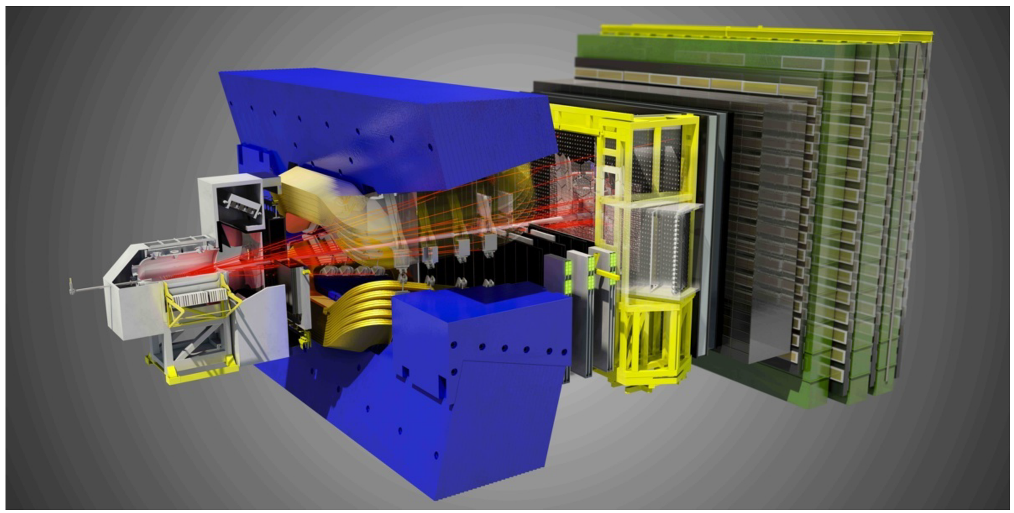
LHCb measurements at 13 TeV with online data analysis exploiting new trigger and real time alignment and calibration

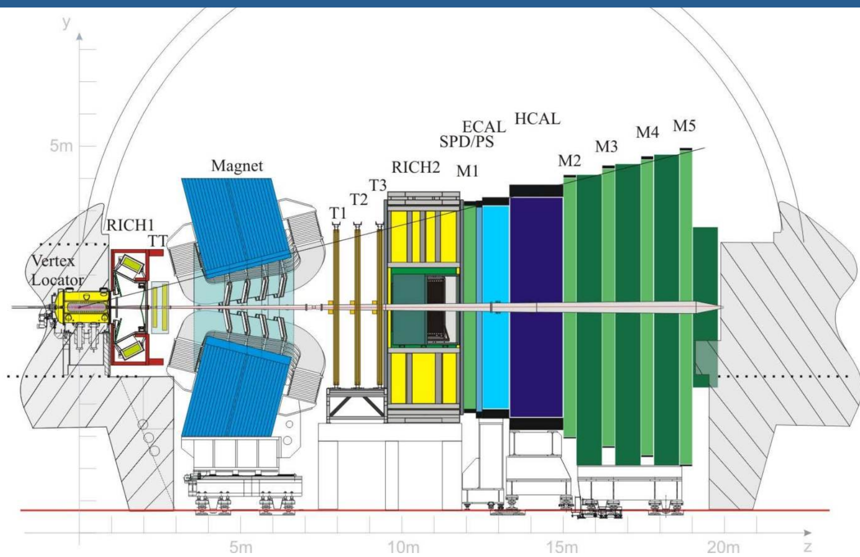


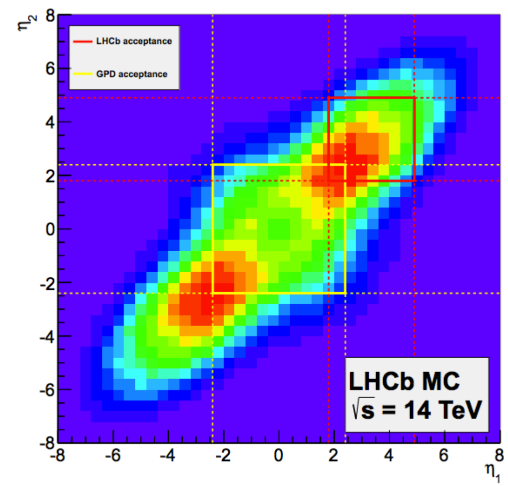
Barbara Storaci

on behalf of the LHCb Collaboration

LHC Ski 2016, April 14th 2016

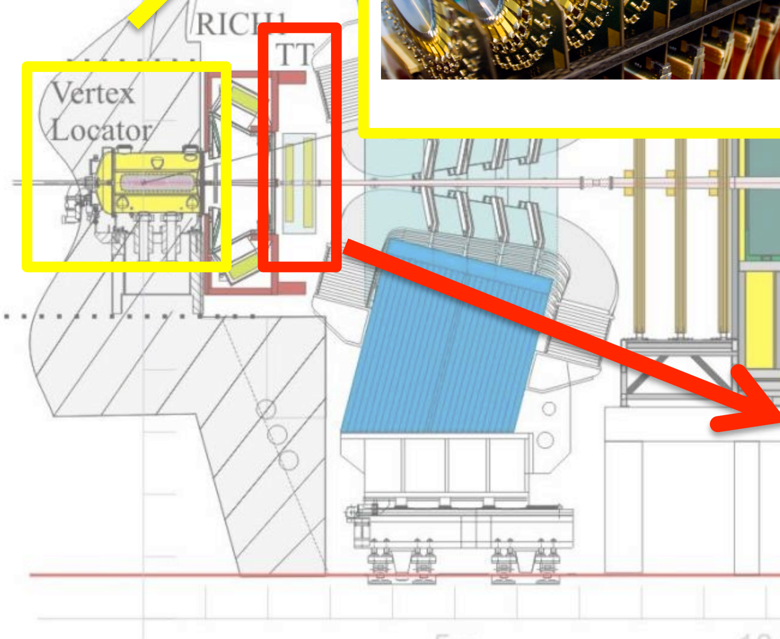
The LHCb experiment





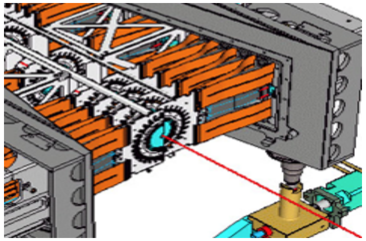
- LHCb is the dedicated heavy flavor physics experiment at LHC
- Single arm forward spectrometer, covering a pseudorapidity range unique among the LHC detectors
- Its primary goal is to look for indirect evidence of new physics in CP-violation and rare decays of beauty and charms hadrons
- This requires:
  1. Excellent tracking (momentum, impact parameters and primary vertex resolution)
  2. Excellent decay time resolution
  3. Excellent particle identification

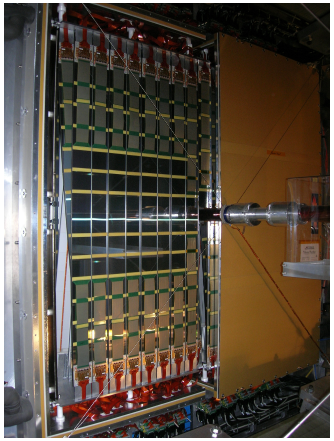
The tracking systems: before the magnet



Vertex Locator (VELO):

- 42 silicon micro-strip stations with r-Phi sensors
- 2 retractable halves, 8mm from beam
- **RunI decay time resolution: ~45fs**





Tracker Turicensis (TT):

- Four planes (0°,+5°,-5°, 0°) of silicon micro-strip sensor, total silicon area of 8m^2
- **Already sensitive to the magnetic field**

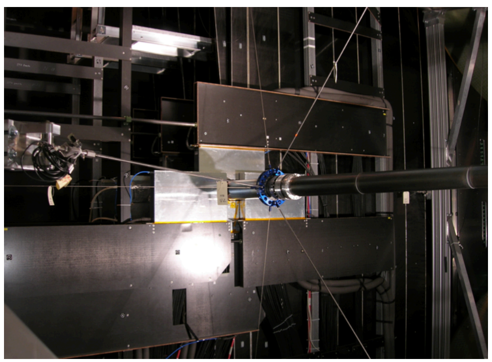
Performance of the LHCb Vertex Locator
JINST 9 (2014) 09007

LHCb Detector Performance
Int.J.Mod.Phys. A30 (2015) 1530022

The tracking systems: after the magnet

Inner Tracker (IT):

- Three stations each with four planes of silicon micro-strip sensors around the beam pipe
- Total silicon area of 4.2m^2
- The detector operate at 0^{o}C.

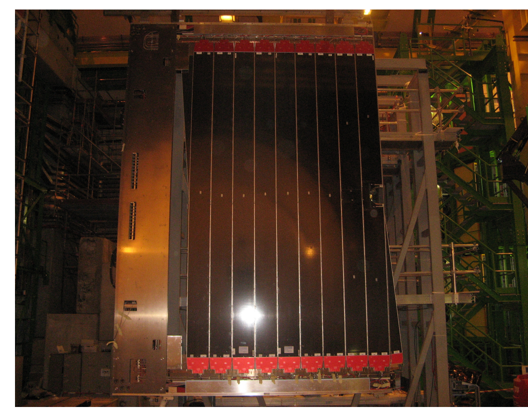


Tracking performance in Run I:

- $\Delta p/p$ = 0.5-1%
- Tracking eff. > 96%

Outer trackers (OT)

- Three stations each with four planes of straw tube
- Gas Mixture Ar/CO_2/O_2 (70/28.5/1.5)

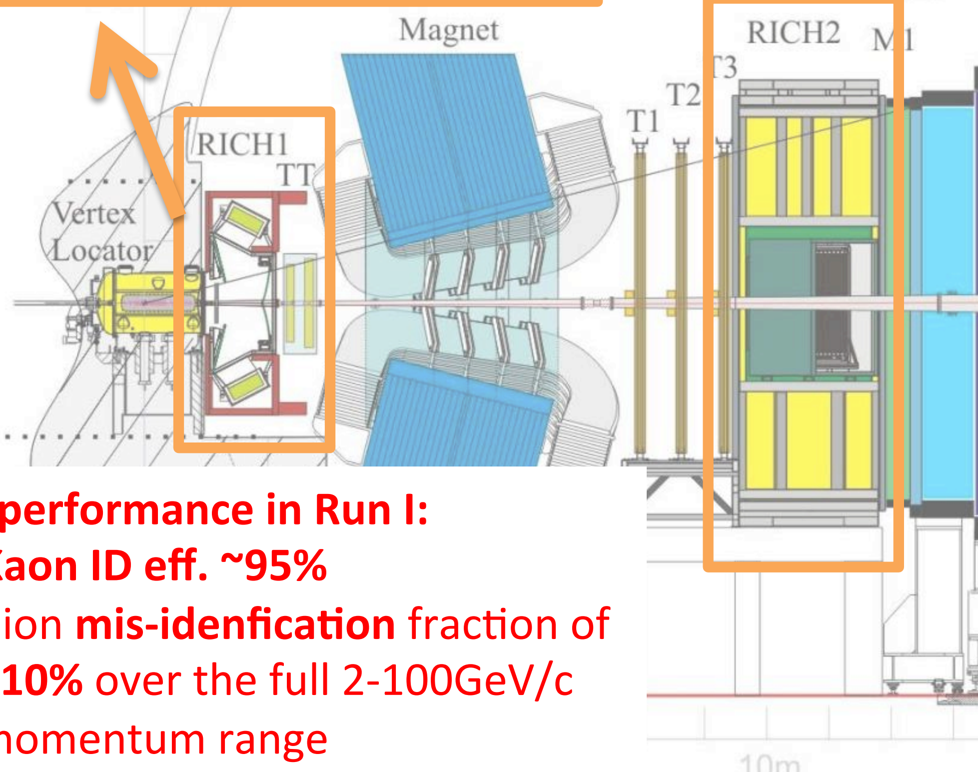


Performance of the LHCb Outer Tracker
[JINST 9 (2014) P01002]

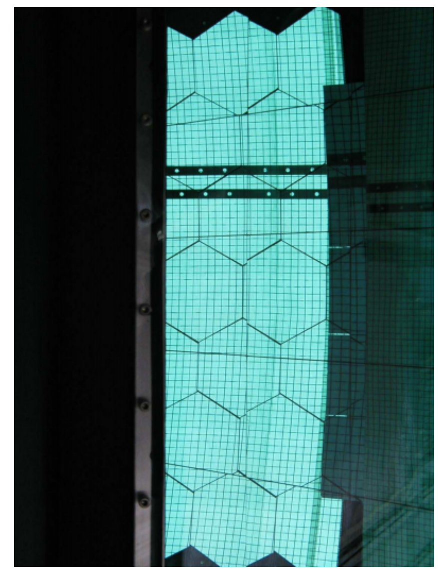
LHCb Detector Performance
[Int.J.Mod.Phys. A30 (2015) 1530022]

The PID systems: RICH detectors

- RICH1:
  - Upstream of the magnet
  - C_4F_{10} radiator
  - 2<p<40 GeV/*c*



- RICH2:
  - Downstream of the magnet
  - CF_{10} radiator
  - 15<p<100 GeV/*c*
  - 15-120 mrad



RICH2 spherical mirrors

PID performance in Run I:
- **Kaon ID eff. ~95%**
- Pion **mis-idenfication** fraction of **~10%** over the full 2-100GeV/c momentum range

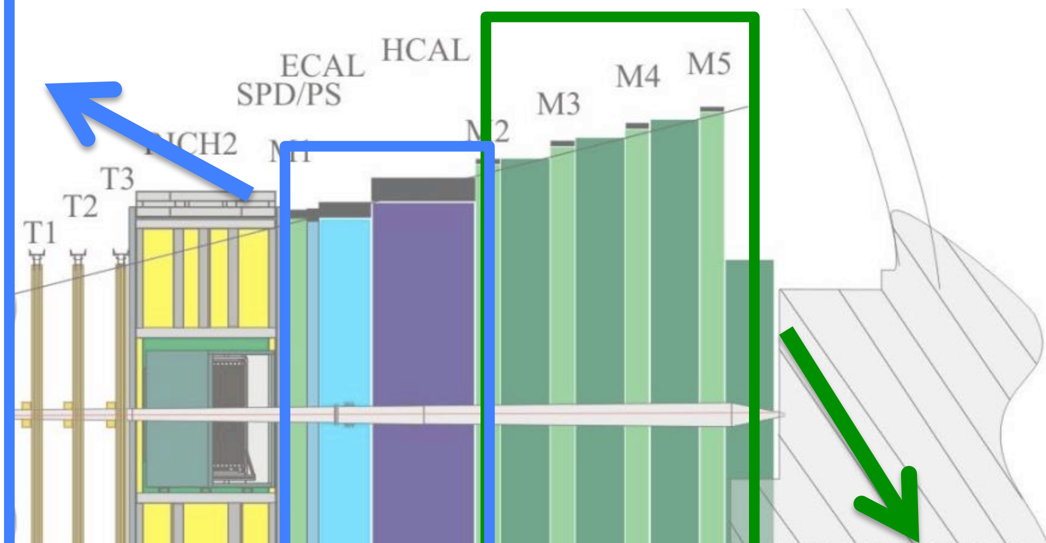
Performance of the LHCb RICH detector
[Eur.Phys.J. C73 (2013) 2431]()

LHCb Detector Performance
[Int.J.Mod.Phys. A30 (2015) 1530022]()

The trigger and PID systems

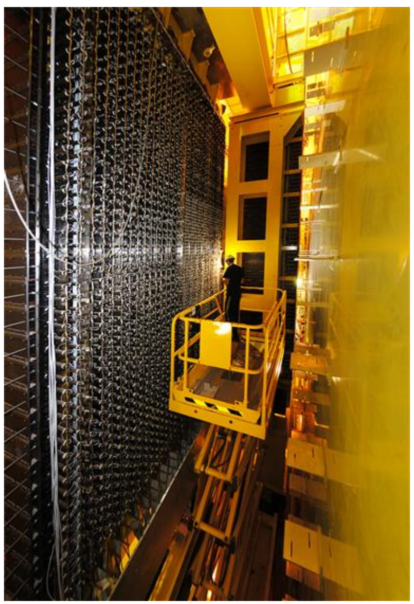
Performance of the Muon Identification system
JINST 8 (2013) P10020

Muon ID eff. In Run I ~97%



Electromagnetic and hadronic calorimenters (ECAL and HCAL)

- Scintillator planes + absorber material planes
- Used in the hardware trigger (L0) selection



Muon system

- 5 stations, each equipped with 276 multi-wire proportional chambers
- Inner part of the first station equipped with 12 GEM detectors
- Used in L0 trigger selection

LHCb Detector Performance
Int.J.Mod.Phys. A30 (2015) 1530022

Importance of the alignment (I)

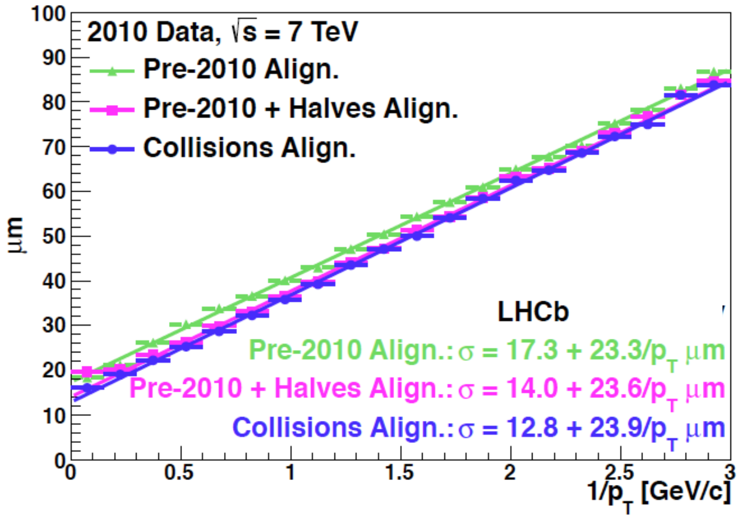
- Physics performance relies on the spatial alignment of the detector and the accurate calibration of its subcomponents:
  1. Accurate alignment of the VELO essential for primary vertices discrimination, excellent impact parameter (IP) and proper time resolution

IPx resolution vs $1/p_T$

RunI data

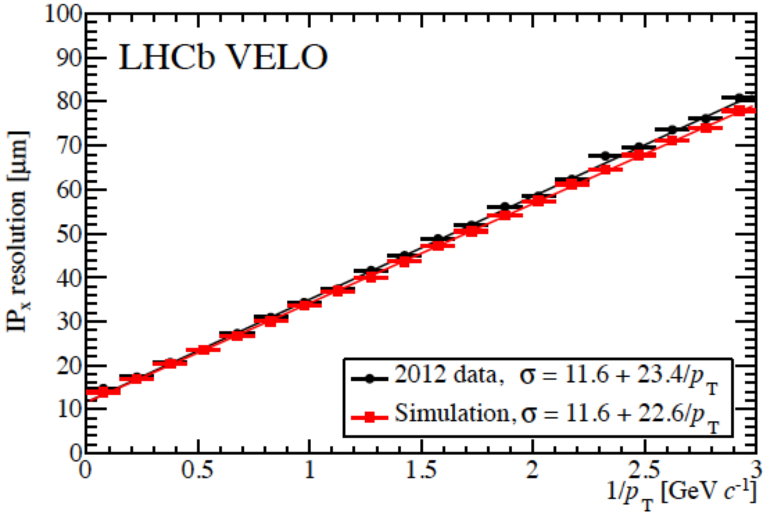
First alignment

σIP (high pT) = **14.0 µm**



Latest alignment

σIP (high pT) = **11.6 µm**



Int.J.Mod.Phys. A30 (2015) 1530022

Importance the alignment (II)

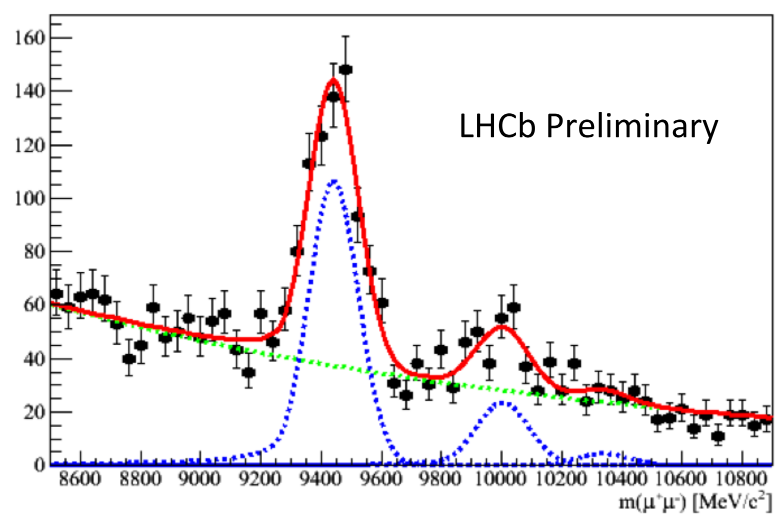
- Physics performance relies on the spatial alignment of the detector and the accurate calibration of its subcomponents:
  2. Better alignment of the tracking system improves the mass resolution

Invariant mass distribution for $\Upsilon \rightarrow \mu^+\mu^-$

RunI data

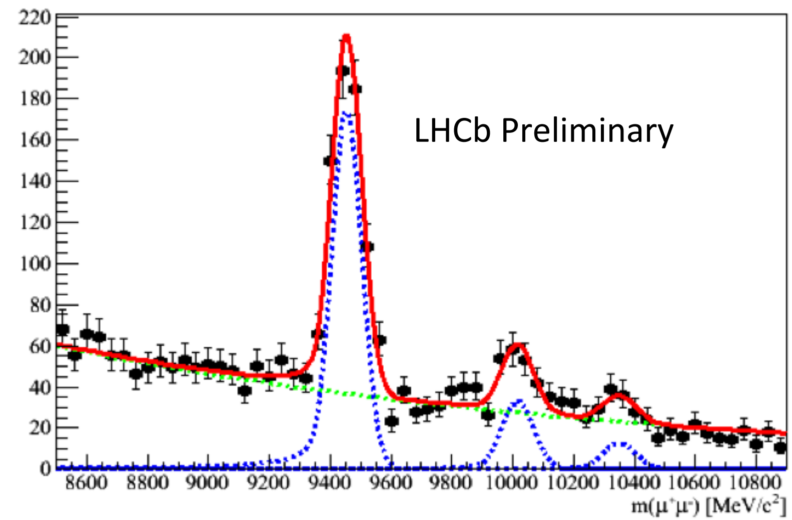
First alignment

σ_Υ = **92 MeV/c²**



Better alignment

σ_Υ = **49 MeV/c²**



Idea

Novel concept in HEP:
Being able to do physics directly on the HLT output

Advantages:

- No need of offline data processing (data available ~ immediately after HLT2 has processed them)
- Raw event size can be much smaller → possibility to reduce the pre-scaling of high branching ratio channels (like for charm physics)

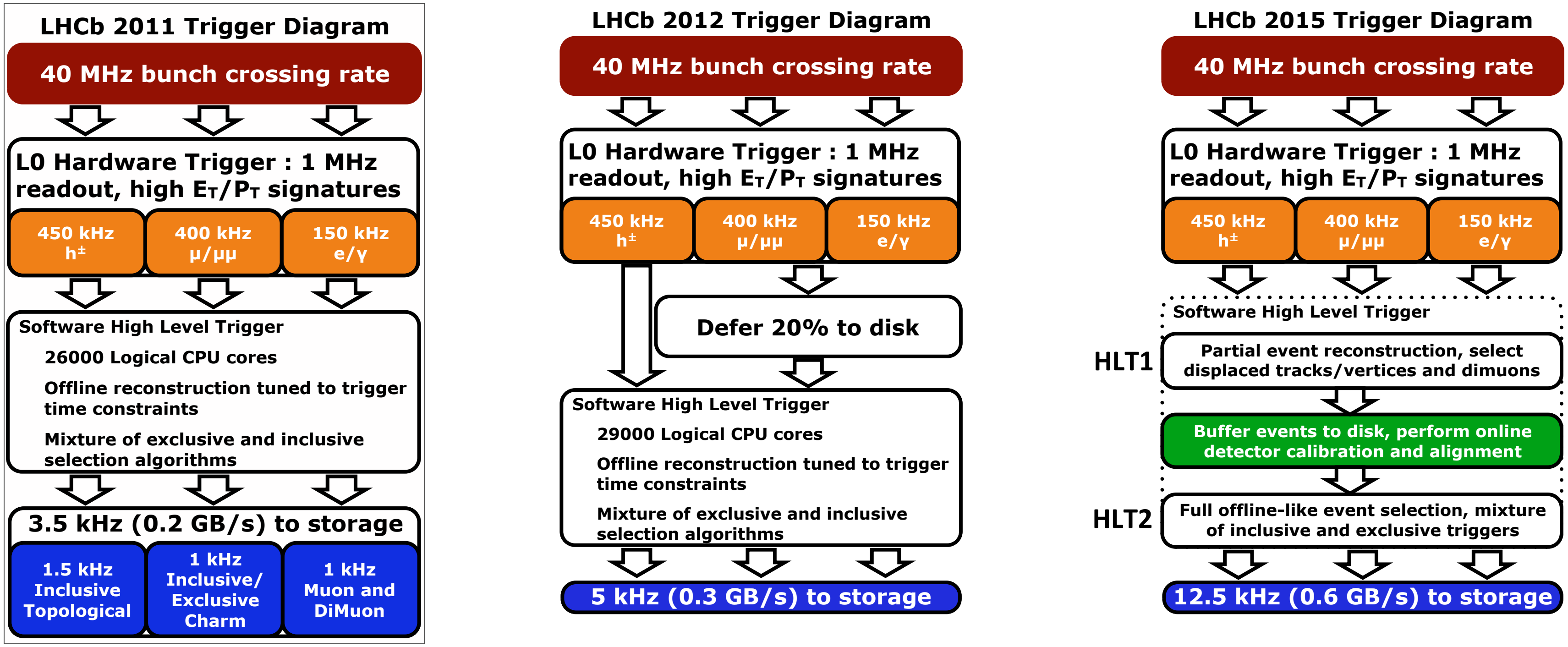
↓

Do much more physics with the given resources!

Still a difficult challenge:

- Managing to do the full reconstruction in few hundreds ms achieving offline performance (same or better than in RunI)
- Managing to do the full alignment and calibration of the detectors in real-time
- Being able to select efficiently many signals already at trigger level

Evolution of the LHCb HLT



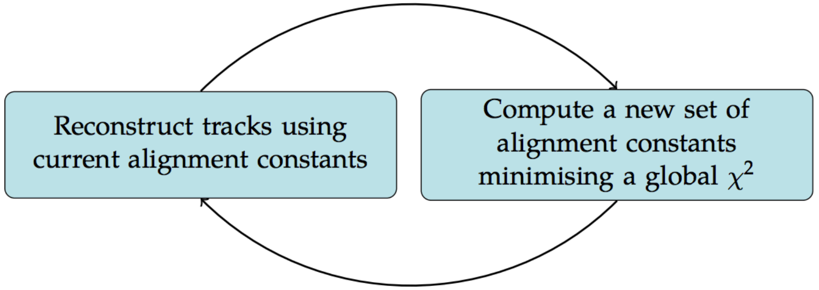
- In 2012 introduced the *deferred trigger*: keep the trigger farm busy between fills
- 2015-2016: *split trigger*
  - All 1st stage (HLT1) output stored on disk (5PB in 2015, 10PB in 2016)
  - Enough time to perform alignment and calibration tasks between HLT1 and the 2nd stage (HLT2) → HLT2 uses offline-quality calibration
  - Possible to perform physics directly at HLT level (5kHz of the 12.5 kHz to Turbo)

Alignment & calibration framework

- General Strategy
  - Automatic evaluation at regular intervals, e.g. per fill or per run depending on the task
  - Dedicated data sample to perform alignment or calibration collected with specific trigger selection line for each task
  - Compute the new alignment or calibration constants in **few minutes**
  - Update the constants only if needed
  - **The same new alignment and calibration constants will be used both by the trigger and the offline reconstruction**

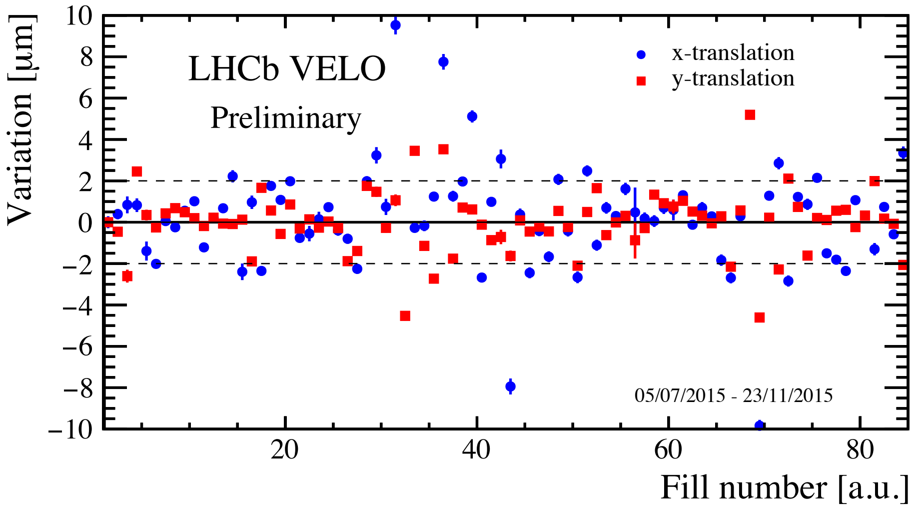
Alignment:

- Evaluation of the parameters by iterative process
  - Analyser (multiple nodes): perform reconstruction
  - Combination of output, fits/minimization -> extract constants



Iterate until χ^2 difference is below threshold

Real-time alignment performance



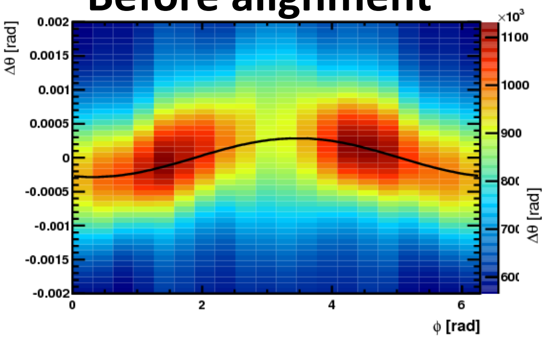
Tracking systems:

- Alignment of about **700 elements**
- Run automatically for each fill
- Time required **~7 minutes** each tasks
- Updates:
  - Each 2/3 fills for the VELO
  - After each magnet polarity switch for the tracker
  - Only after hardware intervention for the muon

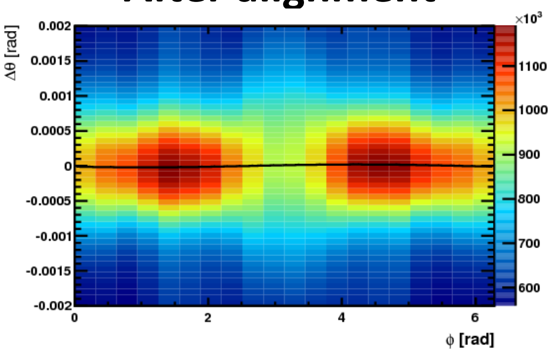
RICH systems:

- Alignment of **110 mirror pairs**
- Run as monitoring each few fills (no update expected)
- Time needed **~20min**
- RICH information can be used in HLT: fully calibrated system

Before alignment



After alignment

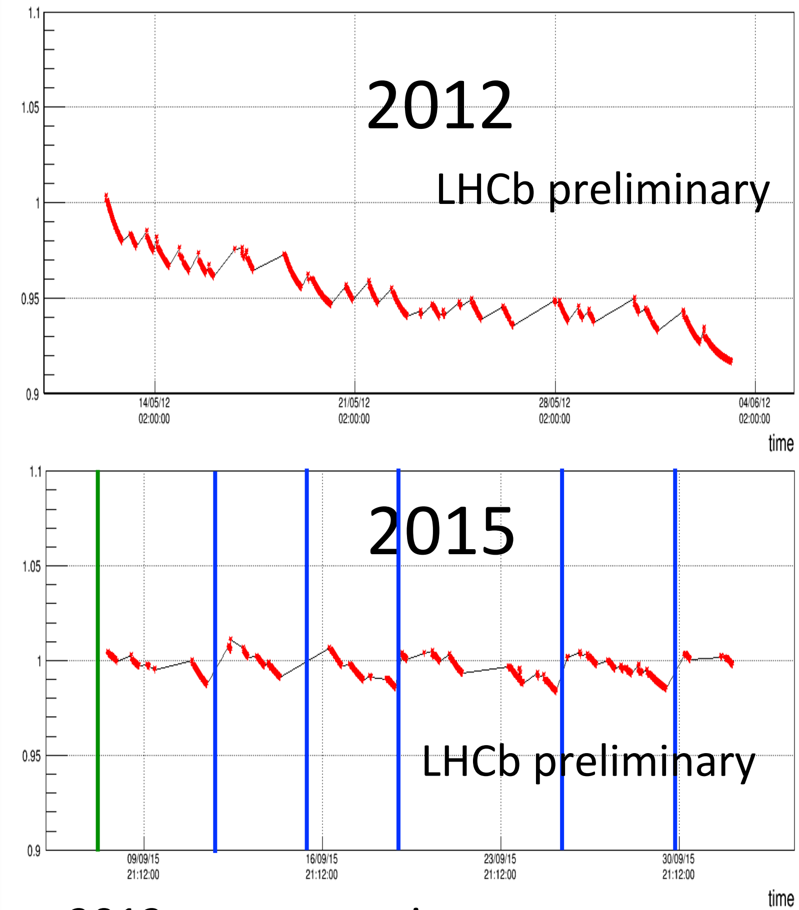


Real-time calibration performance

- Calibration of the RICH and OT system to guarantee stable condition during data taking
- Introduced in Run II the LED corrections for ECAL and HCAL are automatically performed/updated every fill
  - ~15 minutes to have the corrections available

Stable L0 conditions

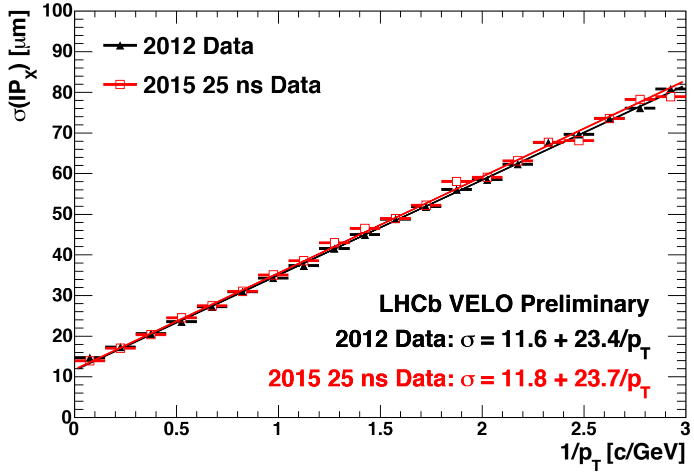
LED average over 456 cells in the very central part of ECAL



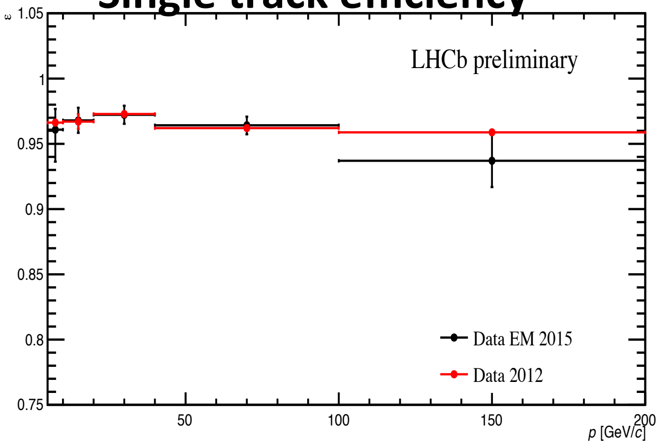
2012 – no corrections
2015: green line – π^0 based calibration; blue lines – LED based corrections

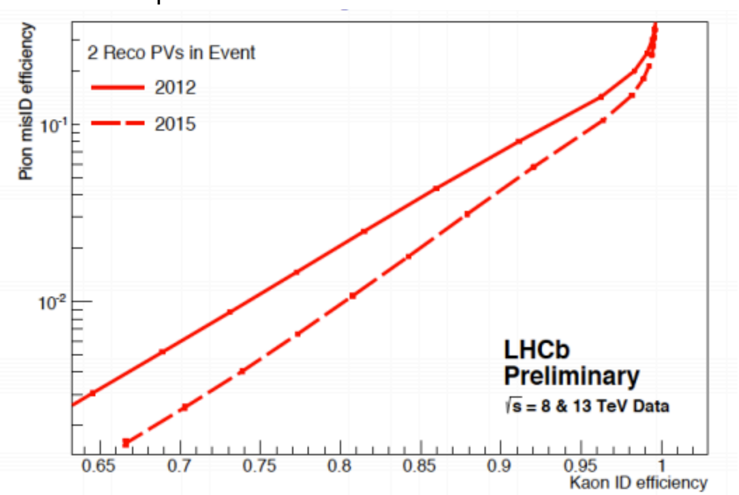
Run II performance

Same or better than the offline performances for tracking and PId in Run I but directly at trigger level now!!!



Single track efficiency

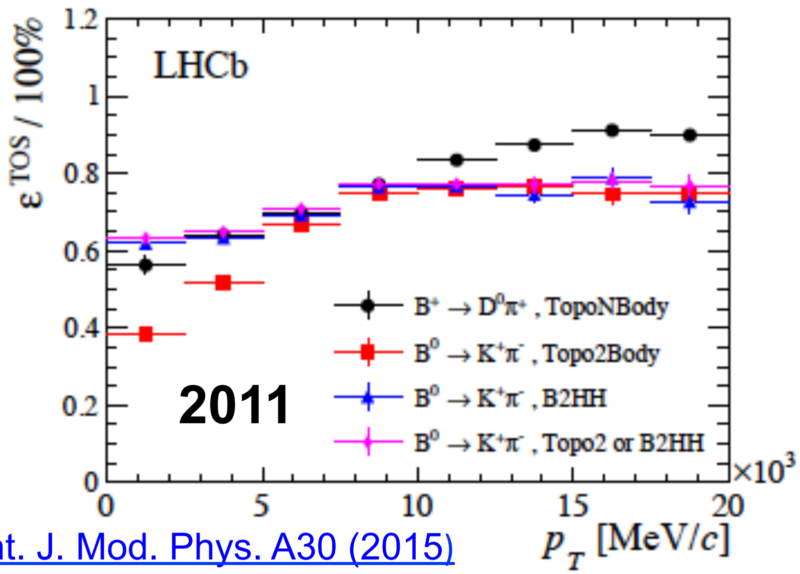




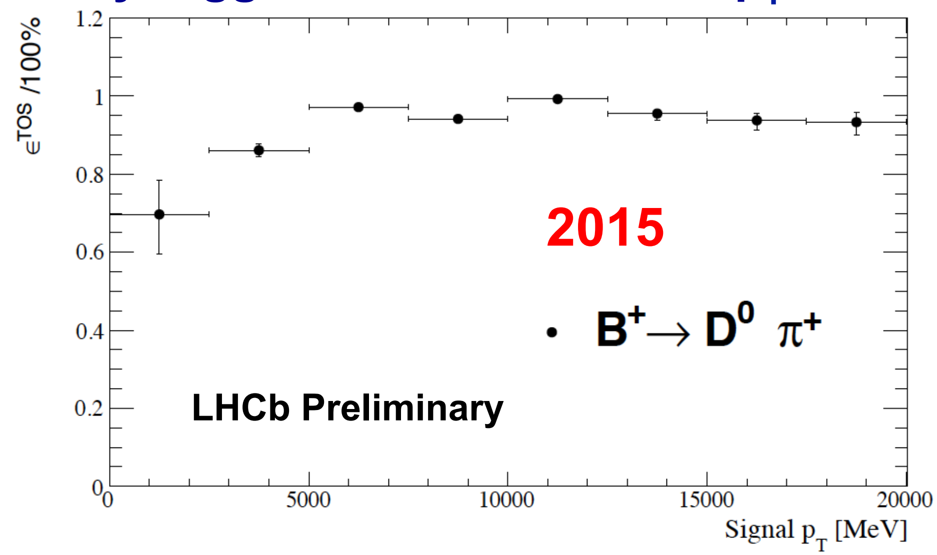
Trigger performance in Run II

- **Improvement of the trigger efficiency thanks to e.g.**
  - Run the same offline reconstruction in HLT2
  - Having the detector fully calibrated and aligned
  - Using PID selection in the trigger

Efficiency of the HLT2 inclusive beauty trigger as a function of B p_T



Int. J. Mod. Phys. A30 (2015)



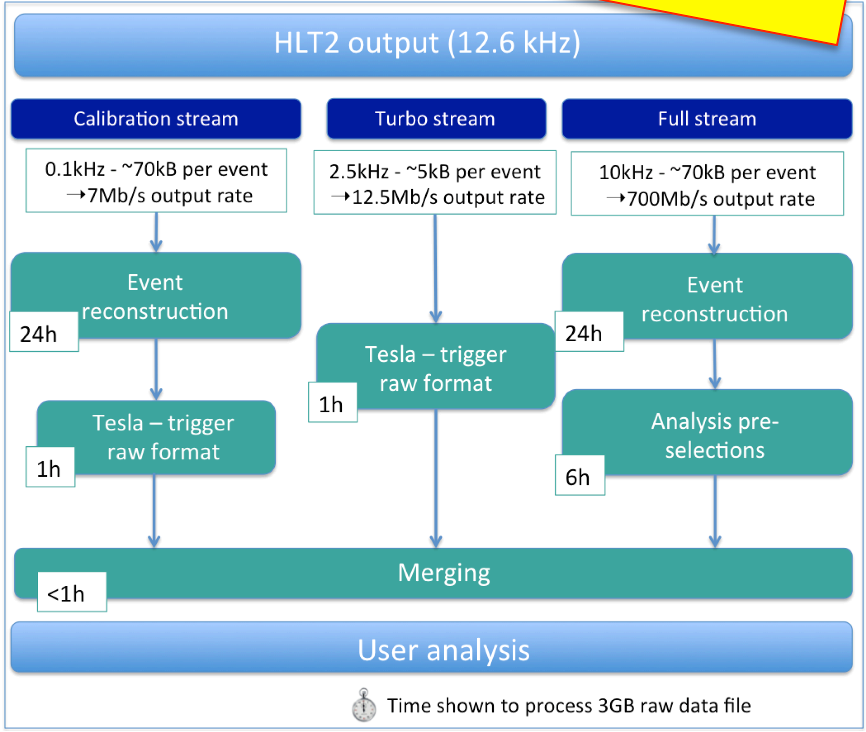
Efficiency for $B^+ \to D^0\pi^+$ is ~75%

Efficiency for $B^+ \to D^0\pi^+$ is >90%

The Turbo stream

In 2016 same reconstruction online and offline also for the calorimeter

- HLT reconstruction as offline one
- Introduced Turbo stream to saves HLT candidates only:
  - Reduced event size:
    - Full event ~70kB
    - **Turbo event ~5kB**
  - No need of offline reconstruction: possible to perform analysis immediately
  - Dedicated ~2.5 kHz of the output stream (10 KHz for the full stream)
- **New features in 2016:** persistency of the reconstruction info for the full event, higher level variables (i.e. hits in a cone region around the track) available for few lines: possible to do charm spectroscopy!



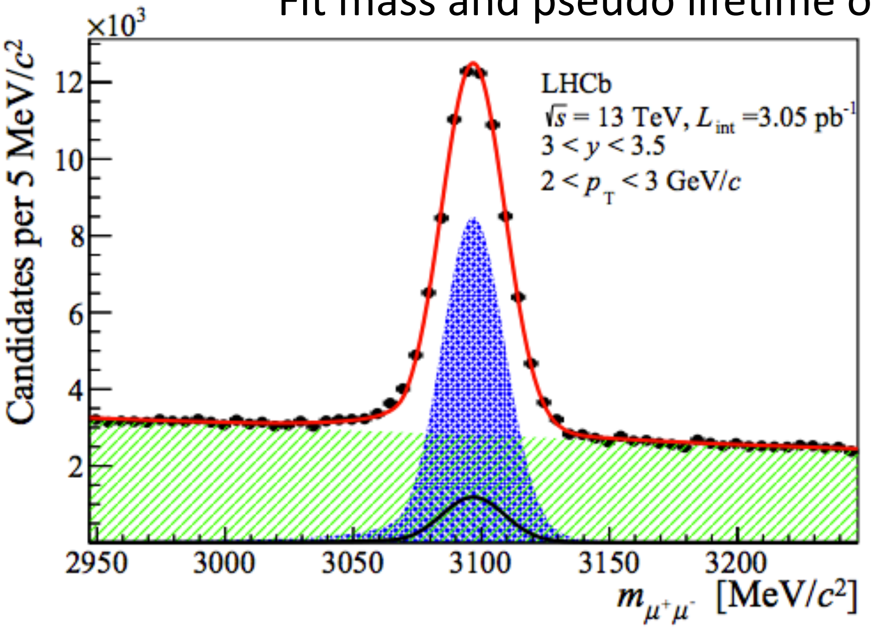
Of the 420 HLT2 lines 2016 physics programme, 150 choose Turbo: ~60 new lines with respect to 2015 data taking

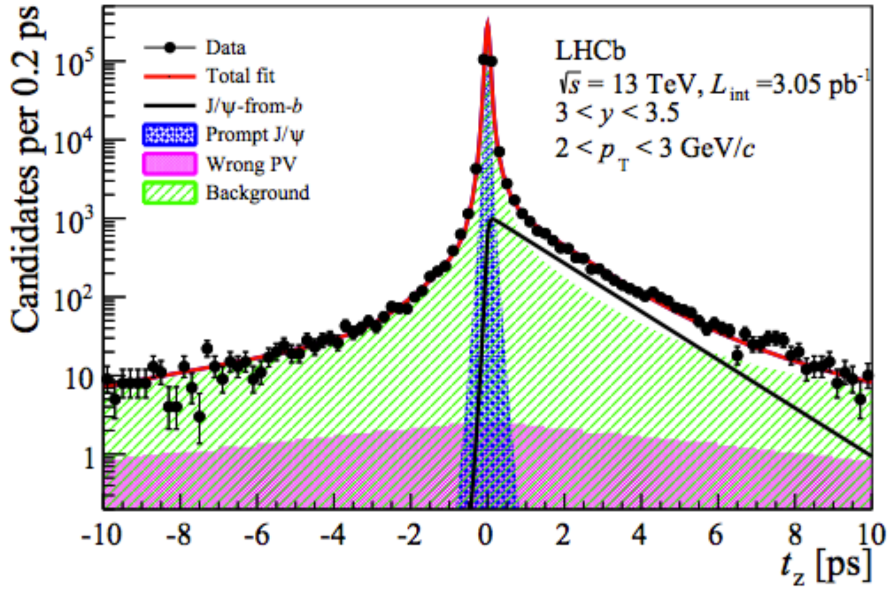
J/ψ production cross-section

$\int Ldt = 3.05 \pm 0.12\,\mathrm{pb}^{-1}$

JHEP 10 (2015) 172

Analysis find ~10^6 candidates directly from the trigger
No further reconstruction, all necessary info is persisted from the trigger
Fit mass and pseudo lifetime of J/ψ in p_T and y bins





Mass resolution of 12 MeV/c^2 consistent with Run I offline

Secondary J//ψ's from b-hadrons estimated using a pseudo-lifetime

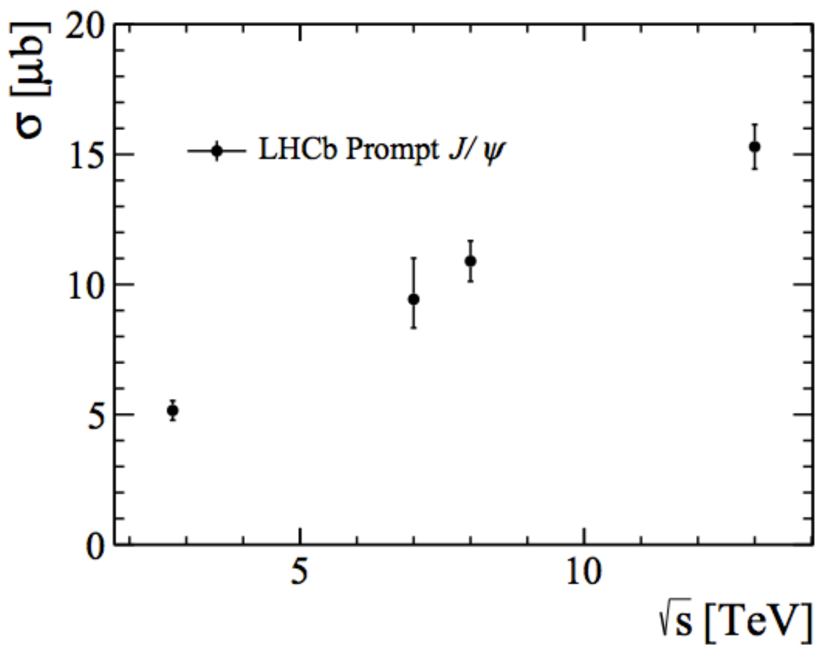
$$t_z = \frac{(z_{J/\psi} - z_{PV}) \cdot M_{J/\psi}}{p_z}$$

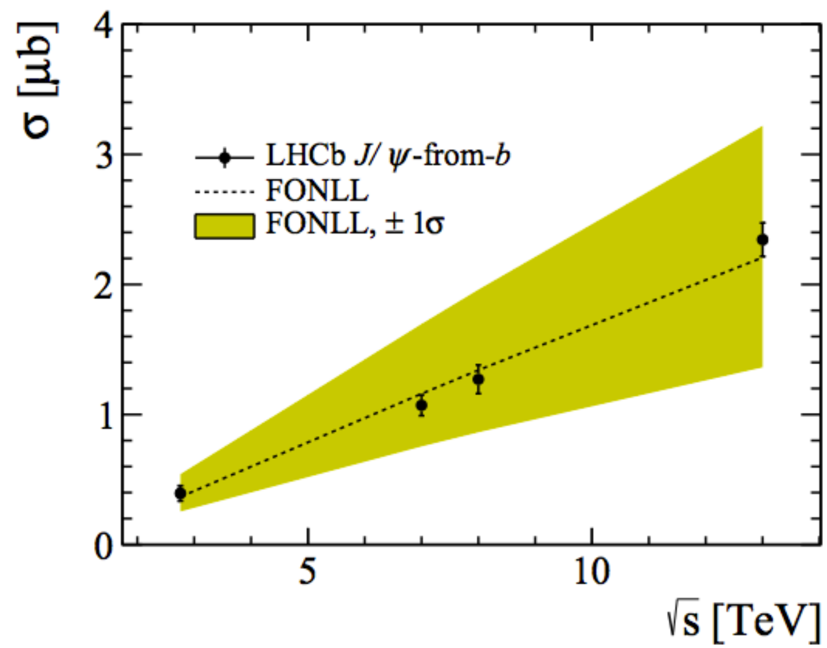
J/ψ production cross-section

$\int Ldt = 3.05 \pm 0.12\,\mathrm{pb}^{-1}$ JHEP 10 (2015) 172

Integrated J/ψ cross-section in acceptance p_T < 14 GeV, 2<y<4.5

- σ(prompt) = 15.30 ± 0.03 ± 0.86 μb
- σ(from b) = 2.34 ± 0.01 ± 0.13 μb
- Total σ(pp → bbX) = 515 ± 2 ± 53 μb (using BR(b→J/ψX)



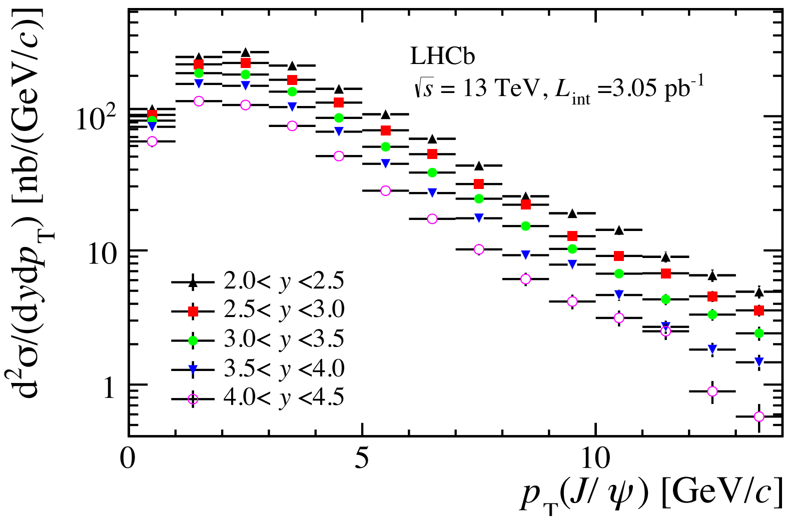


FONLL: M. Cacciari, M. Greco, P. Nason: JHEP (9805 (1998) 007

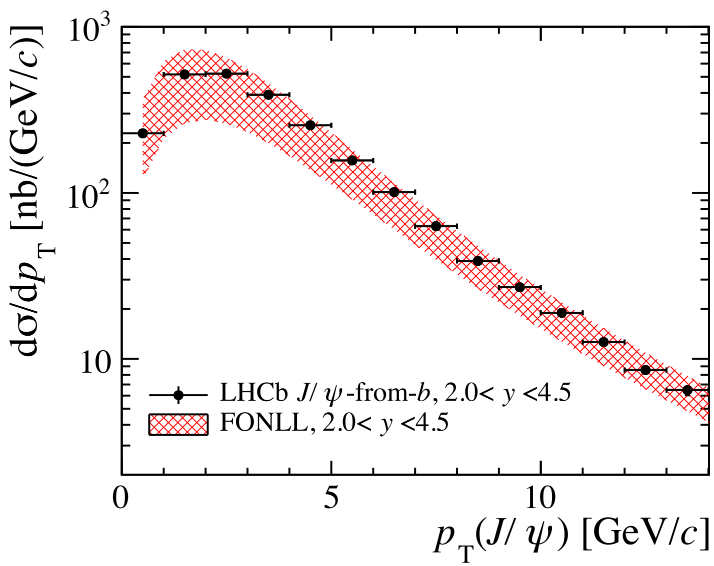
J/ψ production cross-section

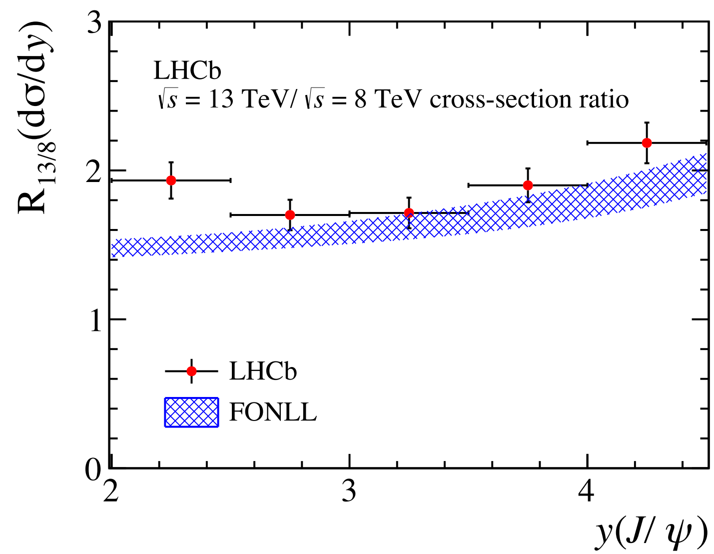
$\int L dt = 3.05 \pm 0.12\,\mathrm{pb}^{-1}$

[JHEP 10 (2015) 172]



1. Double differential cross-section for J/ψ from-b mesons (prompt in backup) as a function of p_T in bins of y. Similar studies for the fraction of J/ψ from-b mesons.
2. Data/theory comparison for cross section (prompt in backup)
3. Data/theory comparison for ratio of differential cross section between measurement at √s = 13 and 8 TeV as a function of y





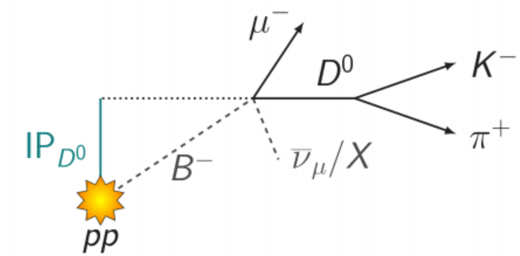
FONLL: M. Cacciari, M. Greco, P. Nason: JHEP 9805 (1998) 007

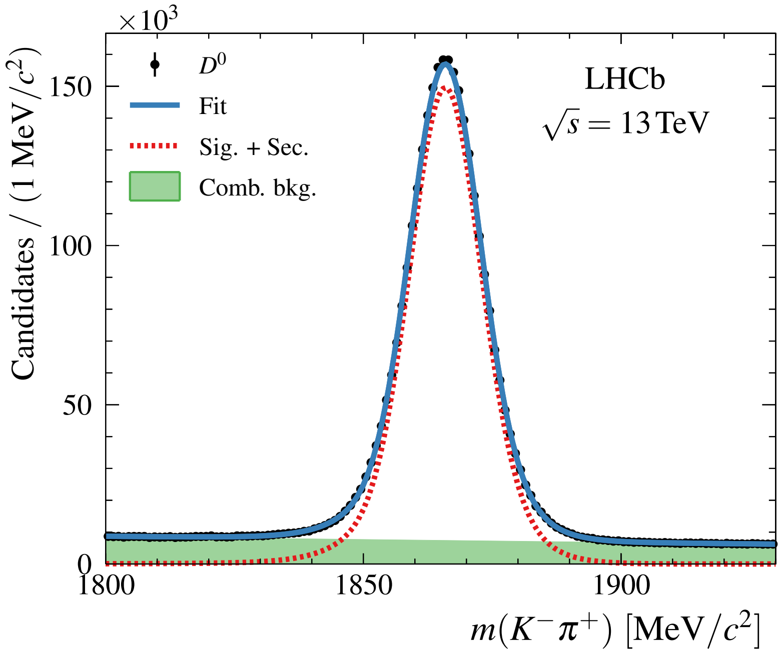
NRQCDL: H.-S. Shao, H.Han, Y.-Q. Ma, C. Meng, Y.-J. Zhang, K.-T. Chao, JHEP 1505 (2015) 103

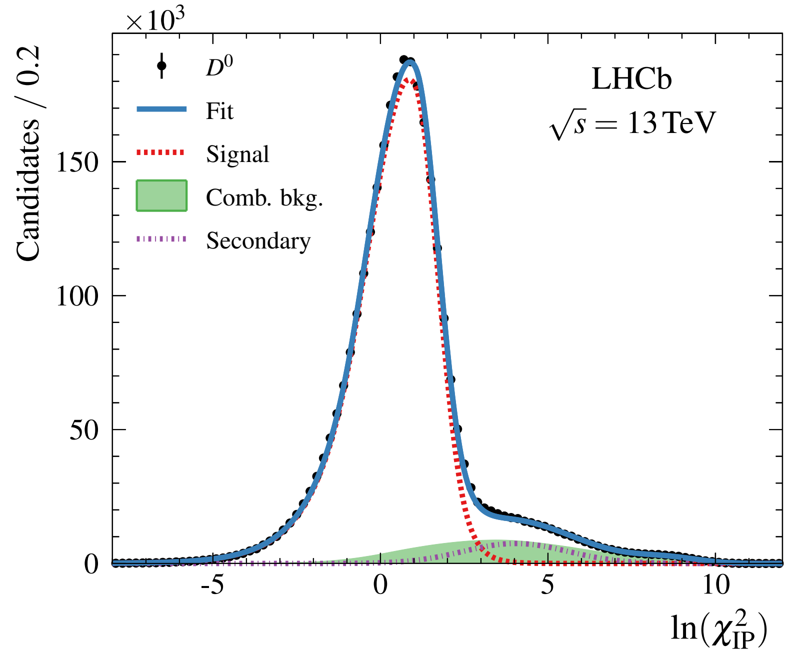
Charm production cross-section

$\int Ldt = 4.98 \pm 0.19\,\mathrm{pb}^{-1}$ JHEP 1603 (2016) 159

- Measure prompt production of D^0, $D^\pm$, $D^\pm_s$, $D^{*\pm}$ (only D^0 presented, other in the backup)
- Kinematic range: p_T<15 GeV/c, 2<y<4.5
- Separate prompt from secondary signal using impact parameter (IP) significance
- Simultaneous fit in all p_T, y bins of mass and IP significance



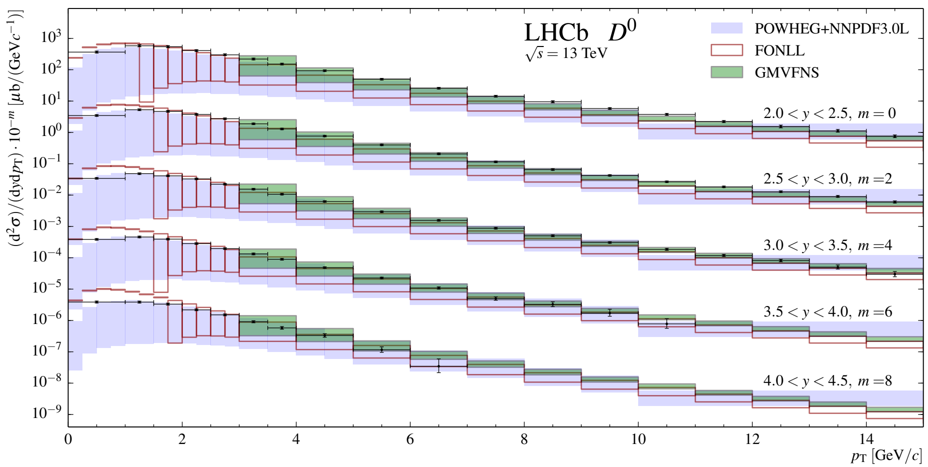


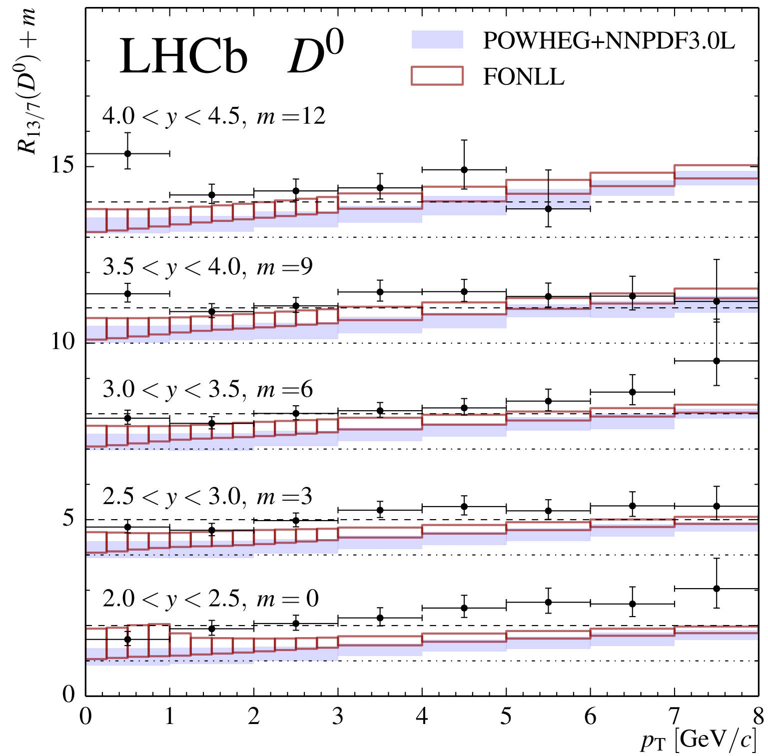


Charm production cross-section

$\int Ldt = 3.05 \pm 0.12\,\text{pb}^{-1}$

JHEP 1603 (2016) 159





- Measure individual charm hadron cross-sections in p_T-y bins (shown D^0 case)
- Comparison with theory predictions:
  - Data have a tendency of being on the high side respect to predictions
  - Tendency of data of growing with p_T more than expected

FONLL: M. Cacciari, M. Mangano, P. Nason JHEP 1511 (2015) 009

POWHEG+NNPDF3.0L: R. Gauld, J. Rojo, L. Rottoli, J. Talbert Eur.Phys.J. C75 (2015) no.12, 610

GMVFNS: B. Kniel, G. Kramer, I. Schienbein, H. Spiesberger EPJ C72 (2012) 2082

Charm production cross-section

$\int L dt = 3.05 \pm 0.12\,\mathrm{pb}^{-1}$

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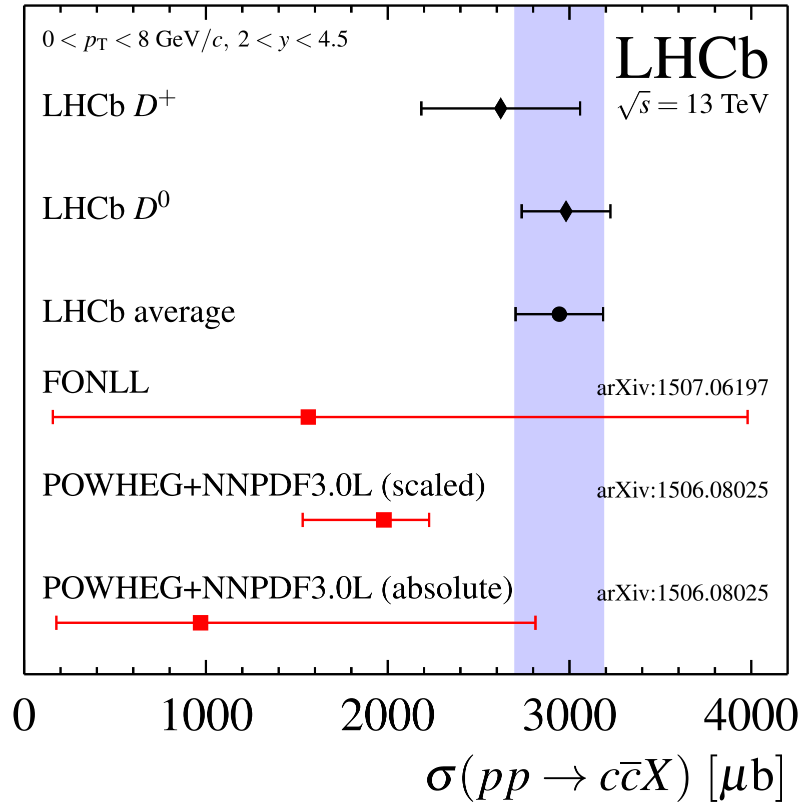
Measure individual charm hadron cross-sections:

$$\sigma(pp \to D^0 X) = 2460 \pm 3 \pm 130\,\mu\mathrm{b}$$
$$\sigma(pp \to D^+ X) = 1000 \pm 3 \pm 110\,\mu\mathrm{b}$$
$$\sigma(pp \to D_s^+ X) = 460 \pm 13 \pm 100\,\mu\mathrm{b}$$
$$\sigma(pp \to D^{*+} X) = 880 \pm 5 \pm 140\,\mu\mathrm{b}$$

Combine with fragmentation fractions from e^+e^- colliders for $c\bar{c}$ cross-sections [PDG]



Integrated $c\bar{c}$ cross-section in acceptance pT<8 GeV, 2<y<4.5

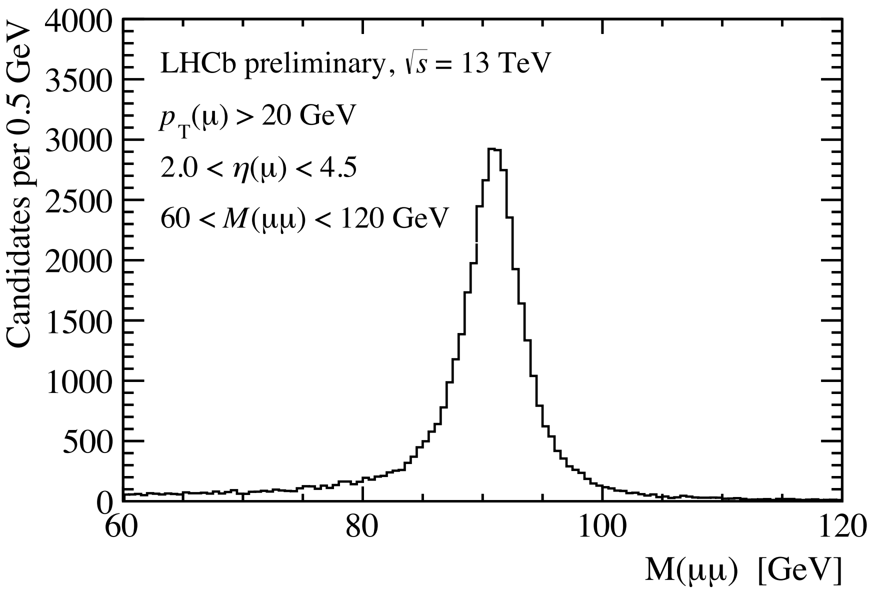
$$\sigma(pp \to c\bar{c}X) = 2940 \pm 3\,(\mathrm{stat}) \pm 180\,(\mathrm{syst}) \pm 160\,(\mathrm{frag})\,\mu\mathrm{b}$$

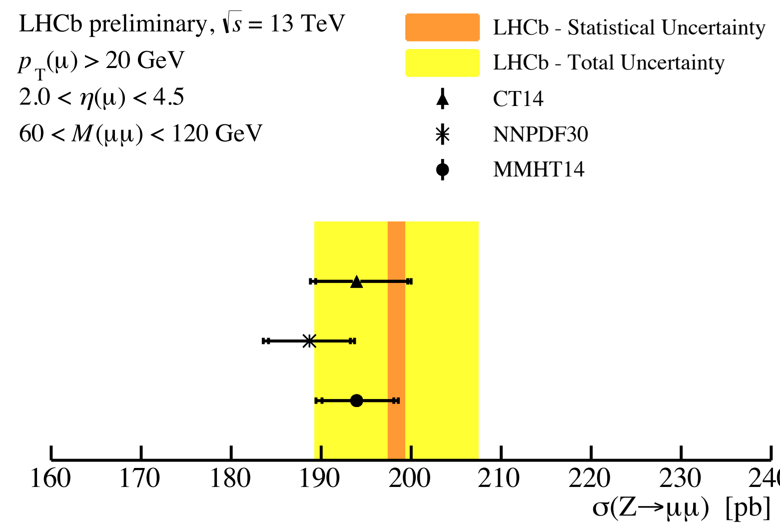
Z→μ⁺μ⁻ production cross-section

$\int Ldt \sim 300\ \mathrm{pb}^{-1}$

LHCb-CONF-2016-002

- Measurement already done by LHCb at √s = 7 and 8 TeV [JHEP 1508 (2015) 039, JHEP 1601 (2016) 155]
- Analysis requires both muons satisfy p_T > 20 GeV, 2.0 < y <4.5 and





- Comparison of data and theory predictions as a function of boson rapidity:
  - The results do not favour one specific parton distribution function(PDF), but the differences between the PDF sets suggest that with more data LHCb can play important role constraining PDFs.

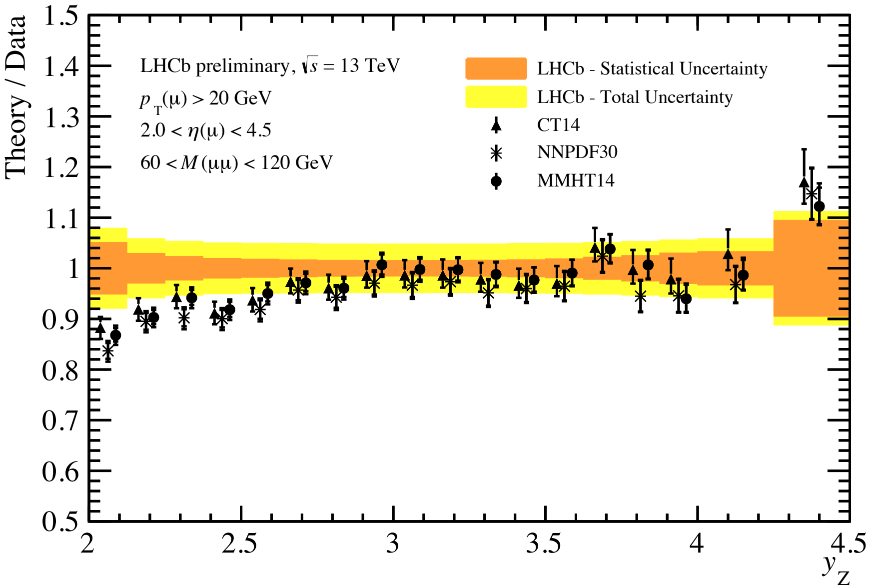
NNPDF30: JHEP 1504 (2015) 040
MMHT14: Eur. Phys. C75 (2015) no. 5, 204

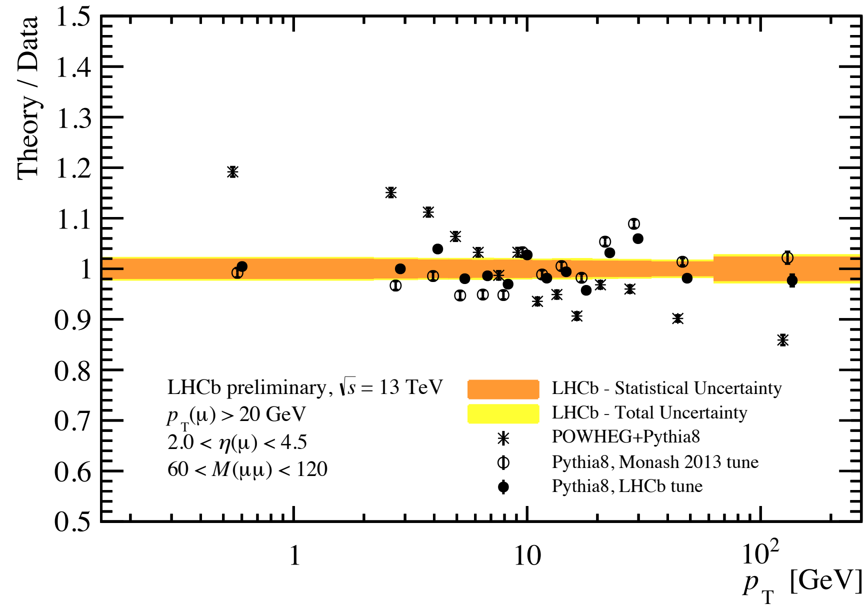
$Z \rightarrow \mu^+\mu^-$ production cross section

$\int Ldt \sim 300\ \mathrm{pb}^{-1}$ LHCb-CONF-2016-002

Comparison of data with theory predictions (differential cross-section plots in the backups)

Ratios of the theoretical predictions to data





- The different PDFs describes well the LHCb data
- The LHCb data as a function of p_T agree better with PYTHIA 8 than with PWEHEG +PYTHIA 8 predictions.
- The specific LHCb tune of PYTHIA 8 does not perform significantly better

Conclusions

- **LHCb is the first HEP experiment with a full calibration, alignment and reconstruction done in real-time**
- Provided new calibration and alignment constants for each run or fill in **few minutes**
- Possible to monitor in few hours quantities that in Run I were monitored only few times in a year (like during TS)
- The Turbo Stream allowed to:
  - Increase the physics reach by saving more data in less space (important for high branching ratio channels)
  - Physics analysis doable ~24h after the data taking
- LHCb measured several production cross-section measurements at 13 TeV (first cross-section measurements presented one week after the data taking):
  - Prompt J/ψ
  - J/ψ from-B
  - Total $b\bar{b}$
  - D^0, $D^{\pm}$, $D^{\pm}_s$, $D^{*\pm}$
  - Total $c\bar{c}$
- $Z \to \mu^+\mu^-$ production cross-section at 13 TeV preliminary results presented

Backups

J/ψ production cross-section

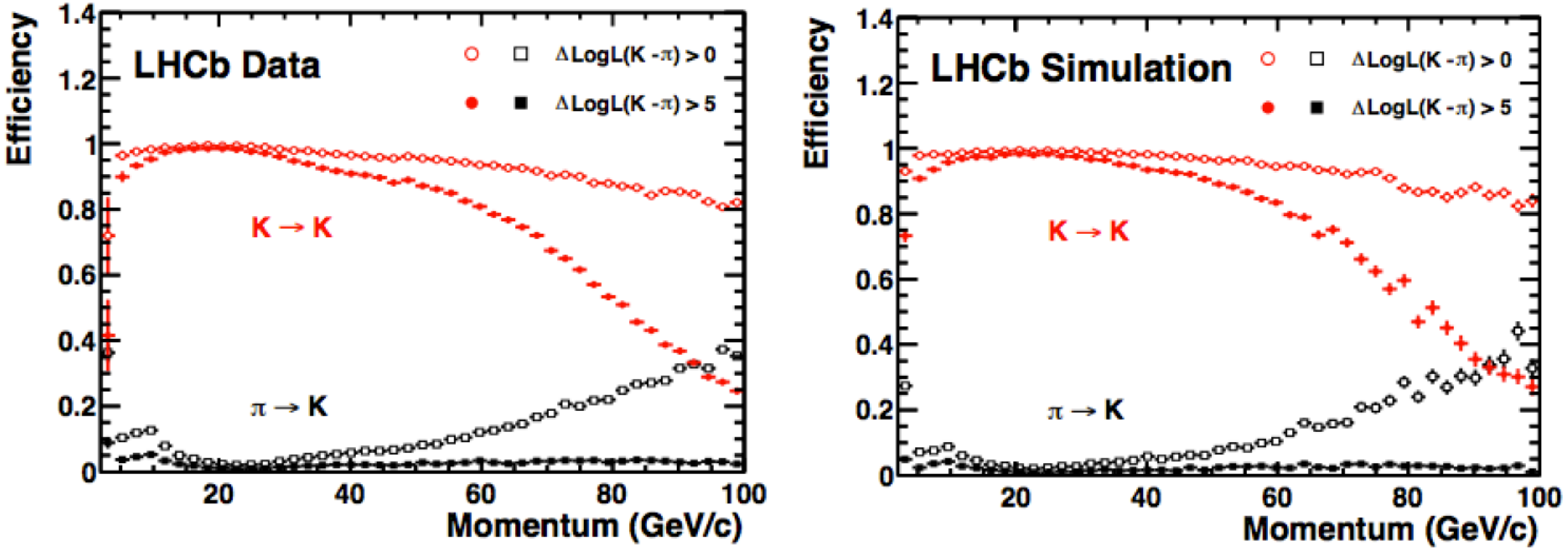


Figure 39: Kaon identification efficiency and pion misidentification rate as measured using data (left) and from simulation (right) as a function of track momentum [81]. Two different $\Delta\log\mathcal{L}(\mathrm{K}-\pi)$ requirements have been imposed on the samples, resulting in the open and filled marker distributions, respectively.

LHCb Detector Performance
Int.J.Mod.Phys. A30 (2015) 1530022

J/ψ production cross-section

$$\int L dt = 3.05 \pm 0.12\,\mathrm{pb}^{-1}$$

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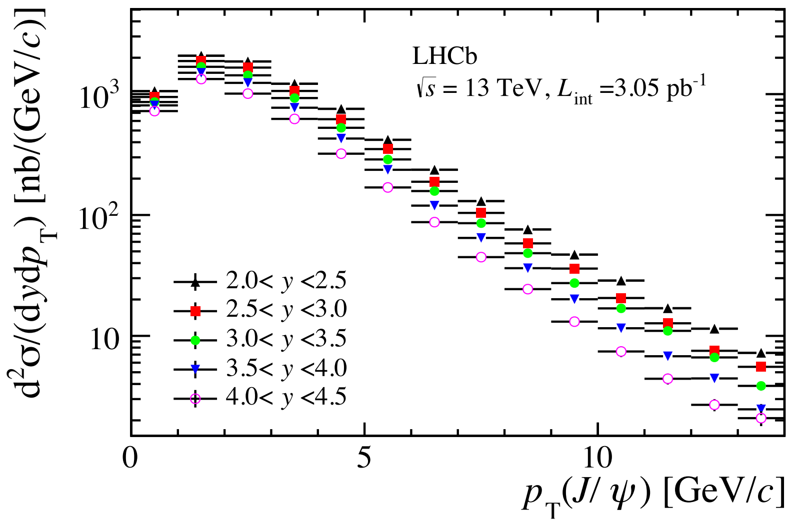
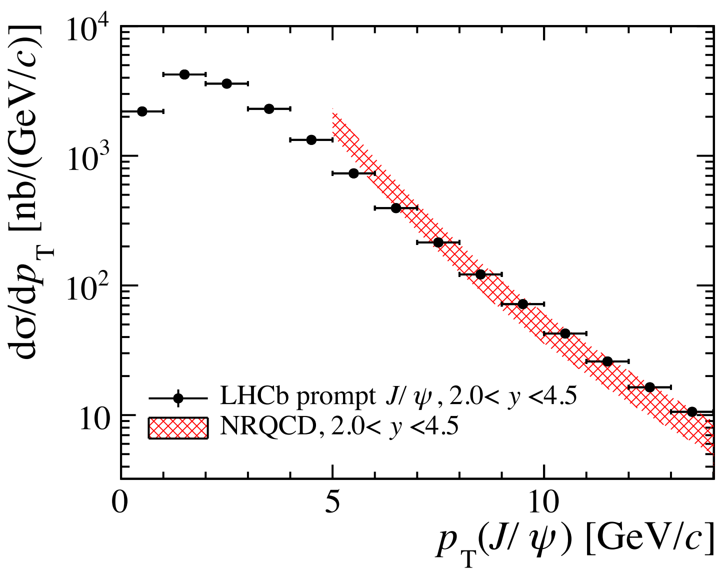
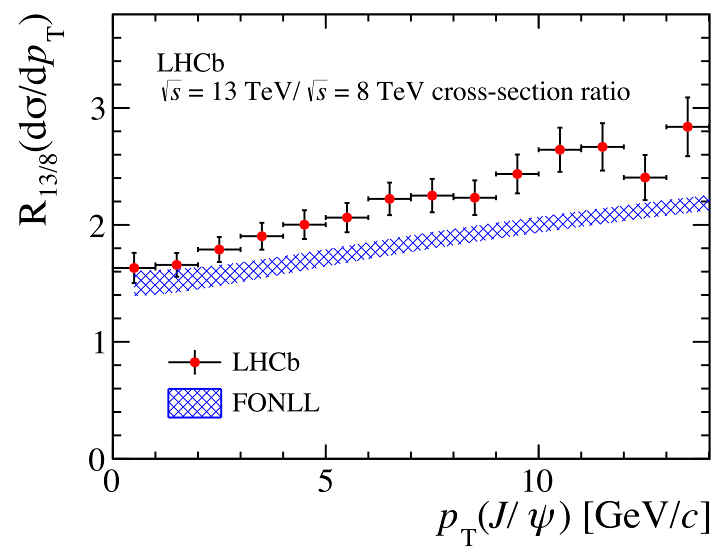


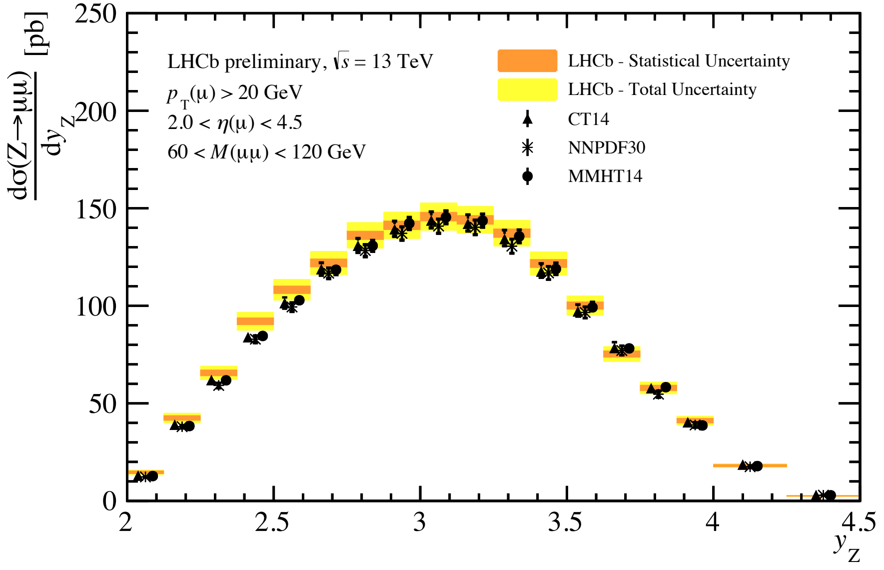
1. Double differential cross-section for promt J/ψ
2. Data/theory comparison for double cross section (prompt) as function of p_T
3. Data/theory comparison for ratio of differential cross section between measurement at √s = 13 and 8 TeV as function of p_T



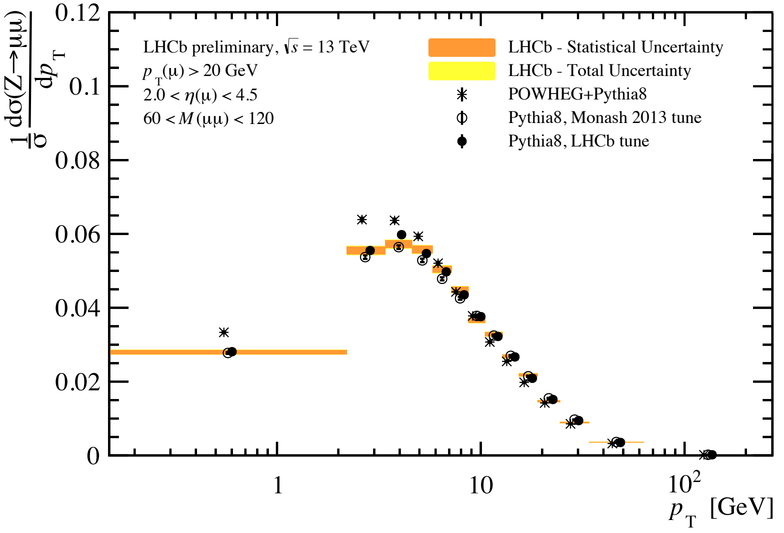


FONLL: M. Cacciari, M. Greco, P. Nason: JHEP 9805 (1998) 007

NRQCDL: H.-S. Shao, H.Han, Y.-Q. Ma, C. Meng, Y.-J. Zhang, K.-T. Chao, JHEP 1505 (2015) 103



LHCb preliminary, $\sqrt{s}$ = 13 TeV
$p_T(\mu) > 20$ GeV
$2.0 < \eta(\mu) < 4.5$
$60 < M(\mu\mu) < 120$ GeV
LHCb - Statistical Uncertainty
LHCb - Total Uncertainty
CT14
NNPDF30
MMHT14
$\frac{d\sigma(Z\to\mu\mu)}{dy_Z}$ [pb]
y_Z



LHCb preliminary, $\sqrt{s}$ = 13 TeV
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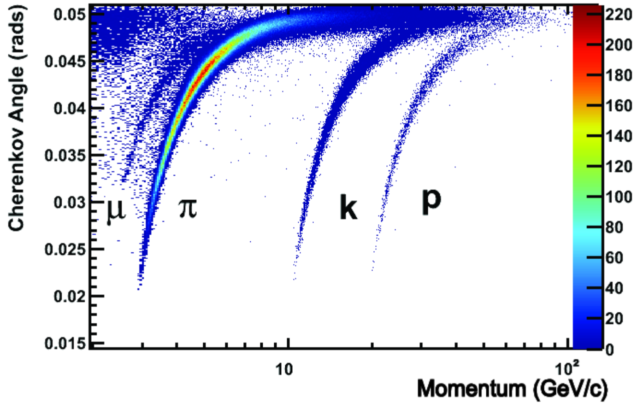
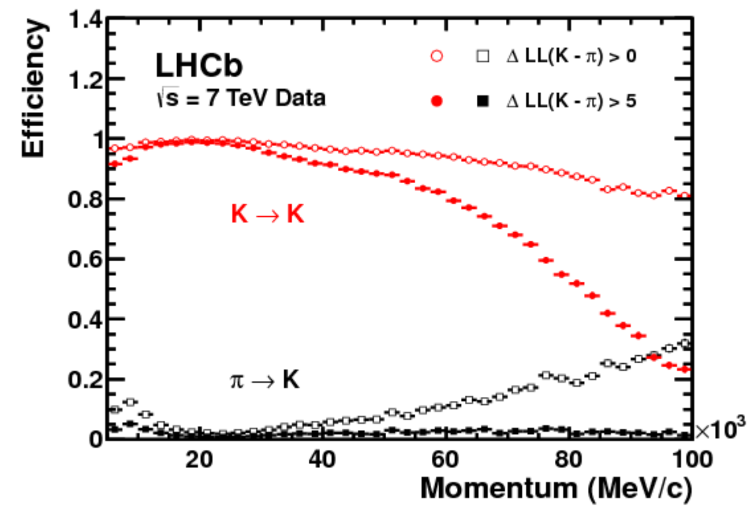
$2.0 < \eta(\mu) < 4.5$
$60 < M(\mu\mu) < 120$
LHCb - Statistical Uncertainty
LHCb - Total Uncertainty
POWHEG+Pythia8
Pythia8, Monash 2013 tune
Pythia8, LHCb tune
$\frac{1}{\sigma}\frac{d\sigma(Z\to\mu\mu)}{dp_T}$
p_T [GeV]

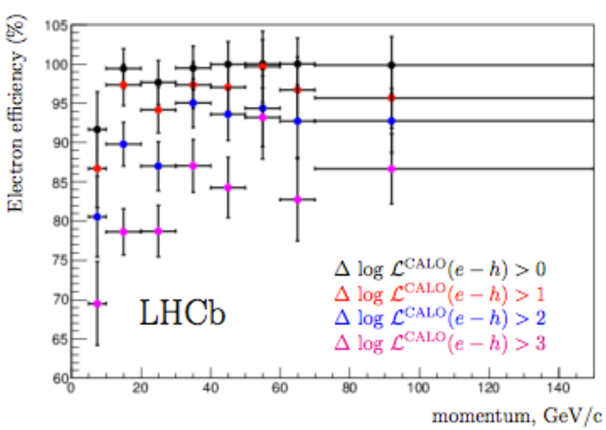
The PID performances



Capability to distinguish particles (especially π-K) in a the momentum range 2-100 GeV/*c*)

Kaon identification efficiency ~95% with a pion **mis-idenfication** fraction of **~10%** over the full 2-100GeV/c momentum range (tight selection)





Electron identification efficiency >91% with a hadron mis-idenfication fraction of **few % p>10 GeV/*c*** (intermediate selection)

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New resources in 2015

- HLT farm nearly doubled from Run I:
  - ~27k physical cores
  - Farm nodes added for RunII are about 2x more powerful than previous nodes
- Event can be buffered after HLT1: 5PB disk space

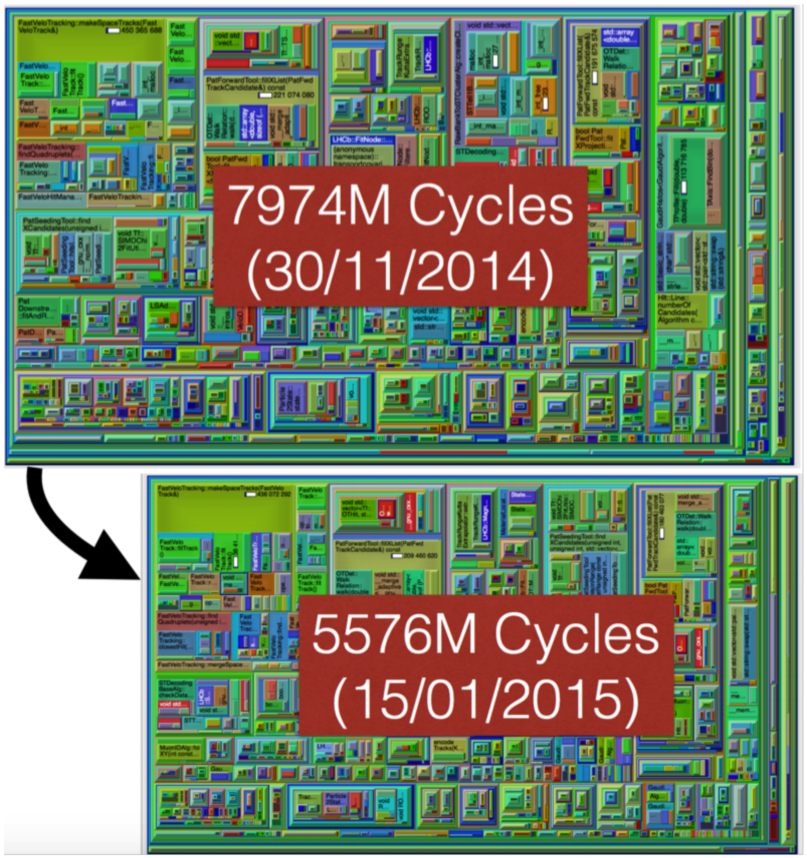
Reconstruction chain optimization

Optimization of the reconstruction chain

- In order to maintain full reconstruction efficiency, while keeping within a strict timing budget many improvements were needed:
    1. Optimization of the code (e.g. vectorization)
    2. Changes to the reconstruction chain and optimization of the pattern algorithm

Optimization of the reconstruction chain

1. **Optimization of the code (e.g. vectorization):**



Examples

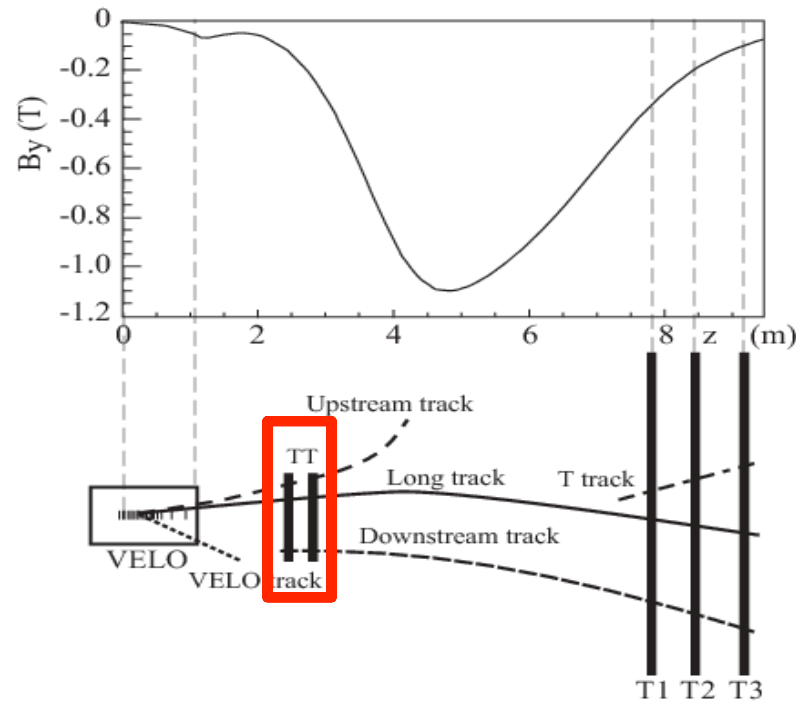
- Identified hot spots by profiling
  - **Vectorisation (track fit, magnetic field)**
- Caching (material description)
- Fast approximations
- Algorithms tuning and re-implementation

=> Possible to gain order of ~30% in several algorithms

Optimization of the reconstruction chain

2. Changes to the reconstruction chain and optimization of the pattern algorithm:

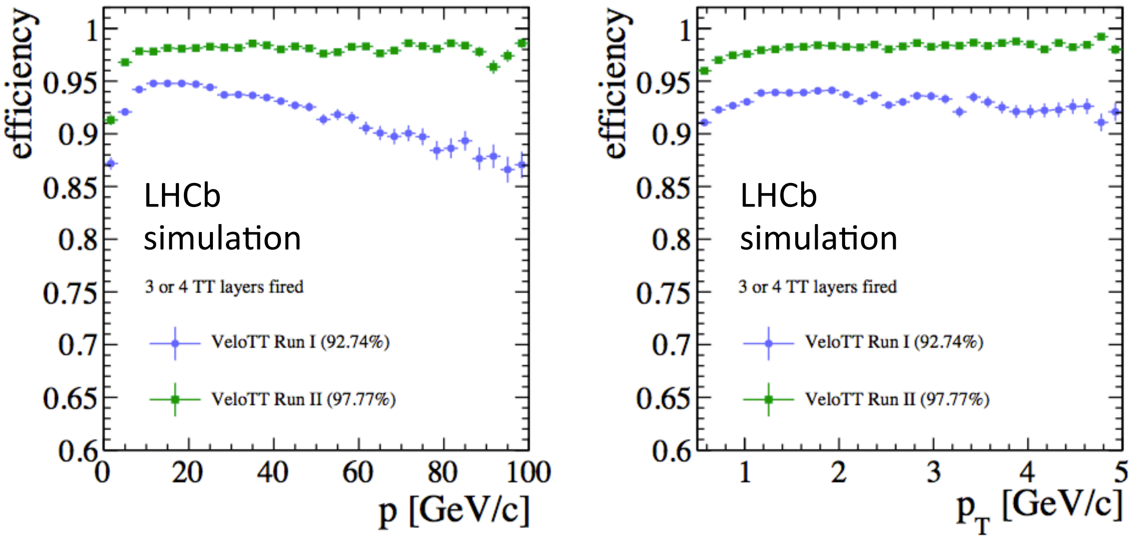
- Velo tracks can be extended to the TT detector



Advantages:

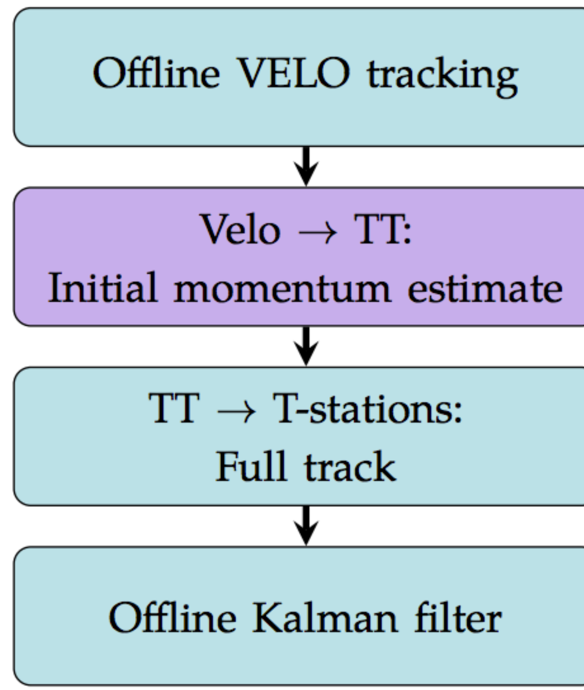
- The TT detector is already in the magnetic field: possible to estimate q/p (resolution ~15%)
- Momentum estimate used to pre-select tracks at an early stage
- Charge estimate allows greatly reduced search windows downstream of the magnet

Optimization of the reconstruction chain



VELO-TT performance:

- More than **97% efficient** for tracks with p_T>200 MeV that have hits in at least three layers
- **~5% better performance** than previous code (never used since it was too slow)



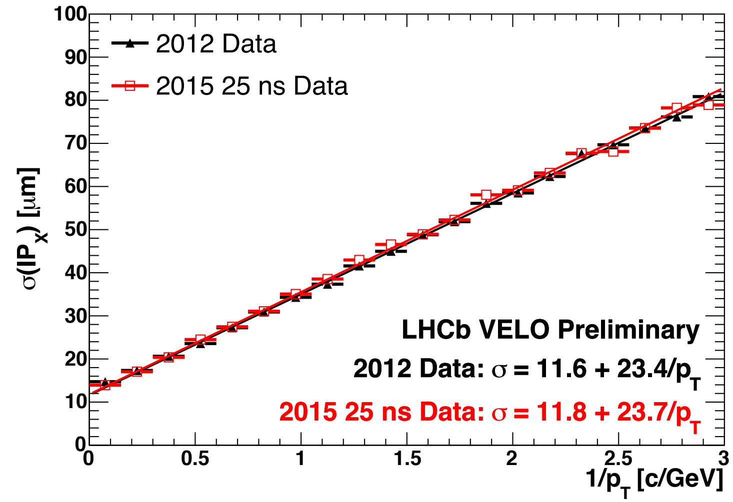
New reconstruction chain:

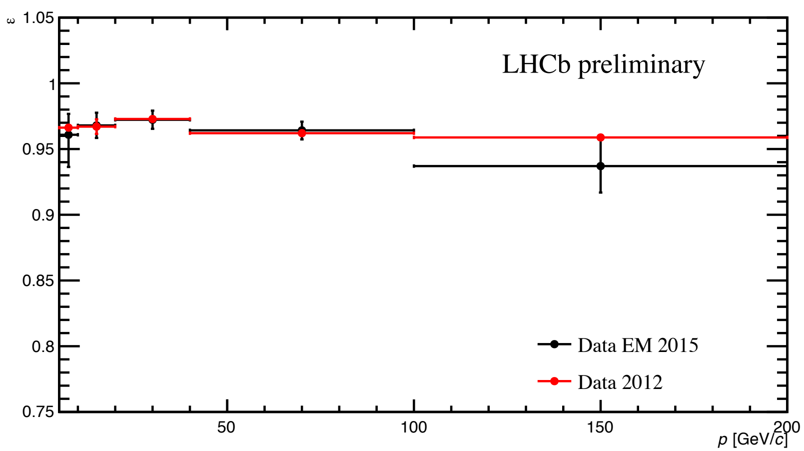
- **~3 times faster**
- Better or equivalent performance as in Run I
- Tracks with a **p_T>500MeV** already available at **HLT1** level (in Run I p_T>1.3 GeV) **without any IP requirements needed.**

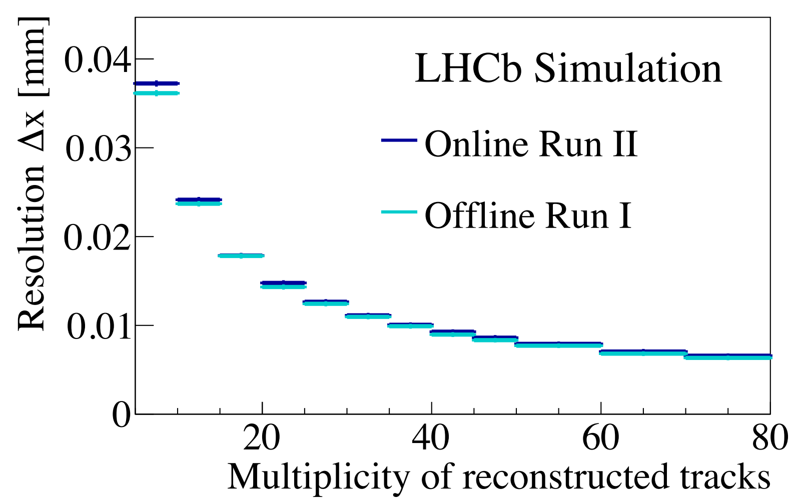
- **Gains >50% signal efficiency for charm physics**
- **Enable lifetime unbiased triggers for hadronic final states (world first!)**

The new chain at work

- **IP resolution comparable with 2012 data**
- Stable between different fills
- Compatible results with 50 and 25 ns data







Tracking efficiency comparable with 2012 data

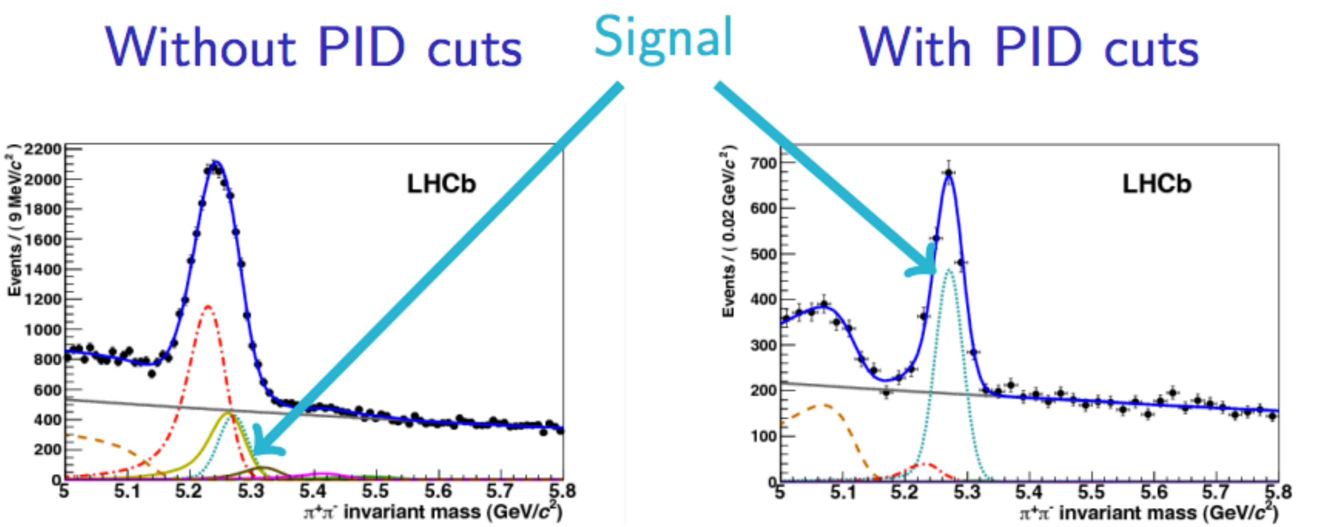
Comparable resolution to Run I for the PV reconstruction with 70% smaller fraction of fake primary vertices

Still a difficult challenge:

- ~~Managing to do the full reconstruction in … achieving offline performance (same or better than in RunI):~~ DONE!
- Managing to do the full alignment and calibration of the detectors in real-time
- Being able to select efficiently many signals already at trigger level

Importance of the calibration

- Complete calibration of the RICH detectors needed for exclusive selection using hadron particle identification criteria
  - Improve purity and mass resolution
  - PID requirements allows exclusive selection and optimization of the rate



Invariant mass distribution for $B^0 \to \pi\pi$ decay ($B^0 \to \pi\pi$, $B^0 \to K\pi$, $B^0 \to$ 3-bodies, $B_s \to KK$, $B_s \to K\pi$, $\Lambda_b \to pK$, $\Lambda_b \to p\pi$)

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Real-time Alignment and Calibration(I)

- General Strategy
  - Automatic evaluation at regular intervals, e.g. per fill or per run depending on the task
  - Dedicated data sample to perform alignment or calibration collected with specific trigger selection line for each task
  - Compute the new alignment or calibration constants in **few minutes**
  - Update the constants only if needed
  - **The same new alignment and calibration constants will be used both by the trigger and the offline reconstruction**

Advantages:

- Have the same performance online and offline
- More effective trigger selection
- Stability of the alignment quality, hence physics performance
- Some analysis performed directly on the trigger output

Real-time Alignment and Calibration(II)

- Technicalities:
  - Constants expected to change: updated in real-time (each fill, run, …)
  - Constants expected to be stable: monitoring
    - Took advantage of the farm computing power

Calibration Farm tasks:

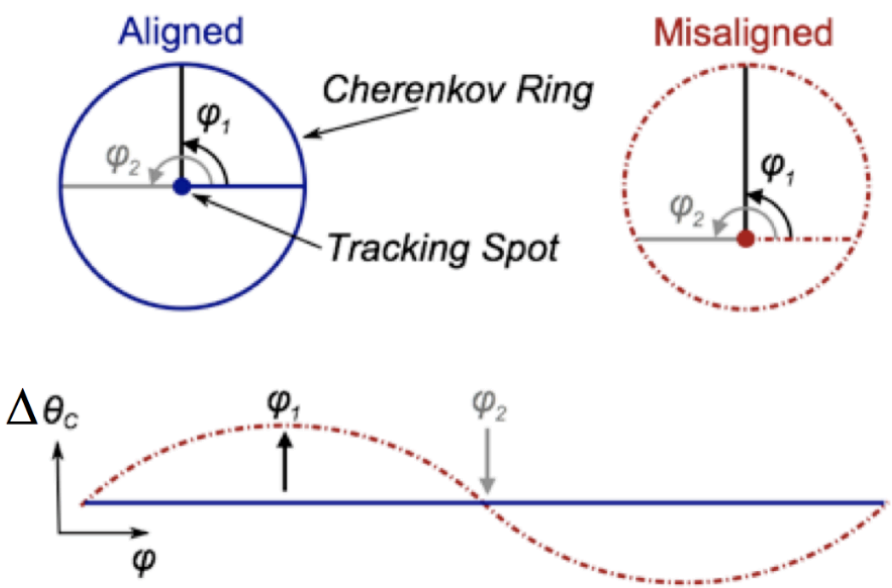
- RICH refractive index and HPD image calibration
- Calorimeter calibration
- OT-t_0 calibration

Online Farm tasks:

- VELO and tracker aligment
- Muon alignment
- RICH mirror alignment
- Calorimeter π^0 calibration

RICH Mirror alignment: logic

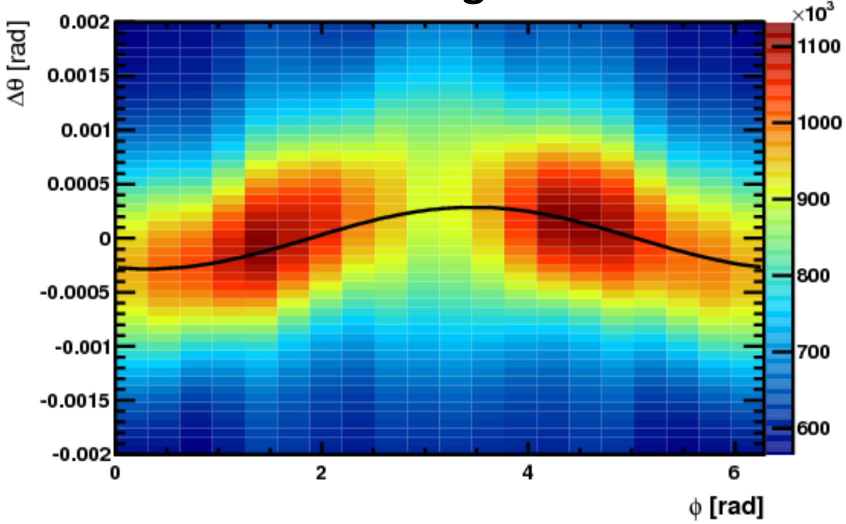
- Cherenkov photons focused on photon-detector plane by spherical and flat mirrors
- An imaginary track reflected through the RICH mirrors should be in the center of the Cherenkov ring
- The distribution of the Δθ against φ results in a sinusoidal distribution in case of misalignment of the mirrors
- Fit the distribution to calculate alignment constants



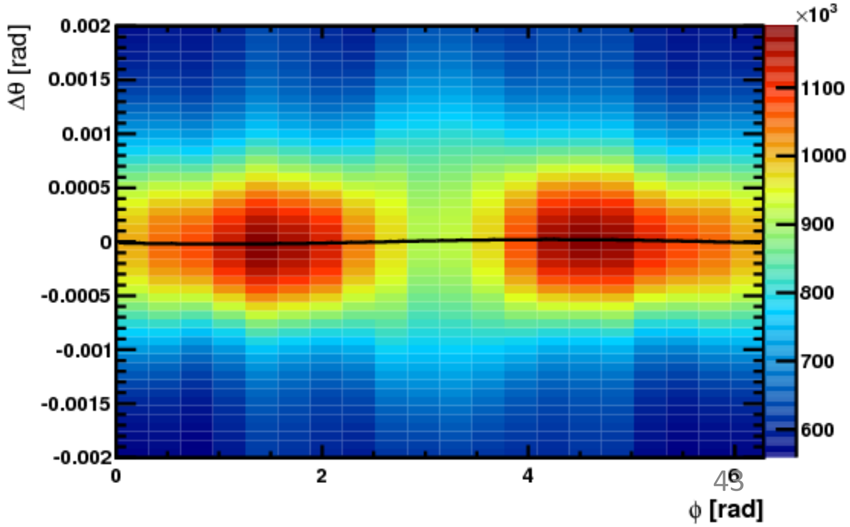
RICH mirror alignment: at work

- Mirror pairs to align:
  - RICH1: 16
  - RICH2: 94
- 1090 alignment constants
- **Re-optimization of the code** and HLT-selection of the high momentum tracks to be run in the online environment
- Same framework as the tracking alignment:
  - Analysers: photon reconstruction done in parallel
  - Iterator: fit of the $\Delta\theta$ distribution on a single node
- Used as monitoring (if enough statistics available potentially each fill)

Before alignment



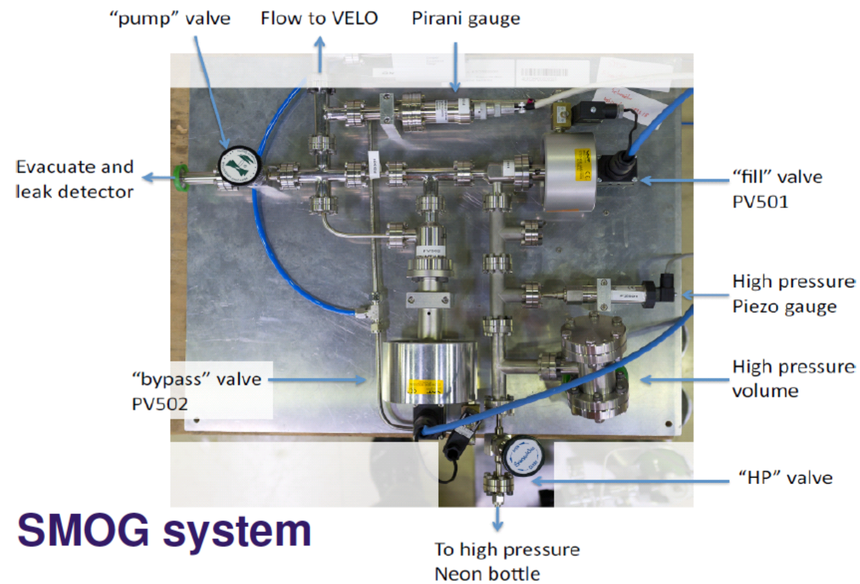
After alignment



SMOG system

- System to inject gas in the VELO region
  - **LHCb is able to do fix target physics (unique opportunity at LHC)**
  - Possibility to have a second method to measure the luminosity
    - **Traditional Van der Meer scans**: with LHC moving the beams with respect to each other in small steps
    - **Beam Gas Imaging Method** with SMOG to reconstruct beam shape at the interaction point

SMOG: System for Measuring the Overlap with Gas

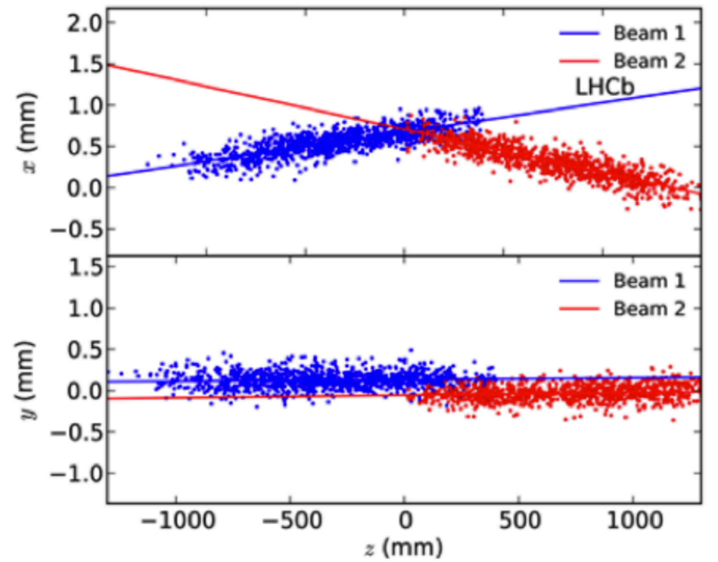


Best precise measurement of the luminosity **at LHC** with **1.1%** of uncertainty in Run I [JINST 9 (2014) 12, P12005]

For EM delivered a luminosity measurement with **3.8% of uncertainty in few weeks**

Luminosity measurement

- In LHCb two techniques used to measure the luminosity:
  - **Traditional Van der Meer scans**: with LHC moving the beams with respect to each other in small steps
  - **Beam Gas Imaging Method** with SMOG to reconstruct beam shape at the interaction point
- The combination of the two techniques allowed in RunI to achieve the **best precise measurement** of the luminosity **at LHC** with **1.1%** of uncertainty [JINST 9 (2014) 12, P12005]
- Only beam gas imaging method available for the EM timescale
- Delivered a luminosity measurement with **3.8% of uncertainty in few weeks** (measurement 10th of June, first results presented at EPS the 22th of July)
- Further analysis to combine the two methods ongoing



Only HLT1 is used for this measurement: the new HLT split allowed to write very fast data to disk increasing the precision of the measurement (~1%)