Searching for Confining Hidden Valleys at the LHC(b)

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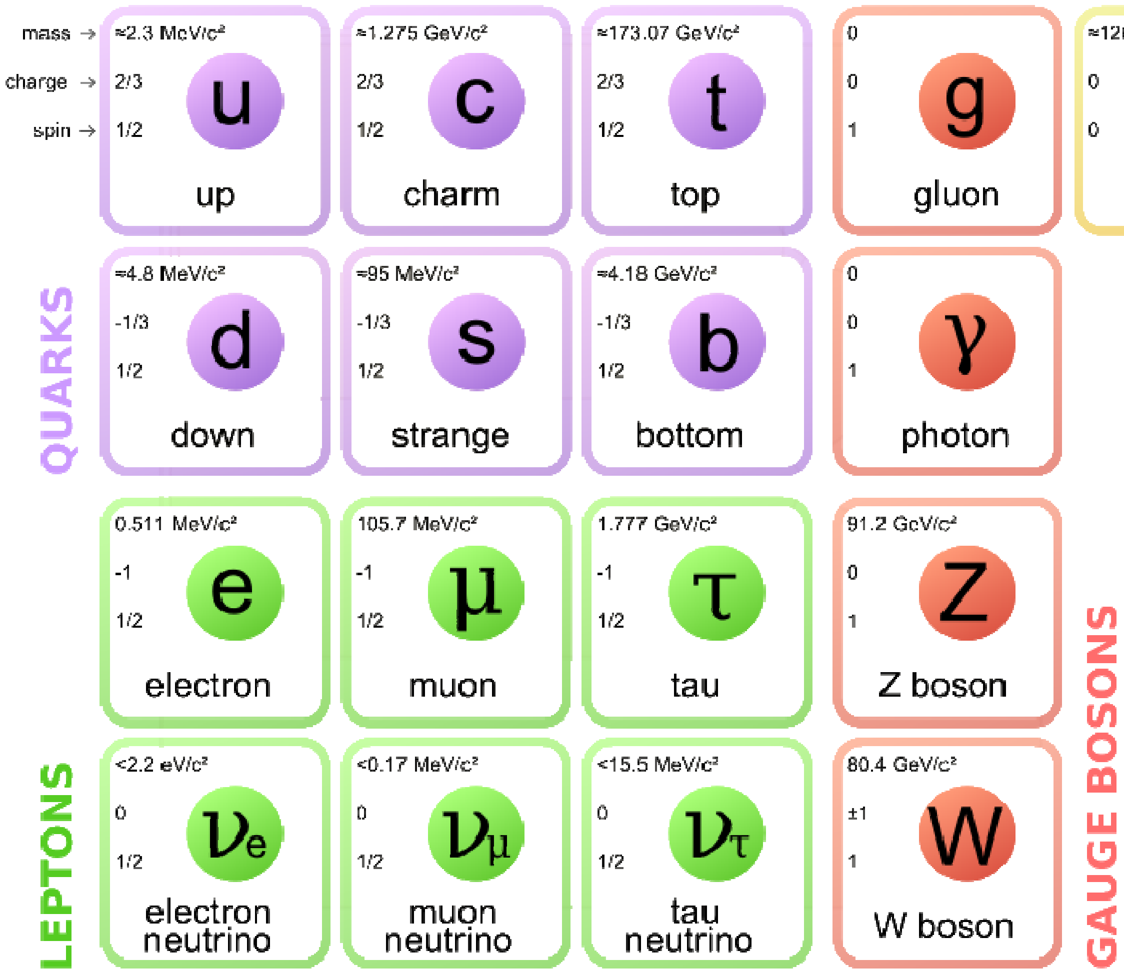
Jan. 2018

with Aaron Pierce, Bibhushan Shakya,Yuhsin Tsai
arXiv:1708.05389 [hep-ph]

Current Status of Particle Physics



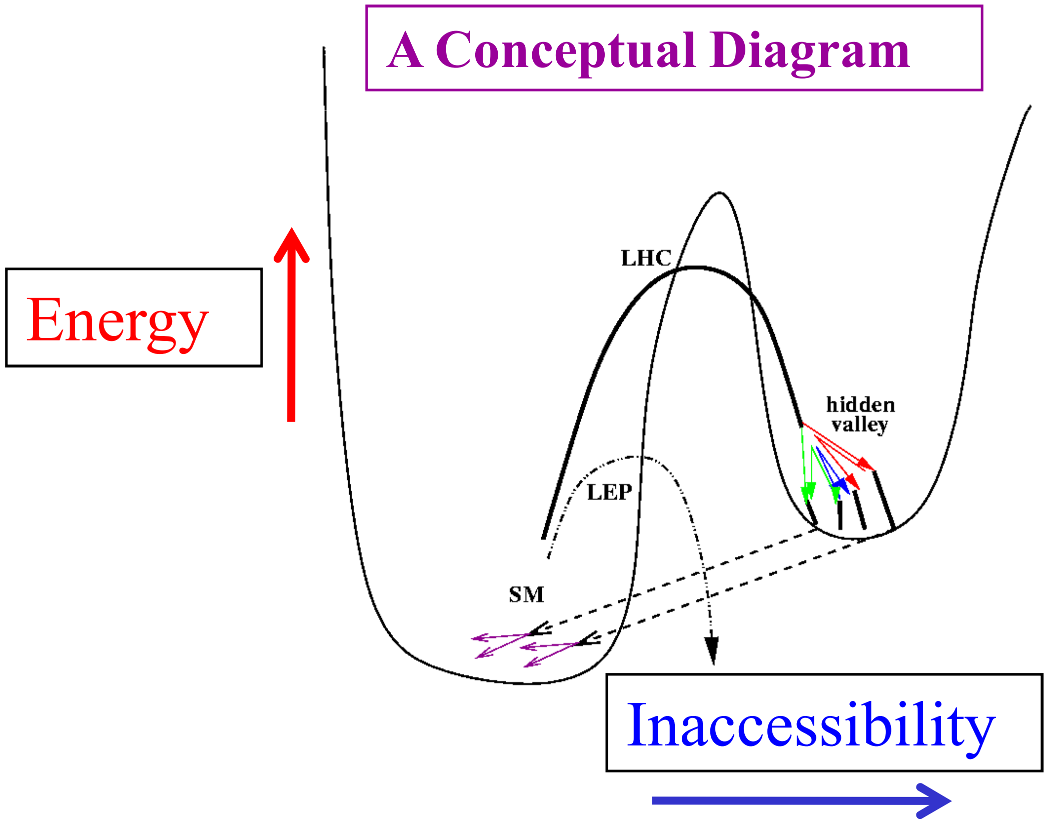
+ Dark Sector may or may not be related to DM

Non-Abelian Dark Sector

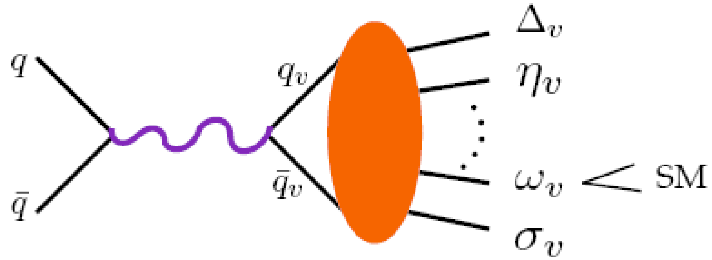
Dark Sector remains largely unknown.

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

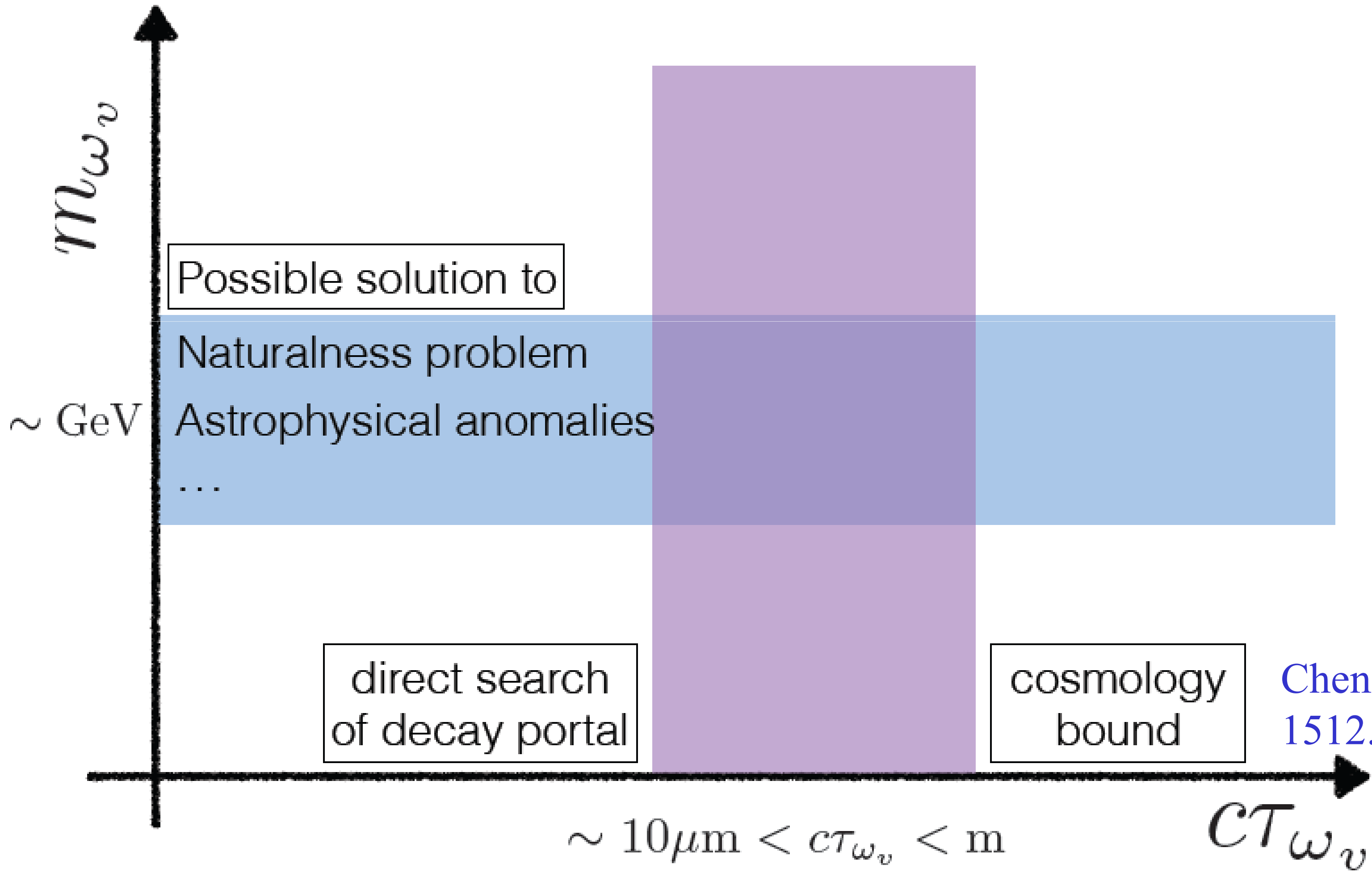
- Generically classified as Hidden Valley models.



M. Strassler and K. Zurek (06′)



Preferred parameter space



Cheng et. al.
1512.02647

Non-Abelian Dark Sector

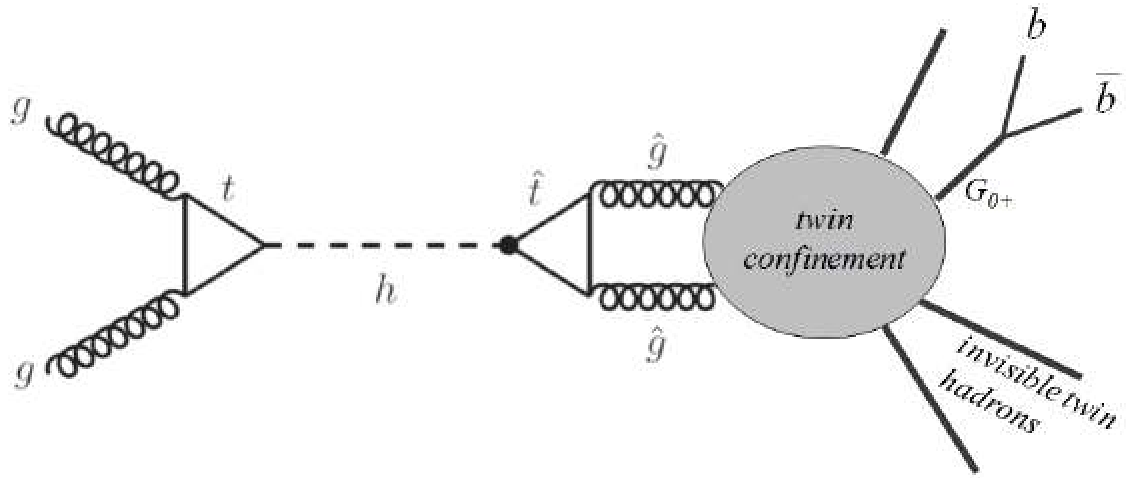
Dark Sector remains largely unknown.

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:

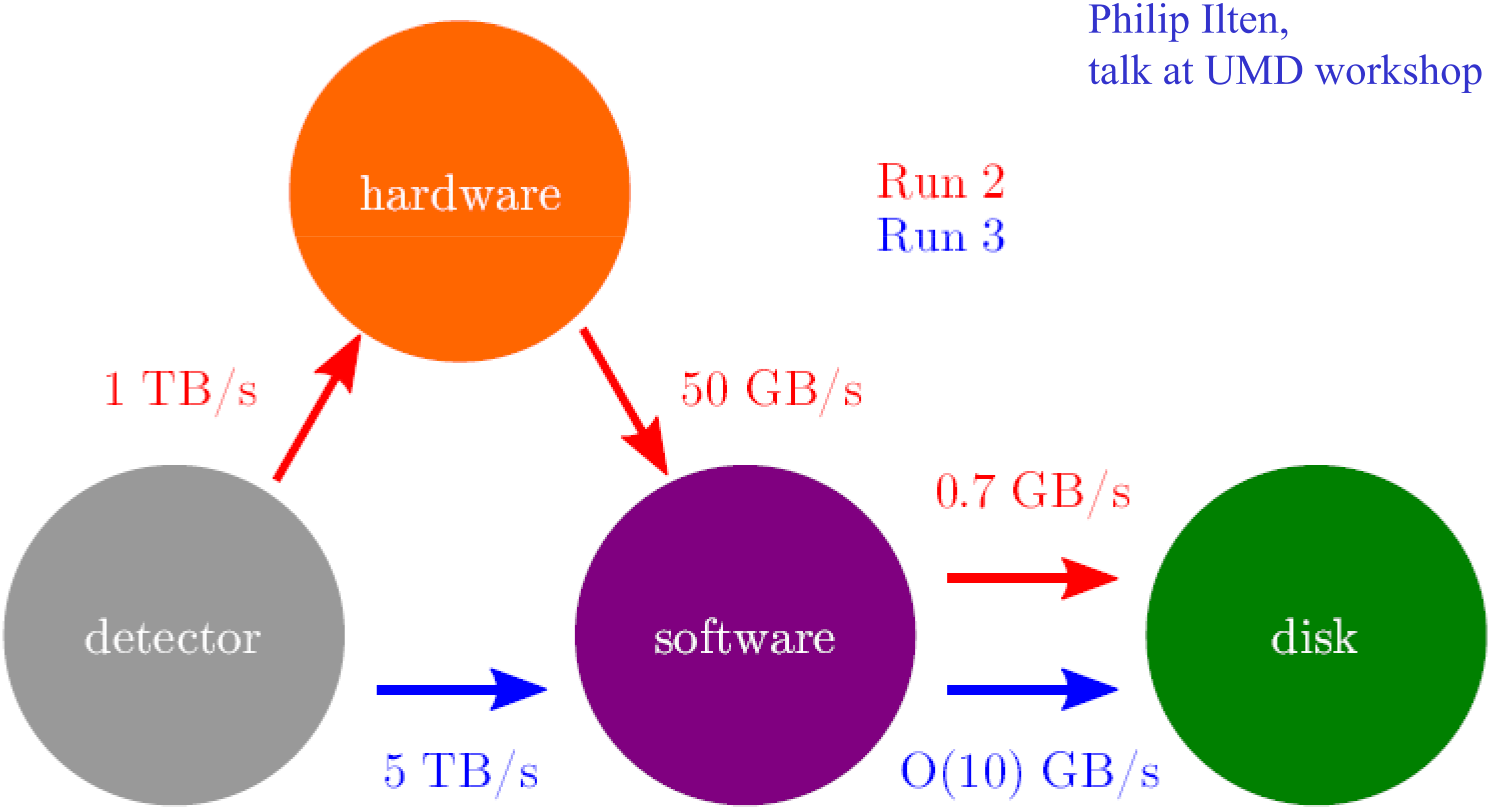
Search for long-lived particles decaying to jet pairs
Eur. Phys. J. C75 (2015) 152

but also with two hidden pions in the final states.

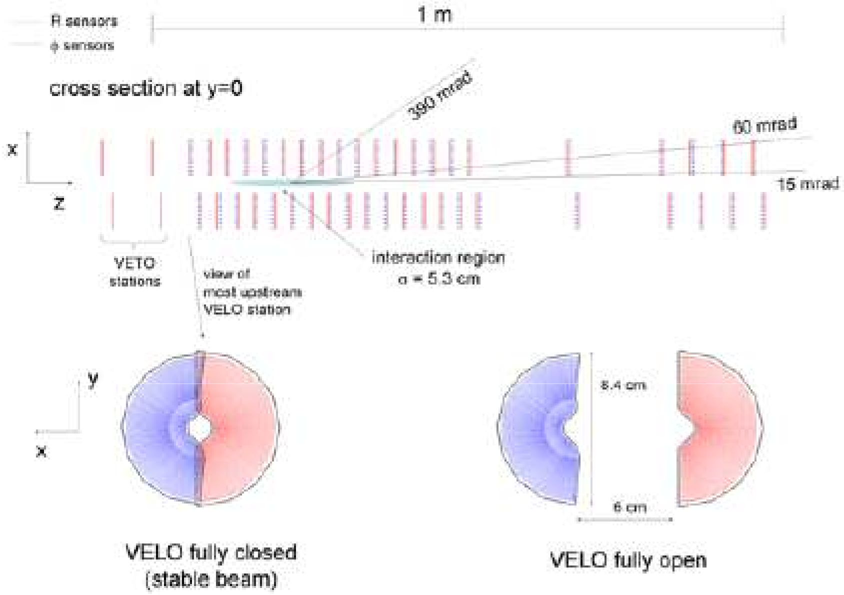
LHCb trigger

LHCb provides an ideal environment to study soft exotic objects!

Philip Ilten,
talk at UMD workshop



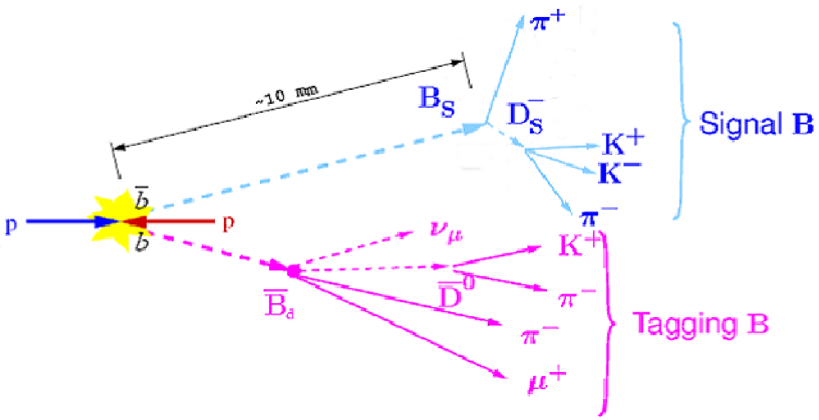
LHCb VELO



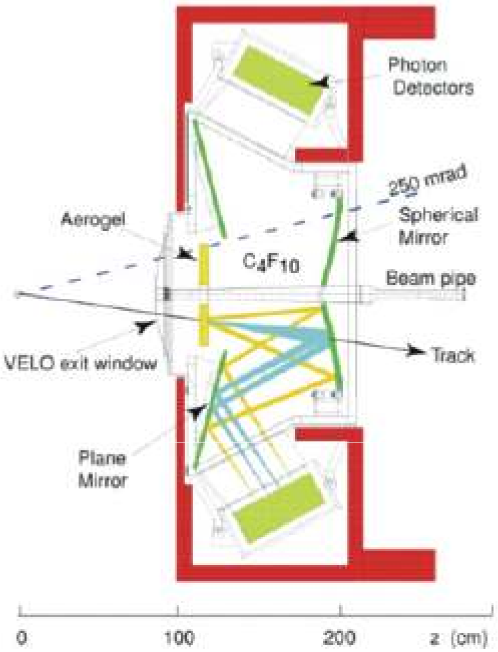
Timing Resolution

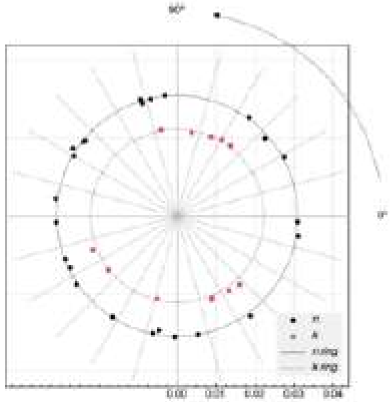
$$\approx 50\,\mathrm{fs}\;(15\,\mu\mathrm{m})$$

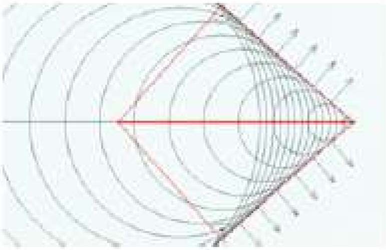
Gives a good measurement of displaced vertex



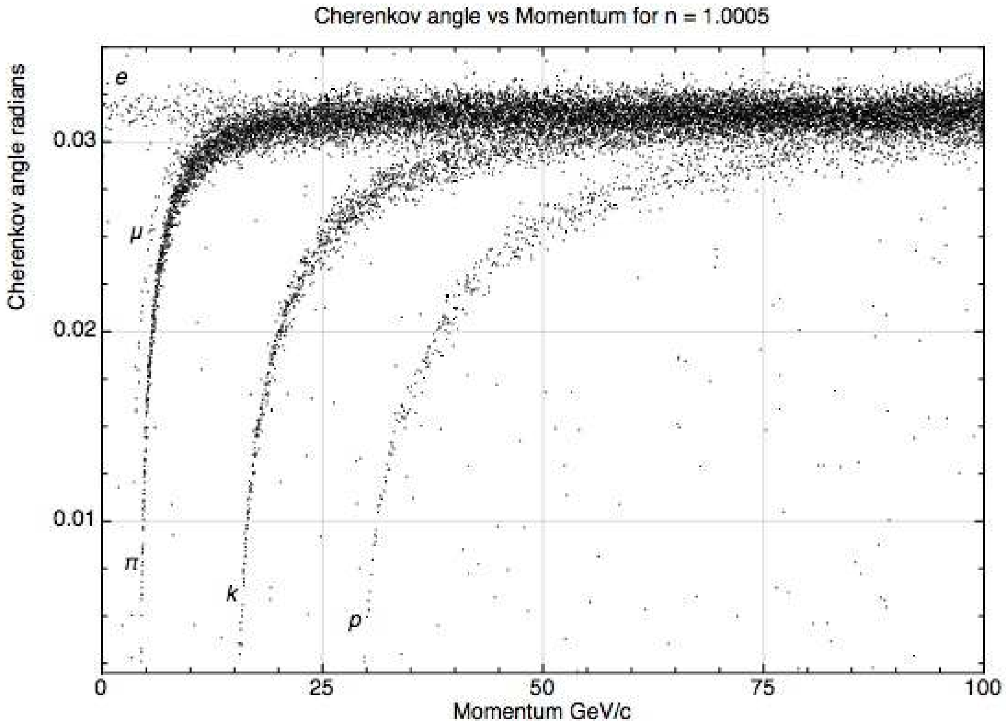
LHCb RICH







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



DV search at LHCb

LHCb = Particle spectrometer + High energy collision

Excellent invariant-mass & vertex resolution

Excellent tool to see light & long-lived particles produced by heavy mediator and decay into SM mesons / charged leptons

Showering & Hadronization in the Dark Sector

Showering with out RG running + Lund String Model:

⇨ Pythia 8

Showering with RG running + Lund String Model:

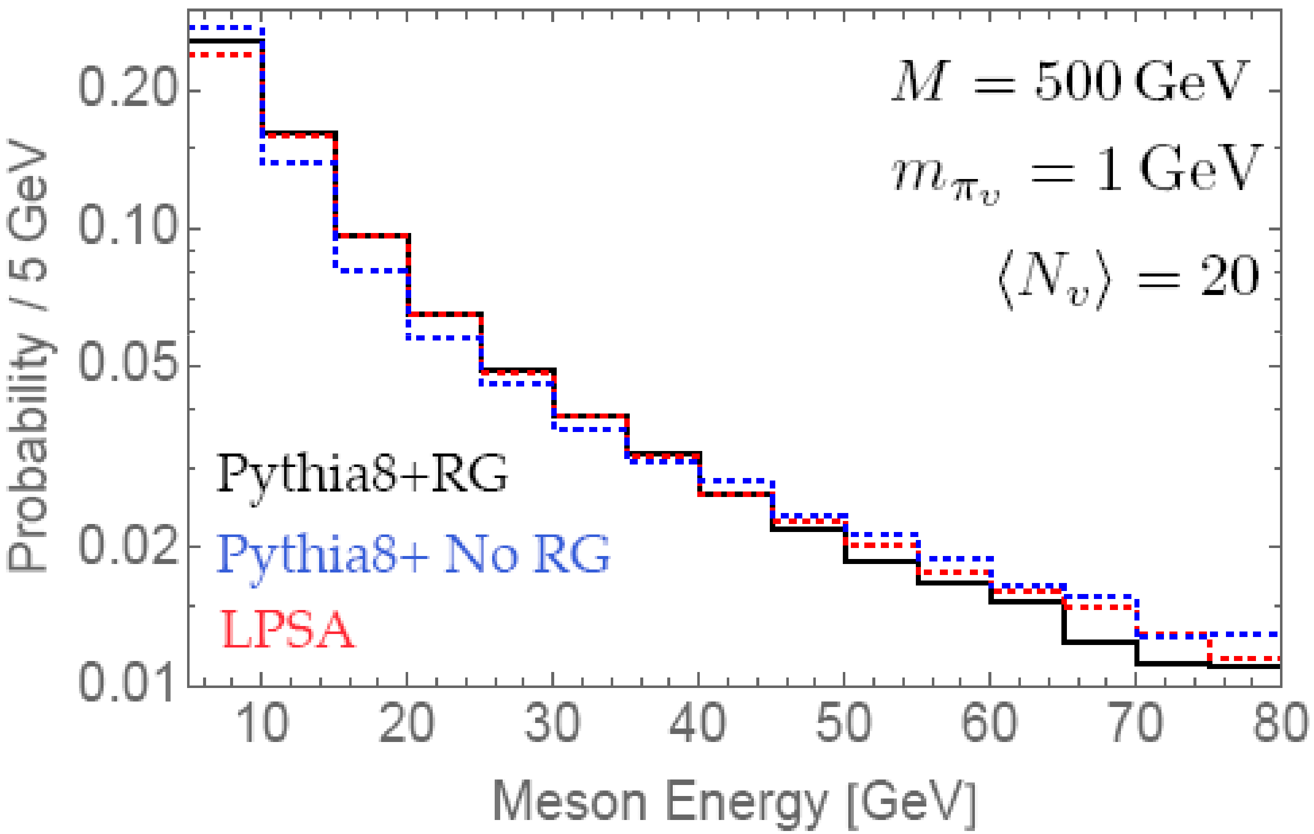
⇨ Pythia 8 with patch from Schwaller, Stolarski, and Weiler (15')

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



Di-muon channel

Displaced muon search at LHCb

We adopt cuts from the displaced A′ analysis in

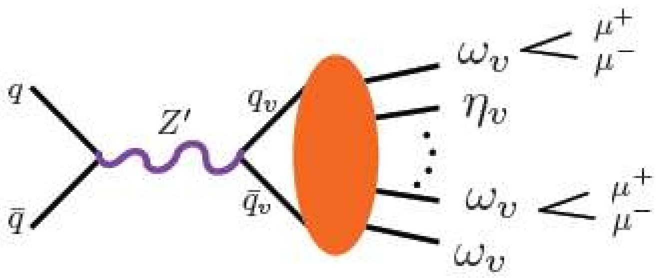
P. Ilten, Y. Soreq, J. Thaler, M. Williams, W. Xue, 1603.08926

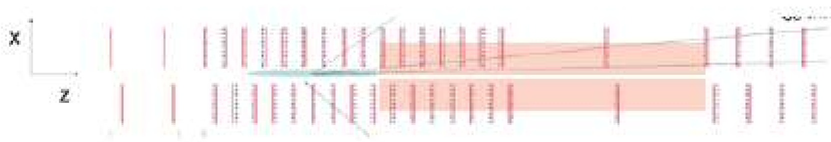
$\eta(\mu^{\pm}) \in [2,5]$, $p(\mu^{\pm}) > 10\,\mathrm{GeV}$, $p_T(\mu^{\pm}) > 0.5\,\mathrm{GeV}$

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

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

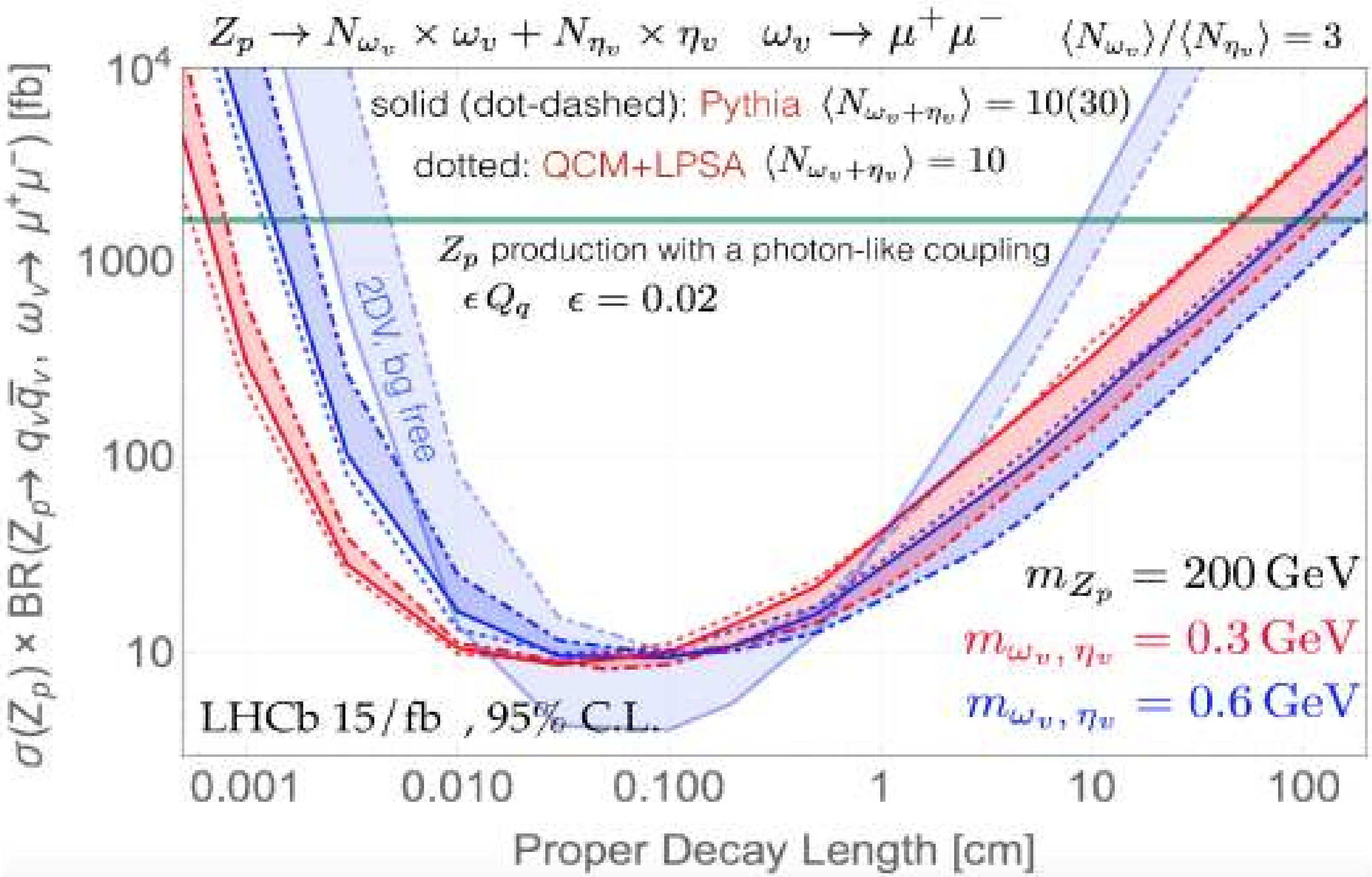
$\ell_T \in [6\,\mathrm{mm},\ 22\,\mathrm{mm}]$ $\ell_z \in [2.6\,\mathrm{cm},\ 50\,\mathrm{cm}]$ (we include this second cuts)



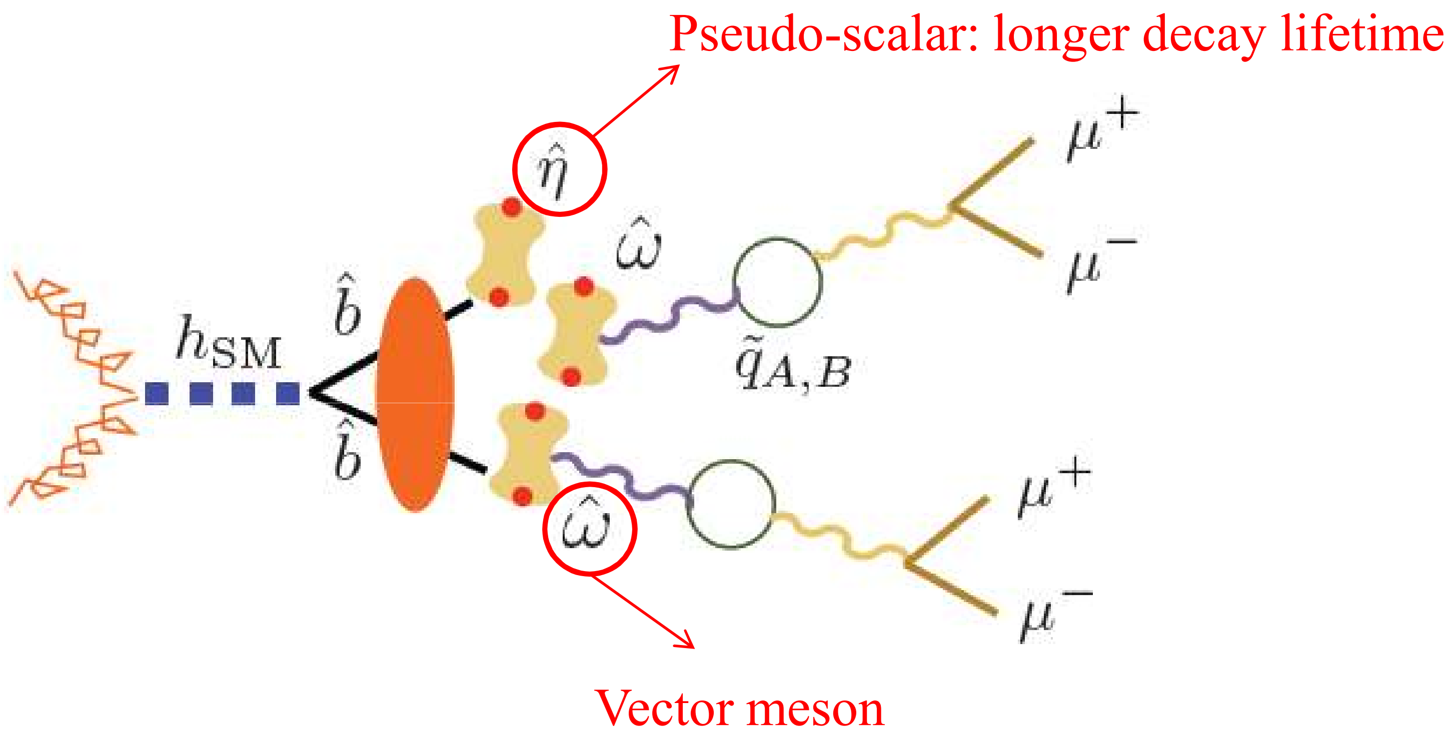


~ 25 events / mass bin at 15 / fb at 13 TeV (Run III)

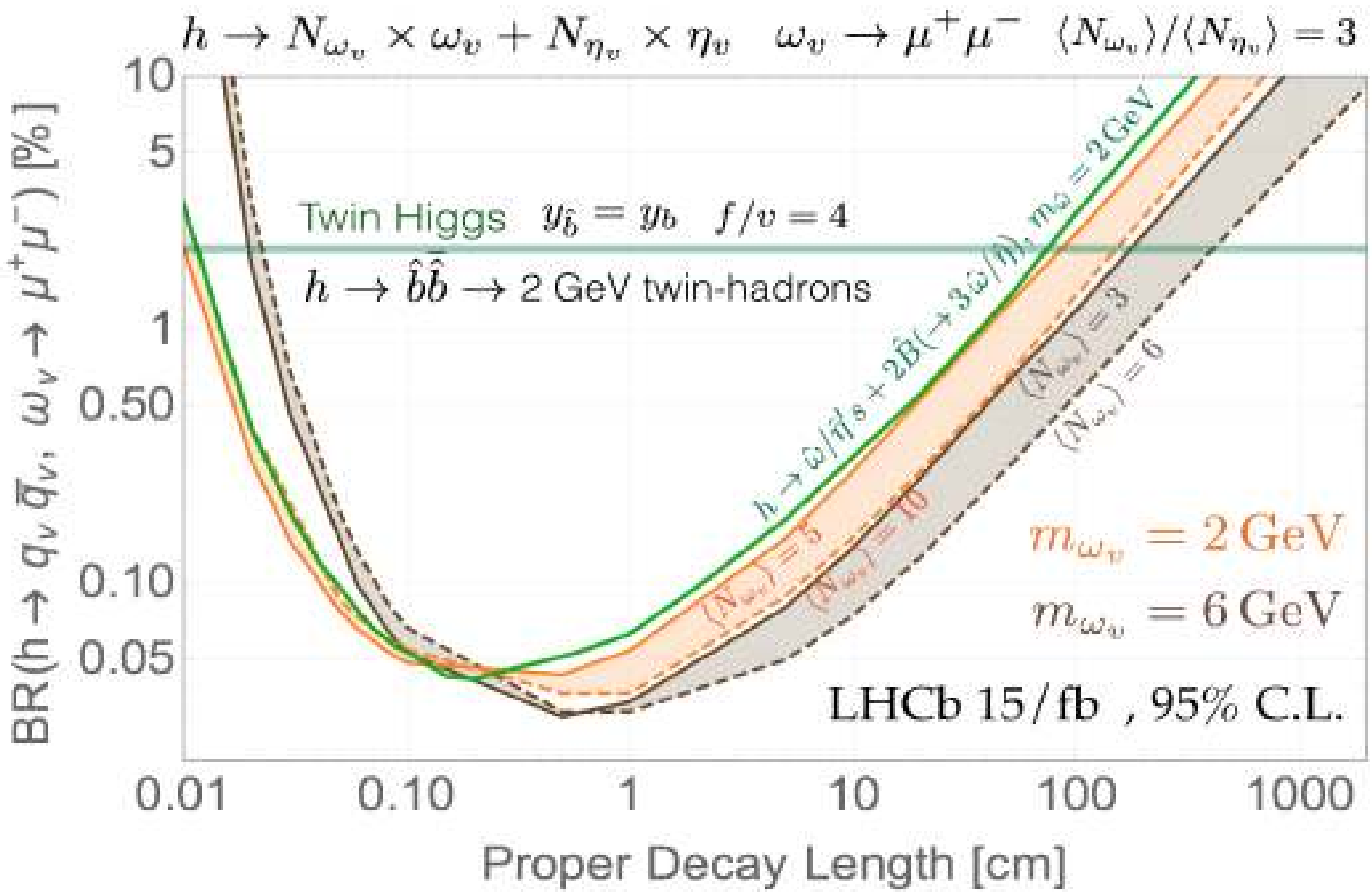
LHCb reach limits: Z’



Applications in Twin Higgs Models



LHCb reach limits: Twin Higgs model



LHCb vs ATLAS/CMS

ATLAS/CMS has:

20 times higher luminosity.

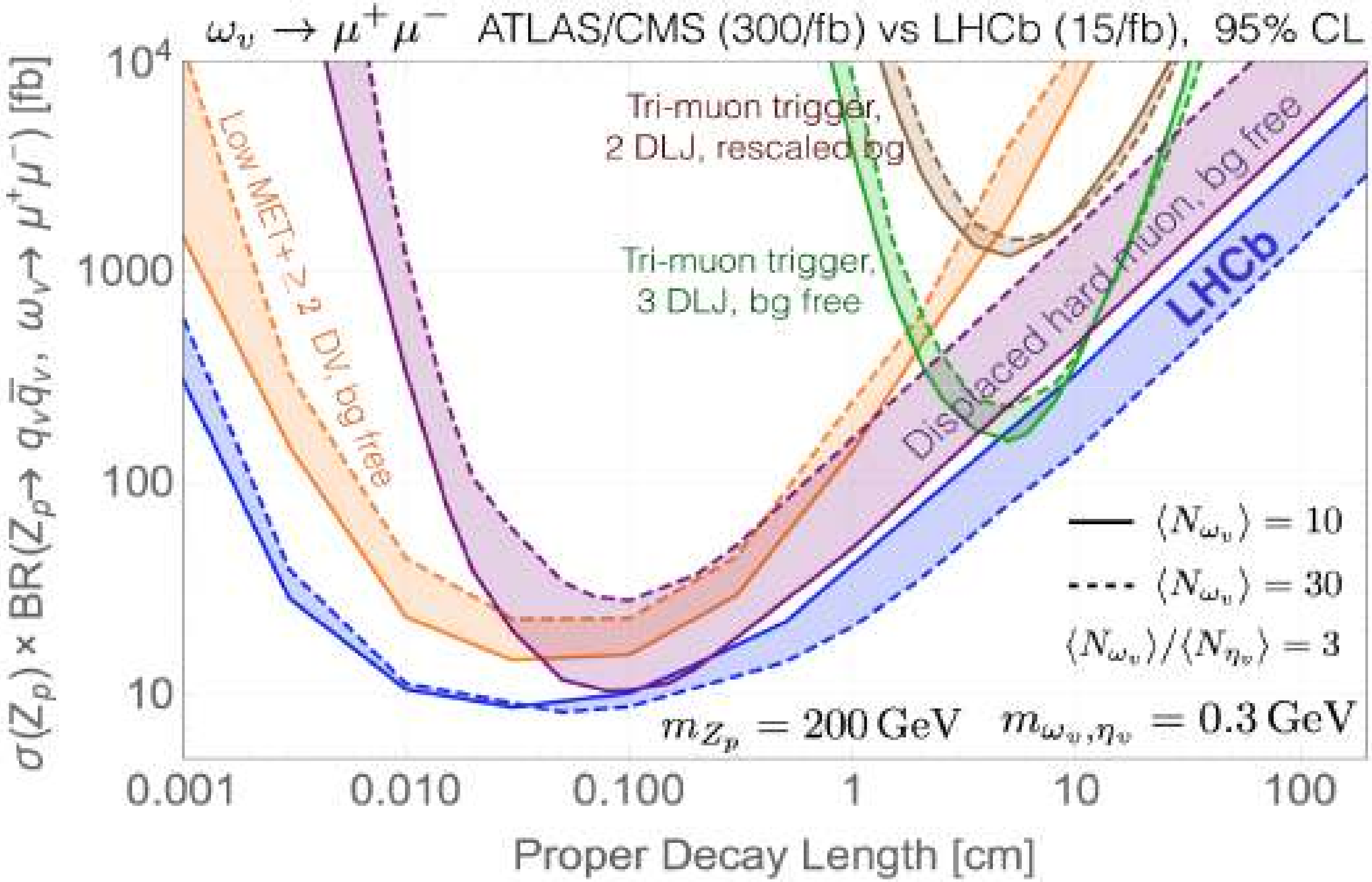
10 times better angular coverage.

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

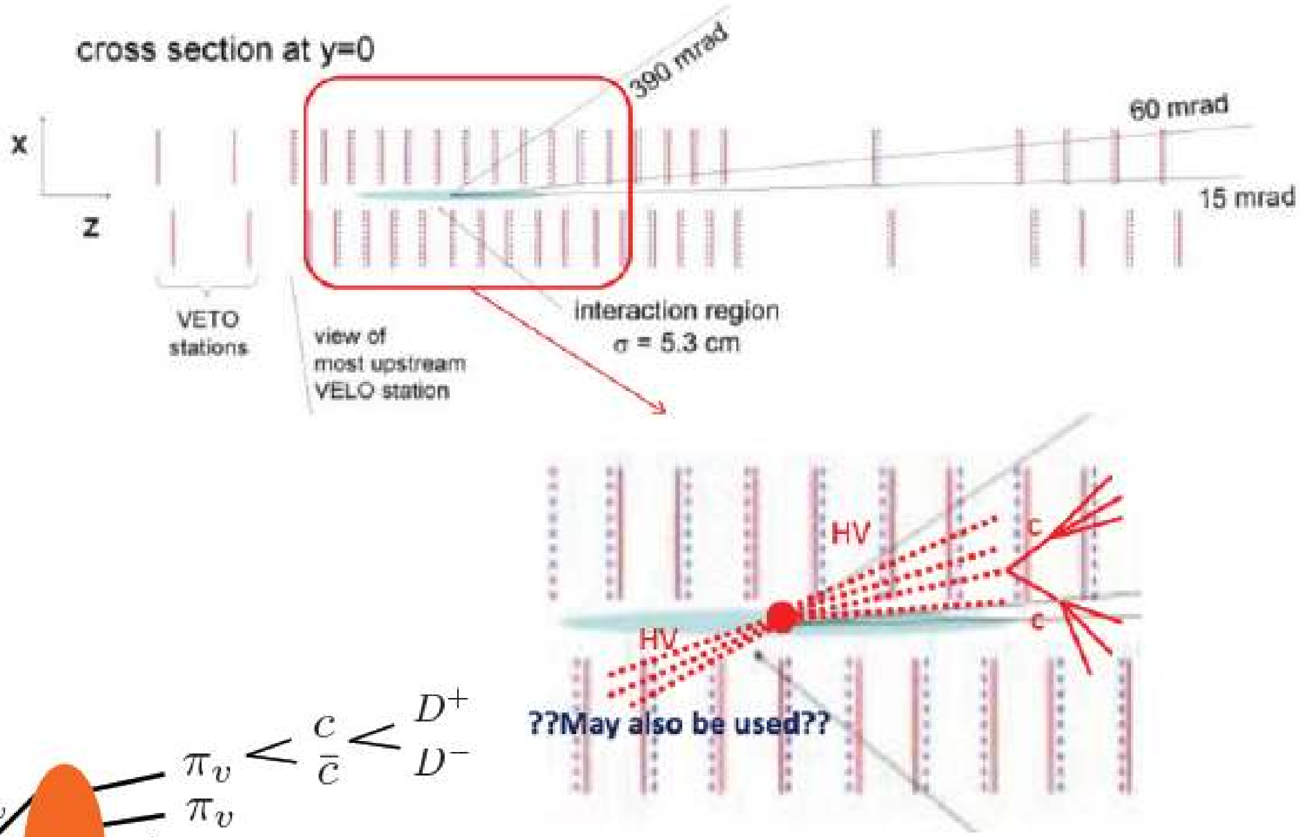
Trigger strategy:

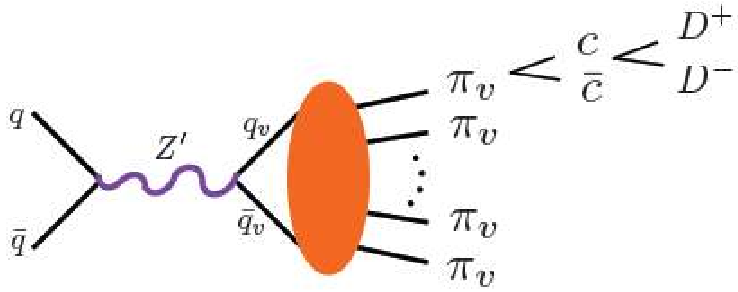
- Multiple displaced soft muons
- MET
- Hard displaced muon

LHCb vs ATLAS/CMS

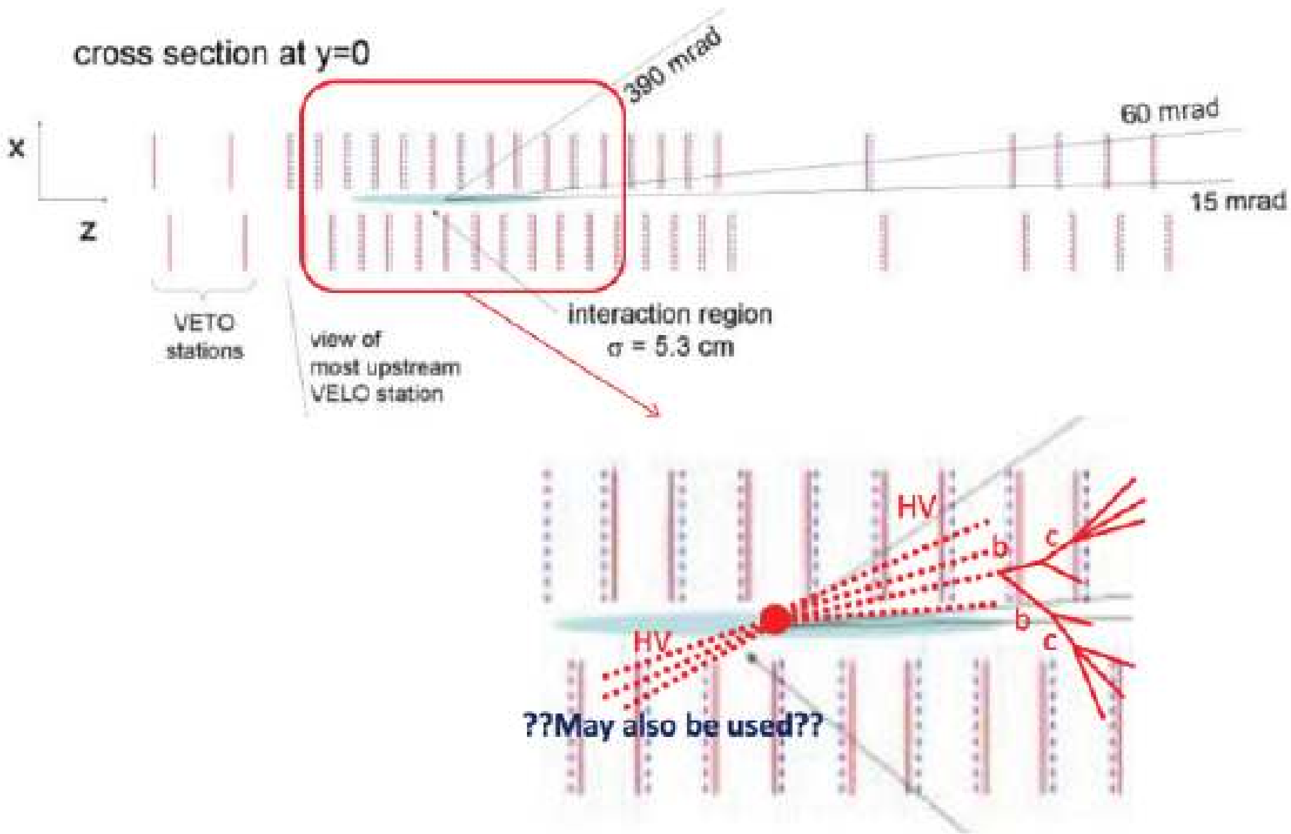


Hadronic Decay Channels: D-meson





Hadronic Decay Channels: B-meson



Hadronic Decay Channels: D-meson

The most conservative search channel:

- Both D-mesons are well-reconstructed.

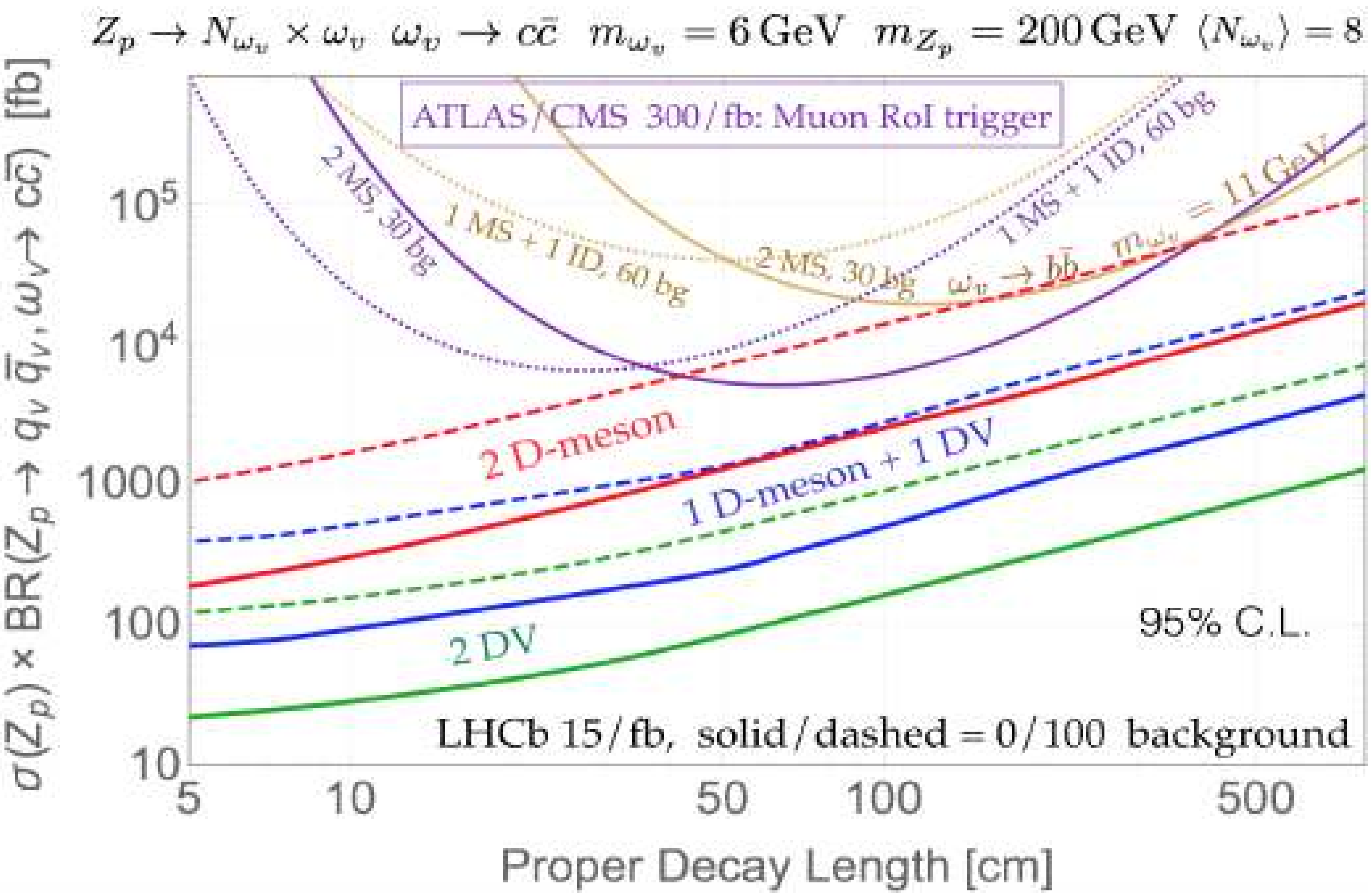
A less conservative search channel:

- 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



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.

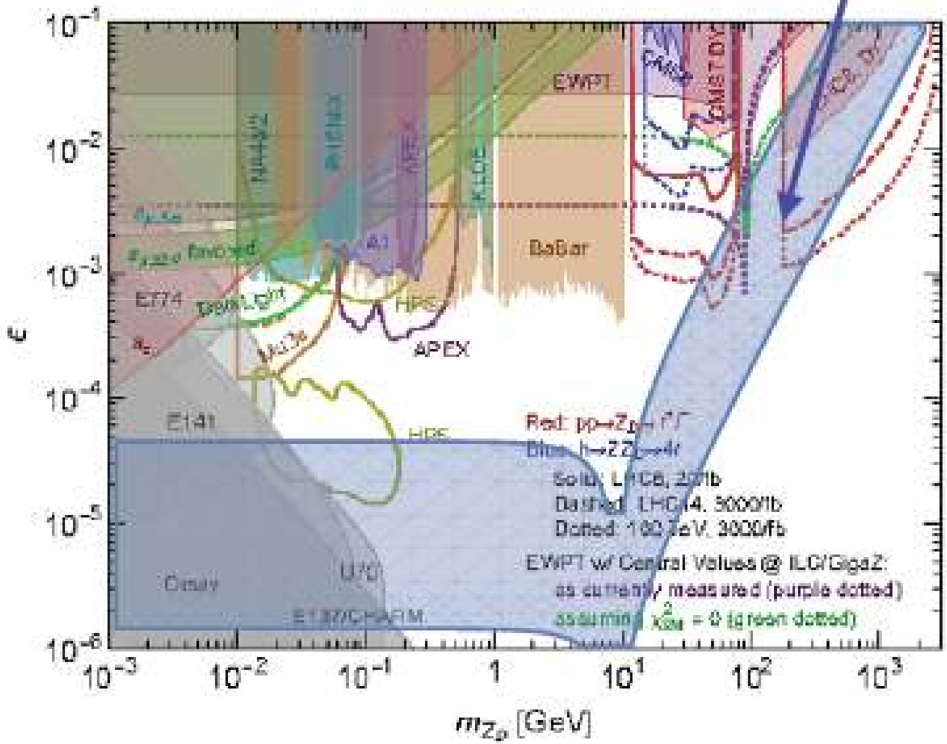
Di-muon channel:
Better reaches than various searches at ATLAS/CMS.

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:
Similar or better than D-meson pair channel.

Applications in Twin Higgs Models

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

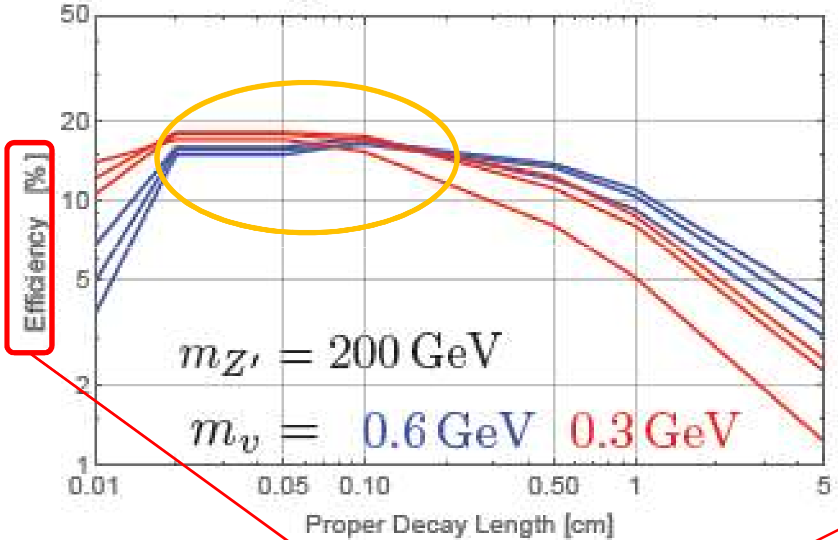


$$c\tau_{\hat{\omega}} \simeq 20\,\text{cm}\left(\frac{m_{A'}}{100\,\text{GeV}}\right)^4\left(\frac{10^{-3}}{\epsilon}\right)^2\left(\frac{3\,\text{GeV}}{\Lambda}\right)^5$$

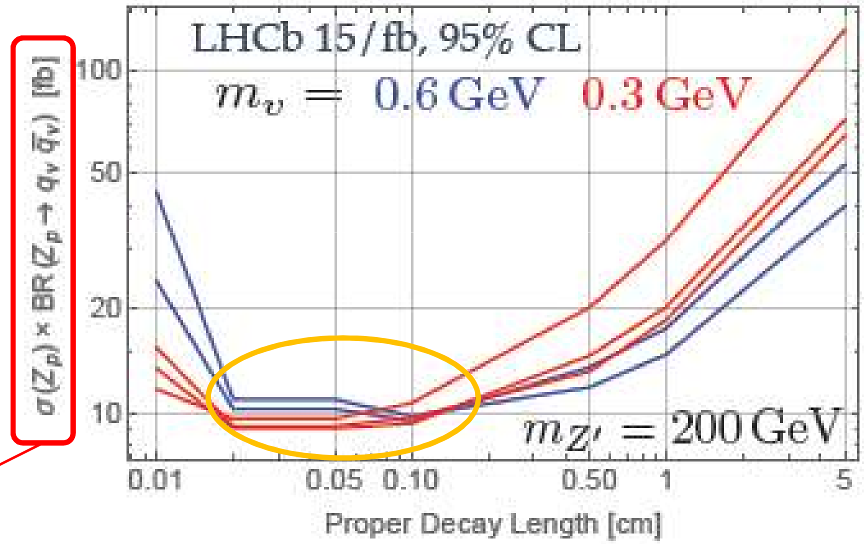
LHCb Di-muon limit

Short decay lifetime :

Signal efficiency



Bound on v-quark production



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

DV + muon : muon $P_T >$ 50 GeV

DV + electron: electron $P_T >$ 120 GeV

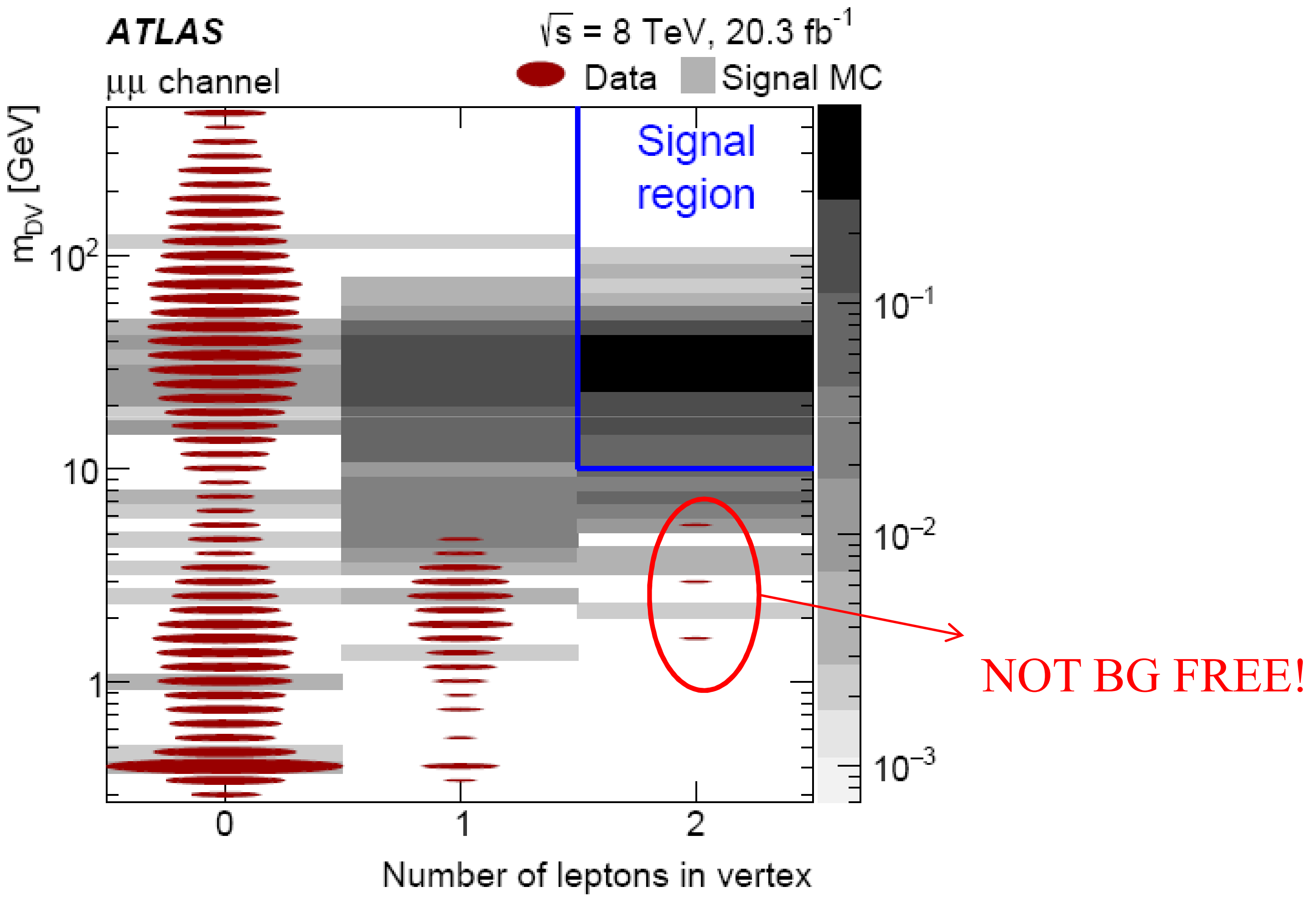
DV + jet: 4 j > 90 GeV, 5 j > 65 GeV, 6 j > 55 GeV

DV + MET: MET > 180 GeV

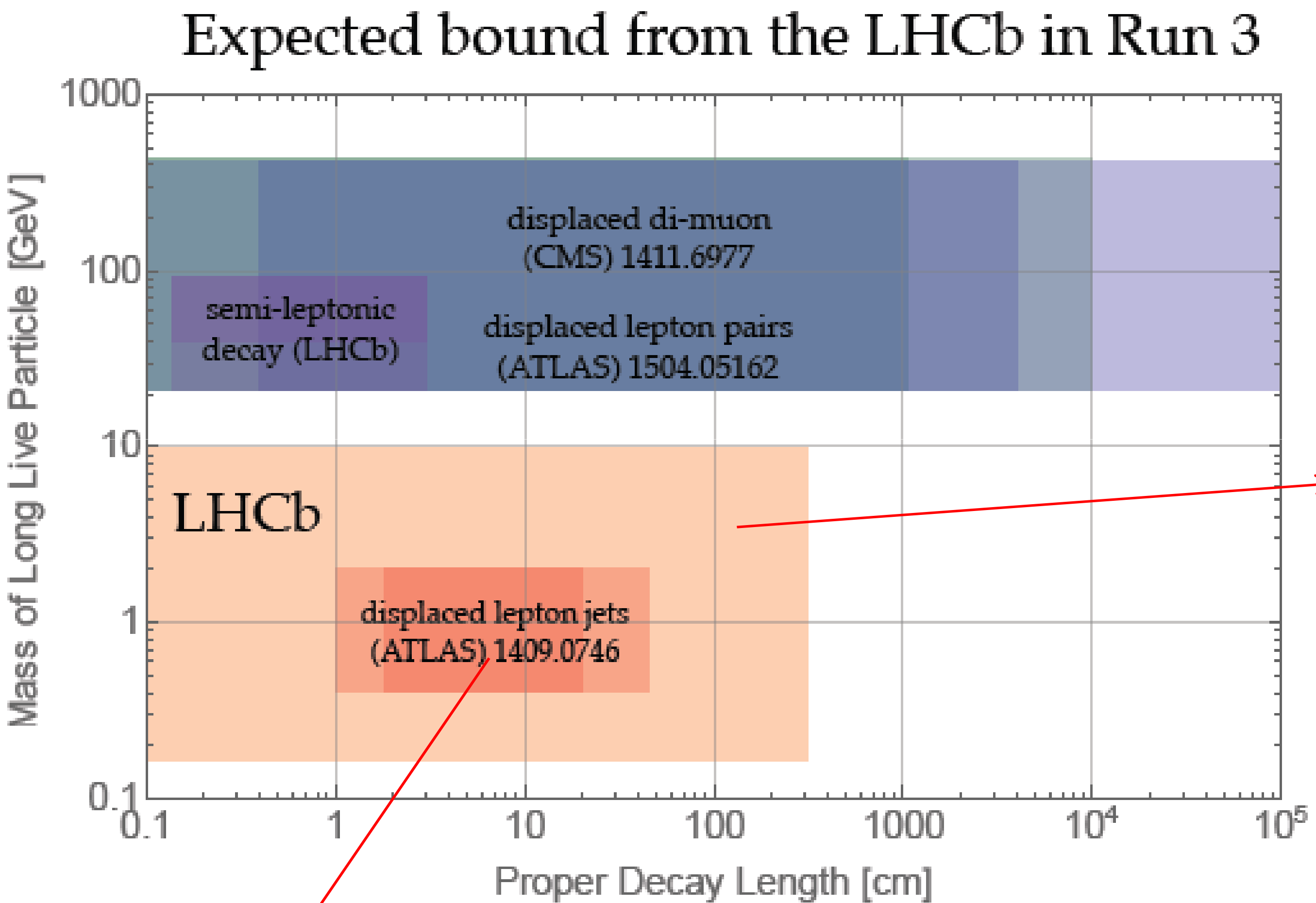
DV : muon $P_T >$ 10 GeV, d > 2.5 mm, Inv Mass > 10 GeV

need to remove

LHCb vs ATLAS/CMS



Hidden Valley searches at the ATLAS/CMS



More suitable for dark showering processes.

Usually require $m_{\rm LLP} > 15$ 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.

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

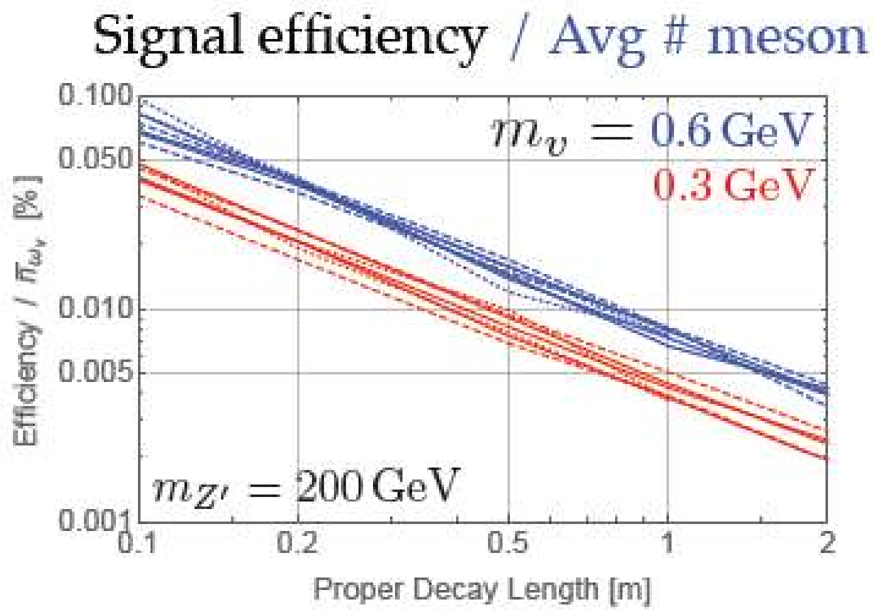
- Interacting with material:

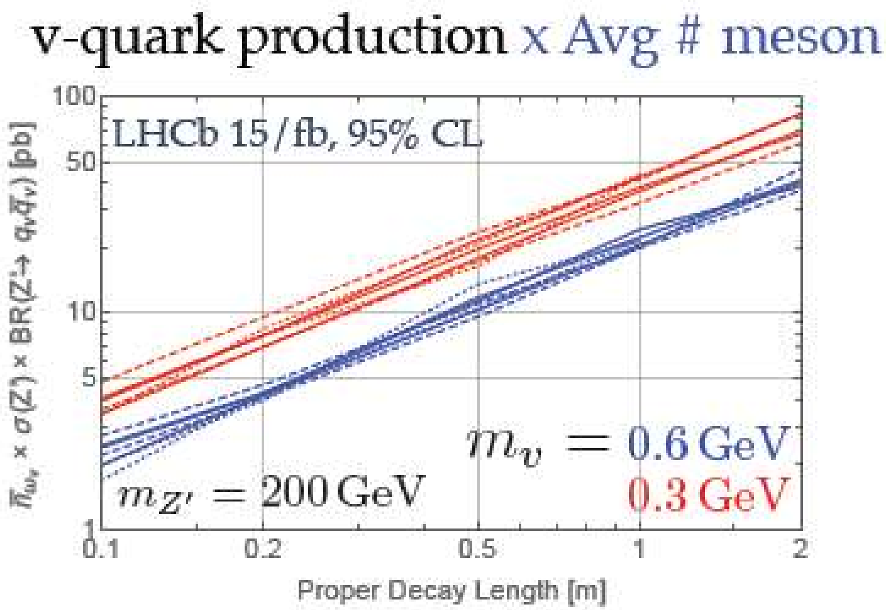
  A careful detector simulation is needed,
  may be eliminated by vertex location.

⇨ ~ 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

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

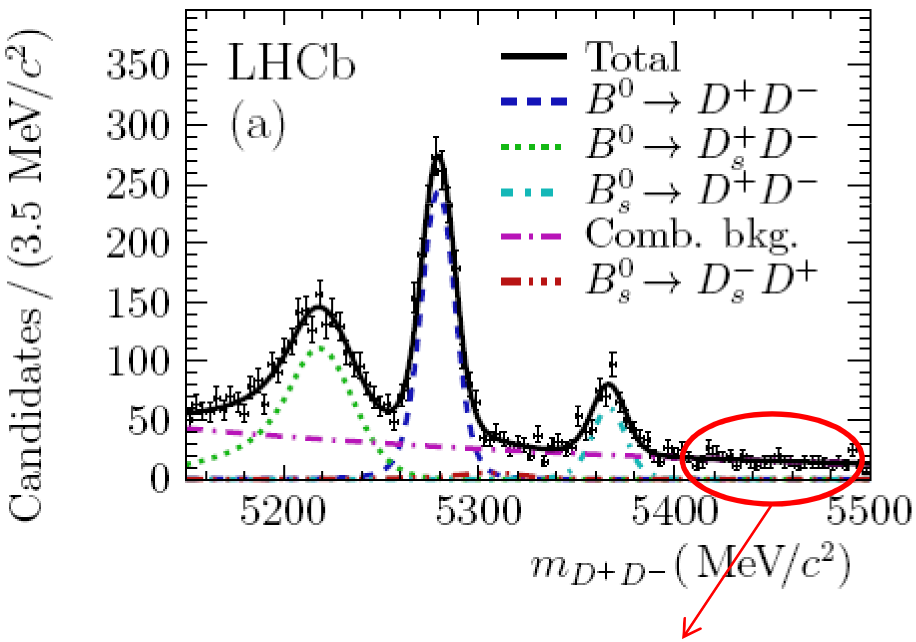
$$D^+ \to K^- \pi^+ \pi^-,\ D^+ \to K^- K^+ \pi^+$$

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

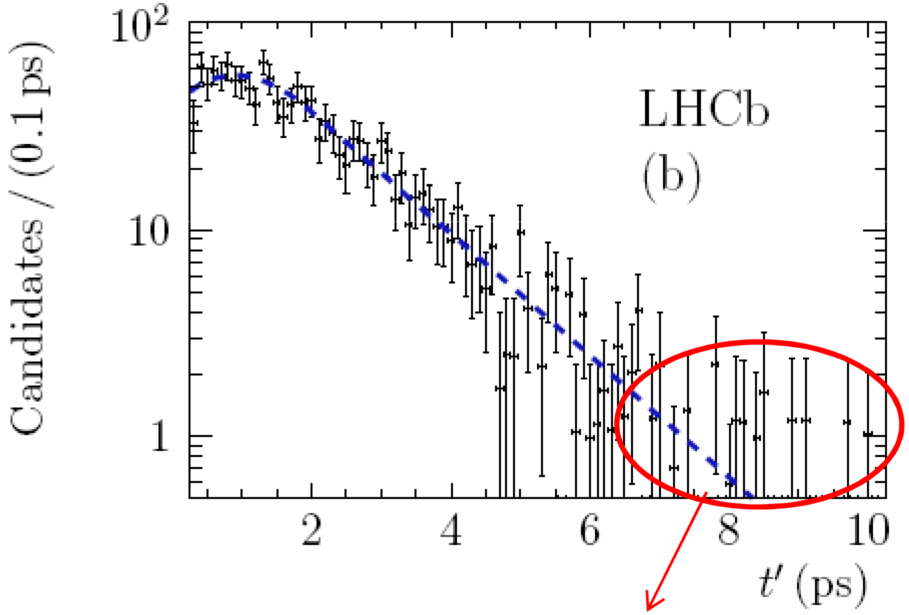
Hadronic Decay Channels: D-meson

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.



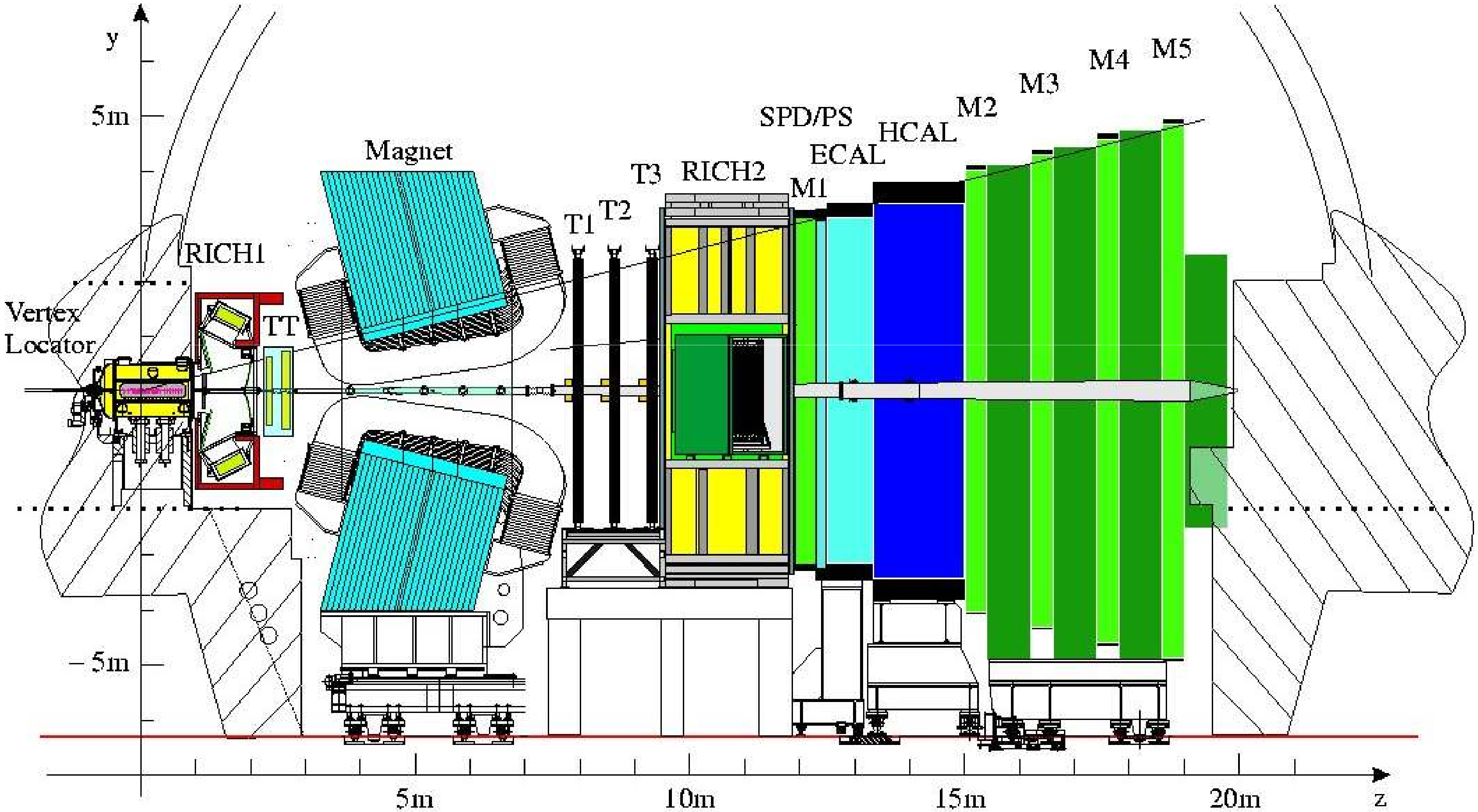
BG is highly suppressed by requiring large displacement.

LHCb 101

⇩

Usually used to search for new physics indirectly, through heavy flavor physics.

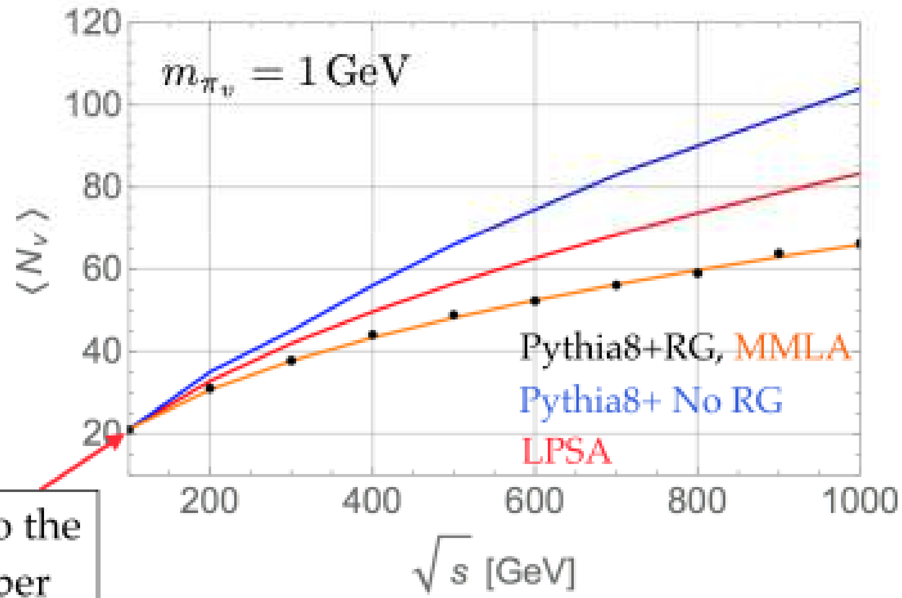
LHCb 101



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

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