Z portal to a Confining Hidden Sector

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CERN-TH

3rd FCC Physics and Experiments Workshop

January 16, 2020

Z portal to a Confining Hidden Sector

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based on 1906.02198 [JHEP] + in progress

with H.-C. Cheng (UC Davis), C. Verhaaren (UC Irvine), L. Li (HKUST)

Introduction

A **confining hidden sector** is generic in Neutral Naturalness theories

Naturalness-inspired hidden sectors

- A **confining hidden sector** is generic in Neutral Naturalness theories

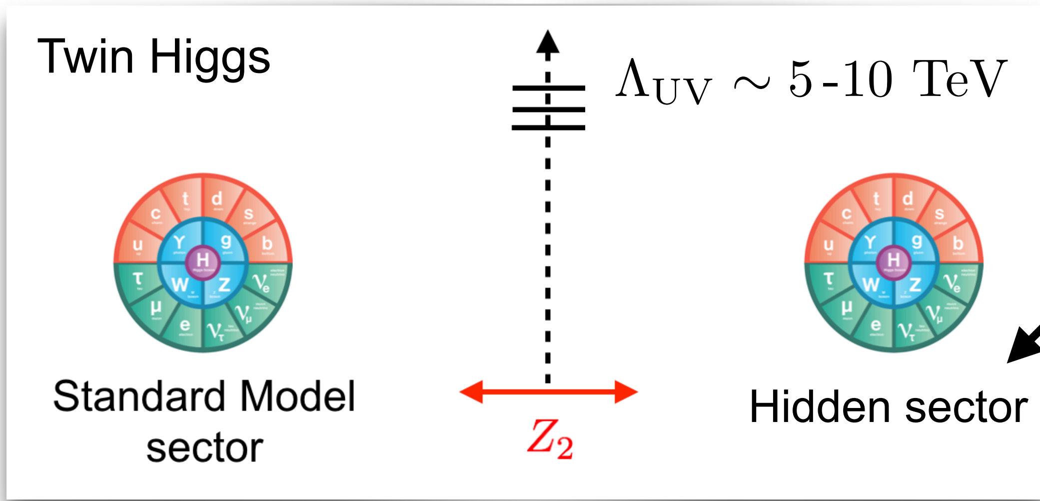
- **Neutral Naturalness =** models that solve little hierarchy problem with **color-neutral** Top Partners
- Many proposals: Twin Higgs, Folded SUSY, Tripled Top, Hyperbolic Higgs, …
- Phenomenology is strikingly non-standard, new paradigm for searches

[Chacko, Goh, Harnik 2005]
[Burdman, Chacko, Goh, Harnik 2006]
[Cheng, Li, Salvioni, Verhaaren 2018]
[Cohen, Craig, Giudice, McCullough 2018]

Neutral Naturalness

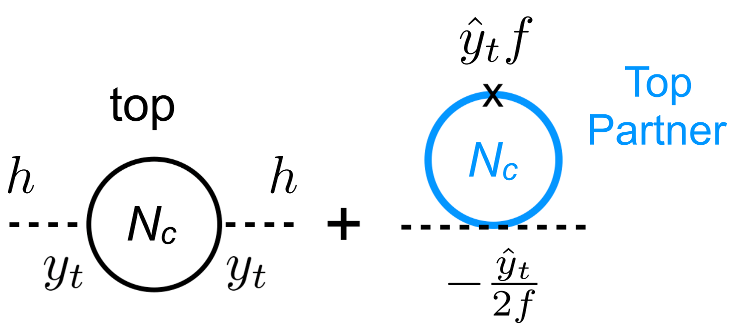
- A **discrete symmetry** relates the SM to the hidden sector

[Chacko, Goh, Harnik, 2005]



Has own *SU*(3) color symmetry

- 1 loop:



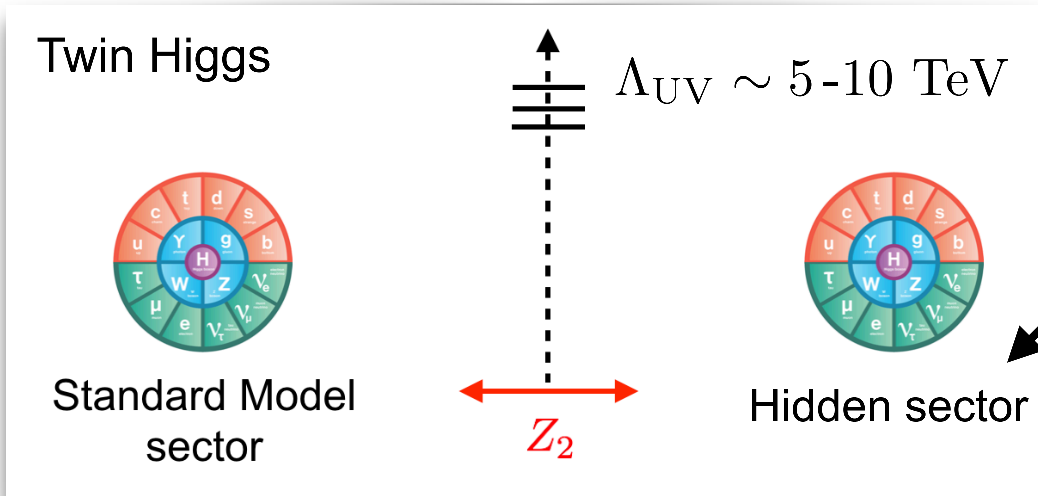
$$y_t \xleftrightarrow{Z_2} \hat{y}_t$$

quadratic corrections to Higgs mass cancel out

Hidden confinement

- A **discrete symmetry** relates the SM to the hidden sector

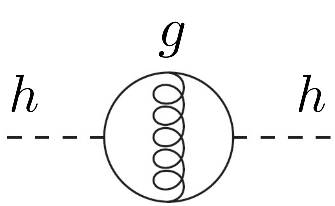
[Chacko, Goh, Harnik, 2005]



Has own *SU*(3) color symmetry

- 2 loops:

[Craig, Katz, Strassler, Sundrum, 2015]



$$m_{h,\mathrm{IR}}^2 \approx m_h^2(\Lambda_{\mathrm{UV}}) + \left[\frac{3y_t^2 g_s^2}{8\pi^4} + \frac{3(y_t^2 - \hat{y}_t^2)}{4\pi^2}\right]_{\Lambda_{\mathrm{UV}}} \Lambda_{\mathrm{UV}}^2$$

if hidden color is only global

Hidden confinement

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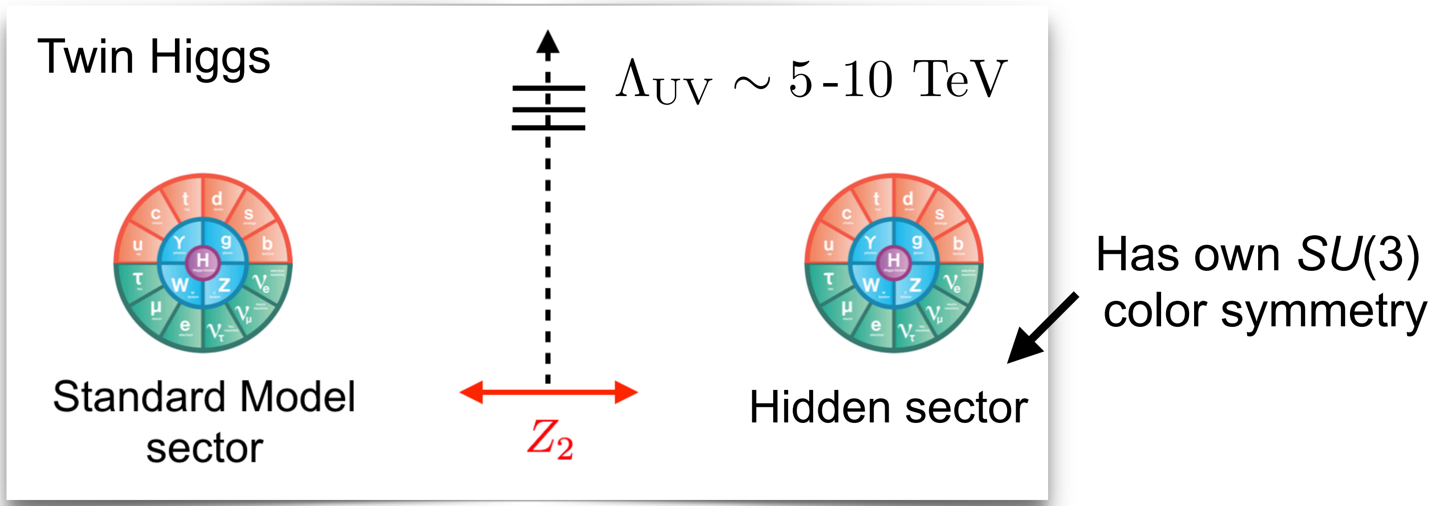

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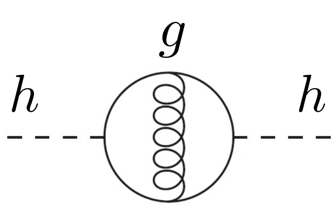


$$m^2_{h,{\rm IR}} \approx m_h^2(\Lambda_{\rm UV}) + \left[\frac{3y_t^2 g_s^2}{8\pi^4} + \frac{3(y_t^2 - \hat{y}_t^2)}{4\pi^2}\right]_{\Lambda_{\rm UV}} \Lambda_{\rm UV}^2$$

gauge hidden *SU*(3) with $g_s \simeq \hat{g}_s$ at $\Lambda_{\rm UV}$, **confines at** $\Lambda \gtrsim \Lambda_{\rm QCD}$

Hidden confinement

- Confining hidden sector with $0.1 \lesssim \Lambda/\mathrm{GeV} \lesssim 10$ is generic expectation in Neutral Naturalness

- Details depend on

  ➡ Mass spectrum of hidden matter

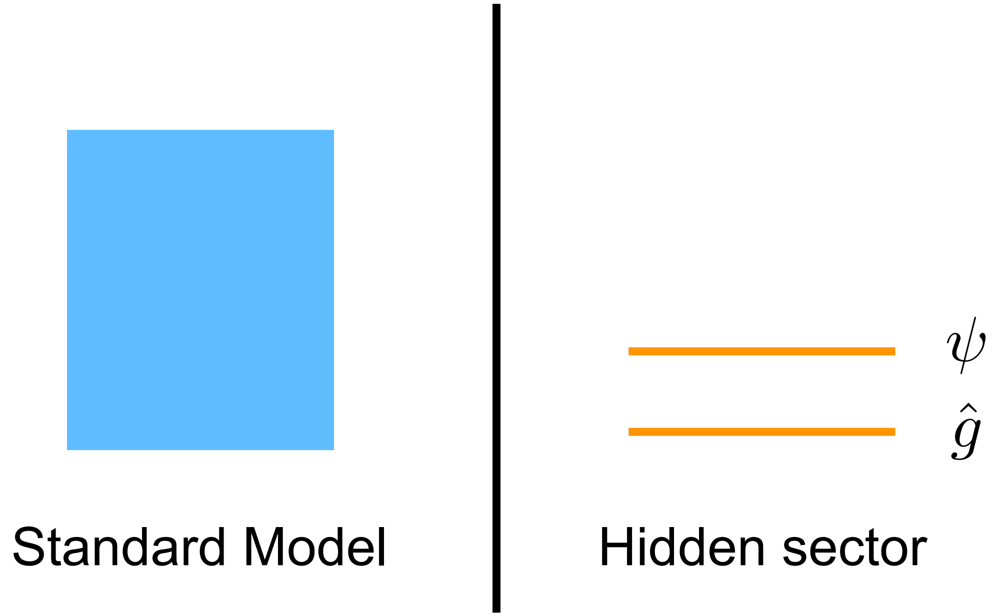
  ➡ Portals to SM: Higgs is mandatory, others?

  ➡ Additional interactions within hidden sector?

- Many models exist, aim to identify **representative cases** with distinct phenomenology, to set motivated targets for experimental searches

In this talk

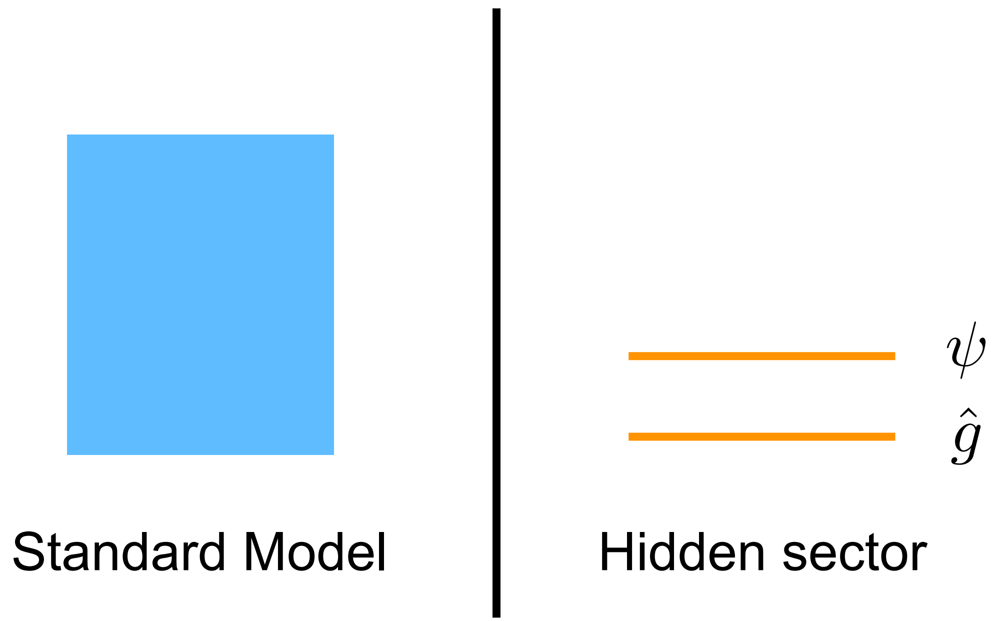
- Hidden QCD with 1 light fermion flavor



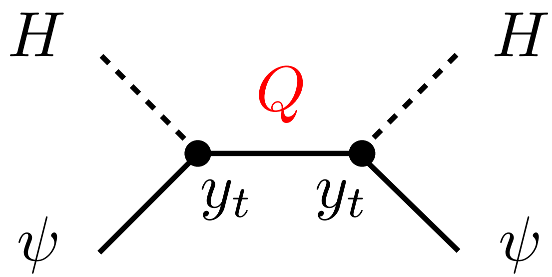
In this talk

- Hidden QCD with 1 light fermion flavor
- Connected to SM by Higgs and *Z* portals

$$\mathcal{L}_6 \sim \frac{y_t^2}{M^2}\left(iH^\dagger \overleftrightarrow{D}_\mu H\,\overline{\psi}_R\gamma^\mu\psi_R + |H|^2 m_\psi\overline{\psi}\psi + \frac{c_g\alpha_d}{12\pi}|H|^2\hat{G}_{\mu\nu}\hat{G}^{\mu\nu}\right)$$



Ultraviolet origin?



ψ is only light flavor in hidden sector

Q are TeV-scale fermions charged under SM electroweak + hidden color

- Fairly common ingredients in Neutral Naturalness:
  - ✓ Typically only 3rd generation is copied, hidden sector has fewer flavors
  - ✓ TeV-scale particles play roles in Higgs mass stabilization
- Examples: **models realizing accidental SUSY,** composite Twin Higgs

[Cheng, Li, Salvioni, Verhaaren, 2019]

Description of Hidden Sector

Phenomenology

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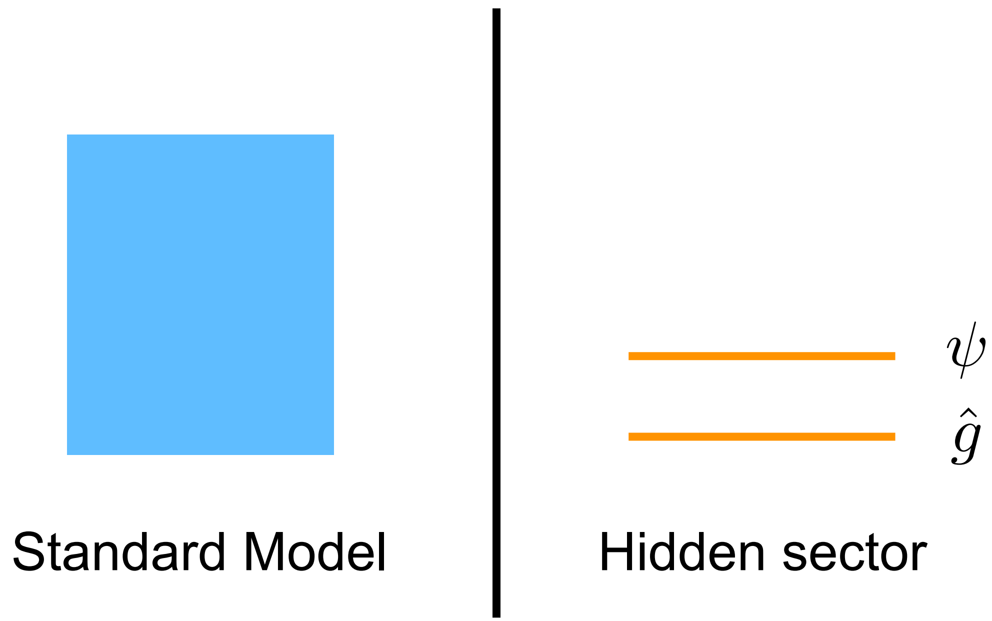

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Higgs portal

$$\mathrm{BR}(h \to \hat{g}\hat{g}) \approx 1.3 \times 10^{-5} \left(\frac{2\ \mathrm{TeV}}{M}\right)^4 \left(\frac{\alpha_d}{0.18}\right)^2 \left(\frac{c_g}{1}\right)^2$$

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Z portal

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

In this talk

- At the LHC, $N_Z / N_h \sim 10^3$
- At FCC-ee, up to 10^{12} Z's versus < 10^7 Higgses

➡ ***Z* decays to hidden sector dominate**

Higgs portal

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The hidden hadrons

- *SU*(3) QCD with 1 flavor: no chiral symmetry ➡ no Goldstone bosons
- Partial results available from lattice: [Farchioni, Montvay, Münster, Scholz, Sudmann, Wuilloud, 2007]

  - ☑ Baryons significantly heavier than mesons
  - ☑ Ratio of scalar/pseudoscalar meson masses: $m_{\hat{S}}/m_{\hat{P}} \approx 1.5$
  - ☐ No info on vector meson

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- **Assume** $$m_{\hat{P}} \lesssim m_{\hat{V}} < m_{\hat{S}}$$

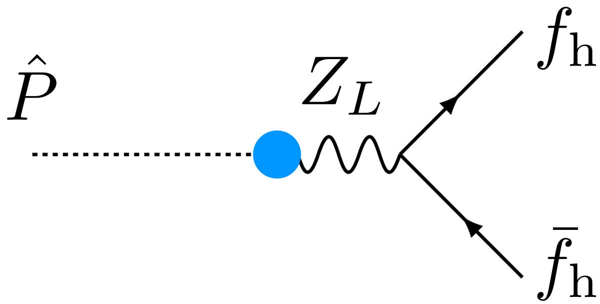
$$0^{-+} \qquad\qquad 1^{--} \qquad\qquad 0^{++} \qquad\qquad (J^{PC})$$

- Mesons decay back to visible sector through *Z* and *h* portals

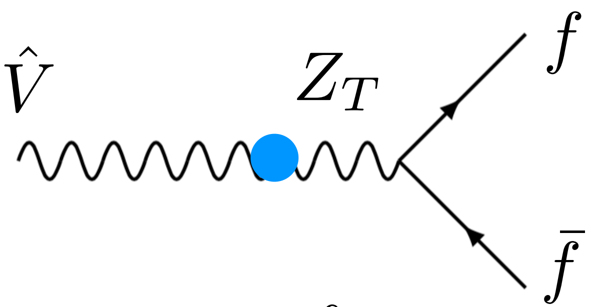
Hidden meson decays

- It turns out, **all** lightest mesons decay dominantly via ***Z* portal**

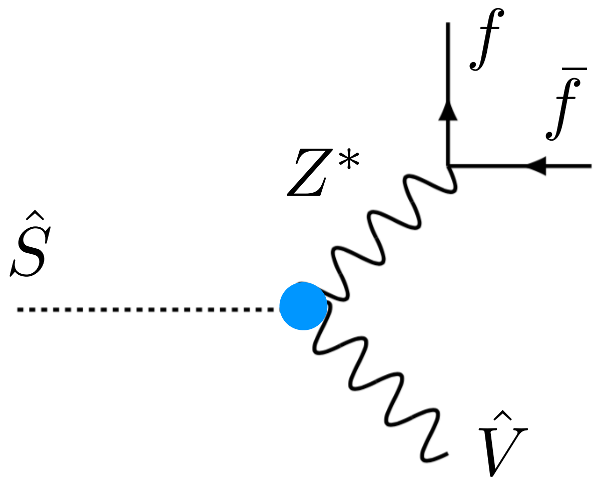
- Pseudoscalar



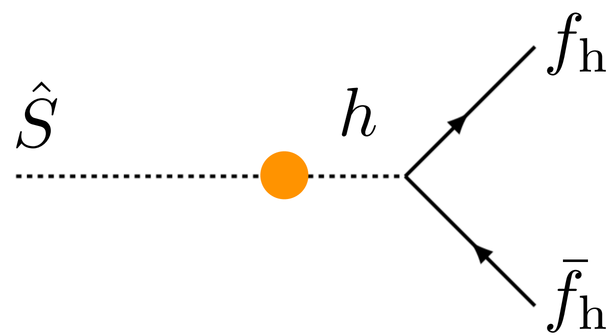
- Vector



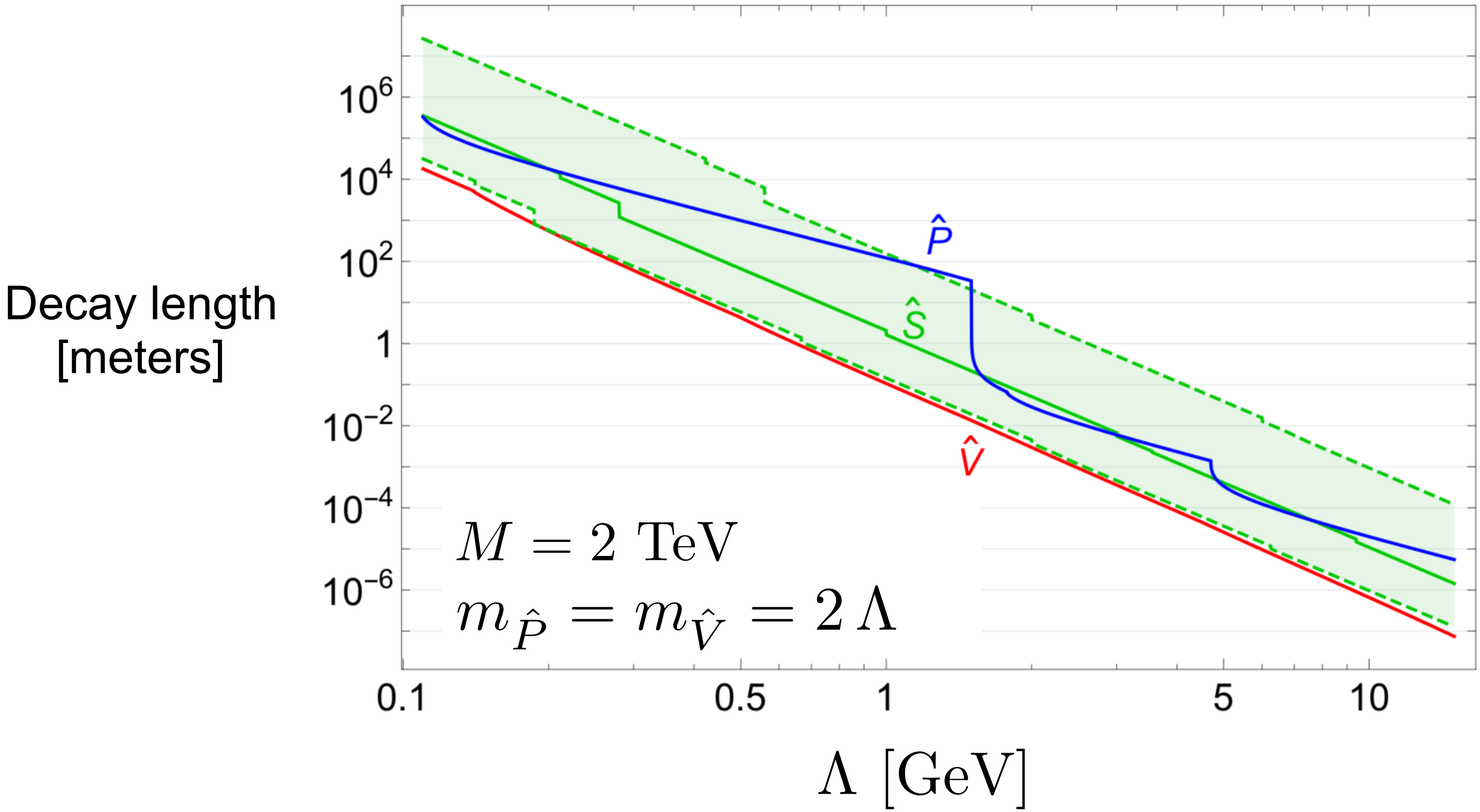
- Scalar



$\gg$



Hidden meson decays



Two main parameters determine pheno:

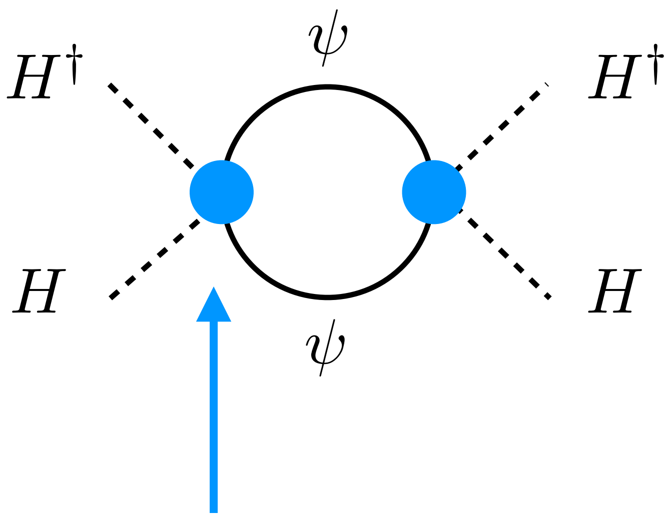
- Hidden confinement scale Λ
- Mediation scale M

Description of Hidden Sector

Phenomenology

Indirect vs direct probes

- EW precision tests:



$$\frac{y_t^2}{M^2}\left(iH^\dagger \overleftrightarrow{D}_\mu H\,\overline{\psi}_R\gamma^\mu\psi_R\right)$$

$$\Delta\widehat{T} = \frac{4}{3}\,\frac{N_d y_t^2}{16\pi^2}\,\frac{m_t^2}{M^2}$$

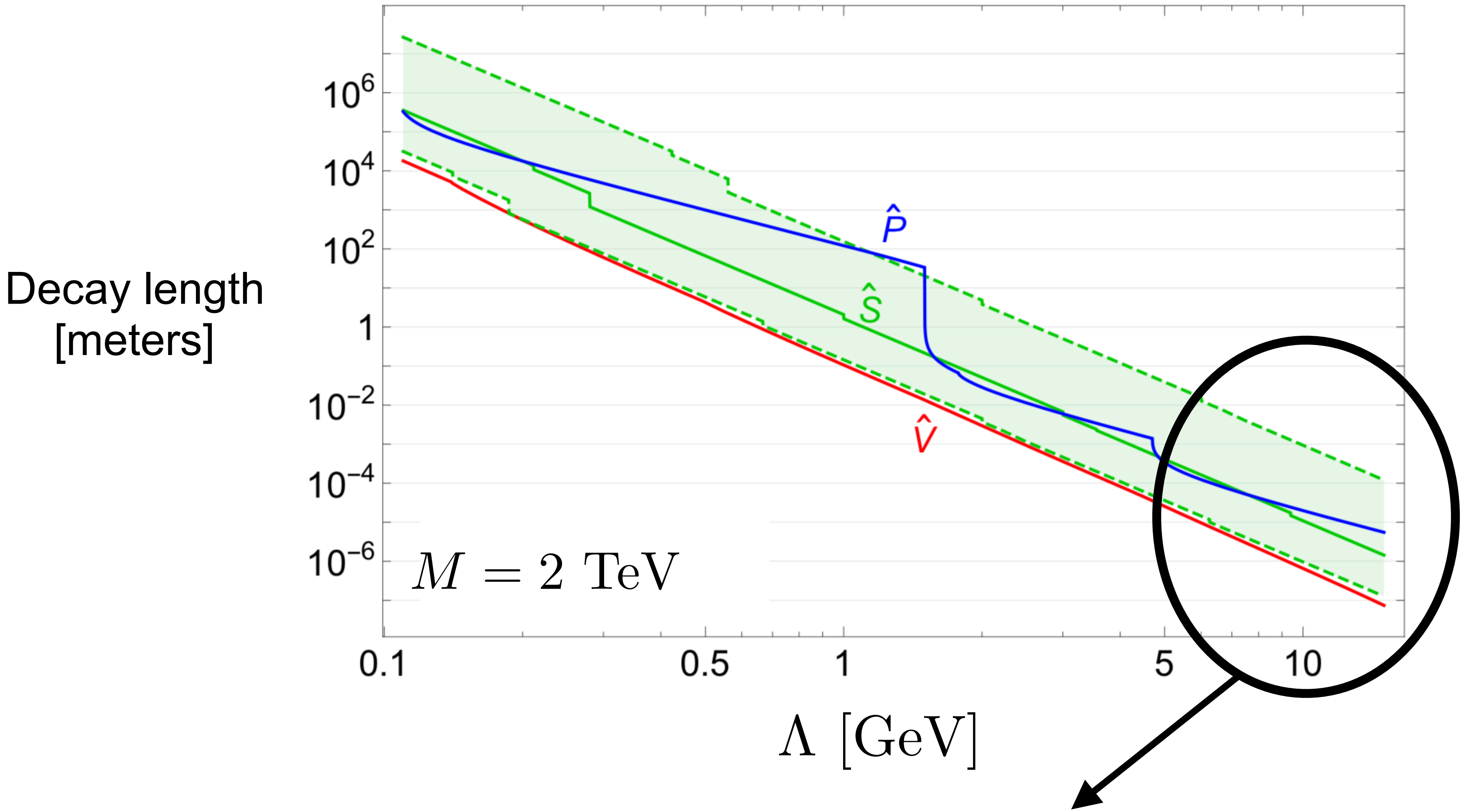
$$\Delta\widehat{T} \lesssim 10^{-3} \quad \rightarrow \quad M \gtrsim 0.9 \text{ TeV}$$

FCC-ee:

$$\Delta\widehat{T} \lesssim 10^{-4} \quad \rightarrow \quad M \gtrsim 2.7 \text{ TeV}$$

- **Can direct probes do better?** *Z* decays to hidden hadrons

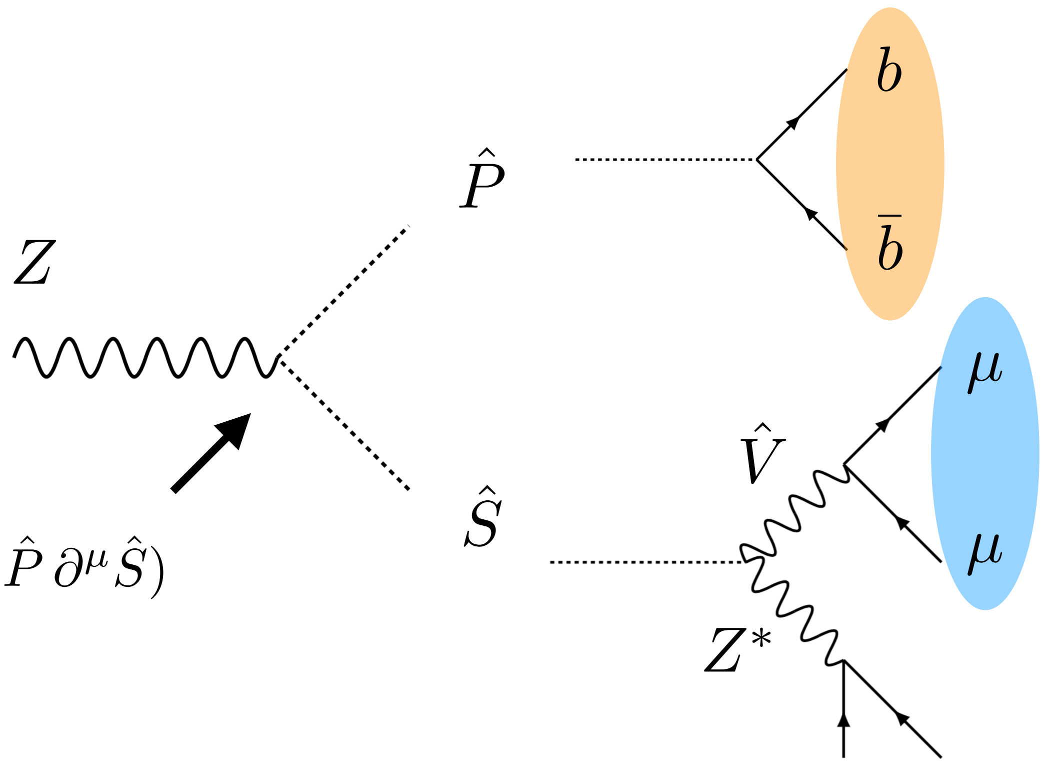
Phenomenology/1



$$\Lambda \gtrsim 10 \text{ GeV}, \, M \sim \text{few TeV} : Z \to 2 \text{ mesons, prompt decays}$$

Phenomenology/1

- If mesons have masses of 10-30 GeV, the *Z* decays to 2-body final states
- Example:



$$\hat{g}_Z Z_\mu(\hat{S}\,\partial^\mu \hat{P} - \hat{P}\,\partial^\mu \hat{S})$$

$$\Rightarrow \quad Z \to (b\bar{b})(\mu\mu) + X$$

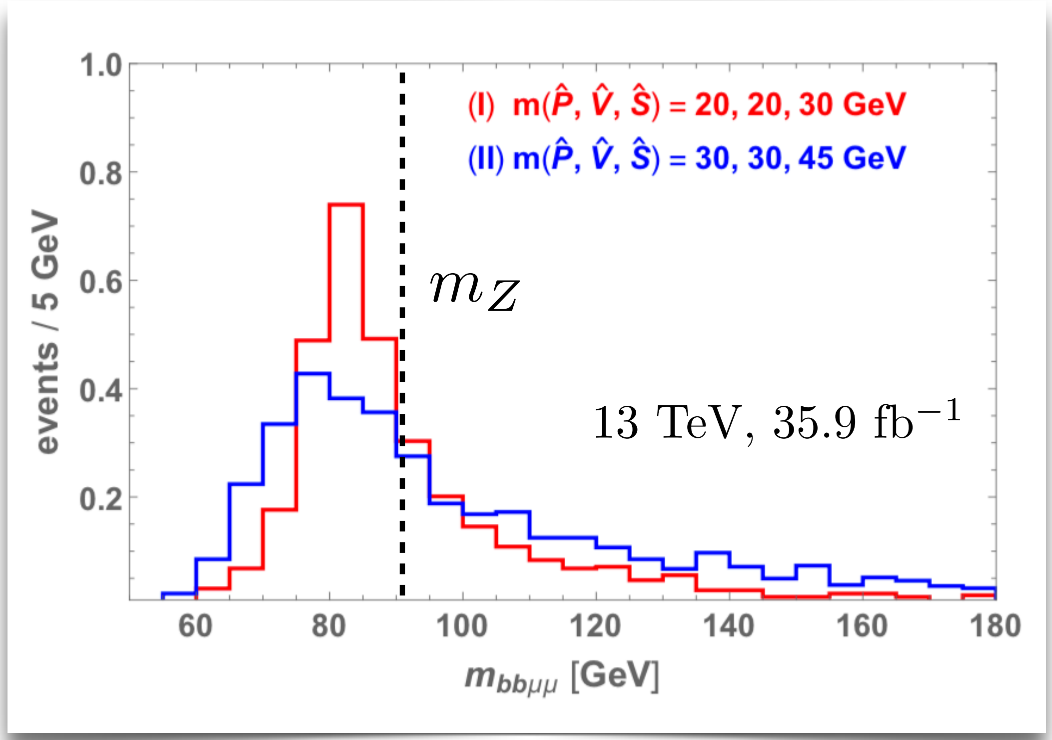
Phenomenology/1

- No dedicated LHC search yet, but can learn from $h \to aa \to (b\bar{b})(\mu\mu)$
- CMS analysis:

[**CMS**, 1812.06359]

$$p_T^{\mu 1,2} > 20, 9\ \mathrm{GeV}, \qquad p_T^{b1,2} > 20, 15\ \mathrm{GeV}$$

- For *Z* signal, selection efficiency ~ 10 times smaller than for Higgs (!)



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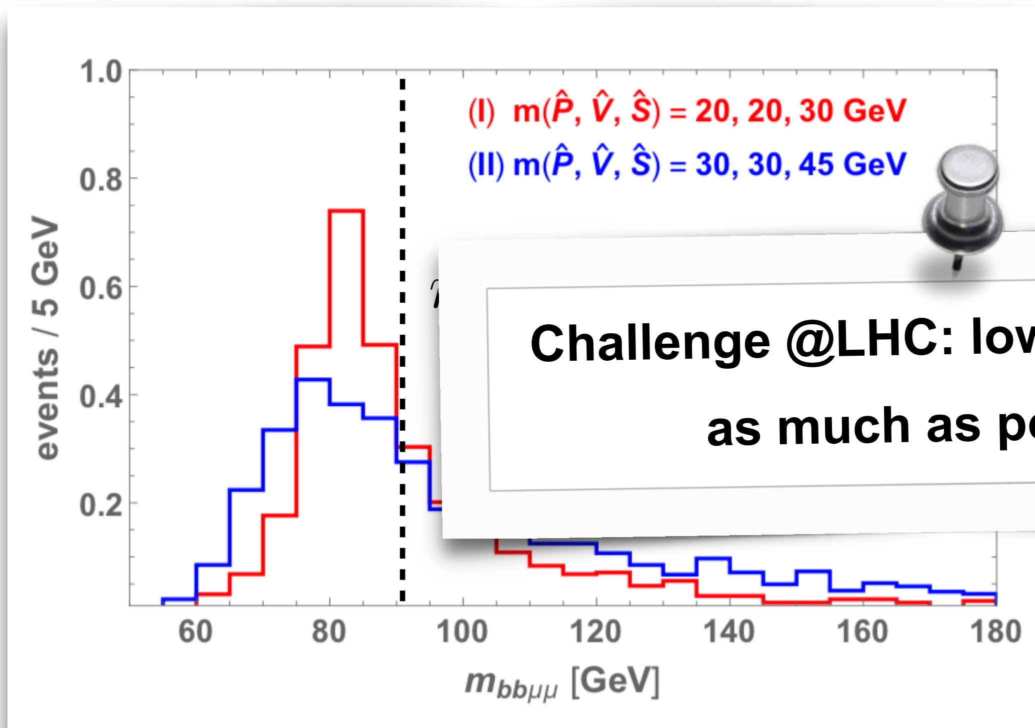
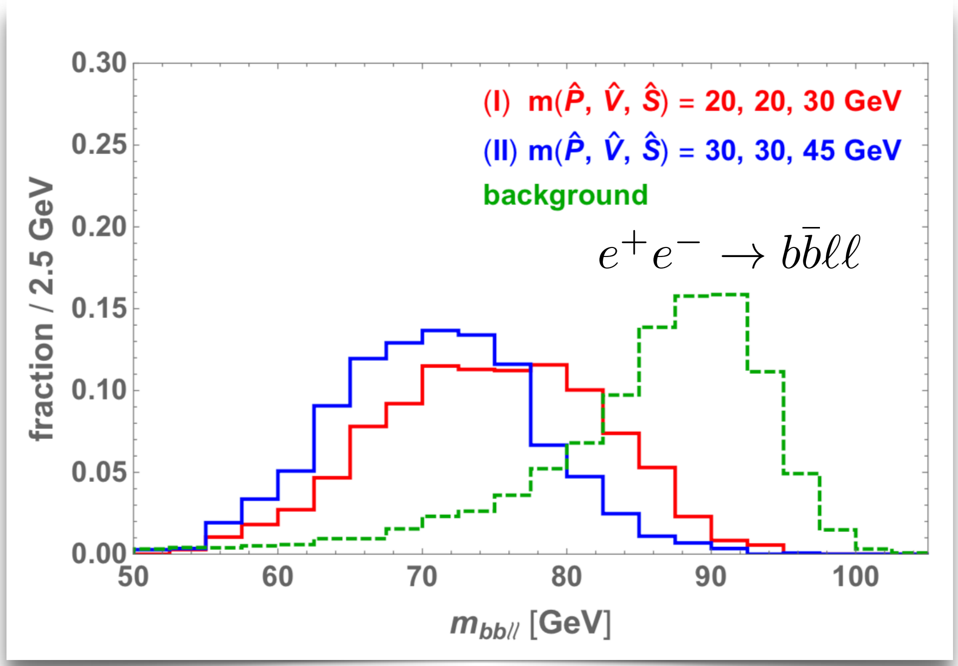


Challenge @LHC: lower thresholds as much as possible

Phenomenology/1

- At GigaZ factory, background is negligible after cuts



$$|m_{\ell\ell} - m_{\hat{V}}| < 0.5 \text{ GeV}$$

$$m_{bb} \in [m_{\hat{P}} - 10 \text{ GeV}, m_{\hat{P}} + 5 \text{ GeV}]$$

$$m_{bb\ell\ell} < 85 \text{ GeV}$$

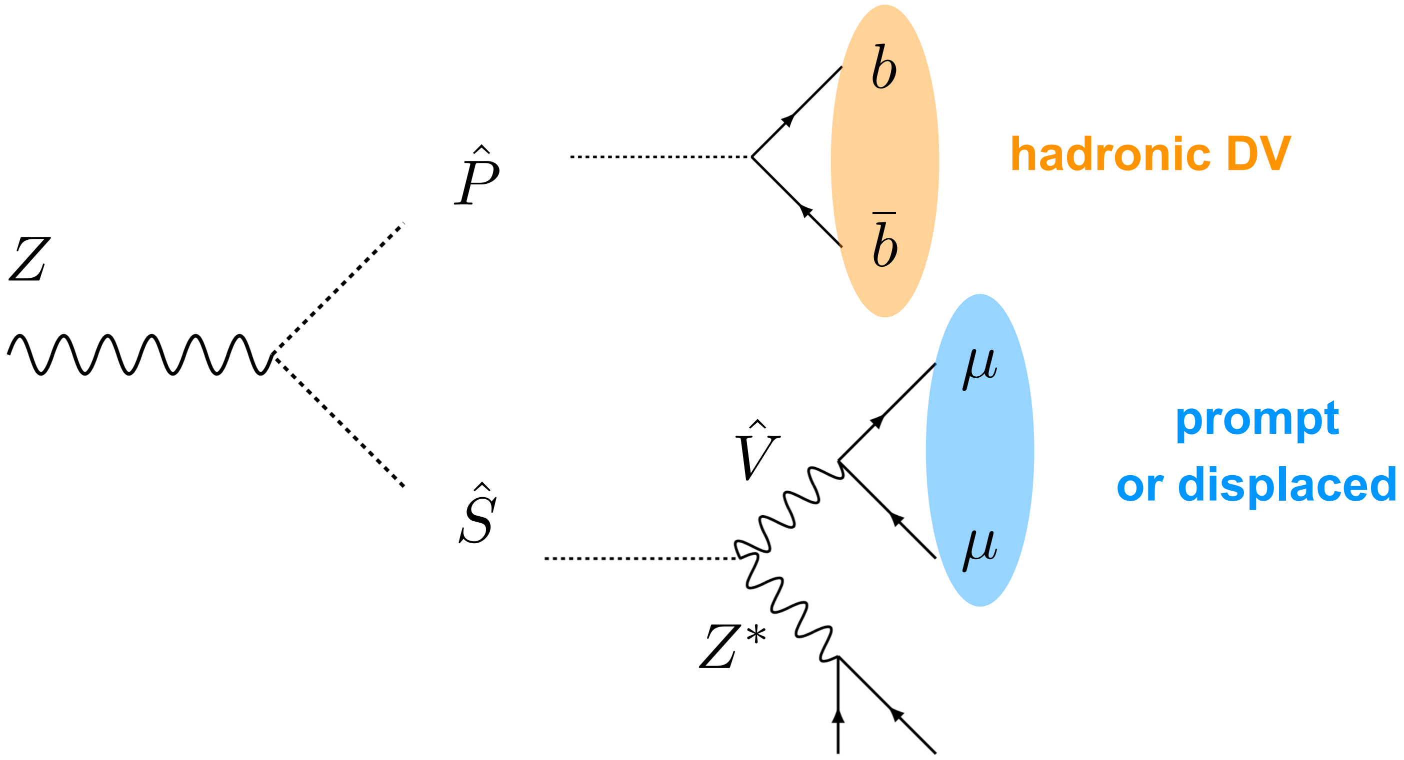
$$N_B < 0.1 \text{ events}$$

- Sensitivity on mediation scale:

$$(\mathrm{I}) \quad M \gtrsim 5.4 \text{ TeV} \left(\frac{\mathcal{B}_{\hat{P}\hat{S}}}{1}\right)^{1/4} \qquad (\mathrm{II}) \quad M \gtrsim 5.2 \text{ TeV} \left(\frac{\mathcal{B}_{\hat{P}\hat{S}}}{1}\right)^{1/4} \qquad (\text{GigaZ})$$

Phenomenology/1

- For larger $M \gtrsim 5\ \mathrm{TeV}$, at least some of the mesons become **long-lived**



$$\mathrm{BR}(Z \to \overline{\psi}\psi) \sim M^{-4}, \quad c\tau_{\mathrm{meson}} \sim M^4$$

Phenomenology/1

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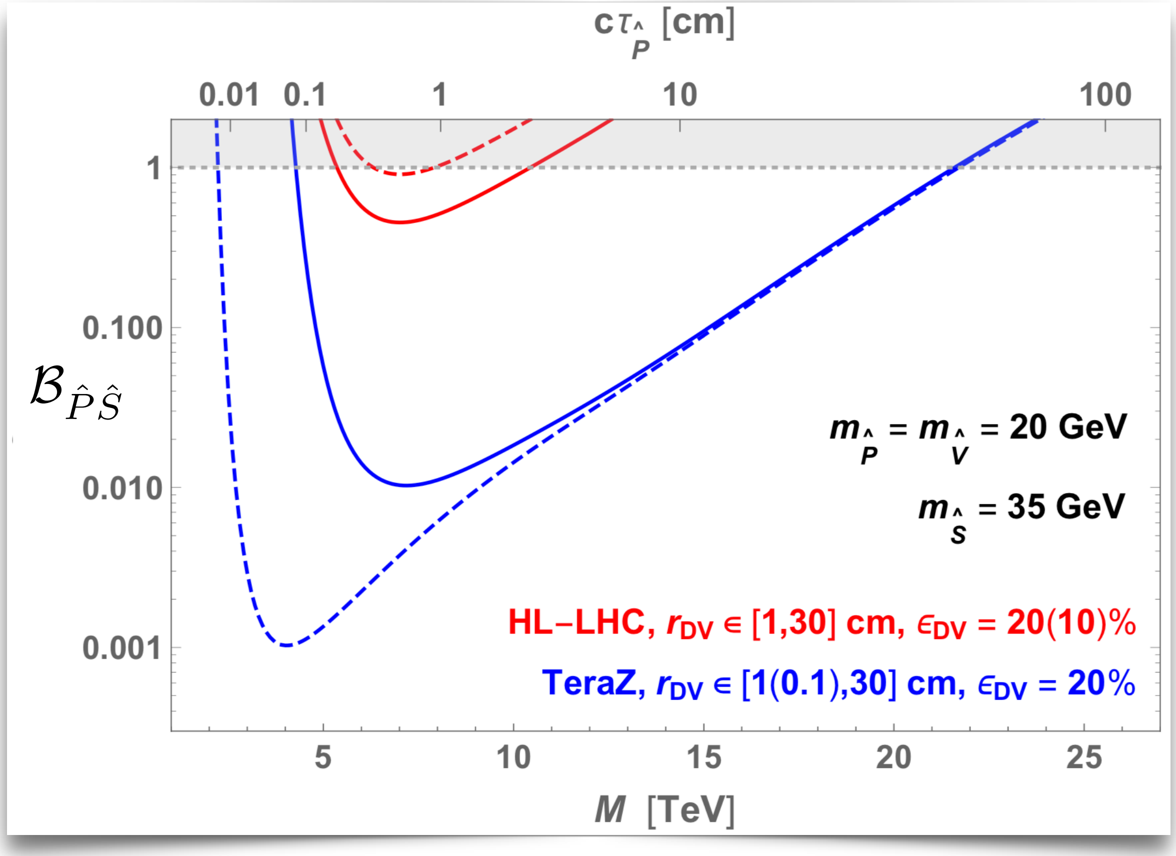
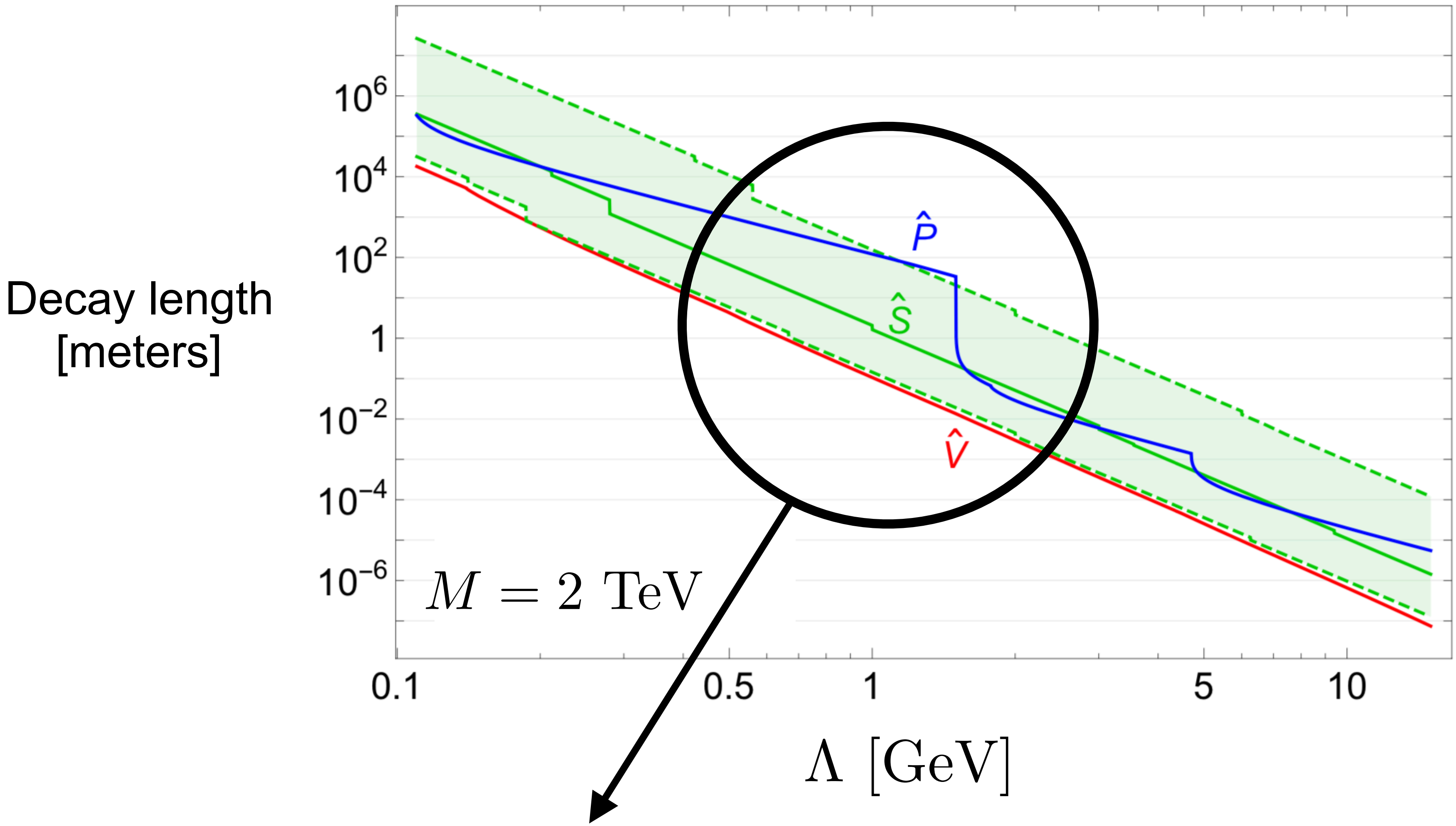


At TeraZ, reach up to *M* ~ 20 TeV

Phenomenology/2



$$\Lambda \lesssim 2\text{-}3 \text{ GeV} : \; Z \to \text{hidden jets, long-lived mesons}$$

Phenomenology/2

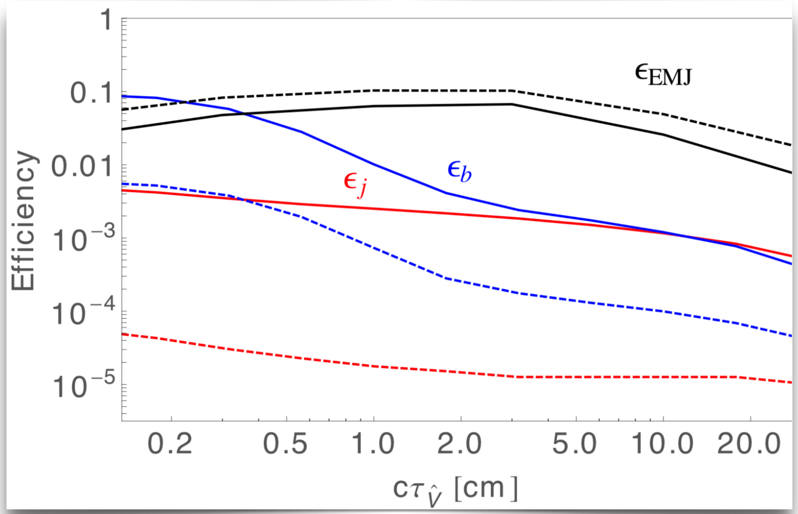
- Hidden jets made of long-lived mesons
- Similarities with emerging/semi-visible jets, **but** relatively soft production mode and democratic $\hat{V} \to f_{\mathrm{SM}} \bar{f}_{\mathrm{SM}}$

[Schwaller, Stolarski, Weiler, 1502.05409]
[Cohen, Lisanti, Lou, 1503.00009]

- **LHC:** ATLAS and CMS searches not sensitive, **best reach @ LHCb**
  Resolve single $\hat{V} \to \mu\mu$ decay inside the VELO

- ***Z* factory:** use LHC tracker resolution for conservative estimate
  (checked it against CMS search for emerging jets) [CMS 1810.10069]

Phenomenology/2

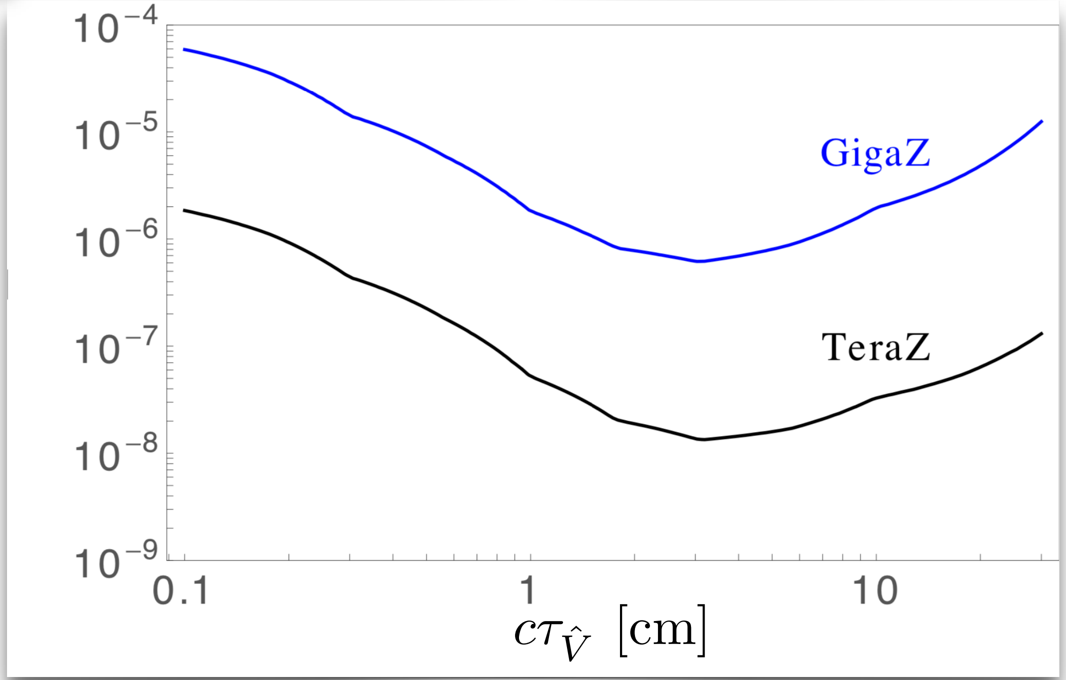


Solid: $N_{\rm tracks} \geq 5, \quad N_\ell = 0, 1$

Dashed: $N_{\rm tracks} \geq 3, \quad N_\ell \geq 2$

(leverage $\hat{V} \to \ell\ell$ decays)

$\mathrm{BR}(Z \to \overline{\psi}\psi)$



[Cheng, Li, Salvioni, Verhaaren 2019]

Message

- Neutral Naturalness motivates a **confining hidden sector** at $0.1 \lesssim \Lambda/\mathrm{GeV} \lesssim 10$
- Here: 1-flavor hidden QCD, coupled to SM via Higgs **and *Z* portal**
- Indirect sensitivity via EWPO, but **much stronger direct potential** @FCC-ee
  A trillion *Z* bosons give extraordinary reach on exotic decays: $M \sim 20\ \mathrm{TeV}$
- More to learn: multi-flavor case in progress
  [Cheng, Li, Salvioni, Verhaaren]
- For *Z* decays to hidden sectors that contain Dark Matter, extensive analysis done in [Liu, Wang, Wang, Xue, 1712.07237]

Backup

Phenomenology/2

- For $m_{\hat{V}} \lesssim \mathrm{GeV}$, other production mechanisms become important: Bremsstrahlung, meson decays, Drell-Yan, …

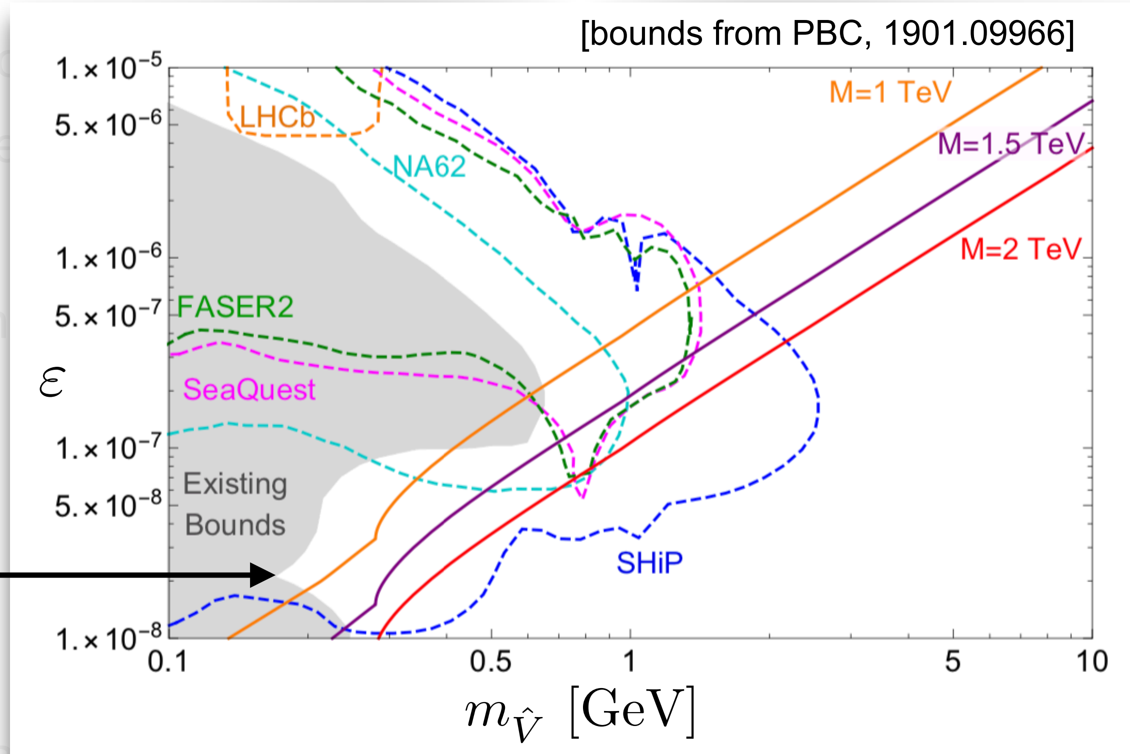
- Hidden fermions have no electric charge, vector meson couples to neutral current

$$\mathcal{L} = -A_D^\mu \left(\varepsilon\, e J_\mu^{\mathrm{EM}} + \varepsilon_Z \frac{g_Z}{2} J_\mu^{\mathrm{NC}} \right)$$

- No global analysis available yet.
  To gain first impression, approximate $\hat{V}$ as "kinetically mixed dark photon" with

$$\varepsilon \approx 10^{-7} \left(\frac{m_{\hat{V}}}{\mathrm{GeV}} \right)^2 \left(\frac{2\ \mathrm{TeV}}{M} \right)^2$$

Phenomenology/2



effect of

$\mathrm{BR}(\hat{V} \to \nu\nu)$

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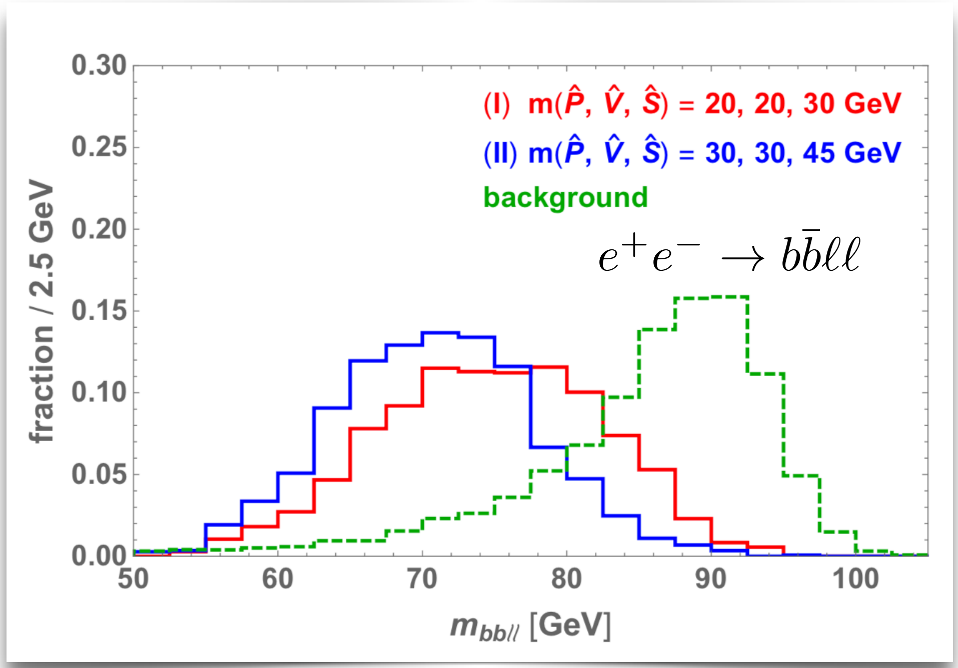

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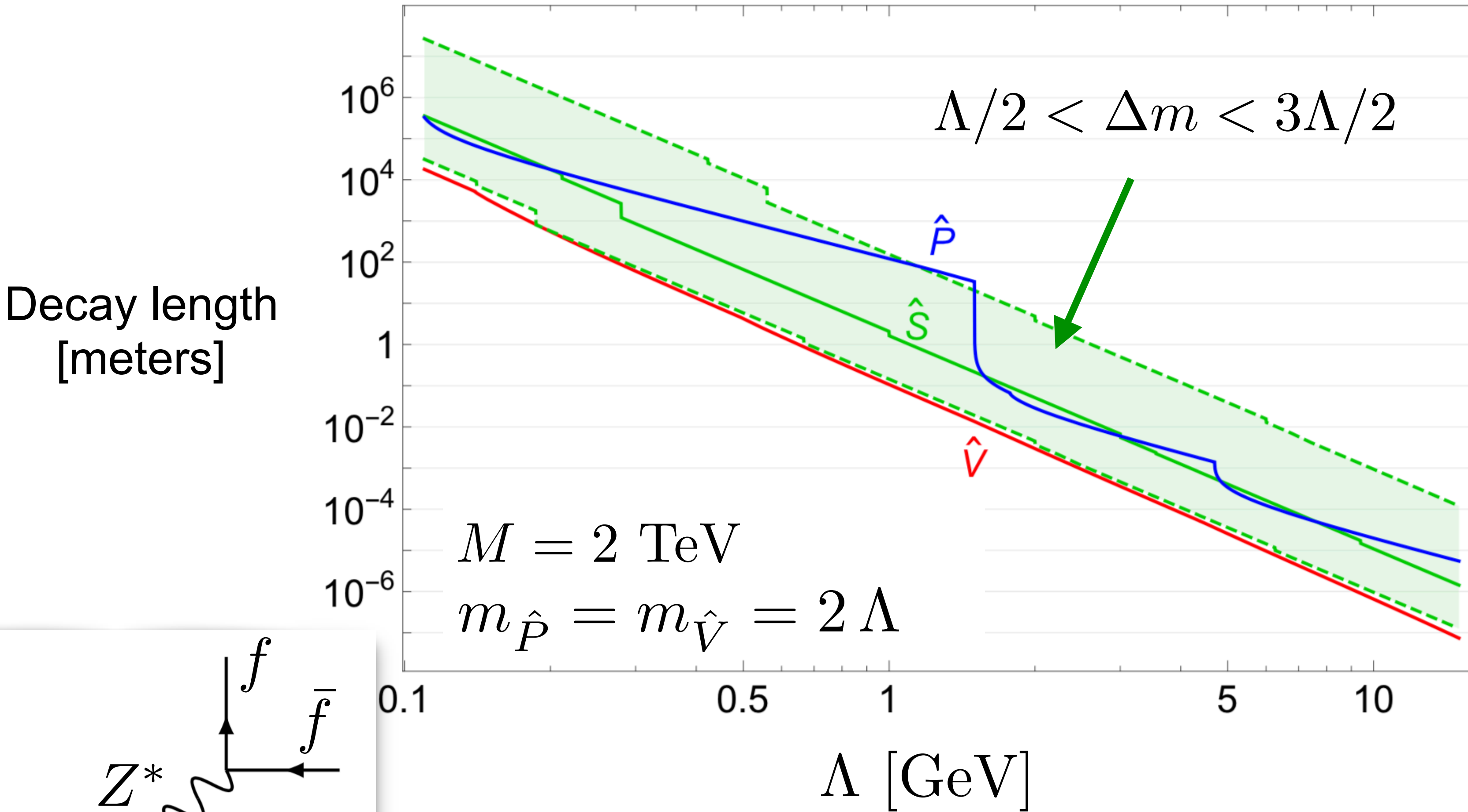
$$N_B < 0.1 \text{ events}$$

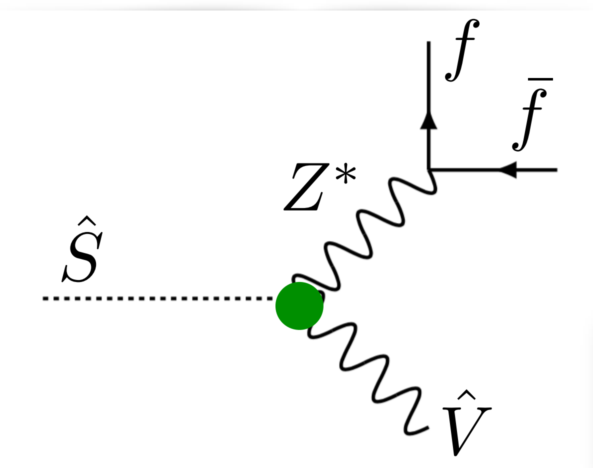
- **At LEP1 ?** $N_Z^{\text{total}} \approx 2.2 \times 10^7$

[hep-ex/0509008]

$$N_S \approx 28\, \mathcal{B}_{\hat{P}\hat{S}} \left(\frac{2\text{ TeV}}{M}\right)^4 (\mathcal{A}\,\epsilon)_{\text{tot}}$$ but $\epsilon_b \sim 0.3$, sensitivity marginal at best

Hidden meson decays





$$\Gamma_{\hat{S}} \propto (\Delta m)^7$$

$$\Delta m \equiv m_{\hat{S}} - m_{\hat{V}}$$

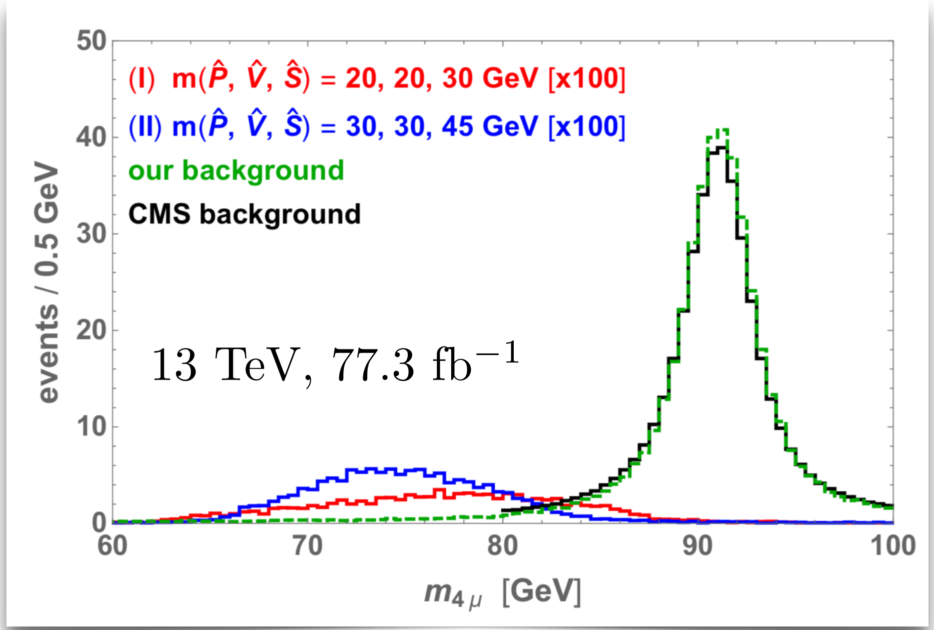
Phenomenology/1

- At LHC, very clean final state from $Z \to \hat{V}\hat{S} \to (\mu\mu)(\mu\mu) + X$
- Start from CMS search for light Z', but implement our own analysis

[**CMS**, 1808.03684]

$$|m(\mu_1^+\mu_1^-) - m(\mu_1^+\mu_1^-)| \text{ or}$$

$$|m(\mu_1^+\mu_2^-) - m(\mu_2^+\mu_1^-)| < 1 \text{ GeV}$$



now

$$\text{(I)} \quad M \gtrsim 1.5, 2.0, 3.3 \text{ TeV} \left(\frac{\mathcal{B}_{\hat{V}\hat{S}}}{0.1}\right)^{1/4}$$

HL-LHC

Meson decays

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

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

$$\left(|\psi(0)|^2 = \frac{\Lambda^3}{4\pi}\right)$$

$$\Gamma(\hat{S} \to f\bar{f}) = \frac{18 N_d N_c^f}{\pi} (\lambda_{h\psi\psi}\lambda_{hff})^2 \frac{|\psi'(0)|^2}{m_h^4} \frac{\left(1 - \frac{4m_f^2}{m_{\hat{S}}^2}\right)^{3/2}}{\left(1 - \frac{m_{\hat{S}}^2}{m_h^2}\right)^2}$$

$$\lambda_{h\psi\psi} = 2c_g \mu_\psi m_t^2/(3bvM^2) \text{ where } b = 11 - 2N_l/3$$

$$\Gamma(\hat{S} \to \hat{V} f\bar{f}) \sim \frac{\alpha_Z^2 N_f}{16\pi} \frac{m_t^4}{M^4} \frac{k^7}{m_Z^4} |\varepsilon_{if}|^2 \qquad k = \frac{m_{\hat{S}}^2 - m_{\hat{V}}^2}{2m_{\hat{S}}} = \Delta m \left(1 - \frac{\Delta m}{2m_{\hat{S}}}\right)$$

$$\frac{\Gamma(\hat{S} \to \bar{b}b)}{\Gamma(\hat{S} \to \hat{V} f\bar{f})} \sim \frac{c_g^2}{b^2} \frac{8N_d N_c}{\pi N_f} \frac{y_t^2 y_b^2}{\alpha_Z^2} \frac{m_Z^4}{m_h^4} \frac{\mu_\psi^2}{m_t^2} \frac{\Lambda^7}{k^7} \approx 10^{-5} \left(\frac{\Lambda}{5\text{ GeV}}\right)^2 \left(\frac{\mu_\psi}{\Lambda}\right)^2 \left(\frac{\Lambda}{k}\right)^7 \left(\frac{c_g}{4}\right)^2,$$

Long-lived heavy mesons

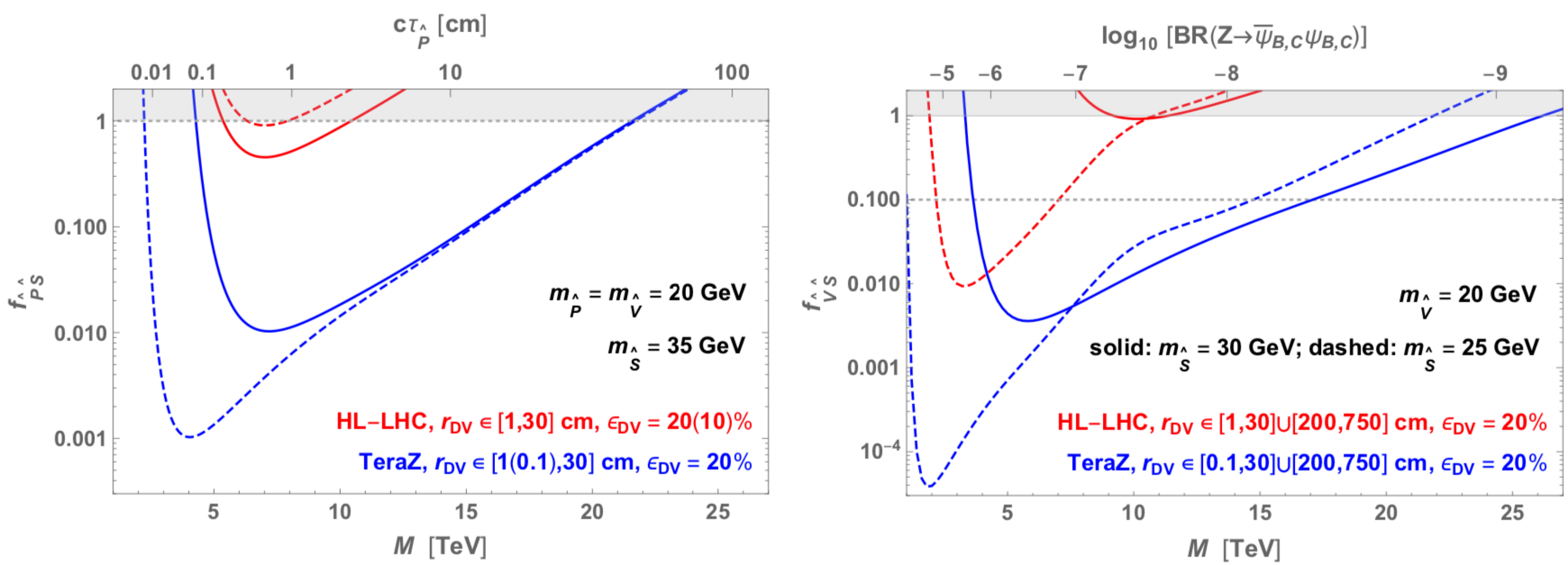


FIG. 5: *Left:* projected bounds on $f_{\hat{P}\hat{S}}$ from future searches for $Z \to \hat{P}\hat{S}$, where $\hat{P}$ is long-lived while $\hat{S} \to (\hat{V} \to \ell\ell) f\bar{f}$. *Right:* projected bounds on $f_{\hat{V}\hat{S}}$ from future searches for $Z \to \hat{V}\hat{S}$, where $\hat{S}$ is long lived while $\hat{V} \to \ell\ell$. All bounds are at 95% CL, assuming negligible SM background. We take $\ell = \mu$ (e or μ) at the LHC (TeraZ), and the dilepton pair must be prompt at the LHC, but can be displaced at TeraZ. The dotted gray lines correspond to the educated guesses $f_{\hat{P}\hat{S},\hat{V}\hat{S}} \sim 1, 0.1$ discussed in Subsec. IV A.

Meson FCNC decays

By matching to Eq. (27) we identify

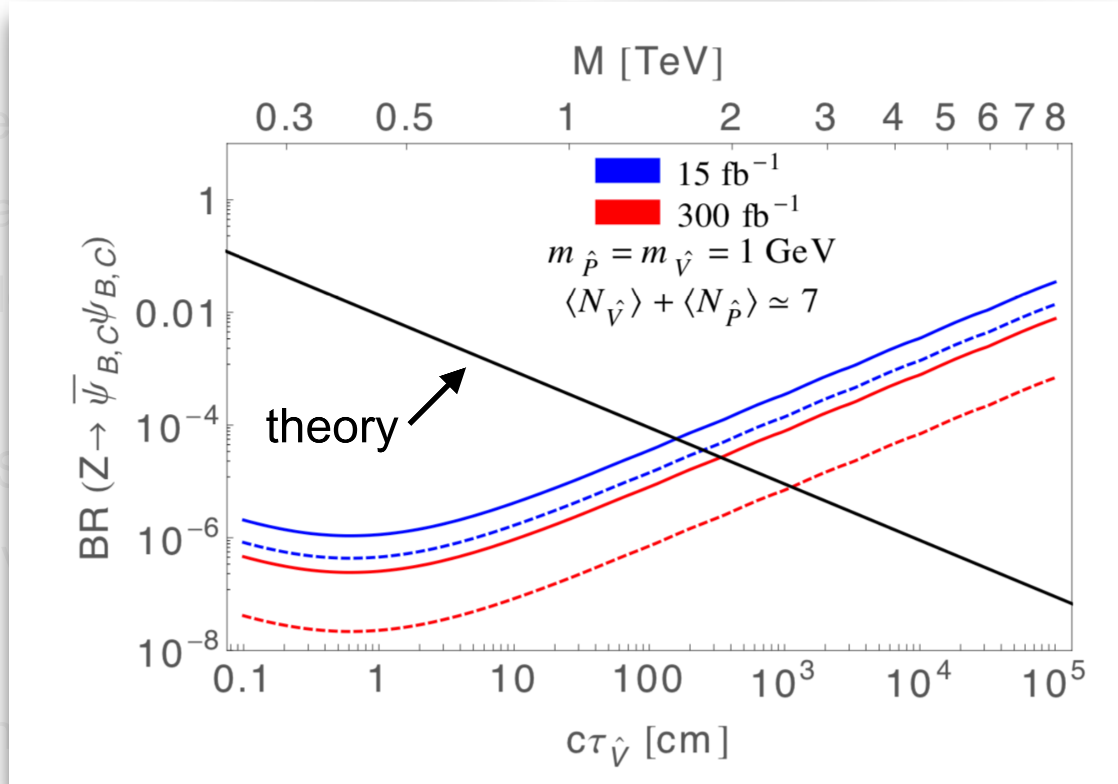
$$\varepsilon_Z \simeq g_Z \sqrt{\frac{N_d}{2} \frac{m_t^2}{M^2} \frac{|\psi(0)| m_{\hat{V}}^{1/2}}{m_Z^2}} \approx 3.2 \times 10^{-7} \left(\frac{\Lambda}{1\,\mathrm{GeV}}\right)^{3/2} \left(\frac{m_{\hat{V}}}{2\,\mathrm{GeV}}\right)^{1/2} \left(\frac{2\,\mathrm{TeV}}{M}\right)^2 , \qquad (53)$$

where we have assumed $m_{\hat{V}} \ll m_Z$ and included an extra factor of $\sqrt{2}$ to account for the two hidden sectors B, C.[18] Very recently, Ref. [67] derived strong FCNC decay bounds on ε_Z for a generic light vector X_μ. In our setup, though, the NP contribution to a given SM final state should be smaller than the corresponding perturbative rate, $\mathrm{BR}(B \to K f \bar{f})_{\mathrm{NP}} \lesssim \mathrm{BR}(B \to K \psi \overline{\psi})$, where f is a SM fermion and we have taken B decays as example. This allows us to conservatively estimate

$$\frac{\mathrm{BR}(B \to K f \bar{f})_{\mathrm{NP}}}{\mathrm{BR}(B \to K f \bar{f})_{\mathrm{SM}}} \lesssim \left(\frac{m_t}{M}\right)^4 \frac{\mathrm{BR}(\hat{V} \to \nu \bar{\nu})}{\mathrm{BR}(\hat{V} \to f \bar{f})} , \qquad (54)$$

where we assumed dominance of the Z penguin over the box amplitudes and used Eq. (2). An analogous expression applies to K decays. For any f, the RHS of Eq. (54) is below a percent if $M > 1$ TeV, showing that the precision needed to probe the NP is well beyond the current one [48].[19] We do not expect non-perturbative corrections to change this conclusion.

Phenomenology/2



$$M > 1.6\,(2.0)\ \text{TeV}$$

$$\text{for } L = 15\,(300)\ \text{fb}^{-1}$$

[see also: future displaced dimuon trigger @ CMS, Gershtein and Knapen, 1907.00007]

Theory motivation

- Add **two** copies of MSSM top sector, [Cheng, Li, **ES,** Verhaaren, 2019]

$$SU(3)_A \times SU(3)_B \times SU(3)_C \times SU(2) \times U(1)$$

Superpotential:

$$W = y_t(Q_A H u_A^c + Q_B H u_B^c + Q_C H u_C^c) + M(Q_B Q_B'^c + Q_C Q_C'^c)$$

$$Z_3 \qquad\qquad Z_2$$

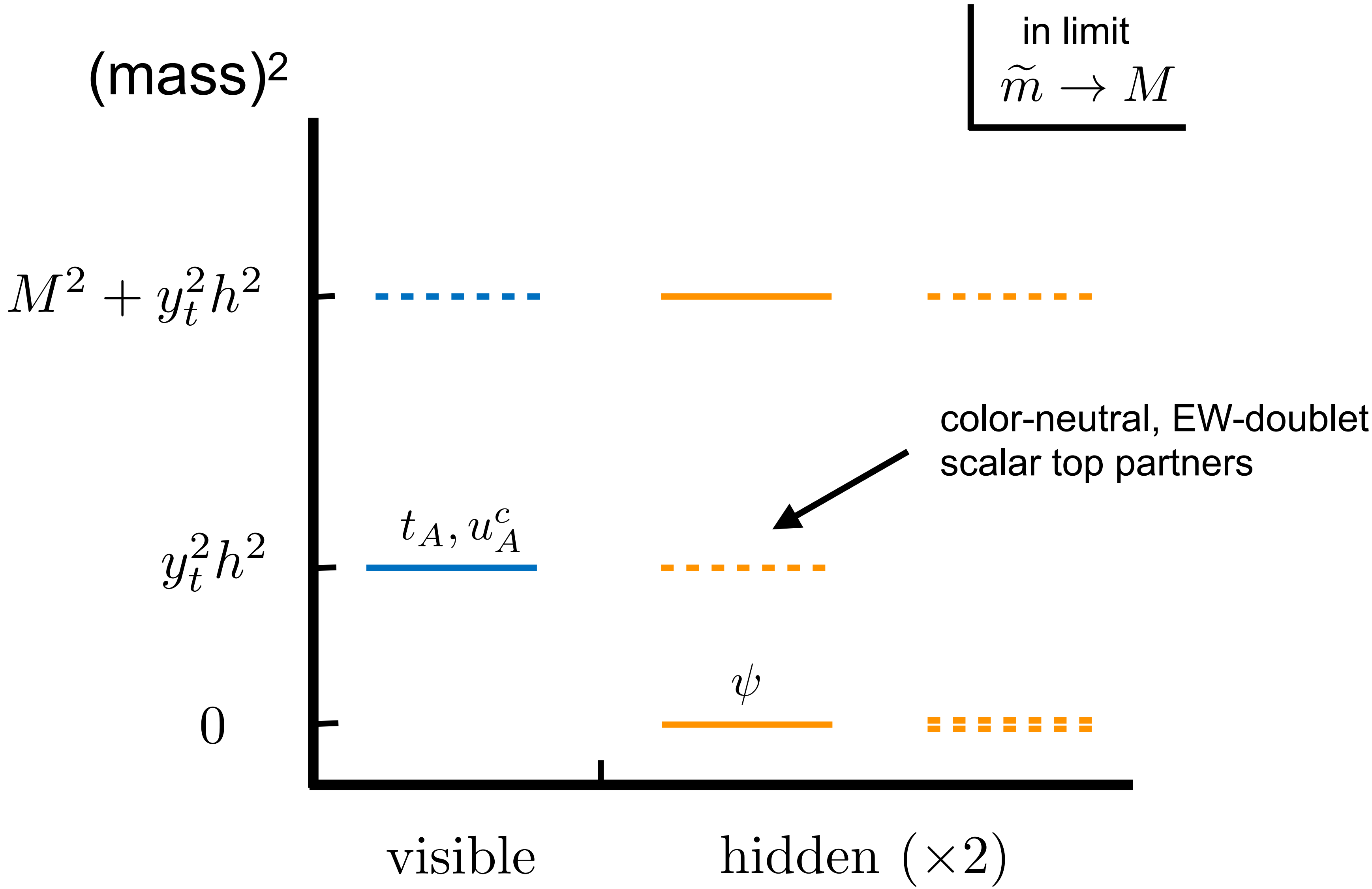
few TeV

Soft masses:

$$V_s = +\widetilde{m}^2(|\widetilde{Q}_A|^2 + |\tilde{u}_A^c|^2) - \widetilde{m}^2(|\widetilde{Q}_B|^2 + |\widetilde{Q}_C|^2)$$

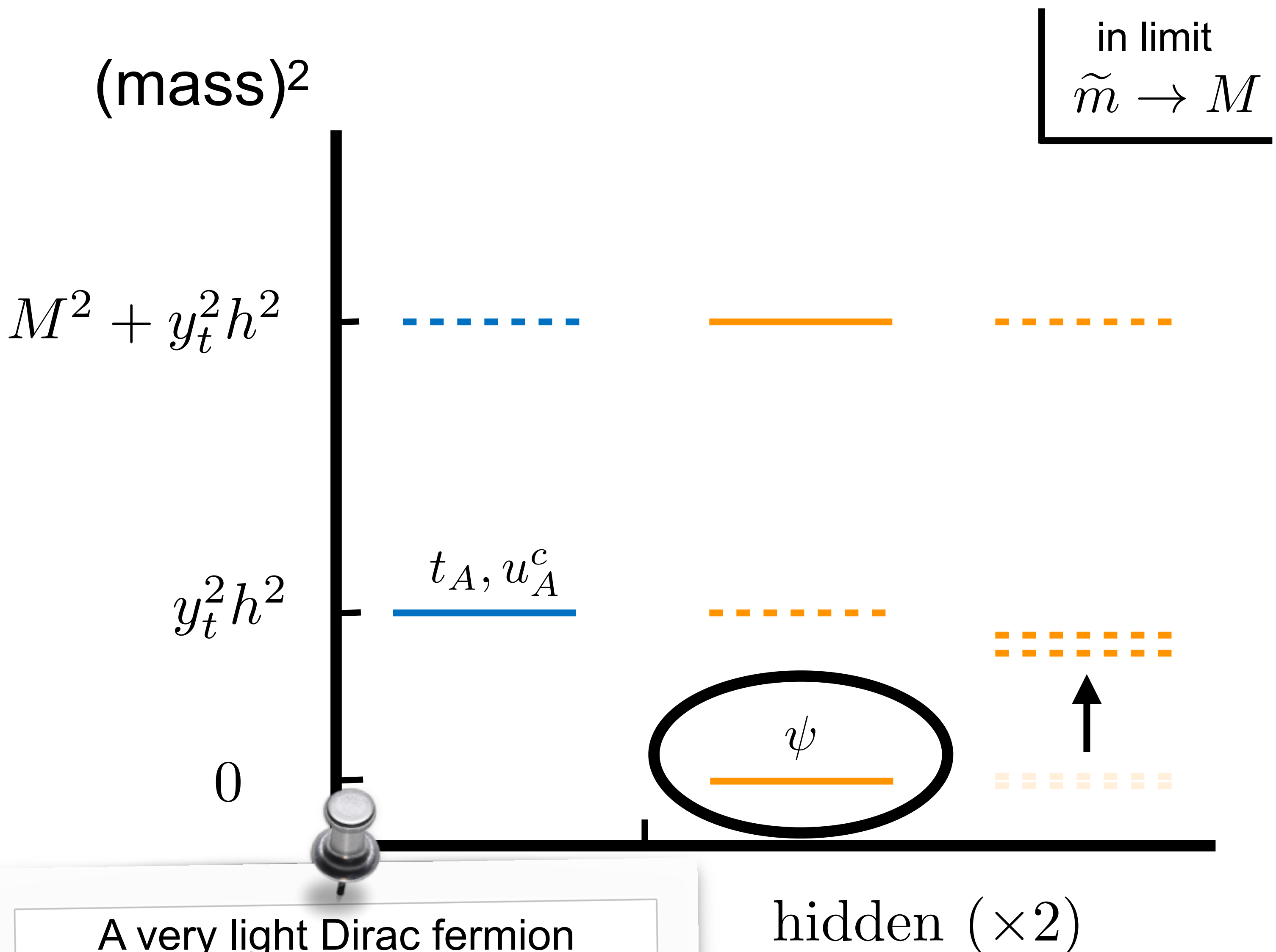
raise colored stops **lower** color-neutral “stops”

Accidental supersymmetry



[Cheng, Li, **ES,** Verhaaren, 2019]

Accidental supersymmetry



A very light Dirac fermion
at bottom of spectrum

[Cheng, Li, **ES**, Verhaaren, 2019]