

LONG-LIVED DARK SECTOR AT LEPTON COLLIDERS

And its relation with composite dark matter

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Nov. 8, 2025

CEPC International Sorkshop

Guangzhou, SCNU

25xx.abcd H-C. Cheng, X. Jiang, LFL, E. Salvioni

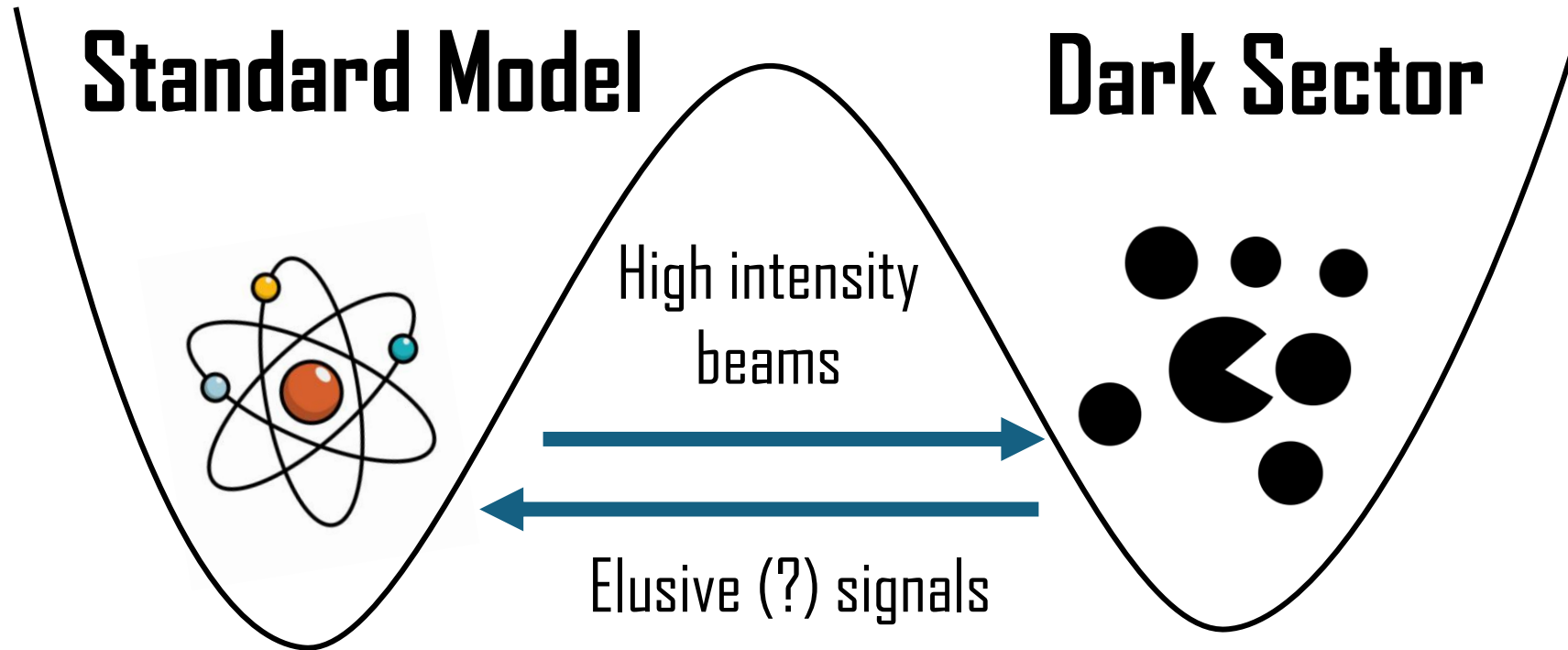
2408.13304 H-C. Cheng, X. Jiang, LFL

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

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



LLP and Portal Interactions

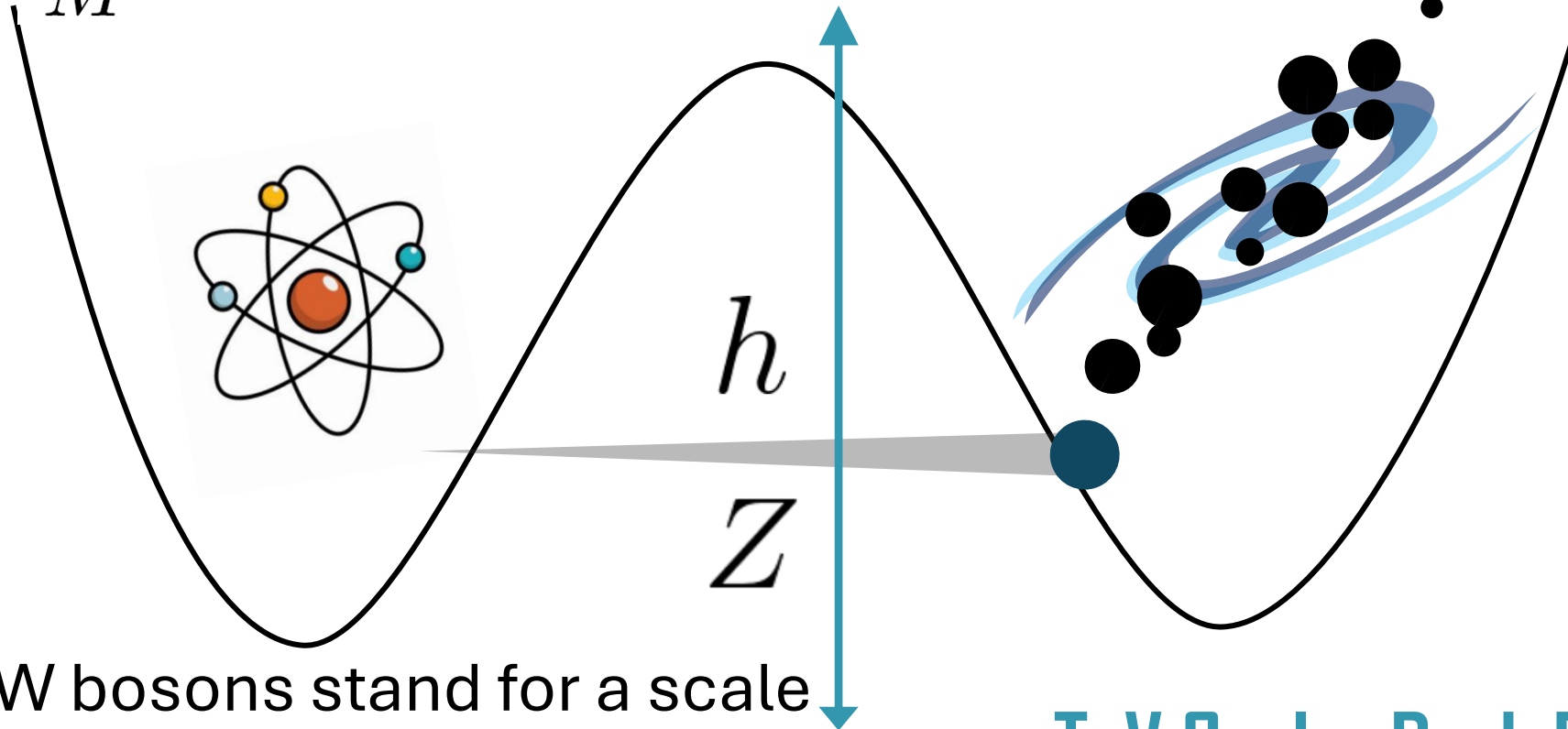


$\epsilon \mathcal{O}_{\text{SM}} J_{\text{Dark}}$ **Relevant portal:** small couplings to keep the valley hidden

$\frac{1}{\Lambda^n} \mathcal{O}_{\text{SM}} J_{\text{Dark}}$ **Irrelevant portal:** Hidden behind EFT

The Electroweak Portal

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

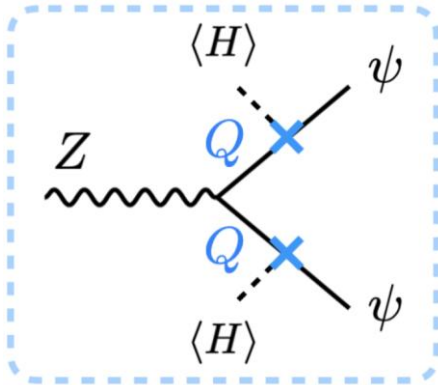


EW bosons stand for a scale of 246 GeV, close enough to TeV+

>TeV Scale $\approx$ Dark Enough

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

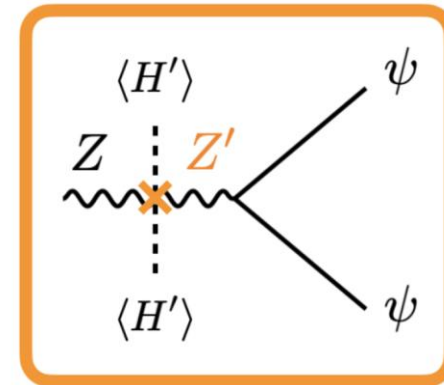
$$\mathcal{L}_{\text{UV}} \supset \bar{Q} Y \psi H \quad \longrightarrow \quad \frac{c}{M^2} \sim \frac{Y^2}{M_Q^2}$$



Heavy fermion doublet
mediation

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

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



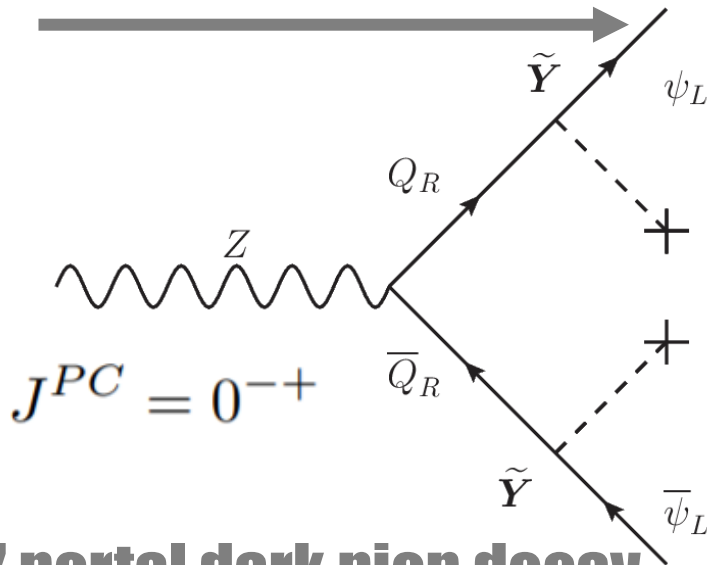
Dark Z' mediation: a Z' heavier or
lighter(!) than Z with mass mixing

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

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

LLP Candidate: Dark Pions

Z portal dark pion production



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**:

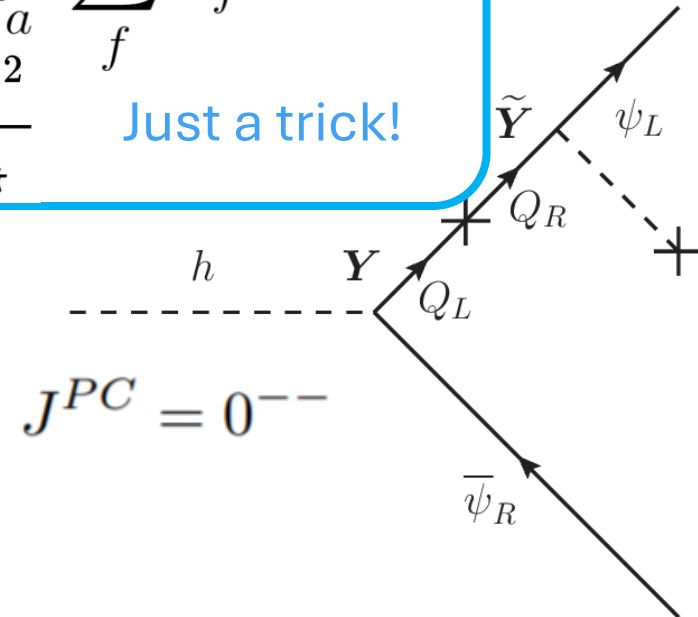
$$\mathcal{L}_a \supset -\frac{\partial_\mu a}{f_a} \sum_f T_f^3 \bar{f} \gamma^\mu \gamma^5 f$$

$$f_a \propto \frac{M^2}{f_{\hat{\pi}}} \quad \text{Just a trick!}$$

Z portal dark pion decay

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

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



The Cheat Sheet for Phenomenology

- Exotic Z branching ratio

$$\text{BR}(Z \rightarrow \psi' \bar{\psi}') \approx 1.8 \times 10^{-4} \left(\frac{N_d \text{Tr}(\mathbf{Y} \mathbf{Y}^\dagger \mathbf{Y} \mathbf{Y}^\dagger)}{3} \right) \left(\frac{1 \text{ TeV}}{M} \right)^4$$

- Easily get long lived

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

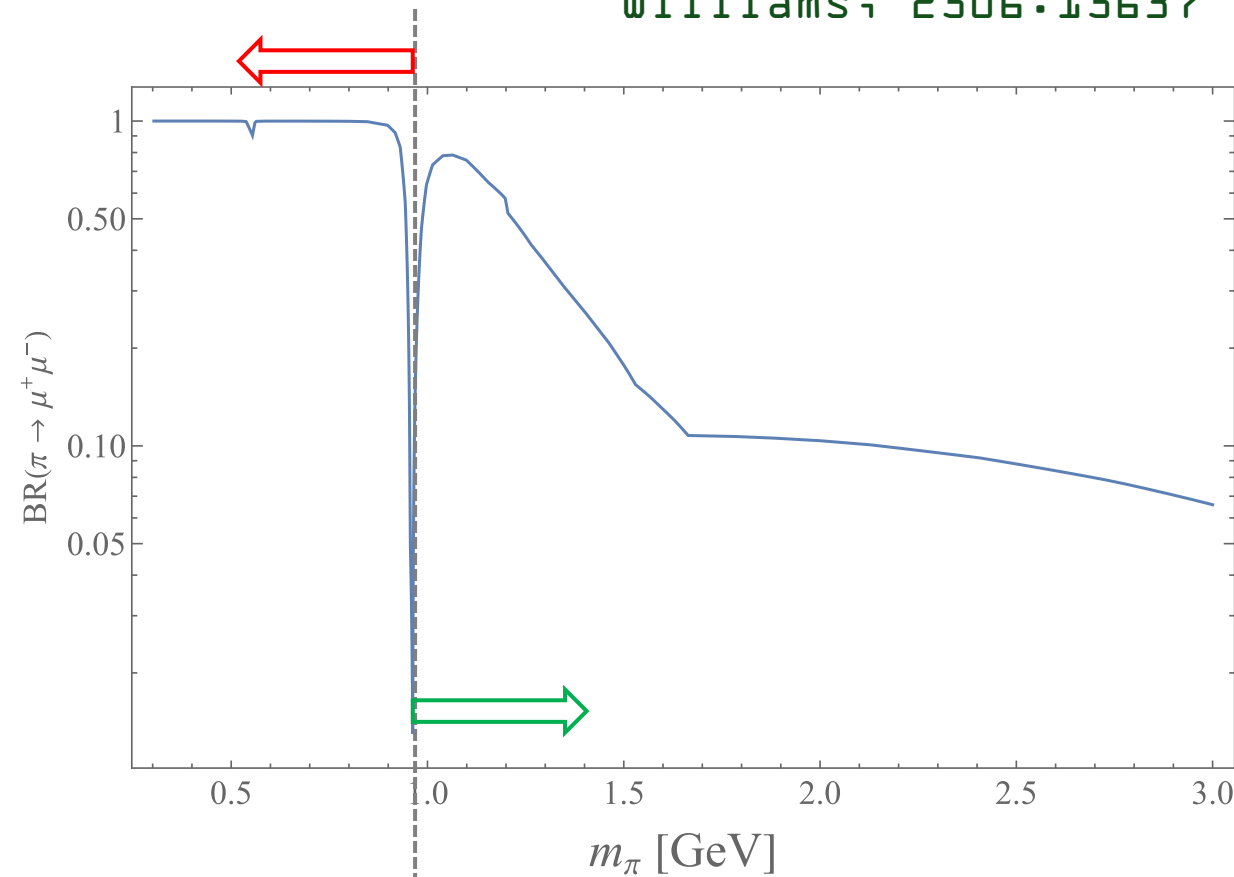
as a composite ALP $f_a \propto \frac{M^2}{f_{\hat{\pi}}}$

See also:

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

$m_\pi < m_\eta$: dimuon
mode dominates

R. Balkin, T. Coren,
Y. Soreq and M.
Williams, 2506.15637



$m_\pi > m_\eta$: dominated by
hadronic modes

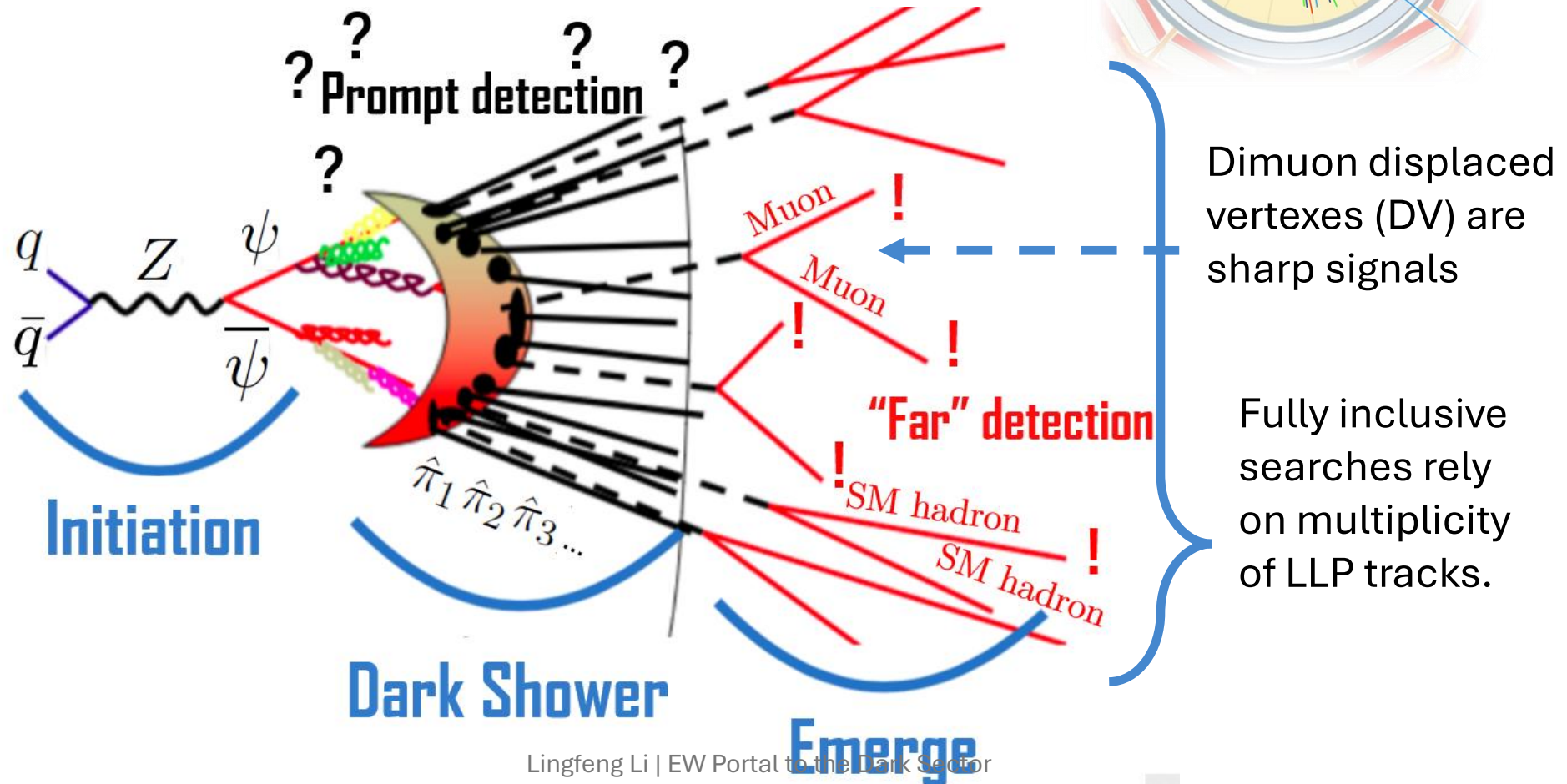
Dark Shower & Emerging Jets

If any dark pion is a LLP $\rightarrow$ emerging energy outside the innermost detector

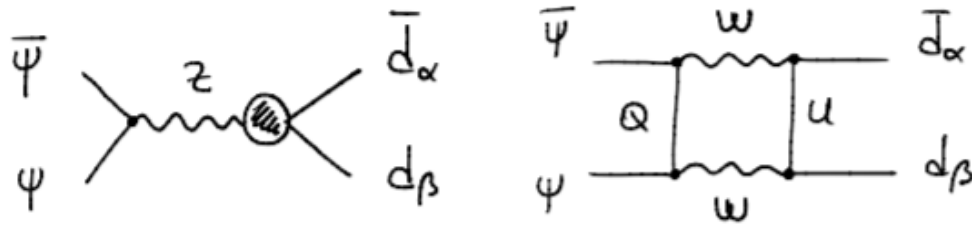
M. J. Strassler and K. M. Zurek, 0604261

P. Schwaller, D. Stolarski and A. Weiler, 1502.05409

T. Cohen, M. Lisanti and H. K. Lou, 1503.00009



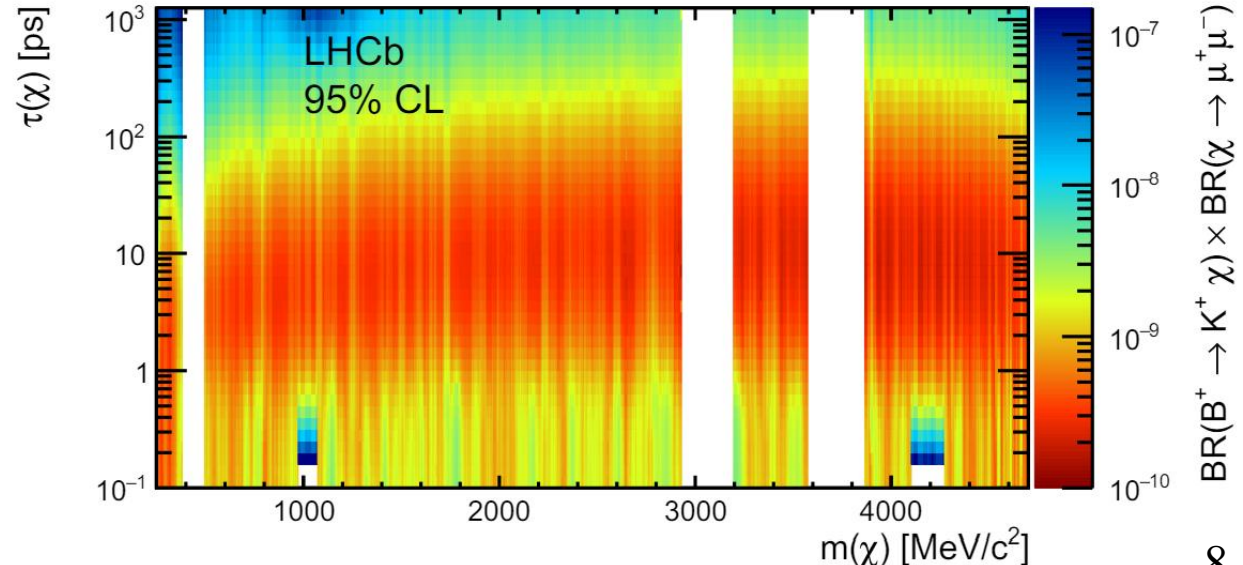
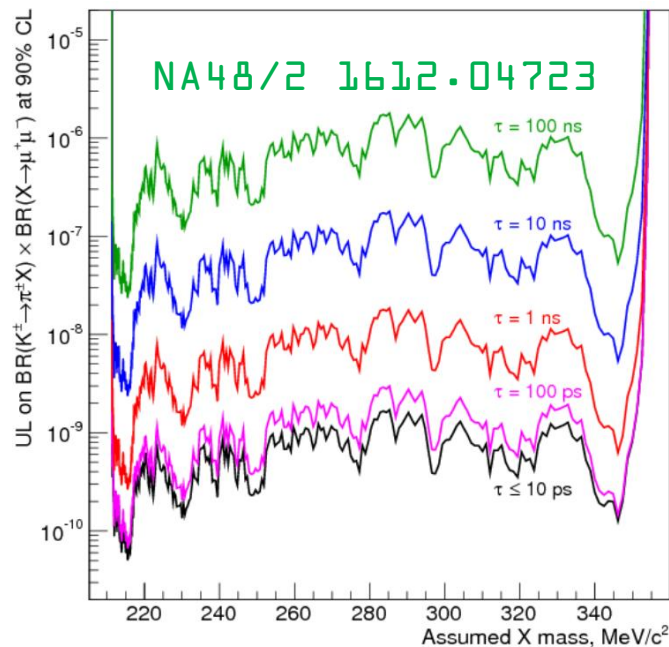
“Flavor Portal” to LLP



➤ 5-10 times larger BR
for inclusive X_s decays

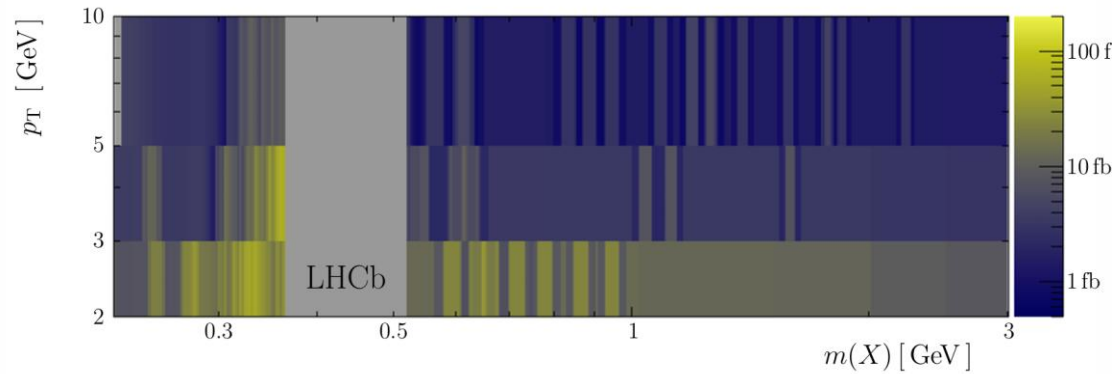
$$\text{BR}(B^{+,0} \rightarrow \{K^+ \hat{\pi}, K^{*0} \hat{\pi}\}) \approx \{0.92, 1.1\} \times 10^{-8} \left(\frac{1 \text{ PeV}}{f_a} \right)^2 \left(\frac{\mathcal{K}_t}{10} \right)^2 \{ \lambda_{BK\hat{\pi}}^{1/2}, \lambda_{BK^*\hat{\pi}}^{3/2} \}$$

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



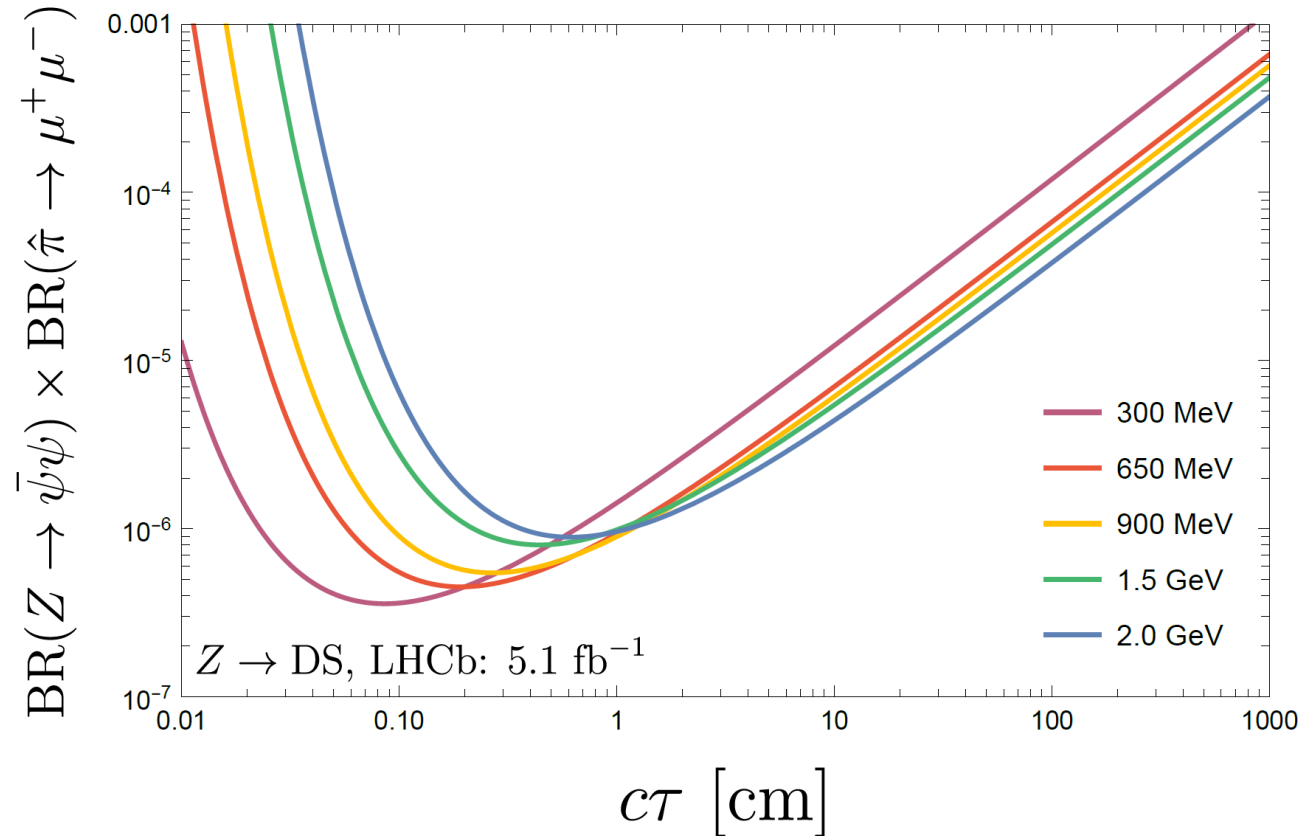
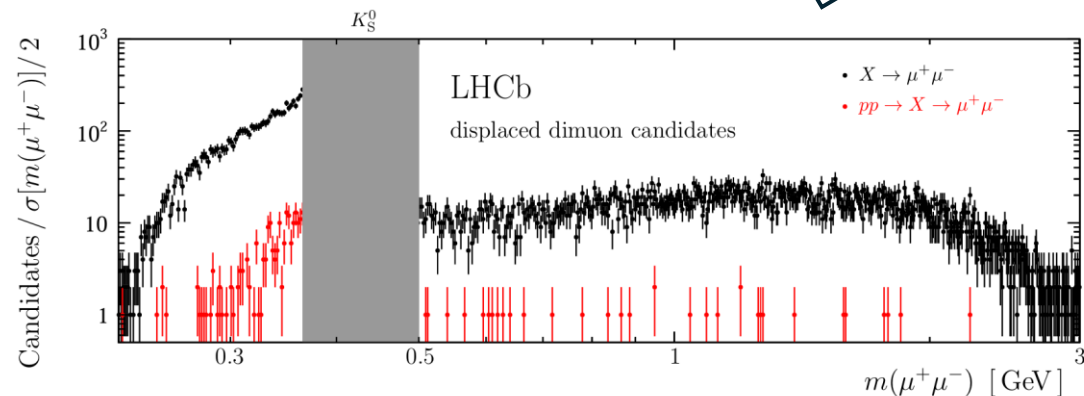
LHCb: “Trigger-free” Searches

See [LHCb, 2007.03923](#)



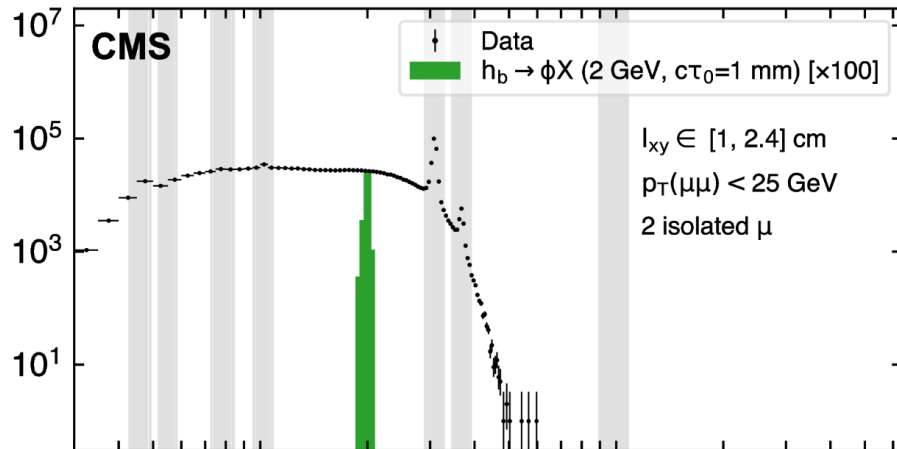
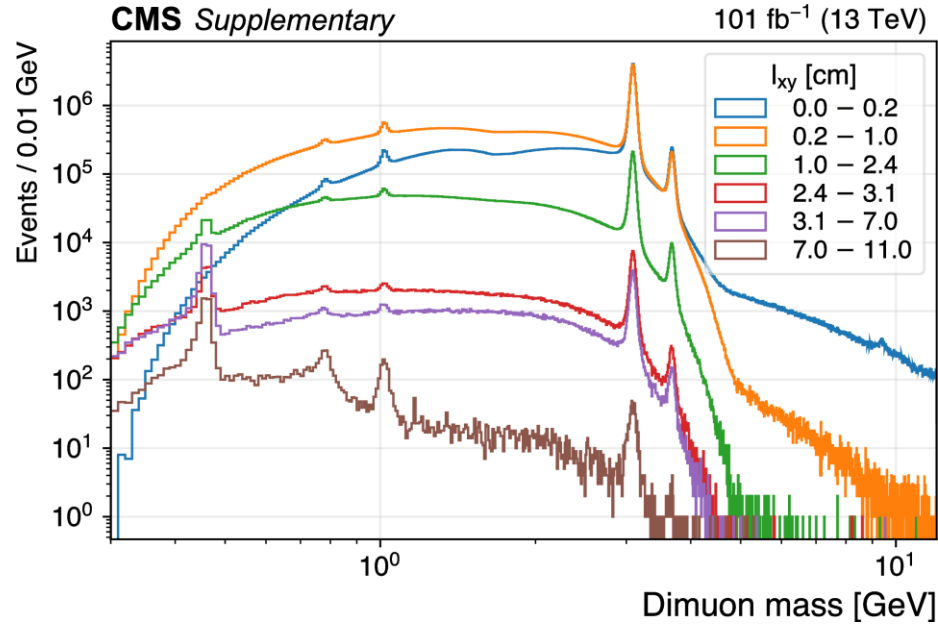
➤ Projected from inclusive displaced dimuon search

➤ Matching with multiple ways to be consistent



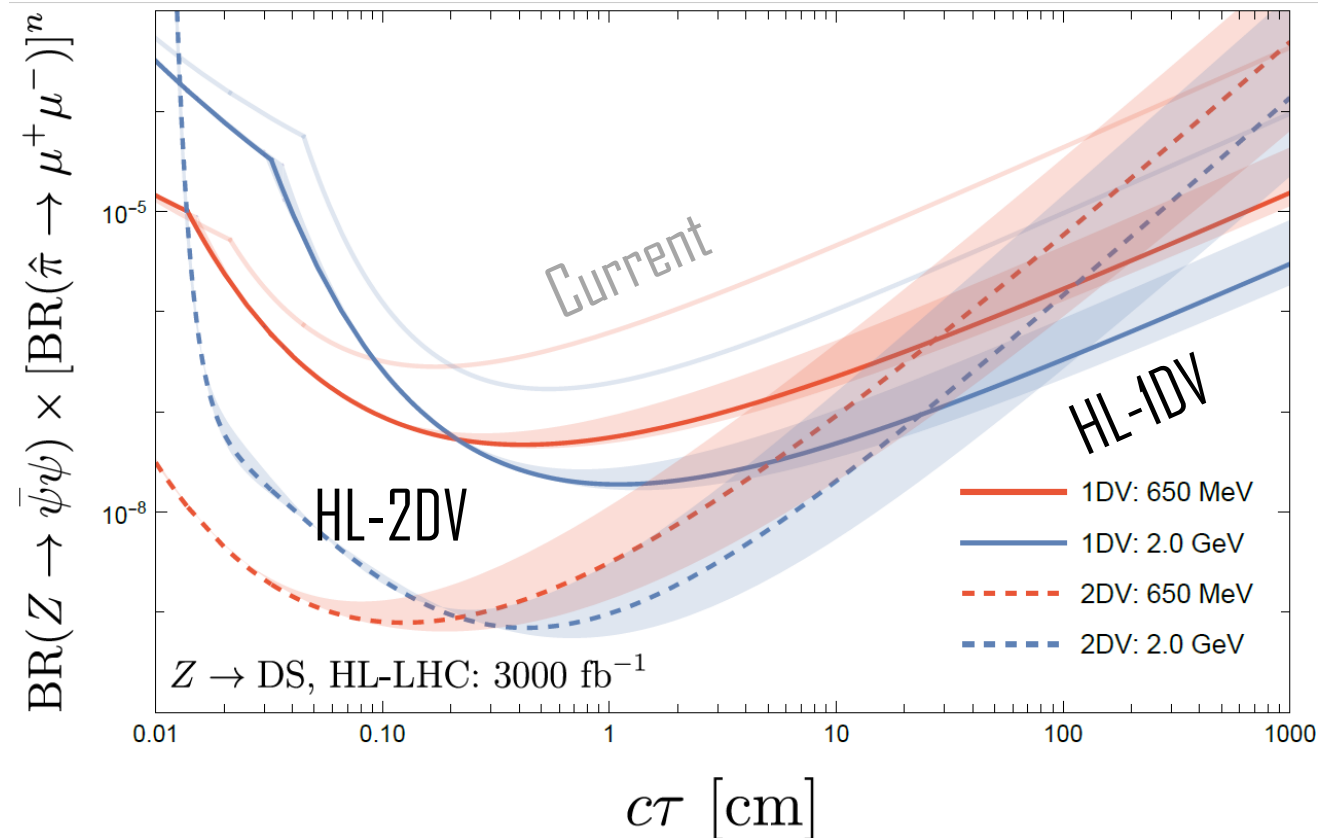
“Model independent” limit for exotic Z decay to DS

CMS: Model-Independent Limits

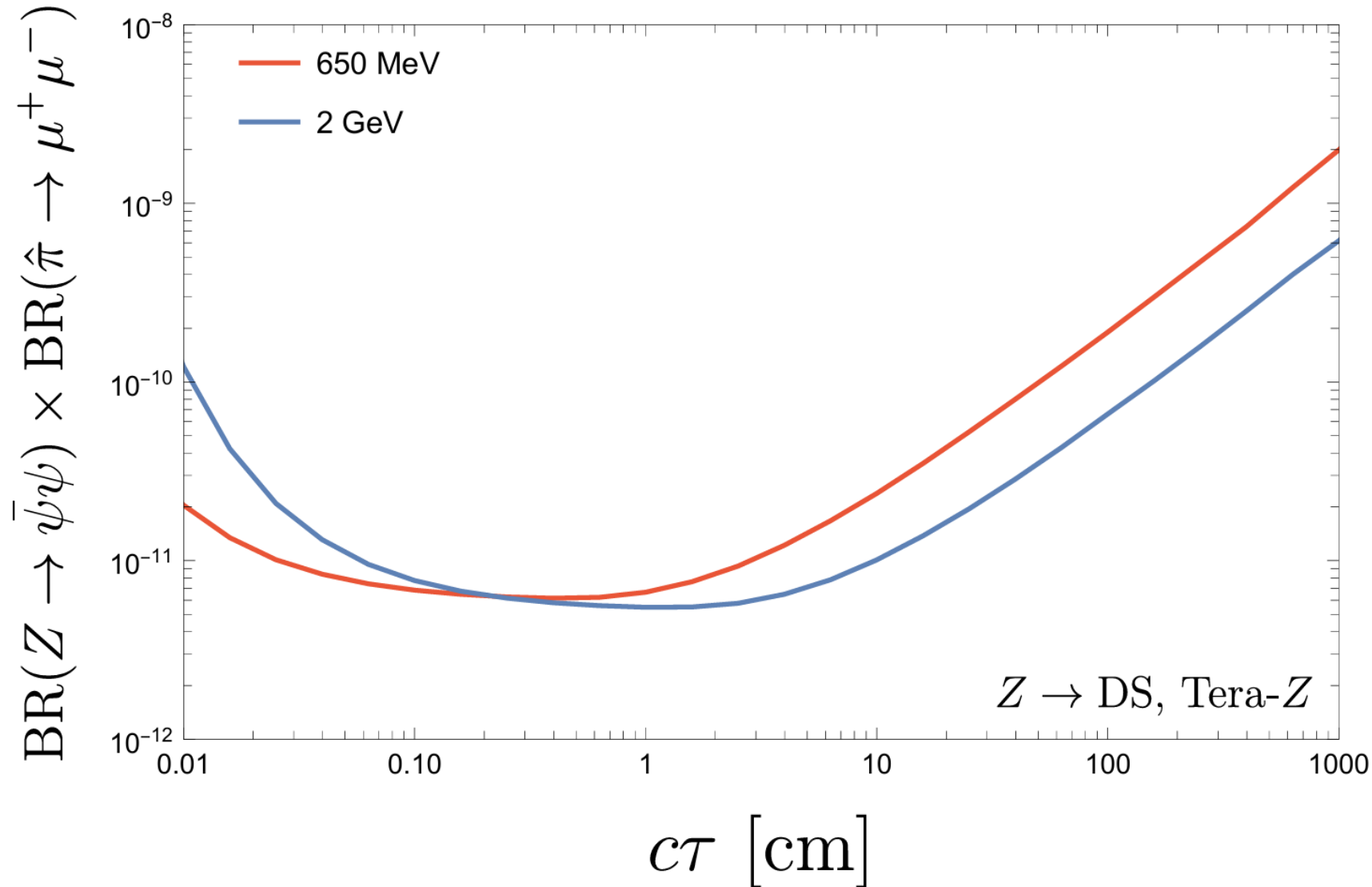


CMS, 2112.13769

- CMS Z exotic limit from dimuon scouting
- HL-LHC limits with 30 times luminosity + detector/algorithm upgrades.....

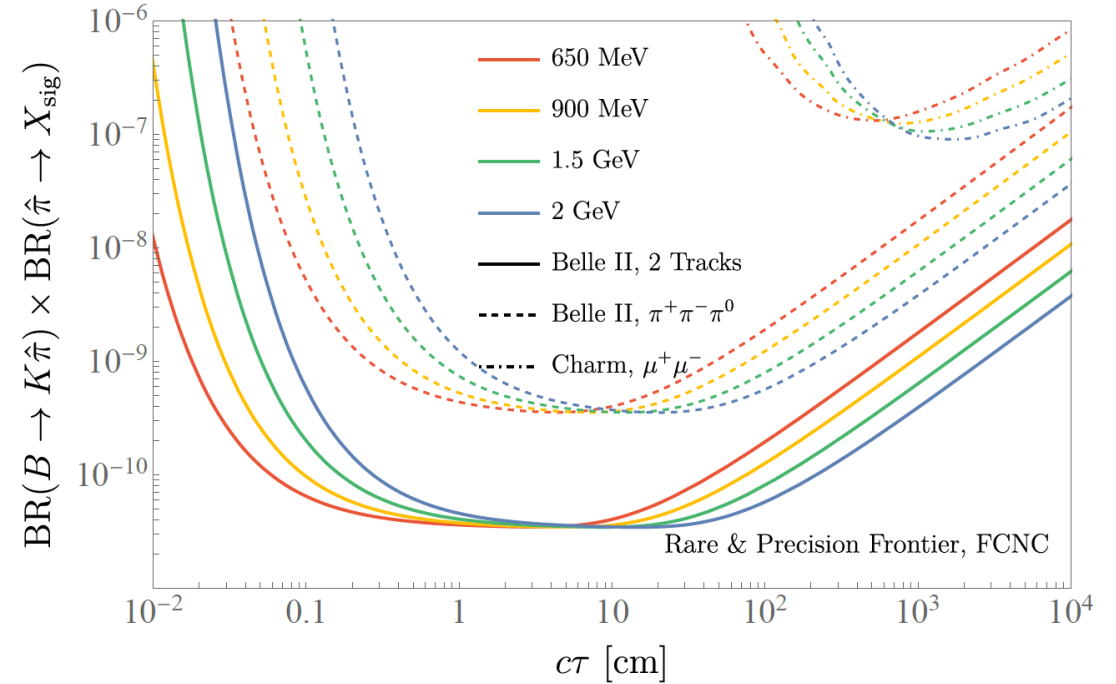
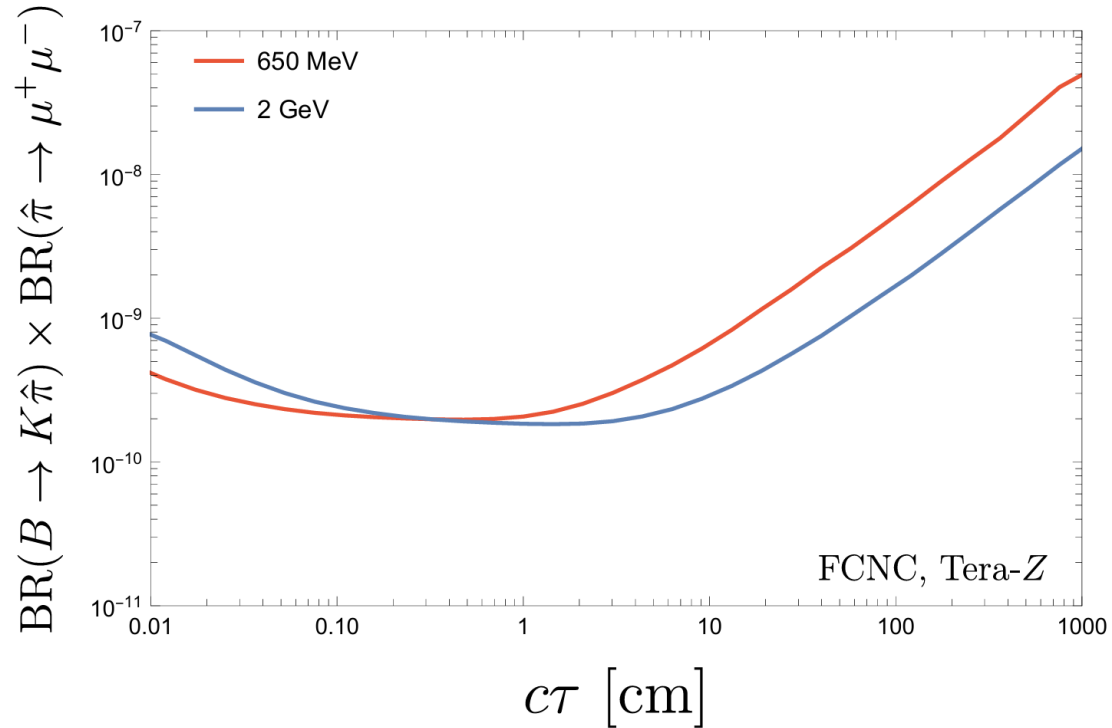


Dark Shower Signals at the Z Pole



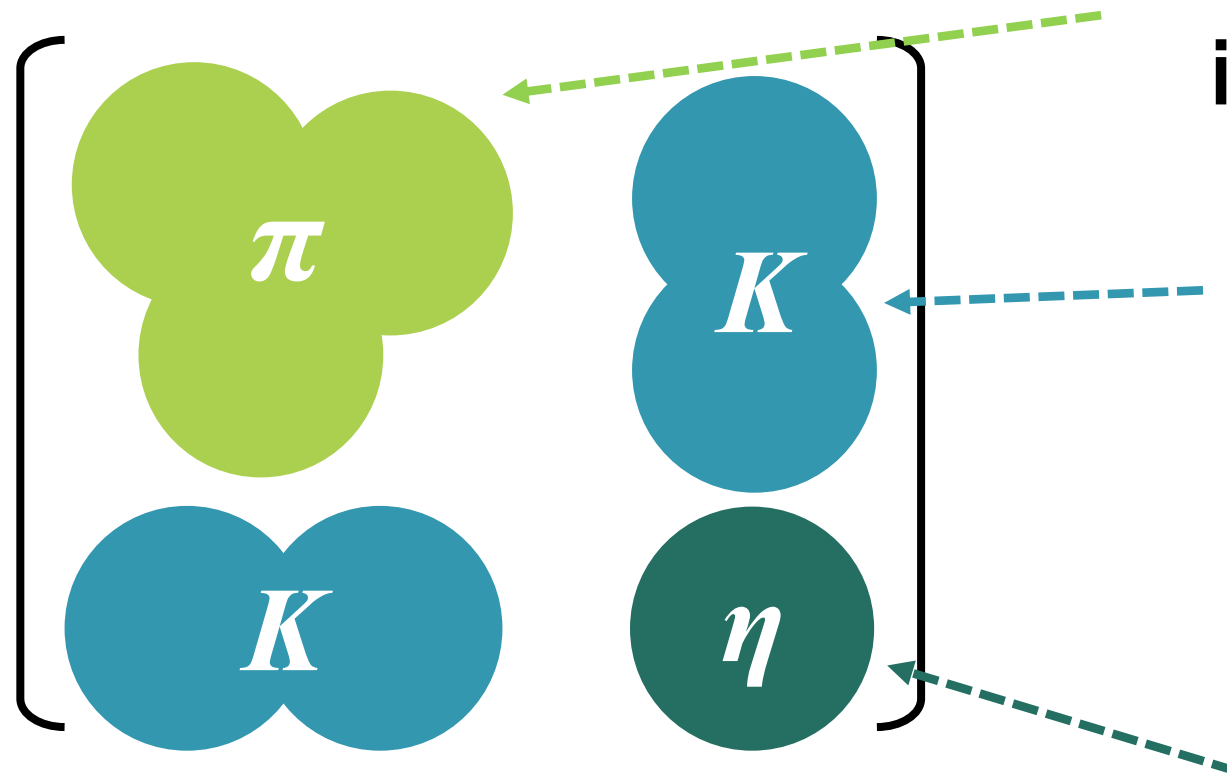
Could extend
to higher
lifetimes with
an associated
far detector

FCNC Limits at Lepton Colliders



*Comparable performance, differences largely due to assumptions and systematics

Speaking of Darkness.....



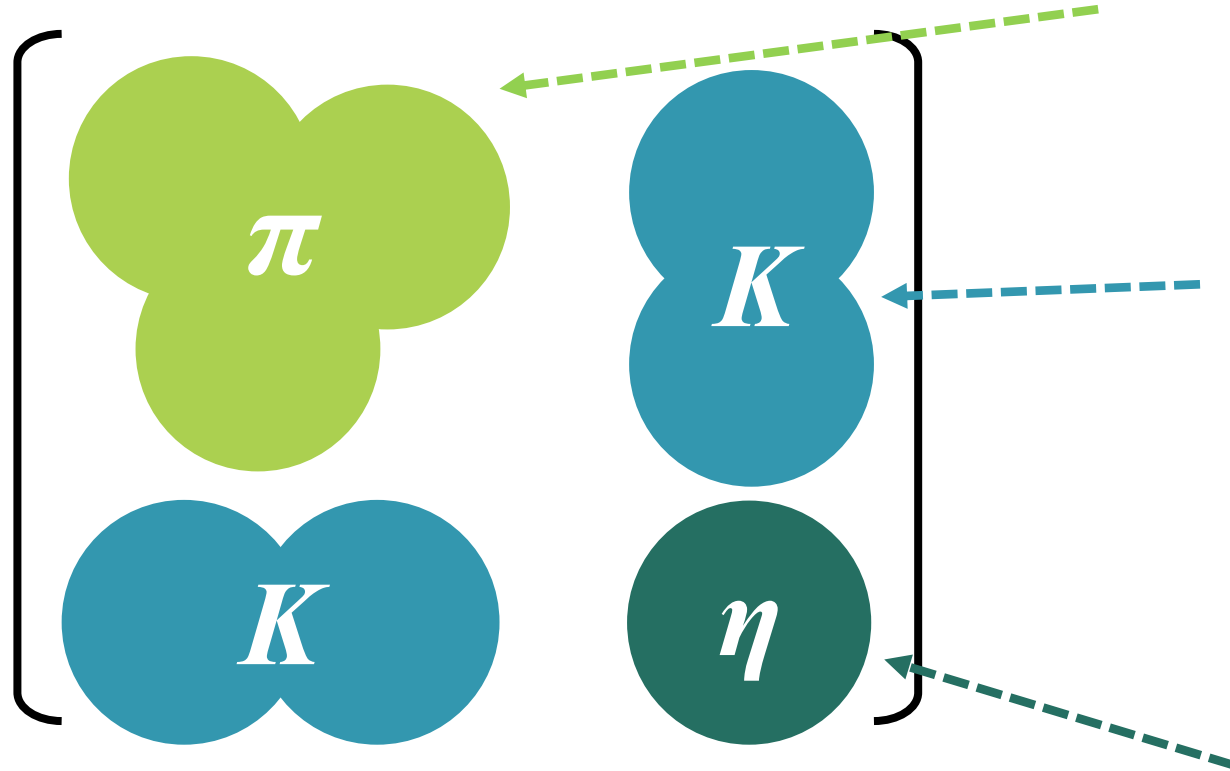
**"Stable" due to SU(2)
isospin symmetry**

**"Stable" due to
strange number
conservation**

**No protection,
unstable**

H-C. Cheng, X. Jiang, LFL,
E. Salvioni, in progress

A SM-like Dark Sector & DM

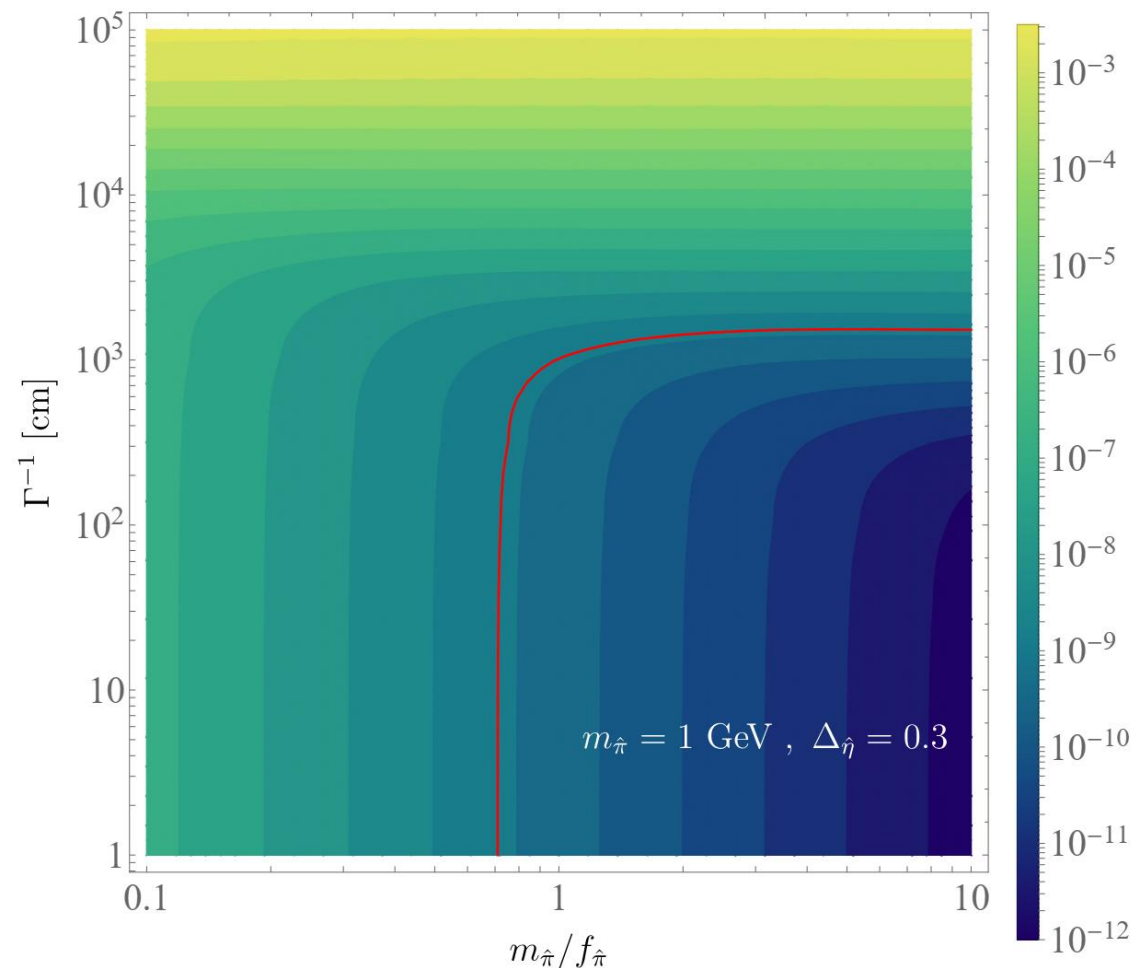
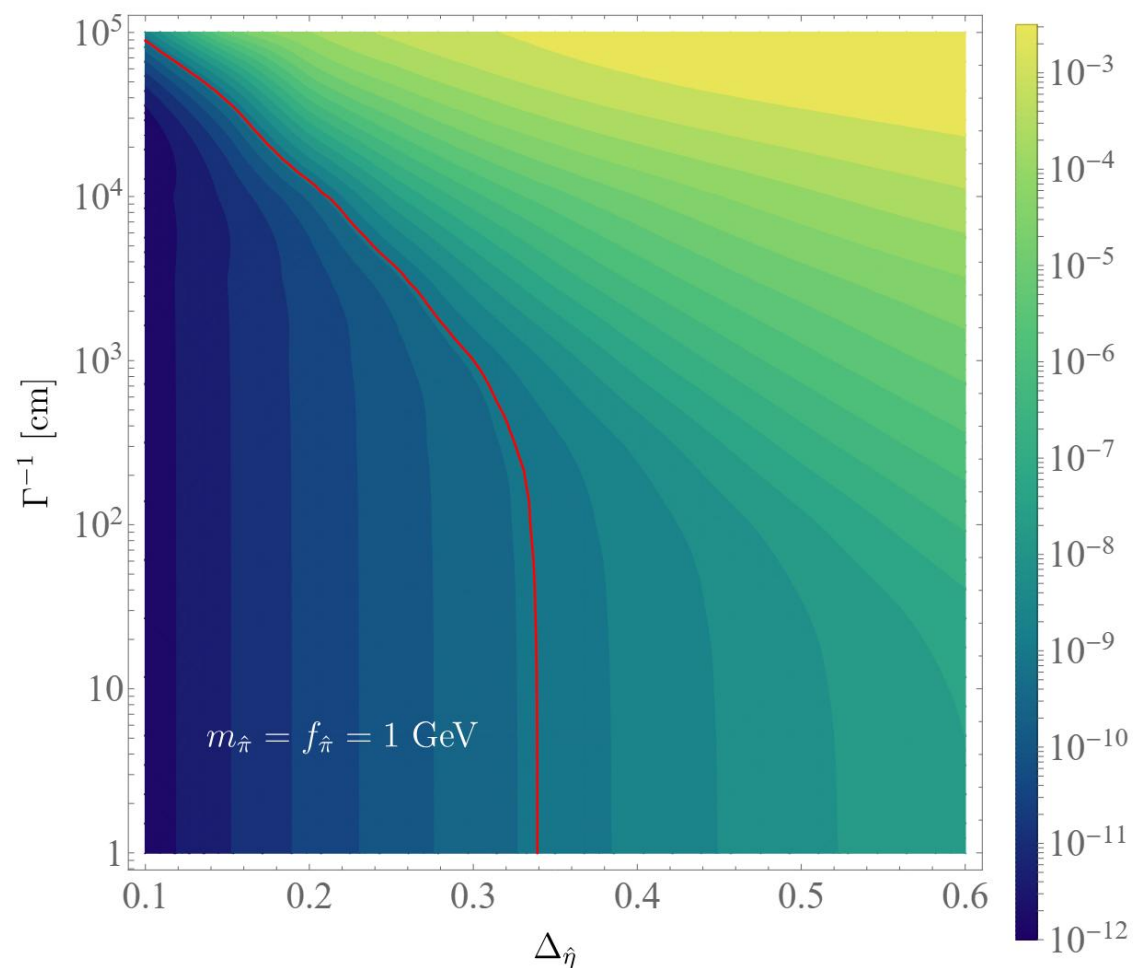


The DM meson, non-interacting and thus invisible

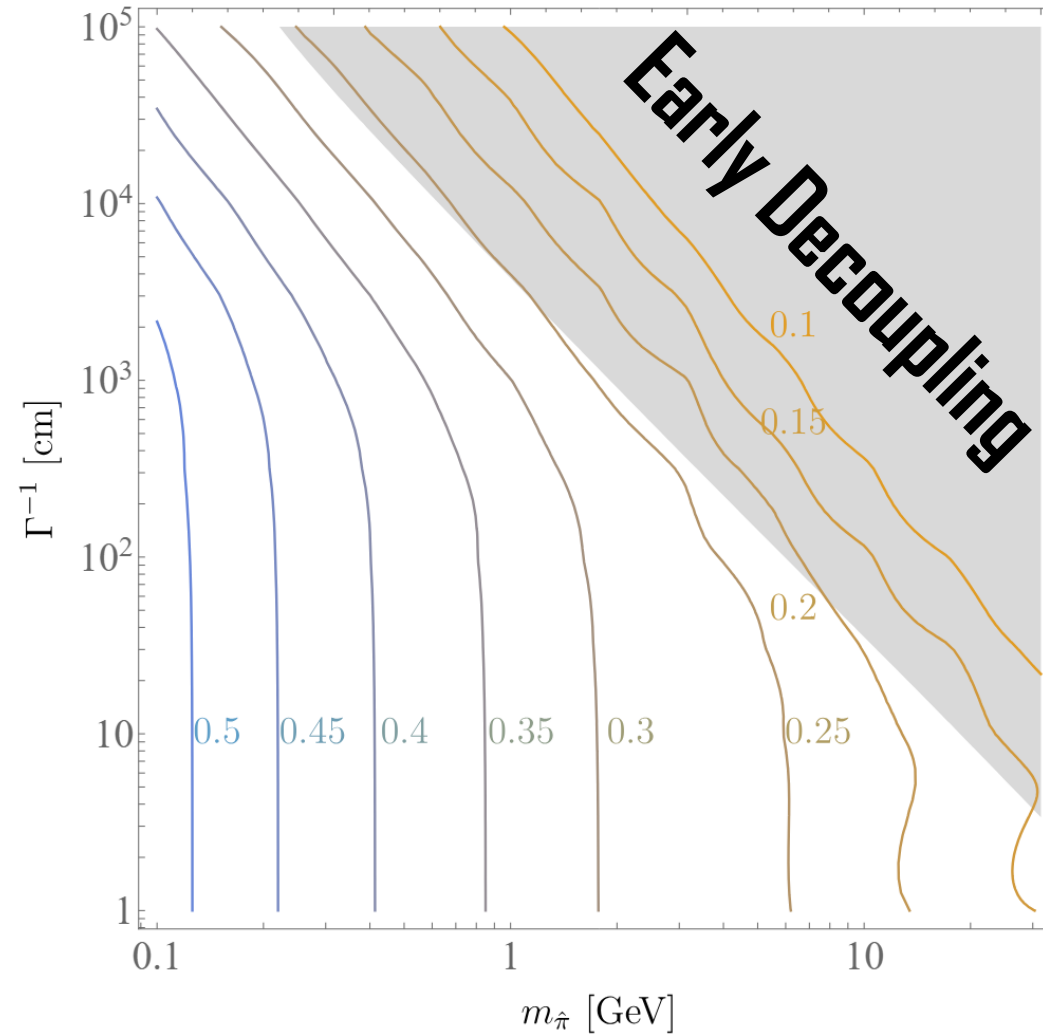
The intermediate, play a significant role in DM production

The messenger: heavy meson that decays, gives LLP Signal

DM Benchmarks



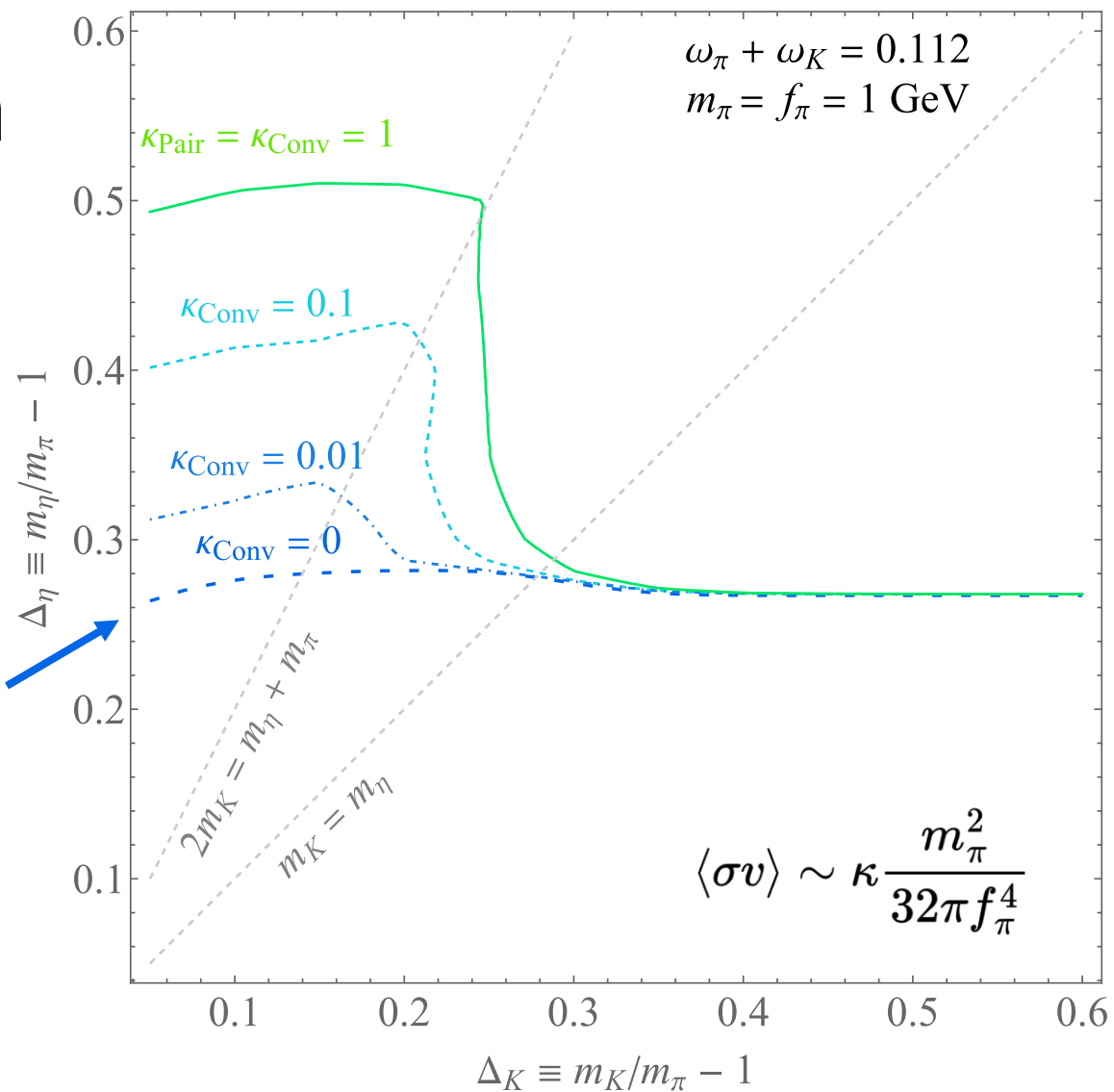
DM Benchmarks



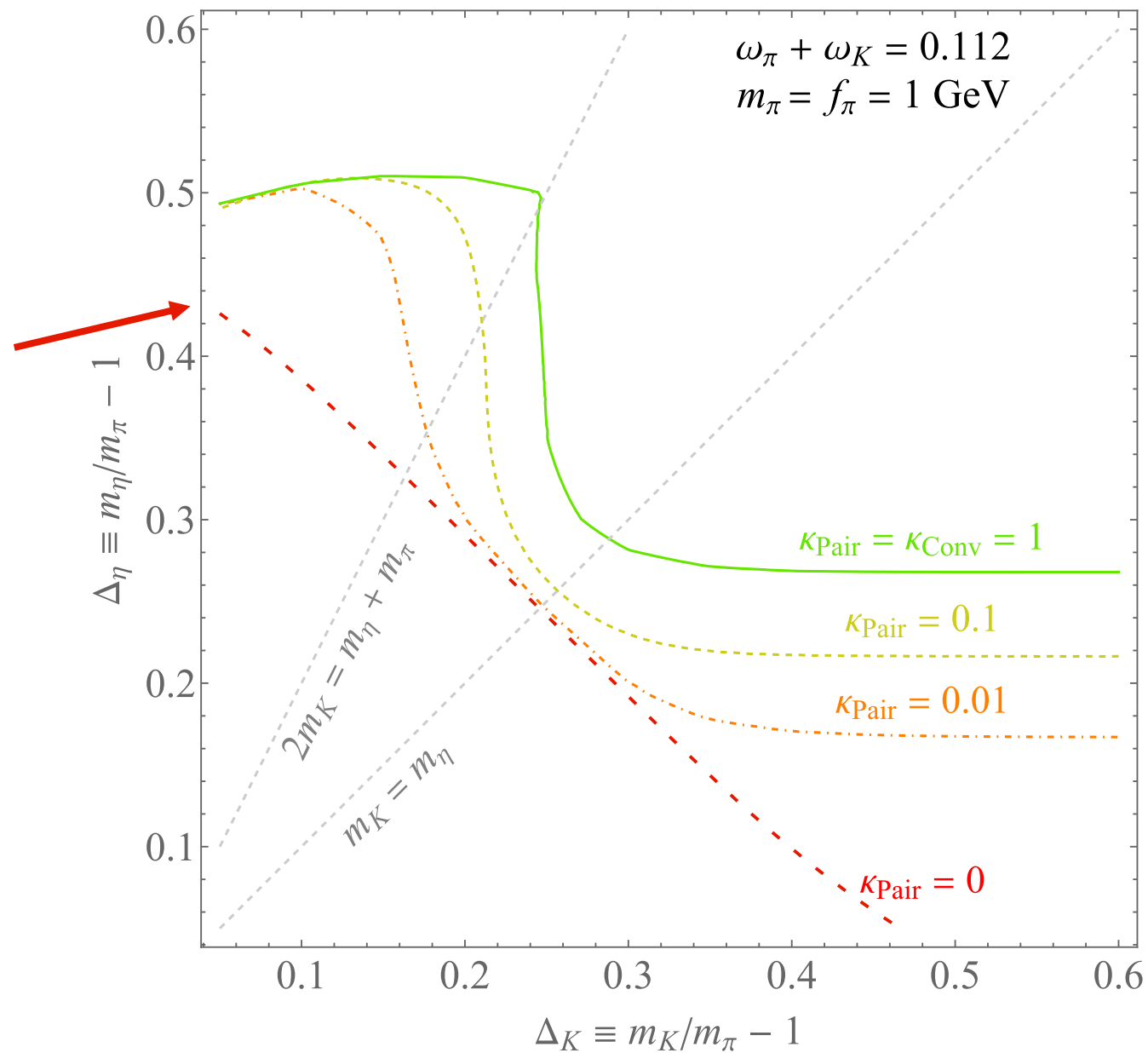
THANK YOU
&
BACKUP SLIDES

Examining Conversion Rates:

No conversion limit,
K as secondary DM



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

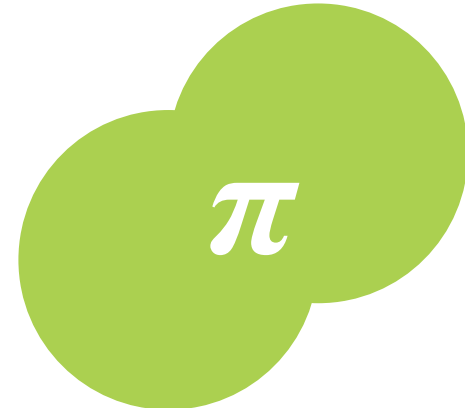
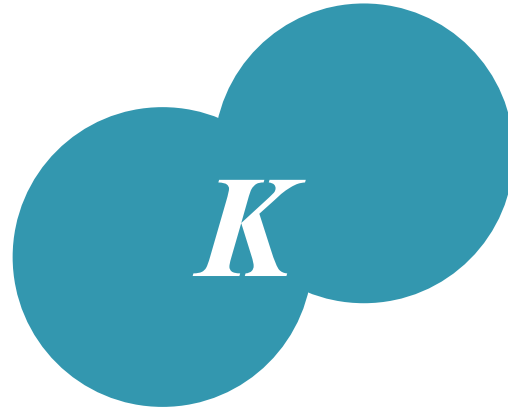


The Model

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

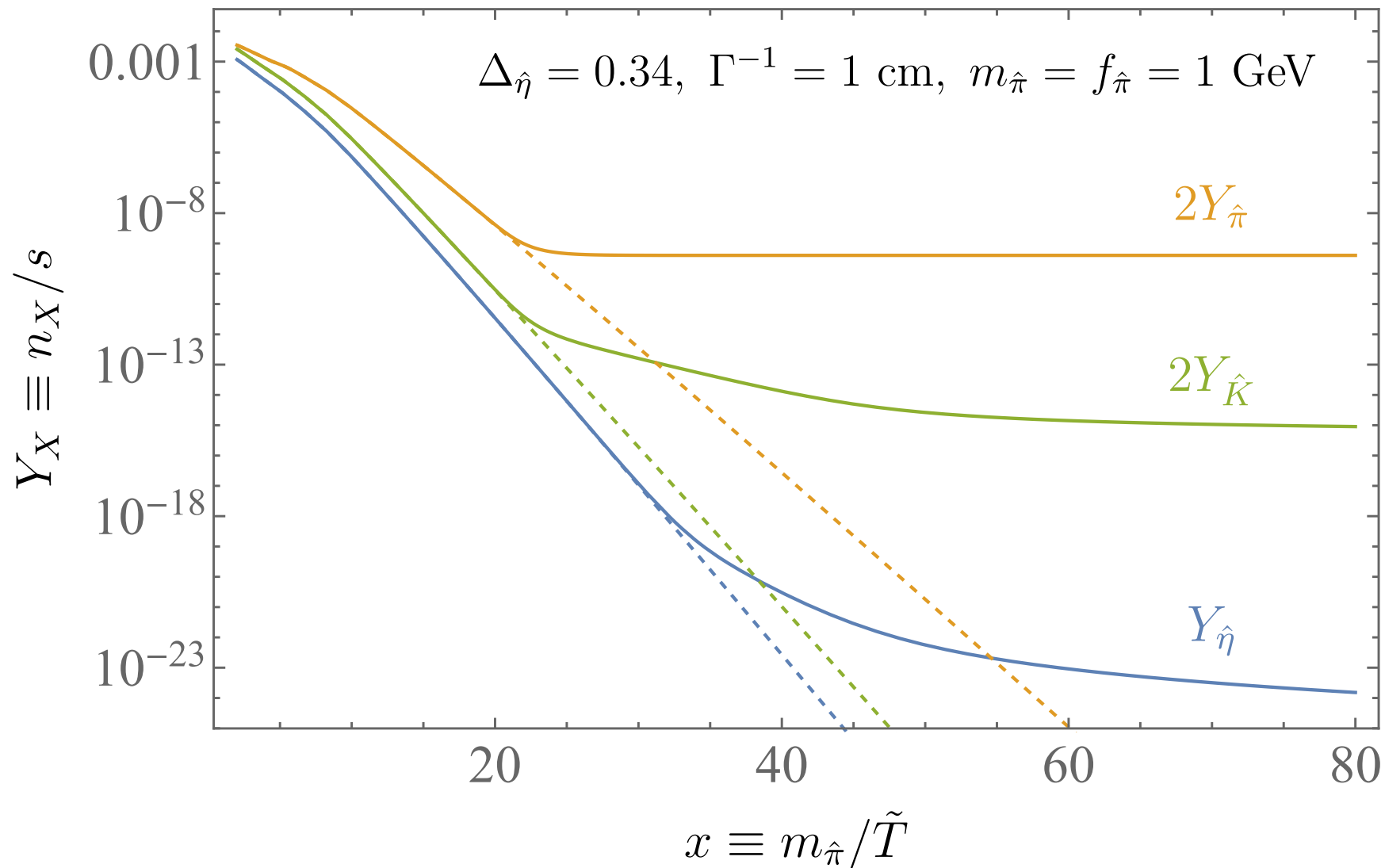
$SU(3)/SO(3) \Rightarrow$ 5 Goldstone bosons

Two π , two K and one η

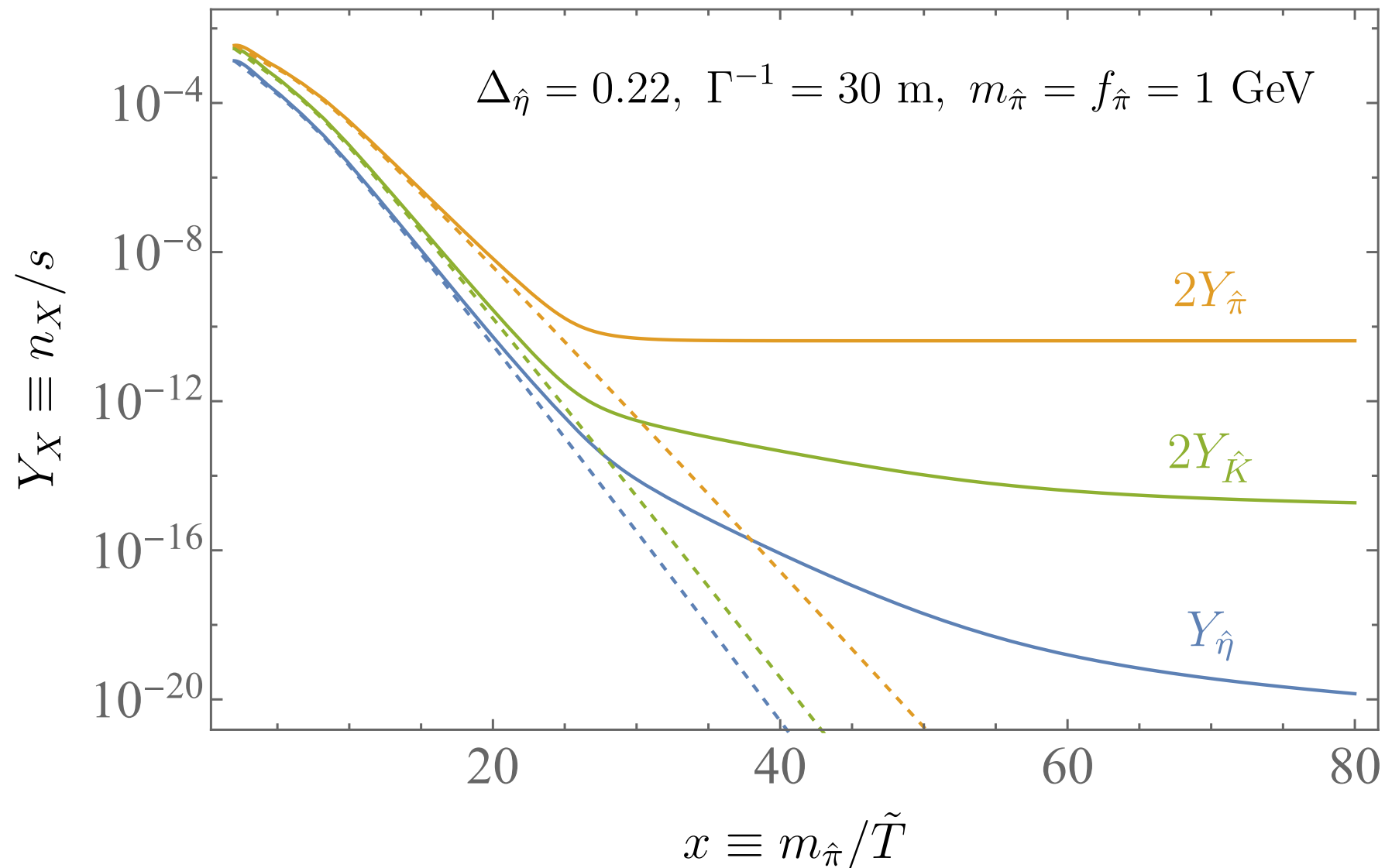


$$m_\eta = (1 + \Delta_\eta) m_\pi > m_K = (1 + \Delta_K) m_\pi > m_\pi$$

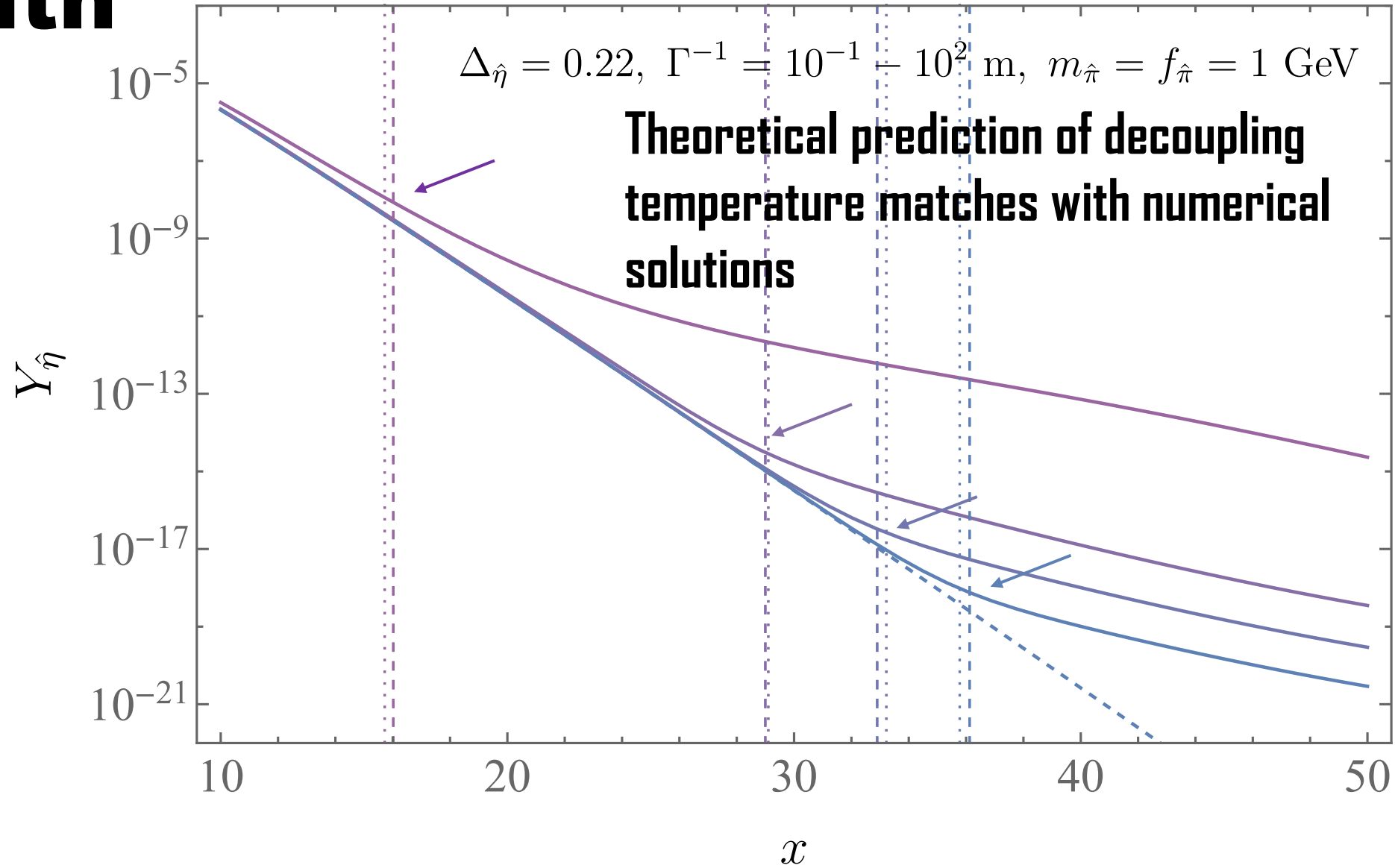
Large Decay Width Limit: Freezeout Controlled by Conversion

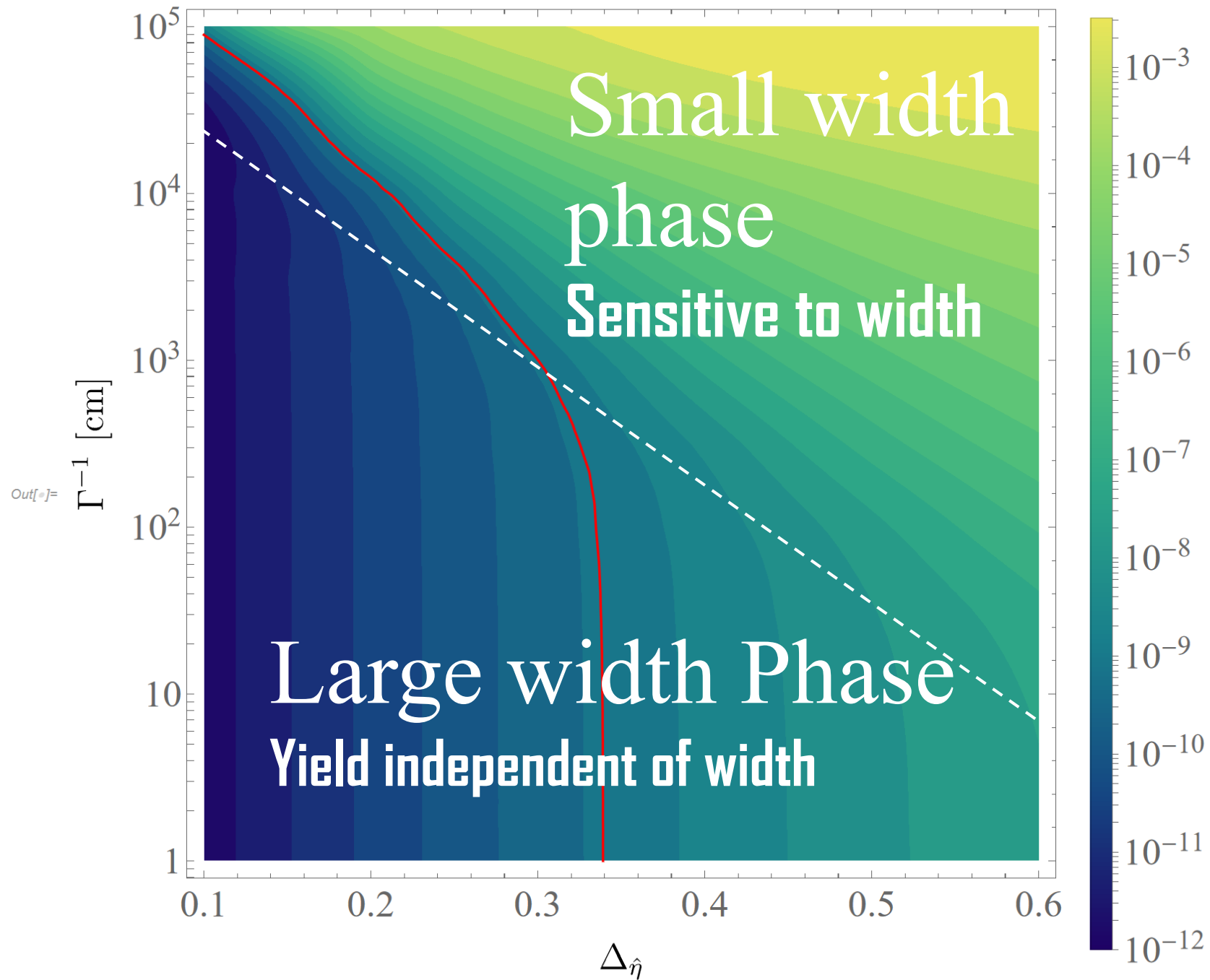


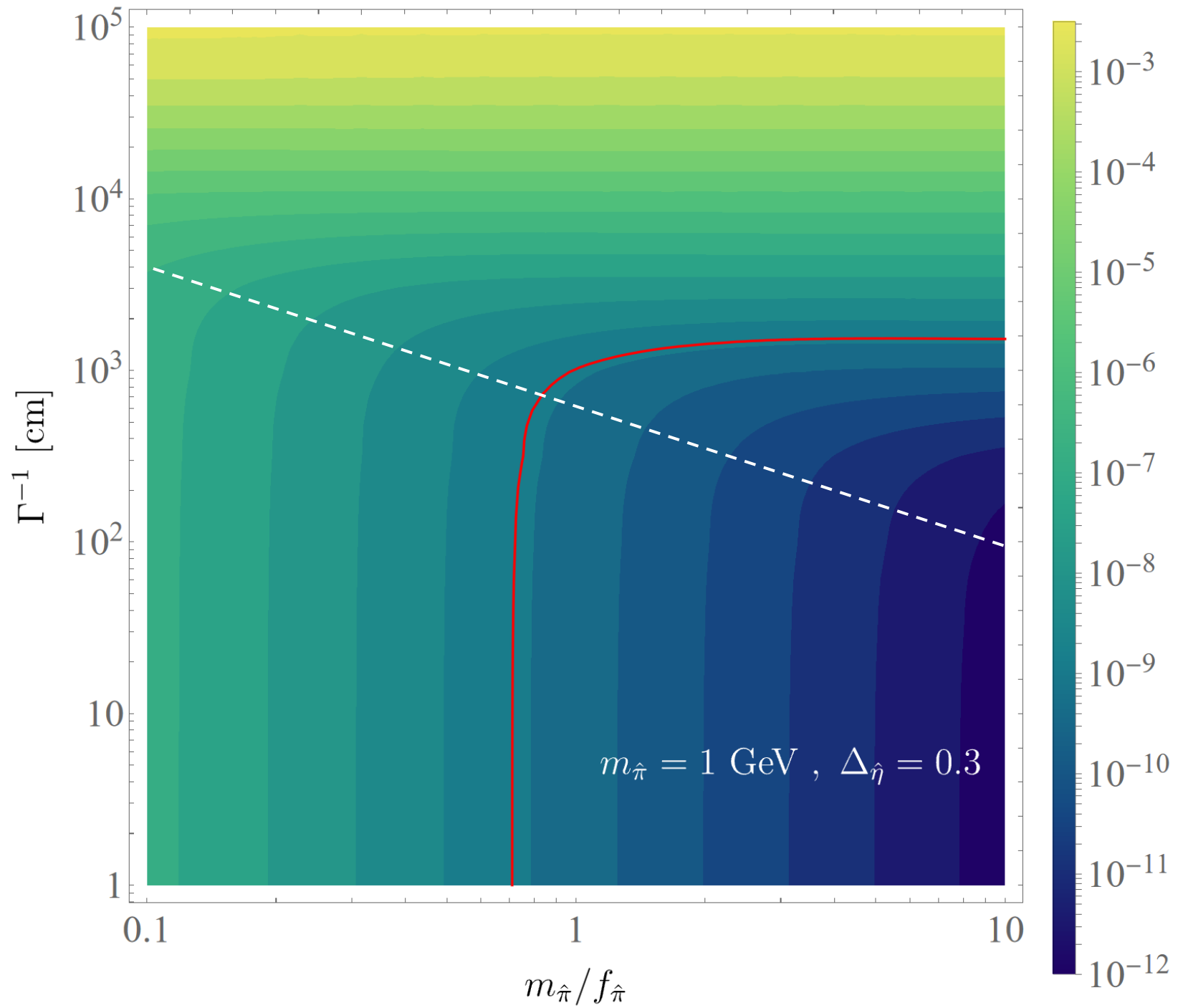
Small Decay Width Limit: Freezeout Controlled by the Decay

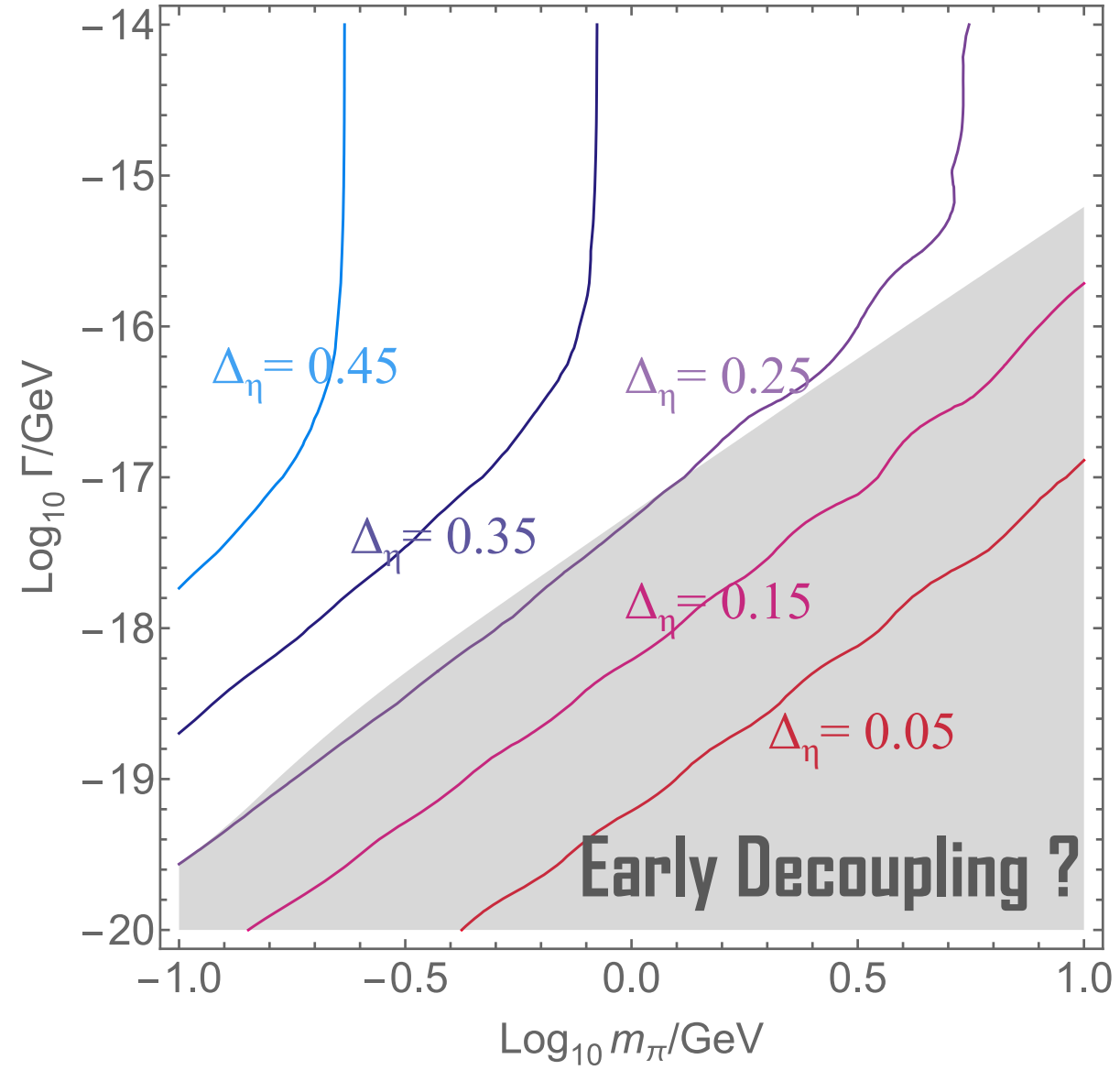


Transition Between Different Decay Width







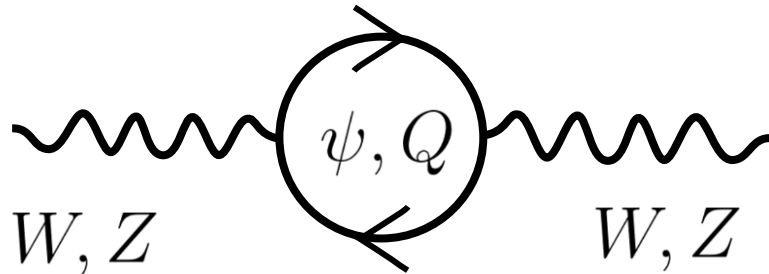


EWPT Corrections

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

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

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

Z' mediation



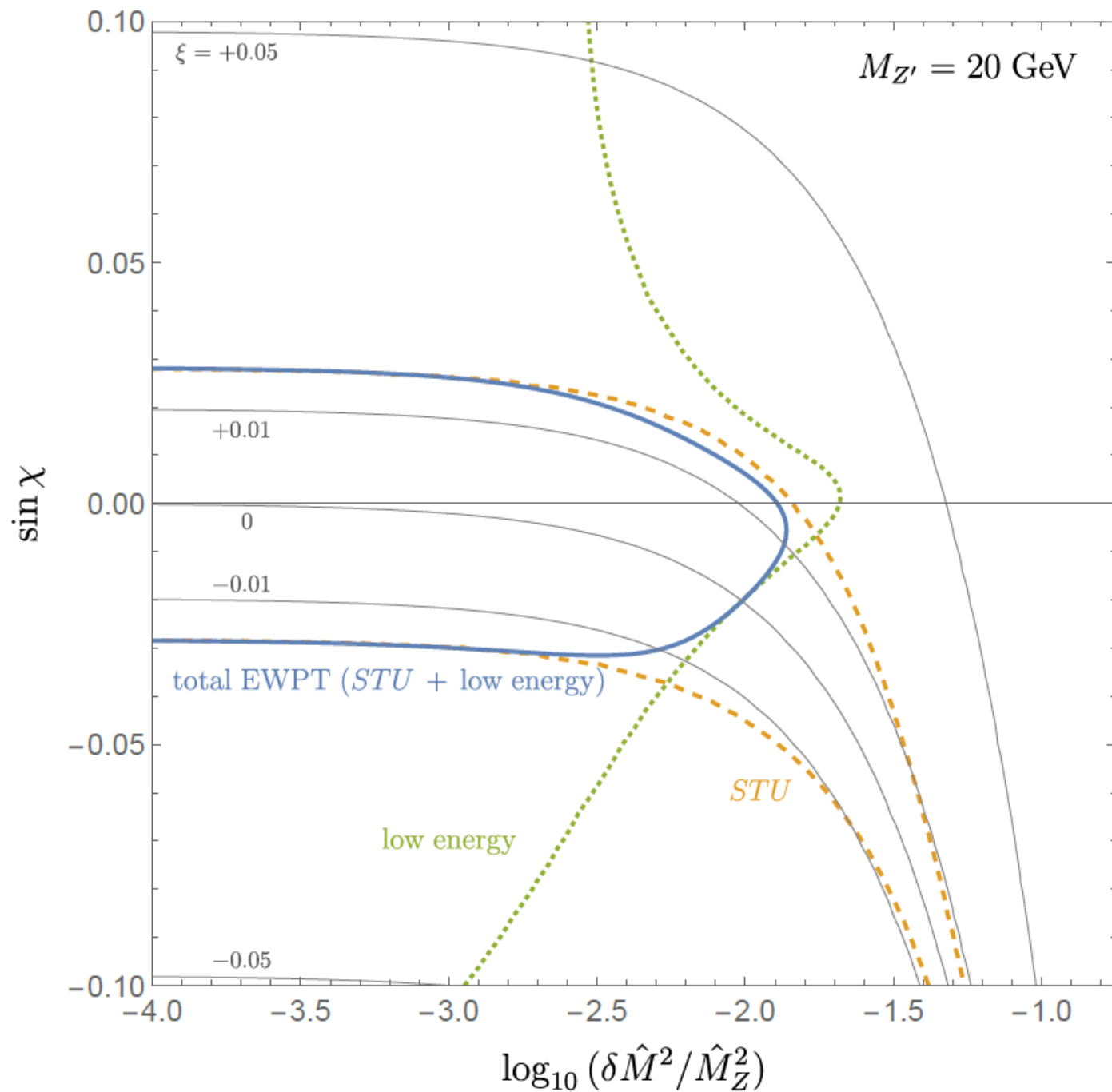
Leading by LEP Z pole observables defined with:

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

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

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

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



Low energy constraints:

e.g. atomic
parity violation,
low energy ee,
ep scattering

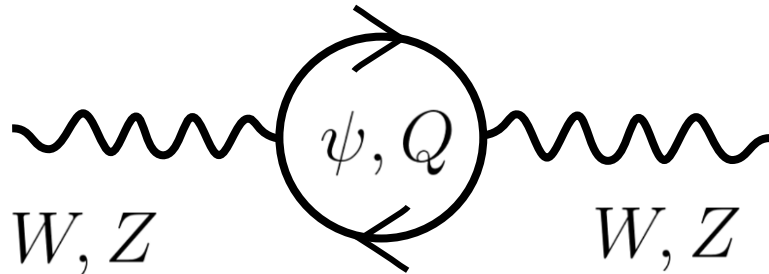
G. Altarelli
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Z' mediation



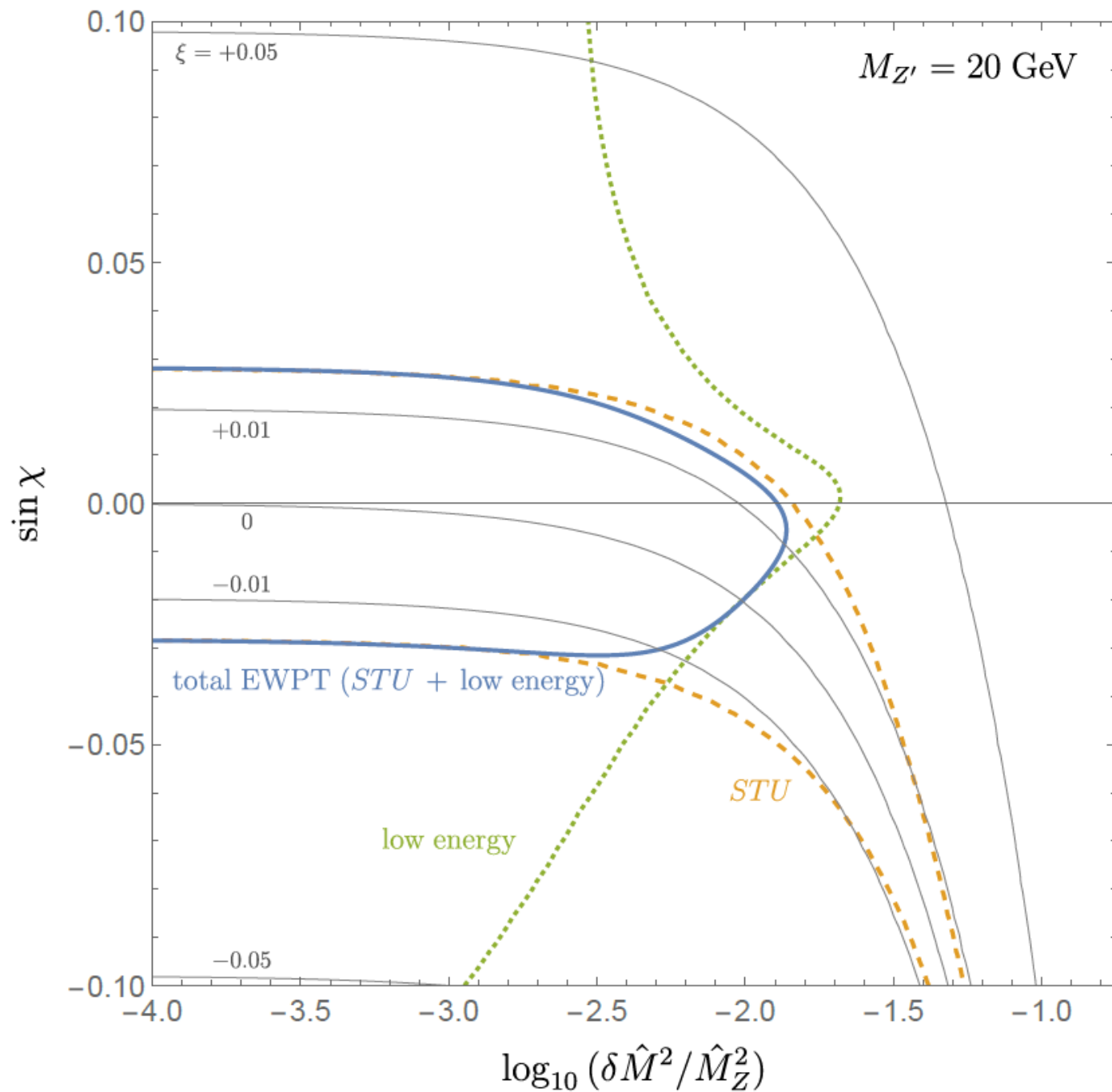
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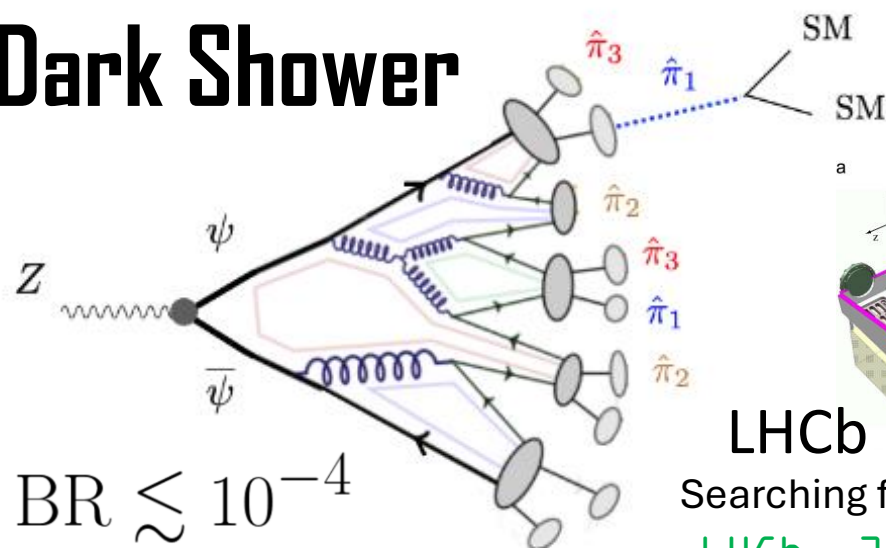
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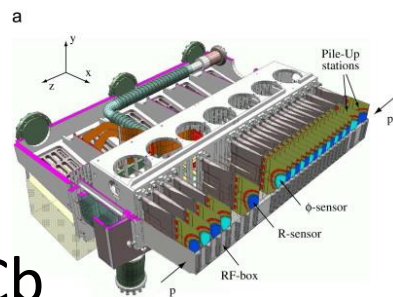
G. Altarelli
et al. 1991

LLP Phenomenology

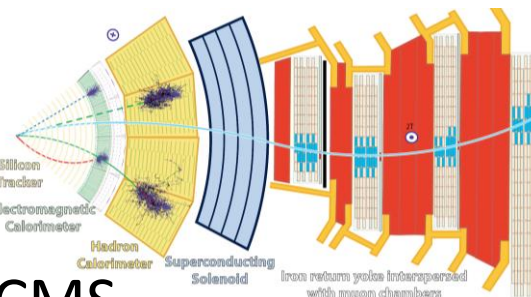
Dark Shower



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



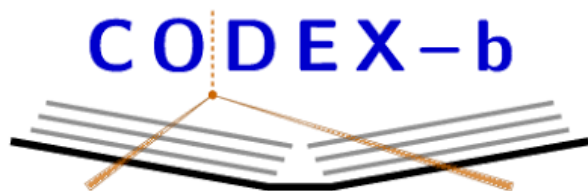
LHCb



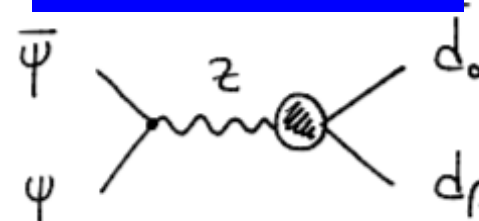
CMS

Searching for displaced dimuon resonances (one or more)

LHCb, 2007.03923; CMS, 2112.13769

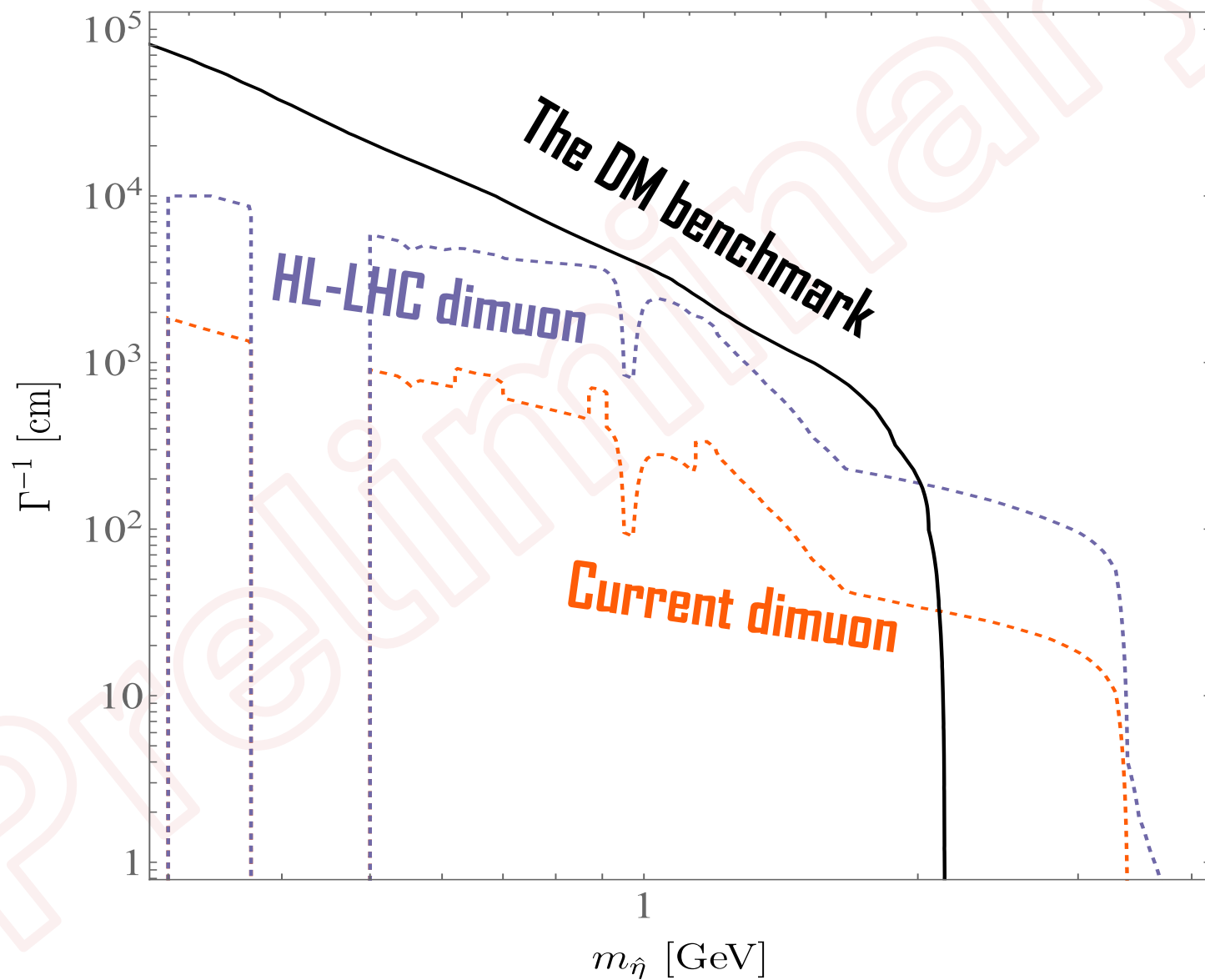


$$BR \approx 10^{-8} \left(\frac{1 \text{ PeV}}{f_a} \right)^2$$



FCNC Decays

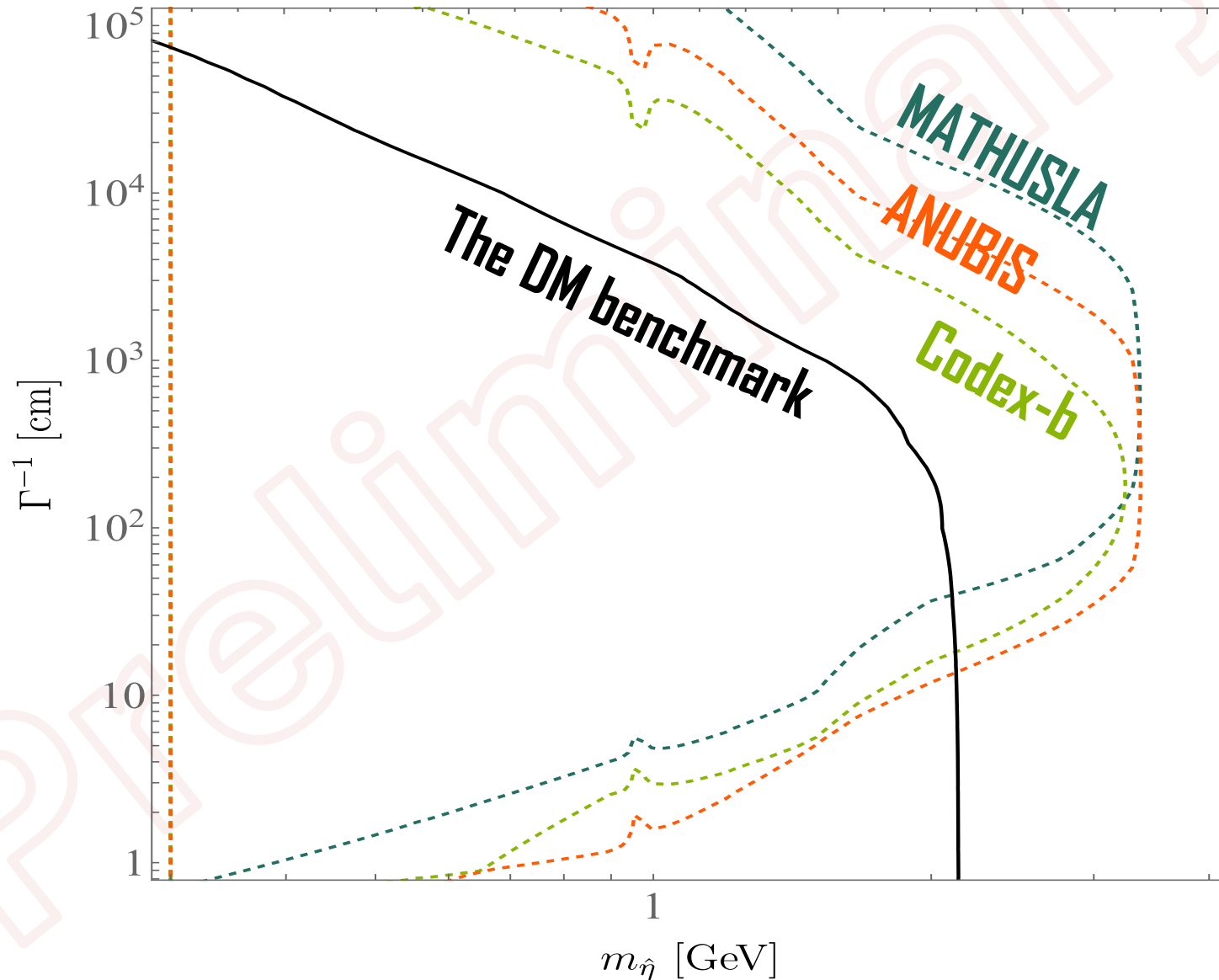
LHC Bounds on Such DM



Only looking for
visible component
decaying to dimuon



Auxiliary Detectors



Inclusive decay
possible for aux.
detectors

