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THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Institute of High Energy Physics
Chinese Academy of Sciences

CEPC

Z Portal to the Dark Sector Through Z' Mediation

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Based on 2311.xxxx

with:

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For CEPC 2023 Workshop

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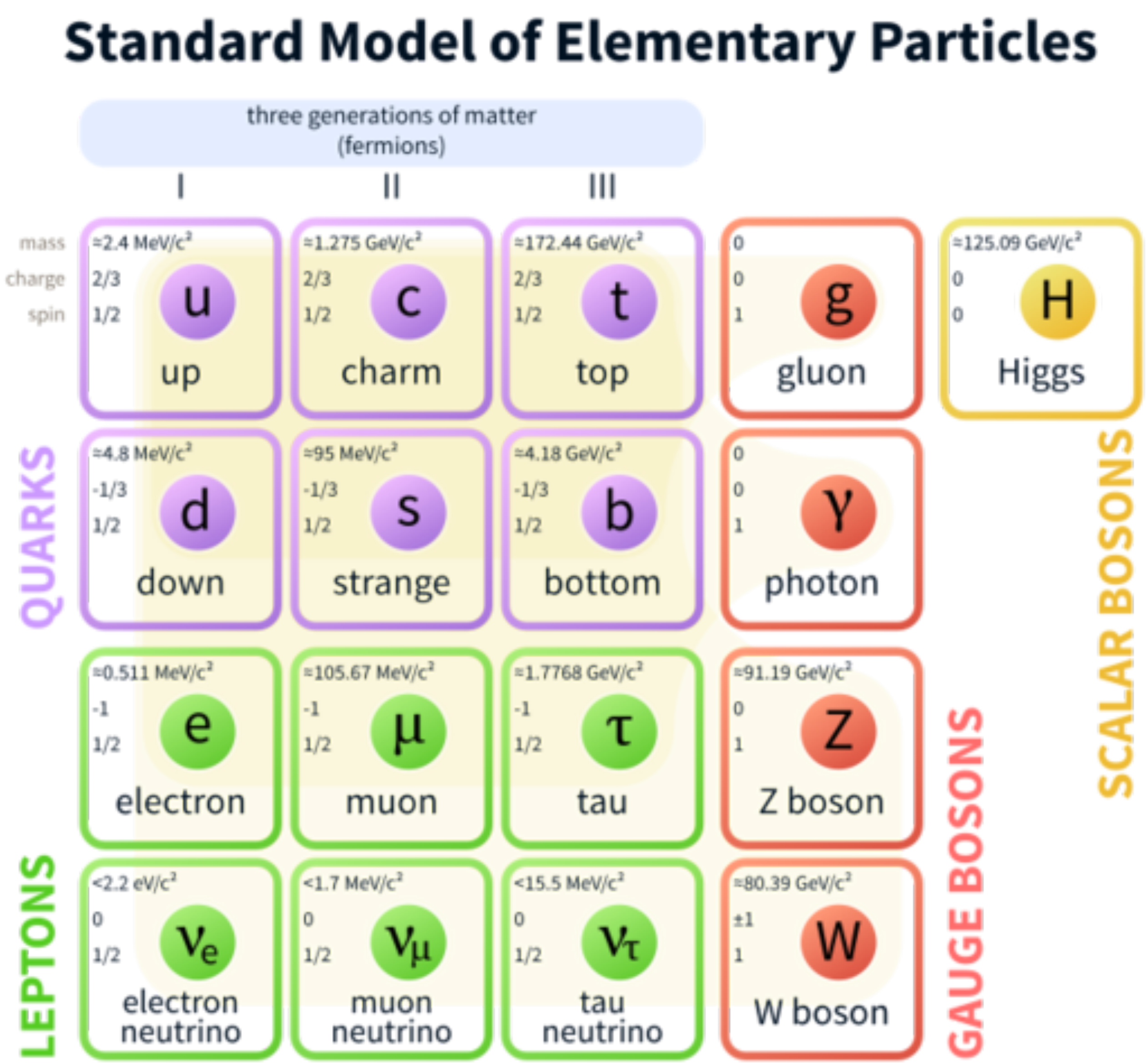
The SM and Beyond



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

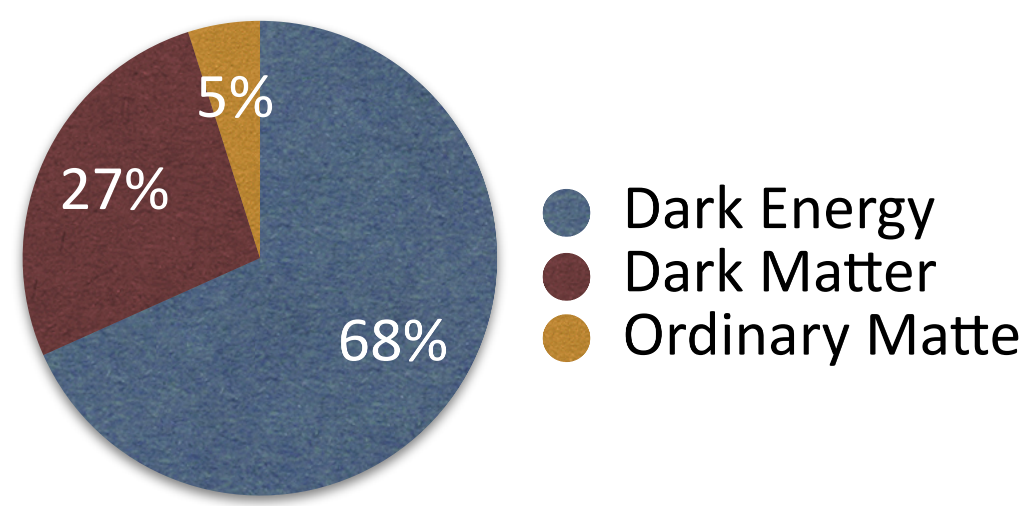
An elegant theory, but:

- Unnatural

Hierarchy! $M_{pl} \gg M_H$

To destabilise the vacuum.

- Absence of dark sector



Universe: mostly dark

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

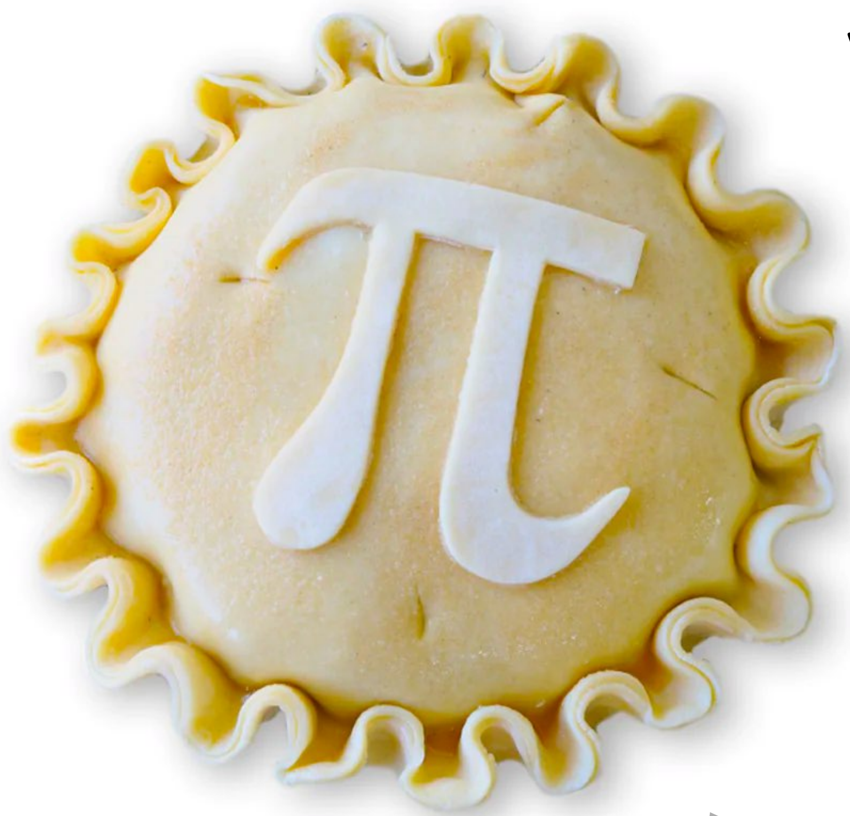
    The (mirror) baryon number stabilises DM.

    [D. Kaplan et al.]

Dark QCD

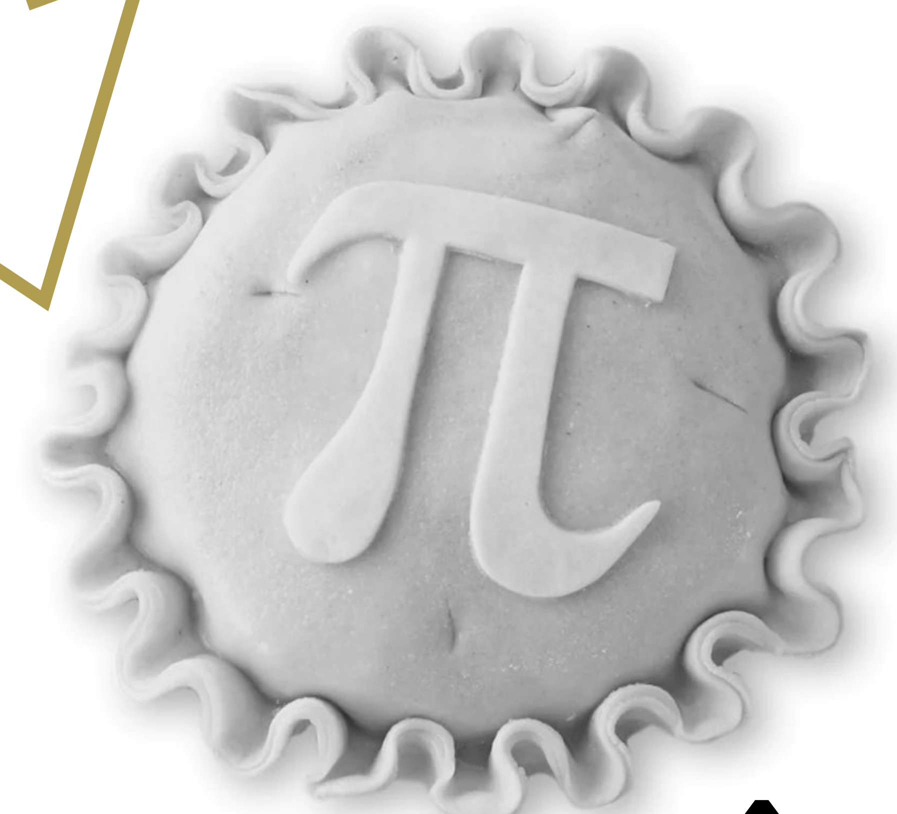
Visible world: π

QCD: hadrons, like pion



an edible pie

a moldy pie

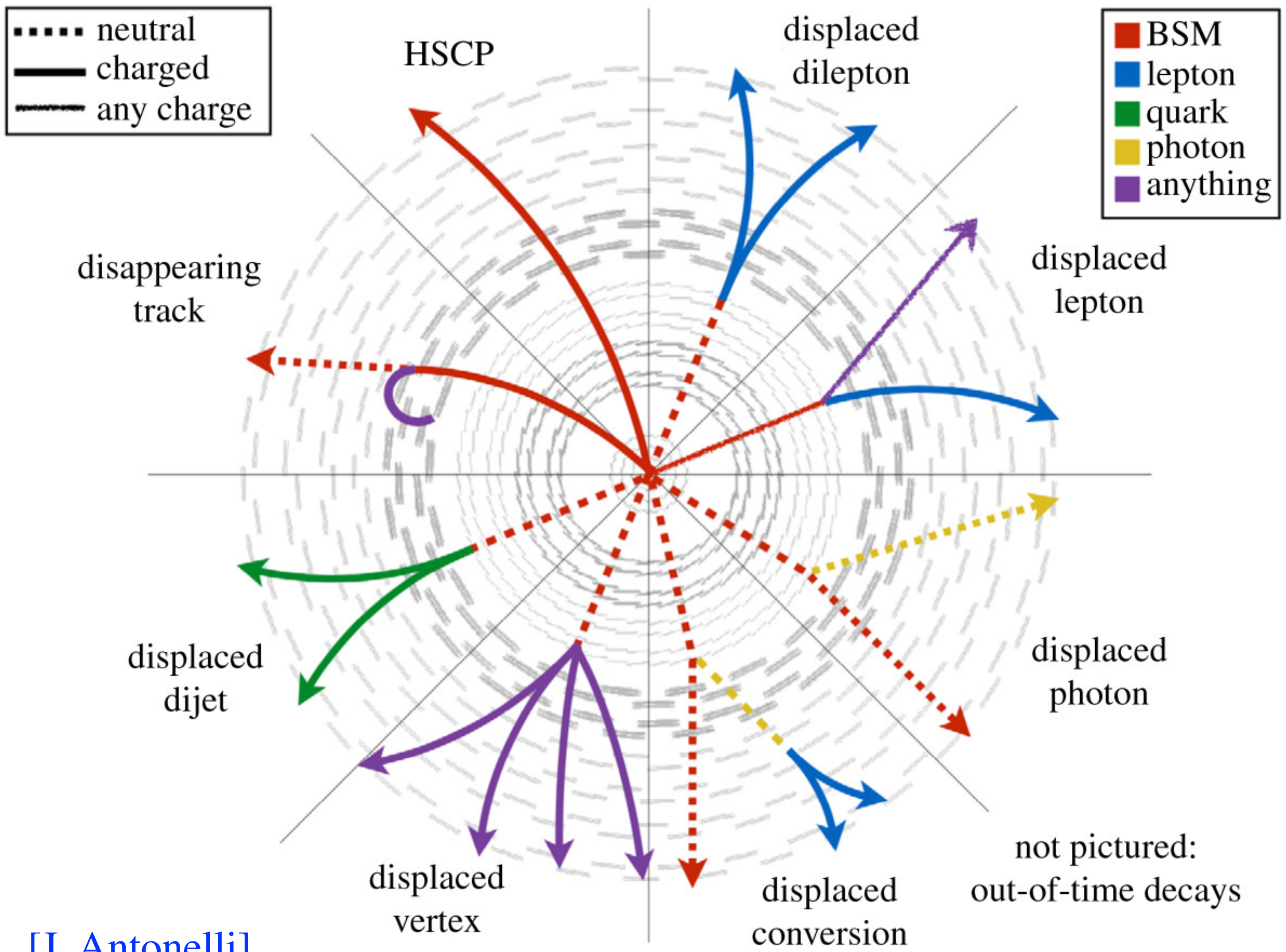


Dark sector: $\hat{\pi}$

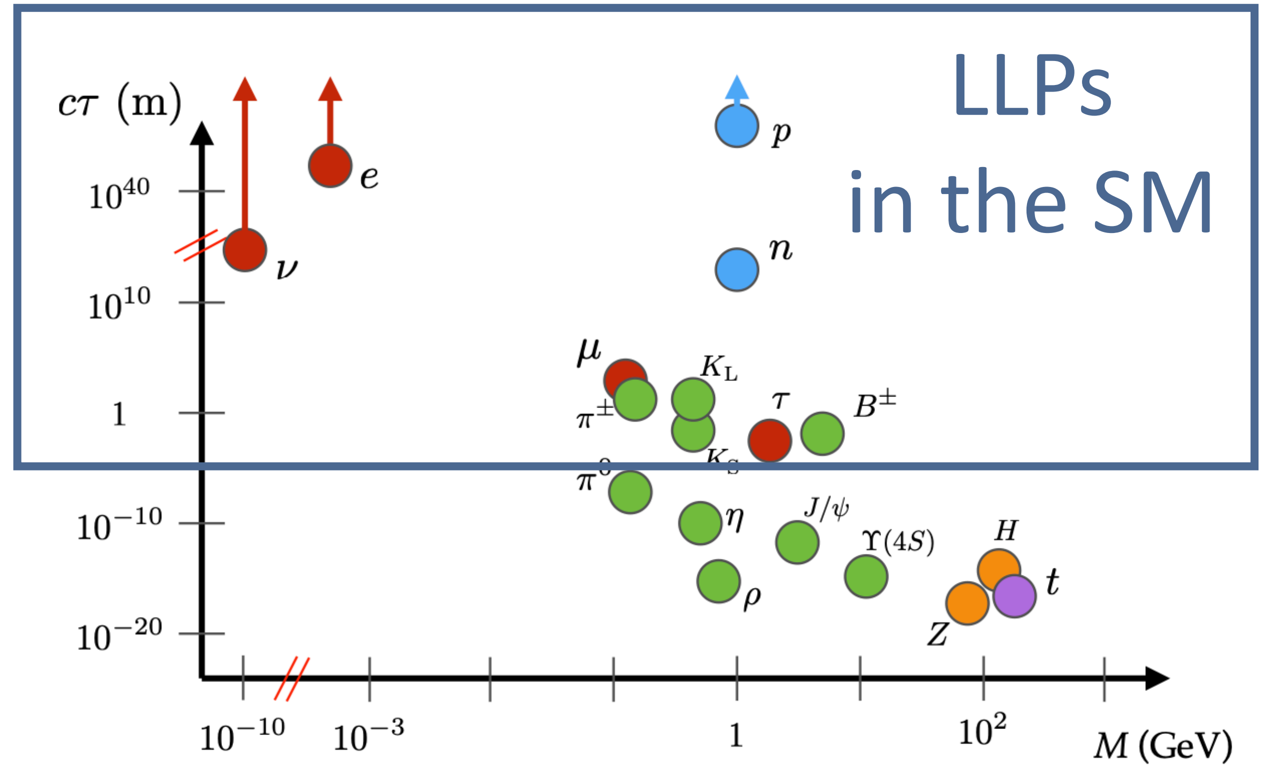
QCD-like: dark hadrons, like dark pion

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]

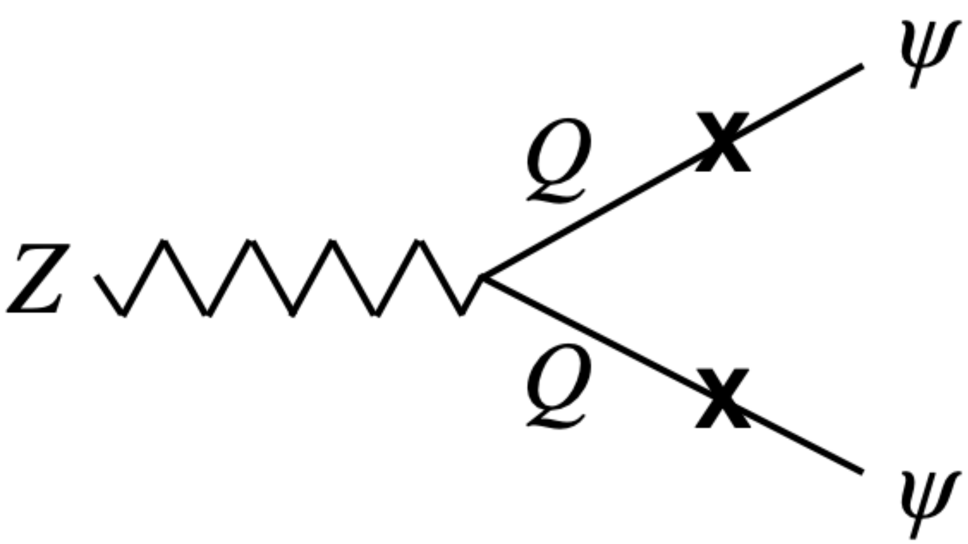
Dark QCD and U(1)’: Mixing with the SM

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

ψ'_i: SM chargeless

To replace Higgs w VEV:

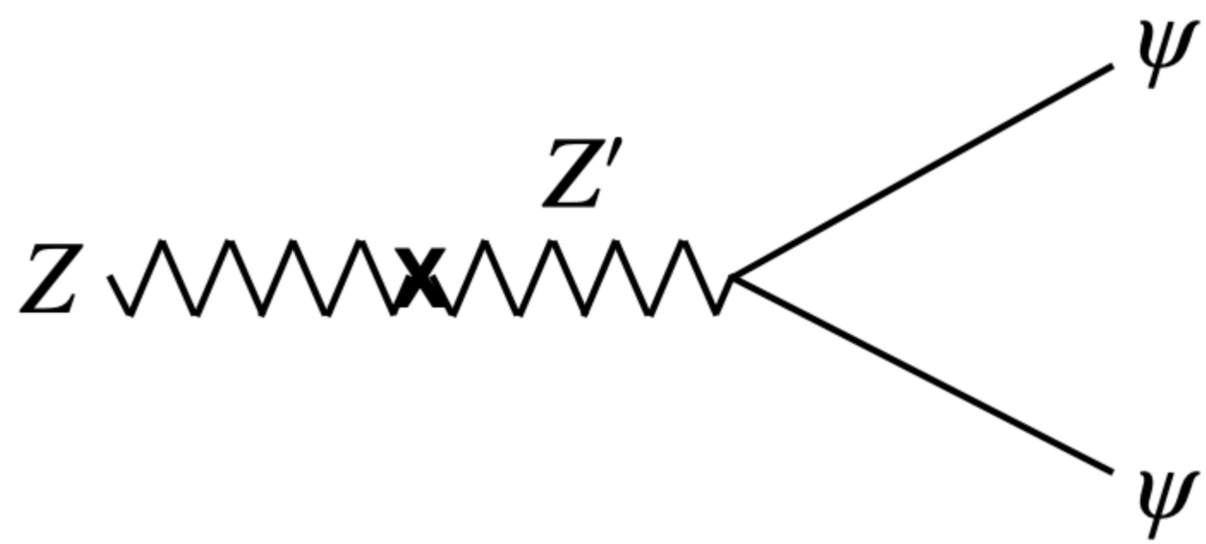
Quark Mixing



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

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

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

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

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

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):

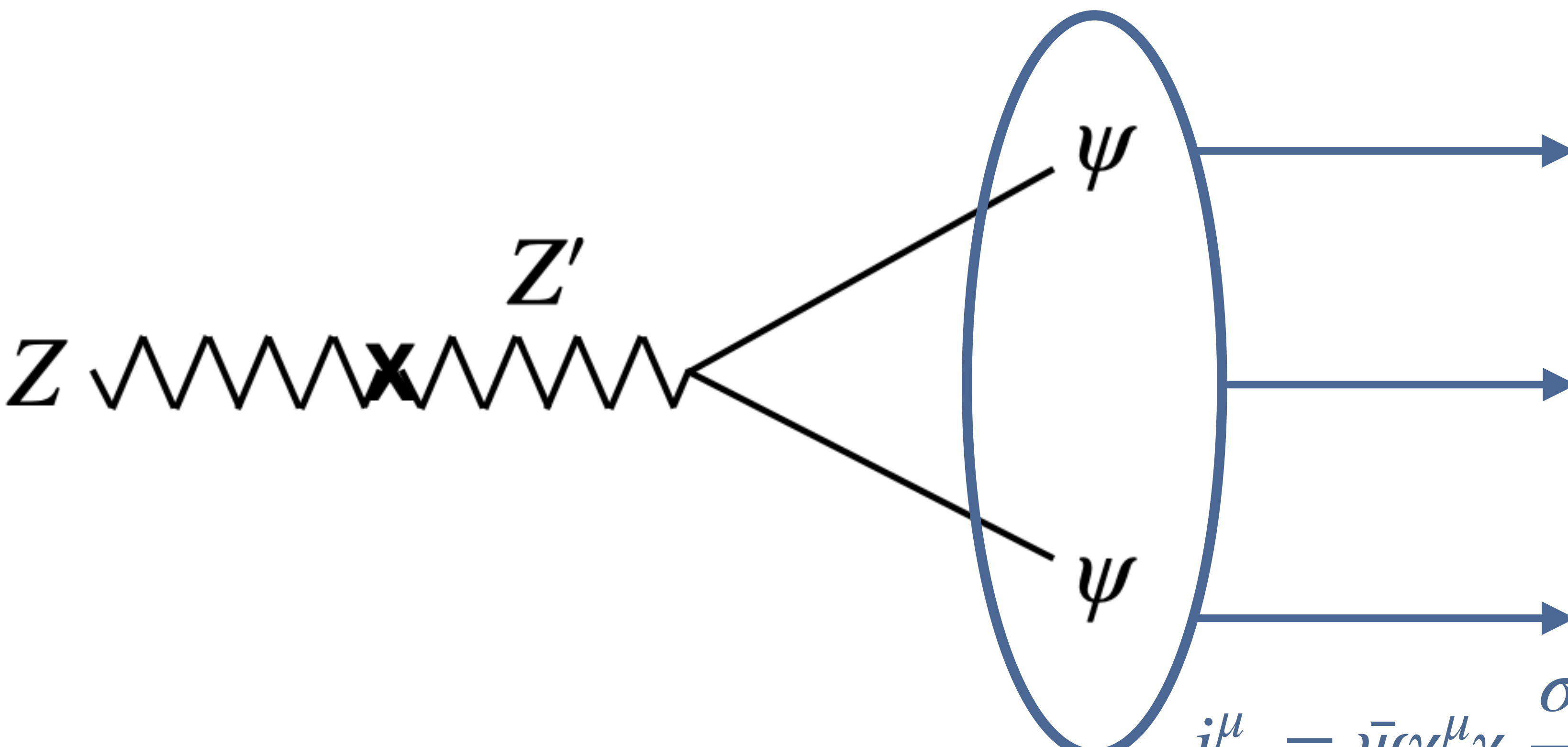
Mainly constrained by ~10 GeV

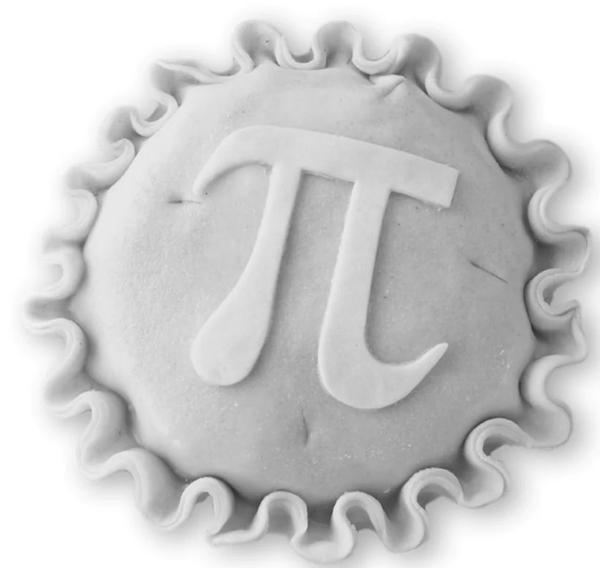
EW precision observables: not strong

Signal: Dark Showers

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

Exotic decay BR of Z(Z’)





$$j^{\mu}_{5a} = \bar{\psi}\gamma^{\mu}\gamma_5\frac{\sigma_a}{2}\psi$$

$$Z(Z') \to \boxed{\bar{\Psi}_D\ \Psi_D} \quad \Longrightarrow \quad \hat{\pi} \quad \text{LLP!}$$

Signal: Flavor FCNC

- Dark hadrons: light enough

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

LLP!

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

[He, Tandean and Valencia]

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

where

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

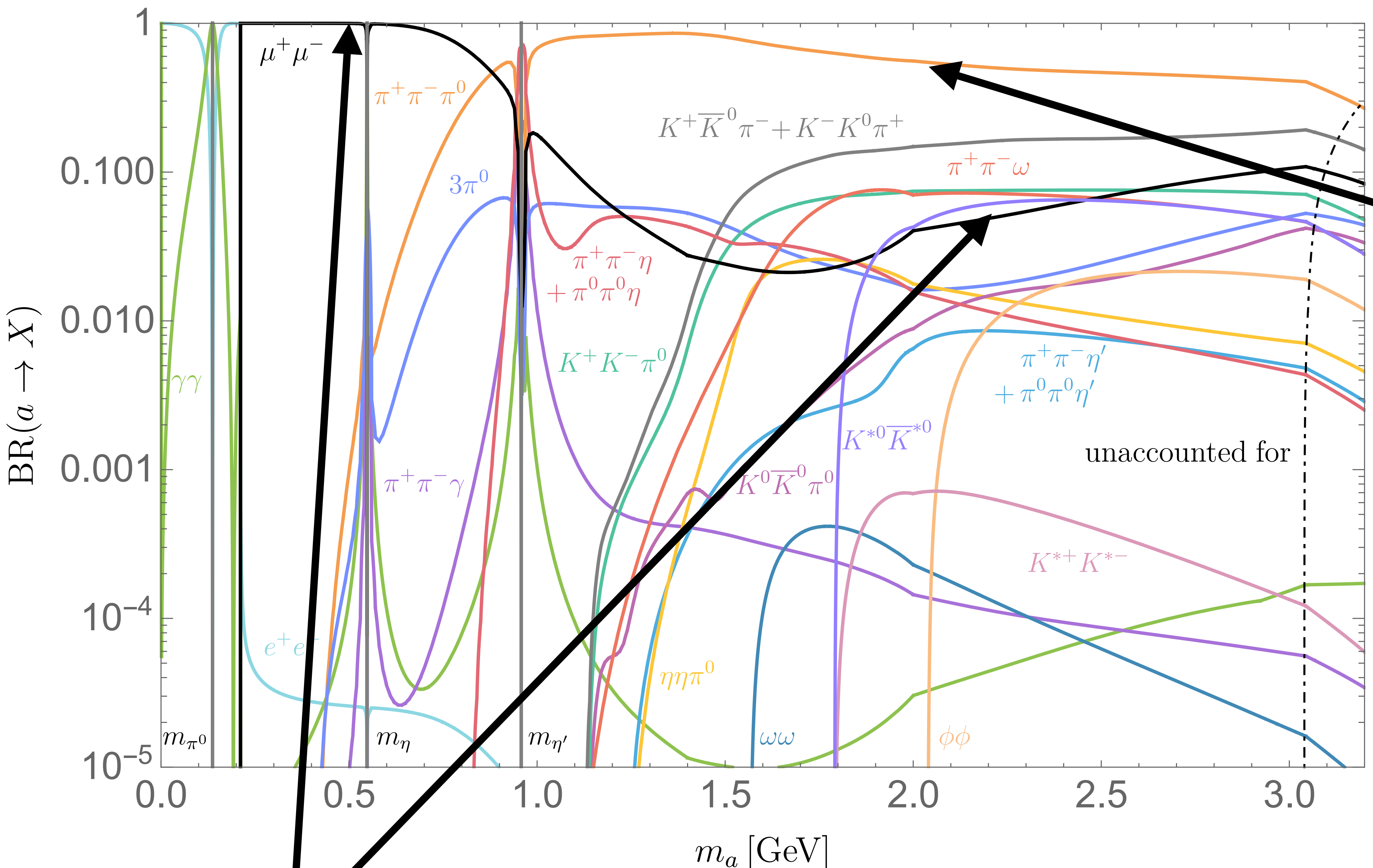
Dark current

SM down-type FCNC

Decay Channels

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

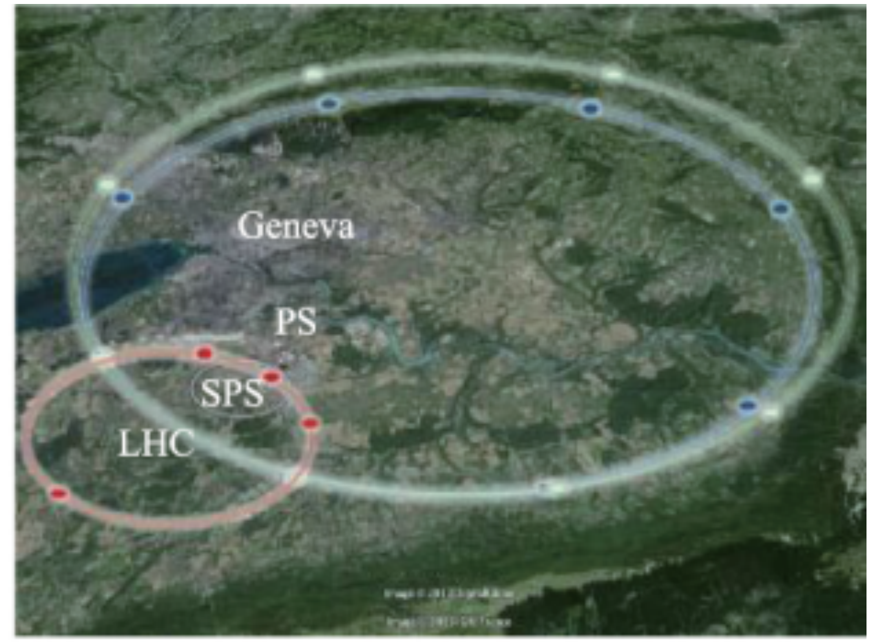
$$\hat{\pi} \to \mu^+\mu^-$$

Excellent Channel!

Z-Factory

CEPC

(a)

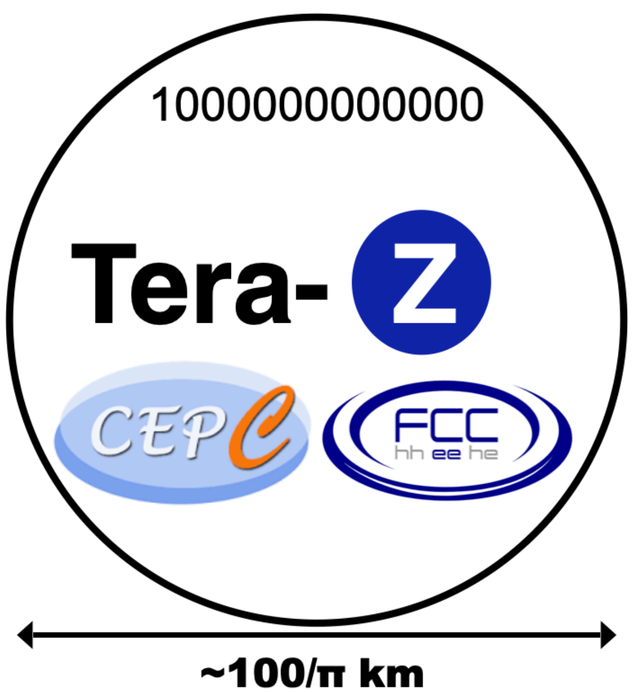


(b)

FCC-ee

e^+e^- circular colliders as Z factories

- Z abundance:



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

a clean env

- 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}

good for flavor

Z-Factory: 4 Tera-Z

- Kinematic and geometric cuts

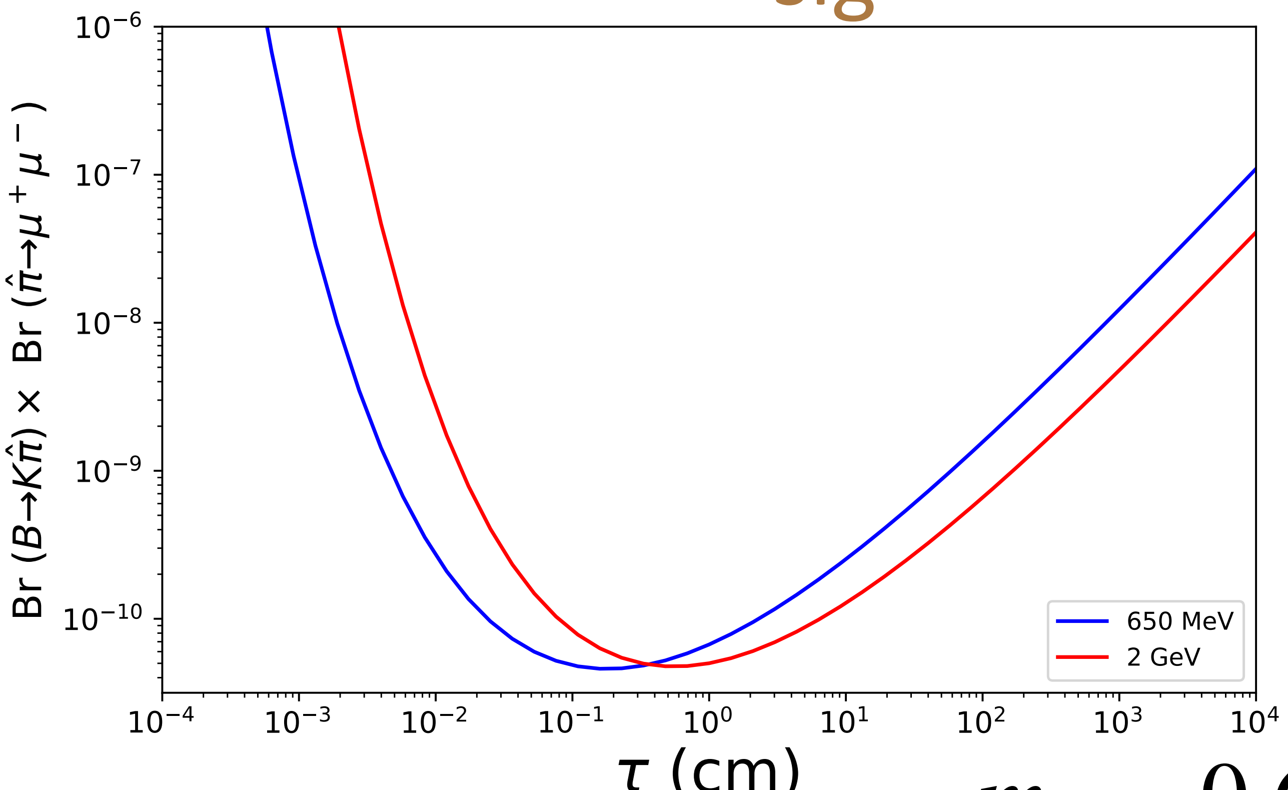
$$p_t^{\mu\mu} > 2\ \text{GeV}, \quad |\eta^{\mu\mu}| < 5$$

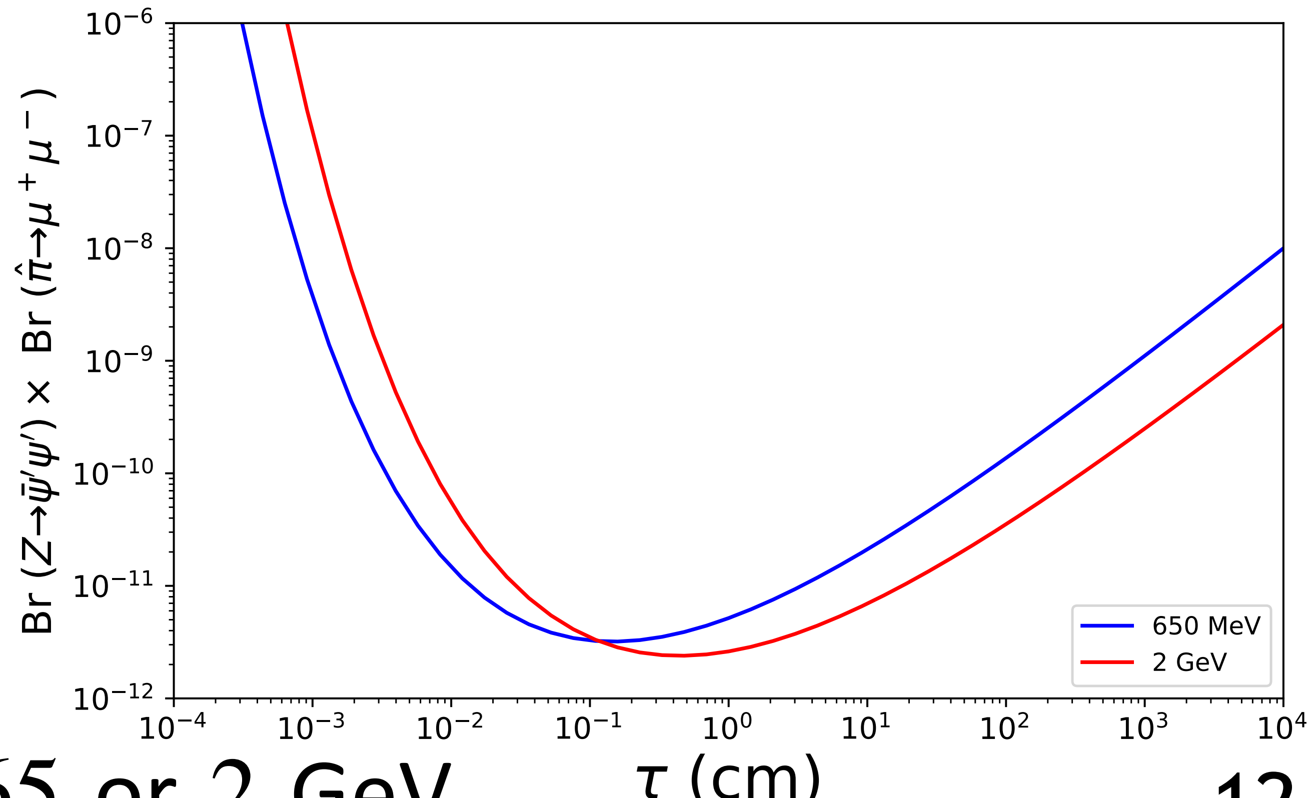
$$|p|^{\mu_i} > 10\ \text{GeV}, \quad p_t^{\mu_i} > 0.5\ \text{GeV}, \quad |\eta^{\mu_i}| < 5 \quad (i = 1, 2)$$

$$0.5 < l_{xy} < 100\ \text{cm}$$

- FCNC and DS

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





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

Z-Factory: 4 Tera-Z

- Kinematic and geometric cuts

$$p_t^{\mu\mu} > 2\ \text{GeV}, \quad |\eta^{\mu\mu}| < 5$$

$$|p|^{\mu_i} > 10\ \text{GeV}, \quad p_t^{\mu_i} > 0.5\ \text{GeV}, \quad |\eta^{\mu_i}| < 5 \quad (i = 1, 2)$$

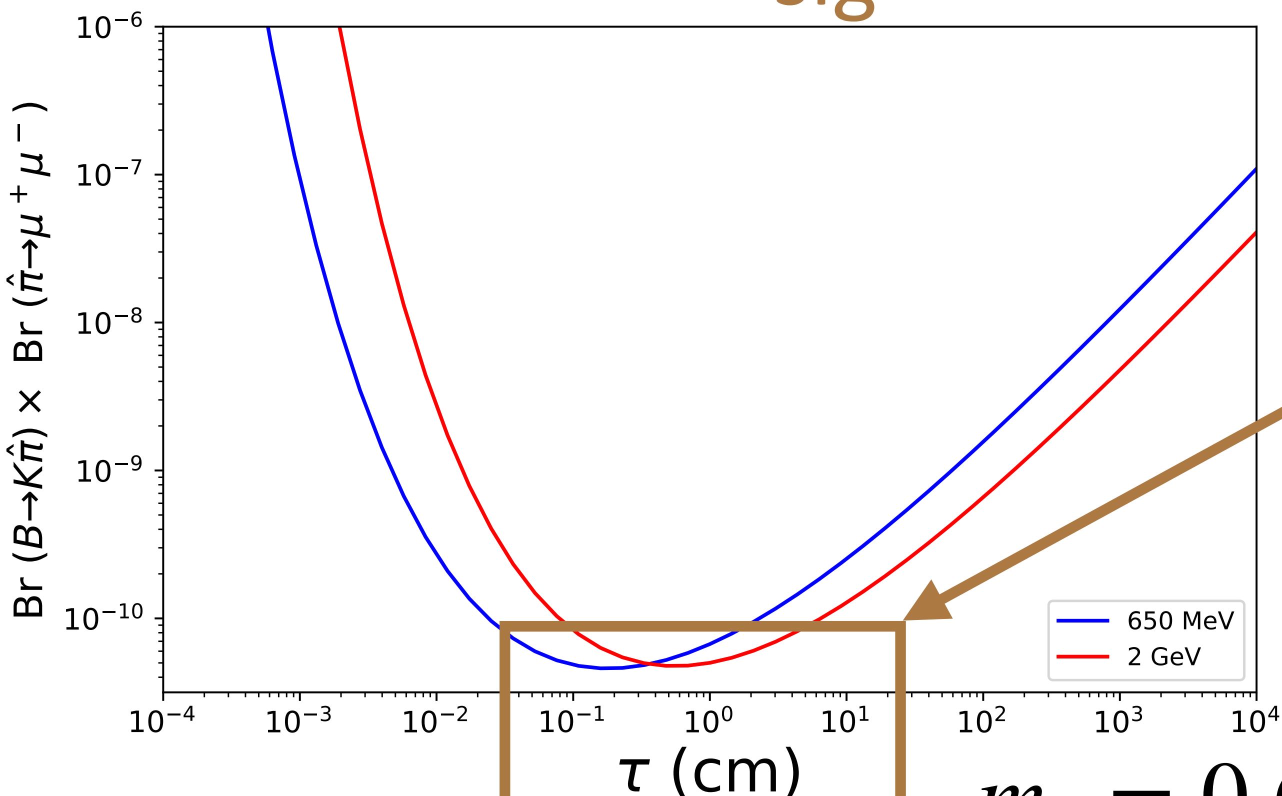
$$0.5 < l_{xy} < 100\ \text{cm}$$

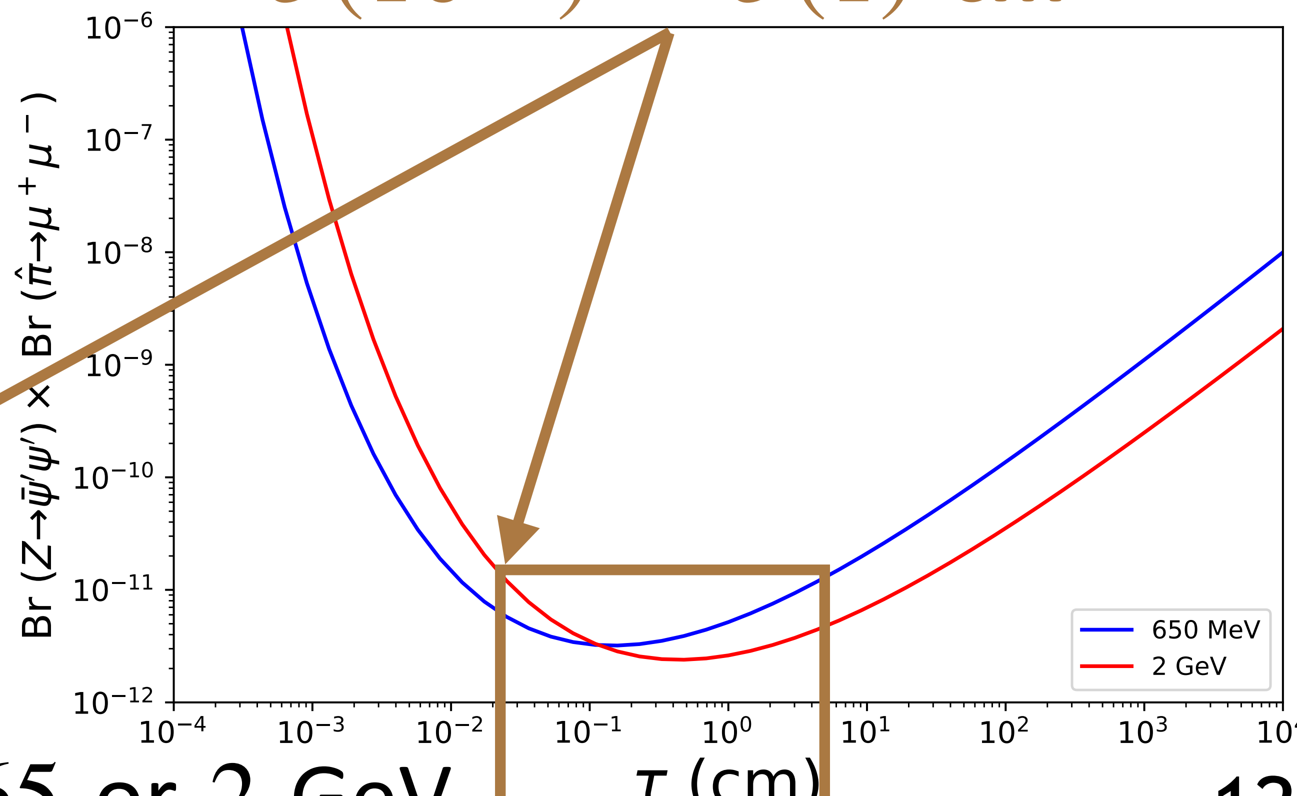
- FCNC and DS

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

Sensitive to Short Lifetime:

$\mathcal{O}(10^{-1}) \sim \mathcal{O}(1)$ **cm**





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

Auxiliary Detectors for LLPs

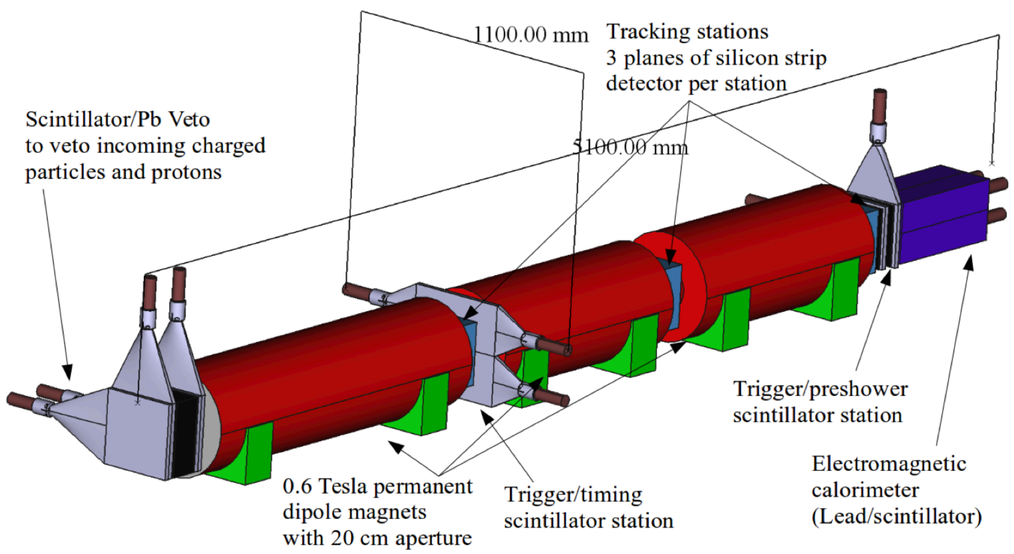
Far detectors: super promising

geom center relative to IP

Detector	Geometry	Displacement (m)	Volume (m)	Luminosity (fb^{-1})	
FASER [30]	Cylinder	0, 0, 480	0.2, 1.5	300	
FASER 2 [30]	Cylinder	0, 0, 480	2, 5	3000	[FASER Collaboration]
MATHUSLA [20]	Box	75, 0, 118	30, 100, 100	3000	[MATHUSLA Collaboration.]
Codex-b [53]	Box	31, 2, 10	10, 10, 10	300	[Berlin, and Kling.]

to be/being installed around the (HL-)LHC(b)

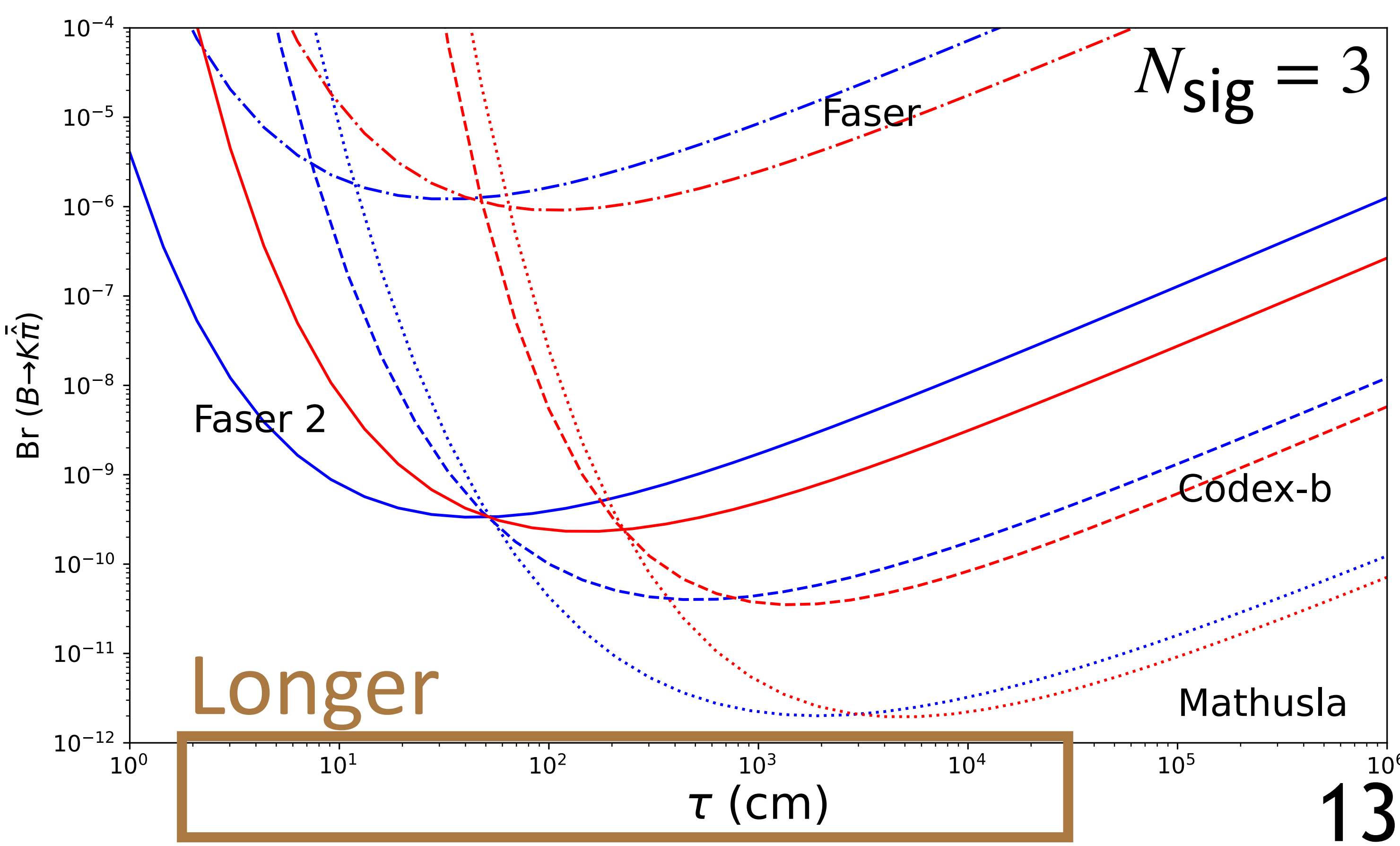
- FASER, for instance



Clean: μ or ν only

A real detector collecting data at Run III now!

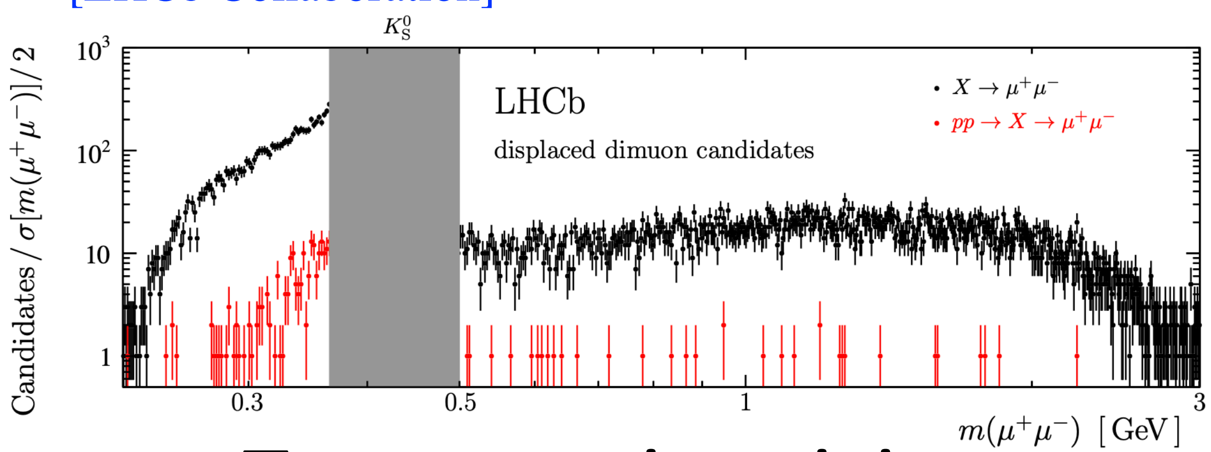
- Limits $m_{\hat{\pi}}$: 0.65 GeV 2.00 GeV



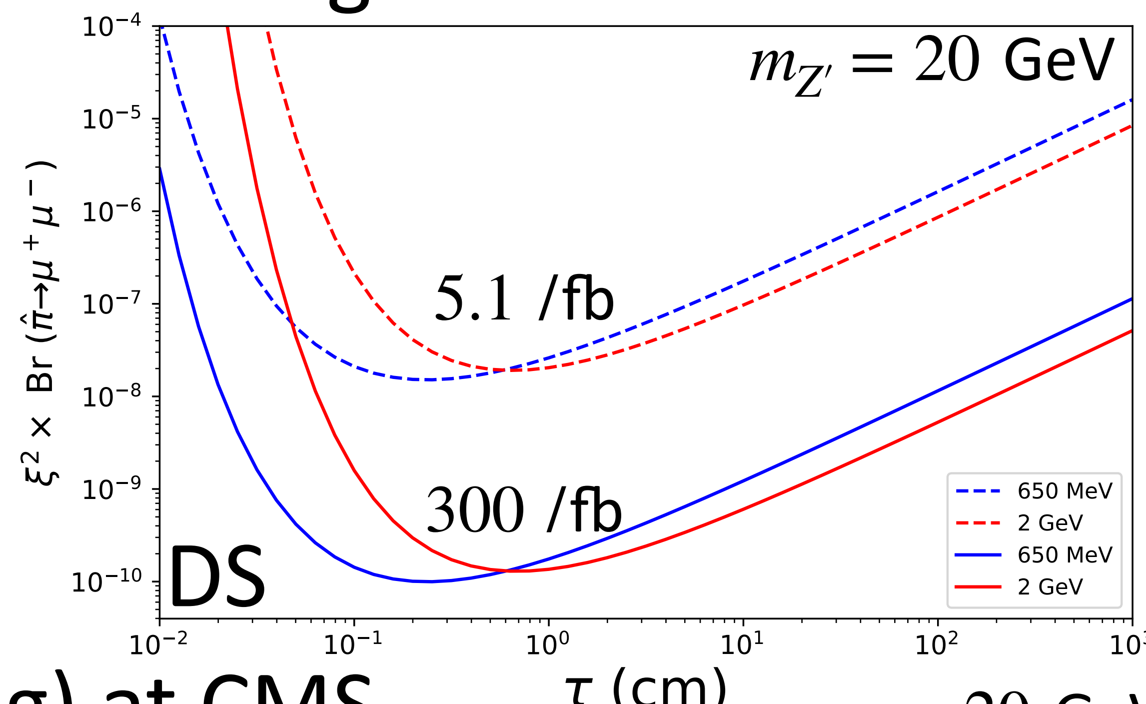
Other Opportunities at (HL-)LHC(b)

- Displaced dimuon candidate search at LHCb;
  low trigger thresholds & high vertex resolutions

[LHCb Collaboration]

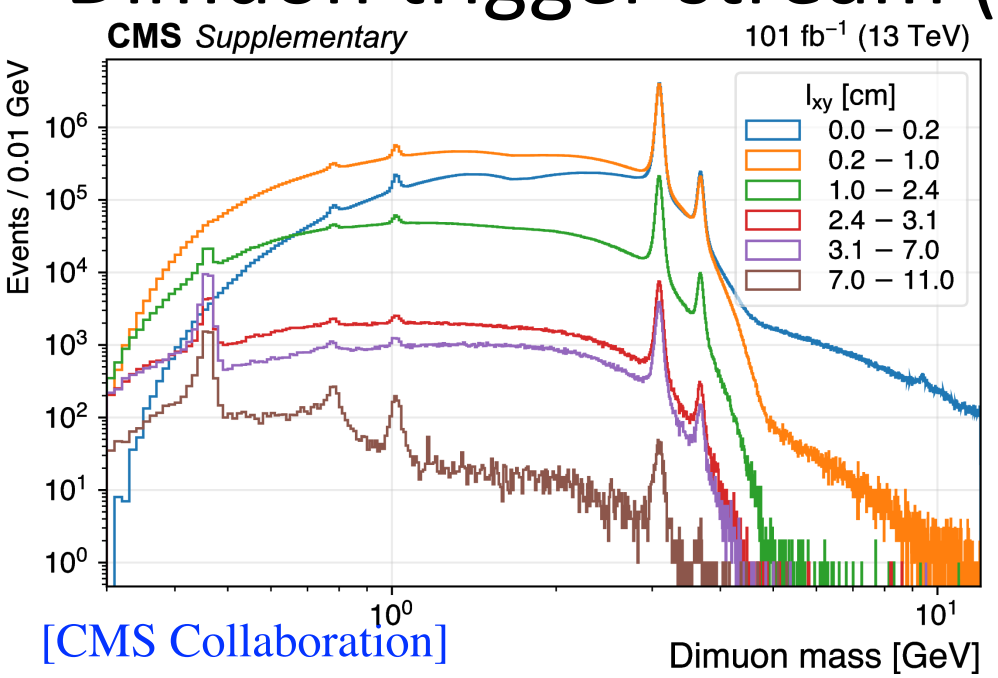


To constrain mixing

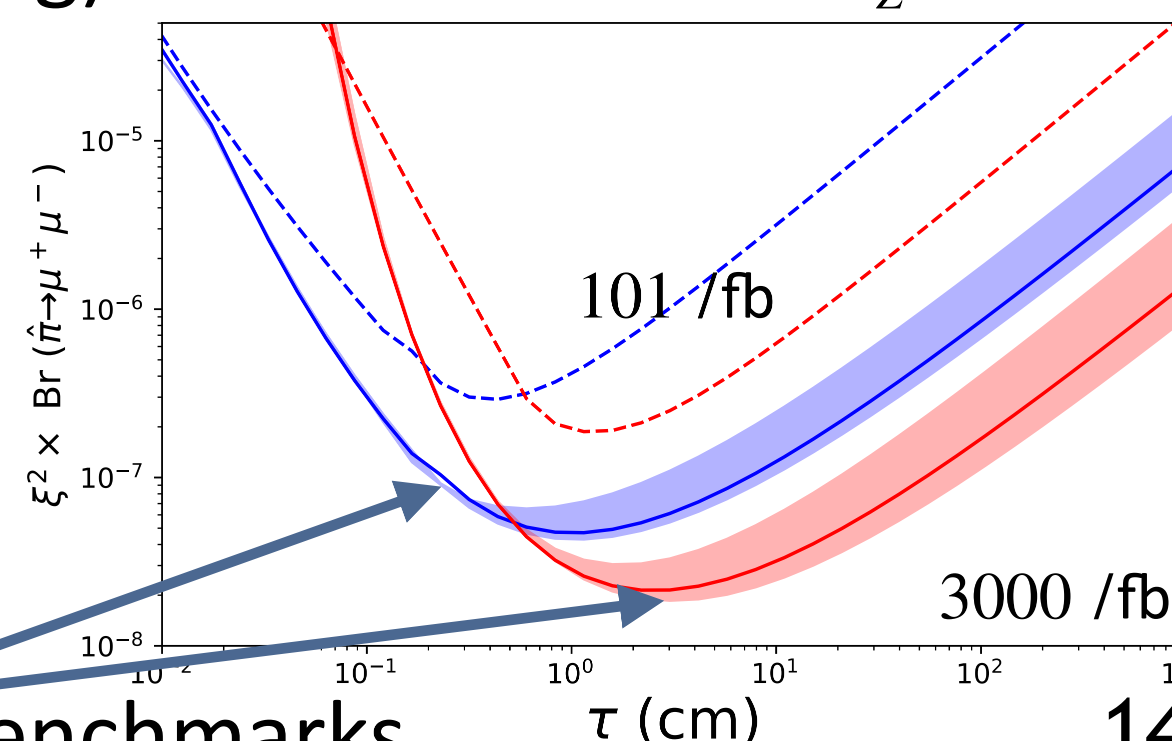


[P. Ilten, et al.]

- Dimuon trigger stream (scouting) at CMS.



[CMS Collaboration]



Band: various trigger benchmarks

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.

- Colliders [CEPC, Far Detectors, (HL-)LHC(b), …]:
  to be promising!

Back-Up

Interactions

Mass eigenstates via rotations:

$$\begin{pmatrix} A_\mu \\ \boxed{Z_{1\mu}} \\ Z_{2\mu} \end{pmatrix} = L^{-1} \cdot \begin{pmatrix} \hat{A}_\mu \\ \hat{Z}_\mu \\ \hat{Z}'_\mu \end{pmatrix}$$

with

$$L = \begin{pmatrix} 1 & -\hat{c}_W \sin\xi \tan\chi & -\hat{c}_W \cos\xi \tan\chi \\ 0 & \cos\xi + \hat{s}_W \sin\xi \tan\chi & -\sin\xi + \hat{s}_W \cos\xi \tan\chi \\ 0 & \sin\xi / \cos\chi & \cos\xi / \cos\chi \end{pmatrix}$$

Dark Z’

Observed Z

$$-\begin{pmatrix} \hat{e} J^\mu_{\rm EM} & \hat{g}_Z \hat{J}^\mu_Z & \hat{g}_D J^\mu_D \end{pmatrix} \begin{pmatrix} \hat{A}_\mu \\ \hat{Z}_\mu \\ \hat{Z}'_\mu \end{pmatrix} = -\begin{pmatrix} \hat{e} J^\mu_{\rm EM} & \hat{g}_Z \hat{J}^\mu_Z & \hat{g}_D J^\mu_D \end{pmatrix} L \begin{pmatrix} A_\mu \\ Z_{1\mu} \\ Z_{2\mu} \end{pmatrix}$$

Constraints on Z'

- Electroweak parameters:

$$\mathcal{L}_{Z_1 f\bar{f}} = -\frac{\bar{Z}e}{s_W c_W}\bar{f}\gamma^\mu(T^3_{Lf} - s_*^2 Q_i)f Z_{1\mu} \ ,$$

[M. Peskin and T. Takeuchi]

[M. Peskin and T. Takeuchi]

$$\bar{Z} = 1 + \frac{\alpha T}{2}\ , \qquad s_*^2 = s_W^2 + \frac{\alpha}{c_W^2 - s_W^2}\left(\frac{S}{4} - s_W^2 c_W^2 T\right),$$

$$\frac{M_W^2}{M_Z^2} = c_W^2 + \frac{\alpha c_W^2}{c_W^2 - s_W^2}\left(-\frac{S}{2} + c_W^2 T + \frac{c_W^2 - s_W^2}{4 s_W^2}U\right).$$

[B. Holdom]

$$S = \frac{4 s_W^2}{\alpha}\left(\frac{c_W^2}{s_W}\xi\tan\chi - c_W^2\xi^2\right)\ , \quad T = \frac{1}{\alpha}\left(2 s_W \xi\tan\chi + \xi^2\left(\frac{M_{Z_2}^2}{M_{Z_1}^2} - 2\right)\right), \quad U = \frac{4 s_W^2}{\alpha}c_W^2\xi^2$$

Constrained by PDG fit

Constraints on Z’

- Low energy parameters: $E \ll M_{Z_{1,\,2}}$

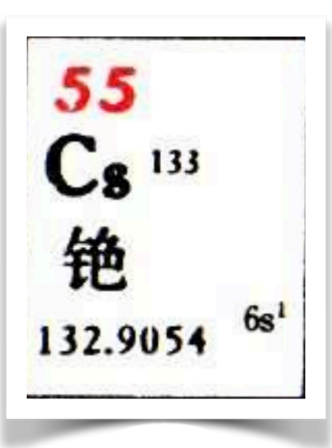
$$\mathcal{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}\rho_*(0)\left[J_3^\mu J_{3\,\mu} - 2s_*^2(0)J_3^\mu J_{\mathrm{EM}\,\mu} + O(J_{\mathrm{EM}}^2)\right]$$

$$\rho_*(0) = 1 + \alpha T + \frac{M_{Z_1}^2}{M_{Z_2}^2}(\xi - s_W \tan\chi)^2\,,$$

$$\frac{s_*^2(0)}{s_W^2} = \frac{s_*^2}{s_W^2} + \frac{M_{Z_1}^2}{M_{Z_2}^2}\left(c_W^2\tan^2\chi - \frac{c_W^2}{s_W}\xi\tan\chi\right)$$

- Atomic Parity Violation (APV)

Weak charge of the Caesium atom:



$$Q_W \approx Q_W^{\rm SM}\left(1 + \delta\rho_*(0) + 2.91\,\delta s_*^2(0)\right)$$

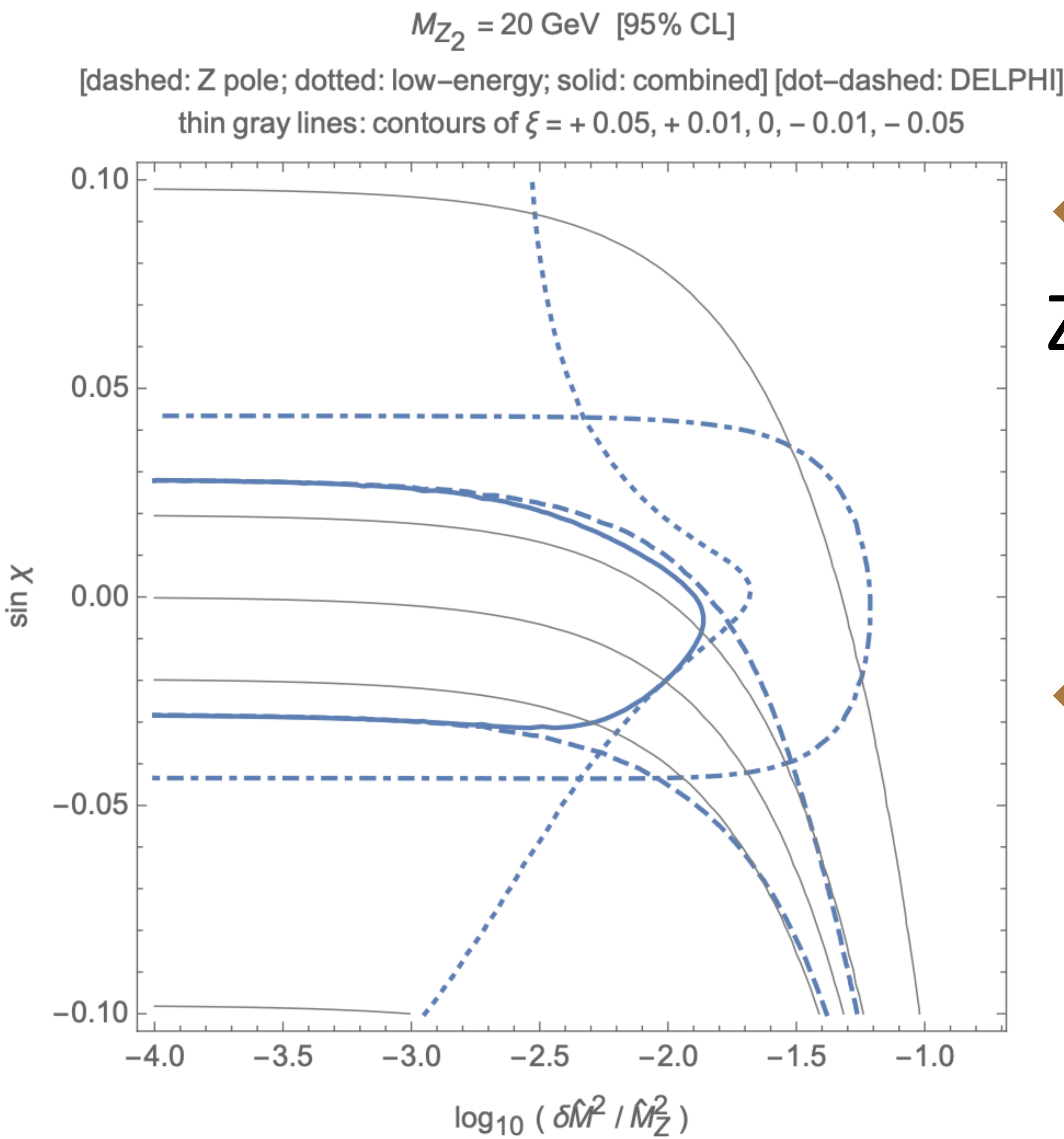
- Parity Violation [K. S. Kumar]

$e^-e^- \to e^-e^-$ at E158 at SLAC.

Effective coupling:

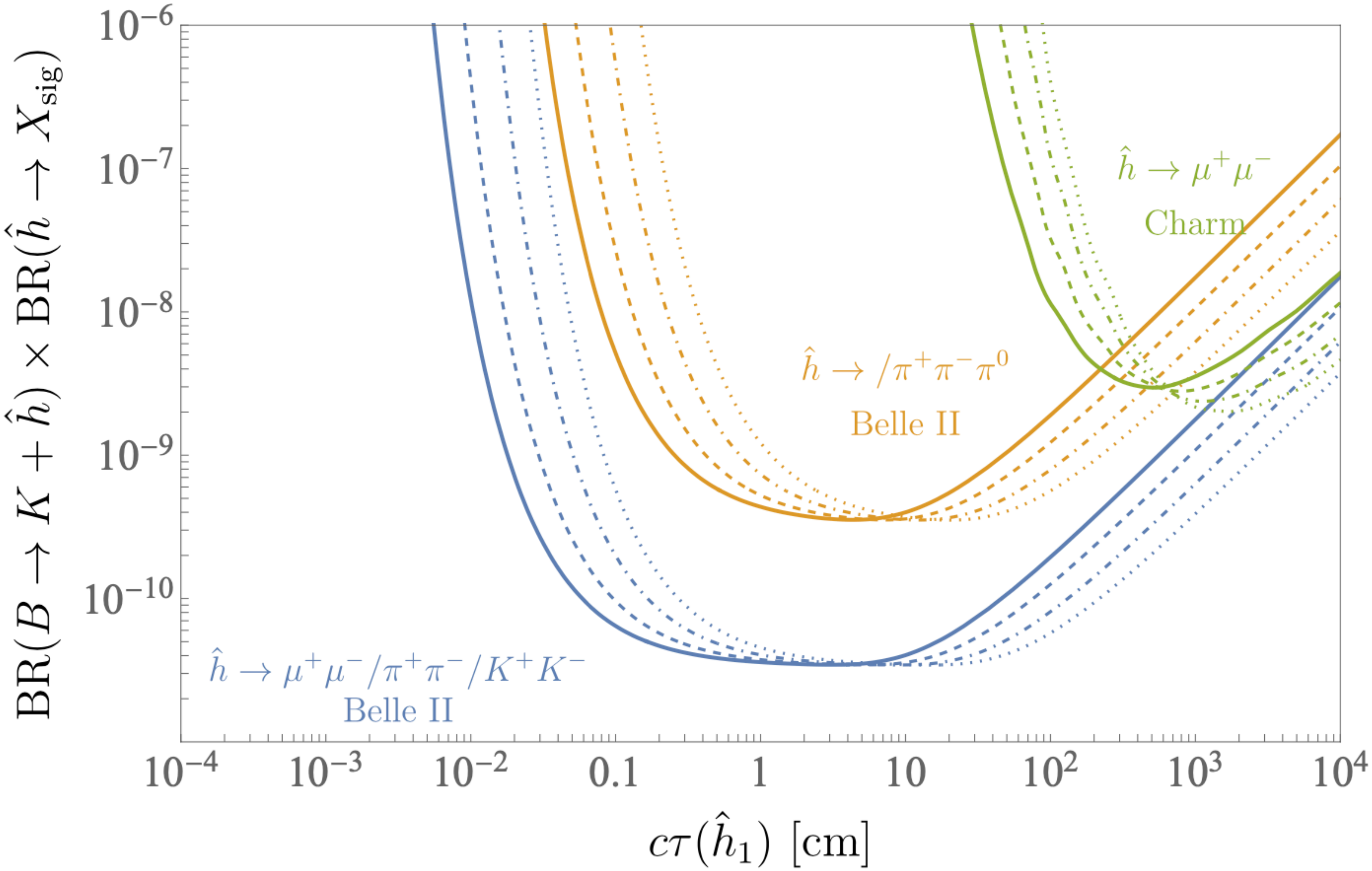
$$g_{AV}^{ee} \approx g_{AV}^{ee,\,\rm SM}\left(1 + \delta\rho_*(0) - 87.0\,\delta s_*^2(0)\right)$$

Constraints on Z'



- Constraints from Z-pole and low-energy observables
- Some room for light Z'

Belle-II



$\hat{h} \to \mu^+\mu^-$
Charm
$\hat{h} \to /\pi^+\pi^-\pi^0$
Belle II
$\hat{h} \to \mu^+\mu^-/\pi^+\pi^-/K^+K^-$
Belle II
$\mathrm{BR}(B \to K + \hat{h}) \times \mathrm{BR}(\hat{h} \to X_{\mathrm{sig}})$
$c\tau(\hat{h}_1)$ [cm]

Opportunities at (HL-)LHC

ATLAS/CMS: larger luminosity and decay vessel.

A dedicated dimuon trigger stream (scouting)

[CMS Collaboration]

Data Scouting in CMS

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Online data taking

Data scouting in collider experiments refers to the use of physics objects reconstructed online during data taking to perform searches and measurements. The technique, pioneered by the CMS experiment, allows events to be recorded for analyis at a rate of several additional kHz with negligible impact on total data volume. Dijet resonance searches have used data scouting to probe resonance masses far lower than those explorable with a standard offline physics analysis, and new developments for LHC Run II enable a wider range of analyses to take advantage of this new trigger paradigm. We describe the scouting technique, give an overview of its past use in CMS, and provide details on the implementation of the scouting streams being used in Run II. We also show results from the first scouting-based physics analysis with 13 TeV data.

[D. Anderson]

Opportunities at (HL-)LHC

CMS

ℓ_{xy} (cm) vs. p_t^μ (GeV)

ℓ_{xy}	3–5	5–8	8–10	10–15	>15 GeV
0–0.2	0.12	0.51	0.6	0.59	0.14
0.2–1	0.12	0.51	0.6	0.56	0.44
1–2.4	0.1	0.43	0.55	0.53	0.52
2.4–3.1	0.07	0.34	0.44	0.52	0.46
3.1–7	0.05	0.24	0.35	0.37	0.36
7–11	0.03	0.15	0.21	0.21	0.19
>11 cm	0	0	0	0	0

HL-LHC

ℓ_{xy}	3–5	5–8	8–10	10–15	>15 GeV
0–0.2	0.1	0.46	0.59	0.59	0.53
0.2–1	0.1	0.46	0.58	0.59	0.53
1–2.4	0.1	0.45	0.58	0.58	0.52
2.4–3.1	0.1	0.45	0.57	0.58	0.52
3.1–7	0.098	0.44	0.56	0.56	0.5
7–11	0.094	0.42	0.53	0.54	0.48
11–20	0.086	0.38	0.49	0.49	0.44
20–40	0.069	0.31	0.39	0.4	0.35
40–90	0.046	0.21	0.26	0.26	0.24
>90 cm	0.017	0.077	0.098	0.099	0.089

ℓ_{xy}	3–5	5–8	8–10	10–15	>15 GeV
0–0.2	0.1	0.46	0.59	0.59	0.53
0.2–1	0.1	0.46	0.59	0.59	0.53
1–2.4	0.1	0.46	0.58	0.59	0.53
2.4–3.1	0.1	0.46	0.58	0.59	0.52
3.1–7	0.098	0.44	0.56	0.56	0.5
7–11	0.088	0.39	0.5	0.5	0.45
11–20	0.064	0.29	0.36	0.37	0.33
20–40	0.028	0.12	0.16	0.16	0.14
40–90	0.0067	0.03	0.038	0.038	0.034
>90 cm	0.0035	0.016	0.02	0.02	0.018

ℓ_{xy}	3–5	5–8	8–10	10–15	>15 GeV
0–0.2	0.1	0.46	0.59	0.59	0.53
0.2–1	0.1	0.46	0.59	0.59	0.53
1–2.4	0.1	0.45	0.57	0.58	0.51
2.4–3.1	0.096	0.43	0.54	0.55	0.49
3.1–7	0.079	0.35	0.45	0.45	0.4
7–11	0.047	0.21	0.27	0.27	0.24
11–20	0.016	0.073	0.093	0.094	0.084
20–40	<0.001	0.0042	0.0054	0.0054	0.0048
40–90	<0.001	<0.001	<0.001	<0.001	<0.001
>90 cm	<0.001	<0.001	<0.001	<0.001	<0.001

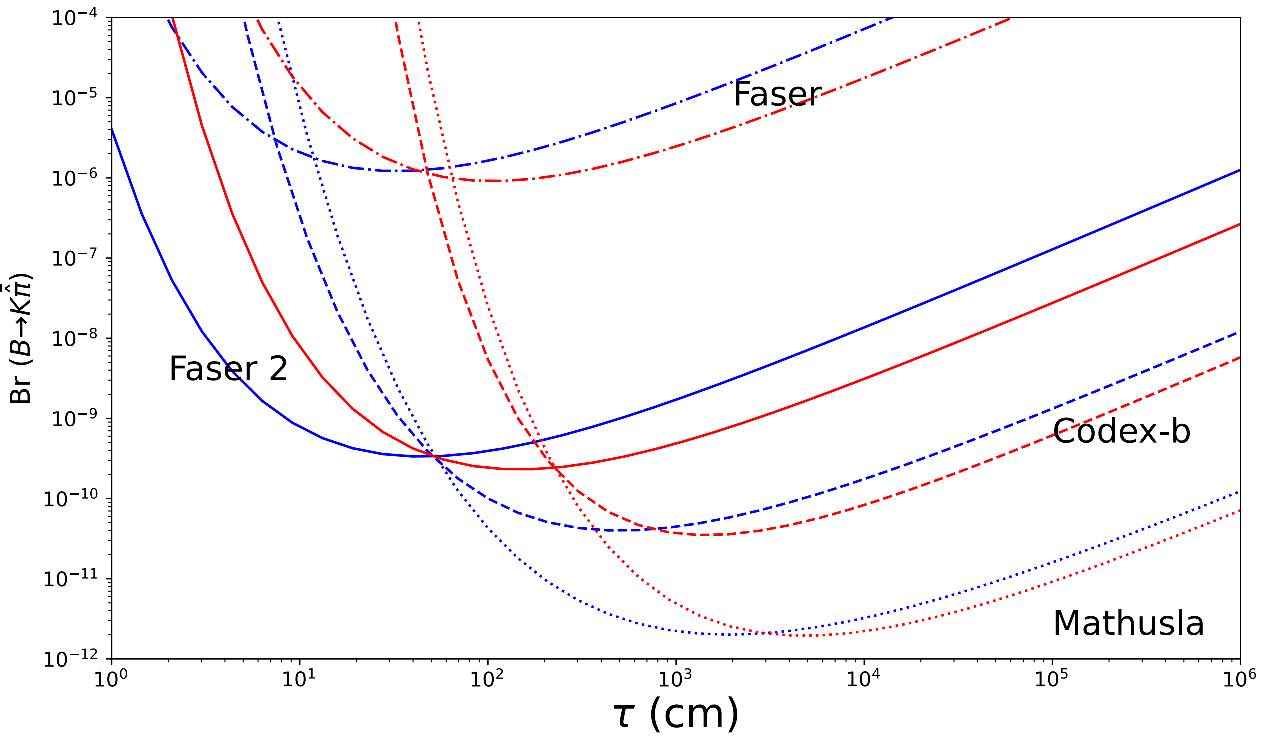
Model-Dependent Constraints

Preliminary

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

$$\frac{1}{f_a^{(b)}} = \frac{\mathrm{Tr}(\sigma_b X'_A) g_D \hat{g}_Z f_{\hat{\pi}} \delta \hat{M}^2}{2 M_{Z_1}^2 M_{Z_2}^2 \cos^2\chi} \approx \frac{1}{1\ \mathrm{PeV}} \frac{\mathrm{Tr}(\sigma_b X'_A) g_D}{\cos^2\chi} \left(\frac{f_{\hat{\pi}}}{1\ \mathrm{GeV}}\right) \left(\frac{\delta\hat{M}^2/M_{Z_1}^2}{10^{-2}}\right) \left(\frac{60\ \mathrm{GeV}}{M_{Z_2}}\right)^2$$

A switch from model-independent study (using auxiliary detectors for example):



$\Longrightarrow$