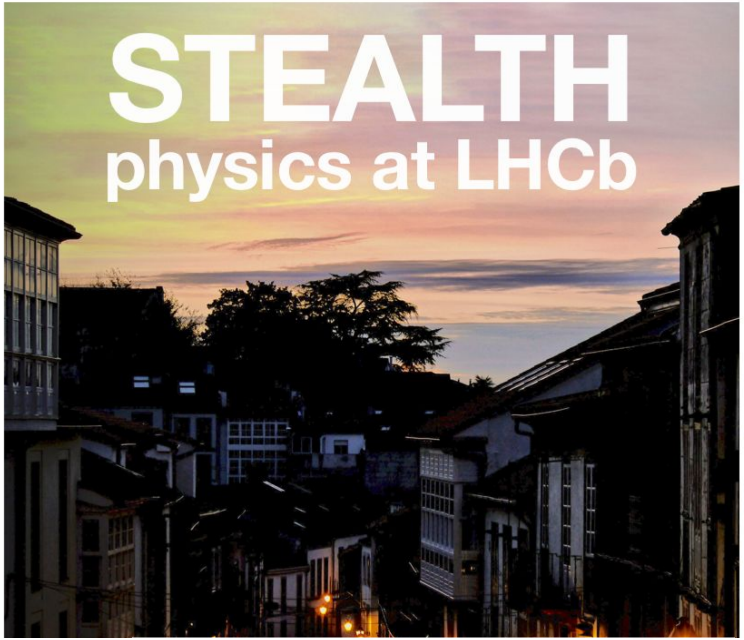
# LHCb reconstruction and PID

Murilo Rangel
on behalf of the LHCb Collaboration

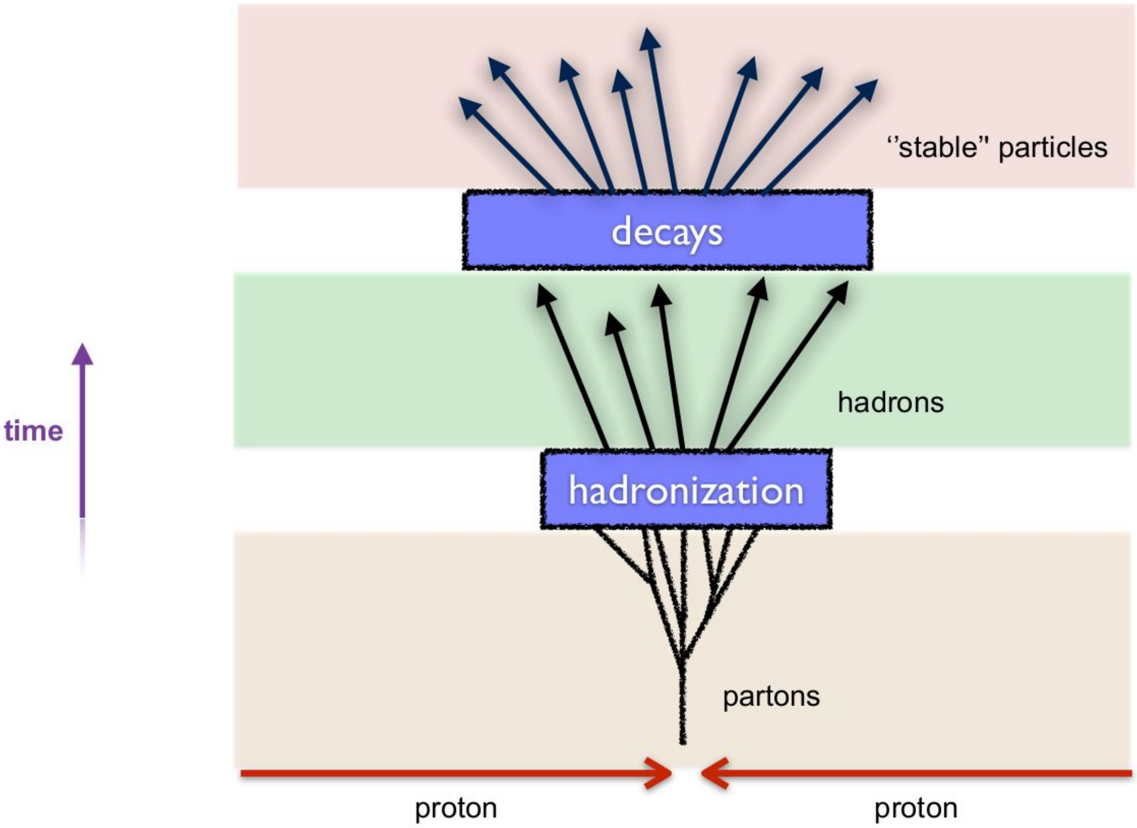



CERN
LHCb
lape
Instituto de Física
Universidade Federal do Rio de Janeiro
FAPERJ
CNPq

## Outline

→ Brief review of LHCb detector performance

- → Tracking reconstruction
- → Particle Identification
- → Jets and Displaced vertex
- → Forward shower detector and Fixed target
- → Alignment and Calibration




Lifetimes > $10^{-8}$ [s]:
p,n,e,γ,μ,π,K,$K_L^0$



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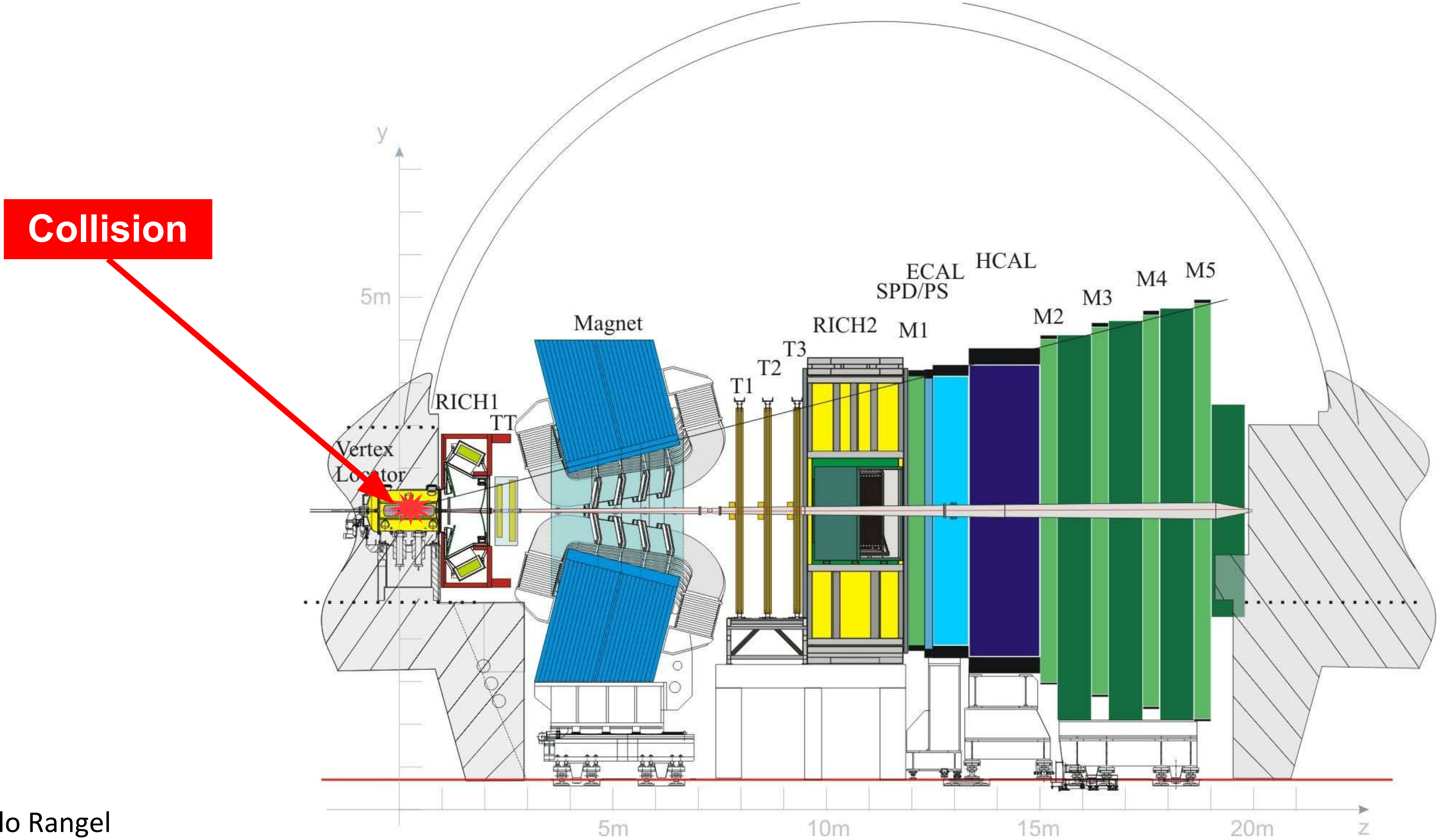
**LHCb** is a single arm spectrometer fully instrumented in the forward region (2.0<η<5.0)

Designed for heavy flavour physics and also exploited for general purpose physics

[Int. J. Mod. Phys. A 30, 1530022 (2015)]



**LHCb**

→ Unique coverage complementary to ATLAS/CMS

→ Soft trigger and forward acceptance

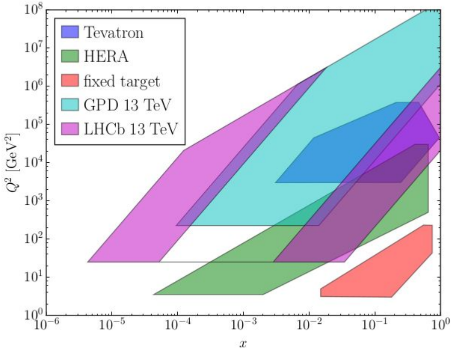
→ lower masses reach

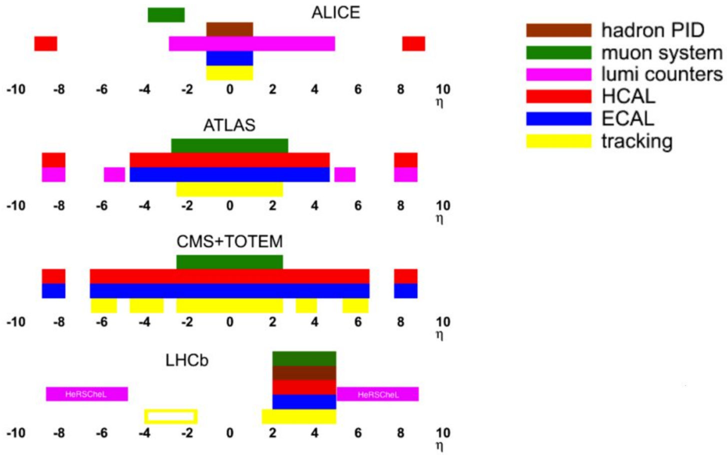
→ Excellent secondary/tertiary vertex reconstruction

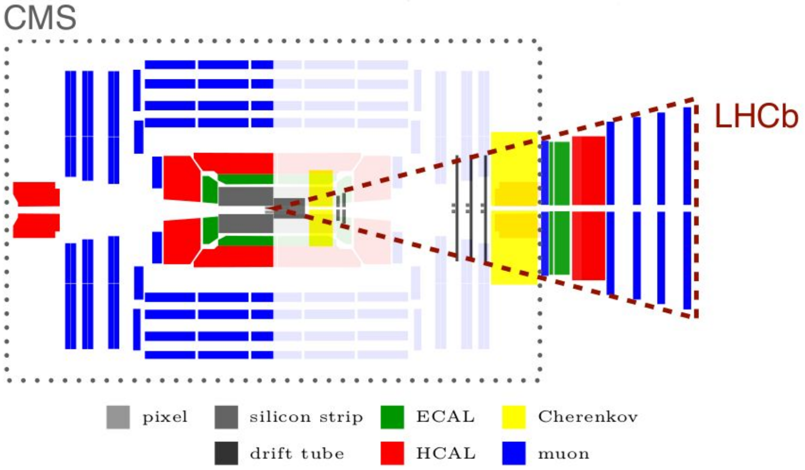
→ lower lifetimes reach (~ 1 ps).

→ Fixed target physics program

$$\sigma = \int xfx(f_1, x_1, Q^2)xfx(f_2, x_2, Q^2)\hat{\sigma}\, dx_1 dx_2, \quad Q^2(x) = e^{\pm 2y}x^2 s$$



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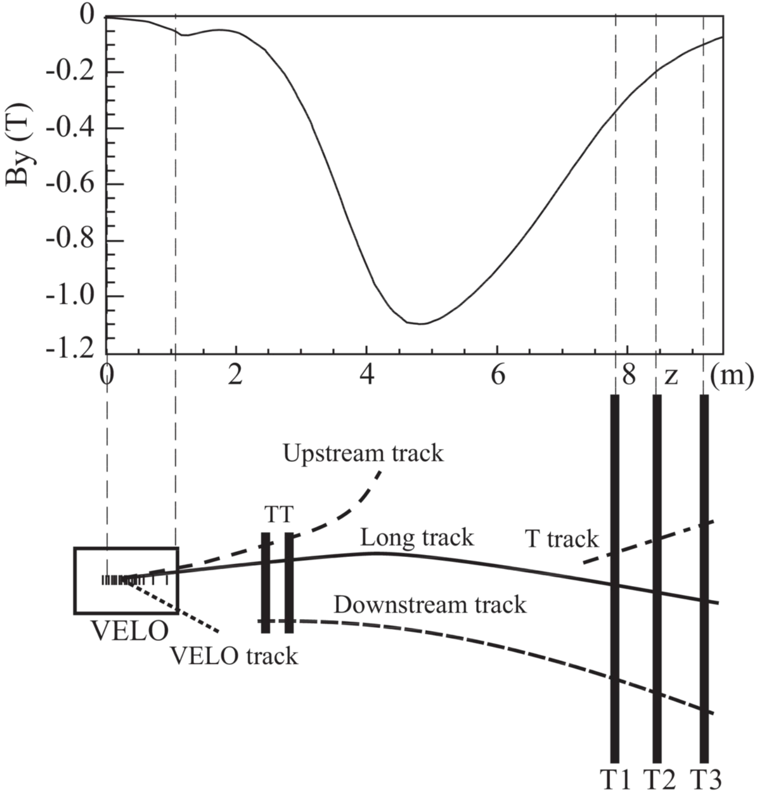
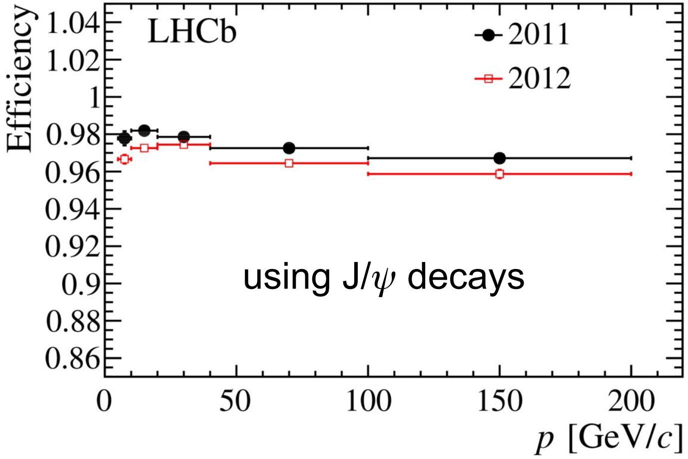
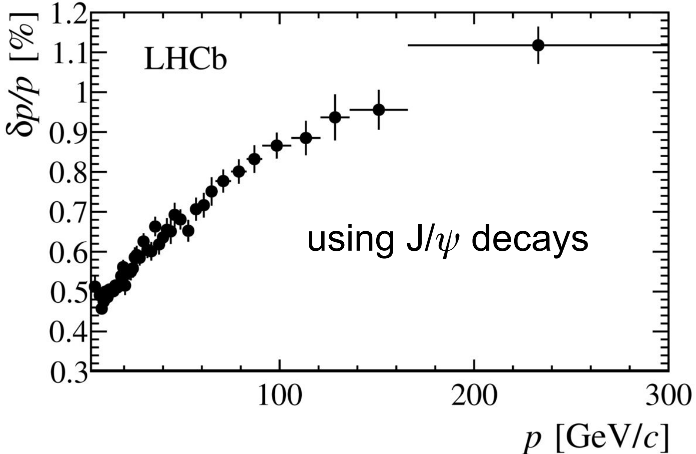
# Tracking system

[Int. J. Mod. Phys. A 30, 1530022 (2015) + JINST 10 (2015) P02007]

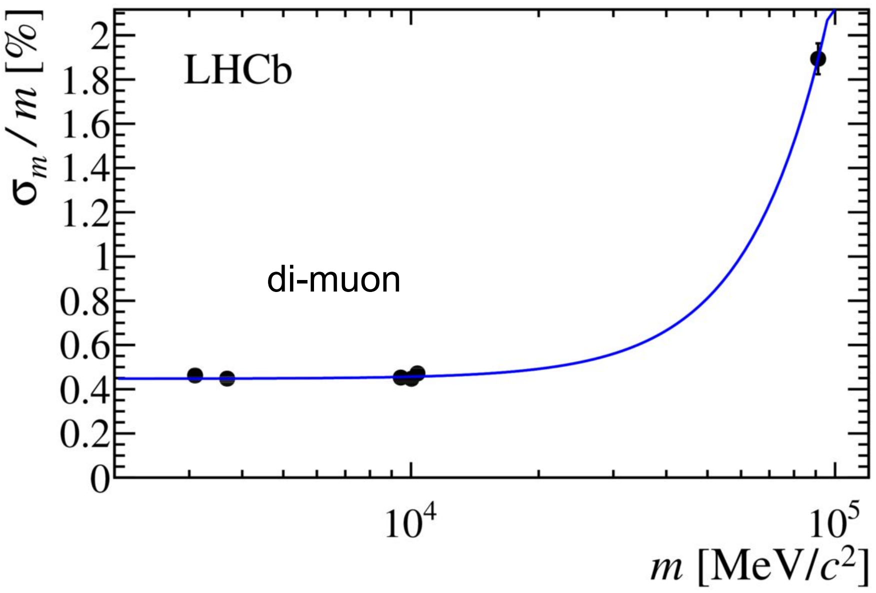


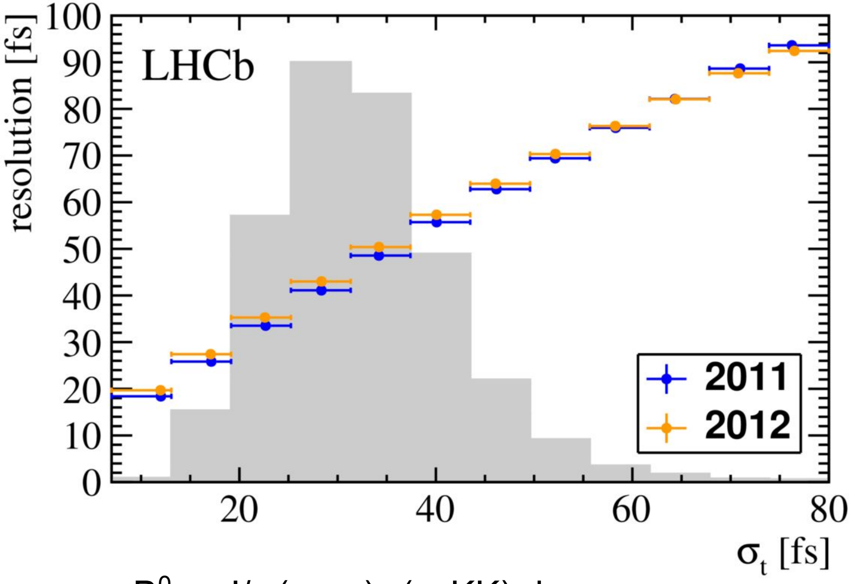



# Tracking system

[Int. J. Mod. Phys. A 30, 1530022 (2015) + JINST 10 (2015) P02007]

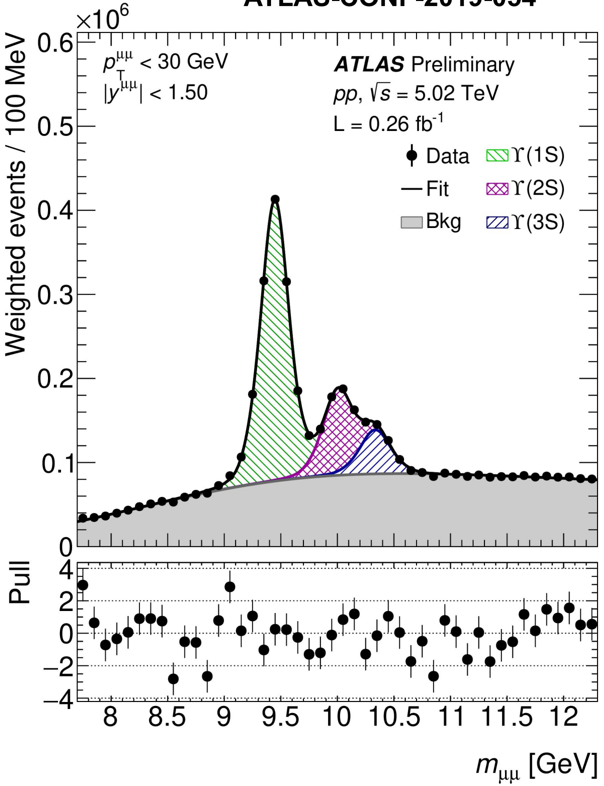


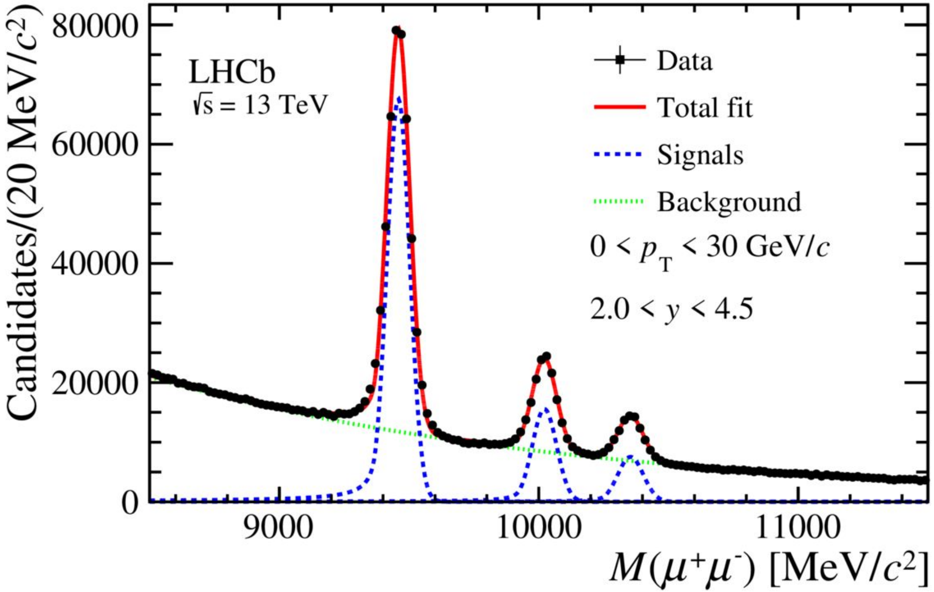

$B^0_s \to J/\psi(\to\mu\mu)\varphi(\to KK)$ decays

# Comparison with ATLAS

**ATLAS-CONF-2019-054**

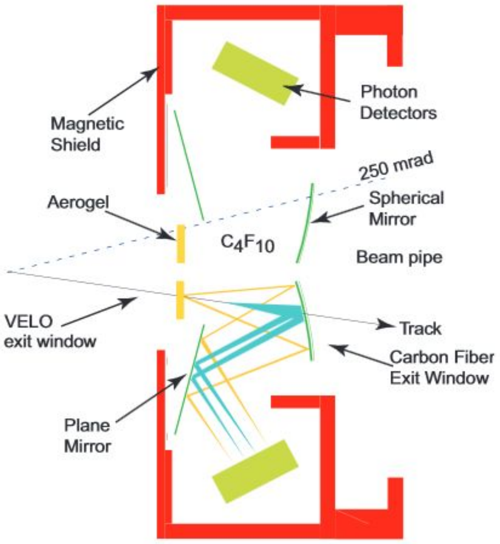


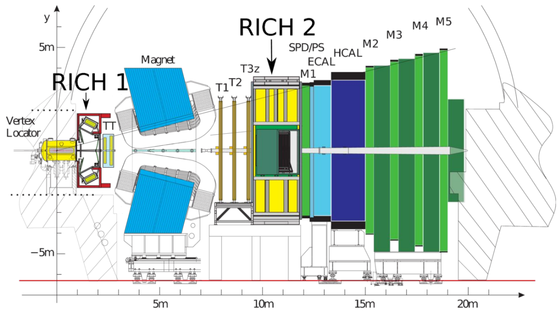

**JHEP 07 (2018) 134**

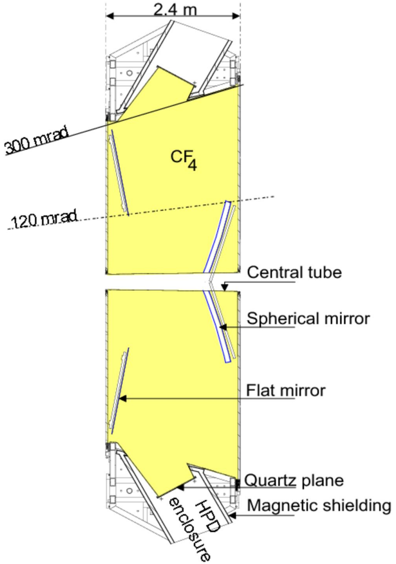


# Particle identification - Rich

[Int. J. Mod. Phys. A 30, 1530022 (2015) + JINST 8 (2013) P10020 + EPJ. C 73 (2013) 2431 + EPJ T&I 2019 6:1]




**RICH 1**

...Upstream of the magnet

...$C_4F_{10}$ radiator

...3 < p < 40 GeV/c

**RICH 2**

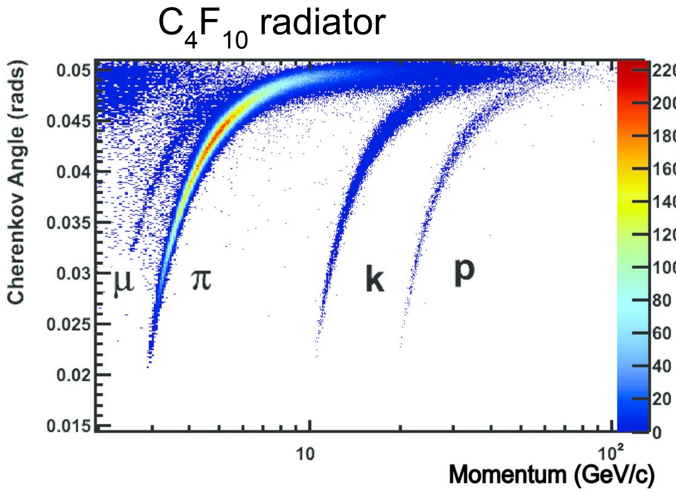
...Downstream of the magnet

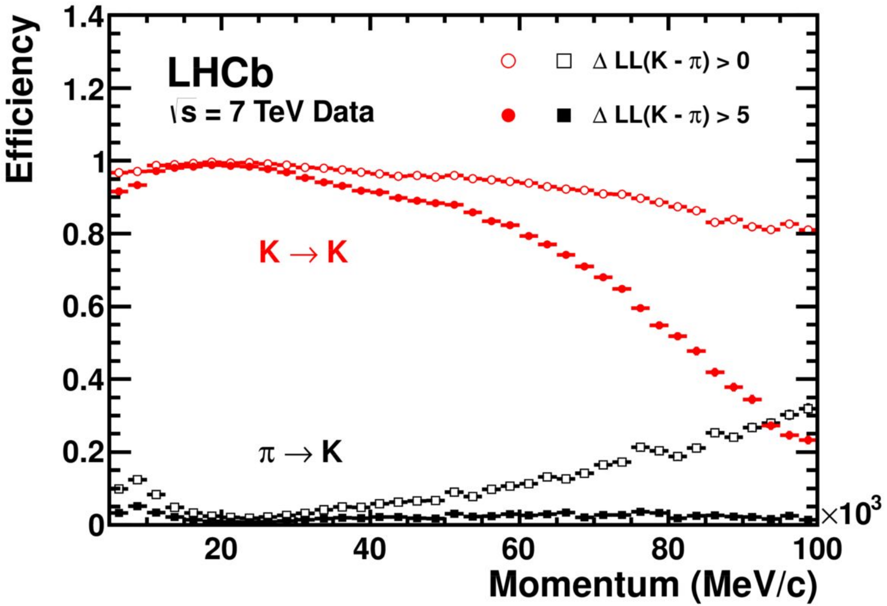
...$CF_4$ radiator

...15 < p < 100 GeV/c

# Particle identification - Rich

[Int. J. Mod. Phys. A 30, 1530022 (2015) + JINST 8 (2013) P10020 + EPJ. C 73 (2013) 2431 + EPJ T&I 2019 6:1]



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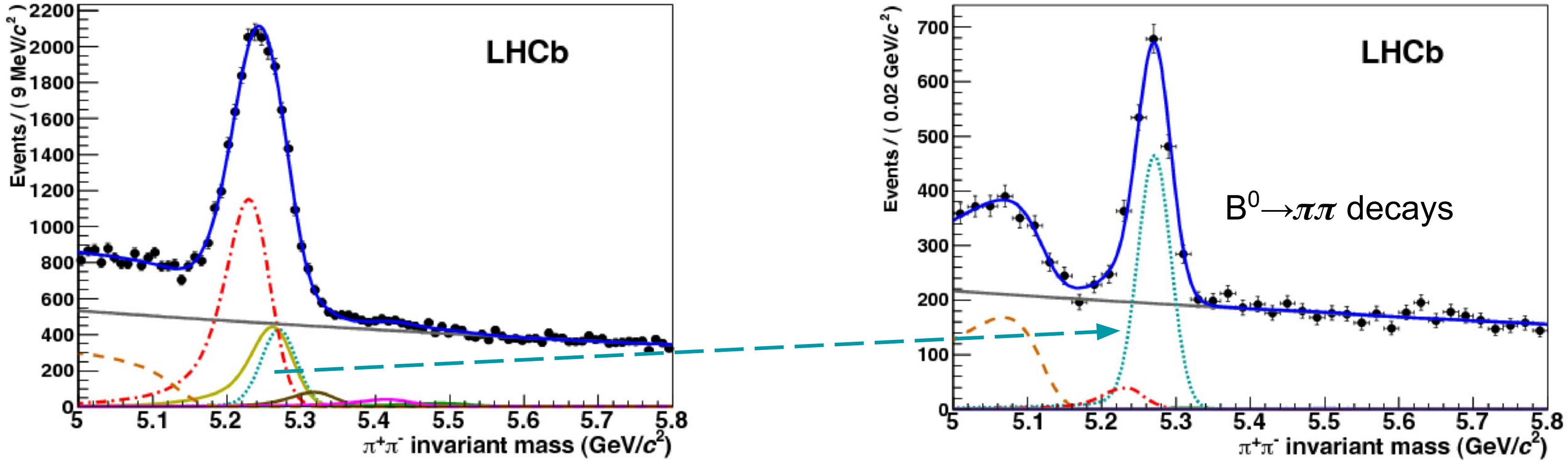
# Particle identification - Rich

[Int. J. Mod. Phys. A 30, 1530022 (2015) + JINST 8 (2013) P10020 + EPJ. C 73 (2013) 2431 + EPJ T&I 2019 6:1]

**Before PID** **After PID**



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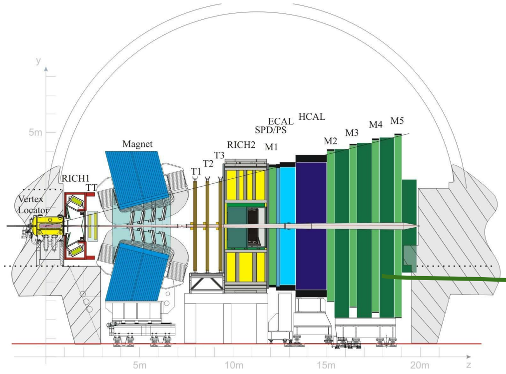
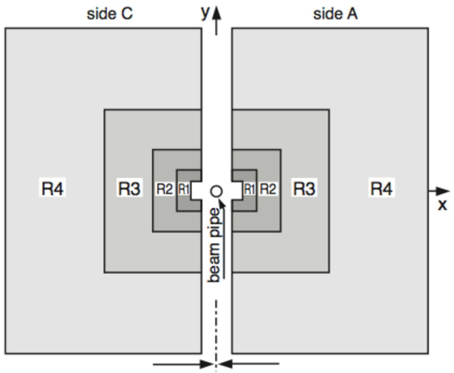
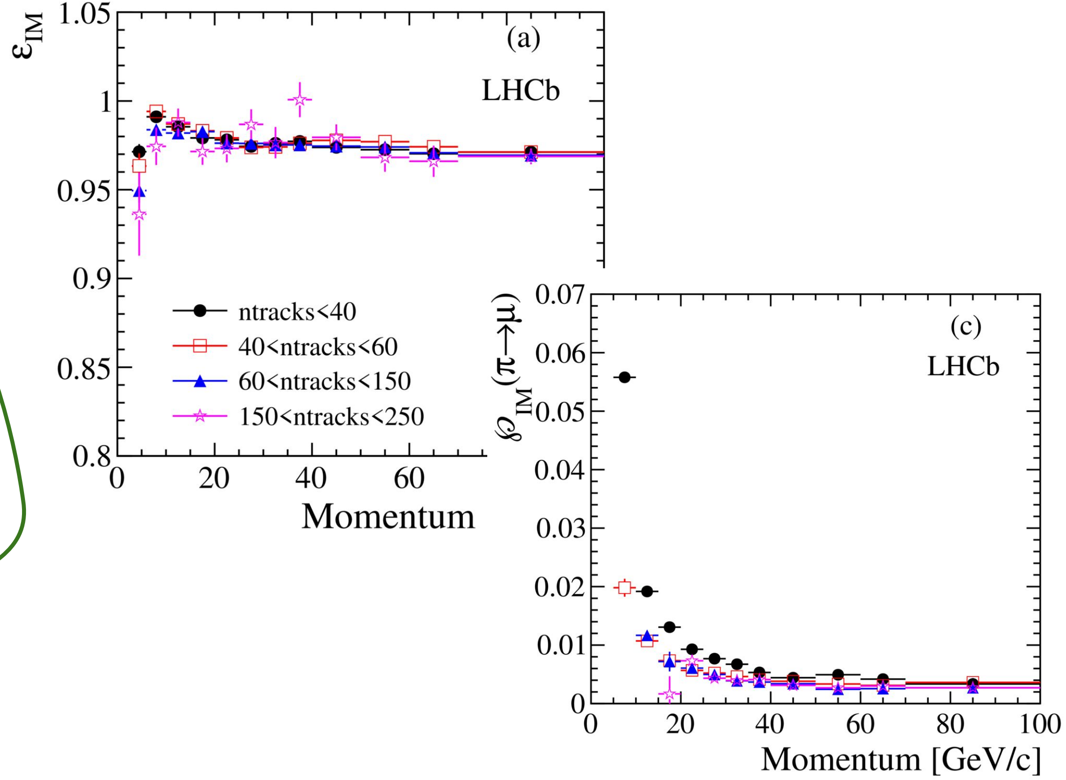
# Particle identification - Muon

[Int. J. Mod. Phys. A 30, 1530022 (2015) + JINST 8 (2013) P10020 + EPJ. C 73 (2013) 2431 + EPJ T&I 2019 6:1]




...5 stations = 1 before + 4 after calorimeters
...stations are divided in 4 regions

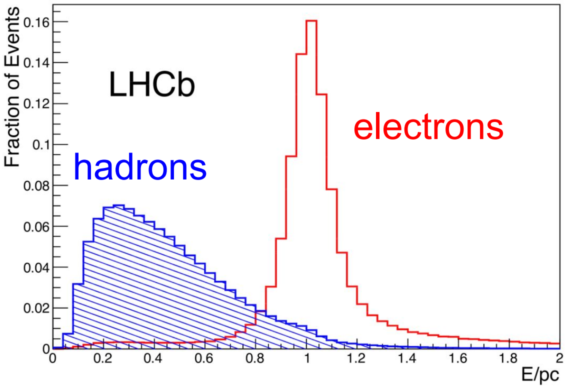


# Particle identification - Calorimeter

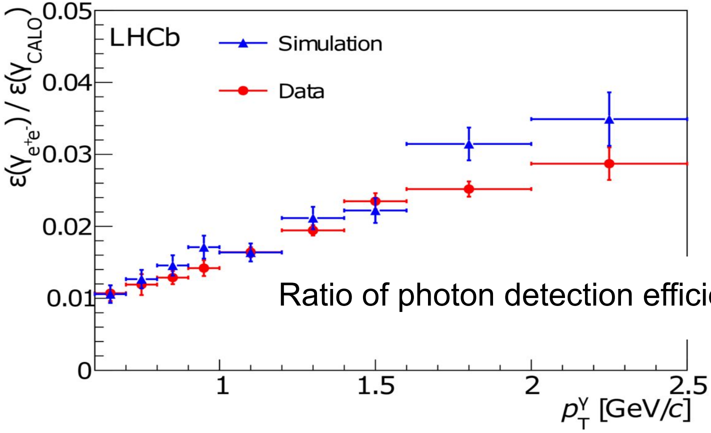
[Int. J. Mod. Phys. A 30, 1530022 (2015) + JINST 8 (2013) P10020 + EPJ. C 73 (2013) 2431 + JINST 14 (2019) P11023]

**ECAL**

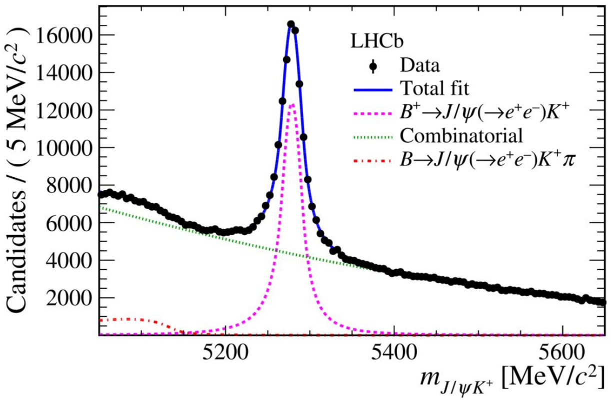



$$\text{ECAL: } \frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E/\text{GeV}}} \oplus 1\%,$$

$$\text{HCAL: } \frac{\sigma_E}{E} = \frac{69\%}{\sqrt{E/\text{GeV}}} \oplus 9\%.$$




Ratio of photon detection efficiencies



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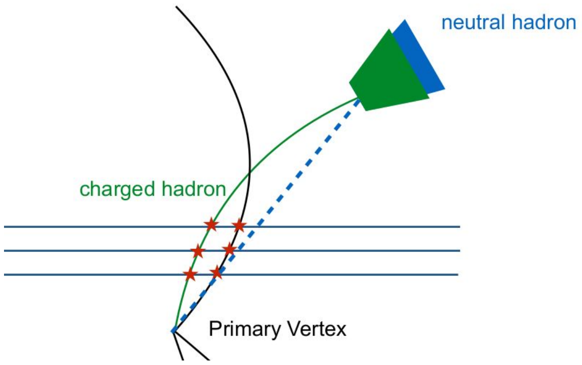
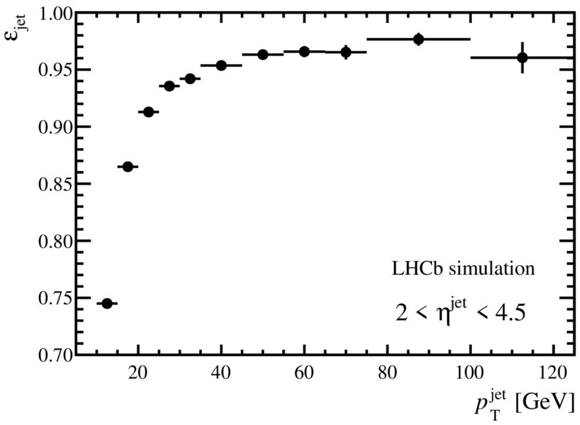
# Jets Reconstruction

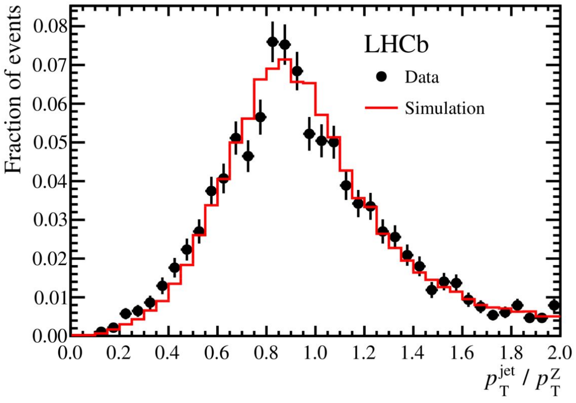
[JHEP 01 (2014) 33 + JINST 10 P06013]

**Particle Flow** approach with neutral recovery

- Jets reconstructed using anti-$k_T$ (R=0.5)
- Simulation modeling studied with Z+jet
- High efficiency on both online and offline reconstruction



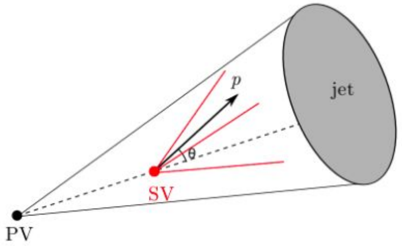



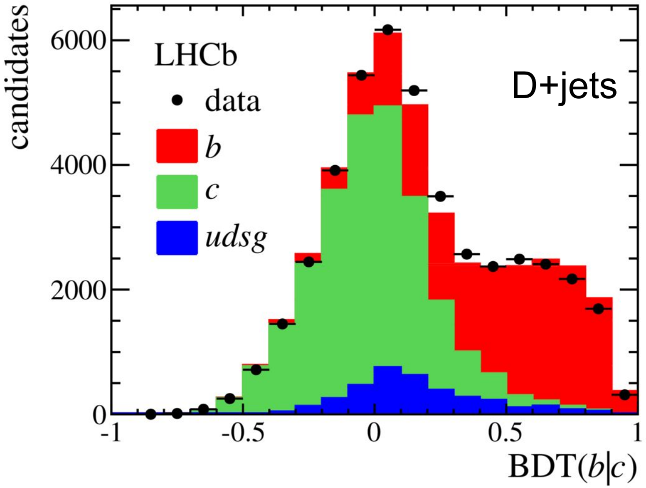



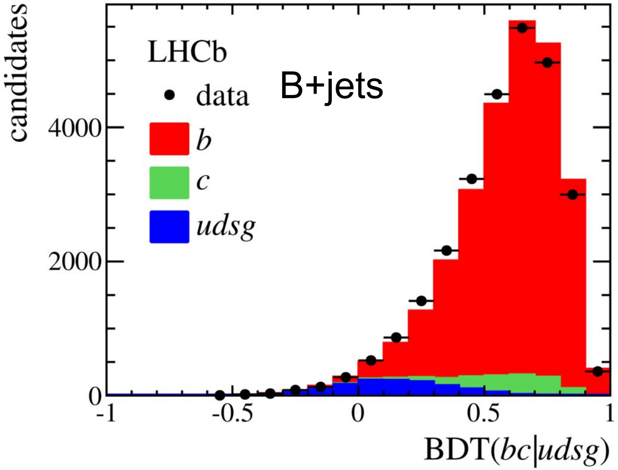
# Jets Reconstruction

[JHEP 01 (2014) 33 + JINST 10 P06013]

**Heavy-flavour tag** calculated with BDT



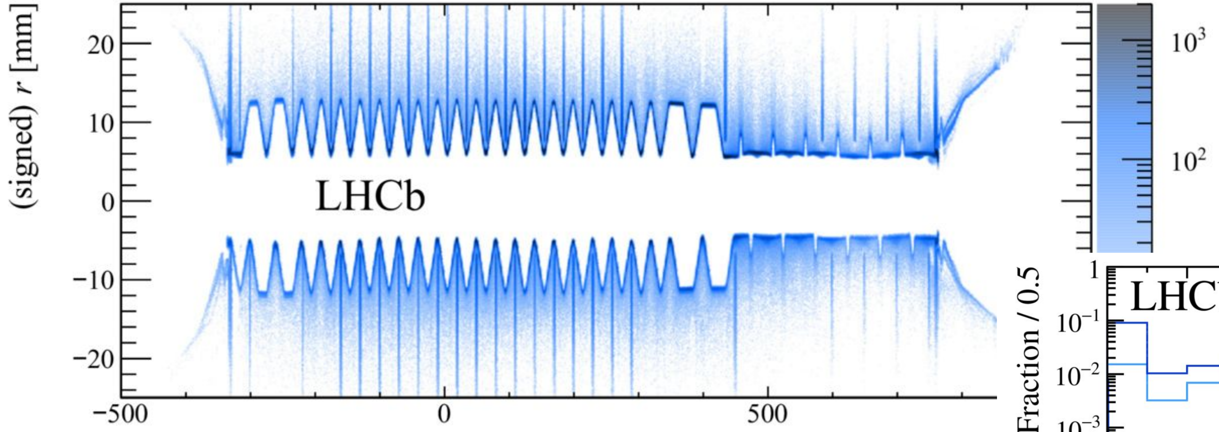



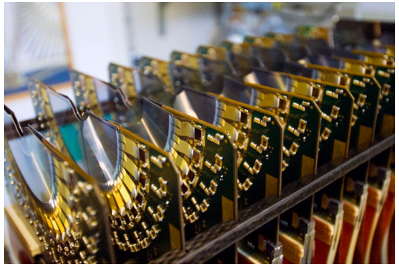



# Displaced vertices reconstruction

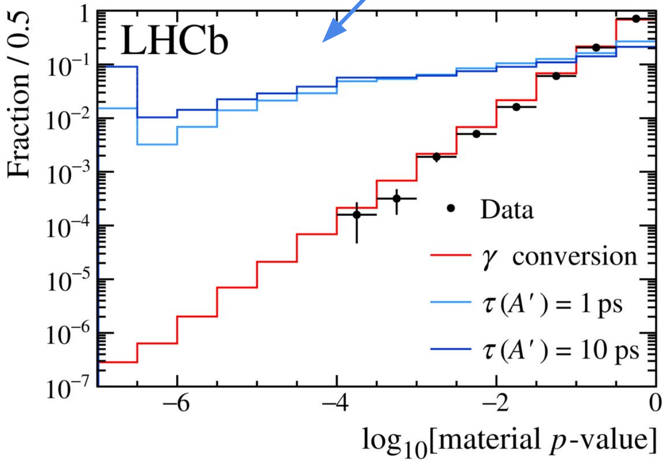
[JINST 13, P06008 (2018)]

**Displaced vertices** are mimicked by instrumental background are particle interactions with VELO material ...using data-driven method for determining a p-value for the SV-from-material hypothesis



dark-photon distributions



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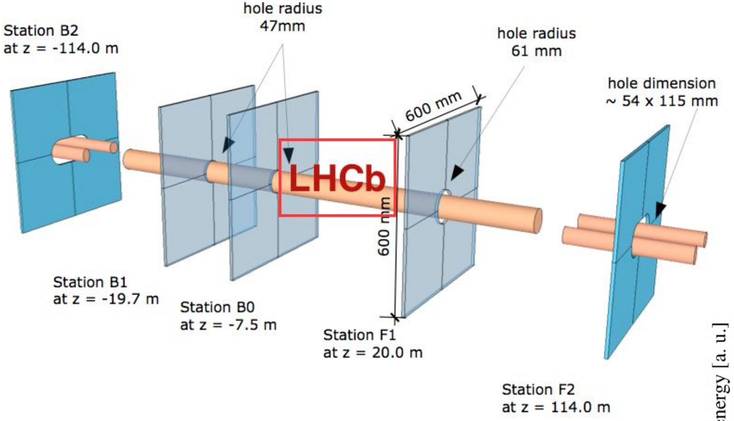
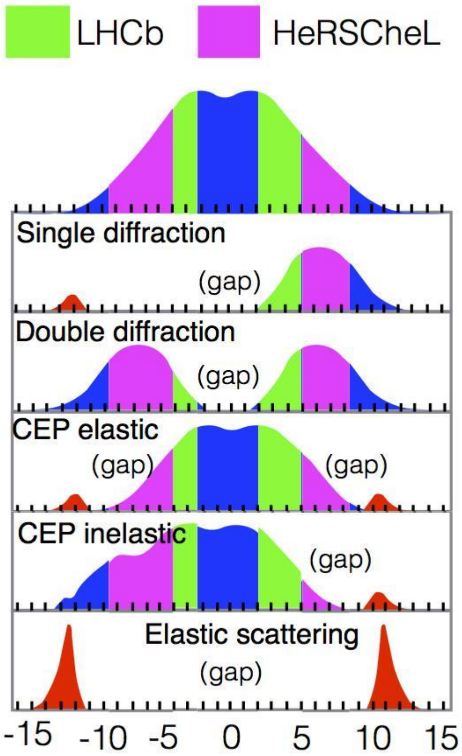
# Forward showering - Herschel

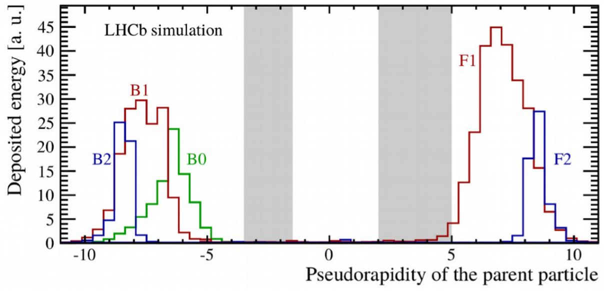
[JINST 13 (2018) no.04, P04017]

**H**igh **R**apidity **S**hower **C**ounters for **L**HCb – HERSCHEL
- installed at the end of 2014 → increase pseudorapidity coverage
- 5 stations with 4 scintillators with PMT
- able to detect forward particle showers and veto events




**Examples**:
R. O. Coelho, et al. arXiv:2002.06027
D. Aloni, et al, Phys.Rev.Lett. 123 (2019) no.7, 071801
C. Baldenegro, et al. Phys.Lett. B795 (2019) 339-345
S. Knapen, et al. Phys.Rev.Lett. 118 (2017) no.17, 171801

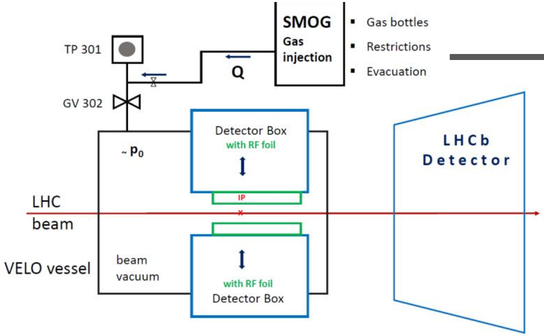


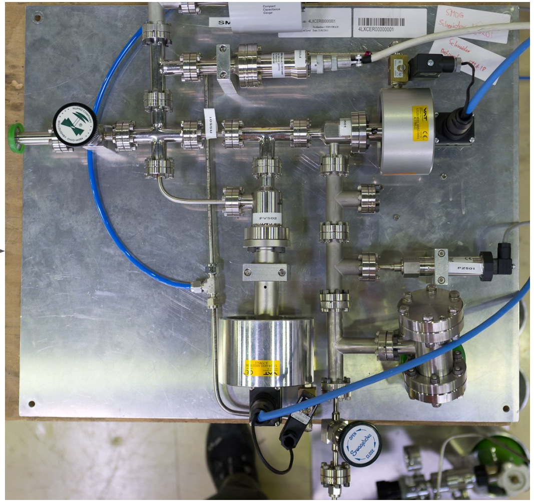
# SMOG

[PRL 121, 222001 (2018) + PRL 122, 132002 (2019)]

→LHCb is able to inject gas in the interaction region and become a fixed target experiment using SMOG device.
→6.5 TeV protons can collide with different gas
→Run 2 collected data with p(Pb) with Ne/He/Ar
→Run 3 upgrade already in place (LHCB-TDR-020)

| Gas species | He | Ne | Ar | Kr | Xe | $H_2$ | $D_2$ | $N_2$ | $O_2$ |
|---|---|---|---|---|---|---|---|---|---|
| $\theta_{SMOG2}$ ($10^{12}$ cm$^{-2}$) | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 |
| Intensity ($10^{15}$ particles/s) | 5.80 | 2.58 | 1.82 | 1.36 | 1.01 | 4.08 | 2.89 | 1.09 | 1.03 |
| Flow rate ($10^{-5}$ mbar l/s) | 21.4 | 9.6 | 6.8 | 4.68 | 3.75 | 15.02 | 10.07 | 4.05 | 3.83 |
| $\theta_{SMOG}$ ($10^{12}$ cm$^{-2}$) | 0.92 | 0.41 | 0.29 | 0.20 | 0.16 | 1.30 | 0.92 | 0.35 | 0.33 |
| $\theta_{SMOG2}/\theta_{SMOG}$ | 10.9 | 24.4 | 34.5 | 25.0 | 31.3 | 7.7 | 10.9 | 28.6 | 30.3 |





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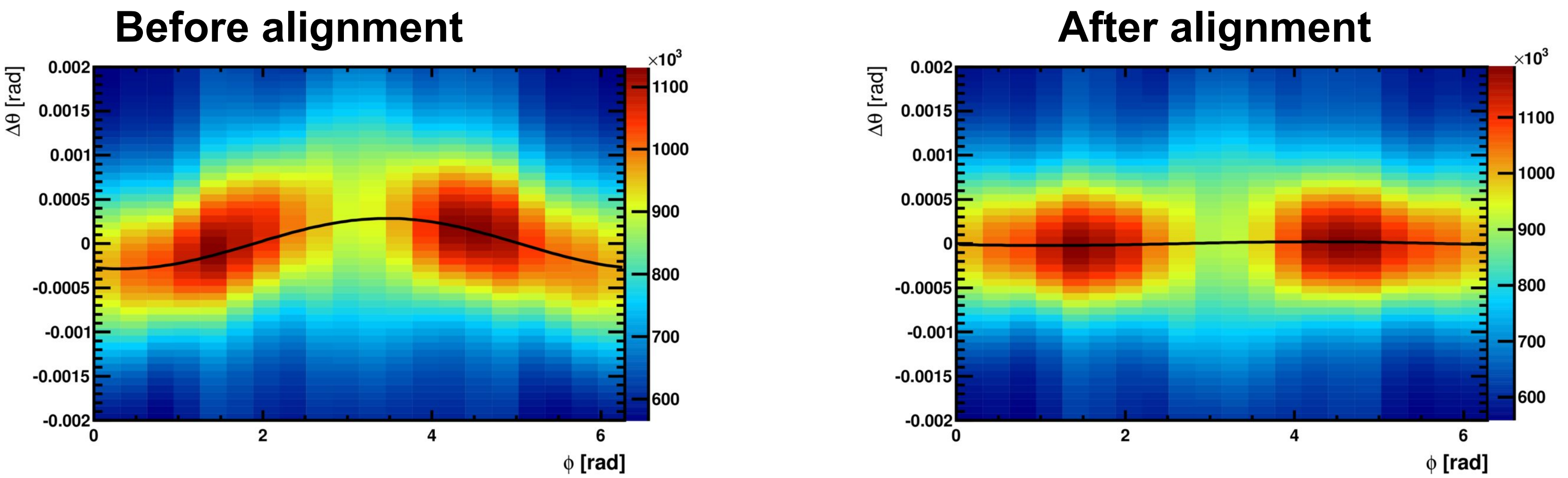
# Alignment and Calibration

[Int. J. Mod. Phys. A 30, 1530022 (2015) + JINST 14 (2019) P04013]

**In Run 2,** alignment and calibration parameters were calculated in real-time
...guarantee stability of the detector performance that may vary due to temperature, pressure, magnetic field change, mechanical intervention, ….
...same performance online and offline
...efficiency of trigger selection

## Rich2



# Alignment and Calibration

[Int. J. Mod. Phys. A 30, 1530022 (2015) + JINST 14 (2019) P04013]

**In Run 2,** alignment and calibration parameters were calculated in real-time
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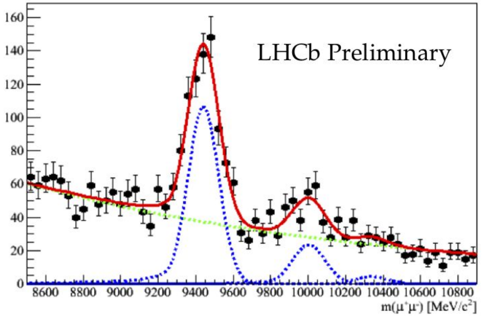
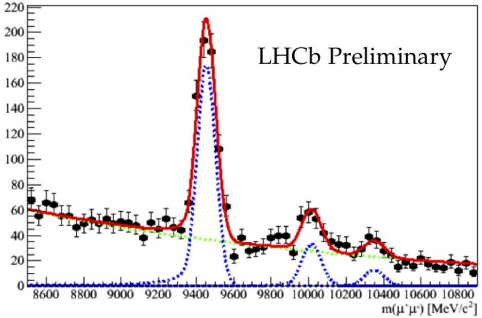
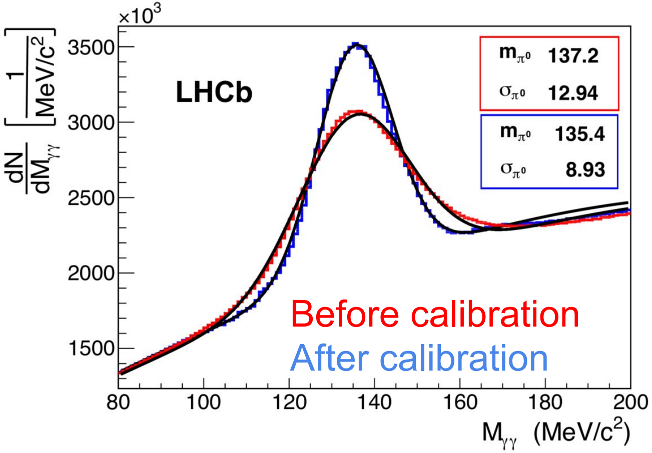



**~50% improvement in mass resolution**



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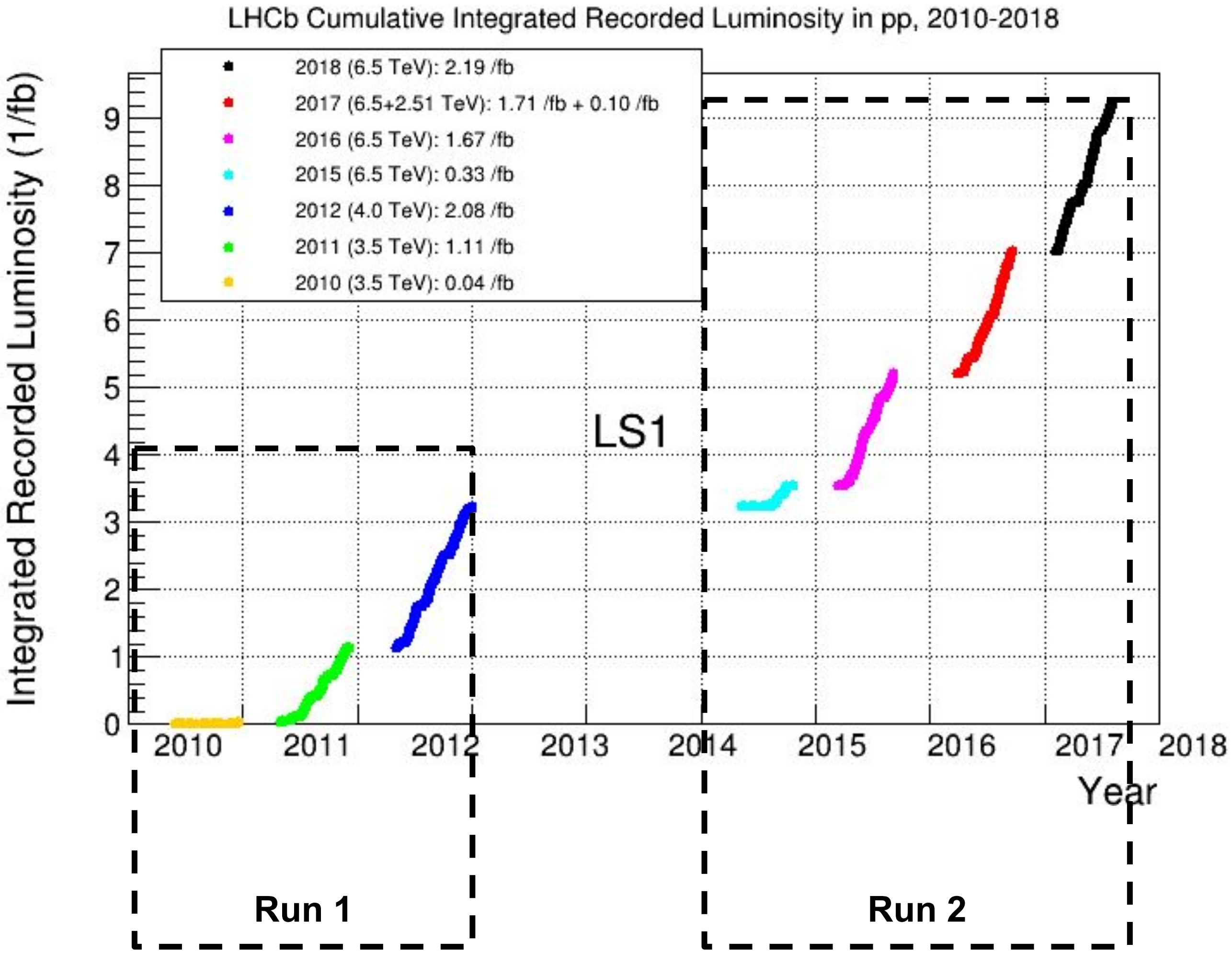
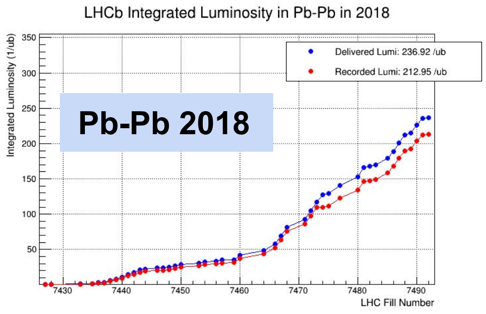
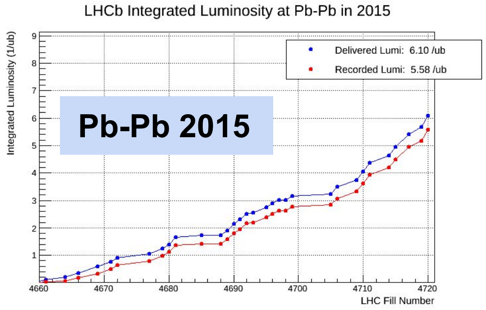
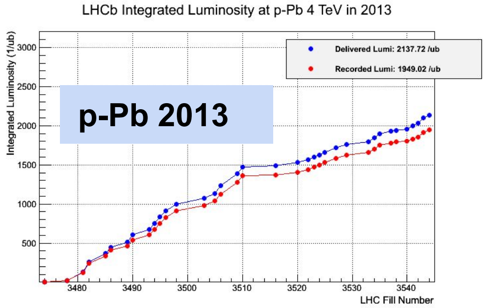

LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2018
2018 (6.5 TeV): 2.19 /fb
2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
Integrated Recorded Luminosity (1/fb)
Year
LS1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

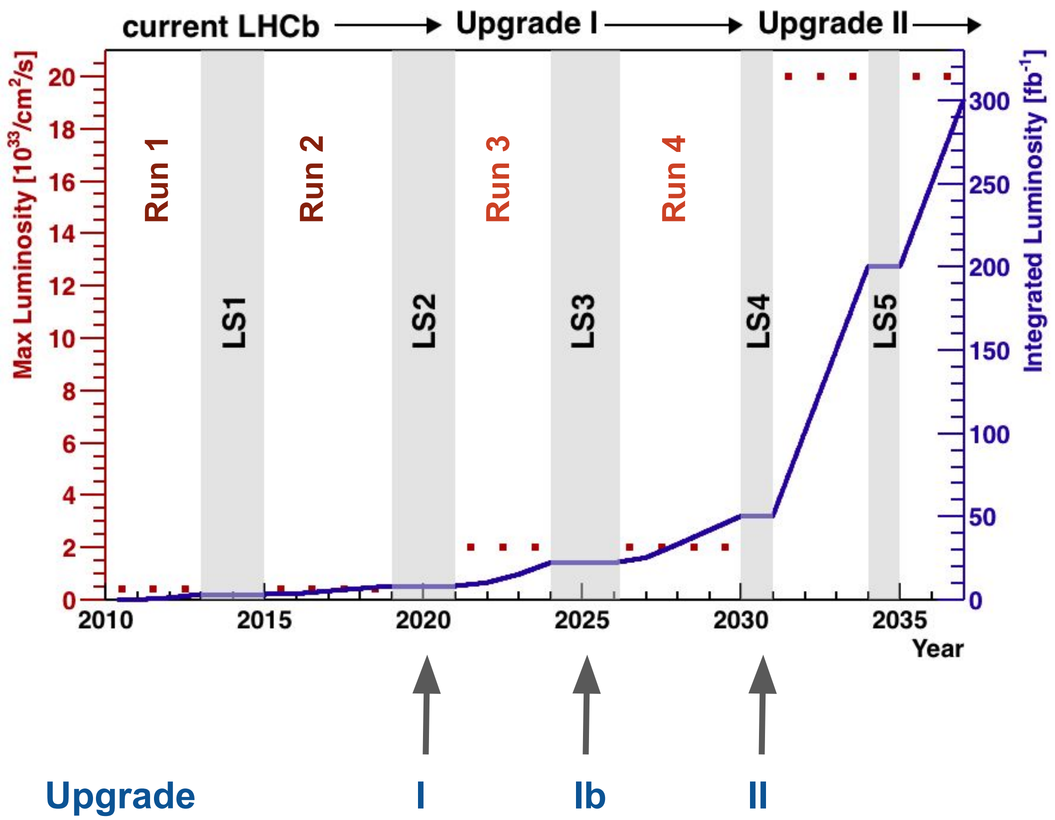

LHCb Integrated Luminosity in Pb-Pb in 2018
Delivered Lumi: 236.92 /ub
Recorded Lumi: 212.95 /ub
Pb-Pb 2018
Integrated Luminosity (1/ub)
LHC Fill Number


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

# LHCb Upgrade

arXiv:1808.08865 [hep-ex]




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

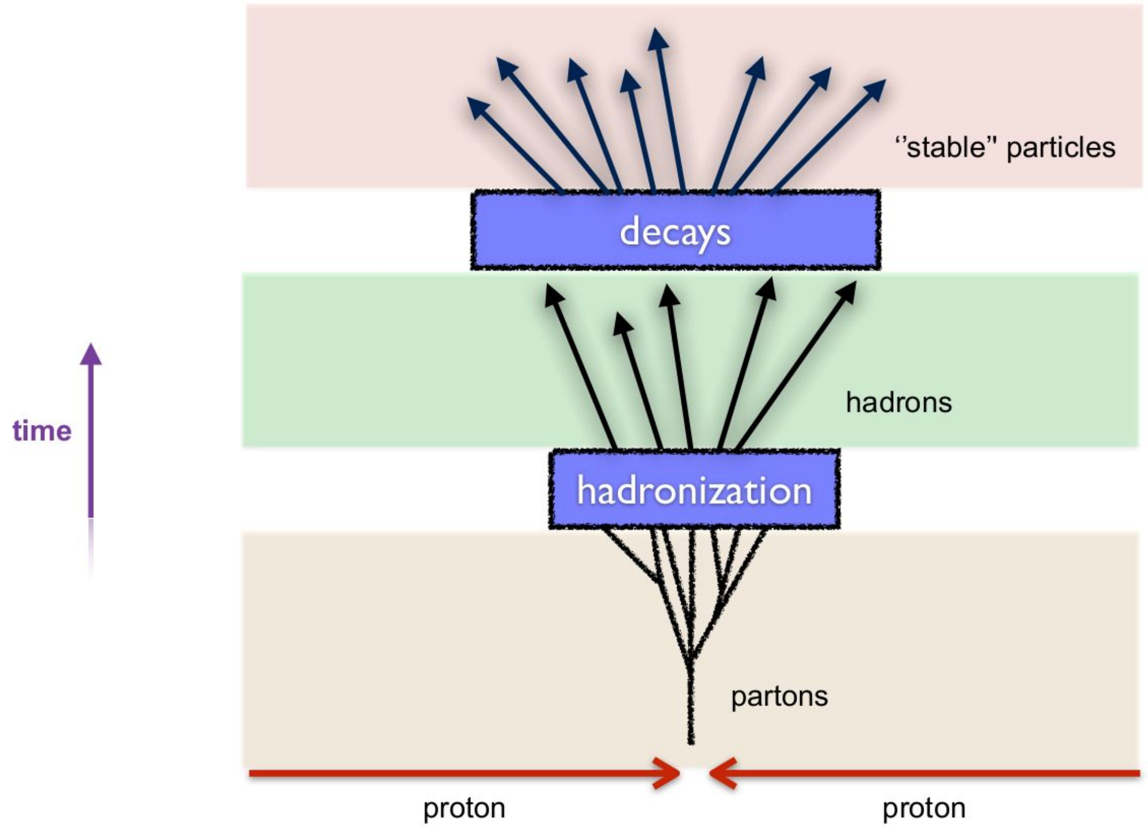
# Summary

★ Brief review of the LHCb reconstruction and PID

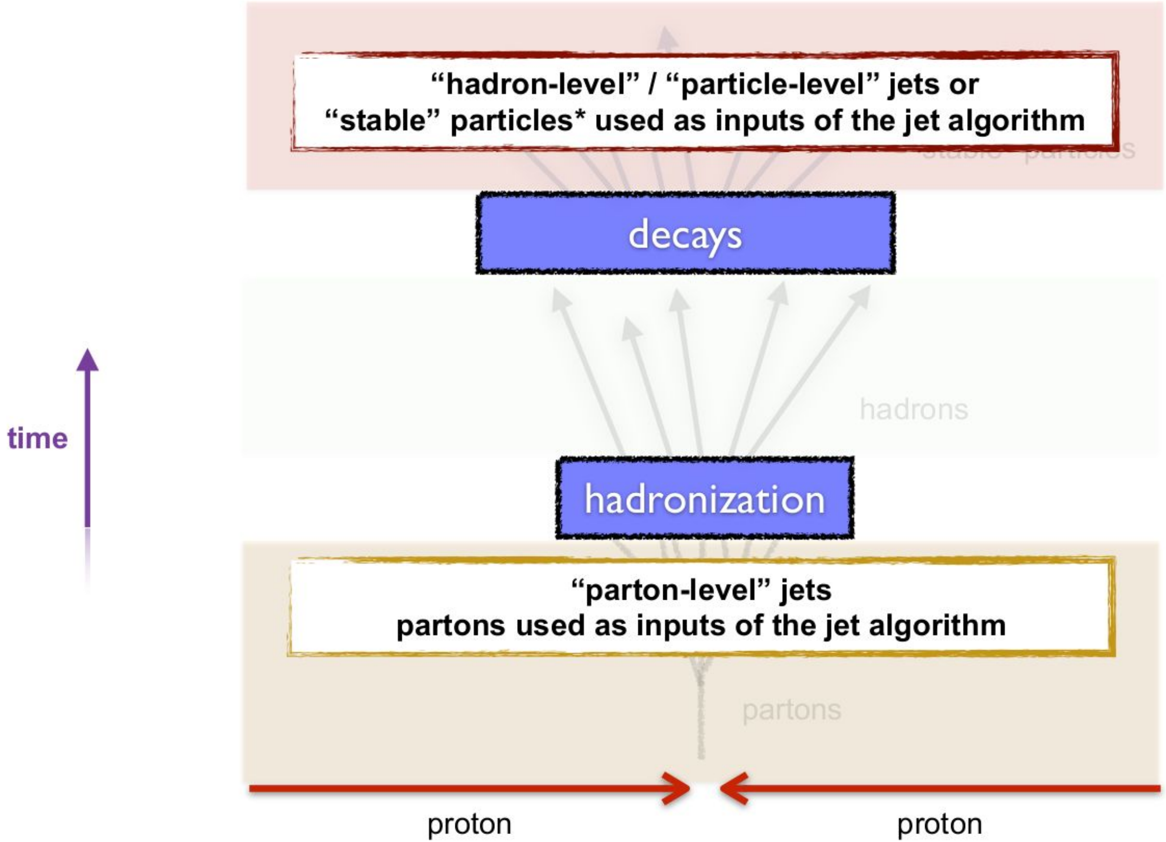
★ Analyses explore the unique LHCb capabilities for
. separating primary, secondary and tertiary vertices with excellent resolution
. triggering on soft particles

↠ Future and other related results can be found here

# THANK YOU



"stable" particles
decays
hadrons
time
hadronization
partons
proton
proton




*Neutrinos are excluded

+ Algorithms that combine nearest particles

- Cambridge/Aachen algorithm: combine particles nearest each other
- "kT" algorithm: preference for combining lower-momentum particle pairs first, then moving on to higher-momentum pairs
- "anti-kt" algorithm collects particles around the hardest particle first. It guarantees "cone-like geometry" with well-defined borders around the highest-$k_T$ particles and it maintains the infrared safety and collinear safety of sequential recombination family

+ These algorithms correspond to *p*=0, *p*=1 and *p*=-1.

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$

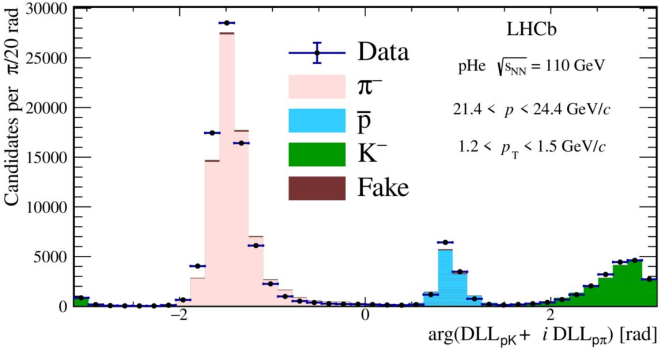
LHC experiments use largely the **FastJet** package.

1. **FastJet User Manual**
Matteo Cacciari (Paris, LPTHE & Diderot U., Paris), Gavin P. Salam (CERN & Princeton U. & Paris, LPTHE), Gregory Soyez (Saclay, SPhT). Nov 2011. 69 pp.
Published in **Eur.Phys.J. C72 (2012) 1896**
CERN-PH-TH-2011-297
DOI: 10.1140/epjc/s10052-012-1896-2
e-Print: **arXiv:1111.6097 [hep-ph] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service
Detailed record - Cited by 3166 records 1000+

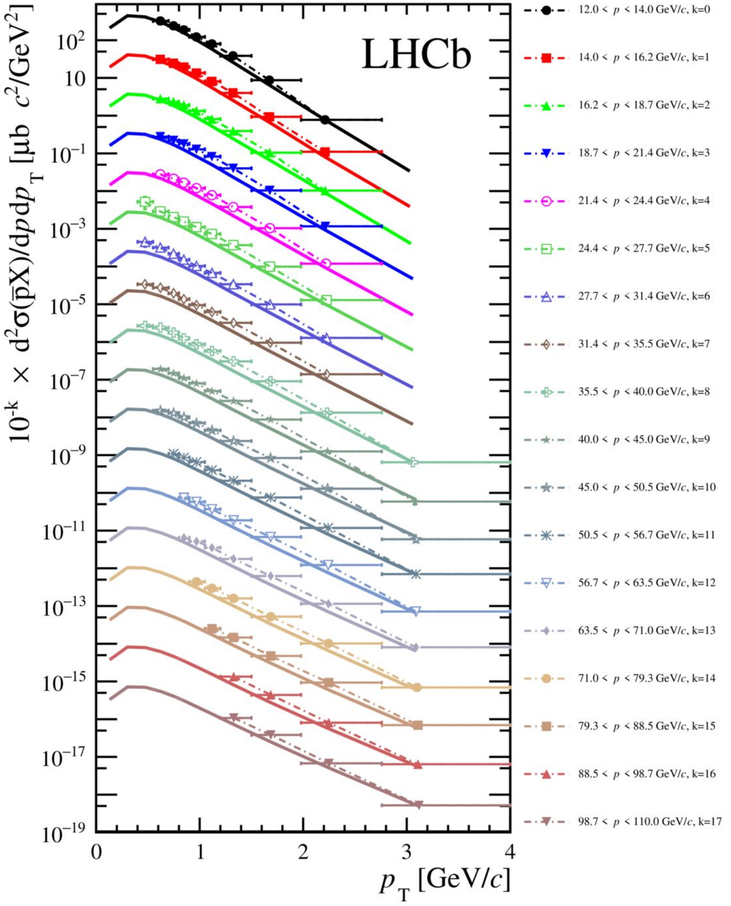
# Antiproton production in pHe collisions

PRL 121, 222001 (2018)

33.7 million reconstructed pHe collisions for about 1.4 million antiprotons

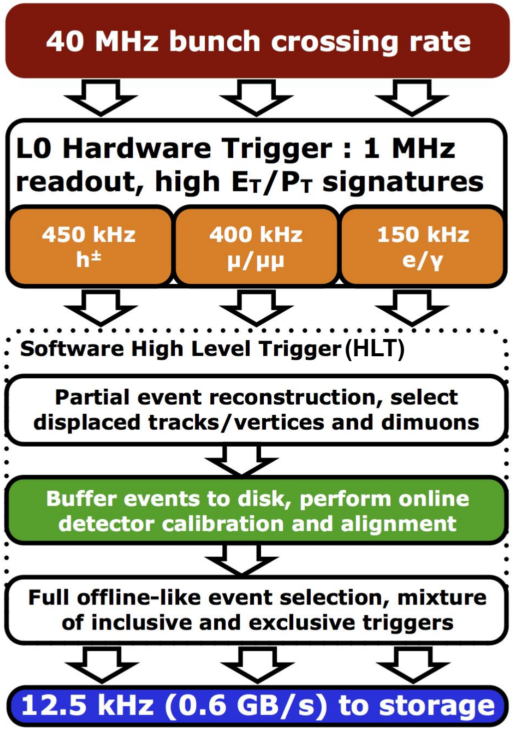



→ First measurement of antiproton production in p-He collisions
→ Significant excess of anti-proton production over the EPOS
→ Measured range of the antiproton kinematic spectrum are crucial for interpreting the precise anti-proton cosmic ray measurements from the PAMELA and AMS-02 experiments by improving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



# Run 2 trigger

LHCb Run II Trigger Diagram (2015 - 2019)



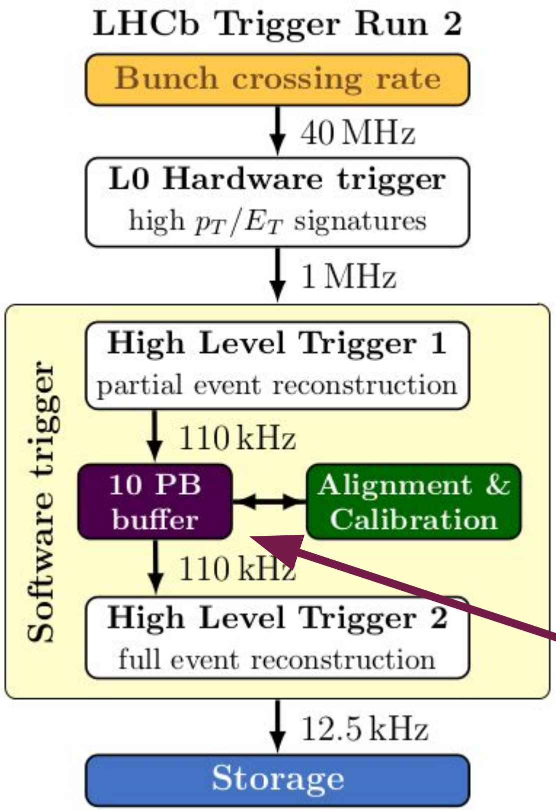

JINST 14 (2019) no.04, P04013

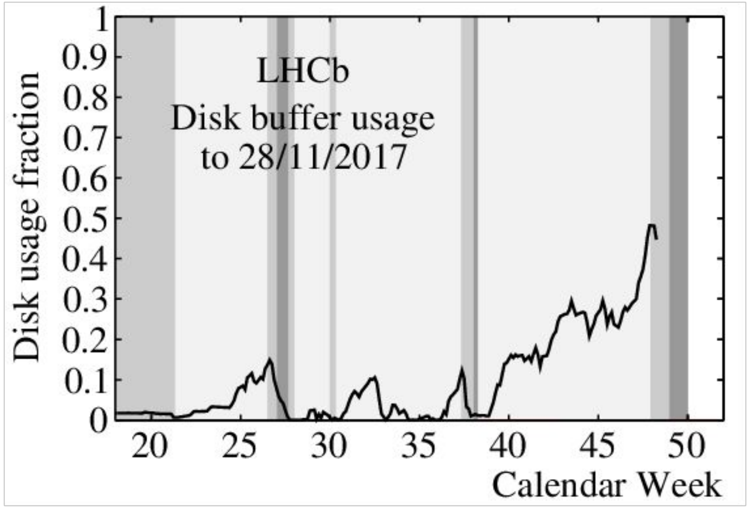
**Trigger structure**:

- 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

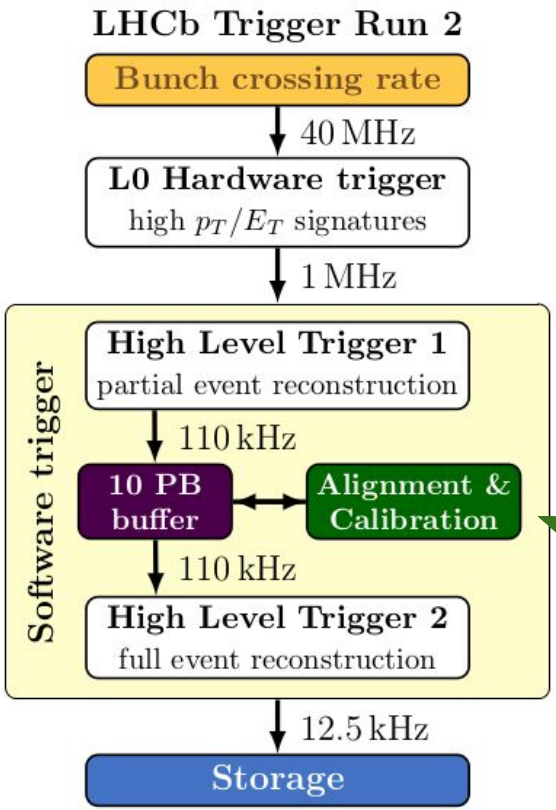


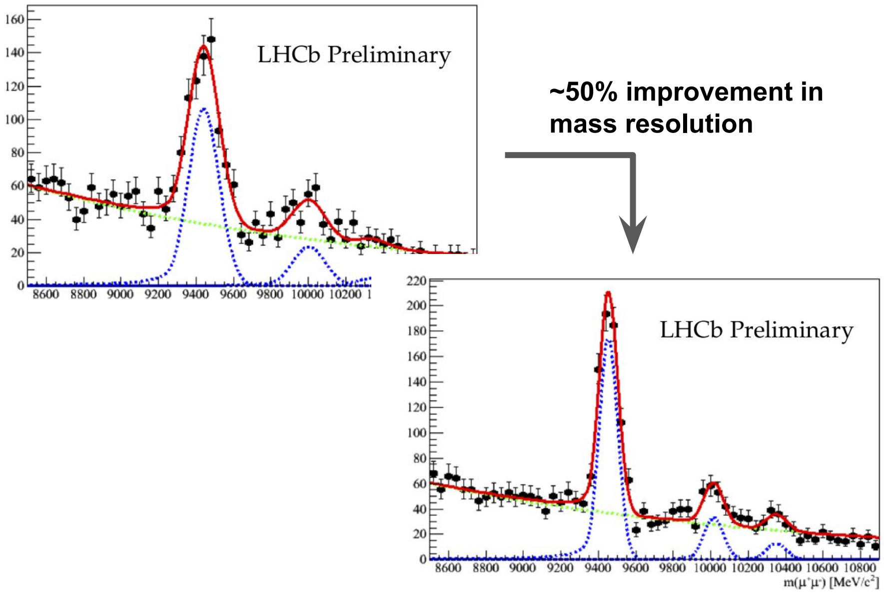

♯ HLT Farm with 10 PB disk space
♯ At an average event size of 55 kB with 100 kHz: up to 2 weeks before HLT2 has to be executed
♯ 2x trigger CPU capacity since Farm is used twice for HLT (excess used for simulation)

JINST 14 (2019) no.04, P04013

# Run 2 trigger




JINST 14 (2019) no.04, P04013

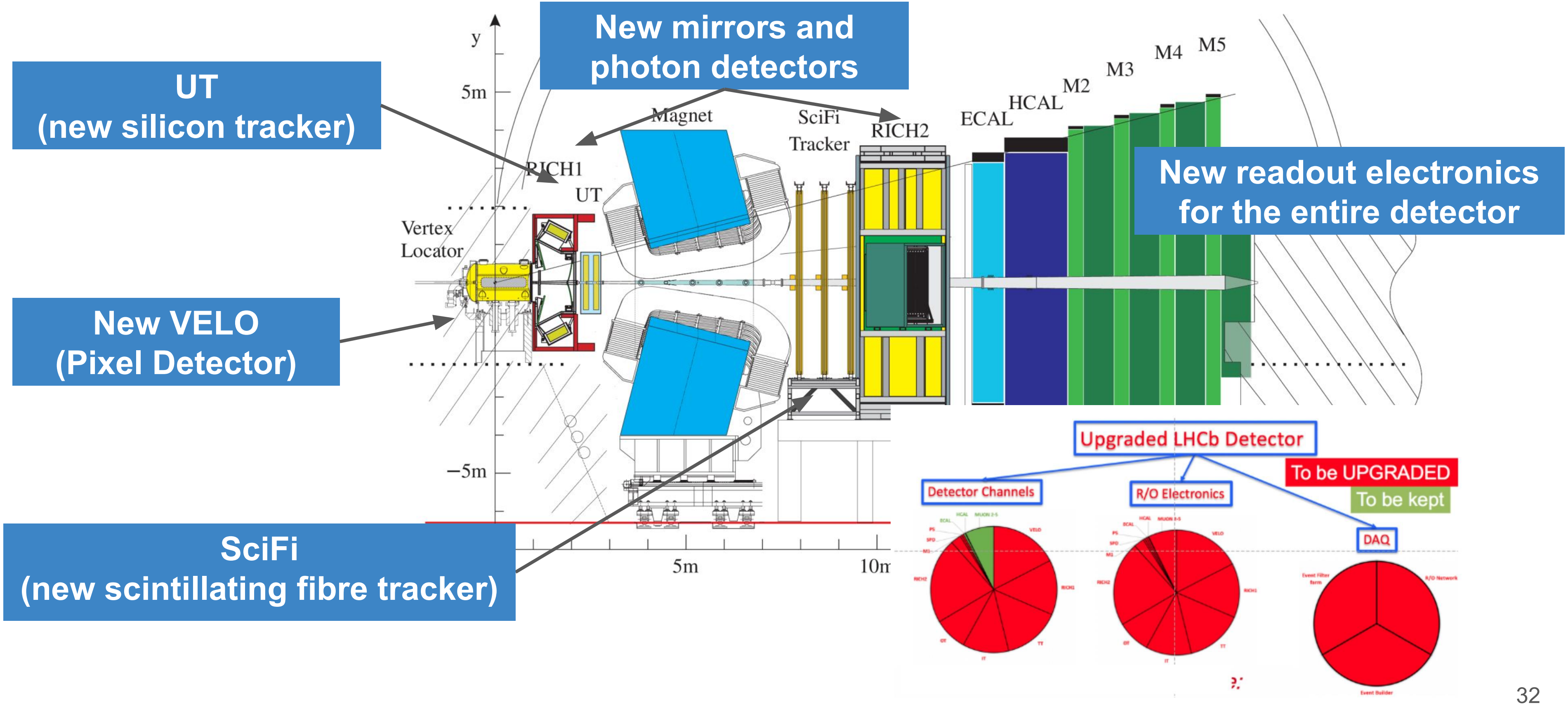



**~50% improvement in mass resolution**

♯ 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

# LHCb Upgrade

CERN-LHCC-2012-007

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# LHCb Trigger - Upgrade I

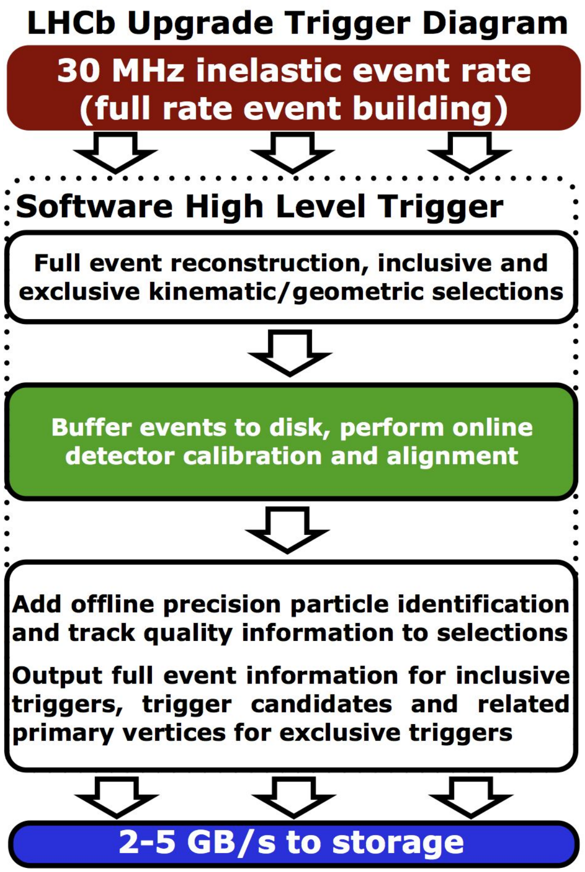
JINST 14 (2019) P04006

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




LHCb Real Time Analysis Project



Murilo Rangel

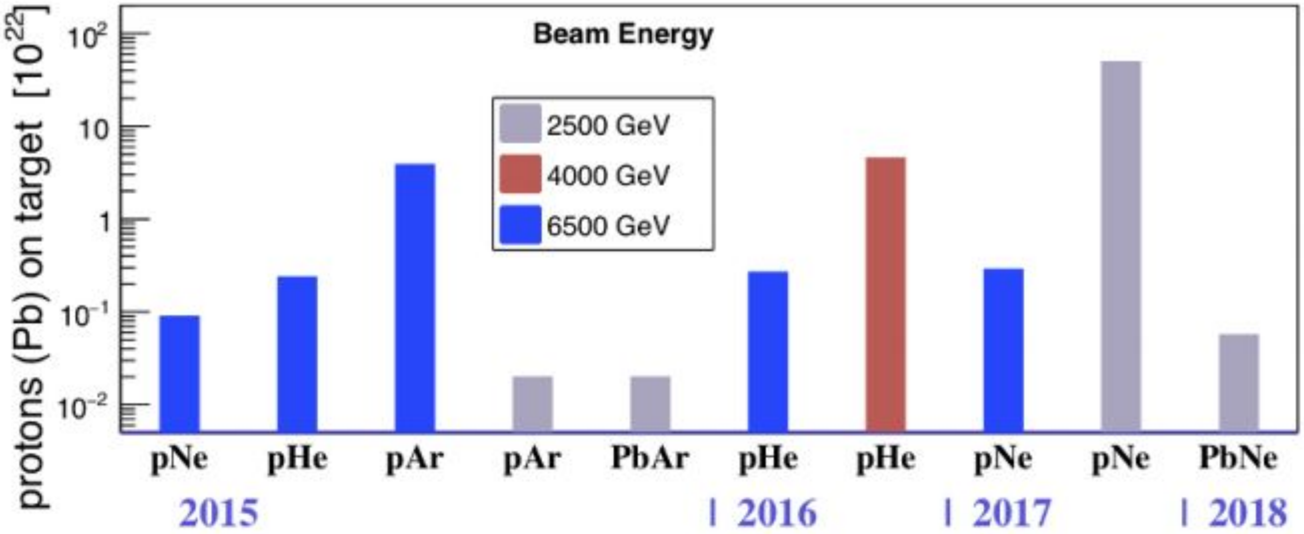
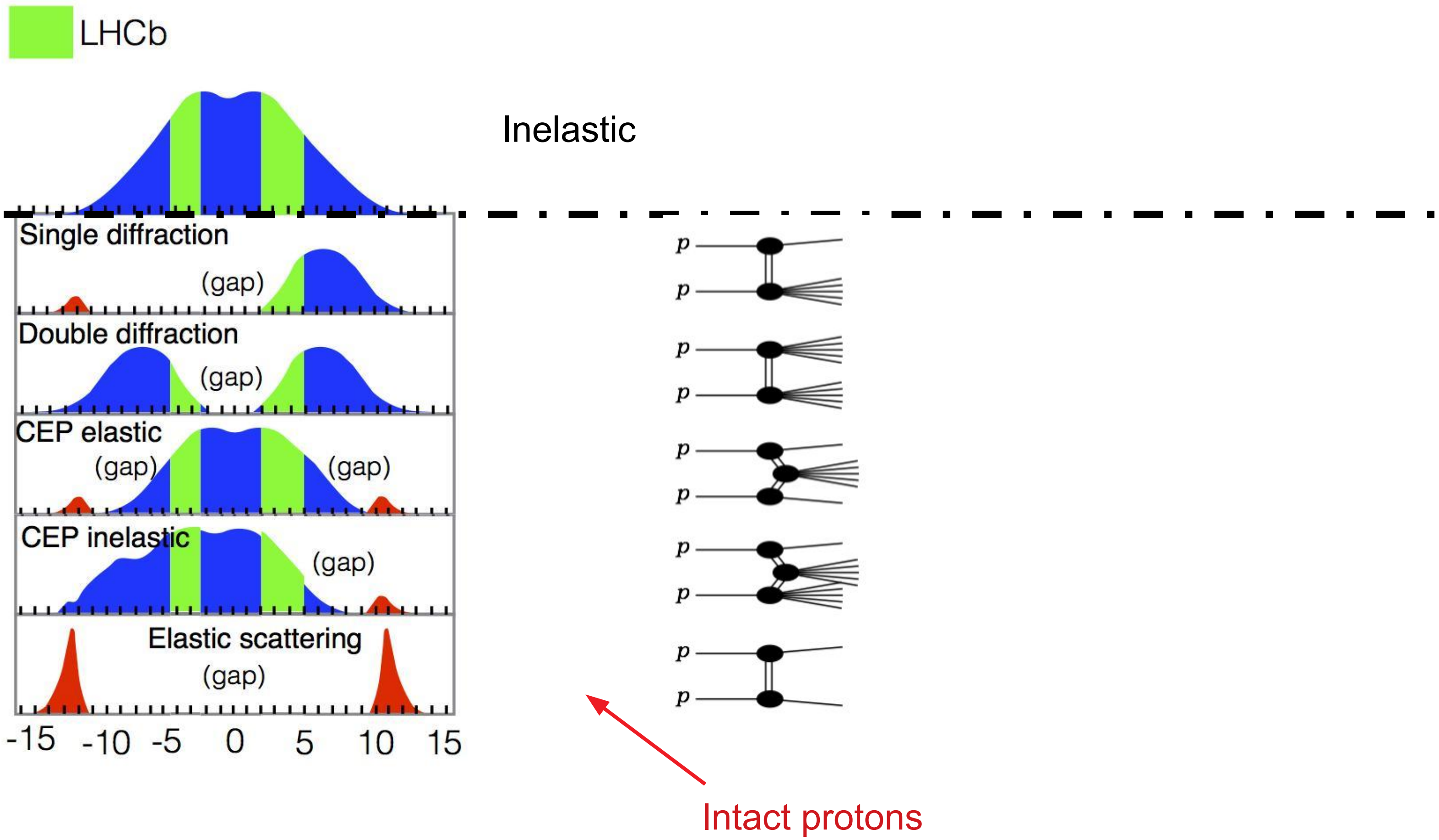
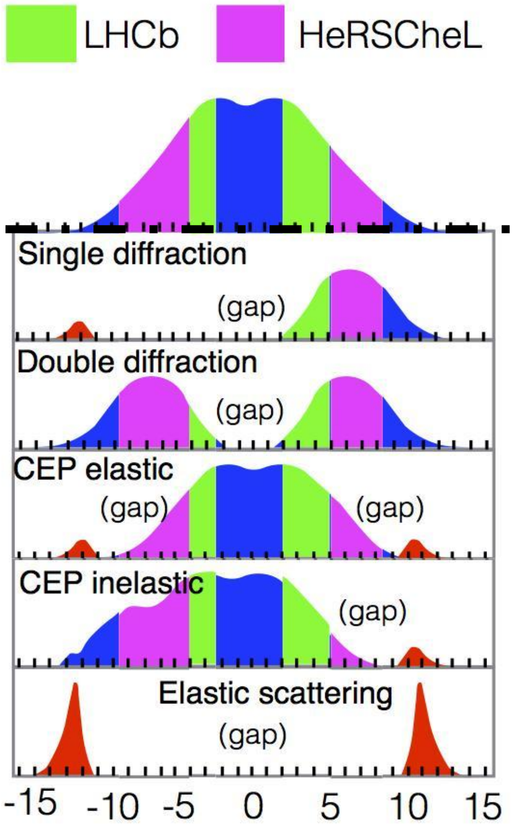


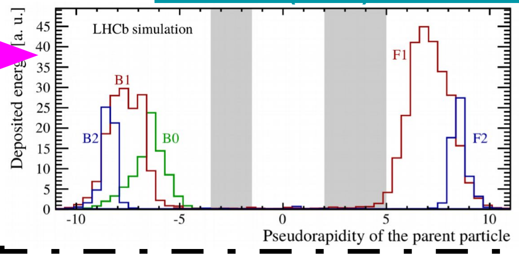

Figure 1: Dedicated SMOG runs collected since 2015. Beam-gas collisions have been recorded using different gas types (He, Ar, Ne) and beam energies.

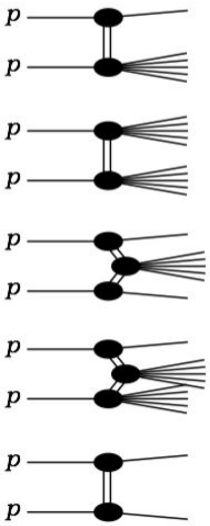

LHCb
Inelastic
Single diffraction
(gap)
Double diffraction
(gap)
CEP elastic
(gap)
(gap)
CEP inelastic
(gap)
Elastic scattering
(gap)
-15 -10 -5 0 5 10 15
p
p
Intact protons

JINST 13 (2018) no.04, P04017




Inelastic



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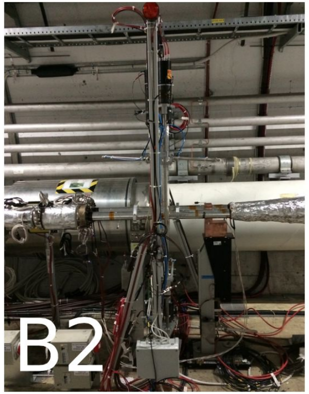
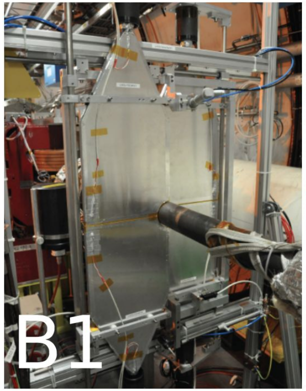
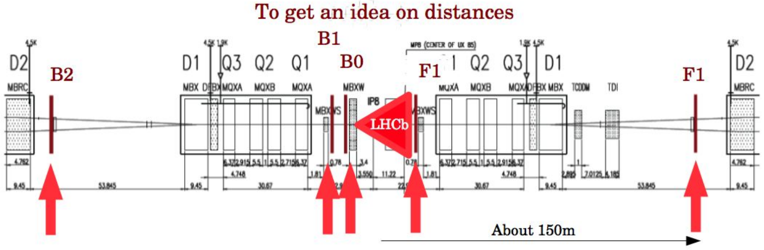
-114m -19.7m -7.5m

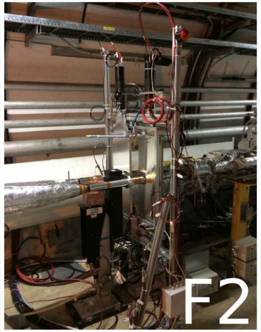


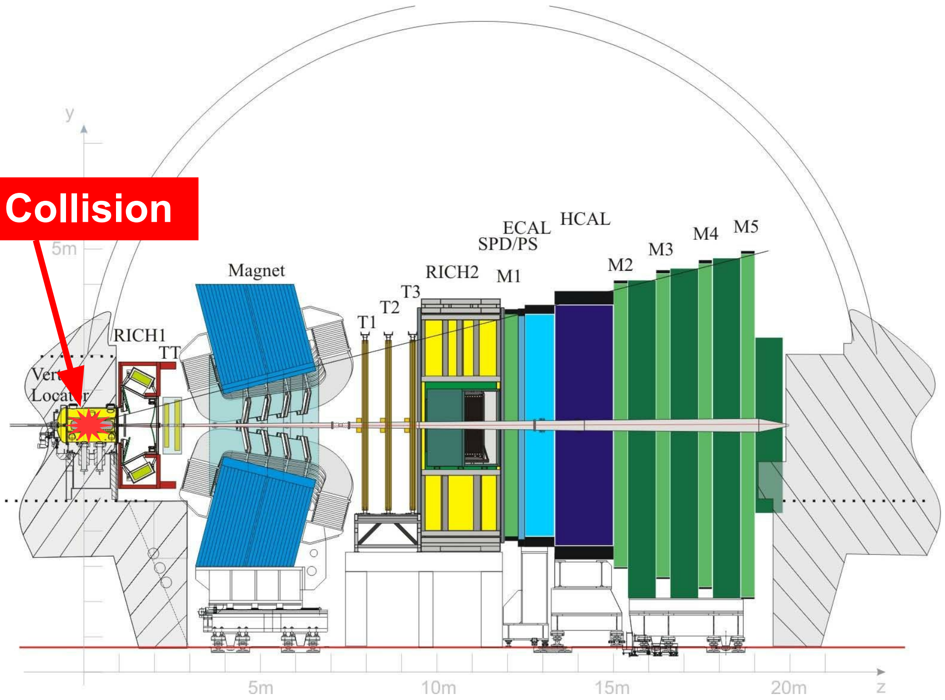




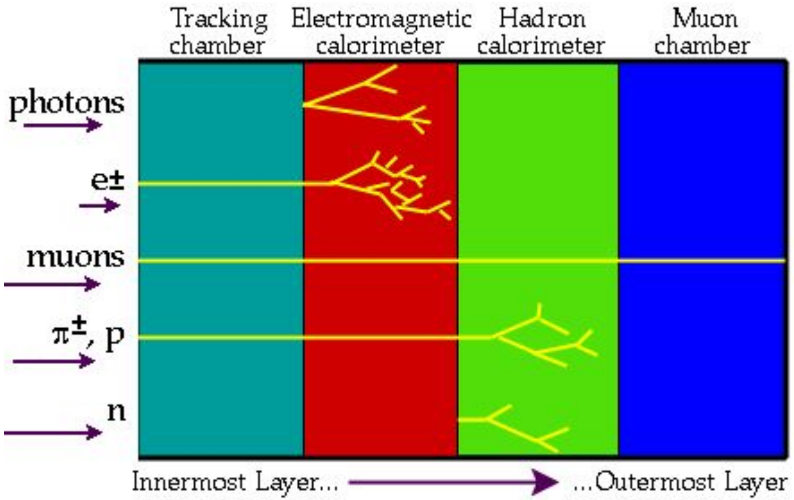

20m 114m

**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)]







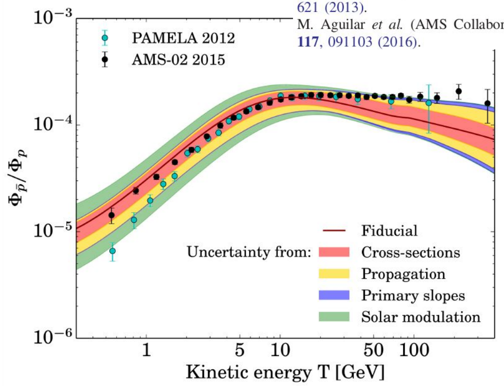

https://particleadventure.org/

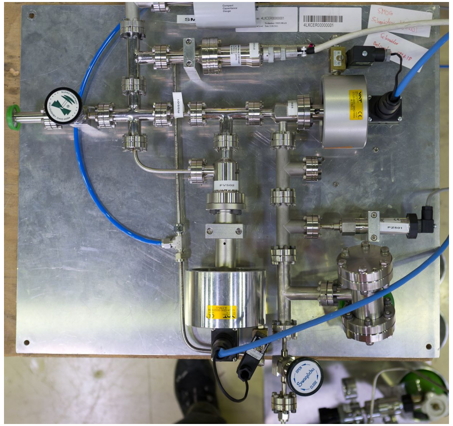
# SMOG

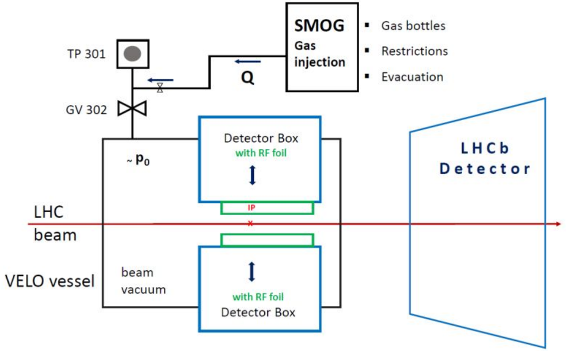
[PRL 121, 222001 (2018)]

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 SMOG device.
→6.5 TeV protons collide with He at $\sqrt{s}$ = 110.5 GeV
→0.4/nb acquired in 2016