Dark Showers with the Z Portal

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w/ Xuhui Jiang, Lingfeng Li and Ennio Salvioni, to appear soon
and HC, Lingfeng Li and Ennio Salvioni, arXiv:2110.10691

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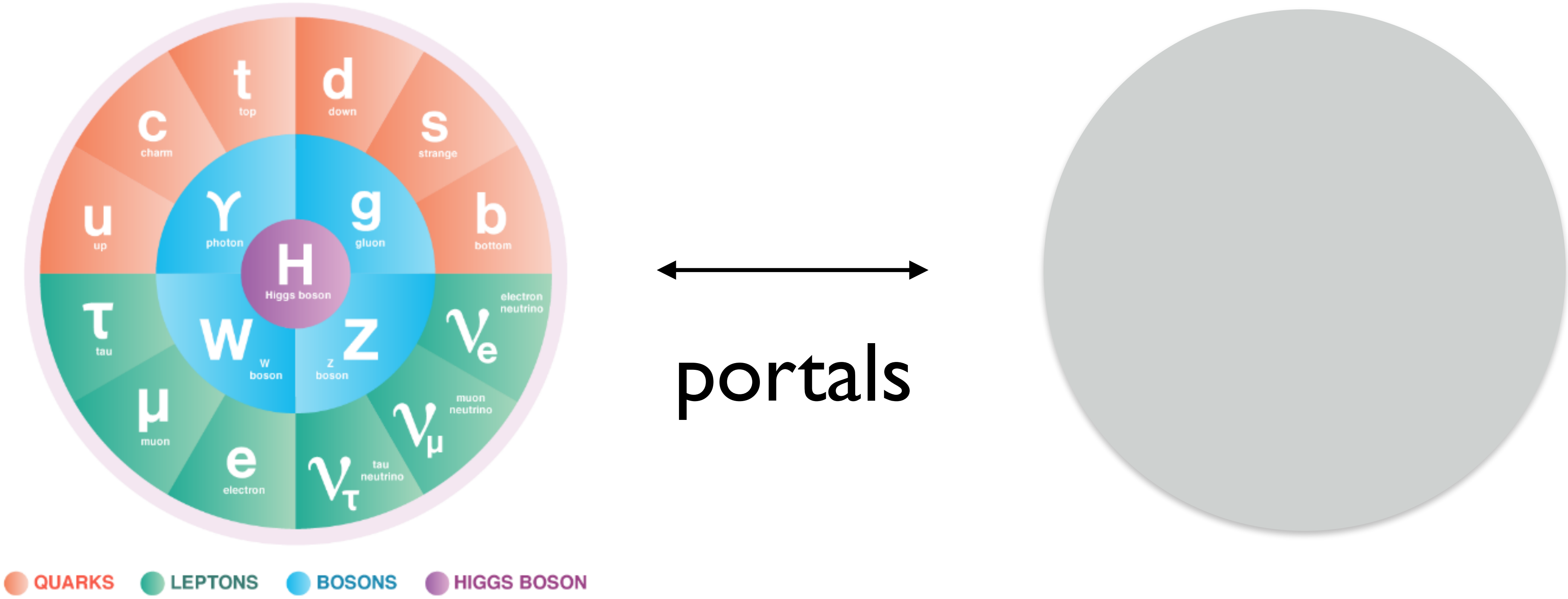
Introduction



SM

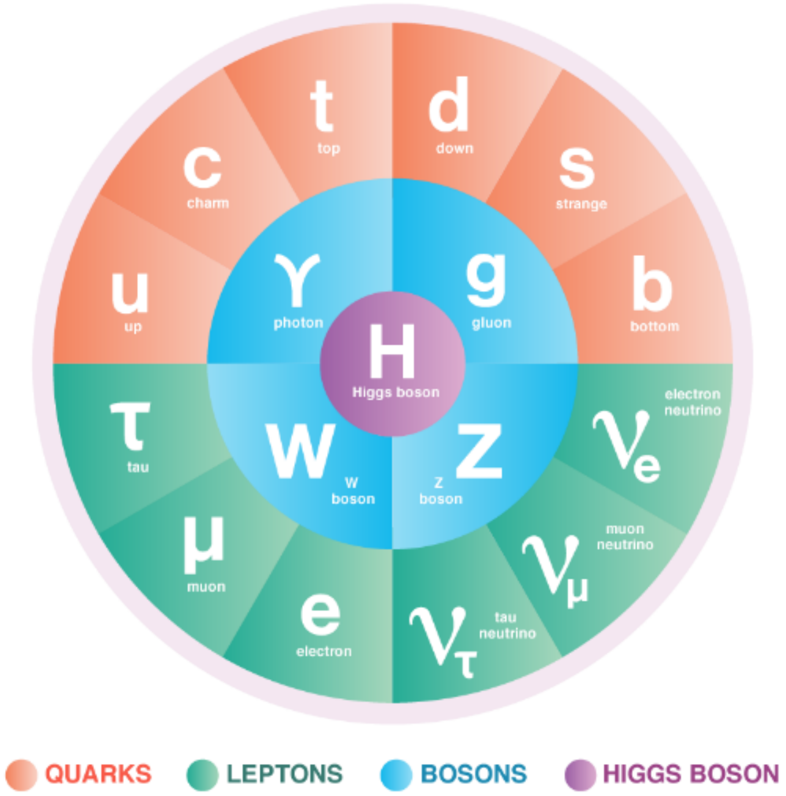
portals

Dark sector

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

Introduction

SM



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portals

Dark sector

$G^a_{D,\mu\nu}, \psi$

Dark QCD

- Neutral Naturalness, Cosmological Relaxation, Dark baryon or SIMP dark matter.
- Dark showers at LHC. If (some) light dark hadrons decay back to SM ⇒ semi-visible jets, emerging jets with displaced vertices, missing energies, depending on the lifetimes.

Dark QCD

- If no light dark quarks, the lightest dark hadron is dark glueball (0^{++}). It can mix with Higgs and its phenomenology was studied, e.g., Fraternal Twin Higgs model (Craig et al 1501.05310).

- With light dark quarks, the lightest dark hadrons are expected to be pseudo scalars (dark pions). [Focus of this talk]

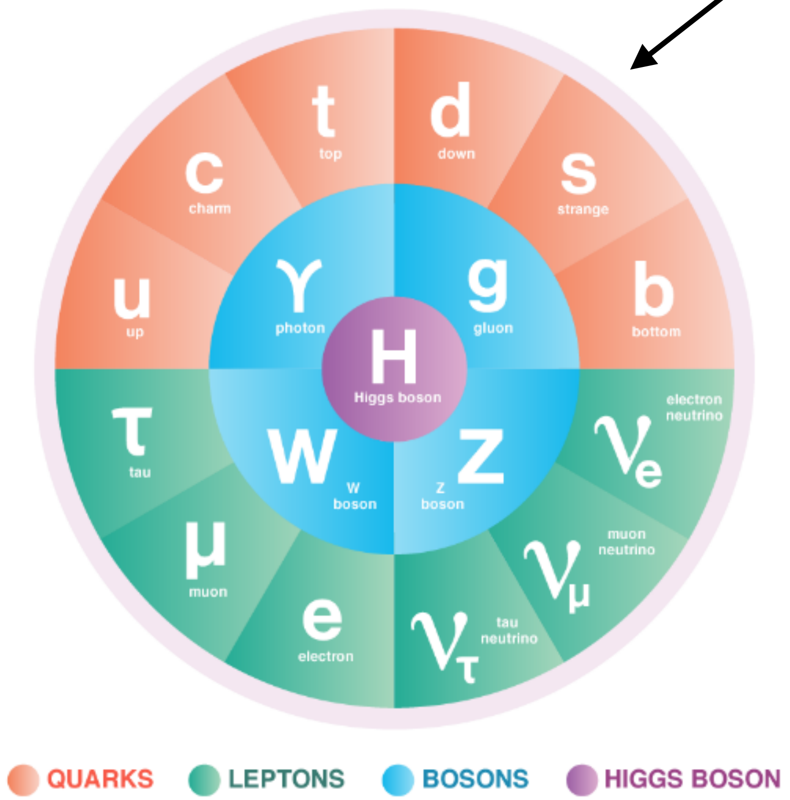
- Above dark pions, there are vector mesons. If the decay of vector mesons to dark pions is closed, they may directly decay back to SM, contributing to the signals.

$G^a_{D,\mu\nu}$, ψ

Dark QCD

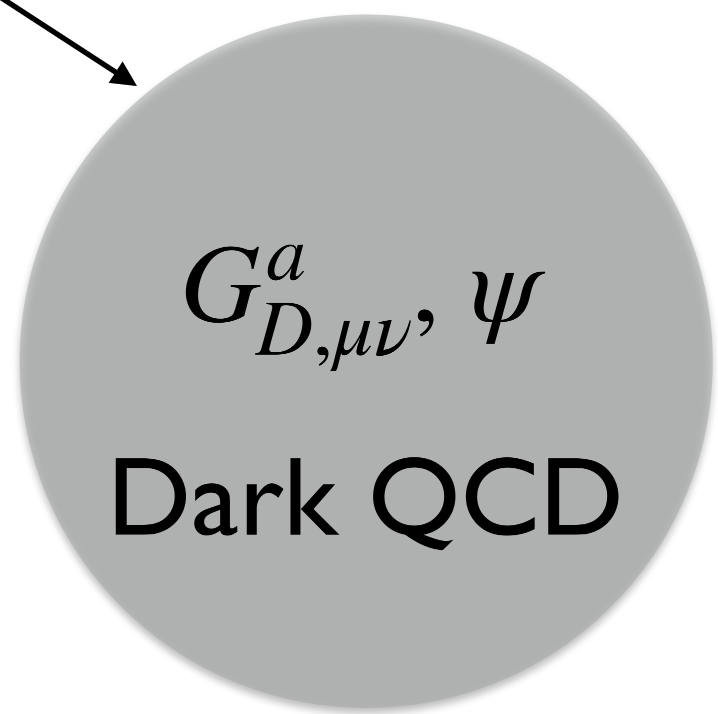
Portal interactions

Heavy states (X_{DK}, Z', etc), dark hadrons typically long-lived



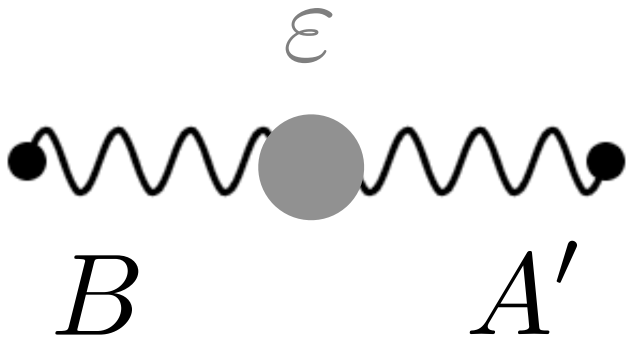
Z, h

Z, h decays serve as the main production at LHC, typically mediate displaced decays



$G^a_{D,\mu\nu}, \psi$

Dark QCD

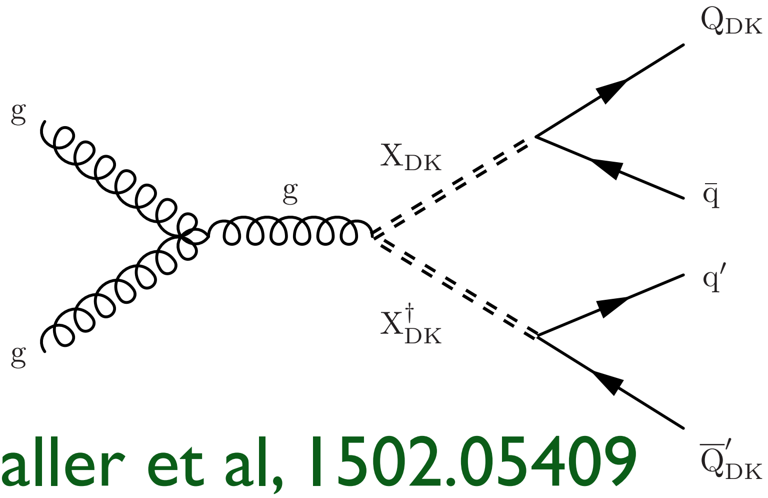


Tested at intensity frontier, prompt decays possible.

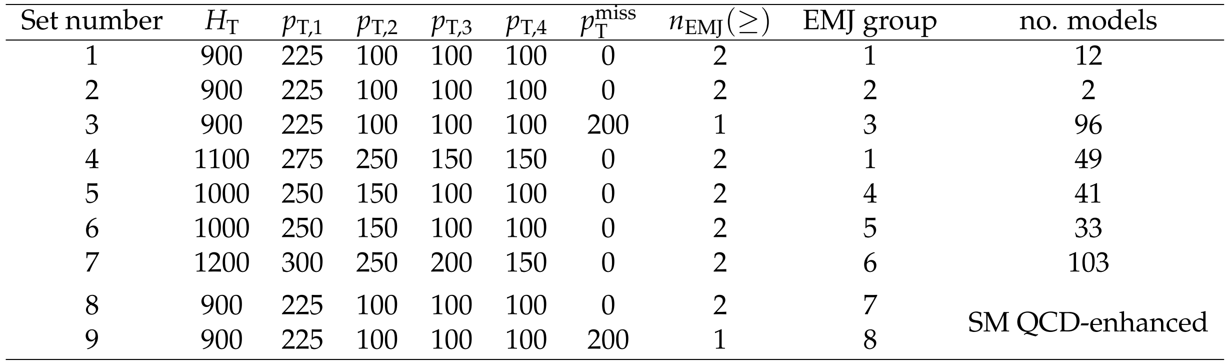
Dark Shower Searches

- Current emerging jet, semi-visible jet, and mono-X searches mostly based on high-scale mediation models. They rely on hard object to trigger and have high p_T cuts. The constraints on mediator masses typically reach a few TeV.

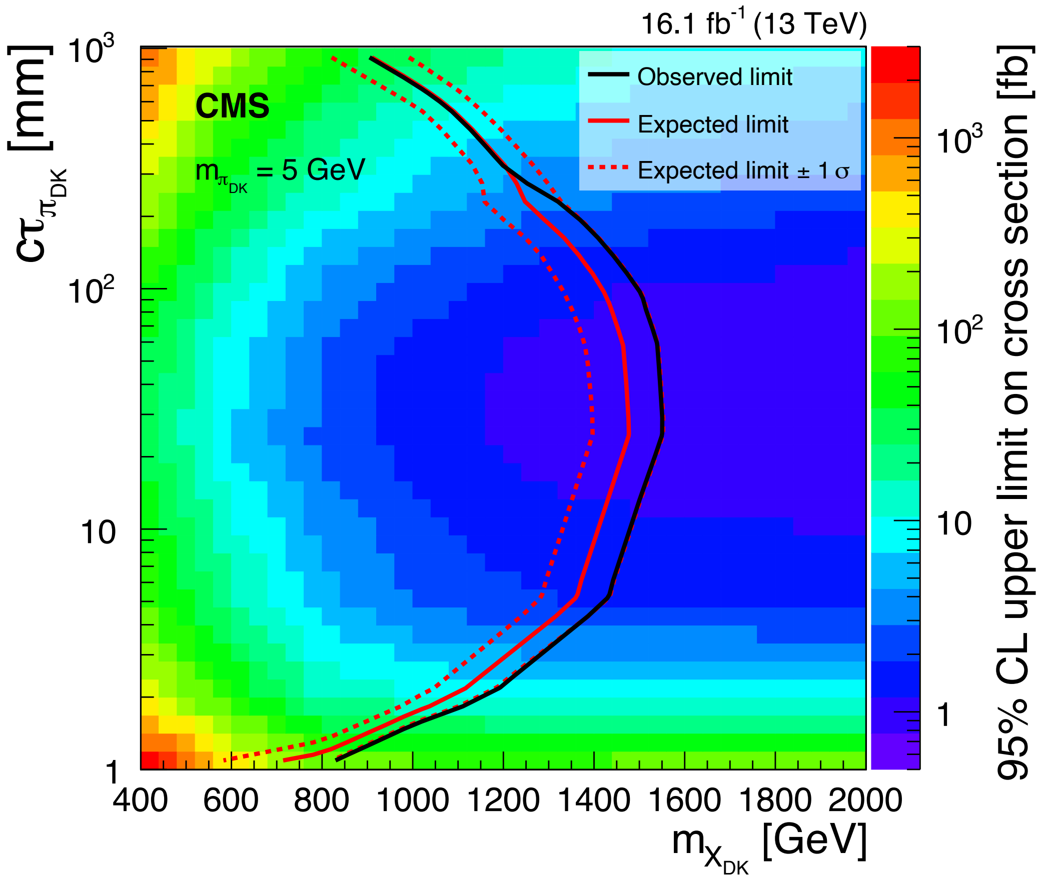
E.g., CMS emerging jet search, 1810.10069



Schwaller et al, 1502.05409

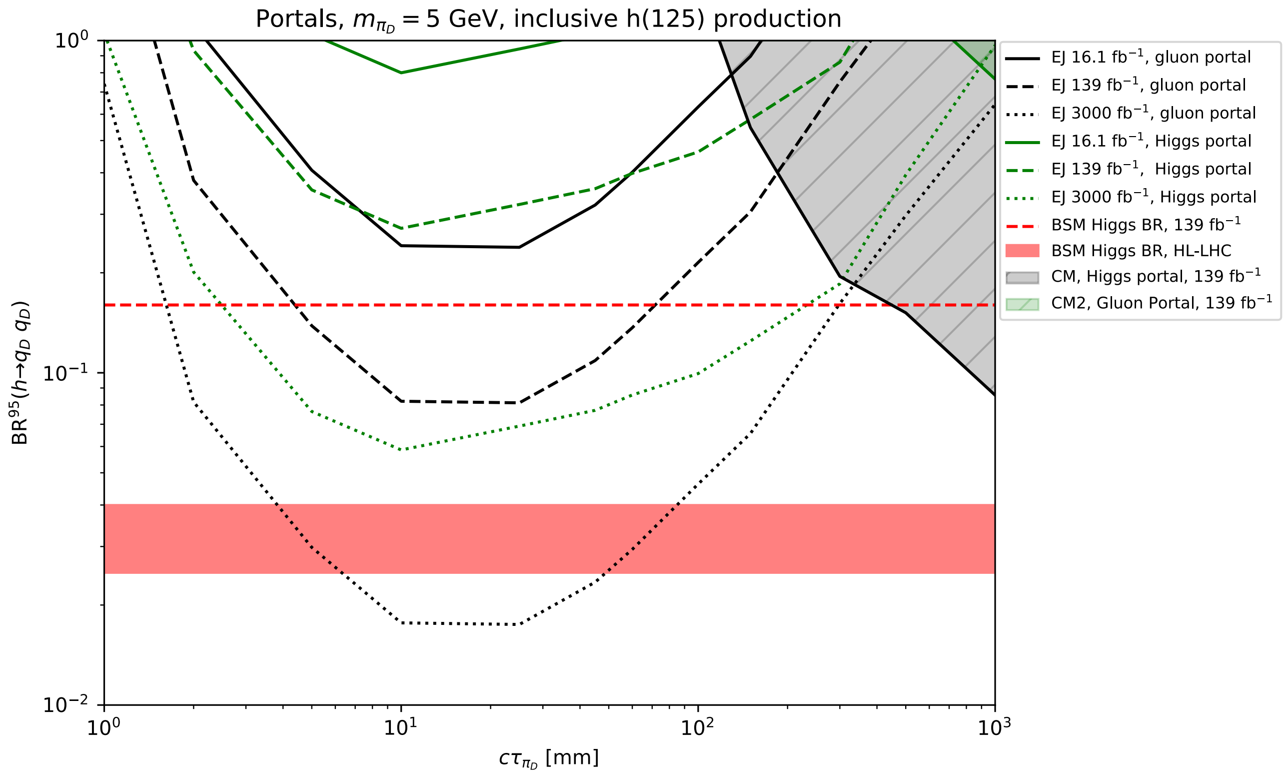


Set number	H_T	$p_{T,1}$	$p_{T,2}$	$p_{T,3}$	$p_{T,4}$	p_T^{miss}	$n_{EMJ}(\geq)$	EMJ group	no. models
1	900	225	100	100	100	0	2	1	12
2	900	225	100	100	100	0	2	2	2
3	900	225	100	100	100	200	1	3	96
4	1100	275	250	150	150	0	2	1	49
5	1000	250	150	100	100	0	2	4	41
6	1000	250	150	100	100	0	2	5	33
7	1200	300	250	200	150	0	2	6	103
8	900	225	100	100	100	0	2	7	SM QCD-enhanced
9	900	225	100	100	100	200	1	8	



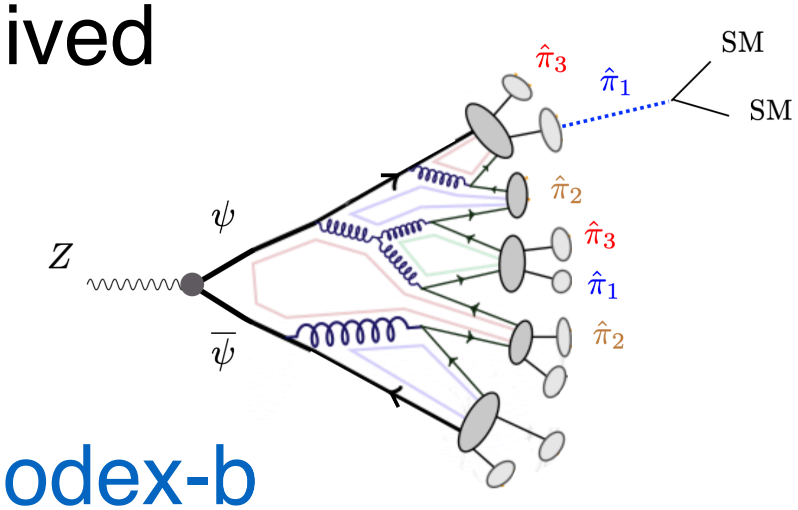
Dark Shower Searches

- These searches do not directly apply to dark showers from Z or Higgs portal. There is no hard object to trigger and the final state p_T's are too small to pass the cuts.
  - Requiring extra hard jets from ISR or associate production greatly reduces the rate. Recasting the current CMS emerging jet search to these cases gives limited reaches. (Carrasco & Zurita, 2307.04847)

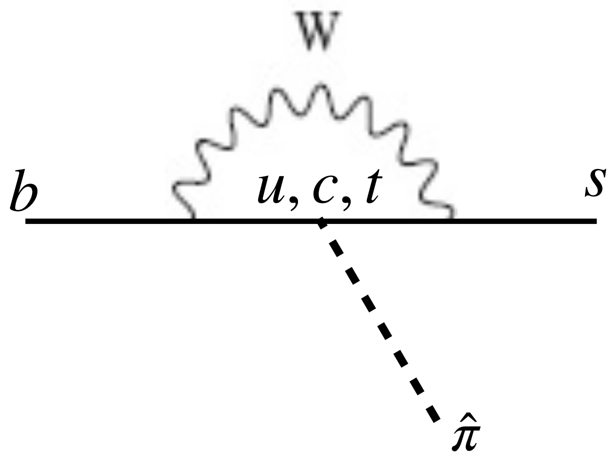


Dark Shower Searches

- The lightest dark hadrons are typically long-lived with Z portal. They can be searched at
  - Data scouting at CMS
  - LHCb with excellent VELO
  - Auxiliary detectors such as MATHUSLA, Codex-b
  - Future Z factories



- The meson FCNC decays to light dark hadrons provide complementary tests. They can be searched or constrained, in addition to the above experiments, at
  - LHC forward detectors, e.g., FASER, FASER 2
  - Flavor factories, e.g., Belle II
  - Fixed-target or beam dump experiments, e.g., CHARM



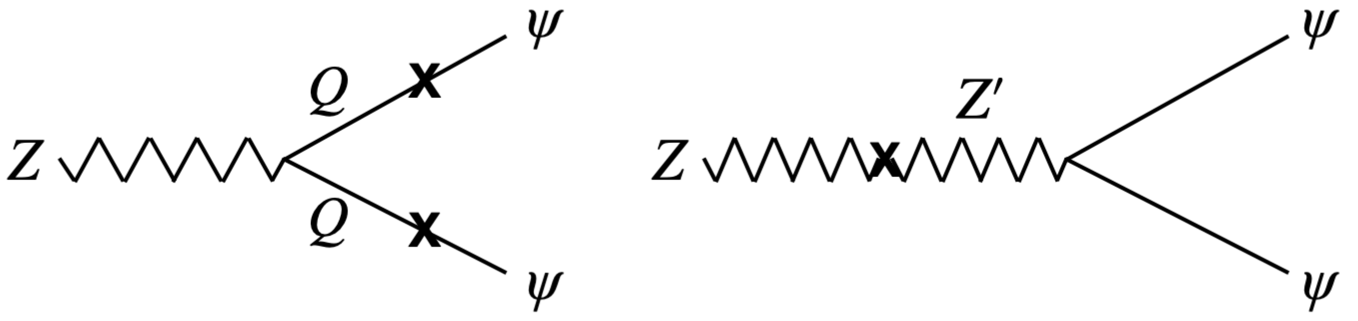
Z-portal

- An interesting scenario which is less studied.

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

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

1. Light dark quarks 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 quark are charged under a dark U(1) which mixes with Z after EW breaking.



Heavy Doublet Mixing Model

- SU(N_d) dark QCD, with a confining scale Λ.
- *N* flavors of SM-singlet dark quarks ψ_i, $i = 1, \cdots, N$.
- *N* heavy dark quarks, $Q_i \sim \mathbf{2}_{1/2}$ under SU(2)$_W$×U(1)$_Y$.

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

$$M \sim \text{TeV} \gg \Lambda, \qquad \omega, \frac{Y\widetilde{Y}v^2}{M} \ll \Lambda$$

Cosmological relaxation, Graham, Kaplan, Rajendran, 1504.07551,
Tripled top neutral naturalness, HC, Li, Salvioni, Verhaaren, 1803.03651.

Constraints on Heavy Doublet Model

- For $\widetilde{Y} \approx 0$ (or $Y \approx 0$), motivated by chiral symmetry on ψ_L to suppress ω, Z portal dominates. (If $Y \sim \widetilde{Y} \neq 0$, Higgs portal becomes important.)

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

$\Delta\mathrm{Br}(Z \to \mathrm{inv}) \lesssim 10^{-3} \Rightarrow\ Y \sim 1$ allowed

- Precision EW constraint due to heavy fermions:

$$\widehat{T} \simeq \frac{N_d}{16\pi^2} \sum_{i=1}^{N} \frac{v^2}{3M_i^2} \left(y_i^4 + \tilde{y}_i^4 + \frac{1}{2} y_i^2 \tilde{y}_i^2 \right) \qquad M \gtrsim 0.9\,\mathrm{TeV}\ Y^2 \left(\frac{N_d N}{6} \right)^{1/2}$$

- Direct searches of heavy doublets: $Q \to W/Z + \psi$. Assuming ψ results in missing energy, recasting SUSY searches gives $M \gtrsim 1.1\,\mathrm{TeV}$

Dark $Z' - Z$ Mixing Model

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm dark} + \mathcal{L}_{\rm mix},$$

$$\mathcal{L}_{\rm SM} \supset -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{W}^3_{\mu\nu}\hat{W}^{3\mu\nu} + \frac{1}{2}\hat{M}_Z^2\hat{Z}_\mu\hat{Z}^\mu - \hat{e}\sum_f \bar{f}\gamma^\mu\left(\frac{Y_f}{\hat{c}_W}\hat{B}_\mu + \frac{T^3_{Lf}}{\hat{s}_W}\hat{W}^3_\mu\right)f, \quad (2.2)$$

$$\mathcal{L}_{\rm dark} = -\frac{1}{4}\hat{Z}'_{\mu\nu}\hat{Z}'^{\mu\nu} + (D_\mu\Phi)^* D^\mu\Phi - g_D\sum_{j=1}^{N}\left(\overline{\psi}_j\gamma^\mu x^j_L P_L\psi_j + \overline{\psi}_j\gamma^\mu x^j_R P_R\psi_j\right)\hat{Z}'_\mu \quad (2.3)$$

$$-\frac{1}{4}G^D_{a\,\mu\nu}G^{D\,\mu\nu}_a + \sum_{j=1}^{N} i\overline{\psi}_j \not{D}_G\psi_j - \sum_{i,\,j=1}^{N}\left(\overline{\psi}_{Li}m_{ij}\psi_{Rj} + \overline{\psi}_{Li}\zeta^1_{ij}\psi_{Rj}\Phi + \overline{\psi}_{Ri}\zeta^2_{ij}\psi_{Lj}\Phi + \text{h.c.}\right),$$

$$\mathcal{L}_{\rm mix} = -\frac{\sin\chi}{2}\hat{Z}'_{\mu\nu}\hat{B}^{\mu\nu} + \delta\hat{M}^2\hat{Z}'^\mu\hat{Z}_\mu - \kappa\,\Phi^*\Phi H^\dagger H\,, \quad (2.4)$$

f : SM fermions, ψ : dark fermions, $x^i_{L,R}$: dark U(1) charge

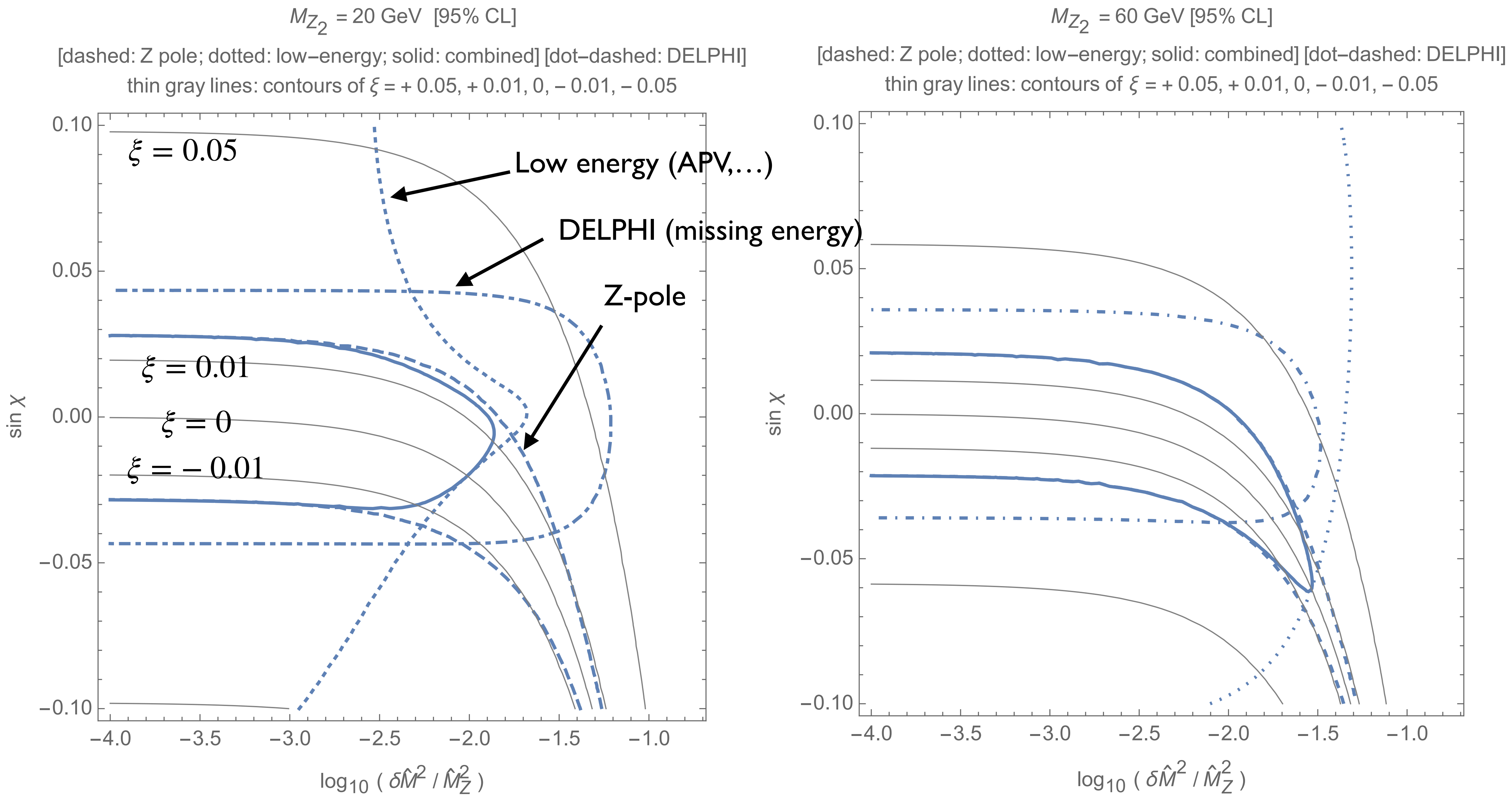
Φ: dark Higgs which breaks U(1), $\hat{Z}'$ obtains a mass item $\frac{1}{2}M^2_{Z'}\hat{Z}'_\mu\hat{Z}'^\mu$

$\sin\chi$: kinetic mixing

$\delta\hat{M}^2$: mass mixing, can arise from a second Higgs doublet which carries the dark U(1) charge

Constraints on Dark Z'

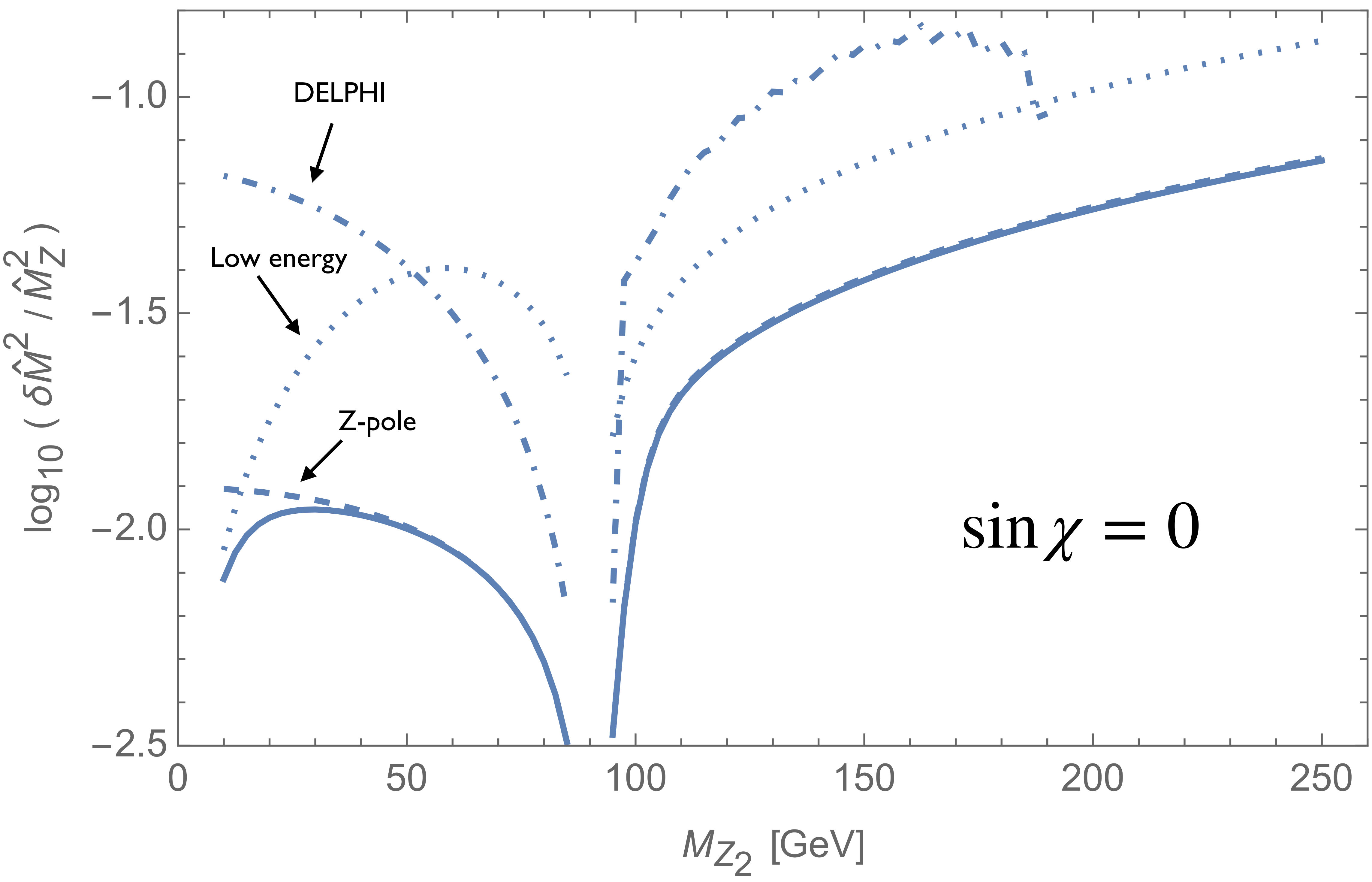
- Strongest constraint coming from EW precision observables for $M_{Z'} \gtrsim \Upsilon$ mass.



ξ :mixing between Z, Z',

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

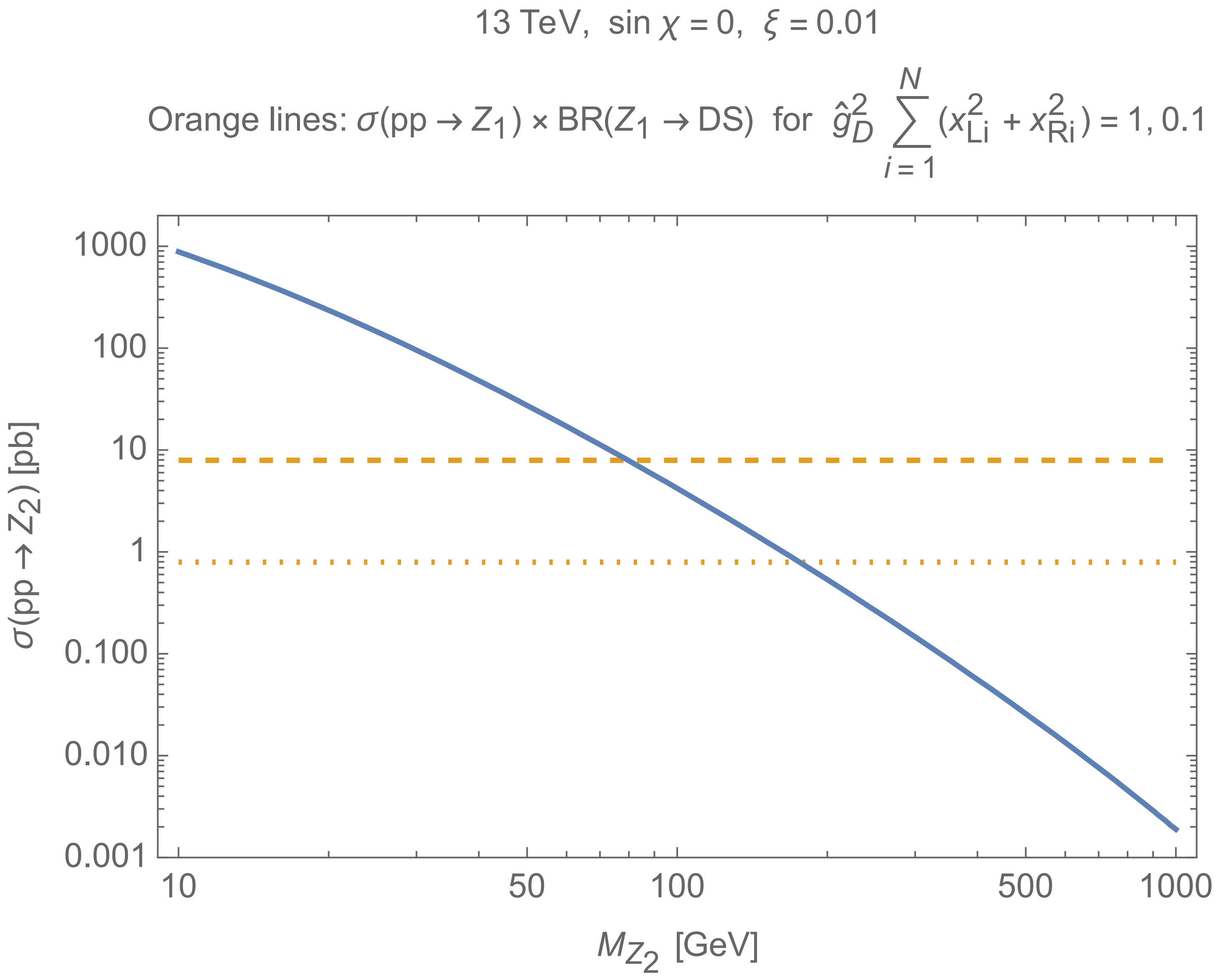
Combined Constraints on Dark Z'



Dark Quark Production from Z , Z' Decays

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

$\mathrm{BR}(Z' \to \psi\overline{\psi}) \approx 1$ but production cross section suppressed by ξ^2

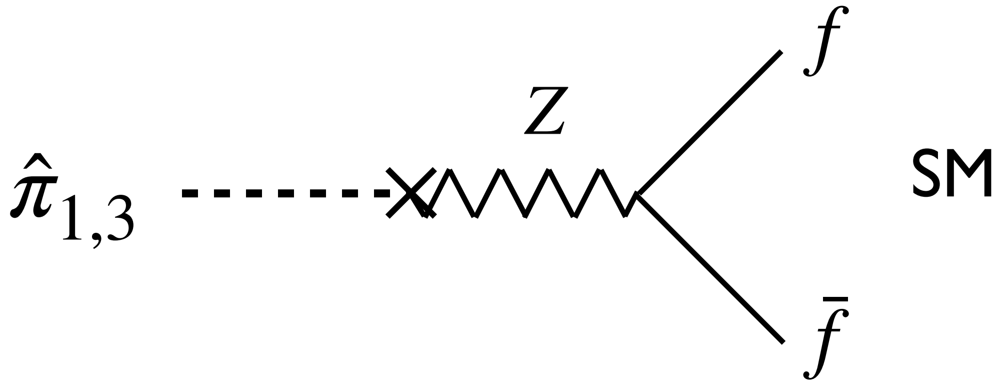


Dark Pion Decays

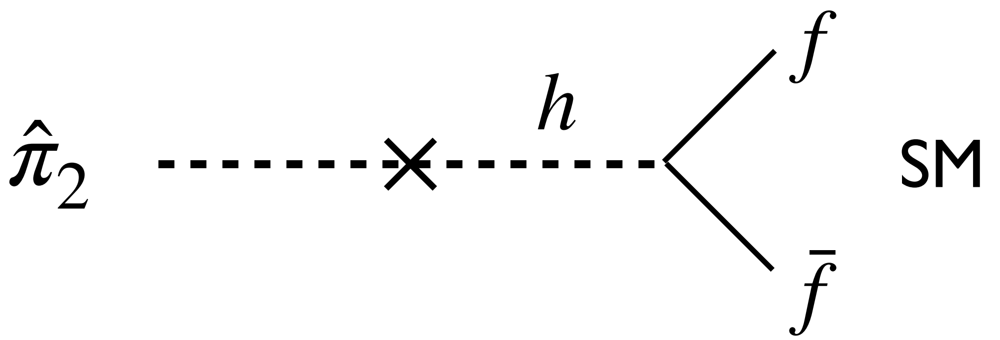
- Dark pions: $\hat{\pi}_a \sim \overline{\psi}' i\sigma_a \gamma_5 \psi'$ (for N=2), ψ' : mass eigenstates

If no CP violation in the dark sector, CP-odd dark pions decay through mixing with Z (and Z'), CP-even dark pions decay through Higgs.

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



$\hat{\pi}_2$, 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.

CP-odd Dark Pions

Integrating out $Z\,(,Z')$ and replacing $\overline{\psi}'i\frac{\sigma_a}{2}\gamma_\mu\gamma_5\psi' \to f_{\hat{\pi}}\partial_\mu\hat{\pi}_a$

$$\mathcal{L}_{\rm eff} \sim \frac{\partial_\mu\hat{\pi}}{f_a}\sum_f c_f\bar{f}\gamma^\mu\gamma_5 f$$ ALP-like interaction

$$c_f = T_L^3(f)$$ maximal isospin violation

- The effective ALP decay constant:

Heavy doublet model: $$f_a \sim \frac{M^2}{Y^2 f_{\hat{\pi}}} \sim 1\ {\rm PeV}\left(\frac{M/Y}{\rm TeV}\right)^2\left(\frac{\rm GeV}{f_{\hat{\pi}}}\right)$$

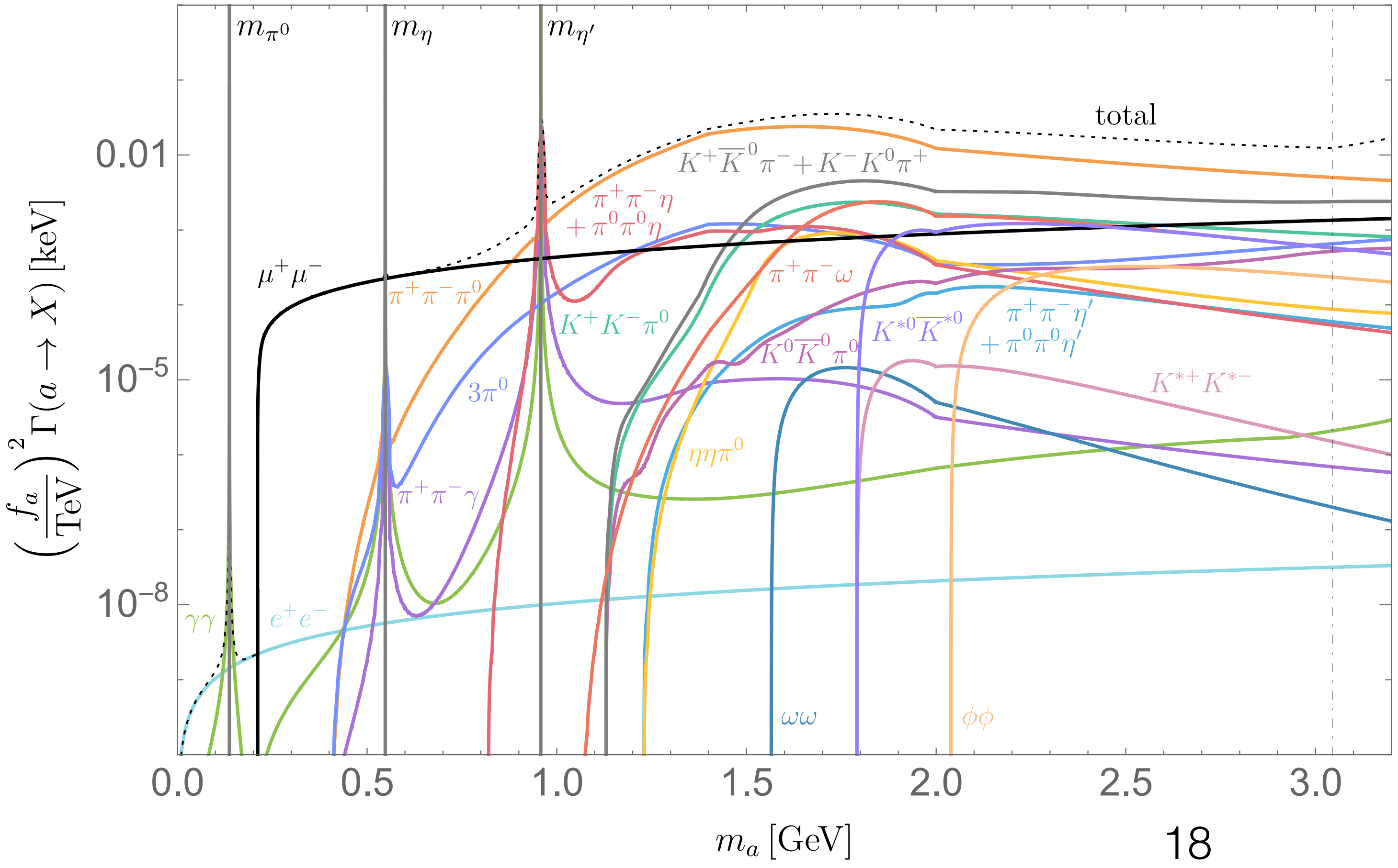
Z' mixing model: $$f_a \sim \frac{2M_{Z_1}^2M_{Z_2}^2}{g_D\hat{g}_Z f_{\hat{\pi}}\delta\hat{M}^2} \sim 1\ {\rm PeV}\left(\frac{10^{-2}}{\delta\hat{M}^2/M_{Z_1}^2}\right)\left(\frac{M_{Z_2}}{60\ {\rm GeV}}\right)^2\left(\frac{\rm GeV}{g_D f_{\hat{\pi}}}\right)$$

$(Z_1 = Z,\ \ Z_2 = Z')$

It requires mass mixing. Kinetic mixing only mixes transverse polarizations, which do not induce pion decays.

Dark Pion Decays

- For $m_{\hat{\pi}} \sim$ GeV we need to consider exclusive final states containing SM hadrons. Applying data driven methods [following Aloni, Soreq, Williams 1811.03474, which considered gluon (quark-universal) couplings],
  - For $m_{\hat{\pi}} < m_{\eta'} \sim 1$ GeV, match ALP EFT to χPT
  - For $m_{\eta'} < m_{\hat{\pi}} \lesssim 3$ GeV, include exchange of scalar, vector, tensor resonances, using as much input from data as possible

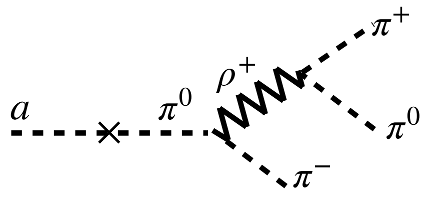


For $m_{\hat{\pi}} = 650$ MeV, $f_a = 1$ PeV, $c\tau \approx 70$ cm

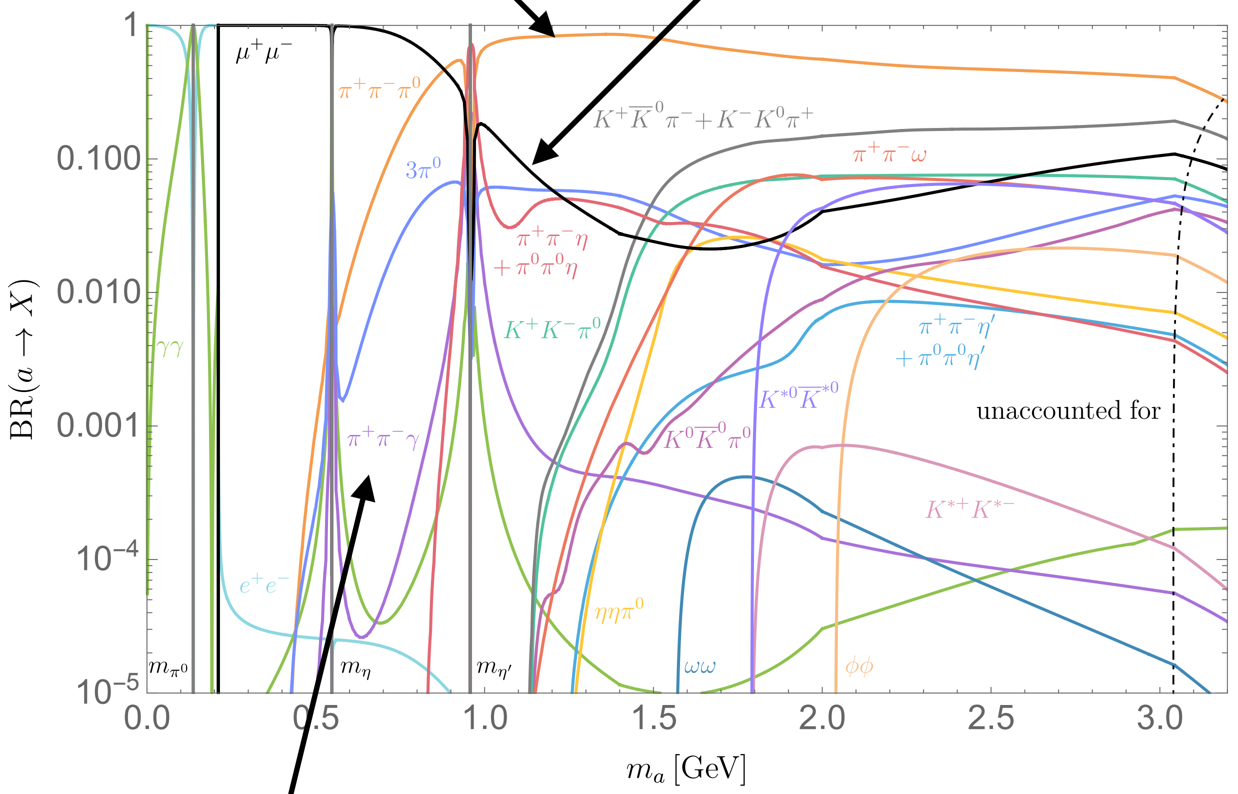
(HC, Li, Salvioni, 2110.10691)

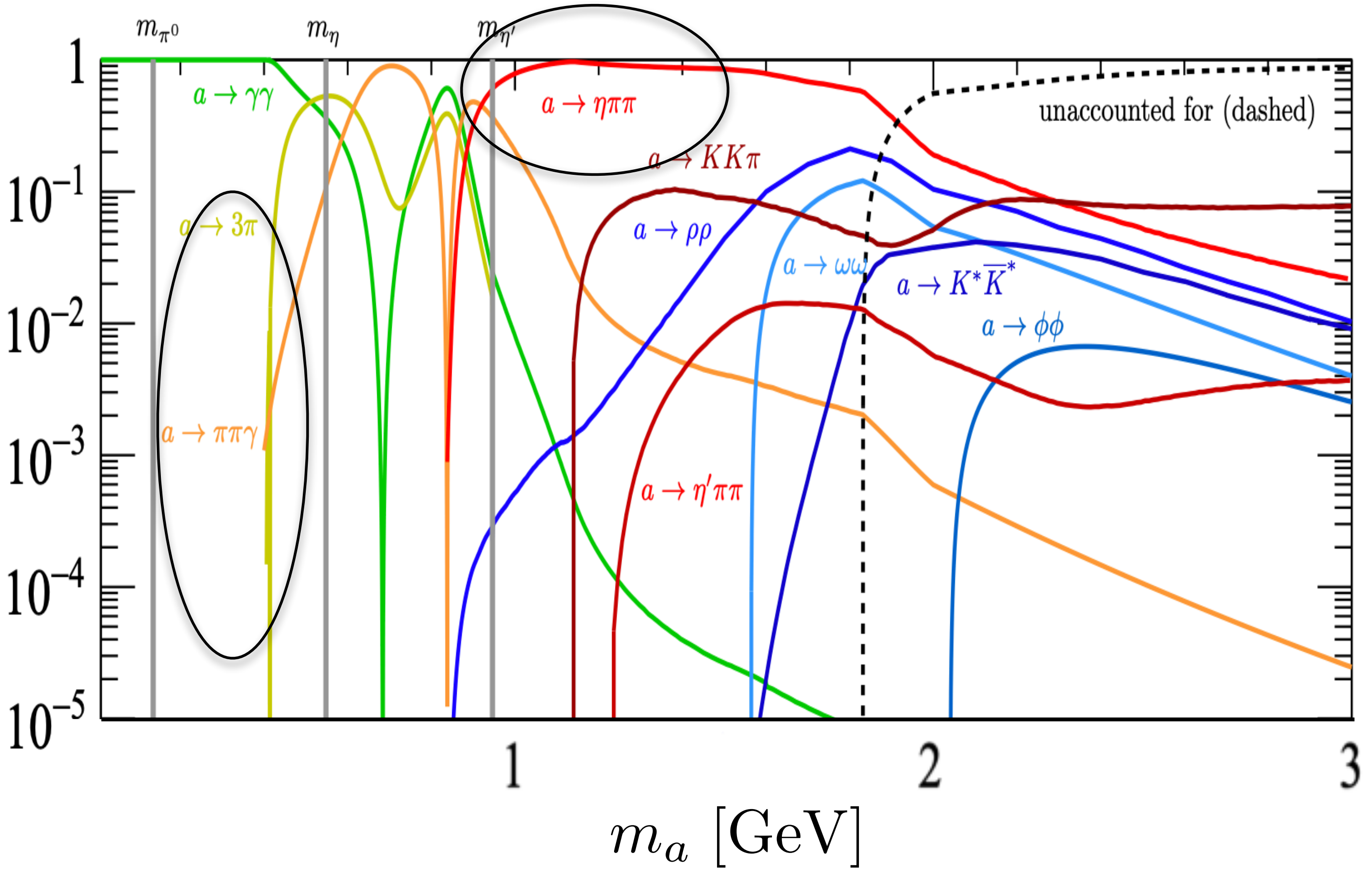
Isospin Violating vs Gluon Couplings

$\pi^+\pi^-\pi^0$ dominates for $m_{\hat{\pi}} \gtrsim 900$ MeV



$\mu^+\mu^- >$ a few % for $m_{\hat{\pi}} \lesssim 3$ GeV





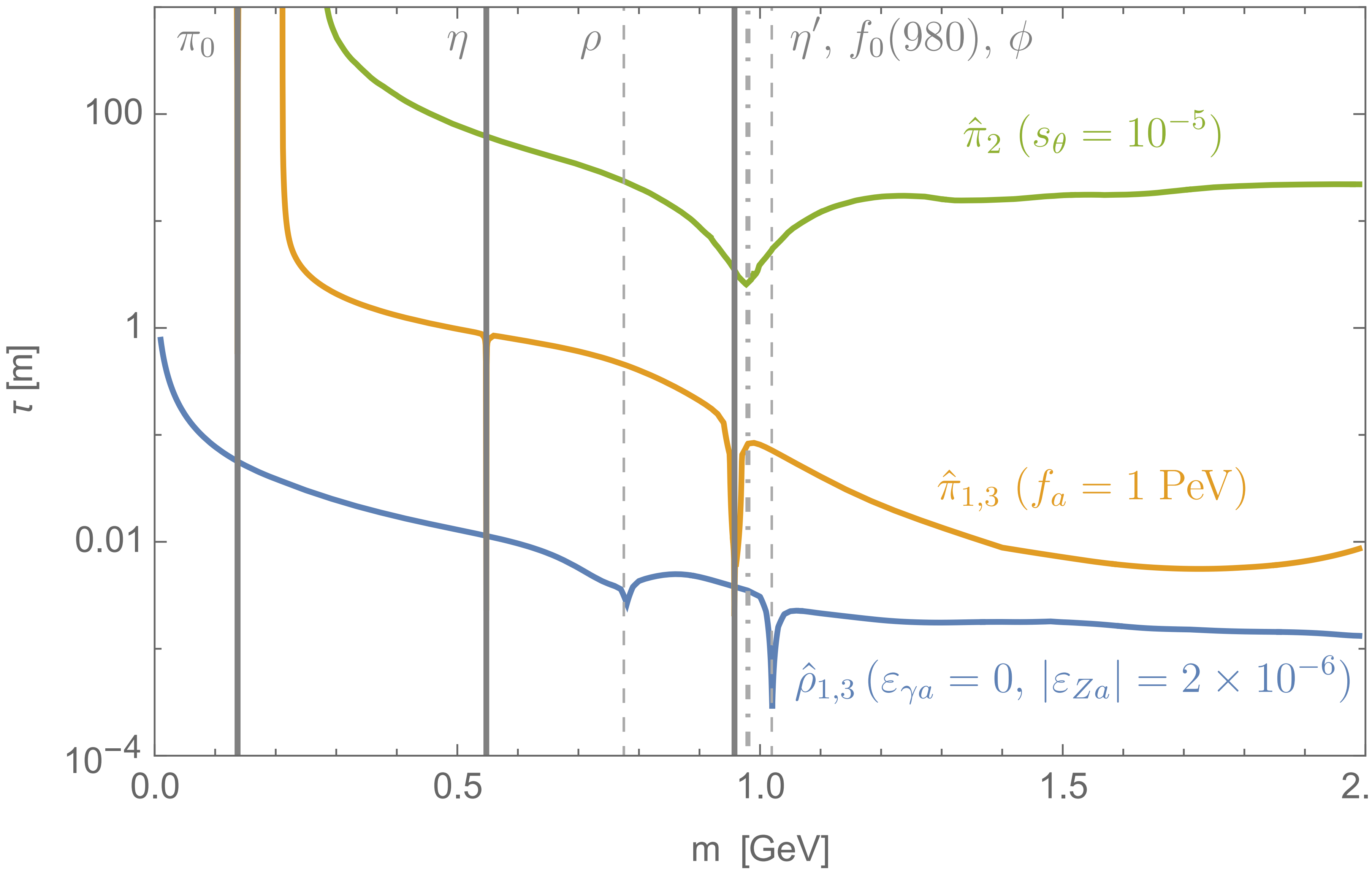
$\pi^+\pi^-\gamma$ negligible

$$\mathcal{L}_{\rm eff} \supset -\frac{\partial_\mu a}{f_a} \sum_f c_f \bar{f} \gamma^\mu \gamma_5 f$$

$$c_f = T^3_L(f)$$

$$\mathcal{L}_{\rm eff} \supset c_g \frac{\alpha_s}{4\pi} \frac{a}{f_a} G^a_{\mu\nu} \widetilde{G}^{\mu\nu\,a}$$

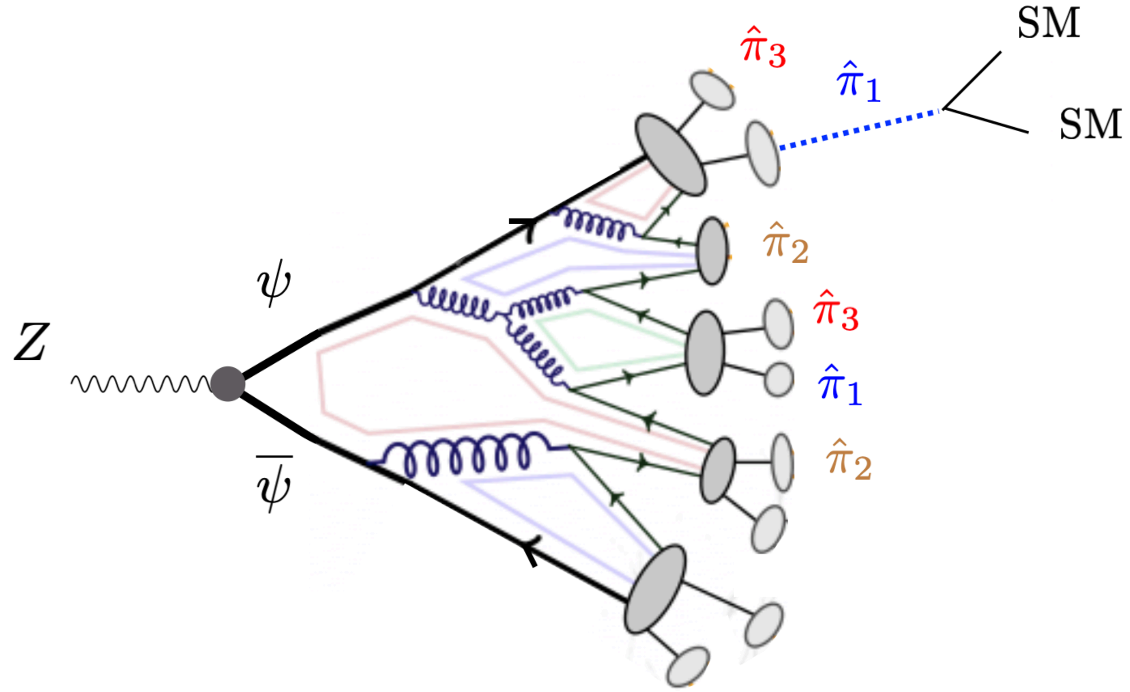
Dark Meson Decay Lengths



- The dark pion decays through Z-portal have decay lengths in the most interesting range of few mm to 100 m for $2m_\mu < m_{\hat{\pi}} < 3$ GeV, $f_a \sim 1$ PeV.
- The typical effective mixing of CP-even dark pion with Higgs $s_\theta \sim 10^{-8}$, implying it most likely decays outside the detectors.

Experimental Searches for Dark Showers

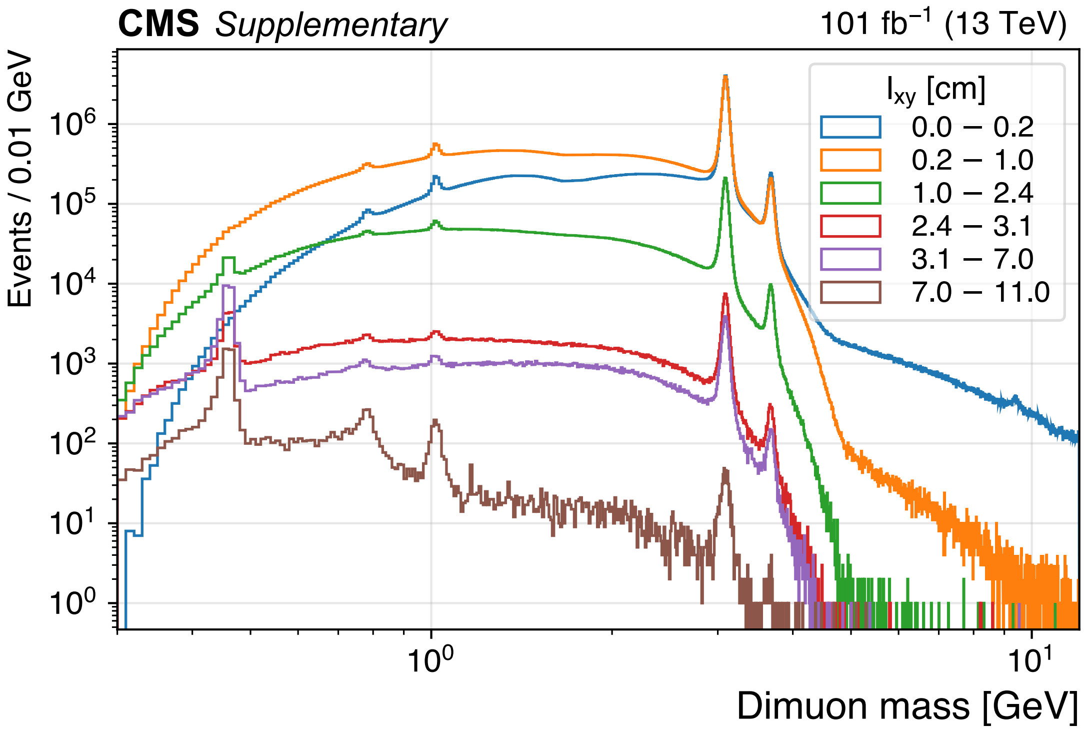
- Z and Z' decays: dark showers at LHC and future colliders

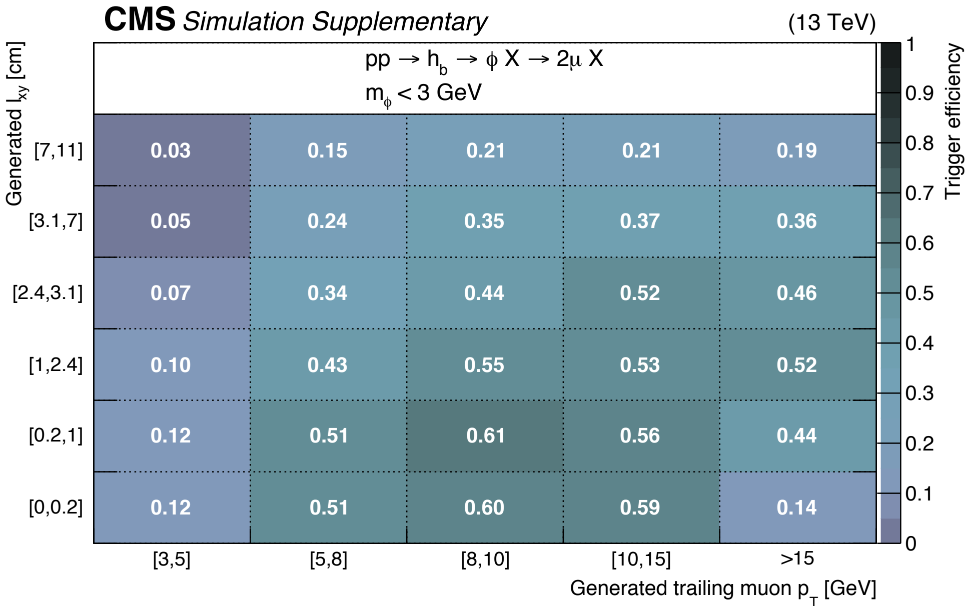


The Hidden Valley Module of Pythia8 is used to simulate the dark shower events.

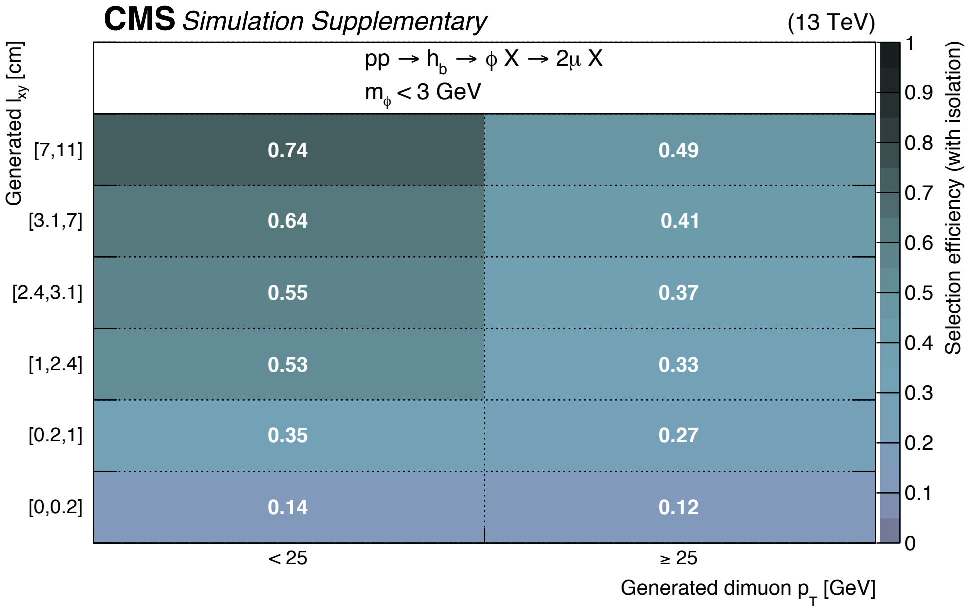
CMS Scouting Search

- CMS 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.





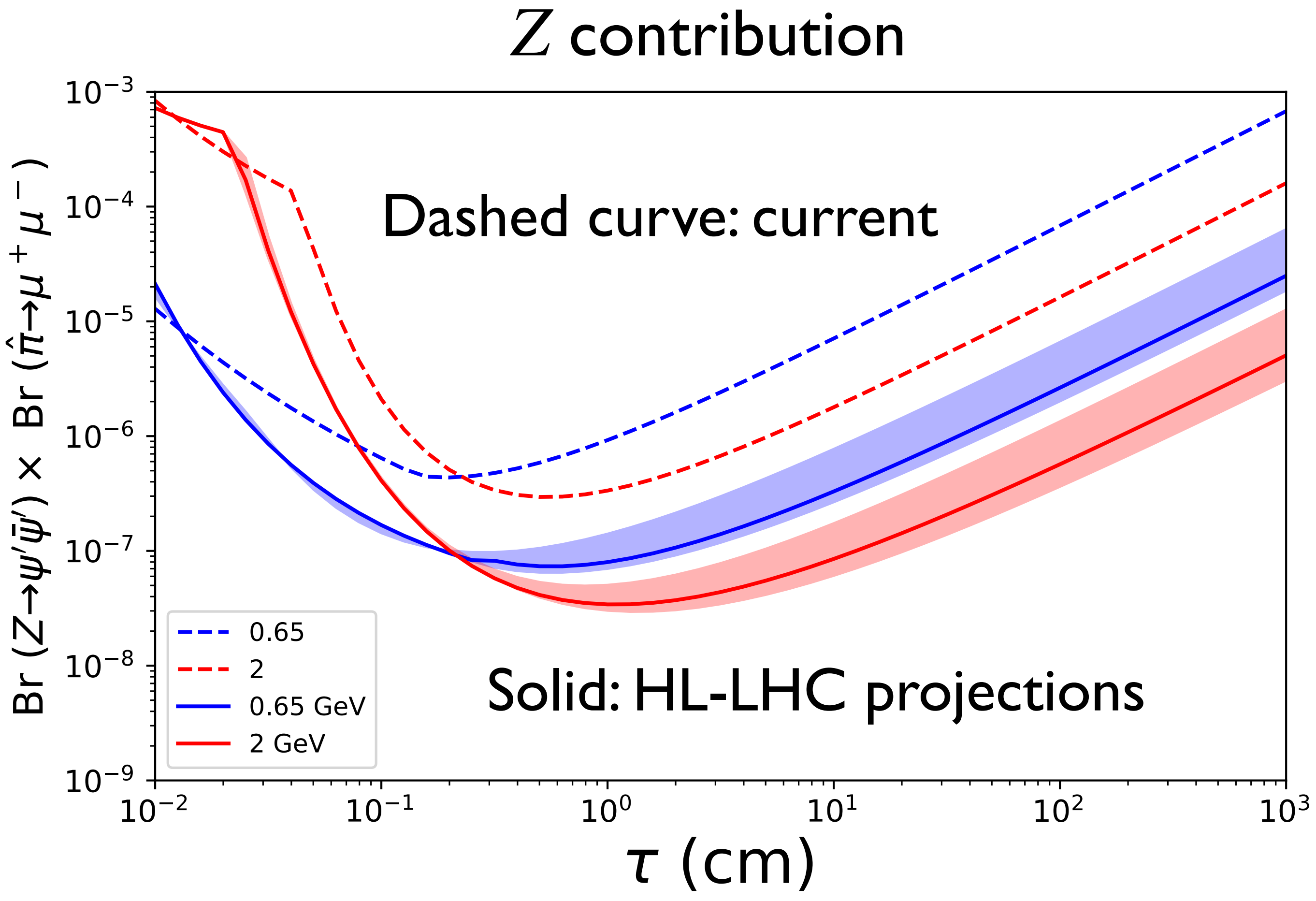
	[3,5]	[5,8]	[8,10]	[10,15]	>15
[7,11]	0.03	0.15	0.21	0.21	0.19
[3.1,7]	0.05	0.24	0.35	0.37	0.36
[2.4,3.1]	0.07	0.34	0.44	0.52	0.46
[1,2.4]	0.10	0.43	0.55	0.53	0.52
[0.2,1]	0.12	0.51	0.61	0.56	0.44
[0,0.2]	0.12	0.51	0.60	0.59	0.14



	< 25	≥ 25
[7,11]	0.74	0.49
[3.1,7]	0.64	0.41
[2.4,3.1]	0.55	0.37
[1,2.4]	0.53	0.33
[0.2,1]	0.35	0.27
[0,0.2]	0.14	0.12

CMS Scouting Search

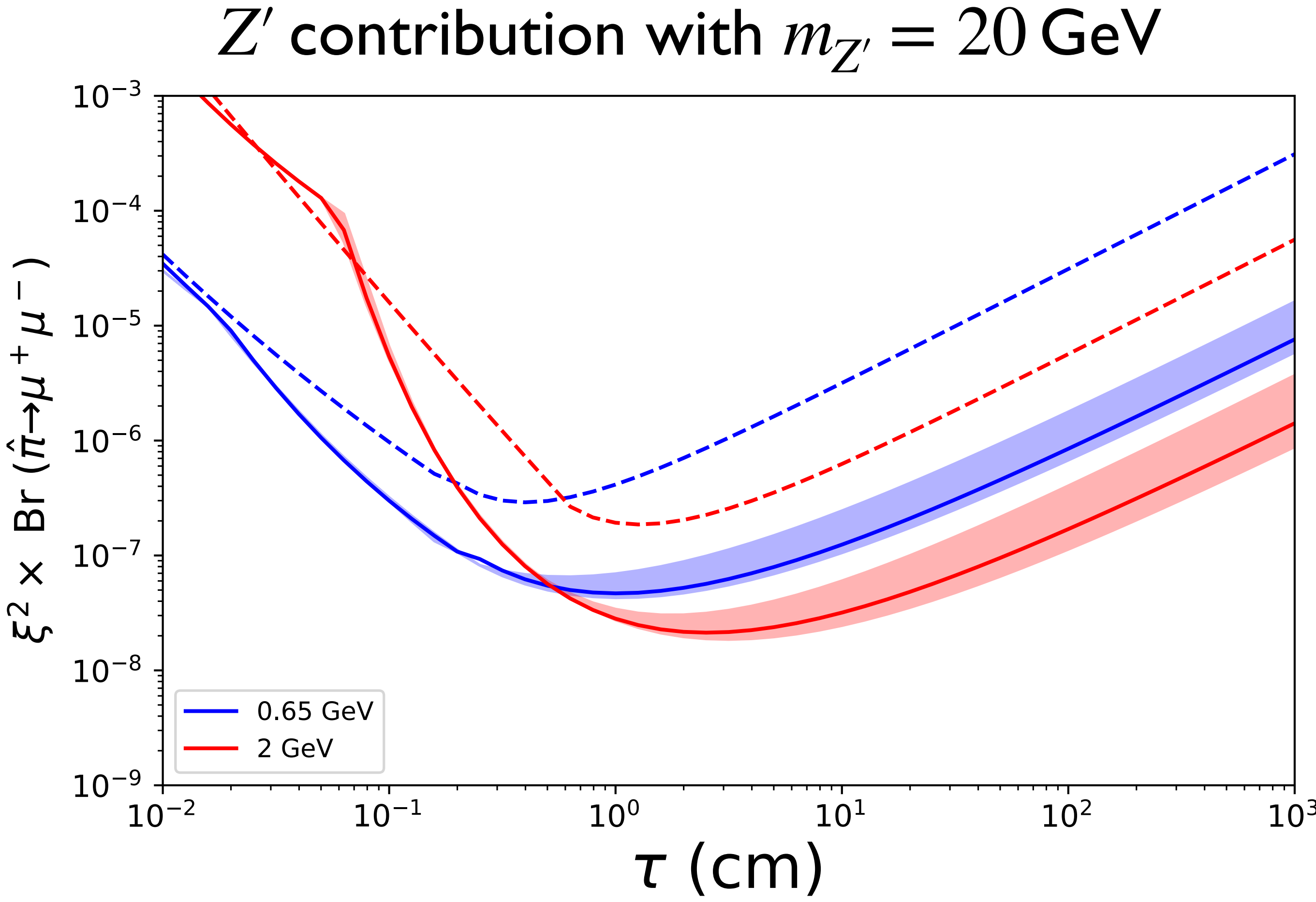
- Recast CMS scouting search, with some conservative assumptions. Model independent bounds (for 1 DV only).



Z contribution

Dashed curve: current

Solid: HL-LHC projections



Z' contribution with $m_{Z'} = 20\,\mathrm{GeV}$

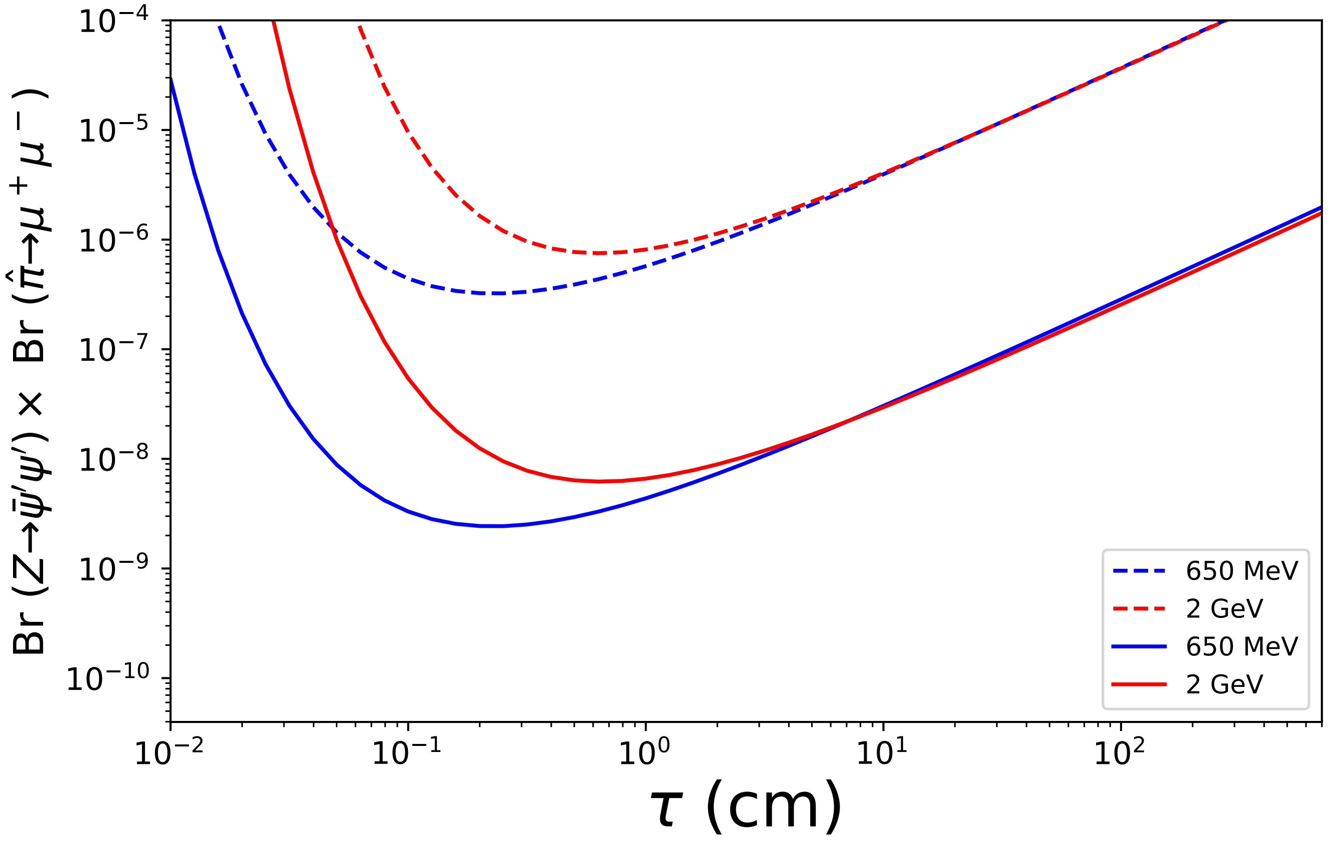
Blue: $m_{\hat{\pi}} = 650\,\mathrm{MeV}$ Red: $m_{\hat{\pi}} = 2\,\mathrm{GeV}$

Preliminary

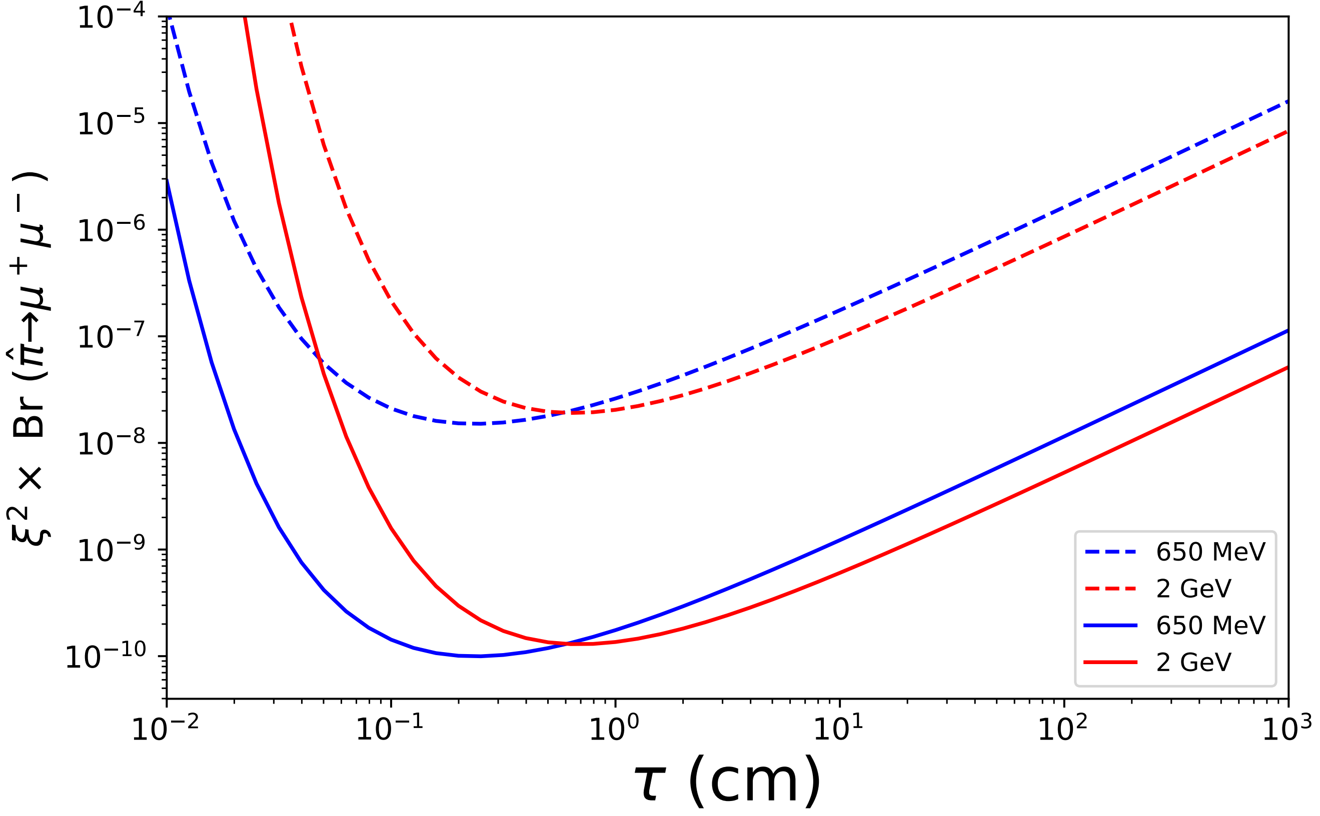
LHCb

- 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.

Z contribution

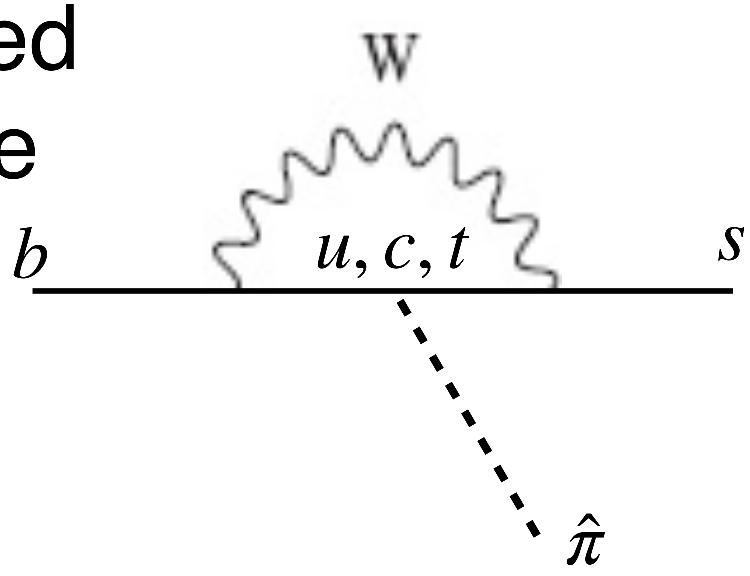


Z' contribution with $m_{Z'} = 20$ GeV



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 f_a.



$$\Gamma(B \to K\hat{\pi}_b) = \frac{m_B^3}{64\pi} \underset{\uparrow}{f_0^K(m_{\hat{\pi}}^2)^2} \left| \frac{\hat{g}^2 V_{ts}^* V_{tb}}{64\pi^2 f_a^{(b)}} \mathcal{K}_t \right|^2 \left(1 - \frac{m_K^2}{m_B^2}\right)^2 \underset{\uparrow}{\lambda_{BK\hat{\pi}}^{1/2}}$$

form factor

phase space

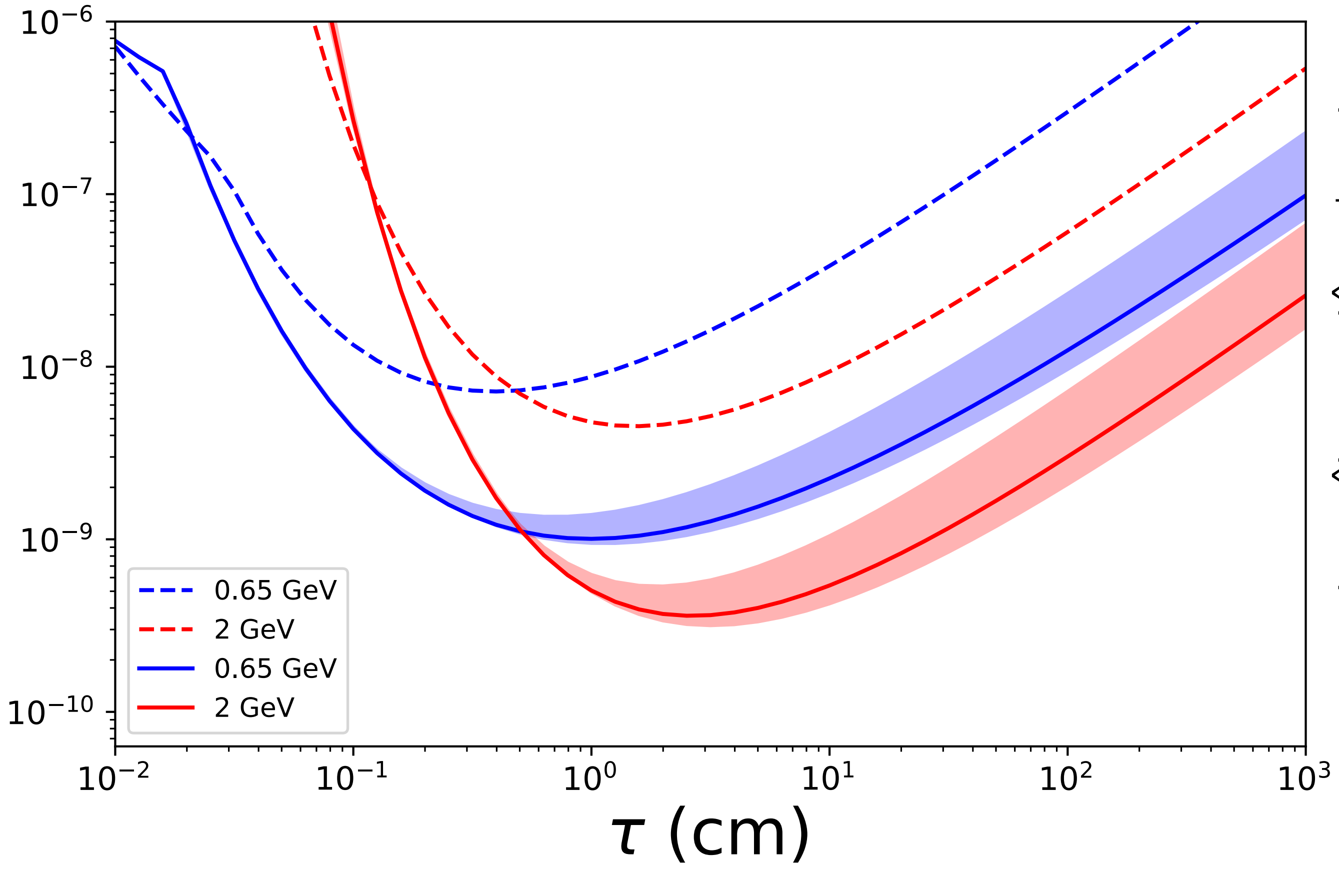
$\mathcal{K}_t$:Loop integral, ~ 5-16 for cutoff 300 GeV - 1 TeV

Cutoff determined by heavy fermions (heavy doublet model) or 2nd Higgs doublet (Z' mixing model)

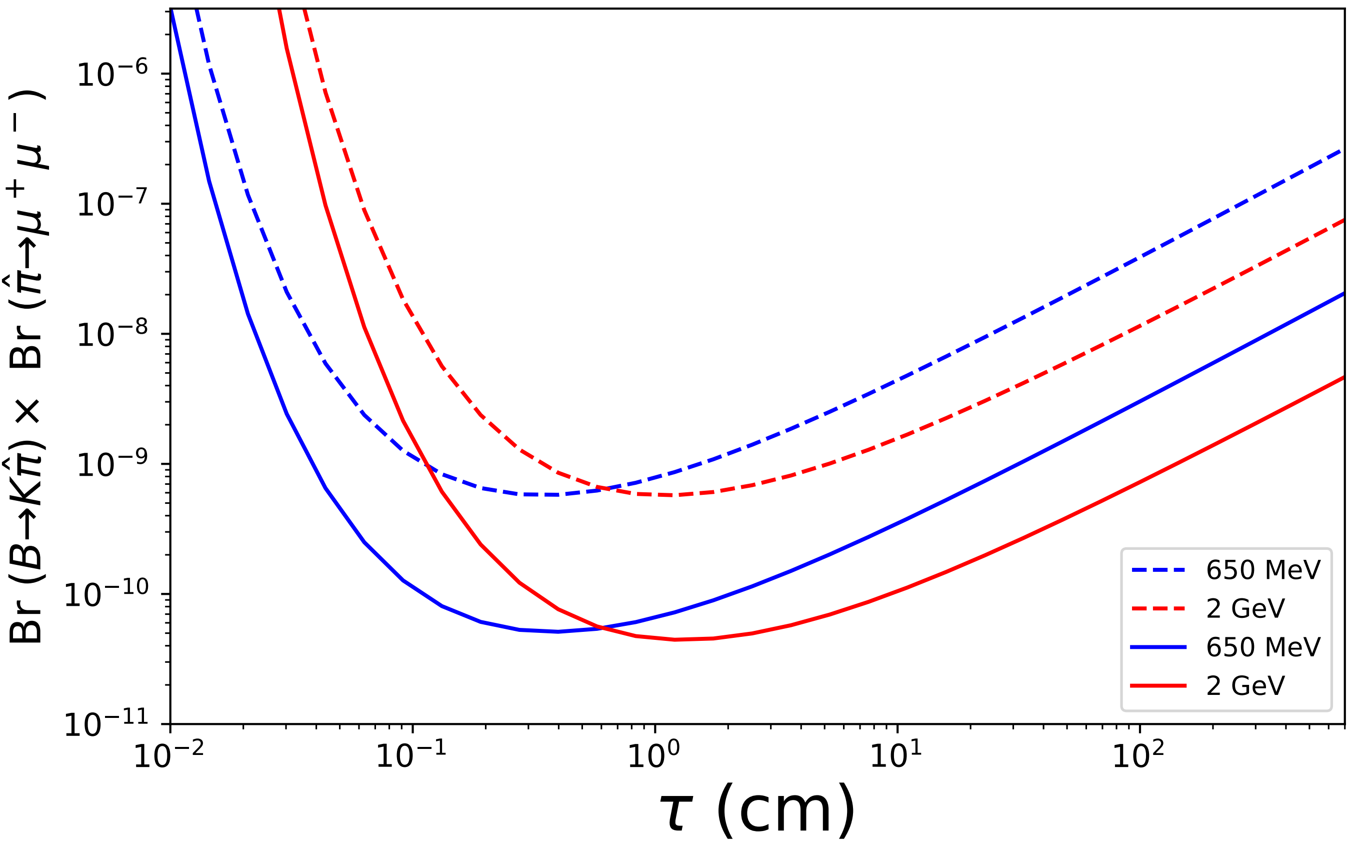
$$\mathrm{BR}(B^{+,0} \to \{K^+\hat{\pi}_b, K^{*0}\hat{\pi}_b\}) \approx \{0.92, 1.1\} \times 10^{-8} \left(\frac{1\ \mathrm{PeV}}{f_a^{(b)}}\right)^2 \left(\frac{\mathcal{K}_t}{10}\right)^2 \{\lambda_{BK\hat{\pi}}^{1/2}, \lambda_{BK^*\hat{\pi}}^{3/2}\},$$

FCNC @ LHC

CMS Scouting



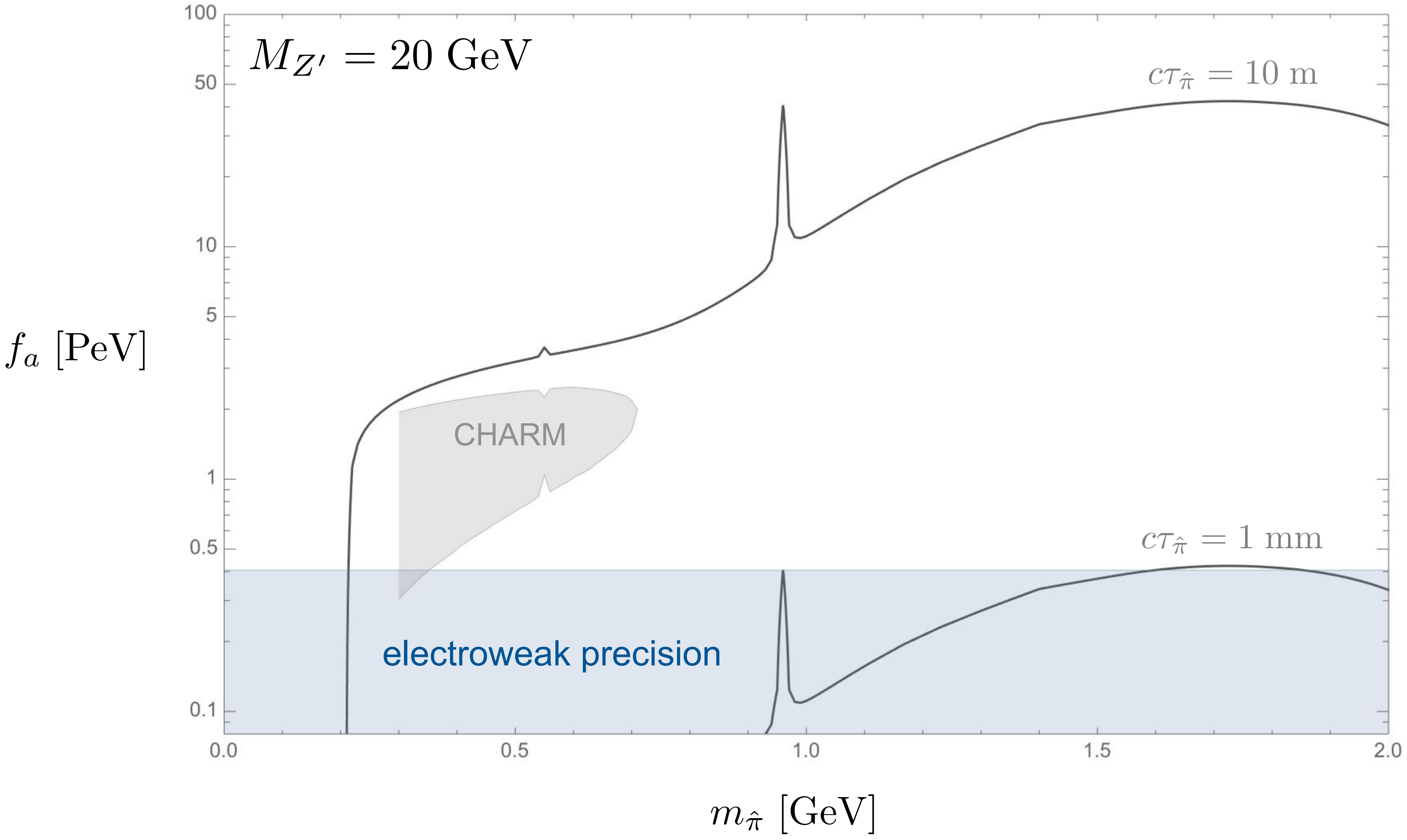
LHCb



Bounds on Benchmark Models

- Z' mixing model:
  $M_{Z'} = 20$ GeV, Tr$(\sigma_{1,3} X'_A) = 1$, $g_D = 0.25$, $f_{\hat{\pi}} = 1$ GeV ,
  $\hat{\pi}_2$ detector stable.

Pre-LHC



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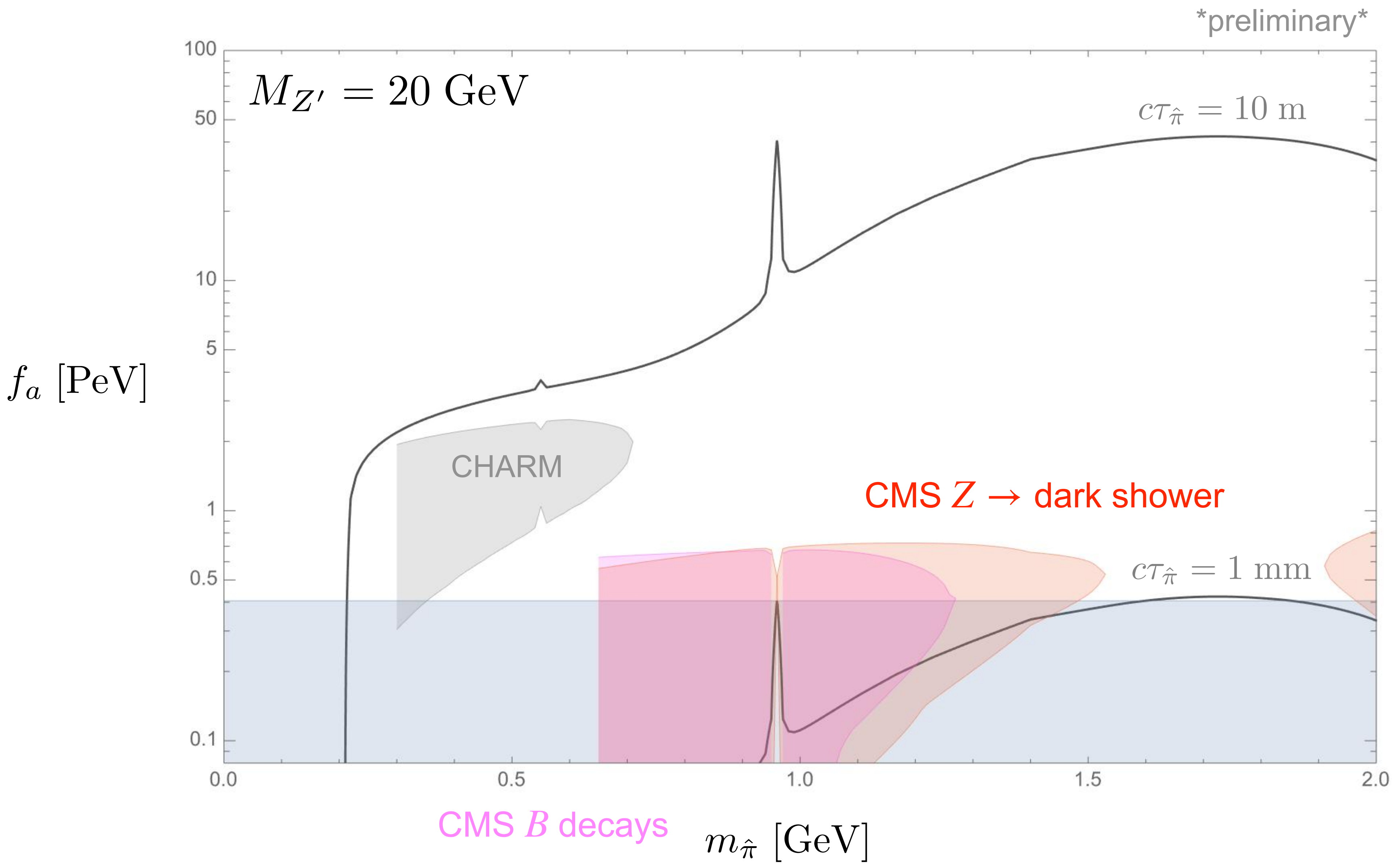

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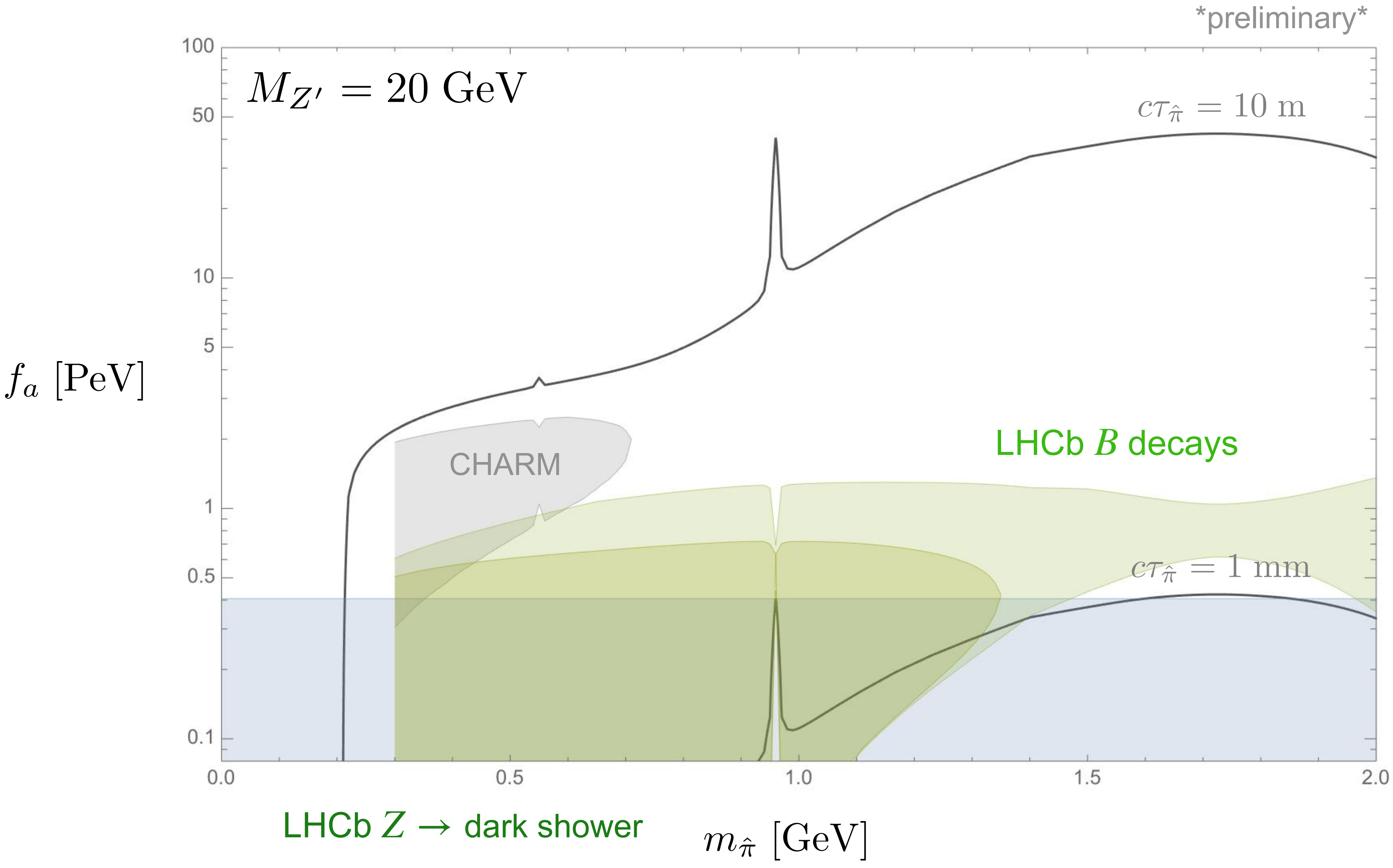

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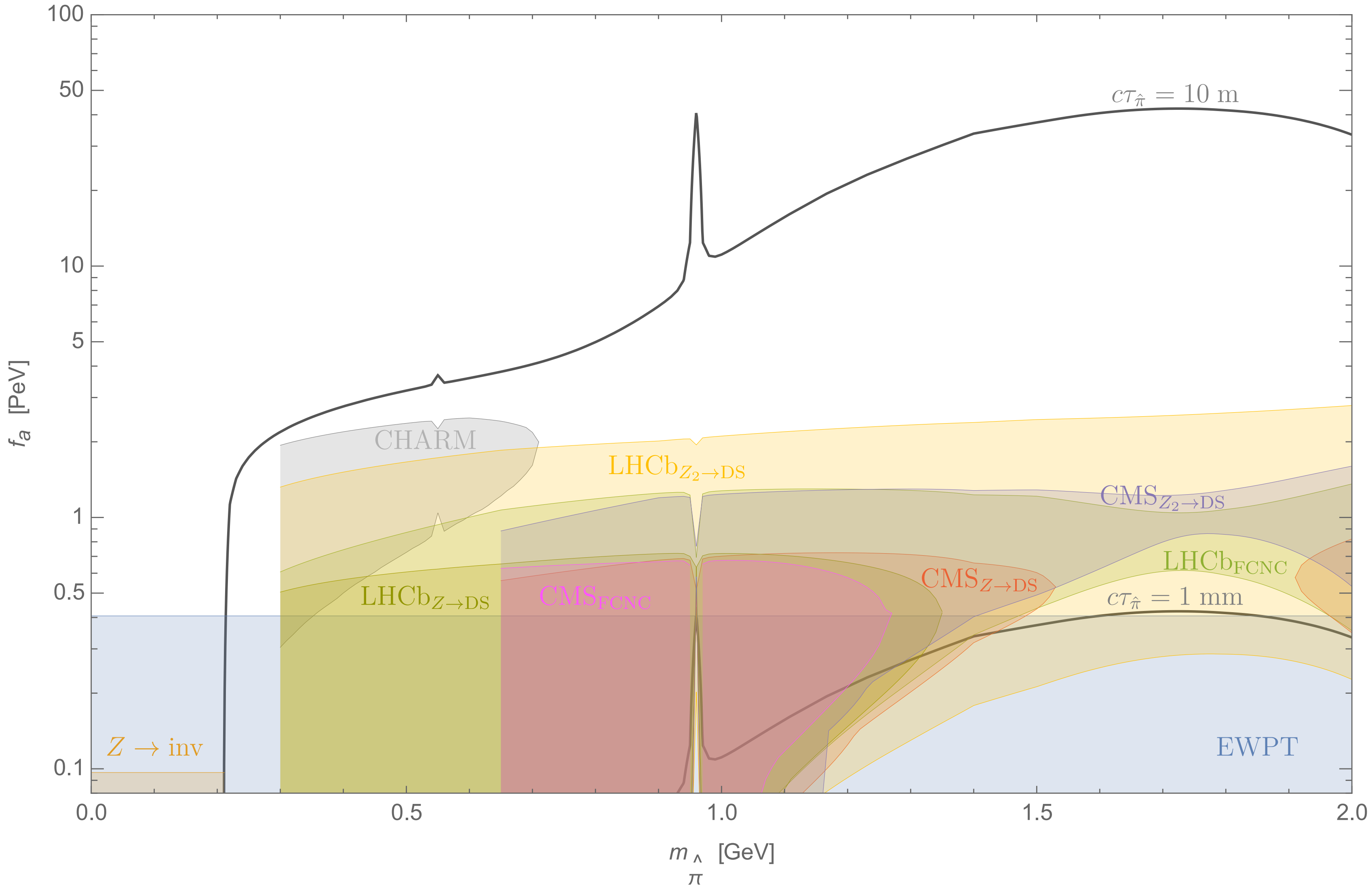
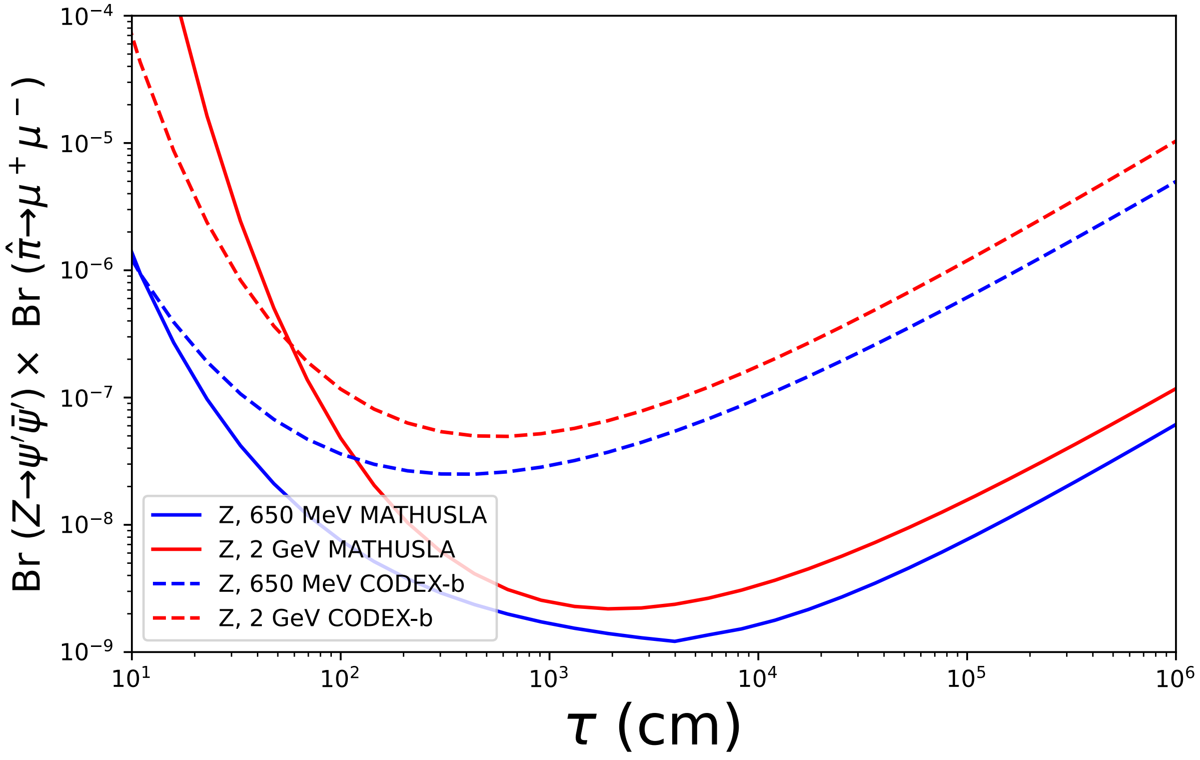
Preliminary

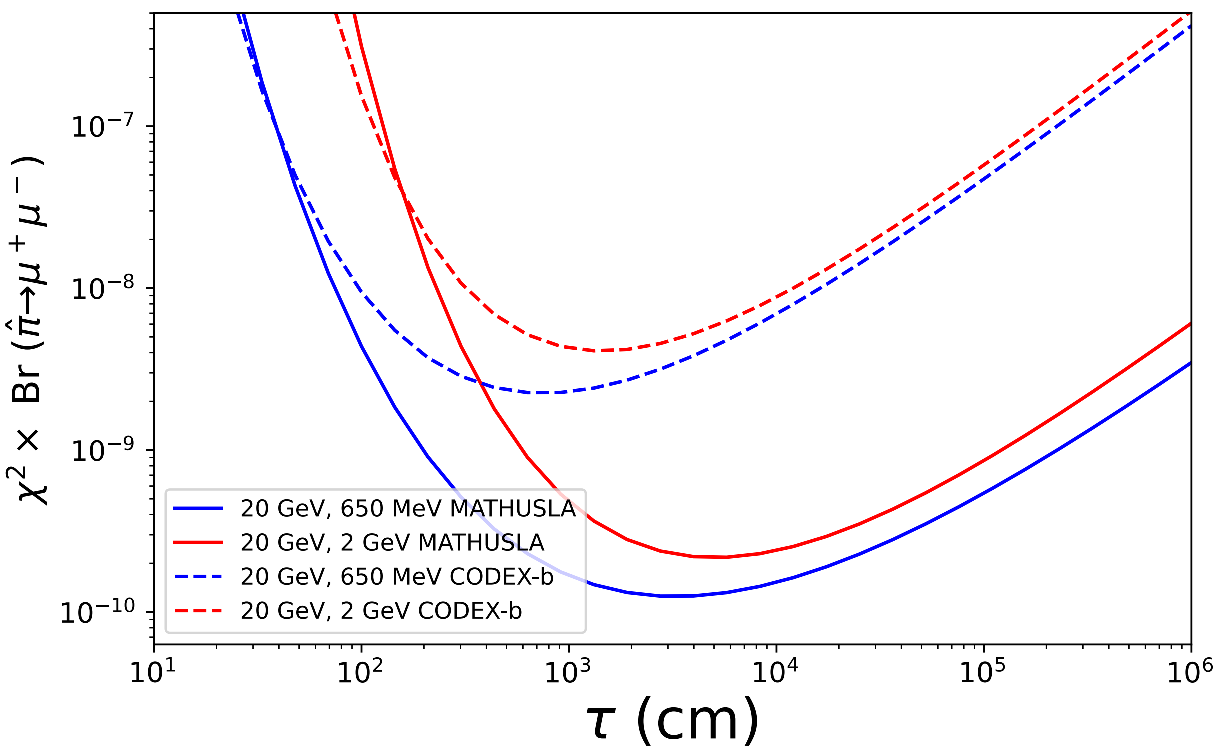


Auxiliary Detectors (Projections)

Z contribution

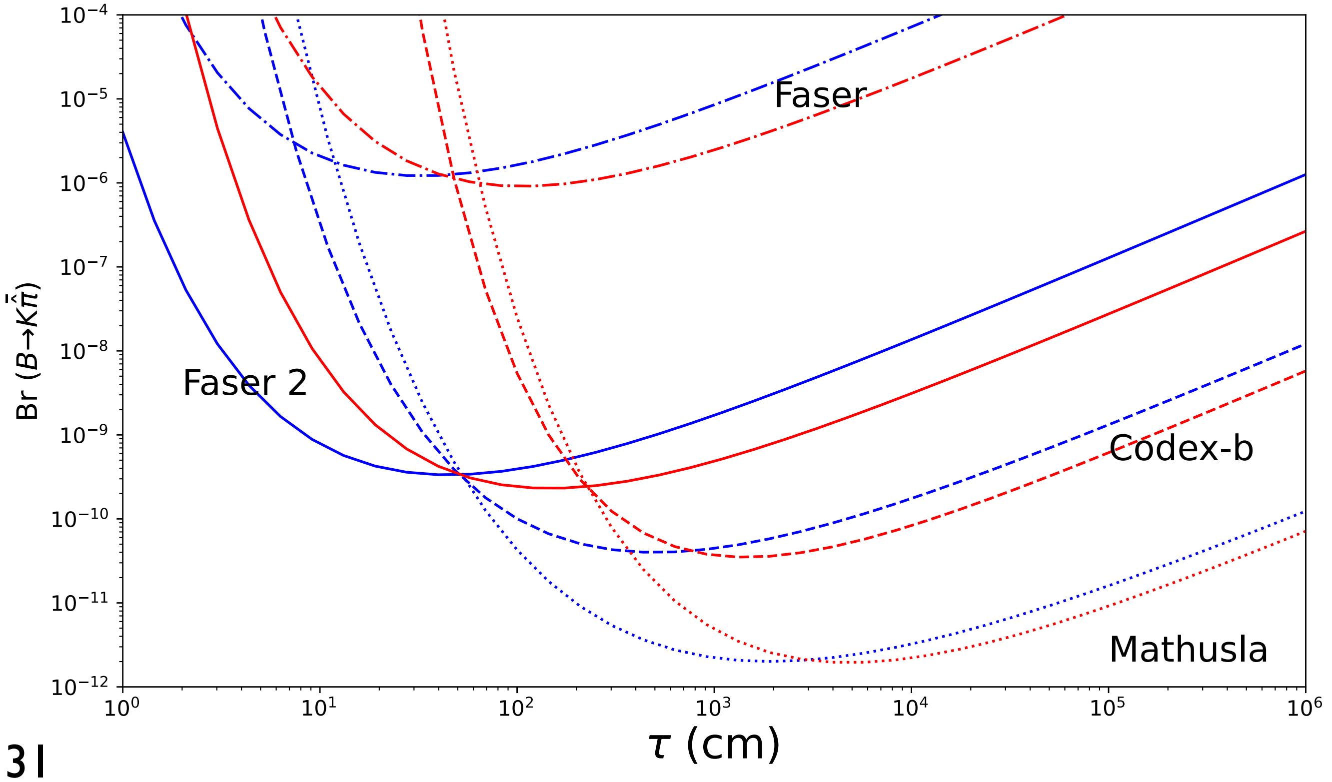


Z' contribution with $m_{Z'} = 20\,$GeV

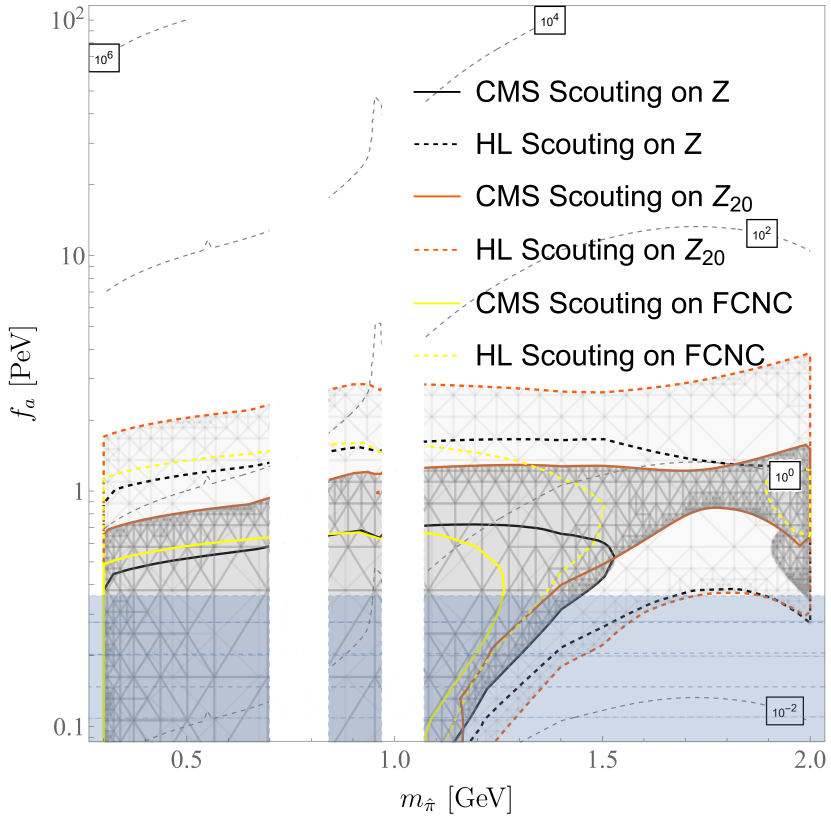


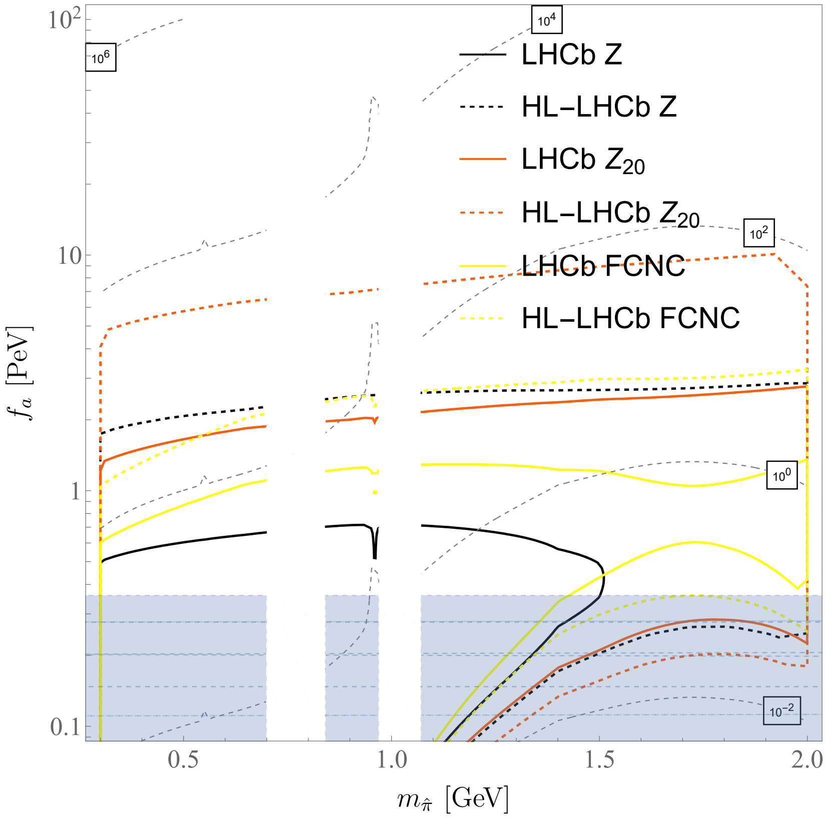
- Dark hadrons with lifetimes > O(m) predominantly decay outside the multipurpose detectors, resulting in reduced sensitivities. Proposed auxiliary detectors targeting LLPs have advantages in this regime. They are sensitive to all charged final state tracks and expected to be essentially background-free.

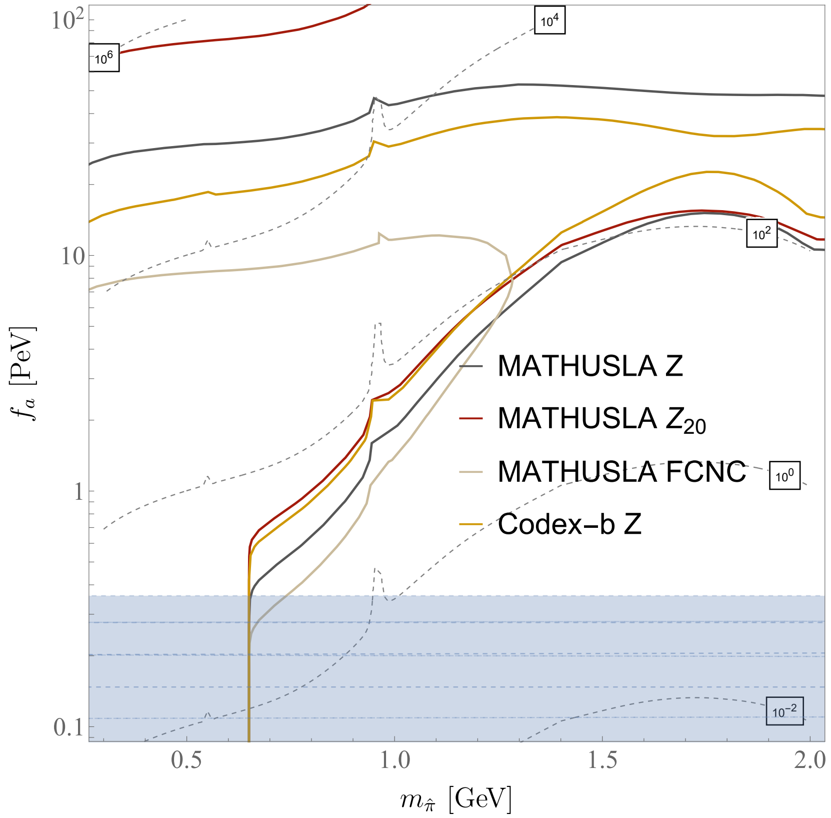
FCNC



Benchmark with Future Projections







Preliminary

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 us a great opportunity to explore this scenario.
- Dark showers from Z-portal decays give interesting but challenging experimental signals.
- We describe two classes of underlying theories and give the phenomenological expectations from some benchmarks.
- New experimental techniques (e.g., data scouting) and new detectors can provide extended reaches for these scenarios.
- FCNC productions of dark hadrons offer complementary probes and can constrain different combinations of model parameters