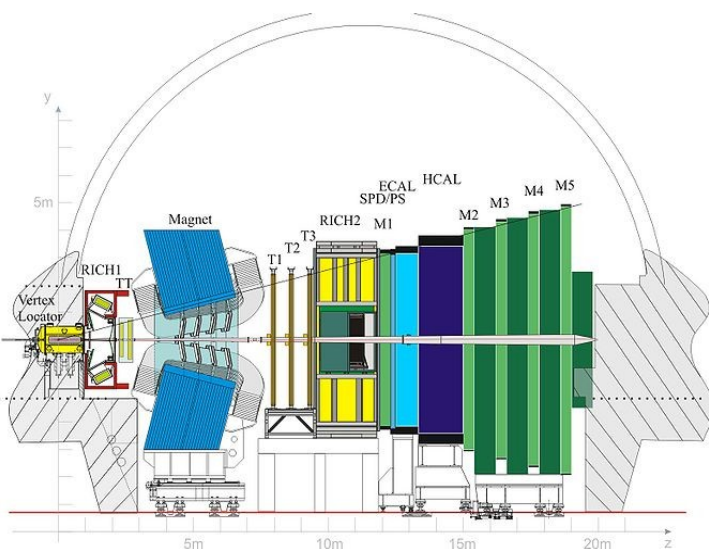
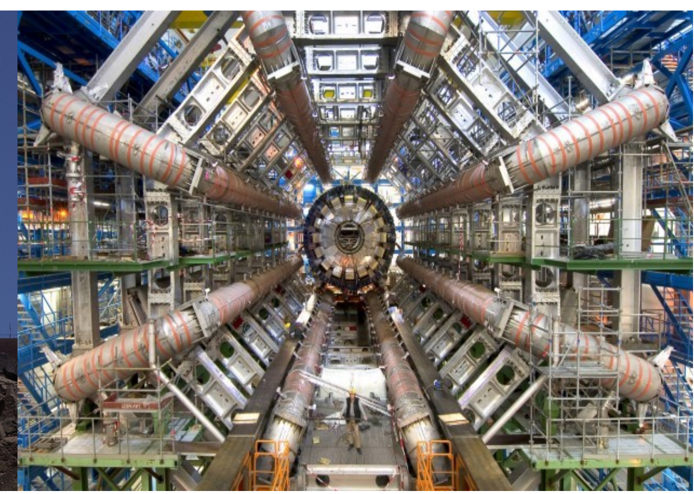
Hidden Valley Search Meets Cosmological Constraint

Lingfeng Li (Hong Kong U. of Sci. and Tech.)
and Yuhsin Tsai (U. of Maryland)

arXiv: 1812.XXXXX or 1901.XXXXX?

**Dec. 2018, NCTS Annual Theory Meeting:
Particles, Cosmology and Strings**





What’s in the dark?

Standard Model

U(1)

$SU(2)_L$

$SU(3)_c$

leptons

quarks

Higgs

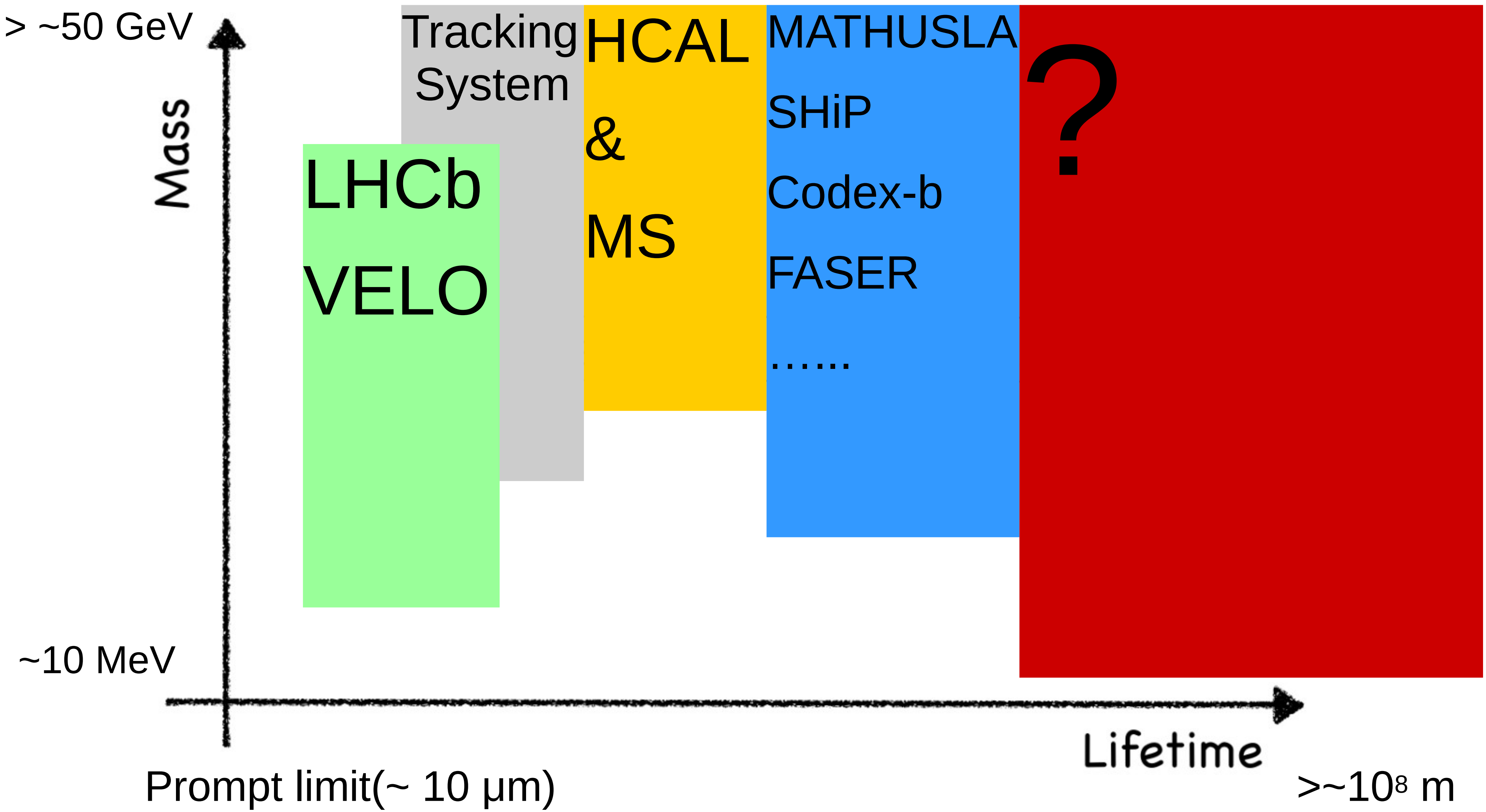
Hidden Sector

Hidden Force

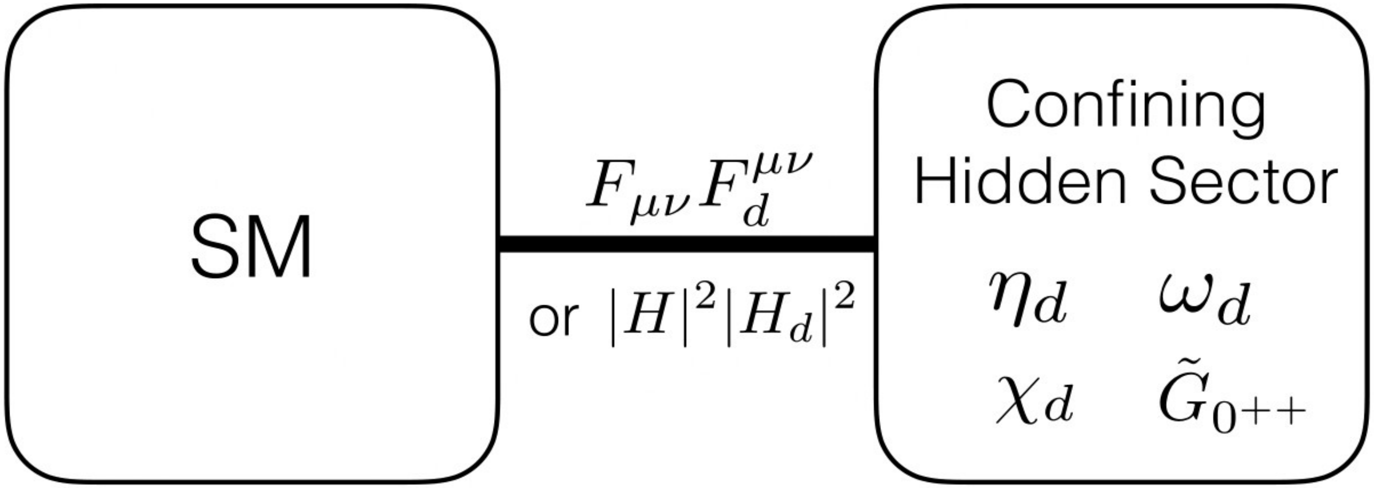
dark photon?

dark QCD?

Hidden Valley models are good, but..



Basic Idea



- Cosmology **can** tell us where and how to look for dark hadrons at a collider.
- We consider the heavy mediator case (mediator mass >~ dark hadron masses)

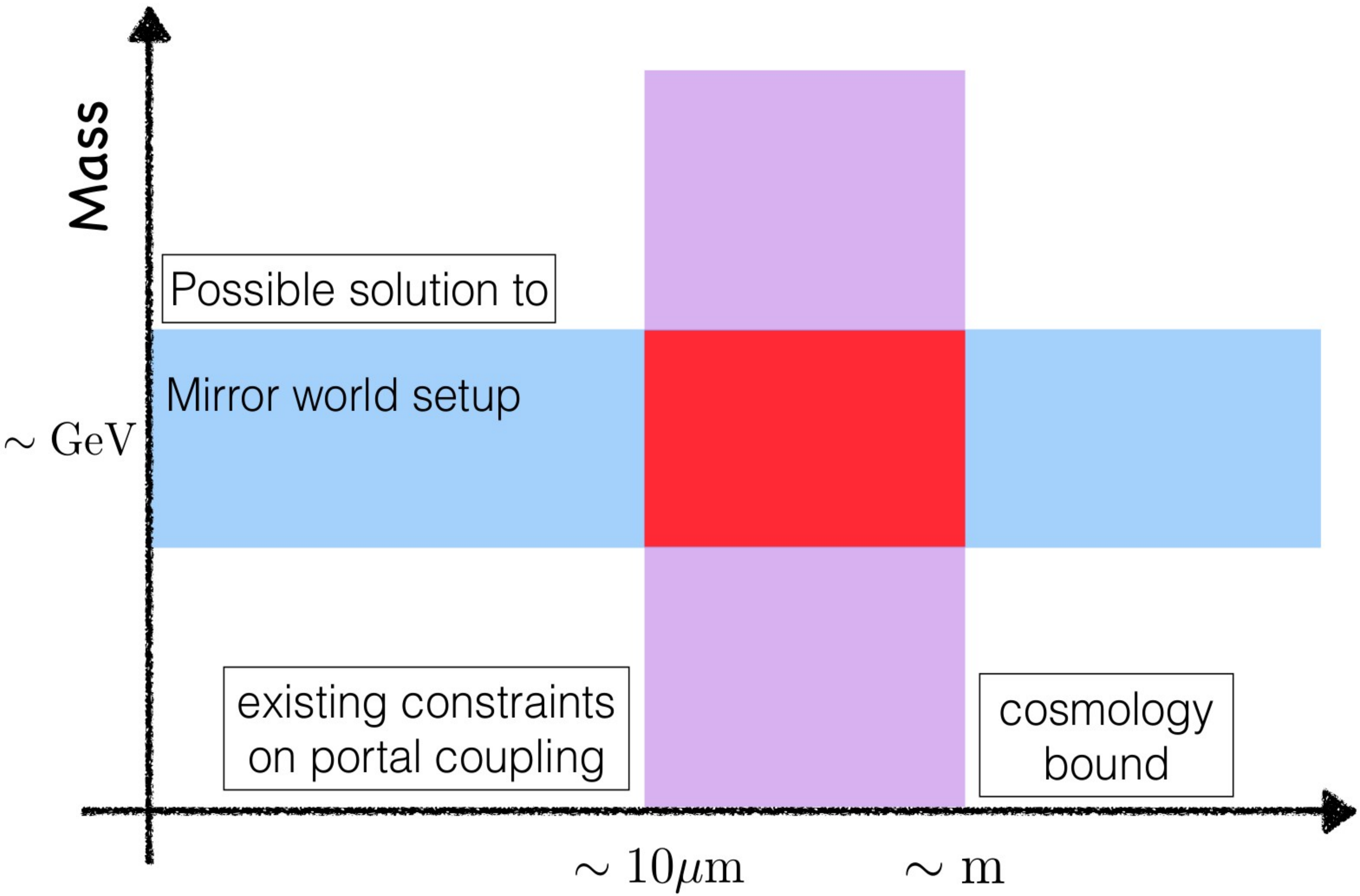
η_d: The pseudoscalar meson (Lightest dark hadron)

χ_d: The scalar meson

ω_d: The vector meson

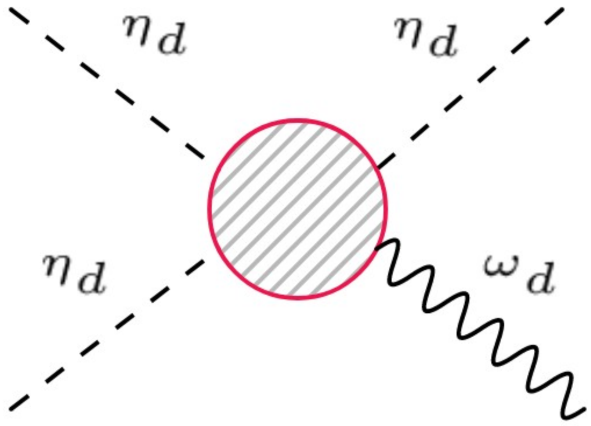
G_{0++}: The dark glueball

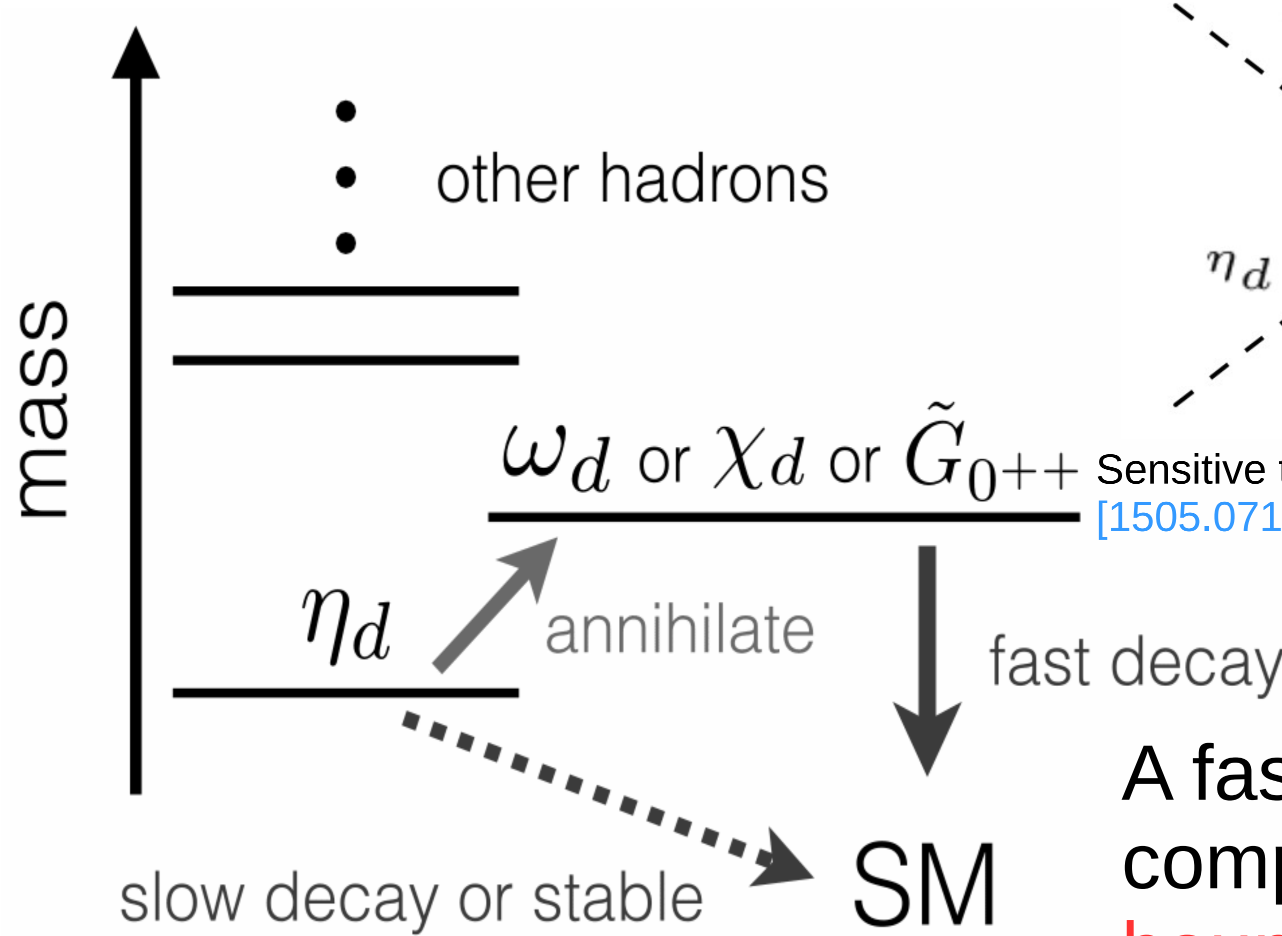
Thanks to Cosmological Constraints



Related discussions in [1512.02647 & 1809.10152]

Inelastic transition process:



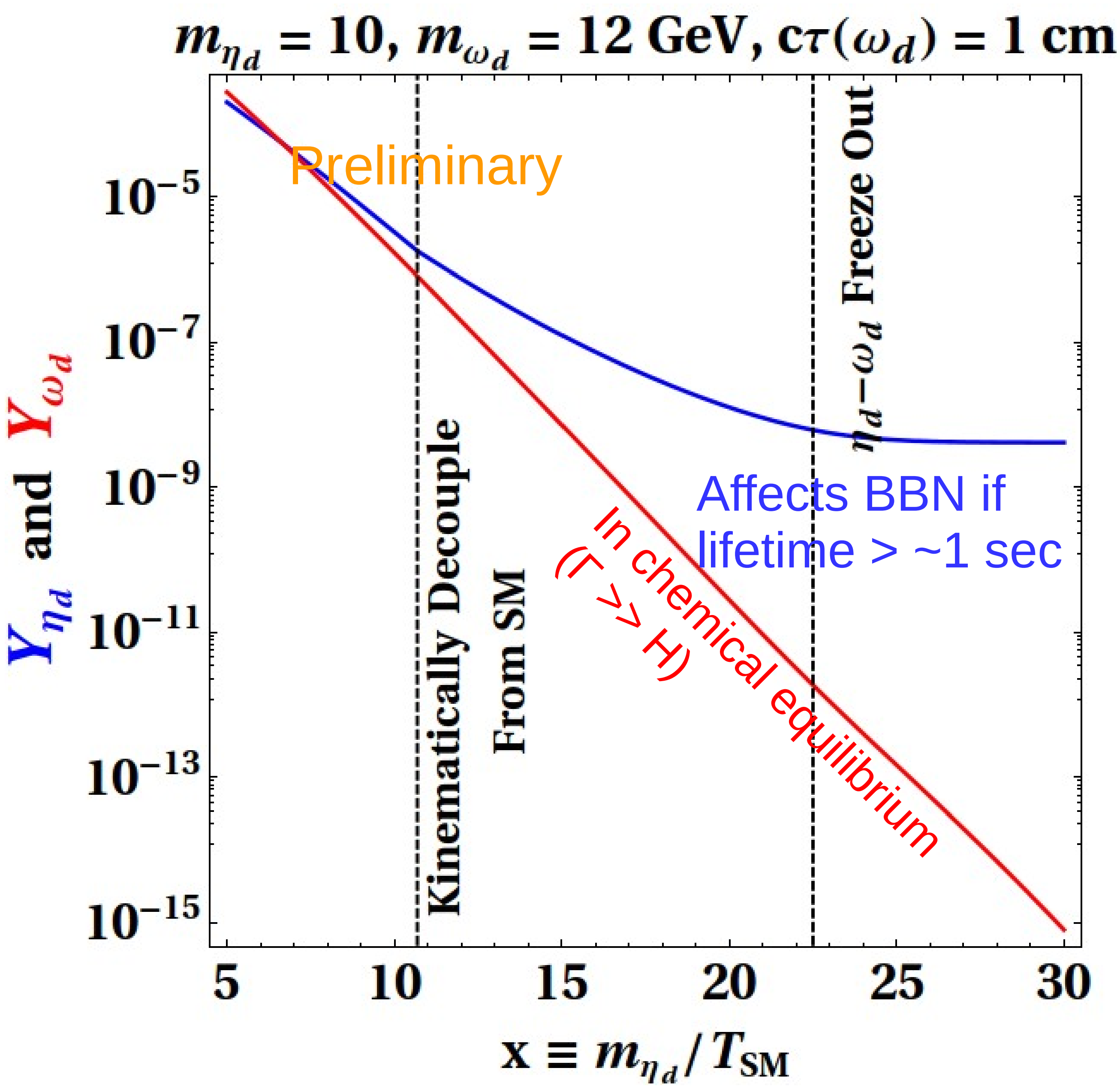


Sensitive to mass gap, for related discussions see [1505.07107,1705.08450,1705.09292,1805.12139]

Slowly decaying/Stable ones become troublesome: BBN/ CMB/ Ω_{CDM} bounds...

A fast decaying component (Collider bounds apply here) that depletes dark hadron number density

Thermal History

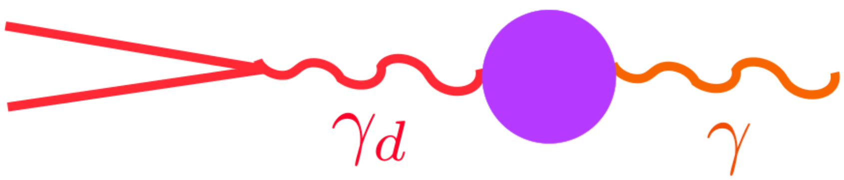


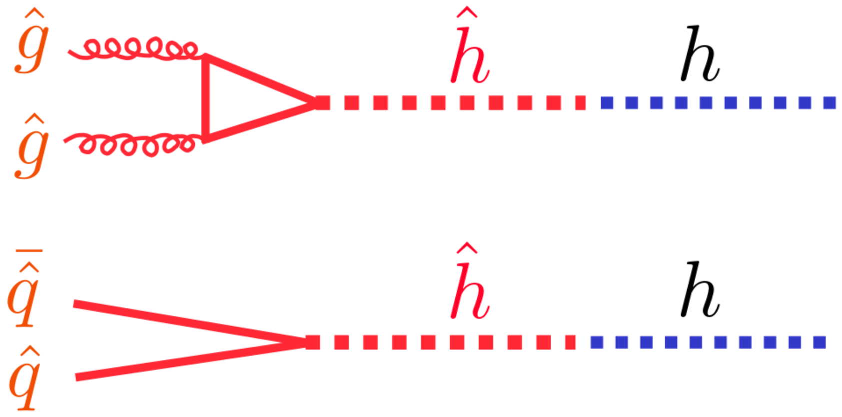
Sensitive to:

- Decay length Γ (kinematic decoupling time)
- ω_d-η_d mass difference Δm (when freeze out happens).

The analytical form is not always precise

Different Models of Hadron Decays





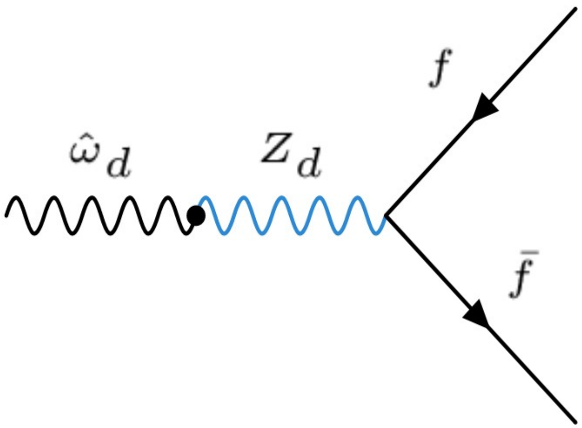
Dark Photon Portal

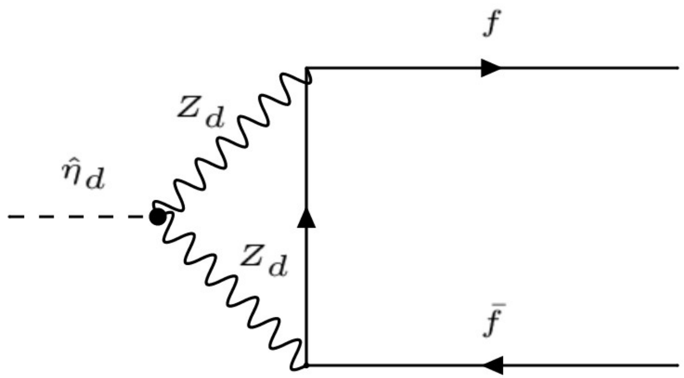
(A Decaying Vector)

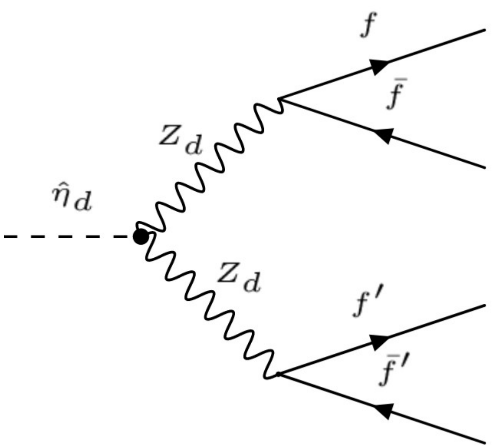
SM Higgs Portal

(A Decaying Scalar)

Dark Photon Portal Models
Vector and Pseudoscalar Decay







Vector Decay: Fast, tree level process

$$\Gamma_{\eta_d\to f\bar{f}} = \frac{9\alpha_D^2 m_{\eta_d}^3}{8\pi^3 f_{\eta_d}^2}\left[\frac{\alpha}{2\pi}\epsilon^2\left(\frac{m_f}{m_{\eta_d}}\right)^2\left(\frac{m_{\eta_d}}{m_{Z_d}}\right)^2\right]^2 .$$

$$\Gamma_{\eta_d\to 4f} = \frac{9\alpha_D^2 m_{\eta_d}^3}{8\pi^3 f_{\eta_d}^2}\left[\frac{\alpha}{2\pi}\epsilon^2\left(\frac{m_{\eta_d}}{2m_{Z_d}}\right)^4\right]^2$$

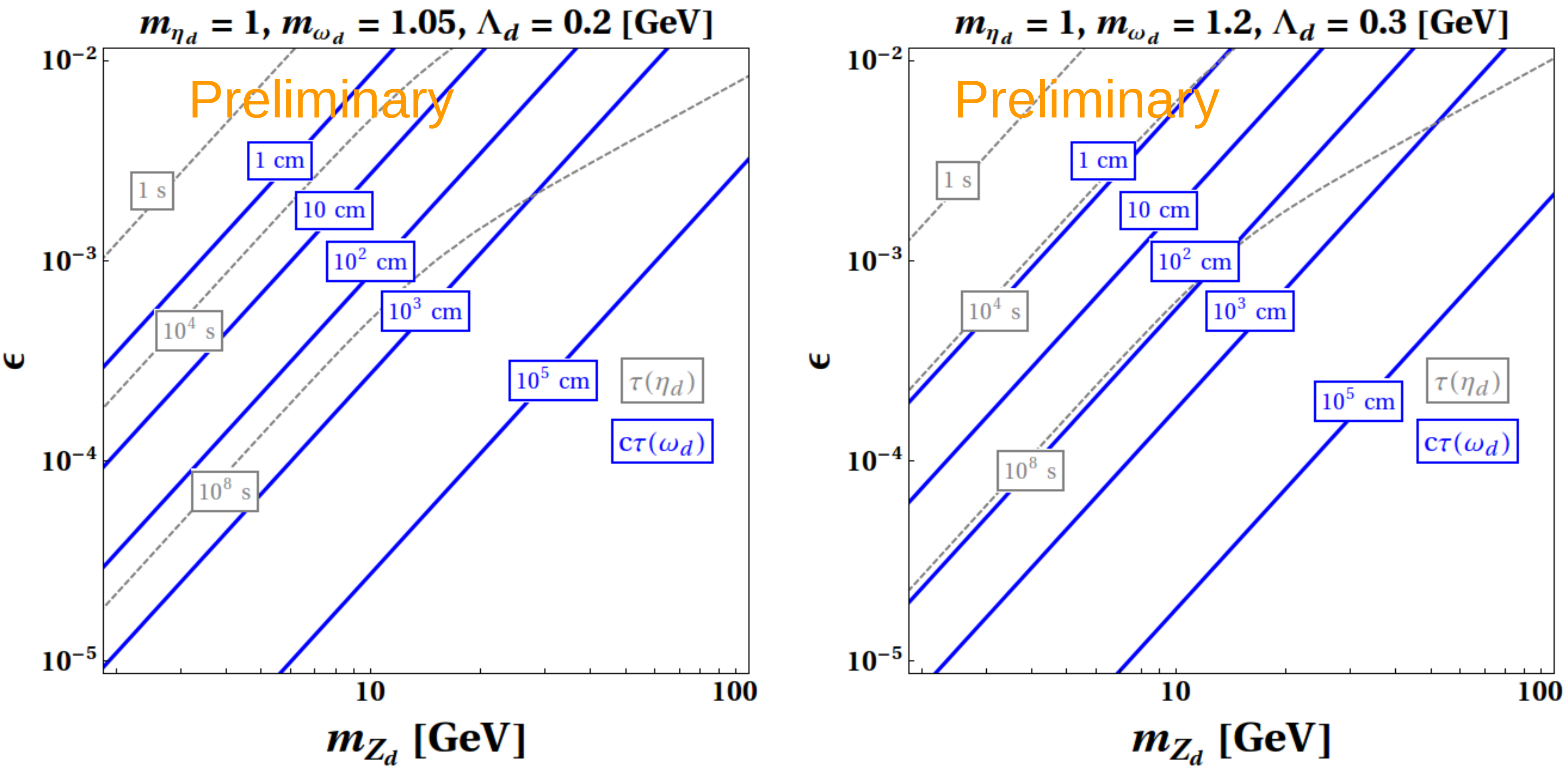
- Still large range of possibility
- Can be out of collider reach if we do not consider the pseudoscalar decay.

Pseudoscalar Decay: Slow, either 2 body (when Z_D is heavy) or 4 body (lighter Z_D) dominanted

- Lifetime longer than ~1 sec,
- Introduces severe constraints during the BBN era

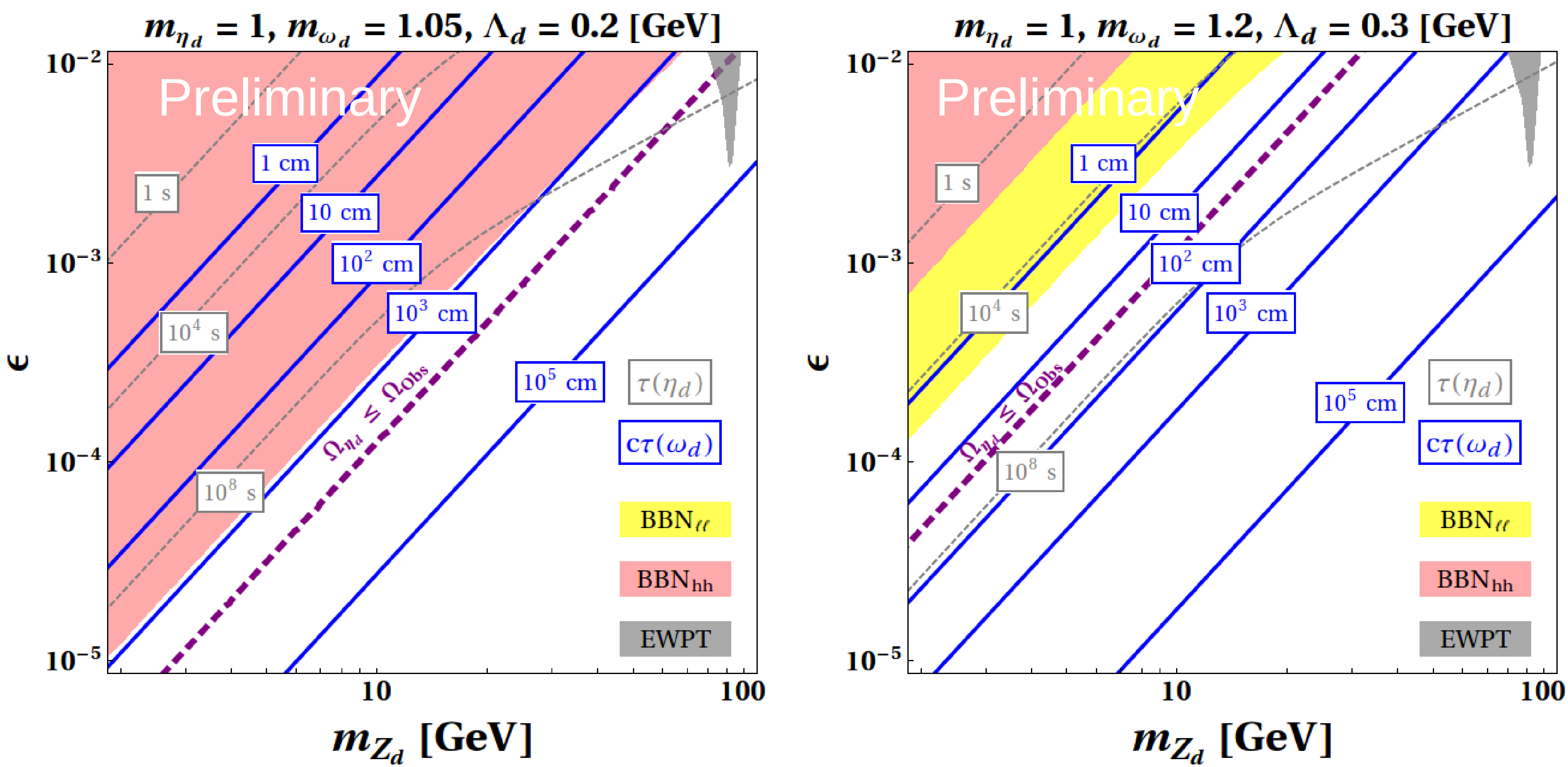
See [1512.02647 & 1805.09345]

Possible Decay Length



Wide range of possible lifetime

Dark Photon Portal Models



Small mass gap:

⇒ weaker cτ upper bounds

(<~10 m), within collider reach

For details about BBN, see [1709.01211]

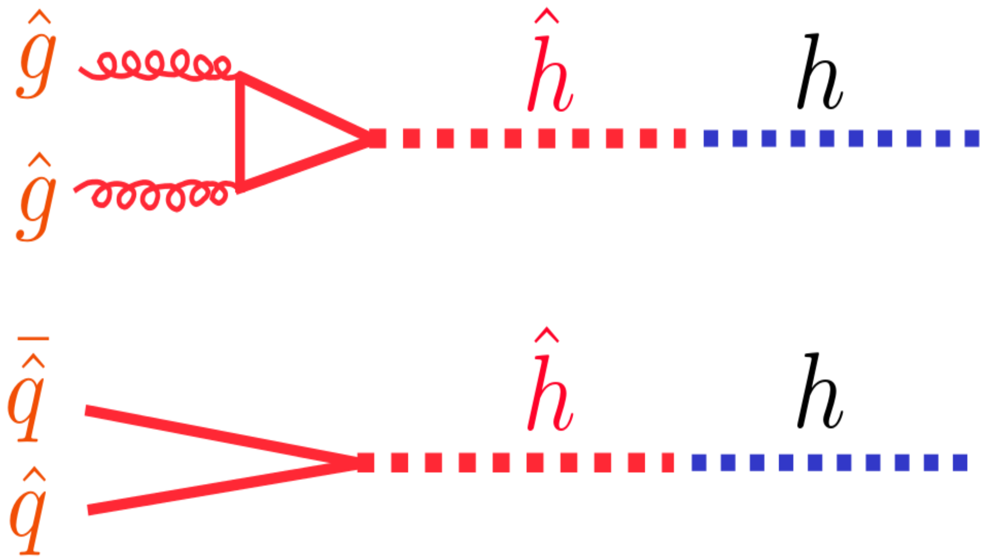
Moderate mass gap

⇒ larger Boltzmann suppression of the vector

⇒ $\omega_d - \eta_d$ freeze out happens earlier

⇒ stronger cτ bounds (< 1 cm)

Higgs Portal Models: Scalar Hadrons Decay



- Scalar Glueball:

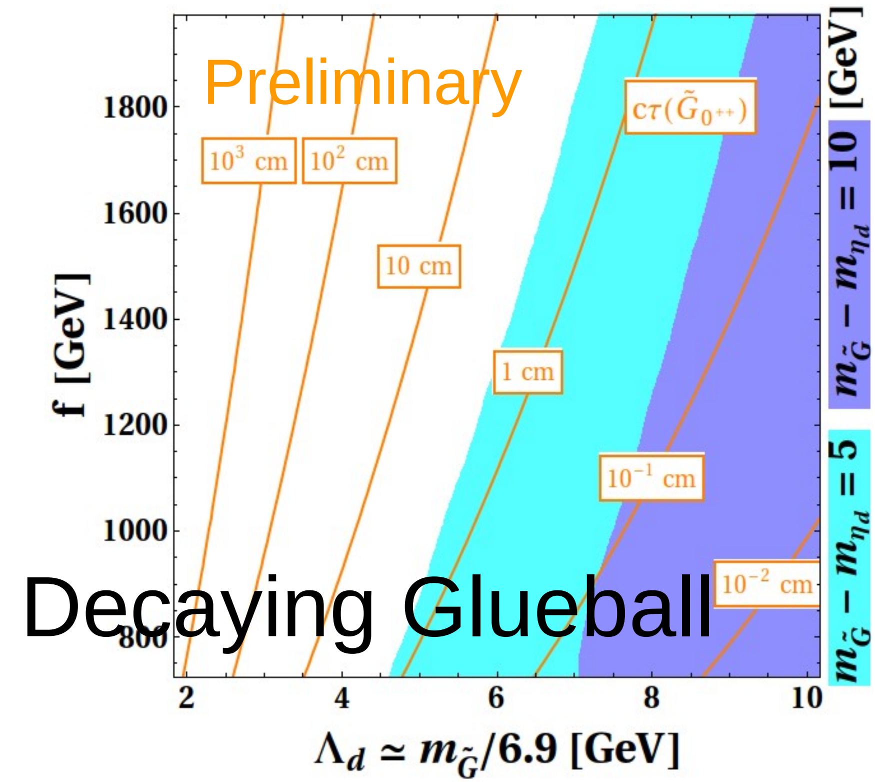
  Mass ~ 7Λ

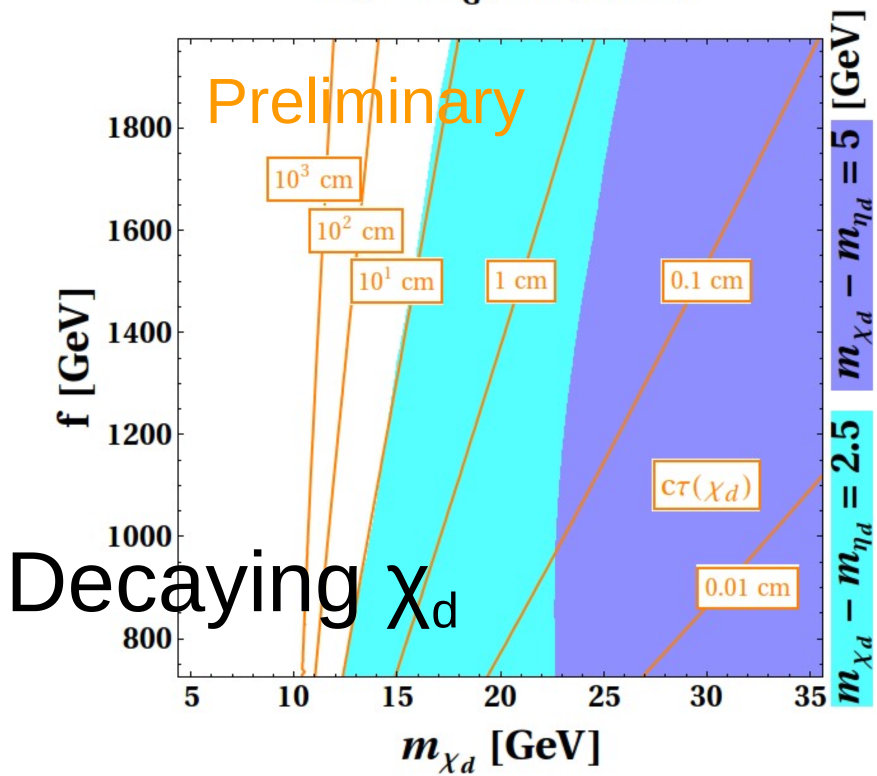
  Decay is loop induced at a higher scale (M), longer lifetime

- Scalar (χ_d) meson

  Mass ~ 2x fermion mass

  Decay much faster

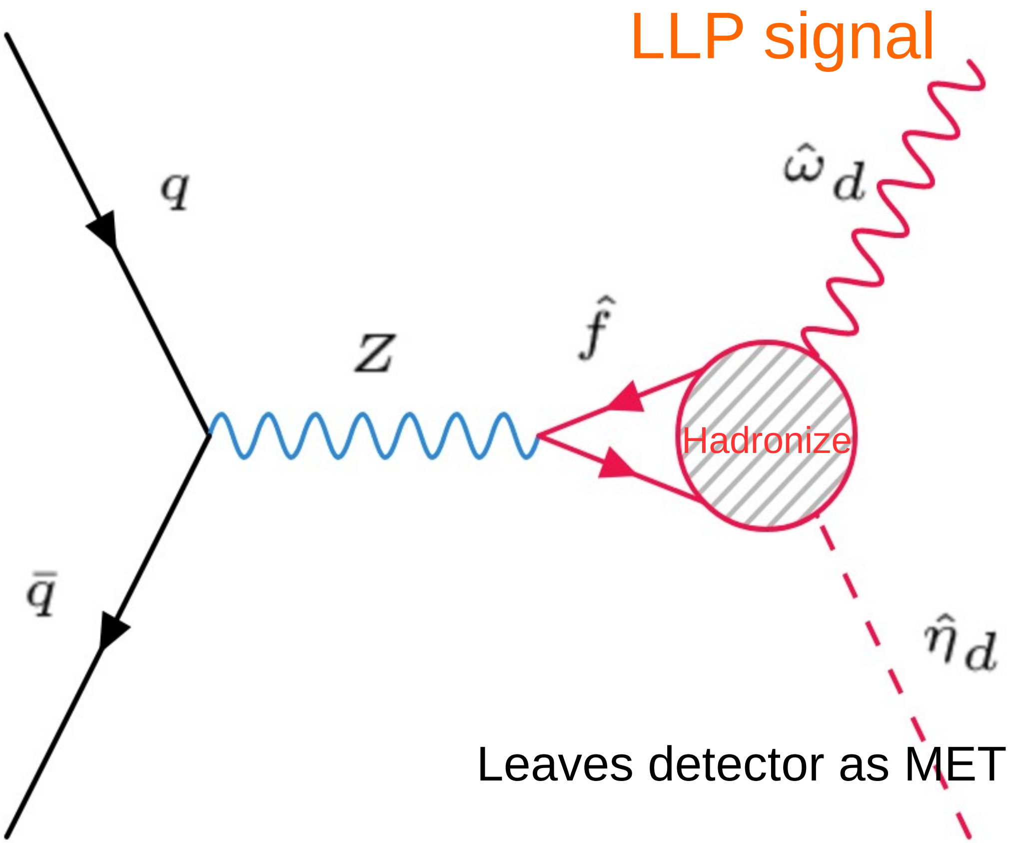




- Short cτ (< 10 cm)
- Heavier mass (> ~15 GeV)
- Hadronic Decays

LLP Detection at Hadron Colliders

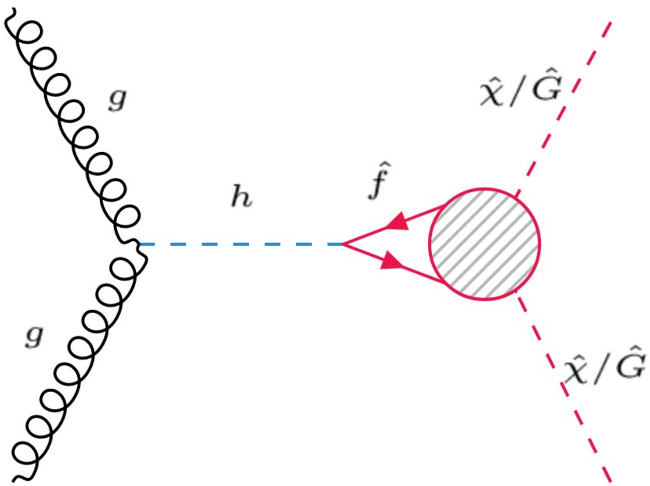
Exotic Z decay from Z_D mixing:



(Not thoroughly discussed, see [1710.07635 & 1712.07237])

Higgs portal:

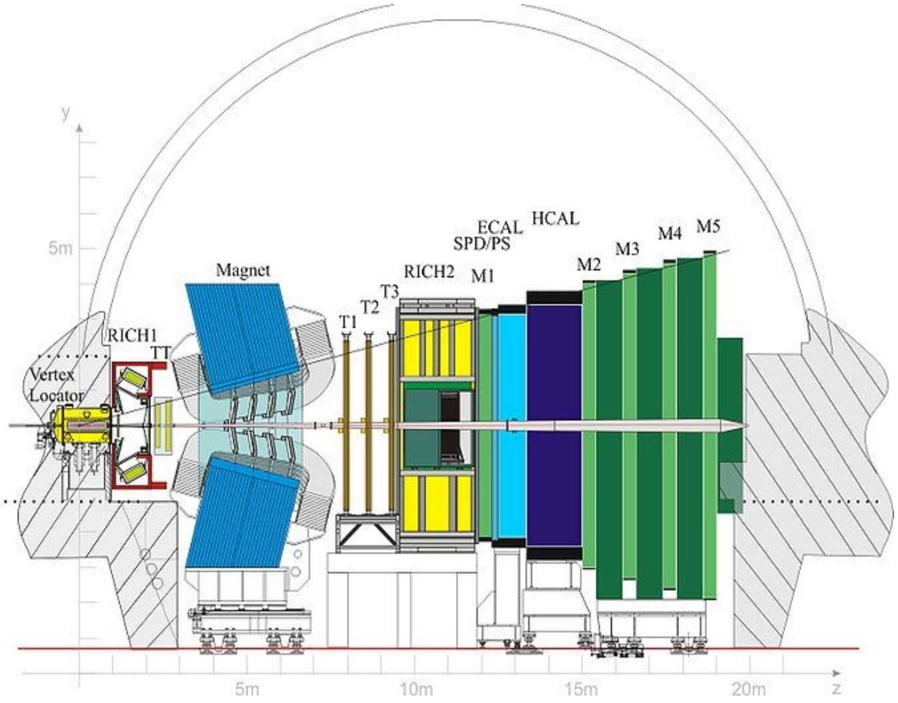
Exotic Higgs decay



LLP Detection at Hadron Colliders

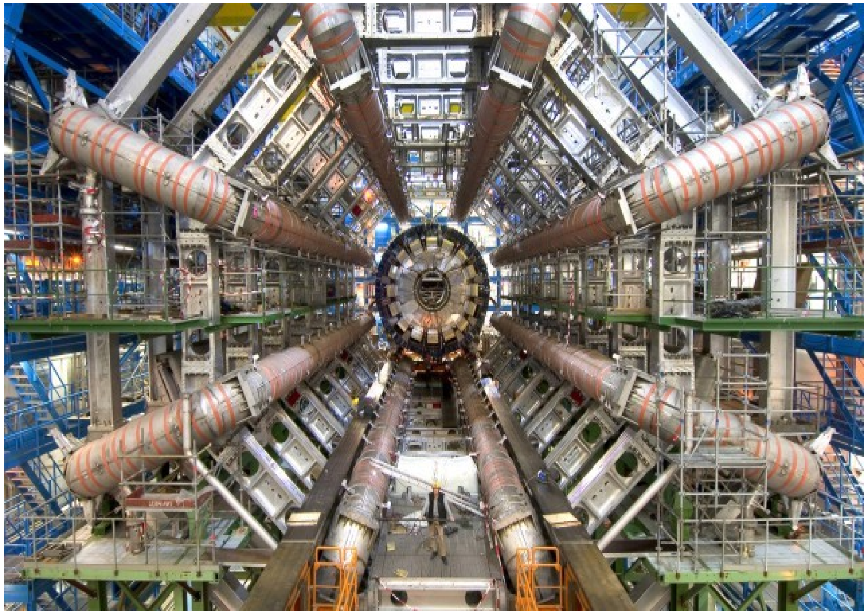
LHCb:

- Sensitive to small length scale (<~1 cm)
- Good at LLP → μμ/ππ/KK, etc.

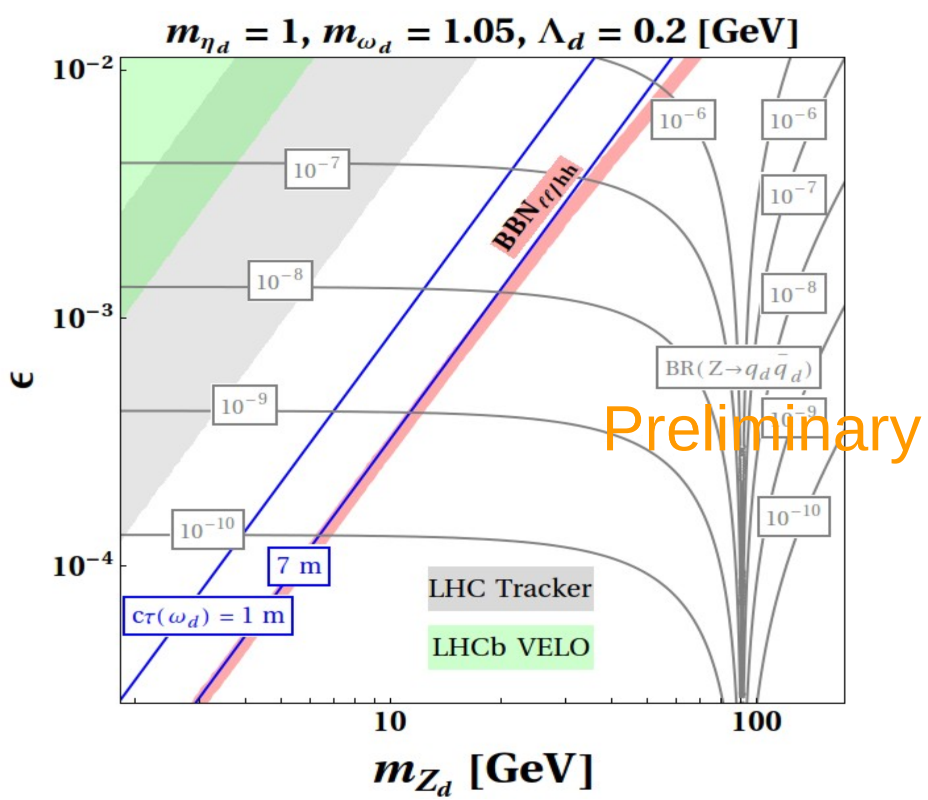


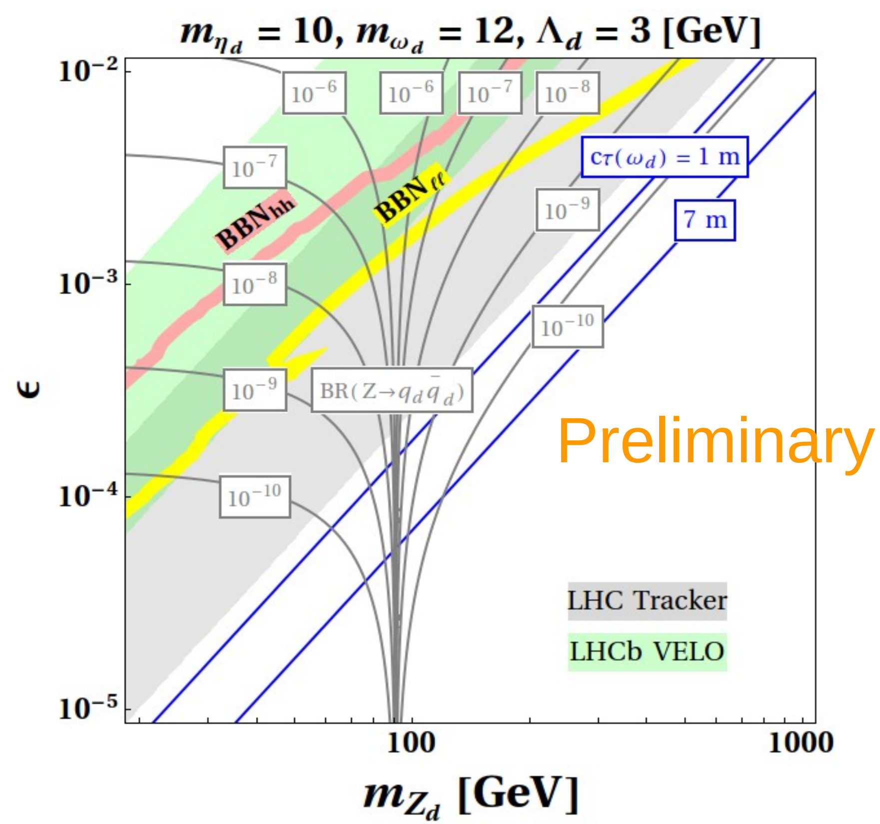
CMS & ATLAS:

- Sensitive to wider range of decay length
- Larger luminosity and coverage
- Larger SM backgrounds



LLPs from Z_D-Z mixing: Exotic Z → dark hadron BR.





Green Shade: Chance to decay inside the LHCb VELO >10%

Gray Shade: Chance to decay inside the LHC Trackers >10%

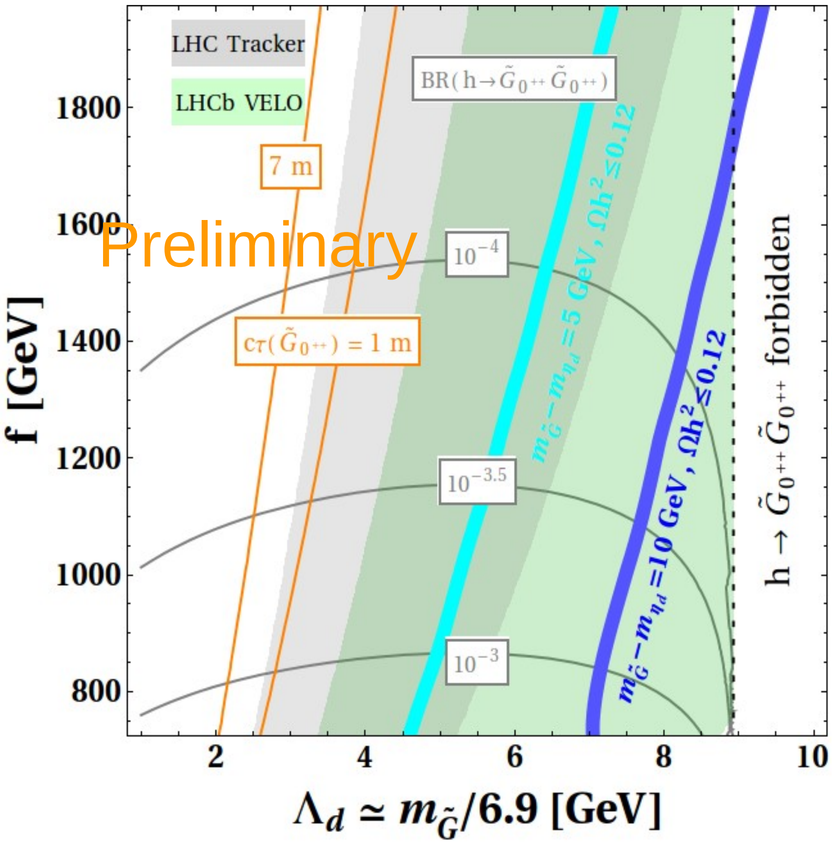
DV(μμ) + X: probe exotic BR down to $O(10^{-6})$ at LHCb and comparable bounds ATLAS/CMS after run III, for cτ ~ 1 cm

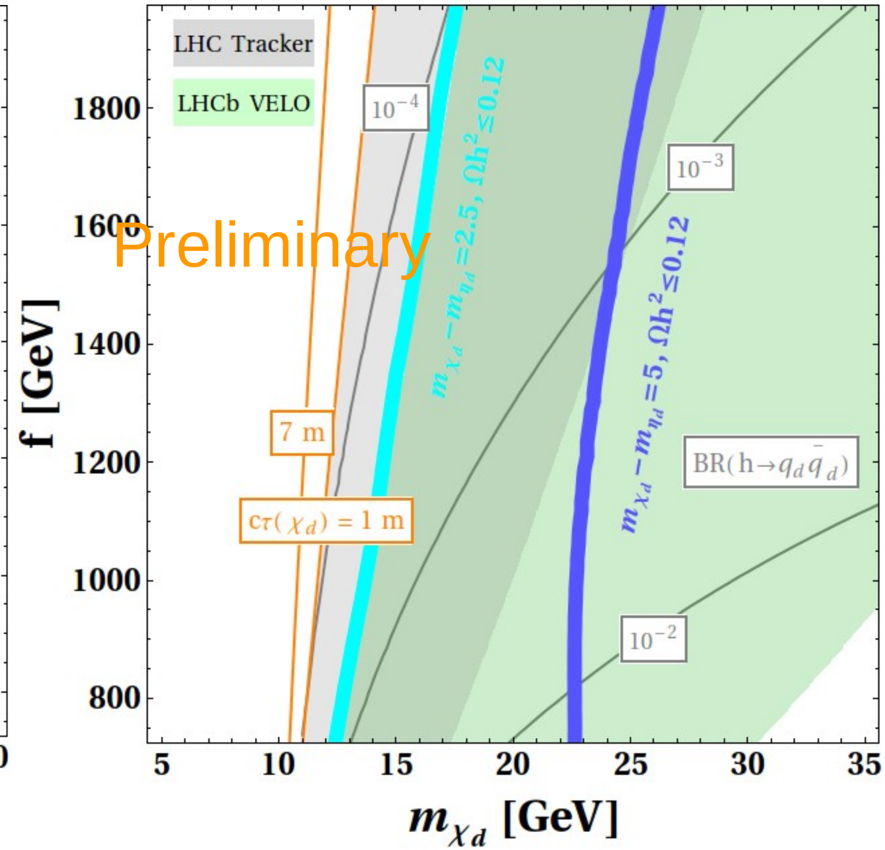
See [1808.03057 & 1806.07396]

LLPs from Higgs Portal Models: Higg Exotic Decays

Displaced vertexes of dijets and short decay length.

Preliminary

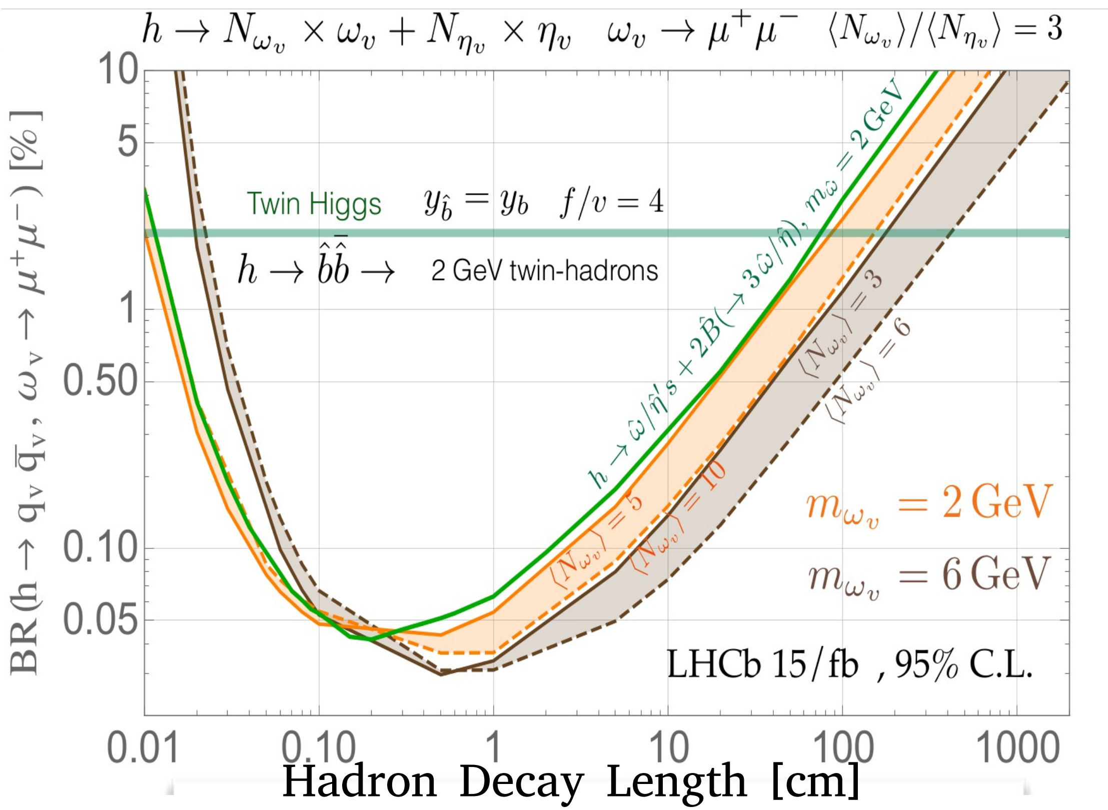




Higgs exotic BR: $O(10^{-3})$ at ATLAS/CMS and $O(10^{-2})$ at LHCb during HL-LHC era

See [1806.07396 & 1808.08865]

Hidden Strong Dynamics



Some numerical results for this scenario when lifetime is short (still in work)

An related alternative scenario in Hsin-Chia's talk on Thursday.

⇑ Some results from [1708.05389]

see also [1502.05409 & 1503.00009]

STAY TUNED!

LHCb can give the leading bound for short length (~1cm) cases

Dinner Time!

Take Home Message:

- Cosmological constraints for hidden valley models can be stronger than often considered.

- Interesting predictions about future LLP searches, in the short length scale.

Backup Slides

Thermal History

$$\frac{dY_h}{dx} = \frac{-1}{3H(x)}\frac{ds}{dx}\Bigg[\langle\sigma_{+2h}v\rangle\, Y_l^2 - \langle\sigma_{-2h}v\rangle\, Y_h^2$$

$$- \langle\sigma_{-h}v\rangle\, Y_h Y_l + \langle\sigma_{+h}v\rangle\, Y_l^2$$

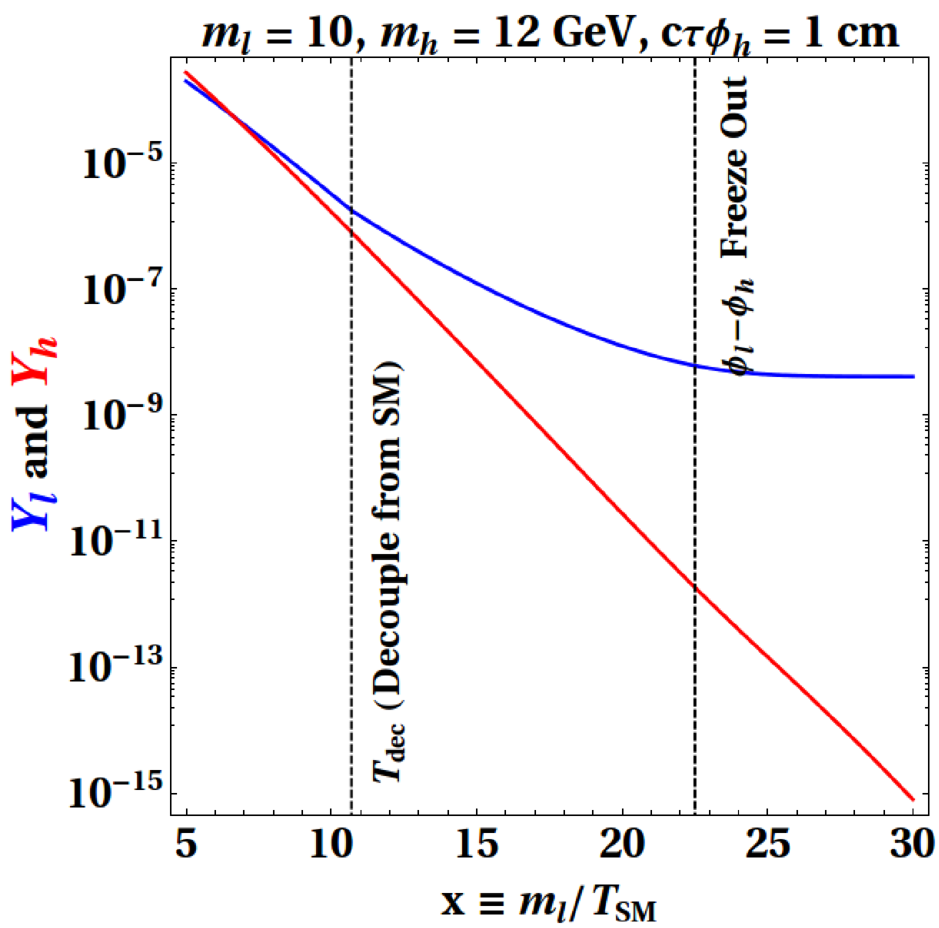
$$- \frac{\langle\Gamma_{\phi_h\to \mathrm{SM}}\rangle_{\hat{T}}}{s} Y_h + \frac{\langle\Gamma_{\phi_h\to \mathrm{SM}}\rangle_{T}}{s} Y_h^{\mathrm{eq}}(T)\Bigg],$$

$$\frac{dY_l}{dx} = \frac{-1}{3H(x)}\frac{ds}{dx}\Bigg[\langle\sigma_{-2h}v\rangle\, Y_h^2 - \langle\sigma_{+2h}v\rangle\, Y_l^2$$

$$+ \langle\sigma_{-h}v\rangle\, Y_h Y_l - \langle\sigma_{+h}v\rangle\, Y_l^2\Bigg].$$

⇑ Solve the Boltzmann Eq. Above, we'll be all good...

Thermal History



$$Y_l(T) \simeq \frac{Y_l^{\rm eq}(\hat{T})}{Y_h^{\rm eq}(\hat{T})} Y_h^{\rm eq}(T)$$

$$\propto \exp\left(\frac{\Delta m T_{\rm dec}}{T^2}\right) \exp\left(-\frac{m_h}{T}\right)$$

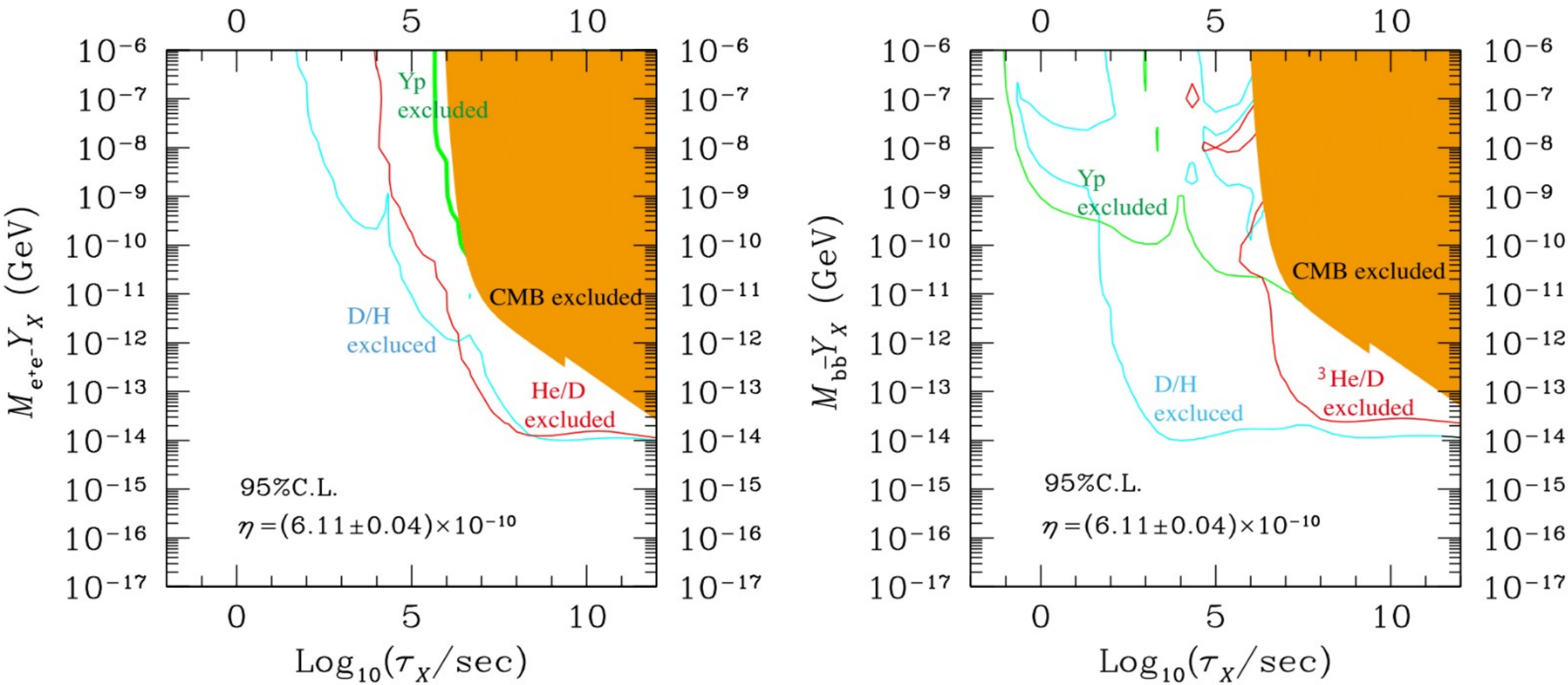
Sensitive to h decay length Γ (related to $T_{\rm dec}$) and Δm (related to freeze out temperature).

Analytical Spoiler:

$$Y_l|_{\rm BBN} \simeq 10^{-4}\left(\frac{1000 m_h^2}{M_P \Gamma_h}\right)^{\frac{{\rm const}\times m_h}{\Delta m}} \exp\left(-{\rm const}\frac{m_h}{\Delta m}\right)$$

Reasonable form but not always precise $\Rightarrow$ Numerical results

BBN Constraint



Taken from [1709.01211]

Estimate the Decay Chance in Valid Detector Volumes

LHCb VELO:

- Distance: 0.1-22 mm
- Pseudorapidity coverage: 2-5

LHC Tracking system:

- Distance: 1-30 cm
- Pseudorapidity coverage [-3,3]

- Z/h exotic decay estimated from MG5 simulations.

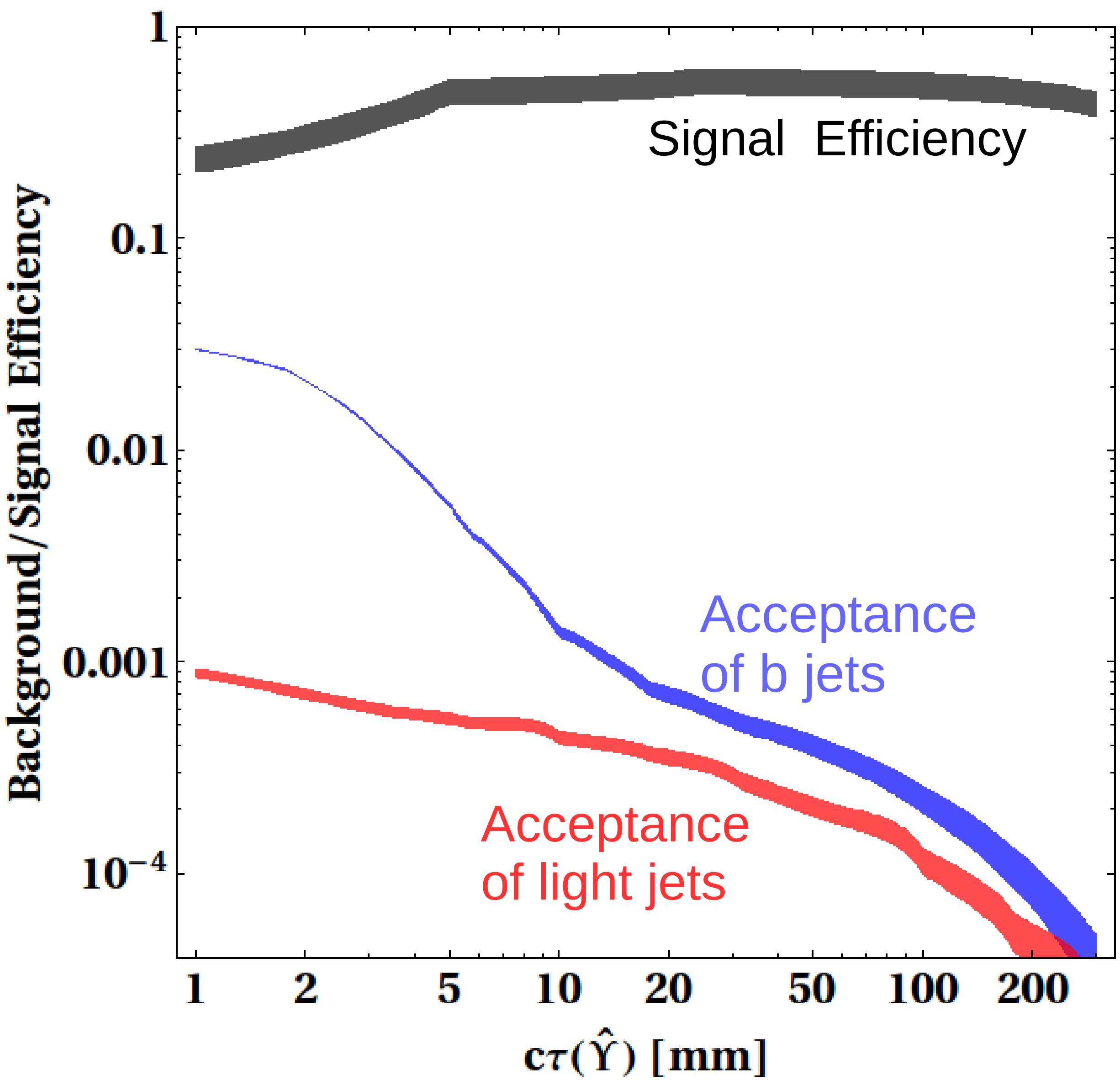
Estimate the di-muon LLP reach

- Z production rate at LHC: ~50 nb
- Luminosity: 15 fb^{-1} at LHCb and 300 fb^{-1} at ATLAS/CMS
- Background for DV(μμ) estimated as ~25
- Assume the DV(μμ) reconstruction efficiency ~0.5
- The $\omega_d \rightarrow \mu\mu$ BR ~10%
- Needed #signal ~10

$\Rightarrow BR(Z \rightarrow 2q_d) \sim O(10^{-6})$

At LHC main detectors, the situation is more complicated due to MET triggering efficiency and background estimation. Reprojected from references.

Tell Emerging Jets from Ordinary Jets (Preliminary)



In collaboration with H.C. Cheng, E. Salvioni and C. Verhaaren