Dark Sectors at Muon Colliders

Tien-Tien Yu (University of Oregon)

INAUGURAL US MUON COLLIDER COMMUNITY MEETING   **August 8, 2024**

Why Muon Colliders for Dark Sectors?

- dark sectors are a sandbox for model building and systematic way of exploring model space

- can give rise to "weird" and unique signatures > help inform detector design

- connection to big questions like nature of dark matter

- muon collider provides synergy to upcoming era of cosmological probes

WIMP Dark Matter

"Minimal Dark Matter": consider dark matter to be the lightest member of an electroweak multiplet

T. Han, Z. Liu, L.-T. Wang, X. Wang [arXiv:2009.11287]

Model $(color, n, Y)$		Therm. target	5σ discovery coverage (TeV)			
			mono-γ	mono-μ	di-μ's	disp. tracks
$(1,2,1/2)$	Dirac	1.1 TeV	—	2.8	—	$3.2 - 8.5$
$(1,3,0)$	Majorana	2.8 TeV	—	3.7	—	$13 - 14$
$(1,3,\epsilon)$	Dirac	2.0 TeV	0.9	4.6	—	$13 - 14$
$(1,5,0)$	Majorana	14 TeV	3.1	7.0	3.1	$10 - 14$
$(1,5,\epsilon)$	Dirac	6.6 TeV	6.9	7.8	4.2	$11 - 14$
$(1,7,0)$	Majorana	23 TeV	11	8.6	6.1	$8.1 - 12$
$(1,7,\epsilon)$	Dirac	16 TeV	13	9.2	7.4	$8.6 - 13$

Higgsino-like → $(1,3,0)$
Wino-like → $(1,3,\epsilon)$

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Higgsino-like
Wino-like

↑
stronger
channel

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Higgsino-like
Wino-like

even more promising!

stronger channel

further enhancements shown in
R. Capdevilla, F. Meloni, J. Zurita [arXiv:2405.08858]

Muon Collider 2σ Reach

($\sqrt{s}$ = 3, 6, 10, 14, 30, 100 TeV)

(1,7,ε)

di–μ $m_{missing}$
mono–μ
mono–γ
mono–γ+2DT
mono–γ+1DT

(1,7,0)

di–μ $m_{missing}$
mono–μ
mono–γ
mono–γ+2DT
mono–γ+1DT

(1,5,ε)

di–μ $m_{missing}$
mono–μ
mono–γ
mono–γ+2DT
mono–γ+1DT

(1,5,0)

di–μ $m_{missing}$
mono–μ
mono–γ
mono–γ+2DT
mono–γ+1DT

(1,3,ε)

di–μ $m_{missing}$
mono–μ
mono–γ
mono–γ+2DT
mono–γ+1DT

(1,3,0)
Wino–like

di–μ $m_{missing}$
mono–μ
mono–γ
mono–γ+2DT
mono–γ+1DT

Thermal Target

(1,2,$\frac{1}{2}$)
Higgsino–like

di–μ $m_{missing}$
mono–μ
mono–γ
mono–γ+2DT
mono–γ+1DT

0.5   1   5   10   50

m_χ(TeV)

T. Han, Z. Liu, L.-T. Wang, X. Wang
WIMPS at High Energy Muon Colliders [arXiv:2009.11287]

Muon Collider **2σ** Reach

$(\sqrt{s} = 3, \ 6, \ 10, \ 14, \ 30, \ 100 \ \text{TeV})$

Muon collider can definitively test Wino and Higgsino WIMPs at 10 TeV!

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T. Han, Z. Liu, L.-T. Wang, X. Wang
WIMPS at High Energy Muon Colliders [arXiv:2009.11287]

4

Muon Collider **2σ** Reach
($\sqrt{s}$ = 3, 6, 10, 14, 30, 100 TeV)

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Comparison with other approaches:

R. Capdevilla, F. Meloni, R. Simoniello, and J. Zurita,
JHEP 06 (2021) 133, [arXiv:2102.11292]

T. Han, Z. Liu, L.-T. Wang, X. Wang
WIMPS at High Energy Muon Colliders [arXiv:2009.11287]

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Comparison with other approaches:

FCC-hh

MuC

R. Capdevilla, F. Meloni, R. Simoniello, and J. Zurita, JHEP 06 (2021) 133, [arXiv:2102.11292]

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T. Han, Z. Liu, L.-T. Wang, X. Wang
WIMPS at High Energy Muon Colliders [arXiv:2009.11287]

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Dark Sector Portals
moving beyond the WIMP
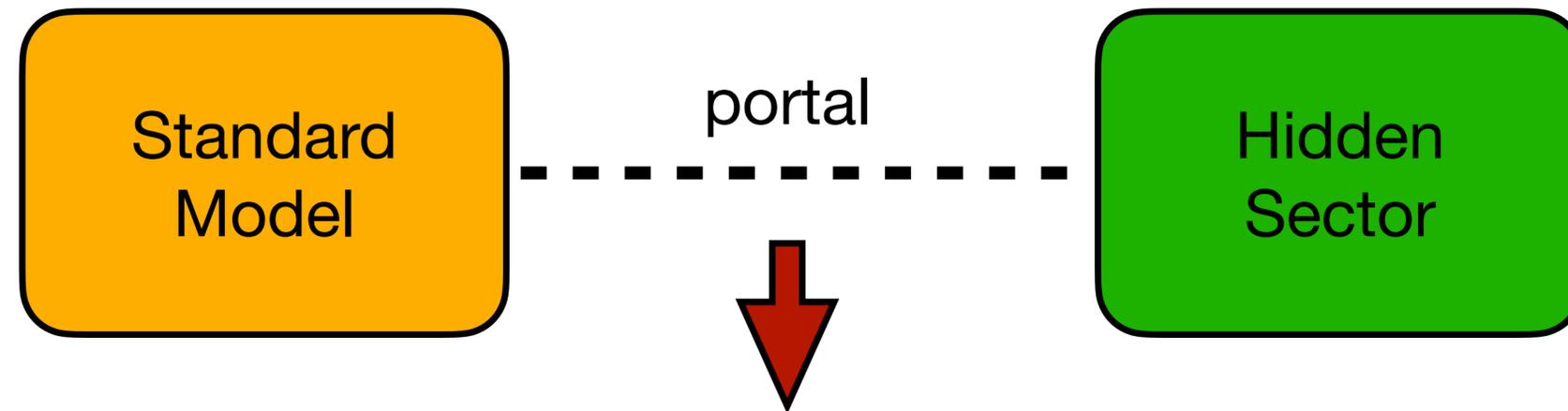
$$\mathcal{L} \supset \begin{cases} (\mu S + \lambda S^2) H^\dagger H & \text{scalar} \\[2ex] \dfrac{a}{f} \, \widetilde{F}_{\mu\nu} F^{\mu\nu} & \text{pseudoscalar} \\[2ex] -\dfrac{\epsilon}{2\cos\theta_W} \, F'_{\mu\nu} F^{\mu\nu} & \text{vector} \\[2ex] y_n L H N & \text{neutrino} \end{cases}$$

Vector Portal
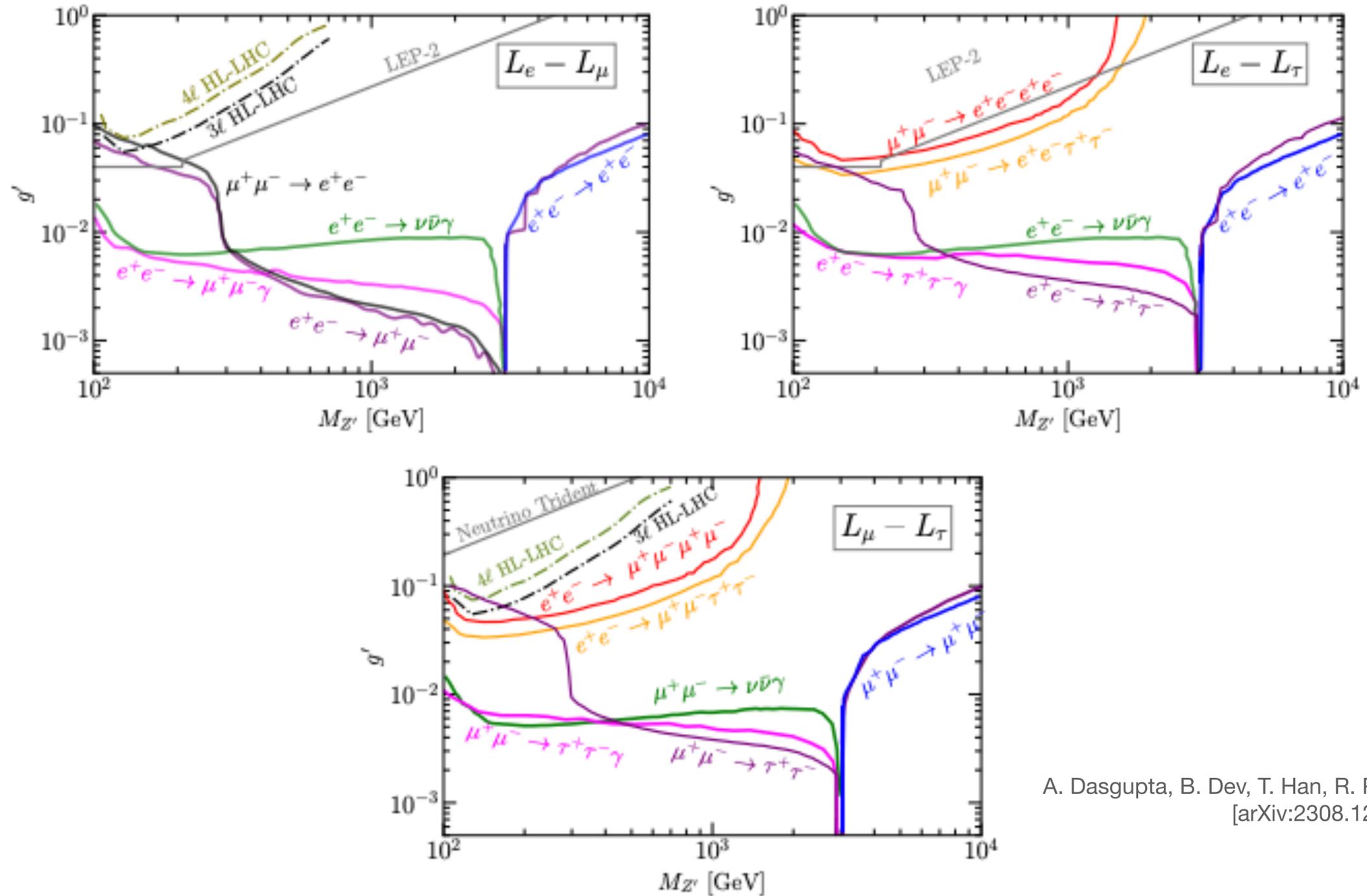
$$\sqrt{s} = 3 \text{ TeV}$$

A. Dasgupta, B. Dev, T. Han, R. Padhan, S. Wang, K. Xie
[arXiv:2308.12804]

Vector Portal

Vector, $\mathrm{BR}(V \to \mu^+\mu^-) = 1$ for $m_V > 2m_\mu$

Vector, $\mathrm{BR}(V \to \mu^+\mu^-) = \min.$ for $m_V > 2m_\mu$
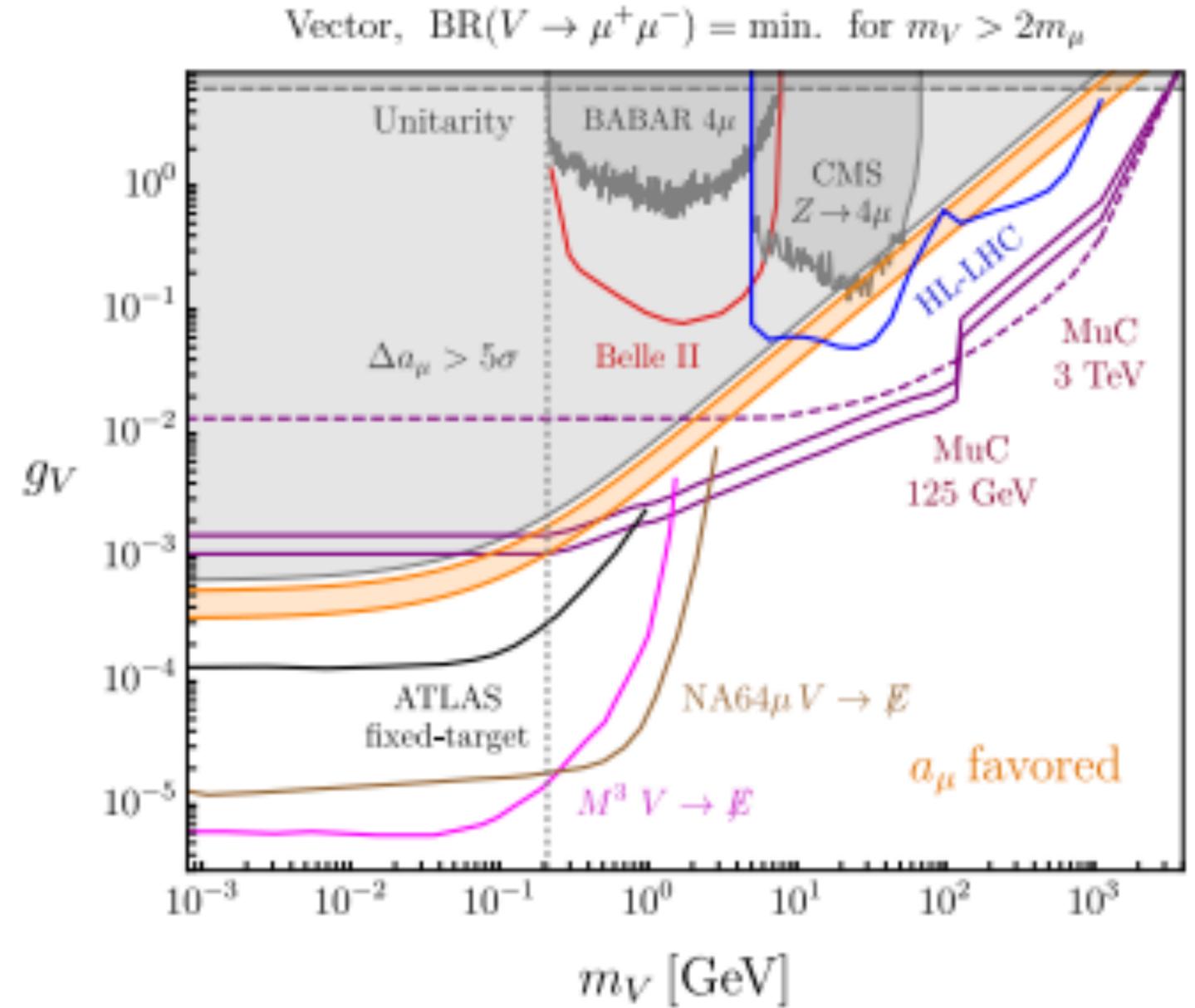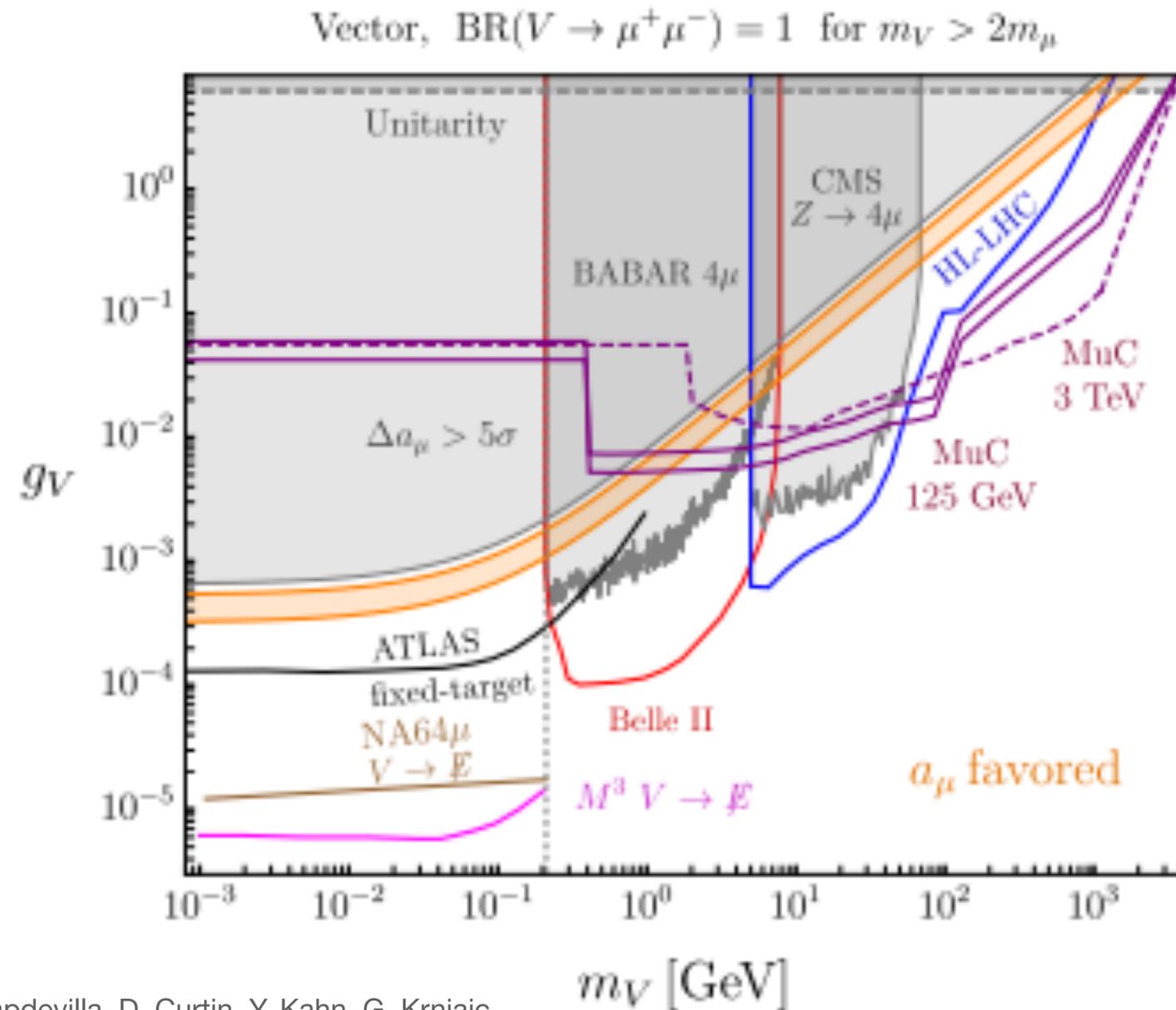
R. Capdevilla, D. Curtin, Y. Kahn, G. Krnjaic
[arXiv:2112.08377]

$$\mathcal{L} \supset g_V V_\gamma (\mu_L^\dagger \bar{\sigma}^\gamma \mu_L + \mu^{c\dagger} \bar{\sigma}^\gamma \mu^c)$$

High-Energy Lepton Collider as a "Vector Boson Collider"

great for scalar and pseudoscalar portal!
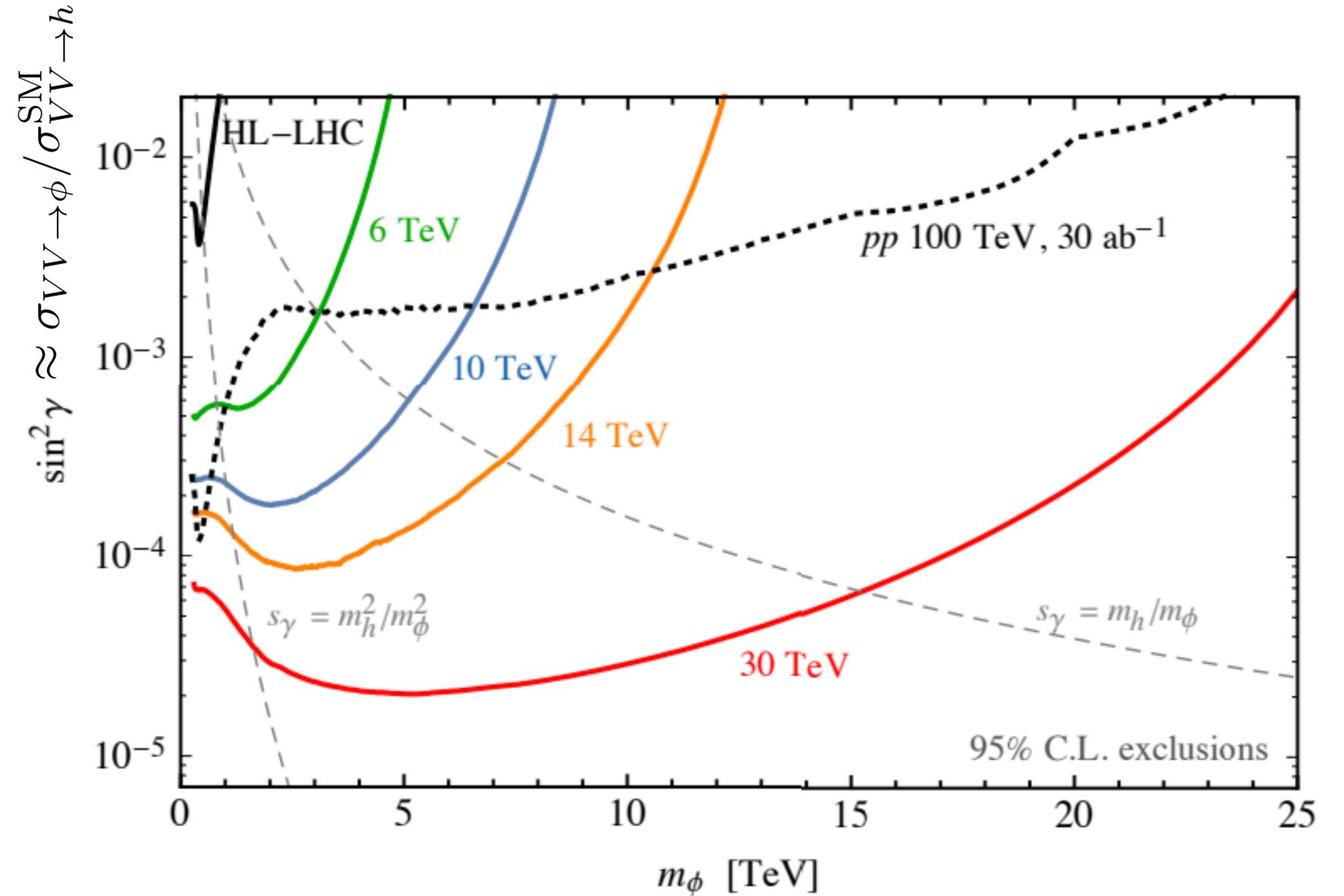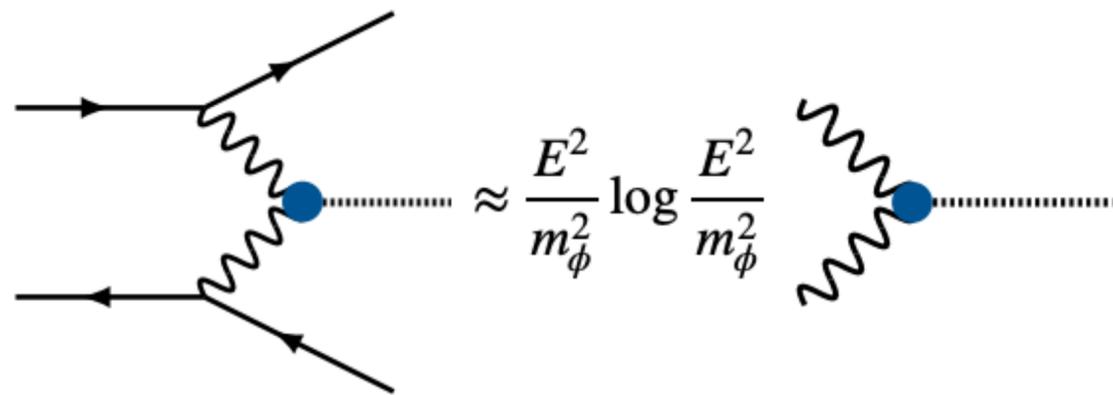
D. Buttazzo, D. Redigolo, F. Sala, A. Tesi
[arXiv:1807.04743] + [arXiv:2103.14043]

Scalar Portal

Scalar, $\mathrm{BR}(S \to \mu^+\mu^-) = 1$ for $m_S > 2m_\mu$

Scalar, $\mathrm{BR}(S \to \mu^+\mu^-) = \min.$ for $m_S > 2m_\mu$
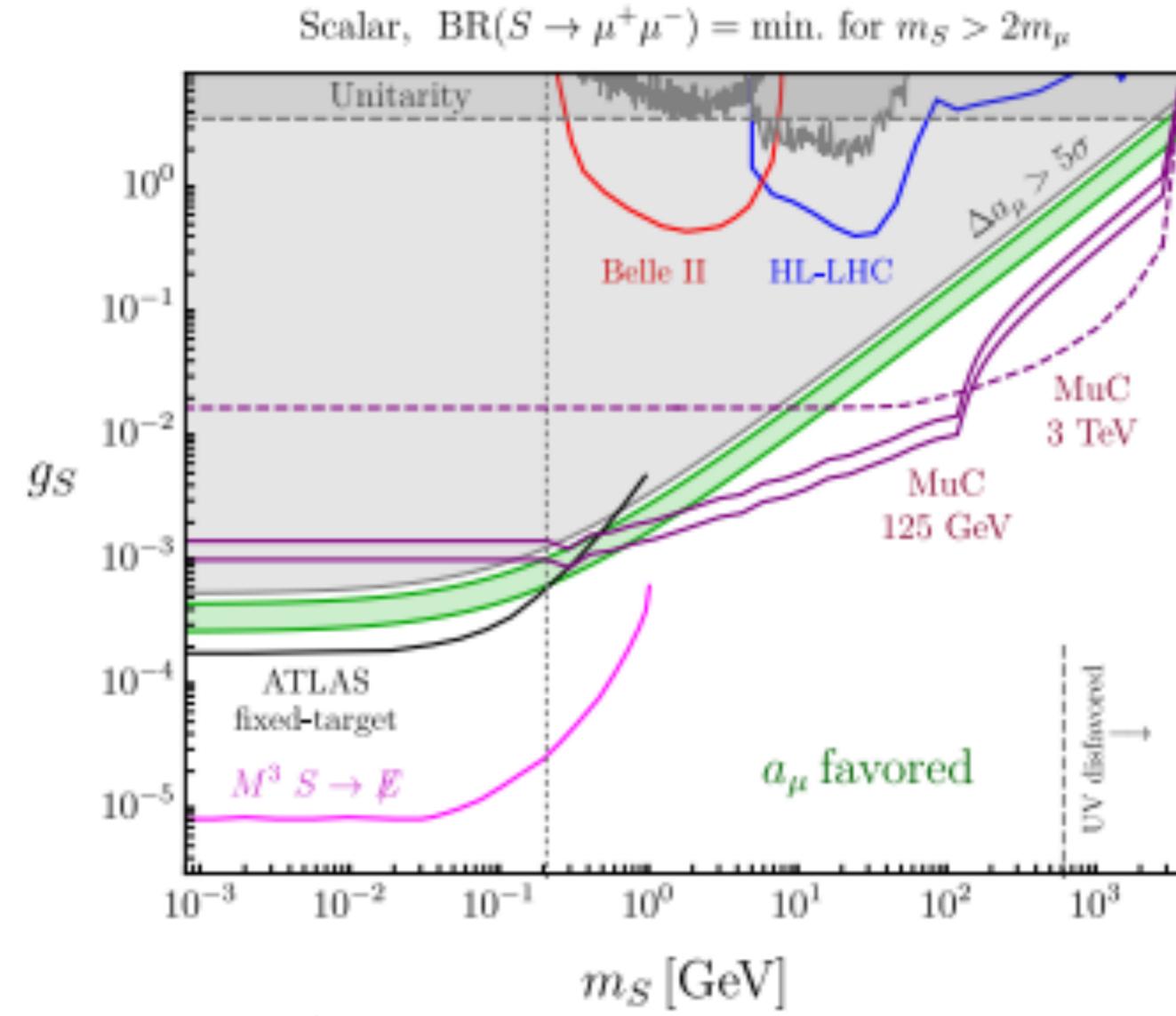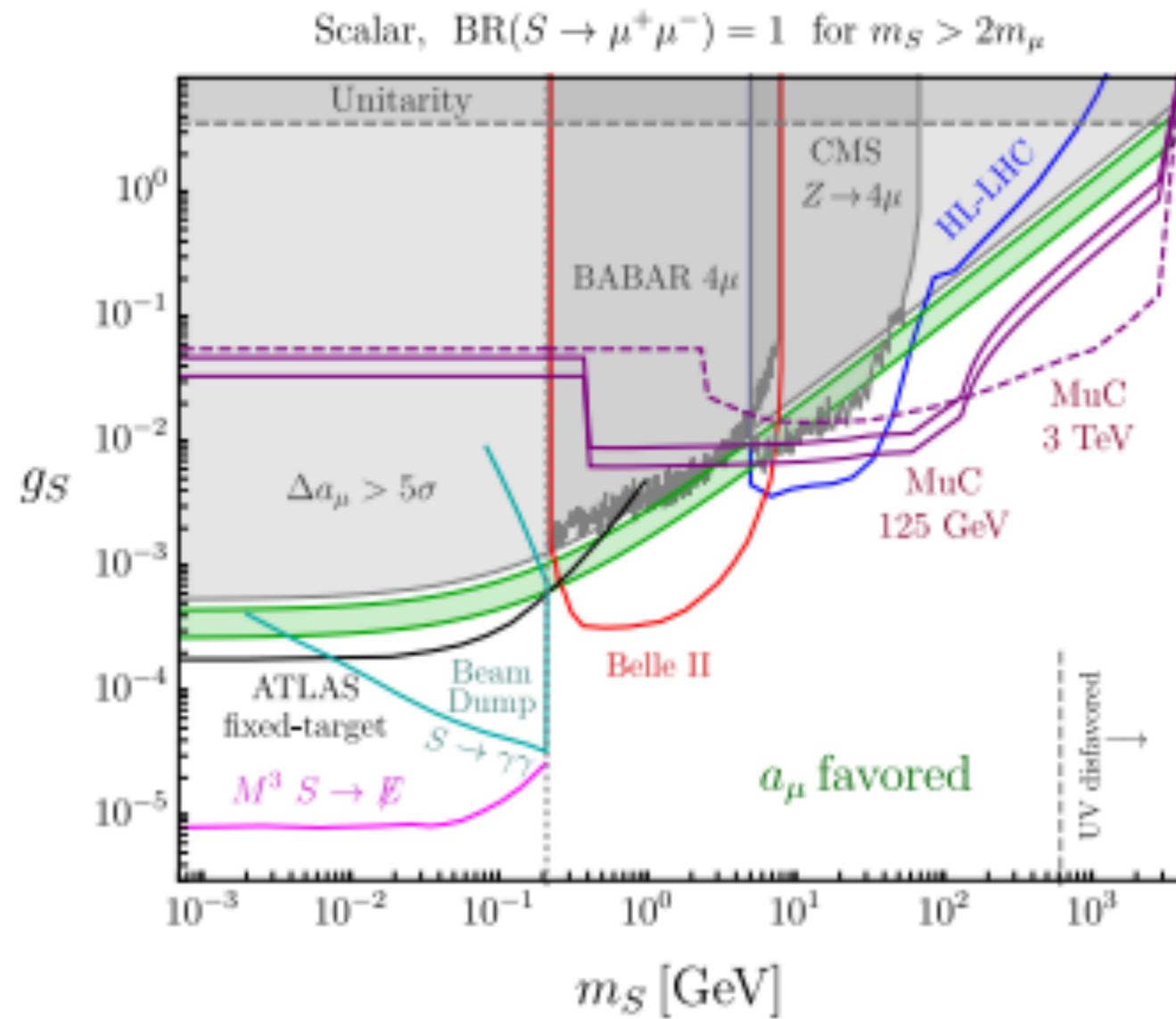
R. Capdevilla, D. Curtin, Y. Kahn, G. Krnjaic
[arXiv:2112.08377]

$$\mathcal{L} \supset g_S S(\mu_L \mu^c + \mu^{c\dagger} \mu_L^\dagger)$$

Pseudoscalar Portal

Axions and ALPs

adapted from
M. Bauer, M. Heiles, M. Neubert, A. Thamm
[arXiv:1808.10323]
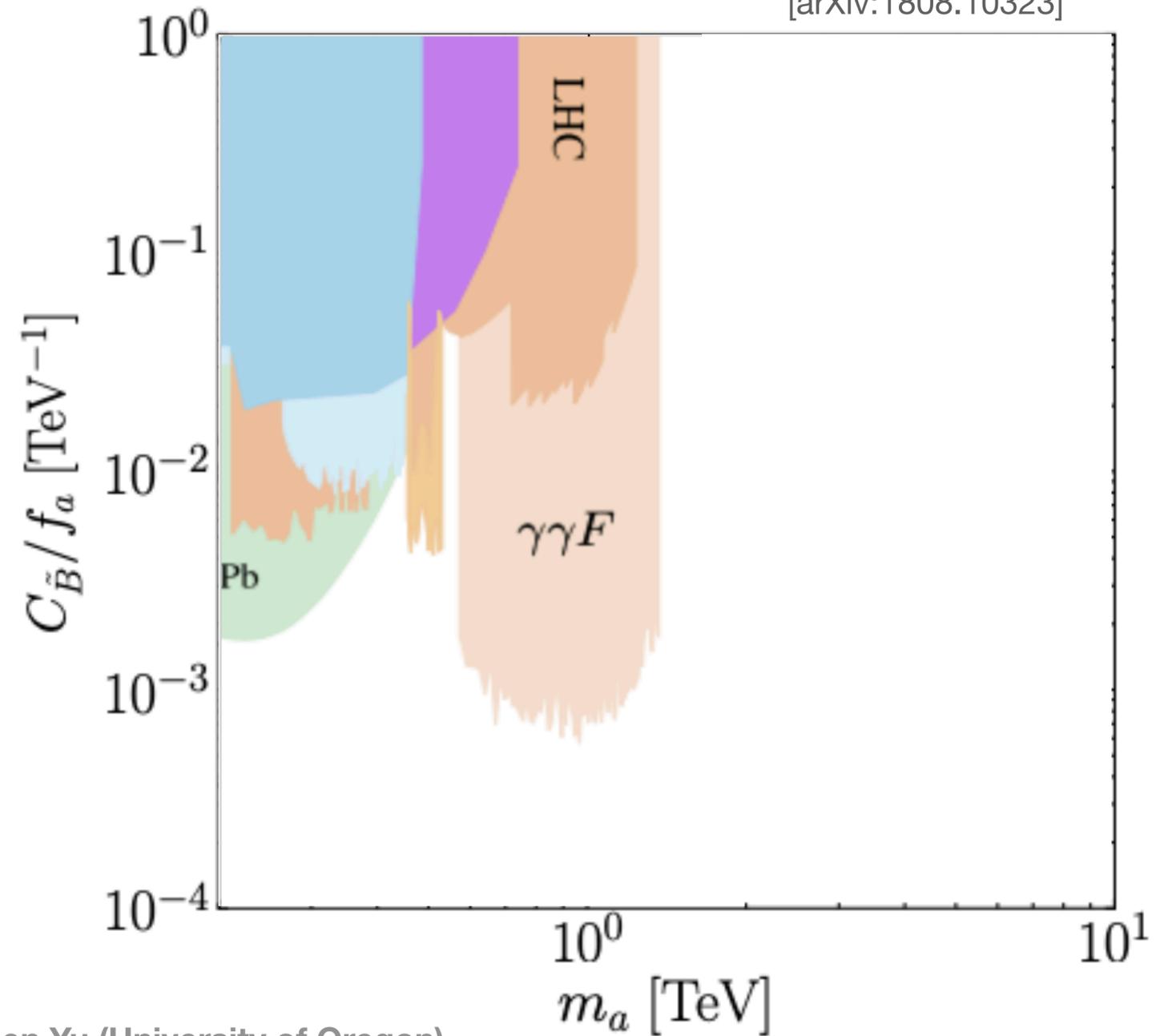
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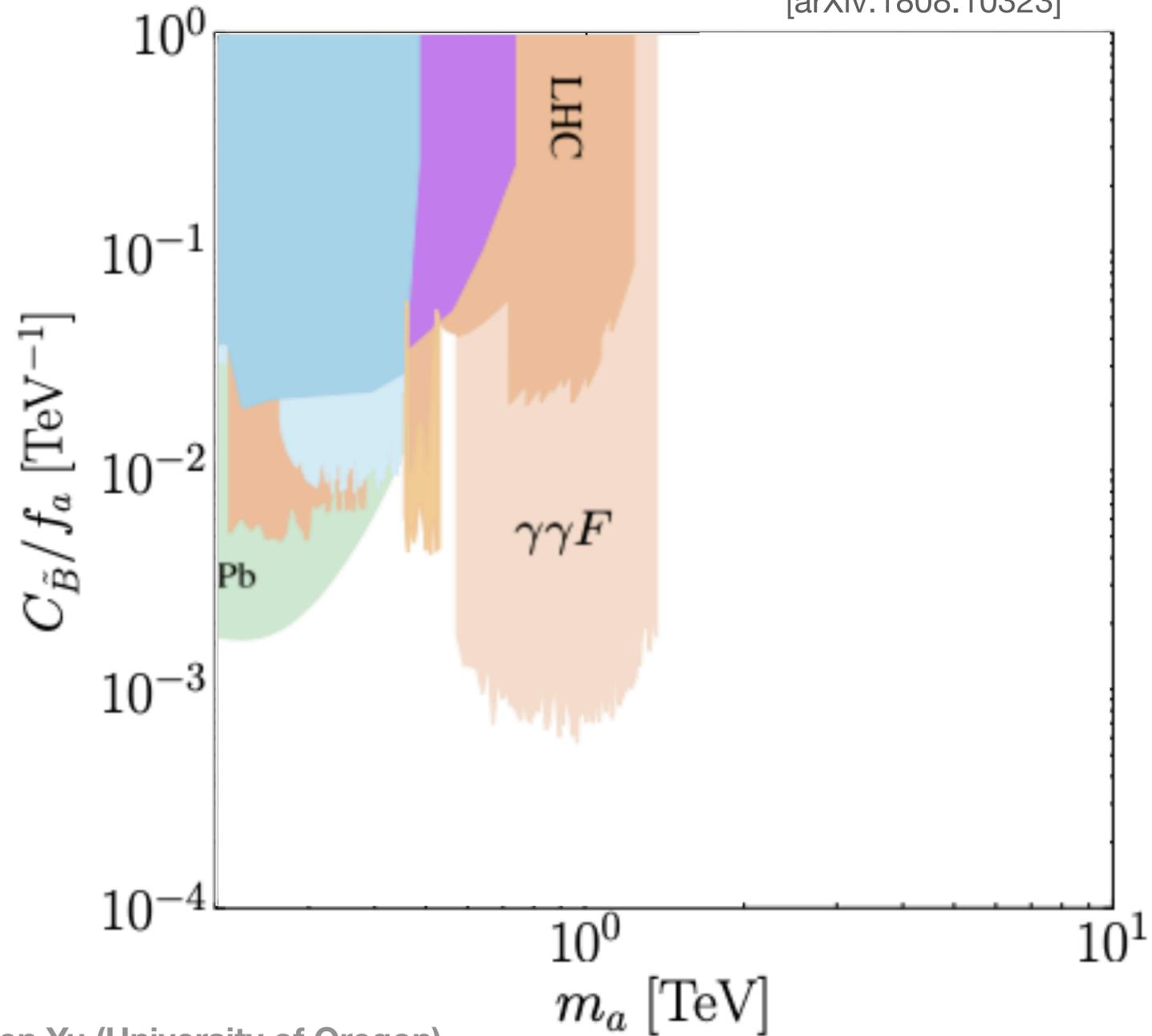
+ T. Han, T. Li, X. Wang
[arXiv:2203.05484]

see also Y. Bao, J. Fan, L. Li
[arxiv:2203.04328]
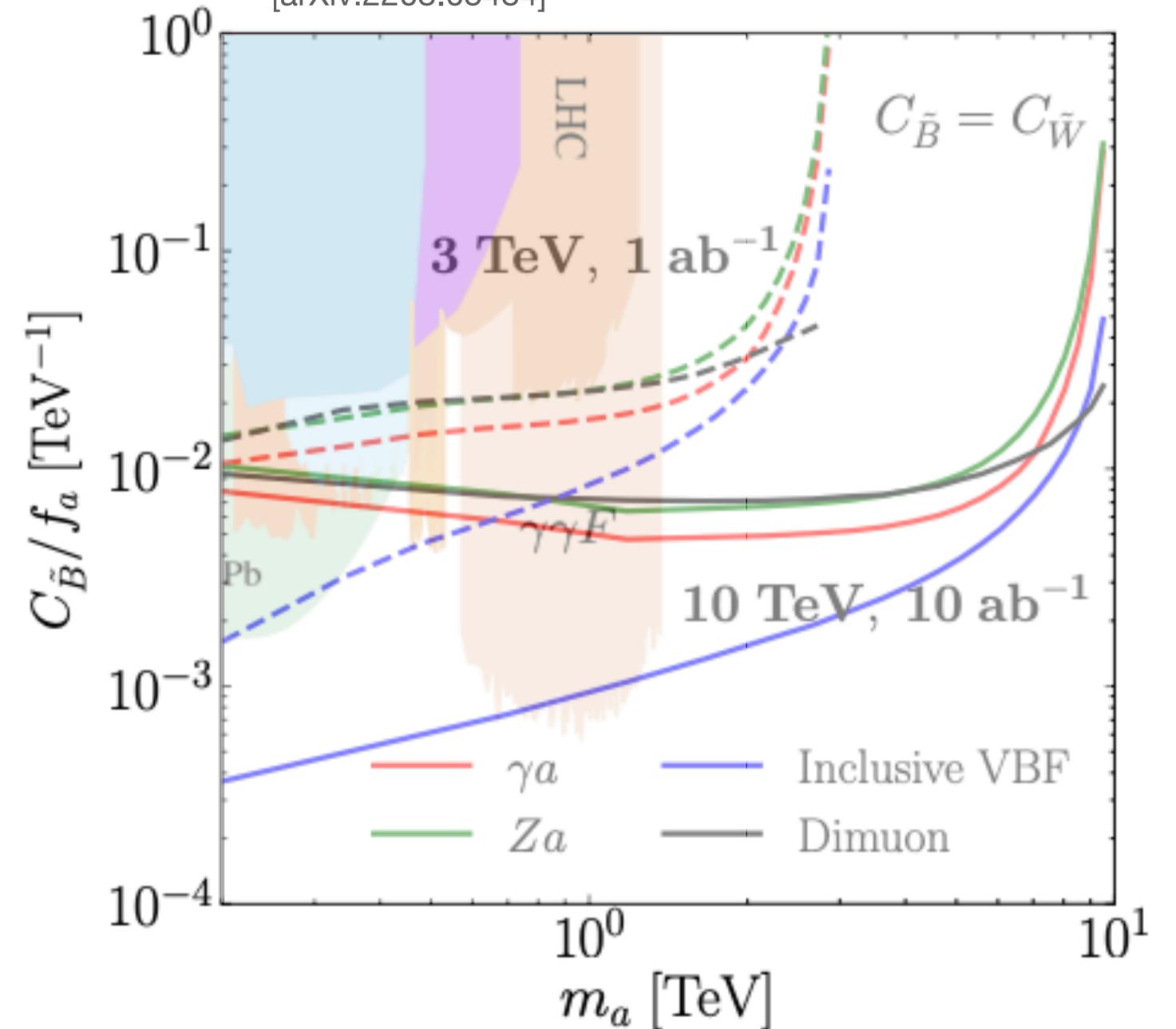
Neutrino Portal

$$\mathcal{L}_\nu \supset -\lambda_\nu \bar{L}\tilde{H}N + h.c.$$
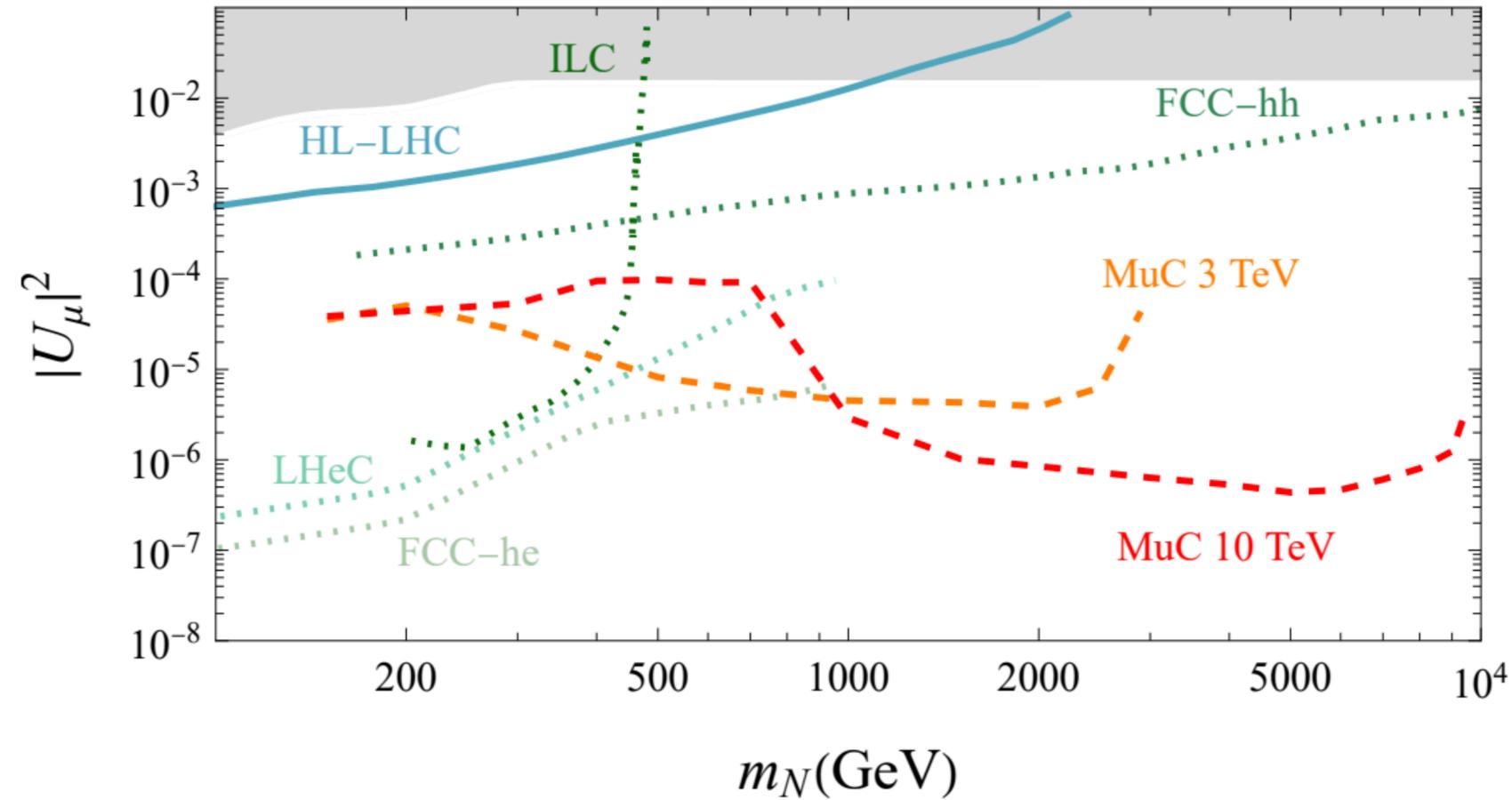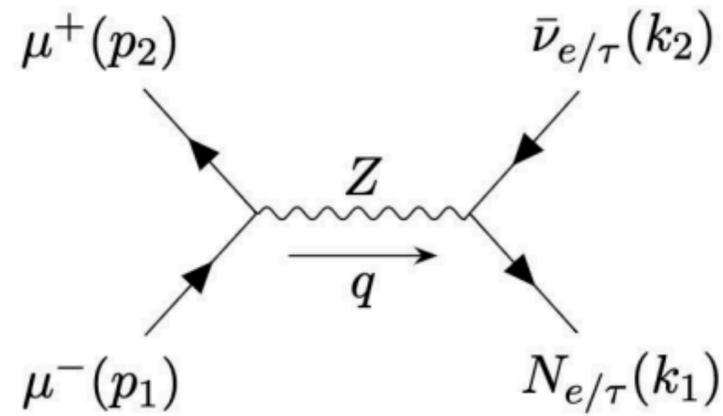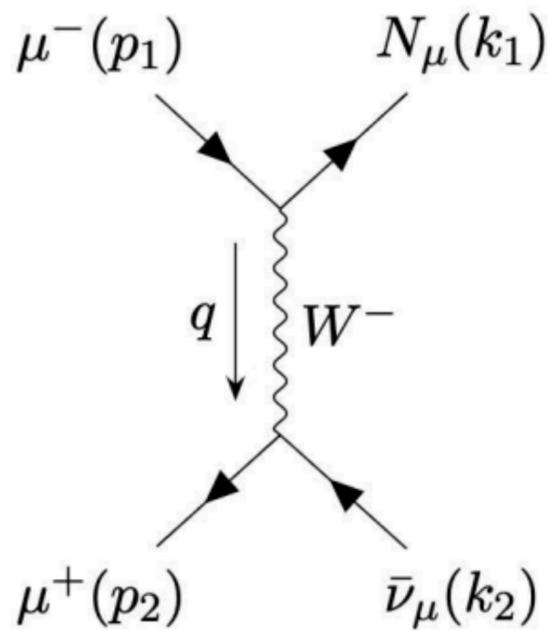
P. Li, Z. Liu, K-F. Lyu
[arXiv:2301.07117]

Case study: flavored dark matter
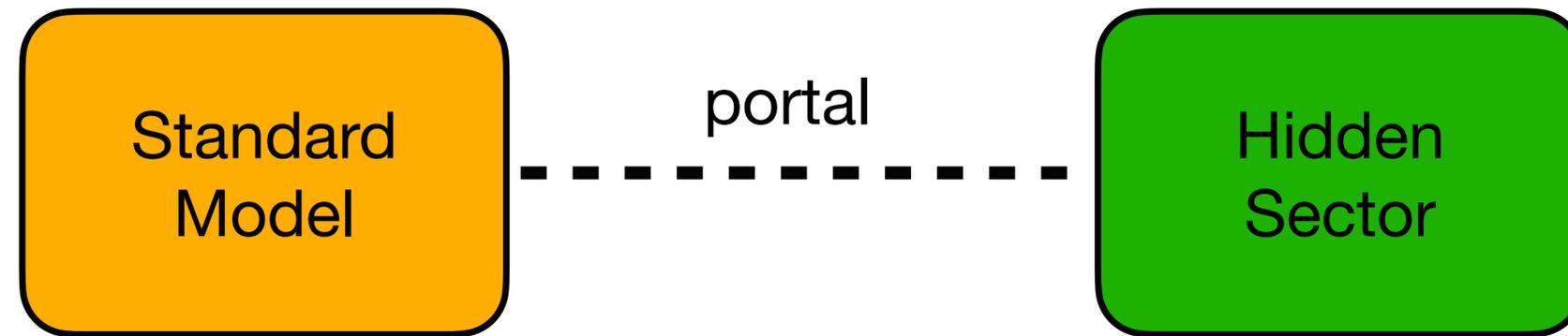
# Other Hidden Sector Models
case study: flavored dark matter
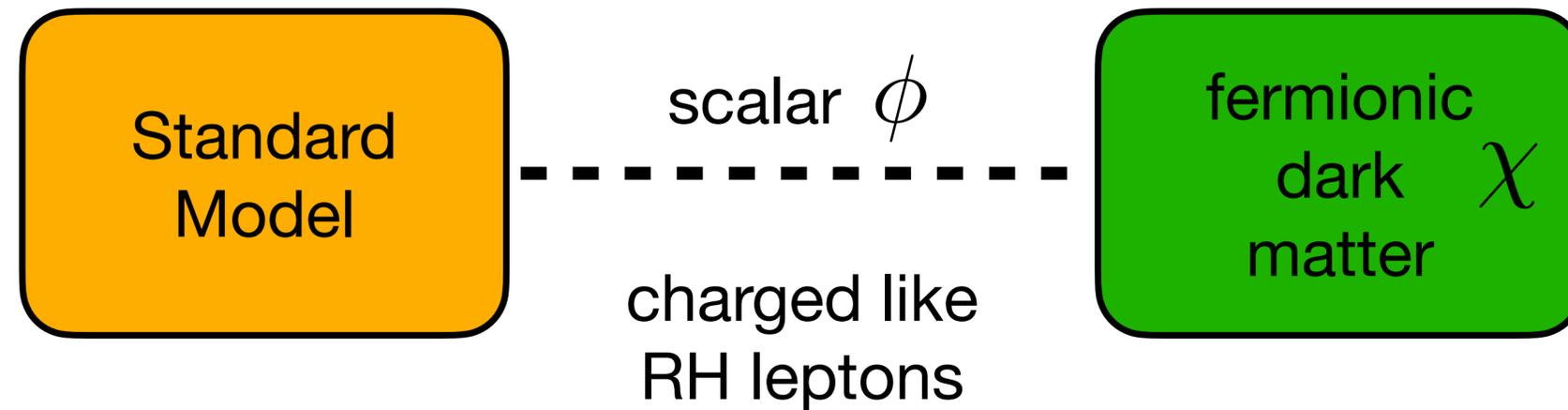
$$\mathcal{L} \supset -m_\chi \bar{\chi}_\alpha \chi^\alpha - m_\phi^2 |\phi|^2 - \lambda_{i,\alpha} \phi \bar{e}_i \bar{\chi}_\alpha$$

flavor indices

P. Asadi, A. Radick, TTY [arXiv:2312.03826]

Lepton-Flavored Dark Matter
relic abundance
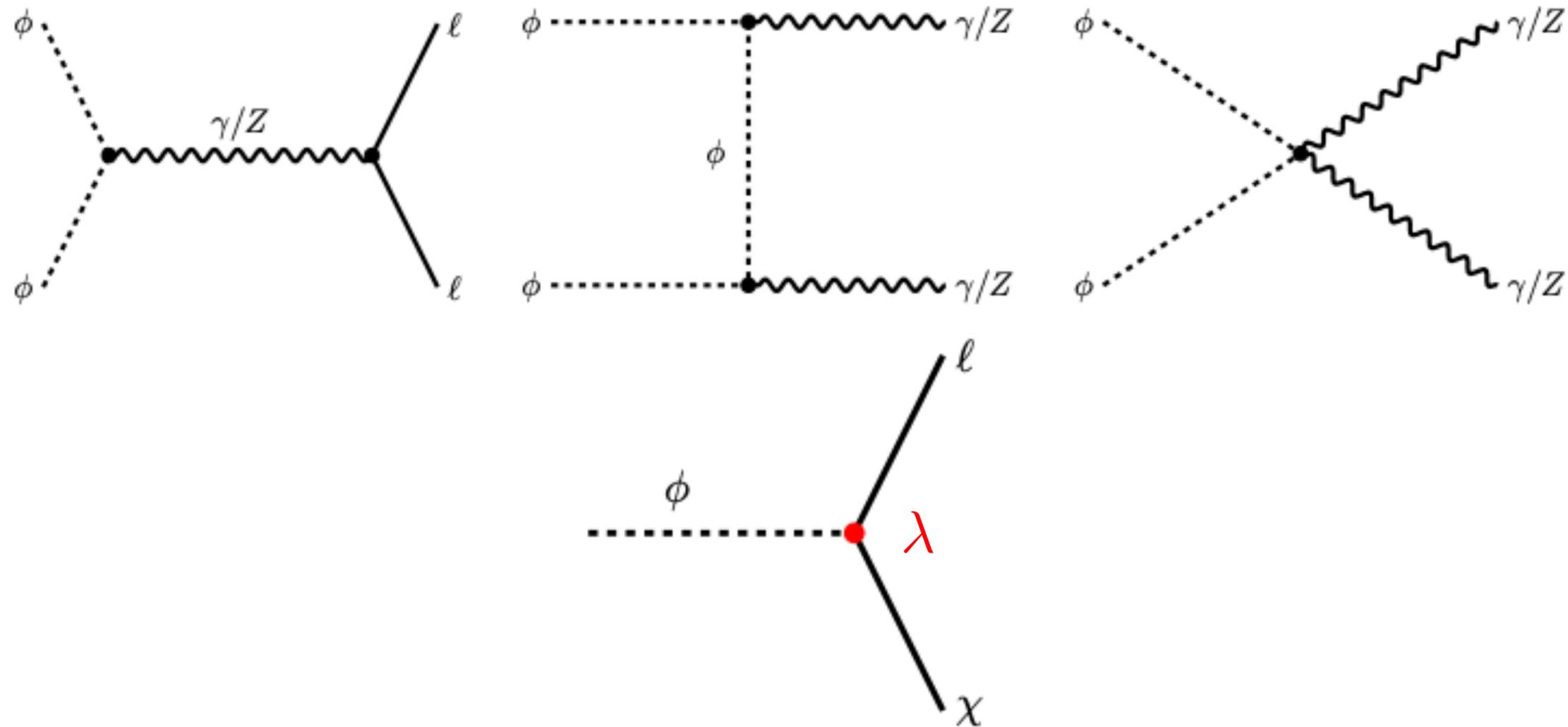
correct relic abundance fixes coupling

Lepton-Flavored Dark Matter

relic abundance

λ required for $\Omega_\chi h^2 = 0.12$
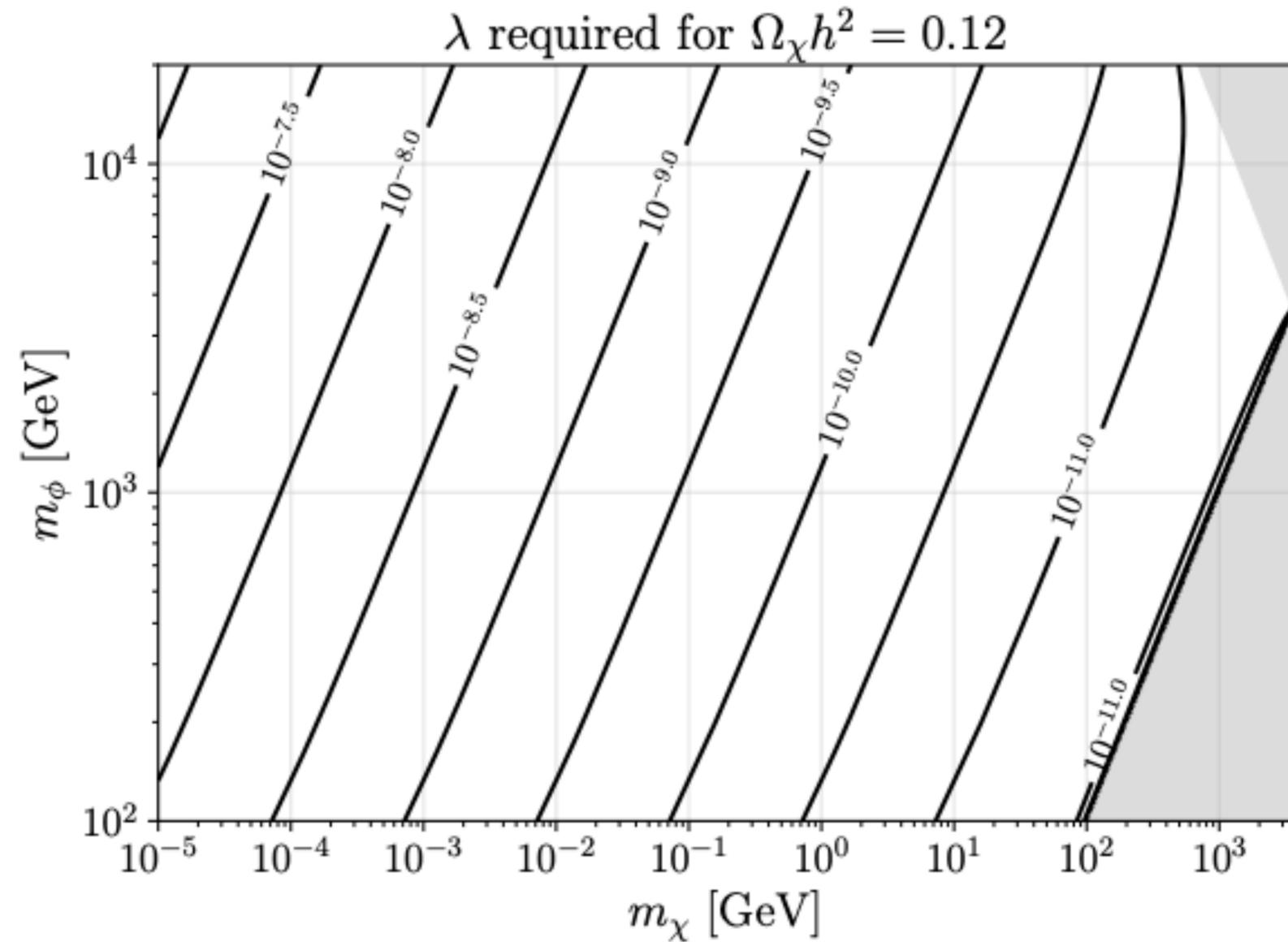
DM must populate
relic abundance

DM parameter space
is fully bounded!

DM must be stable

small λ → Dark Matter χ produced via freeze-in
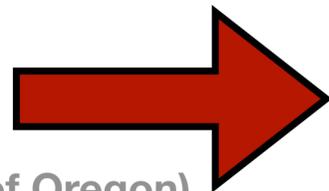
Lepton-Flavored Dark Matter

relic abundance

λ required for $\Omega_\chi h^2 = 0.12$

$m_\chi = 0.5$ TeV, $\tau_\phi = 10^5$ ns

freeze-out

freeze-in

- $Y_\phi(m_\phi = 5.0$ TeV$)$
- $Y_\chi(m_\phi = 5.0$ TeV$)$
- $Y_\phi(m_\phi = 25.0$ TeV$)$
- $Y_\chi(m_\phi = 25.0$ TeV$)$
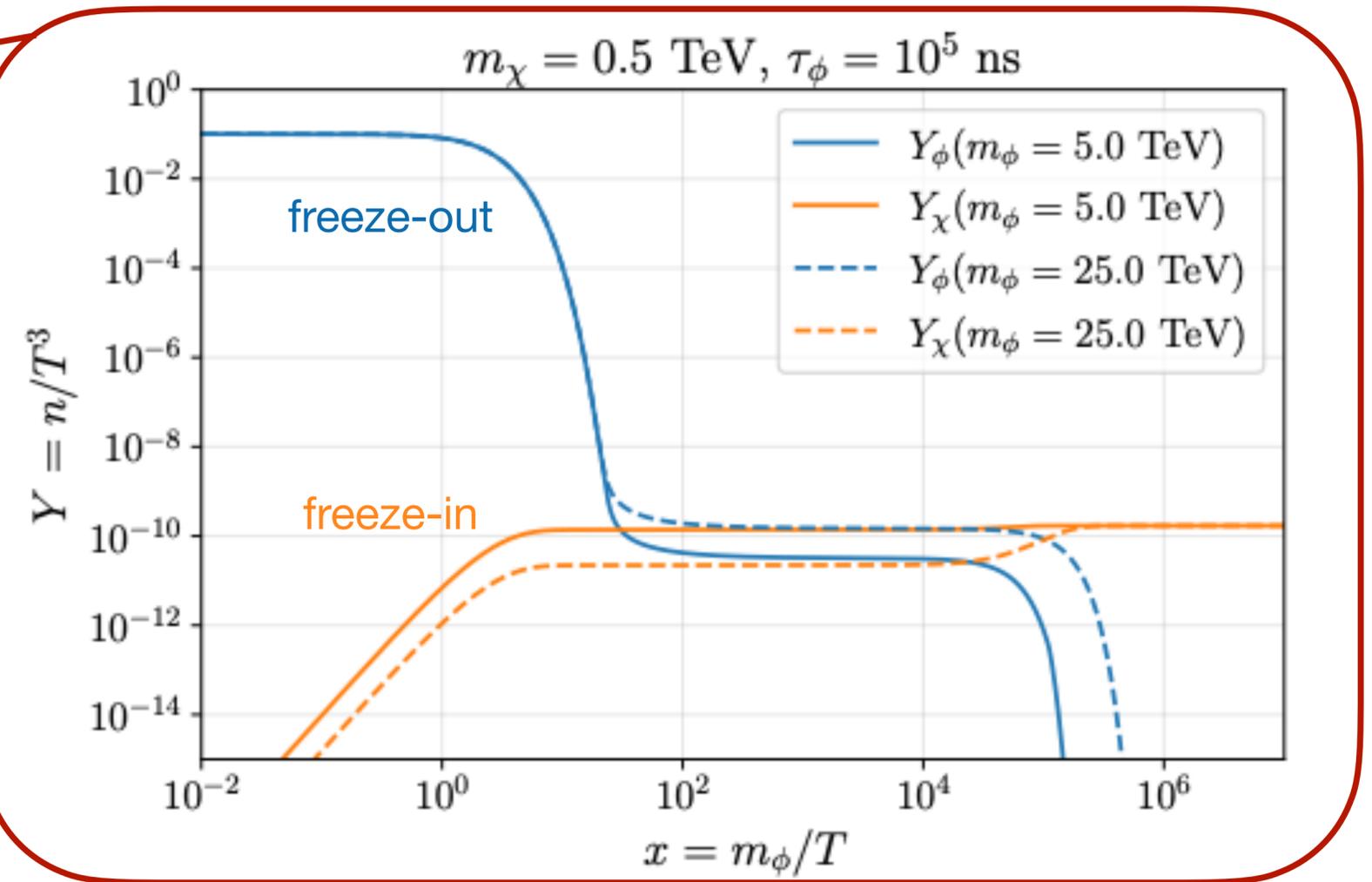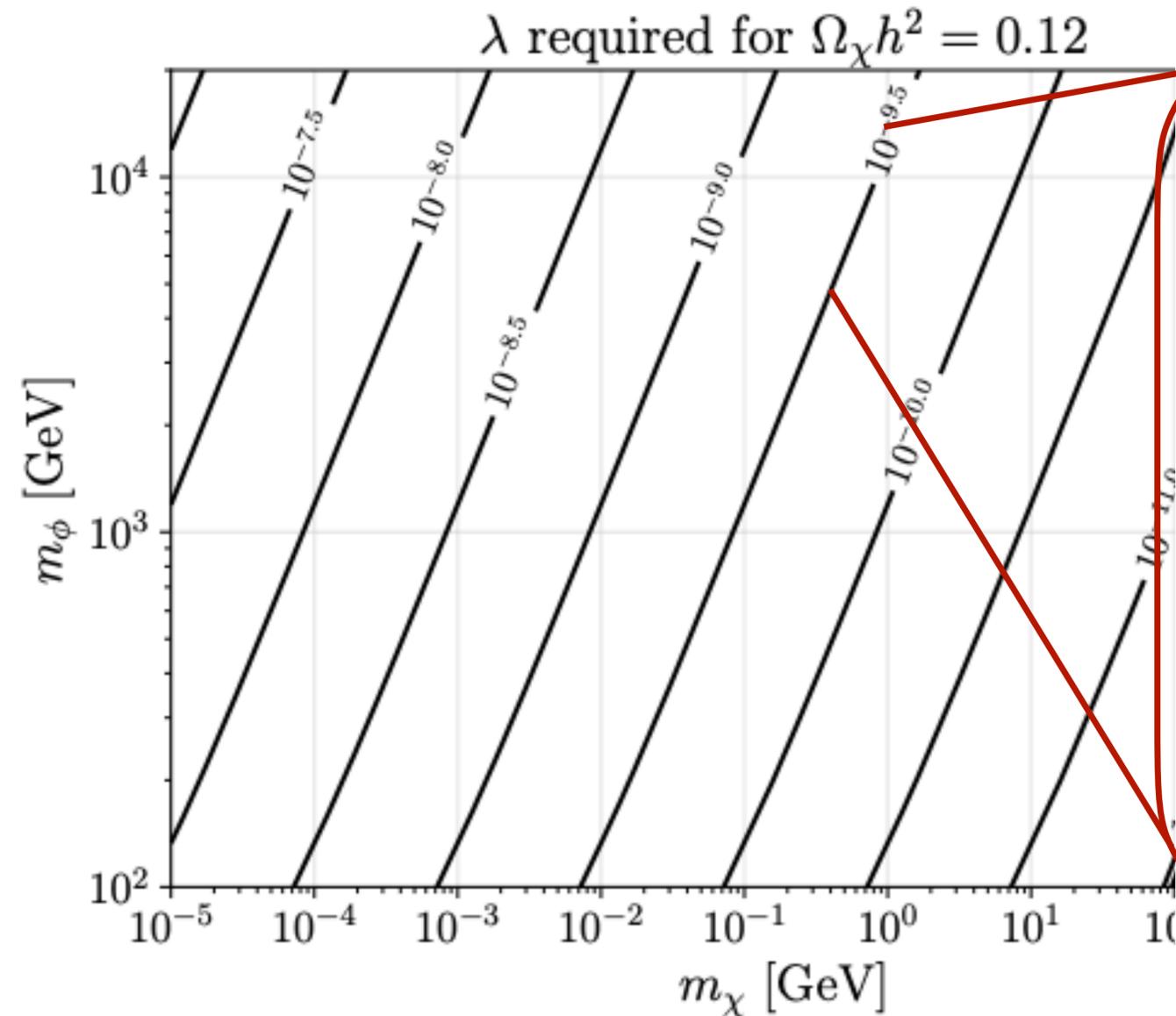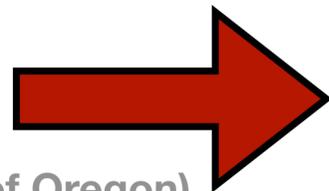
small λ → Dark Matter χ produced via freeze-in

Lepton-Flavored Dark Matter
scalar lifetime
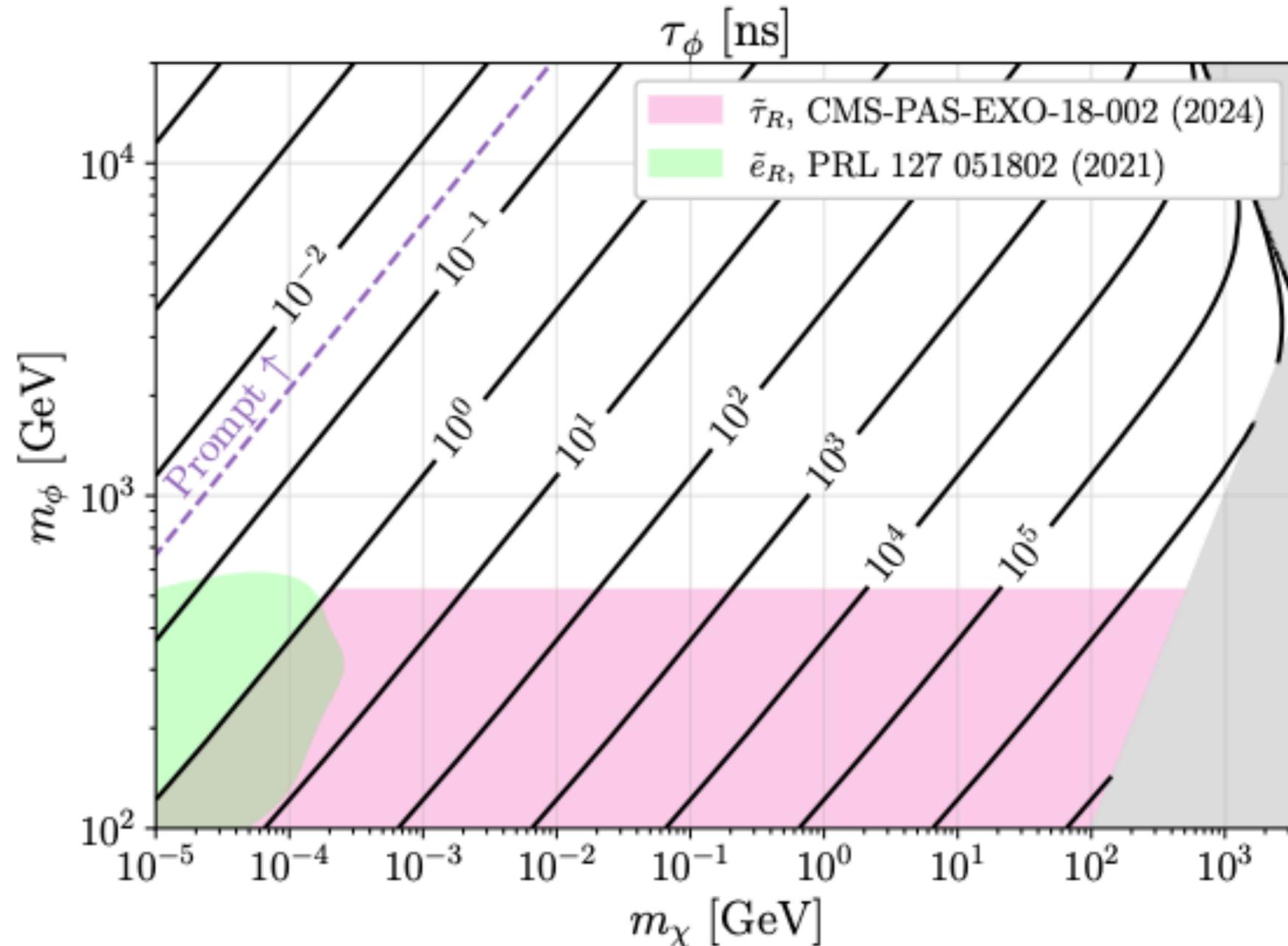
for much of the parameter space,
the scalar mediator is long-lived!

P. Asadi, A. Radick, TTY [arXiv:2312.03826]
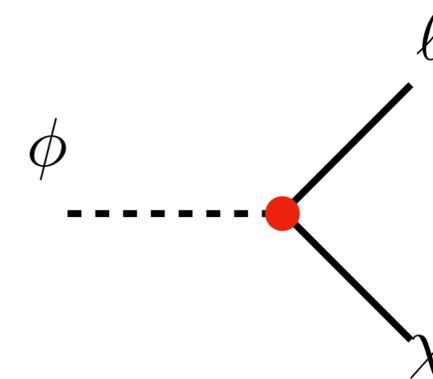
Lepton-Flavored Dark Matter
## production channels at muon collider

Drell-Yan

VBF
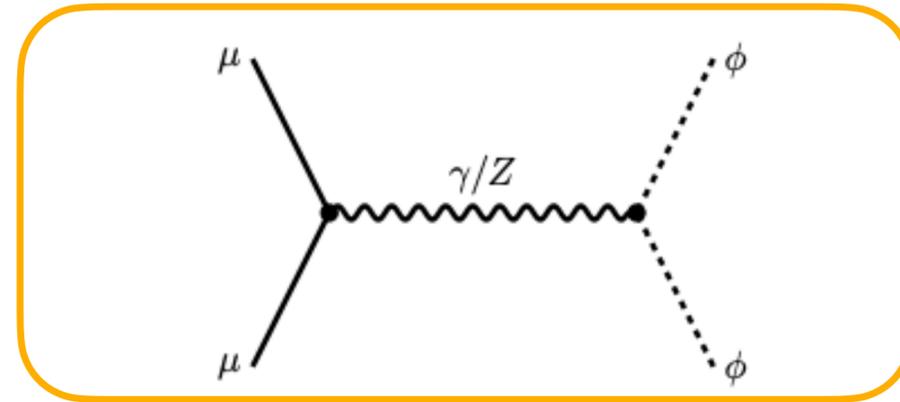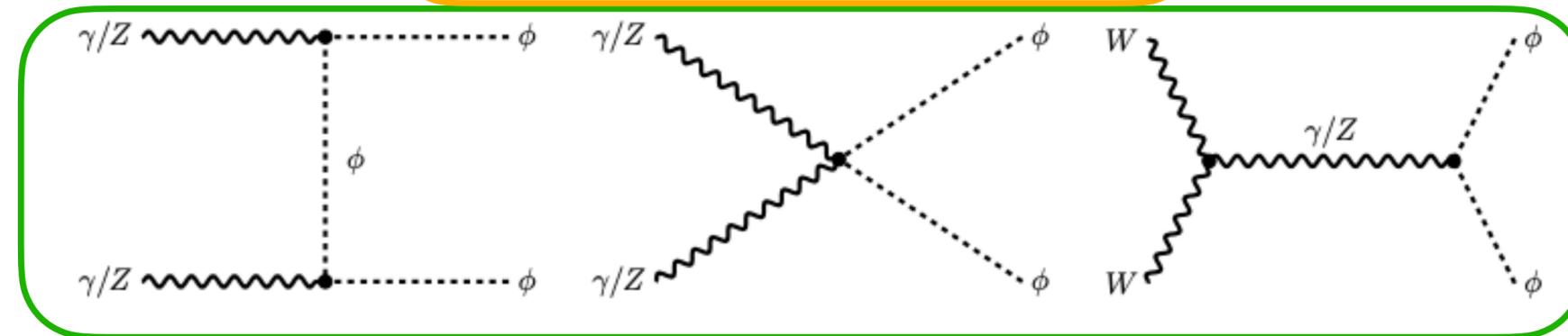
Lepton-Flavored Dark Matter
## collider signatures
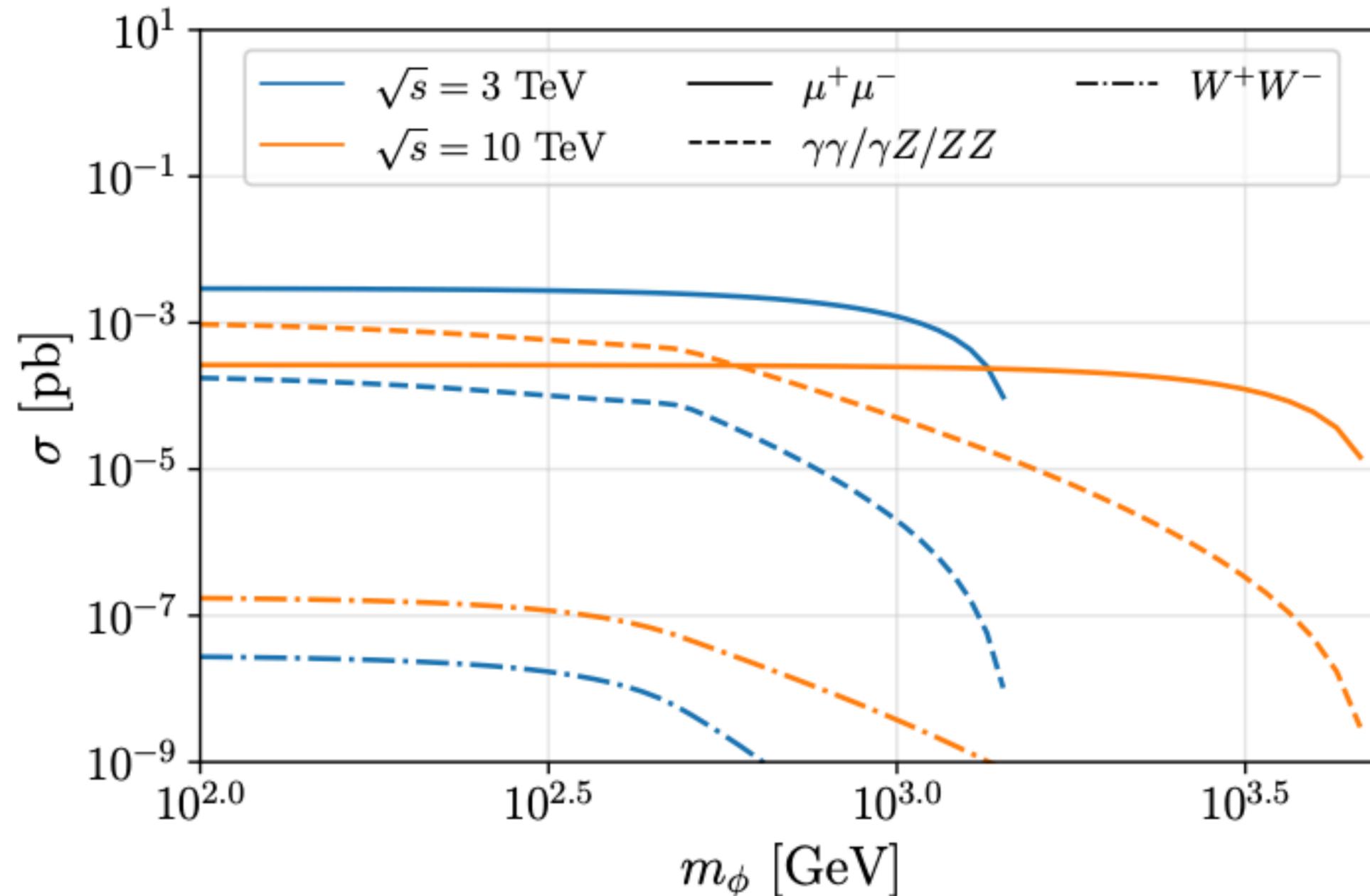
Drell-Yan dominates at higher mediator mass, VBF at lower masses

Combination can lead to interesting LLP signatures

use to help inform detector design

P. Asadi, A. Radick, TTY [arXiv:2312.03826]

Lepton-Flavored Dark Matter

collider signatures

missing energy

χ

ϕ

long-lived charged track

ℓ

displaced lepton

L. Lee, C. Ohm, A. Soffer, TTY [arXiv:1810.12602]
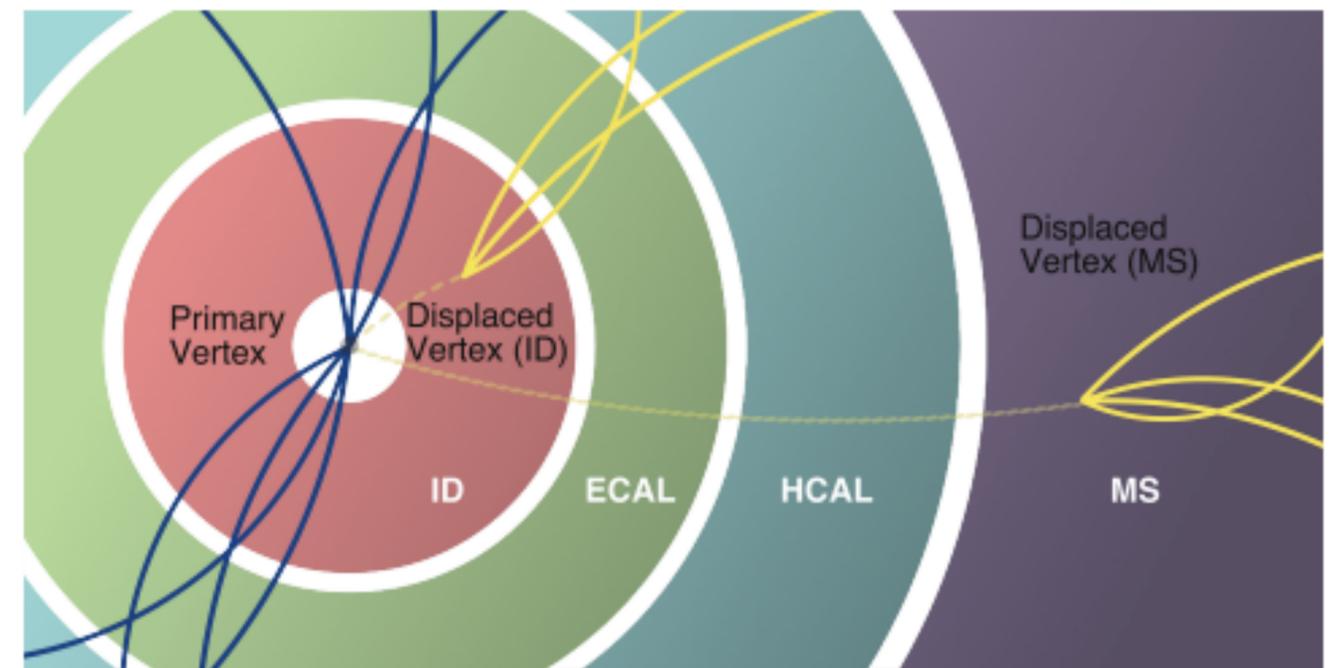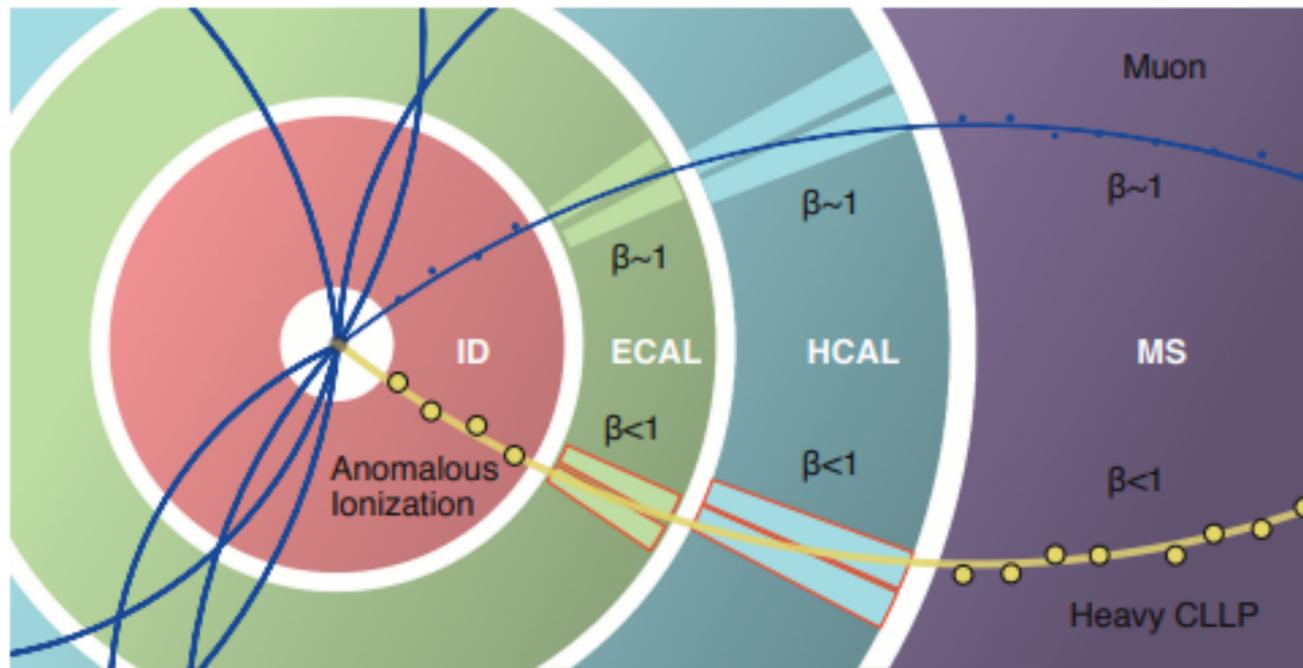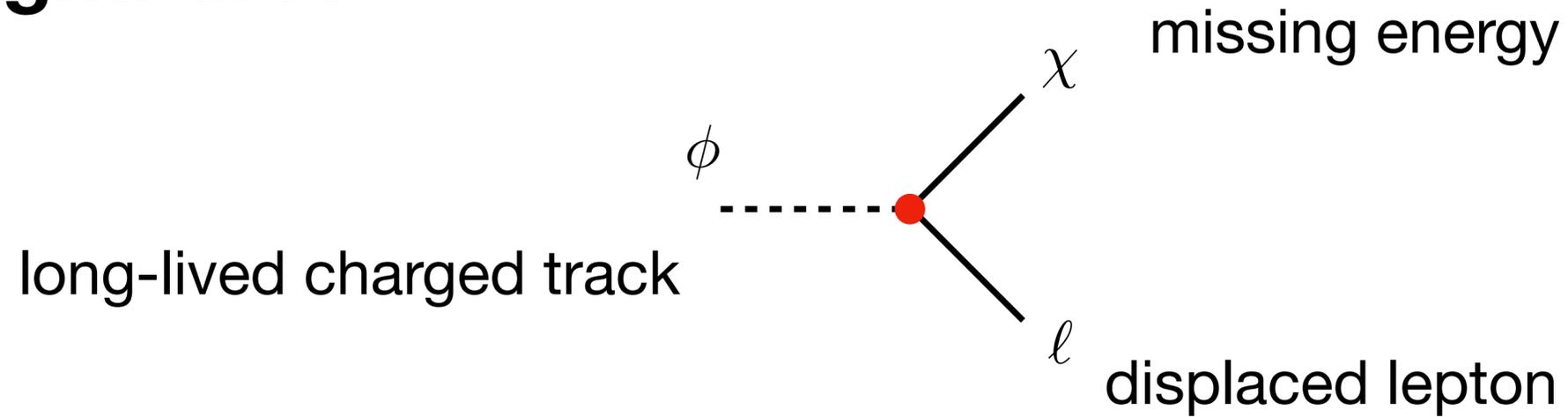
# Lepton-Flavored Dark Matter
LLP collider signatures
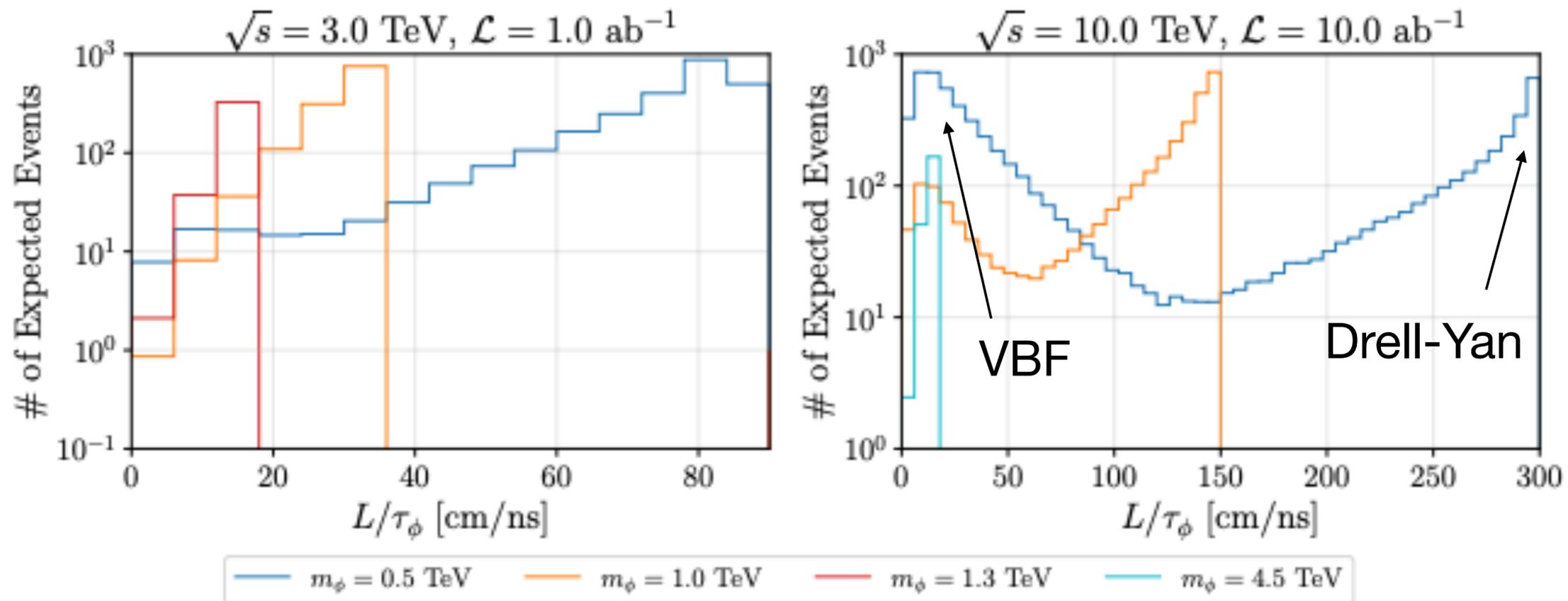
P. Asadi, A. Radick, TTY [arXiv:2312.03826]

Lepton-Flavored Dark Matter
LLP collider signatures

Number of Expected Events ($\sqrt{s} = 3.0$ TeV, $\mathcal{L} = 1.0$ ab^{-1})

Drell-Yan

VBF

Lepton-Flavored Dark Matter
LLP collider signatures

Number of Expected Events ($\sqrt{s} = 10.0$ TeV, $\mathcal{L} = 10.0$ ab^{-1})

Decays in Vertex Detector

Decays in Inner Tracker

Decays in Outer Tracker

Decays in ECAL

Drell-Yan

VBF
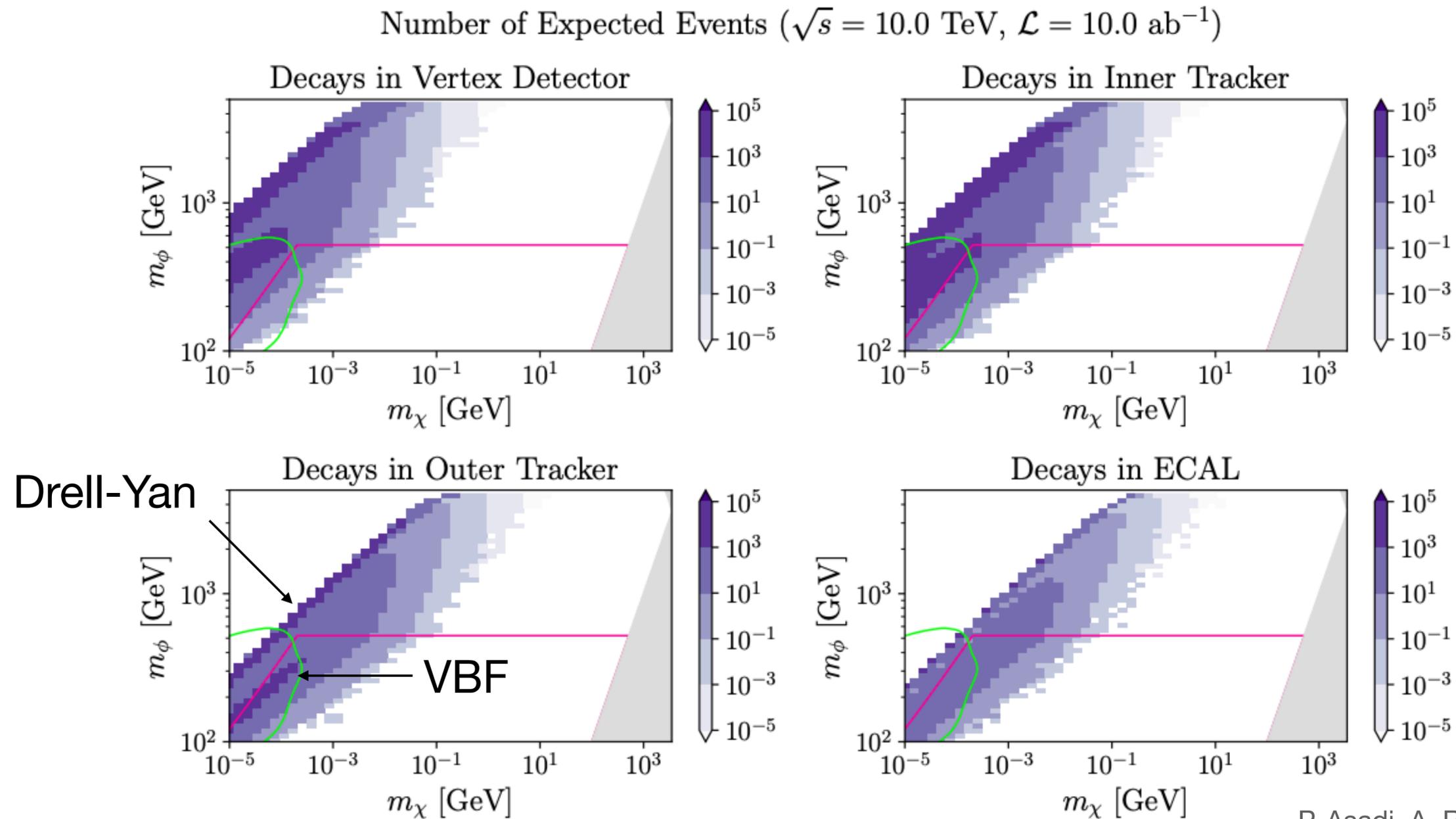
P. Asadi, A. Radick, TTY [arXiv:2312.03826]

Future directions

- implement muon PDFs into study

T. Han, Y. Ma, K. Xie, [arXiv:2103.09844]

see also LePDF: F. Garosi, D. Marzocca, S. Trifinopoulos [arXiv:2303.16964]
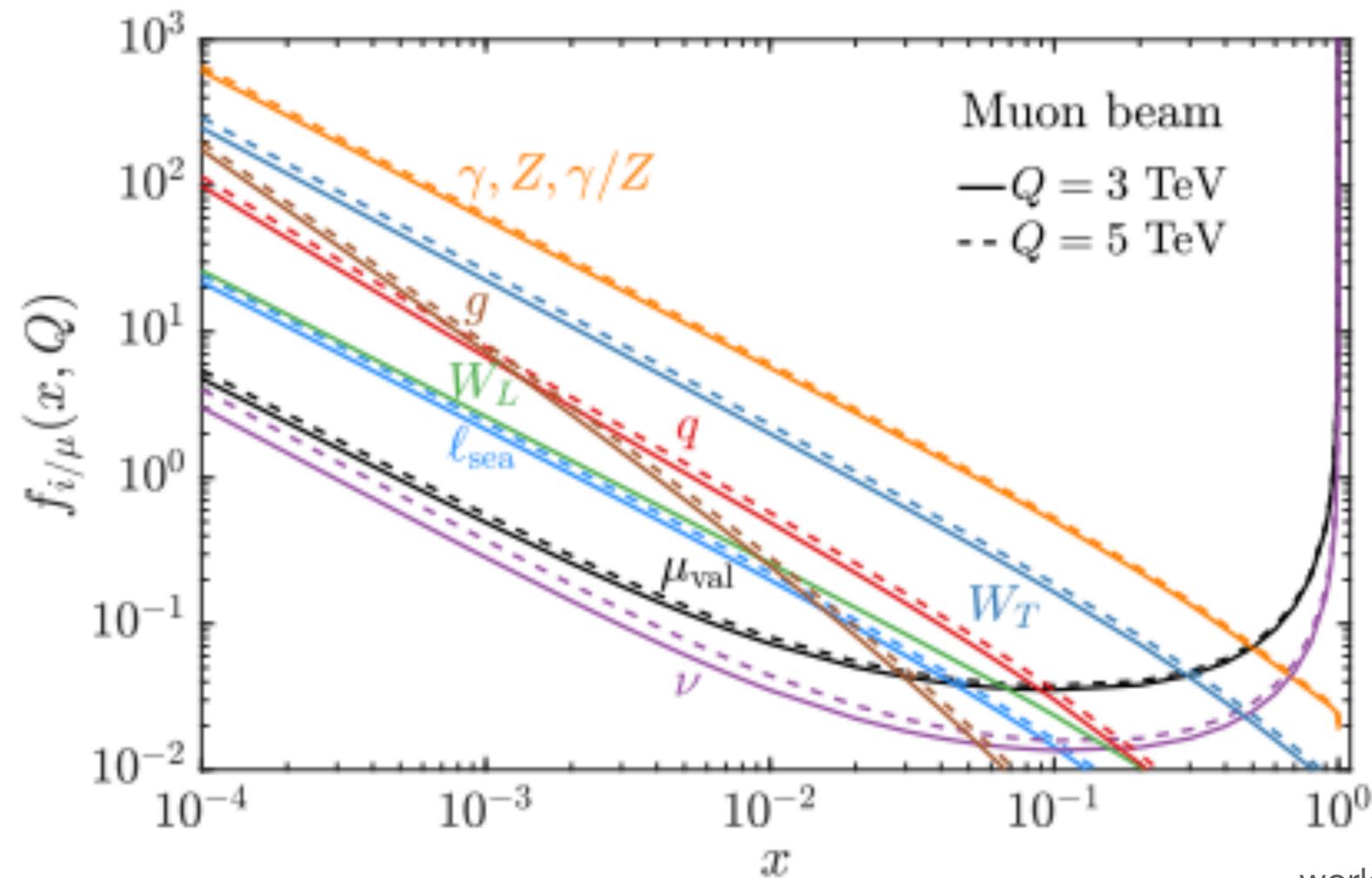
work in progress with P. Asadi, S. Homiller, A. Radick

Future directions

- implement muon PDFs into study

- expand to other models (quark flavored, LH lepton flavored, etc)

$$\mathcal{L}_{\text{int}}^{\text{RH quark}} \supset -\lambda_{i,\alpha}\phi\bar{u}_i\bar{\chi}_\alpha + h.c.$$

$$\mathcal{L}_{\text{int}}^{\text{LH lepton}} \supset -\lambda_{i,\alpha}\Phi^\dagger L_i\bar{\chi}_\alpha + h.c.$$

$$\mathcal{L}_{\text{int}}^{\text{LH quark}} \supset -\lambda_{i,\alpha}\Phi^\dagger Q_i\bar{\chi}_\alpha + h.c.$$

work in progress with P. Asadi, S. Homiller, A. Radick

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- but even before we get to the muon collider…

  - staging can be used as muon beam dump, e.g.

C. Cesarotti, S. Homiller, R. Mishra, M. Reece [arXiv:2202.12302]
expanded upon in C. Cesarotti, R. Gambhir [arXiv:2310.16610]