Dark Operators

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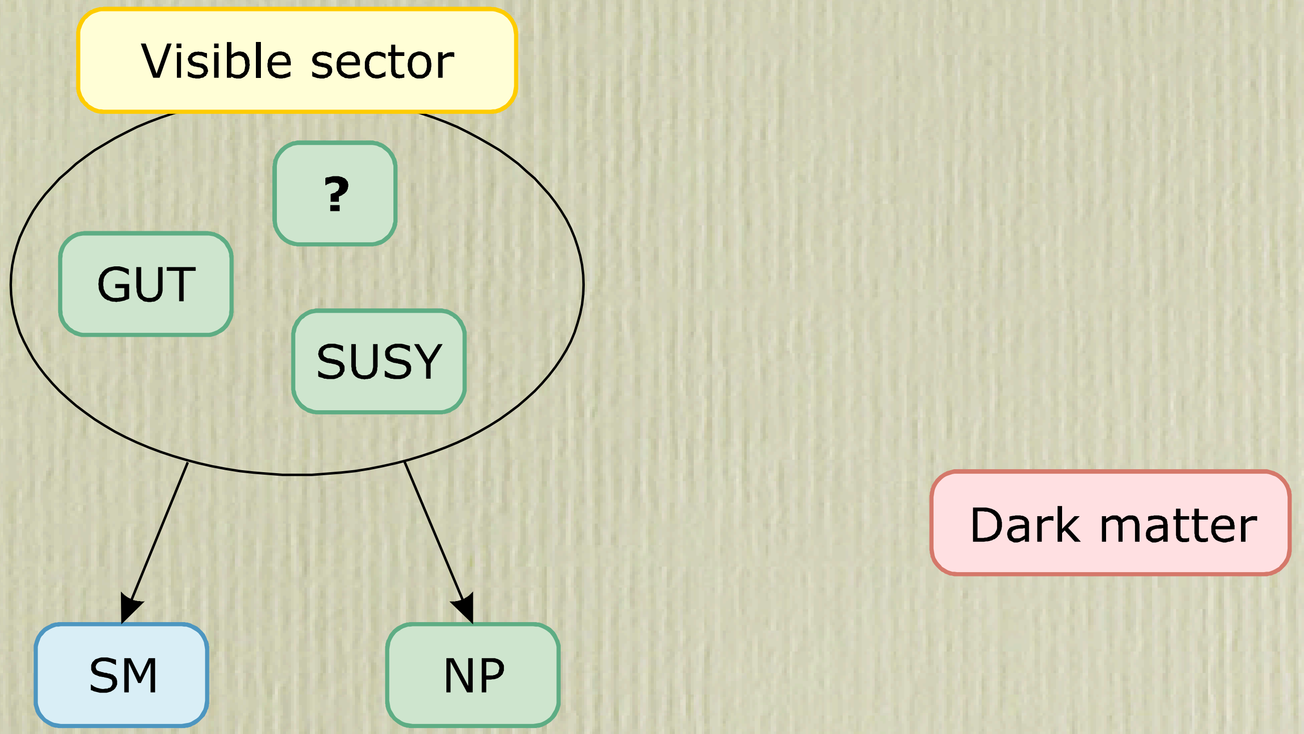
invisibles13
neutrinos, dark matter & dark energy physics

19/07/2013, Lumley Castle

Are there only SM particles at low-energy?

- **Experimentally**:
  - Even very light states could be missed if very weakly interacting,
  - There is dark matter in the Universe; it could be relatively light.
- **Theoretically**: Plenty of models predict new light particles
  - Pseudo-Goldstone scalars (axion, familon,...),
  - U(1) vectors (string, ED,...),
  - Hidden sectors & messengers (SUSY, mirror worlds,...)
  - Many others: millicharged fermions, dilaton, majoron, neutralino, sterile neutrino, gravitino,...

How to probe low-energy particle content?



taken from C. Smith @ LPC - Clermont-Ferrand, 4/2012

- Heavy NP can be projected onto effective gauge-invariant operators built in terms of SM fields.

Buchmuller & Wyler, Nucl.Phys. B268 (1986) 621
Grzadkowski et al., arXiv:1008.4884

$$\mathcal{L}_{SM} + \frac{c_\nu}{\Lambda}(HL)^2 + \frac{c_i}{\Lambda^2}Q_i + \ldots$$

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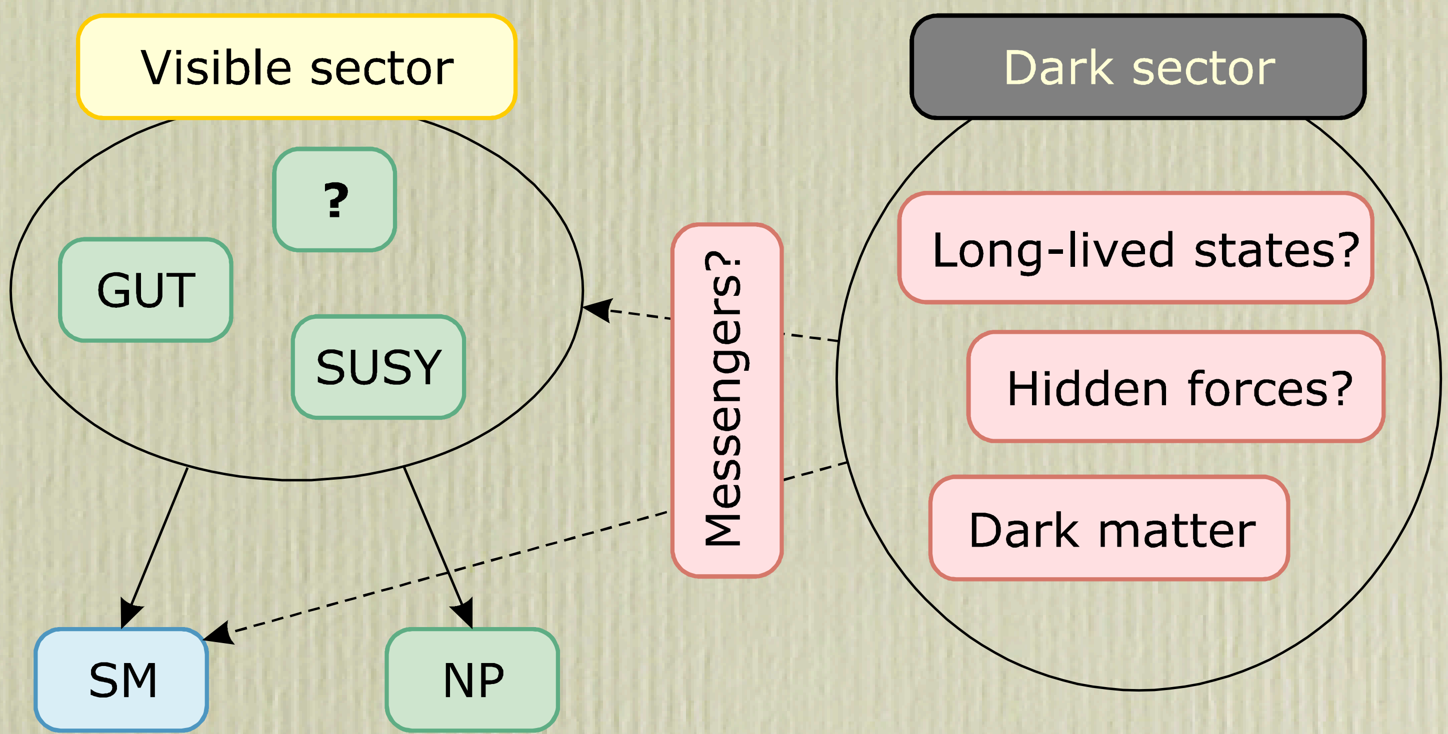

X = dark sector state connected to the SM, or a light messenger.

taken from C. Smith @ LPC - Clermont-Ferrand, 4/2012

- Take X as neutral, but include all possible interactions as SM gauge-invariant effective operators. J. F. K. & C. Smith, 1111.6402

$$\mathcal{L}_{SM} + \frac{c_\nu}{\Lambda}(HL)^2 + \frac{c_i}{\Lambda^2}Q_i + \ldots \quad + \sum_{d\geq 3} \frac{c_i}{\tilde{\Lambda}^{d-4}} Q_i' + \ldots$$

How to probe low-energy particle content?

- Assumptions about the dark state X :
  - Not stable $\Rightarrow$ No DM constraints!
  - Long-lived $\Rightarrow$ Escapes as missing energy.
  - Weakly coupled $\Rightarrow$ Does not affect SM processes.
- $\Rightarrow$ Main impact is then to open new decay channels.

How to probe low-energy particle content?

m_X [GeV]	(decay probes)	(SM width suppression)
100	Higgs boson	loop, helicity, phase-space
10	Quarkonium	Zweig rule
	K & B FCNCs	CKM
1	LFV	neutrino mass
0.1	Light mesons	loop, helicity
0.001	Orthopositronium	phase-space

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Flavor probes of the invisible

J. F. K. & C. Smith, 1111.6402

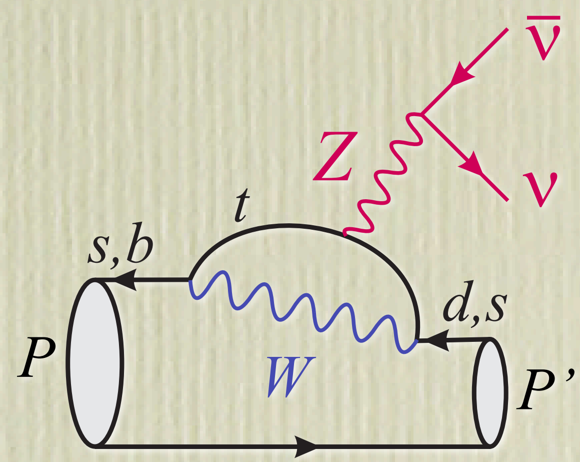
Flavor probes of the invisible

- FCNC meson decays with E_{miss} CKM suppressed in SM

$$d^I \to d^J X \,: \qquad \frac{g^2}{M_W^2}\frac{g^2}{16\pi^2}|V_{tI}^* V_{tJ}|\,,$$

$$\mathcal{B}(K \to \pi E_{miss}) \sim 10^{-11}$$

$$\mathcal{B}(B \to K^{(*)} E_{miss}) \sim 10^{-6}$$

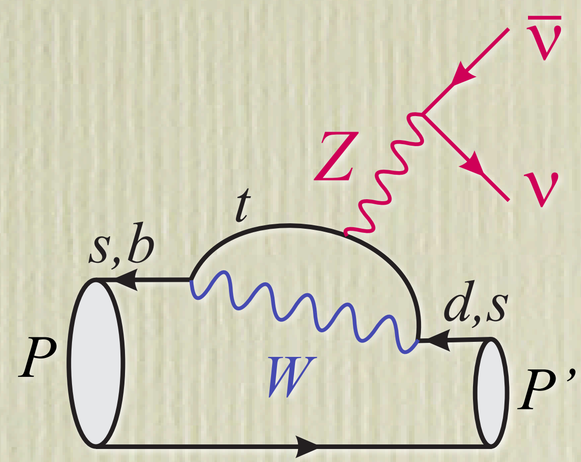


Flavor probes of the invisible

- FCNC meson decays with E_{miss} CKM suppressed in SM

$$d^I \to d^J X \,:\, c^{IJ}\frac{m_I^{n-6}}{\Lambda^{n-4}} \approx \frac{g^2}{M_W^2}\frac{g^2}{16\pi^2}|V_{tI}^* V_{tJ}|\,,$$

(n-dim X-NP ≈ SM)



- Potentially very high X-operator scales probed:

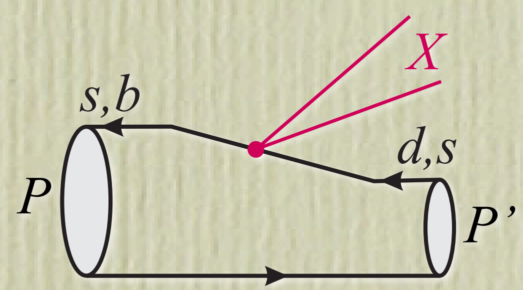
$c^{I\neq J} \sim \mathcal{O}(1)$

	$n=5$	$n=6$	$n=7$
$s \to d$	$3.3 \cdot 10^7$ TeV	130 TeV	2.0 TeV
$b \to d$	$1.3 \cdot 10^5$ TeV	26 TeV	1.5 TeV
$b \to s$	$2.7 \cdot 10^4$ TeV	12 TeV	0.9 TeV

$$\mathcal{H}_{eff}(q^I \to q^J X) = \frac{c^{IJ}}{\Lambda^n}\bar{q}^I q^J \times X$$

Flavor - based classification of dark operators

Flavor-violating ($c^{I\neq J}\neq 0$)



- Bounds directly derived from $d_I \to d_J X$ processes.

- When MFV holds, $c^{IJ} \sim \lambda^{IJ}$ times appropriate chirality flip factors ($m_{I,J}/v$).

$$\lambda^{IJ} = \mathbf{Y}_u^\dagger \mathbf{Y}_u \approx V_{tI}^* V_{tJ} \to \begin{cases} \lambda^{sd} \approx (-3.1 + i1.3) \times 10^{-4} \, , \\ \lambda^{bd} \approx (7.8 - i3.1) \times 10^{-3} \, , \\ \lambda^{bs} \approx (-4.0 - i0.07) \times 10^{-2} \, . \end{cases}$$

Flavor - based classification of dark operators

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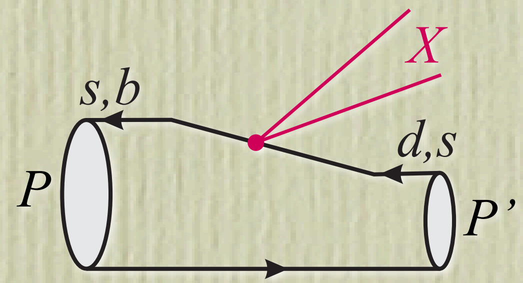
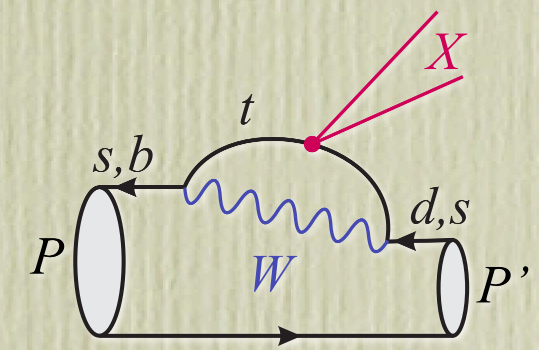


Flavor-conserving ($c^{I\neq J}=0$)

Heavy quark: $q=(c),t$

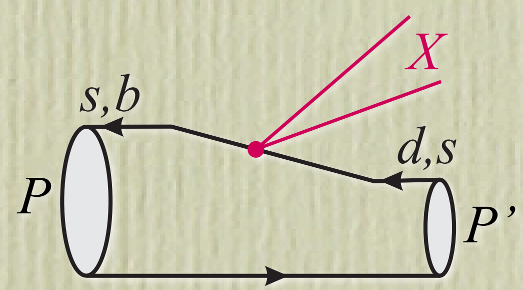


- Same local operator basis, but with the coefficients rescaled as $c^{IJ} \sim c^{tt}\, k^{IJ}$ times appropriate chirality flip factors ($m_{I,J}/v$).

$$k^{IJ}=\frac{g^2}{16\pi^2}\lambda^{IJ}\rightarrow\begin{cases} k^{sd}\approx(-0.8+i0.4)\times 10^{-6}\,, \\ k^{bd}\approx(2.1-i0.8)\times 10^{-5}\,, \\ k^{bs}\approx(-1.1-i0.02)\times 10^{-4}\,. \end{cases}$$

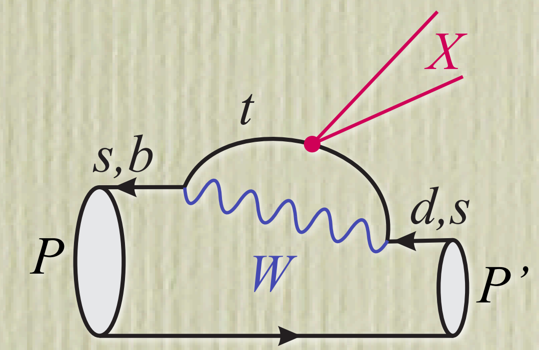
Flavor - based classification of dark operators

Flavor-violating ($c^{I \neq J} \neq 0$)

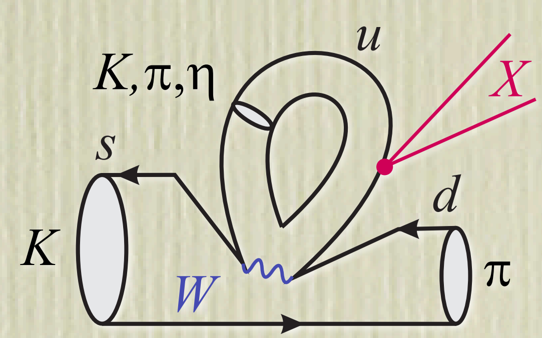


Flavor-conserving ($c^{I \neq J} = 0$)

Heavy quark: $q = (c), t$



Light quarks: $q = u, d, s, (c)$



- Due to small V_{ub}, B decays not competitive.
- For K decays, $q = u$ contributions are dominant but non local, and require controlling long-distance hadronic effects.

Beyond the scaling argument: Kinematics

- Experimentally, rare decays with E_{miss} do not allow for complete kinematical reconstruction.
- Require aggressive background suppressions.
- SM differential rates implicitly assumed in most exp. analyses.

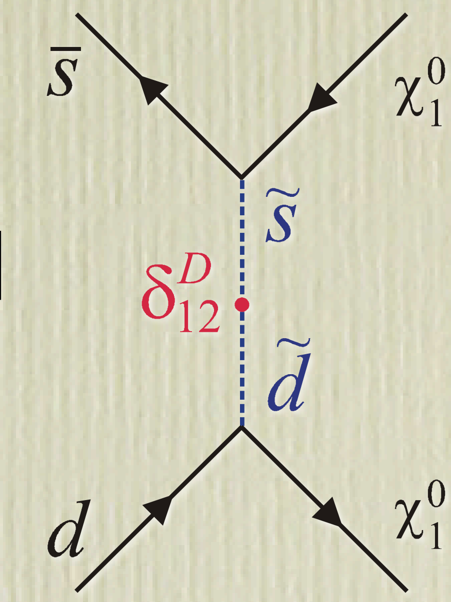
Beyond the scaling argument: Kinematics

Example: Very light neutralinos in $K^+ \to \pi^+ E_{miss}$

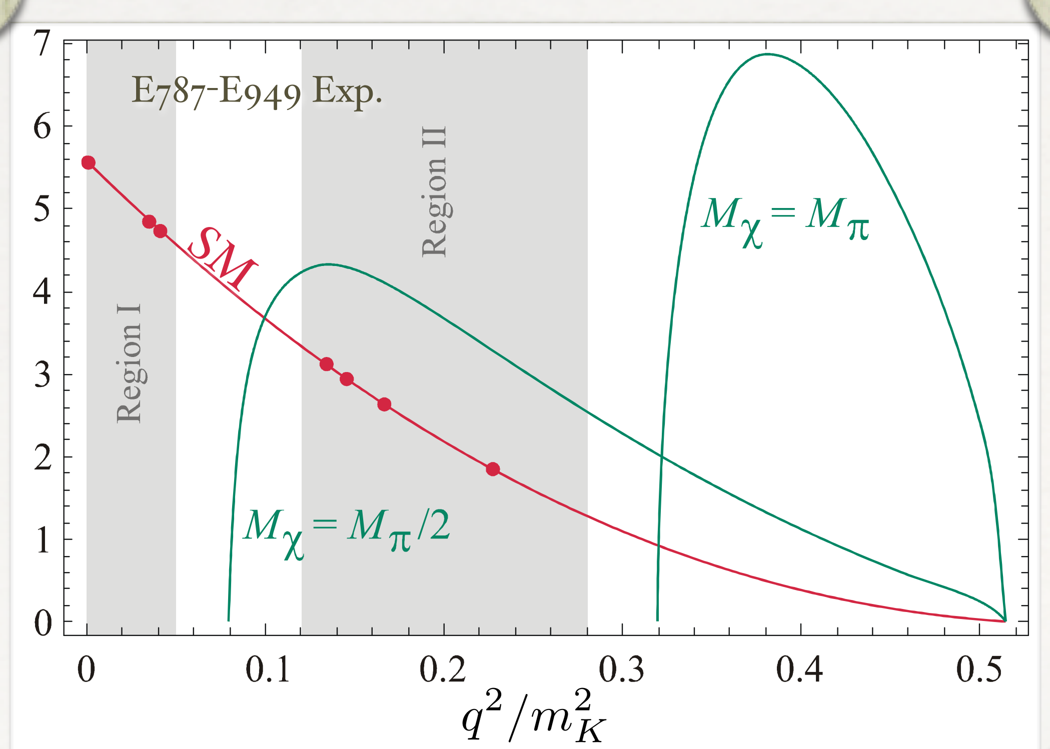
- Effective operators:

$$[\bar{s}\gamma^\mu(1\pm\gamma_5)d][\bar{\chi}\gamma_\mu\gamma_5\chi] \qquad [\bar{s}\gamma^\mu(1\pm\gamma_5)d][\bar{\chi}\gamma_\mu(1\pm\gamma_5)\chi]$$

$$(\delta^{LL,RR}) \qquad (\delta^{LR,RL})$$



flavor violation controlled by squark mixing



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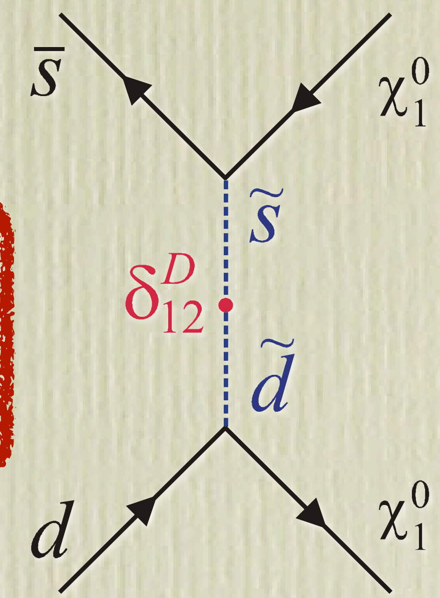

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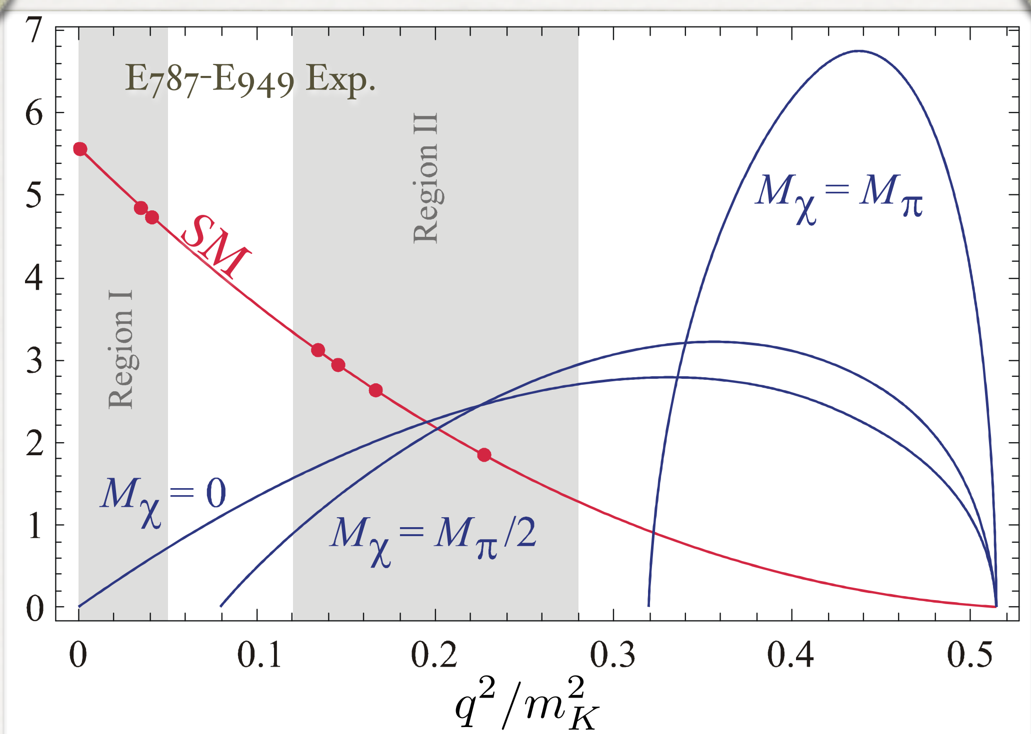


Beyond the scaling argument: Dark gauge invariance

- FCNCs are not conserved in general.
- For spin 1 and 3/2 dark particles $[1/m_X]^2$ terms of polarization (spin) sums not projected out in physical observables.
- Regularization strongly depends on assumed dark sector dynamics (dark gauge invariance breaking).

Beyond the scaling argument: Dark gauge invariance

Example: Weakly coupled dark photon (*A'*)

- $m_{A'}$=0 regular by coupling to conserved current $\mathcal{H}^{\rm int}_{A'} = e' A'_\mu J^\mu_{\rm e.m.}$
- In B sector *t* - loop dominates

$$\mathcal{B}(b \to sA') = |e'/e|^2 \mathcal{B}(b \to s\gamma)^{\rm SM} \qquad \mathcal{B}(b \to s\gamma)^{\rm SM} = (3.15 \pm 0.23) \cdot 10^{-4}$$

Not competitive with flavor blind searches: $|e'/e|^2 < 10^{-3}$

c.f. J. Jaeckel and A. Ringwald, Ann. Rev. Nucl. Part. Sci. 60 (2010) 405

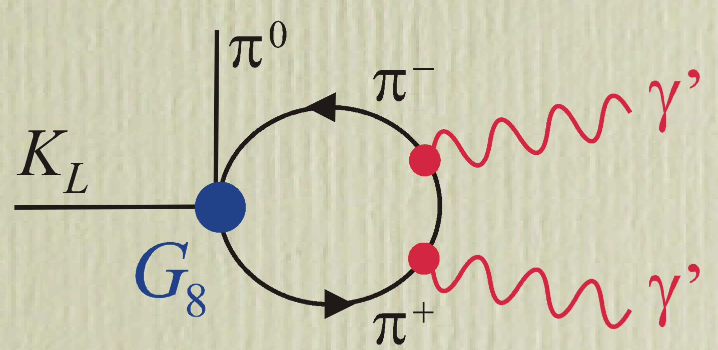
Beyond the scaling argument: Dark gauge invariance

Example: Weakly coupled dark photon (*A'*)

- $m_{A'}$=0 regular by coupling to conserved current $\mathcal{H}^{\rm int}_{A'} = e' A'_\mu J^\mu_{\rm e.m.}$
- In K decays naive estimate

$$|e'/e|^2 \lesssim \frac{\mathcal{B}(K\to n\pi + m\gamma + V)_{\rm exp}}{\mathcal{B}(K\to n\pi + (m+1)\gamma)_{\rm SM}} \sim \frac{10^{-12}}{\mathcal{B}(K\to n\pi + (m+1)\gamma)_{\rm SM}}$$

- LD dynamics strongly suppresses the rate below 2π



Beyond the scaling argument: Dark gauge invariance

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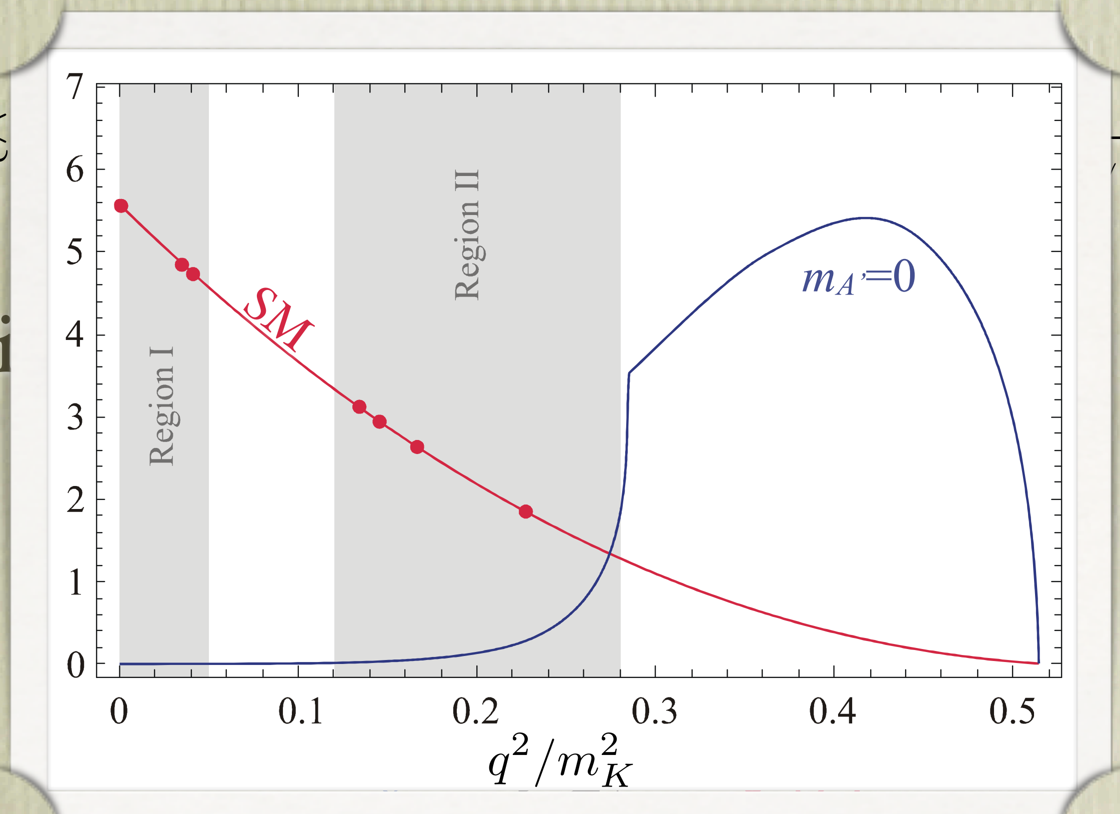
- In K decays naive estimate

$|e'/e|^2 \lesssim$

- LD dynami below 2π



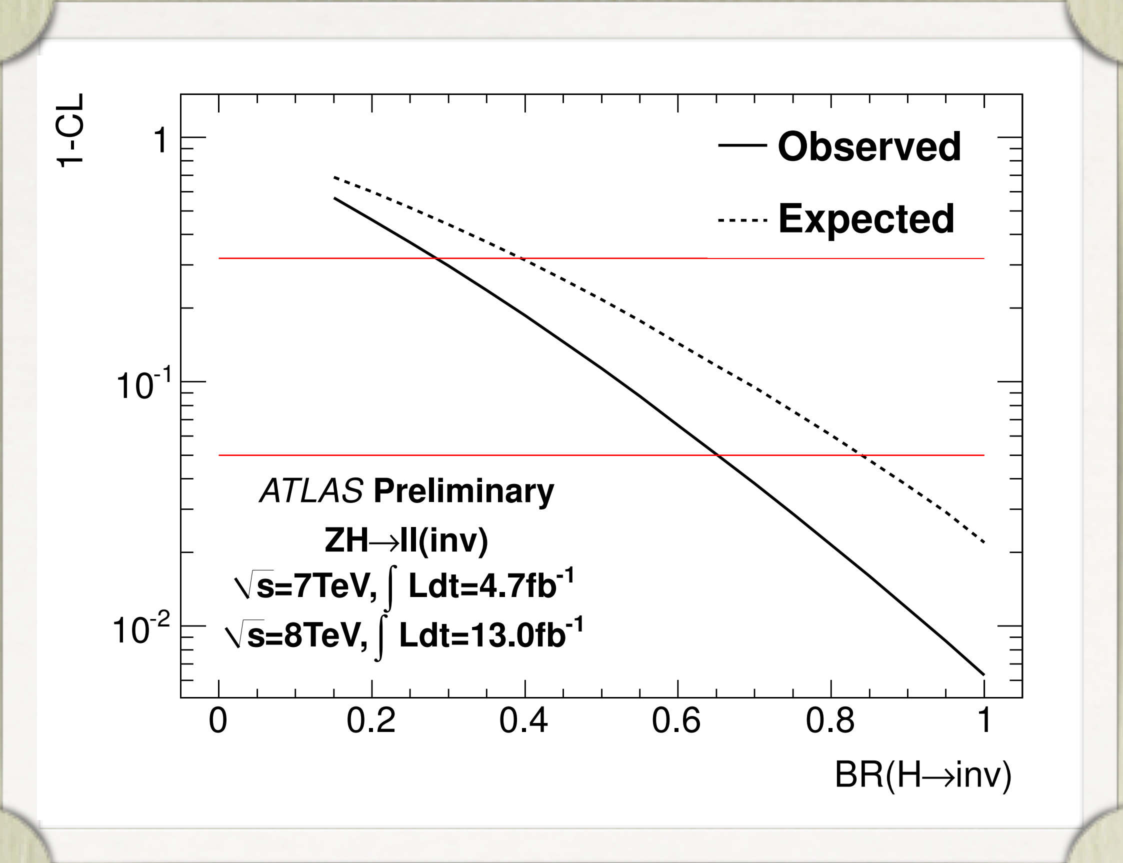
What a light Higgs could tell?

J. F. K. & C. Smith, 1201.4814

What a light Higgs could tell?

- In SM BR(h→inv) ~ 0.1%
- Testing invisible Higgs decays is notoriously difficult
- Assuming SM ZH production rate: BR(h→inv) < 0.65

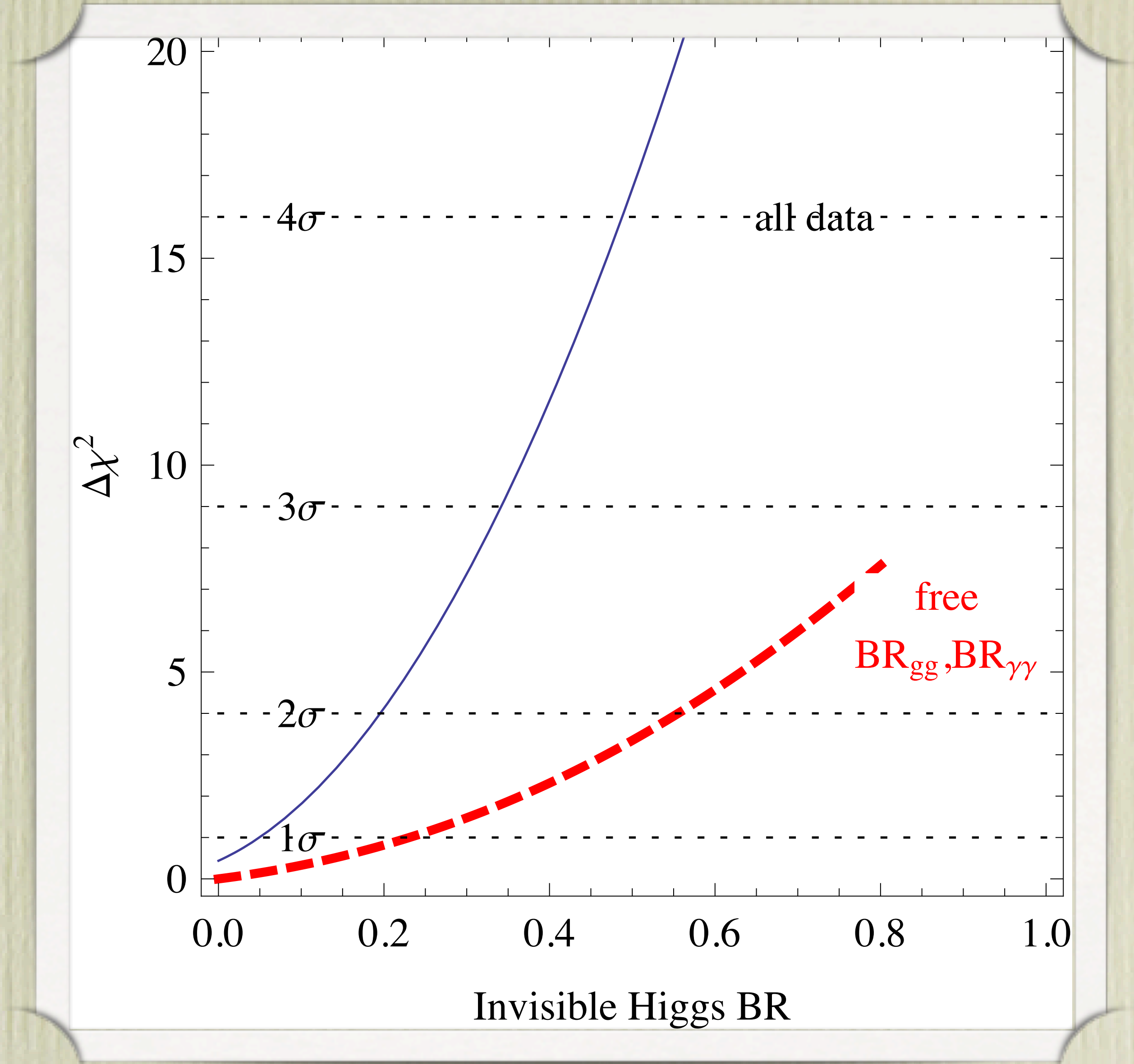
ATLAS-CONF-2013-011



What a light Higgs could tell?

- Total width of SM Higgs unmeasurable at LHC ($\Gamma(h)_{SM} \sim 4 \times 10^{-3}$ GeV)
- Under assumptions of narrow width, absolute $\Gamma(h \to gg)$ can be extracted
- Indirect constraint on BR($h \to inv$) < 0.2 - 0.6

Giardino, Kannike, Raidal, Strumia arXiv:1207.1347



What a light Higgs could tell?

- A light Higgs is very narrow in the SM:

$$\frac{\Gamma_h^{SM}}{M_h} \approx 3 \times 10^{-5} \quad \text{(comparable to } \Gamma_{J/\psi}/M_{J/\psi}\text{)}$$

What a light Higgs could tell?

- A light Higgs is very narrow in the SM:

$$\frac{1}{5} \times \frac{\Gamma_h^{SM}}{M_h} \gtrsim \frac{\Gamma_h^{dark}}{M_h} \sim \frac{1}{8\pi} \left(\frac{M_h^2}{\Lambda_d^2}\right)^{d-4} \quad \Rightarrow \Lambda_5 \gtrsim 10 \text{ TeV} \ , \ \Lambda_6 \gtrsim 1.1 \text{ TeV}$$

possible to probe relatively high NP scales

What a light Higgs could tell?

- A light Higgs is very narrow in the SM
- Lorentz scalar - can couple to most operator structures

$$H^\dagger H \to \frac{1}{2}(v^2 + 2vh + h^2)$$

$$H^\dagger \overleftrightarrow{D}^\mu H \to \frac{ig}{2c_W}(v+h)^2 Z^\mu \qquad \text{when} \quad H \to \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

$$HL \to \frac{1}{\sqrt{2}}(v+h)\nu_\ell$$

What a light Higgs could tell?

- A light Higgs is very narrow in the SM
- Lorentz scalar - can couple to most operator structures
- Most promising channels?
  - Invisible: $h \to \not{E}$
  - Gauge : $h \to \not{E} + (\gamma, Z)$
  - Fermionic: $h \to \not{E} + \text{(fermions)}$

Examples: Spin 0 and 1/2

- Simplest operators are constructed using $H^\dagger H$:

$$\mathcal{H}_{eff}^{0} = \lambda' H^\dagger H \times \phi^\dagger \phi \qquad \mathcal{H}_{eff}^{1/2} = \frac{1}{\tilde{\Lambda}} H^\dagger H \times \bar{\psi}(1, \gamma_5)\psi$$

(Higgs portals)

- Induce both mass correction and invisible decay: $H^\dagger H \rightarrow \frac{1}{2}(v^2 + 2vh + h^2)$

$$\delta m \qquad \Gamma(h \rightarrow \not{E})$$

- Without fine-tuning dark and electroweak mass terms: $m_\phi^2 \approx \bar{m}_\phi^2 + \delta m_\phi^2 \gtrsim |\delta m_\phi^2|$

$$m_\psi \approx \bar{m}_\psi + \delta m_\psi \gtrsim |\delta m_\psi|$$

Examples: Spin 0 and 1/2

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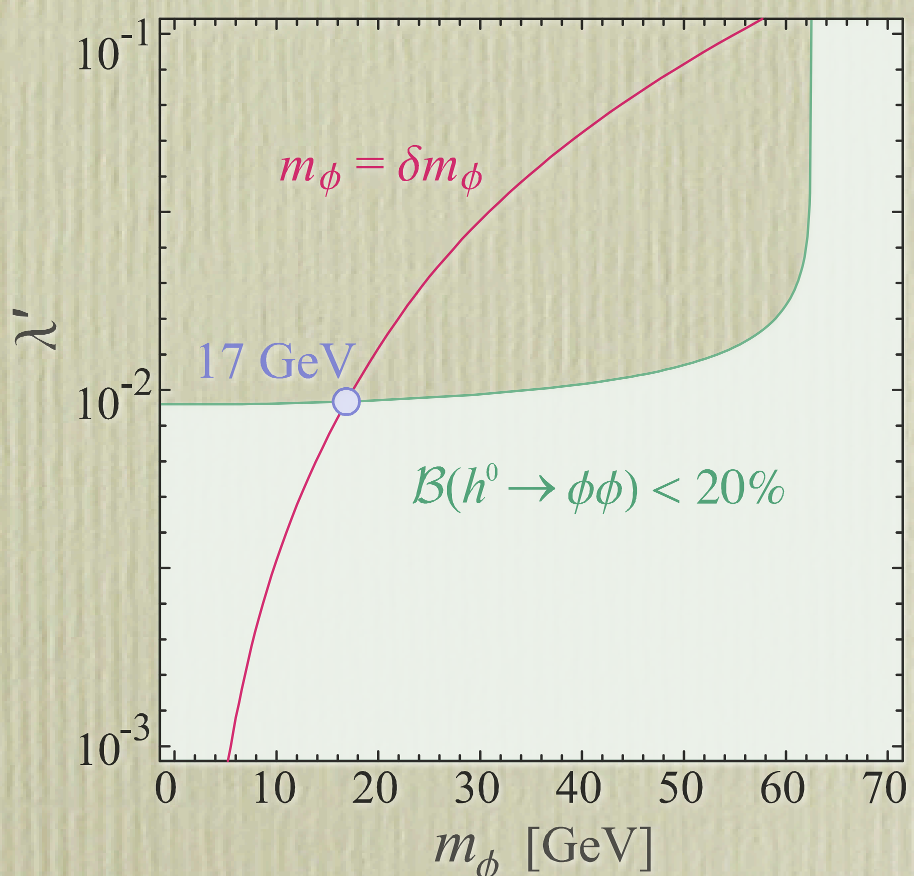
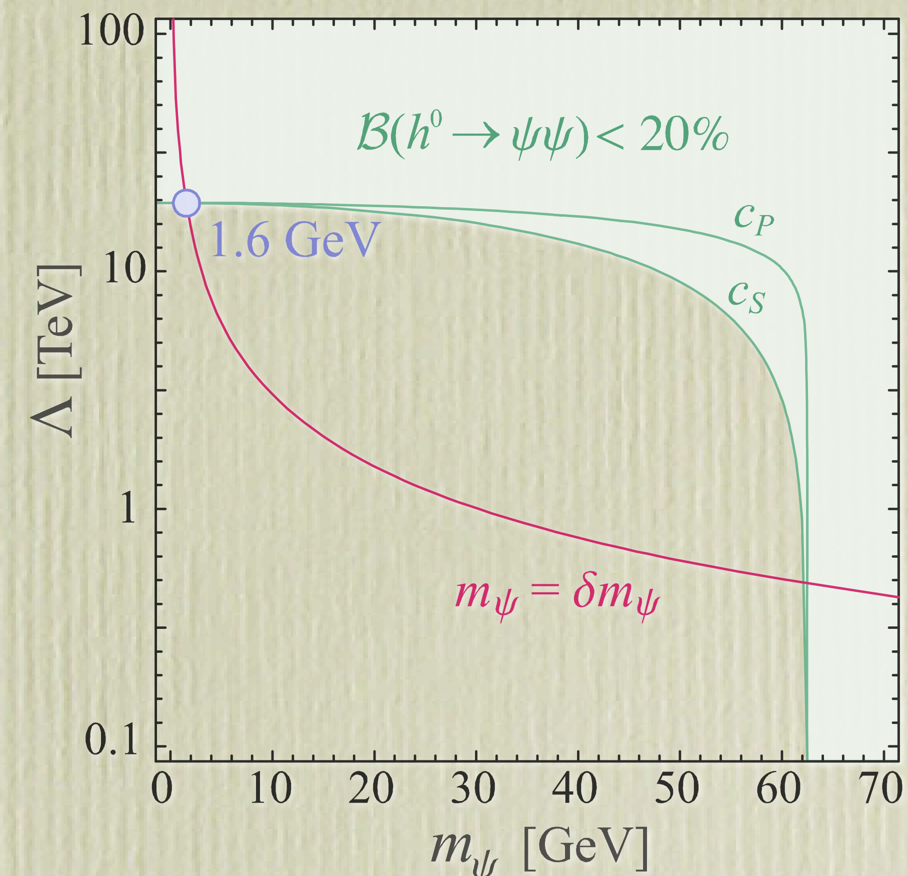




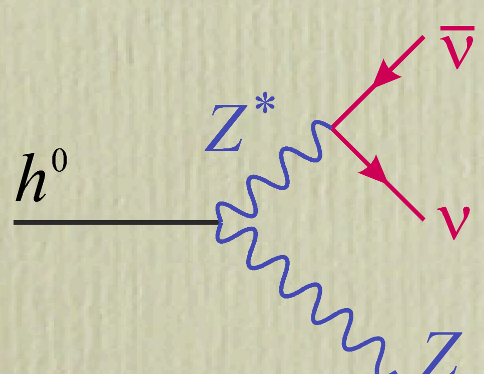
If initially massless (or very light), these dark states must remain light.

Examples: Spin 0 and 1/2

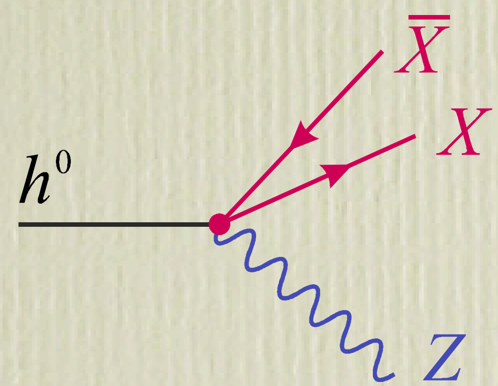
- Other operators & decay channels?
  - Current operators:

$$\frac{1}{\tilde{\Lambda}^2} H^\dagger \overleftrightarrow{\mathcal{D}}^\mu H \times (\phi^\dagger \overleftrightarrow{\partial}_\mu \phi \, , \bar{\psi}\gamma_\mu\psi)$$

Subleading compared to SM at tree-level (same for fermionic operators).



$$\sim \frac{1}{M_Z^2} > \frac{1}{\tilde{\Lambda}^2} \sim$$



Examples: Spin 0 and 1/2

- Other operators & decay channels?
  - Current operators
  - Neutrino portal operators (violating lepton number):

$H\overline{L}^C \times \psi$ - induces neutrino mass

$\frac{1}{\tilde{\Lambda}^2} B_{\mu\nu} H\overline{L}^C \sigma^{\mu\nu} \times \psi$ - may be accessible for γ

$\mathcal{B}(h \to \gamma \nu \psi) \approx 2\%$ for $\tilde{\Lambda} \approx 0.5 TeV$

$\frac{1}{\tilde{\Lambda}^3} H\overline{L}^C LH \times \phi^\dagger \phi$ - dim=7 and 4-body

...

Examples: Spin 3/2

- **Massive spin 3/2 dark states?**

Need to specify dark gauge invariance breaking

- **Hard breaking:** no simple way to regulate the divergences
- **Soft or no breaking:** all effects from gauge-invariant higher dimensional operators

$$\mathcal{H}_{eff}^{3/2} = \frac{1}{\tilde{\Lambda}^3} H^\dagger H \times \bar{\Psi}^{\mu\nu}\Psi_{\mu\nu} + \frac{1}{\tilde{\Lambda}^2} \mathcal{D}_\mu H \bar{L}^C \gamma_\nu \times \Psi^{\mu\nu}$$

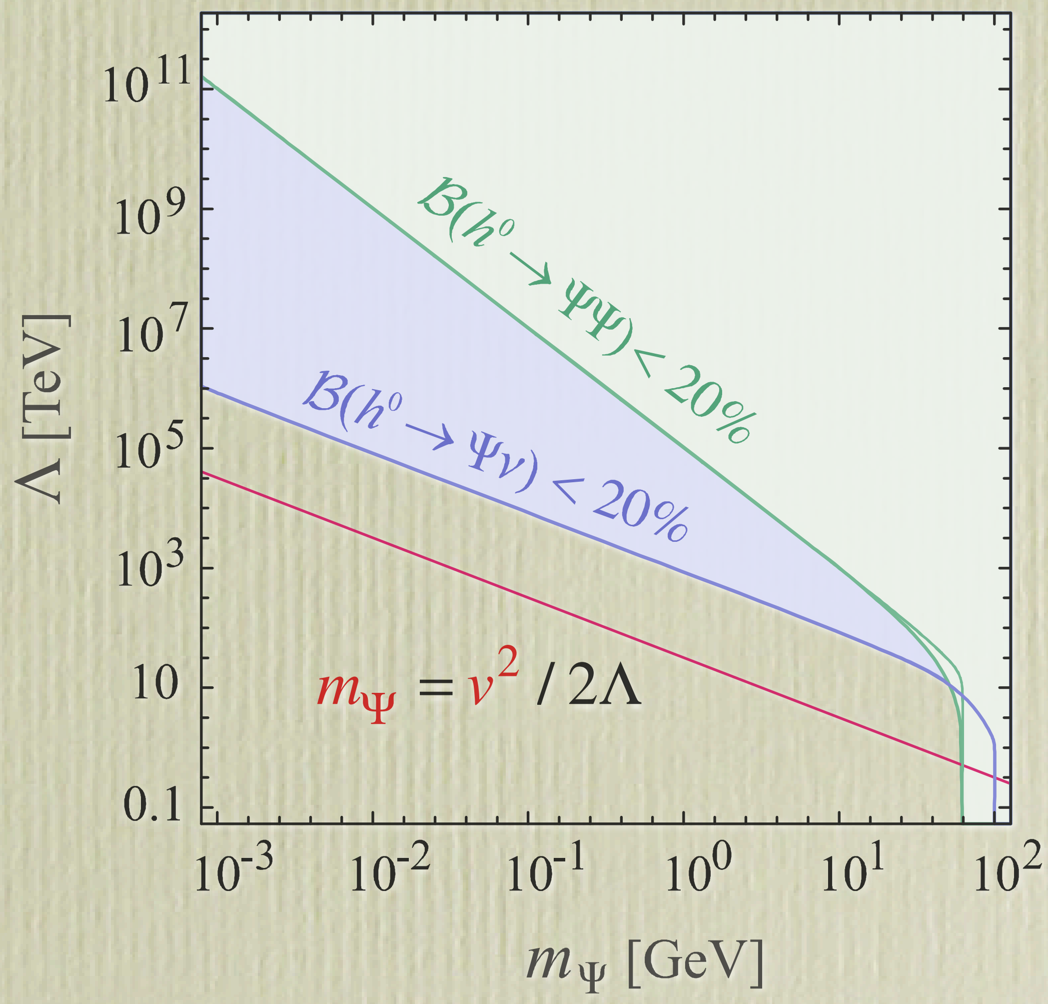
$$(\Psi_{\mu\nu} = \partial_\mu \Psi_\nu - \partial_\nu \Psi_\mu)$$

Requiring $\Gamma(h \to \Psi\Psi, \Psi\nu) < 20\% \times \Gamma_h^{SM}$ imposes $\Lambda \gtrsim 0.7\ TeV$.

Higgs width is our best window for such kind of operators.

Examples: Spin 3/2

- **Massive spin 3/2 dark states?**



When dark gauge invariance is broken, rates are huge!

Conclusions

If light and long-lived “dark” particles exists:

- FCNCs can impose competitive bounds on their interactions with SM

$$K \to n\pi + m\gamma + \not{E}\,, \;\; B \to (0, \pi, \rho, K^{(*)}) + \not{E}$$

(also LFV, rare charm decays, (mono)tops)

- Small width of Higgs offers unique window also well beyond the portals.

$$h \to \not{E}\,,\; h \to \not{E} + (\gamma, Z)\,,\; h \to \not{E} + (fermions)$$

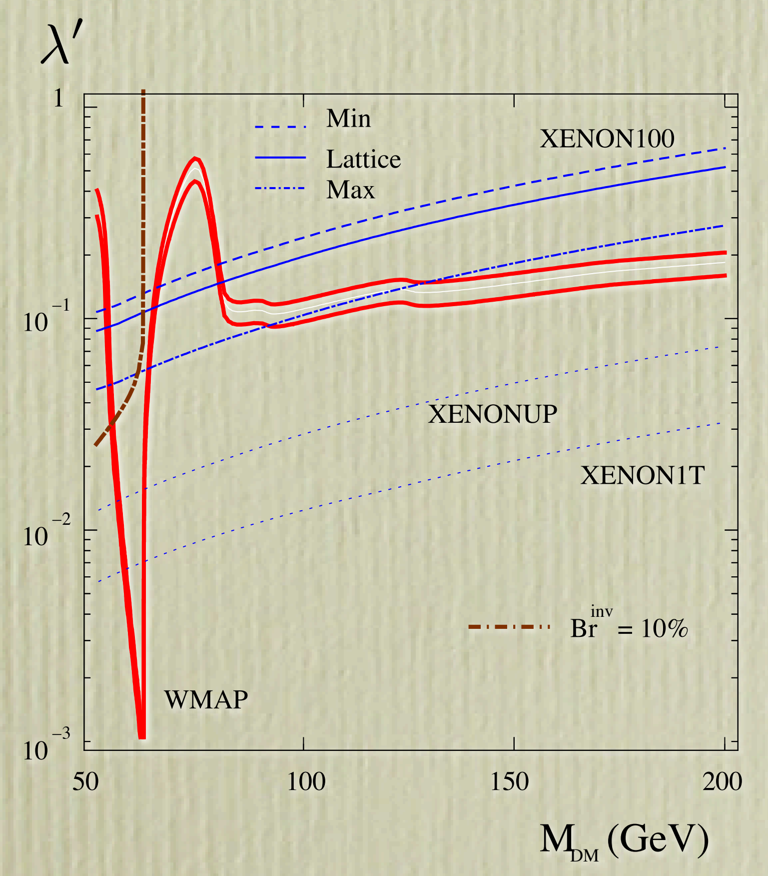
Addendum

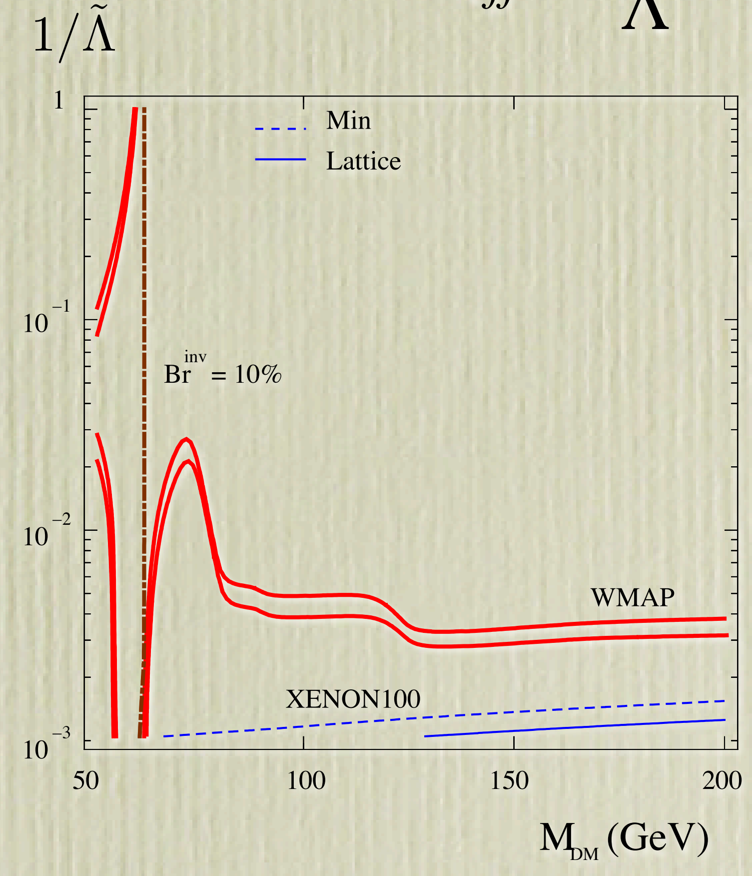
Could such states form thermal relic dark matter?

- Example: Higgs portal DM

$$\mathcal{H}^{0}_{eff} = \lambda' H^\dagger H \times \phi^\dagger \phi$$

$$\mathcal{H}^{1/2}_{eff} = \frac{1}{\tilde{\Lambda}} H^\dagger H \times \bar{\psi}(1, \gamma_5)\psi$$





Djouadi et al., 1112.3299

Excluded or will be probed by next gen. experiments

Addendum

Could such states form thermal relic dark matter?

- What about beyond Higgs portal?

Greljo, Julio, J.F.K., Smith & Zupan, in preparation

- Naive scaling of thermal x-section & constraints:

$$\langle \sigma v \rangle \propto \left(\frac{m_{DM}}{\Lambda} \right)^{2n}$$ (controls relic abundance)

$$\mathcal{B}(h \to \text{invisible}) \sim 10^3 \left(\frac{m_h}{\Lambda} \right)^{2n}$$

$$\frac{\langle \sigma \rangle}{\langle \sigma \rangle_{\text{excl.}}} \sim 10^2 \left(\frac{m_{DM} \beta}{\Lambda} \right)^{2n}$$ (XENON100 bound)

Higgs constraint increases with n (for $m_{DM} < m_h/2$), direct detection sensitivity may decrease!

Addendum

Greljo, Julio, J.F.K., Smith & Zupan, in preparation

- For light DM, circumvent Higgs bound by multi-body decay modes

1. couple to Higgs (& fermionic) currents:

$$H^\dagger \overleftrightarrow{D}^\mu H \equiv H^\dagger \overleftarrow{D}^\mu H - H^\dagger \overrightarrow{D}^\mu H \to \frac{ig}{2c_W}(v_{\rm EW}^2 + 2v_{\rm EW}h + h^2)Z^\mu$$

$$\Gamma^S = H^\dagger \bar{D} Q, \;\; H^\dagger \bar{E} L, \;\; H^{*\dagger} \bar{U} Q, \quad \Gamma^T_{\mu\nu} = H^\dagger \bar{D}\sigma_{\mu\nu} Q, \;\; H^\dagger \bar{E}\sigma_{\mu\nu} L, \;\; H^{*\dagger}\bar{U}\sigma_{\mu\nu} Q$$

Mostly excluded by (in)direct detection experiments

Addendum

Greljo, Julio, J.F.K., Smith & Zupan, in preparation

- For light DM, circumvent Higgs bound by multi-body decay modes

2. LNV (neutrino) portal:

$$\mathcal{L}_{\rm eff}^{d=8} = \frac{(i\bar{\psi}\gamma_5\psi)(L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl})}{\Lambda^4}$$

  - Does not contribute to neutrino mass
  - Requires low EFT cut-off Λ~1TeV
  - Explicit renormalizable UV model can be constructed

Addendum

Greljo, Julio, J.F.K., Smith & Zupan, in preparation

- For light DM, circumvent Higgs bound by extending low energy particle content

  Simplest examples with extended Higgs sectors:

  - THDM + DM

    He et al., 0811.0658
    Bai et al., 1212.5604
    ...

  - SM + scalar SM singlet + DM

    Barger et al., 0811.0393
    Arina et al., 1004.3953
    Piazza & Pospelov, 1003.2313
    ...

  (effectively decouple DM interactions generating correct relic abundance from 125GeV Higgs)

Backup

Examples: Spin 1 and 3/2

- Leading operators break a dark gauge invariance:

$$\mathcal{H}^{1}_{eff} = \varepsilon_H H^\dagger H \times V_\mu V^\mu + i\varepsilon'_H H^\dagger \overleftrightarrow{\mathcal{D}}^\mu H \times V_\mu$$

$$\mathcal{H}^{3/2}_{eff} = \frac{c_\Psi}{\tilde{\Lambda}} H^\dagger H \times \overline{\Psi}^\mu (1, \gamma_5) \Psi_\mu + \frac{c'_\Psi}{\tilde{\Lambda}} \mathcal{D}_\mu H \overline{L}^C \times \Psi^\mu$$

- Consequently, decay rates are singular in the massless limit

$$\sum_{pol} \varepsilon_k^\mu \varepsilon_k^\nu = -P_V^{\mu\nu}$$

$$P_X^{\mu\nu} = g^{\mu\nu} - \frac{k^\mu k^\nu}{m_X^2}$$

$$\sum_{spin} u_k^\mu \overline{u}_k^\nu = -(\not{k} + m_\Psi)\left(P_\Psi^{\mu\nu} - \tfrac{1}{3} P_\Psi^{\mu\rho} P_\Psi^{\nu\sigma} \gamma_\rho \gamma_\sigma\right)$$

Need to specify dark gauge invariance breaking

Examples: Spin 1 and 3/2

- **Hard breaking:** (dark SSB or Stückelberg)

For instance, in the SM:

$$\Gamma(h \to WW) \sim g^4 v^2 P_W^{\mu\nu} P_{W,\mu\nu} \xrightarrow{M_W \to 0} \frac{g^4 v^2}{M_W^4} + \ldots \xrightarrow{M_W \sim gv} \frac{1}{v^2} + \ldots$$

Thus impose: $m_V \sim \varepsilon_H v_{dark}$

Examples: Spin 1 and 3/2

- **Hard breaking:** (dark SSB or Stückelberg)

  The $H^\dagger H$ operator automatically regulates its massless limit: $\varepsilon_H H^\dagger H \times V_\mu V^\mu$

$$\delta m_V^2 = \varepsilon_H v^2 \qquad \Gamma(h \to VV) \sim \varepsilon_H^2 \frac{v^2 M_h^3}{m_V^4}$$

$$m_V^2 \approx \delta m_V^2: \ \Gamma(h \to VV) \gtrsim 80 \times \Gamma_h^{SM} \quad (\text{for } M_h \approx 125\ GeV)$$

  - Dark decay must be forbidden: $\delta m_V > M_h / 2$
  - A large dark mass must soften the singularity

$$m_V^2 = \bar{m}_V^2 + \delta m_V^2 = \varepsilon_H (v_{dark}^2 + v^2) \text{ with } v_{dark} > 1.1\ TeV$$

Examples: Spin 1 and 3/2

- **Hard breaking:** (dark SSB or Stückelberg)

  The $H^{\dagger}D^{\mu}H$ operator fails at regulating its massless limit: $\varepsilon'_H H^{\dagger}\overleftrightarrow{D}^{\mu}H \times V_{\mu}$

$$\delta m_V^2 = -\varepsilon_H'^2 v^2 < 0!$$

$$\Gamma(h \to ZV) \sim g^2 \varepsilon_H'^2 \frac{v^2 M_h^3}{M_Z^2 m_V^2}$$

$$m_V^2 \approx -\delta m_V^2 : \ \Gamma(h \to ZV) \gtrsim 15 \times \Gamma_h^{SM} \Rightarrow m_V > M_h - M_Z$$

(for $M_h \approx 125\ GeV$)

Z-V mixing: $\delta\rho \Rightarrow m_V < 2.4\ GeV$

EW mass window completely closed

Examples: Spin 1 and 3/2

- **No breaking:** (kinematic mixing or dark charge for the Higgs)

$$\mathcal{L}_{kin} = \frac{\chi}{2} B_{\mu\nu} \times V^{\mu\nu}$$ need to redefine V-B

Examples: Spin 1 and 3/2

- **No breaking:** (kinematic mixing or dark charge for the Higgs)

$$\mathcal{L}_{kin} = \mathcal{D}_\mu H^\dagger \mathcal{D}^\mu H - i\frac{\lambda}{2} H^\dagger \overleftrightarrow{\mathcal{D}}^\mu H \times V_\mu + \frac{\lambda^2}{4} H^\dagger H \times V_\mu V^\mu$$

After diagonalizing the mass:
The dark vector is massless and entirely decoupled!

Holdom, Phys.Lett. B166 (1986) 196

Dominant effects then come from higher - dimensional operators:

Typically, $\Gamma(h \to VV, ZV, \gamma V, f\bar{f}V) < 20\% \times \Gamma_h^{SM}$ requires $\tilde{\Lambda} \gtrsim 1 TeV$.

Examples: Spin 1 and 3/2

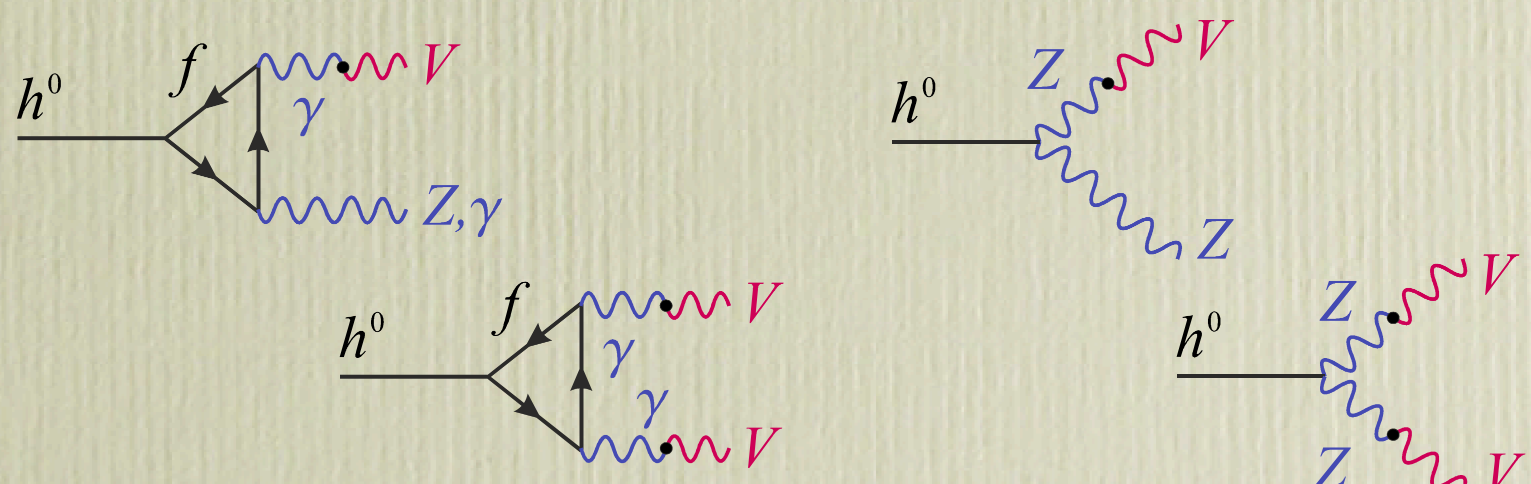
- **Soft breaking:** $\mathcal{L}_{kin} = \frac{\chi}{2} B_{\mu\nu} \times V^{\mu\nu} + \frac{\bar{m}_V^2}{2} V_\mu V^\mu$

  vector mass changes the diagonalization, and upsets its elimination

  Holdom, Phys.Lett. B166 (1986) 196

$$B_{\mu\nu} \times V^{\mu\nu} \to c_W J_\mu^{em} \times V^\mu - s_W m_V^2 Z_\mu \times V^\mu$$

dark field has some couplings to fermions & Higgs



All are very suppressed (δρ,...)