IPhT
Institut de Physique Théorique
DRF-INP UMR 3681

Light Dark Sectors through the Fermion Portal

Sebastian A. R. Ellis
IPhT, CEA Saclay

Based on:
JHEP 07 (2020) 053
arXiv:2001.01490
L. Darmé, SARE, T. You

Mesons and dark matter

Many reasons to consider connections, e.g.:

- Dark sector could be *SU(N)* – glueball DM

e.g. Faraggi & Pospelov (2002)
Feng & Shadmi (2011)
Boddy et al (2014)
Many more

- SIMP DM – dark pions as DM

e.g. Hochberg et al (2014)
Hochberg et al (2015)
Many more

- Production of sub-GeV dark sector from mesons

this talk

  Production of mesons from sub-GeV dark sector

dark sector

/dɑːk ˈsɛktə/

Noun: Umbrella term for BSM states w/ feeble or no interactions w/ SM, typically related to Dark Matter

"We hope to discover the nature of Dark Matter, and explore the dark sector"

Why go beyond mono-particle DM solution?

2 components: e.g. Inelastic DM

$$\psi = \begin{pmatrix} \eta \\ \xi^c \end{pmatrix}$$

$$\phi = \phi_1 + i\phi_2$$

Tucker-Smith & Weiner (2001)

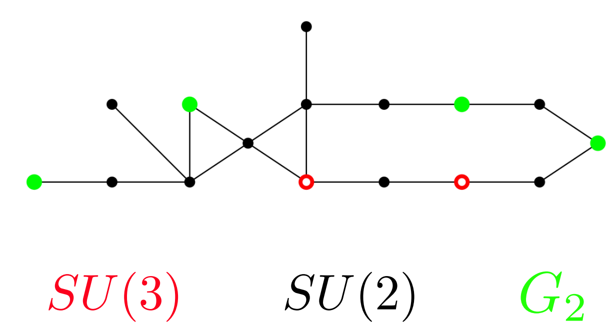
Dark Higgs mechanism

$$|D_\mu \phi|^2 + V(\phi)$$

$$m_V \sim g_D v_\phi$$

see e.g. Reece (2018)

Top-down considerations



see e.g. Halverson & Langacker (2018)

dark sector

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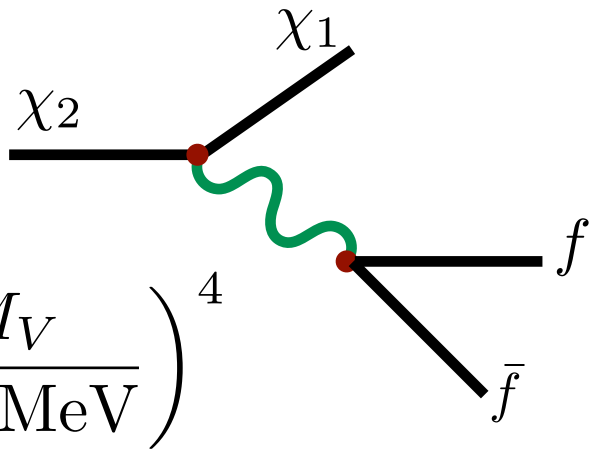
Consequence of feeble coupling in multi-state dark sector:

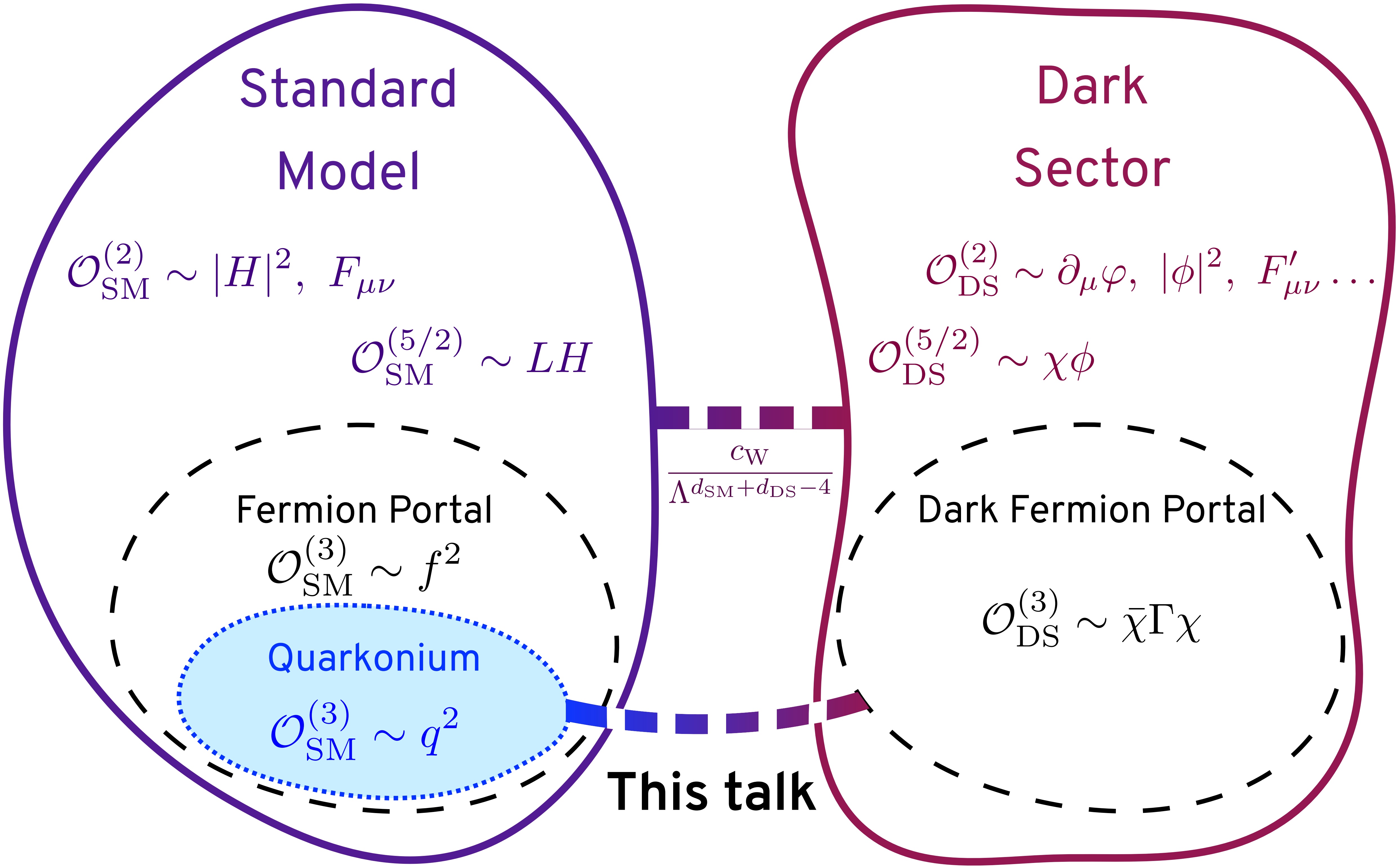
long-lived particles



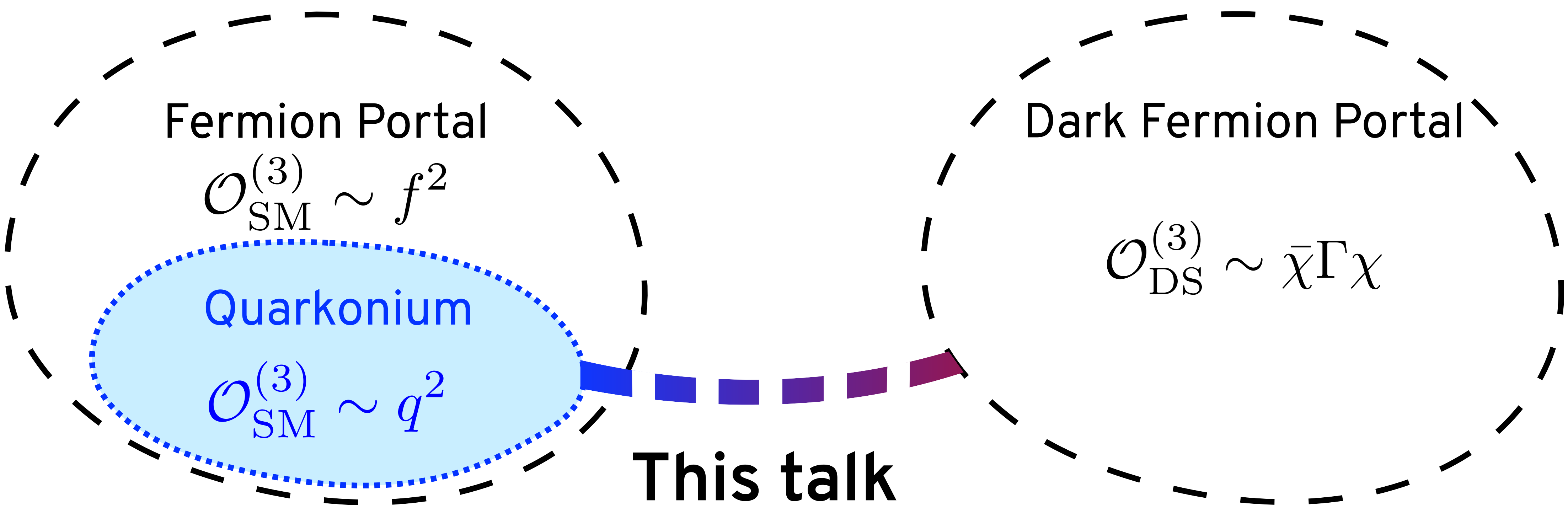
$$c\tau_{\chi_2} \sim 100\ \mathrm{m} \cdot \left(\frac{10^{-4}}{g_D \epsilon}\right)^2 \left(\frac{5\ \mathrm{MeV}}{\Delta_\chi}\right)^5 \left(\frac{M_V}{100\ \mathrm{MeV}}\right)^4$$

Particularly relevant given current interest in *intensity frontier* experiments e.g. beam dumps, Belle-II, etc.

Thinking with portals



The Fermion Portal



This talk

$$\frac{1}{\Lambda^2}(\bar{\chi}\Gamma\chi)\mathcal{O}^{(3)}_{\rm SM}$$

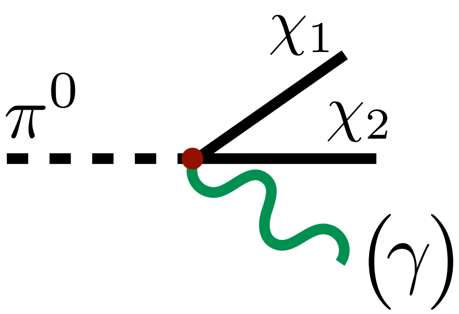
Structures: $\Gamma \subset \{\gamma_\mu,\ \gamma_\mu\gamma_5,\ \gamma_5\}$

Couplings: $g_u^{ij},\ g_d^{ij},\ g_l^{ij}$ Limits: $\Lambda/\sqrt{g}$

Dark Sector Production

- Light meson decay $\pi^0 \to \gamma\chi\chi$ $\pi^0 \to \chi\chi$

associated decay dark decay



- Heavy meson decay (charm, bottom)

Beam Dumps

- Direct production $pp \to \chi\chi, \ pp \to j\chi\chi, \ ee \to \chi\chi, \ ee \to \gamma\chi\chi$

LHC *LEP, BaBar, Belle-II*

- Bremsstrahlung* $p(e)N \to p(e)N\chi\chi$

Beam Dumps

*not considered in detail

Meson Decay

$$N_{\text{prod}} = \mathcal{N}_M \times \text{BR}(M \to \bar{\chi}_1 \chi_2 (+X)) \propto \left(\frac{M_M}{\Lambda}\right)^4$$

experiment-specific operator-dependent

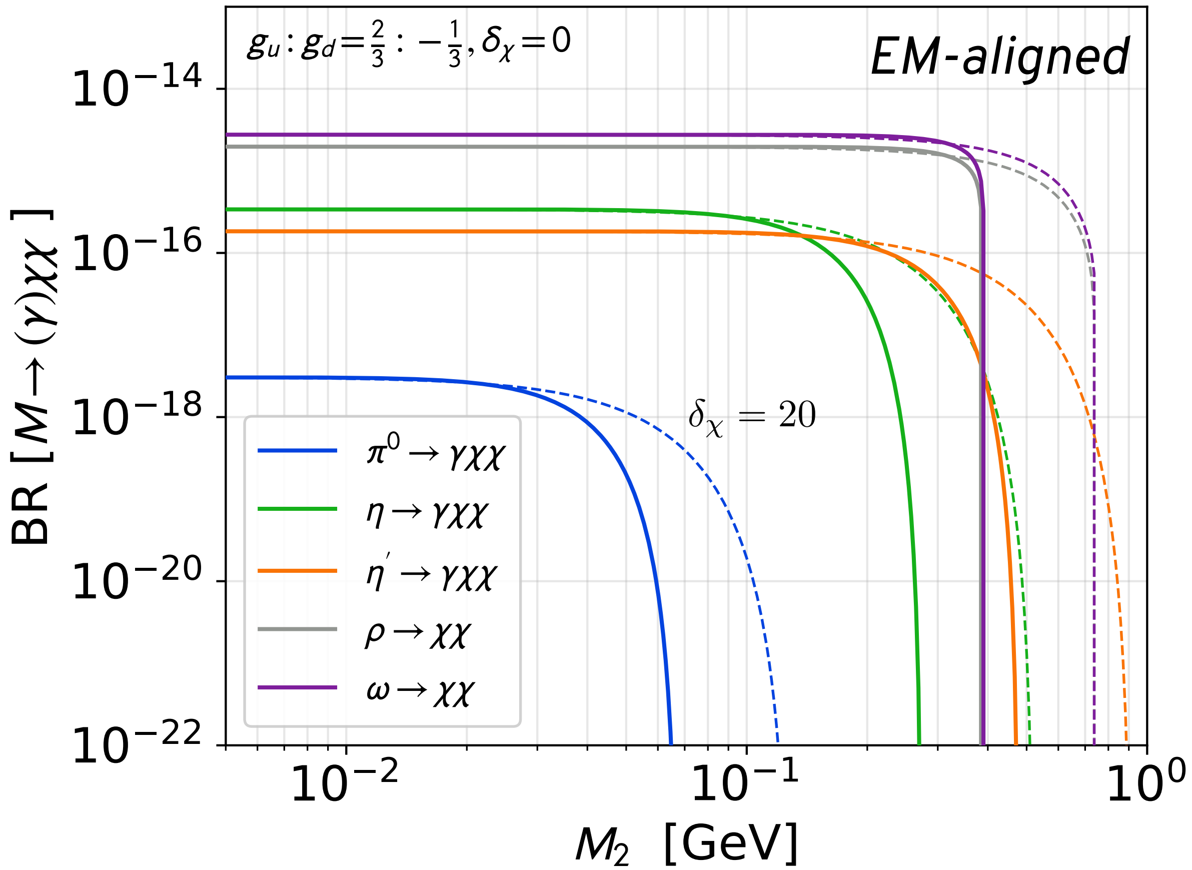
Meson decay	Vector current	Axial-vector current	Dark photon	Γ_M (GeV)
$\pi \to \gamma XX$	$g_{\pi^0} = 2g_u + g_d$	/	$e\varepsilon$	$7.7 \cdot 10^{-7}$
$\eta \to \gamma XX$	$g_\eta = 1.5g_u - 0.7g_d + 0.6g_s$	/	$e\varepsilon$	$1.3 \cdot 10^{-6}$
$\eta' \to \gamma XX$	$g_{\eta'} = 1.2g_u - 0.6g_d - 0.9g_s$	/	$1.3\ e\varepsilon$	$2.0 \cdot 10^{-4}$
$\rho \to XX$	$g_\rho = 1.3g_u - 1.3g_d$	/	resonant	0.15
$\omega \to XX$	$g_\omega = 1.2g_u + 1.2g_d$	/	resonant	$8.5 \cdot 10^{-3}$
$\pi \to XX$	/	$\tilde{g}_{\pi^0} = (\tilde{g}_u - \tilde{g}_d)/\sqrt{2}$	/	$7.7 \cdot 10^{-7}$
$\eta \to XX$	/	$\tilde{g}_\eta = 0.6\tilde{g}_u + 0.6\tilde{g}_d - 0.9\tilde{g}_s$	/	$1.3 \cdot 10^{-6}$
$\eta' \to XX$	/	$\tilde{g}_{\eta'} = 0.5\tilde{g}_u + 0.5\tilde{g}_d + 1.1\tilde{g}_s$	/	$2.0 \cdot 10^{-4}$

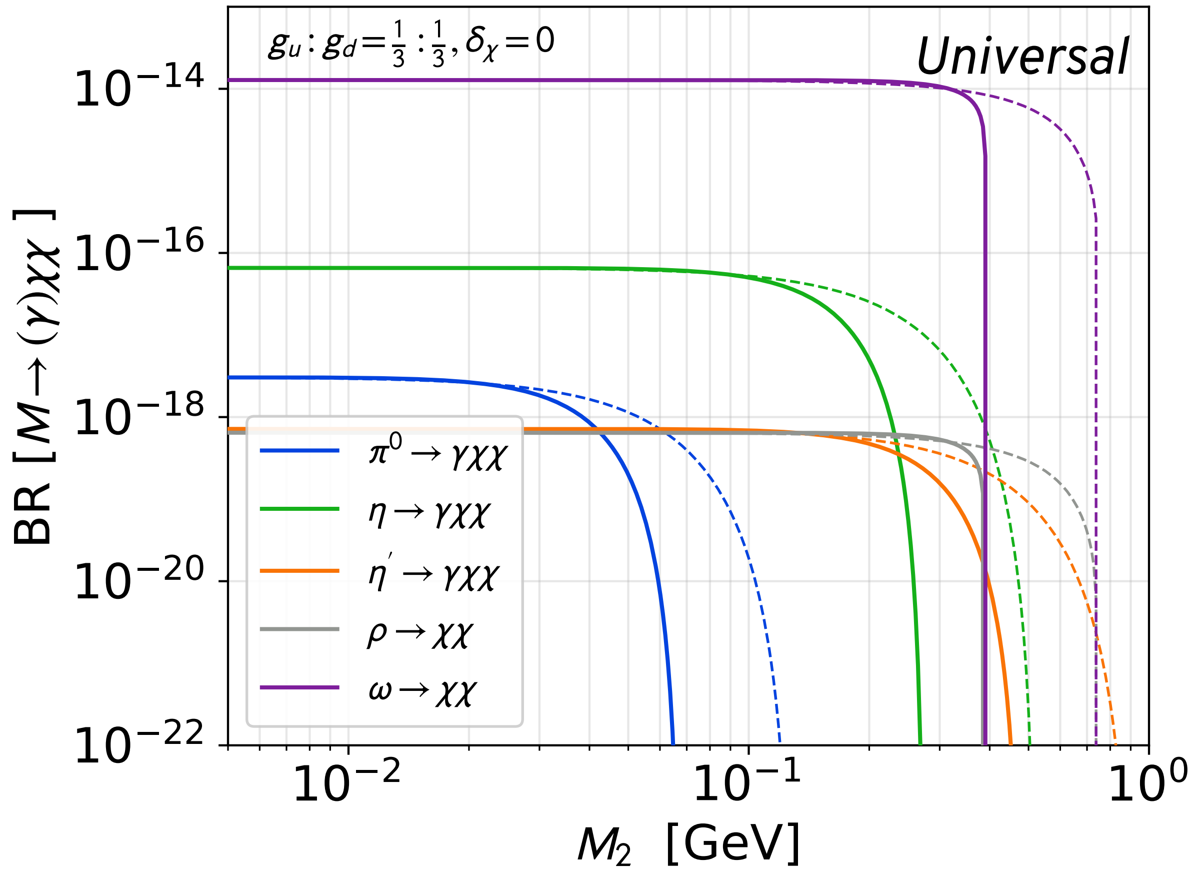
Experiment	E_{beam}	Target	PoT	N_{π^0}	N_η	$N_{\eta'}$	N_ρ	N_ω
CHARM [27]	400 GeV	Cu	$2.4 \cdot 10^{18}$	2.4	0.3	0.03	0.3	0.25
LSND [26]	0.8 GeV	Water	$0.92 \cdot 10^{23}$	0.14	0.	0	0	0
MiniBooNE [28]	8 GeV	Fe	$1.86 \cdot 10^{20}$	2.4	0.1	0	0.1	0.1
SHiP [33]	400 GeV	W / Pb*	$2 \cdot 10^{20}$	10	1	0.08	1.1	1
NOνA [46]	120 GeV	C	$3 \cdot 10^{20}$	1	1/30	1/300	1/30	1/30
SeaQuest [34]	120 GeV	Fe	$1.44 \cdot 10^{18}$	3.5	0.4	0.04	0.4	0.4
HL-LHC (barn) [30]	14 TeV	pp	$\mathcal{L} = 3$ ab^{-1}	4.3	0.5	0.05	0.5	0.5

Meson Decay

$$N_{\text{prod}} = \mathcal{N}_M \times \text{BR}(M \to \bar{\chi}_1 \chi_2 (+X)) \propto \left(\frac{M_M}{\Lambda}\right)^4$$

experiment-specific operator-dependent





Vector coupling

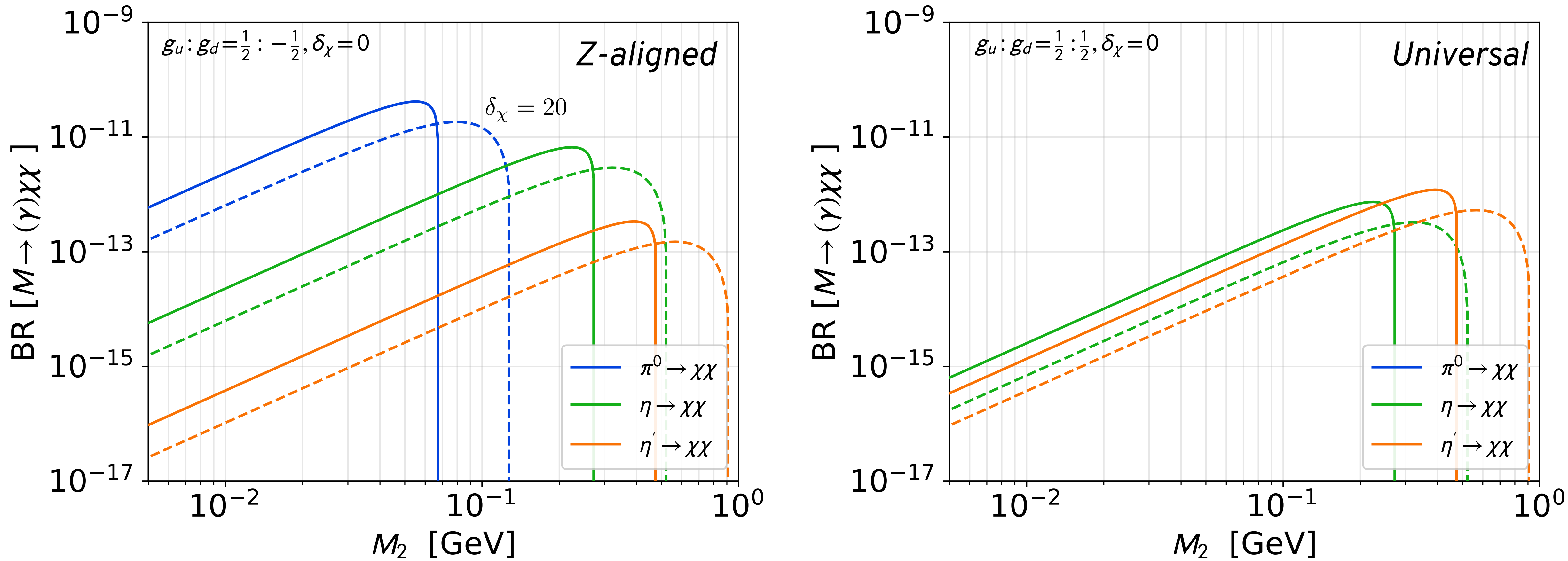
$$\Lambda = 1 \text{ TeV}$$

$$\delta_\chi \equiv \frac{|M_2| - |M_1|}{|M_1|}$$

Meson Decay

$$N_{\rm prod} = \mathcal{N}_M \times {\rm BR}(M \to \bar{\chi}_1 \chi_2 (+X)) \propto \left(\frac{M_M}{\Lambda}\right)^4$$

experiment-specific operator-dependent



Axial Vector coupling

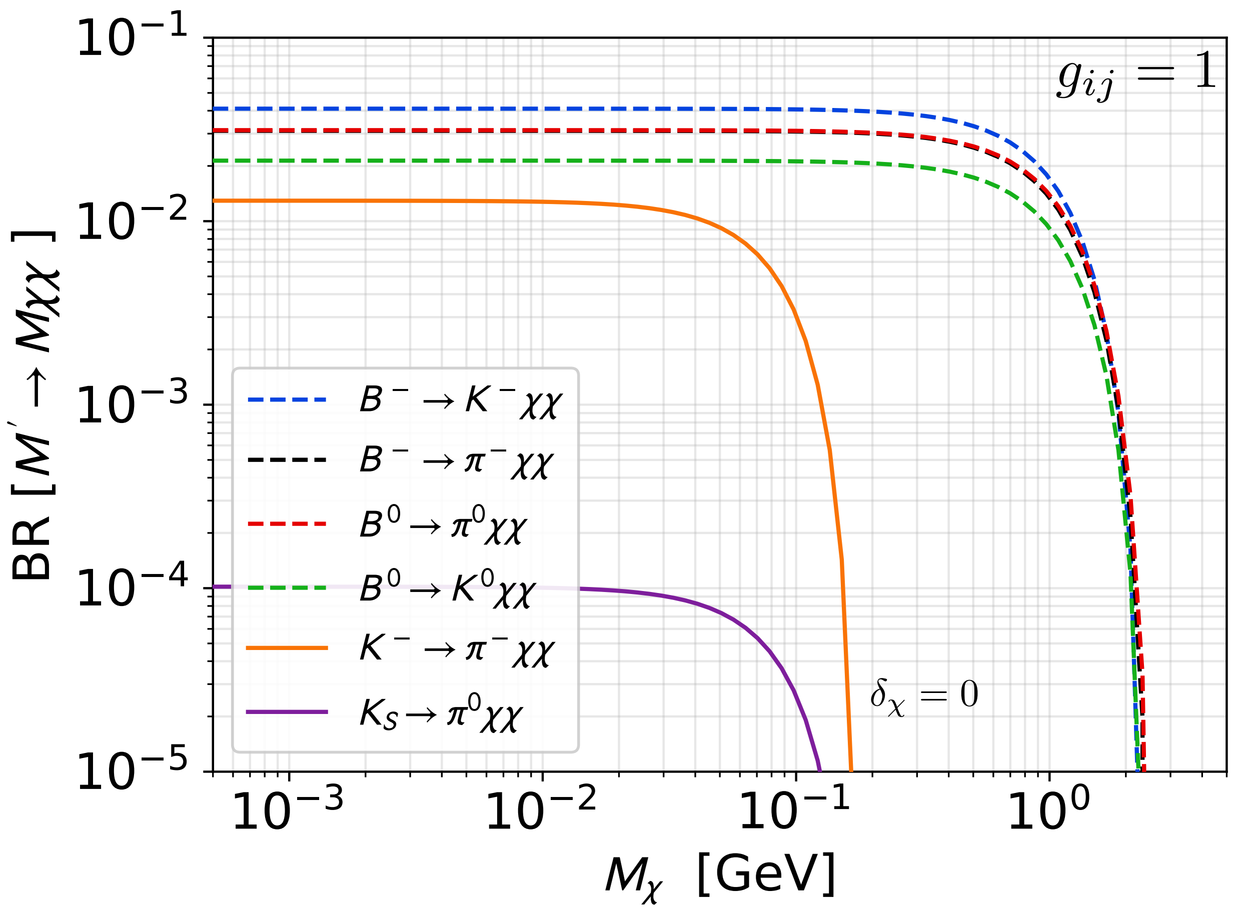
$$\Lambda = 1 \text{ TeV}$$

$$\delta_\chi \equiv \frac{|M_2| - |M_1|}{|M_1|}$$

Heavy Meson Decay

$$N_{\rm prod} = \mathcal{N}_M \times {\rm BR}(M \to \bar{\chi}_1\chi_2(+X)) \propto \left(\frac{M_M}{\Lambda}\right)^4$$

experiment-specific operator-dependent



$$\mathcal{L} \supset \sum_{ij} \frac{g_{ij}}{\Lambda^2}(\bar{\chi}_1\gamma_\mu\chi_2)(\bar{q}_i\gamma^\mu q_j)$$

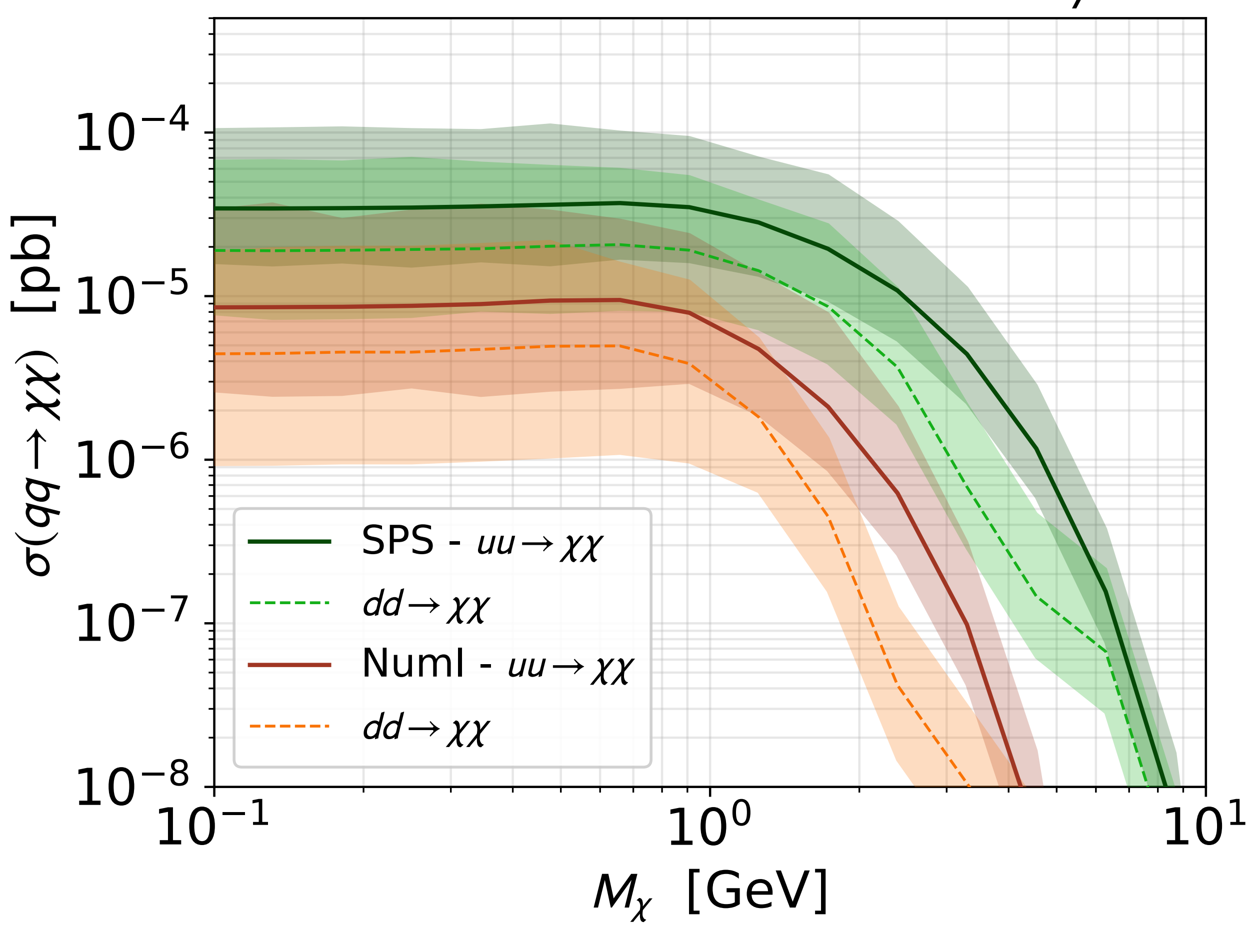
Vector coupling

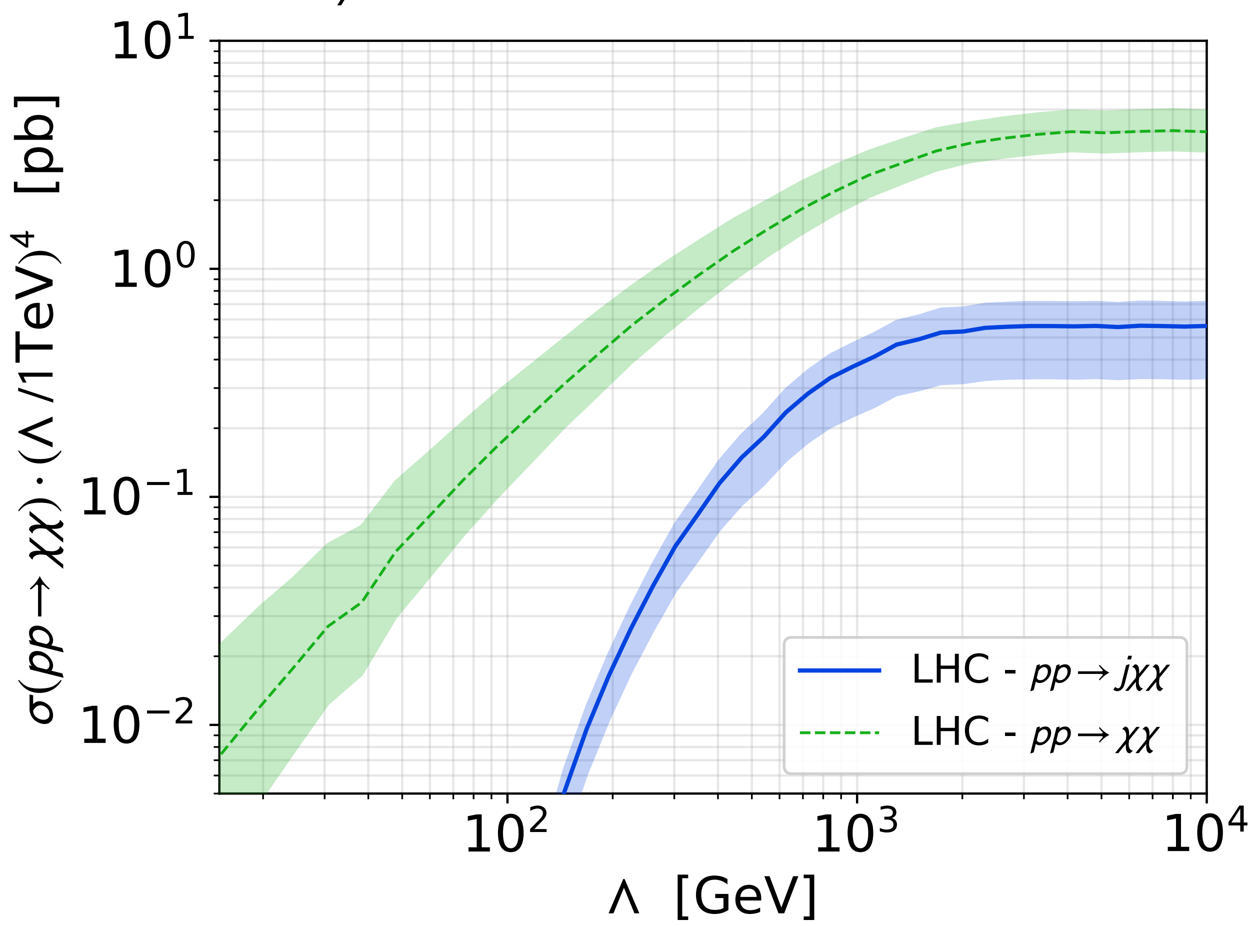
$$\Lambda = 1 \text{ TeV}$$

$$\delta_\chi \equiv \frac{|M_2| - |M_1|}{|M_1|}$$

Direct Production

Uncertainty from PDF scale – 2x and 1/2x





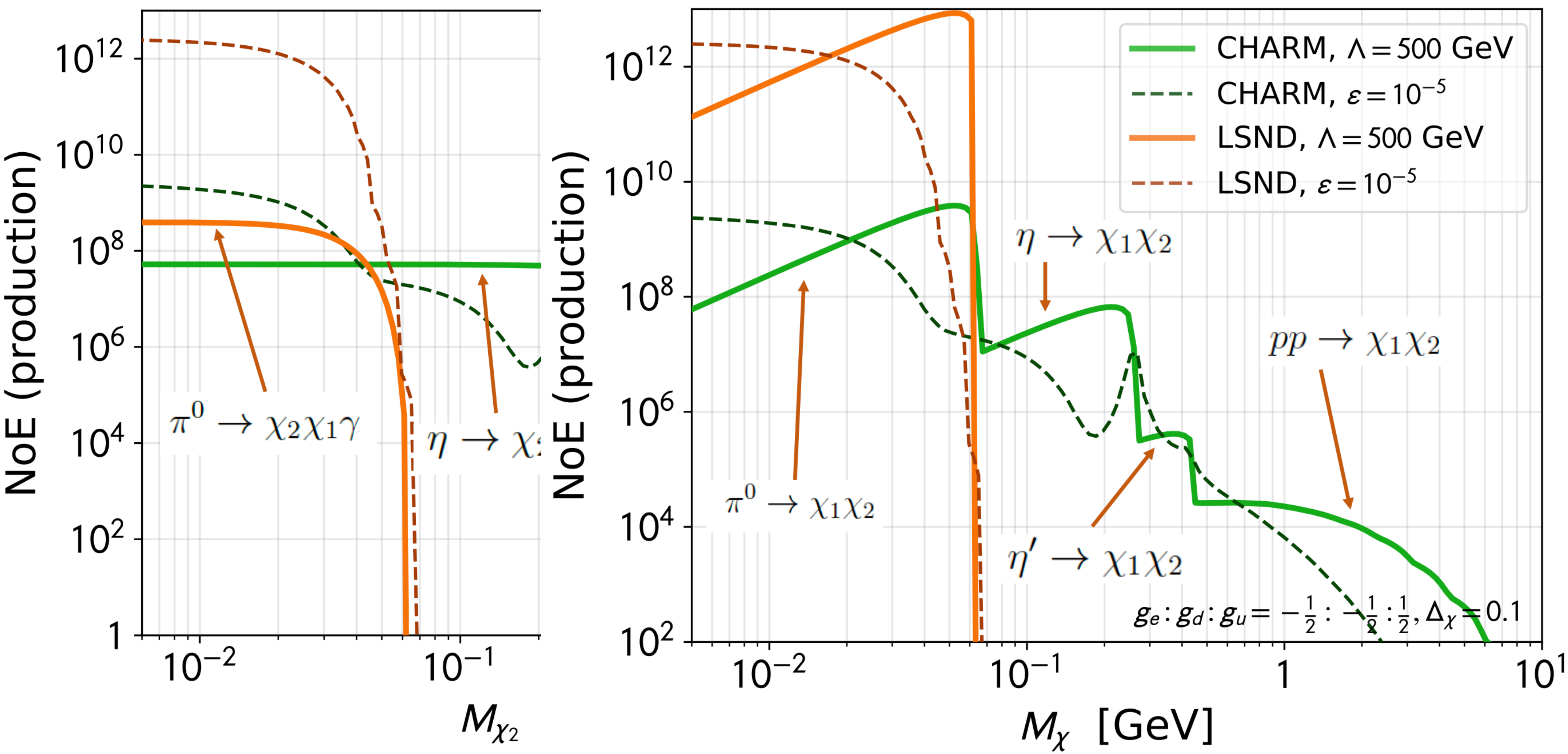
$\Lambda = 1\ \mathrm{TeV}$

$$\sigma_{pp\to\bar{\chi}\chi} = 2\int_0^1\int_0^1 dx_1 dx_2 \left(f_u^p f_{\bar{u}}^p g_u^2 + f_d^p f_{\bar{d}}^p g_d^2\right)\sigma_{q\bar{q}\to\bar{\chi}\chi}$$

$$\sigma_{pn\to\bar{\chi}\chi} = \int_0^1\int_0^1 dx_1 dx_2 \left(f_u^p f_{\bar{d}}^p + f_d^p f_{\bar{u}}^p\right)(g_u^2 + g_d^2)\sigma_{q\bar{q}\to\bar{\chi}\chi}$$

Putting it all together

Vector coupling, EM-aligned *Axial Vector coupling, Z-aligned*



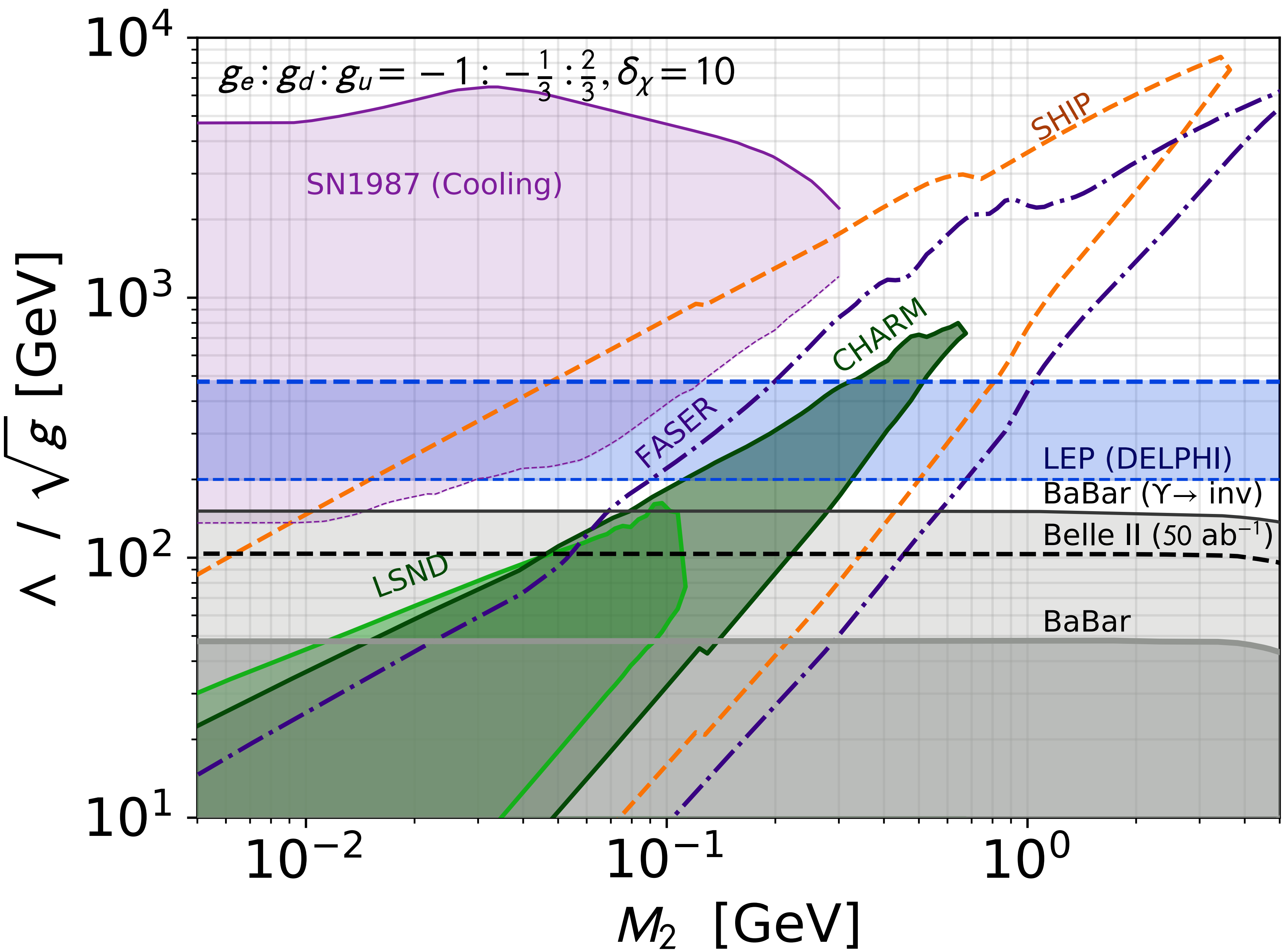
Obtaining limits

$$\mathcal{N} \simeq \mathcal{N}_{\rm prod} \times \mathcal{E} \times \mathcal{P}_{\rm sig}$$

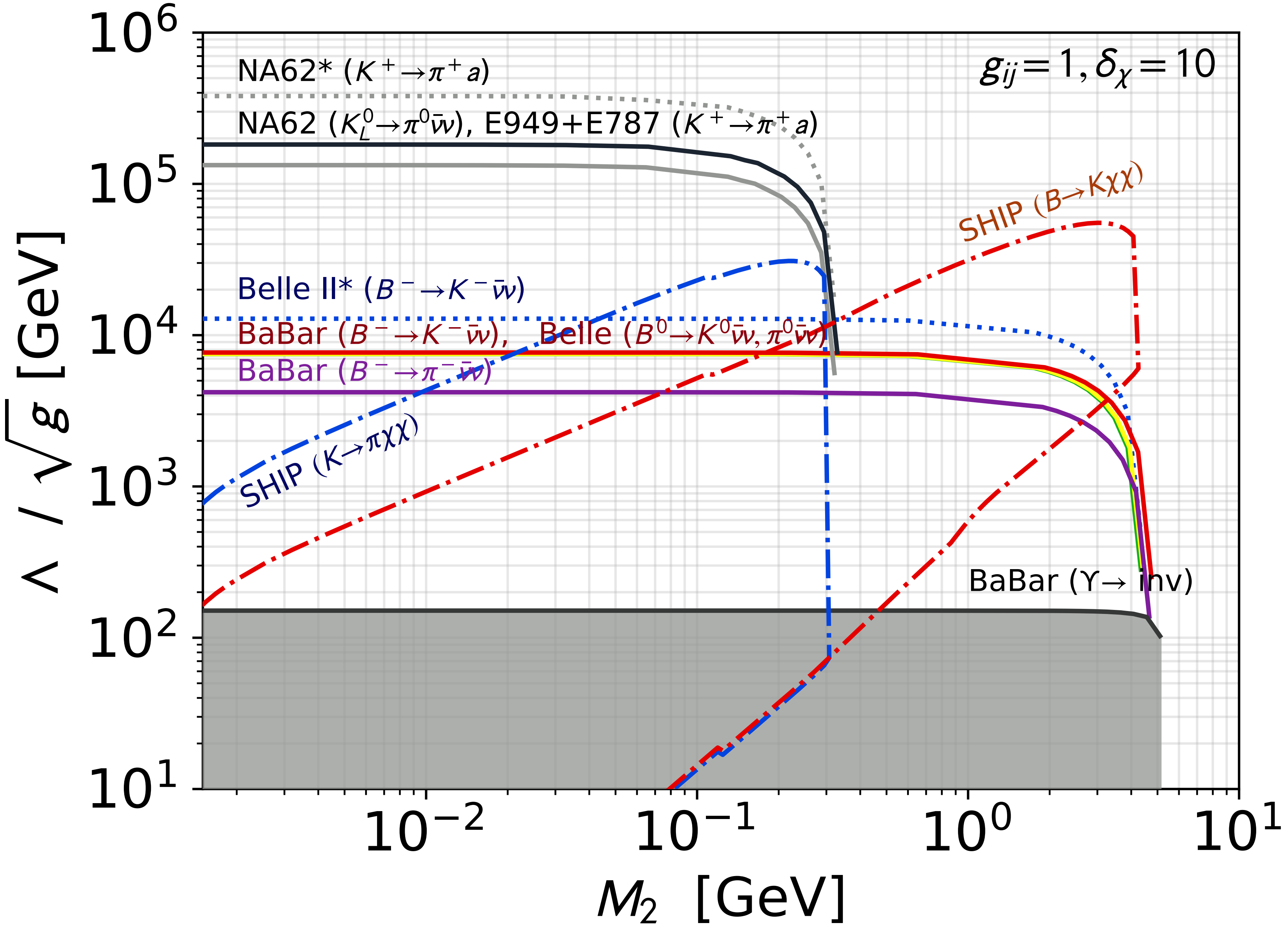
- Most limits in literature come from inelastic DM (iDM), w/ heavy state decaying via off-shell DP — *need recasting into EFT language*
  - Rescale for production rates $$\Lambda_{\rm lim} \sim 400 \text{ GeV} \cdot \sqrt{g} \left(\frac{0.001}{\epsilon_{\rm lim}}\right)^{1/2} \left(\frac{\mathcal{N}_{\rm prod}^{\rm EFT}}{\mathcal{N}_{\rm prod}^{\rm iDM}}\right)^{1/8}$$
  - Recompute detection efficiency for various mass splittings
  - Use upper limits to compute lower limits — *conservative lower limits*
- Bump searches ineffective when mediator integrated out — weakening of mono-X searches

Decays of heavier dark sector state into mesons crucial

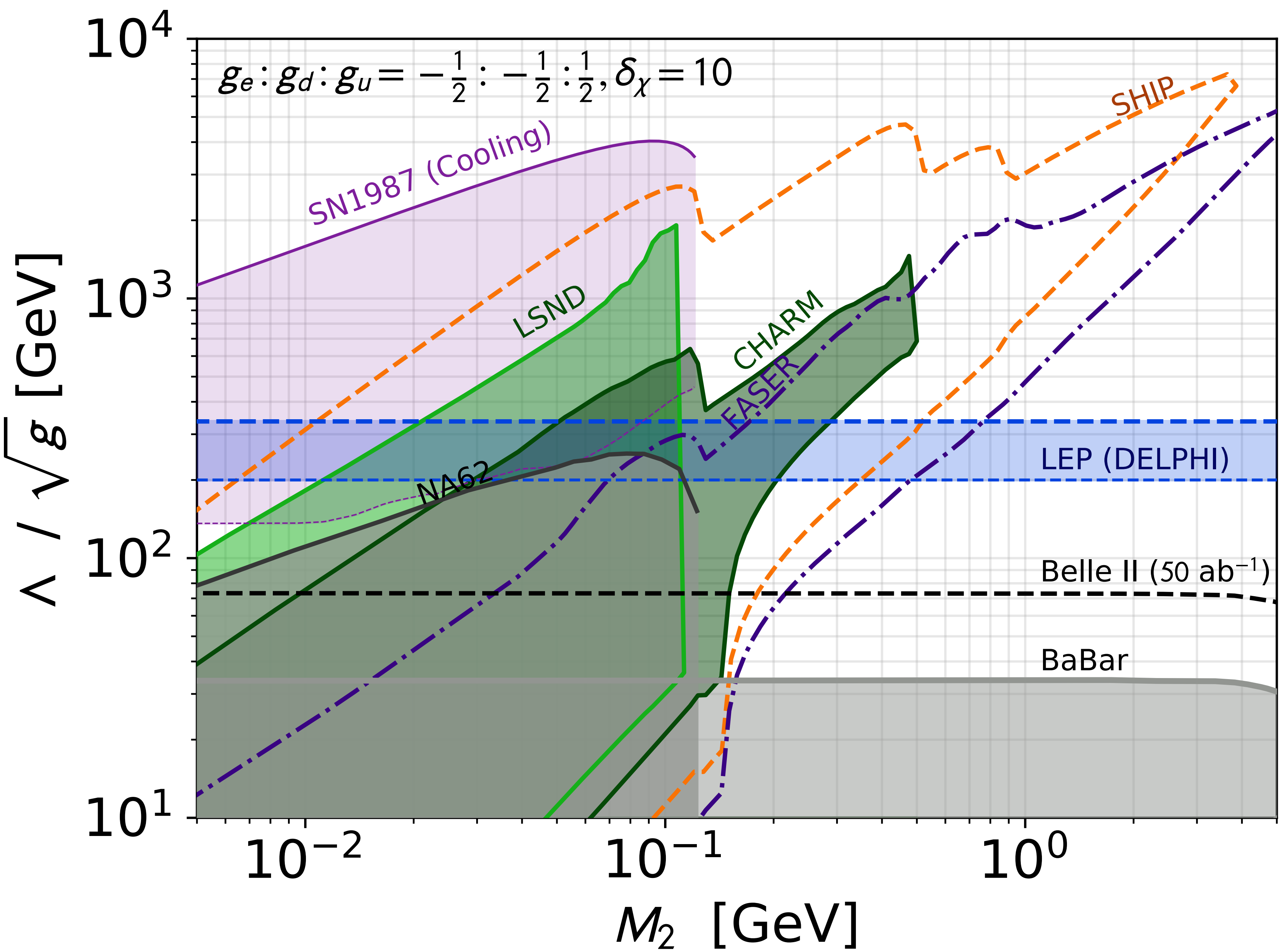
Limits – *Vector coupling, EM-aligned*



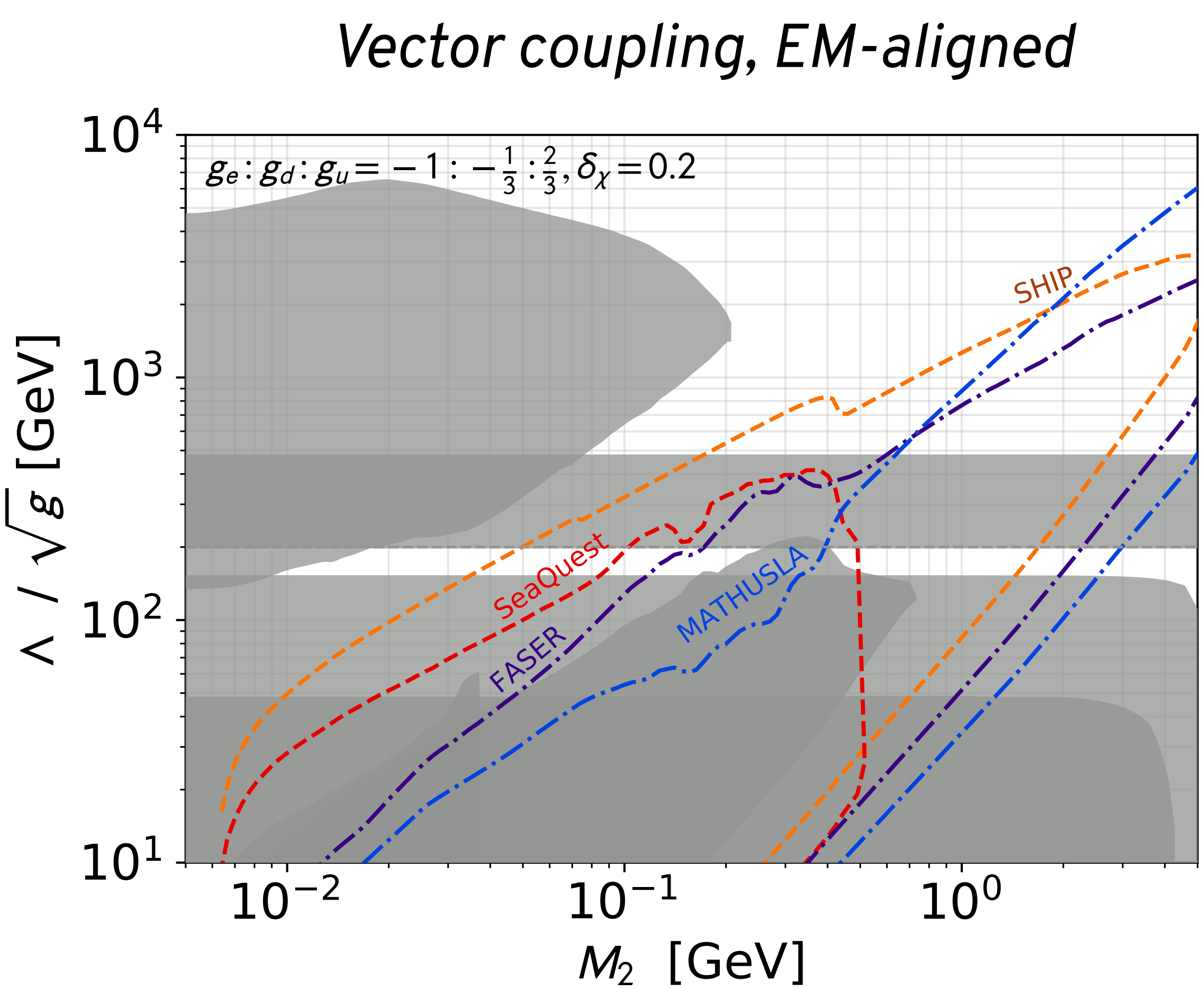
Limits – *Vector coupling, Heavy Mesons*

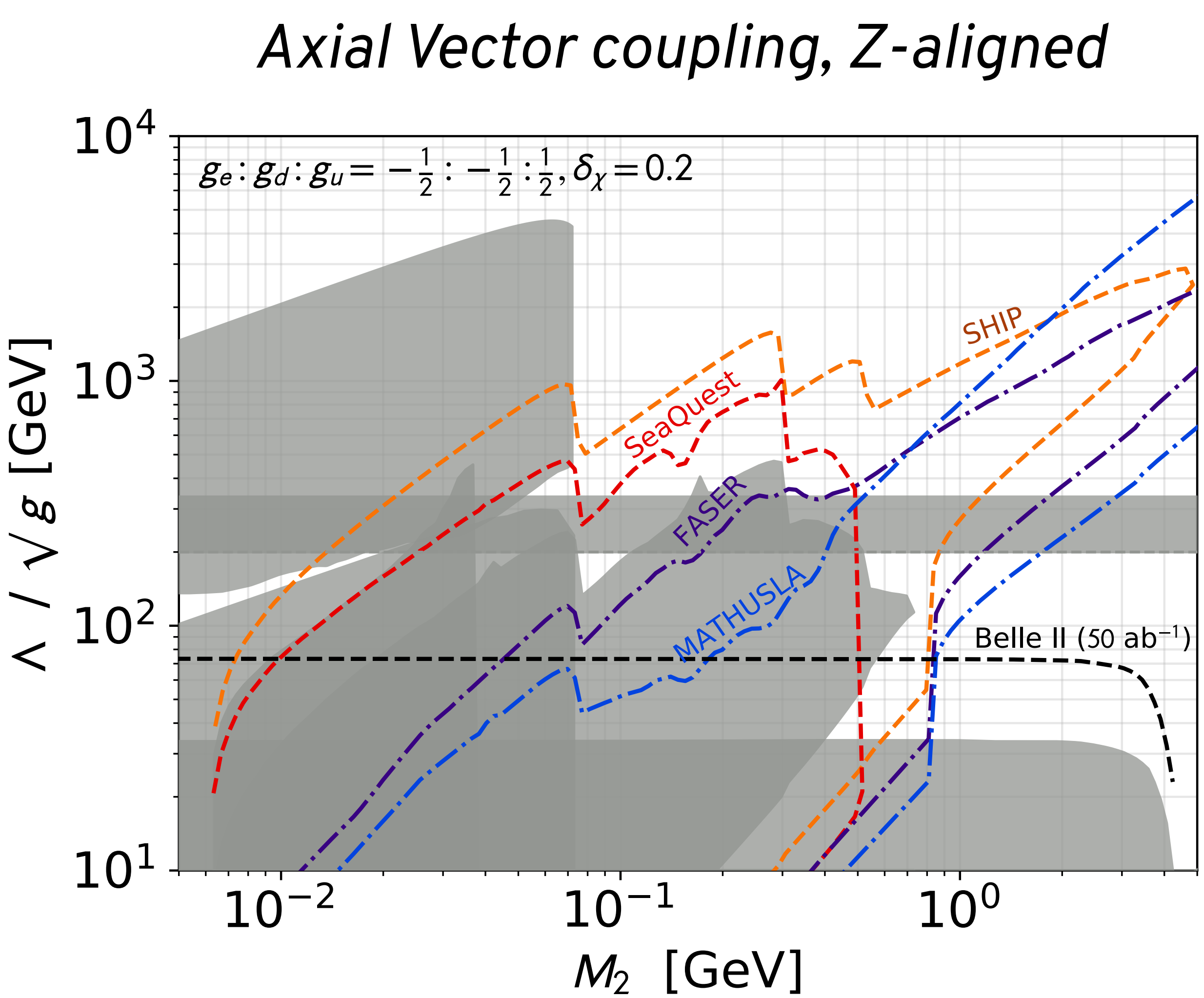


Limits – *Axial Vector coupling, Z-aligned*



Future sensitivity



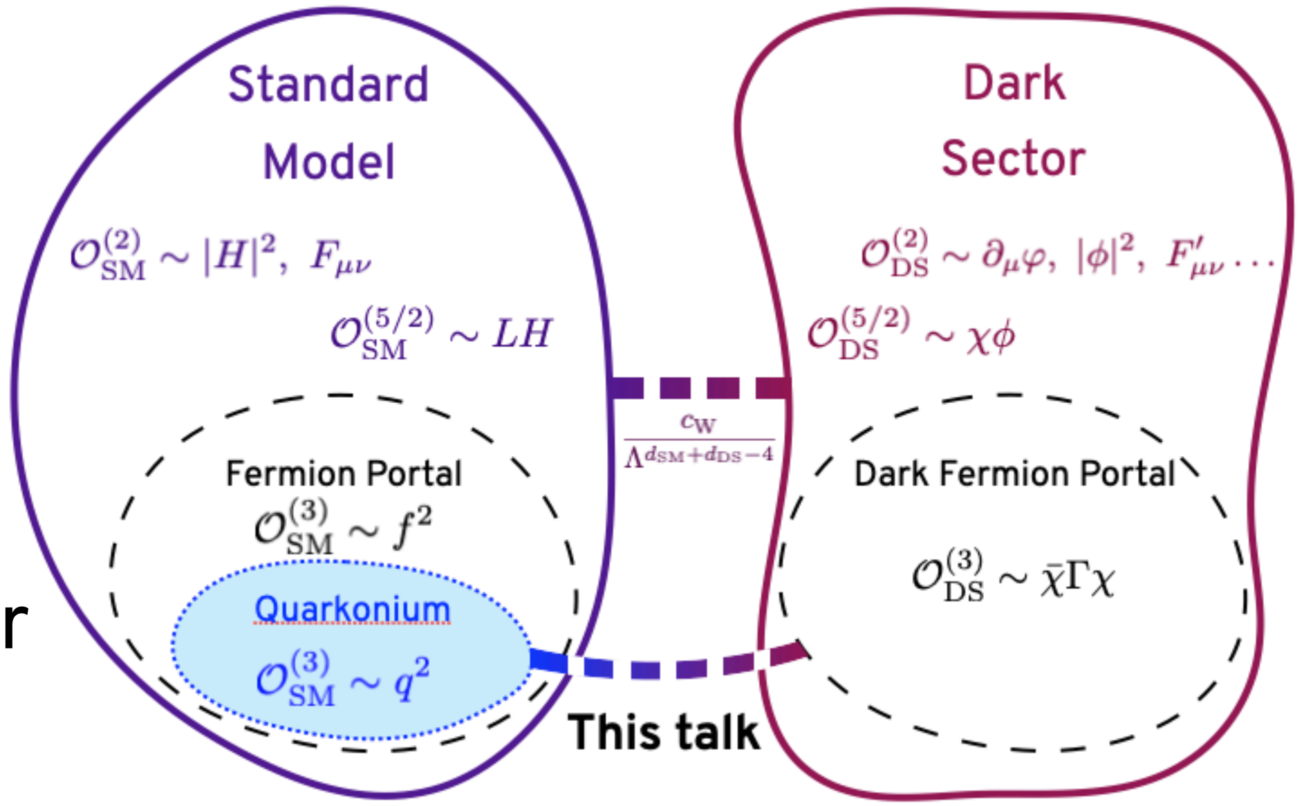


Conclusion

Important to go beyond mono-particle DM

Multi-particle Dark Sectors give rise to **long-lived particles** — critical target for intensity frontier

EFT provides *natural framework* to study connection to general dark sector



Fermion portal (quarkonium in particular) provides rich phenomenology to be tested

Code for re-casting available at https://github.com/Luc-Darme/DarkEFT

BACKUP

Meson Decays in detail

3-body light mesons:

$$\Gamma_{P,\gamma} = \frac{2g_P^2}{\pi f_\pi^2 \Lambda^4}\frac{\alpha_{\rm em}}{3(4\pi)^5}\int_{(|M_1|+|M_2|)^2}^{M_P^2} ds \frac{s(M_P^2-s)^3}{M_P^3} \times \begin{cases} \sqrt{1-4M_1^2/s}(1+2M_1^2/s) & \text{small } \delta_\chi\text{, V} \\ 2(1-4M_1^2/s)^{3/2} & \text{small } \delta_\chi\text{, AV} \\ (2+M_2^2/s)(1-M_2^2/s)^2 & \text{non-degenerate} \end{cases}$$

g_P *as defined on slide 8*

2-body light mesons:

$$\Gamma_U = \frac{g_U^2 f_\pi^2}{24\pi}\frac{M_U^3}{\Lambda^4}\left(1-\frac{(M_2-M_1)^2}{M_U^2}\right)^{3/2}\left(1-\frac{(M_2+M_1)^2}{M_U^2}\right)^{1/2}\left(2+\frac{(M_2+M_1)^2}{M_U^2}\right)$$

g_U *as defined on slide 8*

3-body heavy mesons:

$$\Gamma_{P\to P'\chi\chi} \simeq \frac{g_{PP'}^2|f_+(0)|^2}{\Lambda^4}\frac{M^8-8M^6M'^2+8M^2M'^6-M'^8+24M^4M'^4\log M/M'}{768\pi^3M^3}$$

obtained from lattice

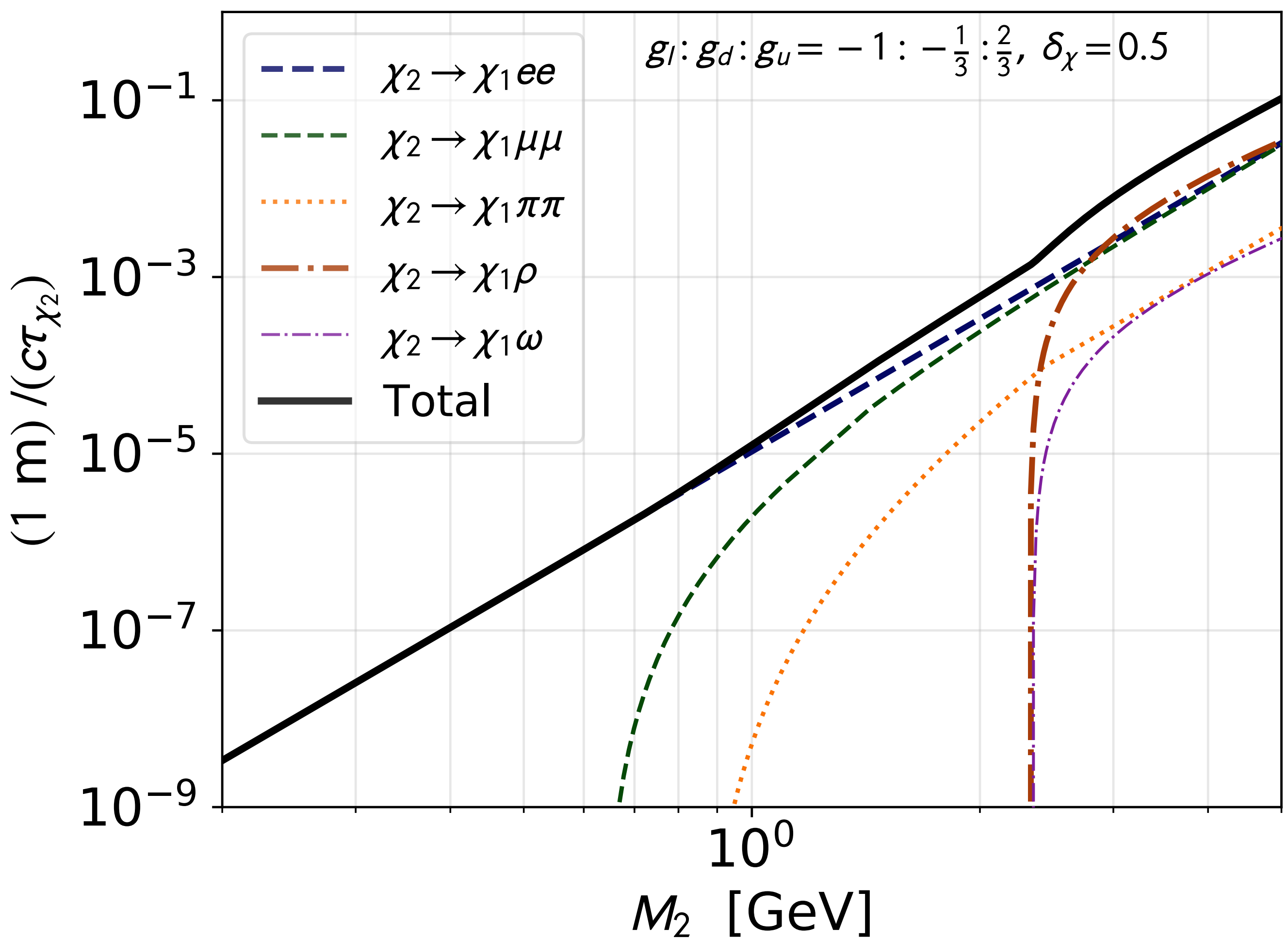
***QCDSF** (2010)*

In massless DS limit

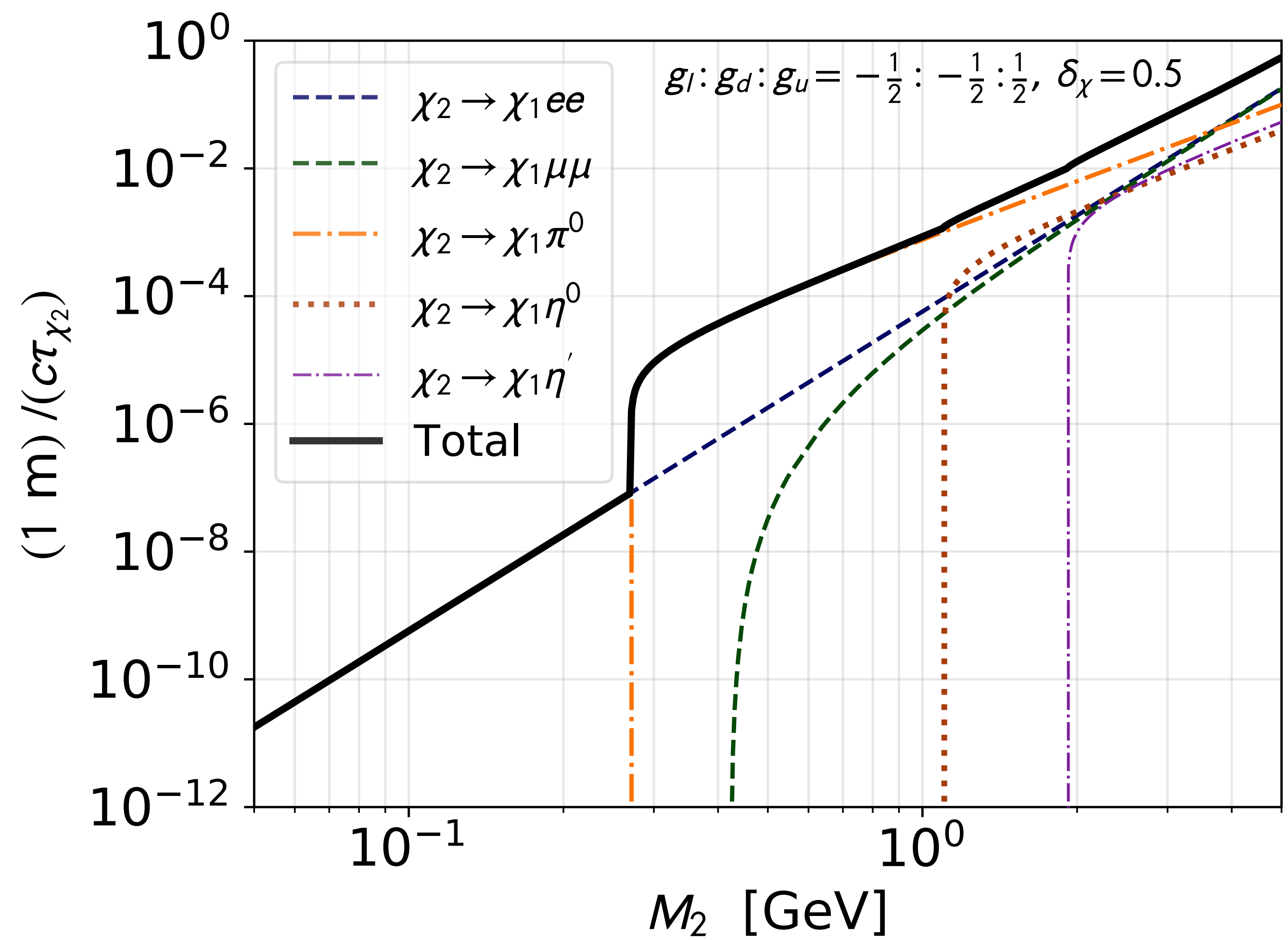
Decays of dark sector states

$$\Gamma_2 = \frac{g_l^2}{\Lambda^4}\frac{M_2^5}{\pi^3}\mathcal{G}(M_1, M_2)$$

Vector coupling, EM-aligned



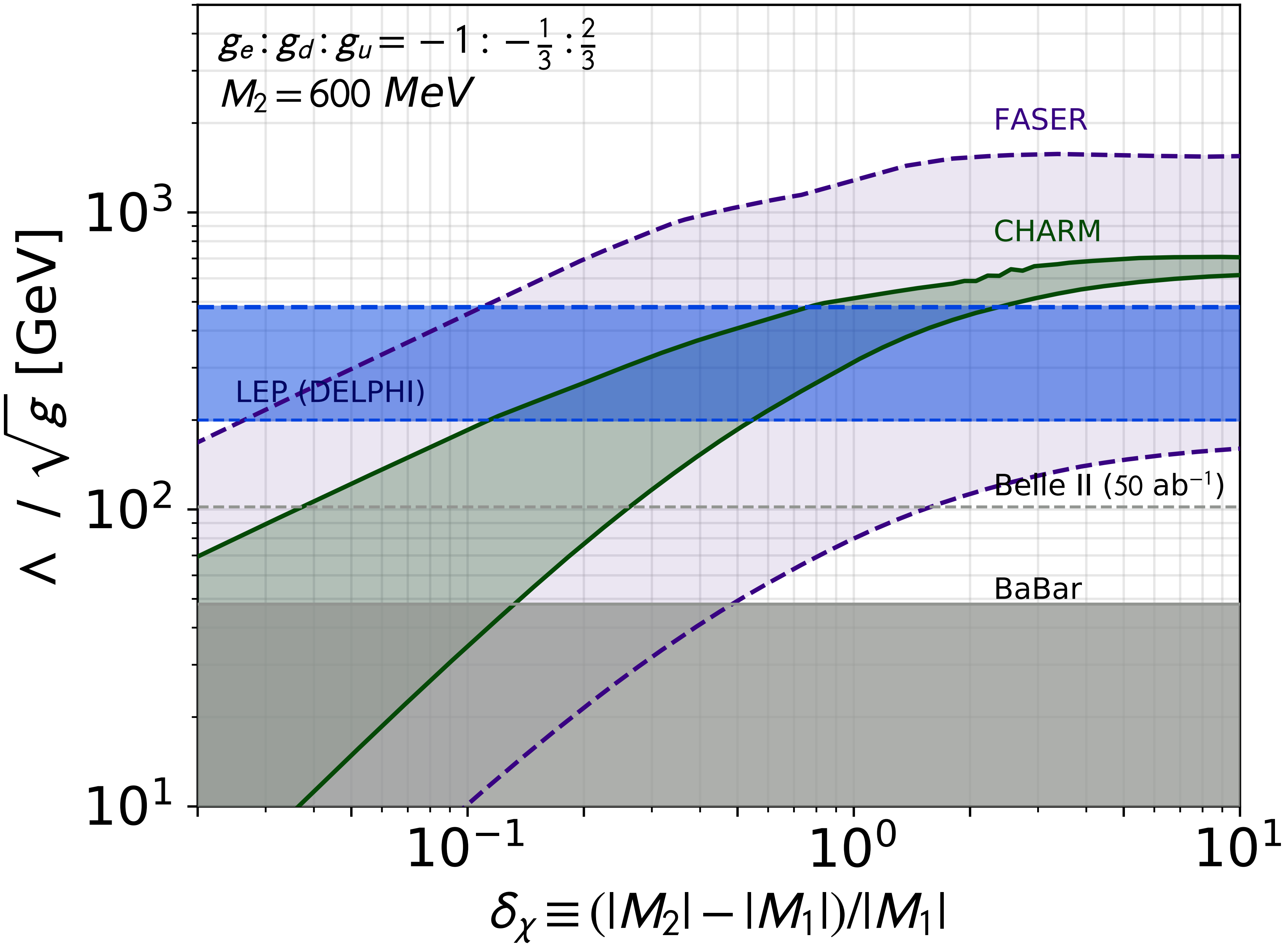
Axial Vector coupling, Z-aligned



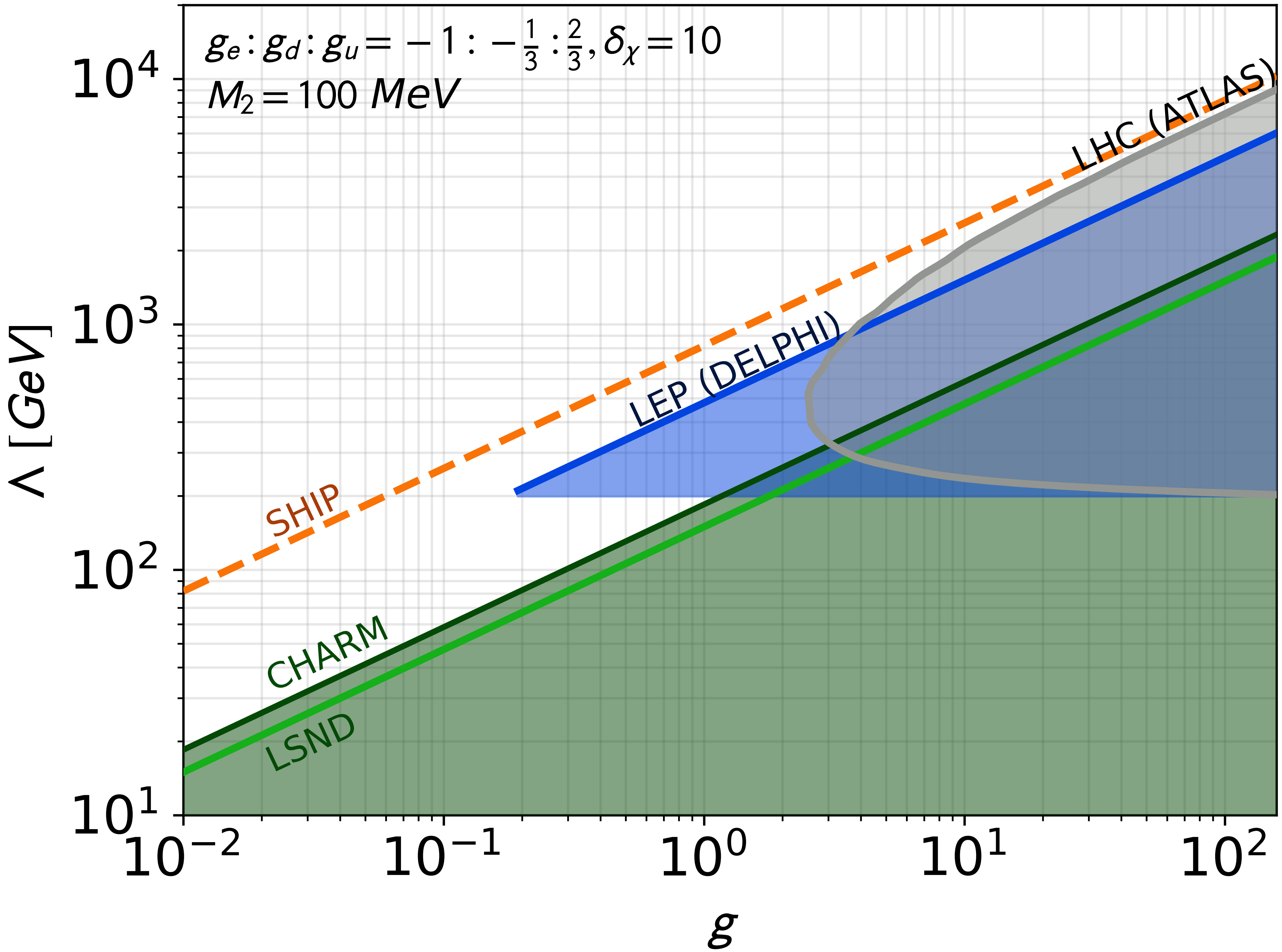
$$\mathcal{G}^V = \begin{cases} \frac{1}{60M_1^5}(\Delta_\chi^2 - M_l^2)^{5/2}, & \textit{degenerate} \\ \frac{1}{384}\left(1 - \frac{2M_1}{M_2}\right), & \textit{saturation} \end{cases}$$

$$\mathcal{G}^{A-V} = \begin{cases} \frac{1}{60M_1^5}(\Delta_\chi^2 - M_l^2)^{3/2}(\Delta_\chi^2 + 6M_l^2), \\ \frac{1}{384}\left(1 + \frac{2M_1}{M_2}\right), \end{cases}$$

Dependence on mass splitting

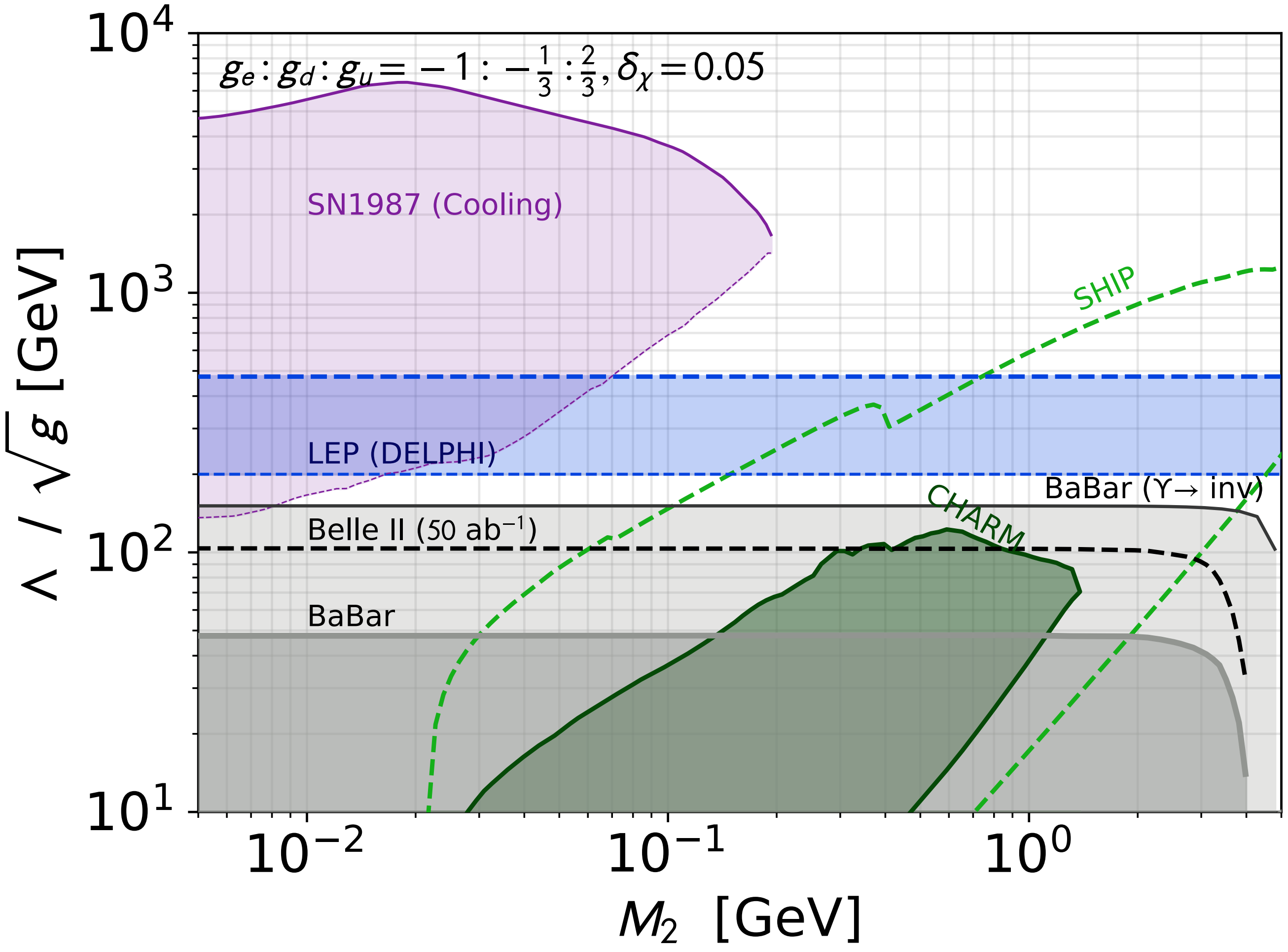


Dependence on coupling



Small mass splittings

Vector coupling, EM-aligned



Axial Vector coupling, Z-aligned