

ICHEP 2016

# *New strategies in LHCb trigger for Run 2*



*Barbara Sciascia (INFN)  
on behalf of LHCb Collaboration*



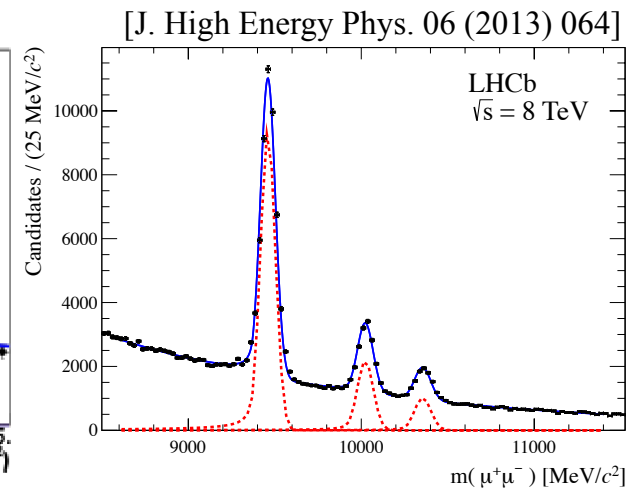
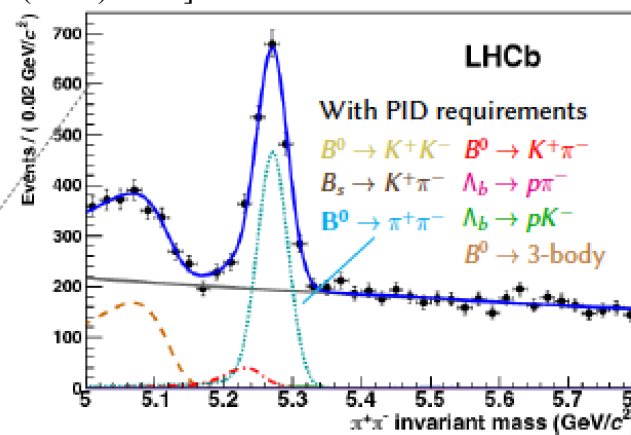
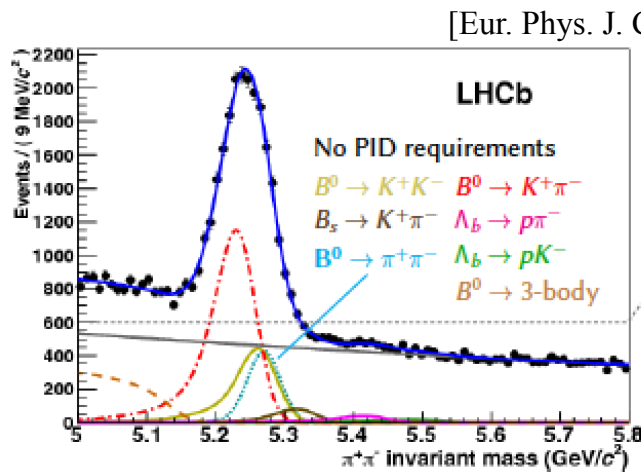
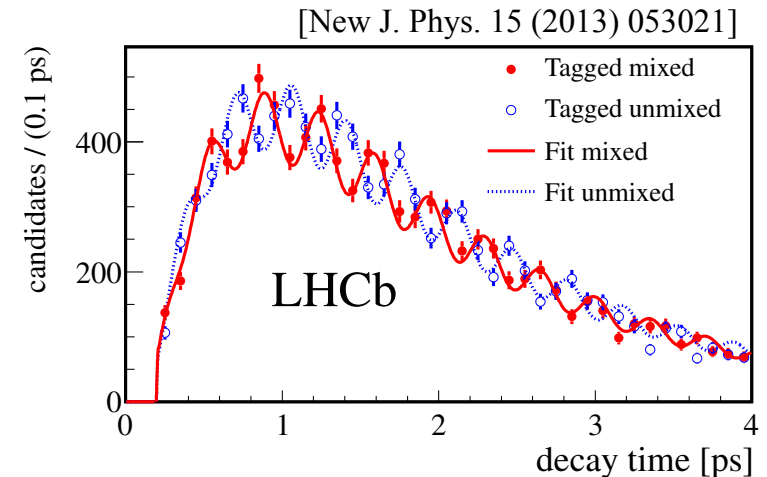
# LHCb experiment

**LHCb is the heavy flavour experiment at the LHC.**

Main goal: indirect search for New Physics in CP violation and rare decays of beauty and charm hadrons.

Can profit of:

- **Excellent decay time resolution;**  
[O(45 fs) for B mesons, depending on decay];
- **Excellent tracking:** momentum [ $\delta p/p$  0.5%], impact parameter and primary vertex resolution;
- **Excellent particle identification;**
- **(Very) High statistics samples.**



Title (long version): **Prompt physics analysis from the trigger candidates at LHCb: strategy and new dedicated Turbo and Calibration streams.**

- **The LHCb trigger system**
- **“Turbo” stream**: novel data processing to maximise the LHCb (charm) physics output.
- **Calibration stream**: provides suitable samples to evaluate Tracking and Particle Identification performance.



**Complementary information can be found in other ICHEP contributions:**

**The LHCb trigger in Run II (poster, 8 Aug)**

[<http://indico.cern.ch/event/432527/contributions/1071501/>]

**Novel real-time calibration and alignment at LHCb for Run II**

[<http://indico.cern.ch/event/432527/contributions/1071500/>]

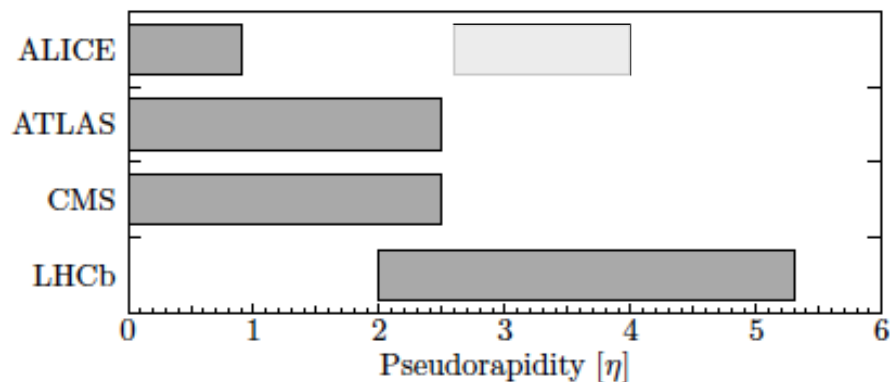
**LHCb distributed computing in Run II and its evolution towards Run III**

[<http://indico.cern.ch/event/432527/contributions/1072441/>]

**Study on the performance of the Particle Identification Detectors at LHCb after the LHC First Long Shutdown**

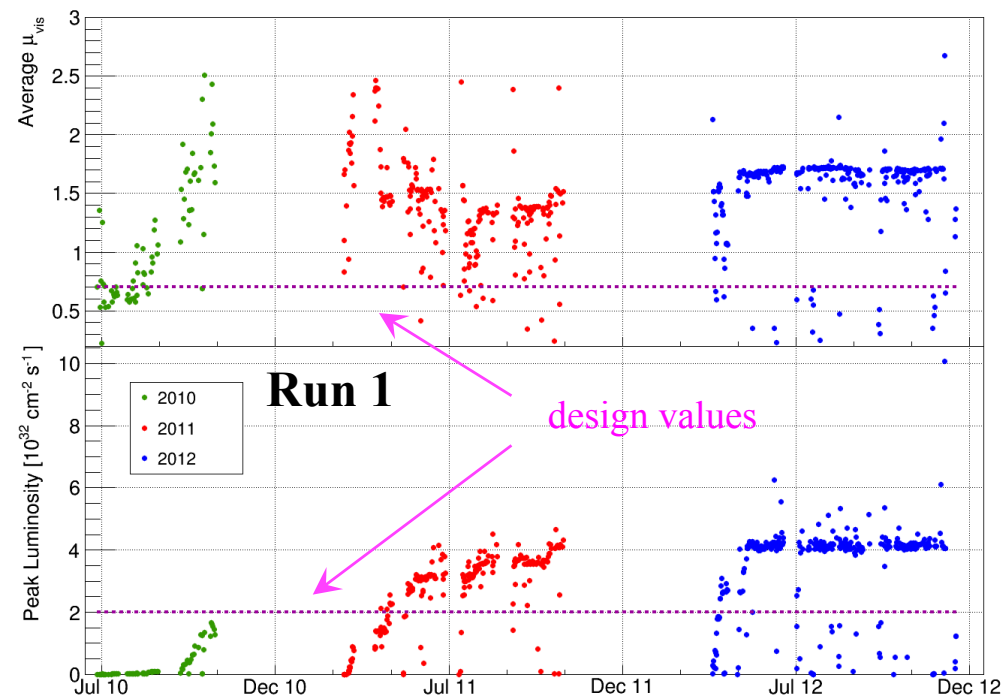
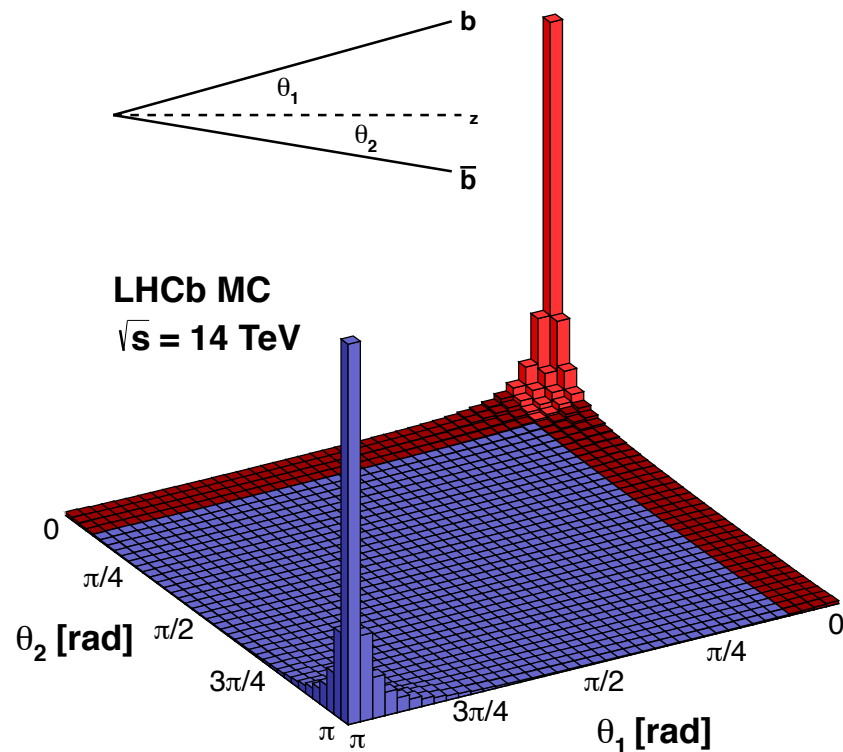
[<http://indico.cern.ch/event/432527/contributions/1071498/>]

# Data taking

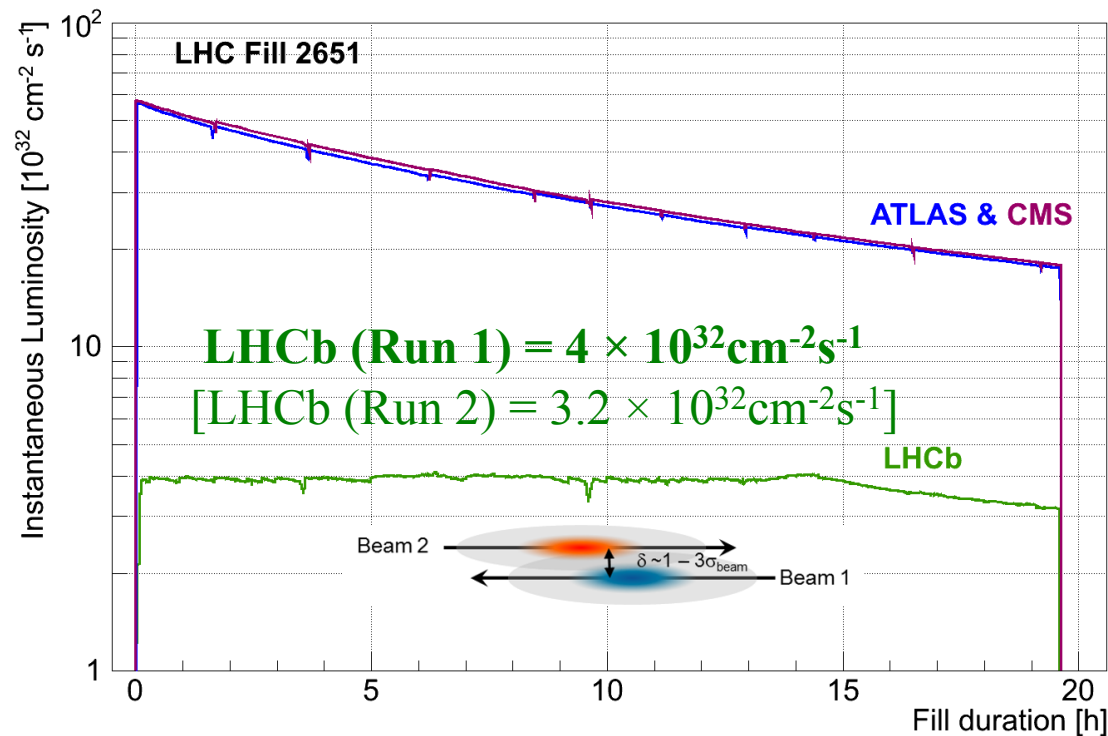


## Large $\sigma(bb)$ and $\sigma(cc)$ in LHC hadron collisions:

- $\sigma(bb) \sim 30$  kHz and  $\sigma(cc) \sim 600$  kHz cc [at 8 TeV, in acceptance]
- $\sigma(bb) \sim 45$  kHz and  $\sigma(cc) \sim 1$  MHz cc [at 13 TeV, in acceptance]  
[HF cross section  $\sim 2\times$  with respect to Run 1]
- Bunch spacing 25 ns (smaller pileup)



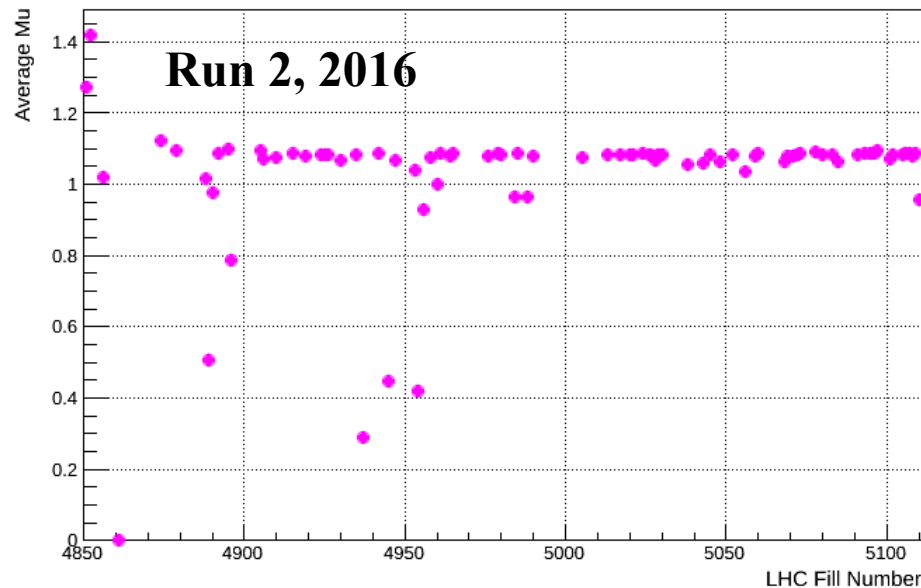
# Data taking



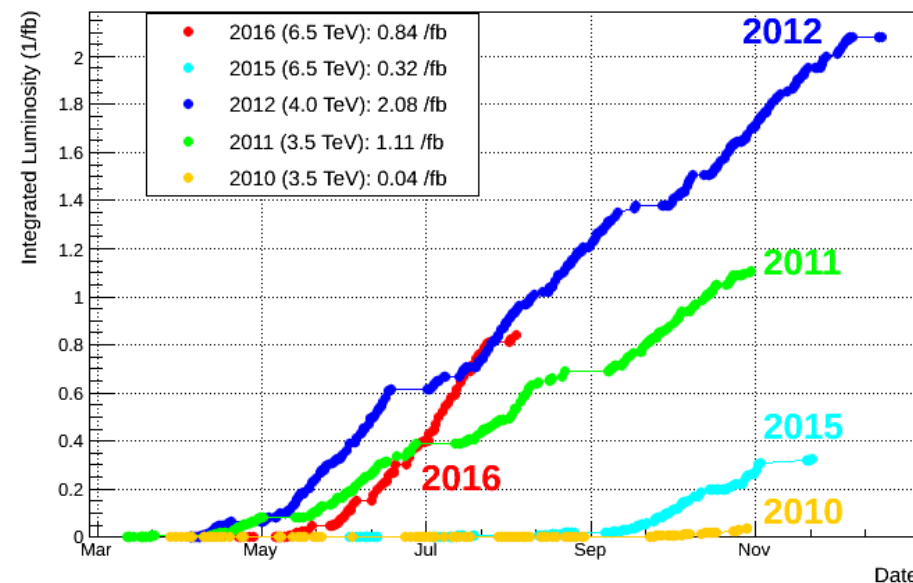
## Luminosity leveling:

- stable running and trigger conditions for LHCb even with LHC running at high luminosity
- run at stable average number of visible collisions per bunch crossing: collect very homogeneous dataset ease the online and offline processing.

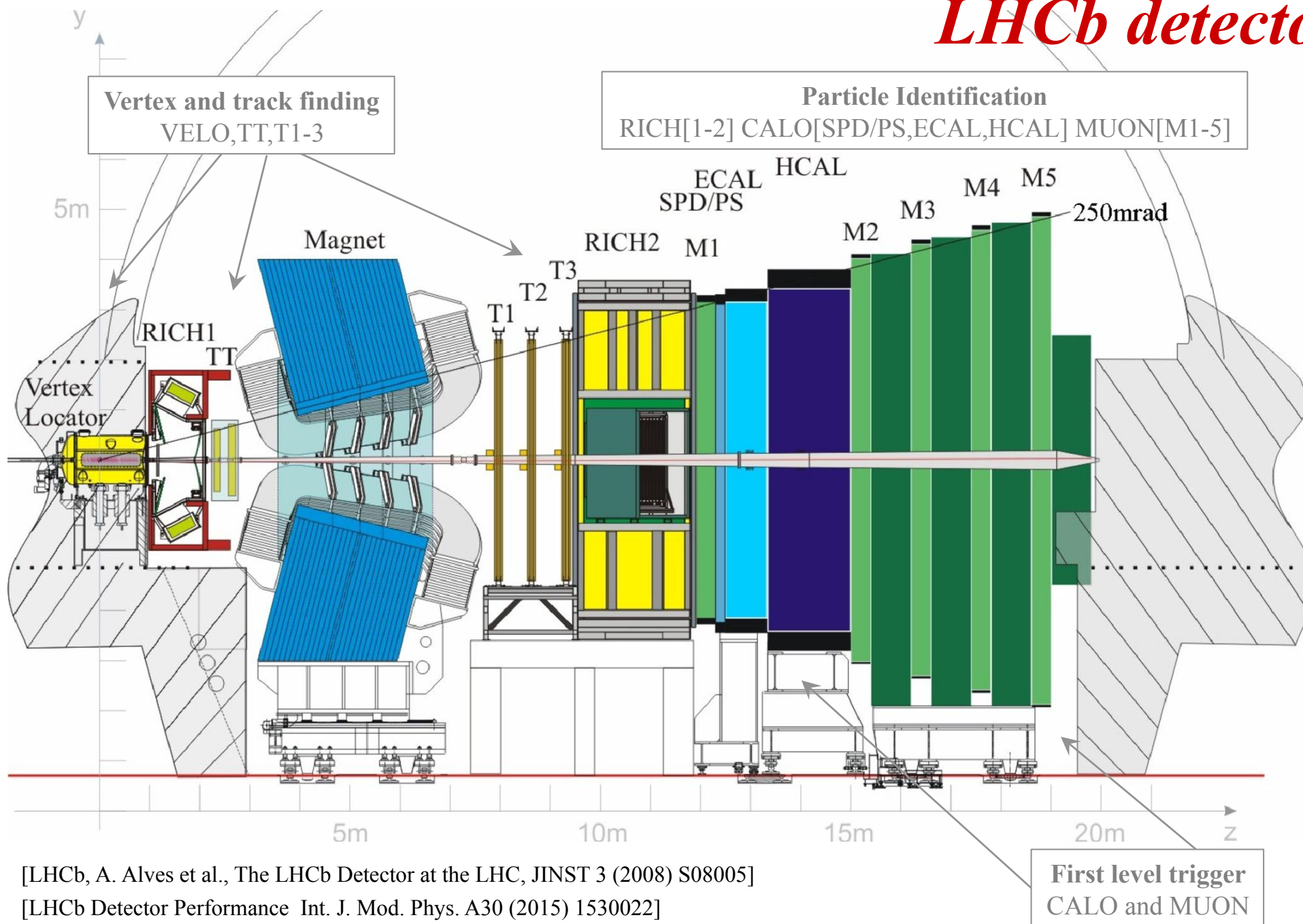
LHCb Average Mu at p-p in 2016



LHCb Integrated Luminosity in pp collisions 2010-2016



# *LHCb detector*

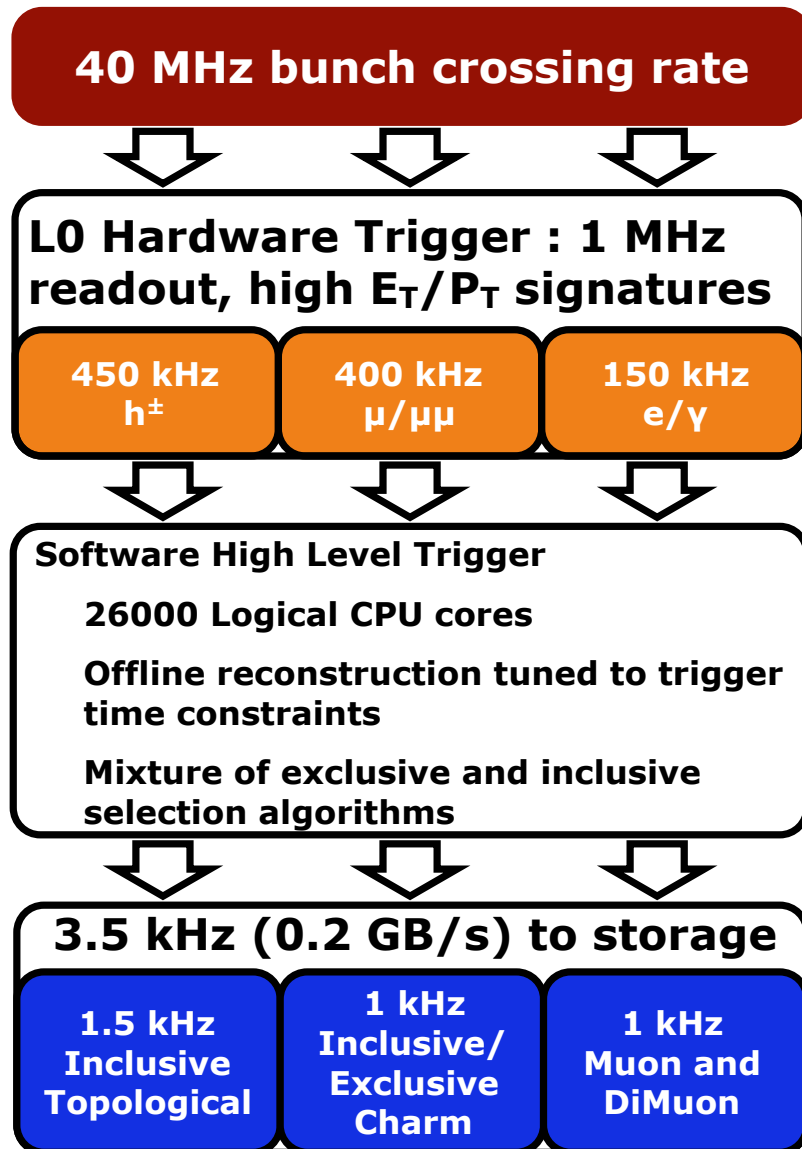


[LHCb, A. Alves et al., The LHCb Detector at the LHC, JINST 3 (2008) S08005]

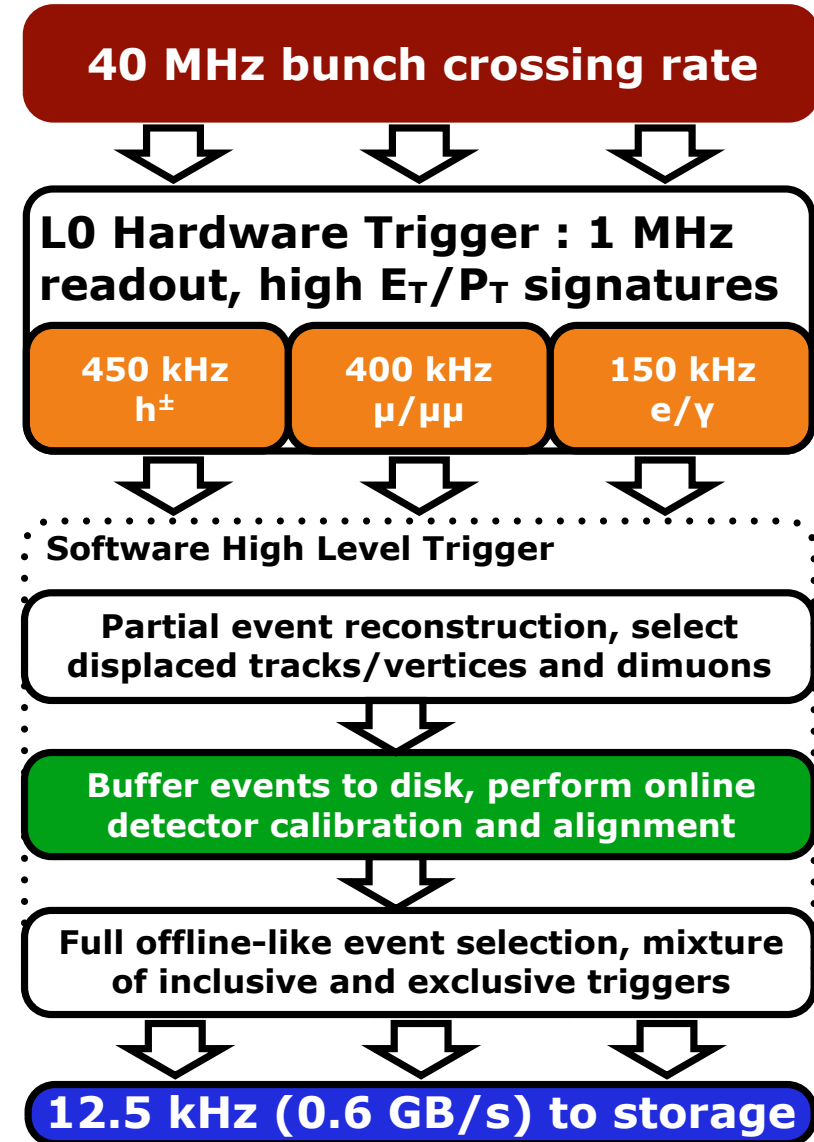
[LHCb Detector Performance Int. J. Mod. Phys. A30 (2015) 1530022]

# *LHCb trigger system at glance*

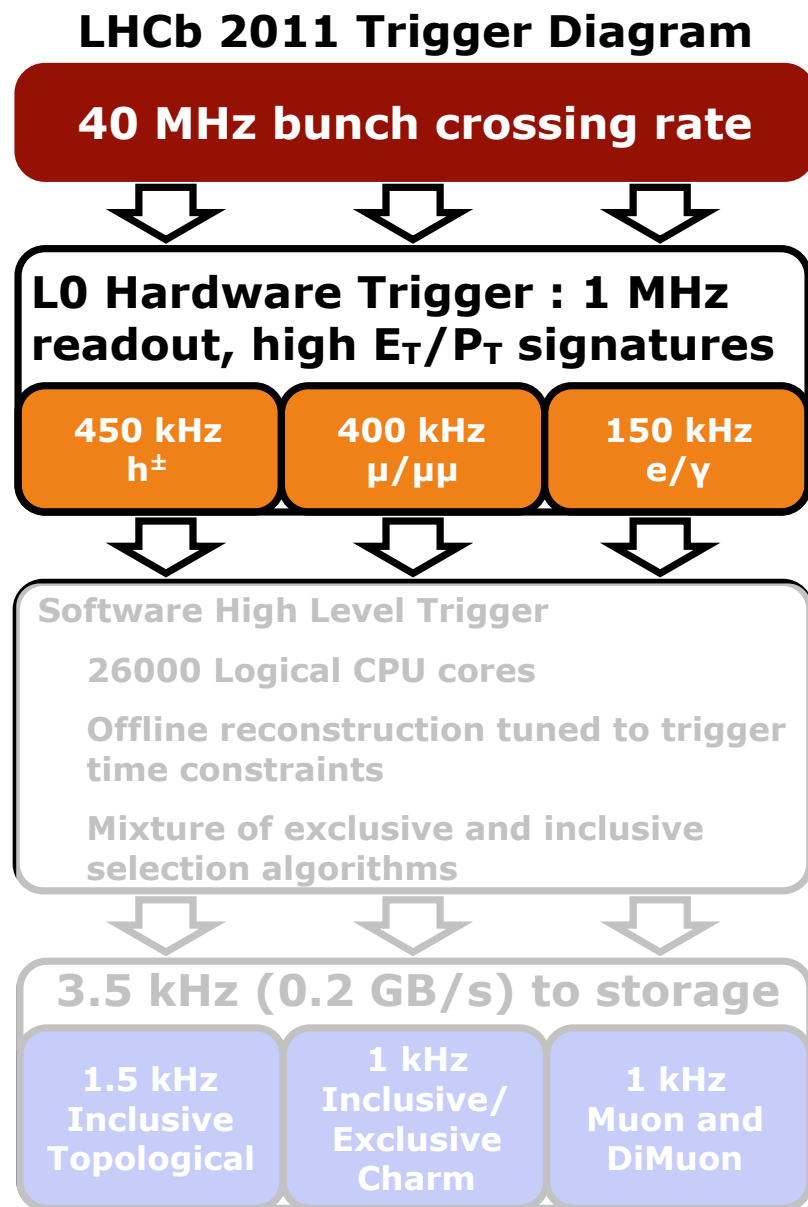
**LHCb 2011 Trigger Diagram**



**LHCb 2015 Trigger Diagram**



# Trigger system: hardware level [L0]



Reduce bunch crossing-rate to  $\sim 1$  MHz  
 [fixed latency of  $4 \mu\text{s}$ ]  
 [LHCb detector read out at 1 MHz]

**Muon trigger** [2012 thresholds]:

- Single Muon:  $p_T > 1.76 \text{ GeV}$
- Di Muon:  $(p_{T1} \times p_{T2}) > 1.6 \text{ GeV}^2$

**Calorimeter trigger** [2012 thresholds]:

- Hadrons:  $E_T > 3.7 \text{ GeV}$
- Photons and electrons:  $E_T > 3 \text{ GeV}$

**Low multiplicity triggers**

**Filters out very complex events**

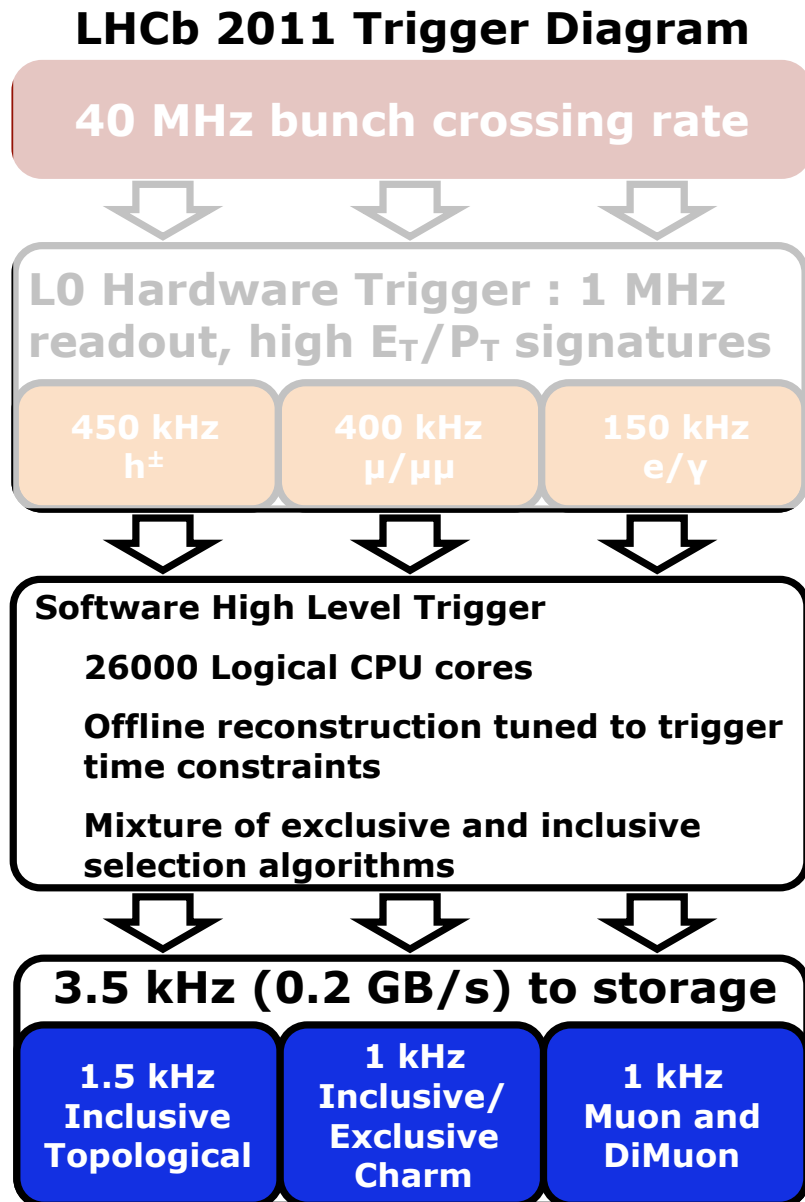
Run 1, Run 2, and beyond:

- **same in Run 2 as in Run 1**  
 [optimized thresholds in Run 2]
- removal planned for Run 3  
 [LHCb detector readout at 40 MHz]
- requires redesigned DAQ and trigger
- **recovers L0 hadron efficiency at low  $p_T$**

[LHCb Trigger and  
 Online Upgrade TDR,  
 LHCb-TDR-016]

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

# Trigger system in Run 1



## Software trigger (HLT)

- Runs on HLT farm
- Splits in two stages: HLT1 and HLT2

**HLT1** performs a **partial event reconstruction** and an inclusive selection of signal candidates

**HLT2** [ $\sim 40$  kHz input rate]

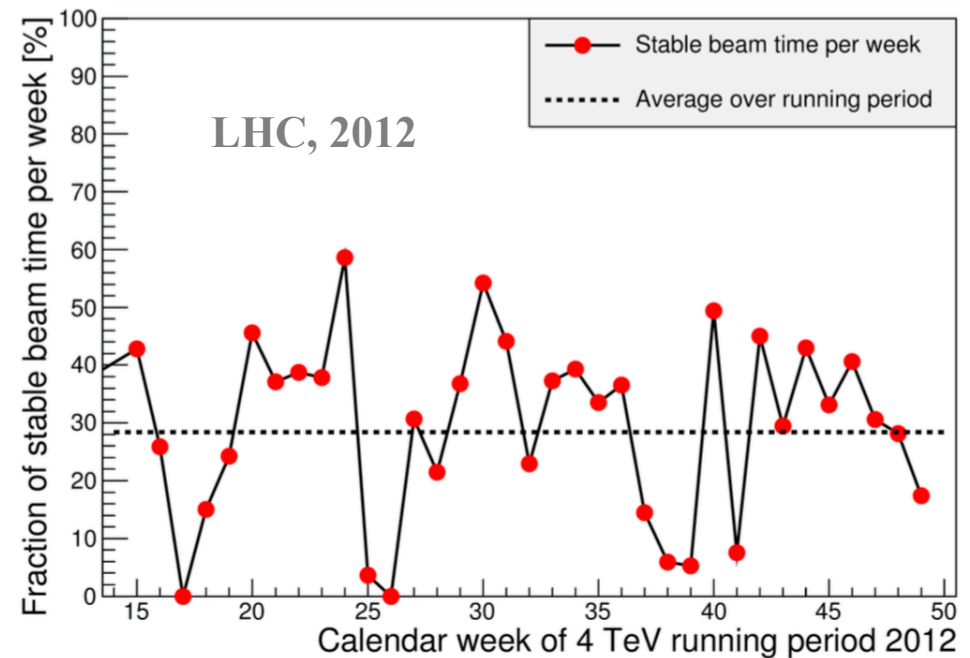
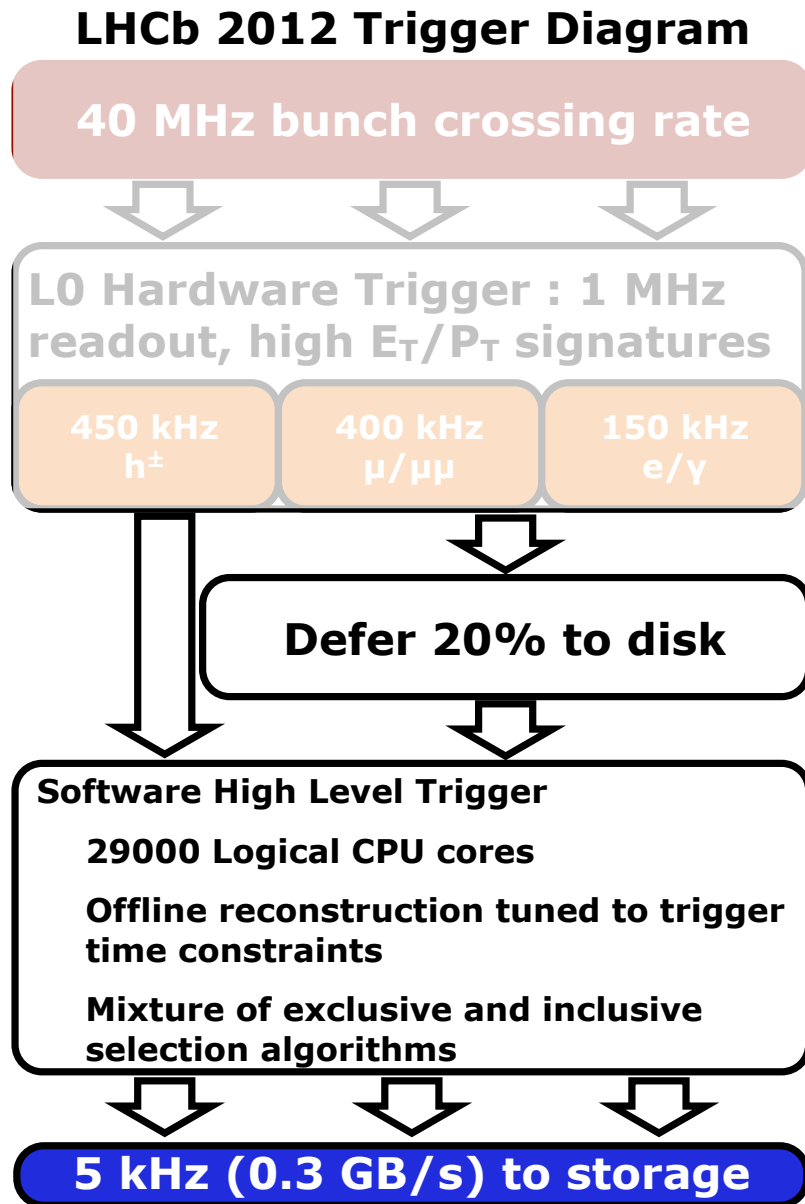
- **full simplified** event reconstruction, with **preliminary alignment and calibration** of the detector and only **marginal use of RICH PID information**
- a set of inclusive and exclusive selections

**Output: 200 MB/s (2011)**

[saved for later offline analysis]

Total time budget:  $O(35 \text{ ms})/\text{event}$

# Trigger system in Run 1



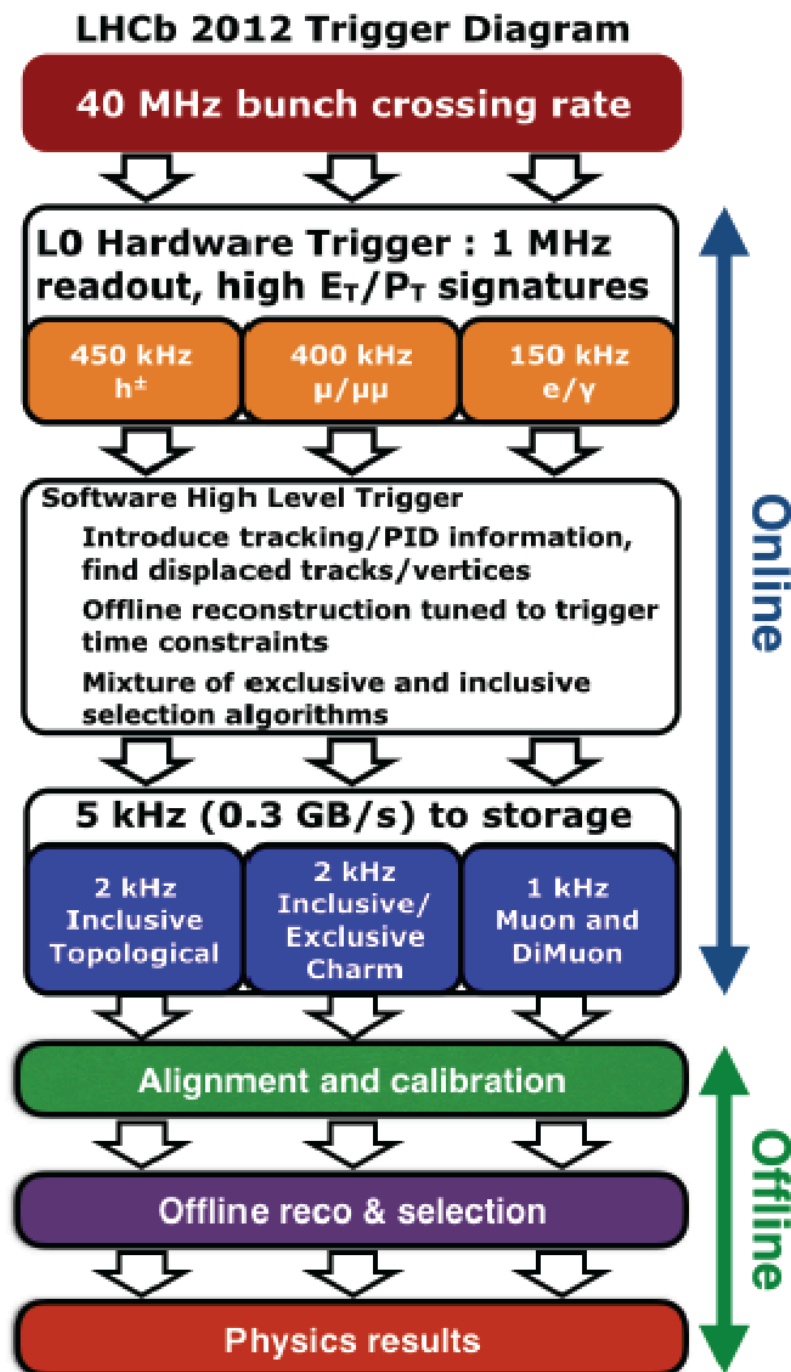
Same hardware trigger (L0)

- **20% of L0 events buffered** to allow processing out of fill

[Journal of Physics: Conference Series 513 (2014) 012006]

**Software trigger (HLT)**

- HLT2 [ $\sim 80$  kHz input rate]
- **Output: 300 MB/s (2012)**



## *Trigger system in Run 1*

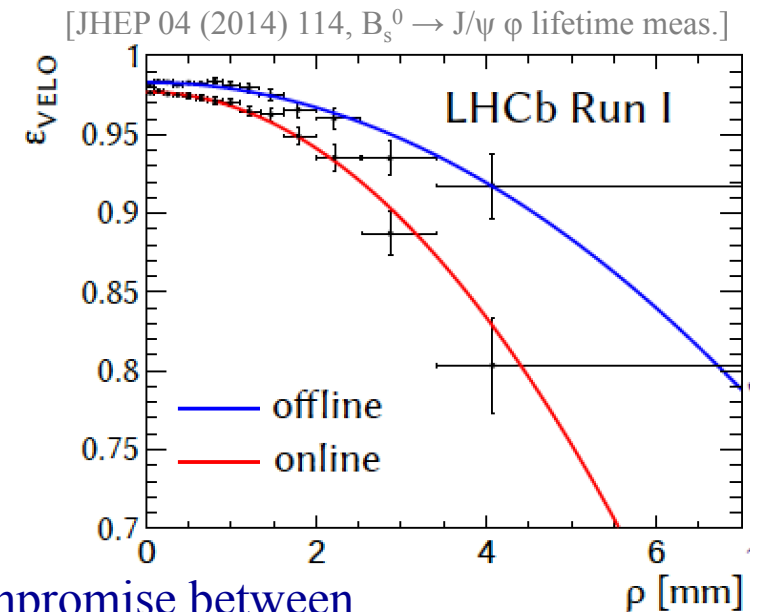
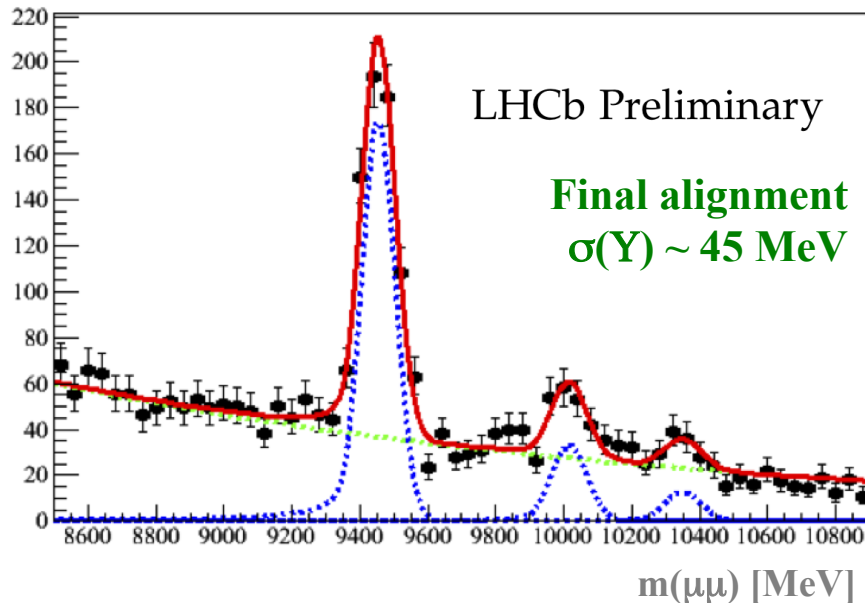
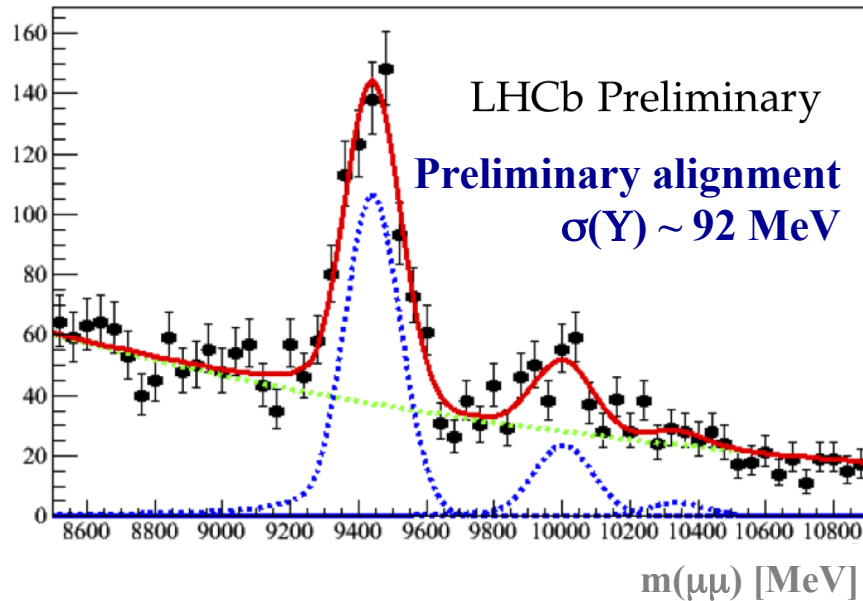
**Online:** compromise between performance and stringent timing requirements.

### **Differences:**

pattern recognition, detector alignment and calibration, candidate selection

**Offline:** best available performance without stringent timing requirements.

# Trigger system in Run 1



**Online:** compromise between performance and stringent timing requirements.

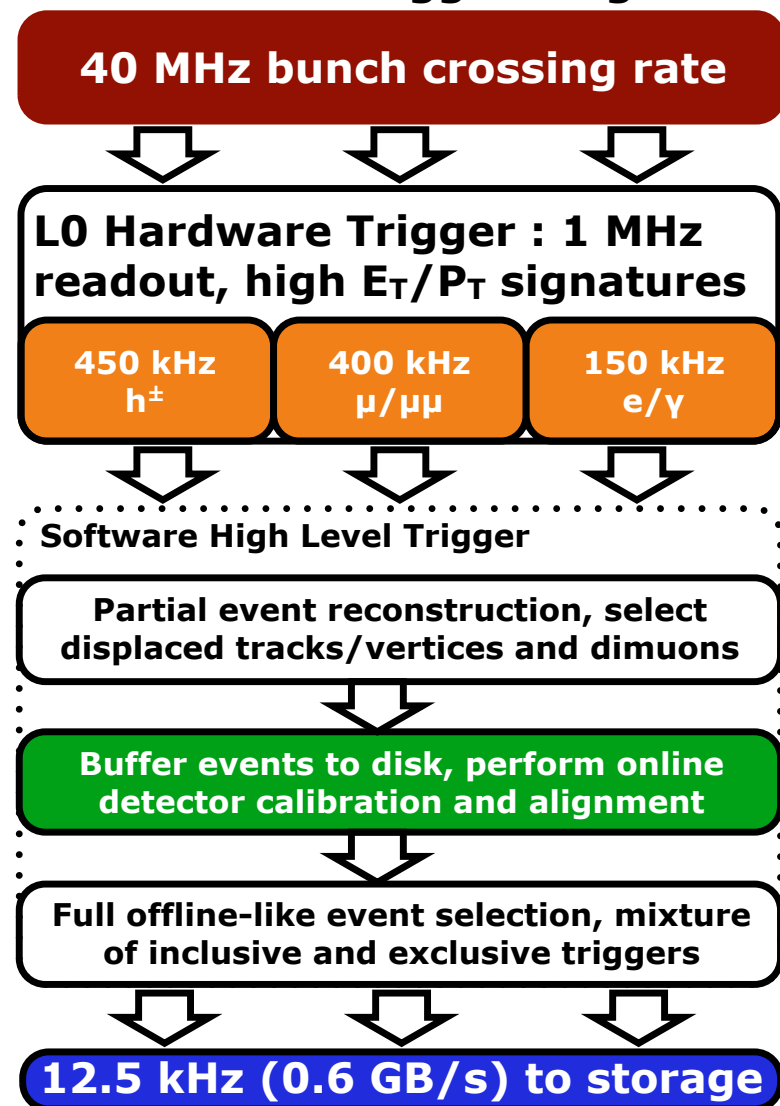
**Differences:**  
pattern recognition, detector alignment and calibration, candidate selection.

**Offline:** best available performance without stringent timing requirements.

# Trigger system in Run 2

[Journal of Physics: Conference  
Series 513 (2014) 012006]

## LHCb 2015 Trigger Diagram



### Run 2:

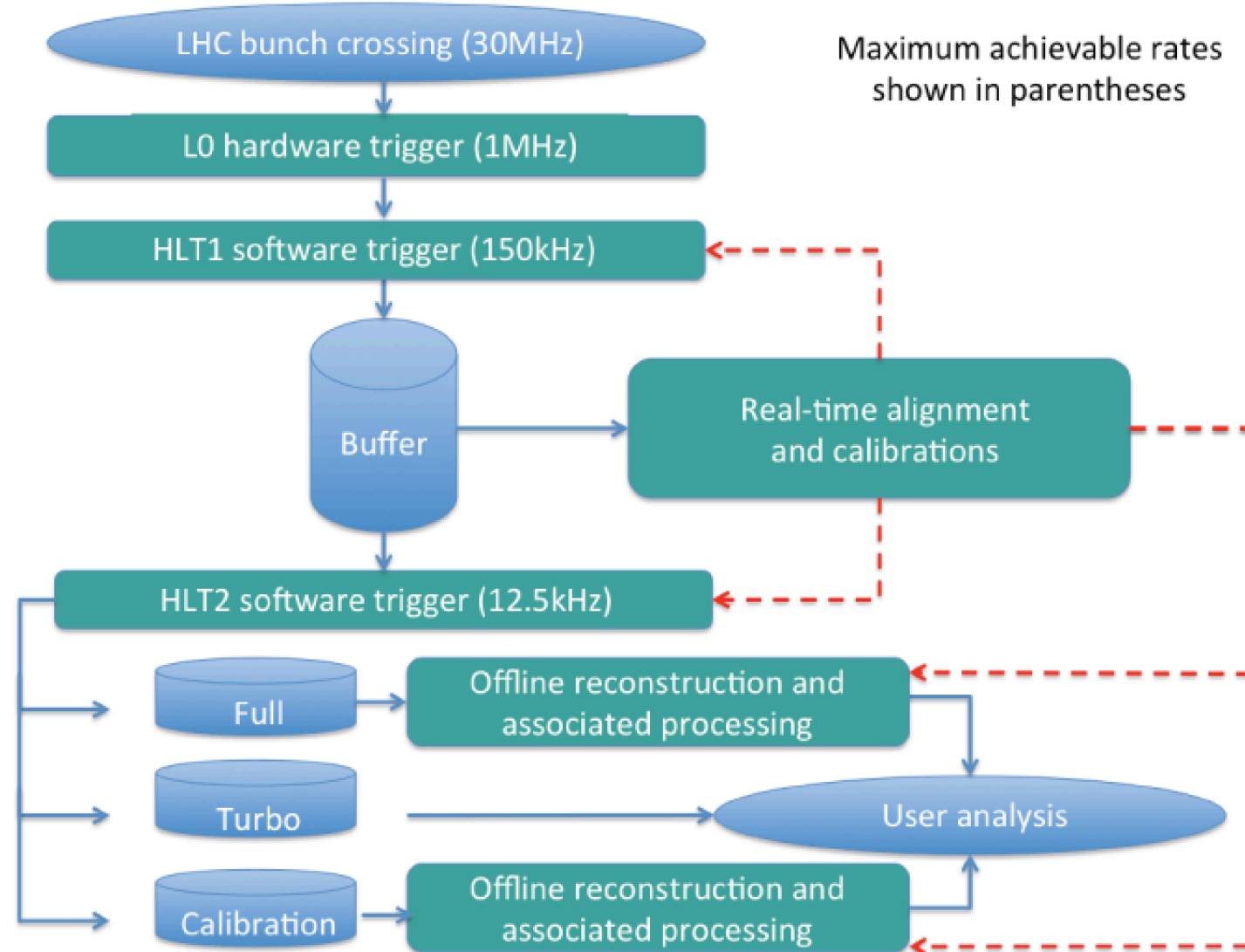
- *HLT splits in two applications: HLT1 and HLT2*
- **All events buffered after HLT1**
- **Alignment and calibration run on dedicated HLT1 samples**
- Online same reconstruction as offline

[see R. Aaij talk in this session, Real-time calibrations and alignments, <http://indico.cern.ch/event/432527/contributions/1071500/>]

### Advantages with respect to Run 1 model:

- Saves time: if alignment and calibration applied after data taking, **reconstruction run twice**
- Saves money: uses less computing resources
- More physics: imperfectly reconstructed data in trigger implies not optimized event selection.

# *Data processing model in Run 2*



[arXiv: 1604.05596v1]

# Turbo stream strategy

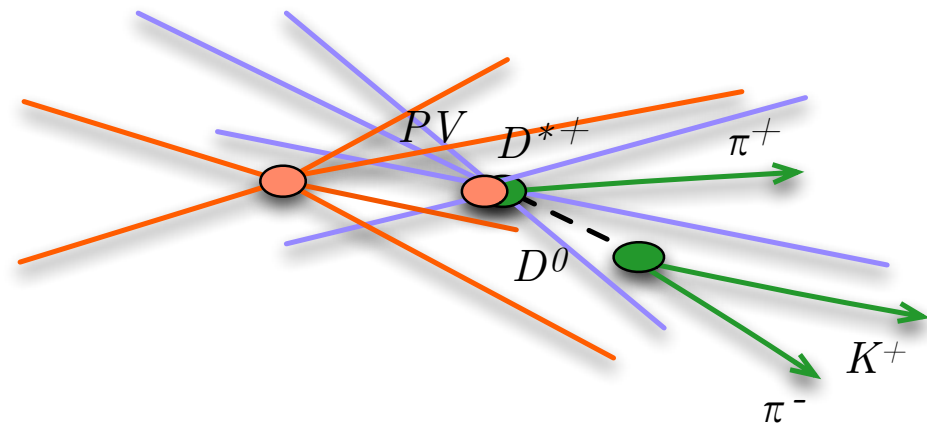
## New concept:

Use the trigger reconstruction (of offline quality) to perform physics measurements.

## Full stream:

- Save raw event;
- Reconstruction of full event [70 kB/event];
- Analysis pre-selections.

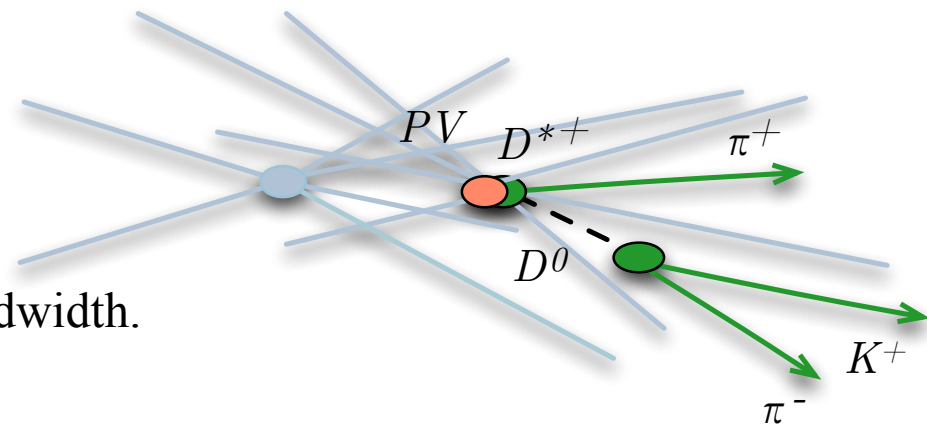
**Total time for single 3GB raw file: ~30h.**



## Turbo stream:

- Save only candidate information;
- Removal of raw event;
- Restore trigger information;
- Typical decay costs O(kB) in raw event.
- Smaller events: higher rate for the same bandwidth.

**Time < 1h**



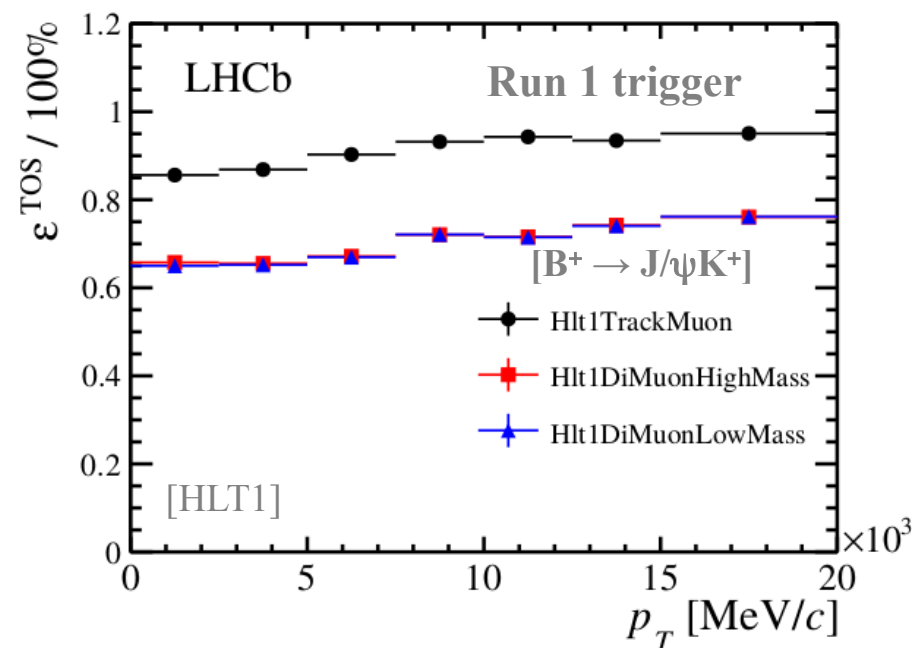
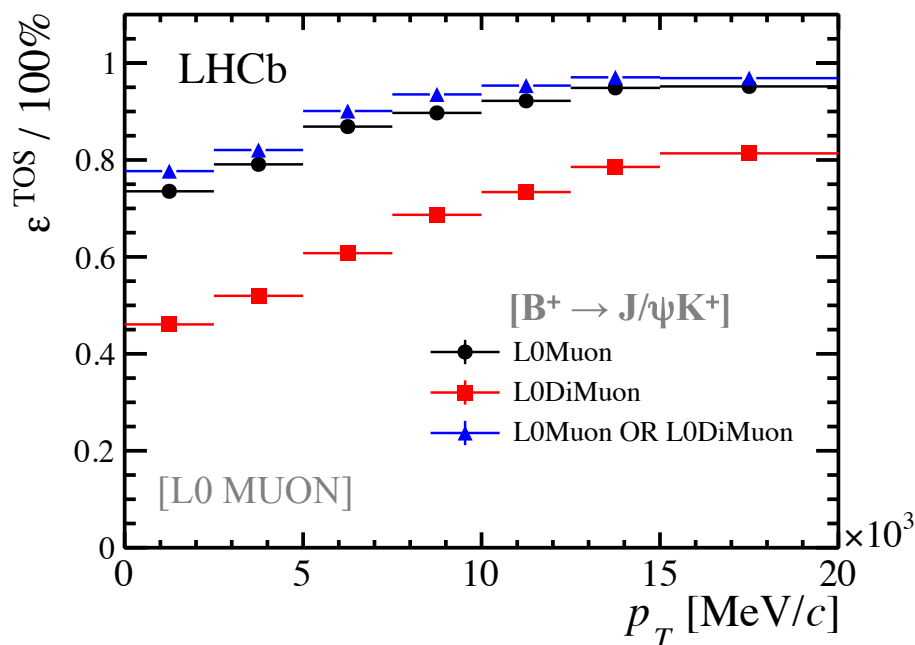
*e.g. Results from charm physics can profit of a high rate of smaller events with respect to a lower rate of larger ones.*

# *Saving trigger objects [Run 1]*

**Run 1:** limited information on selected candidates was placed in to the raw banks.

- These contained particle momenta and mass hypotheses (imposed by the trigger line) information, along with track  $\chi^2$  information where appropriate.
- Very useful for monitoring.
- Required for data-driven trigger efficiencies.

[calculated via the TISTOS method (arXiv:1310.8544):  $\epsilon_{\text{TOS}} = N_{\text{TOS\&TIS}}/N_{\text{TIS}}$   
 [TOS = Triggered on selection, TIS = triggered independent of selection.]



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

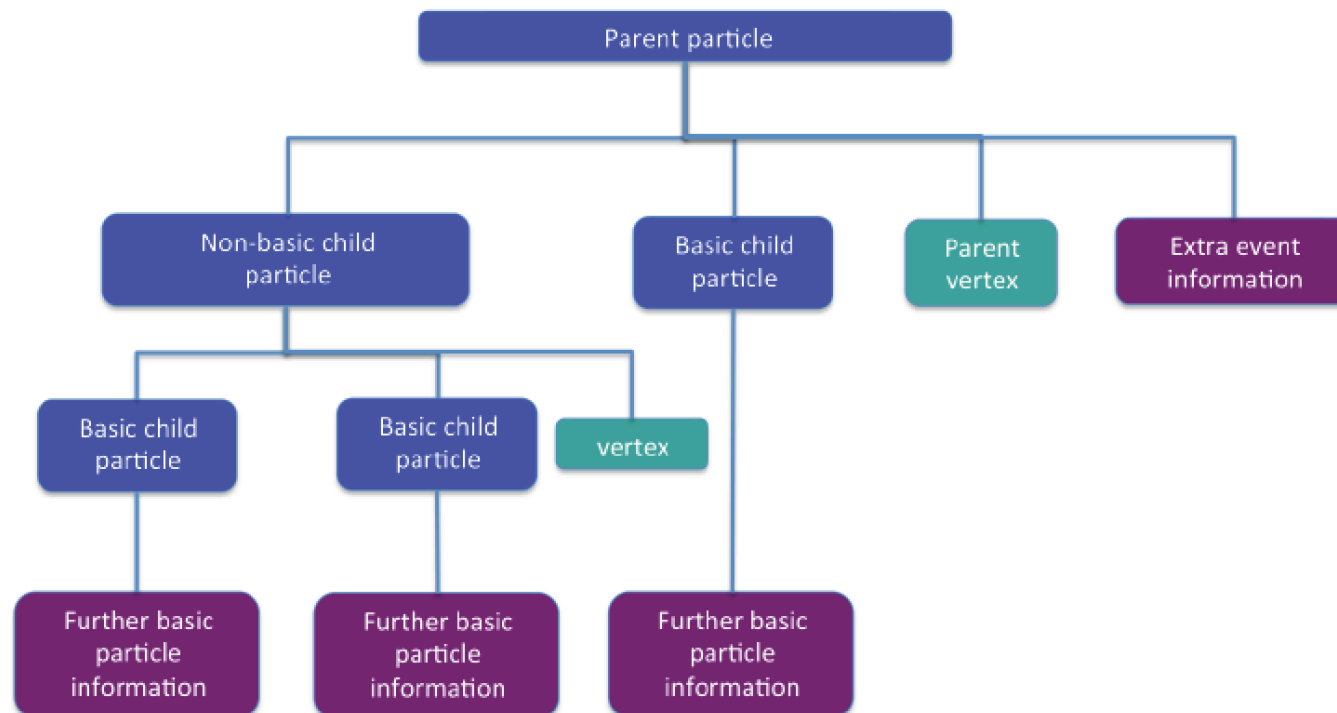
# *Saving trigger objects [Run 2]*

## Run 2:

- offline quality of the information in the trigger allows to make and publish measurements.
- for trigger lines sent to the Turbo stream, much more information on the decay is saved.

The **structure of stored objects** includes (to name a few):

- particles - full position and momentum covariance matrices;
- PID -  $\Delta\ln(\mathcal{L})$  for all mass hypotheses, ingredients for neural network PID variables;
- Intermediate vertices -  $\chi^2$ , position, full covariance matrices.



# *Restoring trigger objects [Tesla]*

LHCb has published over 320 papers since the beginning of LHC data taking.

Made possible by the common analysis framework:

- easy access to information on reconstructed candidates.
- addition of tools to production jobs allows easy access to:
  - + Kinematic information (4-momenta,...),
  - + geometric information (impact parameter, flight distance,...),
  - + global information (run number, event number, ...),
  - + ...

**Use the existing infrastructure also for Turbo data.**

**Tesla program** fills the gap between Full and Turbo data format.

- Restore decays from the raw event of unlimited complexity.  
[ $A \rightarrow m * B(\rightarrow n * C(...))$ ].
- Resulting output can be used for measurements in the same way as the Full stream.

**$\Rightarrow$  Analysis pre-selection stage is essentially moved inside the trigger.**



# Validation of Turbo stream

**Turbo stream is a new concept for Run 2:**

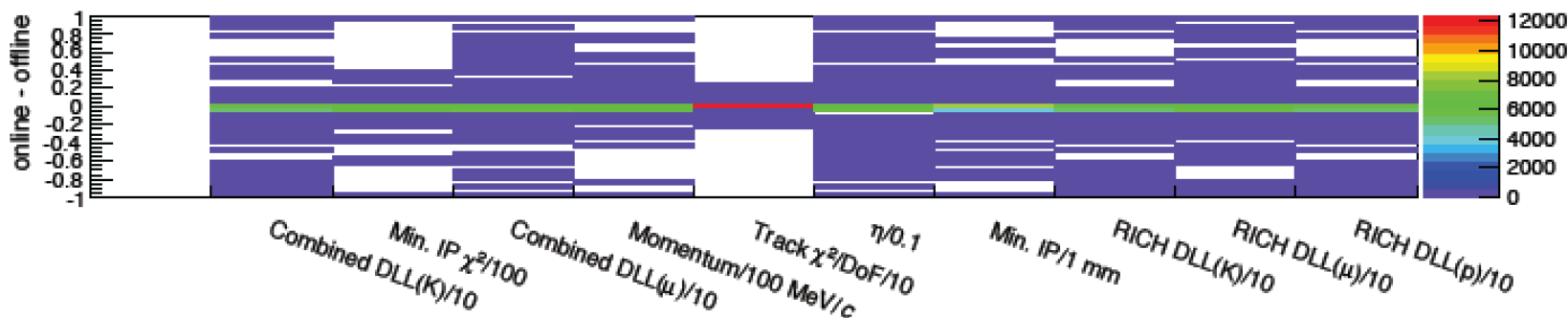
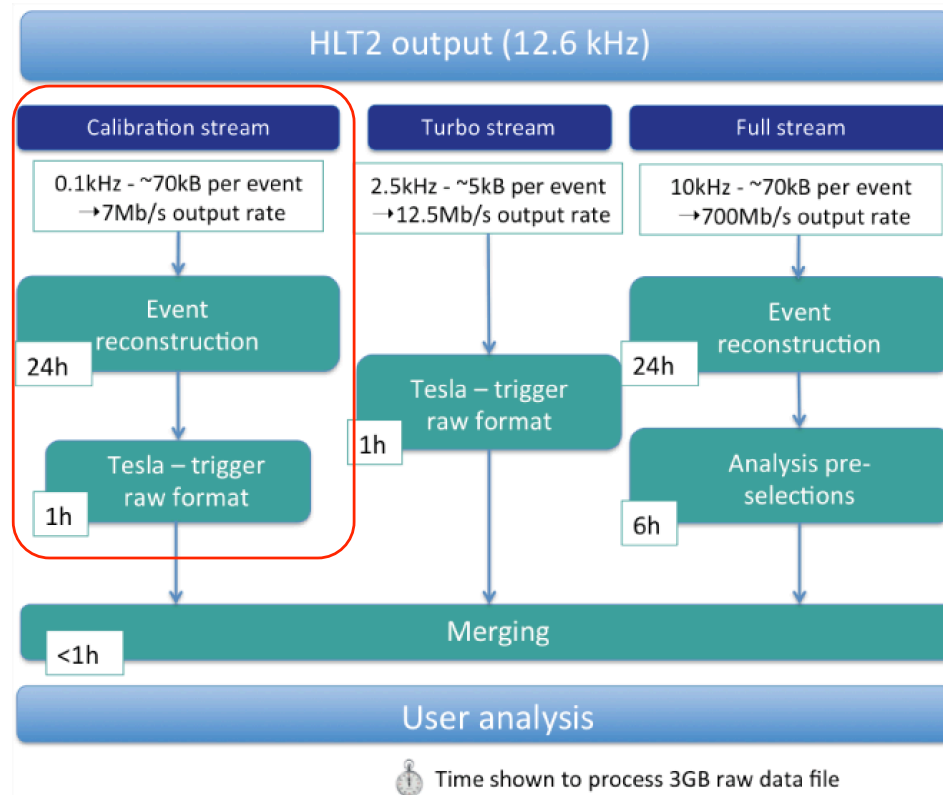
- for initial commissioning of the Turbo stream, the complete raw event has been archived.

[On the long term raw event will be discarded]

## Calibration workflow

- dedicated to the calibration samples;
- manage online/trigger information plus full raw event (can be reconstructed).

Calibration workflow has proved to be a key tool for the quality validation of “online” analysis [TURBO stream and Tesla application]



# Turbo stream and Tesla application

**Turbo stream is a new concept for Run 2:**

- for initial commissioning of the Turbo stream, the complete raw event has been archived.

[On the long term raw event will be discarded]



Online since yesterday: R. Aaij et al, **Tesla: An application for real-time data analysis in High Energy Physics**, Computer Physics Communications (2016) doi:10.1016/j.cpc.2016.07.022. arXiv:1604.05596 [physics.ins-det]



## Tesla: An application for real-time data analysis in High Energy Physics<sup>\*</sup>

R. Aaij<sup>a</sup>, S. Amaro<sup>b</sup>, L. Anderlini<sup>c</sup>, S. Benson<sup>a,\*</sup>, M. Cattaneo<sup>a</sup>, M. Clemencic<sup>a</sup>, B. Coururier<sup>a</sup>, M. Frank<sup>a</sup>, V.V. Gligorov<sup>d</sup>, T. Head<sup>e</sup>, C. Jones<sup>f</sup>, I. Komarov<sup>g</sup>, O. Lupton<sup>h</sup>, R. Matev<sup>a</sup>, G. Raven<sup>h</sup>, B. Sciascia<sup>i</sup>, T. Skwarnicki<sup>j</sup>, P. Spradlin<sup>k</sup>, S. Stahl<sup>a</sup>, B. Stora<sup>l</sup>, M. Vesterinen<sup>m</sup>

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### ABSTRACT

Upgrades to the LHCb computing infrastructure in the first long shutdown of the LHC have allowed for high quality decay information to be calculated by the software trigger making a separate offline event reconstruction unnecessary. Furthermore, the storage space of the triggered candidate is an order of magnitude smaller than the entire raw event that would otherwise need to be persisted. Tesla is an application designed to process the information calculated by the trigger, with the resulting output used to directly perform physics measurements.

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### 1. Introduction

The LHCb experiment, one of the four main detectors situated on the Large Hadron Collider in CERN, Geneva, specialises in precision measurements of beauty and charm hadrons decays. At the nominal LHCb luminosity of  $4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$  during 2012 data taking at 8 TeV, around 30 k beauty (b) and 600 k charm (c) hadron pairs pass through the LHCb detector each second. Each recorded collision is defined as an event that can possibly contain a decay of

interest. The efficient selection of beauty and charm decays from the  $\sim 30 \text{ M}$  proton-proton collisions per second is a significant Big Data challenge.

An innovative feature of the LHCb experiment is its approach to Big Data in the form of the High Level Trigger (HLT) that is split into two components with a buffer stage between [1]. The HLT is a software application designed to reduce the event rate from 1 M to  $\sim 10 \text{ k}$  events per second and is executed on an Event Filter Farm (EFF). The EFF is a computing cluster consisting of 1800 server nodes, with a combined storage space of 5.2 PB, which can accommodate up to two weeks of LHCb data taking [2] in nominal conditions. The HLT application reconstructs the particle trajectories of the event in real time, where real time is defined as the interval between the collision in the detector and the moment

<sup>\*</sup> © CERN on behalf of the LHCb collaboration, licence CC-BY-4.0.

<sup>\*</sup> Corresponding author.

E-mail address: sean.benson@cern.ch (S. Benson).

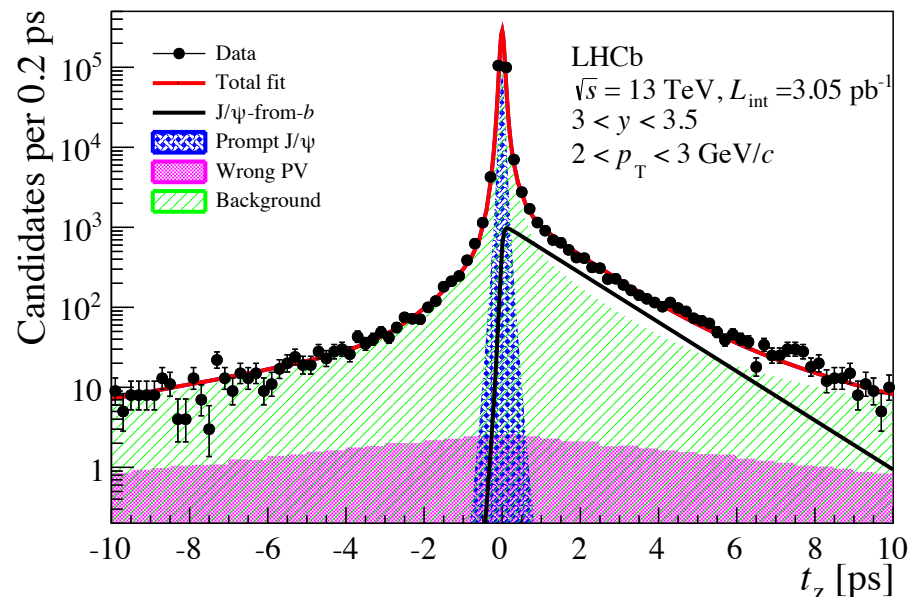
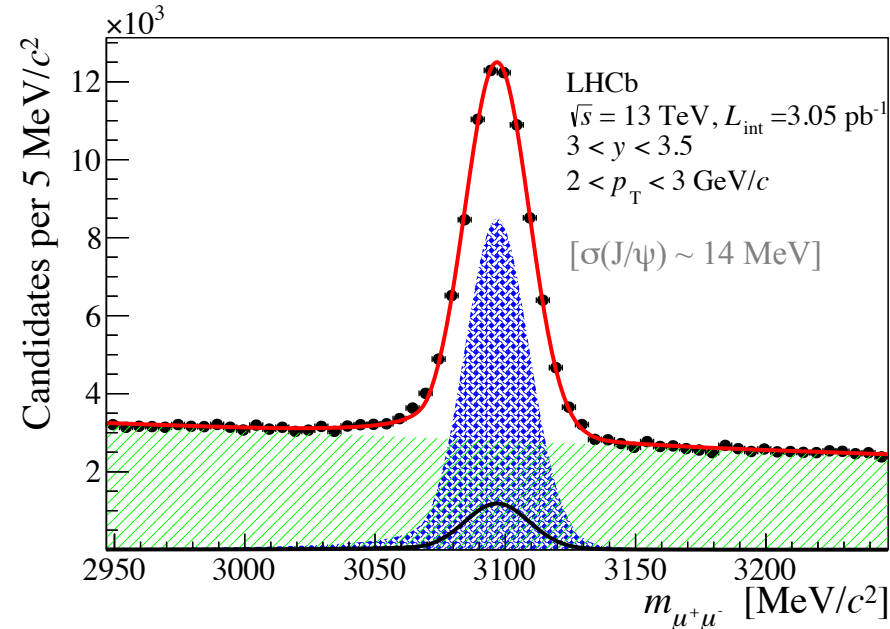
<http://dx.doi.org/10.1016/j.cpc.2016.07.022>  
0010-4655/© 2016 Published by Elsevier B.V.

# “Turbo publications”

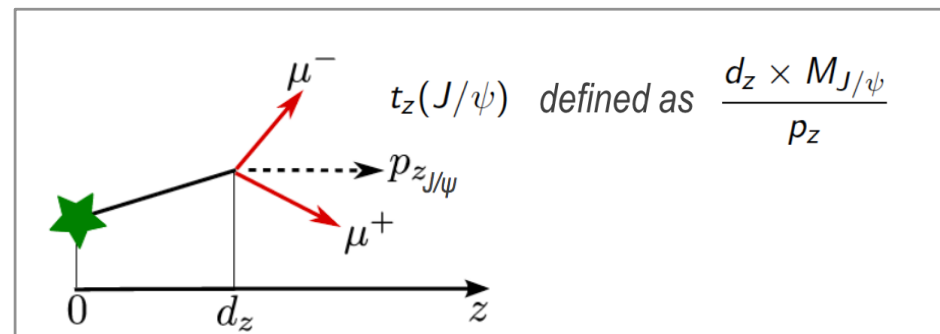
**Online has offline quality: use it for physics!**  
[Turbo Stream + Tesla Application]

Measurement of the  $J/\psi$  production cross-section in early Run 2 data pioneered in the usage of the Turbo stream technique for selection of the decay candidates.

The preliminary result was out 1 week after data taking. [dataset:  $3.05 \pm 0.12 \text{ pb}^{-1}$ ]



**Measurement of forward  $J/\psi$  production cross-sections in  $pp$  collisions at 13 TeV**  
[JHEP10 (2015) 172]



# “Turbo publications”

## Measurement of prompt charm production cross-sections in $pp$ collisions at 13 TeV

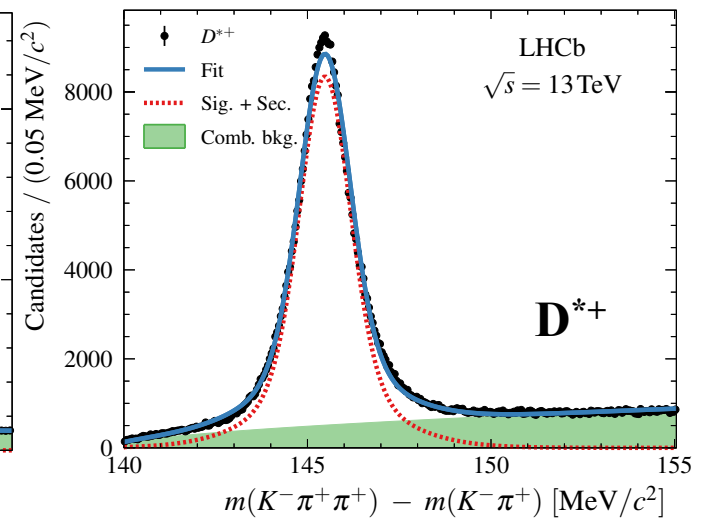
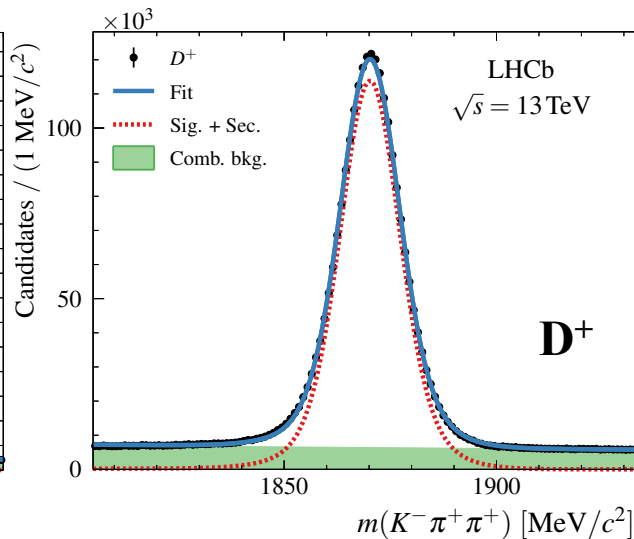
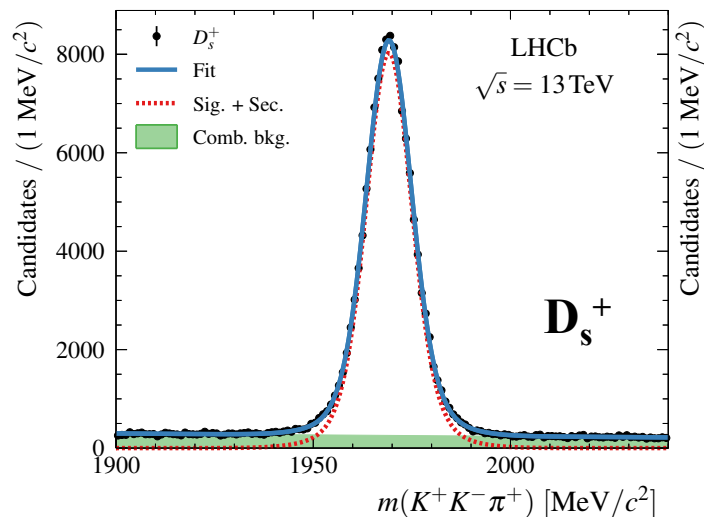
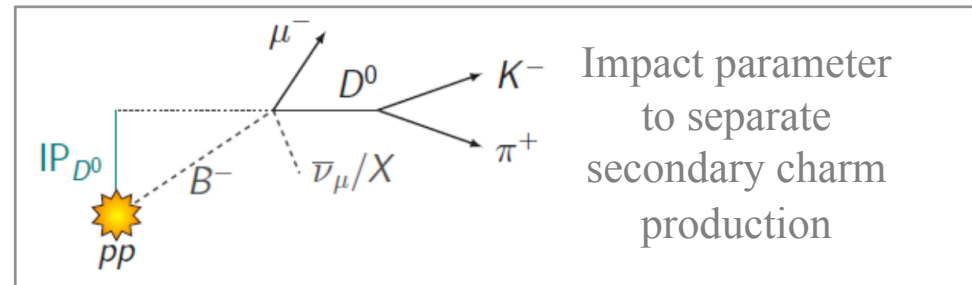
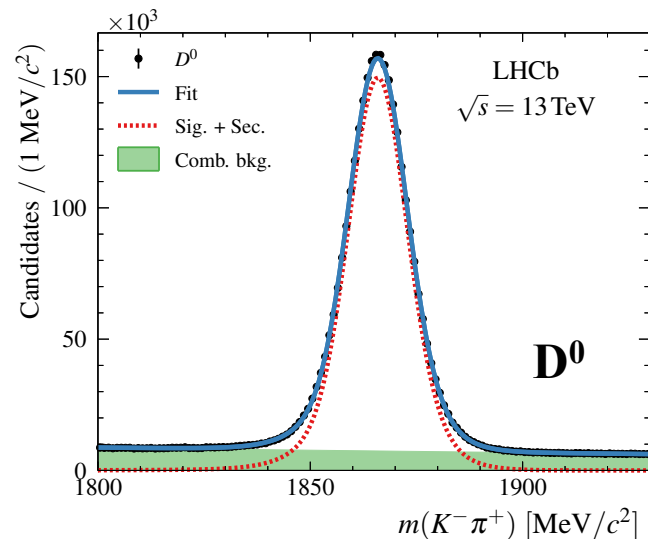
[JHEP 03 (2016) 159]

[dataset:  $4.98 \pm 0.19 \text{ pb}^{-1}$ ]

Online has offline quality: use it for physics!

[Turbo Stream + Tesla Application]

- Ideal for high yield exclusive modes (charm).
- Almost background free directly from trigger due of offline quality tracking.



# *Real-time analysis [TURBO++]*

In Turbo data only the information about the selected decay is available.

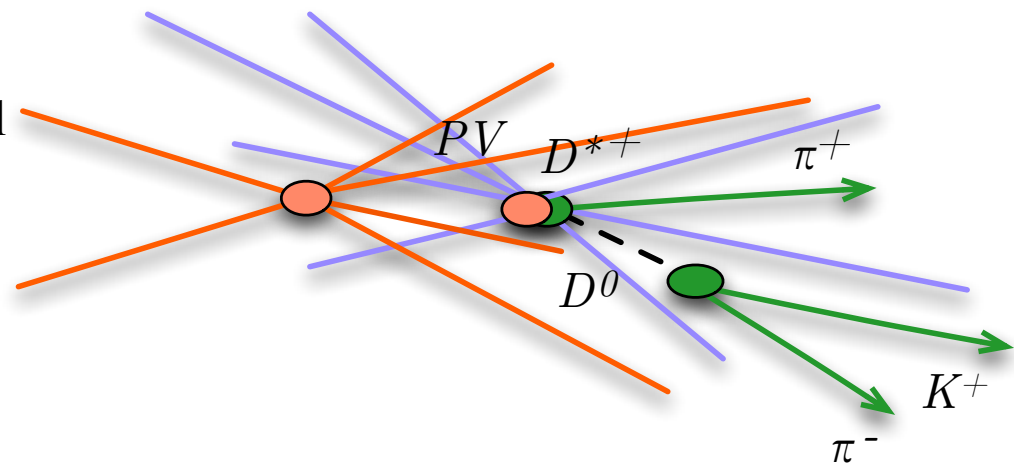
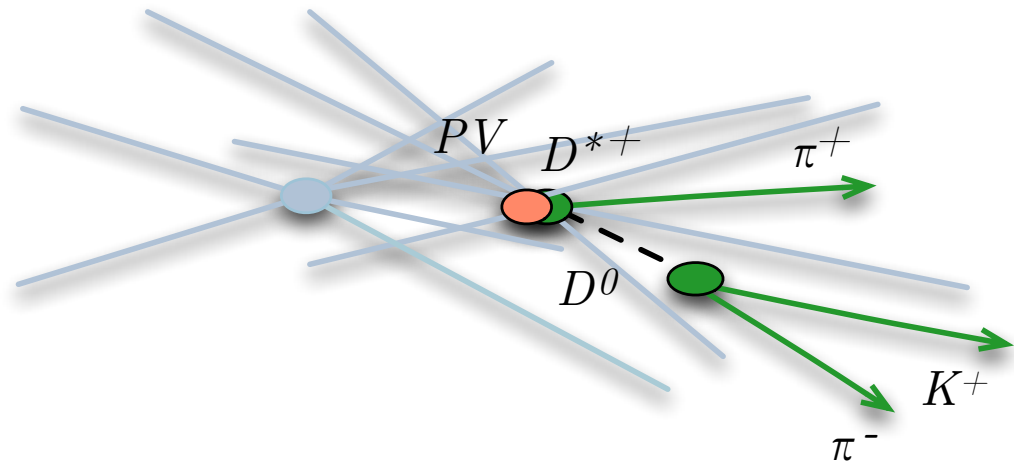
This limits the physics outcome from Turbo.

## New in 2016

Can persist HLT candidate + any reconstructed objects (like isolation).

Event size of 50 kB, including a minimal subset of the raw data.

Can do qualitatively new things on HLT output. Entire analysis can be done on trigger output, incl. flavour tagging [e.g. in charm spectroscopy:  $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+$ ].

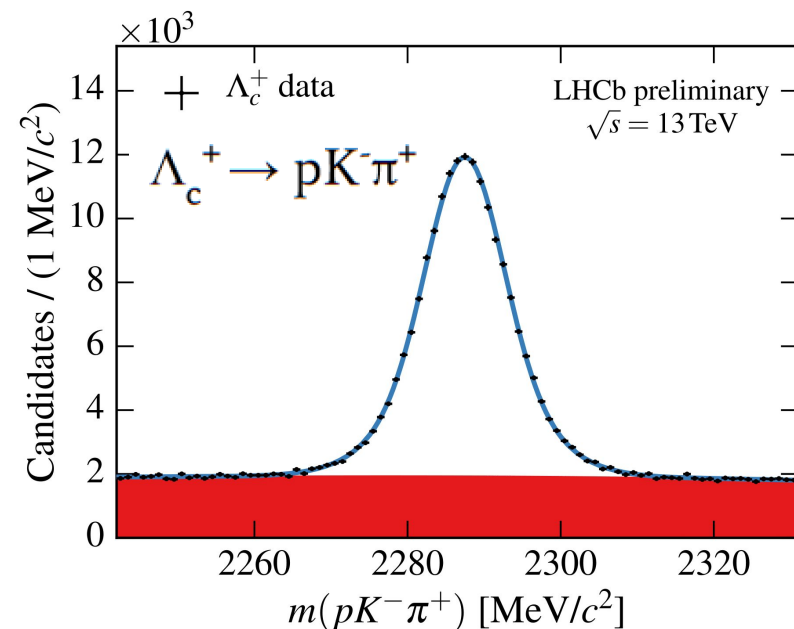
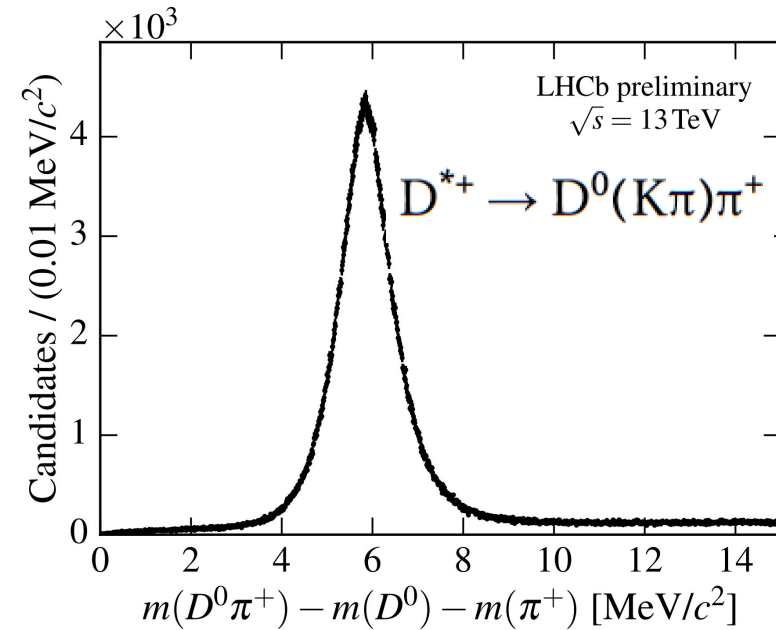
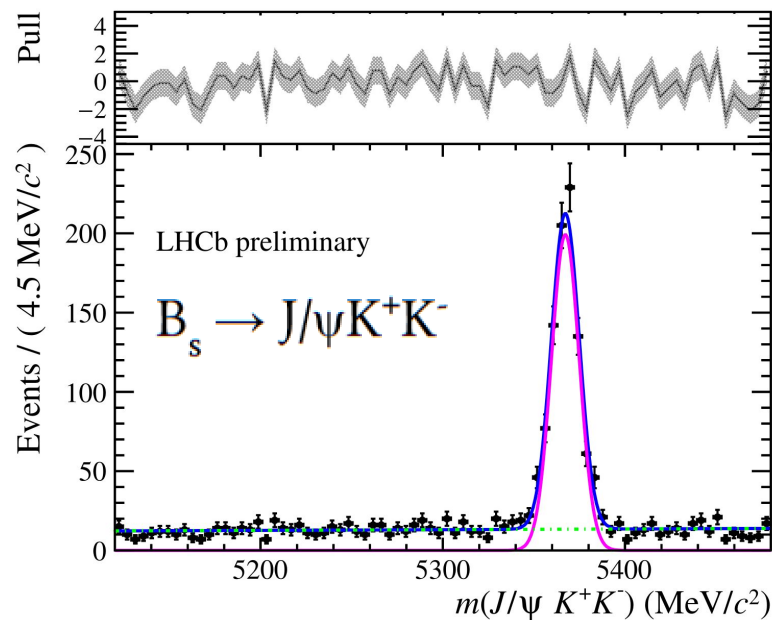


# Real-time analysis [TURBO++]

## New in 2016

Successful use of the TURBO++  
with the new 2016 data.

Samples available right after the  
Hlt2 run.

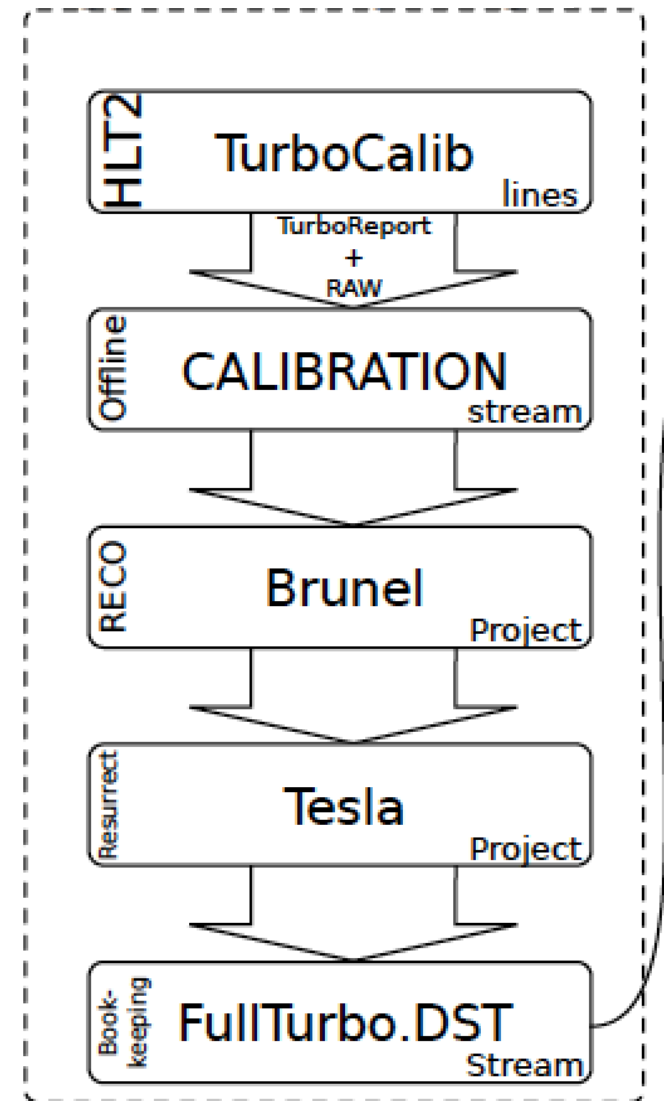


# Strategy for calibration samples in Run 2

[LHCb-PUB-2016-020]

**The potential physics outcome of Run 2 challenges also the samples selected for the PID/tracking calibration.**

- Larger statistics to have smaller statistical uncertainty;
- Allow for systematic studies including those requiring low-level [raw] information (e.g. detector induced charge asymmetries);
- Allow for development of new algorithms in view of the LHCb upgrade;
- Allow to study performance for combined online/offline selections, i.e. persist trigger information and allow for offline reconstruction.



# Particle Identification

## Data driven PID performance

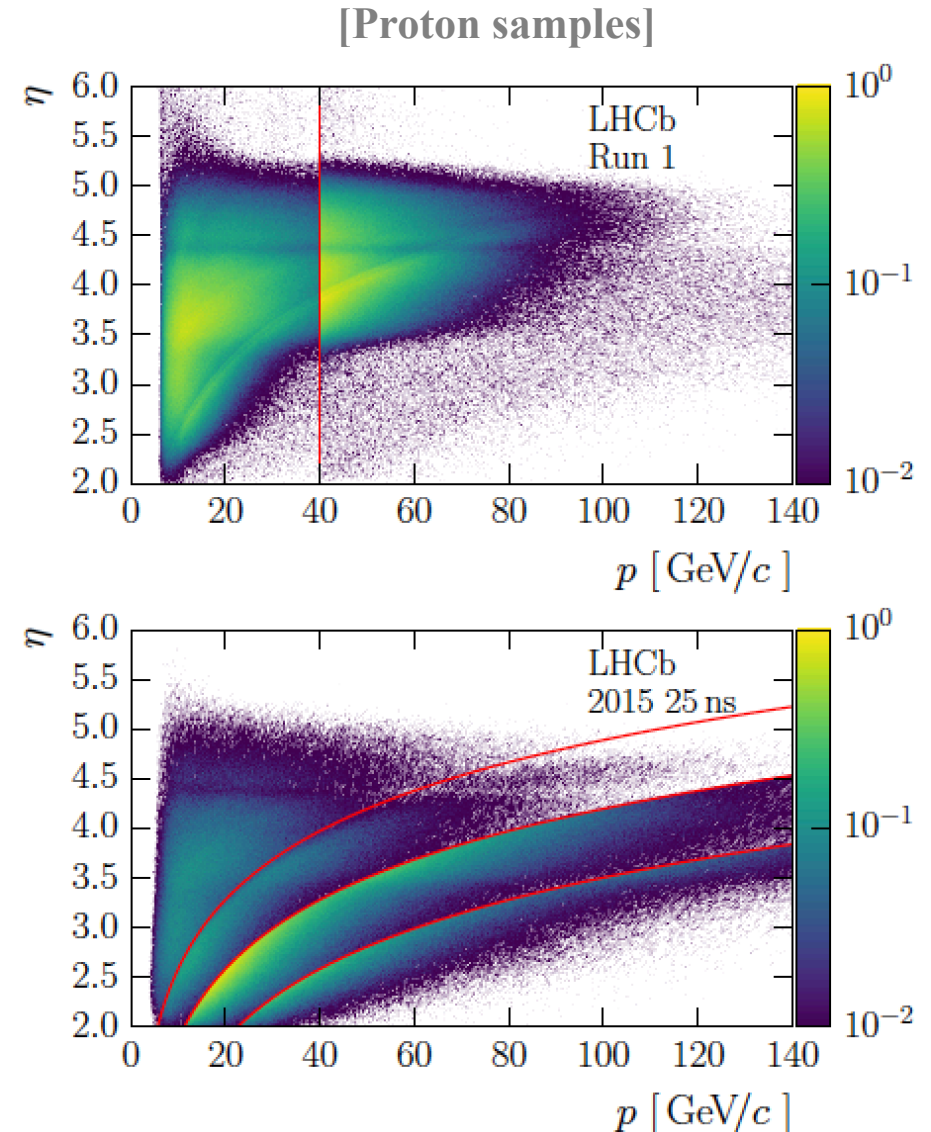
### PID samples [Run 1 and Run 2]:

- low-multiplicity modes with large BRs
- without using PID variables (e.g.  $D^0 \rightarrow K\pi$ )
- tag-and-probe method (e.g.  $J/\psi \rightarrow \mu\mu$ )

Species	Soft	Hard
$e^\pm$	—	$J/\psi \rightarrow e^+e^-$
$\mu^\pm$	$D_s^+ \rightarrow \mu^+\mu^-\pi^+$	$J/\psi \rightarrow \mu^+\mu^-$
$\pi^\pm$	$K_s^0 \rightarrow \pi^+\pi^-$	$D^* \rightarrow D^0\pi^+, D^0 \rightarrow K^-\pi^+$
$K^\pm$	$D_s^+ \rightarrow K^+K^-\pi^+$	$D^* \rightarrow D^0\pi^+, D^0 \rightarrow K^-\pi^+$
$p^\pm$	$\Lambda^0 \rightarrow p\pi^-$	$\Lambda^0 \rightarrow p\pi^-, \Lambda_c^+ \rightarrow pK^-\pi^+$

### Selected directly in the trigger [Run 2]:

- larger statistics
  - easier trigger-decorrelation
- [Muon and CALO are used in L0 and HLT1]



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### Full information can be found in:

Study on the performance of the Particle Identification Detectors at LHCb after the LHC First Long Shutdown

Marianna Fontana on behalf of the LHCb collaboration

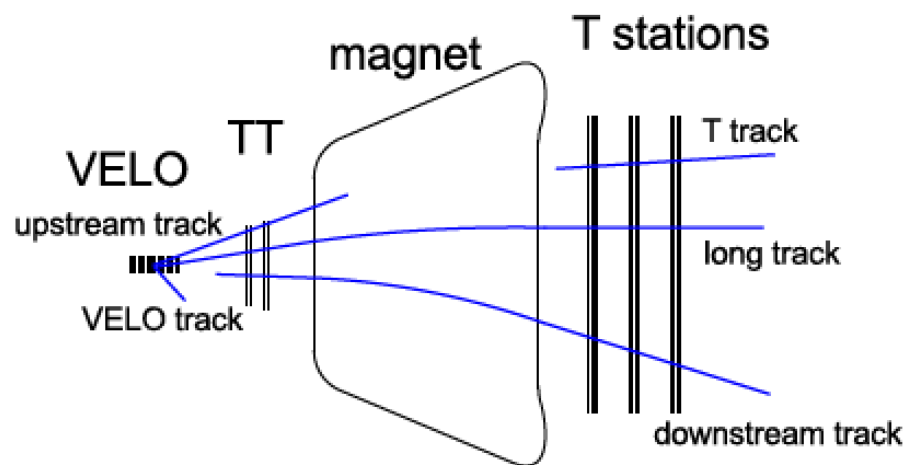
INFN Cagliari and CERN

ICHEP conference 2016  
Chicago, Illinois, 3 - 10 August 2016



[<http://indico.cern.ch/event/432527/contributions/1071498/>]

# *Track reconstruction*



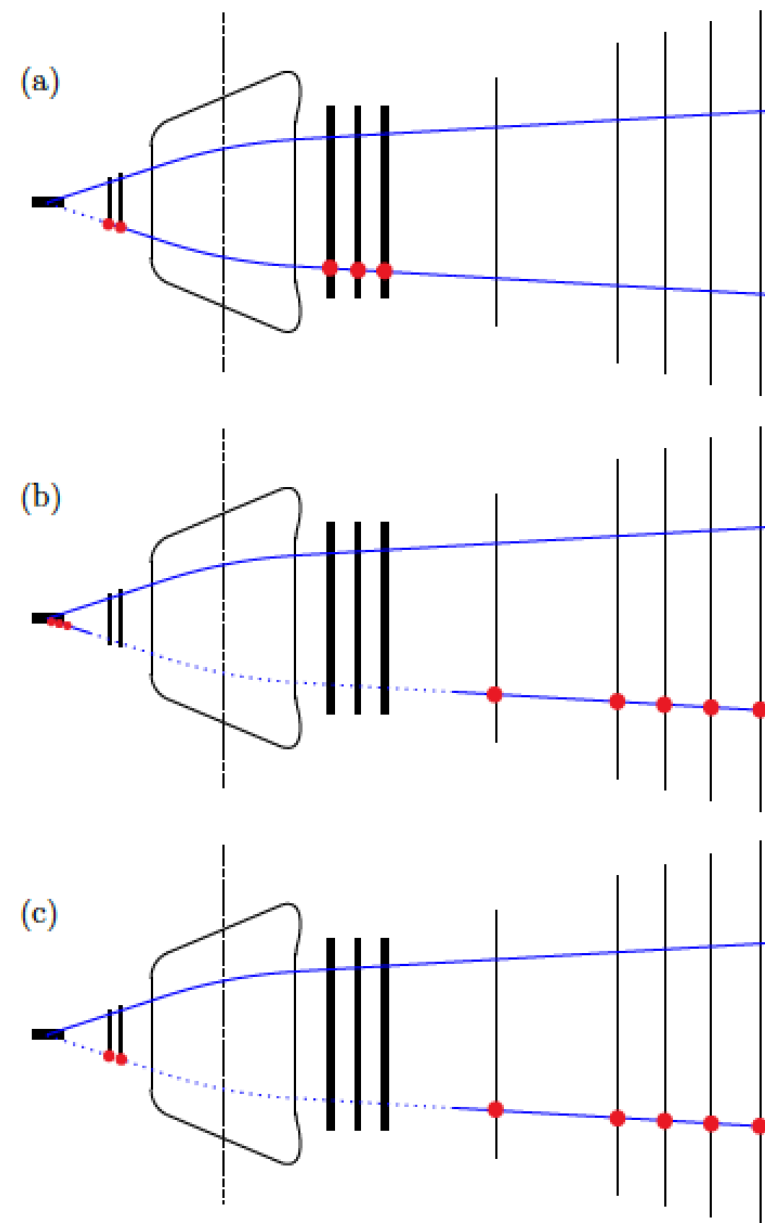
**Use data-driven method to measure track reconstruction efficiency.**

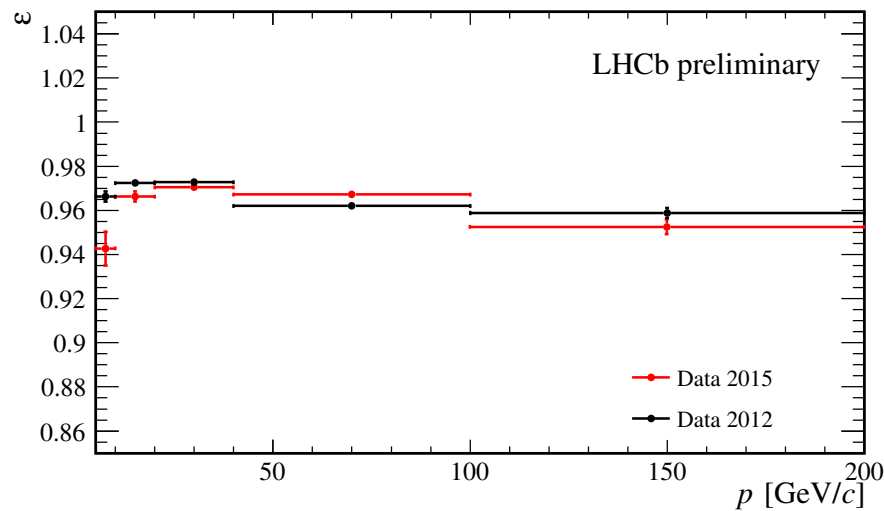
**Tracking samples [Run 1 and Run 2]:**

- Tag-and-probe approach with  $J/\psi \rightarrow \mu\mu$  decays.

- Probe track is only partially reconstructed, not using information from at least one sub-detector which is probed.

Calibration workflow allows to determine online/offline performance





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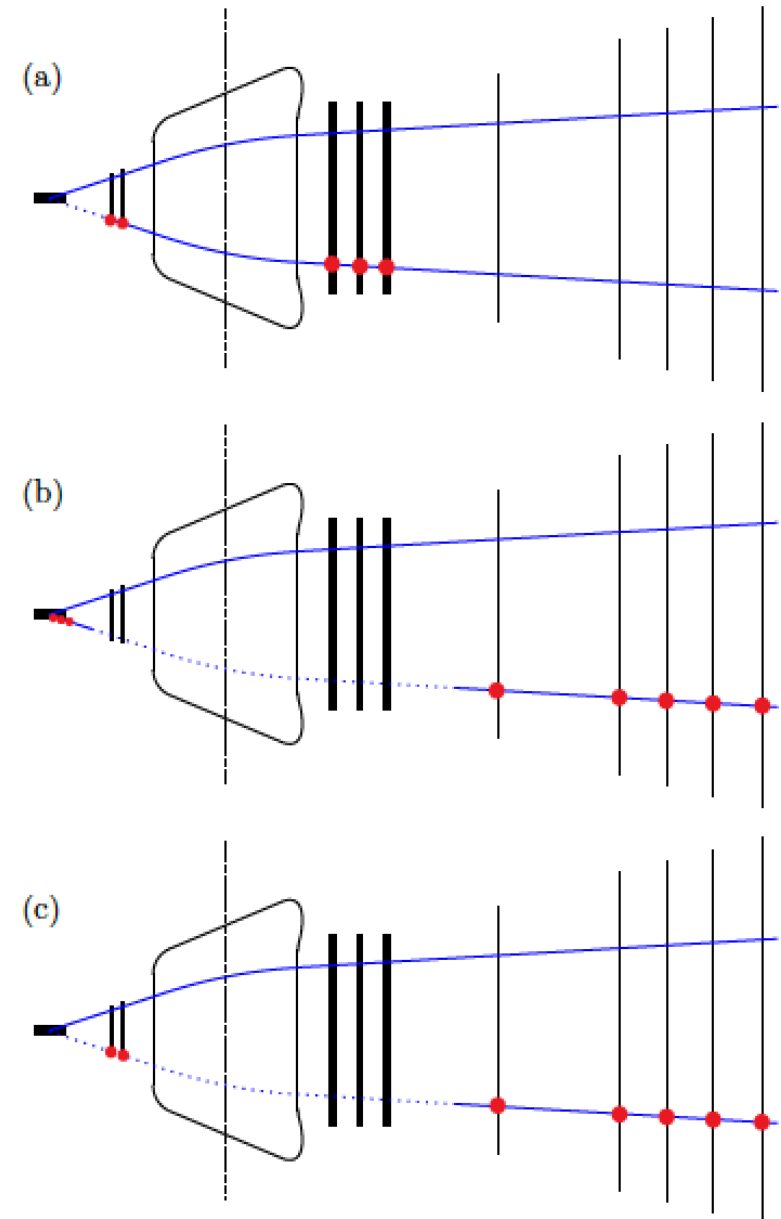
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Calibration workflow allows to determine online/offline performance

# *Track reconstruction*



# Conclusions

The LHCb computing model has evolved to accommodate within a constant budget the expanding physics program of the experiment.

Full offline-quality reconstruction available online.  
[Calibration and alignment running online]

**TURBO stream:** do physics with trigger objects

- More physics per byte;
- **Turbo**: save exclusive decays;
- **Turbo++**: can save all reconstructed objects;
- Results already published and more to come.

**Calibration stream:** select suitable and abundant samples for data-driven PID and Tracking performance evaluation.



*“All I’m saying is now is the time to develop the technology to deflect an asteroid.”*

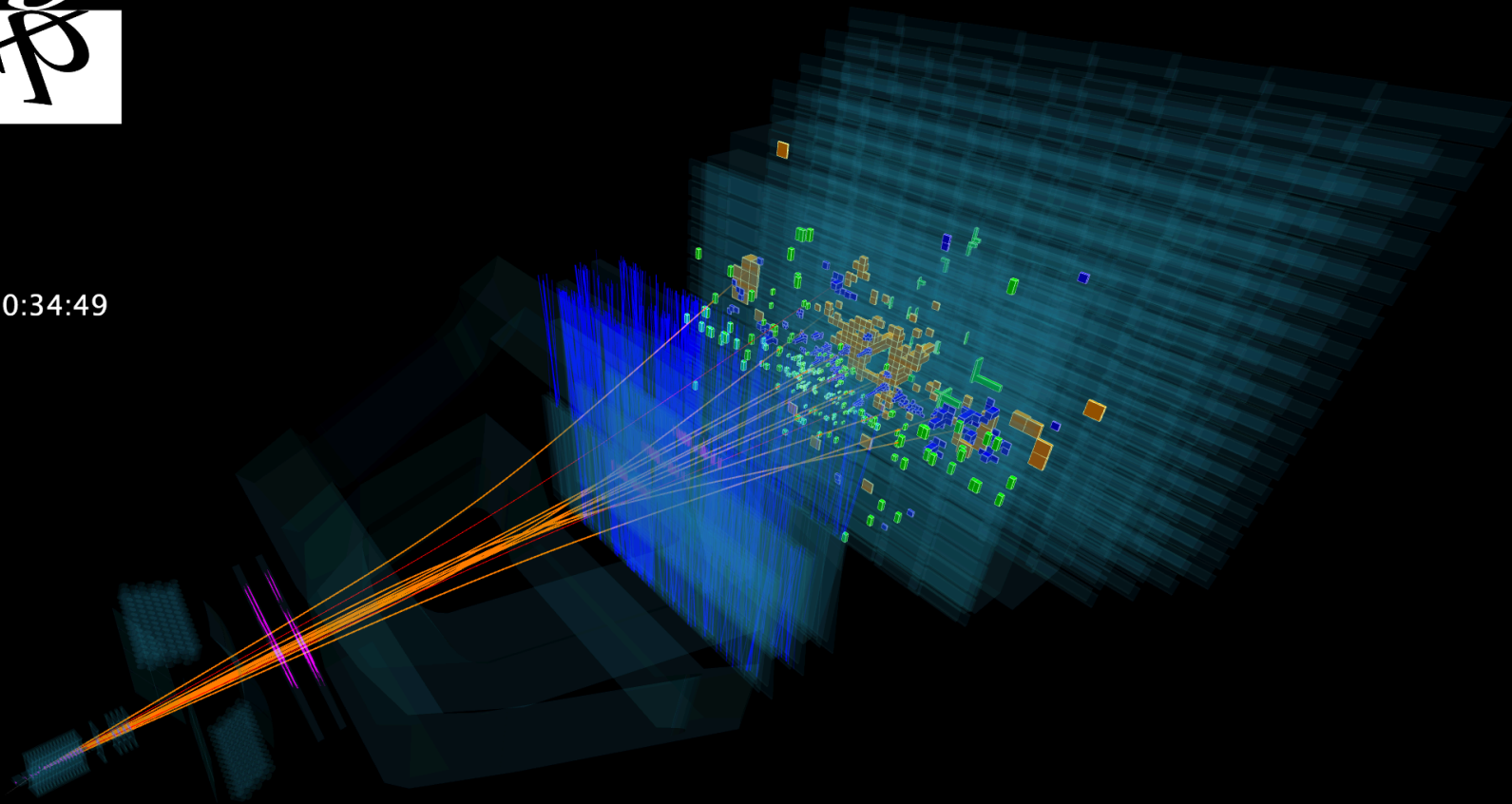
***Run 2 gives the opportunity to put new approaches under full test,  
with potential expansion in the upgraded LHCb experiment (Run 3).  
A working model for future experiments.***

# *Backup information*

Open Controls

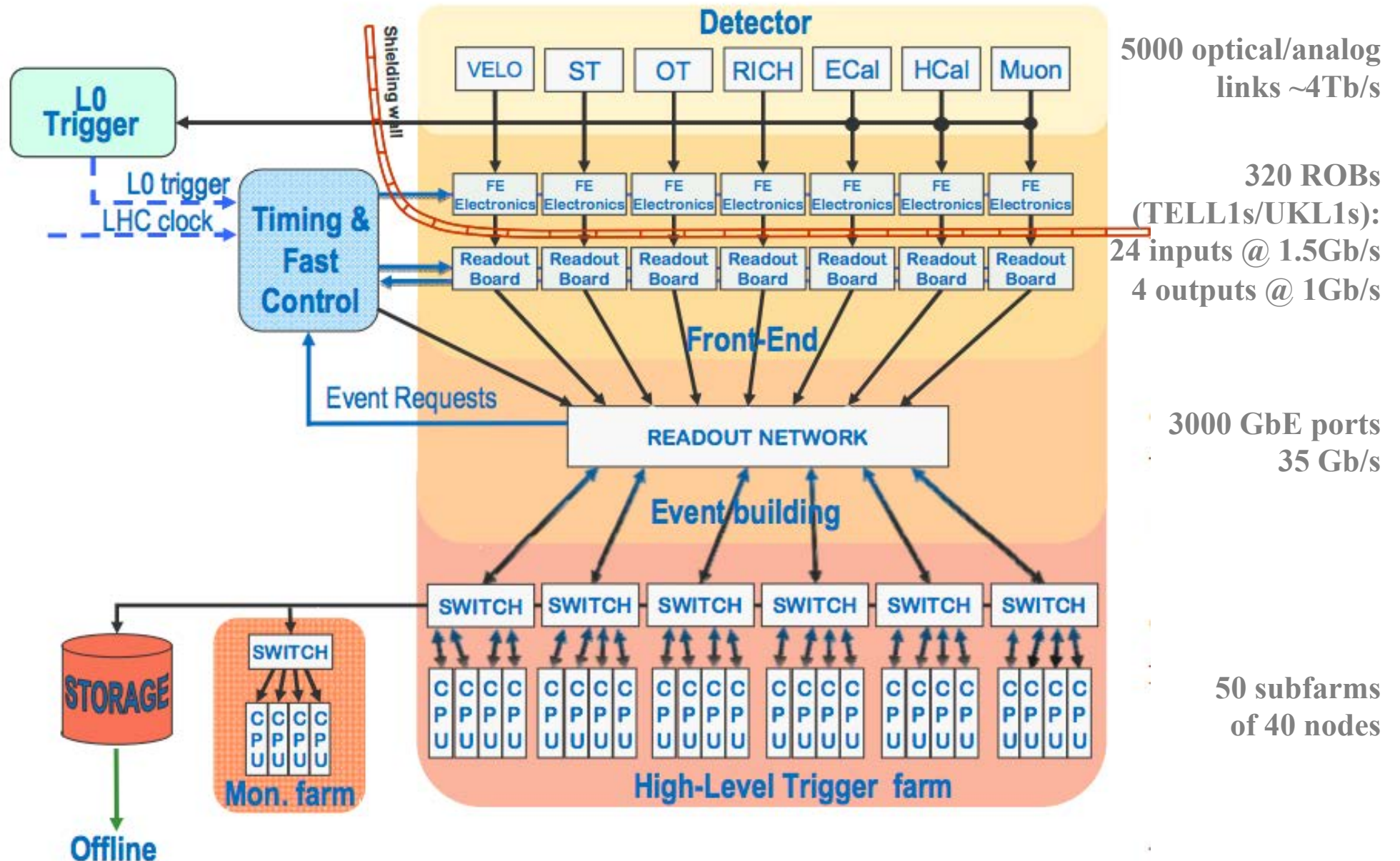


Event 24238378  
Run 172949  
Sat, 23 Apr 2016 10:34:49

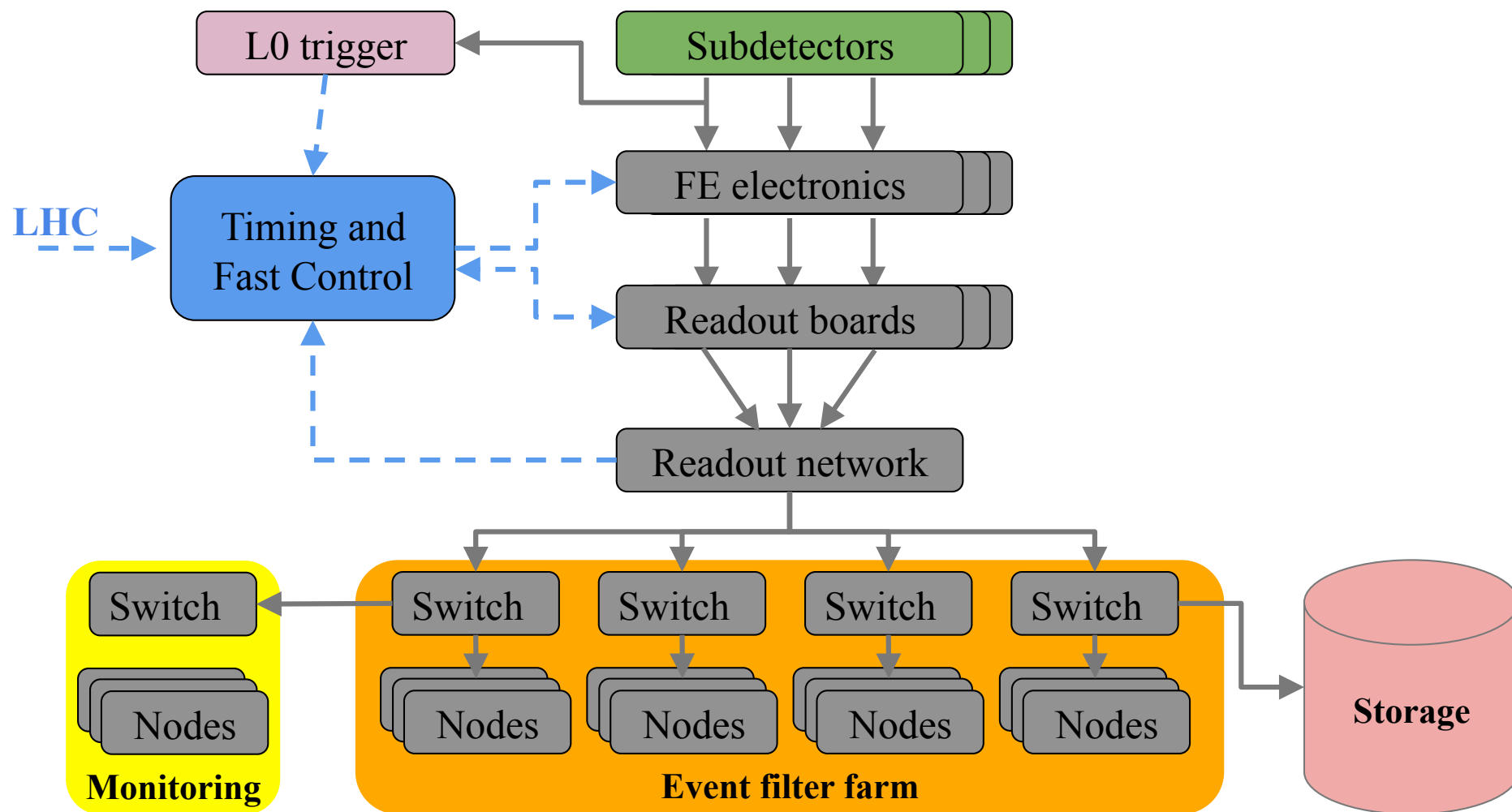


[Run 2 ,year 2: physics commissioning with stables beams]

# Online system architecture



# Online system architecture



[JINST 3 (2008) S08005]

# *LHCb event filter farm*

62 homogeneous sub-farms

50880 logical cores

800 new nodes in Run 2  
[almost double performance]

Servers alone cost >5 MCHF

	CPU	# cores	RAM	disk
920 x	Intel x5650	12 (24)	24 GB	2 TB
100 x	AMD 6272	16 (32)	32 GB	2 TB
800 x	Intel E5-2630v3	16 (32)	32 GB	4 TB



# HLT2 in Run 2

## Full event reconstruction:

- Start from HLT1 vertices and tracks
- Reconstruct all tracks
- [In Run 1  $p_T > 300$  MeV, no redundancy]
- Neutral particles, RICH, Muon and Calo PID
- Full particle identification for long tracks
- [new in Run 2]

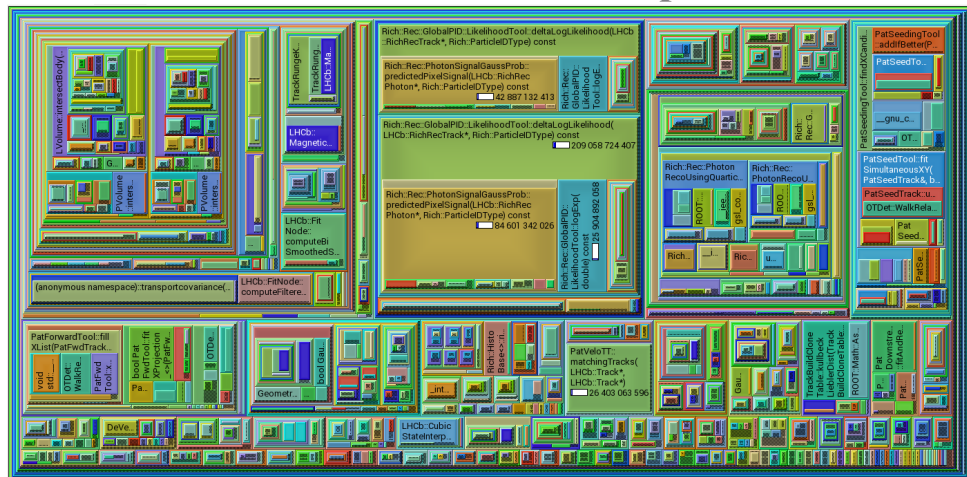
Same strategy as offline

[tracking: a factor  $\sim 2$  faster in HLT]

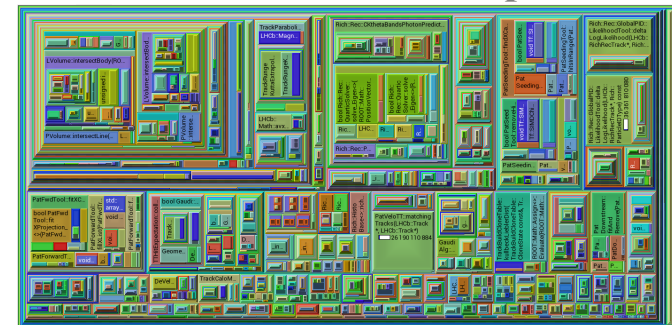
[ $\sim 30\%$  overall offline]

	Run I	Run II
HLT 1 time	$\sim 20$ ms	$\sim 35$ ms
HLT 1 rate	$\sim 80$ kHz	$\sim 150$ kHz
HLT 2 time	$\sim 150$ ms	$\sim 650$ ms
HLT 2 rate	$\sim 5$ kHz	$\sim 12.5$ kHz

2012 CPU Heat Map

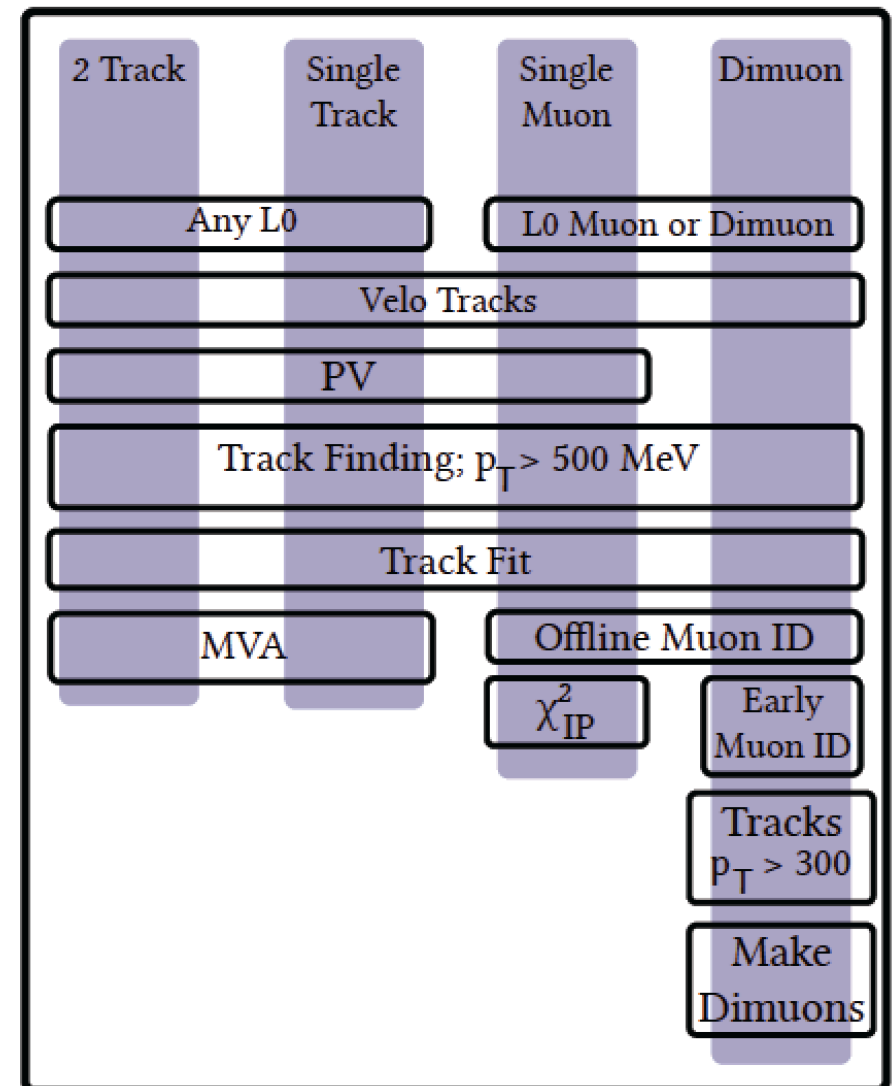


2015 CPU Heat Map



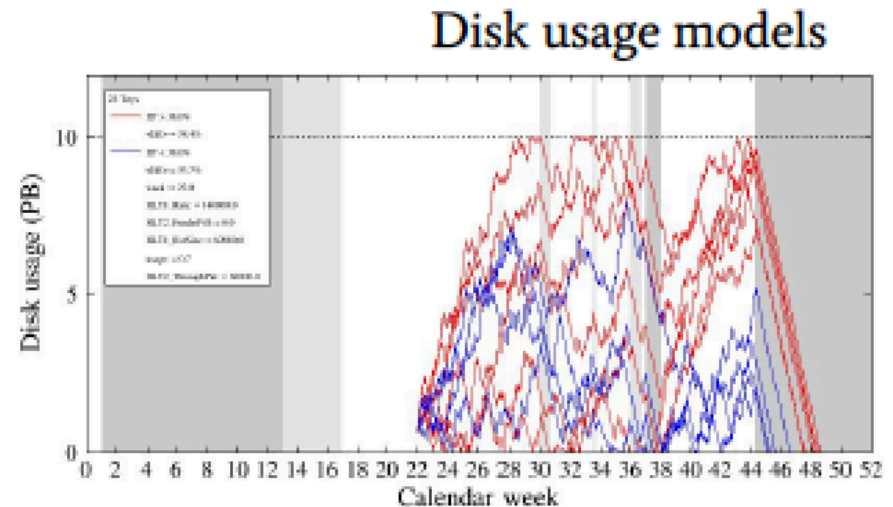
# *HLT1: overview of event reconstruction*

- Inclusive selections:
  - Single and two track MVA selections
  - $\sim 100$  kHz
- Inclusive muon selections
  - Single and dimuon selections
  - Additional low  $p_T$  track reconstruction
  - $\sim 40$  kHz
- Exclusive selections
  - Lifetime unbiased beauty and charm selections
  - Selections for alignment
- Low multiplicity trigger for central exclusive production analyses

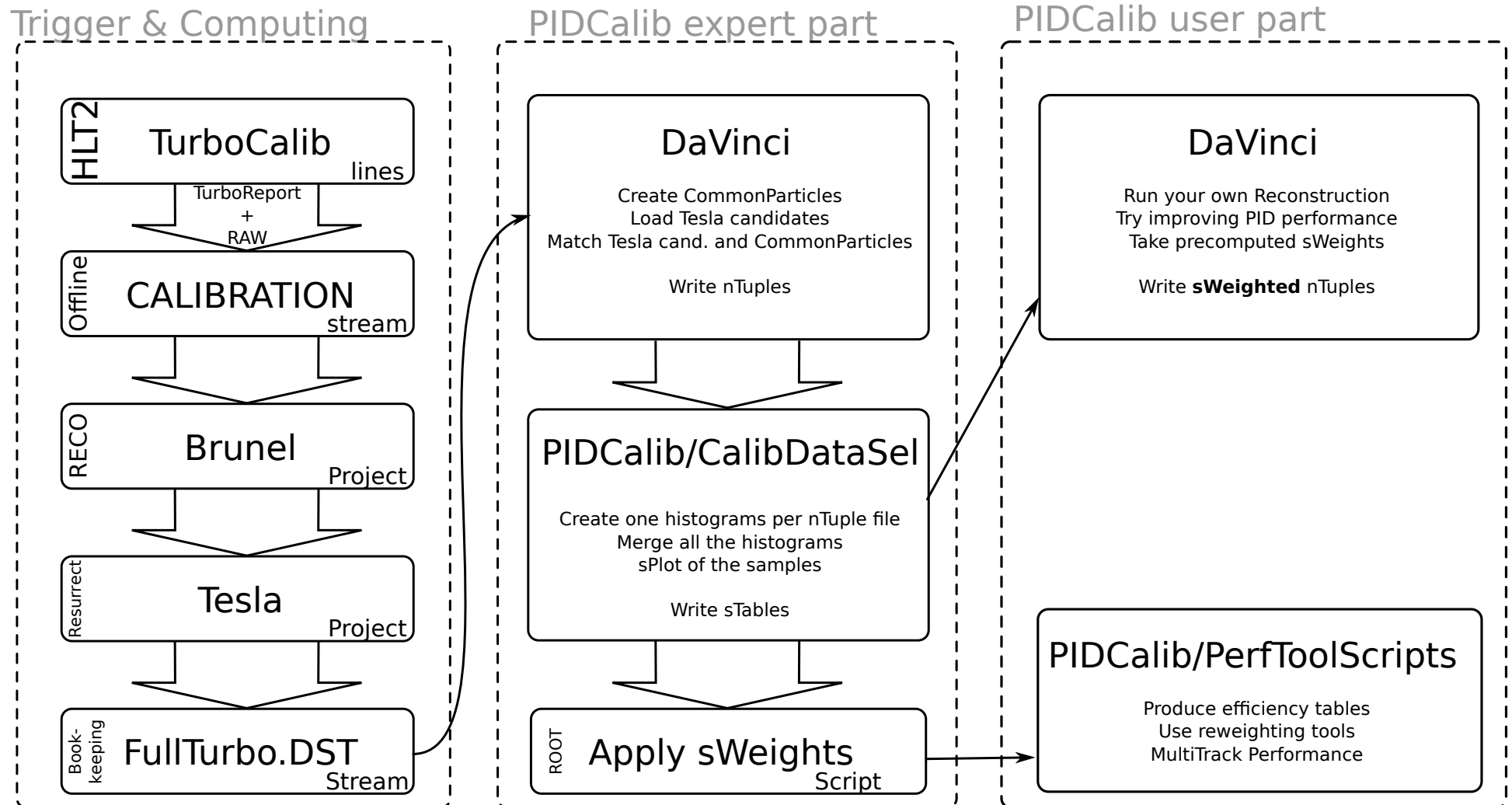


# *Deferred trigger*

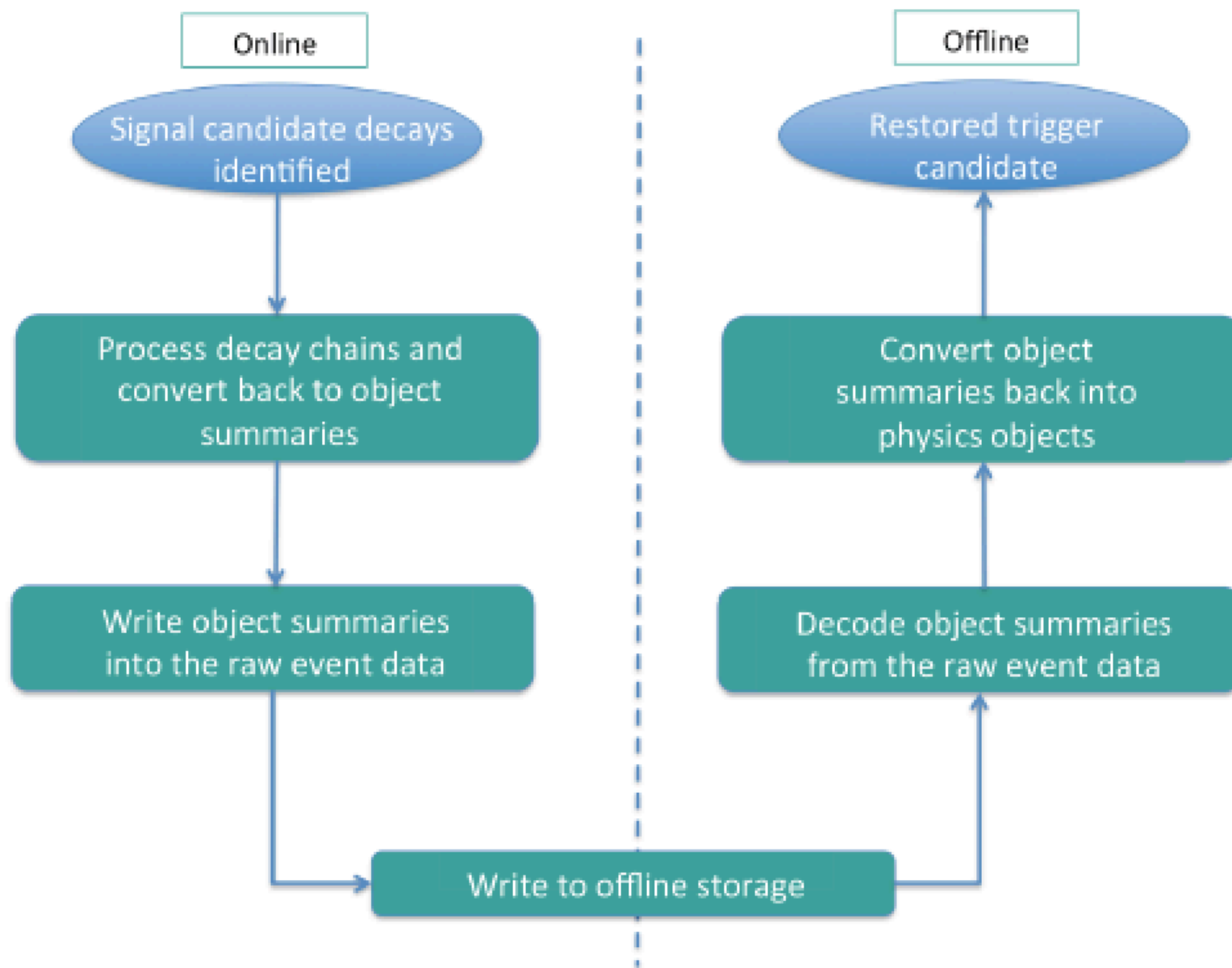
- Stable beams ~35% of the time
- Buffer events to disk and process between fills
- Run I
  - Defer 20% of L0 accepted events
  - Effectively 25% more CPU
- Run II
  - Defer 100% of HLT 1 accepted events
  - More efficient use of buffers due to larger real-time reduction
  - Save 100% of events at 150 kHz instead of 20% at 1 MHz
  - Use HLT 1 output for calibration and alignment
  - 10 PiB in farm (half in 2015)
  - Sufficient buffer given LHC's performance comparable to 2015



# *PID data flow*



# *Turbo data and Tesla restoring information*

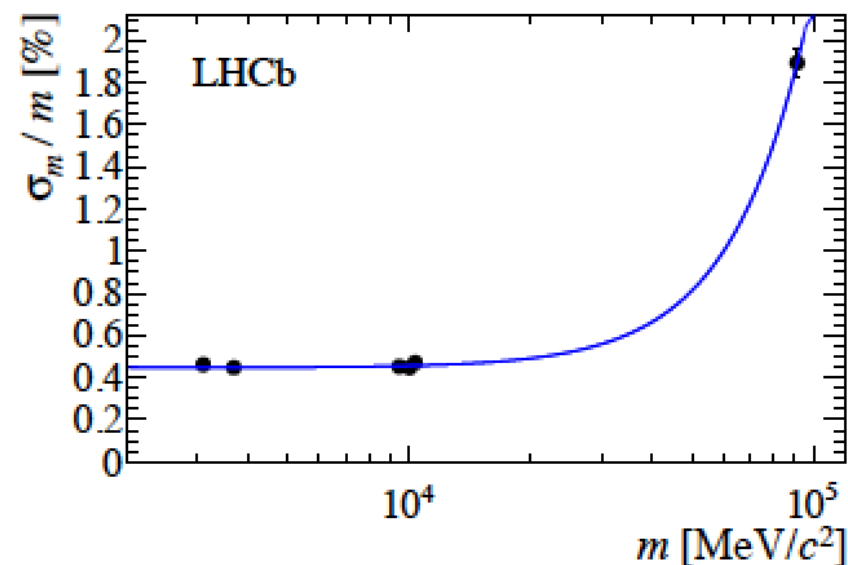
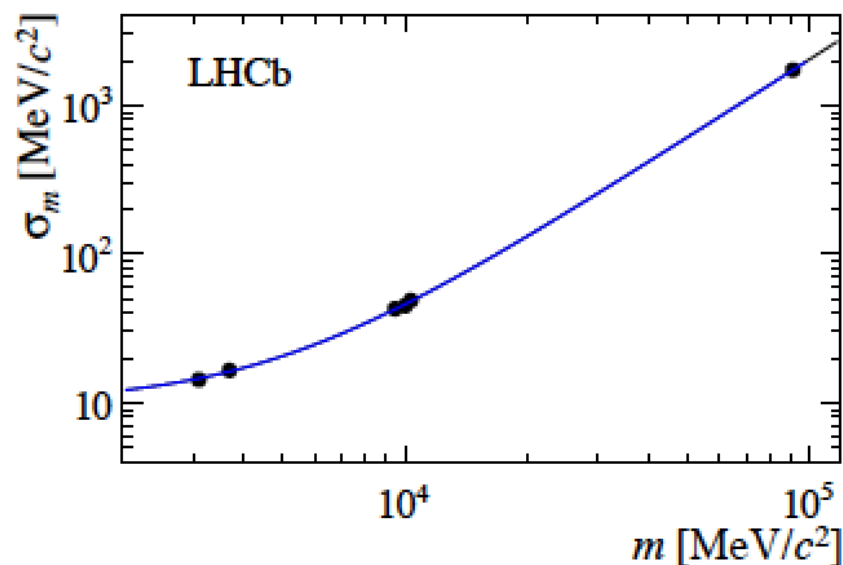


[arXiv: 1604.05596v1]

# Mass resolutions

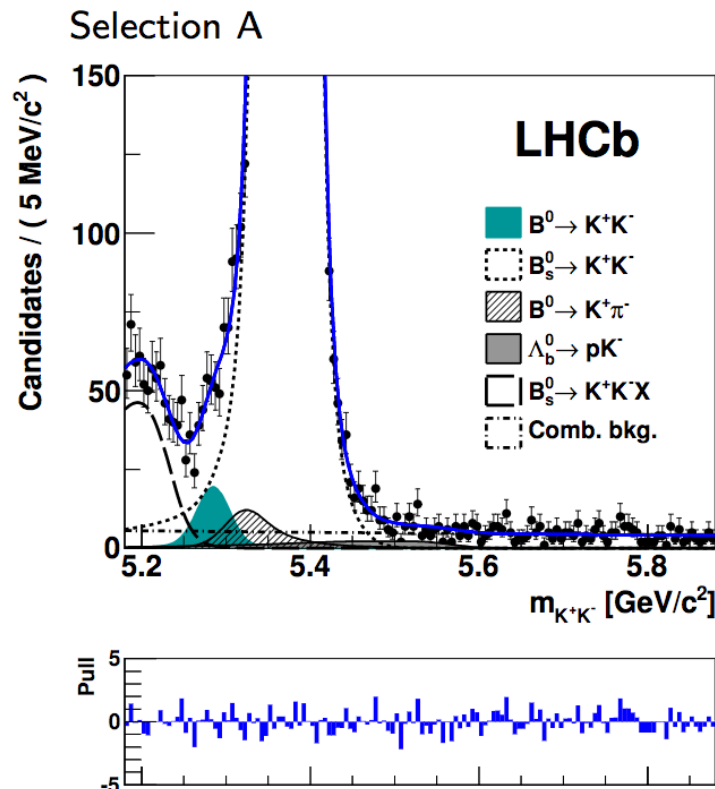
Table 2. Mass resolution for the six different dimuon resonances.

Resonance	Mass resolution ( $\text{MeV}/c^2$ )
$J/\psi$	$14.3 \pm 0.1$
$\psi(2S)$	$16.5 \pm 0.4$
$\Upsilon(1S)$	$42.8 \pm 0.1$
$\Upsilon(2S)$	$44.8 \pm 0.1$
$\Upsilon(3S)$	$48.8 \pm 0.2$
$Z^0$	$1727 \pm 64$



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

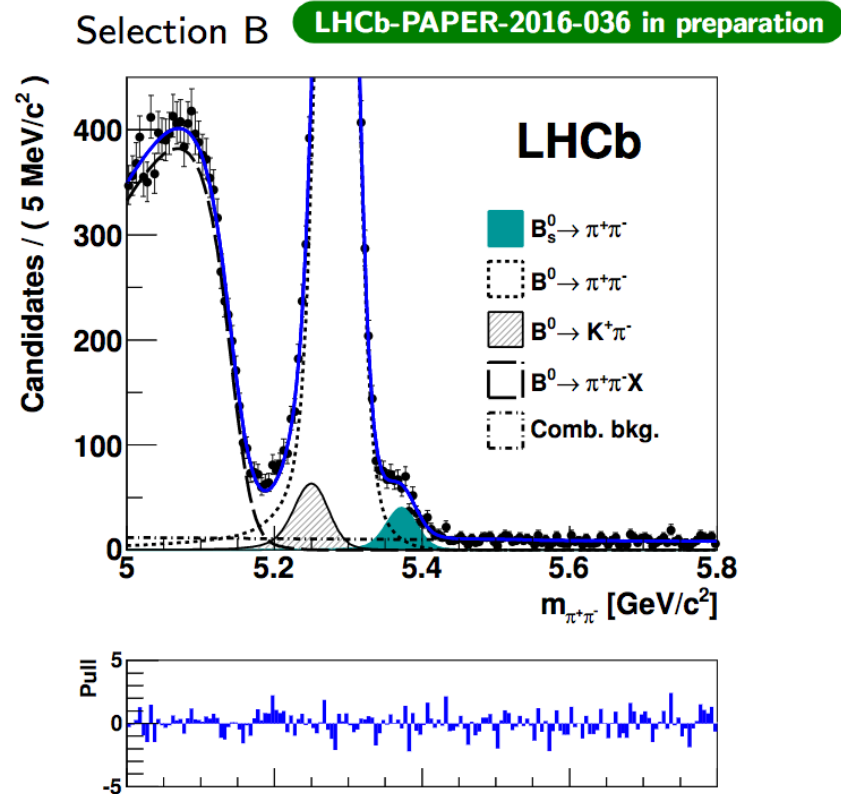
## Preliminary Results from the 2-body Invariant Mass Fit



$$N_{B^0 \rightarrow K^+K^-} = 201.1 \pm 32.7 \pm 13.5$$

$$N_{B^0 \rightarrow K^+\pi^-} = 105010 \pm 430 \pm 990$$

→ 5.8 $\sigma$  significance achieved!  
(inc. systematics)



$$N_{B_s^0 \rightarrow \pi^+\pi^-} = 455.0 \pm 35.2 \pm 24.2$$

$$N_{B^0 \rightarrow K^+\pi^-} = 71300 \pm 310 \pm 610$$

Uncertainties:  $\pm$  stats.  $\pm$  syst.

# Tracking efficiency: details

Table 2: Selection requirements on the tag and probe tracks and on the combination into a  $J/\psi$  candidate for the three different methods.

	VELO method	T-station method	Long method
Tag	Long track used in single muon trigger		
	$\chi^2/\text{ndf}(\text{track}) < 5$ $p > 5.0 \text{ GeV}/c$ $p_T > 0.7 \text{ GeV}/c$	$\text{DLL}_{\mu\pi} > 2$ $\chi^2/\text{ndf}(\text{track}) < 3$ $p > 7.0 \text{ GeV}/c$ $p_T > 0.5 \text{ GeV}/c$	$\text{DLL}_{\mu\pi} > 2$ $\chi^2/\text{ndf}(\text{track}) < 2$ $p > 10 \text{ GeV}/c$ $p_T > 1.3 \text{ GeV}/c$ $\text{IP} > 0.5 \text{ mm}$
Probe	Downstream track $p > 5.0 \text{ GeV}/c$ $p_T > 0.7 \text{ GeV}/c$	VELO-muon track $p > 5.0 \text{ GeV}/c$ $p_T > 0.5 \text{ GeV}/c$	TT-muon track $p > 5.0 \text{ GeV}/c$ $p_T > 0.1 \text{ GeV}/c$
$J/\psi$	$M_{\mu\mu} \in [2.9, 3.3] \text{ GeV}/c^2$ $\chi^2/\text{ndf}(\text{vertex}) < 5$ $N_{J/\psi} = 1$	$M_{\mu\mu} \in [2.7, 3.5] \text{ GeV}/c^2$ $\chi^2/\text{ndf}(\text{vertex}) < 5$ $N_{J/\psi} = 1$ $p > 7.0 \text{ GeV}/c$	$M_{\mu\mu} \in [2.6, 3.6] \text{ GeV}/c^2$ $\chi^2/\text{ndf}(\text{vertex}) < 5$ $N_{J/\psi} = 1$ $\text{IP} < 0.8 \text{ mm}$

[JINST 10 (2015) P02007]