2401.08785 + 240u.vwxyz w/ H-C. Cheng, X. Jiang, E. Salvioni

2110.10691 w/ H-C. Cheng, E. Salvioni

EW PORTAL TO THE HIDDEN VALLEY

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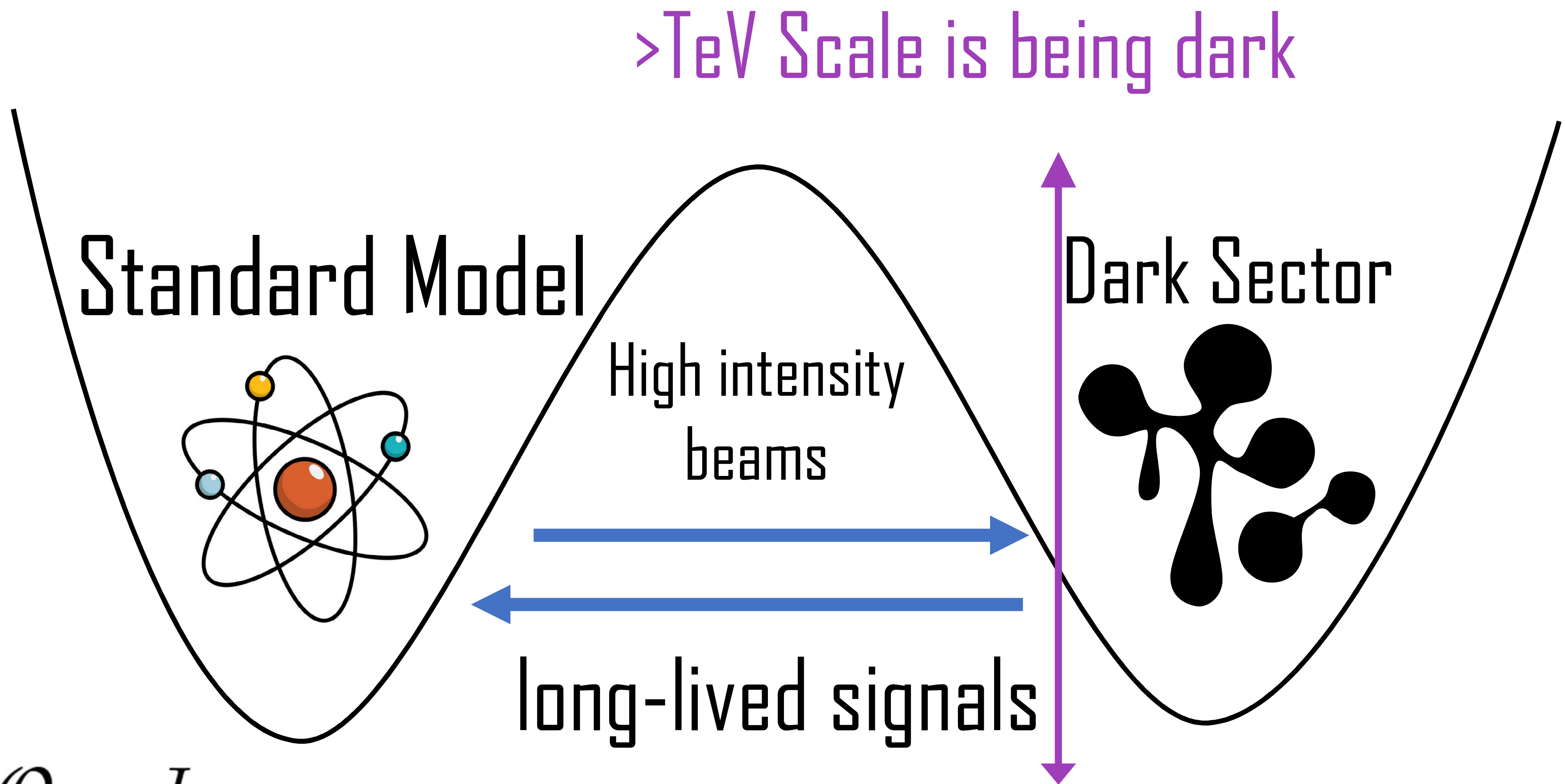
Brown University

May 15, 2024 Pittsburgh

DPF-PHENO 2024

Hidden Valley Models

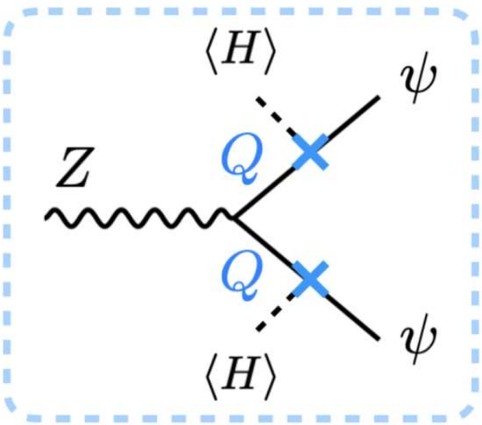


$\epsilon \mathcal{O}_{\rm SM} J_{\rm Dark}$ **Relevant portal:** small couplings to keep the valley hidden

$\frac{1}{\Lambda^n} \mathcal{O}_{\rm SM} J_{\rm Dark}$ **Irrelevant portal:** Hidden behind EFTs

The EW Portal: $\frac{c}{M^2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\overline{\psi}\gamma^\mu\psi)$ from Two UV Models

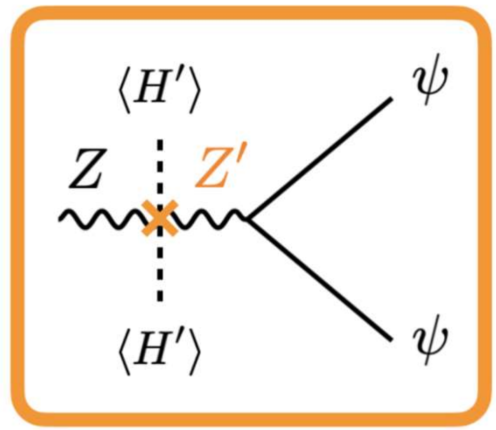
$$\mathcal{L}_{\rm UV} \supset \overline{Q} Y \psi H \longrightarrow \frac{c}{M^2} \sim \frac{Y^2}{M_Q^2}$$



Heavy fermion doublet model: a heavy scale above TeV

H-C. Cheng, LL, E. Salvioni, 2110.10691

$$\mathcal{L}_{\rm UV} \supset \delta\hat{M}^2 Z^\mu Z'_\mu \longrightarrow \frac{c}{M^2} \sim \frac{g_D^2 \delta\hat{M}^2}{m_Z^2 m_{Z'}^2}$$



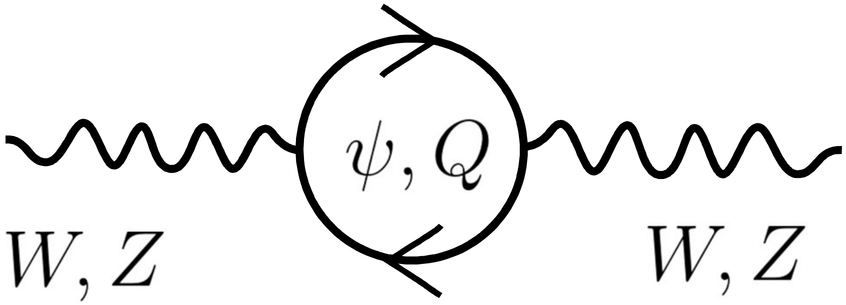
Dark Z' model: a Z' heavier or lighter(!) than Z, must have a mass mixing

H-C. Cheng, X. Jiang, LL, E. Salvioni, 2401.08785

EWPT

Peskin, Takeuchi, 1992

Doublet mediation



Leading by EW loops with mixing

L. Lavoura, J. P. Silva, 1993; C. Anastasiou, E. Furlan, J. Santiago, 0901.2117

$$S \simeq -\frac{y^2 v^2 (1 + 6 \log \frac{M^2}{M_Z^2})}{72\pi M^2}$$

$$T = \frac{N_c y^4 v^2}{48\pi^2 \alpha M^2}$$

Z' mediation

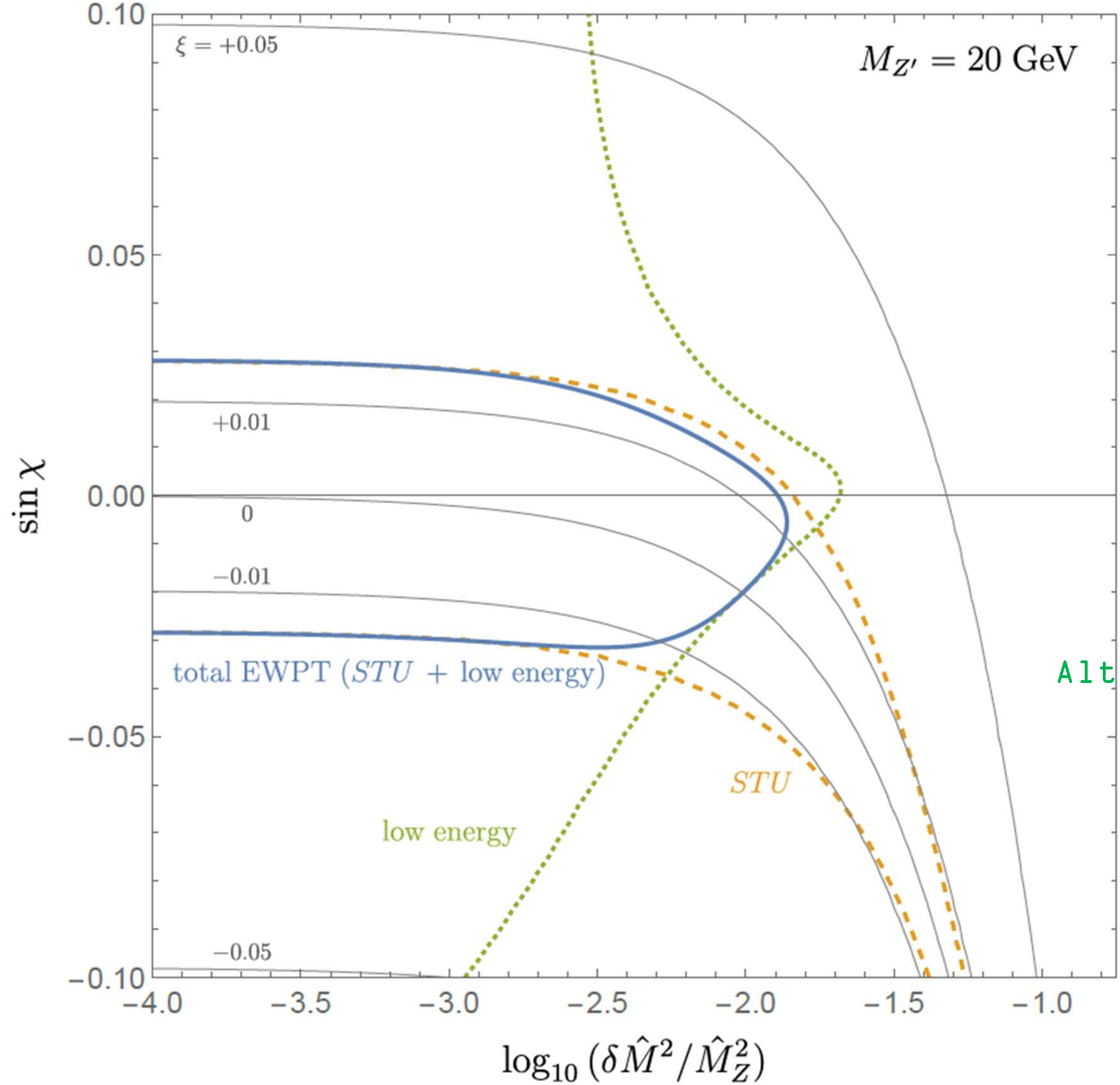
Leading by LEP Z pole observables defined with:

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

B. Holdom, 1991; G. Altarelli et. al, 1991

$$S = \frac{4 s_W^2}{\alpha}\left(\frac{c_W^2}{s_W}\xi t_\chi - c_W^2 \xi^2\right)$$

$$T = \frac{1}{\alpha}\left(2 s_W \xi t_\chi + \xi^2 \left(\frac{M_{Z'}^2}{M_Z^2} - 2\right)\right)$$



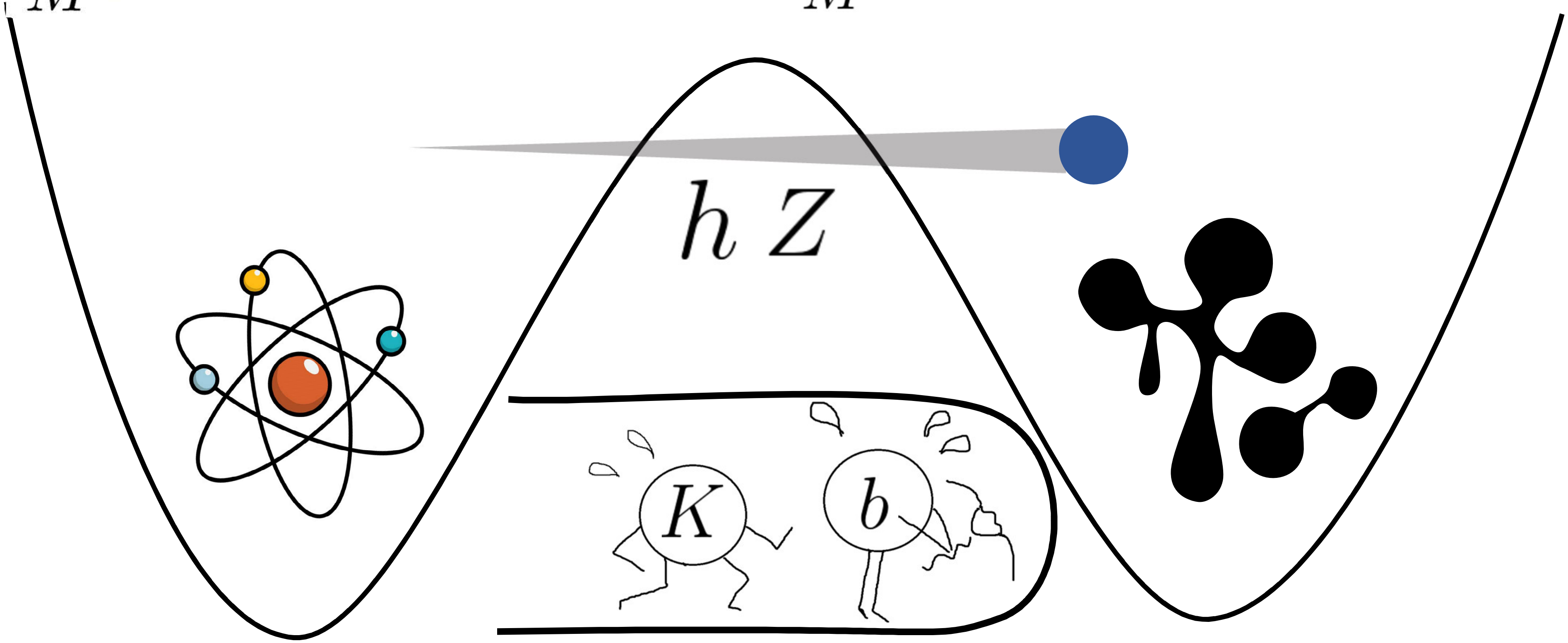
Low energy constraints:

e.g. atomic parity violation, low energy ee, ep scattering

Altarelli et al. 1991

The Flavor Portal

$$\frac{c}{M^2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\overline{\psi}\gamma^\mu\psi) \Rightarrow \frac{\mathcal{K}}{M^2}(\bar{d}_i\gamma^\mu d_j)(\bar{\psi}\gamma_\mu\psi)$$



Typical:

$$\mathrm{BR}(B \to \psi\bar{\psi} + X_s) \lesssim 10^{-7} \qquad \mathrm{BR}(K \to \psi\bar{\psi} + \pi) \lesssim 10^{-10}$$

W. Altmannshofer, A. Crivellin, H. Haigh, G. Inguglia and J. Martin Camalich, 2311.14629; J. Martin Camalich, M. Pospelov, P. N. H. Vuong, R. Ziegler and J. Zupan, 2002.04623; M. K. Gaillard, M. B. Gavela, R. Houtz, P. Quilez and R. Del Rey, 1805.06465……

Now I am going to introduce the (Confining) Dark Force

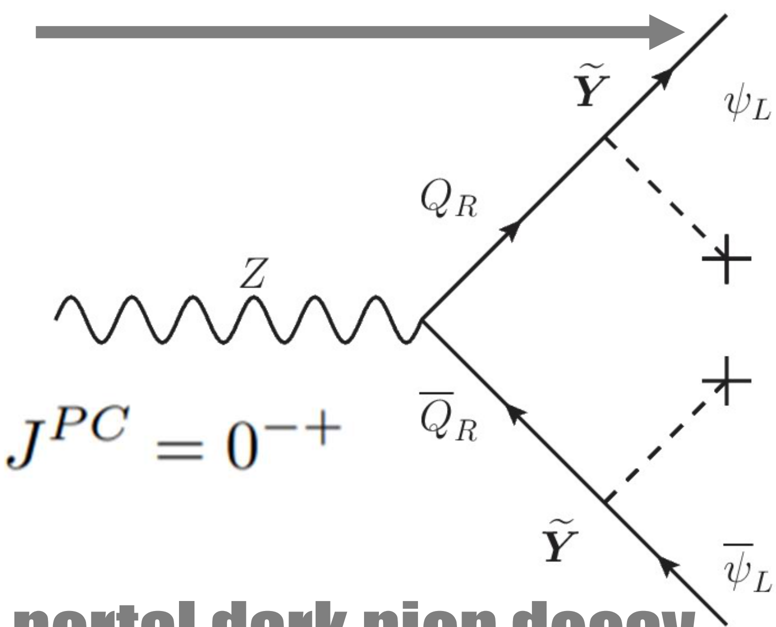
- ❑Dark fermions form dark hadrons
- ❑Welcomed in many models such as neutral naturalness, ALP, ……

See e.g. Talks from Christopher Verhaaren and Kathryn Zurek…

- ❑They are long-lived in general
  - ❑Dark matter(?)
  - ❑Phenomenology
- ❑A lot of fun from dark symmetries

Two Flavor, Three Dark Pions

Z portal dark pion production



Z portal dark pion decay

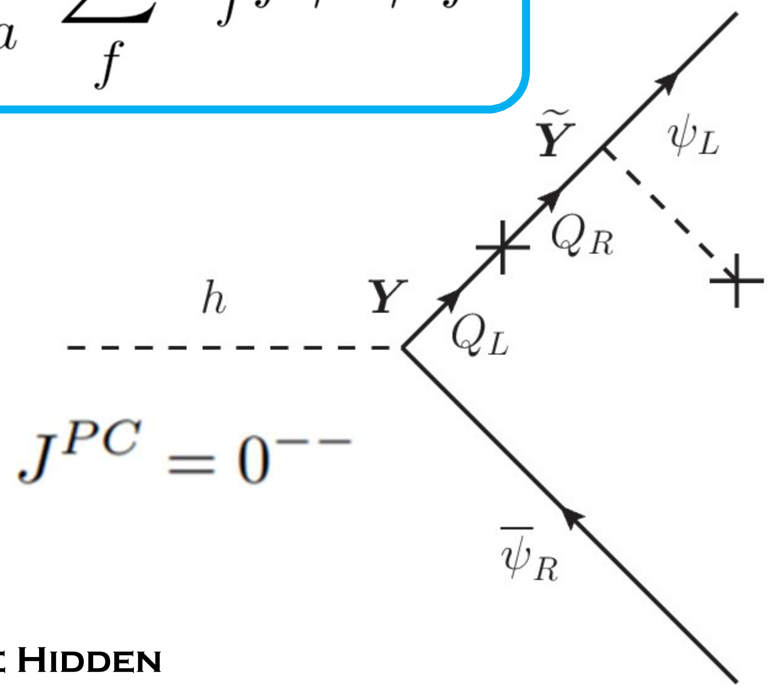
Dark pions rearrange into CP eigenstates (like K_S and K_L in the SM)

The π_1 and π_3 decay via Z portal, ALP-like (axion-like-particle) with effective ALP decay constants:

$$\mathcal{L}_a \supset -\frac{\partial_\mu a}{f_a} \sum_f T_f^3 \bar{f} \gamma^\mu \gamma^5 f$$

The π_2 mix with the Higgs since it's CP-even, with mixing angle:

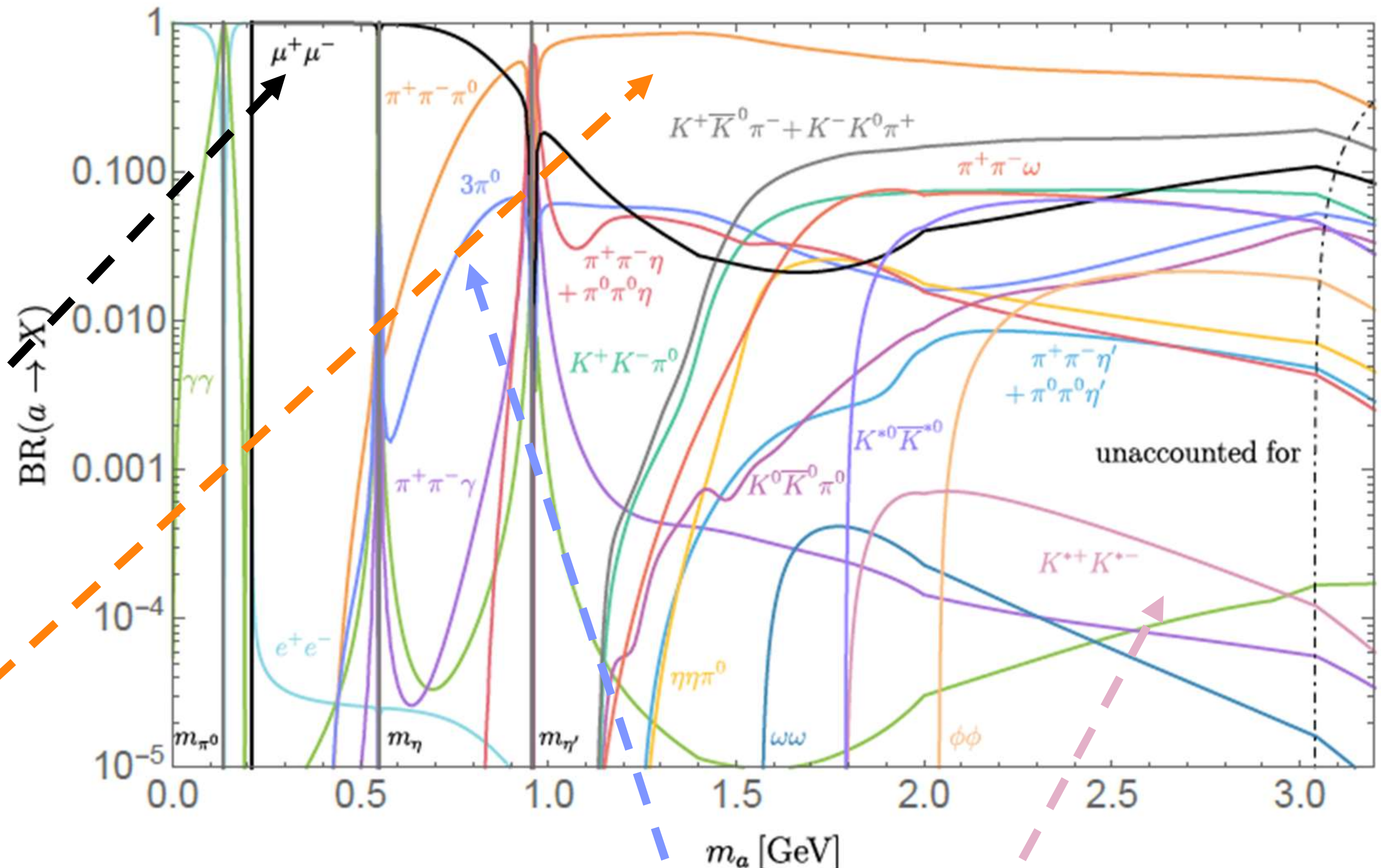
$$\mathcal{L}_s \supset -\sin\theta_s \frac{m_f}{v} s \bar{f} f \ , \ \theta_s \lesssim 10^{-6}$$



Dark Pion Decays (ALP-Like)

ALP with arbitrary flavor diagonal couplings

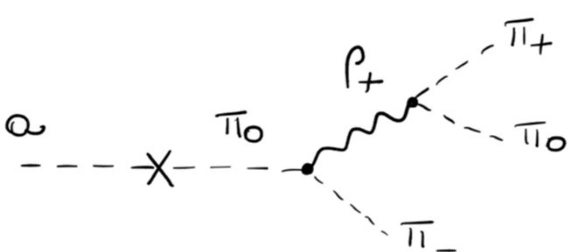
See also D. Aloni, Y. Soreq and M. Williams, 1811.03474



$m_\pi < m_{\eta'}$: dimuon mode dominates

$m_\pi > m_{\eta'}$: PPP modes (mostly SM $\pi^+\pi^-\pi^0$)

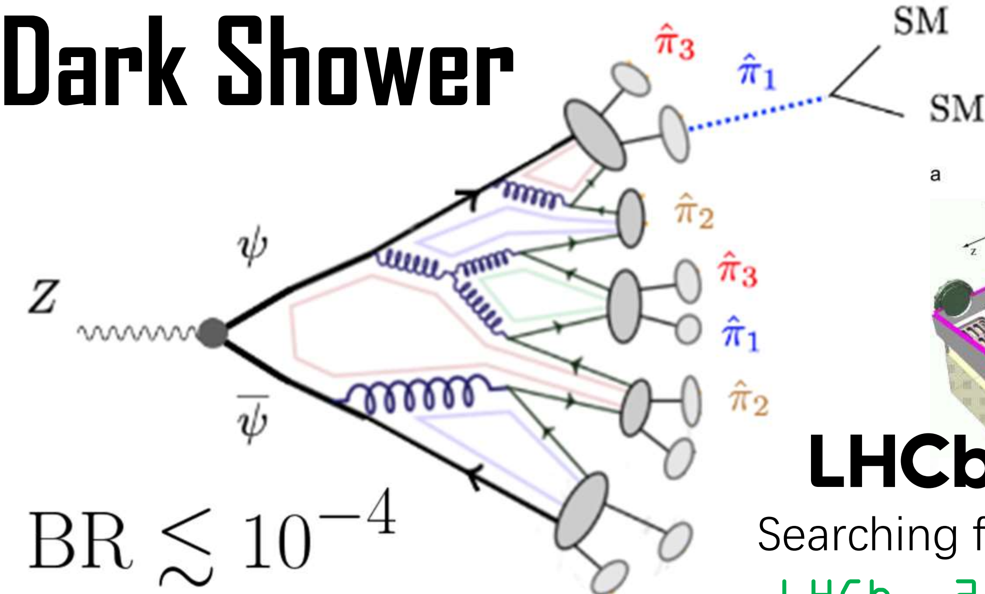
SM isospin suppressed modes



$$f_a \sim \frac{M^2}{f_{\hat{\pi}} Y^2} \text{ or } \frac{m_Z^2 m_{Z'}^2}{f_{\hat{\pi}} \delta M^2} \sim \mathcal{O}(\mathrm{PeV})$$

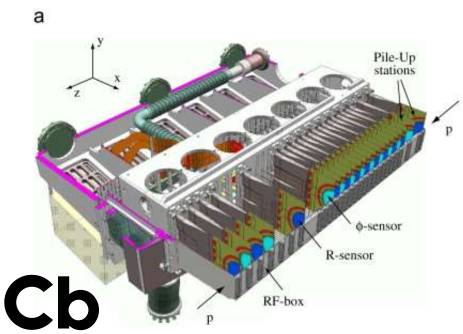
LHC Phenomenology

Dark Shower

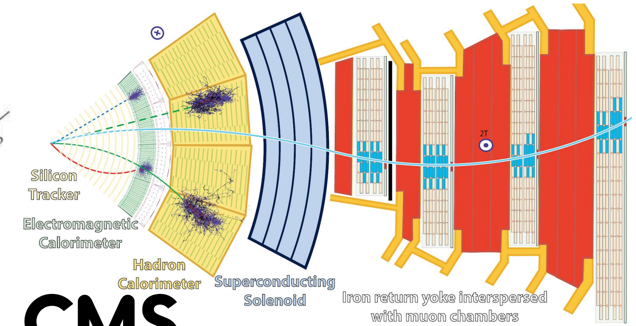


$$\mathrm{BR} \lesssim 10^{-4}$$

Signal: Muon rich jet-like structure with long-lived tracks &MET



LHCb



CMS

Searching for displaced dimuon resonances (one or more)

LHCb, 2007.03923; CMS, 2112.13769

Belle II

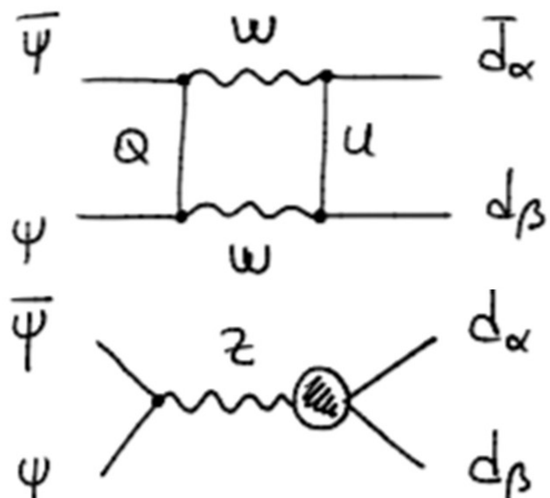
CODEX-b

FPF Forward Physics Facility

MATHUSLA

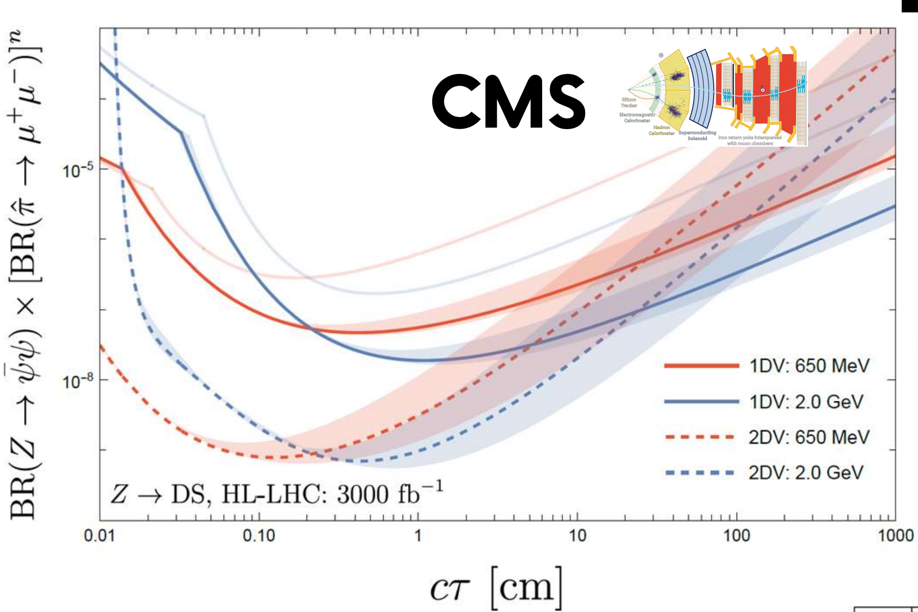
FASER

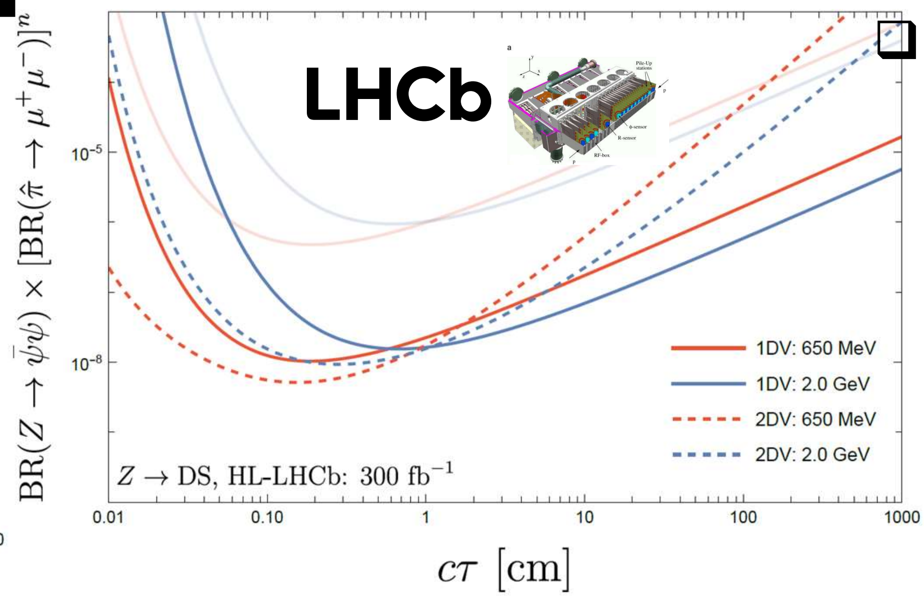
$$\mathrm{BR} \approx 10^{-8} \left(\frac{1\ \mathrm{PeV}}{f_a}\right)^2$$



FCNC Decays

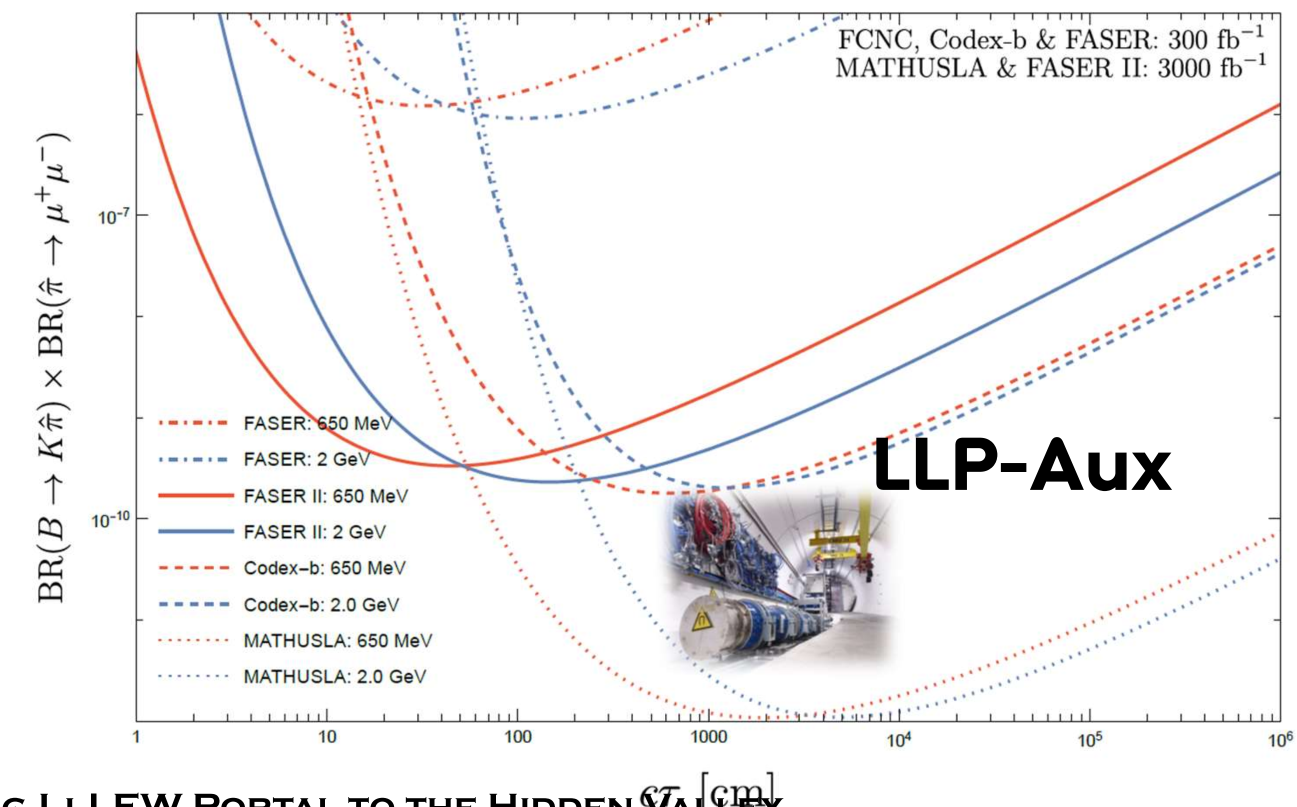
Model-Independent Limits



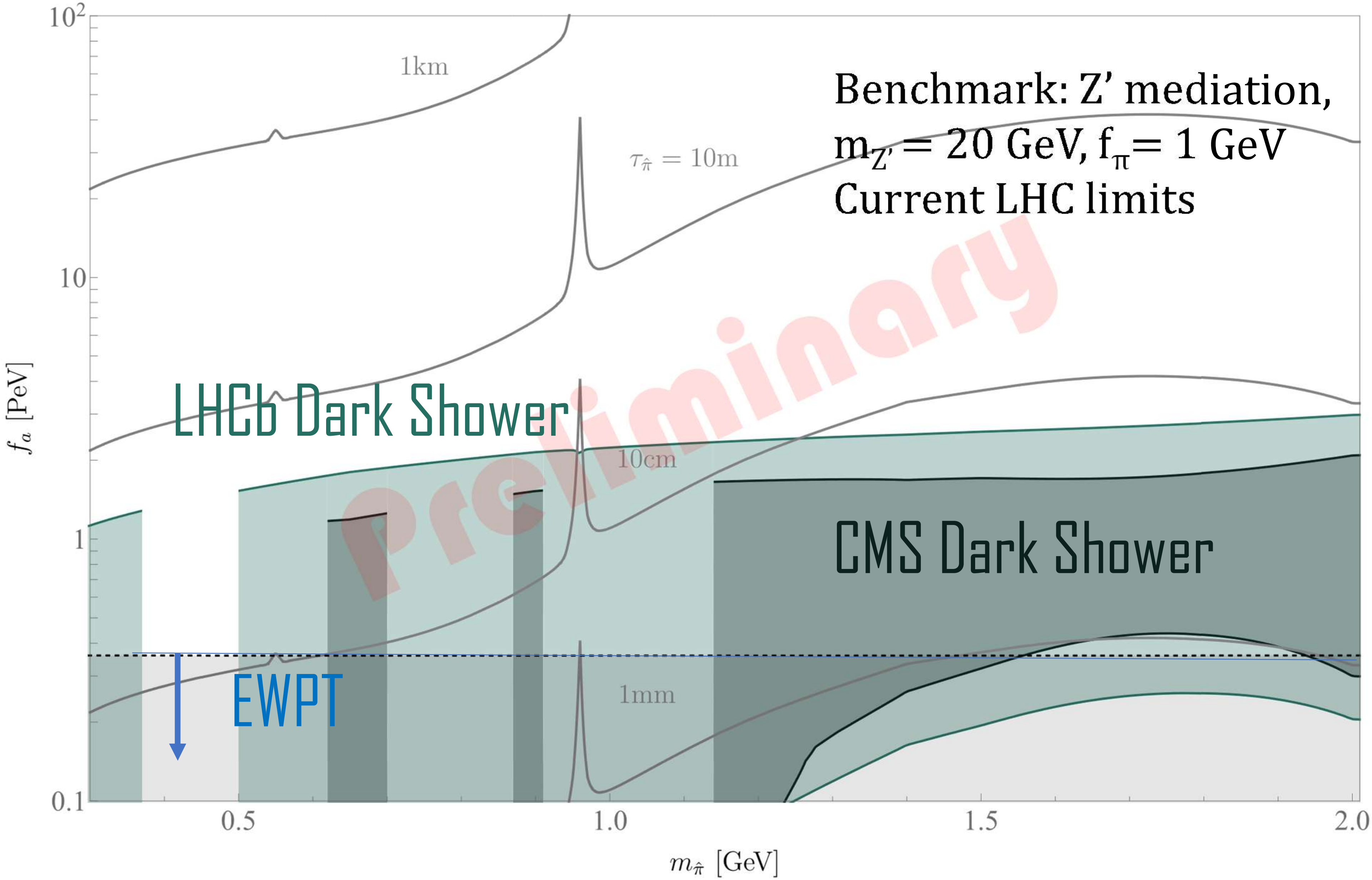


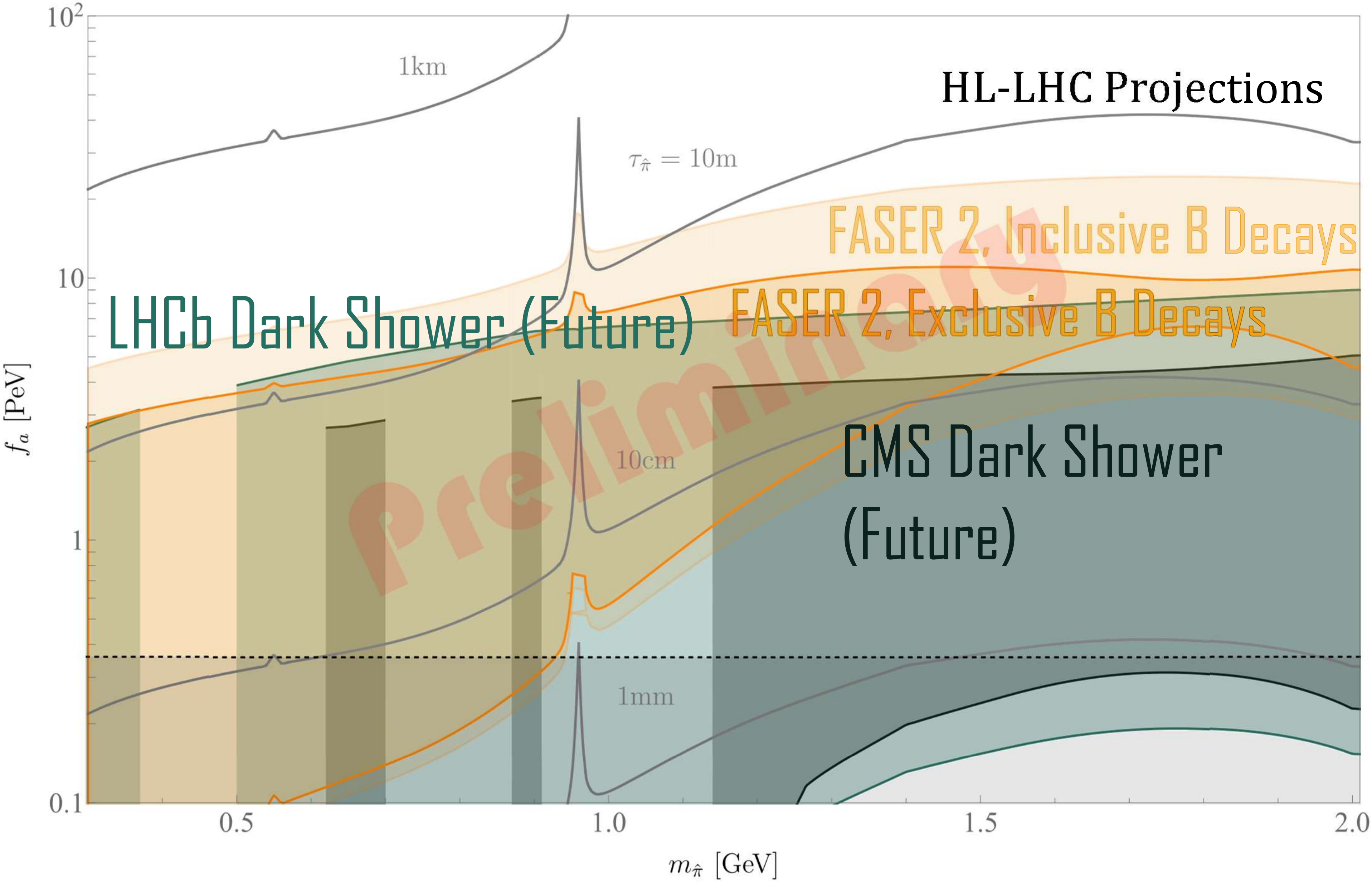
- Z boson initiated dark shower limits at LHC

- Exclusive B FCNC limits at various auxiliary LLP detectors, even more when include more final states

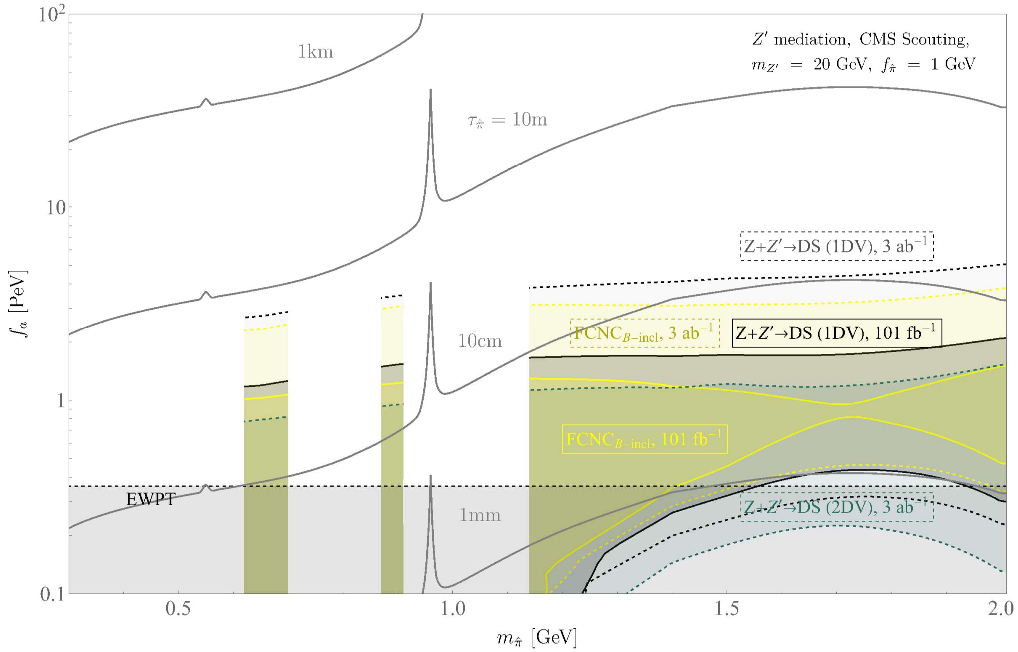


Model Benchmarks

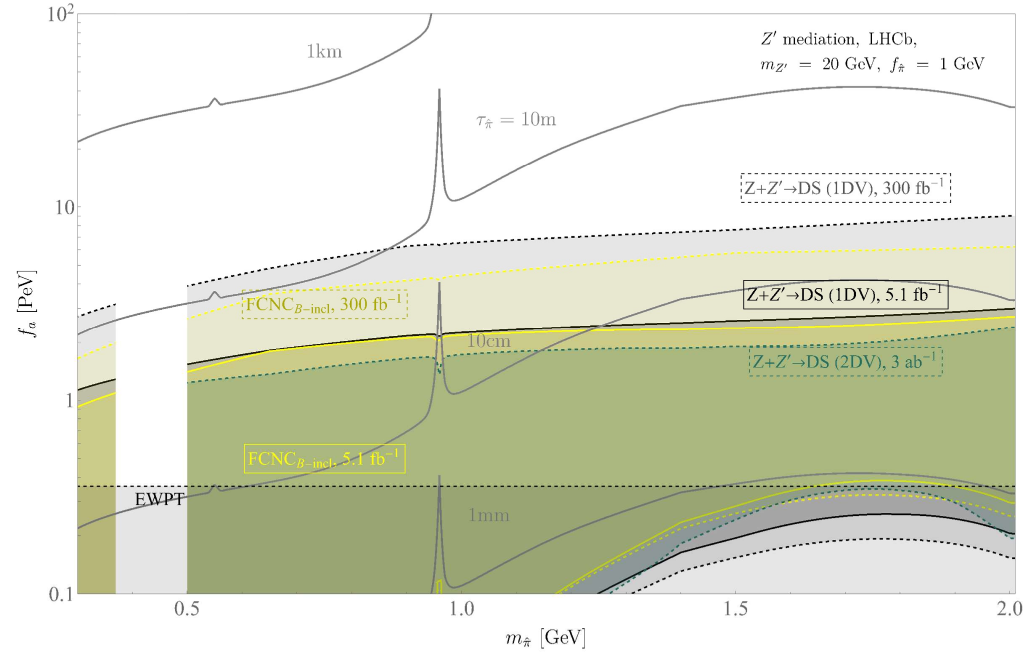



HL-LHC Projections
FASER 2, Inclusive B Decays
FASER 2, Exclusive B Decays
LHCb Dark Shower (Future)
CMS Dark Shower
(Future)
Preliminary
1km
$\tau_{\hat{\pi}} = 10$m
10cm
1mm
f_a [PeV]
$m_{\hat{\pi}}$ [GeV]
10^2
10
1
0.1
0.5
1.0
1.5
2.0

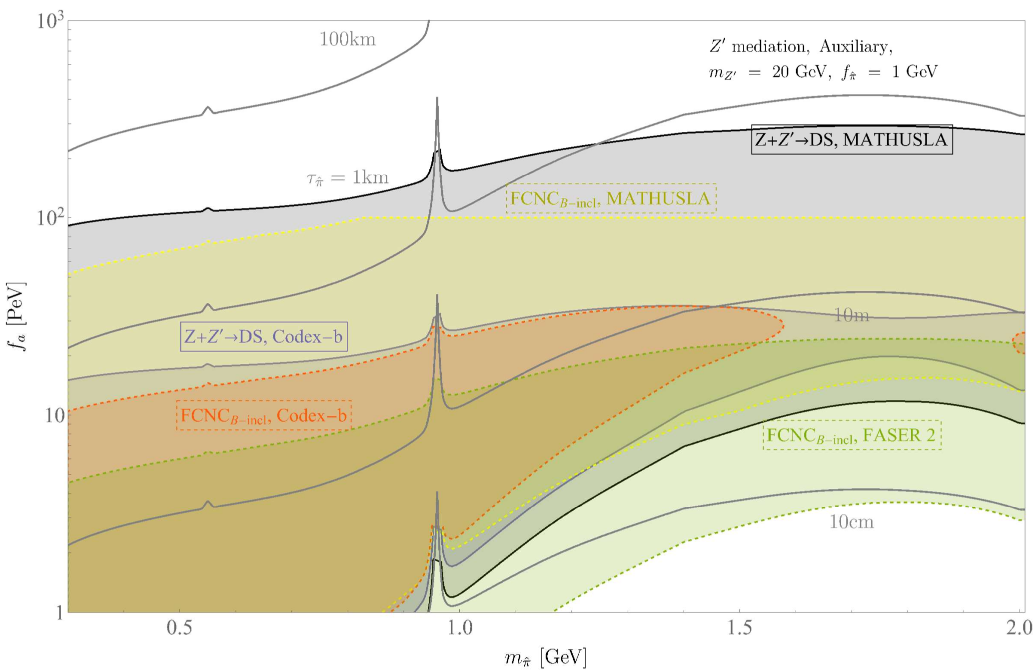
A Lot More...



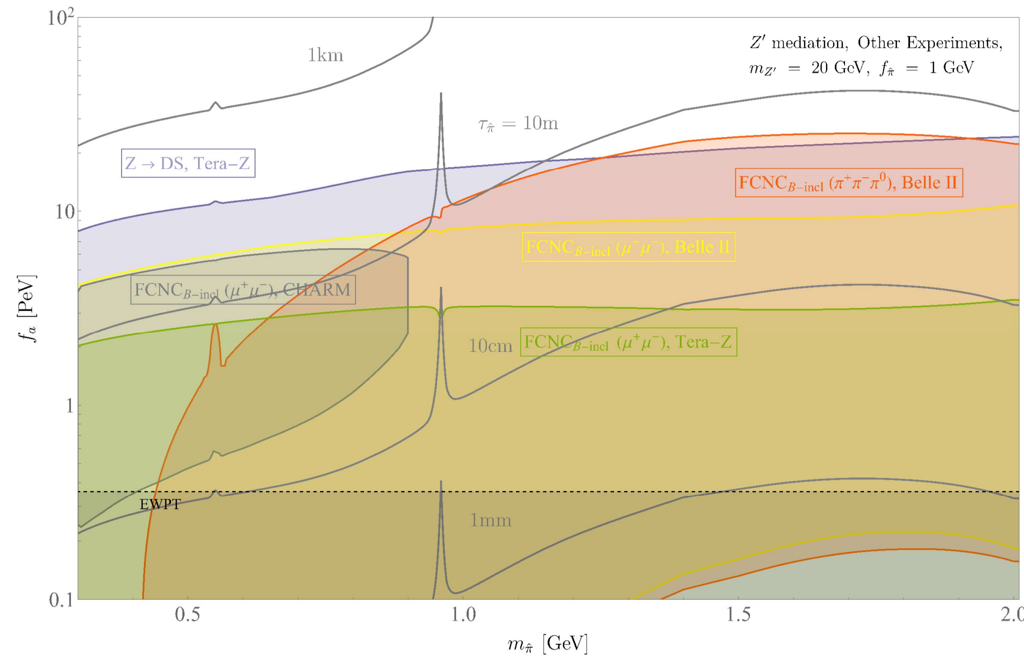
Z' mediation, CMS Scouting,
$m_{Z'}$ = 20 GeV, $f_{\hat{\pi}}$ = 1 GeV
1km
$\tau_{\hat{\pi}}$ = 10m
10cm
1mm
Z+Z'→DS (1DV), 3 ab^{-1}
FCNC$_{B\text{-incl}}$, 3 ab^{-1}
Z+Z'→DS (1DV), 101 fb^{-1}
FCNC$_{B\text{-incl}}$, 101 fb^{-1}
Z+Z'→DS (2DV), 3 ab^{-1}
EWPT
f_a [PeV]
$m_{\hat{\pi}}$ [GeV]



Z' mediation, LHCb,
$m_{Z'}$ = 20 GeV, $f_{\hat{\pi}}$ = 1 GeV
1km
$\tau_{\hat{\pi}}$ = 10m
10cm
1mm
Z+Z'→DS (1DV), 300 fb^{-1}
FCNC$_{B\text{-incl}}$, 300 fb^{-1}
Z+Z'→DS (1DV), 5.1 fb^{-1}
Z+Z'→DS (2DV), 3 ab^{-1}
FCNC$_{B\text{-incl}}$, 5.1 fb^{-1}
EWPT
f_a [PeV]
$m_{\hat{\pi}}$ [GeV]



Z' mediation, Auxiliary,
$m_{Z'}$ = 20 GeV, $f_{\hat{\pi}}$ = 1 GeV
100km
$\tau_{\hat{\pi}}$ = 1km
10m
10cm
Z+Z'→DS, MATHUSLA
FCNC$_{B\text{-incl}}$, MATHUSLA
Z+Z'→DS, Codex−b
FCNC$_{B\text{-incl}}$, Codex−b
FCNC$_{B\text{-incl}}$, FASER 2
f_a [PeV]
$m_{\hat{\pi}}$ [GeV]



Z' mediation, Other Experiments,
$m_{Z'}$ = 20 GeV, $f_{\hat{\pi}}$ = 1 GeV
1km
$\tau_{\hat{\pi}}$ = 10m
10cm
1mm
Z → DS, Tera−Z
FCNC$_{B\text{-incl}}$ ($\pi^+\pi^-\pi^0$), Belle II
FCNC$_{B\text{-incl}}$ ($\mu^+\mu^-$), Belle II
FCNC$_{B\text{-incl}}$ ($\mu^+\mu^-$), CHARM
FCNC$_{B\text{-incl}}$ ($\mu^+\mu^-$), Tera−Z
EWPT
f_a [PeV]
$m_{\hat{\pi}}$ [GeV]

Summary

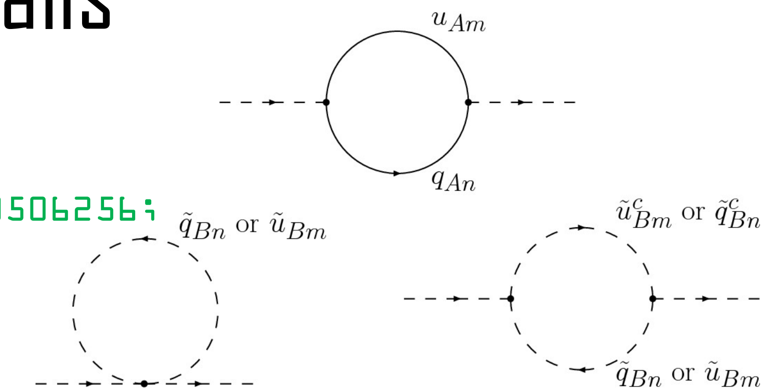
- EW portal to the dark is a generic feature we can and should search for now
- Two classes of underlying theories: doublet fermion and light Z' portal
- Dark pions make LLP, generated by dark shower
- A lot of limits are casted for now and future
- FCNC decays offer complementary probes, good target for future LLP detectors

Backup Slides

The Dark Force for Confinement

- Neutral naturalness calls for a non-QCD color

Z. Chacko, H.-S. Goh, and R. Harnik, 0506256;
G. Burdman, Z. Chacko, H.S. Goh and R. Harnik, 0609152;
H-C. Cheng, LL, E. Salvioni, and C. Verhaaren, 1803.03561



- Makes good dark matter candidate

Y. Hochberg, E. Kuflik, H. Murayama, T. Volansky, J. Wacker, 1411. 3727;
A.Katz, E. Salvioni, and B. B. Shakya, 2006.15148;
H-C. Cheng, X. Jiang, LL, E. Salvioni, In Prep.

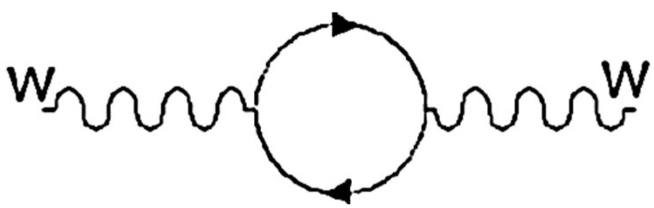
P. Schwaller, D. Stolarski, A. Weiler, 1502.05409;
CMS, 1810.10069;
S. Knapen, J. Shelton, D. Xu, 2103.01238;
S. Born, R. Karur, S. Knapen, J. Shelton, 2303.04167;
J. Carrosco, J. Zirita, 2307.04847

- Rich collider phenomeonolgy

Indirect/Precision Constraints

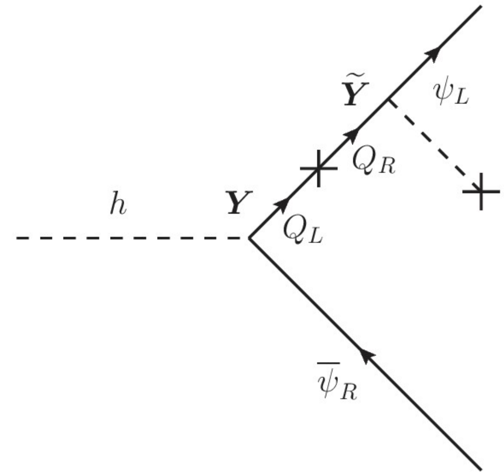
$$M \gtrsim 0.9\,\text{TeV}\; Y^2 \left(\frac{N_d N}{6}\right)^{1/2}$$

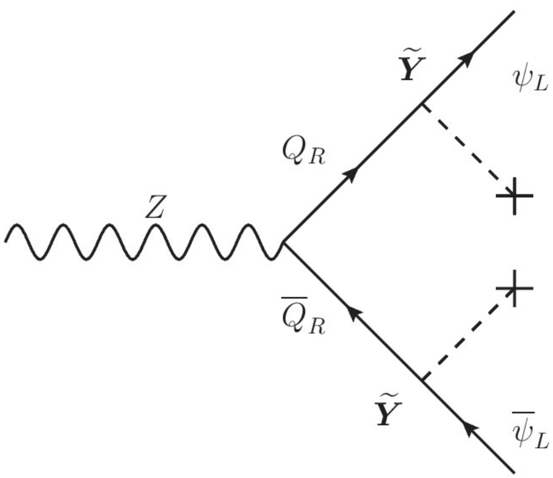
From EW oblique parameter T < O(10^{-3})



$$M \gtrsim 0.4\ \text{TeV} \left(\frac{N_d \text{Tr}(\mathbf{Y}\mathbf{Y}^\dagger \widetilde{\mathbf{Y}}\widetilde{\mathbf{Y}}^\dagger)}{3\times 10^{-4}}\right)^{1/2}$$

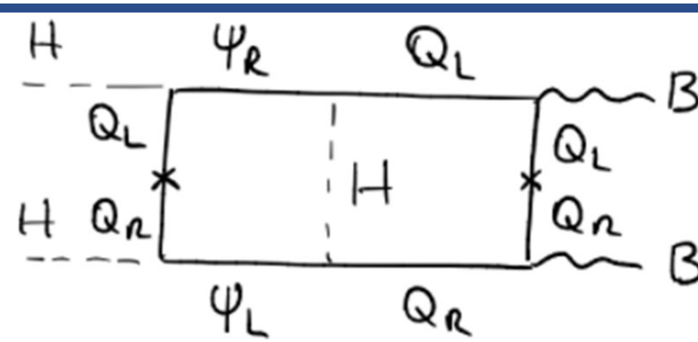
From Higgs invisible decay BR < 13%





$$M \gtrsim 0.8\,\text{TeV}\; Y \left(\frac{N_d N}{6}\right)^{1/4}$$

From Z invisible decay width <~2 MeV

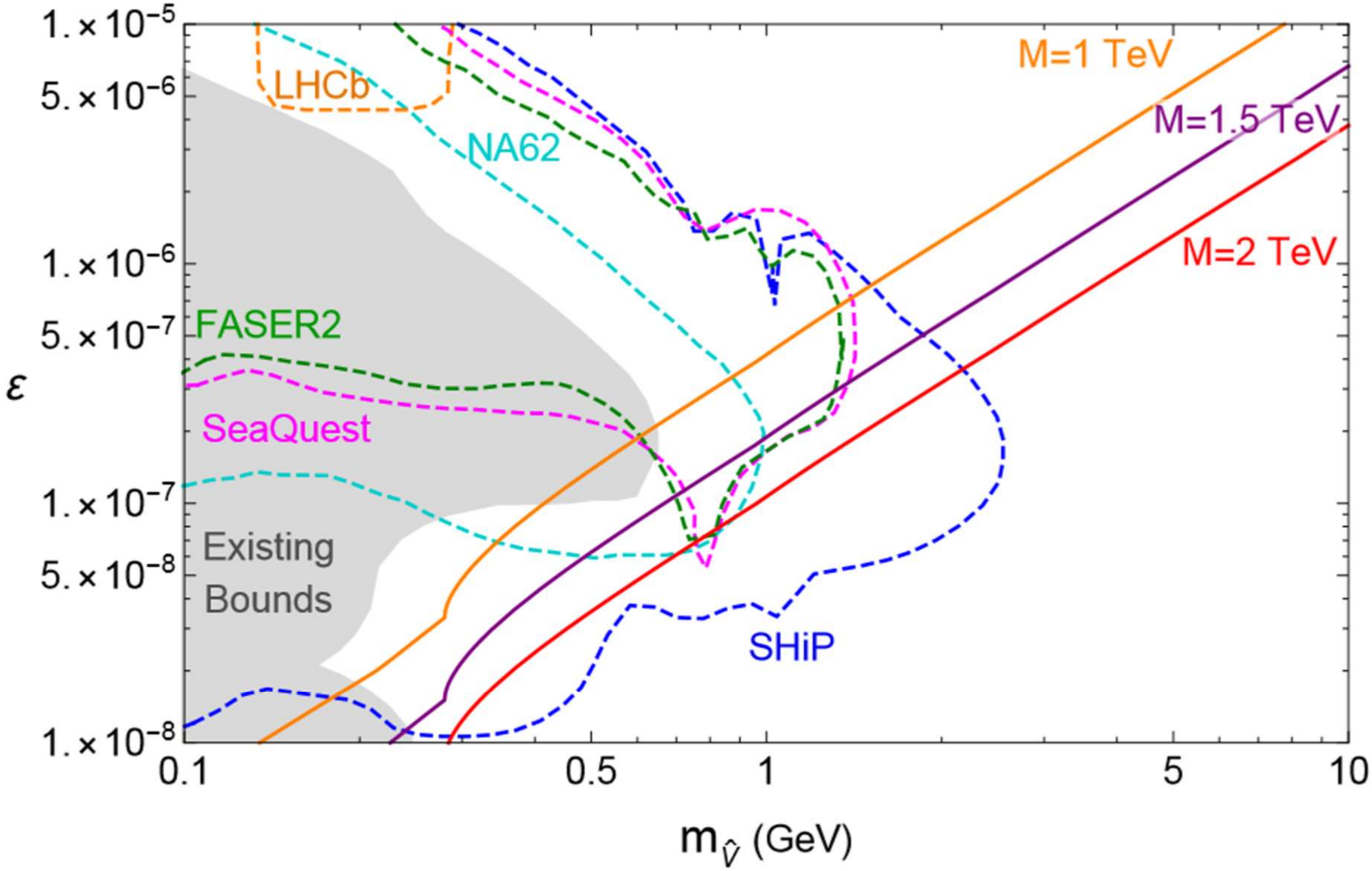


$$M \gtrsim 1.5\ \text{TeV}\ \ Y\widetilde{Y}$$

From electron EDM

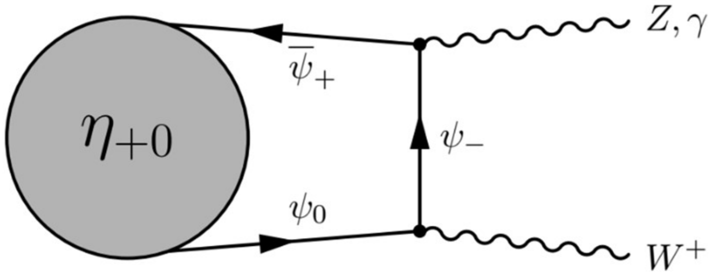
if CP is violated maximally

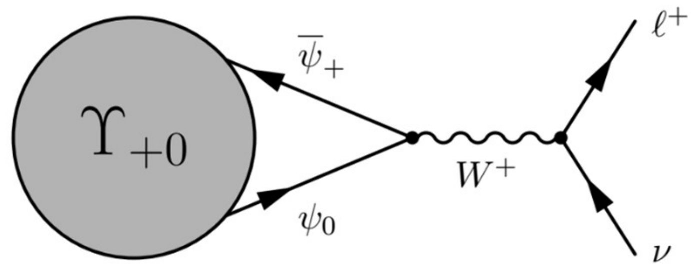
Dark Photon Mode of Production



$$\varepsilon_{\rm eff} \sim \frac{1}{2}\sqrt{\frac{\alpha_Z}{\alpha}}\,\varepsilon_Z \approx 3.8\times 10^{-7}\left(\frac{\Lambda}{1\,{\rm GeV}}\right)^{3/2}\left(\frac{m_{\hat{V}}}{2\,{\rm GeV}}\right)^{1/2}\left(\frac{2\,{\rm TeV}}{M}\right)^{2}$$

Phenomenology (Original TT)

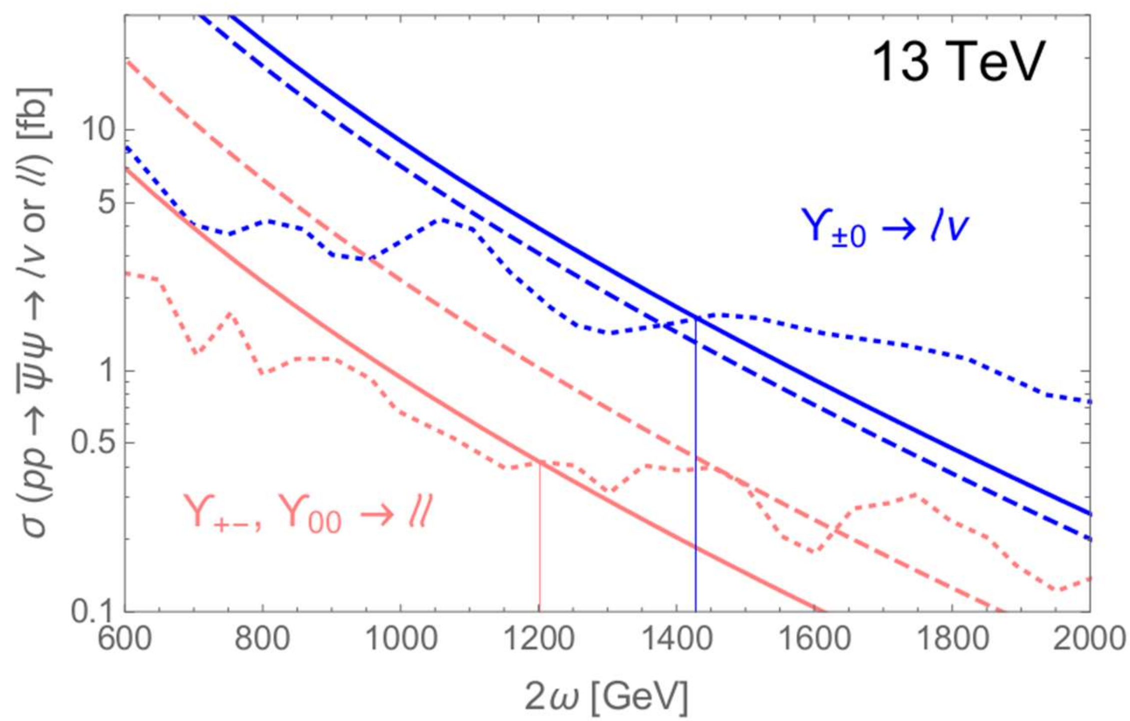




- Quirky bound states
- de-excite and annihilate e

The two leading channels are just dilepton (Z'- like) and lepton+MET (W' -like).

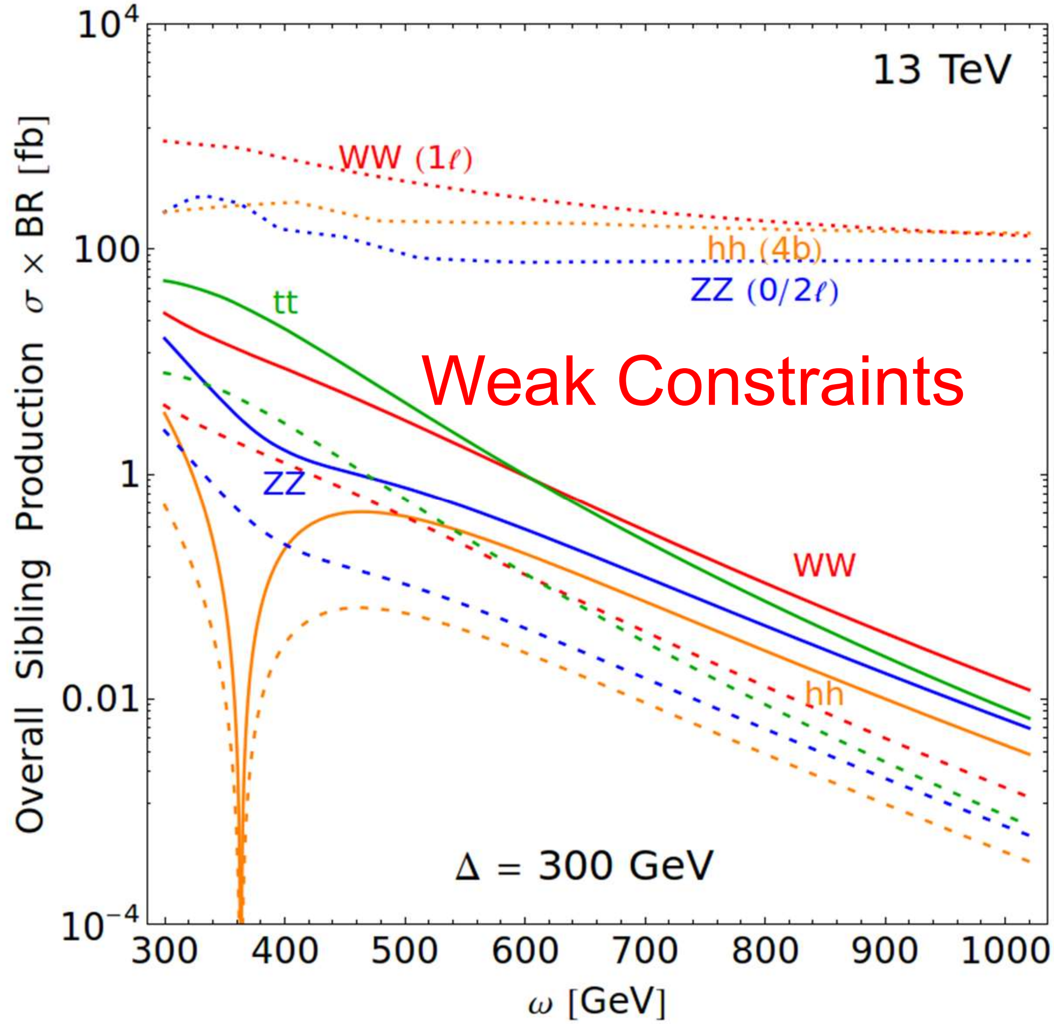
Strong constraints (~700 GeV) on ω



Phenomenology (Original TT)

Neutral sfermion:
(superpartner, SU(2) singlet, mass~Δ.

Pair produced (as bound states) from fermion pair decays when $\Delta < \omega$



Exotic BR of Z

- As a vector, Z couple to both LL and RR, but RR dominates for larger mixing:

$$\frac{g_Z}{2}\sin^2\theta_R\,\overline{\psi}_{BR}\gamma^\mu\psi_{BR}Z_\mu \simeq \frac{g_Z}{2}\frac{m_t^2}{M^2+m_t^2}\overline{\psi}_{BR}\gamma^\mu\psi_{BR}Z_\mu$$

- Introduces exotic BR(Z) that's controlled by M only (PS not included)

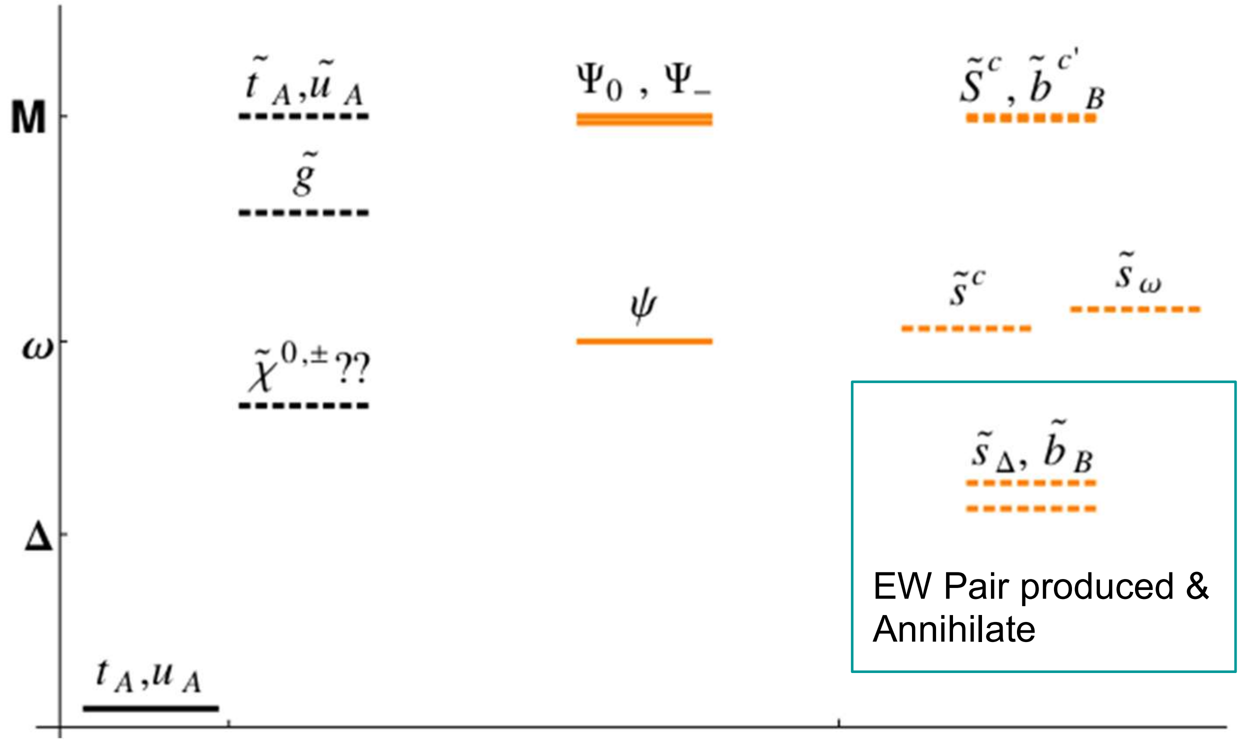
$$\Gamma(Z\to\overline{\psi}_B\psi_B)\simeq\frac{N_d\,g_Z^2}{96\pi}\frac{m_t^4}{(M^2+m_t^2)^2}m_Z\left(1-\frac{m_\psi^2}{m_Z^2}\right)\sqrt{1-\frac{4m_\psi^2}{m_Z^2}}$$

$$\mathrm{BR}(Z\to\overline{\psi}_{B,C}\psi_{B,C})\approx 2.2\times10^{-5}\left(\frac{2\,\mathrm{TeV}}{M}\right)^4.$$

- Exotic BR of h is not large (<~O(10^{-4})), the constraints are weaker than those from Z decays (~10^3 more Z than h at LHC)

A Cartoon of Revised TT Model: The not So Interesting Case

It could be just like this (when Δ < ω):



Nothing (very) interesting happens

The constraints are similar to the previous case, too weak in general

Soft SUSY Breaking Terms

$$m_{ij}^2 = m_{P_i}^2 + m_{\overline{P}_j}^2 - \frac{2}{b} \sum_k T_{r_k} \left(m_{P_k}^2 + m_{\overline{P}_k}^2 \right)$$

$$\begin{array}{c|c} & \widetilde{m}_P^2 \; \widetilde{m}_P^2 \; \widetilde{m}_P^2 \\ \begin{array}{c} \widetilde{m}_{\overline{P}_2}^2 \\ \widetilde{m}_{\overline{P}_2}^2 \\ \widetilde{m}_{\overline{P}_1}^2 \end{array} & \left(\begin{array}{c} Q_A \\ \hline \\ \end{array} \right) \end{array} \qquad \begin{array}{c|c} & \widetilde{m}_P^2 \; \widetilde{m}_P^2 \; \widetilde{m}_P^2 \\ \begin{array}{c} \widetilde{m}_{\overline{P}}^2 \\ \widetilde{m}_{\overline{P}}^2 \\ \widetilde{m}_{\overline{P}}^2 \end{array} & \left(\begin{array}{c} Q_{B,C} \\ \hline \\ \end{array} \right) \end{array}$$

$$\begin{array}{c|c} & \widetilde{m}_P^2 \; \widetilde{m}_P^2 \; \widetilde{m}_P^2 \\ \begin{array}{c} \widetilde{m}_{\overline{P}_2}^2 \\ \widetilde{m}_{\overline{P}_2}^2 \\ \widetilde{m}_{\overline{P}_1}^2 \end{array} & \left(\begin{array}{c} u_A^c \\ \hline \\ \\ \end{array} \right) \end{array} \qquad \begin{array}{c|c} & \widetilde{m}_P^2 \; \widetilde{m}_P^2 \; \widetilde{m}_P^2 \\ \begin{array}{c} \widetilde{m}_{\overline{P}_1}^2 \\ \widetilde{m}_{\overline{P}_1}^2 \\ \widetilde{m}_{\overline{P}_2}^2 \end{array} & \left(\begin{array}{c} u_{B,C}^c \\ \hline \\ \\ \end{array} \right) \end{array}$$

Soft SUSY Breaking Terms

$$\widetilde{m}^2_{Q_{B,C}} = \widetilde{m}^2_P + \widetilde{m}^2_{\overline{P}} - \widetilde{m}^2_P - \widetilde{m}^2_{\overline{P}} = 0,$$

$$\widetilde{m}^2_{u^c_{B,C}} = \widetilde{m}^2_P + \widetilde{m}^2_{\overline{P}_1} - \widetilde{m}^2_P - \frac{2}{3}\widetilde{m}^2_{\overline{P}_1} - \frac{1}{3}\widetilde{m}^2_{\overline{P}_2} = \frac{\widetilde{m}^2_{\overline{P}_1} - \widetilde{m}^2_{\overline{P}_2}}{3},$$

$$\widetilde{m}^2_{Q_A,u^c_A} = \widetilde{m}^2_P + \widetilde{m}^2_{\overline{P}_2} - \widetilde{m}^2_P - \frac{2}{3}\widetilde{m}^2_{\overline{P}_2} - \frac{1}{3}\widetilde{m}^2_{\overline{P}_1} = \frac{\widetilde{m}^2_{\overline{P}_2} - \widetilde{m}^2_{\overline{P}_1}}{3} = -\,\widetilde{m}^2_{u^c_{B,C}}$$

Hidden Glueballs

- $\Lambda_{B/C} \gtrsim 5$ GeV $\Rightarrow$ lightest hidden glueball (0^{++}) mass $\gtrsim 35$ GeV.
- 0^{++} hidden glueball's decay is similar to fraternal twin Higgs (FTH) or Folded SUSY, via mixing with the SM Higgs.

Long-Lived Compared to Similar Models

$$c\tau_{0^{++}} \sim 1.2\,\mathrm{m}\left(\frac{5\,\mathrm{GeV}}{\Lambda_{\mathrm{QCD}_{B,C}}}\right)^7\left(\frac{\omega}{500\,\mathrm{GeV}}\right)^4\left(\frac{\Delta}{300\,\mathrm{GeV}}\right)^4\left(\frac{100\,\mathrm{GeV}}{\delta m}\right)^4. \tag{3}$$

- Suppressed $h \rightarrow$ hidden glueball branching ratio.

Higgs Potential

$$V_{h^2} = -\frac{N_c y_t^2 h^2}{8\pi^2}\left[-\left(M^2-\Delta^2\right)\ln\left(1-\frac{\Delta^2}{M^2}\right)-\frac{\Delta^4}{\omega^2-\Delta^2}\ln\frac{M^2}{\Delta^2}\right.$$
$$\left.+\frac{\omega^4(M^2-\Delta^2)}{(M^2-\omega^2)(\omega^2-\Delta^2)}\ln\frac{M^2}{\omega^2}\right]$$

$\sim \omega^2 \ln M^2 /(16\pi^2)$ when $\Delta \to 0$

$$\approx -\frac{N_c y_t^2 h^2}{8\pi^2}\left[\frac{\omega^4}{\omega^2-\Delta^2}\ln\frac{M^2}{\omega^2}-\frac{\Delta^4}{\omega^2-\Delta^2}\ln\frac{M^2}{\Delta^2}+\Delta^2\right]+O\left(M^{-2}\right)$$

$$V_{h^4} = \frac{N_c y_t^4 h^4}{16\pi^2}\left\{\frac{3}{2}+\frac{2\omega^2(M^2-\Delta^2)(M^2\Delta^2-\omega^4)}{(M^2-\omega^2)^2(\omega^2-\Delta^2)^2}+\ln\frac{M^2}{y_t^2h^2}+\ln\left(1-\frac{\Delta^2}{M^2}\right)\right.$$
$$\left.+\frac{\Delta^4(\Delta^2-3\omega^2)}{(\omega^2-\Delta^2)^3}\ln\frac{M^2}{\Delta^2}-\left[\frac{\omega^4(\omega^2-3M^2)}{(M^2-\omega^2)^3}+\frac{\omega^4(\omega^2-3\Delta^2)}{(\omega^2-\Delta^2)^3}\right]\ln\frac{M^2}{\omega^2}\right\}$$

$$\approx \frac{N_c y_t^4 h^4}{16\pi^2}\left\{\frac{3}{2}+\frac{2\omega^2\Delta^2}{(\omega^2-\Delta^2)^2}+\ln\frac{M^2}{y_t^2h^2}+\frac{\Delta^4(\Delta^2-3\omega^2)}{(\omega^2-\Delta^2)^3}\ln\frac{M^2}{\Delta^2}\right.$$
$$\left.-\frac{\omega^4(\omega^2-3\Delta^2)}{(\omega^2-\Delta^2)^3}\ln\frac{M^2}{\omega^2}\right\}+O(M^{-2}).$$

$\sim (4.5\, m_t^4+3 \ln \omega^2 /m_t^2)/(16\pi^2)$ when $\Delta \to 0$

Hidden Quark Mixing Angles

Fermion mass matrix: $-\begin{pmatrix} u'_B & t_B \end{pmatrix} \mathcal{M} \begin{pmatrix} u^c_B \\ t'^c_B \end{pmatrix}$ $\quad \mathcal{M} = \begin{pmatrix} \omega & 0 \\ y_t h & M \end{pmatrix}$

ω – M mixing

$$\begin{pmatrix} u'_B \\ t_B \end{pmatrix} \to R(\theta_L) \begin{pmatrix} U'_B \\ T_B \end{pmatrix}, \qquad \begin{pmatrix} u^c_B \\ t'^c_B \end{pmatrix} \to R(\theta_R) \begin{pmatrix} U^c_B \\ T'^c_B \end{pmatrix}, \qquad R(\theta) \equiv \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Left/ Right handed components gets very different mixing angle:

$$\sin\theta_L = \frac{m_\psi}{M} \sin\theta_R \simeq \frac{\omega y_t h}{M^2 + y_t^2 h^2}, \qquad \sin\theta_R \simeq \frac{y_t h}{\sqrt{M^2 + y_t^2 h^2}}$$

Both L/R component get EW interaction via mixing with M states

Will introduce substantial difference between h and Z decay

Exotic BR of h

- The scalar higgs couple to LR, therefore decay suppressed by the small $\sin\theta_L$:

$$\frac{y_t}{\sqrt{2}} \sin\theta_L \cos\theta_R \, h \, \overline{\psi}_B \psi_B \simeq \frac{y_t}{\sqrt{2}} \frac{\widetilde{\Lambda} \, m_t M}{(M^2 + m_t^2)^{3/2}} \, h \, \overline{\psi}_B \psi_B$$

- Relatively unimportant due to the suppression and rate (~10^3 times more Z than h @14TeV)

$$\Gamma(h \to \overline{\psi}_B \psi_B) \simeq \frac{N_d y_t^2}{16\pi} \frac{\omega^2 \, m_t^2 M^2}{(M^2 + m_t^2)^3} \, m_h \left(1 - \frac{4 m_\psi^2}{m_h^2}\right)^{3/2} .$$

$$\mathrm{BR}(h \to \overline{\psi}_{B,C} \psi_{B,C}) \approx 1.6 \times 10^{-6} \left(\frac{\omega}{0.5\,\mathrm{GeV}}\right)^2 \left(\frac{2\,\mathrm{TeV}}{M}\right)^4$$

$$\mathrm{BR}(h \to g_{B,C} g_{B,C}) \approx 1.8 \times 10^{-4} \left(\frac{\alpha_d}{0.17}\right)^2 \left(\frac{2\,\mathrm{TeV}}{M}\right)^4 \left(\frac{c}{4}\right)^2$$

Meson Decay Lifetime

$$\Gamma(\hat{V} \to f\bar{f}) = N_d N_c^f \frac{\pi\alpha_Z^2}{12} \frac{m_t^4}{(M^2+m_t^2)^2} \frac{m_{\hat{V}}^2 |\psi(0)|^2}{m_Z^4} \frac{\left(1-\frac{4m_f^2}{m_{\hat{V}}^2}\right)^{1/2}}{\left(1-\frac{m_{\hat{V}}^2}{m_Z^2}\right)^2} \left[v_f^2\left(1+\frac{2m_f^2}{m_{\hat{V}}^2}\right)+a_f^2\left(1-\frac{4m_f^2}{m_{\hat{V}}^2}\right)\right]$$

$$c\tau_{\hat{V}} \sim 0.02\ \text{mm}\ \left(\frac{10\ \text{GeV}}{m_{\hat{V}}}\right)^2 \left(\frac{5\ \text{GeV}}{\Lambda}\right)^3 \left(\frac{M}{2\ \text{TeV}}\right)^4$$

$$\Gamma(\hat{P} \to f\bar{f}) = N_d N_c(f)\, 2\pi\alpha_Z^2 \frac{m_t^4}{(M^2+m_t^2)^2}\, a_f^2\, \frac{\mu_\psi^2 m_f^2}{m_Z^4} \frac{|\psi(0)|^2}{m_{\hat{P}}^2} \left(1-\frac{4m_f^2}{m_{\hat{P}}^2}\right)^{1/2}$$

$$c\tau_{\hat{P}} \sim 0.3\,\text{mm}\ \left(\frac{m_{\hat{P}}}{10\ \text{GeV}}\right)^2 \left(\frac{5\ \text{GeV}}{\Lambda}\right)^5 \left(\frac{\Lambda}{\mu_\psi}\right)^2 \left(\frac{M}{2\ \text{TeV}}\right)^4$$

$$\Gamma(\hat{S} \to \hat{V} f\bar{f}\,) \sim \frac{\alpha_Z^2 \sin^4\theta_R N_f}{16\pi} \frac{k^7}{m_Z^4} |\varepsilon_{if}|^2$$

$$c\tau_{\hat{S}} \sim 0.1\,\text{mm}\ \left(\frac{5\ \text{GeV}}{\Lambda}\right)^5 \left(\frac{\Lambda}{k}\right)^7 \left(\frac{M}{2\ \text{TeV}}\right)^4$$

2 Body Limit

Leading BR: Z → PS: $\hat{g}_Z Z_\mu (\hat{S}\,\partial^\mu \hat{P} - \hat{P}\,\partial^\mu \hat{S})$

Subleading BR: Z → VS, VP, VV

$$c_{\hat{V}\hat{S}(\hat{P})} \hat{g}_Z \mu_\psi \, Z_\mu \hat{V}^\mu \hat{S}\,(\hat{P})$$

$$c_{\hat{V}\hat{V}} \hat{g}_Z (m_{\hat{V}}^2 / m_Z^2)\, \epsilon^{\mu\nu\rho\sigma} Z_\mu \hat{V}_\nu \partial_\rho \hat{V}_\sigma$$

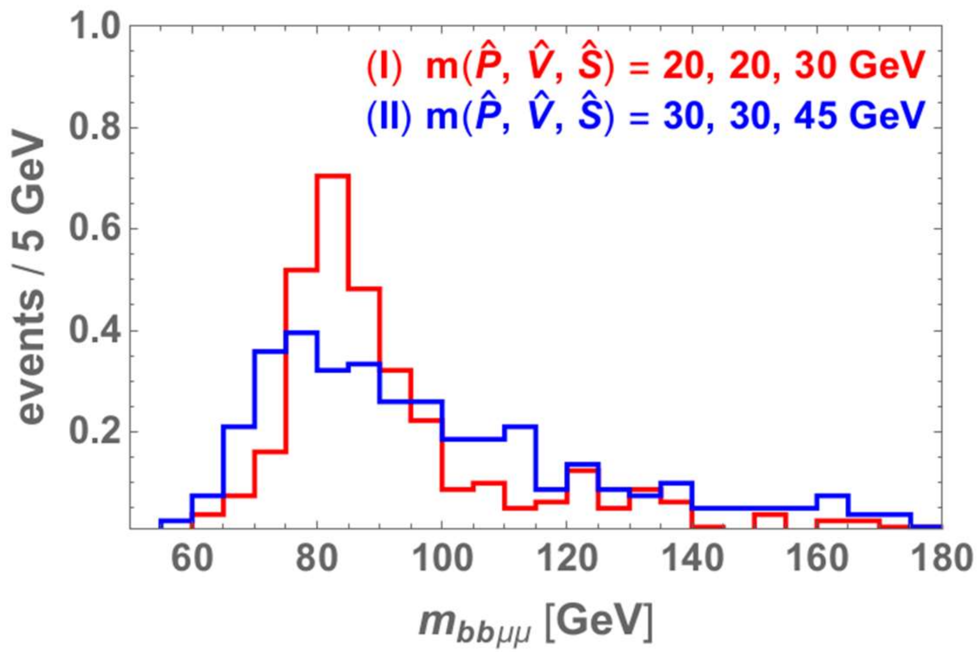
Suppressed by ~ meson mass/m_Z

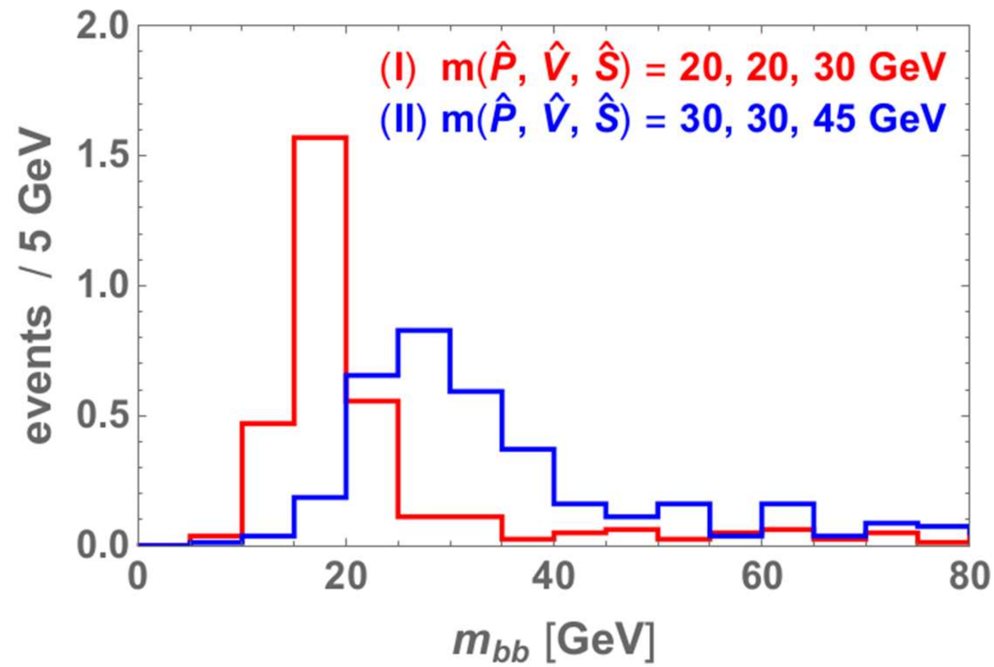
Define f_{XY} = BR(Z/h→XY)/BR(Z/h→ψψ)< 1

See also : [J. Liu, L.-T. Wang, X.-P. Wang, and W. Xue, 1712.07237]

- Since we focus mostly on LHC, need leptons (from V decay) as the trigger.

Prompt Limit – Z→bbμμ+X





$$Z \to (\hat{P} \to b\bar{b})(\hat{S} \to \hat{V} f \bar{f} \to \mu\mu f \bar{f})$$

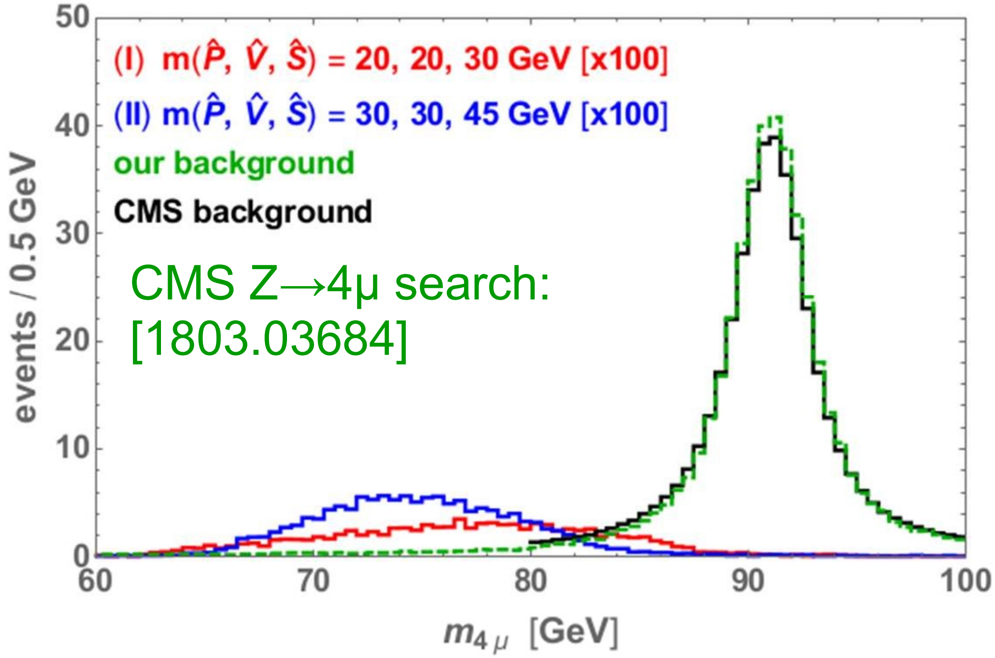
The analysis is similar to h→aa→b̄bμμ with similar cuts.
[CMS Collaboration, 1812.06359]

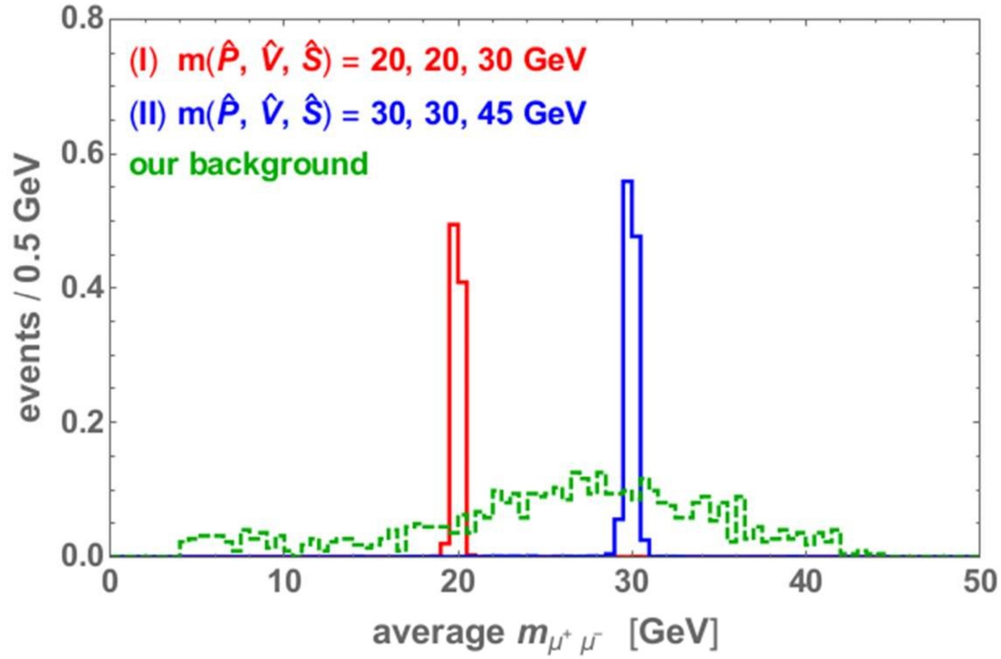
$$\text{(I)} \quad M \gtrsim 1.1,\ 1.4,\ 2.0\ \text{TeV} \left(\frac{f_{\hat{P}\hat{S}}}{1}\right)^{1/4}$$

$$\text{(II)} \quad M \gtrsim 1.0,\ 1.3,\ 1.7\ \text{TeV} \left(\frac{f_{\hat{P}\hat{S}}}{1}\right)^{1/4}$$

Correspond to 35.9, 300, 3000 fb^{-1}

Prompt Limit – Z→4 lep+(X)





$$Z \to (\hat{V} \to \ell\ell)(\hat{S} \to \hat{V} f \bar{f} \to \ell'\ell' f \bar{f})$$

$$\text{(I)} \quad M \gtrsim 1.5,\ 2.0,\ 3.2\ \text{TeV} \left(\frac{f_{\hat{V}\hat{S}}}{0.1}\right)^{1/4}$$

$$\text{(II)} \quad M \gtrsim 1.5,\ 2.1,\ 3.2\ \text{TeV} \left(\frac{f_{\hat{V}\hat{S}}}{0.1}\right)^{1/4}$$

$$Z \to (\hat{V} \to \ell\ell)(\hat{V} \to \ell'\ell')$$

$$\text{(I)} \quad M \gtrsim 1.6,\ 2.2,\ 3.3\ \text{TeV} \left(\frac{f_{\hat{V}\hat{V}}}{0.1}\right)^{1/4}$$

$$\text{(II)} \quad M \gtrsim 1.6,\ 2.1,\ 3.1\ \text{TeV} \left(\frac{f_{\hat{V}\hat{V}}}{0.1}\right)^{1/4}$$

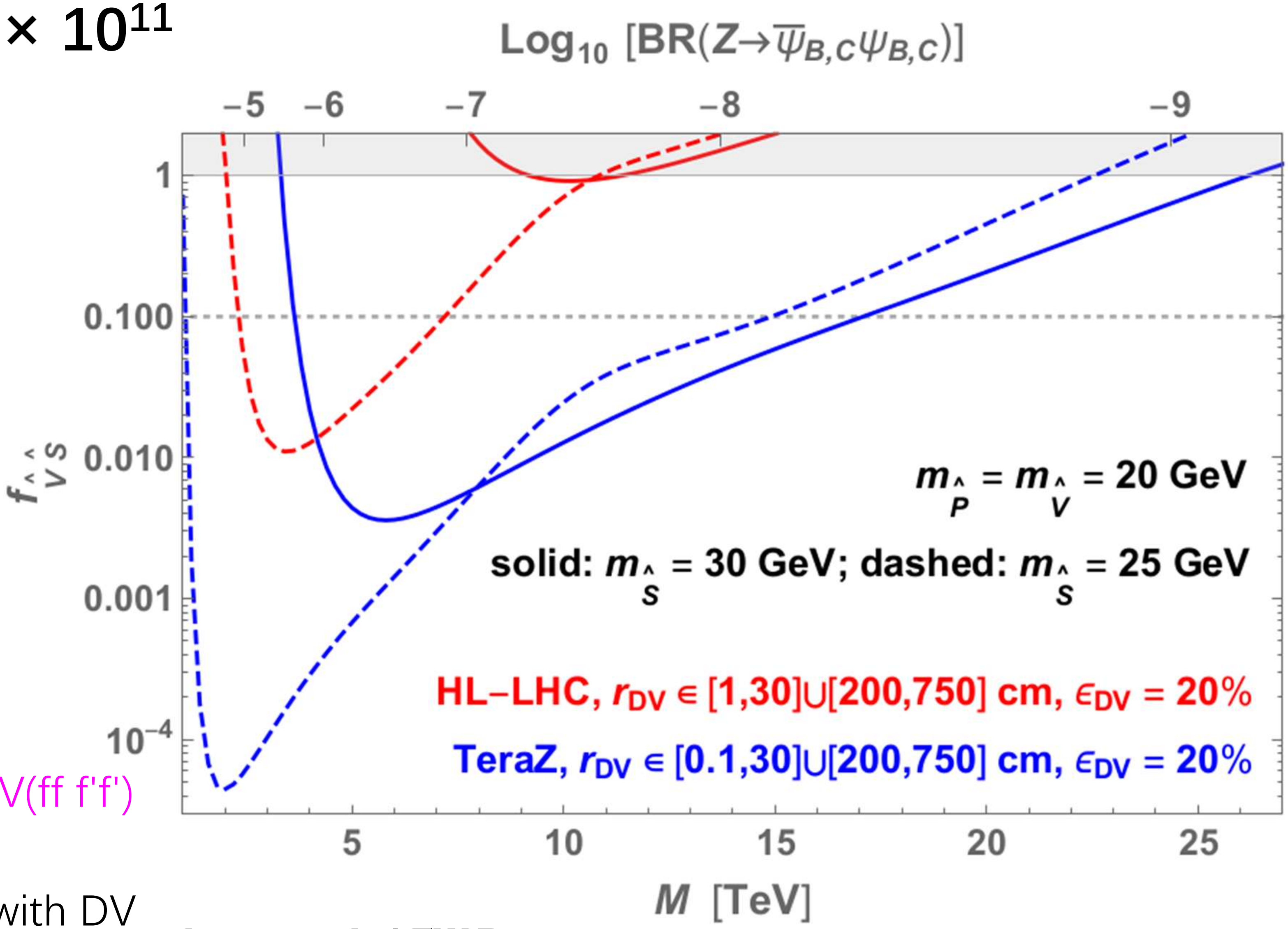
Correspond to 77.3, 300, 3000 fb^{-1}

2 Body Limit: Displaced S decays

HL-LHC: ~1.8 × 10^{11} Z produced

Tera-Z: 10^{12} Z

The hidden hadronization fraction

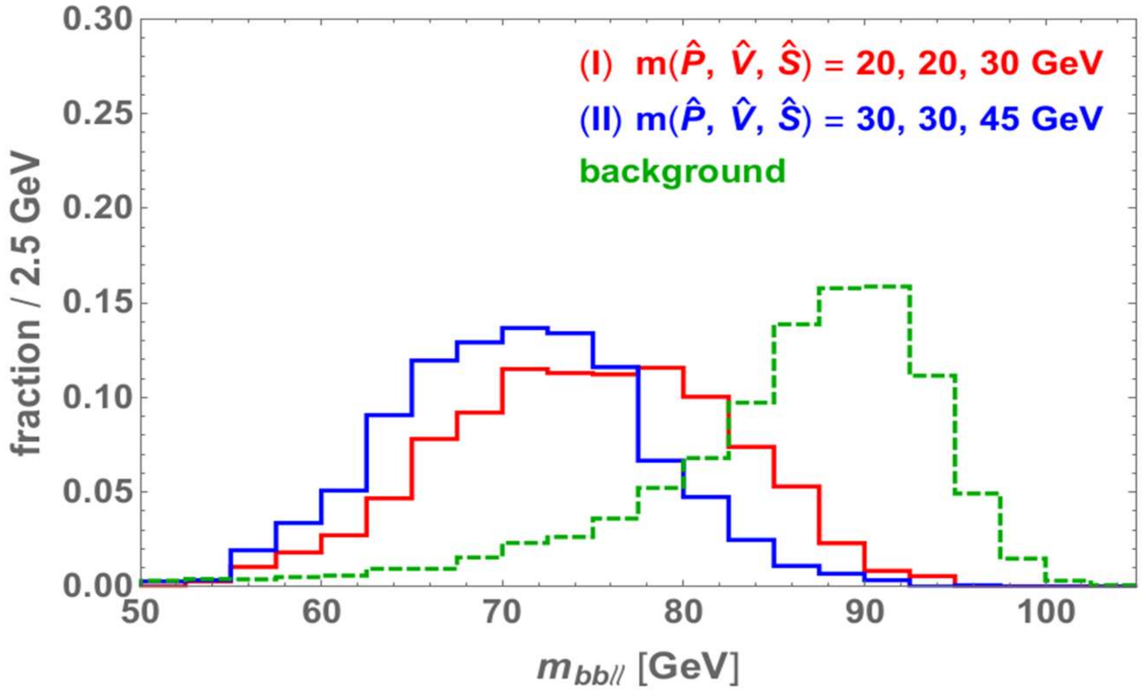


Z → VS → μμ+DV(ff V) →μμ+DV(ff f'f')

Di-muon triggering with DV
-> negligible SM backgrounds

Prospects @ Z Factories

Z factories can provide 10^9 (Giga Z) – 10^{12} (Tera Z) clean Z at Z pole:
Can probe exotic BR(Z) down to O(10^{-8}) (Giga Z) and O(10^{-10}) (Tera Z)



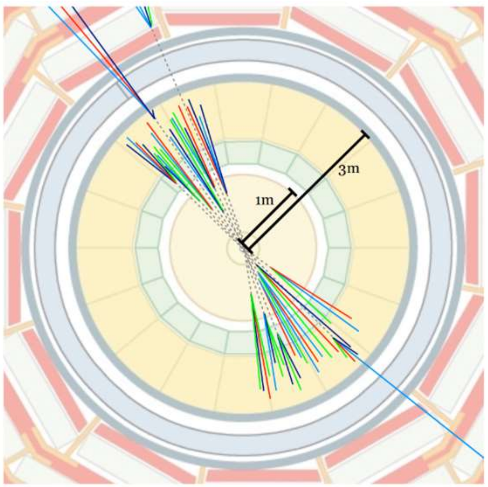
- Better resolution
- Better b tagging
- Lower jet threshold

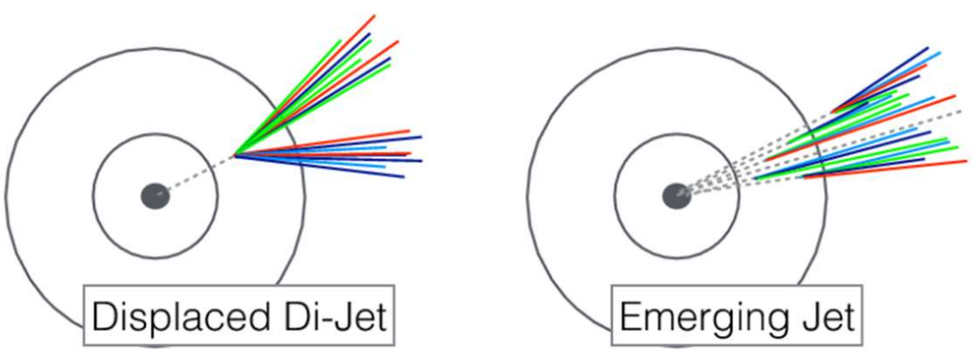
In terms of M: constrain M >~ 5 TeV @ Giga Z

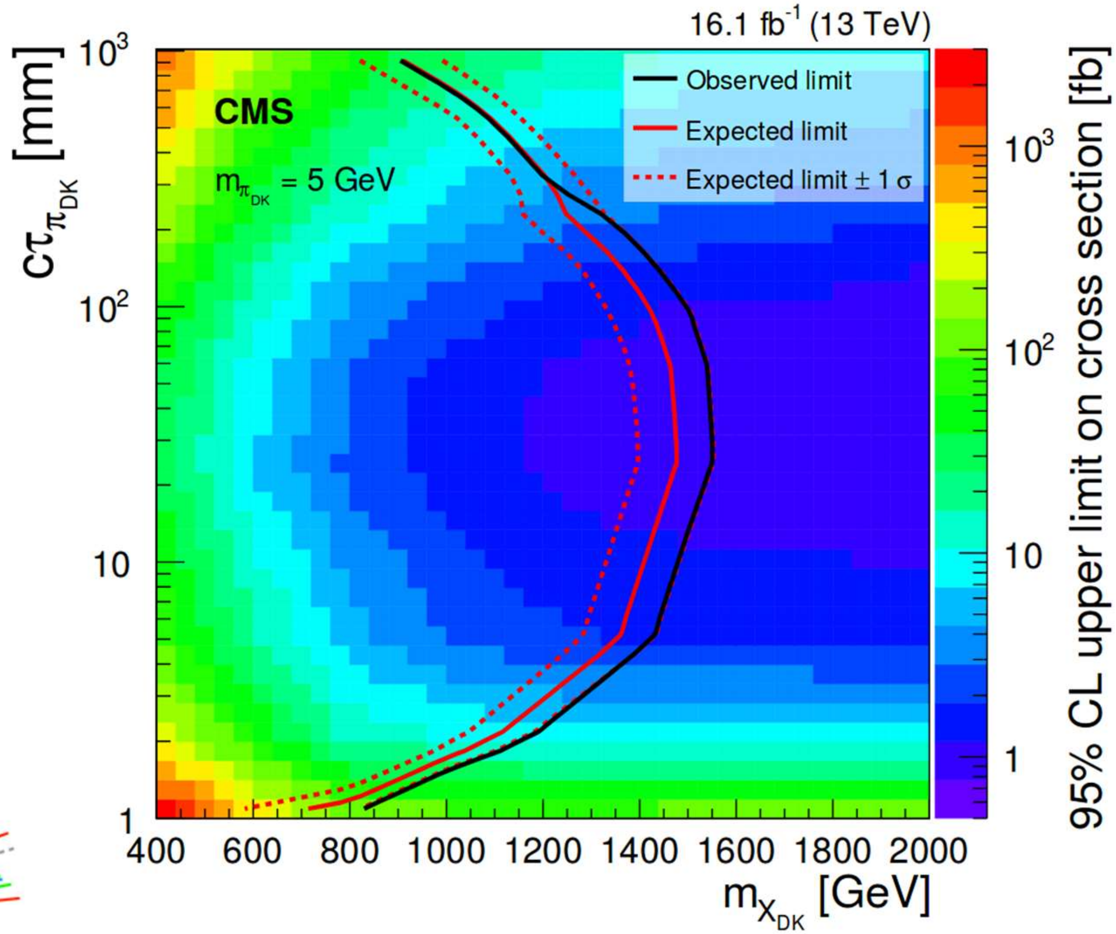
For Tera Z: Need to consider displaced effects

Manybody Limit – Emerging Jets

[P. Schwaller, D. Stolarski and A. Weiler, 1502.05409]



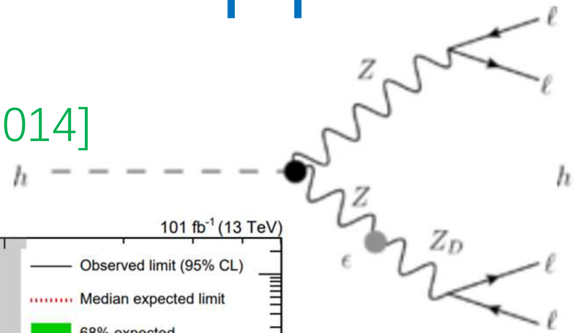


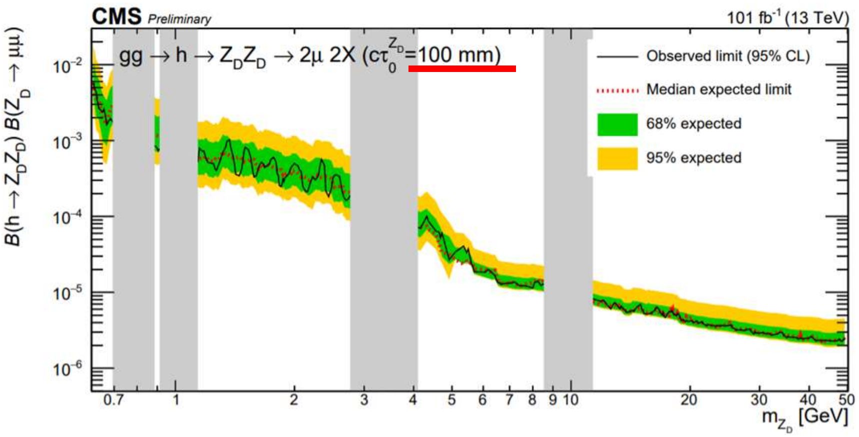


[CMS Collaboration, 1810.10069]

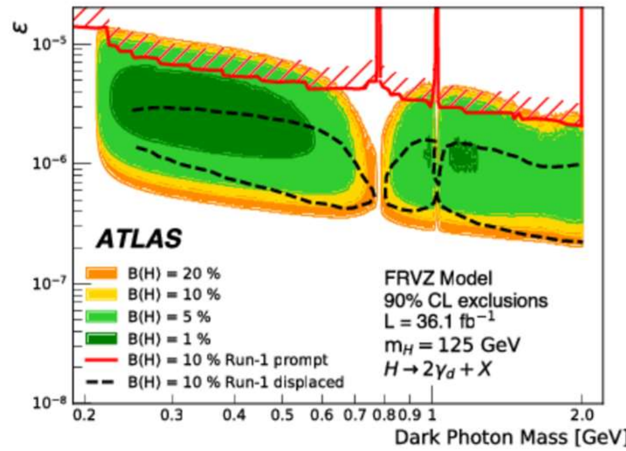
Further Opportunities @ LHC

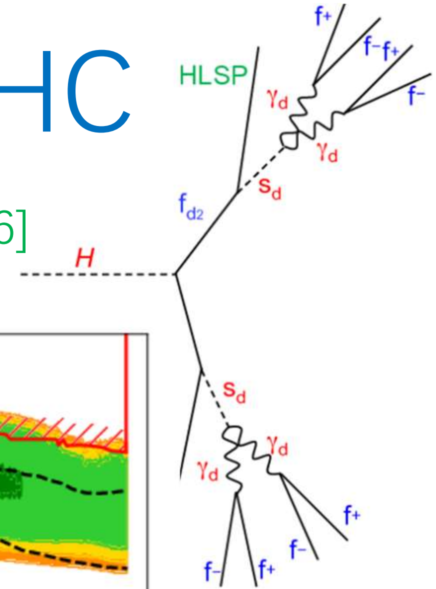
[CMS: CMS-PAS-EXO-20-014]



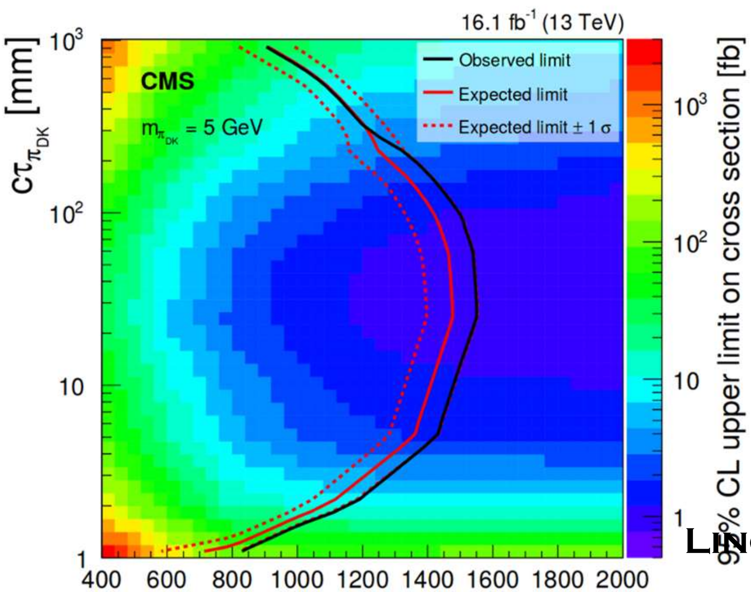


[ATLAS: 1909.01246]

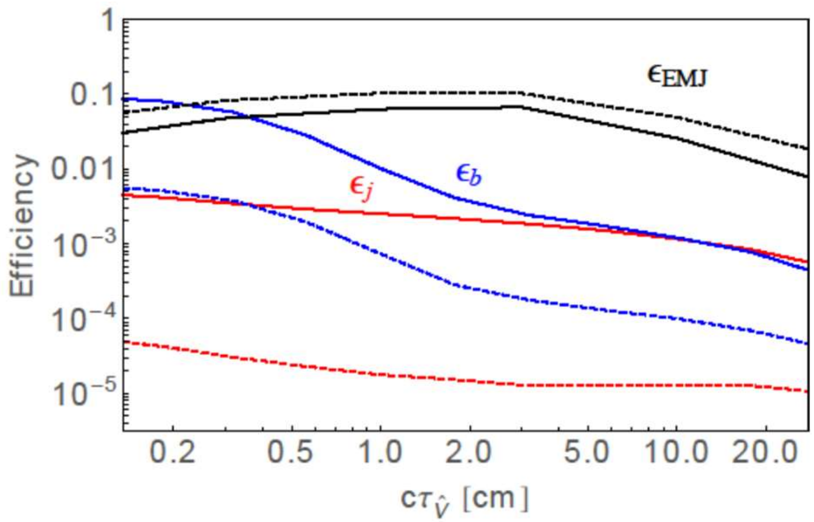




The dark pion searches at ATLAS/CMS benefit from larger luminosities and decay volume.
Reprojection are non-trivial. LLP oriented triggers? [Y. Gershtein and S. Knapen, 1907.00007]



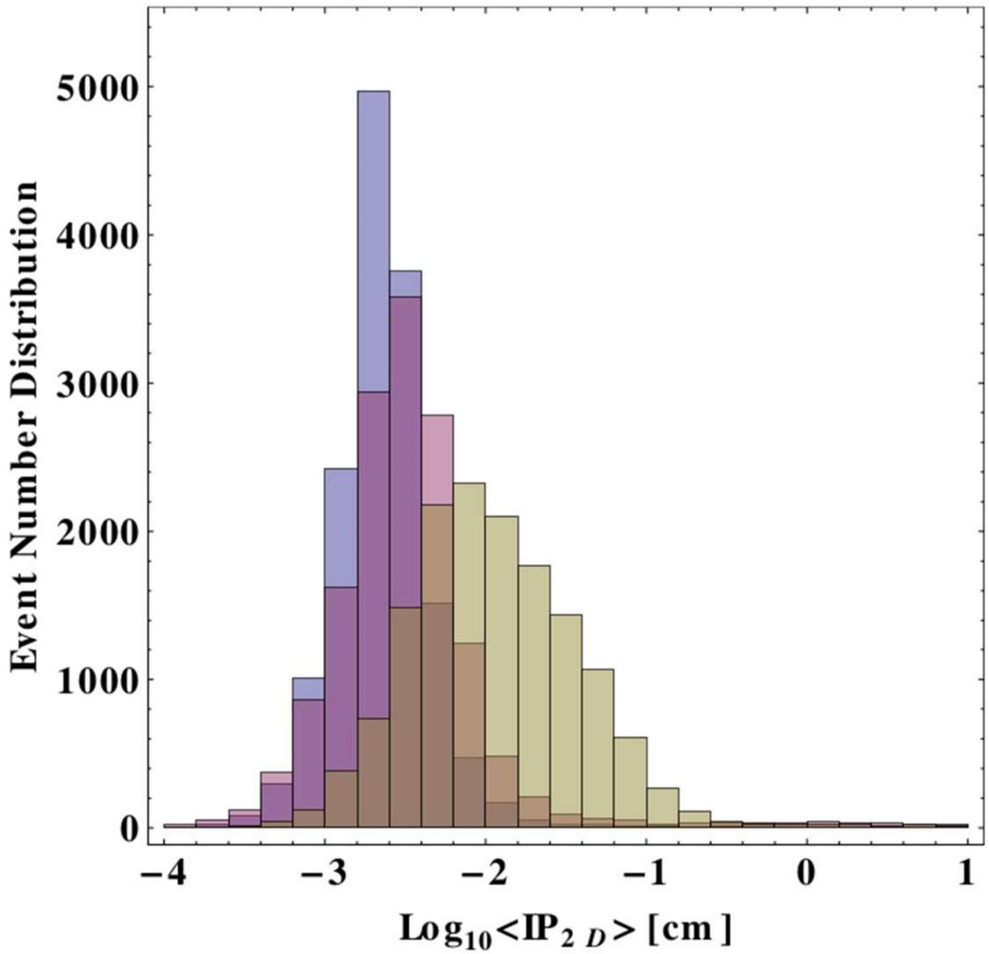
[CMS, 1810.10069]

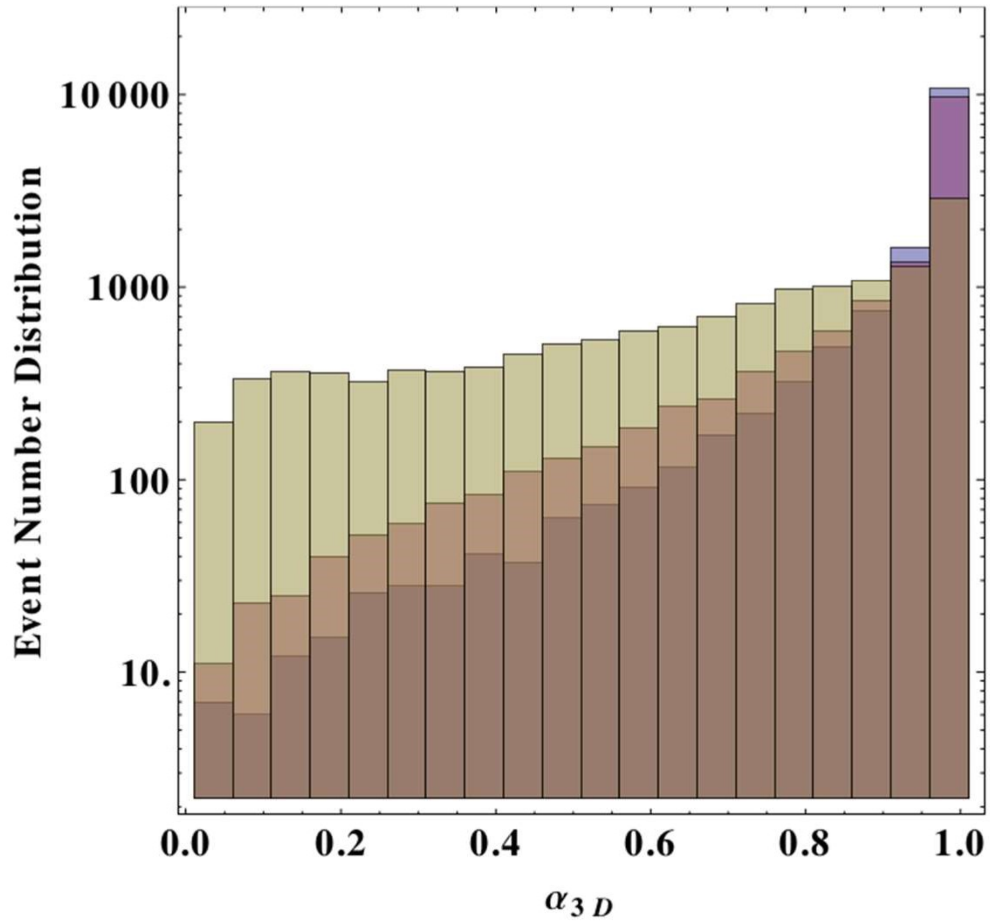


Emerging jet efficiencies for the one-flavor case [H-C. Cheng, LL, E. Salvioni and C. Verhaaren, 1905.03772]

← A fully inclusive emerging jet search will be sensitive to heavier dark pions.

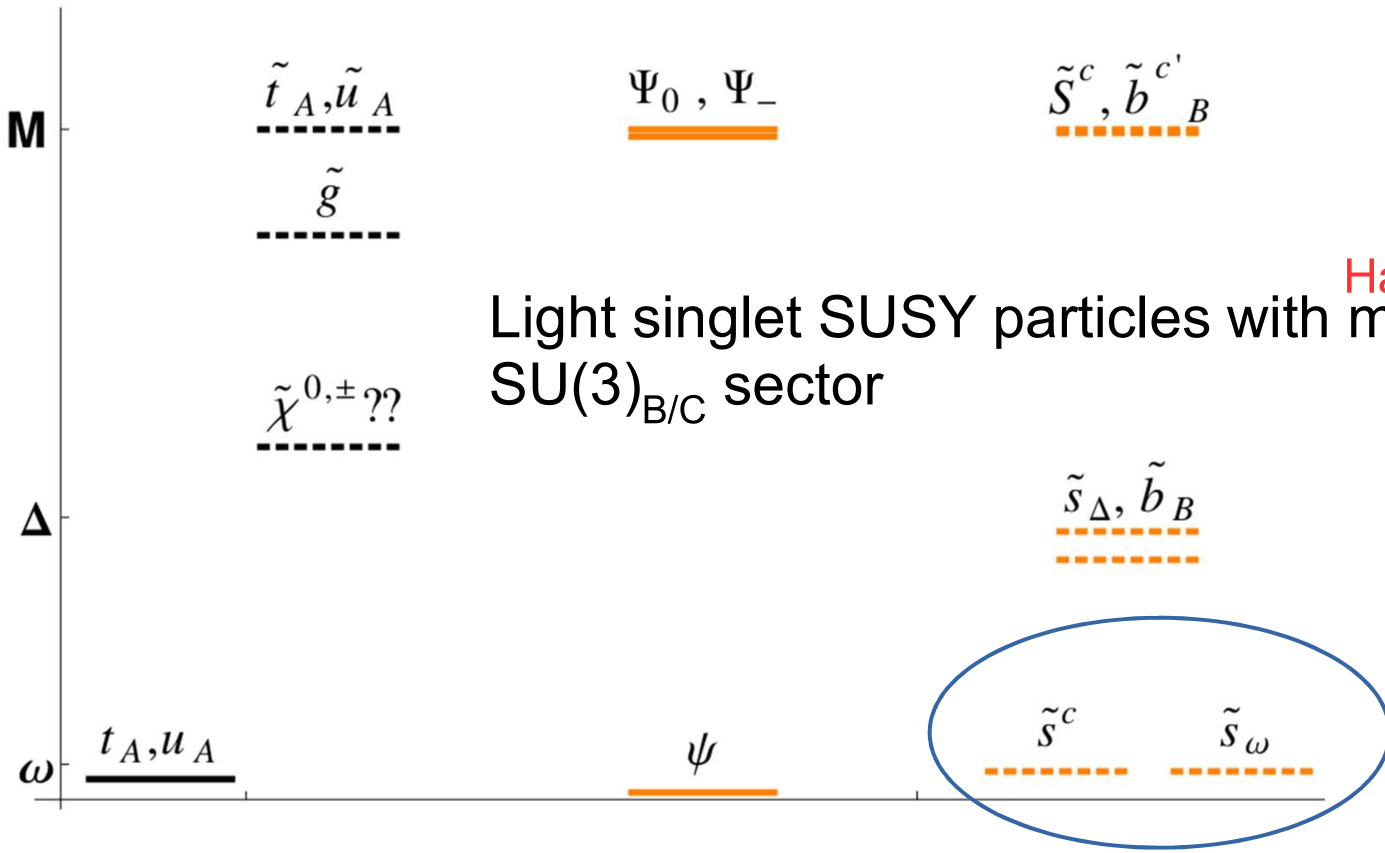
Emerging Jet Discrimination





Off-Topic Thoughts About Exotic Bound States

Spectrum of the revised TT model:

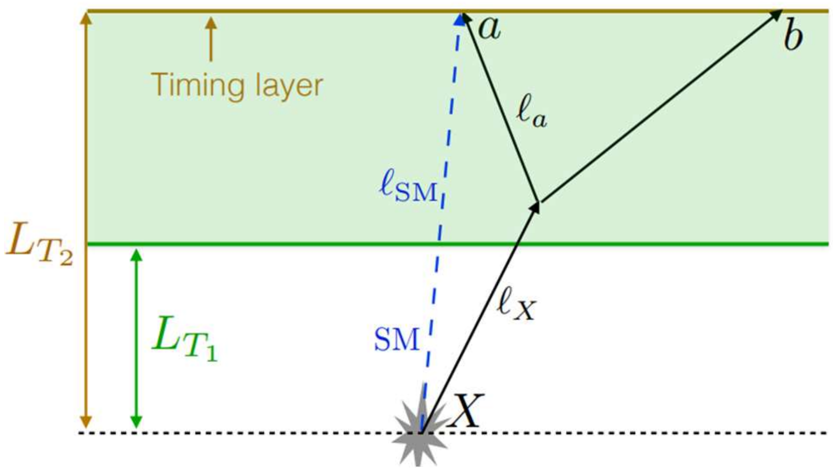


Hard to form bound state and anni

Light singlet SUSY particles with mass O(100) GeV from SUS
$SU(3)_{B/C}$ sector

Remember?

Time Resolution: A Complementary?



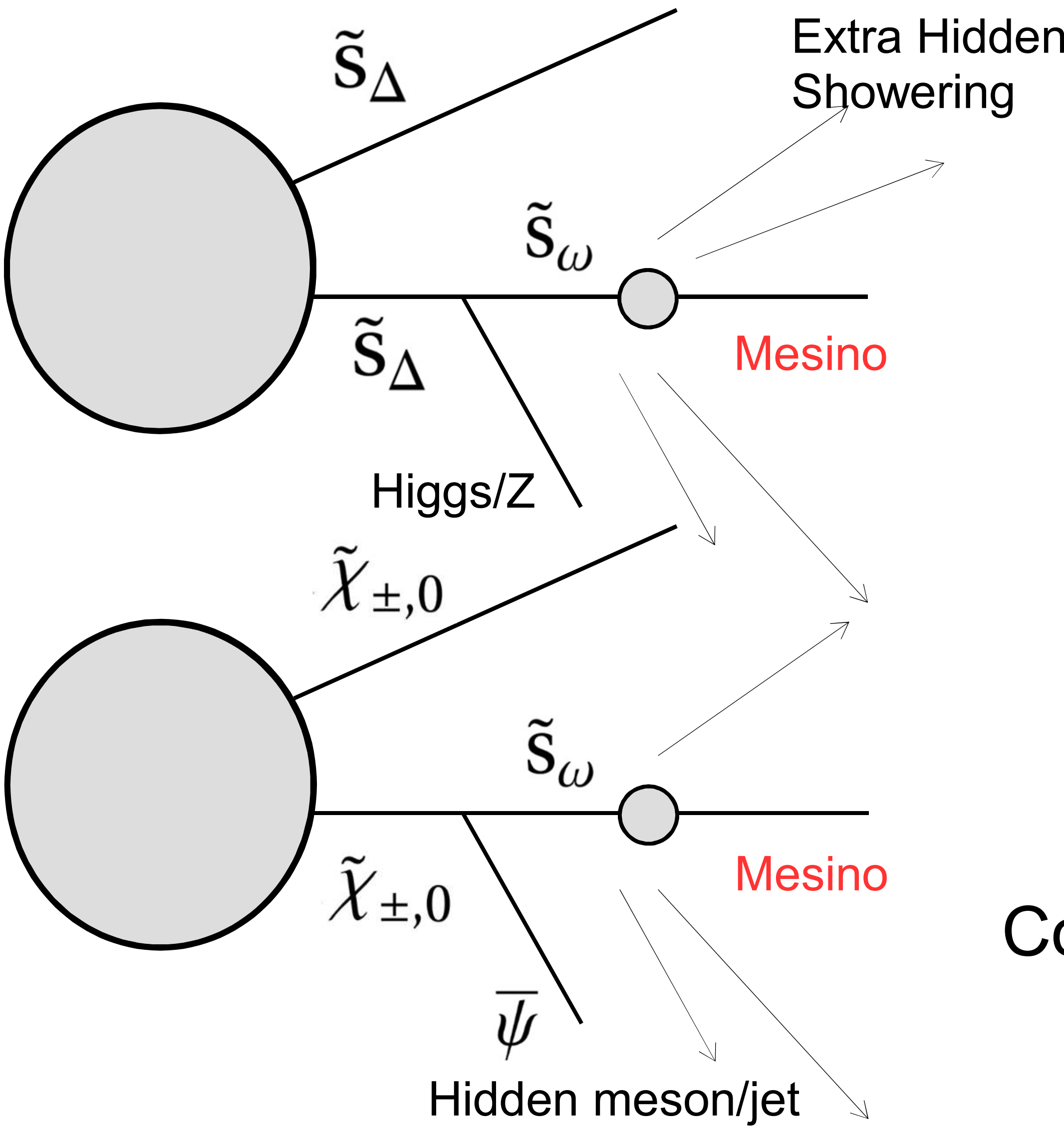
[J. Liu, Z. Liu and L.Wang, 1805.05957]

Interesting topic for the future and may work as extra discriminator for emerging jets.

Due to SM backgrounds and time resolution, a Δt ≈ O(1) ns is required.

⇒ A not very boosted hidden meson (γ~2-3) shall travel O(100) cm before its decay.

Exotic Bound States



Effective Lightest SUSY Particle (ELSP)

Annihilate to light hidden mesons → SM efficiently.
Seems OK as relic density much smaller than $O(10^{-2})$
…

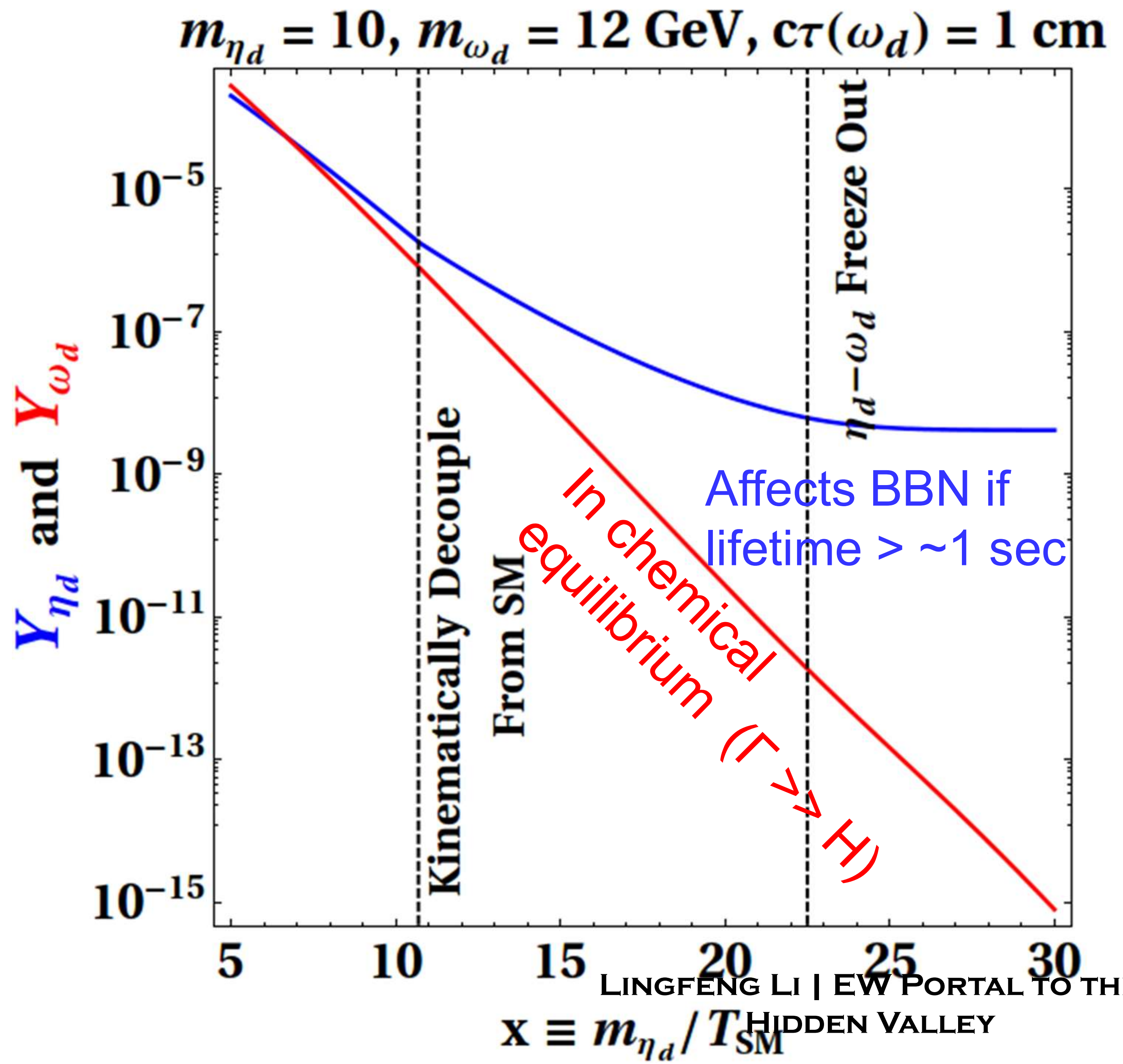
Collider Pheno: Open question

Thermal History

$$\frac{dY_h}{dx} = \frac{-1}{3H(x)}\frac{ds}{dx}\Bigg[\langle \sigma_{+2h} v \rangle \, Y_l^2 - \langle \sigma_{-2h} v \rangle \, Y_h^2 - \langle \sigma_{-h} v \rangle \, Y_h Y_l + \langle \sigma_{+h} v \rangle \, Y_l^2 - \frac{\langle \Gamma_{\phi_h \to \mathrm{SM}} \rangle_{\hat{T}}}{s} Y_h + \frac{\langle \Gamma_{\phi_h \to \mathrm{SM}} \rangle_T}{s} Y_h^{\mathrm{eq}}(T) \Bigg],$$

$$\frac{dY_l}{dx} = \frac{-1}{3H(x)}\frac{ds}{dx}\Bigg[\langle \sigma_{-2h} v \rangle \, Y_h^2 - \langle \sigma_{+2h} v \rangle \, Y_l^2 + \langle \sigma_{-h} v \rangle \, Y_h Y_l - \langle \sigma_{+h} v \rangle \, Y_l^2 \Bigg].$$

Thermal History

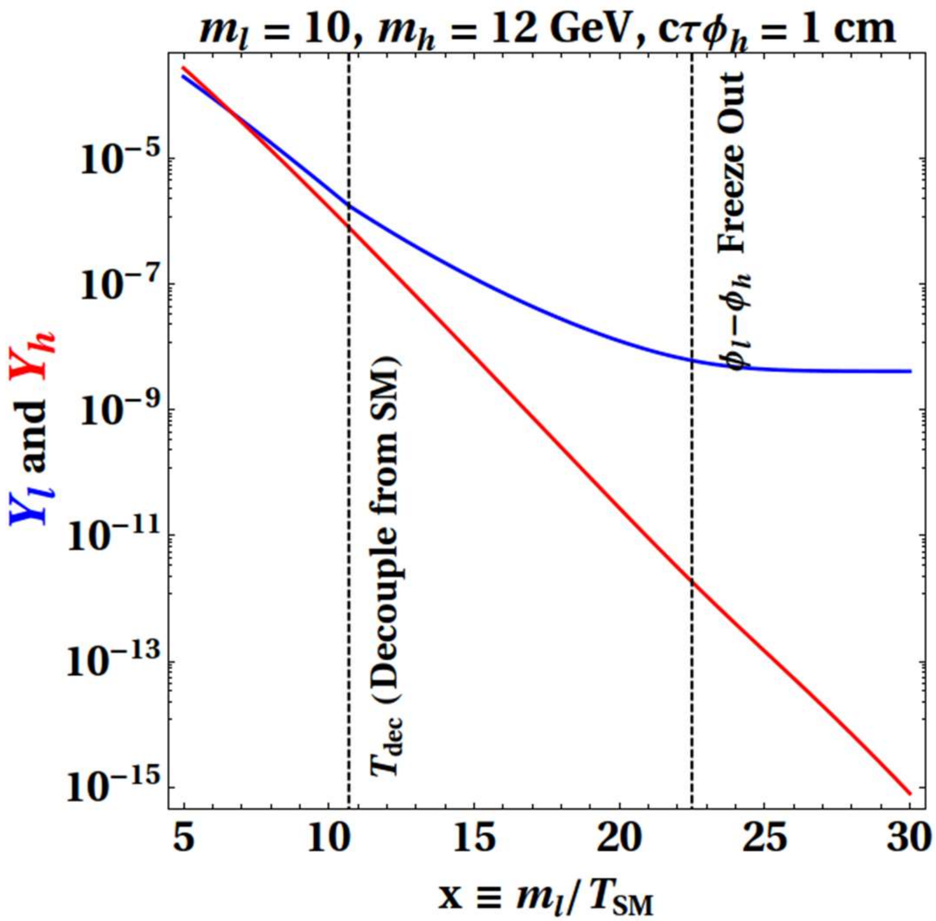


Sensitive to:

- Decay length Γ (kinematic decoupling time)
- ω_d-η_d mass difference Δm (when freeze out happens).

The analytical form is not always precise

Thermal History



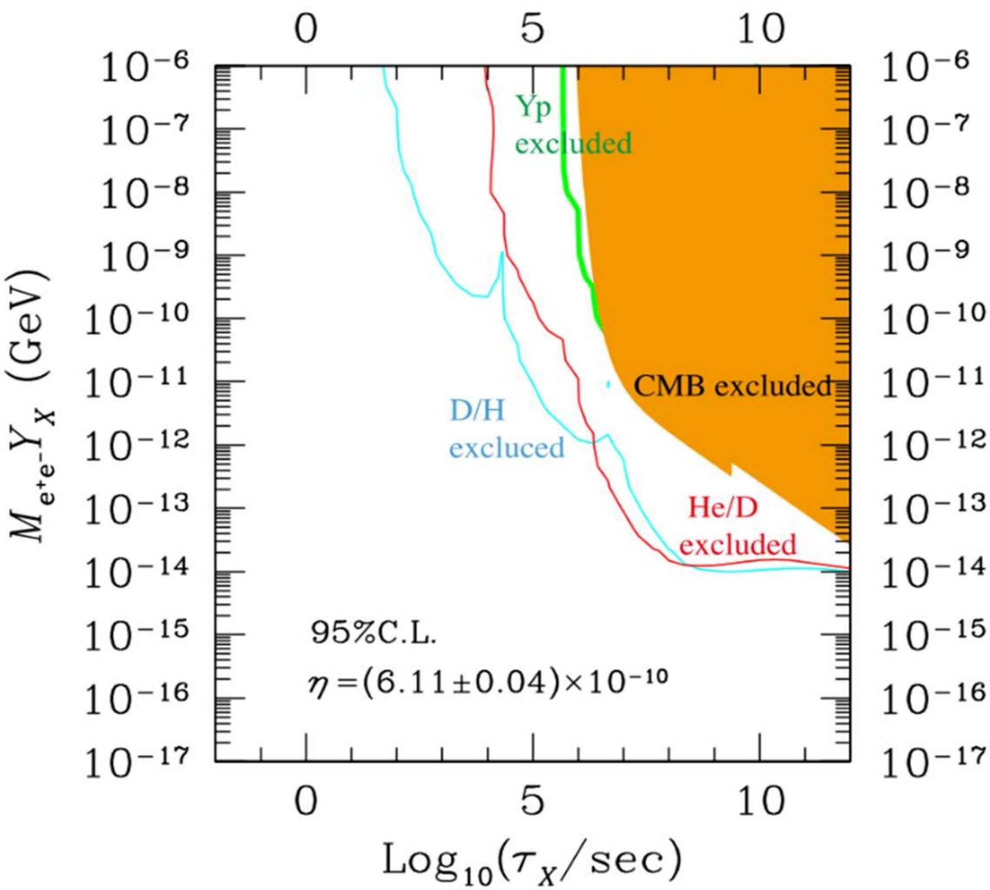
$$Y_l(T) \simeq \frac{Y_l^{eq}(\hat{T})}{Y_h^{eq}(\hat{T})} Y_h^{eq}(T)$$
$$\propto \exp\left(\frac{\Delta m T_{dec}}{T^2}\right) \exp\left(-\frac{m_h}{T}\right)$$

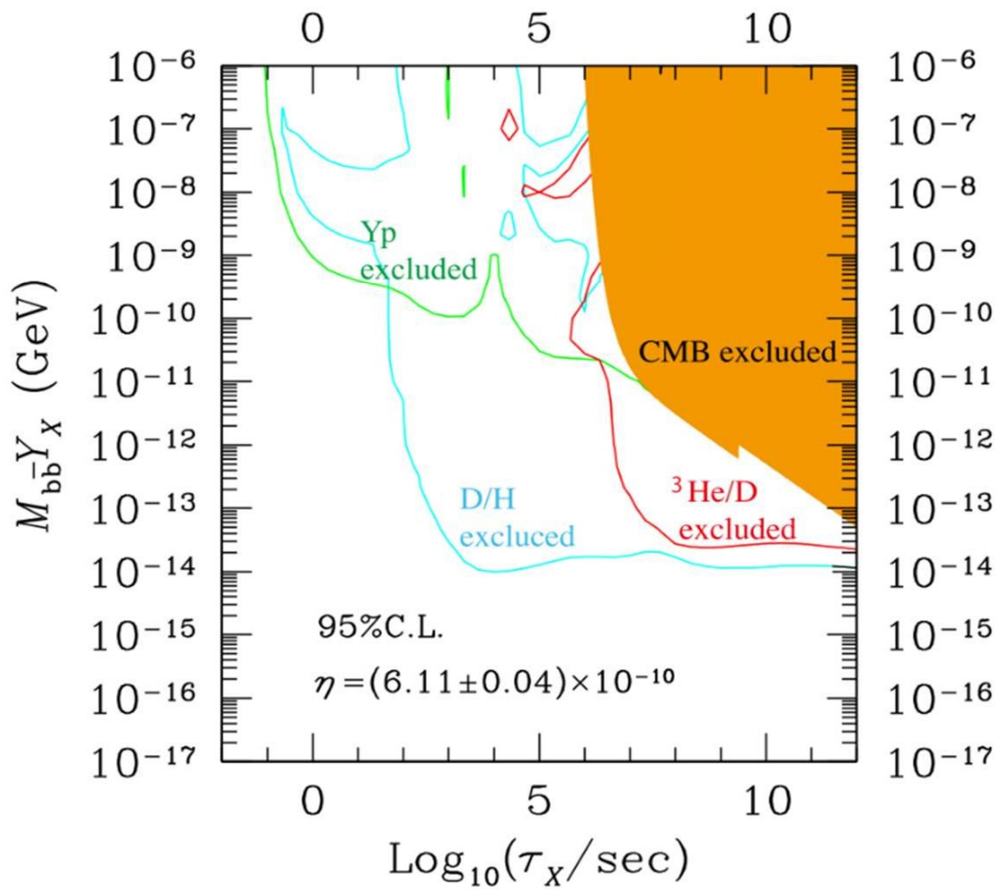
Sensitive to h decay length Γ (related to T_{dec}) and Δm (related to freeze out temperature).

$$Y_l|_{BBN} \simeq 10^{-4} \left(\frac{1000 m_h^2}{M_P \Gamma_h}\right)^{\frac{\text{const} \times m_h}{\Delta m}} \exp\left(-\text{const}\frac{m_h}{\Delta m}\right)$$

Reasonable form but not always precise

BBN Constraint





Taken from [1709.01211]

Outlook

Energy Frontier:

Advanced Triggering (Theme of 27th!)

Time/HGCAL/tracking info (See Jia & Marat's talk)

Full potential of various LLP detectors

Intensity Frontier:

Synergies w/ flavor physics (Belle II etc.)

Synergies w/ neutrino physics (DUNE etc. [Gouvea et. al. 1809.06388])

Full potential of future lepton colliders

Cosmic Frontier:

Cosmological constraints from Ω_{DM} and BBN ([LL, Y. Tsai 1901.09936], Sam's & Patrick's talks)

With more than 2 flavor: WZW interaction -> SIMPs?

Other Frontiers:

Lattice QCD results

Machine Learning for detection

Unexpected new ideas