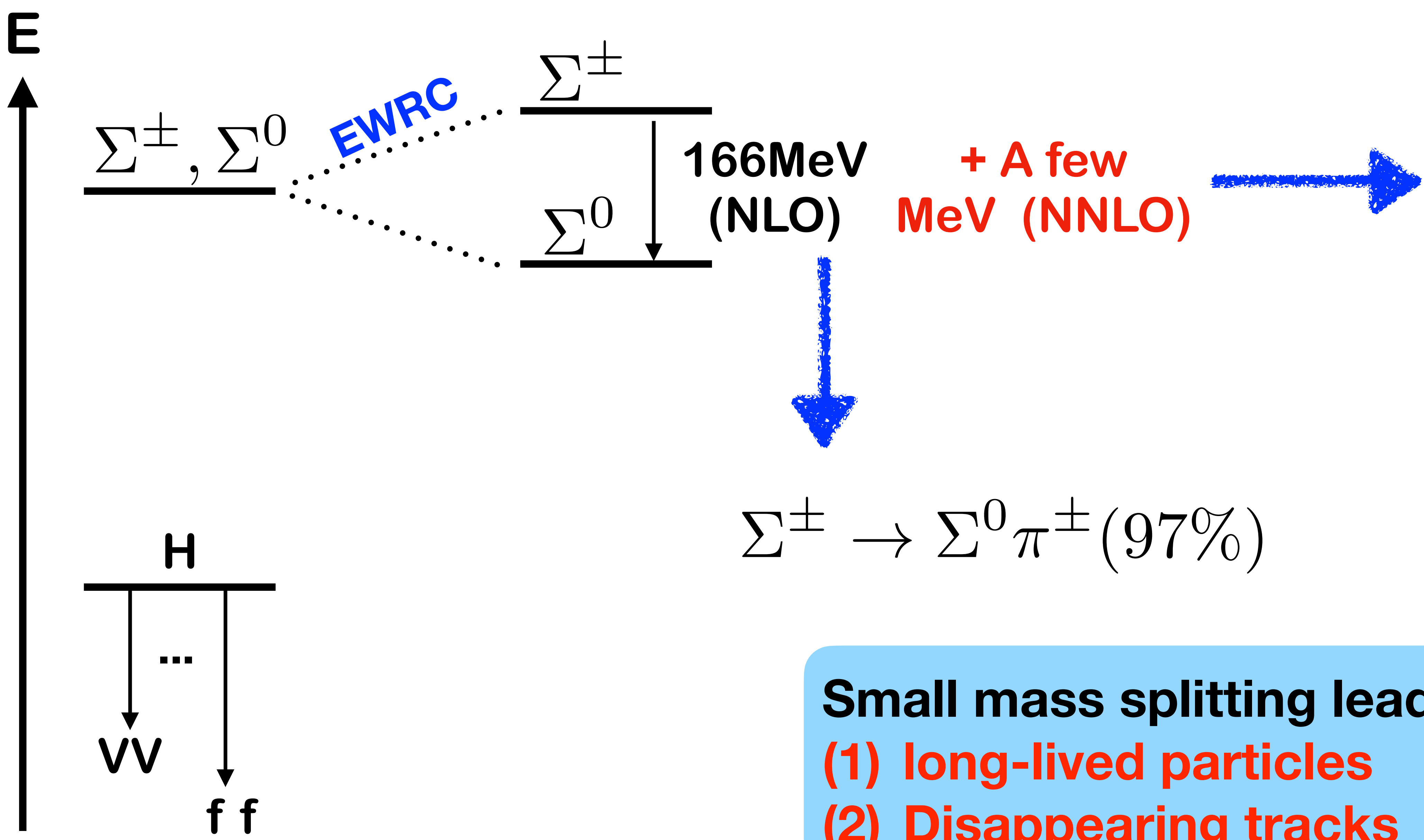


$$\Sigma^\pm \to \Sigma^0 \pi^\pm (97\%)$$

Small mass splitting leads to:

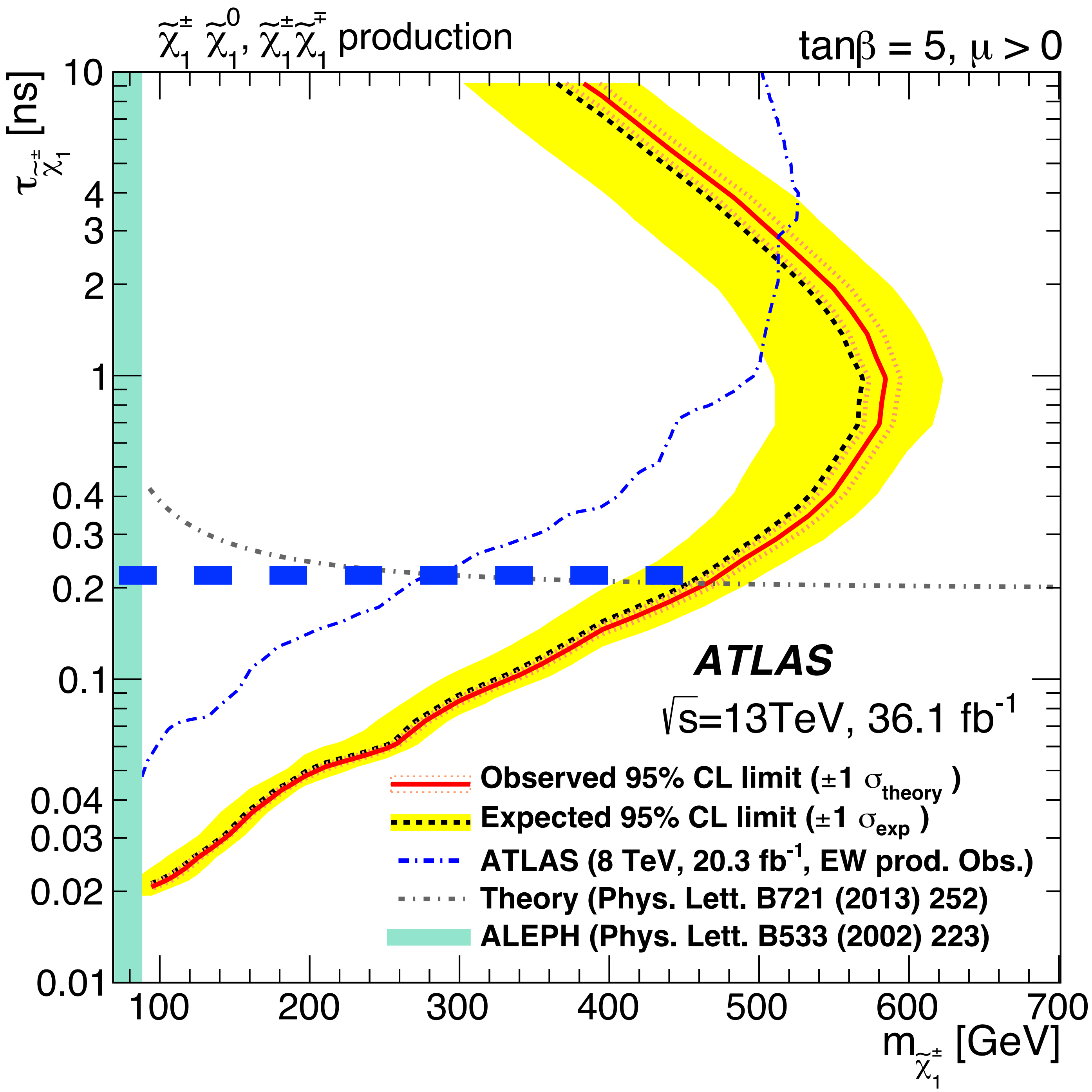
(1) long-lived particles

(2) Disappearing tracks

J. Alimena et al., 2019; T. Hambye et al, 2009; R. Mahbubani et al 2017
Q.H. Cao et al., 2018; L.D. Luzio et al. 2018; Abe et al. 2018; Kuramotoa et al 2019;
...

Reproduction of ATLAS result

C.W. Chiang, G. Cottin, Yong Du,
K. Fuyuto, M.J. Ramsey-Musolf
arXiv: 2003.07867



ATLAS collaboration,
arXiv:1712.02118

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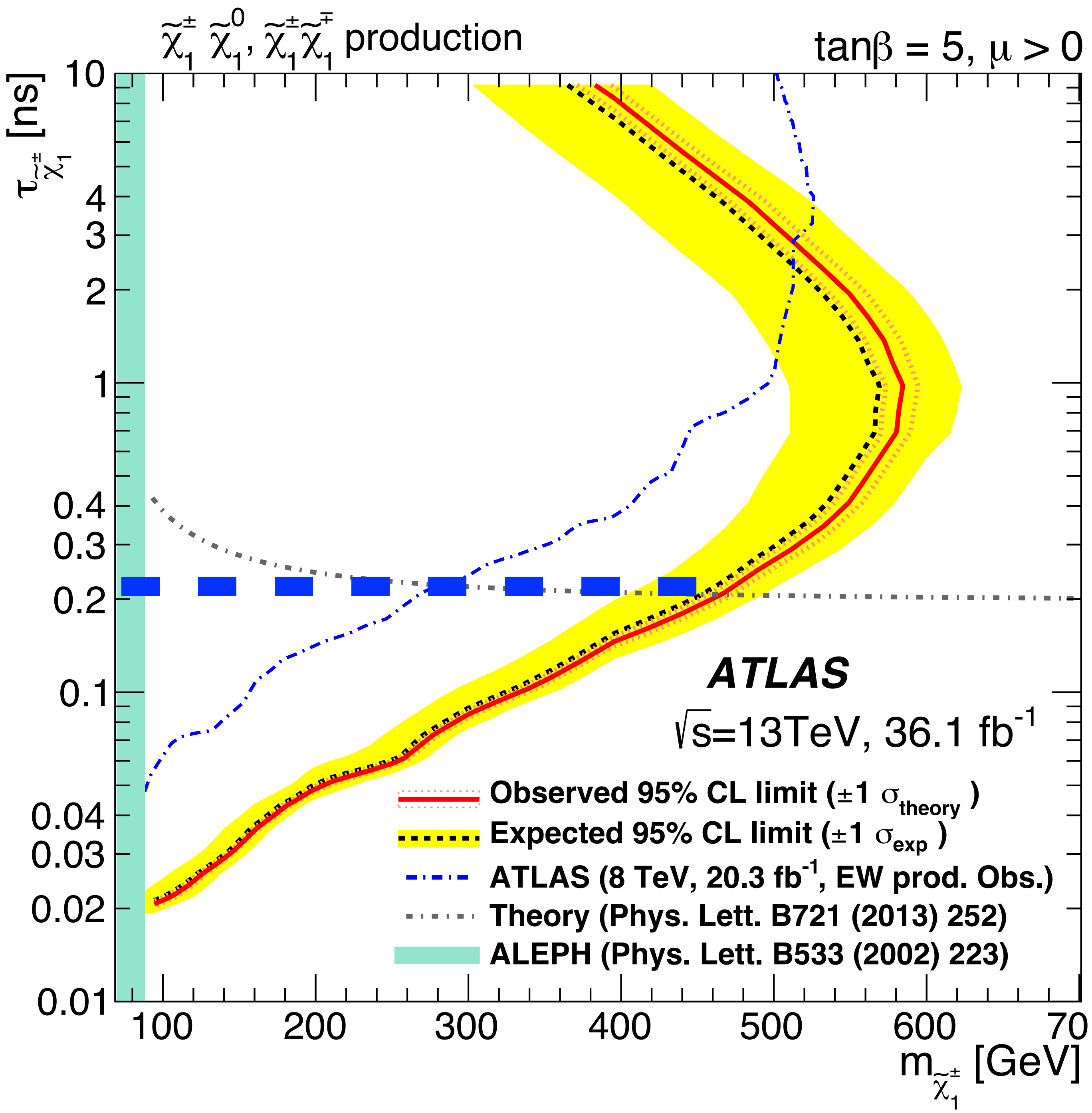

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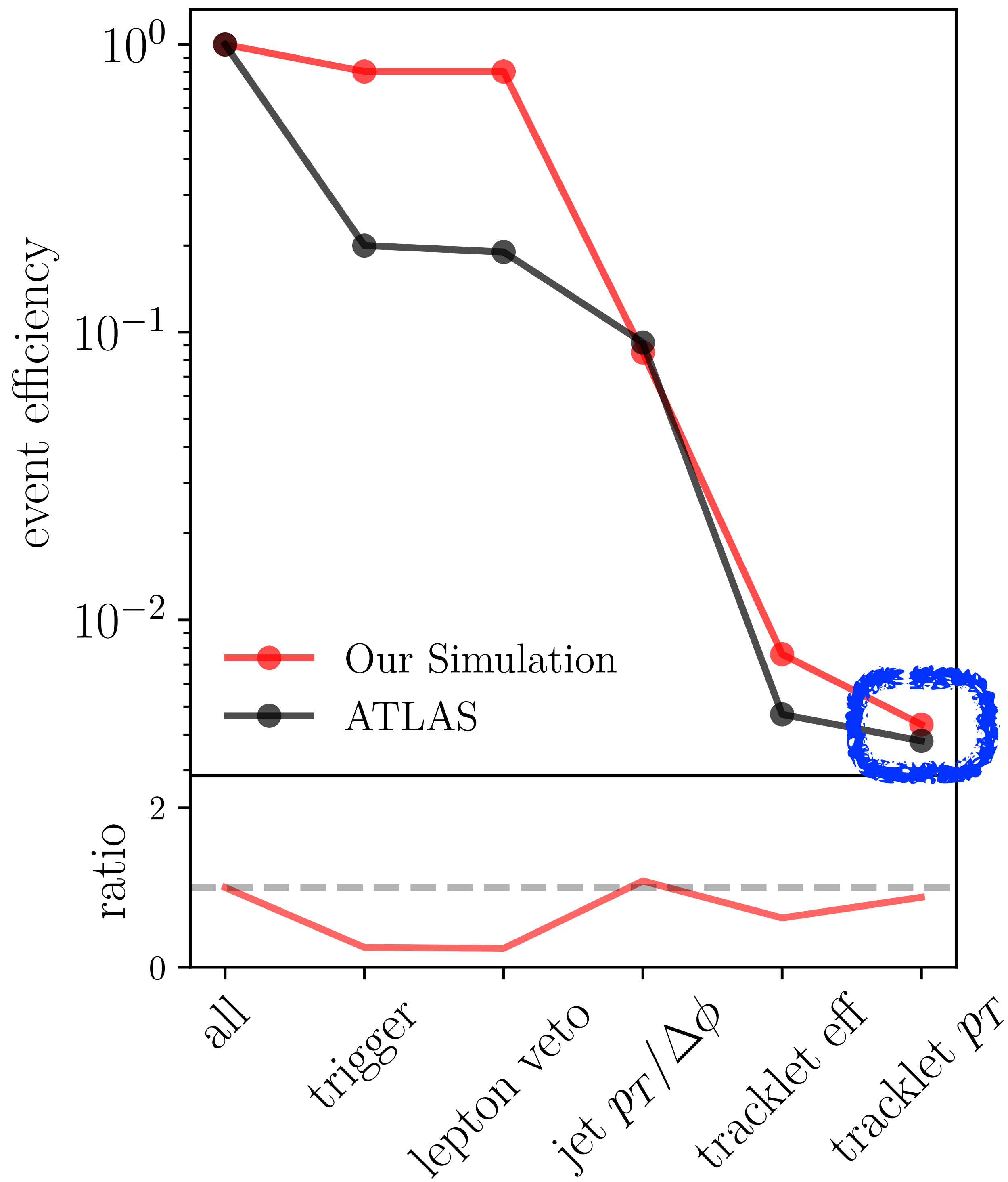
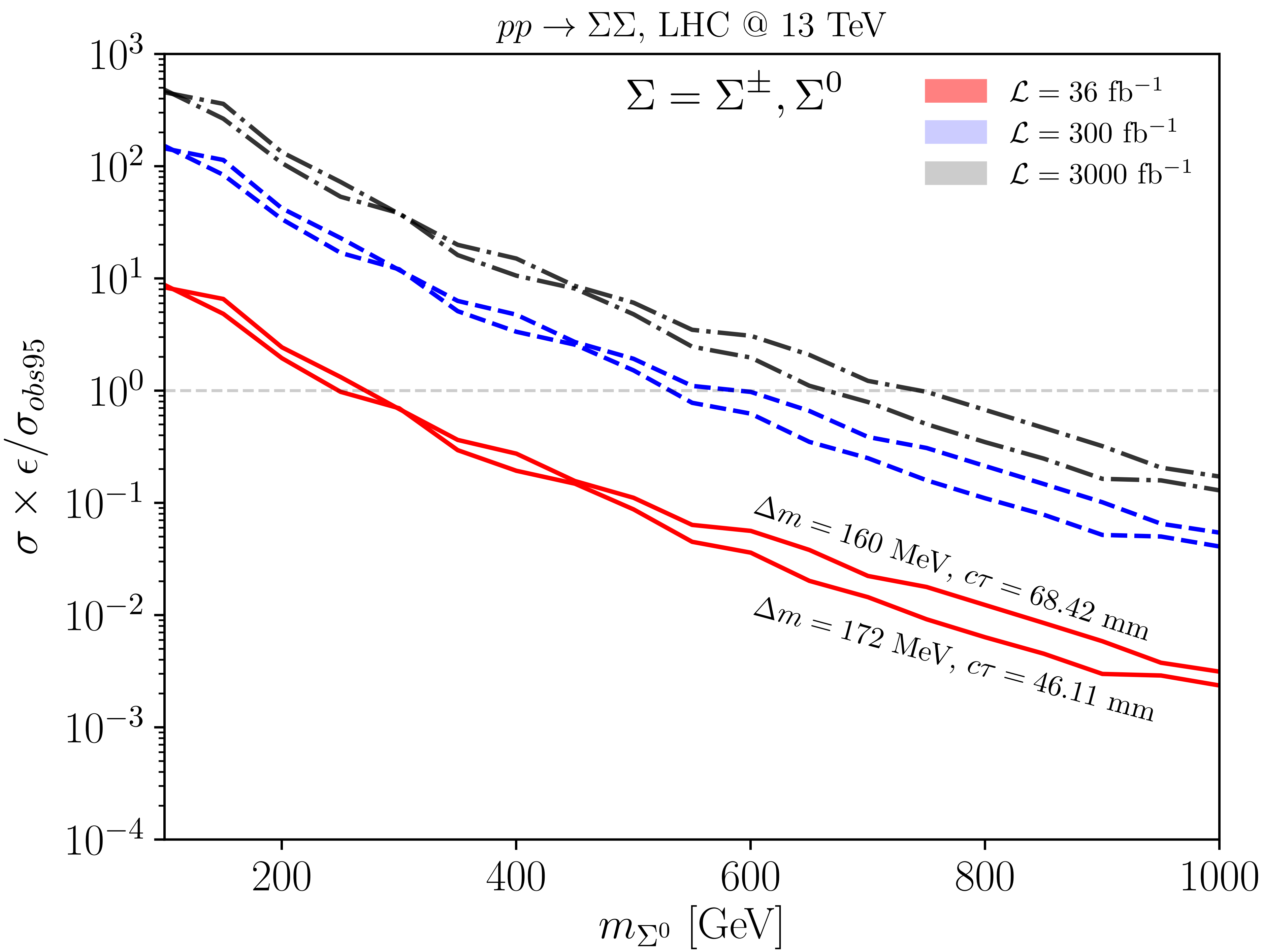


What we find…Collider part

C.W. Chiang, G. Cottin, Yong Du,
K. Fuyuto, M.J. Ramsey-Musolf
arXiv: 2003.07867

(HL-)LHC exclusion from cross section



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FCC-pp discovery with different pileup control

M. Saito, R. Sawada, K. Terashi and S. Asai, 2019

Benchmark	σ [pb]	ϵ	S	B	$S/\sqrt{B}$
$m_{\Sigma^\pm} = 1.1$ TeV, $\overline{\mu} = 200$	5.8×10^{-2}	3.17×10^{-4}	553	673	21.3
$m_{\Sigma^\pm} = 1.1$ TeV, $\overline{\mu} = 500$	5.8×10^{-2}	3.17×10^{-4}	553	8214	6
$m_{\Sigma^\pm} = 3.1$ TeV, $\overline{\mu} = 200$	9.4×10^{-4}	4.69×10^{-4}	13.3	1.9	9.6
$m_{\Sigma^\pm} = 3.1$ TeV, $\overline{\mu} = 500$	9.4×10^{-4}	4.69×10^{-4}	13.3	27	2.6

3TeV triplet DM could be discoverable at FCC-pp

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3TeV triplet DM could be discoverable at FCC-pp

Collider searches are a2 insensitive!

What we find…Combination

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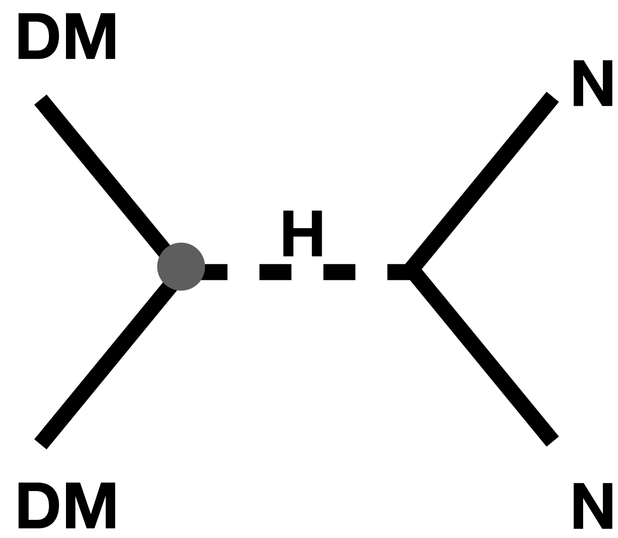
arXiv: 2003.07867

Colliders+relic abundance



What we find...Combination

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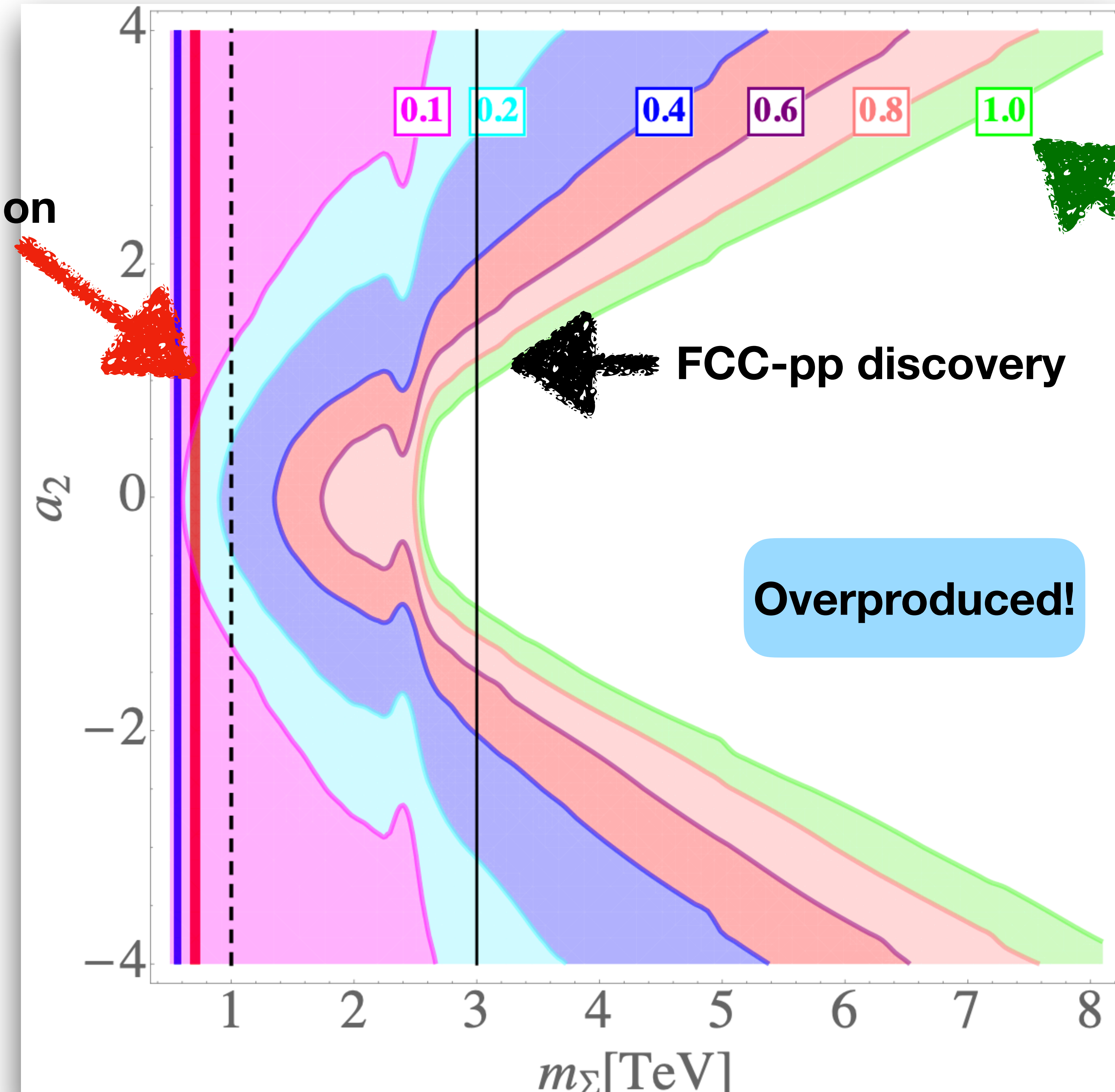
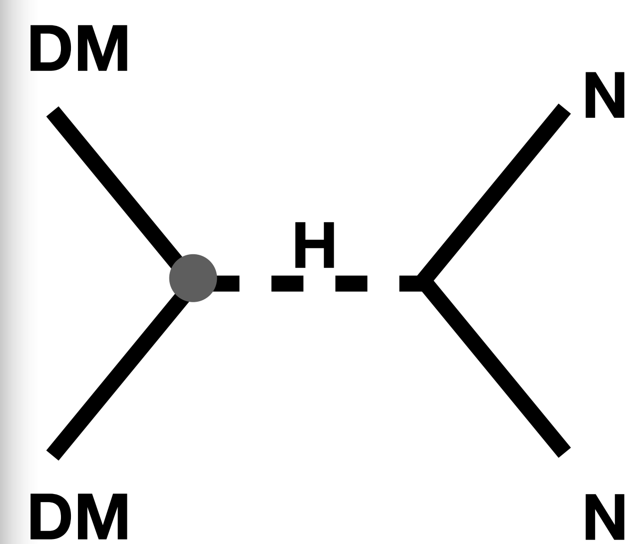
Colliders+relic abundance

LHC exclusion



FCC-pp discovery

$$\mathcal{R} = \frac{\Omega_\Sigma}{\Omega_{DM}}$$



What we find...Combination

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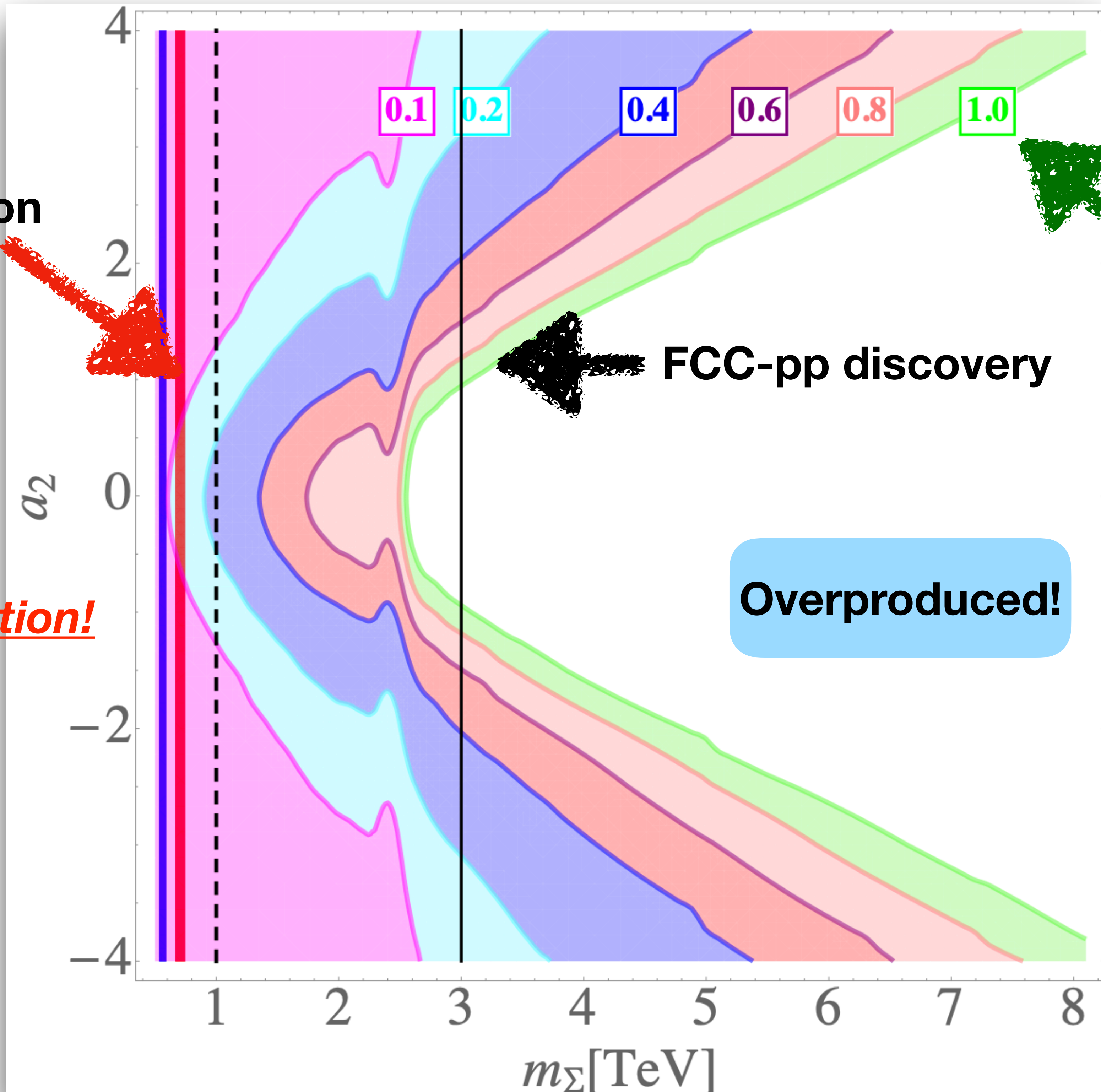
Colliders+relic abundance

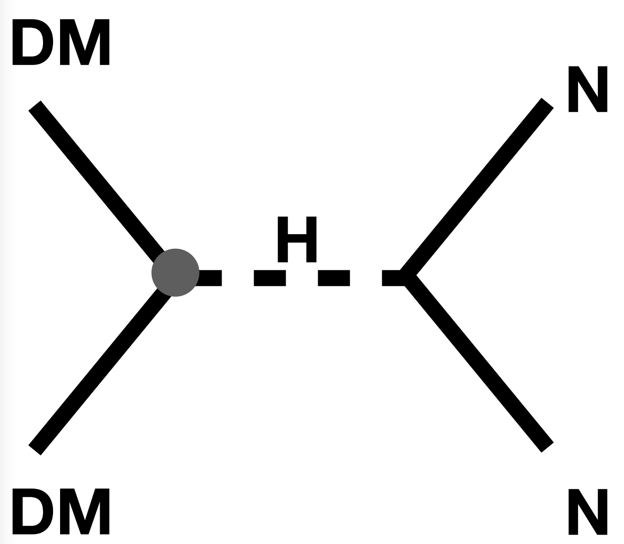
LHC exclusion

DM observation!



FCC-pp discovery

$$\mathcal{R} = \frac{\Omega_\Sigma}{\Omega_{\rm DM}}$$



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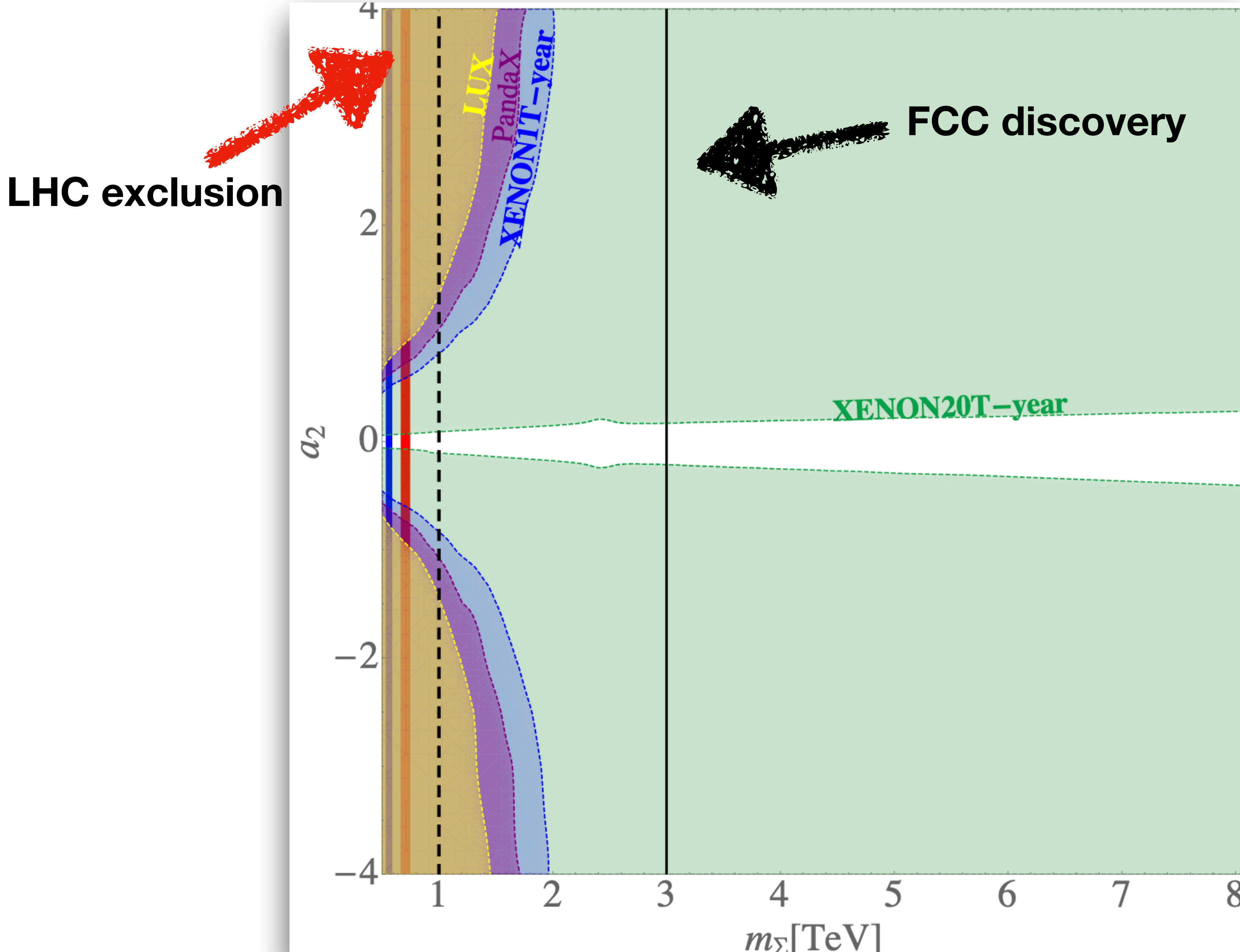
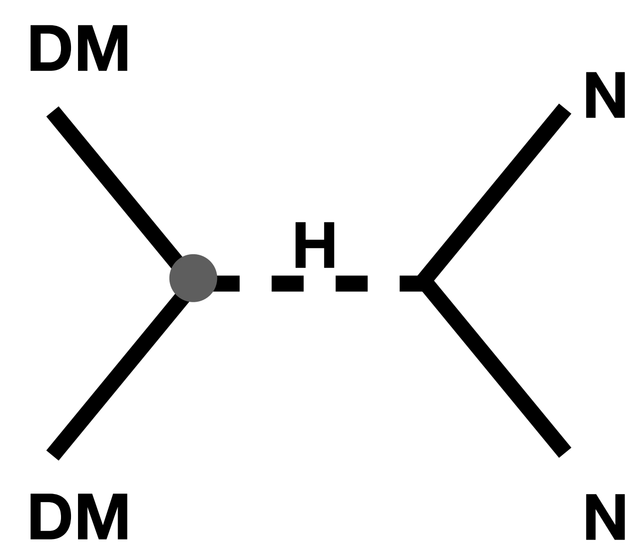


$$\sigma_{\rm SI}^{\rm scaled} \equiv \frac{\sigma_{\rm SI}\Omega h^2}{(\Omega h^2)_{\rm Planck}}$$



What we find…Combination

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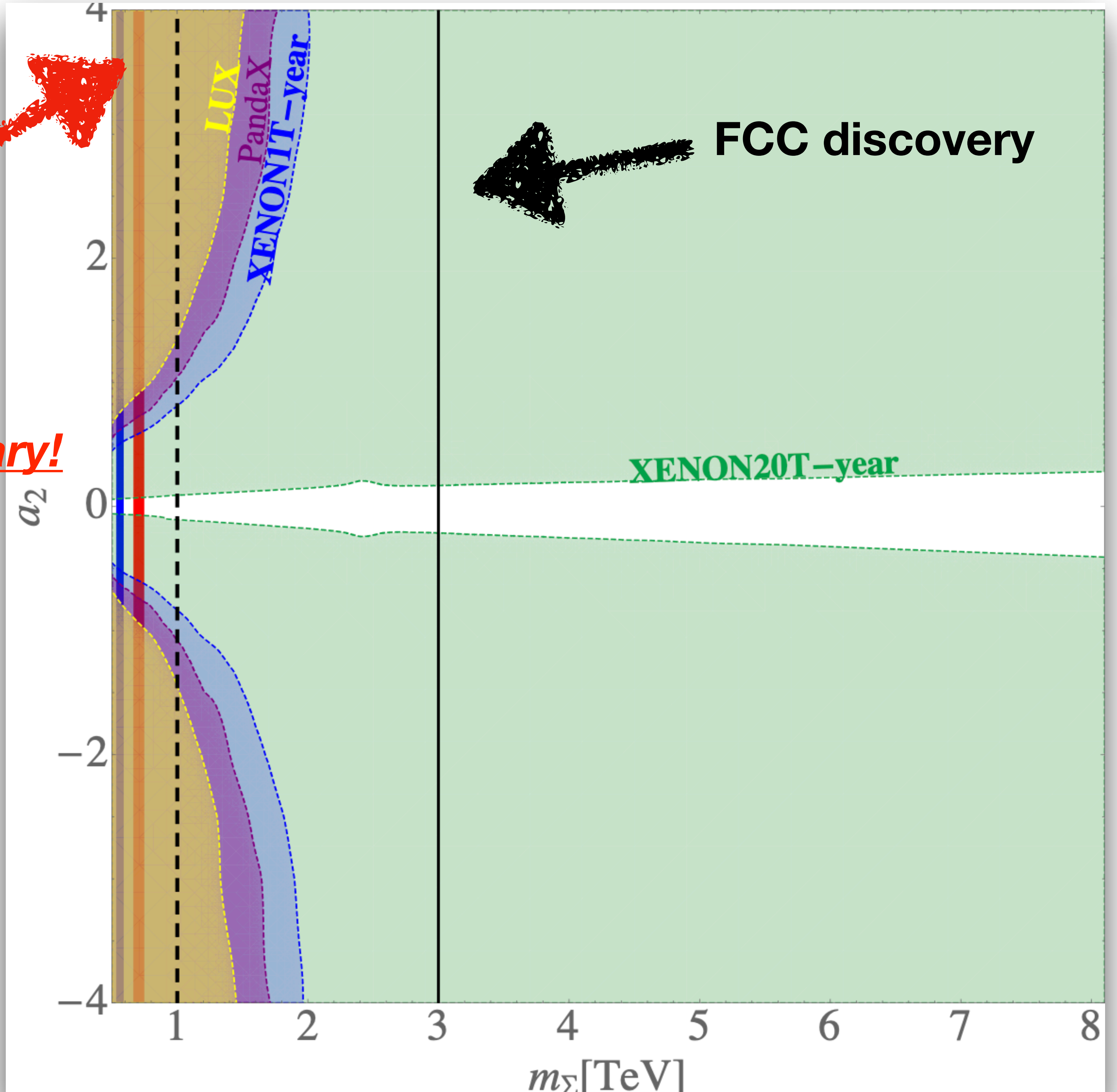
arXiv: 2003.07867

LHC exclusion

Complementary!



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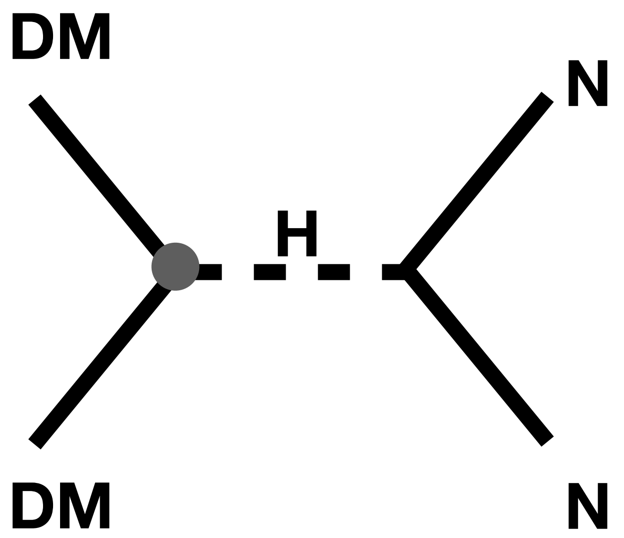


The complex triplet model

In collaboration with Aaron Dunbrack, Michael Ramsey-Musolf, Jiang-Hao Yu

Based on JHEP 01(2019)101

The Complex triplet model

(1) *Neutrino masses (type-II seesaw)*; (2) *BAU (EWBG)*

SM Higgs Doublet

$$\Phi = \begin{bmatrix} \varphi^+ \\ \frac{1}{\sqrt{2}}(\varphi + i\chi) \end{bmatrix}$$

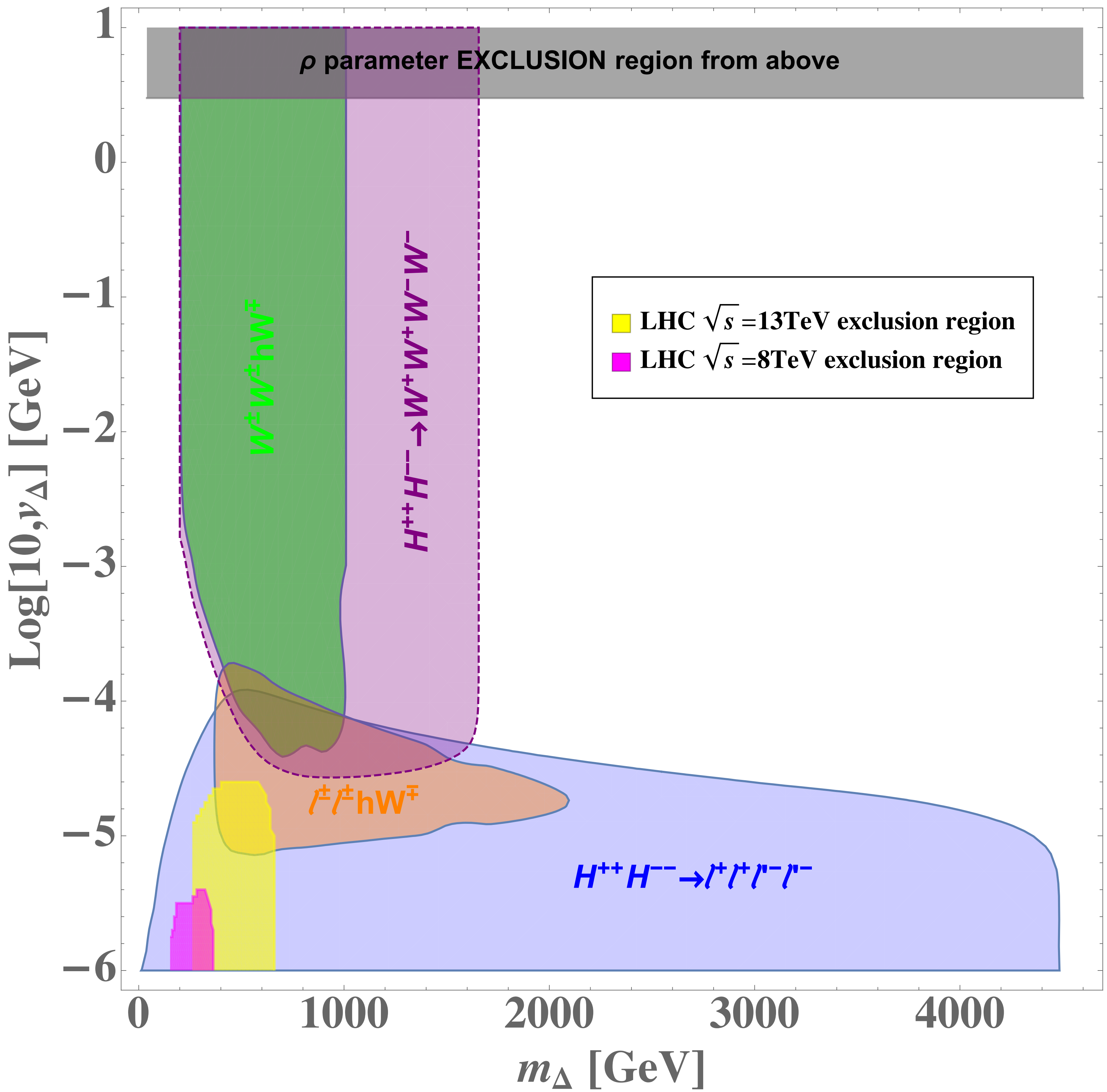
Complex triplet

$$\Delta = \begin{bmatrix} \frac{\Delta^+}{\sqrt{2}} & H^{++} \\ \frac{1}{\sqrt{2}}(\delta + i\eta) & -\frac{\Delta^+}{\sqrt{2}} \end{bmatrix}$$

$\Delta(1,3,2)$

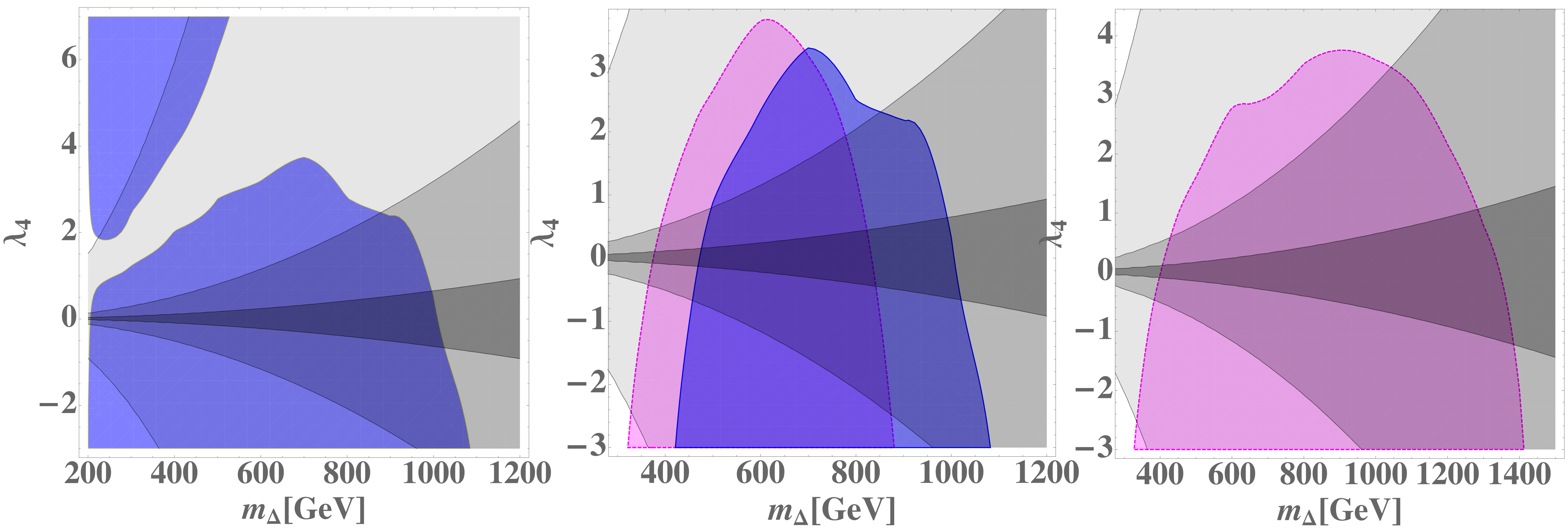
$$V(\Phi,\Delta) = -m^2\Phi^\dagger\Phi + M^2\mathrm{Tr}(\Delta^\dagger\Delta) + \left[\mu\Phi^{\mathrm{T}}\mathrm{i}\tau_2\Delta^\dagger\Phi + \mathrm{h.c.}\right] + \lambda_1(\Phi^\dagger\Phi)^2$$
$$+ \lambda_2\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 + \lambda_3\mathrm{Tr}[\Delta^\dagger\Delta\Delta^\dagger\Delta] + \lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_5\Phi^\dagger\Delta\Delta^\dagger\Phi$$

The Complex triplet model



Higgs portal parameter determination

$hW^{\pm}W^{\mp}W^{\mp}$ $hW^{\pm}\ell^{\mp}\ell^{\mp}$



$v_\Delta = 10^{-1}$ GeV $v_\Delta = 10^{-4}$ GeV $v_\Delta = 10^{-5}$ GeV

$R_{h\gamma\gamma} = 1.16^{+0.20}_{-0.18}$ (LHC)
$R_{h\gamma\gamma} = 1 \pm 0.05$ (FCC-ee)
$R_{h\gamma\gamma} = 1 \pm 0.01$ (FCC-hh)

ATLAS&CMS, JHEP08, 045 (2016)

Contino et al, CERN Yellow Report (2017)

Summary

✱ The real triplet (1,3,0) model in the dark matter scenario:

1. could be discovered up to ~(300) 800GeV at (HL-)LHC. FCC-pp could discover 3 TeV triplet depending on pileup control.
2. XENON1T rules out 1~2TeV triplet (depending on a2), XENON20T would cover almost the entire parameter space.
3. Collider and dark matter direct detection are complementary.

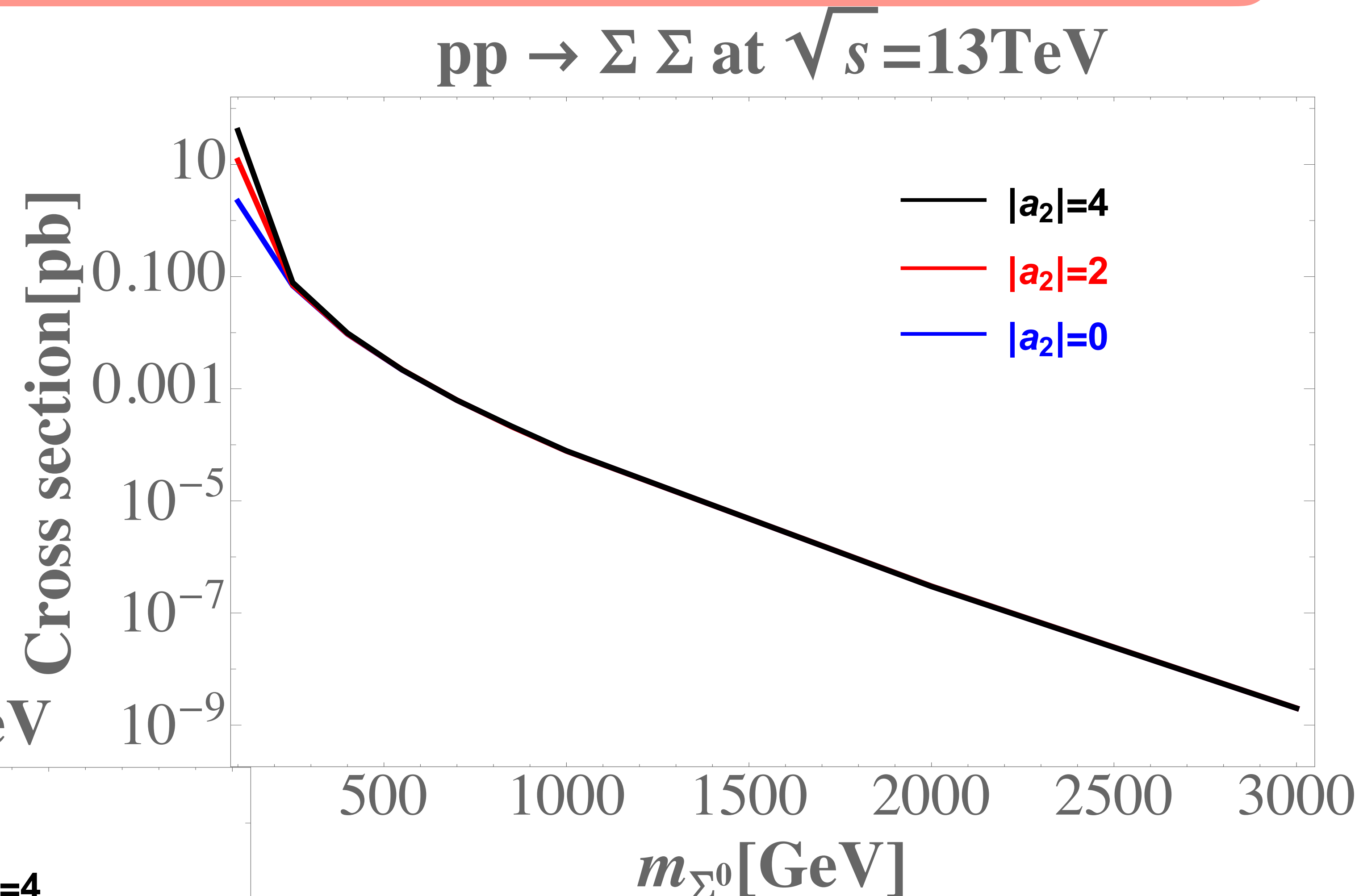
✱ The complex triplet (1,3,2) model:

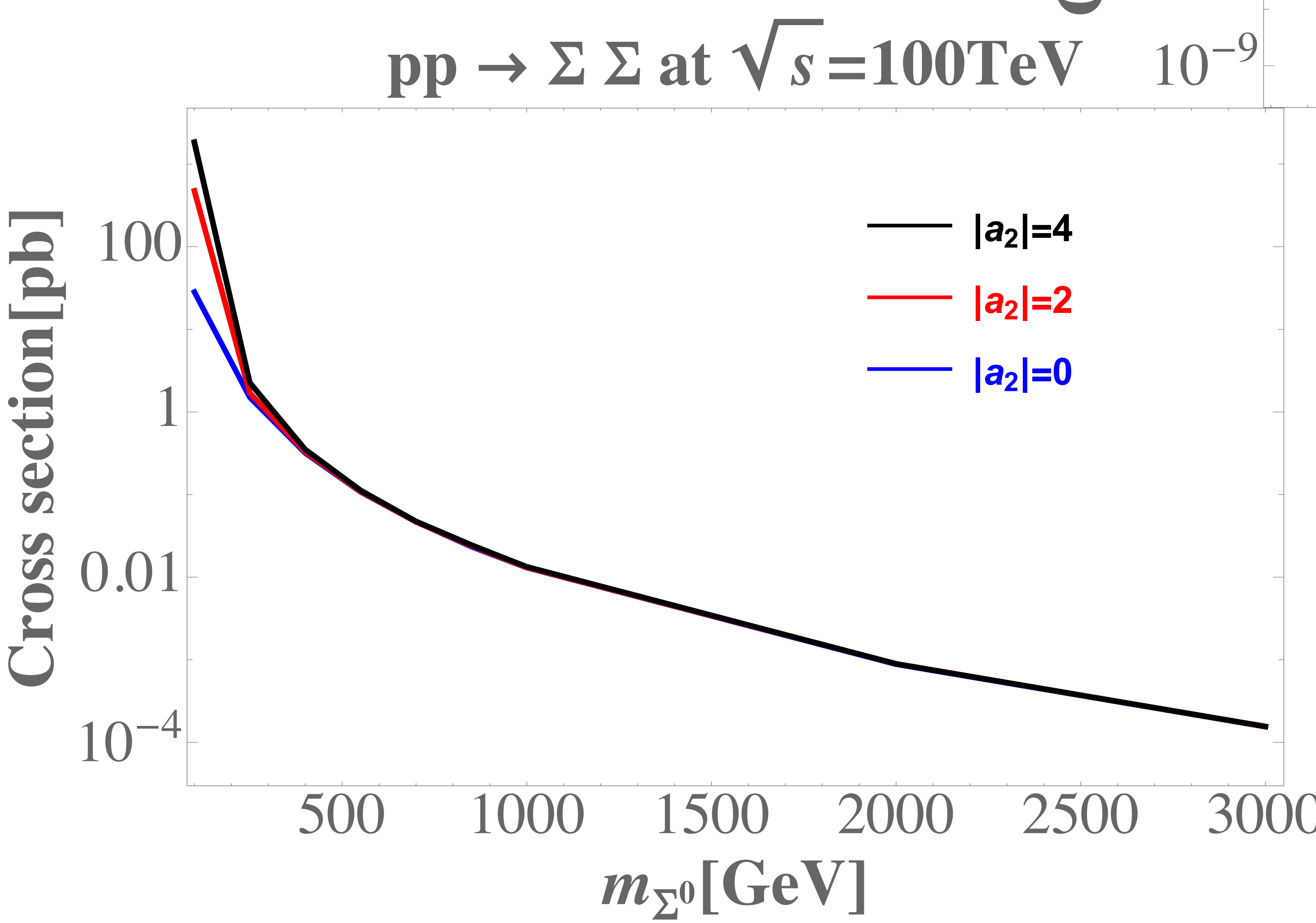
1. FCC-pp could cover a significant portion of its parameter space up to 4TeV.
2. Precision measurements of $h > \gamma\gamma$ help indirectly the Higgs portal parameter determination.

Backup

Production cross section: a2 dependence

13 TeV





100 TeV

C.W. Chiang, G. Cottin, Yong Du, K. Fuyuto, M.J. Ramsey-Musolf arXiv: 2003.07867

Cuts applied for the (HL-)LHC

- Trigger : $\not{p}_T > 140\,\text{GeV}$
- Lepton veto : no electrons or muons
- Jet $p_T/\Delta\phi$: at least one jet with $p_T > 140\,\text{GeV}$, and $\Delta\phi$ between the $\not{p}_T$ vector and each of the up to four hardest jets with $p_T > 50\,\text{GeV}$ to be bigger than 1.0
- Tracklet selection : at least one tracklet (generator-level chargino) with :
  - $p_T > 20\,\text{GeV}$ and $0.1 < |\eta| < 1.9$
  - 122.5 mm < decay position < 295 mm
  - ΔR distance between the tracklet and each of the up to four highest$-p_T$ jets with $p_T > 50\,\text{GeV}$ to be bigger than 0.4
  - we apply the tracklet acceptance × efficiency map[6] provided by ATLAS, which is based on the decay position and η. This is applied to selected tracklets passing the above selections.
- Tracklet p_T : Select tracklets with $p_T > 100\,\text{GeV}$.

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arXiv: 2003.07867

Cuts applied for a 100TeV collider

- Trigger : $\not{p}_T > 1\,\text{TeV}$ or $\not{p}_T > 4\,\text{TeV}$ depending on the benchmark as discussed below.
- Lepton veto : no electrons or muons.
- Jet $p_T/\Delta\phi$: at least one jet with $p_T > 1\,\text{TeV}$, and $\Delta\phi$ between the $\not{p}_T$ vector and each of the up to four hardest jets with $p_T > 50\,\text{GeV}$ to be bigger than 1.0.

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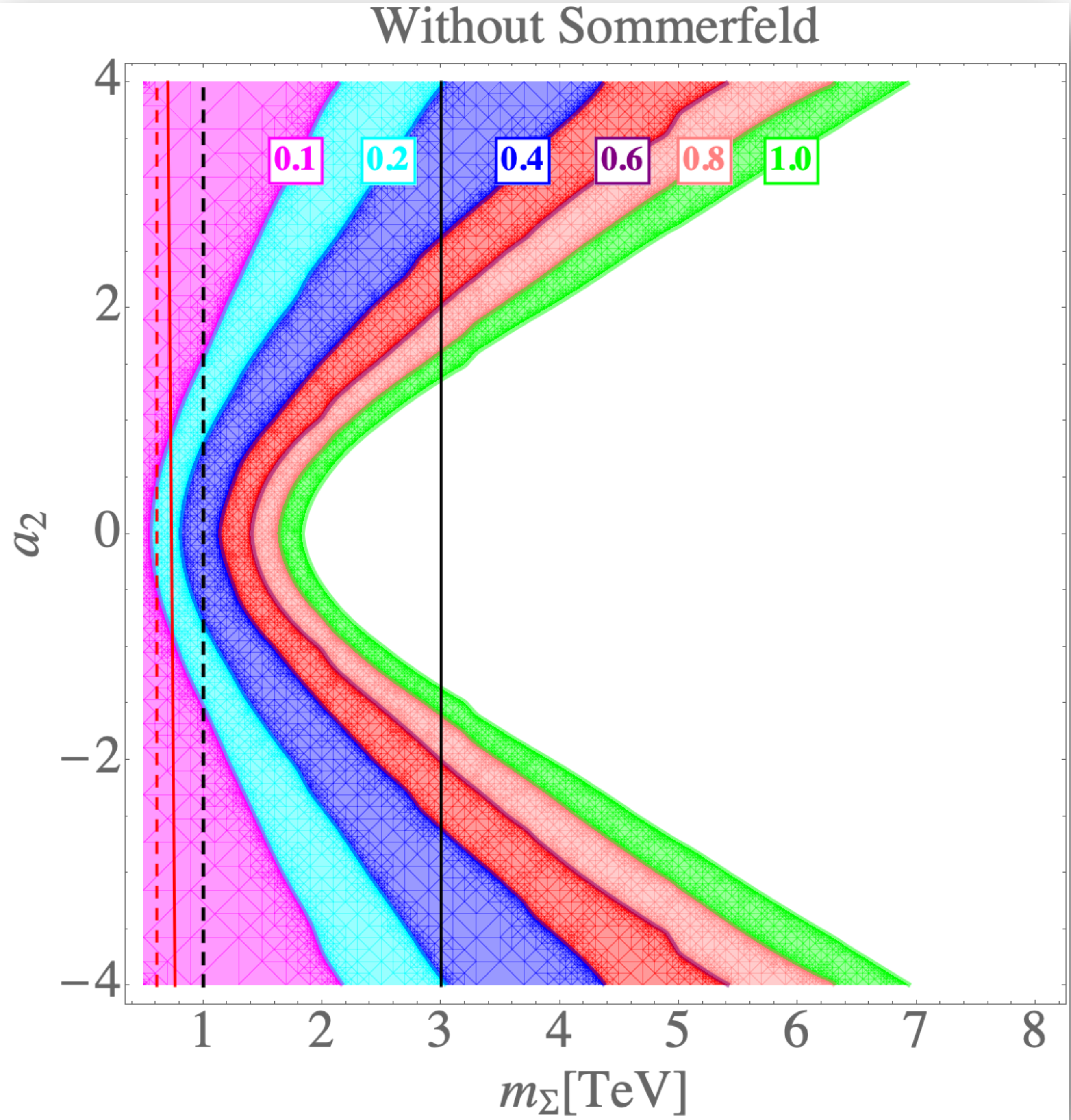
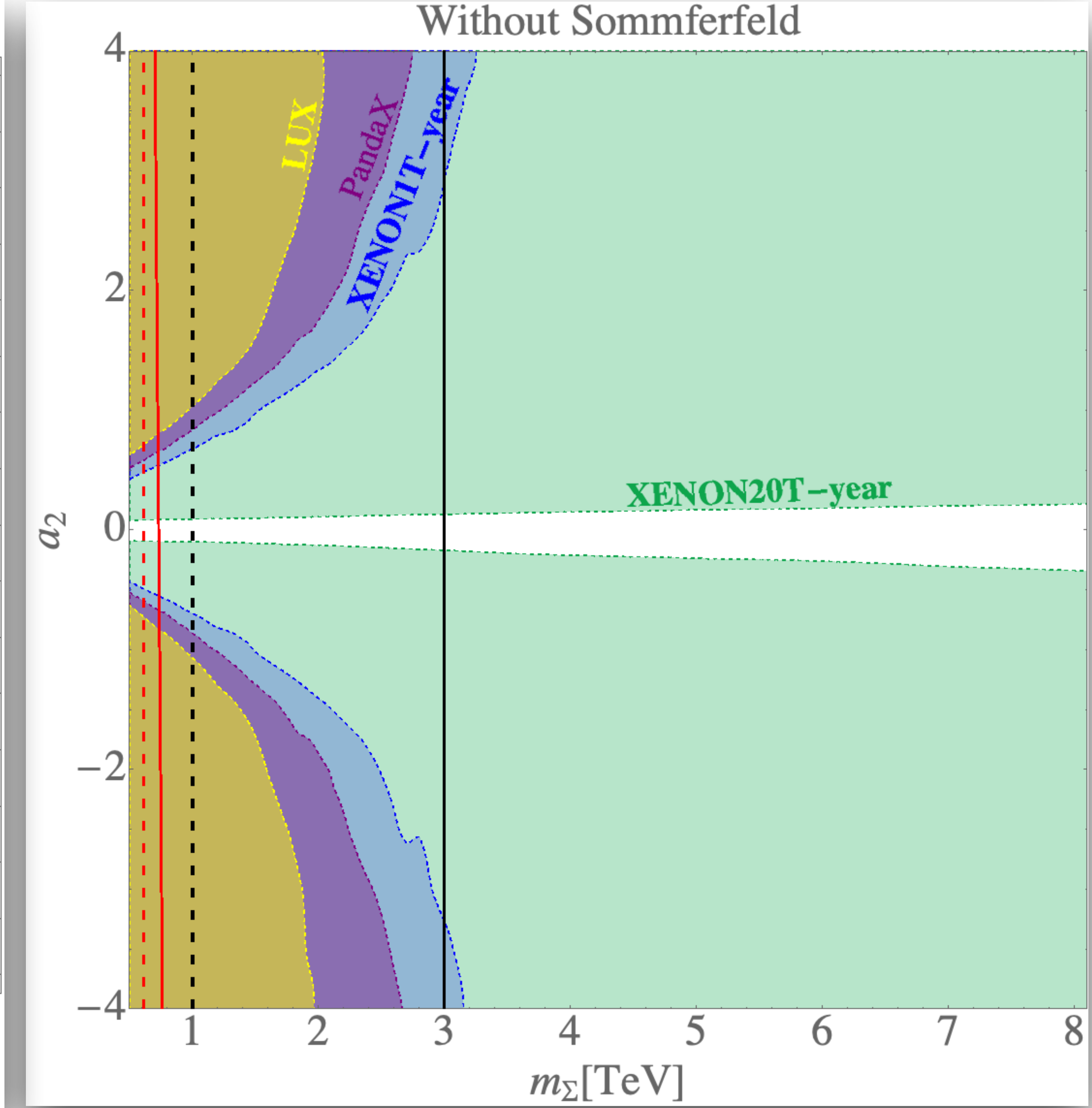
Constraints w/o including the Sommerfeld





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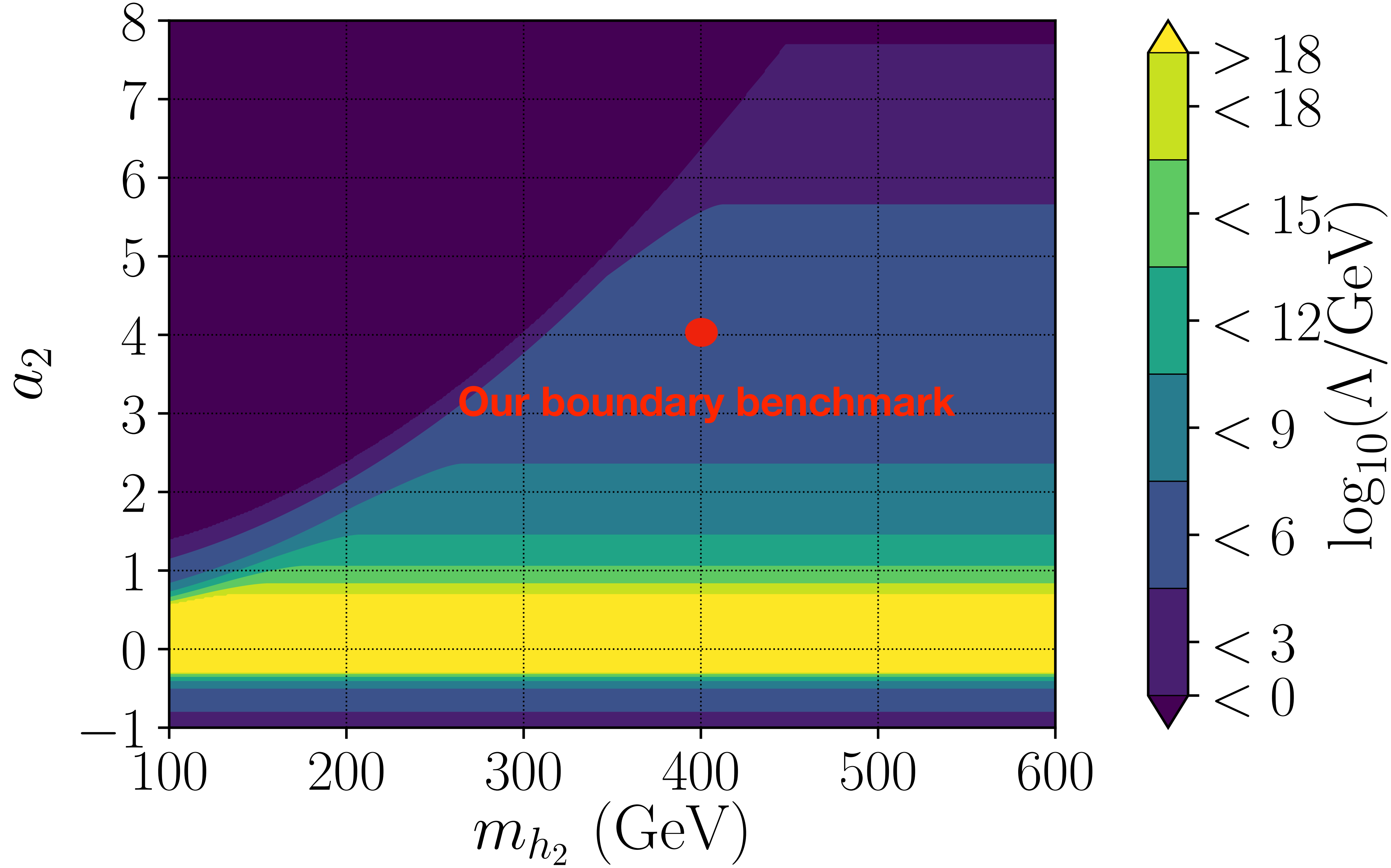
Constraints from perturbativity and perturbative unitarity



Bell et al, arXiv: 2001.05335

Complex triplet

Model key features

$\Delta(1,3,2)$

$$V(\Phi,\Delta) = -m^2\Phi^\dagger\Phi + M^2\mathrm{Tr}(\Delta^\dagger\Delta) + \left[\mu\Phi^{\mathrm{T}}\mathrm{i}\tau_2\Delta^\dagger\Phi + \mathrm{h.c.}\right] + \lambda_1(\Phi^\dagger\Phi)^2$$
$$+ \lambda_2\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 + \lambda_3\mathrm{Tr}[\Delta^\dagger\Delta\Delta^\dagger\Delta] + \lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_5\Phi^\dagger\Delta\Delta^\dagger\Phi$$

$$\rho \equiv \frac{m_W^2}{m_Z^2\cos^2\theta_W} = \frac{1+\frac{2v_\Delta^2}{v_\Phi^2}}{1+\frac{4v_\Delta^2}{v_\Phi^2}}$$

$$\rho = 1.0006 \pm 0.0009$$

PDG, 2016

$$0 \leq v_\Delta \lesssim 3.0\ \ \mathrm{GeV}$$
$$v_\Delta \ll v_\Phi \simeq v$$
$$v = \sqrt{v_\Delta^2 + v_\Phi^2} = 246\,\mathrm{GeV}$$

$$\sin\beta_\pm \sim \sin\beta_0 \sim \sin\alpha \sim \frac{v_\Delta}{v_\Phi} \sim 0$$

Model key features

$$\Delta m = |m_{H^{\pm\pm}} - m_{H^{\pm}}| \approx |m_{H^{\pm}} - m_{H,A}| \approx \frac{|\lambda_5| v_\Phi^2}{8 m_\Delta} \approx \frac{|\lambda_5| v^2}{8 m_\Delta}$$

Determined by mass splitting

$$m_h^2 \simeq 2 v_\Phi^2 \lambda_1 \simeq 2 v^2 \lambda_1, \quad m_H \simeq m_\Delta \simeq m_A, \quad m_{H^\pm}^2 \simeq m_\Delta^2 - \frac{\lambda_5}{4} v_\Phi^2, \quad m_{H^{\pm\pm}}^2 \simeq m_\Delta^2 - \frac{\lambda_5}{2} v_\Phi^2$$

Fixed by SM Higgs mass

$$\lambda_1 \simeq 0.129$$

Basically the mass scale of the triplet

Model key features

$$m_h^2 \simeq 2v_\Phi^2\lambda_1 \simeq 2v^2\lambda_1, \quad m_H \simeq m_\Delta \simeq m_A, \quad m_{H^\pm}^2 \simeq m_\Delta^2 - \frac{\lambda_5}{4}v_\Phi^2, \quad m_{H^{\pm\pm}}^2 \simeq m_\Delta^2 - \frac{\lambda_5}{2}v_\Phi^2$$

Also determines the mass hierarchy

$$\lambda_5 \leq 0: \;\; m_h < m_H \simeq m_A \leq m_{H^\pm} \leq m_{H^{\pm\pm}}$$

Model key features

$$V(\Phi,\Delta) = -m^2\Phi^\dagger\Phi + M^2\mathrm{Tr}(\Delta^\dagger\Delta) + \left[\mu\Phi^{\mathrm{T}}\mathrm{i}\tau_2\Delta^\dagger\Phi + \mathrm{h.c.}\right] + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 + \lambda_3\mathrm{Tr}[\Delta^\dagger\Delta\Delta^\dagger\Delta] + \lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_5\Phi^\dagger\Delta\Delta^\dagger\Phi$$

How determine?

$$\mathrm{Br}(\mathrm{A}\to\mathrm{hZ},\mathrm{H}\to\mathrm{ZZ},\mathrm{H}\to\mathrm{W^+W^-},\mathrm{H^\pm}\to\mathrm{hW^\mp}) = \mathrm{F}(\lambda_4,\lambda_5,\ldots)$$

Model key features

Brief summary

Fixed by SM Higgs mass

$$V(\Phi,\Delta) = -m^2\Phi^\dagger\Phi + M^2\mathrm{Tr}(\Delta^\dagger\Delta) + \left[\mu\Phi^{\mathrm{T}}\mathrm{i}\tau_2\Delta^\dagger\Phi + \mathrm{h.c.}\right] + \lambda_1(\Phi^\dagger\Phi)^2$$
$$+ \lambda_2\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 + \lambda_3\mathrm{Tr}[\Delta^\dagger\Delta\Delta^\dagger\Delta] + \lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_5\Phi^\dagger\Delta\Delta^\dagger\Phi$$

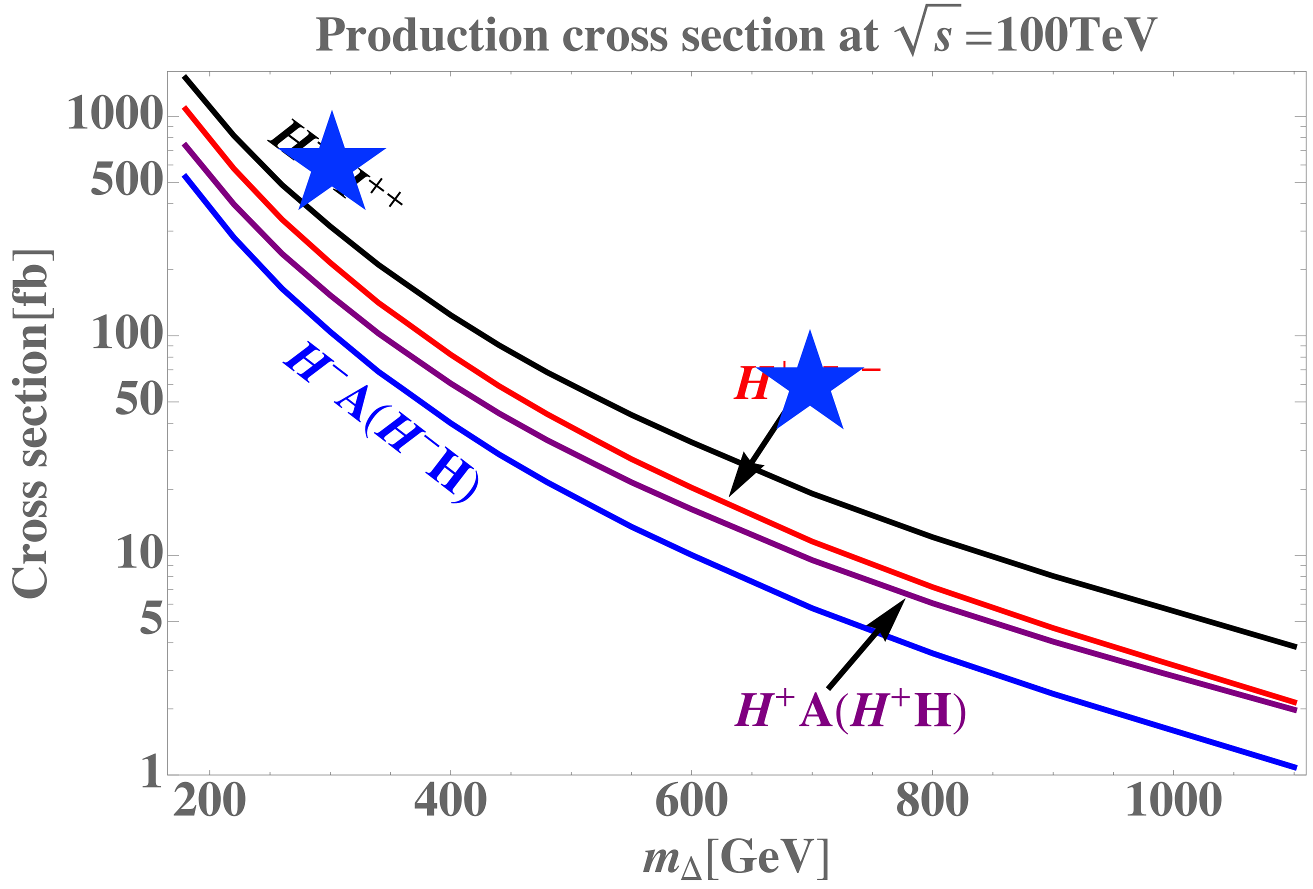
Remain unknown

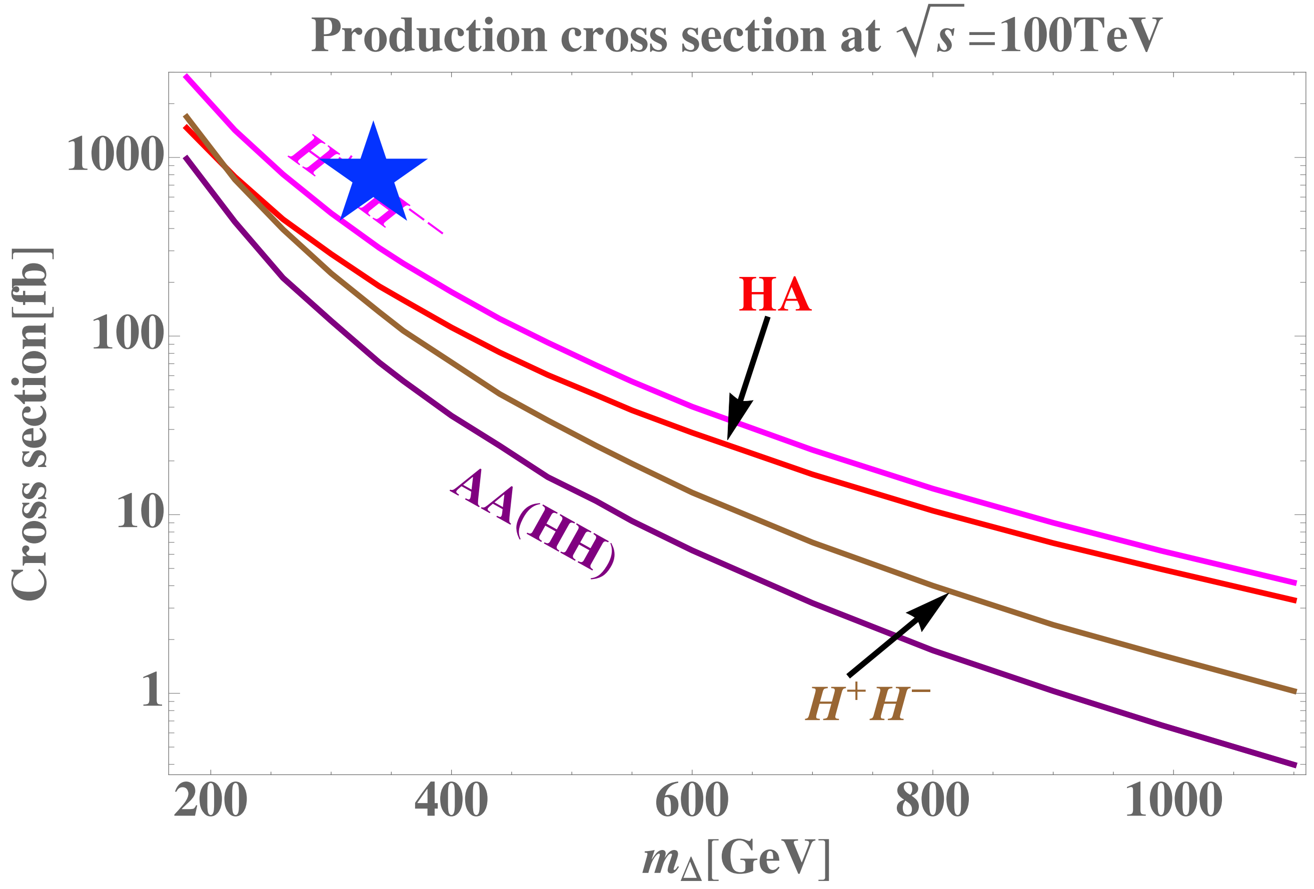
From the BRs

Determined by mass splitting

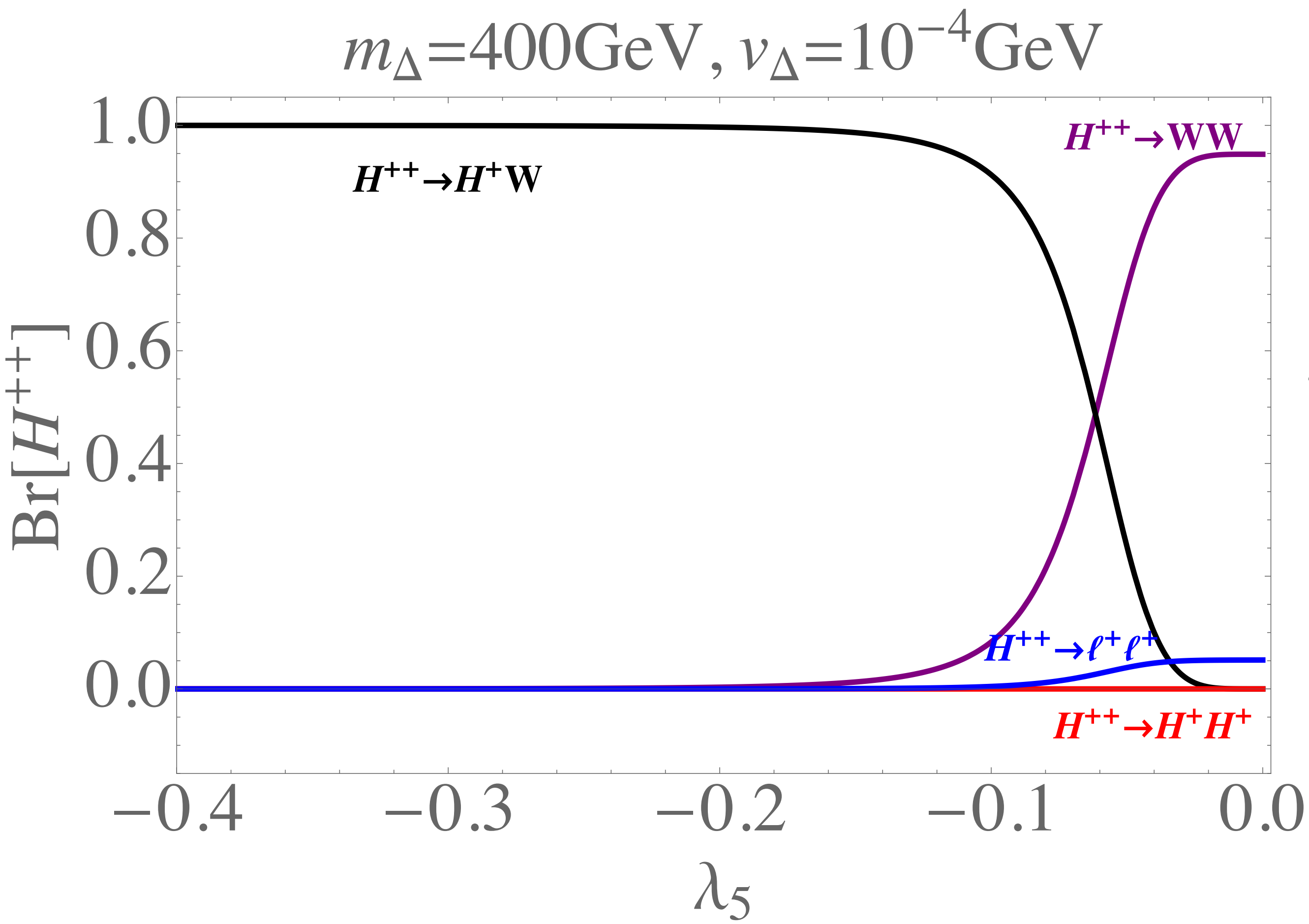
Model discovery

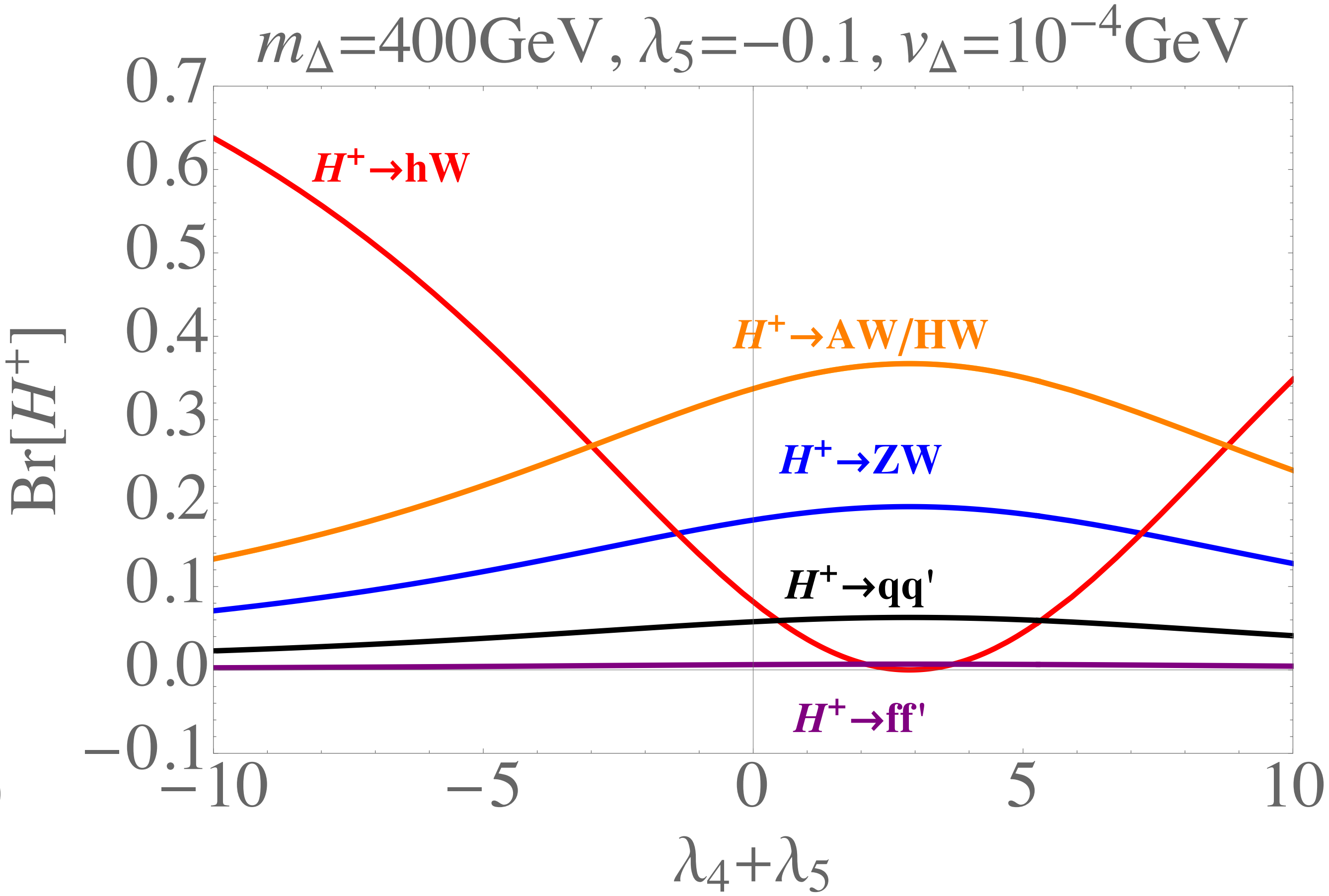
$$\lambda_1 = 0.129, \lambda_2 = 0.2, \lambda_3 = 0, \lambda_4 = 0, \lambda_5 = -0.1$$





Model discovery



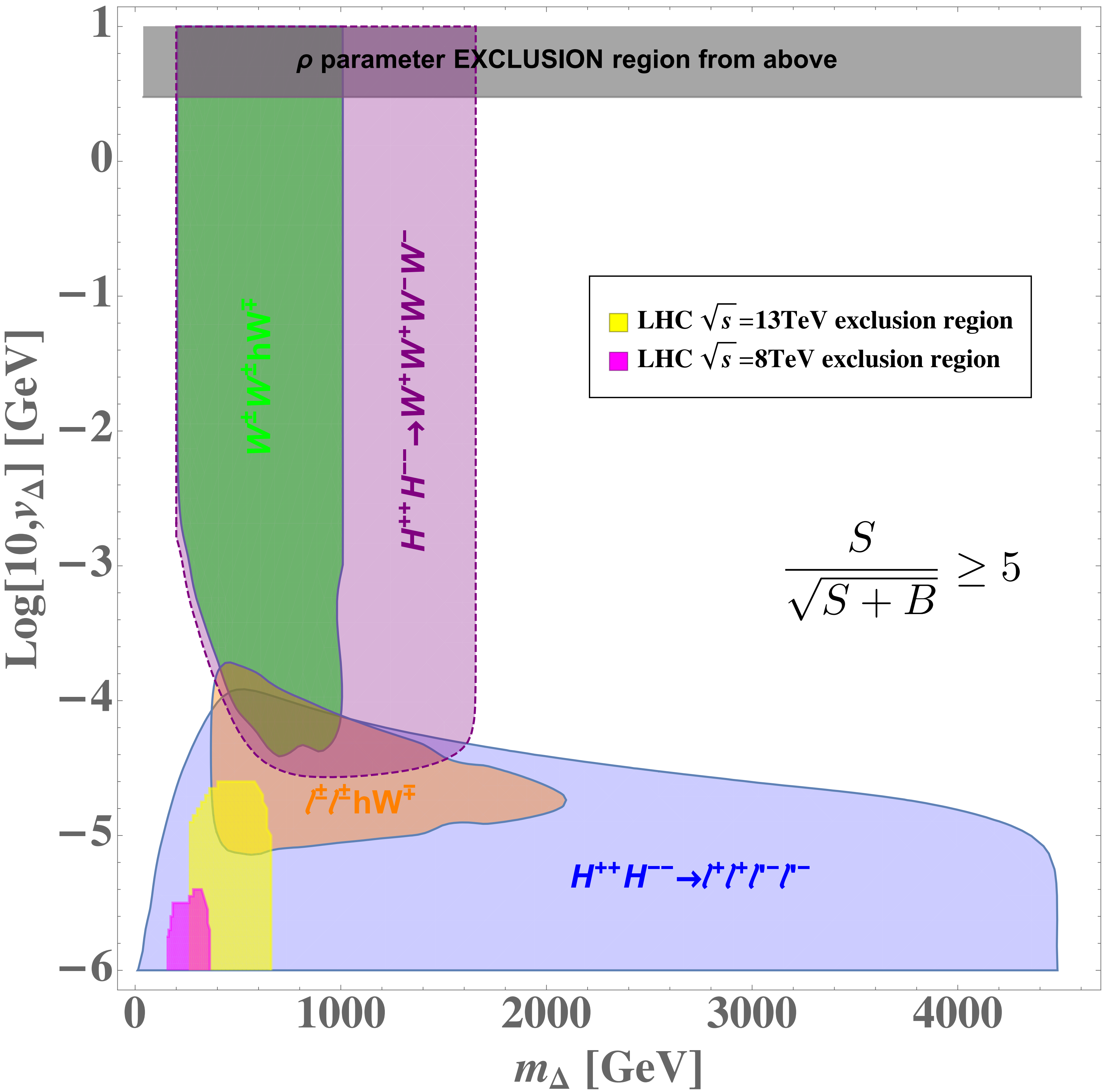


$$\mathrm{pp} \to \mathrm{H}^{++}\mathrm{H}^{--} \text{ and } \mathrm{pp} \to \mathrm{H}^{\pm\pm}\mathrm{H}^{\mp}$$

$$\mathrm{H}^{\pm\pm} \to \ell^\pm\ell^\pm \ (\mathrm{W}^\pm\mathrm{W}^\pm) \text{ and } \mathrm{H}^{\mp} \to \mathrm{hW}^{\mp}$$

small v_Δ large v_Δ

Model discovery



$\lambda_2 = 0.2$

$\lambda_3 = 0$

$\lambda_4 = 0$

$\lambda_5 = -0.1$

ATLAS, JHEP03, 041(2015)

ATLAS, Eur. Phys. J C78 (2018)

$$m^2_{H^{\pm\pm}} \simeq m^2_\Delta - \frac{\lambda_5}{2} v^2_\Phi$$

$$m_\Delta \geq 0\,\mathrm{GeV}$$

$$\Leftrightarrow m_{H^{\pm\pm}} \geq 54.78\,\mathrm{GeV}$$

LEP constraints automatically satisfied

OPAL (1992, 2002)

Higgs portal parameter determination

$$\Delta m = |m_{H^{\pm\pm}} - m_{H^\pm}| \approx |m_{H^\pm} - m_{H,A}| \approx \frac{|\lambda_5| v_\Phi^2}{8 m_\Delta} \approx \frac{|\lambda_5| v^2}{8 m_\Delta}$$

Upon discovery, λ_5 can be determined readily by the mass splitting.

Can determine λ_4 from precise measurements on Br($H^\pm \to hW^\pm$) after discovery.

Parameter scan on the v_Δ-m_Δ plane and BDT analysis for

$$pp \to H^{\pm\pm} H^\mp \to \ell^\pm \ell^\pm h W^\mp / W^\pm W^\pm h W^\mp$$