Constraining Asymmetric Dark Matter using Collider and Direct Detection

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SUSY 2024
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Asymmetric DarK Matter

The Significant asymmetry between matter and anti matter → Baryogenesis

$$\Omega_b \approx \Omega_{DM}/5$$

Planck Collaboration 1807. 06209

→ Similar kind of asymmetry is also expected in the DM abundance

→ Asymmetric Dark Matter

- The ADM hypothesis is well motivated from UV considerations.. Follow very similar type of interactions, masses are also at Gev scale or so.

- The key idea being that efficient annihilation of symmetric part of the ADM relic density requires cou between DM fermions and SM particles are not too weak.

- In view of plethora of DM searches at the LHC and Direct detection experiments, constraints on ADM are studied. Also included the constrained from heating of compact stars.

K.M.zurek, Phys Rept 2014, 1308.0338
Petraki and Volkas, IJMP 2013, 1305.4939

Outline

- The most generalised model independent approach EFT are followed

- DM-quark interactions and its implication

→ LHC Mono-jet searches

→ DD detections are

- DM - Lepton interactions assuming DM leptophilic

Leptophilic DM, motivated from leptogenesis which translated asymmetry in the DM via Sphaleron

→ LEP experiment Mono-photon searches

→ Constraints from the heating of Neutron stars(NS) and White dwarf(WD)

→. Feasibility studies at the FCC-ee

DM interaction and Production

- DM-SM interaction are encoded in the framweowkr of EFT. Dim 5 couplings of DM with Higgs are ignored(Higgs invisible decay BR is highly constrained)

- Assuming DM as the Dirac Fermion and mediators are heavier that the DM mass itself.

$$\mathcal{O}_{\Gamma\Gamma'} = \frac{1}{\Lambda^2}(\bar{\psi}\Gamma\psi)(\bar{\chi}\Gamma'\chi),$$

ψ **SM DIrac Fermions**

$$\Gamma = \{1, \gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu}, \sigma^{\mu\nu}\gamma^5\}.$$

χ **Dark Matter DIrac Fermions**

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Operator	Definition	Scattering	Annihilation
$\mathcal{O}_{ss}$	$\bar{\psi}\psi\bar{f}f$	SI (1)	p-wave
$\mathcal{O}_{pp}$	$\bar{\psi}\gamma^5\psi\bar{f}\gamma^5 f$	SD (q^2)	s-wave
$\mathcal{O}_{sp}$	$\bar{\psi}\psi\bar{f}i\gamma^5 f$	SD (q)	p-wave
$\mathcal{O}_{ps}$	$\bar{\psi}i\gamma^5\psi\bar{f}f$	SI (q)	s-wave
$\mathcal{O}_{vv}$	$\bar{\psi}\gamma^\mu\psi\bar{f}\gamma_\mu f$	SI (1)	s-wave
$\mathcal{O}_{aa}$	$\bar{\psi}\gamma^\mu\gamma^5\psi\bar{f}\gamma_\mu\gamma^5 f$	SD (1)	s-wave $\propto m_q^2/m_\chi^2$
$\mathcal{O}_{va}$	$\bar{\psi}\gamma^\mu\psi\bar{f}\gamma_\mu\gamma^5 f$	SD (v)	s-wave
$\mathcal{O}_{av}$	$\bar{\psi}\gamma^\mu\gamma^5\psi\bar{f}\gamma_\mu f$	SD (v)	p-wave
$\mathcal{O}_{tt}$	$\bar{\psi}\sigma^{\mu\nu}\psi\bar{f}\sigma_{\mu\nu} f$	SD (1)	s-wave
$\mathcal{O}_{pt}$	$\bar{\psi}i\sigma^{\mu\nu}\gamma^5\psi\bar{f}\sigma_{\mu\nu} f$	SI (q)	s-wave

L.T. Wang et al , JCAP, 1008.1591

Relic Density and the Asymmetry

- **The ADM hypothesis assumes, both DM and Anti-DM present unto some era of the evolution of the universe and then by some mechanism asymmetry is generated.**

- **The total DM abundance:**

$$Y_{\rm tot} = Y_\chi + Y_{\overline{\chi}} = (Y_\chi - Y_{\overline{\chi}}) + 2Y_{\overline{\chi}} = Y_{\rm asy} + Y_{\rm sym}$$

$$Y = n/s$$

- **The asymmetric part:**

$$Y_{\rm sym} = 2Y_{\overline{\chi}} = \frac{2Y_{\rm asy}}{\exp\left[Y_{\rm asy}\lambda\left(\frac{a}{x_F} + \frac{3b}{x_F^2}\right)\right] - 1}$$

M.Drees et al , JCAP 2010, 1104.5548

Where $\lambda = \frac{4\pi}{\sqrt{90}} m_\chi M_{\rm pl}\sqrt{g_*},$ **a and b are the co-efficients in the partial wave expansion of** $< \sigma v >$

$$x_{\rm F} = x_{\rm F_0}\left(1 + 0.285\frac{a\lambda Y_{\rm asy}}{x_{\rm F_0}^3} + 1.35\frac{b\lambda Y_{\rm asy}}{x_{\rm F_0}^4}\right) \qquad x_{F_0} = m_\chi/\Gamma$$

The constraint imposed in the ADM model, the symmetric part must be sub-leading to asymmetric part

$$Y_{\rm sym} \leq \frac{1}{100} \times \frac{\Omega_{\rm DM}h^2}{2.76 \times 10^8}\left(\frac{\rm GeV}{m_\chi}\right) < 1\,\%$$

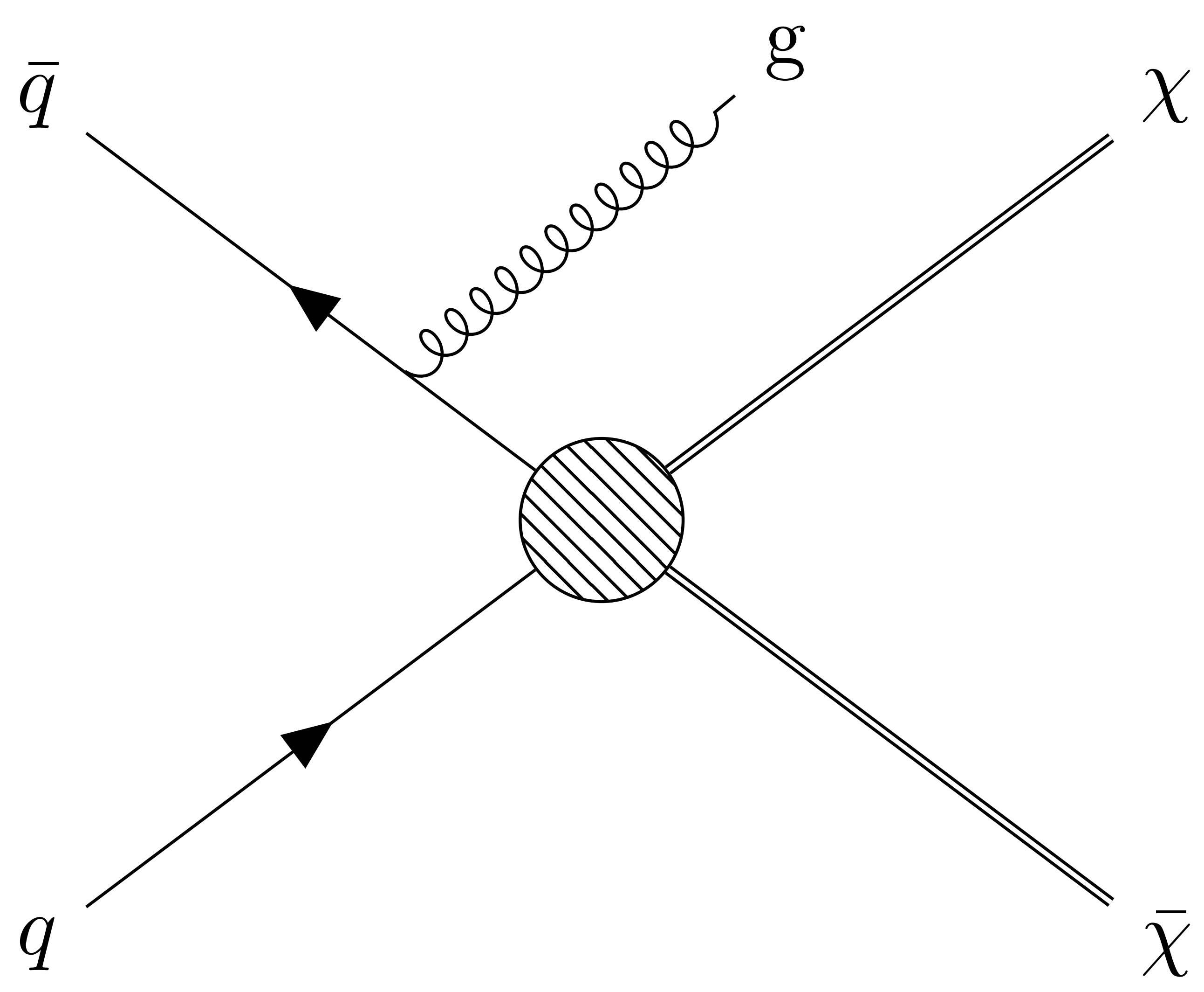
(Say)

March-Russell, Unwin, and West, JHEP 2012, 1203.4854

ADM-quark interactions

The DM-quark interactions constrained by the DD experiments and mono-jet searches at the LHC

March-Russell, Unwin, and West, JHEP 2012, 1203.4854



DM does not give detectable signals and hence need some Other visible particle.

$$pp \to \chi\chi j \to \not{E}_T j.$$

MG5aMC_atNLO + Feynrules UFO+PYTHIA8+Delphes

Selection criteria	σ^{95}(fb)
$p_T^j > 200$ GeV	736
$p_T^j > 1200$ GeV	0.3

ATLAS Collaboration, PRD 2021

$$\sigma_{mes} = \sigma \times A$$

For a given EFT operator, if cross section is larger than the measured one, then the corresponding λ, m_χ are excluded

Direct Detection

- The DD experiments impose stringent constraints on DM-nucleon scattering cross section.
- In EFT approach, those constraints can translate the bounds on

$\rightarrow \quad \Lambda, m_\chi$

$$\sigma_{\rm SI}^{\mathcal{O}_{vv}} \sim \frac{9}{\pi\Lambda^4}\mu_p^2,$$

$$\sigma_{\rm SI}^{\mathcal{O}_{ss}} \sim \frac{1}{\pi\Lambda^4}\mu_p^2 f_p^2,$$

$$\mu_p = m_\chi m_p/(m_\chi + m_p)$$

$$\sigma_{\rm SD}^{\mathcal{O}_{tt}} \sim 4 \times \sigma_{\rm SD}^{\mathcal{O}_{aa}} \sim \frac{16}{\pi\Lambda^4}\mu_p^2 \left(\sum_q \Delta_q^p\right)^2$$

March-Russell, Unwin, and West, JHEP 2012, 1203.4854

Direct Detection experiments by several collaborations:

LZ, Darkside 50, Xenon-nT, Pico 60

LZ collaboration, 2207.03764

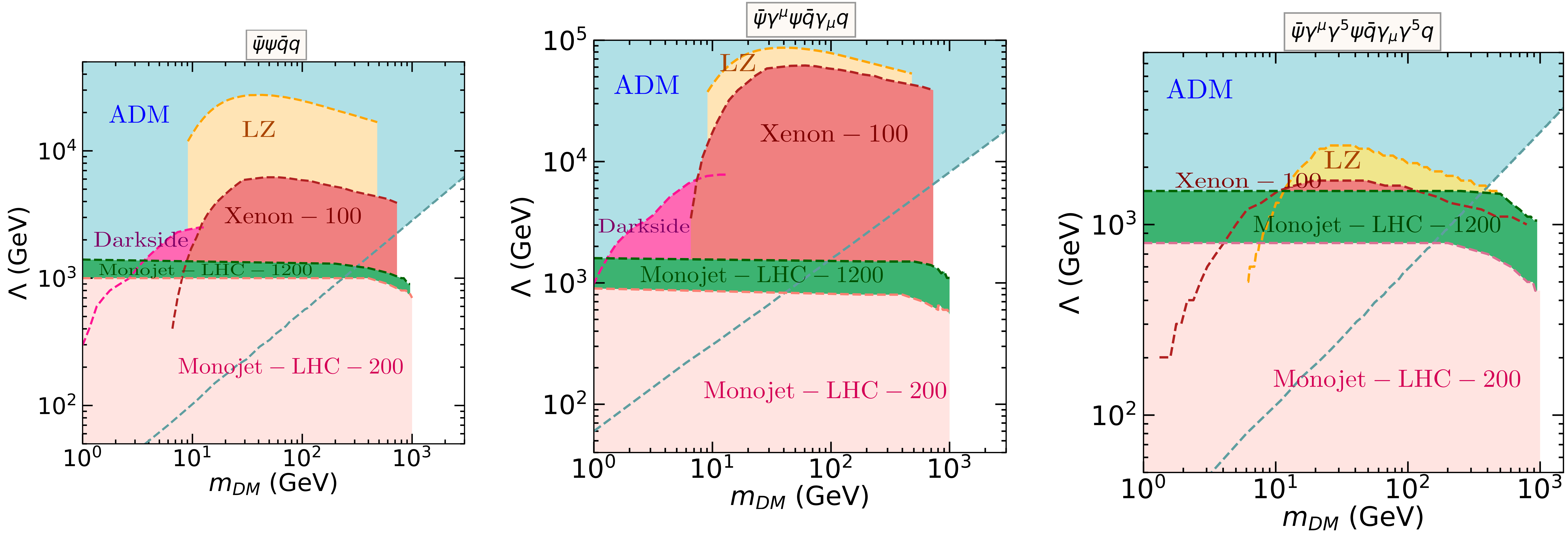
Dark-Side collaboration, PRL 2018,1802.06994

Xenon Collaboration, PRL 2019,1902.03234

Pico Collaboration, PRD 2019,1902.0403

DM-Quark interaction : Constraints

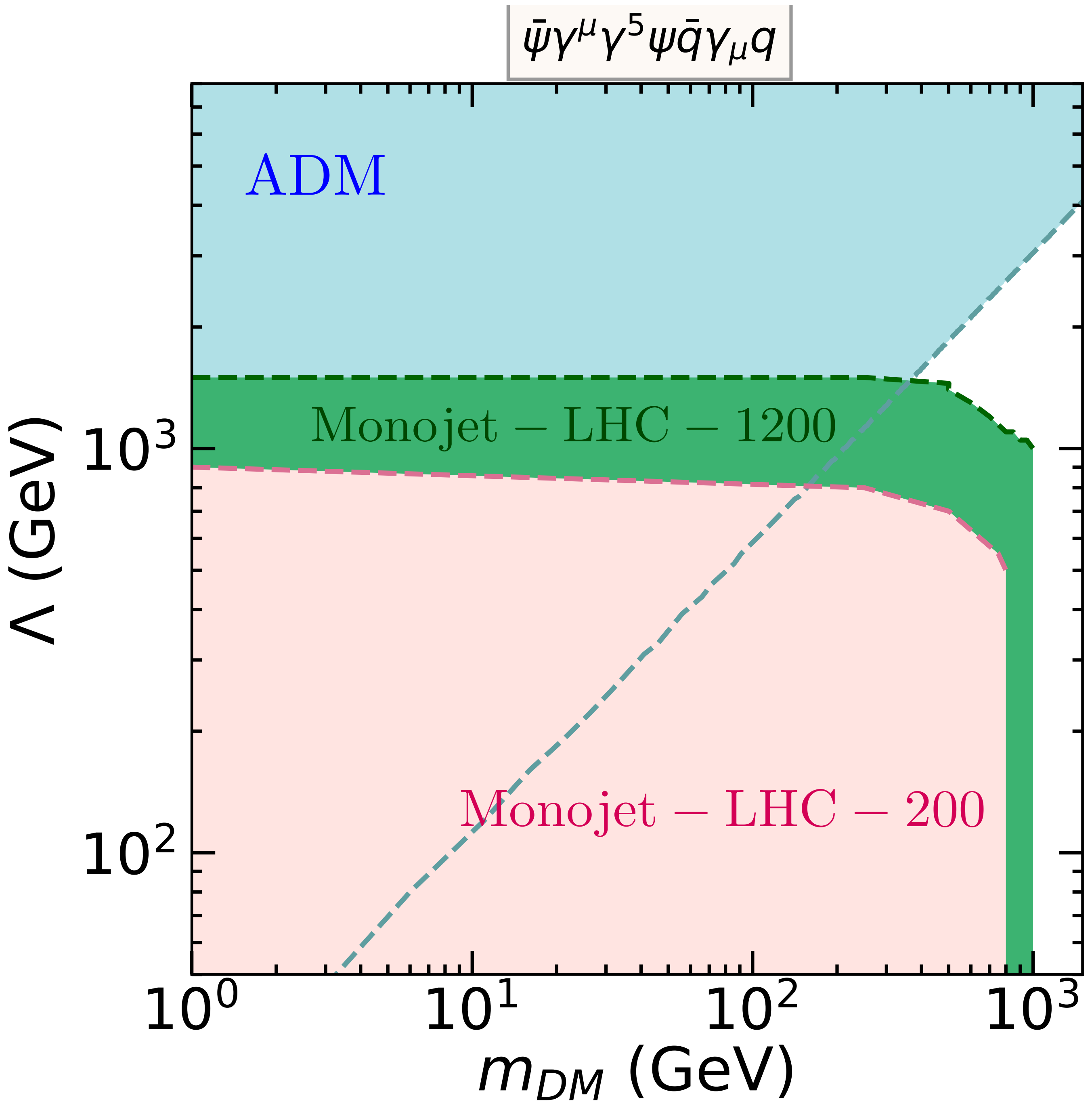
The exclusion region in the plane Λ, m_χ

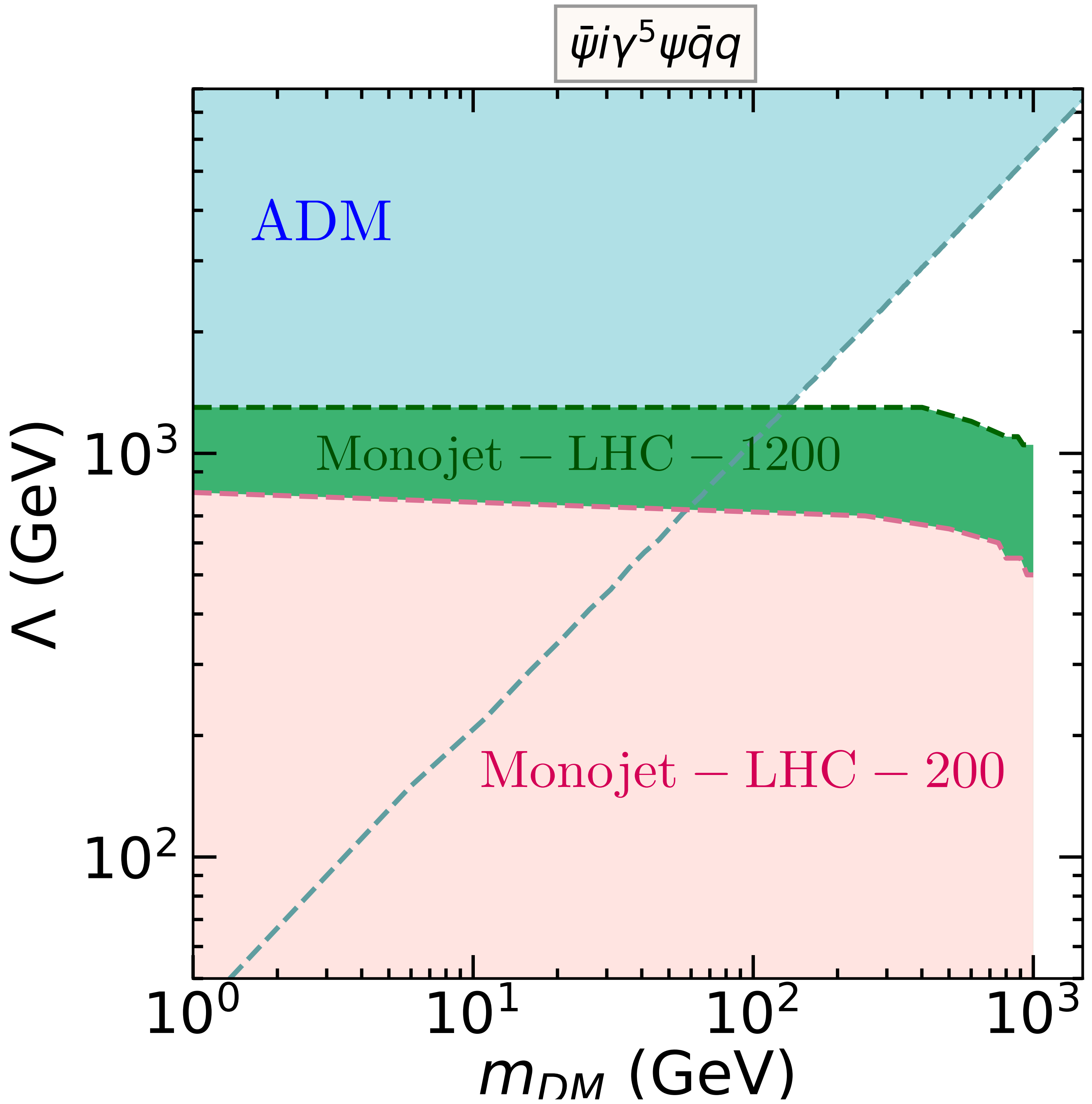


The non suppressed operators: $\mathcal{O}_{ss}$ $\mathcal{O}_{vv}$ $\mathcal{O}_{aa}$

DM-Quark interaction : Constraints

The exclusion region in the plane Λ, m_χ



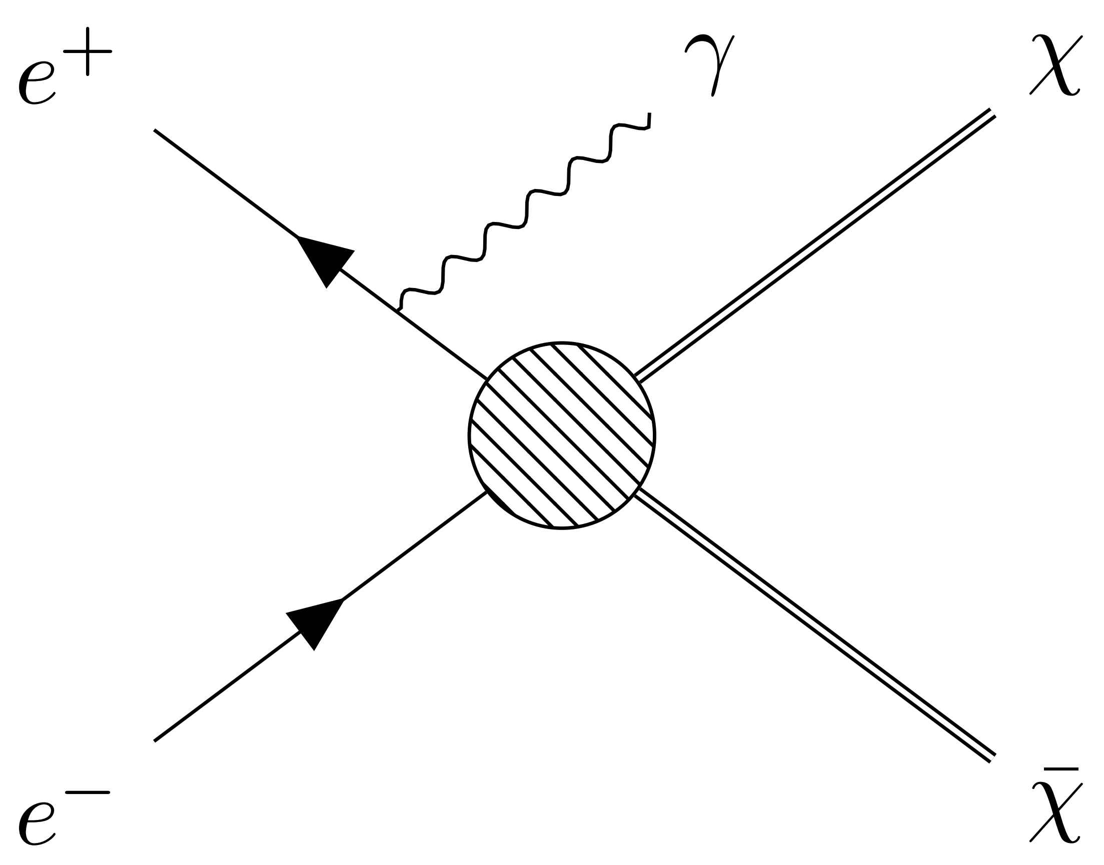


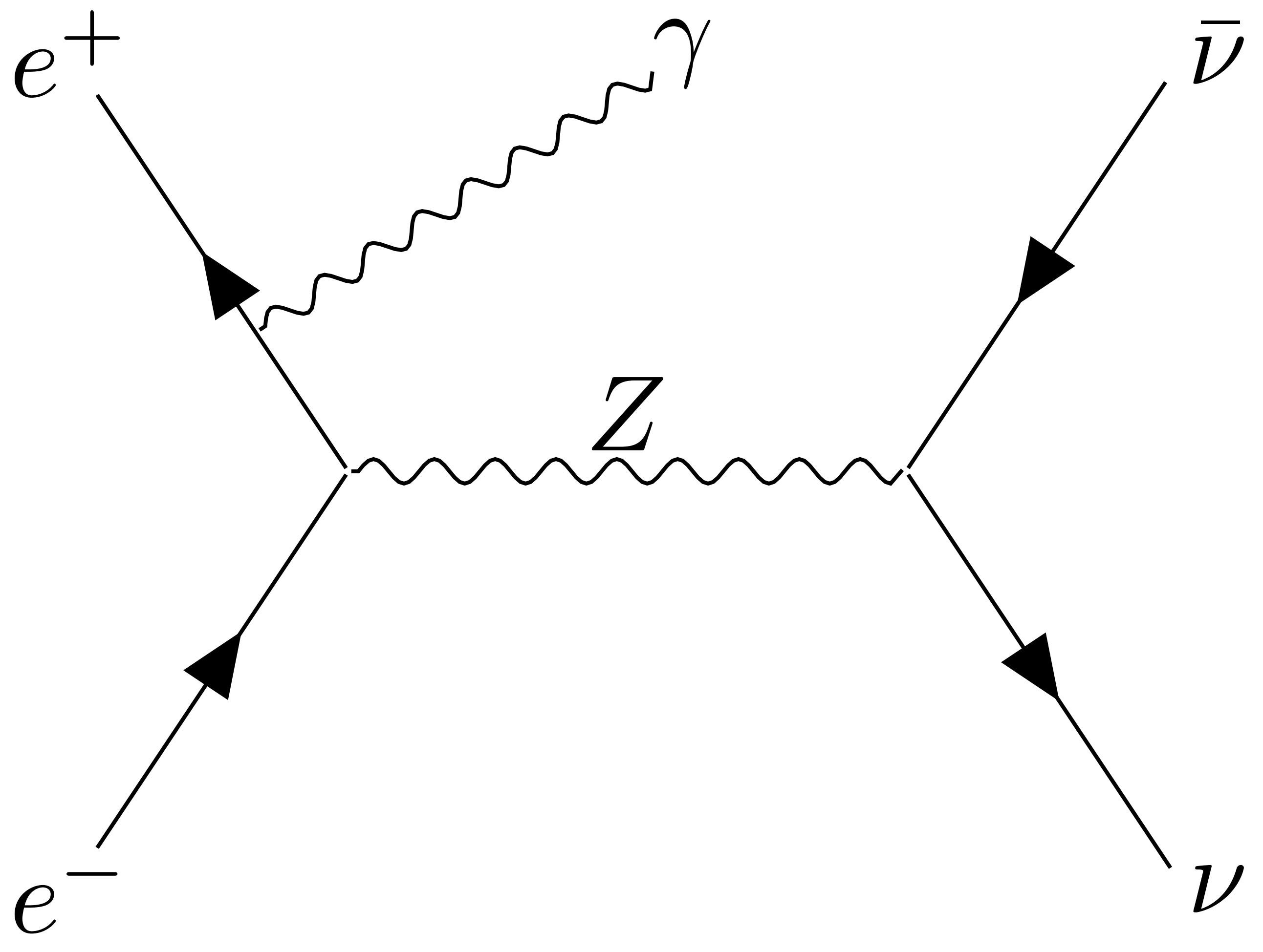
The suppressed operators: $\mathcal{O}_{as}$ $\mathcal{O}_{ps}$

Lepton-DM Interactions

The Leptophilic DM, other constraints will less effective

$$e^+e^- \to \chi\bar{\chi}\gamma \to \not{E}_T\gamma. \quad e^+e^- \to \nu\bar{\nu}\gamma \to \not{E}_T\gamma.$$





Fox, Harnik, Kopp, Tsai,
PRD 2011, 1103.0240

The Mono-photon signal

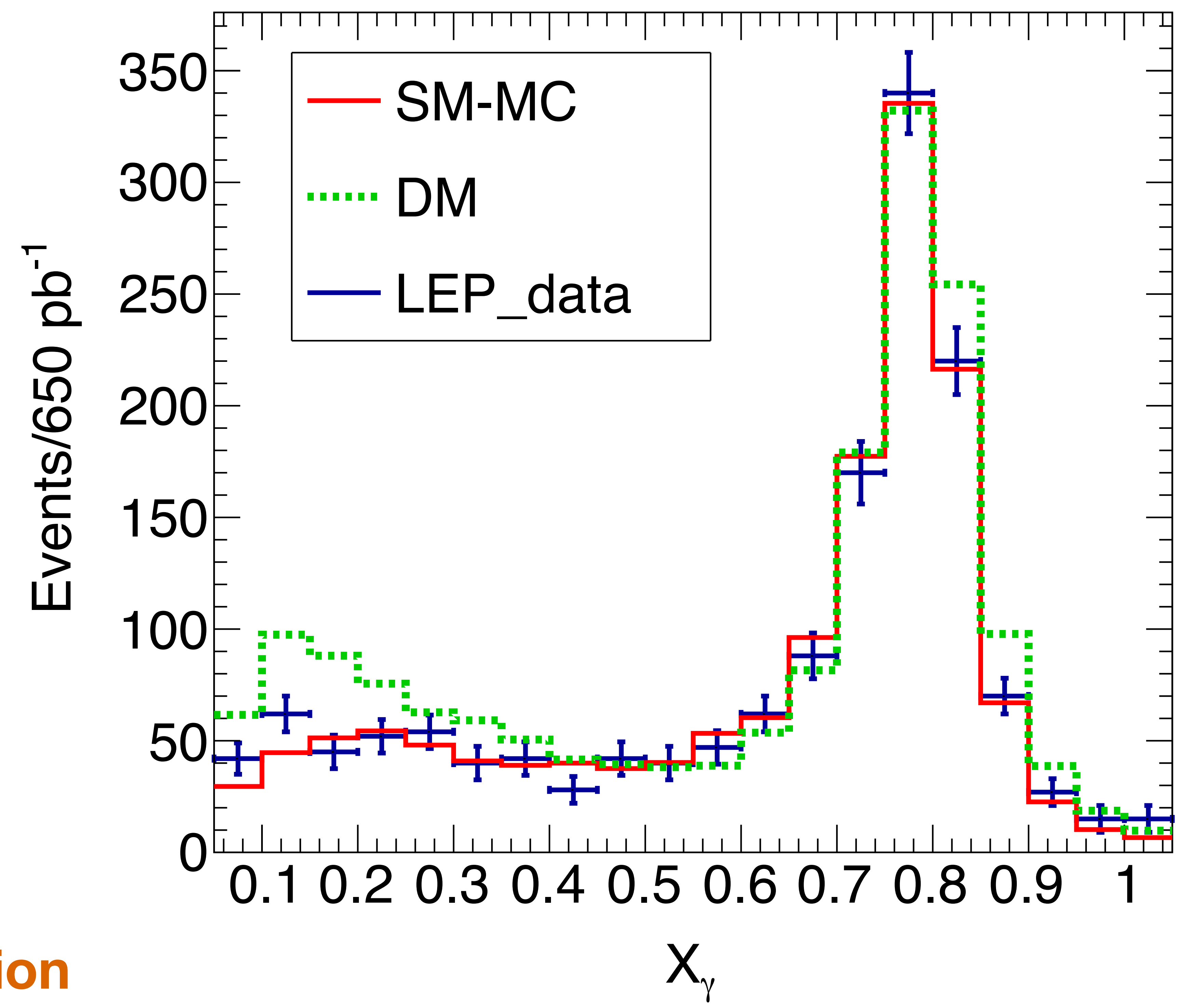
Delphi collaboration
EPJC 2005

Taking into account effects of all operators, we simulate following the analysis of DELPHI(LEP)

MG5aMC_atNLO + Feynrules UFO+PYTHIA8 Included all detector related efficiencies

DM-Lepton Interactions: Simulation validation

MG5aMC_atNLO + Feynrules UFO+PYTHIA8



Delphi collaboration
EPJC 2005

The analysis framework is validated

$$X_\gamma = \frac{E_\gamma}{E_{\text{beam}}},$$

A very agreement is found between SM-MC and data

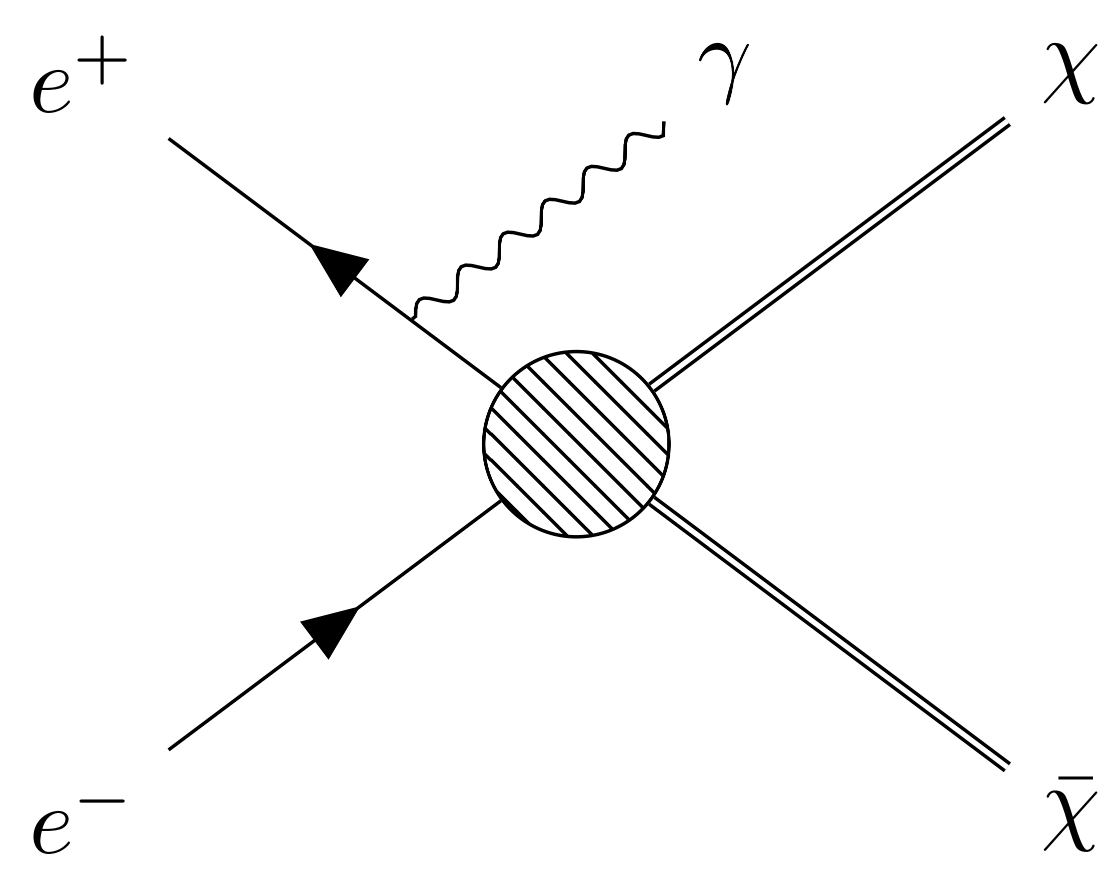
A chi2 analysis between the photon energy distributions for SM-MC and the DM

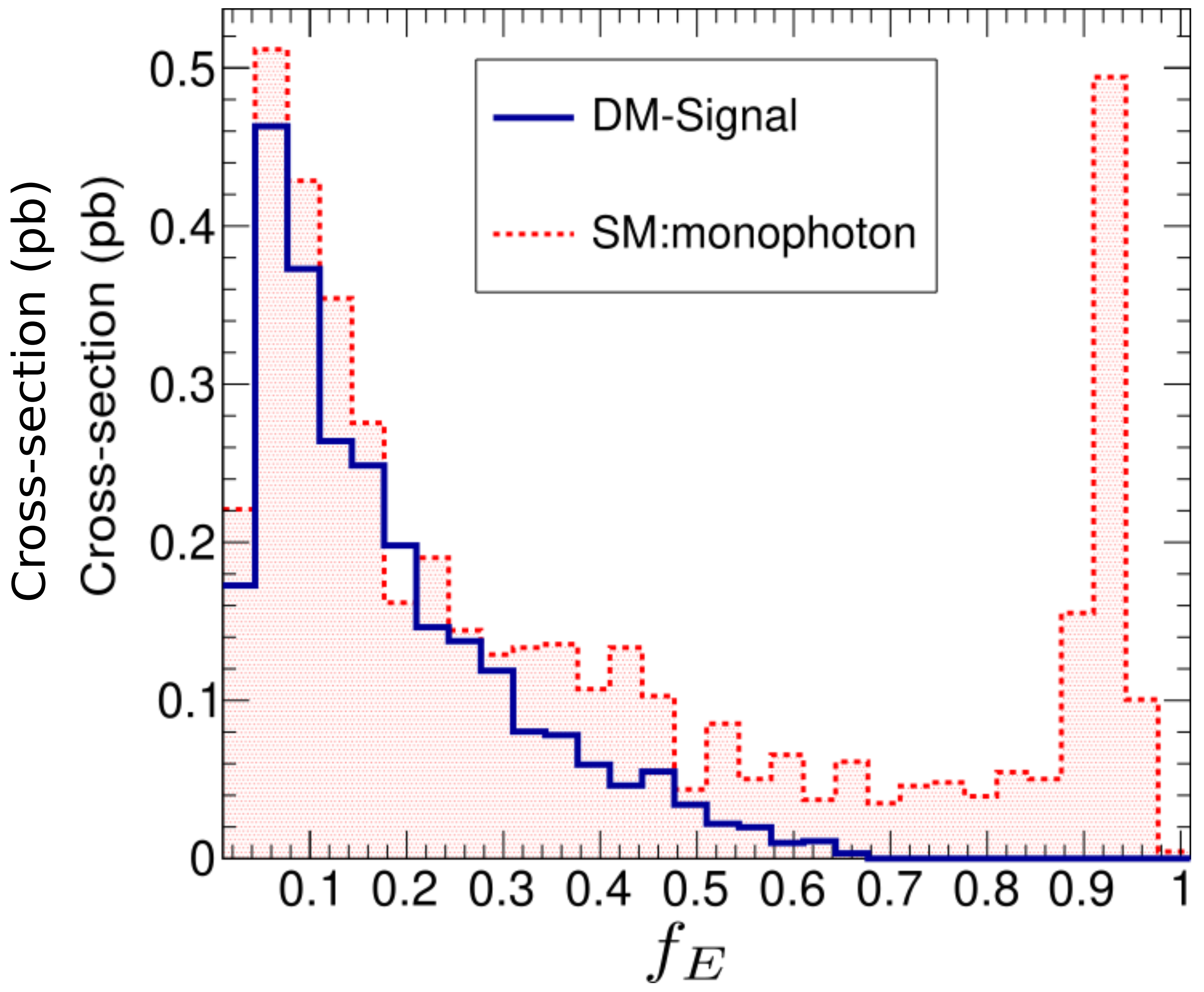
→ Constraining the EFT parameters

DM-Lepton Interactions : FCC-ee

MG5aMC_atNLO + Feynrules UFO+PYTHIA8

The FCC-ee experiment should produce mono events similar to LEP.





$$\sqrt{S} = 365 \text{ GeV}$$

$$\mathscr{L} = 340 \text{ pb}^{-1}$$

$$f_E = E_\gamma / E_{\text{beam}} < 0.3,$$

The analysis is perform, for different choices of Λ, m_χ

→ **Requiring** $S/\sqrt{S+B} > 3$, **parameters are constrained**

Constraints from Compact Stars: Neutron stars and White dwarf

- **The phenomena of DM capture may lead constraints on the EFT model parameters.**

- **The heating of NS due the DM capture can be used to constrain the DM-lepton interaction.**

Bell, Busoni Robles, JCAP 2019, 1904.0983

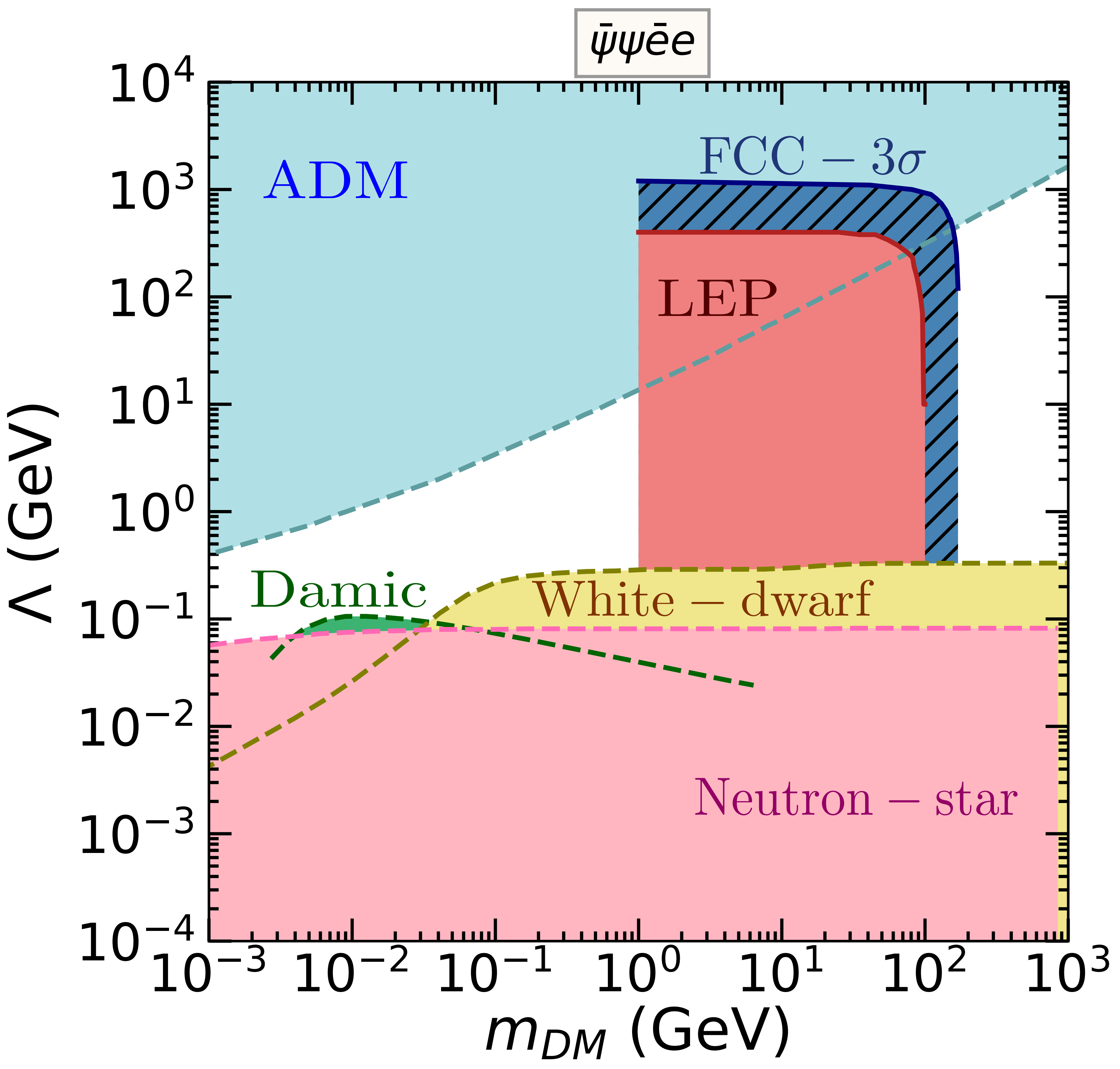
- **The core of the White dwarf is primarily composed of electron gas. The DM can then scatter off electrons or annihilation process $\rightarrow$ heat up.**

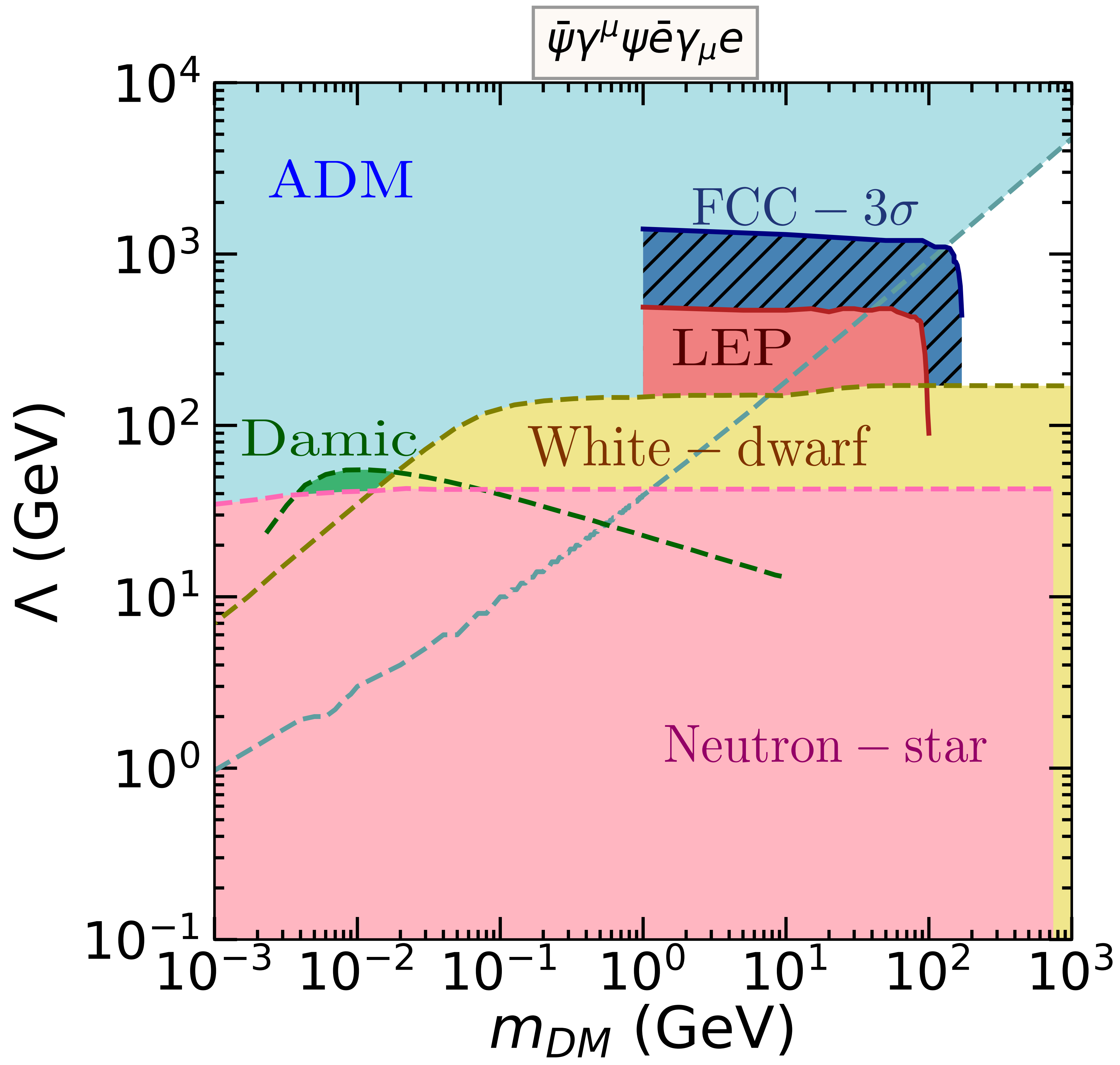
Bell, Busoni, et.al. JCAP 2021, 2104.14367

- **The DAMIC and Super CDMZ also put the strongest constraints on DM-lepton interactions.**

DM-Lepton interactions: Constraints

The exclusion region in the plane Λ, m_χ



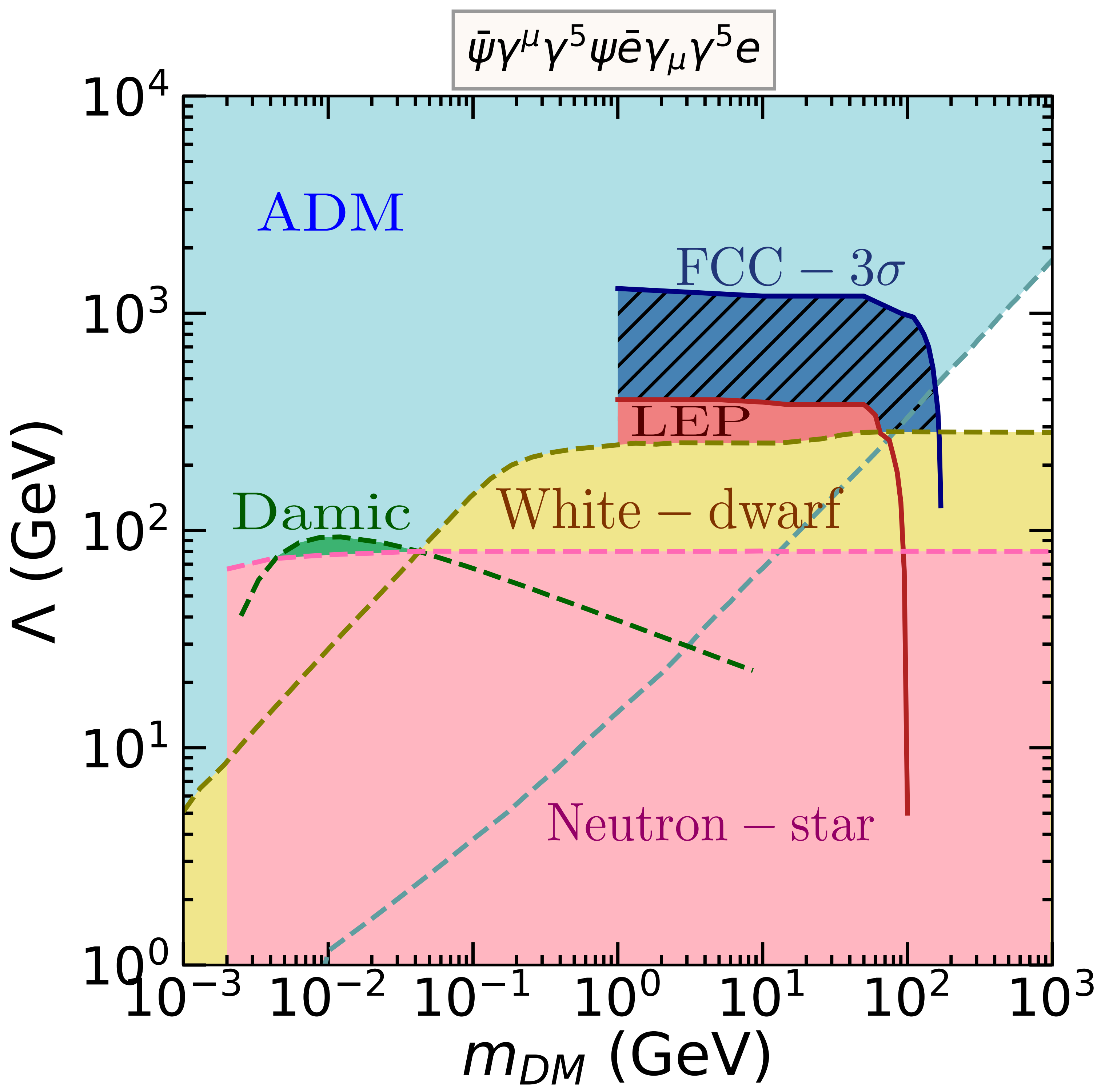


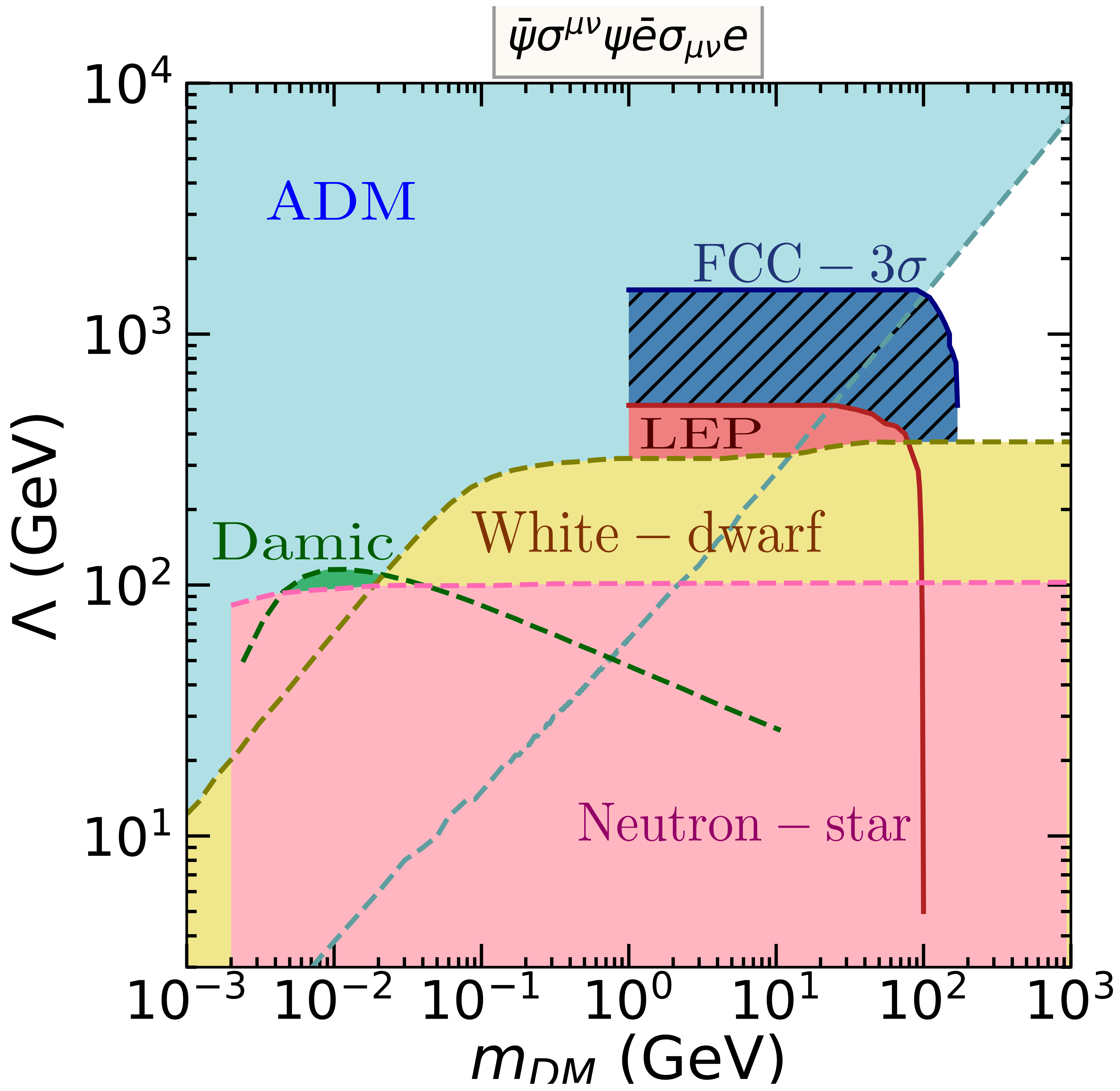
$(\mathcal{O}_{ss} \equiv \frac{1}{\Lambda^2}\bar{\psi}\psi\bar{e}e$

$$\mathcal{O}_{vv} \equiv \frac{1}{\Lambda^2}\bar{\psi}\gamma^\mu\psi\bar{e}\gamma_\mu e$$

Constraints

The exclusion region in the λ, m_χ **plane**



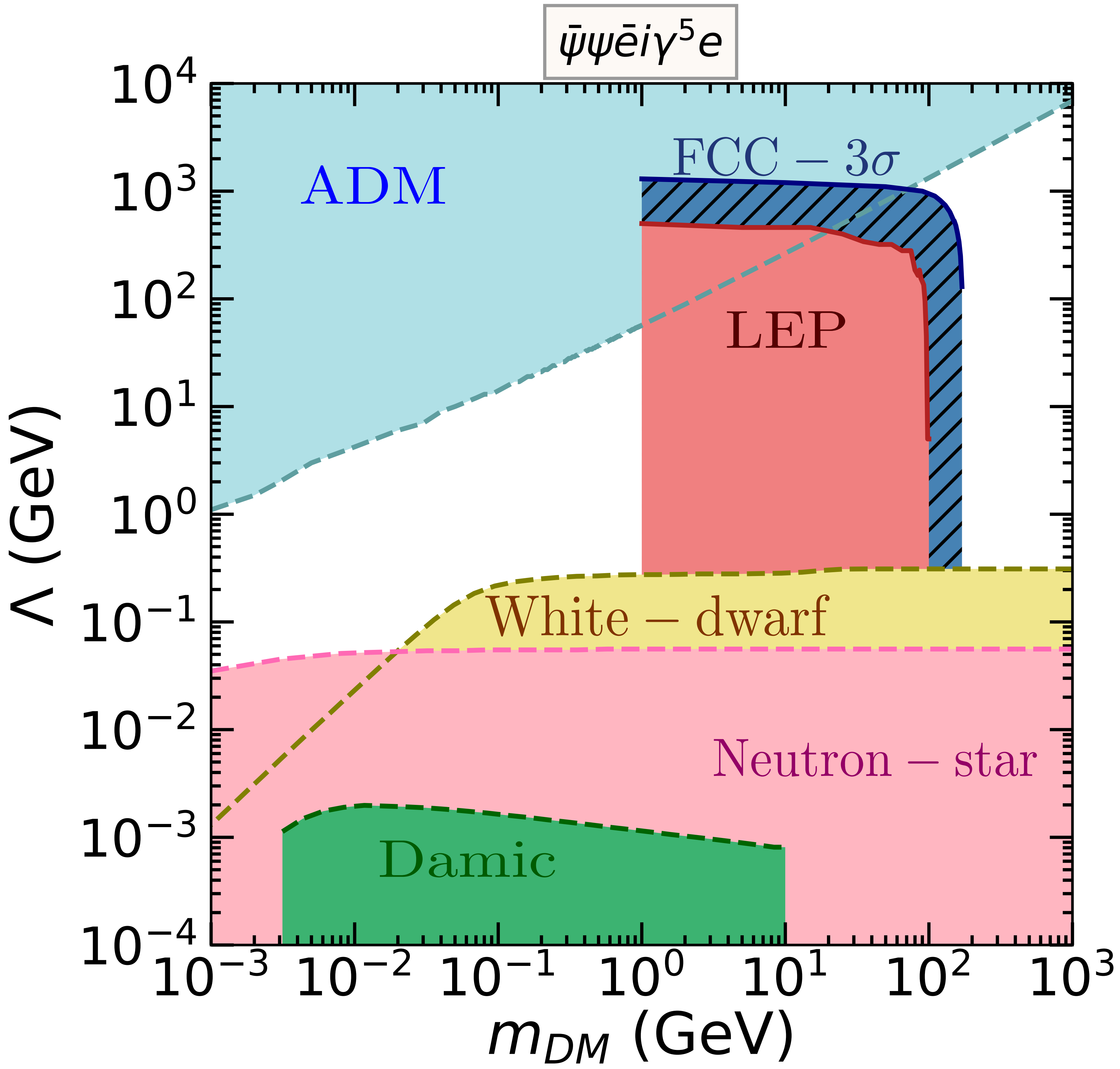


$$\mathcal{O}_{aa} \equiv \frac{1}{\Lambda^2}\bar\psi\gamma^\mu\gamma^5\psi\bar e\gamma_\mu\gamma^5 e$$

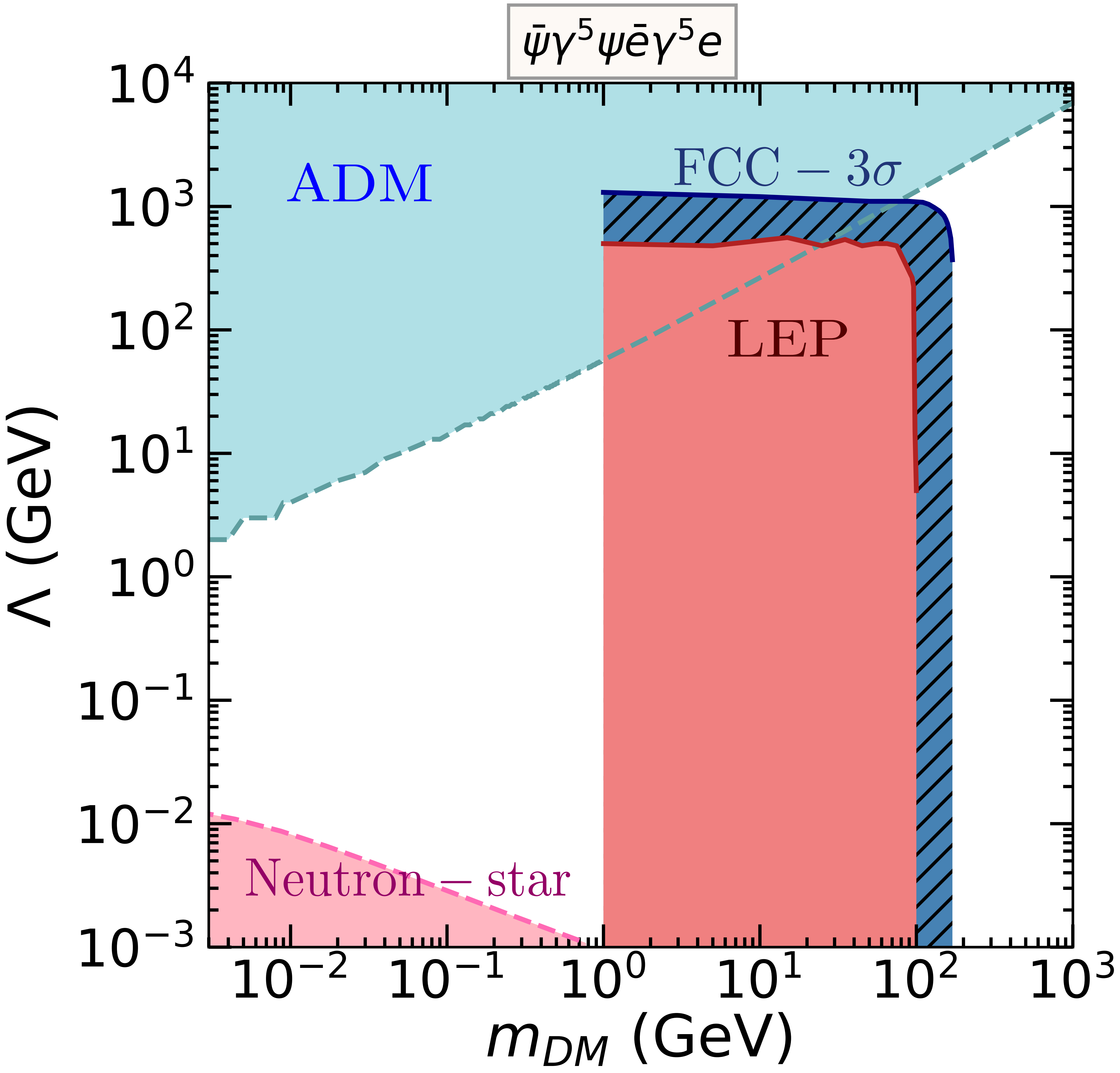
$$\mathcal{O}_{tt} \equiv \frac{1}{\Lambda^2}\psi\sigma^{\mu\nu}\psi\bar e\sigma_{\mu\nu}e$$

DM-Lepton Inetarctions: Constraints

The exclusion region in the plane Λ, m_χ



$$(\mathcal{O}_{sp} \equiv \frac{1}{\Lambda^2}\bar{\psi}\psi\bar{e}i\gamma^5 e)$$



$$(\mathcal{O}_{pp} \equiv \frac{1}{\Lambda^2}\bar{\psi}\gamma^5\psi\bar{e}\gamma^5 e) \text{ (right)}$$

Summary and Outlook

- The detailed study of effective interaction of ADM with quarks and leptons are presented including The future projection for FCC.

- For the DM-quark interaction, DD constraints are found to be severe. In case interactions are suppressed, Mono jet searches become effective. For scalar and vector type of interactions, ADM is ruled out almost up to ~1 TeV

- For the DM-lepton interaction, strongest bounds come from NS and WD studies. Mono-photon searches becomes effective, for range of DM masses 1-100 GeV, except for few other interactions.

- For the DM-lepton interaction, the 3 sigma reach for FCC-ee is presented. It is found that an DM of mass ~200 GeV can be probed for any general kind of effective interactions for the scale ~1 TeV.