Probing Hidden Valley at the LHCb

Yue Zhao

MCTP, University of Michigan

UW – Madison 2017

with Aaron Pierce, Bibhushan Shakya,Yuhsin Tsai
Work in progress

Outline:

Abelian/Non-abelian dark sector

Hidden Valley searches at the ATLAS/CMS

LHCb 101

Showering & Hadronization in the Dark Sector

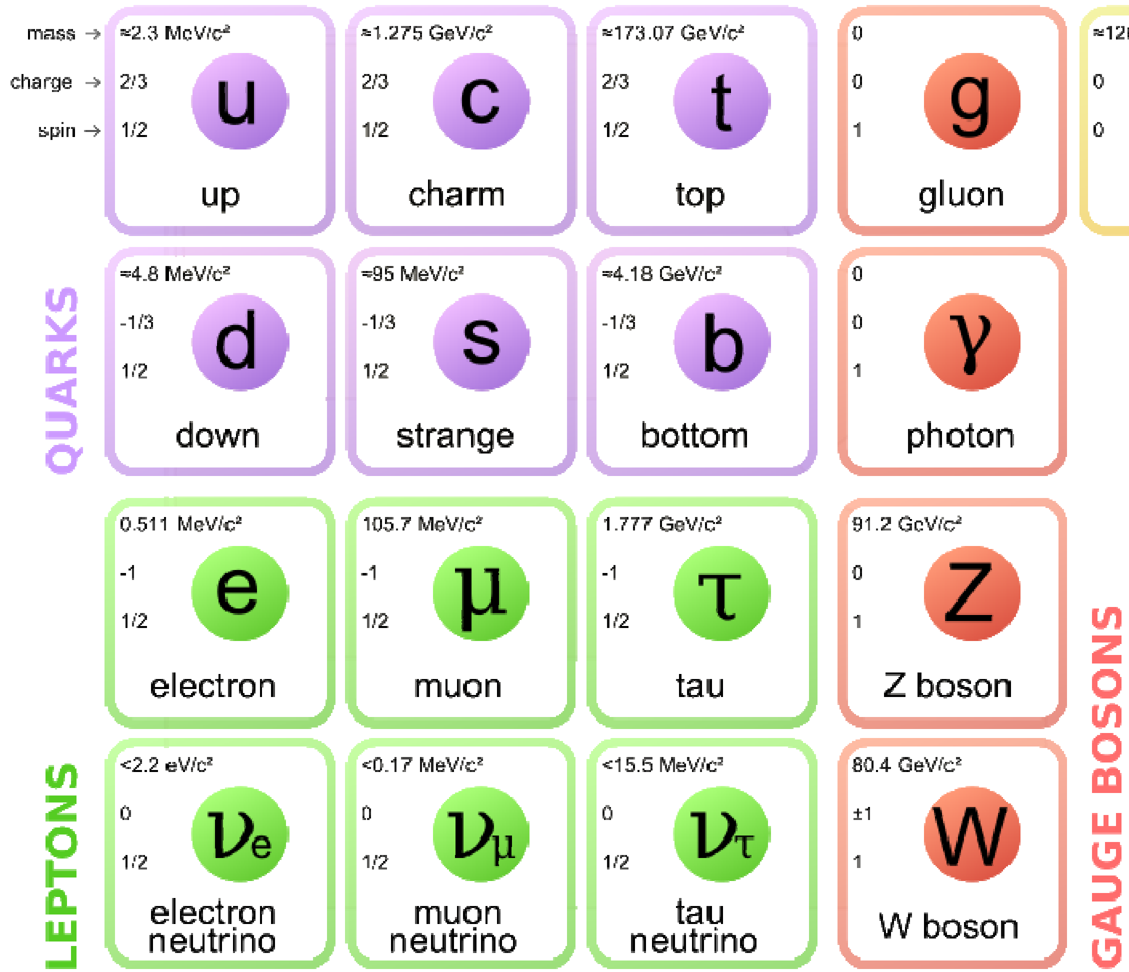
Hidden Valley leptonic channel: Muon pair

- LHCb reach
- LHCb vs ATLAS/CMS

Hidden Valley hadronic channel: D-meson/B-meson pair

Conclusion

Current Status of Particle Physics



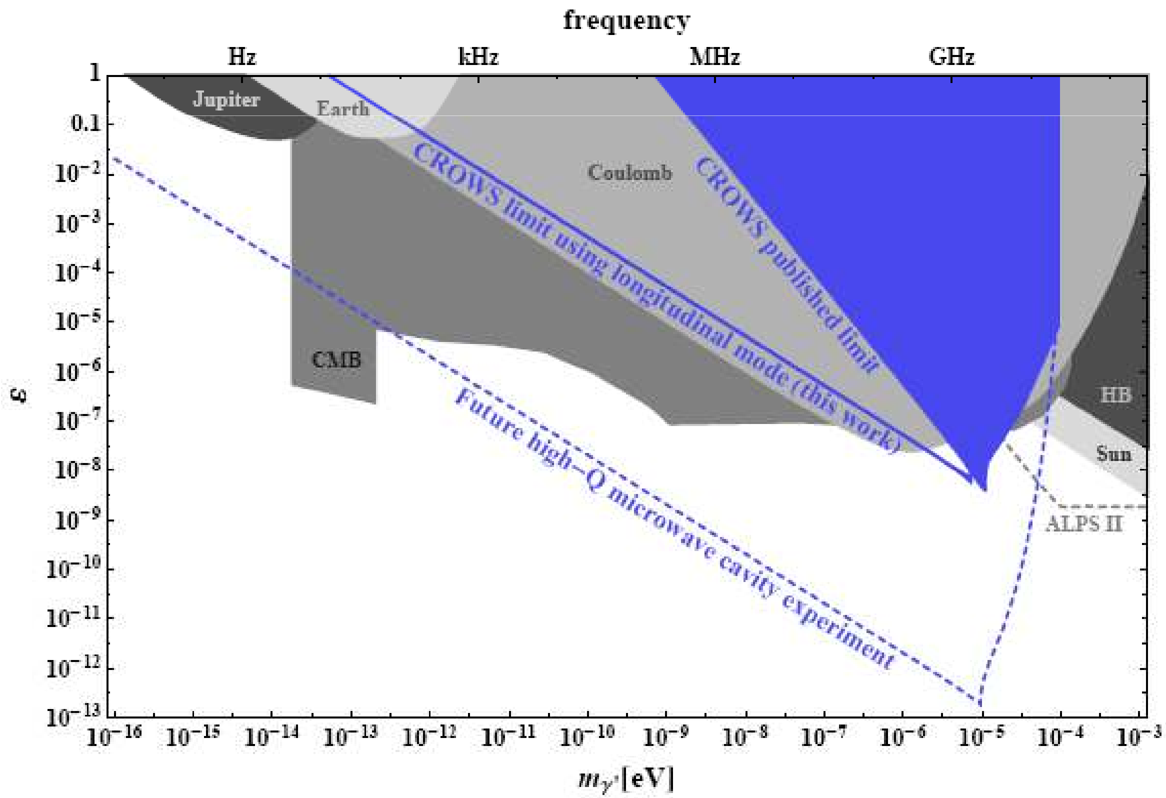
\+ Dark Sector

Abelian Dark Sector

Dark Sector remains largely unknown.

Simplest extension with additional U(1) has been intensively studied!

• Ultra-light dark photon:



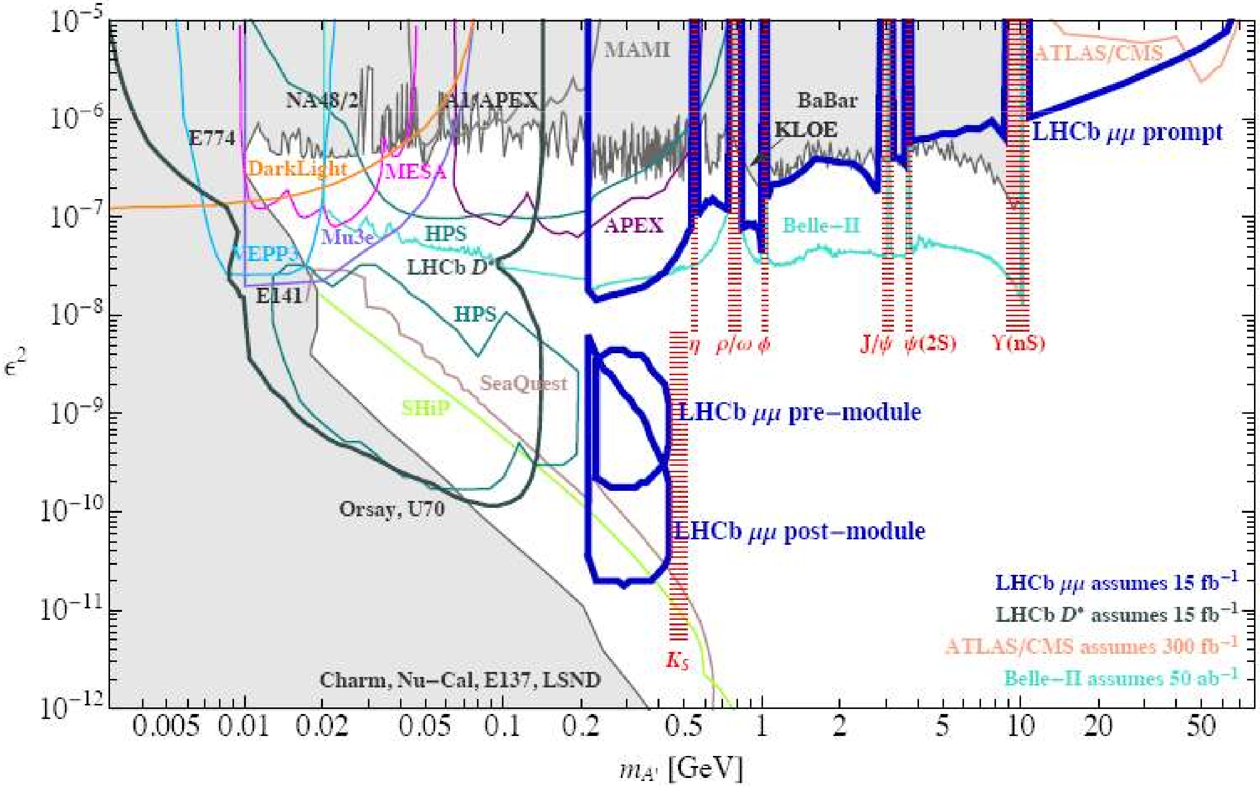
P. W. Graham, J. Mardon, S. Rajendran, Y. Z. Phys.Rev. D90 (2014) no.7, 075017

Abelian Dark Sector

Dark Sector remains largely unknown.

Simplest extension with additional U(1) has been intensively studied!

- MeV~ GeV:



P. Ilten, Y. Soreq, J. Thaler, M. Williams, W. Xue Phys. Rev. Lett. 116, 251803 (2016)

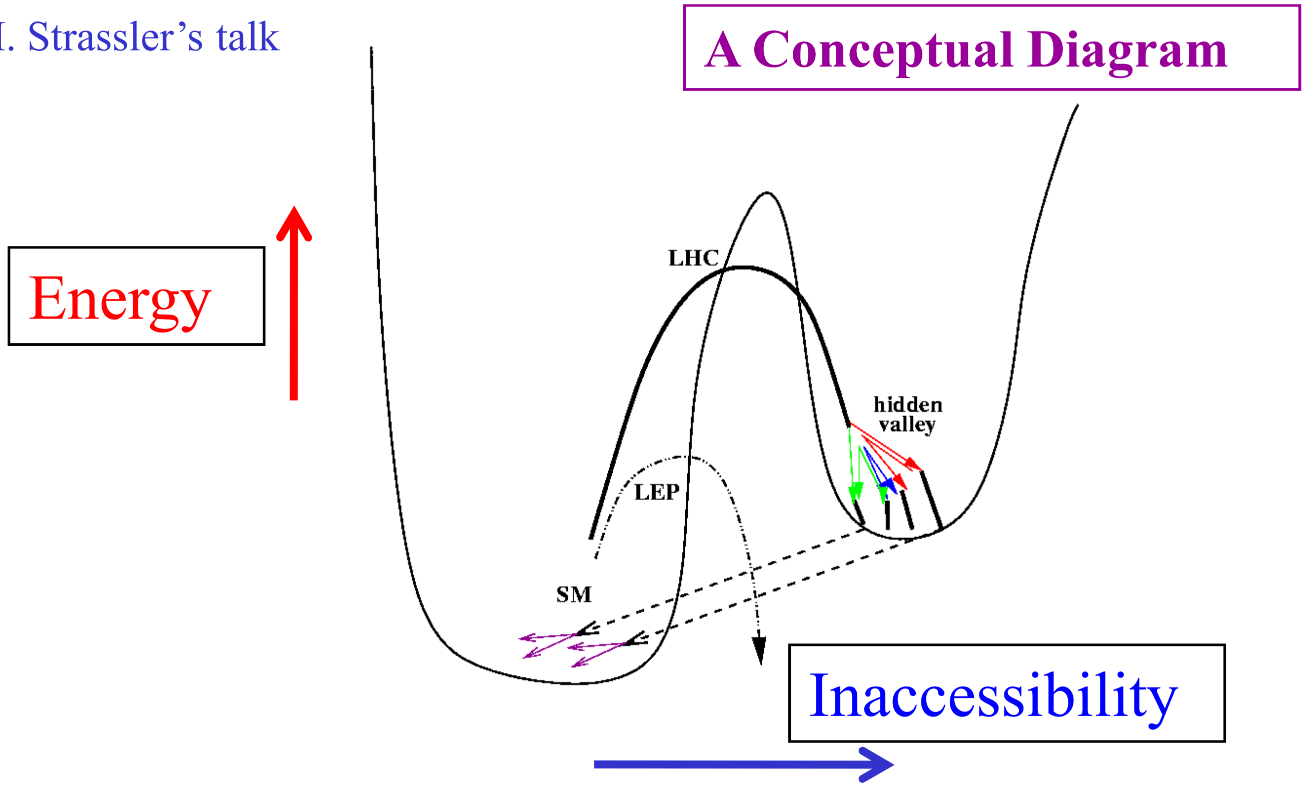
Non-Abelian Dark Sector

Dark Sector remains largely unknown.

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

- Generically classified as Hidden Valley models.

M. Strassler's talk



Non-Abelian Dark Sector

Dark Sector remains largely unknown.

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

- May have interesting astrophysical implications.

Non-Abelian dark matter and dark radiation

M. A. Buen-Abad, G. Marques-Tavares, M. Schmaltz
Phys.Rev. D92 (2015) no.2, 023531

Signatures of Large Composite Dark Matter States

E. Hardy, R. Lasenby, J. March-Russell, S. M. West
JHEP 1507 (2015) 133

-
-
-

Non-Abelian Dark Sector

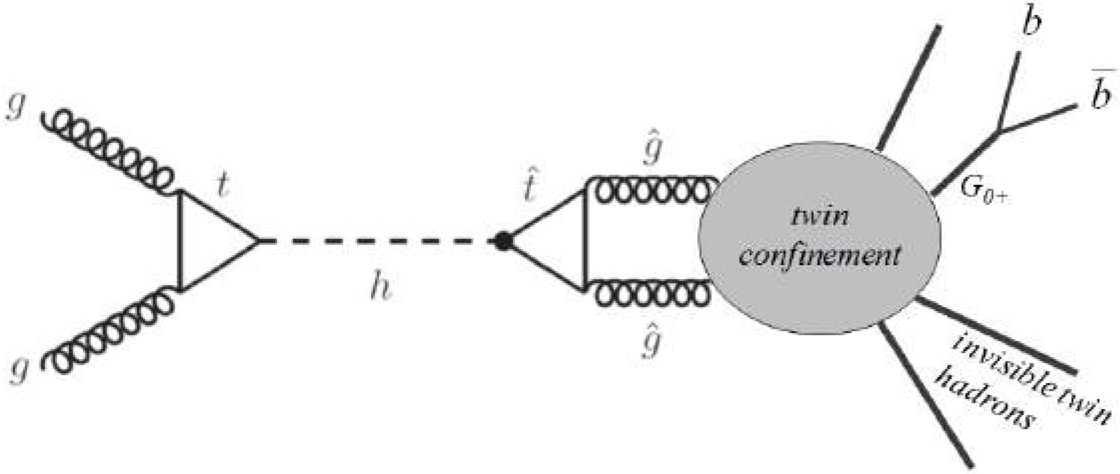
Dark Sector remains largely unknown.

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,

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

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

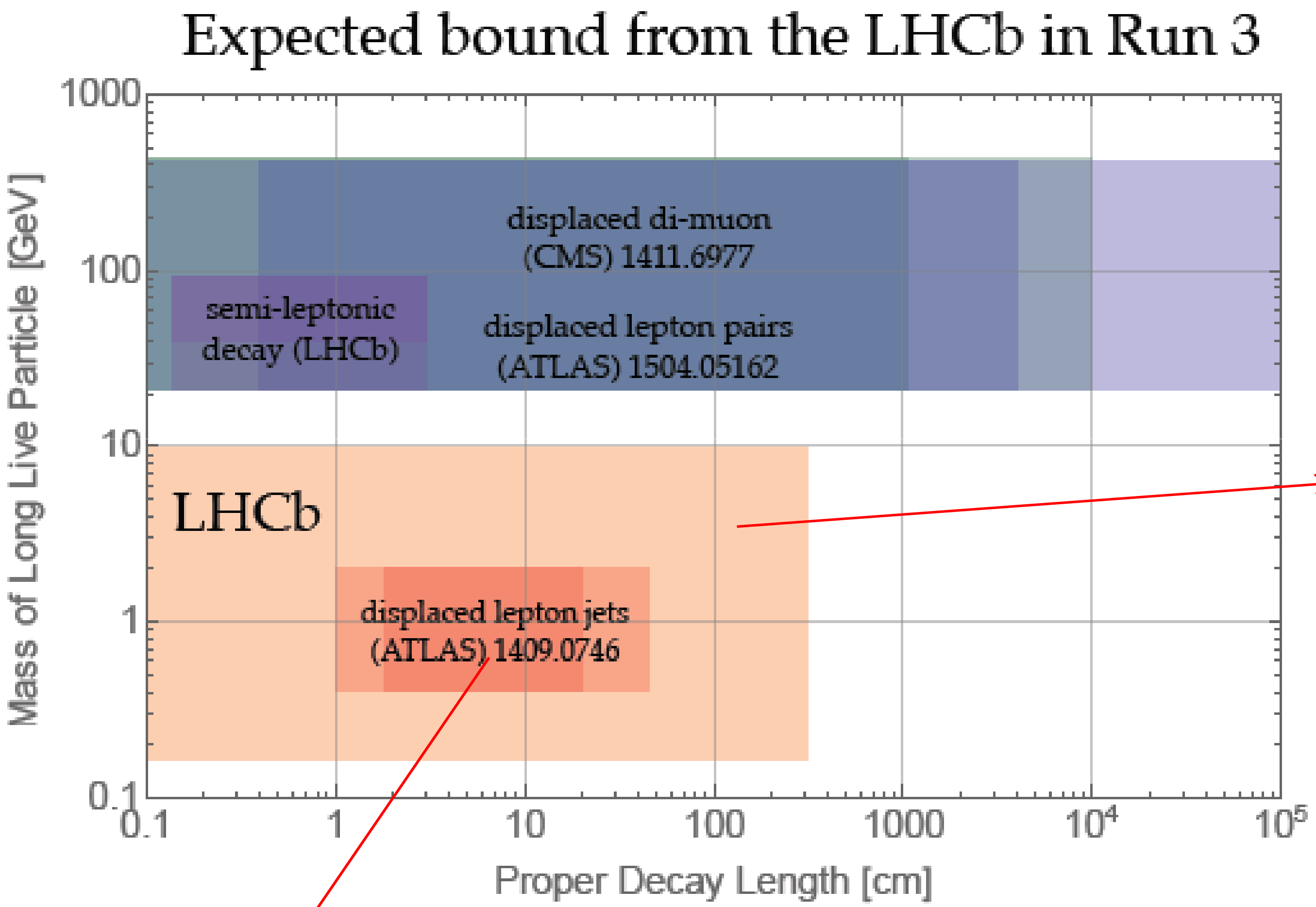
or requiring hidden pions to be very massive.

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.

Hidden Valley searches at the ATLAS/CMS



More suitable for dark showering processes.

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

LHCb 101

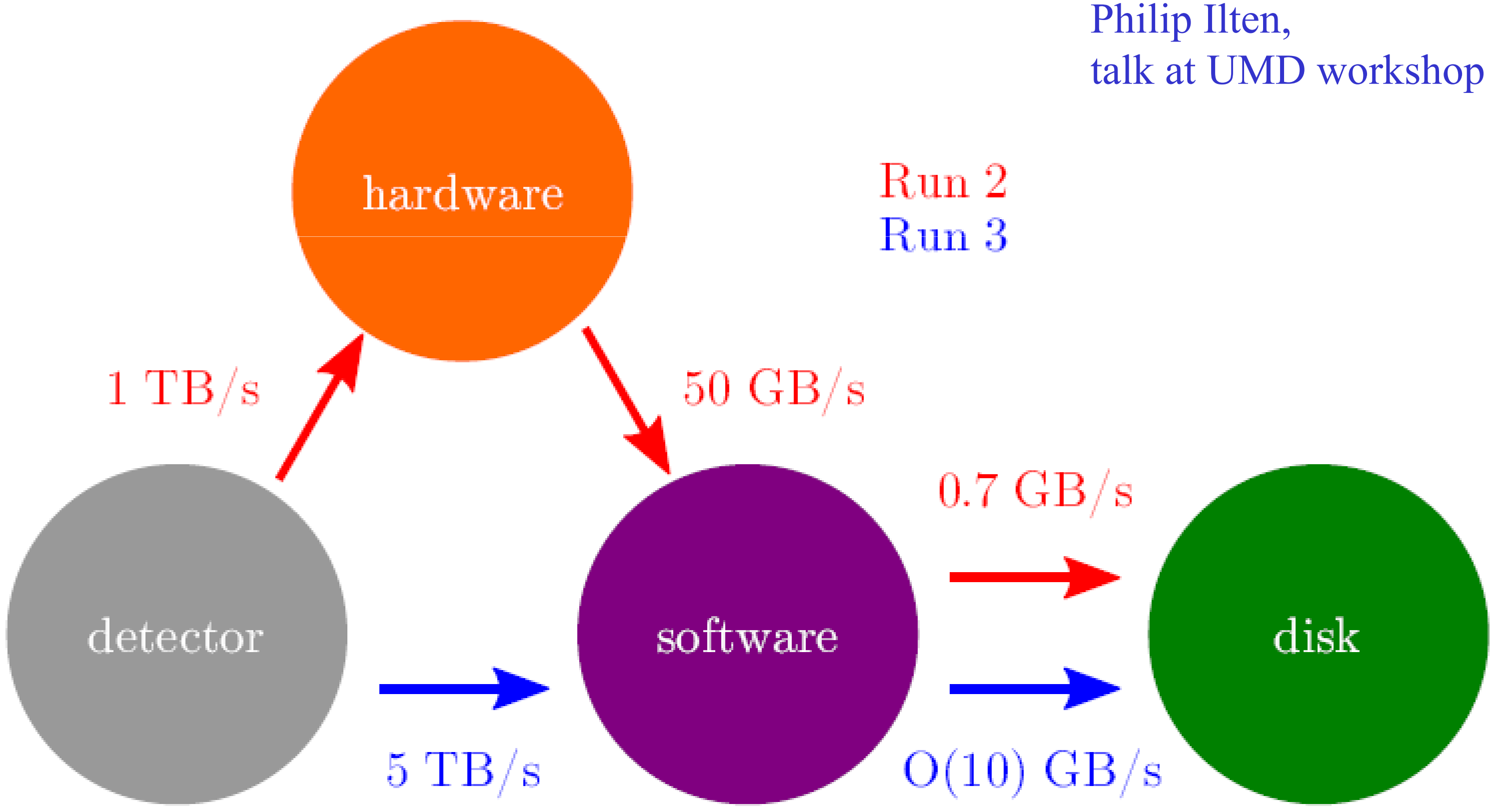
LHCb 101

It exists in reality!

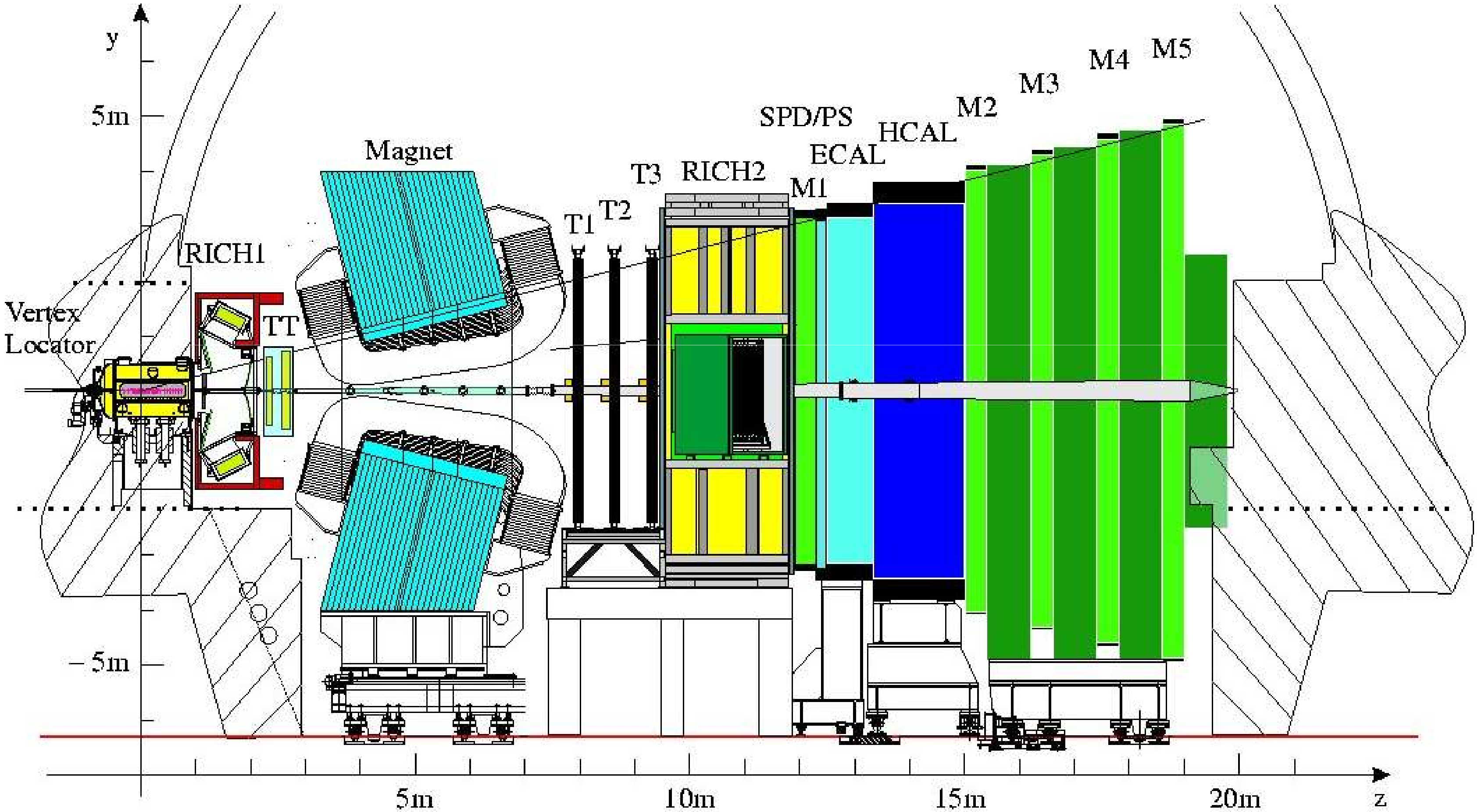
LHCb 101

LHCb provides an ideal environment to study soft exotic objects!

Philip Ilten,
talk at UMD workshop

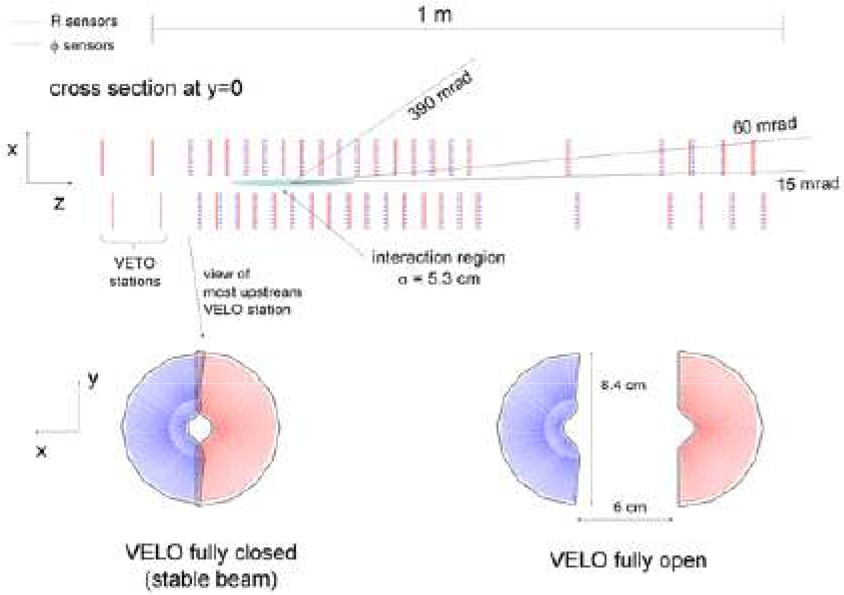


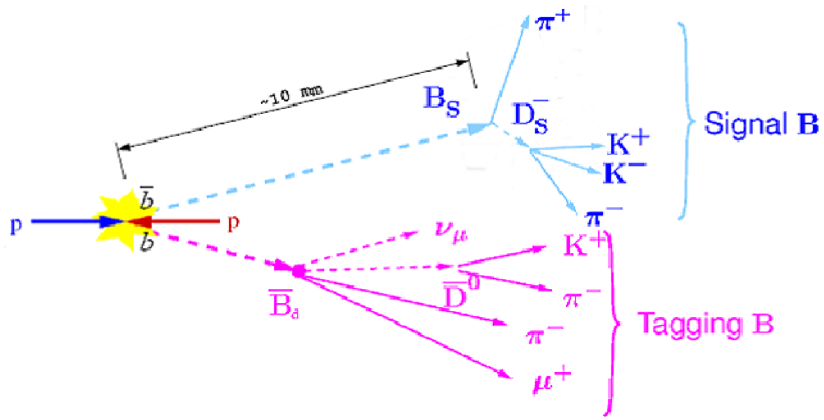
LHCb 101



y
5m
− 5m
Magnet
RICH1
Vertex
Locator
TT
T1
T2
T3
RICH2
M1
SPD/PS
ECAL
HCAL
M2
M3
M4
M5
5m
10m
15m
20m
z

LHCb 101



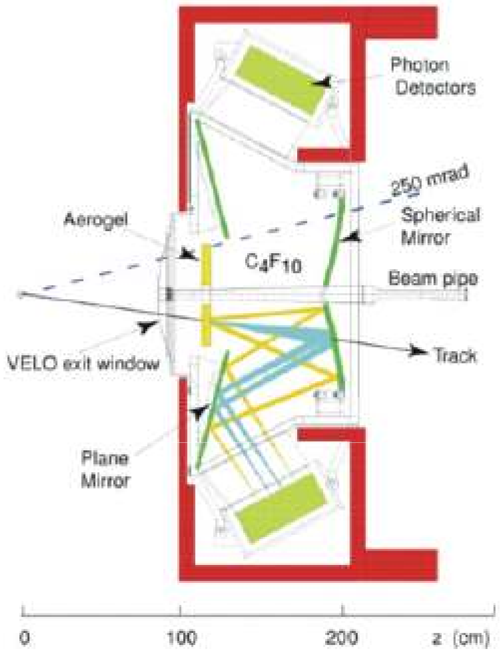


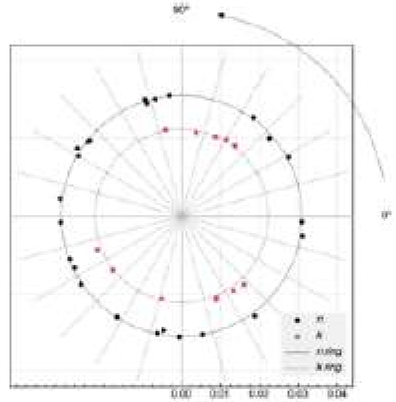
Timing Resolution

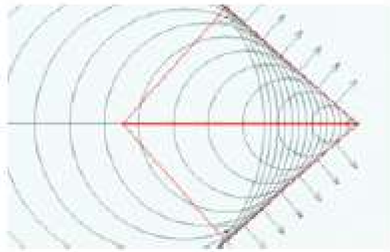
$$\approx 50\,\mathrm{fs}\ (15\,\mu\mathrm{m})$$

Gives a good measurement of displaced vertex

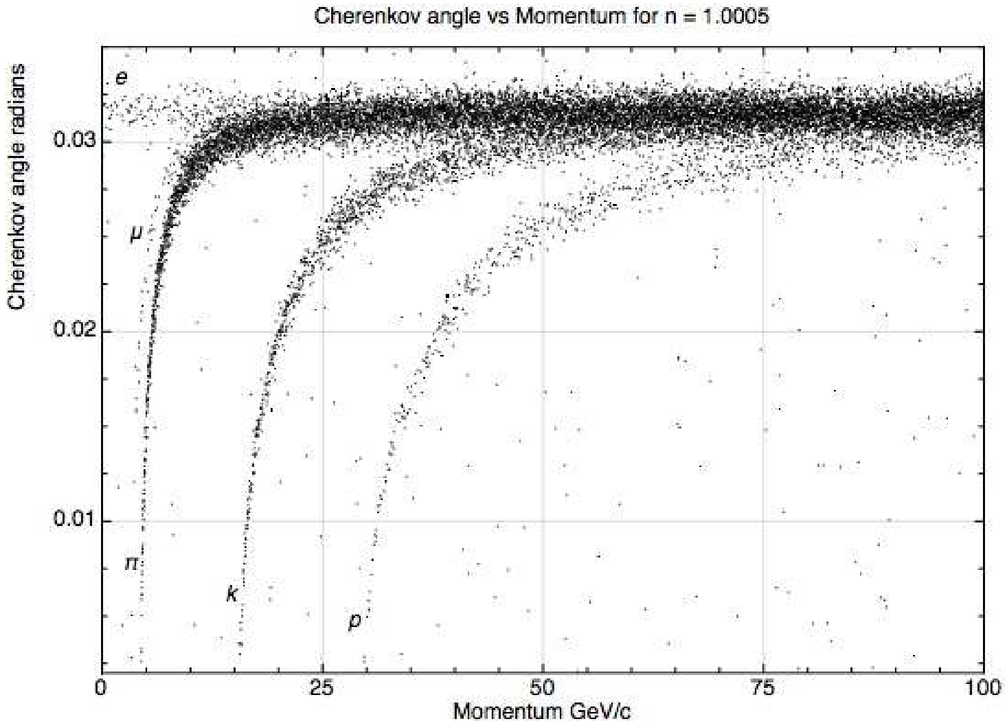
LHCb 101







$$\cos\theta_c = \frac{c}{nv}$$



LHCb 101

VELO: excellent track reconstruction/vertex location reconstruction

RICH1: excellent particle ID

Ideal place to look for soft long-lived particles produced
in high energy processes.

Showering & Hadronization in the Dark Sector

Showering with out RG running + Lund String Model:

⇨ Pythia 8

Showering with RG running + Lund String Model:

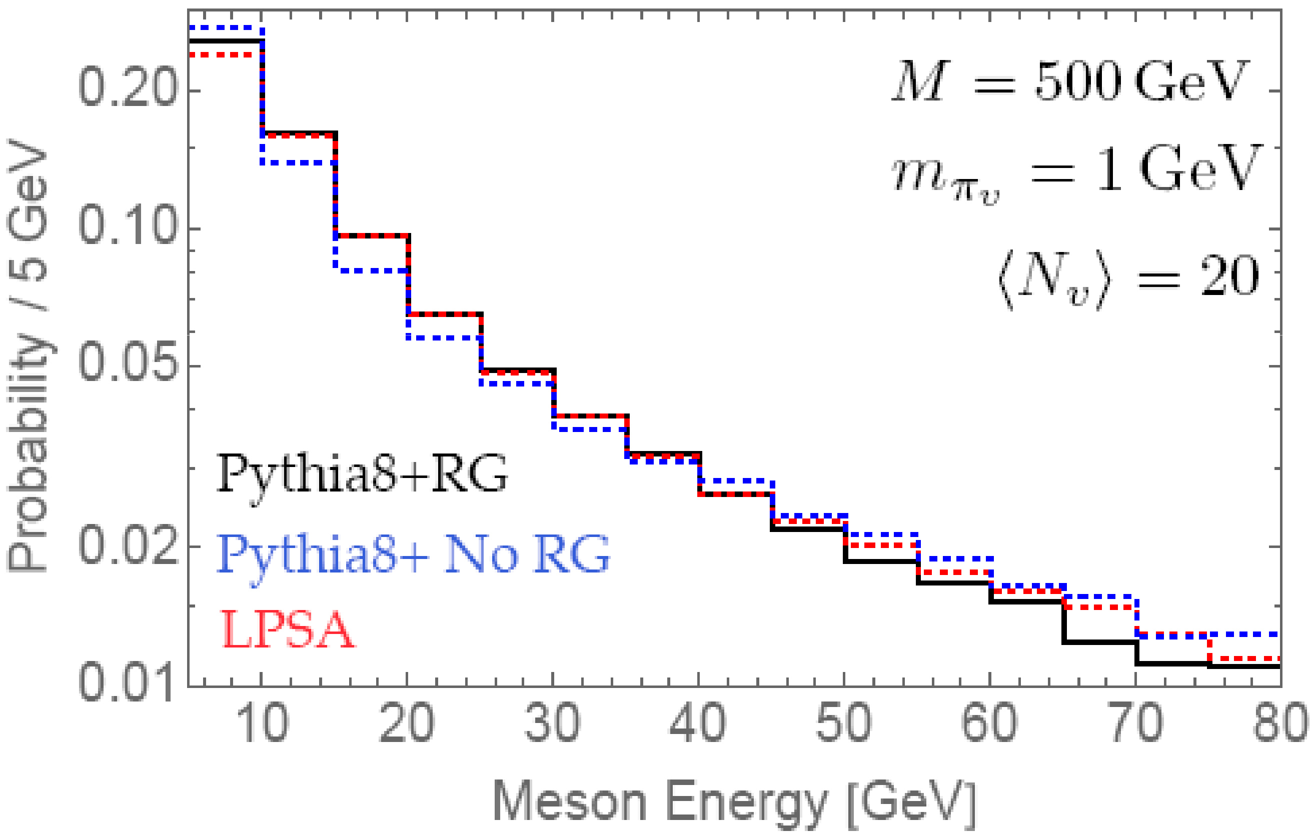
⇨ Pythia 8 with patch from Schwaller, Stolarski, and Weiler (15')

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

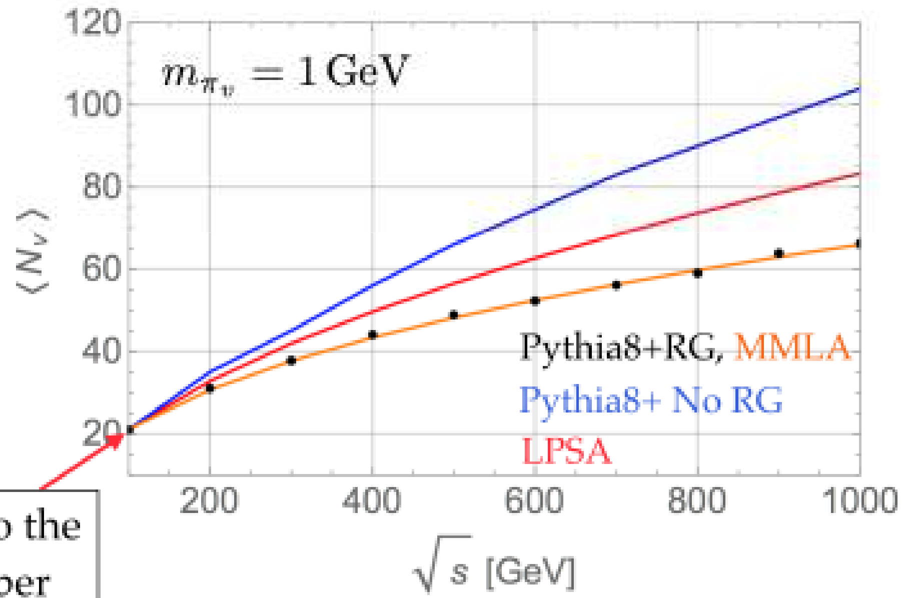
Showering & Hadronization in the Dark Sector

Energy Spectrum



Showering & Hadronization in the Dark Sector

Multiplicity



Normalize to the same number

Want to present the searching result in a $\langle N_v \rangle$ - independent way

Di-muon channel

Displaced muon search at LHCb

We adopt cuts from the displaced A′ analysis in

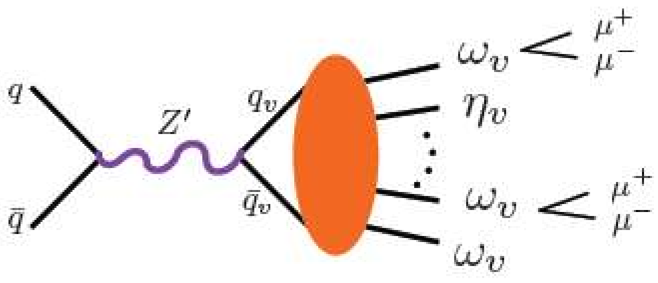
P. Ilten, Y. Soreq, J. Thaler, M. Williams, W. Xue, 1603.08926

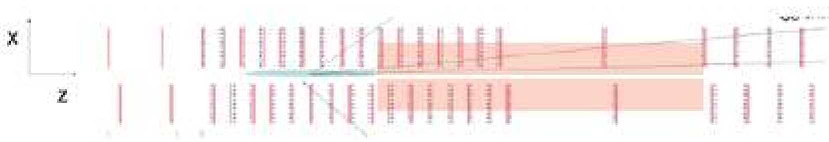
$\eta(\mu^{\pm}) \in [2,5]$, $p(\mu^{\pm}) > 10\,\mathrm{GeV}$, $p_T(\mu^{\pm}) > 0.5\,\mathrm{GeV}$

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

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

$\ell_T \in [6\,\mathrm{mm},\ 22\,\mathrm{mm}]$ $\ell_z \in [2.6\,\mathrm{cm},\ 50\,\mathrm{cm}]$ (we include this second cuts)





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:

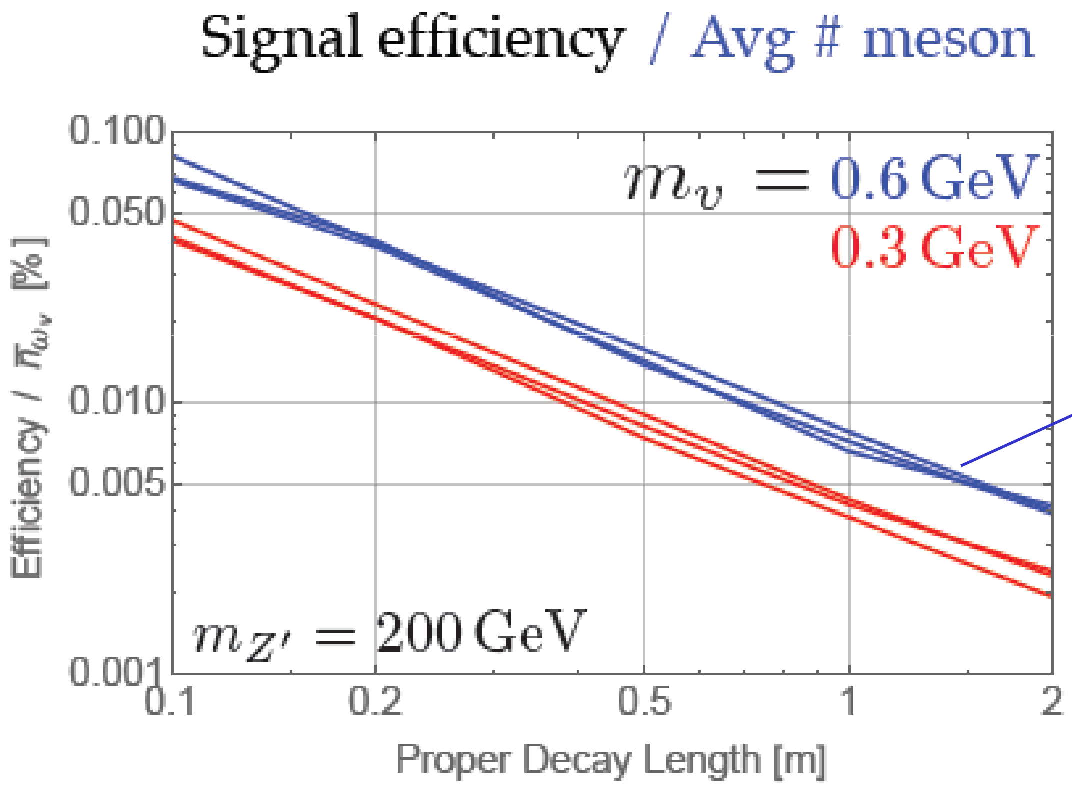
  A careful detector simulation is needed,
  may be eliminated by vertex location.

⇨ ~ 25 events / mass bin at 15 / fb at 13 TeV (Run III)

Signal efficiency vs Multiplicity

Long decay lifetime :

PYTHIA + RG Running



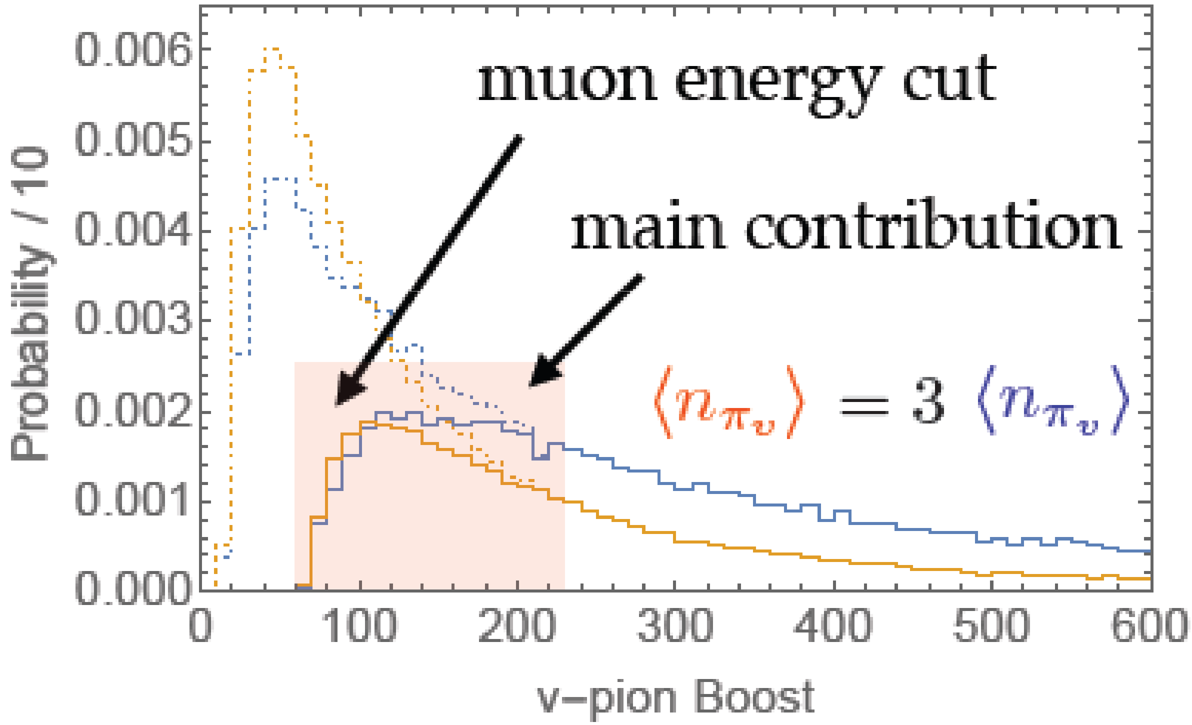
Different choices on average meson number [10, 30]

Acceptance for each meson is approximately a constant!

(A little bit counter-intuitive, more meson implies less boosting.)

Signal efficiency vs Multiplicity

Long decay lifetime :



Mesons from hadronization still peak at low energy regime.

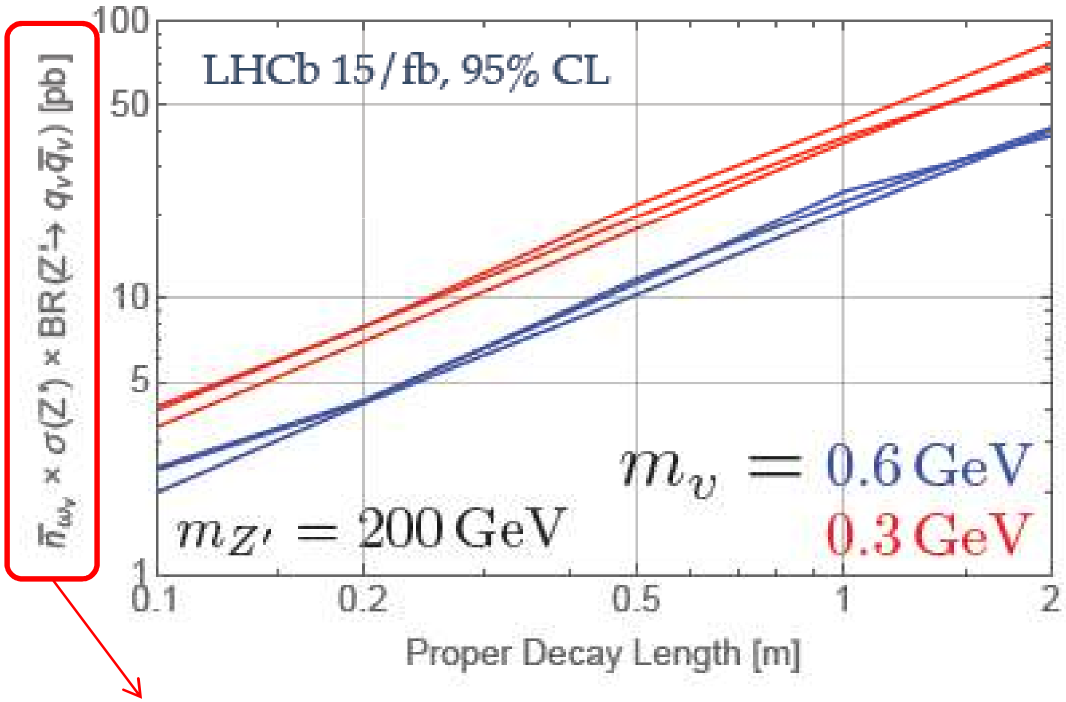
⇨ Acceptance for each meson is not sensitive to $\langle N_{\pi_v} \rangle$

Signal efficiency vs Multiplicity

Long decay lifetime :

PYTHIA + RG Running

v-quark production x Avg # meson

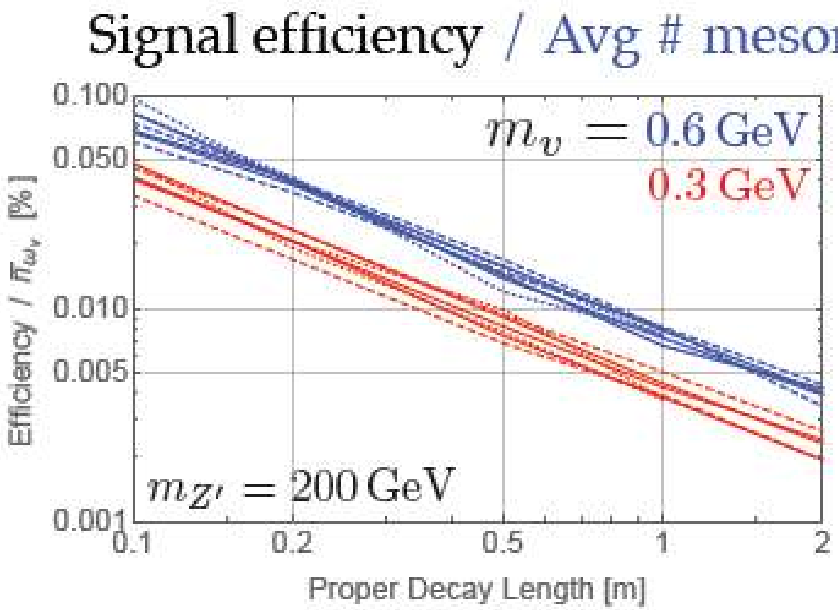


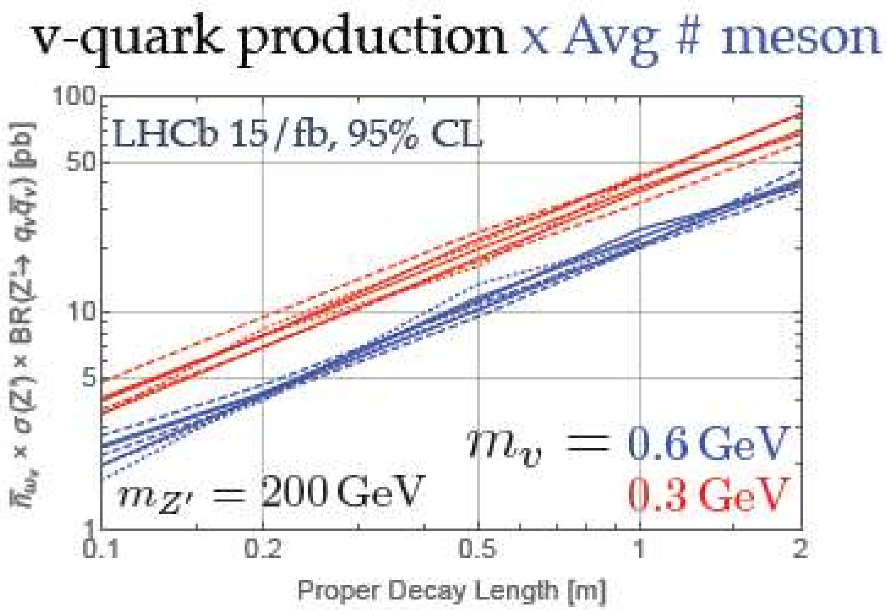
Showering/Hadronization sensitivities are removed.

A good quantity to set limits on!

Signal efficiency vs Multiplicity

Long decay lifetime :

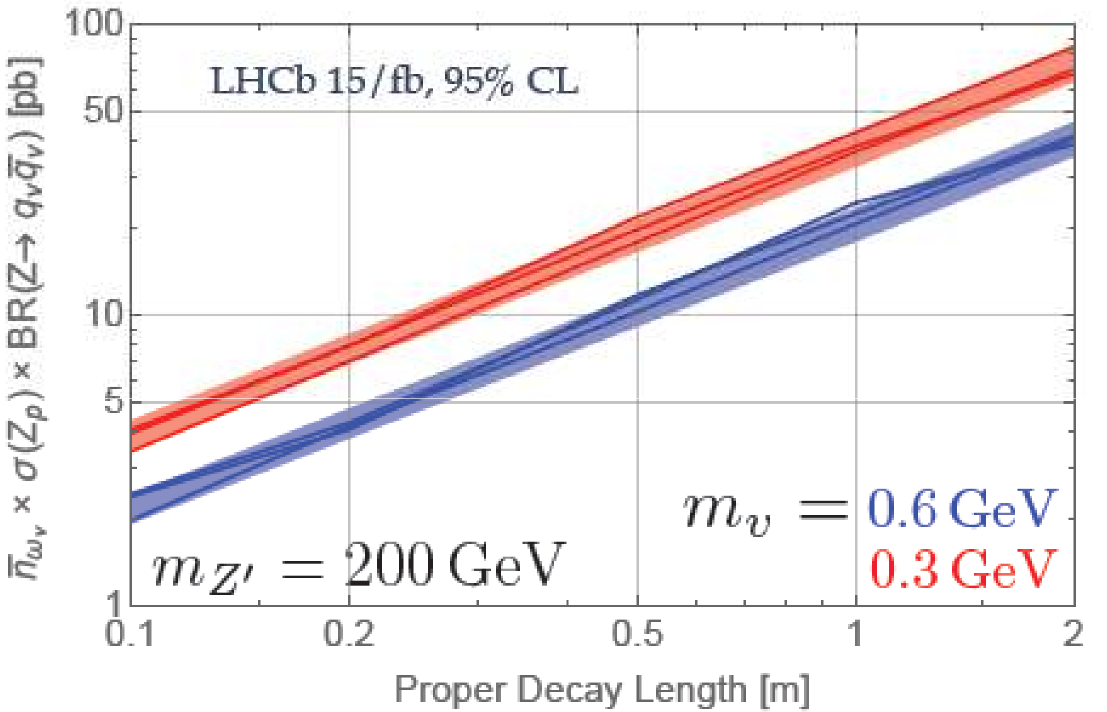




Solid: PYTHIA + RG Running
Dashed: PYTHIA without RG Running
Dotted: LPSA

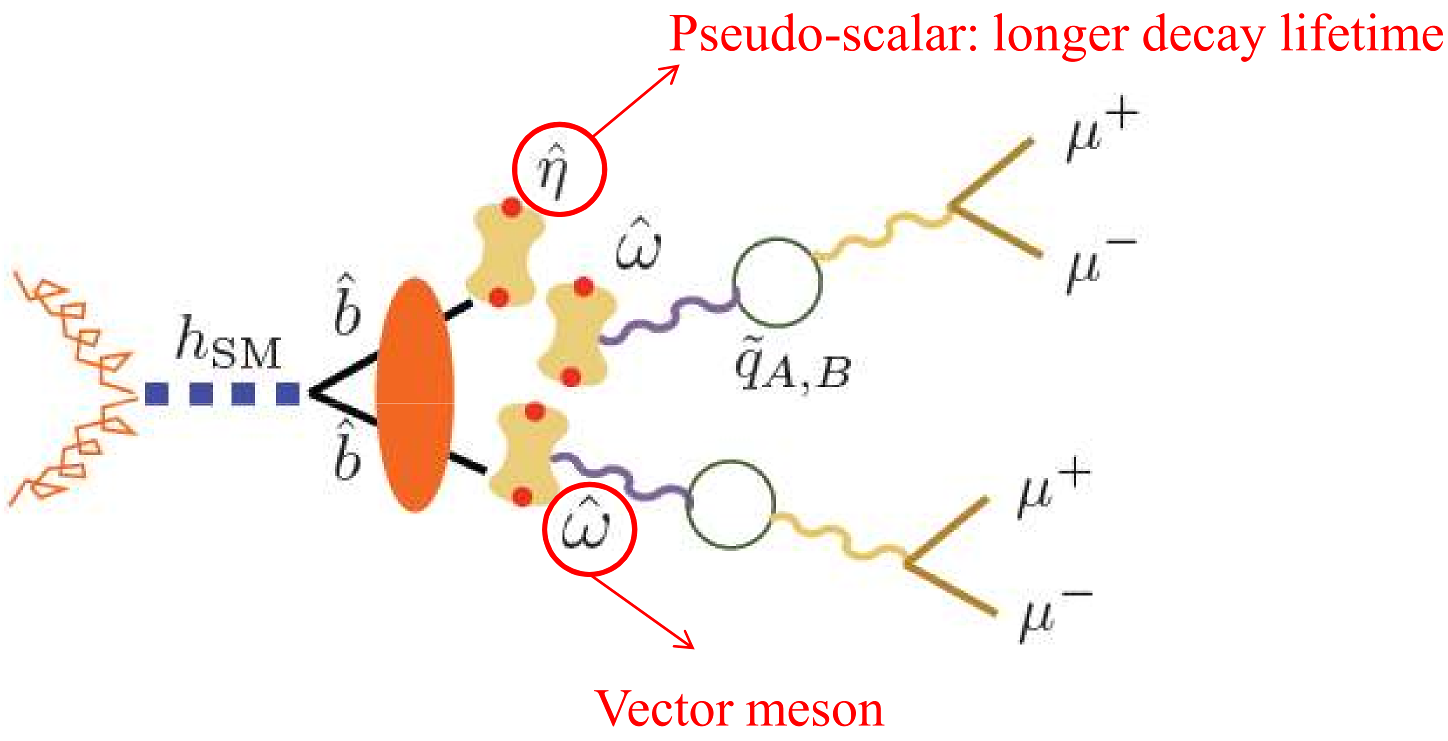
LHCb Di-muon limit

Long decay lifetime :

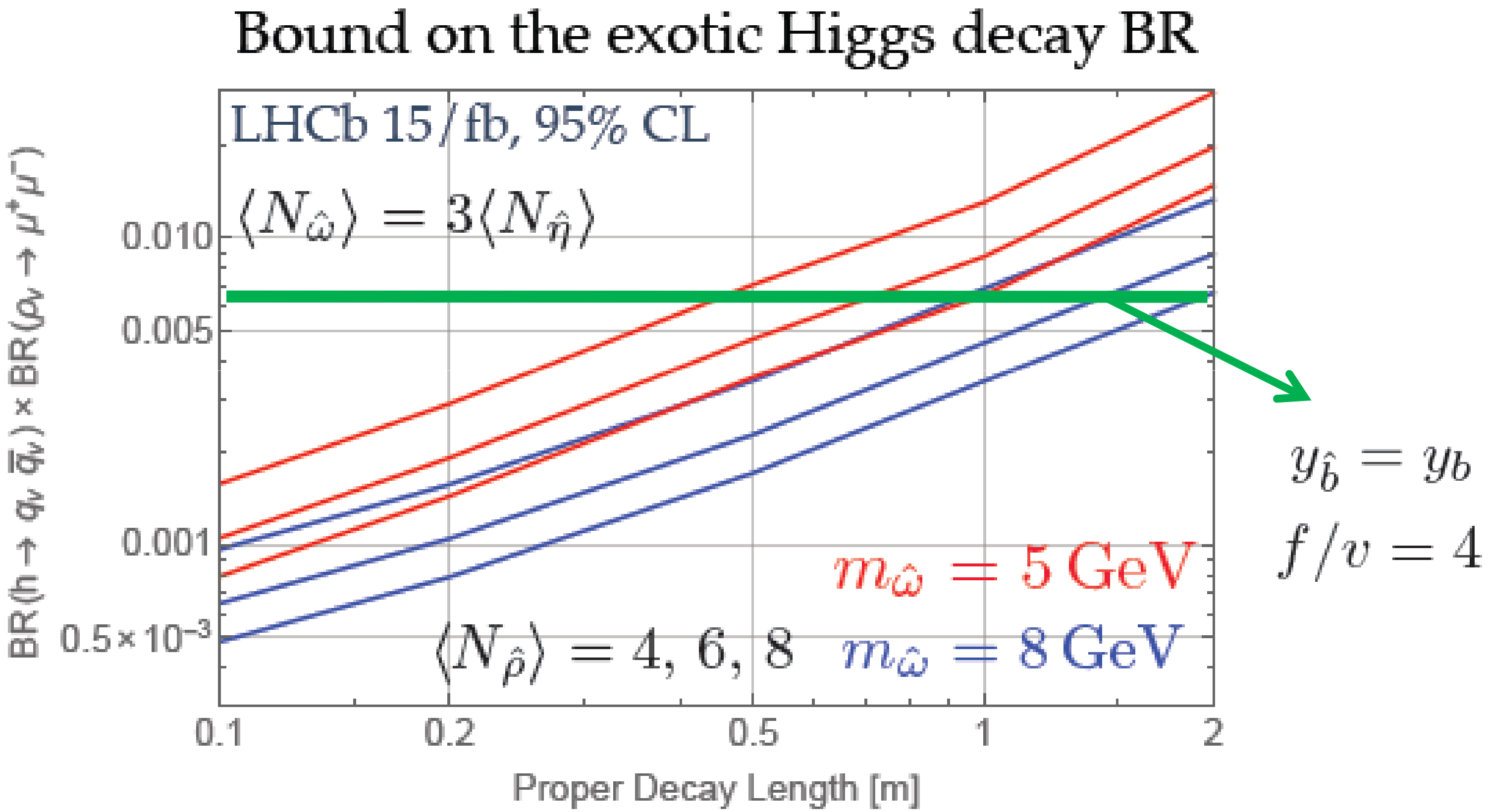


	$c\tau = 10$ cm		$c\tau = 100$ cm	
$\langle N_v \rangle$	600 MeV	300 MeV	600 MeV	300 MeV
10	250 (fb)	400	2 pb	4 pb
30	80	130	670	1.3 pb

Applications in Twin Higgs Models



Applications in Twin Higgs Models



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

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 $P_T \sim O(0.1)\ M / \langle N \rangle$

DV + muon : muon $P_T >$ 50 GeV

DV + electron: electron $P_T >$ 120 GeV

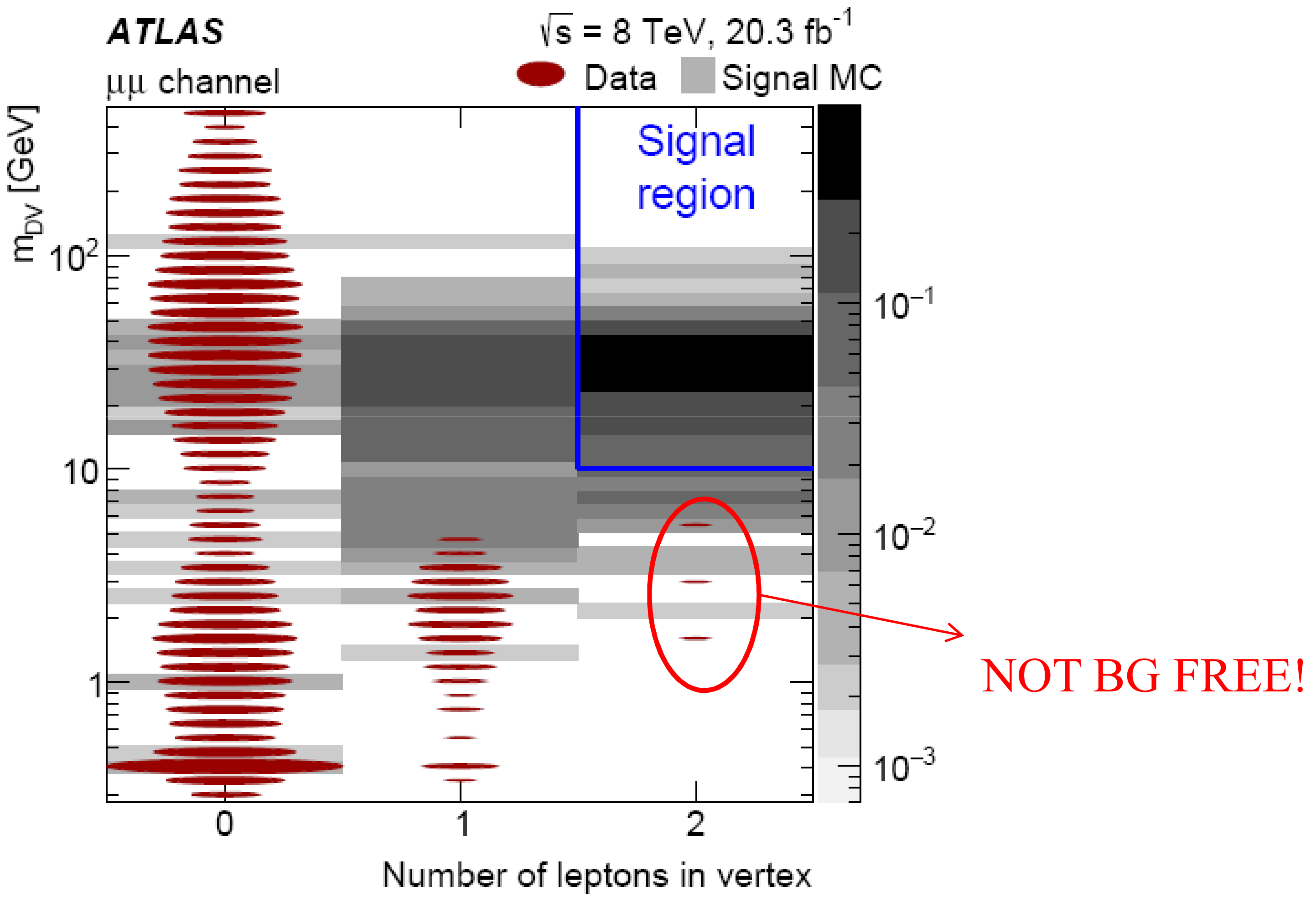
DV + jet: 4 j > 90 GeV, 5 j > 65 GeV, 6 j > 55 GeV

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



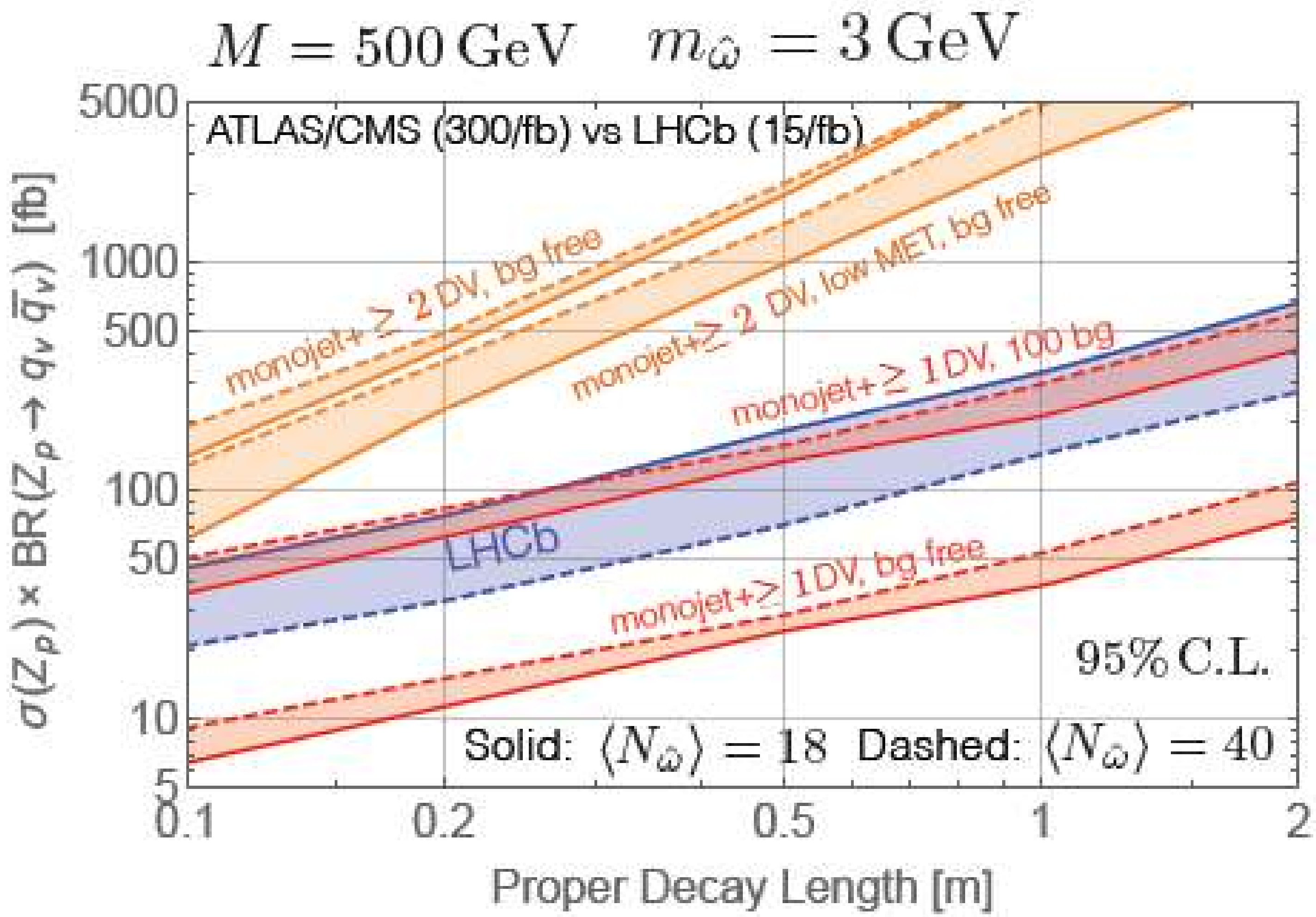
LHCb vs ATLAS/CMS

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

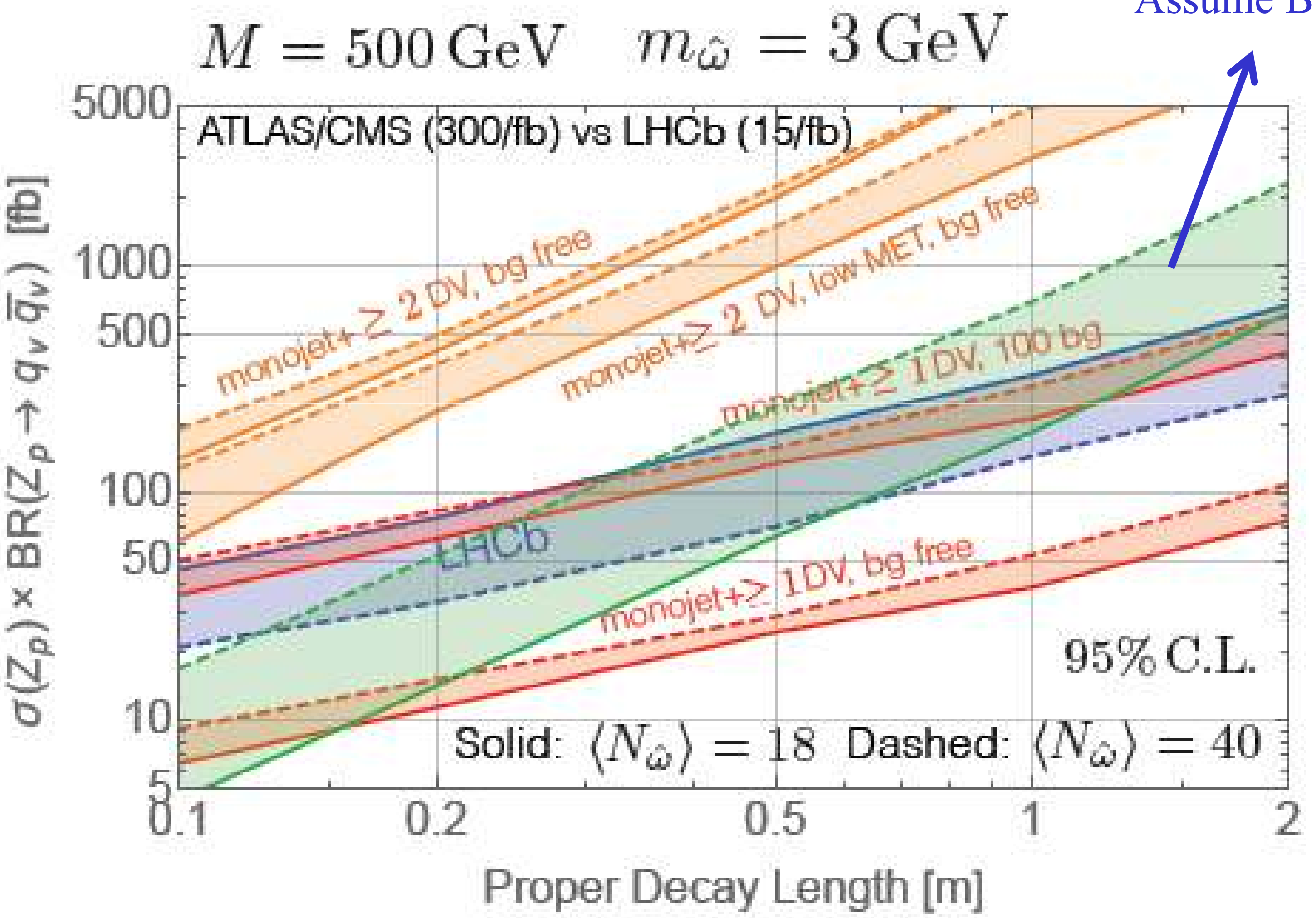
Can be lowered by requiring more DV

LHCb vs ATLAS/CMS

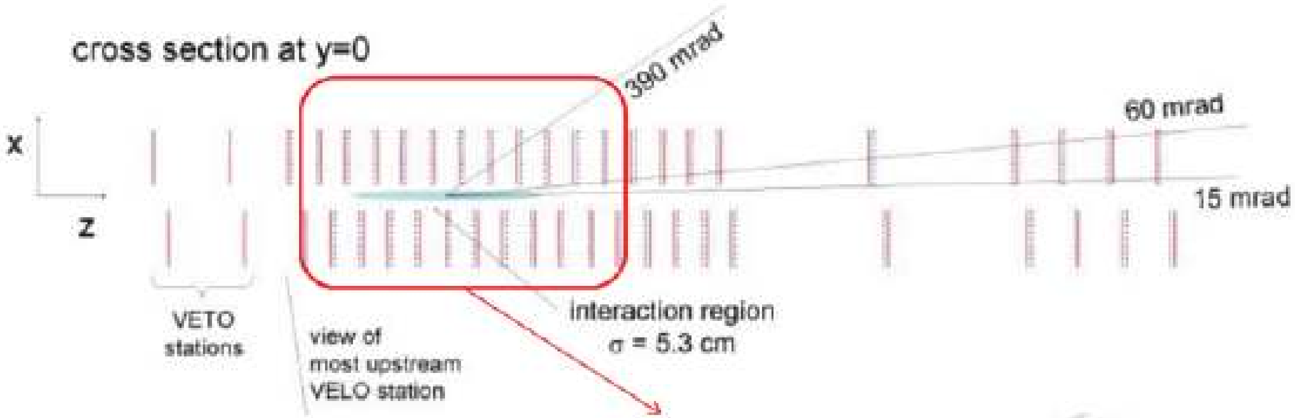


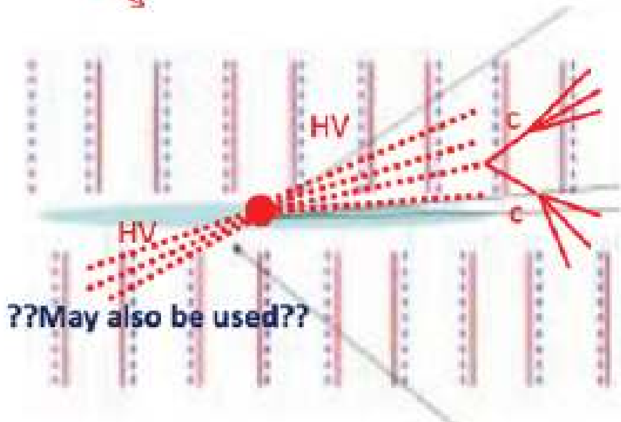
LHCb vs ATLAS/CMS

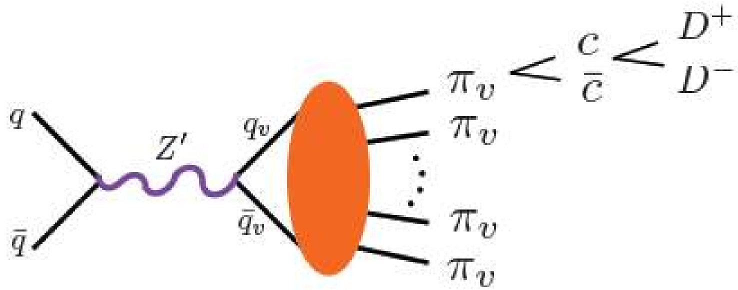
Very optimistic:
reconstruct 2 DV
muon PT > 10 GeV
Assume BG Free.



Hadronic Decay Channels: D-meson







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

$$\eta(D^{\pm}) \in [2,5],\, p_T(D^{\pm}) > 1.8\,\mathrm{GeV},\, H_T(D^{\pm}) > 5\,\mathrm{GeV}$$

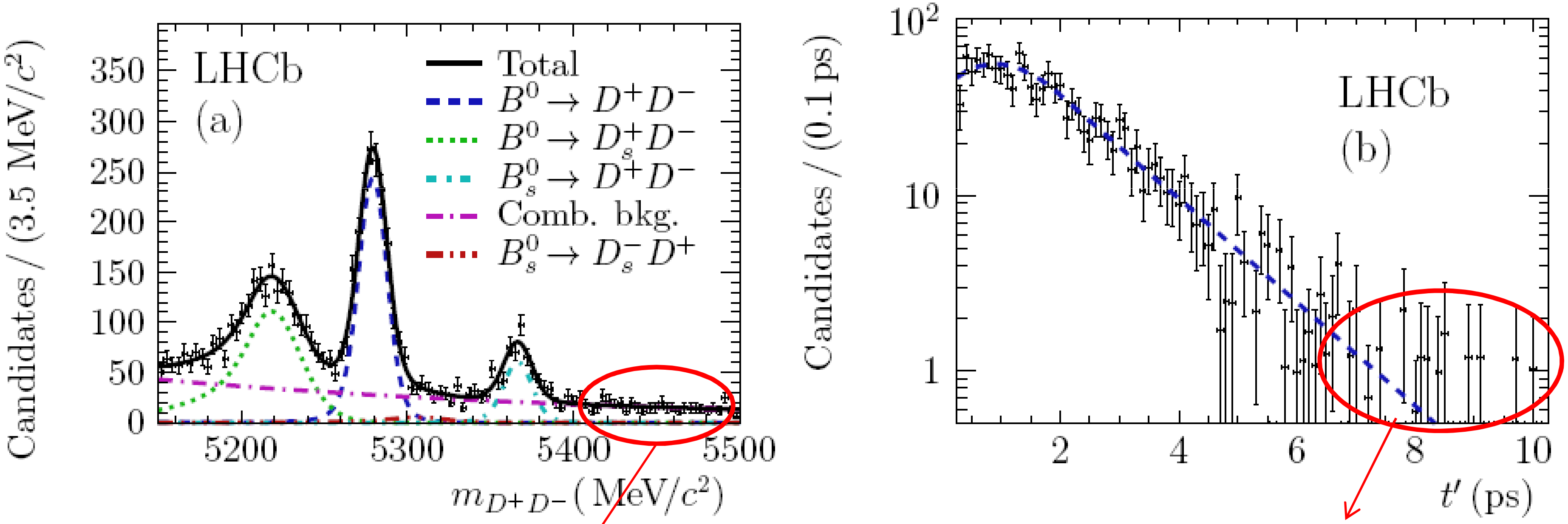
$$D^+ \to K^- \pi^+ \pi^-,\, D^+ \to K^- K^+ \pi^+$$

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.

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



BG is dominated by combinatorics.

BG is highly suppressed by requiring large displacement.

Hadronic Decay Channels: D-meson

The most conservative search channel:

- Both D-mesons are well-reconstructed.

A less conservative search channel:

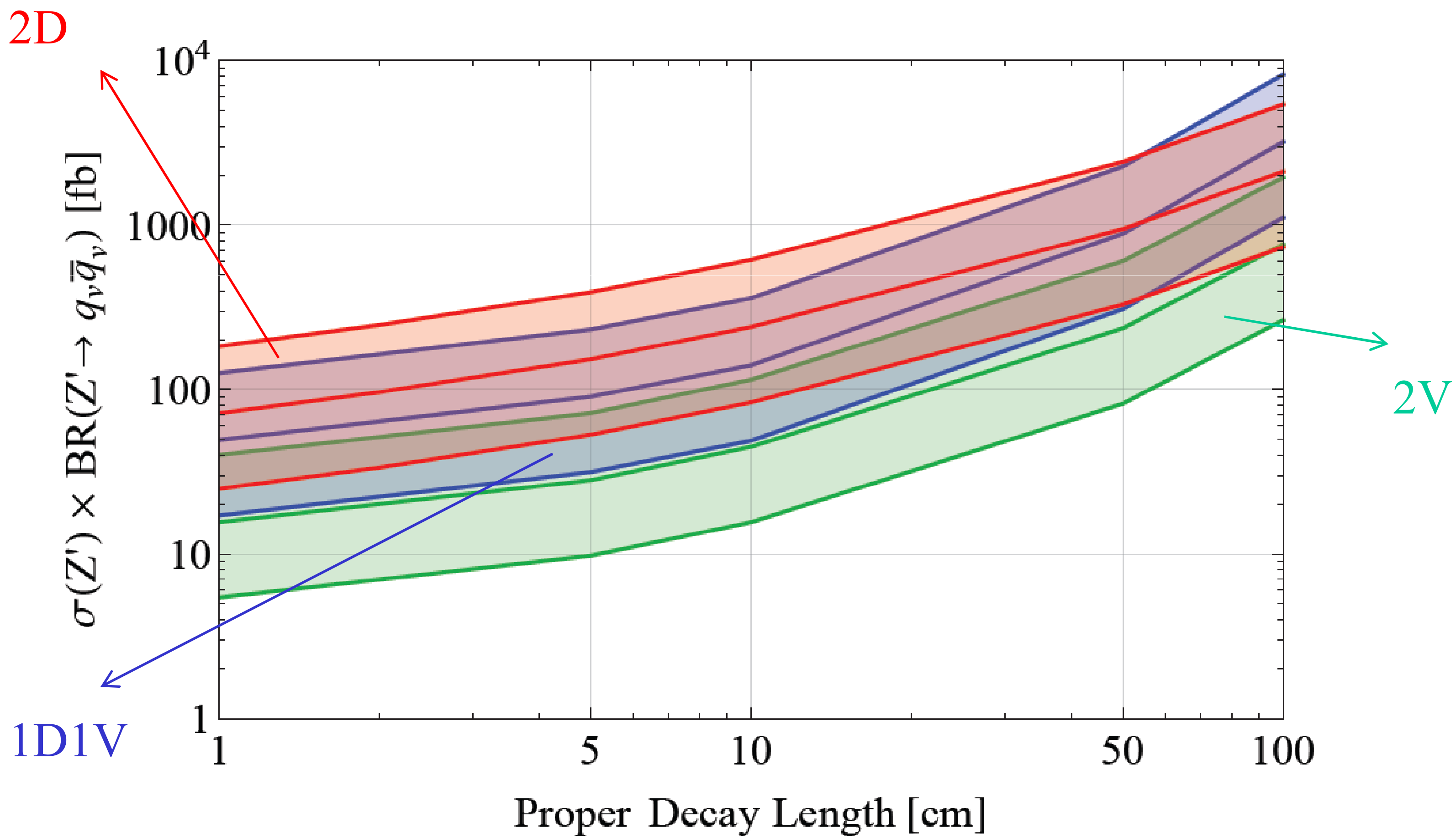
- One D-meson is well-reconstructed.
- A displaced 3-track vertex is nearby the reconstructed D-meson.

An aggressive search channel: (based on pure topology)

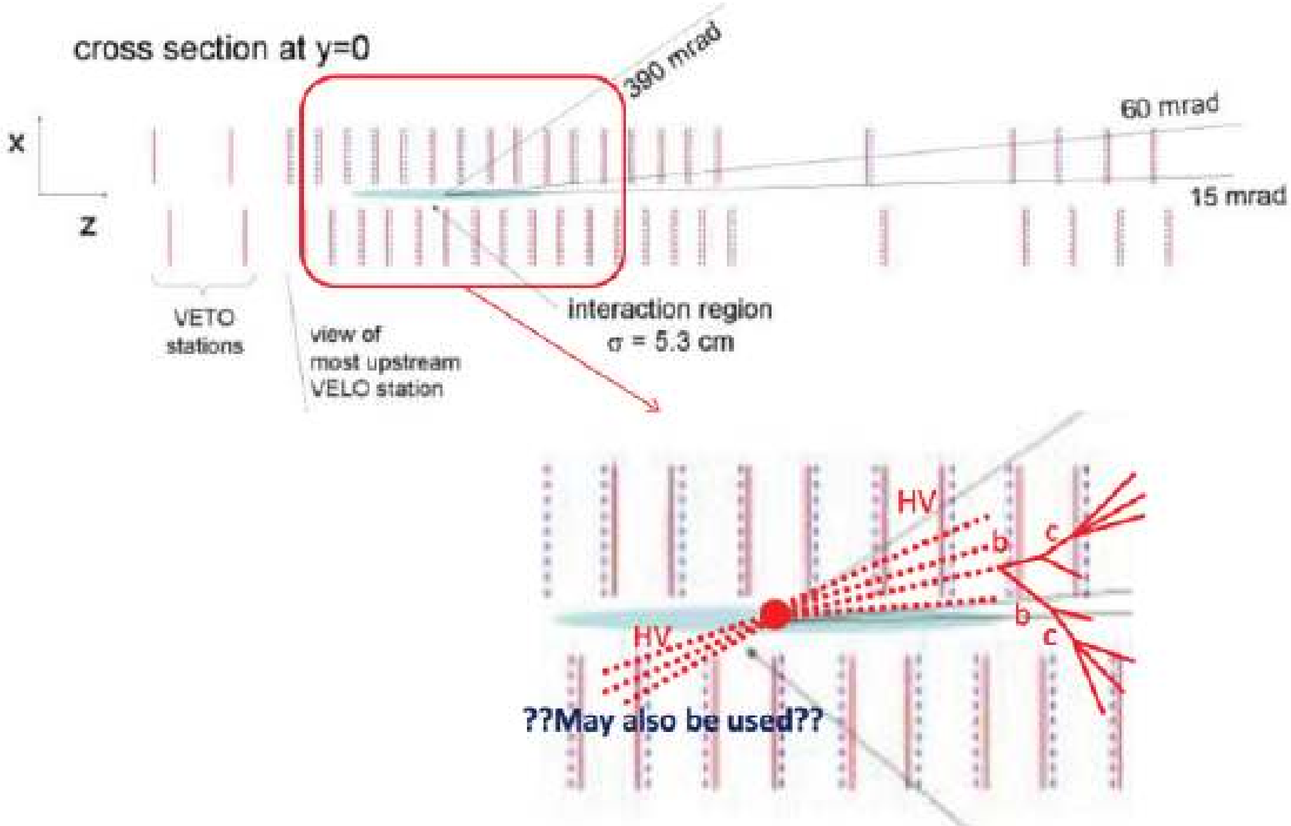
- Two 3-track vertices of displaced charged tracks are reconstructed.
- Both vertices are far away from the PV.
- The transverse separation between vertices ~ O(D-meson lifetime).

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.

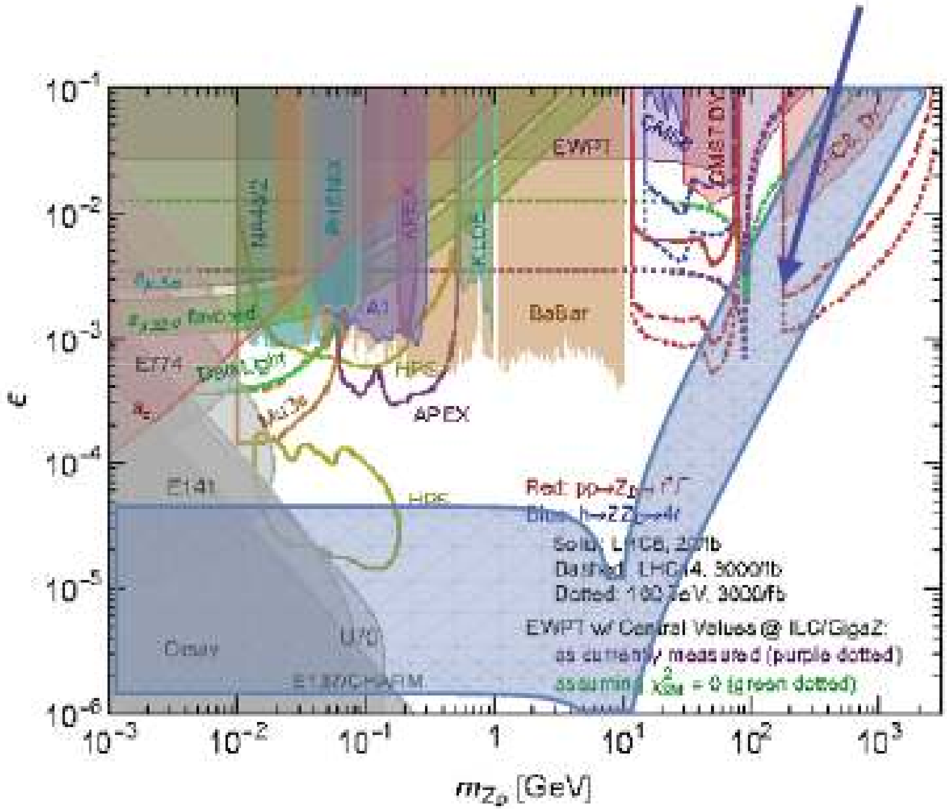
Di-muon channel:
Better /comparable reaches than MET+jet+DV searches at ATLAS/CMS.

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

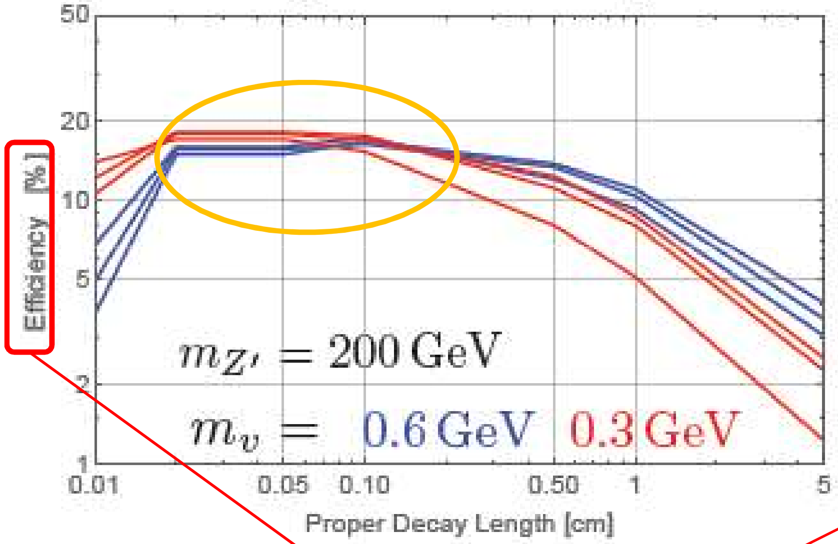
Assume $m_{\hat{\omega}} = 2\hat{\Lambda} = 8\,\mathrm{GeV}$ $\quad 0.1 < c\tau_{\hat{\omega}} < 100\,\mathrm{cm}$

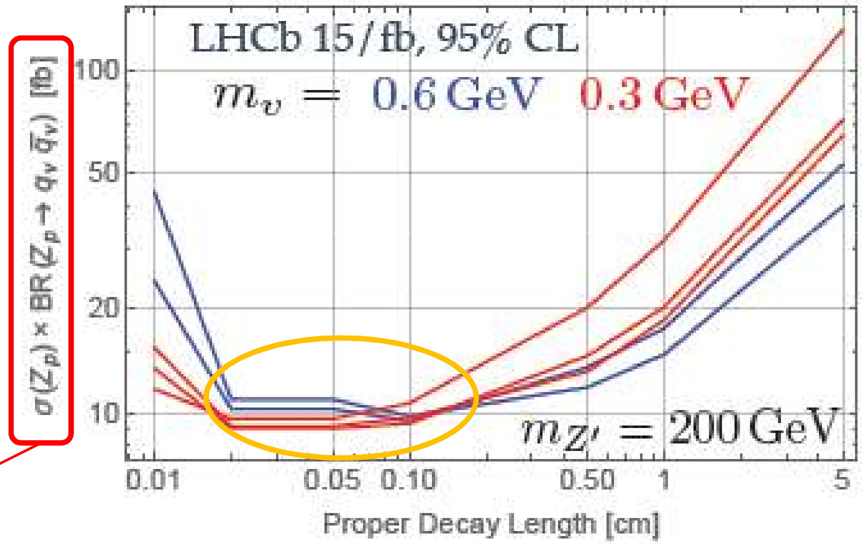


$$c\tau_{\hat{\omega}} \simeq 20\,\mathrm{cm}\left(\frac{m_{A'}}{100\,\mathrm{GeV}}\right)^4\left(\frac{10^{-3}}{\epsilon}\right)^2\left(\frac{3\,\mathrm{GeV}}{\Lambda}\right)^5$$

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.