Light Hidden Mesons through the *Z* Portal

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Technical University of Munich

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EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

LFC 2019

September 12, 2019

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based on 1906.02198 + 1803.03651 [JHEP]

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

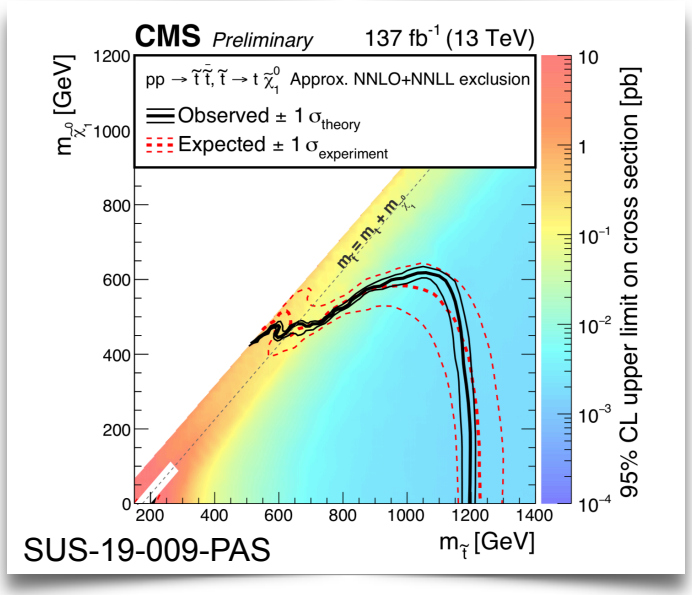
Introduction

- **Hidden sectors** are important possibility for New Physics.
  Enormous range of options
- Motivations from addressing open questions of the Standard Model are key to make progress: Naturalness, Dark Matter, …

Neutral Naturalness

The “missing Top Partner puzzle:”

No signs of stops/vector-like fermions at LHC



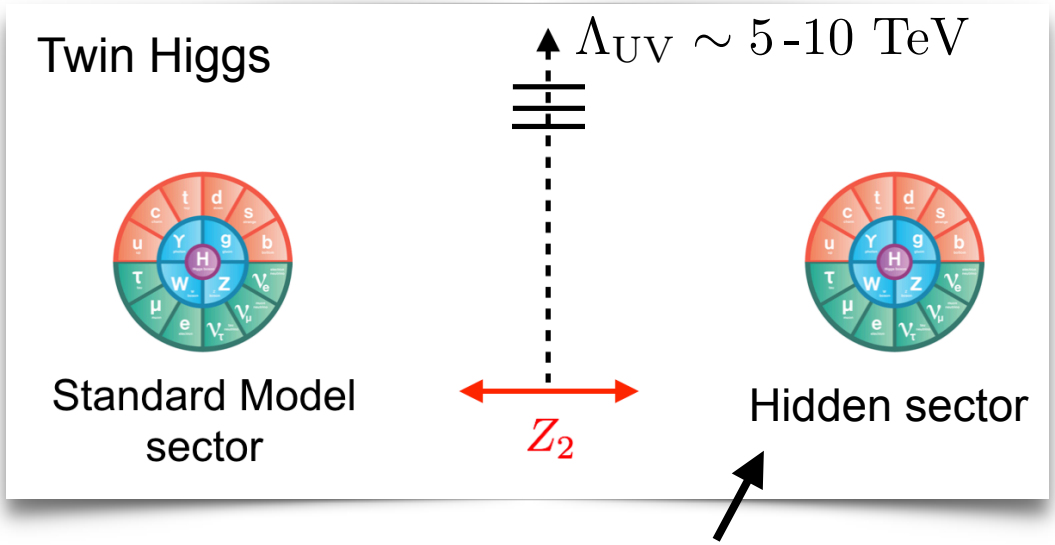
- **Neutral Naturalness:** broad class of theories that solve little hierarchy problem with **color-neutral** Top Partners
- Phenomenology radically non-standard, change of paradigm for searches
- **Confining hidden sector** is a typical expectation

[for more on NN: talk by Stefan Stelzl @ 15:00]

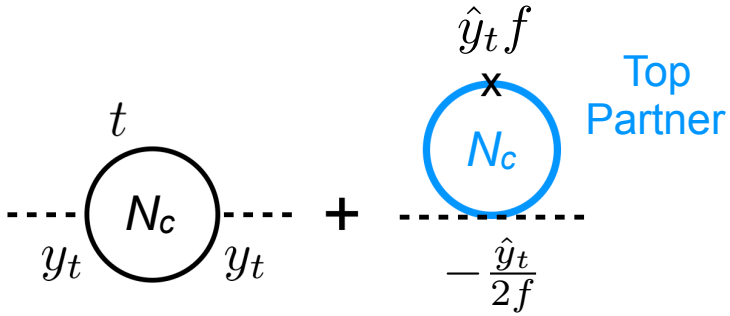
Neutral Naturalness

- A discrete symmetry relates the SM to the hidden sector

[Chacko, Goh, Harnik, 2006]



- 1 loop:



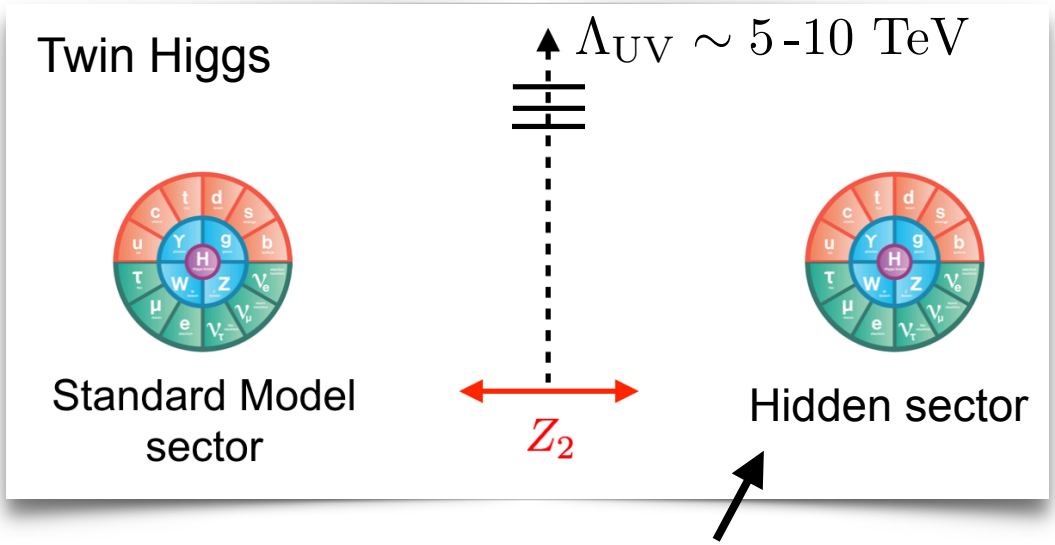
$y_t \overset{Z_2}{\longleftrightarrow} \hat{y}_t$

quadratic corrections to Higgs mass cancel out

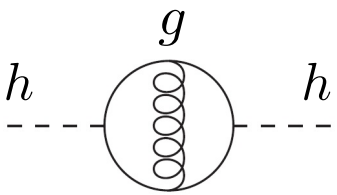
Hidden confinement

- A discrete symmetry relates the SM to the hidden sector

[Chacko, Goh, Harnik, 2006]



- 2 loops:



gauge hidden *SU*(3) with

$$g_s \simeq \hat{g}_s \text{ at } \Lambda_{\rm UV}$$

confines at $\Lambda \gtrsim \Lambda_{\rm QCD}$

Hidden sector

- Confining hidden sector is generic expectation in Neutral Naturalness

- Details depend on

  ➡ Mass spectrum of hidden matter

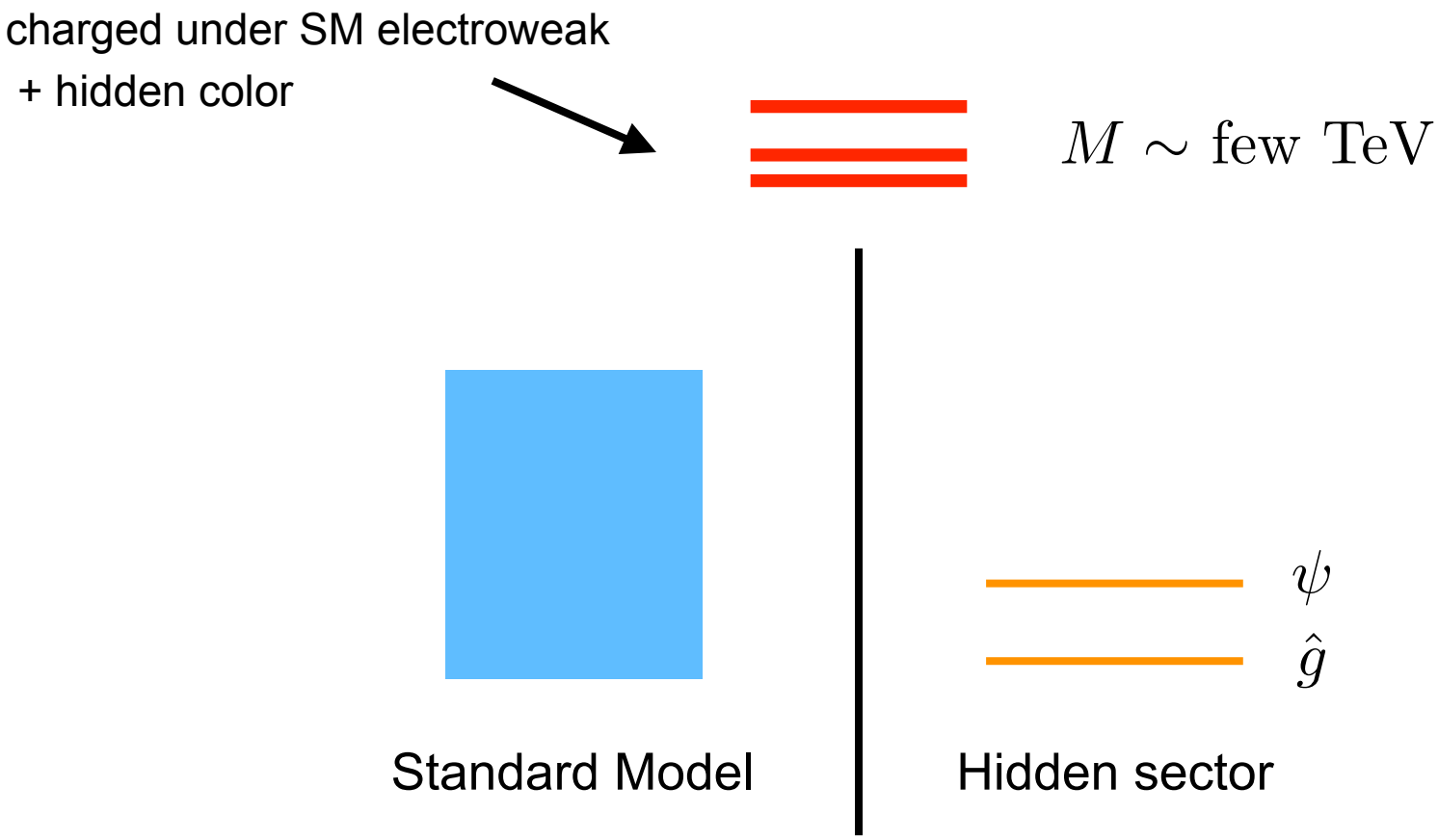
  ➡ Portals to SM: Higgs is mandatory, others?

  ➡ Additional interactions in 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
- Visible and hidden sector connected by BSM particles with ~ TeV masses



Theory background

- Hidden QCD with 1 light fermion flavor
- Visible and hidden sector connected by BSM particles with ~ TeV masses

- Fairly common ingredients in Neutral Naturalness:

  ✓ Typically only 3rd generation is copied, fewer flavors in hidden sector

  ✓ TeV-scale particles play roles in Higgs mass stabilization

- Examples: composite Twin Higgs, **models realizing accidental SUSY**

[Cheng, Li, **ES,** Verhaaren, 2018]
[Cheng, Li, **ES,** Verhaaren, 2019]

(in backup slides; please ask if you want to hear more)

Description of Hidden Sector

Phenomenology

Description of Hidden Sector

Phenomenology

In this talk

- Hidden QCD with 1 light fermion flavor
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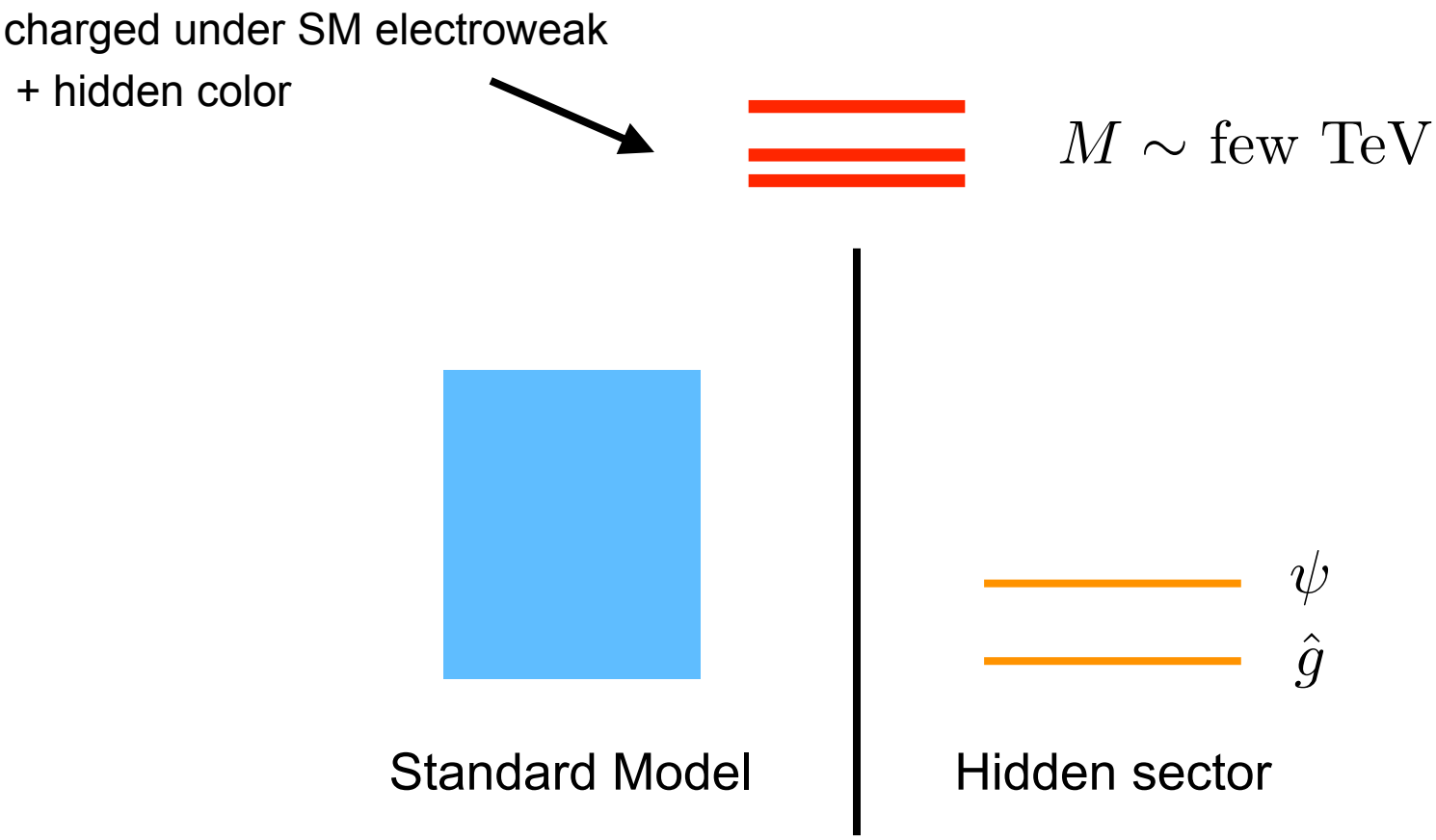
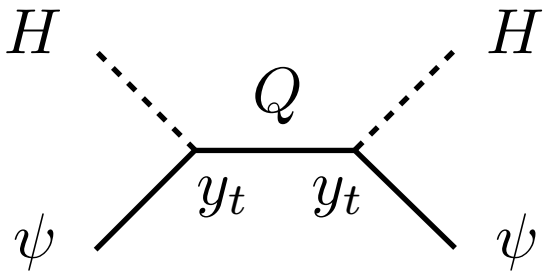


The effective theory

- Integrate out states at M ➡ EFT for Standard Model + hidden sector



$$(\text{mass of } Q) \sim M$$

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

Higgs portal

$$\mathrm{BR}(h \to \hat{g}\hat{g}) \approx 2.0 \times 10^{-4} \left(\frac{\alpha_d}{0.18}\right)^2 \left(\frac{2\ \mathrm{TeV}}{M}\right)^4 \left(\frac{c_g}{4}\right)^2$$

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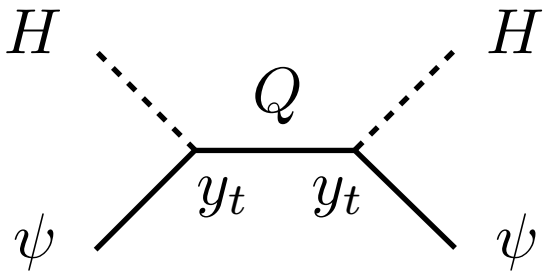

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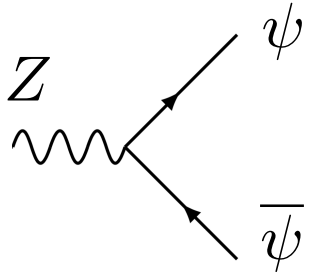
↓ *Z* portal

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



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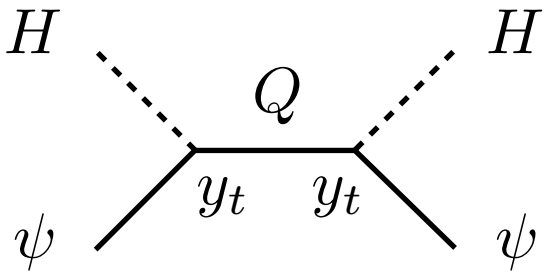

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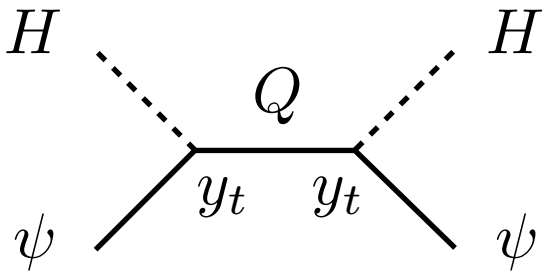
- At the LHC, $\sigma_Z \simeq 55\ \text{nb},\ \sigma_h \simeq 49\ \text{pb}$

➡ $$\frac{N(Z\to\overline{\psi}\psi)}{N(h\to\hat{g}\hat{g})} \sim 120\left(\frac{0.18}{\alpha_d}\right)^2\left(\frac{4}{c_g}\right)^2$$

The effective theory

- Integrate out states at M ➡ EFT for Standard Model + hidden sector



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Focus on *Z* decays to hidden sector

- At the LHC, $\sigma_Z \simeq 55$ nb, $\sigma_h \simeq 49$ pb

➡ $$\frac{N(Z\to\overline{\psi}\psi)}{N(h\to\hat{g}\hat{g})} \sim 120\left(\frac{0.18}{\alpha_d}\right)^2\left(\frac{4}{c_g}\right)^2$$

The hidden hadrons

- *SU*(3) QCD with 1 flavor: no chiral symmetry ➡ no Goldstone bosons
- Some results available from lattice study: [Farchioni, Montvay, Münster, Scholz, Sudmann, Wuilloud, 0706.1131]
  - ☑ Baryons significantly heavier than mesons
  - ☑ Ratio of scalar/pseudoscalar meson masses: $m_{\hat{S}}/m_{\hat{P}} \approx 1.5$
  - ☐ No information about vector meson

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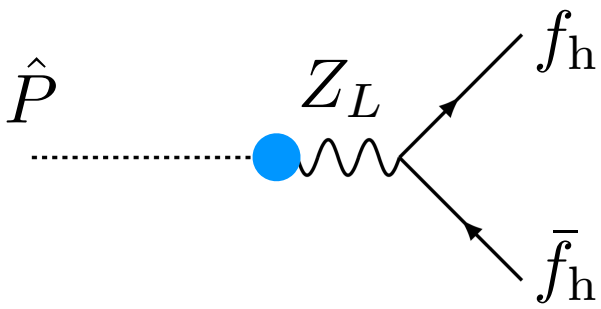
  - ☐ No information about vector meson
- **We assume** $m_{\hat{P}} \lesssim m_{\hat{V}} < m_{\hat{S}}$

0^{-+} 1^{--} 0^{++} (J^{PC})

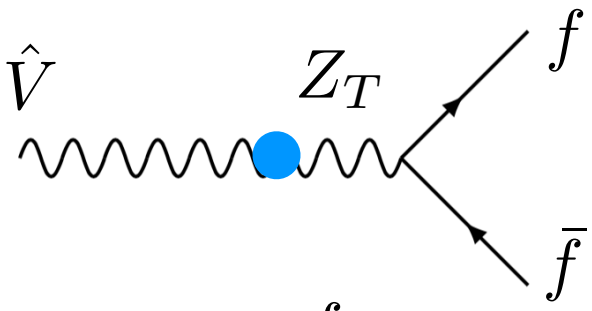
- Mesons decay back to visible sector through *Z* and *h* portals

Hidden meson decays

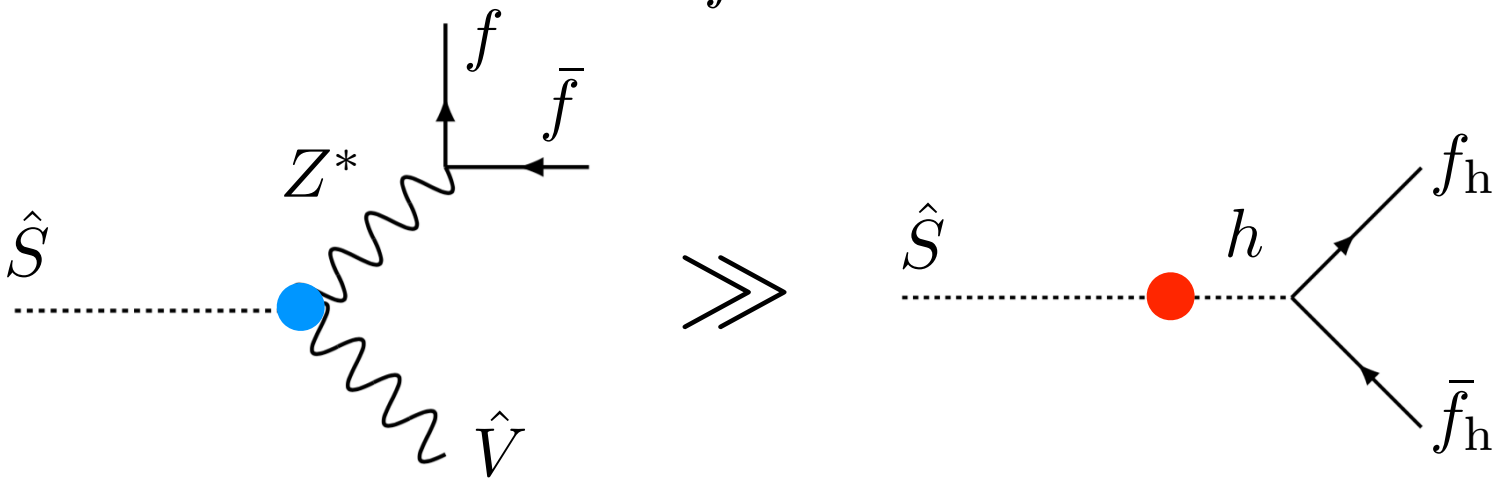
- It turns out, **all** lightest mesons decay dominantly via ***Z* portal**
- Pseudoscalar



- Vector

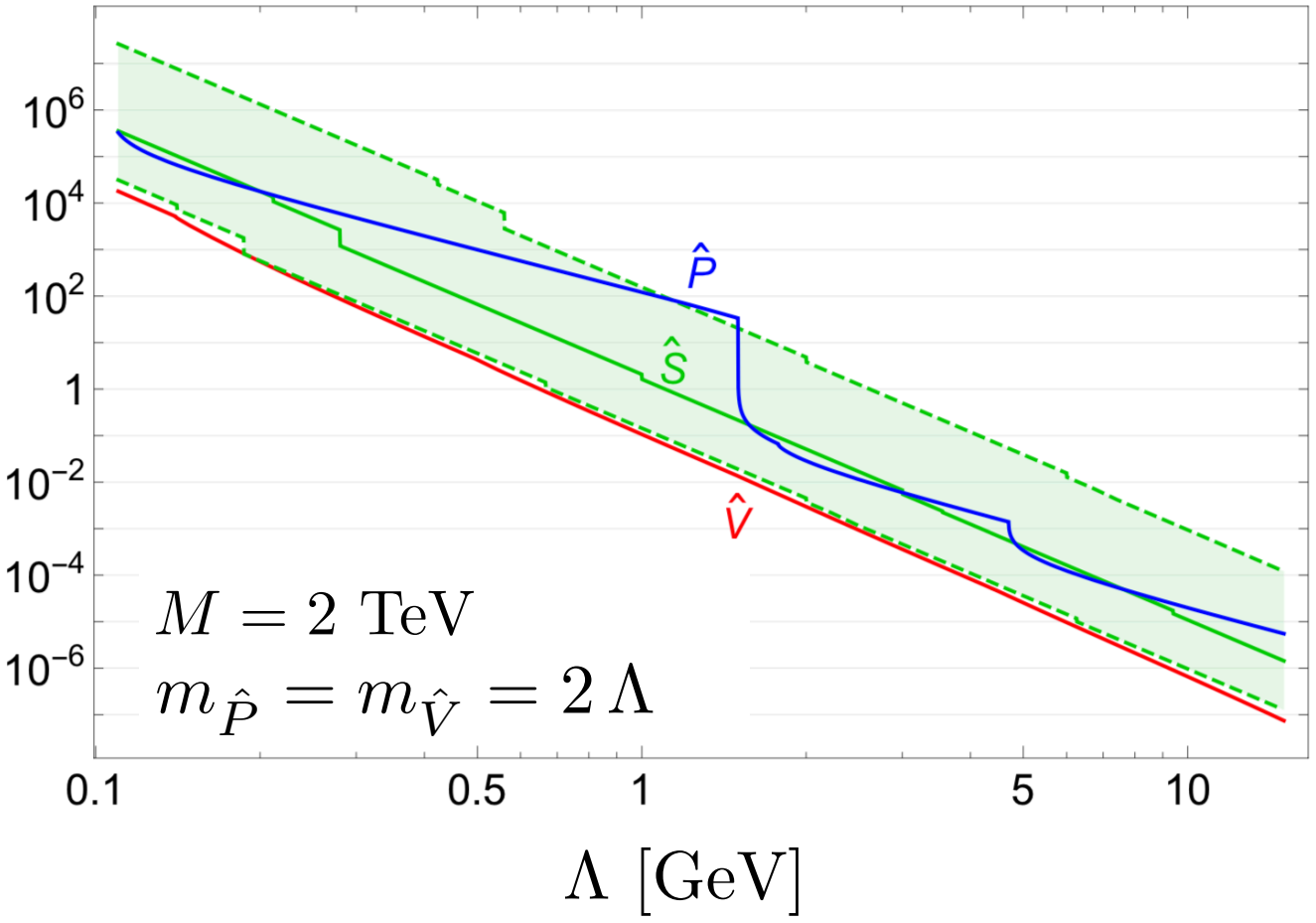


- Scalar



Hidden meson decays

Decay length [meters]

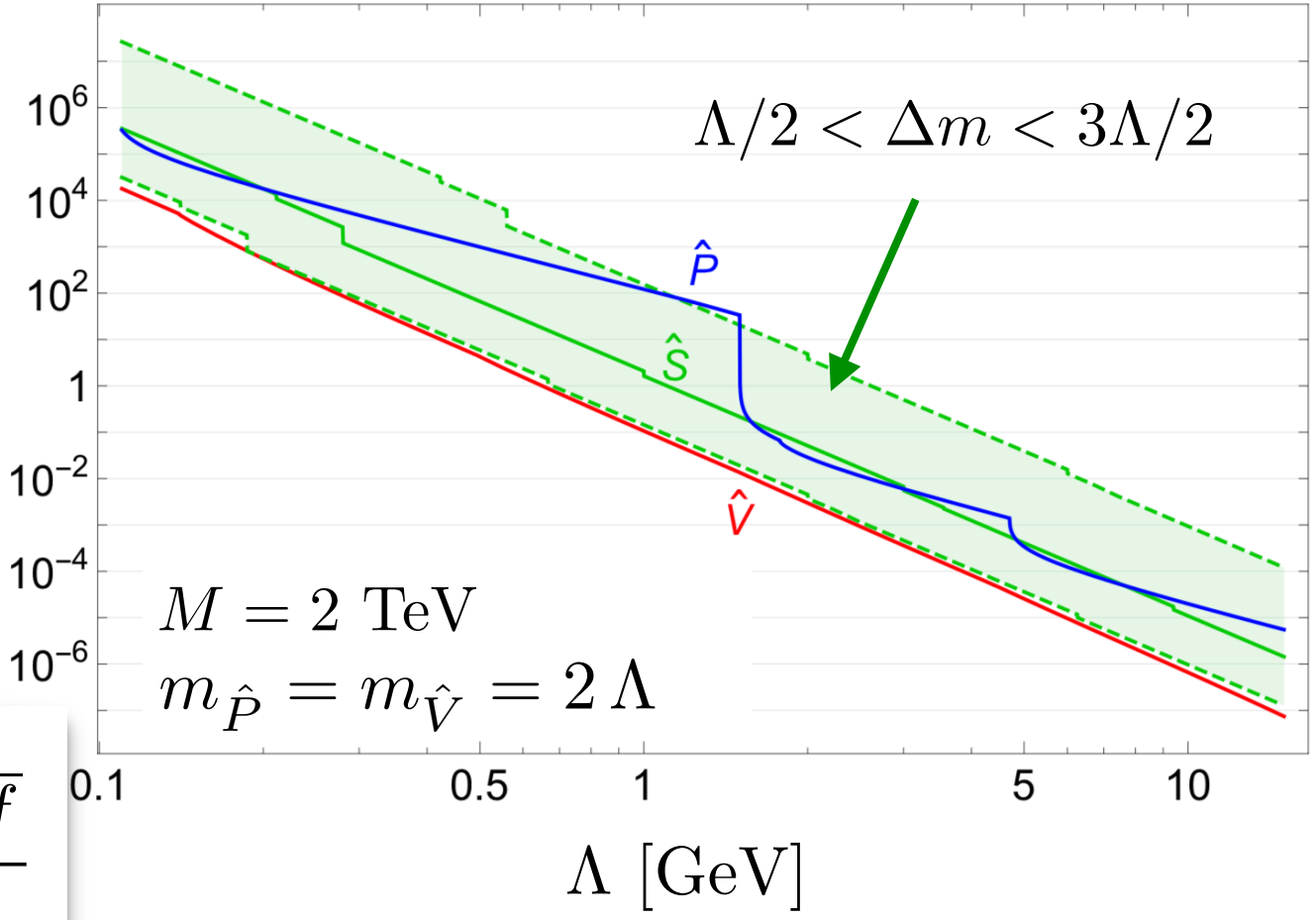


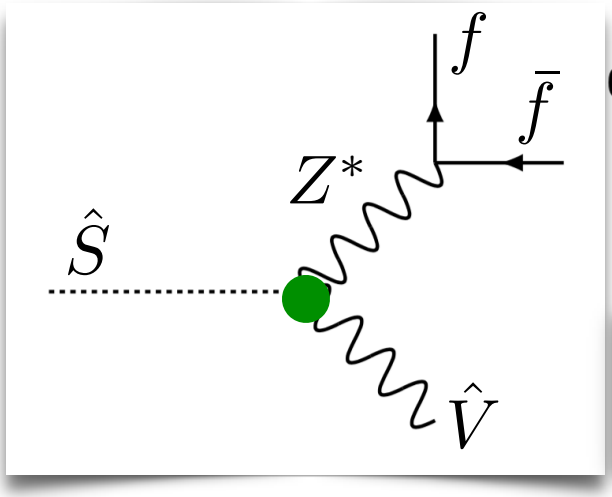
Two main parameters determine pheno:

- Hidden confinement scale Λ
- Mediation scale M

Hidden meson decays

Decay length
[meters]





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

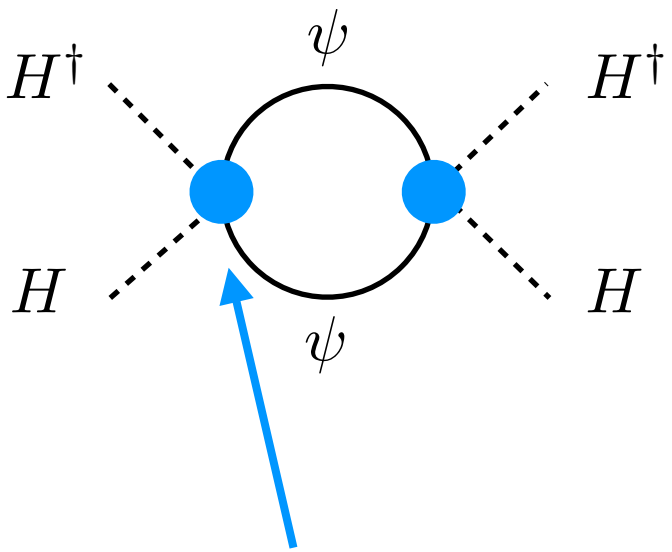
$$\Delta m \equiv m_{\hat{S}} - m_{\hat{V}}$$

Description of Hidden Sector

Phenomenology

Constraints

- An indirect constraint comes from EW precision tests:



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

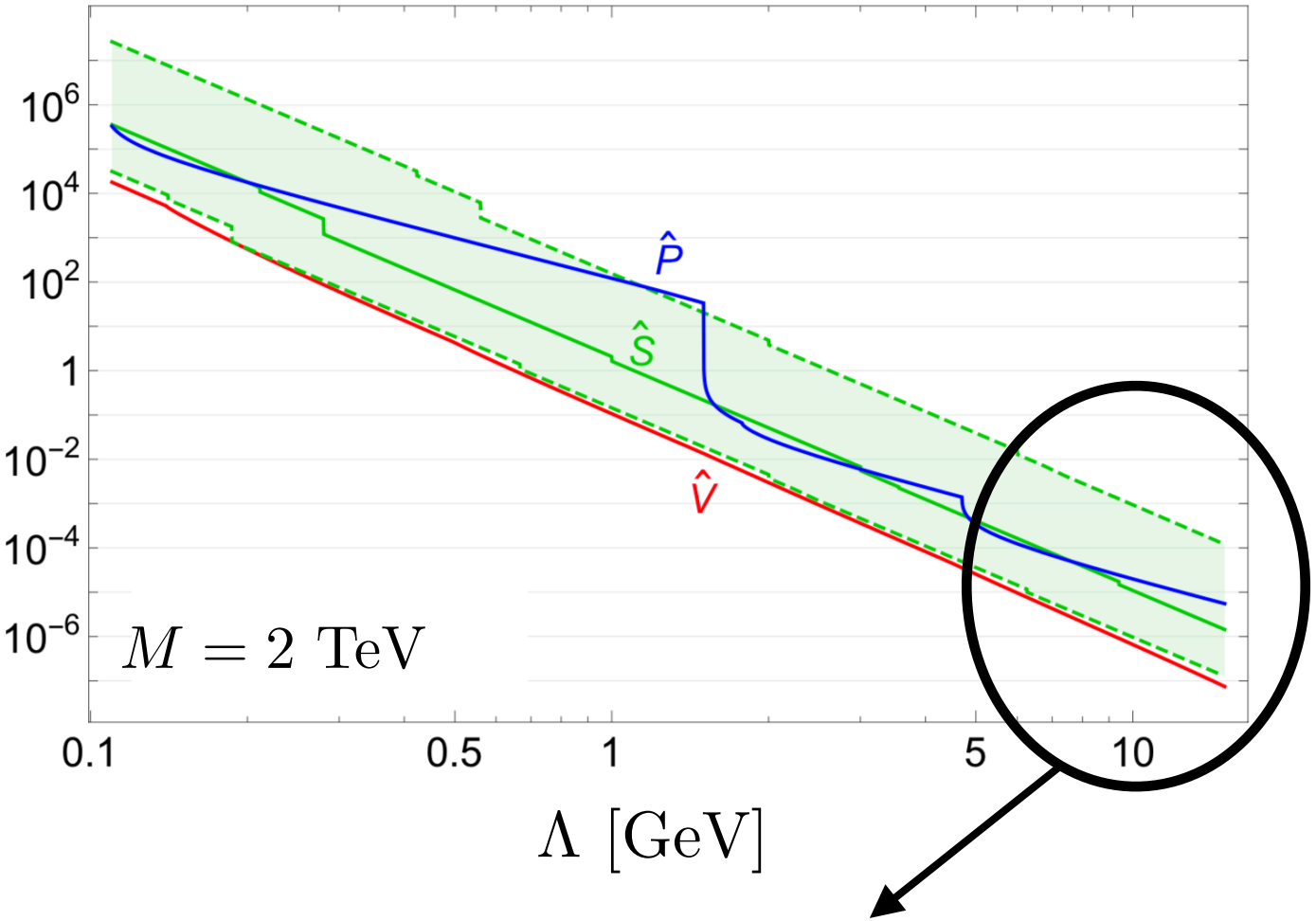
$$\Delta\widehat{T} \lesssim 10^{-3} \quad \rightarrow \quad M \gtrsim 0.9 \text{ TeV}$$

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

- **Explore direct probes** instead: *Z* decays to hidden hadrons

Phenomenology/1

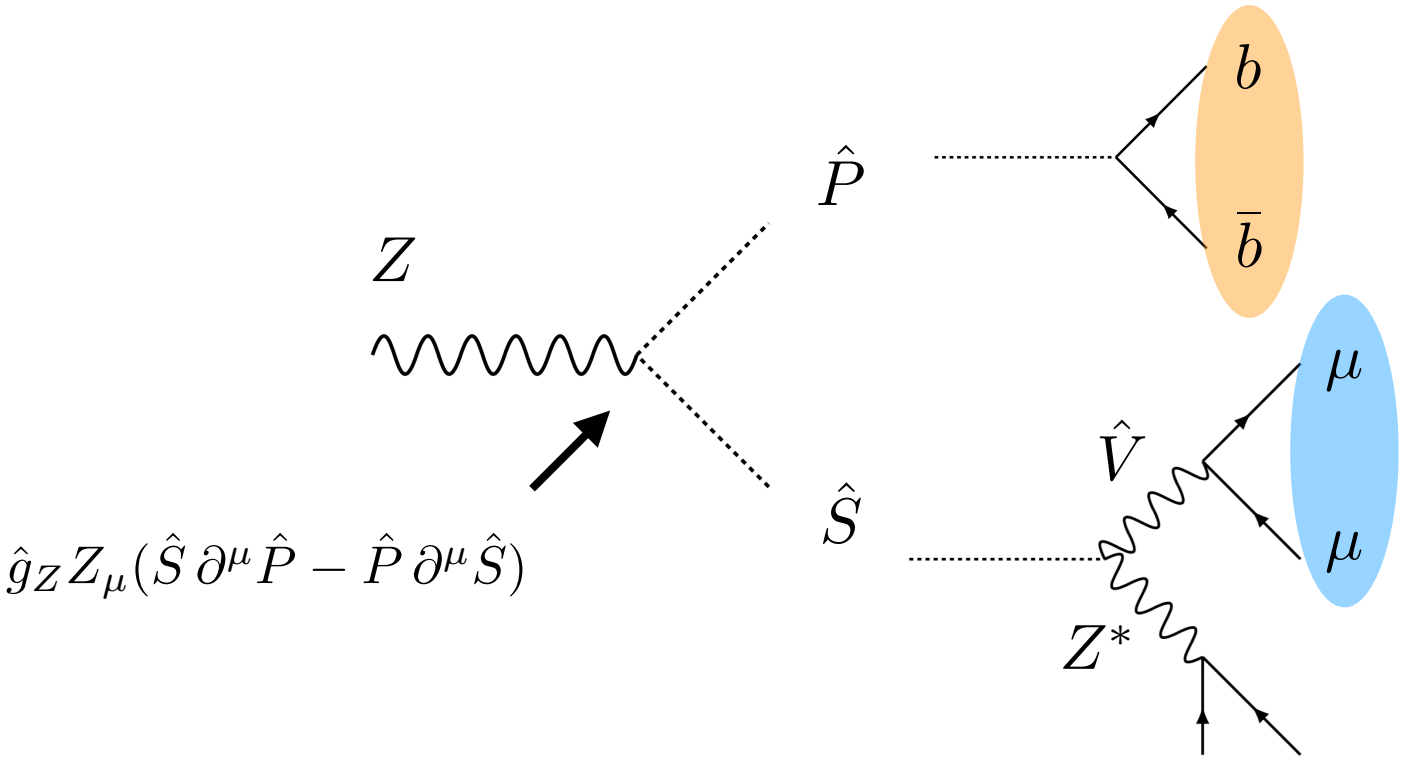
Decay length [meters]



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

Phenomenology/1

- If mesons have masses of *O*(10-30) GeV, *Z* decays to 2-body final states
- Quantitative predictions of BRs are hard. Simply parametrize ignorance



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

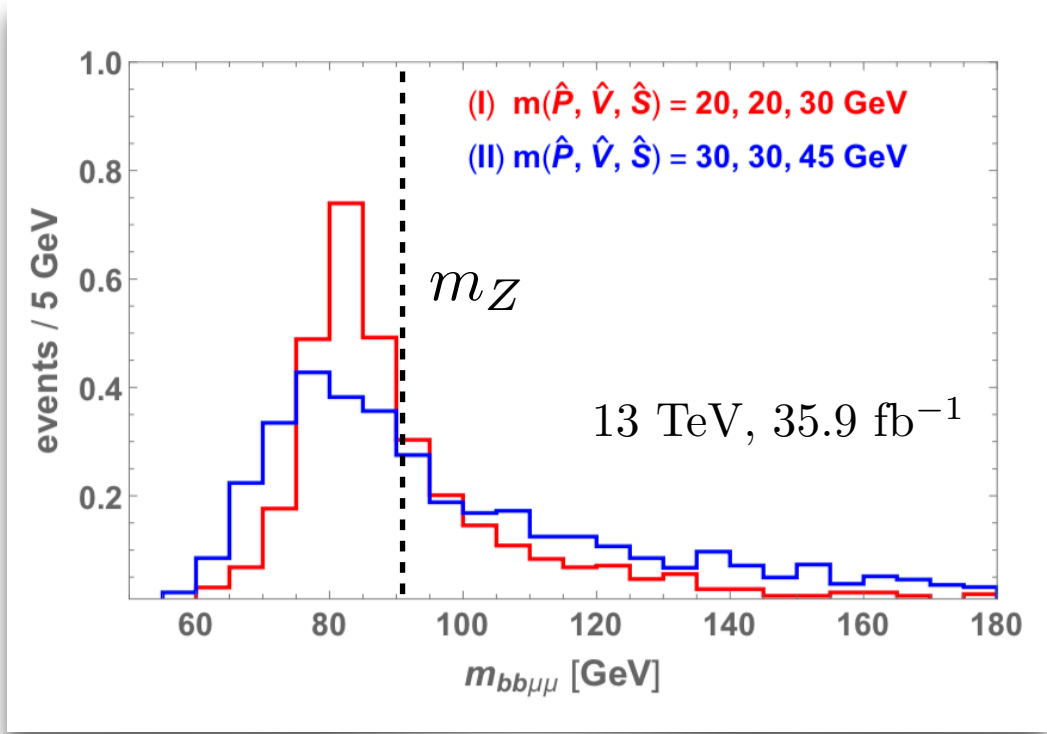
Phenomenology/1

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

[**CMS**, 1812.06359]

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

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



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

- Keeping cuts as soft as possible is key:

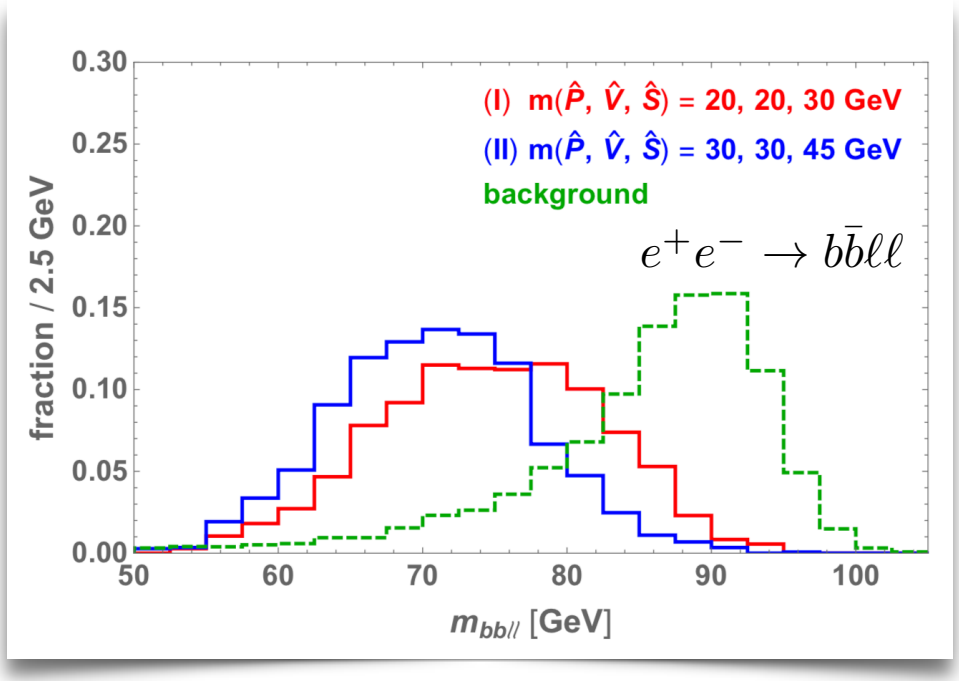
$p_T^{\mu 1,2} > 17,8 \text{ GeV}, \;\; p_T^{b} > 15 \text{ GeV}$ ➡ ~ 2 times larger signal efficiency

- ATLAS analysis has slightly tighter cuts, sensitivity is negligible

[**ATLAS**, 1807.00539]

Phenomenology/1

- At GigaZ factory (10^9 Z bosons), background is negligible after cuts!



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

- Sensitivity on mediation scale:

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

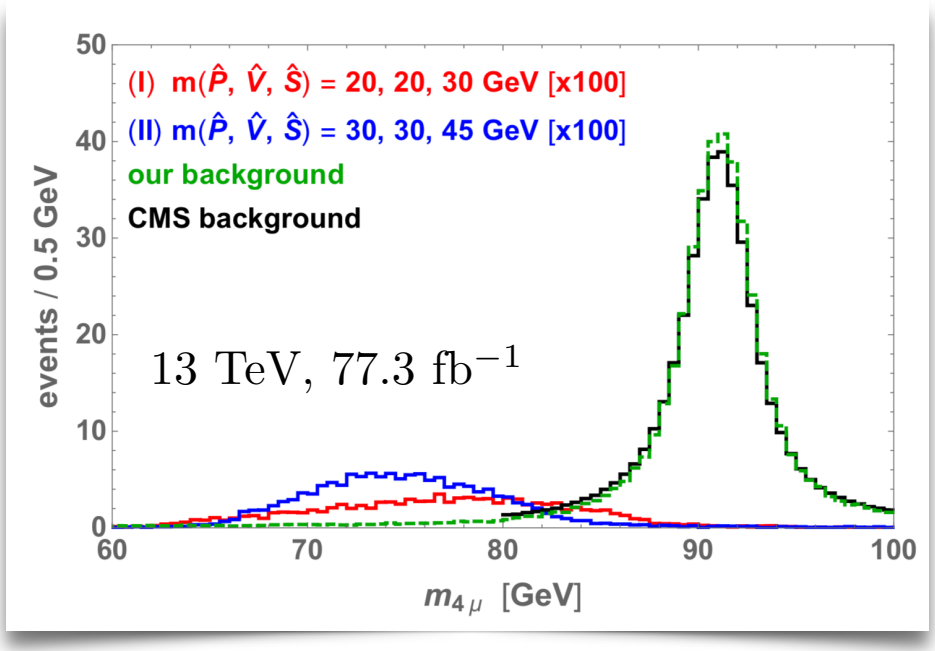
Phenomenology/1

- 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]

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

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



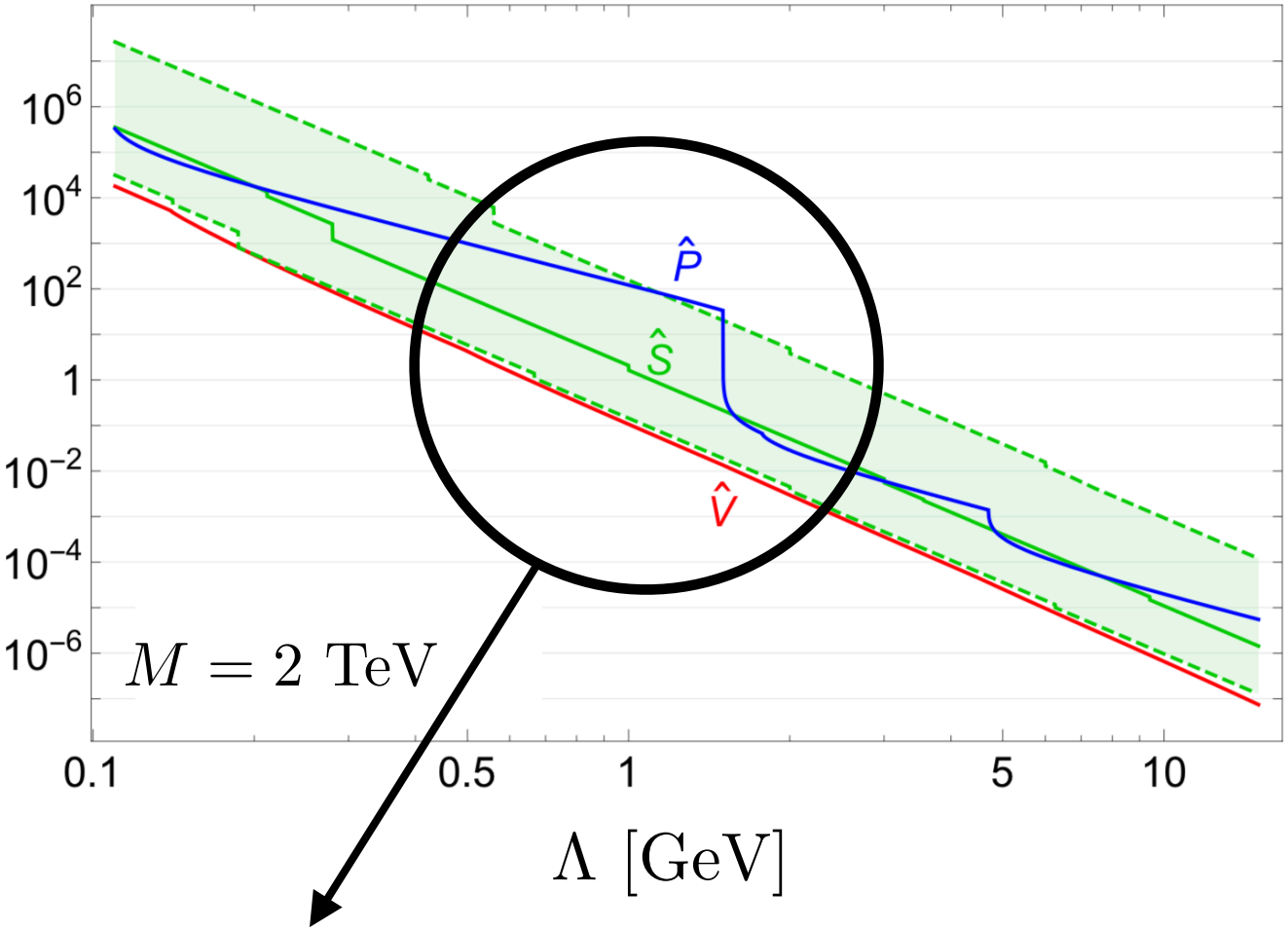
now

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

HL-LHC

Phenomenology/2

Decay length [meters]



$\Lambda \lesssim$ 2-3 GeV : $Z \to$ 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 $\hat{V} \to f_{\rm SM}\bar{f}_{\rm SM}$

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

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

[Pierce, Shakya, Tsai, Zhao, 1708.05389]

- Benchmark:

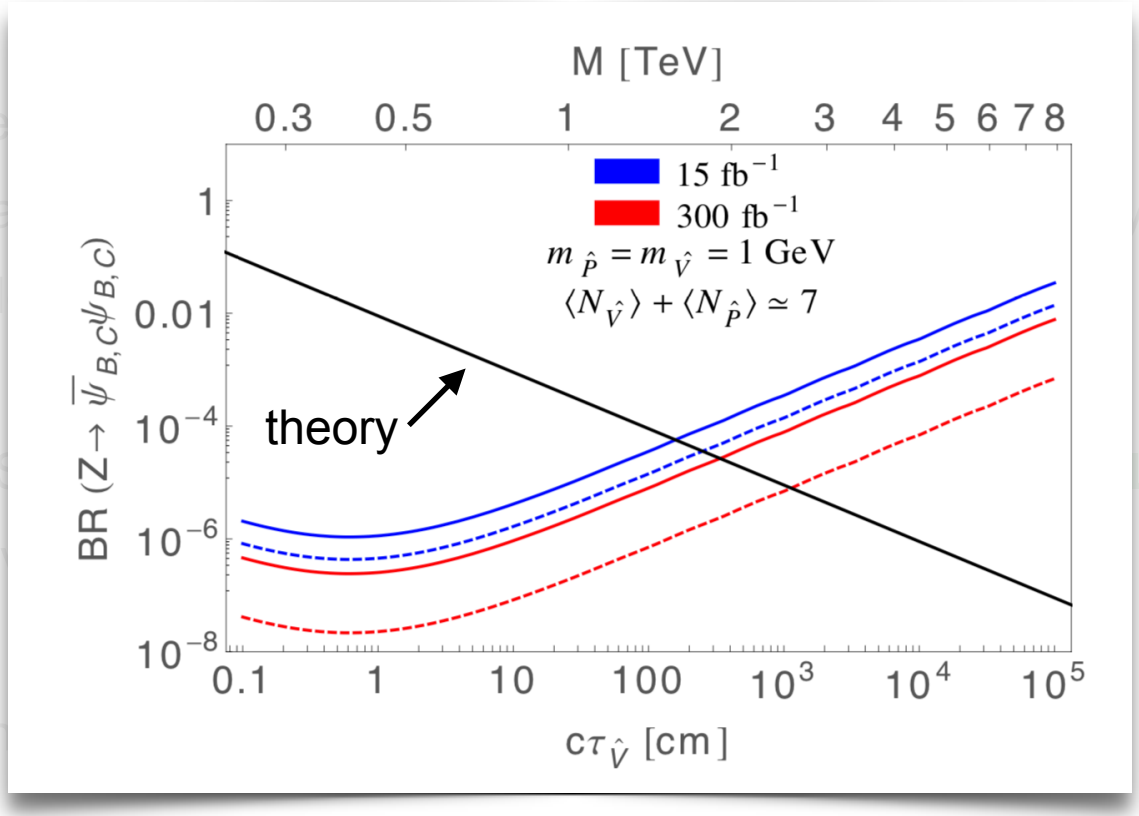
$$m_{\hat{P}} = m_{\hat{V}} = 1 \text{ GeV, neglect heavier hadrons}$$

$$\langle N \rangle \approx 7 \text{ mesons in each jet}$$

$$\frac{N_{\hat{P}}}{N_{\hat{V}}} = \frac{1}{3}$$

$$\hat{P} \text{ assumed stable on collider scales}$$

Phenomenology/2



$M > 1.6\,(2.0)$ TeV
for $L = 15\,(300)$ fb^{-1}

$m_{\hat{P}} = m_{\hat{V}} = 1$ GeV, neglect heavier hadrons

$\langle N \rangle \approx 7$ mesons in each jet

$$\frac{N_{\hat{P}}}{N_{\hat{V}}} = \frac{1}{3}$$

$\hat{P}$ assumed stable on collider scales

Phenomenology/2

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

- Constituents 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

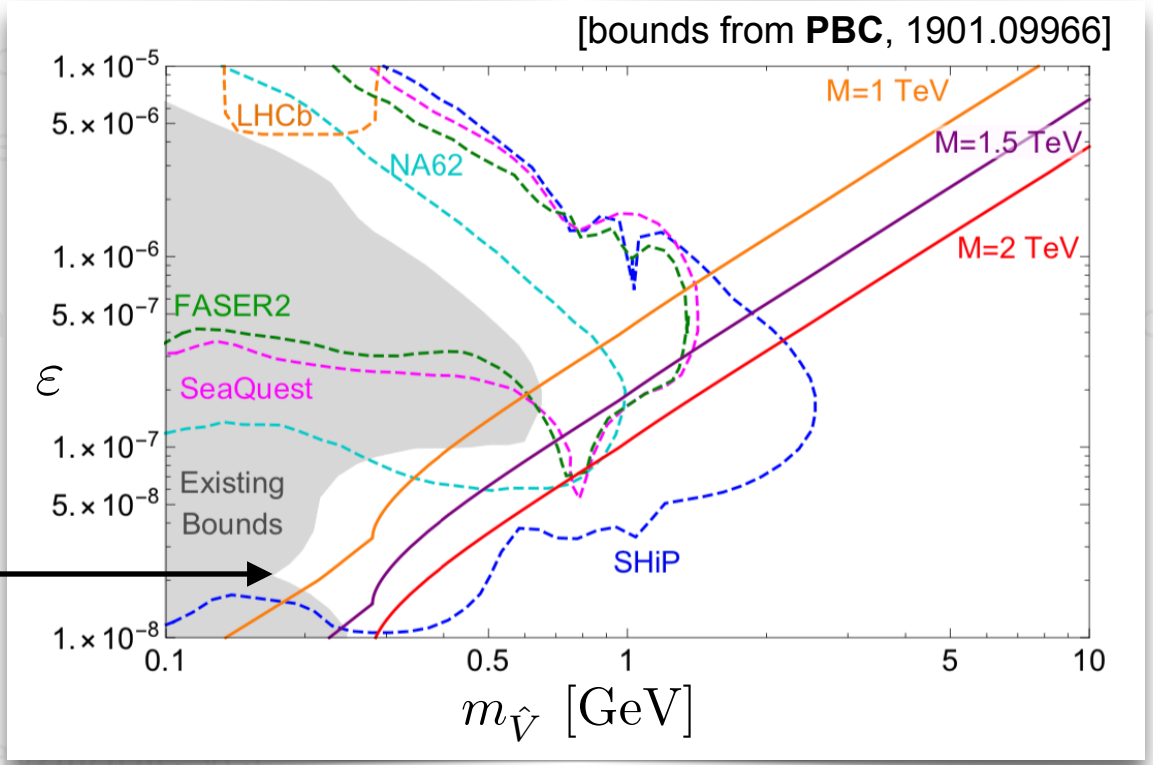
$$\varepsilon_{\mathrm{eff}} \sim \frac{1}{2}\sqrt{\frac{\alpha_Z}{\alpha}}\,\varepsilon_Z \approx 3.8 \times 10^{-7} \left(\frac{\Lambda}{1\,\mathrm{GeV}}\right)^{3/2} \left(\frac{m_{\hat{V}}}{2\,\mathrm{GeV}}\right)^{1/2} \left(\frac{2\,\mathrm{TeV}}{M}\right)^2$$

Phenomenology/2

- For $m_{\hat{V}} \lesssim$ GeV, [illegible] Bremsstrahlung, me[illegible]
- Constituents have m[illegible] current
- No global analysis a[illegible]

included

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



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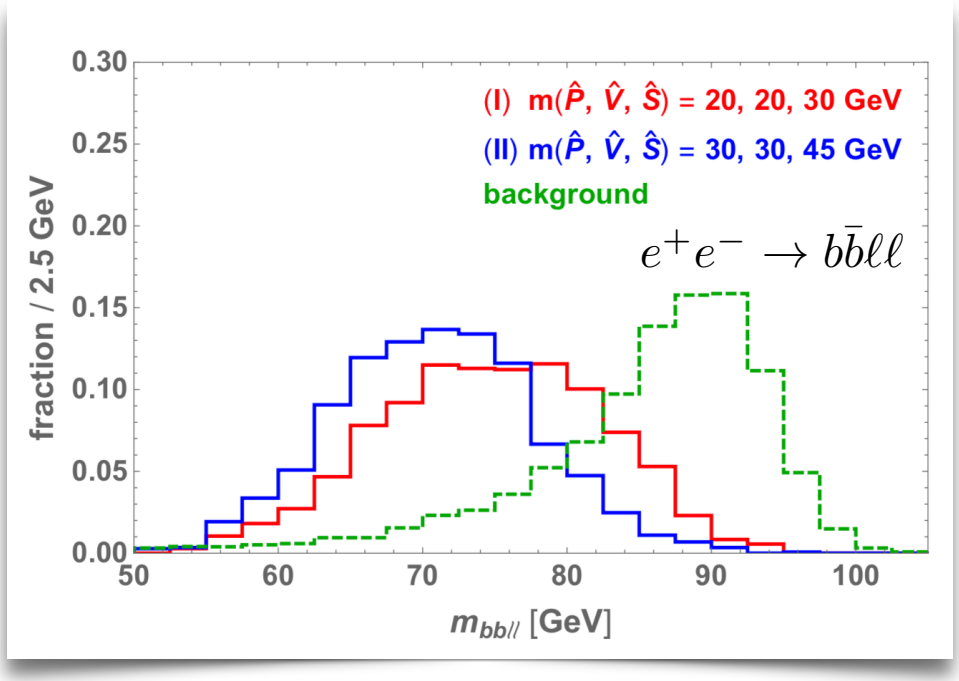
Summary

- Neutral Naturalness theories strongly motivate **confining hidden sectors at** $0.1\ \mathrm{GeV} \lesssim \Lambda \lesssim 15\ \mathrm{GeV}$
- Motivated by SUSY realization, studied 1-flavor hidden QCD coupled to SM via Higgs **and *Z* portal**
- *Z* portal dramatically increases reach on hidden sector, thanks to large statistics collected at LHC and future *Z*-factory. Rich phenomenology:
  - For $\Lambda \sim O(10)\ \mathrm{GeV}$: *Z* decays to prompt mesons
  - For $\Lambda \sim O(1)\ \mathrm{GeV}$: *Z* decays to hidden jets, signals at intensity frontier from hidden vector meson
- Add to wishlist: more input from lattice?

Backup

Phenomenology/1

- At GigaZ factory (10^9 Z bosons), background is negligible after cuts!



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

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

[hep-ex/0509008]

$$N_S \approx 28\, f_{\hat{P}\hat{S}} \left(\frac{2\ \text{TeV}}{M}\right)^4 (\mathcal{A}\,\epsilon)_{\text{tot}}$$

but $\epsilon_b \sim 0.3$, no sensitivity for $M = 2$ TeV

Theory background

- Hidden QCD with 1 light fermion flavor
- Visible and hidden sector connected by BSM particles with ~ TeV masses

- Fairly common ingredients in Neutral Naturalness
- Examples: composite Twin Higgs, **models based on accidental SUSY**

[Cheng, Li, **ES,** Verhaaren, 2018/2019]

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

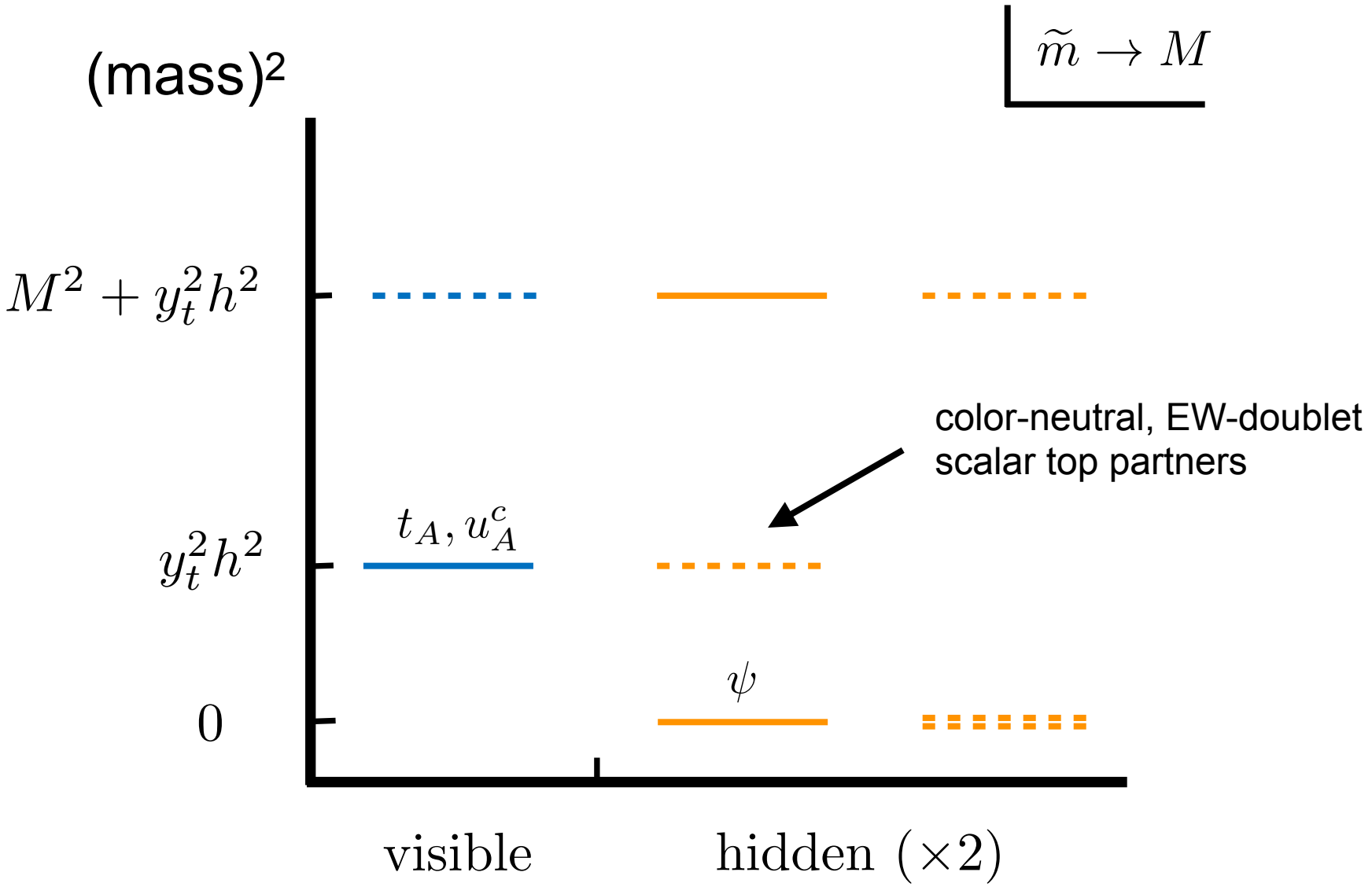
Superpotential: $W = y_t(Q_A H u^c_A + Q_B H u^c_B + Q_C H u^c_C) + M(Q_B Q'^c_B + Q_C Q'^c_C)$

Z_3 Z_2

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

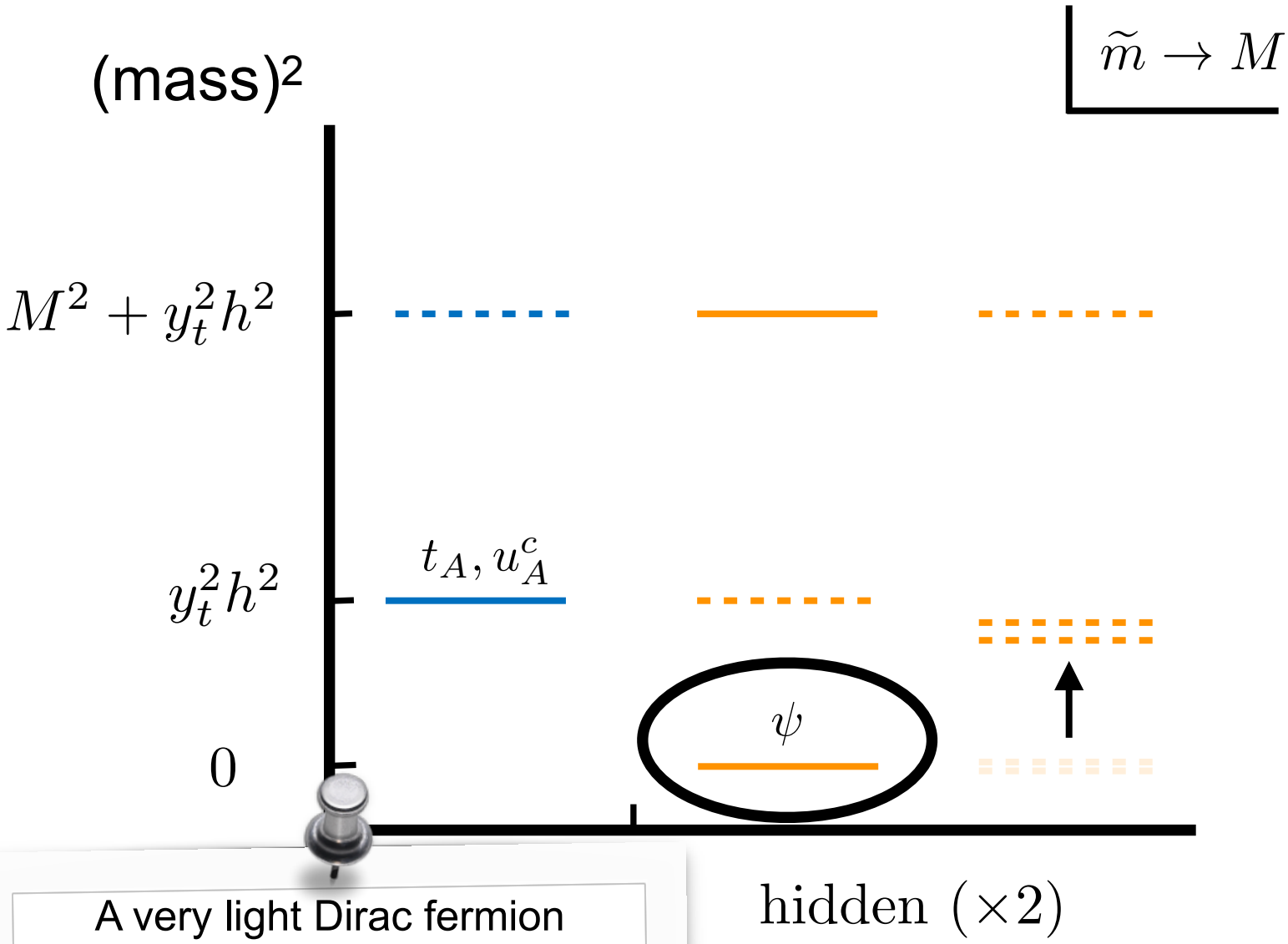
raise colored stops **lower** color-neutral stops

Accidental supersymmetry



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

Accidental supersymmetry



A very light Dirac fermion at bottom of spectrum

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