First LHCb results from pp collisions at 13 TeV

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on behalf of the LHCb Collaboration

AGH-UST

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Outline

- Introduction – LHCb Detector
- Highlights from RUN I
- Real-time detector calibration and alignment
- Enhanced Trigger for RUN II
- Improved tracking
- Selected results from with 13 TeV collision data
- Summary

LHCb Collaboration

- ~ 900 members
- 64 institutes
- 16 countries
- **More than 250 published papers**!

The Mission

- Precise CPV studies with beauty and charm hadrons
- Rare decays of b and c hadrons
- EW and QCD physics in the forward direction
- Production and spectroscopy in p-p collisions
- Exotica(pentaquarks!)
- Heavy ion data taking

Introduction – LHCb detector

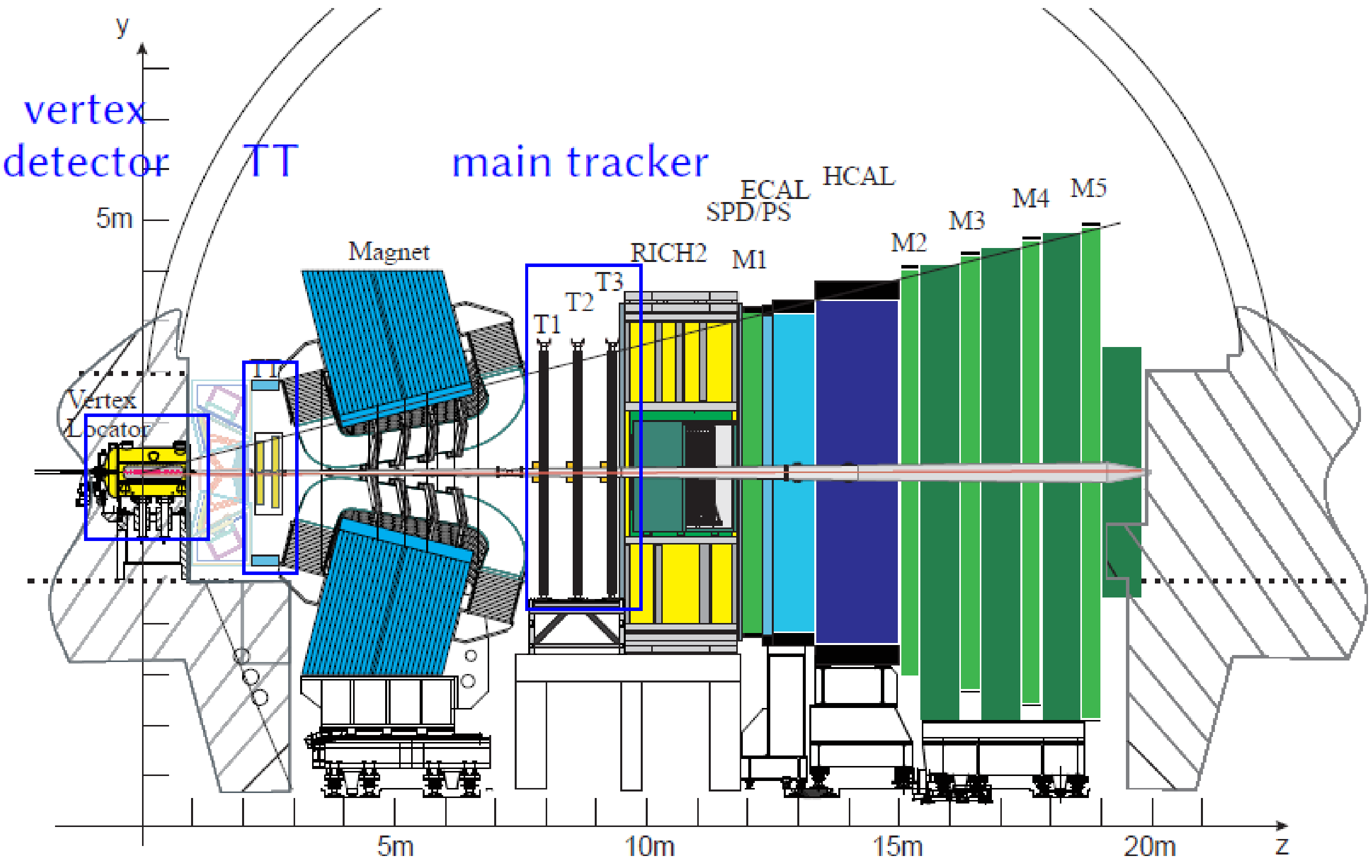
- **LHCb** is dedicated for studying **heavy quark flavour physics**
- It is a **single arm forward spectrometer** with pseudo rapidity coverage **$2 < \eta < 5$**
- Precise tracking system
  - Vertex detector **VELO**
  - Upstream and downstream tracking stations
  - 4 Tm warm dipole magnet
- Particle identification system
  - RICH detectors
  - Calorimeters
  - Muon stations
- Partial information from calorimeters and muon system contribute to **L0 trigger** (hardware) that works at LHC clock – **40 MHz**
- **Full** detector readout at **1 MHz**

Introduction – LHCb detector

- Although LHCb became a versatile general purpose forward physics experiment its main goal is **precise flavour physics**
- **Complementary** approach w.r.t. Atlas and CMS
  - **Indirect** searches for New Physics using quantum loops
- In order to accomplish this we need to **provide**
  - superb **tracking** – momentum resolution $\frac{\Delta p}{p} \sim \mathbf{0.3 - 0.5}\,\%$
  - excellent **vertexing** (primary and secondary) and geometrical **impact parameter** resolutions
  - **decay time resolution** $\sim \mathbf{40 - 50}\,\boldsymbol{fs}$ (depending on the decay mode)
  - excellent **PID** (Particle IDentification)

Introduction – LHCb detector

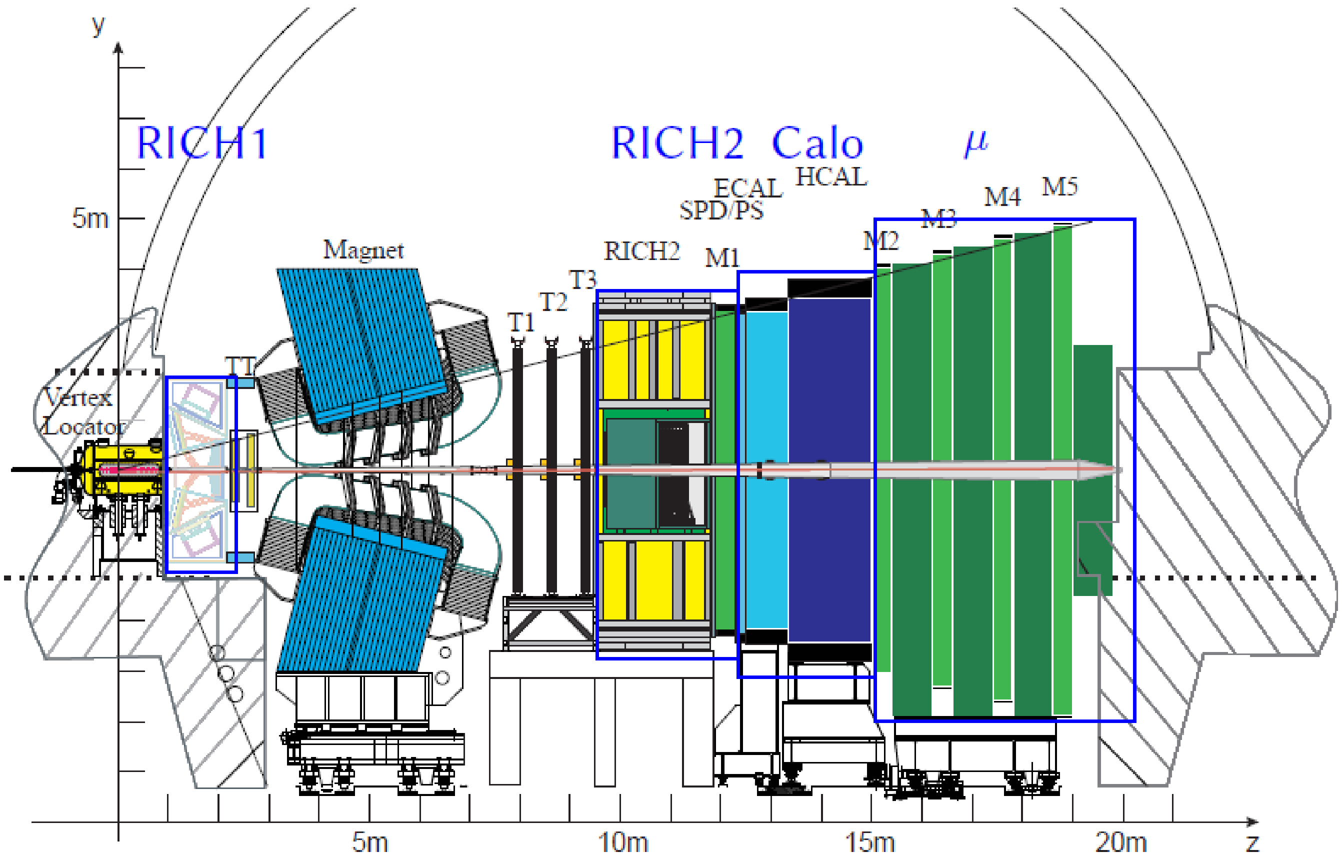
- Tracking system – precise momentum reconstruction, vertexing, decay time resolution



[JINST 3 (2008) S08005]

Introduction – LHCb detector

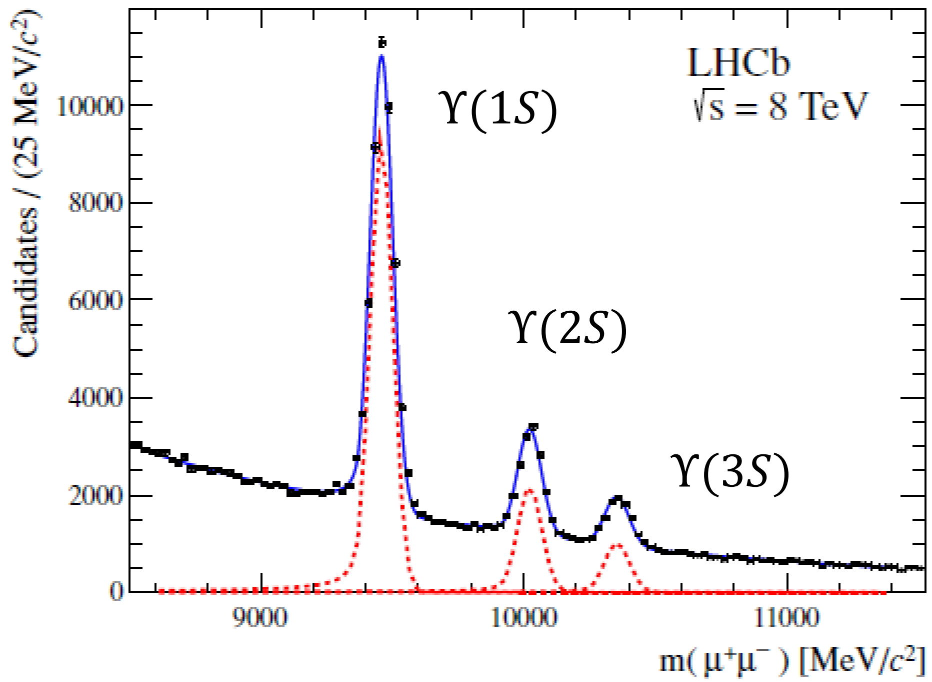
- Excellent PID using RICH detectors (cover different momentum range), calorimeters and muon chambers in concert



[JINST 3 (2008) S08005]

LHCb detector performance

- Performance of the LHCb detector is constantly checked – its performance has a direct impact on physics results
- **Mass resolution**



[J. High Energy Phys. 06 (2013) 064]

LHCb detector performance

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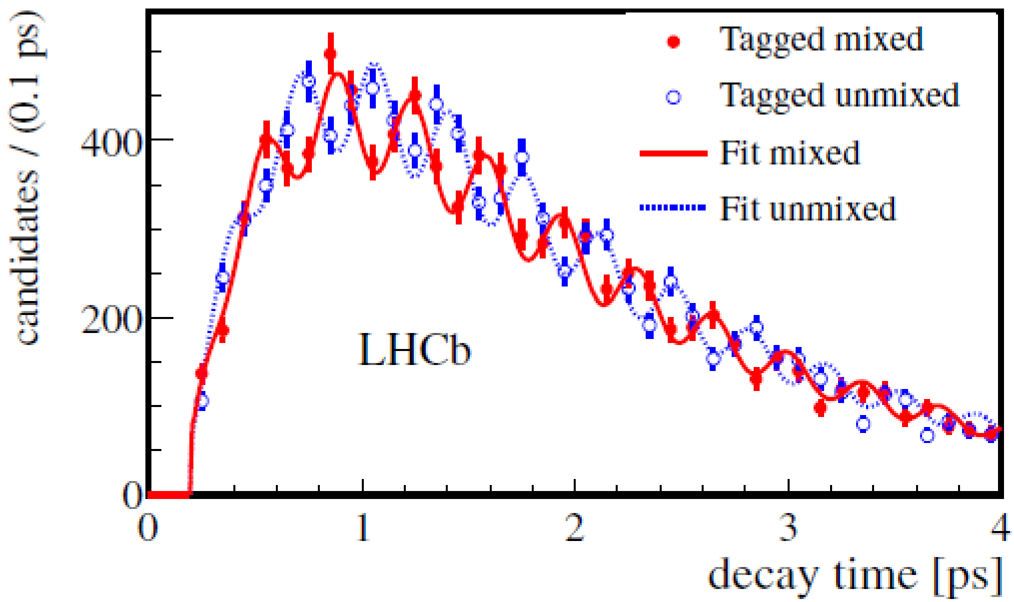
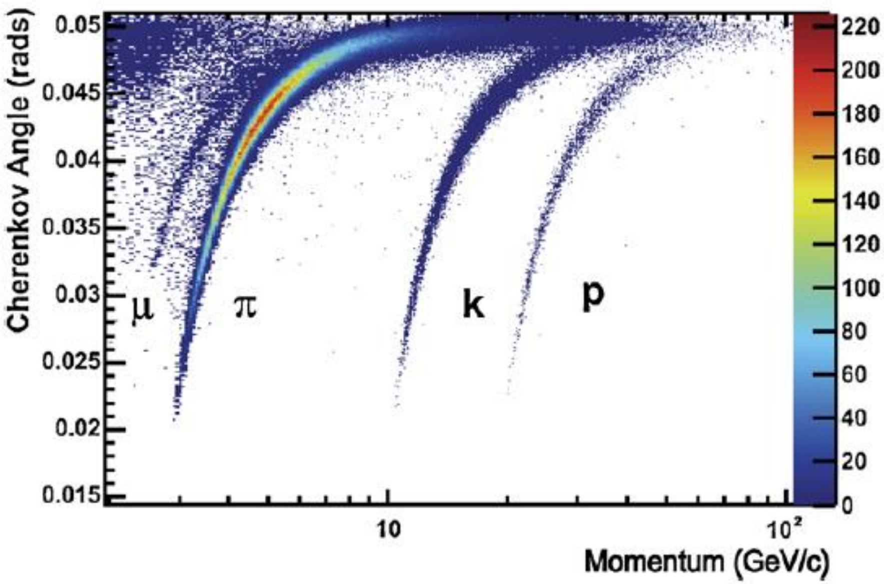
- **Decay time**

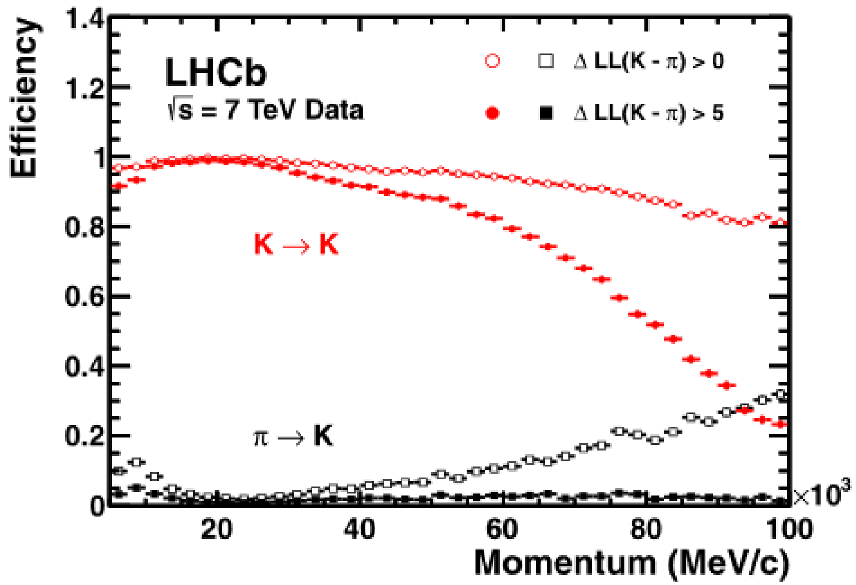


[New J. Phys. 15 (2013) 053021]

LHCb detector performance

- Performance of the LHCb detector is constantly checked – its performance has a direct impact on physics results
- **PID**



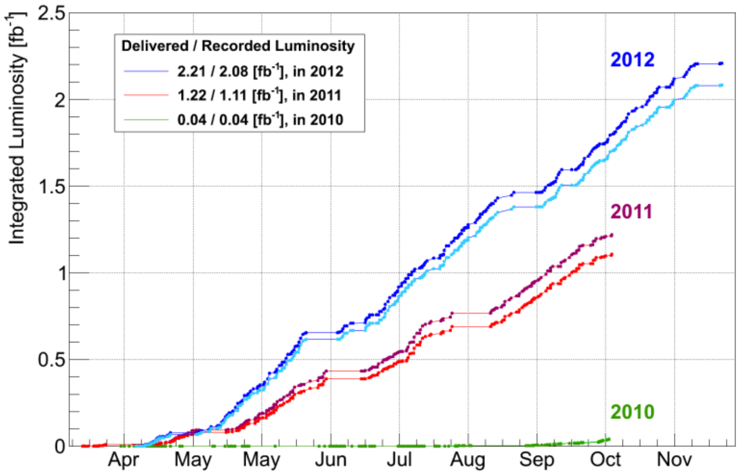


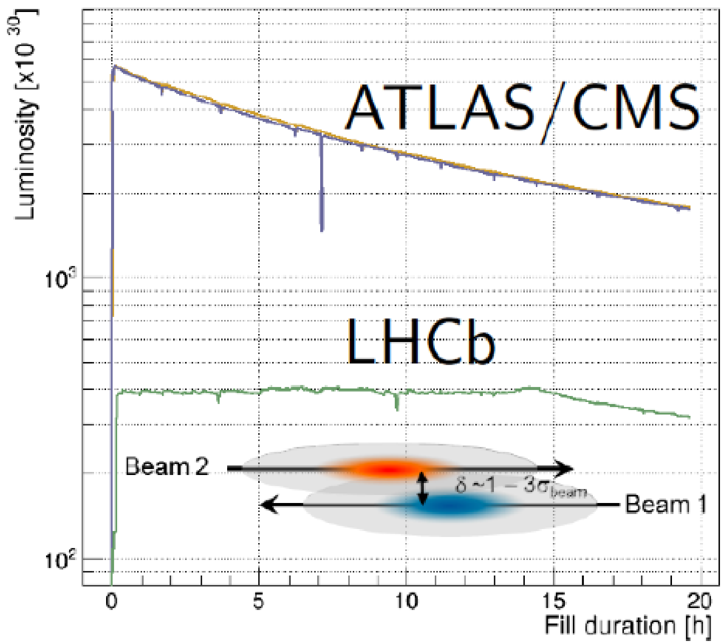
[Eur. Phys. J. C 73 (2013) 2431]

Highlights from RUN I

Operation conditions of the LHCb in 2011 / 2012

- **Beam energy** 3.5 / 4.0 [TeV] (15 % increase of the $b\bar{b}$ x-section)
- Keep the luminosity at L_{inst} = 4.0 x 10^{32} [$cm^{-2}s^{-1}$] both years at the constant value by the means of **leveling**
- Average number of **visible interactions** per x-ing slightly higher μ = 1.4 / 1.6
- HLT (High Level Trigger) **input** ~ 1.0 MHz, **output** ~ 3.0 / 5.0 kHz (upgraded HLT farm and revisited code)
- **Collected** ~ 1.2 / 2.1 fb^{-1} of collision data





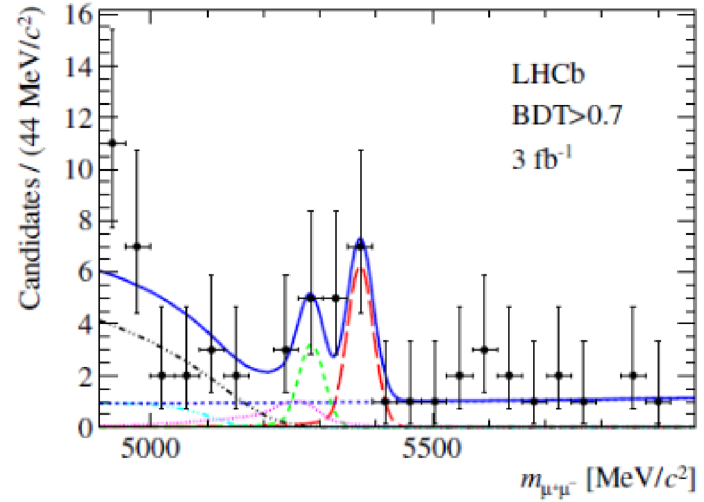
Highlights from RUN I

$B^0_{d(s)} \to \mu^+\mu^-$

- Full data sample from Run I analysed

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.9\,^{+1.1}_{-1.0}(\text{stat})\,^{+0.3}_{-0.1}(\text{syst})) \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.7\,^{+2.4}_{-2.1}(\text{stat})\,^{+0.6}_{-0.4}(\text{syst})) \times 10^{-10}$$

[Phys. Rev. Lett. 111 (2013) 101804]

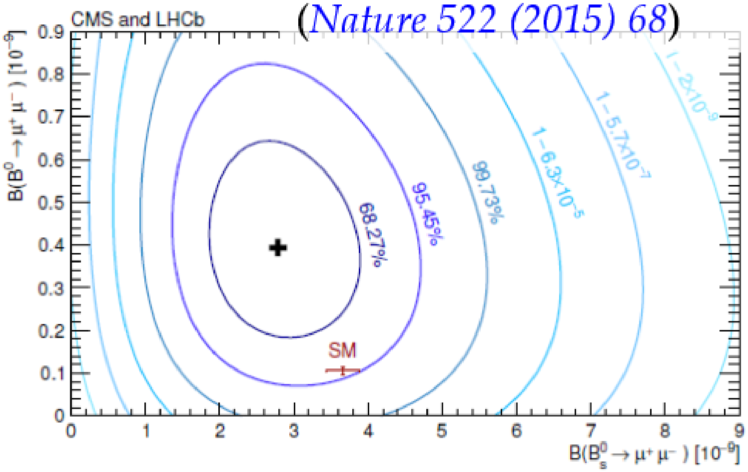


Combined with CMS (joint likelihood fit)

6.2σ observation of $B_s \to \mu\mu$
3.0σ evidence for $B_d \to \mu\mu$

$$\boxed{\begin{aligned}\mathcal{BR}(B_s \to \mu^+\mu^-) &= 2.8^{+0.7}_{-0.6} \times 10^{-9}\\ \mathcal{BR}(B_d \to \mu^+\mu^-) &= 3.9^{+1.6}_{-1.4} \times 10^{-10}\end{aligned}}$$

(*Nature 522 (2015) 68*)



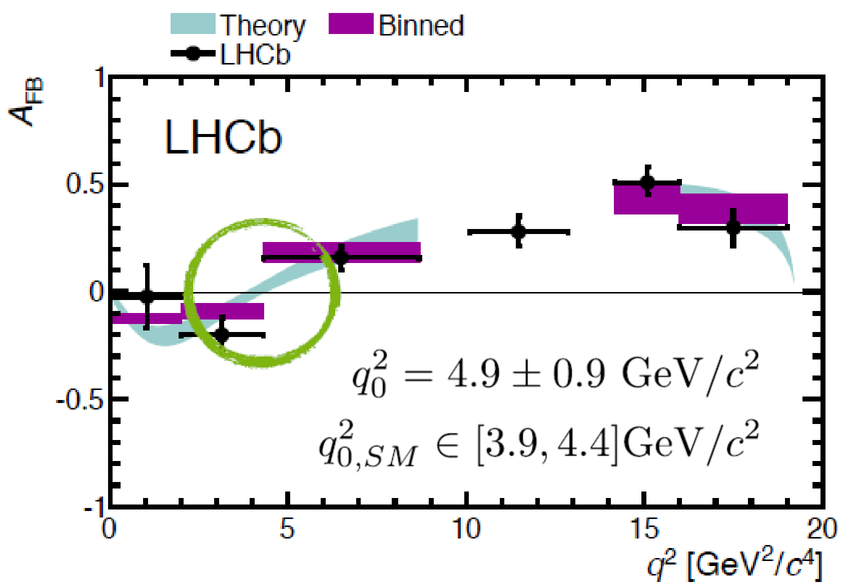
Ratio B_s/B_d BF's agreement with SM at 2.3σ

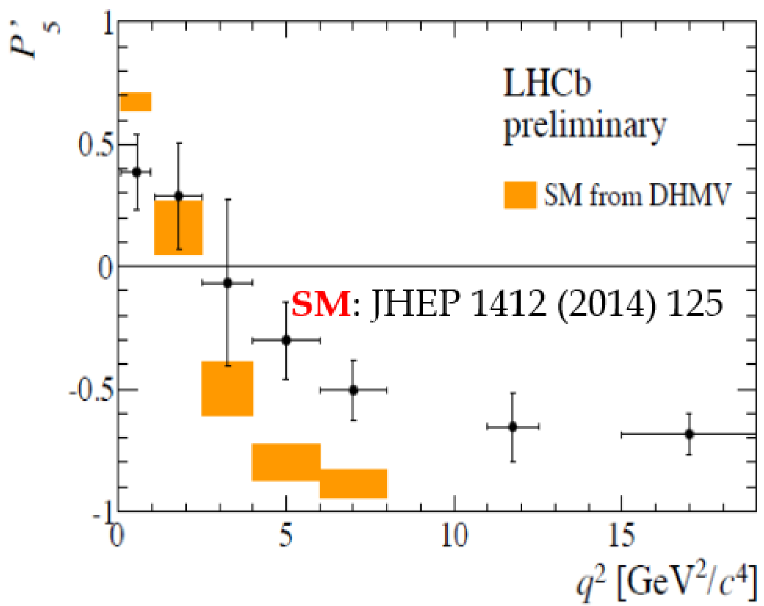
Highlights from RUN I

$B^0 \rightarrow K^*\mu^+\mu^-$: NP in loops

- Observed forward-backward asymmetry very similar to that predicted by the SM – **world best measurement**
- Cannot clearly state any discrepancy – sample limitation
- New base of observables proposed
- Reduced dependency on hadronic form factors
- Observed discrepancy may be a hint of new heavy neutral Z' particle

[LHCb-CONF-2015-002]





[PRL 111, 191801 (2013)], new paper summarising Run I results is under way

Highlights from RUN I

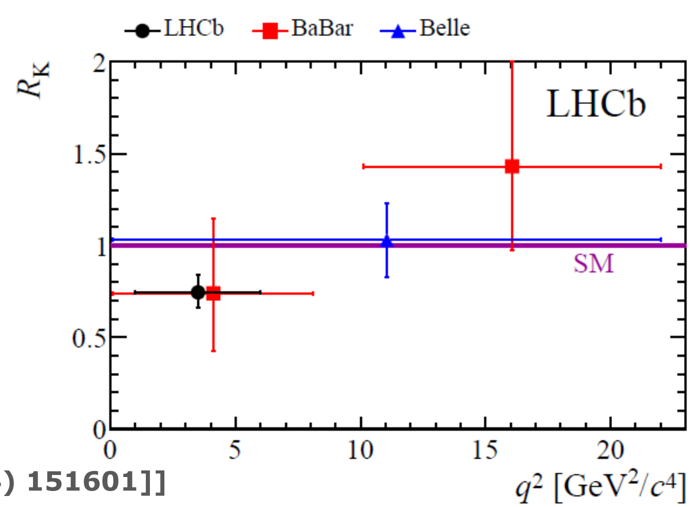
Lepton universality tests with $B^+ \to K^+ l^+ l^-$

- Measured the ratio of branching fractions

$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+ \mu^+ \mu^-]}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+ e^+ e^-]}{dq^2} dq^2}$$

- The most precise results to date
- Observed deviation from the SM close to 3 σ

$$R_K = 0.745^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})$$



[Phys. Rev.Lett. 113 (2014) 151601]]

Highlights from RUN I - Summary

LHCb:

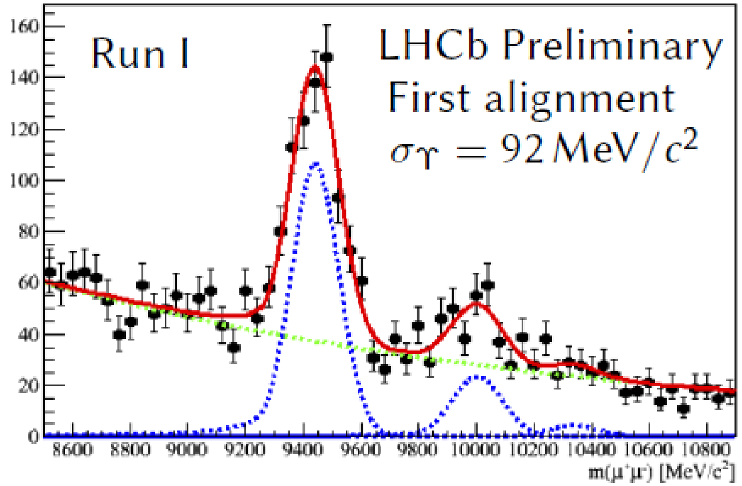
- Superb performance – greatly exceeded any expectations
- Stable operation at inst. luminosity **100%** higher than nominal
- **General purpose detector in forward direction**
- Many world leading results
- **Over 250 papers published!**

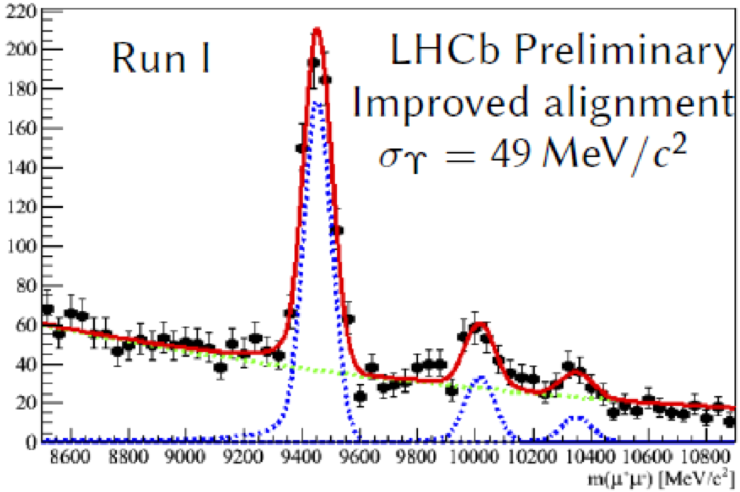
The SM is standing tall:

- No conclusive BSM physics discovered
- There is still room for NP!
- Need push **precision** to the limits in order to challenge theoretical predictions
- **Some intriguing anomalies ($\sim 3 - 4\,\sigma$) are present**
- **Need more data to check if this is New Physics looking over our shoulders…**

Real-time detector alignment and calibration

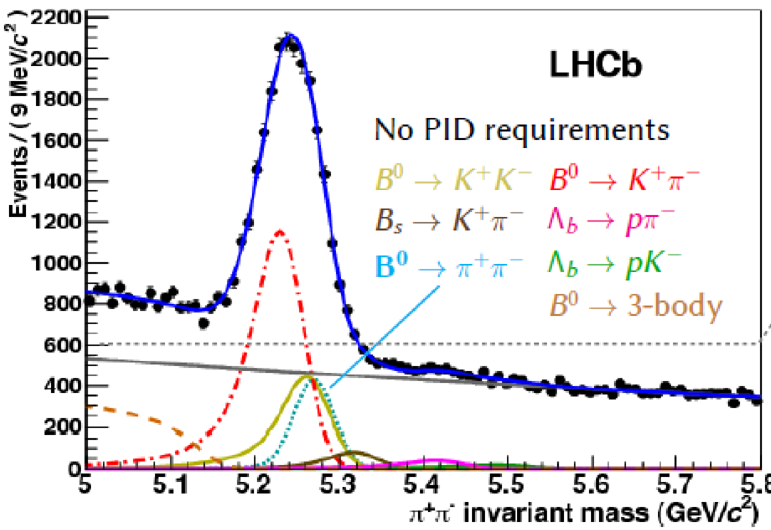
- **Novel** approach to on-line trigger system for a HEP experiment
  - Provide **off-line quality** tracking in real-time
  - Need to have robust and reliable procedure for **fill-by-fill calibration and alignment**
- Detector alignment has critical impact on physics performance of the experiment
  - Topological trigger (separation of beauty and charm)
  - Momentum resolution $\frac{\Delta p}{p}$

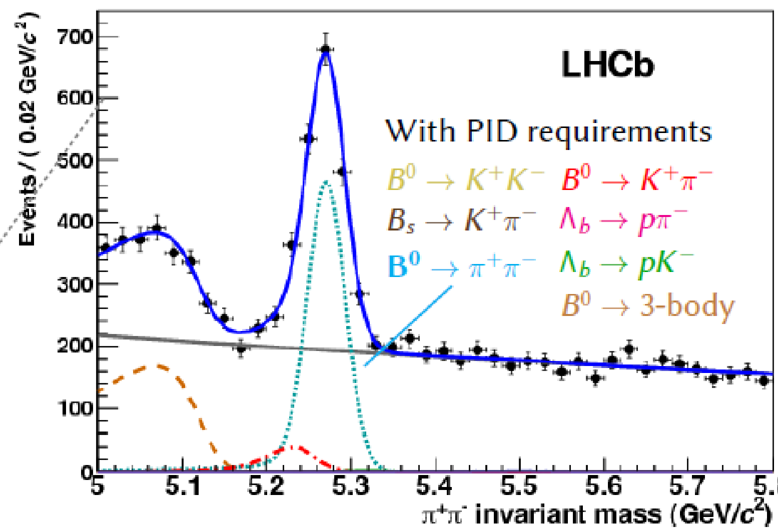




Real-time detector alignment and calibration

- Harsh hadronic environment
- Selection criteria must be tight in order to select required signal samples containing hadronic decays
- Must provide excellent RICH calibration





[Eur. Phys. J. C 73 (2013) 2431]

LHCb Trigger - Introduction

- **RUN I** (already heavily revised comparing to the original specs)

Machine

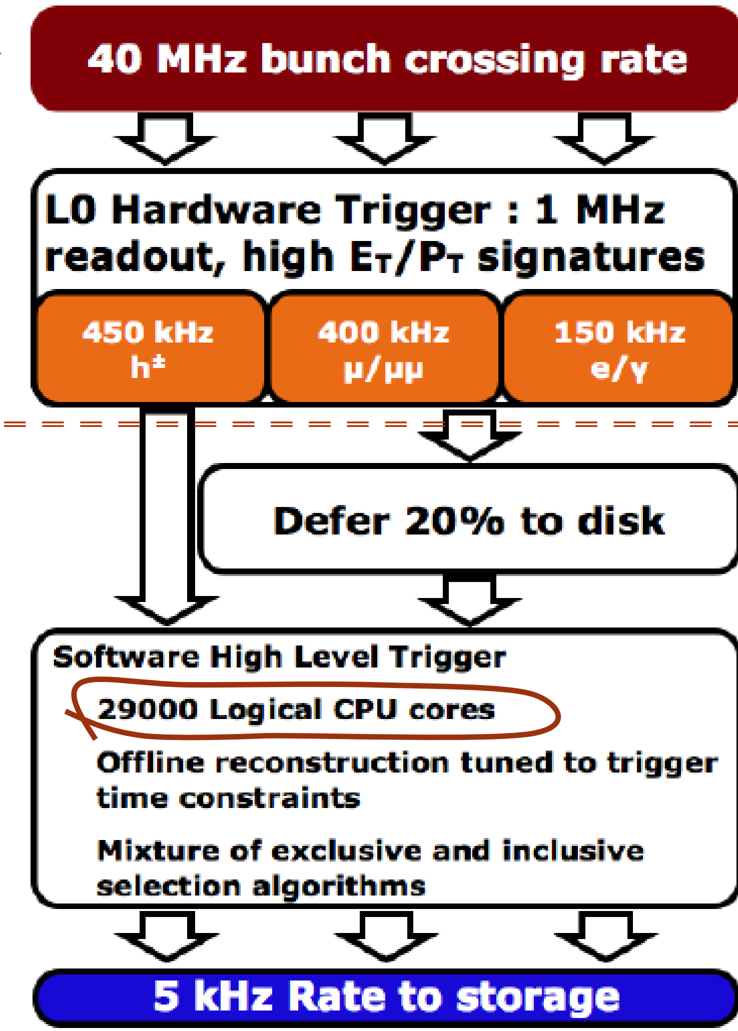
Hardware trigger layer – **L0**

1 MHz full detector read-out

Software trigger layer – **HLT**

Data buffer

Storage



Enhanced trigger for RUN II

- **RUN II** (major revision of the trigger system)

Machine

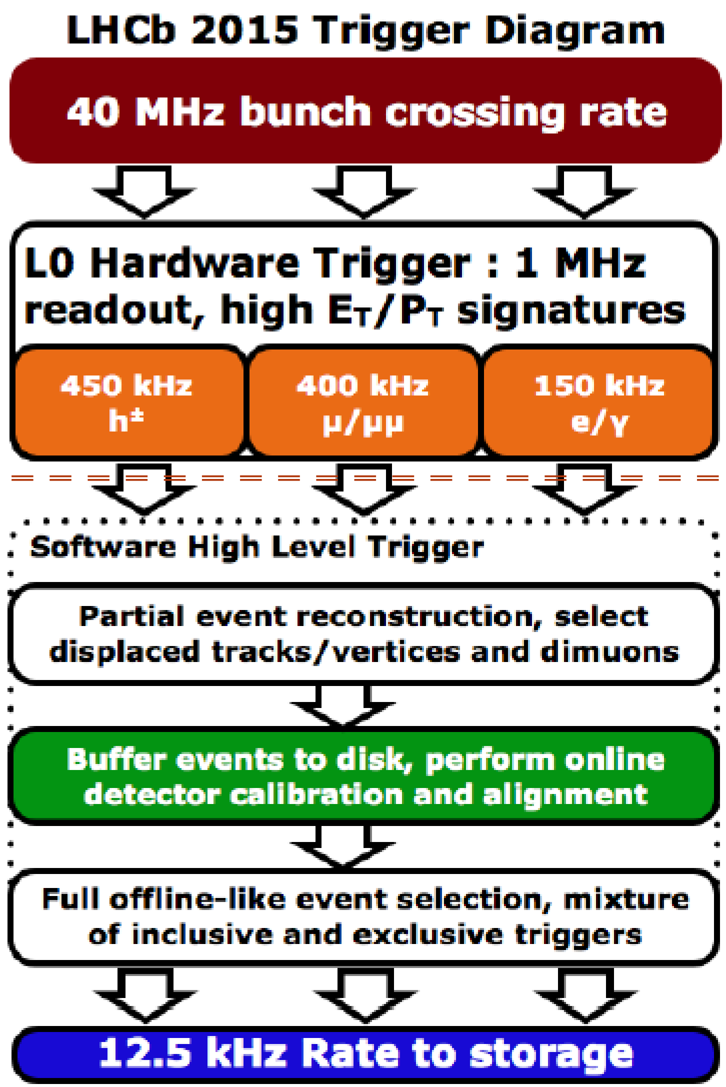
Hardware trigger layer – **L0**

1 MHz full detector read-out

Splitted– HLT

Data buffer

Storage



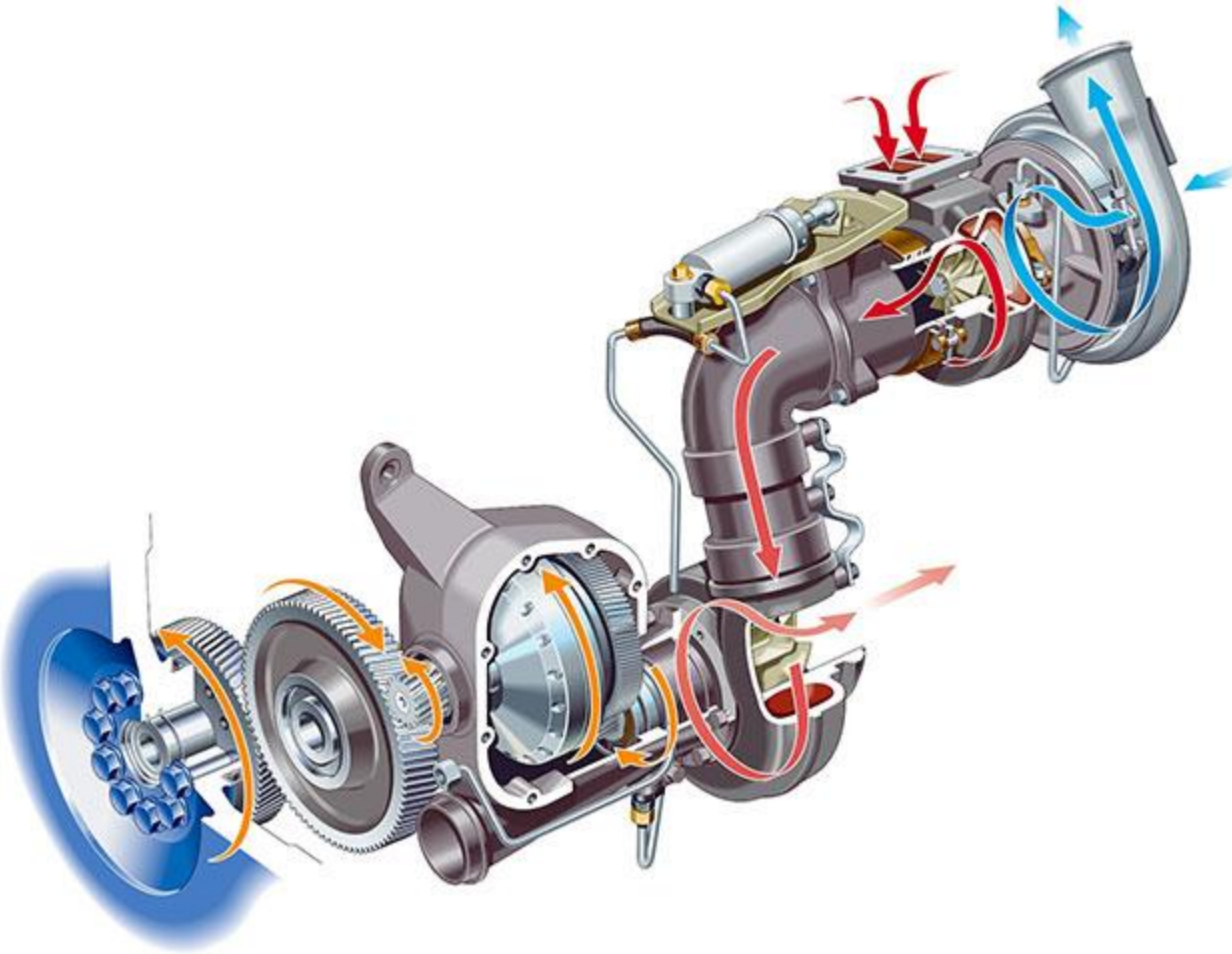
Enhanced trigger for RUN II - alignment

- The procedure uses **tracks reconstructed** in the LHCb tracker and muon stations
- **Iterative** approach
  - Perform reconstruction using the „**old**” alignment consts.
  - Determine new consts. by global χ^2 minimisation
  - **Repeat** the above till **below** the threshold ($\Delta\chi^2$)
- New set of parameters are ready for HLT2 processing **after several minutes**
- The most sensitive part is the **vertex detector** – new parameters are calculated for **each fill**
- Other tracking detectors much more stable (new consts. needed every few weeks)
- **RICH** mirrors alignment included in this framework

Enhanced trigger for RUN II - calibration

- **RICH** calibration
  - Gas refractive index
  - HPD images distorted due to electric/magnetic field
- Drift time in **gaseous tracking** detectors
  - Mismatch between the LHC and LHCb clocks
- **Calorimeter** calibration
  - Gain equalisation
    - Occupancy method
    - Neutral pion mass position

That’s not all – introducing TURBO

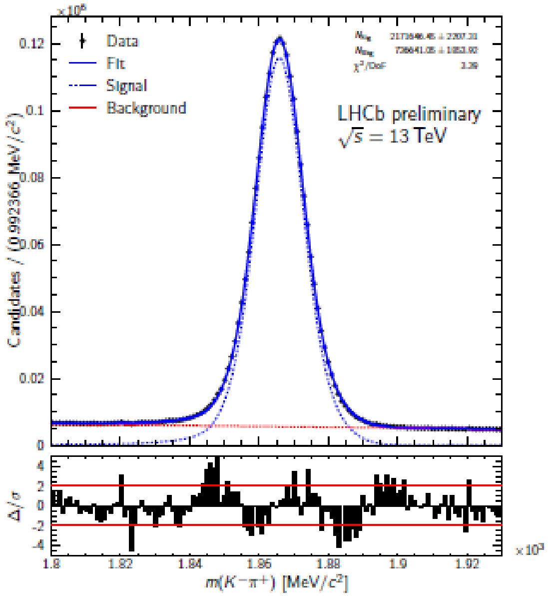


That's not all – introducing TURBO

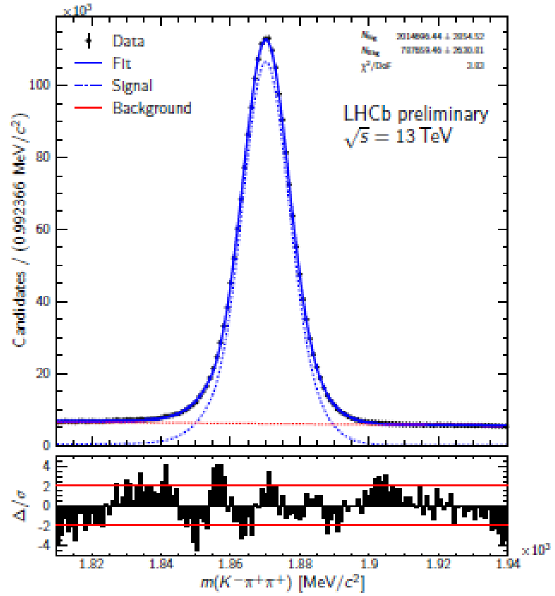
- **This idea is quite amazing!**
- Out of the $12.5\ kHz$ of the output stream $\boldsymbol{\sim 5\ kHz}$ is dedicated to the **TURBO stream**
- The central idea is to save only the **trigger level objects** that caused it to „**fire**"
  - **Tracks** and **vertices**
  - **No raw data** is stored for the TURBO
- Huge gain
  - The event size is **much smaller**
  - **No** reprocessing
  - Analysis much faster
- Used for **high yield** exclusive modes (charm)

That’s not all – introducing TURBO

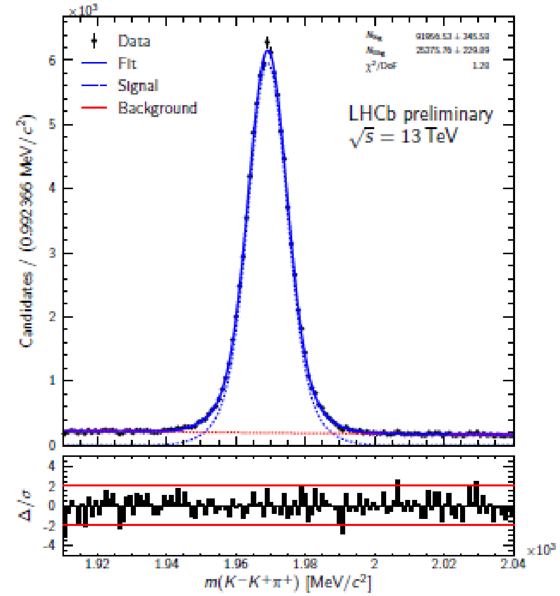
- **The TURBO** stream has been commissioning this year and is performing superbly
- Below plots obtained directly after the HLT



$D^0 \to K^-\pi^+$



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



$D_s^+ \to K^-K^+\pi^+$

- Background almost non existent – tribute for the excellent LHCb tracking performance – off-line tracking quality in the HLT
- The number of events is much higher than that in RUN I

Selected resuts for the RUN II data

- The LHCb detector started to collect data at $\sqrt{s} = 13\ TeV$
- Thanks to excellent performance of the tracking and PID LHCb is well suited for contributing to various QCD tests in the forward direction
  - Unique kinematical coverage at LHC
- Will present cross-section measurements for:
  - prompt J/ψ mesons
  - J/ψ mesons from b-hadrons
  - prompt charm mesons
- Previously performed for $\sqrt{s} = 2.76\ TeV, 7\ \mathrm{TeV}$ and $8\ TeV$

Selected resuts for the RUN II data

- **The measurement technique**
  - The double-differential cross-section expressed as a function of the transverse momentum and rapidity

$$\frac{d^2\sigma_i(H)}{dp_T dy} = \frac{1}{\Delta p_T \Delta y} \cdot \frac{N_i(H \to f + \text{c.c.})}{\varepsilon_{i,\text{tot}}(H \to f) \cdot \Gamma(H \to f) \cdot \mathcal{L}_{\text{int}}}$$

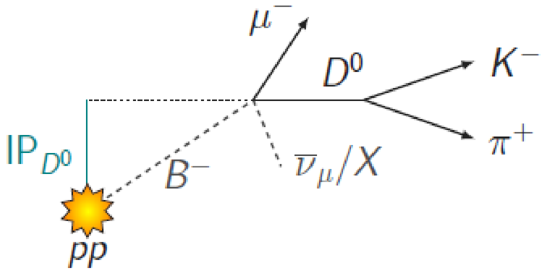
  - Count events N_i decaying to a given final state f
  - The main experimental difficulty is to distinguish prompt decays coming from the PV from the secondary signal
    - use pseudo-lifetime for J/ψ
    - and impact parameter significance for open charm decays
  - Luminosity – precise measurement thanks to the **SMOG**
    - $\mathcal{L}_{int}^{J/\psi, b\bar{b}} = (3.05 \pm 0.12)\, pb^{-1}$
    - $\mathcal{L}_{int}^{c\bar{c}} = (4.98 \pm 0.19)\, pb^{-1}$

Selected resuts for the RUN II data

- **Signal extraction**
  - J/ψ meson production studied using the $J/\psi \to \mu^+\mu^-$ decay mode
  - The fraction of J/ψ's originating from b-hadron decays estimated using **pseudo-lifetime** variable

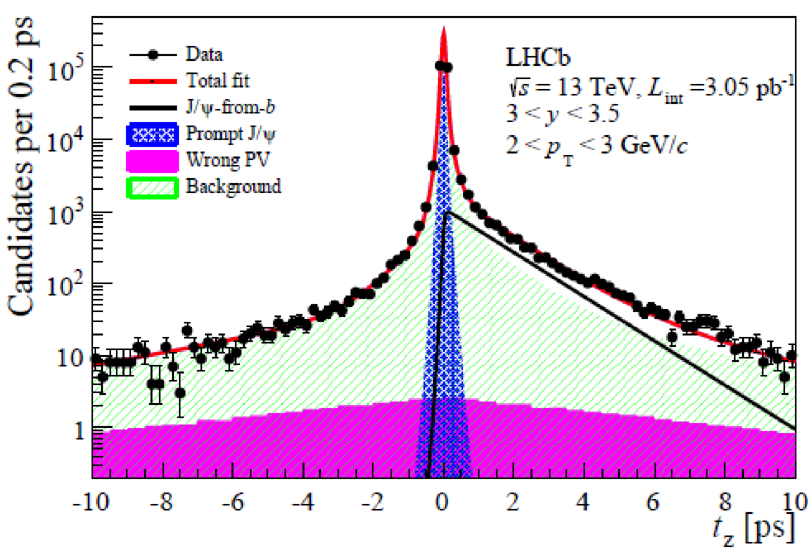
$$t_z = \frac{(z_{J/\psi} - z_{PV}) \cdot M_{J/\psi}}{p_z}$$

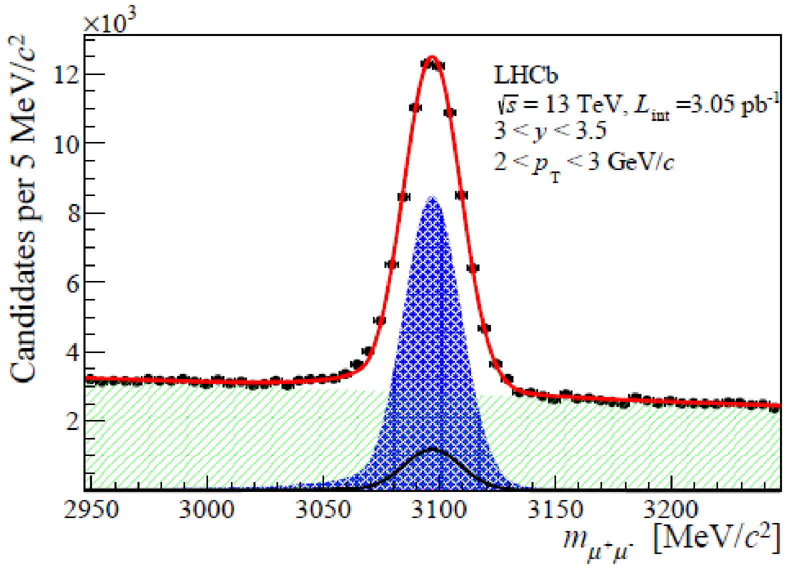
  - For the charm mesons studies the following decay modes were used: $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D_s^+ \to K^-K^+\pi^+$ and $D^{*+} \to D^0\pi^+$
  - Use **impact parameter** significance, χ^2_{IP}, to separate the secondary charm mesons



Selected resuts for the RUN II data

- **Signal extraction J/ψ**
  - 2D unbinned extended ML fits for each $p_T - y$ bin





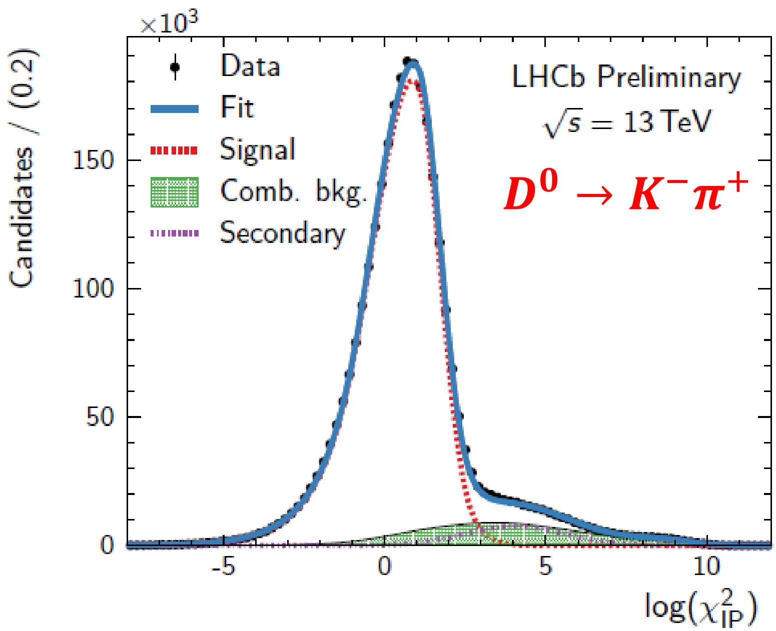
Separate secondary J/ψ mesons

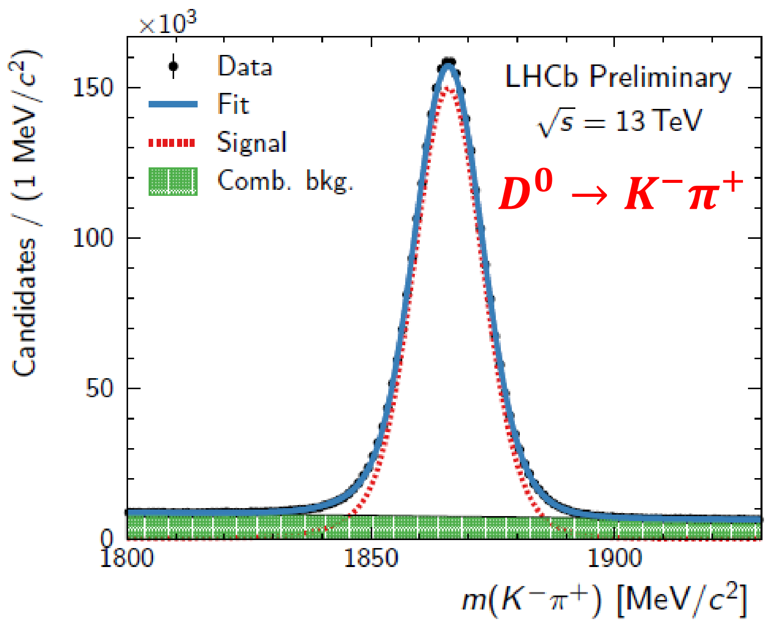
Distinguish signal and bkg. by fitting the mass $m_{\mu^+\mu^-}$

[arXiv:1509.00771]

Selected resuts for the RUN II data

- **Signal extraction charm**
  - Two 1D binned extended ML fits performer simultaneously for all bins





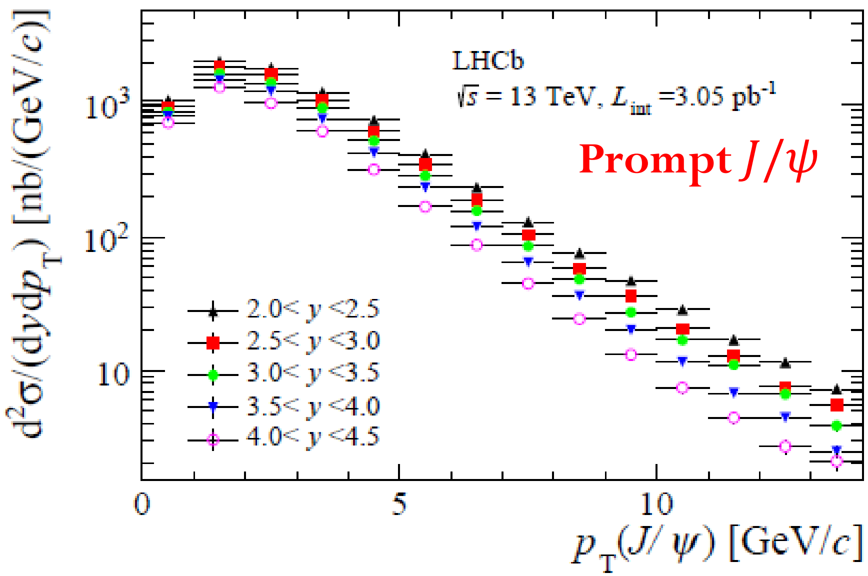
Separate secondary mesons using χ^2_{IP}

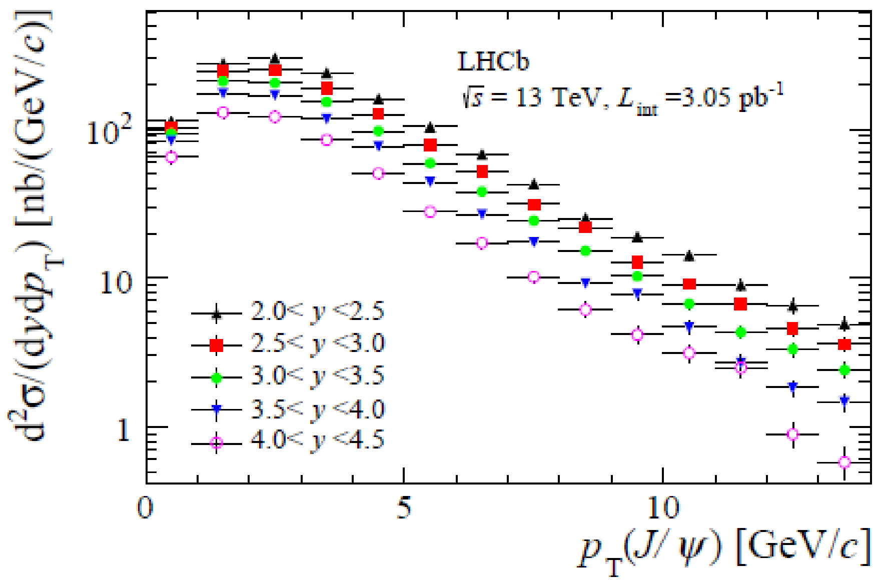
Separate signal and bkg. by fitting the mass of a given decaying hadron

[ArXiV:1510.01707]

Selected resuts for the RUN II data

- ❑ J/ψ cross-section measurement (prompt and secondary)





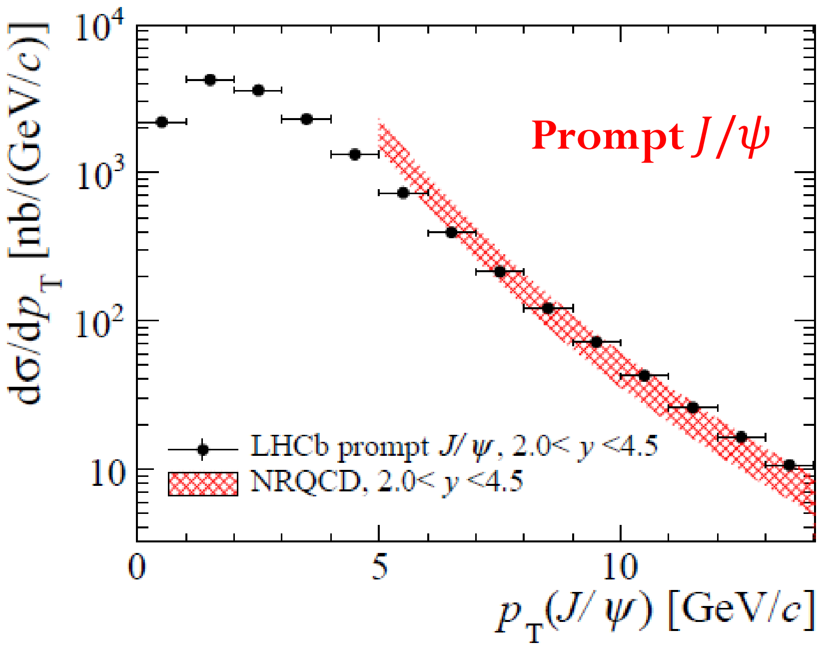
$$\sigma^{J/\psi}_{prompt} = 15.30 \pm 0.03\,(stat) \pm 0.86\,(sys)\,\mu b$$

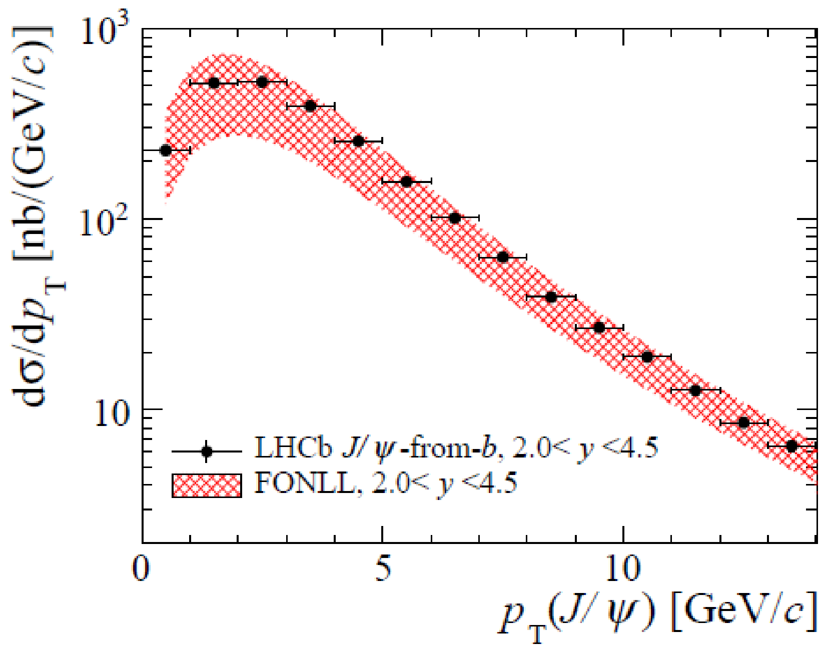
$$\sigma^{J/\psi}_{from-B} = 2.34 \pm 0.01\,(stat) \pm 0.13\,(sys)\,\mu b$$

$$\sigma^{b\bar{b}} = 515.0 \pm 2.0\,(stat) \pm 53.0\,(sys)\,\mu b$$

Selected resuts for the RUN II data

- Comparison with theory - J/ψ production
  - cross sections integrated over rapidity - $2 < y < 4.5$





NRQCD model for the prompt J/ψ production

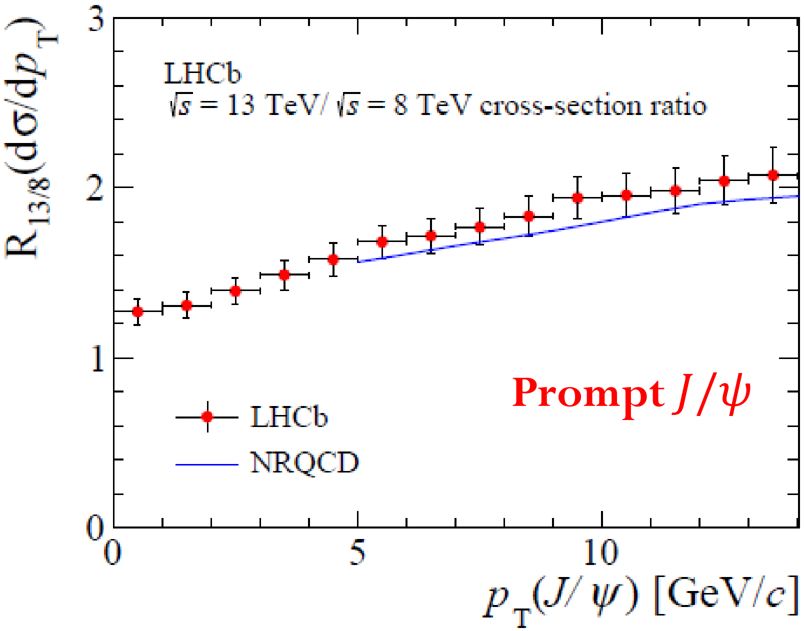
[Shao et al., JHEP 1505 (2015) 103]

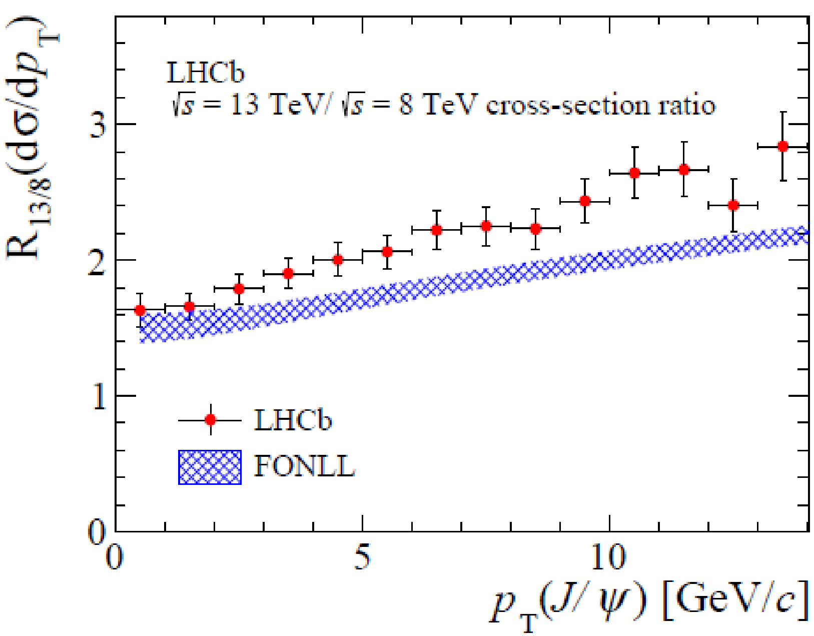
FONLL model for the b-hadron J/ψ production

[Cacciari et al., JHEP 1210 (2012) 137]

Selected resuts for the RUN II data

- Can also compare the results from $13\,TeV$ data sample with the previously measured cross-sections at $8\,TeV$





NRQCD model for the prompt J/ψ production

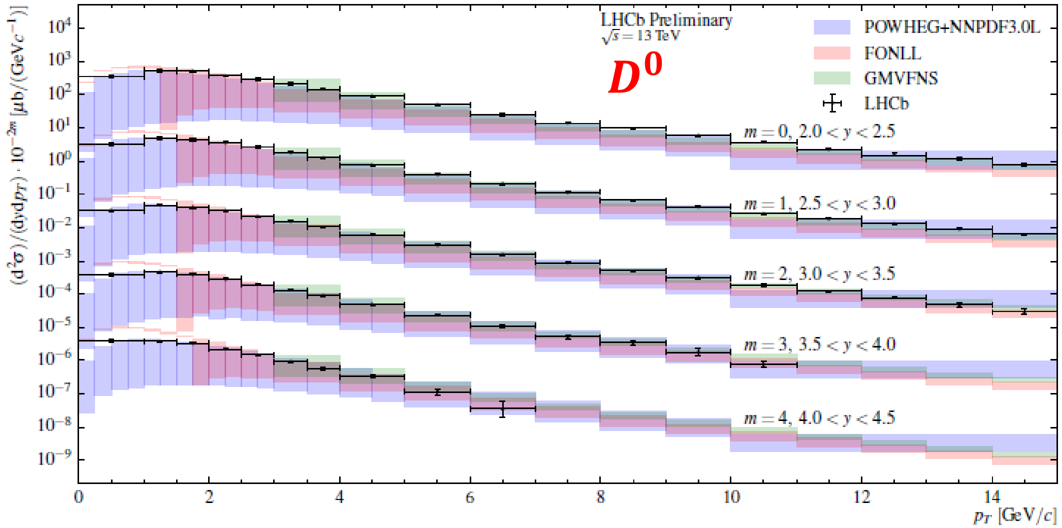
[Shao et al., JHEP 1505 (2015) 103]

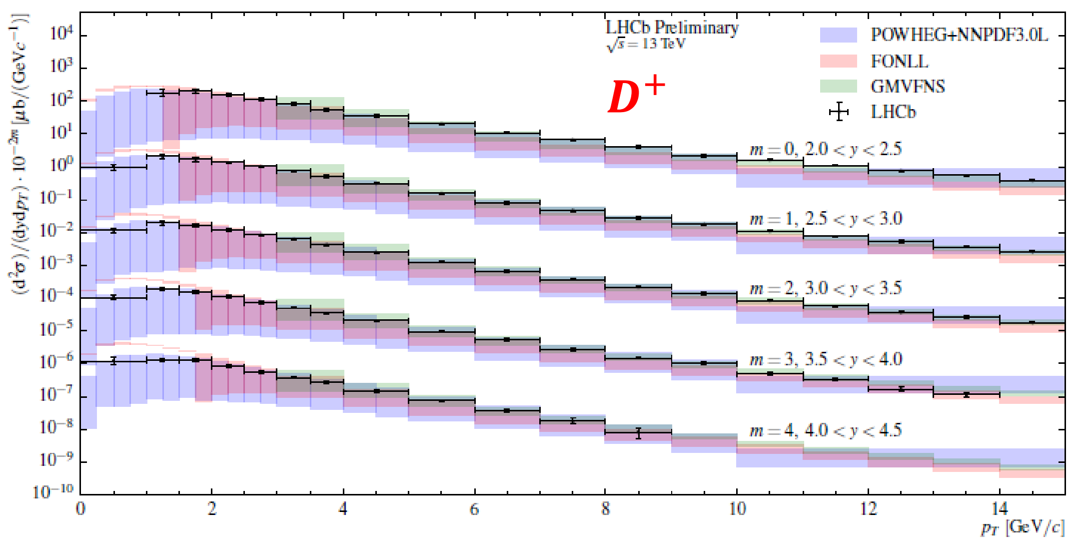
FONLL model for the b-hadron J/ψ production

[Cacciari et al., JHEP 1210 (2012) 137]

Selected resuts for the RUN II data

- Charm meson cross-sections





Selected resuts for the RUN II data

- Measured values for respective charm mesons (μb)

$$\sigma_{prompt}^{D^0} = 3370 \pm 4\,(stat) \pm 200\,(sys)\ \mu b$$

$$\sigma_{prompt}^{D^+} = 1290 \pm 8\,(stat) \pm 190\,(sys)\ \mu b$$

$$\sigma_{prompt}^{D_s^+} = 460 \pm 13\,(stat) \pm 100\,(sys)\ \mu b$$

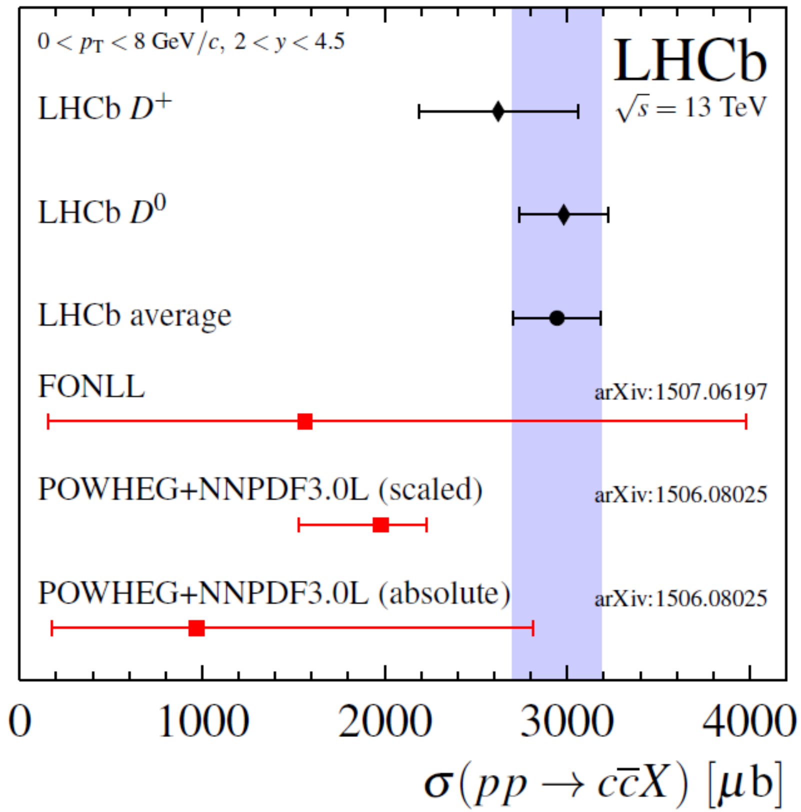
$$\sigma_{prompt}^{D^{*+}} = 880 \pm 5\,(stat) \pm 140\,(sys)\ \mu b$$

- The integrated cross-sections are given in the LHCb acceptance that is defined as follow
  - rapidity range $2 < y < 4.5$
  - transverse momentum of charm meson $0 < p_T < 8\ GeV$

Selected resuts for the RUN II data

- Evaluate total $c\bar{c}$ production cross-section
  - use fragmentation fractions from electron colliders
  - include D^0 and D^+ results only (D_s^* and D^{*+} much smaller)

$$\sigma^{c\bar{c}} = 2940 \pm 3(stat) \pm 180(sys) \pm 160(frag)\ \mu b$$



Summary

- First data taken at $13\,TeV$ after the LS1 period
- Updated trigger performs very well
- Measured various cross-sections using new TURBO stream (selection done at the trigger level)
  - prompt J/ψ
  - J/ψ from b-hadrons
  - total $b\bar{b}$
  - charm mesons D^0, D^+, D_s^+, D^{*+}
  - total $c\bar{c}$
- Two papers are under way

[LHCb-PAPER-2015-037 for J/ψ and $b\bar{b}$]

[LHCb-PAPER-2015-041 $c\bar{c}$]

Back-up

Enhanced trigger for RUN II

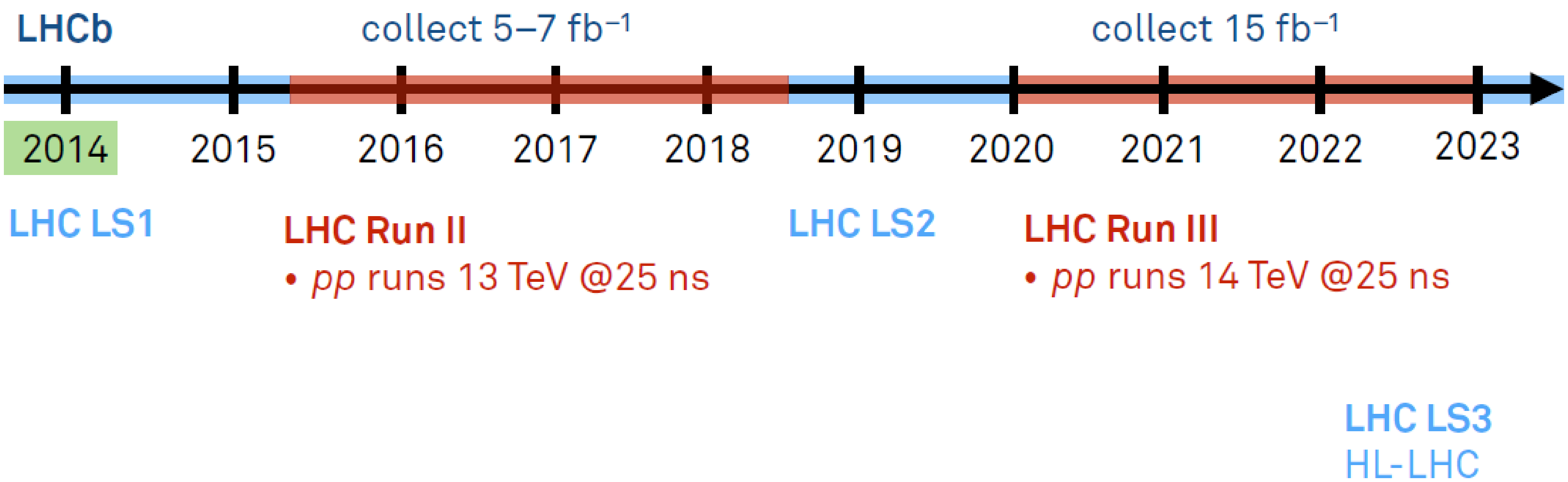
- **RUN I** (already heavily revised comparing to the original specs)
- **L0 trigger** (implemented in hardware)
  - Particles with high p_T or E_T measured by the muon system or calorimeters
  - Max output rate $\sim 1.1\ MHz$ – full event read-out
- **HLT** (High Level Trigger – software implementation)
  - Tunable software platform
  - Run in a huge CPU farm (~ 29000 logical cores)
  - Split into two stages – **HLT1** and **HLT2**
  - HLT1 – L0 decision confirmation
  - HLT2 – inclusive and exclusive selection lines for physics
  - ~ 20% of L0 data defered to local disks (data buffer), processing performer during inter-fill gaps

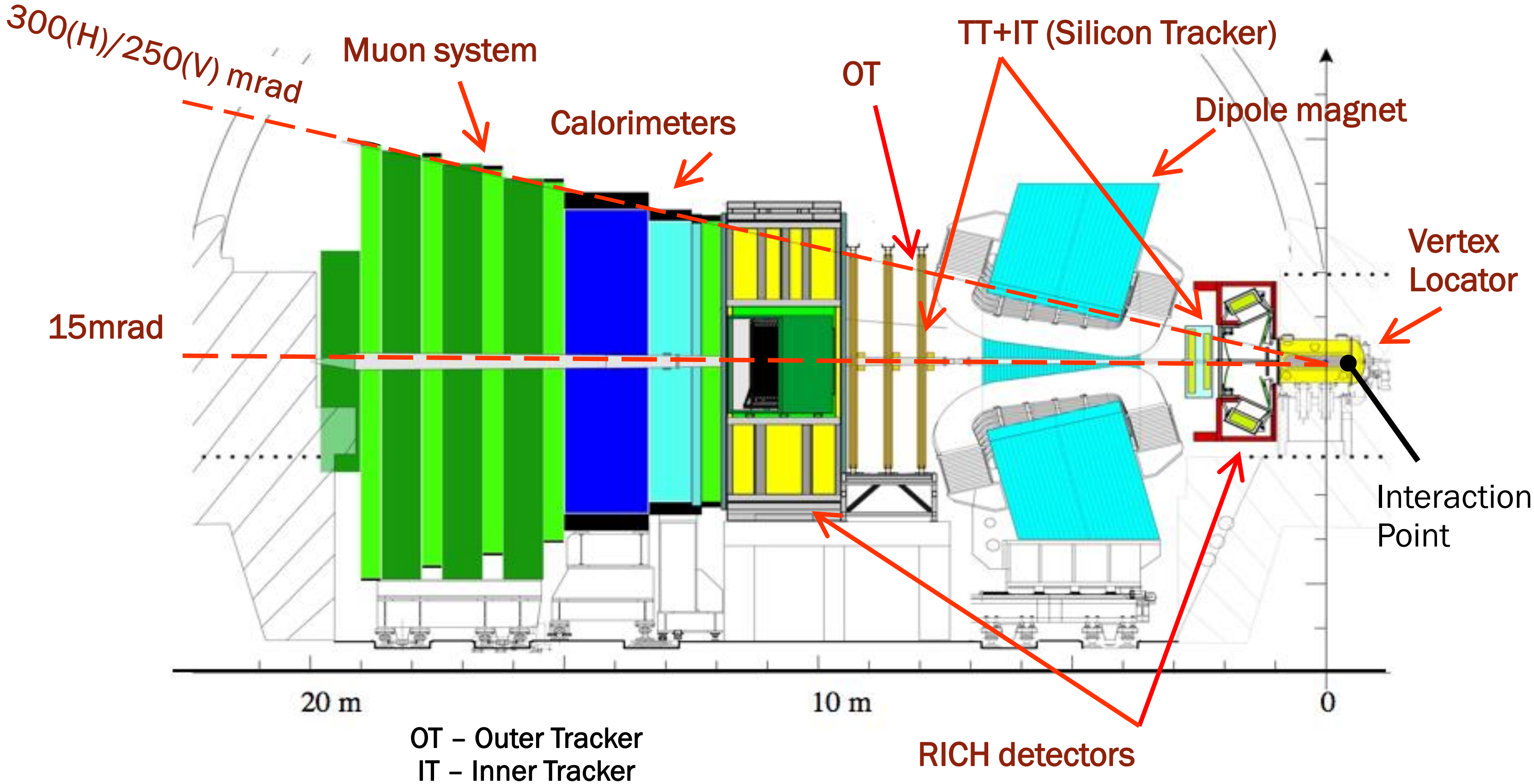
Enhanced trigger for RUN II

- **Novel trigger design for RUN II**
- L0 part remains virtually the same
- **New HLT**
- Refreshed filter farm (CPU/disks) and enhanced software allow for **off-line quality tracking in real-time**!
- Split of the **HLT1** and **HLT2**
  - All data that passed the HLT1 are **deferred to disks**
  - Quasi real-time detector **alignment** and **calibration** before executing the HLT2
  - **Off-line quality tracking available on-line**!
  - Contains PID
  - No need for time consuming track reprocessing – tracking is done only once by the trigger

Summary

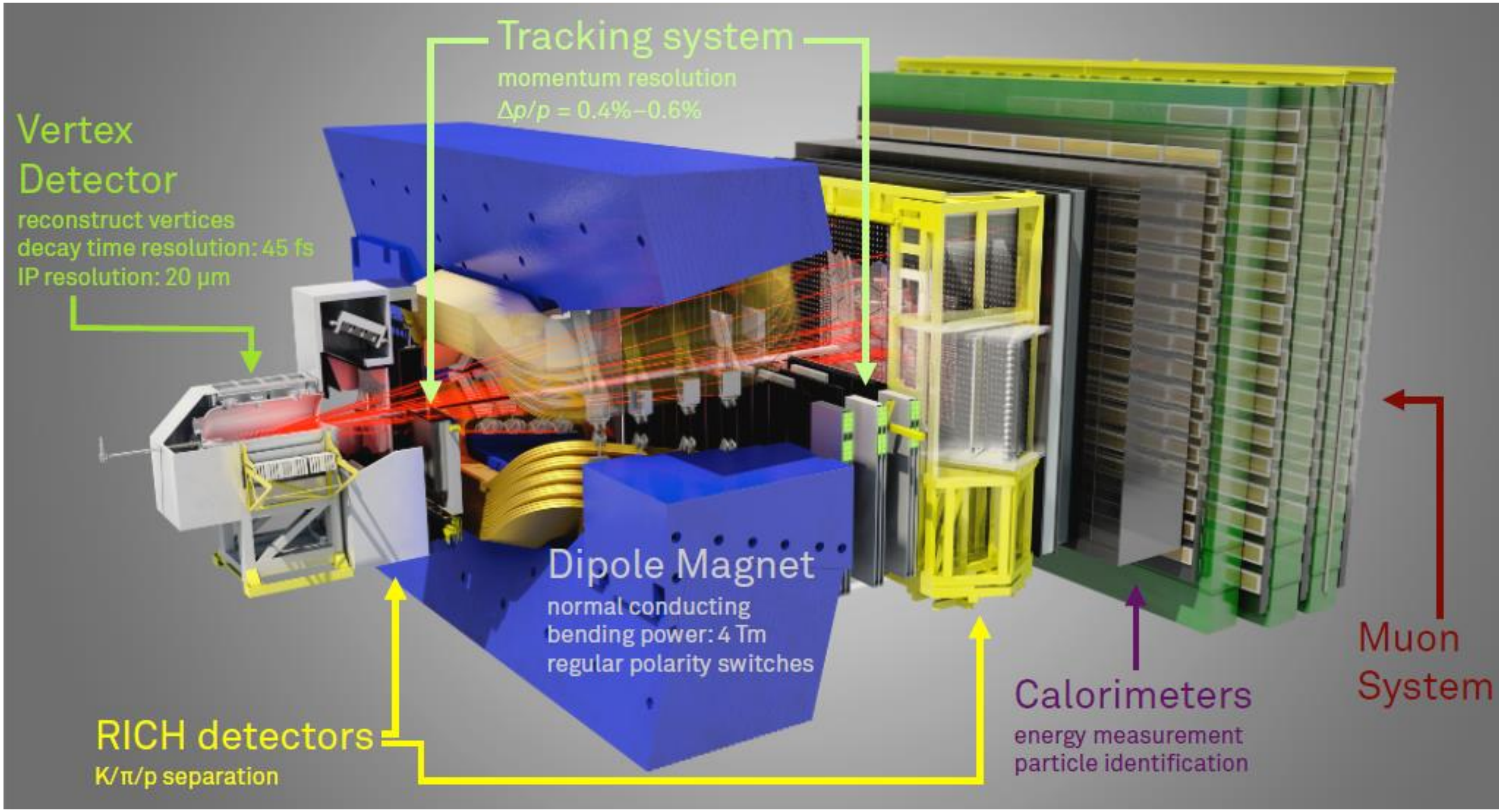
Run II and the upgrade road map





OT – Outer Tracker
IT – Inner Tracker
TT – Trigger Tracker

- Single arm spectrometer geometry
- Fully instrumented in rapidity range $2 < \eta < 5$
- Capable of reconstructing backward tracks ($-4 < \eta < -1.5$)


Tracking system
momentum resolution
Δp/p = 0.4%–0.6%
Vertex
Detector
reconstruct vertices
decay time resolution: 45 fs
IP resolution: 20 μm
Dipole Magnet
normal conducting
bending power: 4 Tm
regular polarity switches
RICH detectors
K/π/p separation
Calorimeters
energy measurement
particle identification
Muon
System

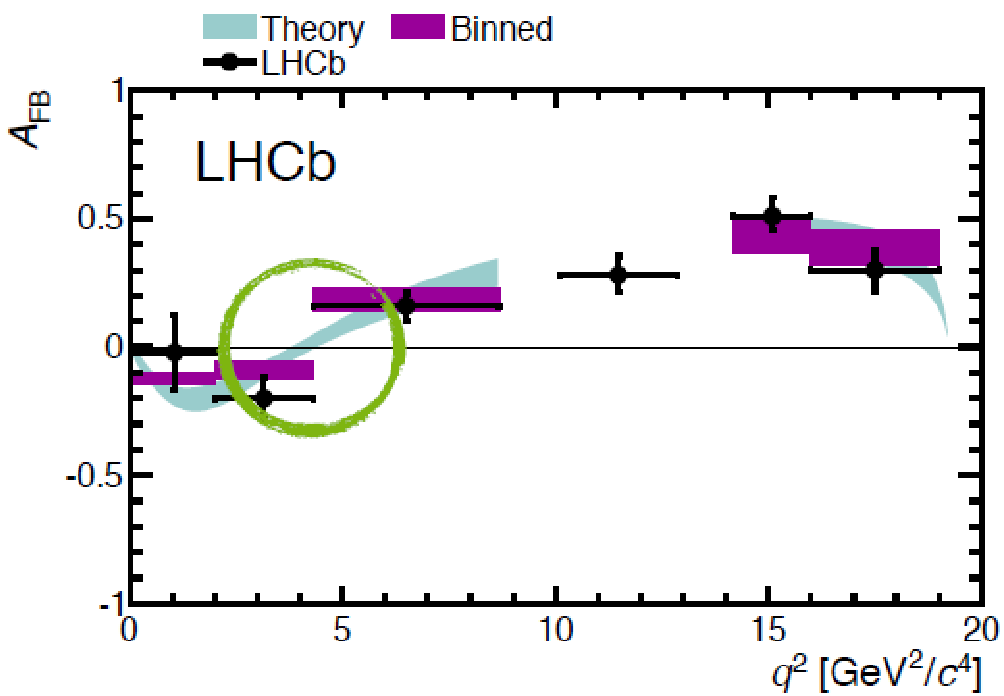
Highlights from RUN I

$B^0 \to K^*\mu^+\mu^-$: NP in loops

- The largest sample collected
- Clear theoretical quantity
- Sensitive to Wilson coefficients
- World's best measurement

$$q_0^2 = 4.9 \pm 0.9 \text{ GeV}/c^2$$

$$q_{0,SM}^2 \in [3.9, 4.4]\text{GeV}/c^2$$



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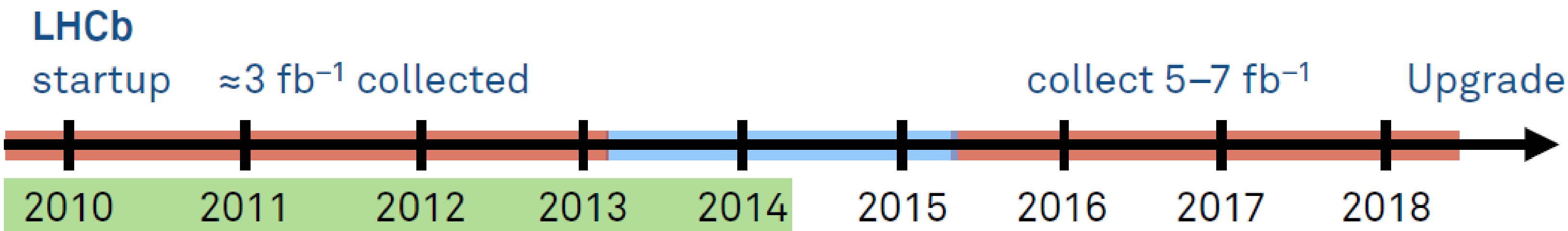
Data taking road map for LHCb before the upgrade



LHC Run I

- *pp* runs @50 ns
  - 7 TeV (2010,2011)
  - 8 TeV (2012)
- Pb Pb run @2.76 TeV
- *p* Pb run @5 TeV

LHC LS1

- repair splices
- consolidation

LHC Run II

- *pp* runs 13 TeV @25 ns
- L_{peak} 2×10^{34} cm^{-2} s^{-1}