Confining Hidden Valley Models at the LHC

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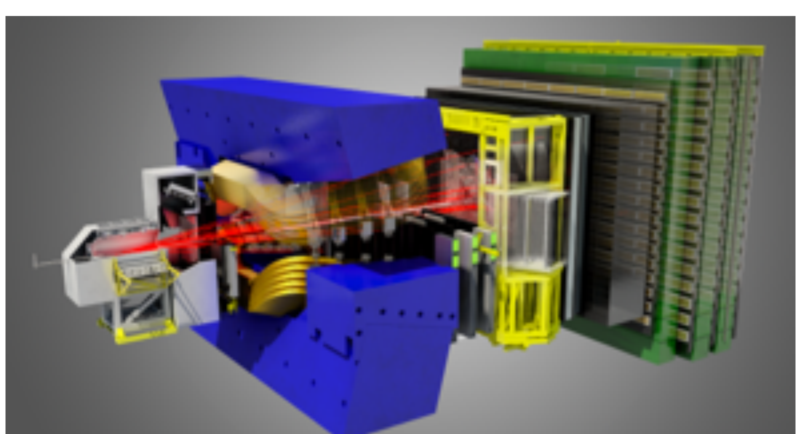
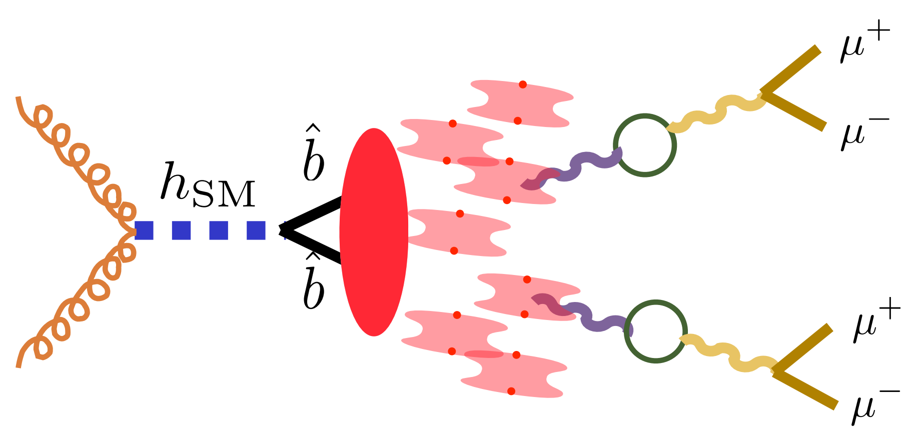
Theory Meets Experiment, Nikhef, Oct 26, 2018





What's in the dark?

Standard Model

U(1)

$SU(2)_L$

$SU(3)_c$

leptons

quarks

Higgs

Hidden Sector

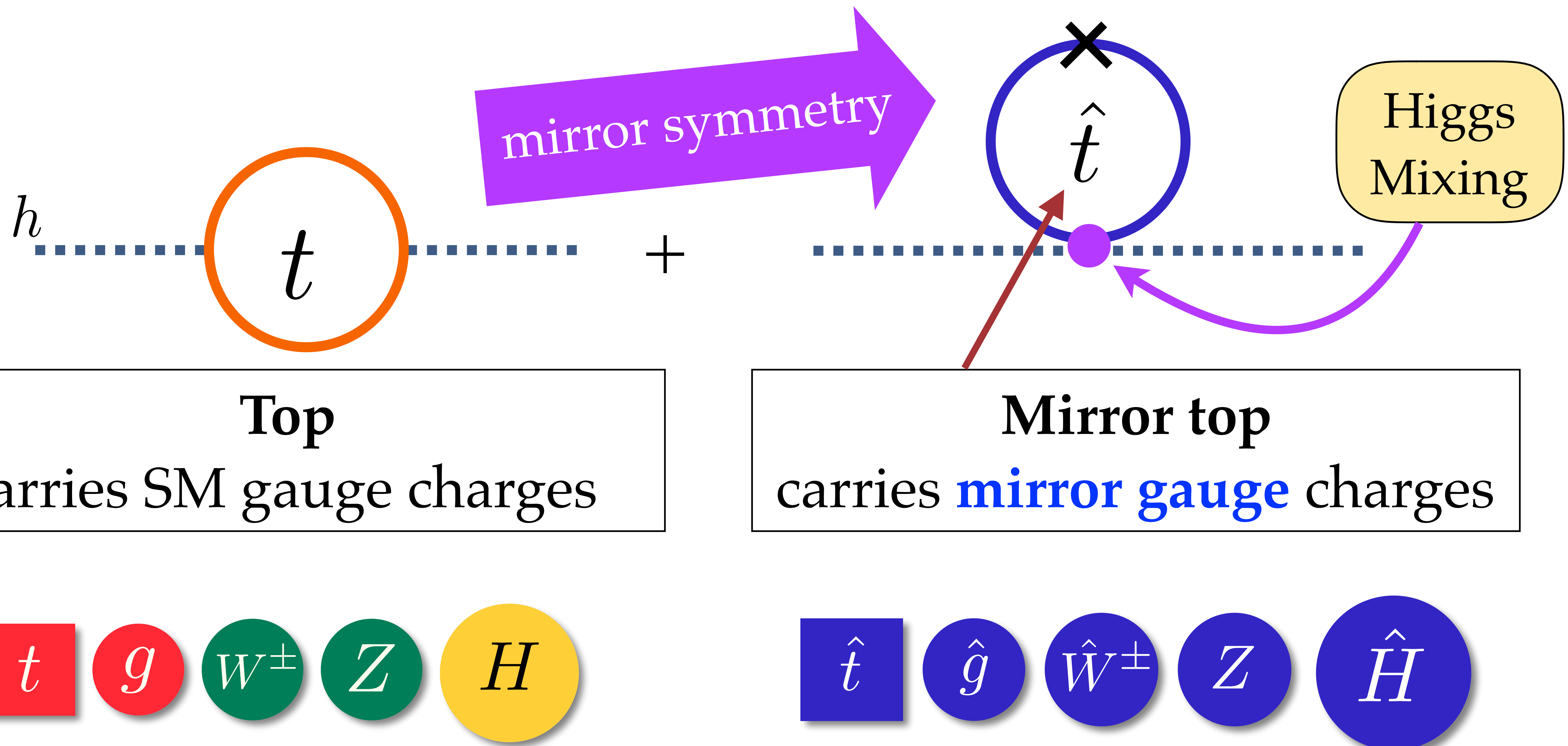
Hidden Force

dark photon?

dark QCD?

One example: Twin Higgs

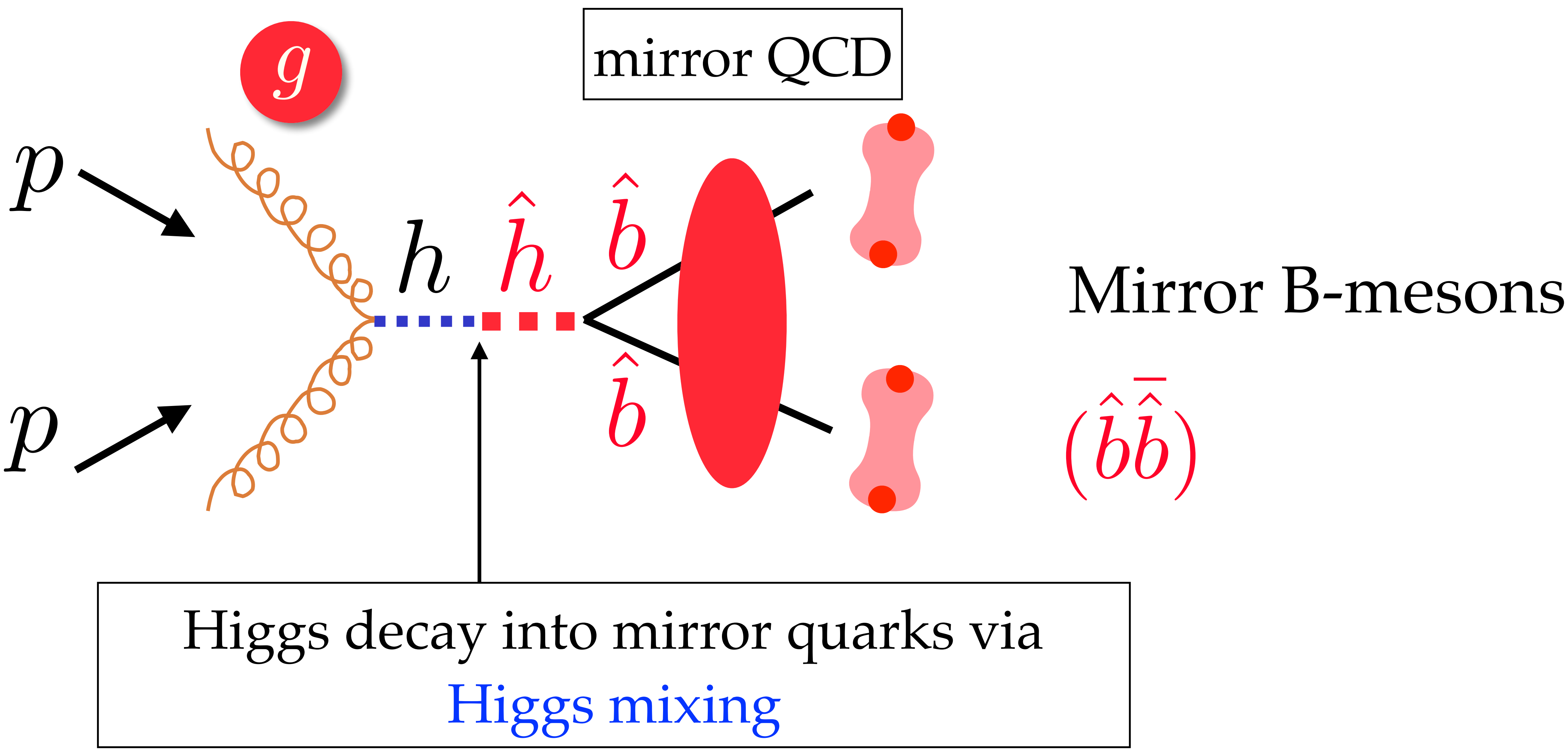
Chacko, Goh, Harnik (2005)



Mirror copy of the relevant particles

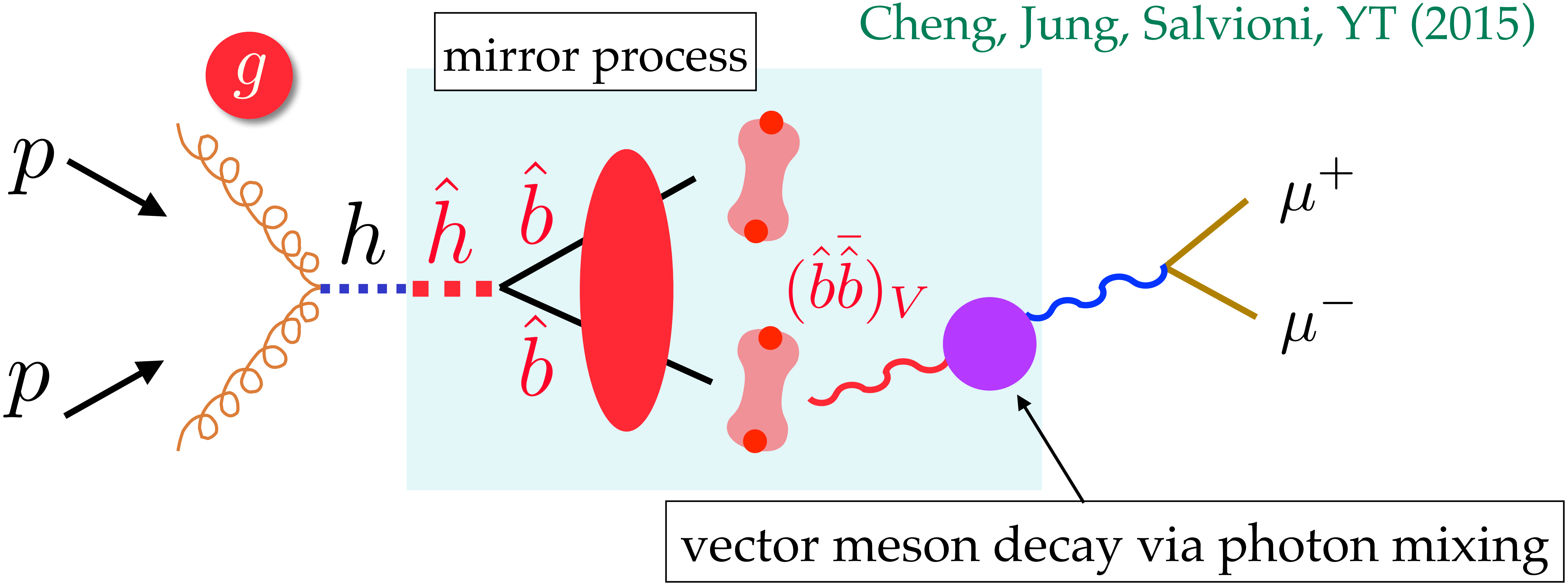
Collider signatures?

E.g., SM Higgs decay into twin particles



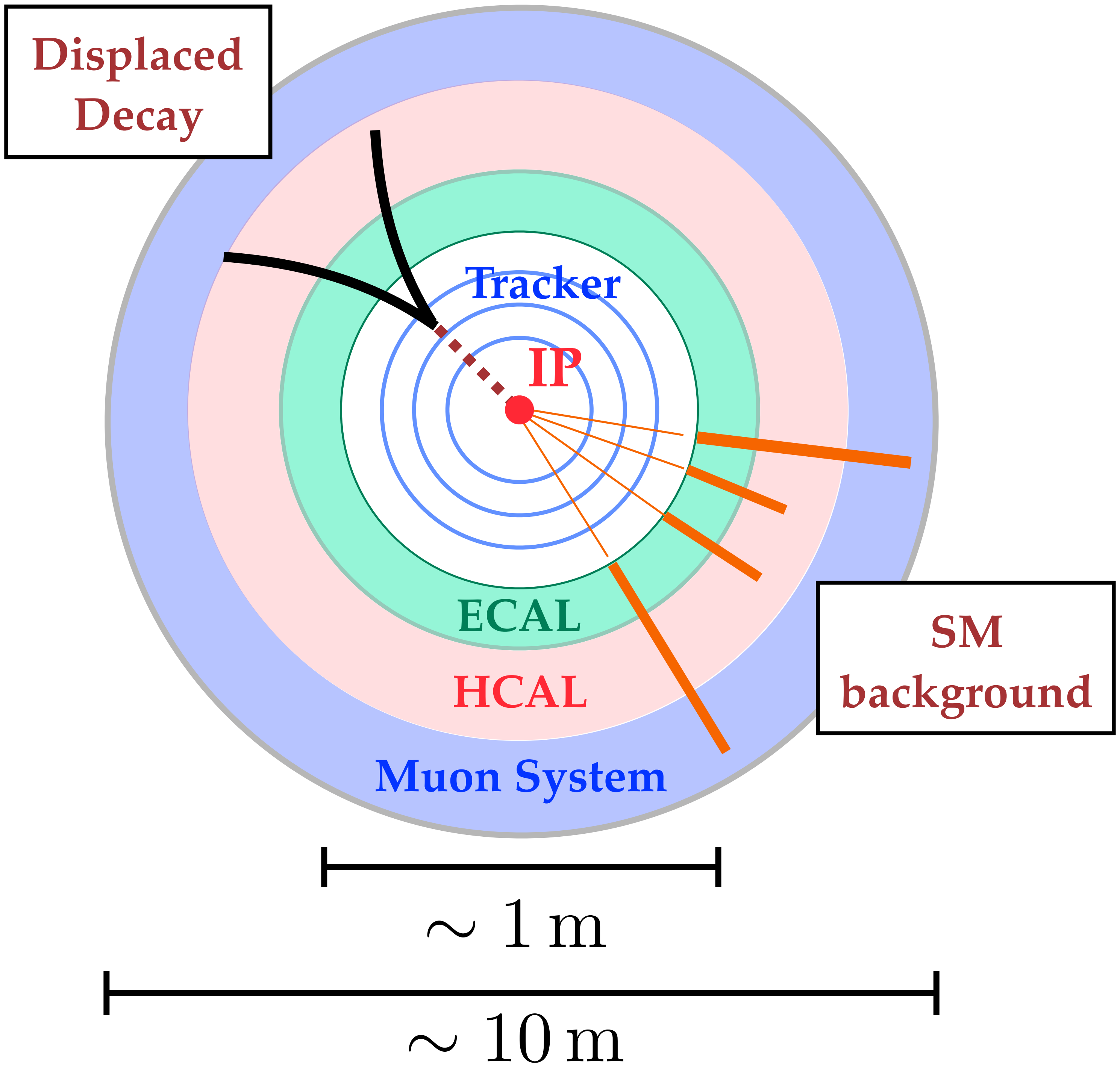
E.g., SM Higgs decay into twin particles

Cheng, Jung, Salvioni, YT (2015)

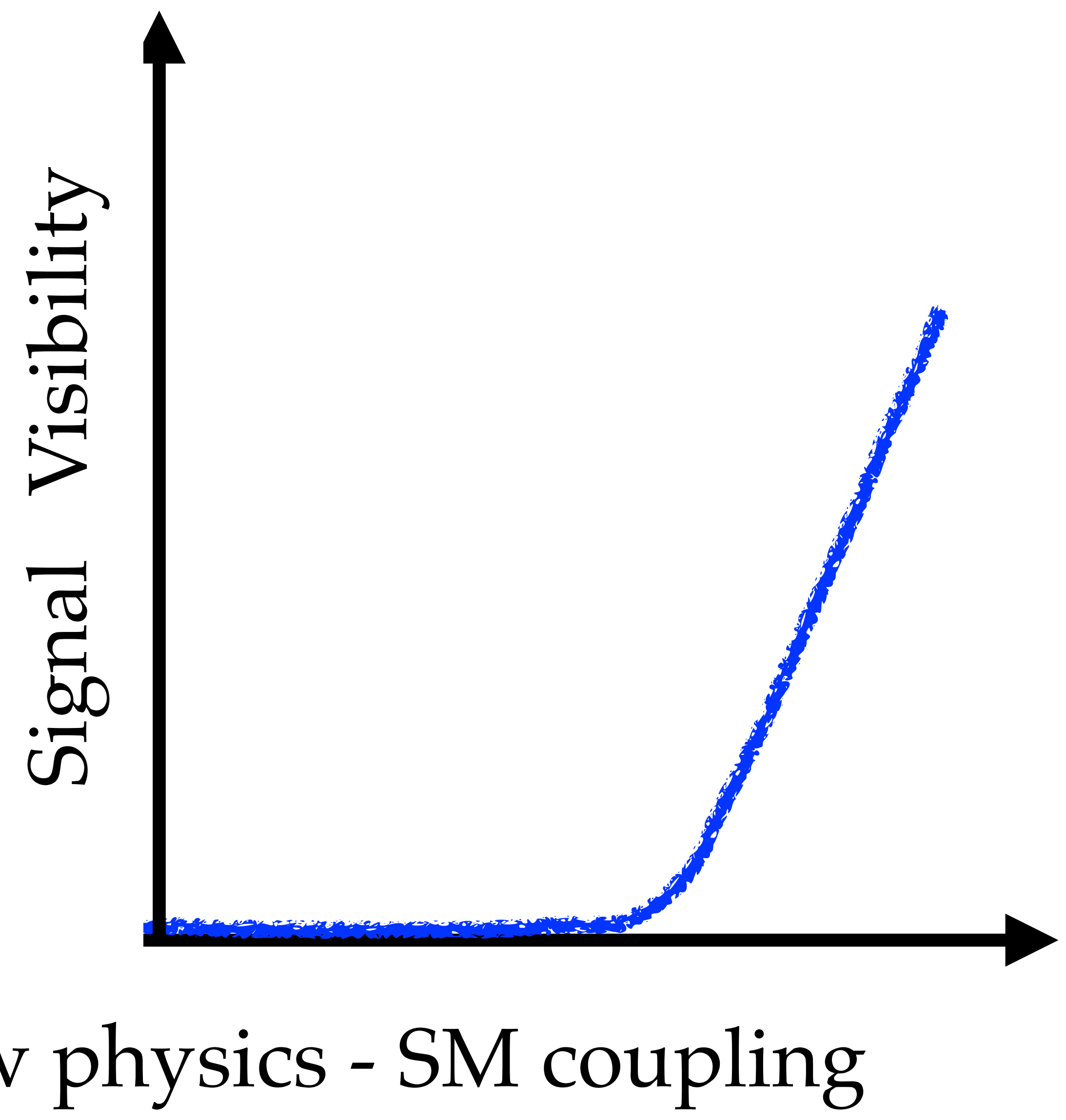


Mirror mesons **SLOWLY** decay into SM particles

If the coupling is so small => Long-lived particles



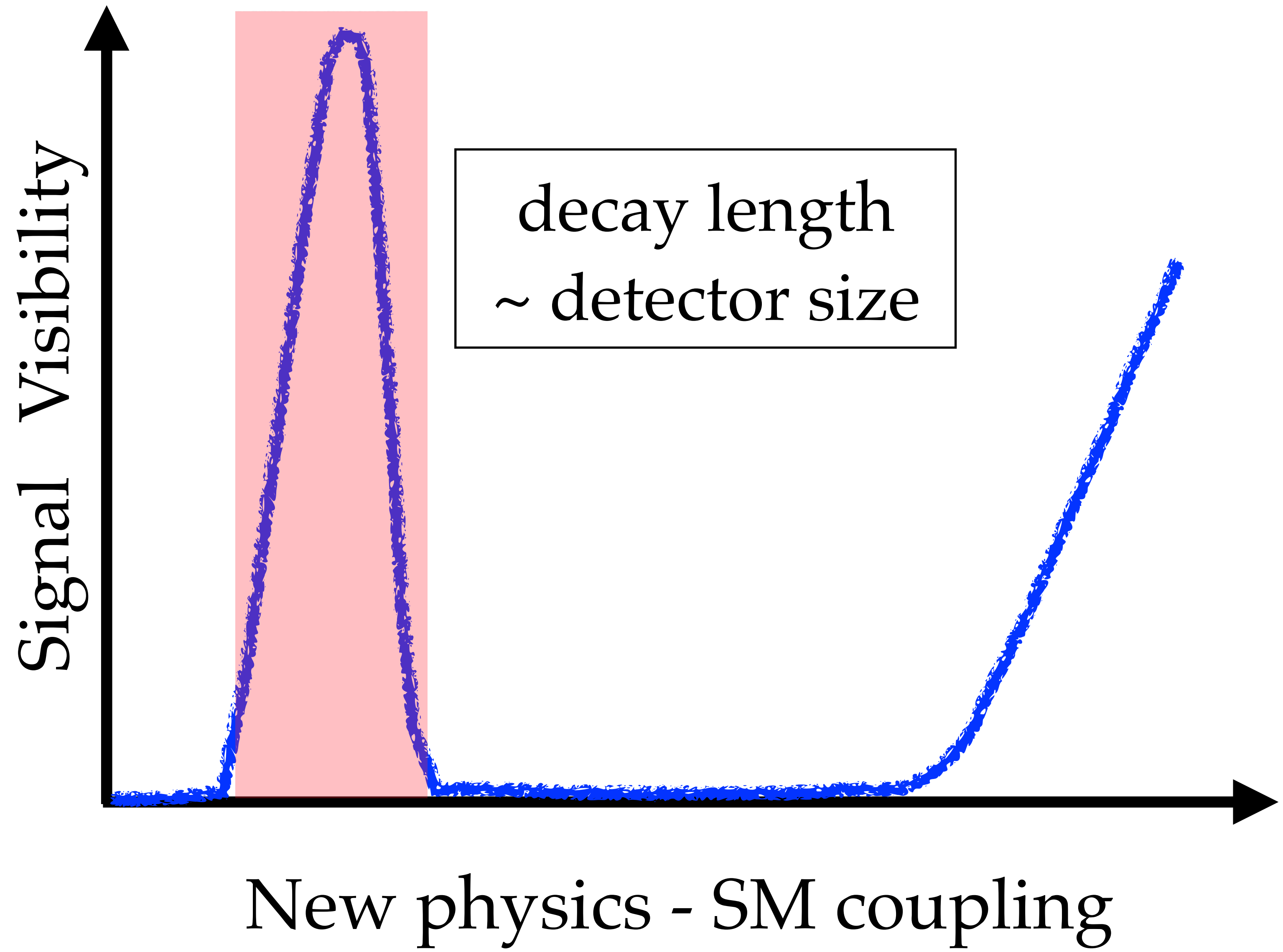
Normal story: smaller coupling => bad

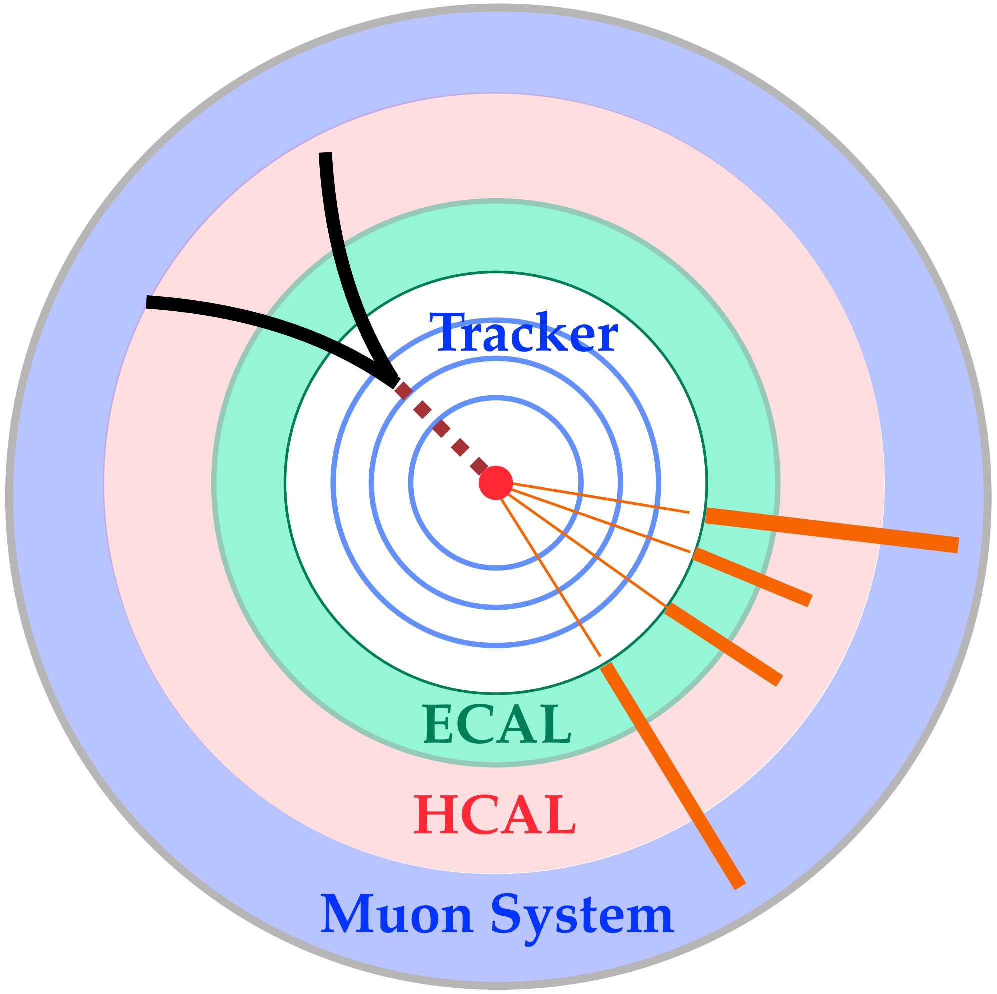


Long-lived Particle (LLP) search

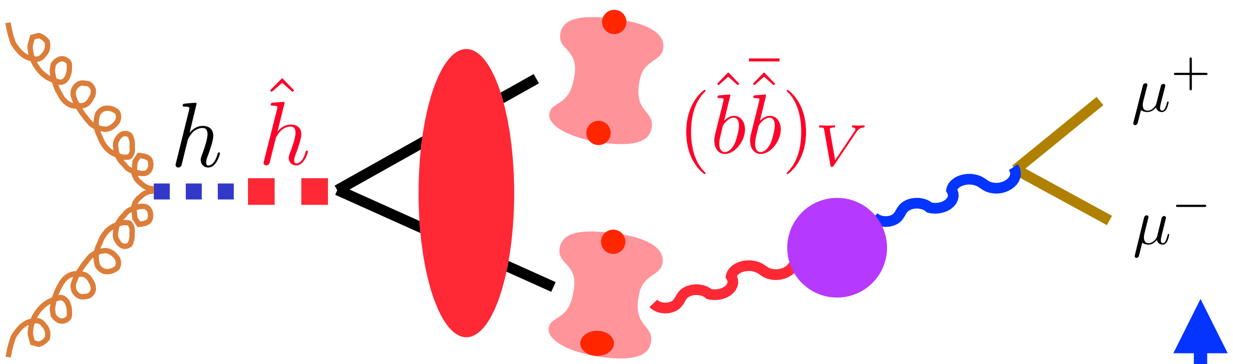
Not the main focus before
but increasingly being studied!

decay length
~ detector size



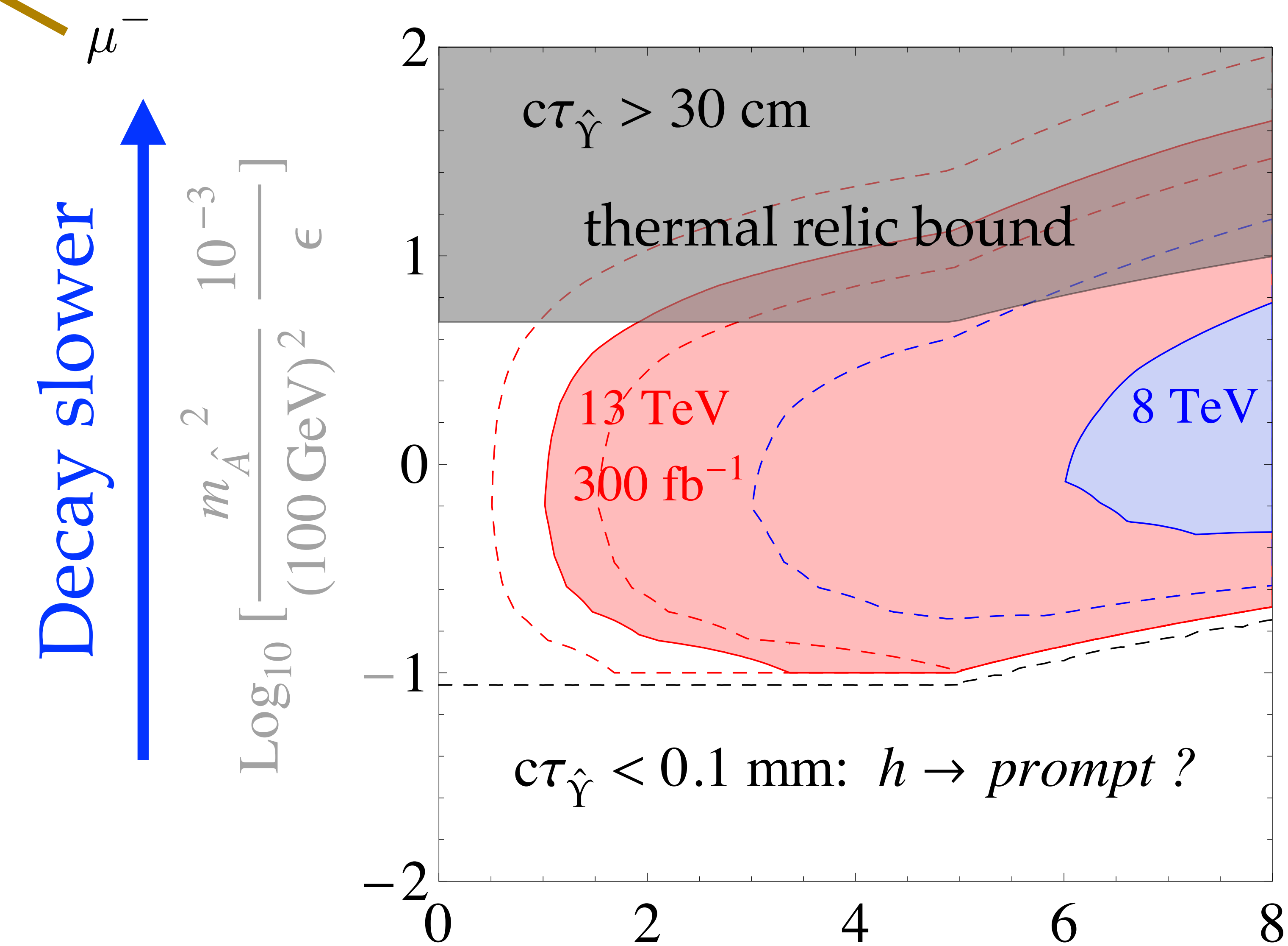


LHC search of displaced muon pairs



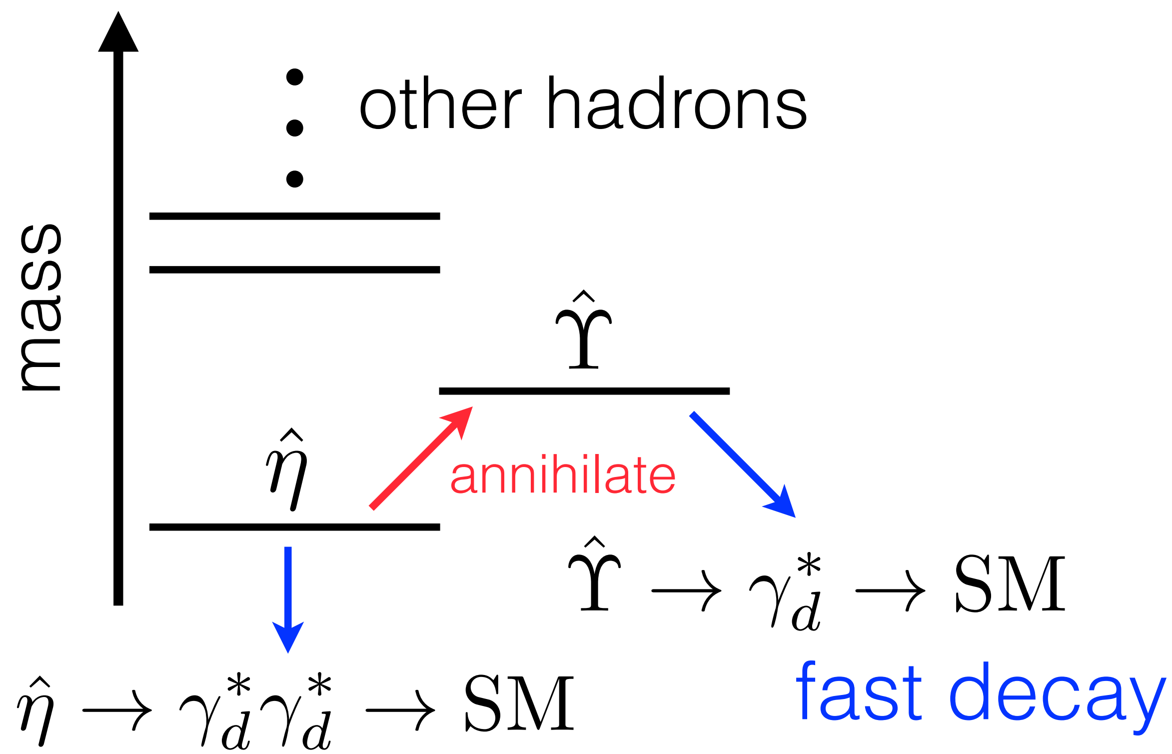
Using CMS displaced di-muon search (1411.6977)

Cheng, Jung, Salvioni, YT (2015)



Mirror bottom mass (GeV)

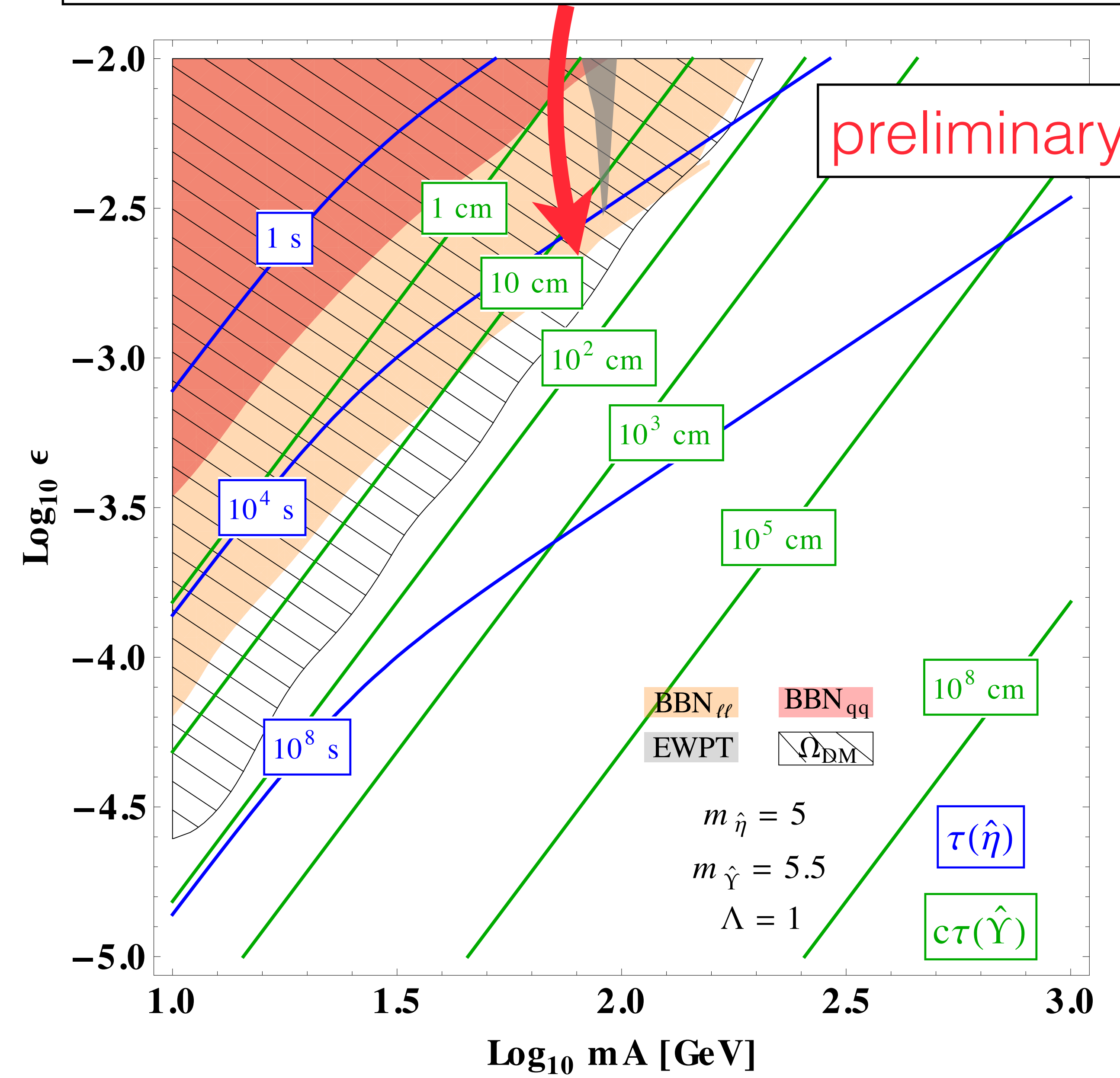
e.g., dark hadrons couple via photon mixing



slower decay, ruins BBN

- need to annihilate the lightest state into heavier (easier to decay) states
- the heavier meson needs to decay in SM quickly while the annihilation is efficient

vector meson has a ~ m scale upper bound on decay lifetime

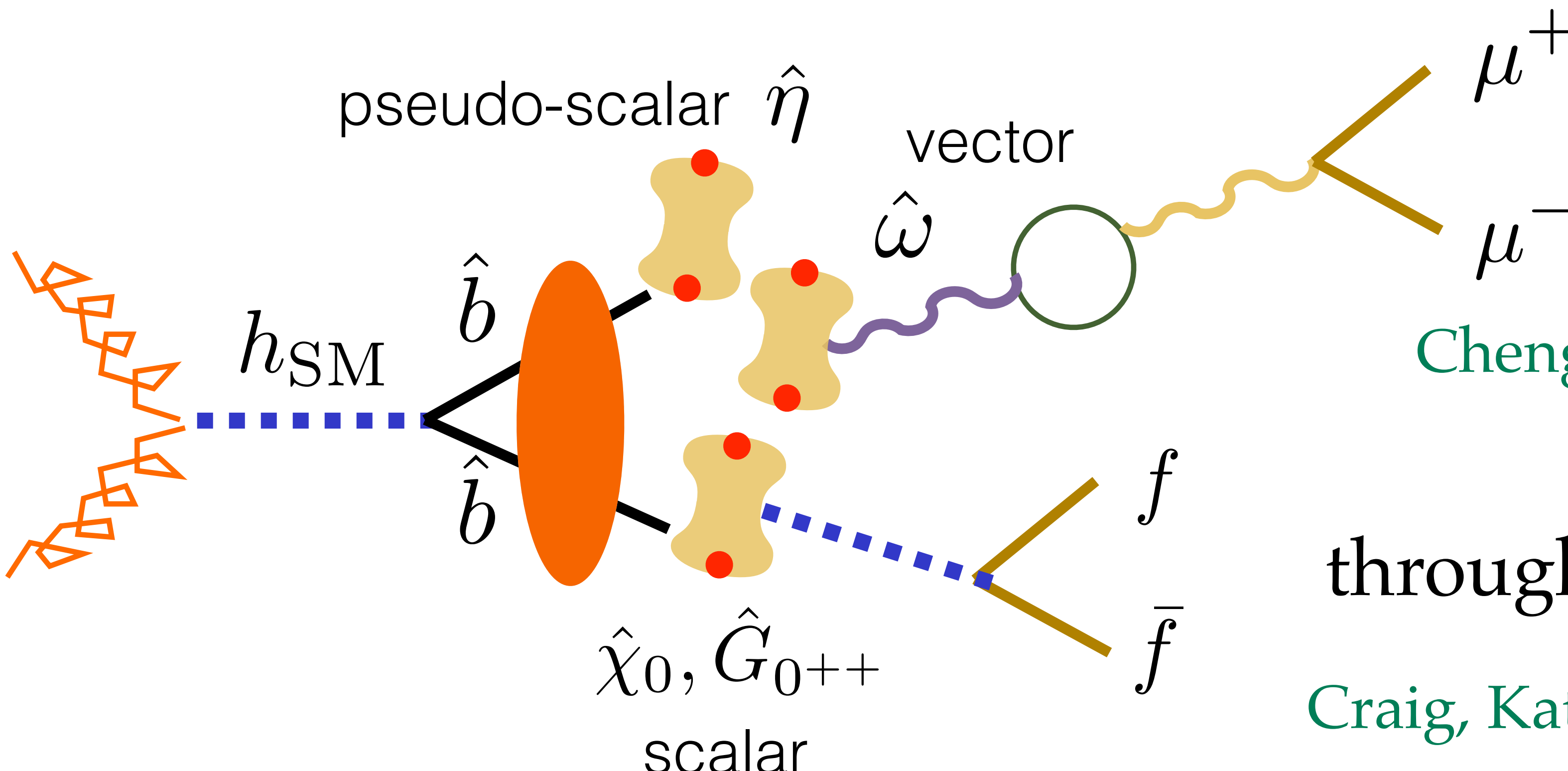


Li & YT (in preparation), also see 1512.02647

Dark shower signals

Example: from Twin Higgs models

twin hadron **mass** ~ SM mesons (MeV to GeV scale)



through photon mixing

Cheng, Jung, Salvioni, YT (2015)

through Higgs portal

Craig, Katz, Strassler, Sundrum (2015)

Curtin, Verhaaren (2015)

Cheng, Jung, Salvioni, YT (2015)

Dark hadrons can be quite soft

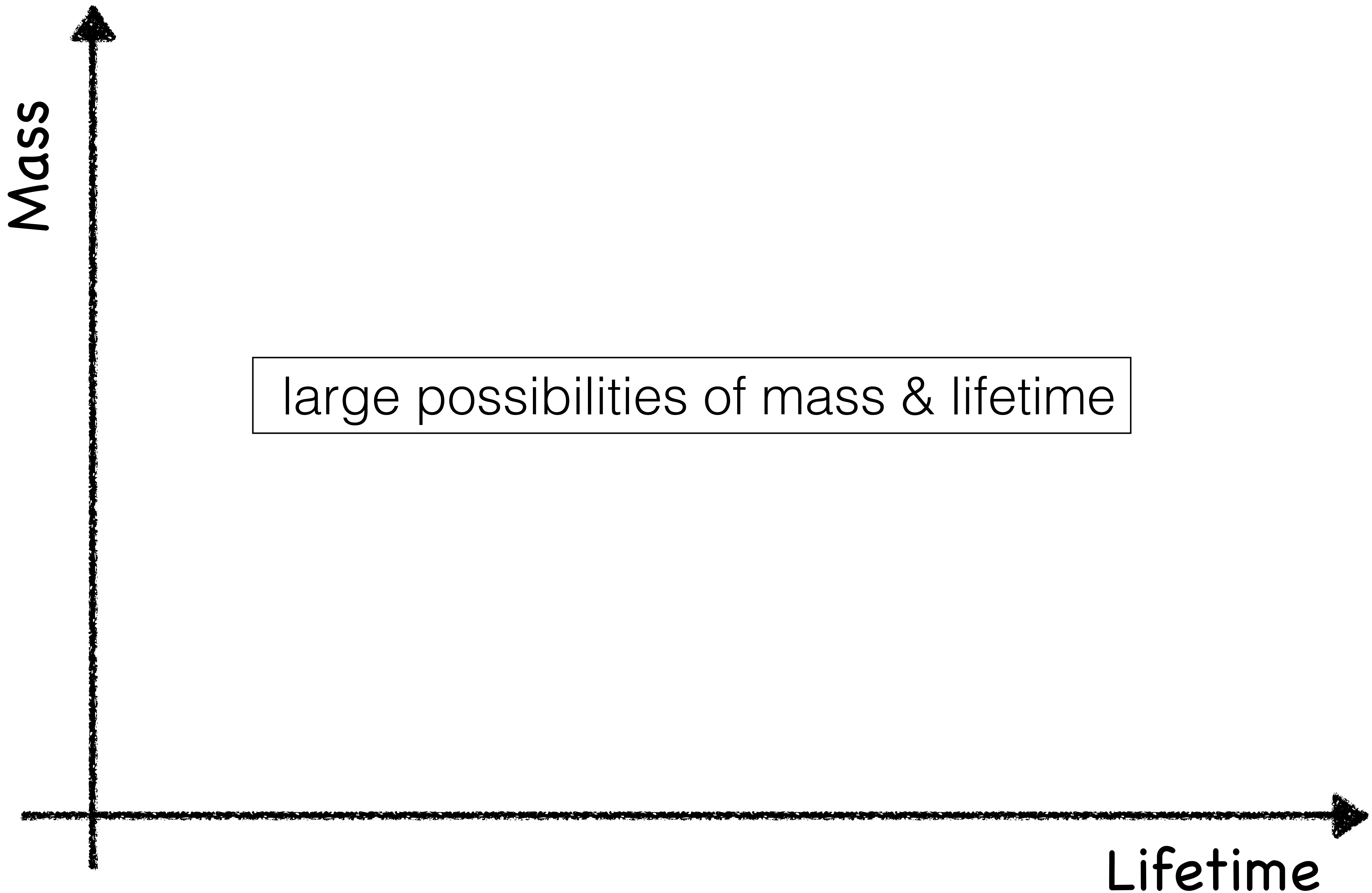
If Higgs decays into > 4 dark mesons,

each of the dark meson has $pT < 20$ GeV

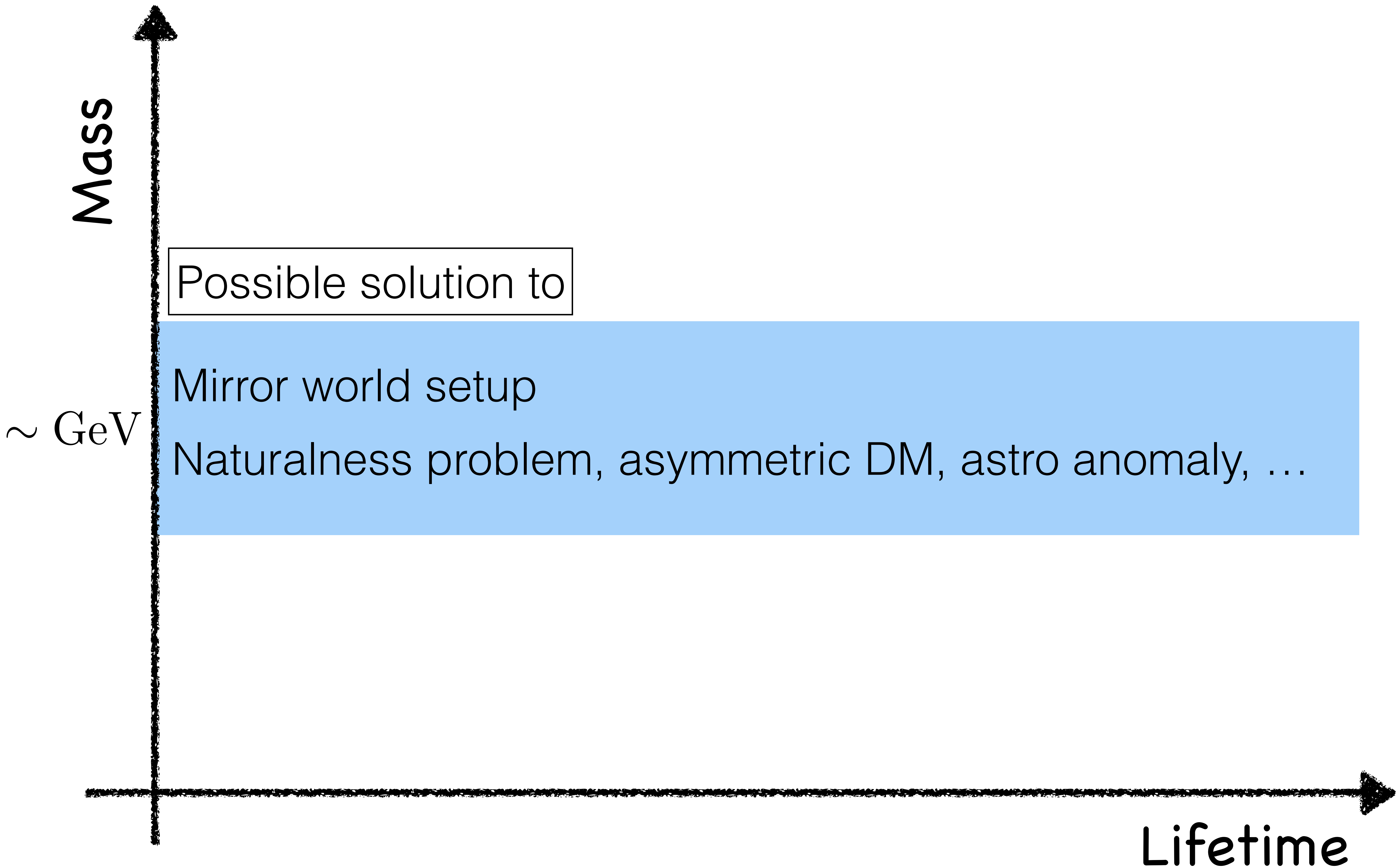
Easy to get low pT signals from dark hadrons

Not easy for ATLAS/CMS (?), easier for the LHCb!

Mass / lifetime of dark mesons?



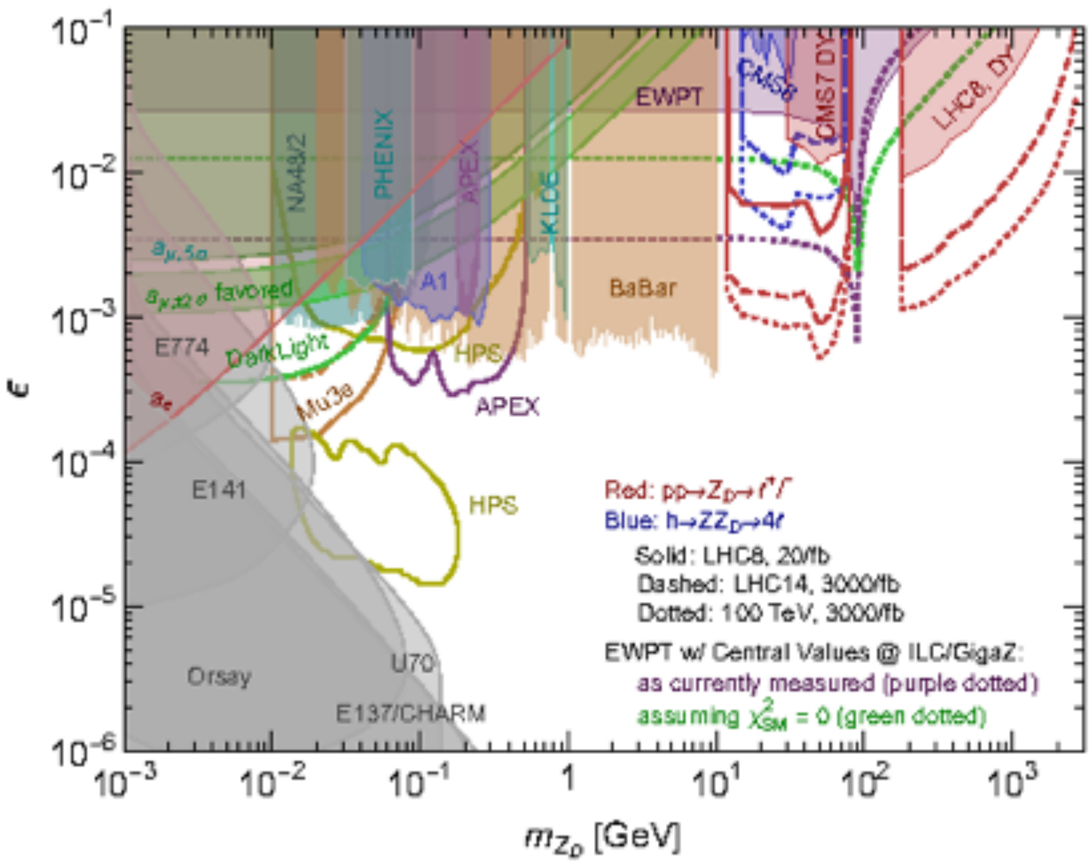
Mirror sector setup prefers ~< GeV LLP mass



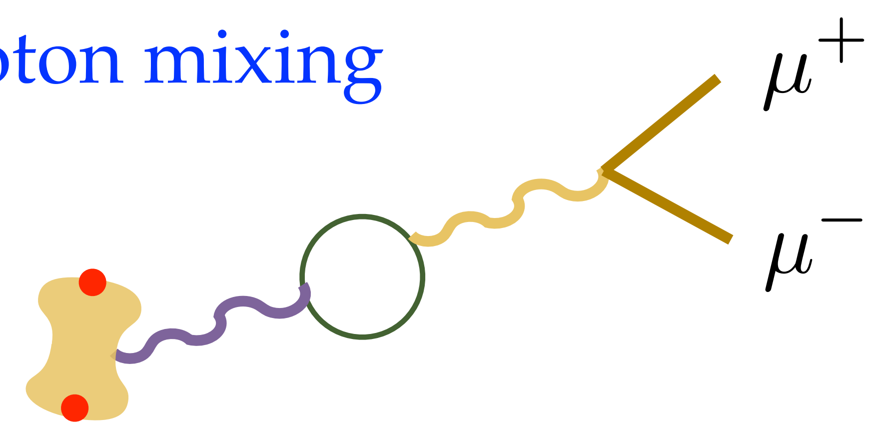
How long do dark hadrons have to live?

Hidden hadron **lifetime** (e.g. from photon mixing)

for ~ GeV meson, dark photon search => $c\tau_{\omega_v} > 10\mu\text{m}$

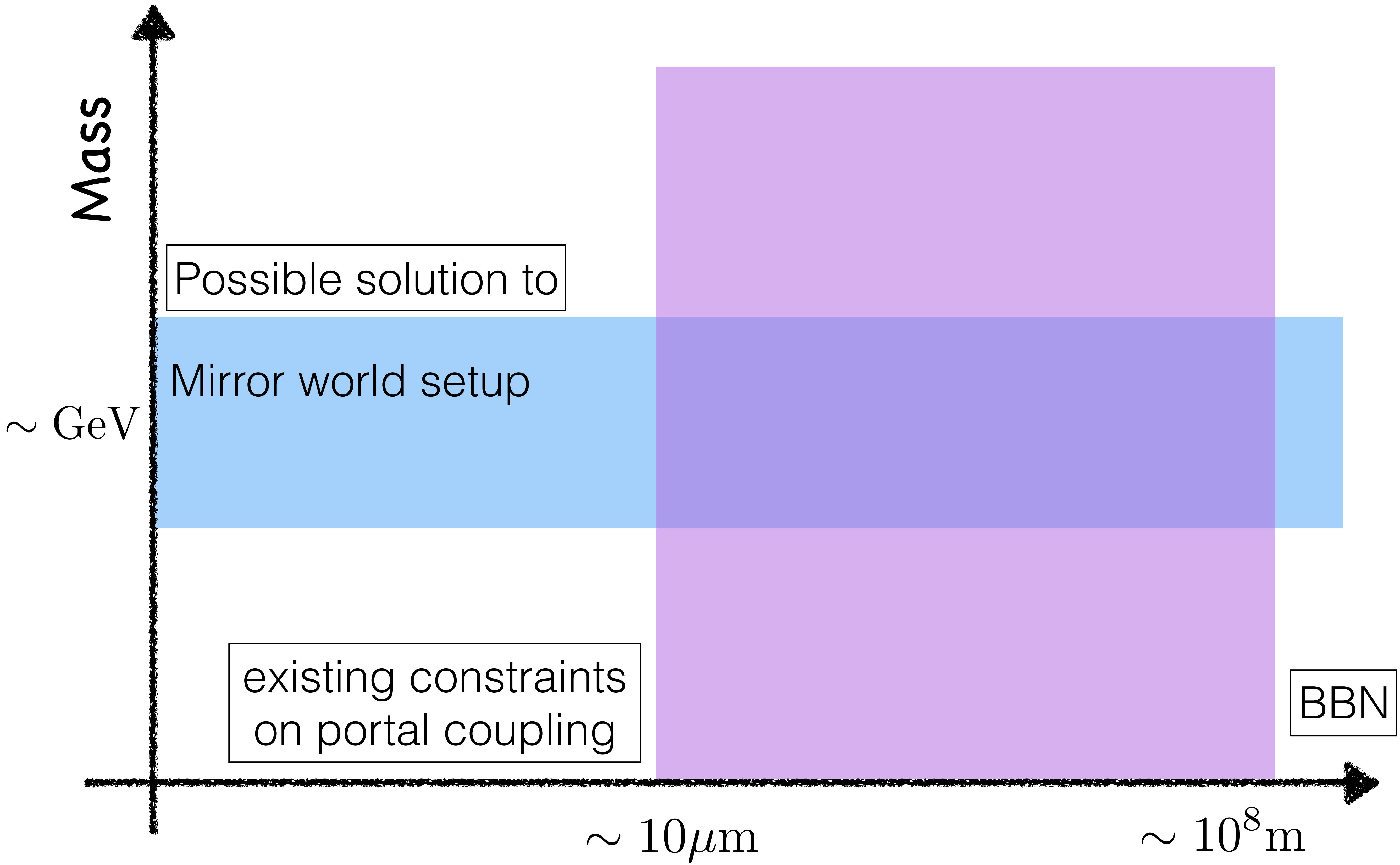


through photon mixing

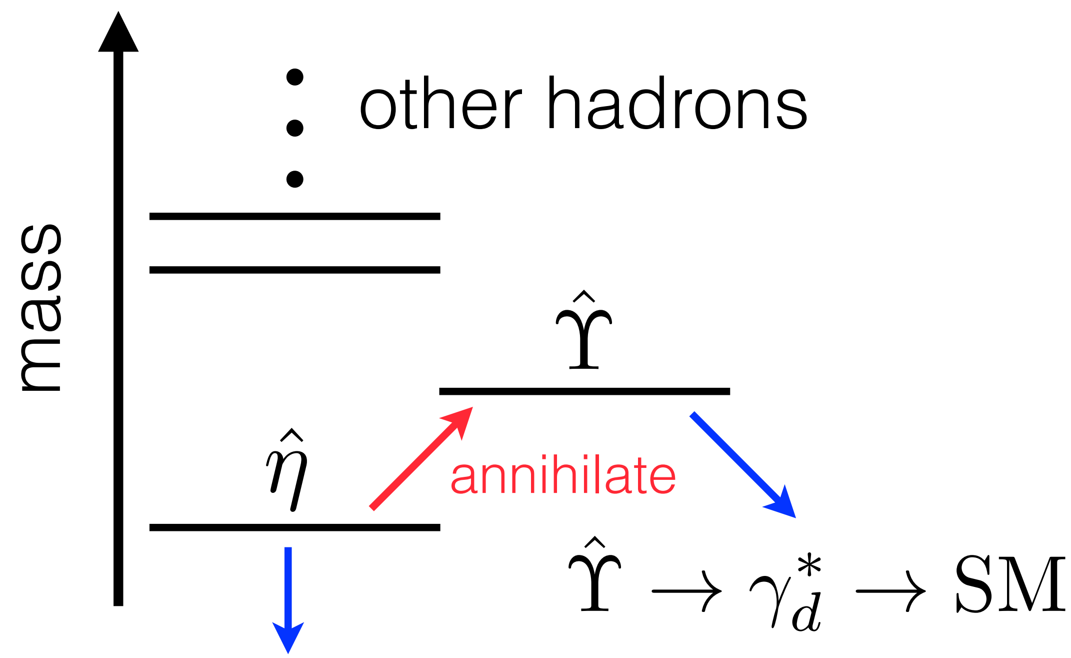


$$c\tau_{\hat{\omega}} \simeq 0.1\,\text{m}\left(\frac{\text{GeV}}{m_{\hat{c},\hat{s}}}\right)^3\left(\frac{m_{\hat{A}}}{20\,\text{GeV}}\right)^4\left(\frac{10^{-3}}{\epsilon}\right)^2\left(\frac{\text{GeV}}{\hat{\Lambda}_{QCD}}\right)^2$$

In general, lifetime can be >> LHCb size



e.g., dark hadrons couple via photon mixing

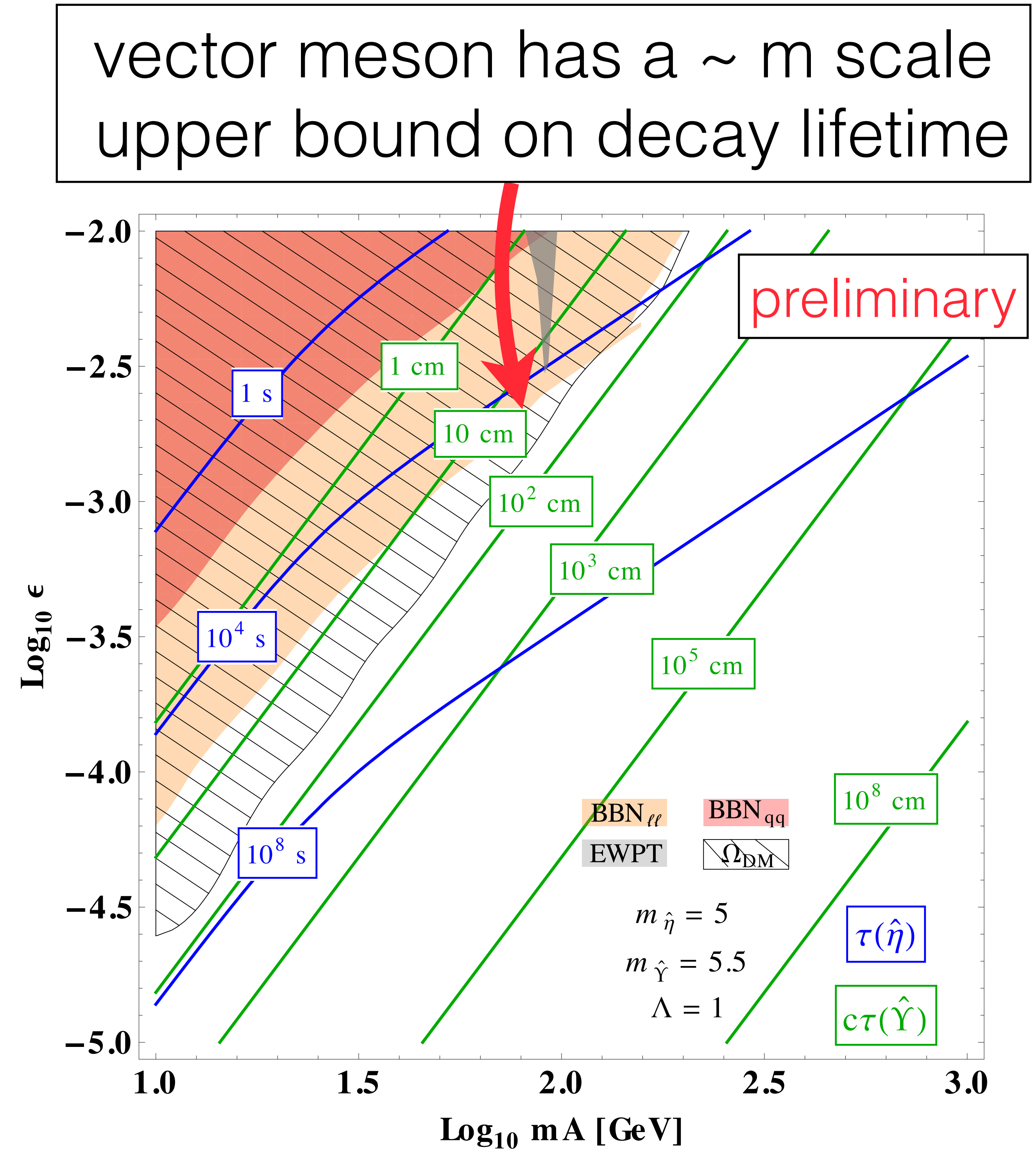


$\hat{\eta} \to \gamma_d^* \gamma_d^* \to \mathrm{SM}$

fast decay

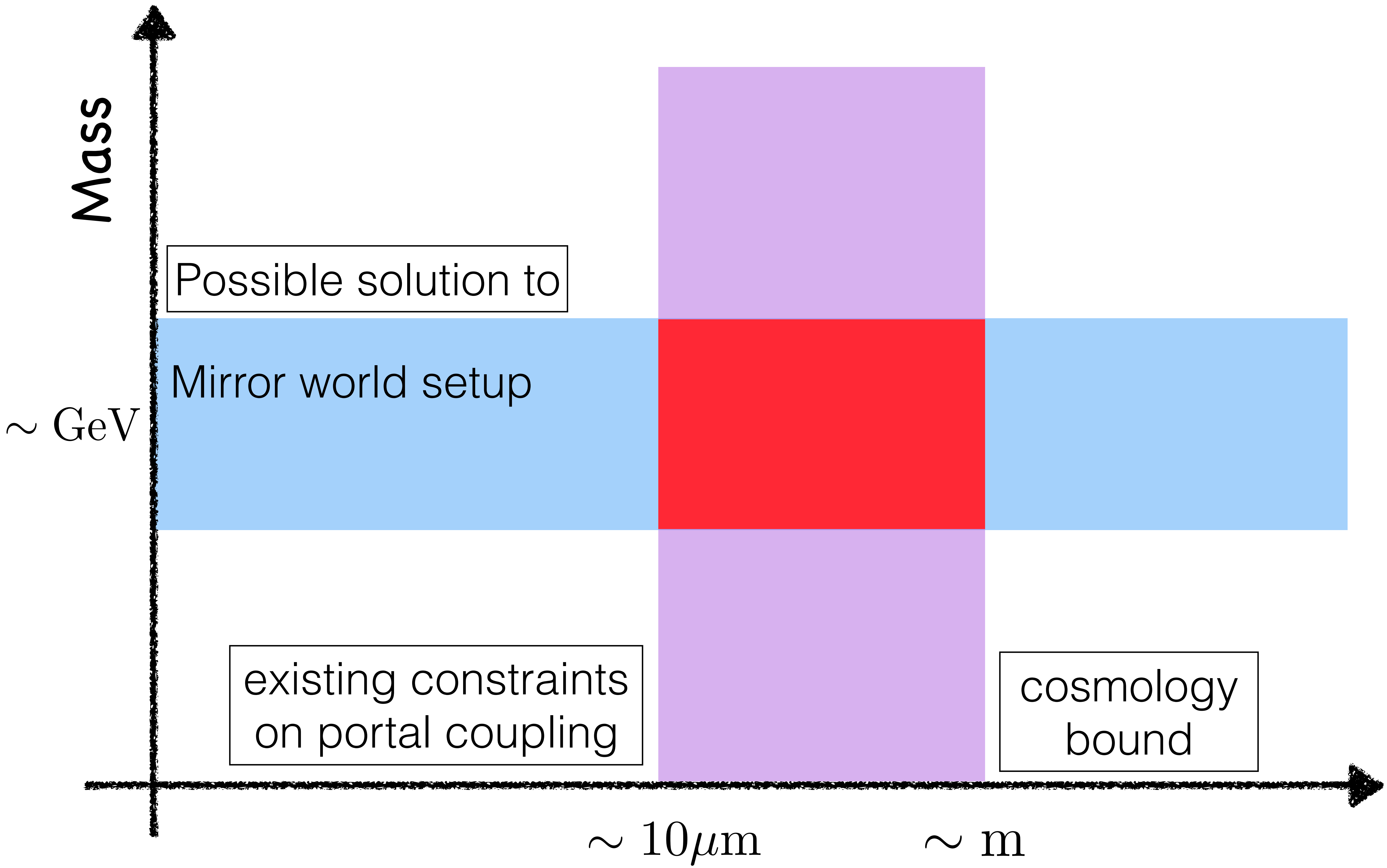
slower decay, ruins BBN

- need to annihilate the lightest state into heavier (easier to decay) states
- the heavier meson needs to decay in SM quickly while the annihilation is efficient



Li & YT (in preparation), also see 1512.02647

LHCb VELO can be large enough



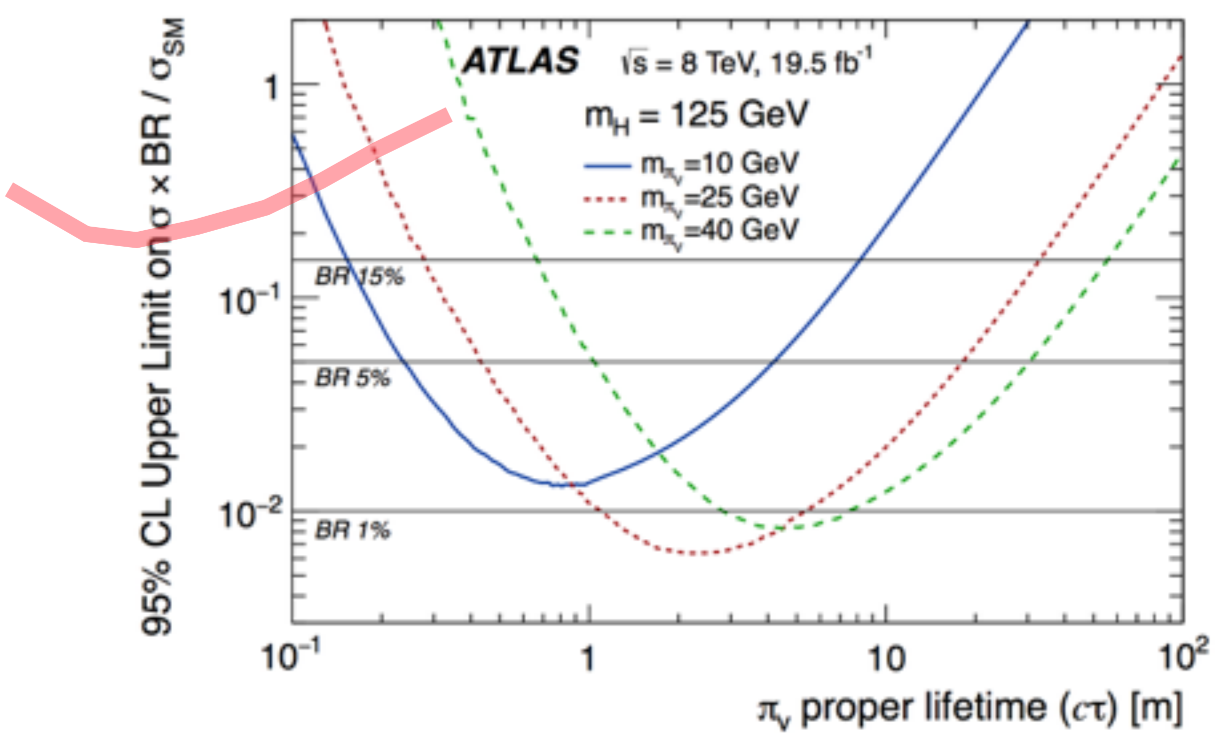
Good at constraining ~ cm scale lifetimes

LLP to jet jet

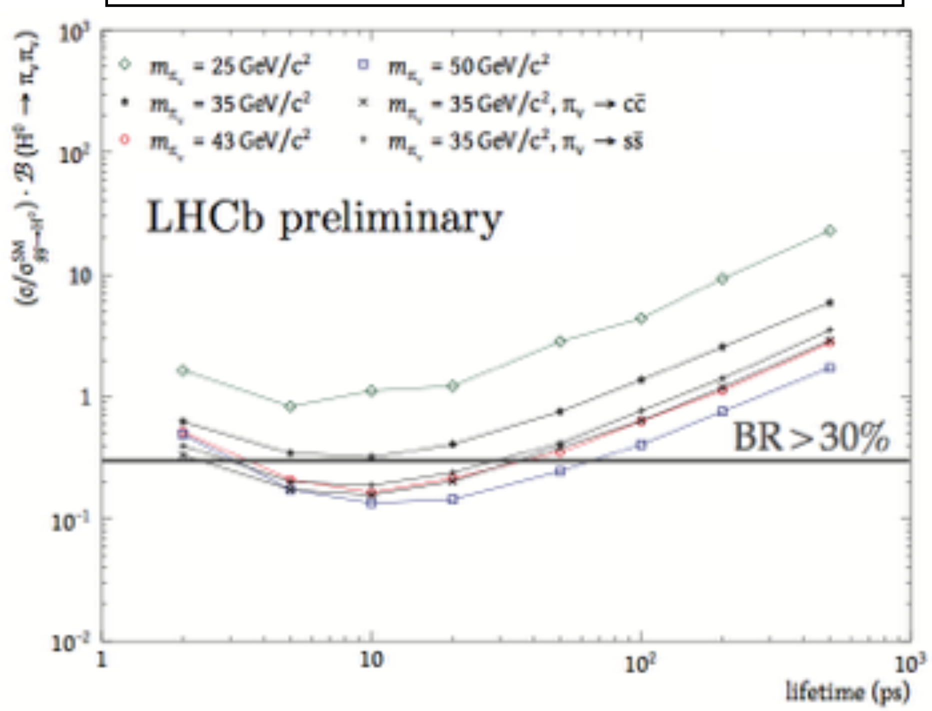
NEW

LHCb-PAPER-2016-065

Displaced hadronic jets ATLAS 1504.03634

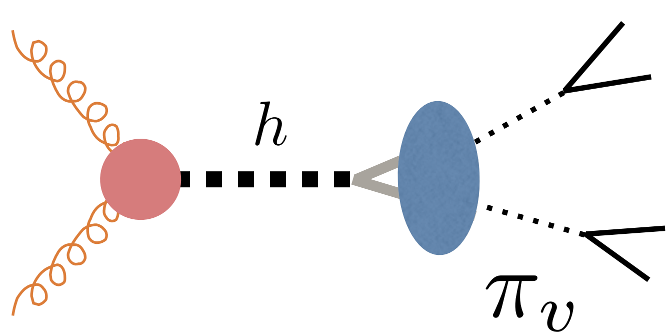


2 / fb of 7 & 8 TeV data



$\sim 0.01\,\mathrm{m}$

Talk by Martino Borsato



$m_{\pi_v} > 10\,\mathrm{GeV}$

Displaced muon search at LHCb

We adopt cuts from the dark photon analysis proposed in

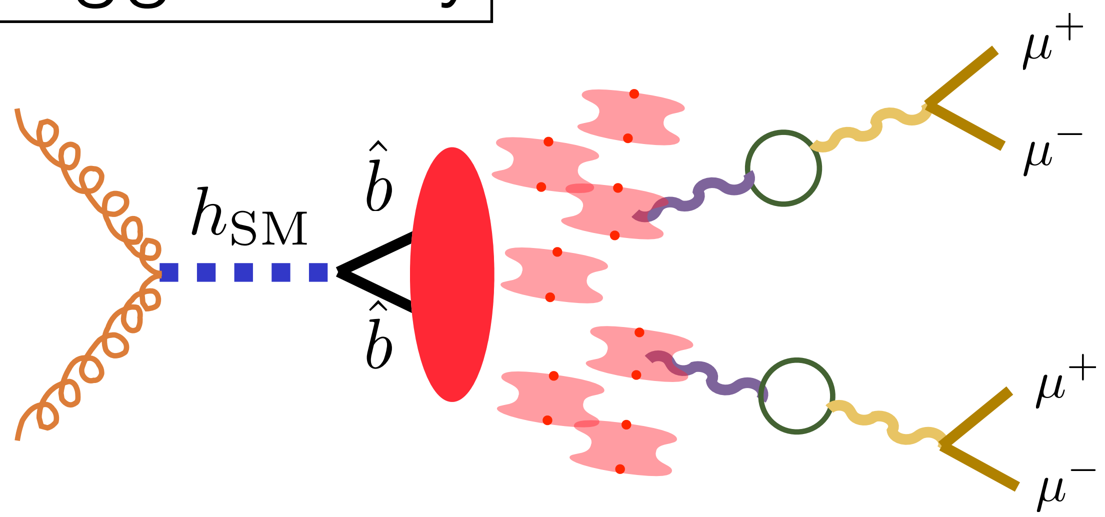
P. Ilten, Y. Soreq, J. Thaler, M. Williams, W. Xue, 1603.08926

$\eta(\mu^{\pm}) \in [2,5]$, $p(\mu^{\pm}) > 10\,\mathrm{GeV}$, $p_T(\mu^{\pm}) > 0.5\,\mathrm{GeV}$

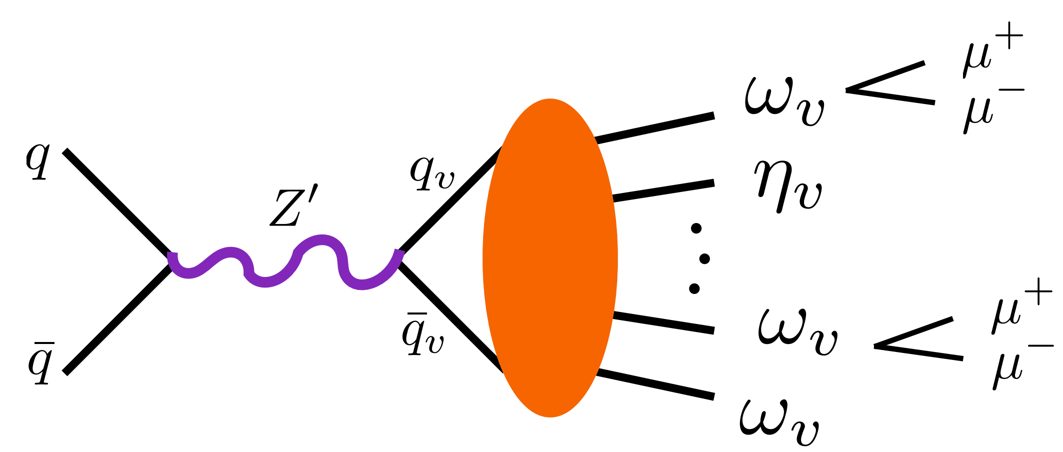
Muon id efficiency $\epsilon_{\mu}^{2} \approx 0.50$

$\eta(\omega_v) \in [2,5]$, $p_T(\omega_v) > 1\,\mathrm{GeV}$ $\qquad \ell_T \in [6\,\mathrm{mm},\ 22\,\mathrm{mm}]$

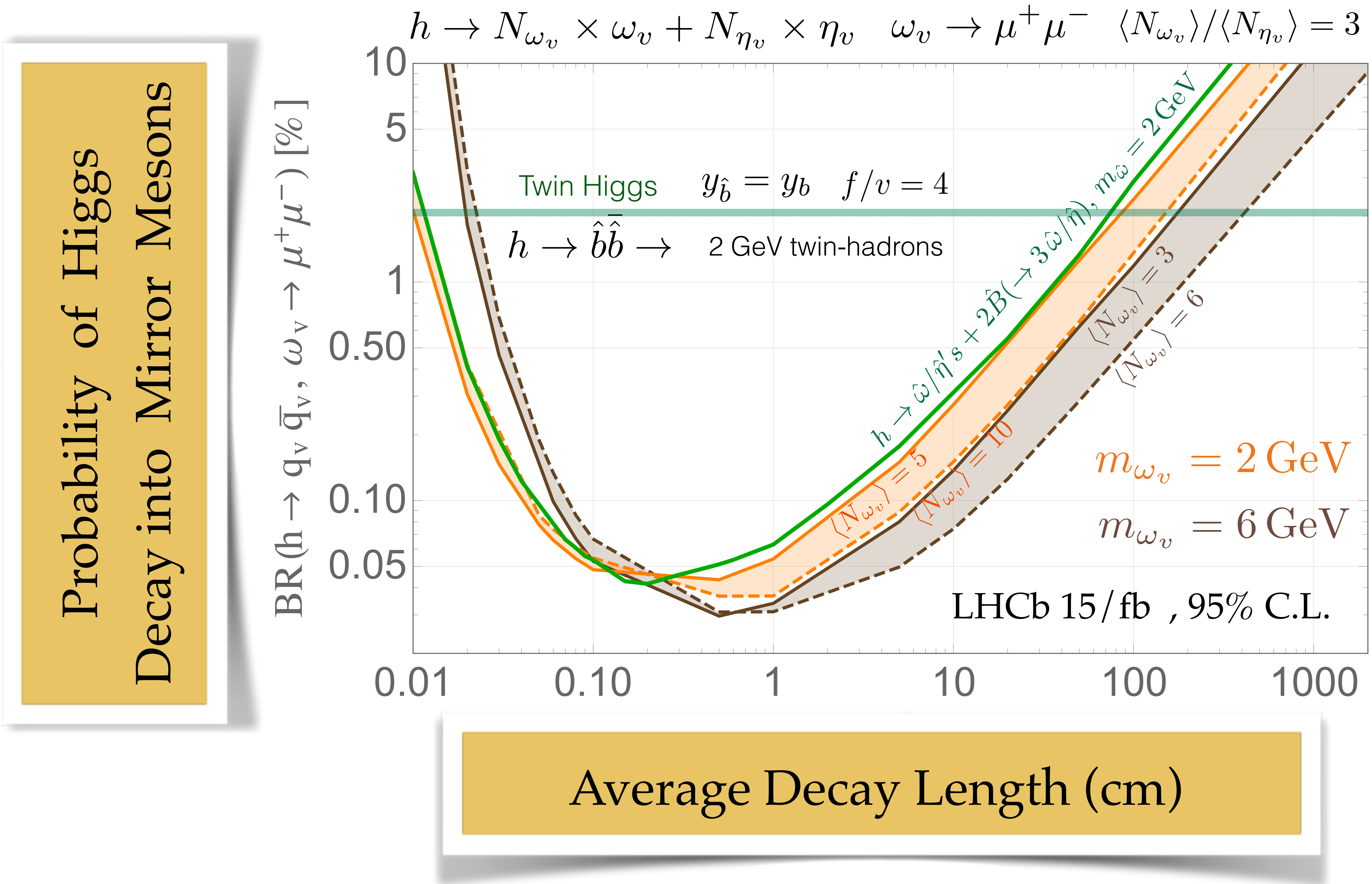
Higgs decay



Z' model



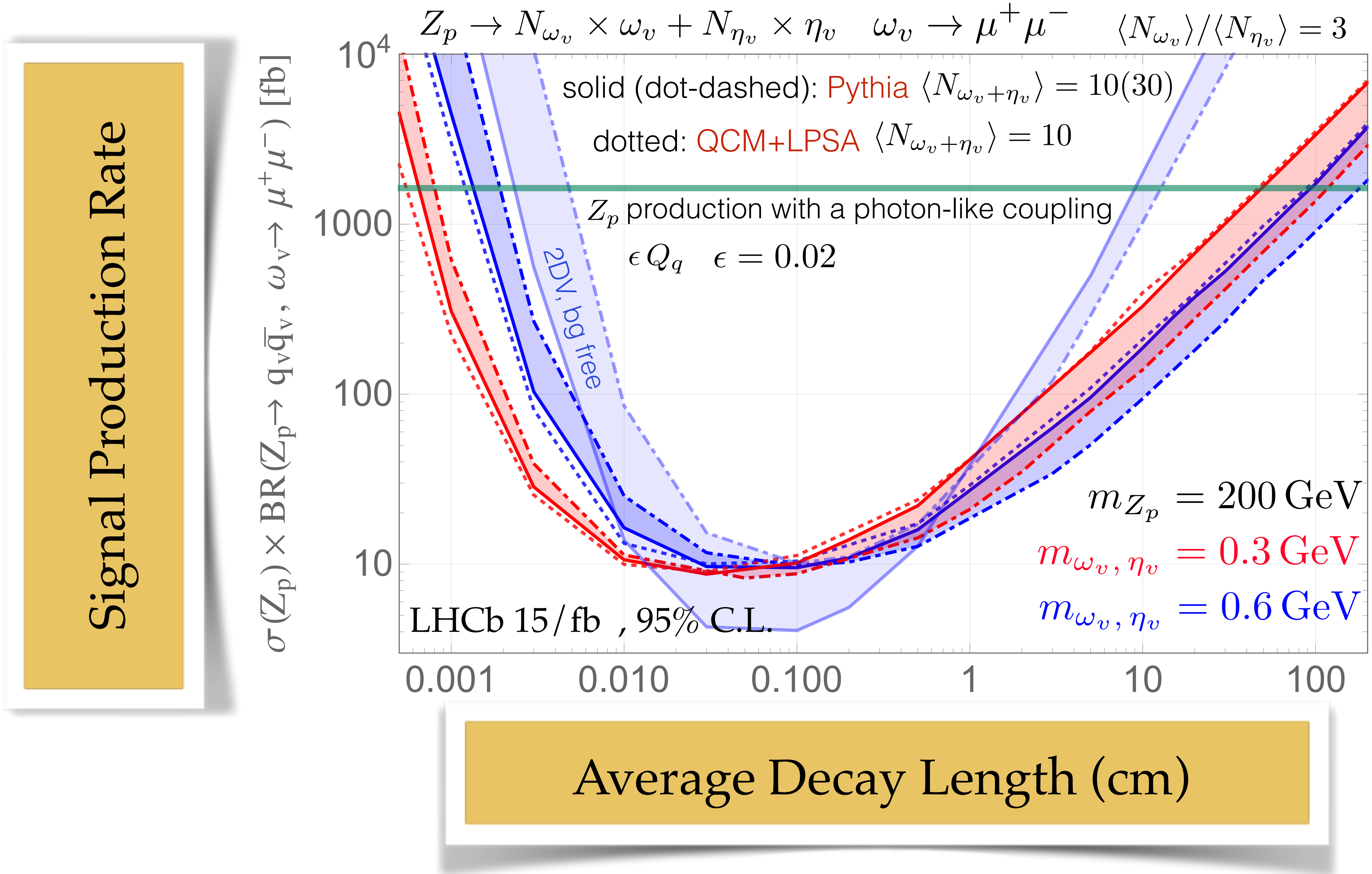
LHCb constraint on the exotic Higgs decay



Pierce, Shakya, YT, Zhao (2017)

Z′ decays into dark hadrons

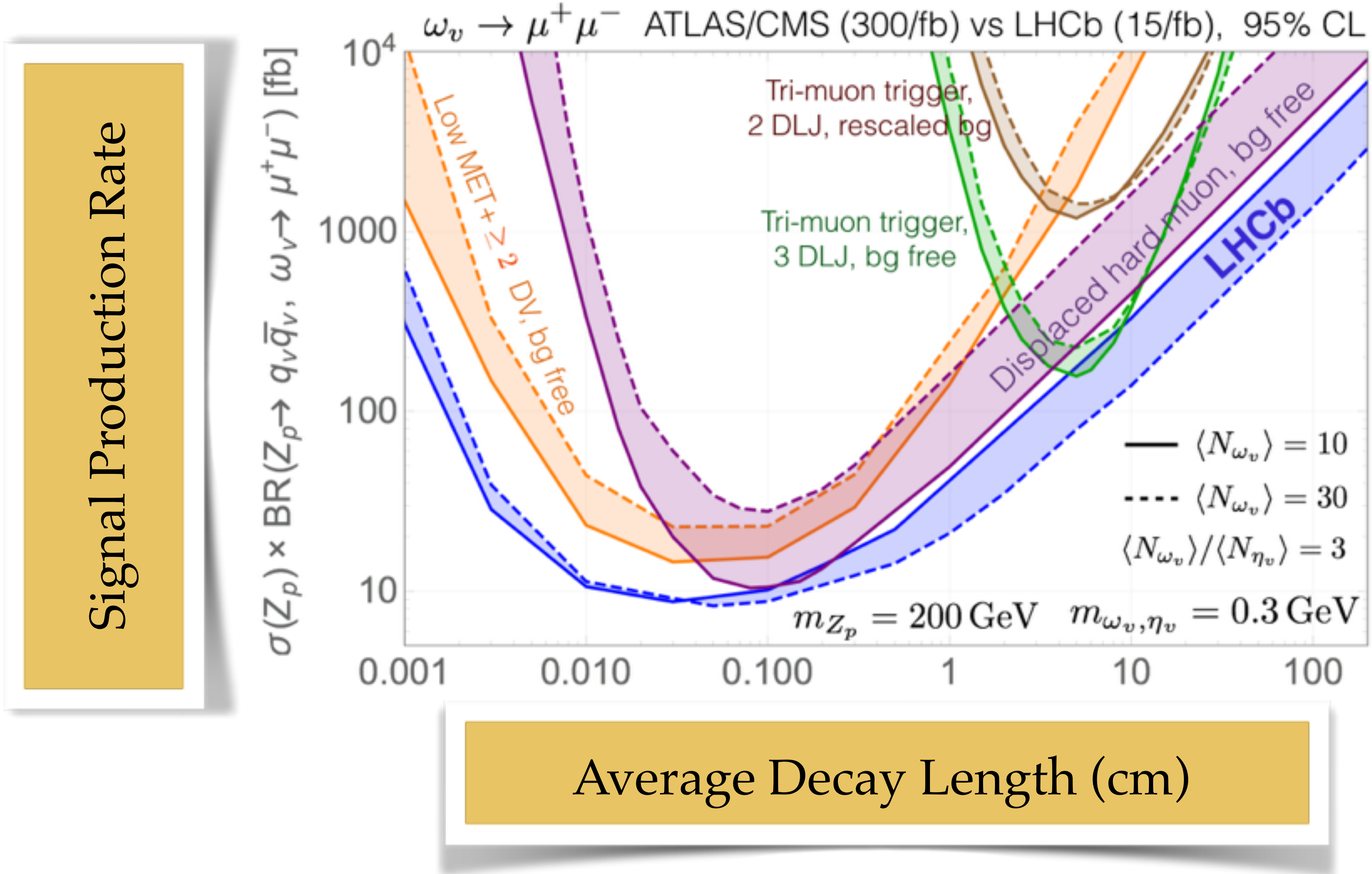
when average muon pT ~ 3 - 9 GeV



Pierce, Shakya, YT, Zhao (2017)

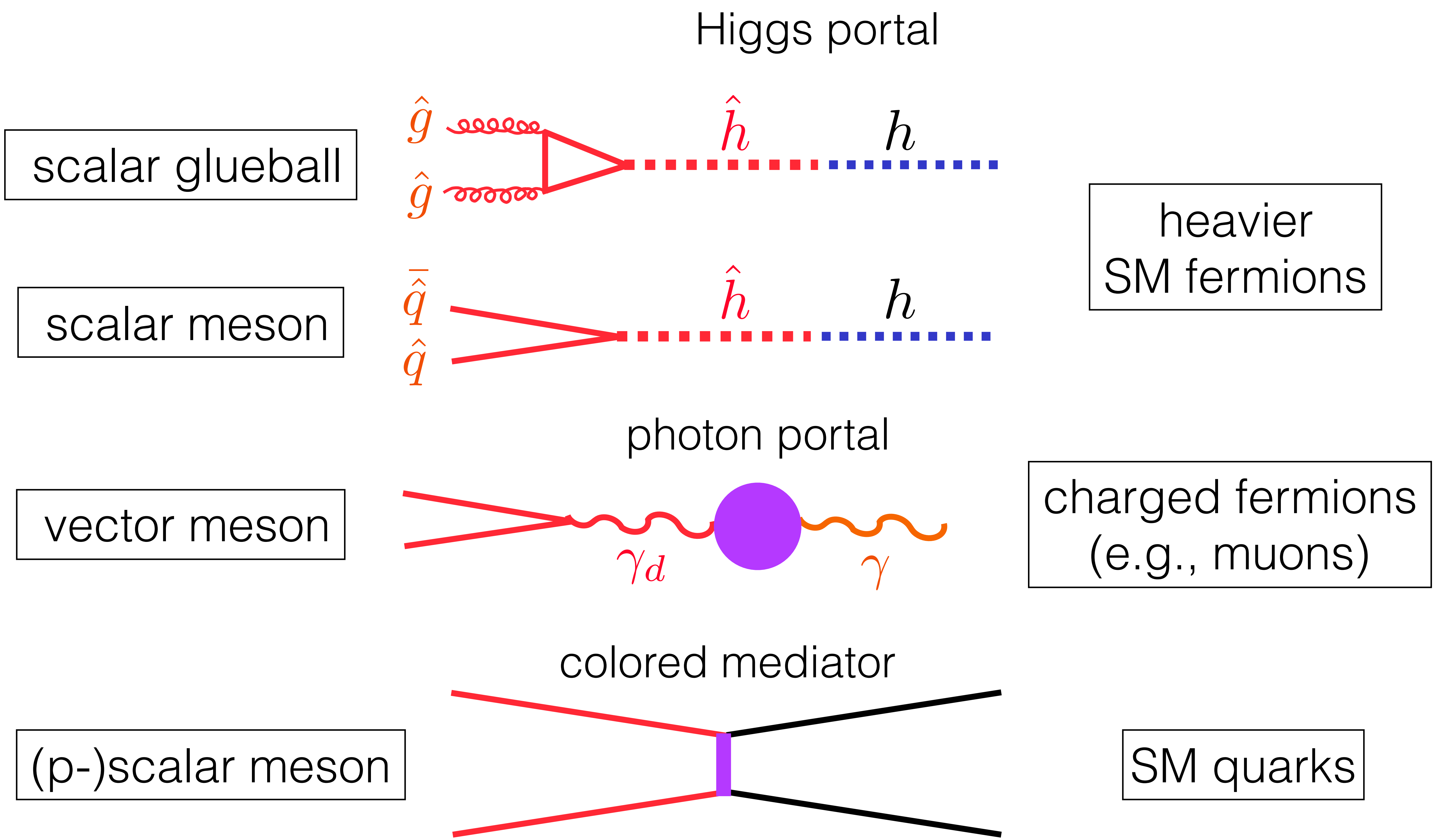
A rough comparison to the ATLAS / CMS searches

when average muon pT ~ 3 - 9 GeV



Pierce, Shakya, YT, Zhao (2017)

Different ``portals" connect SM & Dark



Dark hadrons can easily decay hadronically

Low mass (< 10 GeV) hadronic LLP decay is hard to search at ATLAS/CMS (?)

In LHCb, if decay final states are hadrons that are easy to identify, such as kaons, pions, baryons,…
sub-GeV hadronic LLP decay can be achievable

E.g., displace decay into D-mesons

Based on the LHCb $B^0 \to D^+ D^-$ search 1608.06620

Consider $D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$ $D^0 \to K^- 2\pi^+ \pi^-$

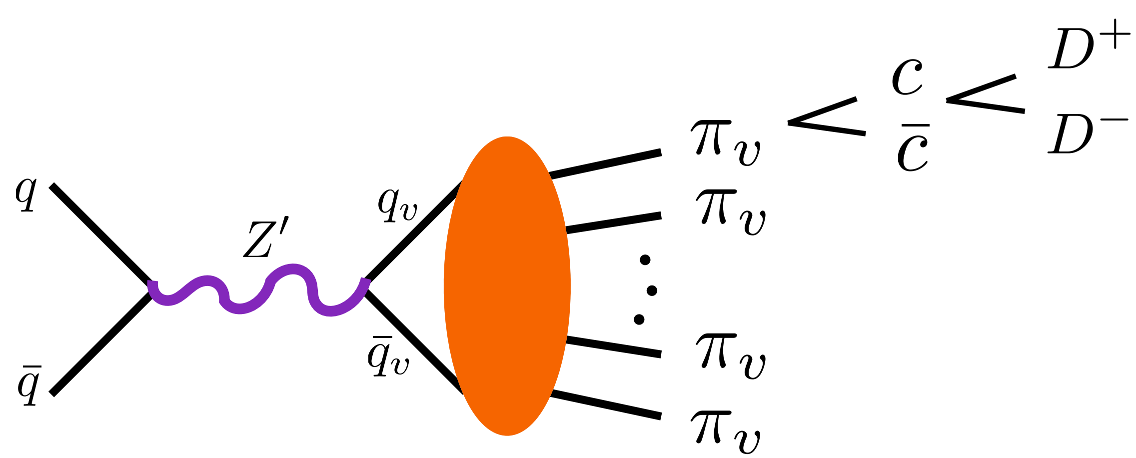
(9.5% Br) (8% Br)

2 reconstructed D-mesons

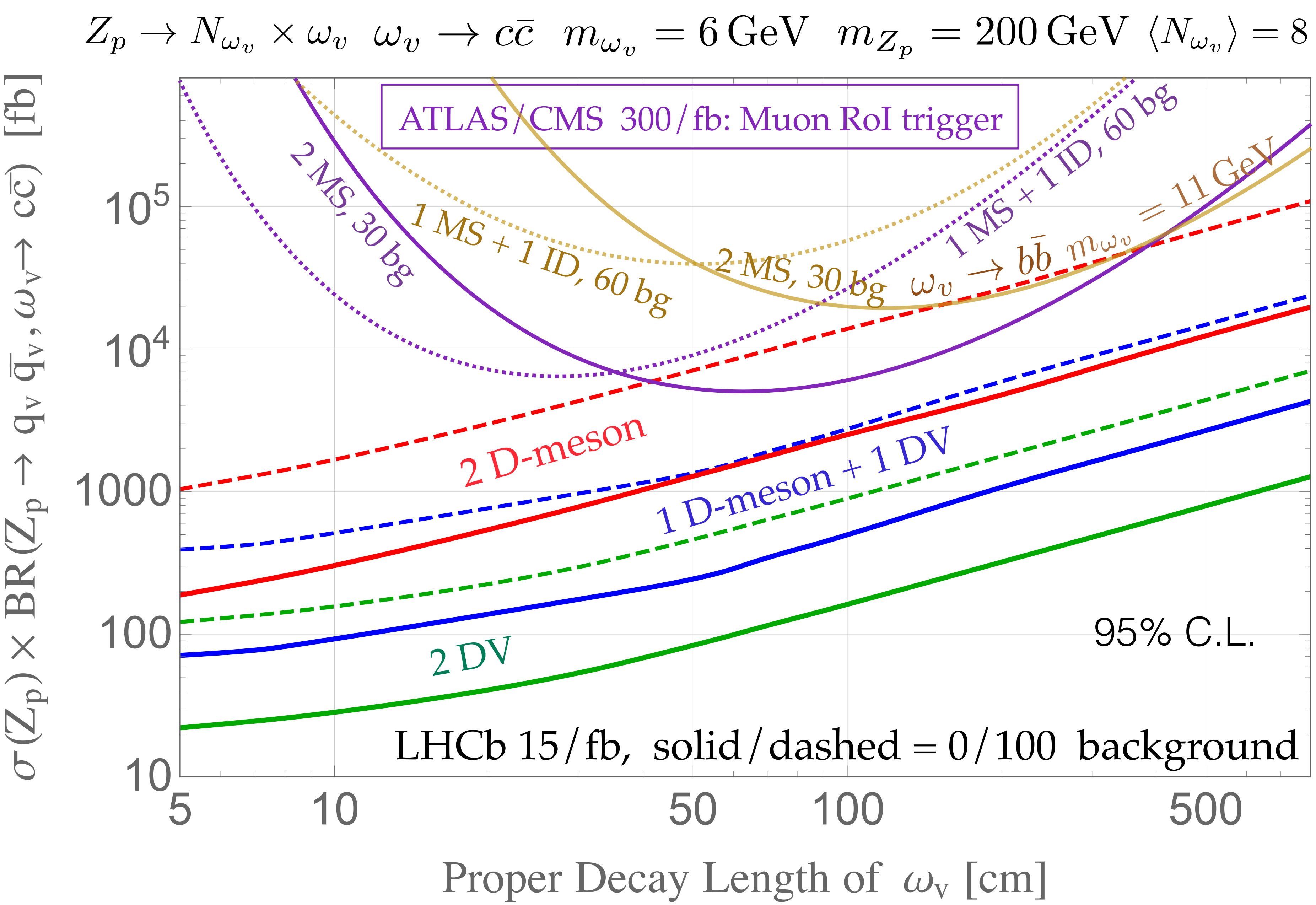
track pT > 0.1 GeV, D-meson HT > 1.8 GeV
DV p > 10 GeV, total D-meson pT > 5 GeV
$\ell > 10c\tau_D$

1 D-meson + 1 DV (>= 3 tracks)

2 DV (>= 3 tracks)



HV decay into D-mesons



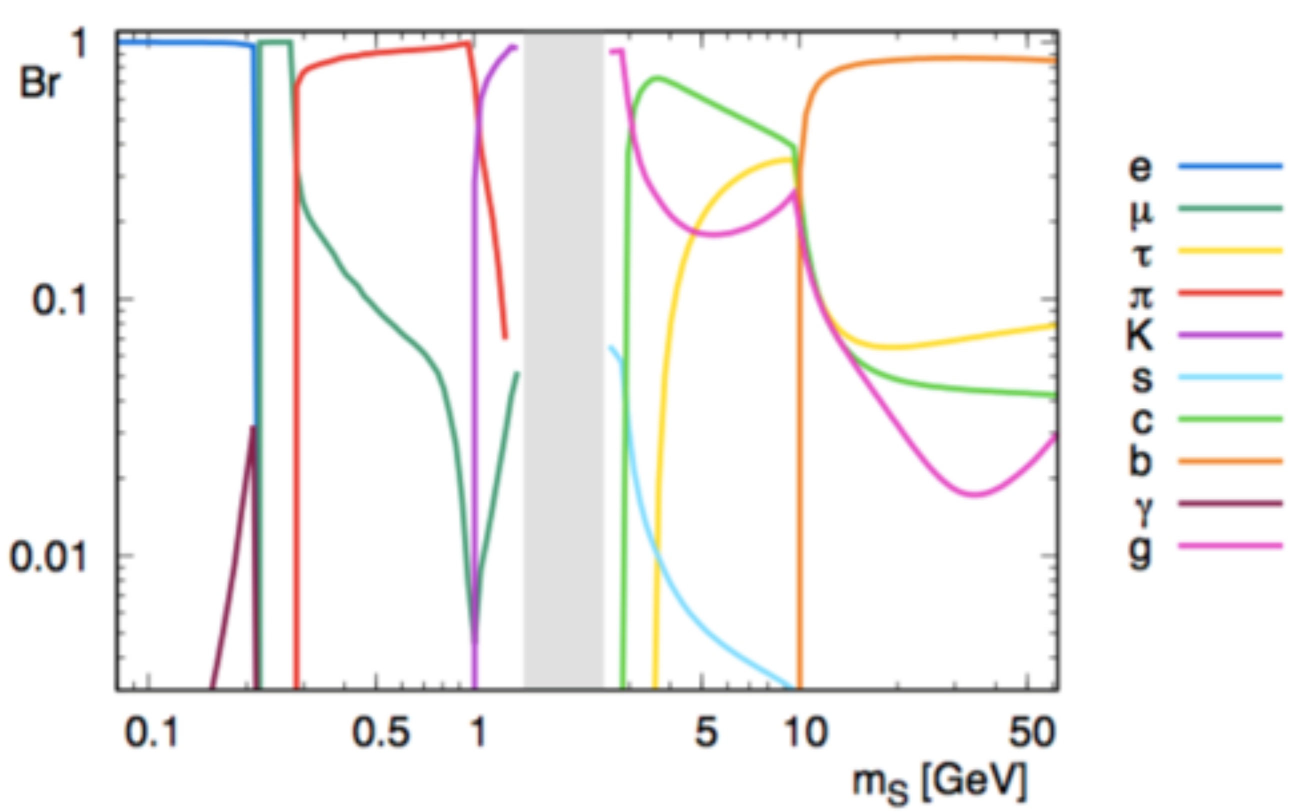
Pierce, Shakya, YT, Zhao (2017)

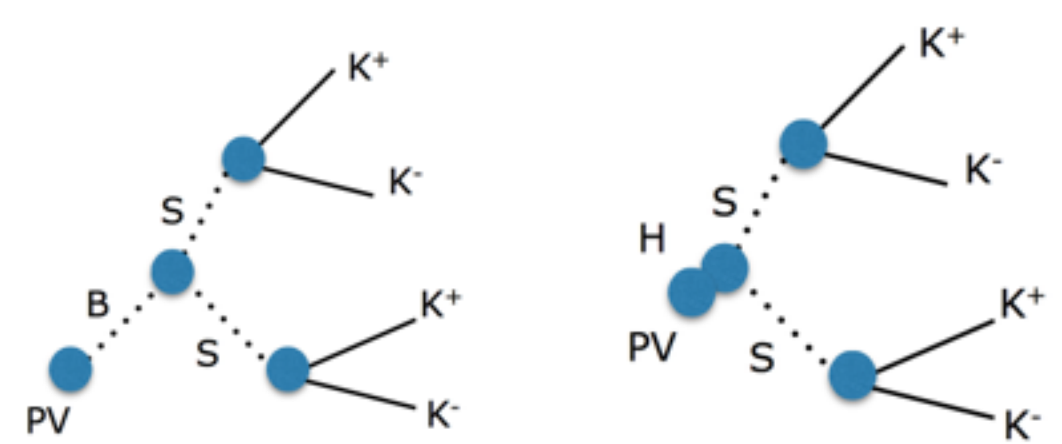
More exclusive search on the LLP decay

Shuve, Pospelov, YT, Vidal, Zurita (in progress)

different signature, but similar idea

$$-\mathcal{L}_S = \frac{\lambda_S}{4} S^4 + \frac{m_0^2}{2} S^2 + \lambda S^2 H^\dagger H$$

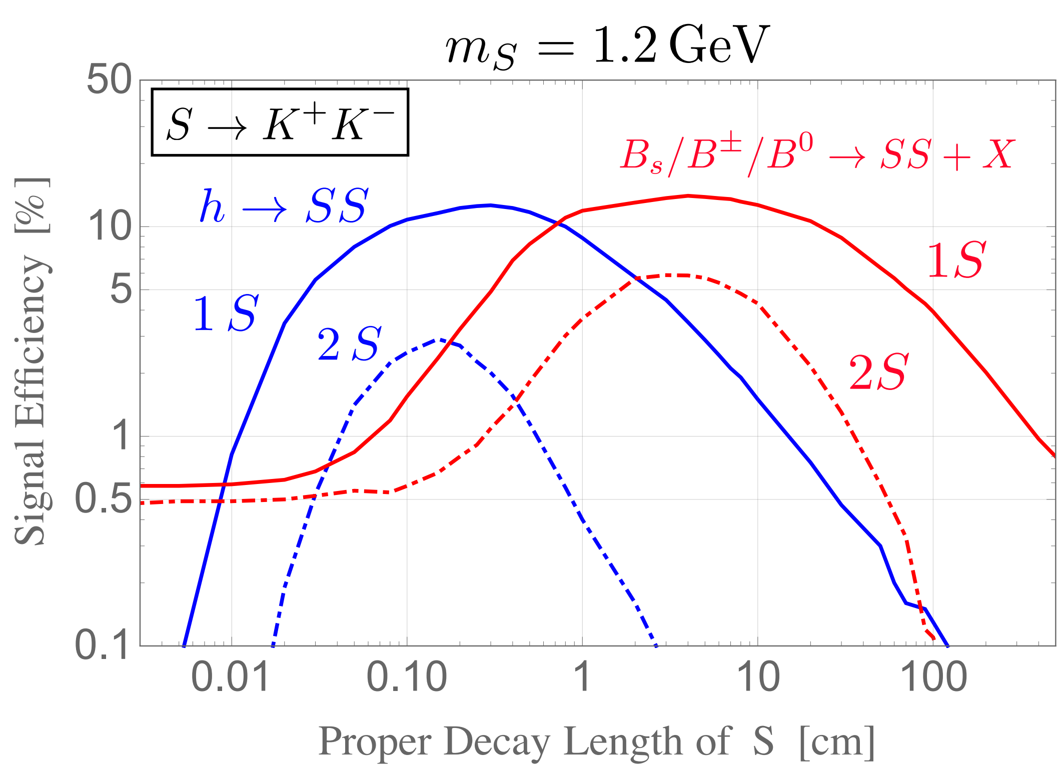


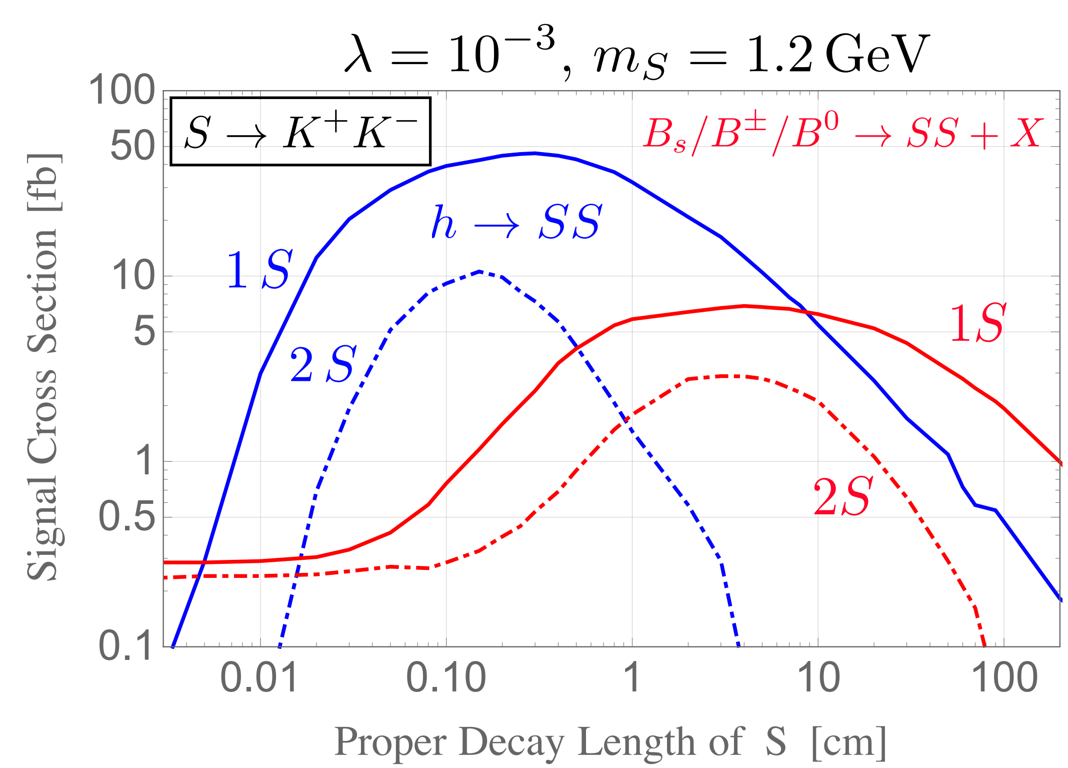


background can be low
with tight isolation cuts
+ mass resolution + kaon id

- Look at H or B yields for m(S)=1.2 GeV/c^2, and BR(S → K^+K^-) = 1
  - K p_T > 0.5 GeV/c and 2 < η < 5 for every kaon
  - S decay location 2 < ρ < 25 mm , z < 400 mm

    (ρ in cylindrical coordinates)





very^2 preliminary: with 15/fb of data, probe the 2S cross ~ 2 fb

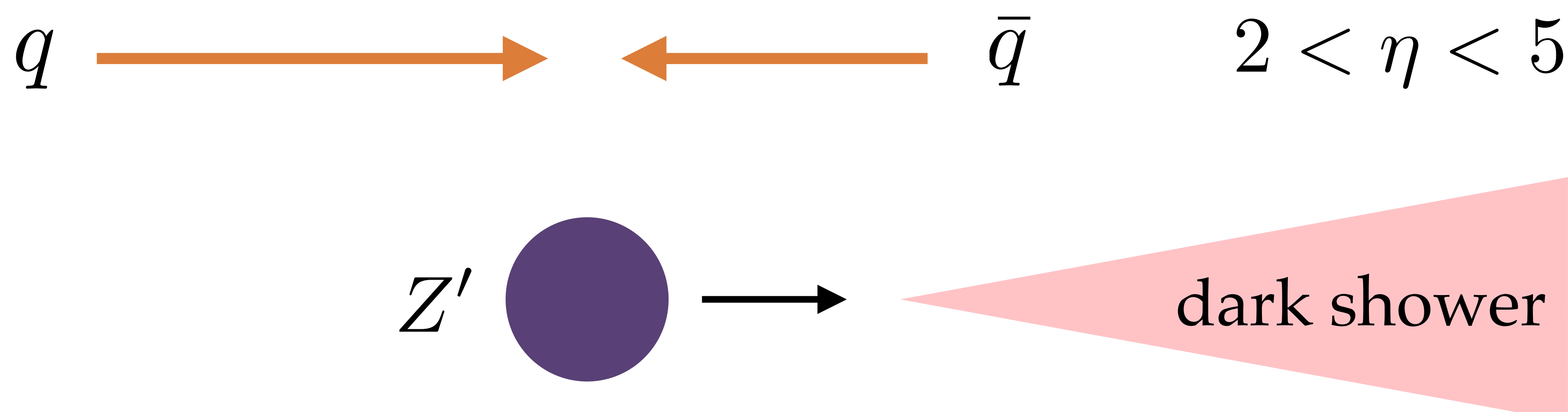
Backup Slides

SM		Twin
y_t	$=$	$y_{\hat{t}}$
SU(3) x SU(2) gauge couplings	$=$	SU(3) x SU(2) gauge couplings
EWSB scale v	$\simeq$	EWSB scale f
Other Yuakwa couplings	$\sim$	Other Yuakwa couplings
U(1)Y coupling	$\sim$	U(1)Y coupling

Low pt requirement

Good for high multiplicity decay from a light mediator

For a 500 GeV Z' decaying into 30 mesons, average meson pT ~ 10 GeV

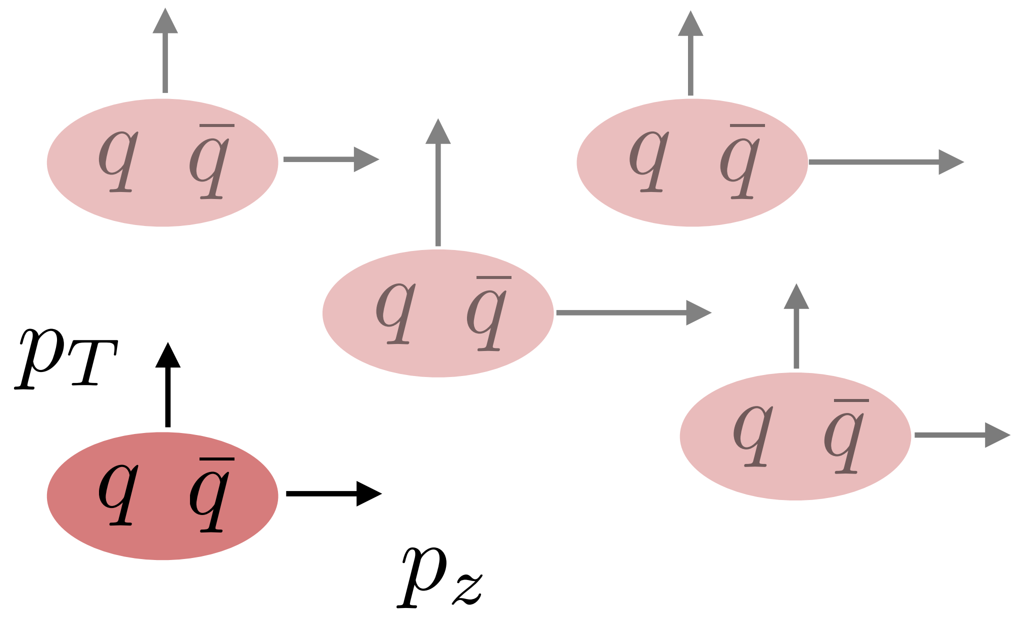


$2 < \eta < 5$ at LHCb

For 500 GeV Z′, geometrical acceptance ~ 30% of ATLAS / CMS

Quark-combination model + Longitudinal Phase Space Approximation

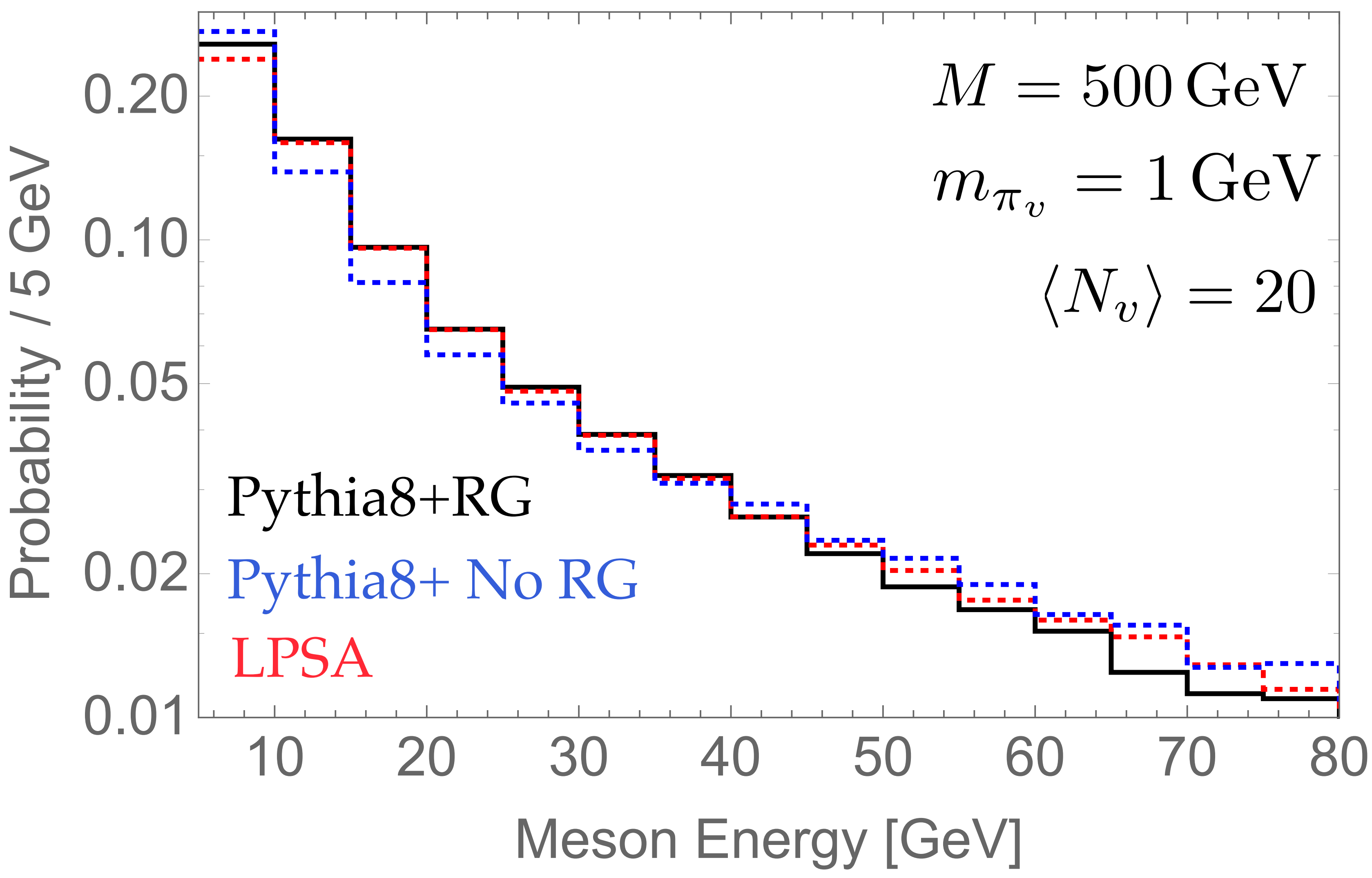
See the discussion in Han, Si, Zurek, Strassler (07')



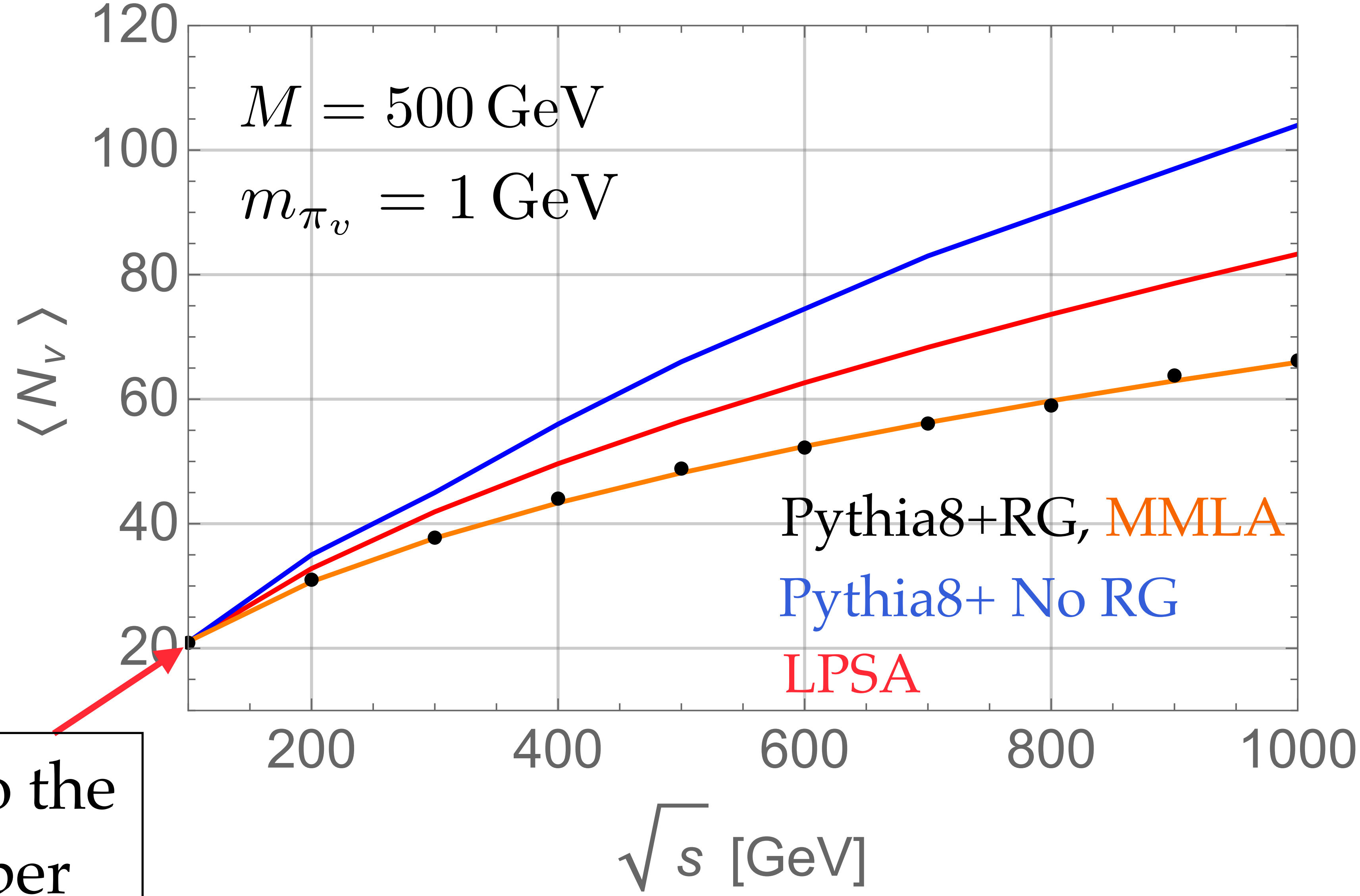
Assume the mesons have a uniform rapidity distribution along the original qqbar => gives longitudinal momentum

For transverse momentum, Prob $\propto \prod_i \exp(-p_{Ti}^2/\bar{\sigma}^2)\delta(\sum \vec{p}_{Ti})$

Energy spectrum from different S/H schemes



Multiplicity from different S/H schemes



Normalize to the same number

Cannot predict the multiplicity