Dark Showers with the Z Portal

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HC, Lingfeng Li and Ennio Salvioni, arXiv:2110.10691
HC, Xuhui Jiang, Lingfeng Li and Ennio Salvioni, arXiv: 2401.08785 + 2407.xxxxx

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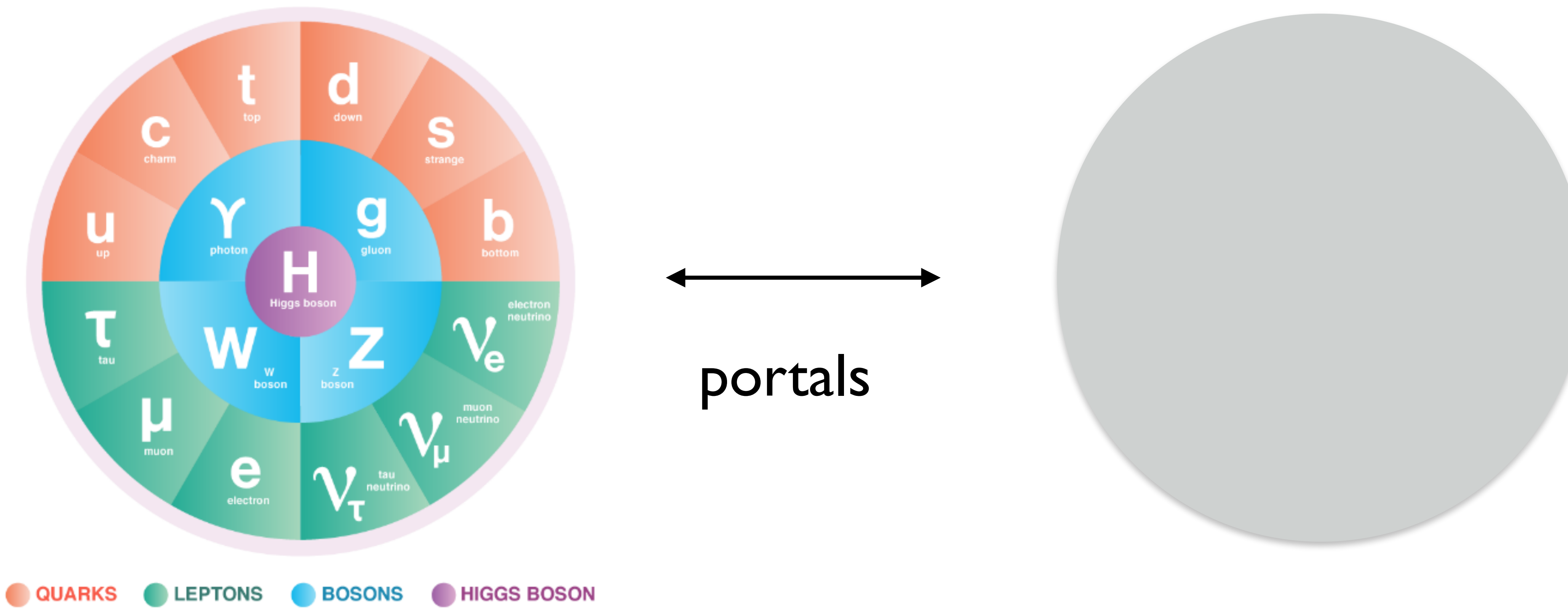
Introduction

SM

Dark sector



- Motivated by many important physics questions: naturalness of EW scale, dark matter, …
- Novel experimental signatures: new targets and challenges for experimental searches.

Portal interactions

- Heavy states (> TeV, X_{DK}, Z', etc)
- Higgs or Z
- Dark photon kinetically mixed with photon
- Neutrinos

Z-portal

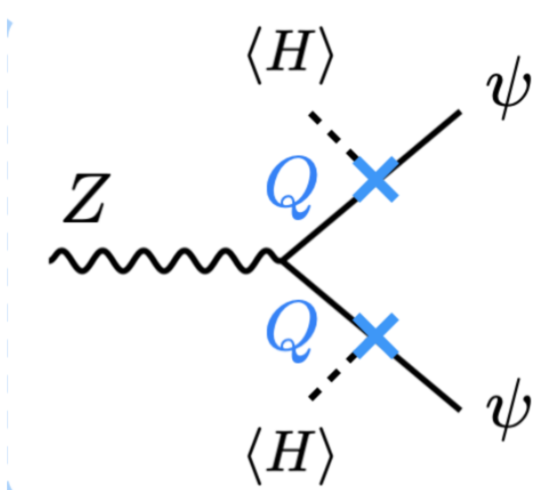
- An interesting scenario which is less studied.

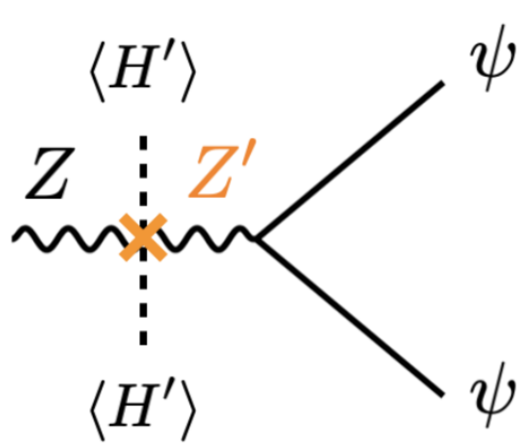
$\sigma(pp \to Z) \approx 54.5; (58.9); \mathrm{nb},$ $\sigma(pp \to h) \approx 48.6; (54.7); \mathrm{pb}$ for $13(14)$TeV

- Light dark particles should be neutral under SM. How do they couple to Z?

1. Light dark particles mix with heavy EW doublet fermions. (HC, L. Li, E. Salvioni, C.B. Verhaaren, 1906.02198, HC, L. Li, E. Salvioni, 2110.10691)

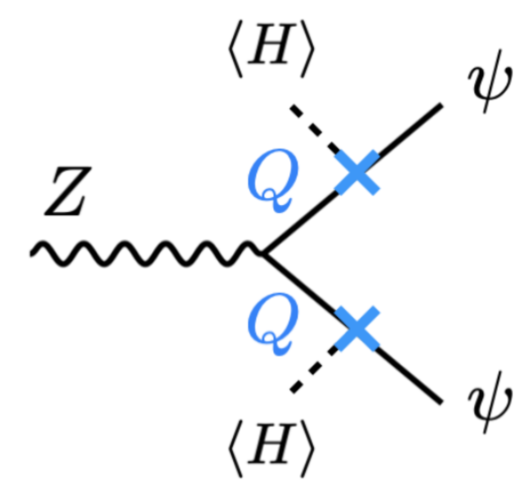
2. Light dark particle are charged under a dark U(1) which mixes with Z after EW breaking. (HC, X. Jiang, L. Li, E. Salvioni, 2401.08785)





EW Precision Constraints

- Heavy doublet mixing model:



$M \gtrsim 0.9\,\text{TeV}\ Y^2$ **from *T*-parameter**

Heavy doublet mass

Yukawa coupling between light and heavy states

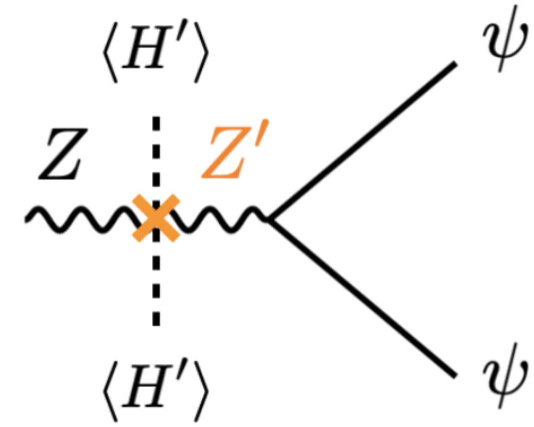
- Other constraints comparable or weaker

- Couplings of light eigenstates to Z suppressed by

$$\frac{Y^2 v^2}{M^2} \lesssim \text{few} \times 10^{-2}$$

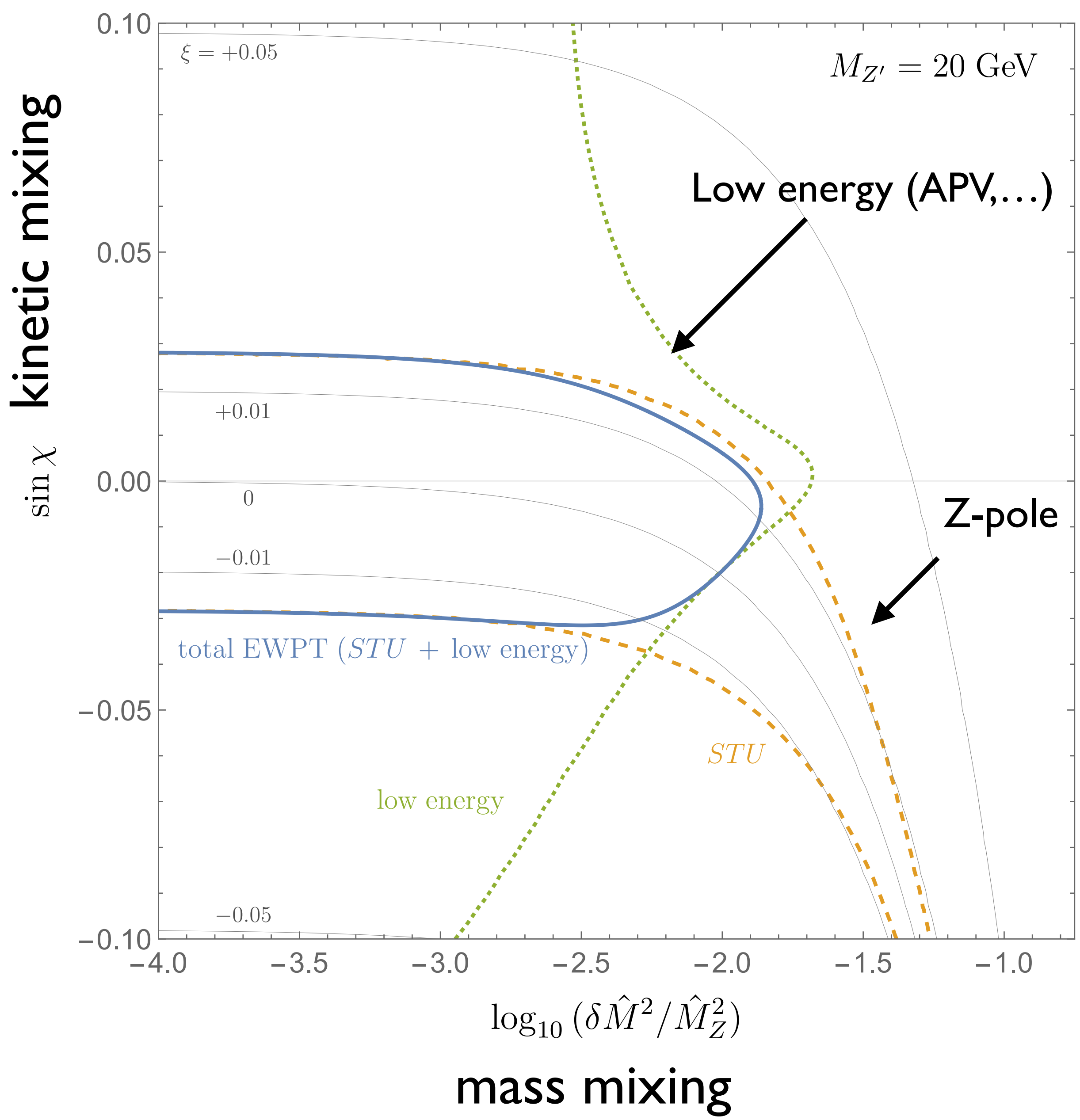
EW Precision Constraints

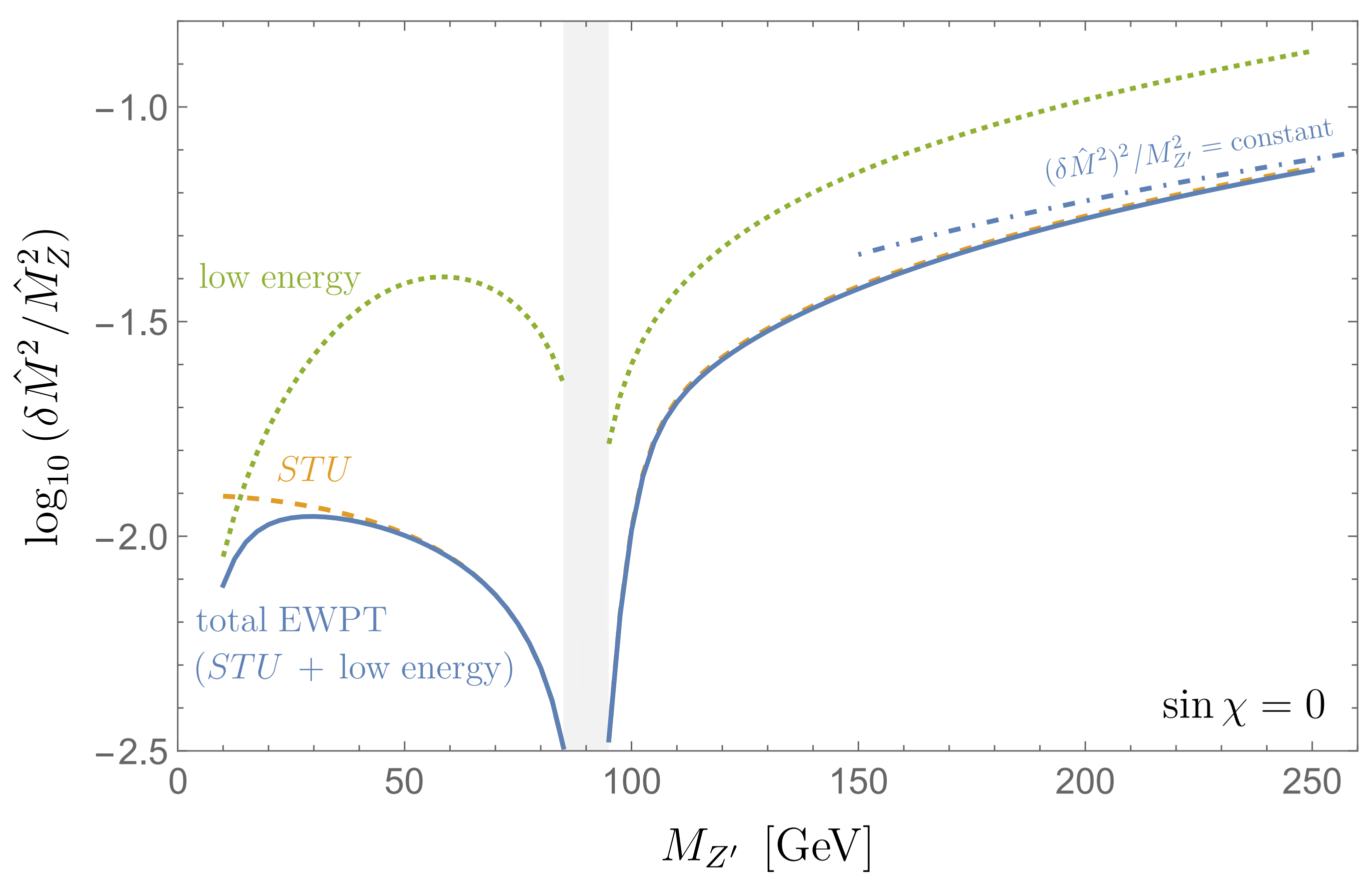
- $Z - Z'$ mixing model: Z pole data and low energy observables (for $M_{Z'} \gtrsim \Upsilon$ mass).



ξ :overall mixing between Z, Z'

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



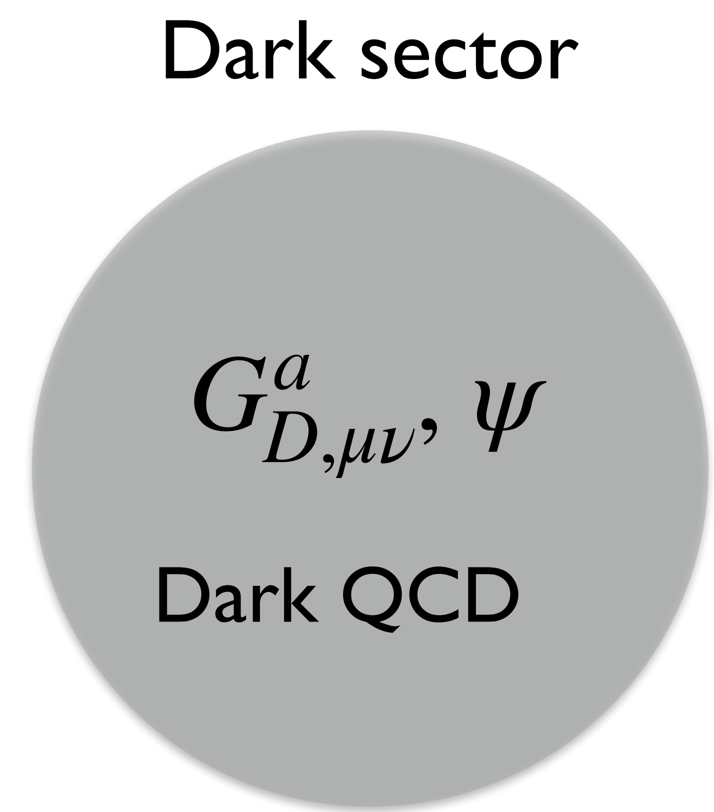


Dark QCD

- Motivated by solutions to the hierarchy problem (neutral naturalness, cosmological relaxation) and dark matter (SIMP, dark baryon).

- Interesting collider signals from dark showers at LHC. If (some) light dark hadrons decay back to SM $\Rightarrow$ semi-visible jets, emerging jets with displaced vertices, missing energies, depending on the lifetimes.

- The lightest dark hadrons are expected to be pseudo scalars (dark pions) if there are light dark quarks. [Focus of this talk]



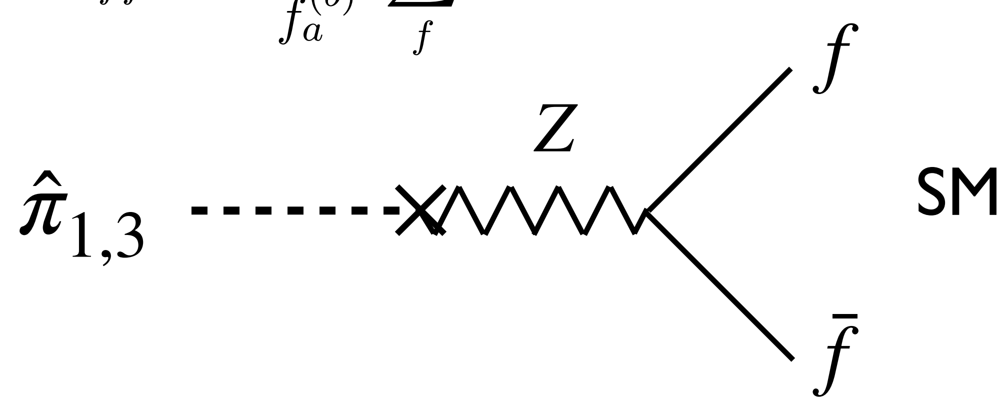
Dark Pion Decays

Dark pions: $\hat{\pi}_a \sim \overline{\psi}' i\sigma_a\gamma_5\psi'$ (for N=2), ψ' : mass eigenstates

- CP-odd dark pions behave like ALP and decay through mixing with the longitudinal mode of Z (and Z') with effective ALP decay constants $f_a \gtrsim$ PeV for $f_{\hat{\pi}} \sim 1$ GeV

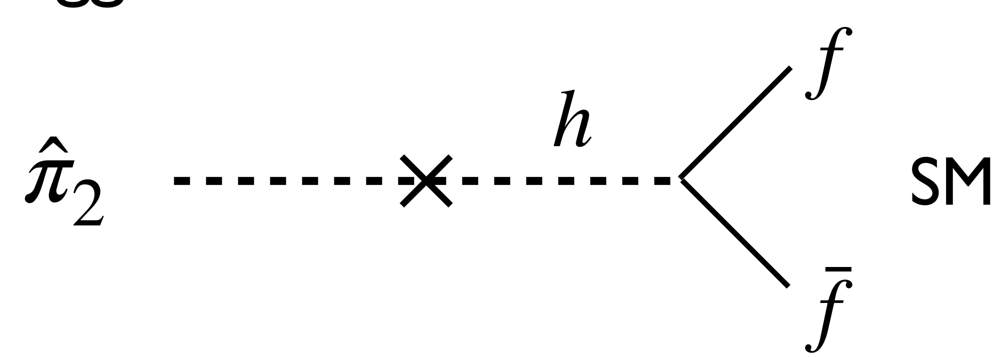
$$\mathcal{L}_{\hat{\pi}f\bar{f}} = -\frac{\partial_\mu\hat{\pi}_b}{f_a^{(b)}}\sum_f a_f\bar{f}\gamma^\mu\gamma_5 f$$

$\hat{\pi}_{1,3}$, CP odd $(J^{PC} = 0^{-+})$



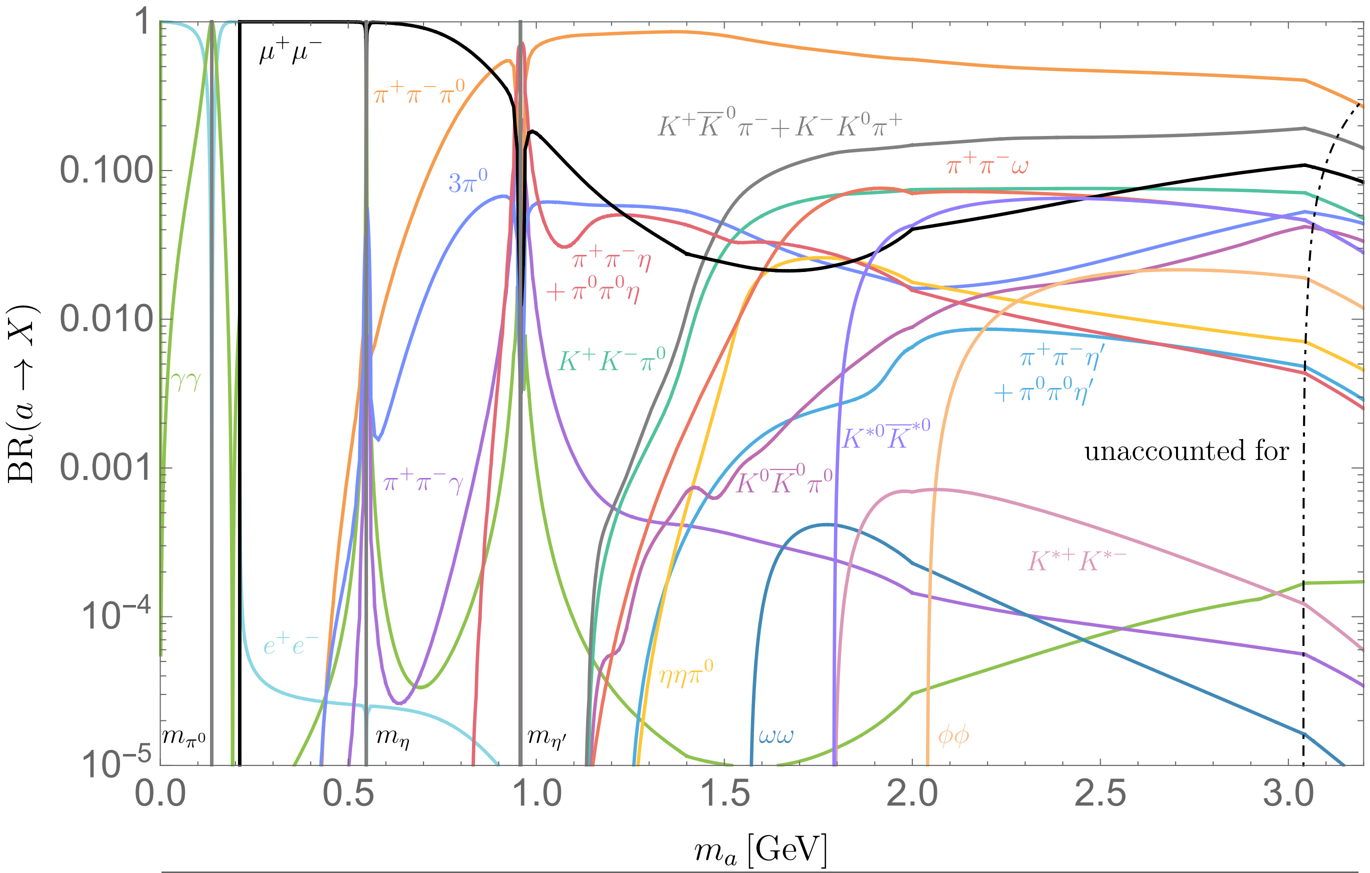
- CP-even dark pions decay through Higgs

$\hat{\pi}_2$, CP even $(J^{PC} = 0^{--})$



*Without a conserved U(1) flavor symmetry, $\hat{\pi}_1, \hat{\pi}_2$ are distinct states.
*They will mix if CP is violated in the dark sector.

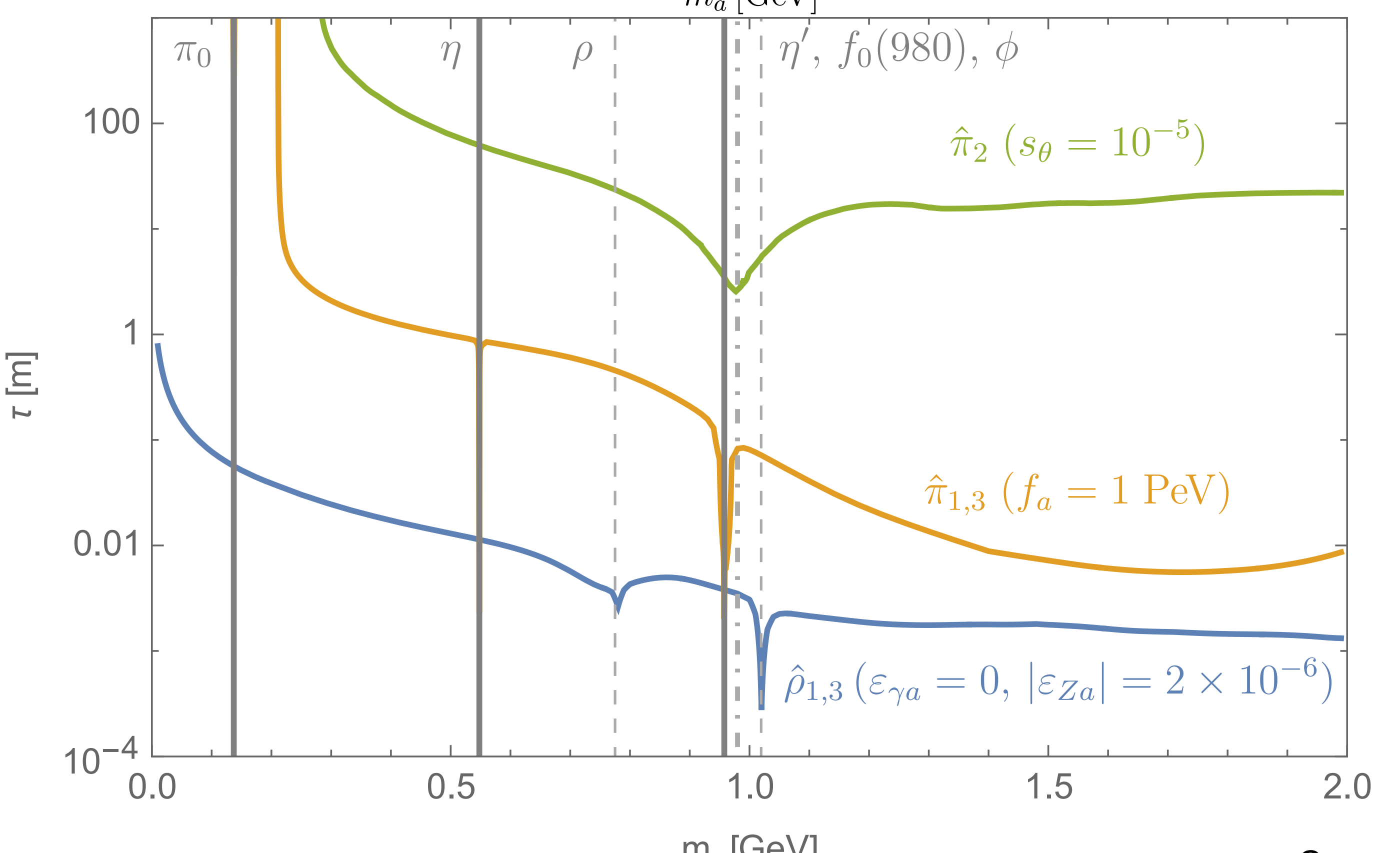
Dark Pion Decays



(CP-odd)

HC, Li, Salvioni, 2110.10691, using data driven method (Aloni et al, 1811.03474)

$\mathrm{Br}(\hat{\pi} \to \mu^+\mu^-) \gtrsim$ few% for $2m_\mu < m_{\hat{\pi}} \lesssim 3$ GeV

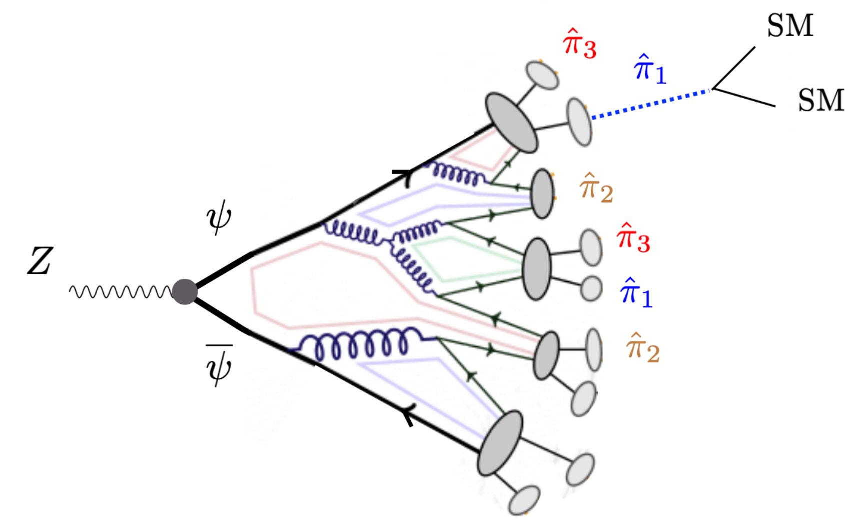


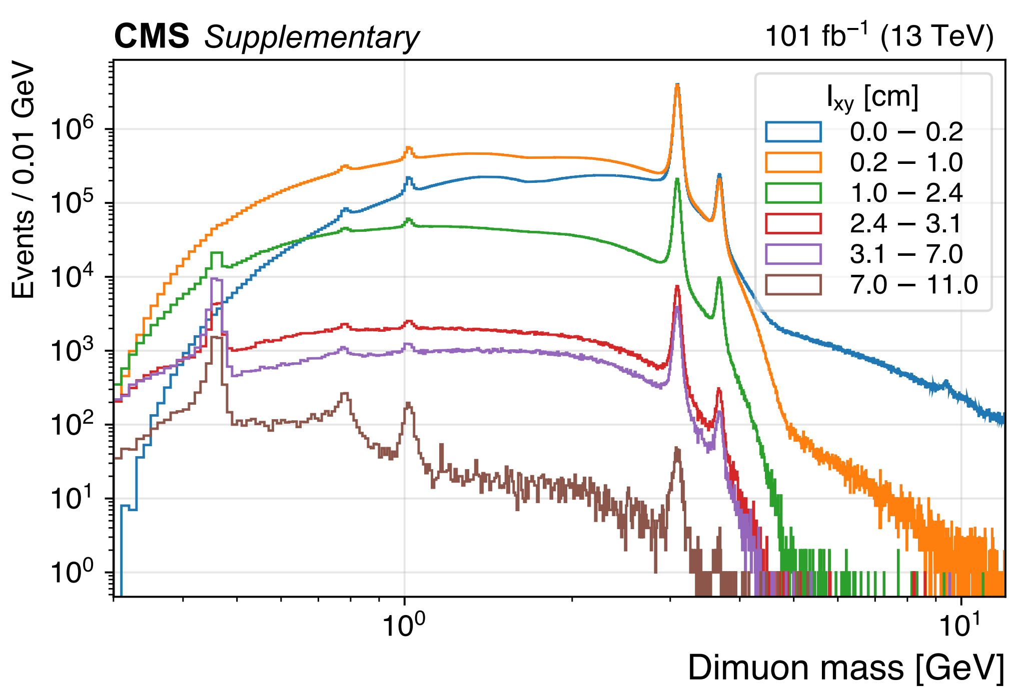
For $2m_\mu < m_{\hat{\pi}} < 3$ GeV, $f_a \sim 1$ PeV, dark pion decays through Z-portal have decay lengths in the most interesting range of few mm to 100 m at colliders.

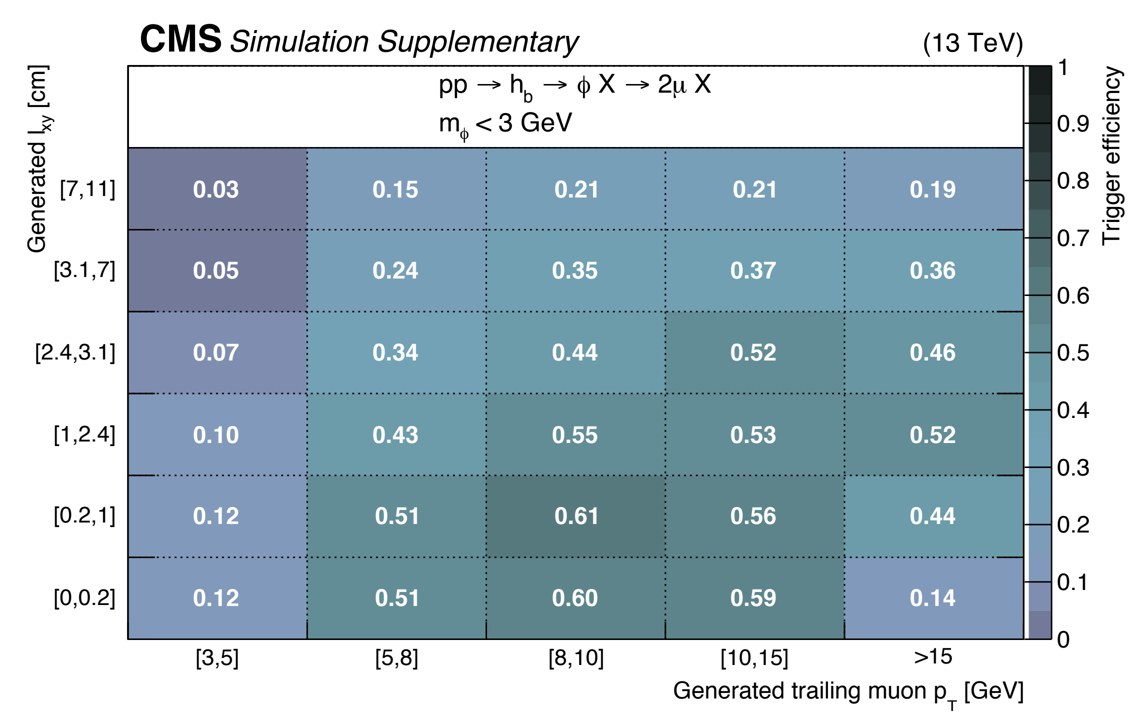
Dark Shower Searches

The final states of dark showers from *Z* decays are soft, therefore hard to trigger. On the other hand, dark pions are typically long-lived. Displaced decays give a great handle.

- CMS scouting search (2112.73169): Reduces the trigger threshold online. Data containing muon pairs that pass low-level triggers are recorded, keeping only simplified information of the events.

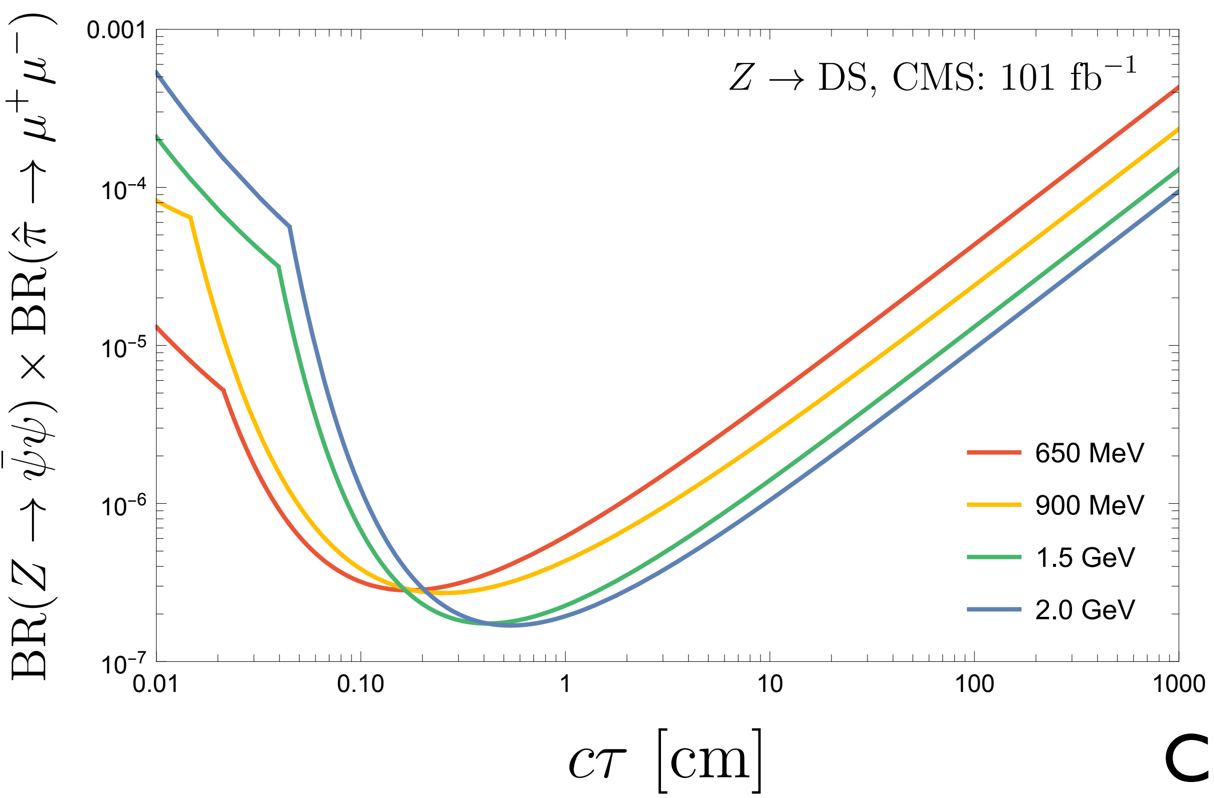




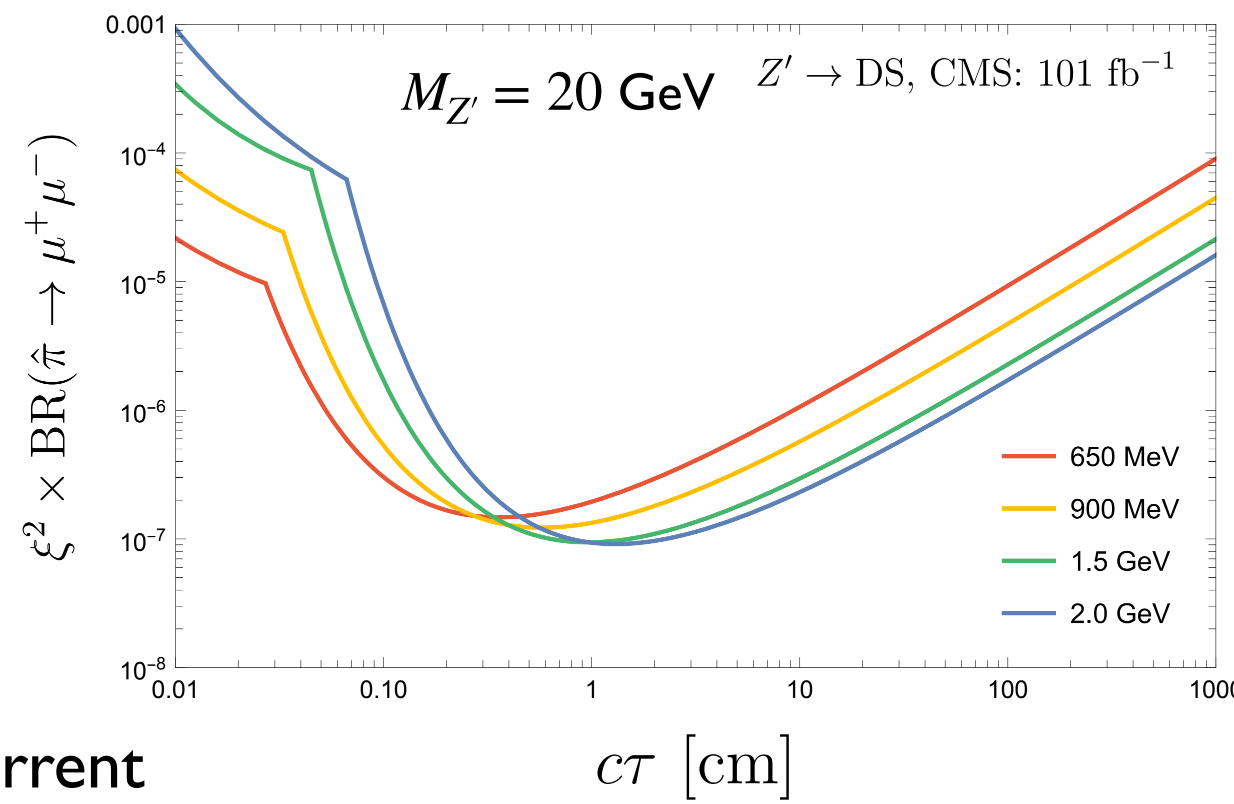


CMS Scouting Search

- Recast CMS scouting search (using the Hidden Valley module in PYTHIA8), with some conservative assumptions. Model independent bounds (for 1 DV).

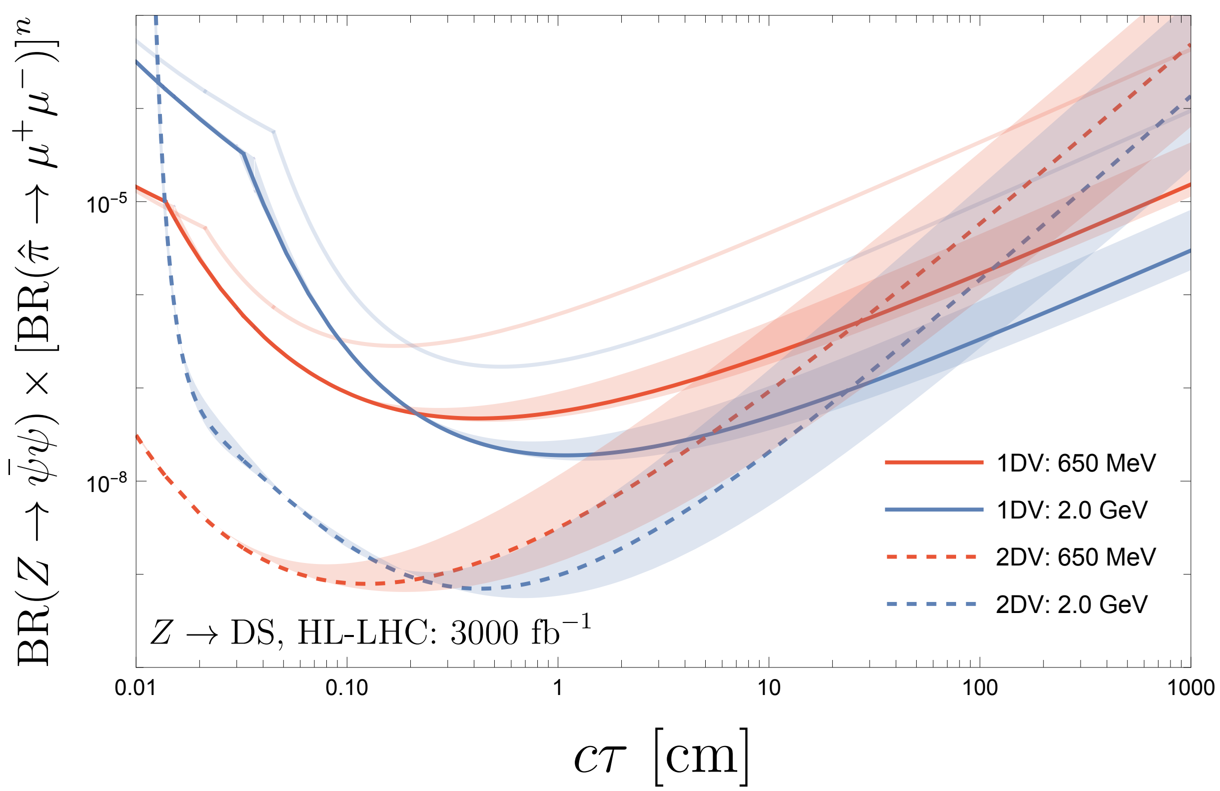


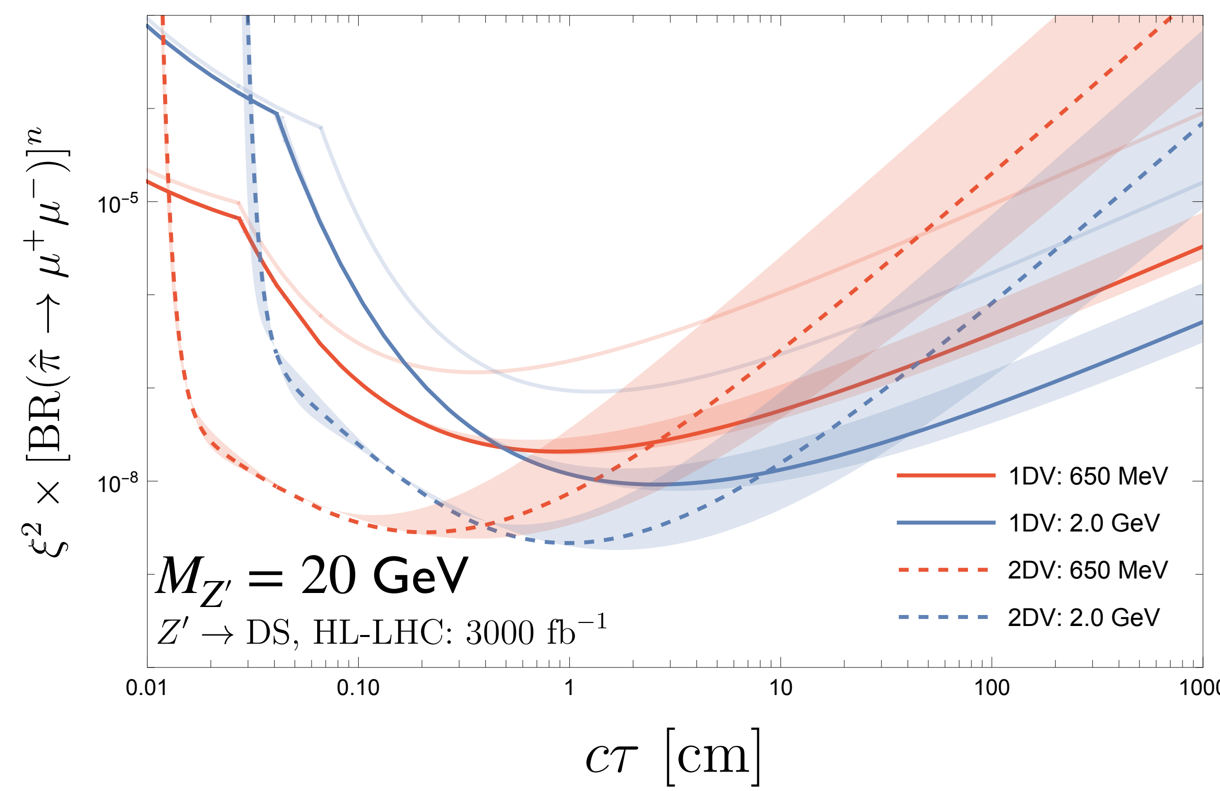
Current



CMS Scouting Search

- Future projections (with assumptions of improved trigger efficiency and extended l_{xy} reach 11 cm → ~ 90 cm):

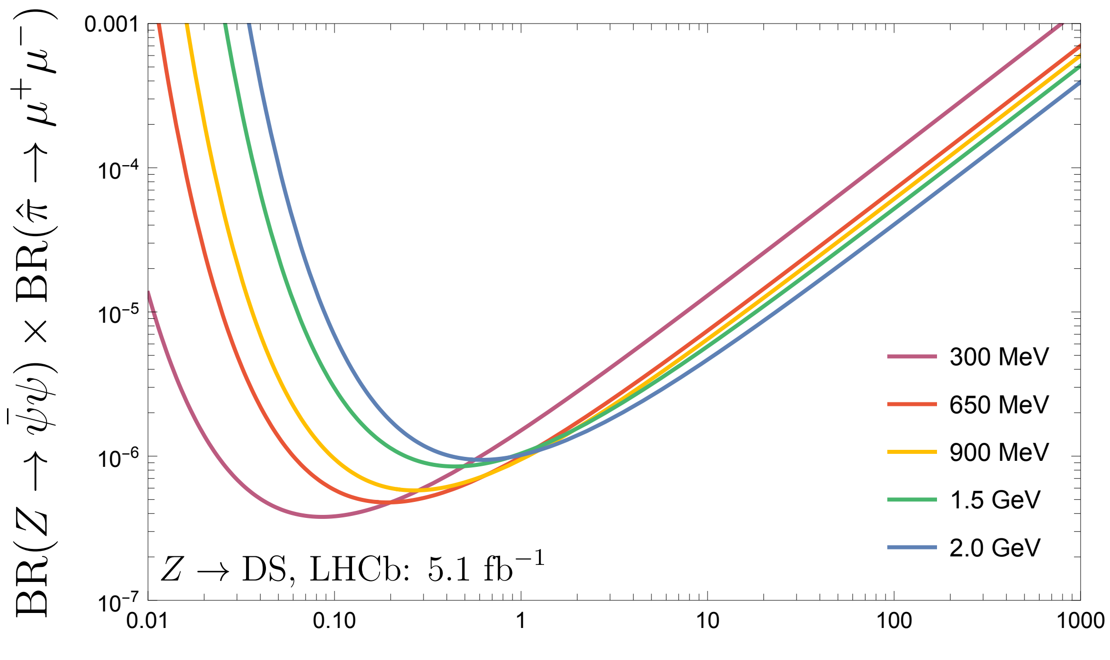


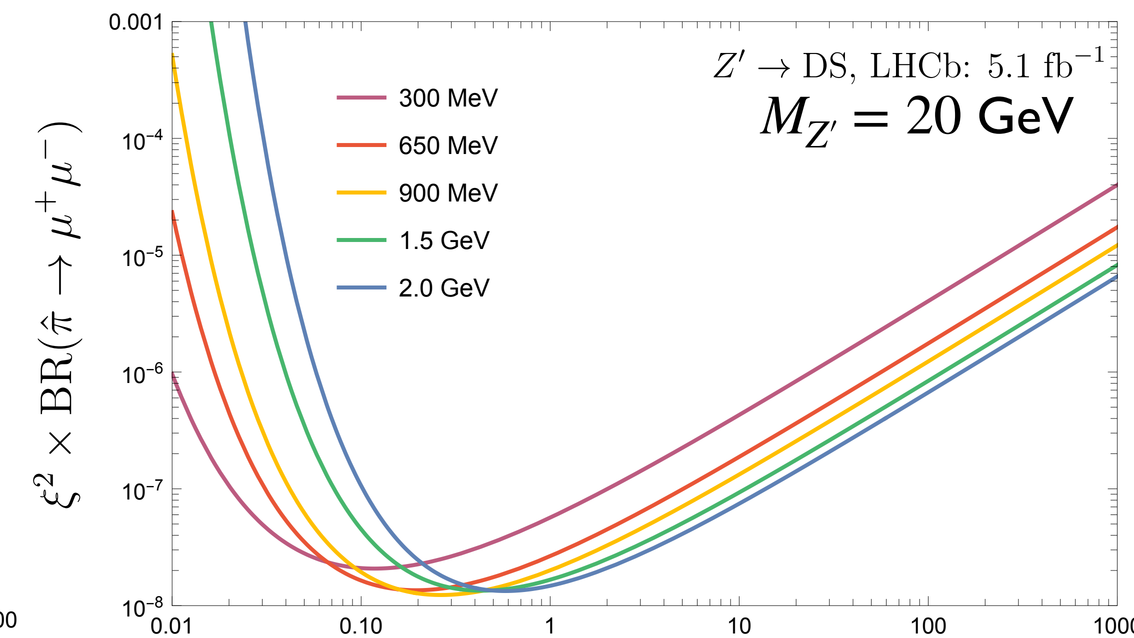


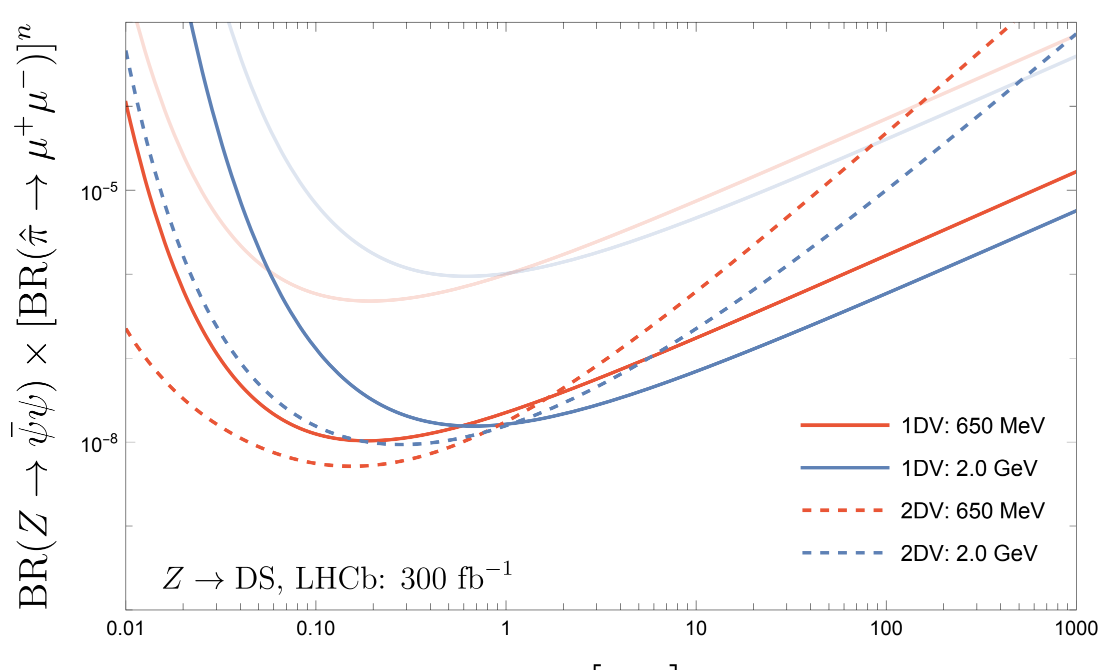
For 2DV, we assume each DV's trigger and detector efficiencies are independent, and the overall efficiency is the product of the two. It should be background free and is most effective when the dark pion lifetime makes the trigger efficiency optimal.

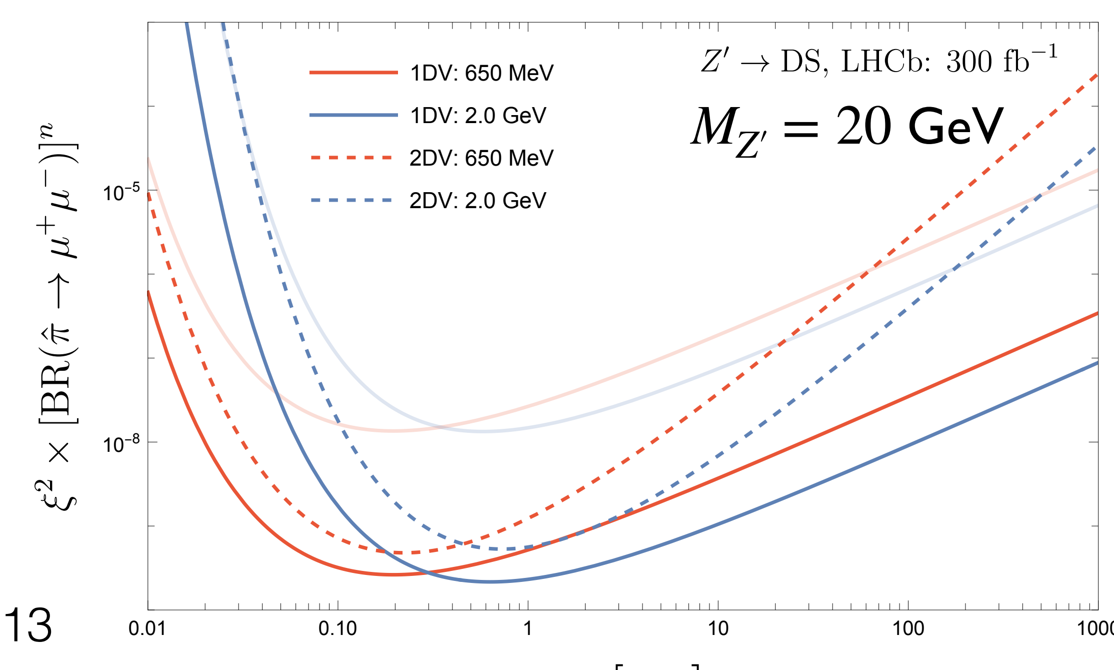
LHCb

- LHCb detector with low trigger thresholds and high vertex resolutions is powerful to look for dimuon DV’s from dark showers, especially for lifetime smaller than O(cm). Recast follows the LHCb analysis, 2007.03923.



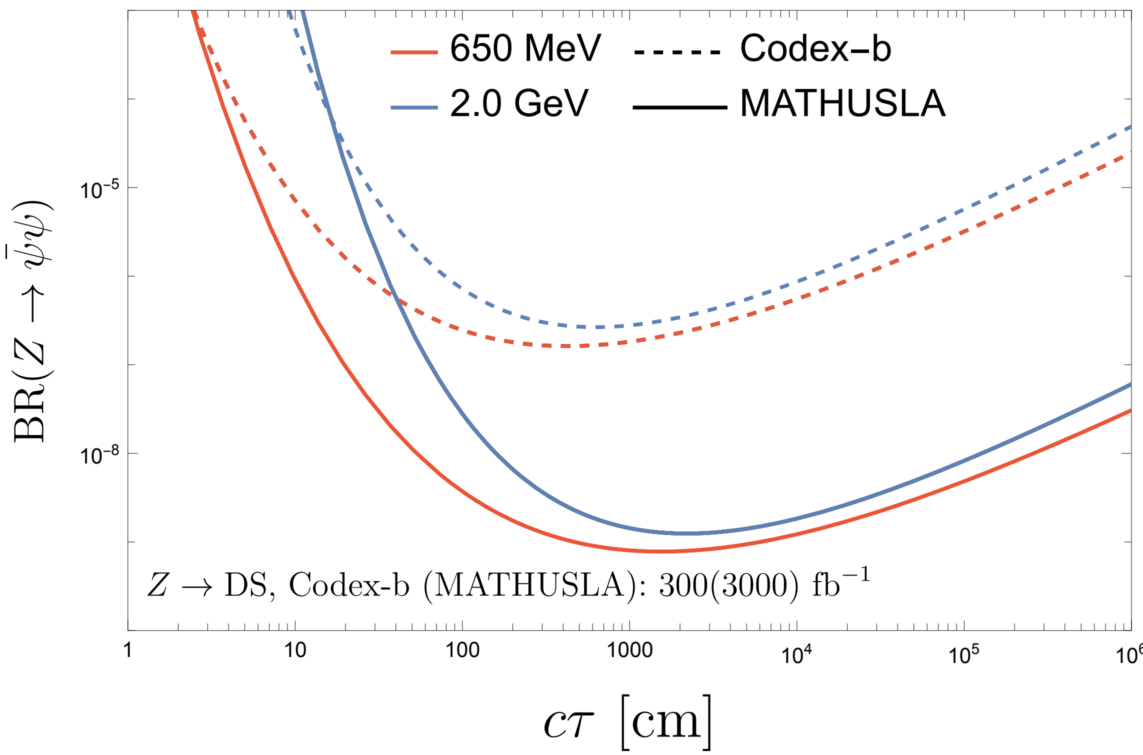


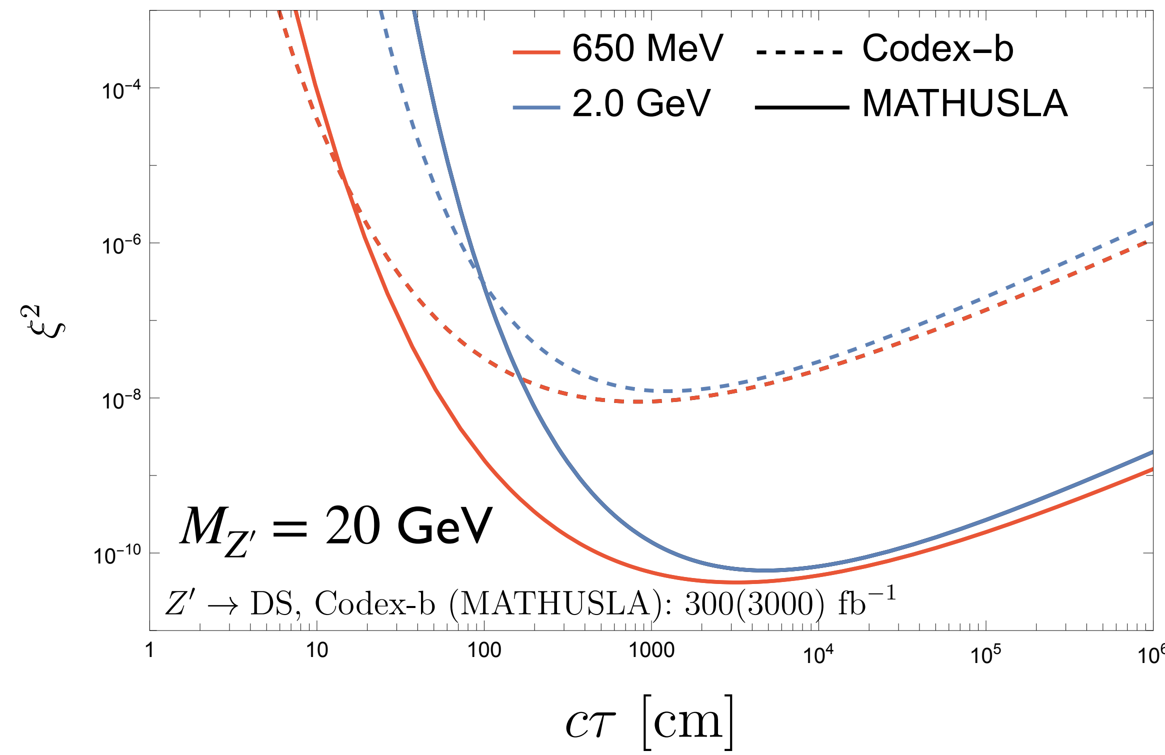




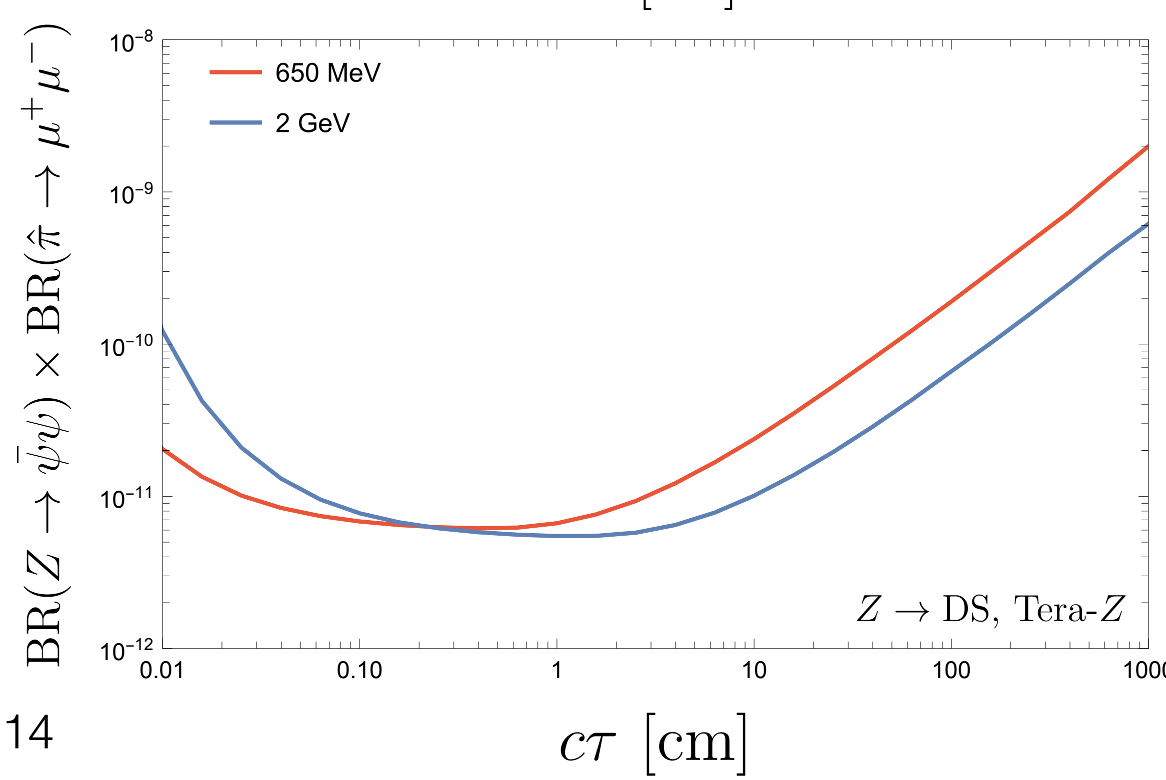
Auxiliary Detectors and Z-Factory

- Auxiliary detectors are good for longer dark pion decay lengths. They are expected to be mostly background free.





*MATHUSLA and Codex-b reaches are based on original designs. They may need to be scaled down with the budget/space limitations.

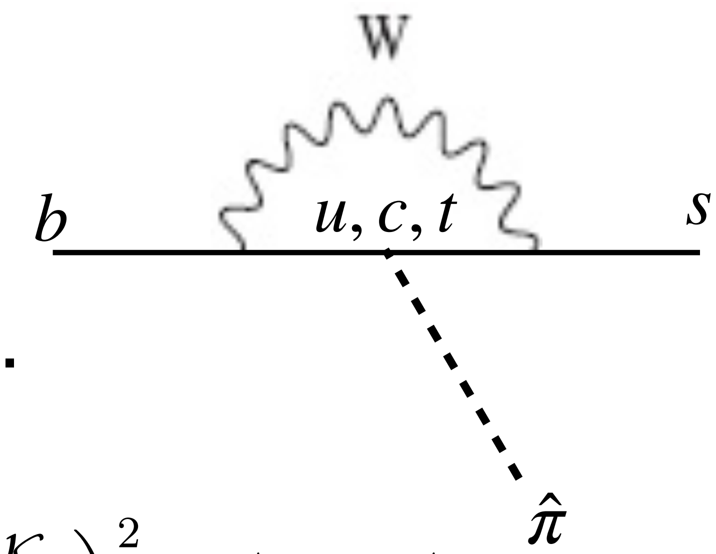


Tera-Z: $p_{T,\mu} > 0.5$ GeV, $|p_\mu| > 10$ GeV and $|\eta_\mu| < 5$

$p_{T,\mu\mu} > 2$ GeV $\quad l_{xy} \in [0.5, 100]$ cm

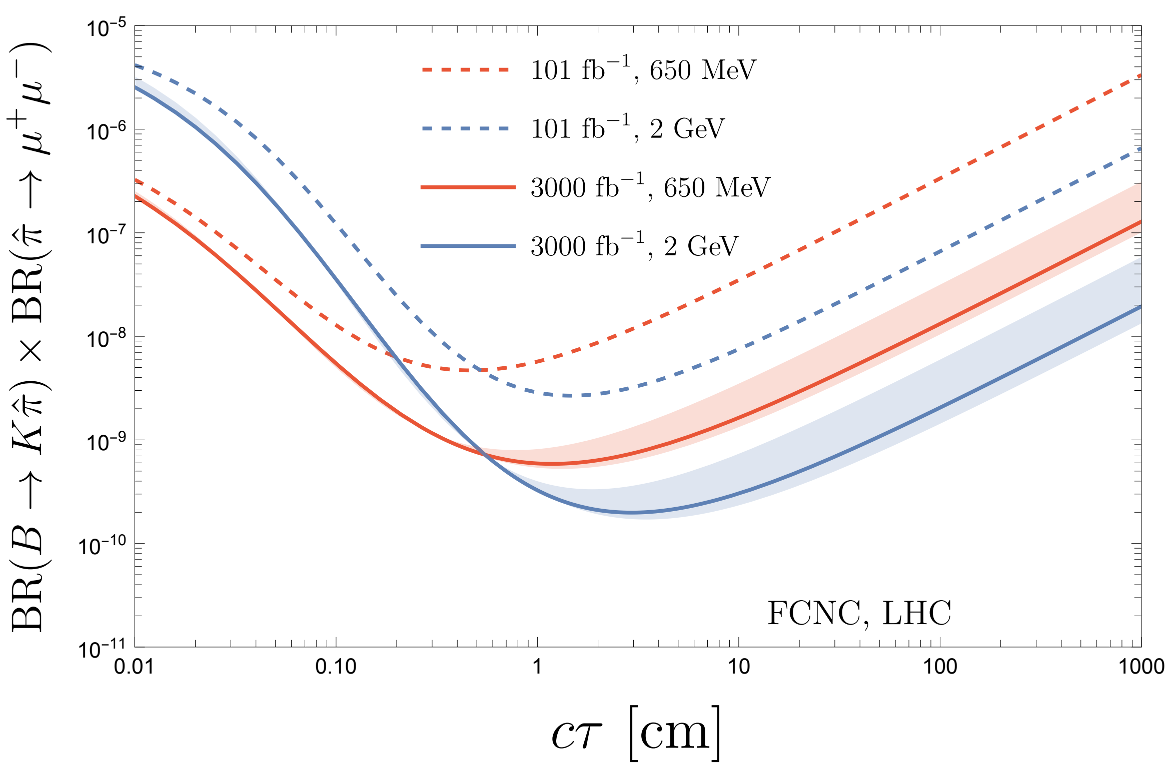
Dark Hadron Production from FCNC

- Light dark hadrons can also be produced by Meson (B, D, K) FCNC decays if the phase space is open. For dark pions, production mainly depend effective ALP decay constant f_a.

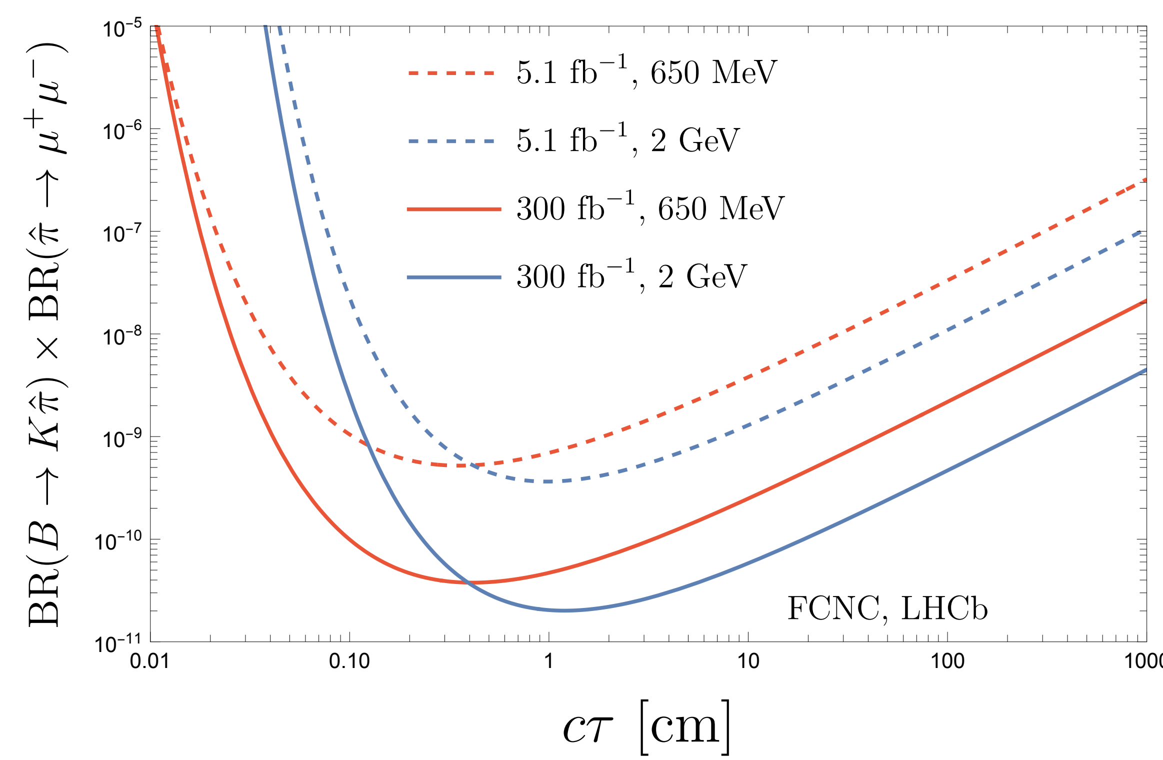


$$\mathrm{BR}(B^{+,0} \to \{K^+\hat{\pi}_b, K^{*0}\hat{\pi}_b\}) \approx \{0.92, 1.1\} \times 10^{-8} \left(\frac{1\ \mathrm{PeV}}{f_a^{(b)}}\right)^2 \left(\frac{\mathcal{K}_t}{10}\right)^2 \{\lambda^{1/2}_{BK\hat{\pi}}, \lambda^{3/2}_{BK^*\hat{\pi}}\},$$

CMS Scouting



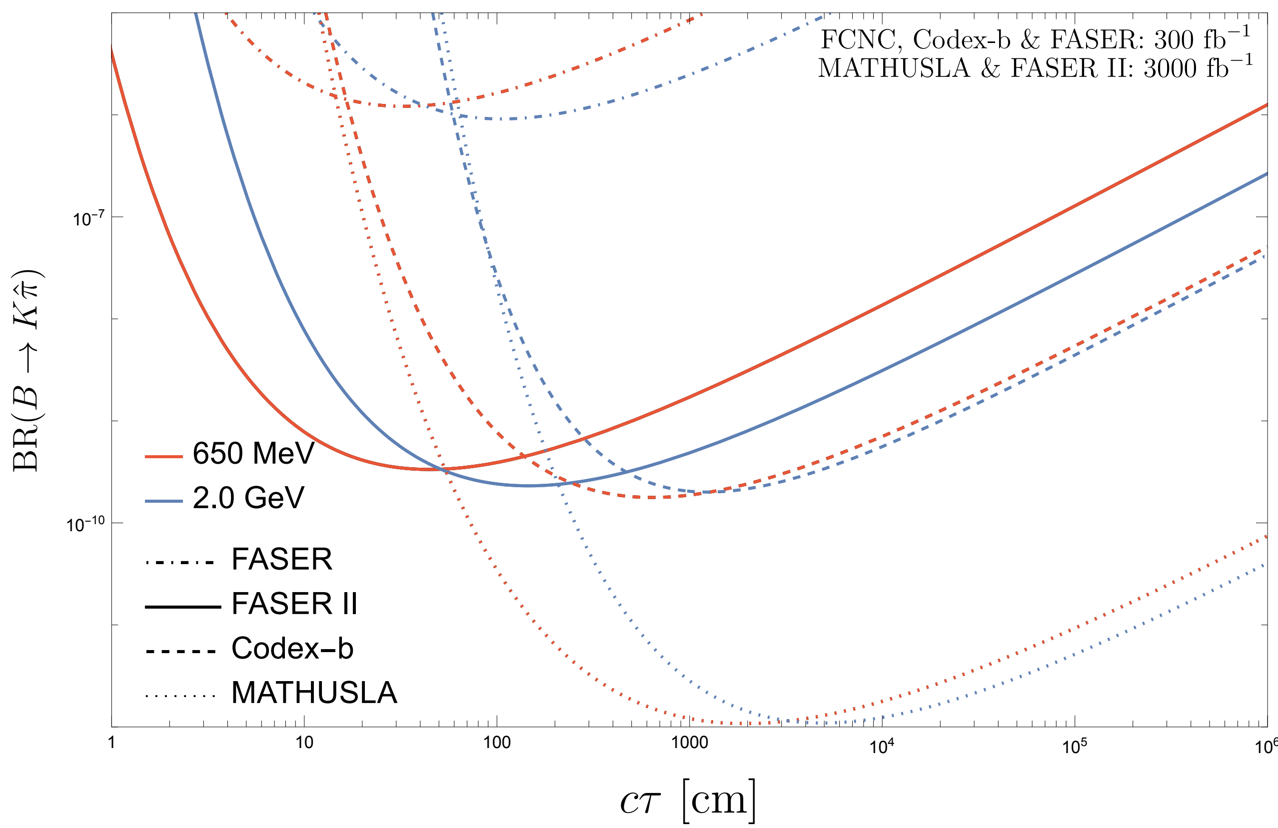
LHCb



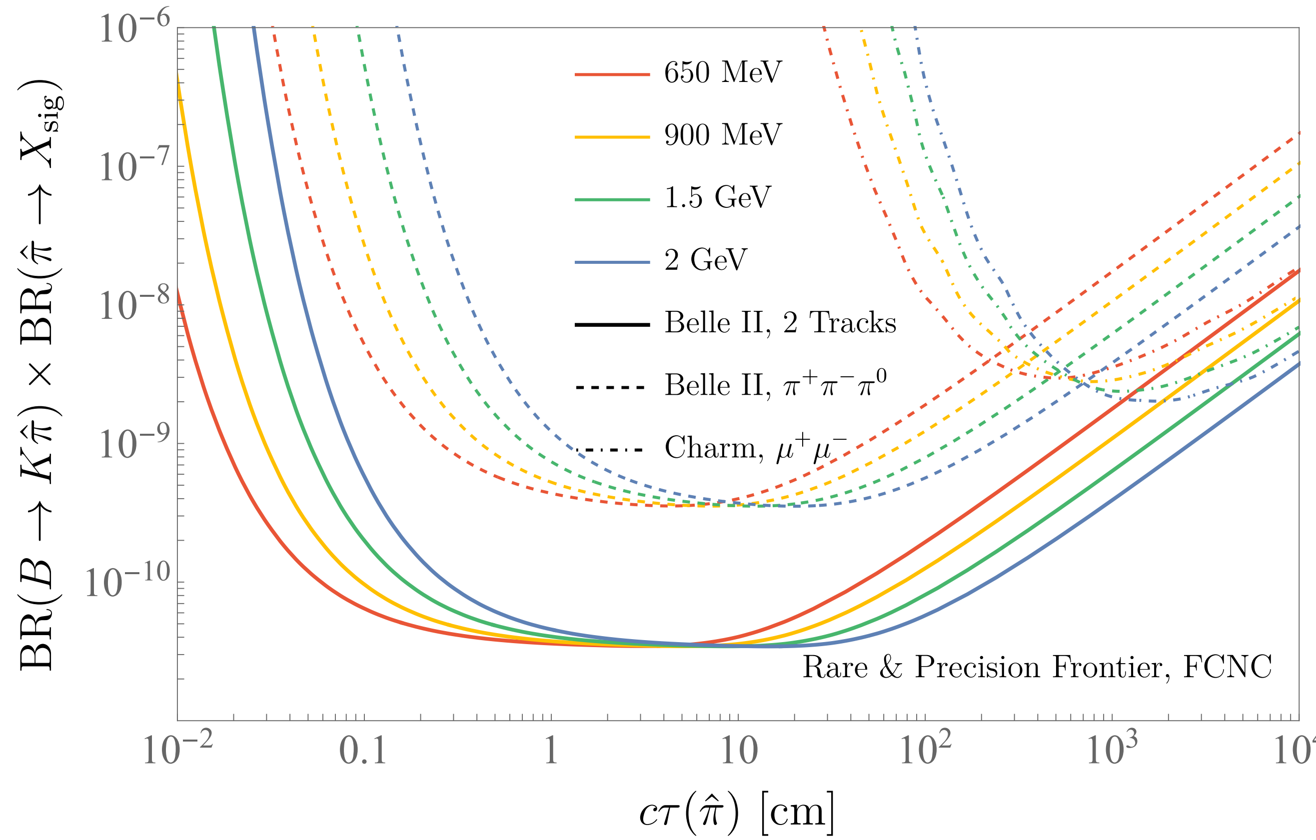
Dashed: current; Solid: future HL-LHC projection

FCNC Reaches from Other Experiments

Auxiliary detectors



B-factory and fixed target exp

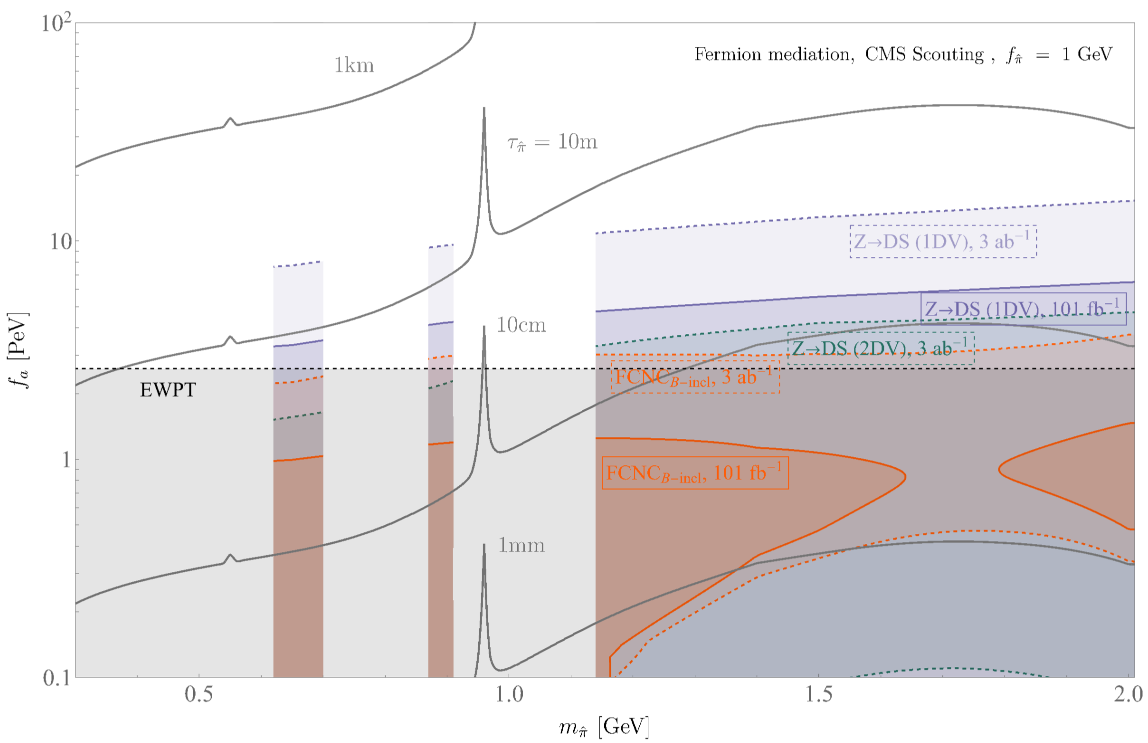


Bounds on Benchmark Models

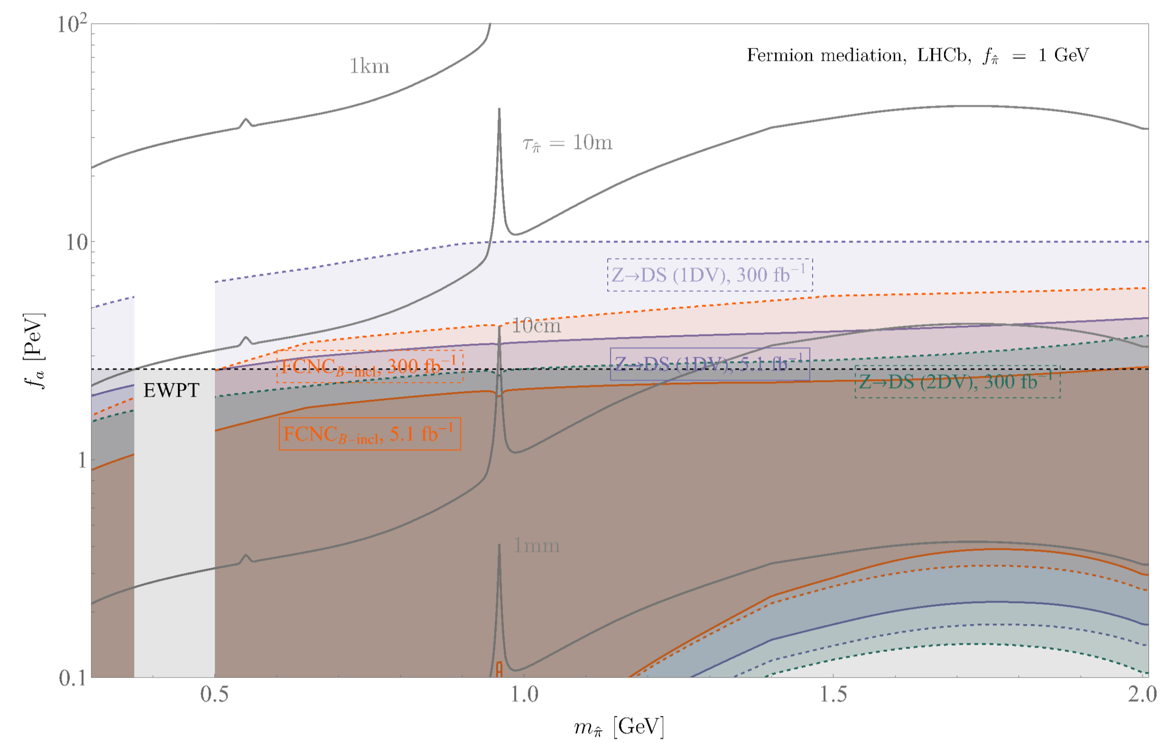
- To compare reaches of different experiments and production mechanisms, specific benchmark models are needed to obtain model-dependent bounds.

Fermion doublet mixing model: $\tilde{Y} = 0$, set $\tilde{\pi}_1, \tilde{\pi}_3$ lifetimes equal by choosing $y_{11} = y_{12}(1+\sqrt{2})$, $y_{21} = y_{22} = 0$

CMS scouting



LHCb

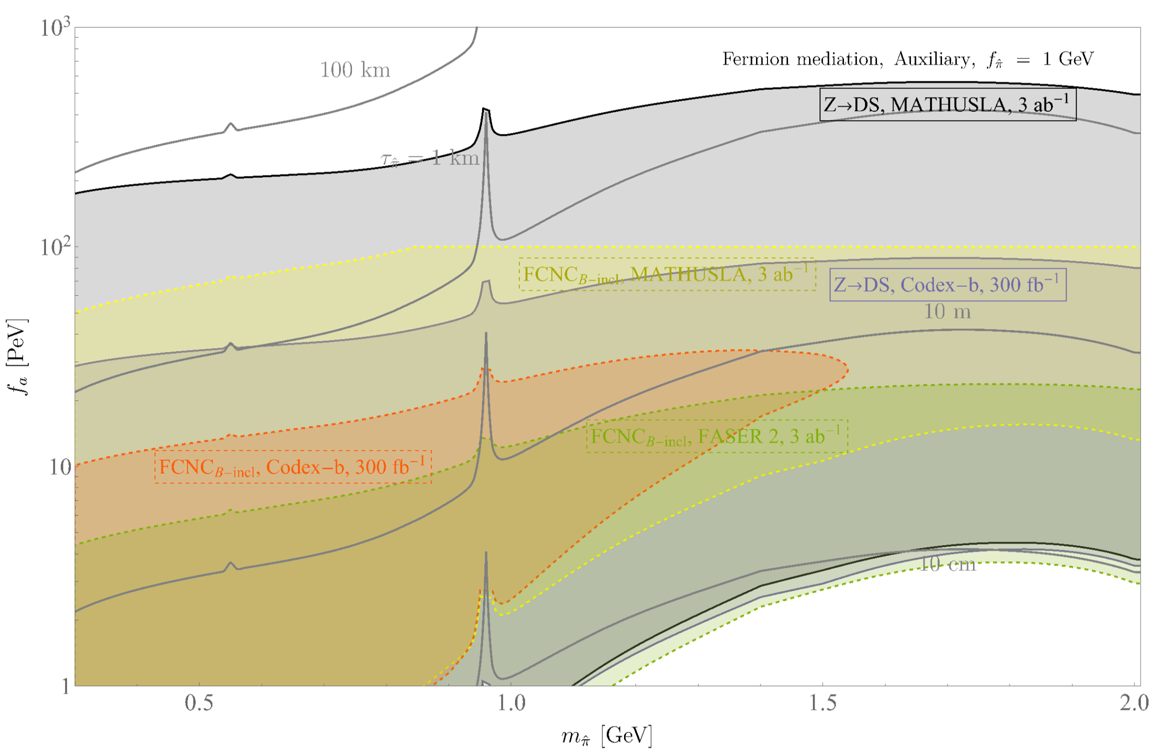


The relative strengths of dark shower and FCNC reaches depends on $f_{\hat{\pi}}$.
For $f_{\hat{\pi}} = 1$ GeV, DS > FCNC. Dark shower reaches decrease as $f_{\hat{\pi}}$ increases.

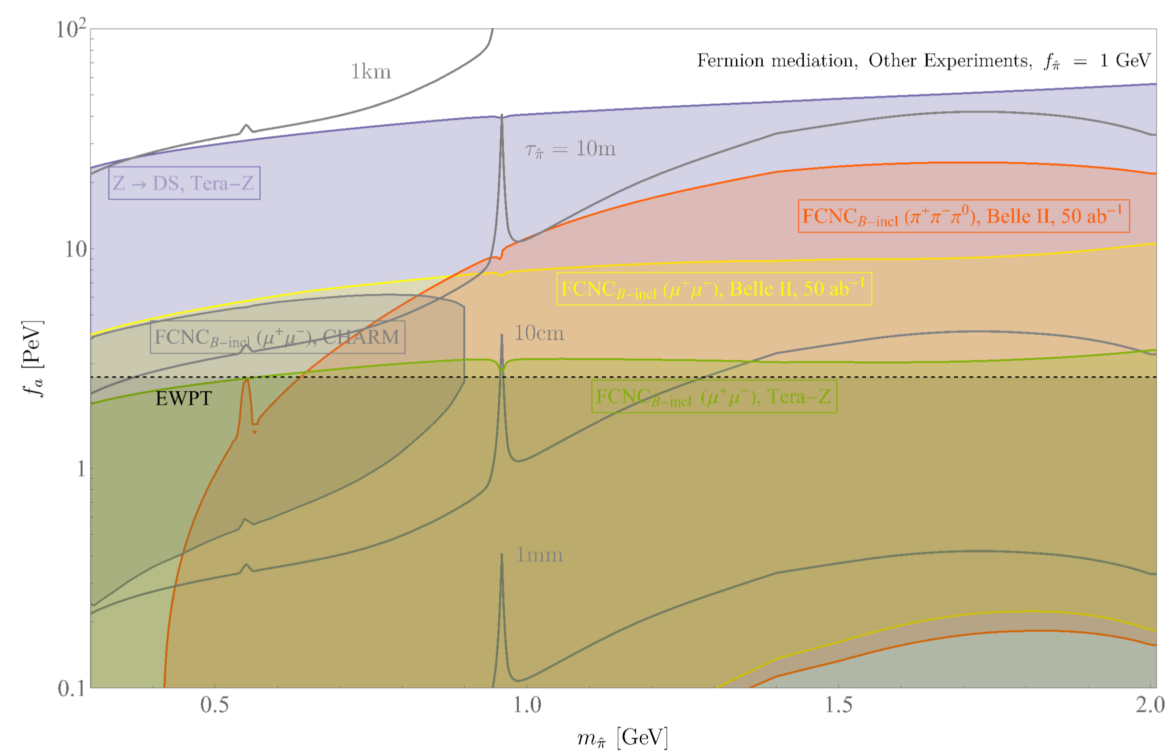
Reaches of Benchmark Models

- Higher f_a implies longer decay length. Experiments sensitive to longer decay lengths have strong reaches in f_a.

Auxiliary detectors



Intensity frontier



Conclusions

- The Z boson can be an interesting portal to the dark sector. More than 10^{11} Z bosons will be produced at HL-LHC, providing a great opportunity to explore this scenario.
- Dark showers from Z-portal decays give exciting experimental signals, which are quite challenging. New search strategies and techniques (e.g. data scouting and parking) will be crucial to explore them.
- Additional auxiliary detectors at the LHC (FASER, MATHUSLA, CODEX-b) will be helpful for dark pions with longer decay lengths. A future *Z*-factory will be very powerful in extending the search reaches. Other fixed target experiments and Belle II provide complementary tests through FCNC meson decays.