DARK PION DARK MATTER AND PHENOMENOLOGY

HIDDEN VALLEY

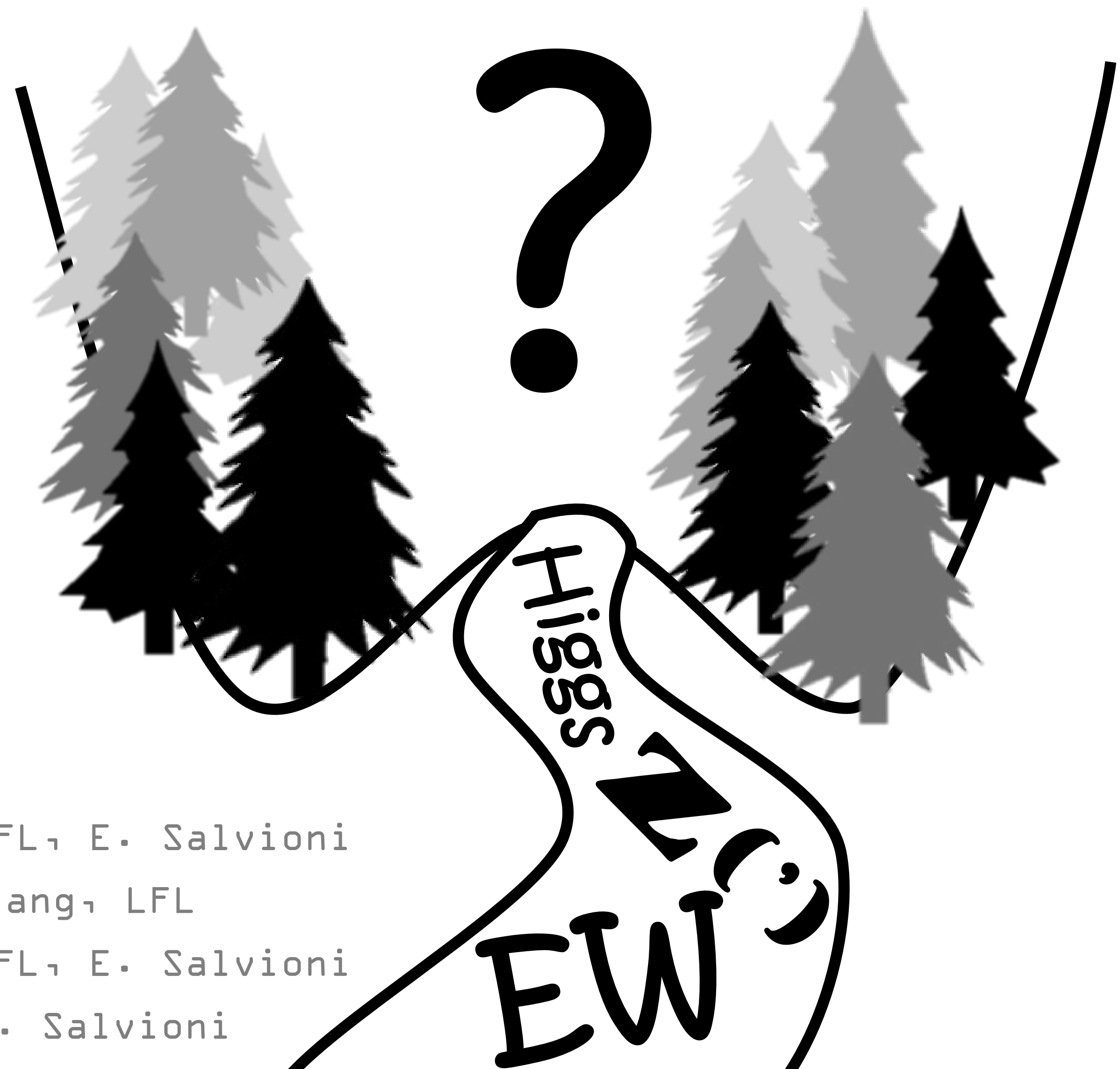
Lingfeng Li

李凌风

Mar.5 , 2026

Flavour Physics Lecture

味物理讲座



26xx.abcde H-C. Cheng, X. Jiang, LFL, E. Salvioni

2408.13304 H-C. Cheng, X. Jiang, LFL

2401.08785 H-C. Cheng, X. Jiang, LFL, E. Salvioni

2110.10691 H-C. Cheng, LFL, E. Salvioni

The overview of this talk

The Electroweak Portal…

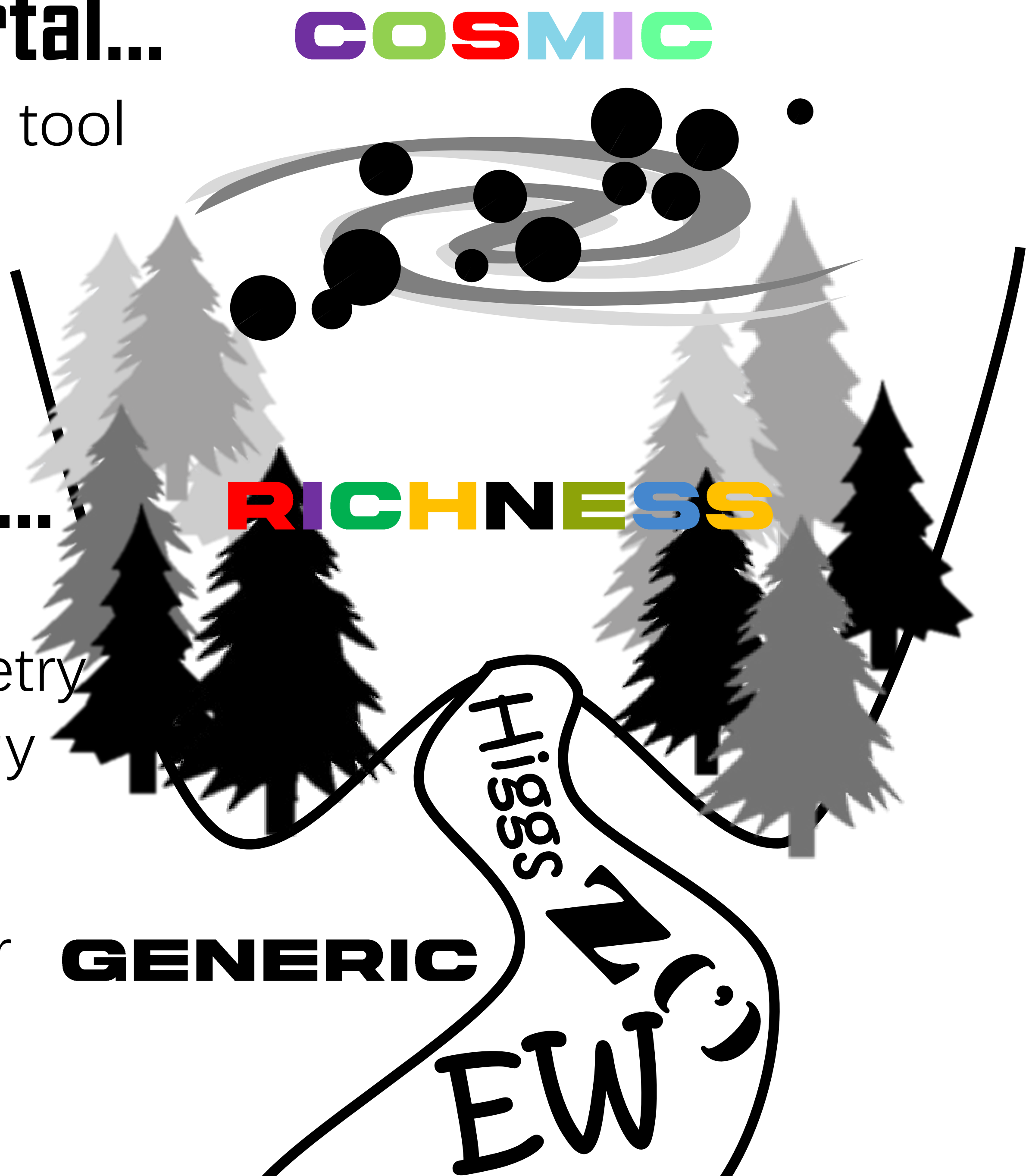
- The legacy of SM as a tool
- "Irrelevant" portal EFT
- EW precision tests
- Flavor portal

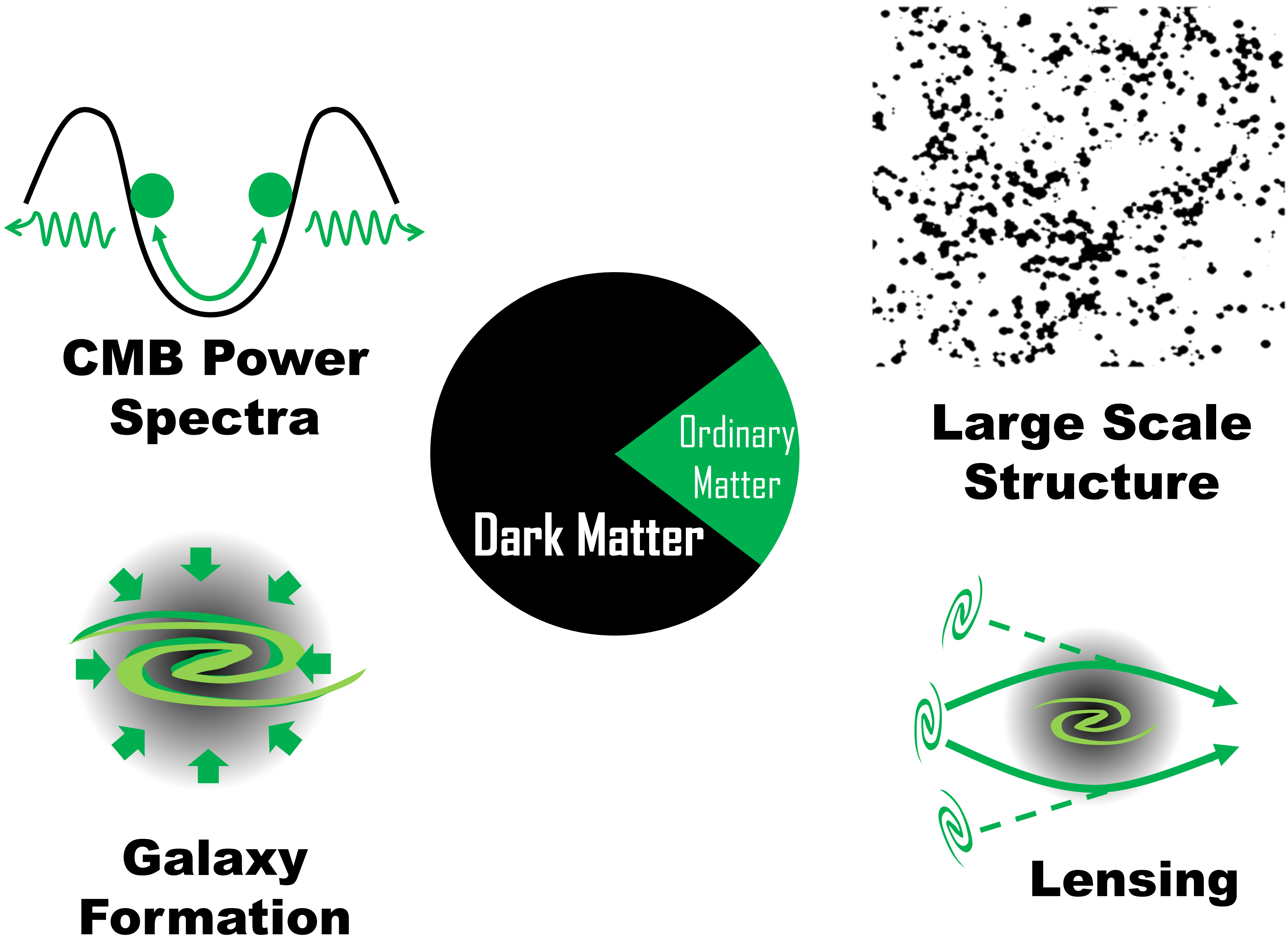
To the Hidden Valley …

- Long-lived particles
- Dark hadrons & symmetry
- UV& IR Phenomenology

…and Beyond

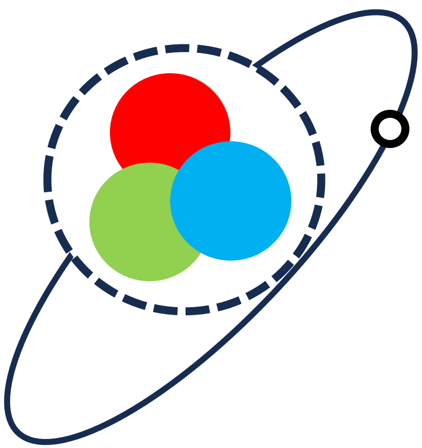
- Composite Dark Matter
- Cosmological Probes

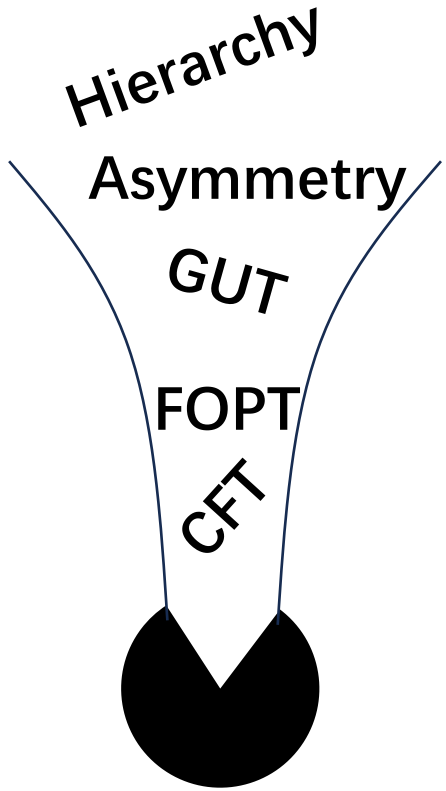



CMB Power
Spectra
Ordinary
Matter
Dark Matter
Large Scale
Structure
Galaxy
Formation
Lensing

Motivation of Compositeness

“Baryons” are Composite



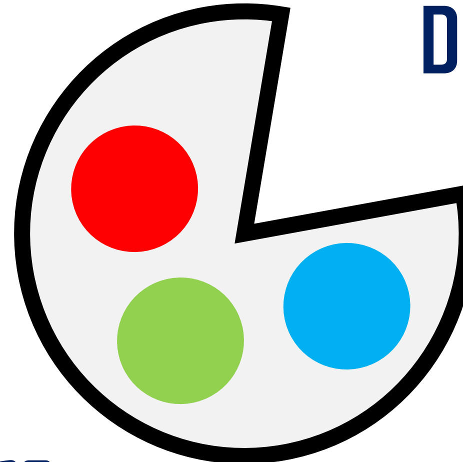


UV Model Building

“Minimal” Setup (?)

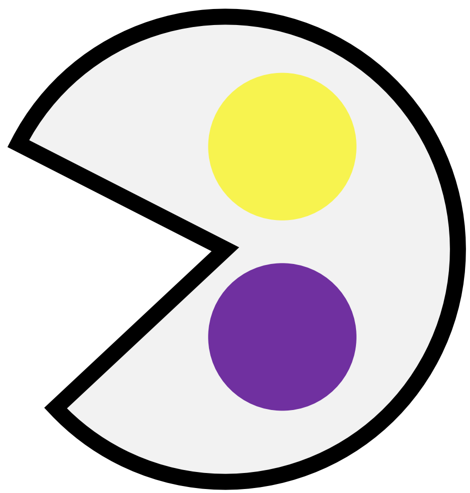
Unique Dynamics & Phenomena

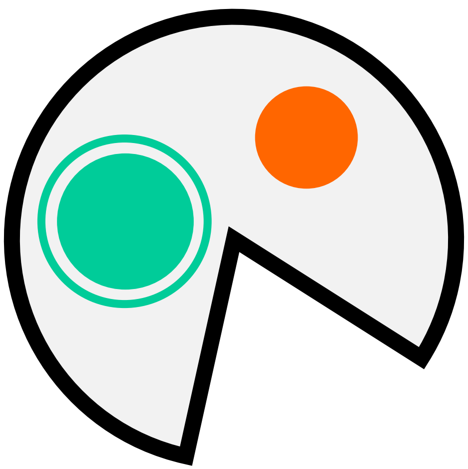
Composite DM Candidates



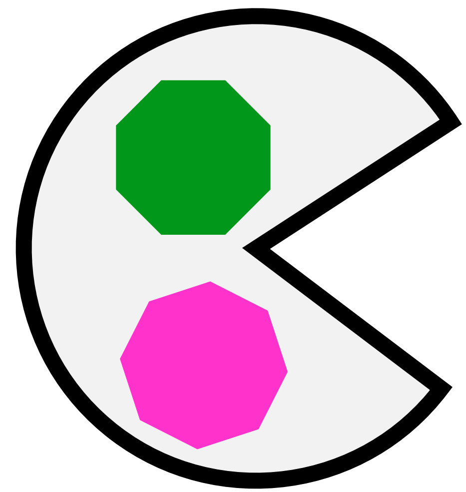
Dark Baryons

Dark Mesons



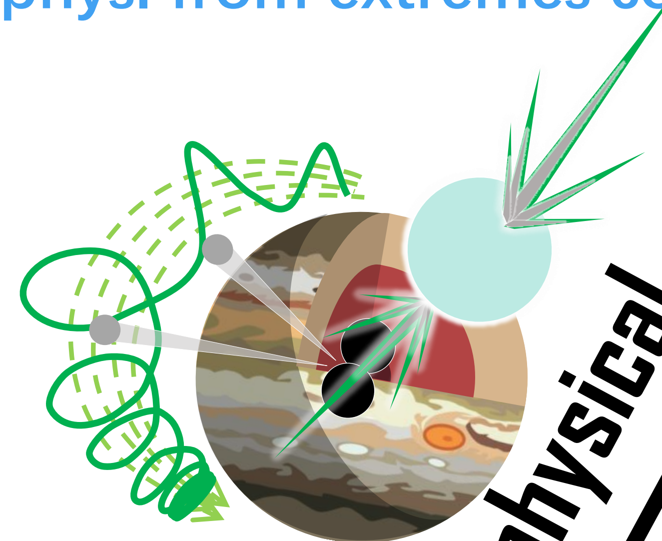


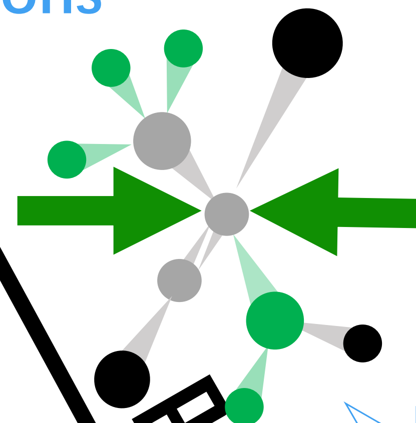
Dark R-hadrons



Dark Glueballs

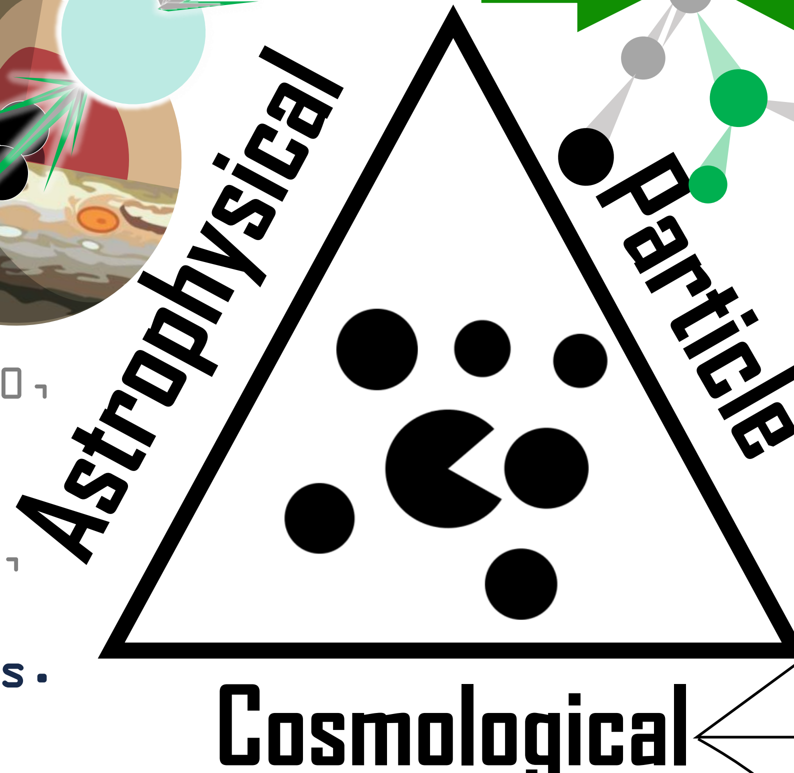
- Planetary science implications
- New phys. from extremes conditions



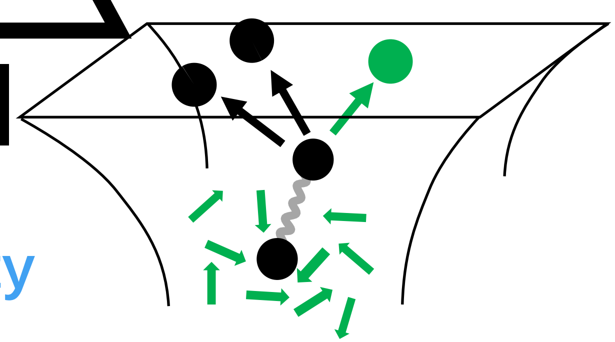


S. Chai, J. Gu, LFL JHEP 05, 292 (2024); T.S. M. Ho, X. H. Jiang, T. H. Kwok, LFL, T. Liu, Phys. Rev. D 109, no.9, 093004 (2024);

- Pheno of Hidden Valley
- Flavor tests of SM
- Machine learning developments



J. Fan, LFL, JHEP 10, 186 (2022); J. Fan, LFL, C. Sun, 2501.12440; S. Yan , LFL , J. Fan, JHEP 06, 028 (2024), **Phys. Rev. Lett. 135, 231801 (2025)**

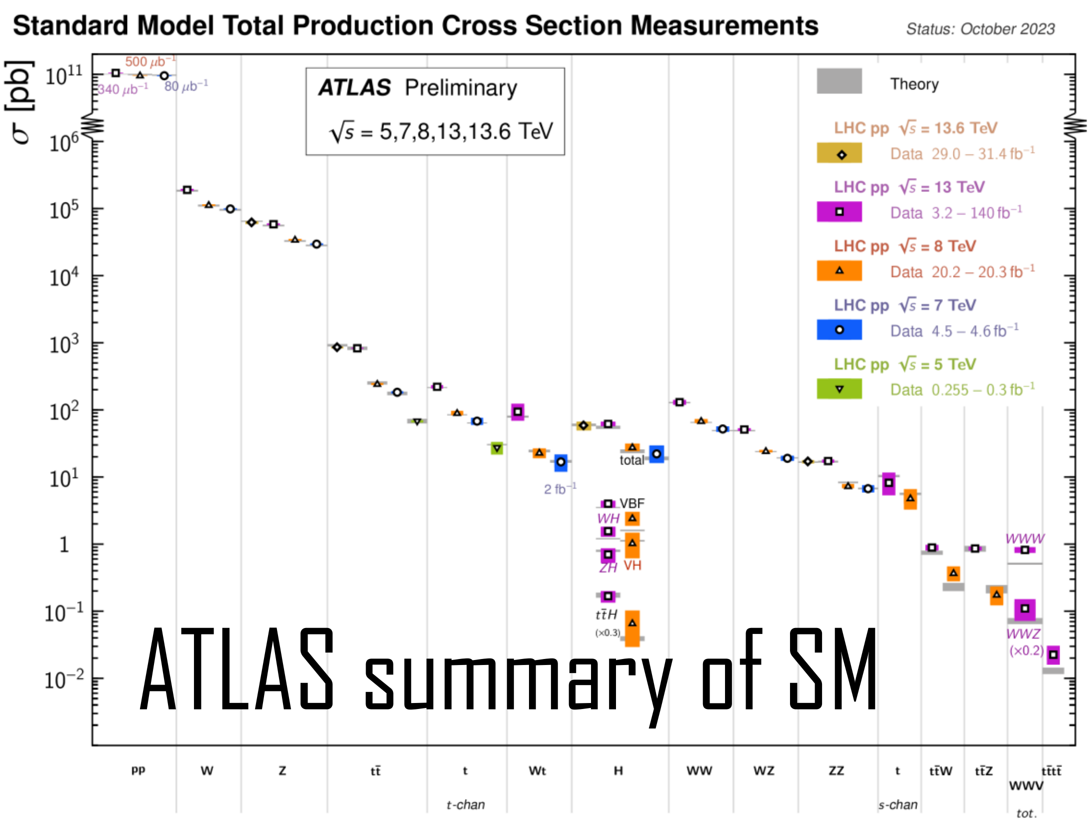


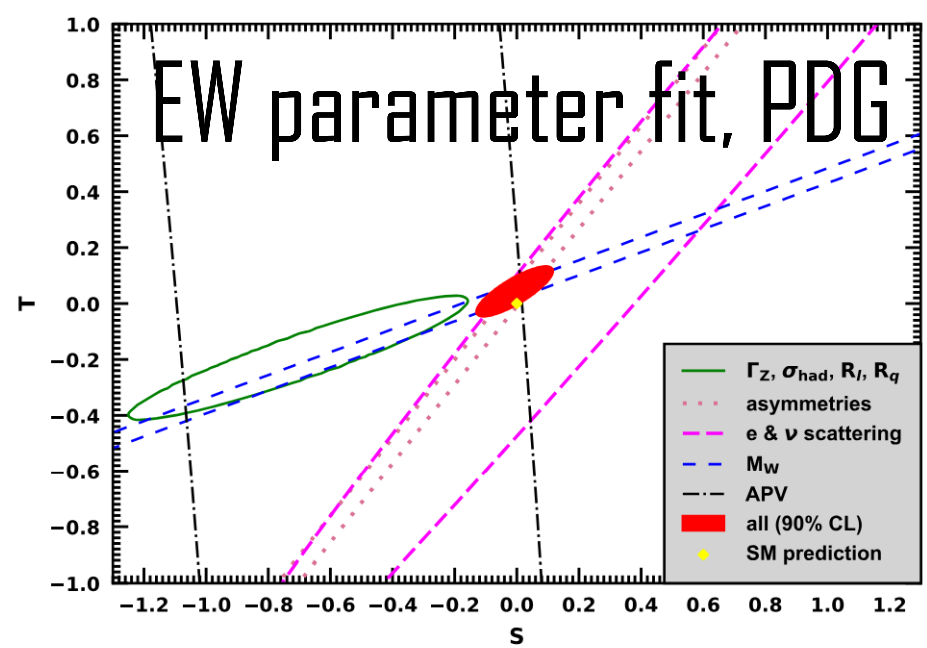
- Primordial features & Non-Gaussianity
- Ultralight DM and axion physics

LFL, S. Lu, Y. Wang, S. Zhou, JHEP 07, 231 (2020);L. Fong, LDL, T. Liu, H. Luu, T. Qiu, H. Tye, JCAP 08, 057 (2021); **Y. Bao, J. Fan, LFL, Phys. Rev. Lett. 130, no.24, 241001 (2023);** X. Chen, J. Fan, LFL, JHEP 12, 197 (2023)

SM Legacy as Tools

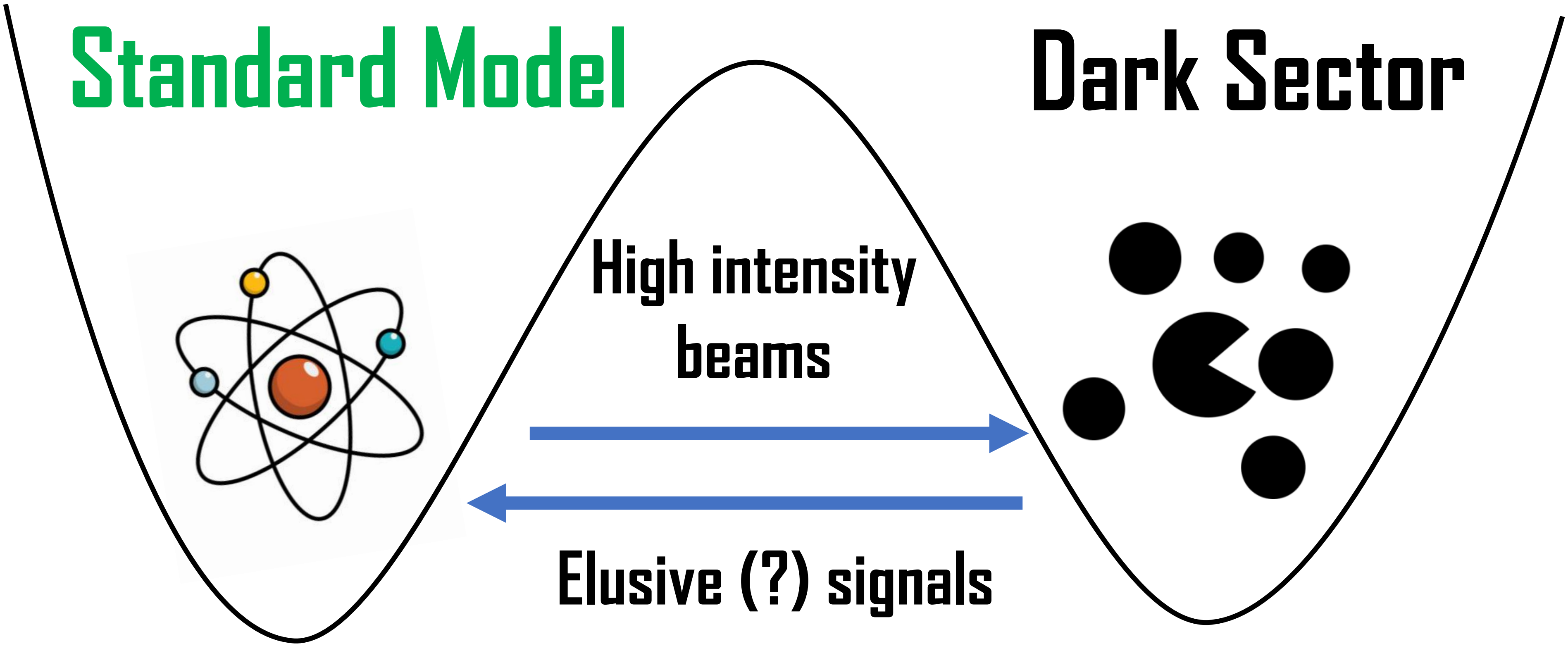
- ➢ SM is "complete" and known with reasonable precision





- ➢ What can we learn from all these?

The Irrelevant Portal

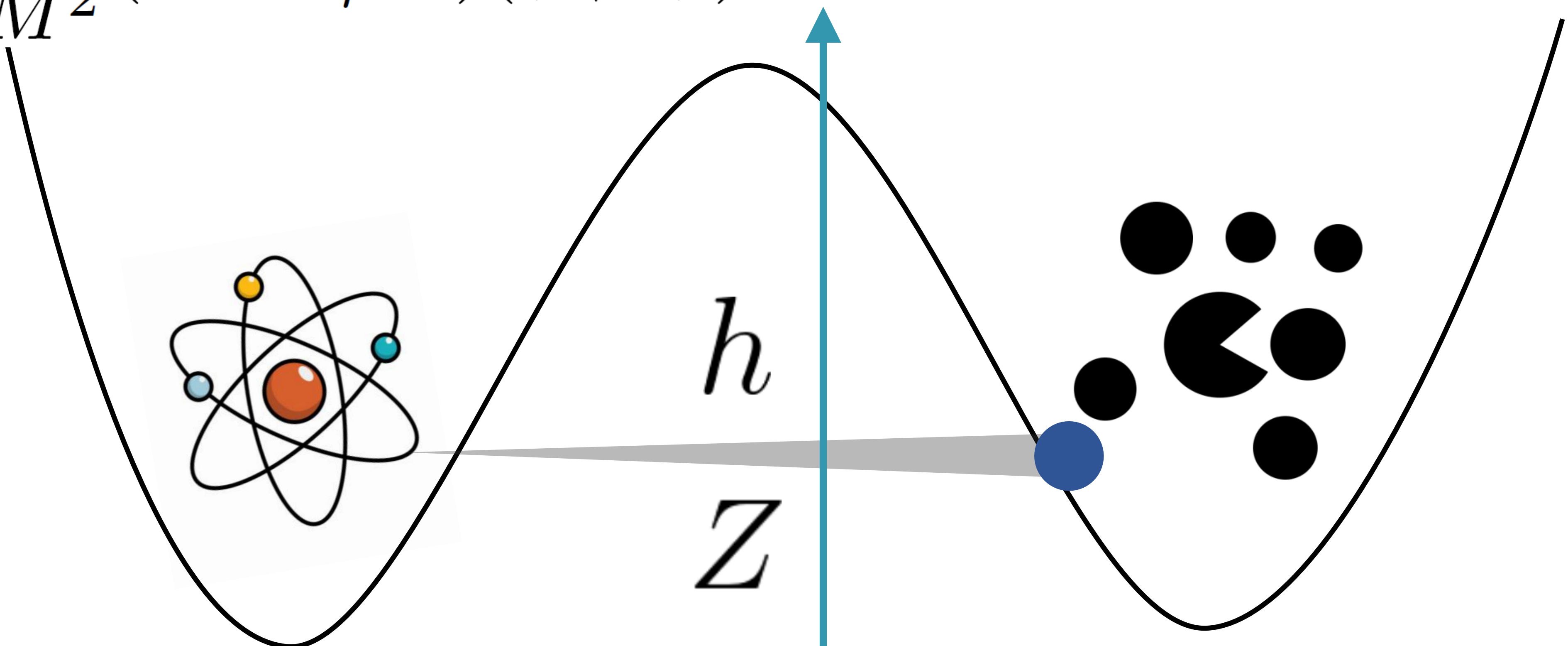


$\epsilon \mathcal{O}_{\rm SM} J_{\rm Dark}$ **Relevant portal:** small couplings to keep the valley hidden

$\frac{1}{\Lambda^n} \mathcal{O}_{\rm SM} J_{\rm Dark}$ **<u>Irrelevant portal</u>:** Hidden behind EFT

The Electroweak Portal

$$\frac{c}{M^2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\overline{\psi}\gamma^\mu\psi)$$

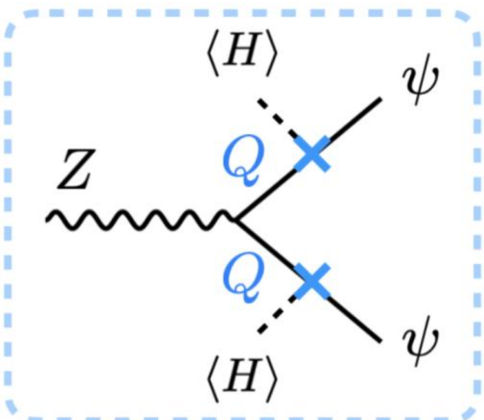


EW bosons stand for a scale of 246 GeV, close enough to TeV+

>TeV Scale≈Dark Enough

The EW Portal: $\frac{c}{M^2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\overline{\psi}\gamma^\mu\psi)$ from Two UV Setups

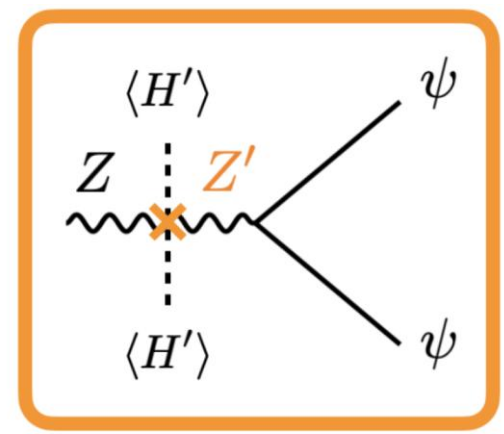
$$\mathcal{L}_{\rm UV} \supset \overline{Q} Y \psi H \longrightarrow \frac{c}{M^2} \sim \frac{Y^2}{M_Q^2}$$



Heavy fermion doublet mediation

H-C. Cheng, LFL, E. Salvioni, 2110.10691

$$\mathcal{L}_{\rm UV} \supset \delta\hat{M}^2 Z^\mu Z'_\mu \longrightarrow \frac{c}{M^2} \sim \frac{g_D^2 \delta\hat{M}^2}{m_Z^2 m_{Z'}^2}$$



Dark Z' mediation: a Z' heavier or lighter(!) than Z with mass mixing

H-C. Cheng, X. Jiang, LFL, E. Salvioni, 2401.08785

See also Y. C. San , M. Perelstein, and P. Tanedo, 2022

Exotic BR of Z

A key phenomenon for EW portal models

As the doublet mediation benchmark:

$$\mathrm{BR}(Z \to \psi' \overline{\psi}') \approx 1.8 \times 10^{-4} \left(\frac{N_d \mathrm{Tr}(\boldsymbol{Y}\boldsymbol{Y}^\dagger \boldsymbol{Y}\boldsymbol{Y}^\dagger)}{3} \right) \left(\frac{1\,\mathrm{TeV}}{M} \right)^4$$

For the Z' mediation :

$$\mathrm{BR}(Z \to \psi' \overline{\psi}') \approx 1.4 \times 10^{-4} \left(\frac{N_d}{3} \right) \left(\frac{\boxed{\xi}}{0.01} \right)^2 g_D^2 \sum_i (x_{Li}^2 + x_{Ri}^2)$$

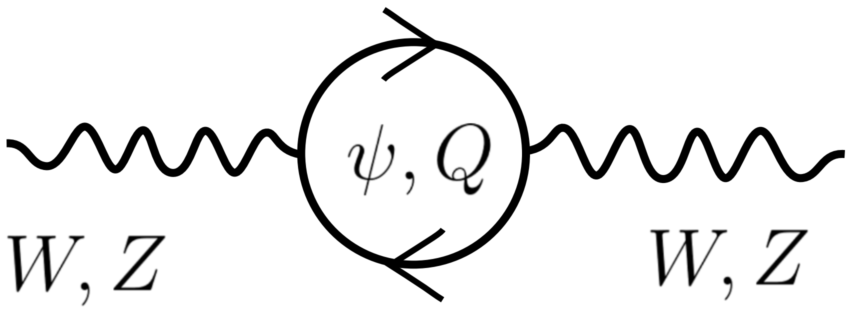
The effective mixing angle $\xi \sim \dfrac{\delta M^2}{M_Z^2 - M_{Z'}^2}$

Exotic BR of h is not large ($<\sim 10^{-4}$), the constraints are weaker than those from Z decays ($\sim 10^3$ more Z than h at LHC)

EWPT Corrections

M.E. Peskin, T. Takeuchi, 1990
M.E. Peskin, T. Takeuchi, 1992

Doublet mediation



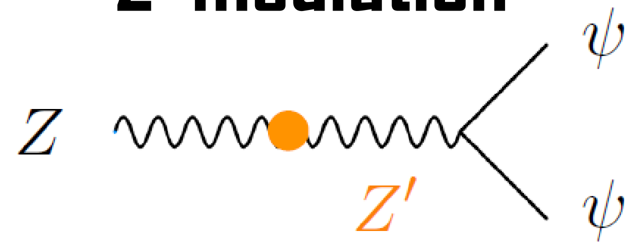
Leading by EW loops with mixing

L. Lavoura, J. P. Silva, 1993;
C. Anastasiou, E. Furlan, J. Santiago, 2009

$$S \simeq \frac{2N_d}{45\pi M^2}\Big(\frac{5Y^2v^2}{2} - 3m_Z^2(1-2s_W^2+2s_W^4)\Big)$$

$$T \simeq \frac{N_d\, y_{11}^4 v^4}{48\pi s_W^2 m_W^2 M^2}$$

Z′ mediation



Leading by LEP Z pole observables defined with:

$$\mathcal{L}_{Zf\bar{f}} = -\frac{\bar{Z}e}{s_W c_W}\bar{f}\gamma^\mu(T^3_{Lf} - s_*^2 Q_f) f Z_\mu$$

B. Holdom, 1991; G. Altarelli et. al, 1991

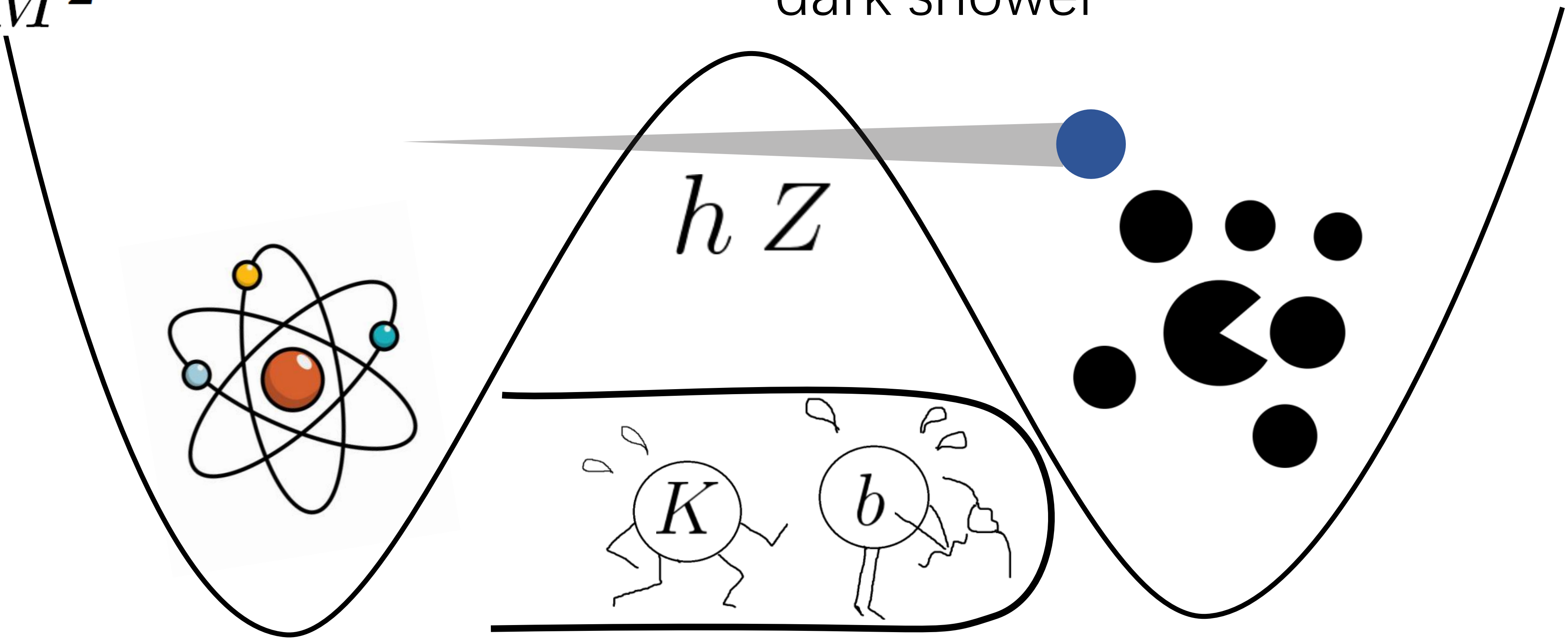
$$S = \frac{4s_W^2}{\alpha}\left(\frac{c_W^2}{s_W}\xi t_\chi - c_W^2\xi^2\right)$$

$$T = \frac{1}{\alpha}\left(2s_W\xi t_\chi + \xi^2\left(\frac{M_{Z'}^2}{M_Z^2} - 2\right)\right)$$

The Flavor Portal

$$\frac{c}{M^2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\overline{\psi}\gamma^\mu\psi)$$

Tree level, meson decay and dark shower



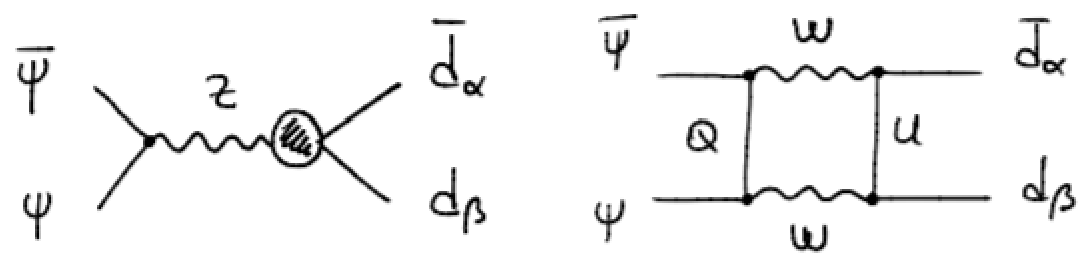
$$\frac{\mathcal{K}}{M^2}(\bar{d}_i\gamma^\mu d_j)(\bar{\psi}\gamma_\mu\psi)$$

W. Altmannshofer, A. Crivellin, H. Haigh, G. Inguglia and J. Martin Camalich, 2311.14629; J. Martin Camalich, M. Pospelov, P. N. H. Vuong, R. Ziegler and J. Zupan, 2002.04623; M. K. Gaillard, M. B. Gavela, R. Houtz, P. Quilez and R. Del Rey, 1805.06465, T. Li, M.A. Schmidt and M. Yuan, 2506.08342……

Flavor Portal from EW only

$\Gamma_{B,K,\cdots}$ are suppressed by $(M_W)^{-4}$ in SM.

Inami, Lim 1980
X.G. He, J. Tandean,
G. Valencia, 0909.3638

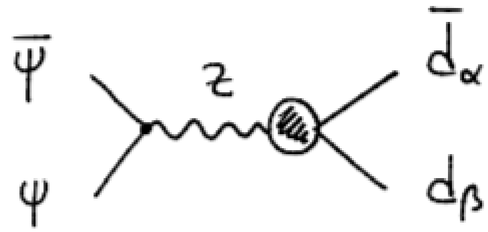


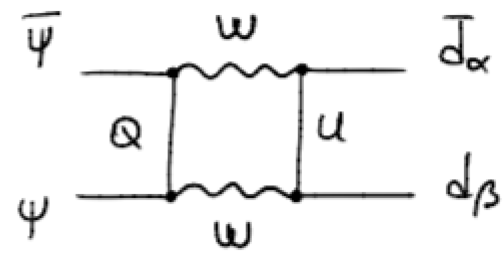
The four-fermion EFT respecting MFV

$$-\frac{c}{M^2}\frac{g^2}{128\pi^2}J_D^\mu \bar{d}_j\gamma_\mu P_L d_i \sum_{q\in u,c,t} V_{qj}^* V_{qi} \mathcal{K}_q$$

Flavor Portal from EW only

Inami, Lim 1980
X.G. He, J. Tandean,
G. Valencia, 0909.3638





In heavy doublet mediation:

$$\mathcal{K}_q \equiv 3 + x_q(\log\frac{\Lambda_{\rm UV}^2}{m_q^2} - 2) \qquad x_q \equiv m_q^2/M_W^2$$

In Z' mediation (the mZ' terms cancel out):

Typically O(10)

$$\mathcal{K}_q \equiv x_q \log\frac{\Lambda_{\rm UV}^2}{M_W^2} + \frac{-7x_q + x_q^2}{2(1-x_q)} - \frac{4x_q - 2x_q^2 + x_q^3}{(1-x_q)^2}\log x_q$$

Γ_{39}	$\pi^+\nu\bar{\nu}$	$(1.14^{+0.40}_{-0.33}) \times 10^{-10}$
Γ_{40}	$\pi^+\pi^0\nu\bar{\nu}$	$< 4.3 \times 10^{-5}$

Does it constrain anything?

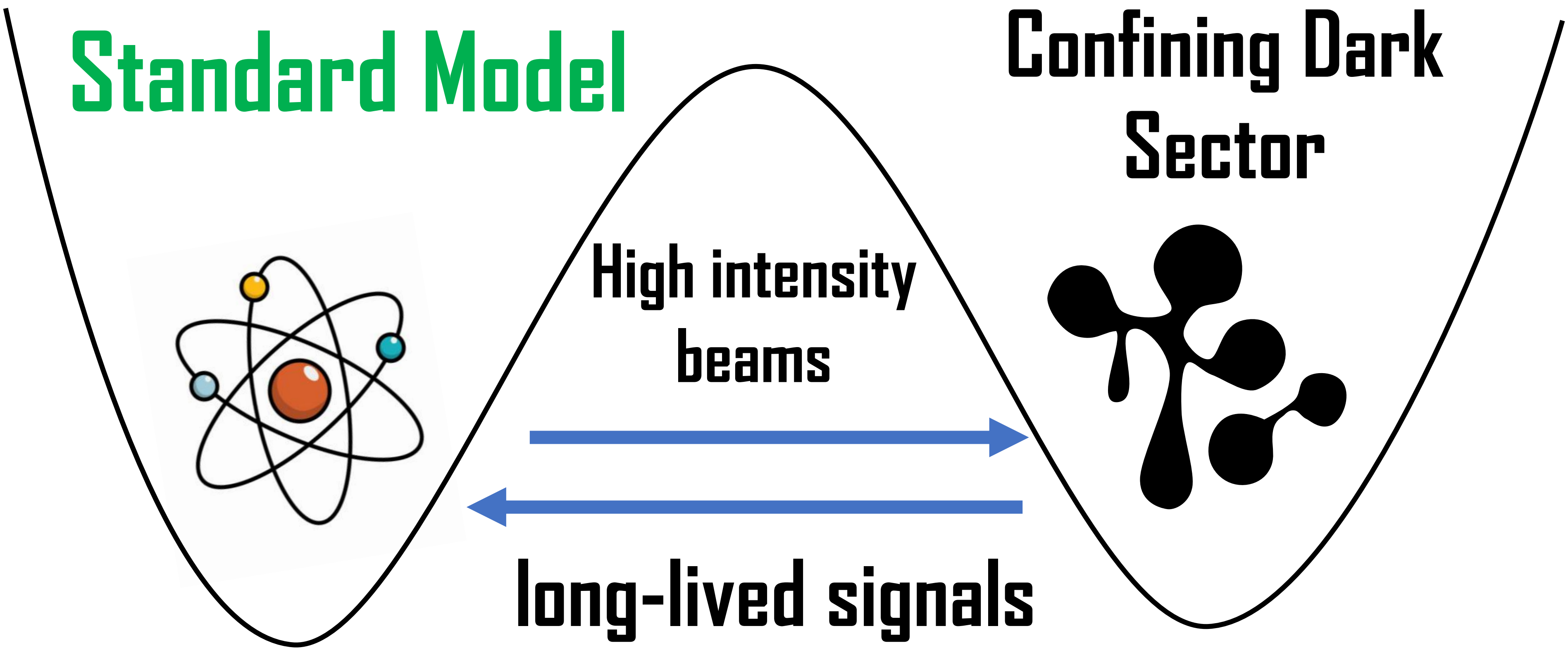
We can barely see the SM Z & W in bsνν and sdνν (for now...)

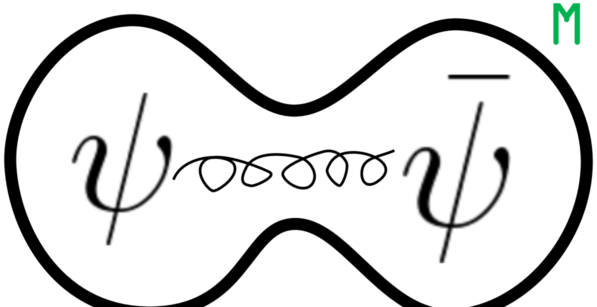
Γ_{582}	$\pi^+\nu\bar{\nu}$	$< 1.4 \times 10^{-5}$
Γ_{588}	$K^+\bar{\nu}\nu$	$< 1.6 \times 10^{-5}$
Γ_{589}	$\rho^+\nu\bar{\nu}$	$< 3.0 \times 10^{-5}$

Want to Kick Things Up?

GENERIC√

Hidden Valley Models





M. J. Strassler and K. M. Zurek, 0604261

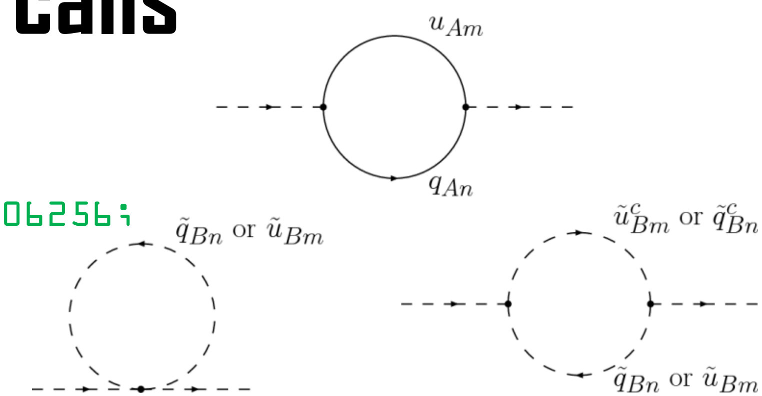
$$\Gamma \sim \mathrm{Tr}[Y^\dagger Y \sigma_{\mathrm{hadron}}] \text{ or } \mathrm{Tr}[X \sigma_{\mathrm{hadron}}]$$

Symmetries Yes

The Dark Force for Confinement

- Neutral naturalness calls for a non-QCD color

Z. Chacko, H.S. Goh, and R. Harnik, 0506256;
G. Burdman, Z. Chacko, H.S. Goh and R. Harnik, 0609152;
H-C. Cheng, LL, E. Salvioni, and C. Verhaaren, 1803.03561



- Makes good dark matter candidate

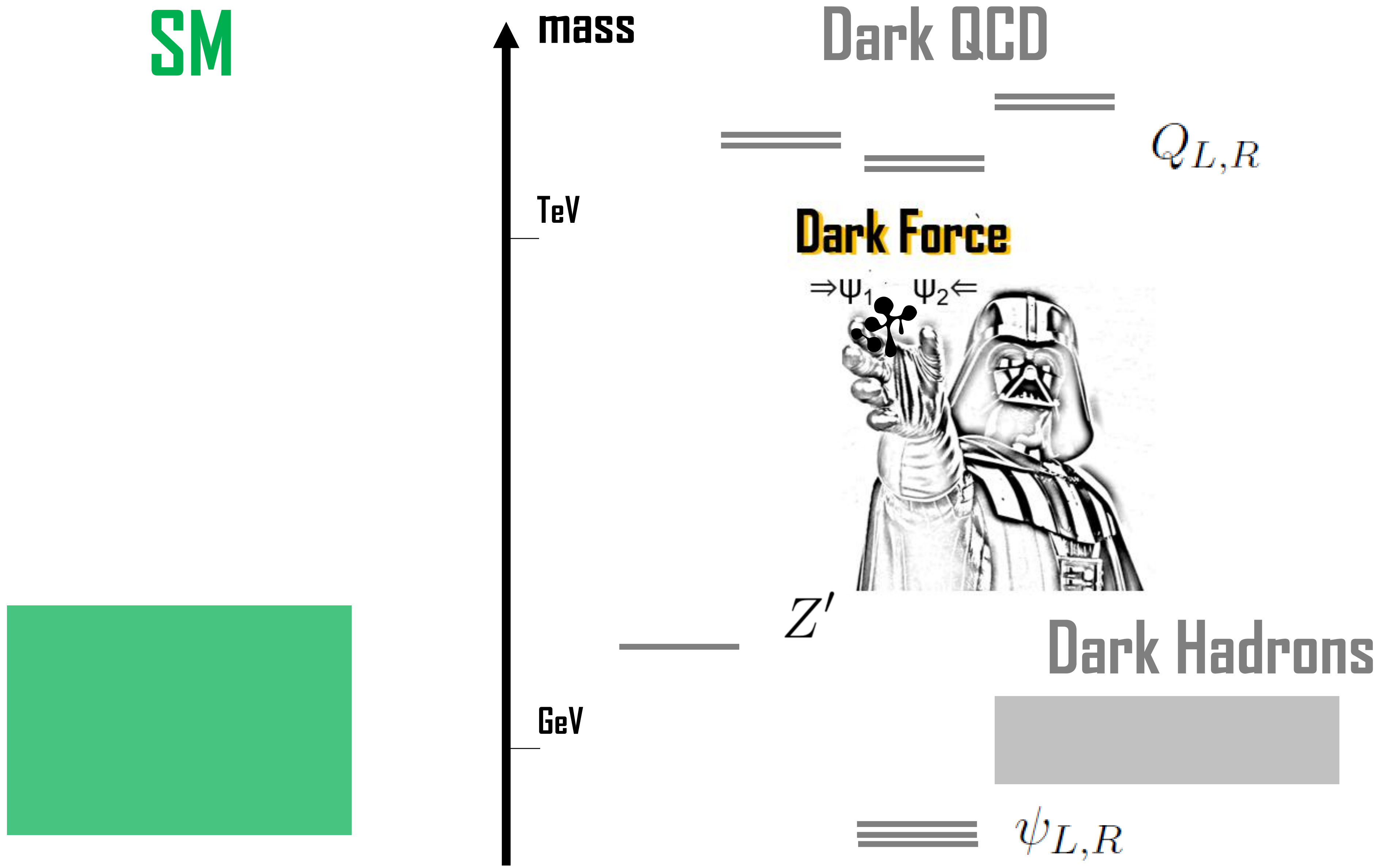
Y. Hochberg, E. Kuflik, H. Murayama, T. Volansky, J. Wacker, 1411. 3727;
A.Katz, E. Salvioni, and B. B. Shakya, 2006.15148;s

P. Schwaller, D. Stolarski, A. Weiler, 1502.05409;
CMS, 1810.10069;
S. Knapen, J. Shelton, D. Xu, 2103.01238;
S. Born, R. Karur, S. Knapen, J. Shelton, 2303.04167;
J. Carrosco, J. Zirita, 2307.04847

- Rich LLP phenomenology

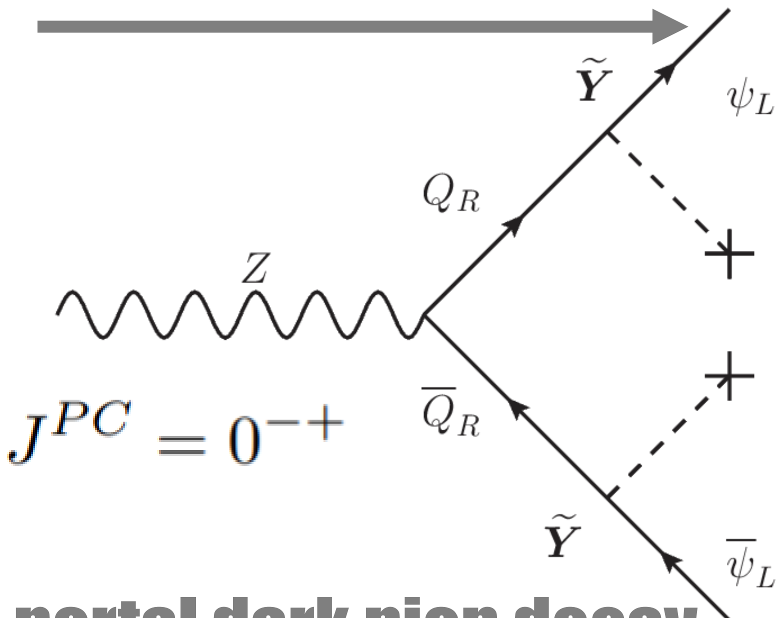
- Duality ? ALPs ? Baryogenesis? ……

The Cartoon of Dark Spectrum



Dark Pions

Z portal dark pion production



Z portal dark pion decay

Dark pions rearrange into CP eigenstates (like K_S and K_L in the SM)

The π_1 and π_3 decay via Z portal, ALP-like (axion-like-particle) with effective ALP decay constants:

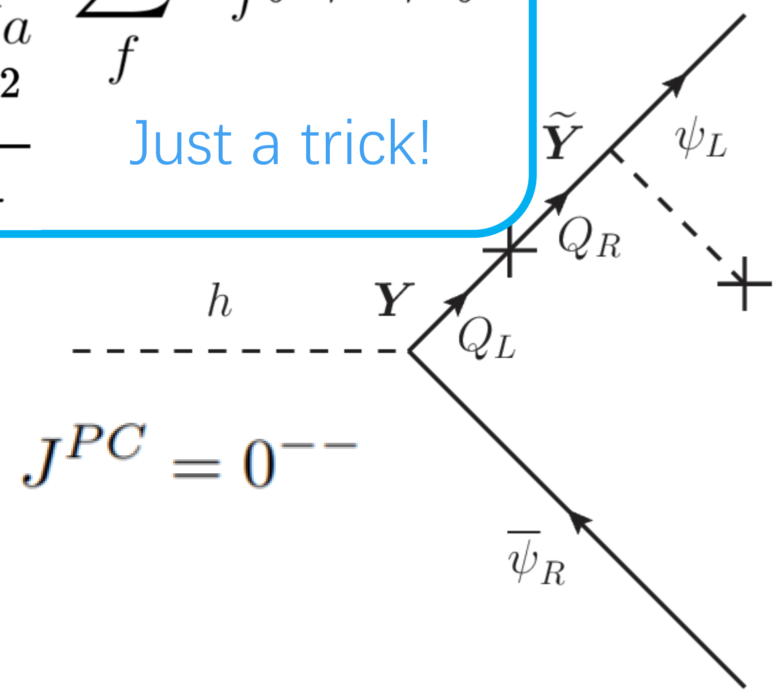
$$\mathcal{L}_a \supset -\frac{\partial_\mu a}{f_a} \sum_f T_f^3 \bar{f} \gamma^\mu \gamma^5 f$$

$$f_a \propto \frac{M^2}{f_{\hat{\pi}}}$$

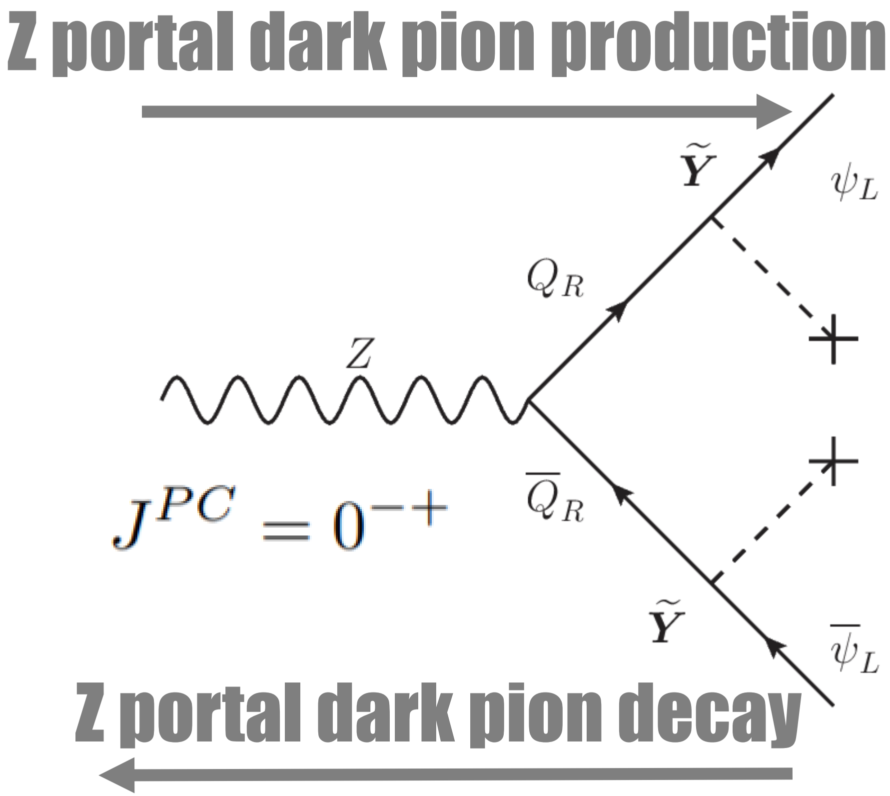
Just a trick!

The π_2 mix with the Higgs since it's CP-even, with mixing angle:

$$\mathcal{L}_s \supset -\sin\theta_s \frac{m_f}{v} s \bar{f} f \ , \ \ \theta_s \lesssim 10^{-6}$$



Dark Pions



Dark pions rearrange into CP eigenstates (like K_S and K_L in the SM)

The π_1 and π_3 decay via Z portal, ALP-like (axion-like-particle) with effective ALP decay constants:

$$\mathcal{L}_a \supset -\frac{\partial_\mu a}{f_a} \sum_f T_f^3 \bar{f} \gamma^\mu \gamma^5 f$$

$$f_a \propto \frac{M^2}{f_{\hat{\pi}}}$$

Just a trick!

$f_{\hat{\pi}}$ The dark meson decay constant, O(confinement scale)

f_a The effective (composite) ALP decay constant, O(PeV) or above

Convenient for the matching with existing ALP searches

Dark (Flavor) Symmetry

- Dark isospin symmetry: identical mass and couplings ⇒ All dark pions stable, DM?

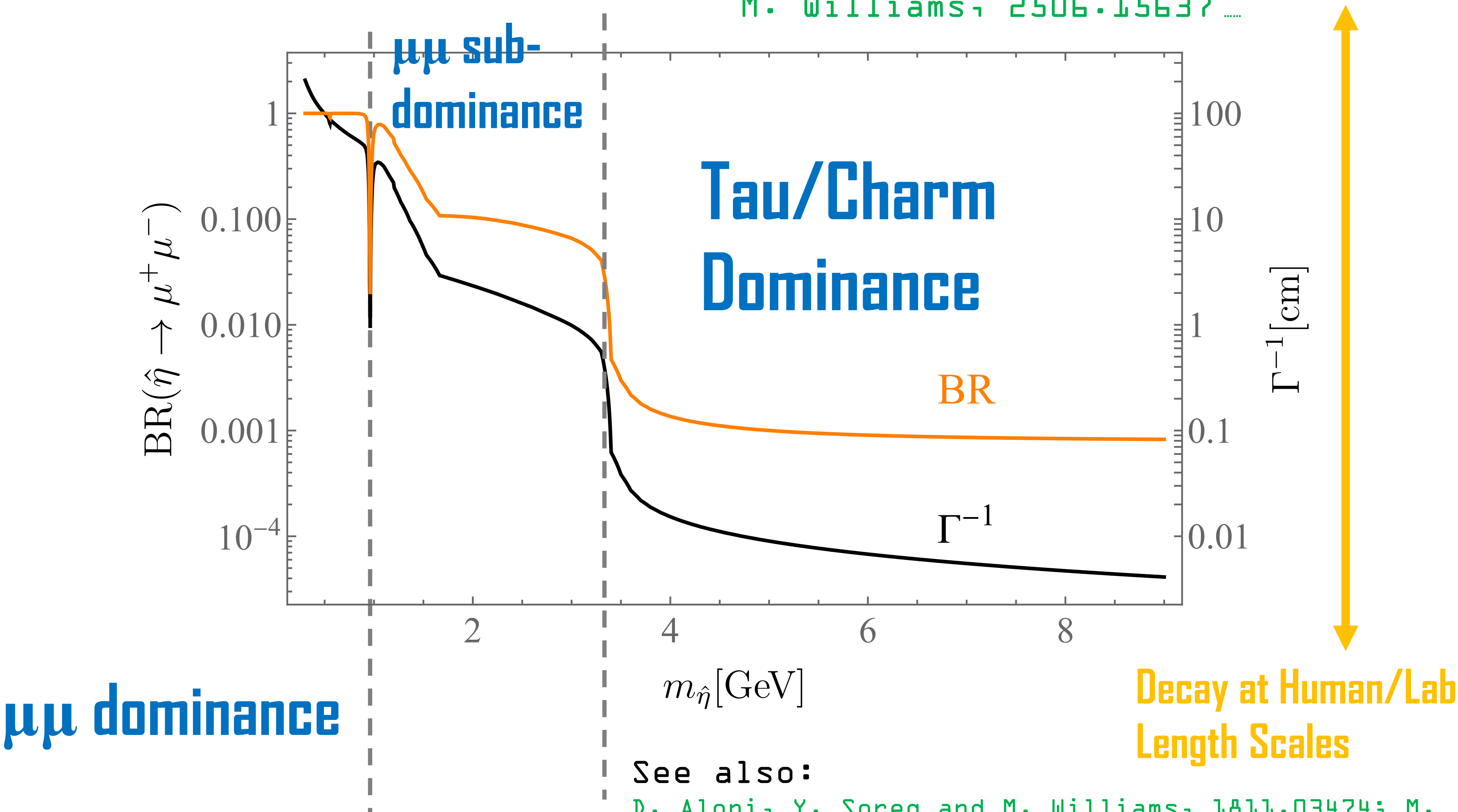
- Dark U(1) symmetry: mass and charge matrix diagonal ⇒ dark pions carrying non-zero U(1) global charge are stable, DM?

- Dark CP-symmetry: all entries above are real ⇒ No mixing between CP-odd and –even species

- ……

Dark Pion Decays (ALP-Like)

Recent Update: R. Balkin, T. Coren, Y. Soreq and M. Williams, 2506.15637 ……

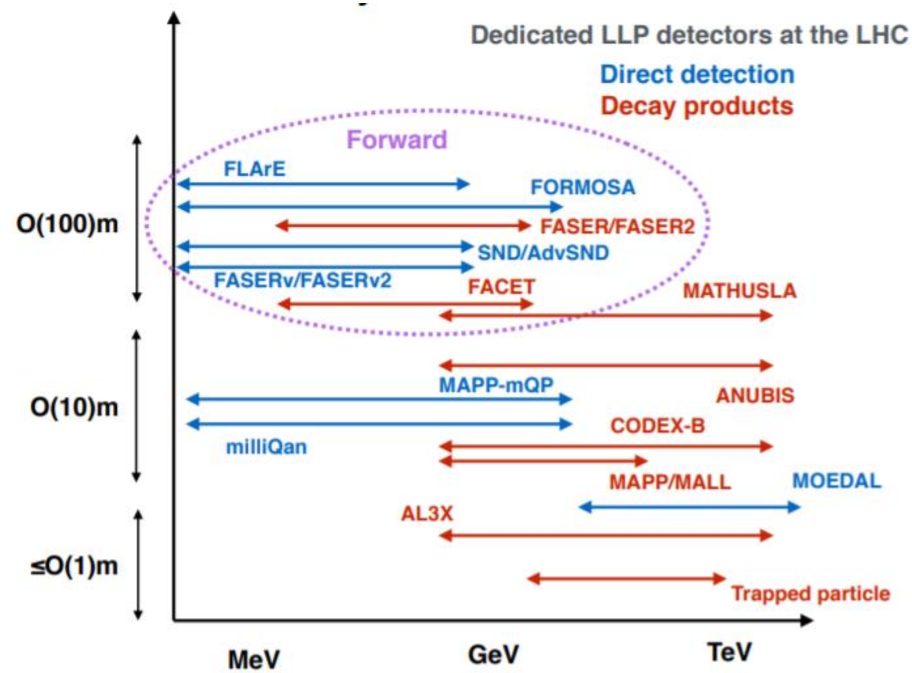


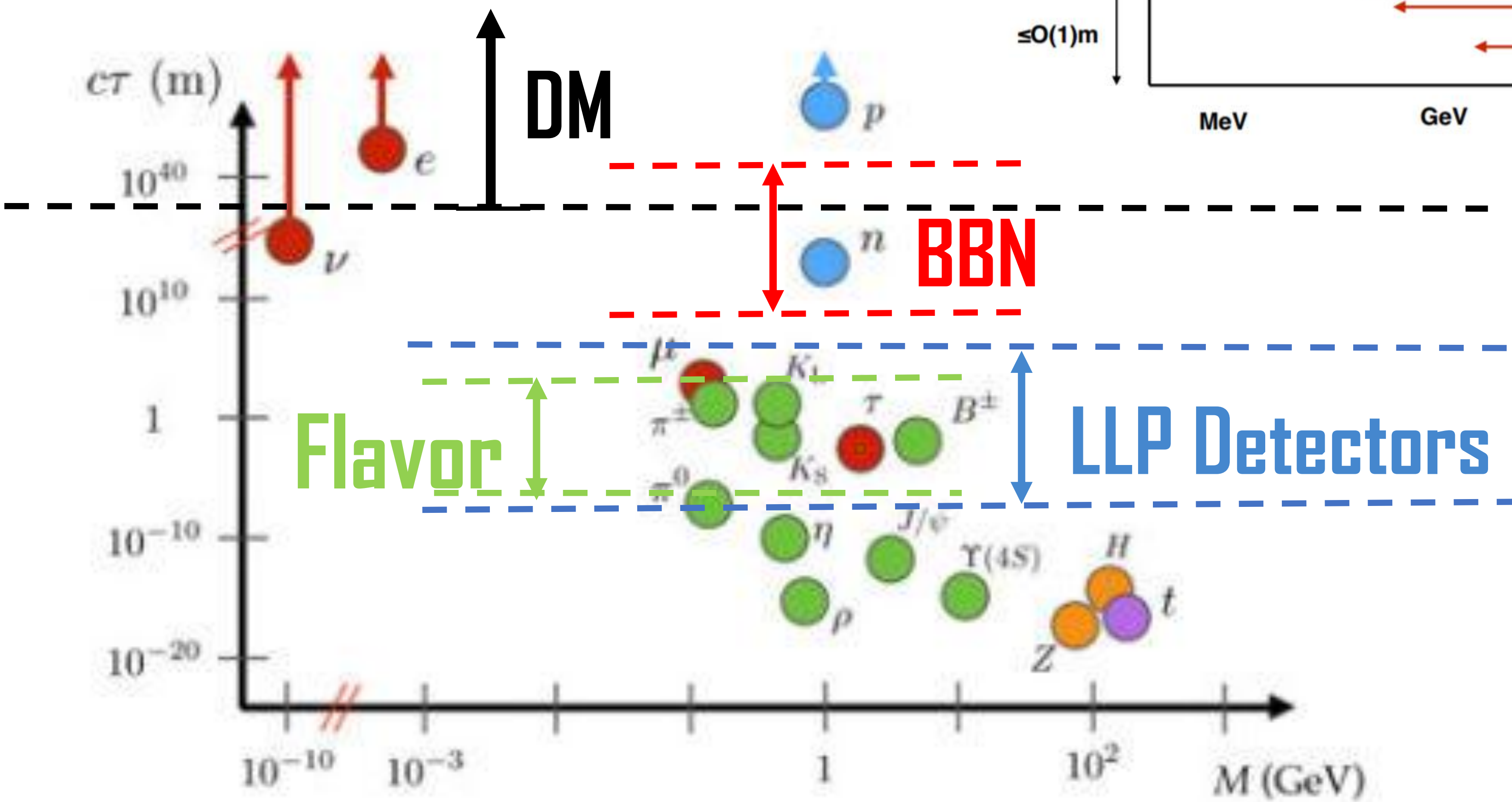
See also:

D. Aloni, Y. Soreq and M. Williams, 1811.03474; M. Ovchynnikov and A.~Zaporozhchenko, 2501.04525; Y. Bai, T. K. Chen, J. Liu and X. Ma, 2505.24822

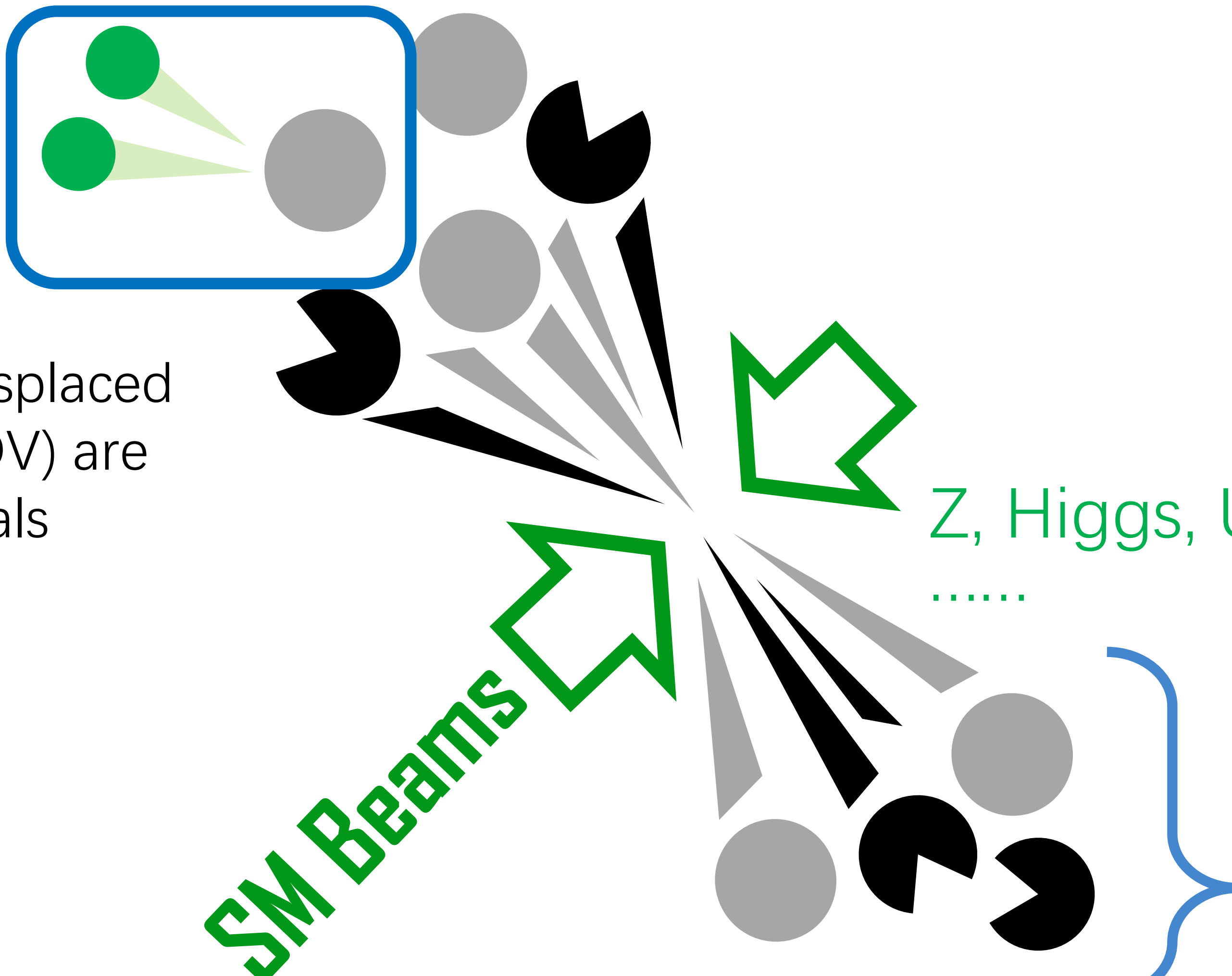
Long-Lived Particles

They are more common and fundamental than it appears





Phenomenology at (Semi-)UV



Z, Higgs, UV mediators
......

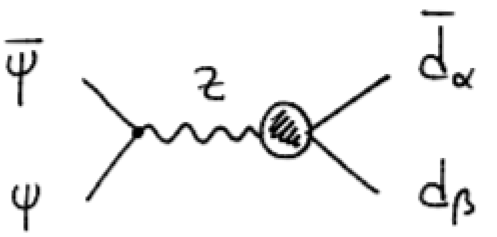
Dimuon displaced vertexes (DV) are sharp signals

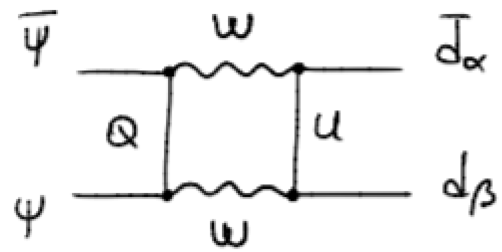
Fully inclusive searches rely on multiplicity of displaced tracks.

If any dark pion is an LLP → emerging energy outside the innermost detector

P. Schwaller, D. Stolarski, A. Weiler, 1502.05409; CMS, 1810.10069; S. Knapen, J. Shelton, D. Xu, 2103.01238; . Born, R. Karur, S. Knapen, J. Shelton, 2303.04167; J. Carrosco, J. Zurita, 2307.04847

IR: Flavor Portal to LLP

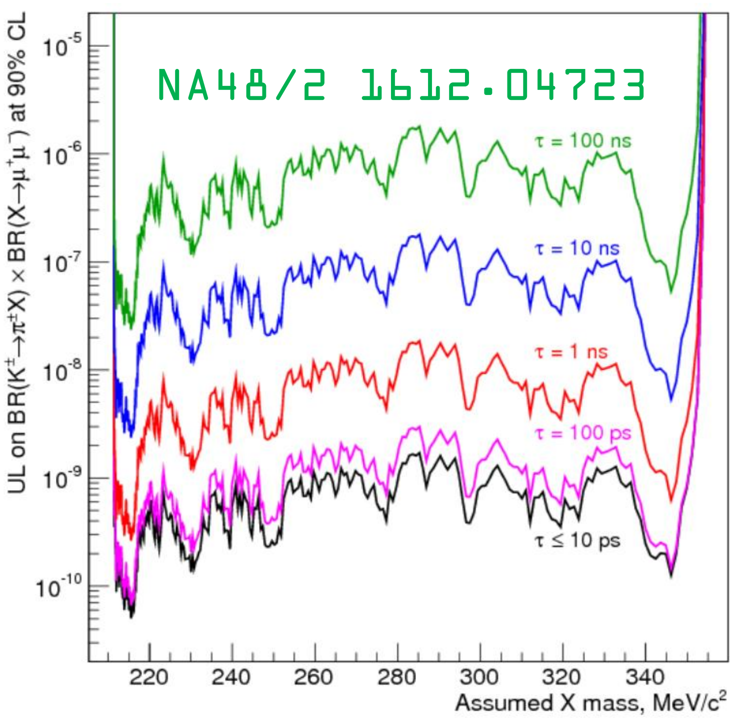




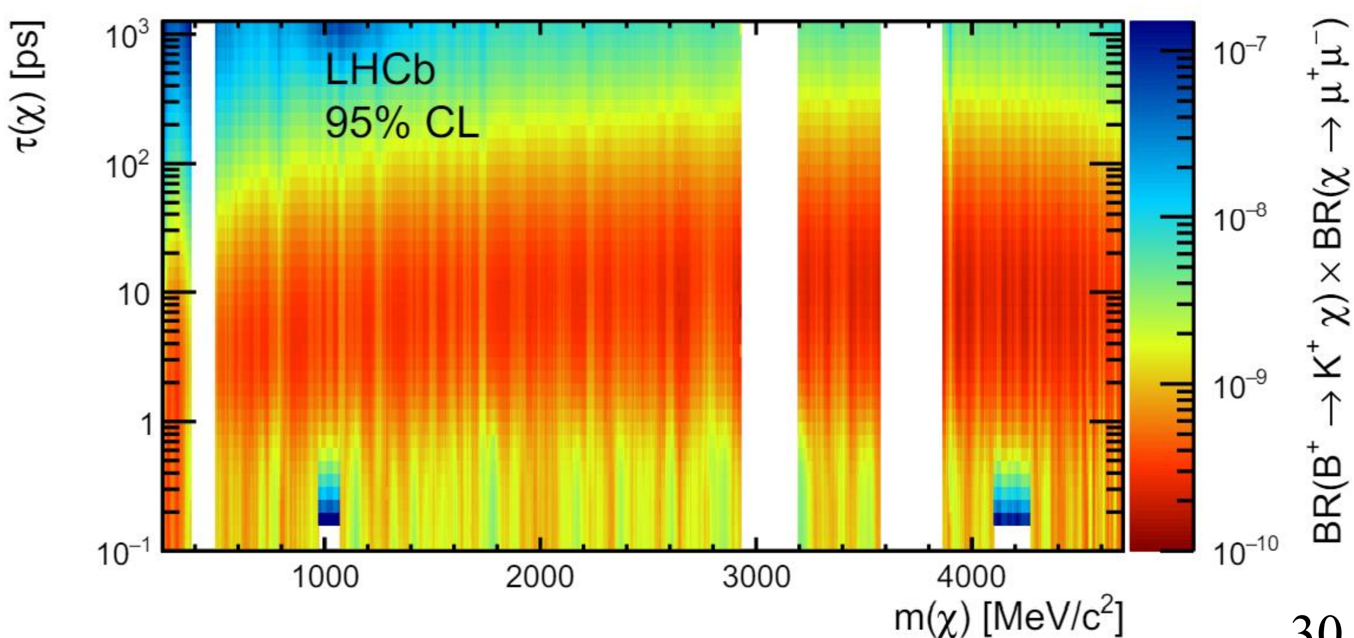
- 5-10 times larger BR for inclusive X_s decays

$$\mathrm{BR}(B^{+,0} \to \{K^+\hat{\pi}, K^{*0}\hat{\pi}\}) \approx \{0.92, 1.1\} \times 10^{-8} \left(\frac{1\ \mathrm{PeV}}{f_a}\right)^2 \left(\frac{\mathcal{K}_t}{10}\right)^2 \{\lambda^{1/2}_{BK\hat{\pi}}, \lambda^{3/2}_{BK^*\hat{\pi}}\}$$

$$\mathrm{BR}(K^+ \to \pi^+\hat{\pi}) \approx 3.9 \times 10^{-11} \left(\frac{1\ \mathrm{PeV}}{f_a}\right)^2 \left(\frac{\mathcal{K}_t}{10}\right)^2 \lambda^{1/2}_{K\pi\hat{\pi}}$$

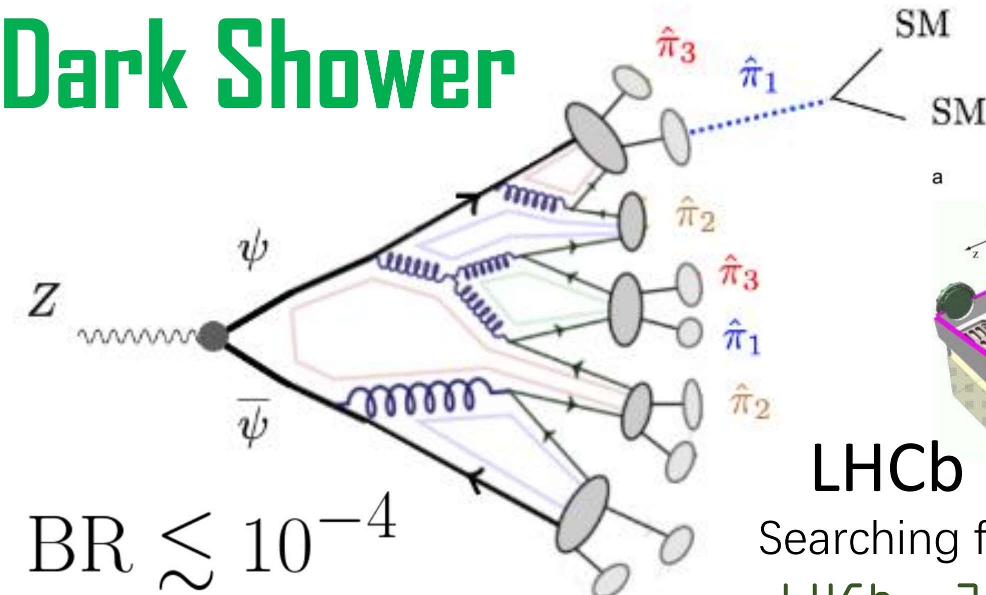


LHCb 1612.07818



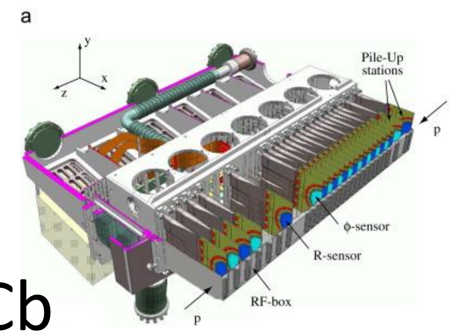
LLP Phenomenology

Dark Shower

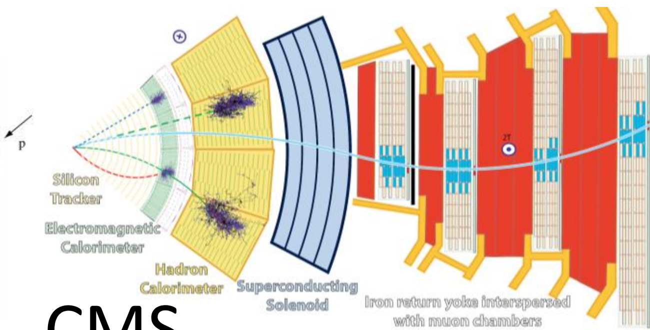


$$\mathrm{BR} \lesssim 10^{-4}$$

Signal: Muon rich jet-like structure with long-lived tracks + MET



LHCb



CMS

Searching for displaced dimuon resonances (one or more)

LHCb, 2007.03923; CMS, 2112.13769

CODEX-b

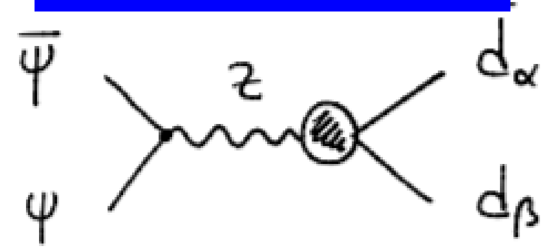
MATHUSLA

FASER

FPF Forward Physics Facility

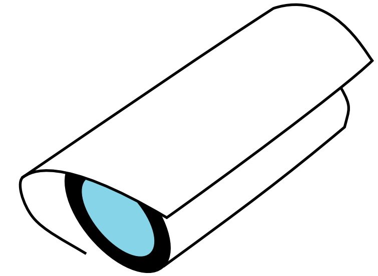
$$\mathrm{BR} \approx 10^{-8}\left(\frac{1\ \mathrm{PeV}}{f_a}\right)^2$$

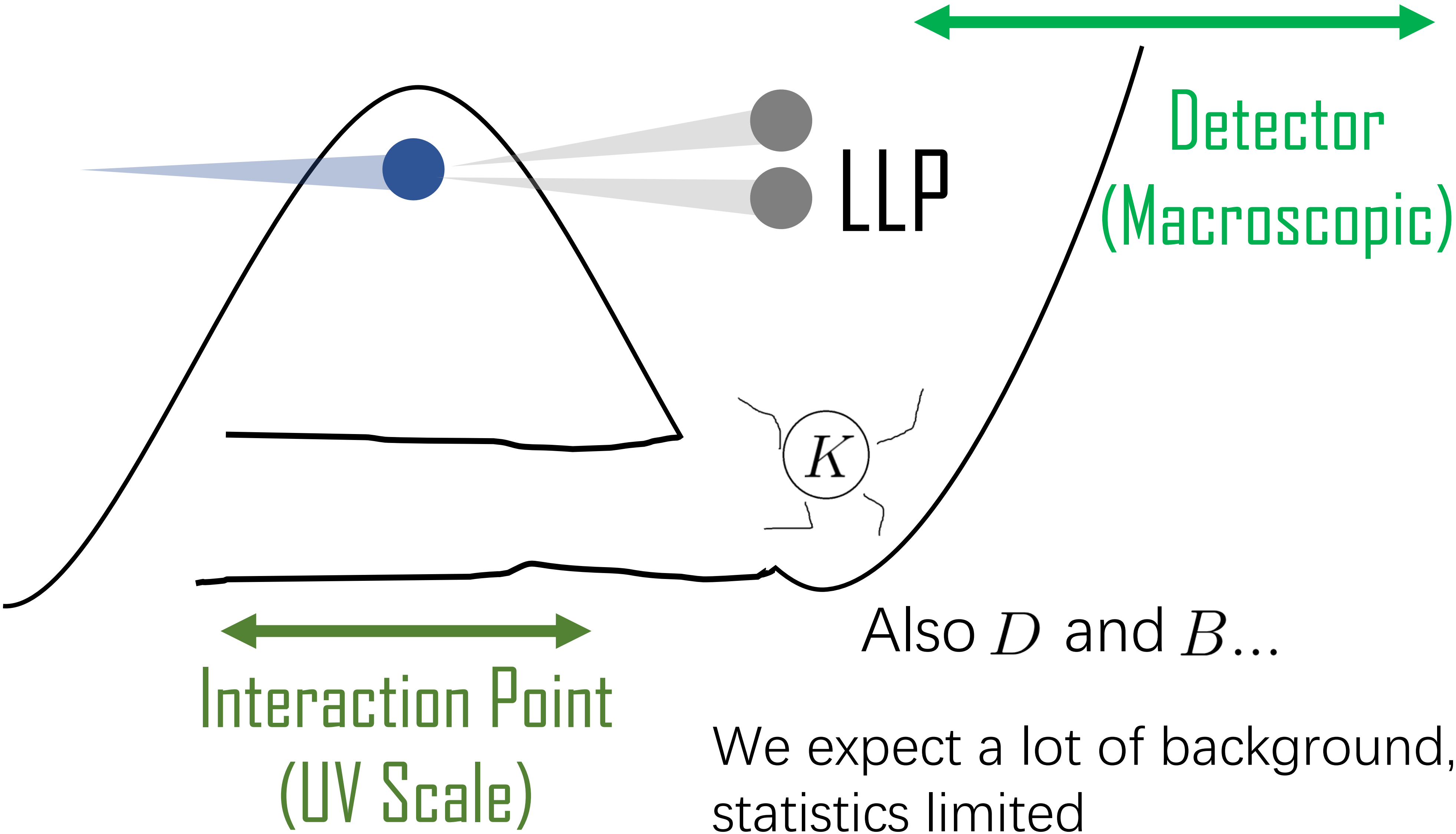
Belle II



FCNC Decays

LLP at LHC Detectors

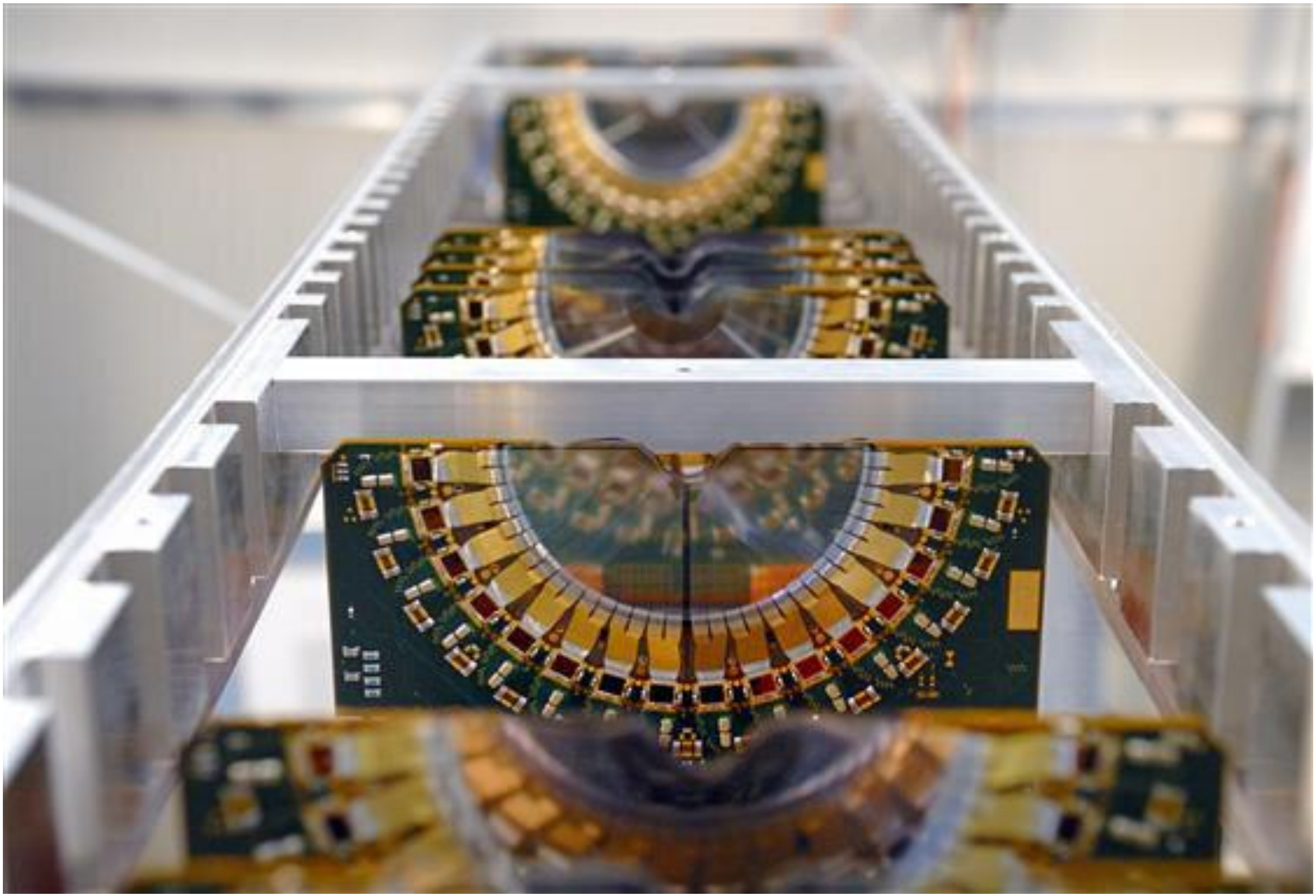




Also D and B...

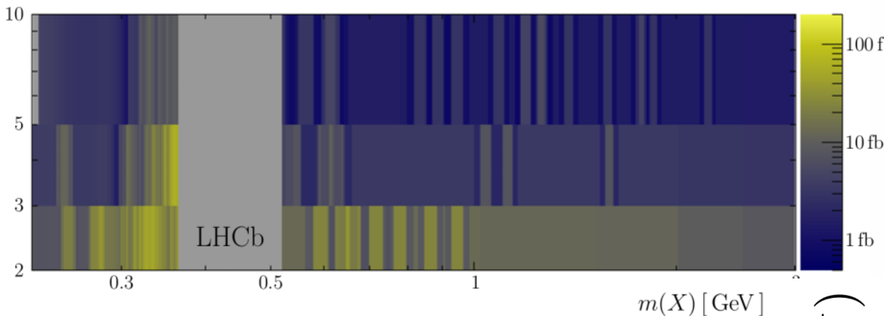
We expect a lot of background, statistics limited

LHCb Vertex Locator (VELO)

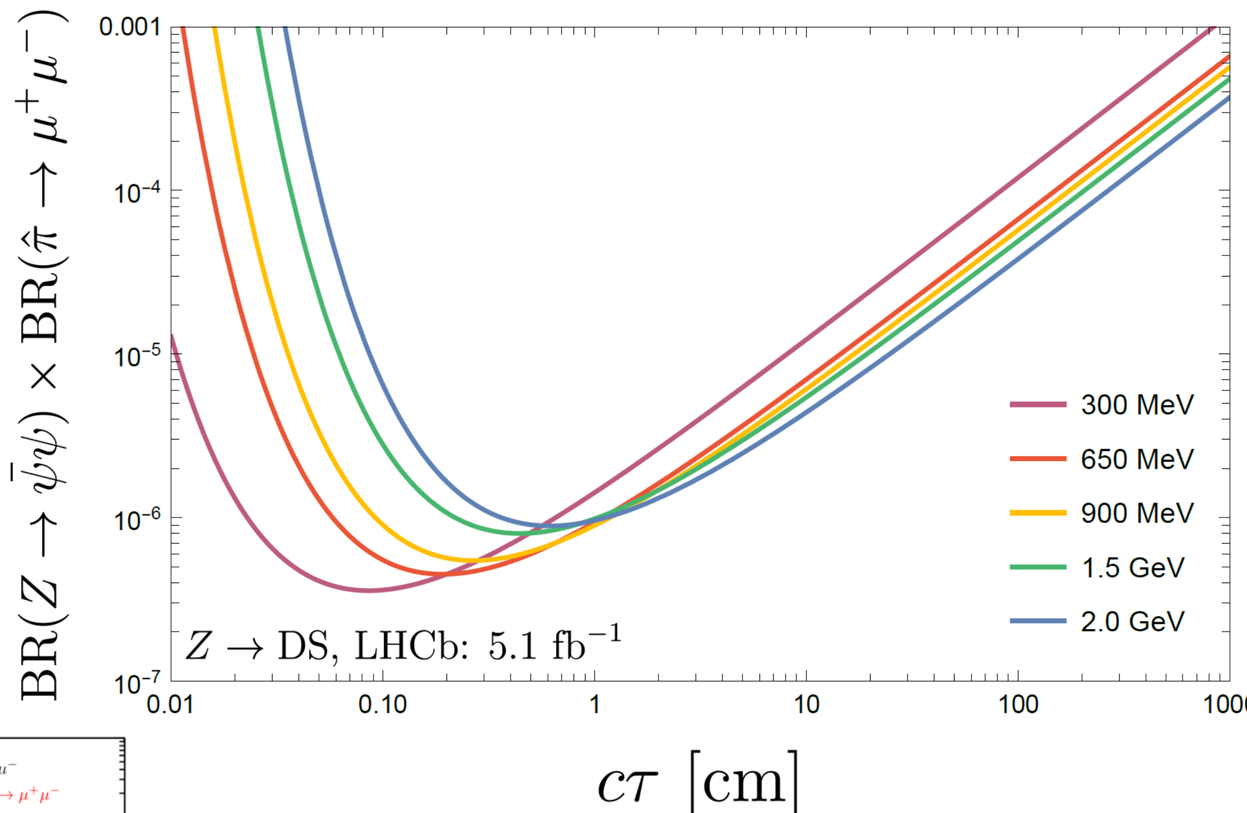


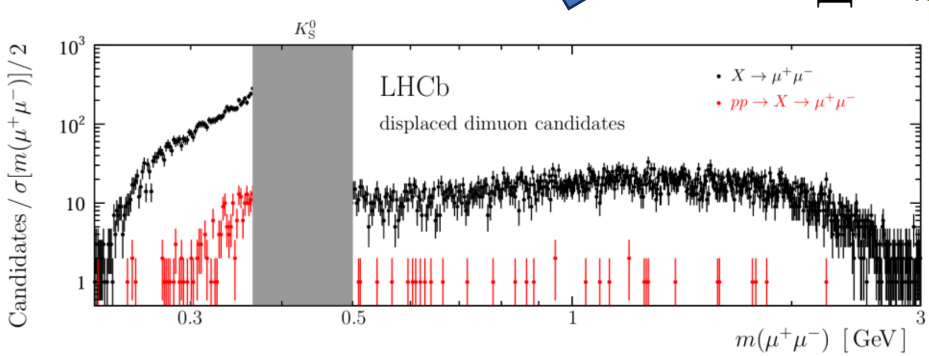
LHCb: "Trigger-free" Searches

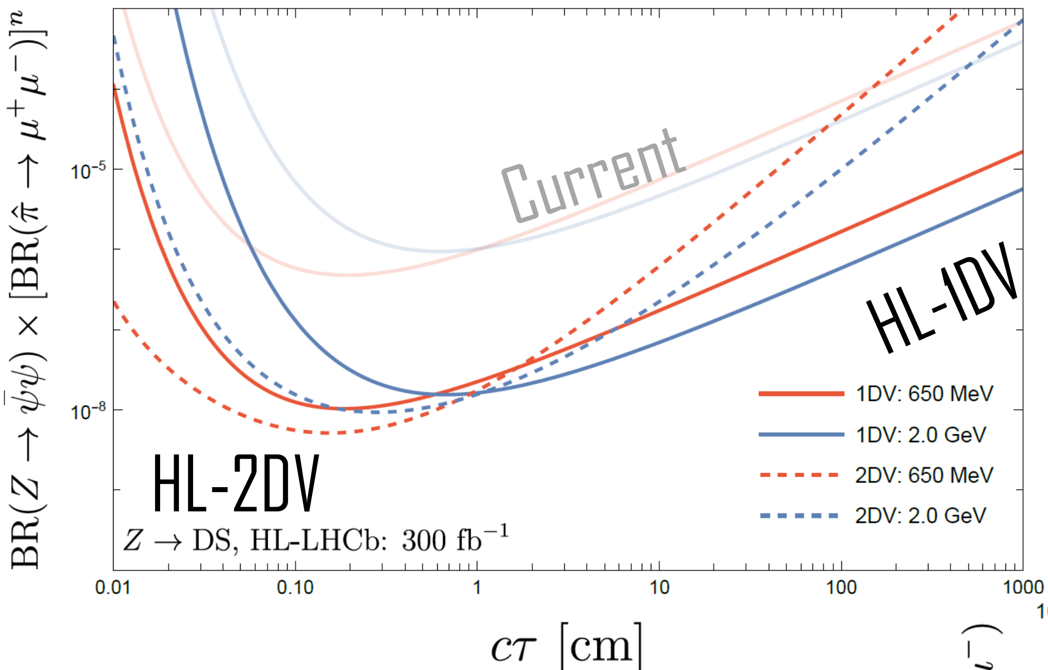
See LHCb, 2007.03923



Matching with multiple ways to calibrate the projection

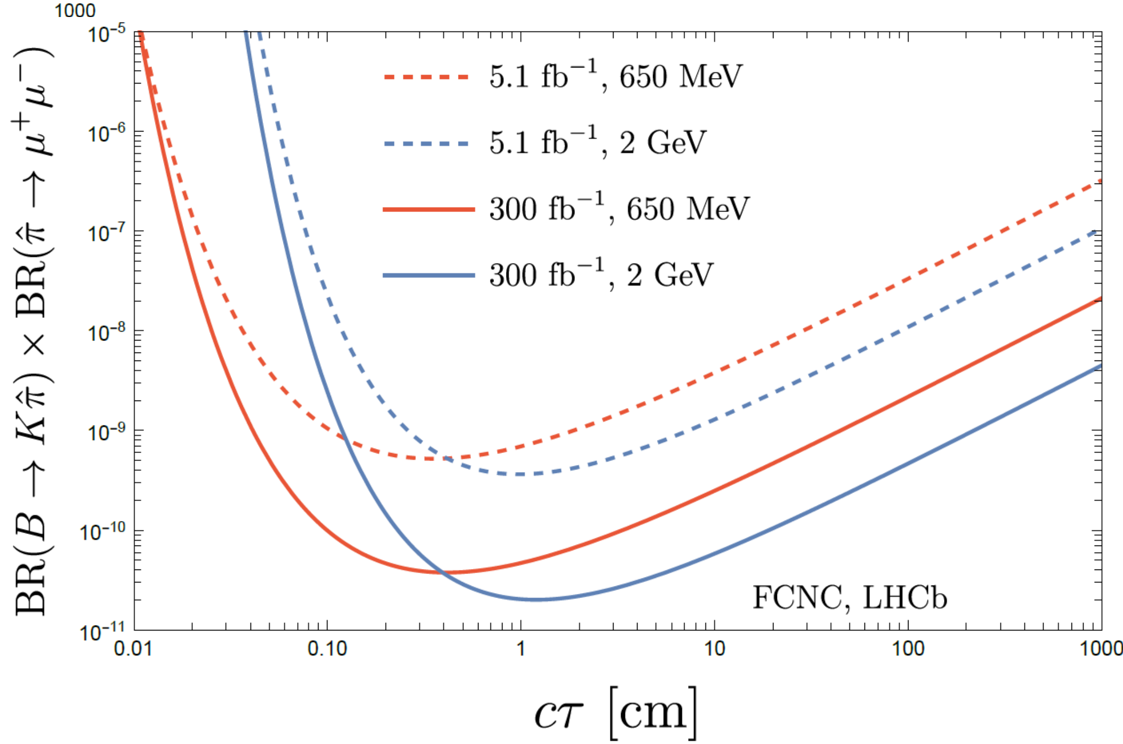






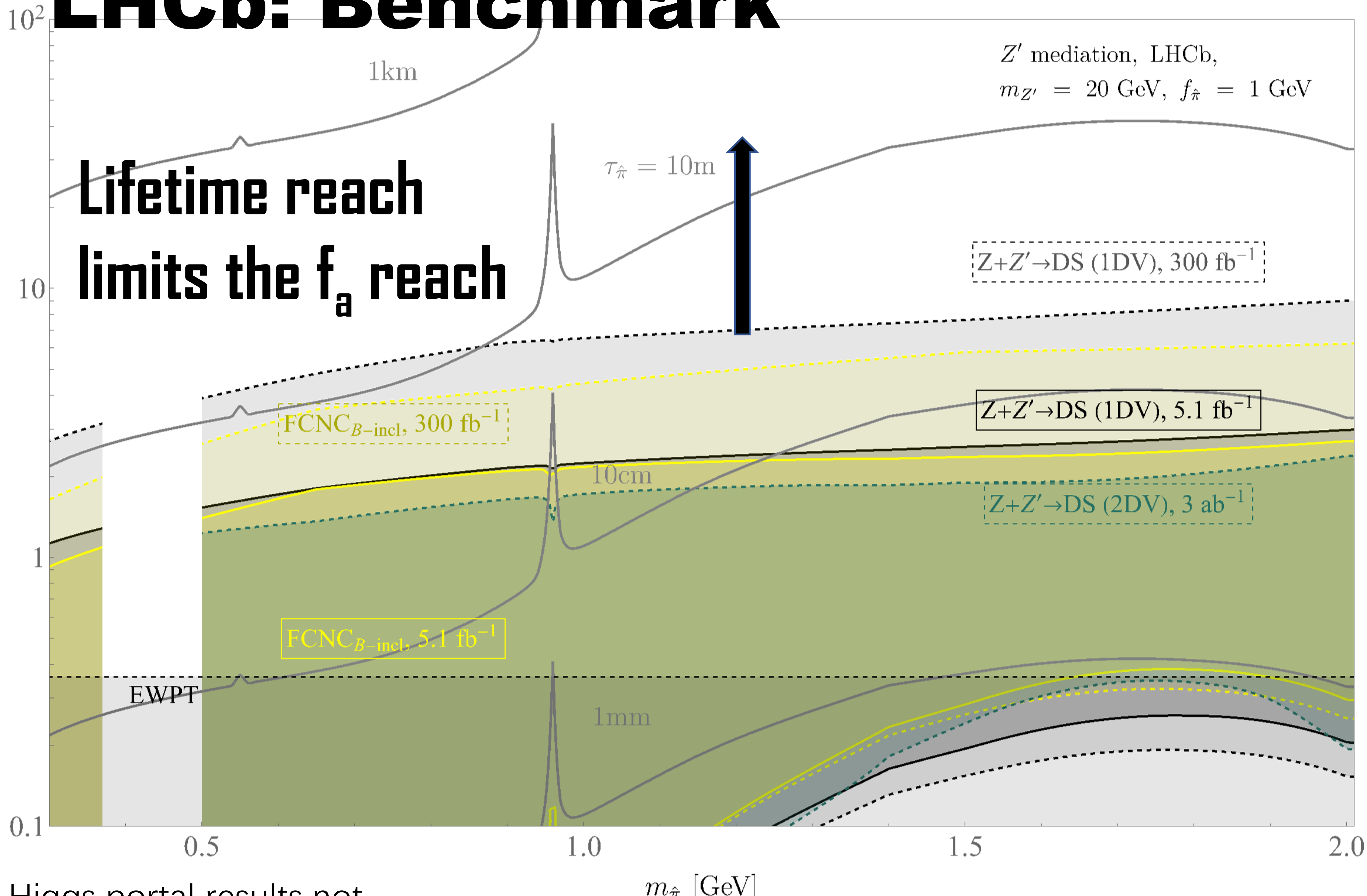
➢ Extended to the HL-LHC era, improve by ~ O(10^2)

➢ Also sensitive to FCNC, unsuppressed B production in the forward region



LHCb: Benchmark

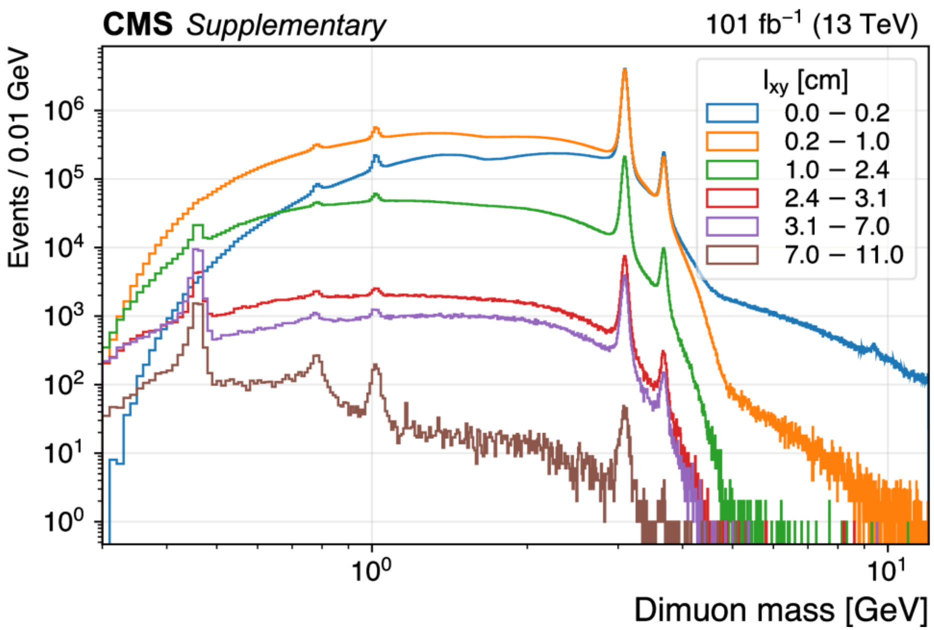
Lifetime reach limits the f_a reach



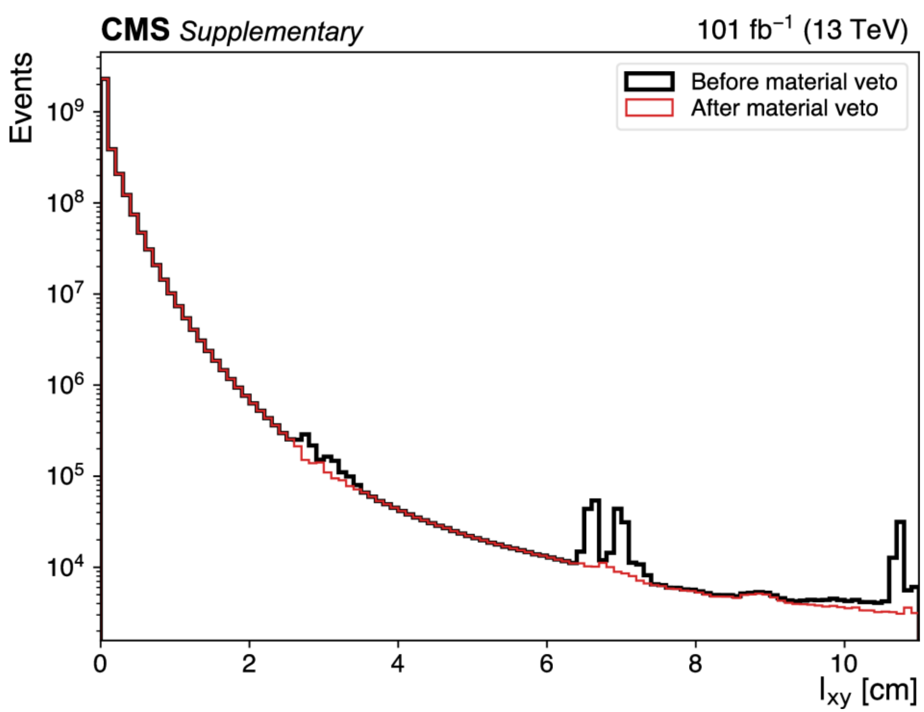
Higgs portal results not shown here

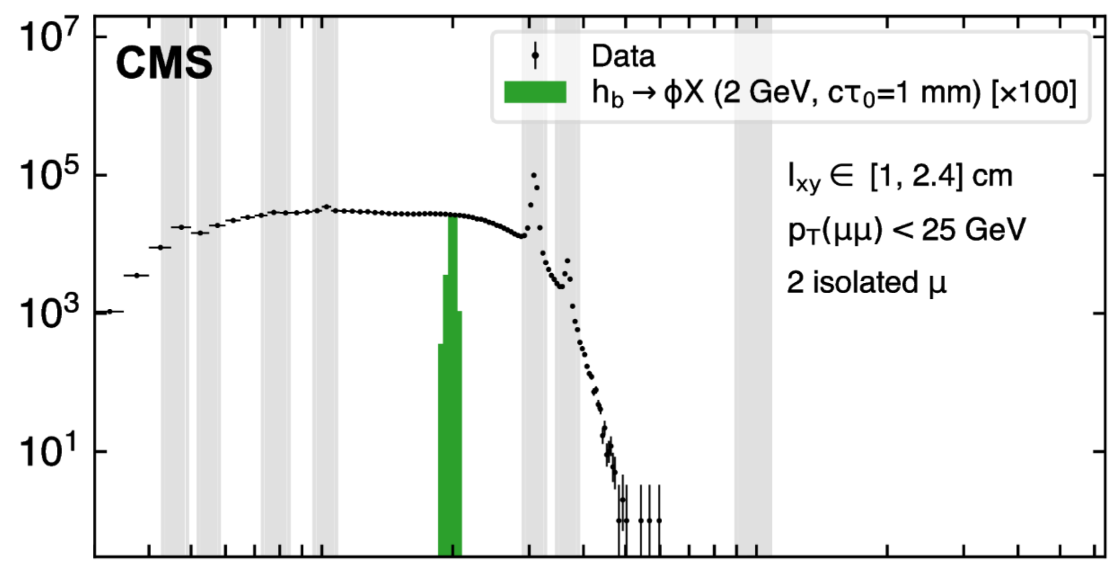
CMS: Dimuon Scouting

CMS, 2112.13769



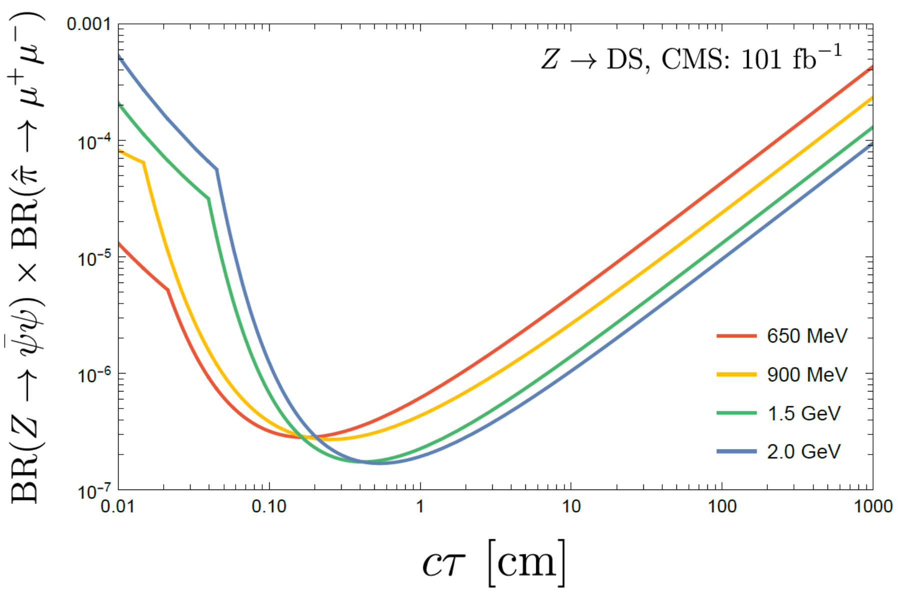
- Drop-out detailed info to boost dimuon trigger rate, useful for low mass resonances
- Not bkg free





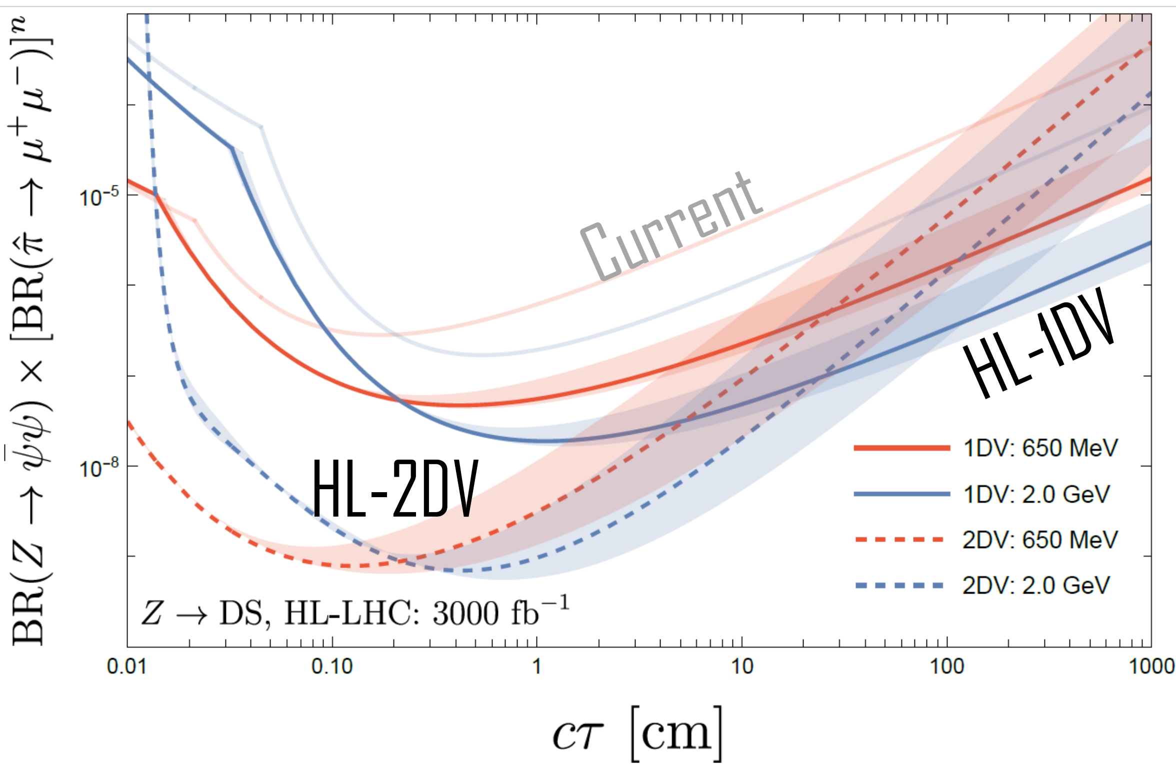
- Applies to Dark shower or FCNC

CMS: Model-Independent Limits



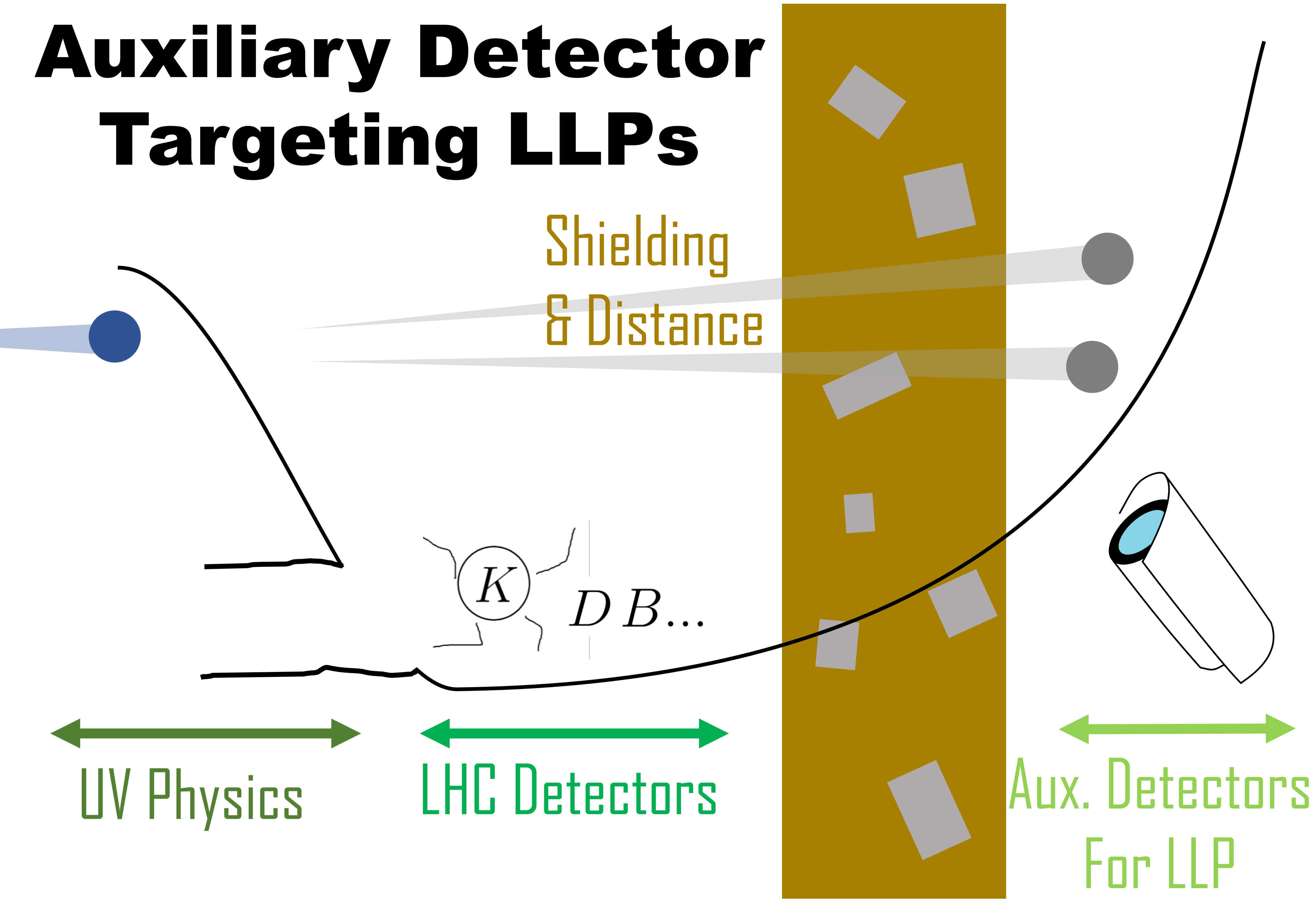
- Current limit with <11 cm transverse displacement
- 30 times luminosity, detector/algorithm upgrades……

↘ HL-LHC limits



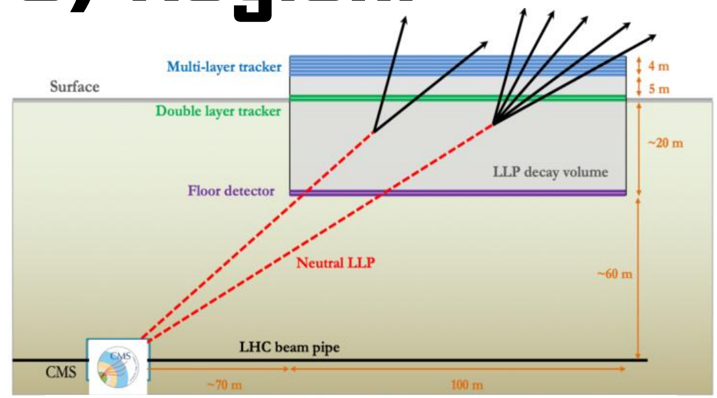
- At HL-LHC, high efficiency to do 2DV search: two dimuon DV with the same mass

Auxiliary Detector Targeting LLPs

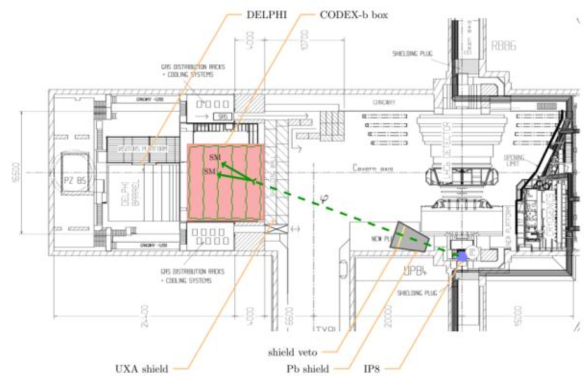


Central ($|\eta| < 5$) Region:

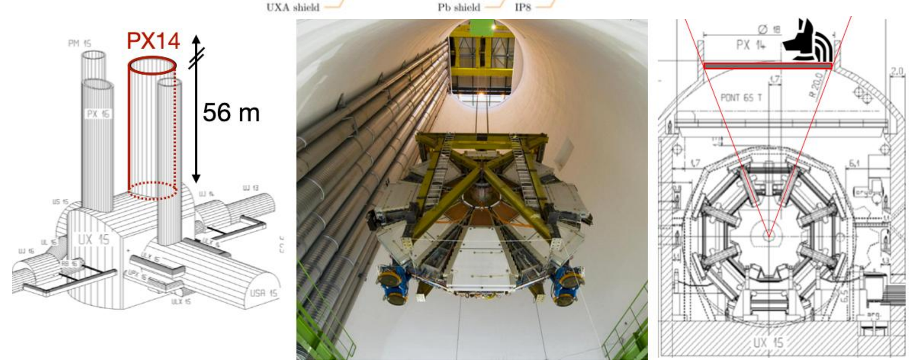
MATHUSLA



CODEX-b



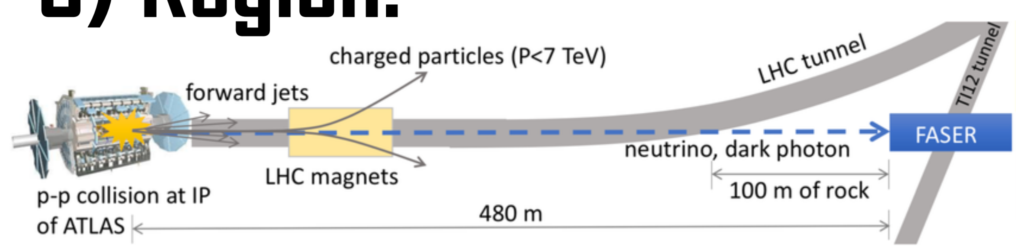
ANUBIS
DETECTOR@
ATLAS
EXPERIMENT



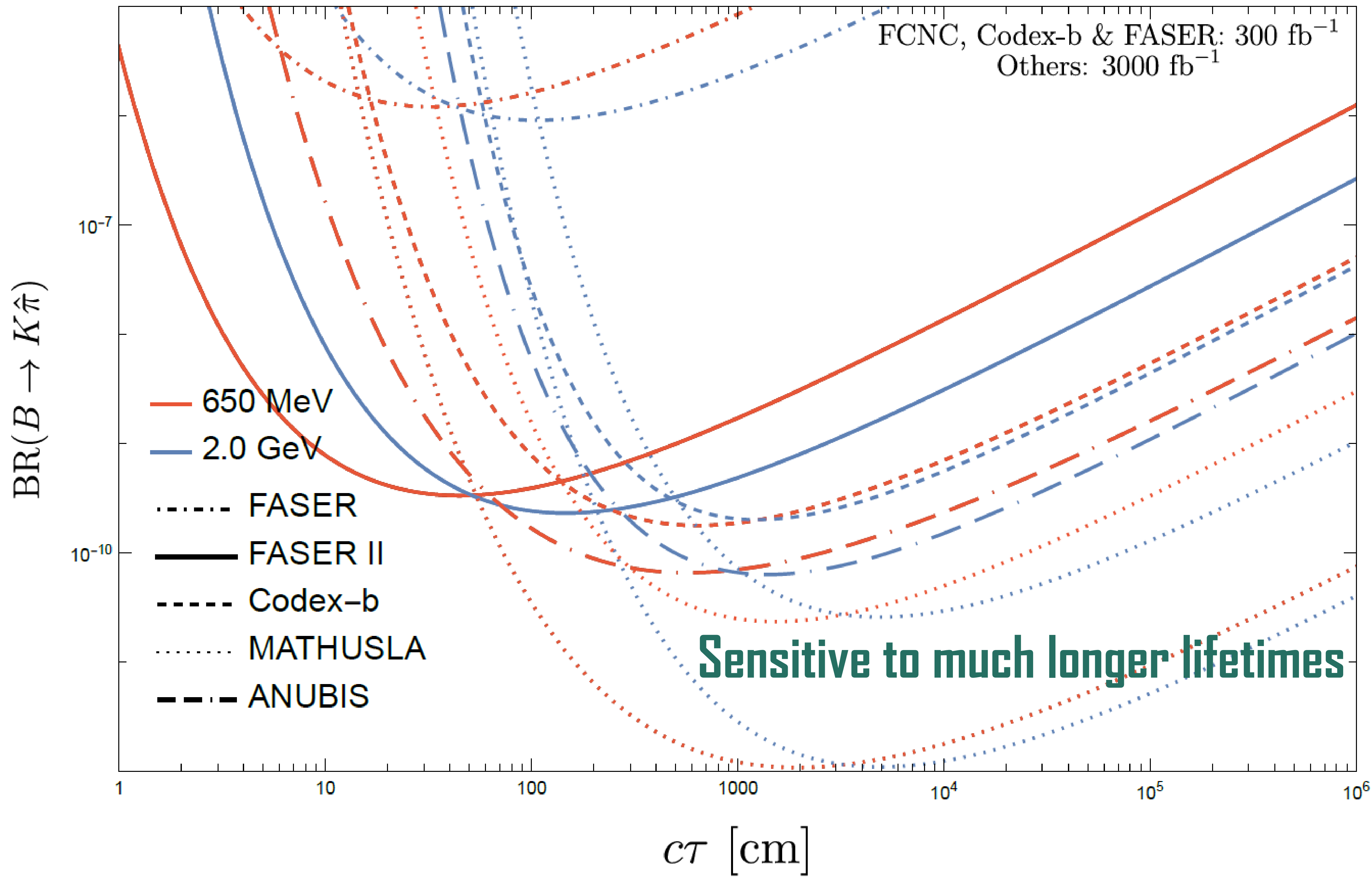
Forward ($|\eta| > 5$) Region:

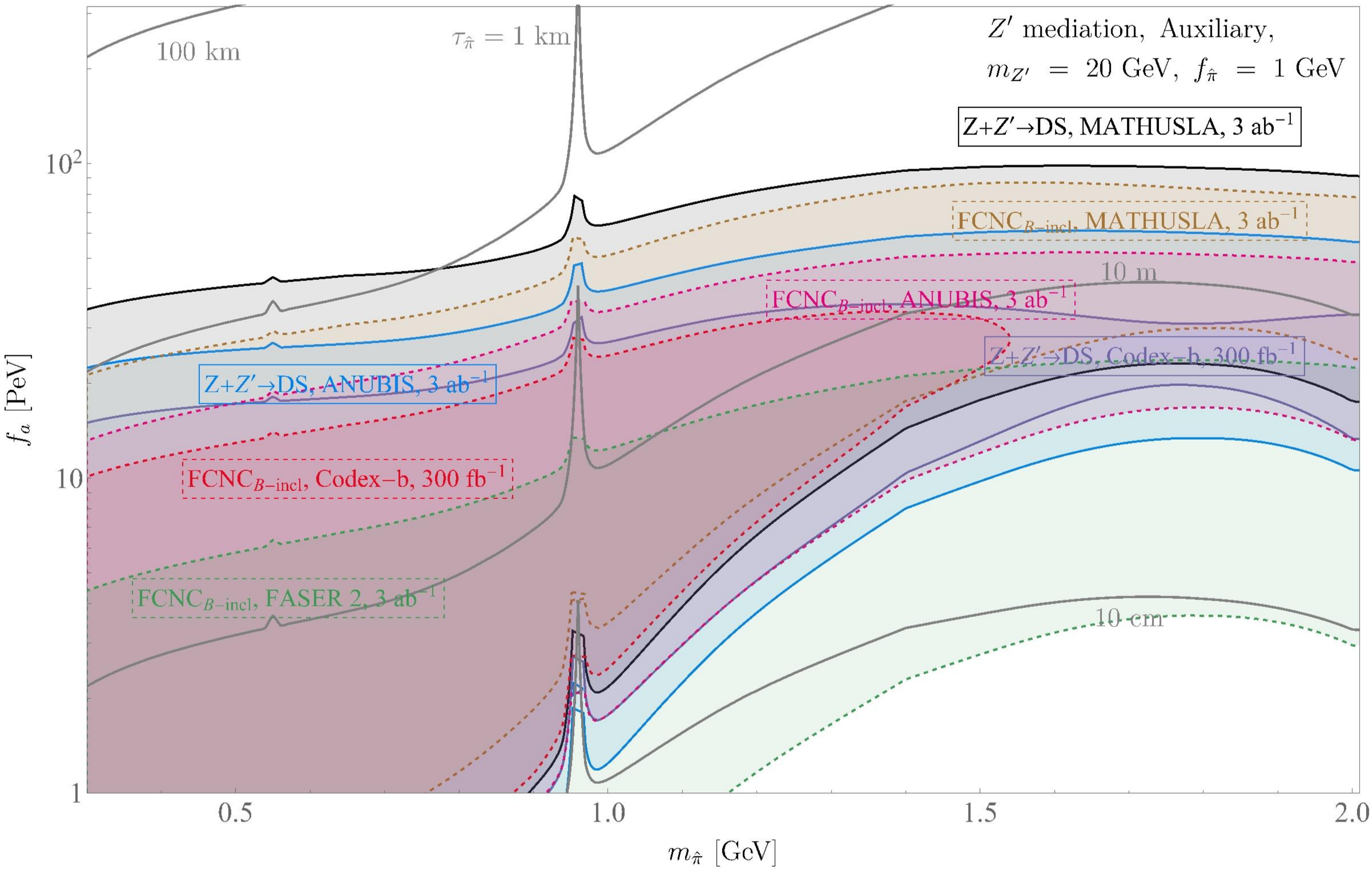
FASER

FPF
Forward Physics Facility



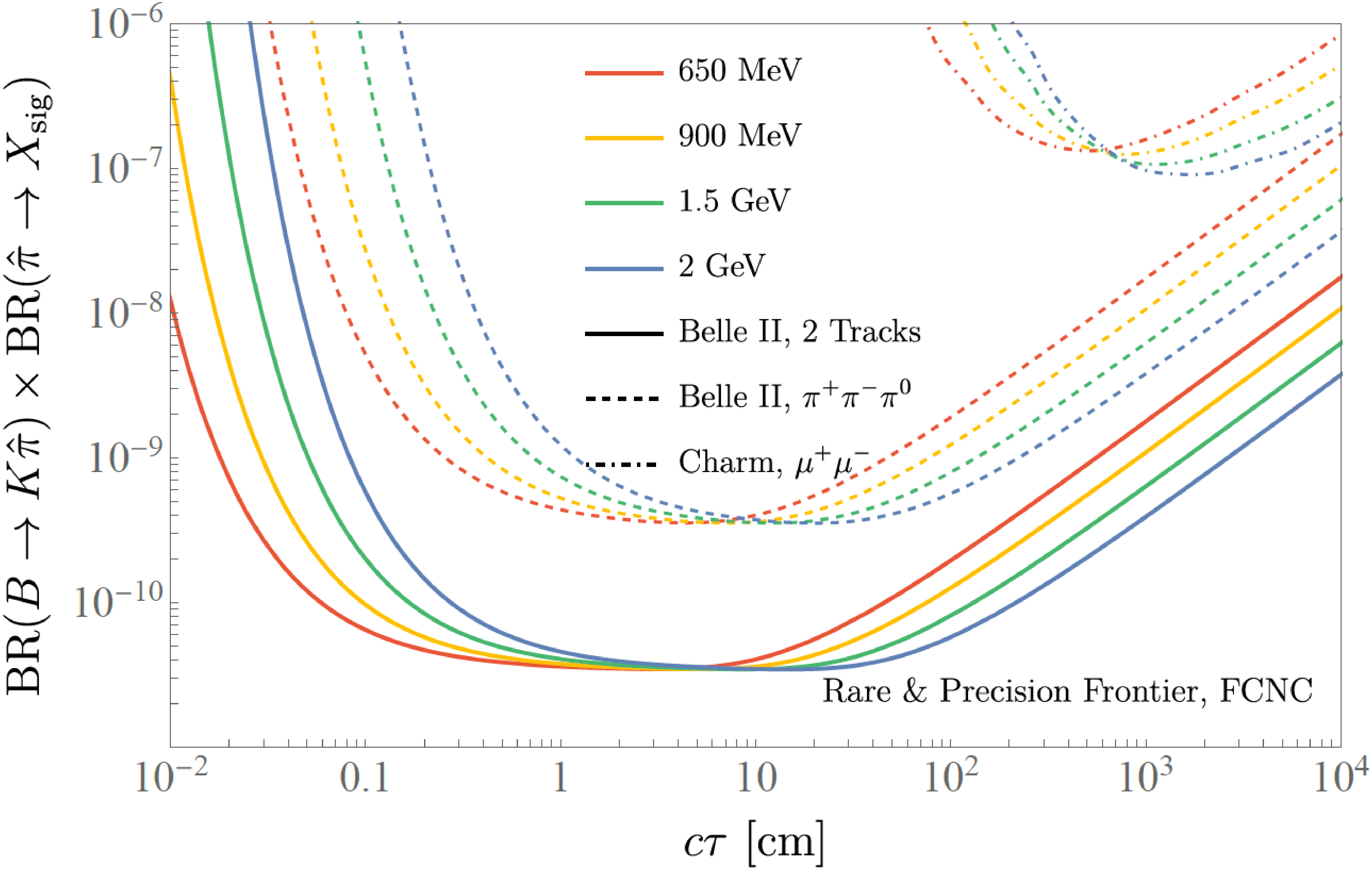
Auxiliary LLP Detectors

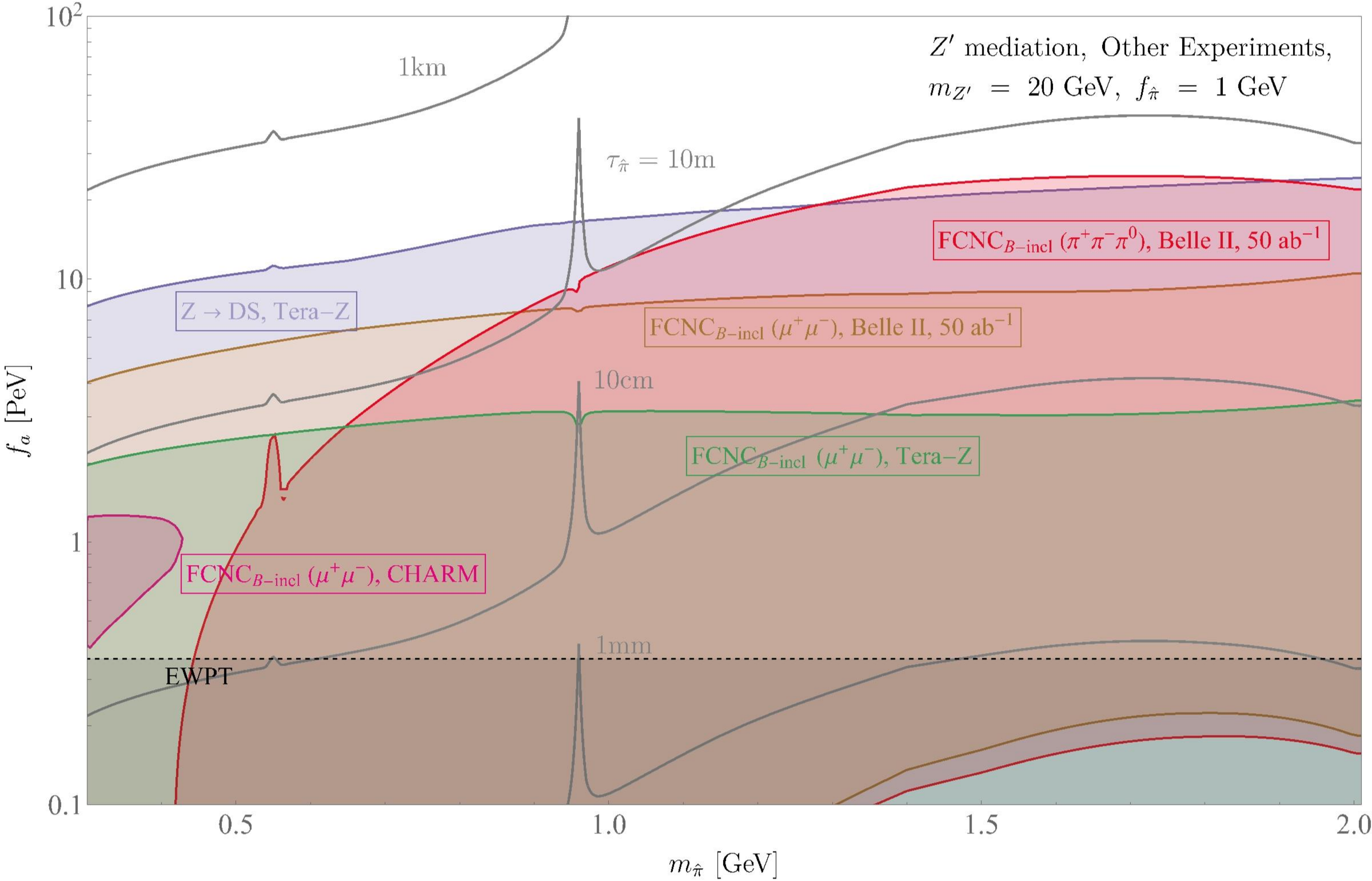




Corresponding f_a range increase up to O(100) PeV

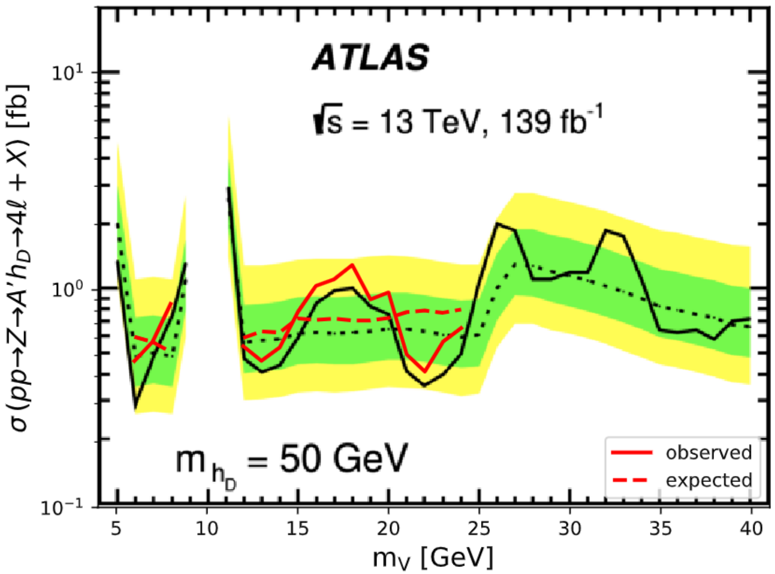
Rare/Precision/Intensity Frontier





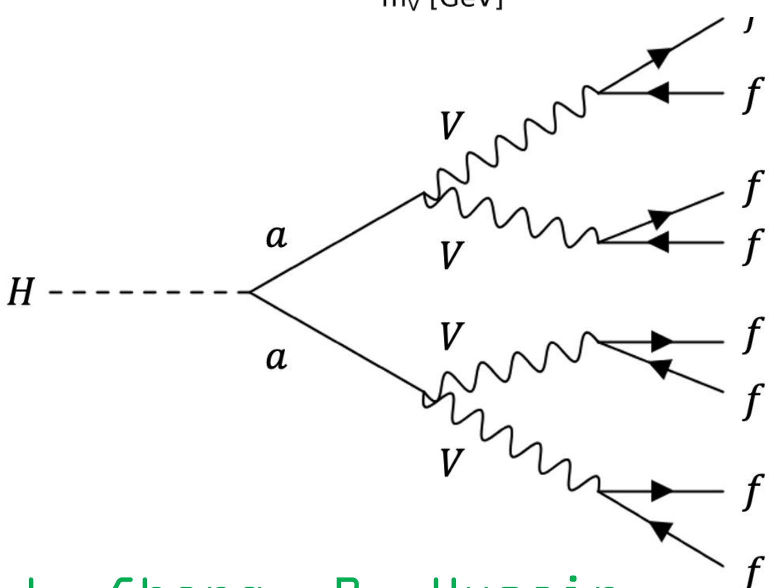
Z' mediation, Other Experiments,
$m_{Z'}$ = 20 GeV, $f_{\hat{\pi}}$ = 1 GeV
1km
$\tau_{\hat{\pi}} = 10$m
10cm
1mm
FCNC$_{B-\text{incl}}$ $(\pi^+\pi^-\pi^0)$, Belle II, 50 ab^{-1}
$Z \to$ DS, Tera–Z
FCNC$_{B-\text{incl}}$ $(\mu^+\mu^-)$, Belle II, 50 ab^{-1}
FCNC$_{B-\text{incl}}$ $(\mu^+\mu^-)$, Tera–Z
FCNC$_{B-\text{incl}}$ $(\mu^+\mu^-)$, CHARM
EWPT
f_a [PeV]
$m_{\hat{\pi}}$ [GeV]
10^2
10
1
0.1
0.5
1.0
1.5
2.0

Prompt Dark Vector from DS

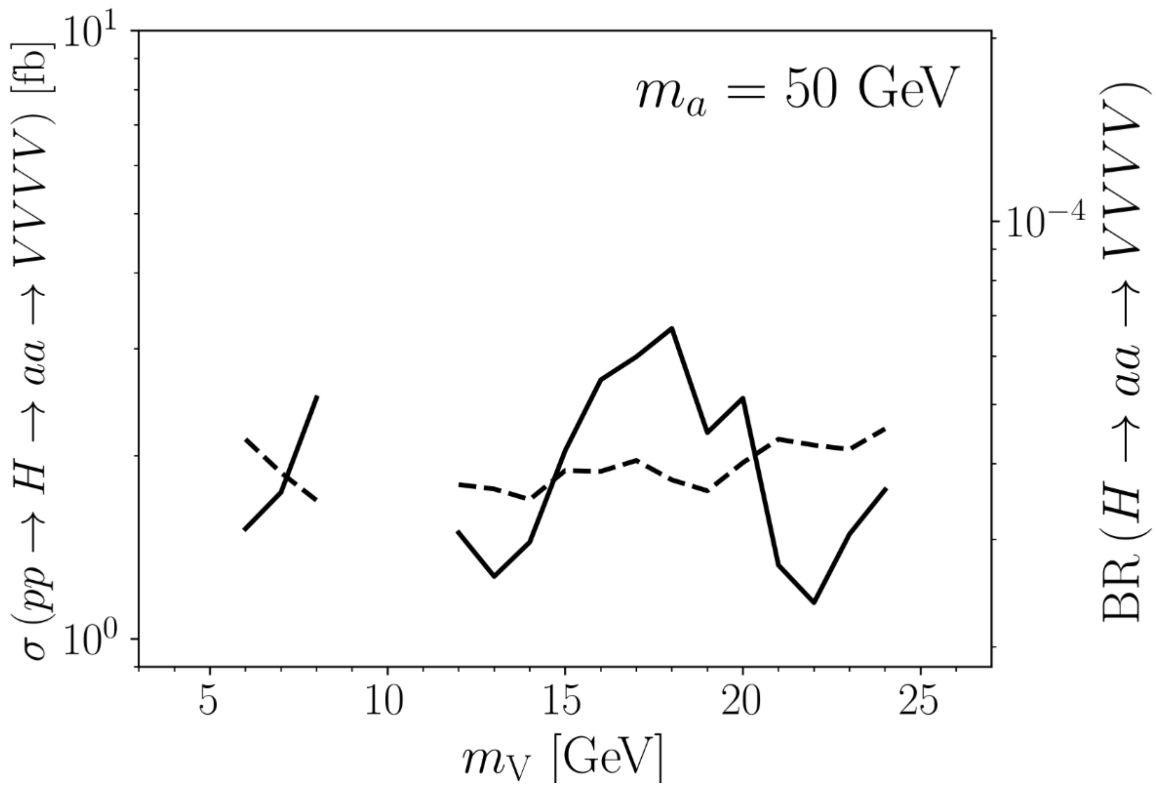


- Exotic Higgs or Z decays
- Recast from ATLAS Z->4(6) lepton exotic searches

ATLAS 2306.07413



J. Cheng, R. Husain, LFL, M. Strassler, 2412.14452 + in prep.

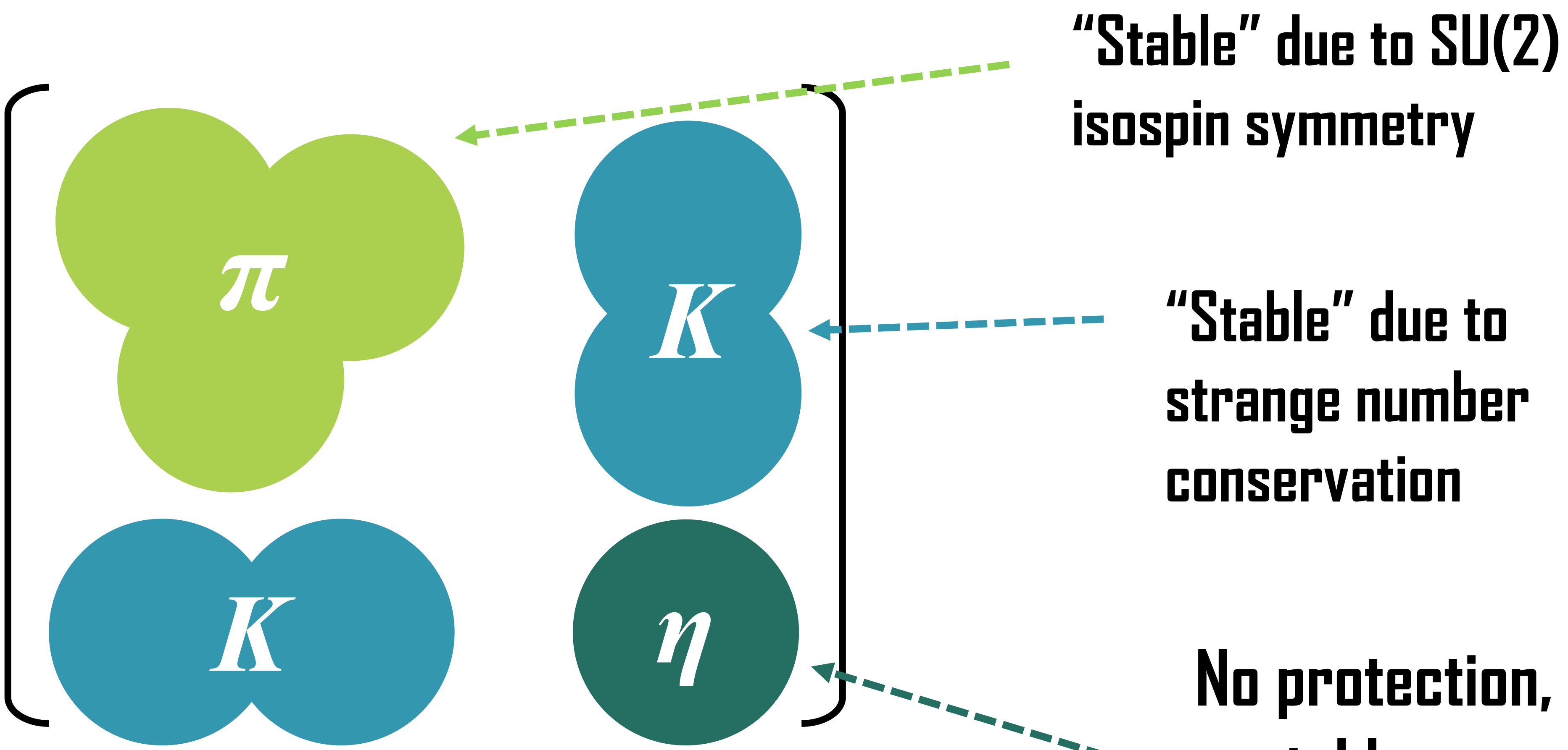


Time to Find out THE Dark but Colorful

GENERIC✓

RICHNESS✓

Back in the SM



Thermal Mechanisms

- η The messenger: heavy meson that decays, contact with the SM
- π The DM meson, non-interacting
- K The intermediate, exists in many models

Y. Hochberg, E. Kuflik, H. Murayama, T. Volansky, J. Wacker, 1411.3727; A. Katz, E. Salvioni, and B. Shakya, 2006.15148……

SIMP-like

Pairwise

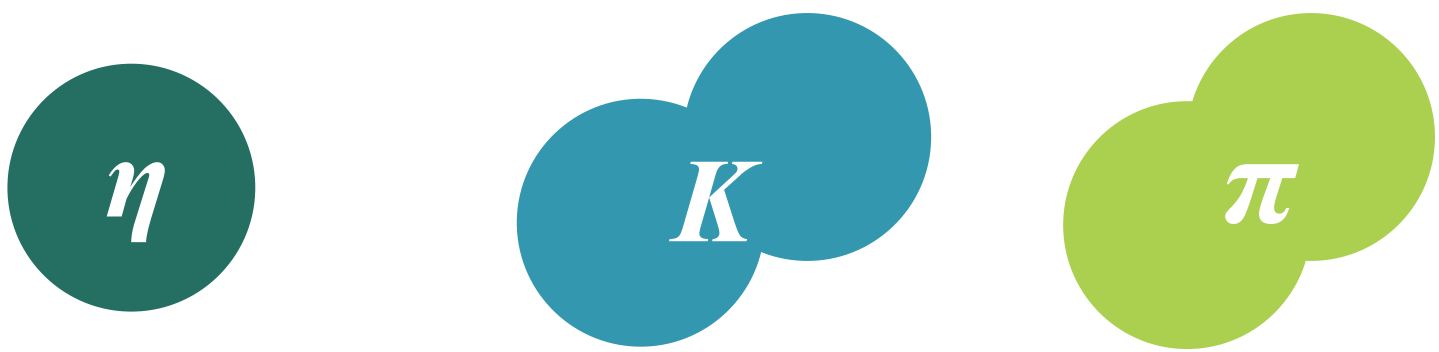
Scattering

The Model

Gauge group: $SO(N_c)$ $N_c \geq 4$

$$SU(3)/SO(3) \Rightarrow$$ 5 Goldstone bosons

Two π, two K and one η



$m_\eta = (1+\Delta_\eta)\, m_\pi >$ $m_K = (1+\Delta_K)\, m_\pi >$ m_π

Leading ChPT Lagrangian (Low Temp)

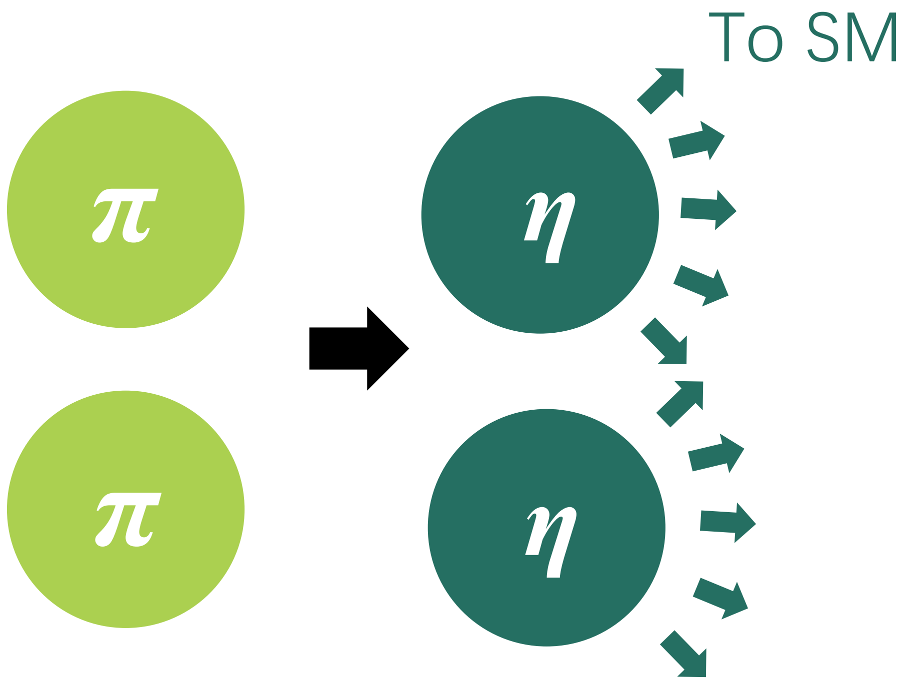
$$\mathcal{L}_2 \supset \frac{1}{24f^2}\Big\{m_{\hat\pi}^2\Big[\hat\eta_0^2 + 2\hat\pi_+\hat\pi_- + 2\hat K_{+1/2}\hat K_{-1/2}\Big]^2 + 2(m_{\hat K}^2 - m_{\hat\pi}^2)\Big[\frac{8}{9}\hat\eta_0^4 + 3\hat\eta_0^2\hat K_{+1/2}\hat K_{-1/2}$$
$$- \sqrt{\frac{2}{3}}(\hat\eta_0\hat K_{+1/2}^2\hat\pi_- + \hat\eta_0\hat K_{-1/2}^2\hat\pi_+) + 2\hat K_{+1/2}^2\hat K_{-1/2}^2 + 2\hat K_{+1/2}\hat K_{-1/2}\hat\pi_+\hat\pi_-\Big]\Big\}$$
$$+ \frac{1}{24f^2}\Big\{4(\partial\hat\pi_+)^2\hat\pi_-^2 + 4\hat\pi_+^2(\partial\hat\pi_-)^2 - 8\partial\hat\pi_+\hat\pi_+\partial\hat\pi_-\hat\pi_- + (\partial\hat K_{+1/2})^2\hat K_{-1/2}^2 + \hat K_{+1/2}^2(\partial\hat K_{-1/2})^2$$
$$- 2\partial\hat K_{+1/2}\hat K_{+1/2}\partial\hat K_{-1/2}\hat K_{-1/2} + 8\hat K_{+1/2}\partial\hat K_{-1/2}\hat\pi_+\partial\hat\pi_- + 8\partial\hat K_{+1/2}\hat K_{-1/2}\partial\hat\pi_+\hat\pi_-$$
$$- 4\hat K_{+1/2}\hat K_{-1/2}\partial\hat\pi_+\partial\hat\pi_- - 4\hat K_{+1/2}\partial\hat K_{-1/2}\partial\hat\pi_+\hat\pi_- - 4\partial\hat K_{+1/2}\hat K_{-1/2}\hat\pi_+\partial\hat\pi_-$$
$$- 4\partial\hat K_{+1/2}\partial\hat K_{-1/2}\hat\pi_+\hat\pi_- - 6\hat\eta_0^2\partial\hat K_{+1/2}\partial\hat K_{-1/2} - 6(\partial\hat\eta_0)^2\hat K_{+1/2}\hat K_{-1/2}$$
$$+ 6\hat\eta_0\partial\hat\eta_0\partial\hat K_{+1/2}\hat K_{-1/2} + 6\hat\eta_0\partial\hat\eta_0\hat K_{+1/2}\partial\hat K_{-1/2} + 2\sqrt{6}\Big[\partial\hat\eta_0\partial\hat K_{-1/2}\hat K_{-1/2}\hat\pi_+$$
$$+ \partial\hat\eta_0\partial\hat K_{+1/2}\hat K_{+1/2}\hat\pi_- - \partial\hat\eta_0\hat K_{+1/2}^2\partial\hat\pi_- - \partial\hat\eta_0\hat K_{-1/2}^2\partial\hat\pi_+ - \hat\eta_0(\partial\hat K_{-1/2})^2\hat\pi_+$$
$$- \hat\eta_0(\partial\hat K_{+1/2})^2\hat\pi_- + \hat\eta_0\partial\hat K_{-1/2}\hat K_{-1/2}\partial\hat\pi_+ + \hat\eta_0\partial\hat K_{+1/2}\hat K_{+1/2}\partial\hat\pi_-\Big]\Big\}.$$

Mass & 4-point interaction terms

Forbidden Composite DM

The lightest dark sector particle, the DM

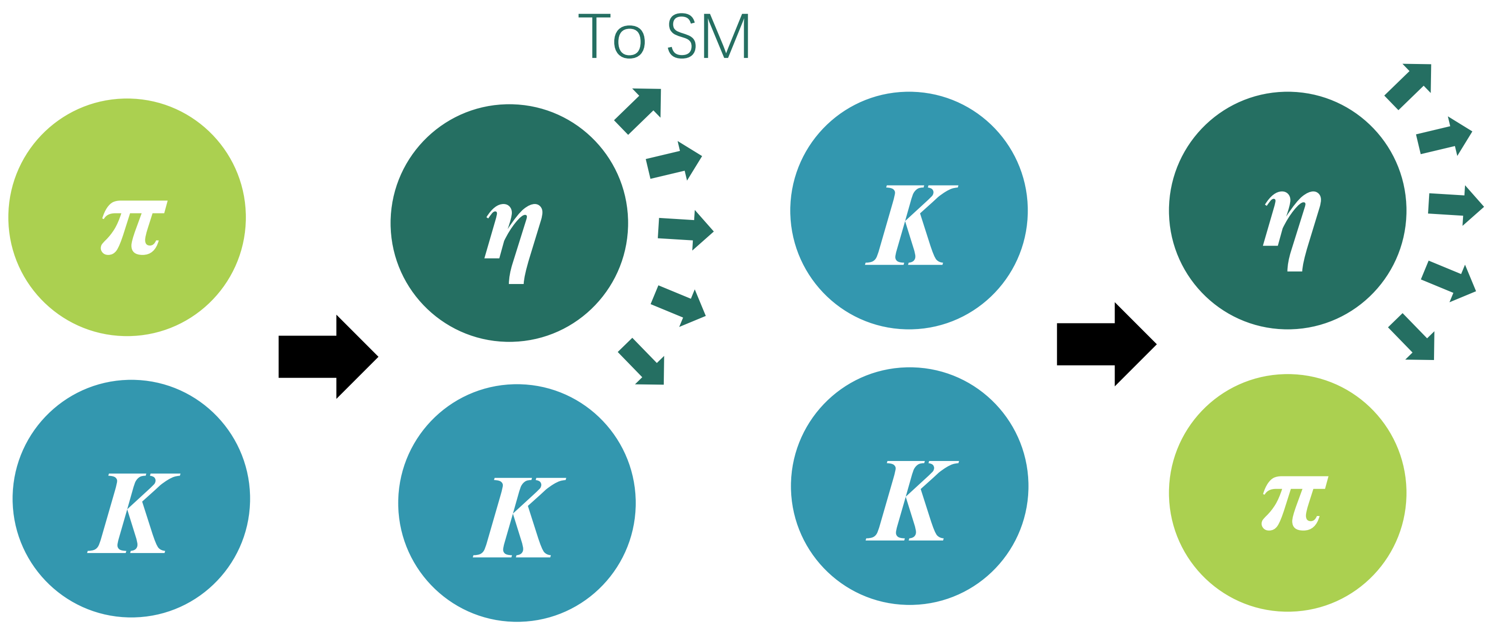
The "excited state", heavier and interacting with the SM



Only energetic particle can go through the mass gap, exponential sensitivity

R.T. D'Agnolo and J.T. Ruderman, 1505.07107; LFL, Y. Tsai, 1901.0993; E. Bernreuther, F. Kahlhoefer, M. Kramer and P. Tunney, 1907.04346……

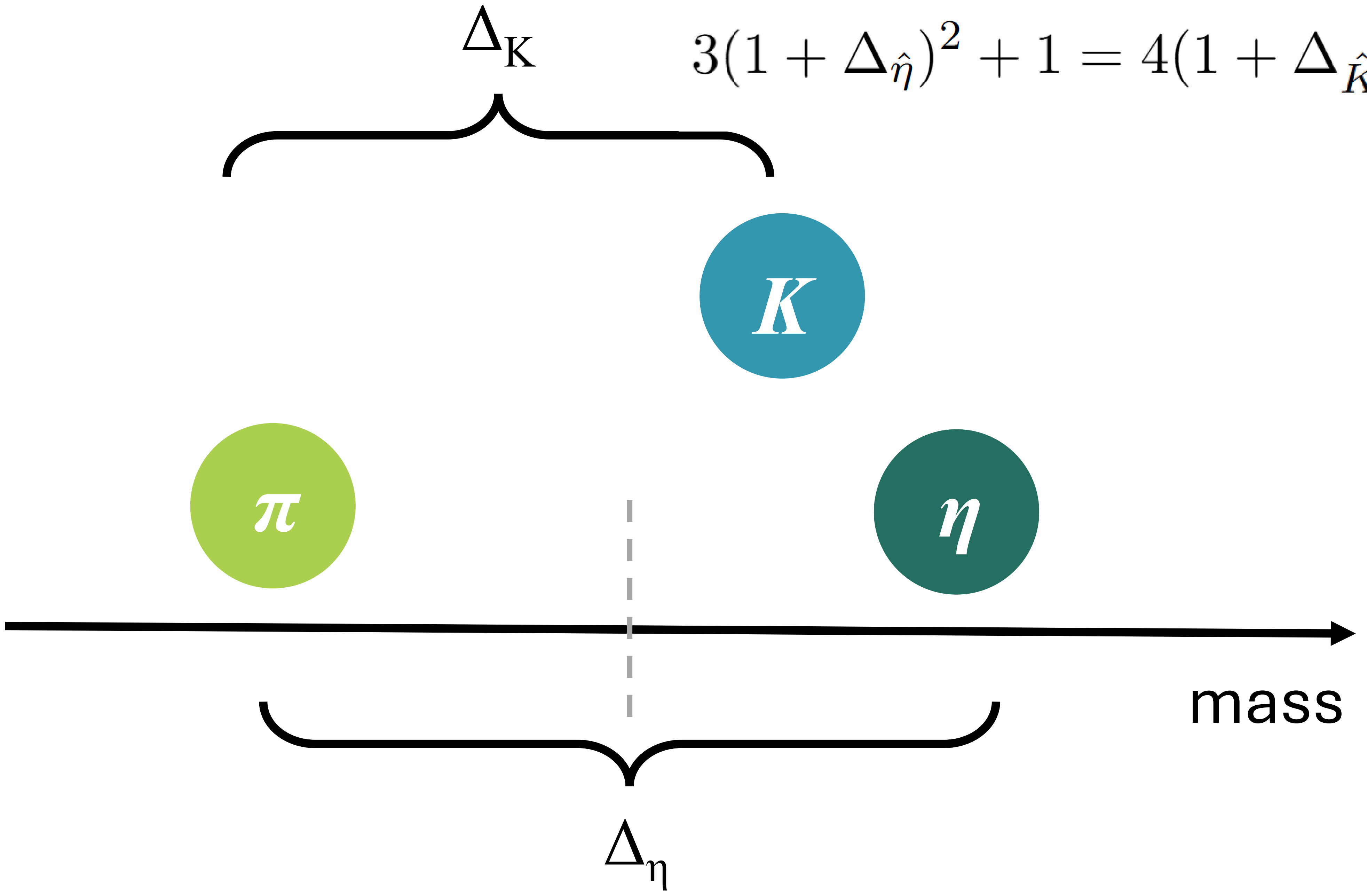
Important Alternative Processes



K assisted conversion, low Boltzmann suppression

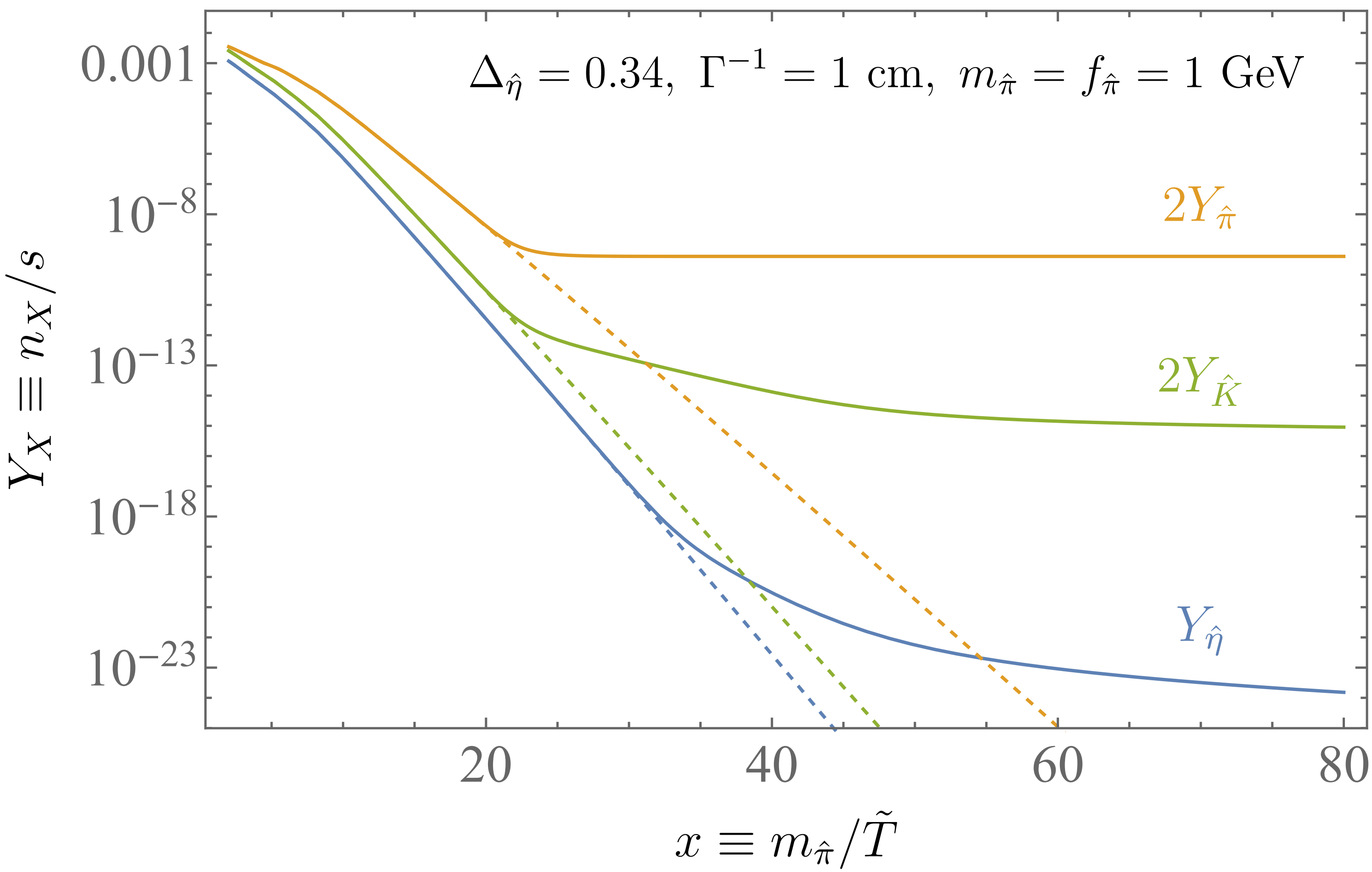
K annihilation, gives indirect detection signals

$$3(1+\Delta_{\hat{\eta}})^2 + 1 = 4(1+\Delta_{\hat{K}})^2$$

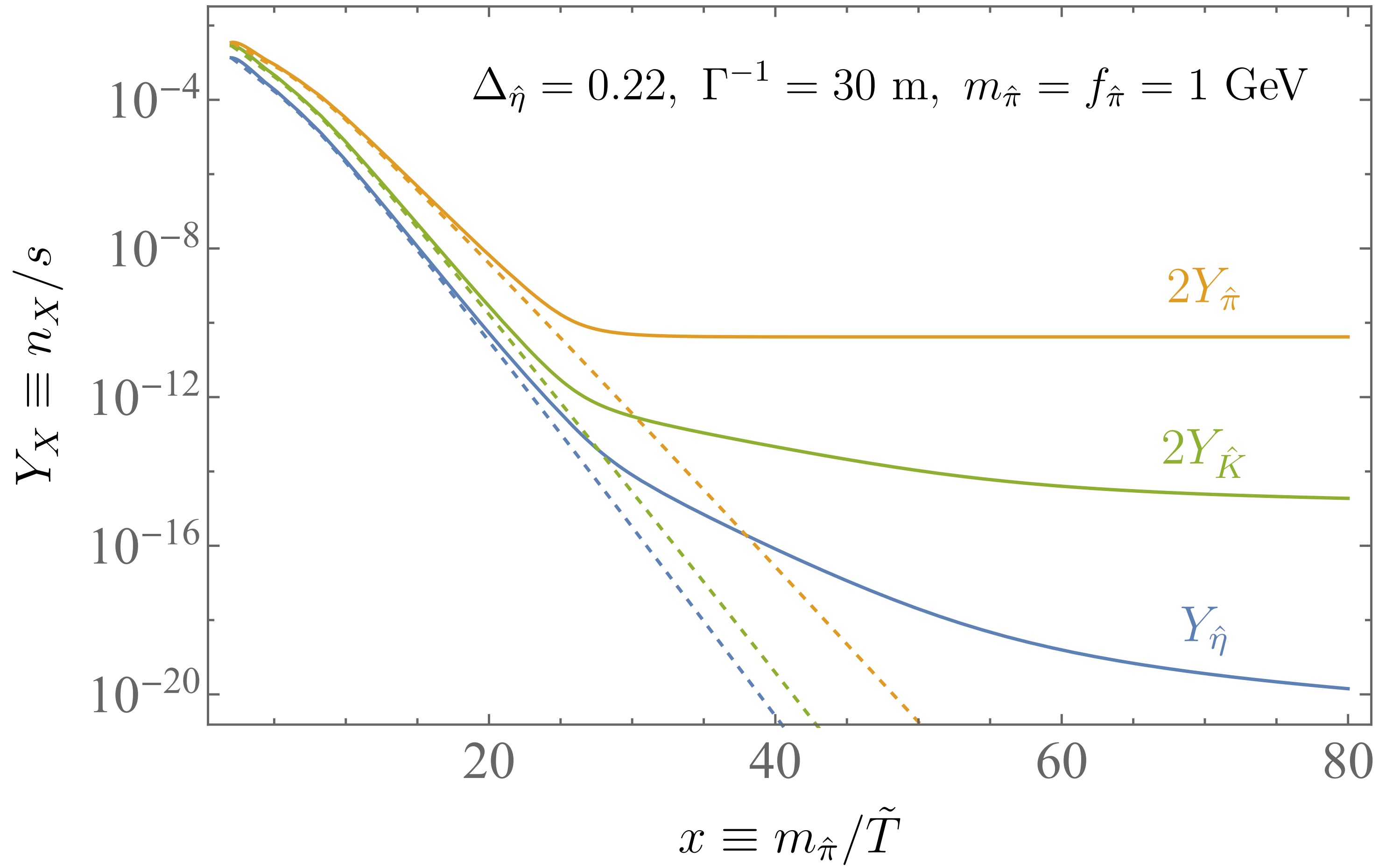


KK tp $\pi\eta$ always onshell and unsupressed

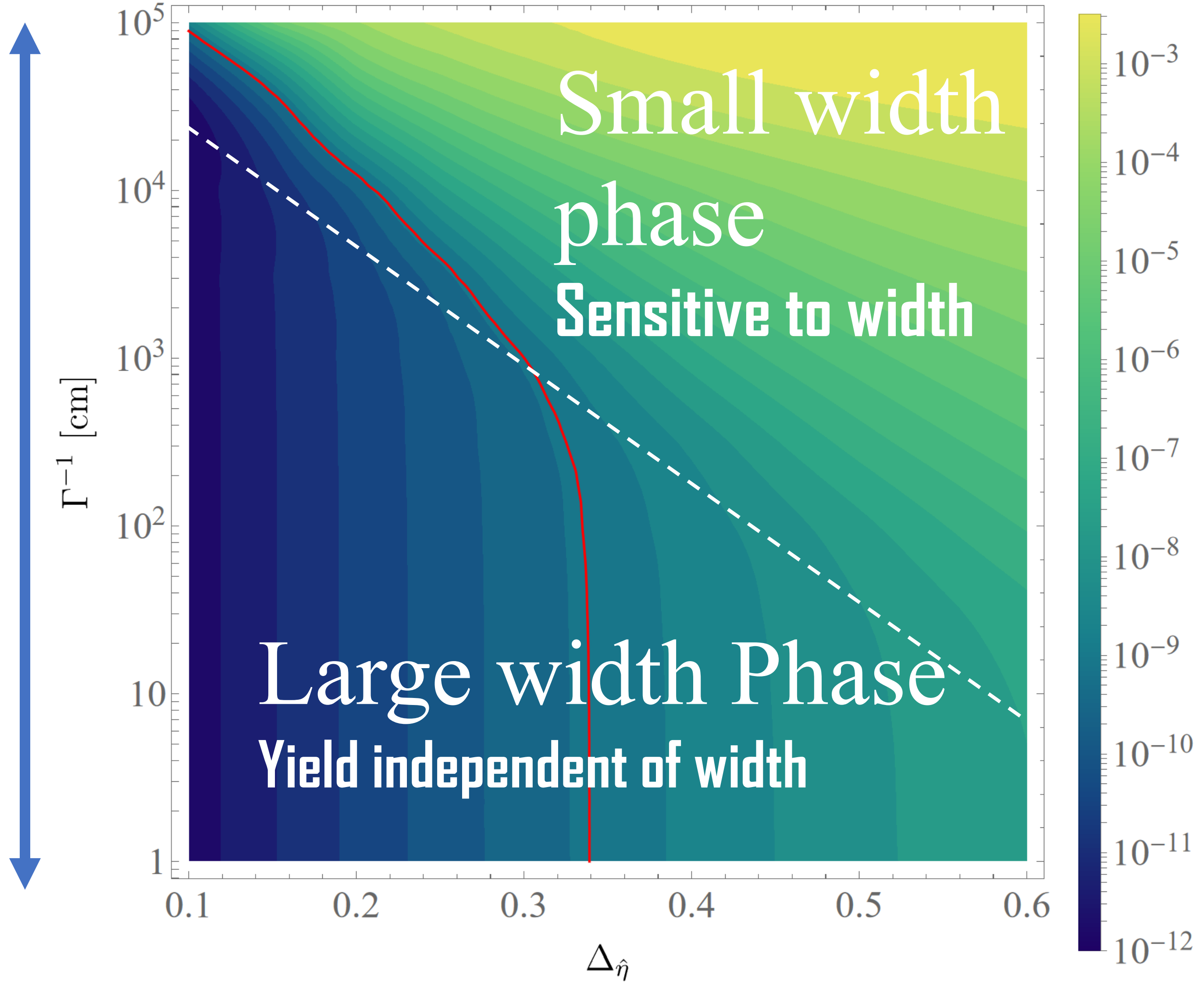
Large Decay Width Limit:
Freezeout Controlled by Conversion

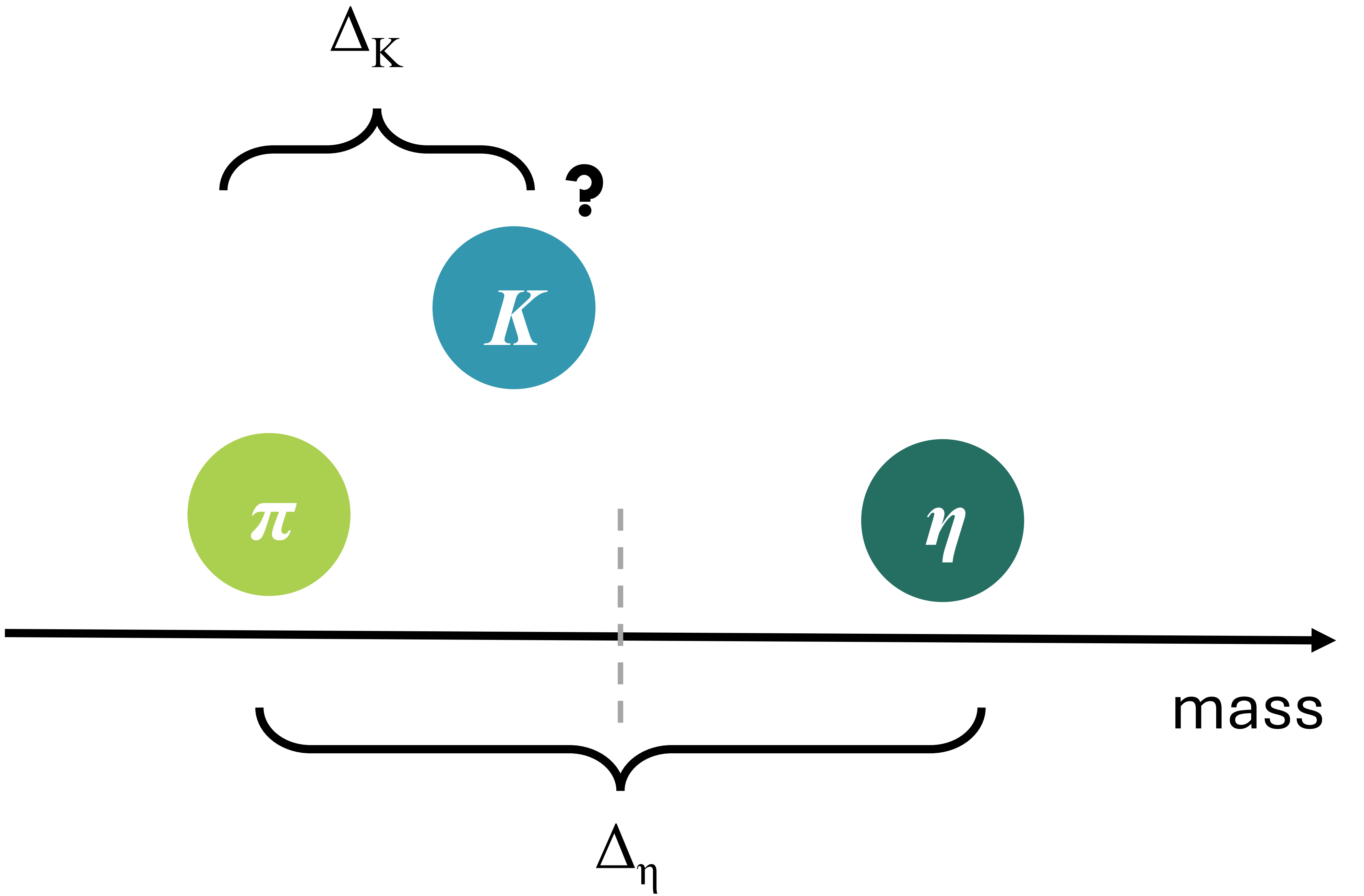


Small Decay Width Limit:
Freezeout Controlled by the Decay

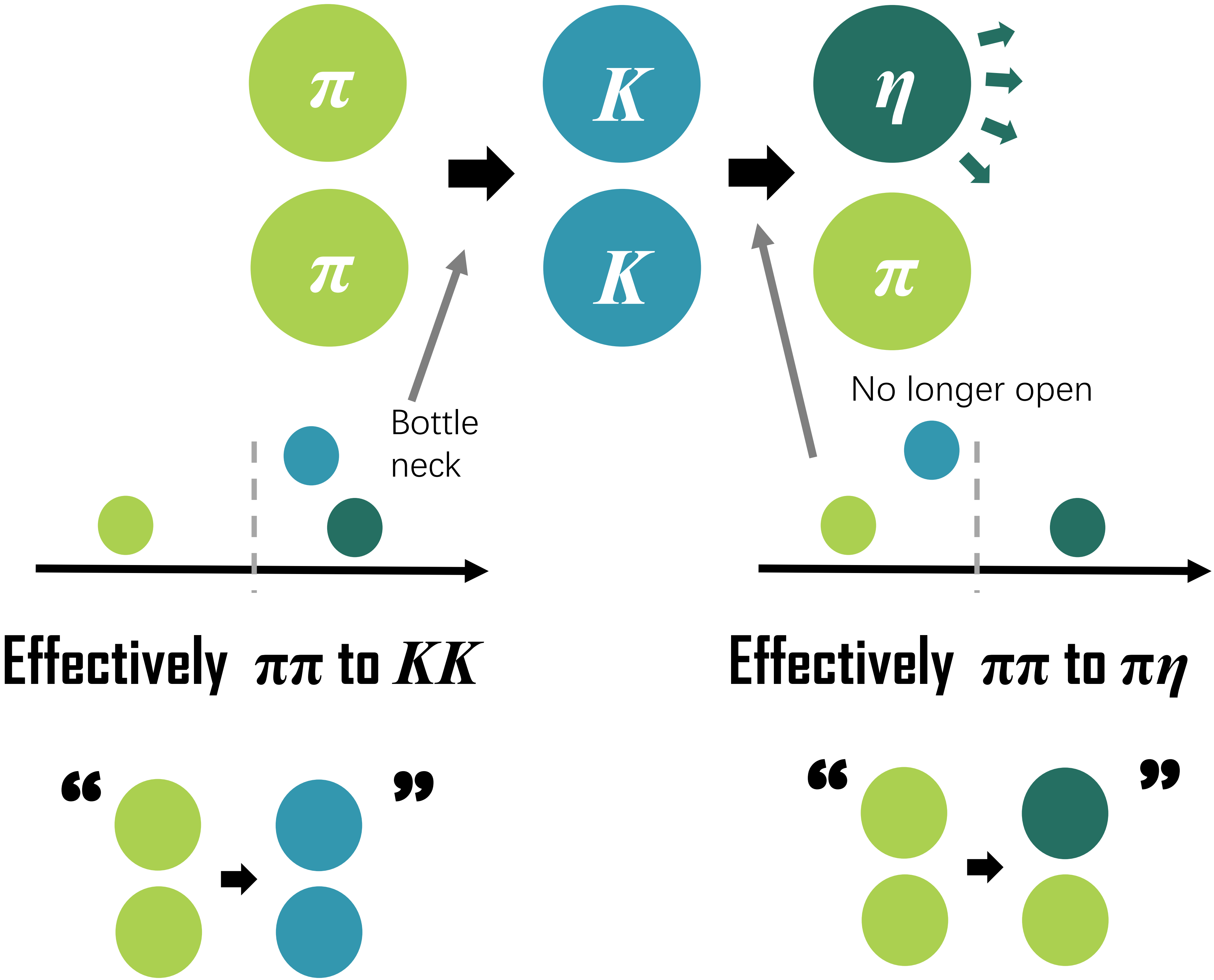


Decay at Human/Lab Length Scales





Δ_K
?
K
π
η
mass
Δ_η

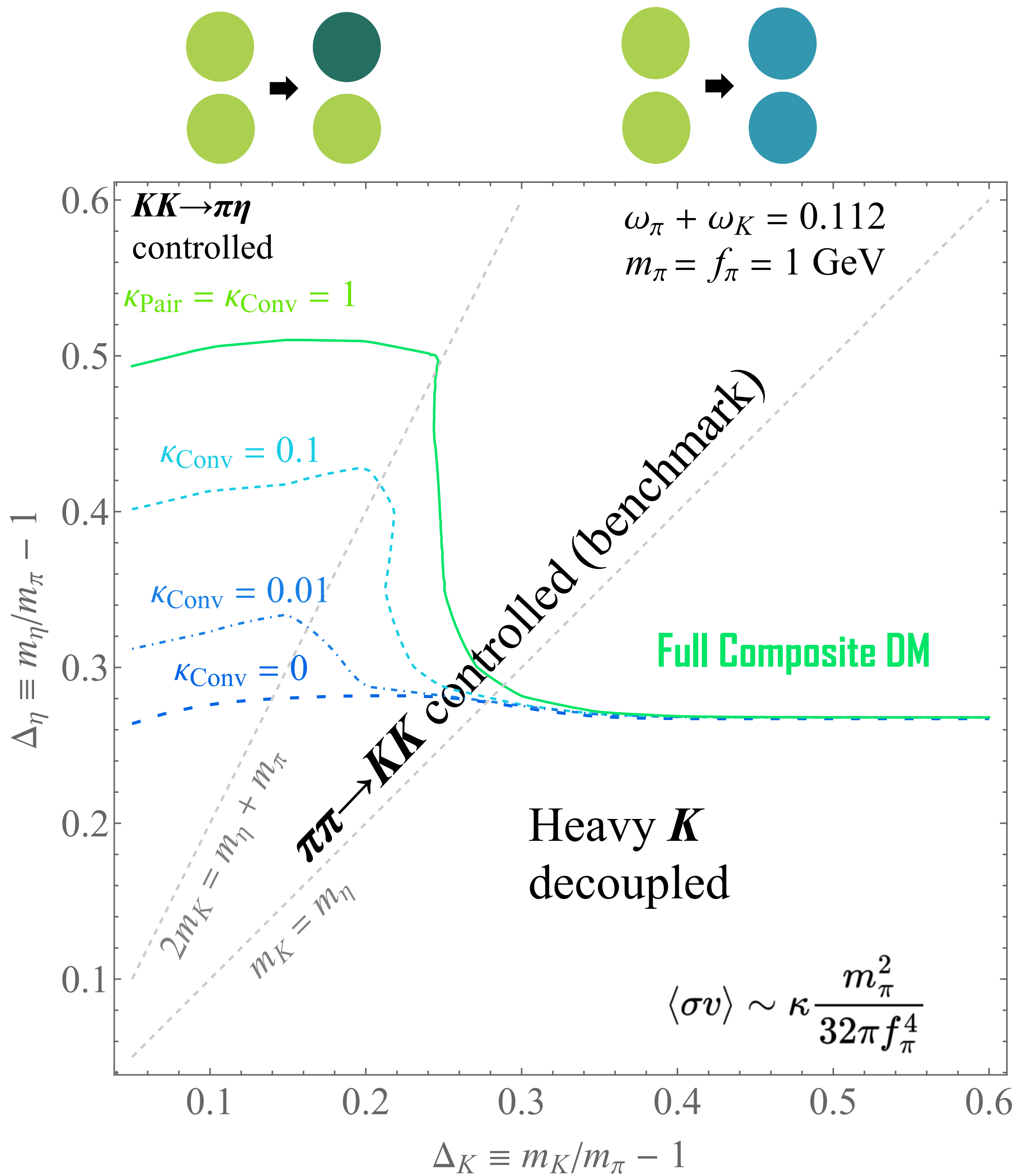


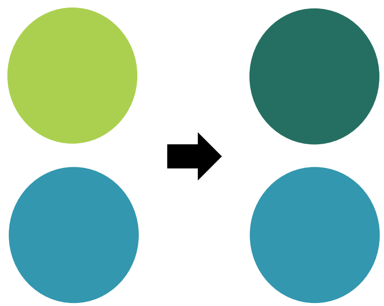
π
K
η
π
K
π
Bottle
neck
No longer open
Effectively ππ to KK
Effectively ππ to πη

Extended Phases

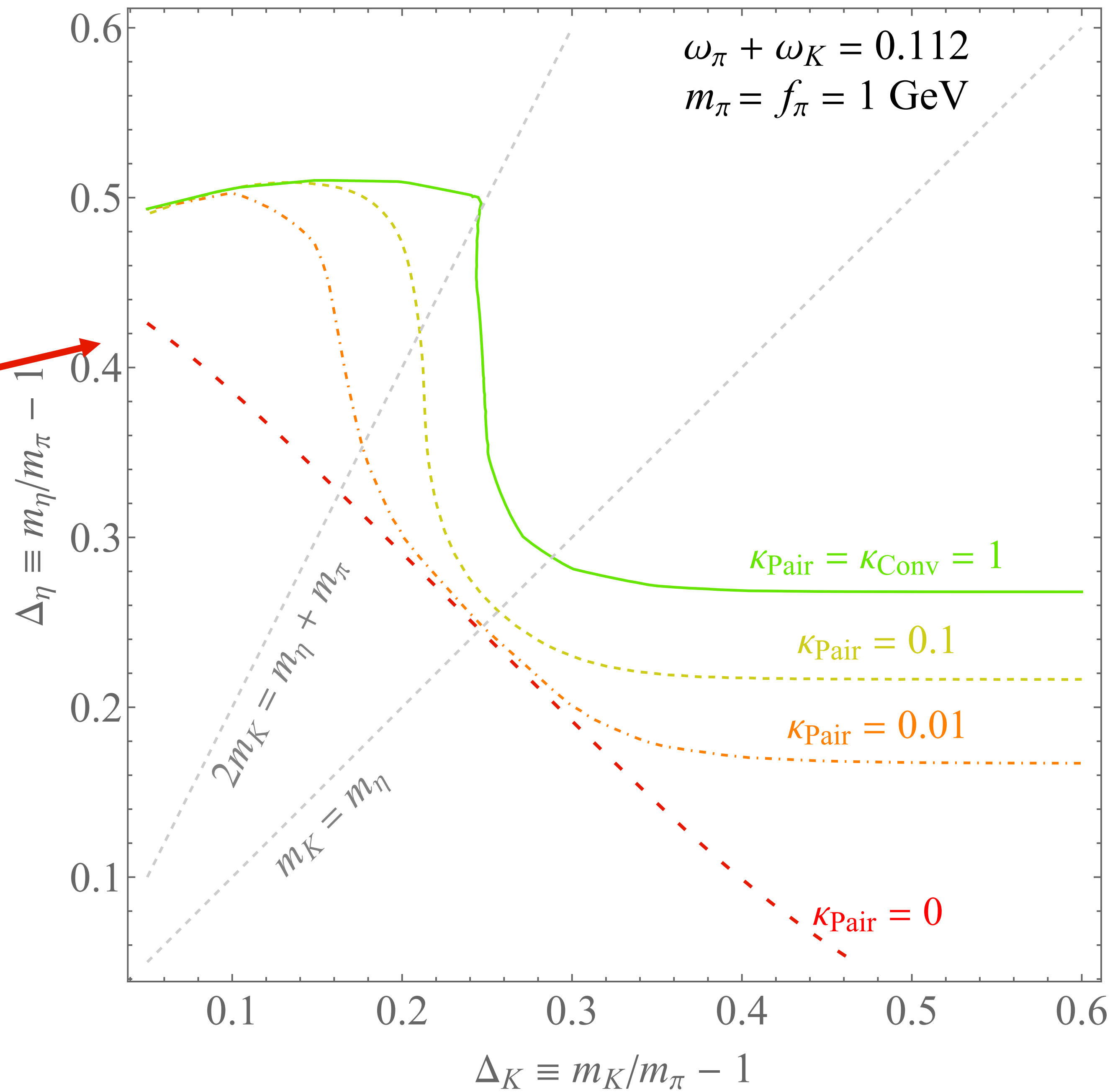
At least 3 extra dynamic phases recognized

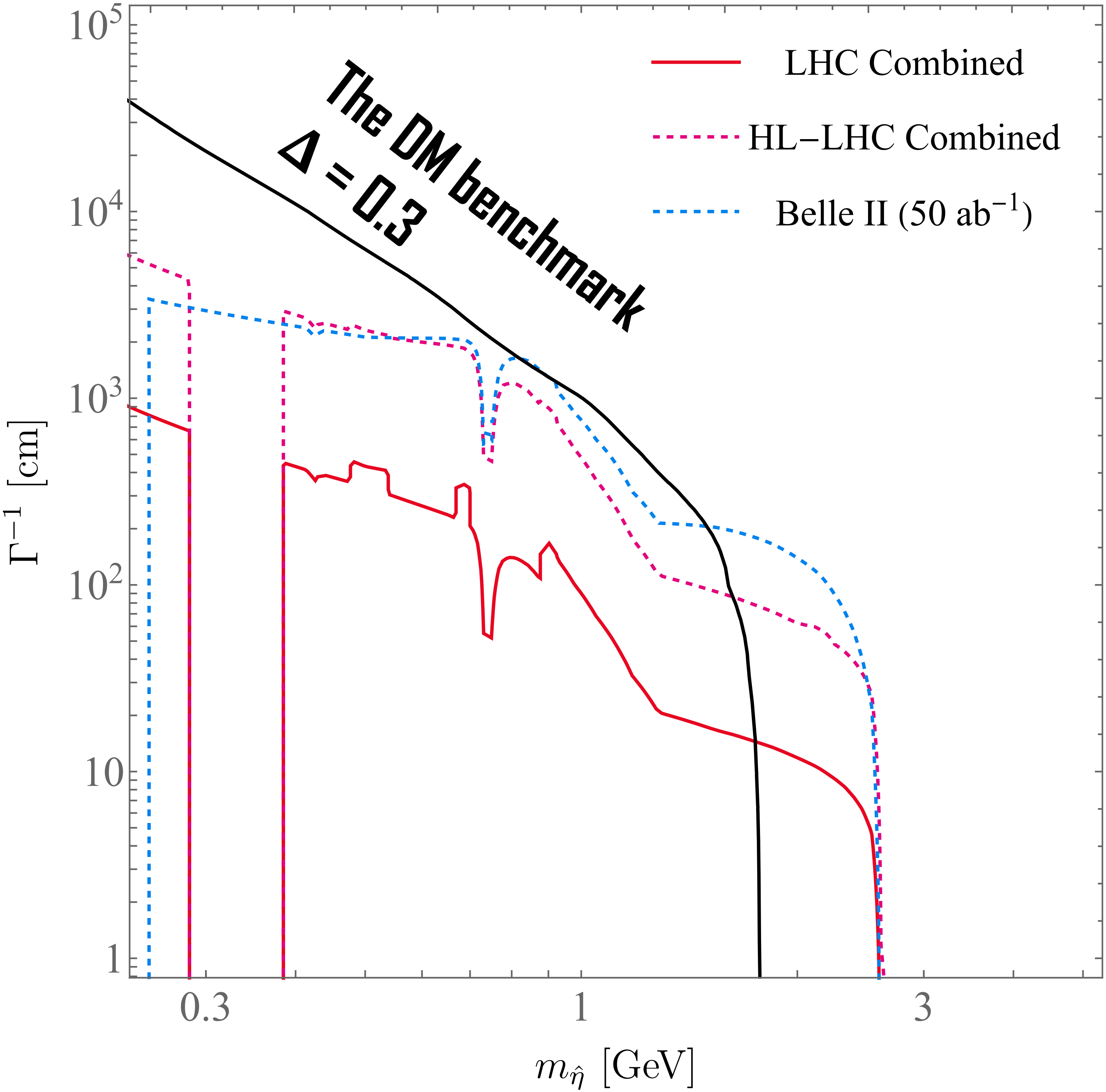
* Assuming all processes having similar cross sections, not necessarily true for realistic models



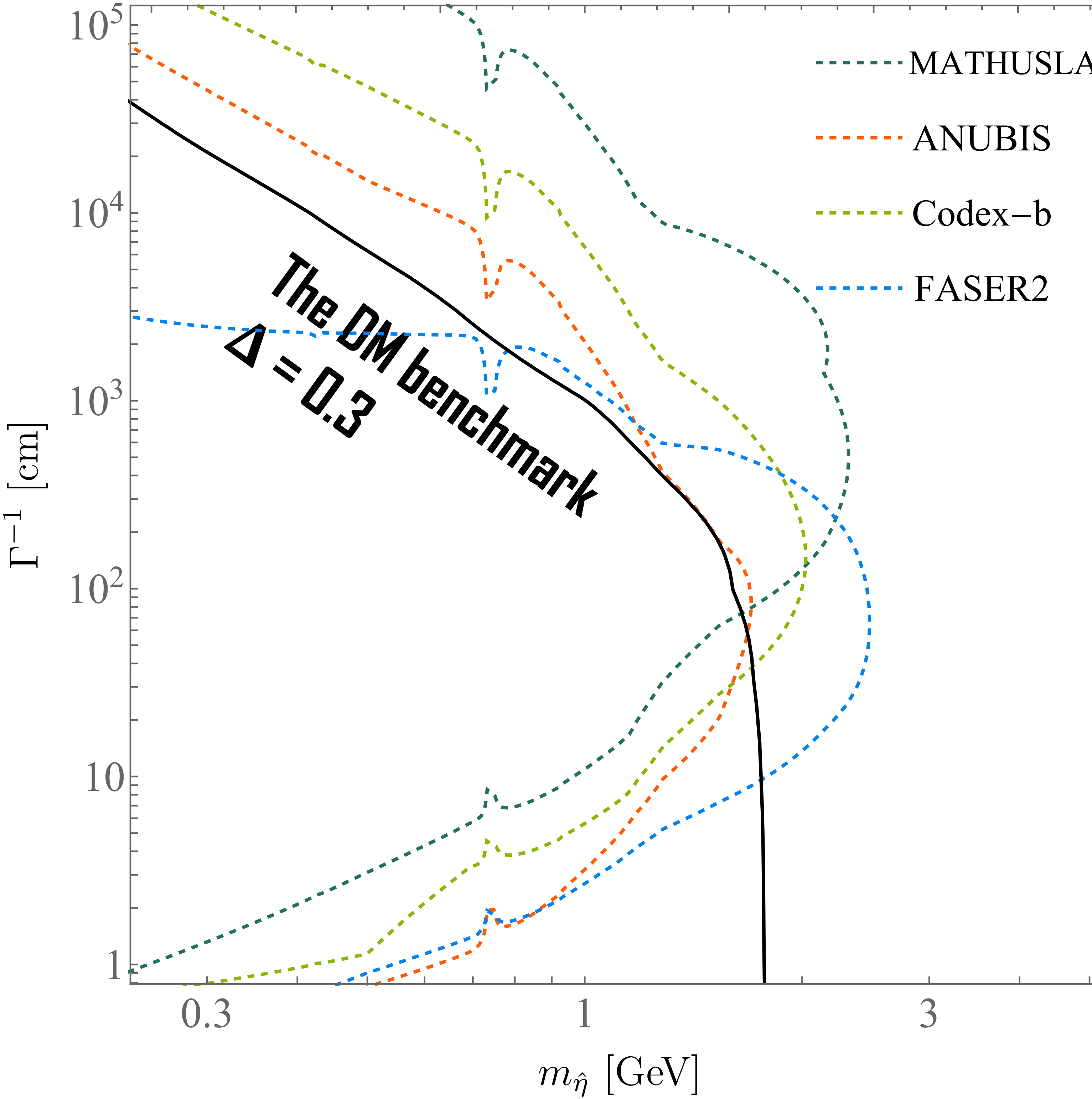


Full $\pi K \rightarrow \eta K$ dominance





LHC Combined
HL−LHC Combined
Belle II (50 ab^{-1})
The DM benchmark
$\Delta = 0.3$
Γ^{-1} [cm]
10^5
10^4
10^3
10^2
10
1
0.3
1
3
$m_{\hat{\eta}}$ [GeV]

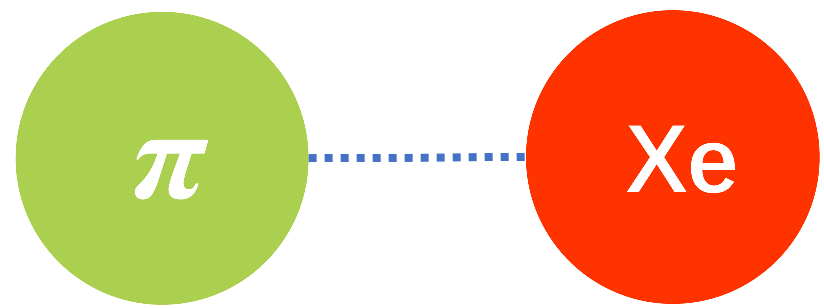


MATHUSLA
ANUBIS
Codex−b
FASER2
The DM benchmark
Δ = 0.3
Γ^{-1} [cm]
$m_{\hat{\eta}}$ [GeV]
10^5
10^4
10^3
10^2
10
1
0.3
1
3

Direct Detection Prospects

The leading Z exchange between DM and SM are forbidden by the same symmetry that stabilizes the DM, the remaining Higgs exchange:

$$\mathcal{L} \supset 4B\frac{y_1\tilde{y}_1}{M_{Q_1}}\pi_+\pi_-|H|^2\,,$$



Nucleon scattering Xsec:

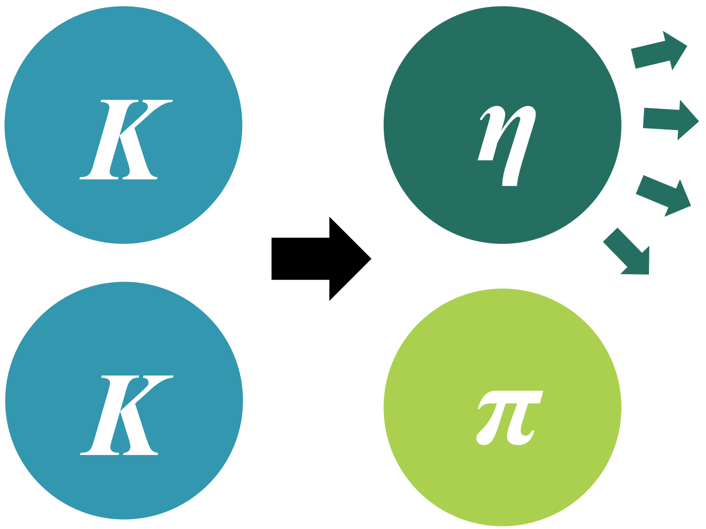
$$\simeq 2.5\times 10^{-45}\,\mathrm{cm}^2\, b^2\left(\frac{m_N}{m_\pi+m_N}\right)^2\left(\frac{f}{\mathrm{GeV}}\right)^2\left(\frac{y_1\tilde{y}_1}{10^{-2}}\right)^2\left(\frac{\mathrm{TeV}}{M_{Q_1}}\right)^2$$

When m > 8 GeV , could be above the neutrino fog

Indirect Detection Prospects

- As forbidden dark matter, usually free from indirect detection

- The remaining secondary Kaon DM can annihilate to SM, strongly depending on how many K remain



The most stringent CMB spectral distortion limit constraints the highly degenerate case (Δ < 1%)

Summary

- EW portal to the dark is a generic feature to be searched
- Dark confinement gives rise to LLP with good motivations
- At GeV scale, current and future limits are projected
- May lead to composite DM and non-trivial cosmology

Backup Slides

Lagrangian (Z' Mediation)

$$\mathcal{L}_{\text{mix}} = -\frac{\sin\chi}{2}\hat{Z}'_{\mu\nu}\hat{B}^{\mu\nu} + \delta\hat{M}^2\hat{Z}'^{\mu}\hat{Z}_{\mu} - \kappa\,\Phi^*\Phi H^\dagger H$$

$$\begin{pmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix} = L^{-1}\begin{pmatrix} \hat{A}_\mu \\ \hat{Z}_\mu \\ \hat{Z}'_\mu \end{pmatrix} \quad L = \begin{pmatrix} 1 & -\hat{c}_W \sin\xi \tan\chi & -\hat{c}_W \cos\xi \tan\chi \\ 0 & \cos\xi + \hat{s}_W \sin\xi \tan\chi & -\sin\xi + \hat{s}_W \cos\xi \tan\chi \\ 0 & \sin\xi / \cos\chi & \cos\xi / \cos\chi \end{pmatrix}$$

$$\tan 2\xi = \frac{-2\cos\chi(\delta\hat{M}^2 + \hat{M}_Z^2\hat{s}_W \sin\chi)}{\hat{M}_{Z'}^2 - \hat{M}_Z^2\cos^2\chi + \hat{M}_Z^2\hat{s}_W^2\sin^2\chi + 2\delta\hat{M}^2\hat{s}_W\sin\chi}$$

Lagrangian (Fermion Mediation)

$$-\mathcal{L}_{\mathrm{UV}} = \overline{Q}_L \boldsymbol{Y} \psi_R H + \overline{Q}_R \widetilde{\boldsymbol{Y}} \psi_L H + \overline{Q}_L \boldsymbol{M} Q_R + \overline{\psi}_L \boldsymbol{\omega} \psi_R + \mathrm{h.c.}$$

$$\begin{aligned}
\mathcal{L}_{\mathrm{EFT}} = &\frac{1}{2} \overline{\psi}_R \boldsymbol{Y}^\dagger \boldsymbol{M}^{-2} \boldsymbol{Y} \left[|H|^2 i \not{D} + i\gamma^\mu H^\dagger D_\mu H \right] \psi_R + \mathrm{h.c.} \\
&+ \frac{1}{2} \overline{\psi}_L \widetilde{\boldsymbol{Y}}^\dagger \boldsymbol{M}^{-2} \widetilde{\boldsymbol{Y}} \left[|H|^2 i \not{D} + i\gamma^\mu H^\dagger D_\mu H \right] \psi_L + \mathrm{h.c.} \\
&- \overline{\psi}_L \boldsymbol{\omega} \psi_R + \overline{\psi}_L \widetilde{\boldsymbol{Y}}^\dagger \boldsymbol{M}^{-1} \boldsymbol{Y} \psi_R |H|^2 + \mathrm{h.c.}\ ,
\end{aligned}$$

Z Pole EWPT (Z' Mediation)

$$\mathcal{L}_{Zf\bar{f}} = -\frac{\bar{Z}e}{s_W c_W}\bar{f}\gamma^\mu(T^3_{Lf} - s_*^2 Q_f)fZ_\mu$$

$$\bar{Z} = 1 + \frac{\alpha T}{2}, \qquad s_*^2 = s_W^2 + \frac{\alpha}{c_W^2 - s_W^2}\left(\frac{S}{4} - s_W^2 c_W^2 T\right)$$

$$S = \frac{4s_W^2}{\alpha}\left(\frac{c_W^2}{s_W}\xi t_\chi - c_W^2\xi^2\right)$$

$$T = \frac{1}{\alpha}\left(2s_W\xi t_\chi + \xi^2\left(\frac{M_{Z'}^2}{M_Z^2} - 2\right)\right)$$

$$U = \frac{4s_W^2}{\alpha}c_W^2\xi^2$$

Flashback I: Accidental SUSY with Neutral Naturalness

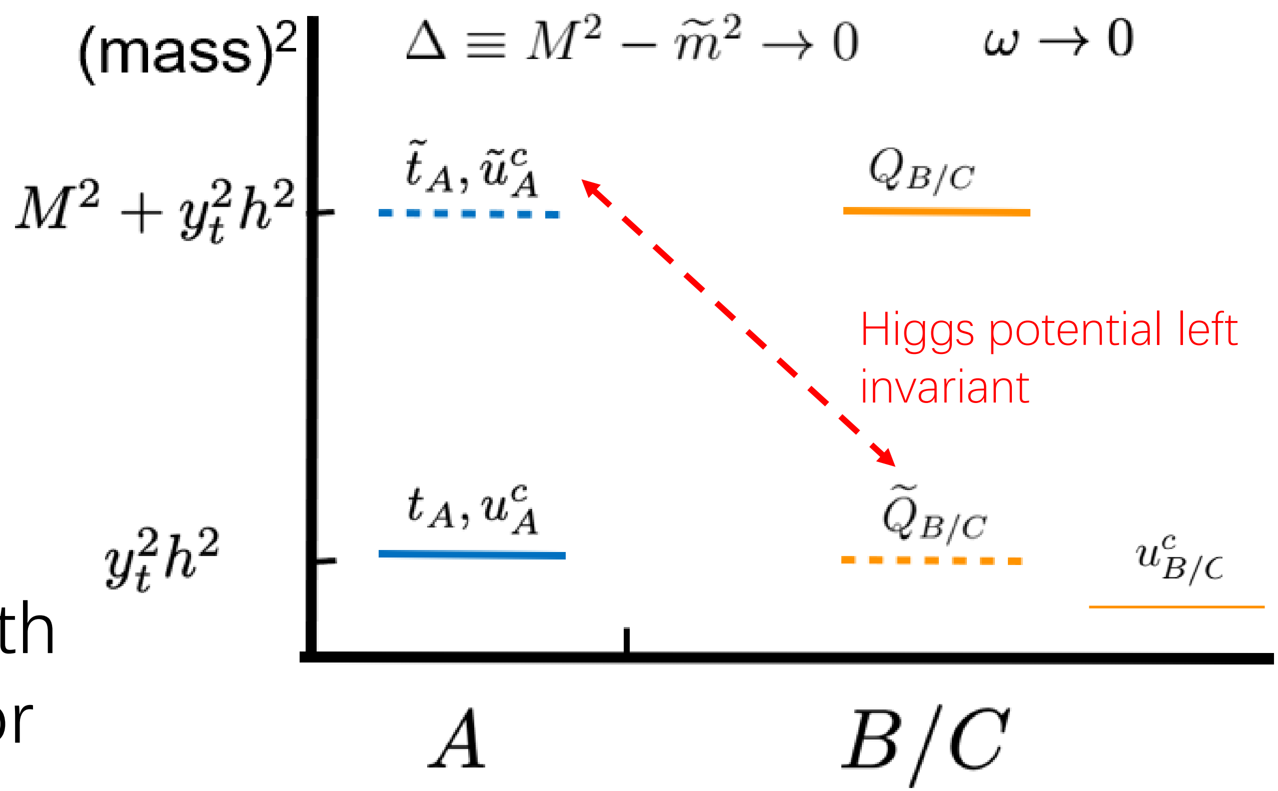
$$W'_{Z_3} = y_t(Q_A H u_A^c + Q_B H u_B^c + Q_C H u_C^c) + \omega(u'_B u_B^c + u'_C u_C^c) + M(Q_B Q_B'^c + Q_C Q_C'^c)$$

$$V'_s = \widetilde{m}^2(|\widetilde{Q}_A|^2 + |\widetilde{u}_A^c|^2) - \widetilde{m}^2(|\widetilde{Q}_B|^2 + |\widetilde{Q}_C|^2)$$

$Q_A \;\; u_A^c$ SM top sector

$$Q_{B,C} = \begin{pmatrix} t_{B,C} \\ b_{B,C} \end{pmatrix} \sim \mathbf{2}_{-1/2}$$

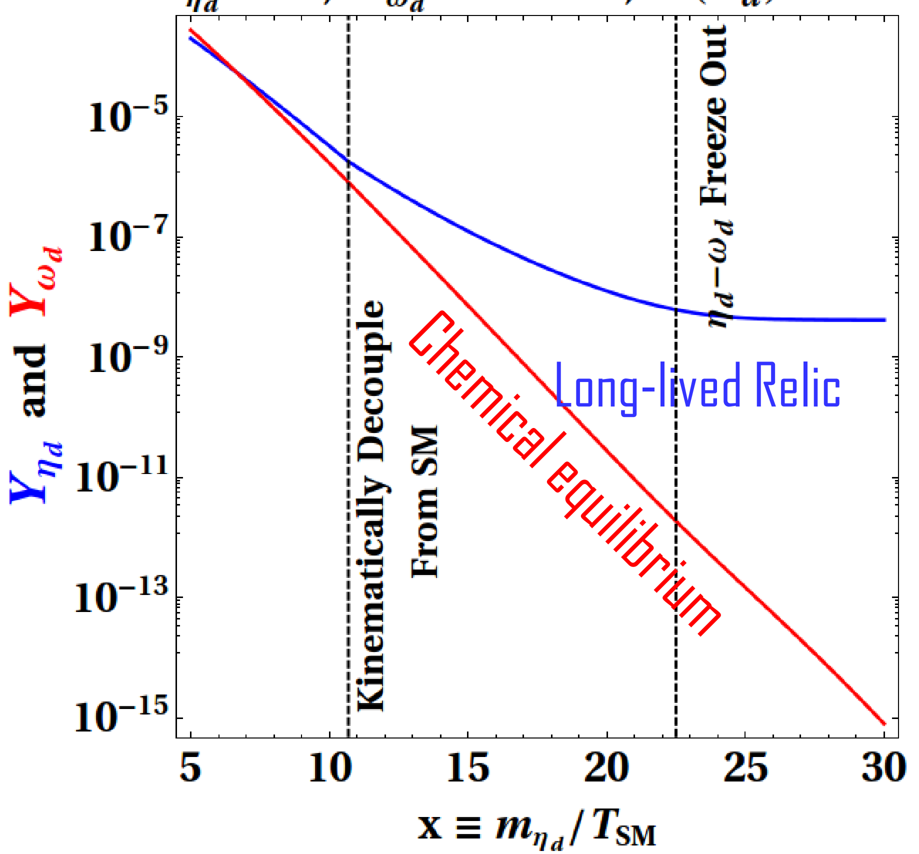
$$u_{B/C}^c \sim \mathbf{1}_0$$



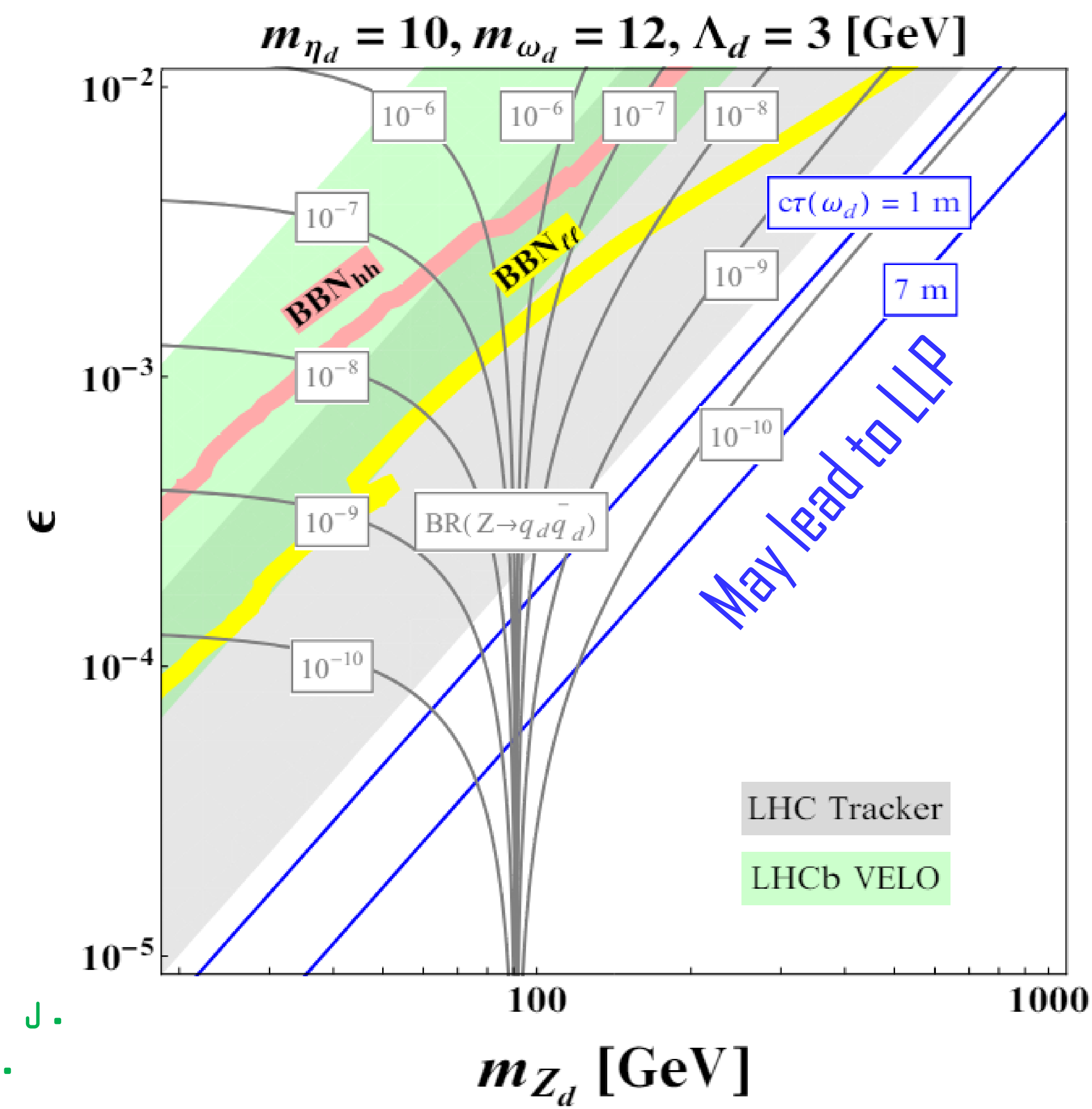
- ➢ Only compatible with the LHC if dark color exists

H-C. Cheng, LL, E. Salvioni and C. Verhaaren, 1905.02198

Flashback II: Composite DM



LL, Y. Tsai, 1901.09936

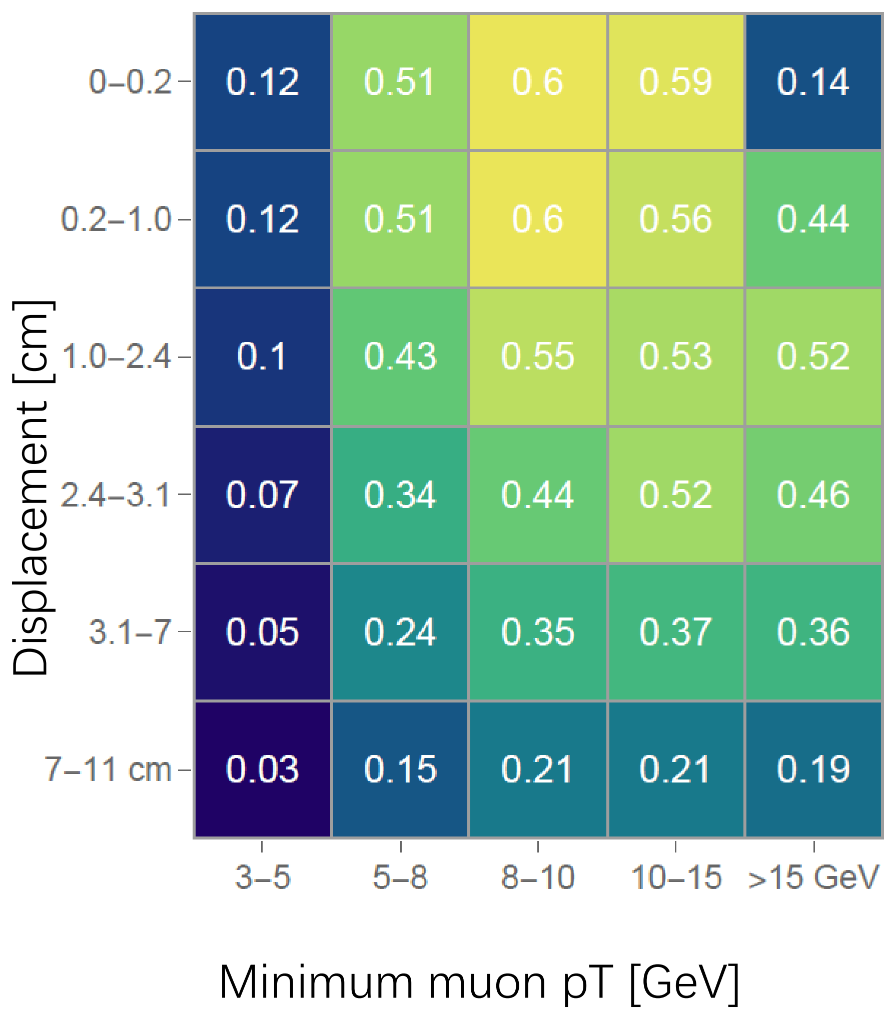


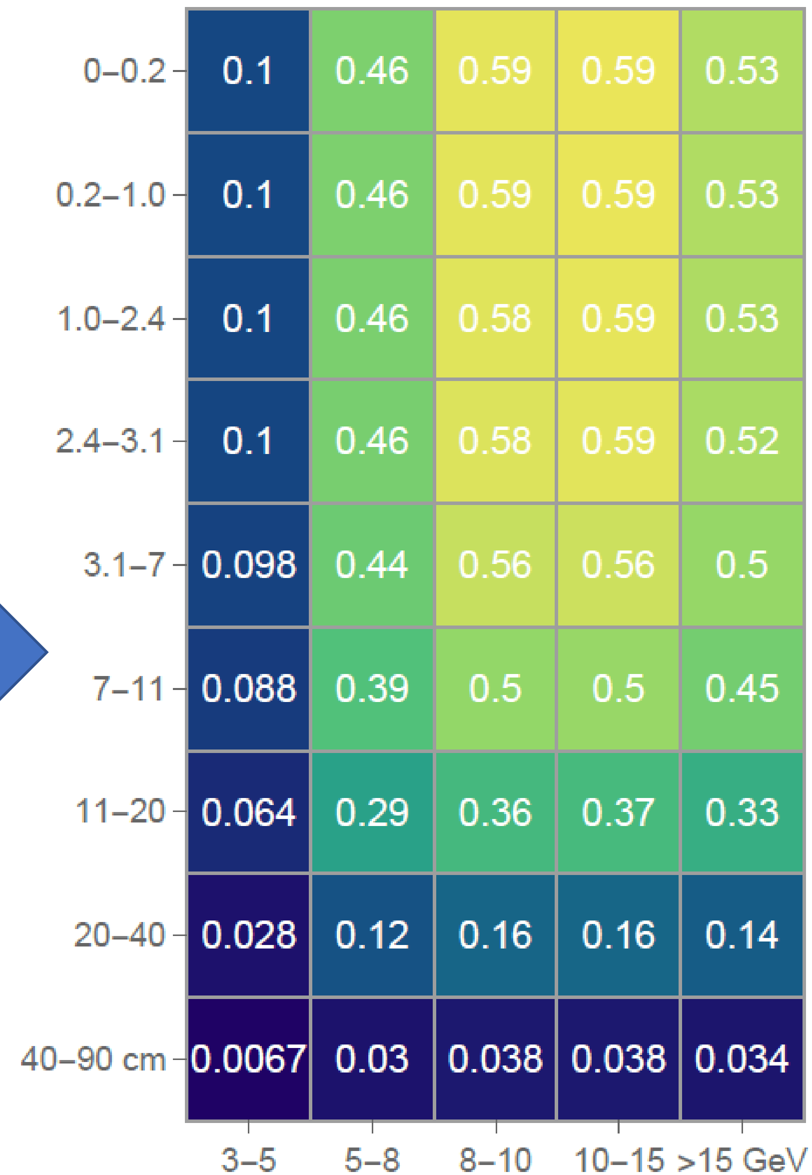
E. Bernreuther, F. Kahlhoefer, M. Kramer and P. Tunney, 1907.04346; S. Koren and R. McGehee, 1908.03559; Y. Hochberg, E. Kuflik, T. Volansky and J. G. Wacker, 1402.5143; Y. Hochberg, E. Kuflik and H. Murayama, 1512.07917

......

Displaced Vertex Efficiency for (HL-)LHC

Current CMS:

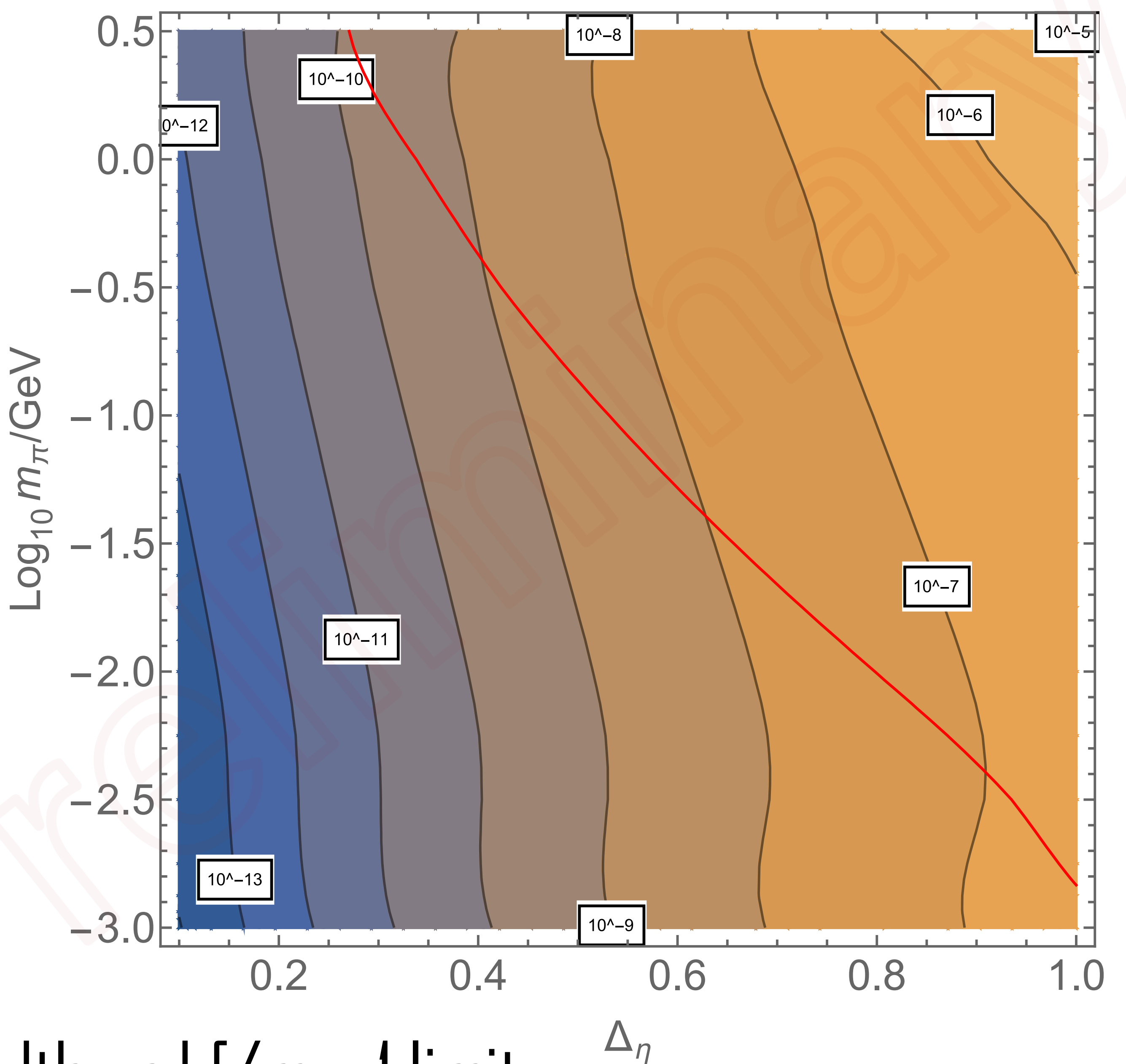




Extended Higgs Sector

$$H \sim \mathbf{2}_{1/2,\,0}\,,\; H' \sim \mathbf{2}_{1/2,\,x_\Phi}\,,\; \Phi \sim \mathbf{1}_{0,\,x_\Phi}$$

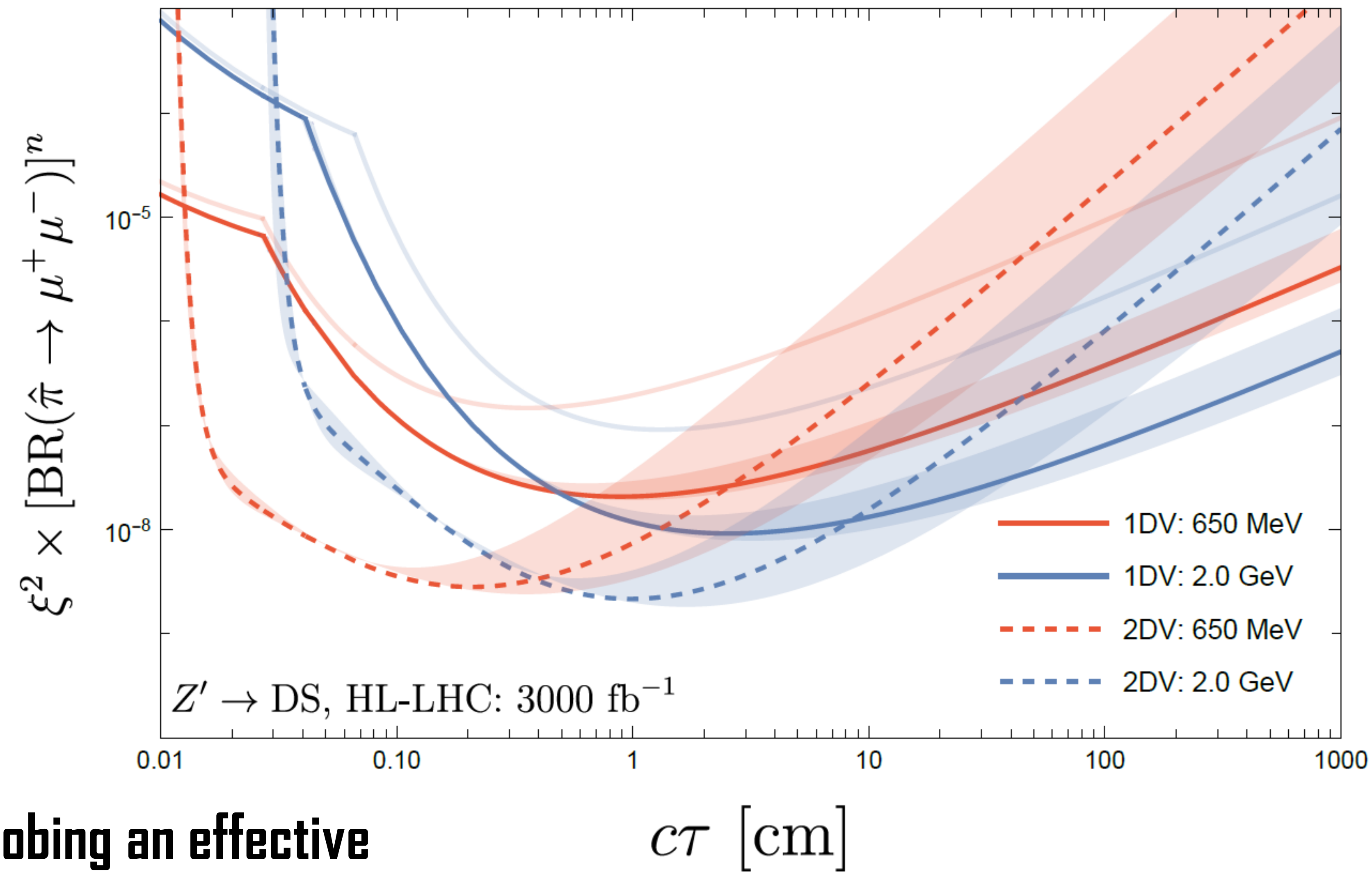
$$V = -\frac{m_H^2}{2}h^2 + \frac{\lambda_H}{4}h^4 + \frac{m_{H'}^2}{2}h'^2 + \frac{\lambda_{H'}}{4}h'^4 - m_\Phi^2\varphi^2 + \lambda_\Phi\varphi^4 - \mu h h'\varphi$$



In large width and f/m = 1 limit

CMS: Results on a Light Z'

Efficiency drop due to soft muons (can't reach the muon chamber of pT<3 GeV)



Still probing an effective mixing of 10^{-3} -10^{-4}

Dark Pion Decays (ALP-Like)

Applies to arbitrary flavor couplings

See also:

D. Aloni, Y. Soreq and M. Williams, 1811.03474

A.1 $a \to \gamma\gamma$

A.2 $a \to \pi^+\pi^-\gamma$

A.3 $a \to \pi^+\pi^-\pi^0$

A.4 $a \to 3\pi^0$

A.5 $a \to \pi^0\pi^0\eta, \pi^+\pi^-$

A.6 $a \to \pi^0\pi^0\eta', \pi^+\pi$

A.7 $a \to \eta\eta\pi^0$

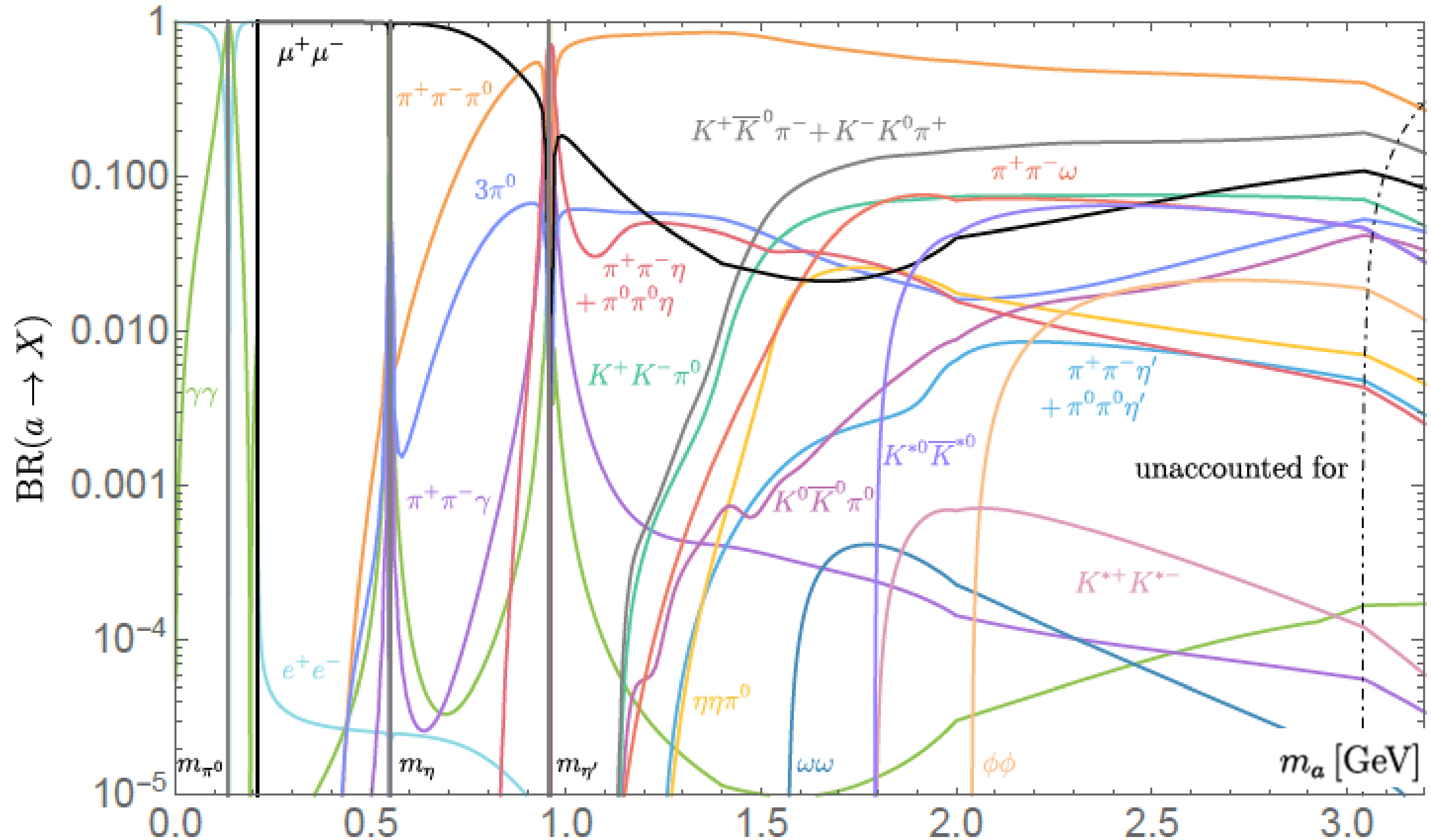
A.8 $a \to K^0\overline{K}^0\pi^0$

A.9 $a \to K^+K^-\pi^0$

A.10 $a \to K^+\overline{K}^0\pi^-, K^-K^0\pi^+$

A.11 $a \to \omega\omega, \phi\phi, K^{*+}K^{*-}, K^{*0}\overline{K}^{*0}$

A.12 $a \to \pi^+\pi^-\omega$



$$\Gamma^{-1}_{(\hat{\pi}\to\mu^+\mu^-)} \simeq 45\ \text{cm} \left(\frac{f_a}{1\ \text{PeV}}\right)^2 \left(\frac{1\ \text{GeV}}{m_{\hat{\pi}}}\right) \sqrt{\frac{m_{\hat{\pi}}^2}{m_{\hat{\pi}}^2 - 4m_\mu^2}}$$