Hunting for Elusive Dark Sectors at the LHC

Ennio Salvioni

Low Mass Resonance Searches at the LHC
February 1, 2021

based on [1906.02198], [2006.15148], [in progress]
with Cheng, Li, Verhaaren and Katz, Shakya
+ some review

symmetry

Dark Sectors

- The visible part of the Universe is extraordinarily complex.
  The hidden part(s) could well display similar complexity

- A light hidden sector that couples weakly to the Standard Model
  is an important possibility for New Physics

- Perhaps, less exotic than one may think: amusing analogy with **neutrinos**
  "Hidden sector" coupled feebly to already-known particles.
  The *W* and *Z* are "heavy mediators" giving dimension-6 operators at low energies

$$\mathcal{L}_6 \sim \frac{g_Z^2}{m_Z^2} \bar{\nu}\gamma^\mu \nu \bar{e}\gamma_\mu e$$

  Theoretical proposal 1930 (Pauli)
  Experimental discovery 1956 (Cowan & Reines)
  Mediators produced on shell 1983 (UA1 & UA2) …

[Contino, Max, Mishra 2012.08537]

Dark Sectors

- Range of options for a dark sector is huge
- Motivations from outstanding problems of the SM are key:
  Hierarchy problem, Dark Matter front and center (though, by no means the only ones)
  Help to identify targets & chart progress

- **Confining hidden sectors** with mass scale

$$\text{few} \times 100\ \text{MeV} \lesssim \Lambda \lesssim \text{few} \times 10\ \text{GeV}$$

  can address either problem (or even both): Neutral Naturalness,
  strongly interacting Dark Matter, …

- The LHC plays unique role in testing these scenarios.
  But, not out of the box: dedicated strategies needed for event selection & analysis

Dark Sectors

This talk: confining hidden sectors with heavy mediators.

Broad theory motivations, “elusive” by nature

Still much to do (EXP and TH) to ensure they won’t be missed @ LHC

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But, not out of the box: dedicated strategies needed for event selection & analysis

Plan

- Introduction
- Theory motivation
- Case study: *Z* portal to dark QCD
    - ✓ Prompt light resonances
    - ✓ LLPs and dark showers
- Invisibly-decaying dark photons

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Typical setup: “dark QCD”

* for simplicity, but $SO(N_d)$ or $Sp(N_d)$ possible too

- $SU(N_d)$ gauge theory,* N_f light dark quarks
- Confinement at scale Λ, dark hadrons form
- Other key ingredients for pheno:
  - ✓ explicit symmetry breaking (quark masses, …)
  - ✓ which portals to SM?

- Theory motivations sharpen the focus.

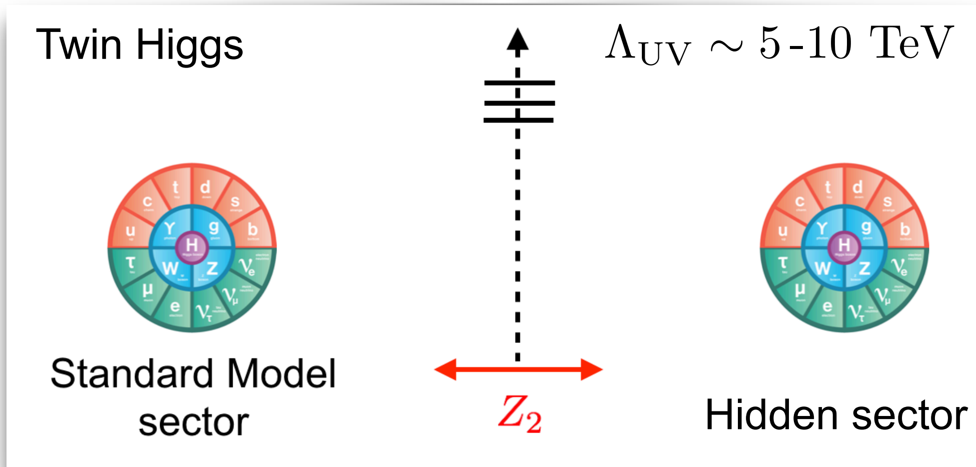
  Aim to identify representative cases with distinct signatures

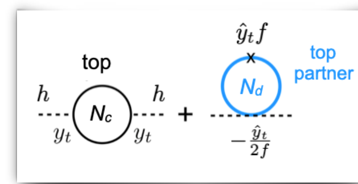
- Important examples: Neutral Naturalness, SIMP Dark Matter

Neutral Naturalness

- Models of EW symmetry breaking with QCD-neutral top partners
- How? Exchange symmetry relates SM and hidden sector:

[Chacko, Goh, Harnik 2005]
[Craig, Katz, Strassler, Sundrum 2015]



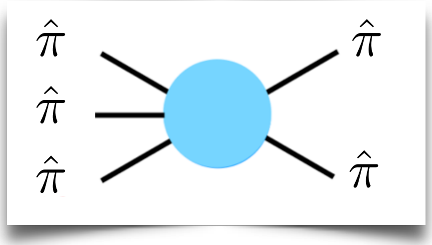


- Cancellation of top + “top partner” loop requires $N_d = 3$ hidden colors
- $g_s(\Lambda_{\rm UV}) \simeq \hat{g}_s(\Lambda_{\rm UV})$ implies hidden confinement at $0.1 \lesssim \Lambda/\text{GeV} \lesssim 10$
- (Dimension-6) Higgs portal always present. Often not alone

$$\mathcal{L}_6 = \frac{\hat{\alpha}_d}{12\pi f^2}|H|^2 \hat{G}_{\mu\nu}\hat{G}^{\mu\nu}$$

SIMP Dark Matter

- "Dark pion DM:" thermal relic abundance set by number-changing processes *within* hidden sector



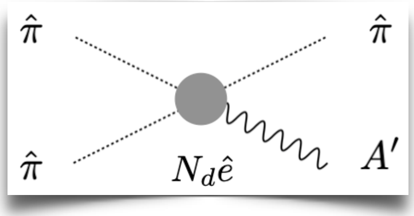
$$m_{\rm DM} \sim \alpha \left(\frac{T_{\rm eq}^2 M_{\rm Pl}}{x_{\rm fo}^4} \right)^{1/3} \sim \alpha \times 100 \text{ MeV}$$

dark strong coupling

Anomalous $3 \to 2$ processes require $N_f \geq 3$

- Suitable symmetries render dark pions stable (or extremely long lived)

- Some mediator to SM is needed. Appealing, popular option: kinetically mixed dark photon. Cannot be too light, otherwise semi-annihilations dominate freeze out



$$2m_{\hat{\pi}} < m_{A'} \lesssim 100 \text{ GeV}$$

EW precision tests (A' - Z mixing)

[Hochberg, Kuflik, Volansky, Wacker 2014]
[+ Murayama 2014]
[Lee, Seo 2015], [Hochberg, Kuflik, Murayama 2015]

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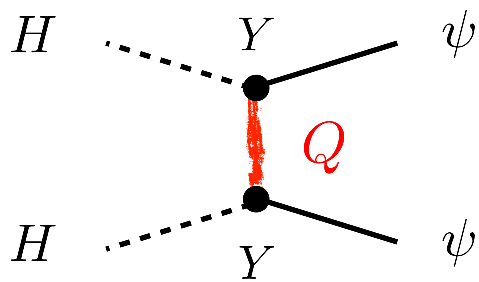
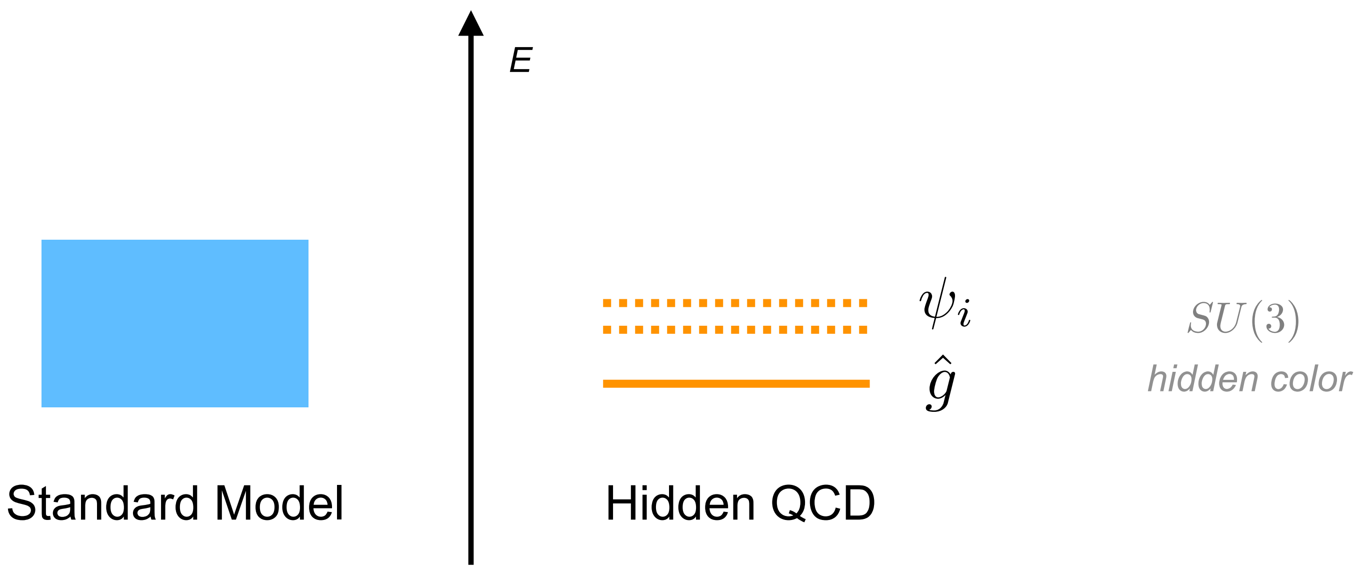
Higgs & *Z* portals to hidden sector

- Motivated by Neutral Naturalness (but keep discussion general)

[Cheng, Li, Salvioni, Verhaaren 1906.02198]



fermion mediator, mass $M \sim \mathrm{TeV}$



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At $E \ll M$, effects of mediator described by

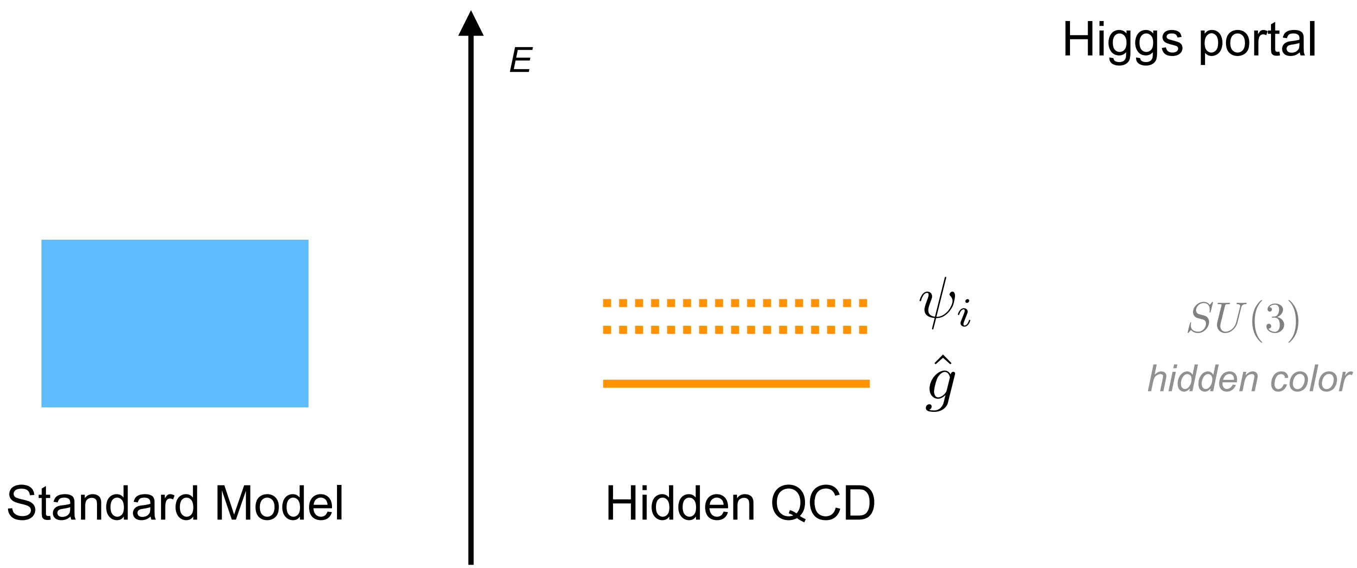
$$\mathcal{L}_6 \sim \frac{Y^2}{M^2}\left(H^\dagger D_\mu H \overline{\psi}\gamma^\mu \psi + \frac{\hat{\alpha}_s}{12\pi}|H|^2 \hat{G}_{\mu\nu}\hat{G}^{\mu\nu}\right)$$

$Z \to \psi\overline{\psi}$

Z portal

$h \to \hat{g}\hat{g}$

Higgs portal



Higgs *vs* *Z* portal

(*take* $Y = y_t \approx 1$)

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Z portal

Higgs portal

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

$$\mathrm{BR}(h \to \hat{g}\hat{g}) \approx 1.6 \times 10^{-5}\left(\frac{2\ \mathrm{TeV}}{M}\right)^4\left(\frac{\hat{\alpha}_s}{0.2}\right)^2$$

- @ LHC, 13 TeV: $\sigma_Z \approx 55\ \mathrm{nb}$, $\sigma_h \approx 49\ \mathrm{pb}$ ⇒ ***Z* decays to hidden sector** dominate

$> 10^{11}$ Z @ HL-LHC!

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- How many flavors of hidden quarks?

$N_f = 1$

- no light “pions,” spectrum (in principle) fully computable on lattice
- vector meson decays to SM
- original motivation from Neutral Naturalness

[Cheng, Li, Salvioni, Verhaaren 1906.02198]

$N_f \geq 2$

- light “pions” are present, dominate the dark parton showers
- vector meson can decay to $\pi\pi$
- much larger freedom as to symmetry pattern

[Cheng, Li, Salvioni, Verhaaren in progress]

Hidden hadron spectrum

- *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 $m_{\eta'}^2 \propto N_f/N_c$
  - ☑ Ratio of scalar/pseudoscalar meson masses: $m_{\hat{S}}/m_{\hat{P}} \approx 1.5$
  - ☐ No info on vector meson

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- Take spectrum

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

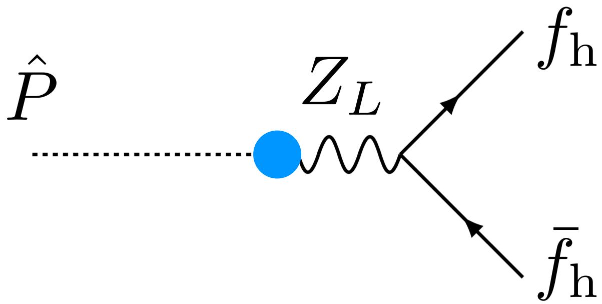
$$0^{-+} \qquad 1^{--} \qquad 0^{++} \qquad (J^{PC})$$

- All mesons decay back to SM through *Z* and *h* portals

Hidden meson decays

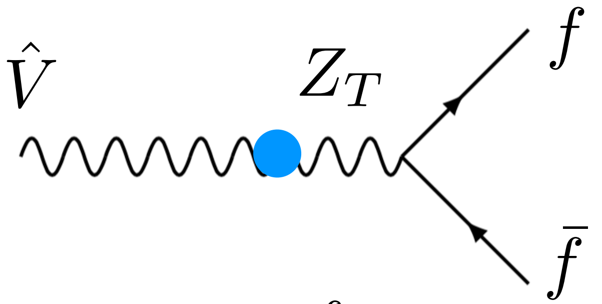
[Cheng, Li, Salvioni, Verhaaren 1906.02198]

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



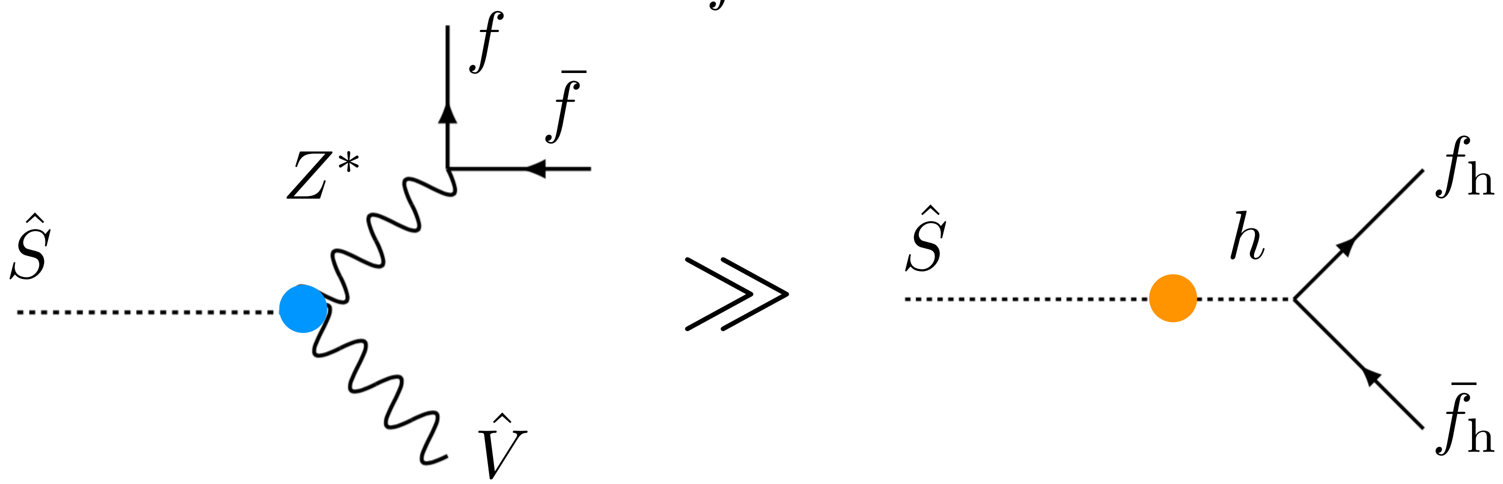
helicity suppressed

- Vector

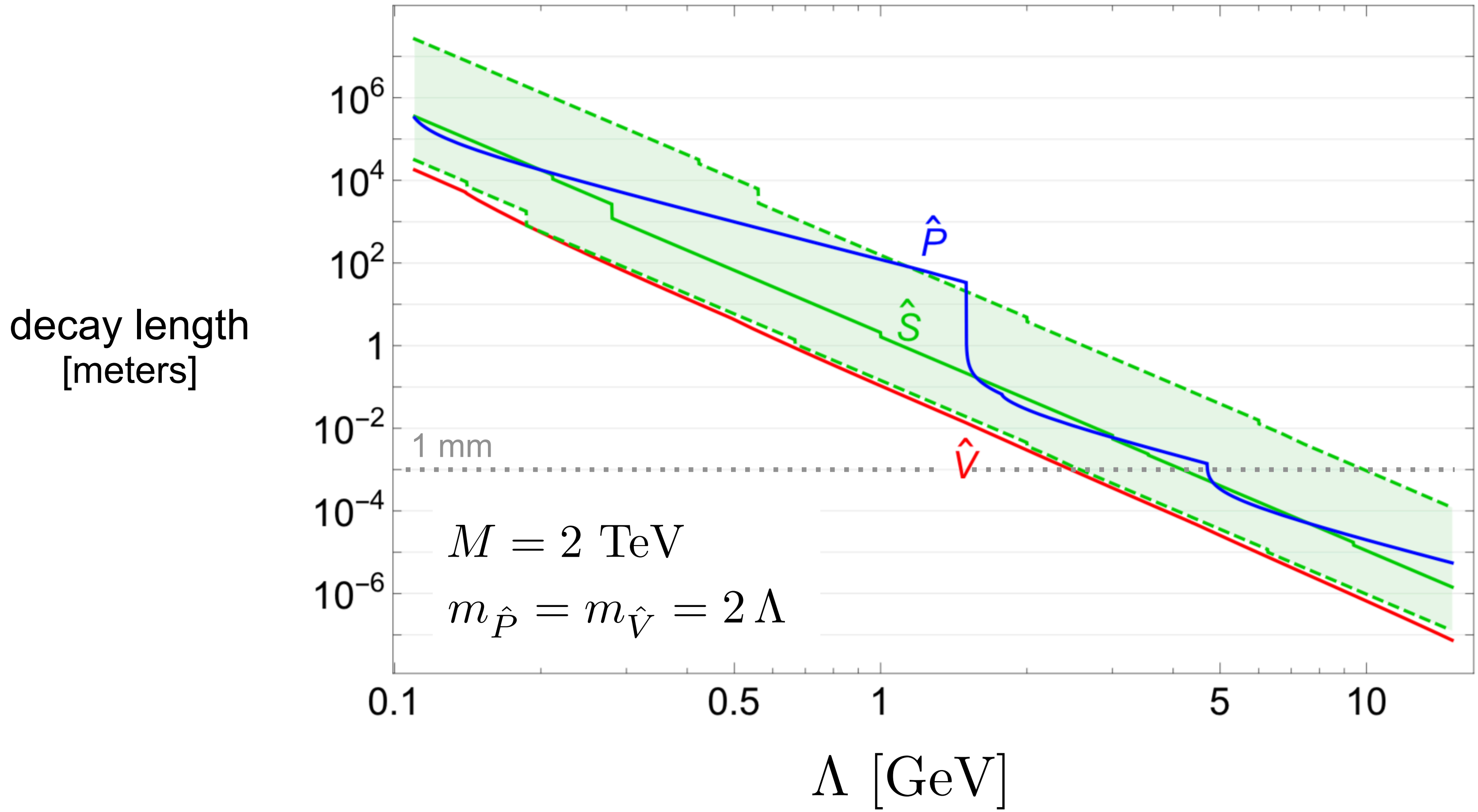


"democratic"

- Scalar



Hidden meson lifetimes

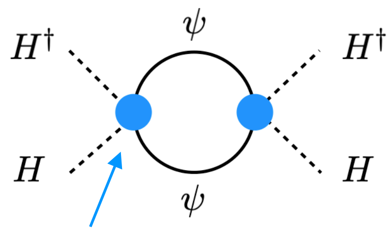


Two main parameters determine pheno:

- Hidden strong scale Λ
- Mediation scale M

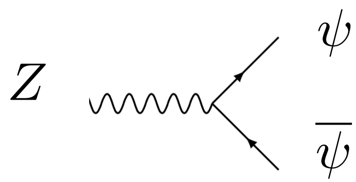
Constraints on the mediation scale

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



$$\frac{y_t^2}{M^2} H^\dagger D_\mu H\, \overline{\psi}\gamma^\mu\psi$$

- Invisible *Z* width $\Delta\Gamma_Z^{\mathrm{inv}} < 2\ \mathrm{MeV} \quad \rightarrow \quad M \gtrsim 0.8\ \mathrm{TeV}$



- Direct searches @ LEP ($\sim 2 \times 10^7$ *Z's*): possibly marginal sensitivity for $M \lesssim \mathrm{TeV}$

- Direct searches @LHC: EW-charged vectorlike fermions, pair produced

$M \gtrsim 1\ \mathrm{TeV}$ is wide open

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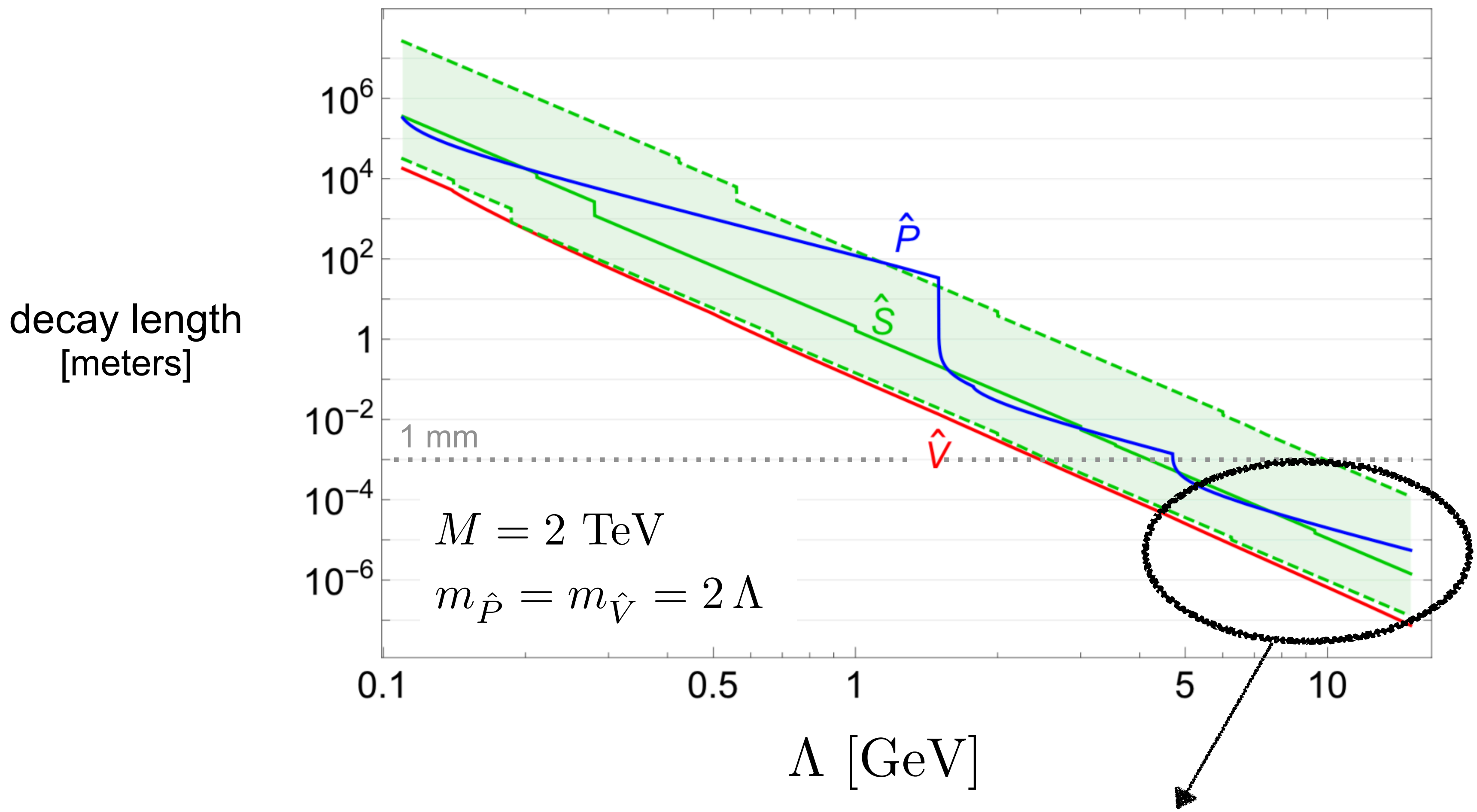
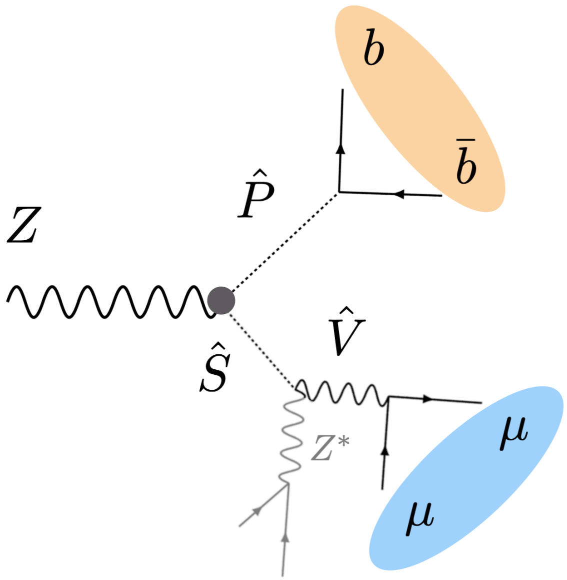


$\Lambda \sim 10$ GeV : $Z \to 2$ hidden mesons, all decays are prompt

Prompt signatures/1

- For $\Lambda \sim 10$ GeV, the Z decays promptly to 2 light resonances.

  Leading process:



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

- No dedicated LHC search (yet), but can learn from searches for $h \to aa \to (b\bar{b})(\mu\mu)$
- p_T cuts are key factor

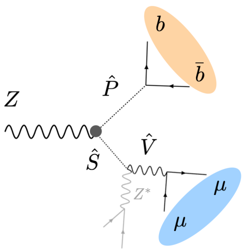
[**ATLAS**, 1807.00539] [**CMS**, 1812.06359]

Prompt signatures/1

[**CMS**, 1812.06359]

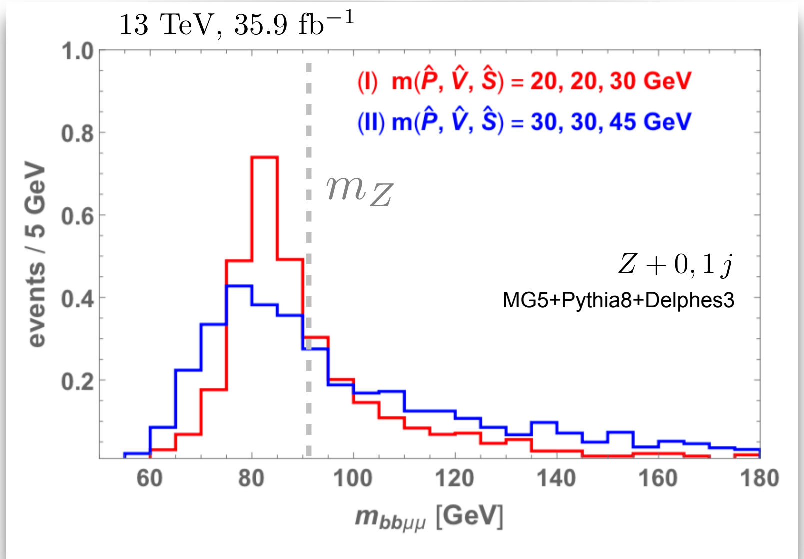
- CMS $h \to aa$ selection: $p_T^{\mu\,1,2} > 20, 9\ \mathrm{GeV}$ $p_T^{b\,1,2} > 20, 15\ \mathrm{GeV}$ $|\eta_{\mu,b}| < 2.4$
- For Z signal, total efficiency

  ~ 10 times smaller than for Higgs



$\sim 0.3\%$ vs $\sim 5\%$

relative “softness” of events evident from total invariant mass →



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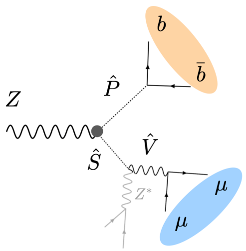

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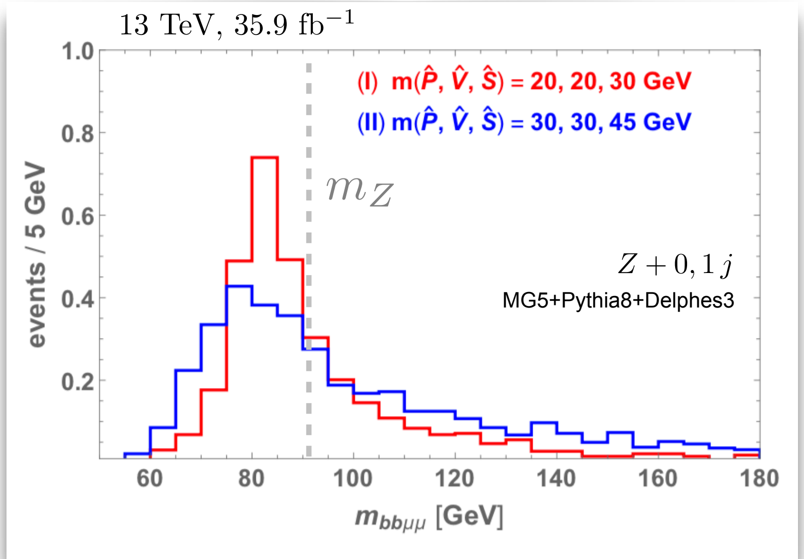


(HLT thresholds)

- Soften cuts: $p_T^{\mu 1,2} > 17, 8\ \mathrm{GeV},\ p_T^{b} > 15\ \mathrm{GeV}$ ➡ efficiency ~ doubles

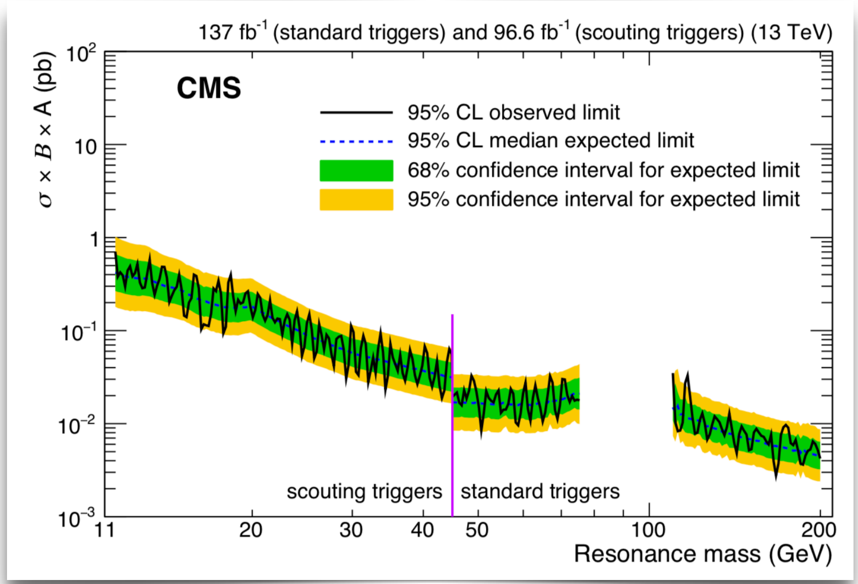
- ATLAS analysis has slightly tighter selection, sensitivity is negligible

$$p_T^{\mu\,1,2} > 27, 7\ \mathrm{GeV}, \qquad p_T^{b} > 20\ \mathrm{GeV}$$

[**ATLAS**, 1807.00539]

Going a different path

- **Scouting/Trigger Level Analysis**
- Store only HLT reconstruction. Typical event size ~ 5 kB, can operate @ higher rates
  E.g. up to 26 kHz for ATLAS low-mass dijets [Boveia, ATL-DAQ-SLIDE-2019-888]
- Dimuon scouting @ CMS: only limited by L1 trigger rate, threshold $p_T^\mu > 4\ \mathrm{GeV}$ for both muons (!!). **Qualitative improvement**
- Recently applied to inclusive dimuon resonance search [**CMS**, 1912.04776]



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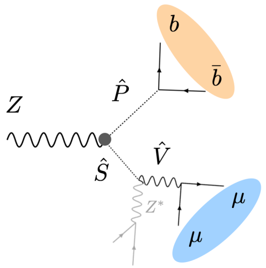
- Recently applied to inclusive dimuon resonance search [**CMS**, 1912.04776]
- For $m_{\hat{V}} = 20$ GeV, limit from inclusive search is comparable to naive $h \to aa$ recast

$$M_{\rm incl} \gtrsim 0.9 \text{ TeV} \left(\frac{\mathcal{B}_{\hat{P}\hat{S}}}{1}\right)^{1/4} \qquad M_{h\to aa} \gtrsim 1.25 \text{ TeV} \left(\frac{\mathcal{B}_{\hat{P}\hat{S}}}{1}\right)^{1/4}$$

Let's look at the b-jets…



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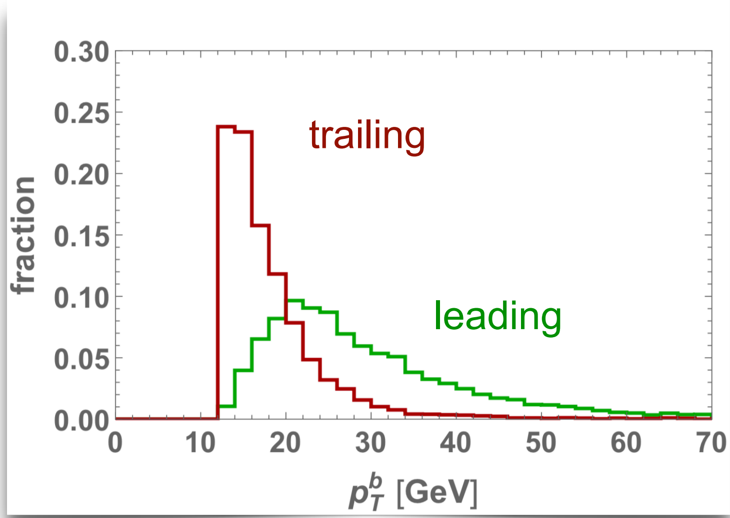
b-jet transverse momenta for signal, after scouting selection on dimuons

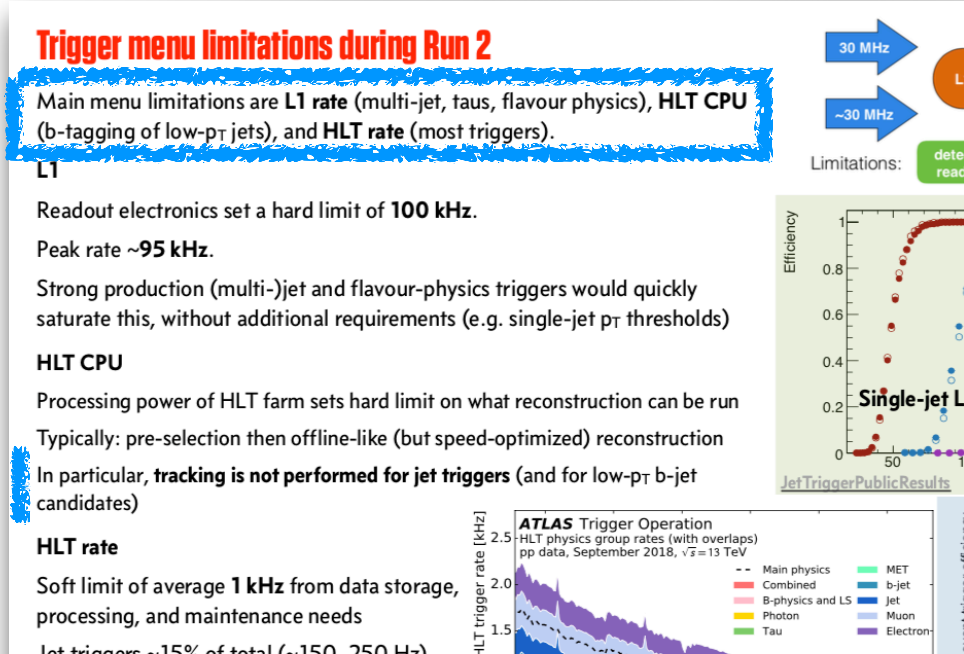


- Feasible to tag these soft *b*'s @ HLT?

challenging, but potential gain is *qualitative*

- In ATLAS, important results with TLA for "low-mass" dijets

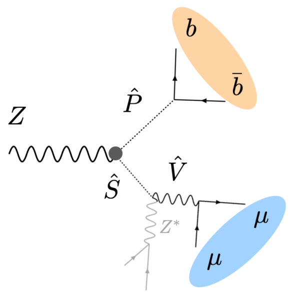
Presumably, similar efforts are ongoing in other channels: leptons, photons… (?)

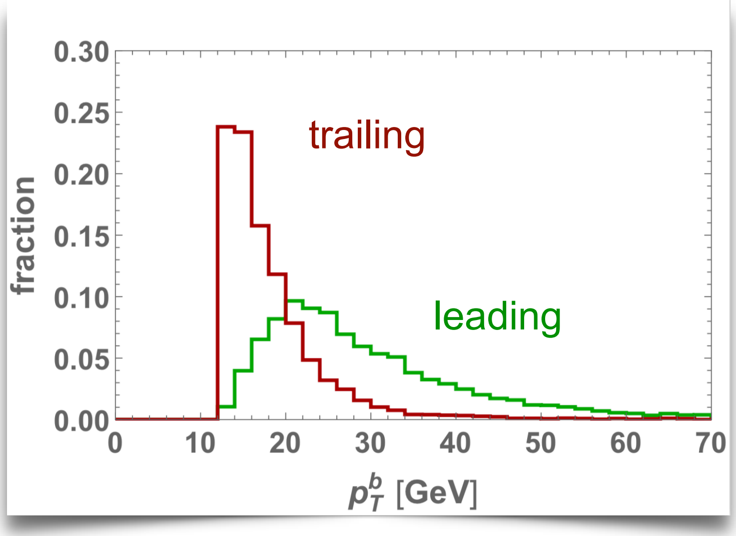


[Boveia, ATL-DAQ-SLIDE-2019-888]

Upgrade opportunities

b-jet transverse momenta for signal,
after selecting 2 muons with $p_T > 4$ GeV





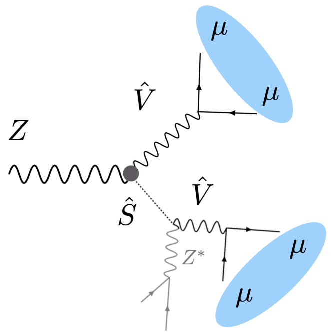
- Alternative strategy: phase II dedicated dimuon triggers, expected threshold $p_T \gtrsim 10$ GeV
  Record full event, offline (low-p_T) *b*-tagging

[ATL-PHYS-PUB-2019-002]

- Two prompt muons pointing to IP.
  Different (easier) compared to collimated or non-pointing case studies

Prompt signatures/2

- Subleading mode (needs chirality flip), but very clean final state:



$$Z \to \hat{V}\hat{S} \to (\mu\mu)(\mu\mu) + X$$

[**CMS**, 1808.03684]

- Here, extract bounds by recasting CMS search for light $U(1)_{\mu-\tau}$ Z-prime.

  Adapt selection to new signal topology

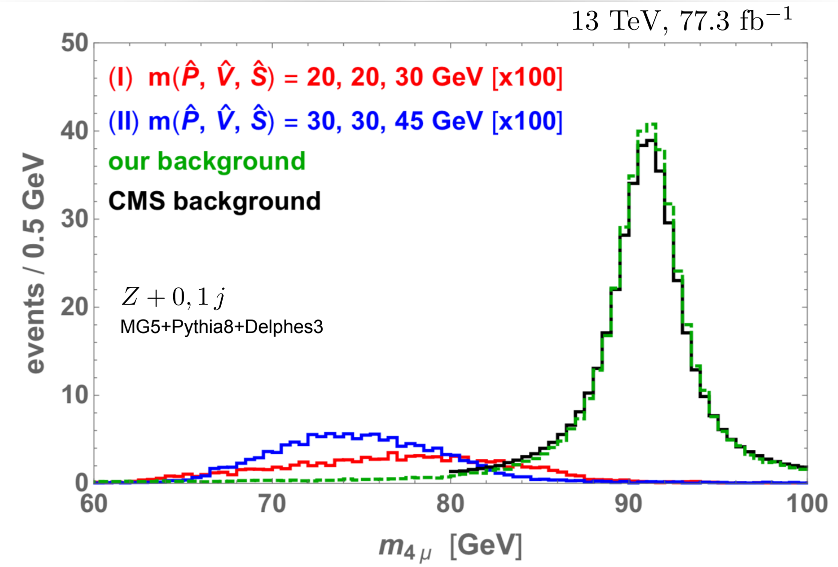
4 μ with $p_T^\mu > 5$ GeV, $|\eta_\mu| < 2.4$, of which ≥ 2 with $p_T^\mu > 10$ GeV and ≥ 1 with $p_T^\mu > 20$ GeV, zero total charge, $m_{\mu^+\mu^-} \in [4, 120]$ GeV for all combinations.

and require two-resonance structure

$$m_{4\mu} \in [60, 90]\ \text{GeV},$$

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

triggers: 2μ, $p_T > 17, 8$ GeV
3μ, $p_T > 12, 10, 5$ GeV



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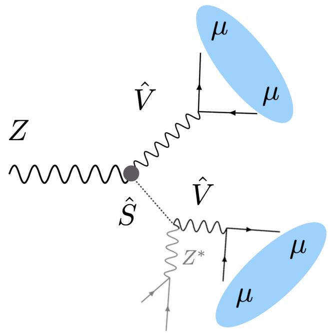

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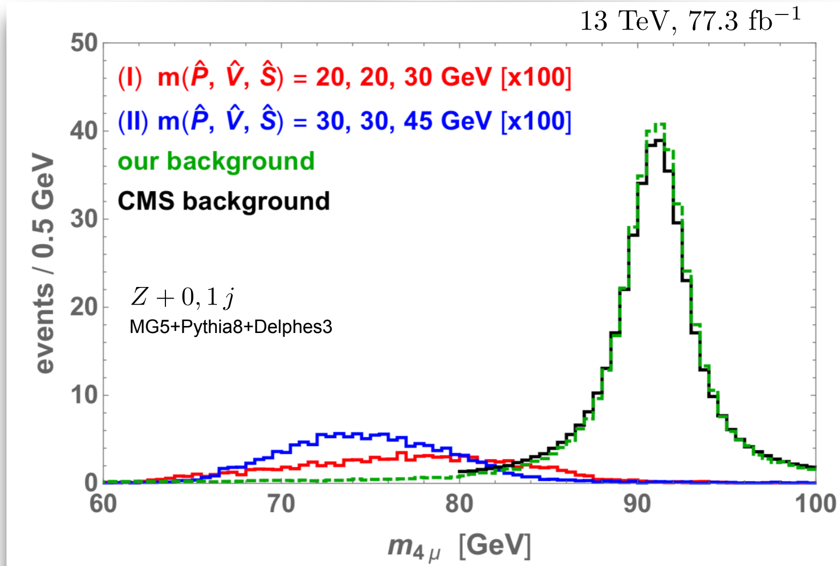
Run 2

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

HL-LHC



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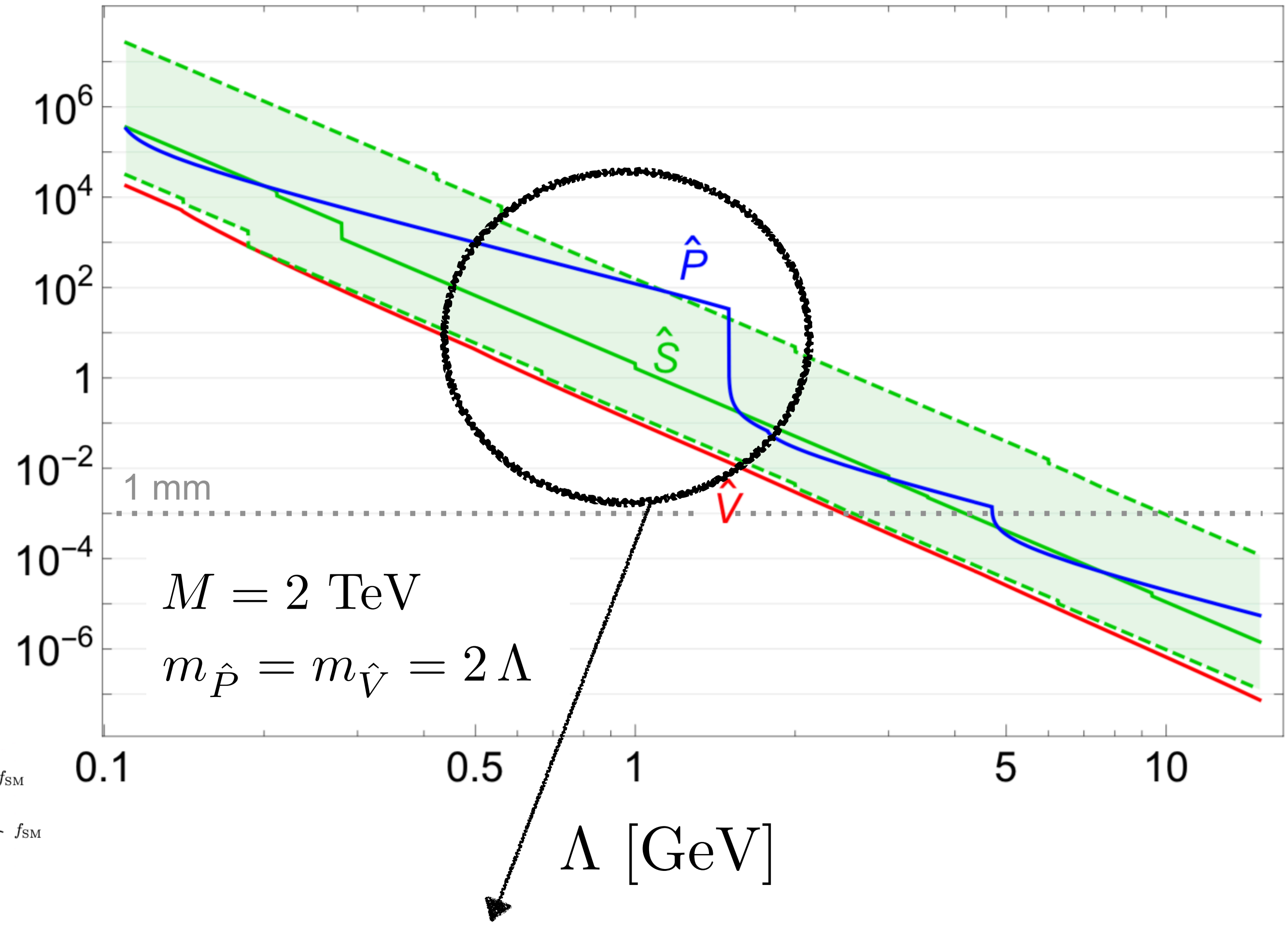
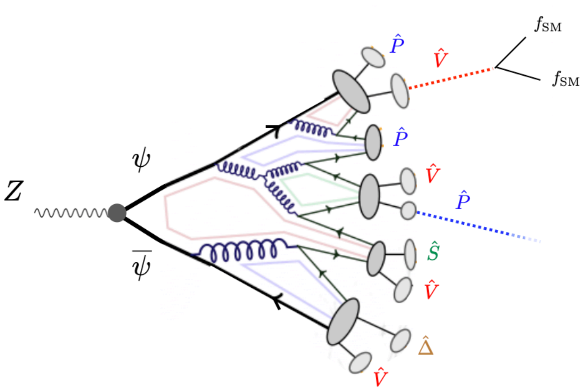
Hidden meson lifetimes





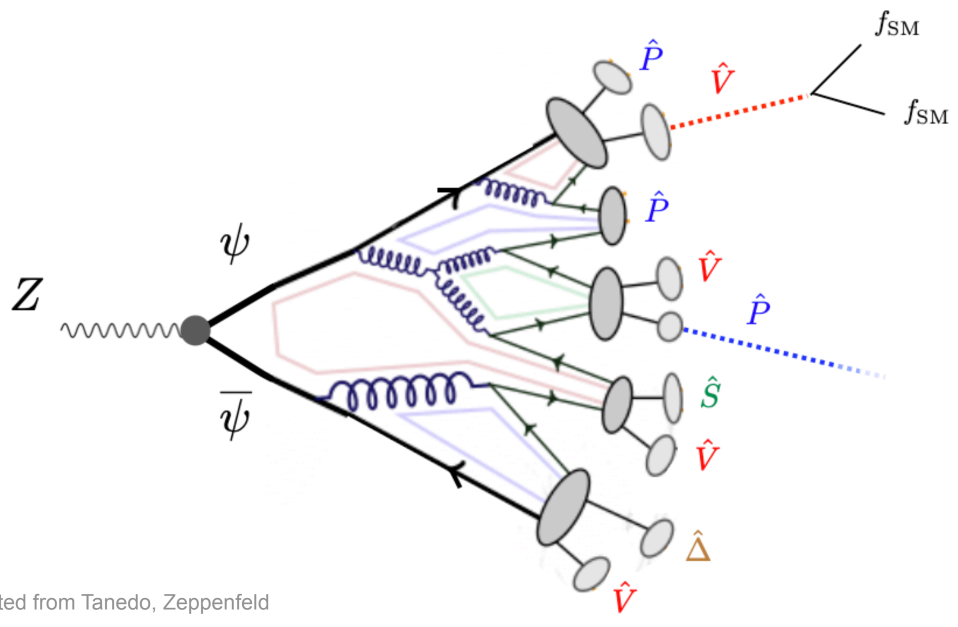
$\Lambda \sim 1$ GeV : $Z \to$ hidden jets, all dark mesons are long-lived

Dark showers/1

- For $\Lambda \sim 1$ GeV all mesons are long lived, so the Z decays to 2 “hidden jets”
- Related to emerging jets/semi-visible jets, but with important differences

[Schwaller, Stolarski, Weiler 2015]
[Cohen, Lisanti, Lou 2015]
[**CMS** 1810.10069]

- pseudoscalar $\hat{P}$ is collider-stable, vector $\hat{V}$ decays democratically to SM, including leptons → sizable missing energy fraction
- production mode is relatively soft (on-shell Z). Very different from e.g. emerging jets @ CMS, here trigger is main issue



adapted from Tanedo, Zeppenfeld

Dark showers/1

- For $\Lambda \sim 1$ GeV all mesons are long lived, so the Z decays to 2 “hidden jets”
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- In [1906.02198] tried $Z +$ jets, $Z(V \to \ell\ell)$. Alas, no match to reach of **LHCb**
  Pick up single $\hat{V} \to \mu\mu$ decay inside the VELO

[Ilten, Soreq, Thaler, Williams, Xue 2016]
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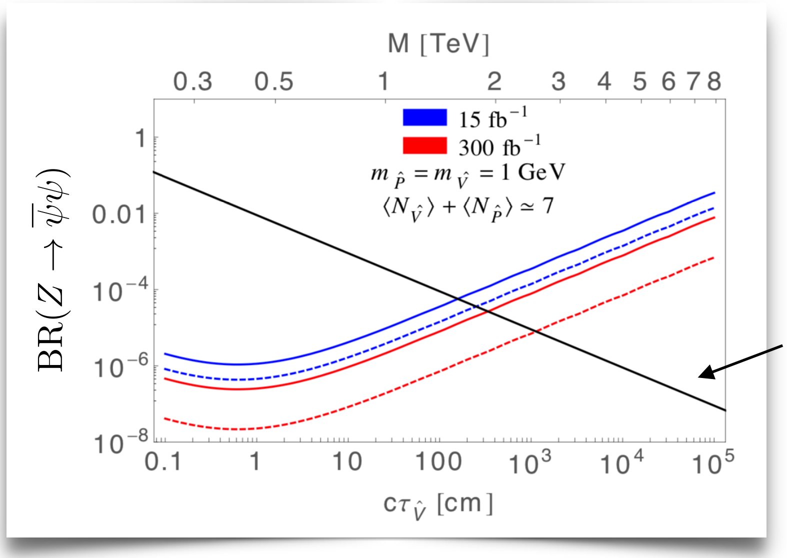

$$\mathrm{BR} \approx \frac{10^{-2}}{c\tau_{\hat{V}}/\mathrm{cm}}$$

Z portal prediction

Benchmark: $m_{\hat{P}} = m_{\hat{V}} = 1$ GeV

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

≈ 7 mesons per jet

(Pythia HV module)

$\ell_T \in [6, 22]$ mm

$p_T^{\hat{V}} > 1$ GeV

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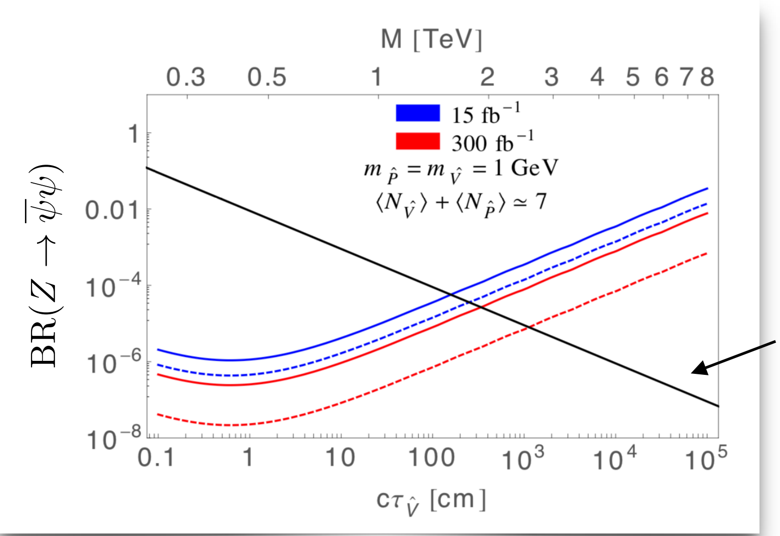

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$M > 1.6\,(2.0)$ TeV "standard" bkg

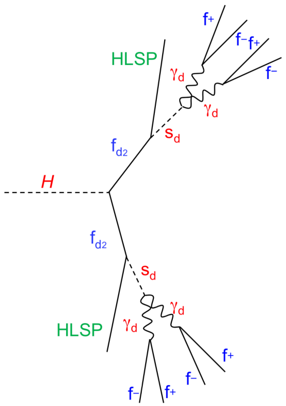
$M > 1.8\,(2.7)$ TeV zero bkg

Dark showers/2

[ATLAS 1909.01246]

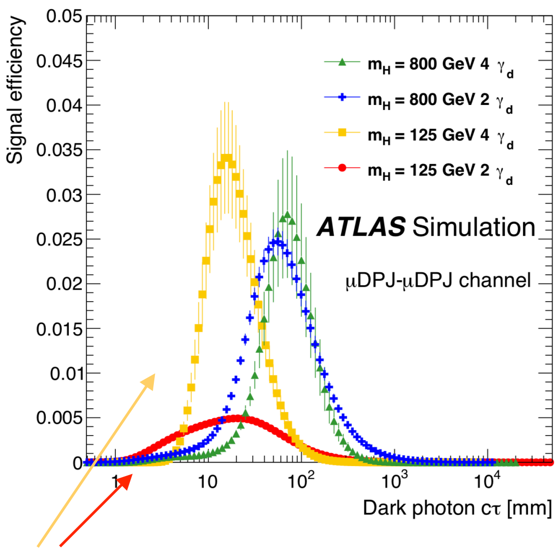
- More recent: search for two "dark photon jets" with dedicated triggers.
  Long-lived DPs decaying to muons in MS or to e/π in HCAL

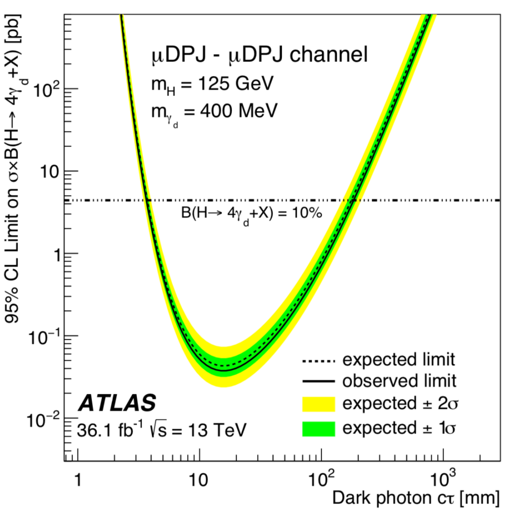
e.g. 3μ trigger, $p_T > 6$ GeV



- Similar: targets ~ GeV mass scale, partly-invisible decay chain.
  Different: dark shower has larger multiplicity, smaller average boost, $\hat{V}$ decays to neutrinos.

- Recast would be clearly interesting





efficiency reduction, if only one dark photon per side

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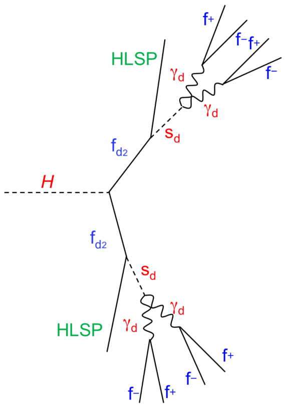

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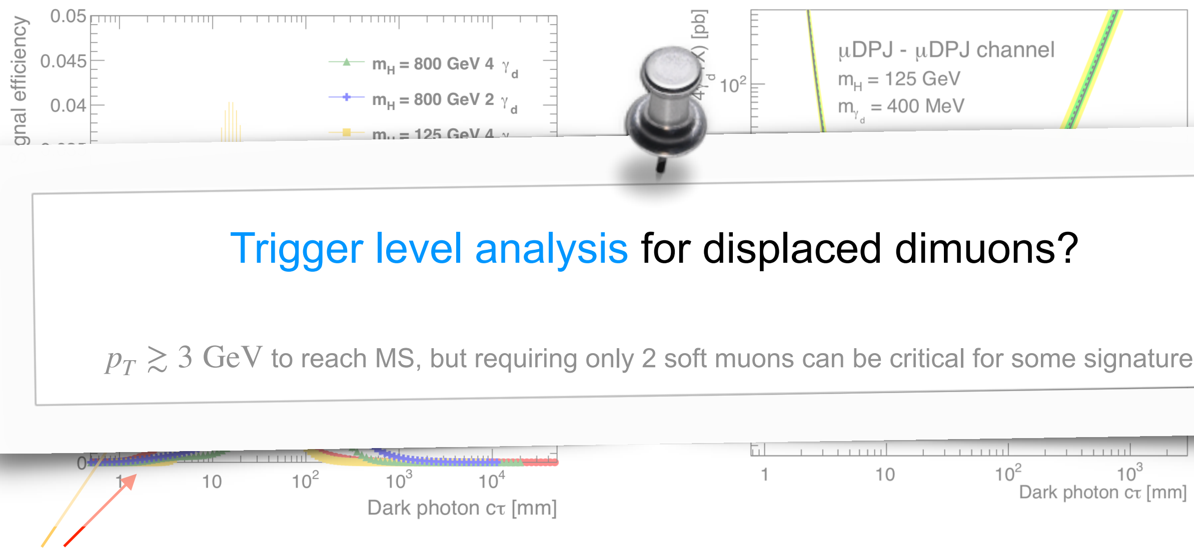


Trigger level analysis for displaced dimuons?

$p_T \gtrsim 3$ GeV to reach MS, but requiring only 2 soft muons can be critical for some signatures

efficiency reduction, if only one dark photon per side

Intensity frontier

- For $m_{\hat{V}} \lesssim \mathrm{GeV}$, intensity frontier experiments are potentially relevant.
  Production via Bremsstrahlung, meson decays, Drell-Yan, …

- Hidden fermion constituents are electrically neutral, vector meson couples dominantly to neutral current

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

generic light dark vector

- No global analysis available yet for this scenario.
  Estimate by approximating $\hat{V}$ as *kinetically* mixed dark photon

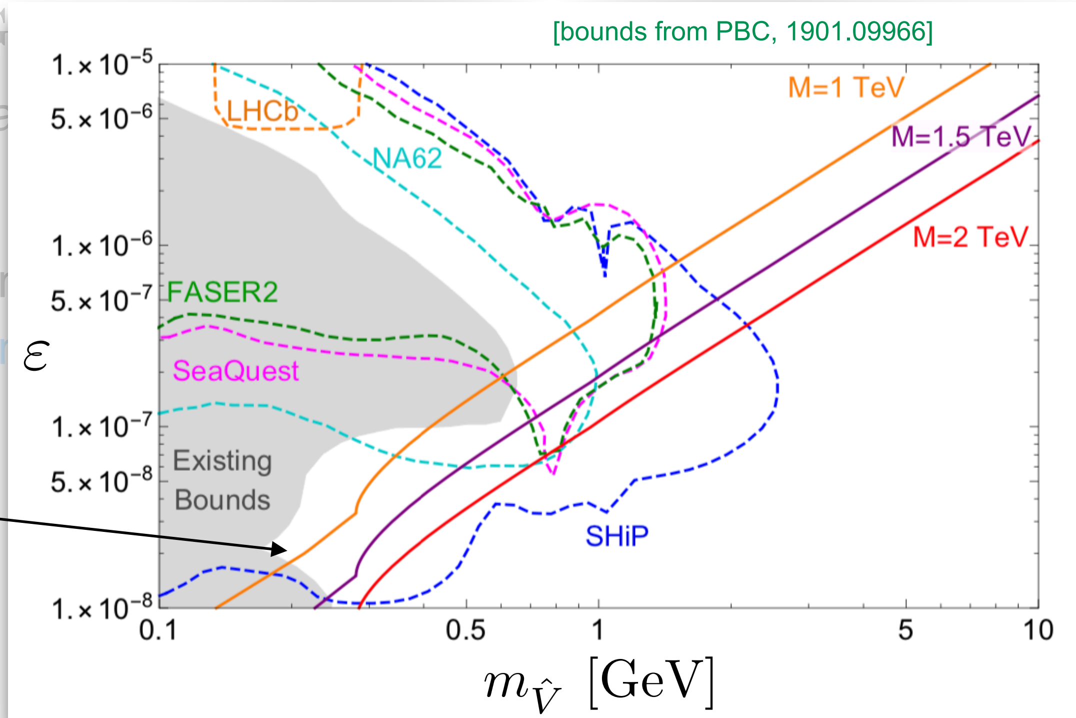
$$\varepsilon_{\mathrm{eff}} \approx 10^{-7} \left(\frac{m_{\hat{V}}}{\mathrm{GeV}} \right)^2 \left(\frac{2\ \mathrm{TeV}}{M} \right)^2$$

neglects differences between EM and weak charges

Z portal @ intensity frontier

- For $m_{\hat{V}} \lesssim$ G … evant.
  Production via …
- Hidden fermion … couples dominantly to …

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



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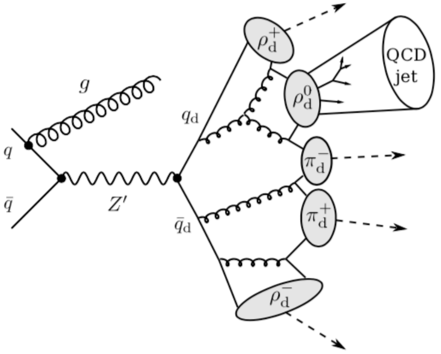
Dark showers/3

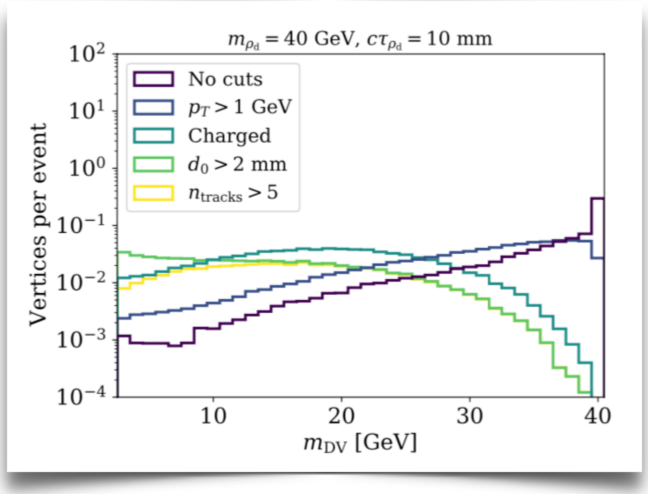


- Partly-invisible dark shower with heavier mesons ($m_{\rm DV} > 10$ GeV) also studied recently. Hadronic-only decays

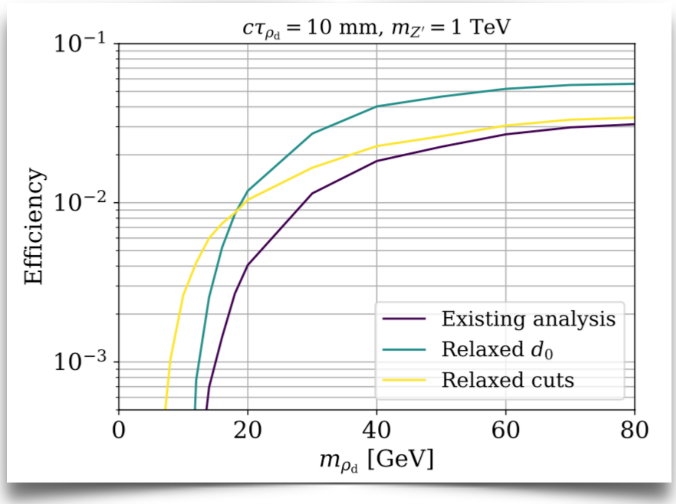
  [Bernreuther et al. 2011.06604]

- ATLAS reconstruction gives bias towards lower DV masses, efficiency loss

  [**ATLAS** 1710.04901]



Can be improved by relaxing $m_{\rm DV} > 5$ GeV, or including tracks with $d_0 < 2$ mm in mass reco



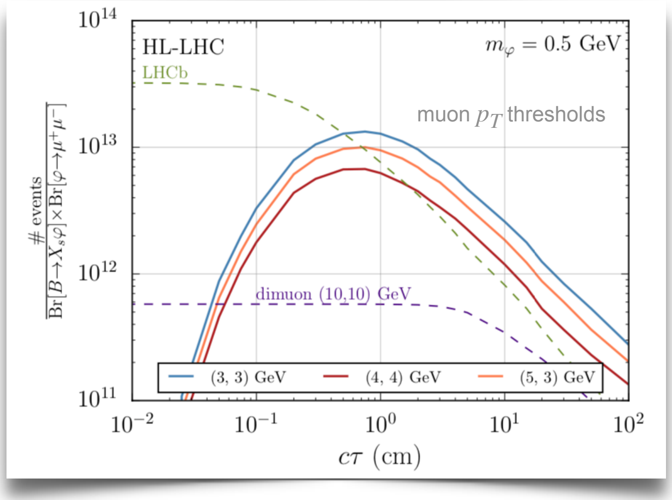
More LLP opportunities

- Proposal for displaced dimuon trigger @ CMS phase II

[Gershtein, Knapen 1907.00007]

- Track stubs in outer tracker enable L1 track triggering.
  Applied to reconstruct vertices with displacement up to ~ 10 cm
  & matched to MS activity to reduce rate

for dark showers: second DV in event?



- Competitive with LHCb for exotic *B* decays

$$B \to X_s \varphi \qquad \varphi \to \mu\mu$$

[Evans, Gandrakota, Knapen, Routray 2008.06918]

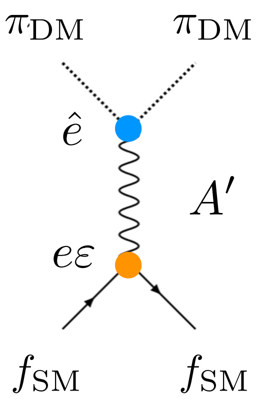
- Also proposed for **hadronic** DV, physics case from light CP-even scalars (and ALPs)

[Gershtein, Knapen, Redigolo 2012.07864]

Plan

- Introduction
- Theory motivation
- Case study: *Z* portal to dark QCD
  - ✓ Prompt light resonances
  - ✓ LLPs and dark showers
- **Invisibly-decaying dark photons**

Invisible resonance: dark photon



- Dark photon in mass range $100\ \mathrm{MeV} \lesssim m_{A'} \lesssim 100\ \mathrm{GeV}$ can be portal to SIMP dark matter

- Properties:

  ✓ ε coupling to SM electromagnetic current, $\varepsilon e c_w Q_f \bar{f}\gamma^\mu f A'_\mu$

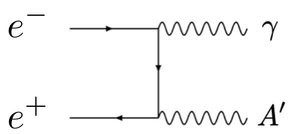
  ✓ dominant decay mode is **invisible** ($m_{A'} > 2\, m_{\pi_{\rm DM}}$, decays to DM)

- Searched for at range of experiments, but important “holes” remain

[Izaguirre et al., Essig et al. 2013]
[Fox, Harnik, Kopp, Tsai 2011]
[Shoemaker, Vecchi 2011]
[Curtin, Essig, Gori, Shelton 2014]
[Hochberg, Kuflik, Murayama 2015]
[LDMX 2018]
…

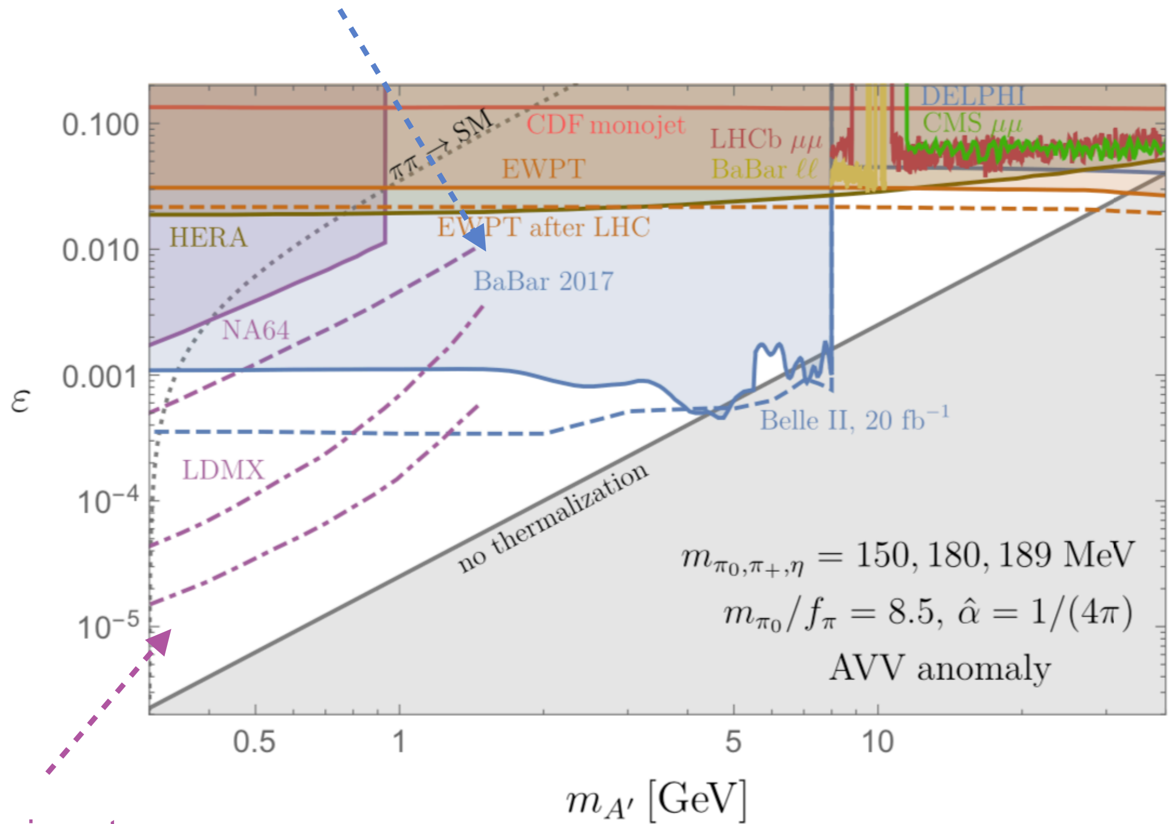
[Katz, Salvioni, Shakya, 2006.15148]

Invisible resonance: dark photon

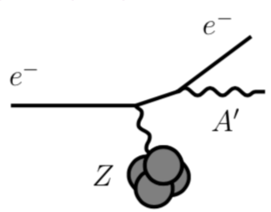


mono-photon at
low-energy e^+e^-

$$m_{A'}^2 = s - 2\sqrt{s}\,E_\gamma^*$$



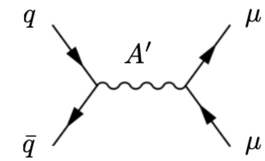
fixed-target experiments



Below 8 GeV, strong sensitivity (past, running or planned)

Invisible resonance: dark photon

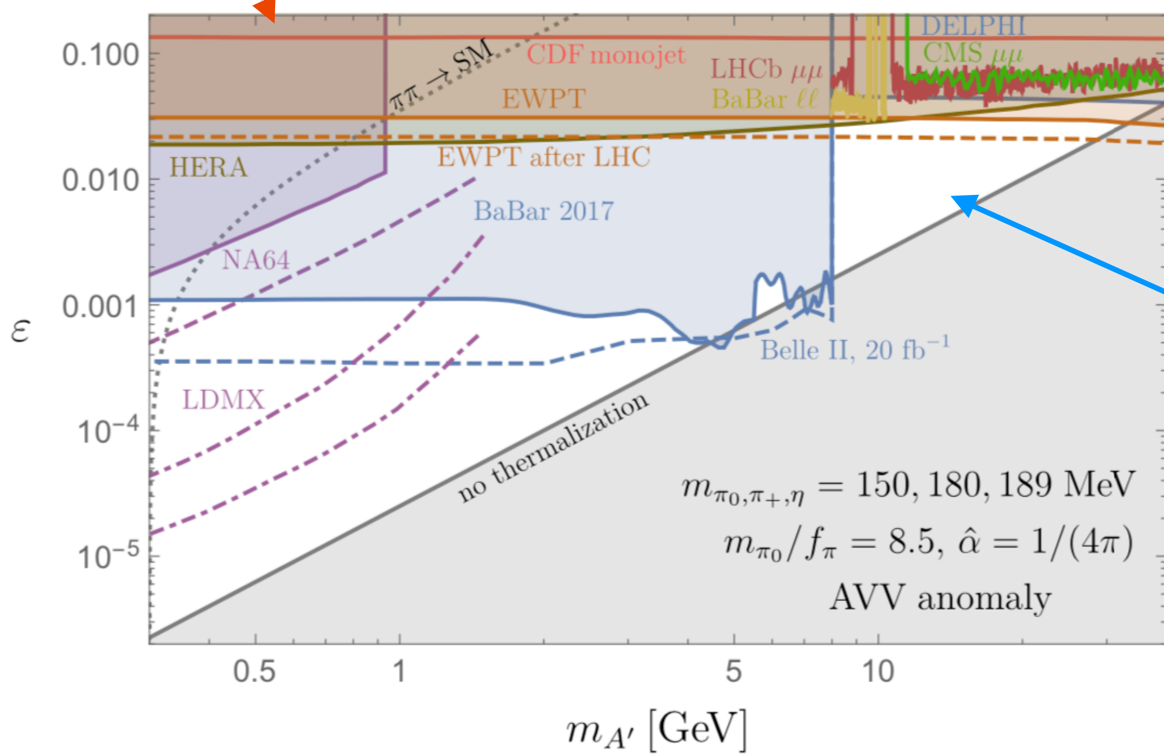
searches for *visible* decays @ LHC



current ATLAS/CMS monojet bounds are weaker than CDF

$\sigma \times \mathrm{BR} \propto \varepsilon^4$

but very sensitive searches



here, LHC is likely the only game in town

$pp \to Z A'$

$pp \to Z \to A' \ell\ell$

$(+\,\text{jets})$

$\ldots$

Above 8 GeV, a challenge (new ideas needed)

strong theory motivation

Outlook

- Strongly coupled hidden sectors @ $\text{few} \times 100 \text{ MeV} \lesssim \Lambda \lesssim \text{few} \times 10 \text{ GeV}$
  and interacting through heavy mediators
  have important motivations from addressing outstanding questions

- We may have gotten the big picture right (the weak scale *is* natural, DM *is* a thermal relic) but the details differ from "traditional" views: Neutral Naturalness, SIMP DM, …

- Require innovative experimental strategies. The LHC has unique role to play, often the only environment where these dark sectors can be probed

- I discussed a few examples highlighting the variety of signatures.
  They range from prompt decays, to dark showers with LLPs, to invisible resonances, …

- Plenty of opportunities for qualitative progress, both in developing new trigger strategies and in analysis techniques. Further exploration necessary on theory side as well

- Much more I haven't touched upon! Looking forward to the discussion

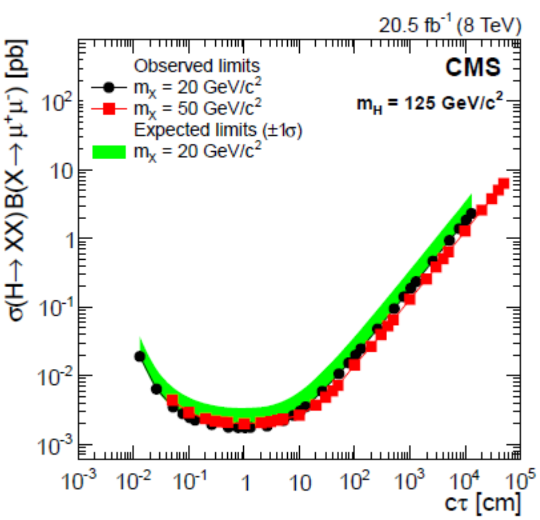
Supplementary material

Interplay with cosmology

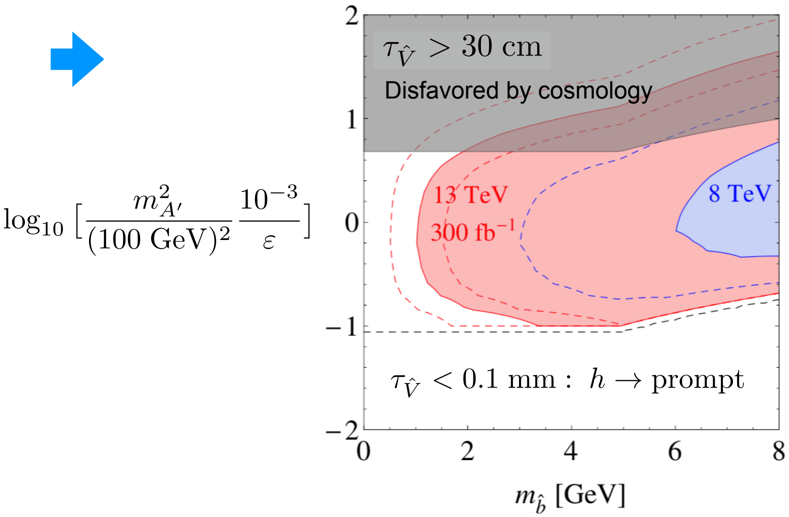
- If only Higgs portal is present, $\hat{P}, \hat{V}$ are metastable and can easily conflict with BBN.
  Can happen for instance in fraternal Twin Higgs
- Include dark photon portal, makes $\hat{V}$ decay efficiently. [Cheng, Jung, Salvioni, Tsai 2015]
  Lightest $\hat{P}$ depleted via (forbidden) conversion to vectors, $\hat{P}\hat{P} \to \hat{V}\hat{V}$

➡ strong upper bound on $\hat{V}$ lifetime to have viable cosmology, promising for LHC

$$h \to \hat{V}\hat{V} \to (\mu\mu)_{\rm DV} + X$$



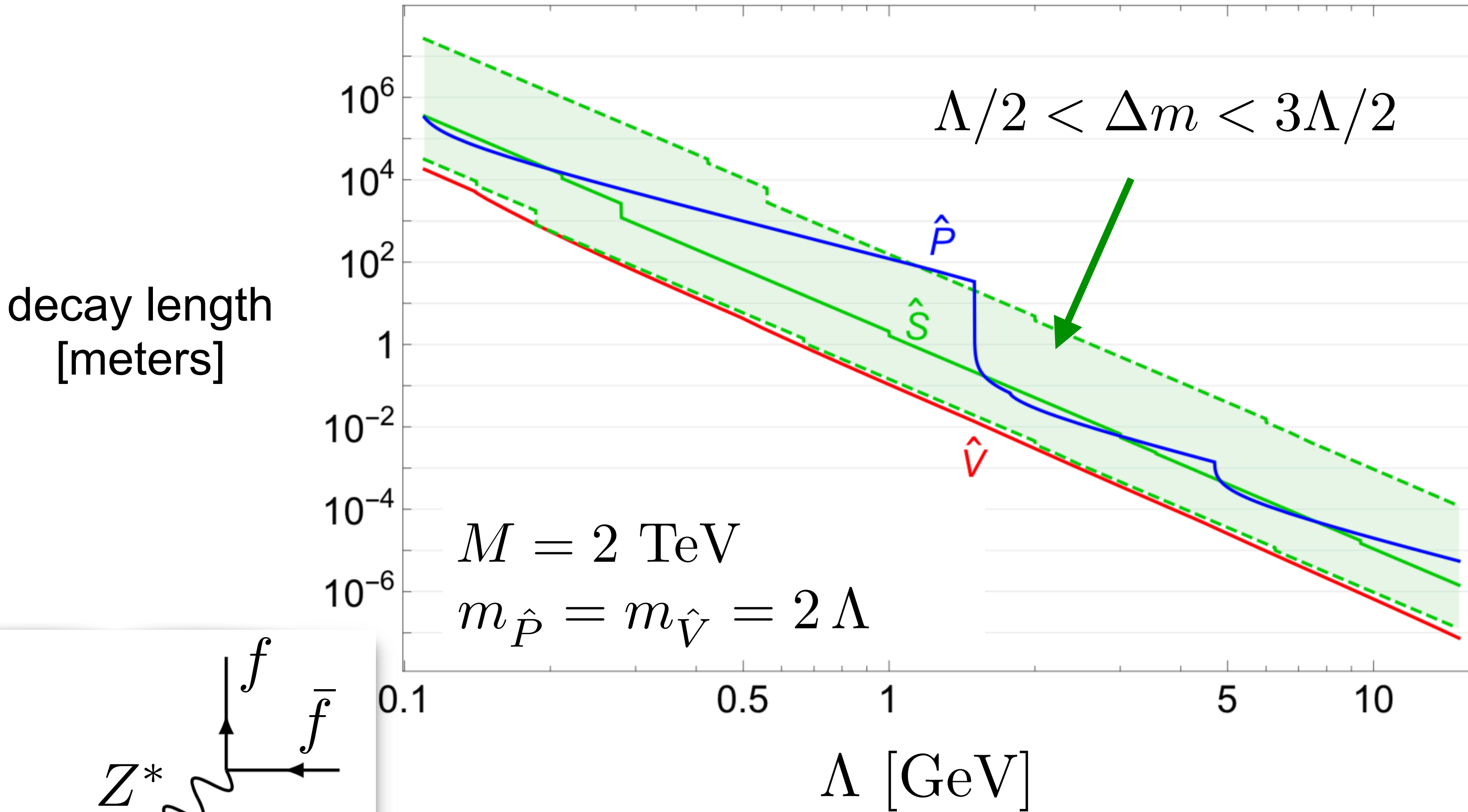
[CMS 1411.6977]

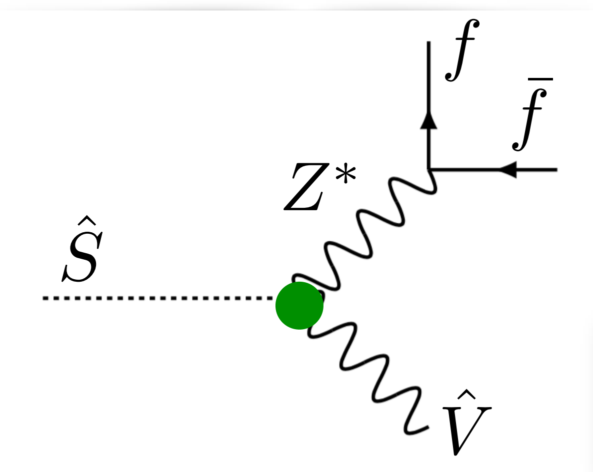


[Cheng, Jung, Salvioni, Tsai 1512.02647]

more detailed analysis in [Li, Tsai 1901.09936]

Hidden meson decays





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

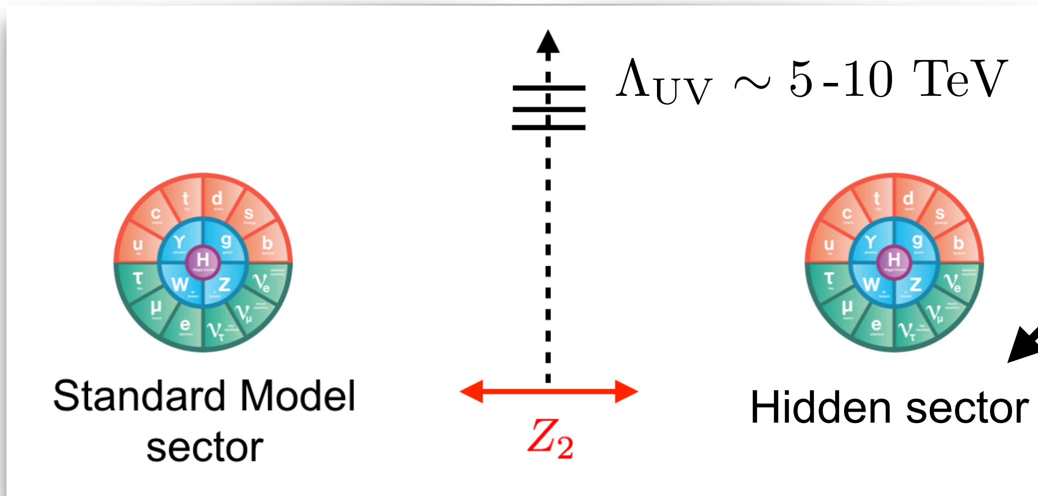
$$\Delta m \equiv m_{\hat{S}} - m_{\hat{V}}$$

Hidden confinement

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

Twin Higgs

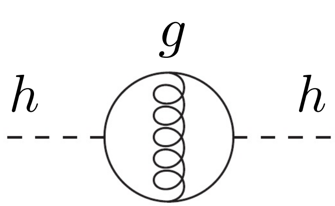
[Chacko, Goh, Harnik 2005]



has own *SU*(3) color symmetry

- 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

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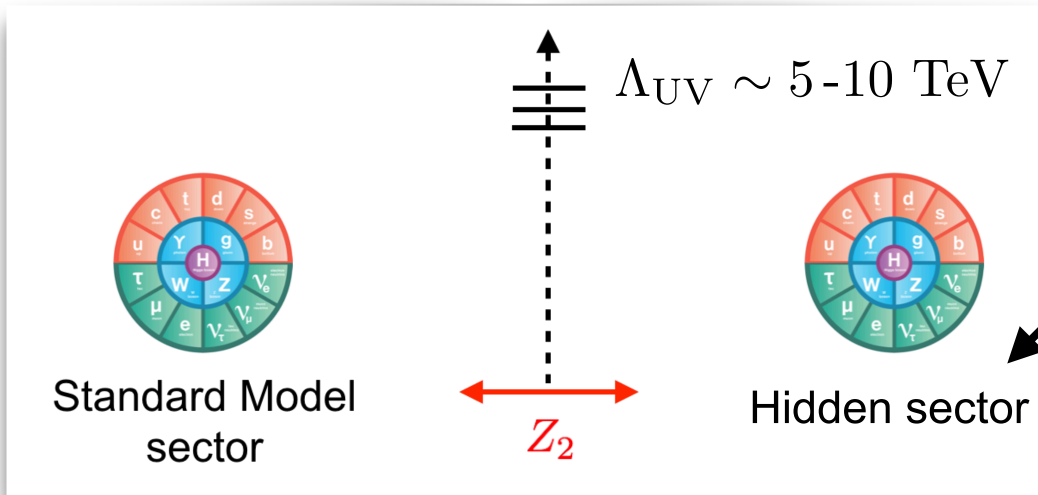

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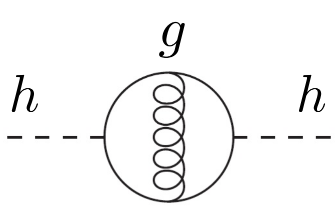

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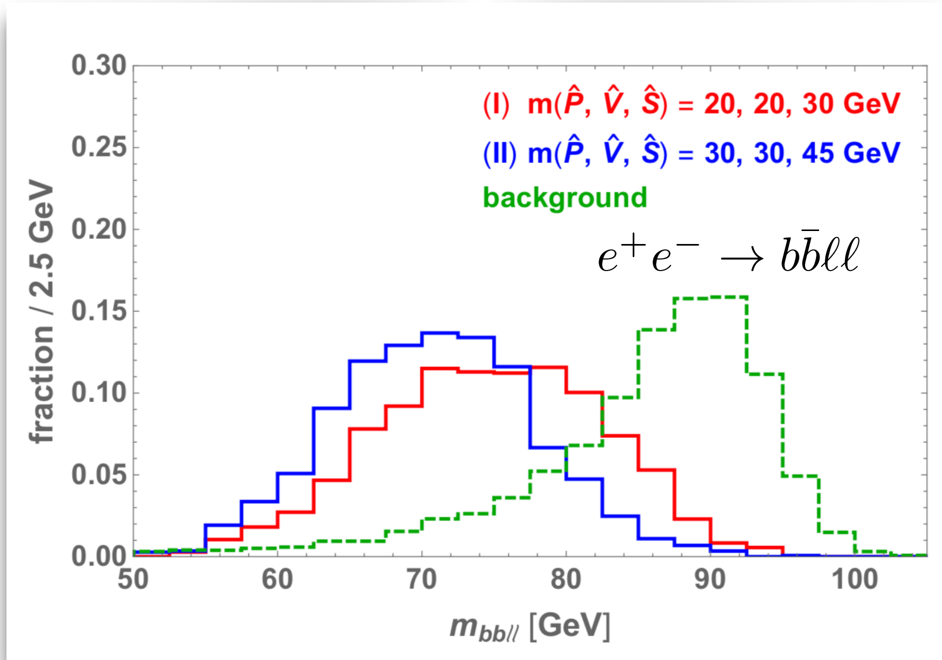
gauge hidden *SU*(3) with $g_s \simeq \hat{g}_s$ at $\Lambda_{\rm UV}$, **confines at** $\Lambda \gtrsim \Lambda_{\rm QCD}$

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:

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

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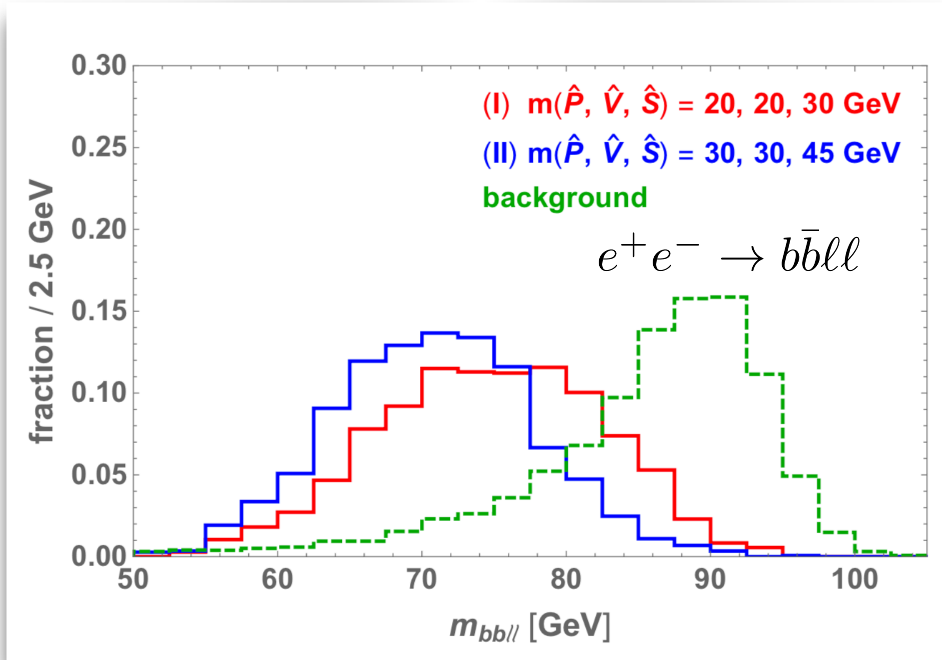

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- **At LEP1 ?** $N_Z^{\text{total}} \approx 2.2 \times 10^7$

[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 $(\epsilon_b^{\text{LEP1}} \sim 0.3)$

Strongly Interacting Massive Particles

Freeze-out happens when:

[Hochberg, Kuflik, Volansky, Wacker 2014]

$$\Gamma_{\rm annihilation} \sim H$$

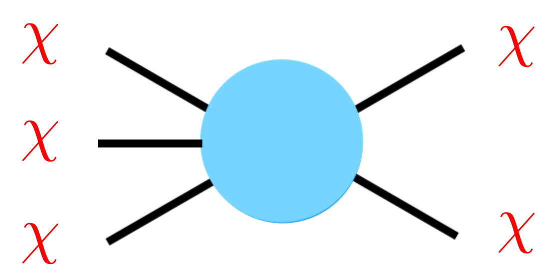
$$= n_{\rm DM}^2 \langle \sigma v^2 \rangle_{3\to 2}$$

$$H \sim \frac{T^2}{M_{\rm Pl}}$$

$$m_{\rm DM} n_{\rm DM} \sim m_p n_b \qquad \langle \sigma v^2 \rangle_{3\to 2} \sim \frac{\alpha^3}{m_{\rm DM}^5}$$

$$n_b \sim s \frac{T_{\rm eq}}{m_p}$$

$$\Gamma_{\rm annihilation} \sim \frac{\alpha^3 T^6 T_{\rm eq}^2}{m_{\rm DM}^7}$$



$$m_{\rm DM} \sim \alpha \left(\frac{T_{\rm eq}^2 M_{\rm Pl}}{x_{\rm fo}^4} \right)^{1/3} \sim \alpha \times 100 \text{ MeV}$$

$$\left(x_{\rm fo} = \frac{m_{\rm DM}}{T_{\rm fo}} \approx 20 \right)$$

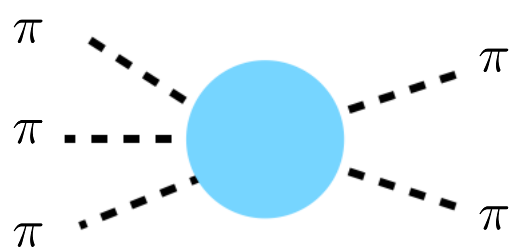
strong coupling ↔ strong scale

A dark copy of QCD

[Hochberg, Kuflik, Murayama, Volansky, Wacker 2014]

- $SU(N_c)$ gauge theory
- N_f light quark flavors $\rightarrow N_f^2 - 1$ (pseudo-) Goldstone bosons
- For $N_f = 3$ (or larger), **Wess-Zumino-Witten action** contains precisely

$$\frac{N_c}{240\pi^2 f_\pi^5} \epsilon^{\mu\nu\rho\sigma} \mathrm{Tr}\big(\Pi\partial_\mu\Pi\partial_\nu\Pi\partial_\rho\Pi\partial_\sigma\Pi\big) \subset \mathcal{L}_{\mathrm{WZW}}$$



[Wess, Zumino 1971]
[Witten 1983]

$$\text{SM: e.g. } K^+K^- \rightarrow \pi^+\pi^-\pi^0$$

- The dark photon connects hidden & visible sectors via kinetic mixing,

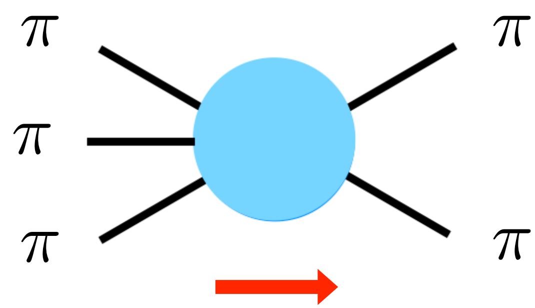
$$\mathcal{L} \supset \frac{1}{2} m_{\hat{A}}^2 \hat{A}_\mu \hat{A}^\mu + \frac{\varepsilon}{2} \hat{F}^{\mu\nu} B_{\mu\nu}$$

The need for a mediator

- Hidden mesons with SM-like mass (~ 100 MeV) obtain relic density through freeze out of $3 \rightarrow 2$ annihilations

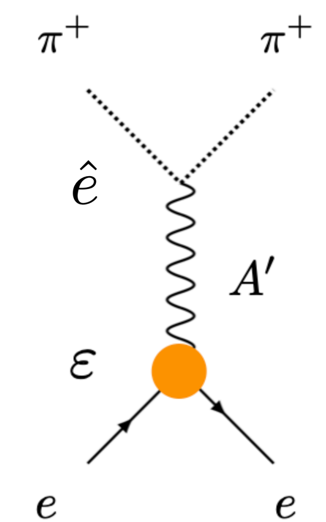
- However, if hidden sector is isolated the DM stays **too warm**

  Too high *T* during structure formation, ruled out



[Carlson, Machacek, Hall 1992]
[de Laix, Scherrer, Schaefer 1995]

- Dark photon mediator



keeps hidden & SM sectors in kinetic equilibrium until freezeout

[Lee, Seo 2015]
[Hochberg, Kuflik, Murayama 2015]

Dark matter self-interactions

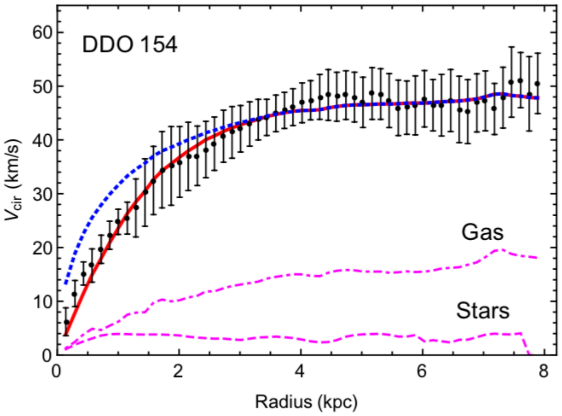
- Mesons undergo $2 \to 2$ scattering in DM halos

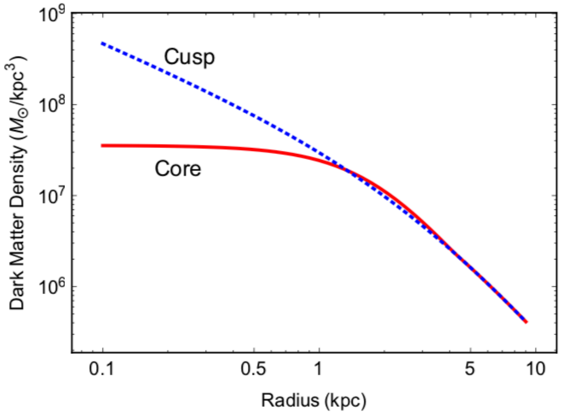
$$\frac{f_\pi^2}{4}\mathrm{Tr}[(D_\mu U)^\dagger D^\mu U] \supset -\frac{r_{abcd}}{24 f_\pi^2}\pi^a\pi^b\partial_\mu\pi^c\partial^\mu\pi^d$$

- Cross section $$\frac{\sigma}{m_\pi} \sim \frac{m_\pi}{16\pi f_\pi^4} \sim (0.1 - 10)\ \frac{\mathrm{cm}^2}{\mathrm{g}}$$

Interesting order of magnitude for small-scale structure "puzzles"

Maybe baryonic effects?





- Bullet cluster and halo shape constraints

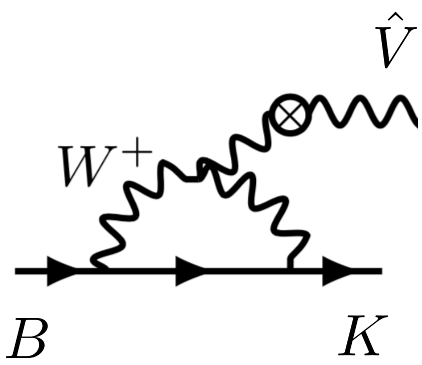
[review by Tulin and Yu, 2017]

$$\frac{\sigma}{m_\pi} \lesssim O(1)\ \frac{\mathrm{cm}^2}{\mathrm{g}}$$

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:



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

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

for $M > 1$ TeV

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

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

Hidden meson decays

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

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

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

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

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

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

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