For CEPC Workshop:
New Physics and Flavor Physics
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Constraints on Long-Lived Particle Search

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Based on 2308.xxxx

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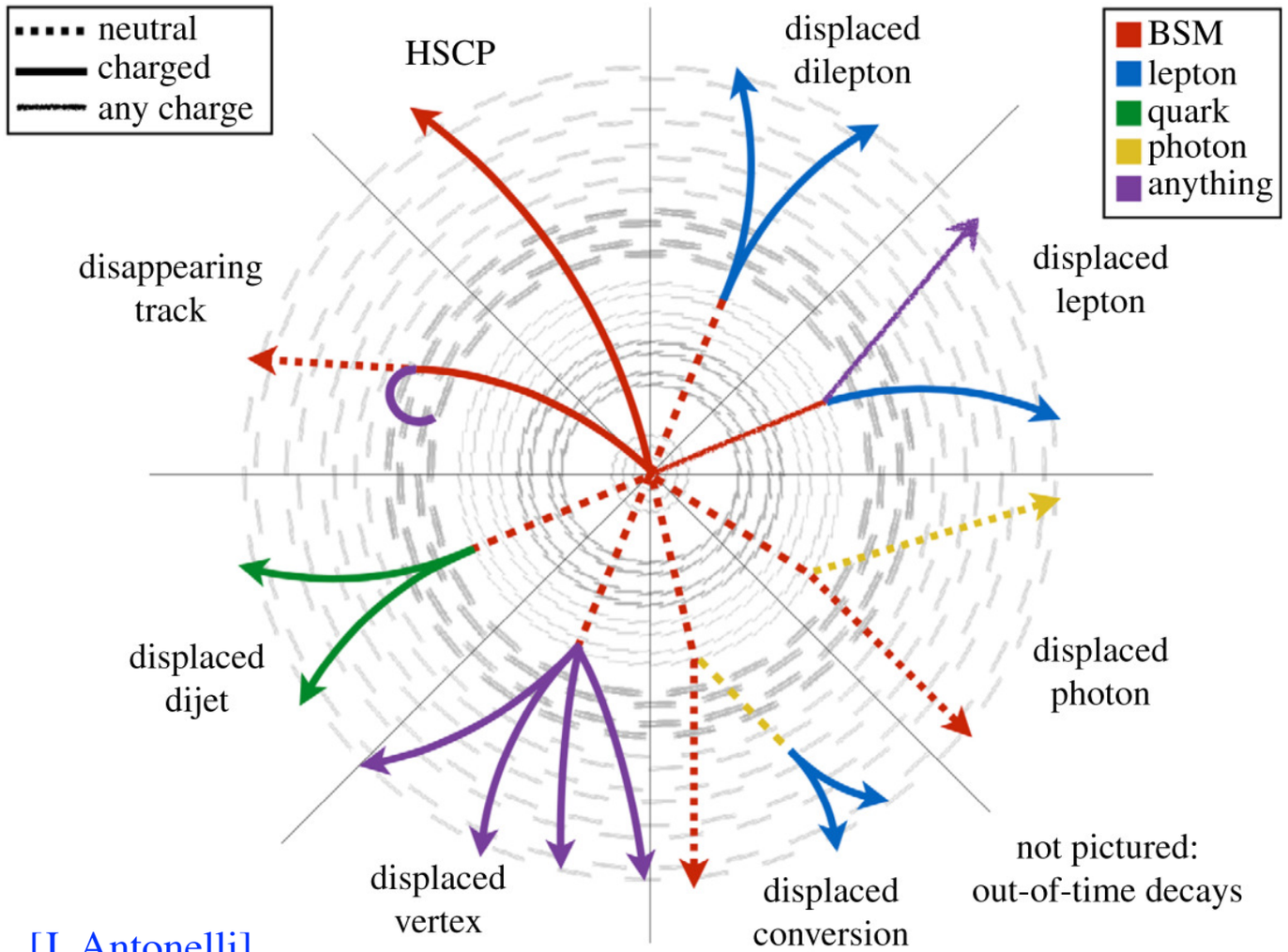
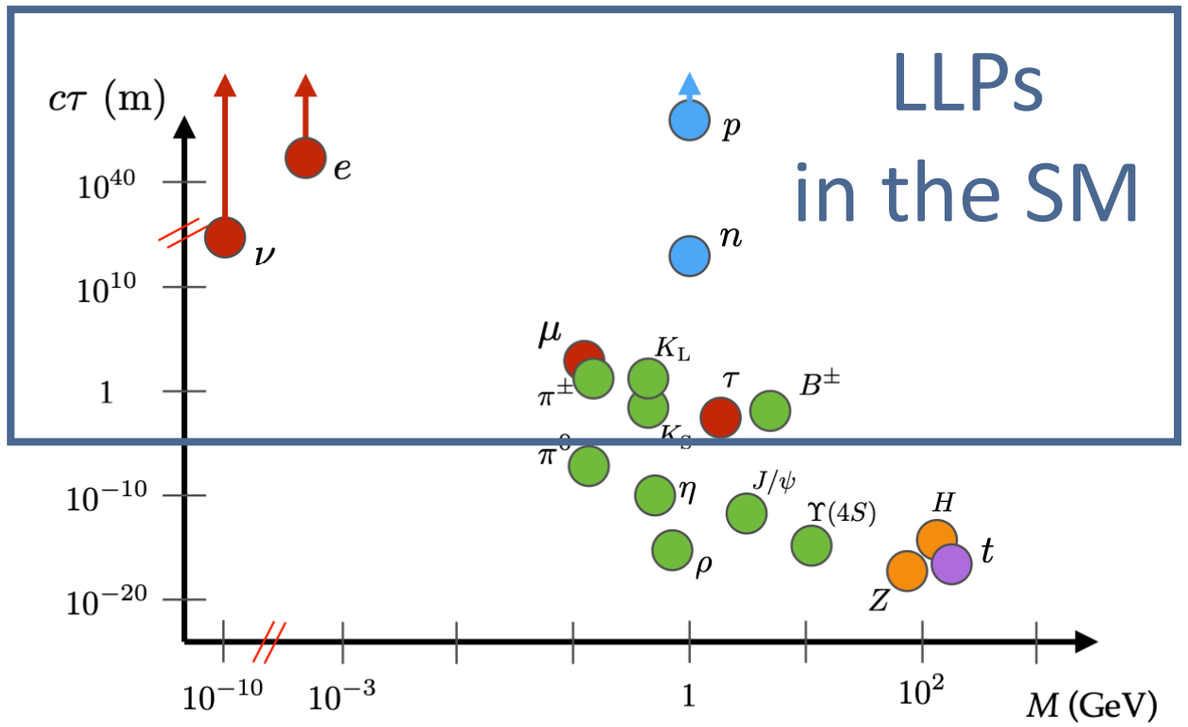
Dark Hadrons: Long-Lived Particles

Suppressed coupling: long-lived



[J. Antonelli]



[T. Adams, et al.]

Dark hadrons?
Displaced decays

Interesting: emerging/semivisible jets containing dark hadrons

[P. Schwaller, et al.] [T. Cohen et al.] [Cheng, Li, and E. Salvioni]

Dark QCD

- The SM $SU(3)_C \times SU(2)_L \times U(1)_Y$

  QCD may give hints on the dark sector.

- Dark QCD Multiple motivations

  - neutral naturalness

    Top partners gauged under hidden SU(3):

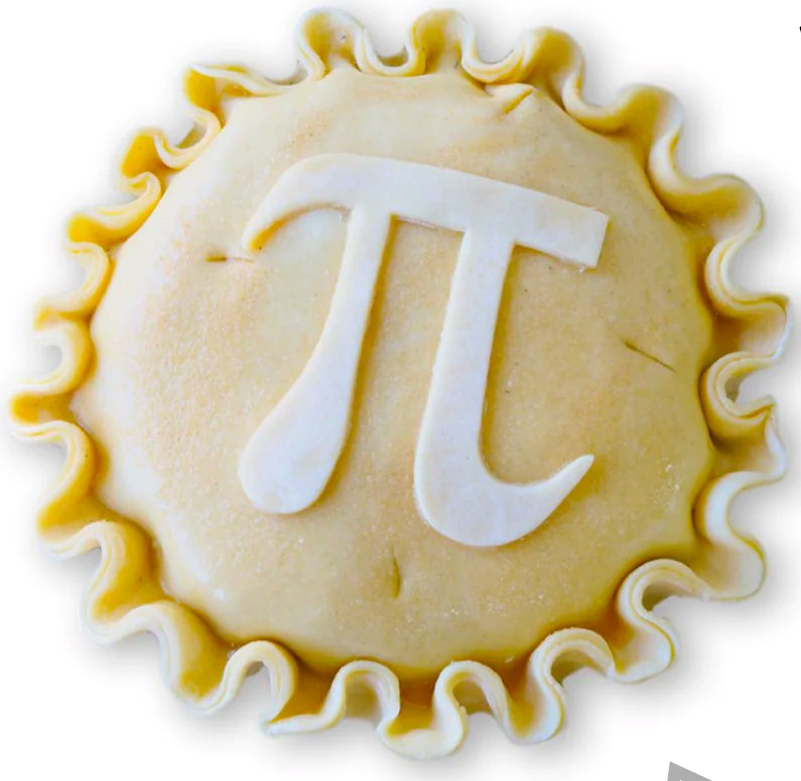
    to avoid strong bounds [Chacko. et al.] [Burdman. et al.]

  - asymmetric dark matter

    The (mirror) baryon number stabilises DM.

    [D. Kaplan et al.]

Dark QCD



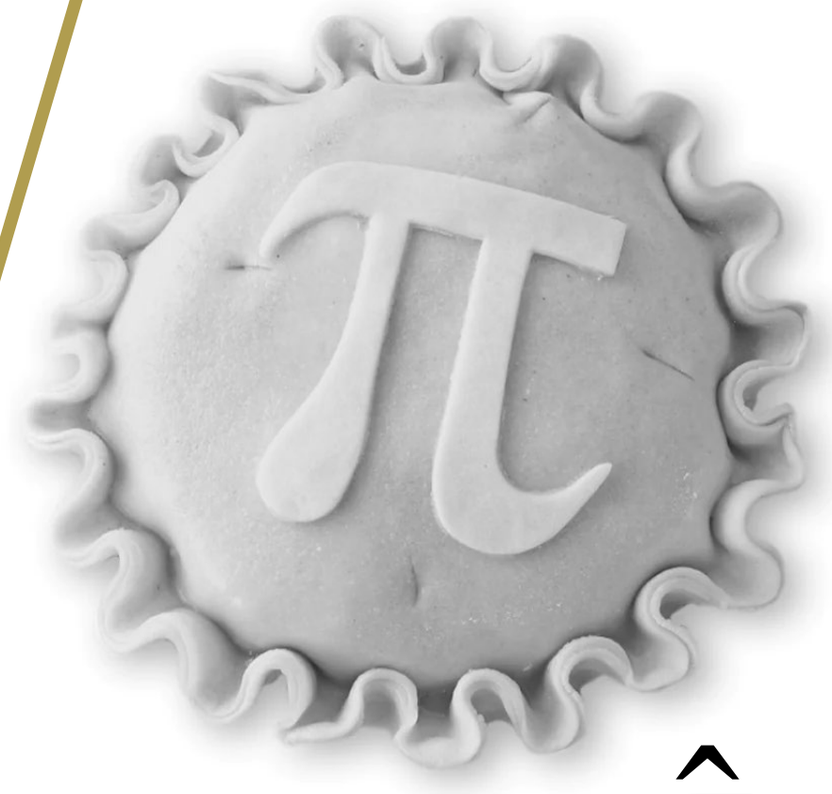
an edible pie

Visible world: π

QCD: hadrons, like pion

Mixing

a moldy pie



Dark sector: $\hat{\pi}$

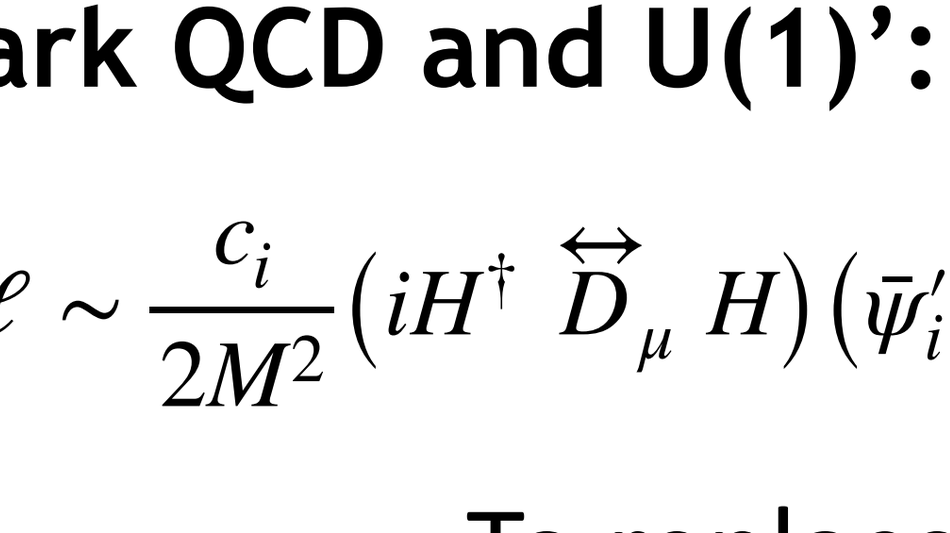
QCD-like: dark hadrons, like dark pion

Dark QCD and U(1)': Mixing with the SM

$$\mathscr{L} \sim \frac{c_i}{2M^2}\left(iH^\dagger \overleftrightarrow{D}_\mu H\right)\left(\bar{\psi}'_i \gamma^\mu \psi'_i\right) \qquad \psi'_i\text{: SM chargeless}$$

To replace Higgs w VEV:

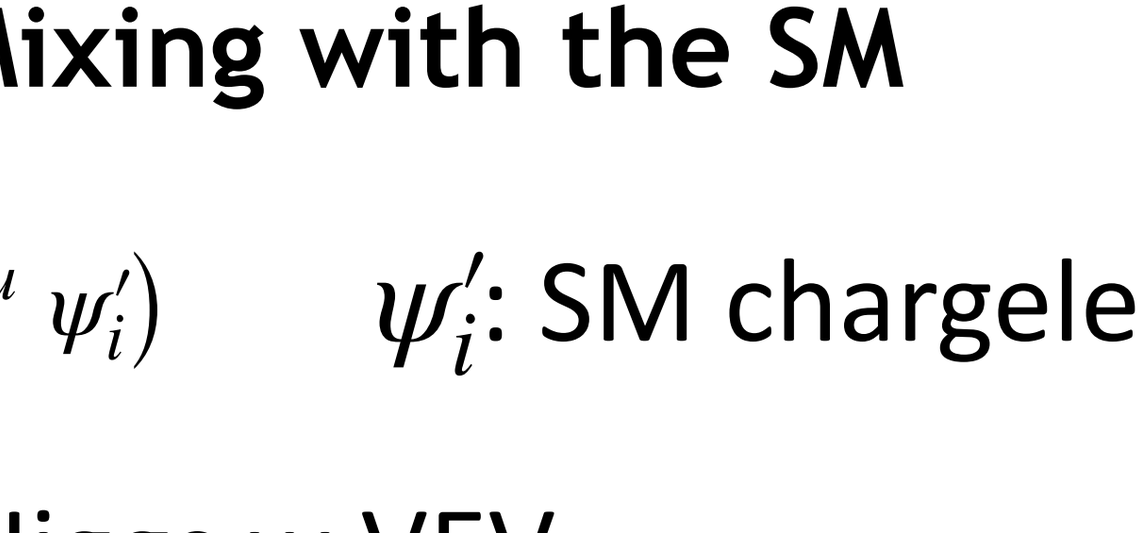
Quark Mixing



Q: heavy EW Doublet

[Cheng. et al.] [Cheng, Li. et al.]

Gauge Mixing



Z': additional U(1)

Dark QCD and U(1)': Mixing with the SM

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

$$\mathcal{L}_{\rm dark} = -\frac{1}{4}\hat{Z}'_{\mu\nu}\hat{Z}'^{\mu\nu} + \frac{1}{2}\hat{M}^2_{Z'}\hat{Z}'_\mu\hat{Z}'^\mu - g_D\sum_{j=1}^{N}\left(\overline{\psi}_j\gamma^\mu x^j_L P_L\psi_j + \overline{\psi}_j\gamma^\mu x^j_R P_R\psi_j\right)\hat{Z}'_\mu \quad (2.3)$$

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

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

Kinetic, mass and scalar mixing

Φ : U(1)' scalar, dominantly for $\hat{M}_{Z'}$

- Heavy Z': to integrate it out: EFTs
- Relative light Z' (above Υ meson mass): ~10 GeV

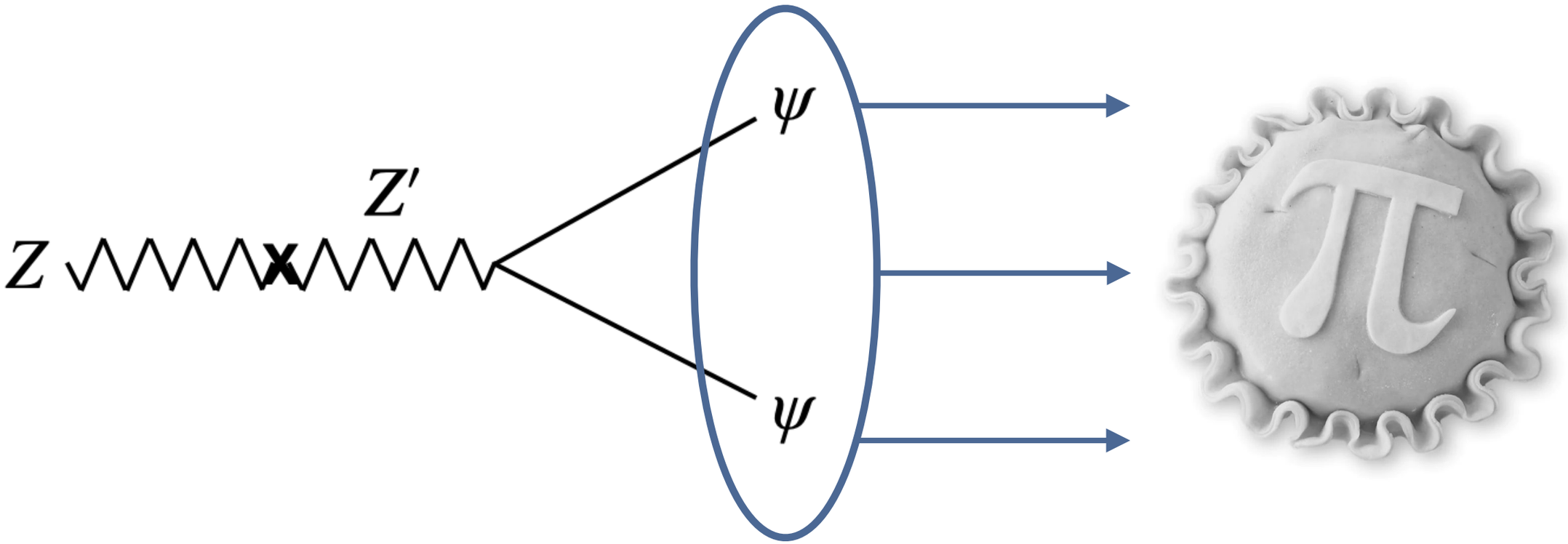
Mainly constrained by

EW precision observables: not strong

Dark Showers

Dark showers (DS) initiated by Z(Z') decays

Exotic decay BR of Z(Z')



$$Z(Z') \rightarrow \boxed{\bar{\psi}_D\ \psi_D} \Longrightarrow \hat{\pi}$$

LLP!

Decays with FCNC

- Dark hadrons: light enough

$$b \to s: \quad B \to K \hat{\pi}$$
$$c \to u: \quad D \to \pi \hat{\pi}$$
$$s \to d: \quad K \to \pi \hat{\pi}$$

LLP!

- Z or Z' as mediator, but EFT reads:

[He, Tandean and Valencia]

$$\mathcal{L}_{\rm eff}^{\rm FCNC} = -\, g_D \hat{g}_Z \frac{\delta \hat{M}^2}{M_{Z_1}^2 M_{Z_2}^2 \cos^2\chi} \frac{\hat{g}^2}{128\pi^2} J_D^\mu \bar{d}_j \gamma_\mu P_L d_i \sum_{q\,\in\, u,c,t} V_{qj}^* V_{qi} \mathcal{K}_q + \text{h.c.}\,,$$

where

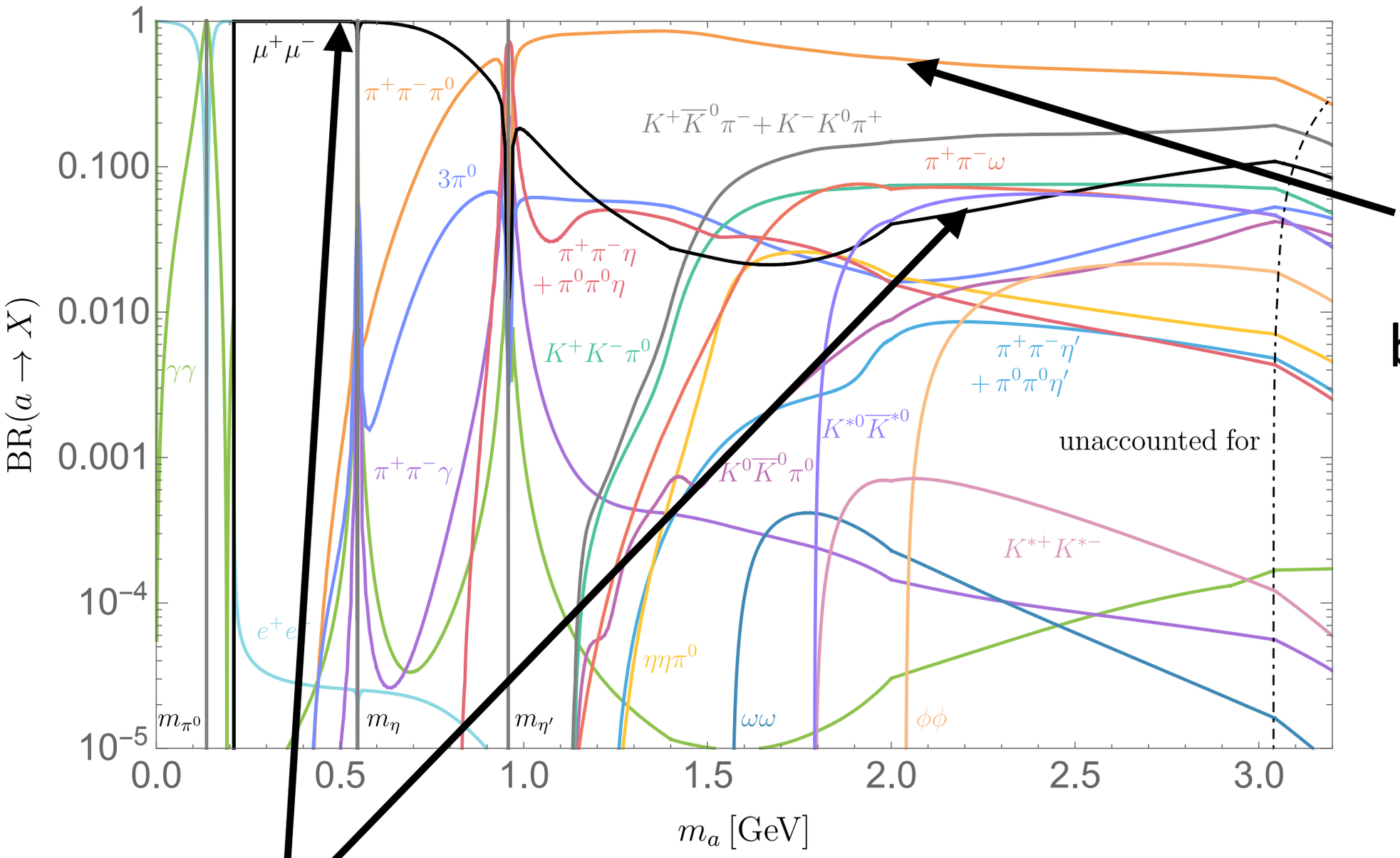
$$\mathcal{K}_q \equiv x_q \log \frac{\Lambda_{\rm UV}^2}{M_W^2} + \frac{-7x_q + x_q^2}{2(1-x_q)} - \frac{4x_q - 2x_q^2 + x_q^3}{(1-x_q)^2} \log x_q\,,$$

Dark current

SM down-type FCNC

Decay Modes

ALP-like dark pion [Cheng, Li, and E. Salvioni]



3-pi channel be important, w dark pion being heavy

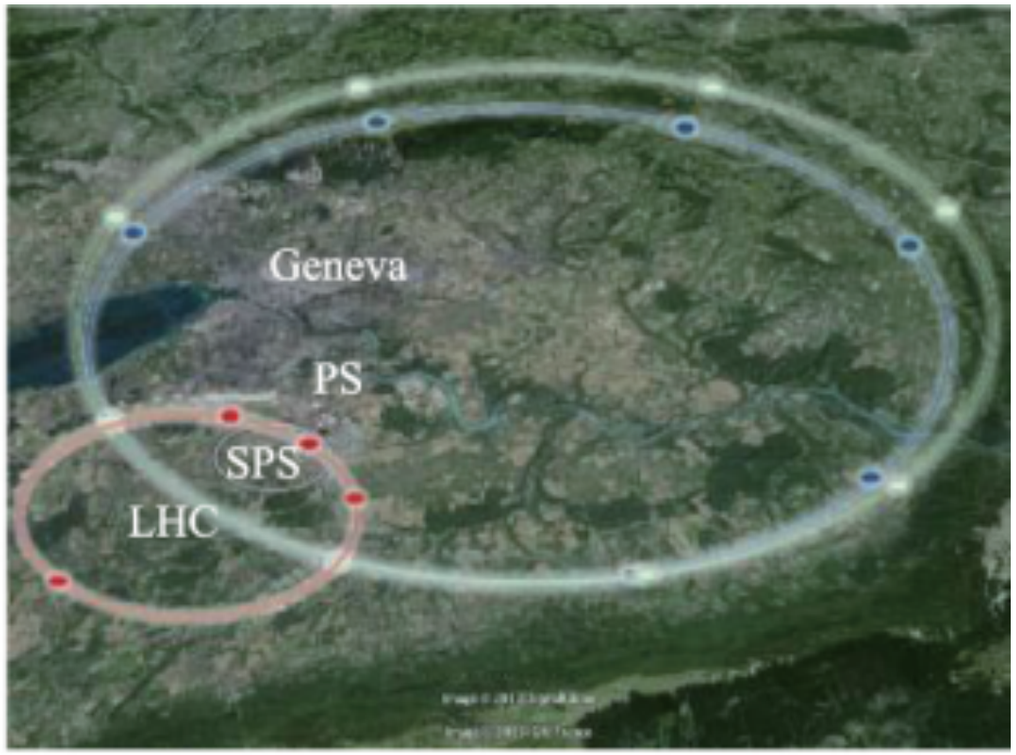
Di-muon dominates at light masses;
Still relevant for heavy cases

$\hat{\pi} \to \mu^+\mu^-$

Excellent Channel!

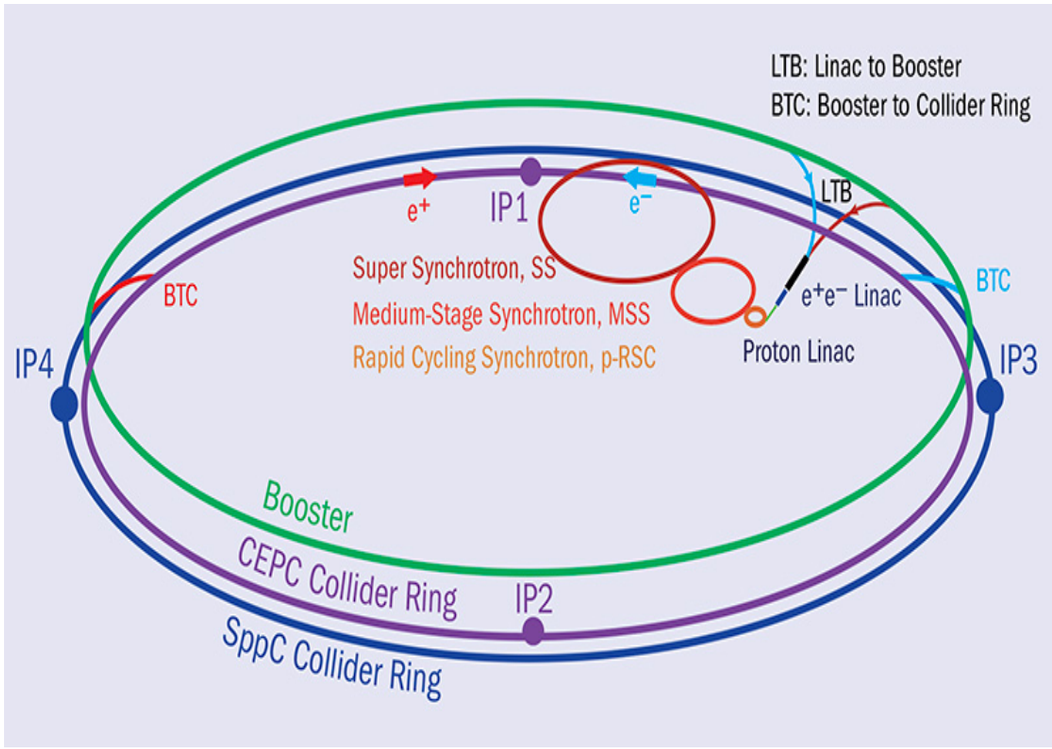
Z-Factory

FCC-ee



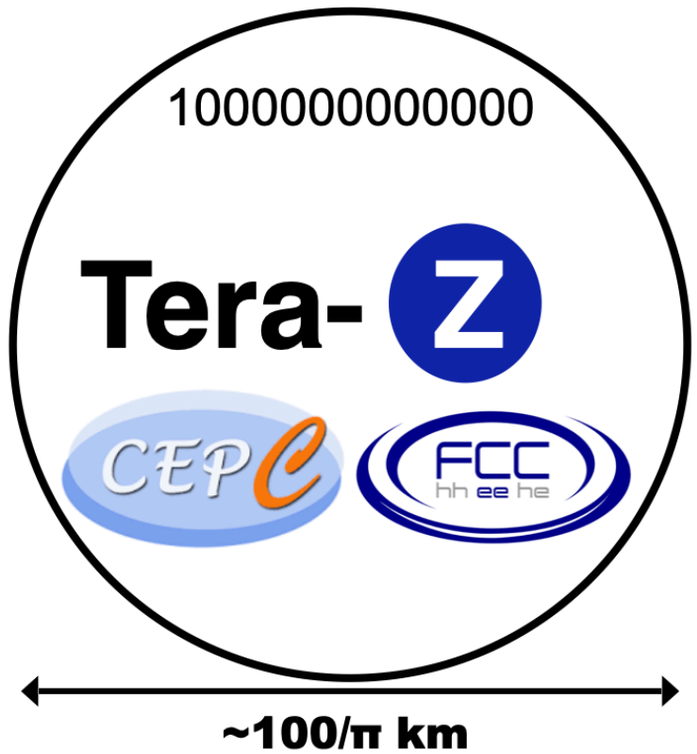
Europe

CEPC



China

e^+e^- circular collider



Z factory

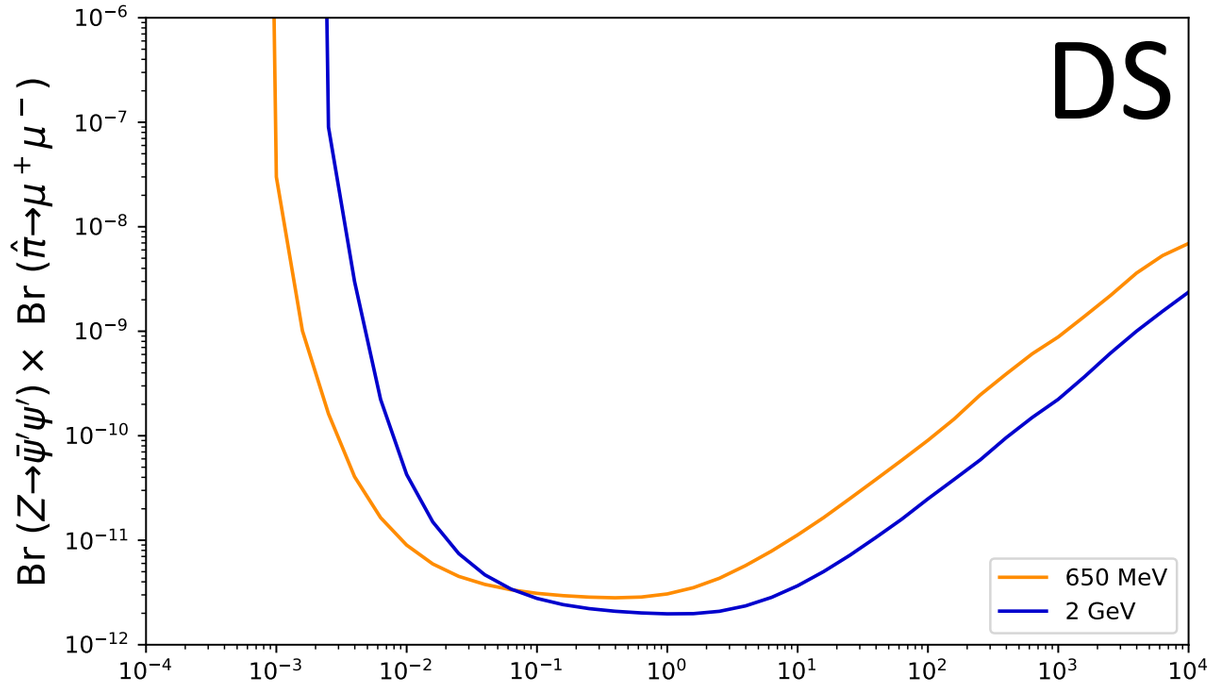
Z-Factory

- Z abundance:

$$\sim \mathcal{O}(10^{12})$$

Clean env for

Z exotic decay studies

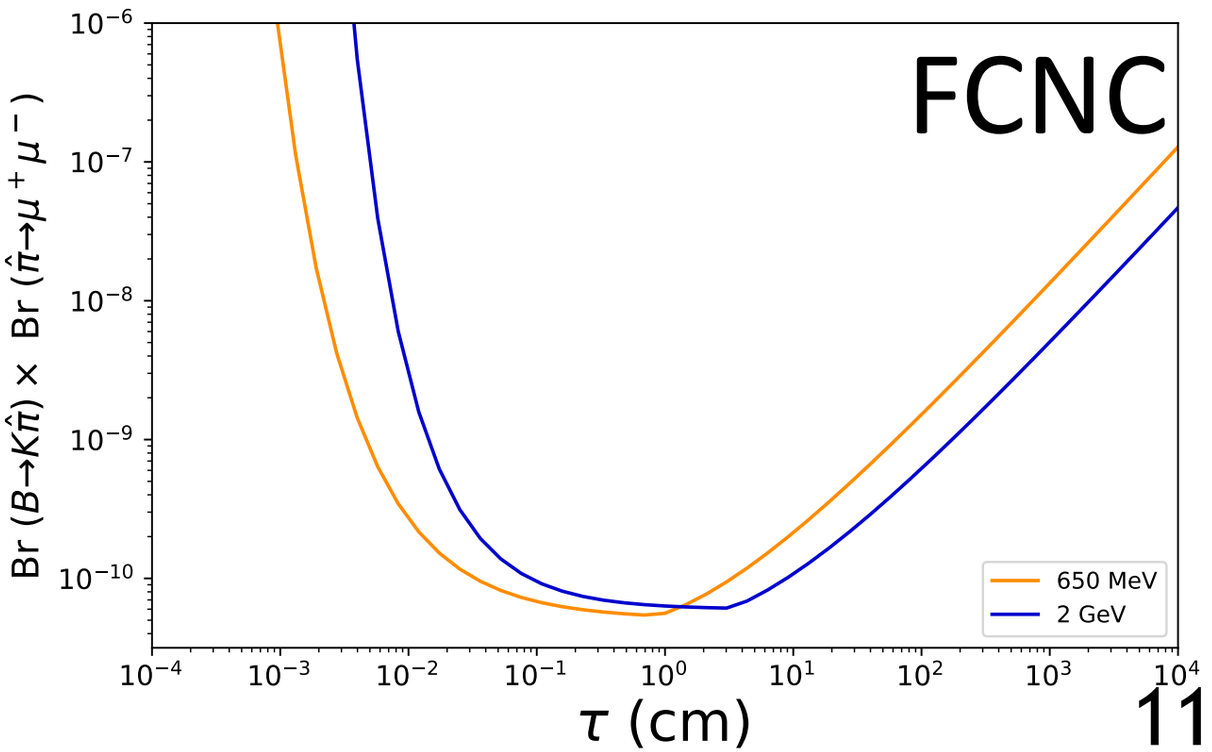


Bkg Free: $N_{\text{sig}} = 3$

4 Tera-Z

- Abundant b-hadrons

	Belle II	LHCb	Tera-Z	10×Tera-Z
B^0, $\bar{B}^0$	5.3×10^{10}	6×10^{13}	1.2×10^{11}	1.2×10^{12}
$B^{\pm}$	5.6×10^{10}	6×10^{13}	1.2×10^{11}	1.2×10^{12}
B_s, $\bar{B}_s$	5.7×10^{8}	2×10^{13}	3.1×10^{10}	3.1×10^{11}
$B_c^{\pm}$	-	4×10^{11}	1.8×10^{8}	1.8×10^{9}
Λ_b, $\bar{\Lambda}_b$	-	2×10^{13}	2.5×10^{10}	2.5×10^{11}



$m_{\hat{\pi}} = 0.65$ or 2 GeV

(HL-)LHC(b)

- Displaced dimuon candidate search at LHCb;

[LHCb Collaboration]

- Dimuon trigger stream (scouting) at CMS.

[CMS Collaboration]

However,

- Large combinatoric backgrounds
- Limited detector geometry

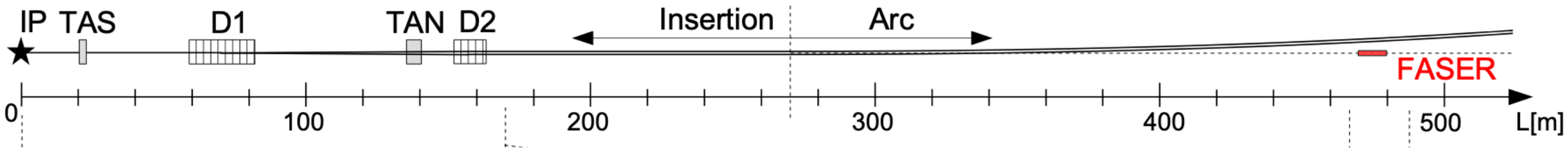
CMS: $\ell_{xy}(\mu^+\mu^-) < 11$ cm

Auxiliary Detectors for LLPs

FASER w cylinder structure to probe forward region

Only muons and neutrinos in the SM

[FASER Collaboration]



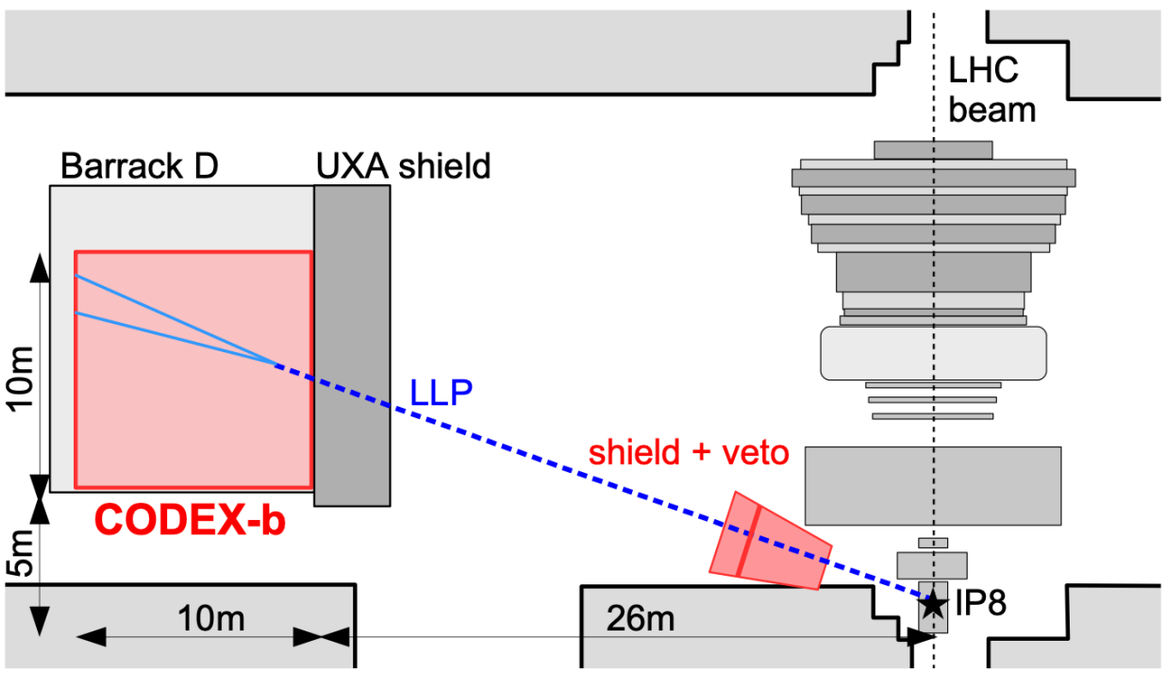
Collider	Luminosity $\mathcal{L}$	Energy	Distance L	Detector Length Δ	Detector Radius R
FASER, LHC	150 fb^{-1}	14 TeV	480 m	1.5 m	10 cm
FASER 2, HL-LHC	3000 fb^{-1}	14 TeV	480 m	5 m	1 m

Run 3: FASER collecting data!

[Kling, and Trojanowski]

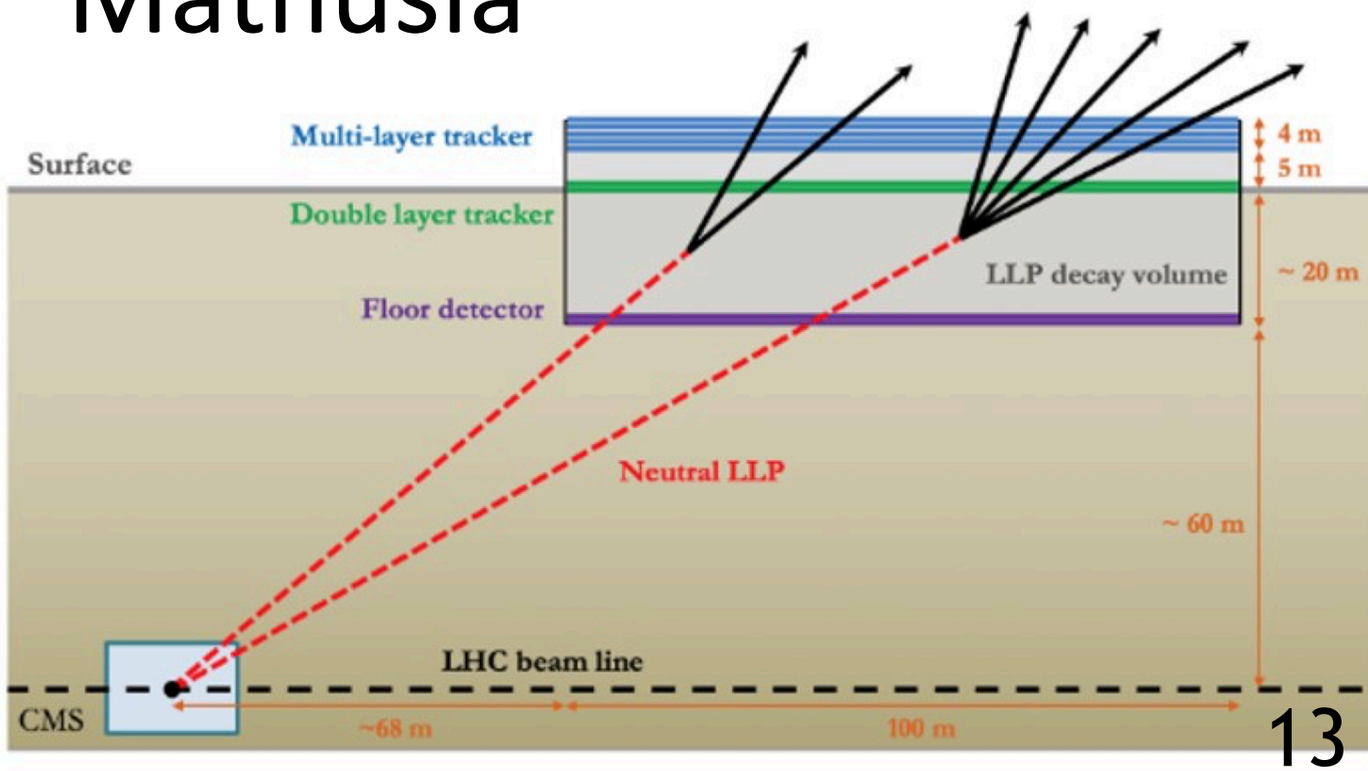
Codex-b

[Berlin, and Kling.]



Mathusla

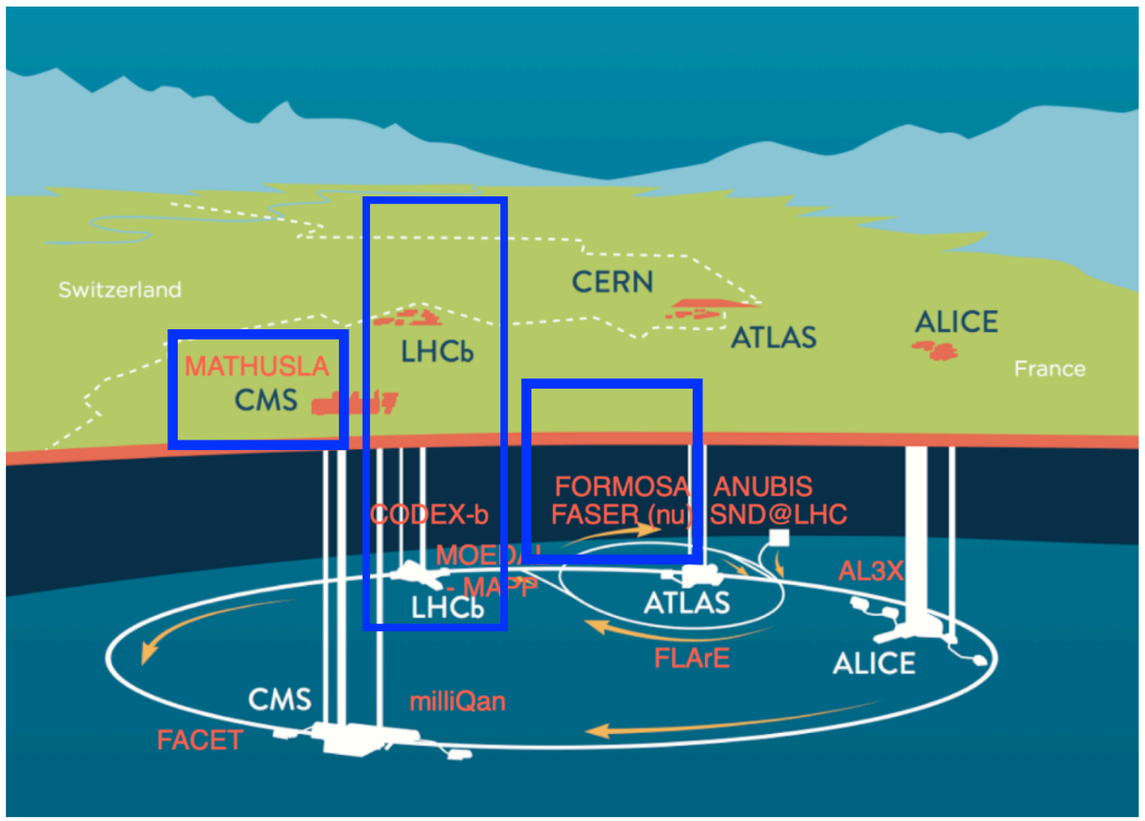
[MATHUSLA Collaboration.]



FCNC at Auxiliary Detectors

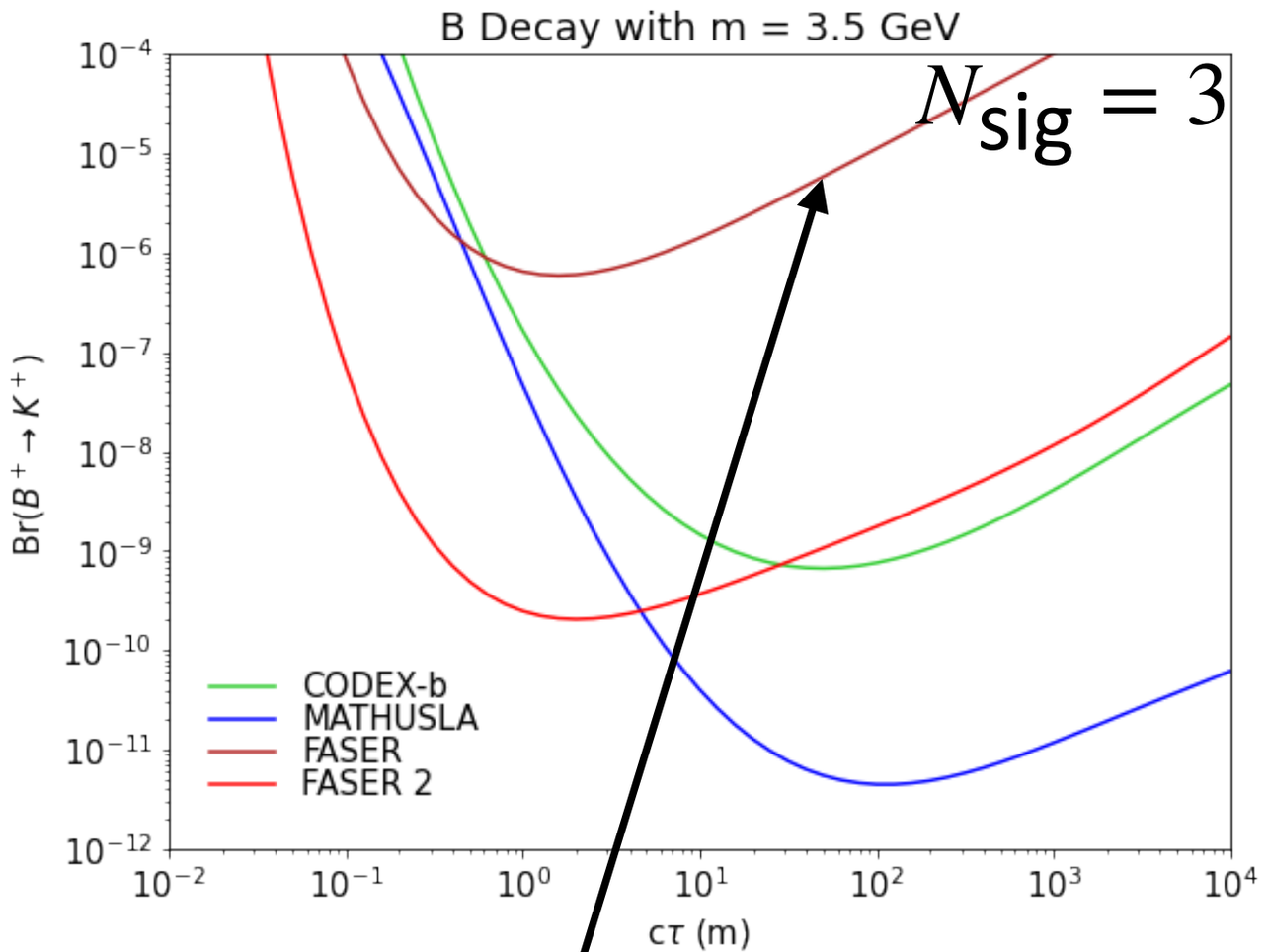
FCNC: $B \to K\,\hat{\pi}\;(b \to s)$, $D \to \pi\,\hat{\pi}\;(c \to u)$, $K \to \pi\,\hat{\pi}\;(s \to d)$

Believe to be bkg free!



[Credit: Royal Society / Emma Torro Pastor]

$m_{\hat{\pi}} = 3.5$ GeV



Different in geometry: sensitive to various lifetime

FASER: to validate soon!

Summary and Many Thanks

- Hints from QCD;
  Dark QCD: dark hadrons, well-motivated.

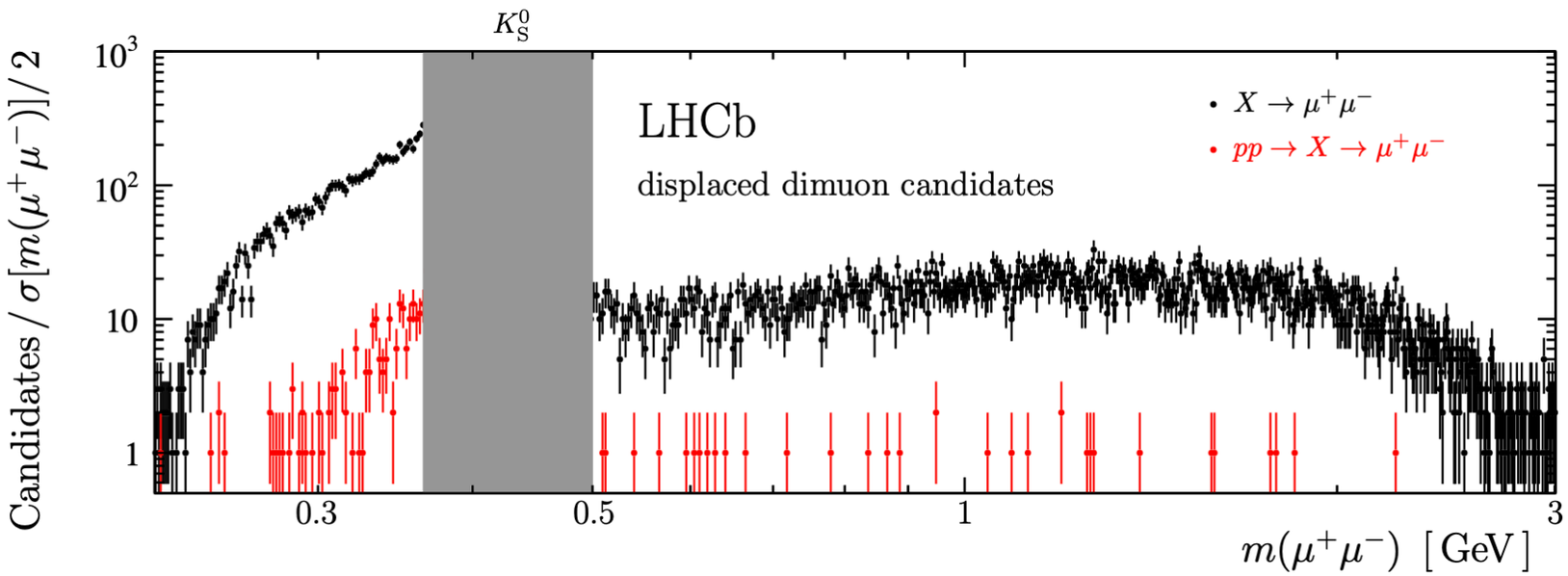
- Dark hadrons to be long-lived,
  as long as with a suppressed coupling.

- Z factories like CEPC,
  and auxiliary detectors like FASER:
  to be promising!

Back-Up

Direct Searches

LHCb: search for di-muon resonances [LHCb Collaboration]

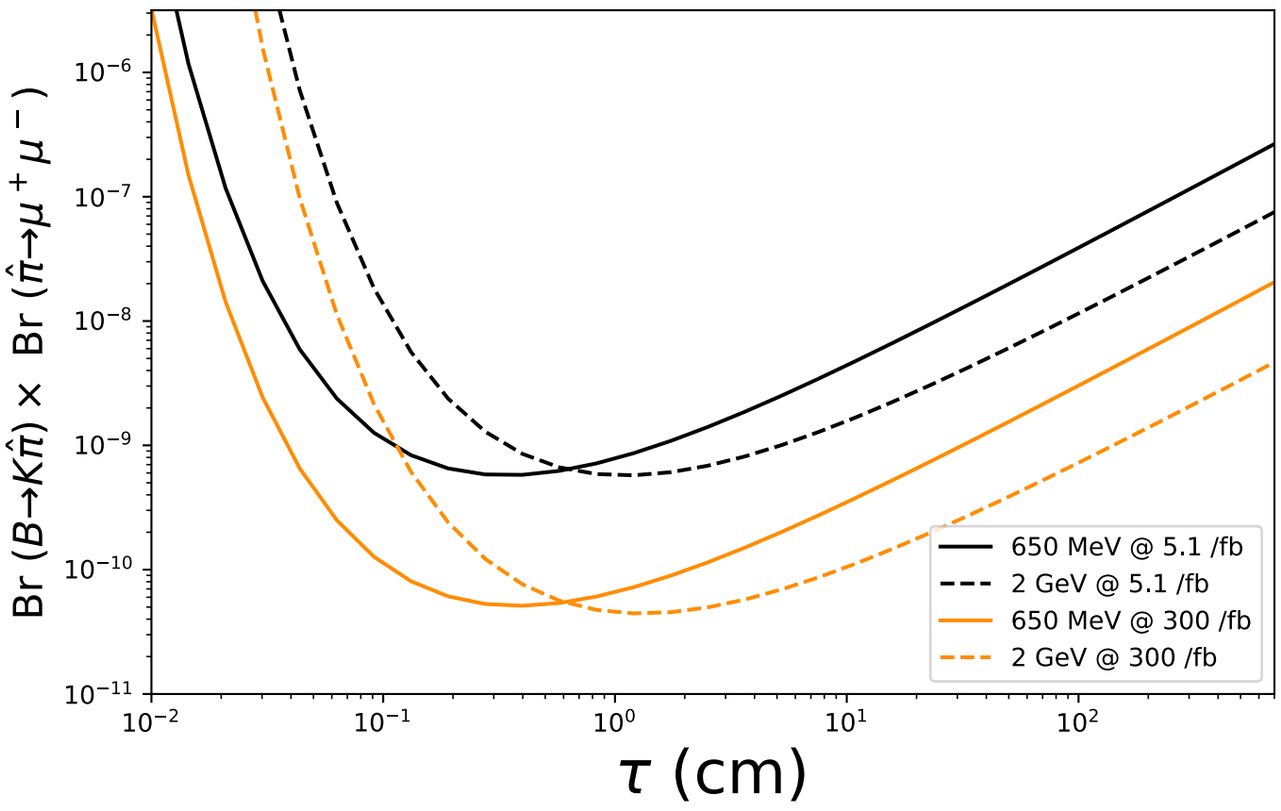


inclusive produced

prompt produced

$5.1\ \text{fb}^{-1}$

$$pp \to \ldots \to B \to K\,\hat{\pi}(\to \mu^+\mu^-)$$



B moves away from PV before its decay.

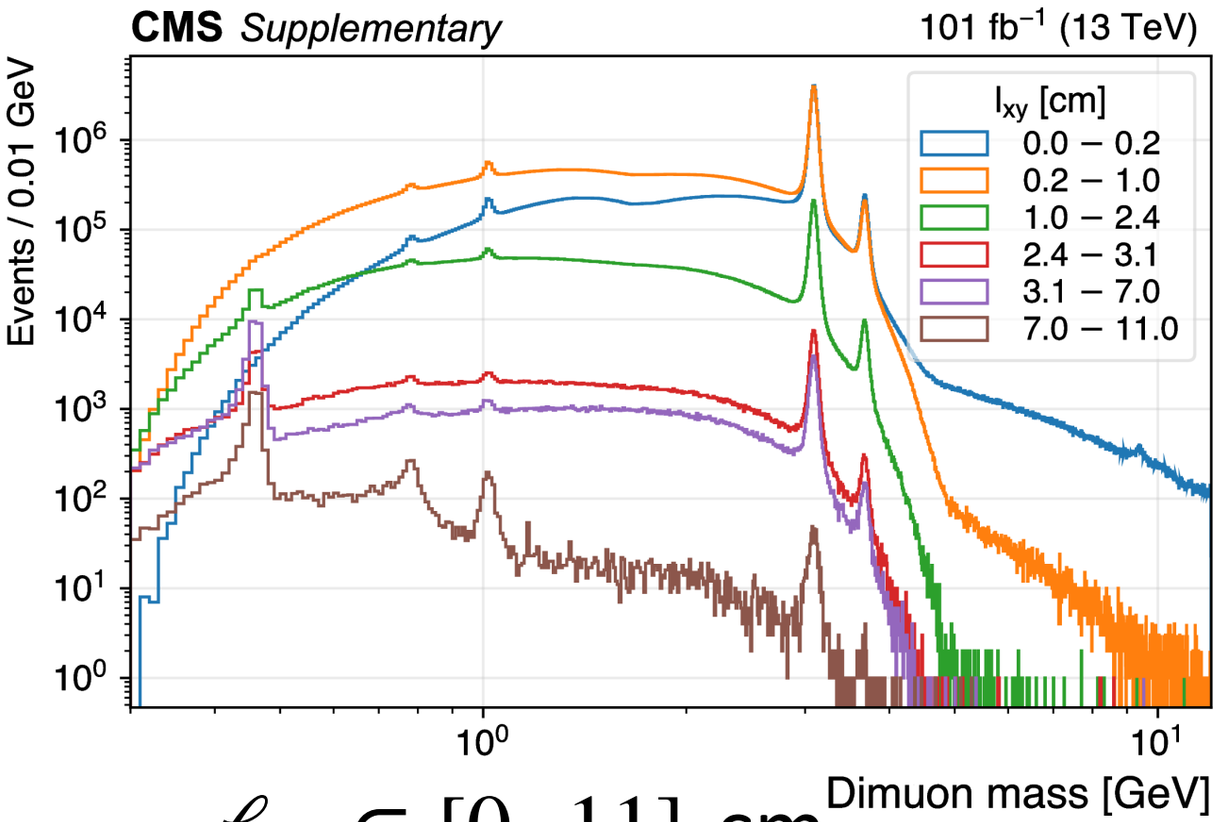
HL-LHCb

$300\ \text{fb}^{-1}$

Opportunities at (HL-)LHC

ATLAS/CMS: larger luminosity and decay vessel.

A dedicated dimuon trigger stream (scouting)

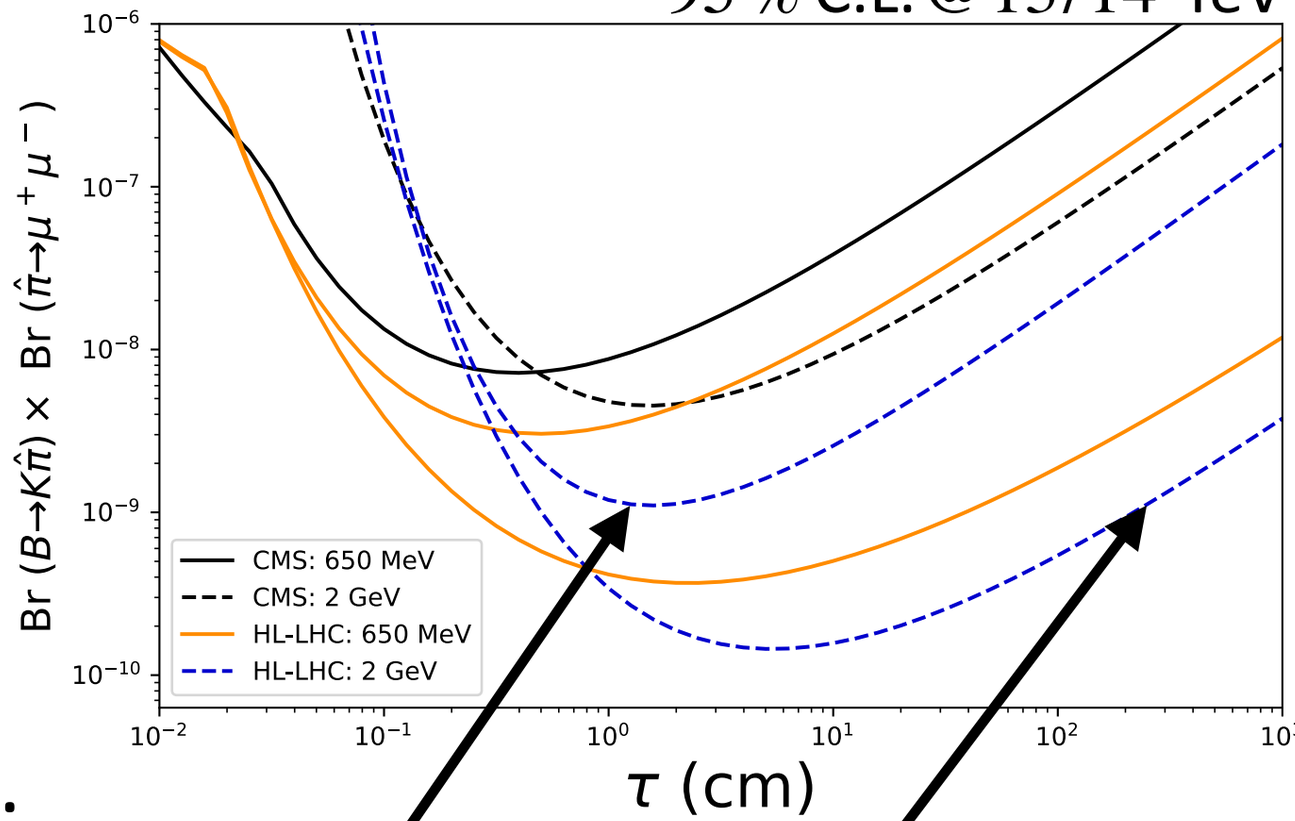


$\ell_{xy} \in [0,\ 11]$ cm

di-muon transverse displacement

[CMS Collaboration]

- Limited by detector geometry
- Large bkg



Benchmarks of trigger efficiency:

But both improved

conservative or aggressive