LHCb results relevant for dark matter searches

Murilo Rangel
on behalf of the LHCb Collaboration

02/09/2019

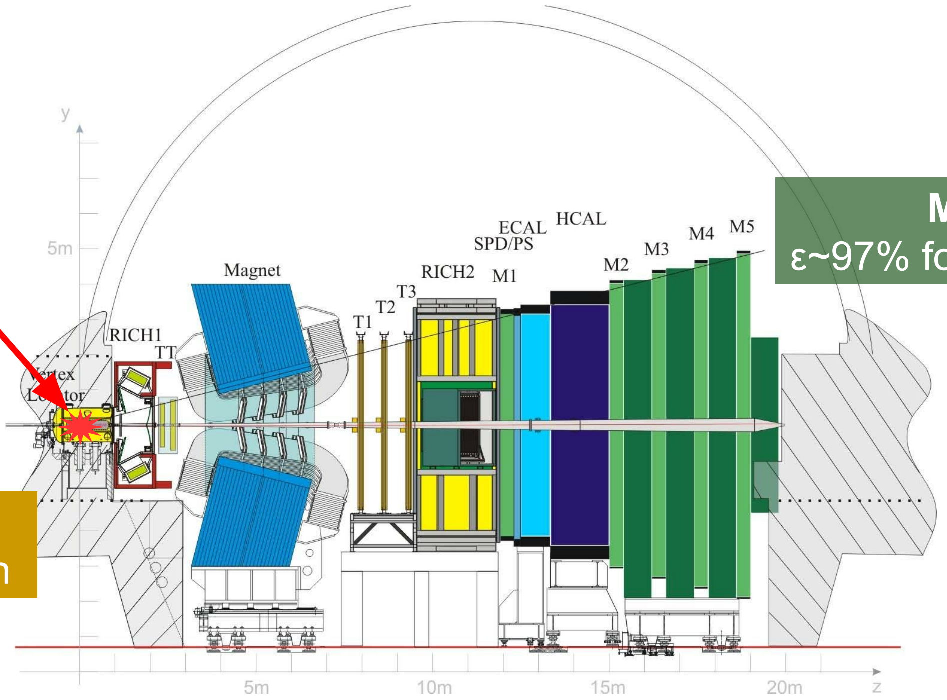
lape

Instituto de Física
Universidade Federal do Rio de Janeiro

LHCb

LHCb is a single arm spectrometer fully instrumented in the forward region (2.0<η<5.0)
Designed for heavy flavour physics and also exploited for general purpose physics
[Int. J. Mod. Phys. A 30, 1530022 (2015)]

Collision



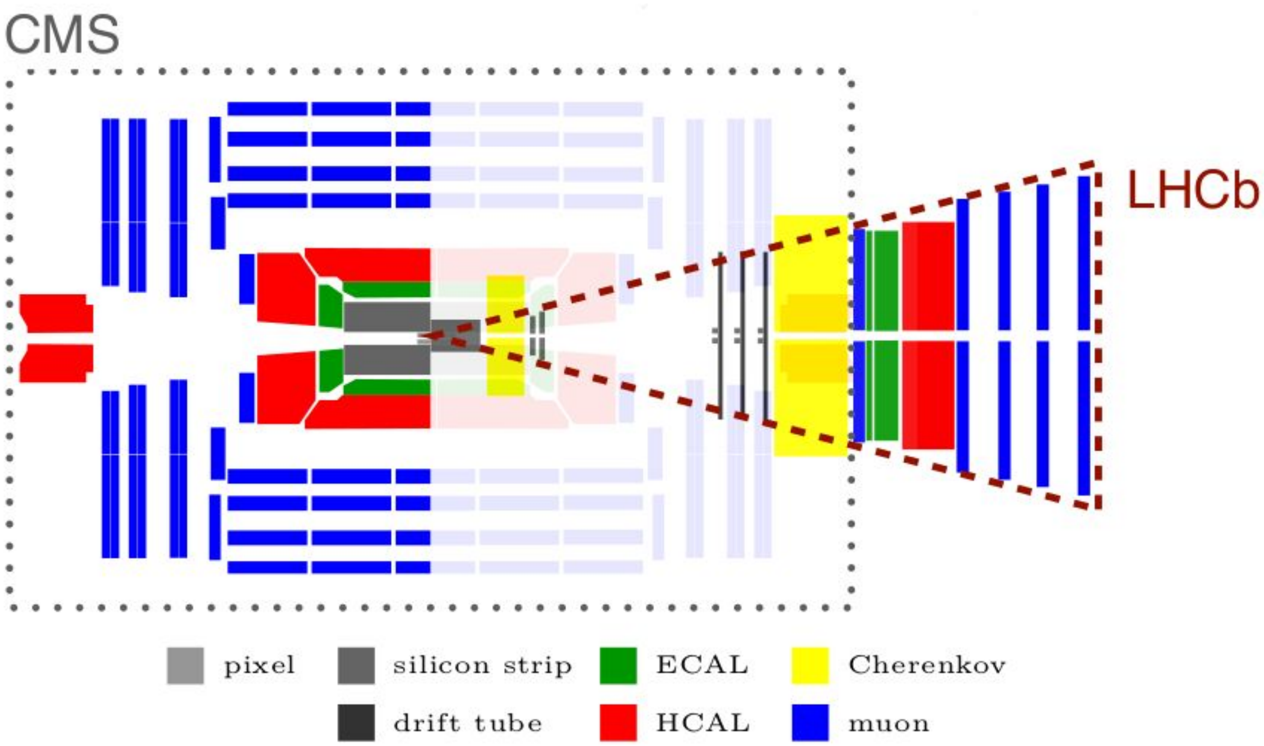
Muon
ε~97% for misID~2%

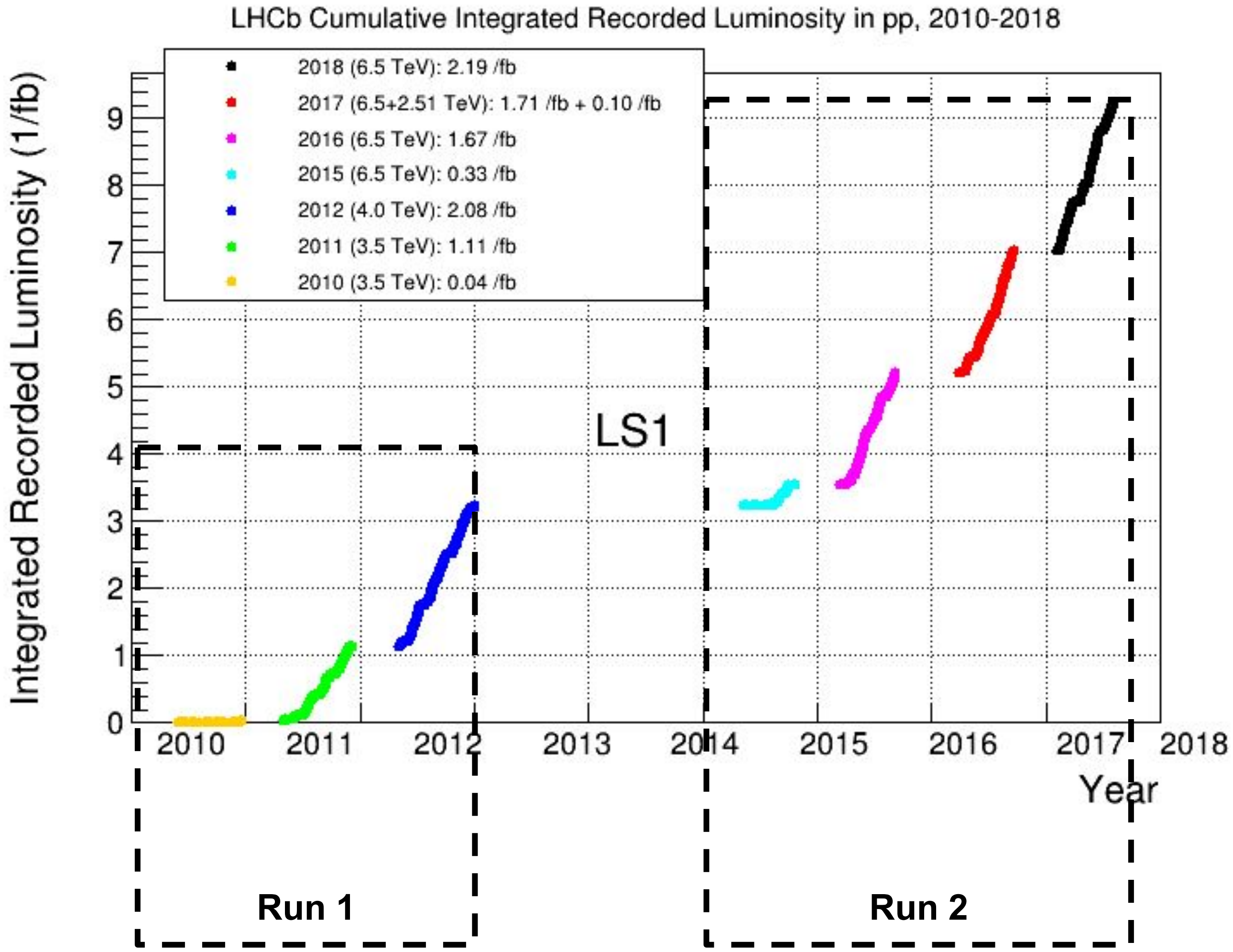
VELO
~20μm IP resolution

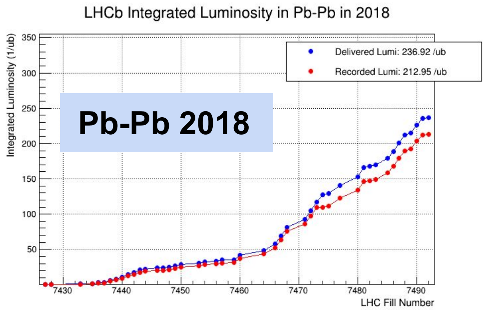
Tracking (magnet)
0.4%-0.6% momentum resolution (0.2-100 GeV)

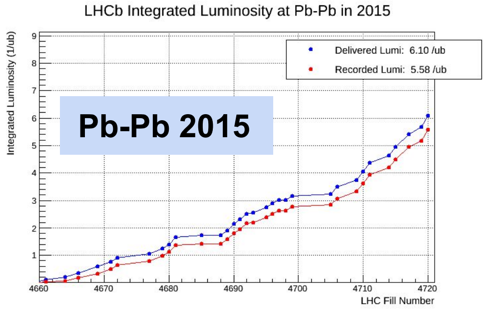
Murilo Rangel

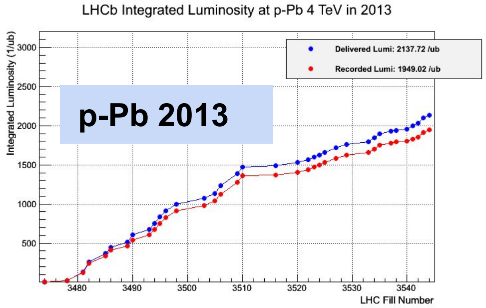
LHCb is a single arm spectrometer fully instrumented in the forward region (2.0<η<5.0)
Designed for heavy flavour physics and also exploited for general purpose physics
[Int. J. Mod. Phys. A 30, 1530022 (2015)]




LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2018
2018 (6.5 TeV): 2.19 /fb
2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
Integrated Recorded Luminosity (1/fb)
Year
LS1
Run 1
Run 2


LHCb Integrated Luminosity in Pb-Pb in 2018
Delivered Lumi: 236.92 /ub
Recorded Lumi: 212.95 /ub
Pb-Pb 2018
Integrated Luminosity (1/ub)
LHC Fill Number


LHCb Integrated Luminosity at Pb-Pb in 2015
Delivered Lumi: 6.10 /ub
Recorded Lumi: 5.58 /ub
Pb-Pb 2015
Integrated Luminosity (1/ub)
LHC Fill Number


LHCb Integrated Luminosity at p-Pb 4 TeV in 2013
Delivered Lumi: 2137.72 /ub
Recorded Lumi: 1949.02 /ub
p-Pb 2013
Integrated Luminosity (1/ub)
LHC Fill Number

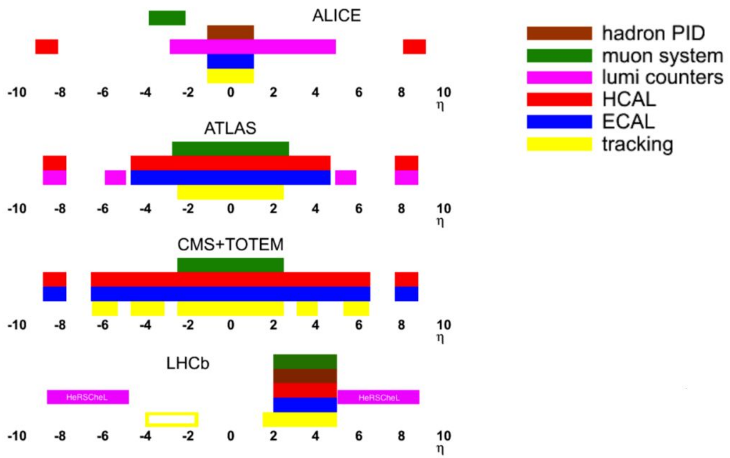
Motivation

Dark Matter and LHCb

→ Unification of Dark Matter and SM phenomenology predicts signatures at LHC.
→ Many signatures can be searched at LHCb
- + Dark bosons
- + Long lived particle (LLP)
- + Rare decays

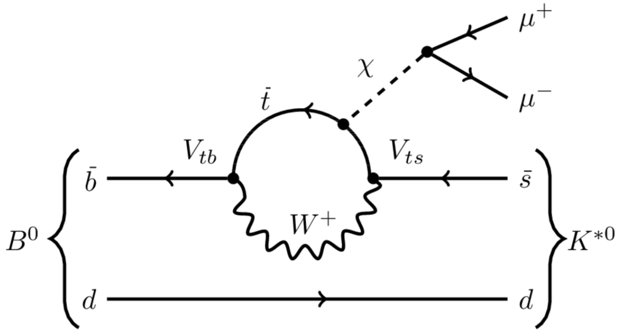
LHCb

→ Unique coverage complementary to ATLAS/CMS
→ Soft trigger and forward acceptance → lower masses reach
→ Excellent secondary/tertiary vertex reconstruction → lower lifetimes (~ 1 ps).



Hidden Sector Bosons in $B^0 \to K^{*0}\mu^+\mu^-$

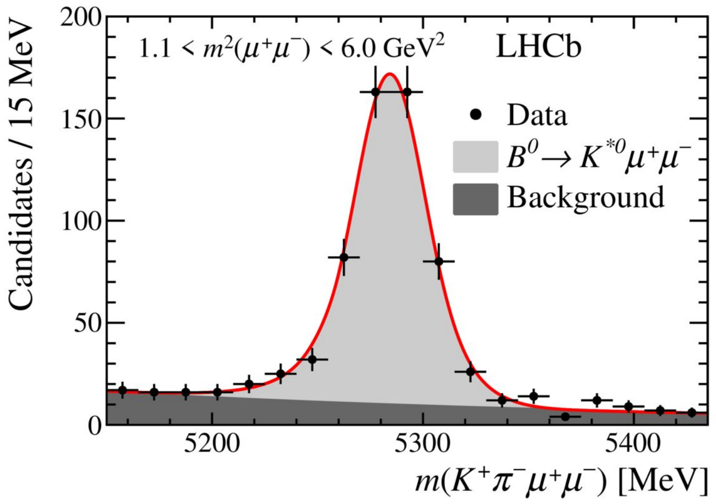
PRL 115, 161802 (2015)



Different models hypothesize a field that could explain inflation, baryon asymmetry and/or dark matter.

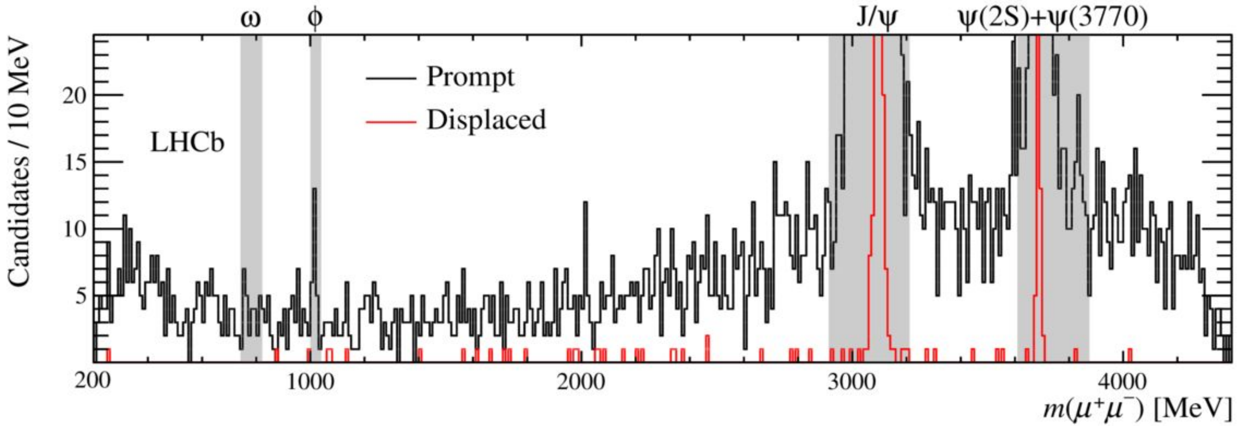
Multivariate selection is applied to reduce the background further using uBoost algorithm.

J. Stevens and M. Williams, uBoost: A boosting method for producing uniform selection efficiencies from multivariate classifiers, JINST 8, P12013 (2013).



Hidden Sector Bosons in $B^0 \to K^{*0}\mu^+\mu^-$

PRL 115, 161802 (2015)

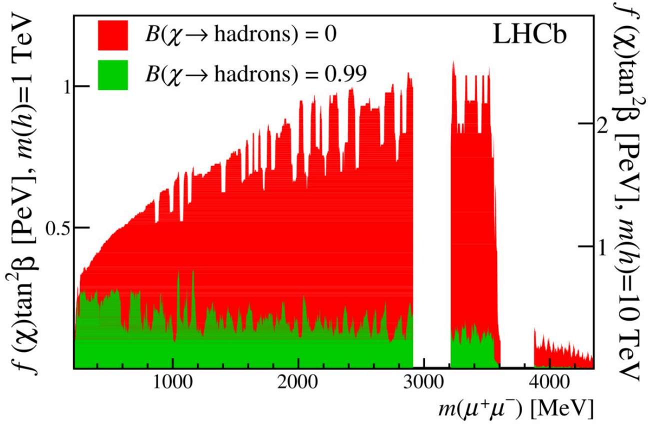


→ Different models hypothesize a field that could explain inflation, baryon asymmetry and/or dark matter

→ Search for a narrow dimuon peak is performed

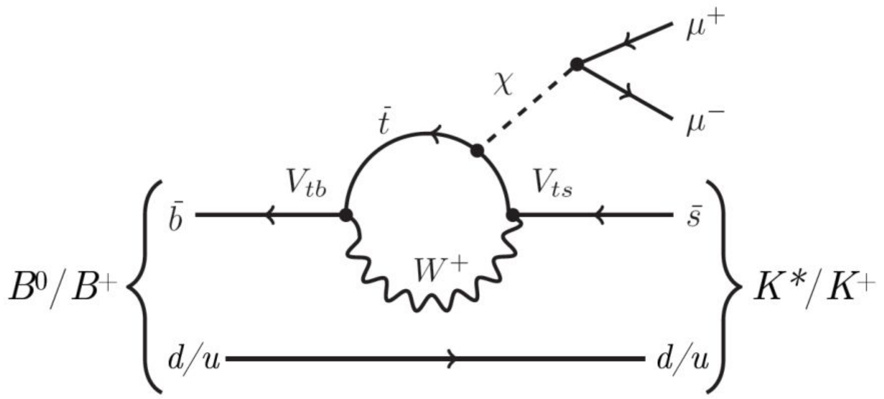
→ Limits for the axion model below are calculated.

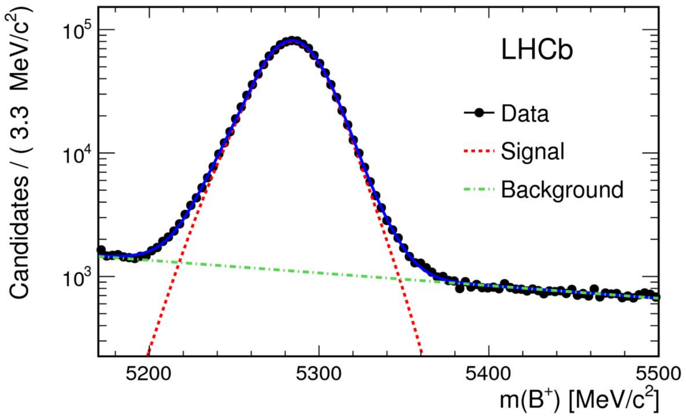
M. Freytsis, Z. Ligeti, and J. Thaler, Constraining the axion portal with $B \to K\ell^+\ell^-$, Phys. Rev. D **81**, 034001 (2010).



Hidden Sector Bosons in $B^+ \to K^+\mu^+\mu^-$

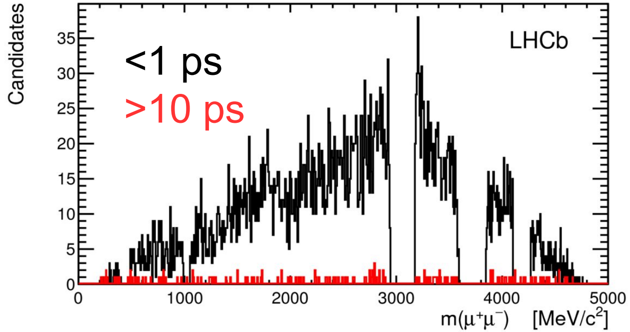
PRD 95, 071101 (2017)



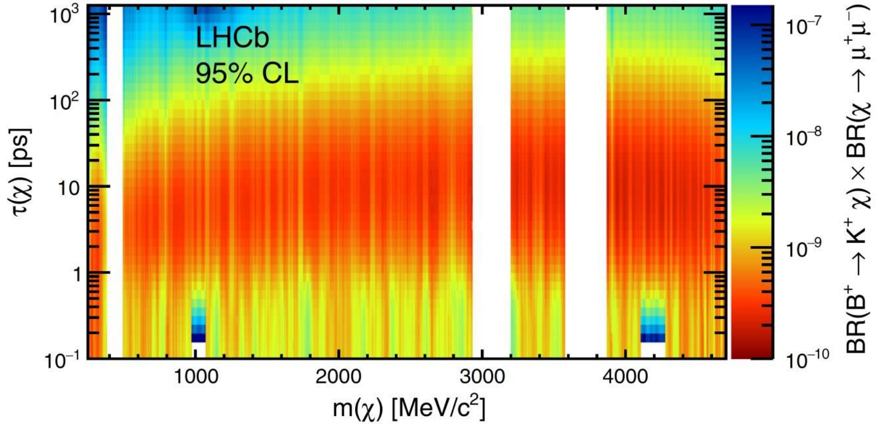


→ Sensitive to DM sector with portals to SM

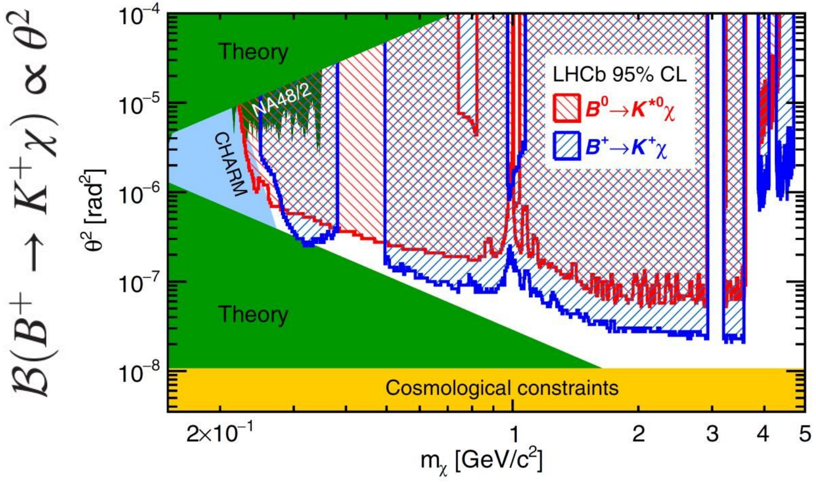
→ Three regions of dimuon decay time are selected to optimize limits using Run I data



PRD 95, 071101 (2017)



→ Model-independent limit with branching fraction normalised to $B^+ \to K^+ \psi(\mu^+\mu^-)$
→ Lifetimes constrained relate to decay lengths ~30 mm to 30 cm



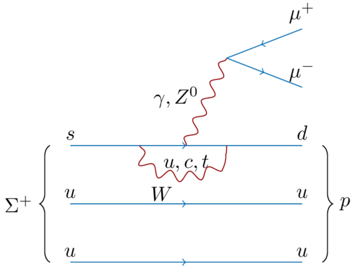
→ Interpretation for the inflaton model described in the references below is given for square of the mixing angle, θ^2.

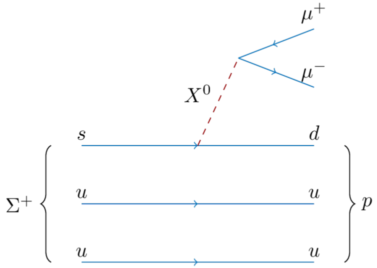
B. Batell, M. Pospelov, and A. Ritz, Multi-lepton signatures of a hidden sector in rare B decays, Phys. Rev. D **83**, 054005 (2011).
F. Bezrukov and D. Gorbunov, Light inflaton hunter's guide, J. High Energy Phys. 05 (2010) 010.
F. Bezrukov and D. Gorbunov, Light inflaton after LHC8 and WMAP9 results, J. High Energy Phys. 07 (2013) 140.

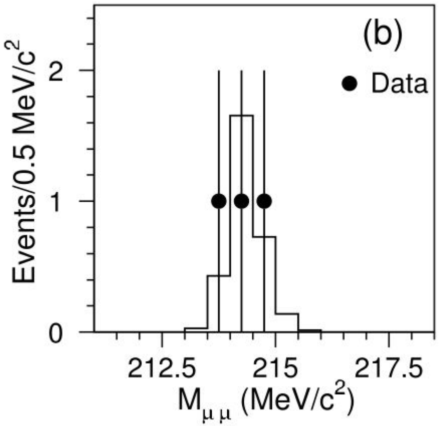
Dark Bosons in s→d

PRL 120, 221803 (2018)

Hints from HyperCP experiment could indicate the existence of dark boson.







H. Park *et al.* (HyperCP Collaboration), Evidence for the Decay $\Sigma^+ \to p\mu^+\mu^-$, Phys. Rev. Lett. **94**, 021801 (2005).

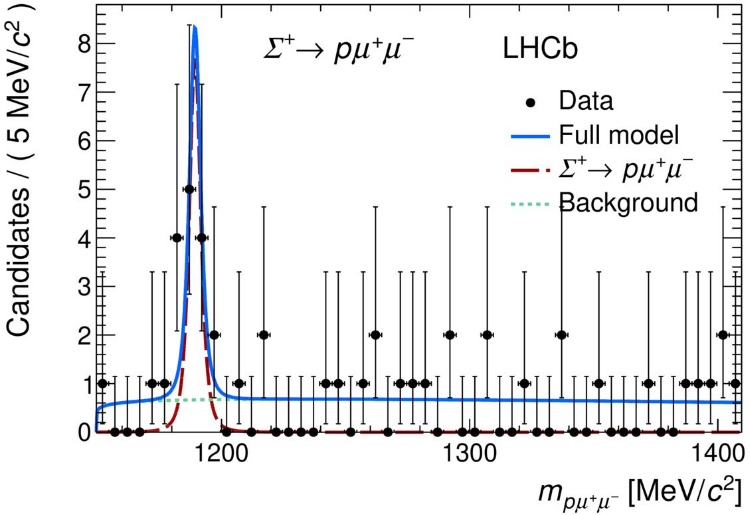
Dark Bosons in s→d

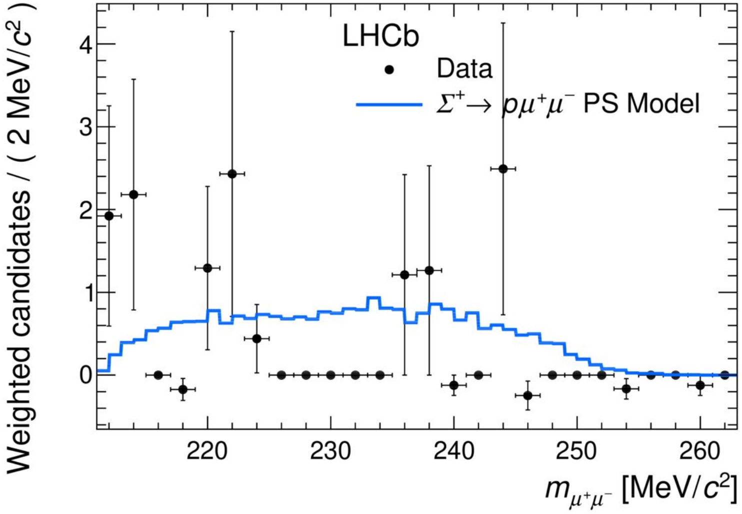
PRL 120, 221803 (2018)

Using Run I data, LHCb found evidence for SM decay

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (2.2^{+1.8}_{-1.3}) \times 10^{-8}$$

No significant peak in the dimuon mass.

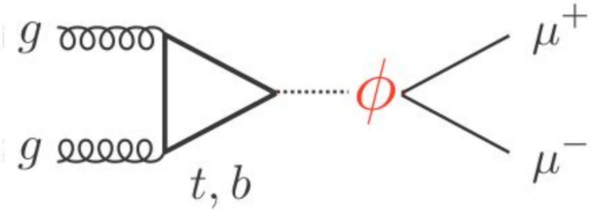




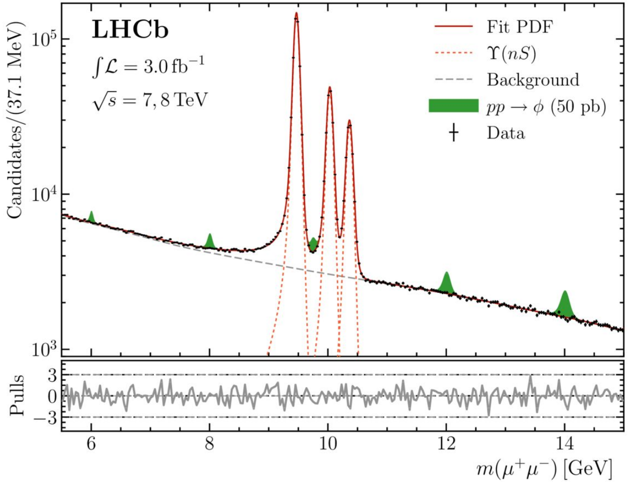
Dark Bosons in gluon fusion

JHEP 09 (2018) 147

Spin-0 particles can be copiously produced at LHC via gluon fusion



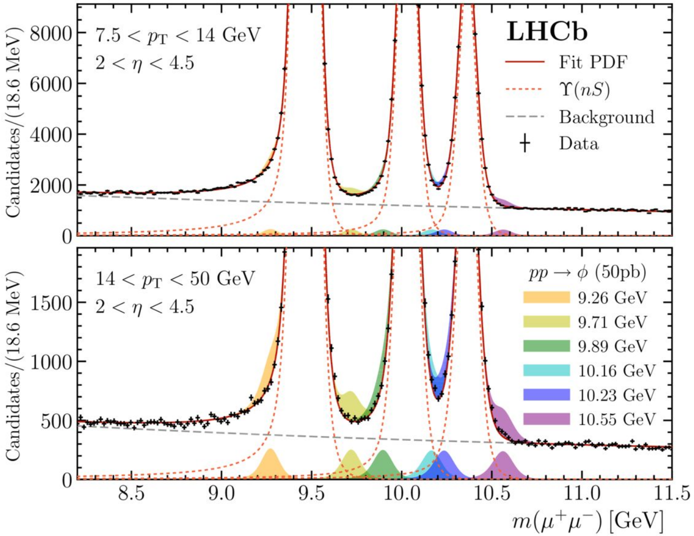
→In the dimuon final state, searches at LHC usually exclude the Υ region.
→Due to the excellent mass resolution, search for a narrow dimuon resonance in the mass region between 5.5 and 15 GeV at LHCb is performed.
→Mass independent multivariate selection is used to maximise the analysis sensitivity.

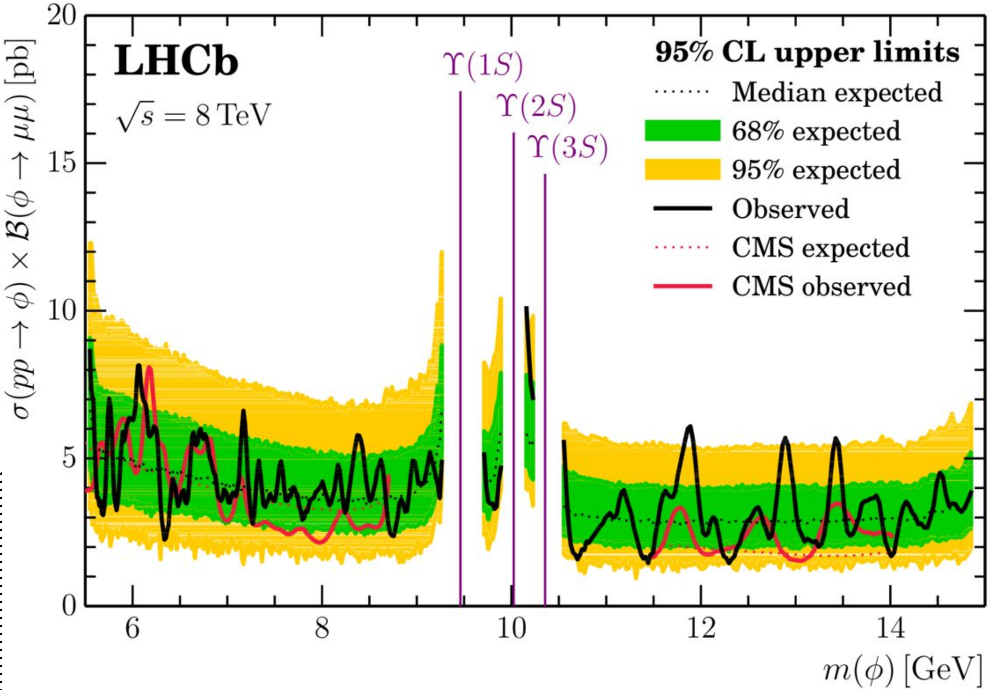


Murilo Rangel

Dark Bosons in gluon fusion

JHEP 09 (2018) 147

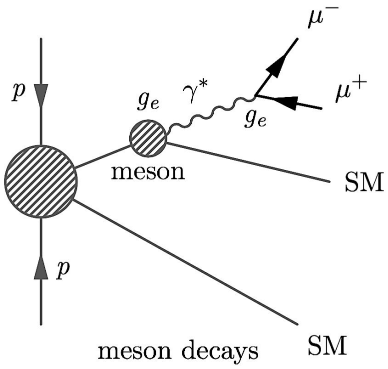


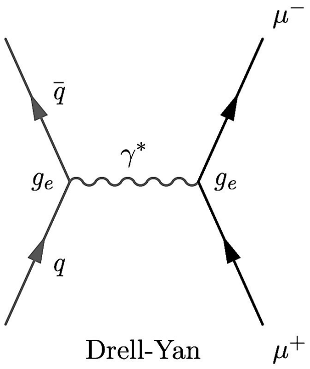


Due to the precise model of tails, LHCb sets first limits for spin-0 hypothetical light dimuon resonance in the mass range between 8.7 and 11.5 GeV.

Dark Photons

PRL 120, 061801 (2018)





electromagnetic current suppression factor

$$n_{\mathrm{ex}}^{A'}[m(A'),\varepsilon^2] = \varepsilon^2 \left[\frac{n_{\mathrm{ob}}^{\gamma^*}[m(A')]}{2\Delta m}\right] \mathcal{F}[m(A')]\, \epsilon_{\gamma^*}^{A'}[m(A'),\tau(A')]$$

off-shell photon

phase-space

A'/γ^* eff ratio, ϵ=1 for prompt

→ Coupling may arise via kinetic mixing between the SM hypercharge and A' field strength tensors

→ A' can decay to pair of muons and search can be normalise to prompt production

→ Search is fully data-driven if very short lifetimes are considered

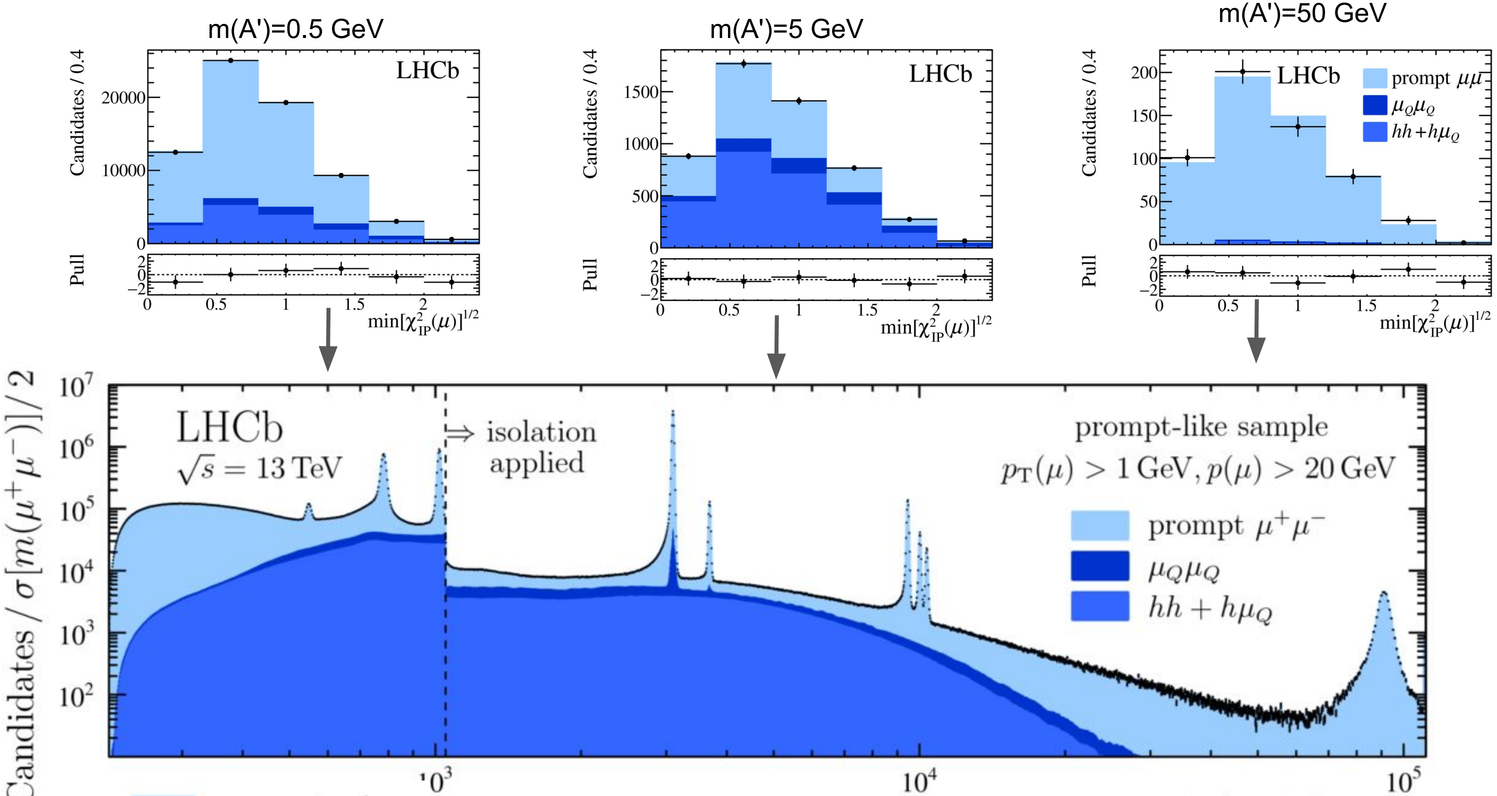
Run II data: L=1.6/fb at 13 TeV

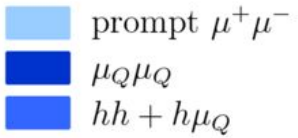
Trigger: Soft p_T muons with no prescale

→ Di-muon masses down to 2m(μ) up to 70 GeV

Dark Photons

PRL 120, 061801 (2018)





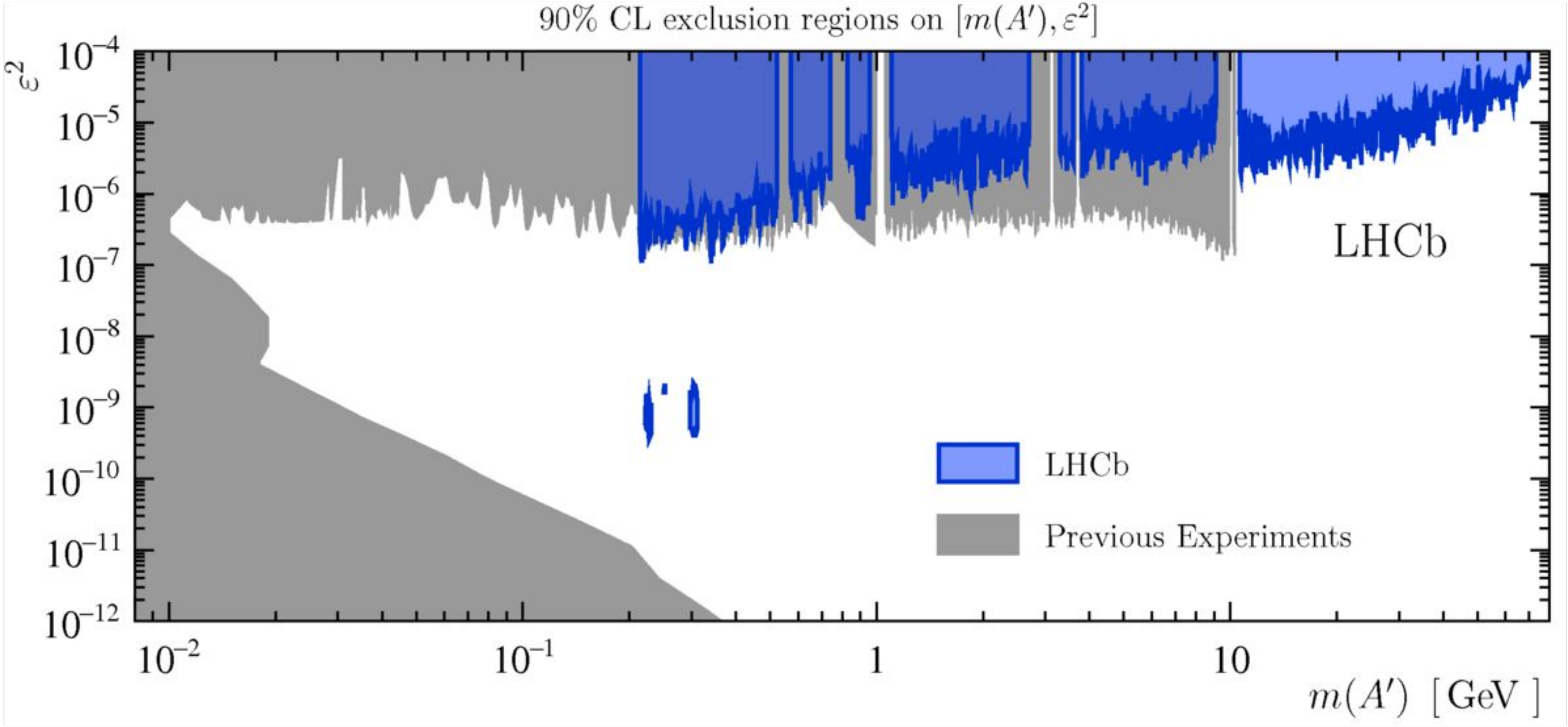
→ derived using J/ψ and Z

→ simulation corrected by data

→ derived using same-sign muons

Dark Photons

PRL 120, 061801 (2018)



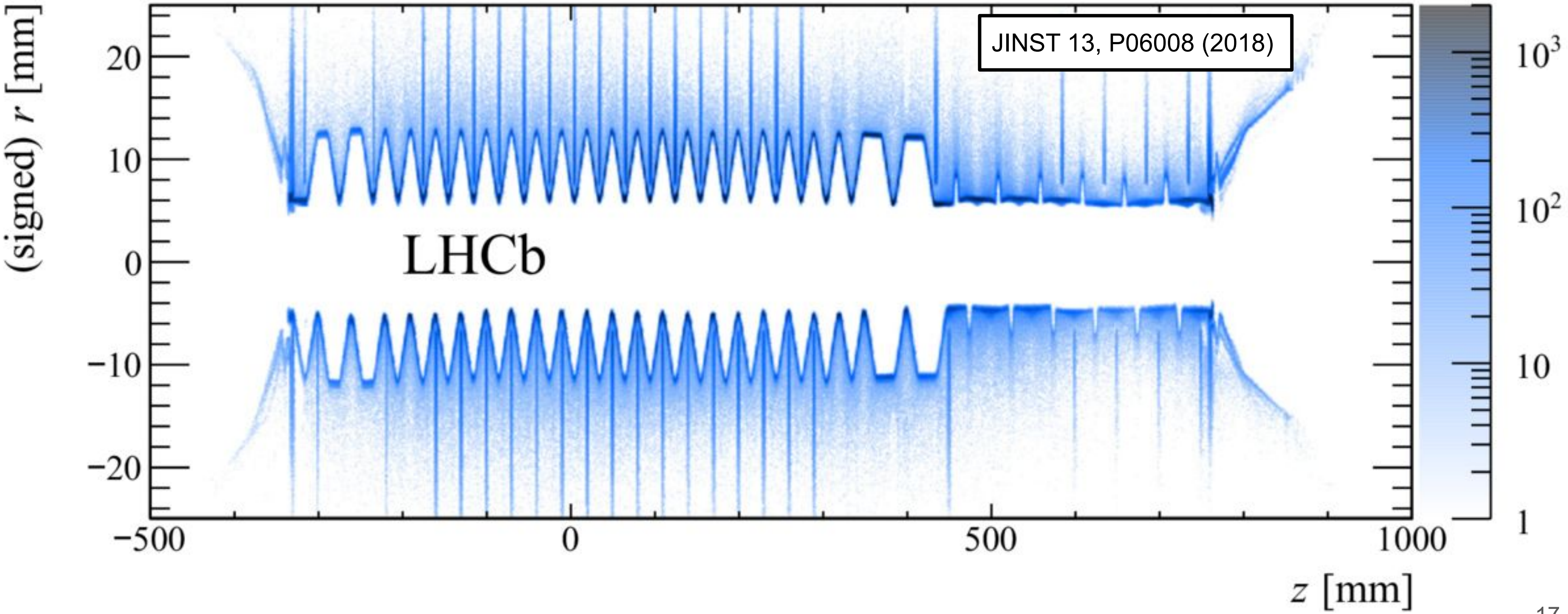
No significant excess found in the prompt-like search.
First search for dark photon masses of 10 GeV.

Murilo Rangel

Dark Photons

PRL 120, 061801 (2018)

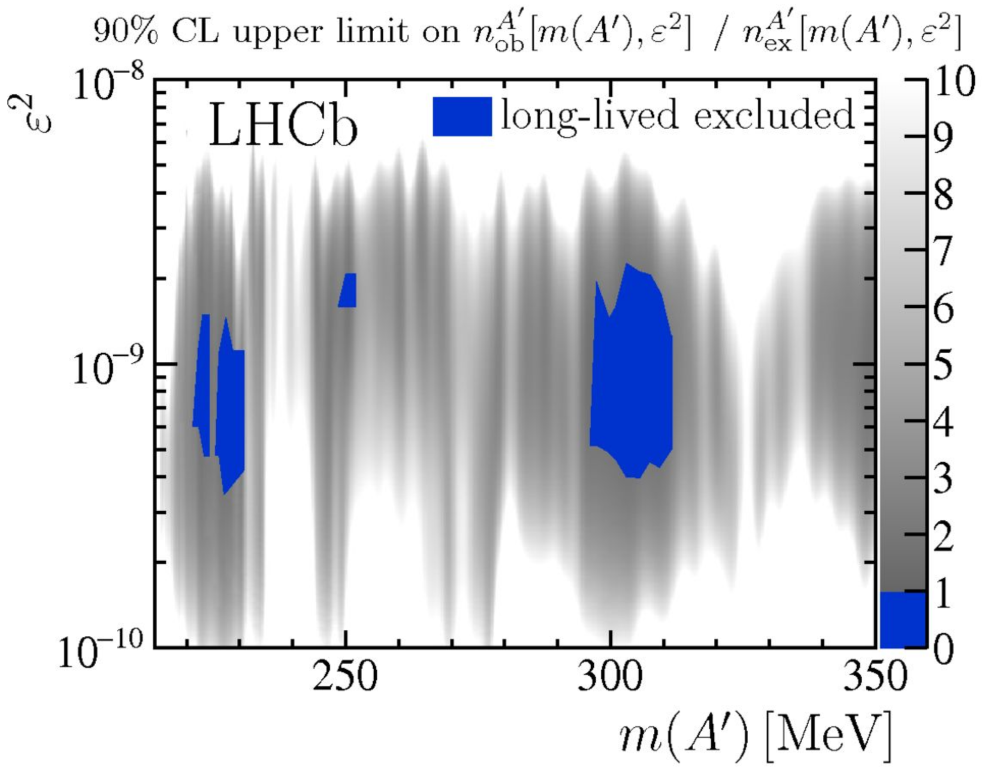
Long-lived search covers lower masses [214-350] MeV
→ Excluded material map using beam-gas collisions (photon conversion background)
based on material interactions from hadrons produced in beam-gas collisions



Dark Photons

PRL 120, 061801 (2018)

Long-lived search covers lower masses [214-350] MeV
→ Excluded material map using beam-gas collisions (photon conversion background)



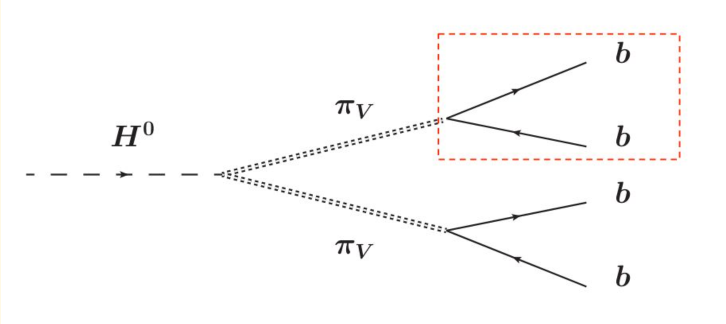
No significant excess found

First displaced search not from beam-dump experiments

LLP → jet pairs

EUR. PHYS. J. C77 (2017) 812

Search for SM Higgs decaying to hidden valley particles
→ Single displaced vertex with two jets

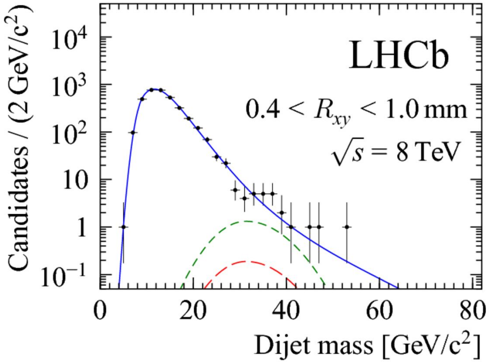


The trigger explores displaced vertex topology and the limits use:

Background model empirically modeled as HF decays material interaction
Signal model obtained in simulation

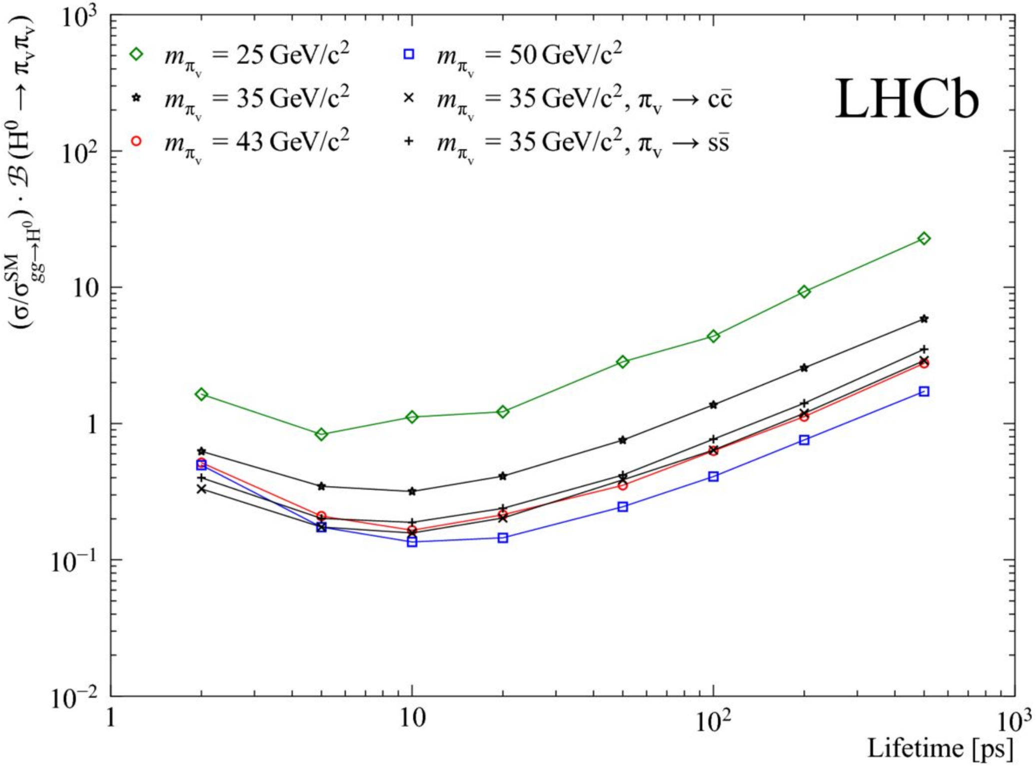
Signal model (35 GeV/c^2, 10 ps) for $\mathcal{B}(H^0 \to \pi_v \pi_v) = 1$.

Best-fit signal model (35 GeV/c^2, 10 ps).



LLP → jet pairs

EUR. PHYS. J. C77 (2017) 812



No significant excess found in the long-lived

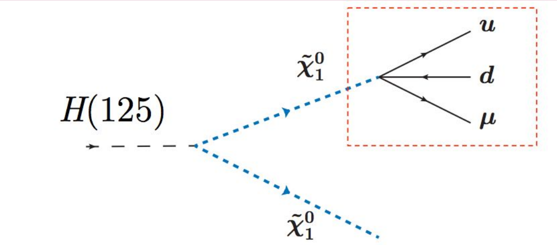
<u>Example</u>: for m_π=50 GeV and τ=[5-50] ps, BR>30% is excluded

Murilo Rangel

LLP → μ+jets

EUR. PHYS. J. C77 (2017) 224

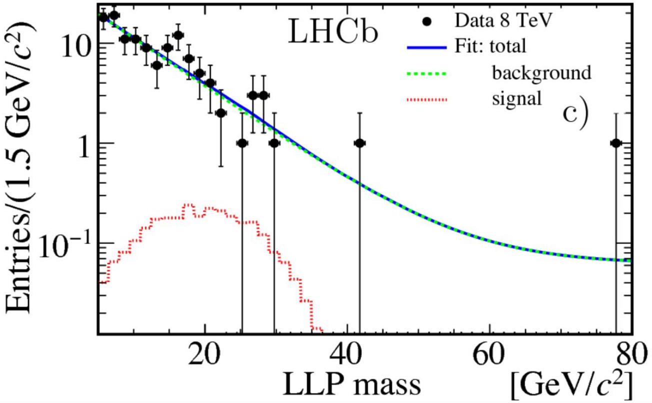
Testing models:
- mSUGRA with R-parity violation
- Four simplified MSSM models
  - Possible decay of Higgs-like particle with mass between 50 and 130 GeV



Trigger on displaced vertex containing a muon and tracks

Selection based on MLP using 7 variables – R_{xy} is the most discriminant

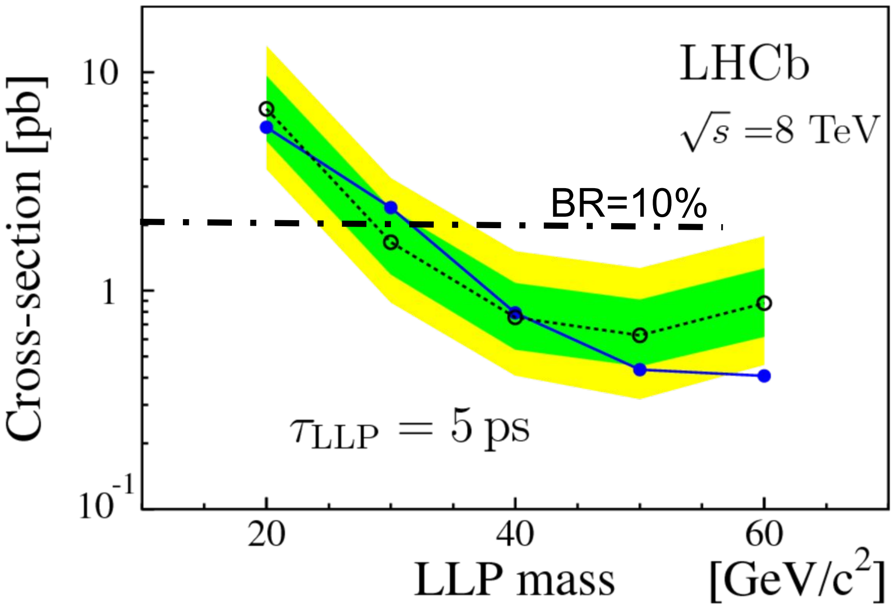
Limit setting from fits to LLP mass
- Background model empirically modeled as two exponentials
- Signal model obtained in simulation



Murilo Rangel

LLP → μ+jets

Eur. Phys. J. C77 (2017) 224



5 models tested and no significant excess found in the long-lived

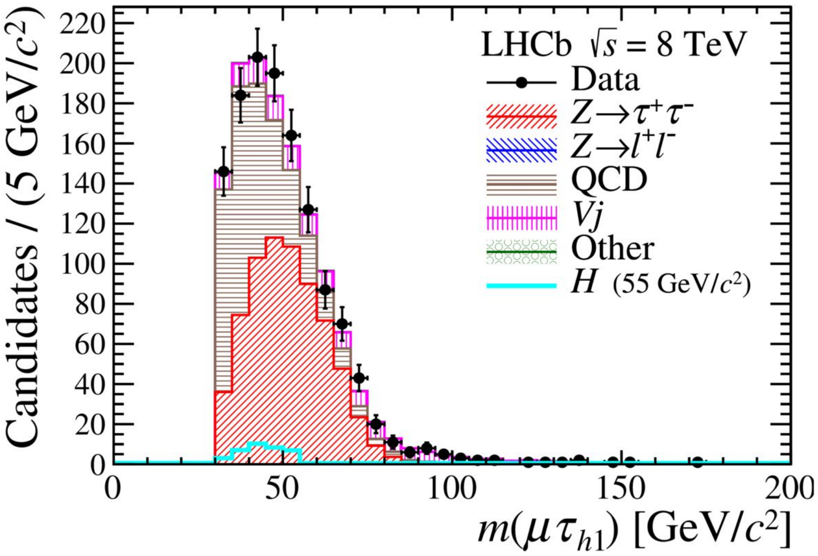
Example above: m(H)=125 GeV, τ(LLP)=5 ps and BR=10%,

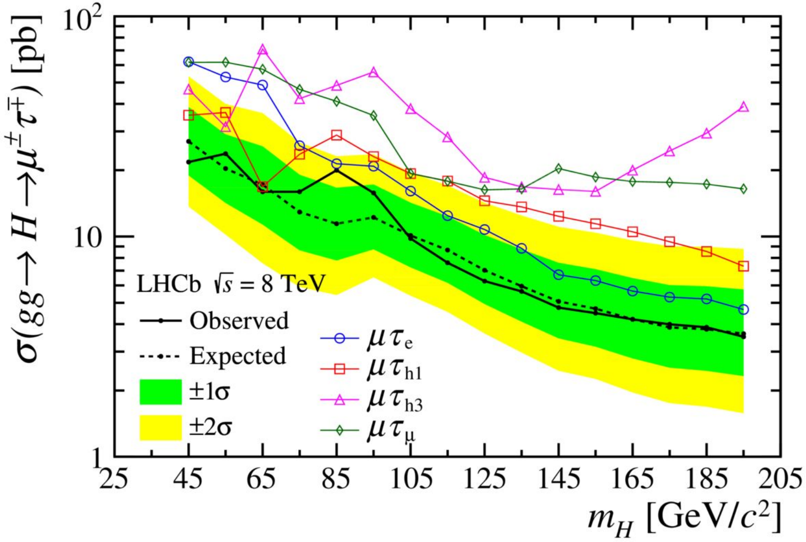
LLP mass < 30 GeV is excluded

H→μτ lepton-flavour-violating decay

EUR. PHYS. J. C78 (2018) 1008

Lepton-flavour-violating decay of Higgs-like particle will indicate the presence of unknown physics.
Four decay channels are analysed and the search is performed for masses between 45 and 195 GeV.





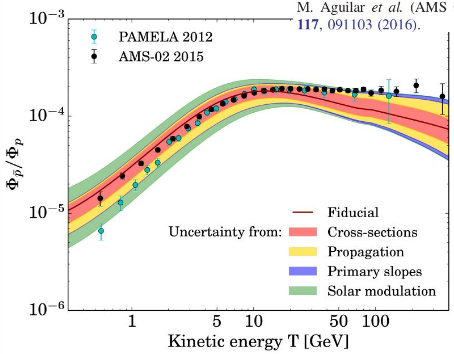
Murilo Rangel

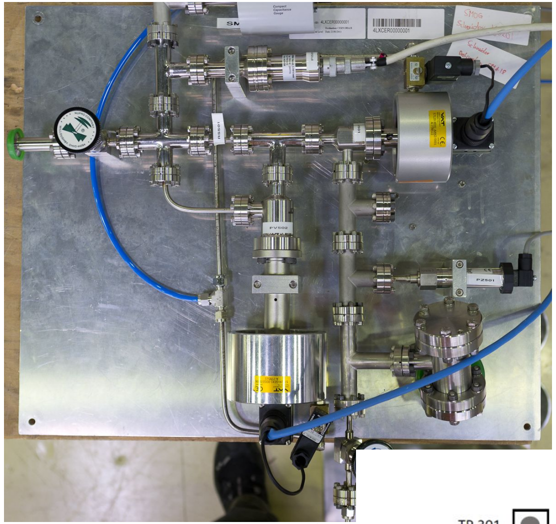
Antiproton production in pHe collisions

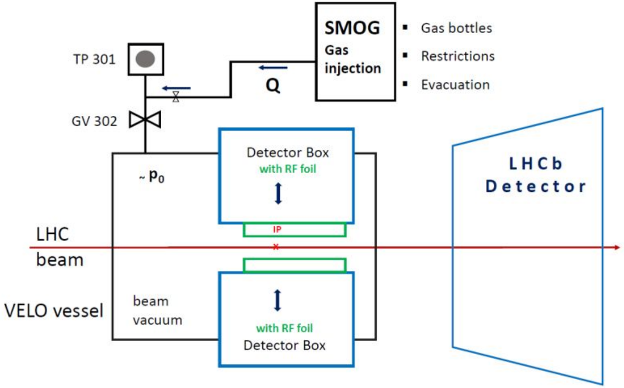
PRL 121, 222001 (2018)

Astroparticle experiments probe dark matter in the universe, but large uncertainties due to the antiproton production cross-section limit their sensitivity.

O. Adriani *et al.* (PAMELA Collaboration), JETP Lett. **96**, 621 (2013).
M. Aguilar *et al.* (AMS Collaboration), Phys. Rev. Lett. **117**, 091103 (2016).





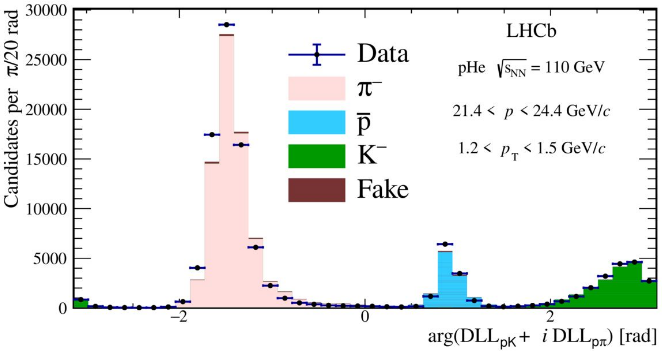


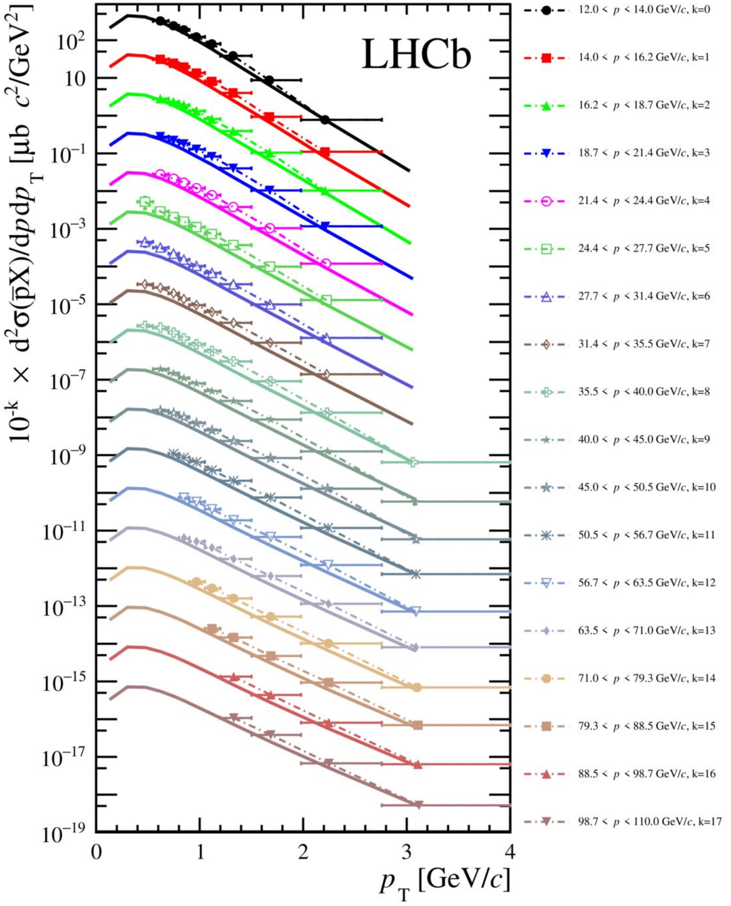
→LHCb is able to inject gas in the interaction region and become a fixed target experiment using <u>SMOG</u> device.
→6.5 TeV protons collide with He at $\sqrt{s}$ = 110.5 GeV
→0.4/nb acquired in 2016

Antiproton production in pHe collisions

PRL 121, 222001 (2018)

33.7 million reconstructed pHe collisions for about 1.4 million antiprotons

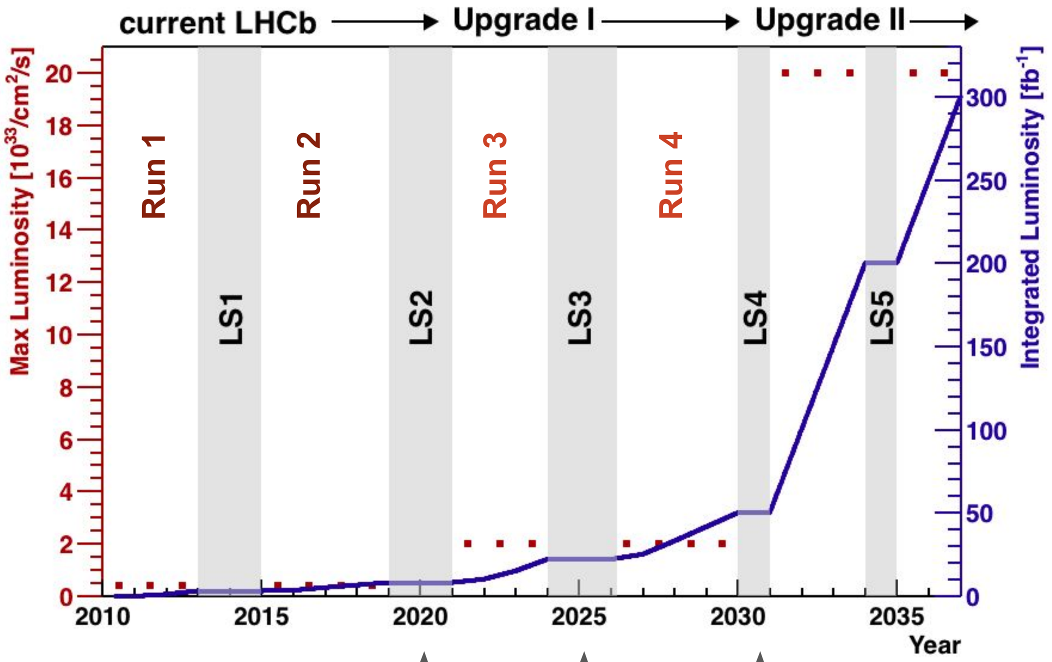




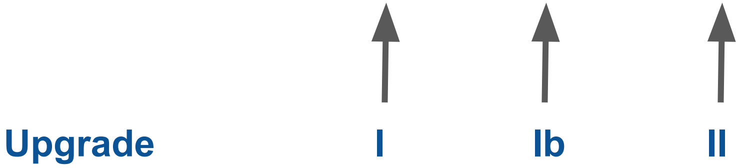
→ First measurement of antiproton production in p-He collisions
→ Significant excess of anti-proton production over the EPOS
→ Measured range of the antiproton kinematic spectrum are crucial for interpreting the precise anti-proton cosmic ray measurements from the PAMELA and AMS-02 experiments by improving the precision of the secondary anti-proton cosmic ray flux prediction

LHCb Upgrade

arXiv:1808.08865 [hep-ex]

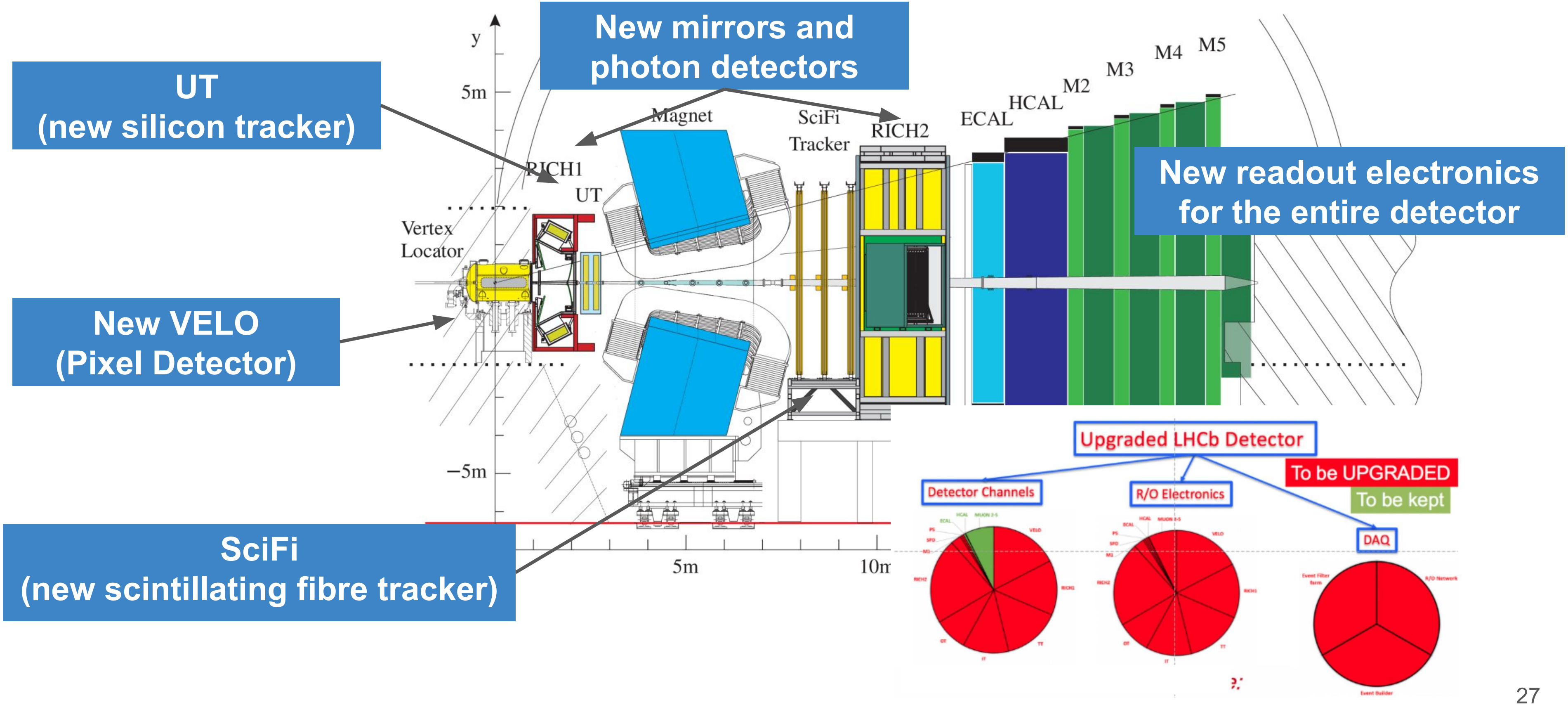


Run 1+2: 9.1/fb
Run 3: 25/fb
Run 4: 50/fb



LHCb Upgrade

CERN-LHCC-2012-007



Murilo Rangel

LHCb Trigger - Upgrade I

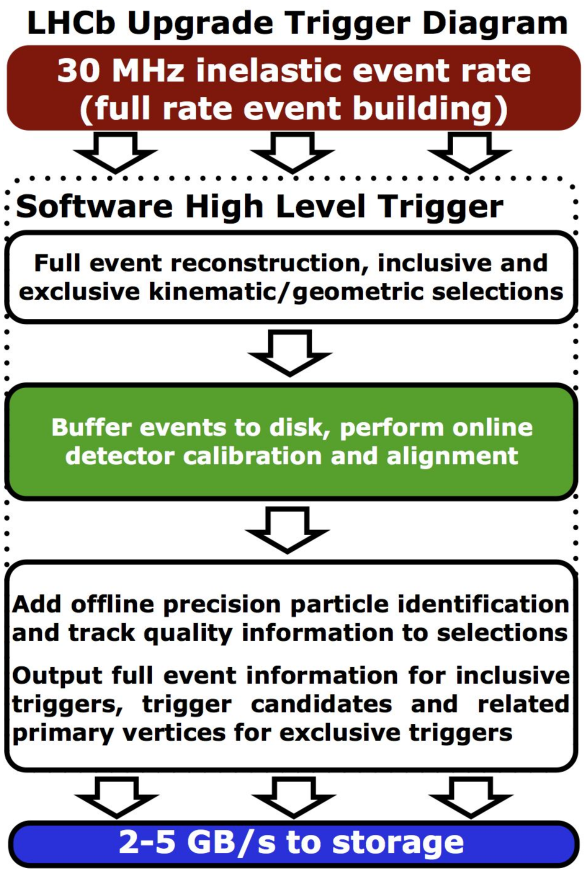
❈ Increase instantaneous luminosity:
$4 \times 10^{32} \rightarrow 2 \times 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

❈ Replacement of tracking detectors
♯ finer granularity to cope with higher particle density
♯ new front-end electronics compatible with 30 MHz readout

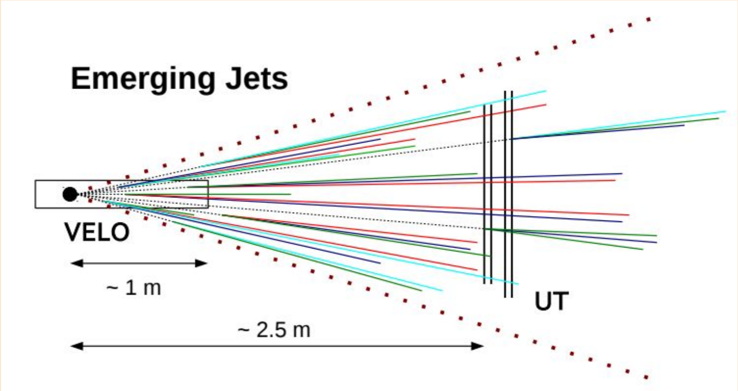
❈ Remove hardware trigger stage and operate software trigger at 30 MHz input rate with 5 x more pileup than Run 2.

❈ HLT1 output: from 100 kHz to 1 MHz
Disk buffer contingency: from weeks to days
HLT2 output: from 0.6 GB/s to 10 GB/s

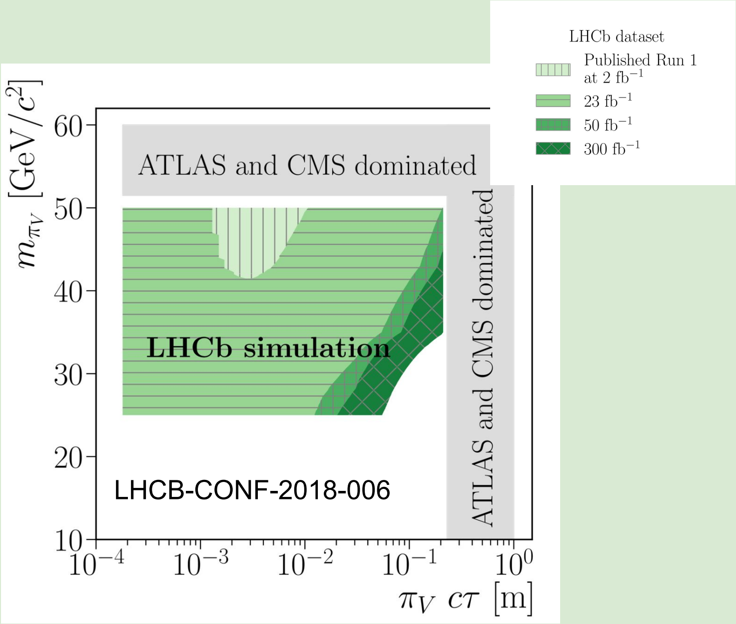
JINST 14 (2019) P04006



Possible trigger on merging jets suggested by Schwaller P., Stolarski D. and Weiler A. [JHEP 1505 (2015) 059]



Extrapolations show good perspective to reach lower masses and lower lifetimes



Murilo Rangel

Summary

★ LHCb has an extensive program of searches sensitive to Dark Matter

★ Analyses explore the unique LHCb capabilities for

. separating primary, secondary and tertiary vertices with excellent resolution

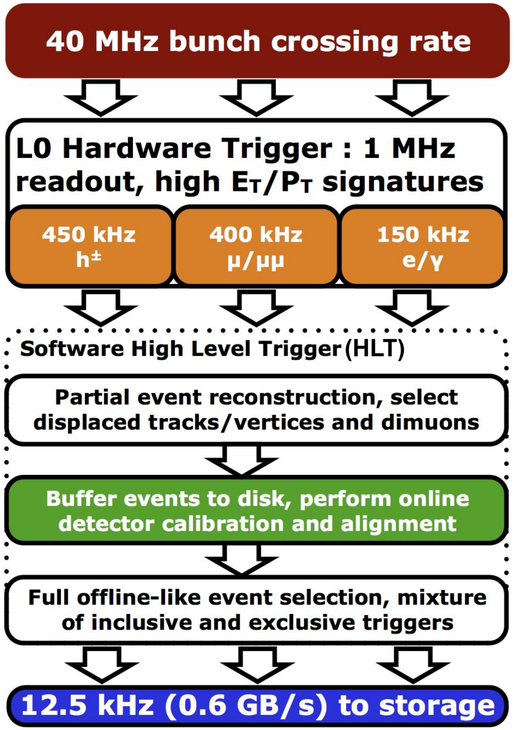
. triggering on soft particles

↠ Future and other related results can be found here

THANK YOU!

Run 2 trigger

LHCb Run II Trigger Diagram (2015 - 2019)



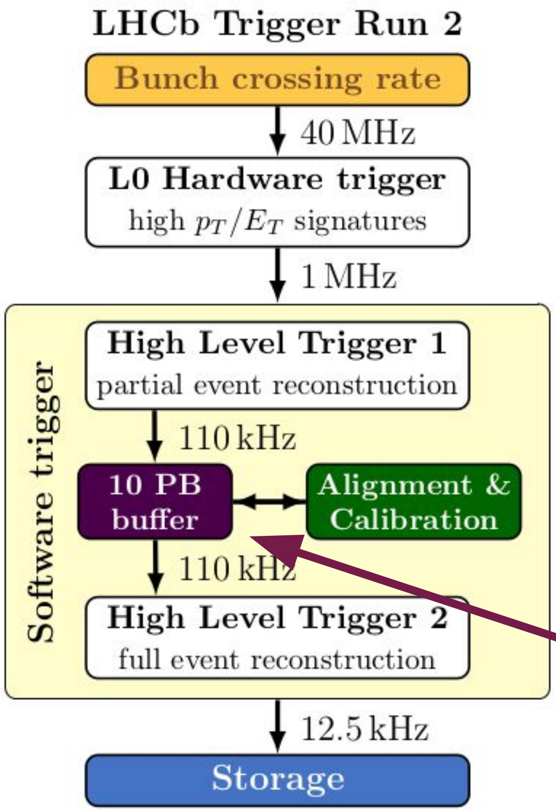
JINST 14 (2019) no.04, P04013

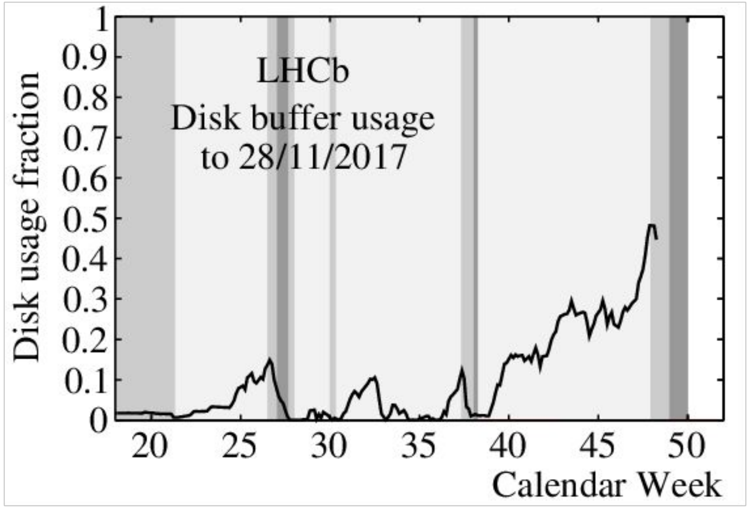
Trigger structure:

- Hardware: energies deposited in calorimeters and muon stations hits are used to bring 40 MHz to 1 MHz

- Software: events built at 1 MHz (~27000 physical cores)
  - HLT1: fast tracking and inclusive selections
    - 1 MHz to 100 kHz
  - HLT2: complete event reconstruction and selections

Run 2 trigger

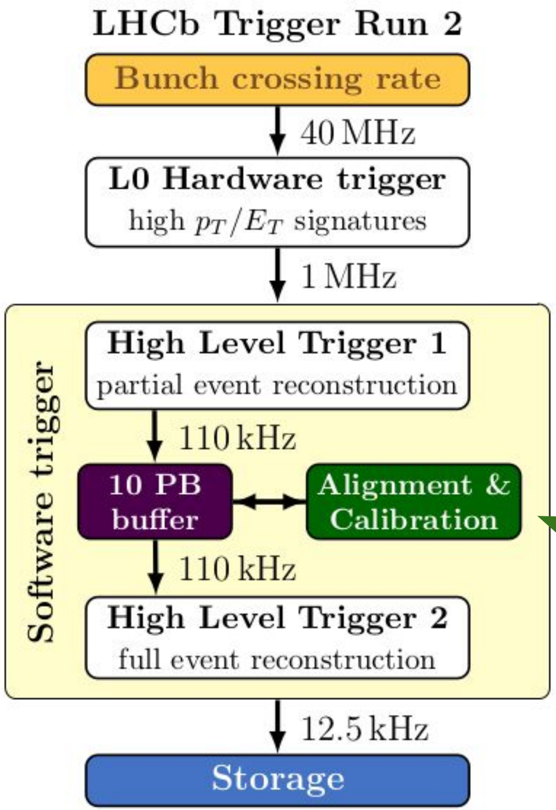




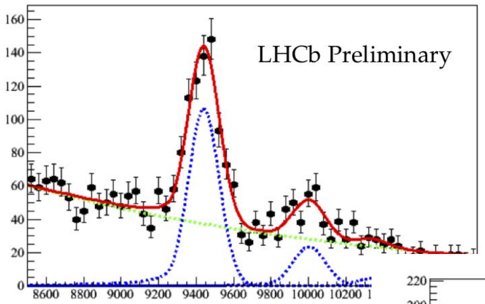
♯ HLT Farm with 10 PB disk space
♯ At an average event size of 55 kB with 100 kHz: up to 2 weeks before HLT2 has to be executed
♯ 2x trigger CPU capacity since Farm is used twice for HLT (excess used for simulation)

JINST 14 (2019) no.04, P04013

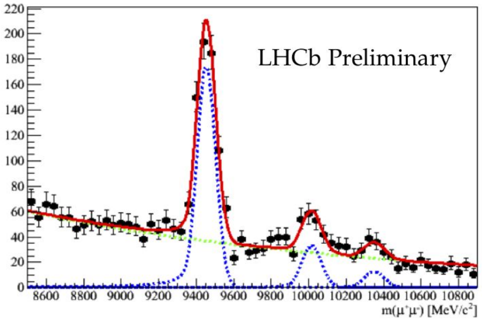
Run 2 trigger



[JINST 14 (2019) no.04, P04013]



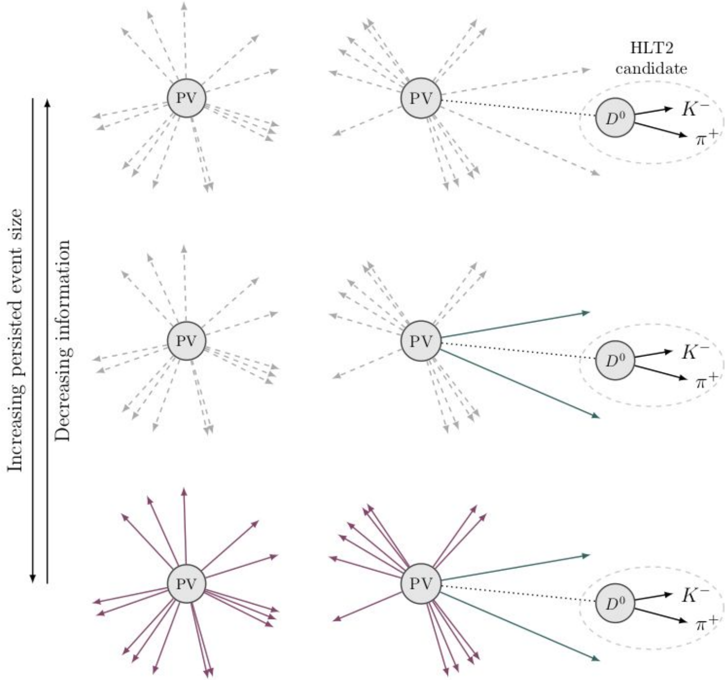
~50% improvement in mass resolution



♯ Real-time alignment and calibration
♯ Dedicated HLT1 trigger lines supply samples for the alignment
♯ Alignment & calibration tasks run in parallel while events are are being processed by HLT1

Run 2 trigger: Turbo

$$\text{Bandwidth}\,[\text{GB}\,\text{s}^{-1}] \propto \text{Trigger output rate}\,[\text{kHz}] \times \boxed{\text{Average event size}\,[\text{kB}]}$$



Turbo data processing model

♯ Analyses that can be done using trigger objects can profit of reduced event size and higher trigger rate.

♯ Event size can be reduced from 70 kB to 7 kB depending on the persistence level

♯ Calibration samples increased, reducing systematic uncertainties on efficiency measurements

♯ 50% of HLT2 trigger lines are Turbo counting 10% of the bandwidth

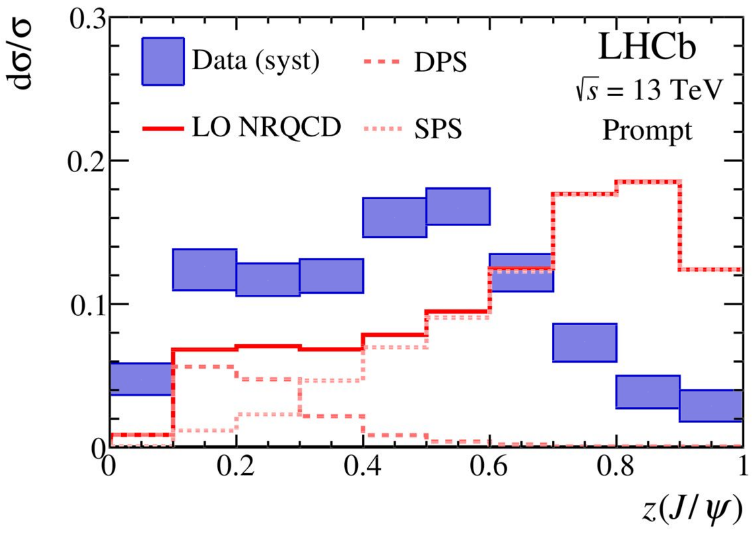
JINST 14 (2019) no.04, P04006

Run 2 Trigger: Turbo Analyses

Study of J/ψ Production in Jets

R. Aaij *et al.* (LHCb Collaboration)
Phys. Rev. Lett. **118**, 192001 – Published 8 May 2017

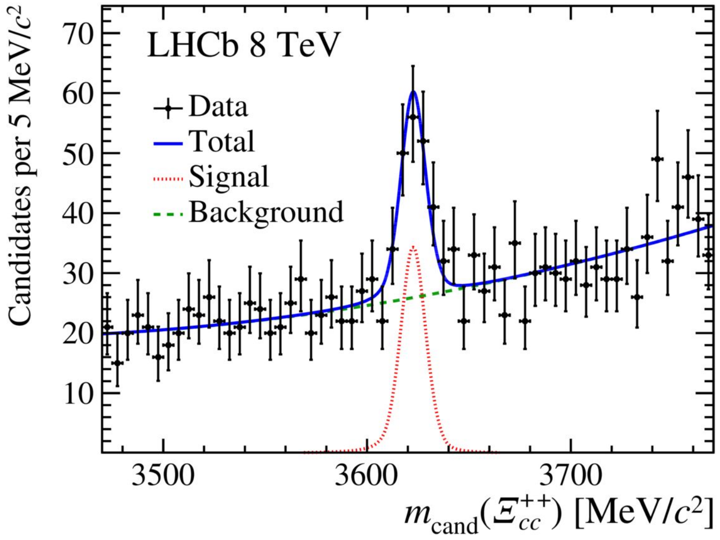
Physics See Viewpoint: Probing Quarkonium Production in Jets



Observation of the Doubly Charmed Baryon Ξ_{cc}^{++}

R. Aaij *et al.* (LHCb Collaboration)
Phys. Rev. Lett. **119**, 112001 – Published 11 September 2017

Physics See Viewpoint: A Doubly Charming Particle

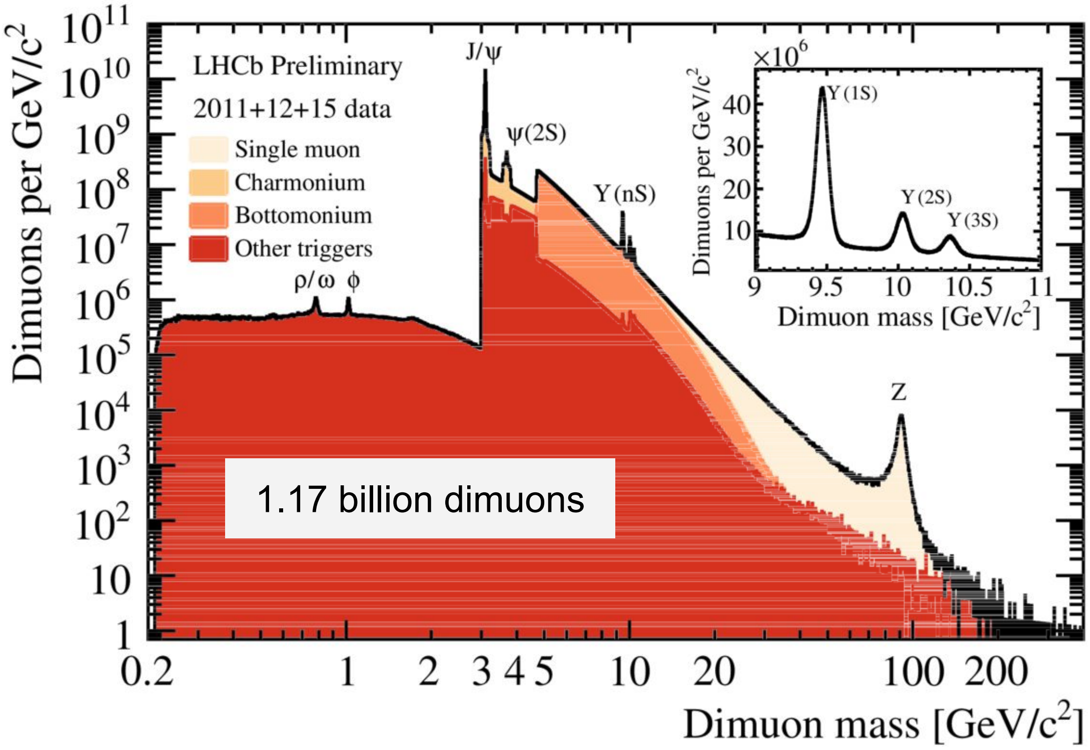


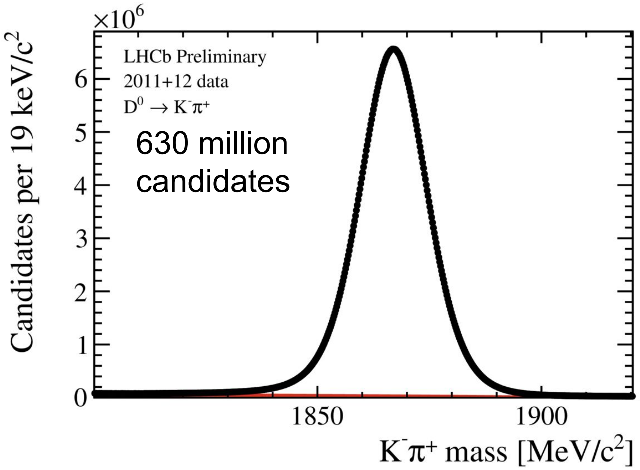
Phys.Rev.Lett. 118 (2017) no.19, 192001

Phys. Rev. Lett. 119, 112001

Run 2 trigger: Plots

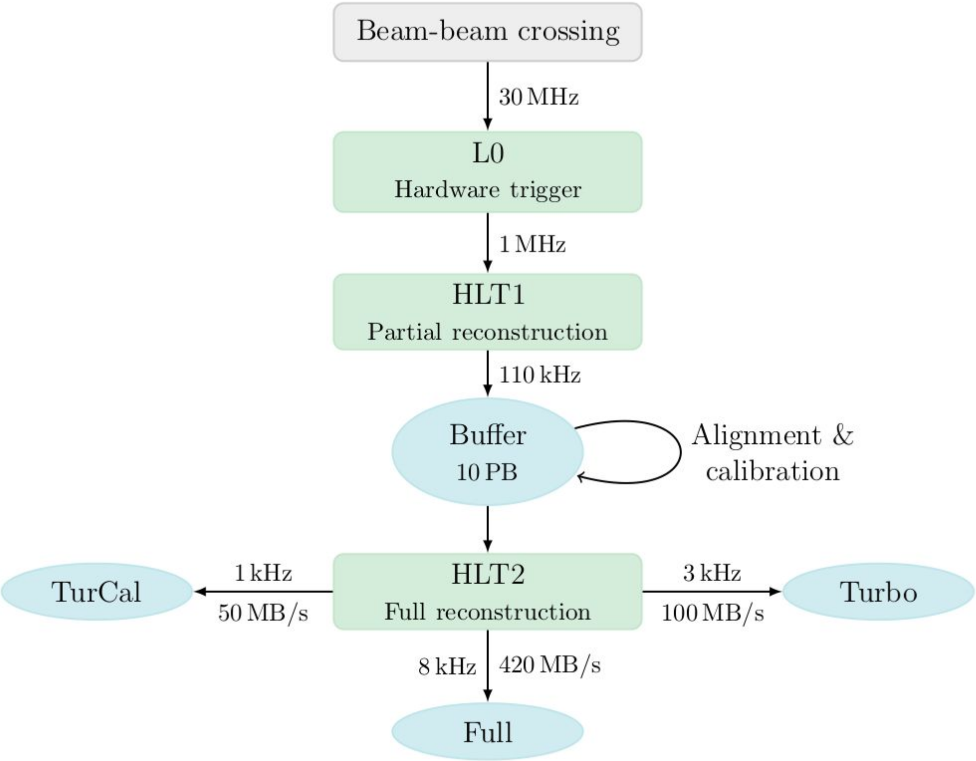
LHCb-CONF-2016-005





Rare events: high efficiency
Copious production: high purity

LHCb Run II trigger



[JINST 14 (2019) no.04, P04006]()

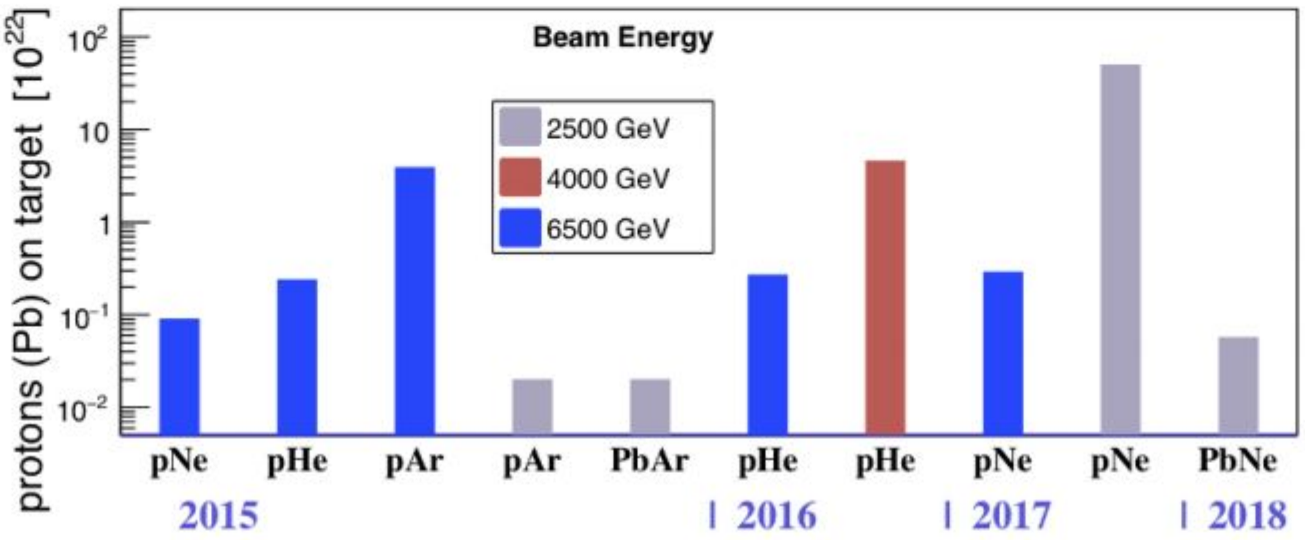


Figure 1: Dedicated SMOG runs collected since 2015. Beam-gas collisions have been recorded using different gas types (He, Ar, Ne) and beam energies.