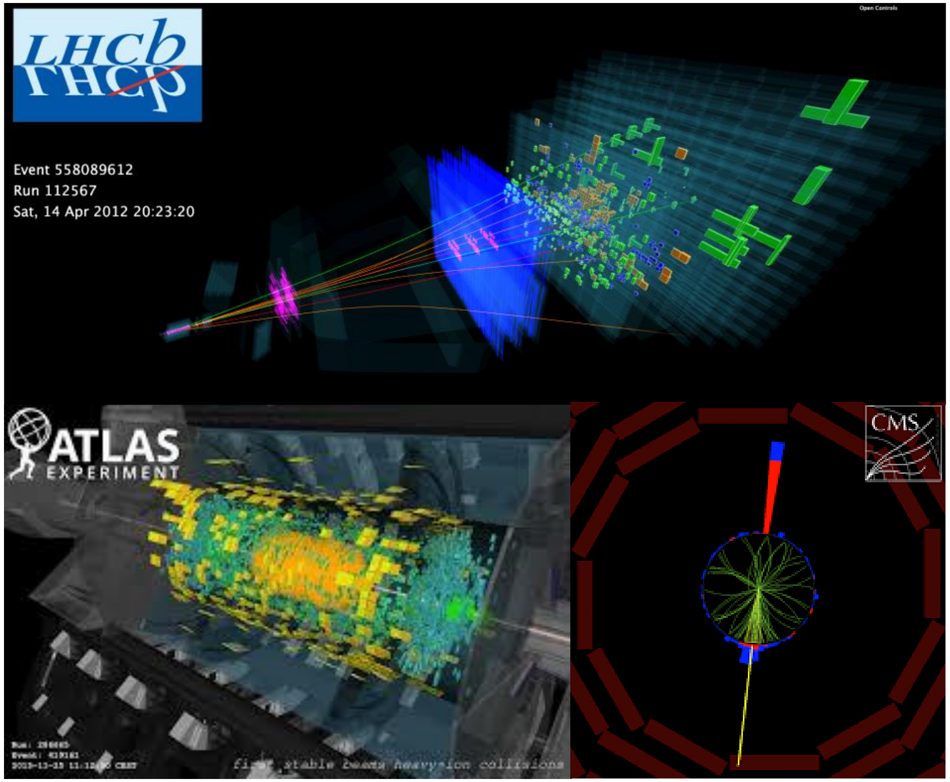
Light Hidden Mesons Inspired by Neutral Naturalness

Lingfeng Li (HKUST)

25, May, 7th workshop of the LHC LLP Community

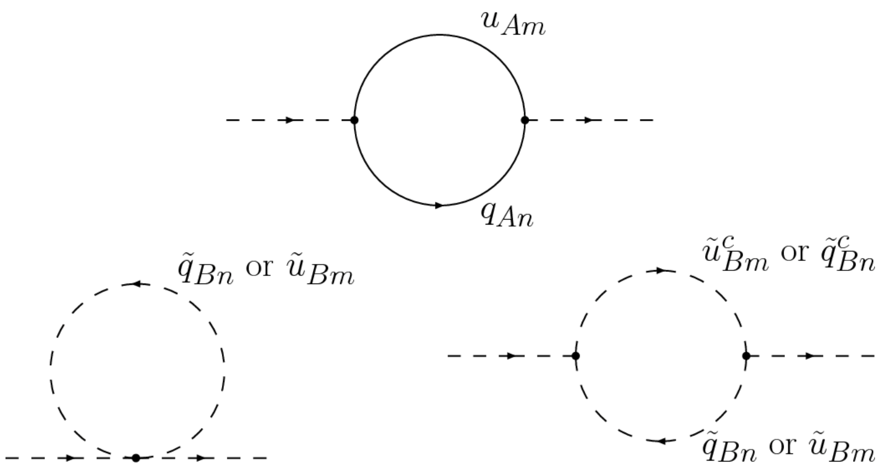
1905.03772 w/ H-C. Cheng, E. Salvioni and C. Verhaaren



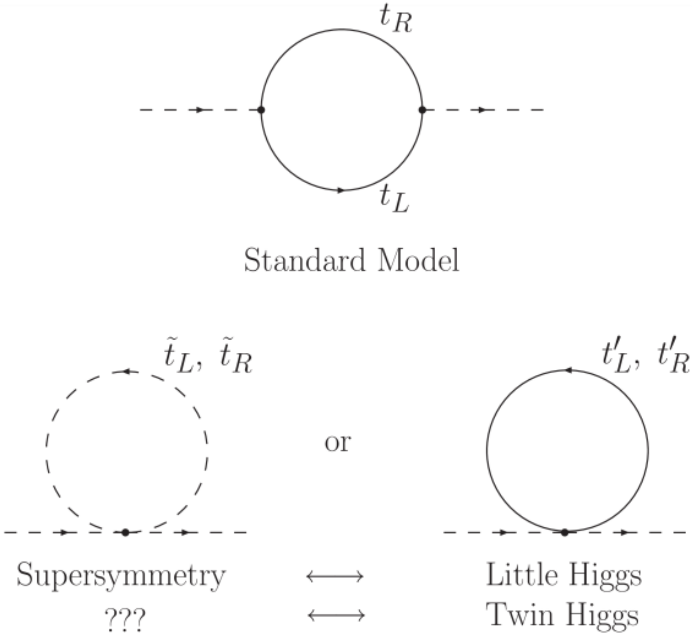
Neutral Naturalness

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]



EW Portal: Quirky bound state formed by EW charged states: **High threshold**
Higgs Portal: Exotic h->XX, X=Glueball, Twin b hadron, etc. **Low threshold**

Low threshold EW Portal Signal?

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Alternate Tripled Top (TT) Model & Accidental SUSY

The superpotential:

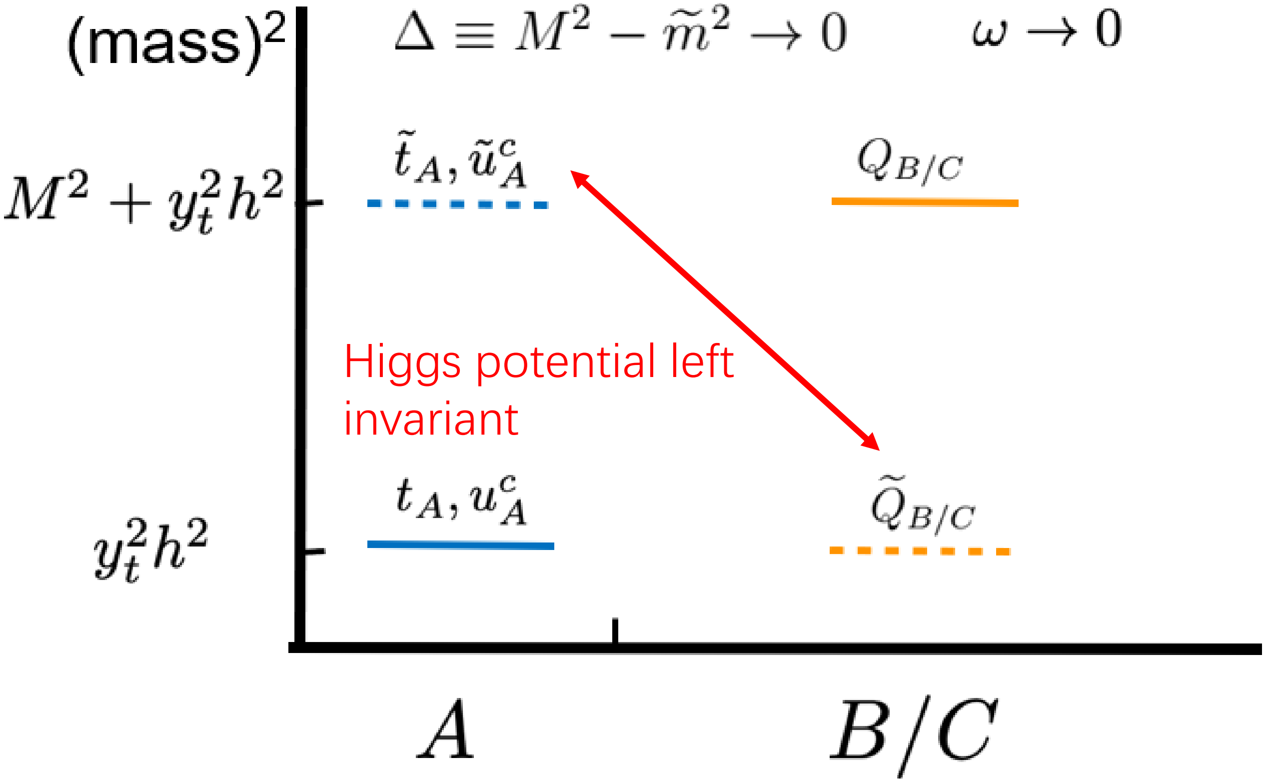
$$W'_{Z_3} = y_t(Q_A H u^c_A + Q_B H u^c_B + Q_C H u^c_C) + \omega(u'_B u^c_B + u'_C u^c_C) + M(Q_B Q'^c_B + Q_C Q'^c_C)$$

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

Q_A u^c_A **SM top sector**

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

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



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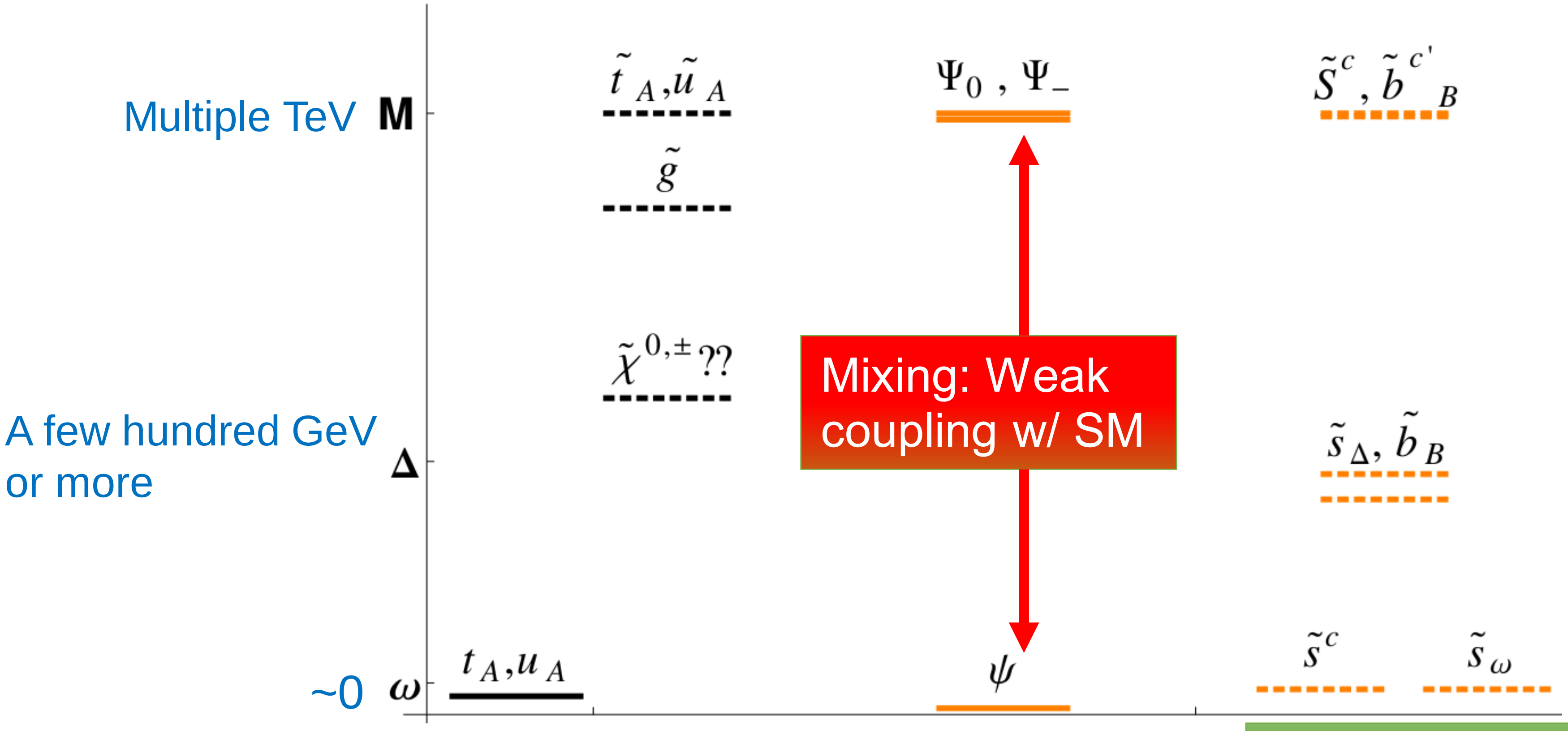
For details of the original model, see our paper [H-C.Cheng, LL, E.Salvioni and C. Verhaareen 1803.03561]

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

A Cartoon of Alternate TT Model: A Case with Much More Fun



Mixing: Weak coupling w/ SM

Hidden meson LLP

As mass > $m_h/2$, no strong constraints

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

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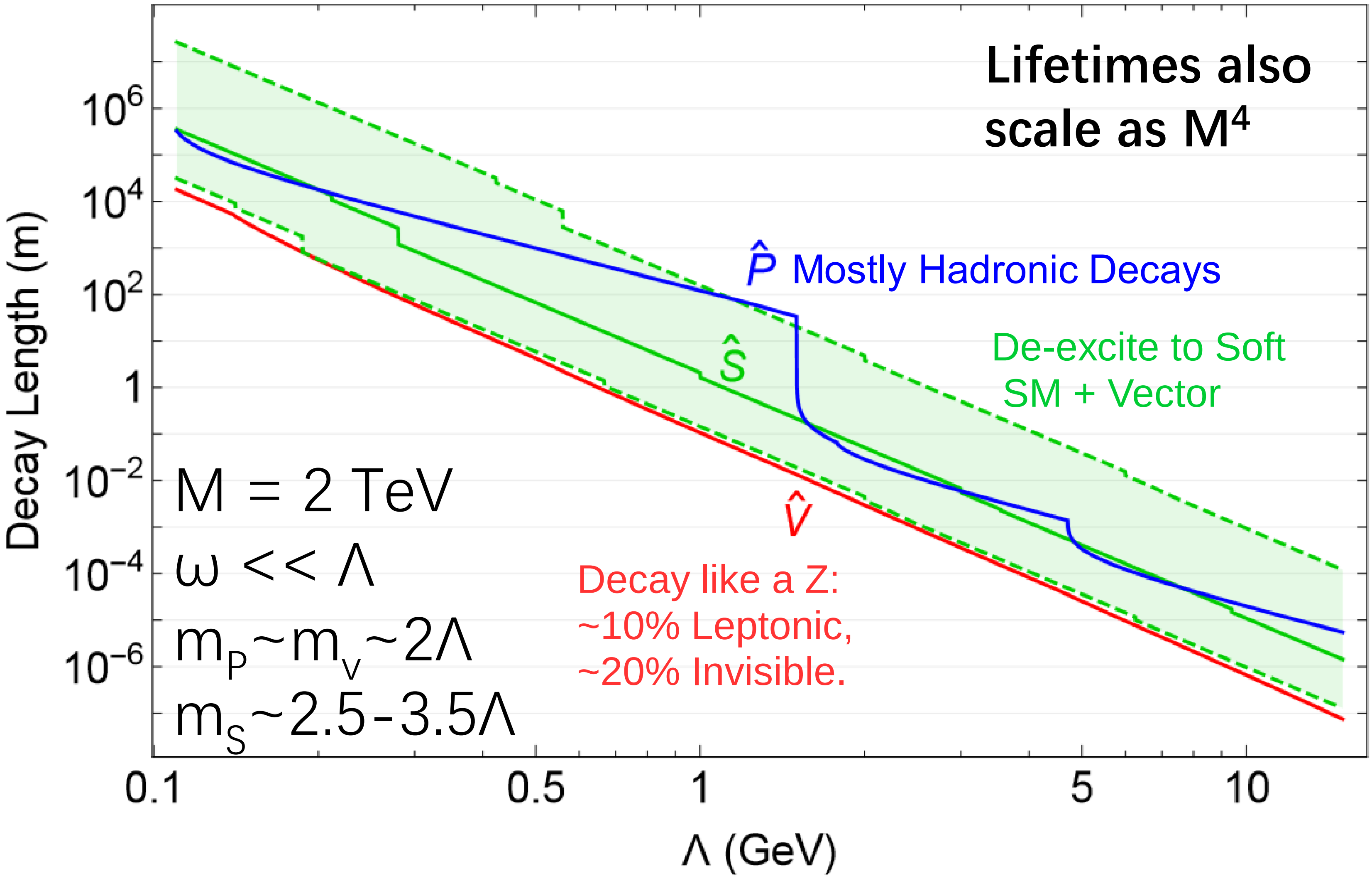
Spectrum & Decay (One-Flavor QCD)



Proper decay length of the Pseudoscalar, Vector and Scalar

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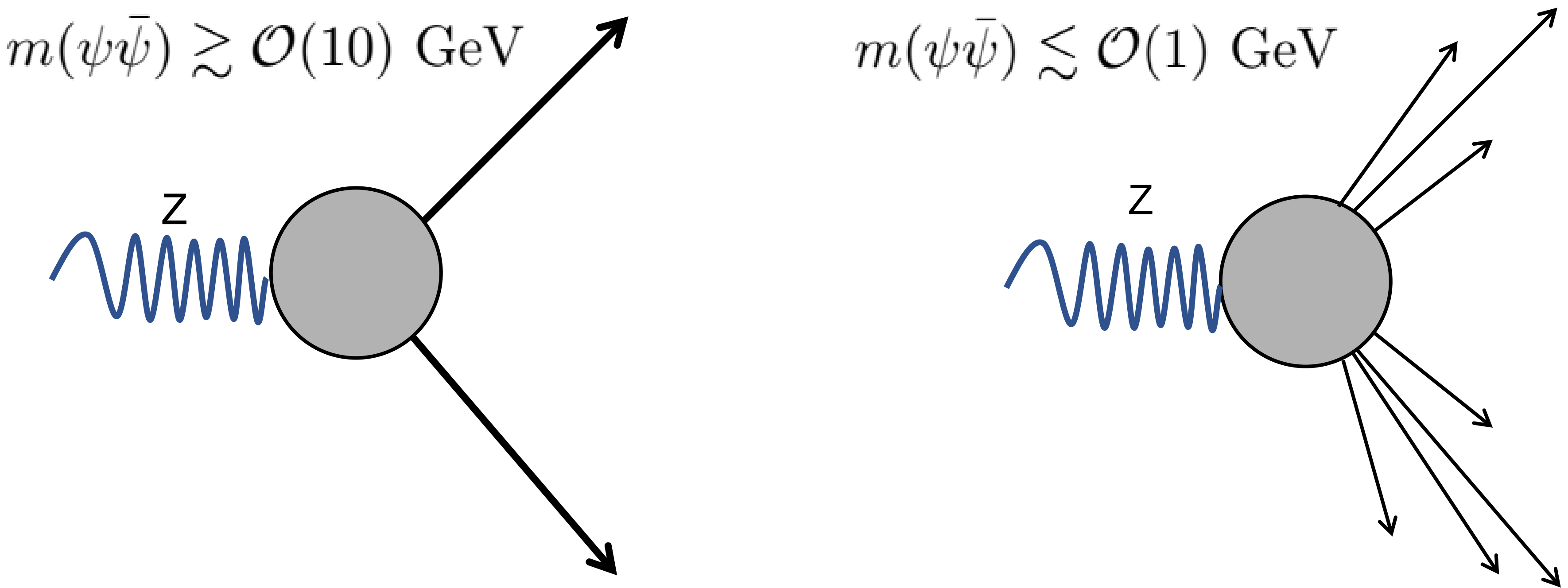
EW Portal Production (Z Exotic Decay)



Effective Z coupling:

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

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

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 produced @ LHC)

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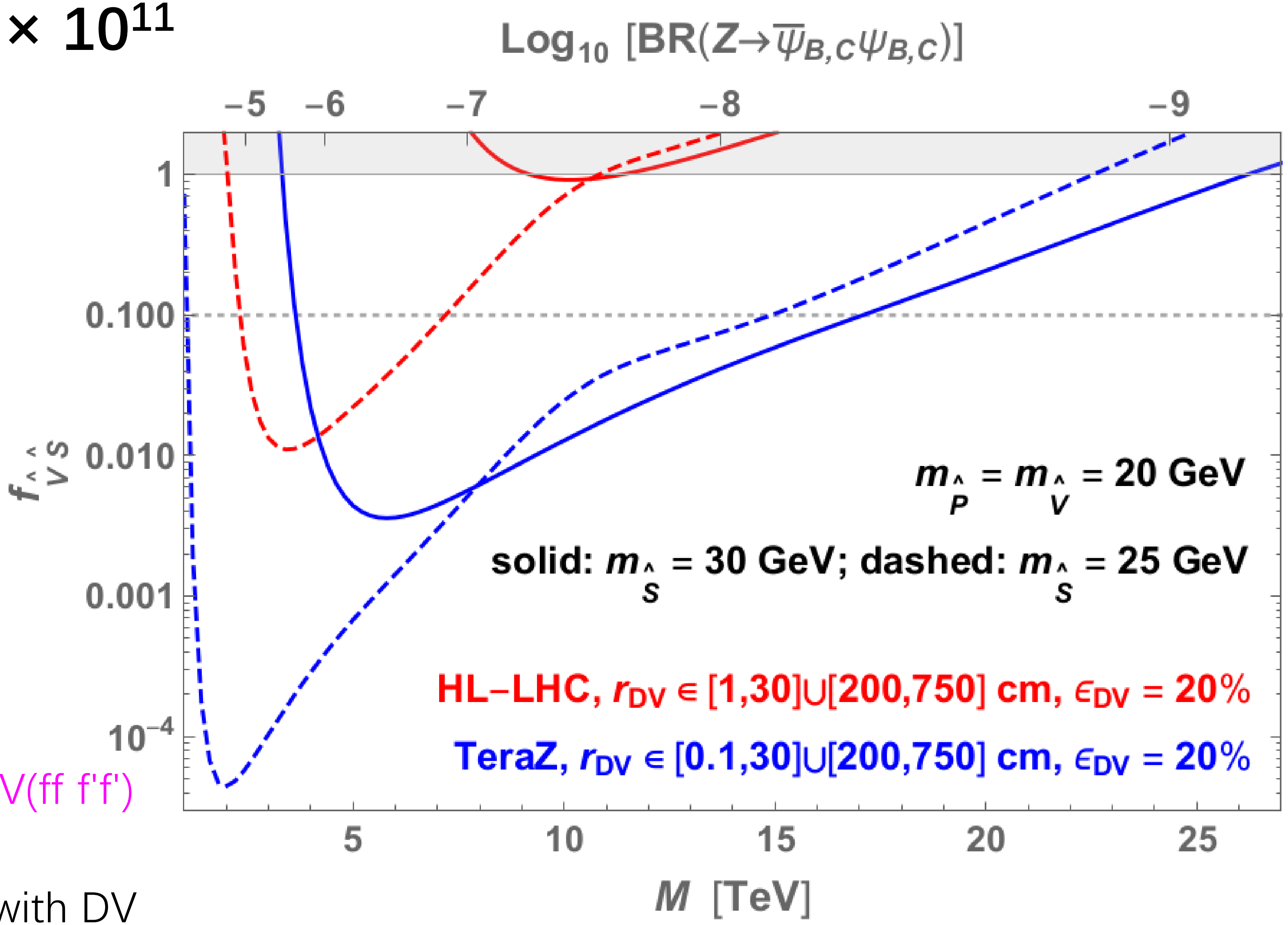
2 Body Limit: Displaced S decays

HL-LHC: ~1.8 × 10^{11} Z produced

Tera-Z: 10^{12} Z

The hidden hadronization fraction

$Z \rightarrow VS \rightarrow \mu\mu + DV(ff\ V) \rightarrow \mu\mu + DV(ff\ f'f')$



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Di-muon triggering with DV

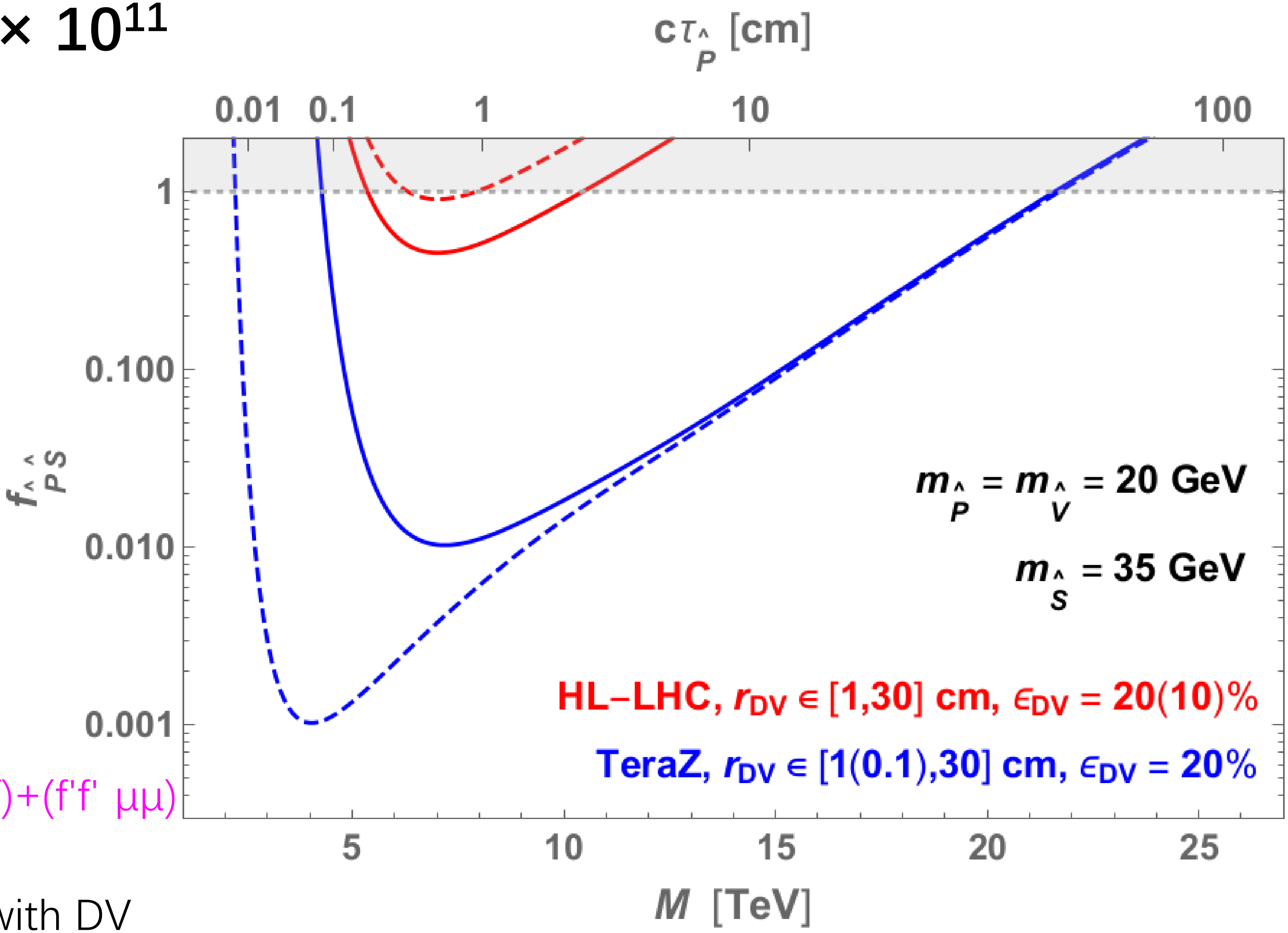
-> negligible SM backgrounds

2 Body Limit:
Displaced P decays

HL-LHC: ~1.8 × 10^{11} Z produced

Tera-Z: 10^{12} Z

The hidden hadronization fraction



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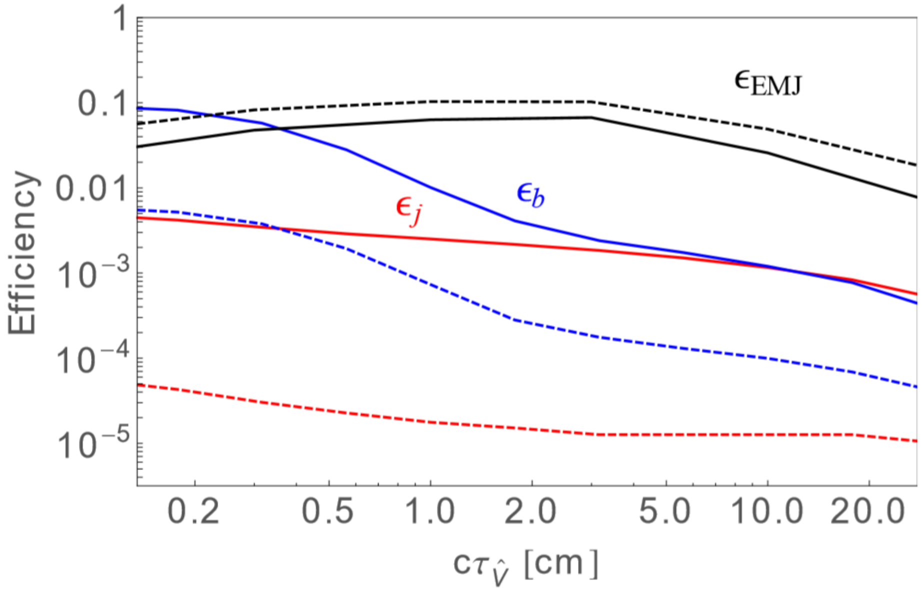
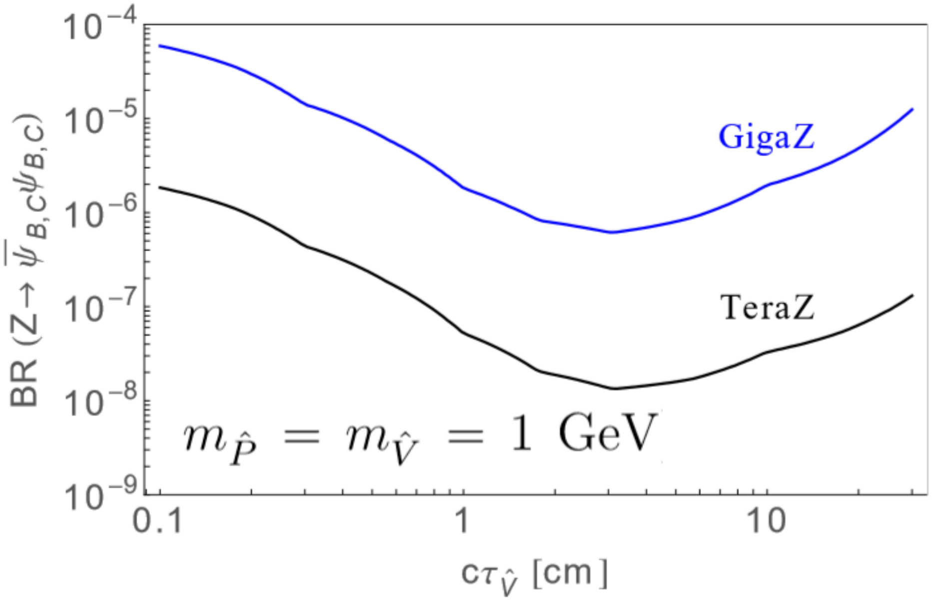
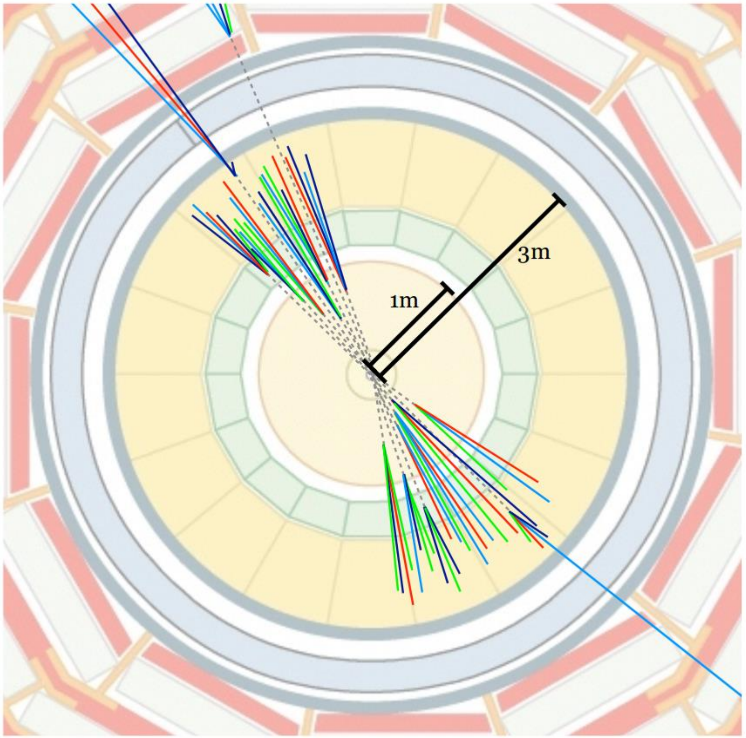
Z → PS → DV(ff)+(f'f' V) →DV(ff)+(f'f' μμ)

Di-muon triggering with DV
-> negligible SM backgrounds

Many body limit:
Emerging Jets @ TeraZ & LHC



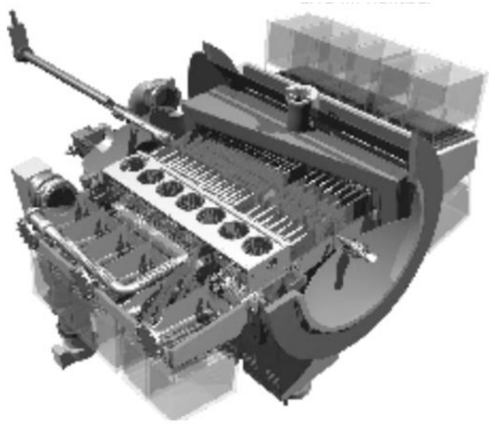




Trying to tag each jet, SM jet as bkg
[CMS Collaboration, 1810.10069]

@LHC, if relying on ZZ → ll recoil +dark jets……
exotic BR(Z) down to O(10^{-4} -10^{-5})

Many body limit: Dark Jets @LHCb



VErtex LOcator (VELO)

High Track Resolution (a few μm after upgrade)

[LHCb VELO Collaboration, 1302.6035]

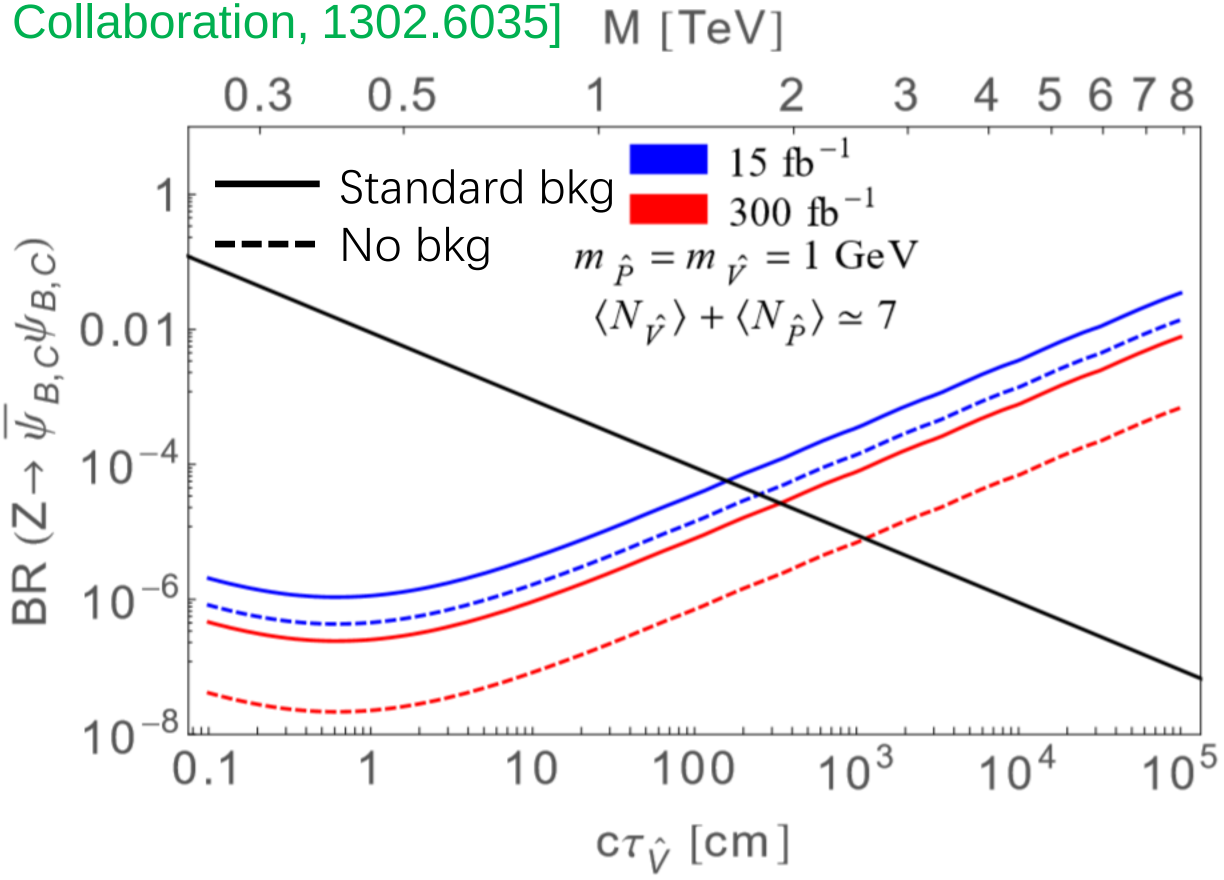
Tigger is no longer an issue

(See Alex's talk)

BR(V→μμ)~5% for m_V ~1 GeV

Find single displaced μμ vertex with stringent isolation cut

[A. Pierce, B. Shakya, Y. Tsai and Y. Zhao, 1708.05389]



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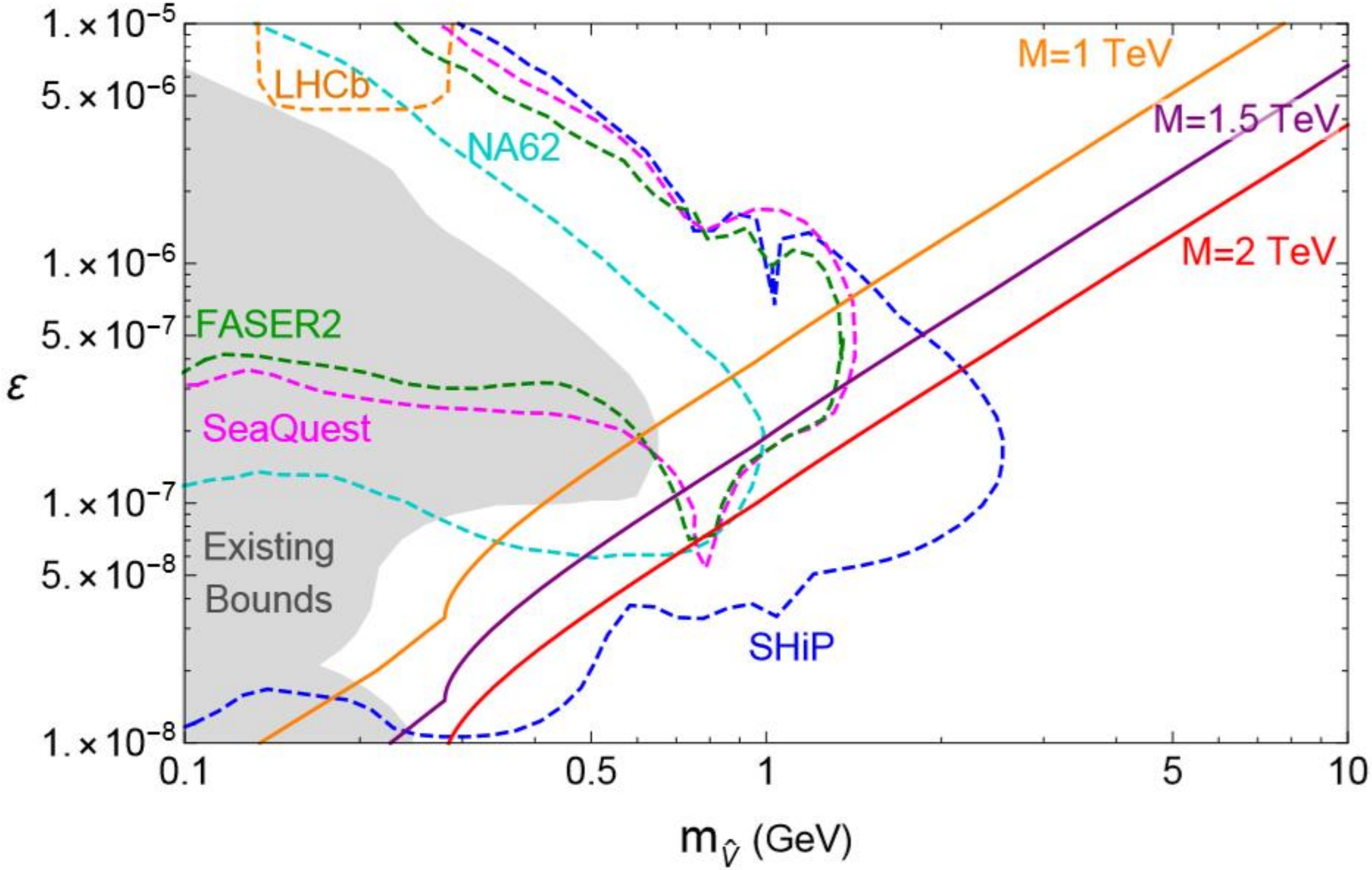
Dark Photon Mode of Production



$$\varepsilon_{\text{eff}} \sim \frac{1}{2}\sqrt{\frac{\alpha_Z}{\alpha}}\,\varepsilon_Z \approx 3.8\times10^{-7}\left(\frac{\Lambda}{1\,\text{GeV}}\right)^{3/2}\left(\frac{m_{\hat{V}}}{2\,\text{GeV}}\right)^{1/2}\left(\frac{2\,\text{TeV}}{M}\right)^{2}$$

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Dark Pion: 2 flavor or more (in work)

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:

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

$\boldsymbol{Y}$, $\widetilde{\boldsymbol{Y}}$, $\boldsymbol{\omega}$, and $\boldsymbol{M}$ are all $N \times N$ matrices in the flavor space

Z & Higgs exotic decays now depending on the Yukawa structure

$$\mathrm{BR}(Z \to \hat{f}\hat{f}) \approx 1.1 \times 10^{-5} \left\{ \mathrm{Tr}\left[\left(\boldsymbol{Y}^\dagger\boldsymbol{Y}\right)\right]^2 + (\boldsymbol{Y} \to \widetilde{\boldsymbol{Y}}) \right\} \left(\frac{2\,\mathrm{TeV}}{M}\right)^4$$

$$\mathrm{BR}(h \to \hat{g}\hat{g}) \approx 1.0 \times 10^{-4} \left(\frac{\alpha_d}{0.18}\right)^2 \left[\mathrm{Tr}\left(\boldsymbol{Y}^\dagger\boldsymbol{Y} + \widetilde{\boldsymbol{Y}}^\dagger\widetilde{\boldsymbol{Y}}\right)\right]^2 \left(\frac{2\,\mathrm{TeV}}{M}\right)^4 \left(\frac{c_Q}{4}\right)^2$$

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Dark Pion: 2 flavor or more (in work)

$$\boldsymbol{m}_\psi = \left(\boldsymbol{\omega} - \widetilde{\boldsymbol{Y}}^\dagger \boldsymbol{M}^{-1} \boldsymbol{Y} v^2\right) \qquad m_{\psi'} \equiv \boldsymbol{m}_{\psi,\text{diag}} = U_L^\dagger \boldsymbol{m}_\psi U_R$$

$$A_{ij} = \left(U_R^\dagger \boldsymbol{Y}^\dagger \boldsymbol{M}^{-2} \boldsymbol{Y} U_R\right)_{ij} \qquad \widetilde{A}_{ij} = \left(U_L^\dagger \widetilde{\boldsymbol{Y}}^\dagger \boldsymbol{M}^{-2} \widetilde{\boldsymbol{Y}} U_L\right)_{ij}$$

Depending on how the flavor(isospin) symmetry is broken, the light dark pions can be either stable or prompt

$$\hat{\pi}_a \sim i(\overline{\psi}'_L \sigma_a \psi'_R - i\overline{\psi}'_R \sigma_a \psi'_L)\ ,$$

$$\hat{\pi}^{(0)} = \hat{\pi}_3, \quad \hat{\pi}^{(\pm)} = (\hat{\pi}_1 \pm i\hat{\pi}_2)/\sqrt{2}$$

$$\Gamma(\hat{\pi}^{(\pm)} \to f f) = \frac{\pi}{8} N_c^f \alpha_Z \left|A_{12} - \widetilde{A}_{12}\right|^2 \frac{m_f^2 f_{\hat{\pi}}^2 m_{\hat{\pi}}}{m_Z^4} \sqrt{1 - \frac{4m_f^2}{m_{\hat{\pi}}^2}},$$

$$\Gamma(\hat{\pi}^{(0)} \to f f) = \frac{\pi}{16} N_c^f \alpha_Z \left|A_{11} - A_{22} - \widetilde{A}_{11} + \widetilde{A}_{22}\right|^2 \frac{m_f^2 f_{\hat{\pi}}^2 m_{\hat{\pi}}}{m_Z^4} \sqrt{1 - \frac{4m_f^2}{m_{\hat{\pi}}^2}}.$$

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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

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Original Tripled Top (TT) Model

The superpotential:

A few TeV

A few hundred GeV

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

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)

$$V_{\rm s} = \widetilde{m}^2\left(|\widetilde{Q}_A|^2 + |\tilde{u}^c_A|^2\right) - \widetilde{m}^2\left(|\tilde{u}^c_B|^2 + |\tilde{u}^c_C|^2\right)\,.$$

A Folded SUSY-like spectrum realized in 4D

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

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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

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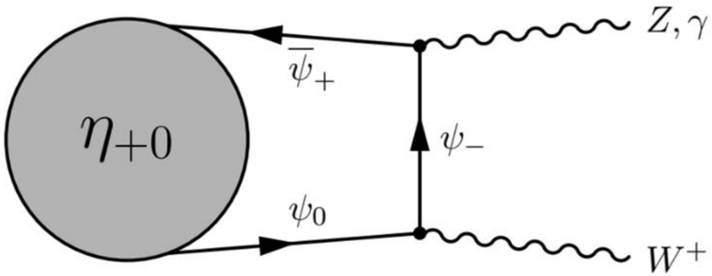
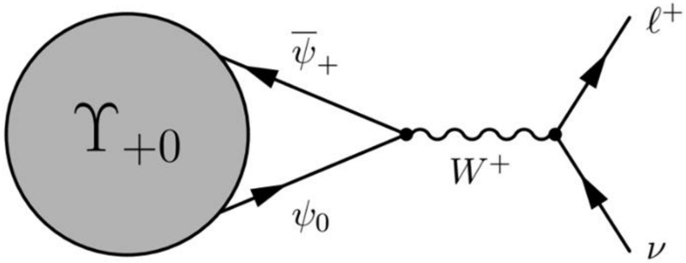
Phenomenology (Original TT)

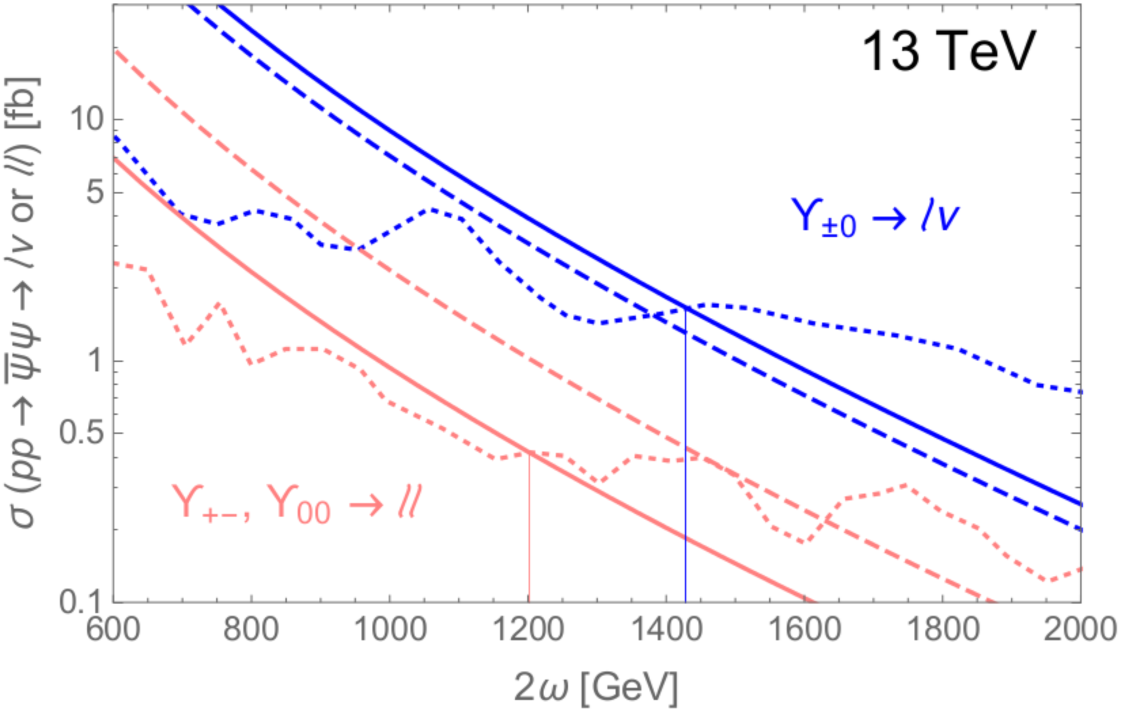




- Quirky bound states
- de-excite and annihilate e

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

Strong constraints (~700 GeV) on ω



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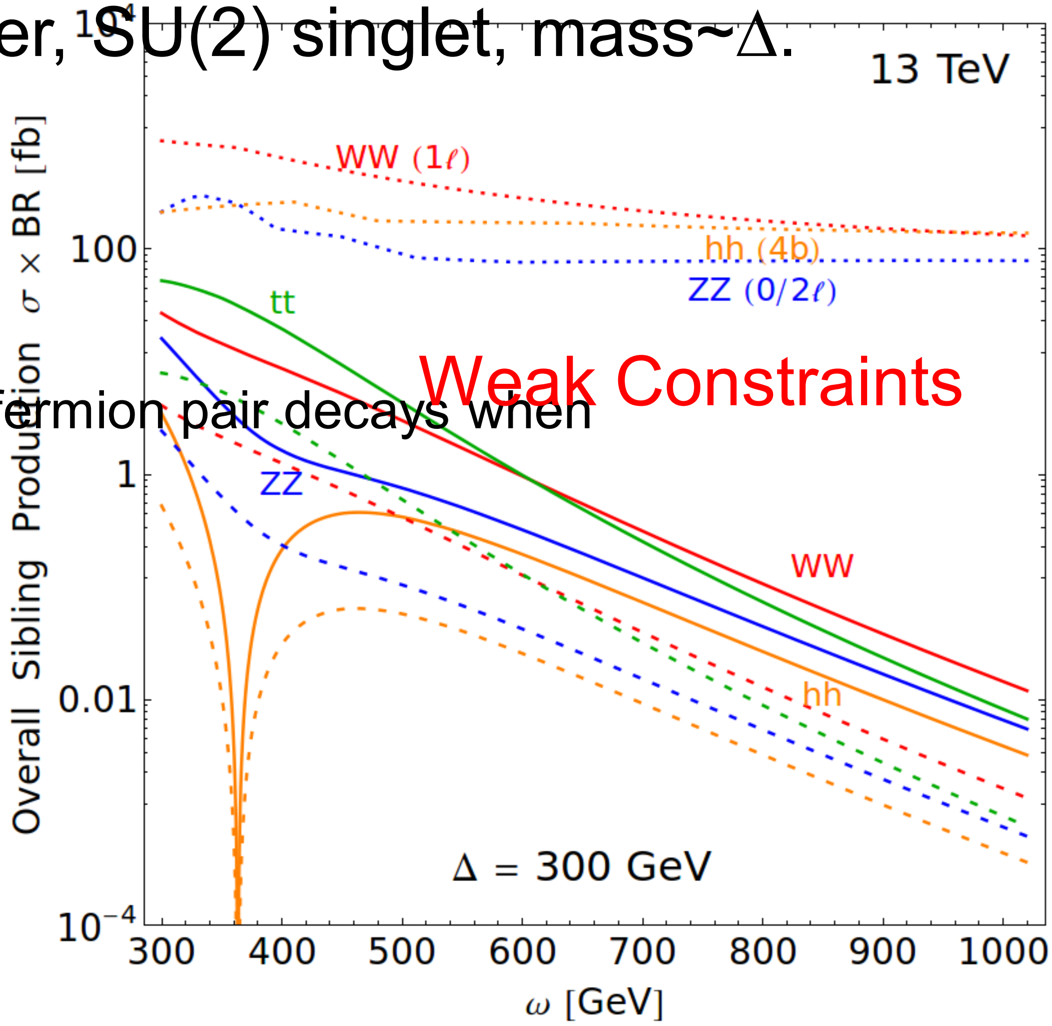
Phenomenology (Original TT)

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

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



Weak Constraints

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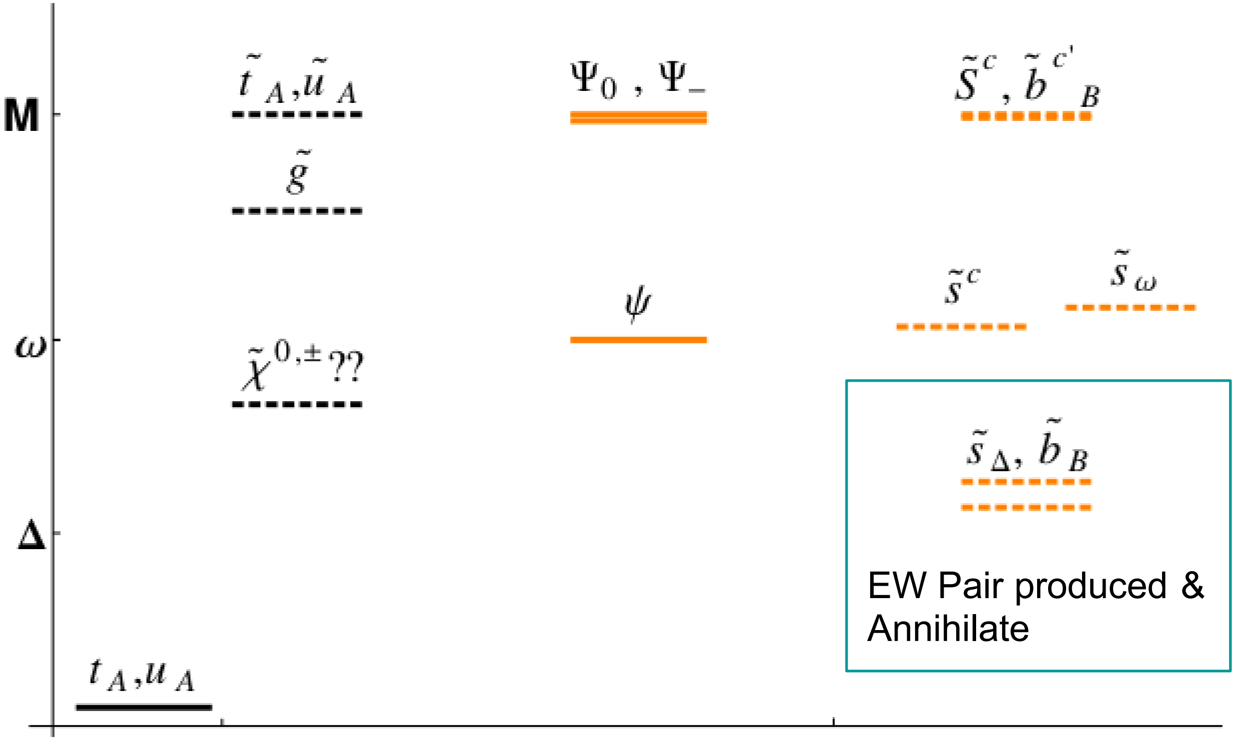
A Cartoon of Revised TT Model: The not So Interesting Case

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



EW Pair produced & Annihilate

Nothing (very) interesting happens

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

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Soft SUSY Breaking Terms

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

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

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

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Soft SUSY Breaking Terms

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

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

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

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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.

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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 $\Delta \to 0$

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

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

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

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

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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

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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)

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

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

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

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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

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

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

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.

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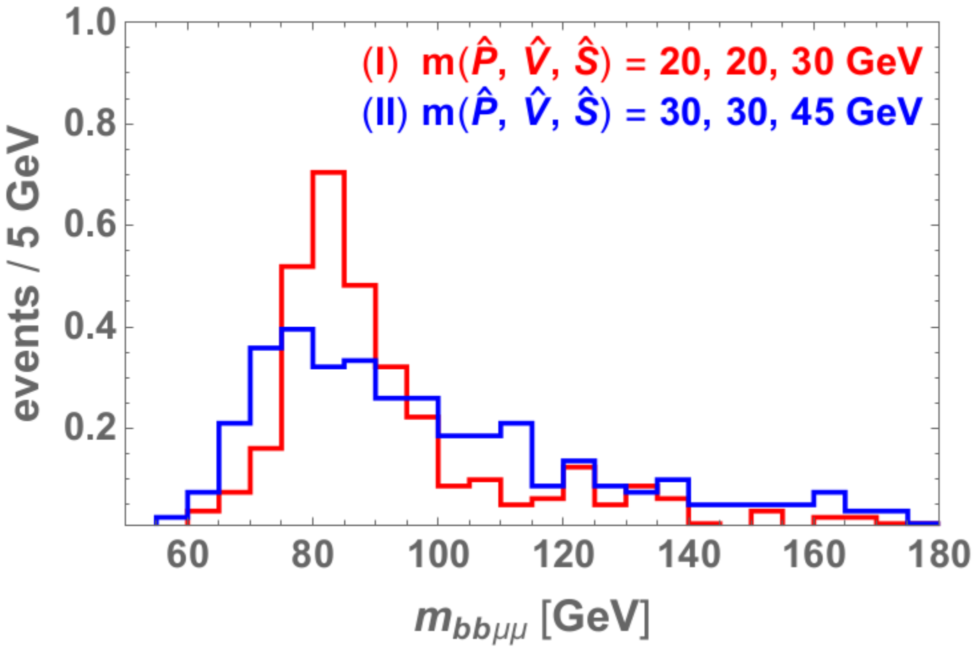
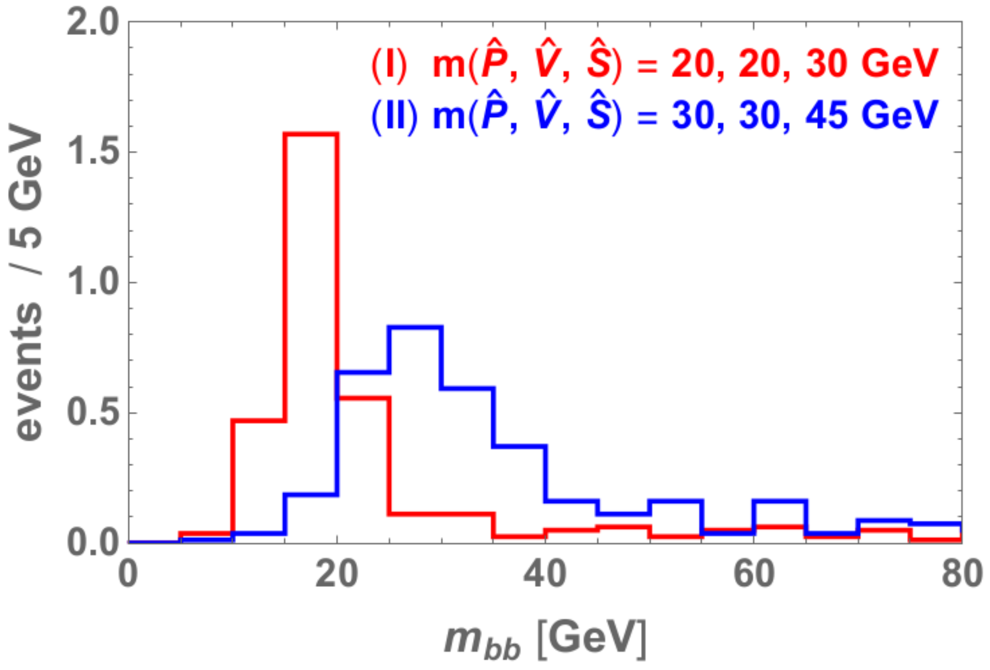
Prompt Limit – Z→bbμμ+X





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

The analysis is similar to h→aa→bb̄μμ 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}

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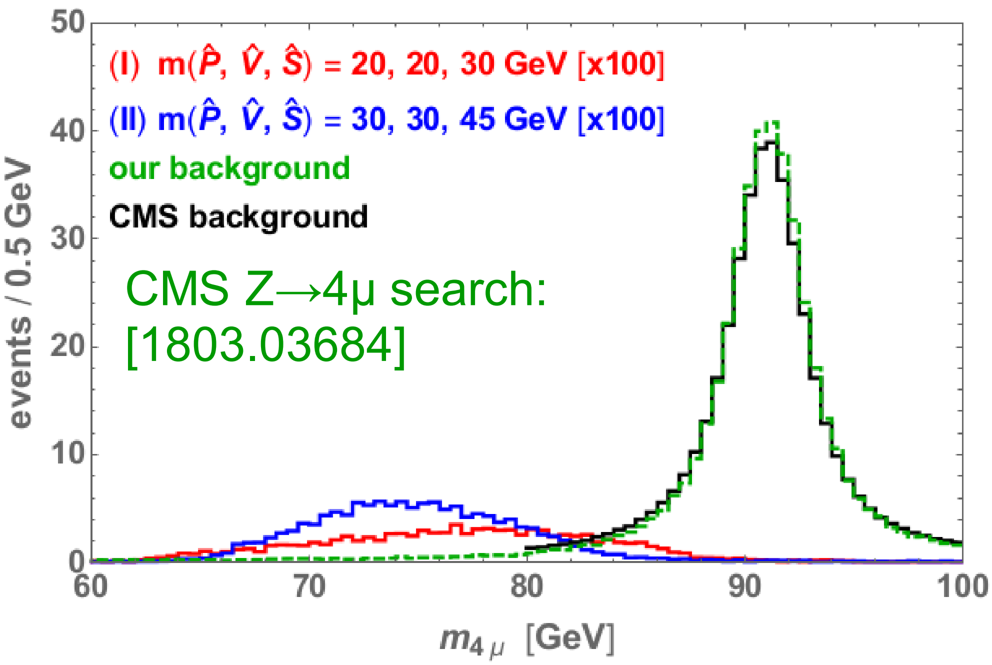
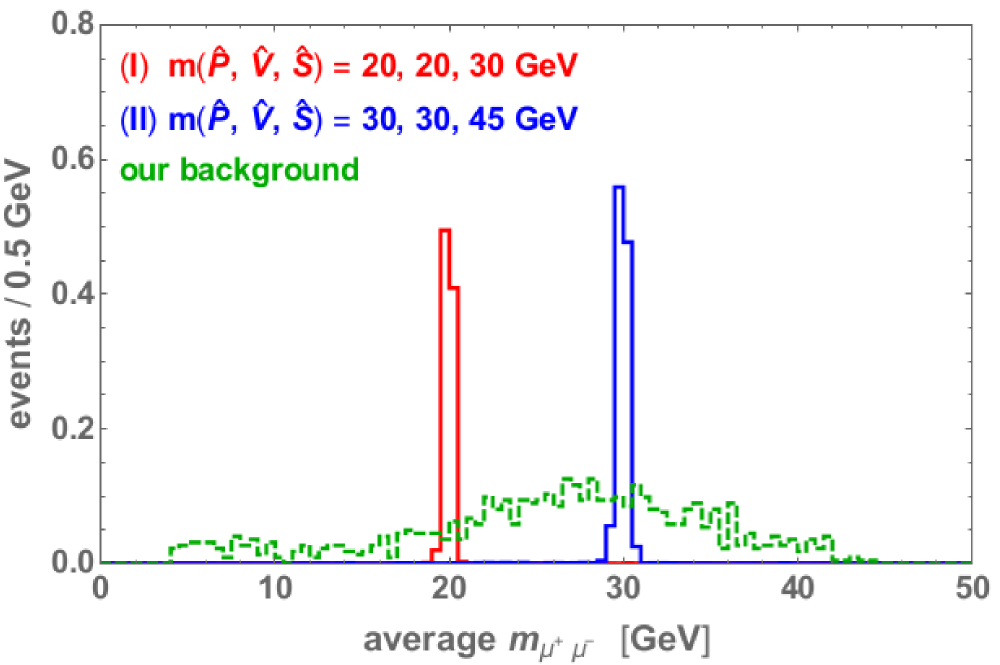
Prompt Limit – Z→4 lep+(X)



CMS Z→4μ search: [1803.03684]



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

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

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

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

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

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

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

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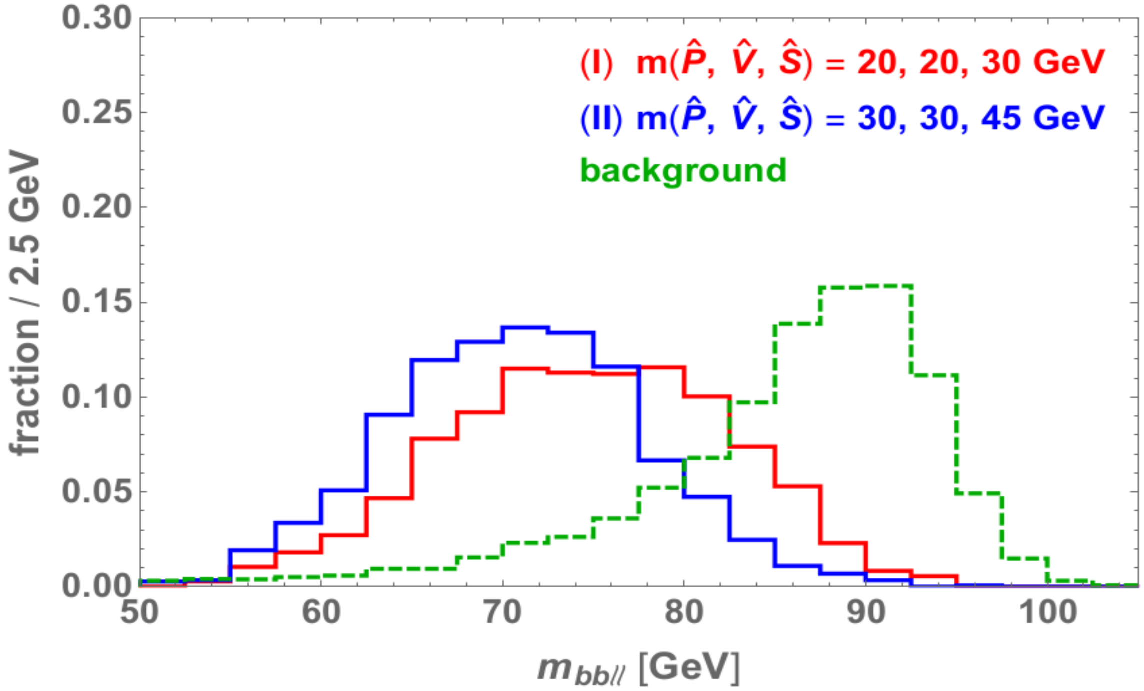
Prospects @ Z Factories

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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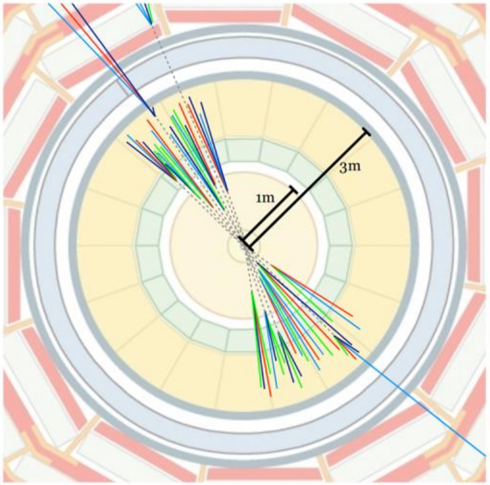
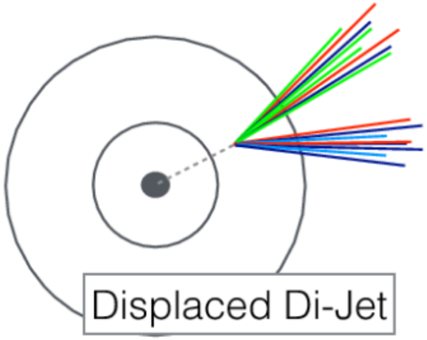
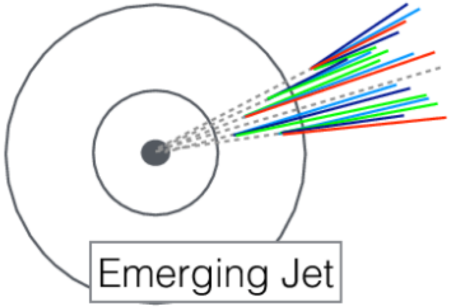
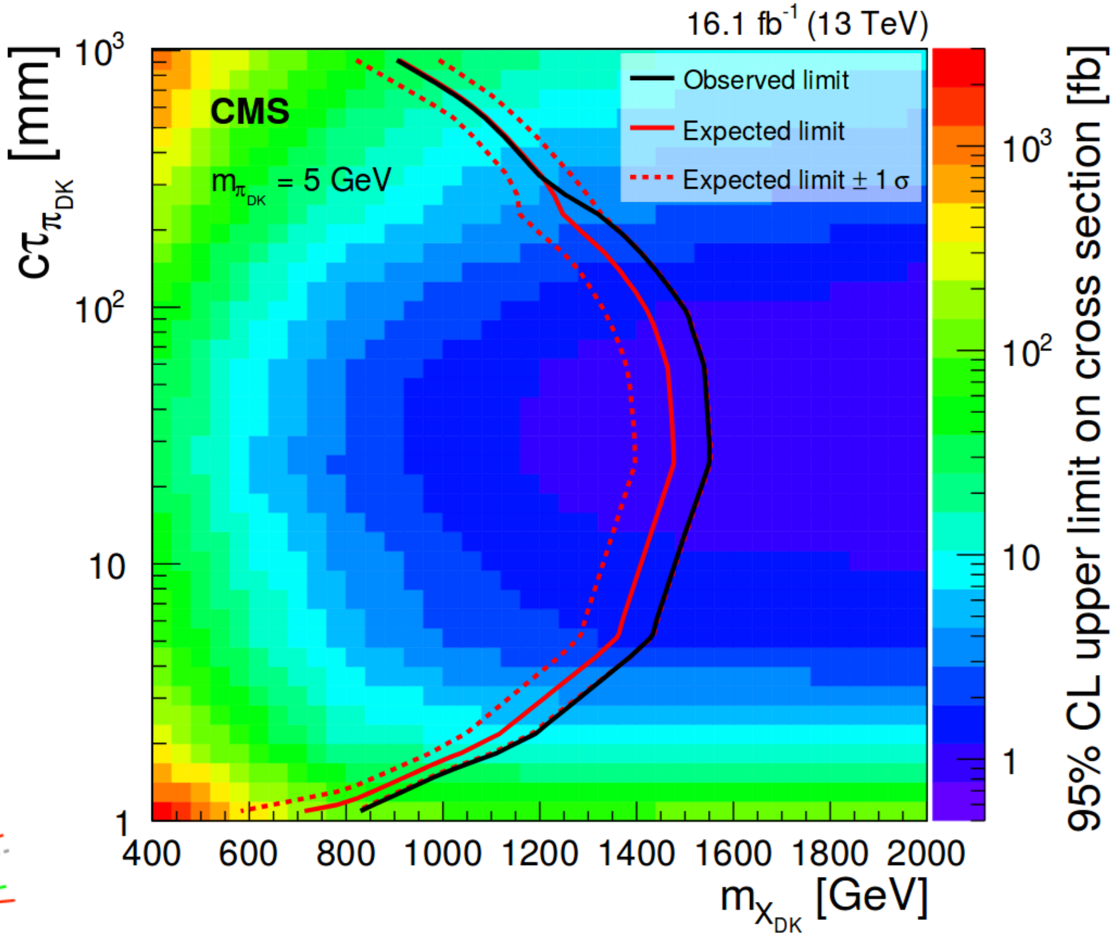
Manybody Limit – Emerging Jets

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









[CMS Collaboration, 1810.10069]

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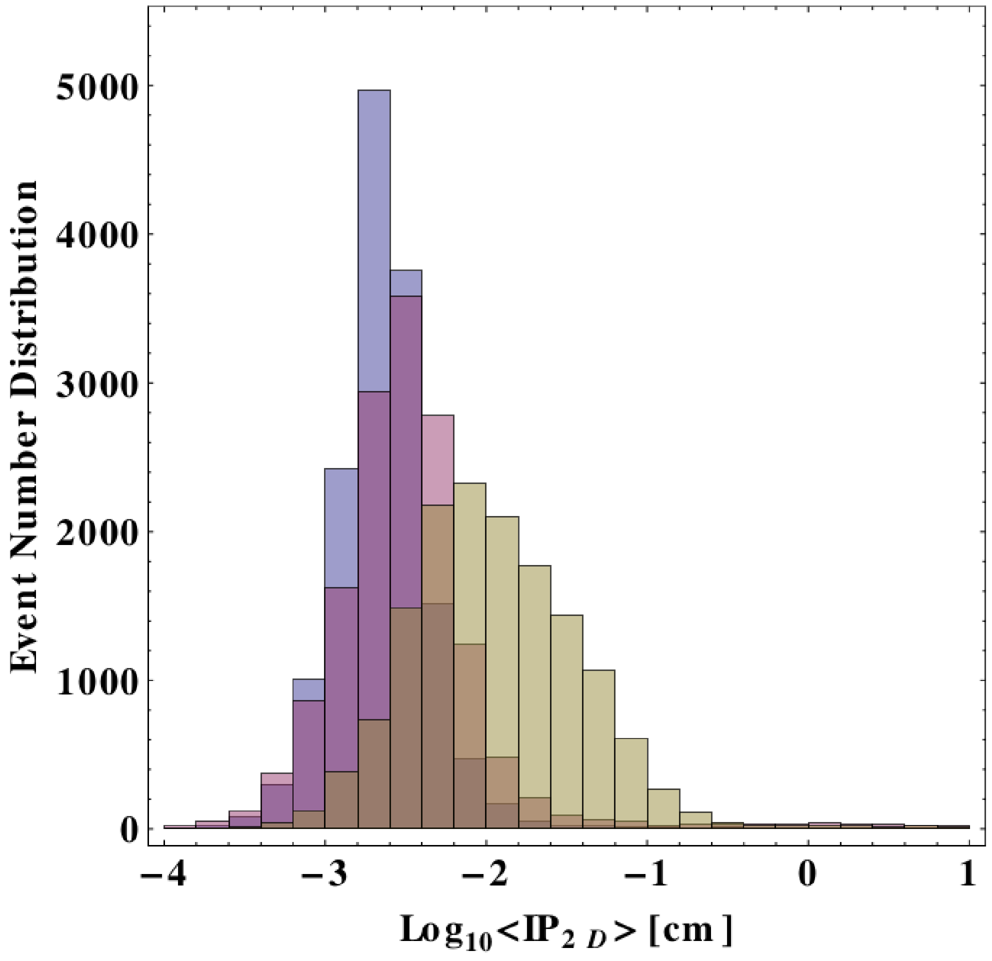
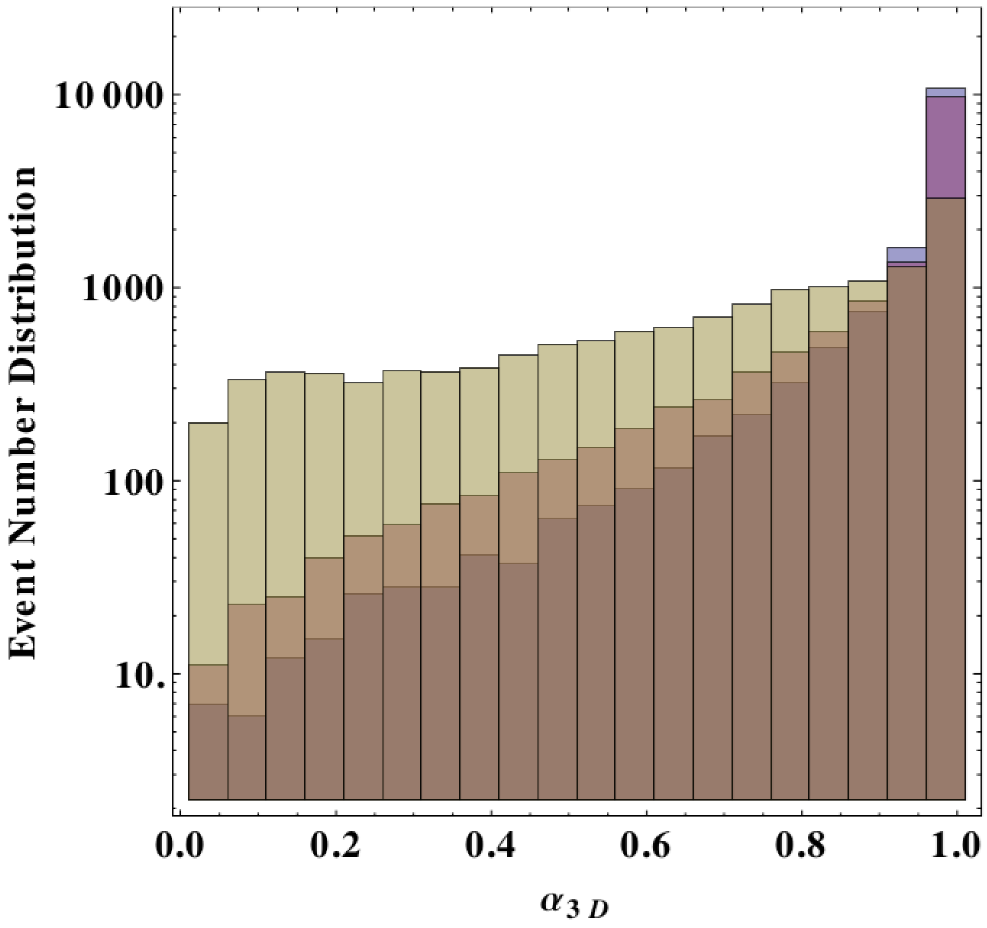
Emerging Jet Discrimination





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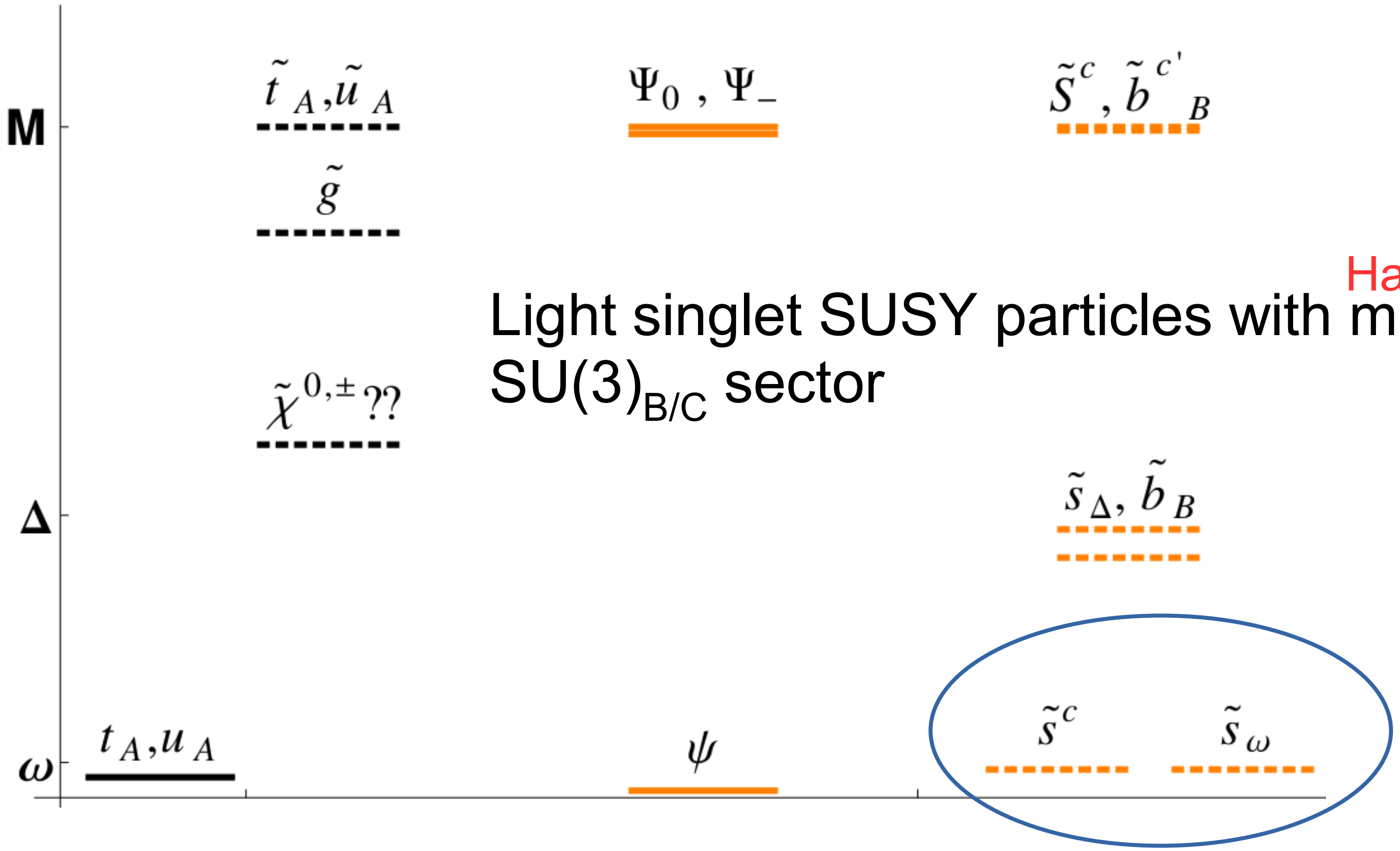
Off-Topic Thoughts About Exotic Bound States

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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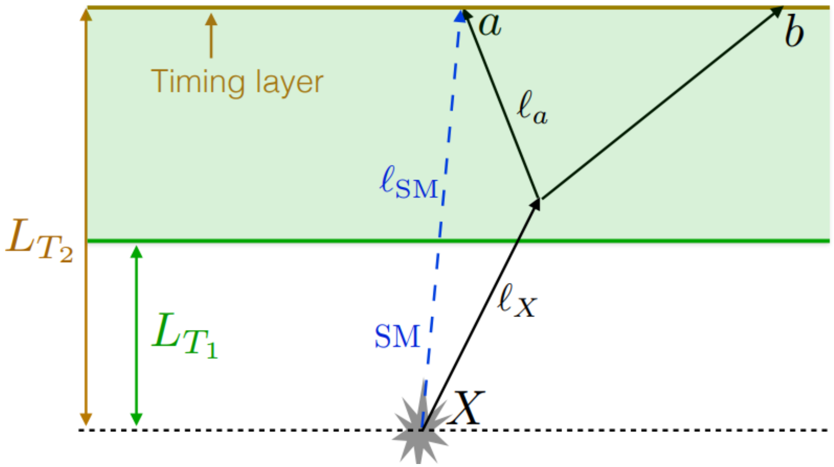
Time Resolution: A Complementary?



[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.

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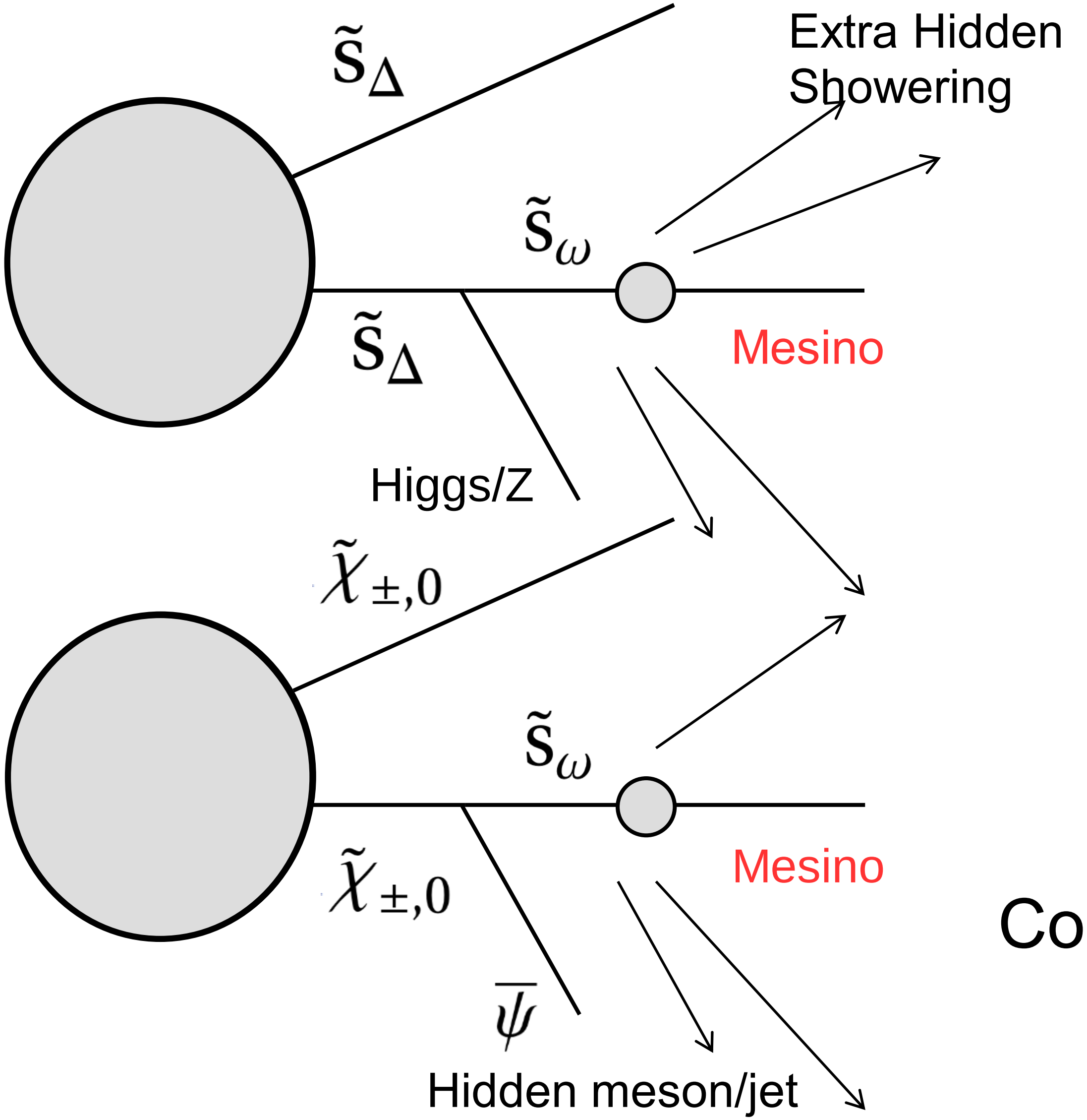
Exotic Bound States



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

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

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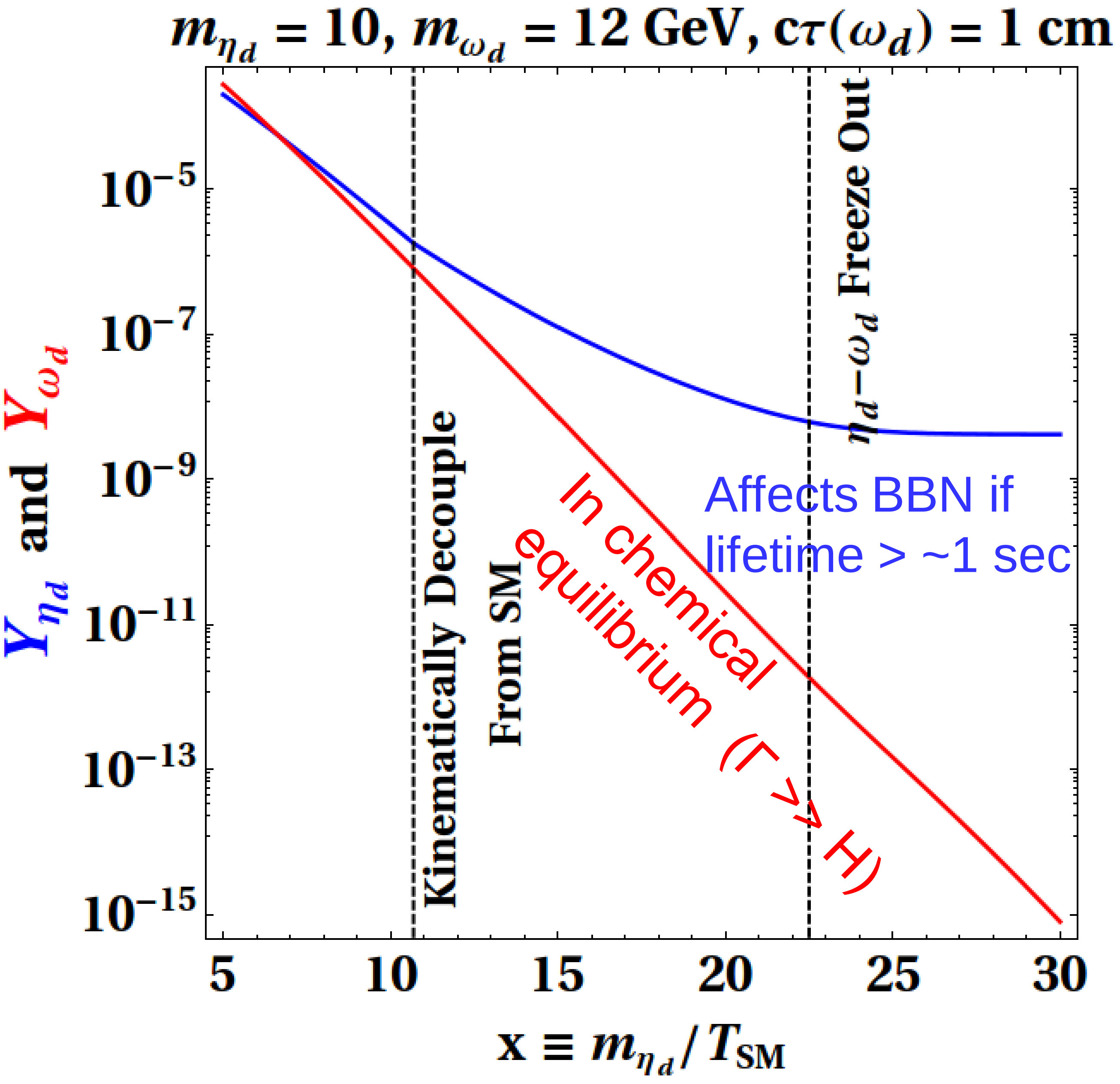
Thermal History



In chemical equilibrium ($\Gamma >> H$)

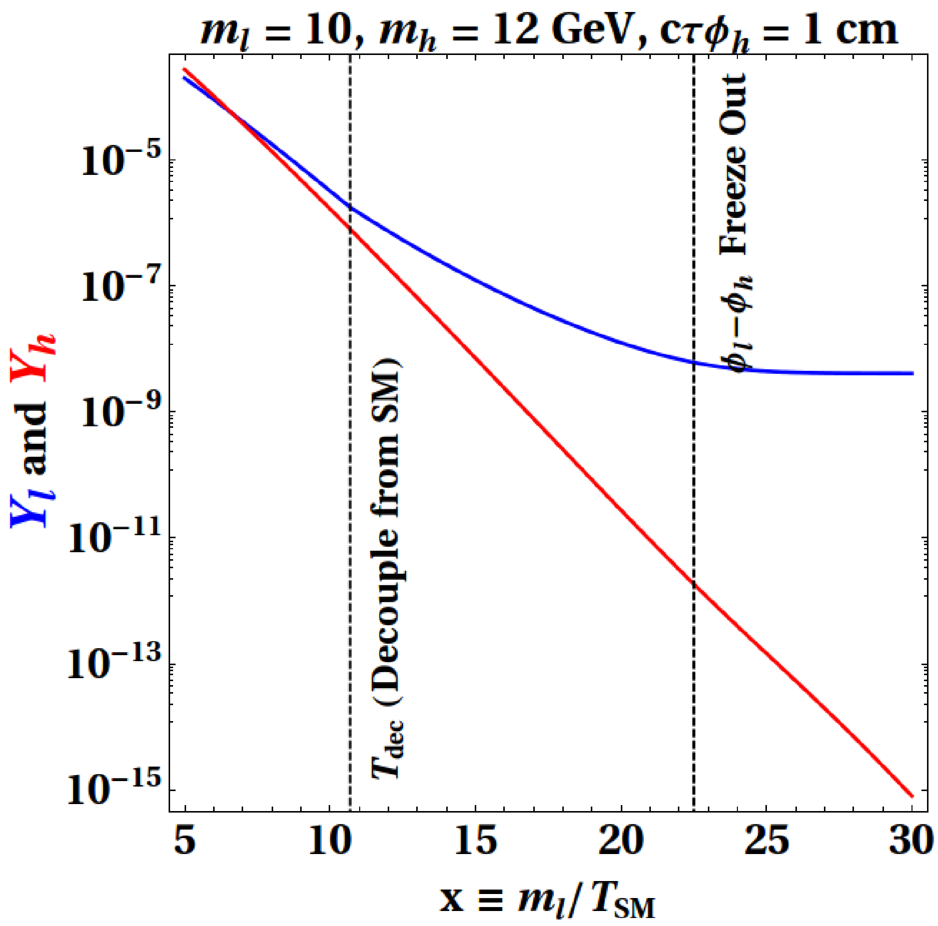
Affects BBN if lifetime > ~1 sec

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



$$Y_l(T) \simeq \frac{Y_l^{\rm eq}(\hat{T})}{Y_h^{\rm eq}(\hat{T})} Y_h^{\rm eq}(T)$$

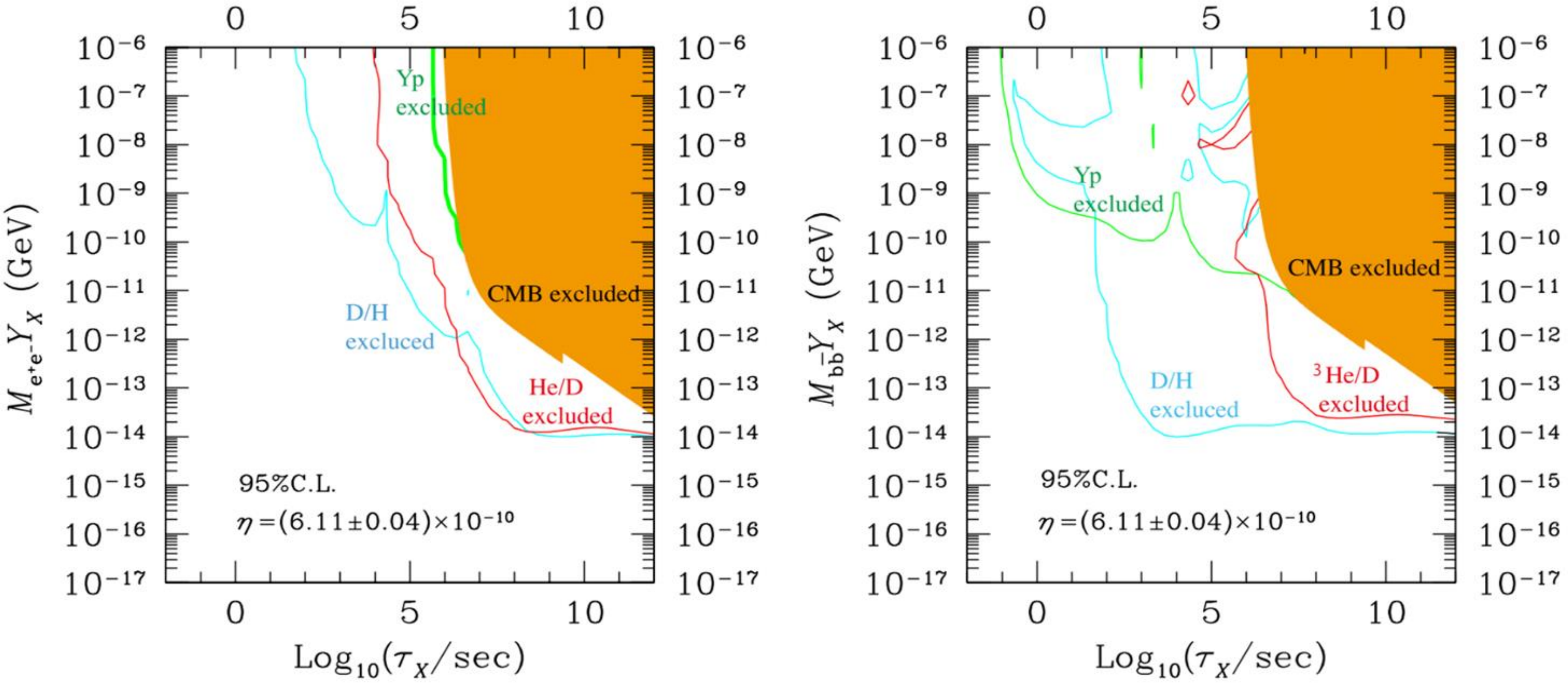
$$\propto \exp\left(\frac{\Delta m T_{\rm dec}}{T^2}\right) \exp\left(-\frac{m_h}{T}\right)$$

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

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

Reasonable form but not always precise

BBN Constraint



Taken from [1709.01211]

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