

# 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.xxxxxx

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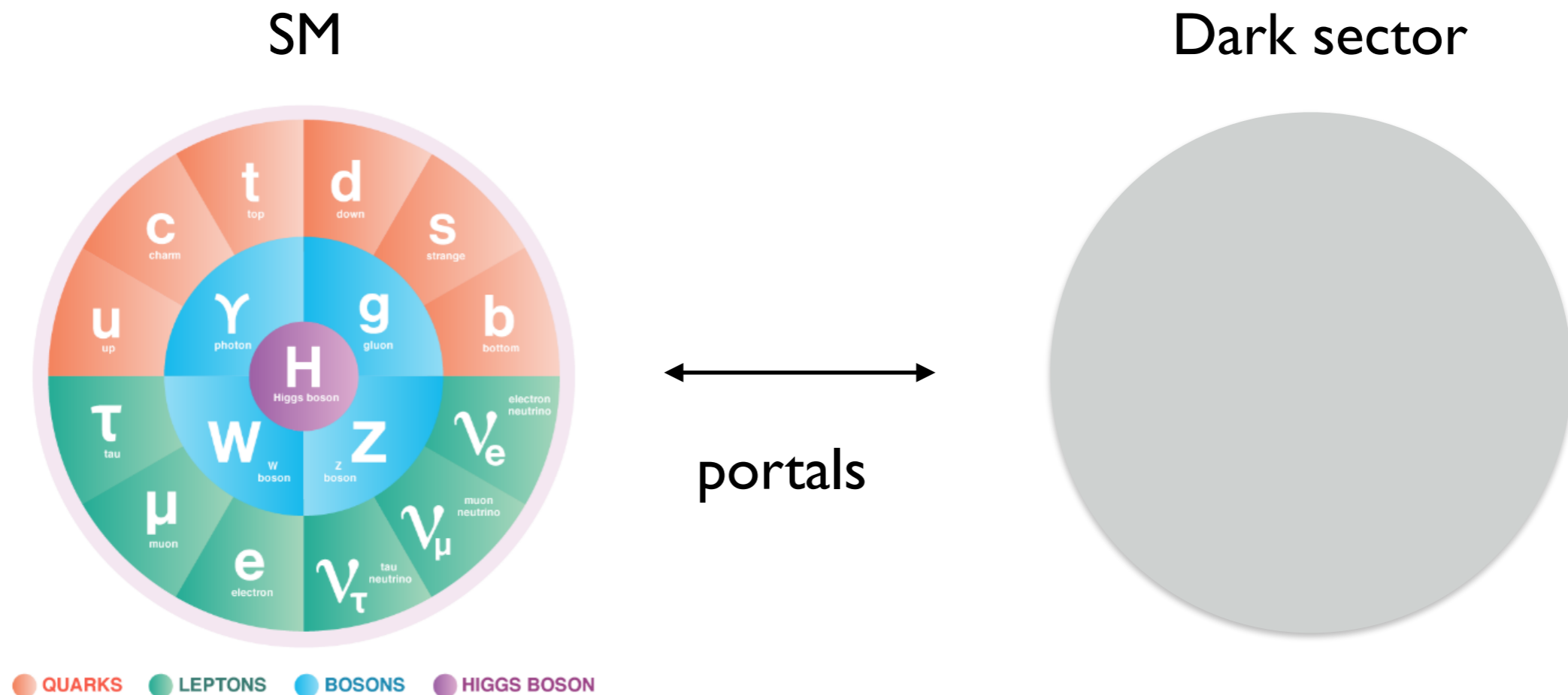
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# Introduction



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

# Portal interactions

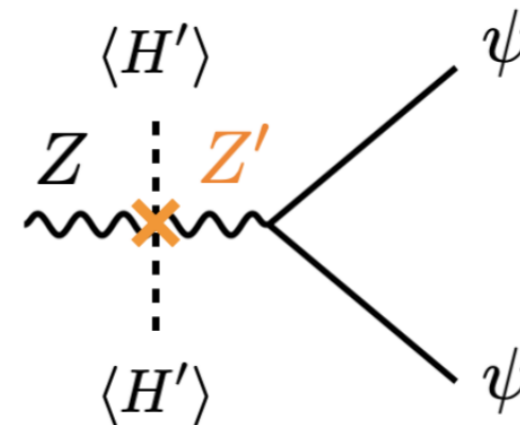
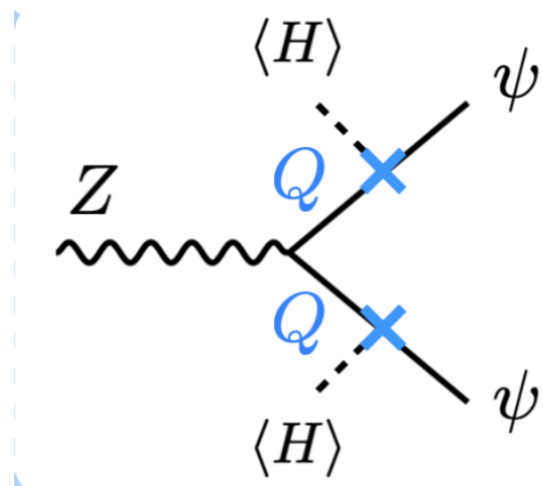
- Heavy states ( $> \text{TeV}$ ,  $X_{DK}$ ,  $Z'$ , etc)
- Higgs or  $Z$
- Dark photon kinetically mixed with photon
- Neutrinos

# Z-portal

- An interesting scenario which is less studied.

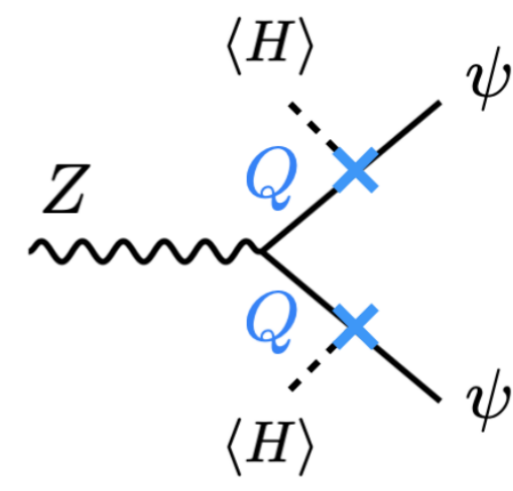
$$\sigma(pp \rightarrow Z) \approx 54.5; (58.9); \text{nb}, \quad \sigma(pp \rightarrow h) \approx 48.6; (54.7); \text{pb} \quad \text{for } 13(14)\text{TeV}$$

- 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 particles 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:



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

Heavy doublet mass

Yukawa coupling between light and heavy states

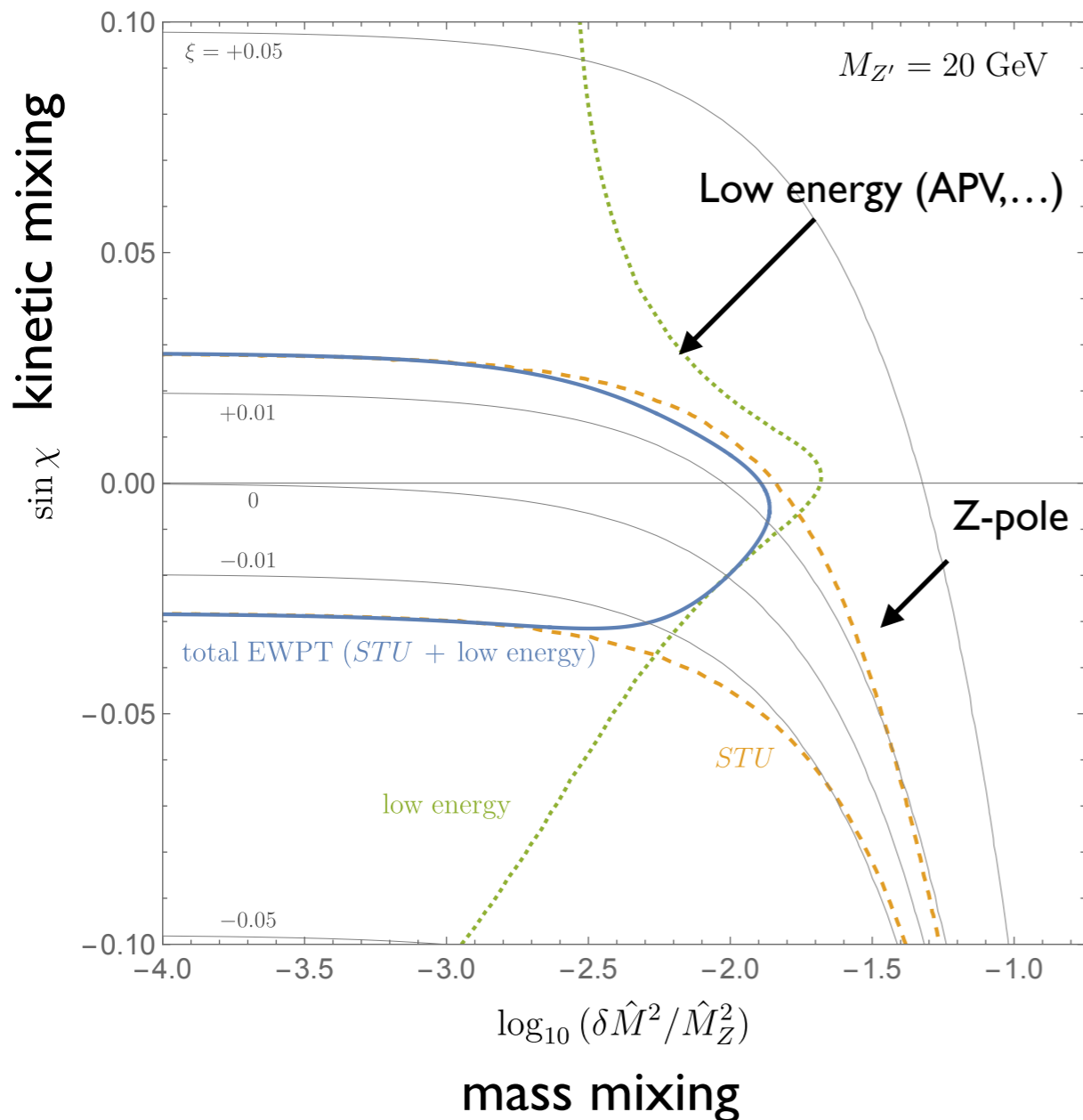
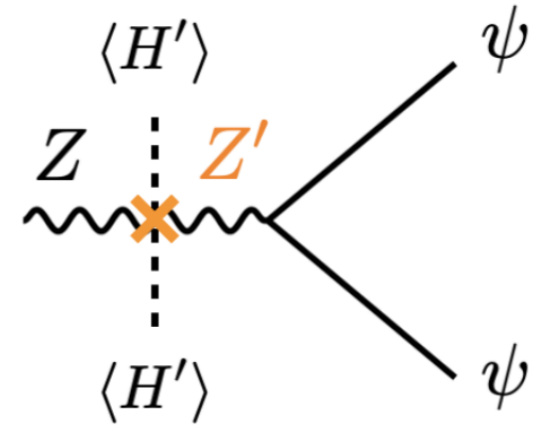
- Other constraints comparable or weaker
- Couplings of light eigenstates to Z suppressed by

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

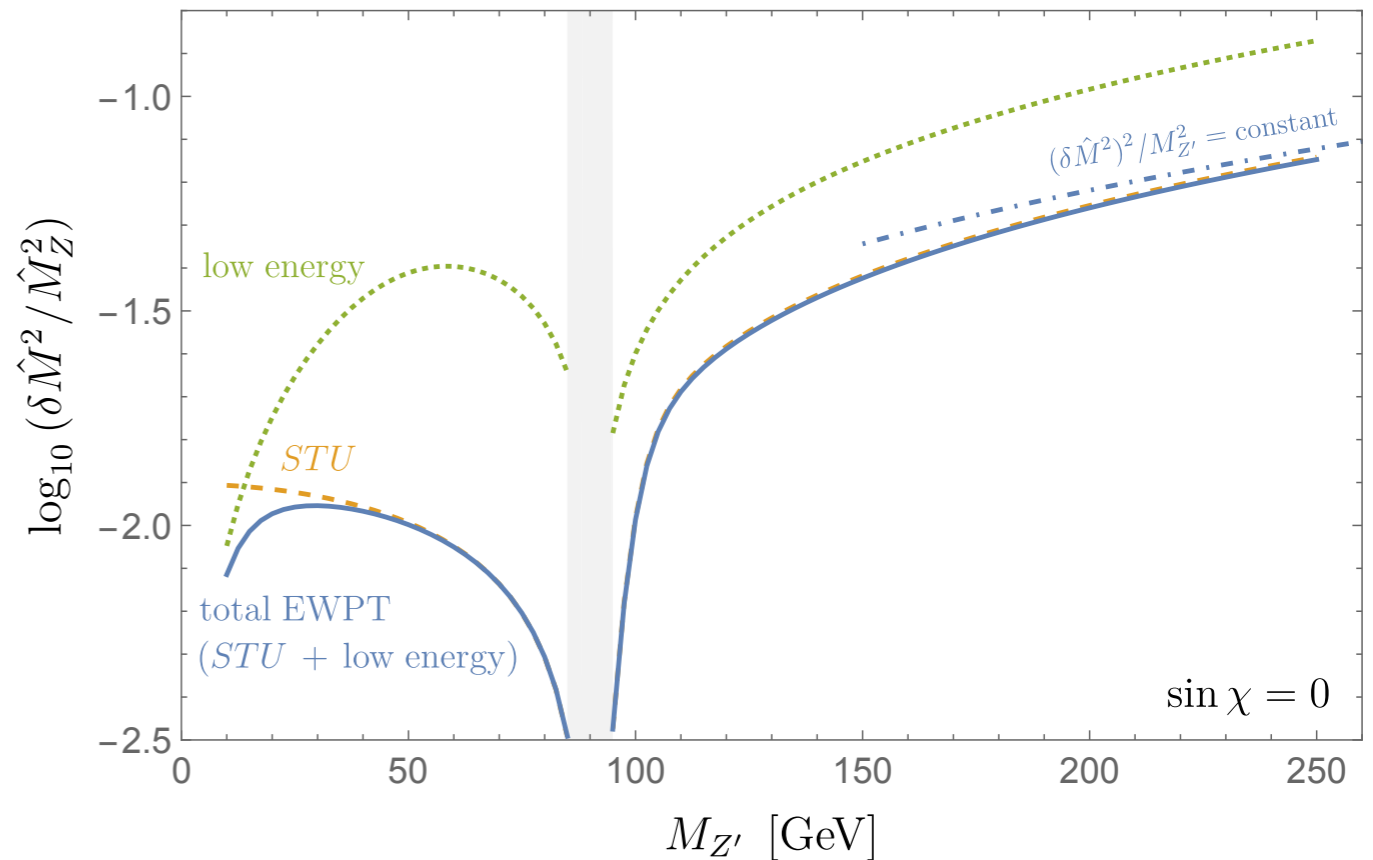
# EW Precision Constraints

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

$\xi$  : 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 sector

$$G_{D,\mu\nu}^a, \psi$$

Dark QCD

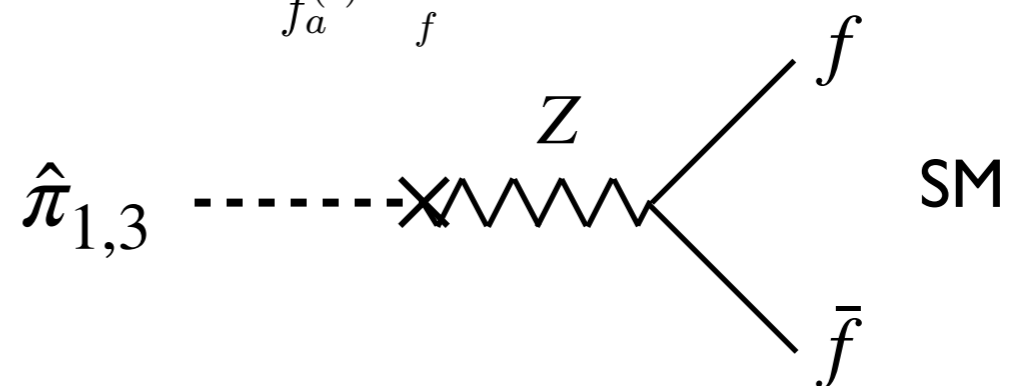
# Dark Pion Decays

Dark pions:  $\hat{\pi}_a \sim \bar{\psi}' i\sigma_a \gamma_5 \psi'$  (for N=2),  $\psi'$  : 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**  $f_a \gtrsim \text{PeV}$  for  $f_{\hat{\pi}} \sim 1 \text{ GeV}$

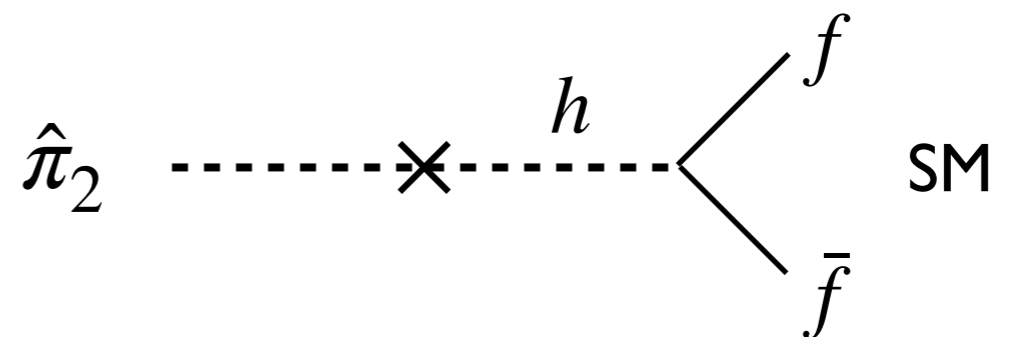
$$\mathcal{L}_{\hat{\pi}f\bar{f}} = -\frac{\partial_\mu \hat{\pi}_b}{f_a^{(b)}} \sum_f a_f \bar{f} \gamma^\mu \gamma_5 f$$

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



- CP-even dark pions decay through Higgs

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

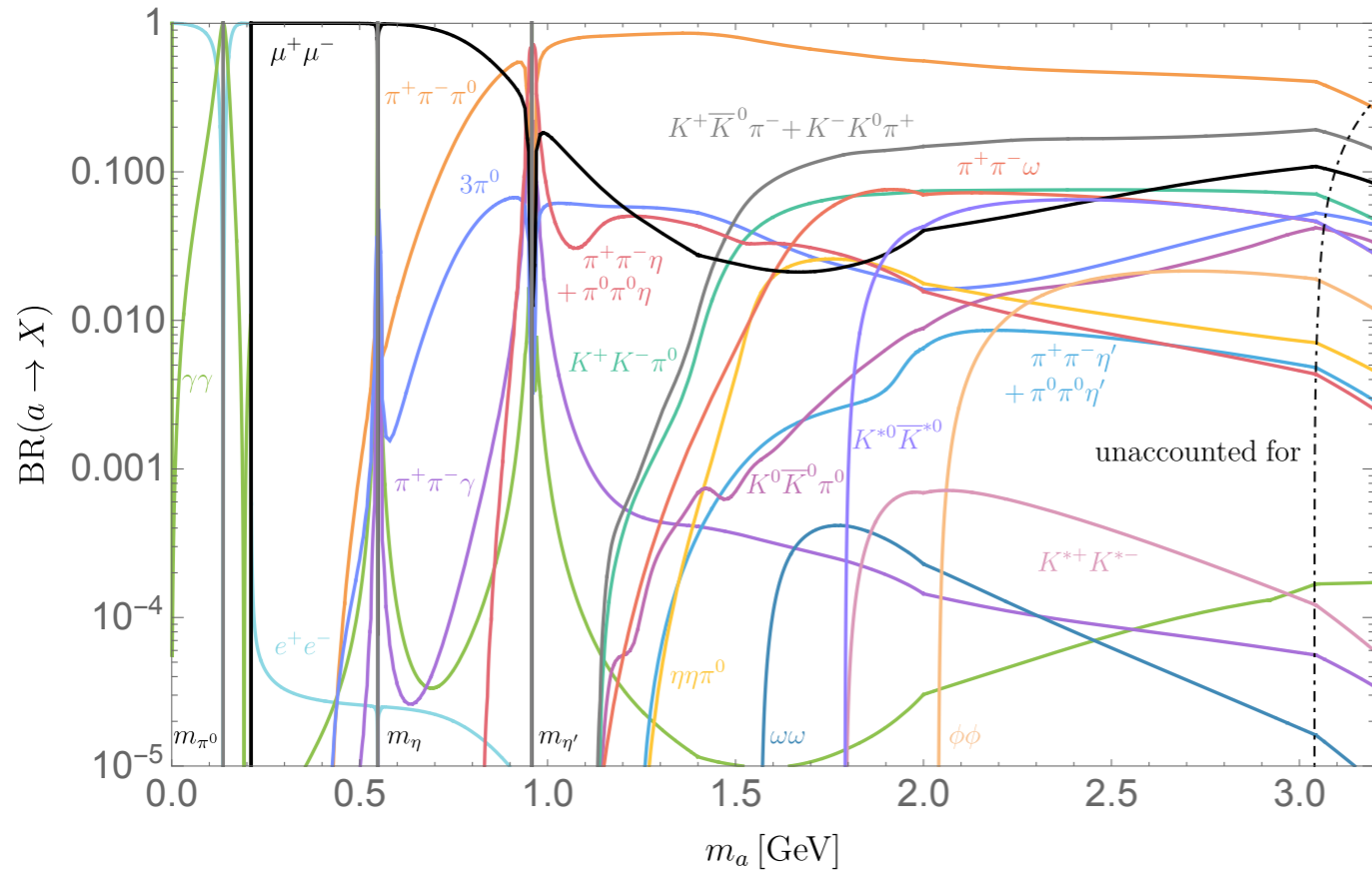


\*Without a conserved  $U(1)$  flavor symmetry,  $\hat{\pi}_1, \hat{\pi}_2$  are distinct states.

\*They will mix if  $CP$  is violated in the dark sector.



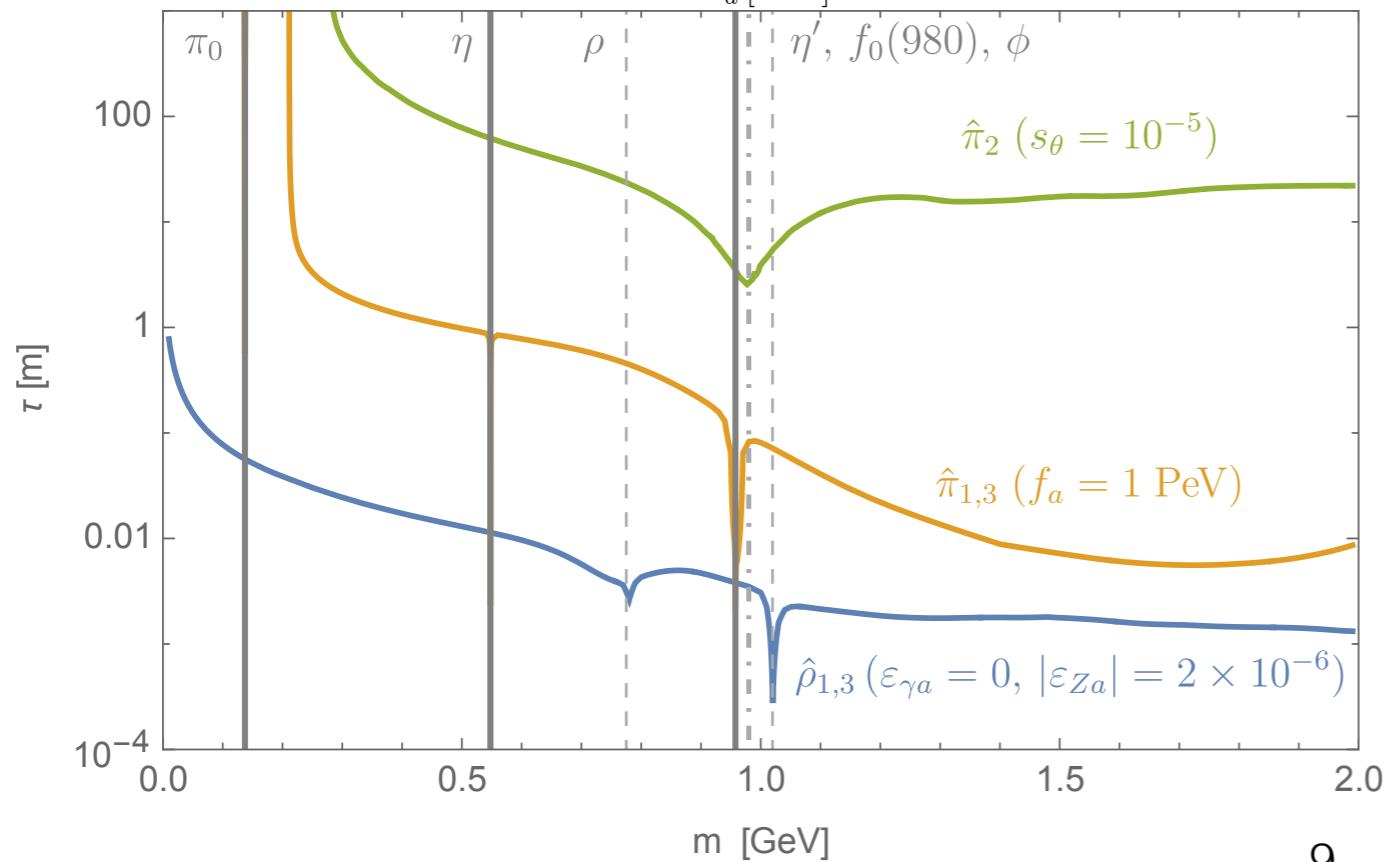
# Dark Pion Decays



(CP-odd)

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

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

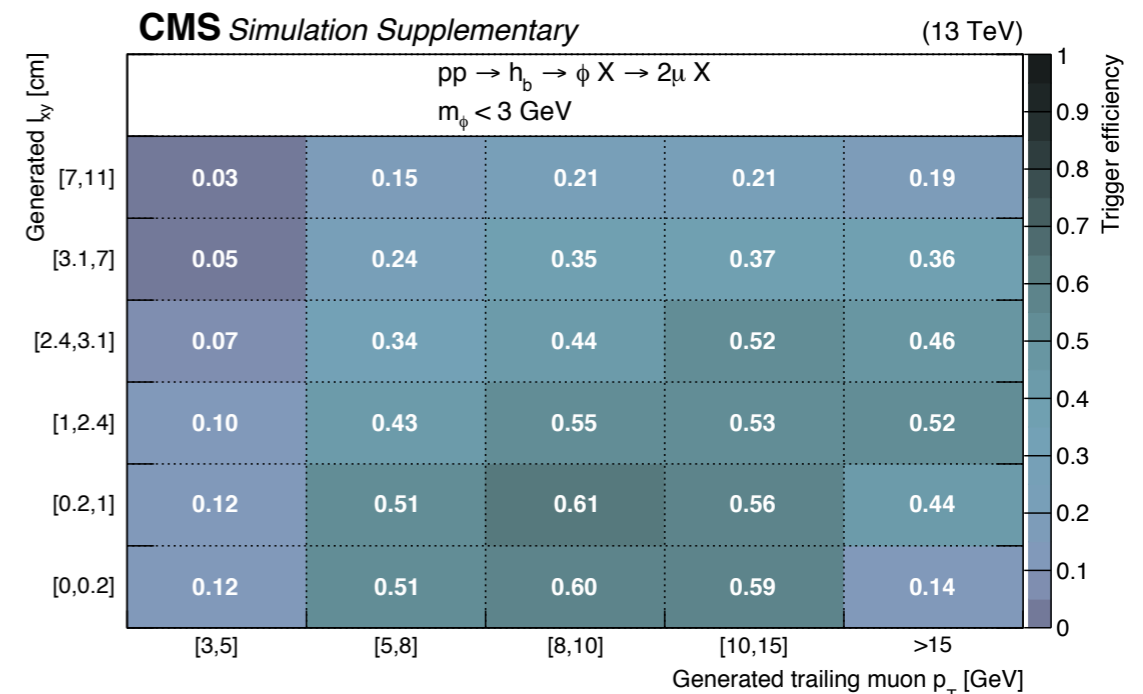
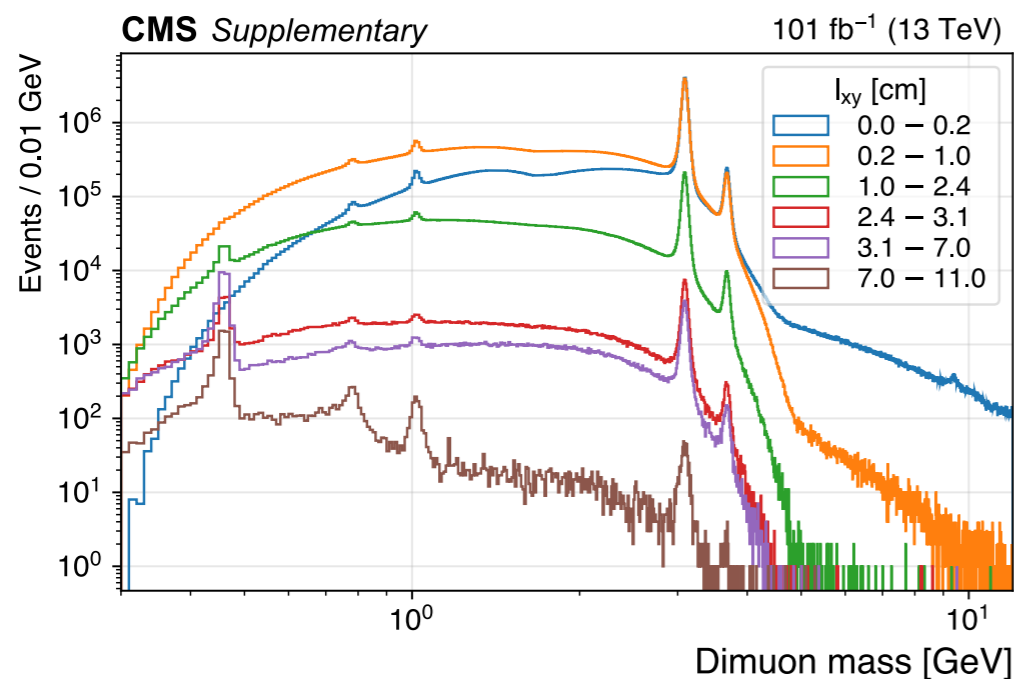
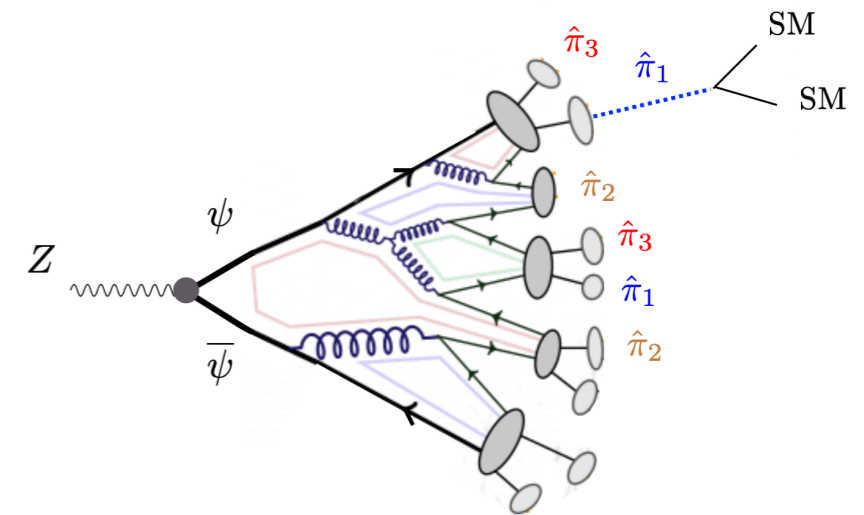


For  $2m_\mu < m_{\hat{\pi}} < 3 \text{ GeV}$ ,  $f_a \sim 1 \text{ PeV}$ ,  
dark pion decays through Z-portal  
have decay lengths in the most  
interesting range of few mm to 100 m  
at colliders.

# Dark Shower Searches

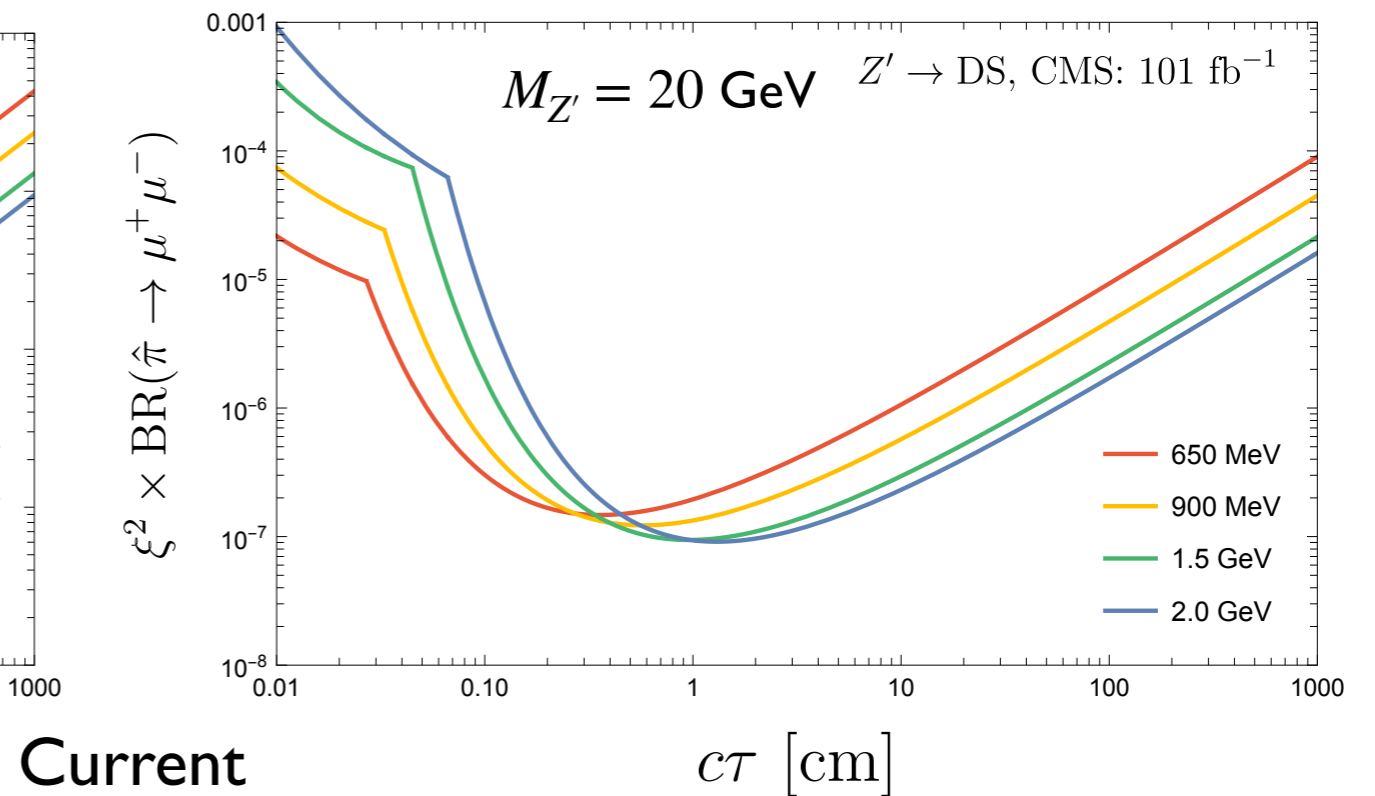
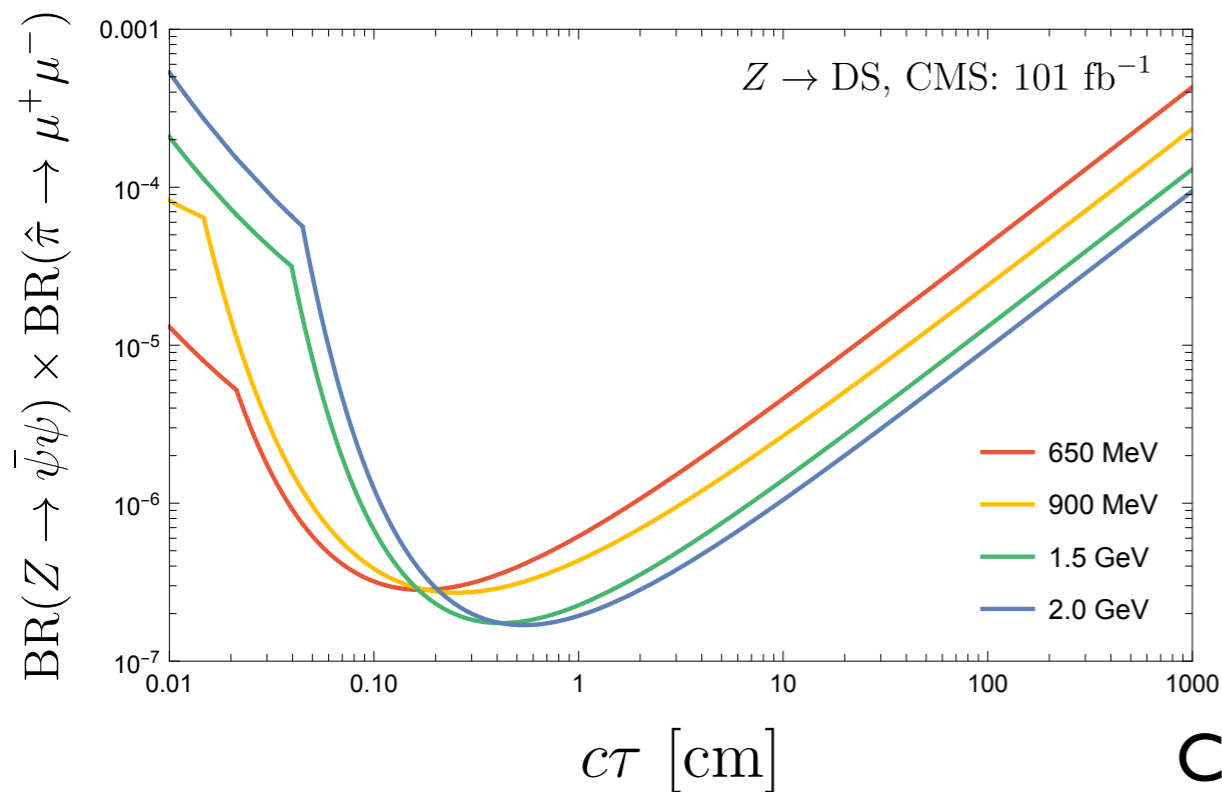
The final states of dark showers from  $Z$  decays are soft, therefore hard to trigger. On the other hand, dark pions are typically long-lived. Displaced decays give a great handle.

- 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.



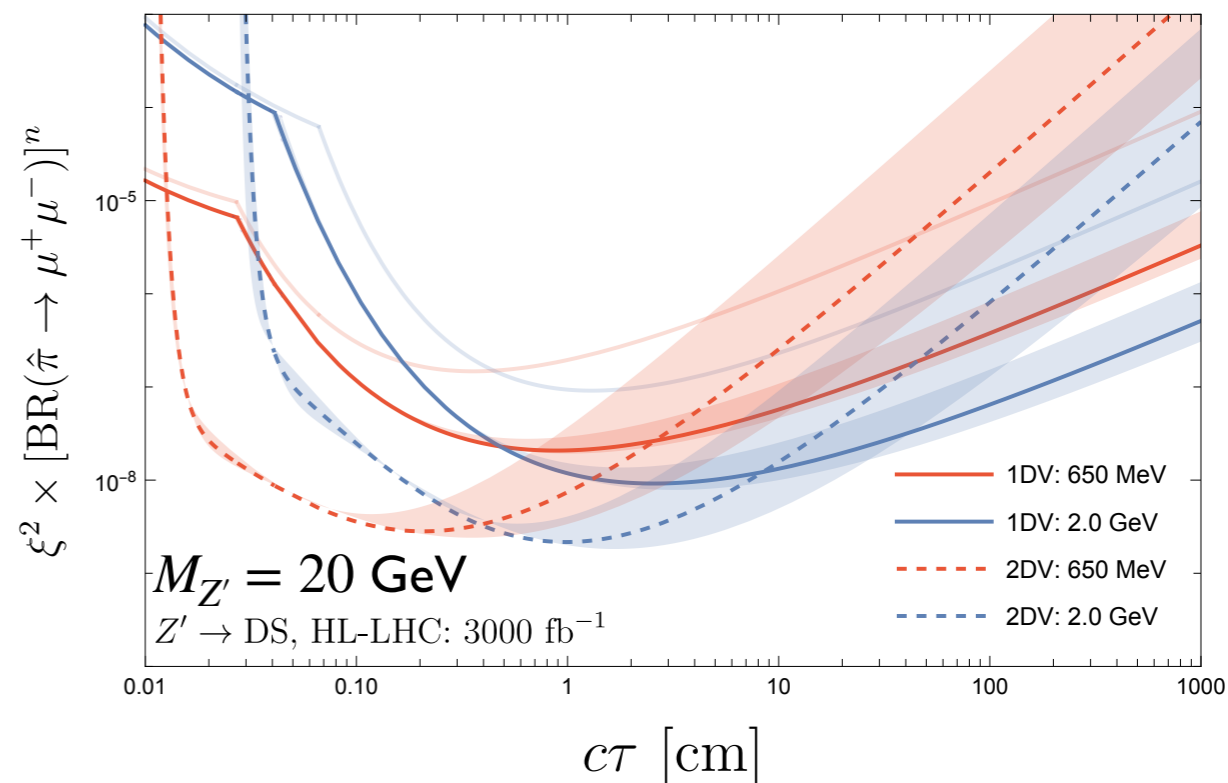
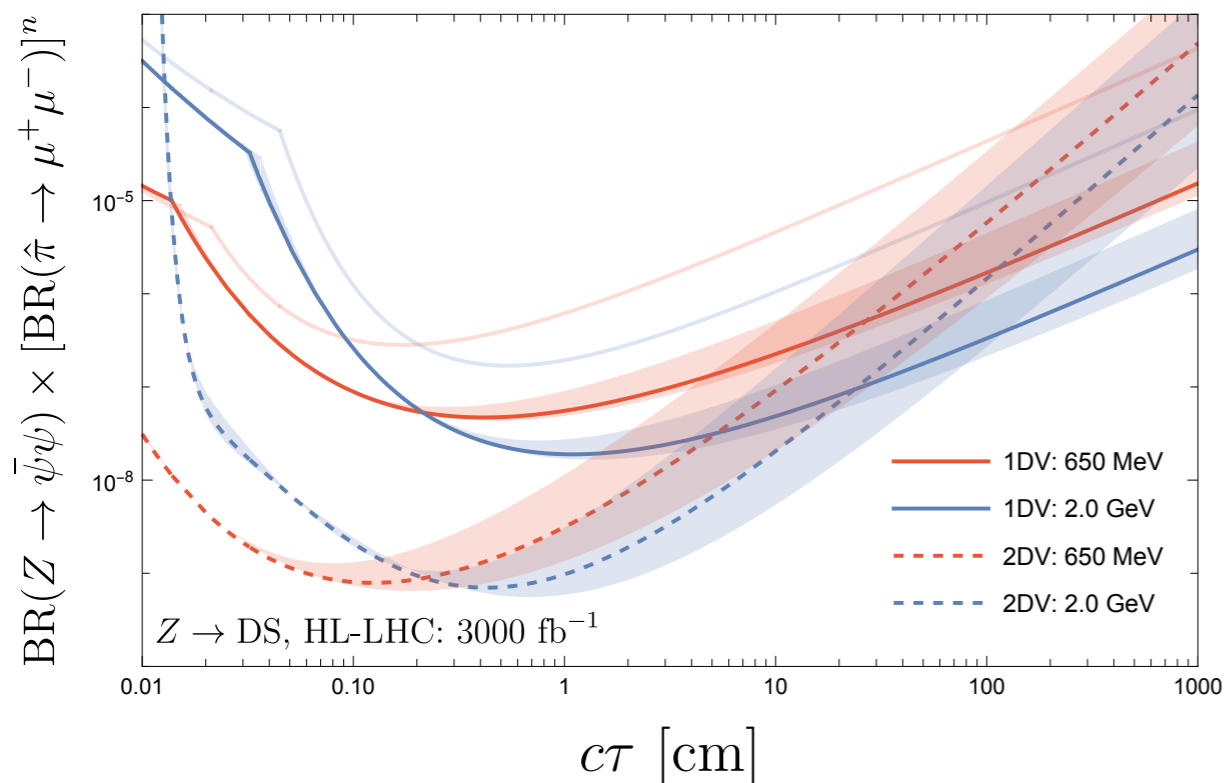
# CMS Scouting Search

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



# CMS Scouting Search

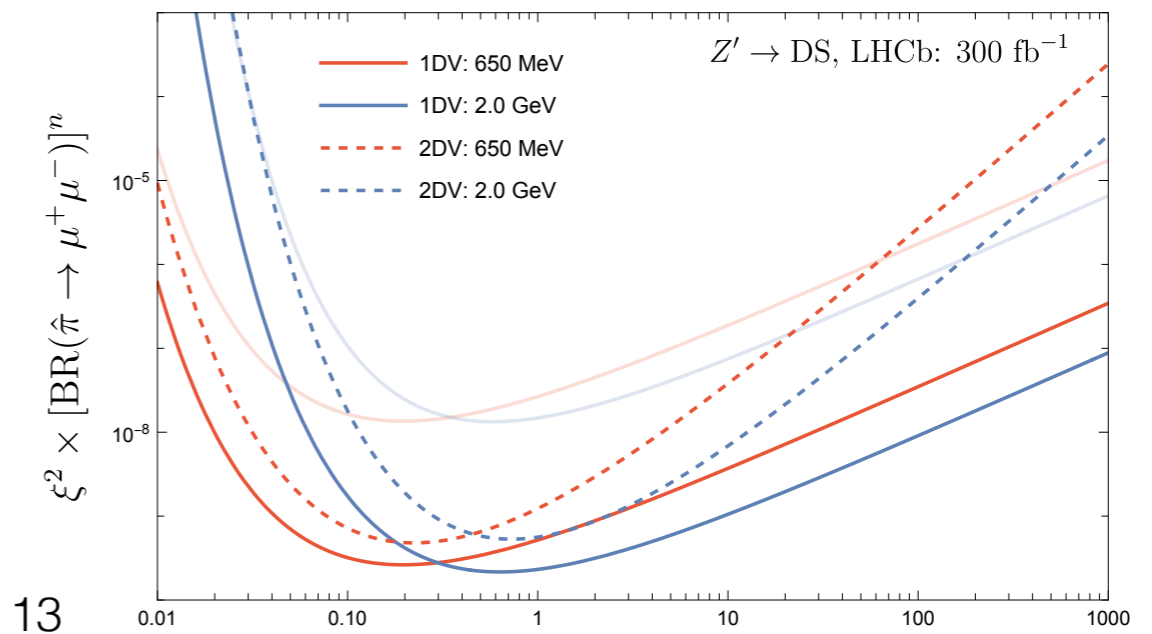
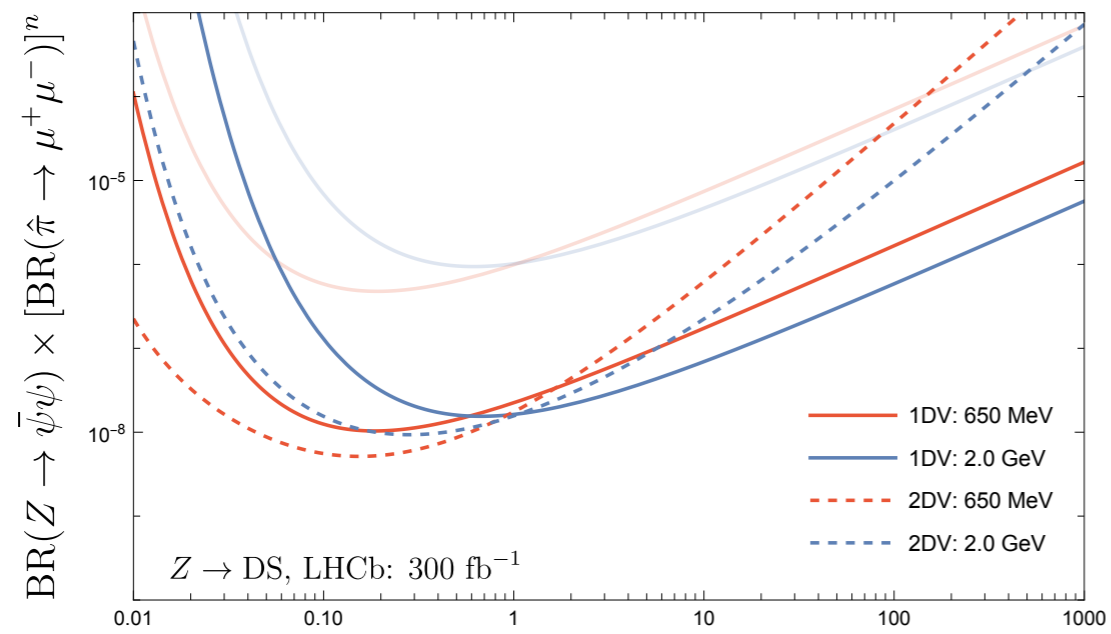
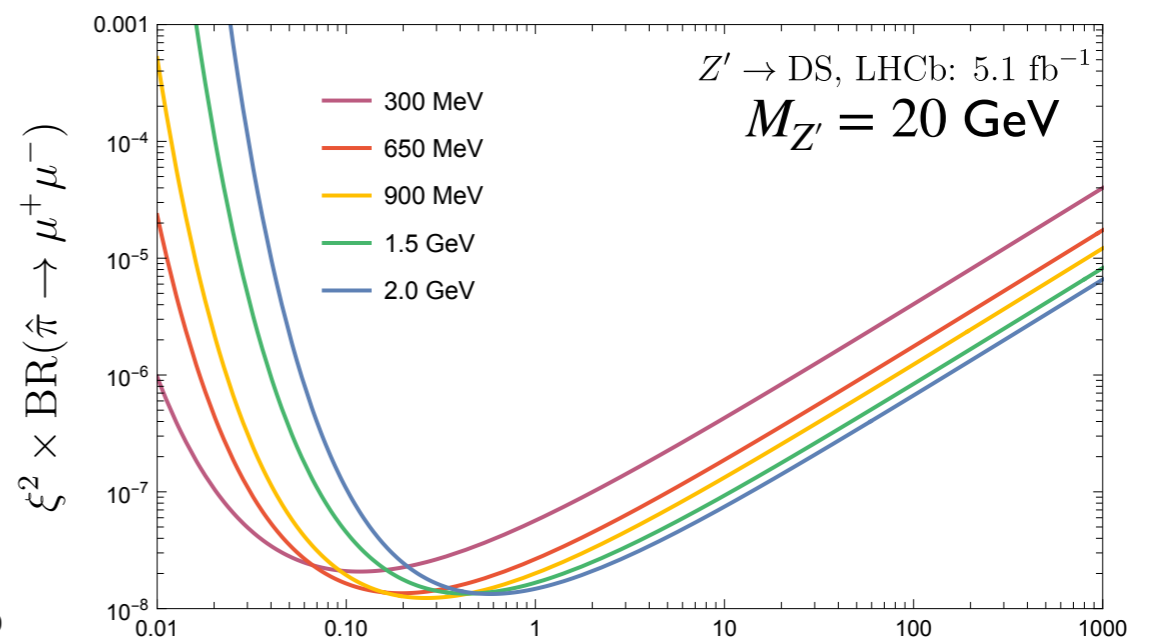
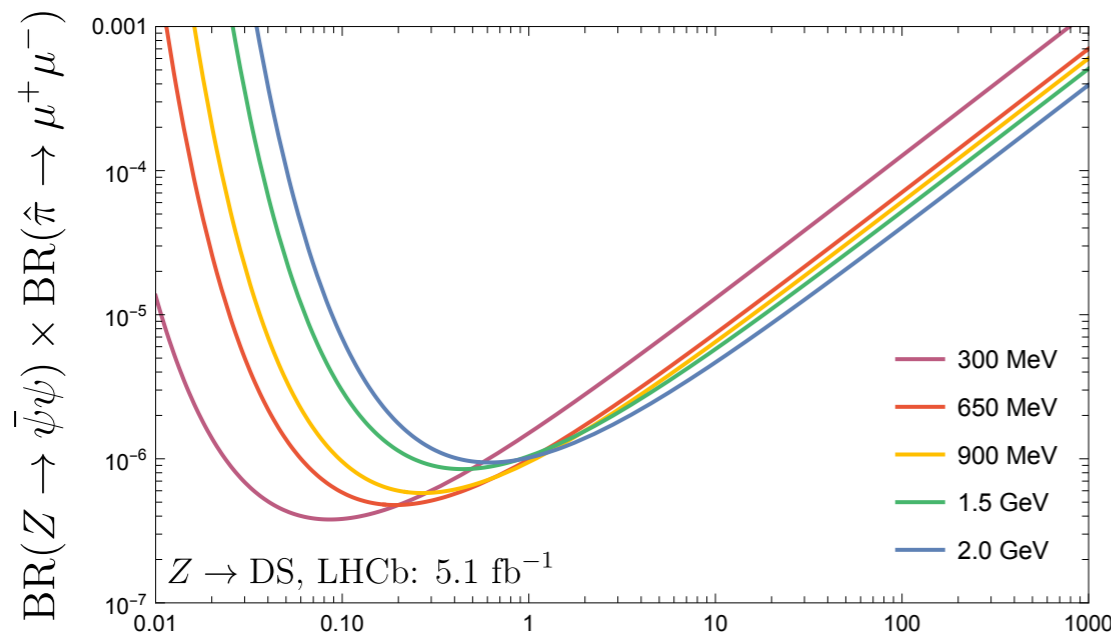
- Future projections (with assumptions of improved trigger efficiency and extended  $l_{xy}$  reach 11 cm  $\rightarrow$   $\sim$  90 cm):



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

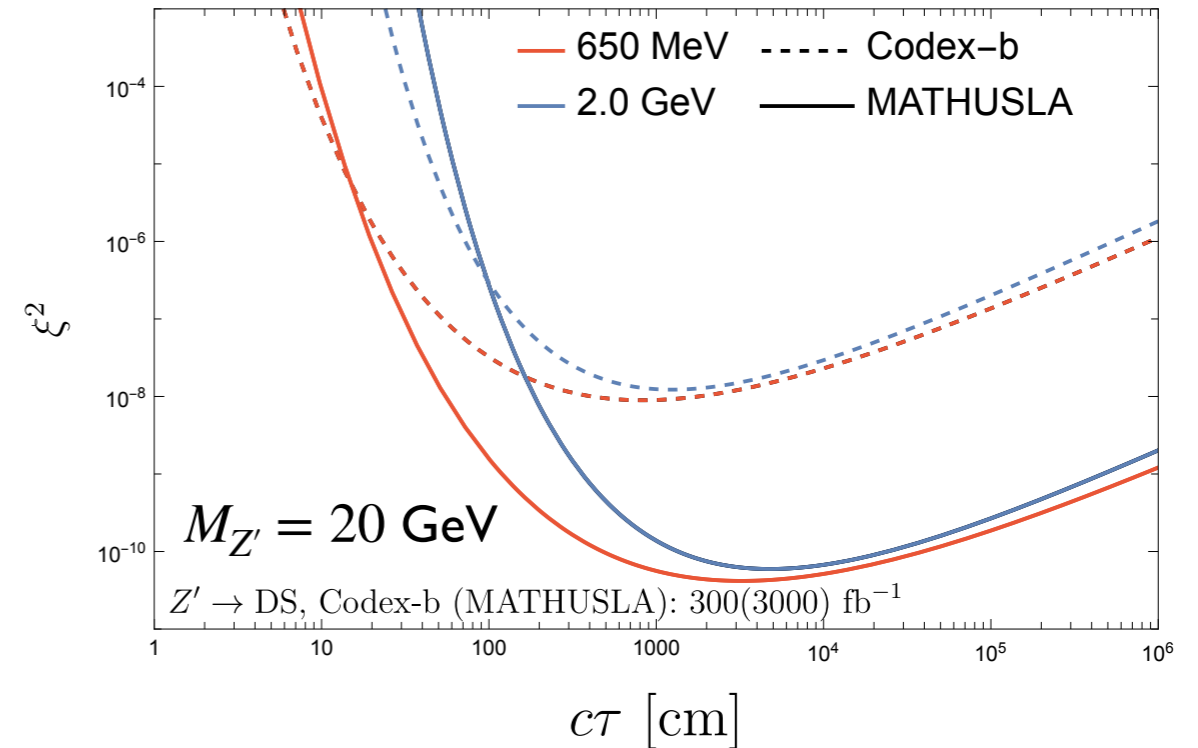
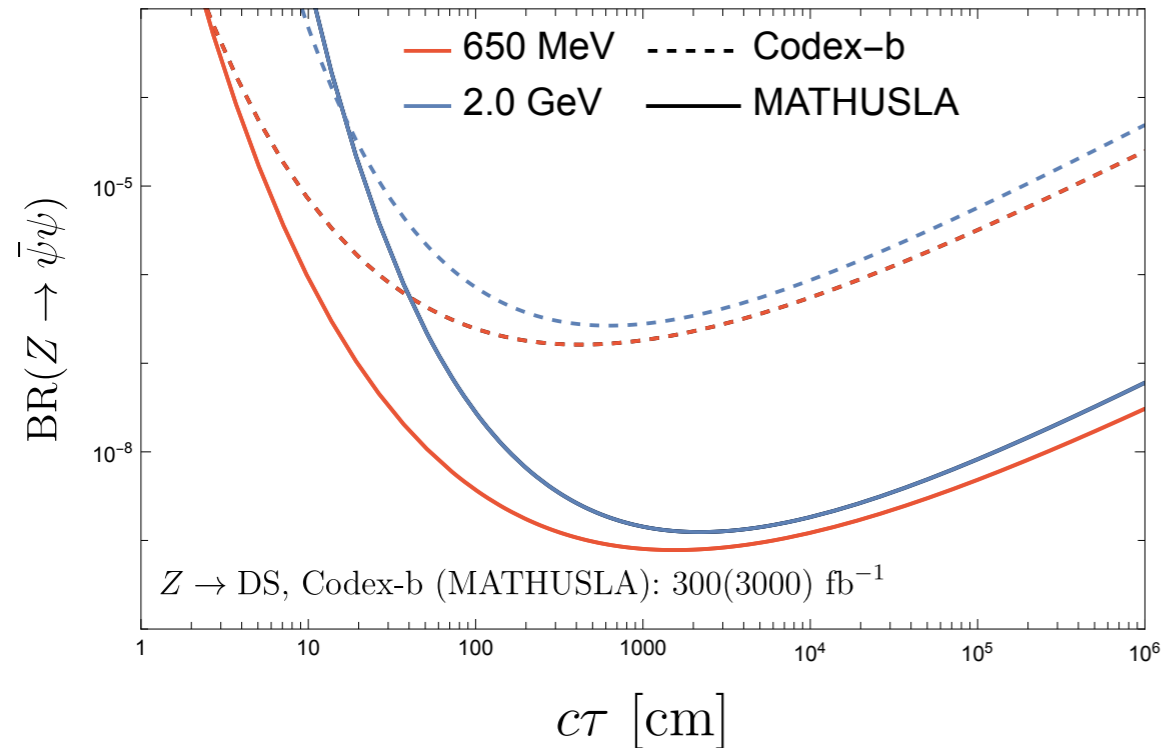
# LHCb

- 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.

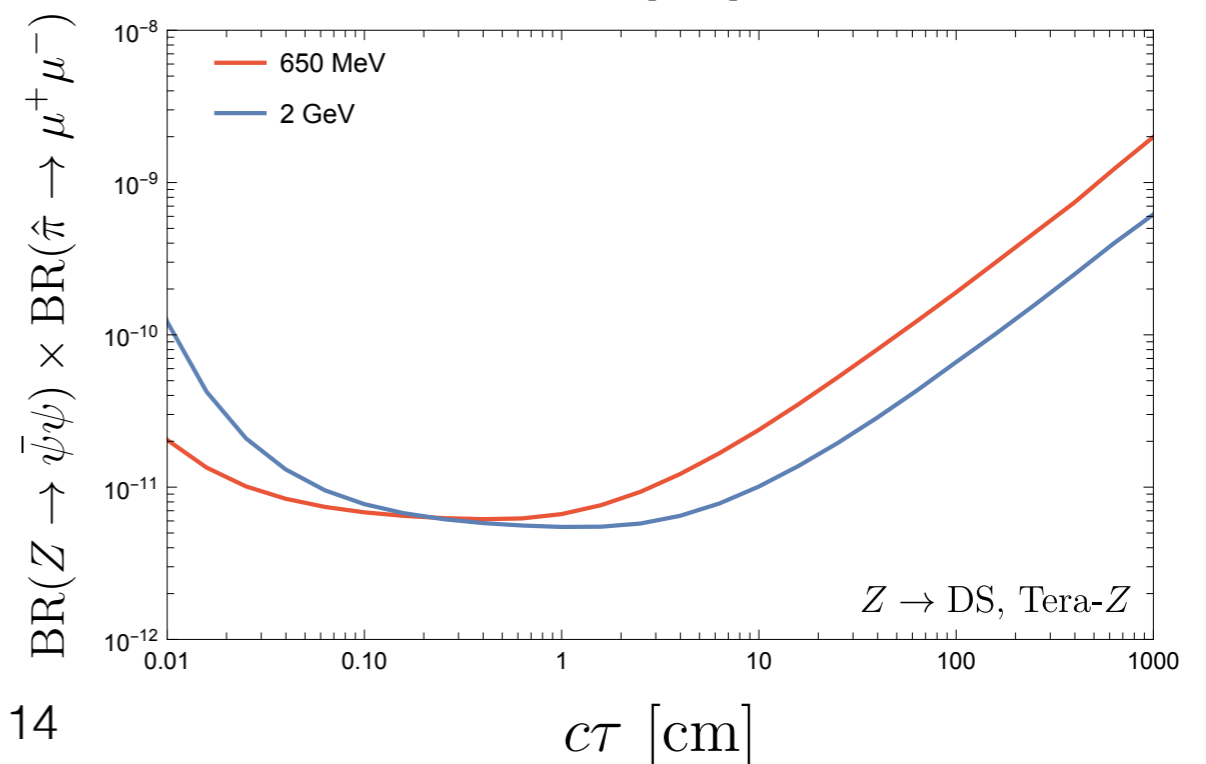


## Tera-Z:

$$p_{T,\mu} > 0.5 \text{ GeV}, |p_\mu| > 10 \text{ GeV and } |\eta_\mu| < 5$$

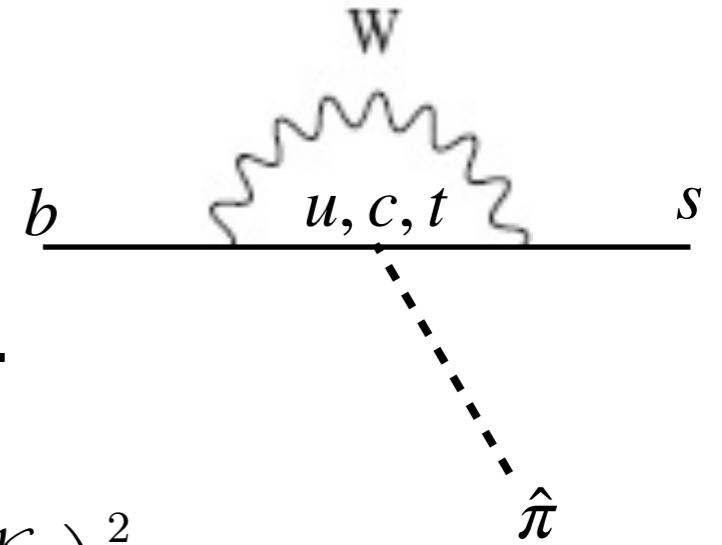
$$p_{T,\mu\mu} > 2 \text{ GeV}$$

$$l_{xy} \in [0.5, 100] \text{ cm}$$



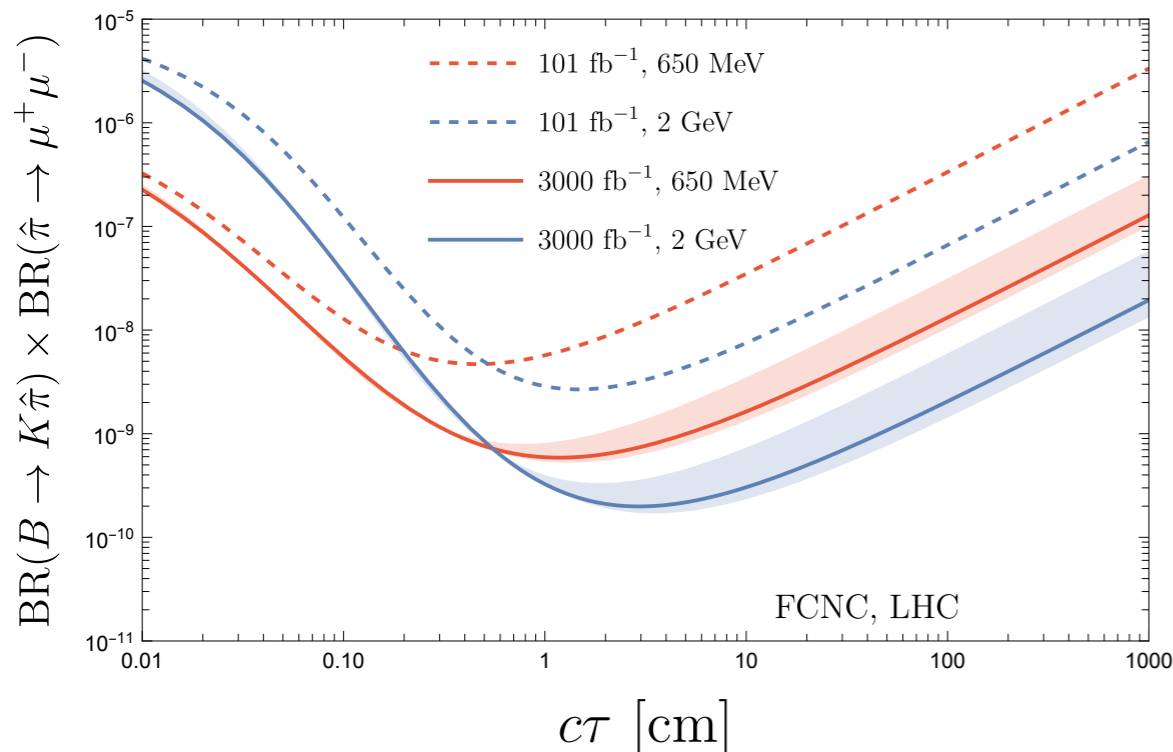
# Dark Hadron Production from FCNC

- 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  $f_a$ .

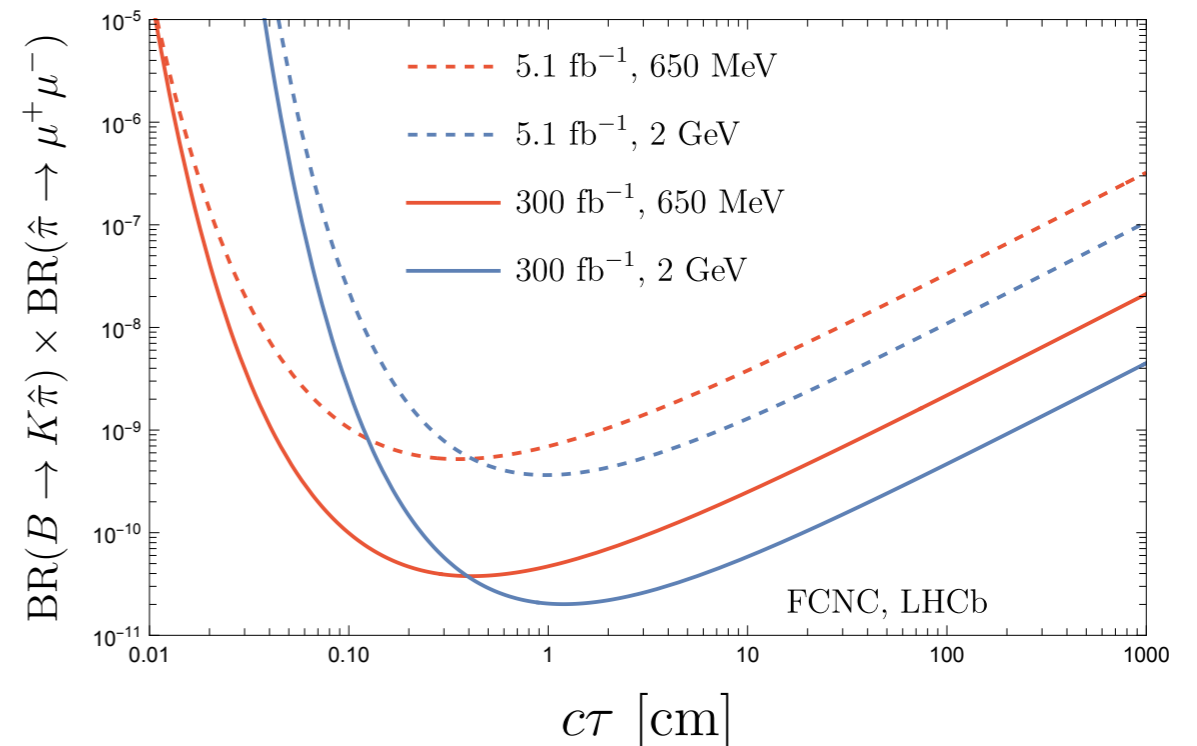


$$\text{BR}(B^{+,0} \rightarrow \{K^+ \hat{\pi}_b, K^{*0} \hat{\pi}_b\}) \approx \{0.92, 1.1\} \times 10^{-8} \left( \frac{1 \text{ PeV}}{f_a^{(b)}} \right)^2 \left( \frac{\mathcal{K}_t}{10} \right)^2 \left\{ \lambda_{BK\hat{\pi}}^{1/2}, \lambda_{BK^*\hat{\pi}}^{3/2} \right\},$$

## CMS Scouting



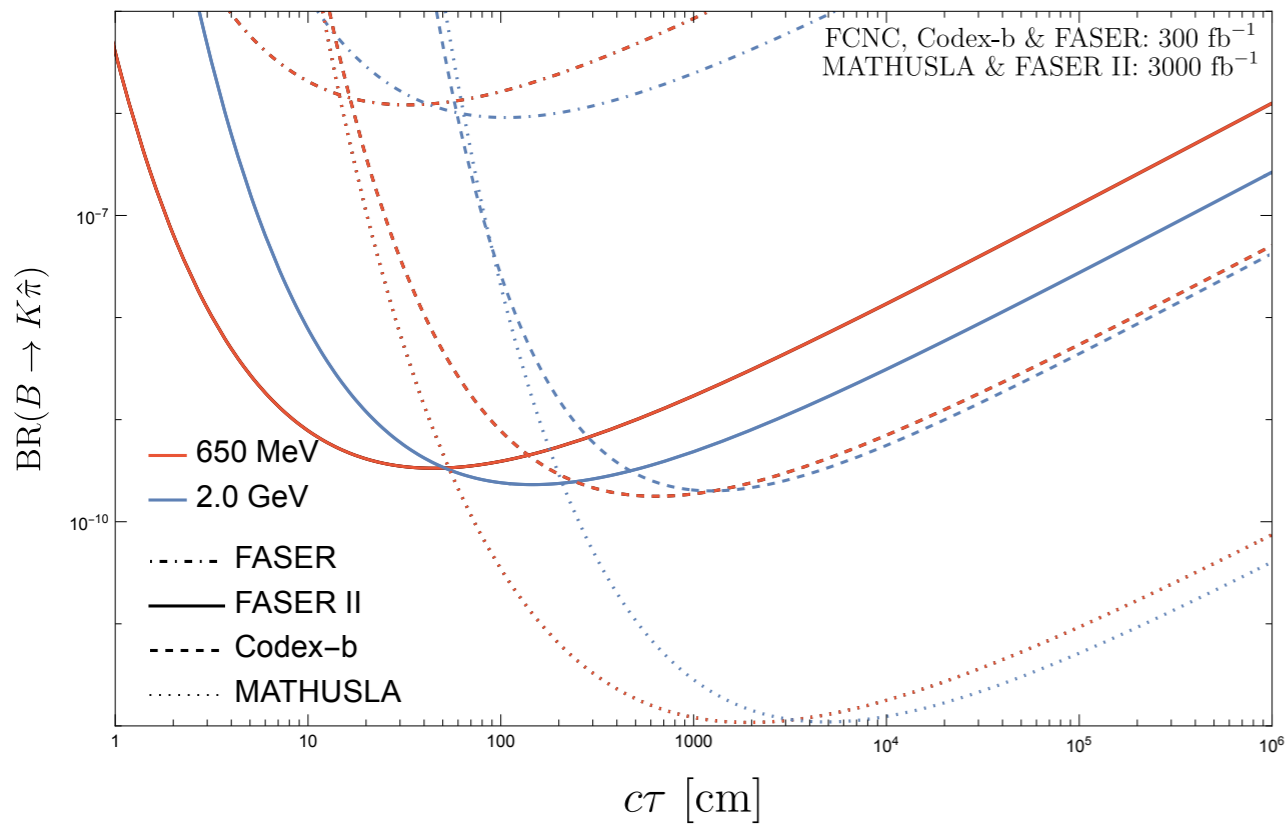
## LHCb



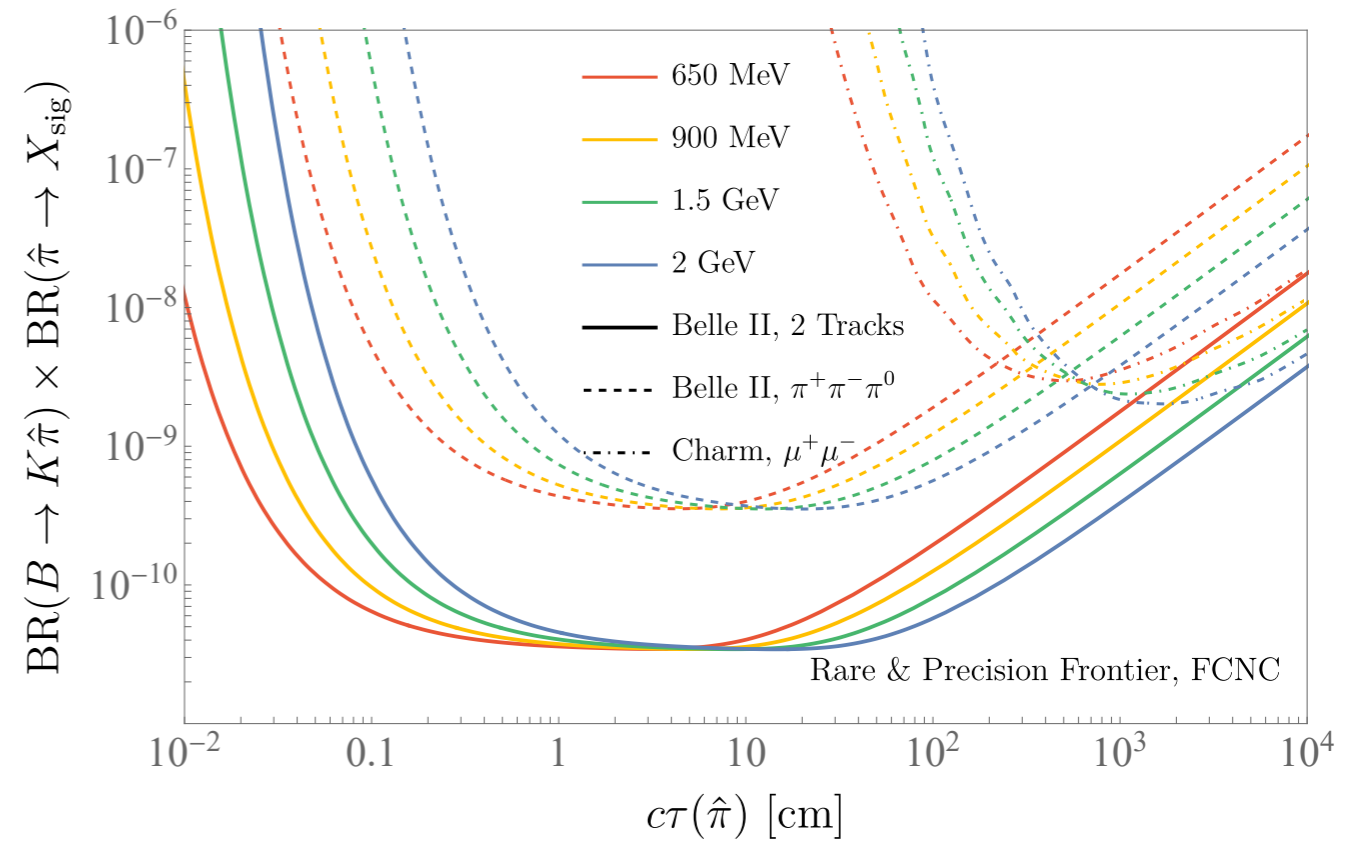
Dashed: current; Solid: future HL-LHC projection

# FCNC Reaches from Other Experiments

## Auxiliary detectors



## B-factory and fixed target exp



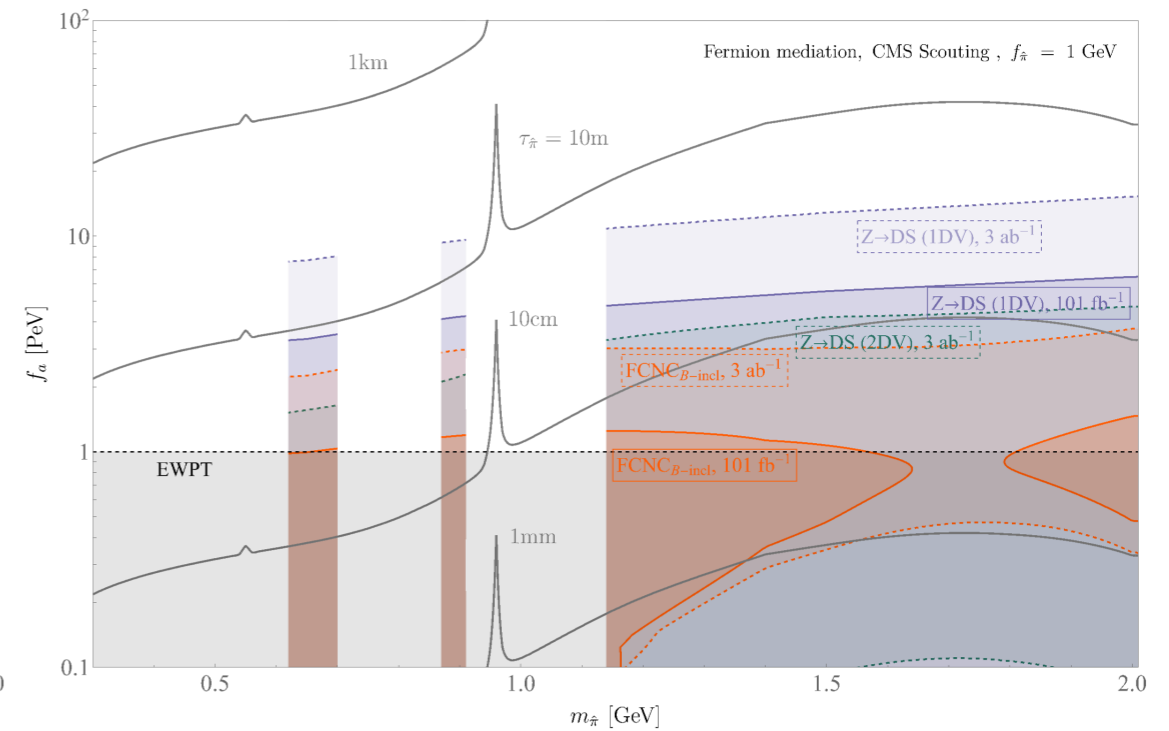
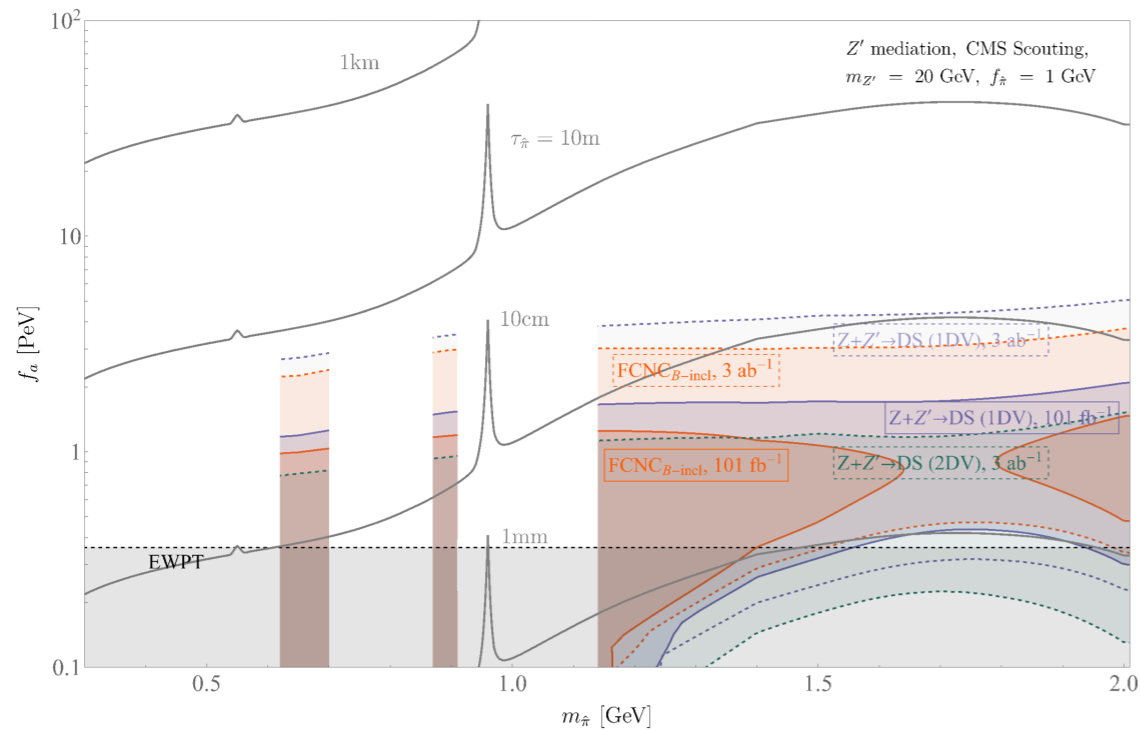


# Benchmark Models

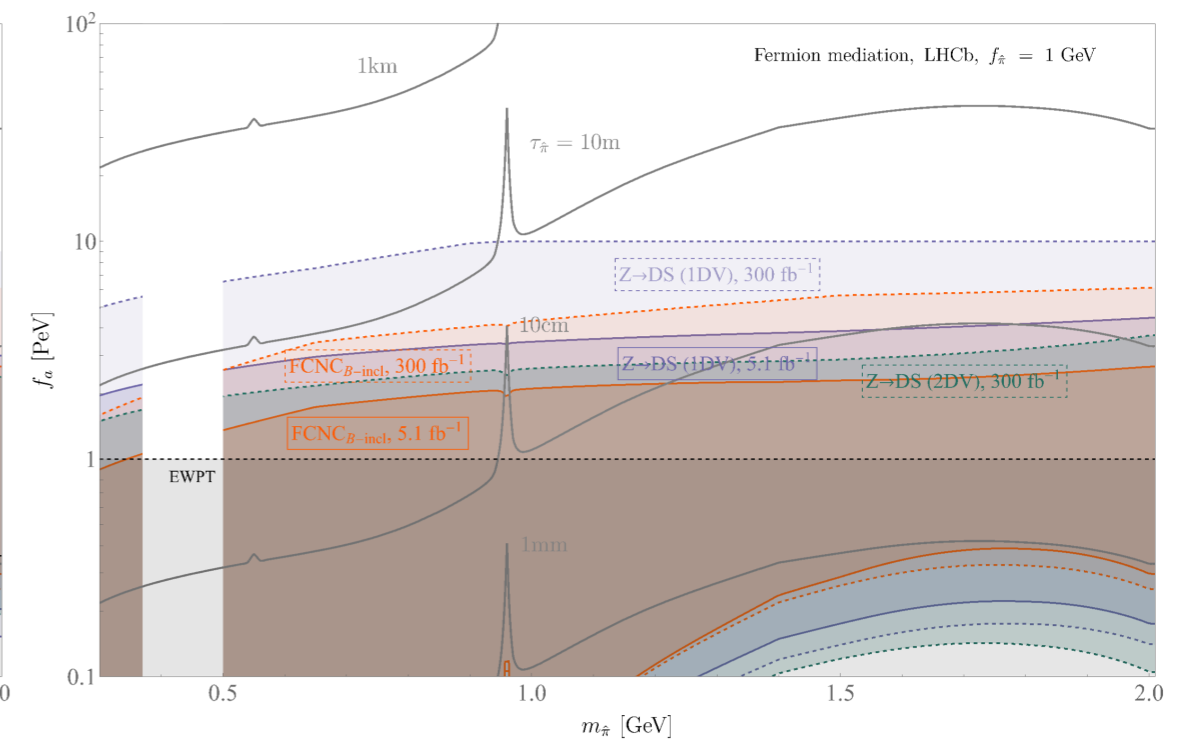
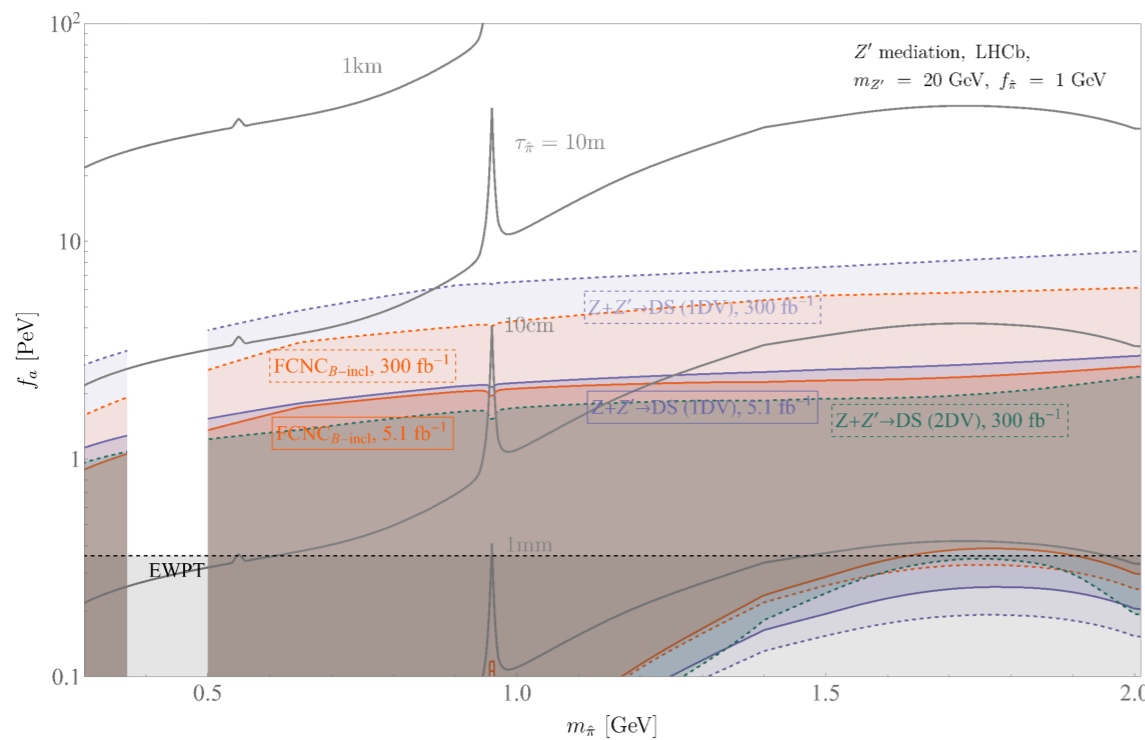
- To compare reaches of different experiments and production mechanisms, specific benchmark models are needed to obtain model-dependent bounds.
  1.  $Z'$  mixing model:  $M_{Z'} = 20$  GeV,  
 $\text{Tr}(\sigma_{1,3} X'_A) = 1$ ,  $g_D = 0.25$ ,  $\hat{\pi}_2$  detector stable.
  2. Fermion doublet mixing model:  $\tilde{Y} = 0$ , set  $\tilde{\pi}_1, \tilde{\pi}_3$  lifetimes equal by choosing  $y_{11} = y_{12}(1 + \sqrt{2})$ ,  $y_{21} = y_{22} = 0$ .(They are for illustrations, don't necessarily represent general results.)
- The relative strengths of dark shower and FCNC reaches depends on  $f_{\hat{\pi}}$ . **Dark shower reaches decrease as  $f_{\hat{\pi}}$  increases.**

# Current Bounds and Future Reaches

## CMS scouting

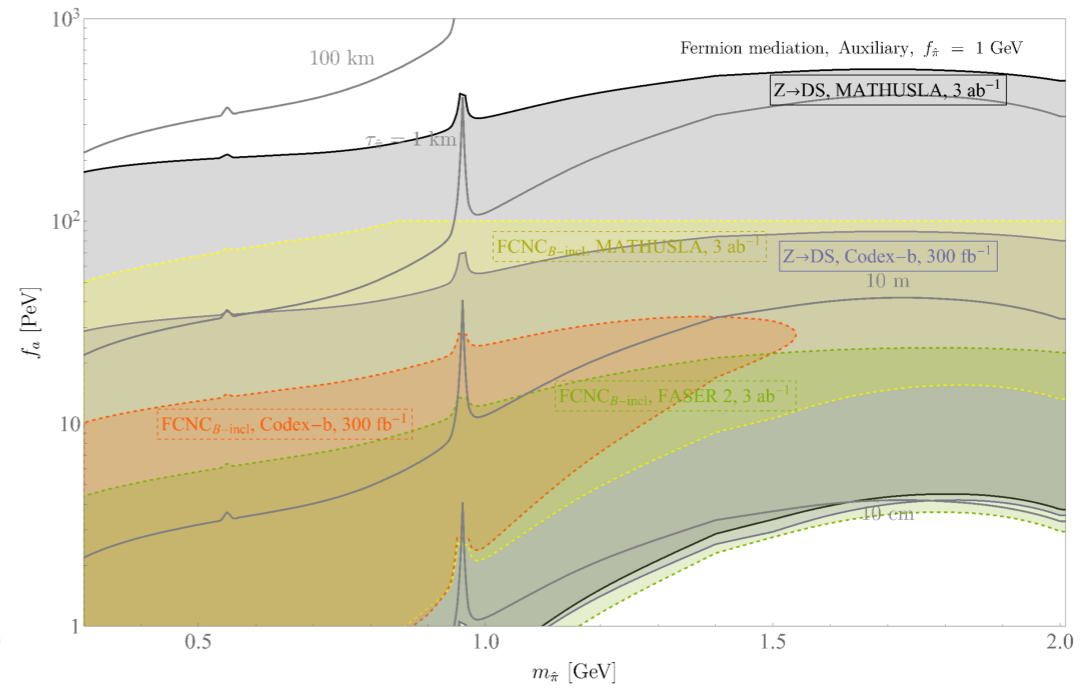
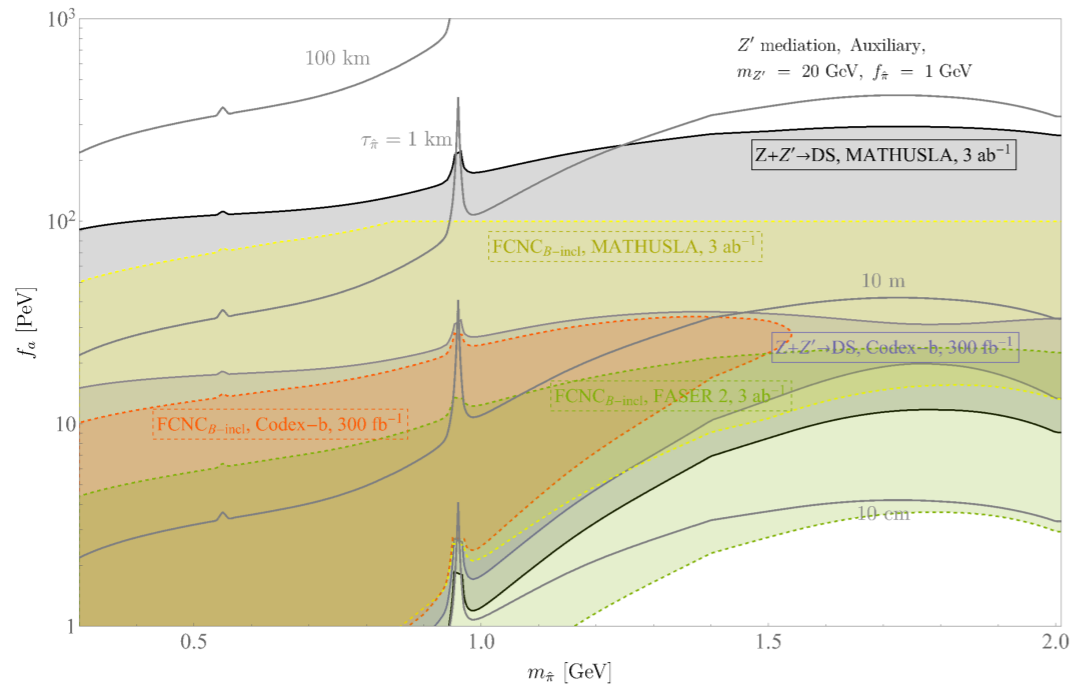


## LHCb

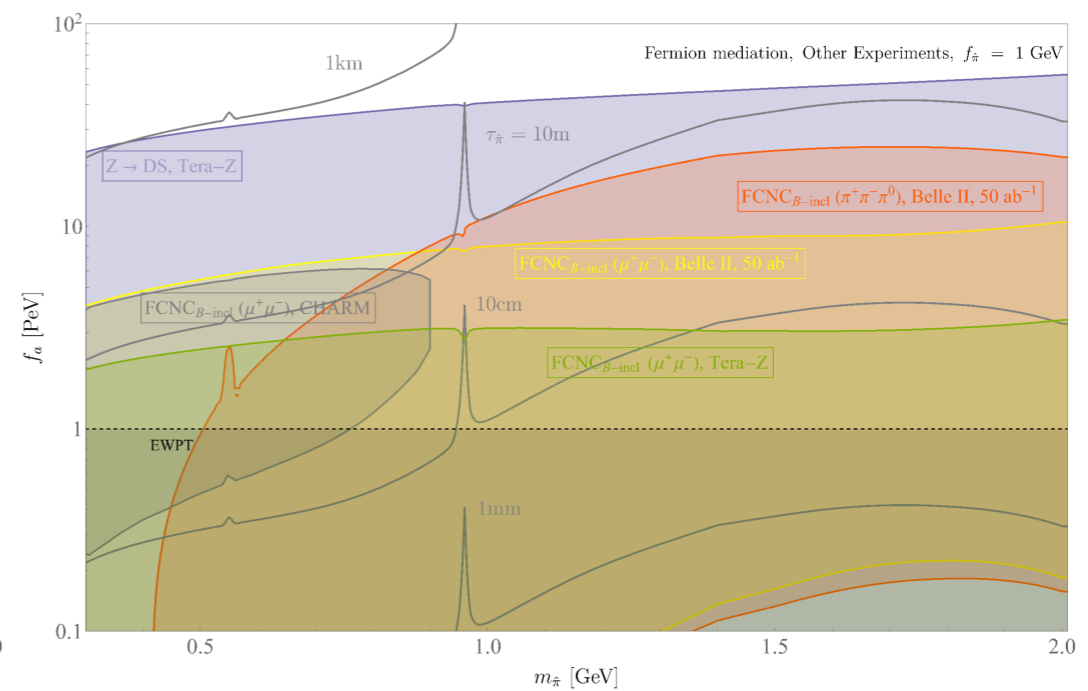
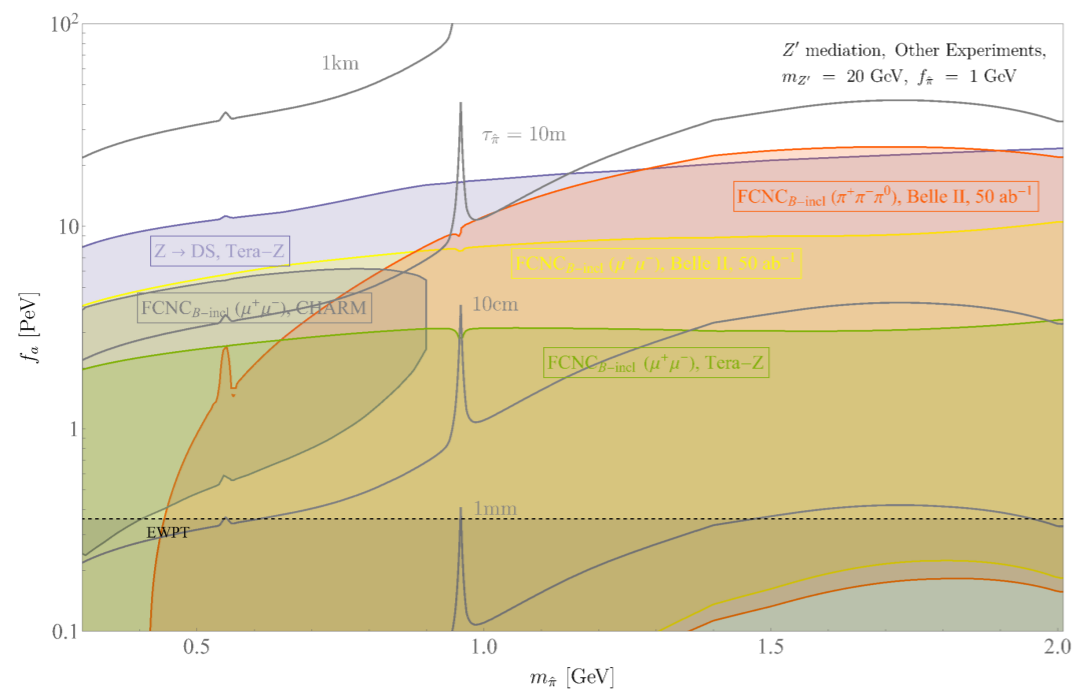


# Reaches of Benchmark Models

## Auxiliary detectors



## Intensity frontier

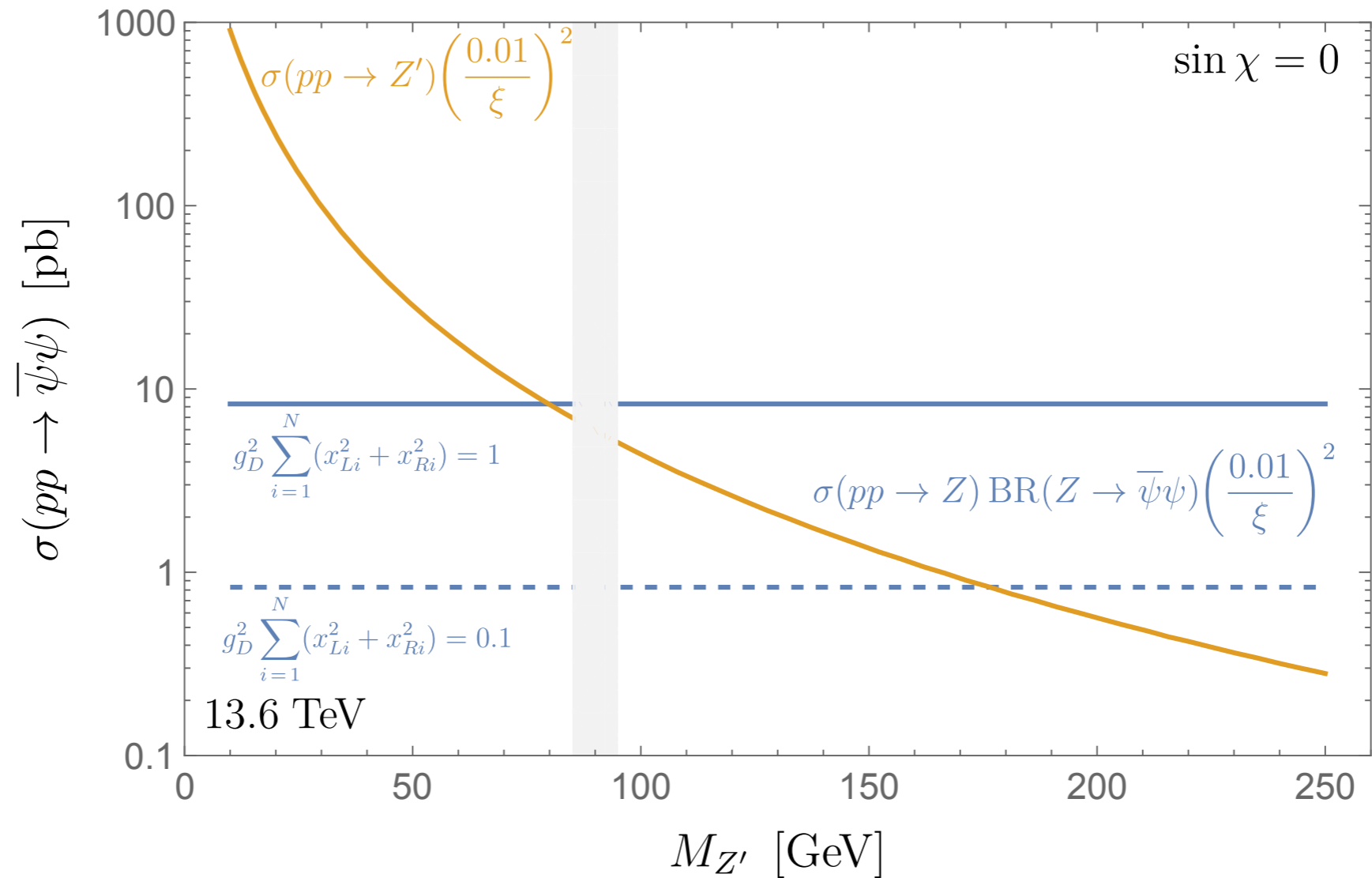


# Conclusions

- 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.

**Backup**

# Dark $Z'$ Production Cross Section at LHC



# Effective ALP Decay Constant for Dark Pions

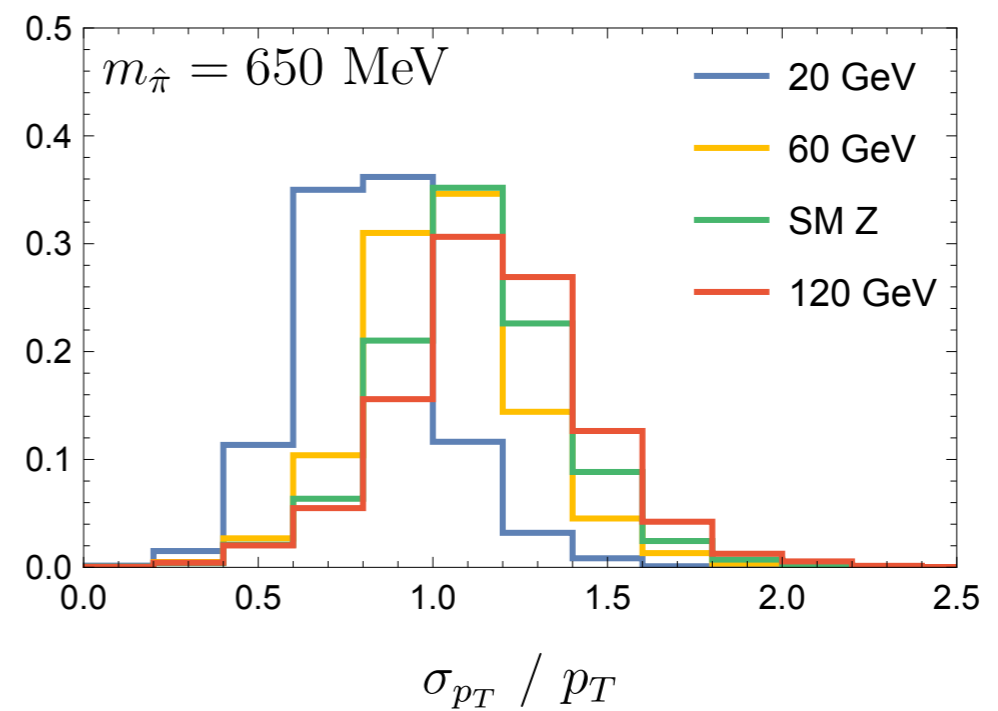
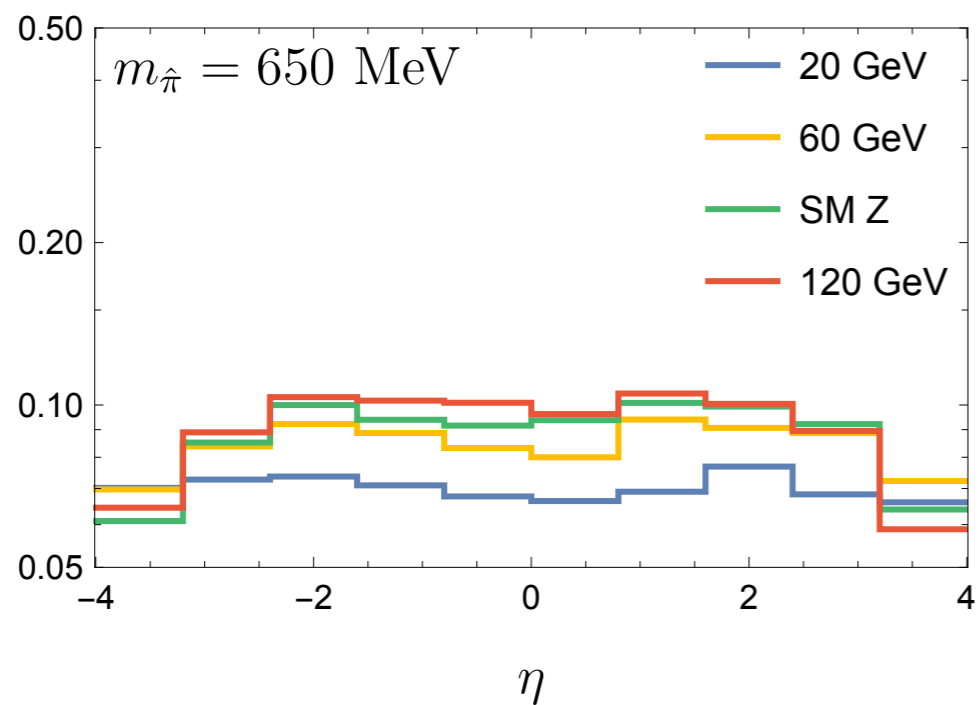
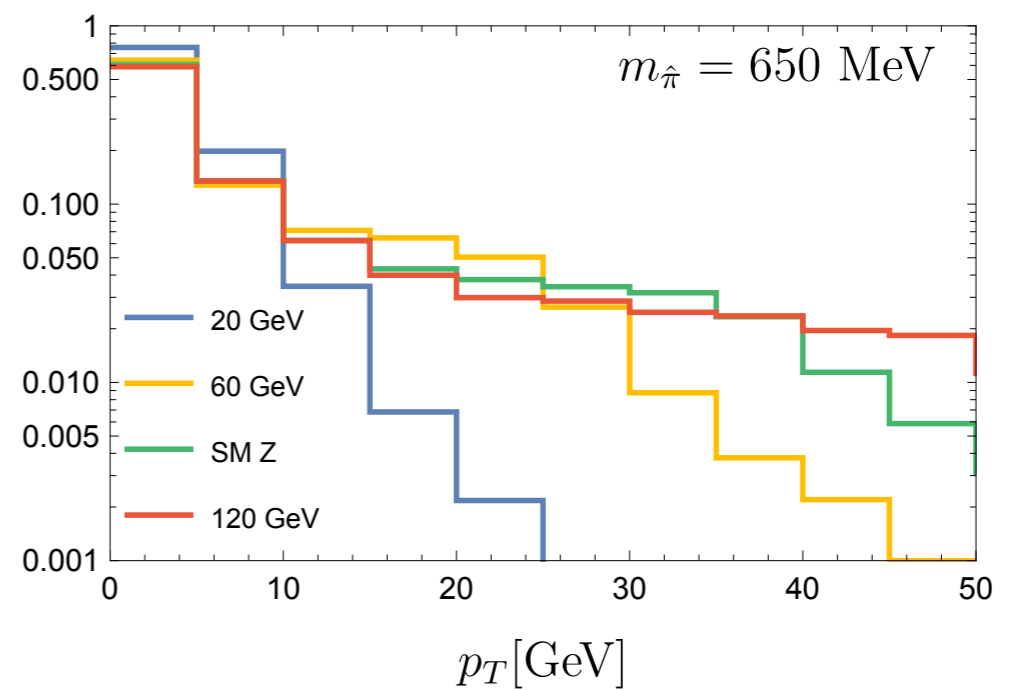
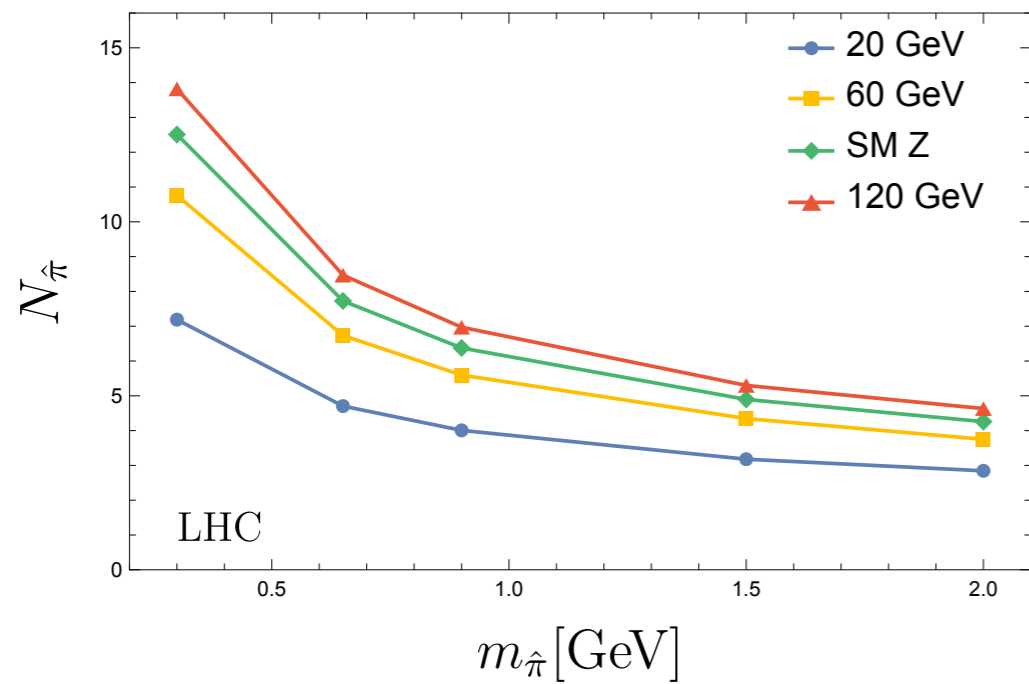
- Heavy doublet mixing model:

$$f_a \sim \frac{M^2}{Y^2 f_{\hat{\pi}}} \sim 1 \text{ PeV} \left( \frac{M/Y}{\text{TeV}} \right)^2 \left( \frac{\text{GeV}}{f_{\hat{\pi}}} \right)$$

- $Z' - Z$  mixing model:

$$f_a \sim \frac{2M_{Z_1}^2 M_{Z_2}^2}{g_D \hat{g}_Z f_{\hat{\pi}} \delta \hat{M}^2} \sim 1 \text{ PeV} \left( \frac{10^{-2}}{\delta \hat{M}^2 / M_{Z_1}^2} \right) \left( \frac{M_{Z_2}}{60 \text{ GeV}} \right)^2 \left( \frac{\text{GeV}}{g_D f_{\hat{\pi}}} \right)$$

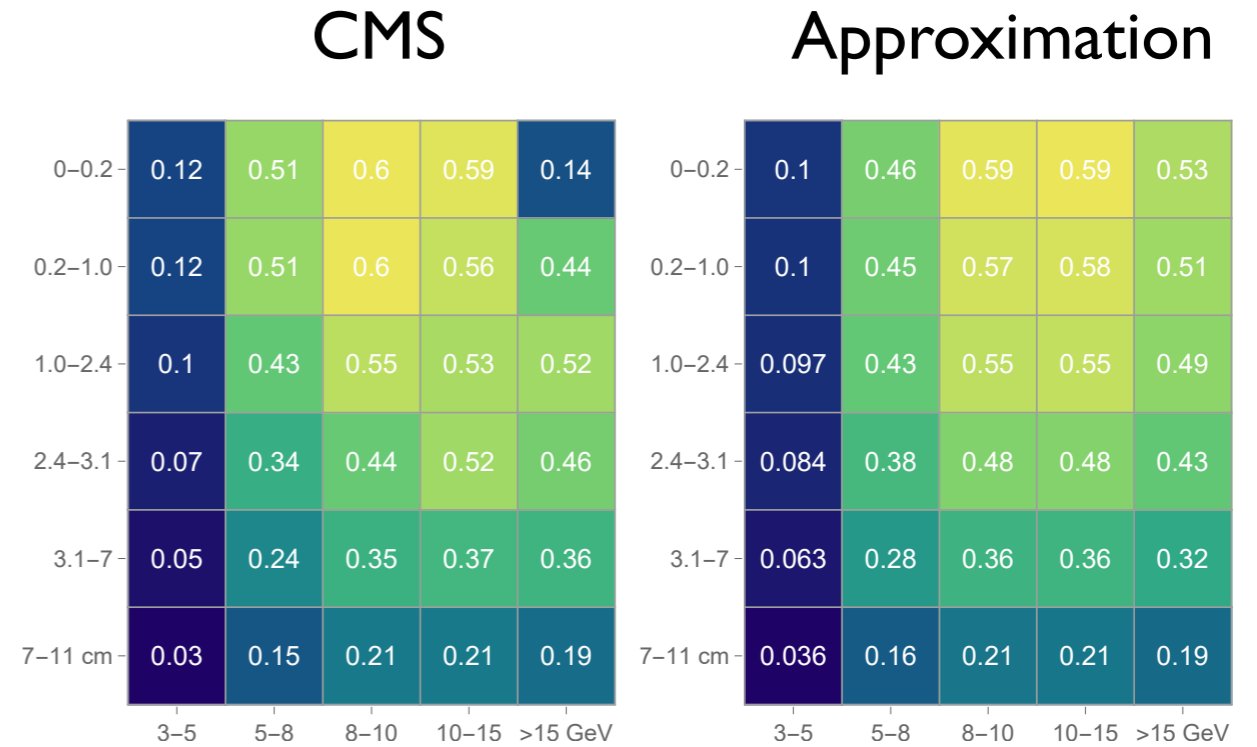
# Dark Pion Kinematic Distributions



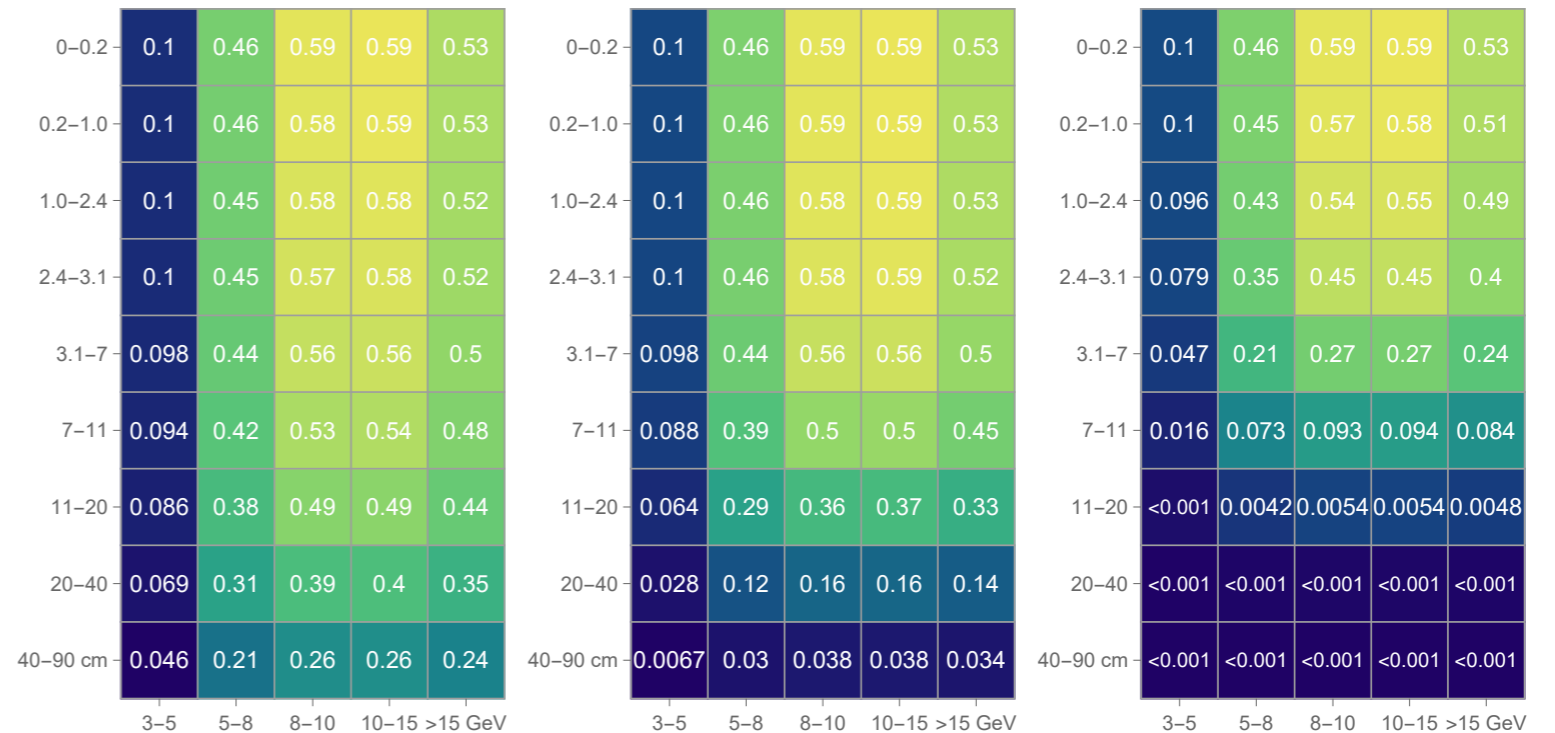
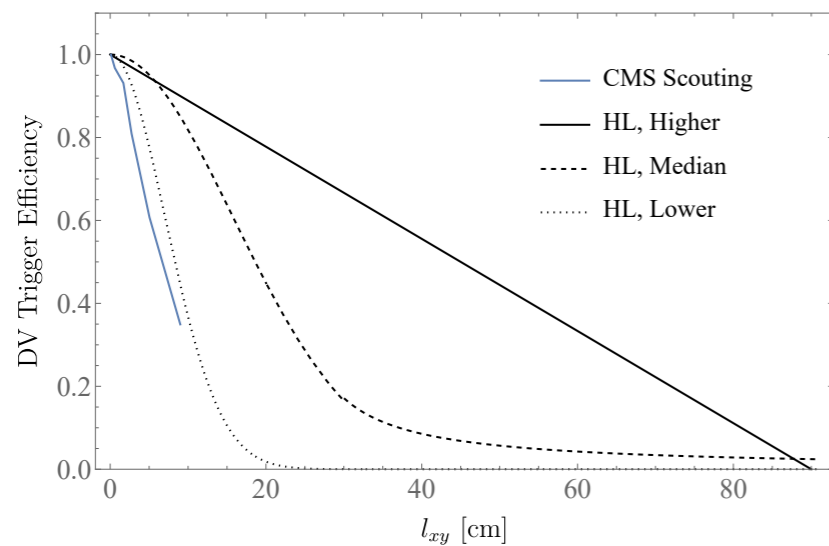


# Projections of HL-LHC CMS Scouting Search

- Approximate CMS efficiency table as a product of 2 functions of  $p_T$  and  $l_{xy}$  only.



- Extend  $l_{xy}$  reach .



# Simplified Auxiliary Detector Descriptions

| Detector      | Geometry | Displacement (m) | Volume (m)   | Luminosity ( $\text{fb}^{-1}$ ) |
|---------------|----------|------------------|--------------|---------------------------------|
| FASER [31]    | Cylinder | 0, 0, 480        | 0.2, 1.5     | 300                             |
| FASER 2 [31]  | Cylinder | 0, 0, 480        | 2, 5         | 3000                            |
| MATHUSLA [22] | Box      | 75, 0, 118       | 30, 100, 100 | 3000                            |
| Codex-b [54]  | Box      | 31, 2, 10        | 10, 10, 10   | 300                             |