Probing Hidden Valley at the LHCb

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PHENO 2017

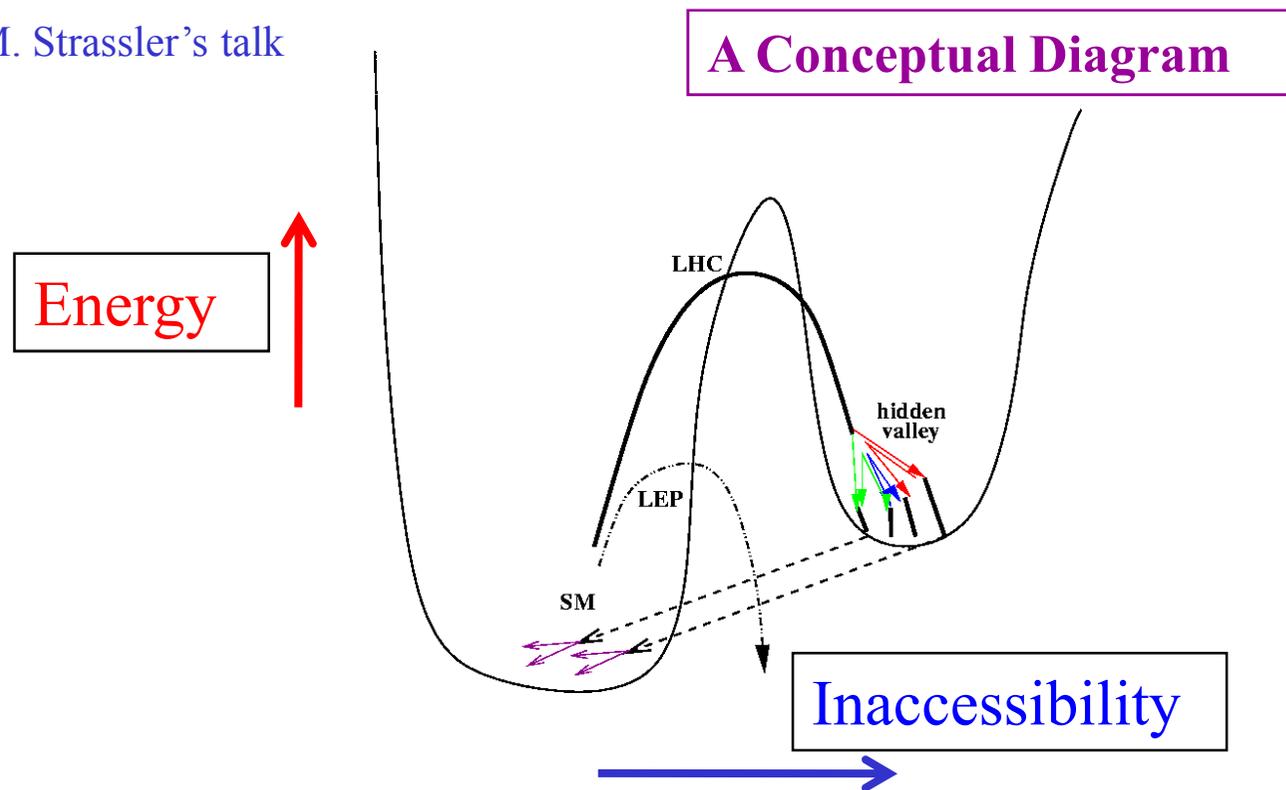with Aaron Pierce, Bibhushan Shakya,Yuhsin Tsai
arXiv:1705.xxxxx

Non-Abelian Dark Sector

Dark Sector remains largely unknown.

Non-abelian choice on Dark Sector remains to be further studies!

• Generically classified as Hidden Valley models.
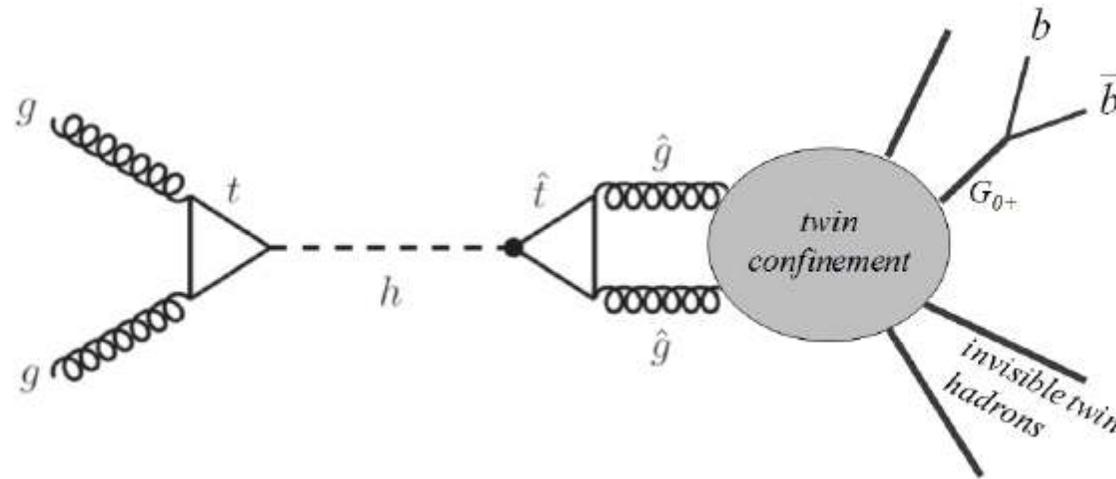
Non-Abelian Dark Sector

Dark Sector remains largely unknown.

Non-abelian choice on Dark Sector remains to be further studies!

• May have close connections to Naturalness solutions (Twin Higgs models)
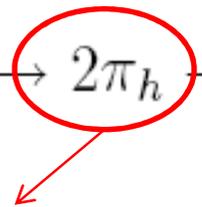
Naturalness in the Dark at the LHC

N. Craig, A. Katz, M. Strassler, R. Sundrum
JHEP 1507 (2015) 105

Hidden Valley searches at the ATLAS/CMS

Many existing searches at the ATLAS/CMS:

Due to non-trivial trigger requirements,
mainly focus on very special hadronization scheme,

$$pp \rightarrow \text{resonance} \rightarrow q_h \bar{q}_h^* \rightarrow 2\pi_h \rightarrow \text{SM}$$

Generically expect many soft hidden pions are produced.
However, SM final states cannot be too soft to be triggered at ATLAS/CMS.
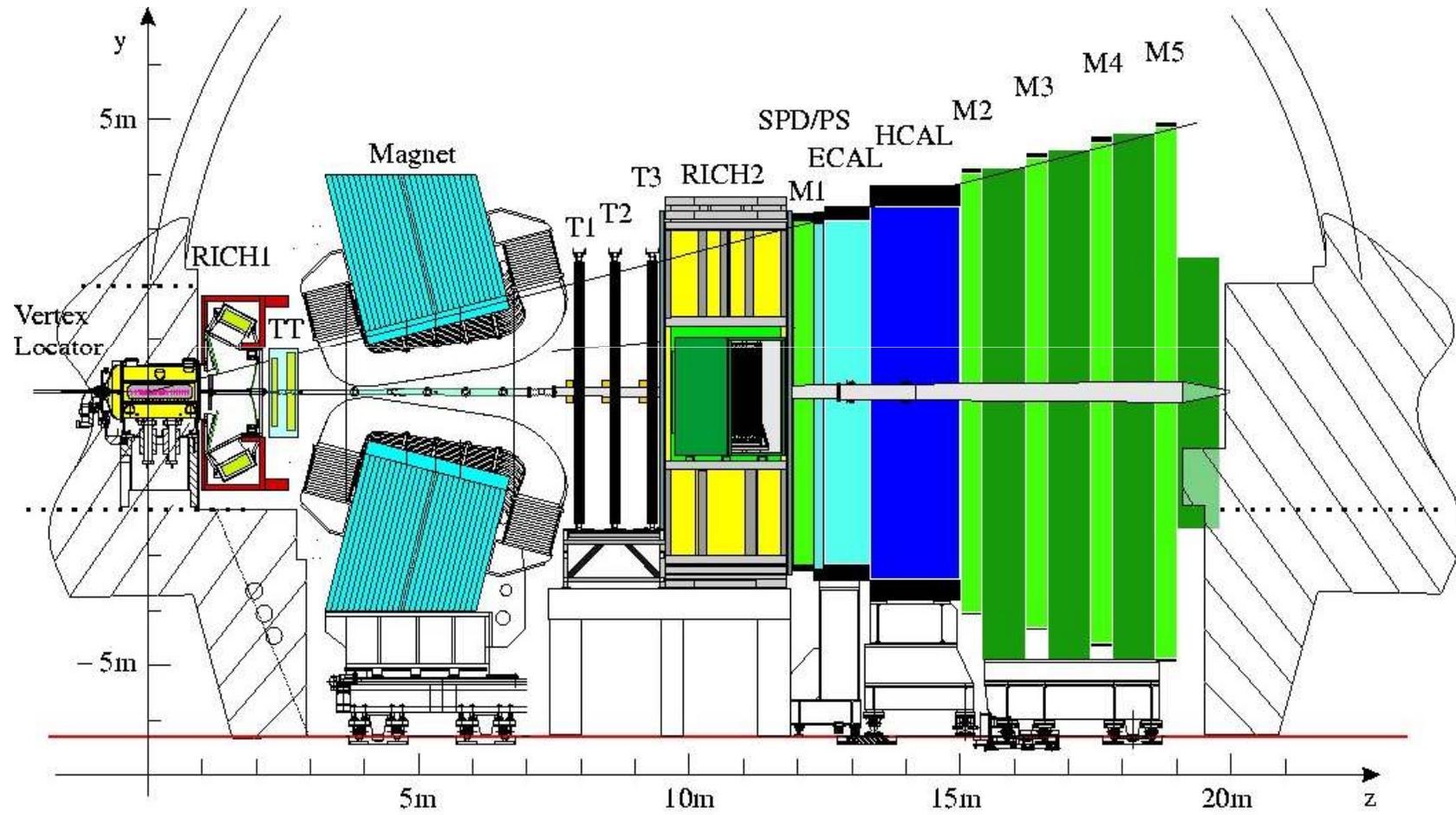
or requiring hidden pions to be very massive.

LHCb: Similar searches are also carried out:

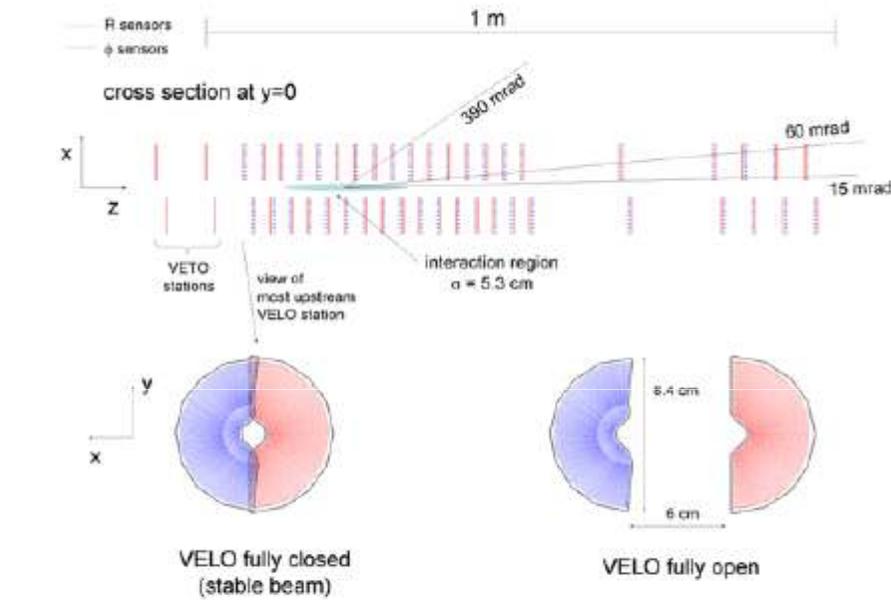Search for long-lived particles decaying to jet pairs
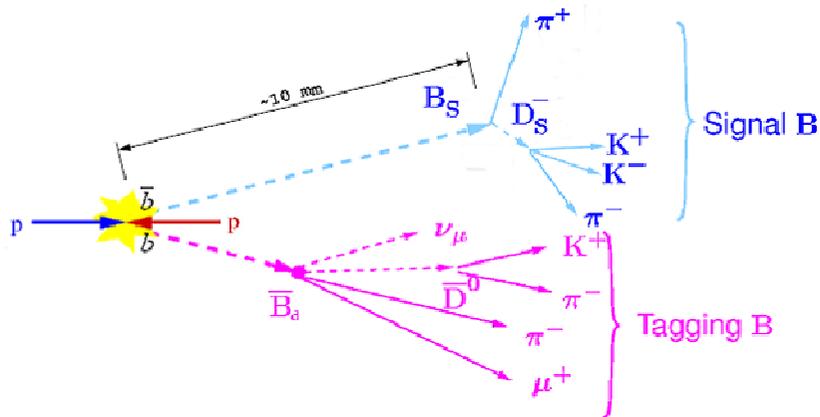Eur. Phys. J. C75 (2015) 152

but also with two hidden pions in the final states.
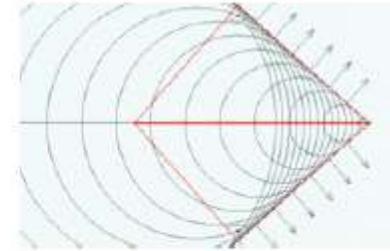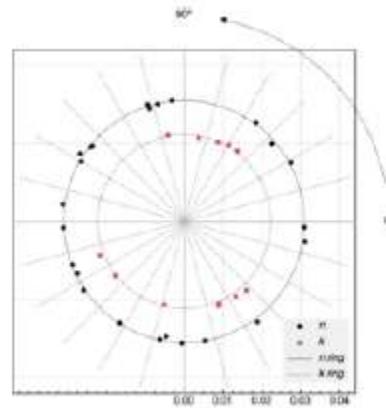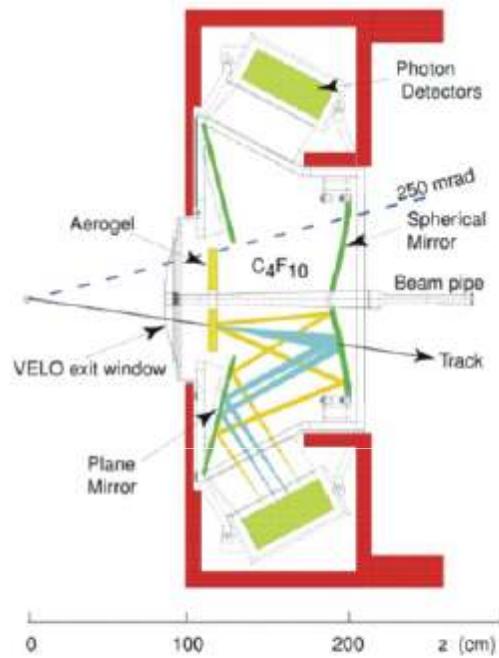
LHCb 101

LHCb 101

Timing Resolution

$$\approx 50\,\text{fs}\,(15\,\mu\text{m})$$

Gives a good measurement
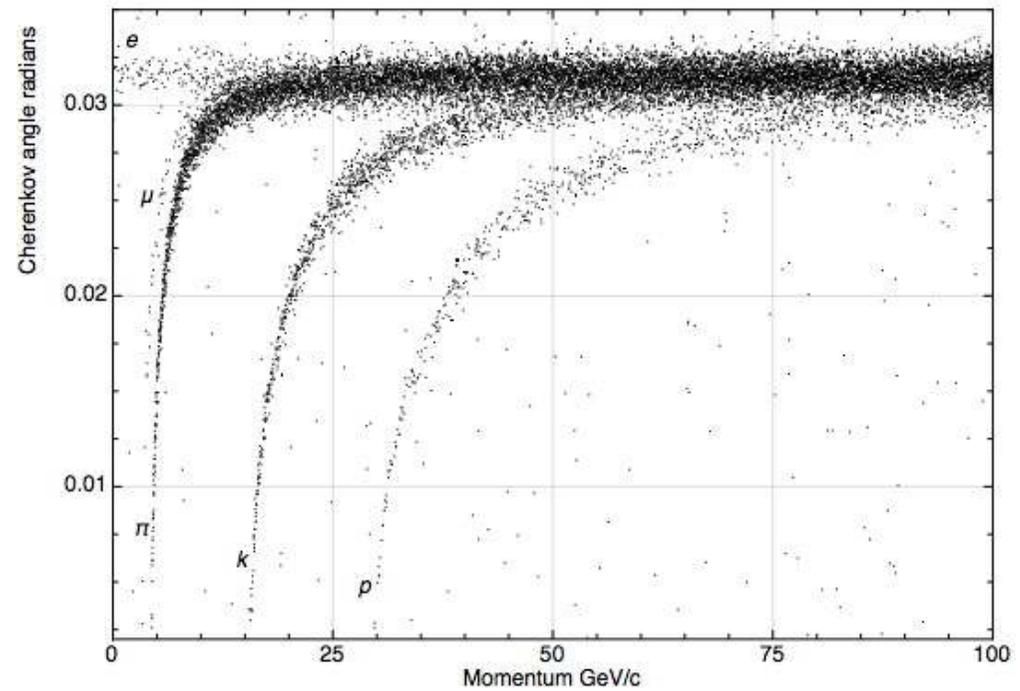of displaced vertex

LHCb 101

$$\cos \theta_c = \frac{c}{n\upsilon}$$

Cherenkov angle vs Momentum for n = 1.0005

Showering & Hadronization in the Dark Sector

Showering with out RG running + Lund String Model:

⟹   Pythia 8

Showering with RG running + Lund String Model:

⟹   Pythia 8 with patch from Schwaller, Stolarski, and Weiler (15')
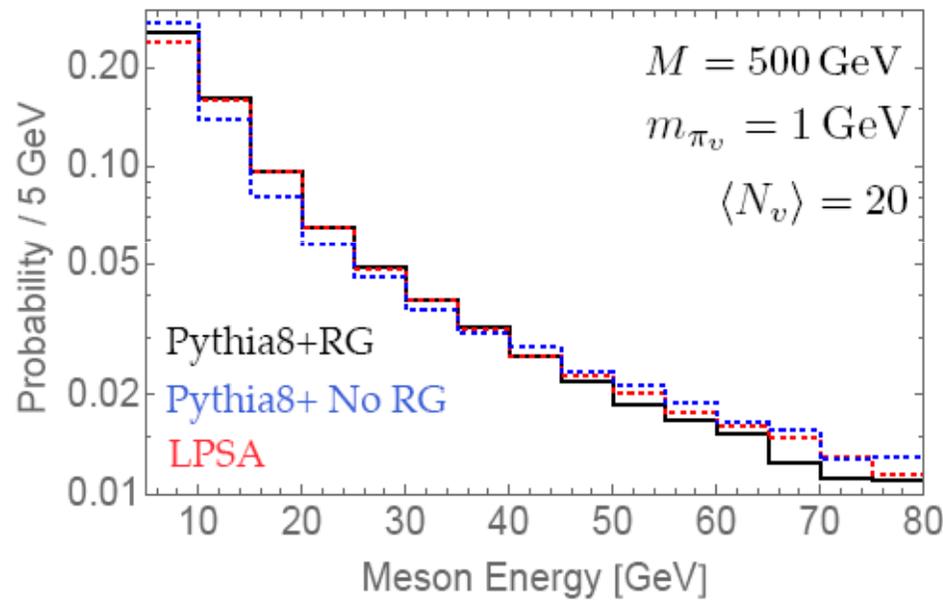
Longitudinal Phase Space Approximation:
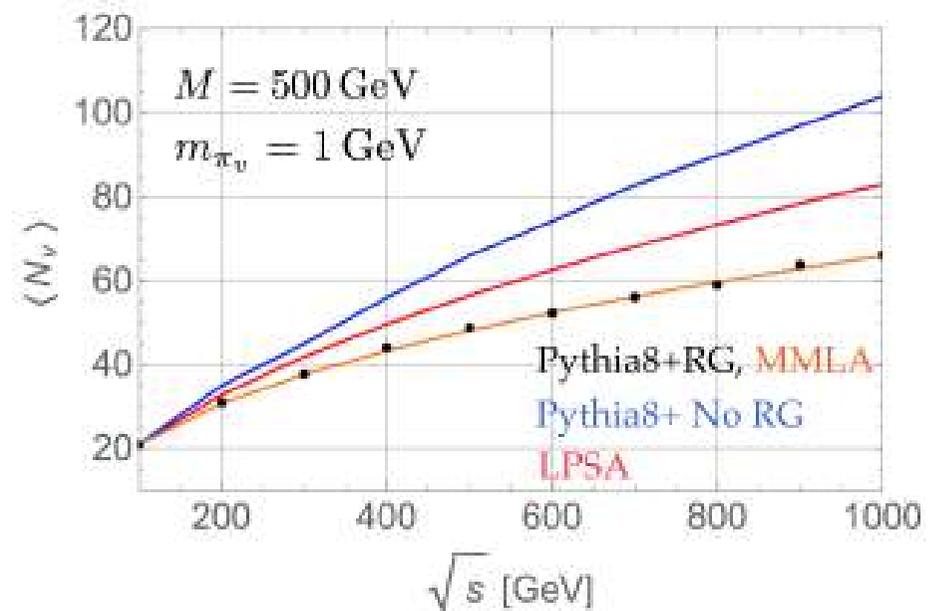Han, Si, Zurek, and Strassler (08')

⟹   Poisson distributed meson multiplicity
Uniformly distributed meson rapidity (rest frame of heavy resonance)
Gaussian distributed transverse momenta

Showering & Hadronization in the Dark Sector

Energy Spectrum

Multiplicity

Di-muon channel

Displaced muon search at LHCb

We adopt cuts from the displaced A' analysis in

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

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

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

$\eta(\omega_v) \in [2, 5]$, $p_T(\omega_v) > 1\,\text{GeV}$

$\ell_T \in [6\,\text{mm}, 22\,\text{mm}]$ $\ell_z \in [2.6\,\text{cm}, 50\,\text{cm}]$ (we include this second cuts)
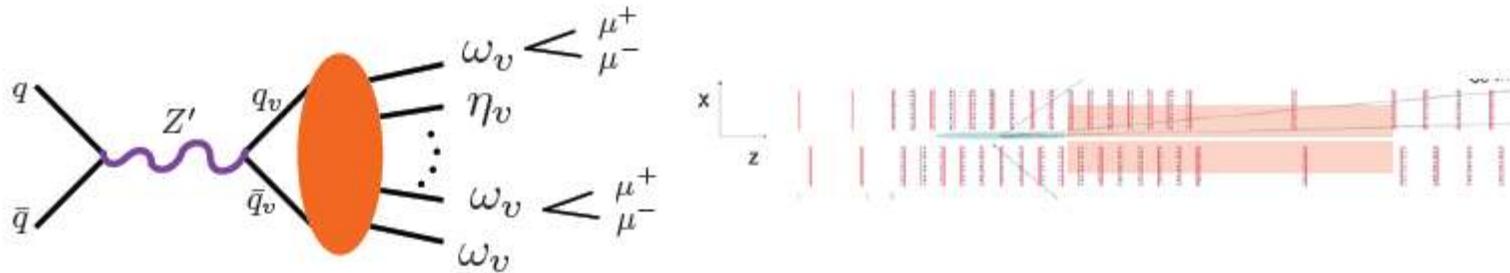
$\Rightarrow$ ~ 25 events / mass bin at 15 / fb at 13 TeV (Run III)

LHCb Di-muon limit

Long decay lifetime :
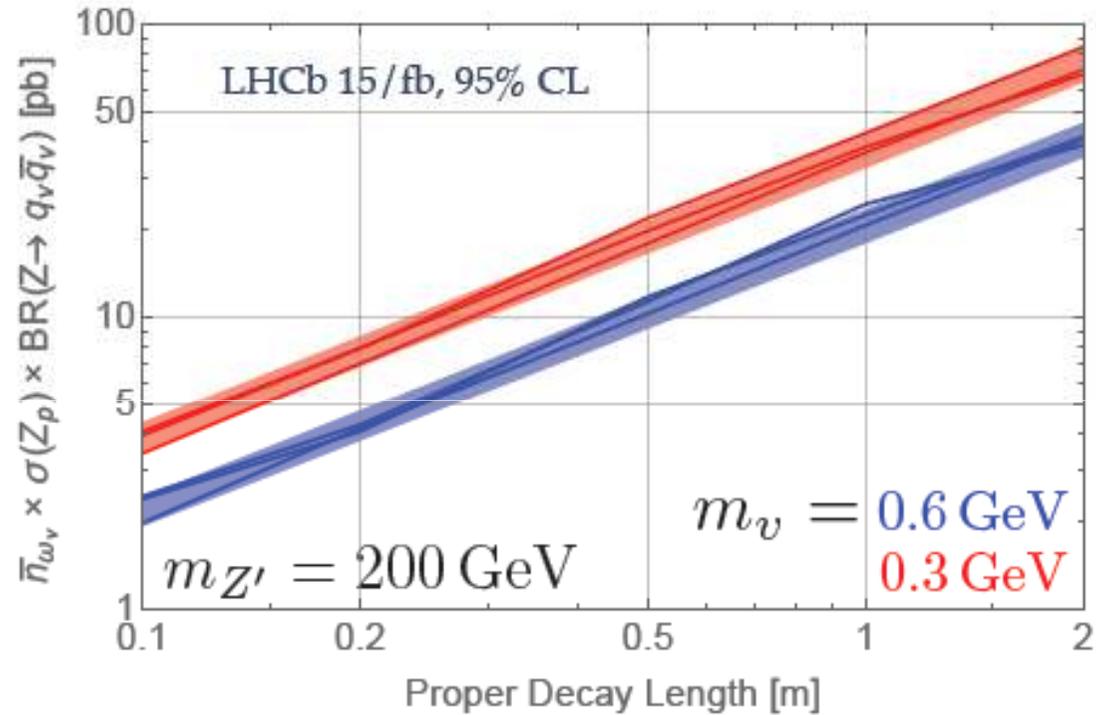
$\langle N_v \rangle$	$c\tau = 10$ cm		$c\tau = 100$ cm	
	600 MeV	300 MeV	600 MeV	300 MeV
10	250 (fb)	400	2 pb	4 pb
30	80	130	670	1.3 pb

Applications in Twin Higgs Models

Pseudo-scalar: longer decay lifetime

Vector meson

Applications in Twin Higgs Models

Bound on the exotic Higgs decay BR
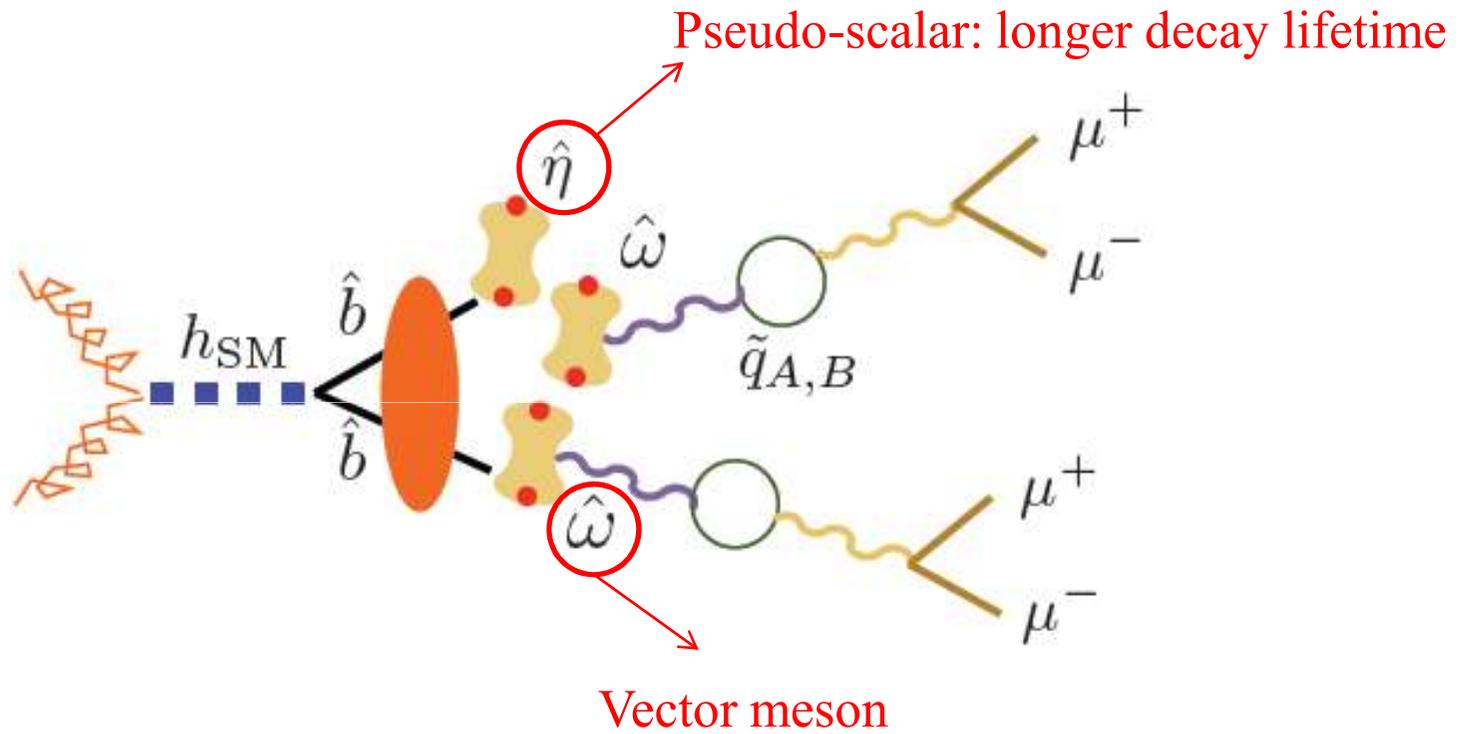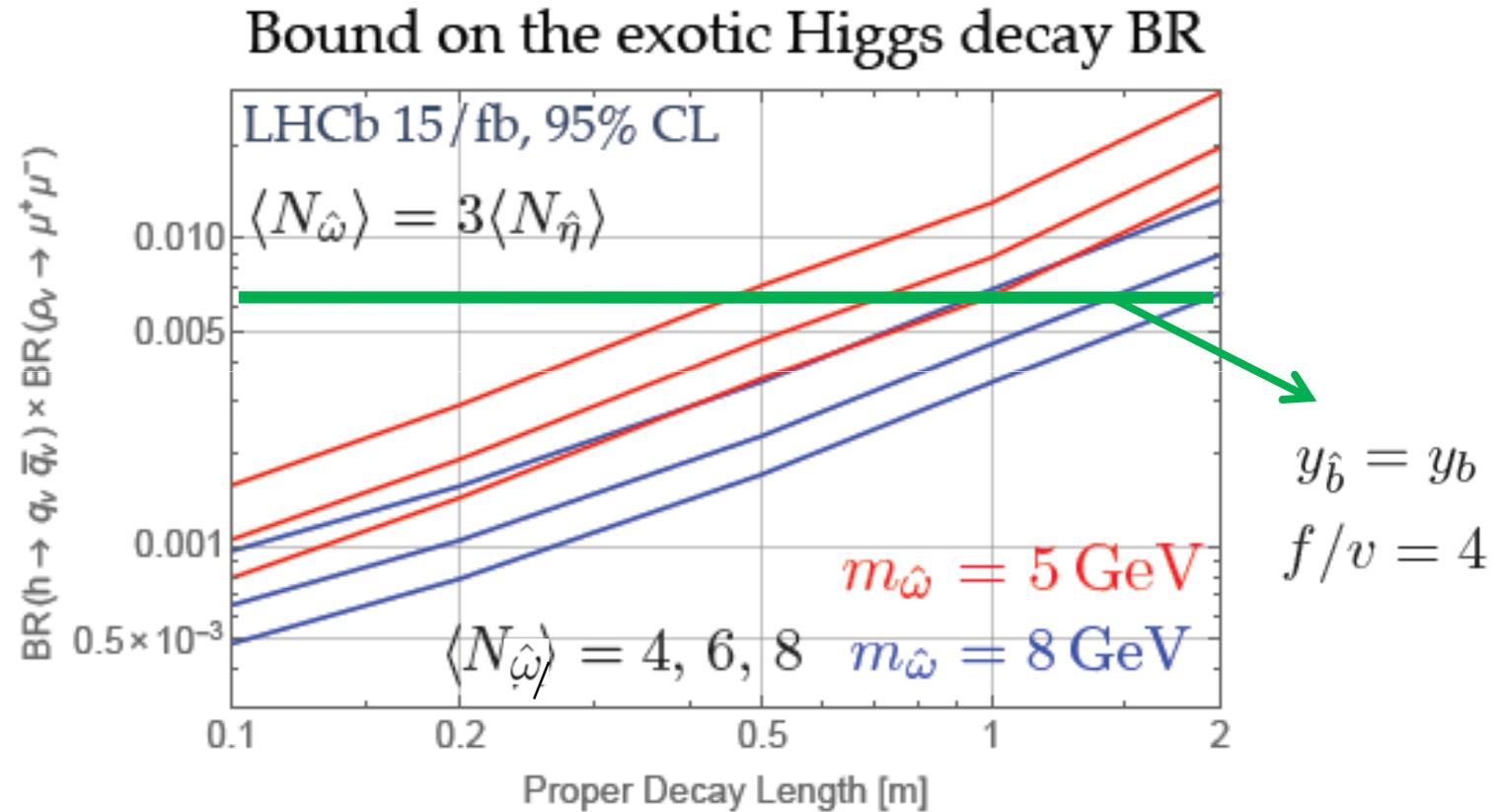
LHCb vs ATLAS/CMS

ATLAS/CMS has:

20 times higher luminosity.

10 times better angular coverage.

Can ATLAS/CMS beat LHCb if optimizing the search strategies?

- Most of hidden mesons escape from the detector.

⇒ Large source of MET.

⇒ First trigger on Mono-jet .
Then look for soft displaced Di-muon pair.

- Large angular coverage at ATLAS/CMS makes it easier to capture DV.

⇒ Lower MET cut with 2 DV.

LHCb vs ATLAS/CMS

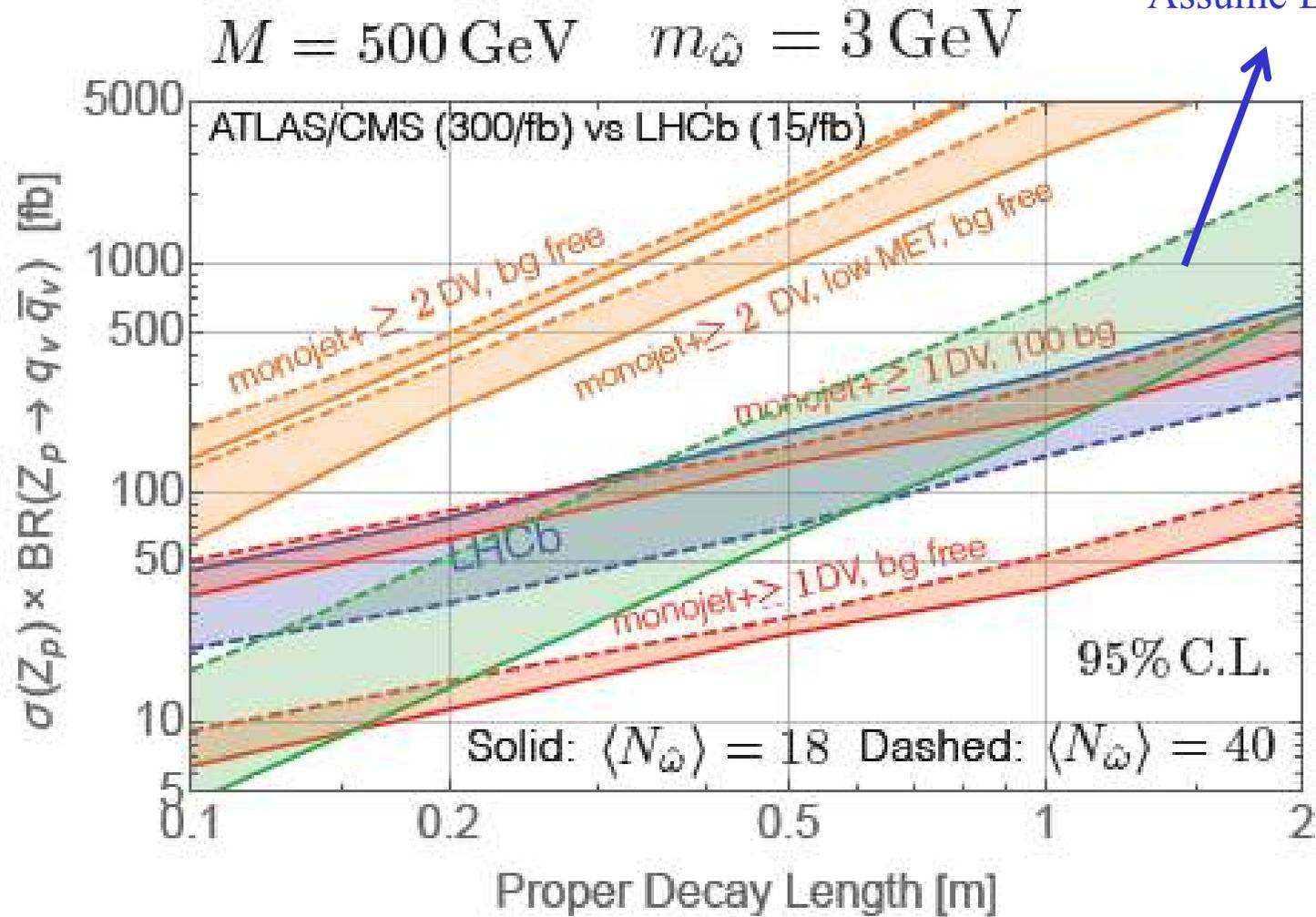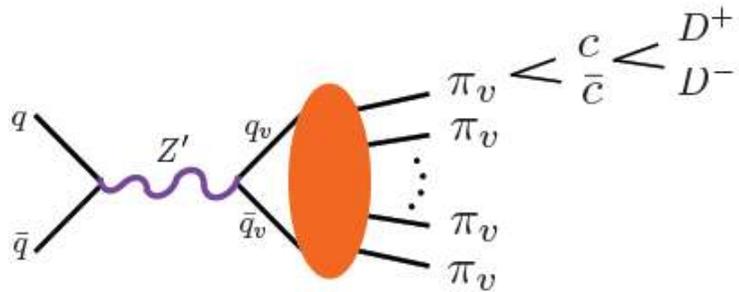Very optimistic: reconstruct 2 DV muon $P_T > 10$ GeV Assume BG Free.

$M = 500\,\mathrm{GeV}$ $m_{\hat{\omega}} = 3\,\mathrm{GeV}$

ATLAS/CMS (300/fb) vs LHCb (15/fb)

$\sigma(Z_p) \times \mathrm{BR}(Z_p \to q_\nu \bar{q}_\nu)$ [fb]

monojet+ $\geq$ 2 DV, bg free

monojet+ $\geq$ 2 DV, low MET, bg free

monojet+ $\geq$ 1 DV, 100 bg

monojet+ $\geq$ 1 DV, bg free

LHCb

95% C.L.

Solid: $\langle N_{\hat{\omega}} \rangle = 18$ Dashed: $\langle N_{\hat{\omega}} \rangle = 40$

Proper Decay Length [m]

Hadronic Decay Channels: D-meson

cross section at y=0

390 mrad

60 mrad

15 mrad

X

Z

VETO stations

view of most upstream VELO station

interaction region
σ = 5.3 cm

HV

HV

c

c

??May also be used??

q

Z'

q_v

$\bar{q}_v$

π_v

π_v

π_v

π_v

$\bar{q}$

$\pi_v < \dfrac{c}{\bar{c}} < \dfrac{D^+}{D^-}$
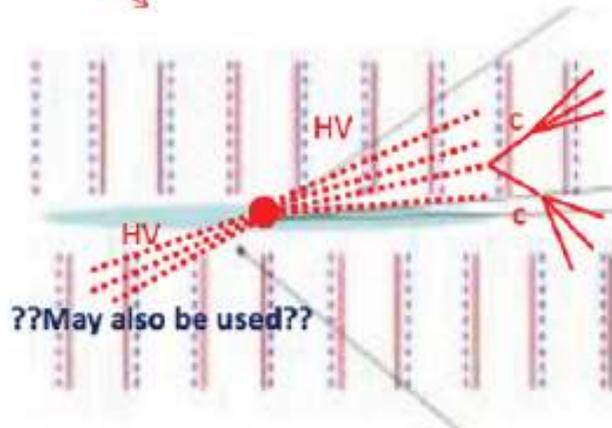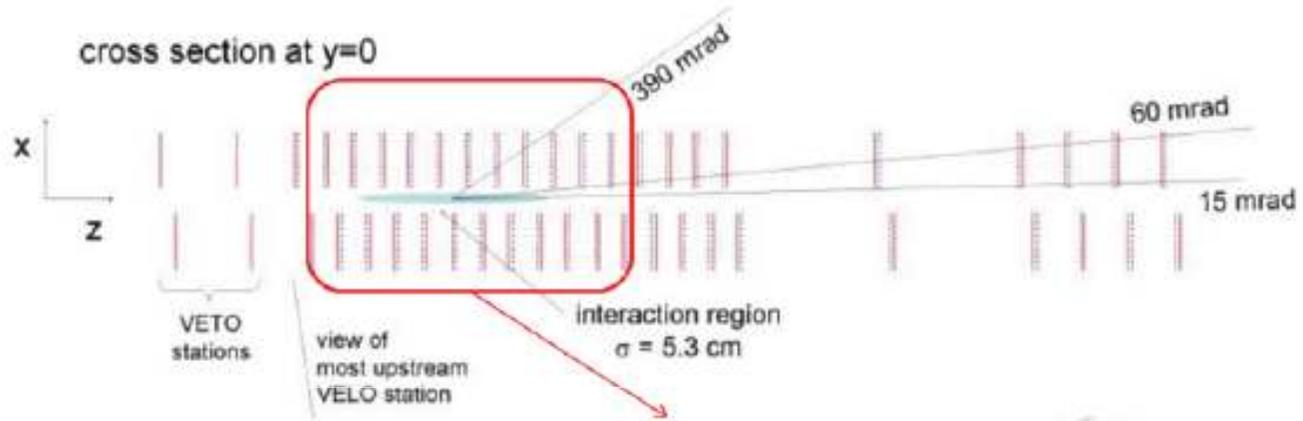
Hadronic Decay Channels: D-meson

The most conservative search channel:

- Both D-mesons are well-reconstructed.

A less conservative search channel:

- One D-meson is well-reconstructed.
- A displaced 3-track vertex is nearby the reconstructed D-meson.

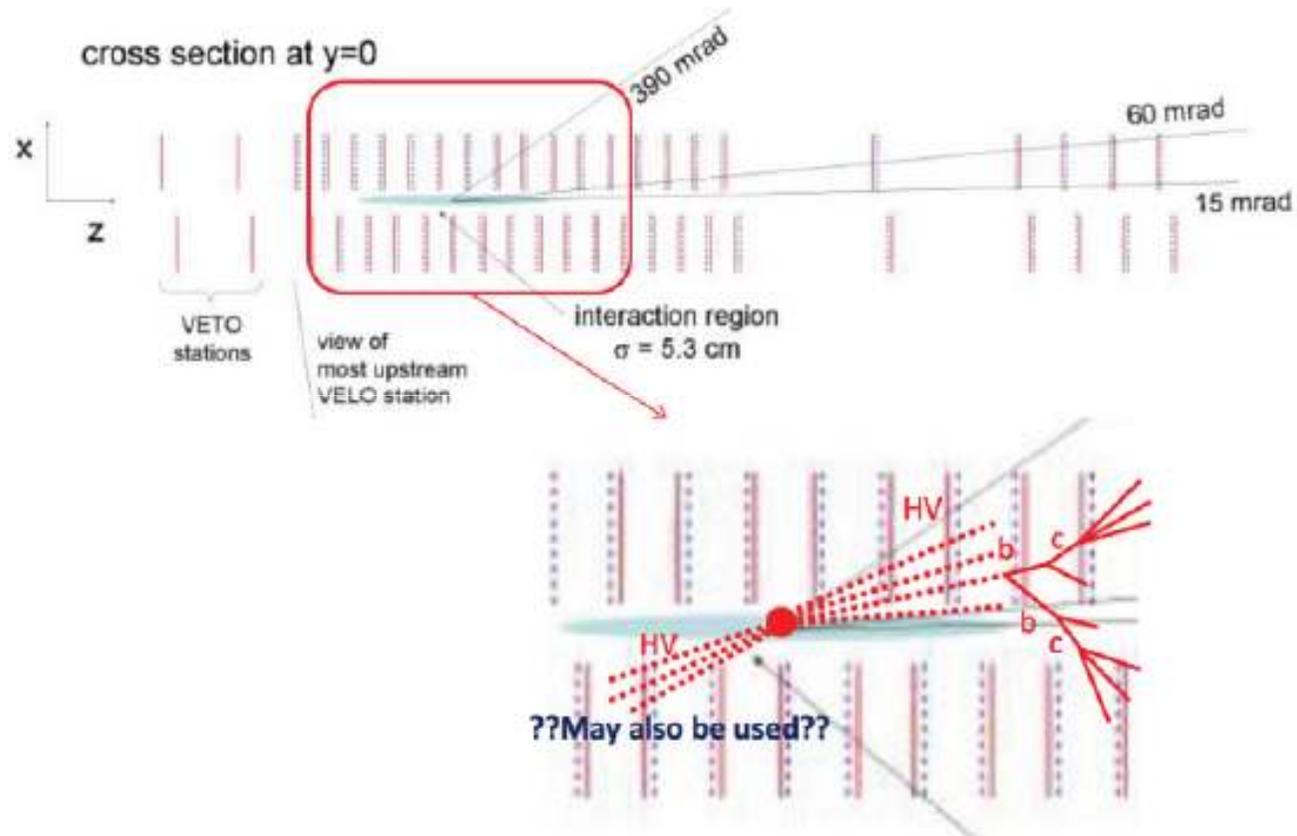An aggressive search channel: (based on pure topology)

- Two 3-track vertices of displaced charged tracks are reconstructed.
- Both vertices are far away from the PV.
- The transverse separation between vertices ~ O(D-meson lifetime).

Hadronic Decay Channels: D-meson

Assume {0, 10, 100} BG with 15 fb^{-1} at 13 TeV.
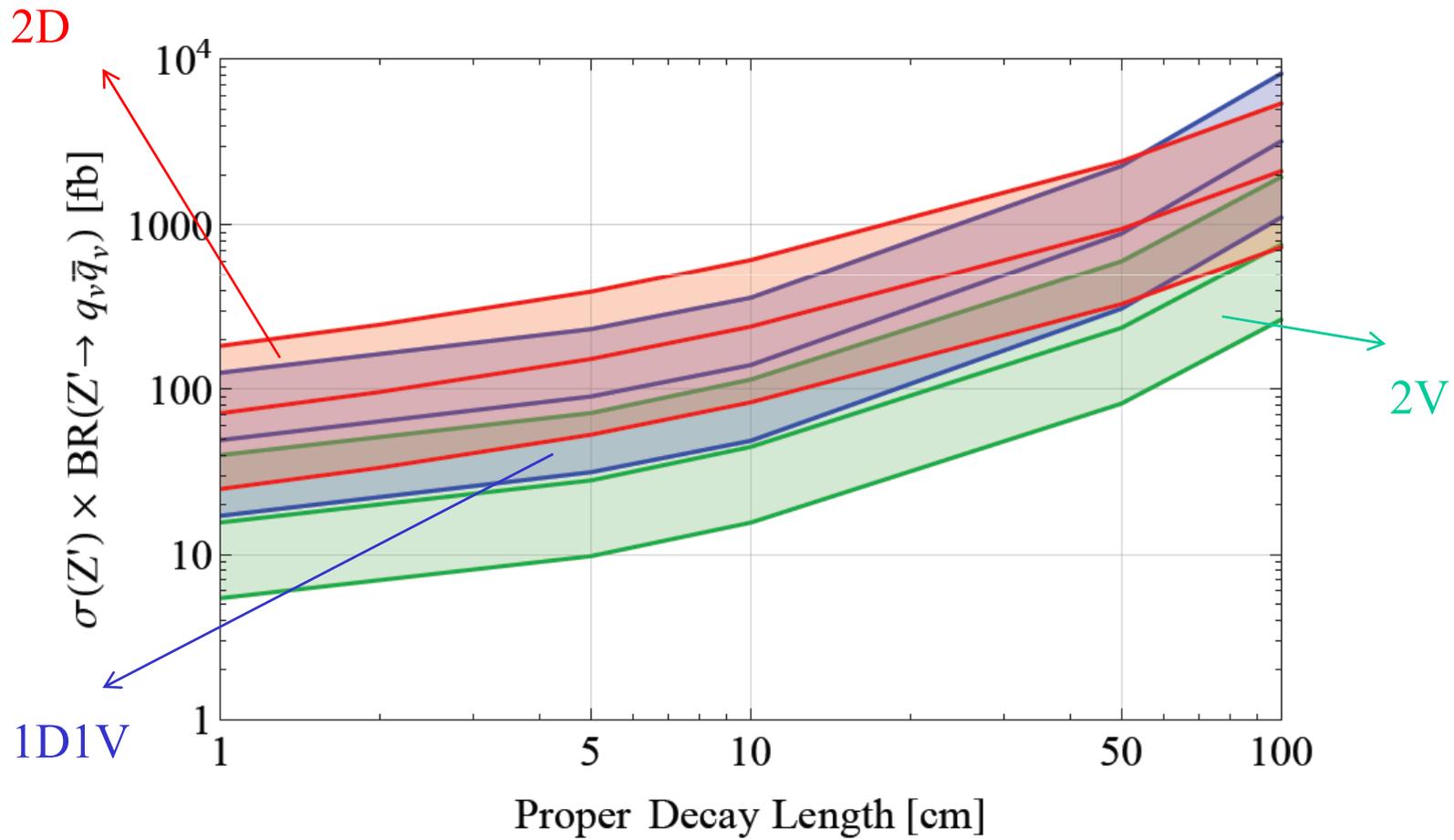
Hadronic Decay Channels: B-meson

Conclusion

The LHCb is very different from the ATLAS/CMS.

    VELO and RICH provide excellent track reconstruction and particle ID.

    An ideal environment to study soft long-lived particles!

    Particularly good at study generic Hidden Valley models.

The LHCb provide promising reaches on Hidden Valley models.

    Di-muon channel:
        Better /comparable reaches than MET+jet+DV searches at ATLAS/CMS.

    D-meson pair channel:
        Two nearby well-reconstructed D-meson.
        One well-reconstructed D-meson with a nearby DV.
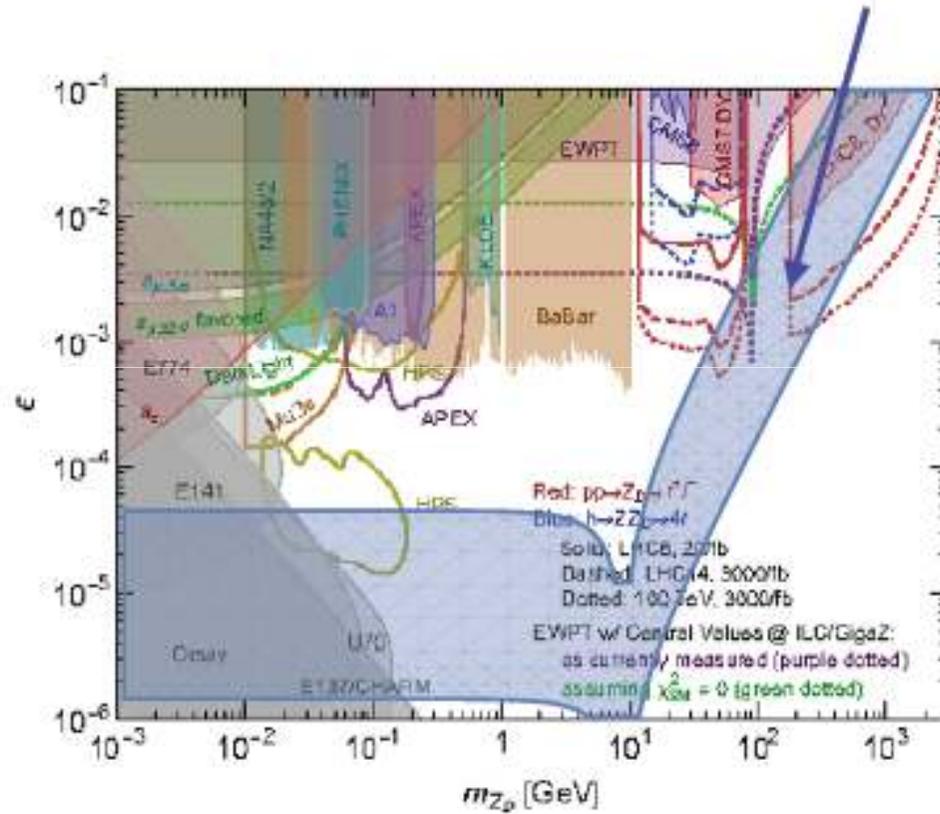   Two nearby DVs (pure topological)

    B-meson pair channel:
        Work in progress, but should be similar to D-meson pair channel.

Applications in Twin Higgs Models

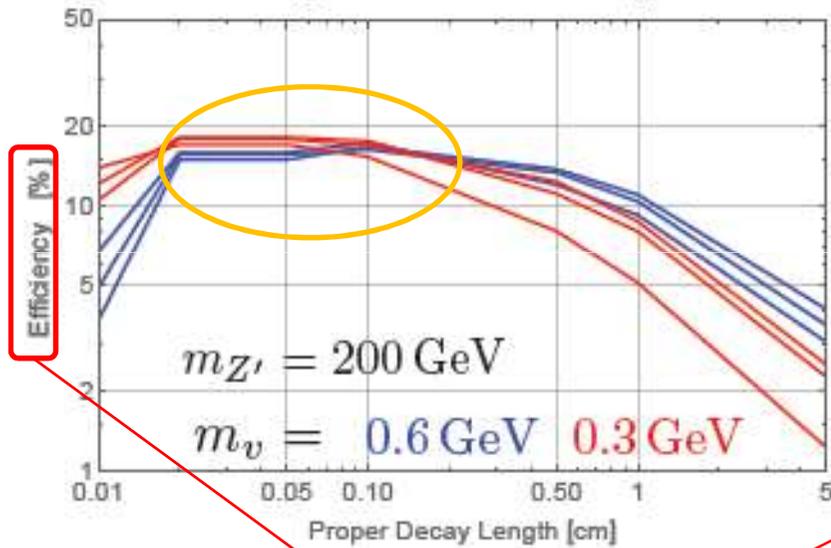Assume $\quad m_{\hat{\omega}} = 2\hat{\Lambda} = 8\,\text{GeV} \qquad 0.1 < c\tau_{\hat{\omega}} < 100\,\text{cm}$

$$c\tau_{\hat{\omega}} \simeq 20\,\text{cm} \left(\frac{m_{A'}}{100\,\text{GeV}}\right)^4 \left(\frac{10^{-3}}{\epsilon}\right)^2 \left(\frac{3\,\text{GeV}}{\Lambda}\right)^5$$
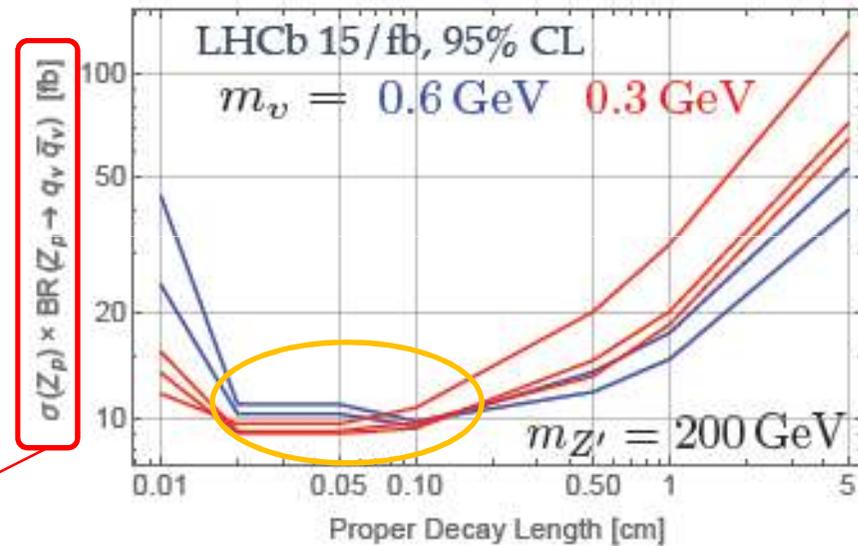
LHCb Di-muon limit

Short decay lifetime :

Chance to have at least one decay in VELO is large.

⟹ Sensitivity has less dependence on $\langle N_{\pi_v} \rangle$

Hard to beat ATLAS/CMS searches, thus do not consider this scenario.

LHCb vs ATLAS/CMS

Di-muon + MET + jet :

Search for massive, long-lived particles using multitrack displaced vertices or displaced lepton pairs in pp collisions at 8 TeV with the ATLAS detector (20 fb^{-1})
Phys. Rev. D 92, 072004 (2015)

muon $P_T \sim O(0.1)$ M / <N>

DV + muon :   muon $P_T > 50$ GeV

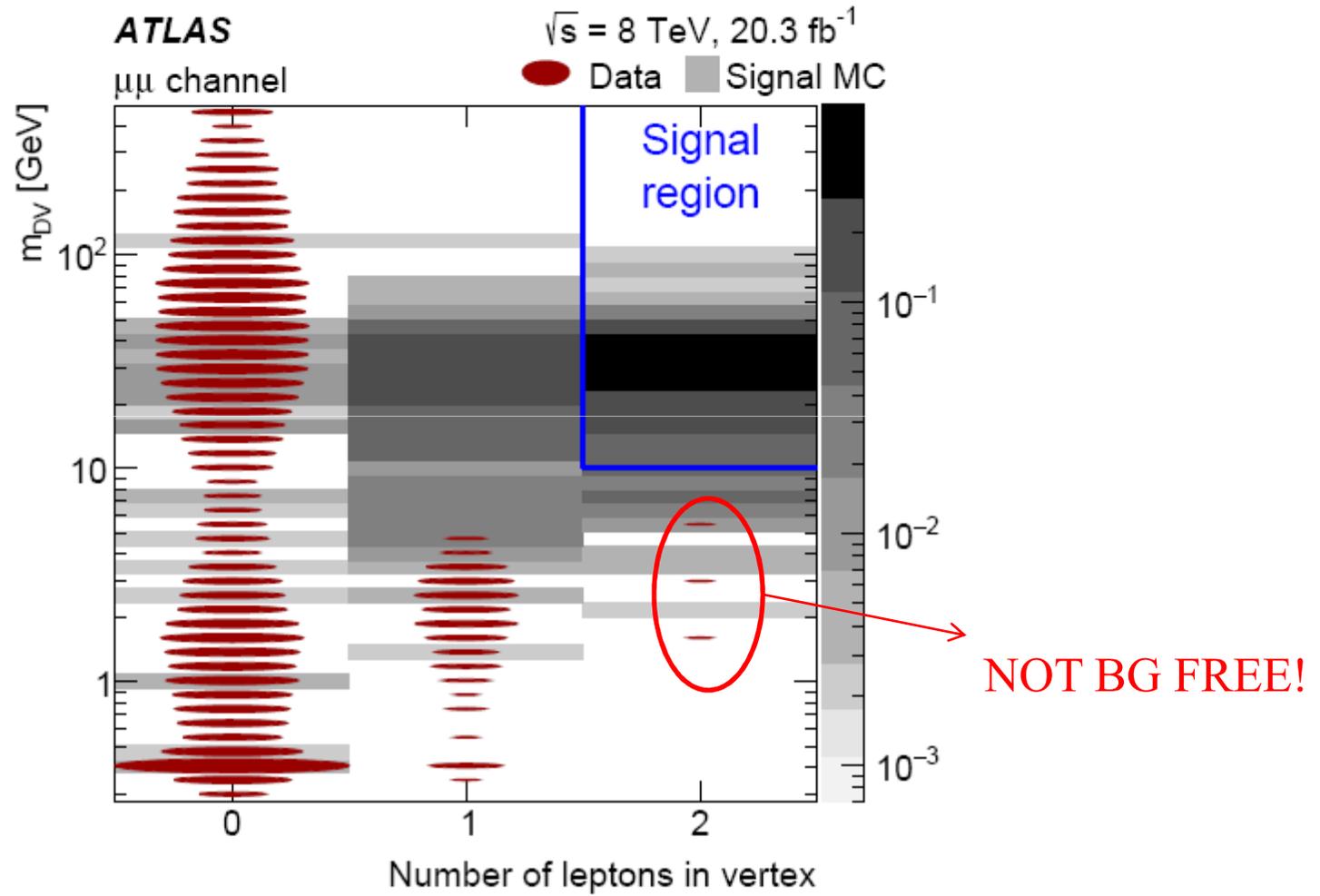DV + electron: electron $P_T > 120$ GeV

DV + jet: 4 j > 90 GeV,   5 j > 65 GeV,   6 j > 55 GeV

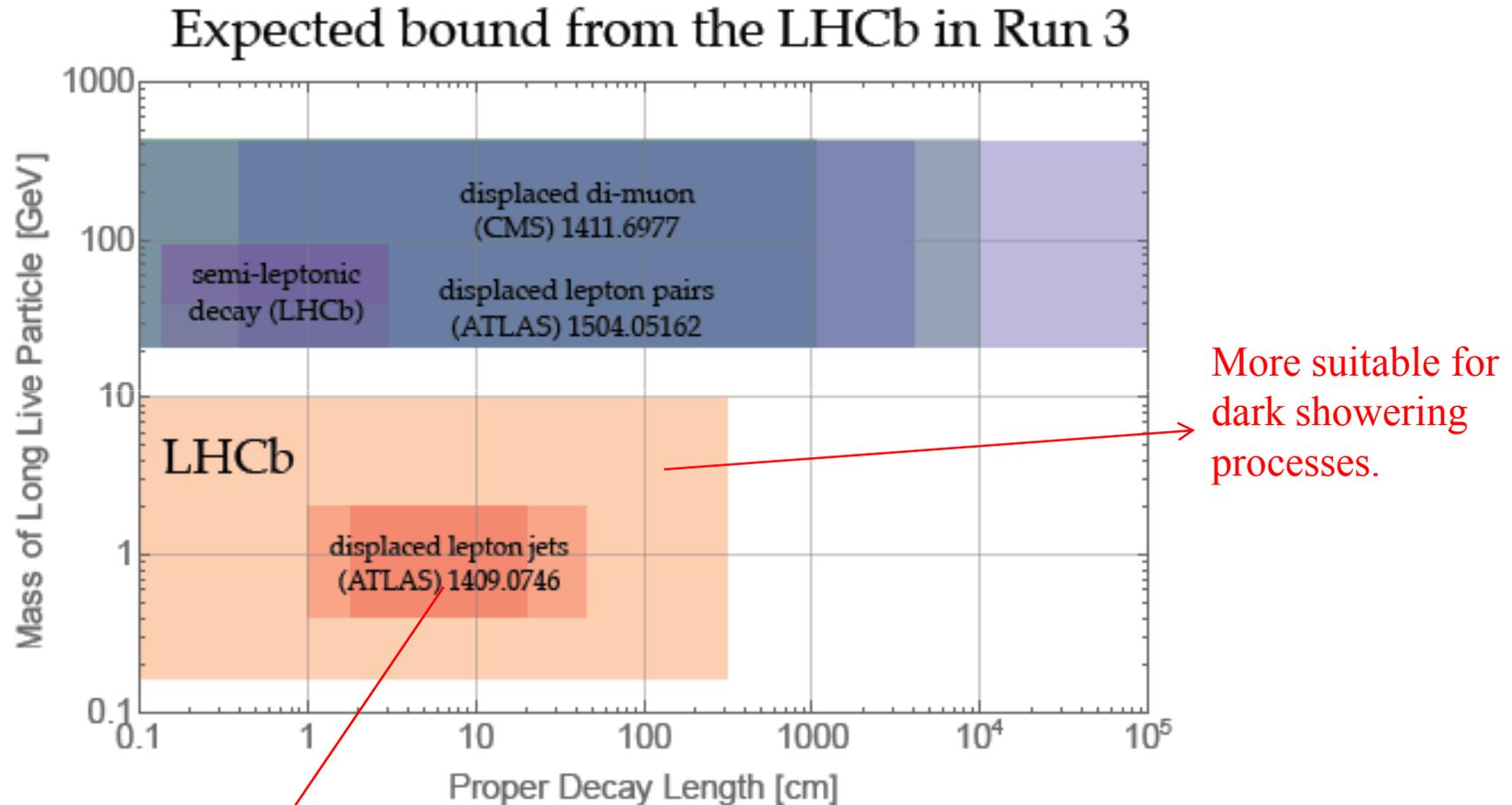DV + MET: MET > 180 GeV

DV : muon $P_T > 10$ GeV,   d > 2.5 mm,   Inv Mass > 10 GeV

need to remove

LHCb vs ATLAS/CMS

NOT BG FREE!

Hidden Valley searches at the ATLAS/CMS

Expected bound from the LHCb in Run 3

More suitable for dark showering processes.

Usually require $m_{LLP} > 15\,\mathrm{GeV}$ & sizable muon pT cut (~ 20 GeV), and assume 1 > few particles decay when presenting the results

Di-muon channel

Possible sources of background:

- Combinatorial background:

  Rescaling the background from $K_S \to \mu^+ \mu^-$ process.

- Fake muon from charged pion:

  Very low muon fake rate at the LHCb.

  $$\epsilon_\pi^2 \approx 10^{-6}$$

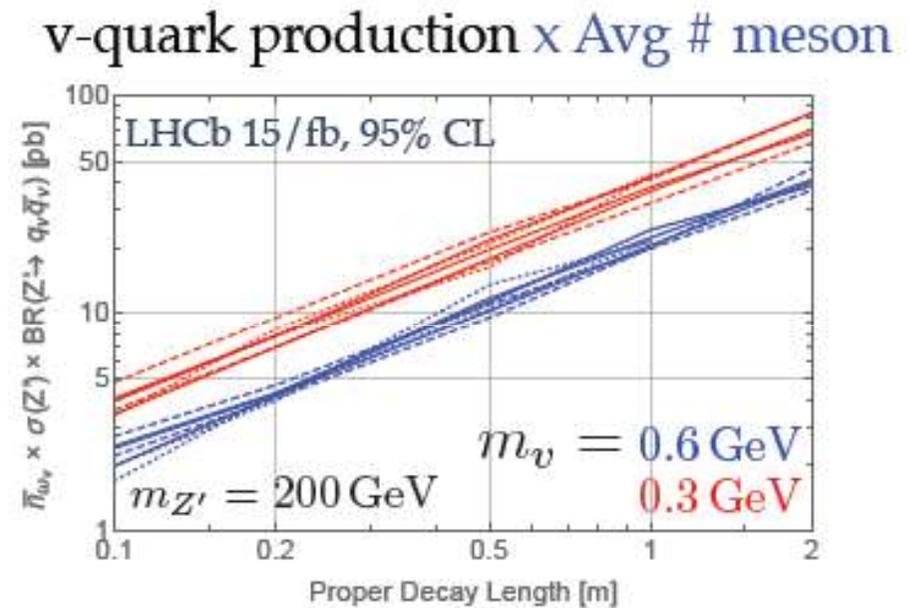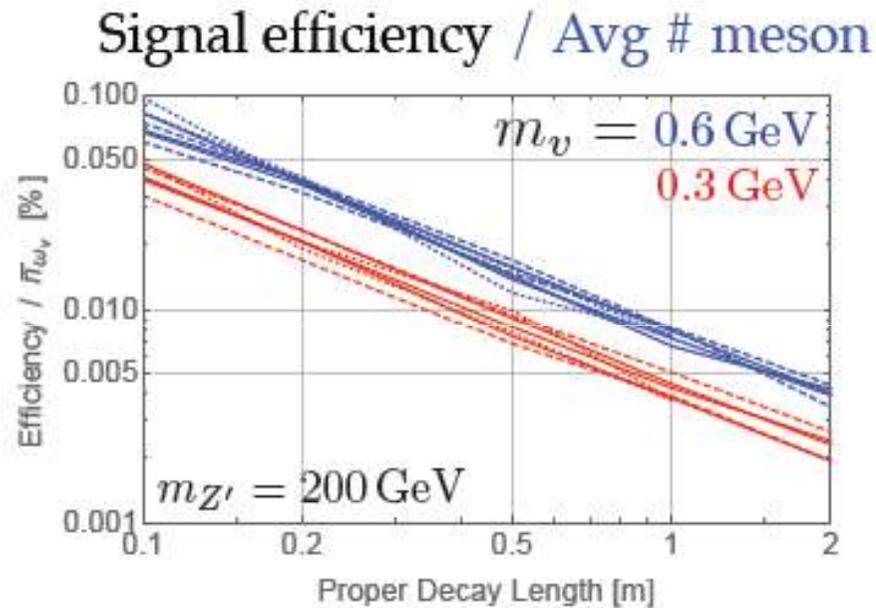- Interacting with material:

  A careful detector simulation is needed,
  may be eliminated by vertex location.

  $\Rightarrow$ ~ 25 events / mass bin at 15 / fb at 13 TeV (Run III)

Signal efficiency vs Multiplicity

Long decay lifetime :

Solid: PYTHIA + RG Running
Dashed: PYTHIA without RG Running
Dotted: LPSA

Hadronic Decay Channels: D-meson

This is similar to $B^0 \to D^+ D^-$ search at the LHCb.

LHCb collaboration: Phys. Rev. Lett. 117, 261801 (2016)

⇨ D-meson reconstruction criteria

$$\eta(D^\pm) \in [2,5], \, p_T(D^\pm) > 1.8\,\text{GeV}, H_T(D^\pm) > 5\,\text{GeV}$$
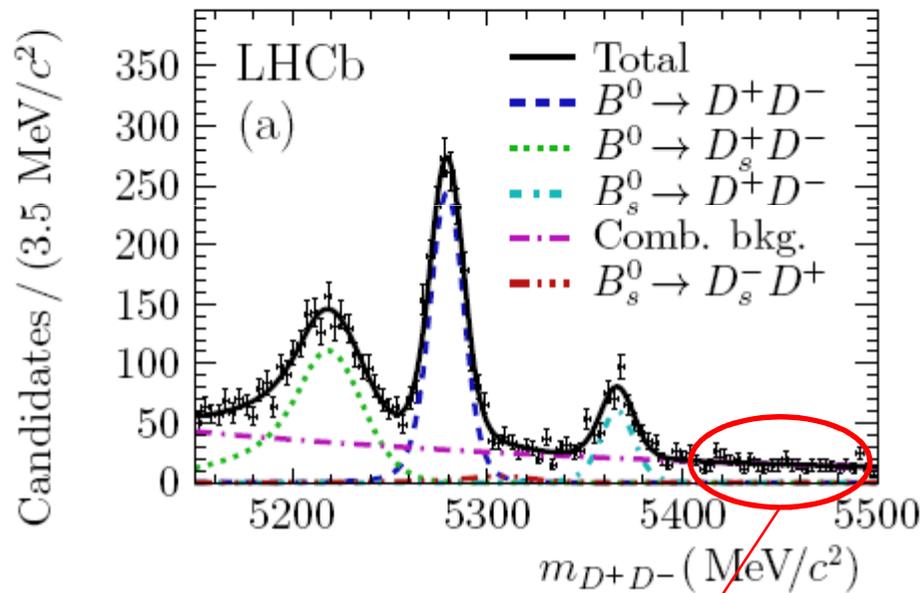
$$D^+ \to K^- \pi^+ \pi^-, \, D^+ \to K^- K^+ \pi^+$$

To properly include track reconstruction efficiency,
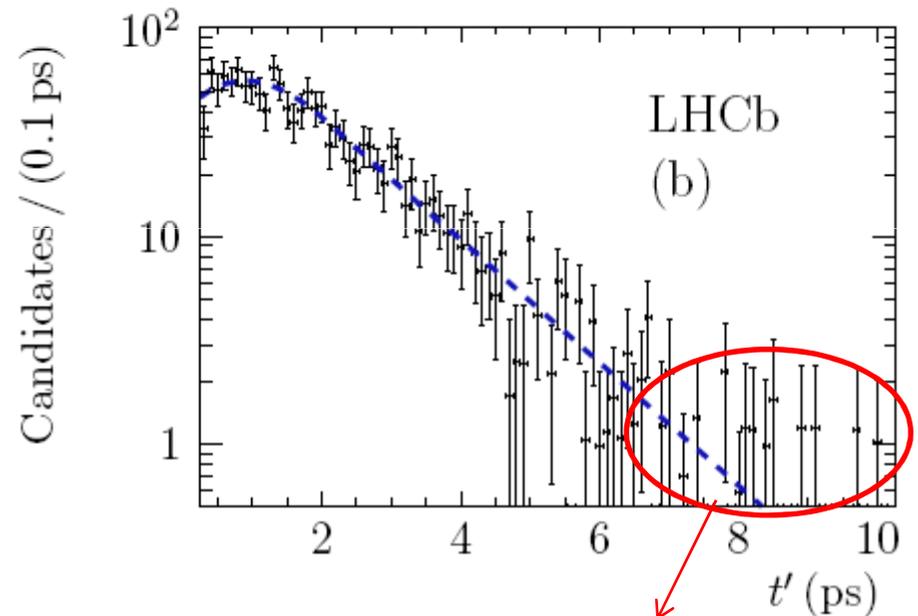require each charged track hitting at least 3 VELO PIXELs.

Hadronic Decay Channels: D-meson

This is similar to $B^0 \to D^+ D^-$ search at the LHCb.

BG is dominated by combinatorics.

BG is highly suppressed by requiring large displacement.

LHCb vs ATLAS/CMS

Reasonable to propose the following analysis at ATLAS/CMS at 13 TeV:

- Leading jet P_T > 120 GeV, MET > 200 GeV

- muon P_T > 10 GeV, $|\eta(\text{jet}, \mu^\pm)| < 2.5$

- $\Delta R > 0.4$ between hidden pion and jet

- At least 1 DV with $\ell_T \in [1, 30]$ cm

Can be lowered by requiring more DV