Light Hidden Mesons Inspired by Neutral Naturalness

Lingfeng Li (HKUST)

26, Aug, SUSY 2021, Beijing

1803.03561 w/ H-C. Cheng, E. Salvioni and C. Verhaaren

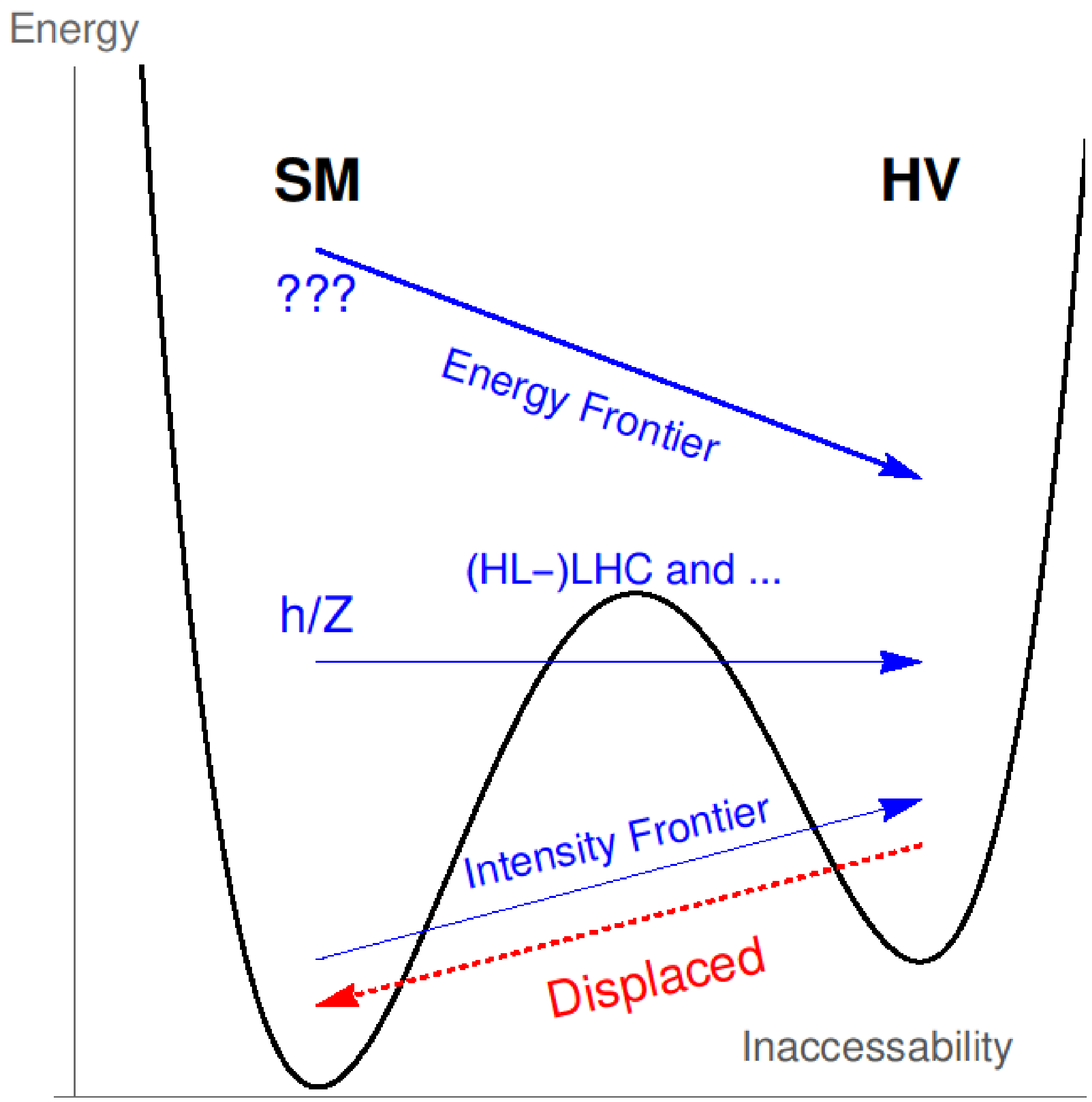
1905.03772 w/ H-C. Cheng, E. Salvioni and C. Verhaaren

210X.abcde w/ H-C. Cheng and E. Salvioni

The Paths to the Hidden Valley

The overview of this talk

- Why a confined light hidden sector
- Two benchmark models: Alternated tripled top & dark pion model
- The Z portal phenomenology
- Several benchmark long-lived particle (LLP) searches

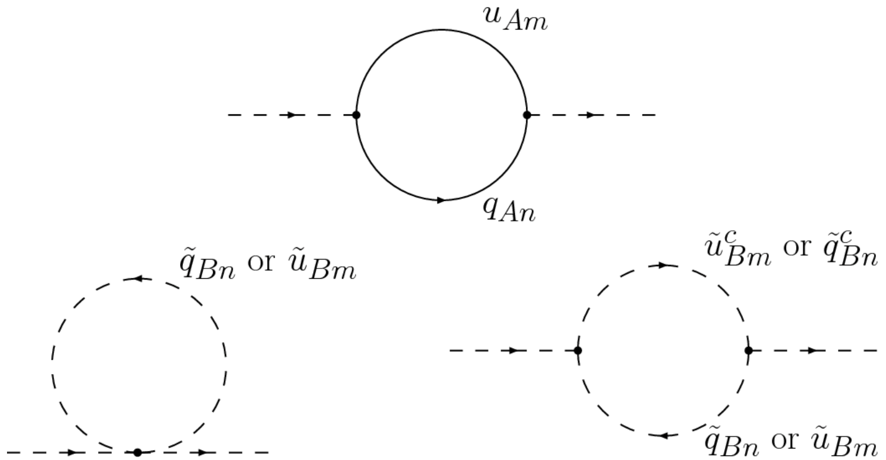


Neutral Naturalness

Top partners gauged under hidden SU(3) to avoid strong bounds

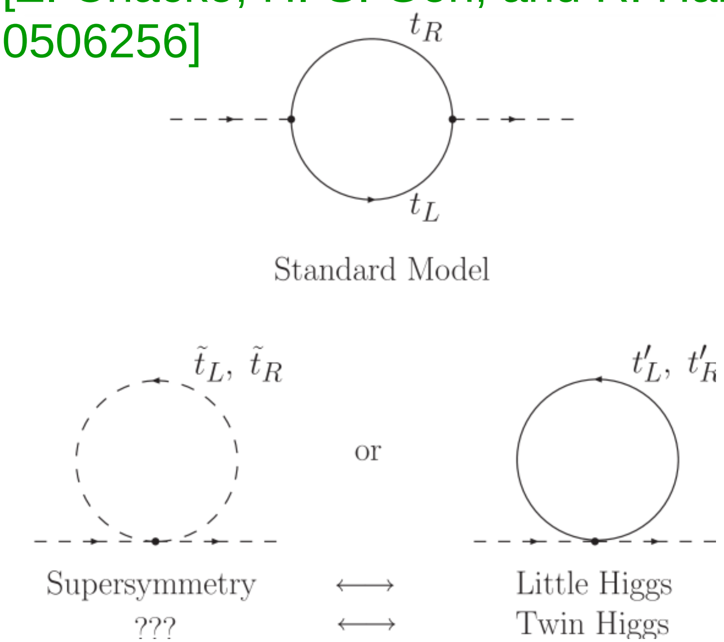
Folded SUSY

[G. Burdman, Z. Chacko, H.S. Goh and R. Harnik, 0609152]



Twin Higgs

[Z. Chacko, H.-S. Goh, and R. Harnik, 0506256]



Leading to confined hidden sector In general.

Higgs Portal: Exotic h->XX, X=Hidden glueball, Twin b hadron, etc.

Z(EW) Portal?

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Original Tripled Top (TT) Model

A few TeV

A few hundred GeV

The superpotential:

$$W_{Z_3} = y_t \left(Q_A H u_A^c + Q_B H u_B^c + Q_C H u_C^c \right) + M (u'_B u_B^c + u'_C u_C^c) + \omega (Q_B Q'^c_B + Q_C Q'^c_C) ,$$

A, B & C: 3 sectors charged under different SU(3), no extra SU(2)/U(1) gauge groups

A soft breaking term:

A few TeV (~M)

$$V_{\rm s} = \widetilde{m}^2 \left(|\widetilde{Q}_A|^2 + |\tilde{u}_A^c|^2 \right) - \widetilde{m}^2 \left(|\tilde{u}_B^c|^2 + |\tilde{u}_C^c|^2 \right) .$$

A Folded SUSY-like spectrum realized in 4D

Alternate Tripled Top (TT) Model & Accidental SUSY

The superpotential:

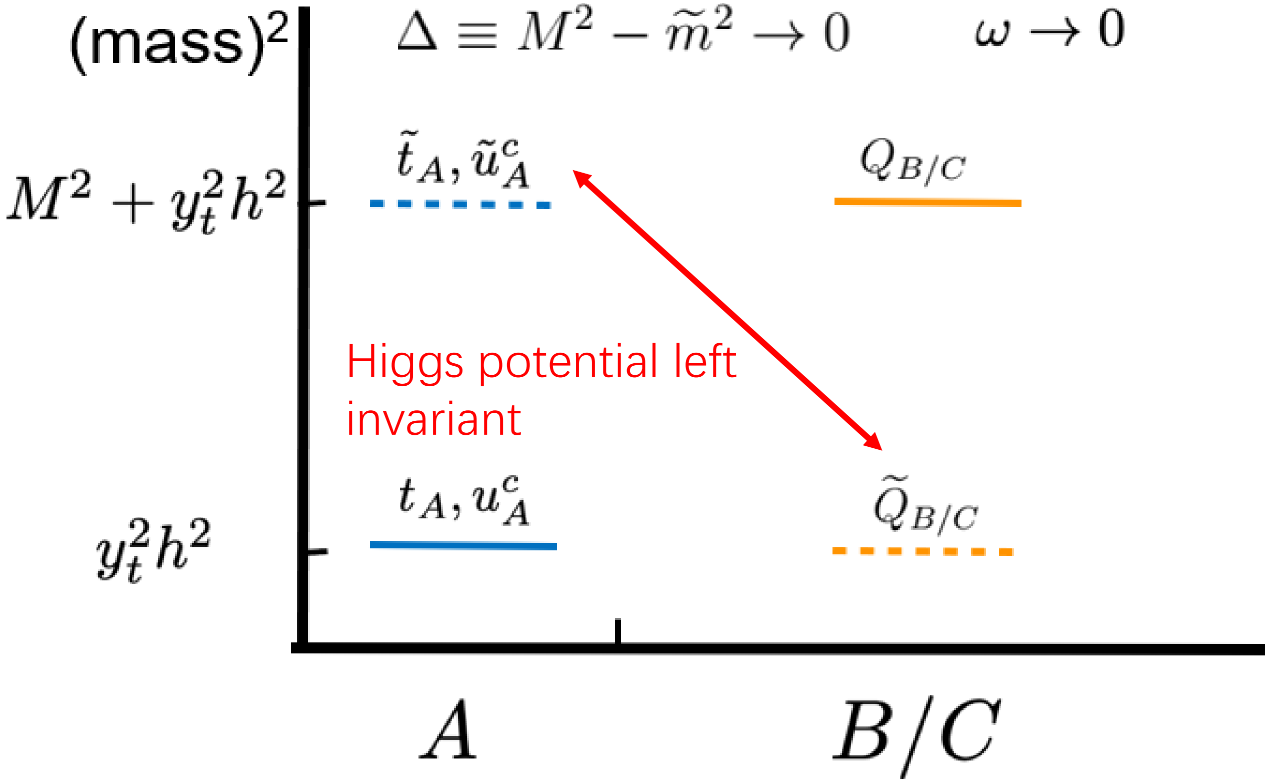
$$W'_{Z_3} = y_t(Q_A H u^c_A + Q_B H u^c_B + Q_C H u^c_C) + \omega(u'_B u^c_B + u'_C u^c_C) + M(Q_B Q'^c_B + Q_C Q'^c_C)$$

$$V'_s = \widetilde{m}^2(|\widetilde{Q}_A|^2 + |\widetilde{u}^c_A|^2) - \widetilde{m}^2(|\widetilde{Q}_B|^2 + |\widetilde{Q}_C|^2)$$

$Q_A \quad u^c_A$ SM top sector

$$Q_{B,C} = \begin{pmatrix} t_{B,C} \\ b_{B,C} \end{pmatrix} \sim \mathbf{2}_{-1/2}$$

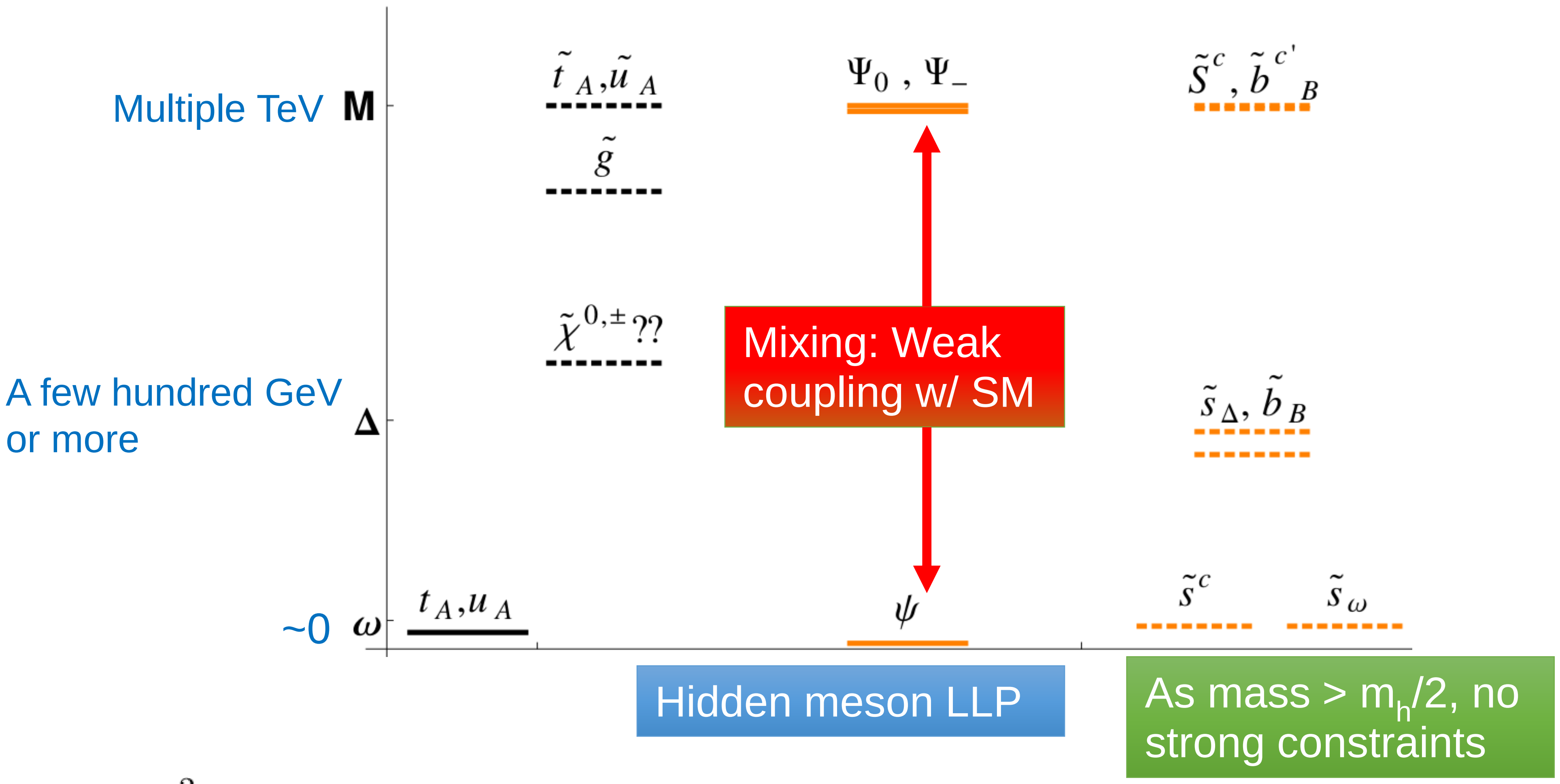
$$u^c_{B/C} \sim \mathbf{1}_0$$



For details of the original model, see our paper [H-C.Cheng, LL, E.Salvioni and C. Verhaareen 1803.03561]

Related Work: [T.Cohen, N.Craig,G.Giudice, M.Mccullough,1803.03647]

A Case with Much More Fun



$$\mathcal{L}_6 = \frac{m_t^2}{M^2 v^2}\left(|H|^2\,\overline{\psi}_R i \not{D} \psi_R + \text{h.c.} + i (D_\mu H)^\dagger H\,\overline{\psi}_R \gamma^\mu \psi_R + \text{h.c.} + c_g \frac{\alpha_d}{12\pi} |H|^2 \hat{G}^a_{\mu\nu} \hat{G}^{a\,\mu\nu}\right)$$

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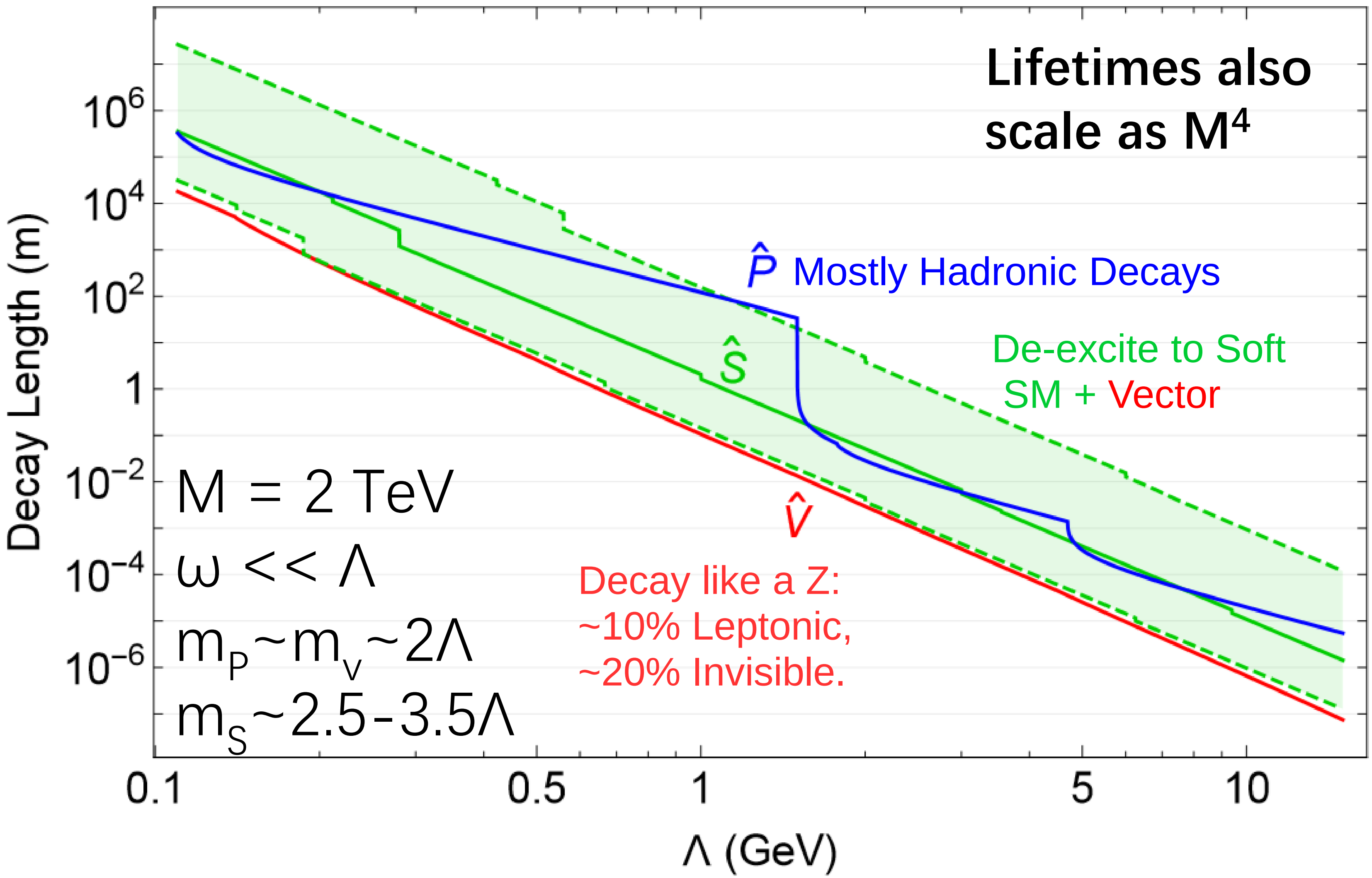
Spectrum & Decay (One-Flavor QCD)



Proper decay length of the Pseudoscalar, Vector and Scalar

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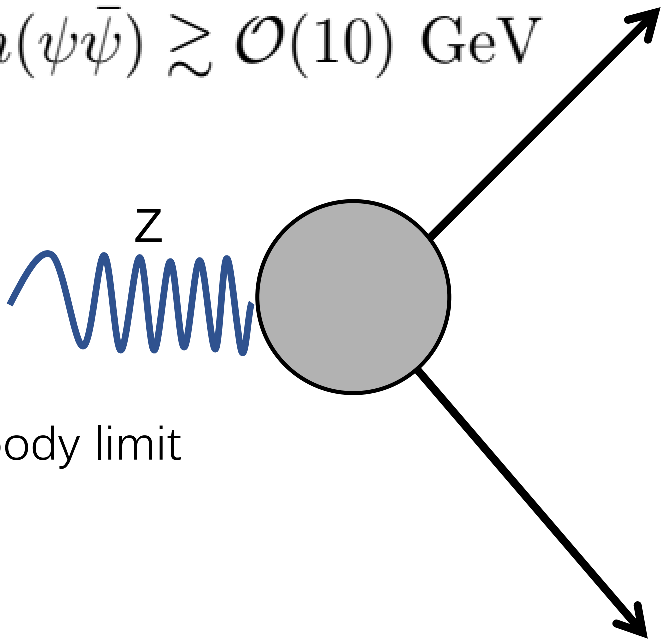
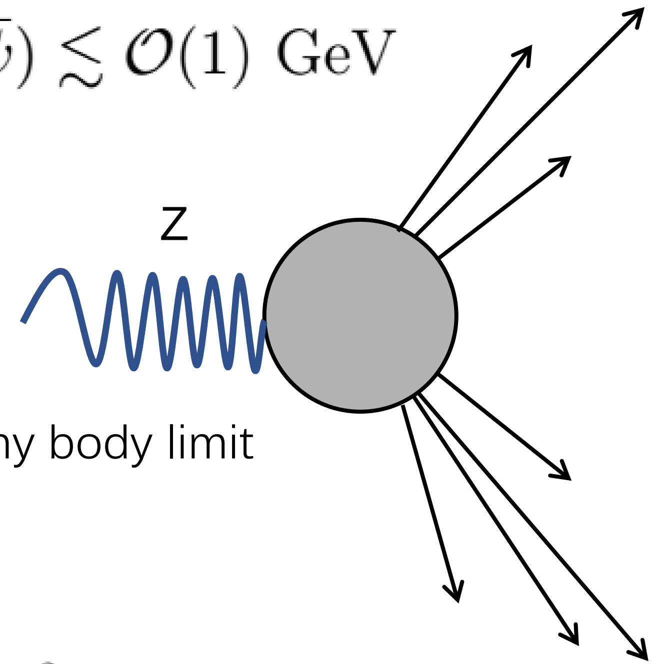
EW Portal Production (Z Exotic Decay)

$m(\psi\bar{\psi}) \gtrsim \mathcal{O}(10)\ \mathrm{GeV}$



2 body limit

$m(\psi\bar{\psi}) \lesssim \mathcal{O}(1)\ \mathrm{GeV}$



Many body limit

Effective Z coupling:

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

$$\mathrm{BR}(Z\to\overline{\psi}_{B,C}\psi_{B,C}) \approx 2.2\times 10^{-5}\left(\frac{2\,\mathrm{TeV}}{M}\right)^4 .$$

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 produced @ LHC)

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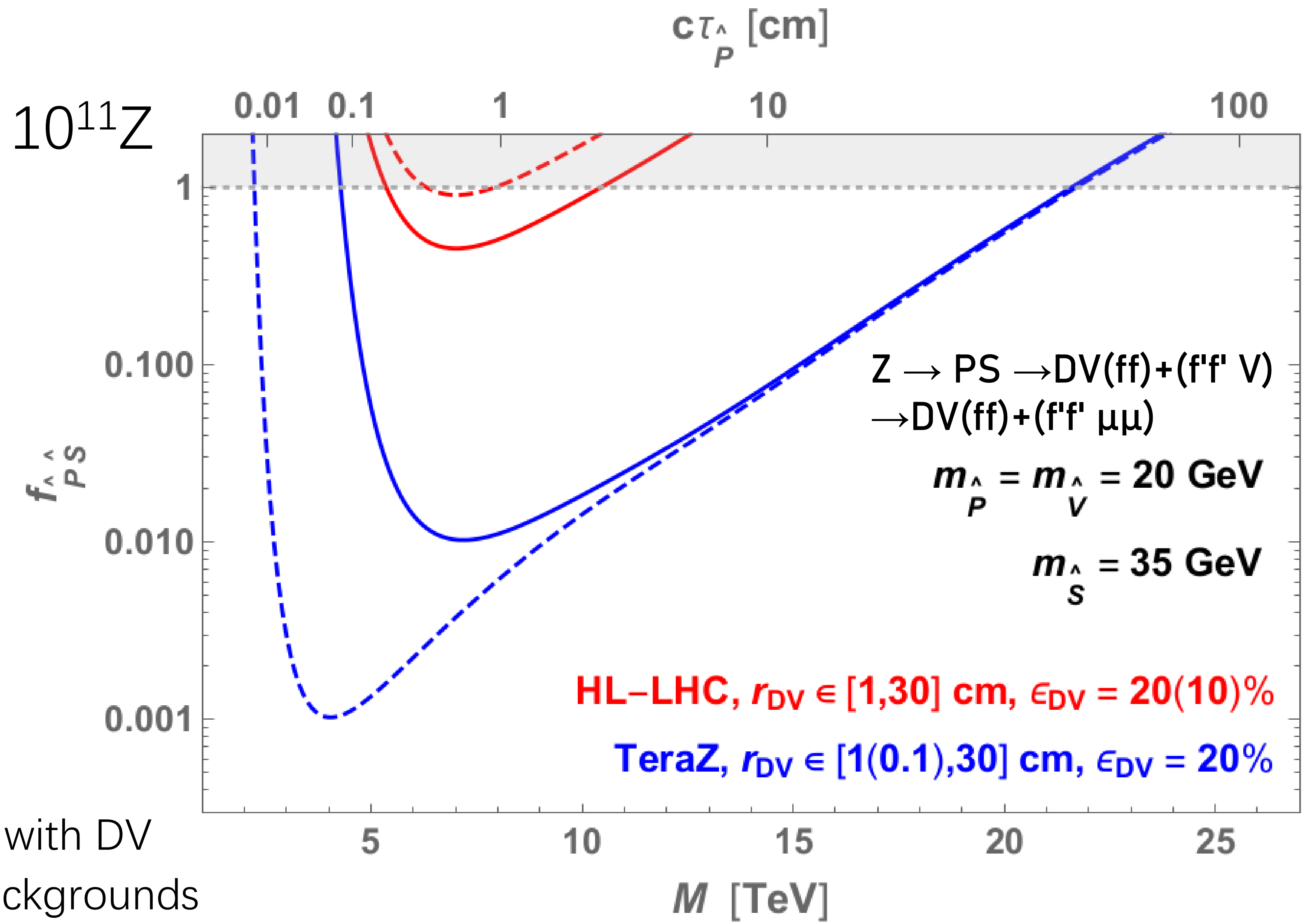
2 Body Limit: Pesudoscalar LLP

HL-LHC: $1.8 \times 10^{11} Z$
Tera-Z: 10^{12} Z

The hidden hadronization fraction



Di-muon triggering with DV
-> negligible SM backgrounds

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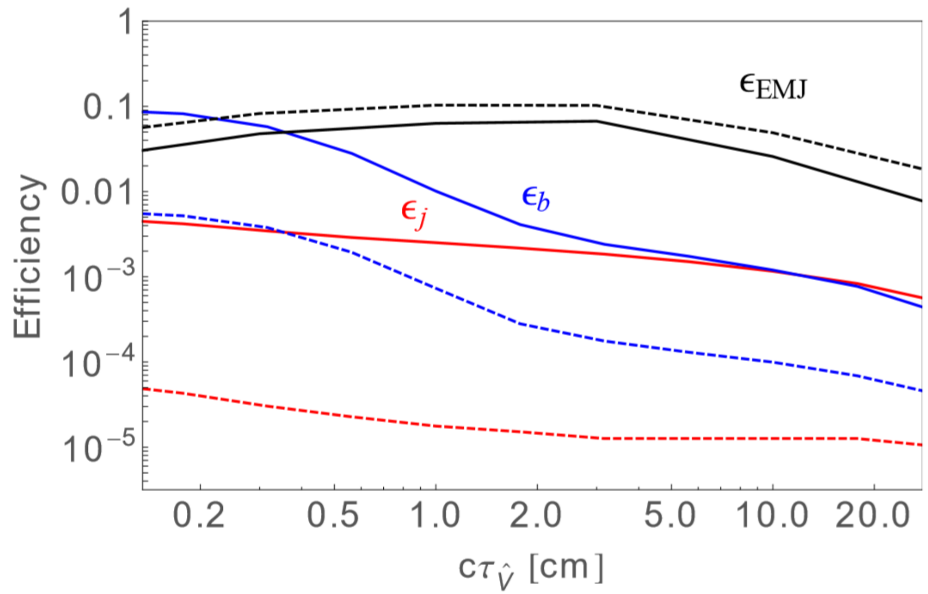
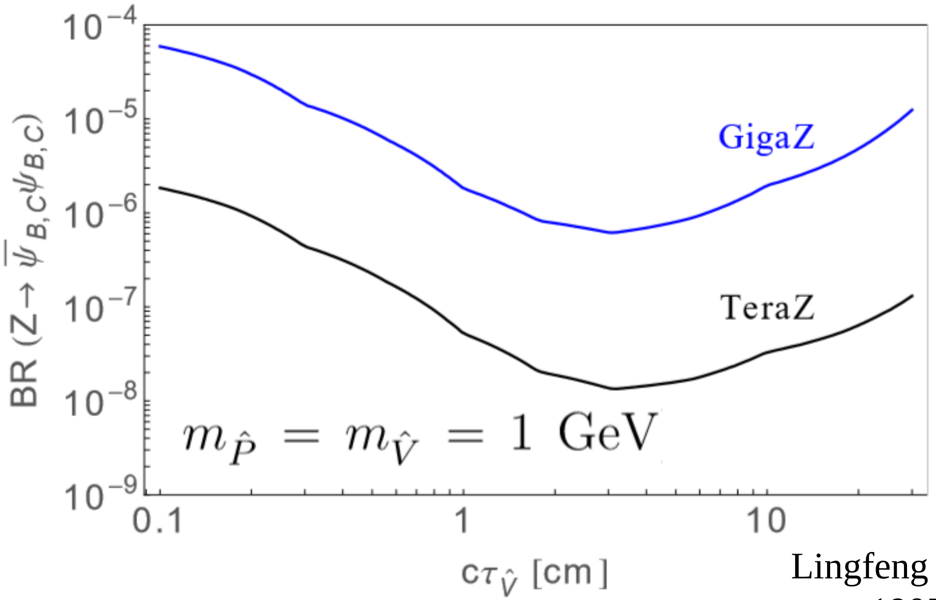
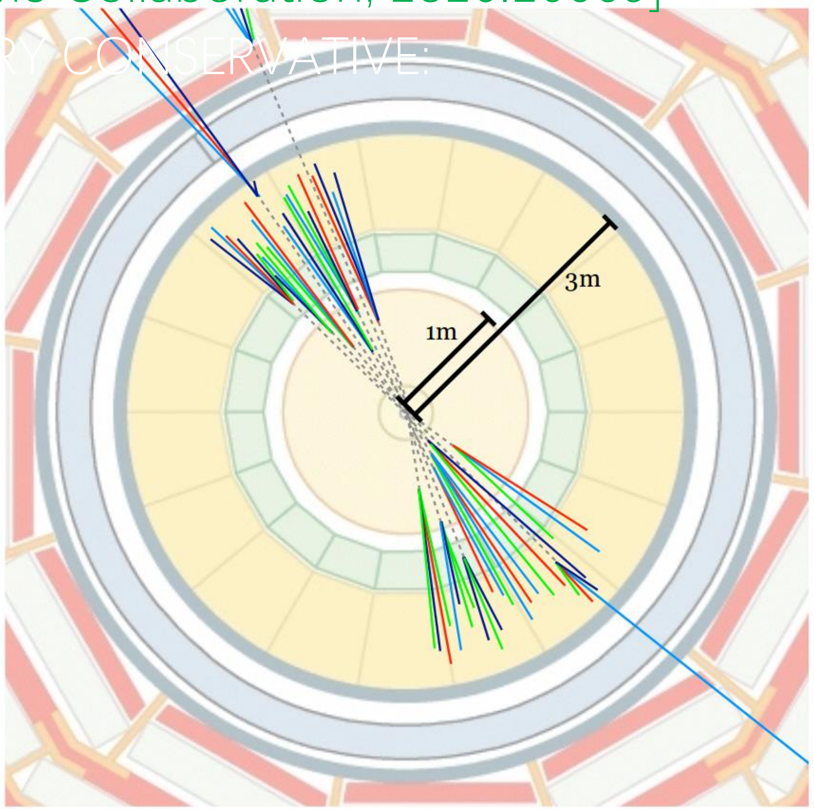
Many Body Limit:
Emerging Jets @ Tera-Z & LHC





Trying to tag each jet, SM jet as bkg

[CMS Collaboration, 1810.10069]



@LHC, low triggering efficiency, relying on ZZ → ll recoil +dark jets, exotic BR(Z)~O(10^{-4} -10^{-5})

Improvement possible if we can trigger dimuons inside EMJ

[Y. Gershtein and S. Knapen, 1907.00007]

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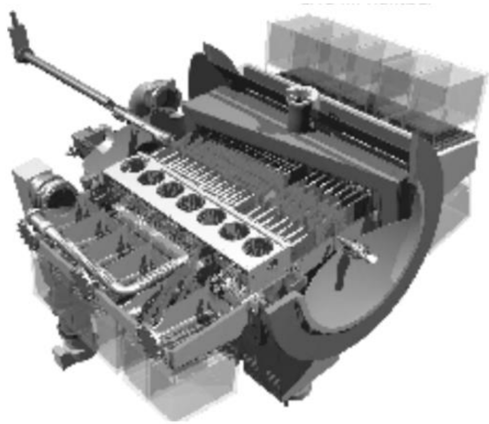
Many body limit @LHCb



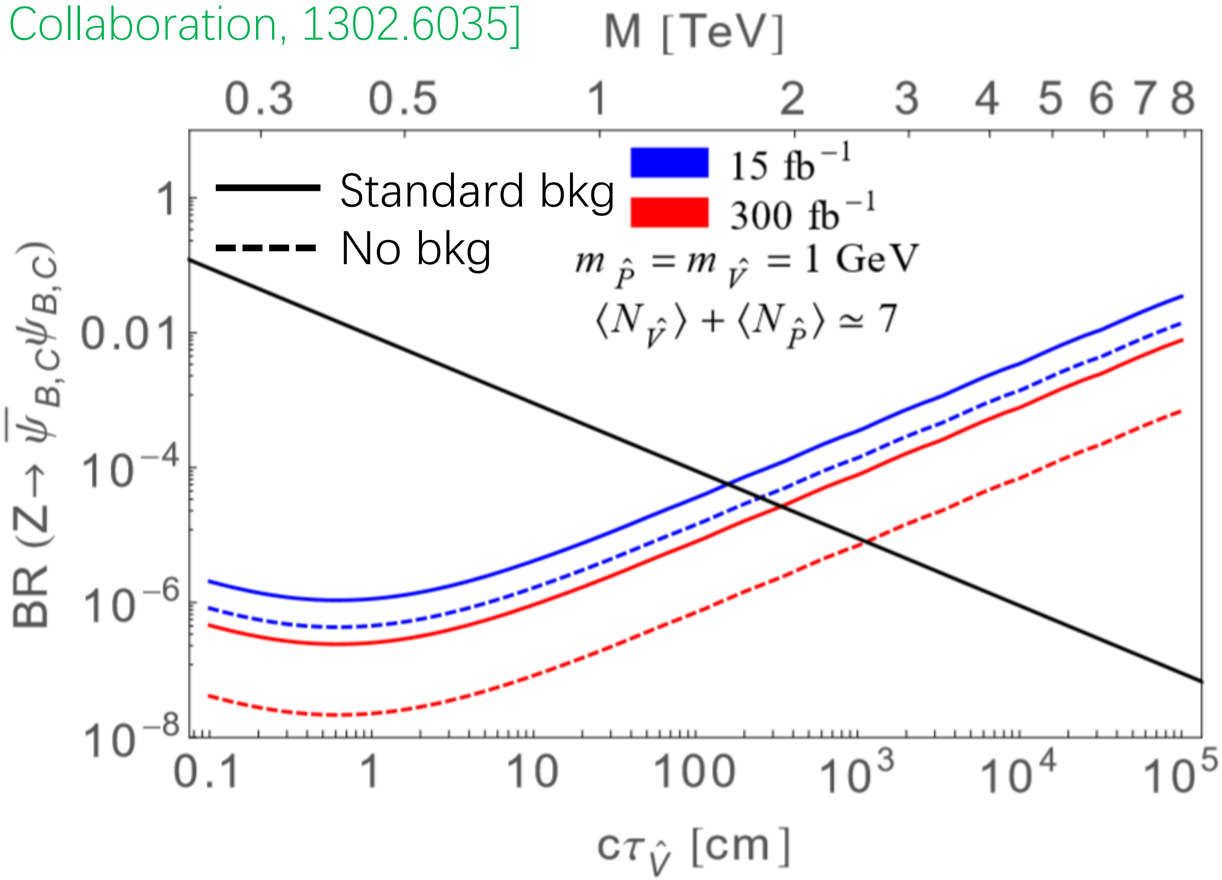
VErtex LOcator (VELO)

High Track Resolution (a few μm after upgrade)
[LHCb VELO Collaboration, 1302.6035]

Tigger would be effective at run 3

BR(V→μμ)~5% for m_V ~1 GeV

Find single displaced μμ vertex within the effective detector volume
[A. Pierce, B. Shakya, Y. Tsai and Y. Zhao, 1708.05389]



Z Portal Dark Pions (Ongoing Project)

Minimally, if sector B and C share the same SU(3) gauge group, we will have two flavors. We can further generalize the relevant Lagrangian as:

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

$$\begin{aligned}\mathcal{L}_{\rm EFT} = & \frac{1}{2}\overline{\psi}_R \boldsymbol{Y}^\dagger \boldsymbol{M}^{-2}\boldsymbol{Y}\left[|H|^2 i\not{D} + i\gamma^\mu H^\dagger D_\mu H\right]\psi_R + \text{h.c.} \\ & + \frac{1}{2}\overline{\psi}_L \widetilde{\boldsymbol{Y}}^\dagger \boldsymbol{M}^{-2}\widetilde{\boldsymbol{Y}}\left[|H|^2 i\not{D} + i\gamma^\mu H^\dagger D_\mu H\right]\psi_L + \text{h.c.} \\ & - \overline{\psi}_L \boldsymbol{\omega}\psi_R + \overline{\psi}_L \widetilde{\boldsymbol{Y}}^\dagger \boldsymbol{M}^{-1}\boldsymbol{Y}\psi_R |H|^2 + \text{h.c.},\end{aligned}$$

Dimension-6 Z portal couplings

Dimension-5 Higgs portal coupling

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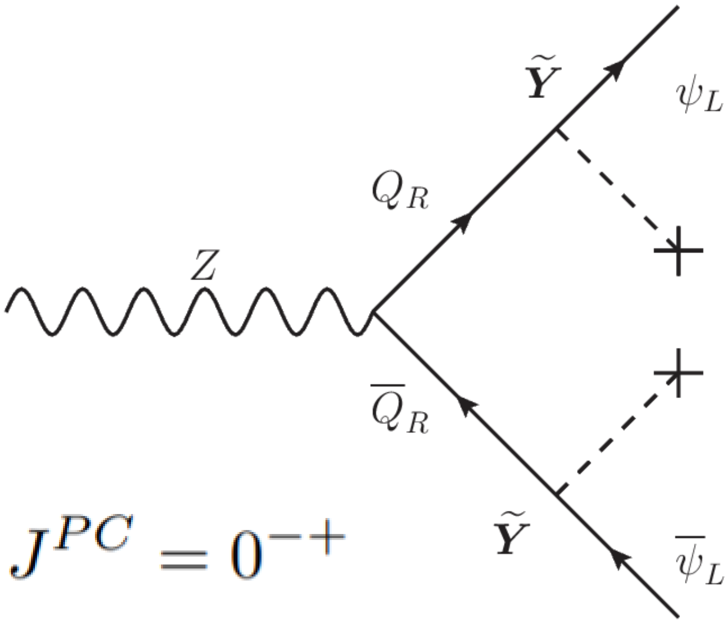
Two Flavor Case, 3 Dark Pions



$$J^{PC} = 0^{-+}$$

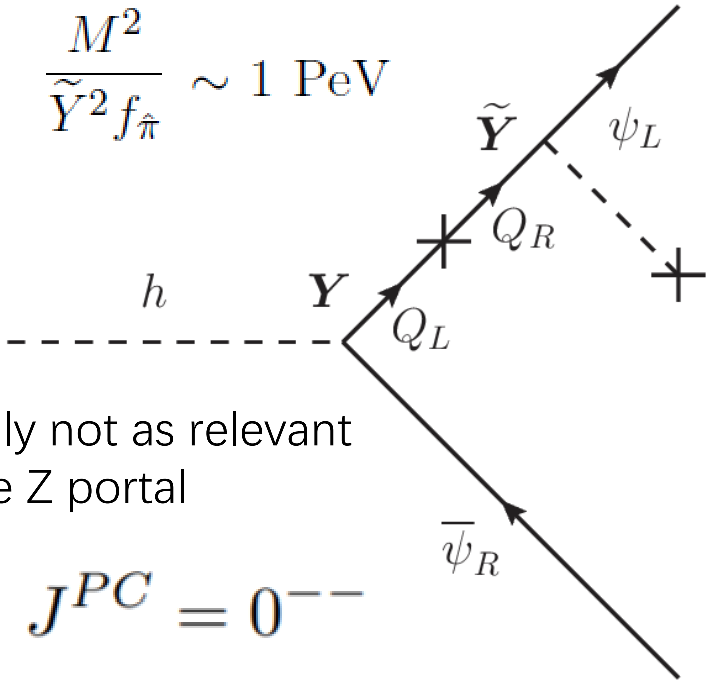
Dark pions rearrange into CP eigenstates (like K_S and K_L in the SM)

The π_1 and π_3 decay via Z porta, behave like ALP (axion-like-particle) with a large decay constant:

$$f_a \sim \frac{M^2}{Y^2 f_{\hat{\pi}}} \quad \text{or} \quad \frac{M^2}{\widetilde{Y}^2 f_{\hat{\pi}}} \sim 1 \text{ PeV}$$

The π_2 decay via its mixing with the Higgs since it's CP-even, well described by the mixing angle:

$$s_\theta^{(2)} \sim 2\pi f_{\hat{\pi}}^2 \frac{v}{m_h^2} \frac{Y\widetilde{Y}}{M} \sim 10^{-6} \left(\frac{Y\widetilde{Y}/M}{10^{-2}\ \text{TeV}^{-1}} \right) \left(\frac{f_{\hat{\pi}}}{\text{GeV}} \right)^2$$



Usually not as relevant as the Z portal

$$J^{PC} = 0^{--}$$

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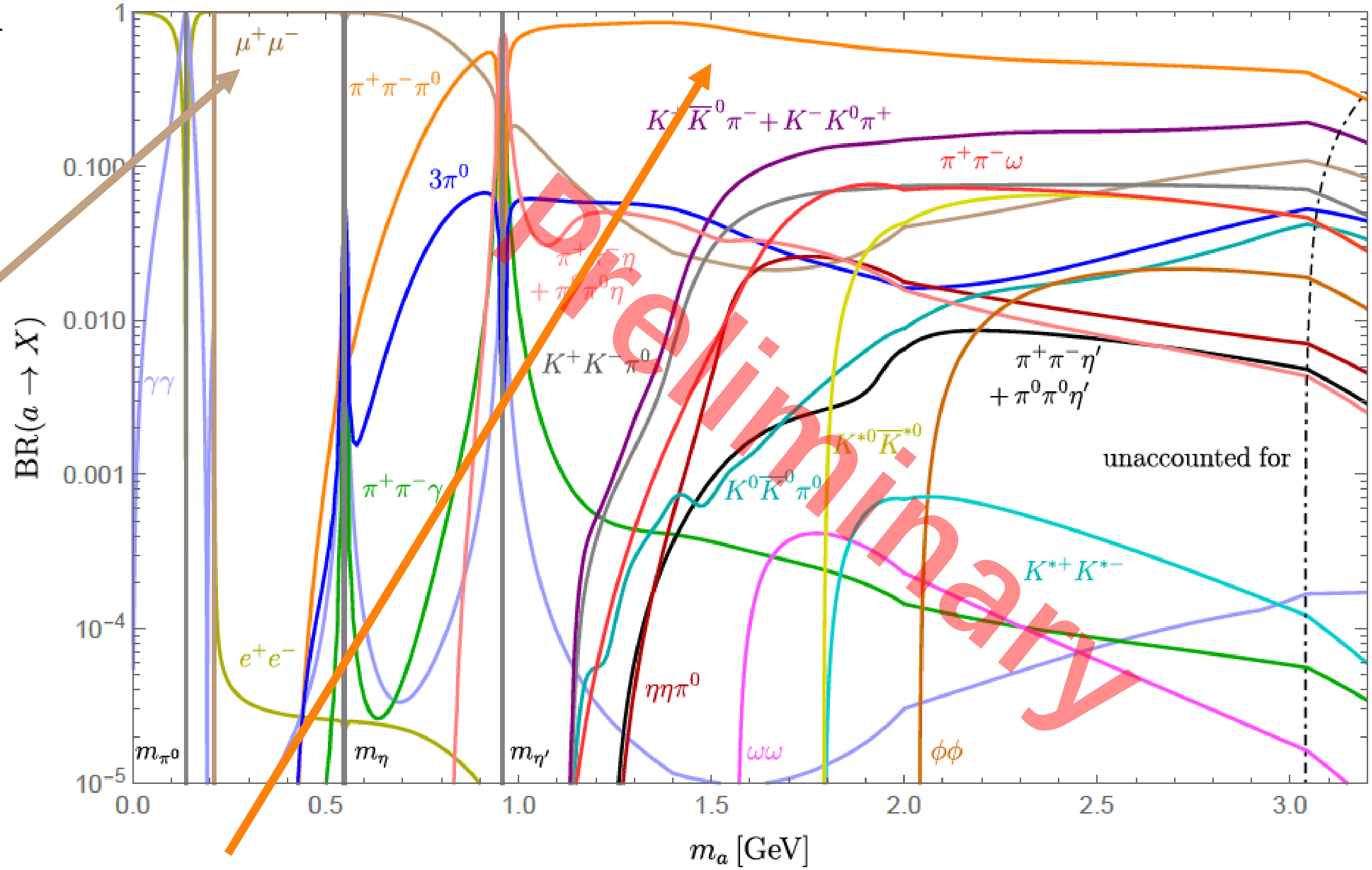
Dark Pion Decays (ALP-Like)

ALP with non-trivial flavor structure, very different from flavor universal case [D. Aloni, Y. Soreq and M. Williams, 1811.03474]

$m_\pi < m_{\eta'}$, dimuon decays



A.1 $a \to \gamma\gamma$

A.2 $a \to \pi^+\pi^-\gamma$

A.3 $a \to \pi^+\pi^-\pi^0$

A.4 $a \to 3\pi^0$

A.5 $a \to \pi^0\pi^0\eta, \pi^+\pi^-\eta$

A.6 $a \to \pi^0\pi^0\eta', \pi^+\pi^-\eta'$

A.7 $a \to \eta\eta\pi^0$

A.8 $a \to K^0\overline{K}^0\pi^0$

A.9 $a \to K^+K^-\pi^0$

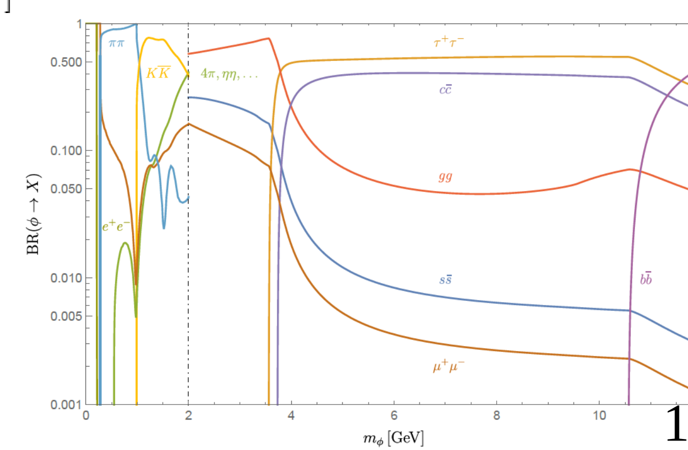
A.10 $a \to K^+\overline{K}^0\pi^-, K^-K^0\pi^+$

A.11 $a \to \omega\omega, \phi\phi, K^{*+}K^{*-}, K^{*0}\overline{K}^{*0}$

A.12 $a \to \pi^+\pi^-\omega$

$m_\pi > m_{\eta'}$, PPP (e.g.,3 pion) decays

Higgs portal decay follows [M. W. Winkler, 1809.01876]



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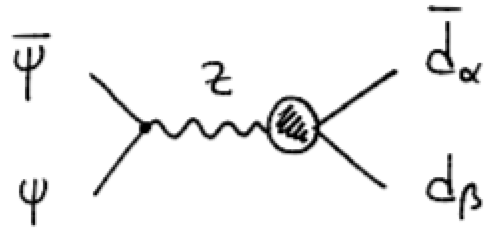
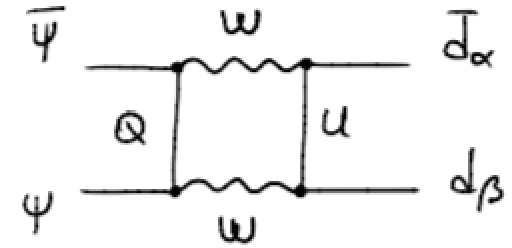
Dark Pion FCNC Decays

Amplitude can be fully adapted from ds→ νν results in [Inami, Lim 1980]





$$\mathcal{L}_{\rm eff} = \frac{G_F}{\sqrt{2}}\frac{g^2}{4\pi^2}\bar{d}_{L\alpha}\gamma_\mu d_{L\beta}\sum_{q=c,t}V^*_{q\alpha}V_{q\beta}$$

$$\sum_{i,k,j=1,2}\overline{\psi}'_i\gamma^\mu\frac{v^2}{2}\left(\frac{(U_L^\dagger\widetilde{\mathbf{Y}}^\dagger)_{ik}(\widetilde{\mathbf{Y}}U_L)_{kj}}{M_k^2}P_L+\frac{(U_R^\dagger\mathbf{Y}^\dagger)_{ik}(\mathbf{Y}U_R)_{kj}}{M_k^2}P_R\right)\psi'_j\overline{D}(x_q,x_u=0;y_k)+\text{h.c.}$$

The four-fermion interaction then followed by the factorization, which should be exact for dark QCD vs. QCD.

$$\langle\hat{\pi}_a X|\mathcal{H}_{\rm eff}|B\rangle = \langle\hat{\pi}_a|\langle X|\mathcal{H}_{\rm eff}|0\rangle|B\rangle = \frac{ig^2}{64\pi^2}V^*_{ts}V_{tb}\langle X|\bar{s}_L\gamma_\mu b_L|B\rangle\frac{p^\mu_{\hat{\pi}}}{f_a^{(a)}}\left[\frac{m_t^2}{m_W^2}\left(\log\frac{M^2}{m_t^2}-2\right)+3\right]$$

small hierarchy of scales, alternative constant terms are important (factor ~ 3 in decay rate)

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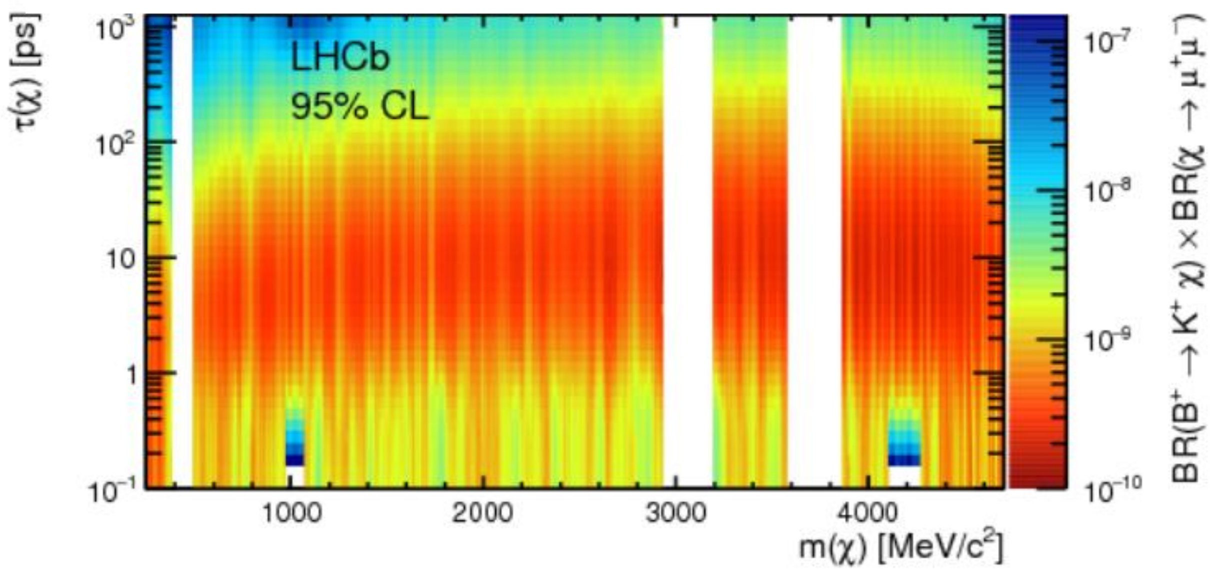
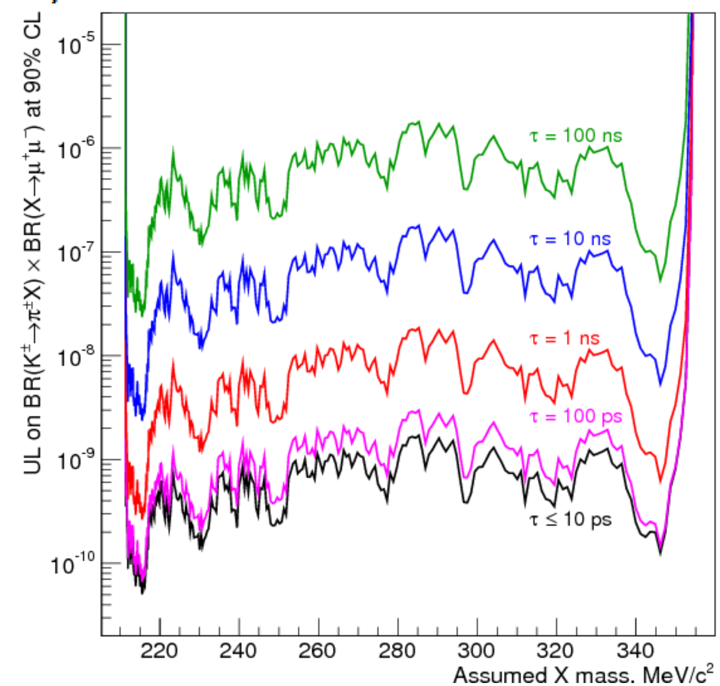
Dark Pion FCNC Decays (II)

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



[LHCb 1612.07818]



[NA48/2 1612.04723]

Kaon FCNC invisible modes give similar constraints as the LLP mode.

$$\mathrm{BR}(K^+ \to \pi^+\hat{\pi}^{(b)}) \approx 3.9 \times 10^{-11} \left(\frac{10^3\ \mathrm{TeV}}{f_a^{(b)}}\right)^2 \lambda^{1/2}_{\pi\hat{\pi}}$$

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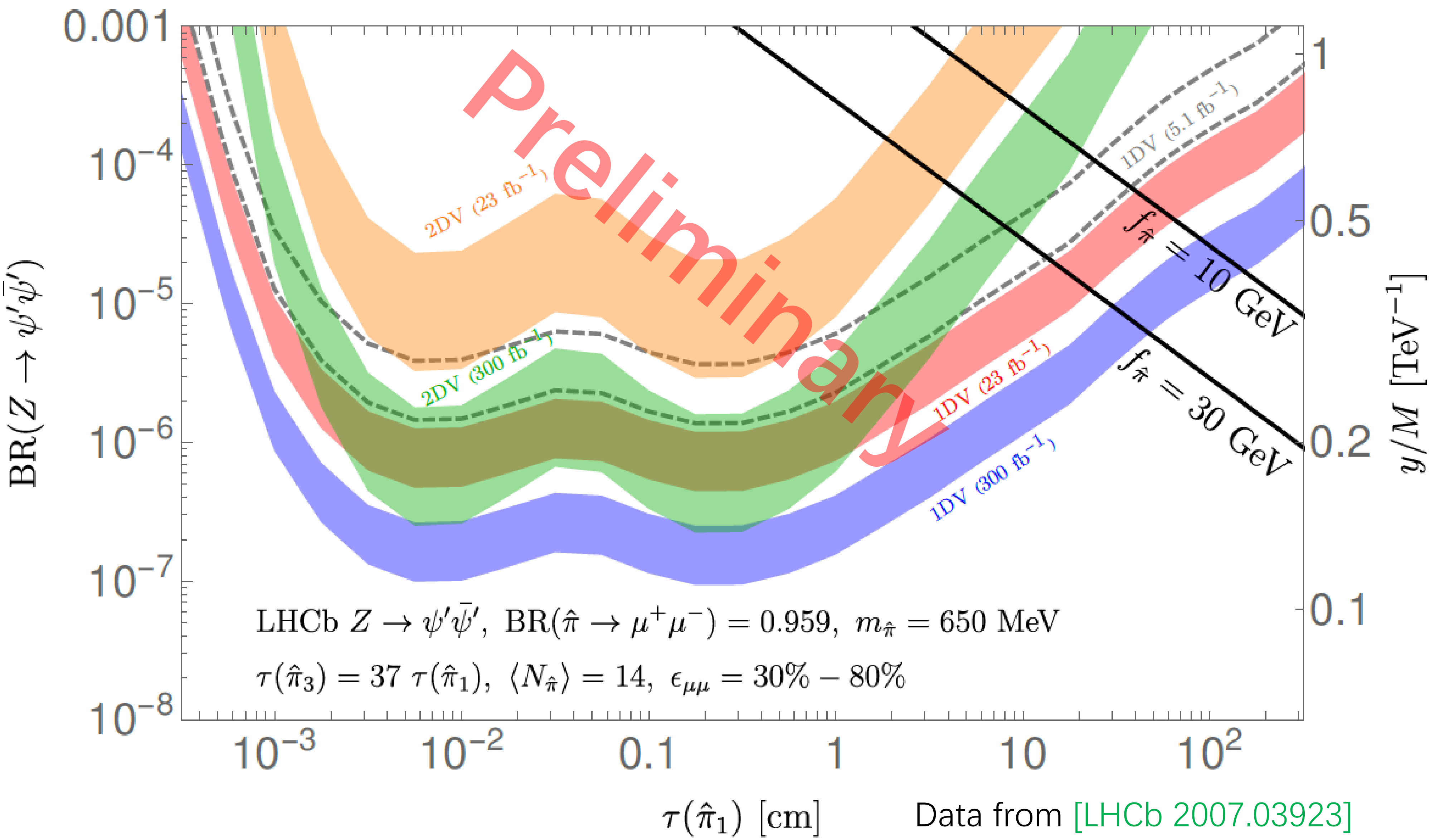
Muon-rich Dark Showers @ LHCb



Data from [LHCb 2007.03923]

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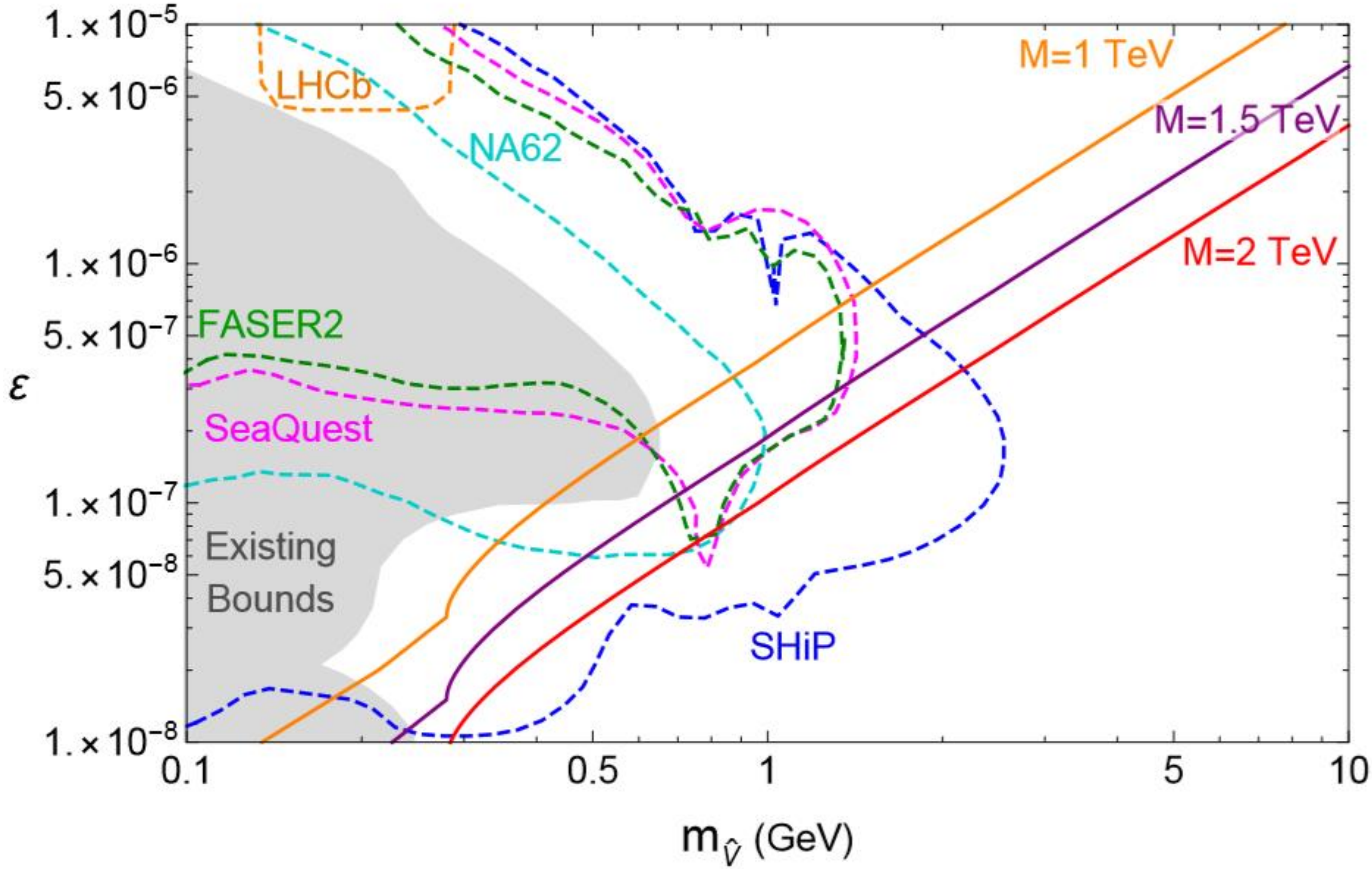
Summary

- Hidden mesons are common in neutral naturalness models and can stem from simple UV structures but provide rich phenomenology.
- We stress the importance of the Z portal.
- Theoretical results for production and decays.
- LHC (ATLAS+CMS+LHCb) plays the key role to study various scenarios, probing the O(TeV) scale.
- A lot of future options (LHC upgrades, future colliders, intensity frontier) to be fully explored.

Backup Slides

Dark Photon Mode of Production



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

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Particle Components

$$Q_{B,C} = \begin{pmatrix} t_{B,C} \\ b_{B,C} \end{pmatrix} \sim \mathbf{2}_{-1/2}\,, \qquad Q'^c_{B,C} = \begin{pmatrix} b'^c_{B,C} \\ t'^c_{B,C} \end{pmatrix} \sim \mathbf{2}_{1/2}\,,$$

- EW Doublet, mass ~ω

Scalar mass not affected by soft breaking terms

$$u^c_{B,C},\, u'_{B,C} \sim \mathbf{1}_0\,.$$

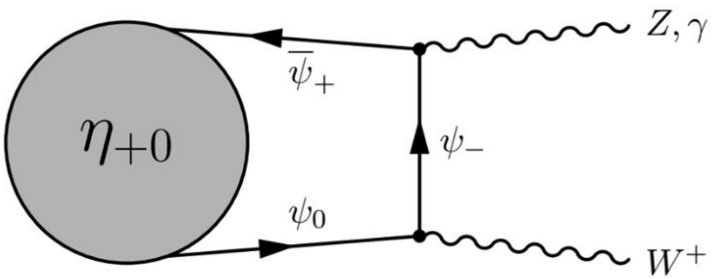
$u_{B/C}$ scalar mass suppressed by soft breaking terms.

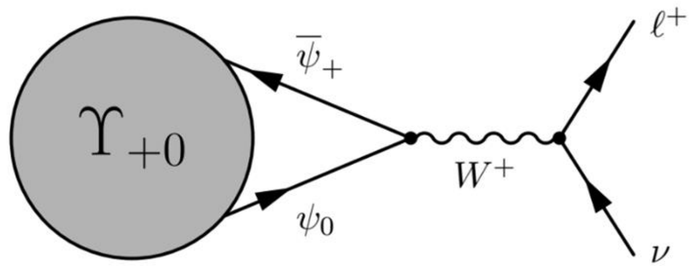
$$\Delta \equiv \sqrt{M^2 - \widetilde{m}^2}$$

The MSSM stop (scalar of Q/u_A) mass get raised by $\widetilde{m}^2$, therefore $u_{B/C}$ are also top partners.

We can assign hyper change that there are electric-neutral states

Phenomenology (Original TT)

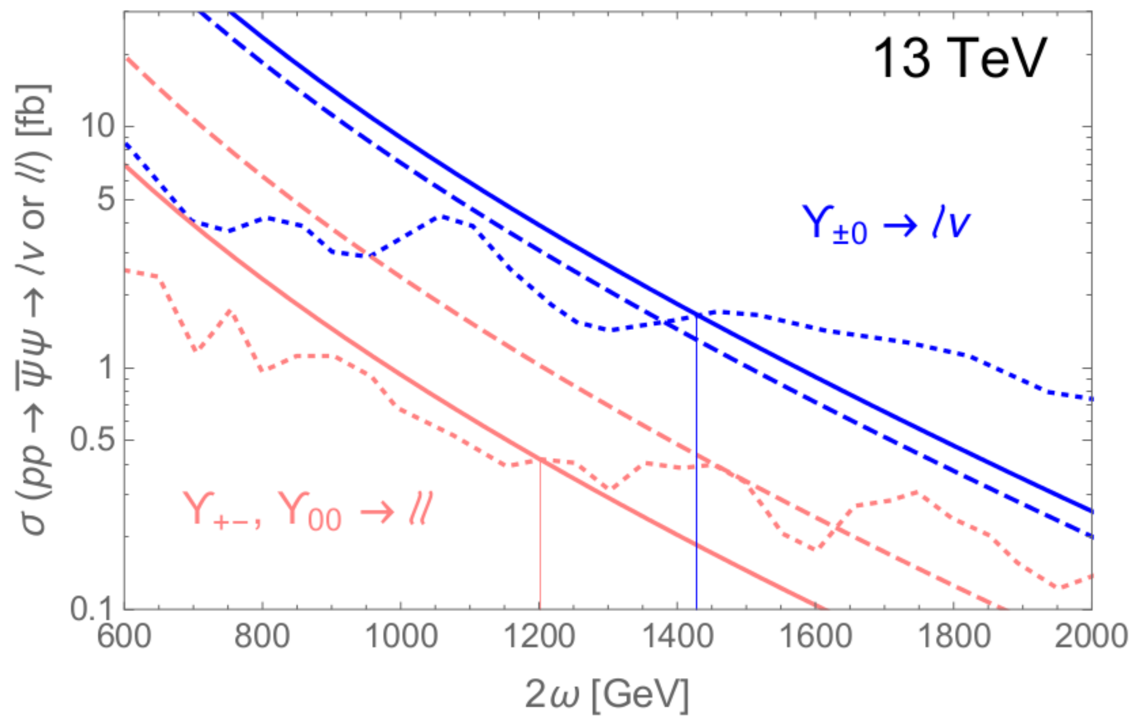




- Quirky bound states
- de-excite and annihilate e

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

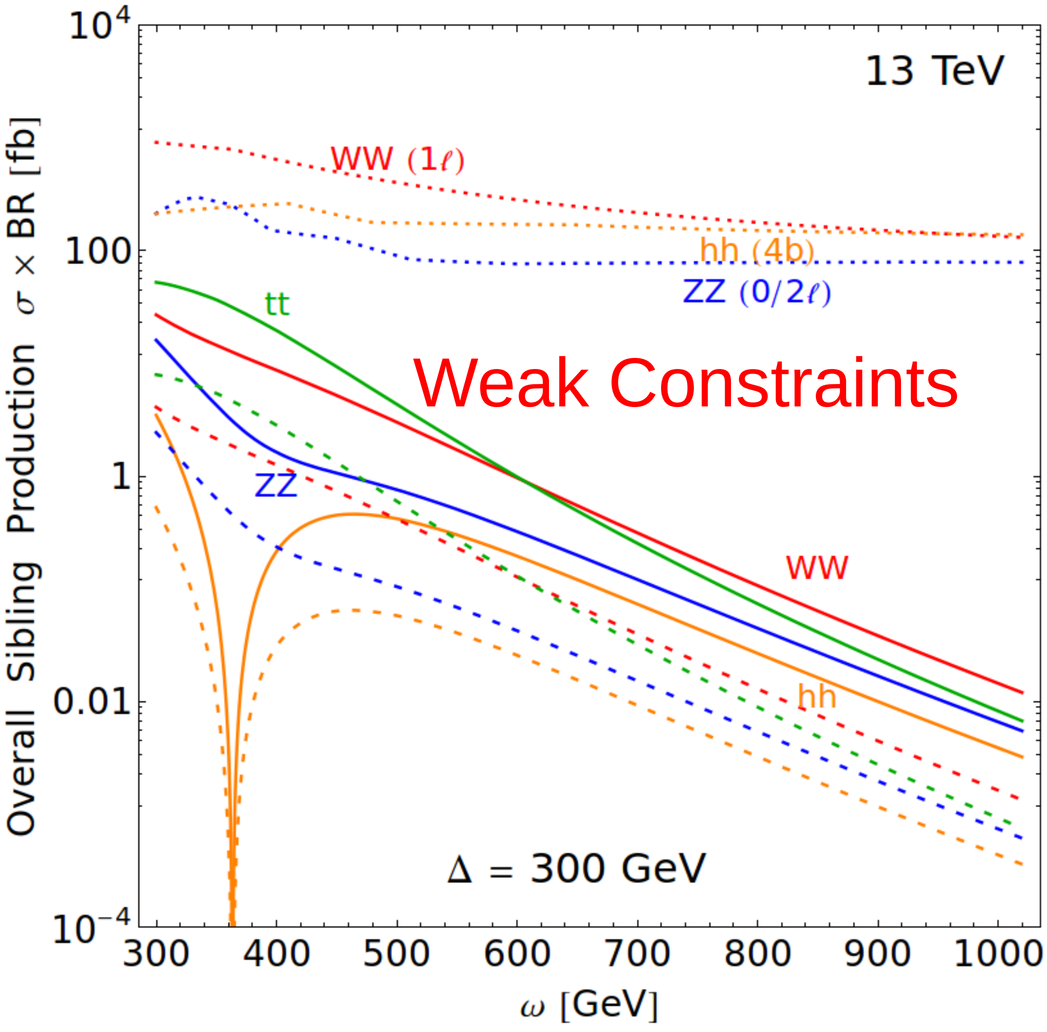
Strong constraints (~700 GeV) on ω



Phenomenology (Original TT)

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

Pair produced (as bound states) from fermion pair decays when Δ < ω



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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)

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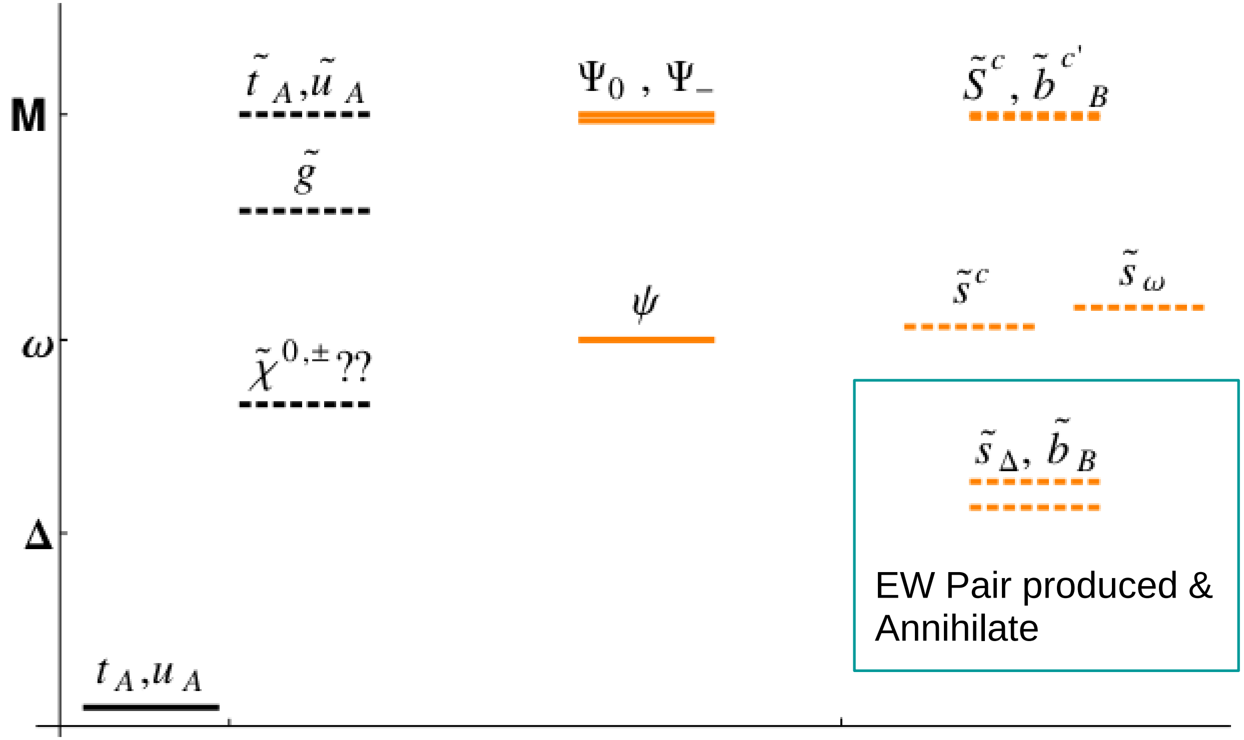
A Cartoon of Revised TT Model: The not So Interesting Case

It could be just like this (when $\Delta < \omega$):



Nothing (very) interesting happens

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

Soft SUSY Breaking Terms

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

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

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

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 $h \to$ hidden glueball branching ratio.

Higgs Potential

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

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

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

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

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

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

Hidden Quark Mixing Angles

Fermion mass matrix:
ω – M mixing

$$-\begin{pmatrix} u'_B & t_B \end{pmatrix} \mathcal{M} \begin{pmatrix} u^c_B \\ t'^c_B \end{pmatrix} \qquad \mathcal{M} = \begin{pmatrix} \omega & 0 \\ y_t h & M \end{pmatrix}$$

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

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 sinθ_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)

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

$$\mathrm{BR}(h\to\overline{\psi}_{B,C}\psi_{B,C})\approx 1.6\times10^{-6}\left(\frac{\omega}{0.5\,\mathrm{GeV}}\right)^2\left(\frac{2\,\mathrm{TeV}}{M}\right)^4$$

$$\mathrm{BR}(h\to g_{B,C}g_{B,C})\approx 1.8\times10^{-4}\left(\frac{\alpha_d}{0.17}\right)^2\left(\frac{2\,\mathrm{TeV}}{M}\right)^4\left(\frac{c}{4}\right)^2$$

Meson Decay Lifetime

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

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

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

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

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

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

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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

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

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

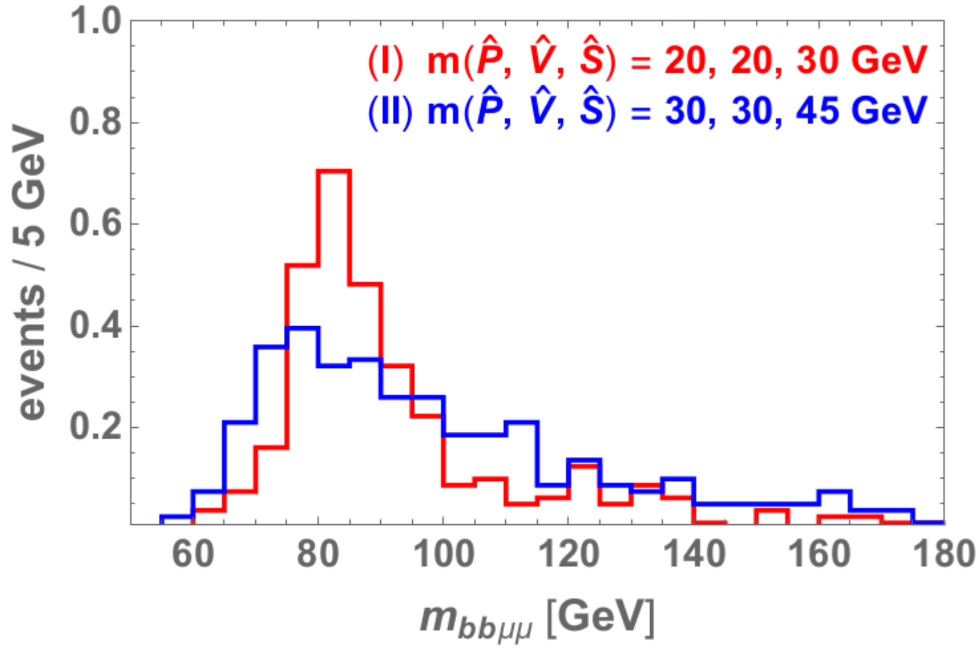
Suppressed by ~ meson mass/m_Z

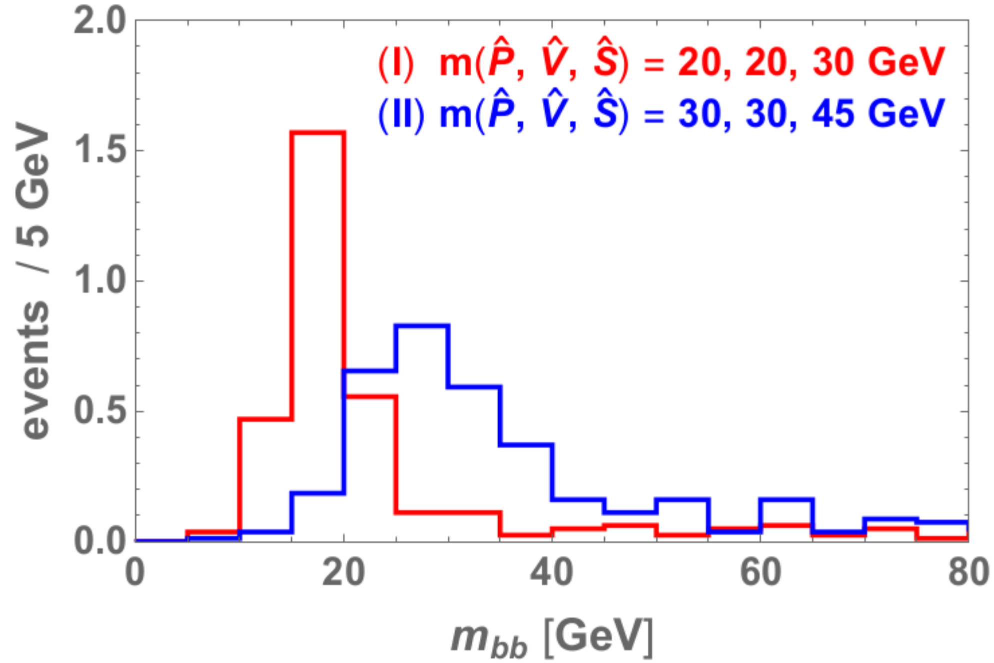
Define f_{XY} = BR(Z/h→XY)/BR(Z/h→ψψ)< 1

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





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

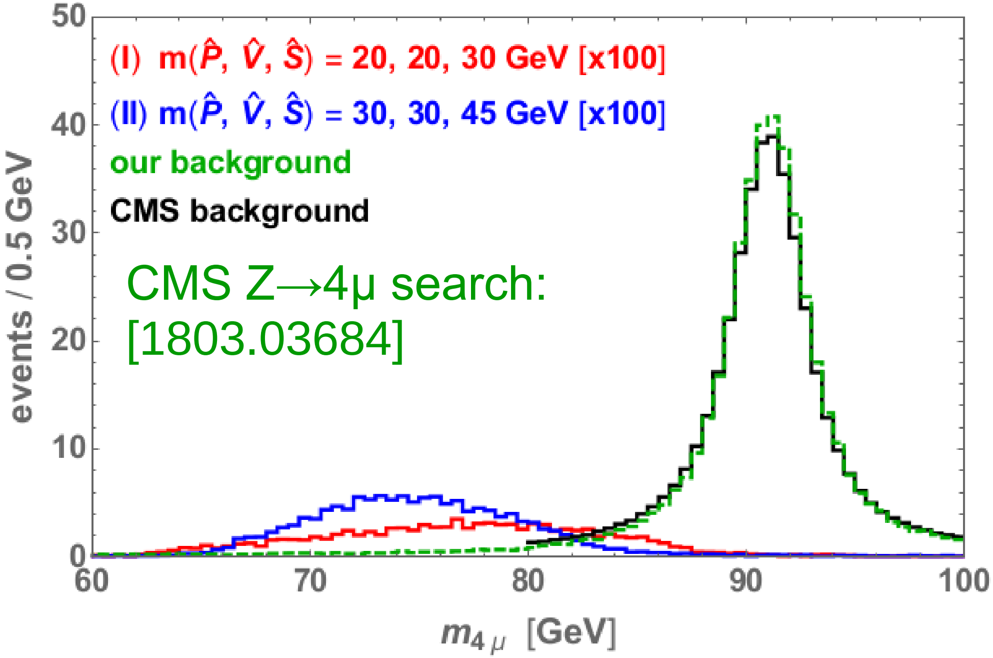
The analysis is similar to h→aa→b̄bμμ with similar cuts.
[CMS Collaboration, 1812.06359]

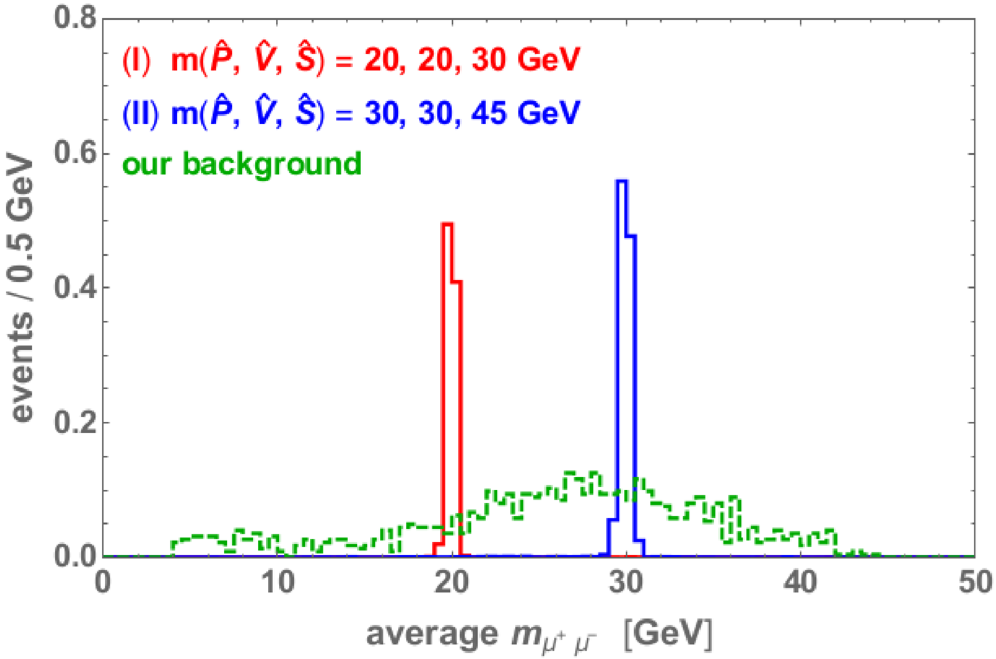
$$\text{(I)} \quad M \gtrsim 1.1,\ 1.4,\ 2.0\ \text{TeV} \left(\frac{f_{\hat{P}\hat{S}}}{1}\right)^{1/4}$$

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

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

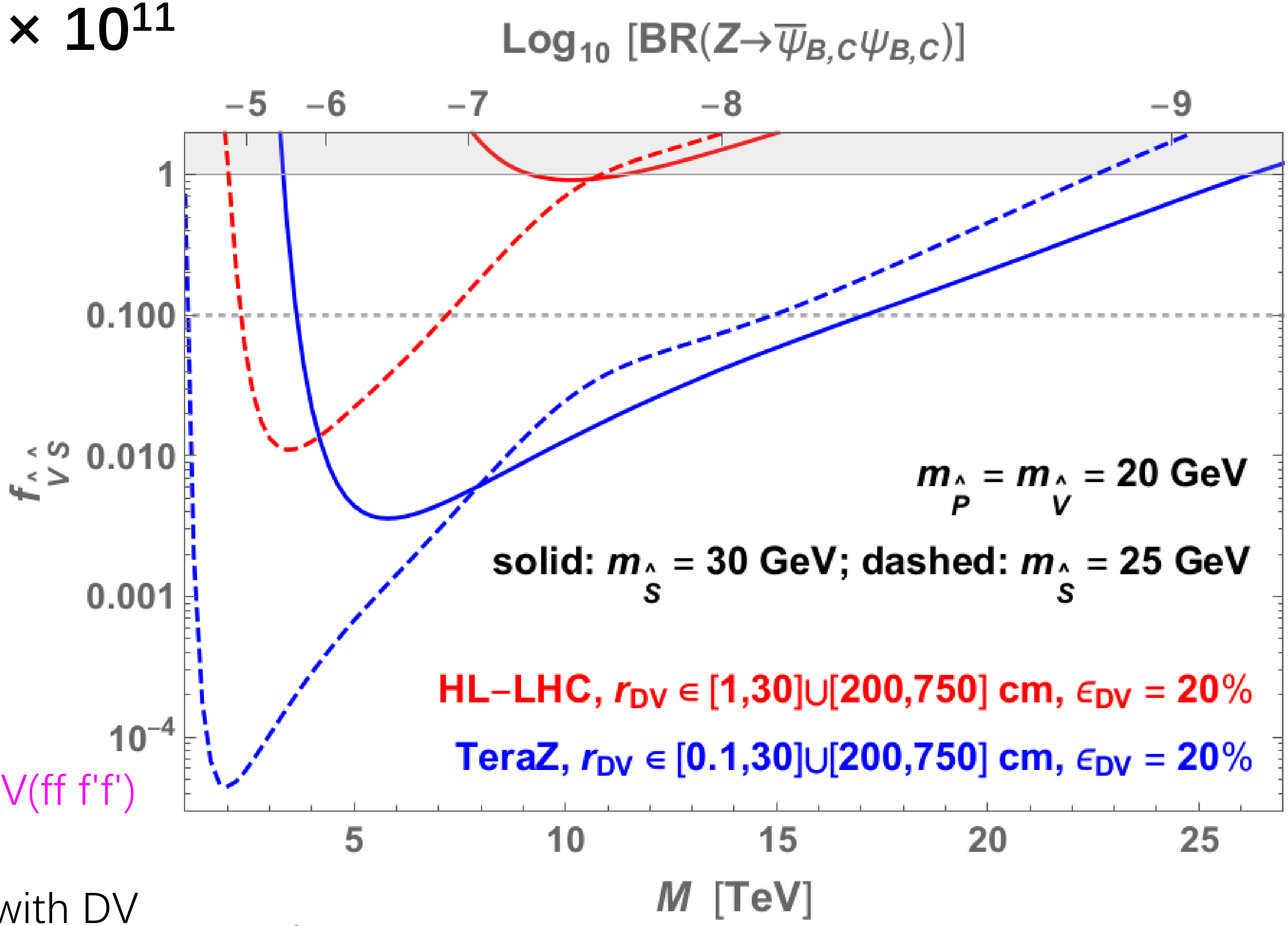
HL-LHC: ~1.8 × 10^{11} Z produced

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



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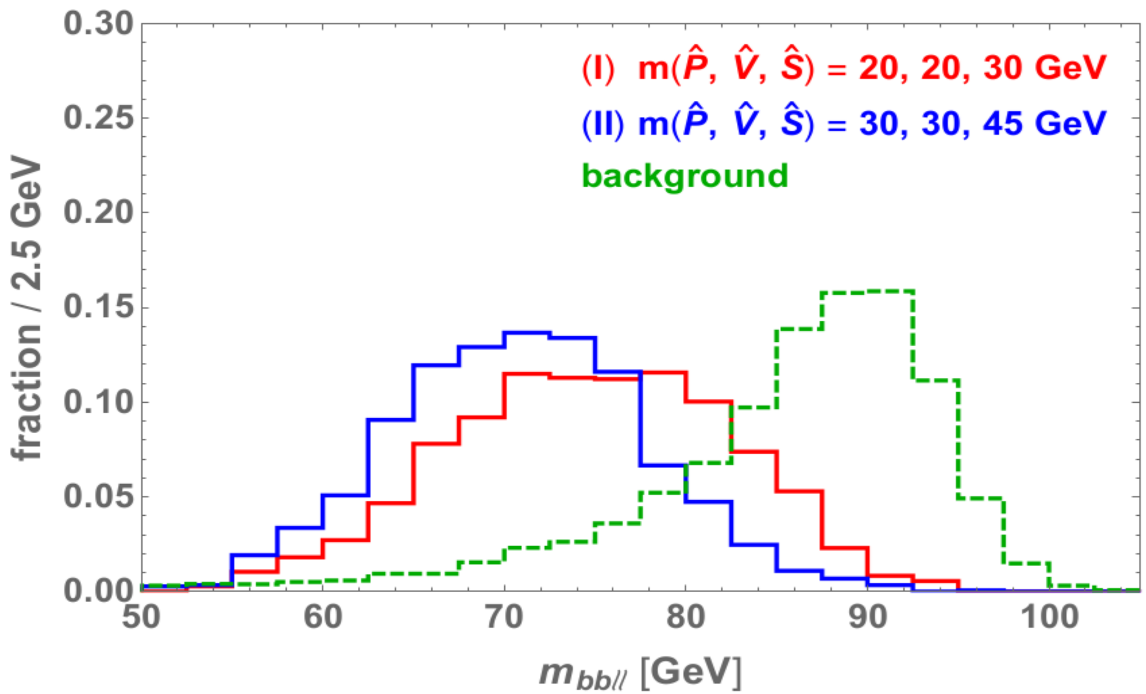
Prospects @ Z Factories

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

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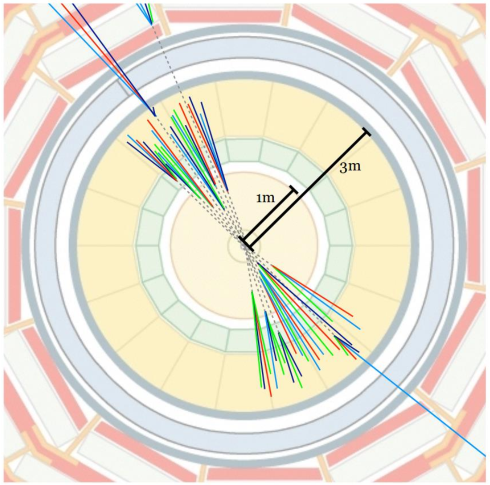
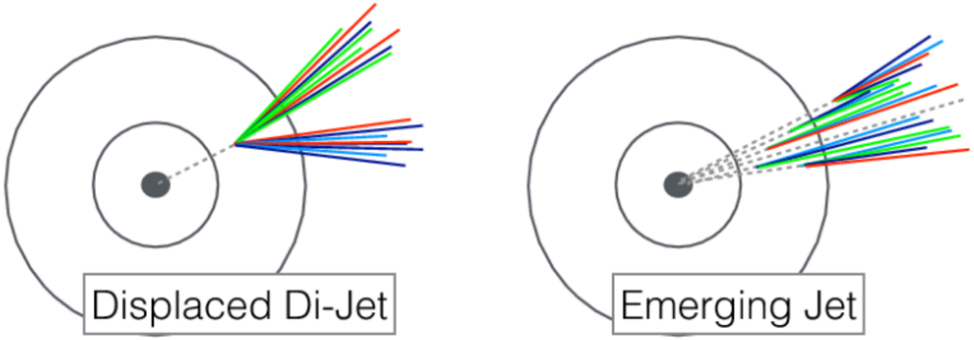
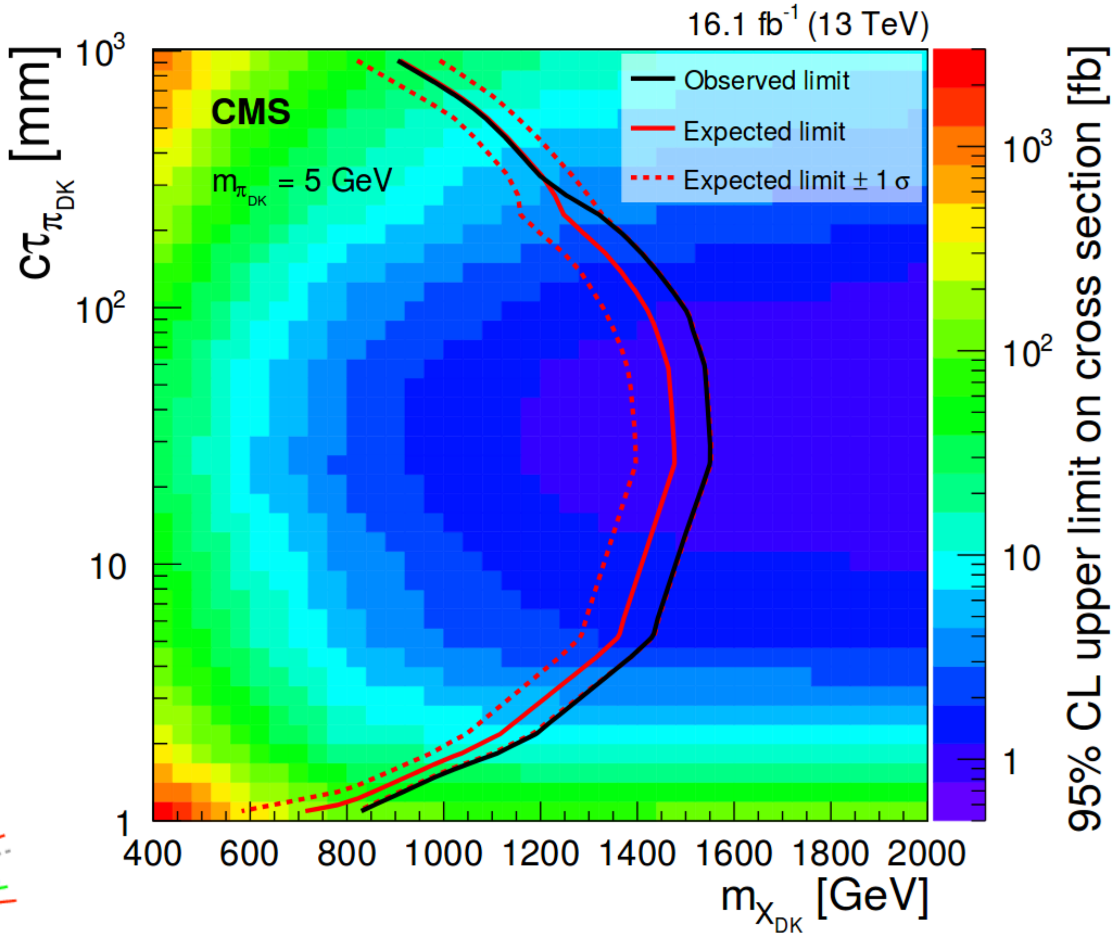
Manybody Limit – Emerging Jets

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

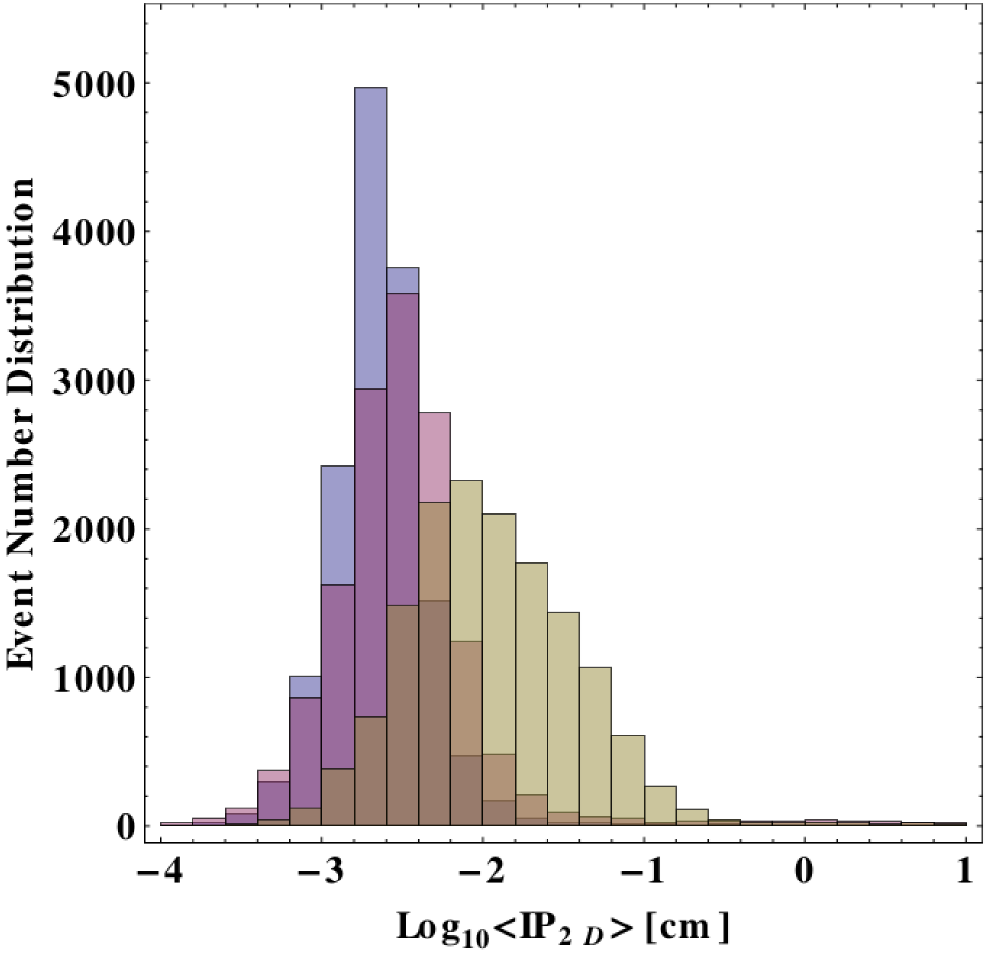


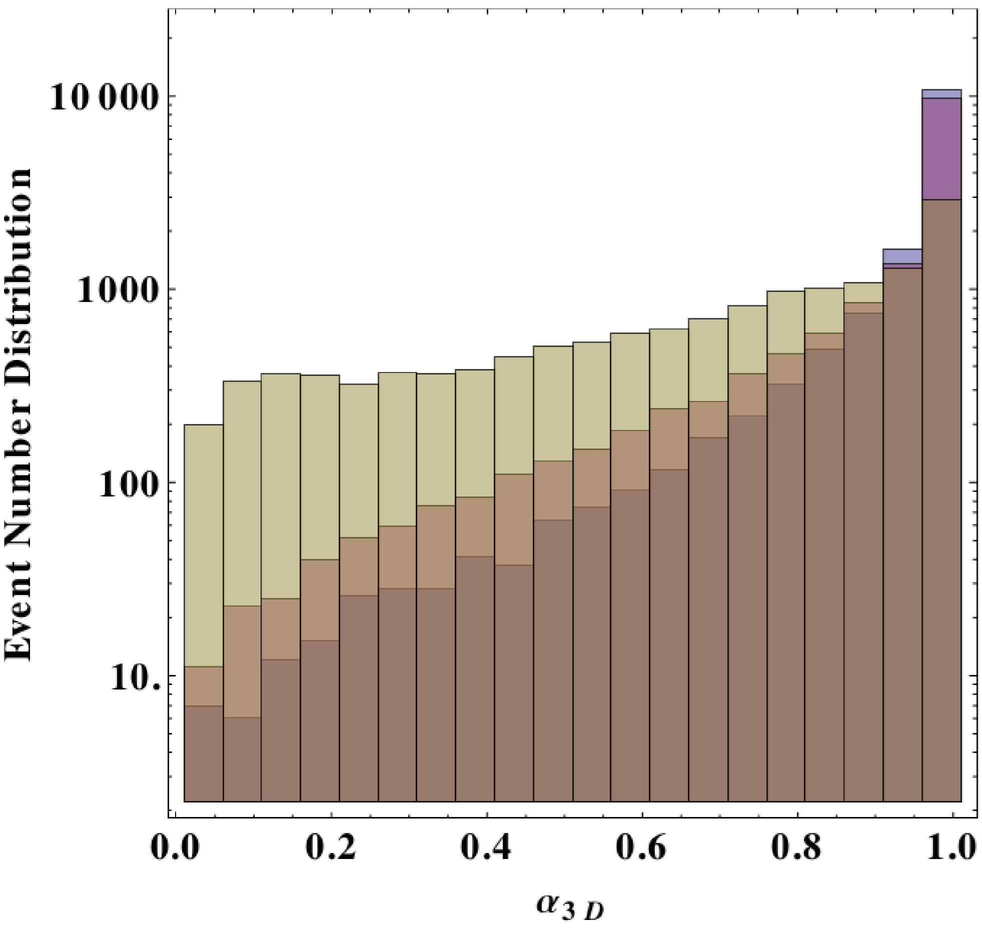




[CMS Collaboration, 1810.10069]

Emerging Jet Discrimination





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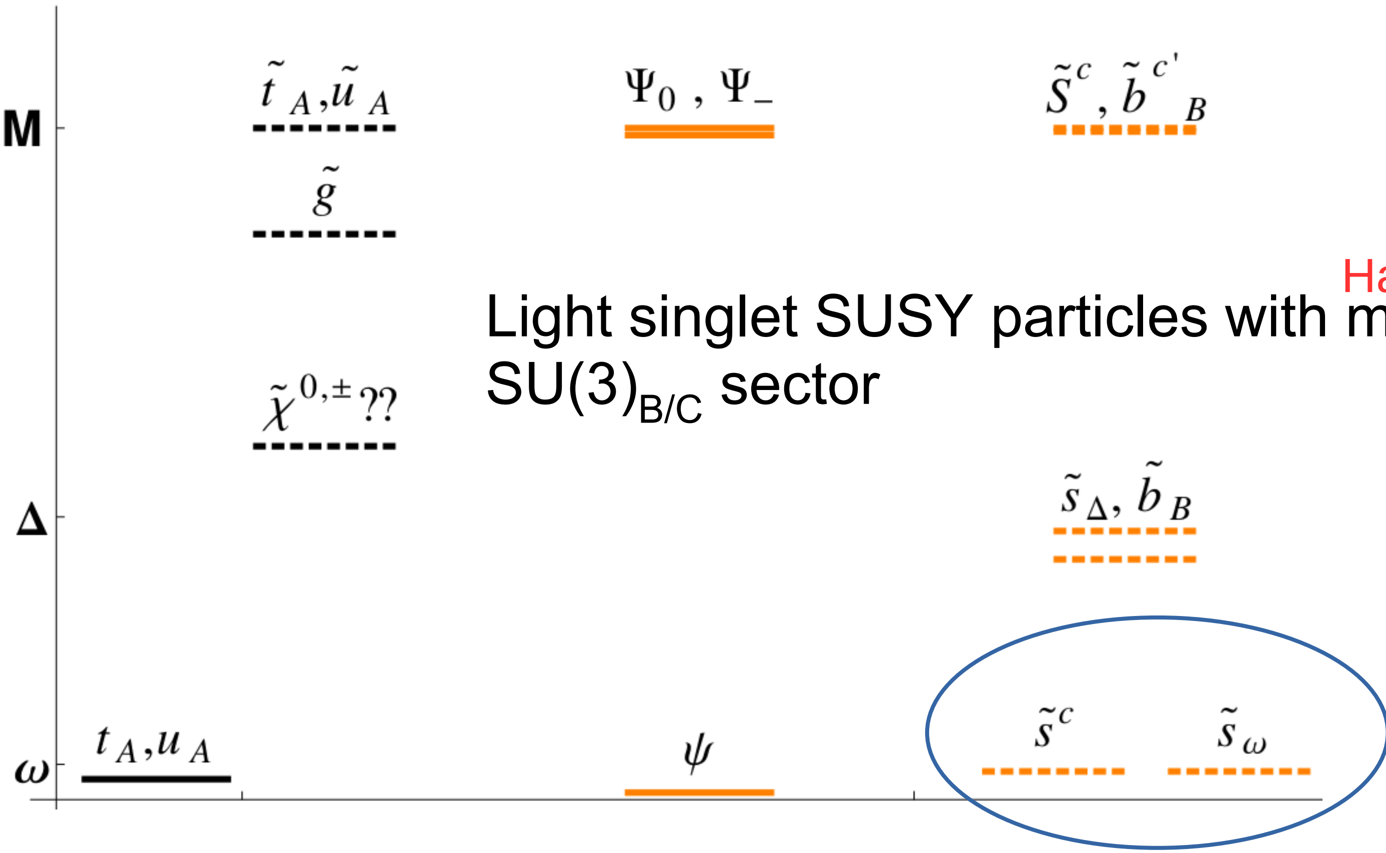
Off-Topic Thoughts About Exotic Bound States

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?

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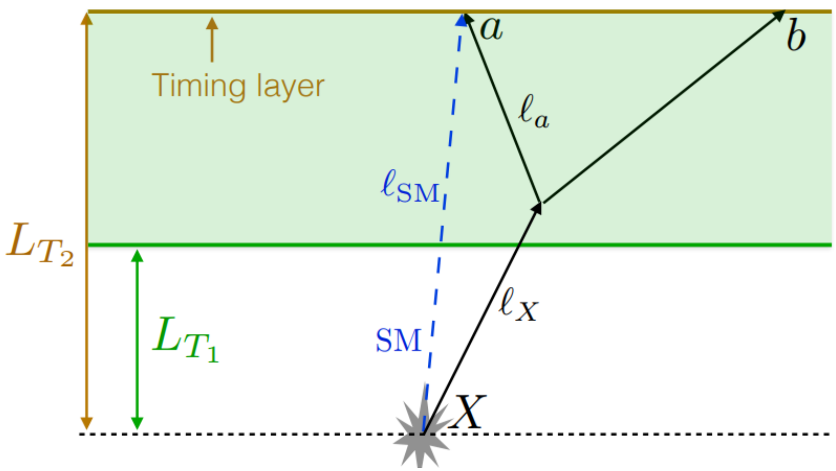
Time Resolution: A Complementary?



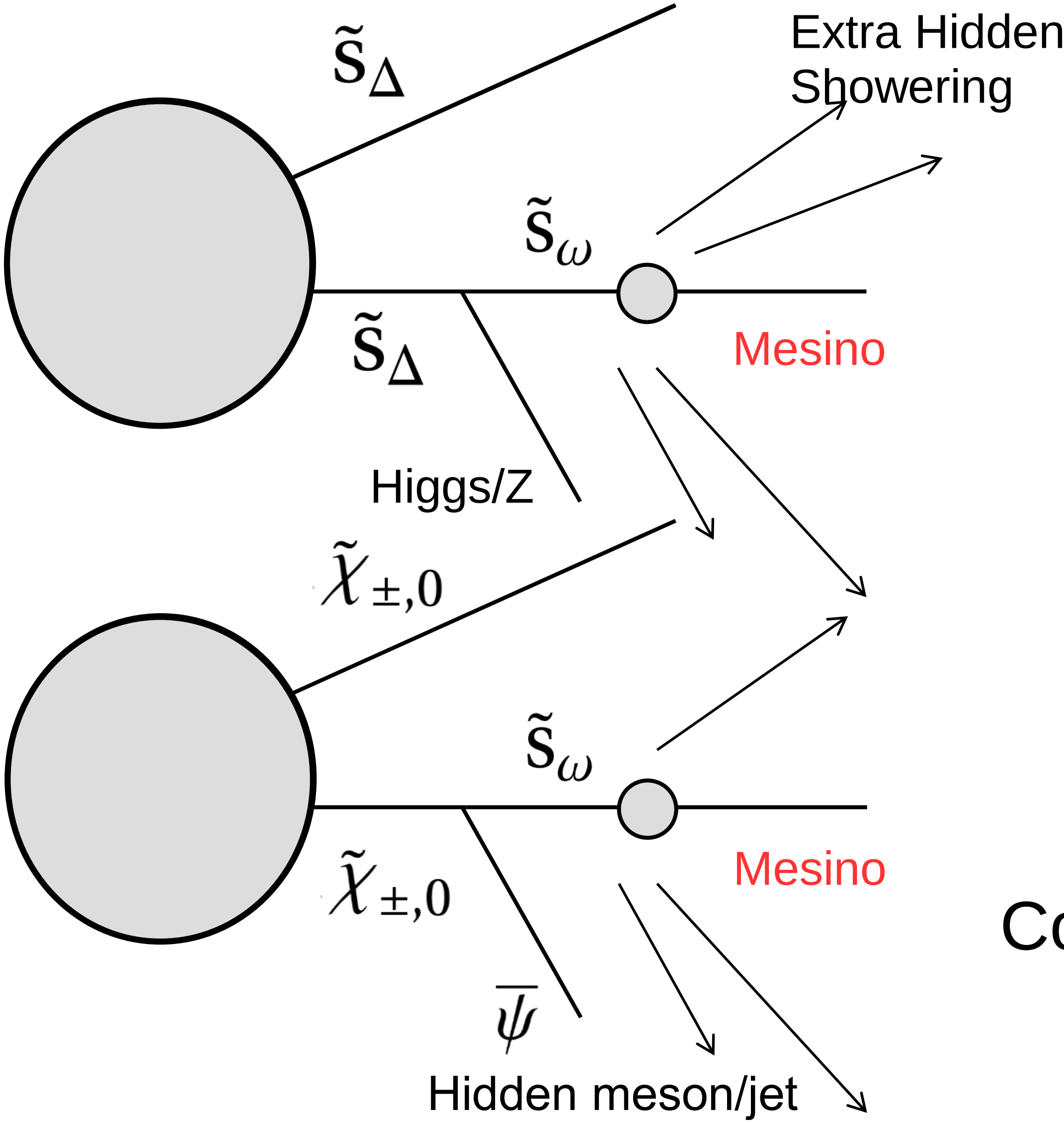
Interesting topic for the future and may work as extra discriminator for emerging jets.

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

Due to SM backgrounds and time resolution, a $\Delta t \approx O(1)$ 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

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Thermal History

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

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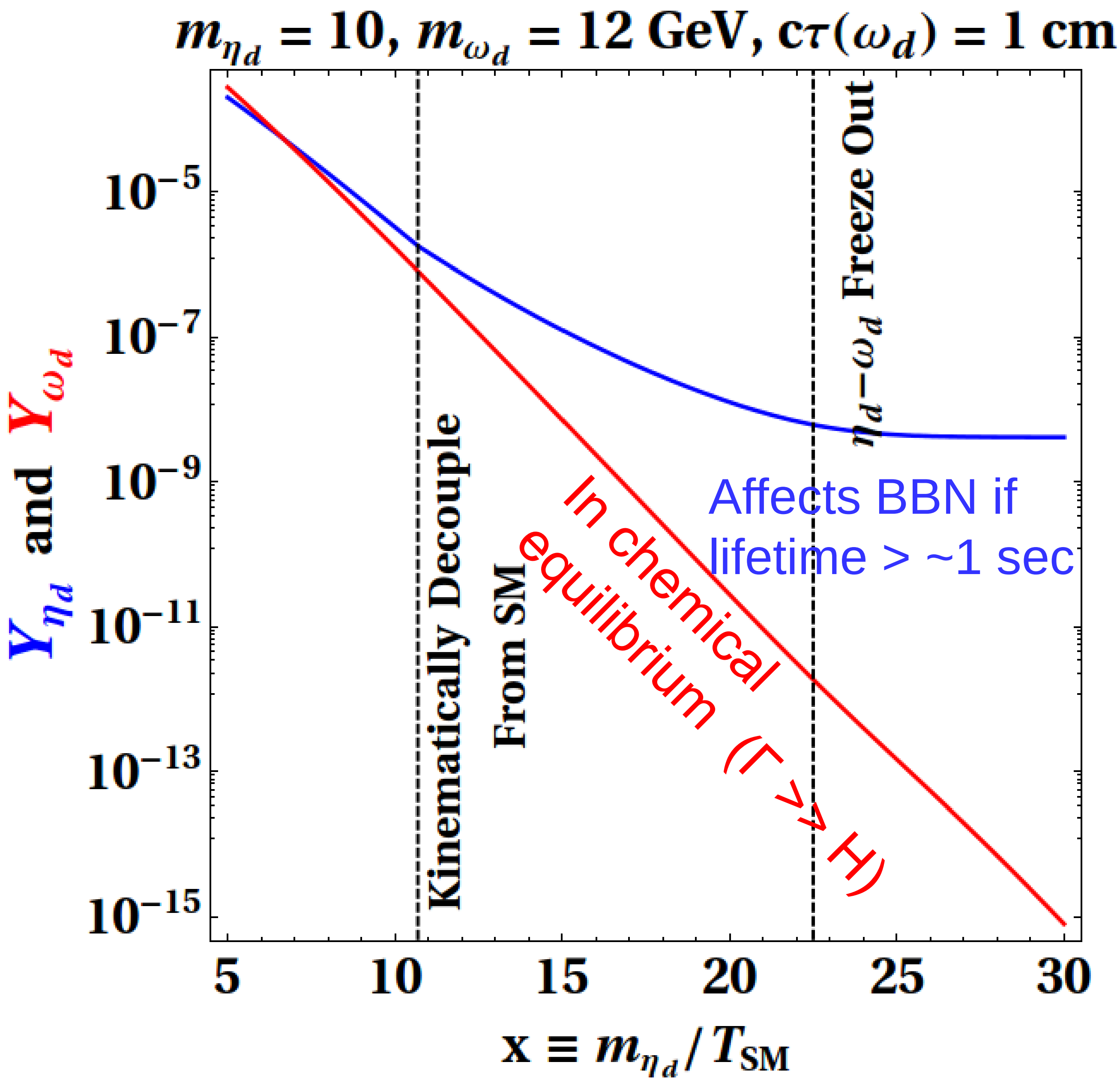
Thermal History

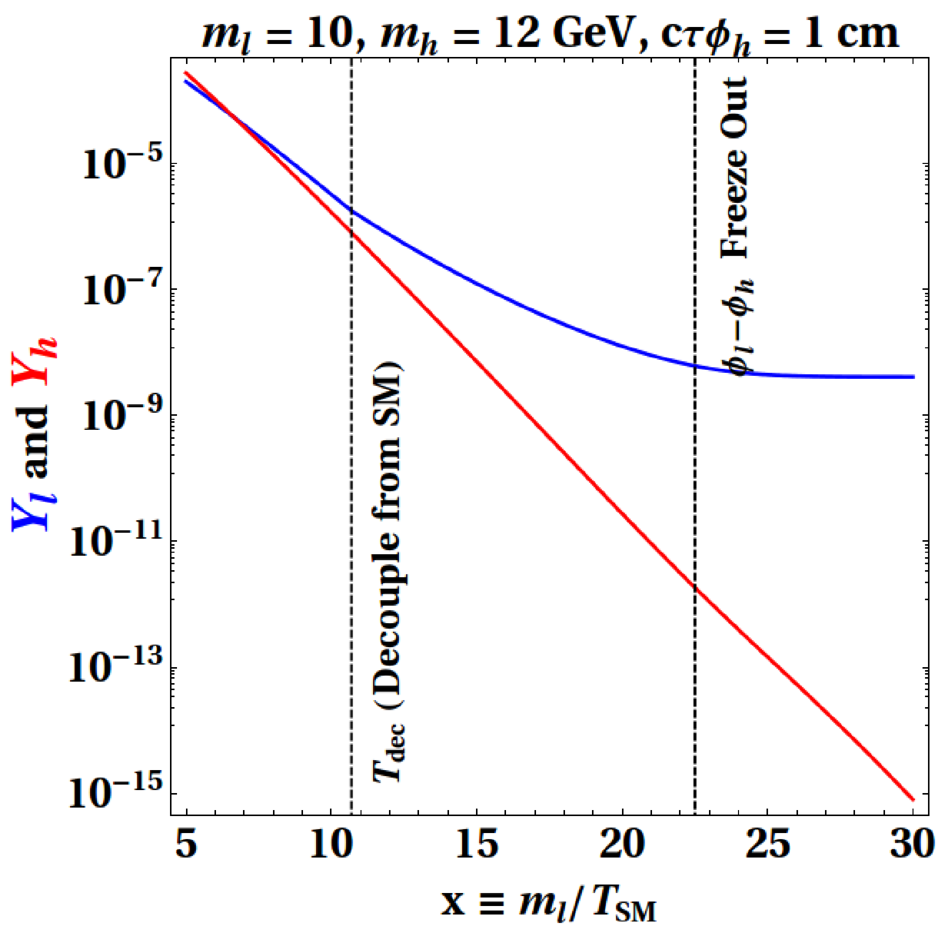


Sensitive to:

- 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).

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

Reasonable form but not always precise

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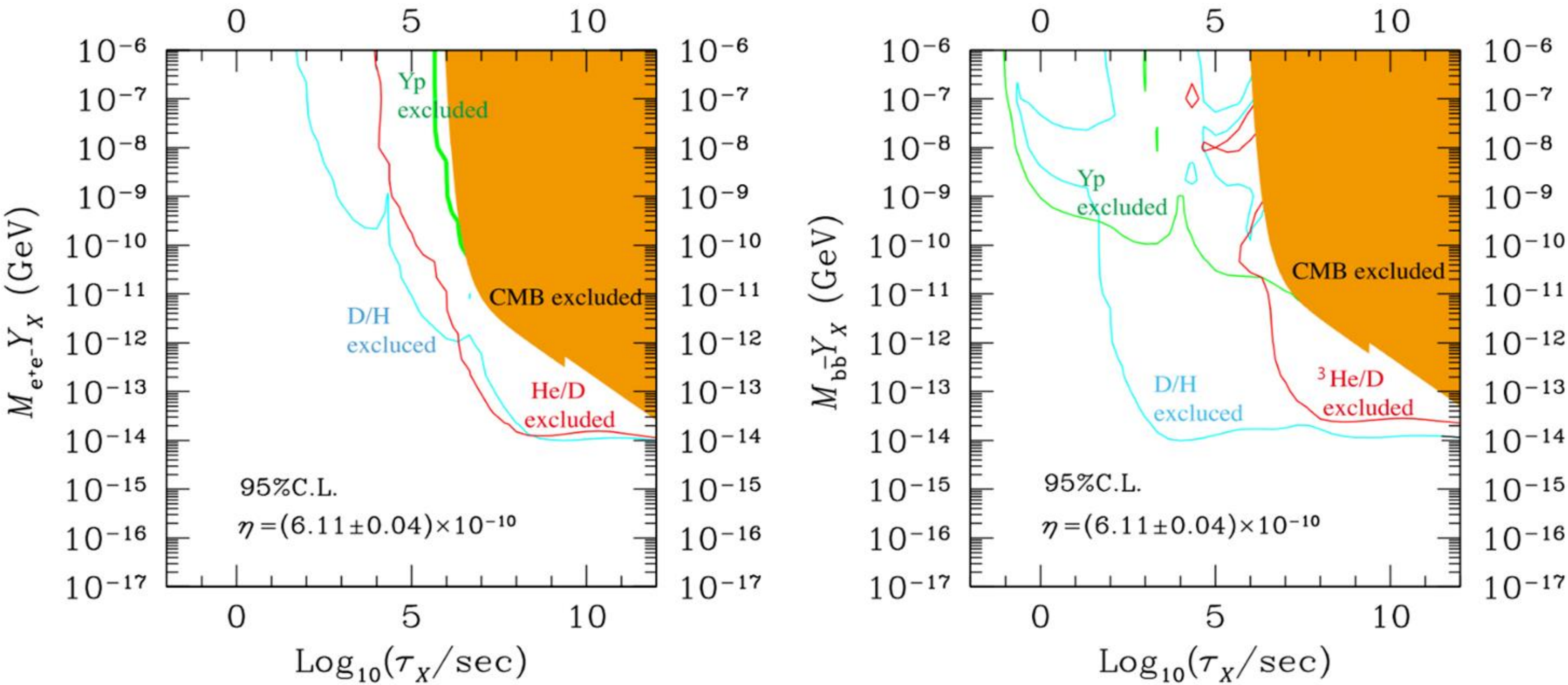
BBN Constraint



Taken from [1709.01211]