Z portal to a Confining Hidden Sector

Ennio Salvioni

CERN

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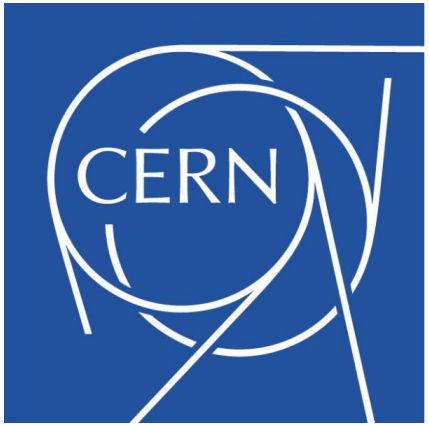

based on [2019, JHEP] **+ in progress**

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

Motivation

from Xabier's intro yesterday

- 3) $\Lambda_{NP} \sim$ 0.1-1 TeV, but it operates in *stealth mode*: heavy mediators, tiny couplings, compressed spectra, sequestered sectors, large backgrounds, …)

Ideal territory for LHCb to explore!

This talk: a confining hidden sector with heavy mediators

Motivation

- **Light hidden sectors** are key area of current & future advances

  at collider experiments (and beyond)

  To me, one of the most promising directions in LHC physics

- Theory space is vast, some theory guidance helps

  to identify targets & chart progress

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- **Light hidden sectors** are key area of current & future advances at collider experiments (and beyond)

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- Important motivation are theories of **Neutral Naturalness**
  [little hierarchy problem solved by symmetry, but **color-neutral** top partners]

- Many proposals: *Twin Higgs(es), Folded SUSY, Tripled Top, Hyperbolic Higgs, …*

[Chacko, Goh, Harnik 2005]
[Burdman, Chacko, Goh, Harnik 2006]
[Cai, Cheng, Terning 2008]
[Serra, Torre 2017]
[Csáki, Ma, Shu 2017]

[Cheng, Li, Salvioni, Verhaaren 2018]
[Cohen, Craig, Giudice, McCullough 2018]
[Serra, Stelzl, Torre, Weiler 2019]
…

Motivation

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- Theory space is vast, some theory guidance helps to identify targets & chart progress

- Important motivation are theories of **Neutral Naturalness**
  [little hierarchy problem solved by symmetry, but **color-neutral** top partners]

- Generic expectation: hidden sector that **confines** at

$$0.1 \lesssim \Lambda/\mathrm{GeV} \lesssim 10$$

Hidden valleys from neutral naturalness

- Many models. Aim to identify **representative cases** with distinct phenomenology → motivated targets for searches

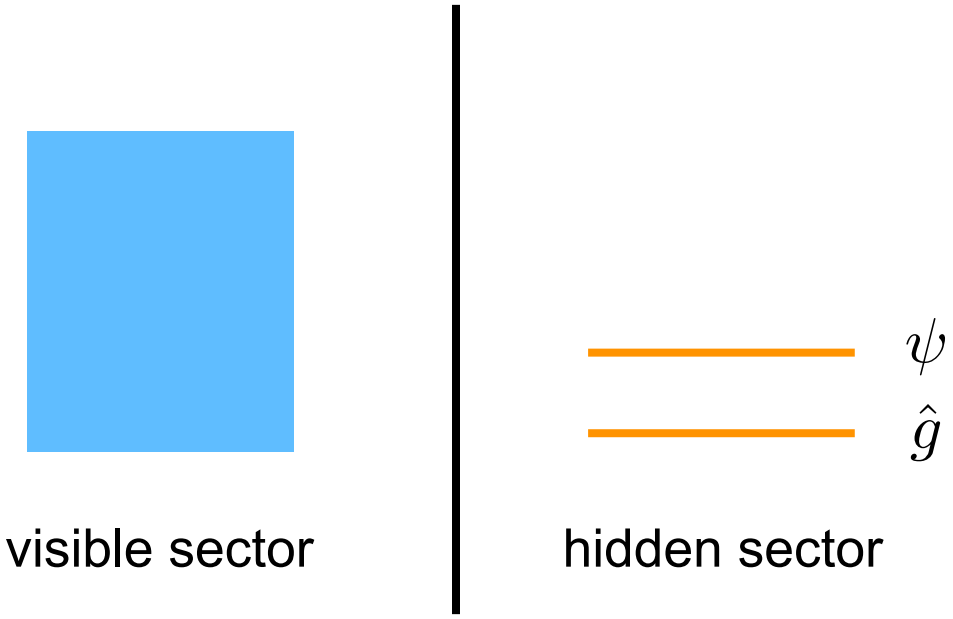
- **Which portals** connect visible and hidden sector?
  Higgs is "mandatory," but others can play key role

- **This talk:** include the ***Z* portal**
  Striking implications for detection prospects

[Cheng, Li, Salvioni, Verhaaren 2019]

In this talk

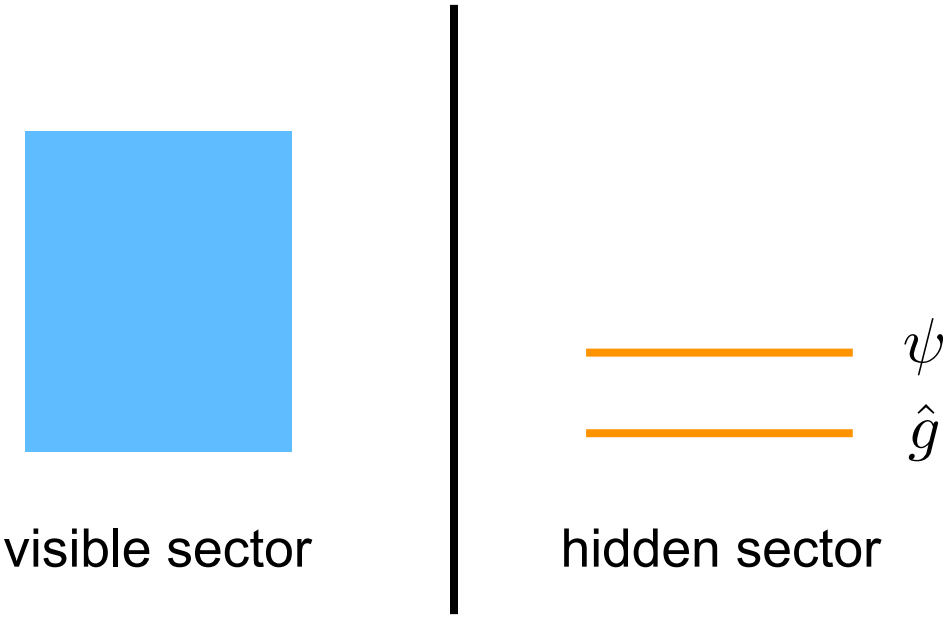
- Hidden QCD with at least 1 light fermion flavor



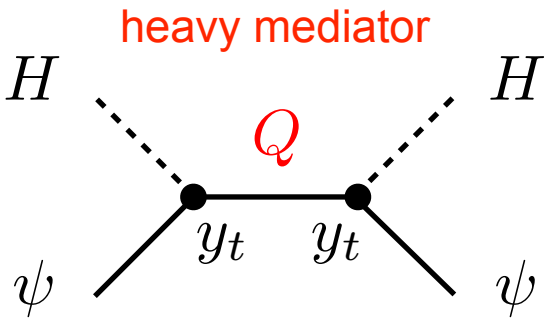
In this talk

- Hidden QCD with at least 1 light fermion flavor
- Coupled 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?



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

- Specific motivation: models with accidental SUSY

  Top partners are scalar EW doublets $\tilde{Q}$, singlets ψ can be naturally light

  ➡ one light flavor in hidden sector

  [Cheng, Li, Salvioni, Verhaaren 2018 + 2019]

- But ingredients are pretty generic

Description of Hidden Sector

Phenomenology

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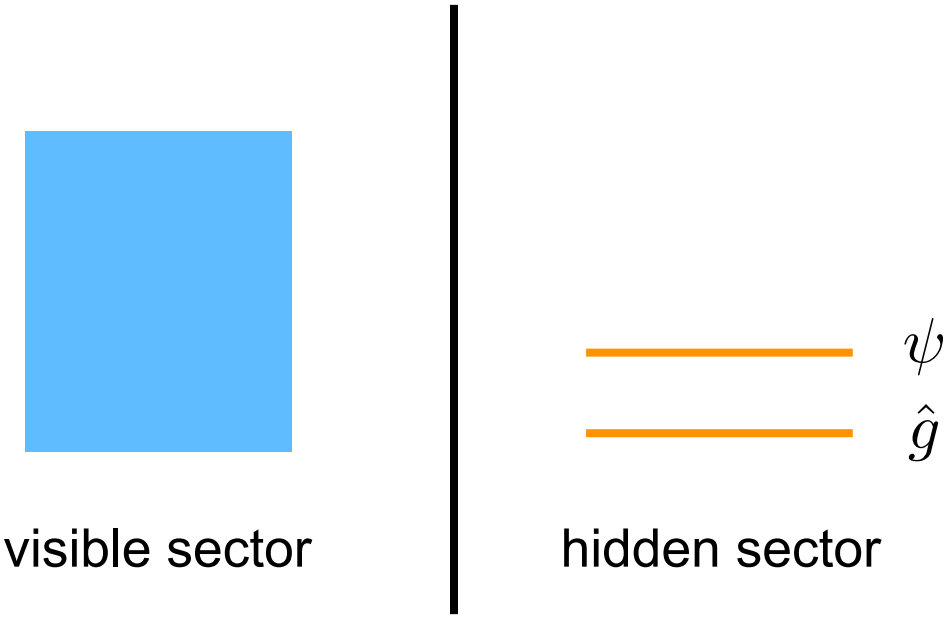

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Higgs portal

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

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

In this talk

- At the LHC, $N_Z / N_h \sim 10^3$

➡ ***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 et al. 2007]
  - ☑ Baryons significantly heavier than mesons $m^2_{\eta'} \propto N_f/N_c$
  - ☑ 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**

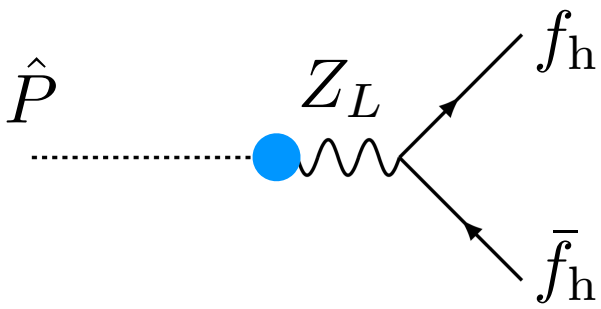
$$m_{\hat{P}} \lesssim m_{\hat{V}} < m_{\hat{S}}$$

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

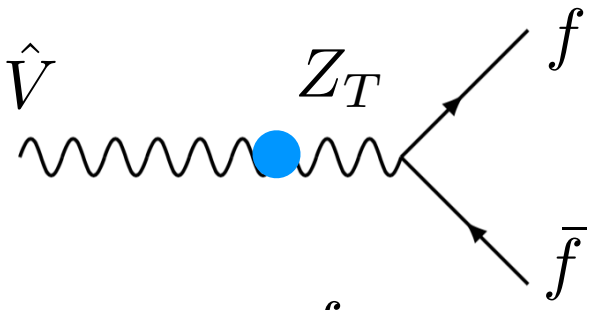
- Mesons decay back to visible sector through *Z* and *h* portals

Hidden meson decays

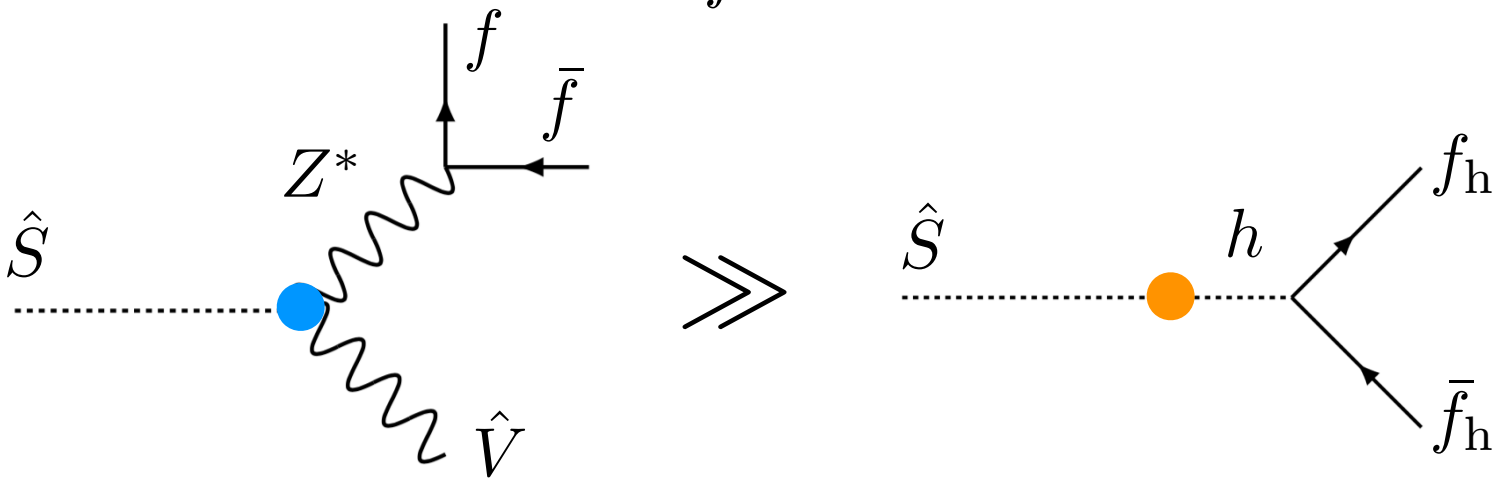
- It turns out, **all** lightest mesons decay dominantly via ***Z* portal**
- Pseudoscalar



- Vector

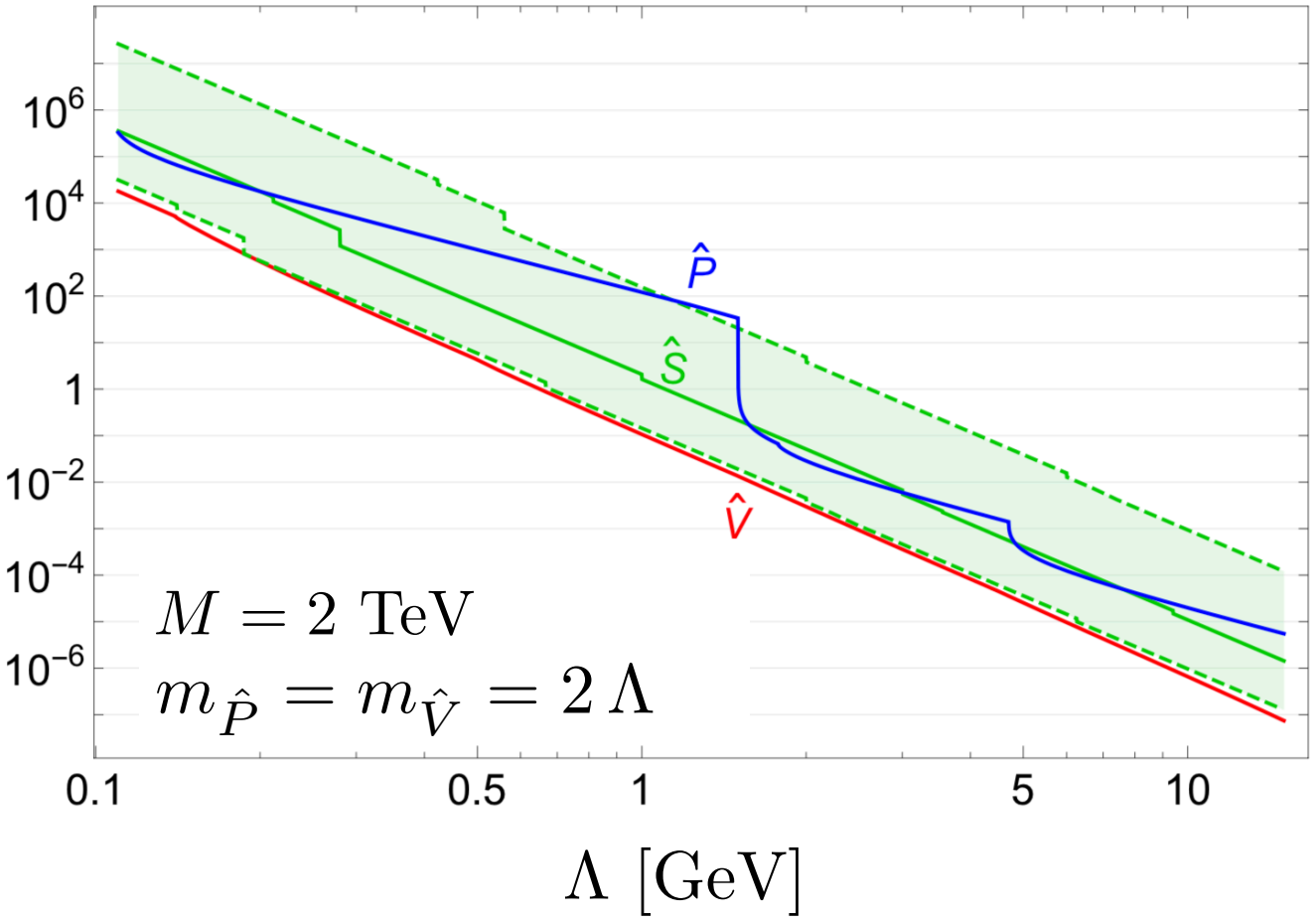


- Scalar



Hidden meson decays

Decay length [meters]



Two main parameters determine pheno:

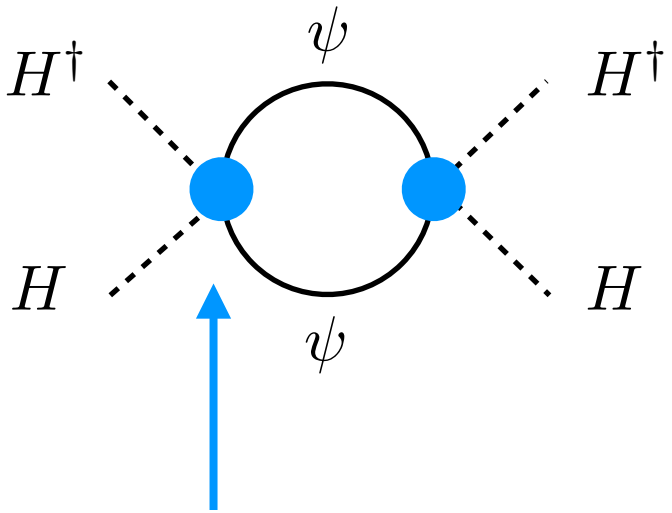
- Hidden confinement scale Λ
- Mediation scale M

Description of Hidden Sector

Phenomenology

Indirect constraint

- EW precision:



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

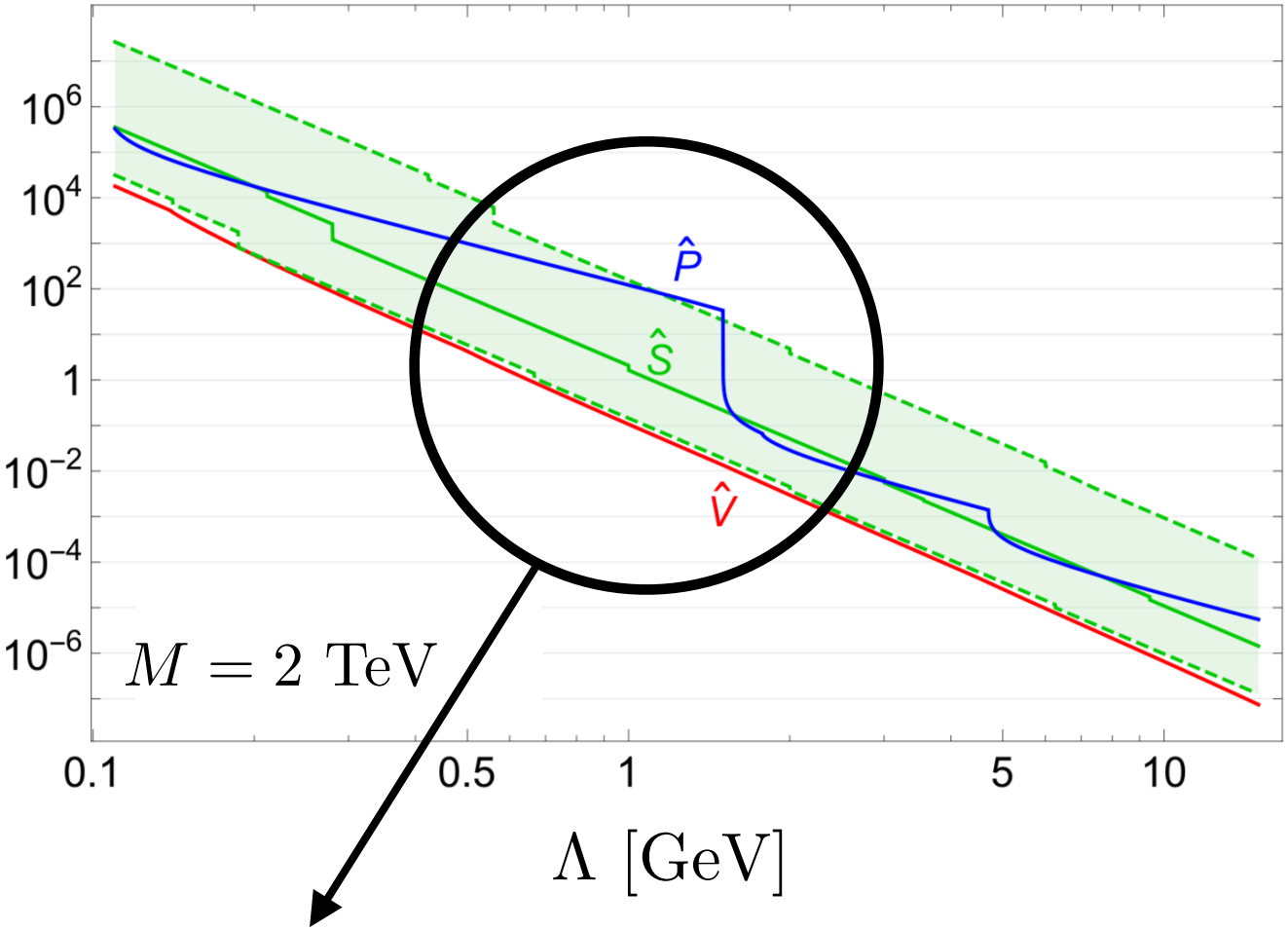
$$\Delta\widehat{T} = \frac{4}{3}\frac{N_d y_t^2}{16\pi^2}\frac{m_t^2}{M^2}$$

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

- **Here:** explore **direct probes**

Phenomenology/1

Decay length [meters]



$\Lambda \sim 1$ GeV : $Z \rightarrow$ hidden jets, long-lived mesons

Phenomenology/1

- 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 2015]
[Cohen, Lisanti, Lou 2015]

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

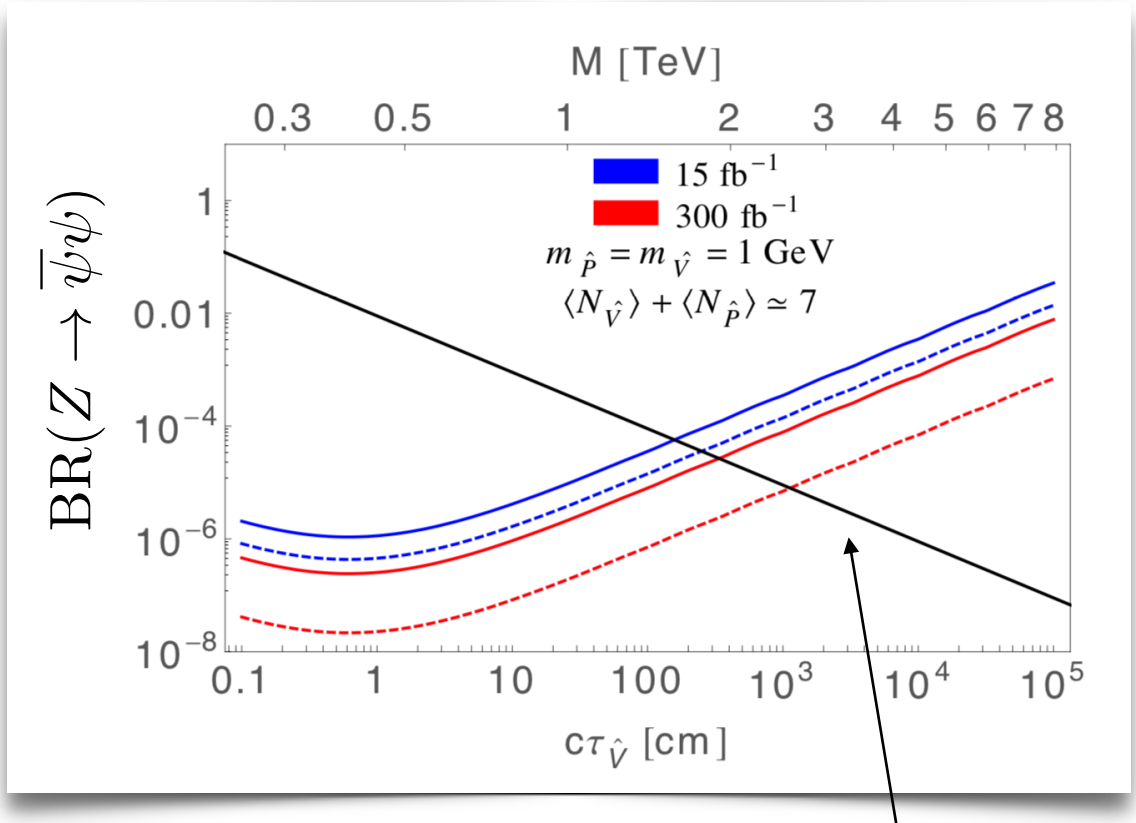
[Pierce, Shakya, Tsai, Zhao 2017]

- Benchmark:

$$m_{\hat{P}} = m_{\hat{V}} = 1\ \text{GeV} \qquad \frac{\langle N_{\hat{P}} \rangle}{\langle N_{\hat{V}} \rangle} = \frac{1}{3}$$

$\hat{P}$ is collider-stable, neglect heavier hadrons

Phenomenology/1



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

$$\ell_T \in [6, 22]\ \text{mm}$$
$$p_T^{\hat{V}} > 1\ \text{GeV}$$

$$\text{BR} \approx \frac{10^{-2}}{c\tau_{\hat{V}}/\text{cm}}$$

background estimate:
[Ilten, Soreq, Thaler, Williams, Xue 2016]

Phenomenology/1

- 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 dominantly to **neutral current**

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

chiral couplings

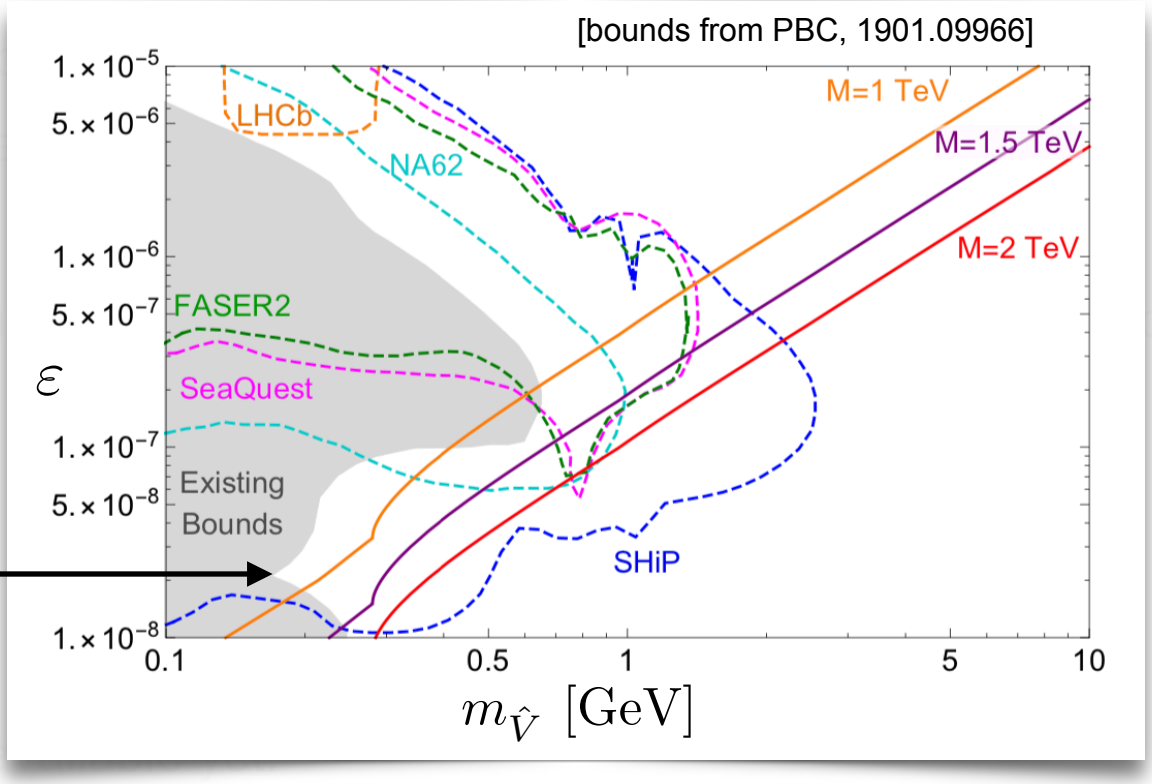
- No global analysis available yet for this scenario.
  To gain first impression, approximate $\hat{V}$ as "kinetically mixed dark photon" with

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

Phenomenology/1

effect of

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



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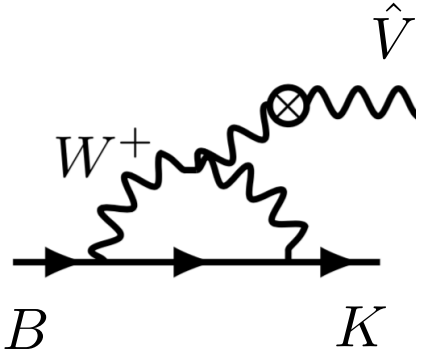
Bounds from meson FCNC decays?

$$\epsilon_Z \simeq g_Z \sqrt{\frac{N_c}{2}} \frac{m_t^2}{M^2} \frac{|\psi(0)| m_{\hat{V}}^{1/2}}{m_Z^2} \approx 3.2 \times 10^{-7} \left(\frac{\Lambda}{1\ \text{GeV}}\right)^{3/2} \left(\frac{m_{\hat{V}}}{2\ \text{GeV}}\right)^{1/2} \left(\frac{2\ \text{TeV}}{M}\right)^2$$

Conservative estimate:



$$\text{BR}(B \to K f \bar{f})_{\text{NP}} \leq \text{BR}(B \to K \bar{\psi} \psi)_{\text{perturbative}}$$

$$\frac{\text{BR}(B \to K f \bar{f})_{\text{NP}}}{\text{BR}(B \to K f \bar{f})_{\text{SM}}} \lesssim \left(\frac{m_t}{M}\right)^4 \frac{\text{BR}(\hat{V} \to \nu \bar{\nu})}{\text{BR}(\hat{V} \to f \bar{f})} < 0.01$$

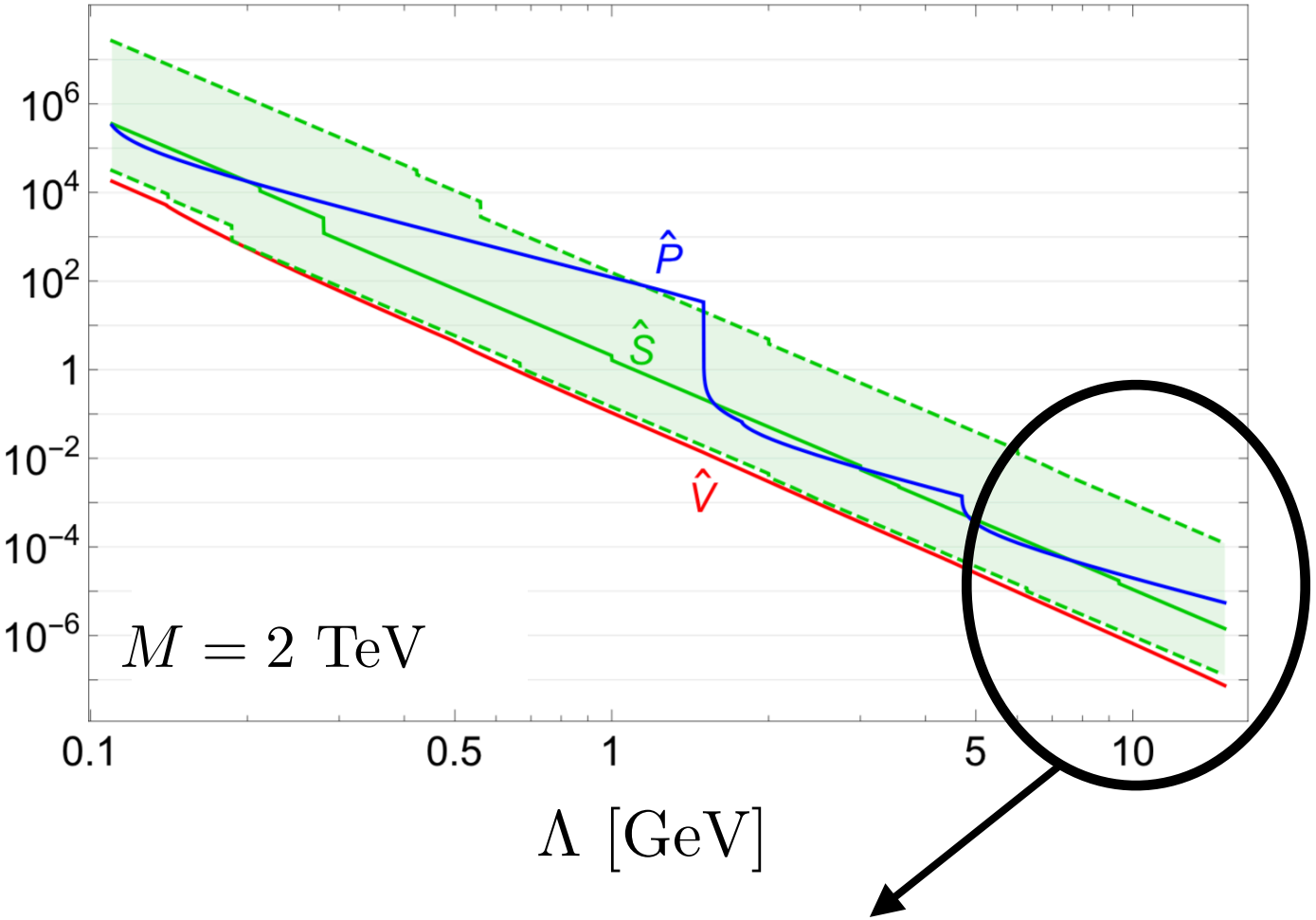
for $M > 1$ TeV

$$\frac{E}{m_{\hat{V}}} \times \frac{m_{\hat{V}}^2}{m_Z^2} \overset{m_{\hat{V}} \to 0}{\longrightarrow} 0$$

see e.g. [Dror, Lasenby, Pospelov 2018]

Phenomenology/2

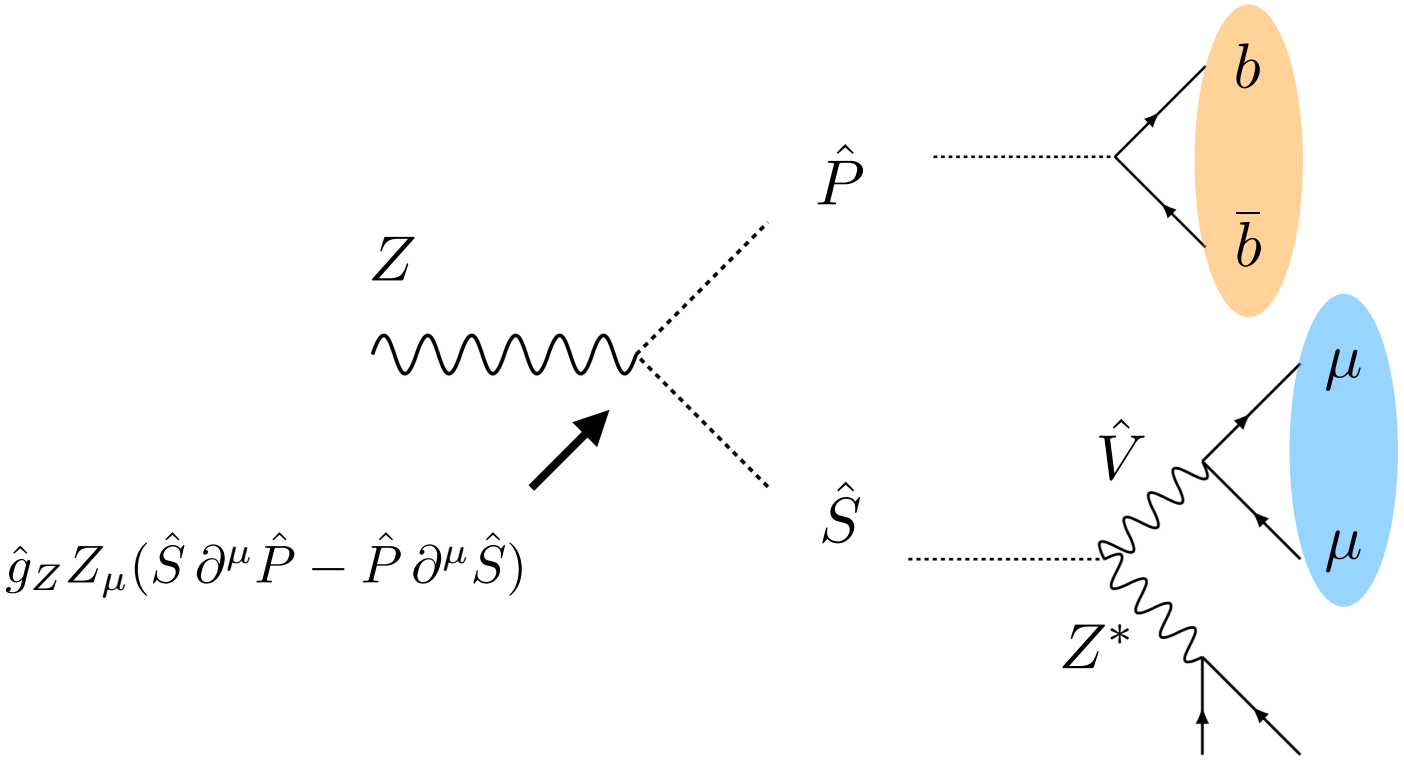
Decay length [meters]



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

Phenomenology/2

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



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

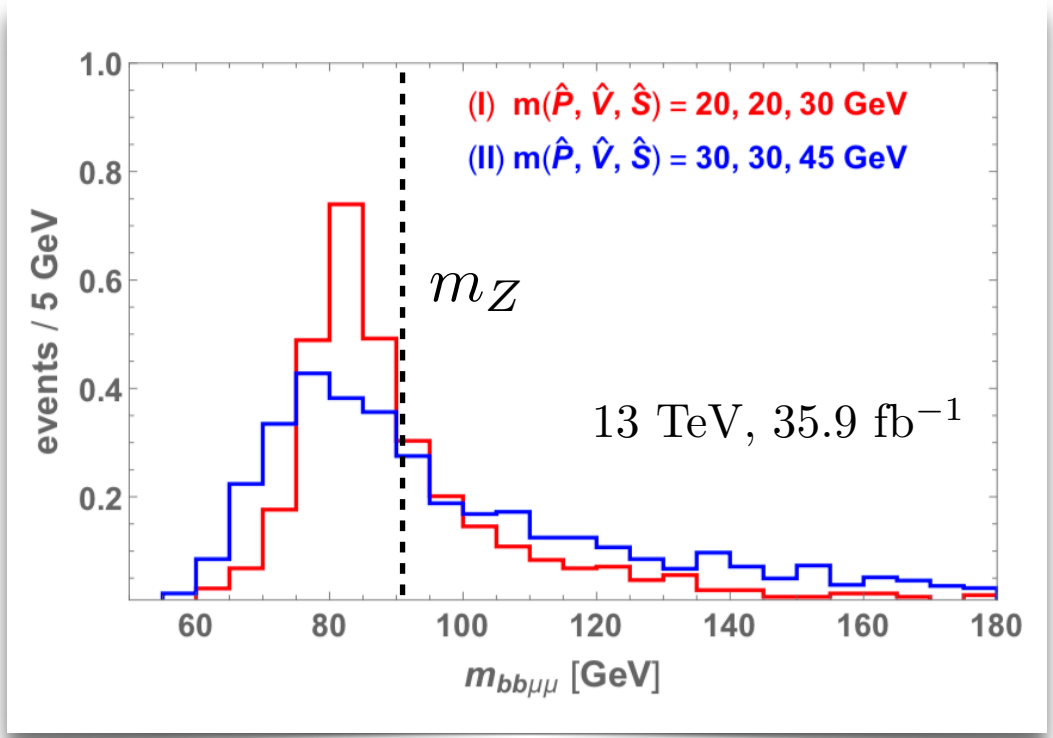
Phenomenology/2

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

[**CMS**, 1812.06359]

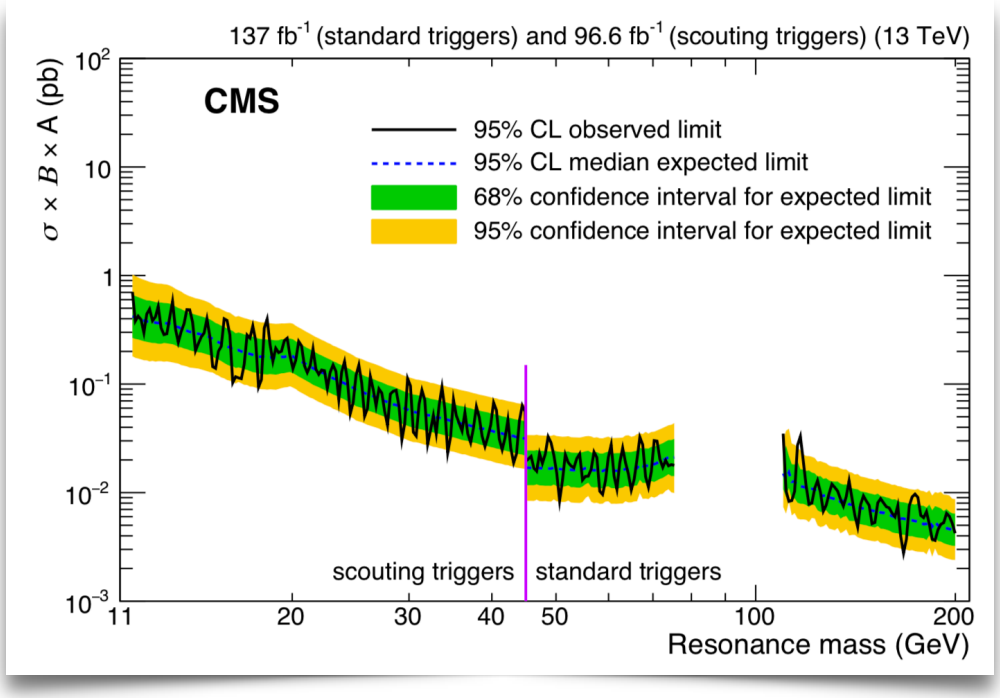
$$p_T^{\mu 1,2} > 20,9 \text{ GeV}, \qquad p_T^{b1,2} > 20,15 \text{ GeV}$$

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



(One) path to improve sensitivity

- Dimuon **scouting** @CMS: limited reconstruction at HLT, can operate at higher rates
- Threshold at L1: $p_T^{\mu} > 4\ \mathrm{GeV}$ for both muons
- Very recently applied to **inclusive** dimuon resonance search [**CMS**, 1912.04776]



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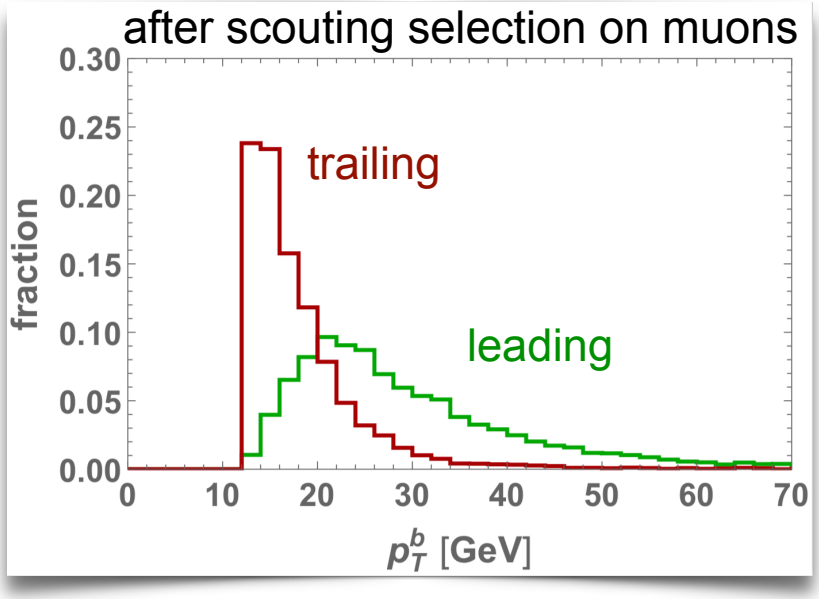
- For $m_{\hat{V}} = 20\ \mathrm{GeV}$, limit from inclusive search is **comparable** to crude recast of *h* → *aa*

$$M_{\mathrm{incl}} \gtrsim 0.9\ \mathrm{TeV} \left(\frac{\mathcal{B}_{\hat{P}\hat{S}}}{1}\right)^{1/4}$$

$$M_{h\to aa} \gtrsim 1.25\ \mathrm{TeV} \left(\frac{\mathcal{B}_{\hat{P}\hat{S}}}{1}\right)^{1/4}$$



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- Key step: select two *b*'s with smallest feasible p_T at HLT
- Ongoing discussion with CMS experimentalists

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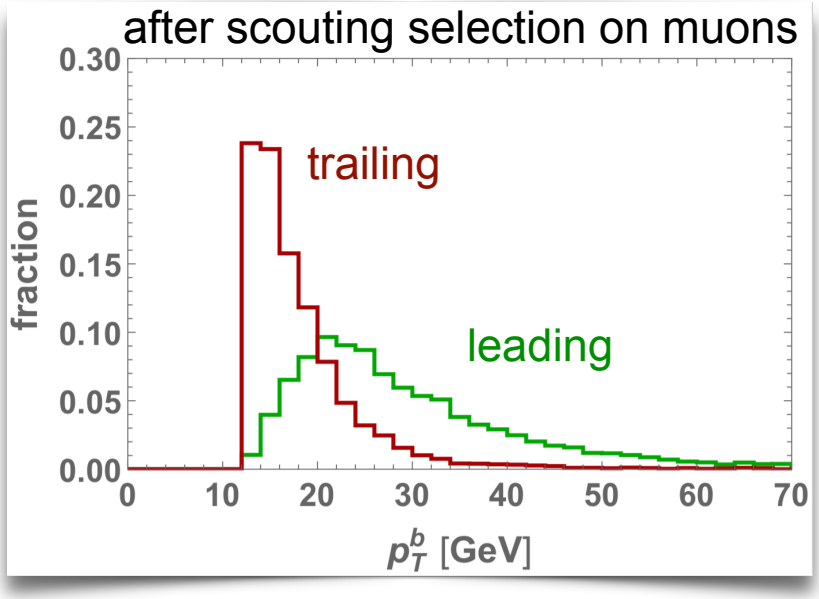

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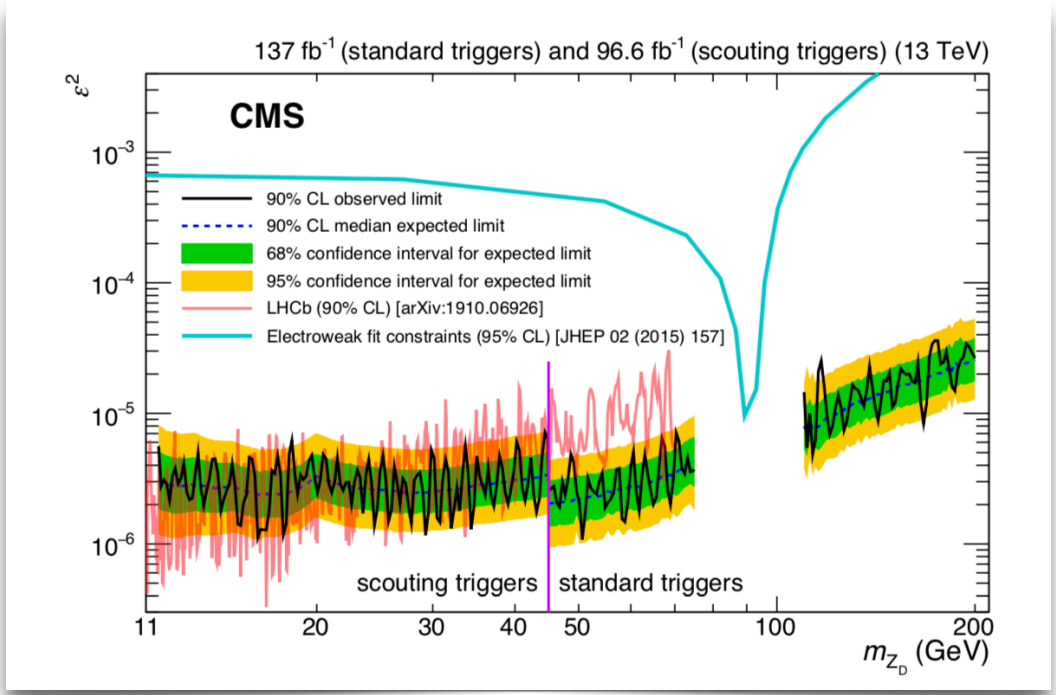
[**LHCb**, 1910.06926]

For inclusive dimuons,
LHCb actually wins at low masses



Prospects

- Neutral Naturalness motivates **confining hidden sector**

  at $0.1 \lesssim \Lambda/\mathrm{GeV} \lesssim 10 \rightarrow$ clear target for colllider experiments

- ***Z* portal** not considered before, striking impact on signatures

- $\Lambda = O(1)\ \mathrm{GeV}$: LHCb has leading sensitivity to hidden jets of long-lived mesons

- $\Lambda = O(10)\ \mathrm{GeV}$: prompt decays. Acceptance is limiting factor, but ideas welcome

- $N_f \geq 2$ scenario: more parameters (quark masses, isospin pattern),

  study in progress. $\hat{\omega}$ decays to pions

[Cheng, Li, Salvioni, Verhaaren, ongoing]

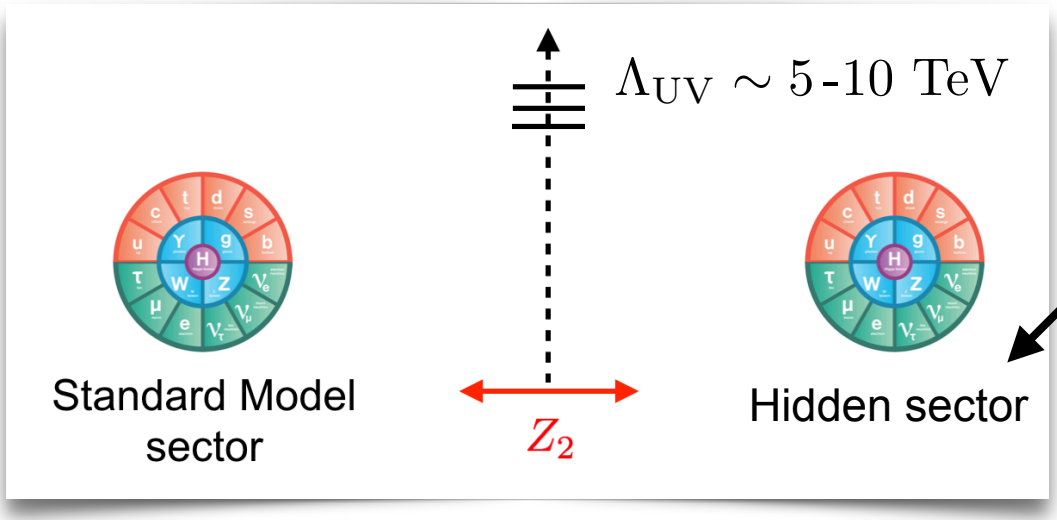
Backup

Neutral Naturalness

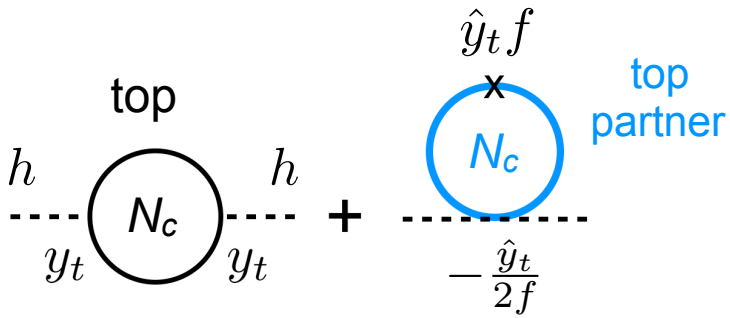
- **Discrete symmetry** relates the SM to hidden sector

Twin Higgs

[Chacko, Goh, Harnik 2005]



- 1 loop:



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

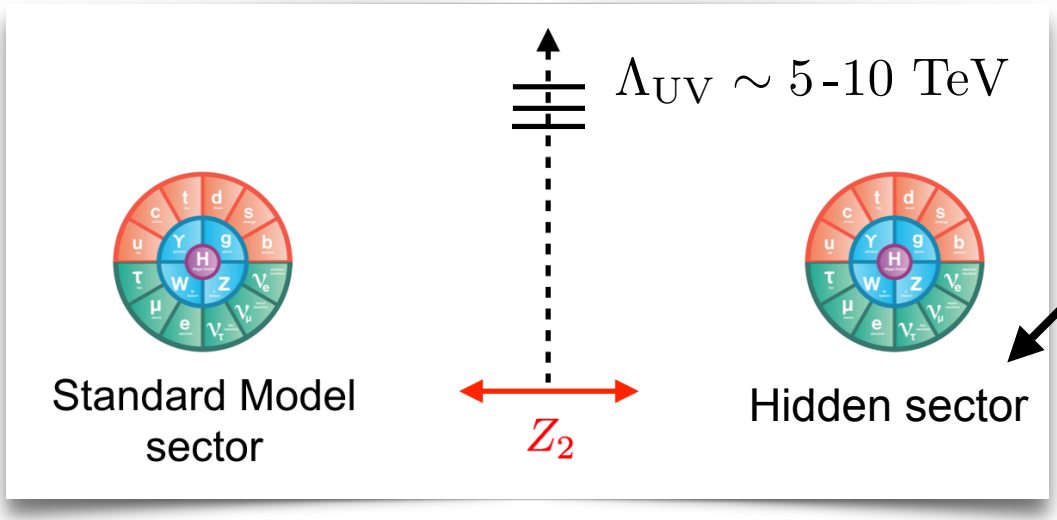
quadratic corrections to Higgs mass cancel out

Hidden confinement

- **Discrete symmetry** relates the SM to hidden sector

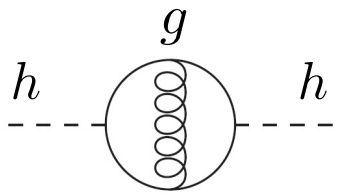
Twin Higgs

[Chacko, Goh, Harnik 2005]



- 2 loops:

[Craig, Katz, Strassler, Sundrum 2015]



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

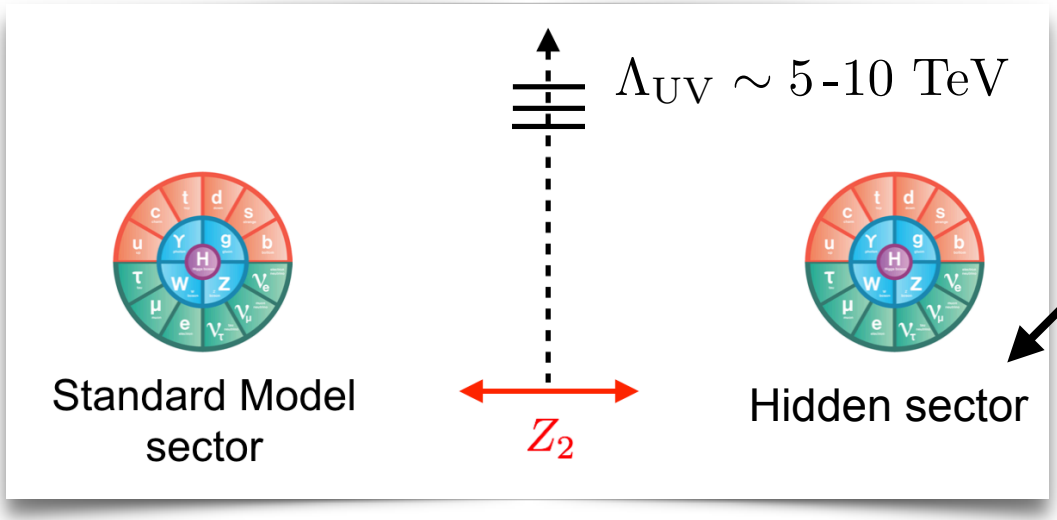
if hidden color is only global

Hidden confinement

- **Discrete symmetry** relates the SM to hidden sector

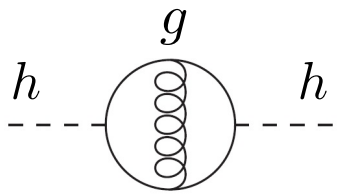
Twin Higgs

[Chacko, Goh, Harnik 2005]



- 2 loops:

[Craig, Katz, Strassler, Sundrum 2015]

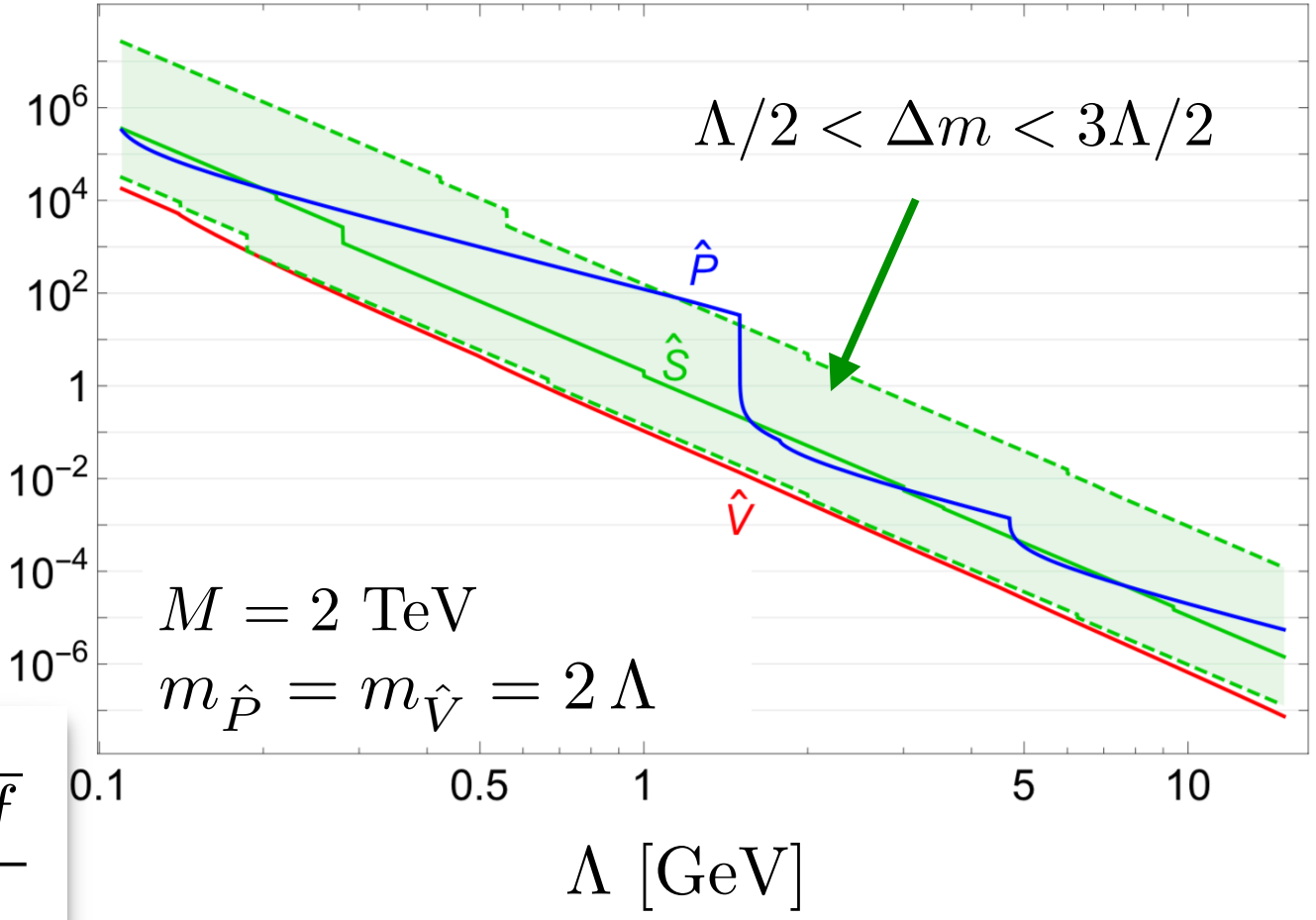


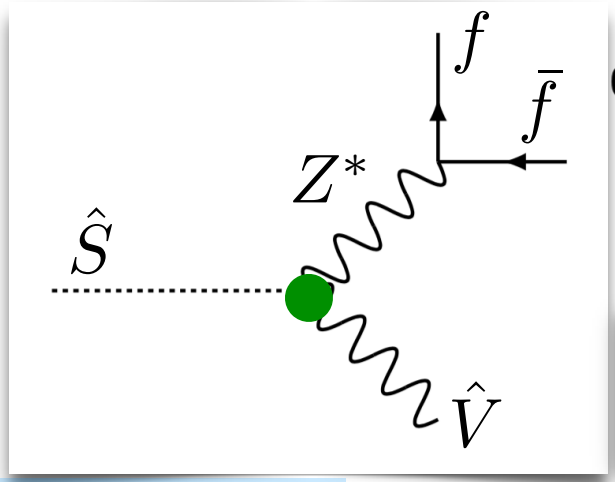
$$m^2_{h,\rm IR} \approx m^2_h(\Lambda_{\rm UV}) + \left[\frac{3y_t^2 g_s^2}{8\pi^4} + \frac{3(y_t^2-\hat{y}_t^2)}{4\pi^2}\right]_{\Lambda_{\rm UV}} \Lambda^2_{\rm UV}$$

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

Hidden meson decays

Decay length [meters]





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

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

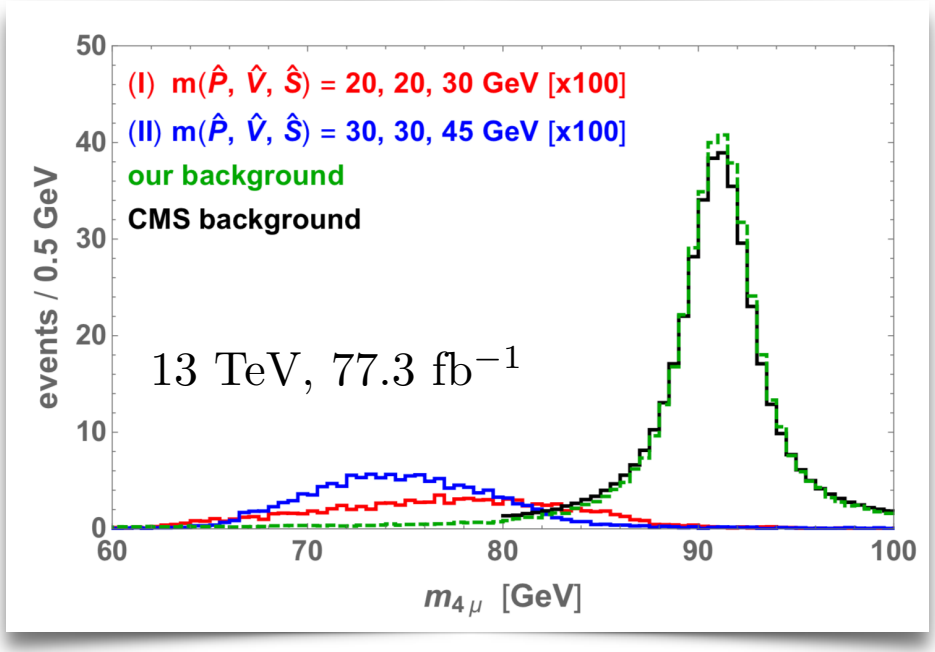
Phenomenology/2

- 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

Hidden meson decays

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

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

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

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

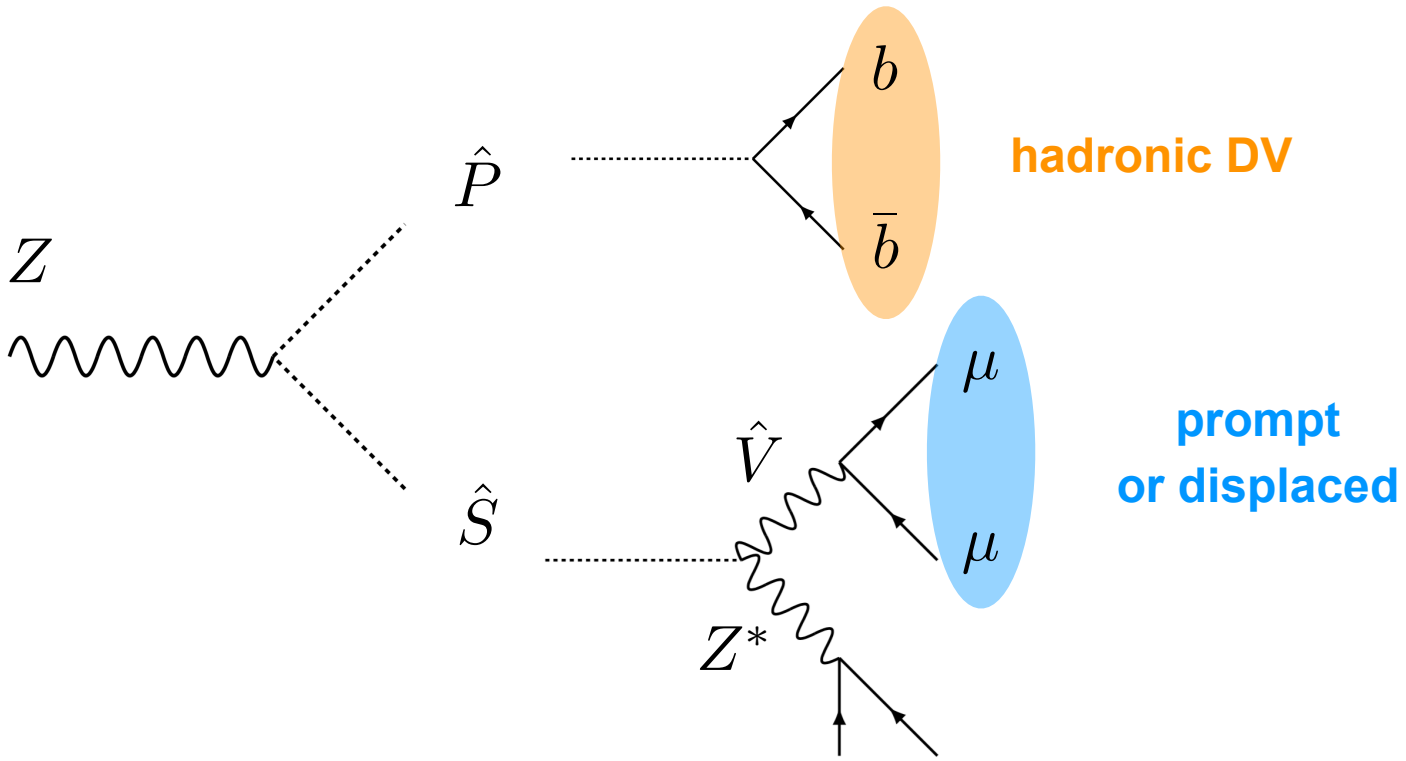
$$\lambda_{h\psi\psi} = 2c_g\mu_\psi m_t^2/(3bvM^2) \text{ where } b = 11 - 2N_l/3$$

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

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

Phenomenology/2

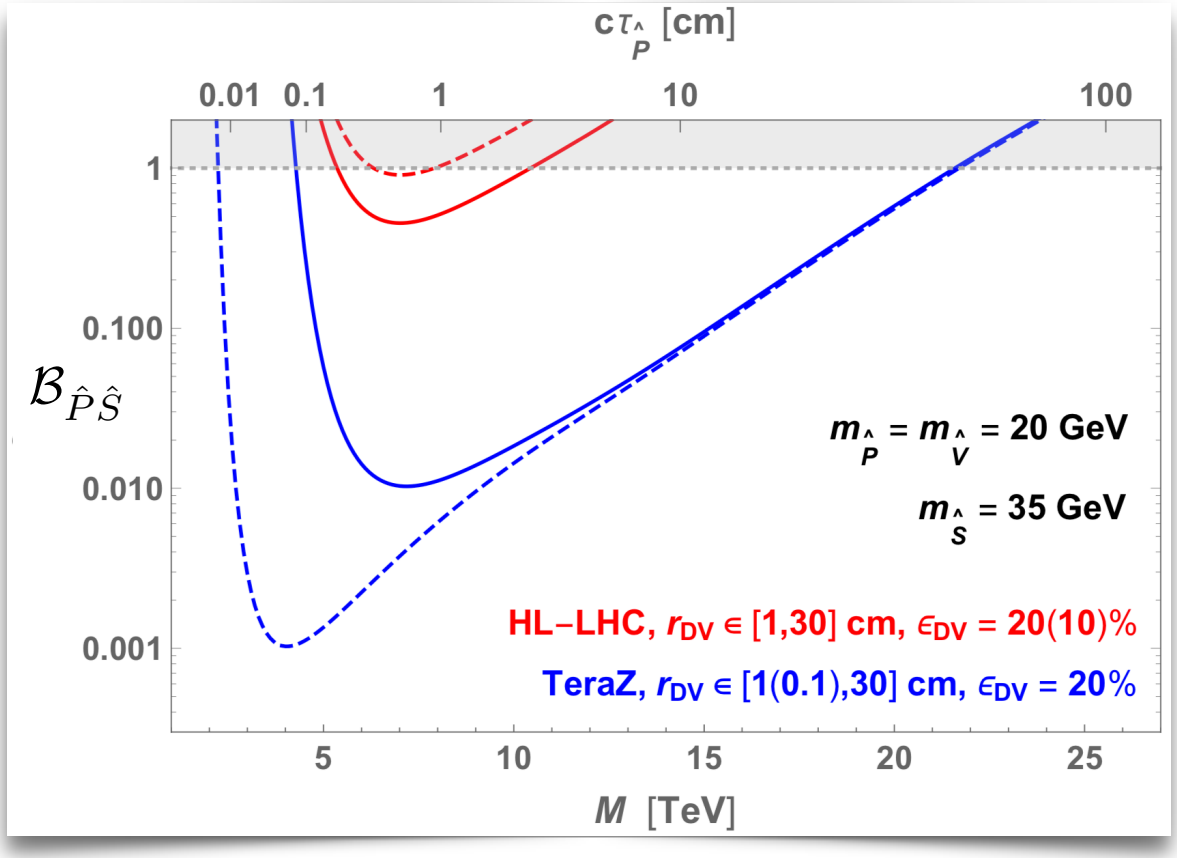
- For larger $M \gtrsim 5\ \mathrm{TeV}$, at least some of the mesons become **long-lived**



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

Phenomenology/2

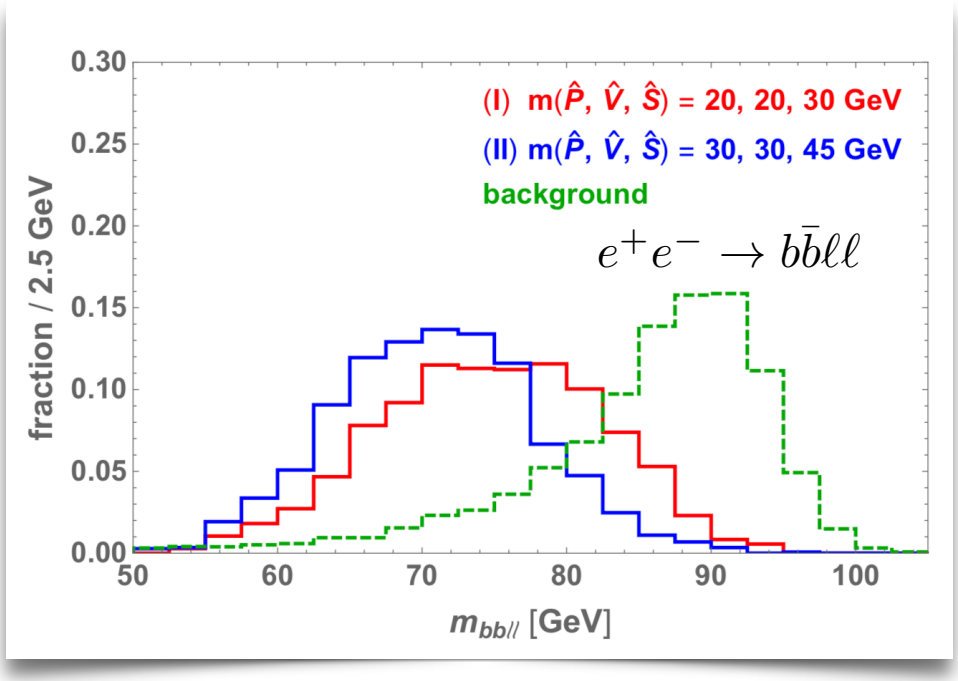
- For larger $M \gtrsim 5\ \mathrm{TeV}$, at least some of the mesons become **long-lived**



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

Phenomenology/2

- At GigaZ factory, background is negligible after cuts



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

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

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

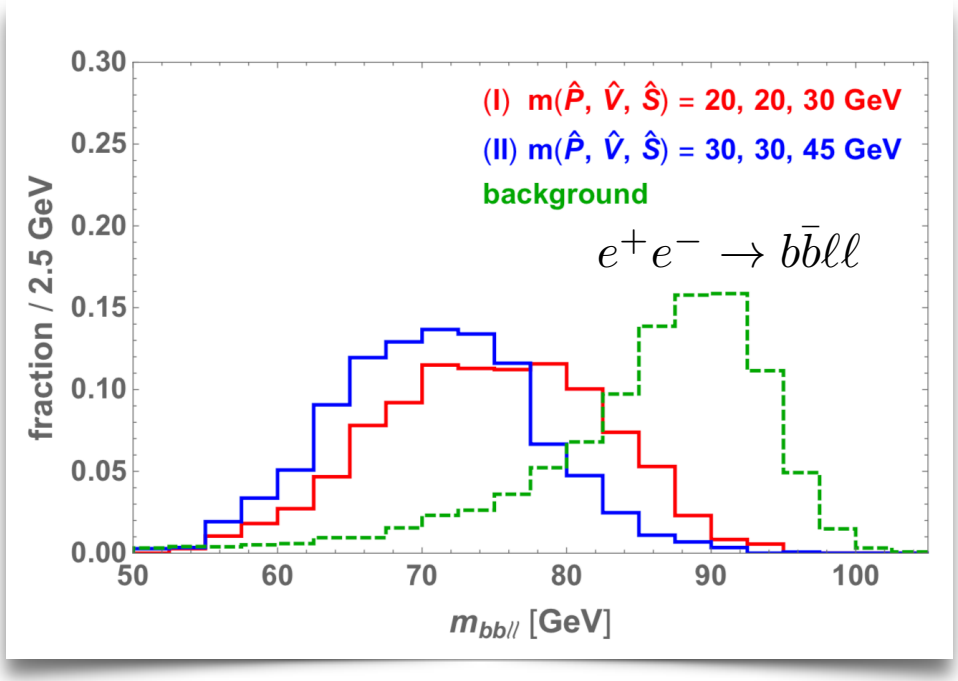
$$N_B < 0.1 \text{ events}$$

- Sensitivity on mediation scale:

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

Phenomenology/2

- At GigaZ factory, background is negligible after cuts



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

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

- **At LEP1 ?** $N_Z^{\text{total}} \approx 2.2 \times 10^7$ [hep-ex/0509008]

$N_S \approx 3.0\, \mathcal{B}_{\hat{P}\hat{S}} \left(\frac{1.2 \text{ TeV}}{M}\right)^4$ sensitivity is marginal at best $(\epsilon_b^{\text{LEP1}} \sim 0.3)$

Theory motivation

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

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

Superpotential:

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

Z_3 Z_2

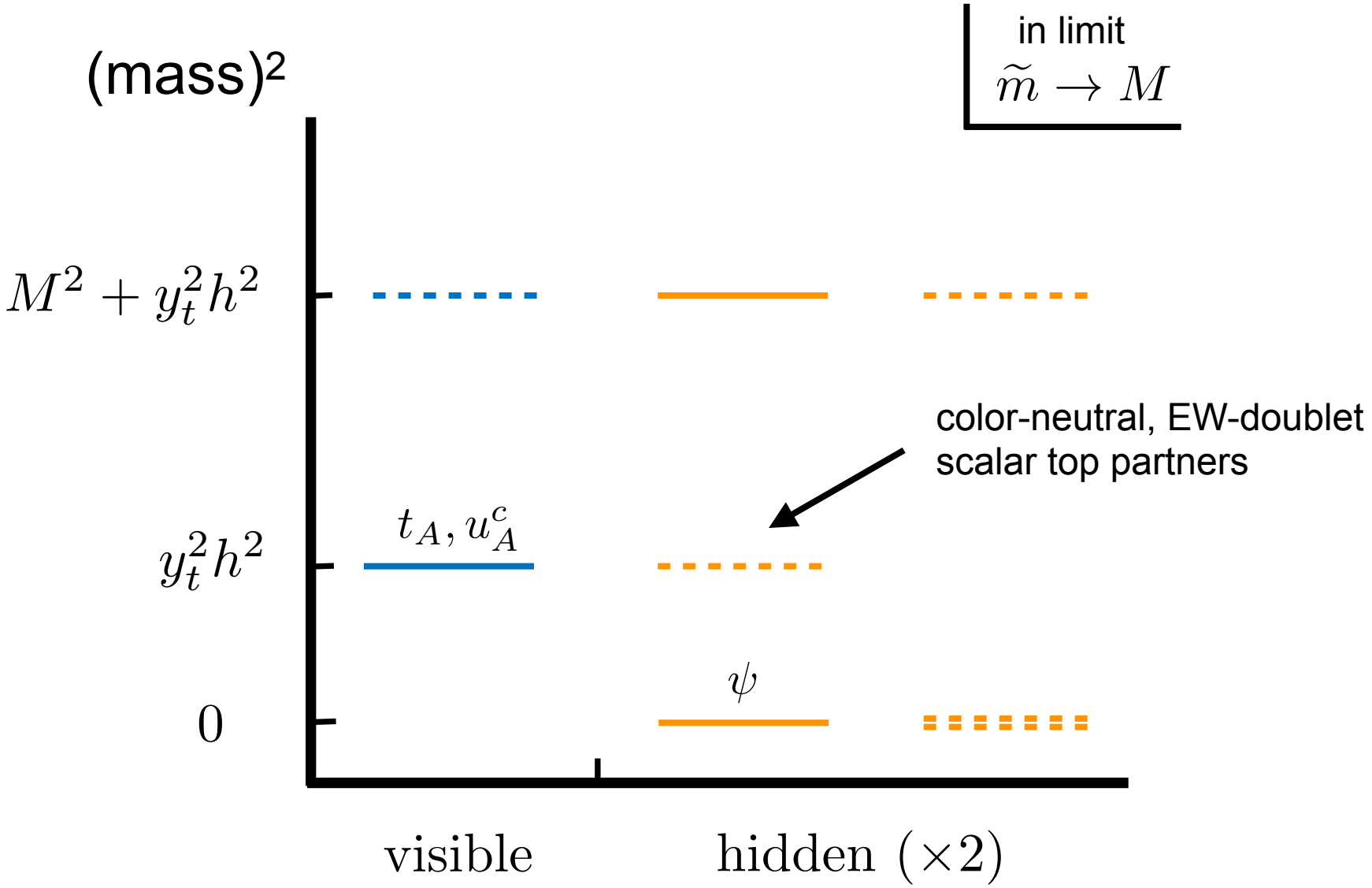
few TeV

Soft masses:

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

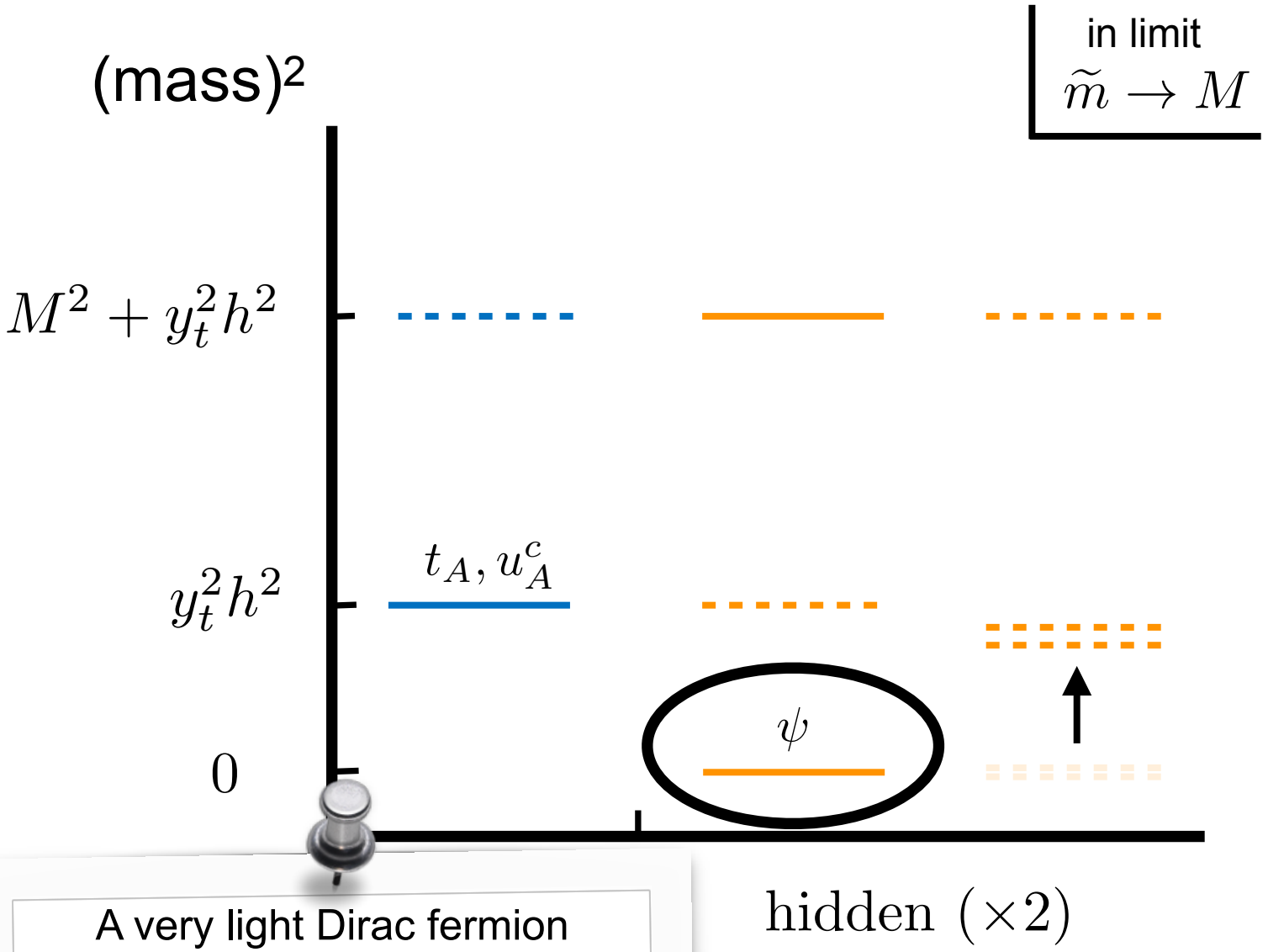
raise colored stops **lower** color-neutral “stops”

Accidental supersymmetry



[Cheng, Li, Salvioni, Verhaaren 2019]

Accidental supersymmetry



A very light Dirac fermion at bottom of spectrum

[Cheng, Li, Salvioni, Verhaaren 2019]