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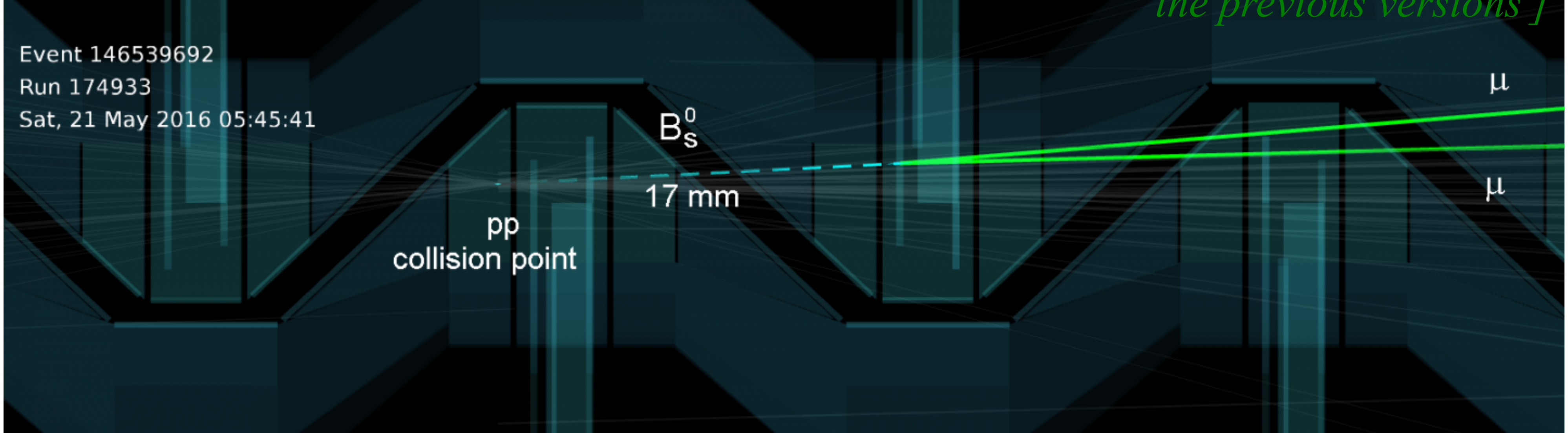
[Acknowledgements to F. Alessio, F. Archilli, C. Gaspar, V. Gligorov, M. Schubiger and V. Vagnoni for some material]

Sapienza University, 3 June 2019
[Updated with respect to the previous versions]



$B_{(s)}\mu\mu$ at LHCb: details behind a successful result

(with bonus tracks about LHCb and future plans)

From your handouts

Aim of these lectures*

* Many thanks to Prof. C. Bini for the provided material.

Experimental Physics:

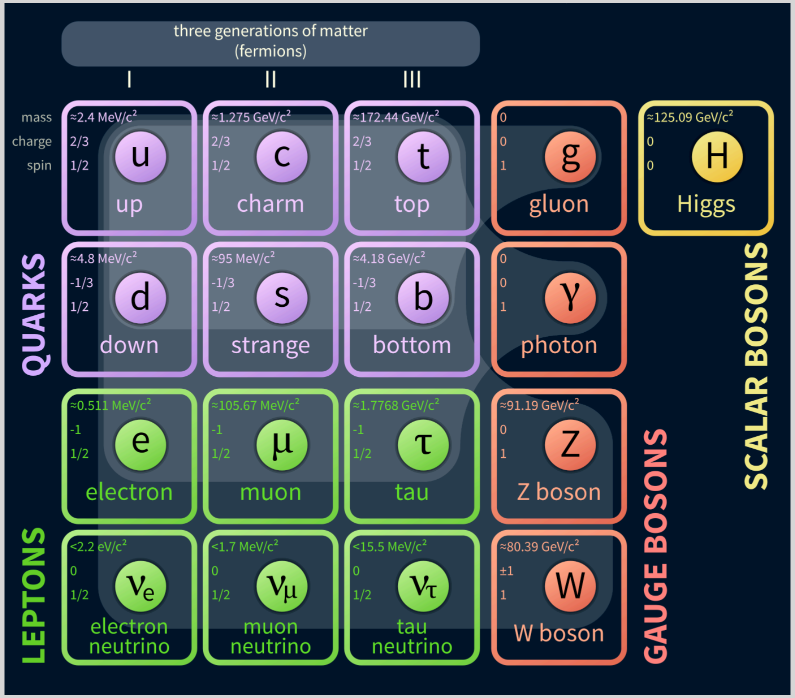
- define the "question to nature"
- design the experiment
- build the experimental apparatus
- run the experiment
- analyze the data and get the "answer"

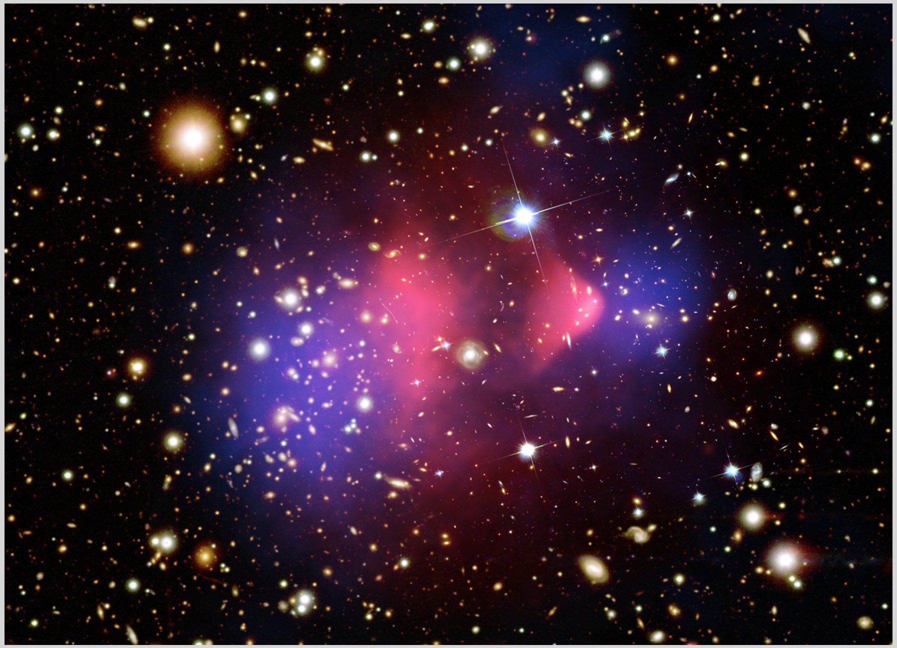
Learn in this course:

- How to design an EPP experiment
- How to analyze data in order to extract physics results

Open points: SM (and beyond)

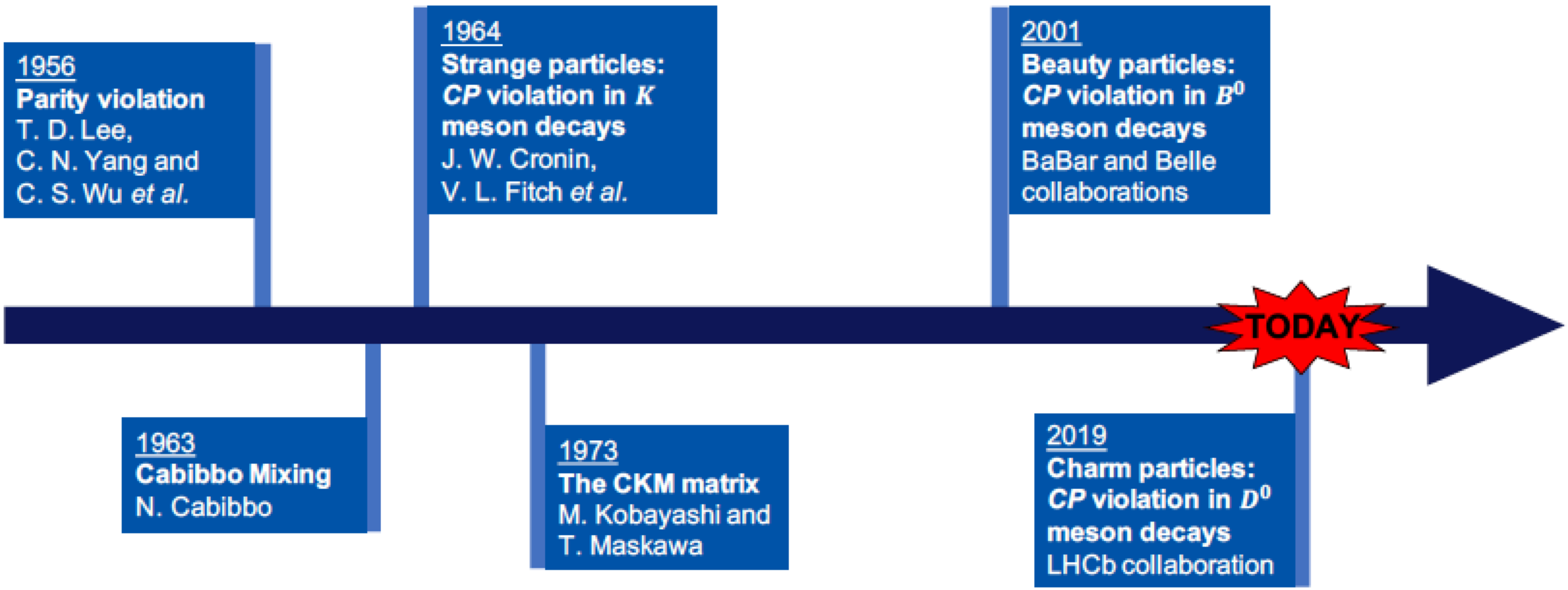
- No explanation for the quark hierarchy
- Why are there 3 families/generations?
- No real explanation for CP violation
- Why it is only found in the weak interaction?
- Mass value of the Higgs boson
- EW and strong unification
- …





- No explanation for baryogenesis
- Dark matter and dark energy
- Neutrino masses
- Gravity
- …

CP violation, key dates



From your handouts

Outline of the Lectures

Short introduction: the goal and the main “numbers”

The language of the random variables and of the statistical inference (a recap of things you already know…)

The Logic of a PP experiment

Quantities to measure in PP

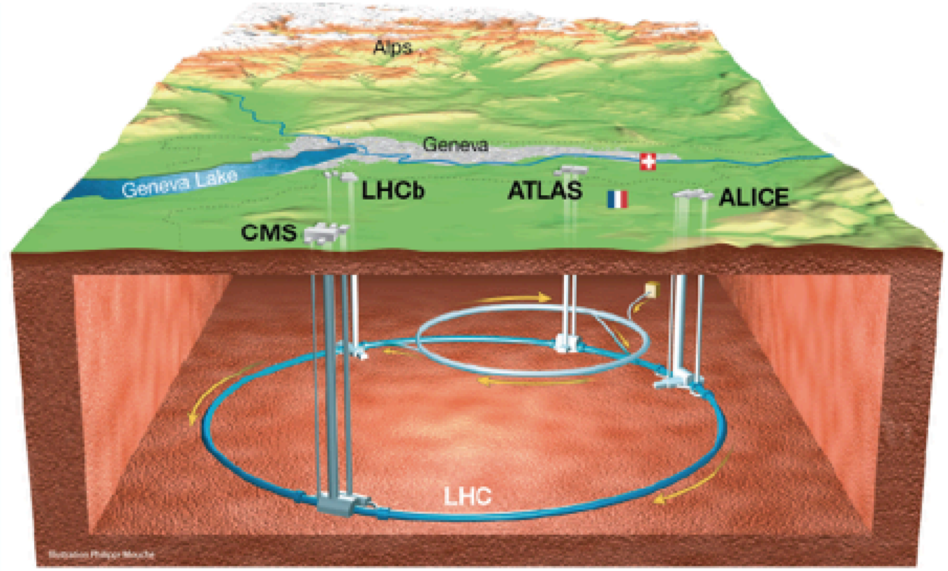
How to analyze data

How to design a PP experiment

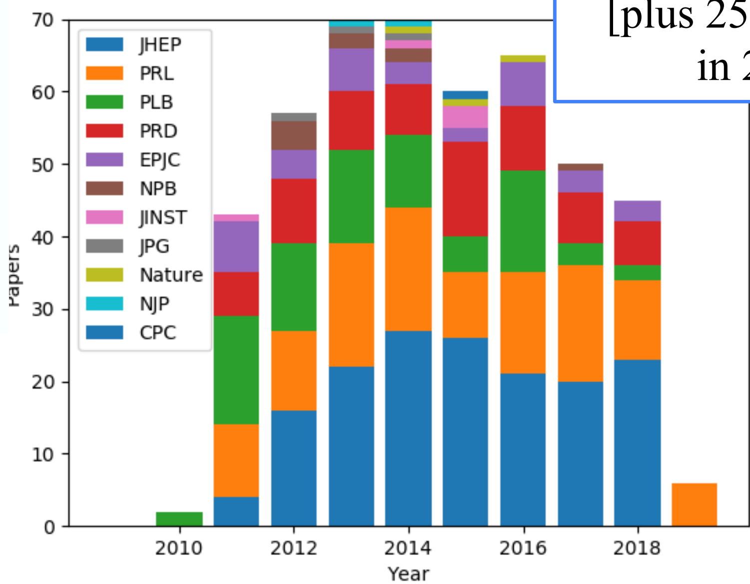
- The projectiles and the targets: cosmic rays, particle accelerators
- The detectors: examples of detector designs

LHCb at LHC in one slide

- 1225 members, from 71 institutes in 16 countries
- Dedicated experiment for precision measurements of CP violation and rare decays of heavy-flavoured hadrons
- pp collision at $\sqrt{s} = 7, 8, 13$ TeV

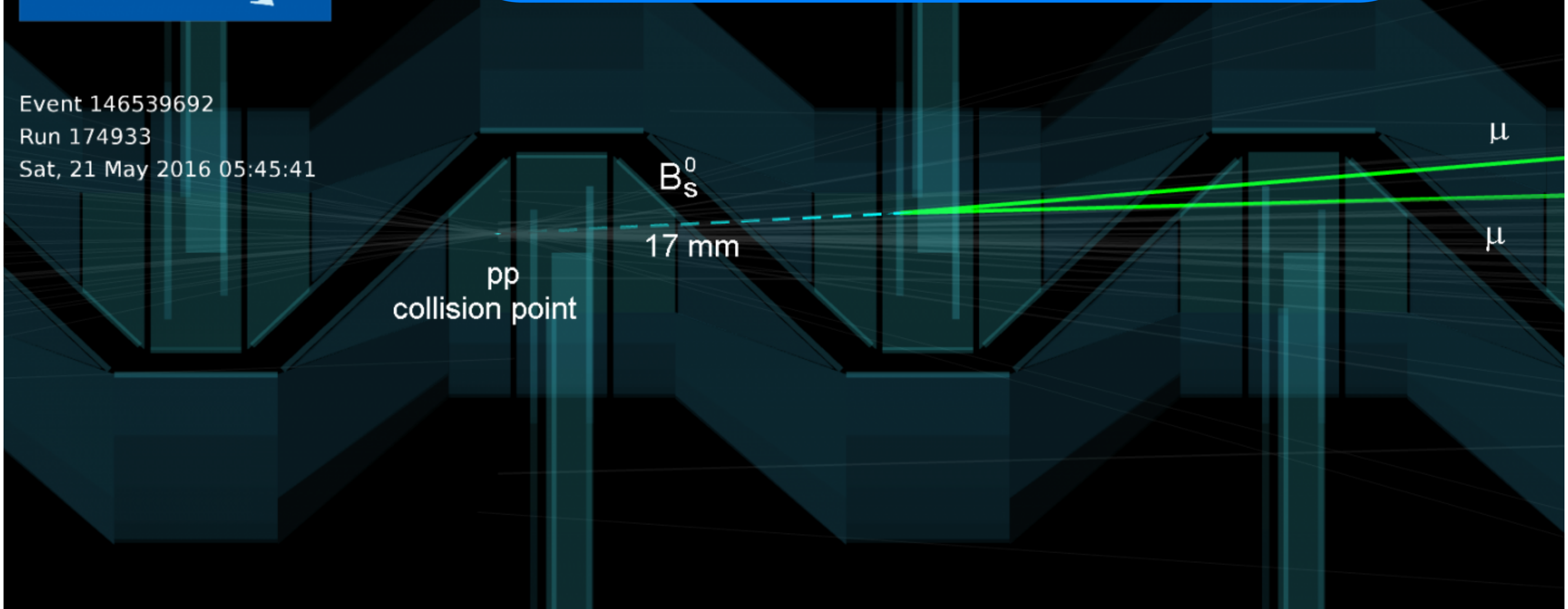


482 total publications [plus 25 submitted in 2019]



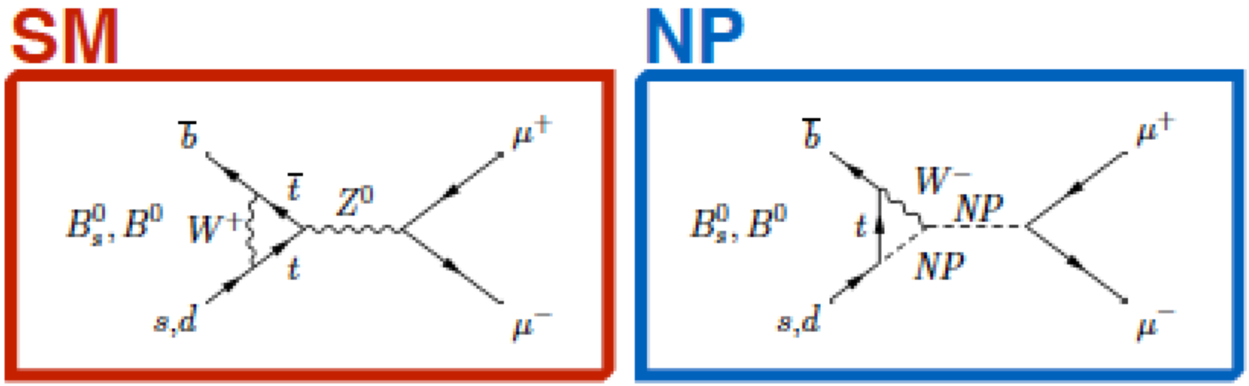
Outline

- $B_{(s)}\mu\mu$: why it worth the effort
- A lot of data
- An excellent detector
- $B_{(s)}\mu\mu$: the measurement
- What next



$B_{(s)}\mu\mu$: rare b decays

- Precise measurement sensitive to New Physics effect beyond the SM.
- Flavour Changing Neutral Currents (FCNC) are suppressed at tree level in the SM.
- NP contributions can arise at the same level of or larger than SM one



- FCNC processes can be described by an effective Hamiltonian describing the four fermion interaction

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}\pi} V_{ts}^* V_{tb} \sum_i [C_i \mathcal{O}_i + C_i' \mathcal{O}_i']$$

- C_i Wilson coefficients
- O_i four-fermion operators

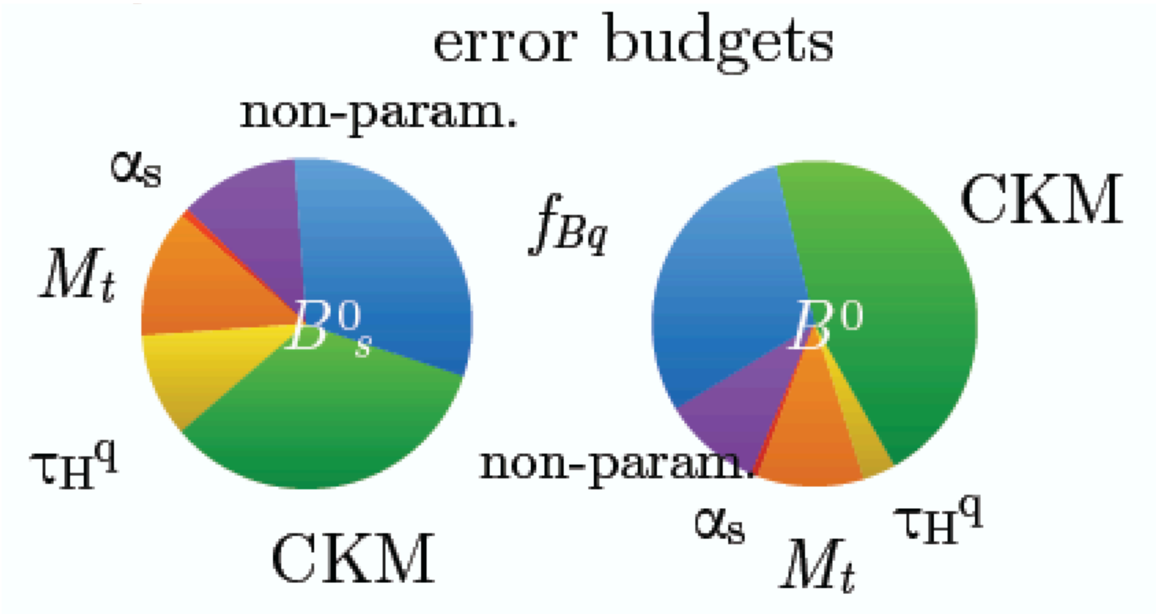
$B_{(s)}\mu\mu$: SM theoretical expectations

CP-averaged time integrated branching fraction predictions:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

[hep-ex/1403.4427]

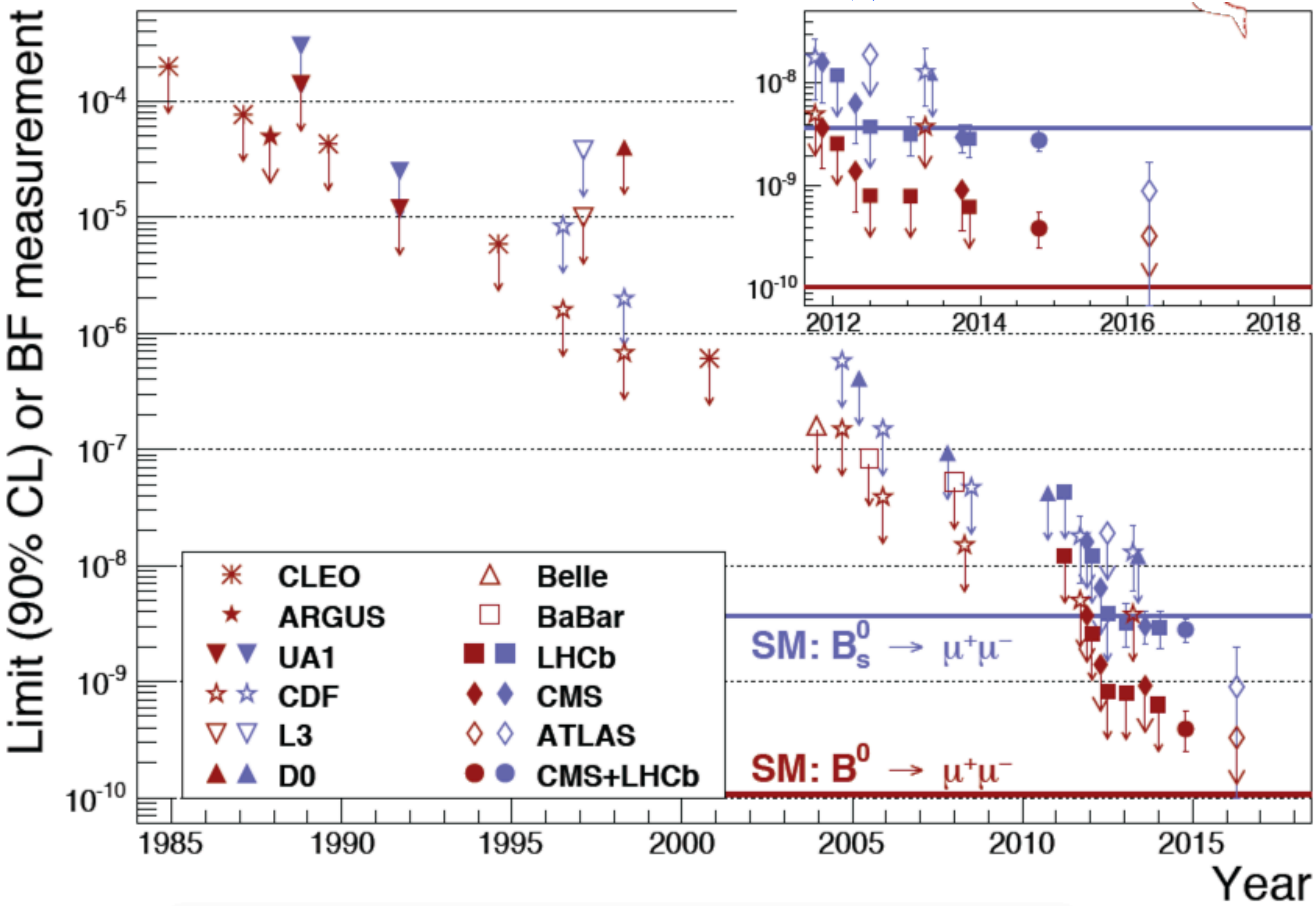
updated with the latest top mass measurement (Tevatron+LHC combination)



Relative accuracy:
B_s: ~6%
B^0: ~8%

[Bobeth et al. PRL 112 (2014) 101801]

$B_{(s)}\mu\mu$: a long story



$B_{(s)}\mu\mu$ at LHC (pre 2017)

- CMS-LHCb combined analysis with Run1 data: [Nature 522, 68-72]
  - **Observation of the $B^0_s \to \mu^+\mu^-$**

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

6.2σ significance observed
compatibility with SM at 1.2σ level

  - **Evidence of $B^0 \to \mu^+\mu^-$**

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$

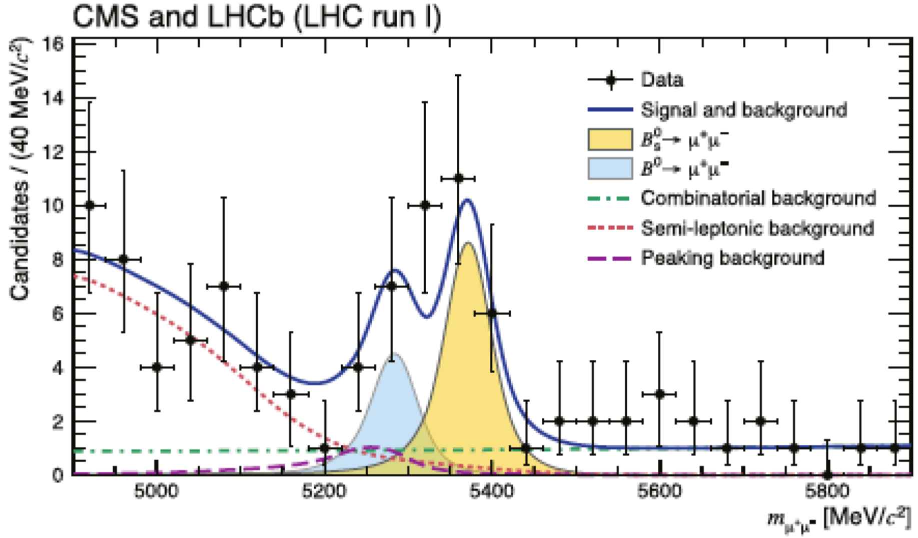
3.0 σ stat. significance
compatibility with SM at 2.2σ level

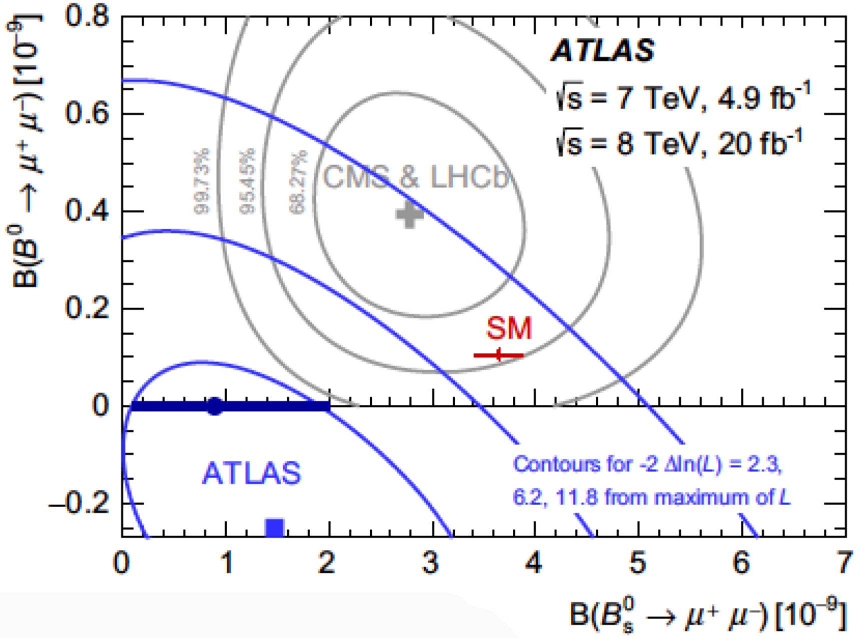
- **ATLAS:** [EPJ C76 (2016) 9, 513]

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 0.9^{+1.1}_{-0.8} \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10} \text{ at 95\% C.L.}$$

Mild tension among experimental results.
Excess on B^0 intriguing, to be investigated





$B_{(s)}\mu\mu$: BR measurement

From "your" lectures

Branching ratio measurement

- Given an unstable particle a, it can decay in several (say N) final states, $k=1,\ldots,N$. If Γ is the ***total width*** of the particle ($\Gamma=1/\tau$ with τ particle lifetime), for each final state we define a "***partial width***" in such a way that

$$\Gamma = \sum_{k=1}^{N} \Gamma_k$$

- The ***branching ratio*** of the particle a to the final state X is

$$B.R.(a \to X) = \frac{\Gamma_X}{\Gamma}$$

- To measure the B.R. the same analysis as for a cross-section is needed. In this case we need the number of decaying particles N_a (not the flux) to normalize:

$$B.R.(a \to X) = \frac{N_{cand} - N_b}{\varepsilon} \frac{1}{N_a}$$

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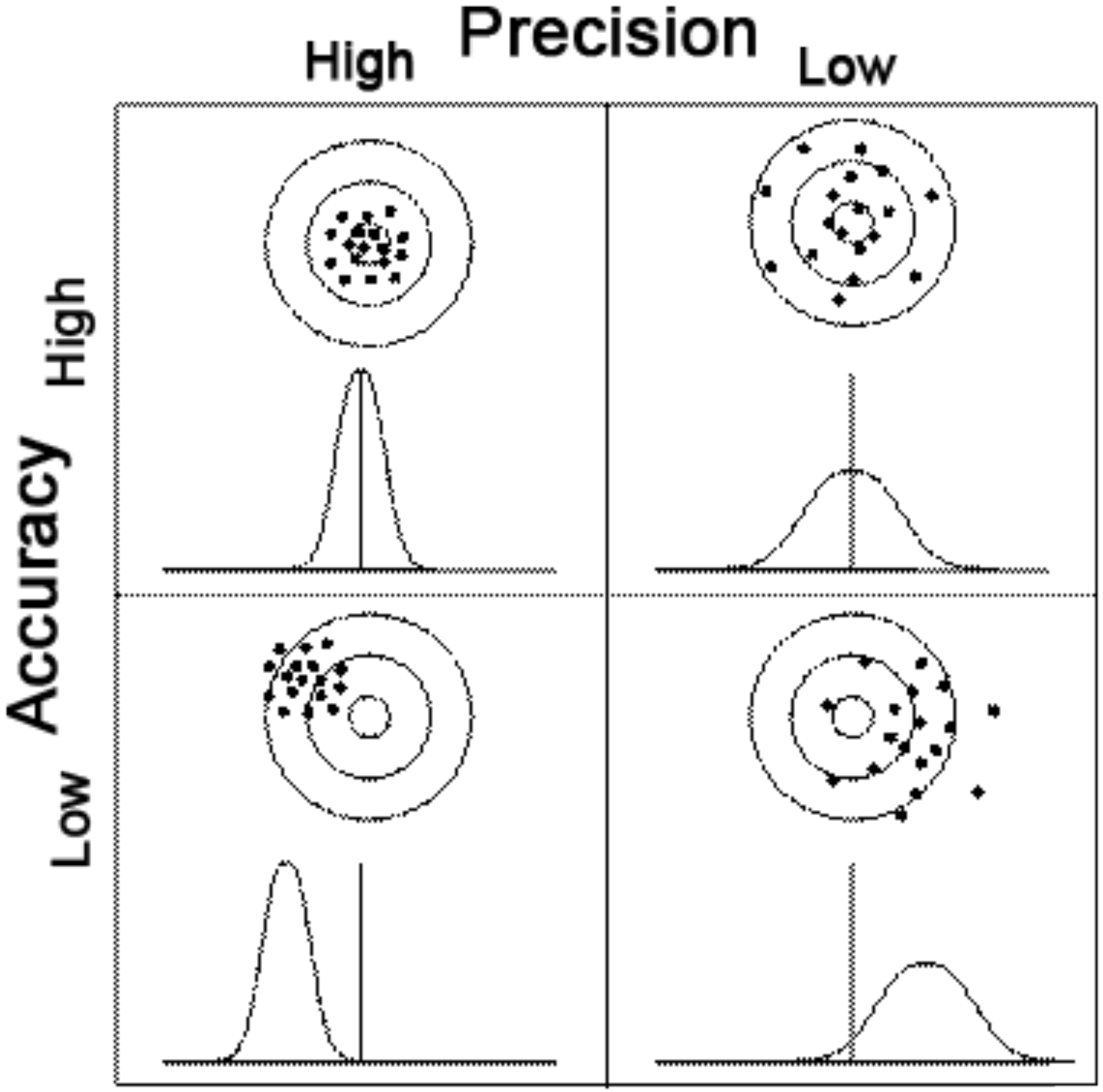
$$B.R.(a \to X) = \frac{N_{cand} - N_b}{\varepsilon} \frac{1}{N_a}$$

$$\mathrm{BR} = \mathrm{BR}_{\mathrm{cal}} \times \frac{\epsilon^{Acc}_{norm}}{\epsilon^{Acc}_{sig}} \times \frac{\epsilon^{RecSel|Acc}_{norm}}{\epsilon^{RecSel|Acc}_{sig}} \times \frac{\epsilon^{Trig|RecSel}_{norm}}{\epsilon^{Trig|RecSel}_{sig}} \times \frac{f_{\mathrm{cal}}}{f_{d(s)}} \times \frac{N_{B^0_{(s)}\to\mu^+\mu^-}}{N_{\mathrm{cal}}}$$

Interlude: statistical vs systematic errors

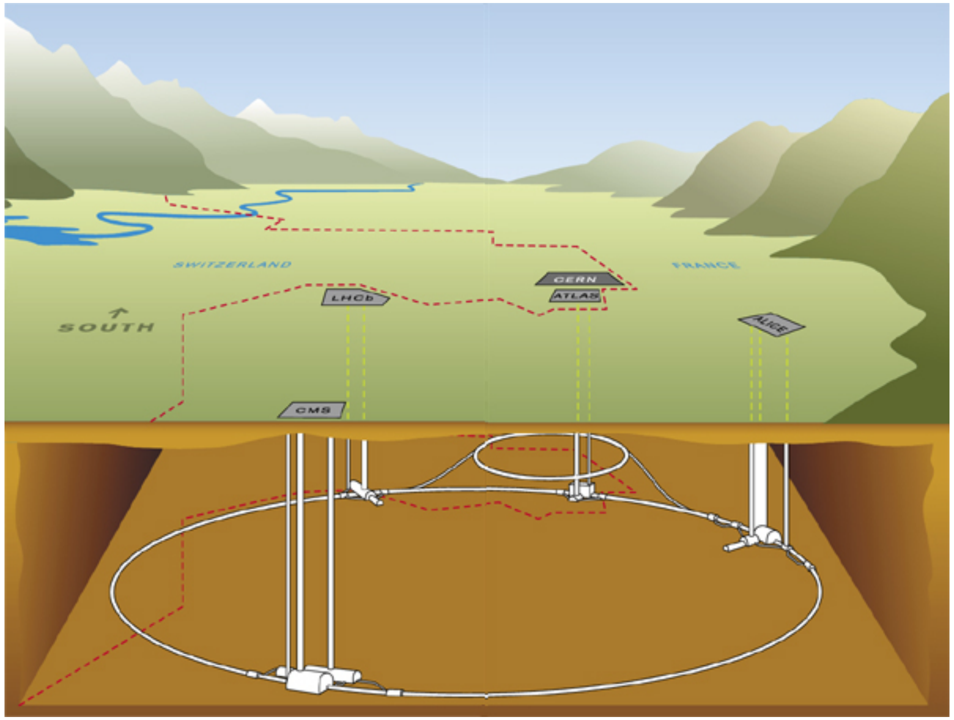
Precision ~ statistical error:
- well defined
- **more (and more) data**
- **Sqrt(n) at work!**

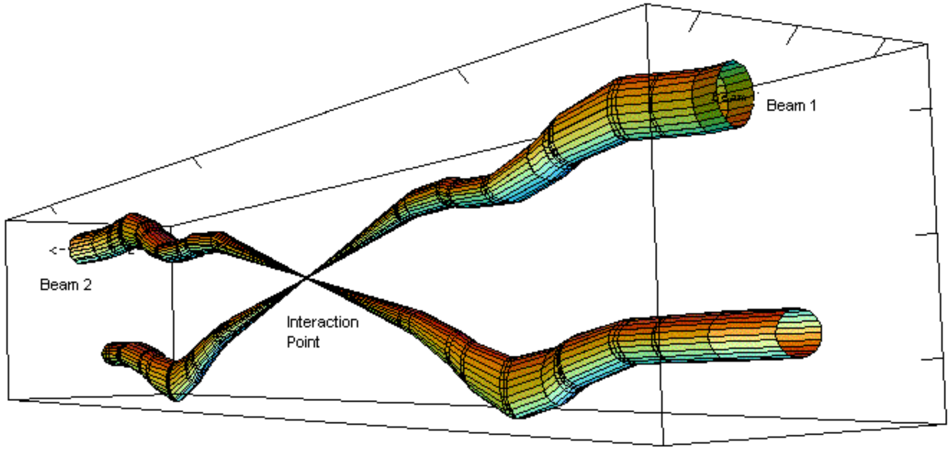


Accuracy ~ systematic:
- a lot of checks
- redundancy
- **you never know…**

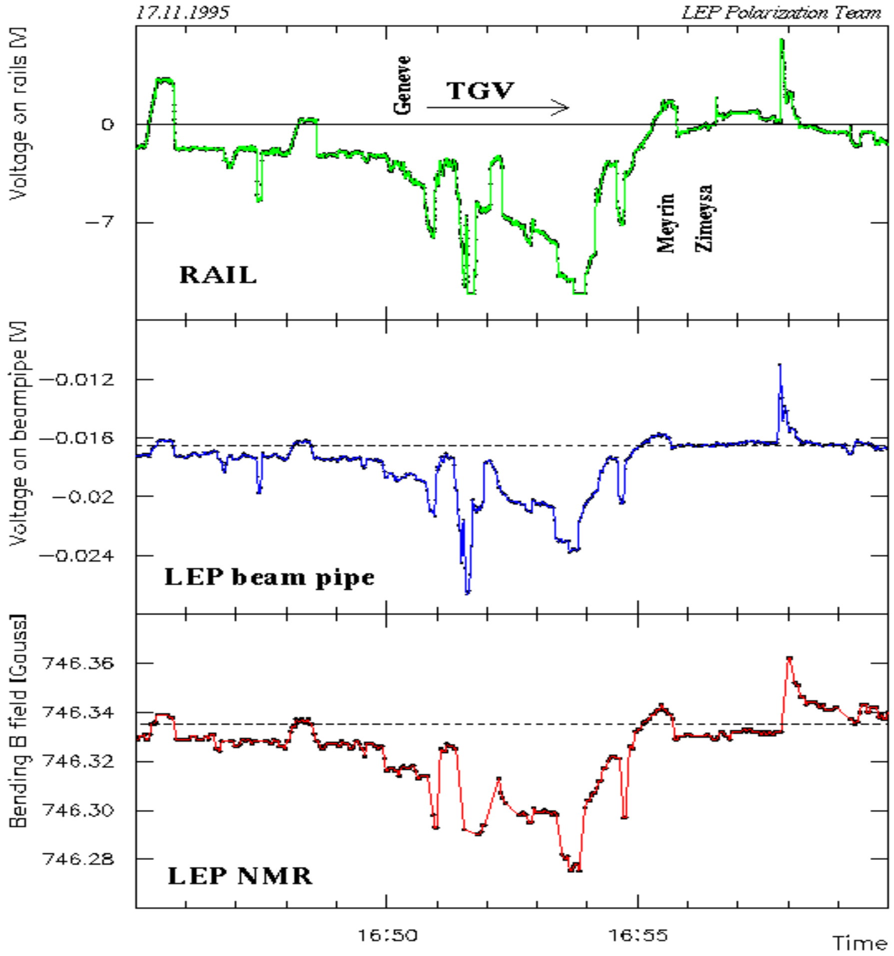
A lot of data: luminosity

$$L \approx \frac{N_1 N_2 f_{bc}}{4\pi\sigma_x\sigma_y}$$



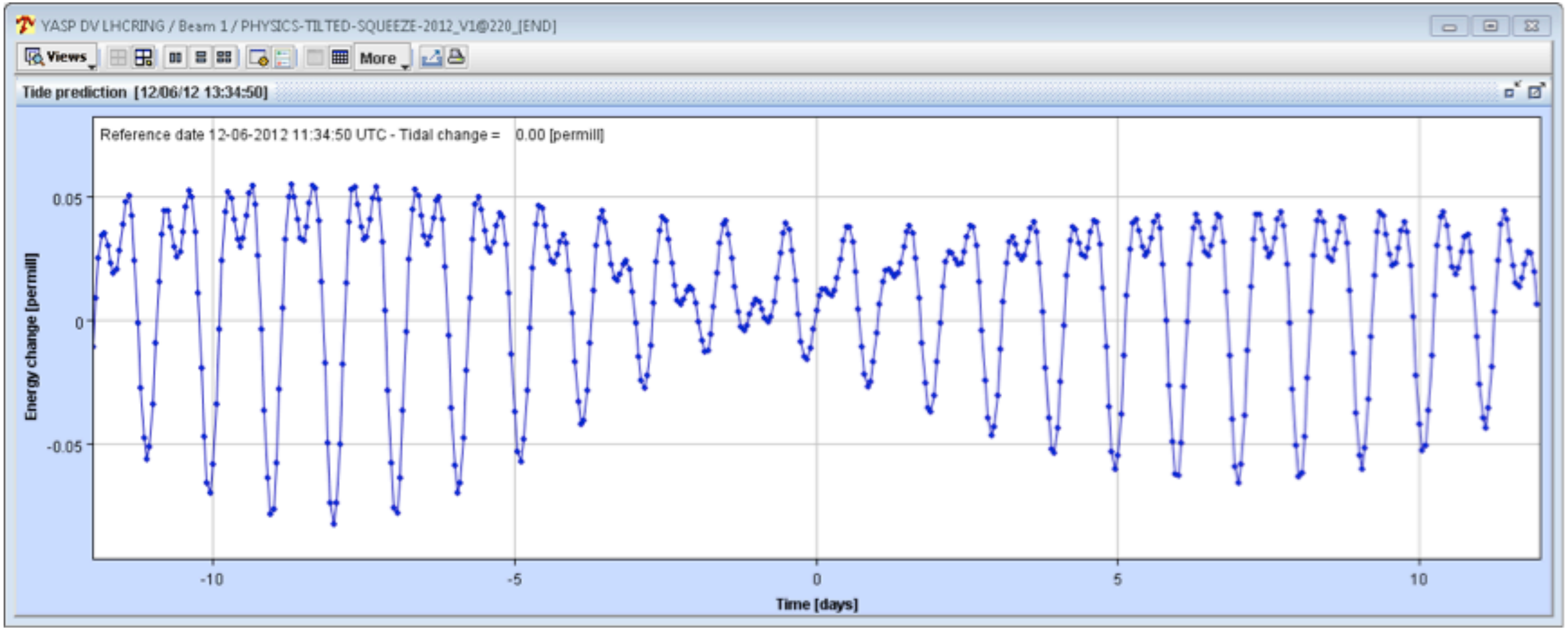


Relative beam sizes around IP1 (Atlas) in collision



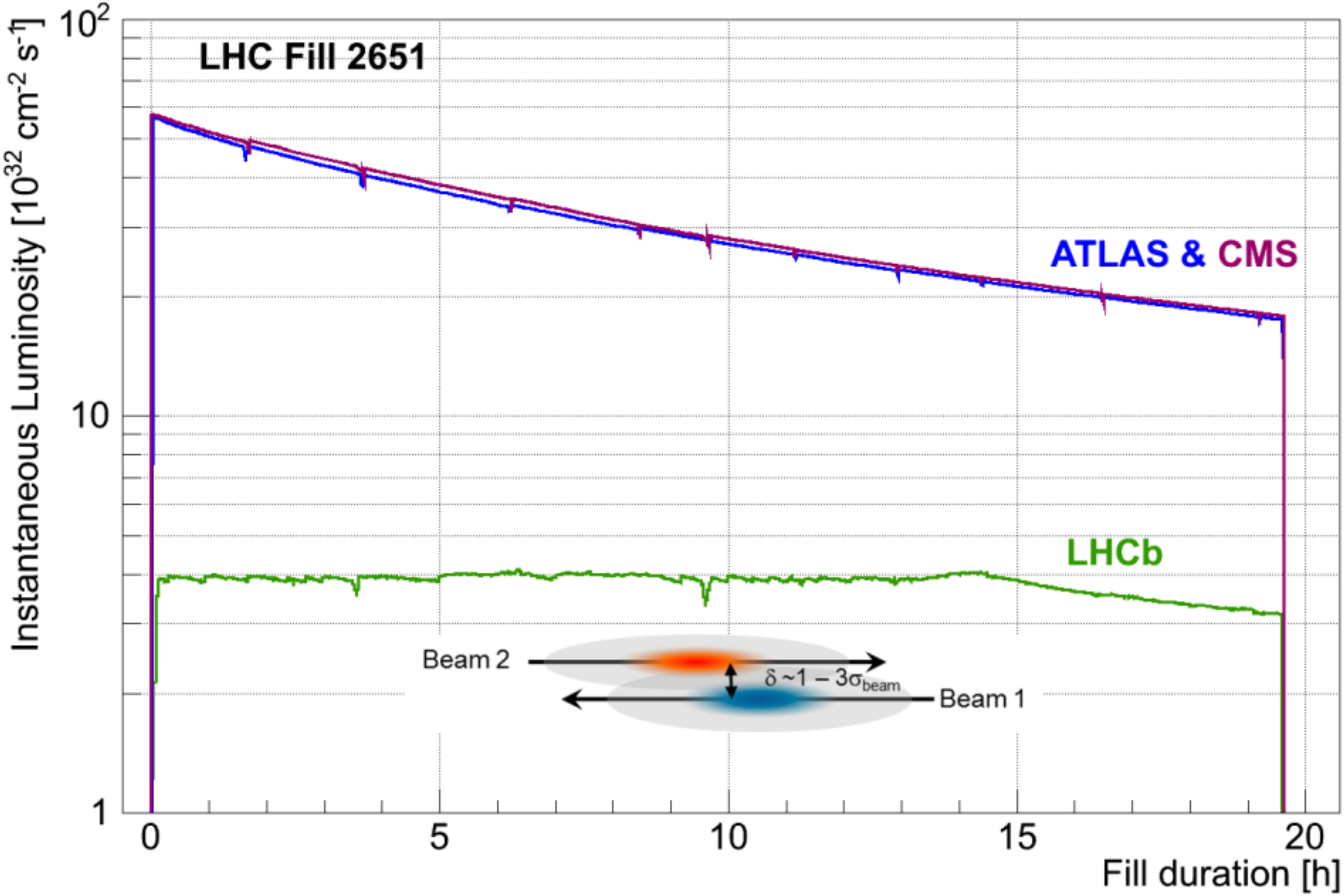
A lot of data: the Moon

["Moon corrections map": small differences in gravitational force across LHC diameter.]

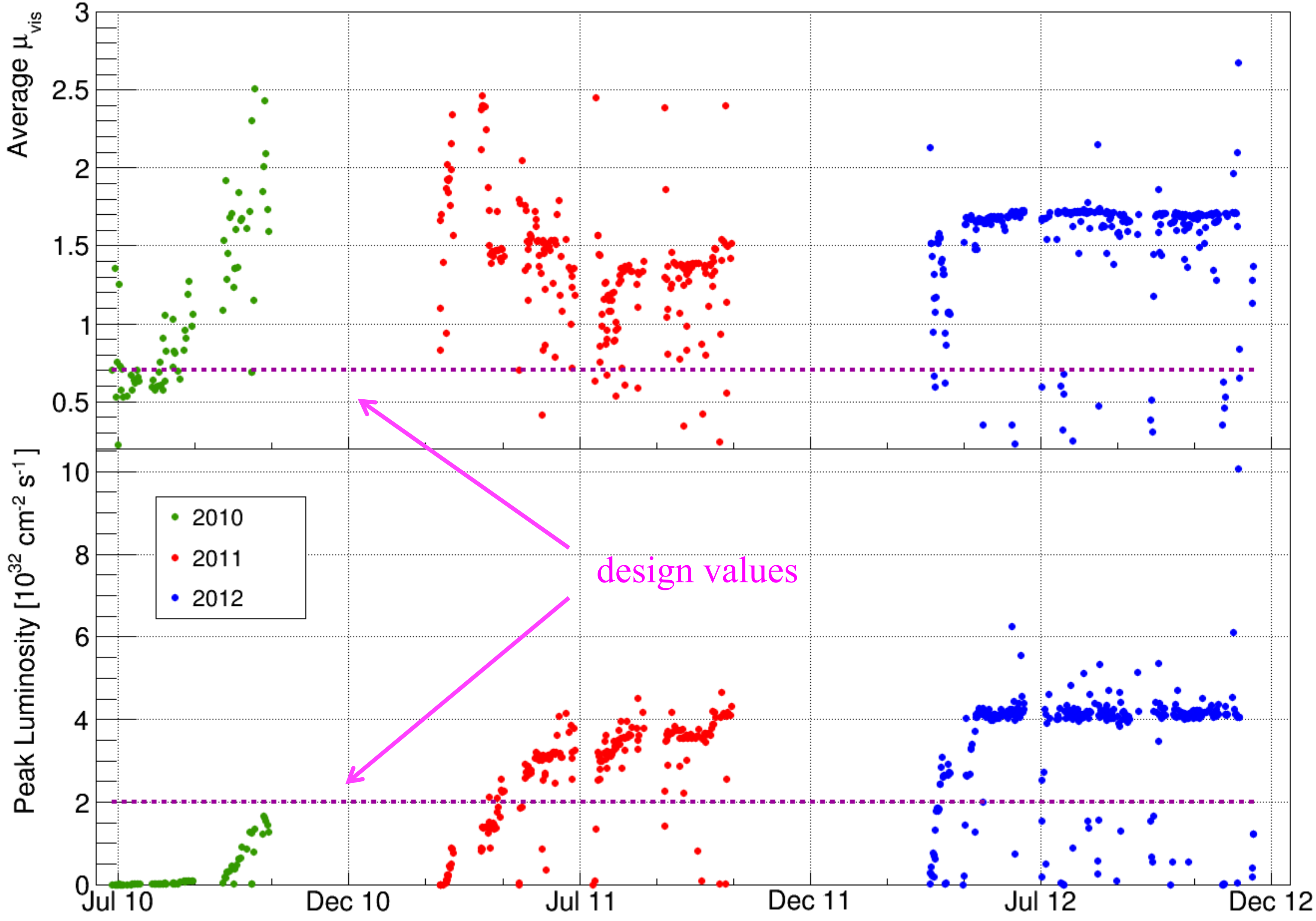


20 days

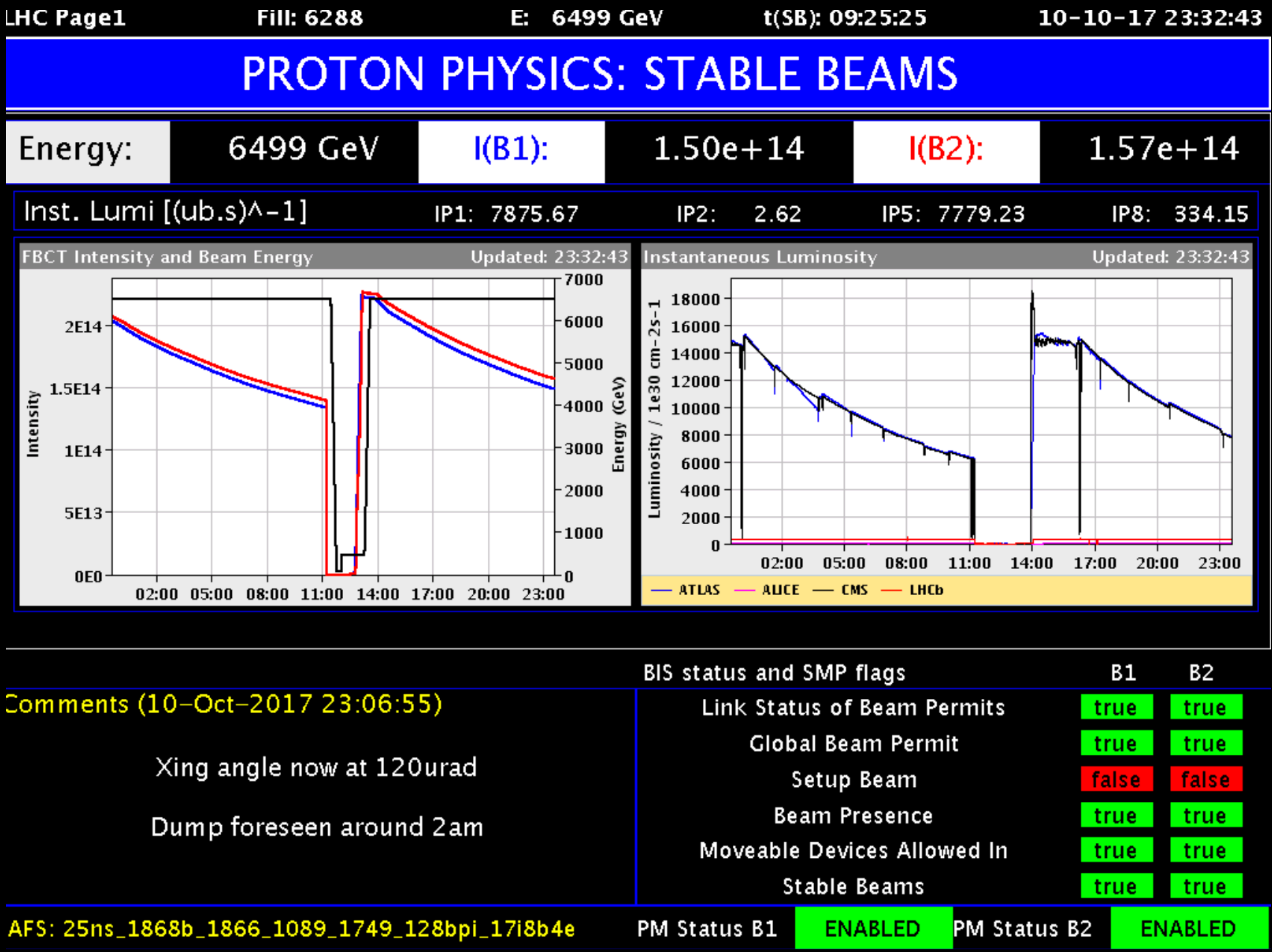
A lot of data: Luminosity leveling



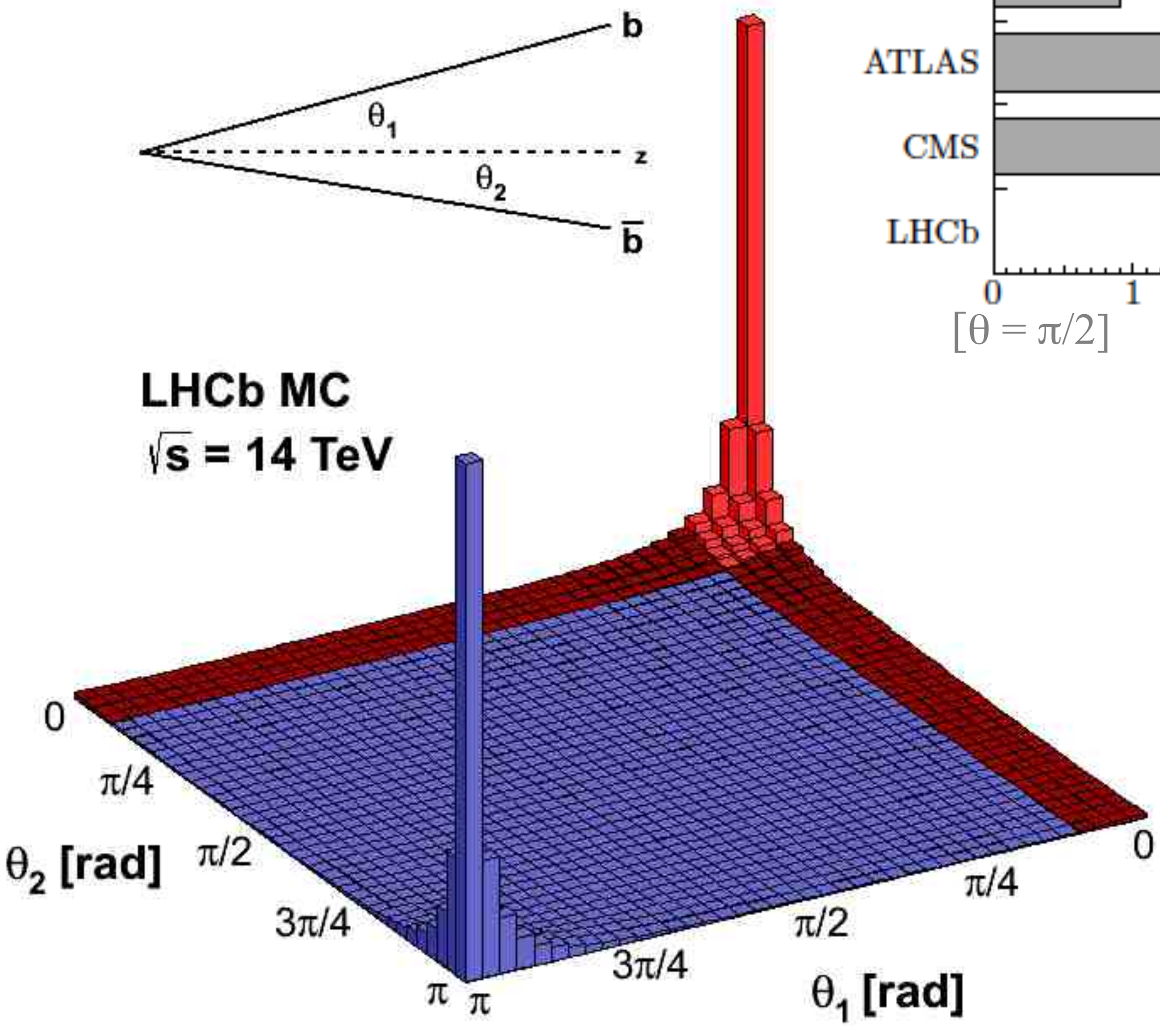
Run1 [2010-2012] operating conditions

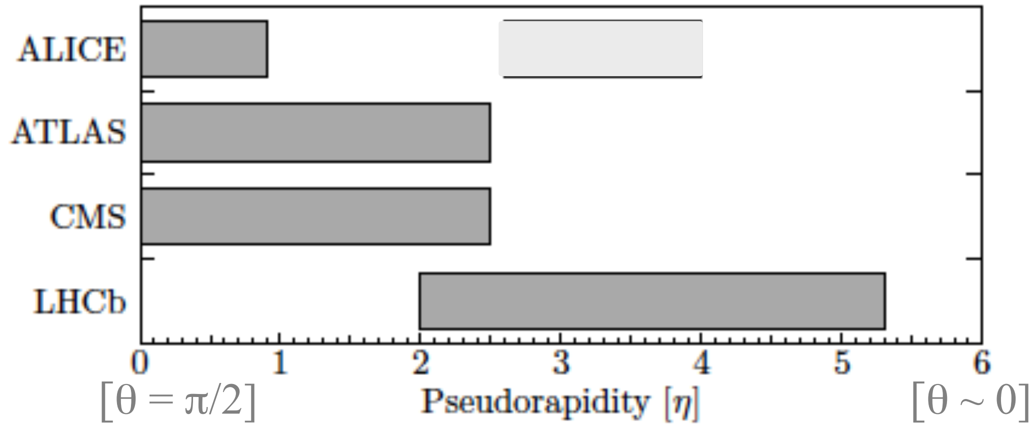


A lot of data: Luminosity leveling



A lot of data: heavy flavor production

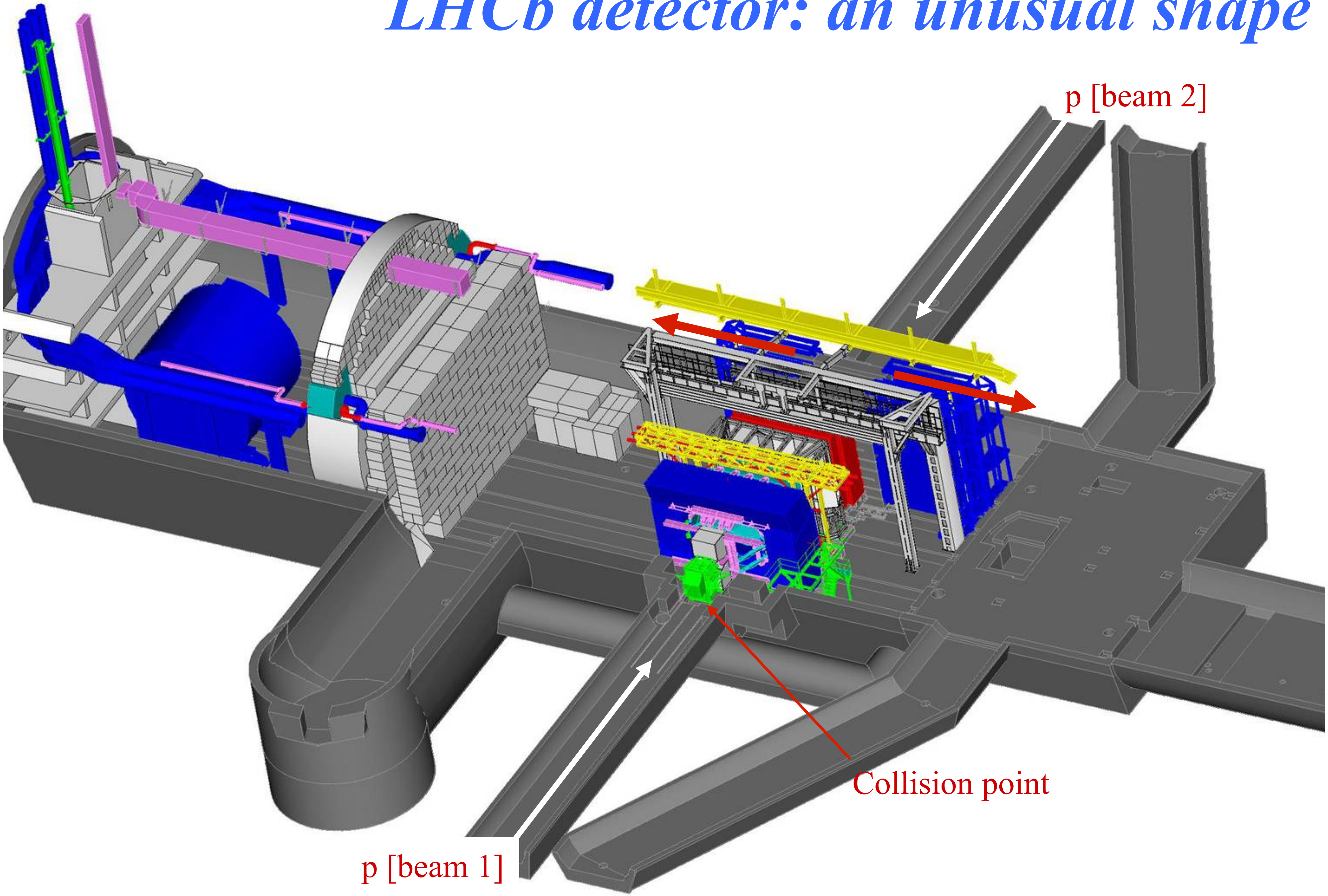




Extremely large σ(bb) and σ(cc) in LHC hadron collisions.

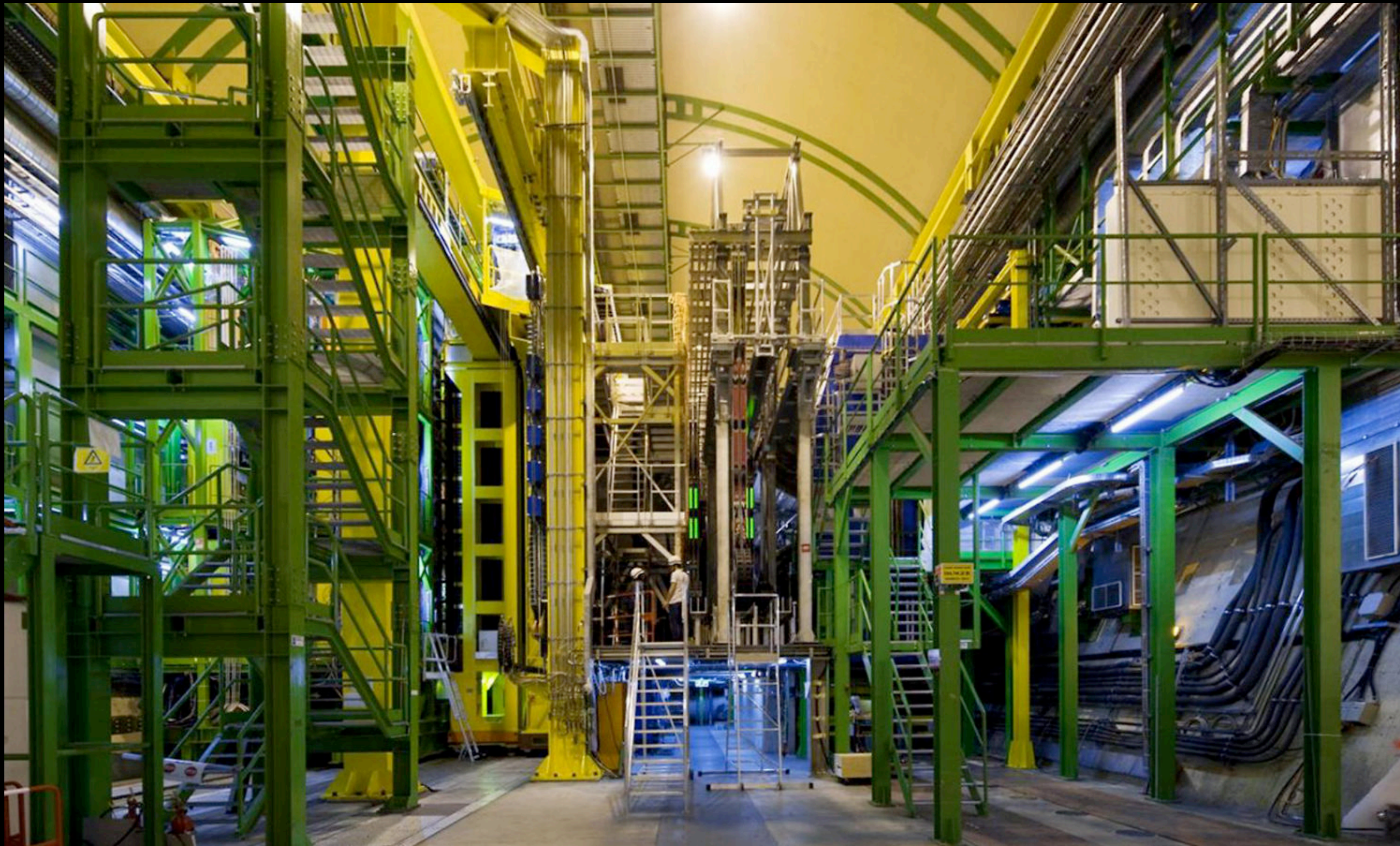
At 13TeV: **σ(bb) ~ 45 kHz** and **σ(cc) ~1MHz** cc in LHCb acceptance (HF cross section x2 with respect Run 1)

LHCb detector: an unusual shape



[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 detector



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

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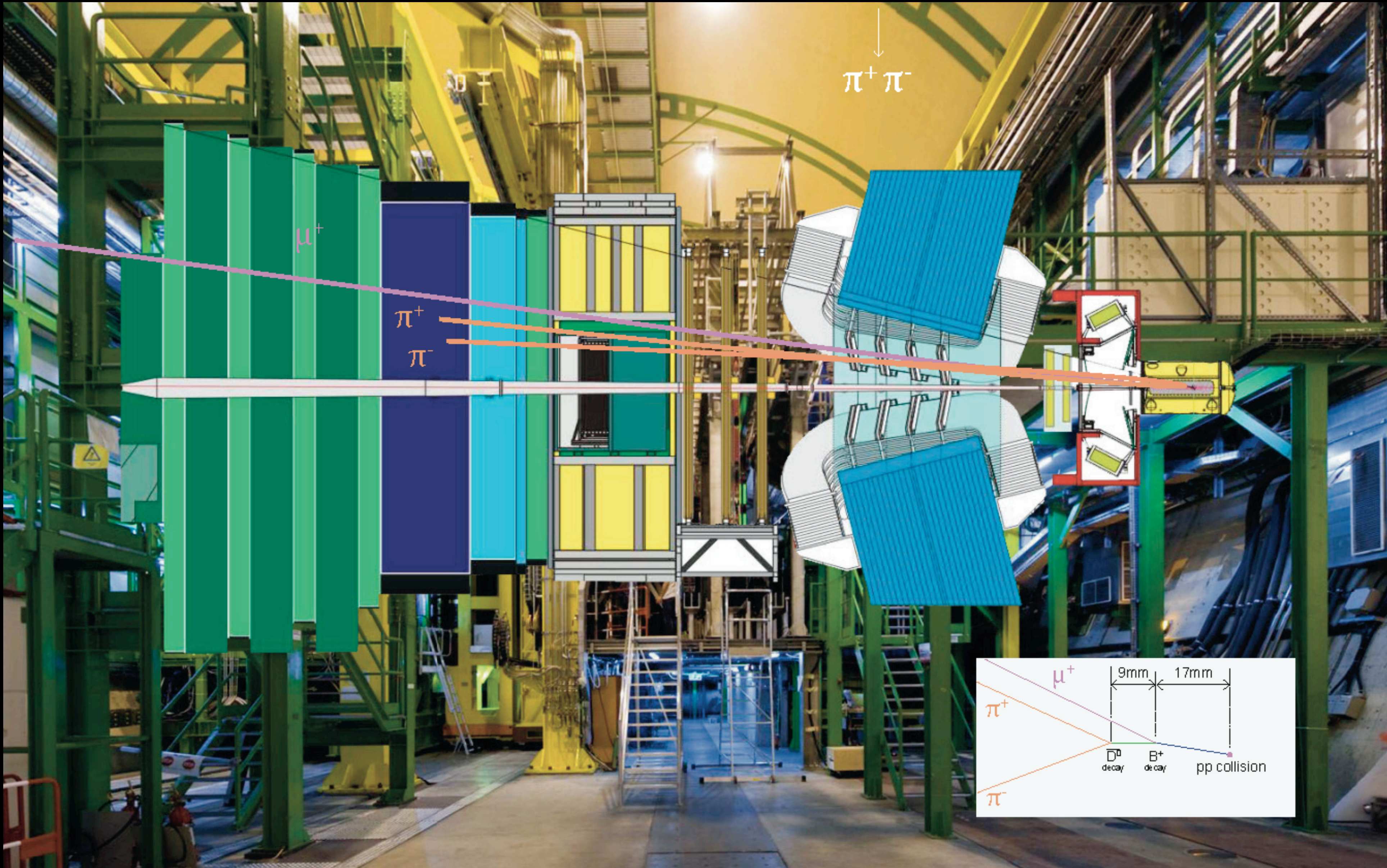
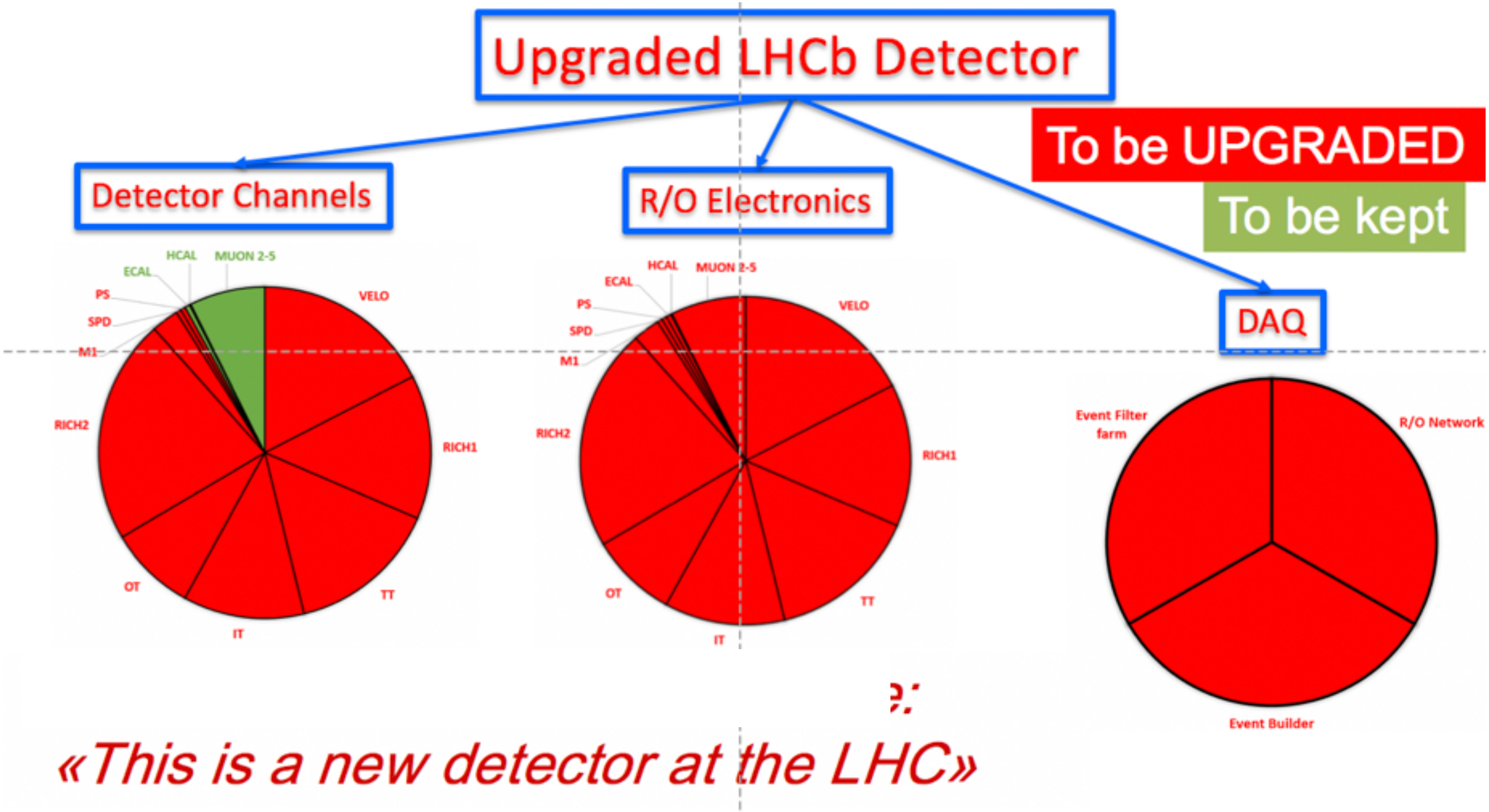
LHCb detector



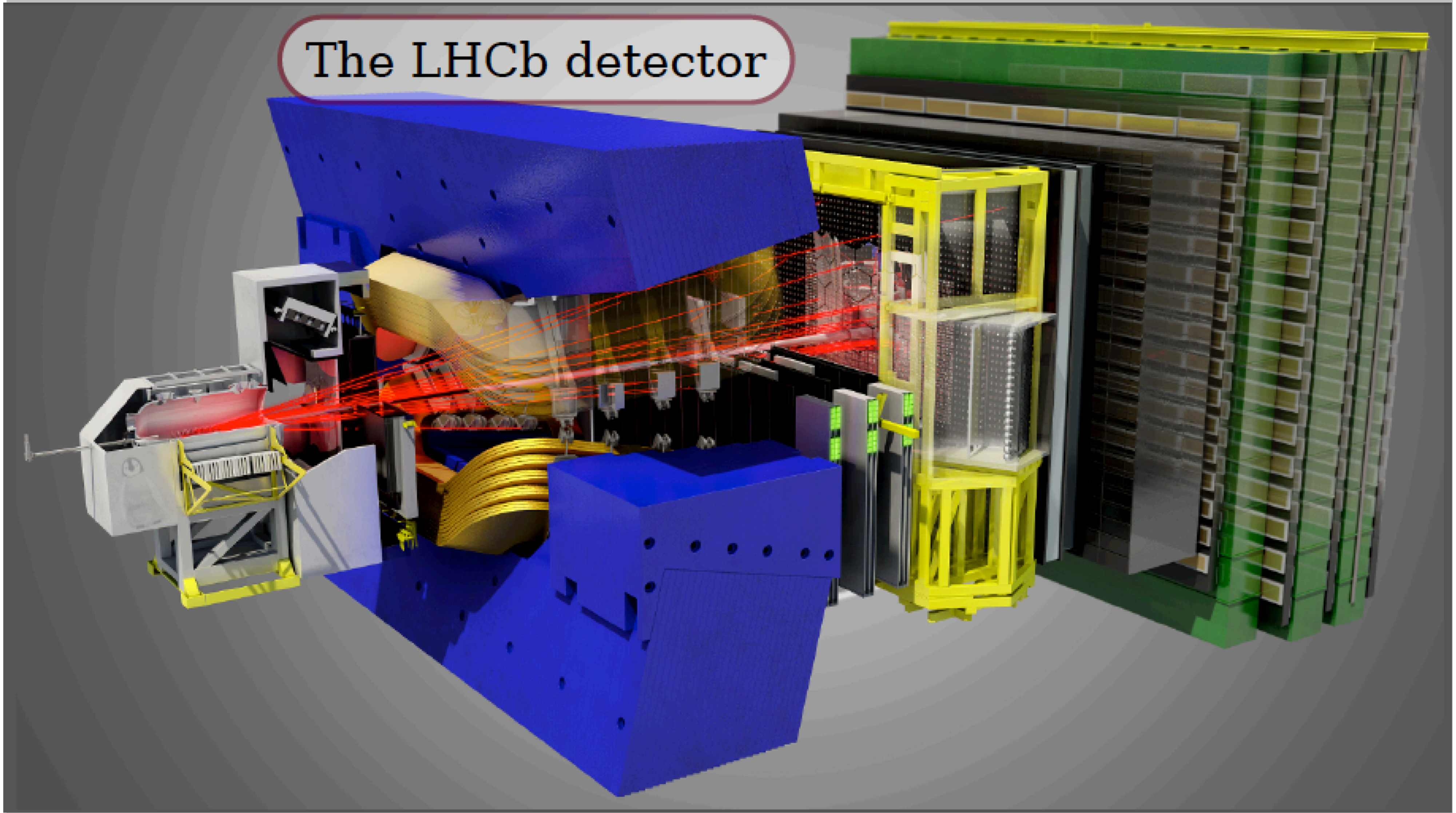
LHCb detector - LS2

[http://lhcb-media.web.cern.ch/lhcb-media/]

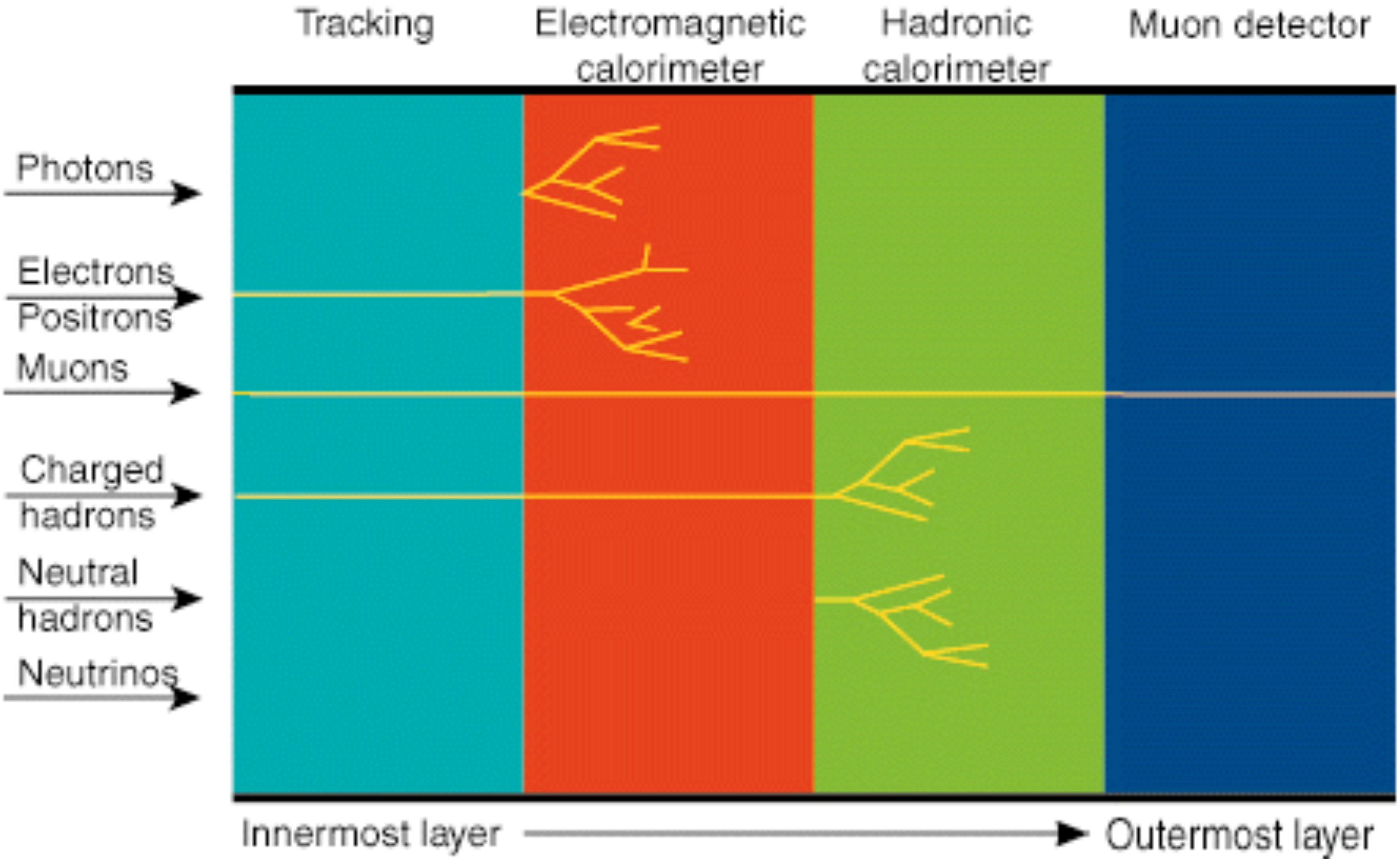
LHCb - towards Run 3



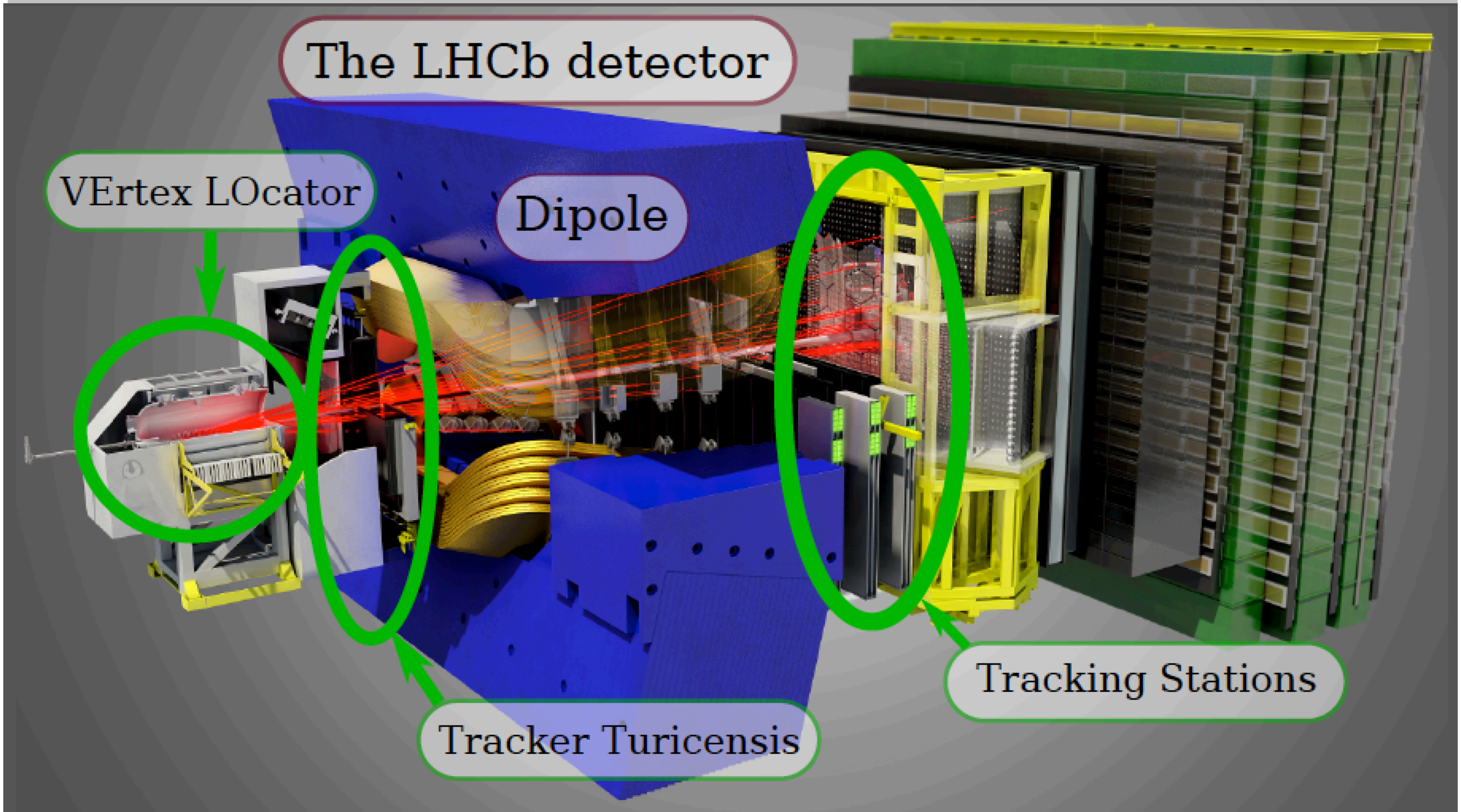
LHCb detector



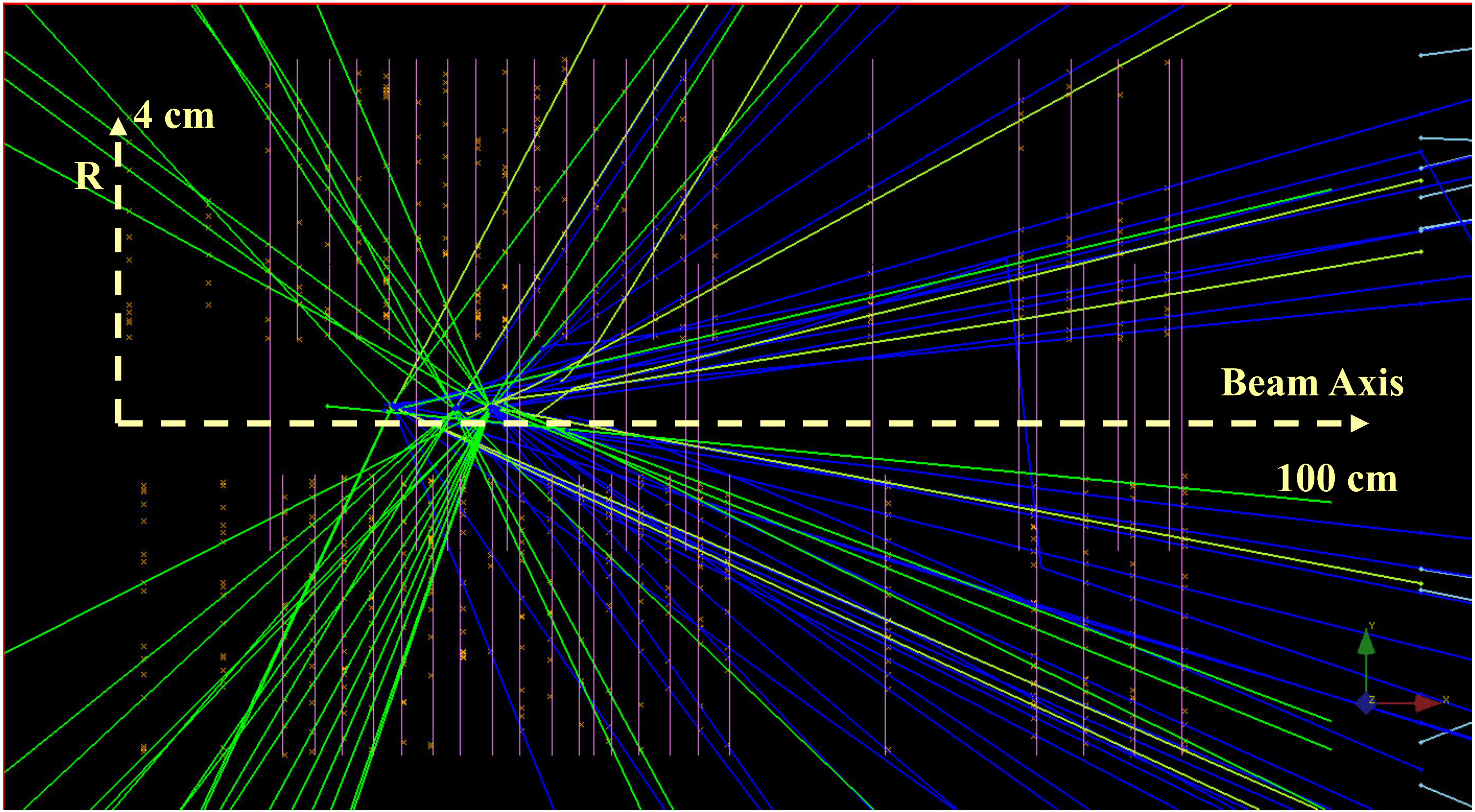
Detectors


Tracking
Electromagnetic calorimeter
Hadronic calorimeter
Muon detector
Photons
Electrons
Positrons
Muons
Charged hadrons
Neutral hadrons
Neutrinos
Innermost layer
Outermost layer

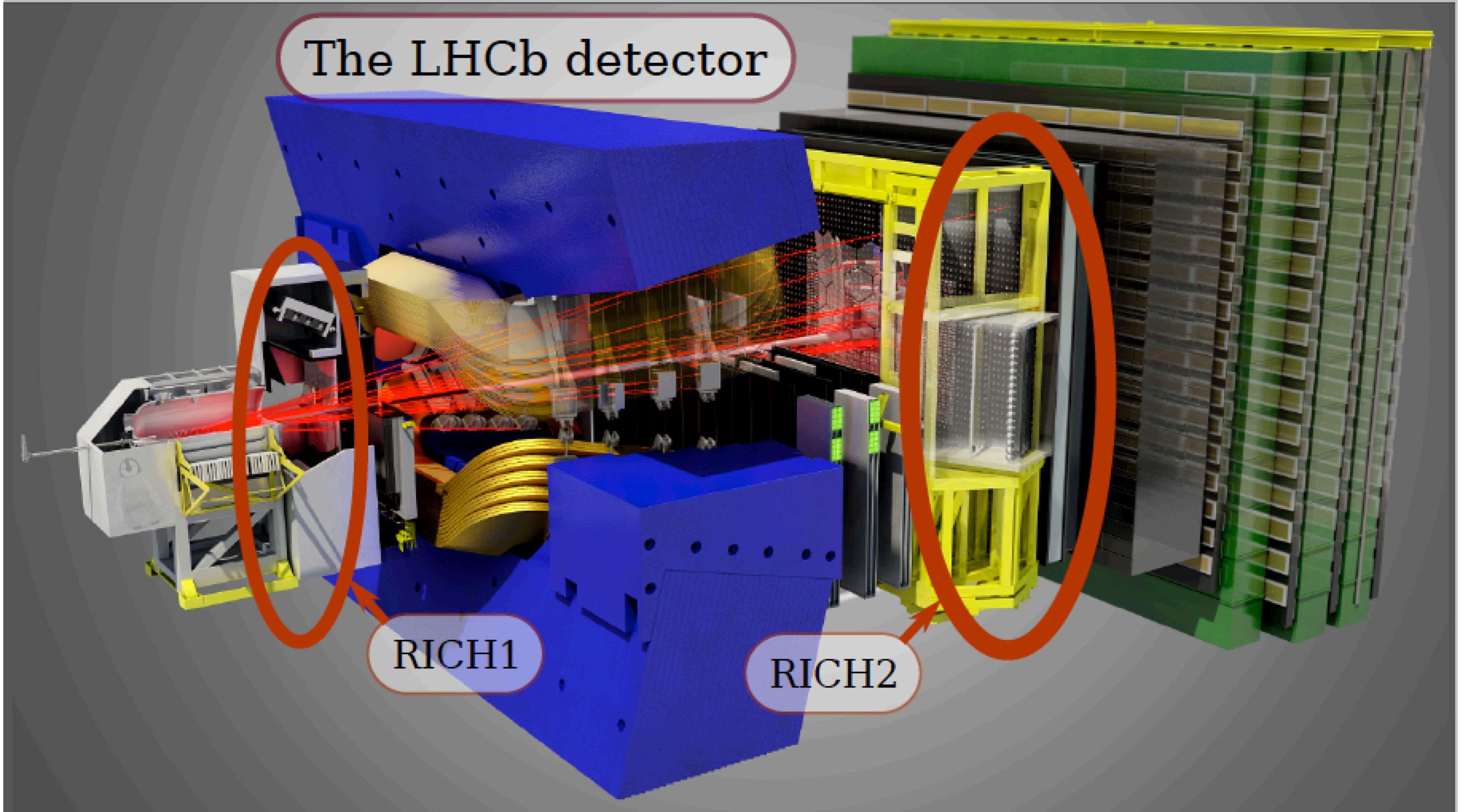
LHCb detector: tracking system



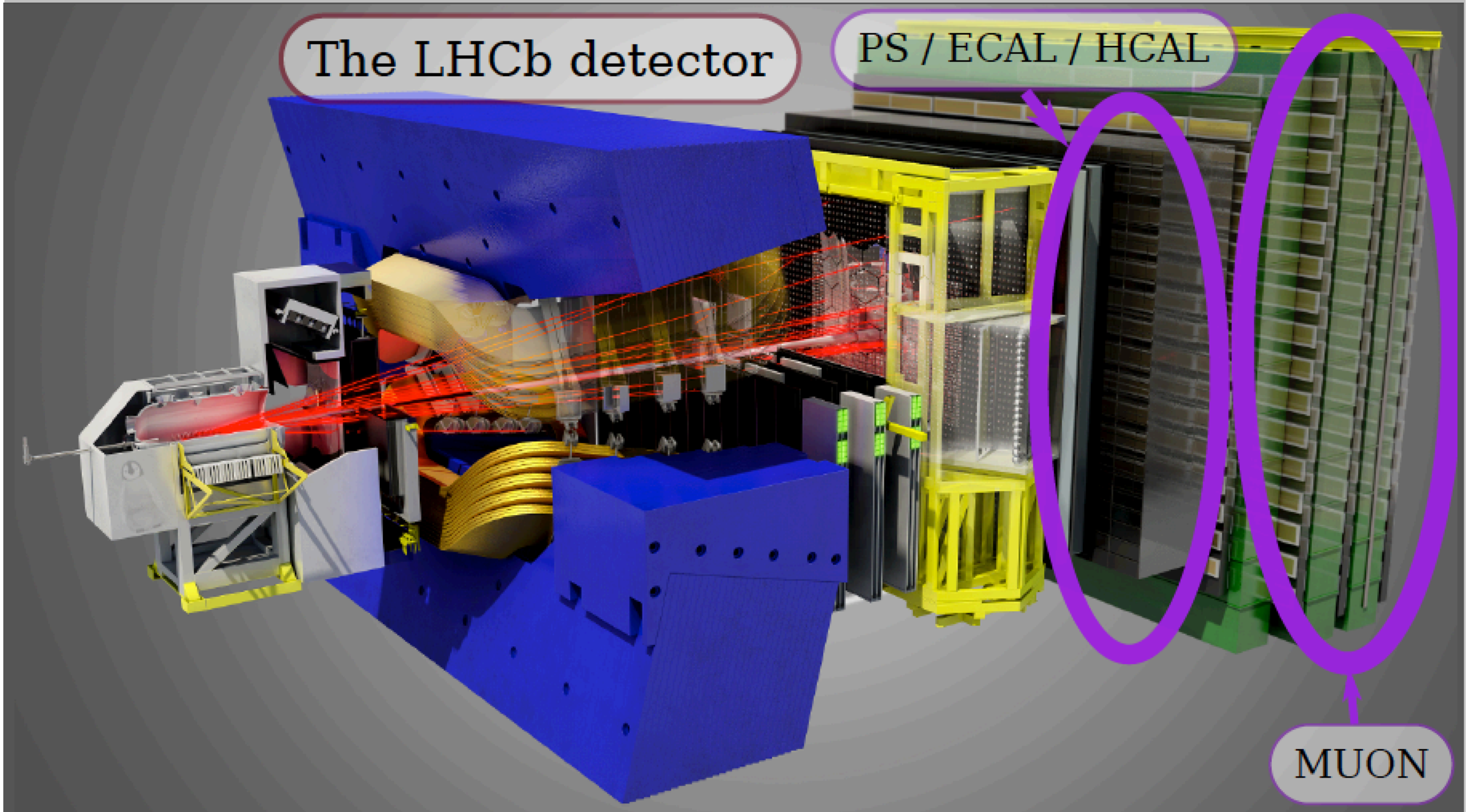
VELO rz view



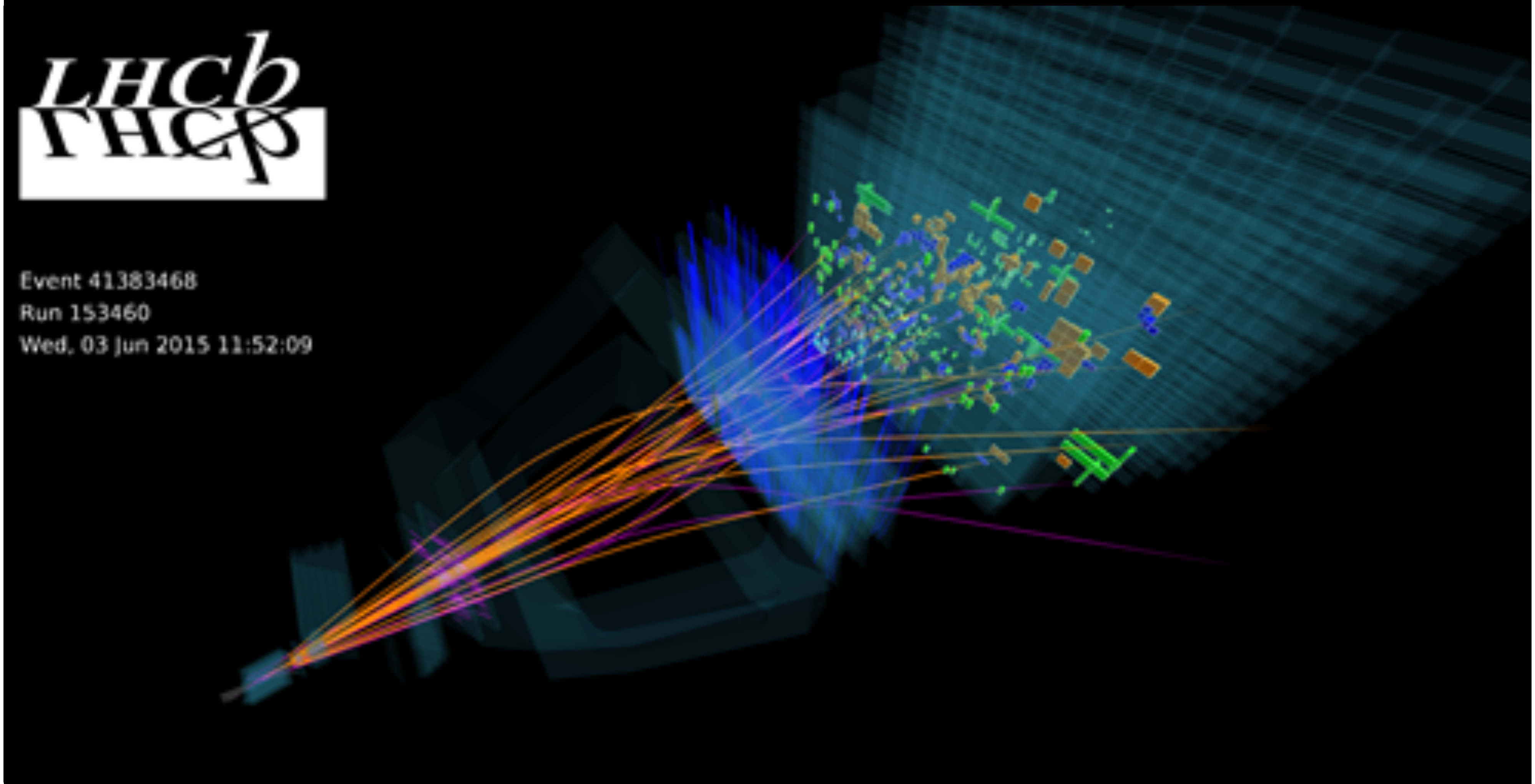
LHCb detector: RICHs



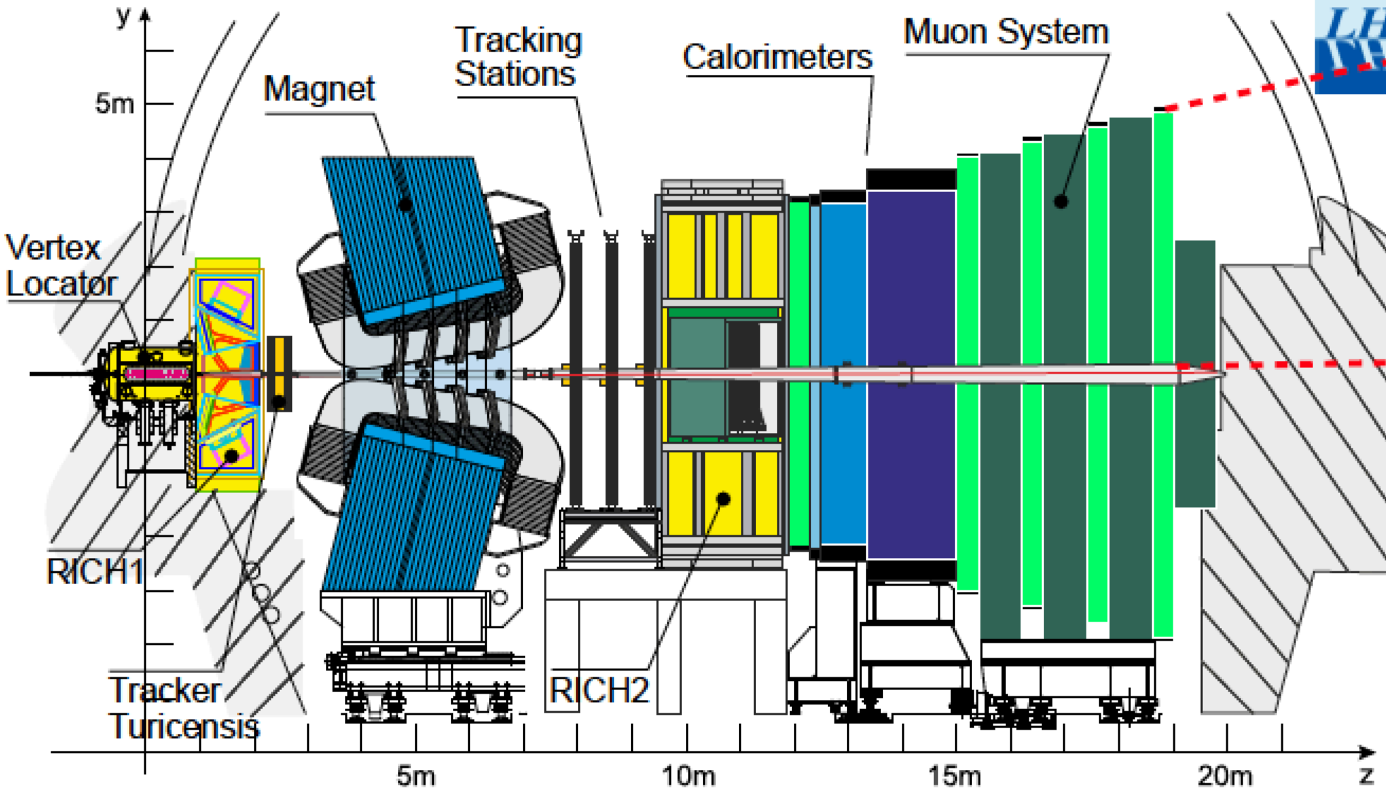
LHCb detector: calorimeter and muon systems



Event display



LHCb detector performance in one slide



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

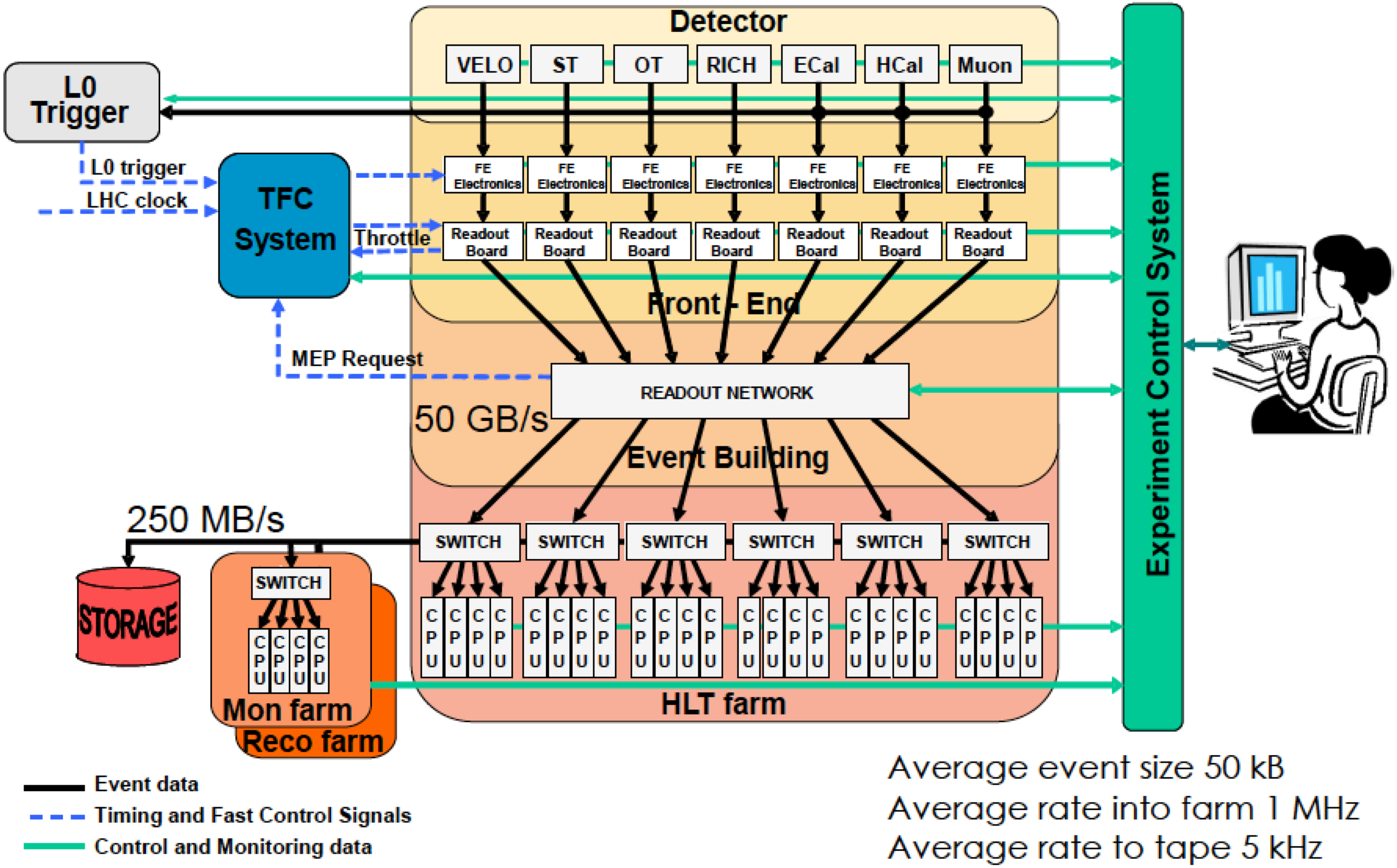
Excellent vertex and IP resolution:
$\sigma(IP) \simeq 24\mu m$ at $p_T = 2GeV$

Muon identification:
$\varepsilon_{\mu} = 98\%$, $\varepsilon_{K\to\mu} = 0.6\%$, $\varepsilon_{\pi\to\mu} = 0.3\%$

Good momentum resolution:
$\sigma(p)/p \simeq 0.4\text{-}0.6\%$ for $p\in(0,100)GeV/c$

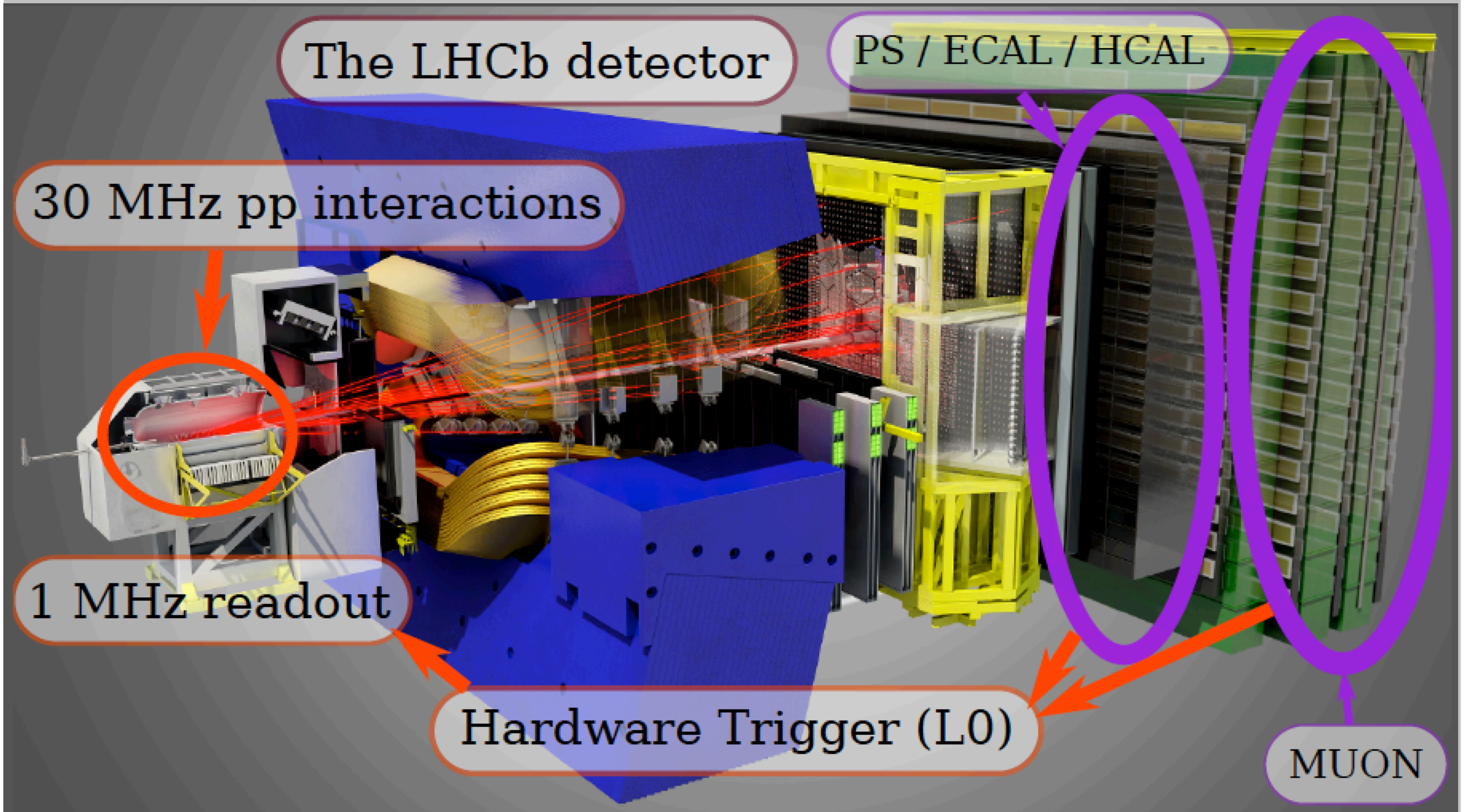
Trigger efficiency:
$\varepsilon_{\mu} = 90\%$ for selected B decays

Collect data (DAQ)



Average event size 50 kB
Average rate into farm 1 MHz
Average rate to tape 5 kHz

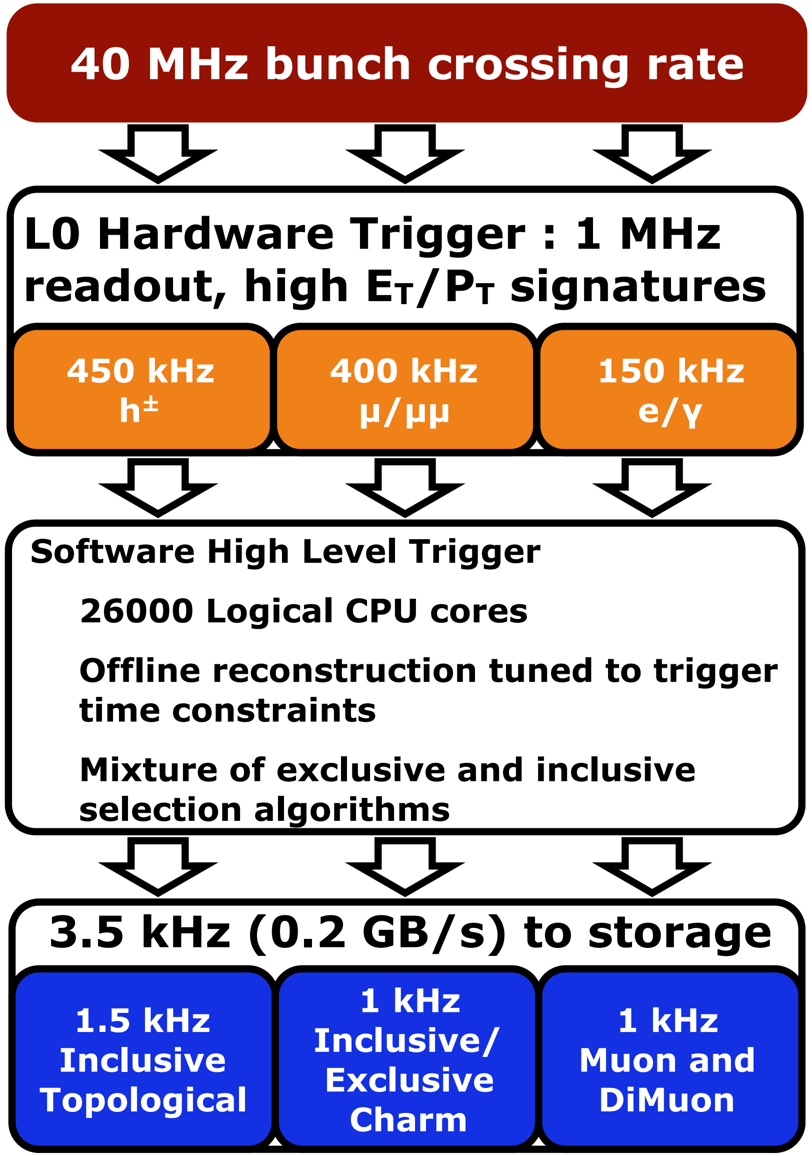
Hardware trigger



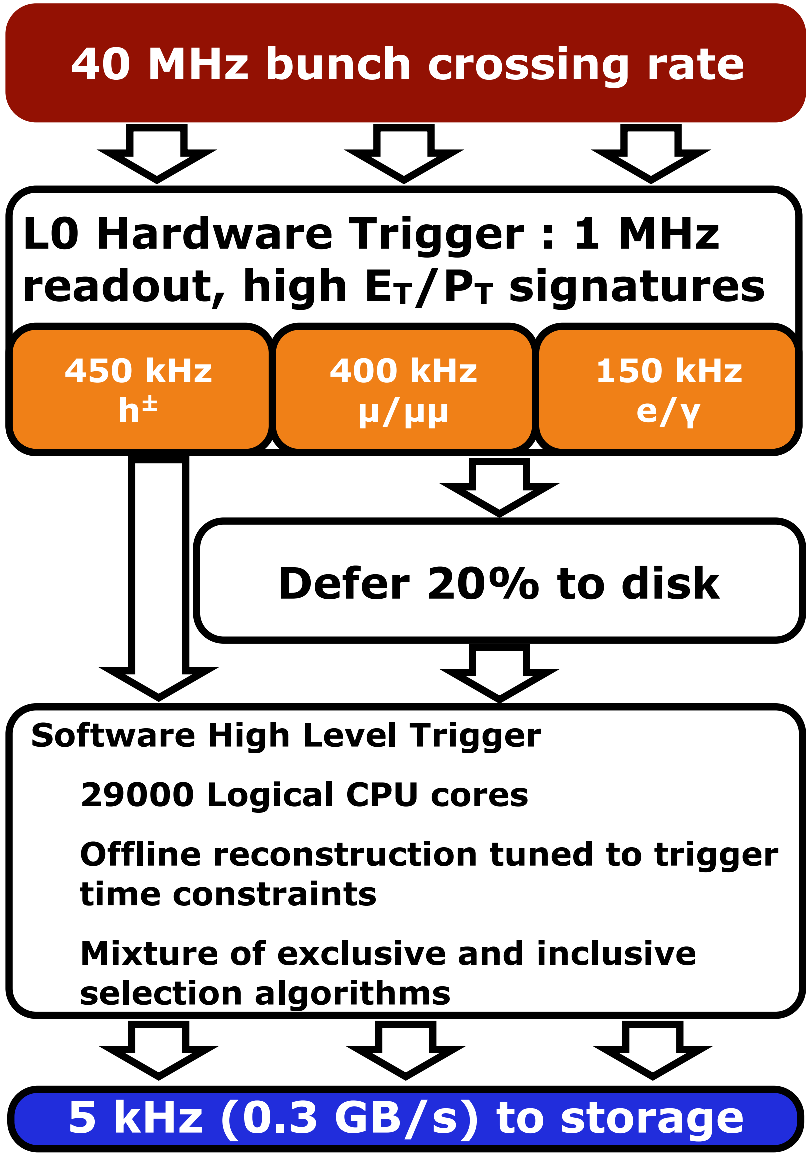
[arXiv:1211.3055; CERN-LHCb-DP-2012-004]
[arXiv:1310.8544v1]

Trigger

LHCb 2011 Trigger Diagram



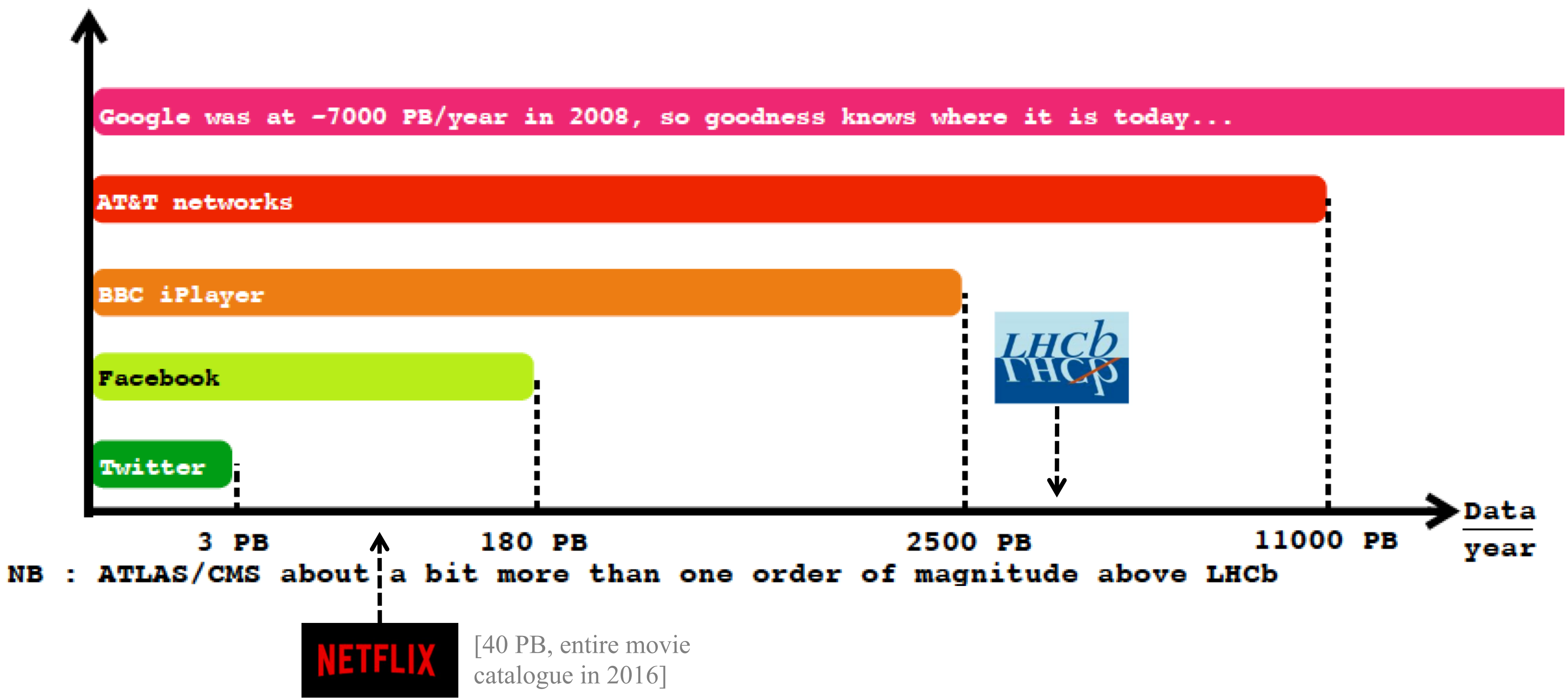
LHCb 2012 Trigger Diagram



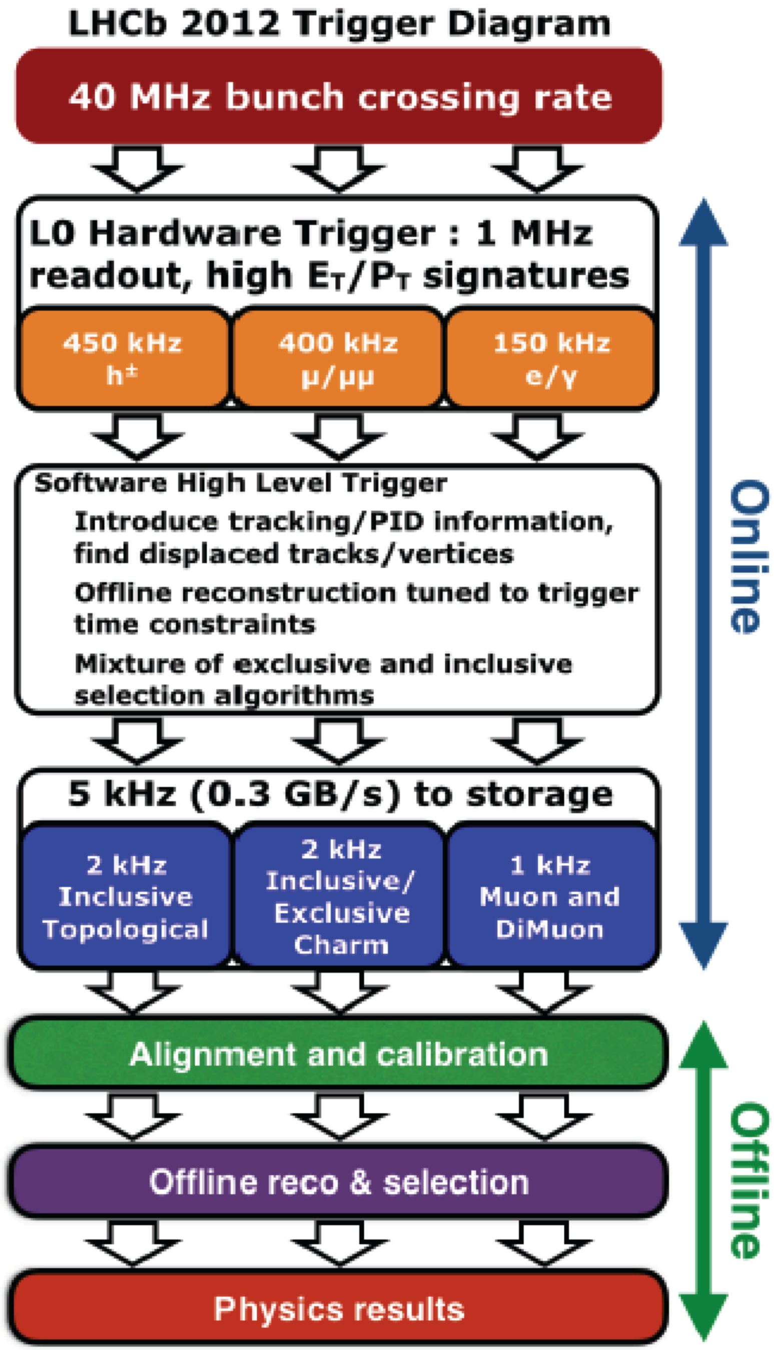
A lot of data… (Interlude)

Input data rate of the LHCb experiment today ~ 1 TB/second

This means about 4000 PB of data every year



Trigger

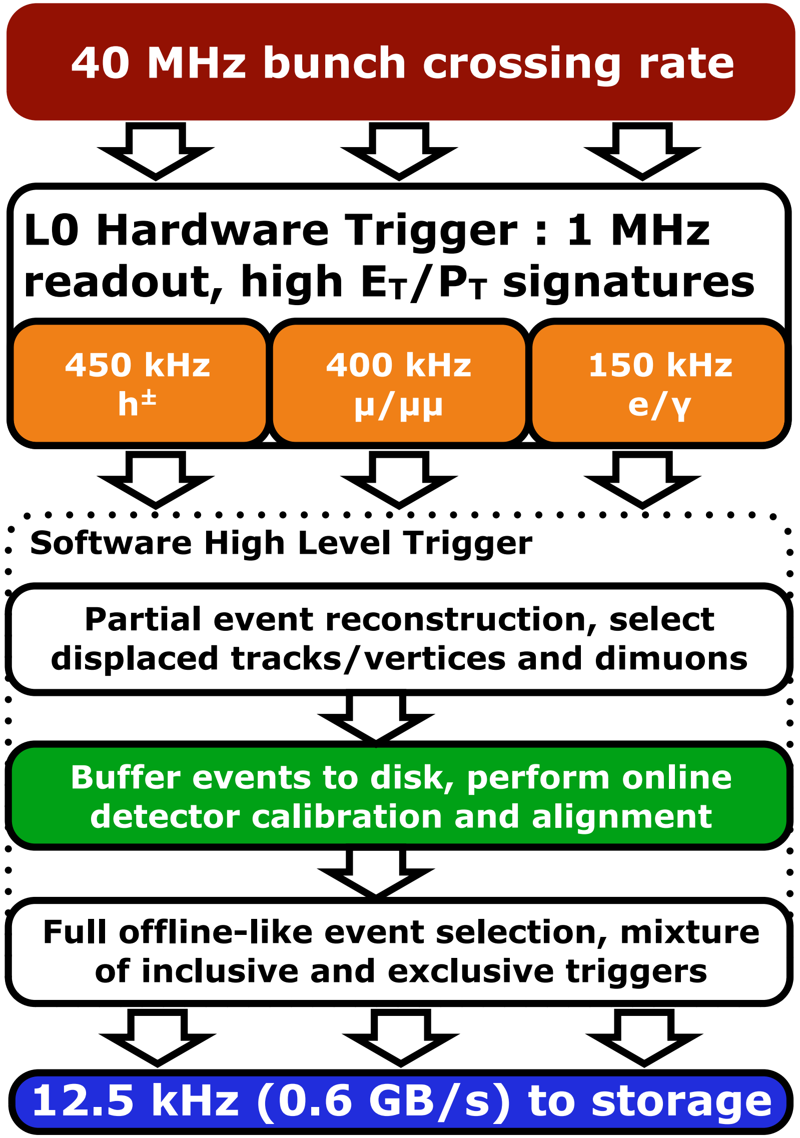


["All I'm saying is <u>now</u> is the time to develop the technology to deflect an asteroid."]
"All I'm saying is <u>now</u> is the time to run data reconstruction only once."

~50k logical cores
~5PiB disk space

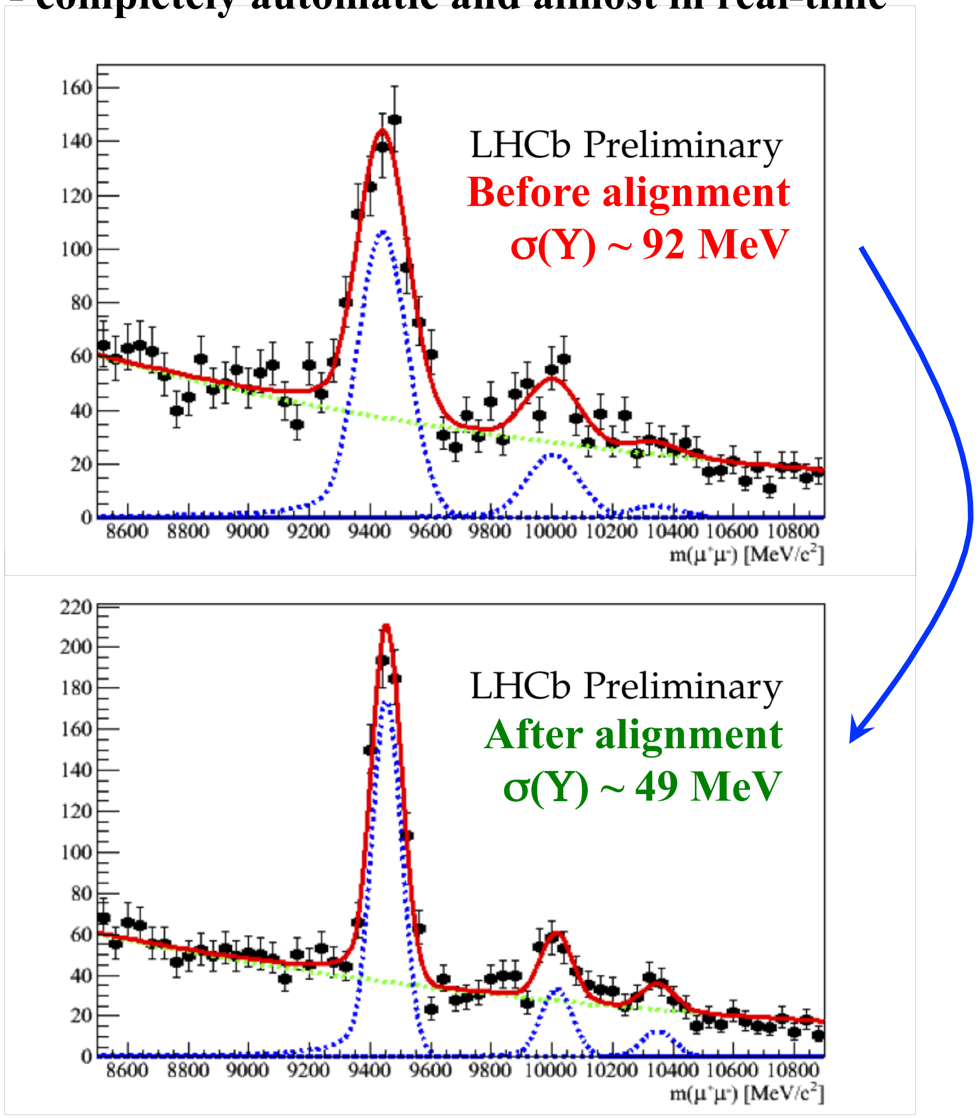
Trigger

LHCb 2015 Trigger Diagram (since 2015)



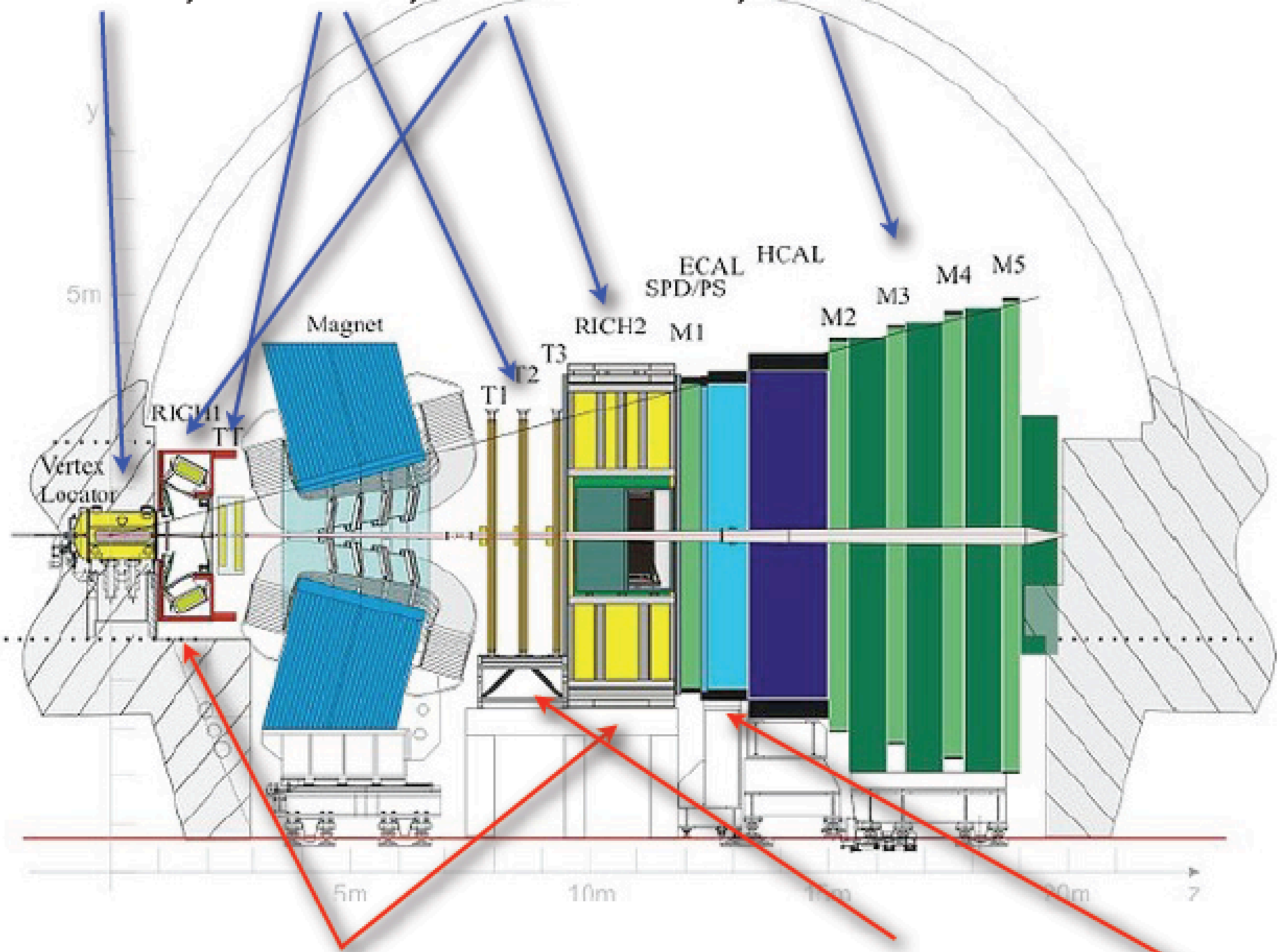
Same online and offline reconstruction and PID

- **prompt alignment and calibration**
- **completely automatic and almost in real-time**



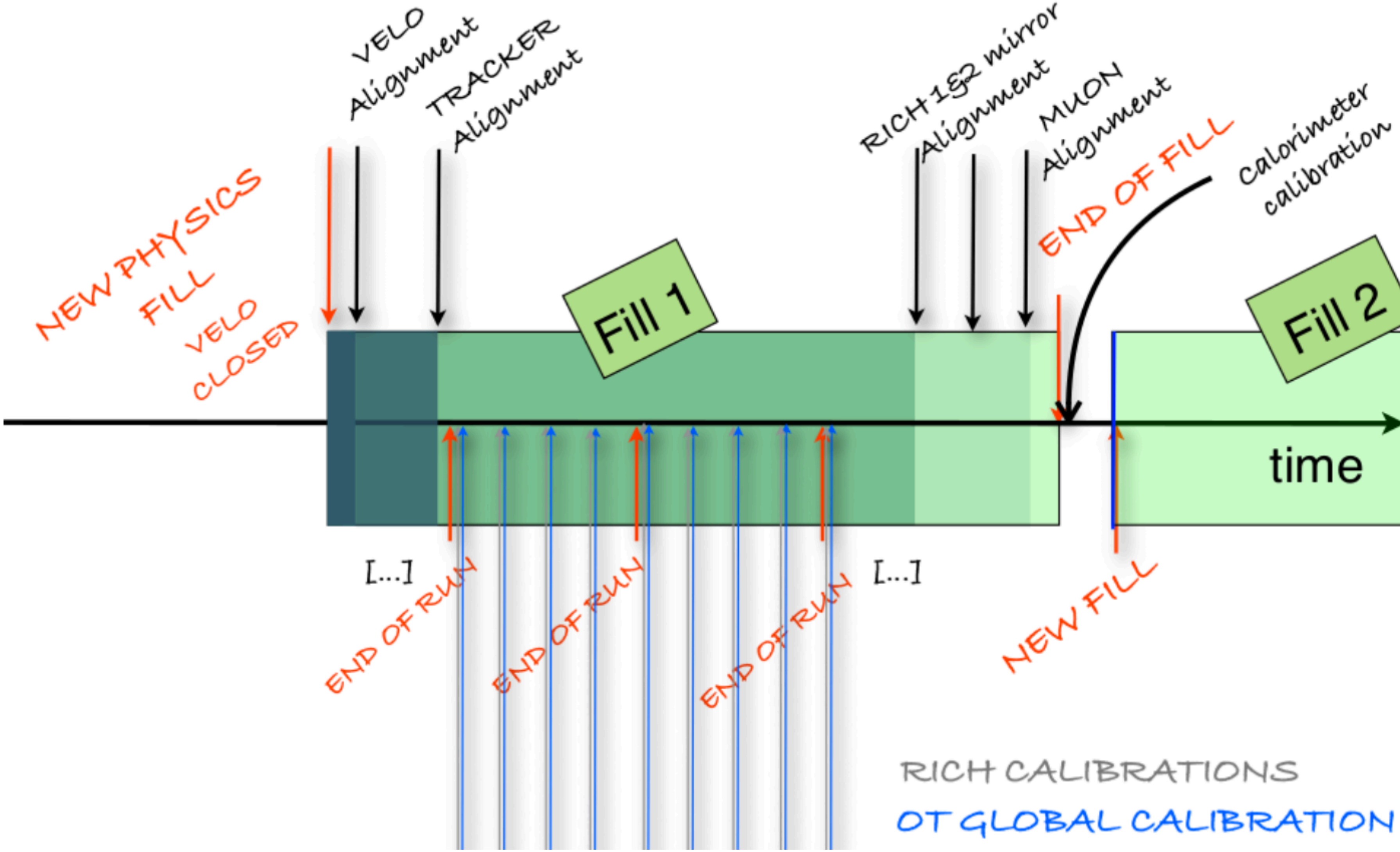
Real-time alignment and calibration

- Alignments: VELO, Trackers, RICH mirrors, Muon

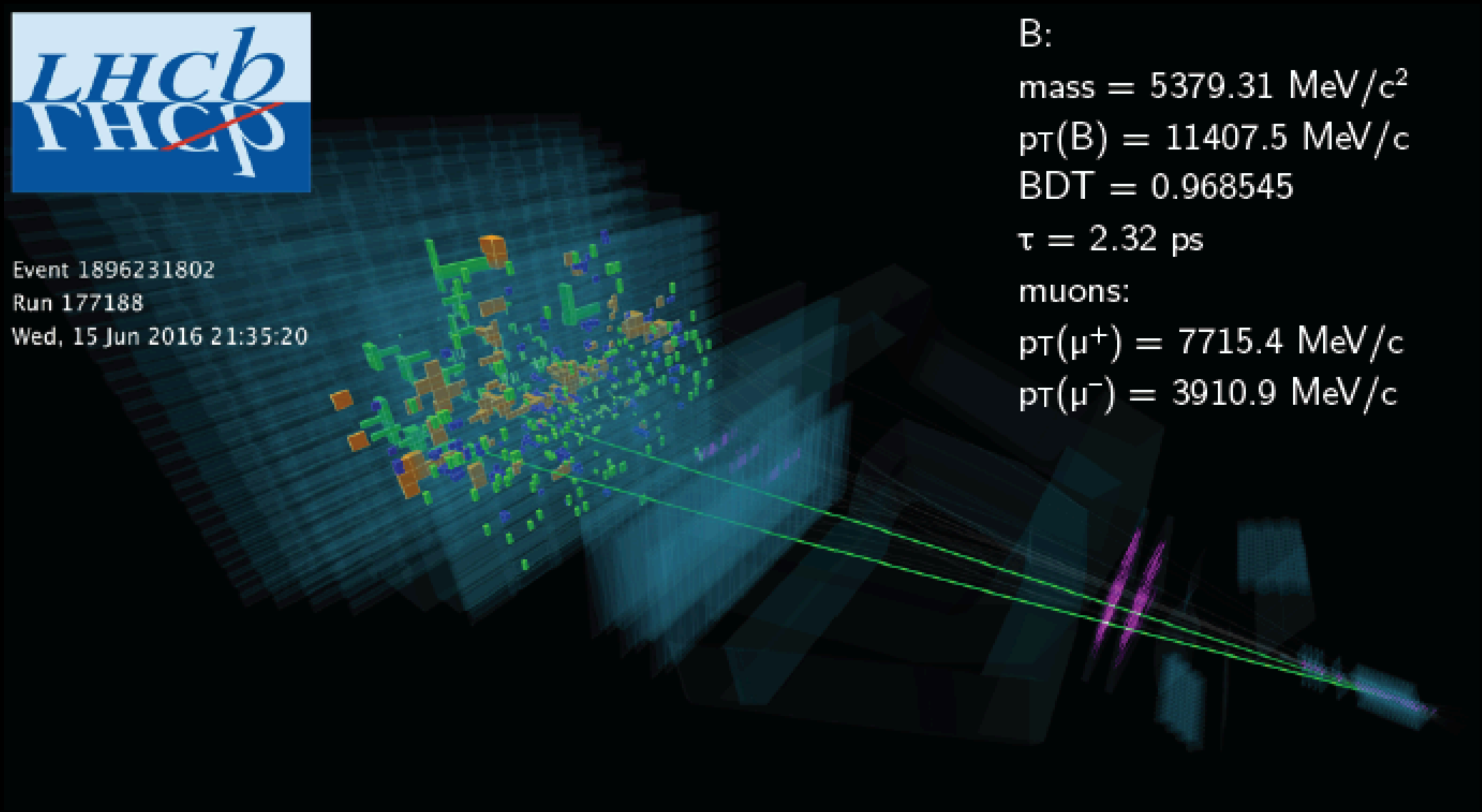


- Calibrations: RICH refractive index and HPDs, OT time, Calorimeters

Almost real-time alignment and calibration

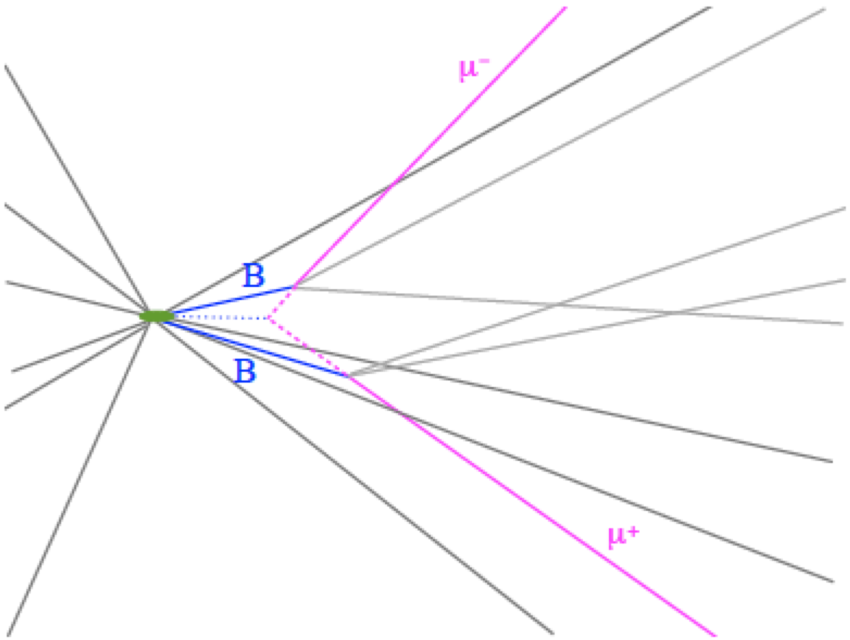


$B_{(s)}\mu\mu$ at LHCb: 2017 edition

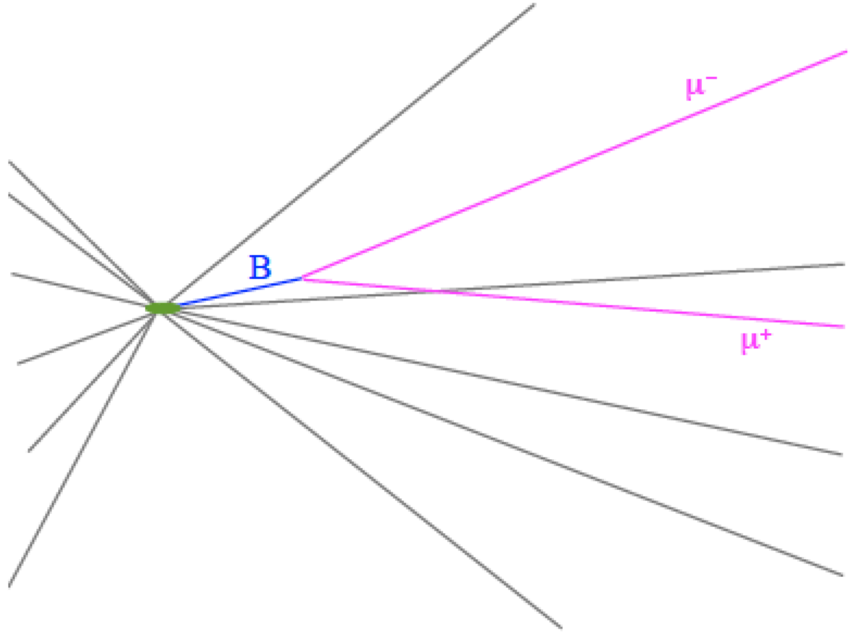


$B_{(s)}\mu\mu$: signal and background

Dominant combinatorial background from $b\bar{b}\rightarrow\mu^+\mu^-X$ decays



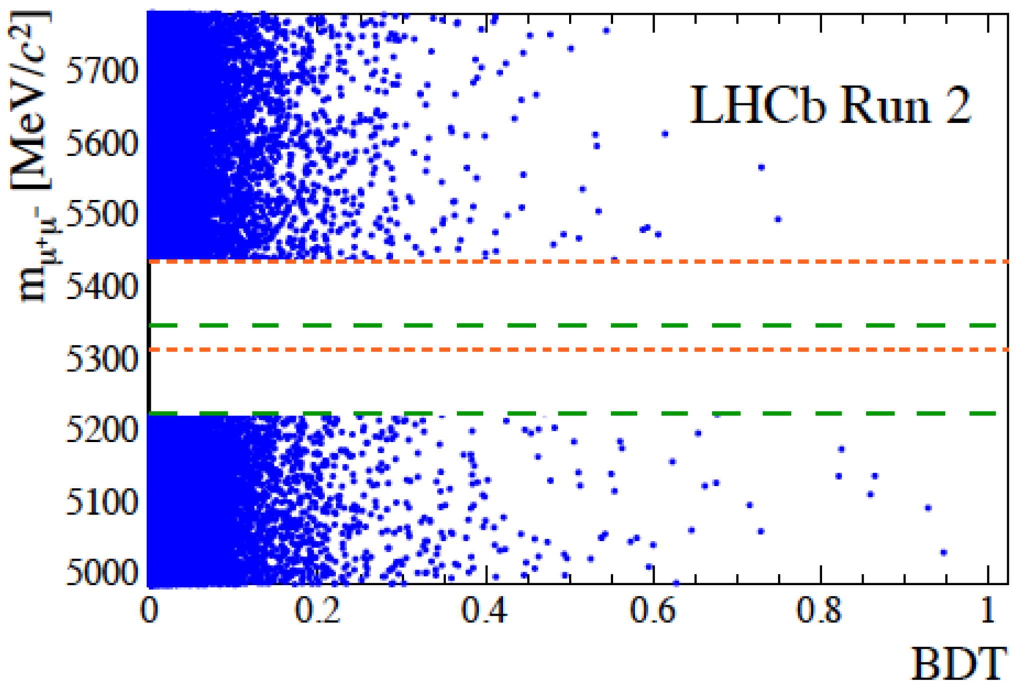
Signal: 2 muons from a single well reconstructed background



$B_{(s)}\mu\mu$: strategy

- A pair of opposite charged muons with and $m_{\mu\mu} \in [4900,6000]$ MeV/c^2 forming good vertex displaced w.r.t. the interaction point; loose MVA selection applied

- **Signal/Background classification in $m_{\mu\mu}$ vs MVA classifier (BDT) plane:**
  - BDT based on kinematic and geometrical variables, trained with MC; calibration for signal with $B^0_{(s)} \to h^+h'^-$ exclusive channels. **Improved in the new analysis, much better BDT performance for combinatorial bkg rejection and tighter PID selection to reject exclusive bkg (optimised for Bd)**



- Search window kept blind until analysis optimised

$B_{(s)}\mu\mu$: strategy

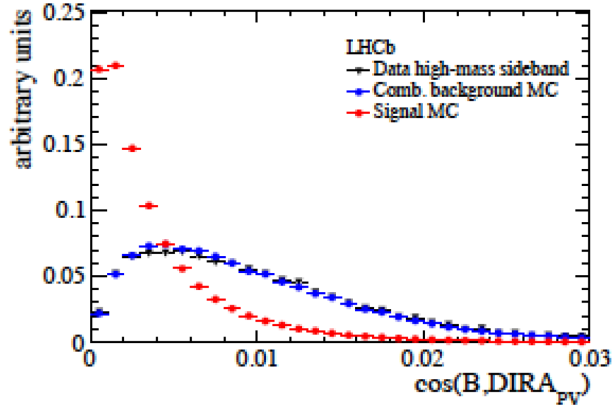
- **Normalisation:**
  - $B^0 \to K\pi$ and $B^+ \to J/\psi K^+$ used as normalisation channels; hadronisation fraction dependence on $\sqrt{s}$ evaluated using $B^+ \to J/\psi K^+$ and $B^0_s \to J/\psi\varphi$
- **Background estimation:**
  - Exclusive background evaluated through a combination of data driven methods, MC and theoretical inputs

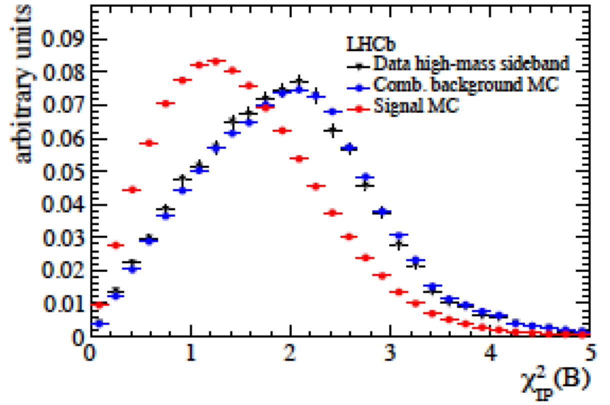
$$\mathrm{BR} = \mathrm{BR}_{\mathrm{cal}} \times \frac{\epsilon^{Acc}_{norm}}{\epsilon^{Acc}_{sig}} \times \frac{\epsilon^{RecSel|Acc}_{norm}}{\epsilon^{RecSel|Acc}_{sig}} \times \frac{\epsilon^{Trig|RecSel}_{norm}}{\epsilon^{Trig|RecSel}_{sig}} \times \frac{f_{\mathrm{cal}}}{f_{d(s)}} \times \frac{N_{B^0_{(s)} \to \mu^+\mu^-}}{N_{\mathrm{cal}}}$$

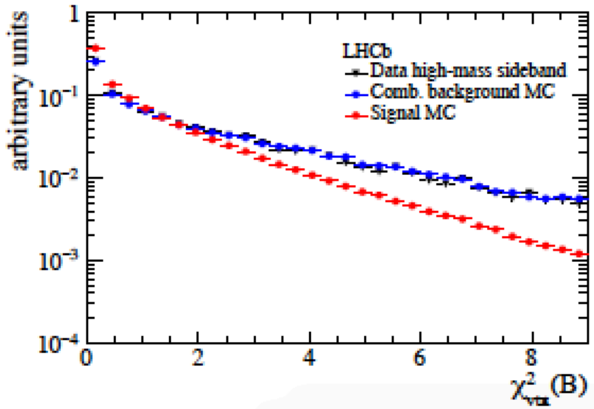
- **Results:**
  - Branching fraction from unbinned likelihood fit
  - Upper limit from CLs method
  - (Effective lifetime measurement)

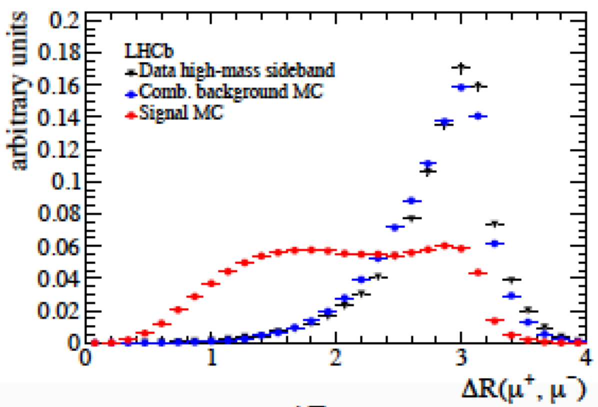
$B_{(s)}\mu\mu$: multivariate classifier (BDT)

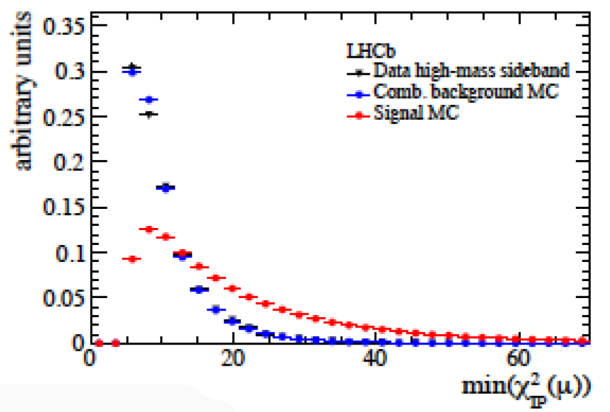
- Isolation variables taken as starting point to train the BDT classifier.
- Optimisation and training on simulated events
- Correlation with invariant mass negligible (below 5%)
- Same definition of the BDT used for Run1 and Run2 datasets while calibration performed independently





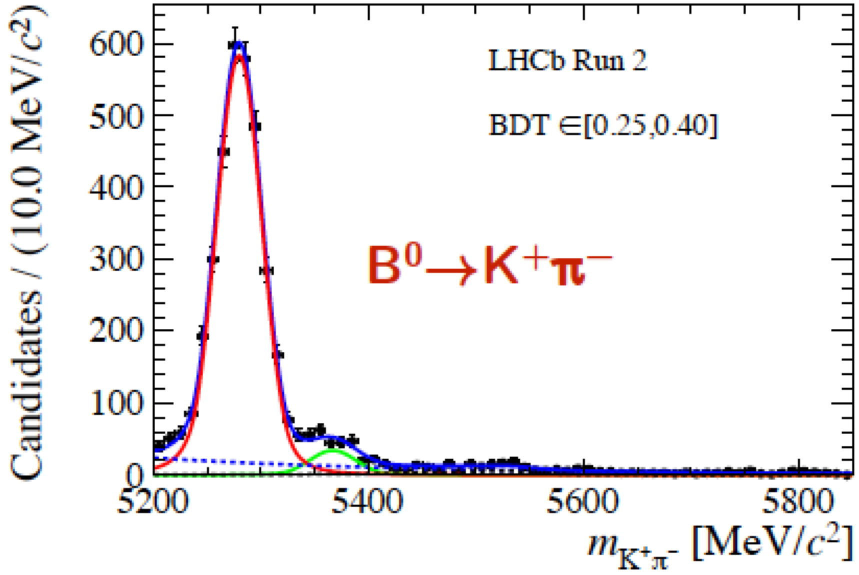


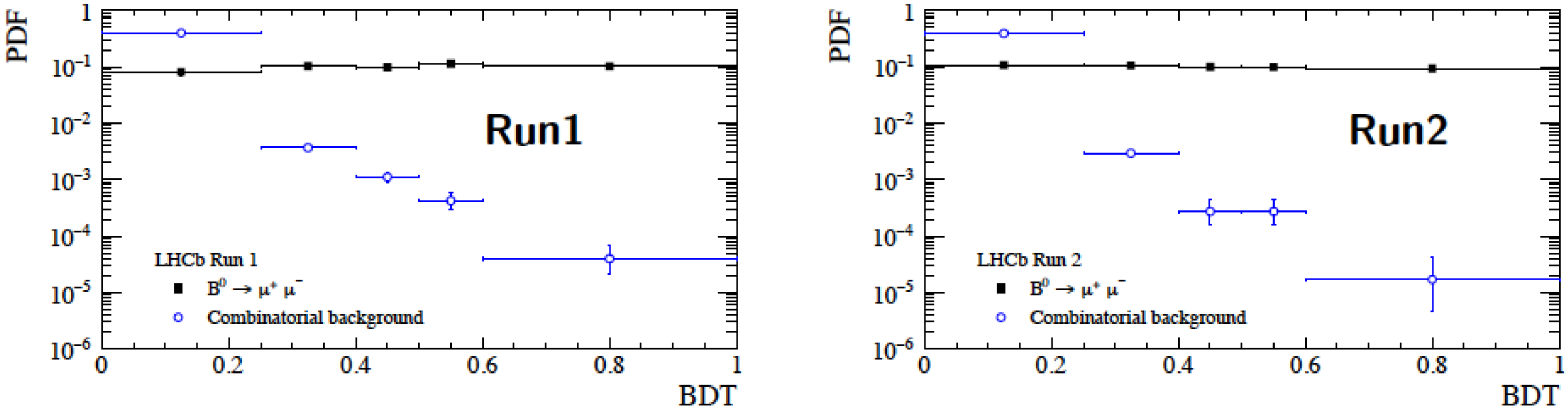




$B_{(s)}\mu\mu$: BDT calibration

- BDT output defined to be **flat for signal**, and peaking at zero for background
- Signal BDT shape from $B^0 \to K^+\pi^-$ events, which have same topology as the signal
- Background BDT shape is evaluated on the di-muon mass sidebands

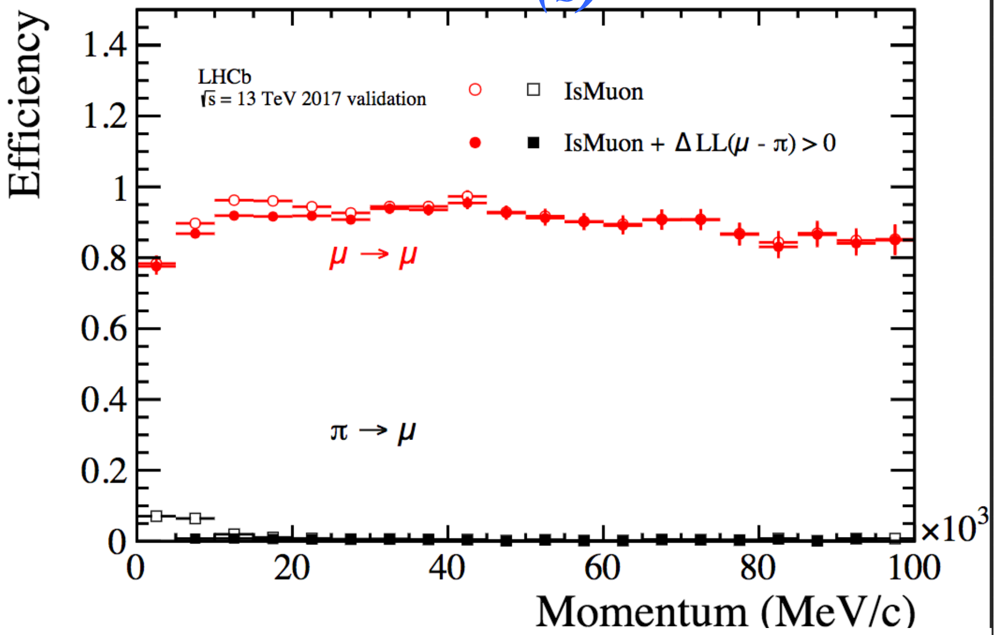




$B_{(s)}\mu\mu$: background sources

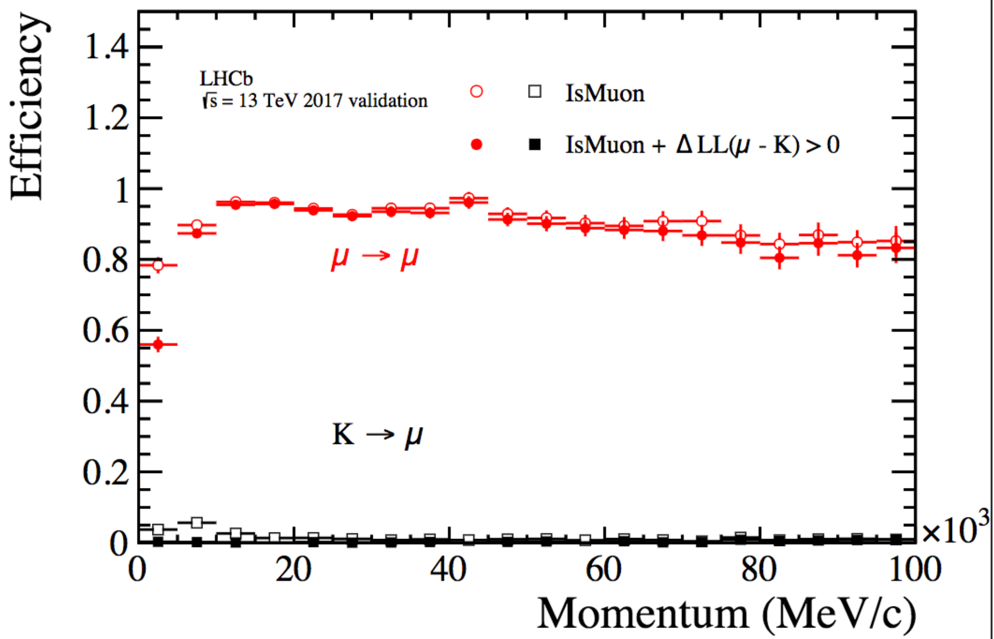
- In addition to the main combinatorial background source described by an **exponential shape**, other two categories populate the lower mass range:
  - Decays with one or two hadrons misidentified as a muon.
    - $B \to h^+h'^-$
    - $B^0 \to \pi^-\mu^+\nu_\mu$
    - $B^0_s \to K^-\mu^+\nu_\mu$
    - $\Lambda^0_b \to p\mu^-\overline{\nu}_\mu$
  - Decays with two real muons.
    - $B_c^+ \to J/\psi(\to\mu^+\mu^-)\mu^+\nu_\mu$
    - $B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$
- Mass and BDT pdfs determined from simulated samples with misID probability calibrated on data.
- Expected yields evaluated by normalising on control channels
- Background x-check from independent fits to $K\mu$ and $\pi\mu$ mass spectrum

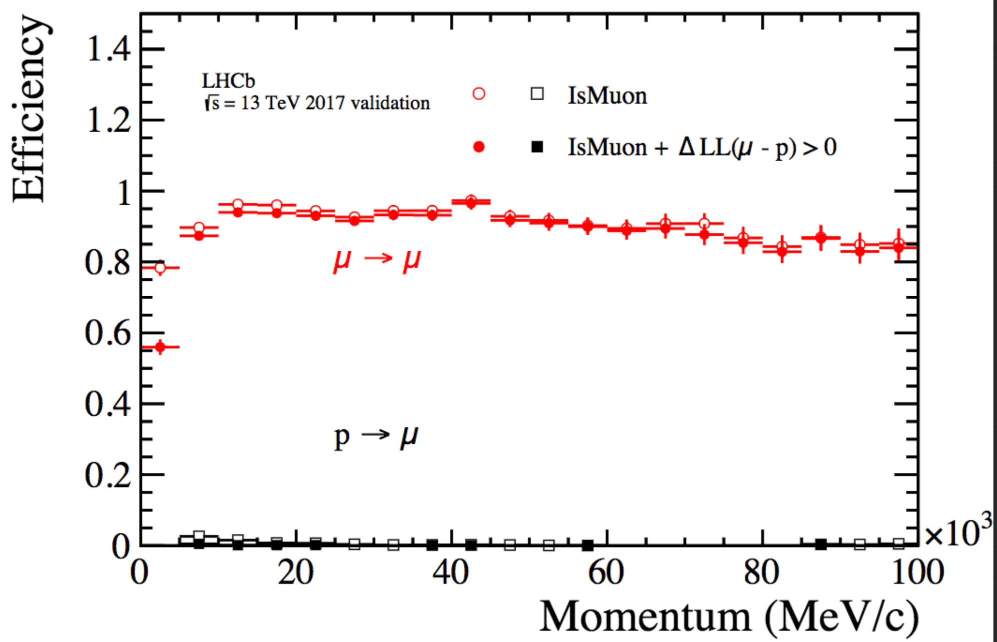
$B_{(s)}\mu\mu$: interlude (mis-Identification)



Branching ratios of background channels:

$B \to h^+h'^-$	$O(10^{-5} - 10^{-6})$
$B^0 \to \pi^-\mu^+\nu_\mu$	$O(10^{-4})$
$B^0_s \to K^-\mu^+\nu_\mu$	$O(10^{-4})$
$\Lambda^0_b \to p\mu^-\overline{\nu}_\mu$	$O(10^{-4})$

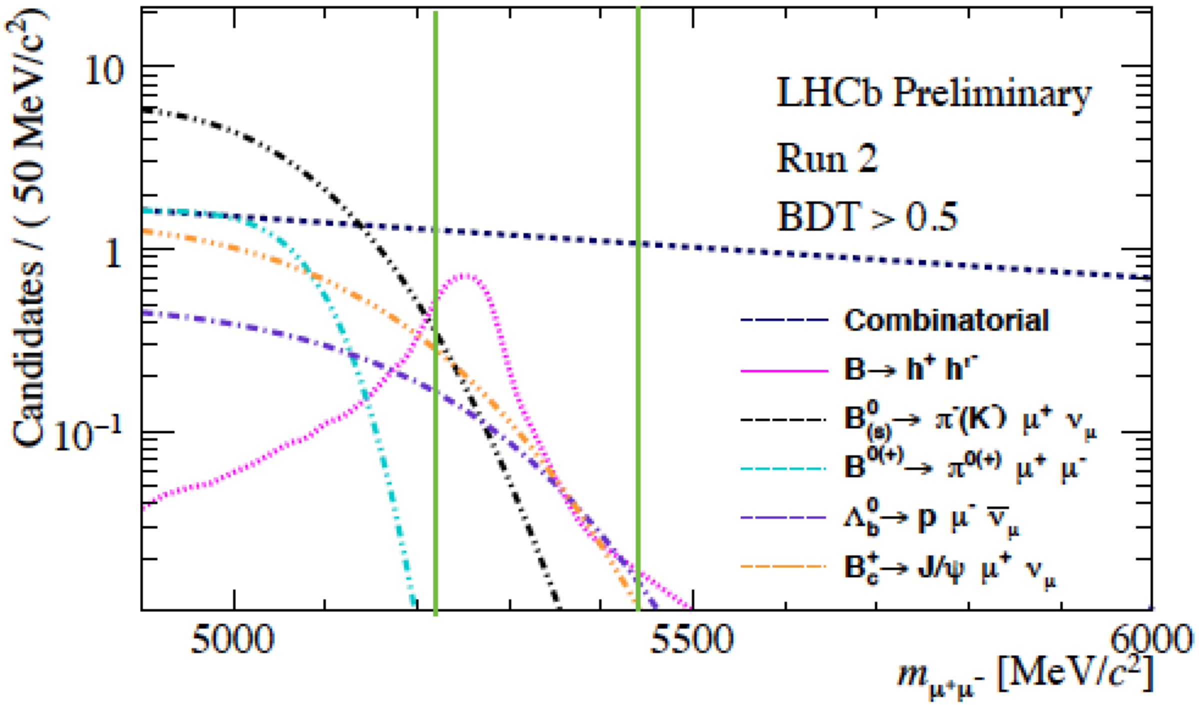




$B_{(s)}\mu\mu$: exclusive backgrounds

Dominant channels in **signal region** and BDT>0.5:

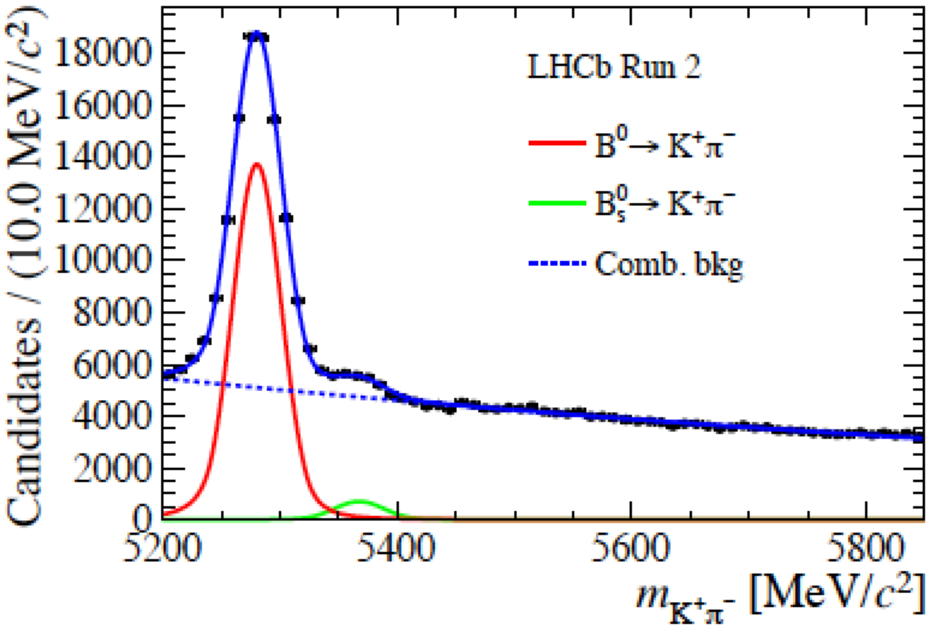
$B \to h^+ h'^-$	2.9 ± 0.3
$B_c^+ \to J/\psi \mu^+ \nu_\mu$	1.2 ± 0.2
$\Lambda^0_b \to p \mu^- \overline{\nu}_\mu$	0.7 ± 0.1
$B^0 \to h^- \mu^+ \nu_\mu$	0.80 ± 0.06



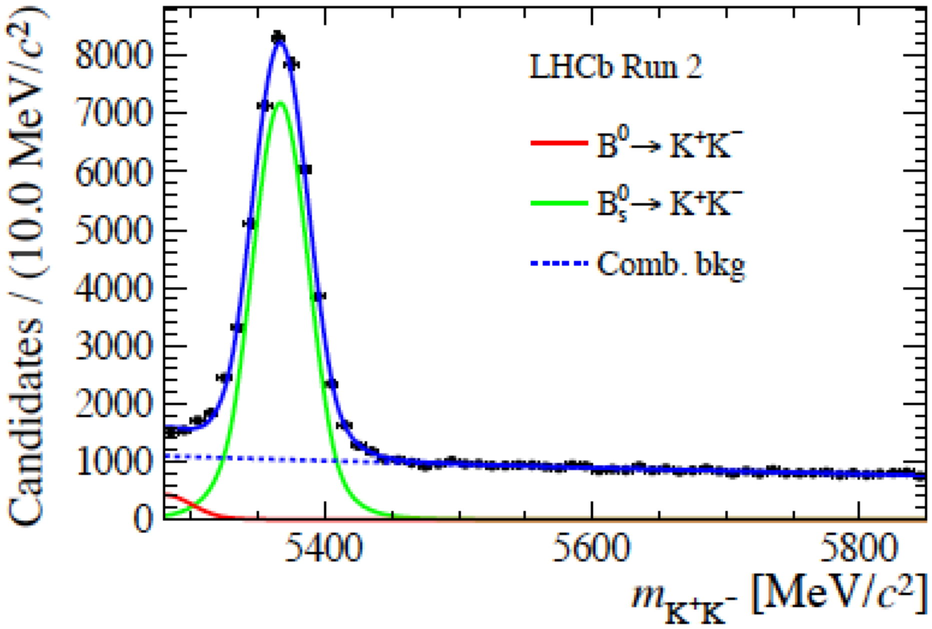
- $B \to h^+ h'^-$ peaking in the signal region. Factor ~2 reduction w.r.t. previous analysis
- $B^{0(+)} \to \pi^{0(+)} \mu^+ \mu^-$ interplay with combinatorial background.
- All these decays taken into account in the final fit.
- Contribution from $B^0_s \to \mu^+ \mu^- \gamma$ and $B^0_s \to \mu^+ \mu^- \nu_\mu \overline{\nu}_\mu$ decays negligible.

$B_{(s)}\mu\mu$: mass calibration

Bd mass



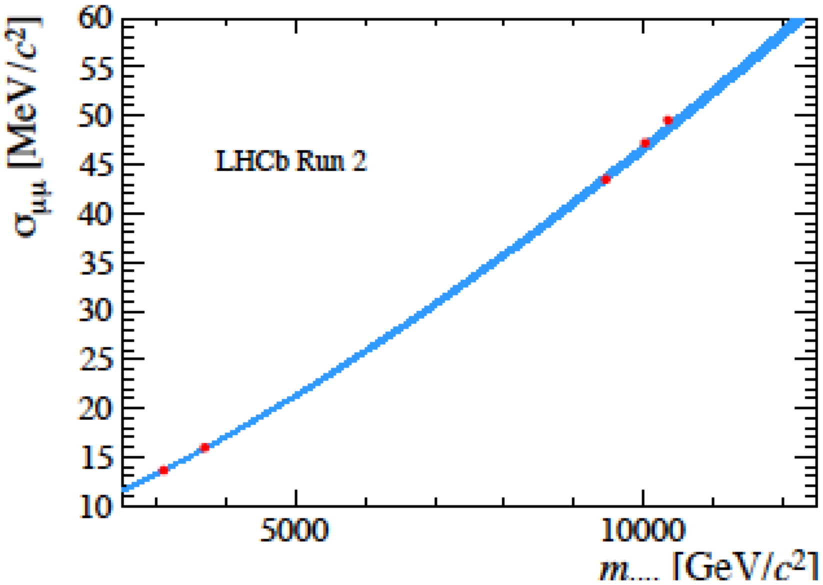
Bs mass

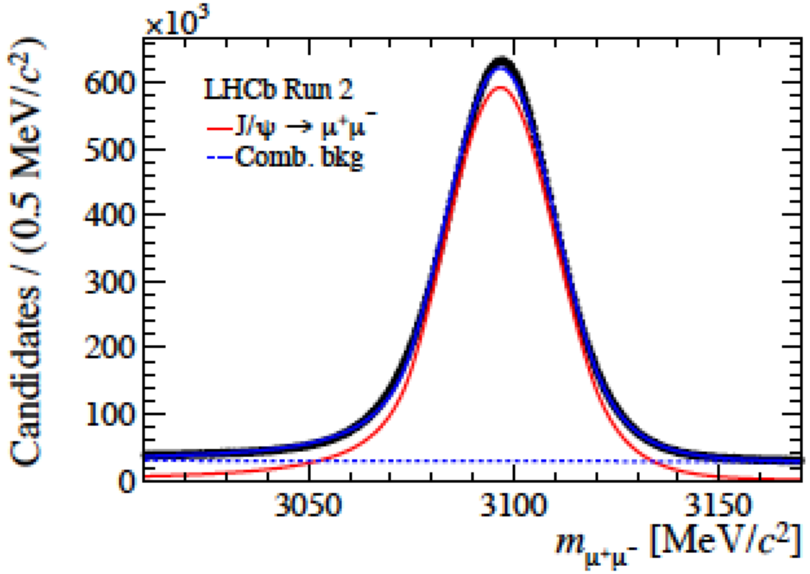


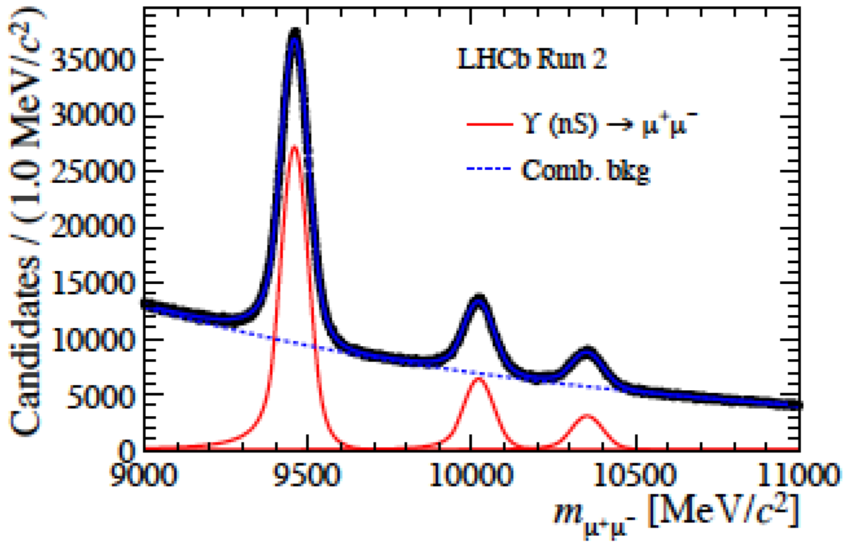
- Determination of mass peak position with well visible exclusive $B\to hh'$ decays

$B_{(s)}\mu\mu$: mass resolution

- Resolution determination from power law interpolation of dimuon resonances: J/ψ, $\psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$
- Mass resolution ~23MeV/c^2
- 1% difference between Run1 and Run2 data

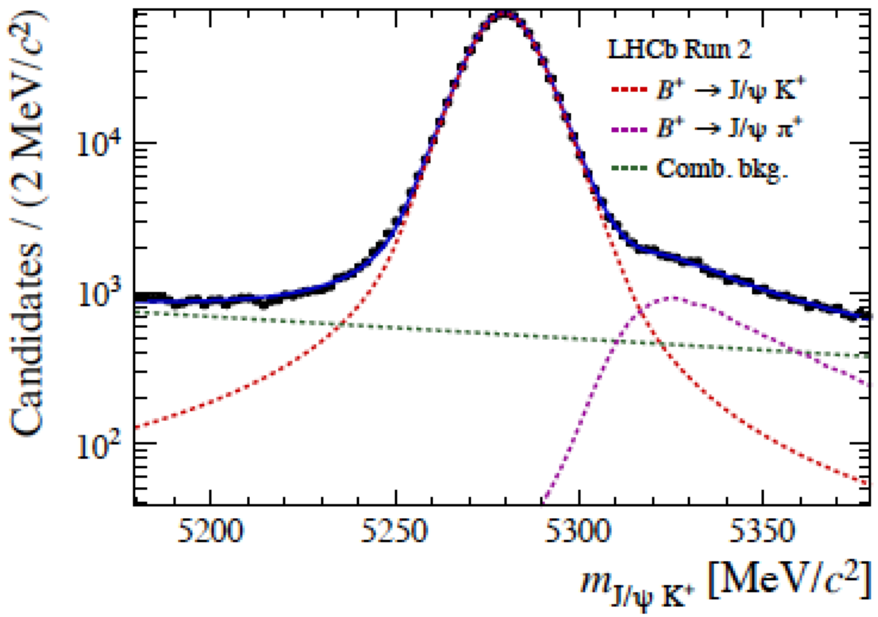


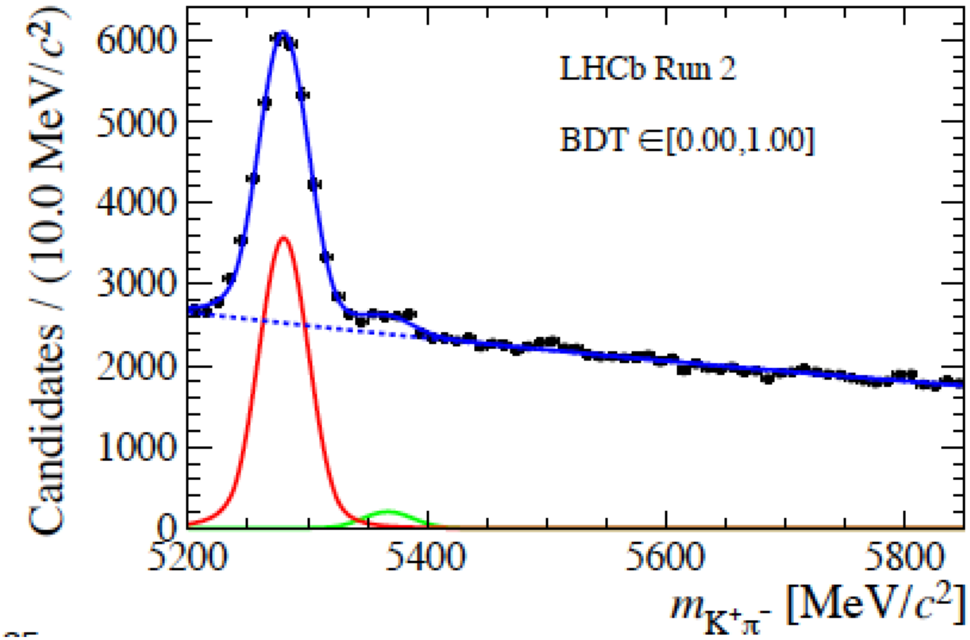




$B_{(s)}\mu\mu$: normalization

- Two control channels used for the normalization: $B^+ \to J/\psi K^+$ and $B^0 \to K^+\pi^-$



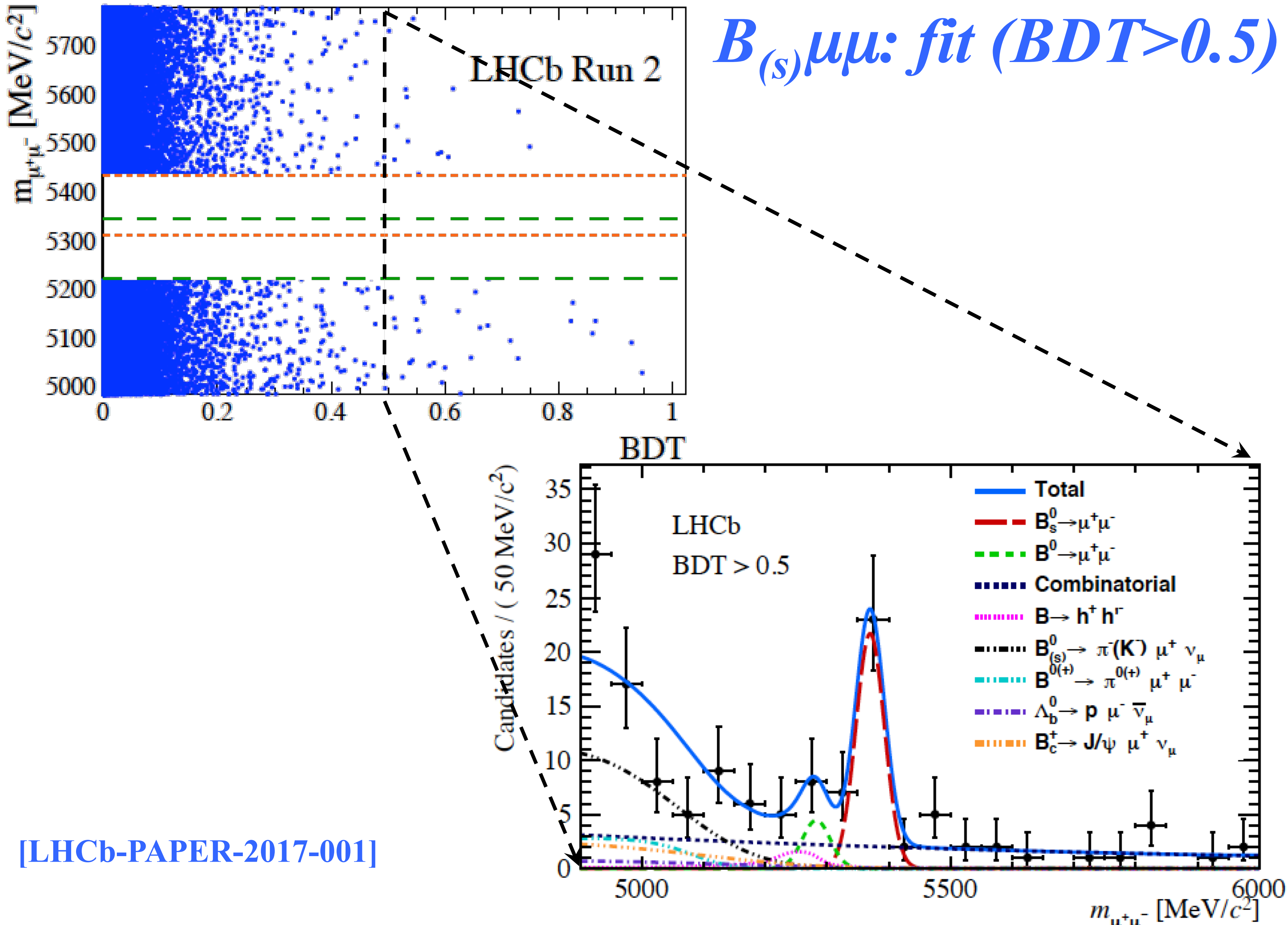


- Measured $(1964\pm1)\times10^3$ $B^+ \to J/\psi K^+$ and $(62\pm3)\times10^3$ $B^0 \to K^+\pi^-$ decays
- Assuming the SM rates, after the selection we expect:
  - **~62 $B^0_s \to \mu^+\mu^-$ events and ~7 $B^0 \to \mu^+\mu^-$ events in the whole BDT range**

$B_{(s)}\mu\mu$: branching ratio fit

- Unbinned maximum likelihood fit on BDT binned di-muon mass spectra:
  - 4 BDT bins in Run1 and 4 BDT bins in Run2 simultaneously considered
    - background dominated region BDT $\in$ [0,0.25] excluded in the final fit
  - mass range [4900,6000] MeV/c^2
- Free parameters: $BF(B^0 \to \mu^+\mu^-)$ and $BF(B^0_s \to \mu^+\mu^-)$ and combinatorial background
- Signal fractions constrained in each BDT bin to expectations
- Exclusive background yields constrained to their expectations

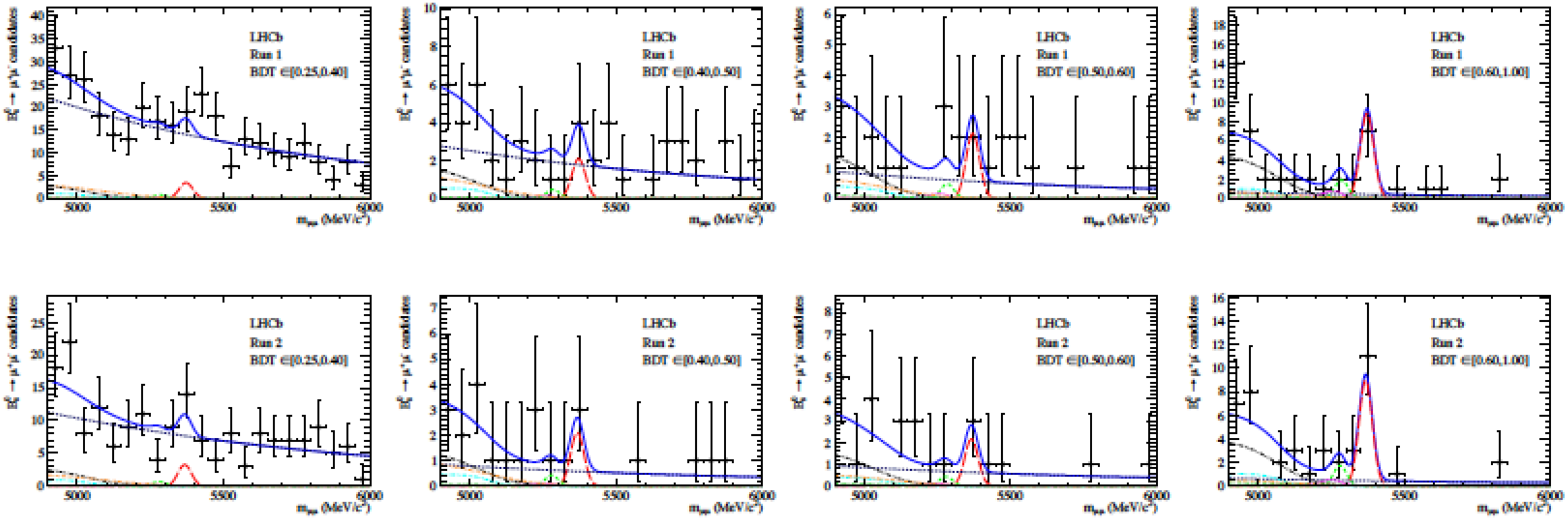
$B_{(s)}\mu\mu$: fit (BDT>0.5)



[LHCb-PAPER-2017-001]

$B_{(s)}\mu\mu$: fit

slices: [0.25-0.4] [0.4-0.5] [0.5-0.6] [0.6-1.0]

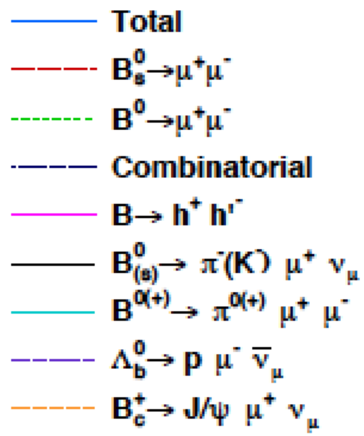


- Fit results:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8 \pm 0.6) \times 10^{-9} \quad 7.8\sigma$$

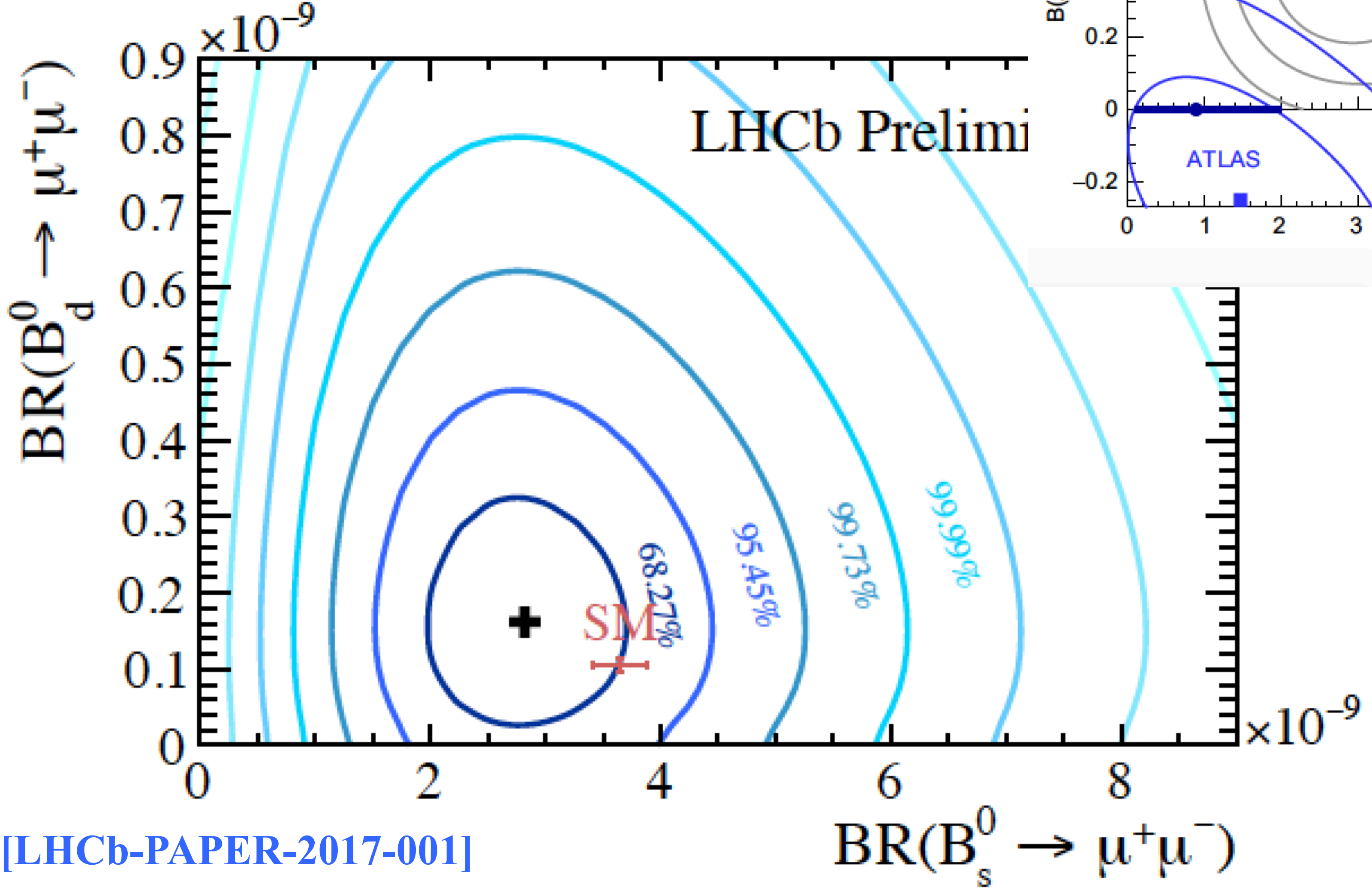
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.6^{+1.1}_{-0.9}) \times 10^{-10} \quad 1.9\sigma$$

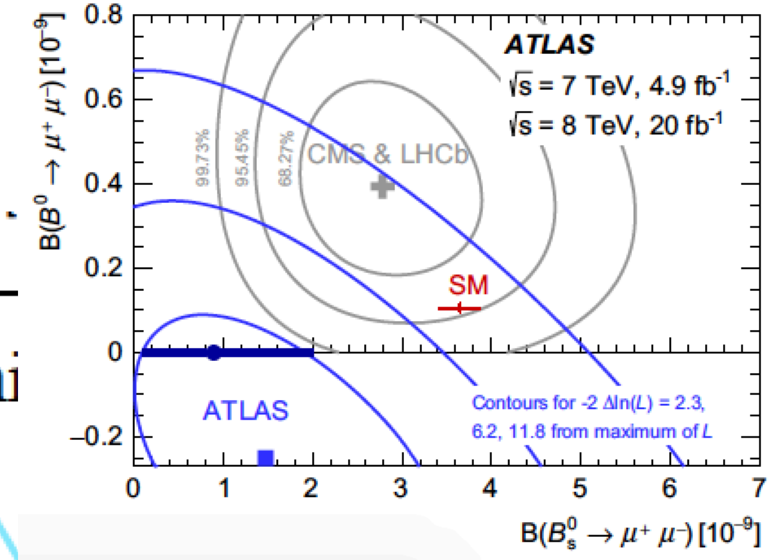
- Systematics from nuisance parameters and background model
- Given no evidence of $B^0 \to \mu^+\mu^-$, upper limit has been evaluated



[LHCb-PAPER-2017-001]

$B_{(s)}\mu\mu$: 2D likelihood profile

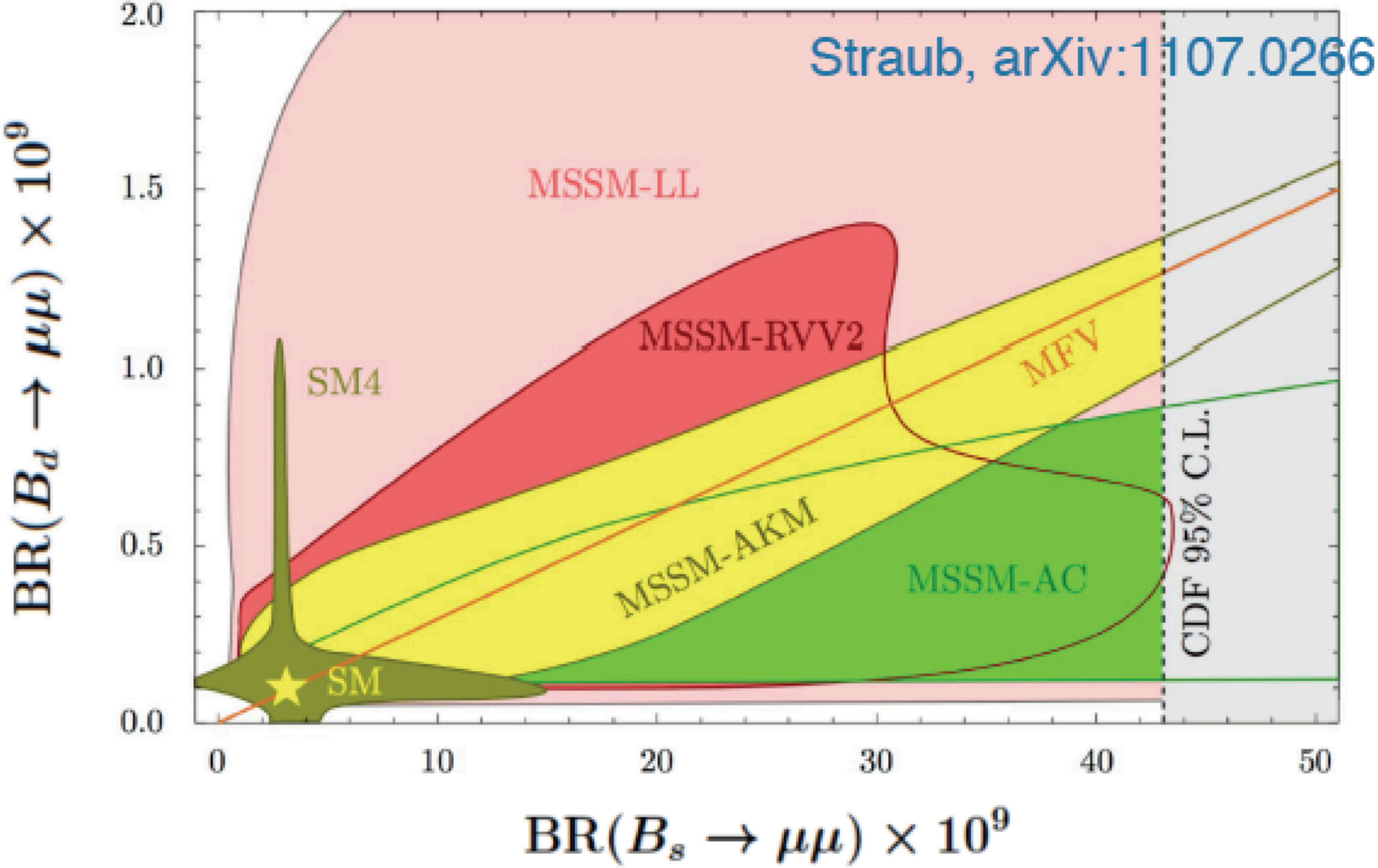




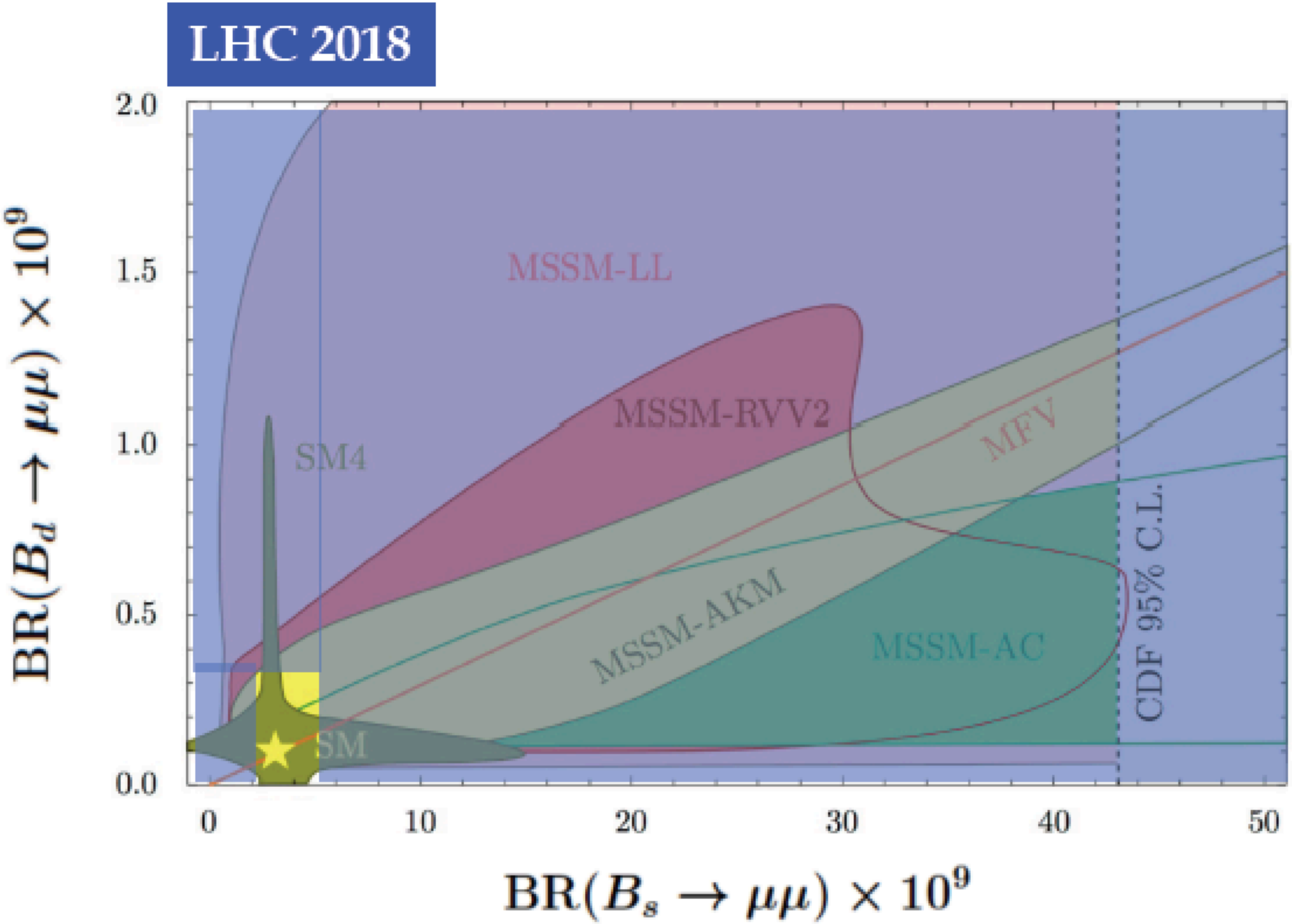
[LHCb-PAPER-2017-001]

$B_{(s)}\mu\mu$: lesson from the past

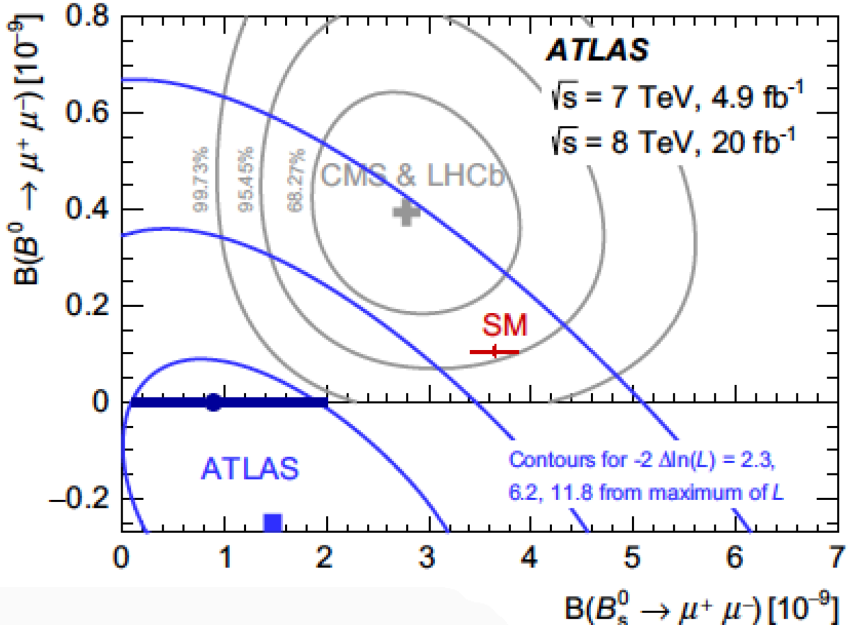
Pre-LHC

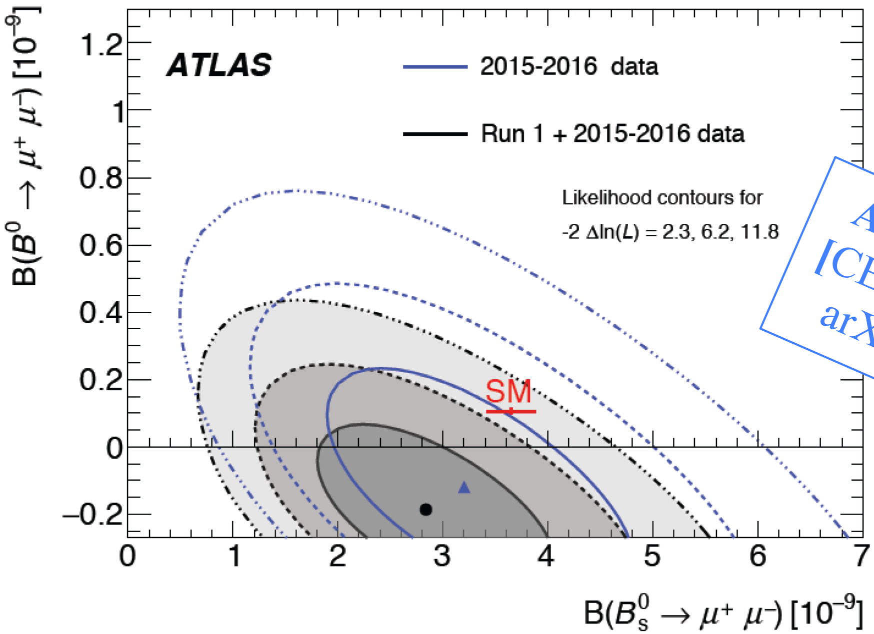


$B_{(s)}\mu\mu$: lesson from the past

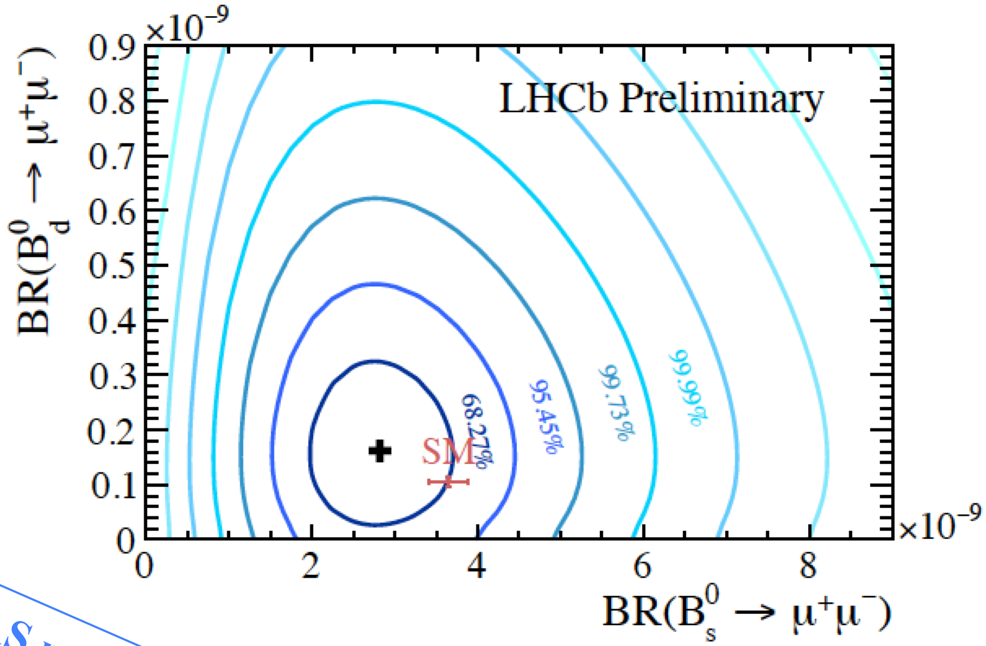


$B_{(s)}\mu\mu$: the story continues!





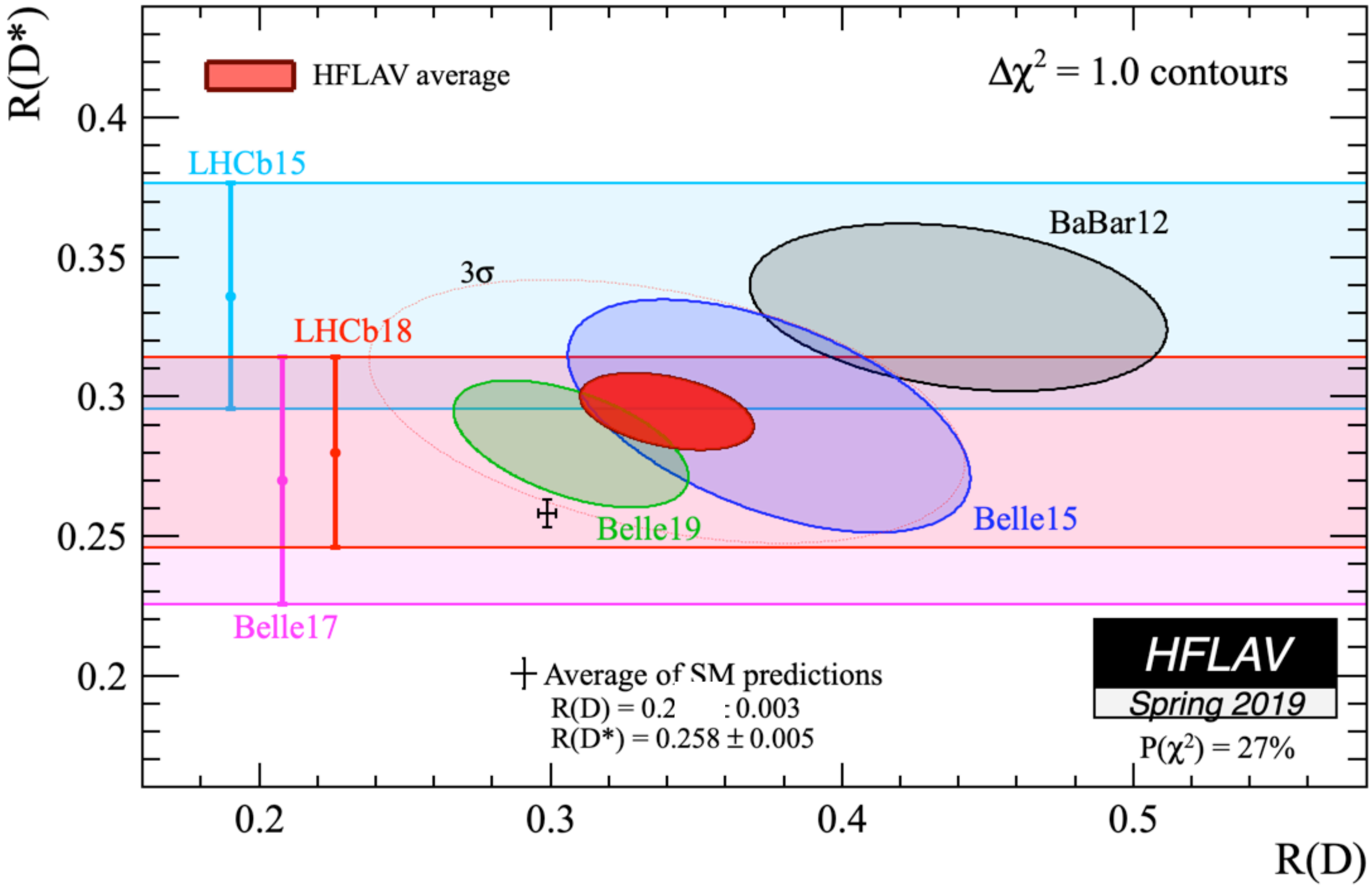
[LHCb-PAPER-2017-001]



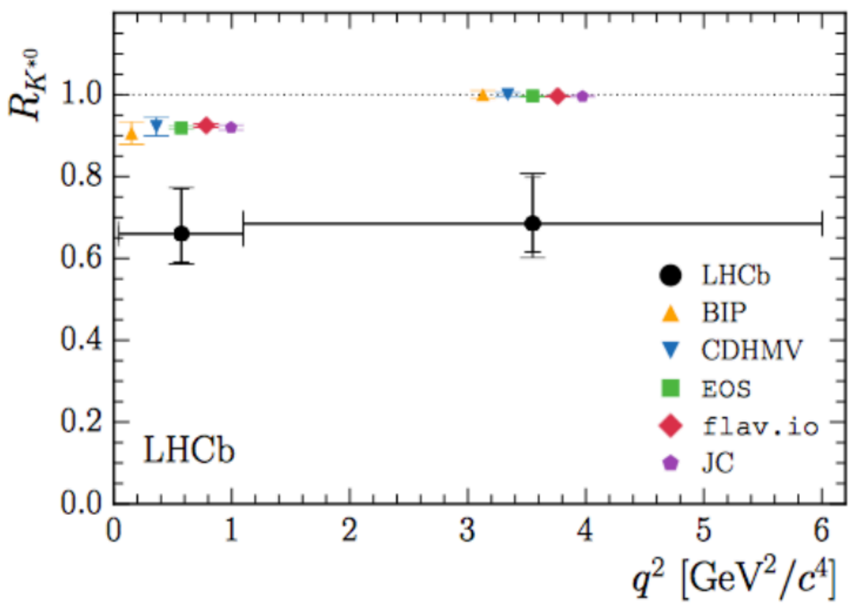
ATLAS new result
[CERN-EP-2018-291
arXiv1812.03017]

What next?

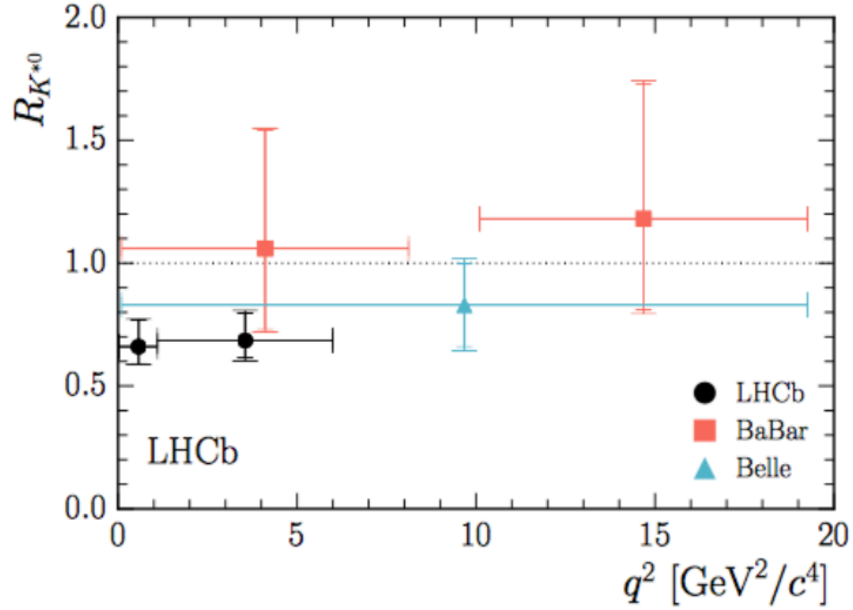
*Intriguing discrepancy wrt SM: R_D and R_D**

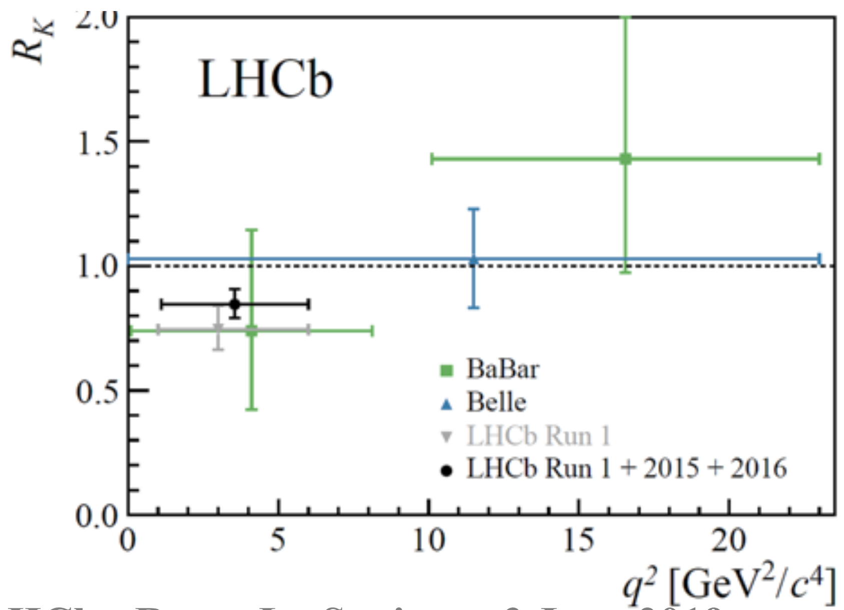


Intriguing discrepancy wrt SM: R_K and R_K*



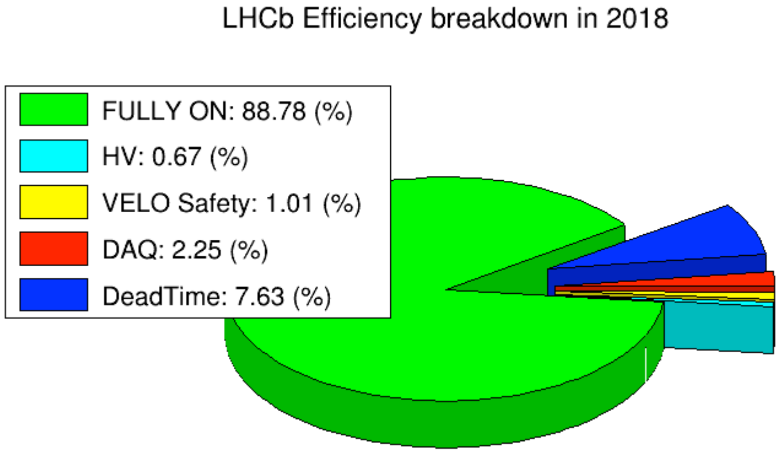
[LHCb-PAPER-2017-013]

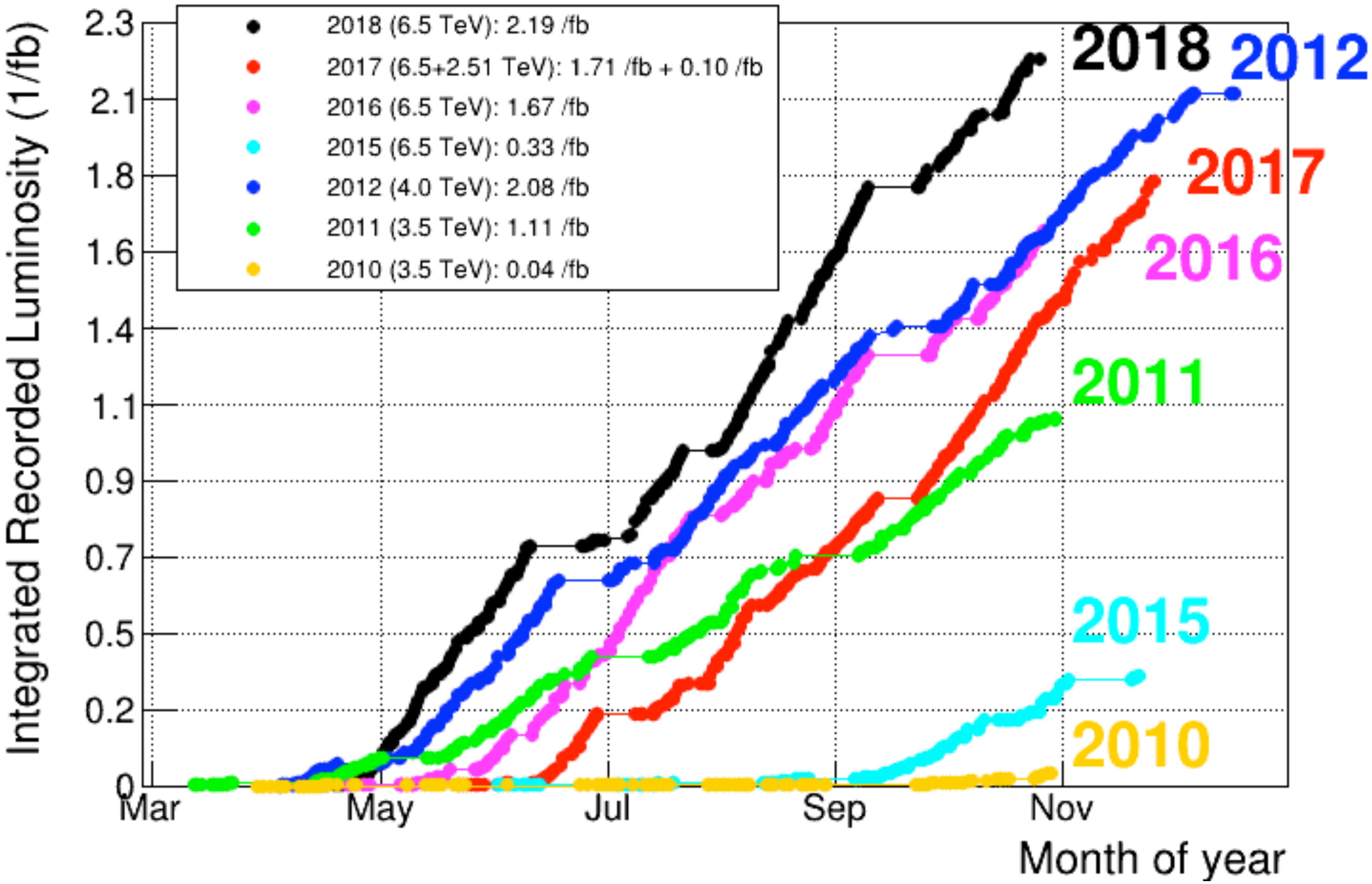




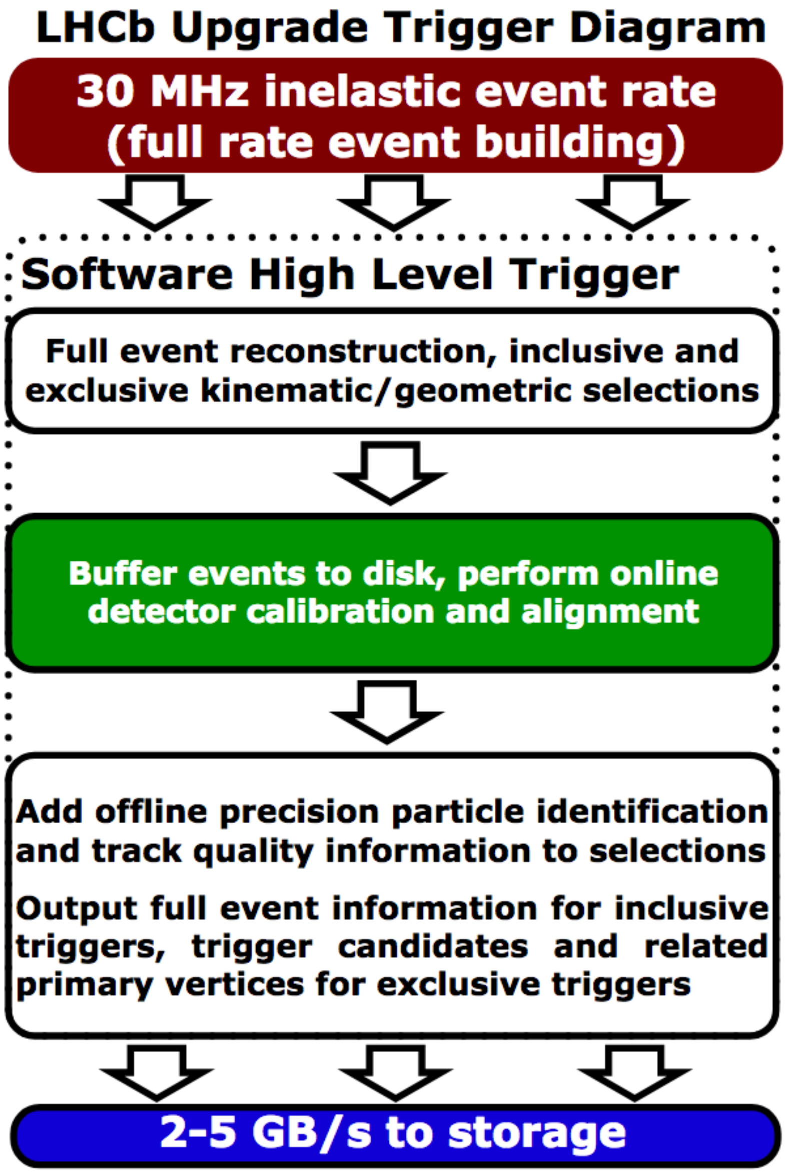
[Moriond:EW, LHCB-PAPER-2019-009]

End of “classic” LHCb

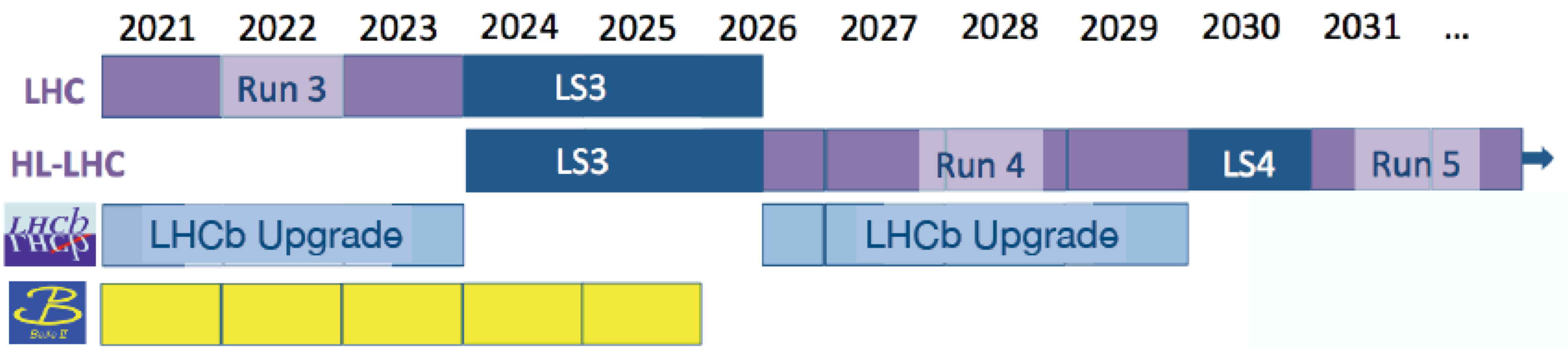




What if ~ every collision is interesting?



Near and far future



LHCb Upgrade

1. **Full software trigger** to allow effective operation at higher luminosities with higher efficiency for hadronic decays.
2. **Luminosity** to be raised (x5) to $2x10^{33}$ $cm^{-2}s^{-1}$.

Summary

- **LHCb measured a lot of "SM results" and some intriguing discrepancies wrt the SM**.

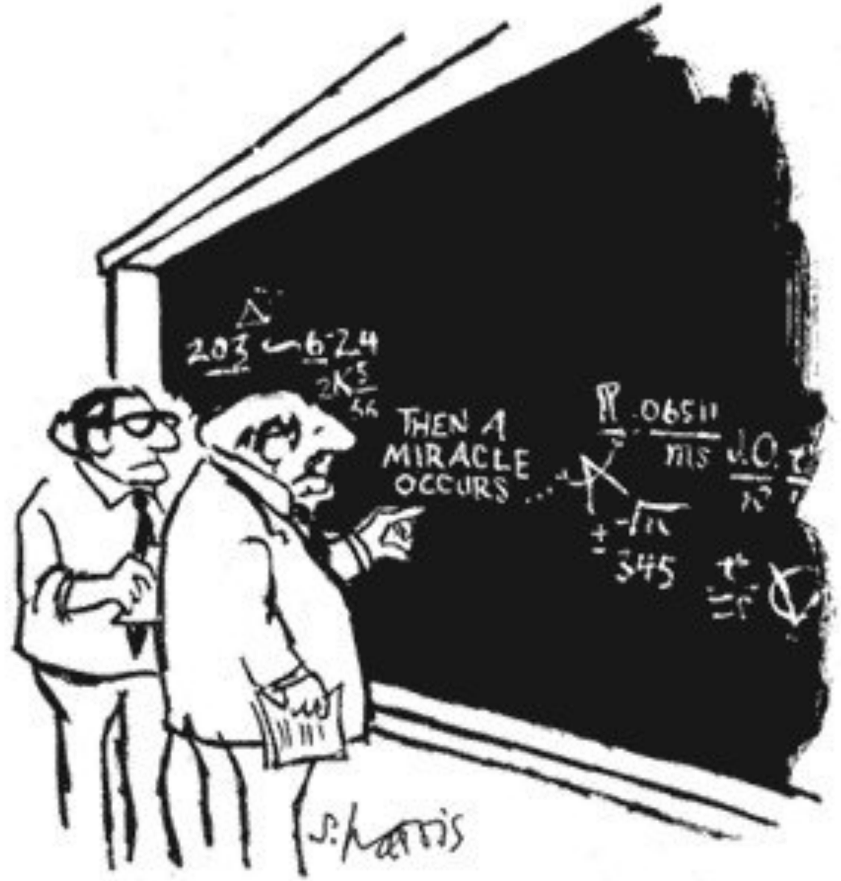
- Completion of Run 2 data analysis can **shed light on beyond SM physics** (starting from $B_{(s)}\mu\mu$).

- LHCb is the first HEP experiment implementing a fully automatic tracking system alignment, PID calibration and track reconstruction in the online system. **A working model for future experiments**.

- Upgrade I: a challenge under many aspects (from detectors to DAQ; new Real Time Analysis project)

- Many ideas and projects for potential further upgrades

- **A lot of (scientific but not only) fun ahead!** aka a lot of interesting projects if you are looking for a thesis.



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

INJECTION
Thanks!

Back up

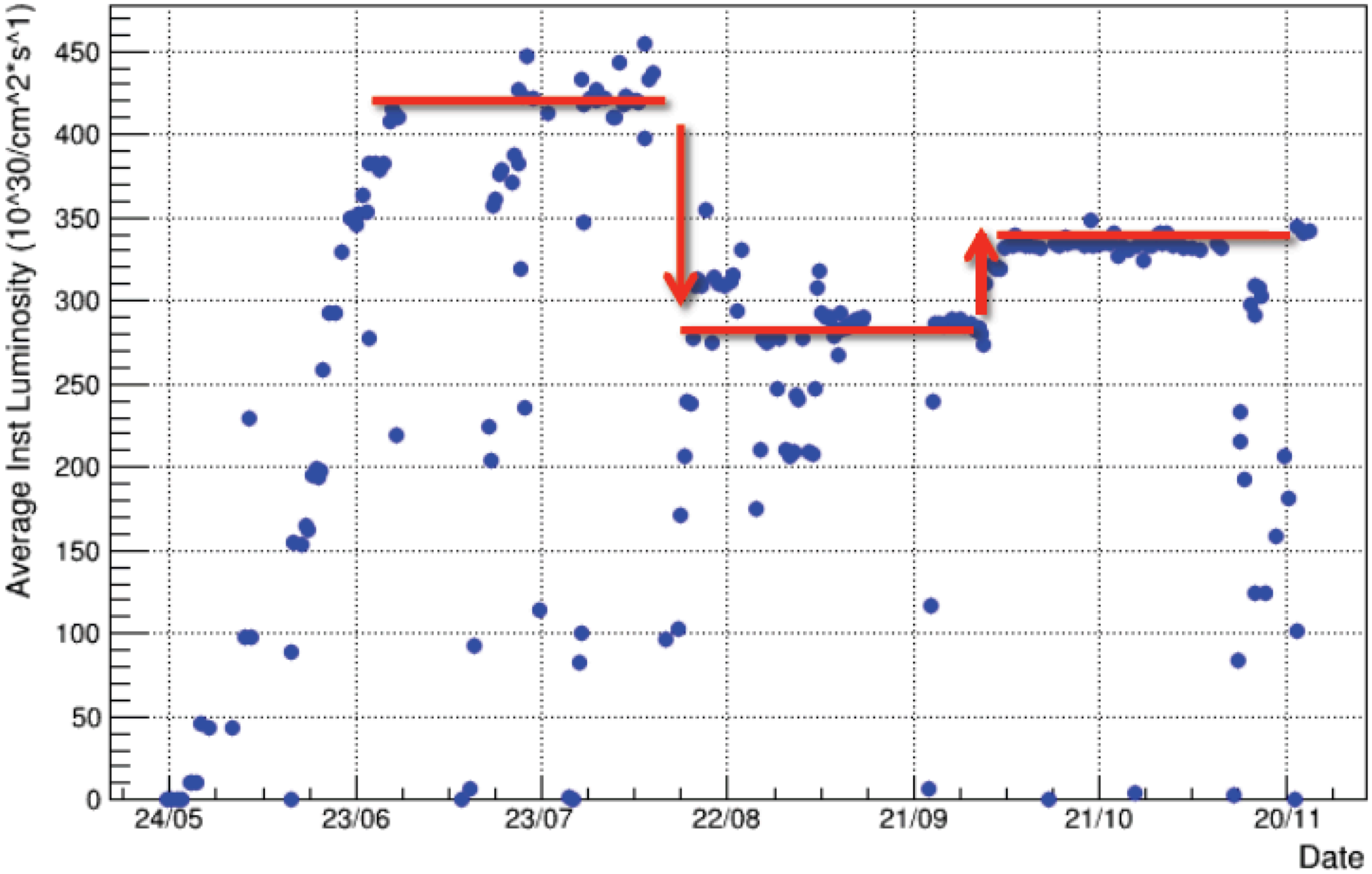
End of "classic" LHCb

147433	03-Dec-2018 09:26		LHC	Comments	Powering test campaign Energy upgrade needed: expected 2 years
147432	03-Dec-2018 07:54		LHCb	Federico Alessio	Got delegation from CCC. Give it back not before 2021...
147431	03-Dec-2018 07:16		LHC	Comments	powering test campaign Energy upgrade needed: expected 2 years
147430	03-Dec-2018 07:04		LHCb	Federico Alessio	Richard and I going down for TFC inspection...
147429	03-Dec-2018 06:45		LHCb	Niels Tuning	> 6am, this is the end of LHCb as we know it. > > Waiting for RP to go into access mode.
147428	03-Dec-2018 06:30		Shift Crew	From Database	Shift Leader Federico Alessio
147427	03-Dec-2018 06:01		LHCb	Federico Alessio	6am, this is the end of LHCb as we know it. Waiting for RP to go into access mode.
147426	03-Dec-2018 05:51		LHC	New State	NO_BEAM; Fill: 7494
147425	03-Dec-2018 04:38		LHC	Comments	This was the last dump of Run2 ! Going to access today, estimate 2 years
147424	03-Dec-2018 03:01		LHC	Comments	Beams back in PS. Preparing for injection NEXT: Quench test MD (lumi from Atlas needed)

Run2 [2017] operating conditions

Due to varying number of bunches and filling scheme:

- Inst. luminosity reduced from 4.2 x 10^{32} to 2.8 x 10^{32} $cm^{-2}s^{-1}$
- Inst. luminosity increased from 2.8 x 10^{32} to 3.4 x 10^{32} $cm^{-2}s^{-1}$

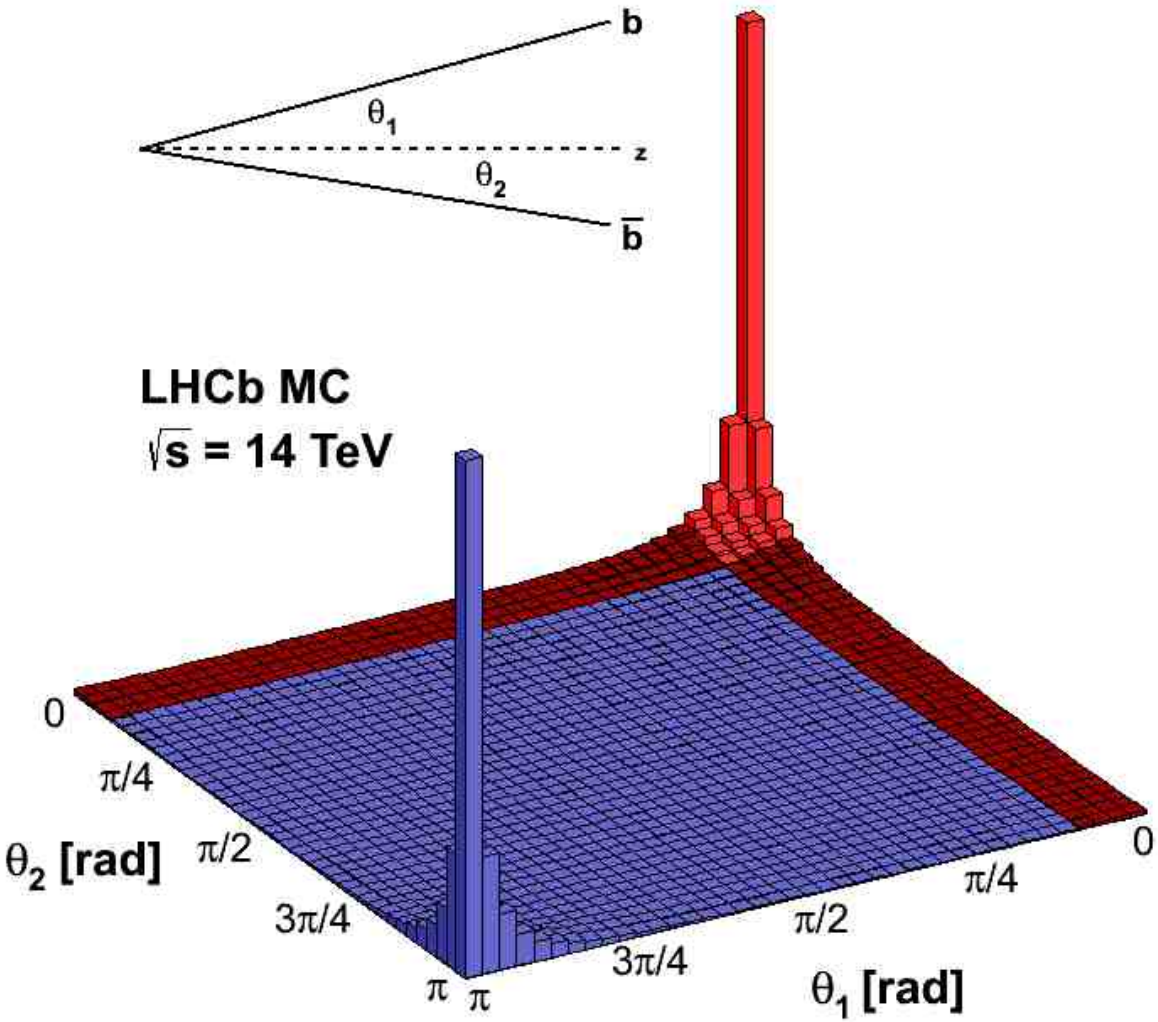


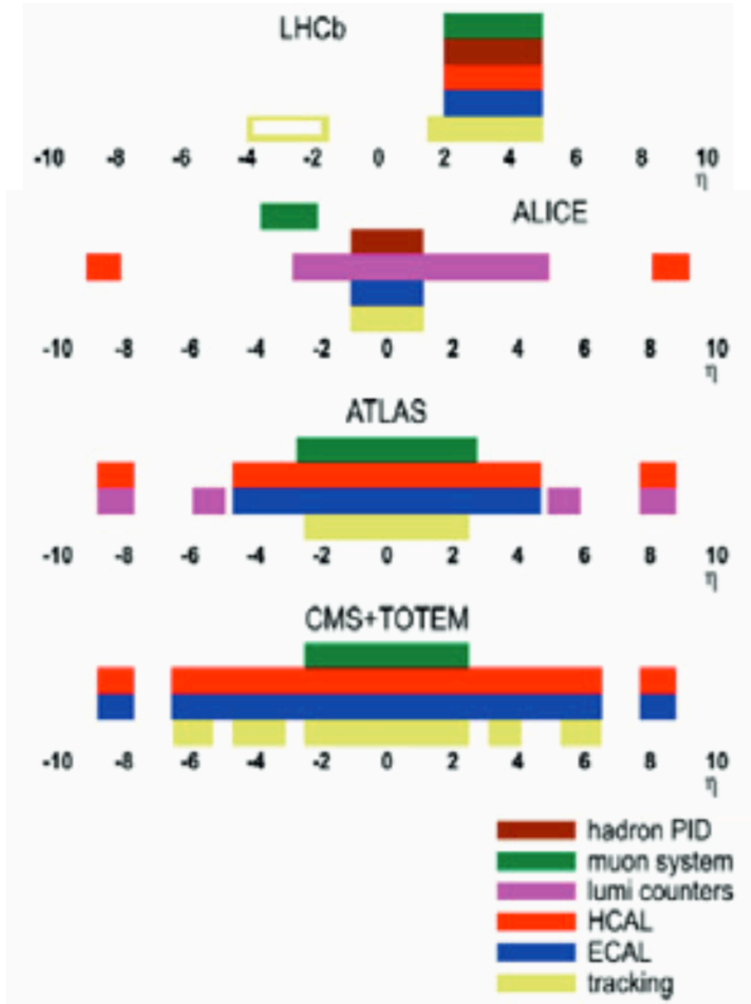
4.2 x 10^{32} $cm^{-2}s^{-1}$

3.4 x 10^{32} $cm^{-2}s^{-1}$

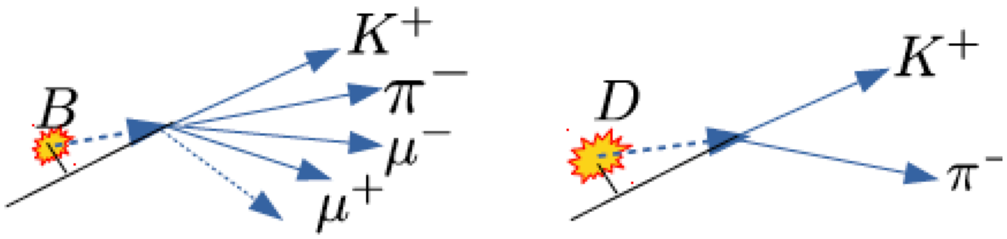
2.8 x 10^{32} $cm^{-2}s^{-1}$

A lot of data: heavy flavor production





HLT1

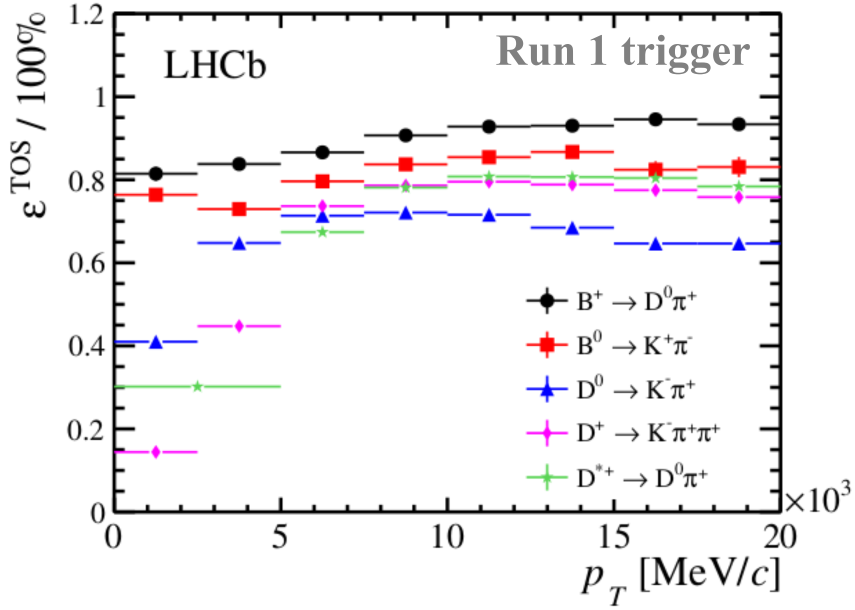


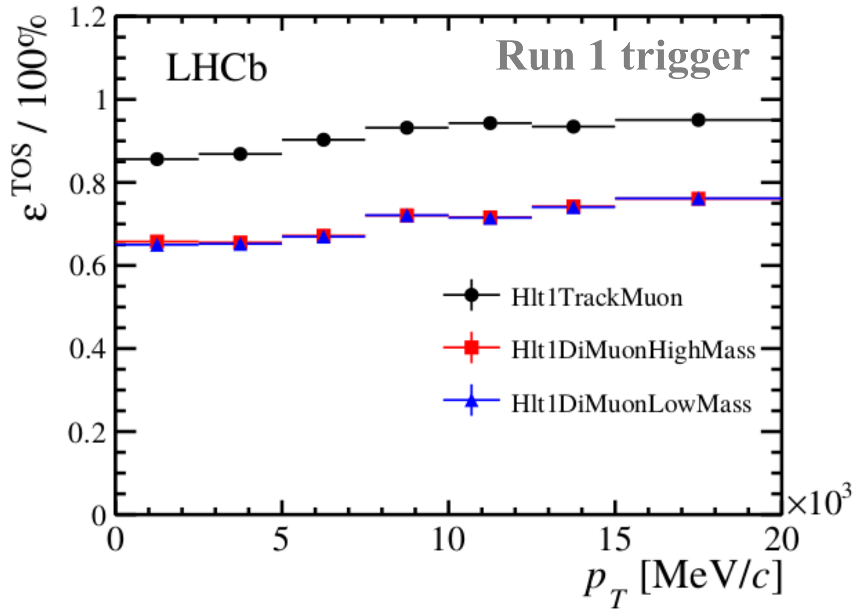
Inclusive trigger:
 Single and two tracks MVA selections (~100 kHz)

Inclusive muon trigger:
 Single and dimuon selections
 Additional low pT track reconstruction (~40 kHz)

Exclusive trigger:
 Lifetime unbiased beauty and charm selections
 Selections for alignment

Low multiplicity trigger for central exclusive production analyses

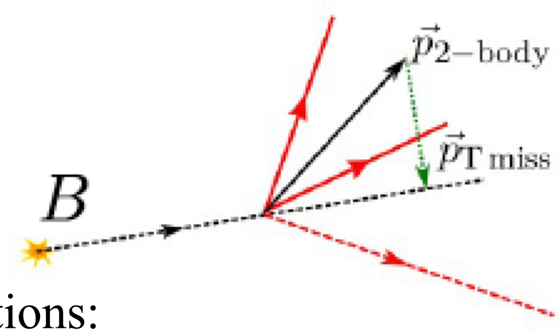




[Int.J.Mod.Phys. A30 (2015) 1530022]

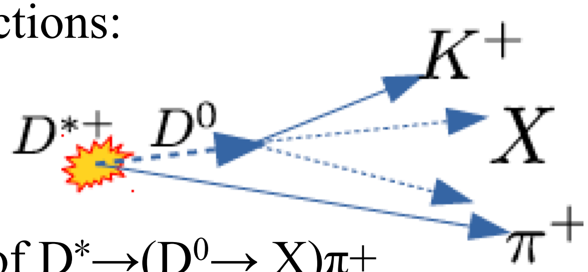
HLT2

12.5 kHz to tape



Inclusive beauty selections:
- MVA based 2, 3, and 4 body detached vertices
- Dimuon selections

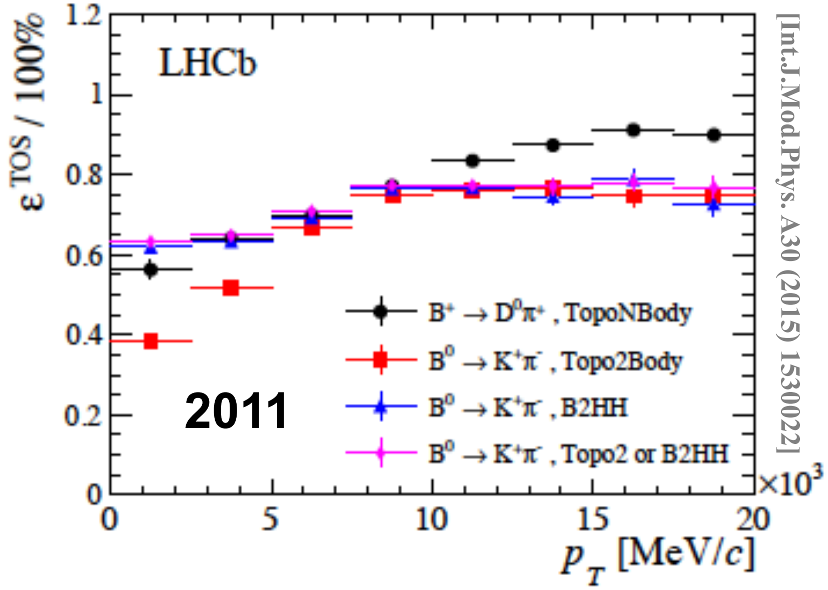
Exclusive beauty selections:
E.g. $B\rightarrow \varphi\varphi$, $B\rightarrow \gamma\gamma$

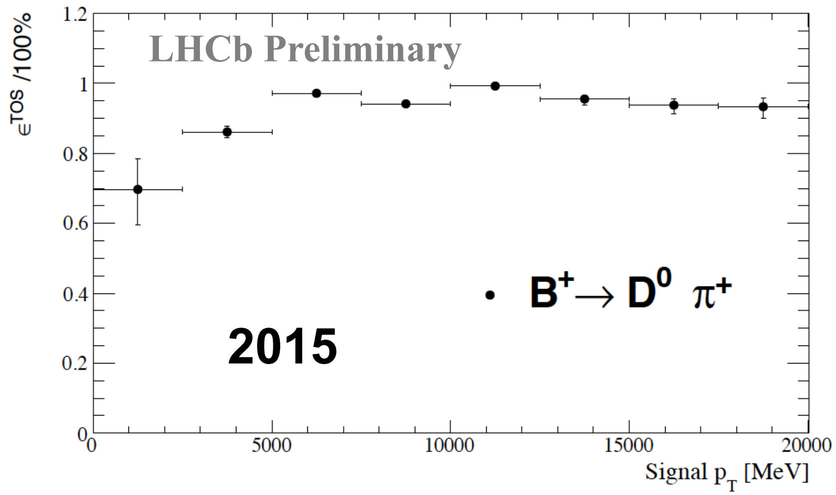


Charm selections
- Inclusive selection of $D^{*}\rightarrow(D^0\rightarrow X)\pi+$
- Charmed baryons
- Final states with K0S
- 2,3,4,5-body final states

Electroweak bosons

Nearly 400 selections in total

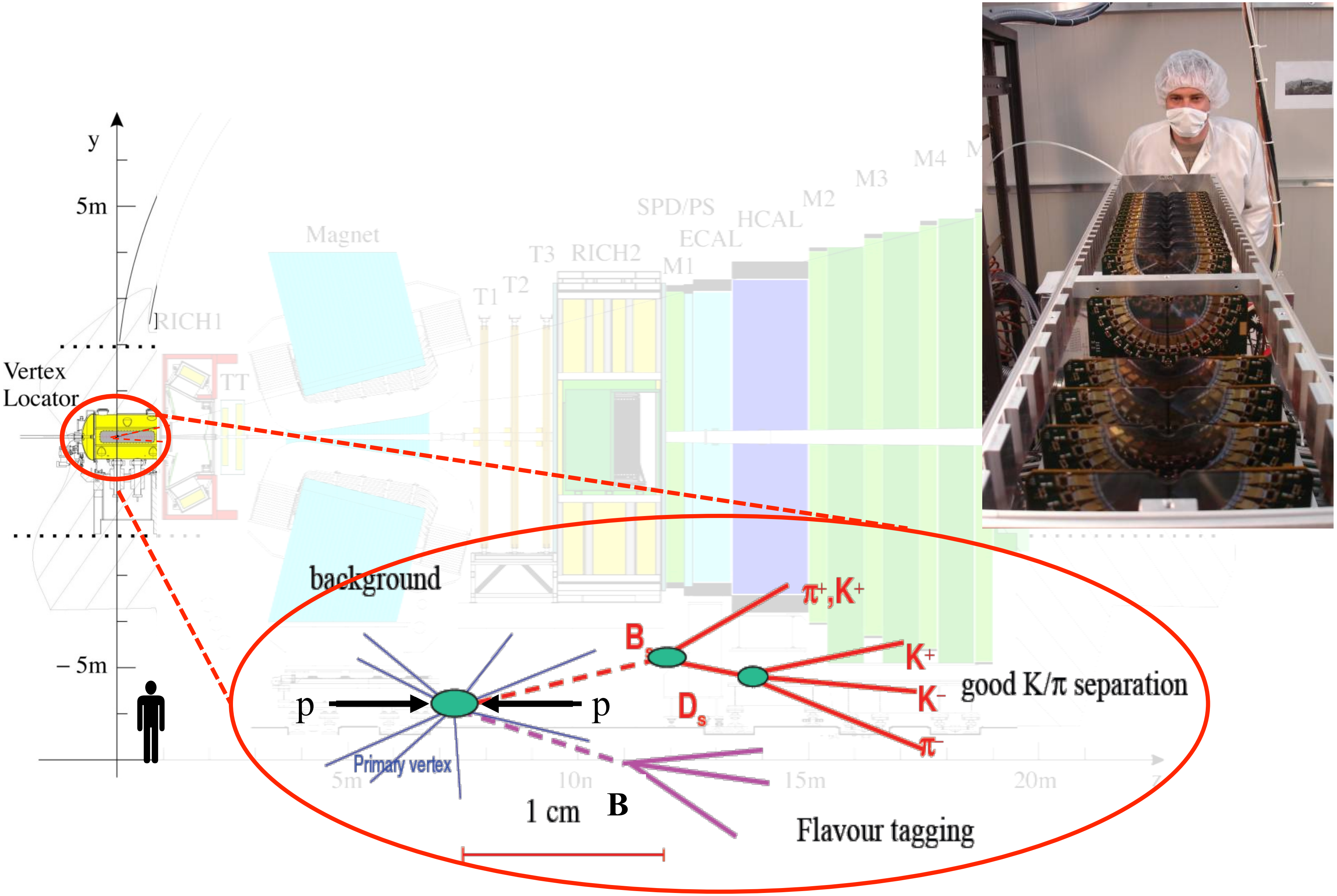




[e.g. HLT2 efficiency for inclusive b trigger: $B^+\rightarrow D^0\pi^+$ increased from ~75% to >90%]

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

VELO

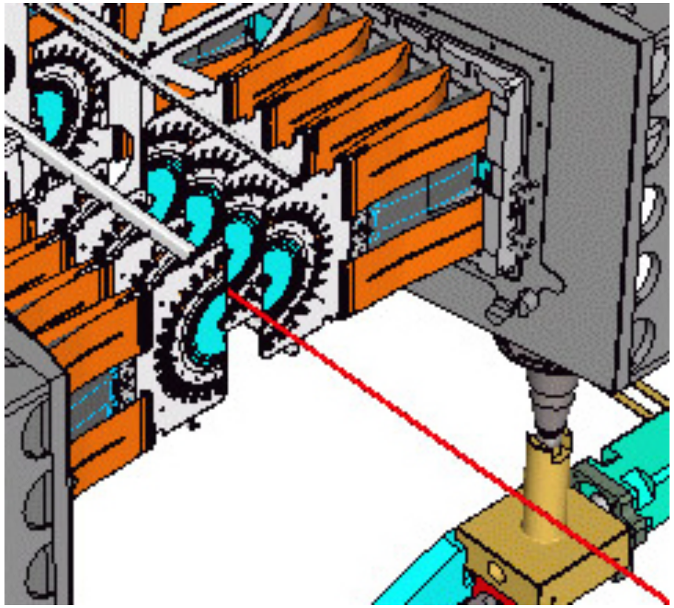


VELO

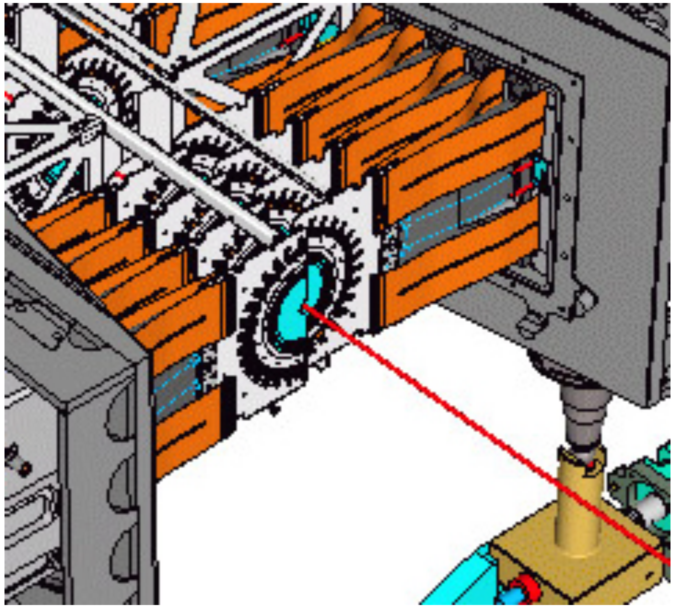
Silicon detector: 42 modules arranged along the beam, each providing a measurement of the r and ϕ coordinates.

Performance (vertex reconstruction)
- **decay time resolution: 45 fs**
- **impact parameter resolution: 20 μm**

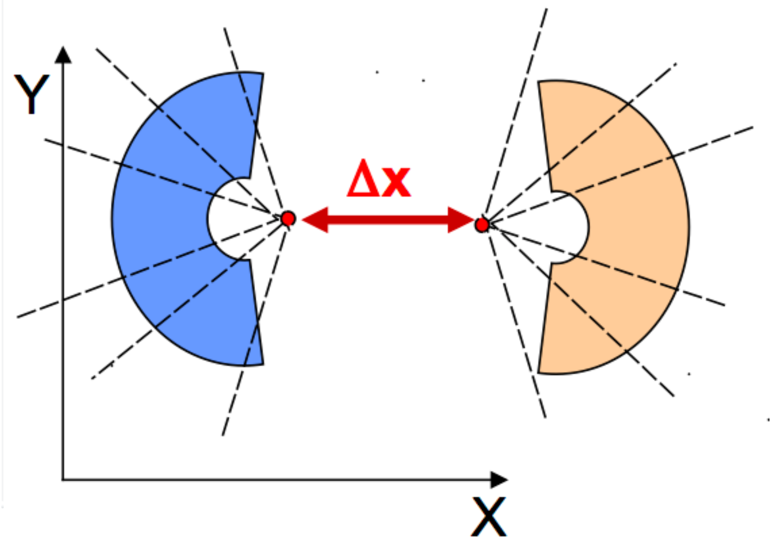
Detector safety: **modules retracted by 29 mm during injection**; 210 s to close; ~750 closing procedures in Run1



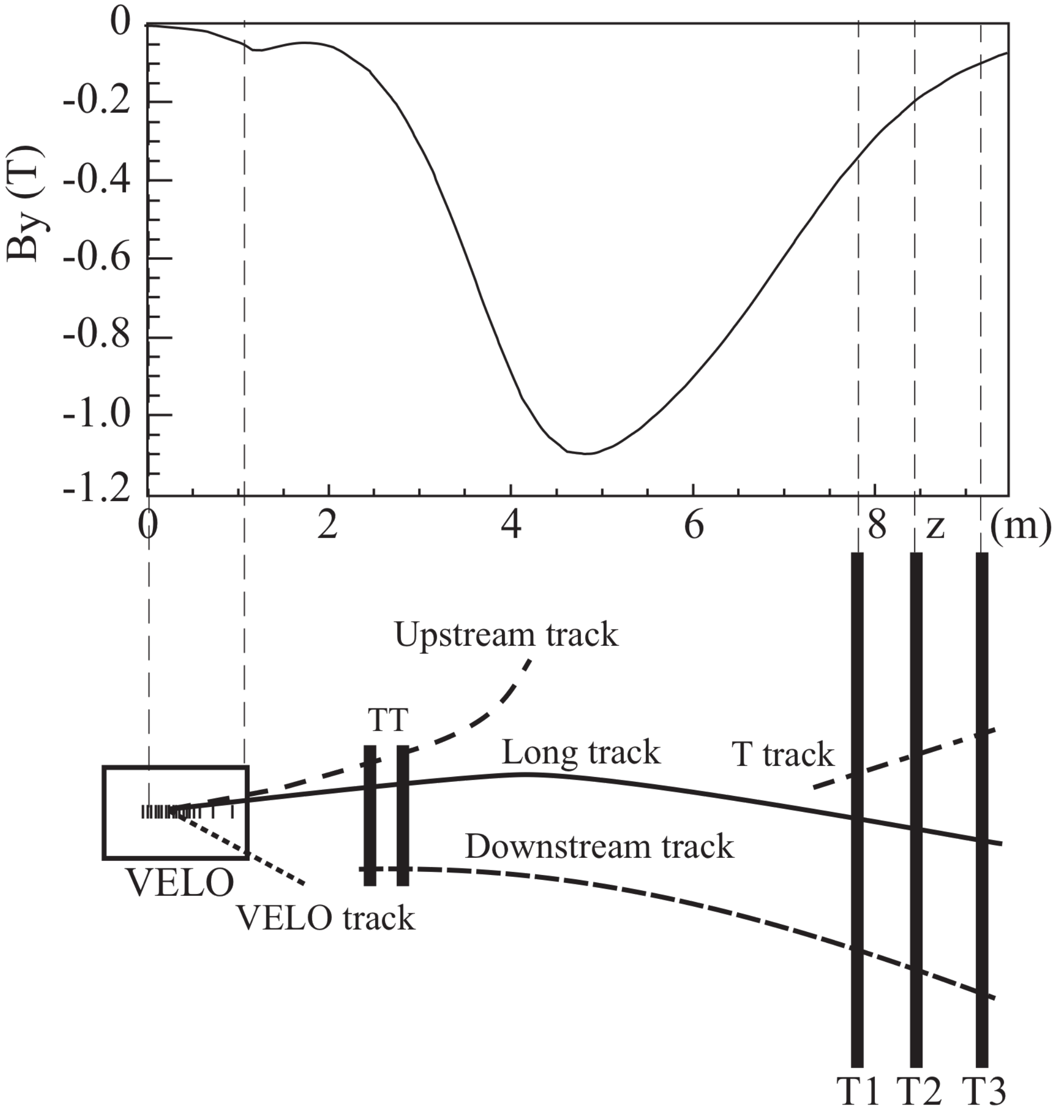
Opened at injection



Closed when stable beam declared

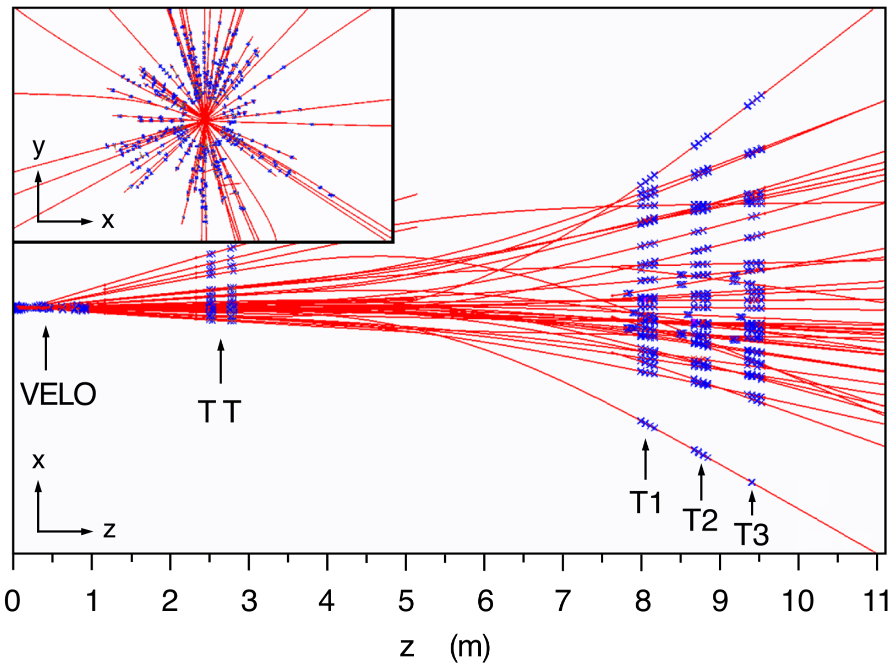


Track reconstruction



Dipole magnet implies an intrinsic charge asymmetry (left-right differences in the detector).

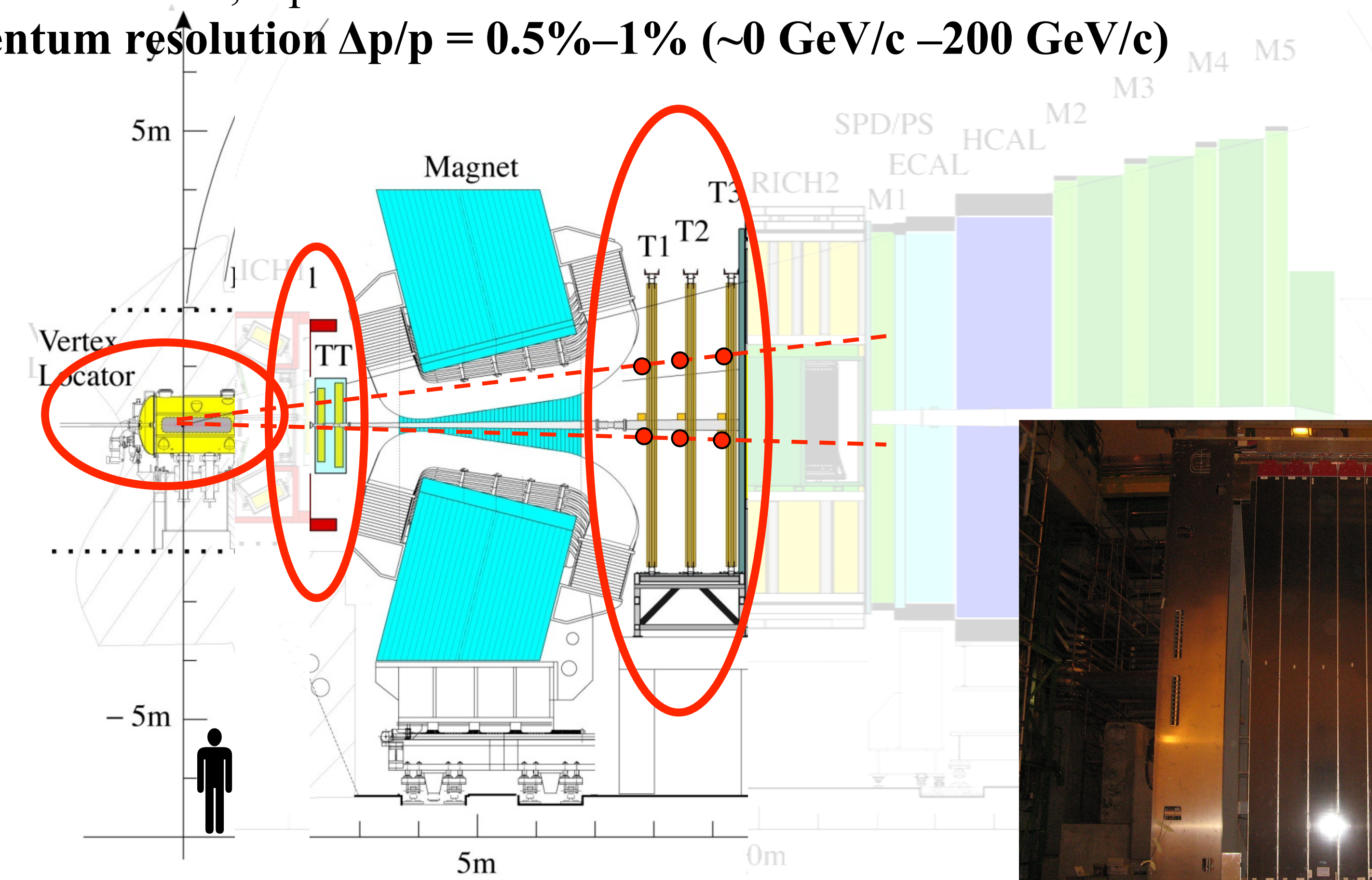
Direction of magnetic field changed regularly and data sets combined.

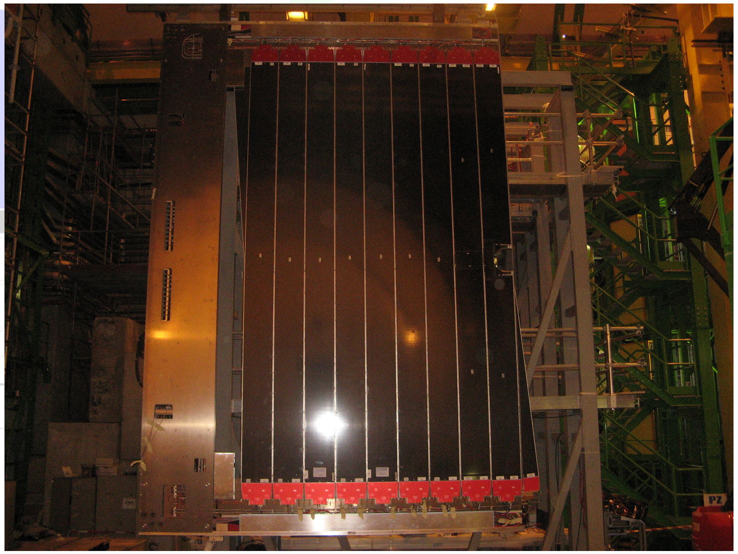


[Performance of the LHCb Outer Tracker JINST 9 (2014) P01002]
[Measurement of the track reconstruction efficiency at LHCb JINST 10 (2015) P02007]

Tracking system

Tracker Turicensis (before the magnet): 4 plans of silicon μ-strip, 8 m^2.
Tracker (after the magnet)
Inner (close to beam pipe): 3 stations, 4 plans of silicon μ-strip, 4.2 m^2.
Outer: 3 stations, 4 plans of straw tubes
Momentum resolution Δp/p = 0.5%–1% (~0 GeV/c –200 GeV/c)

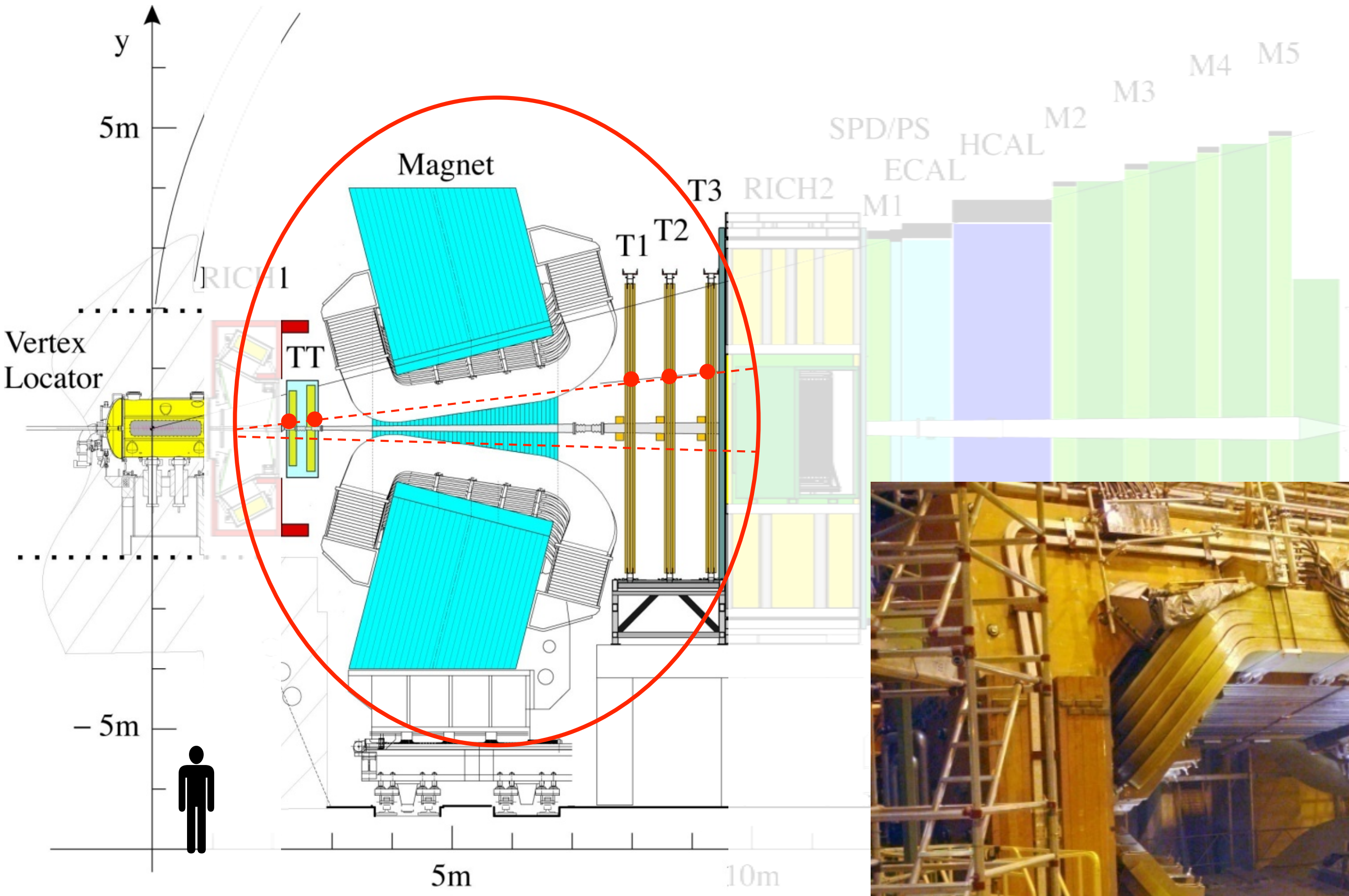


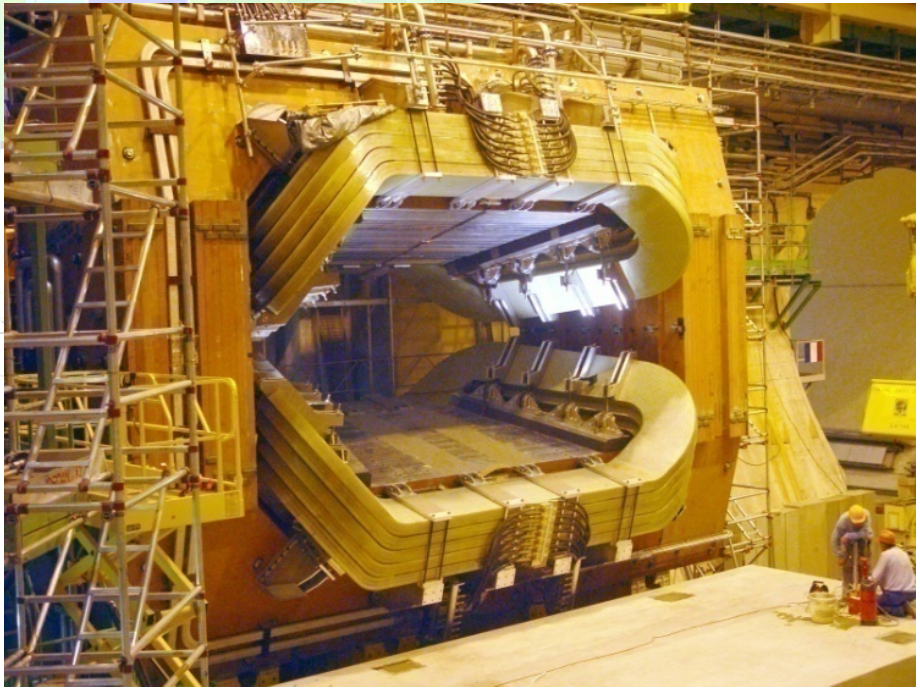


Magnet

Warm **dipole** magnet, bending power: 4 Tm

- Two triplets of magnets to compensate for its effect in LHC.



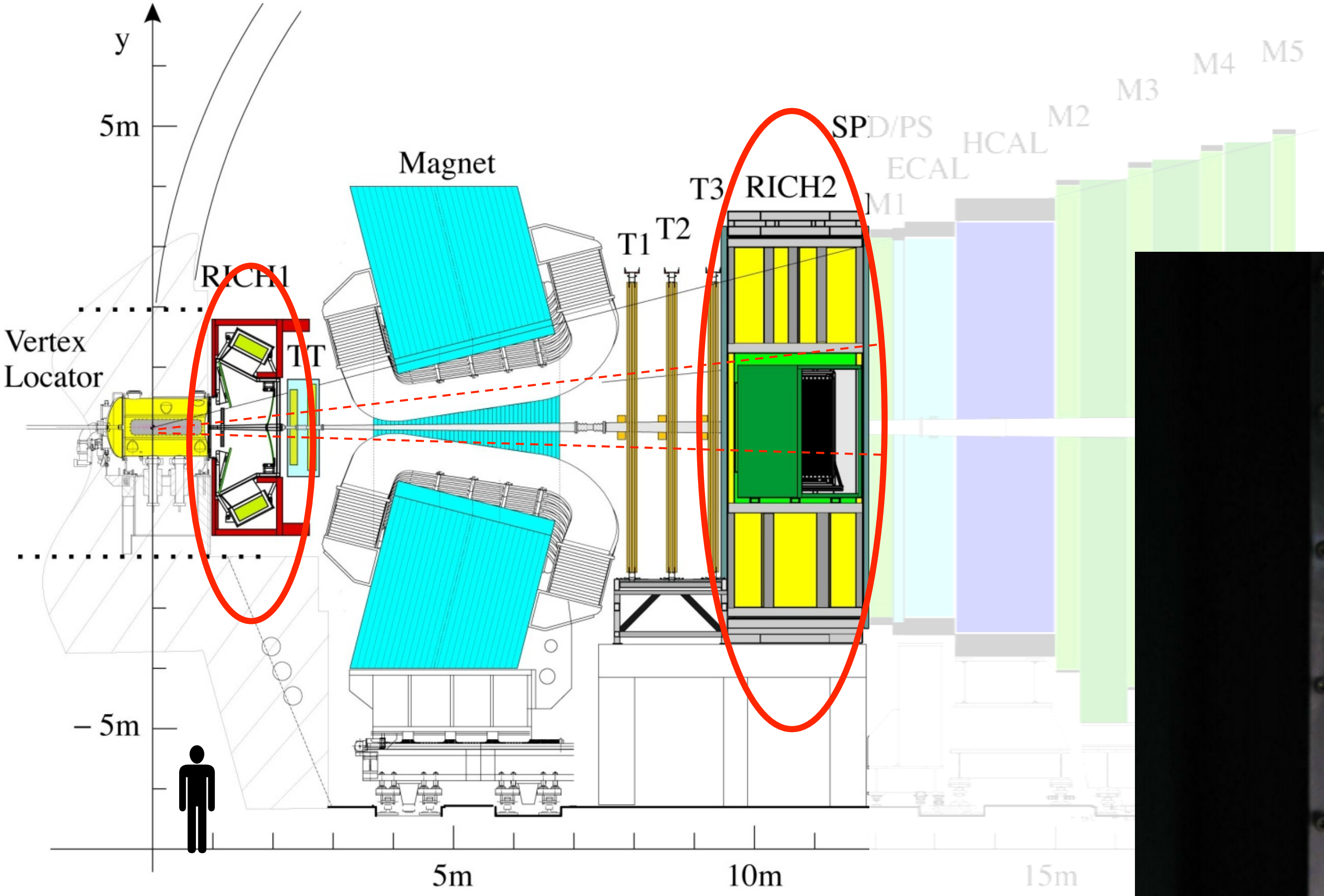


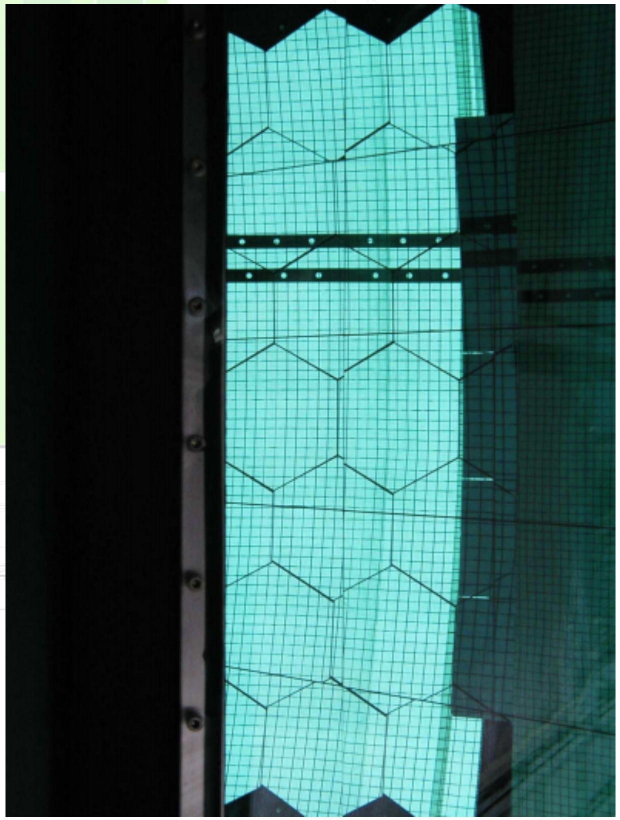
Weight: 1600 t
Power: 4200 kW
Cooling water = 150.000 l/h

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

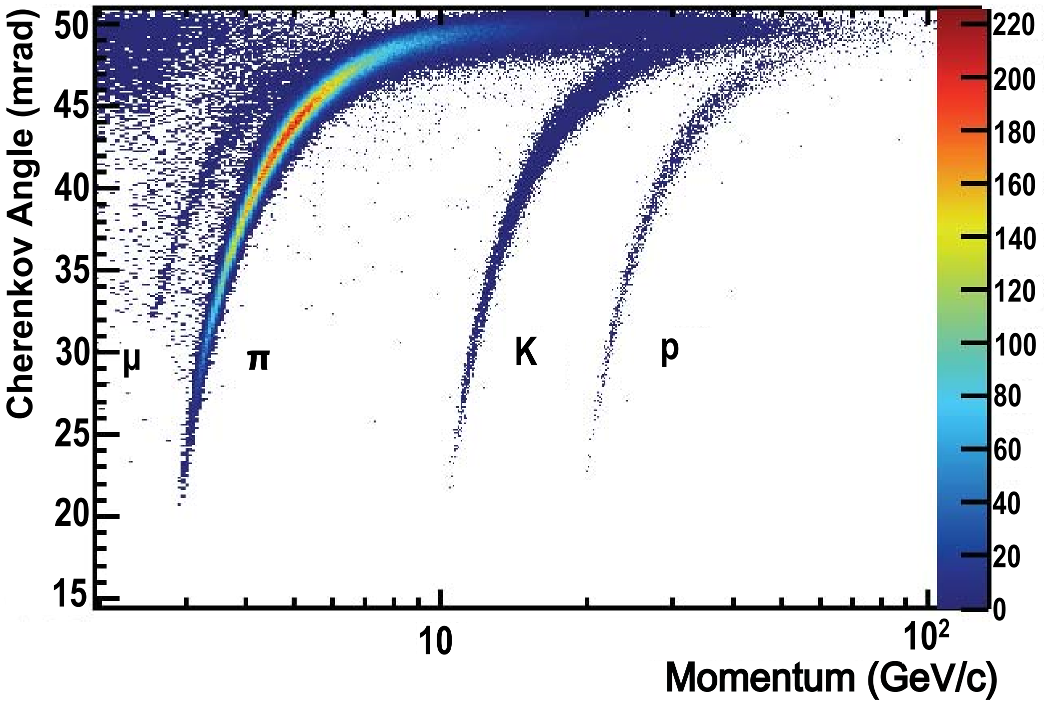
RICH

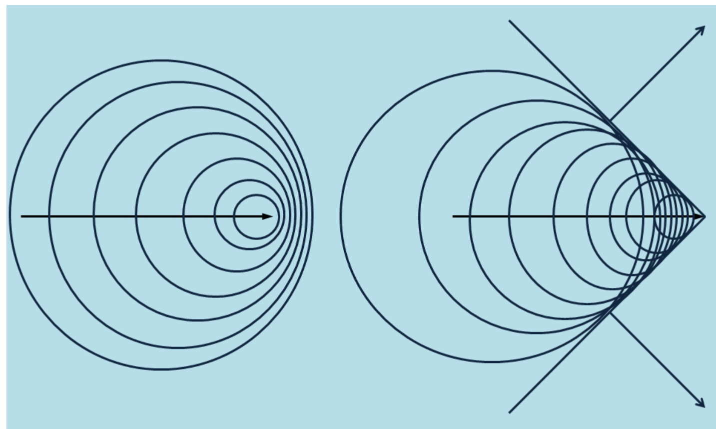
RICH1 (upstream of magnet): 2<p<40 GeV [C_4F_{10}]
RICH2 (downstream of magnet): 15<p<100 GeV [CF_{10}]
Kaon ID ~95% with pion misID ~10% integrated over 2<p<100 GeV



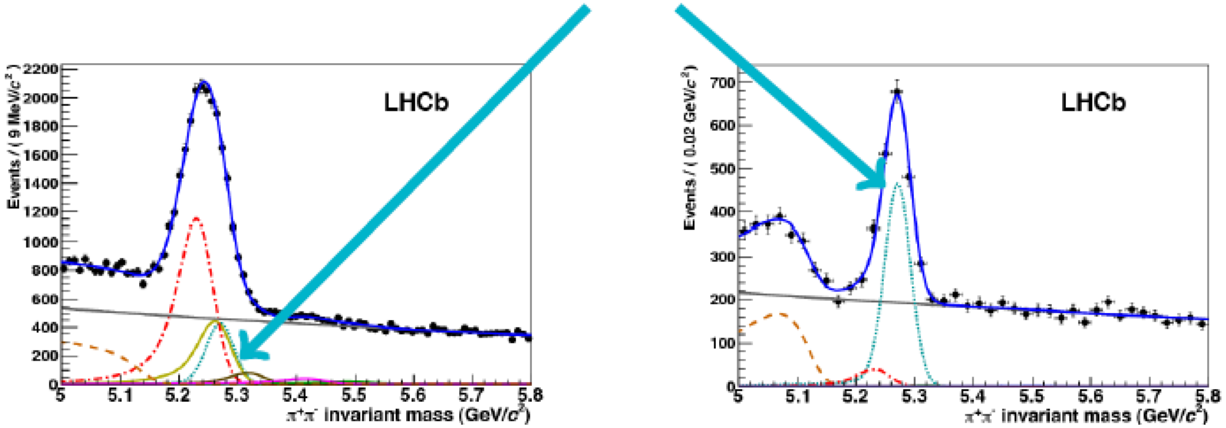


Cherenkov effect





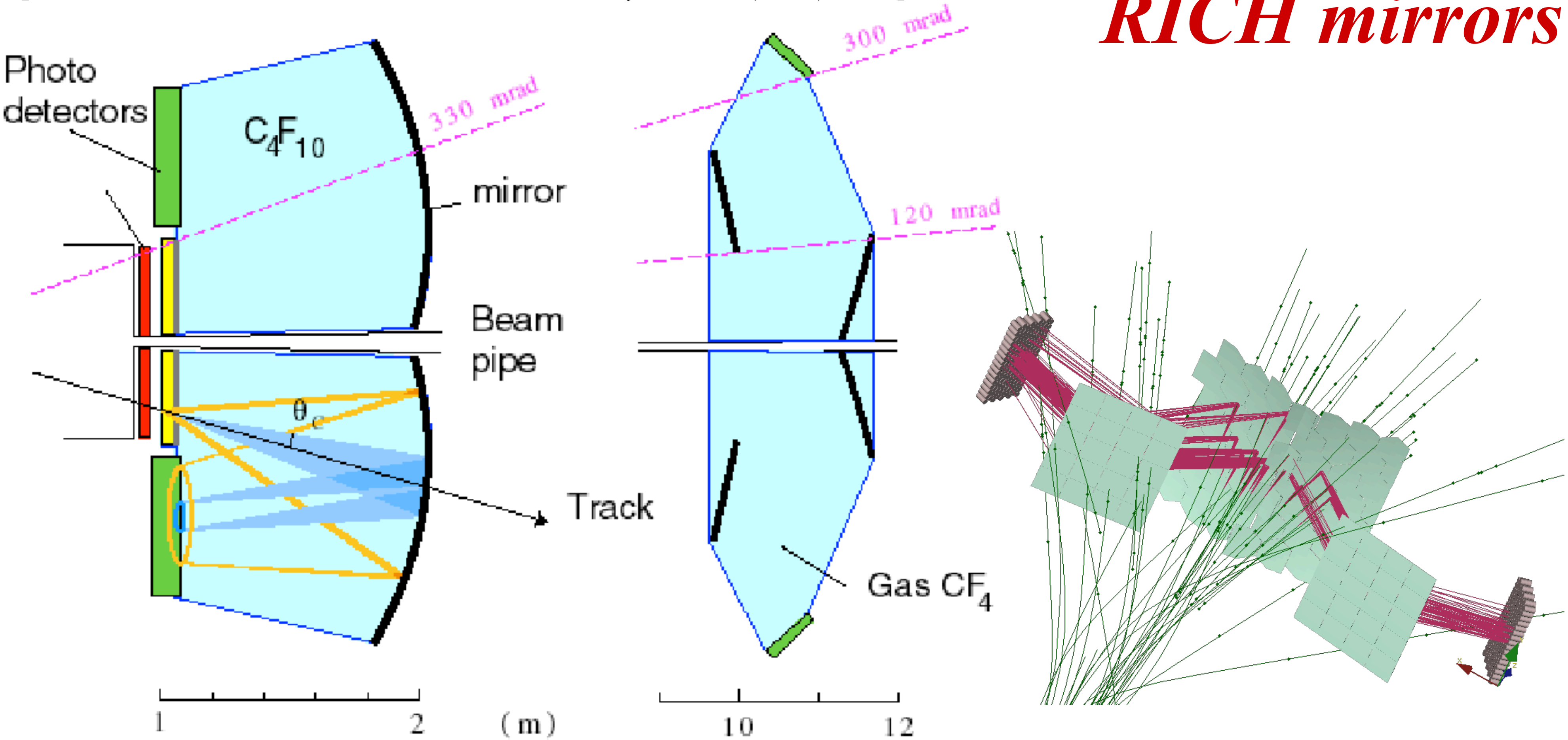
Without PID cuts   Signal   With PID cuts

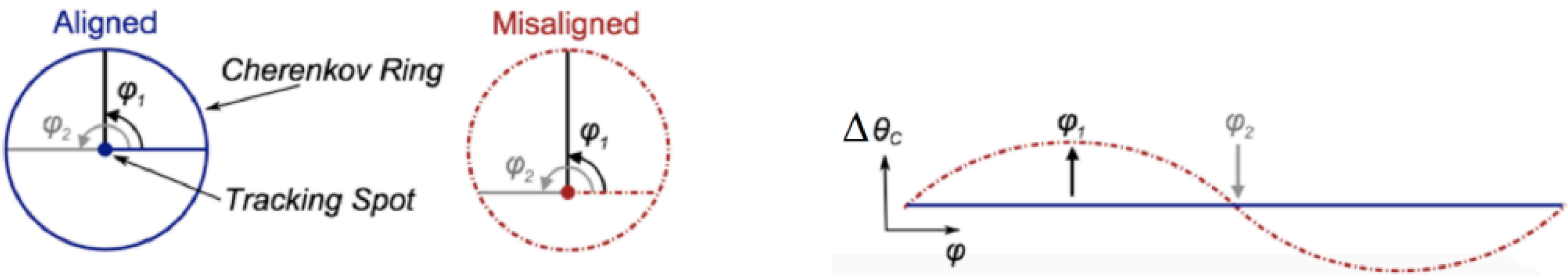


Invariant mass distribution for $B^0 \to \pi\pi$ decay ($B^0 \to \pi\pi$, $B^0 \to K\pi$, $B^0 \to$ 3-bodies, $B_s \to KK$, $B_s \to K\pi$, $\Lambda_b \to pK$, $\Lambda_b \to p\pi$)

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

RICH mirrors

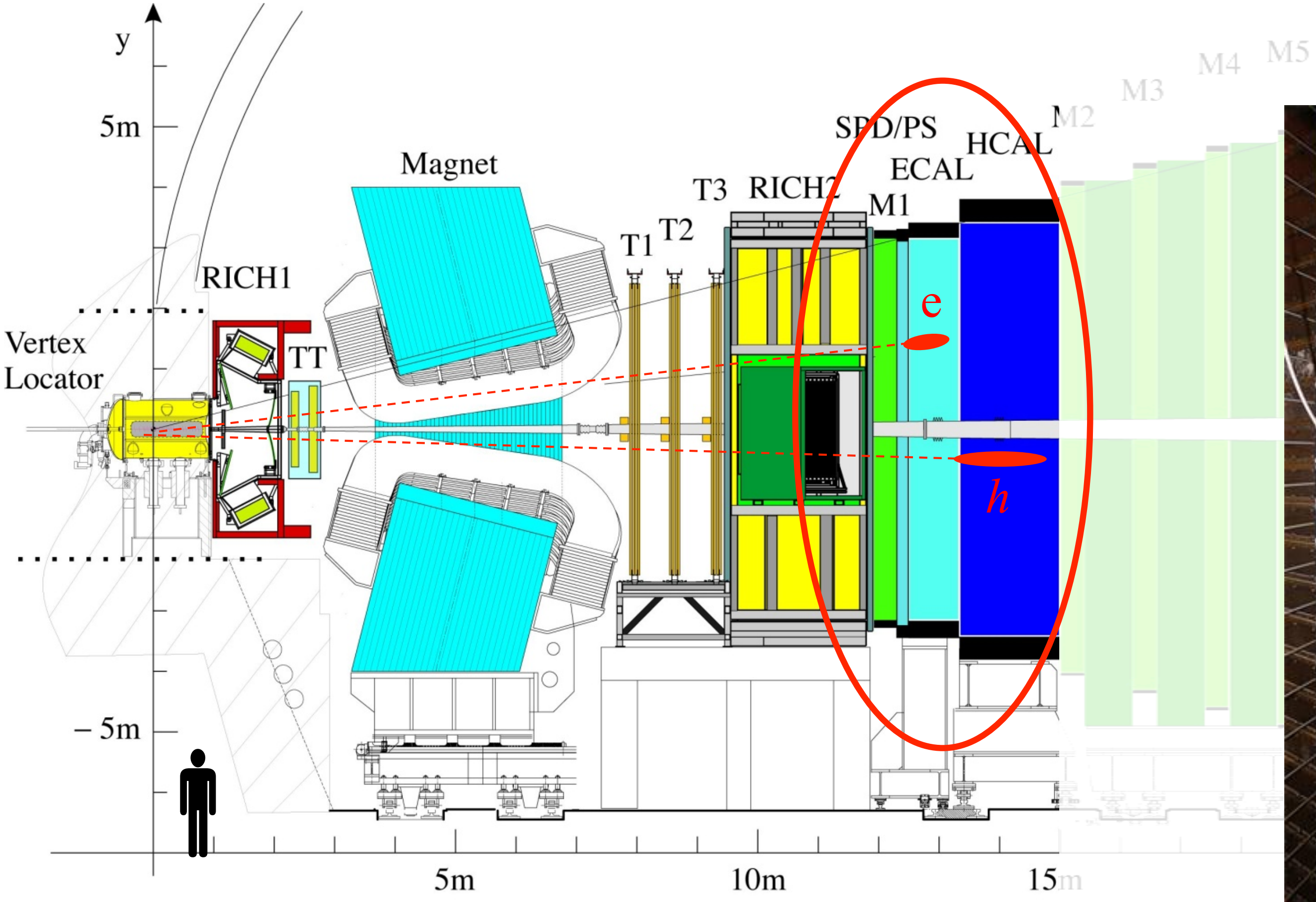


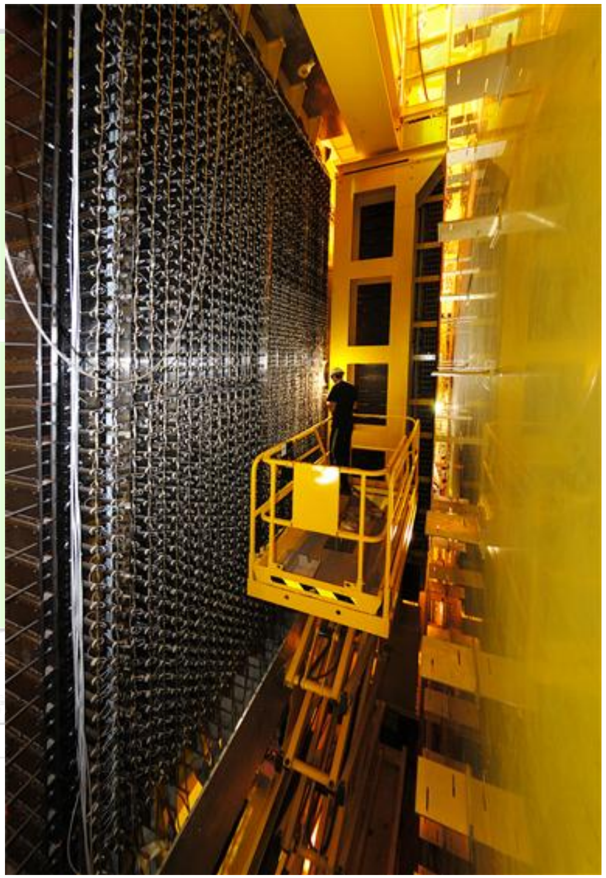


[LHCb Detector Performance Int.J.Mod.Phys. A30 (2015) 1530022]

Calorimeter System

System of calorimeters to maximize γ/e and e/h separation
ECAL, HCAL: scintillator + absorber material planes
$\Delta E/E = 1\ \% \oplus 10\ \%/\sqrt{E}$ (GeV)
Used in the first level of the trigger [L0]





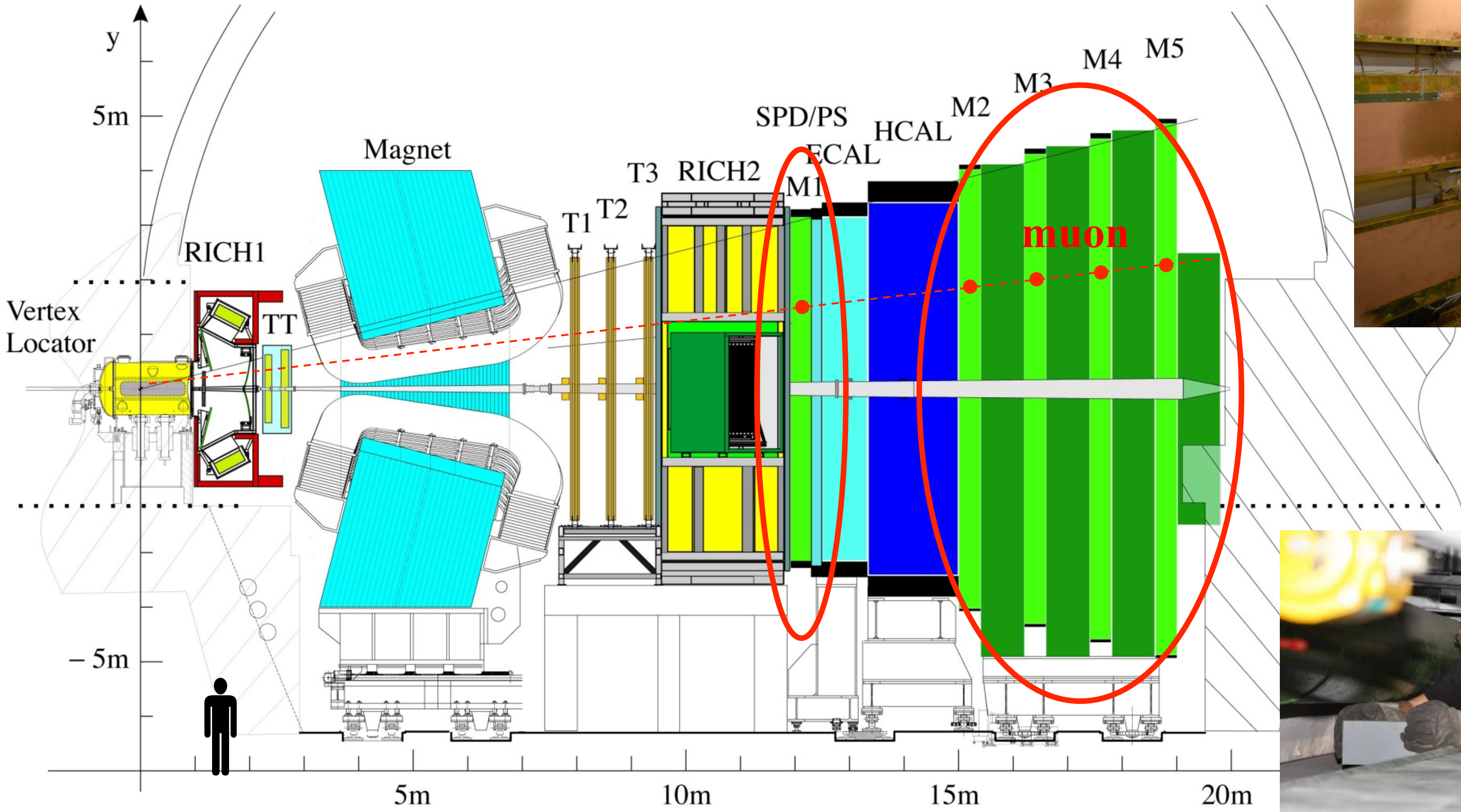
[Performance of the Muon Identification at LHCb JINST 8 (2013) P10020]
[Performance of the LHCb Muon system JINST 8 (2013) P02022]

Muon System

5 stations, each equipped with 276 multi-wire proportional chambers [different size]. Inner part of M1 equipped with 12 GEM detectors

μ identification ε(μ→μ) ~ 97 %, mis-ID ε(π→μ) ~ 1-3 %

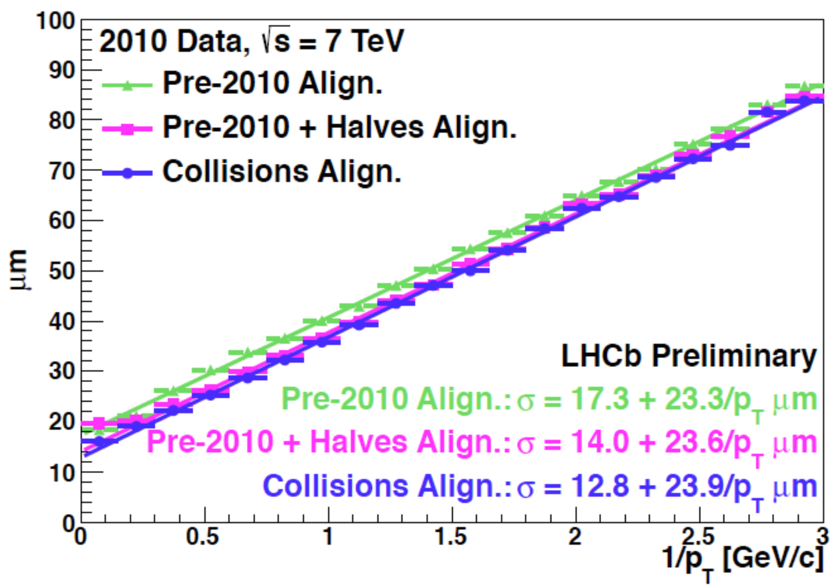
Used in the first level of the trigger [L0]

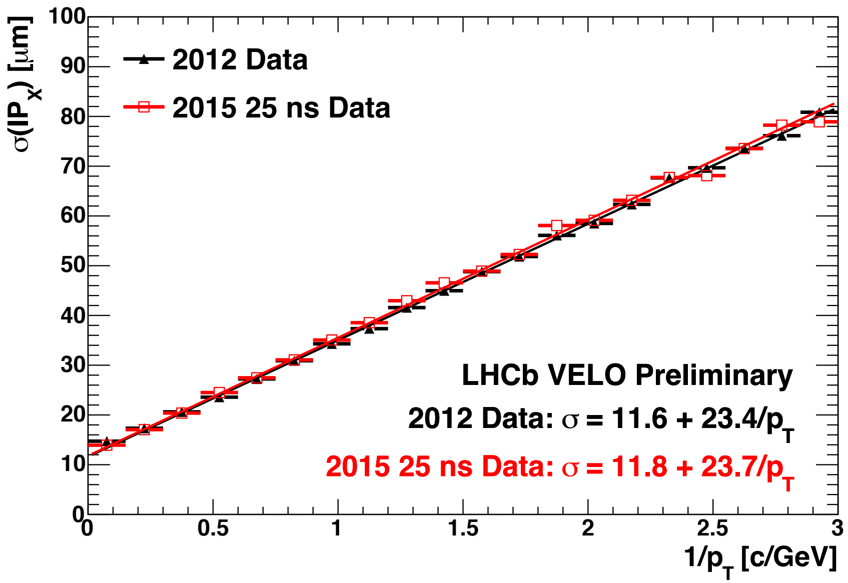


Alignment

Alignments Run on the HLT-farm at the beginning of every fill;

[Automatic update of constants]
- **VELO** alignment: Alignment of both halves for translations and rotations in x, y and z.
- **Tracker** alignment: Alignment of TT, IT and OT for translations in x, rotations and translations in z (online) and translations and rotations in y (offline)

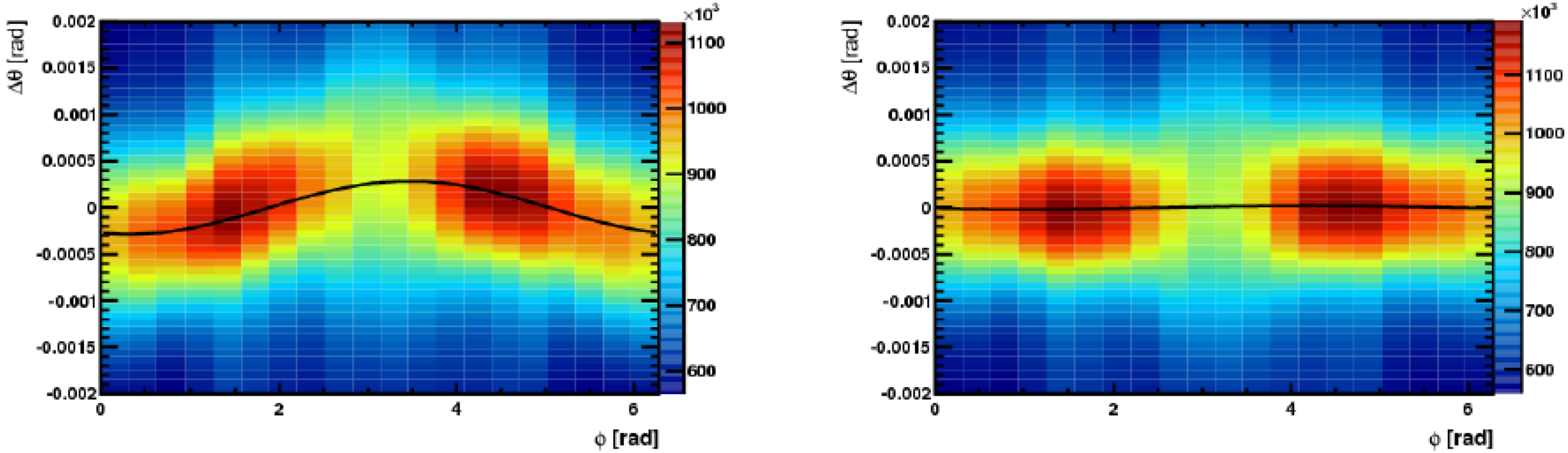




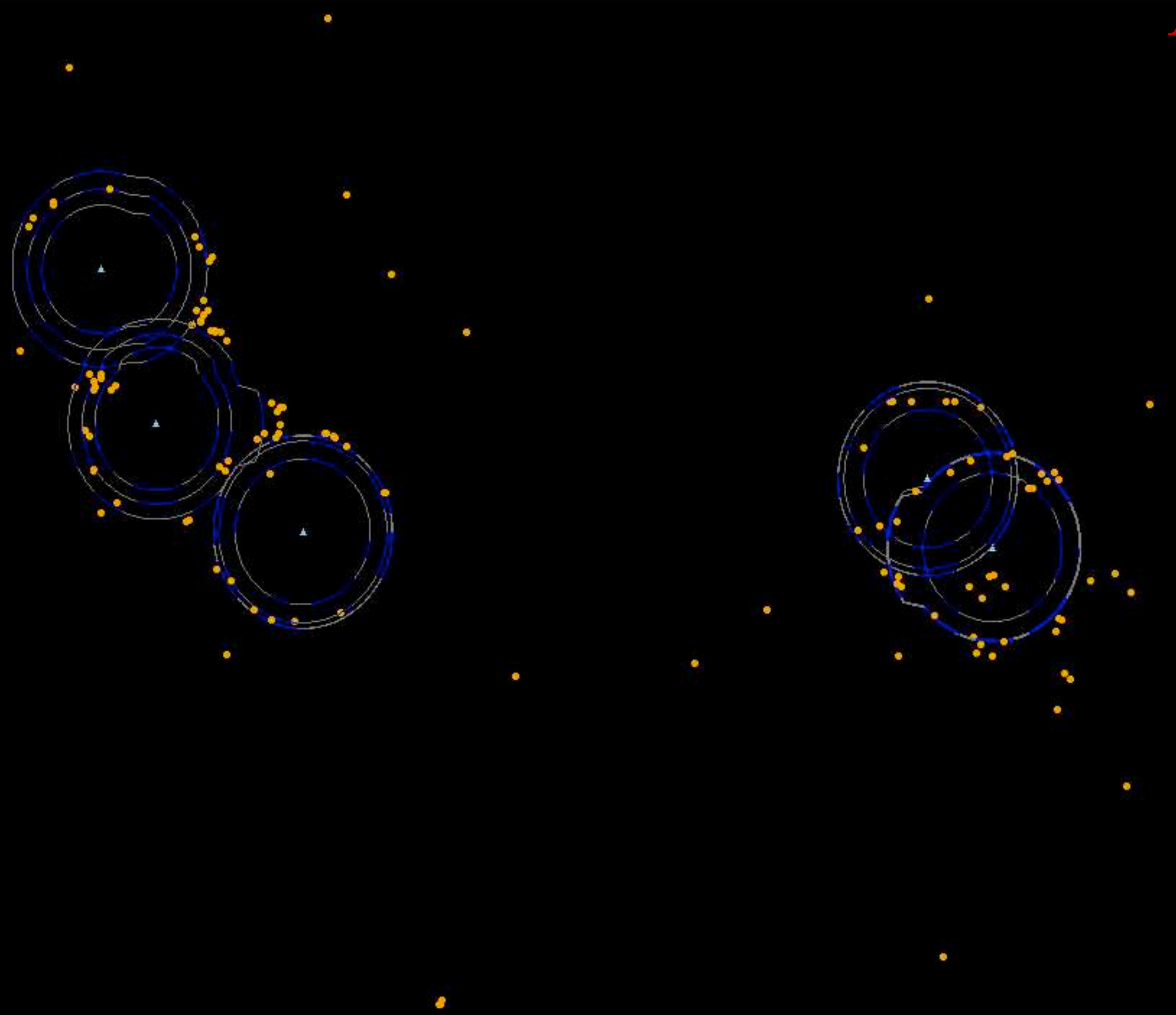
Alignments Run on the HLT-farm at the beginning of every fill;

[Monitor only]
- **RICH** mirror alignment: Alignment of all individual mirrors for rotations around x and y.

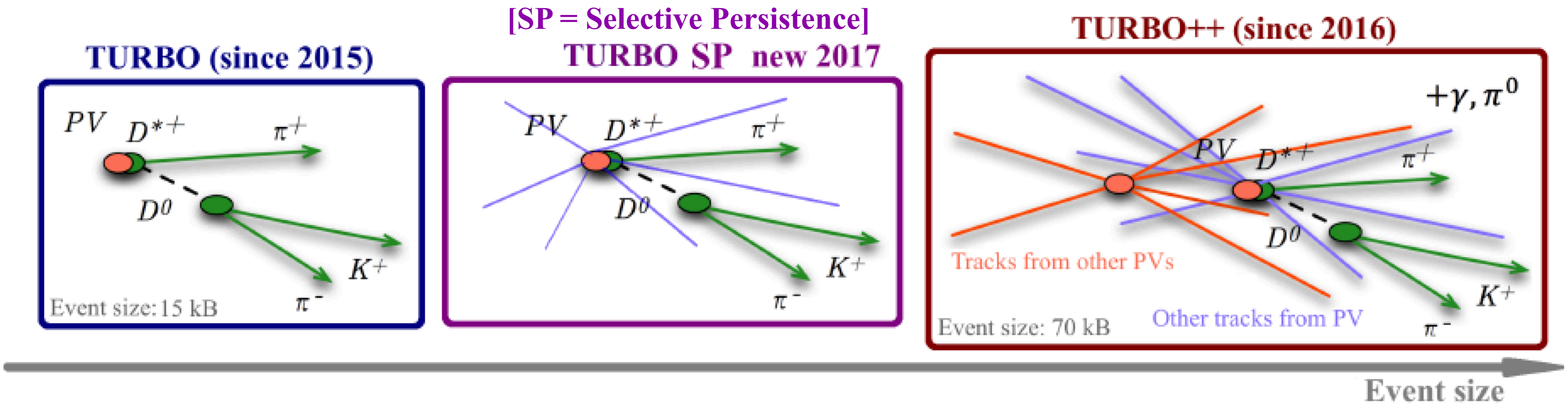
Before mirror alignment | After mirror alignment



RICH



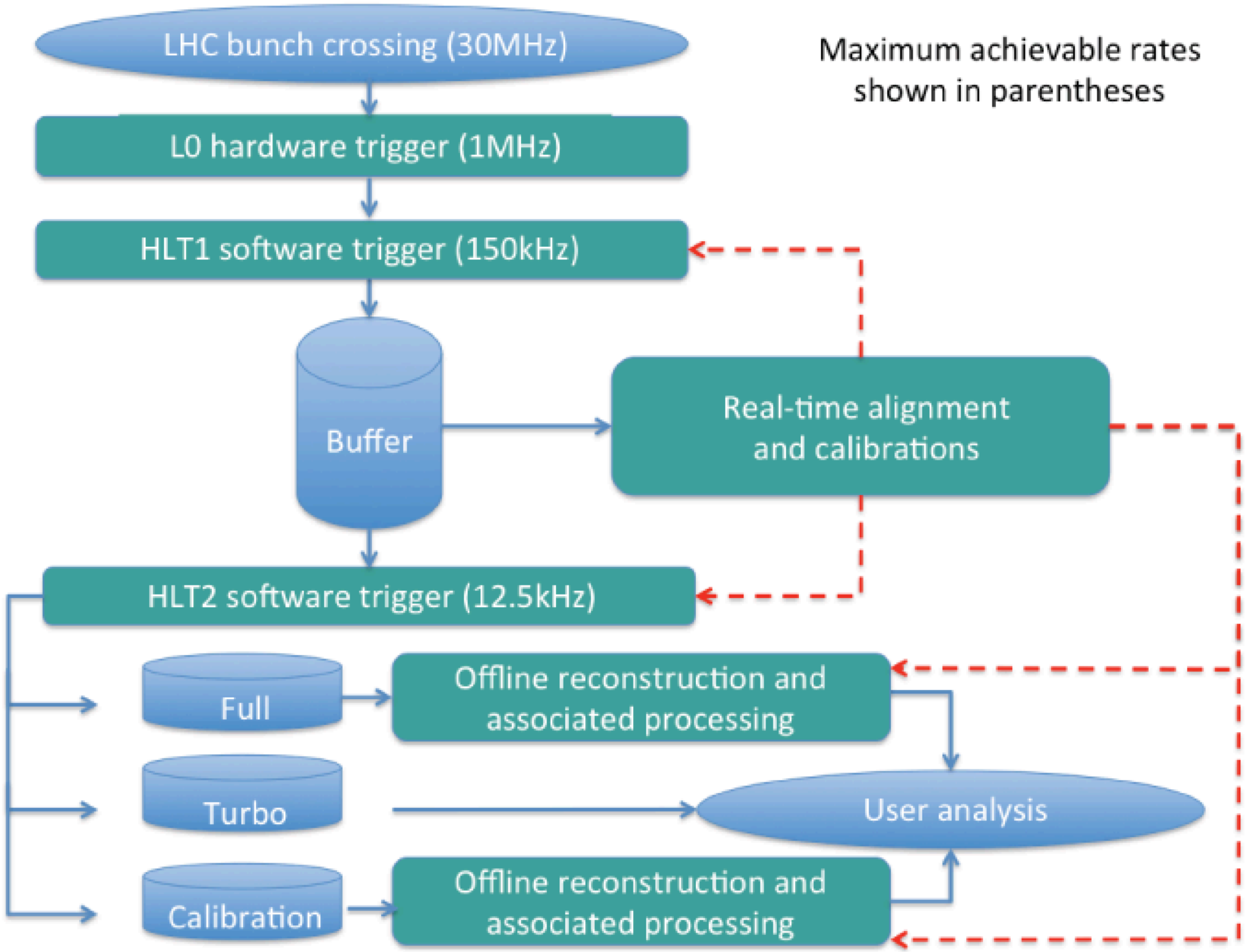
Is every part of the collision interesting?



We are bandwidth limited: increase statistics by reducing event sizes.

Vary number of reconstructed objects and fraction of raw event according to analysis needs

Turbo (SP, ++)



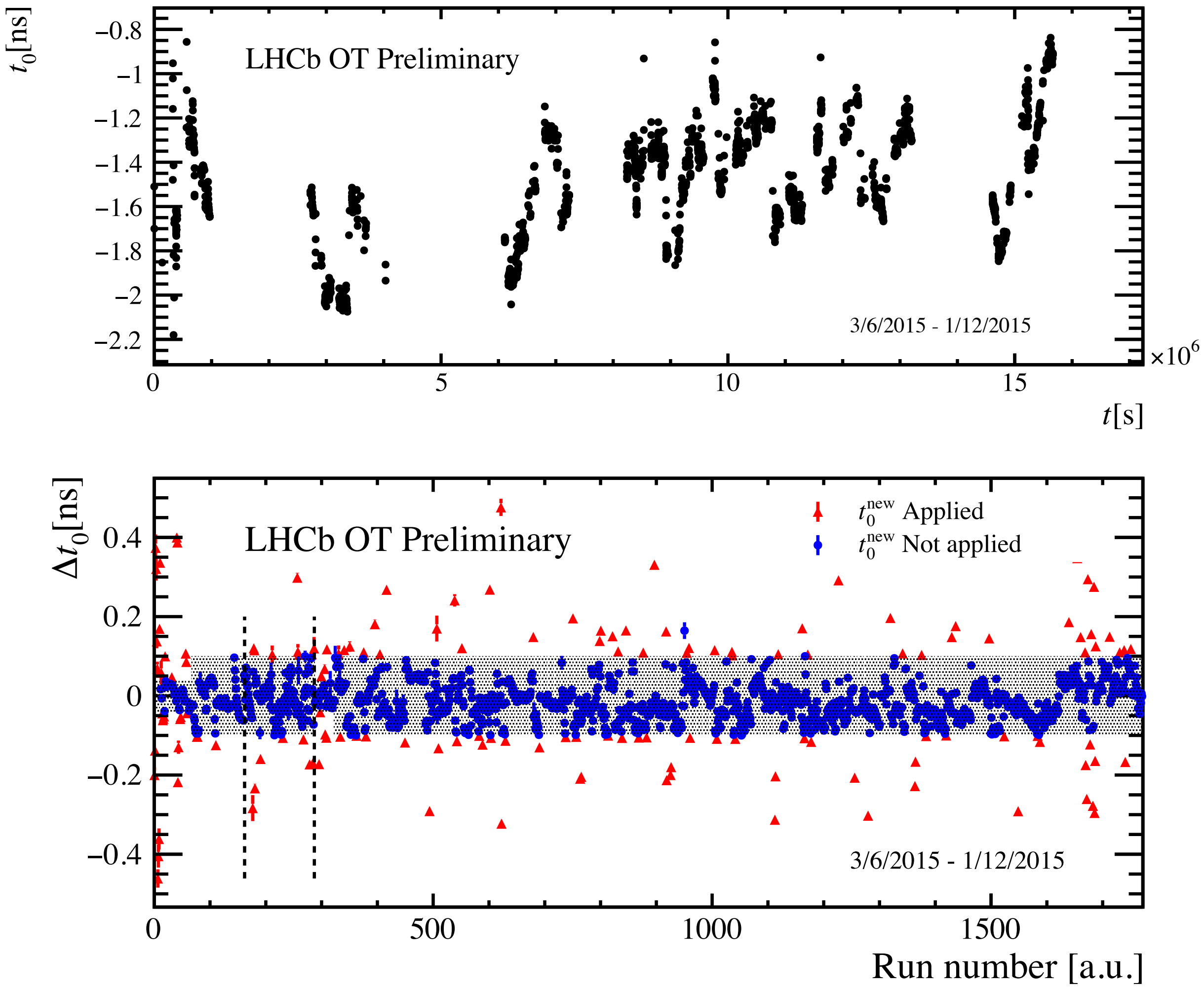
[Tesla : an application for real-time data analysis in High Energy Physics, 1604.05596v1]

Real-time alignment and calibration: tasks

Alignments	Calibrations
1. Velo • Translation in x,y,z • Rotation around x,y,z	1. RICH 1 & 2 • refractive index • HPDs
2. Tracker TT, IT, OT • Translation in x • Translation and rotation in z	2. Tracker OT • Drift time
3. RICH 1 & 2 • Individual mirrors for rotations around local x and y	3. Calorimeter • LED relative calibration • π^0 absolute calibration
4. Muon halves of each station • Translation in x and y	

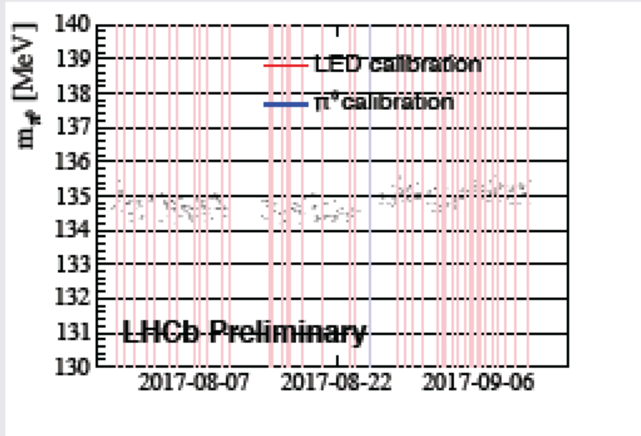
Calibrations run on the monitoring histograms for ~every run:

- **OT calibration**: global time alignment of the OT wrt LHC clock



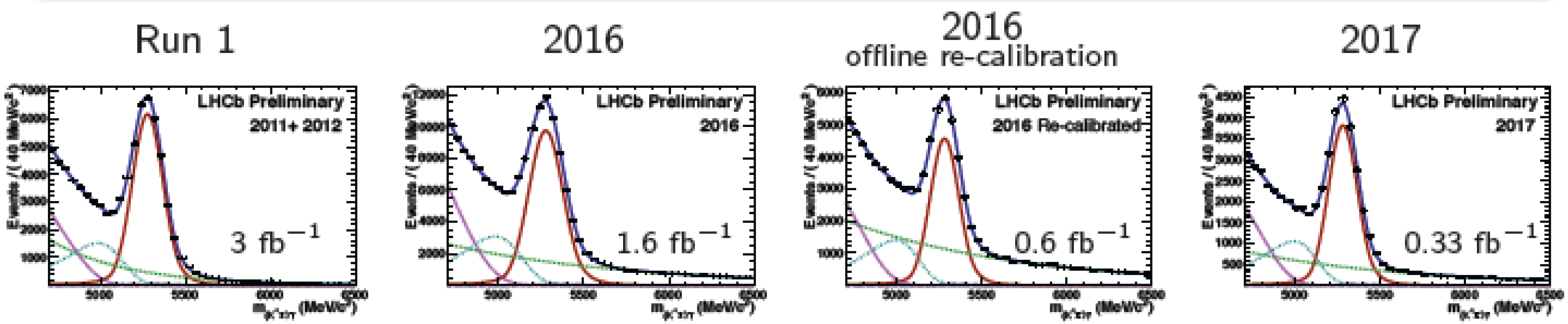
Calorimeter calibration

- **Relative calibration**
  - **After each fill:** LED amplitudes compared with a reference ⇒ **automatic HV update**
  - Reference file adjusted after each absolute calibration



- **Absolute calibration**
  - ≈ **Once per month**
  - Cesium scan for HCAL
  - Fine π^0 calibration for ECAL → Iterative procedure (6016 cells), on HLT farm → Activated in 2017

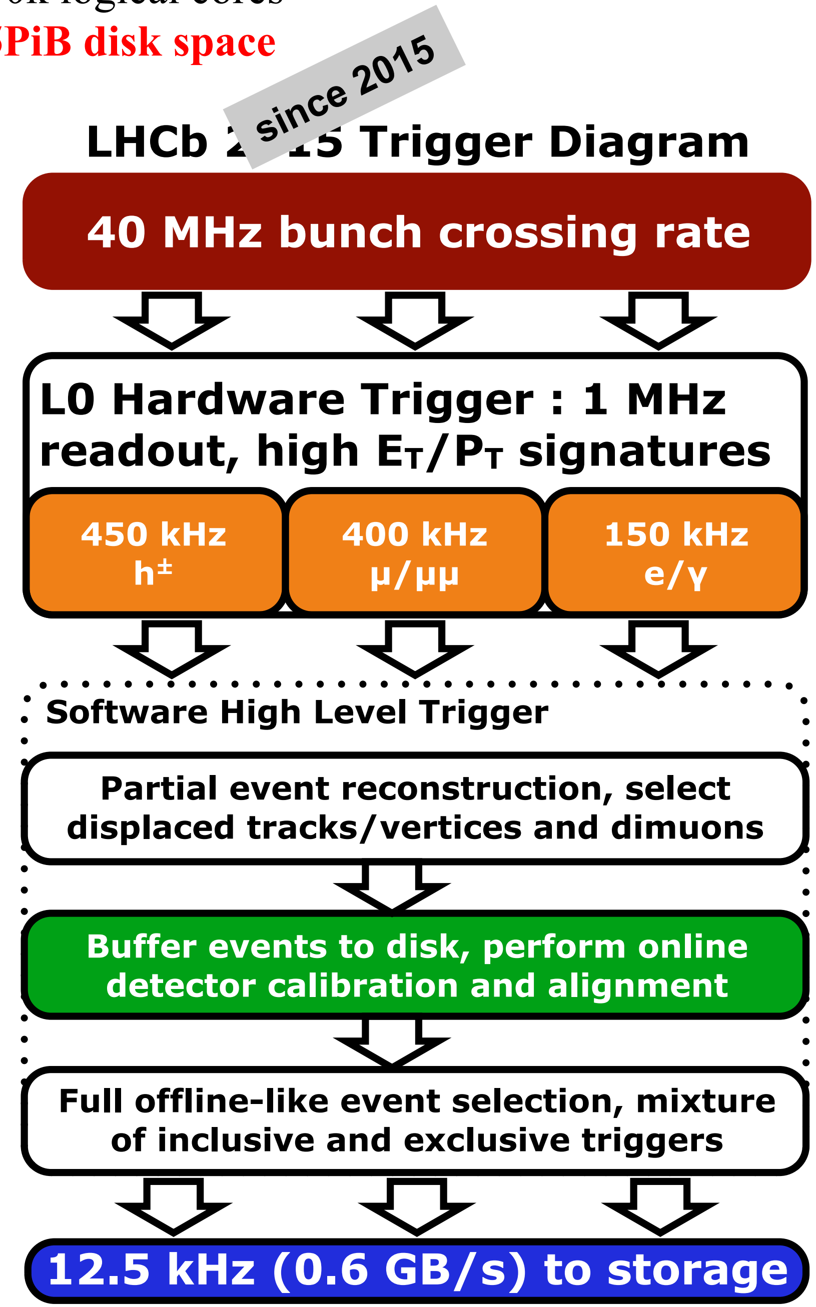
- Effect of the π^0 calibration on radiative decays $B_d^0 \to K^*(\to K^+\pi^-)\gamma$

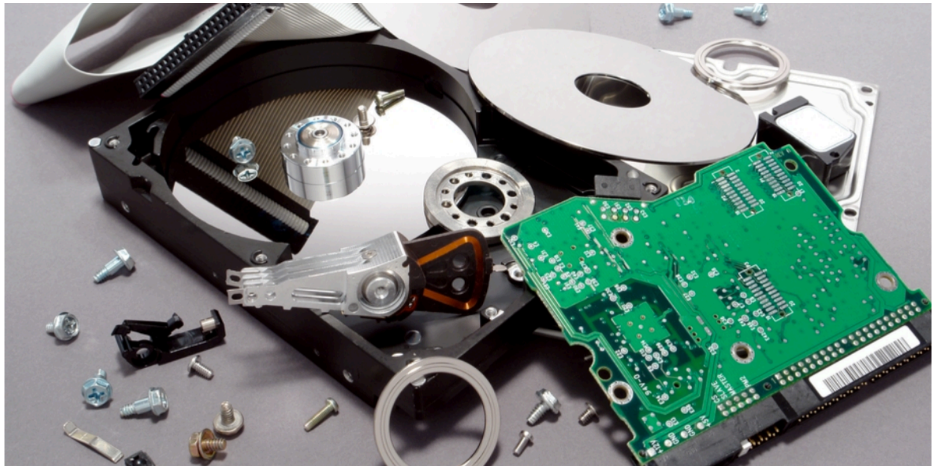


$\sigma = 90.7 \pm 0.6$ MeV $\sigma = 101.3 \pm 0.1$ MeV $\sigma = 84.4 \pm 0.7$ MeV $\sigma = 85.1 \pm 0.7$ MeV

~50k logical cores
~5PiB disk space

Trigger buffer





From 2015 experience, ~1 disk per day is replaced due to unrecoverable errors: until 2015, mirror the 5 PiB of disk space in a second chunk of 5 PiB disks.

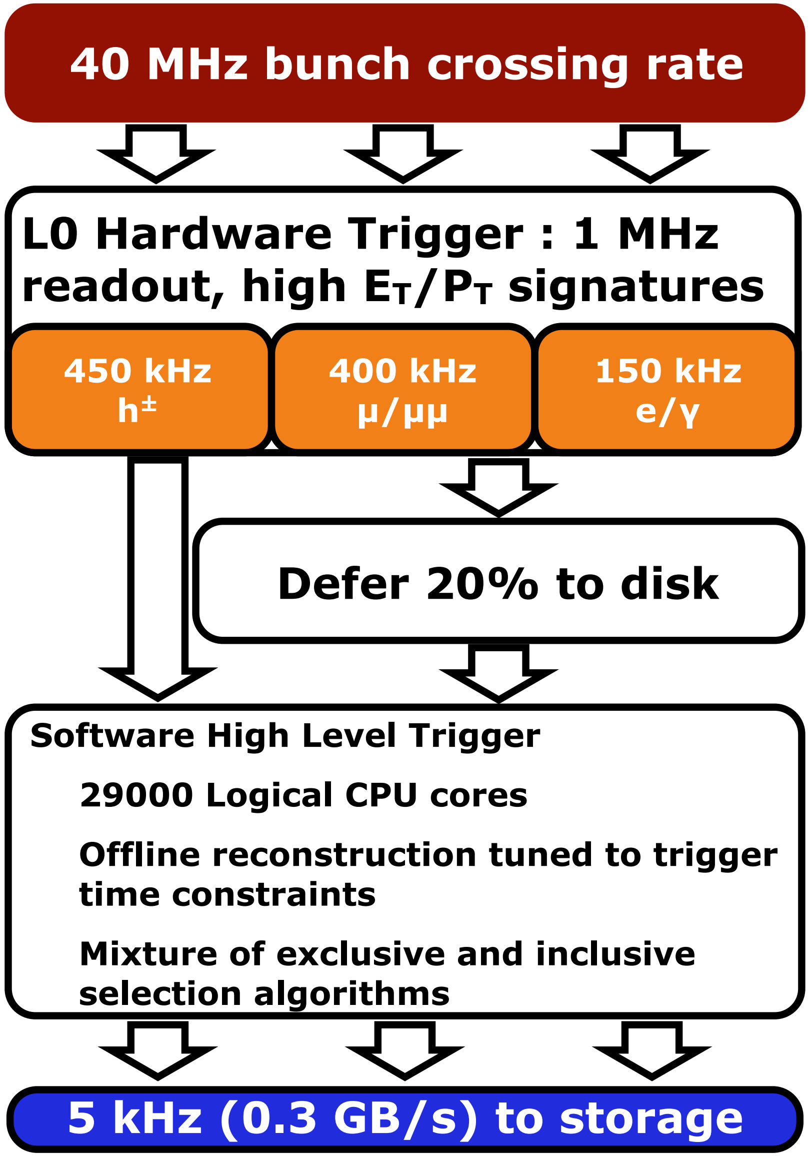
Un-mirroring the disks doubles our buffer with the risk of per mil loss of data: **since 2016 total farm disk space is ~10PiB**.

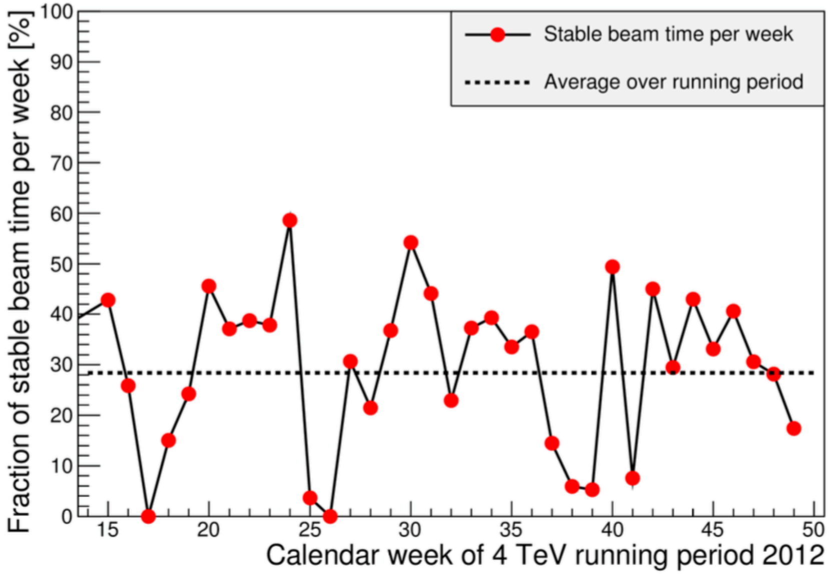
This means more data and/or more time to reconstruct them.

[arXiv:1211.3055; CERN-LHCb-DP-2012-004]
[arXiv:1310.8544v1]

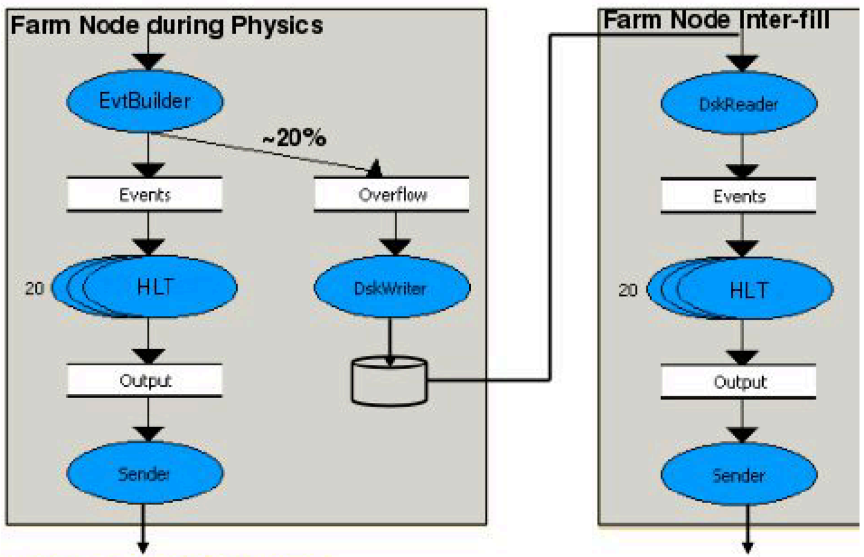
Trigger

LHCb 2012 Trigger Diagram





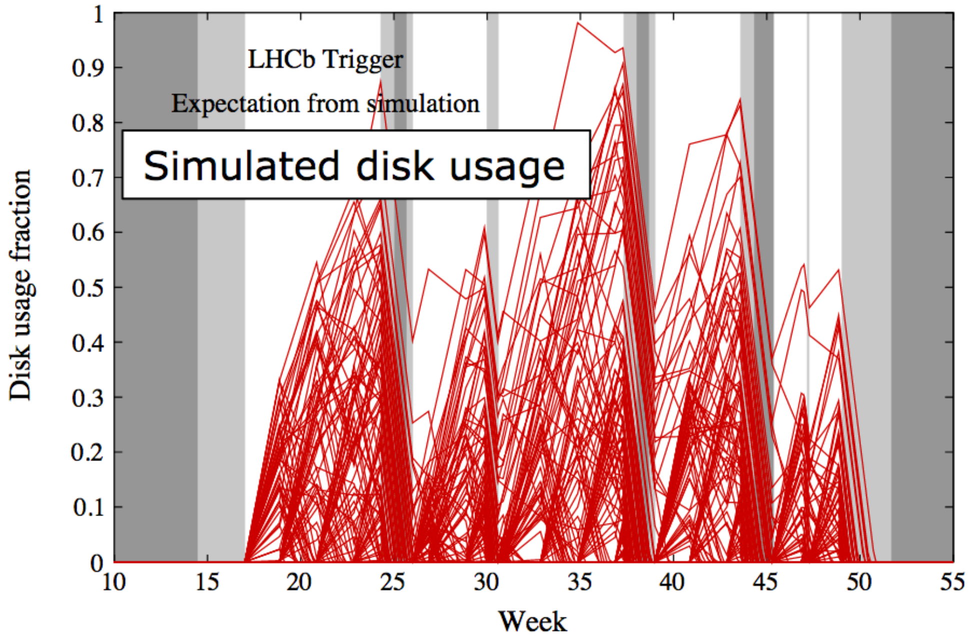
Deferred HLT

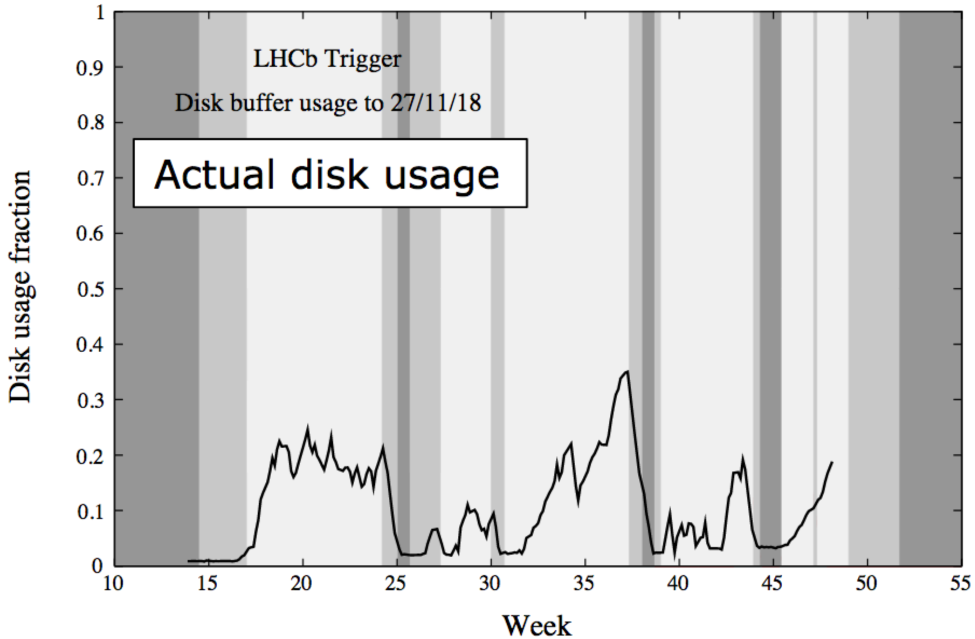


~50k logical cores

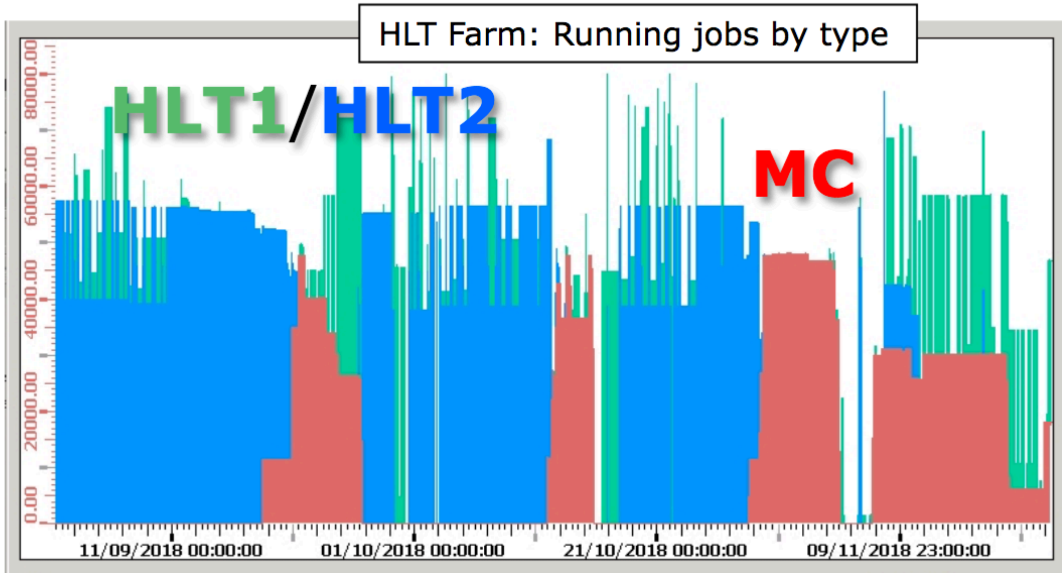
~10PiB disk space

Trigger and online farm



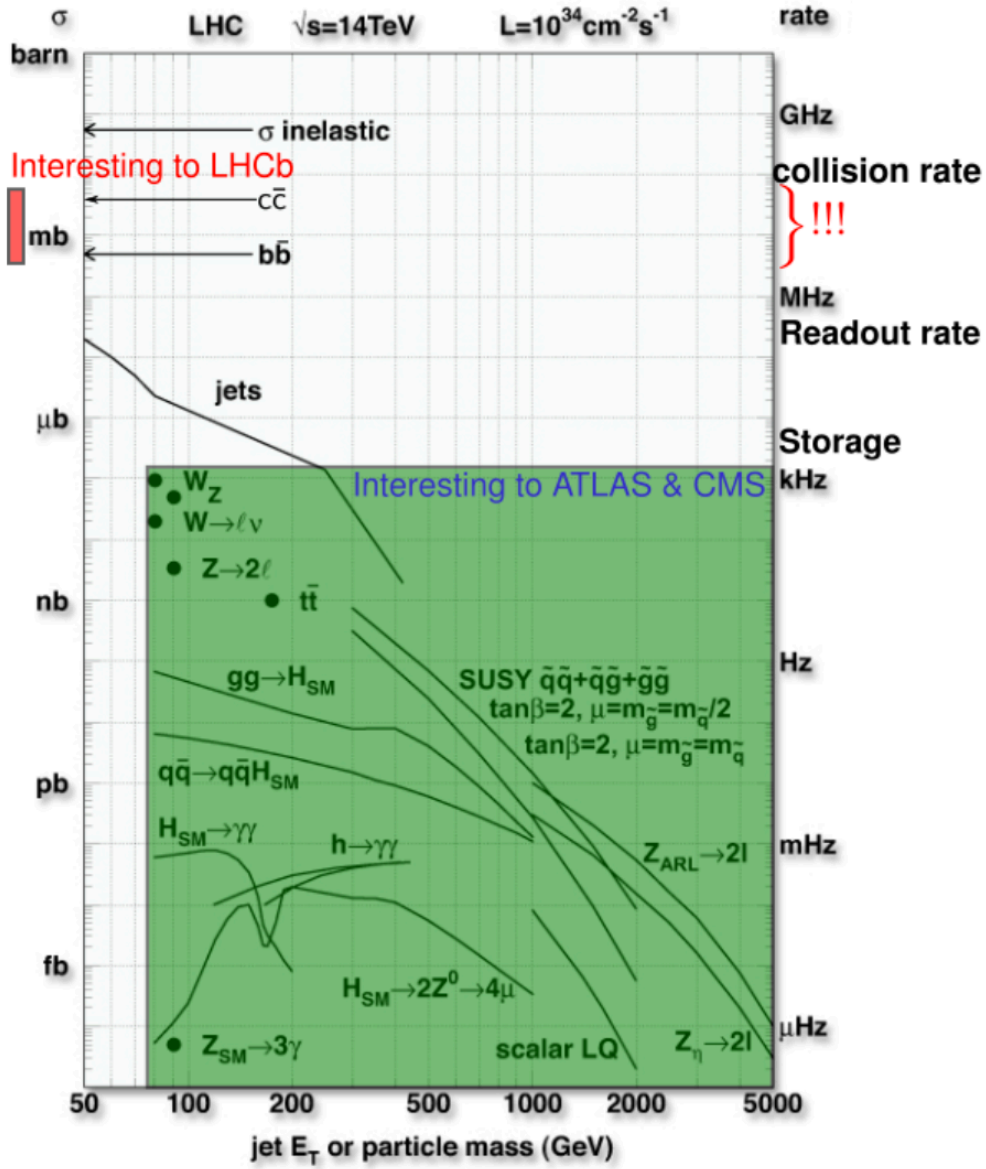


[LHCC, November 2018]

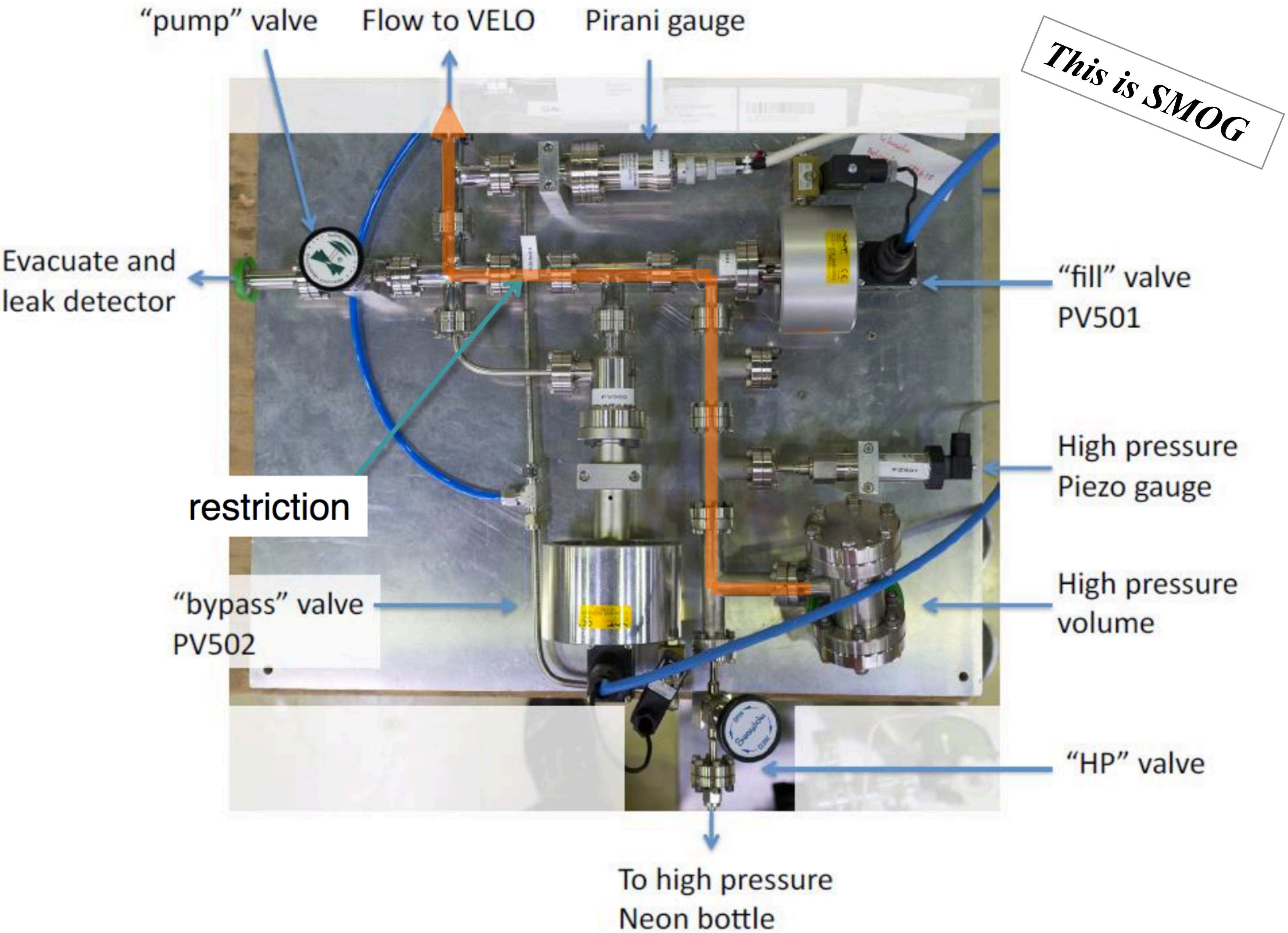


Trigger (Interlude)

- A trigger is needed to reduce storage and readout costs
- A *good* trigger does so by keeping more signal than background
- ATLAS and CMS are interested in signatures in the kHz region
  - Readout at 100kHz is efficient with reasonably straightforward E_T requirements
- LHCb operates at $\mathfrak{L} = 4 \times 10^{32} \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ in Run 2
  - 45kHzof $b\bar{b}$, $\sim$1MHz of $c\bar{c}$
  - 1MHz readout is needed to stay efficient for beauty signals
- But LHCb will operate at $\mathfrak{L} = 2 \times 10^{33} \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ in Run 3...



System for Measuring the Overlap with Gas



SMOG: Beam Gas Imaging

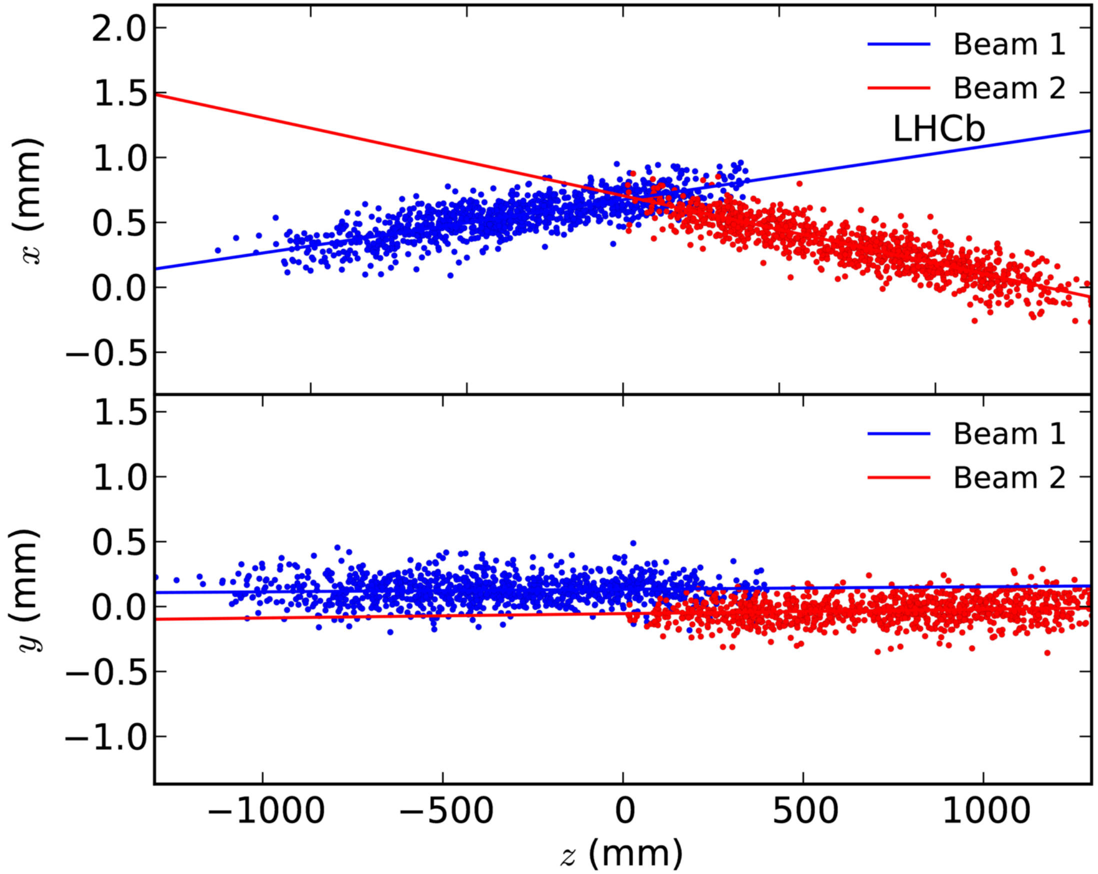
$$N = L\sigma$$

$$L = \frac{kN^2 f}{4\pi\sigma_x^* \sigma_y^*}$$

k = number of bunches = 2808
N = no. protons per bunch = 1.15×10^{11}
f = revolution frequency = 11.25 kHz
σ^*_x, σ^*_y = beam sizes at collision point

Original idea: determine luminosity by measuring beam profiles through beam-gas interaction (BGI).

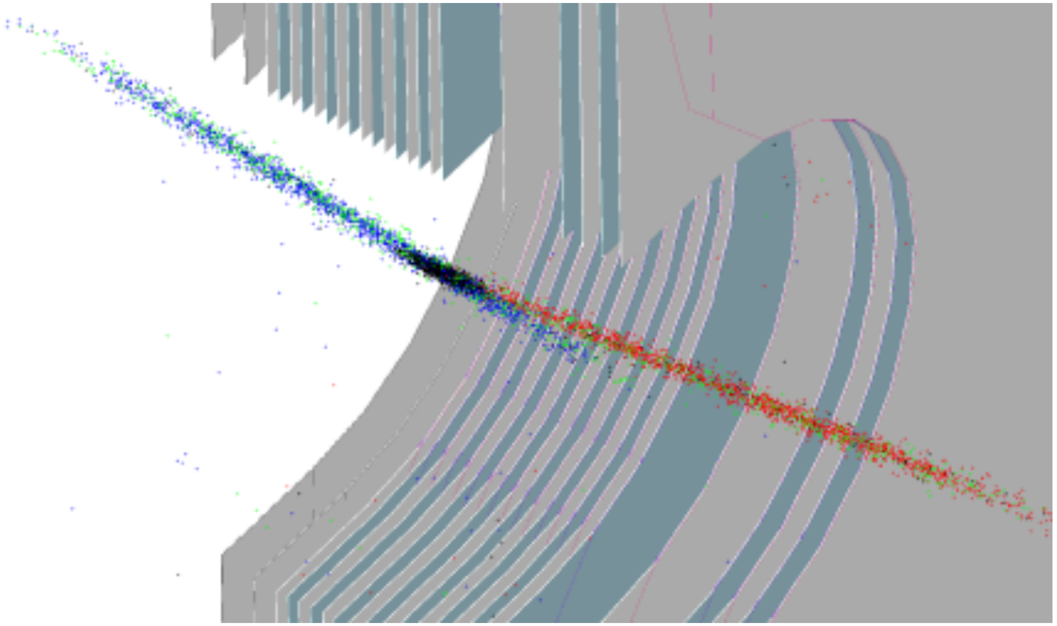
First measurements using beam vacuum ~1×10^{-9} mbar (then increased to ~5×10^{-9} mbar by switching off VELO vacuum pumps).



[arXiv:1410.0149 [hep-ex]]

SMOG: fixed target physics

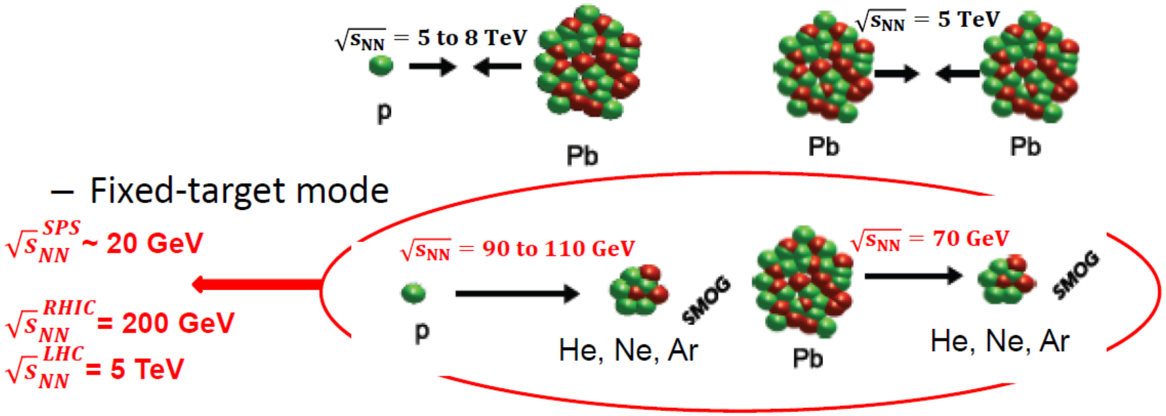
A device to inject gas (Ne) in the beam pipe around the VELO was developed: the SMOG



Pressure of injected gas 1-2 ×10^{-7} mbar
gas removed by two pumps at 20 m;
only noble gases can be used (He, Ne, Ar, maybe Kr and Xe toward end of run)

– Collider mode

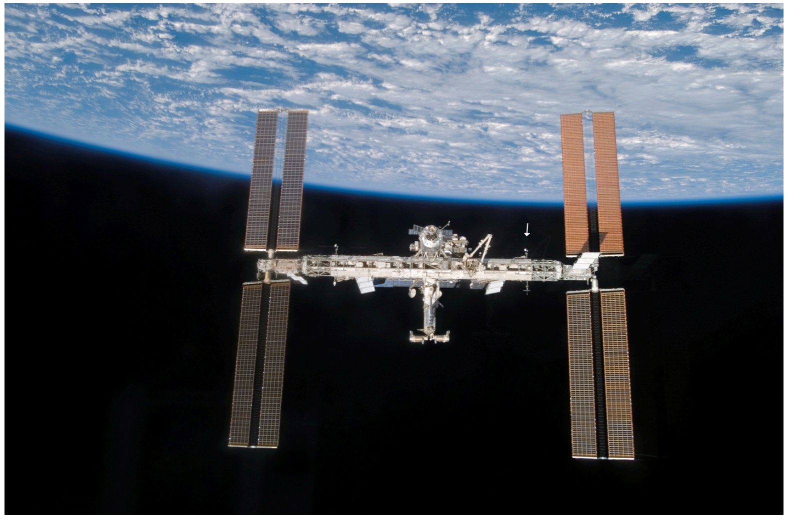
– Fixed-target mode



Presently LHCb is the only experiment capable of studying collisions of LHC beams on nuclei at rest.

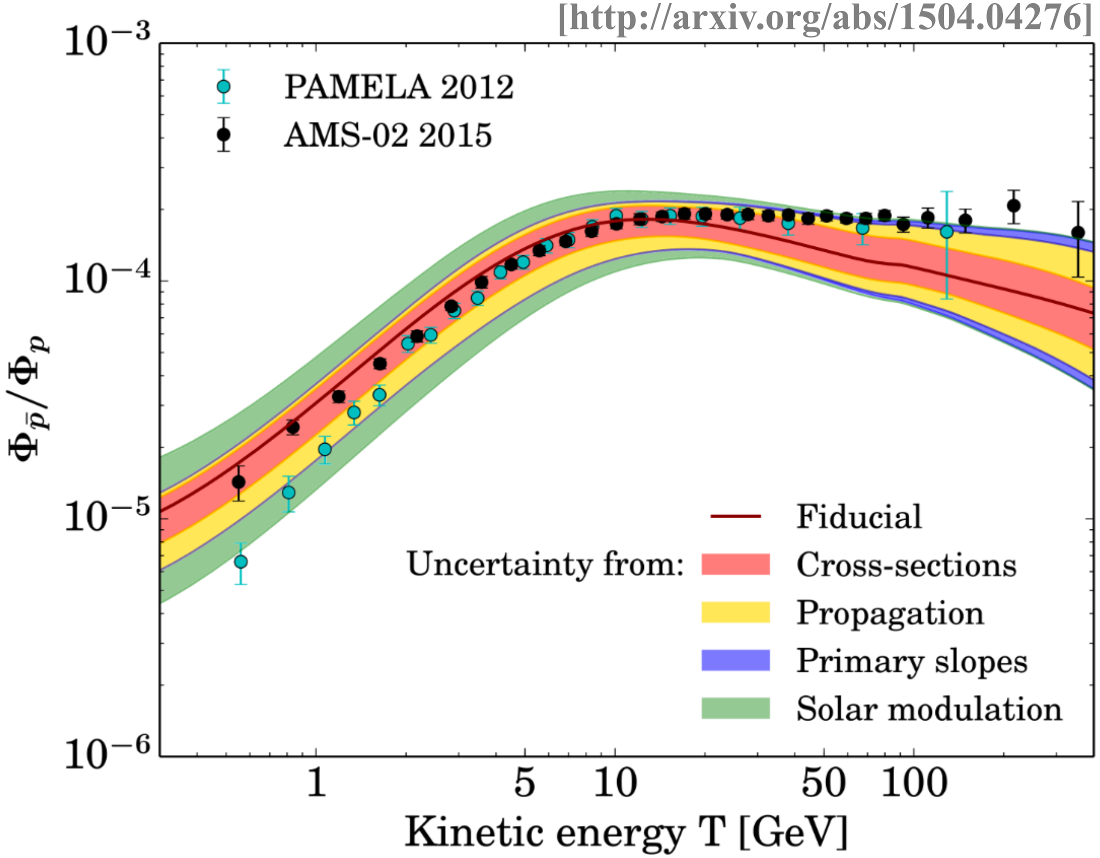
[some references in the back-up]

SMOG: LHCb in the space



[LHCb-PUB-2016-011, https://cds.cern.ch/record/2145943/files/LHCb-PUB-2016-011.pdf]

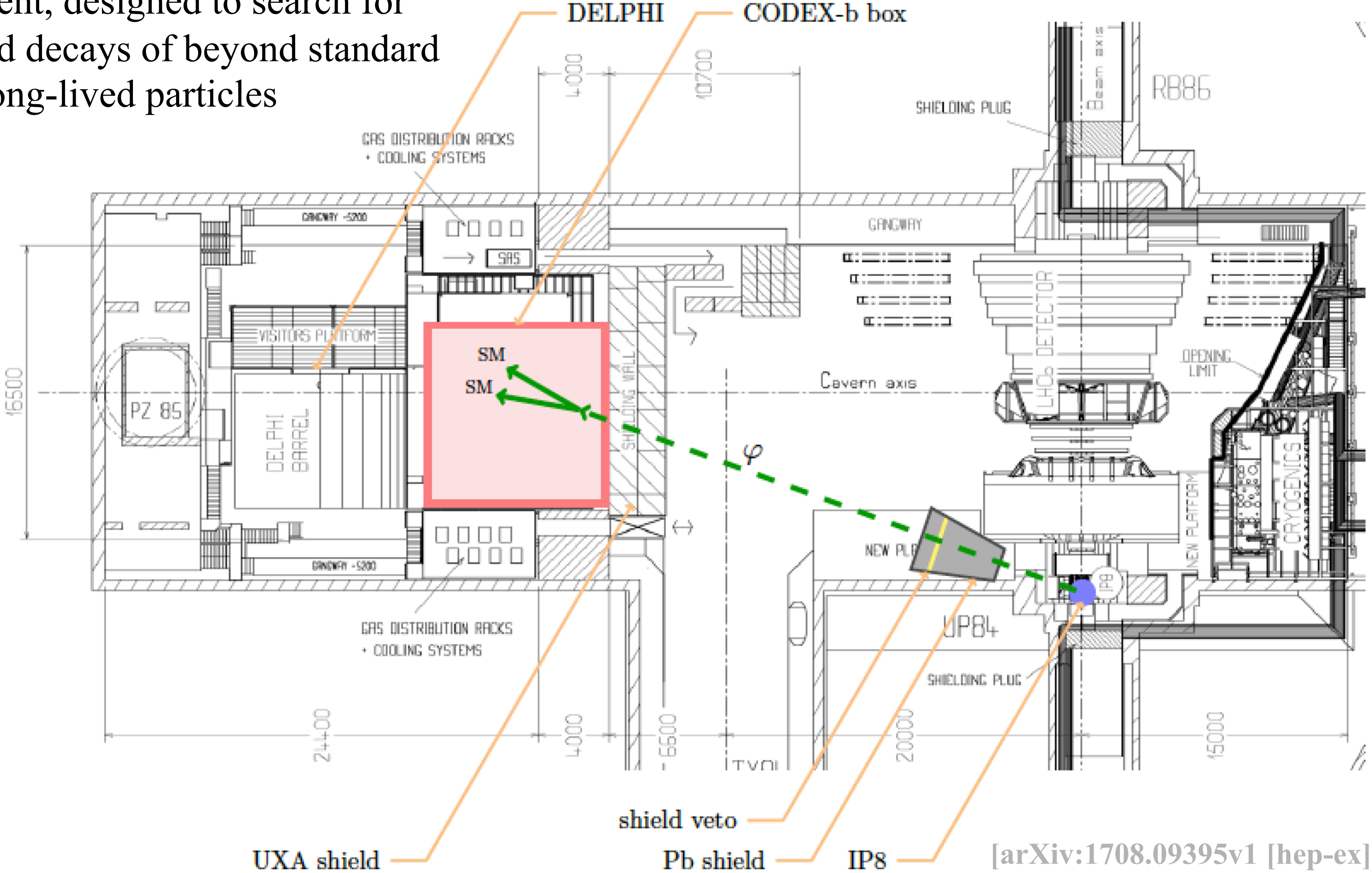
[http://arxiv.org/abs/1504.04276]



The dark side: CODEX-b

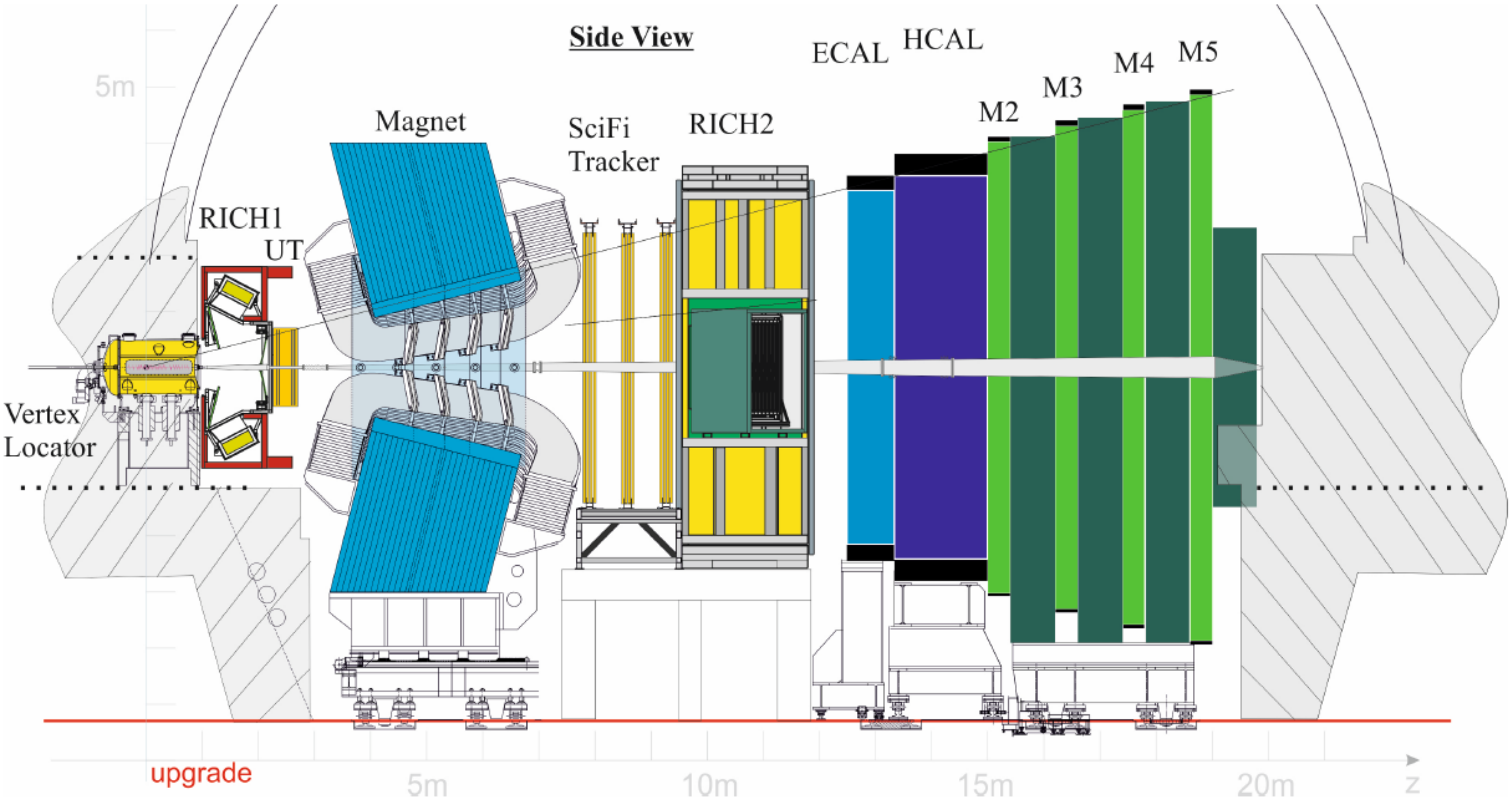
[COmpact Detector for EXotics at LHCb]

Under study: construction of a new detector element at the LHCb experiment, designed to search for displaced decays of beyond standard model long-lived particles



[arXiv:1708.09395v1 [hep-ex]]

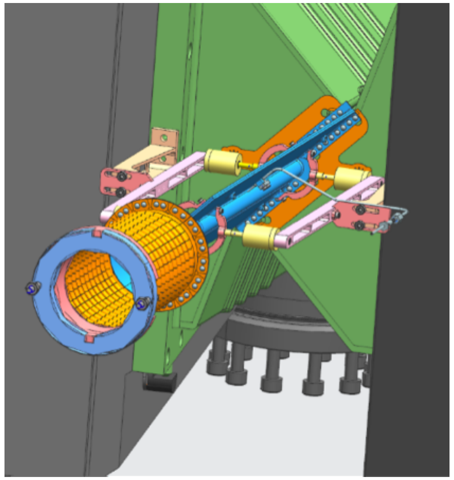
From Blake: Upgrade



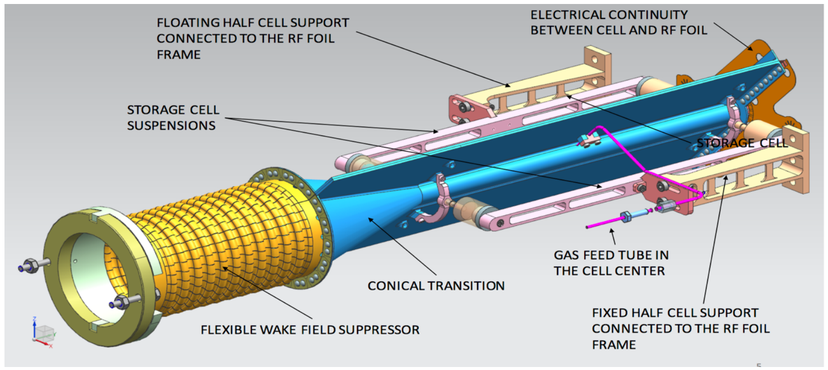
From Blake: SMOG2

- LHCb has a unique fixed target physics programme at LHC [LHCb-PUB-2018-015]
    - Heavy ions
    - Cosmic ray physics
- New SMOG will increase by up to two orders of magnitude the effective target areal density [CERN-LHCC-2019-005 ; LHCB-TDR-020]
- significant increase of the luminosity for fixed-target collisions.
- Additional (Noble) gas species, plus H2, D2, and O2

Dragon illustration in 13th century manuscript - Wikimedia Commons

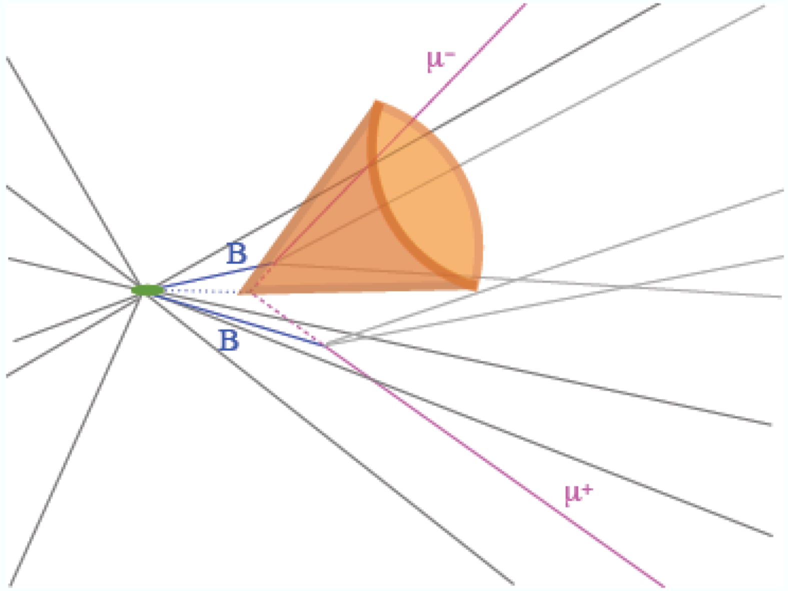


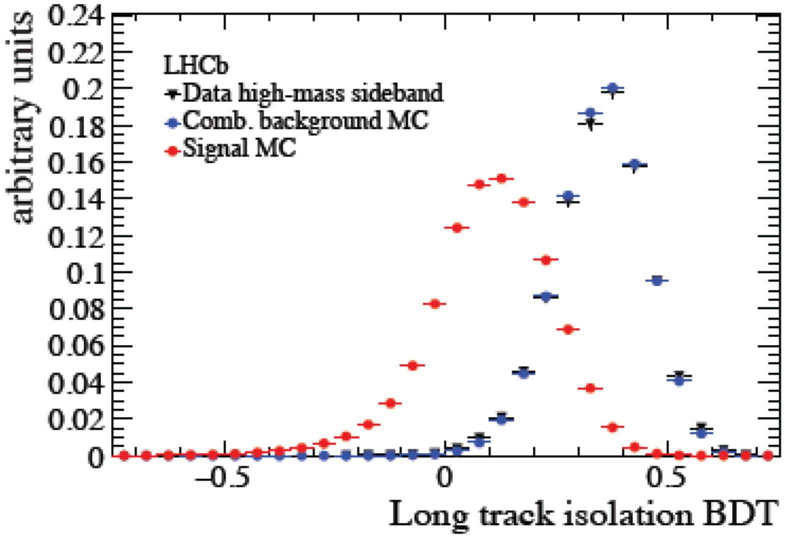
SMOG connected to the VELO RF boxes



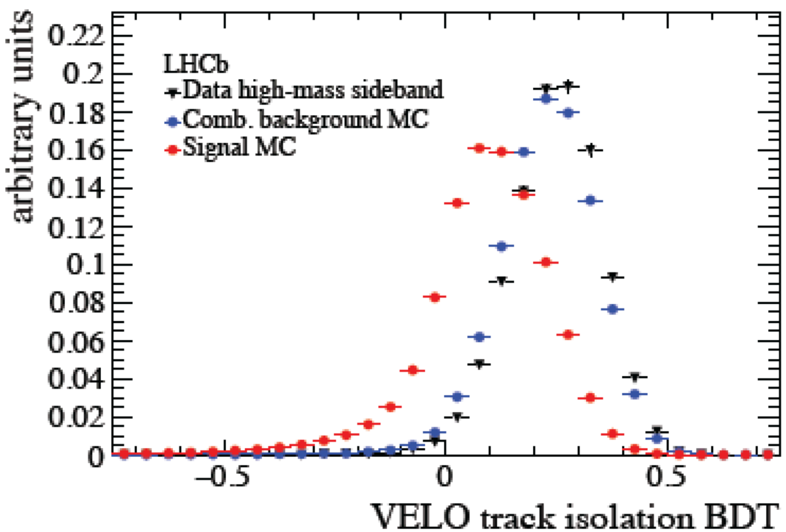
Technical drawing of the gas storage cell to be installed inside the VELO

$B_{(s)}\mu\mu$: muon isolation



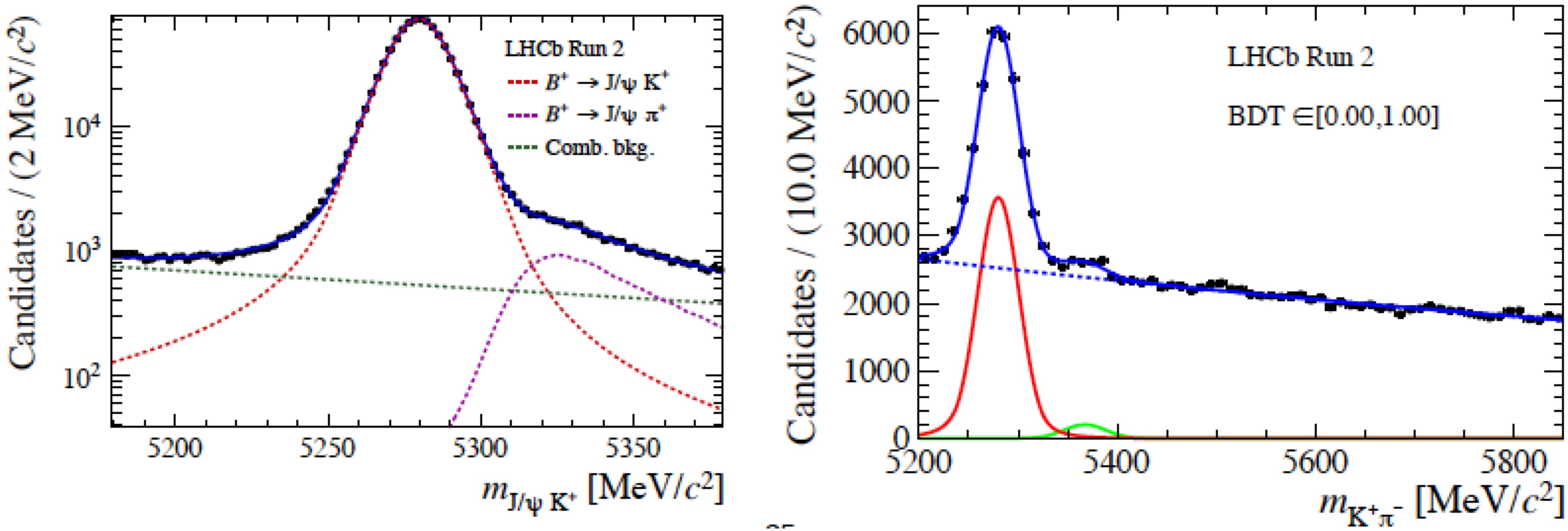


- Previous muon isolation based on rectangular cuts on variables related to the track information
- 2 multivariate classifiers are now used, one with tracks passing through all tracking stations, another with just tracks reconstructed only by the vertex detector.



$B_{(s)}\mu\mu$: normalization

- Two control channels used for the normalization: $B^+ \to J/\psi K^+$ and $B^0 \to K^+\pi^-$



[LHCb-CONF-2013-011]

- Hadronisation fraction from LHCb measurement $f_s / f_d = 0.259 \pm 0.015$
- Values at $\sqrt{s} = 13$TeV scaled according to $B^0_s \to J/\psi\varphi$ and $B^+ \to J/\psi K^+$ ratio

$$C^{Run2}_{fsfd} = (f_s/f_d)_{13TeV}/(f_s/f_d)_{7+8TeV} = 1.068(46)$$

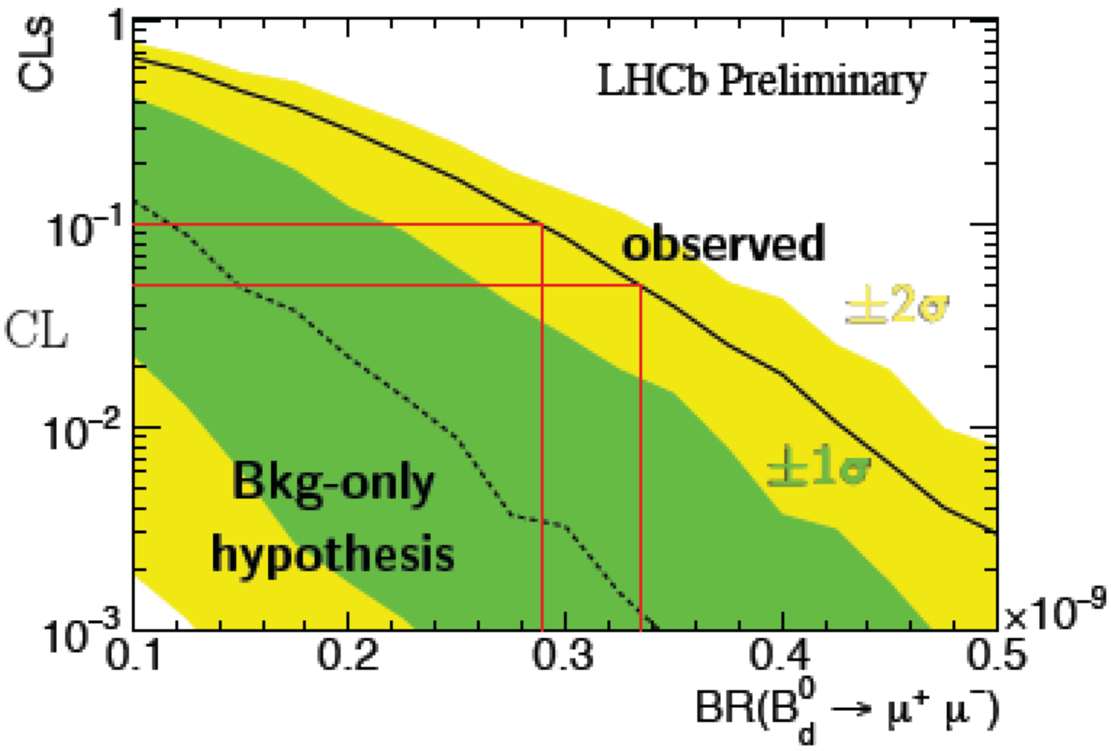
$B^0\mu\mu$: upper limit

- Use CL_s method: evaluate compatibility with background only (CL_b) and signal + background hypotheses (CL_{s+b}); the 95%CL upper limit is defined at $CL_s = CL_{s+b}/CL_b$=0.05

- Observed upper limit:

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \cdot 10^{-10} \text{ @ 95\% CL}$$

- Compatibility with bkg only hypothesis 1-CL_b=0.05



[LHCb-PAPER-2017-001]