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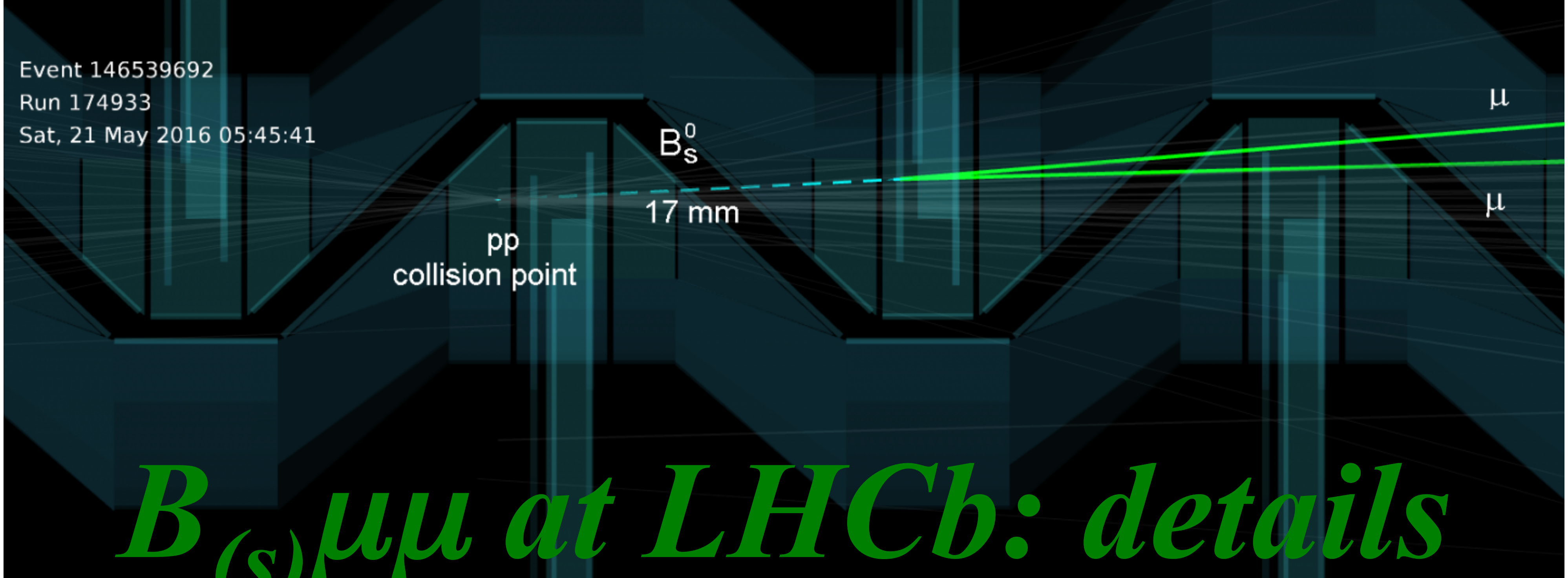
[Acknowledgements to F. Alessio, F. Archilli, C. Fitzpatrick, R. Forty, C. Gaspar, V. Gligorov, G. Passaleva, M. Schubiger , N. Tuning, and V. Vagnoni for some material]

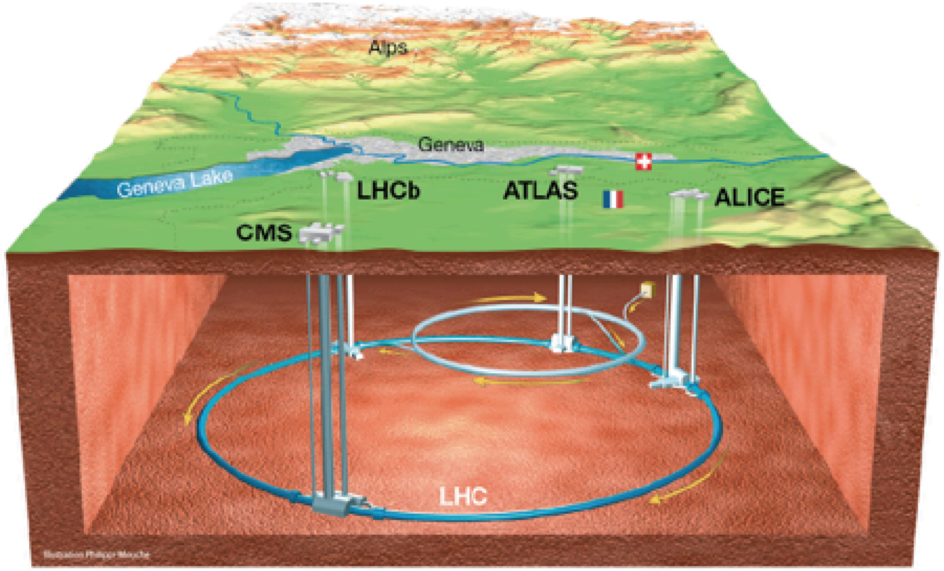


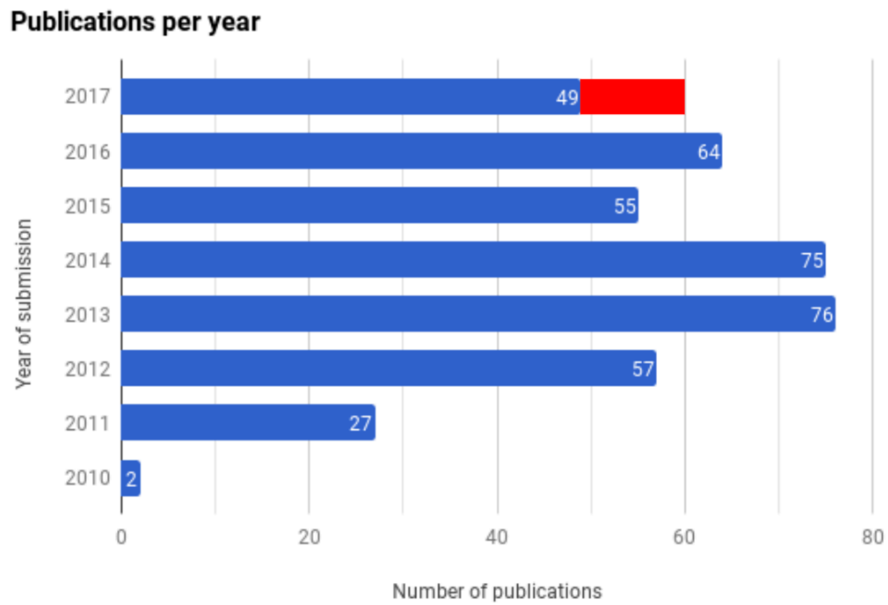
$B_{(s)}\mu\mu$ at LHCb: details behind a successful result

(with bonus tracks about LHCb and future plans)

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





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

From "your" lectures

End of the Introduction

- Present prospects of Elementary Particle experiments:
  - ENERGY frontier → LHC, HL-LHC, ILC, TLEP, ….
  - INTENSITY frontier → flavour-factories, fixed target, …
  - SENSITIVITY frontier → detectors for dark matter, neutrinos, ..
- The general idea is to measure quantities for which you have a clear prediction from the Standard Model, and a hint that a sizeable correction would be present in case of "New Physics".

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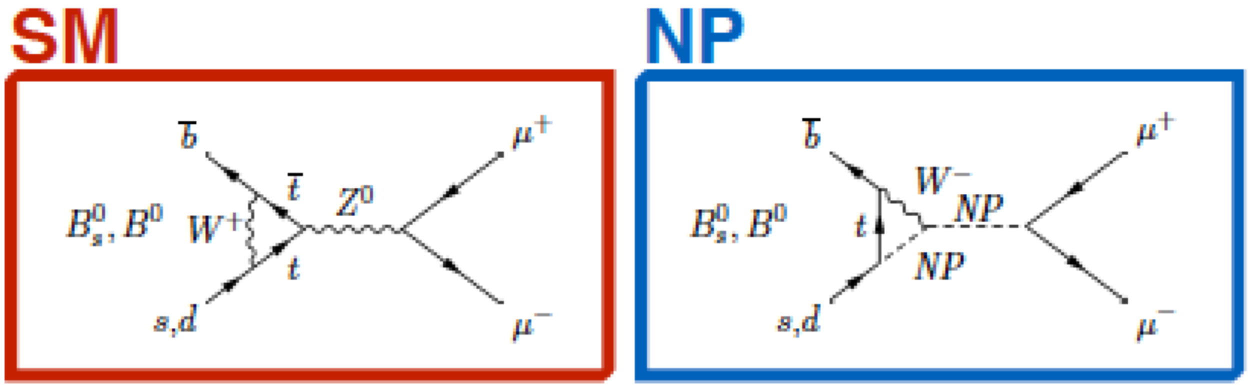
$B_{(s)}\mu\mu$: rare b decays

- 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

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

- C_i Wilson coefficients
- O_i four-fermion operators

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

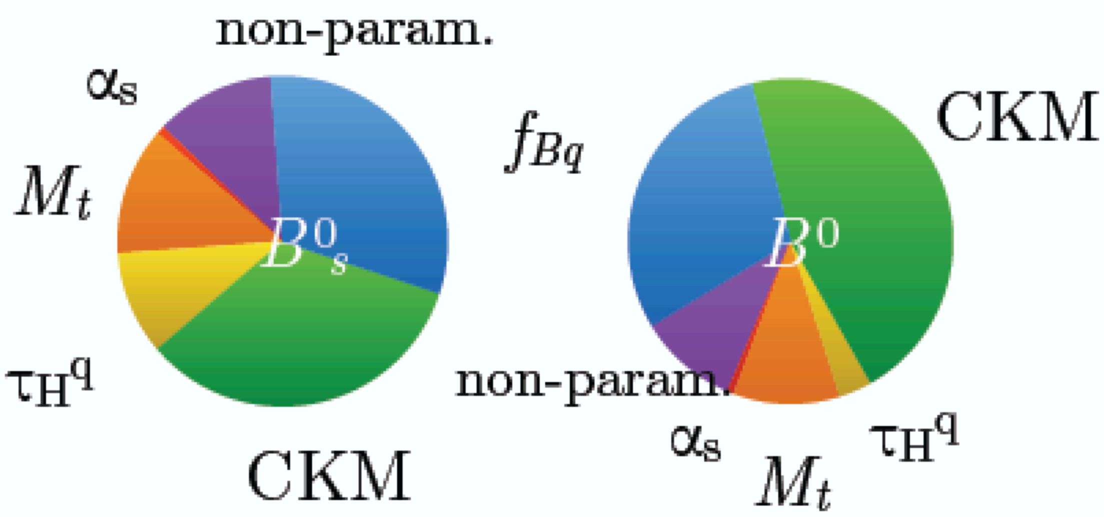
CP-averaged time integrated branching fraction predictions:

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

[hep-ex/1403.4427]

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

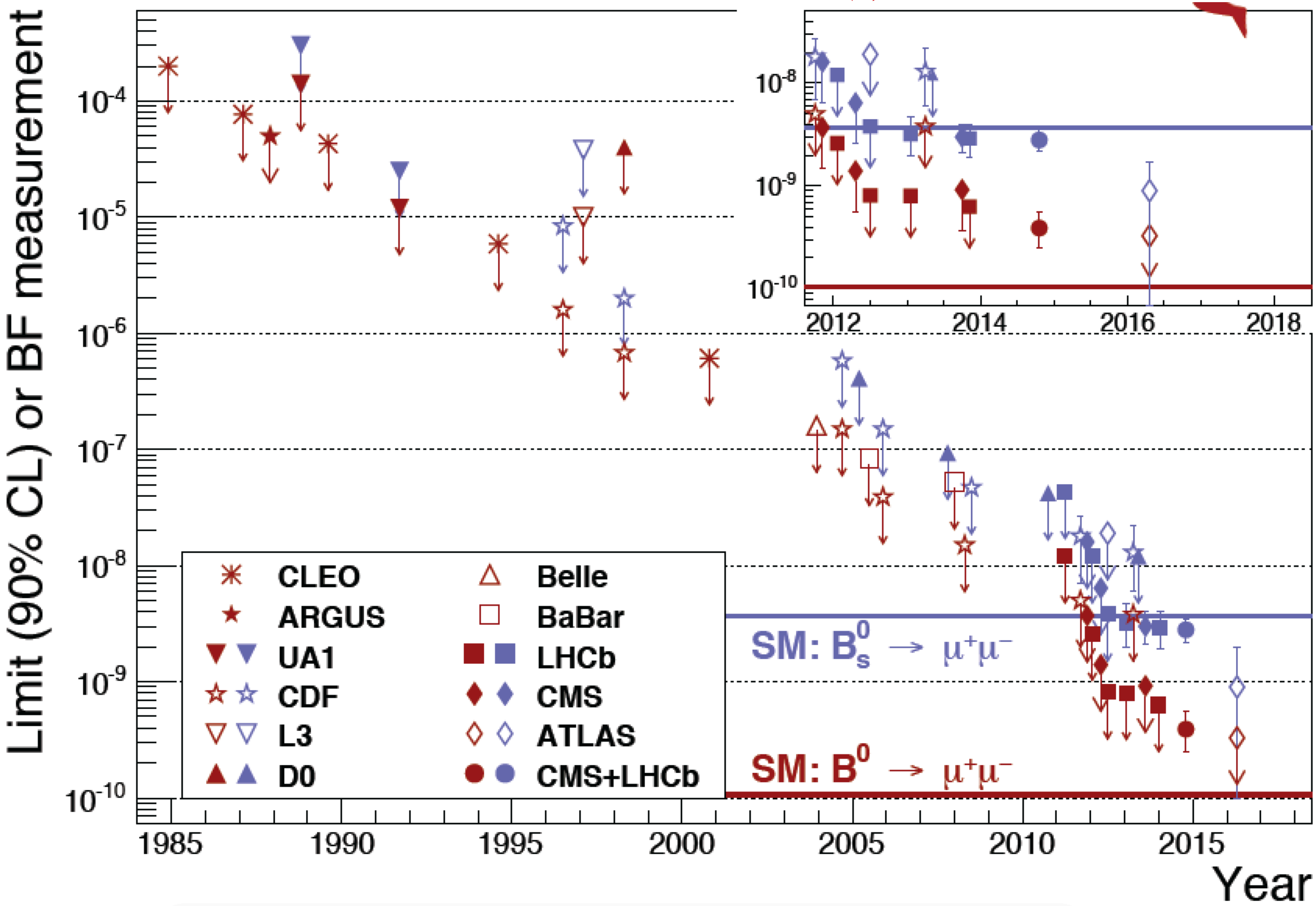
error budgets



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

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

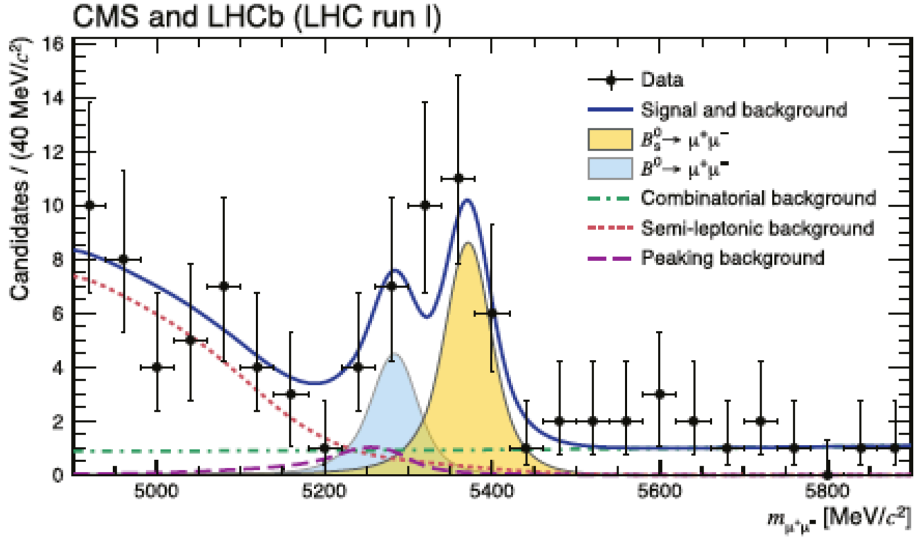
3.0 σ stat. significance
compatibility with SM at 2.2σ level

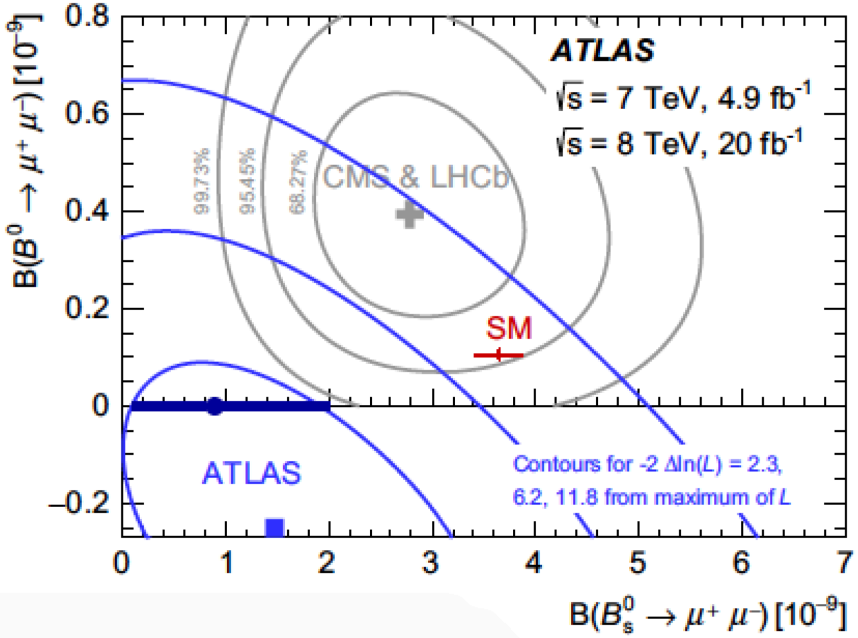
- **ATLAS:** [EPJ C76 (2016) 9, 513]

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

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

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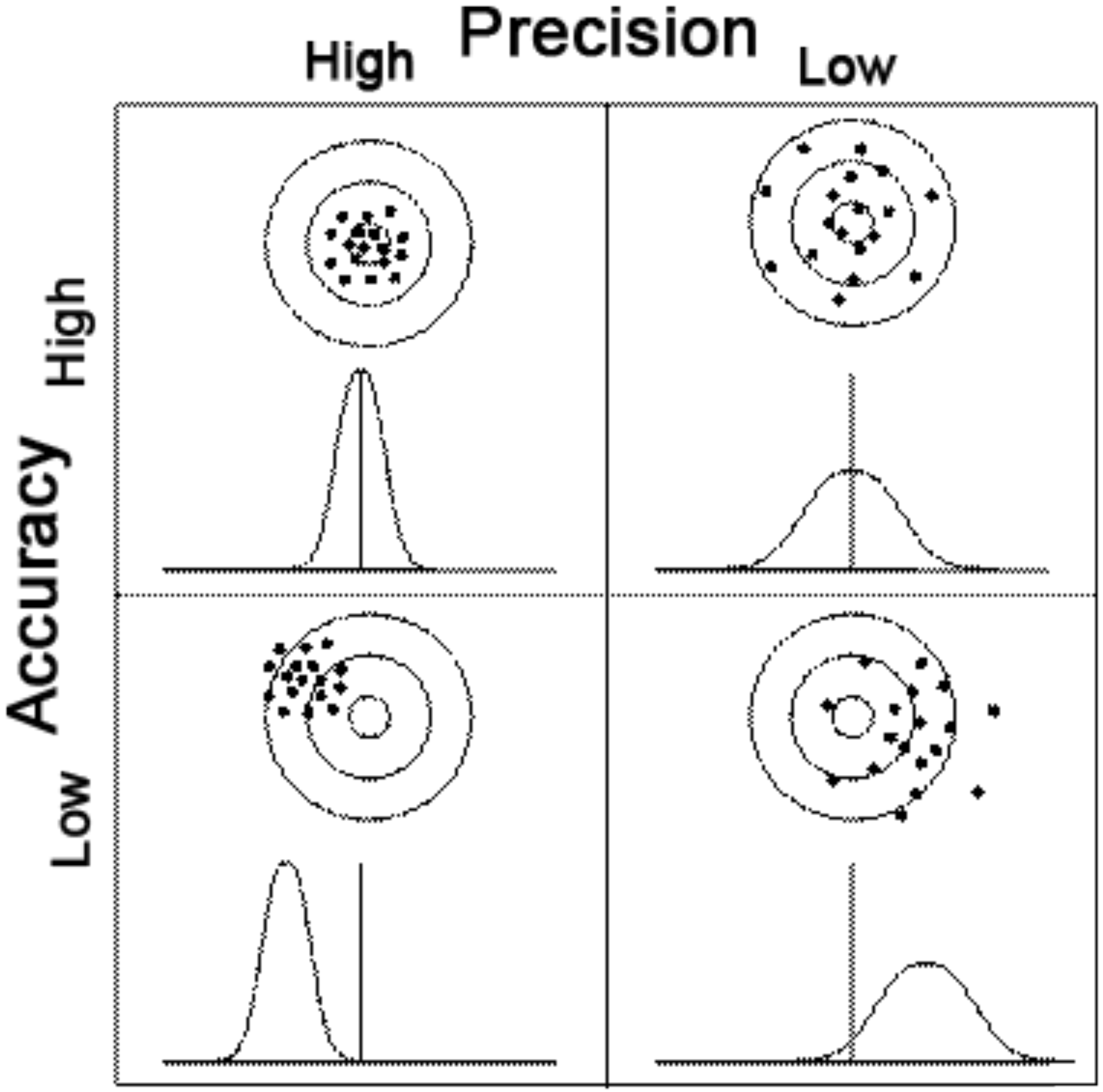
$$B.R.(a \to X) = \frac{N_{cand} - N_b}{\varepsilon} \frac{1}{N_a}$$

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

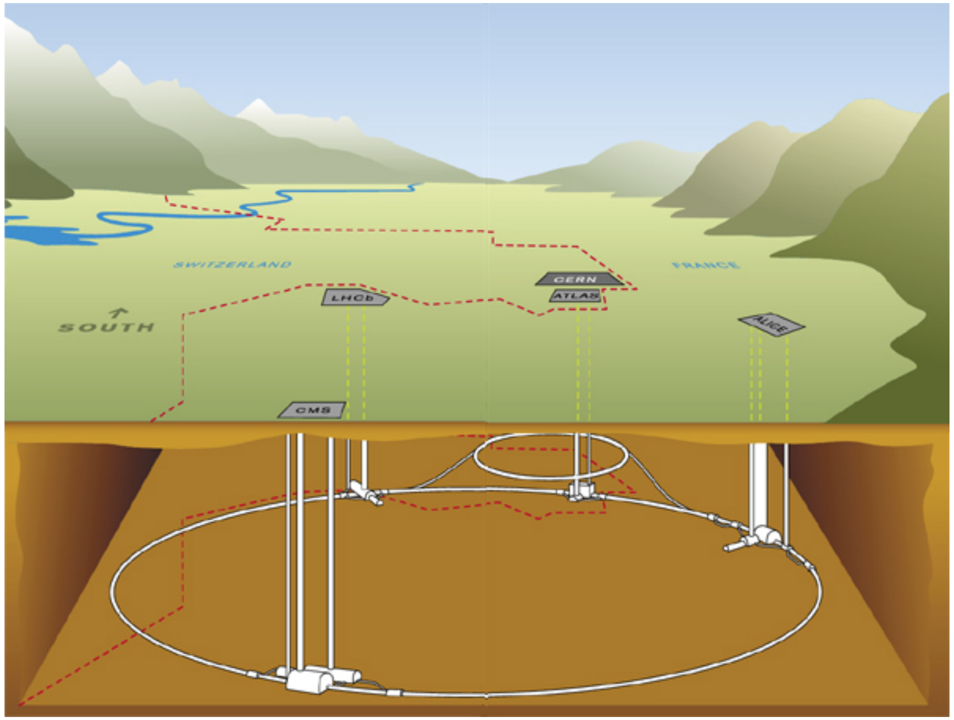
Interlude: statistical vs systematic errors

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

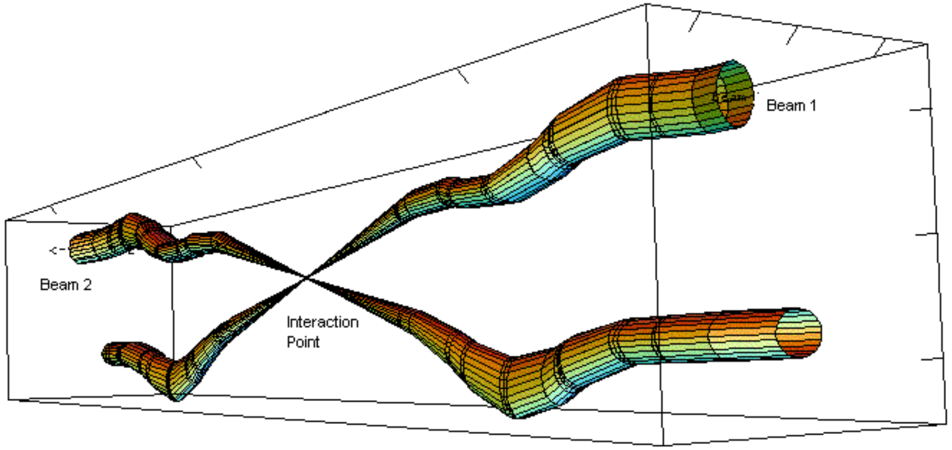


Accuracy ~ systematic:
- a lot of checks
- redundancy
- **you never know…**

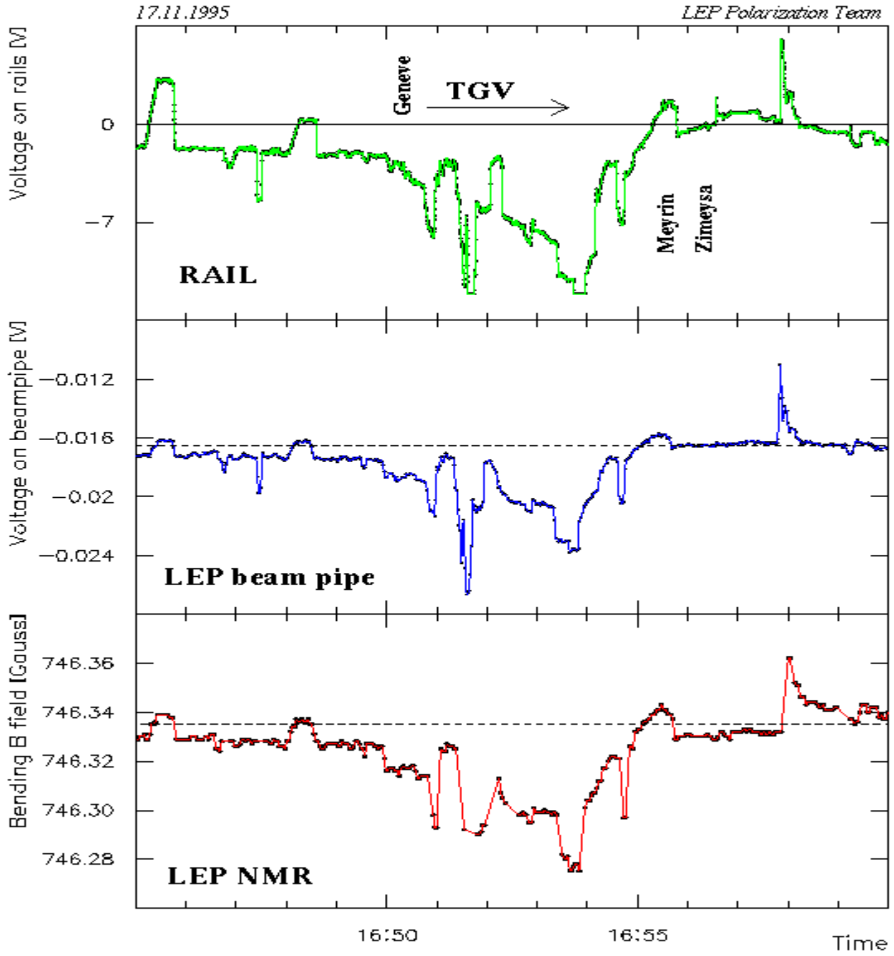
A lot of data: luminosity



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

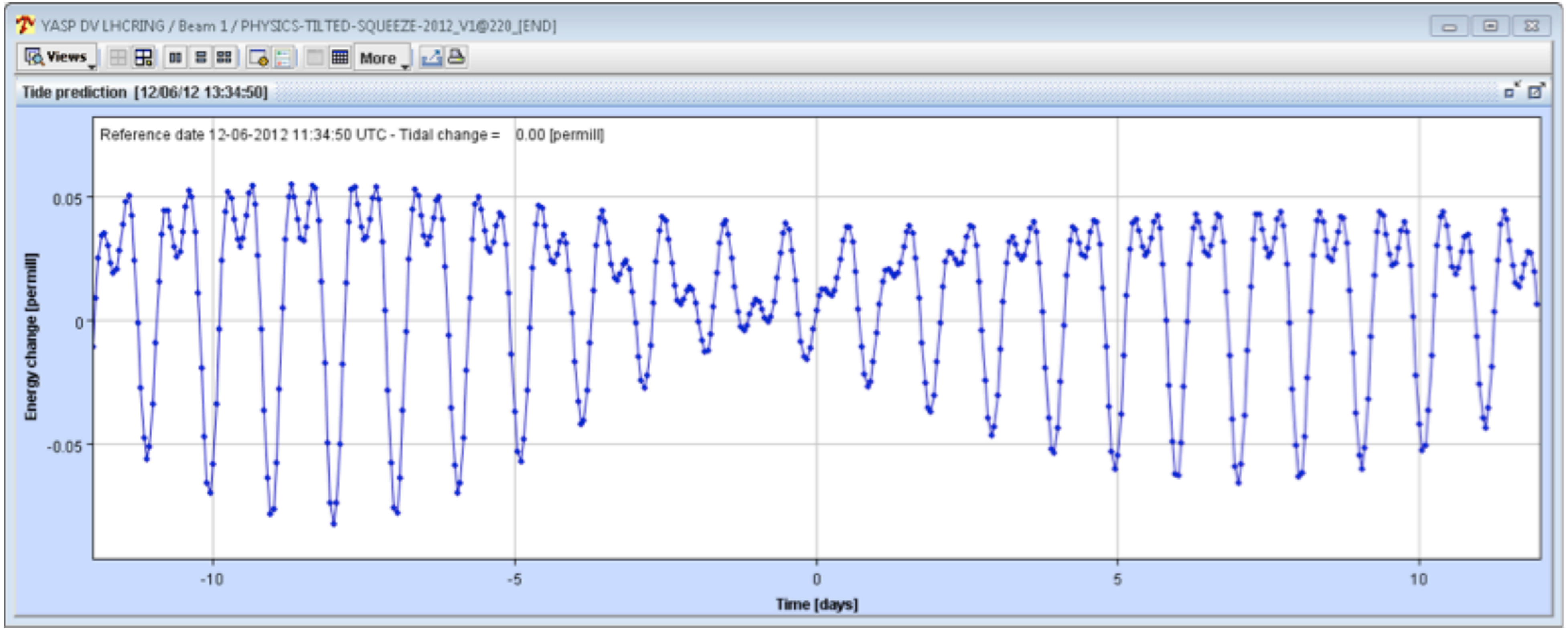


Relative beam sizes around IP1 (Atlas) in collision



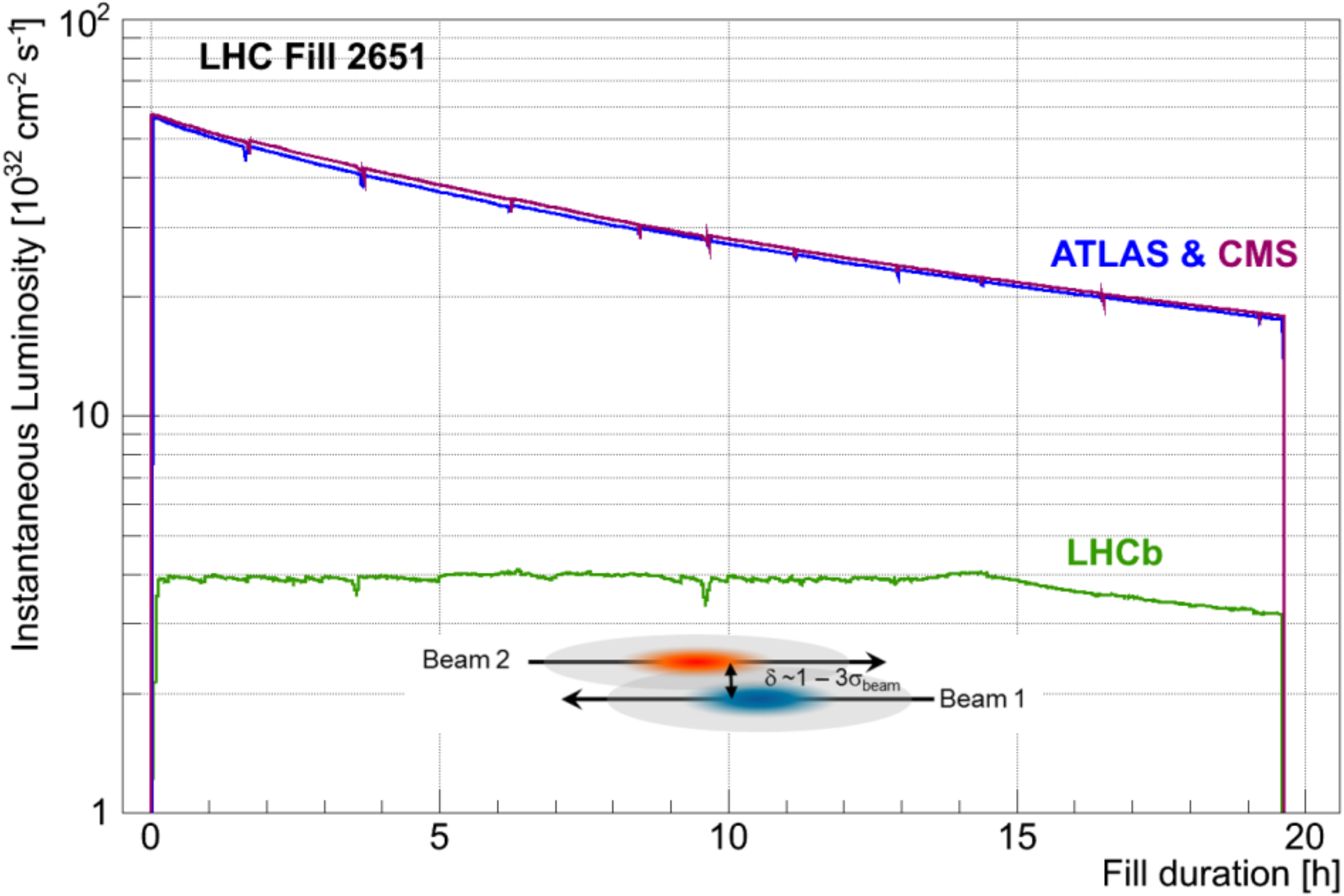
A lot of data: the Moon

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

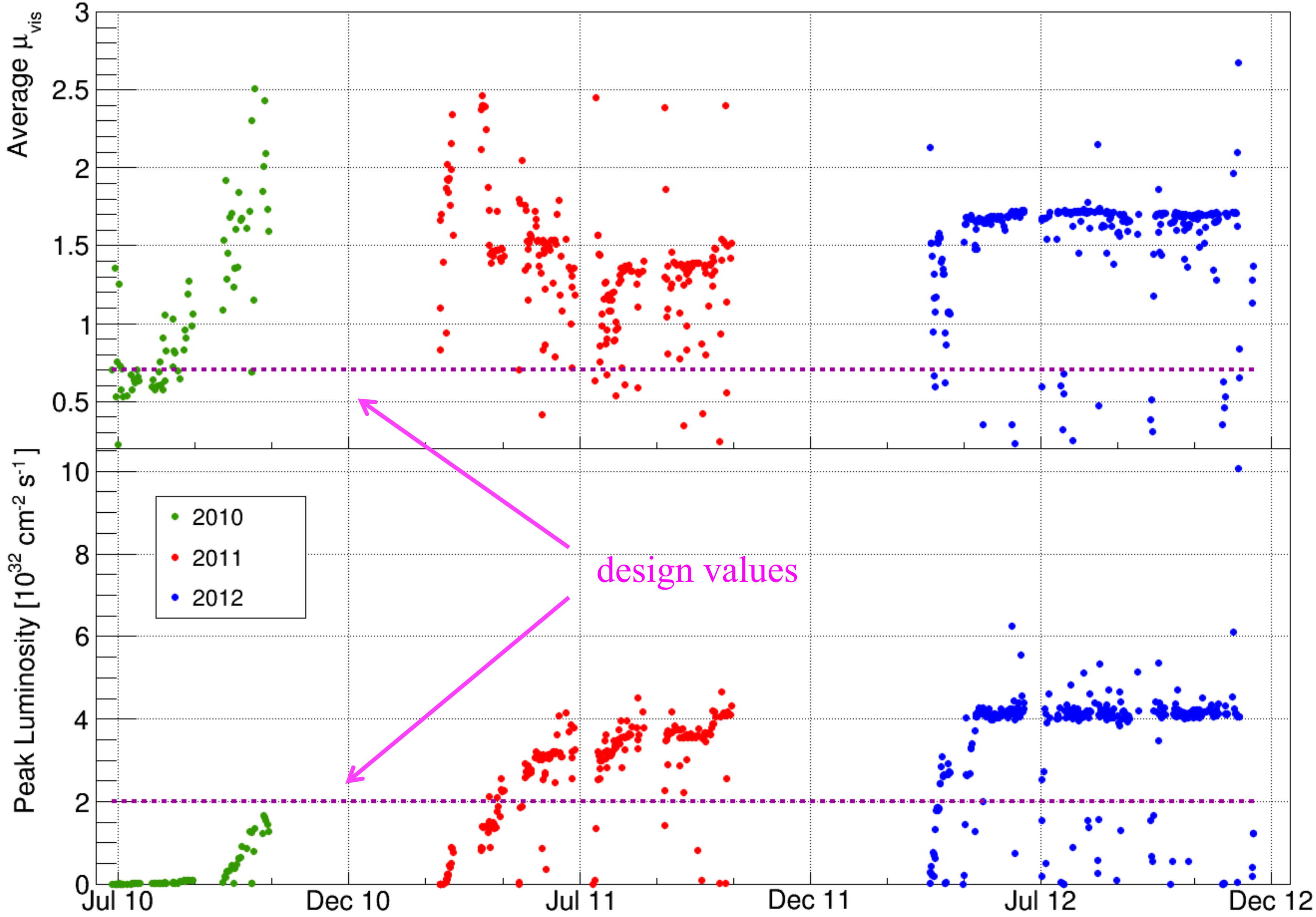


20 days

A lot of data: Luminosity leveling



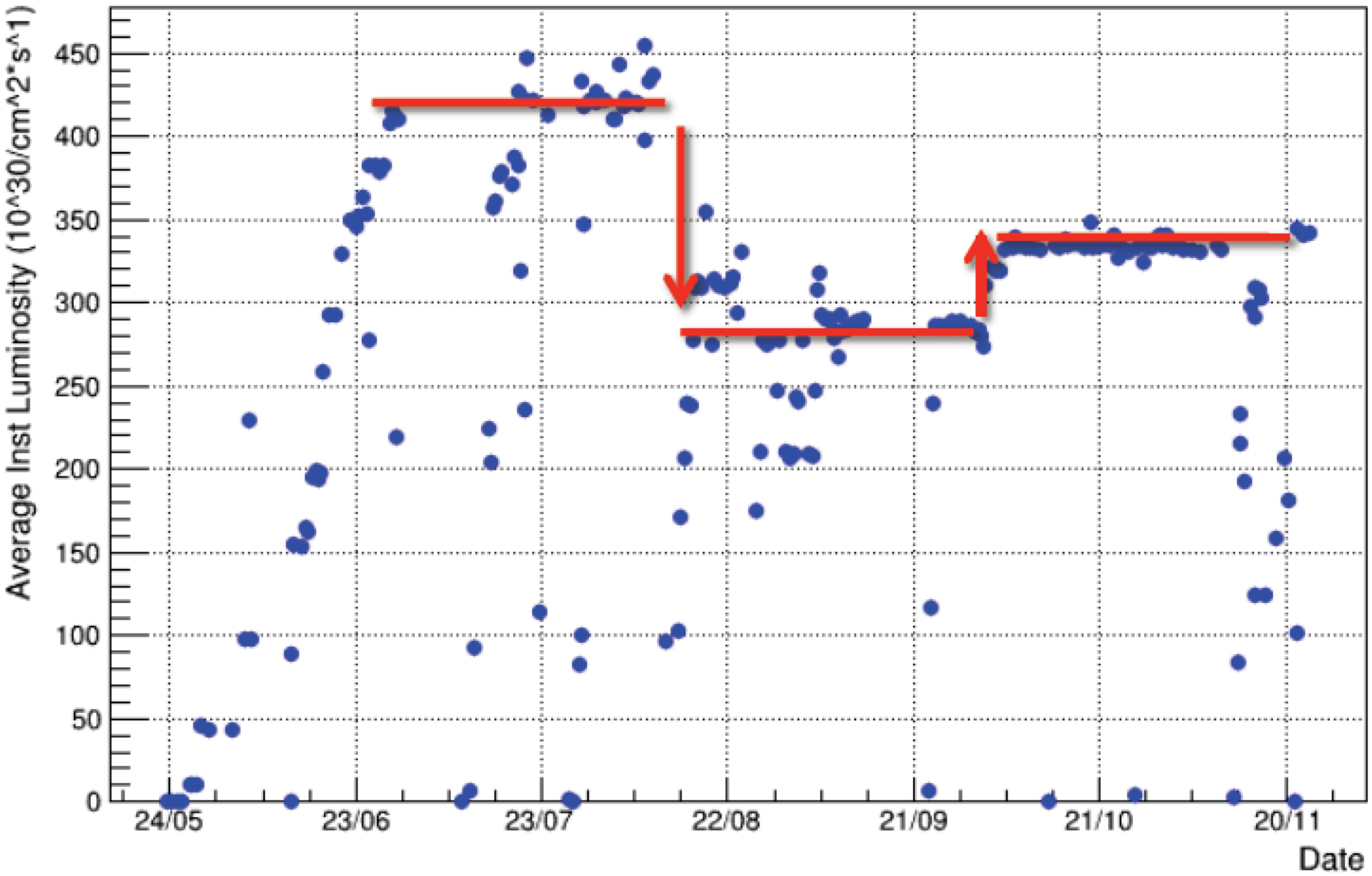
Run1 [2010-2012] operating conditions



Run2 [2017] operating conditions

Due to varying number of bunches and filling scheme:

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

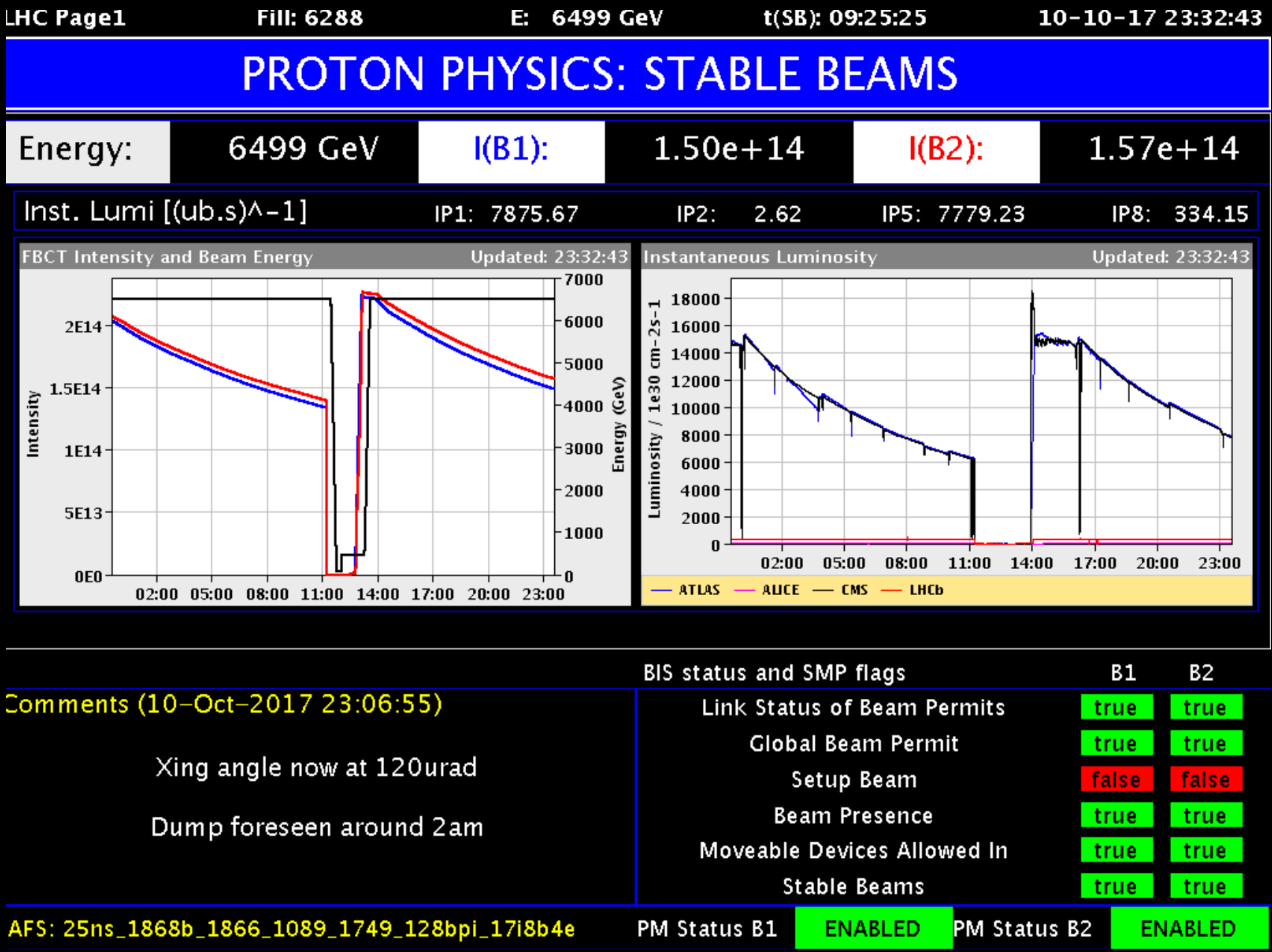


4.2×10^{32} $cm^{-2}s^{-1}$

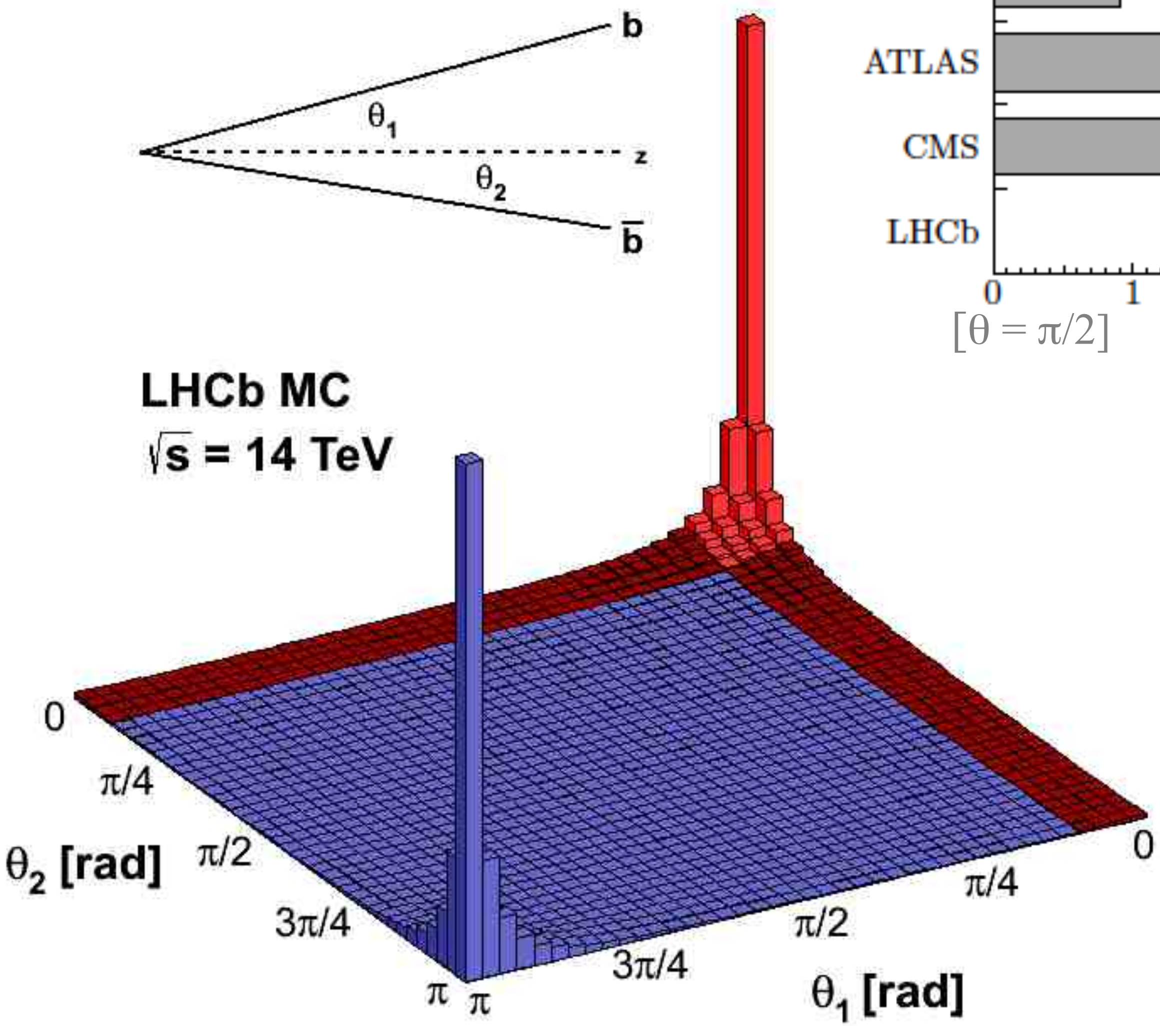
3.4×10^{32} $cm^{-2}s^{-1}$

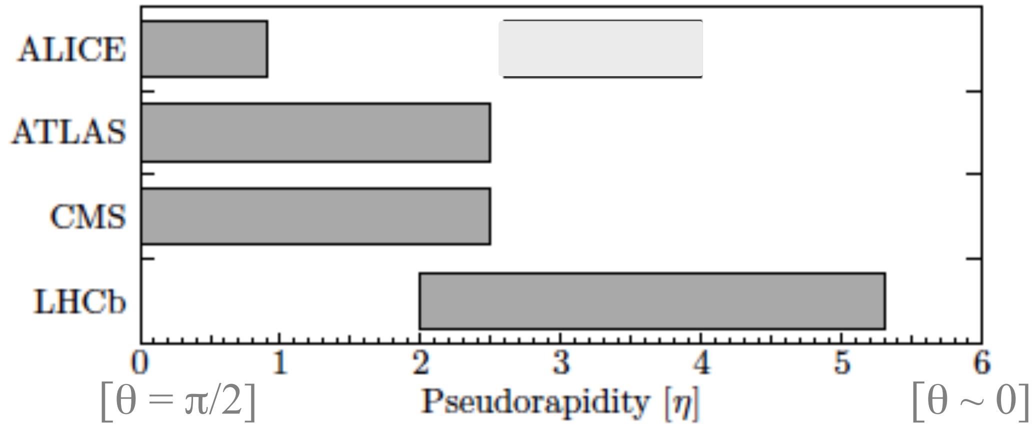
2.8×10^{32} $cm^{-2}s^{-1}$

A lot of data: Luminosity leveling



A lot of data: heavy flavor production

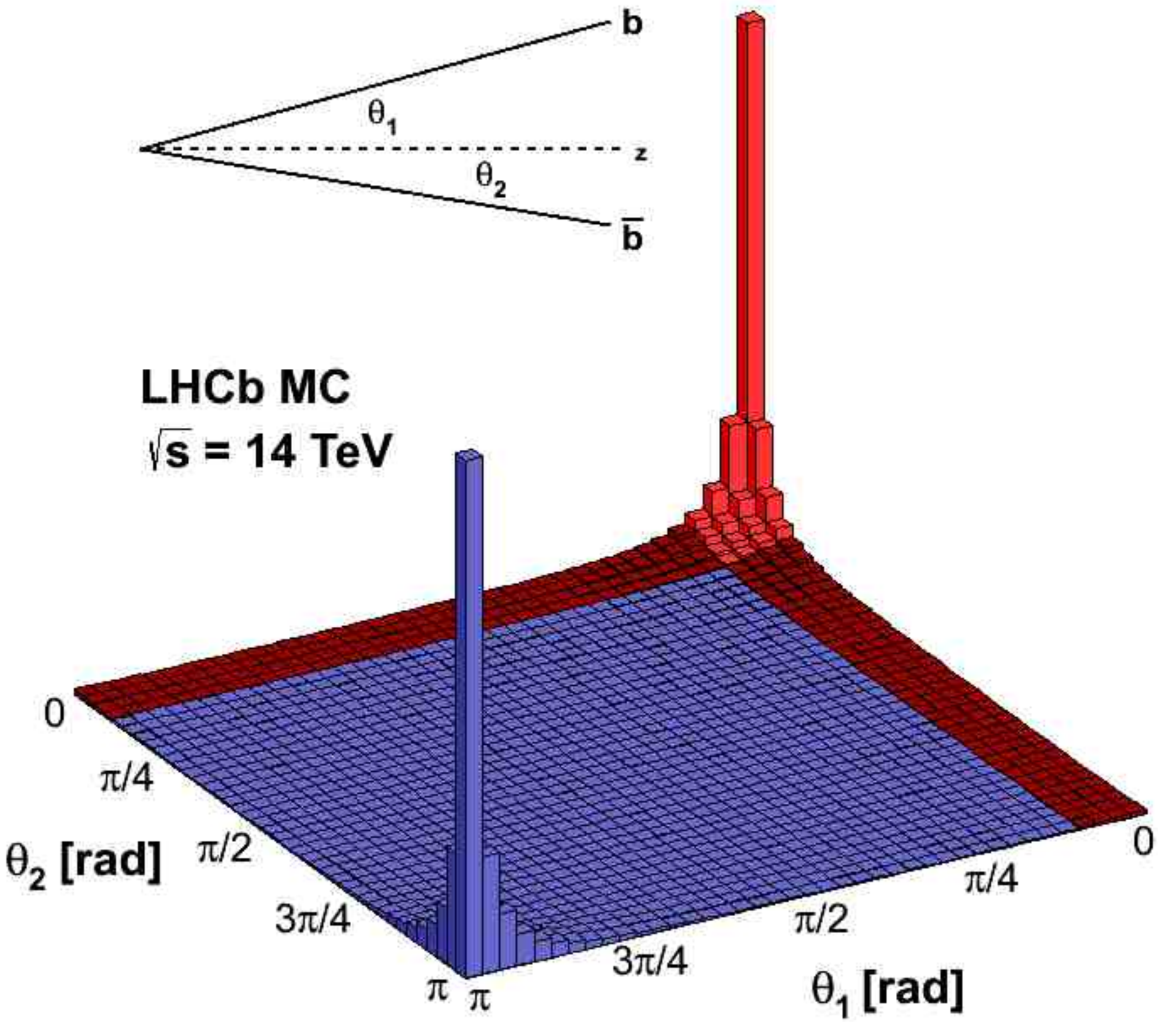


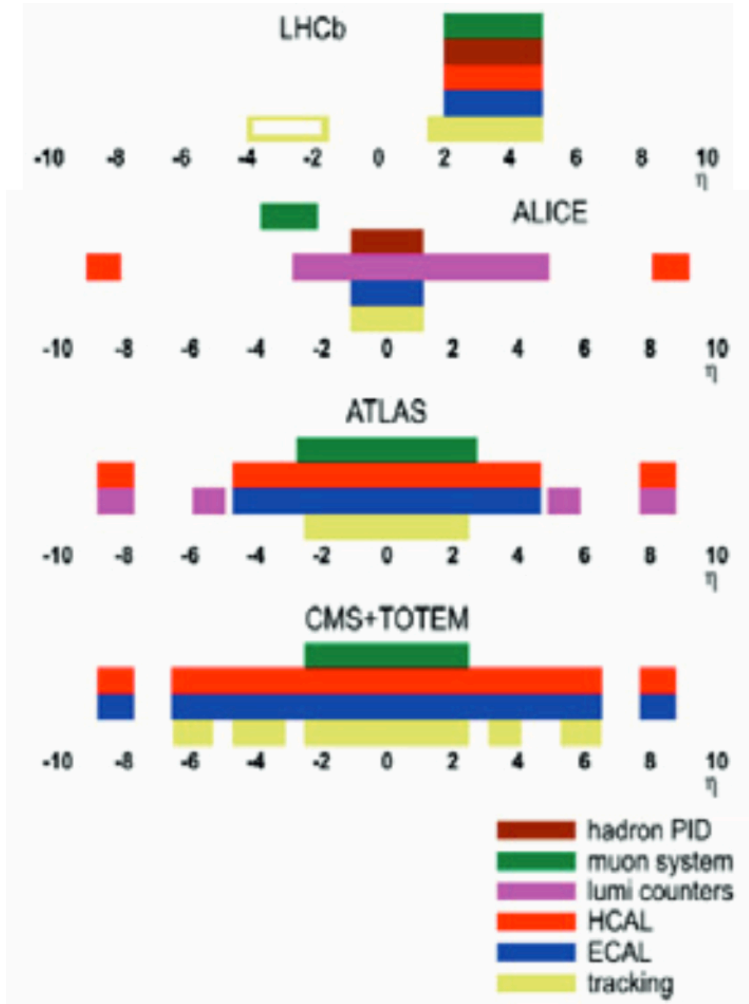


Extremely large σ(bb) and σ(cc) in LHC hadron collisions.

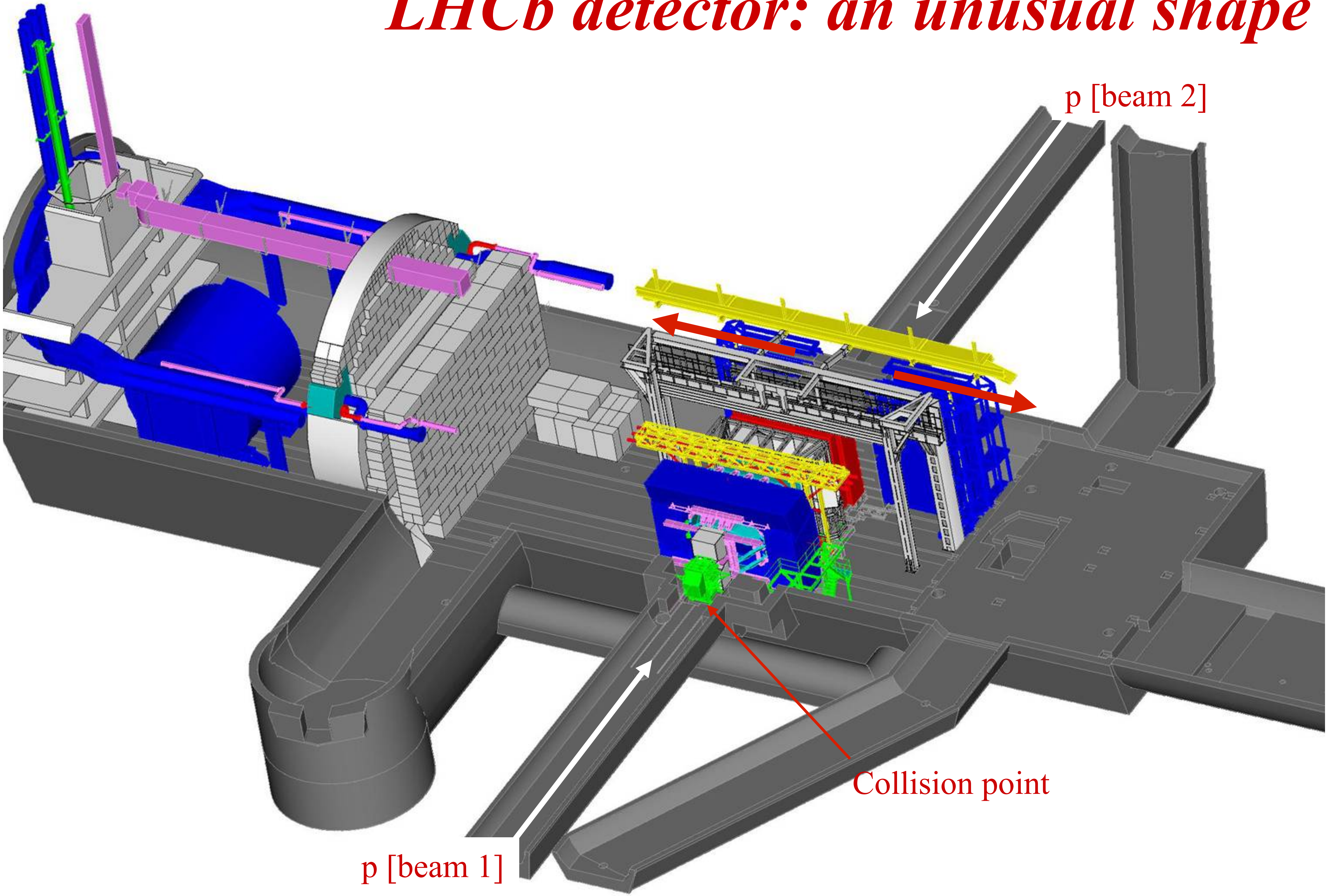
At 13TeV: **σ(bb) ~ 45 kHz** and **σ(cc) ~1MHz** cc in LHCb acceptance (HF cross section x2 with respect Run 1)

A lot of data: heavy flavor production



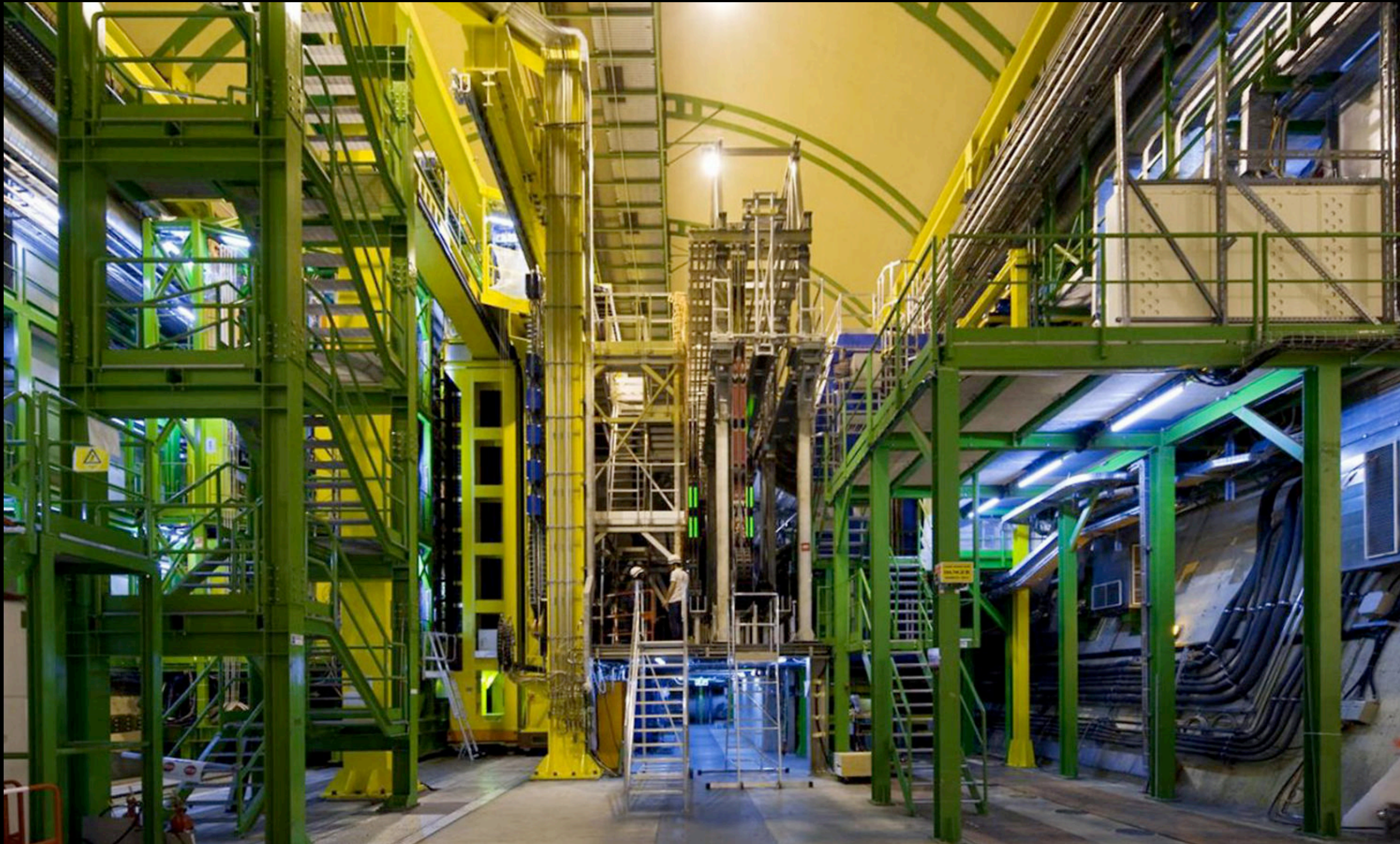


LHCb detector: an unusual shape



[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



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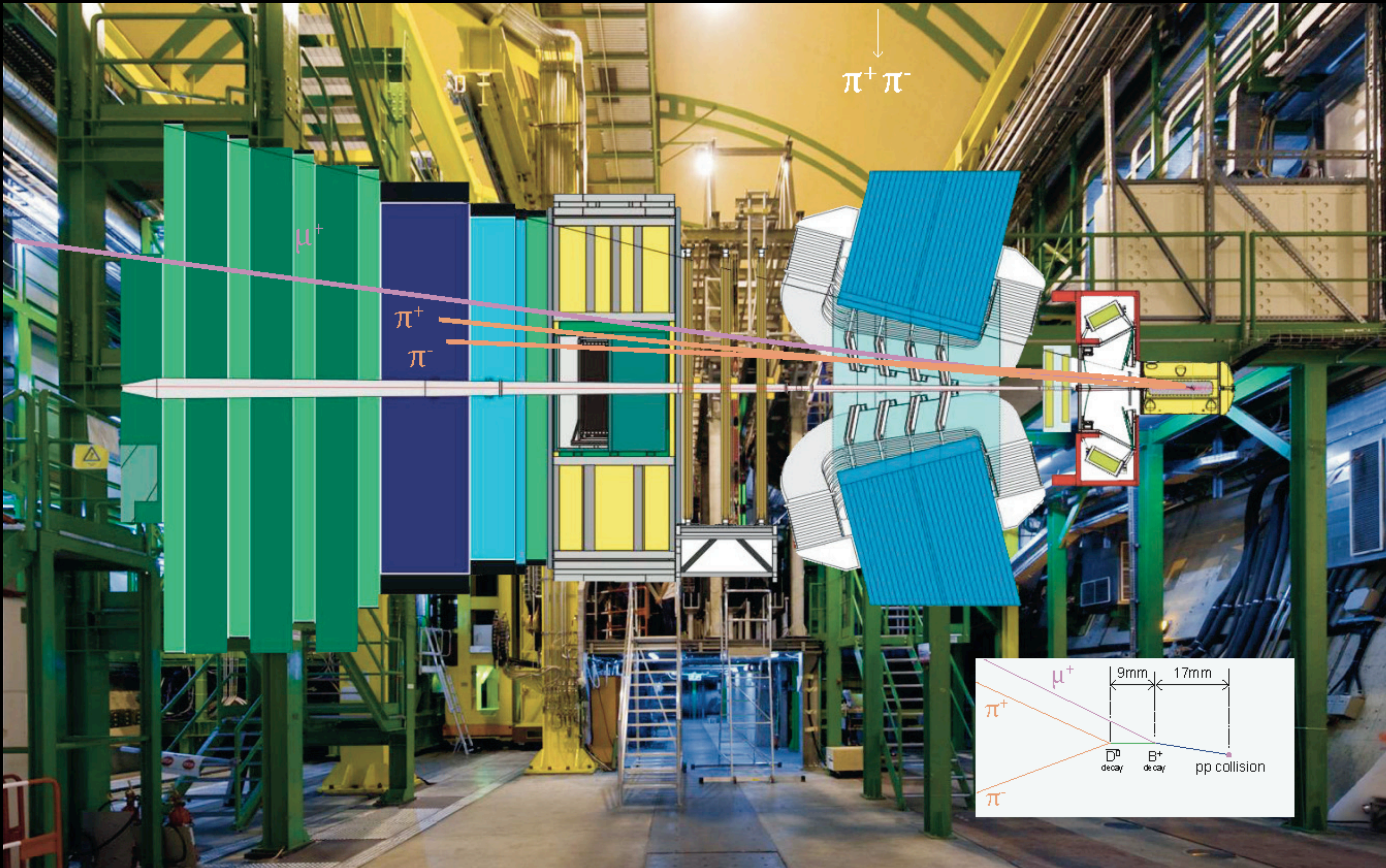
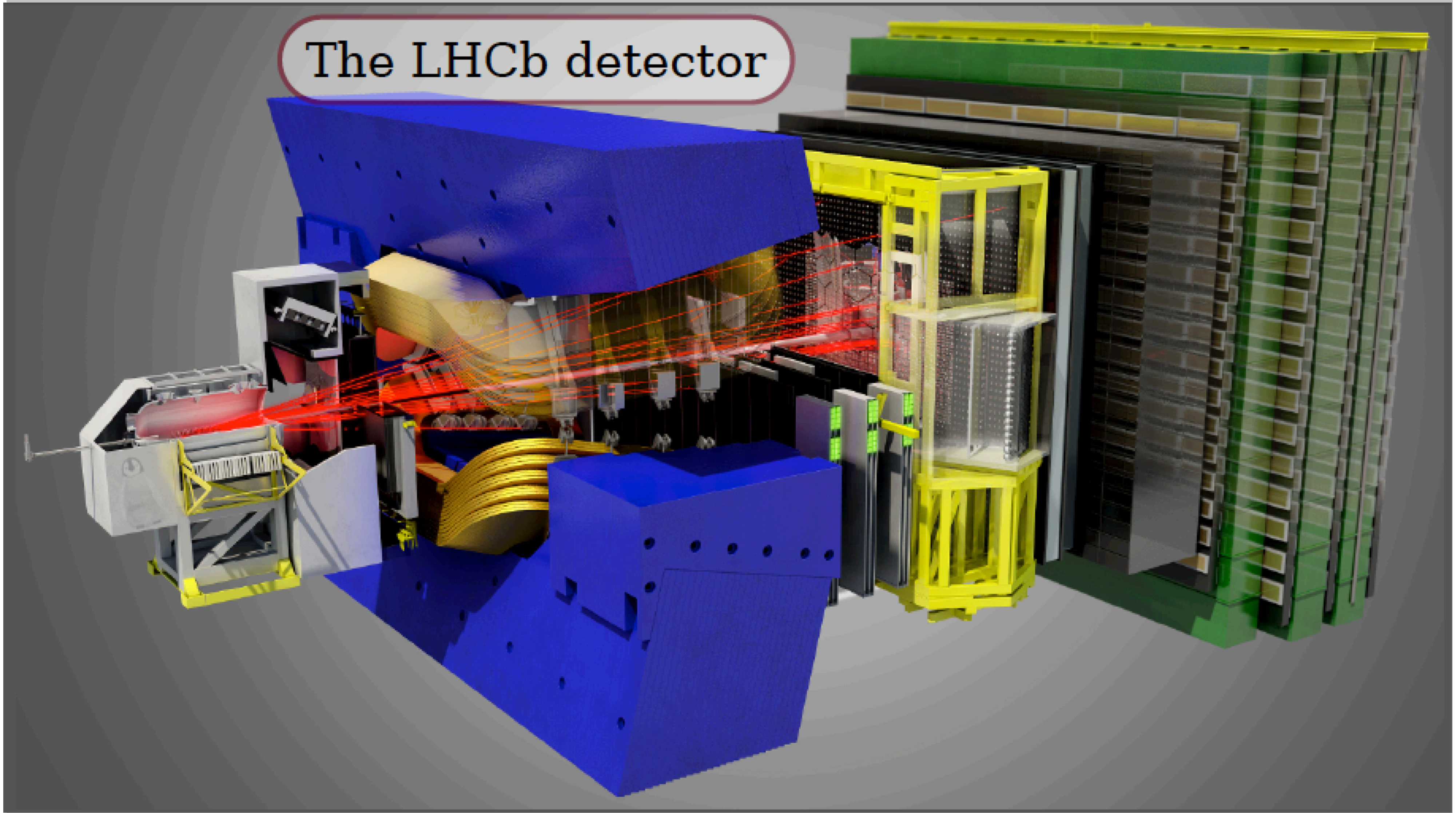
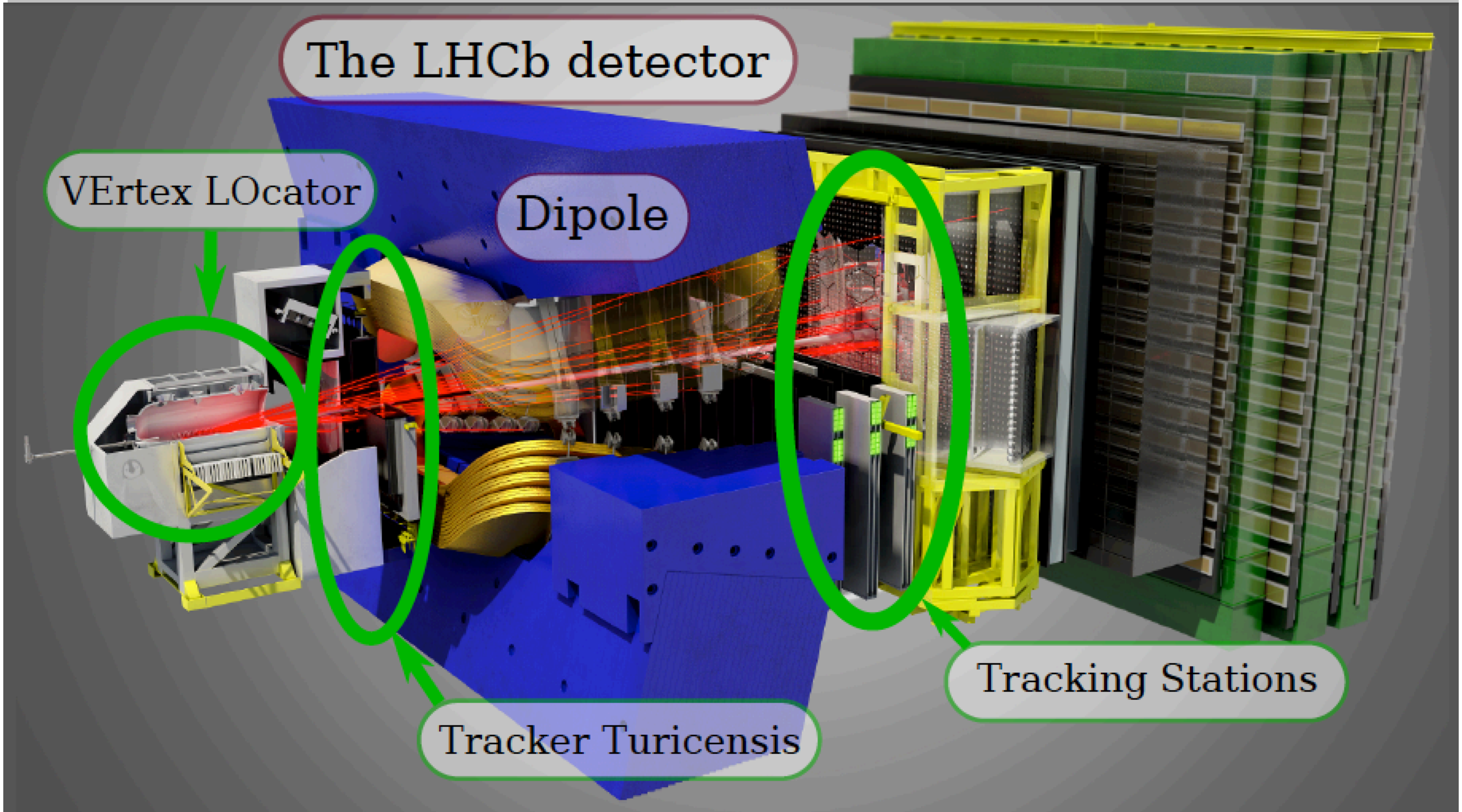
LHCb detector



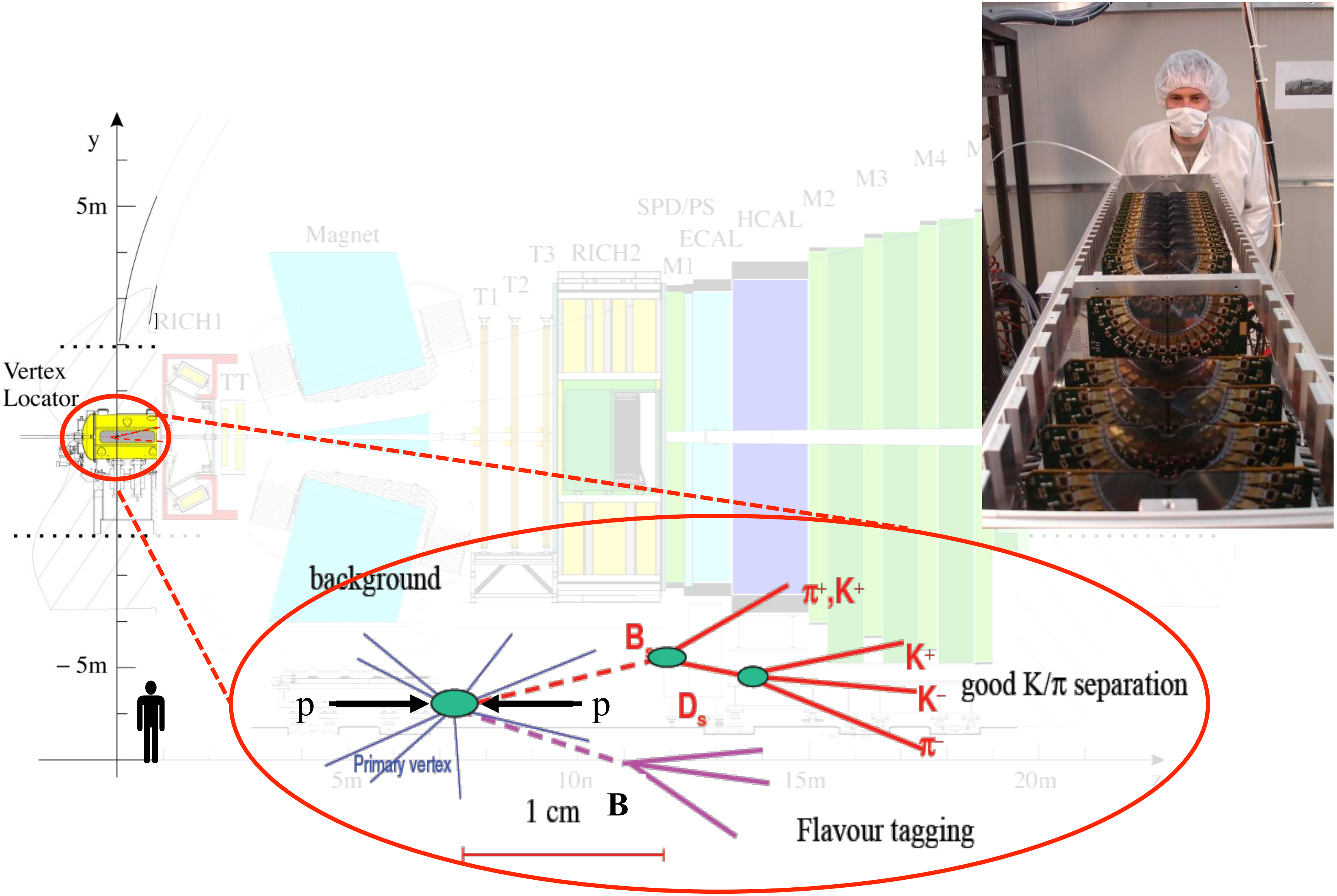
LHCb detector



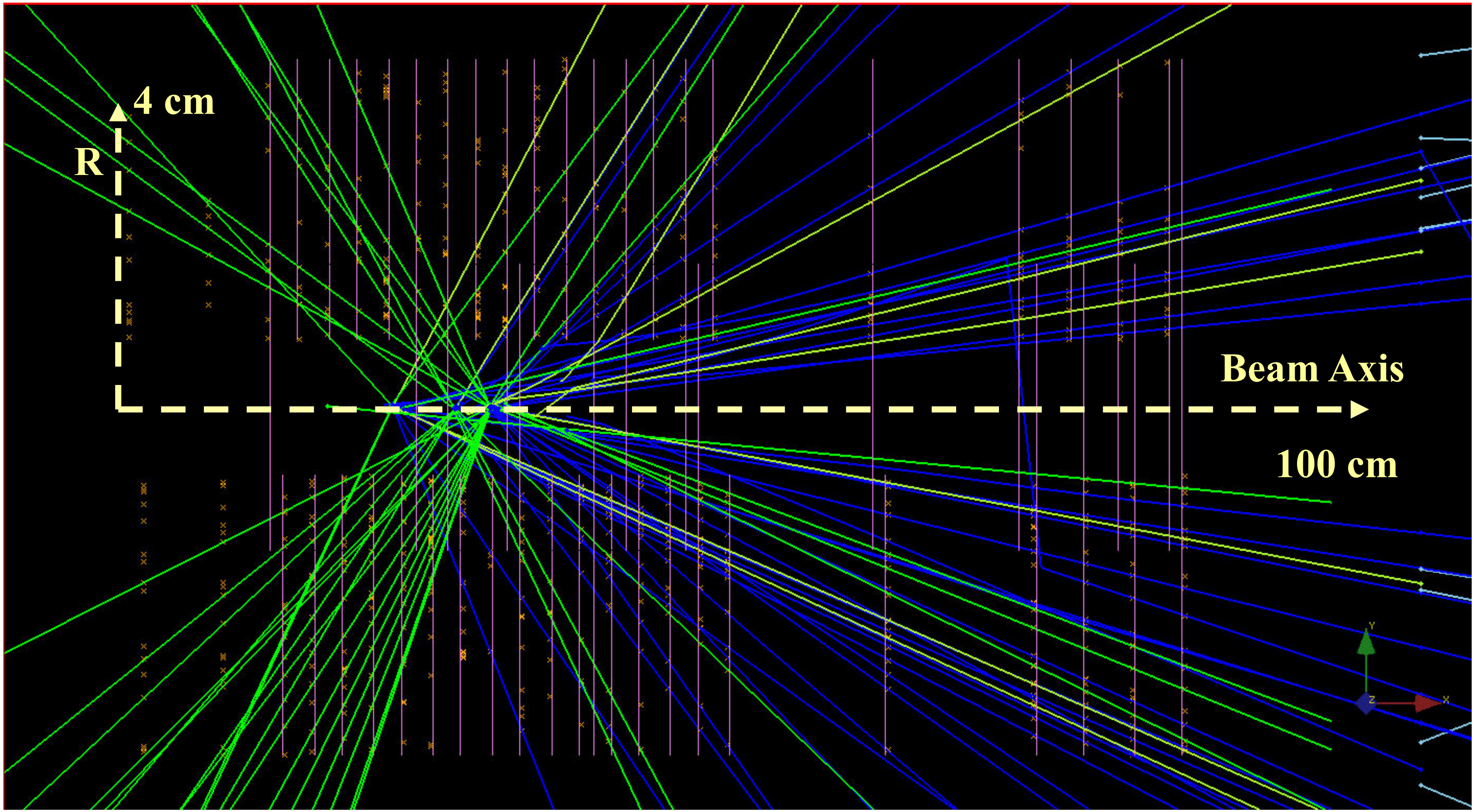
LHCb detector: tracking system



VELO


y
5m
– 5m
Vertex
Locator
Magnet
RICH1
TT
T1
T2
T3
RICH2
SPD/PS
ECAL
HCAL
M1
M2
M3
M4
5m
10m
15m
20m
background
p
p
Primary vertex
B_s
D_s
π^+,K^+
K^+
K^-
π^-
good K/π separation
1 cm
B
Flavour tagging

VELO rz view



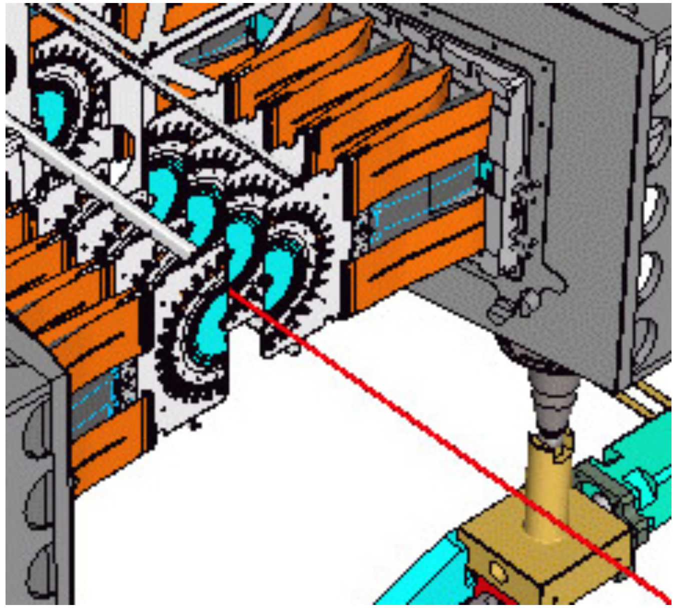
[Performance of the LHCb Vertex Locator JINST 9 (2014) 09007]

VELO

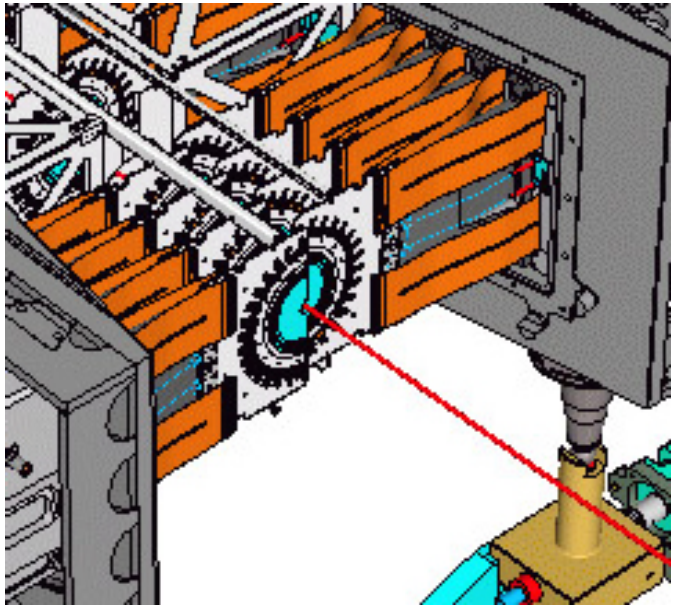
Silicon detector: 42 modules arranged along the beam, each providing a measurement of the r and ϕ coordinates.

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

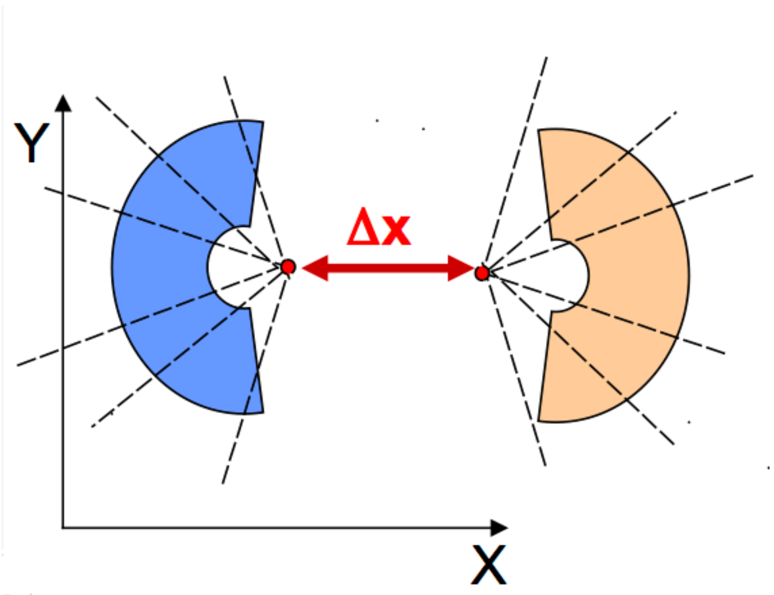
Detector safety: **modules retracted by 29 mm during injection**; 210 s to close; ~750 closing procedures in Run1



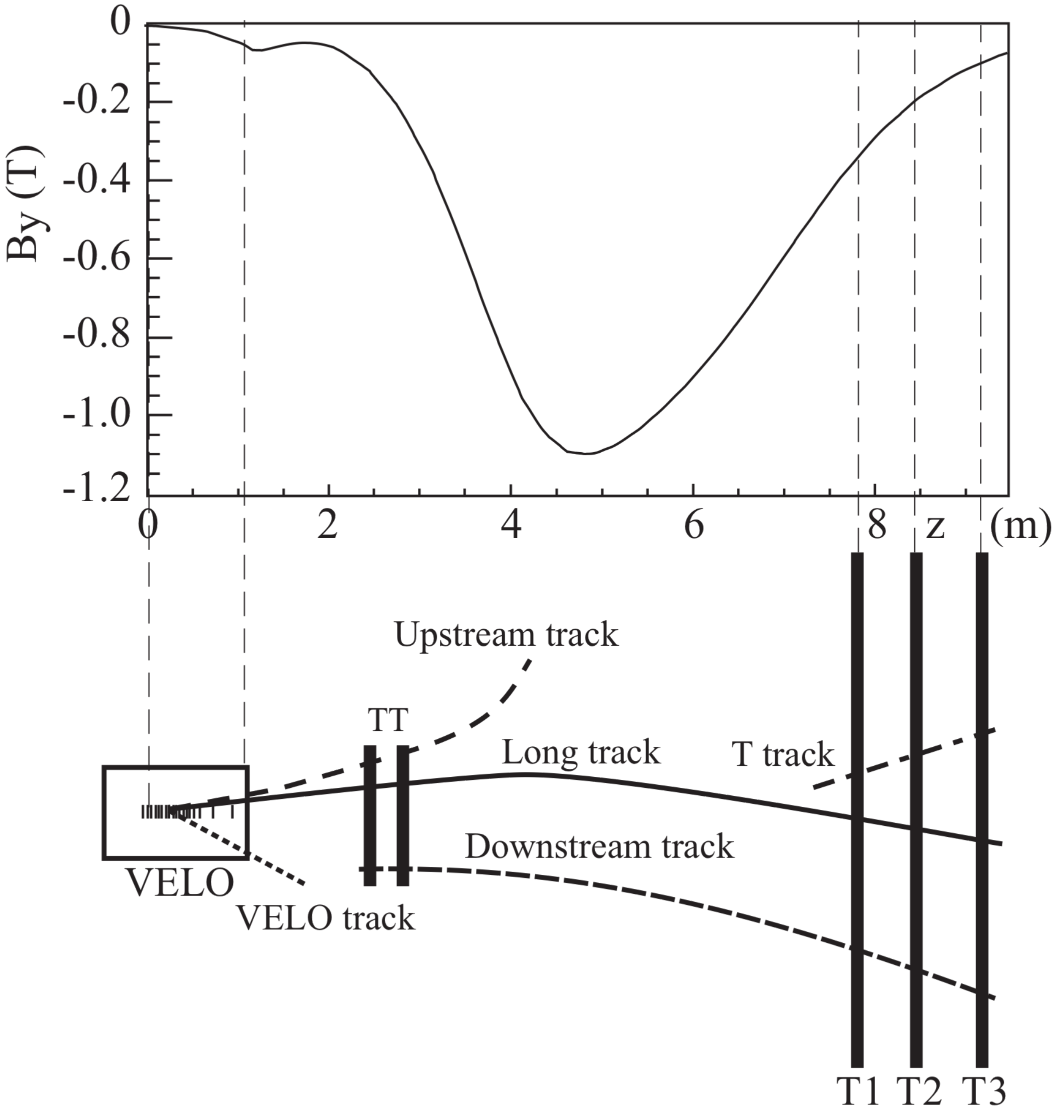
Opened at injection



Closed when stable beam declared

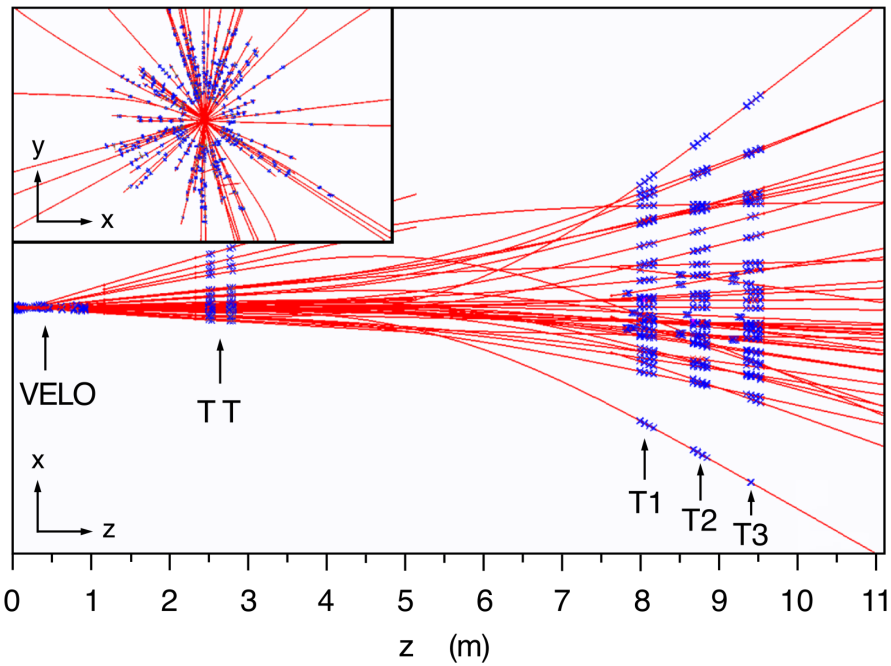


Track reconstruction

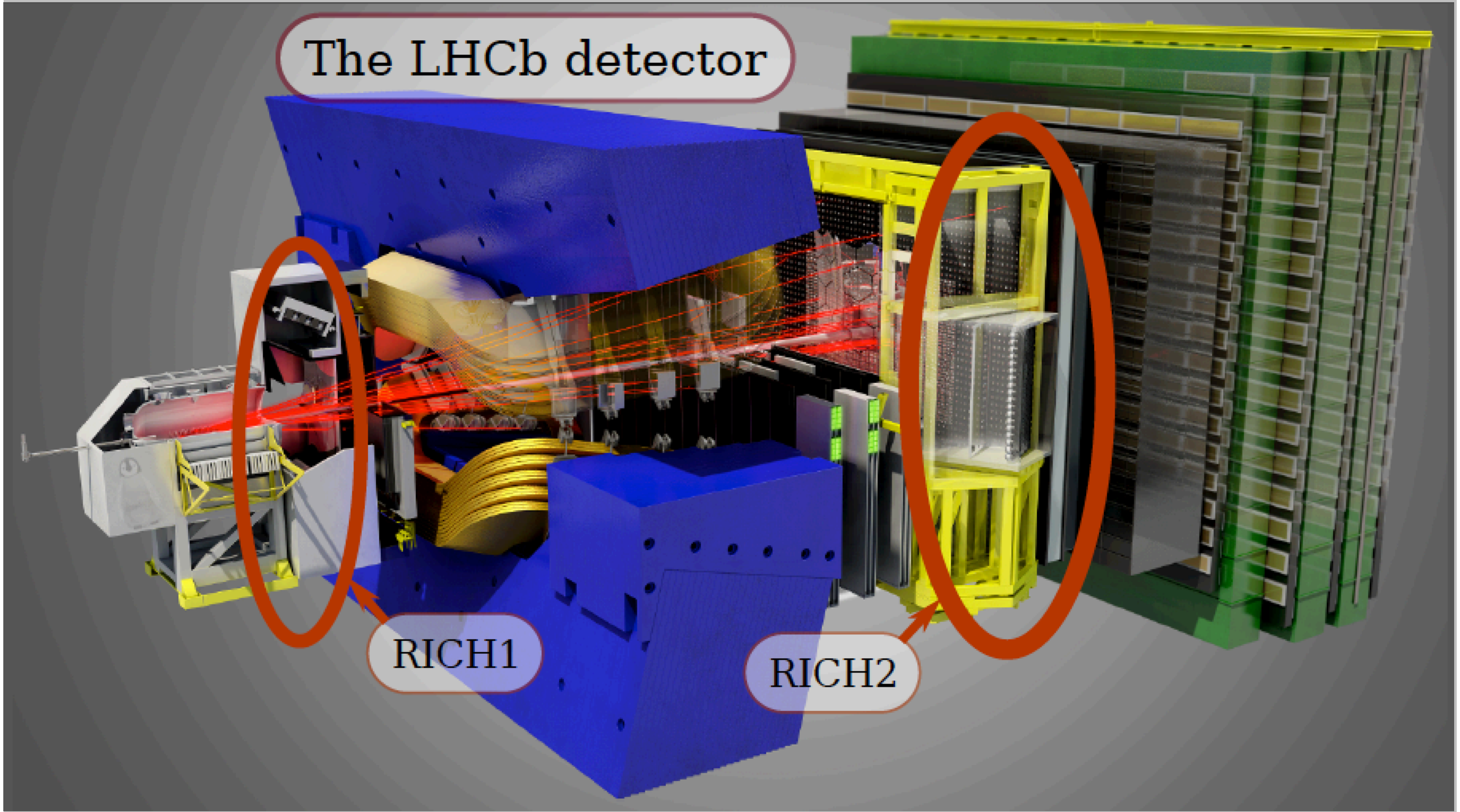


Dipole magnet implies an intrinsic charge asymmetry (left-right differences in the detector).

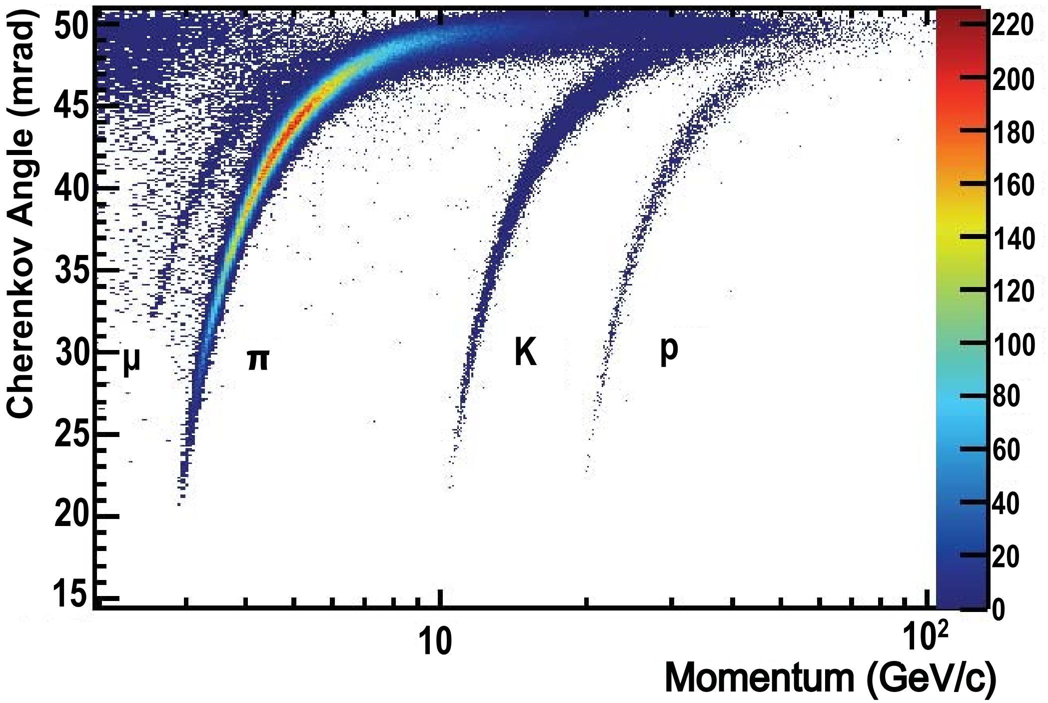
Direction of magnetic field changed regularly and data sets combined.

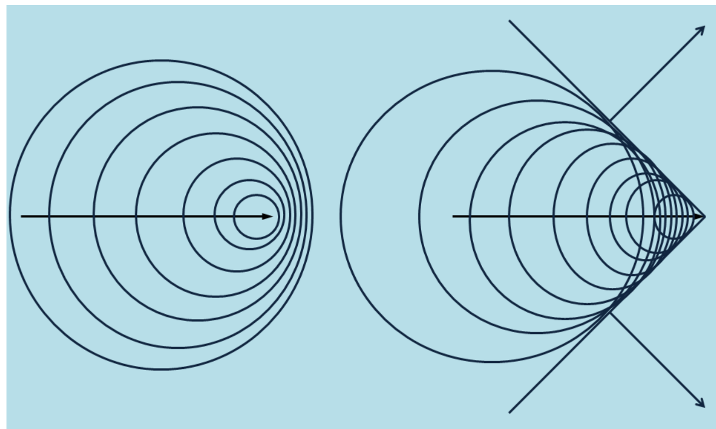


LHCb detector: RICHs

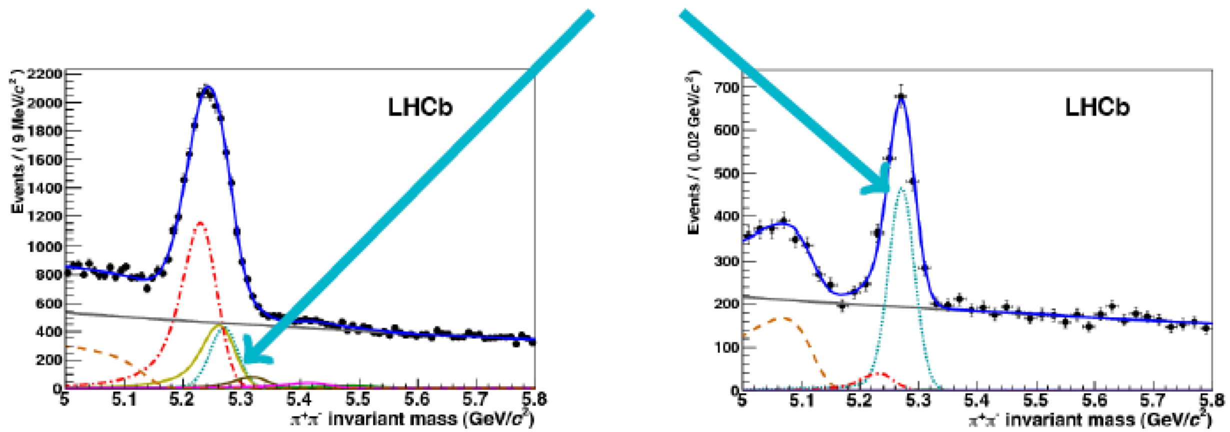


Cherenkov effect





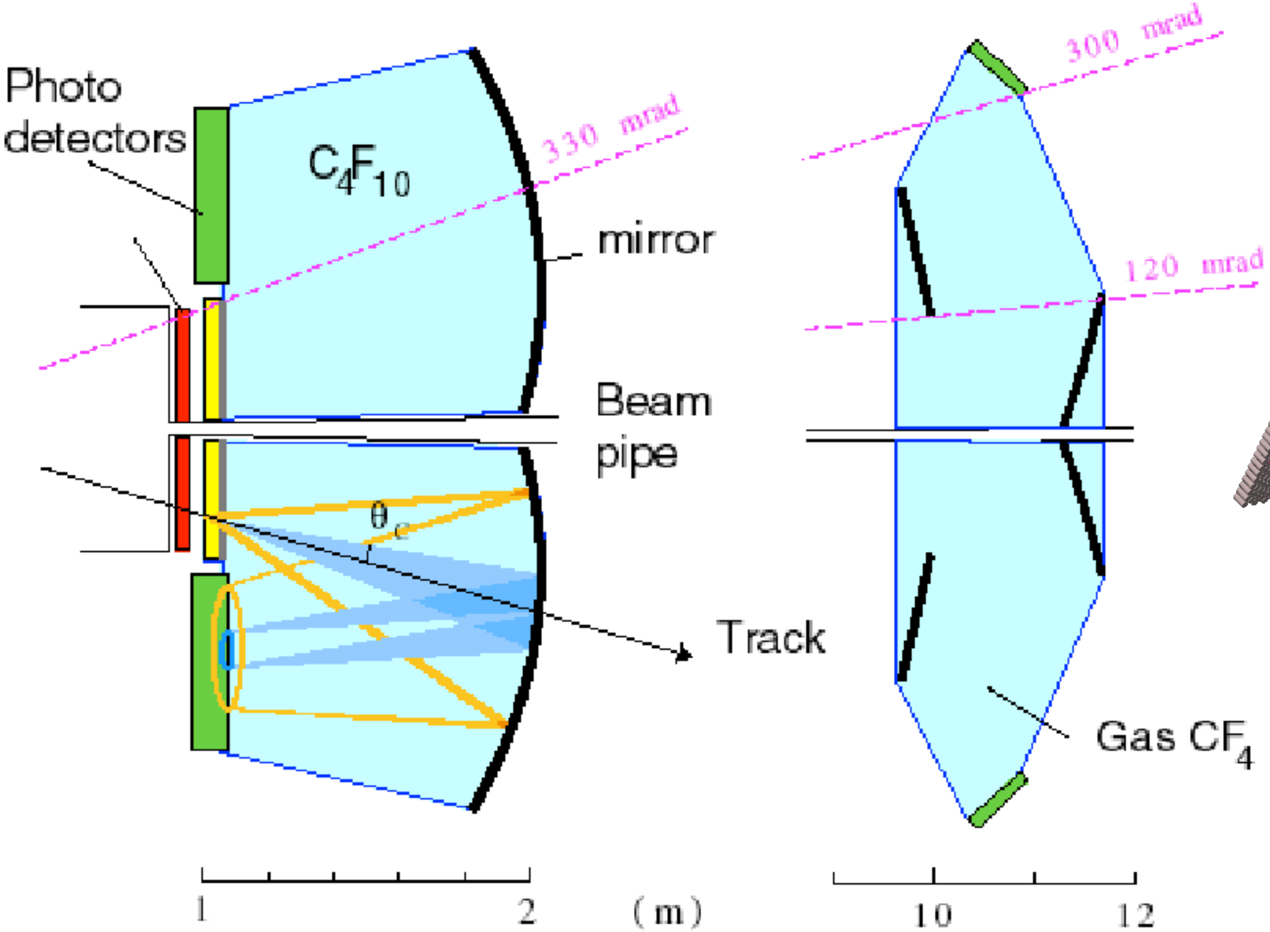
Without PID cuts Signal With PID cuts

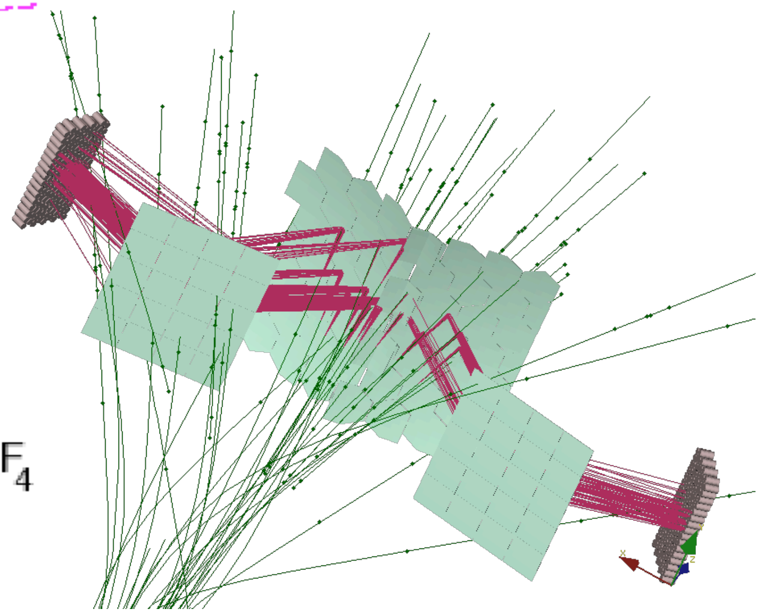


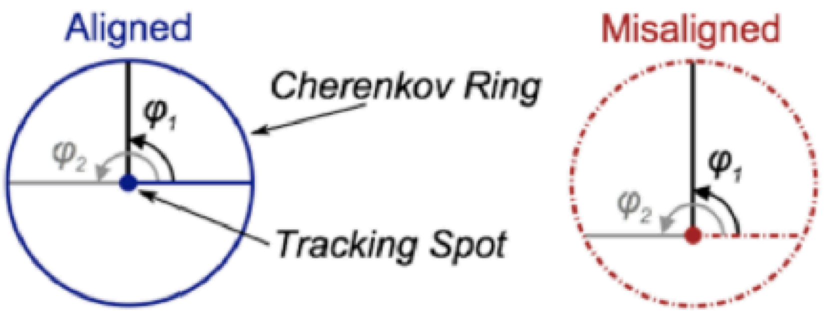
Invariant mass distribution for $B^0 \to \pi\pi$ decay ($B^0 \to \pi\pi$, $B^0 \to K\pi$, $B^0 \to$ 3-bodies, $B_s \to KK$, $B_s \to K\pi$, $\Lambda_b \to pK$, $\Lambda_b \to p\pi$)

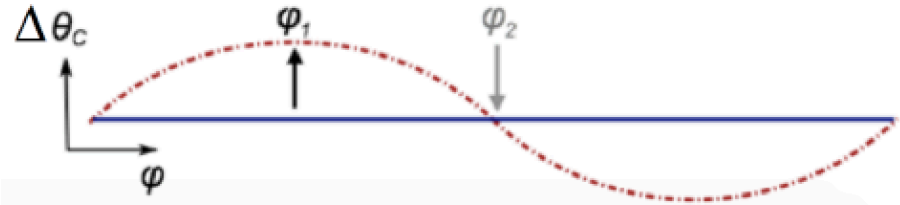
[Performance of the LHCb RICH detector Eur.Phys.J. C73 (2013) 2431]

RICH mirrors

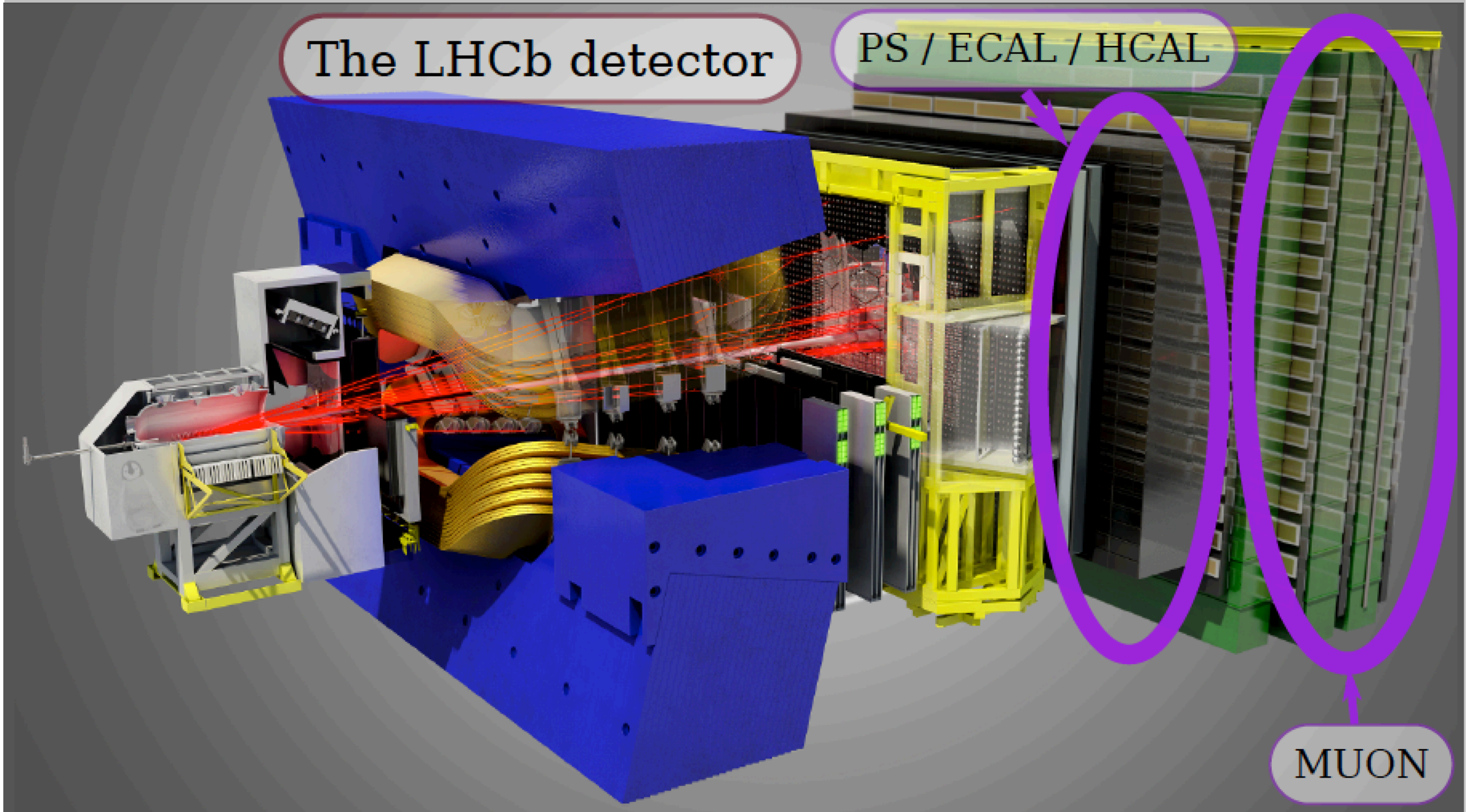




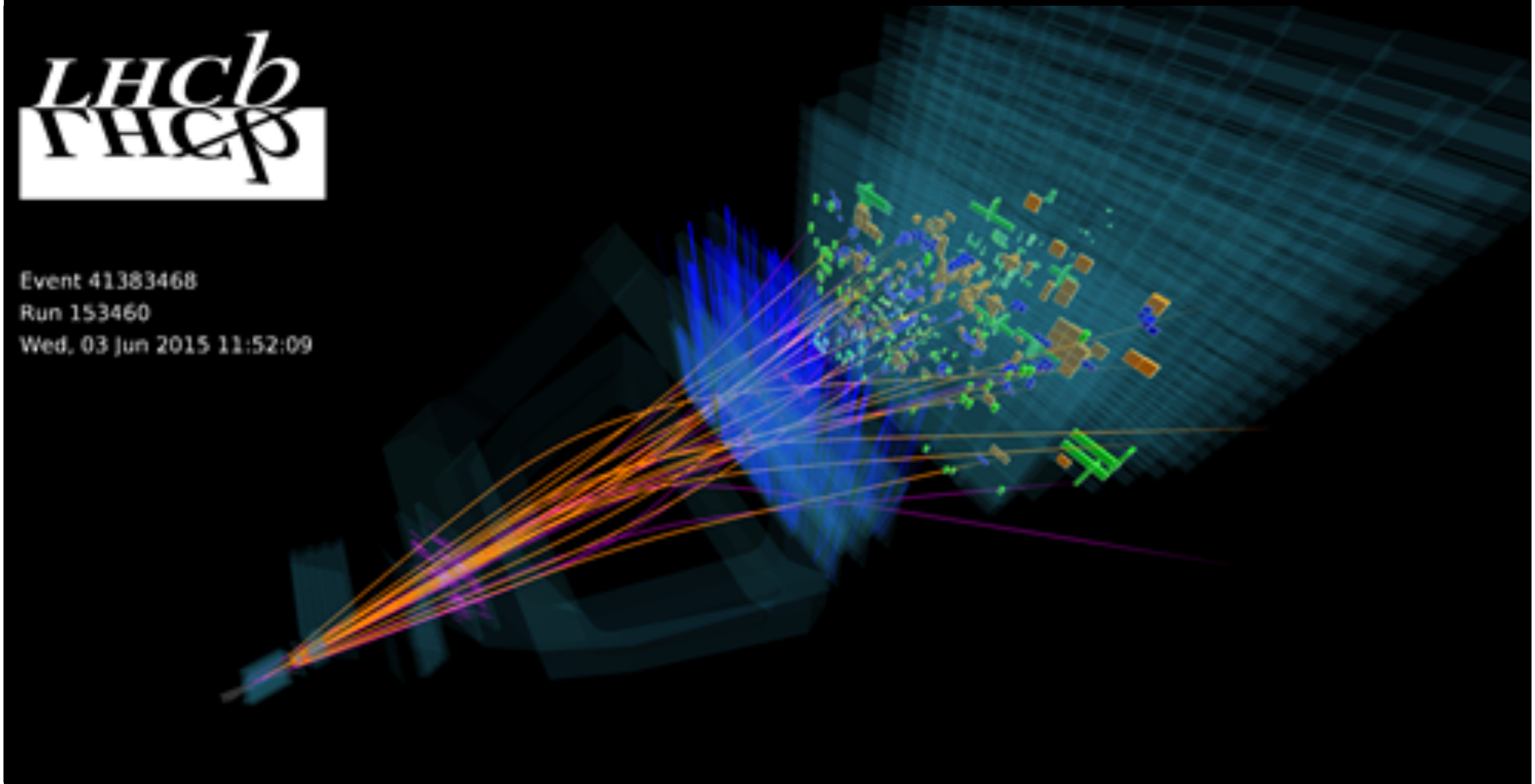




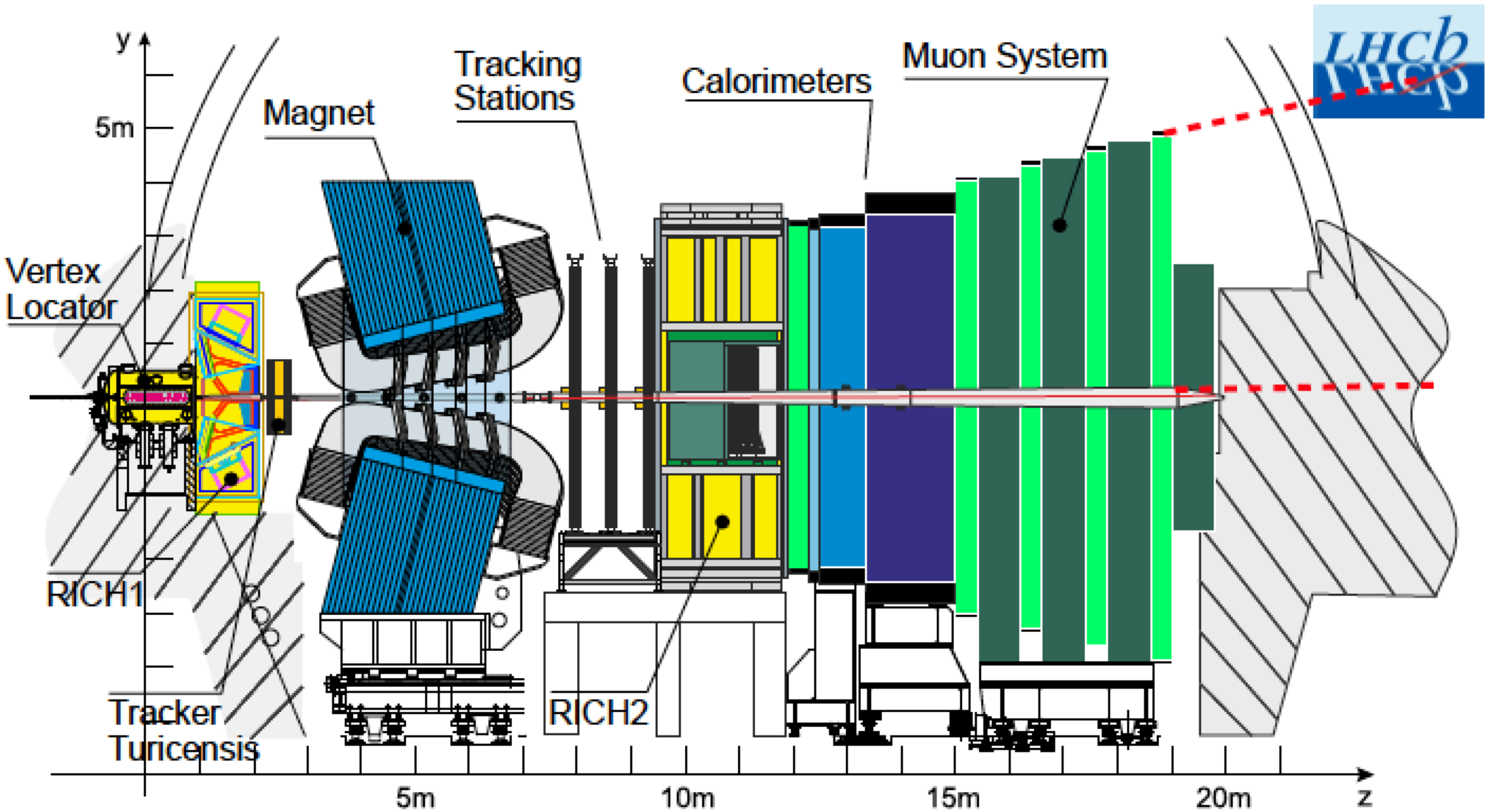
LHCb detector: calorimeter and muon systems



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:

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

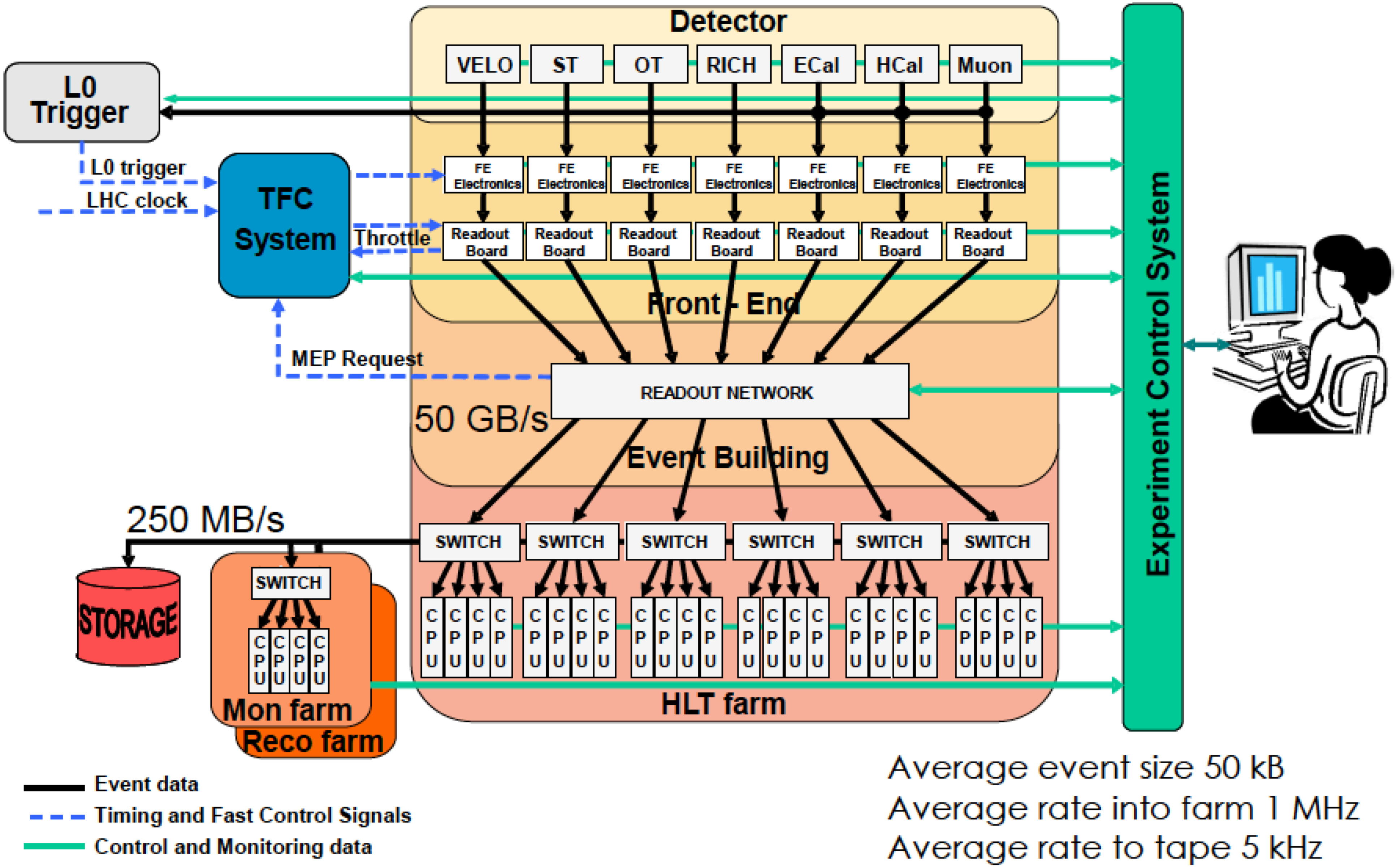
Good momentum resolution:

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

Trigger efficiency:

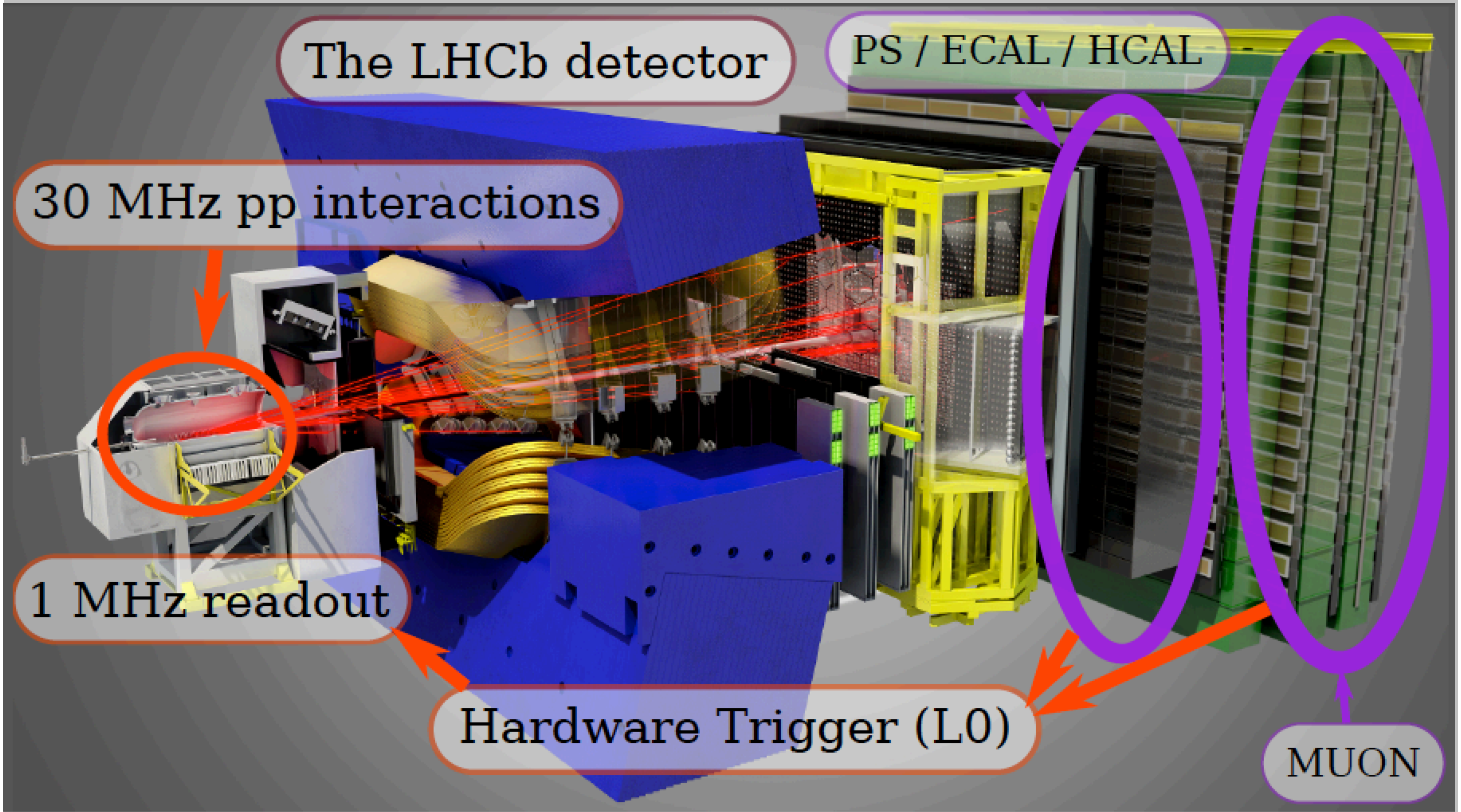
$\varepsilon_\mu = 90\%$ for selected B decays

Collect data (DAQ)



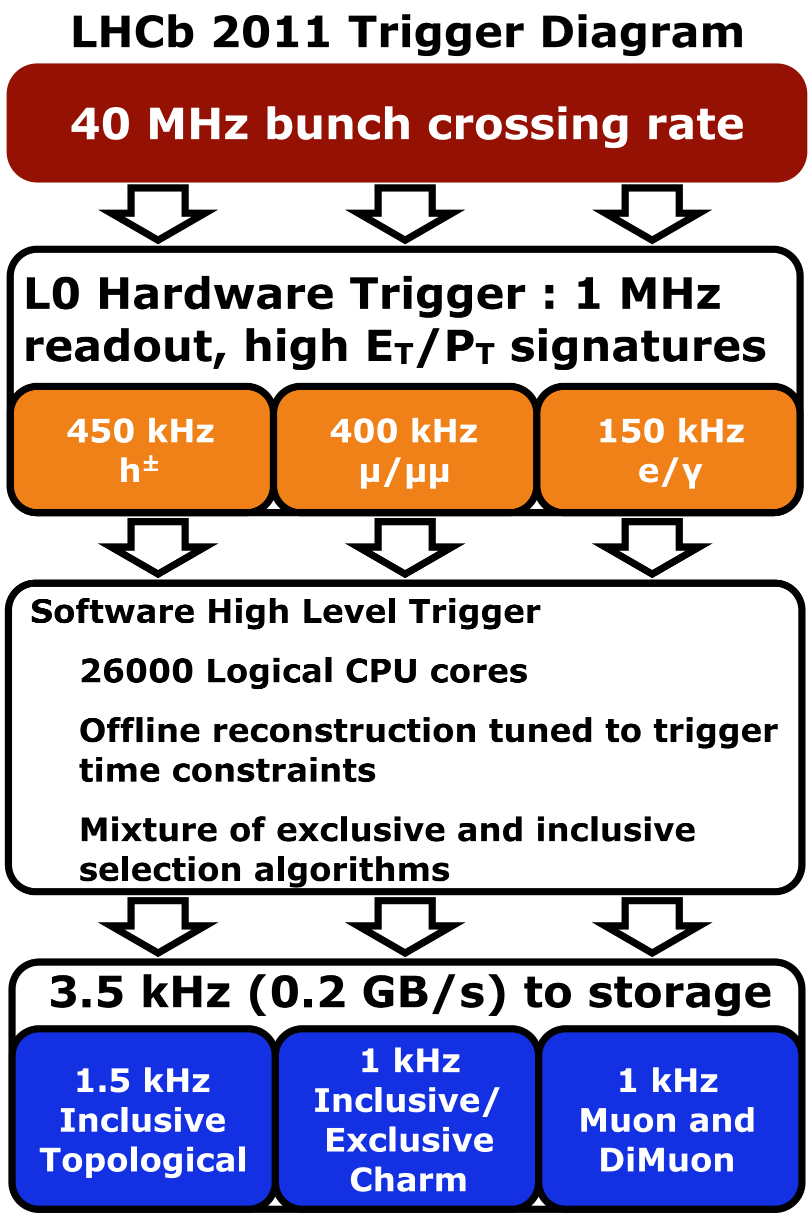
Average event size 50 kB
Average rate into farm 1 MHz
Average rate to tape 5 kHz

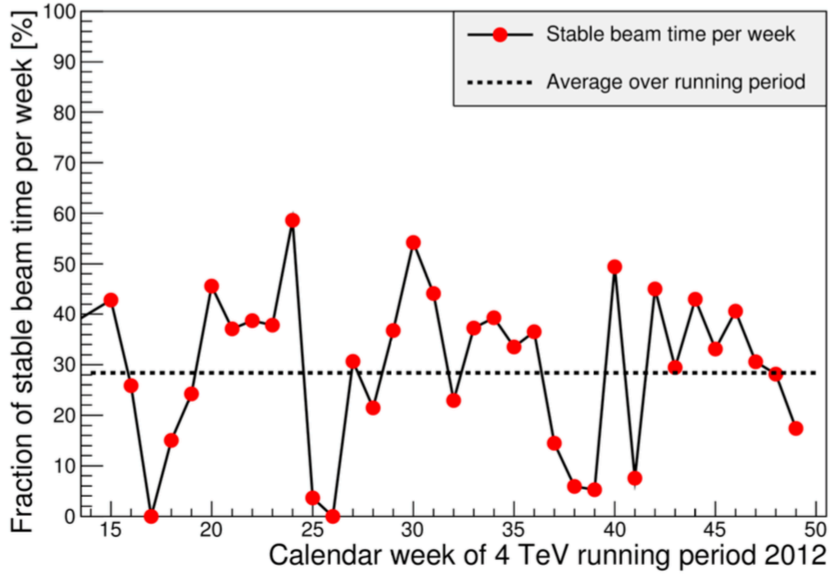
Hardware trigger



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

Trigger

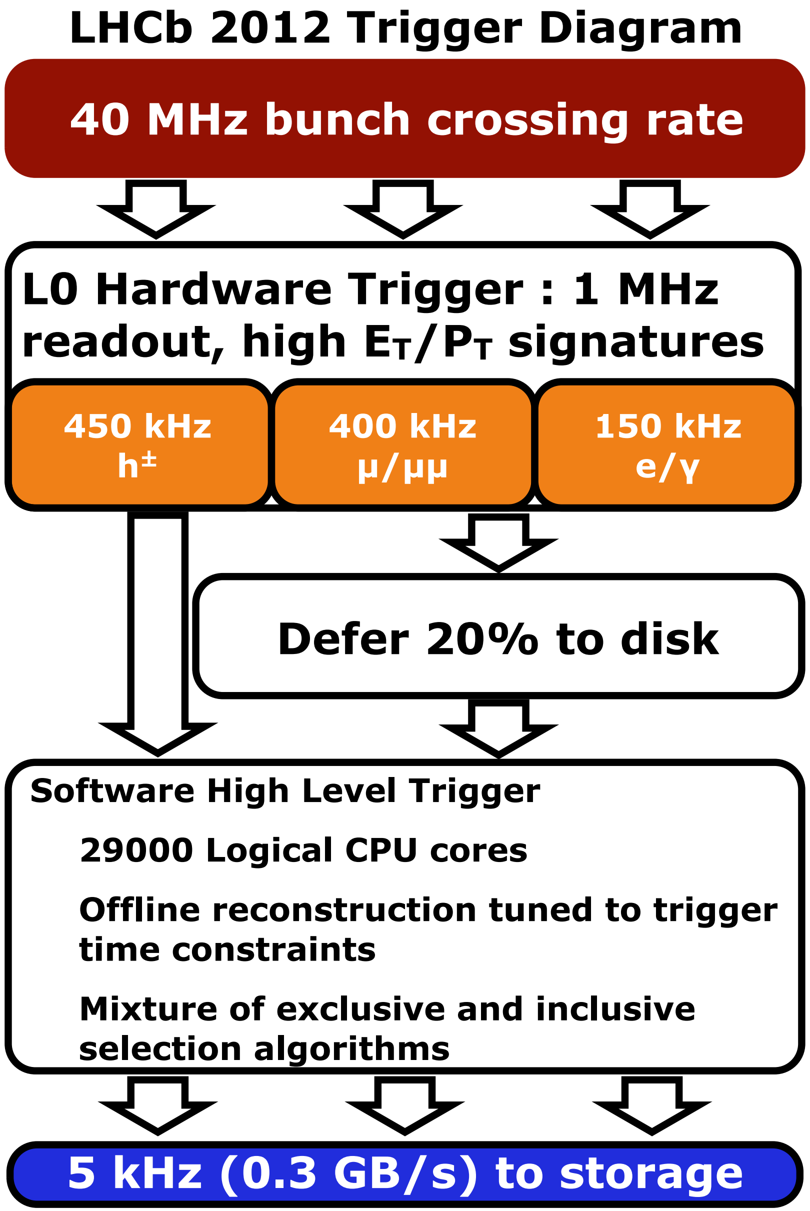


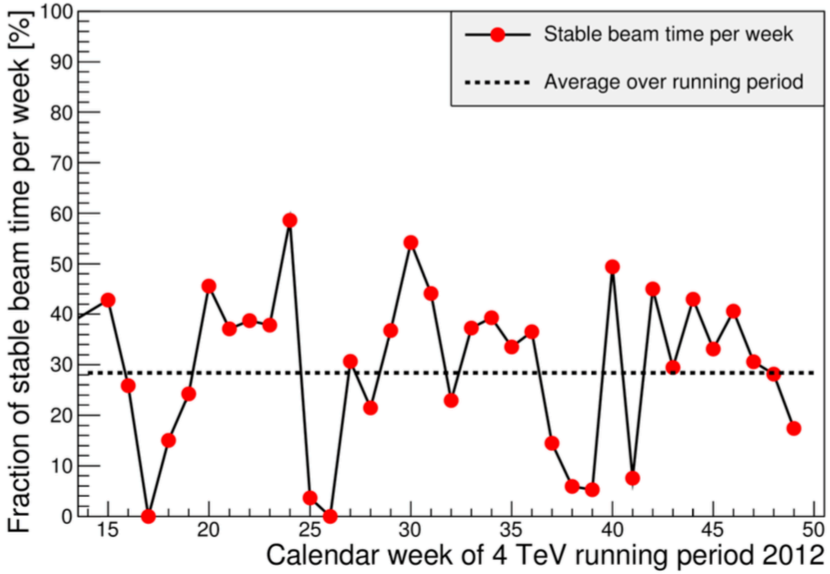


Try to defer computing needs
to time without beam

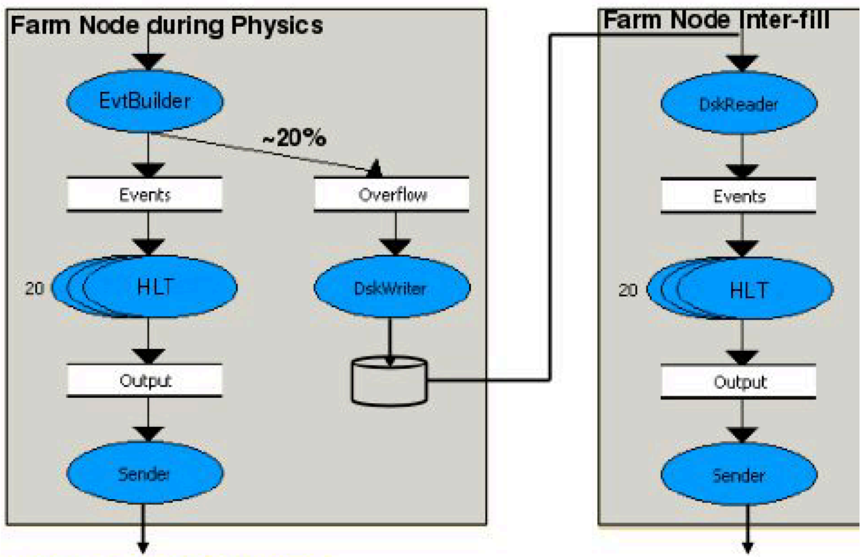
[arXiv:1211.3055; CERN-LHCb-DP-2012-004]
[arXiv:1310.8544v1]

Trigger

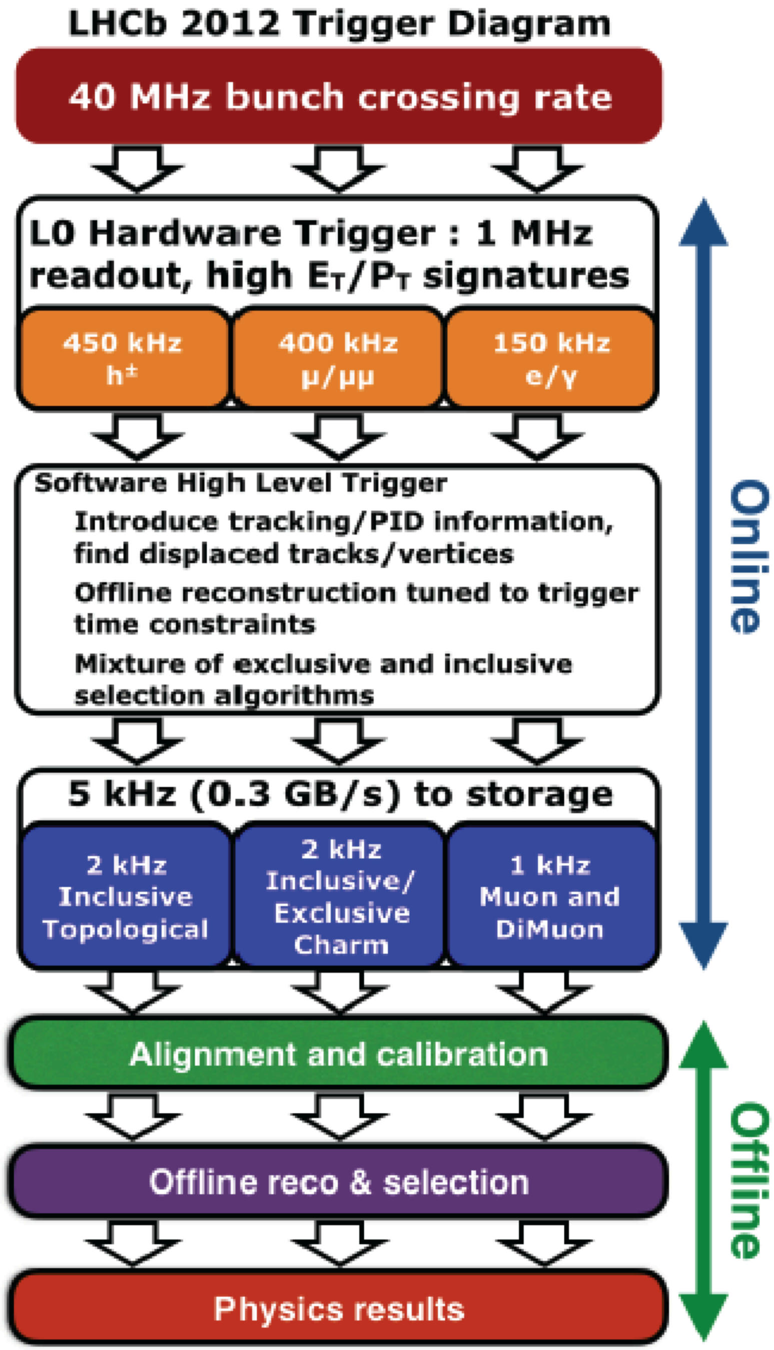




Deferred HLT



Trigger



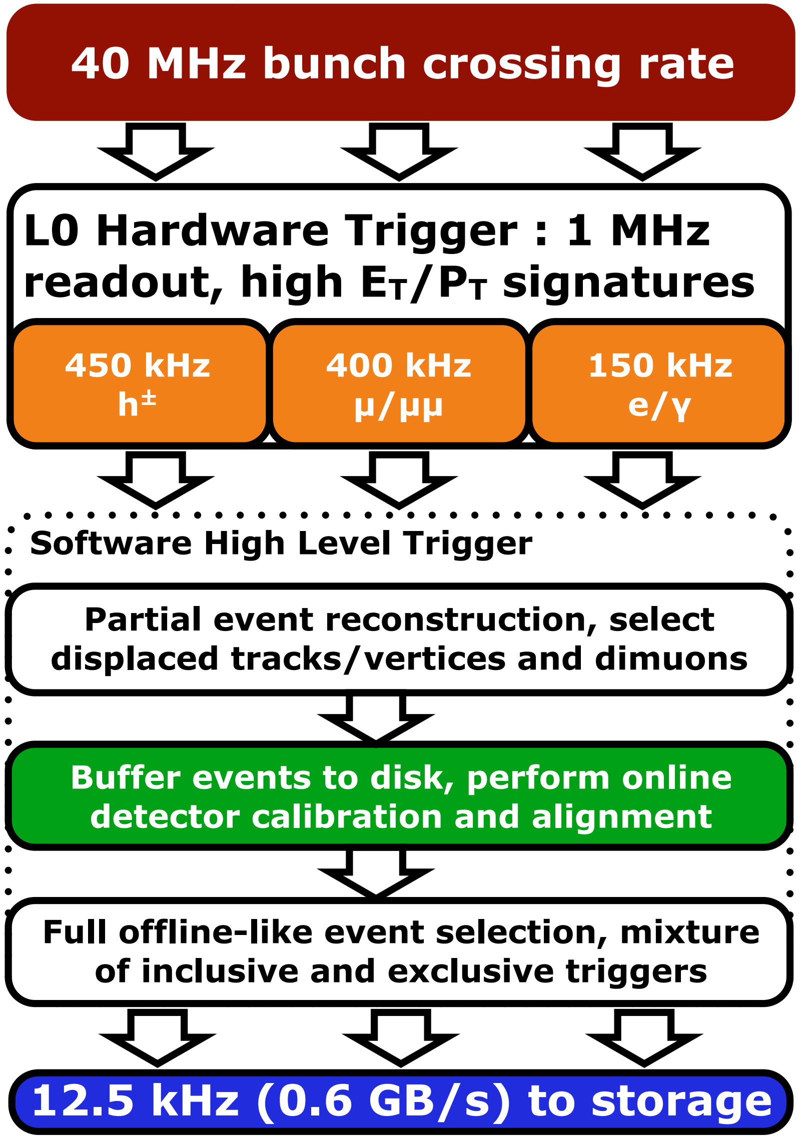
[“All I’m saying is <u>now</u> is the time to develop the technology to deflect an asteroid.”]
“All I’m saying is <u>now</u> is the time to run data reconstruction only once.”

~50k logical cores
~5PiB disk space

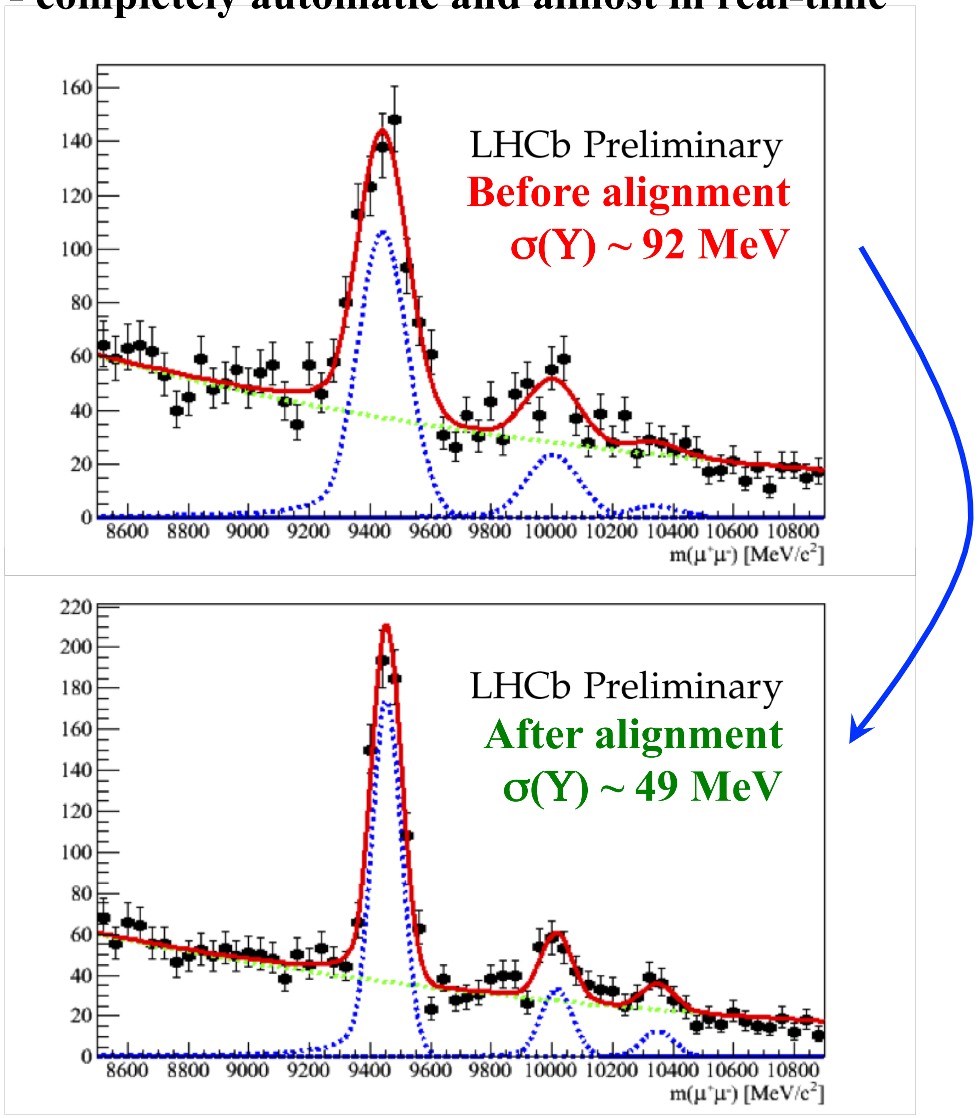
Trigger

since 2015

LHCb 2015 Trigger Diagram

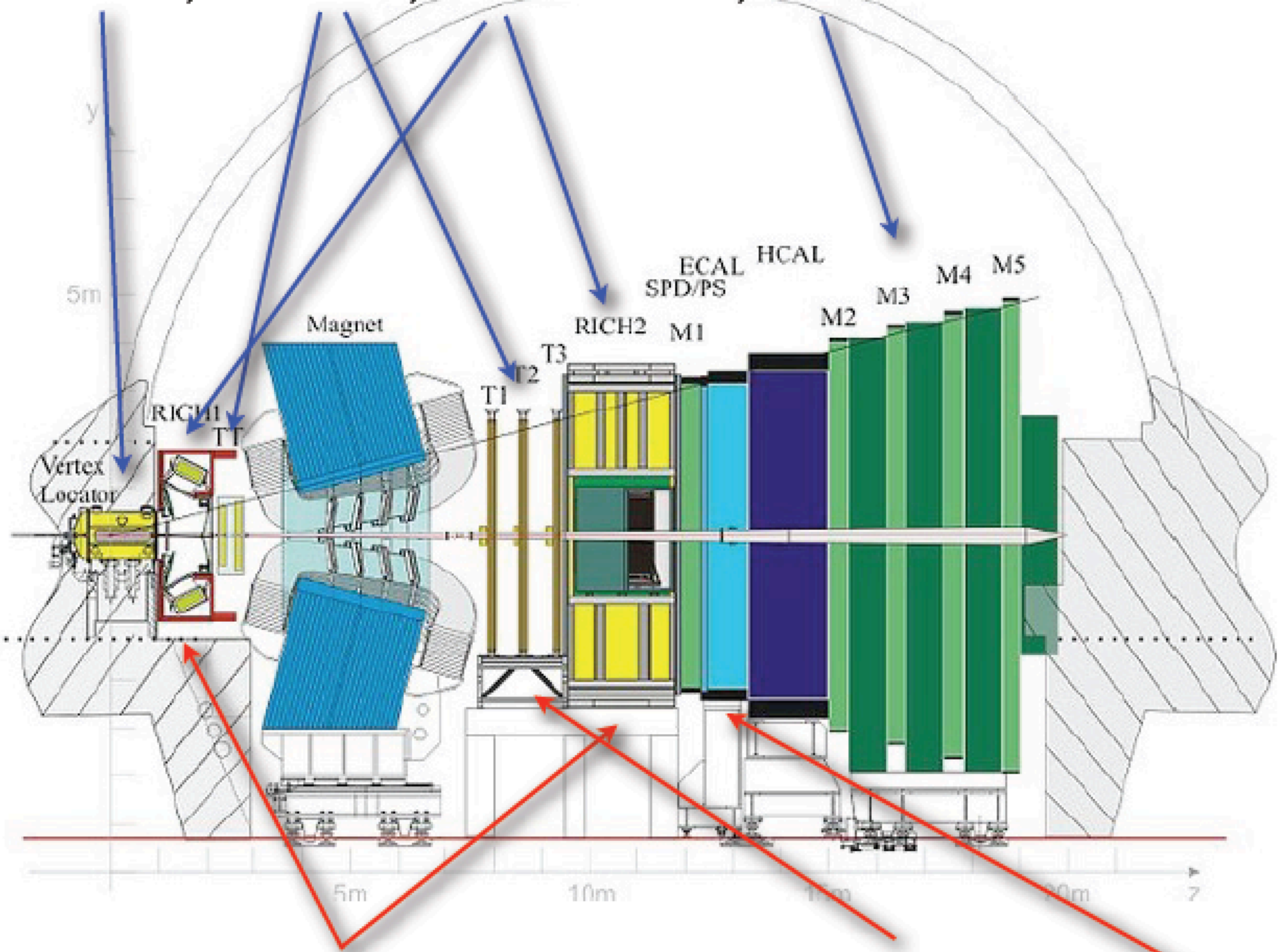


Same online and offline reconstruction and PID
- prompt alignment and calibration
- completely automatic and almost in real-time



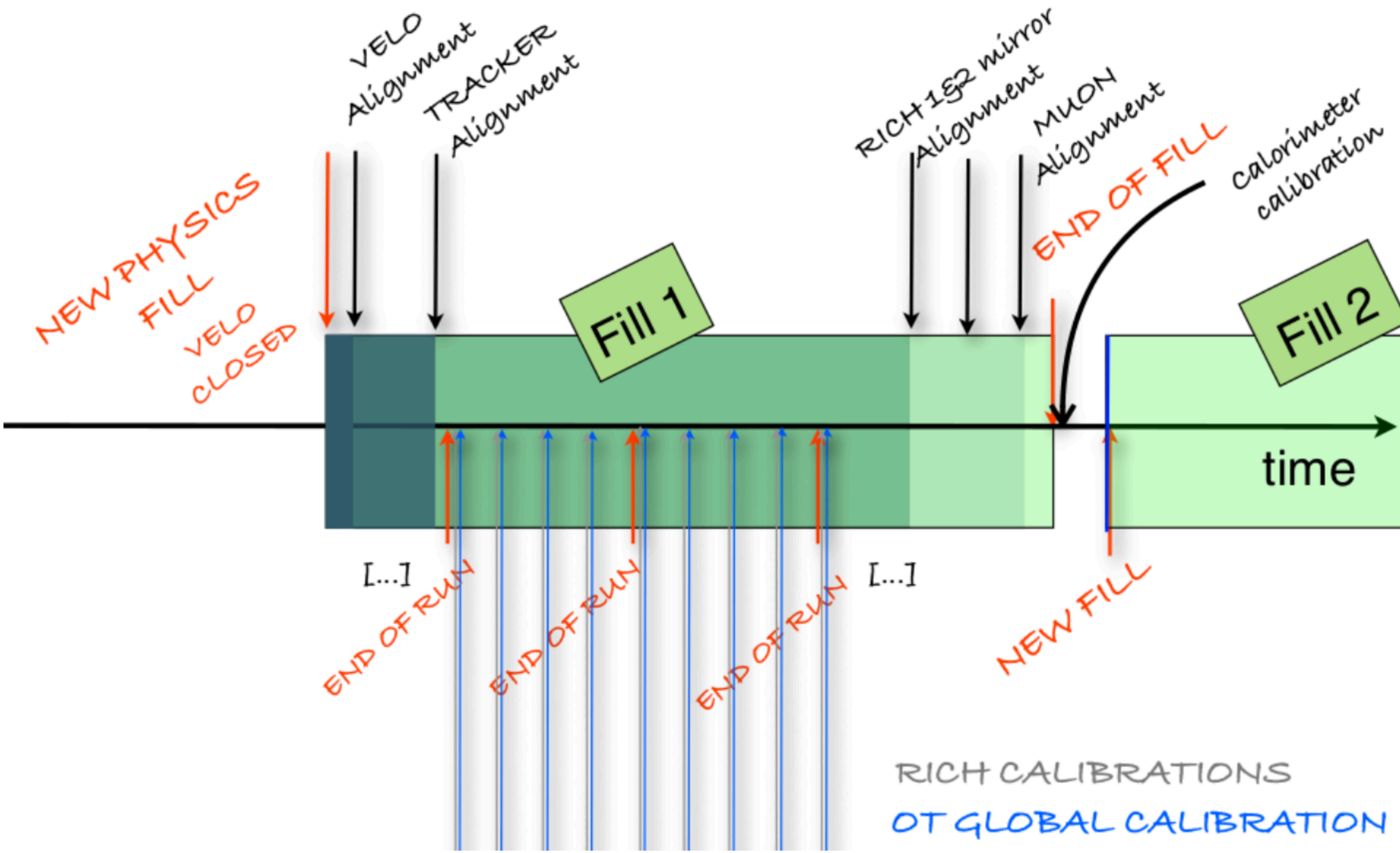
Real-time alignment and calibration

- Alignments: VELO, Trackers, RICH mirrors, Muon



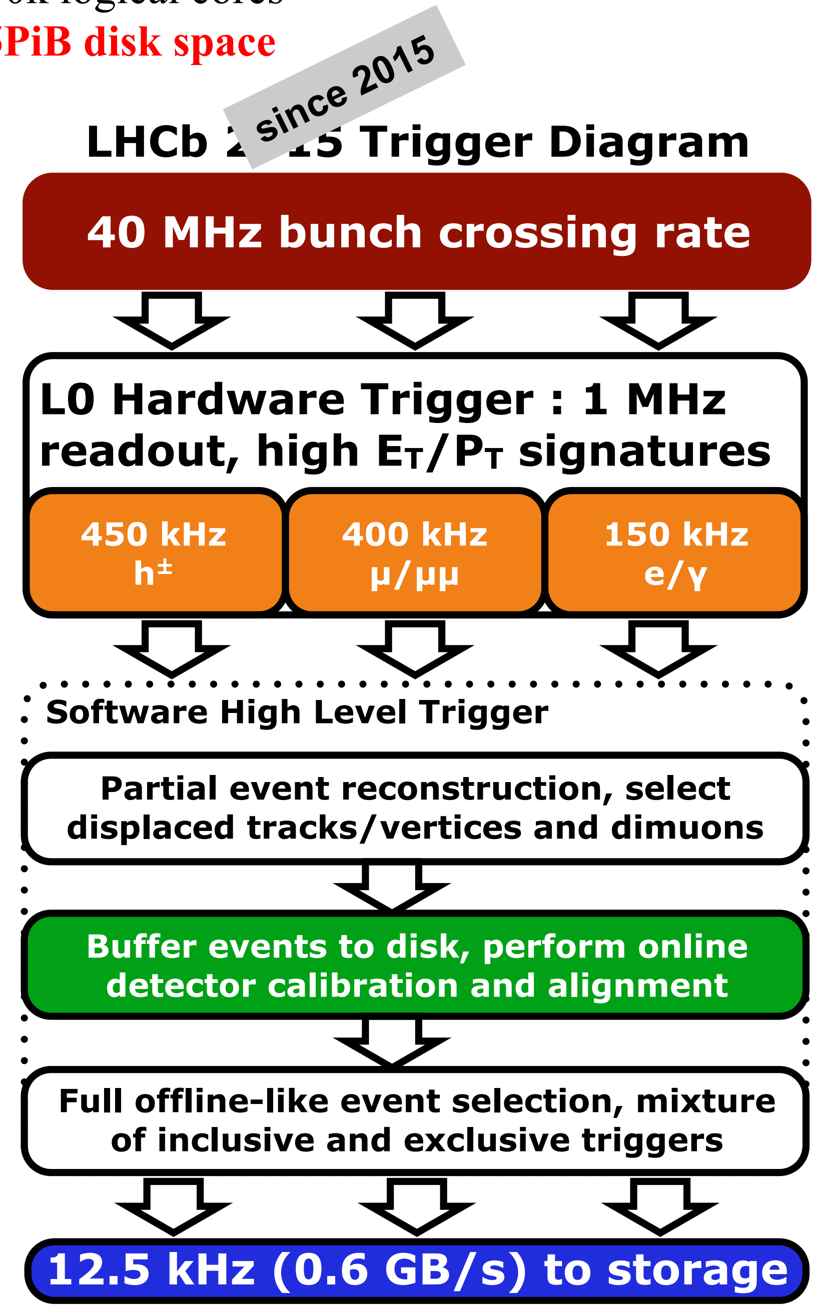
- Calibrations: RICH refractive index and HPDs, OT time, Calorimeters

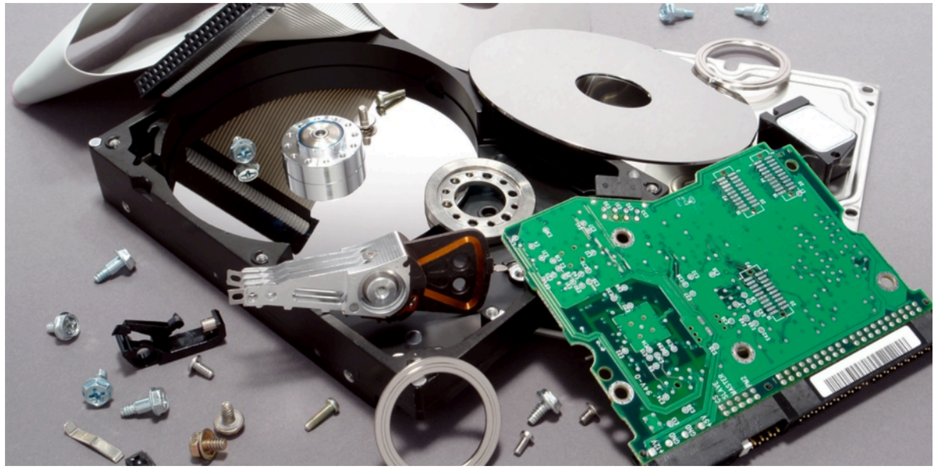
Almost real-time alignment and calibration



Trigger buffer

~50k logical cores
~5PiB disk space





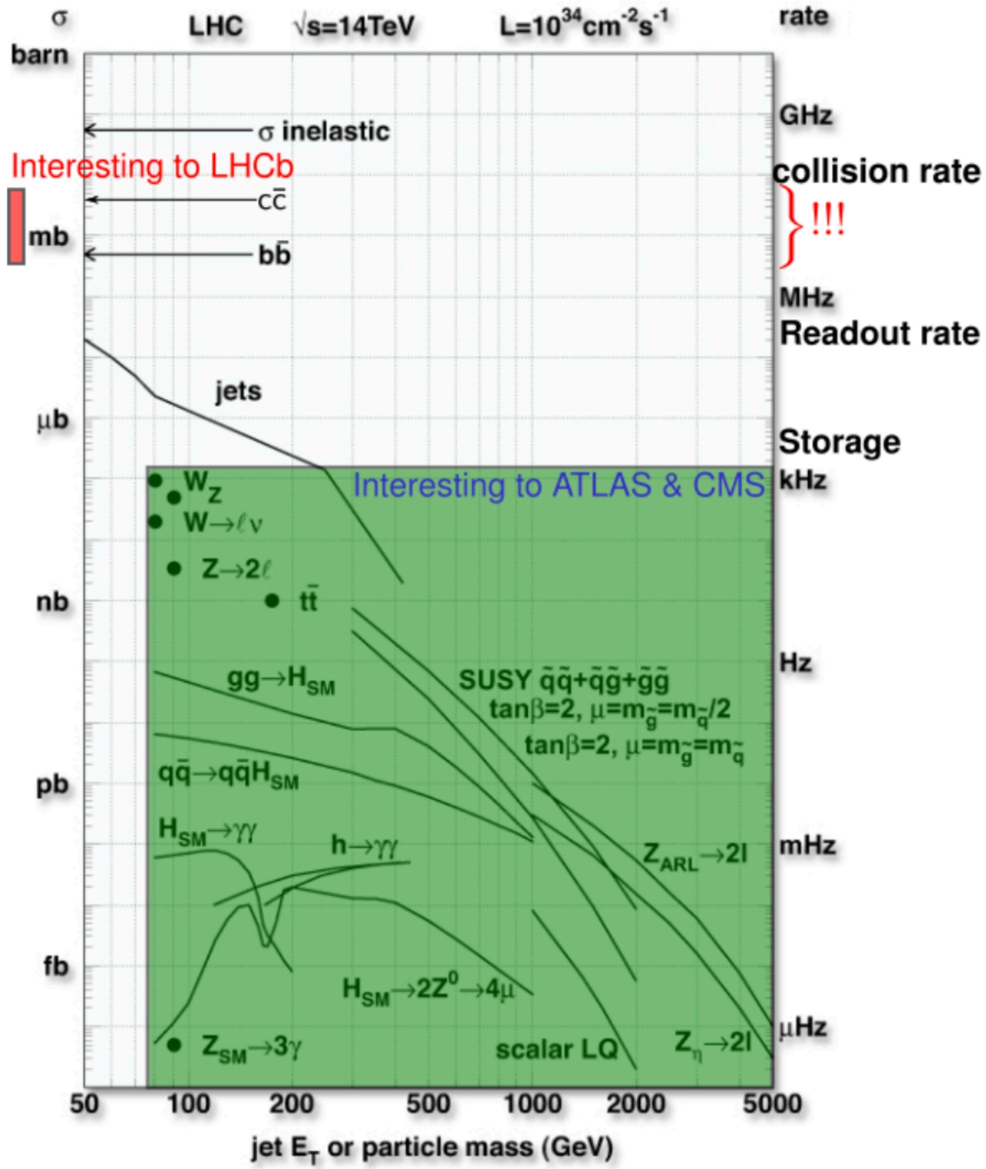
From 2015 experience, ~1 disk per day is replaced due to unrecoverable errors: until 2015, mirror the 5 PiB of disk space in a second chunk of 5 PiB disks.

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.

Trigger (Interlude)

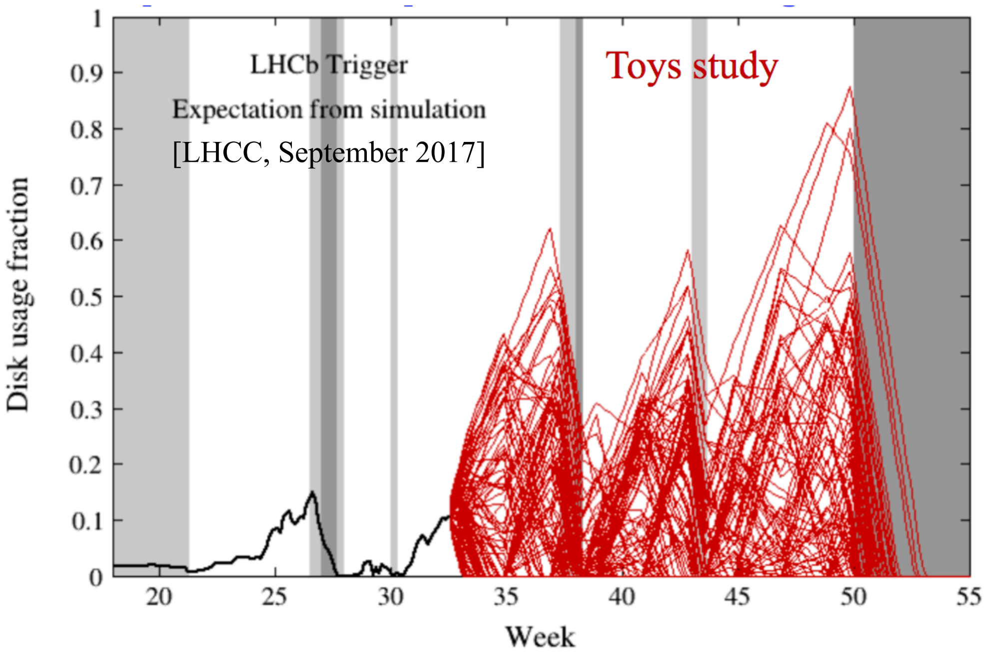
- A trigger is needed to reduce storage and readout costs
- A *good* trigger does so by keeping more signal than background
- ATLAS and CMS are interested in signatures in the kHz region
  - Readout at 100kHz is efficient with reasonably straightforward E_T requirements
- LHCb operates at $\mathfrak{L} = 4 \times 10^{32}\text{cm}^{-2}\,\text{s}^{-1}$ 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 $\mathfrak{L} = 2 \times 10^{33}\text{cm}^{-2}\,\text{s}^{-1}$ in Run 3...

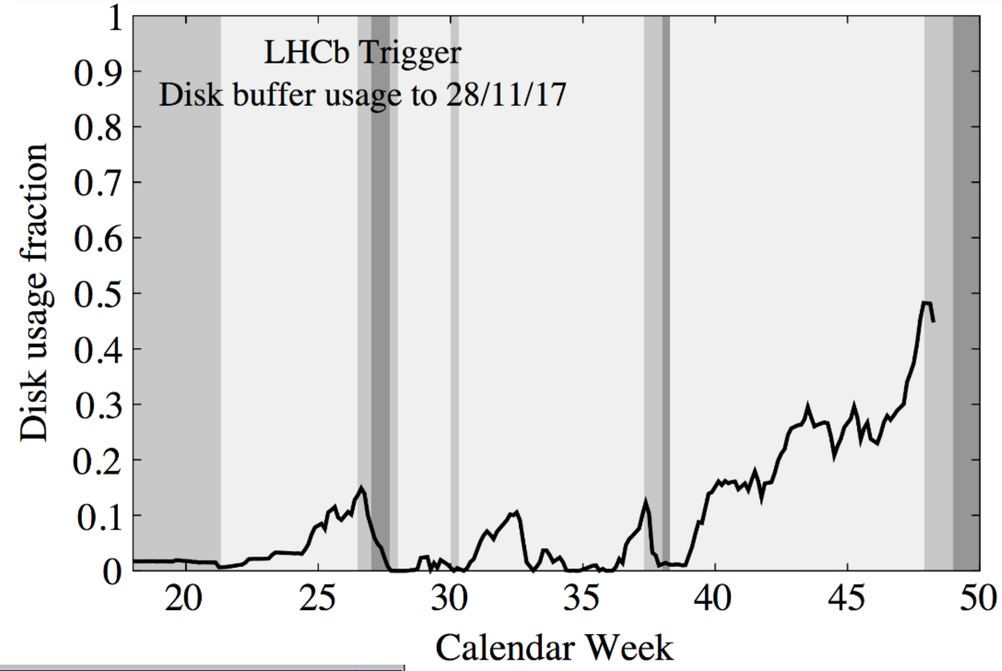


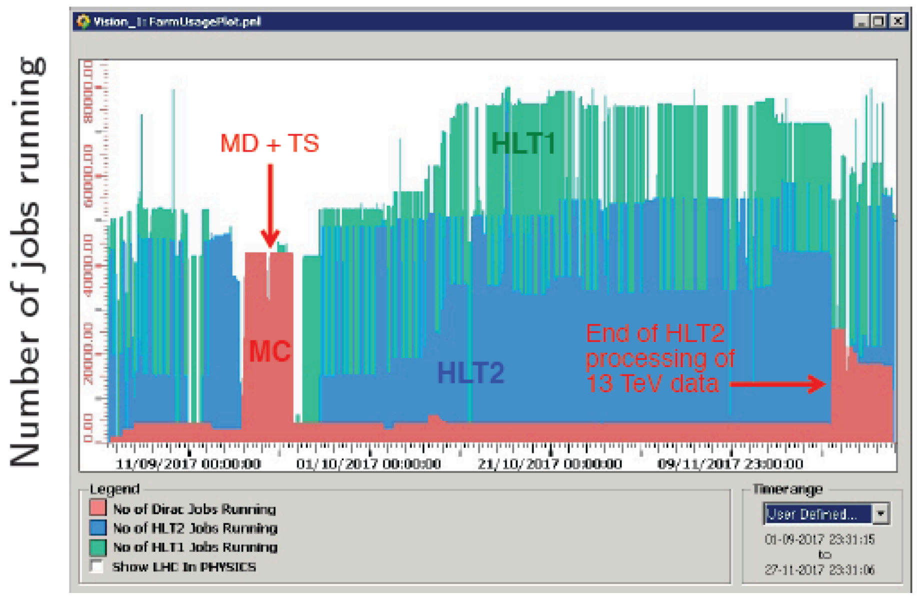
~50k logical cores

~10PiB disk space

Trigger and online farm



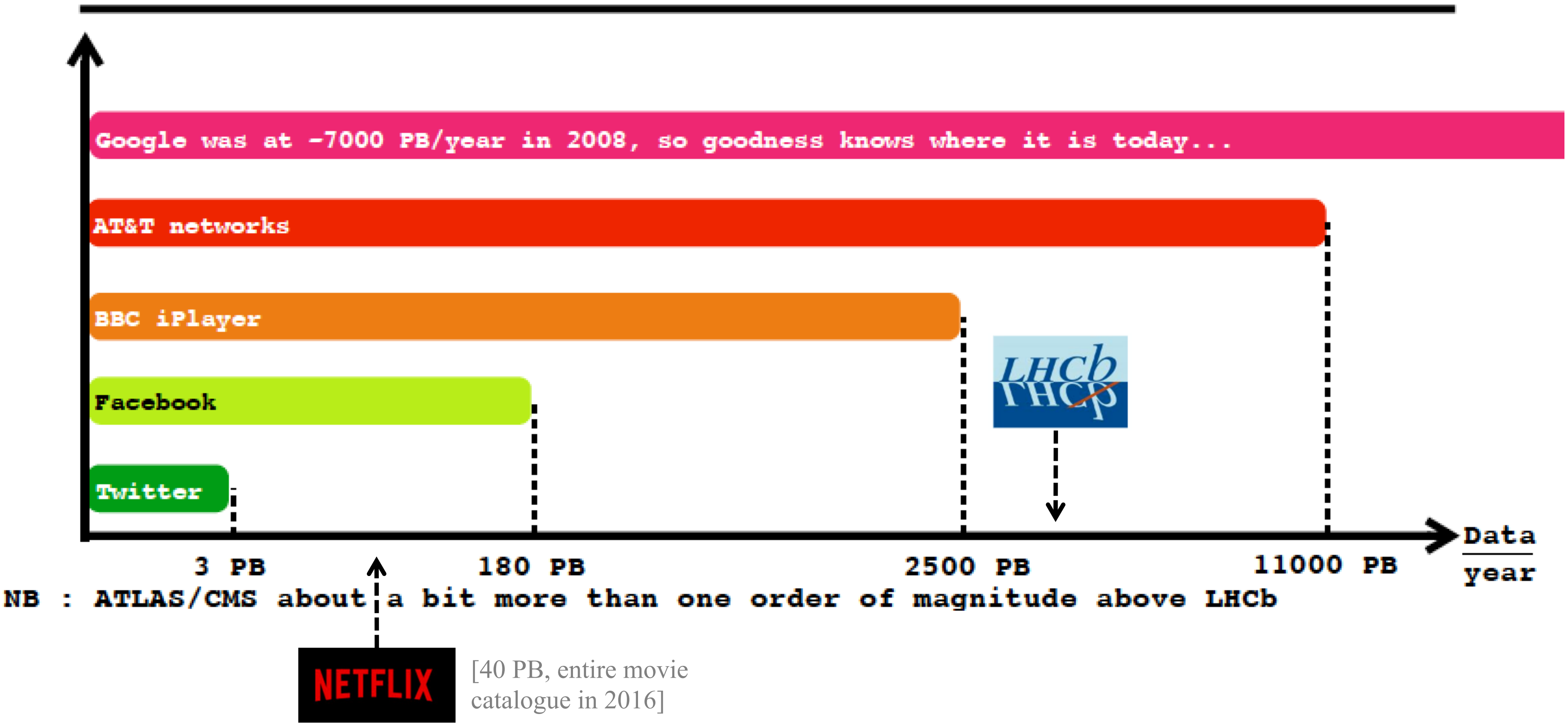




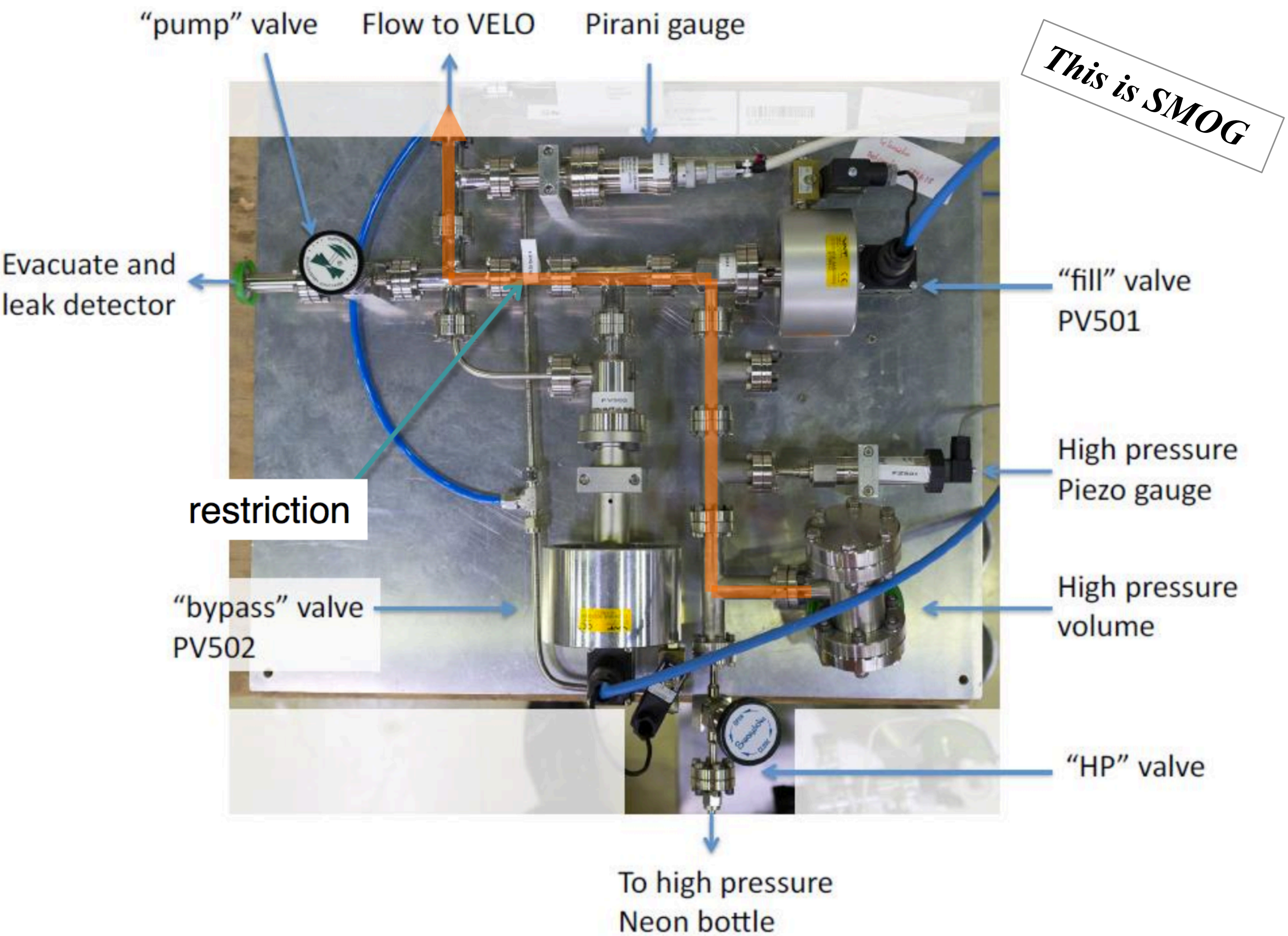
A lot of data… (Interlude)

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

This means about 4000 PB of data every year



System for Measuring the Overlap with Gas



SMOG: Beam Gas Imaging

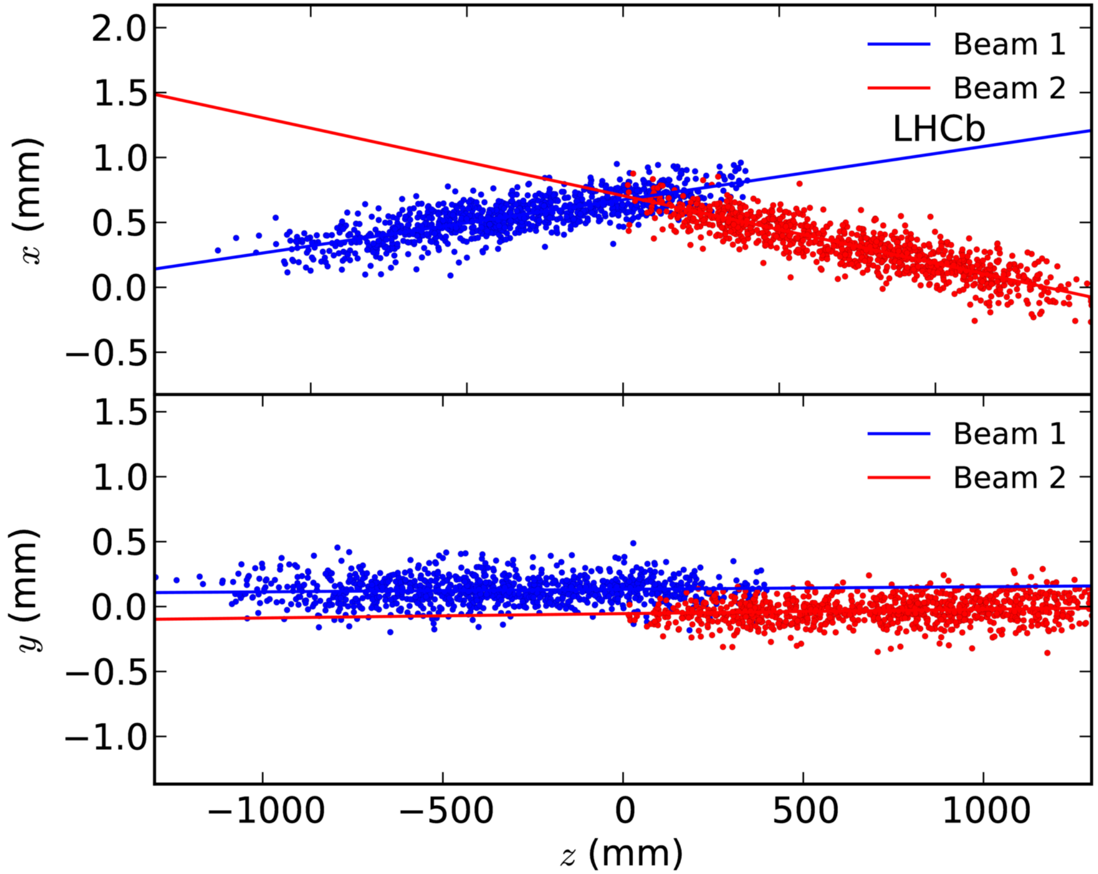
$$N = L\sigma$$

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

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

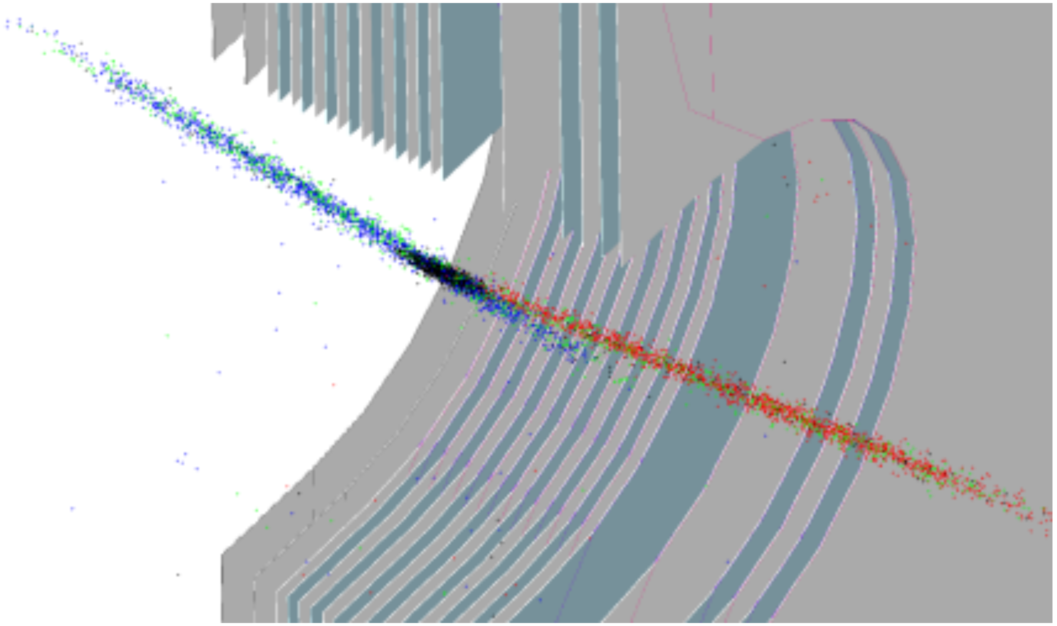
Original idea: determine luminosity by measuring beam profiles through beam-gas interaction (BGI).

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



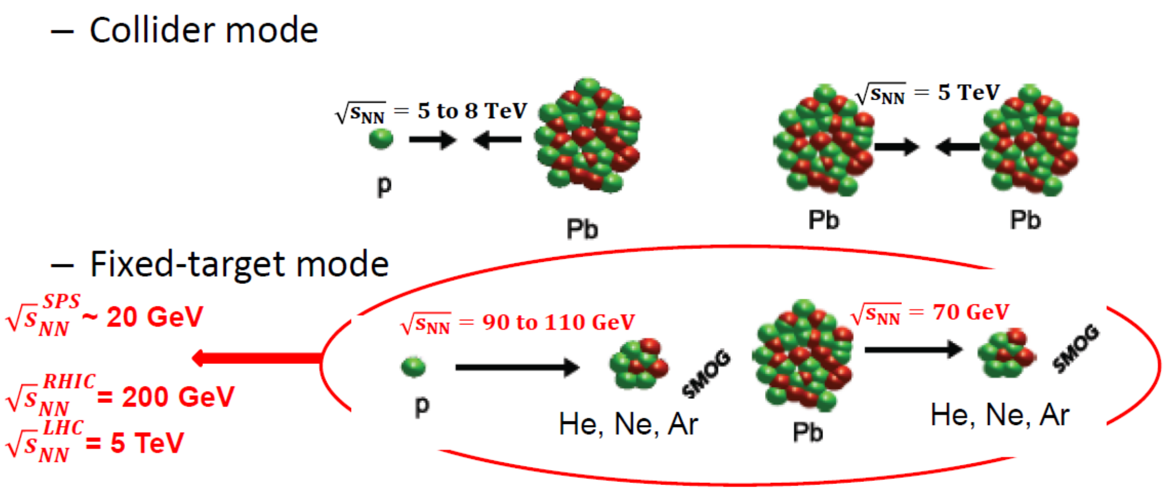
[arXiv:1410.0149 [hep-ex]]

SMOG: fixed target physics



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

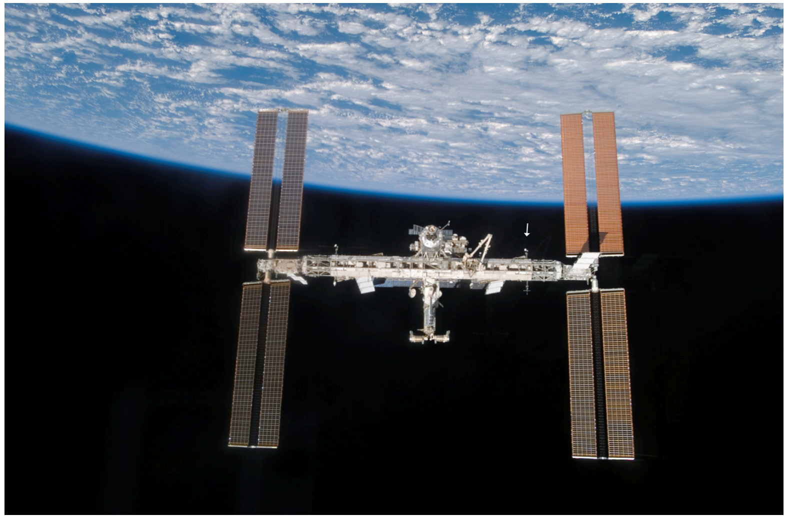
Pressure of injected gas 1-2 $\times 10^{-7}$ mbar
gas removed by two pumps at 20 m;
only noble gases can be used (He, Ne, Ar, maybe Kr and Xe toward end of run)



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

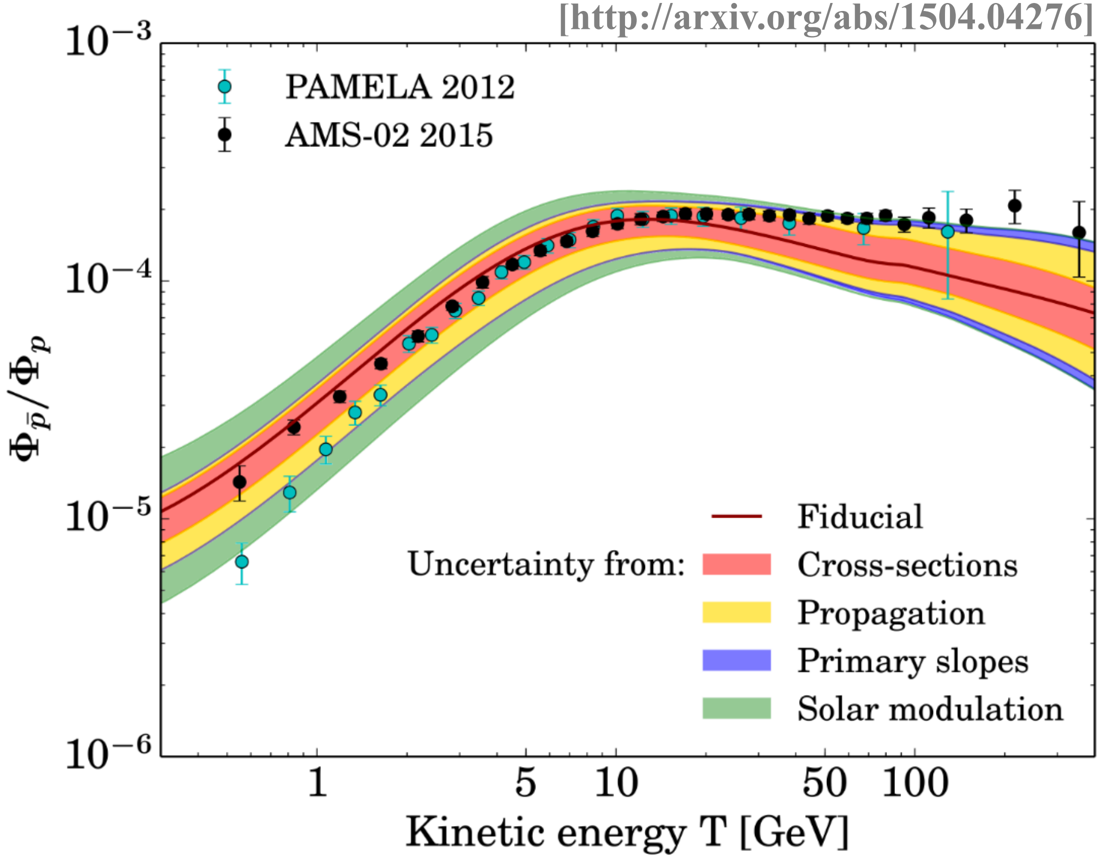
[some references in the back-up]

SMOG: LHCb in the space

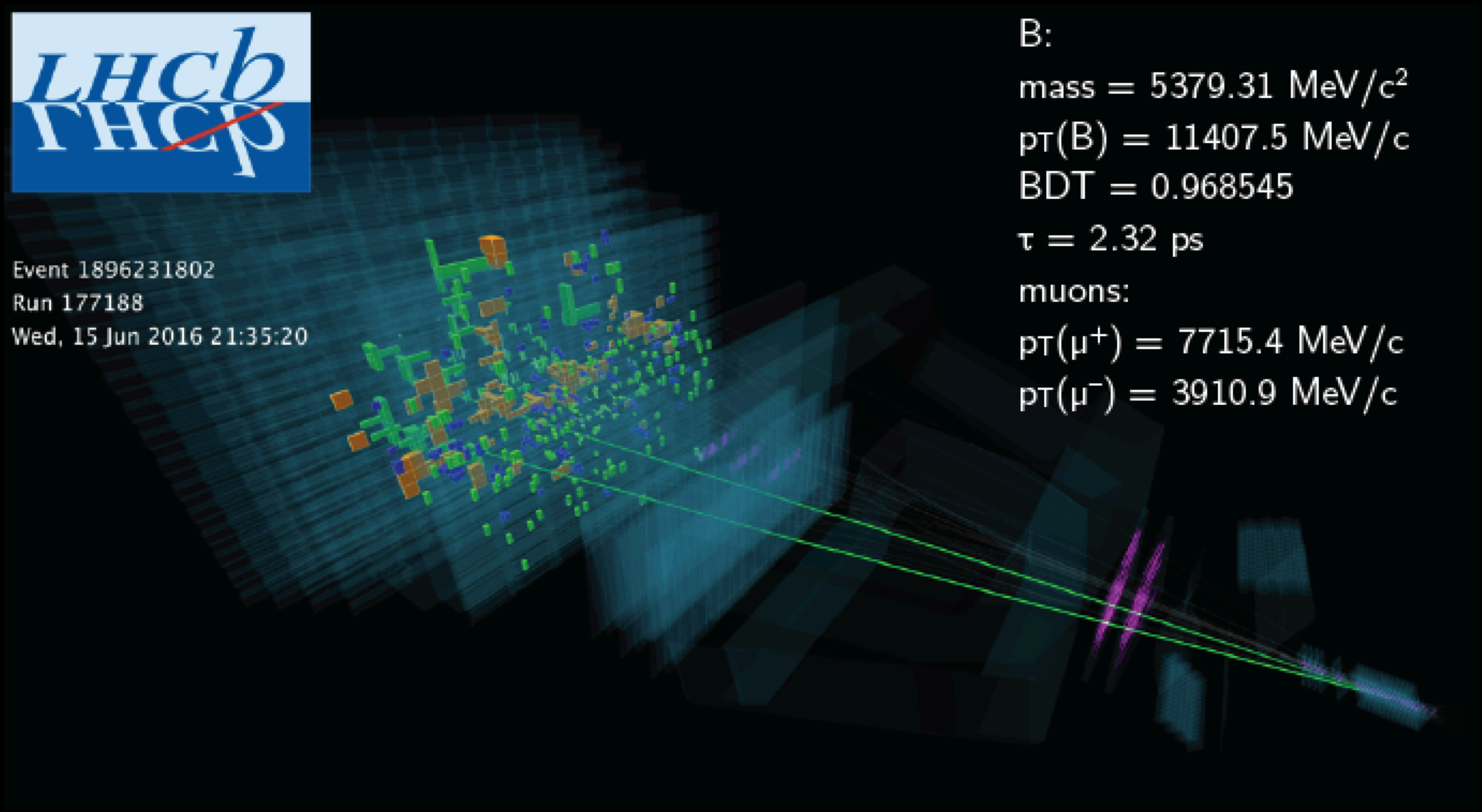


[LHCb-PUB-2016-011, https://cds.cern.ch/record/2145943/files/LHCb-PUB-2016-011.pdf]

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



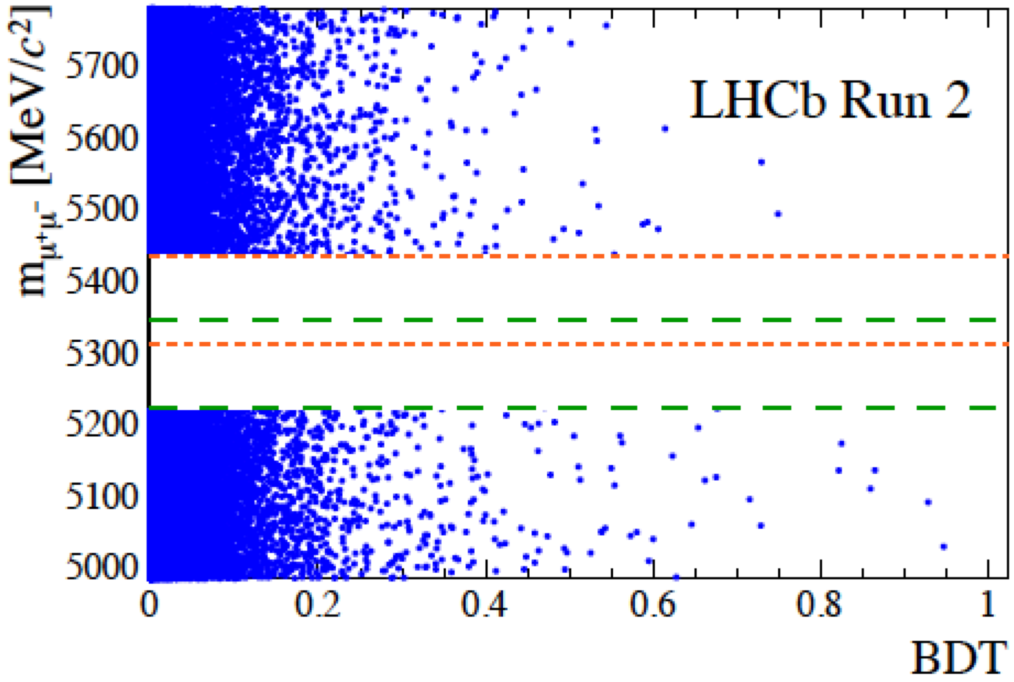
$B_{(s)}\mu\mu$ at LHCb: 2017 edition



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

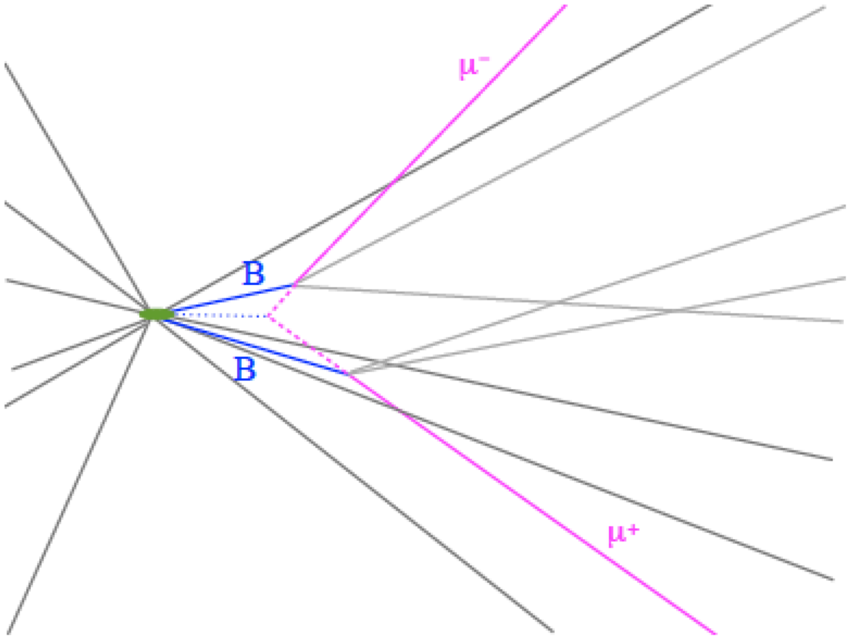
- **Normalisation:**
  - $B^0 \to K\pi$ and $B^+ \to J/\psi K^+$ used as normalisation channels; hadronisation fraction dependence on $\sqrt{s}$ evaluated using $B^+ \to J/\psi K^+$ and $B^0_s \to J/\psi\varphi$
- **Background estimation:**
  - Exclusive background evaluated through a combination of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

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

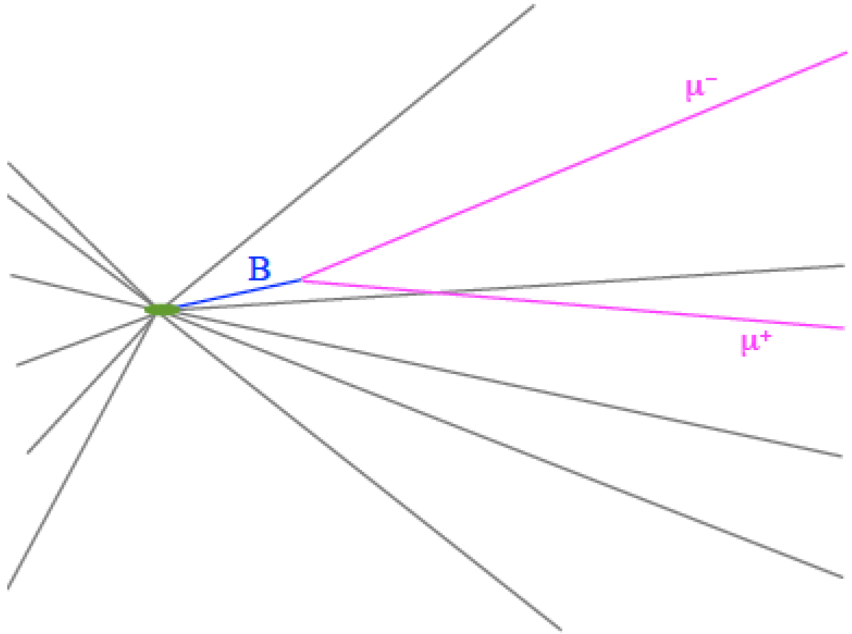
- **Results:**
  - Branching fraction from unbinned likelihood fit
  - Upper limit from CLs method
  - (Effective lifetime measurement)

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

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

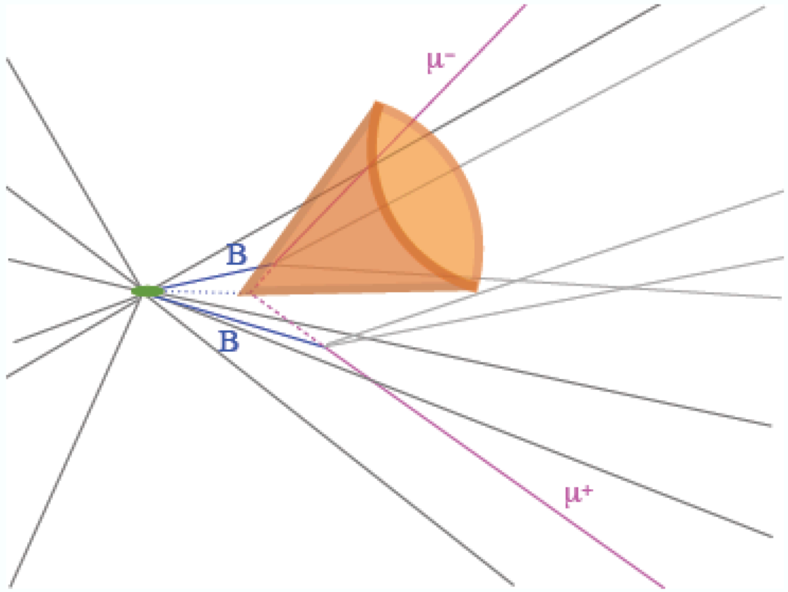


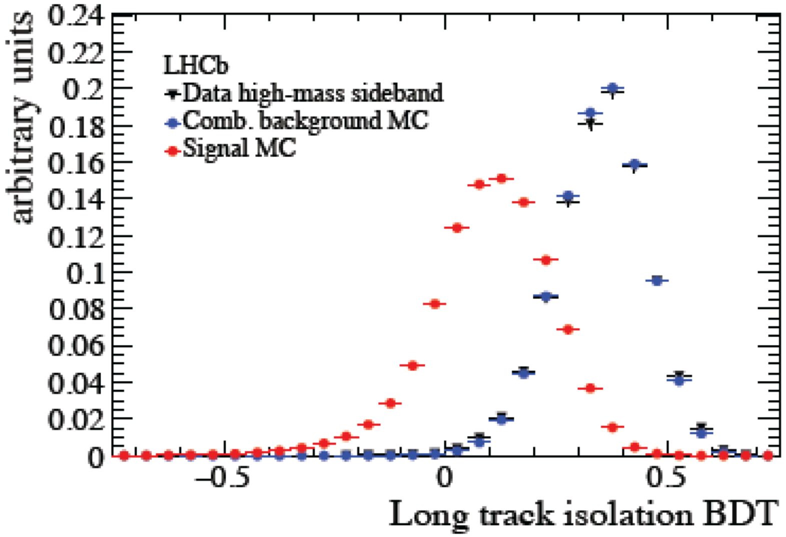
Signal: 2 muons from a single well reconstructed background



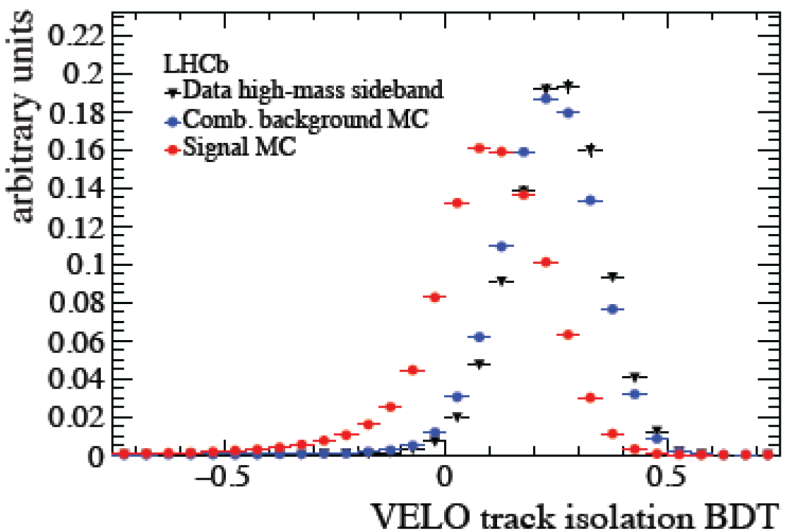
New multivariate classifier trained on simulated events using 7 variables including 2 new isolation variables.

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



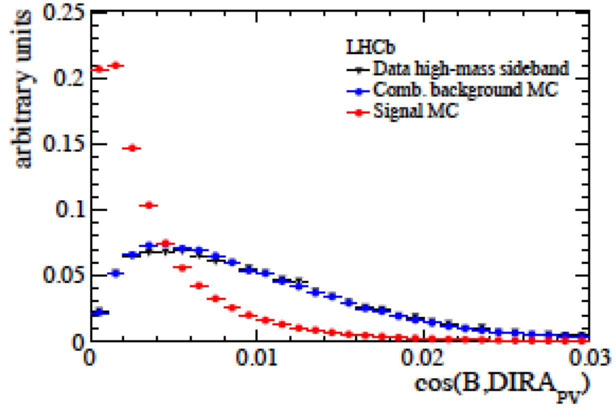


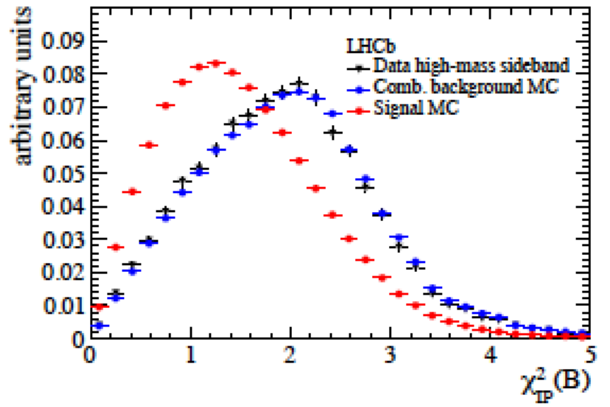
- Previous muon isolation based on rectangular cuts on variables related to the track information
- 2 multivariate classifiers are now used, one with tracks passing through all tracking stations, another with just tracks reconstructed only by the vertex detector.

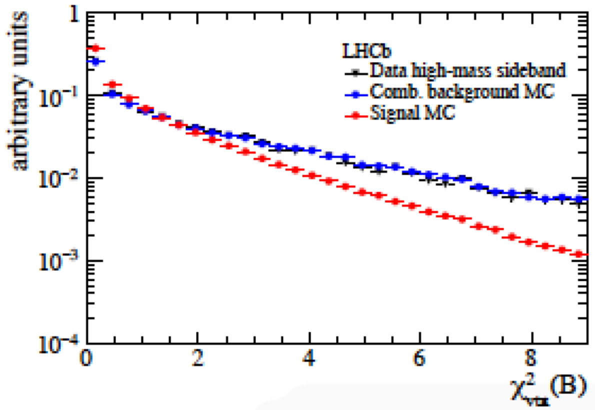


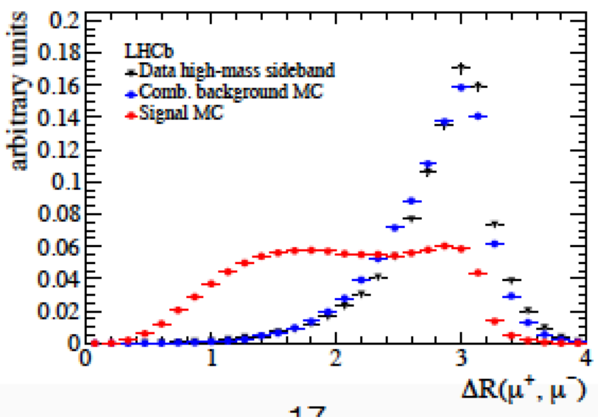
$B_{(s)}\mu\mu$: multivariate classifier (BDT)

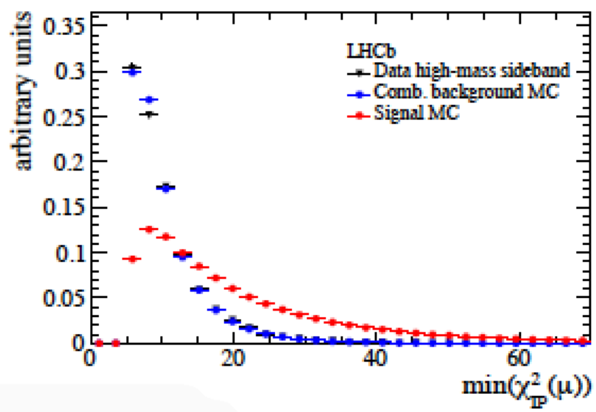
- Isolation variables taken as starting point to train the BDT classifier.
- Optimisation and training on simulated events
- Correlation with invariant mass negligible (below 5%)
- Same definition of the BDT used for Run1 and Run2 datasets while calibration performed independently





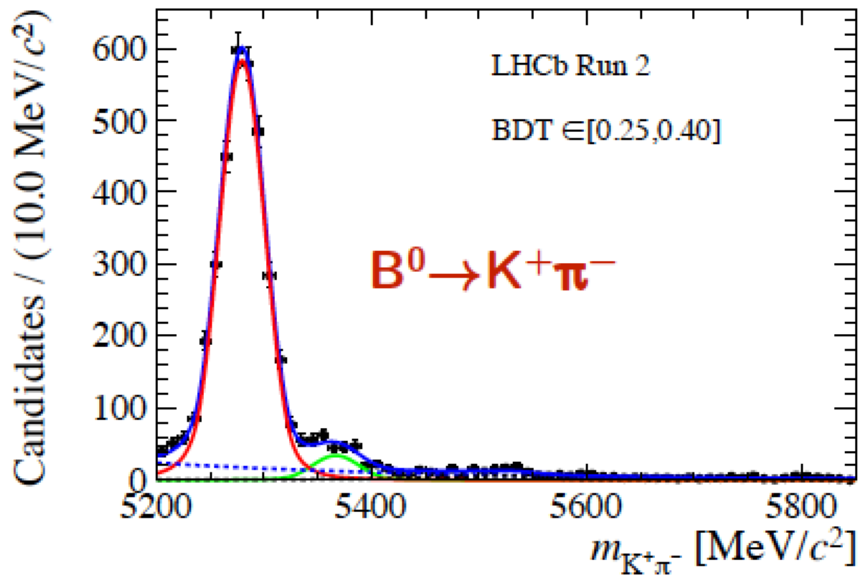


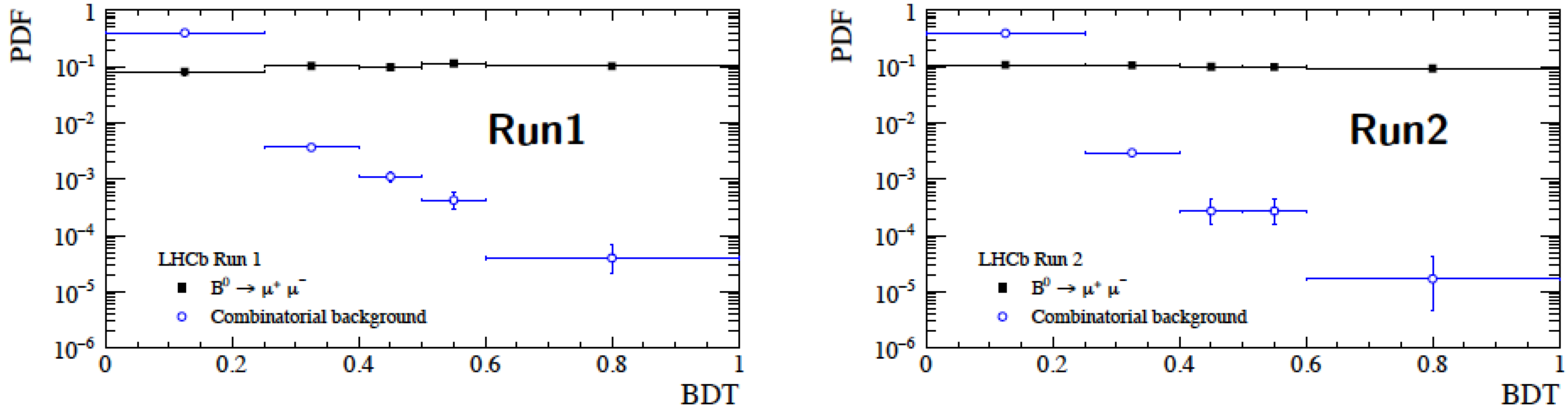




$B_{(s)}\mu\mu$: BDT calibration

- 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

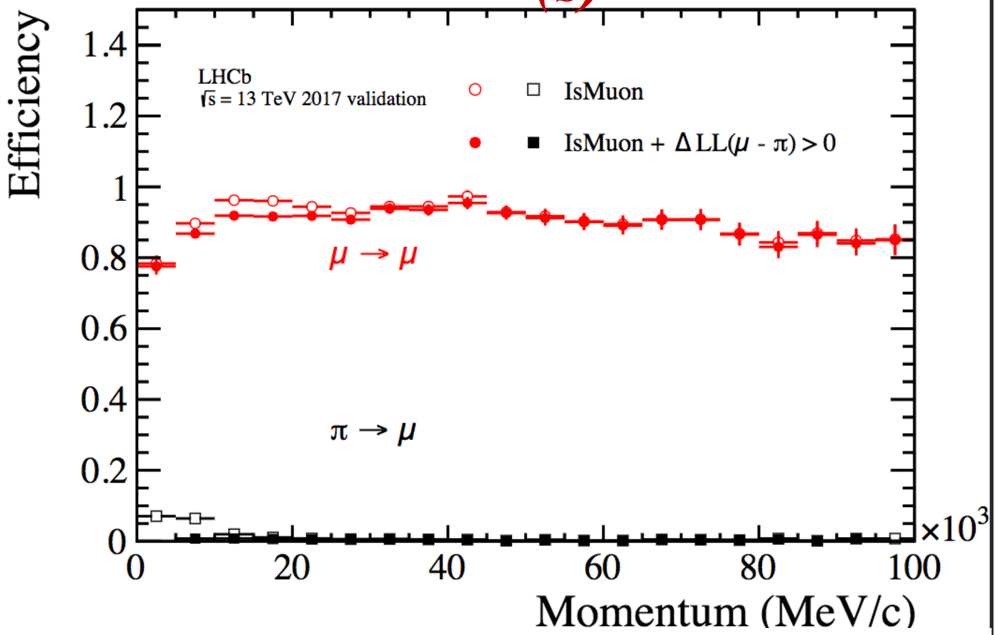
- In addition to the main combinatorial background source described by an **exponential shape,** other two categories populate the lower mass range:

  - **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.**
    - $B_c^+ \to J/\psi(\to\mu^+\mu^-)\mu^+\nu_\mu$
    - $B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$

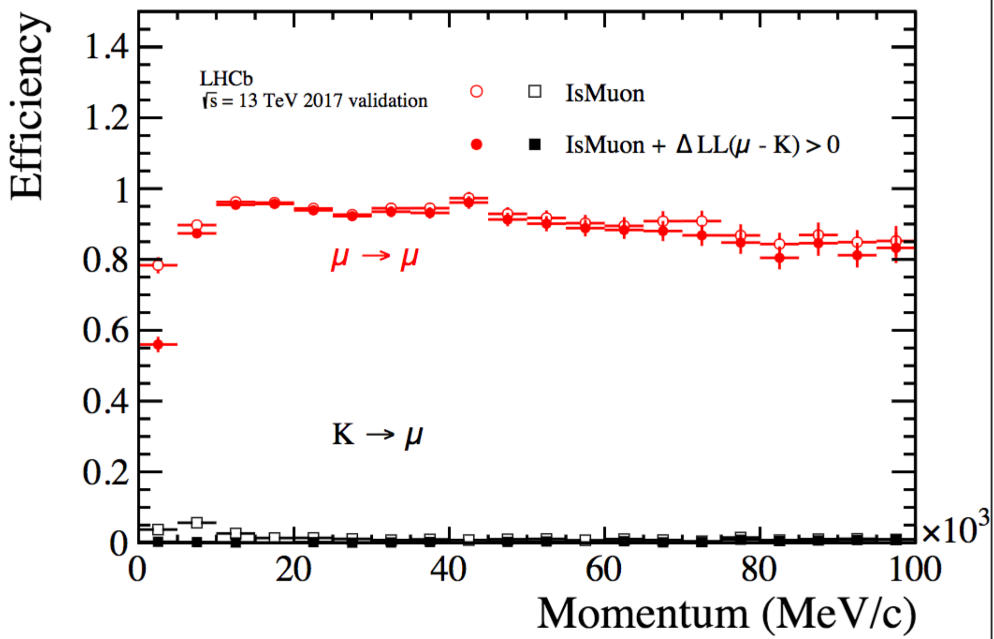
- Mass and BDT pdfs determined from simulated samples with misID probability calibrated on data.
- Expected yields evaluated by normalising on control channels
- Background x-check from independent fits to $K\mu$ and $\pi\mu$ mass spectrum

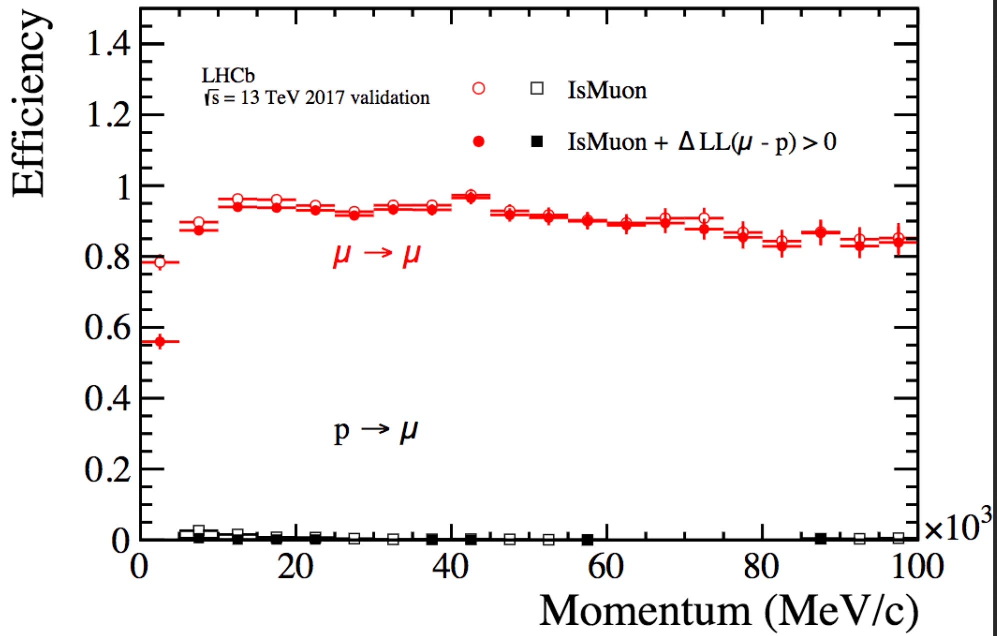
$B_{(s)}\mu\mu$: interlude (mis-Identification)



Branching ratios of background channels:

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

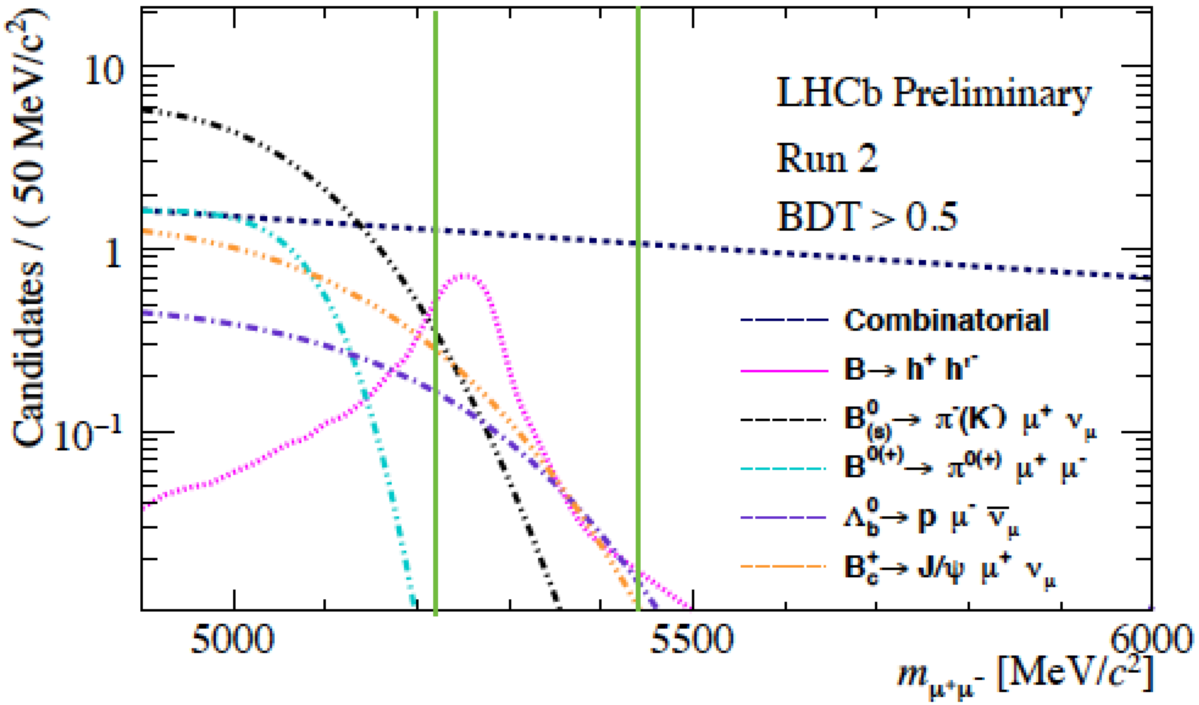




$B_{(s)}\mu\mu$: exclusive backgrounds

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

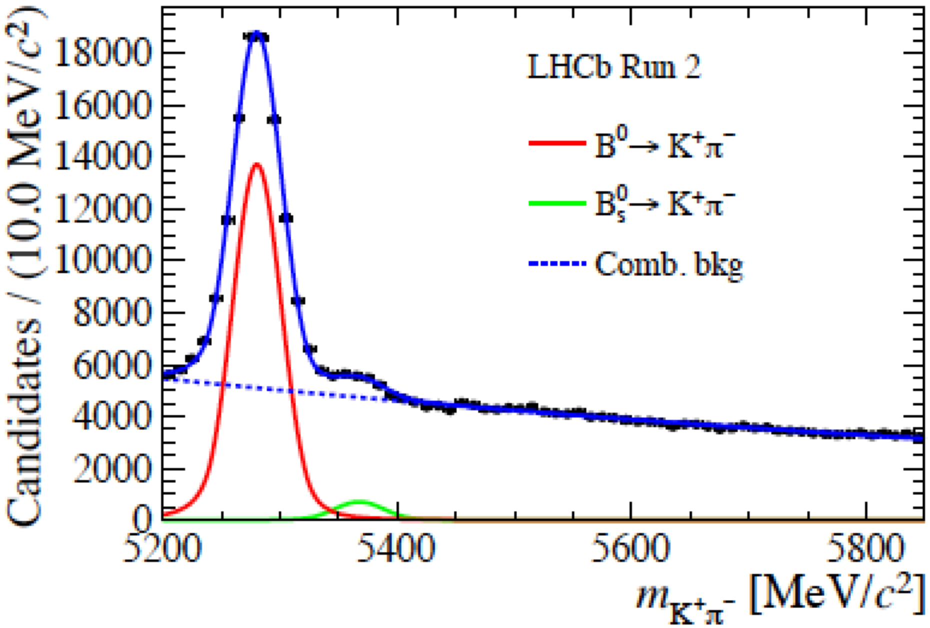
$B \to h^+ h'^-$	2.9 ± 0.3
$B_c^+ \to J/\psi \mu^+ \nu_\mu$	1.2 ± 0.2
$\Lambda^0_b \to p \mu^- \overline{\nu}_\mu$	0.7 ± 0.1
$B^0 \to h^- \mu^+ \nu_\mu$	0.80 ± 0.06



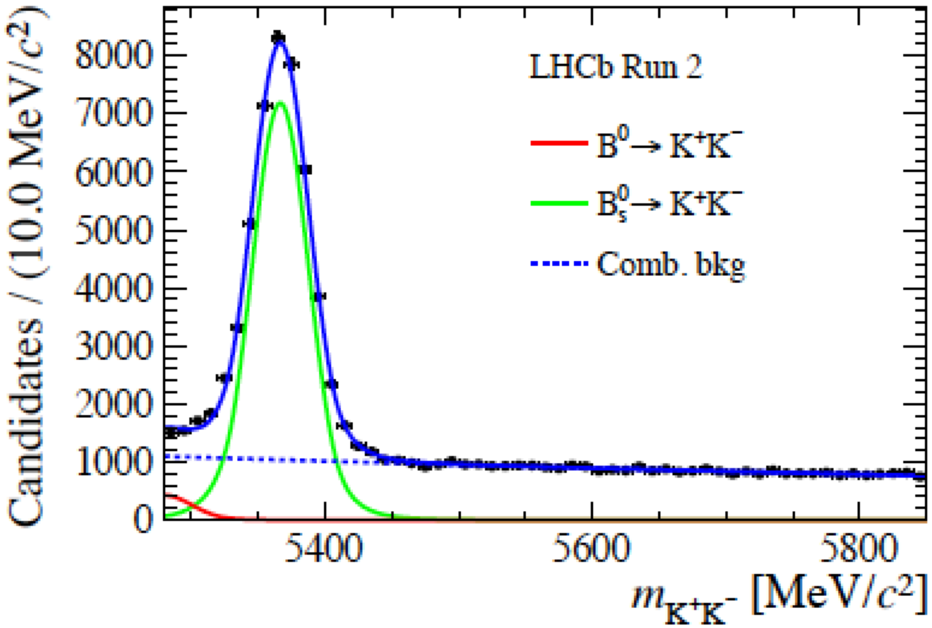
- $B \to h^+ h'^-$ peaking in the signal region. Factor ~2 reduction w.r.t. previous analysis
- $B^{0(+)} \to \pi^{0(+)} \mu^+ \mu^-$ interplay with combinatorial background.
- All these decays taken into account in the final fit.
- Contribution from $B^0_s \to \mu^+ \mu^- \gamma$ and $B^0_s \to \mu^+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

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

B_d mass



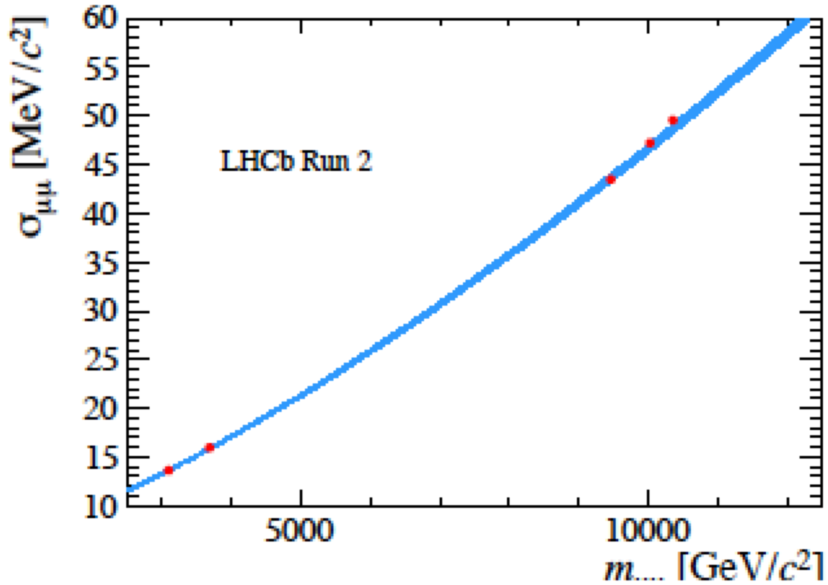
B_s mass

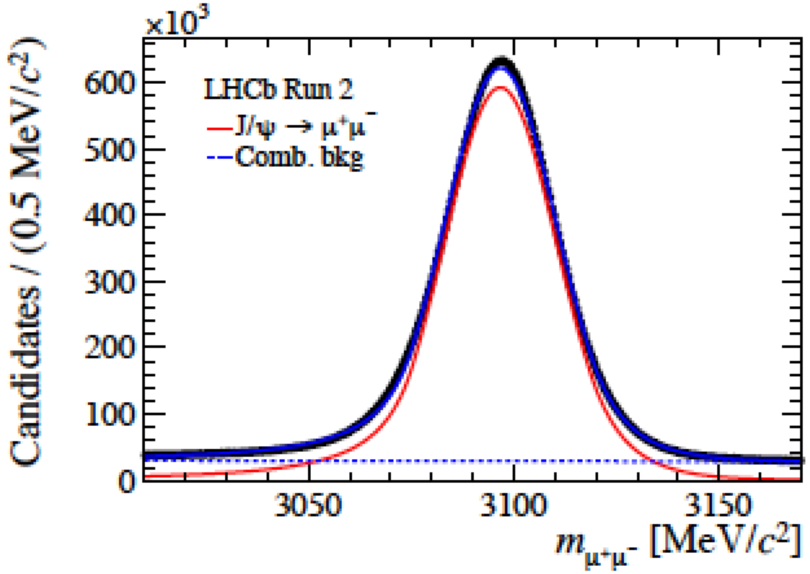


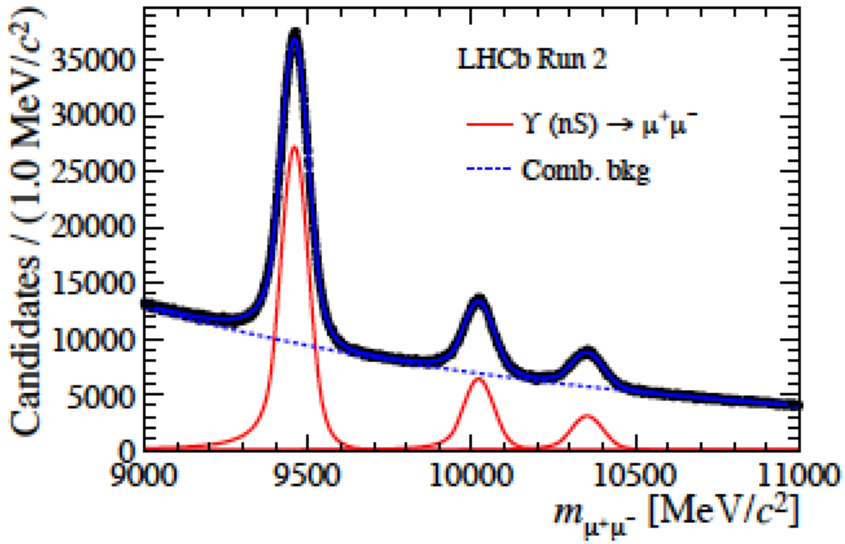
- Determination of mass peak position with well visible exclusive $B \to hh'$ decays

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

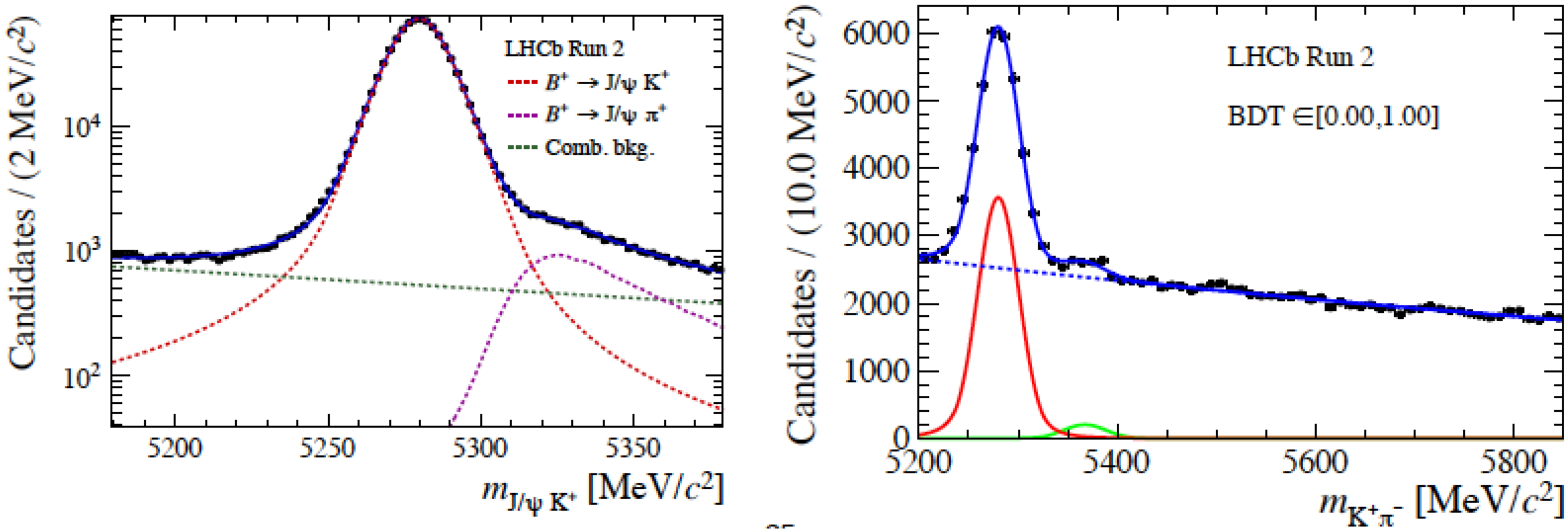






$B_{(s)}\mu\mu$: normalization

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



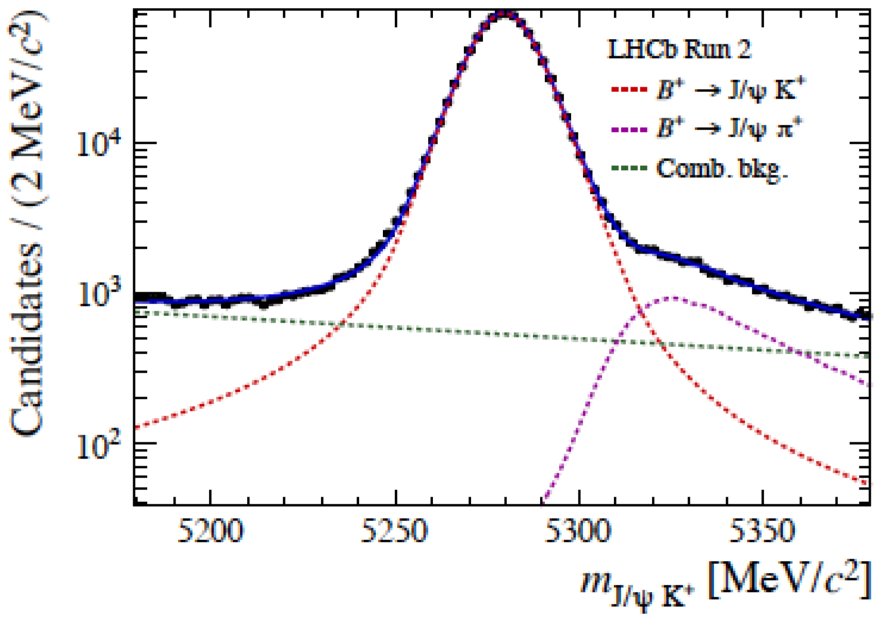
[LHCb-CONF-2013-011]

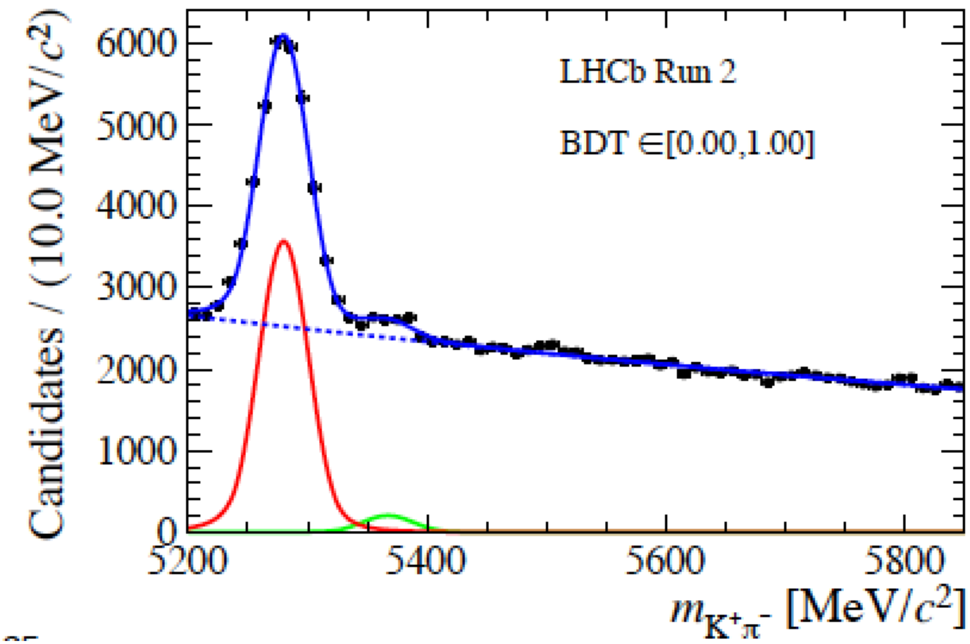
- Hadronisation fraction from LHCb measurement $f_s/f_d = 0.259 \pm 0.015$
- Values at $\sqrt{s} = 13$TeV scaled according to $B^0_s \to J/\psi\varphi$ and $B^+ \to J/\psi K^+$ ratio

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

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

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



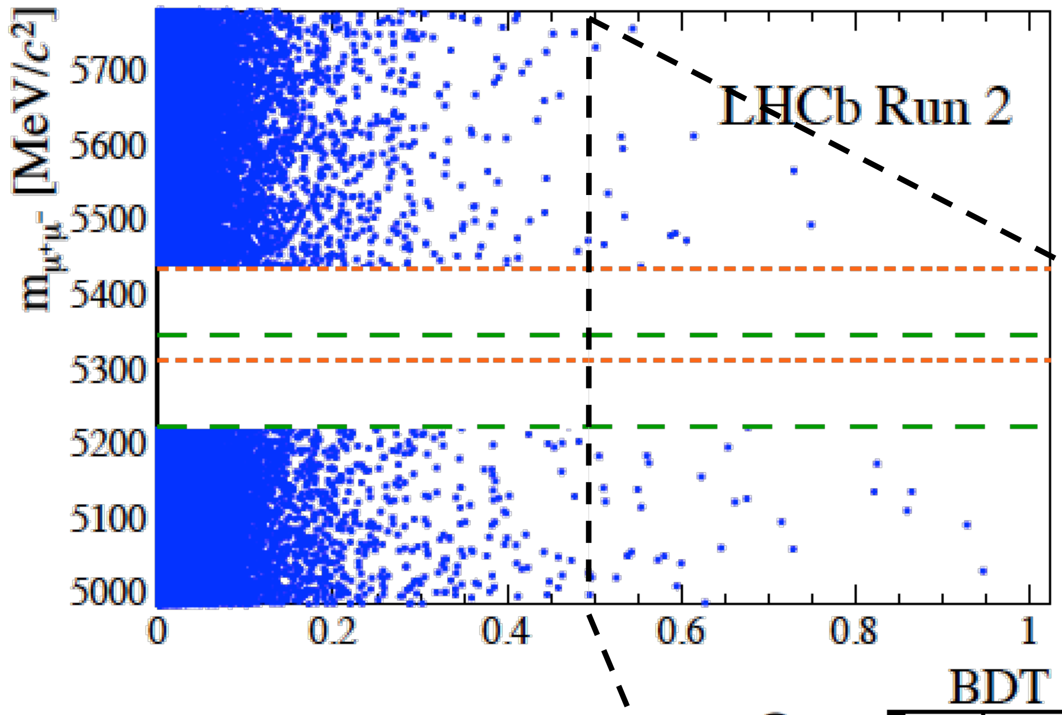


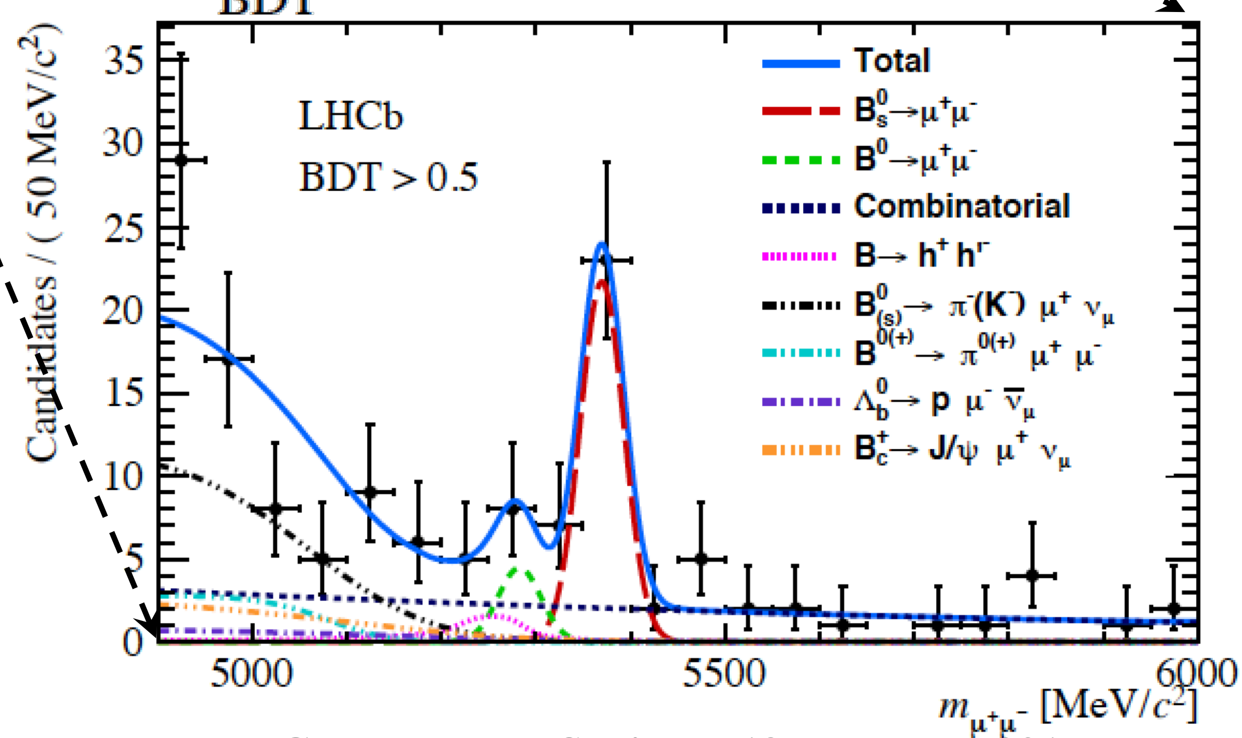
- Measured $(1964\pm1)\times10^3$ $B^+ \to J/\psi K^+$ and $(62\pm3)\times10^3$ $B^0 \to K^+\pi^-$ decays
- Assuming the SM rates, after the selection we expect:
  - **~62 $B^0_s \to \mu^+\mu^-$ events and ~7 $B^0 \to \mu^+\mu^-$ events in the whole BDT range**

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

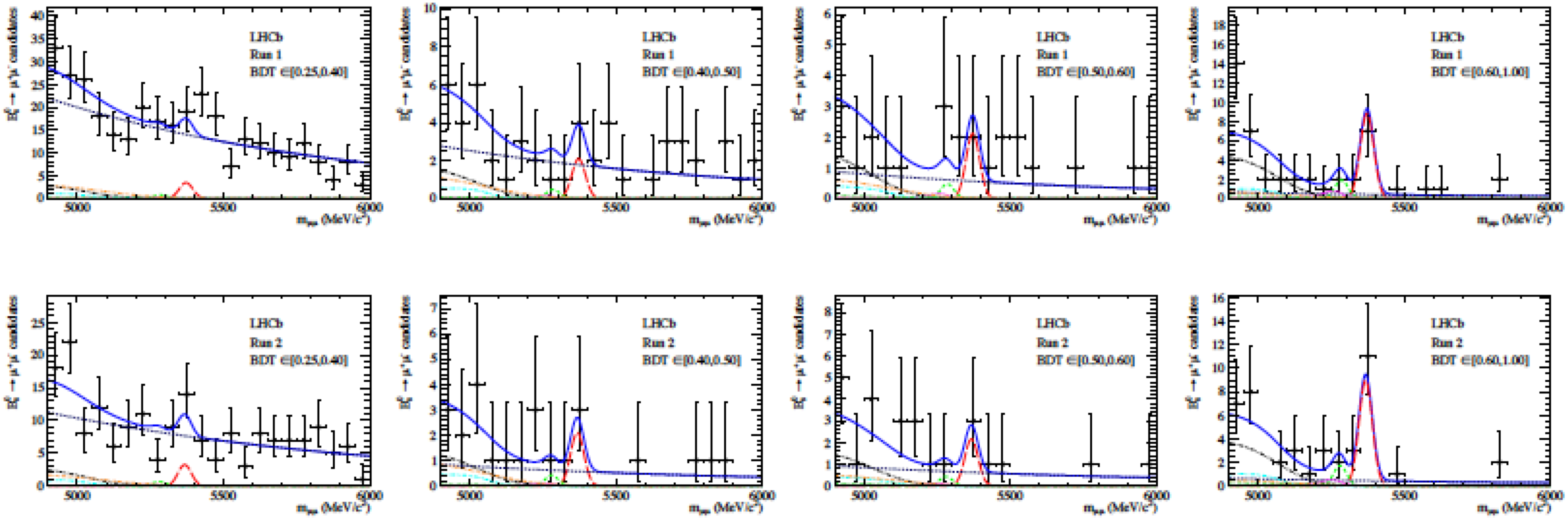




[LHCb-PAPER-2017-001]

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

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

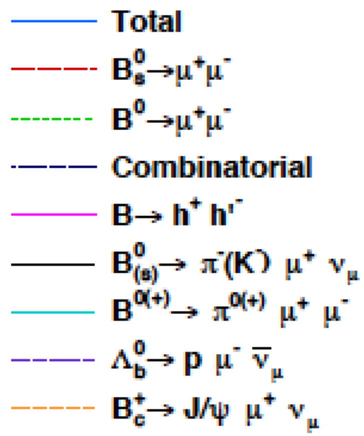


- Fit results:

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

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

- 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]

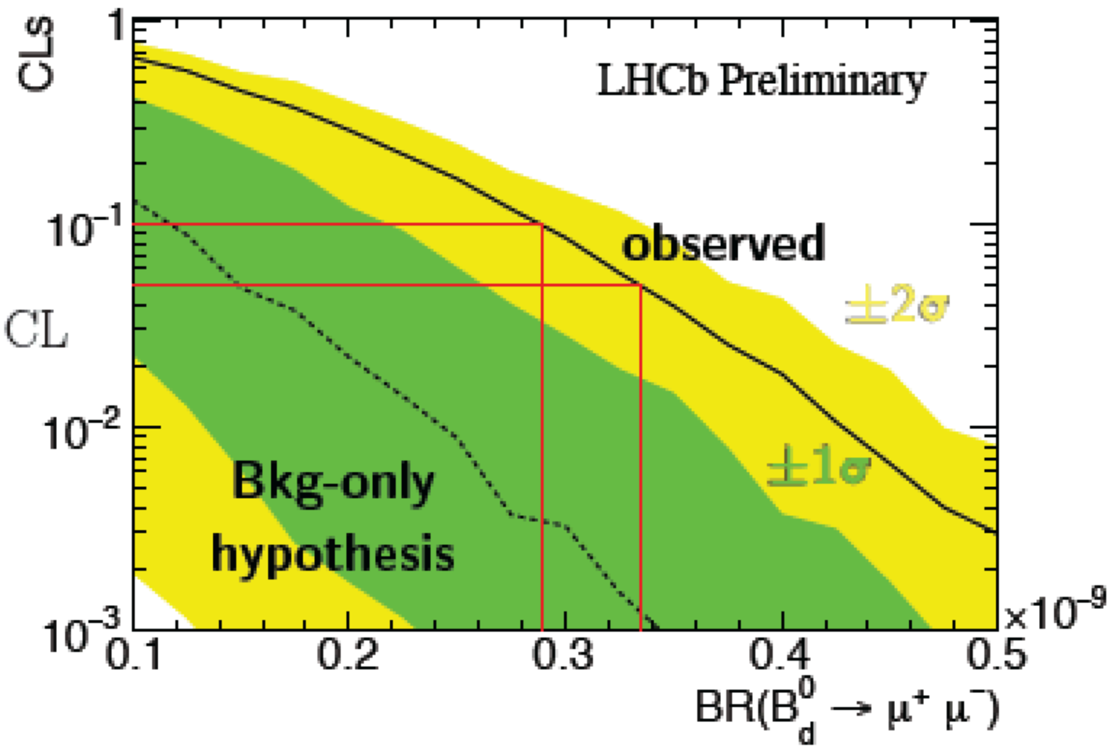
$B^0\mu\mu$: upper limit

- 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:

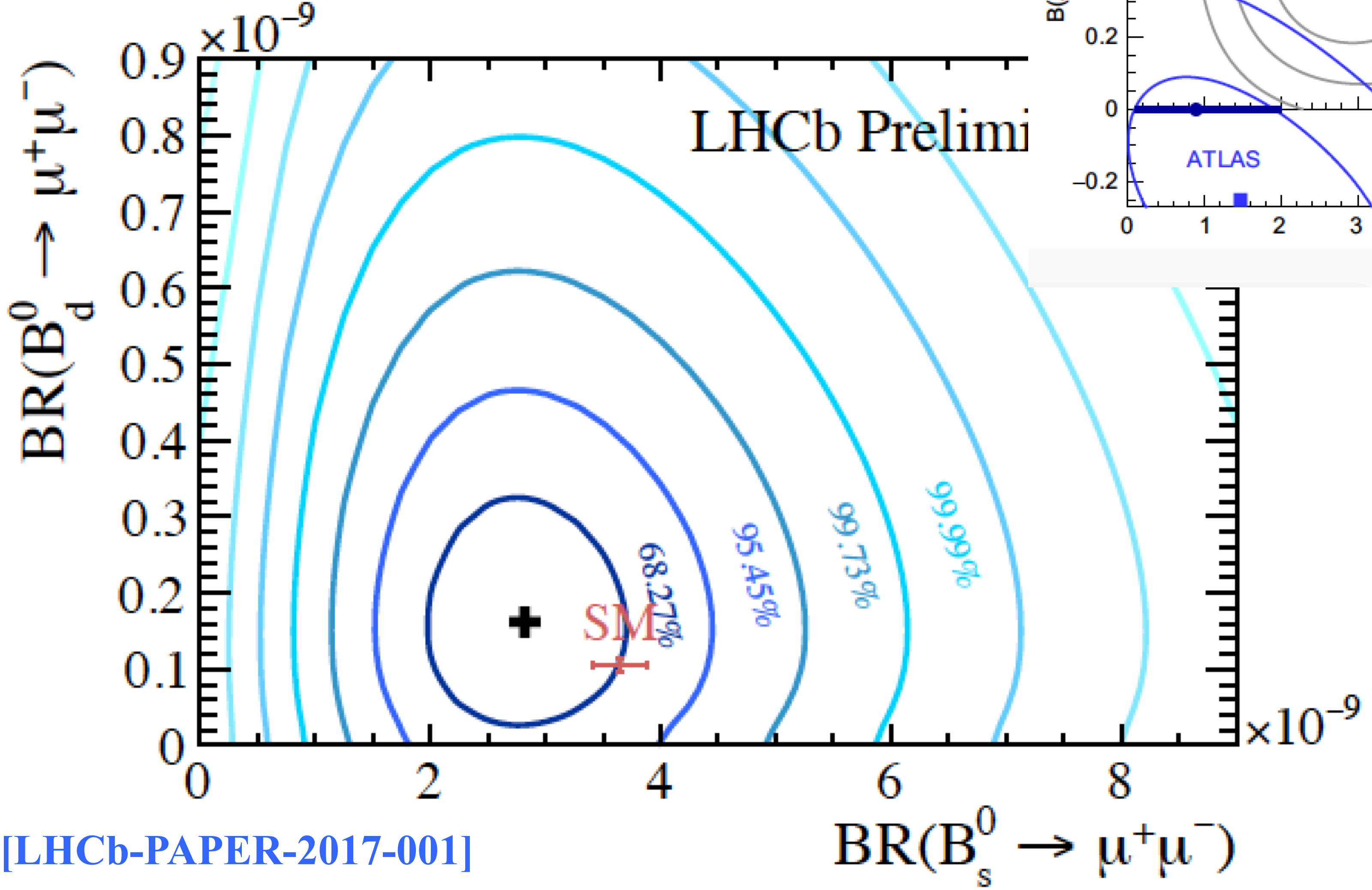
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \cdot 10^{-10} \text{ @ } 95\% \text{ CL}$$

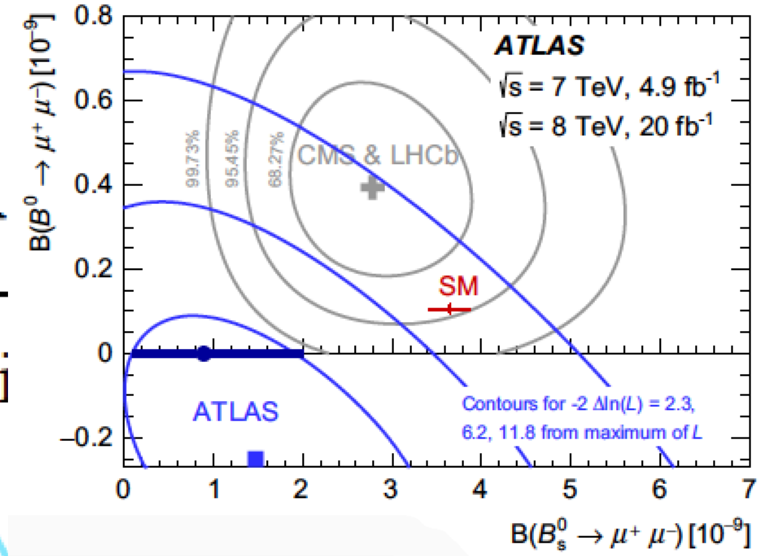
- Compatibility with bkg only hypothesis 1-CL_b=0.05



[LHCb-PAPER-2017-001]

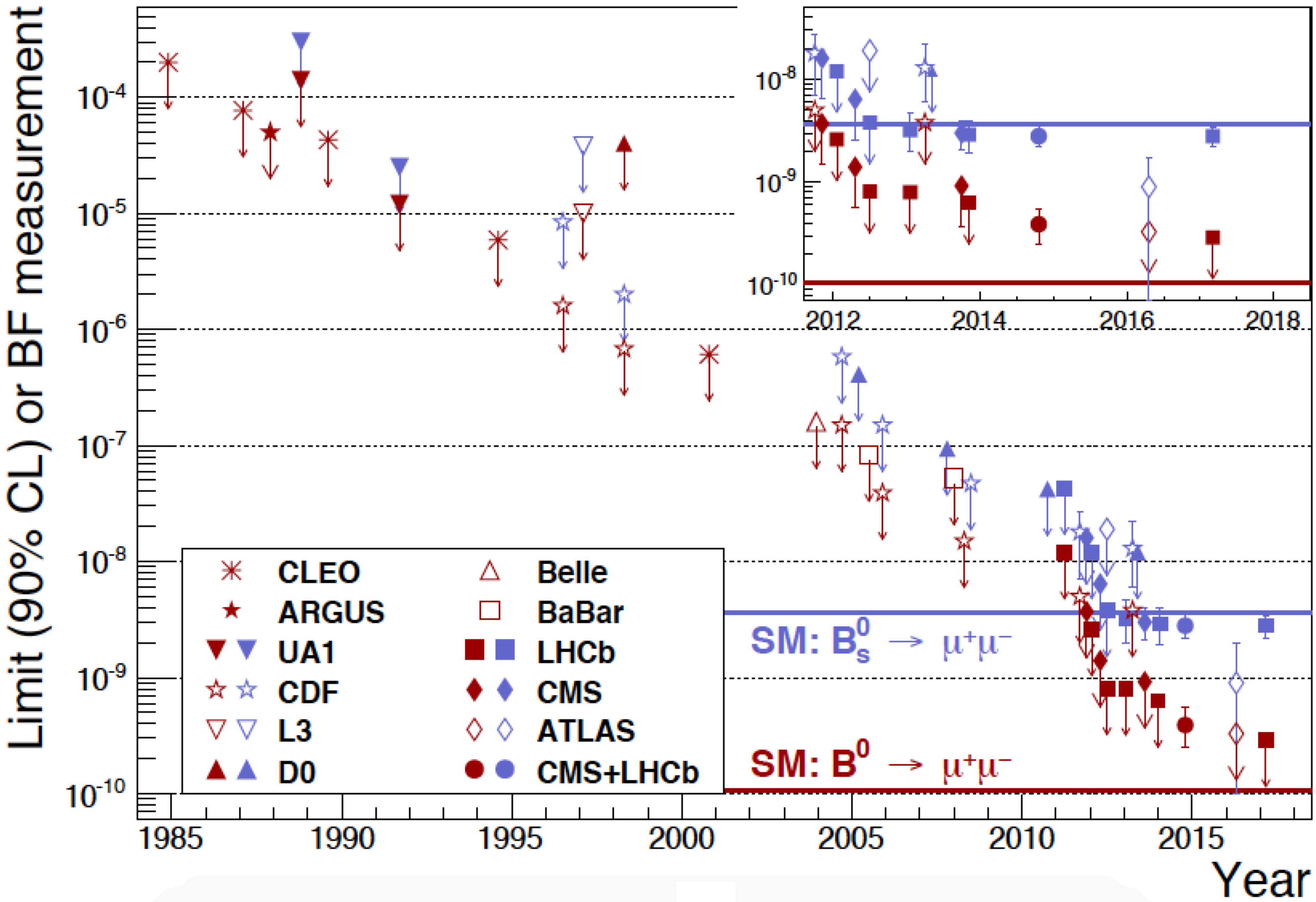
$B_{(s)}\mu\mu$: 2D likelihood profile





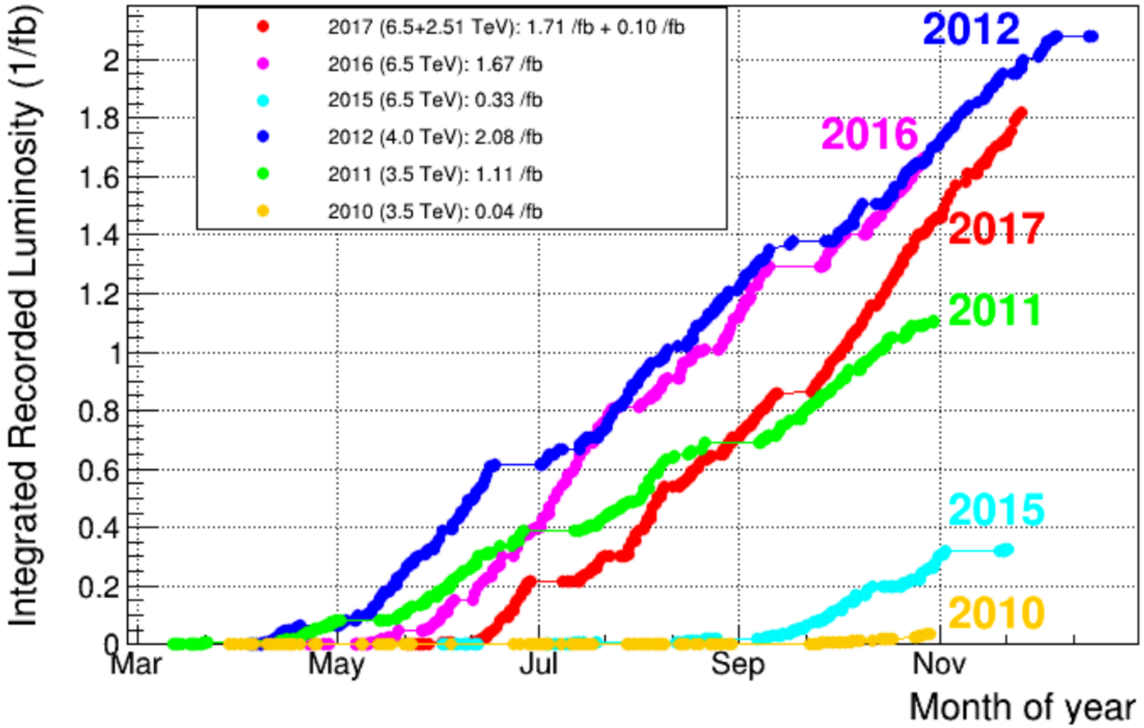
[LHCb-PAPER-2017-001]

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



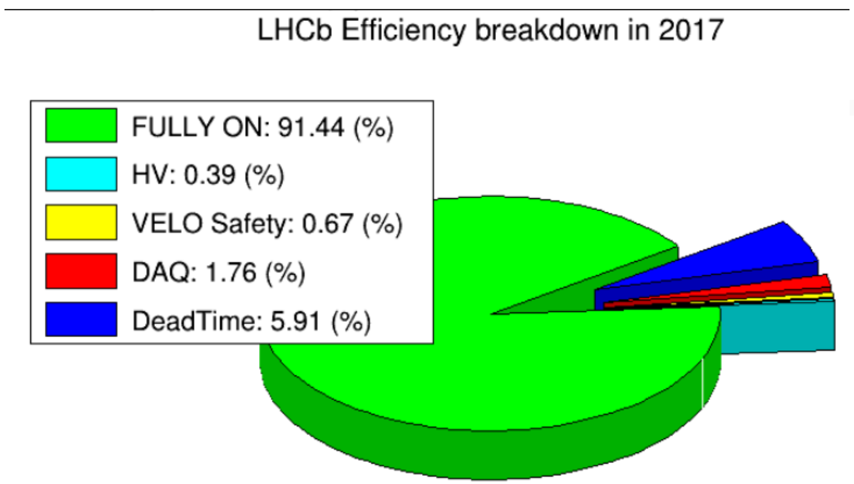
What next?

Near and far future

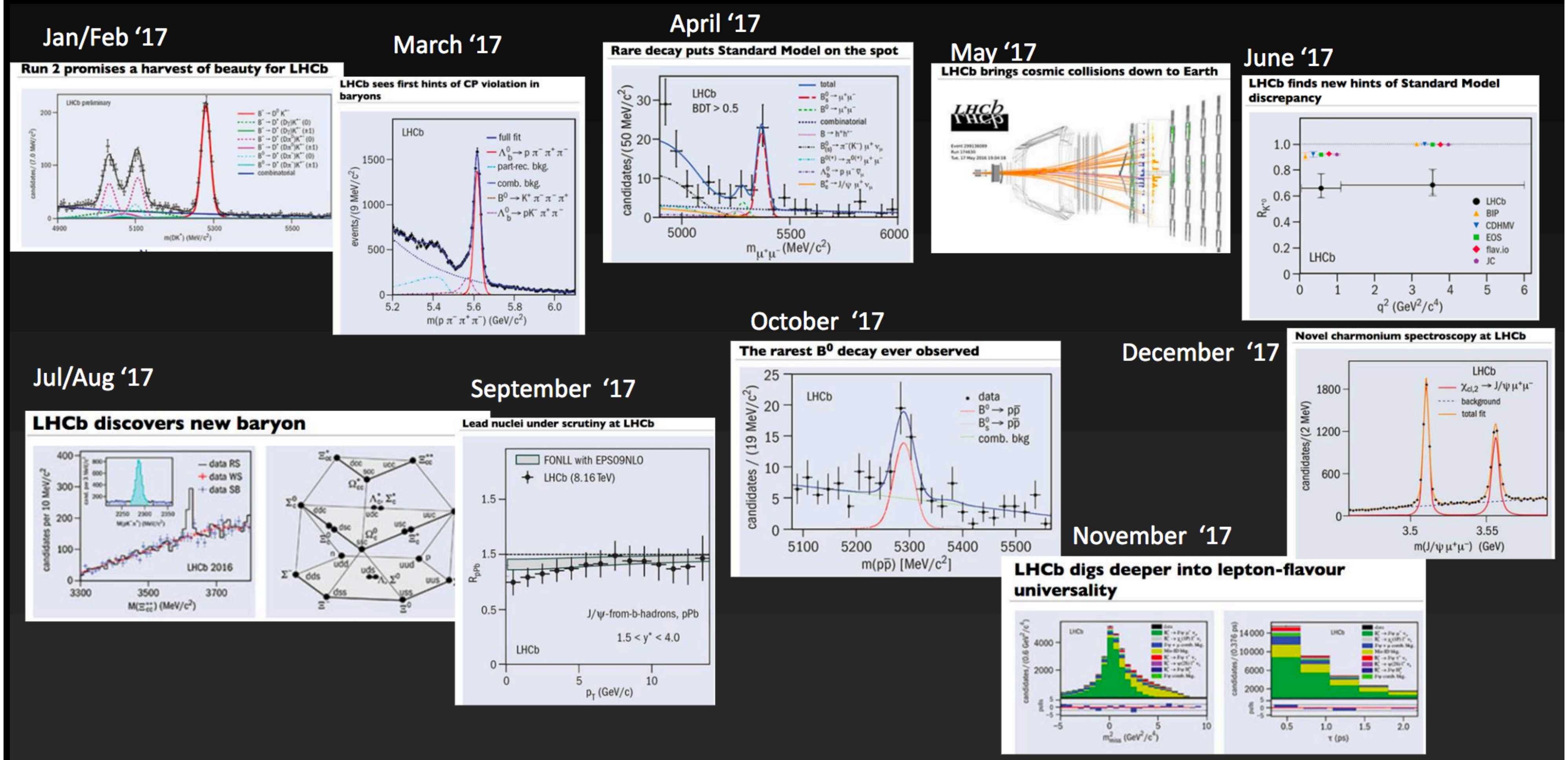


	Recorded Lumi (pb^{-1})	Delivered Lumi (pb^{-1})
2011	1.11	1.22
2012	2.08	2.20
Run-1	3.2	3.4
2015	0.33	0.36
2016	1.67	1.88
2017 (5TeV)	1.71 (0.10)	1.86
Run-2	3.7	4.1
Total	6.9	7.5

2018		2.5
Total		10.0 ?



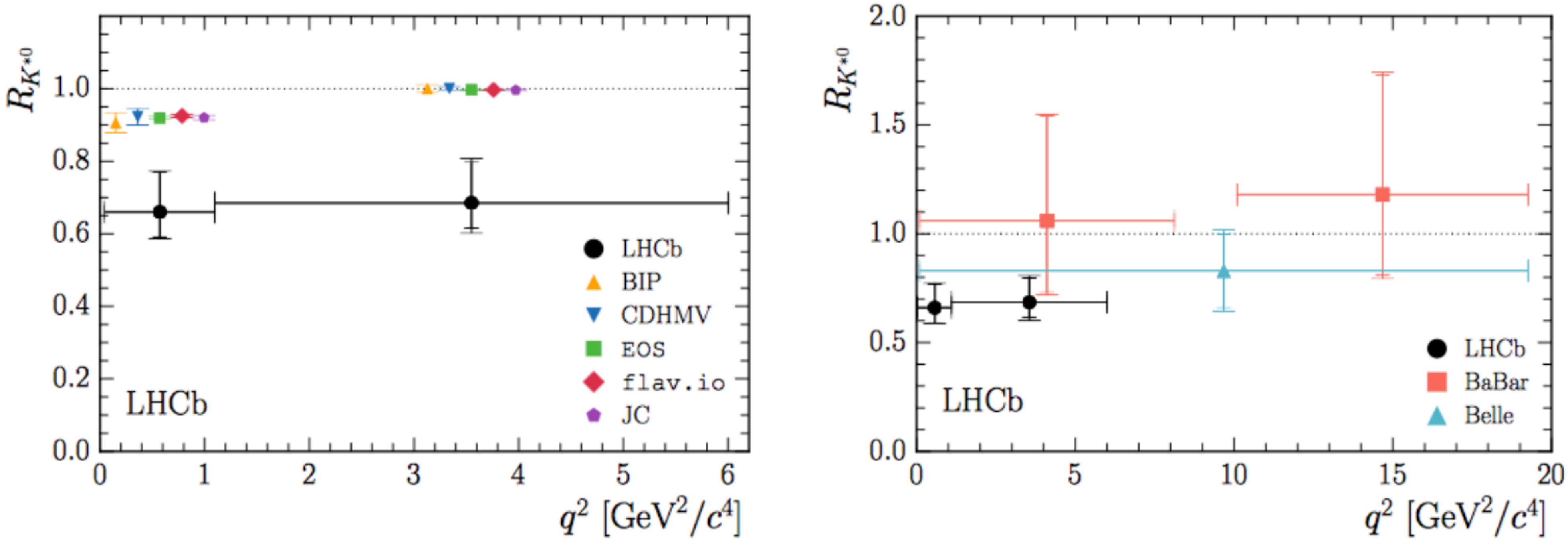
LHCb 2017 results on CERN courier



And a large fraction of Run 2 data set has still to be analysed!

*Intriguing discrepancy wrt SM: RK**

[LHCb-PAPER-2017-013]



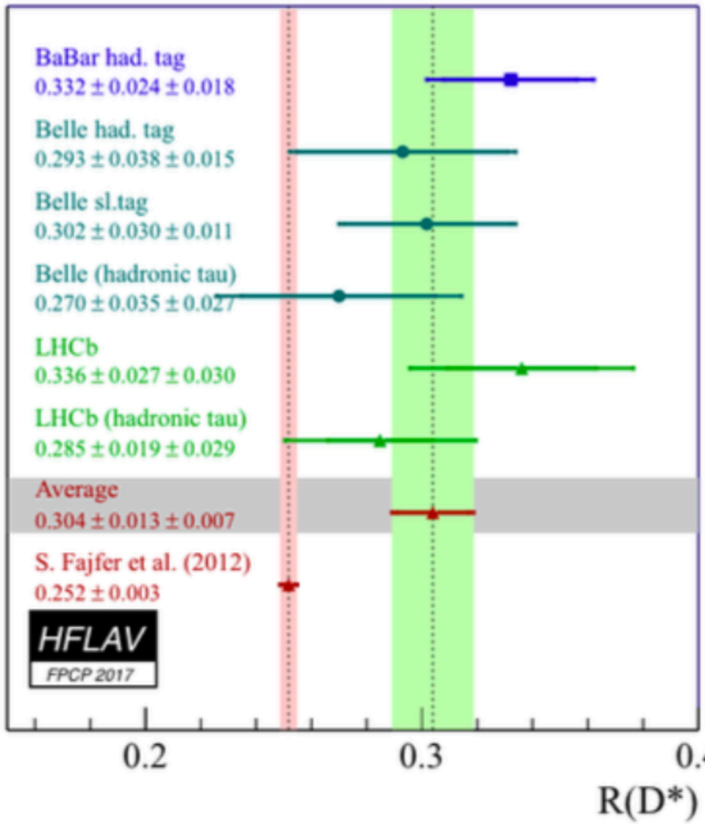
2.1 – 2.4 standard deviations from the Standard Model

$$0.660 \, ^{+\,0.110}_{-\,0.070} \, (\text{stat}) \pm 0.028 \, (\text{syst}) \quad \text{for } 0.045 < q^2 < 1.1 \;\; \text{GeV}^2/c^4$$

$$0.685 \, ^{+\,0.113}_{-\,0.069} \, (\text{stat}) \pm 0.047 \, (\text{syst}) \quad \text{for } 1.1 < q^2 < 6.0 \;\; \text{GeV}^2/c^4$$

2.4 – 2.5 standard deviations from the Standard Model

Intriguing discrepancy wrt SM: RD(*)



PAPER-2017-017

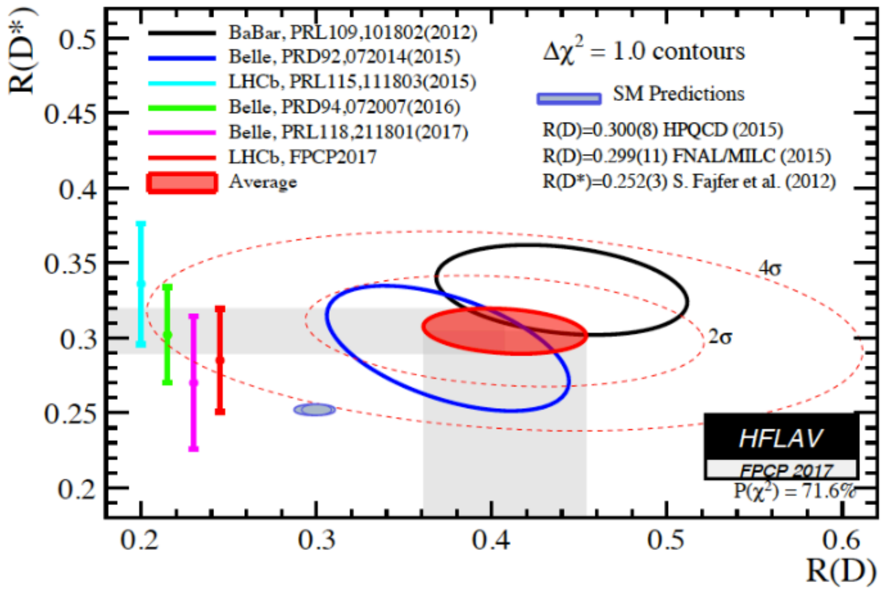
New LHCb measurement gives

$$\mathcal{R}(D^{*-}) = 0.286 \pm 0.019 \pm 0.025 \pm 0.021$$

Compatible with SM expectation

but also fully supporting previous measurements of high value

- R(D) and R(D*) combination at ~4σ from the SM
- Major updates are coming with Run-2 data



What if ~ every collision is interesting?

LHCb Upgrade Trigger Diagram

30 MHz inelastic event rate (full rate event building)

⇩ ⇩ ⇩

Software High Level Trigger

Full event reconstruction, inclusive and exclusive kinematic/geometric selections

⇩

Buffer events to disk, perform online detector calibration and alignment

⇩

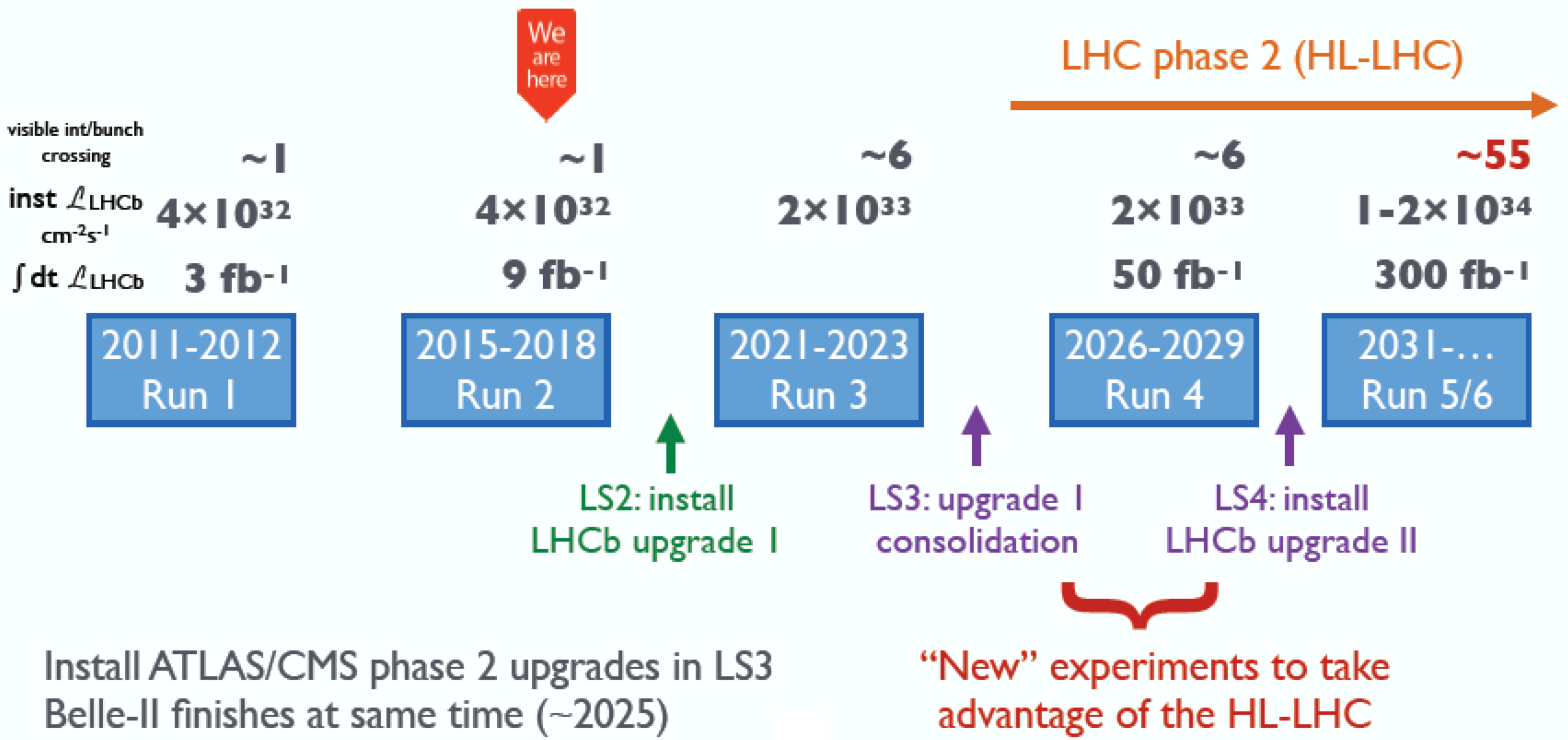
Add offline precision particle identification and track quality information to selections

Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

⇩ ⇩ ⇩

2-5 GB/s to storage

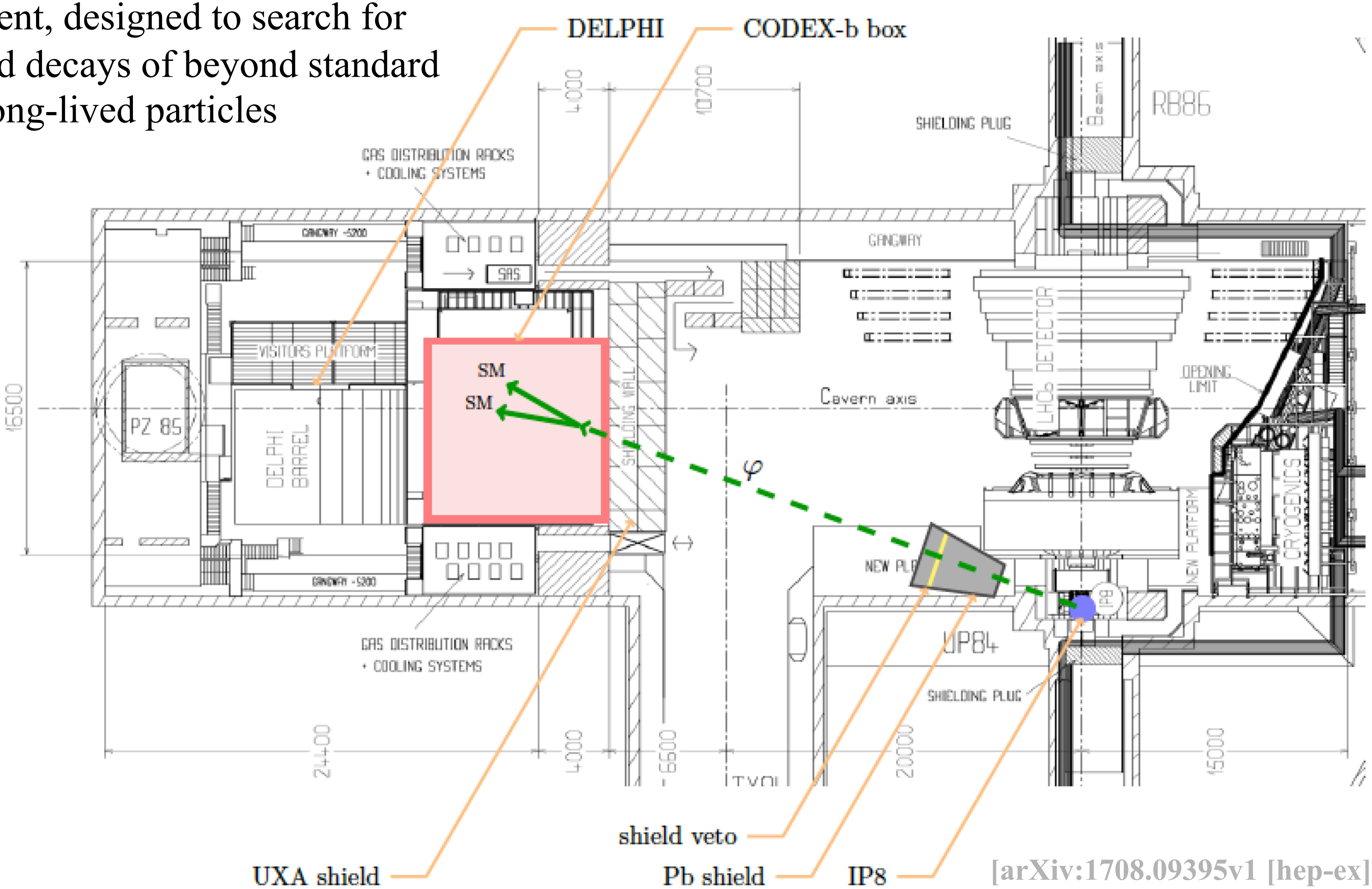
Near and far future



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]]

Summary

- **LHCb found intriguing discrepancies wrt the SM**.

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

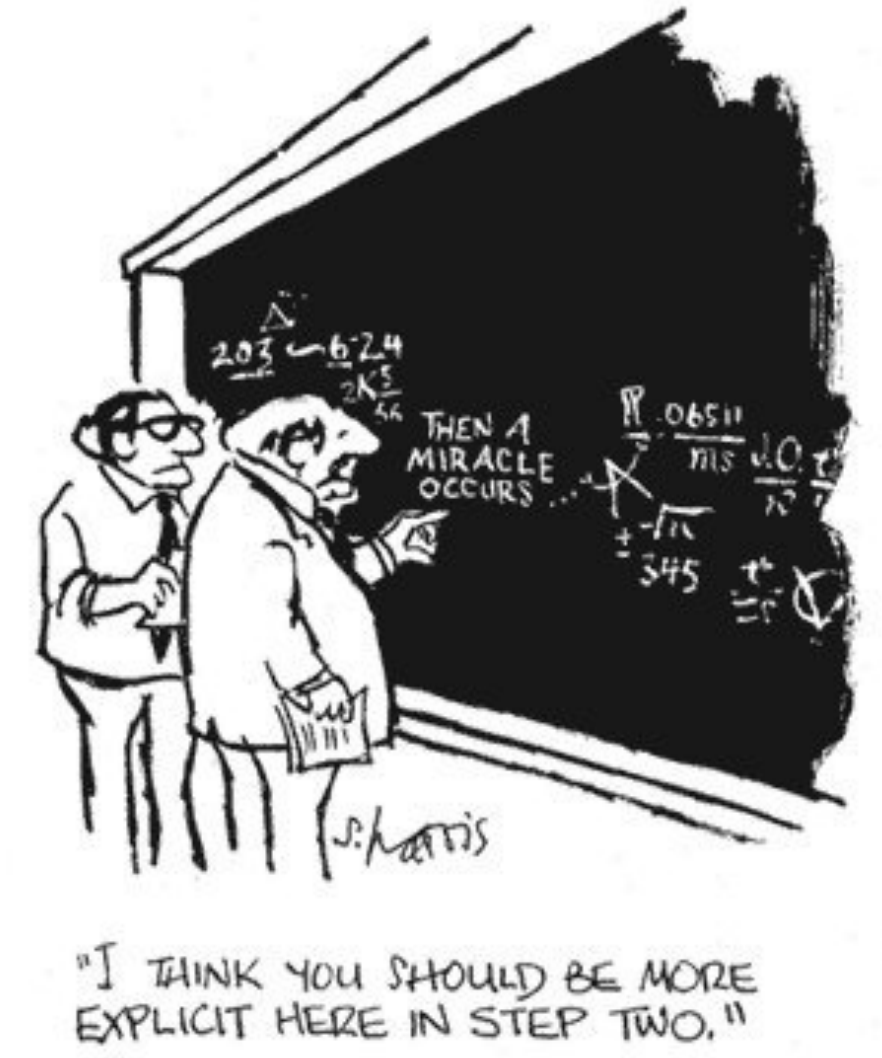
- **Operations make the difference in physics outcome!**

- 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)

- Many ideas and projects for potential further upgrades

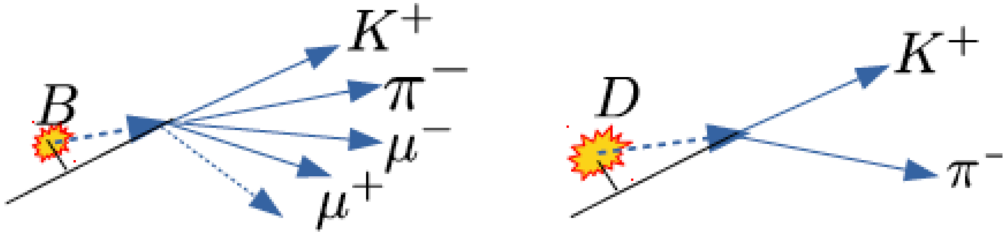
- **A lot of (scientific but not only) fun ahead!**




Thanks!
INJECTION

Back up

HLT1

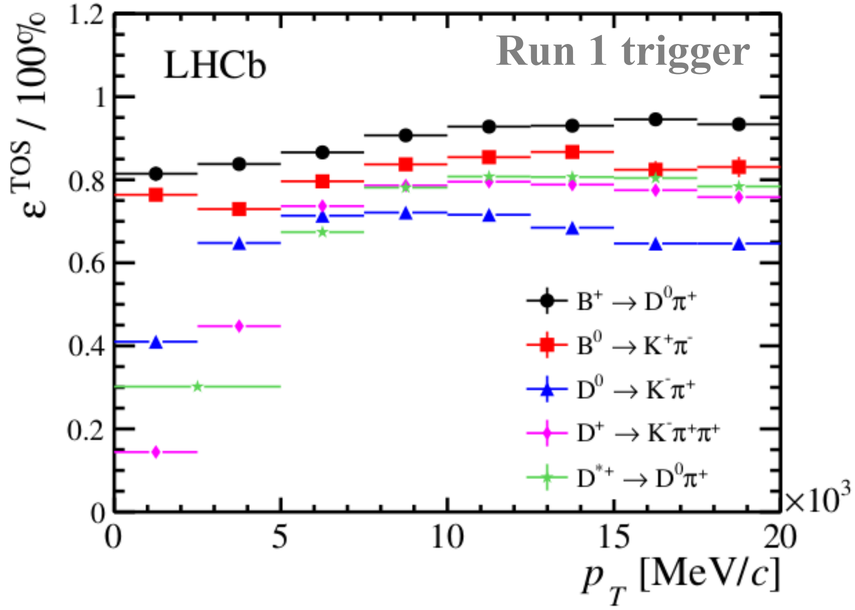


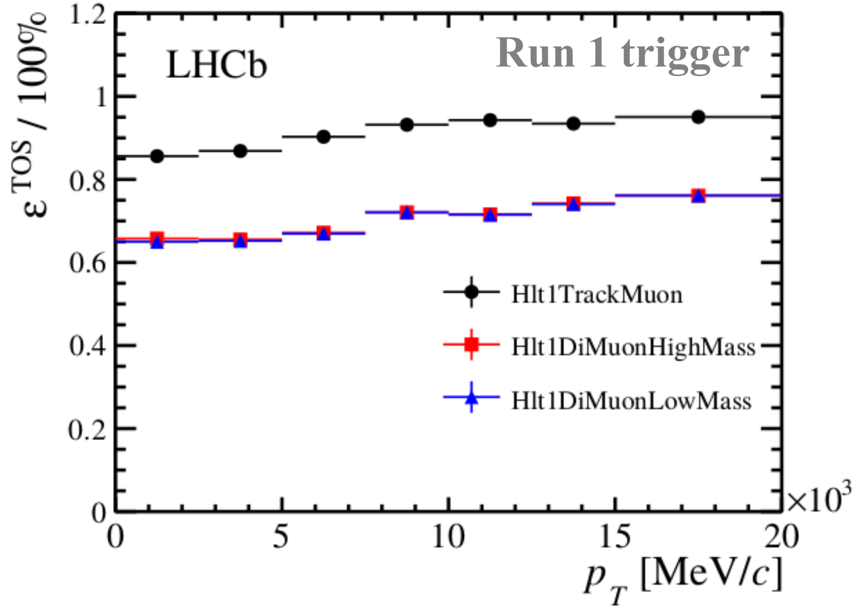
Inclusive trigger:
 Single and two tracks MVA selections (~100 kHz)

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

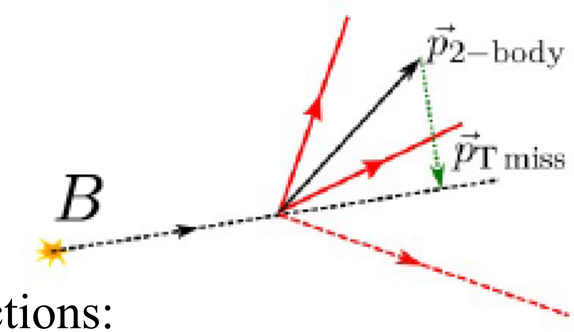




[Int.J.Mod.Phys. A30 (2015) 1530022]

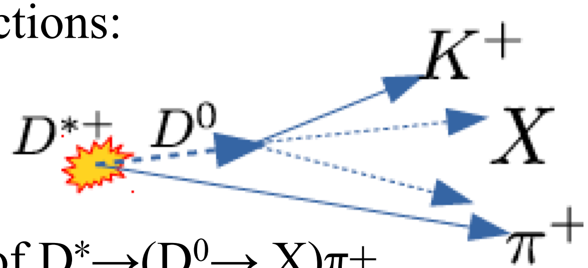
HLT2

12.5 kHz to tape



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

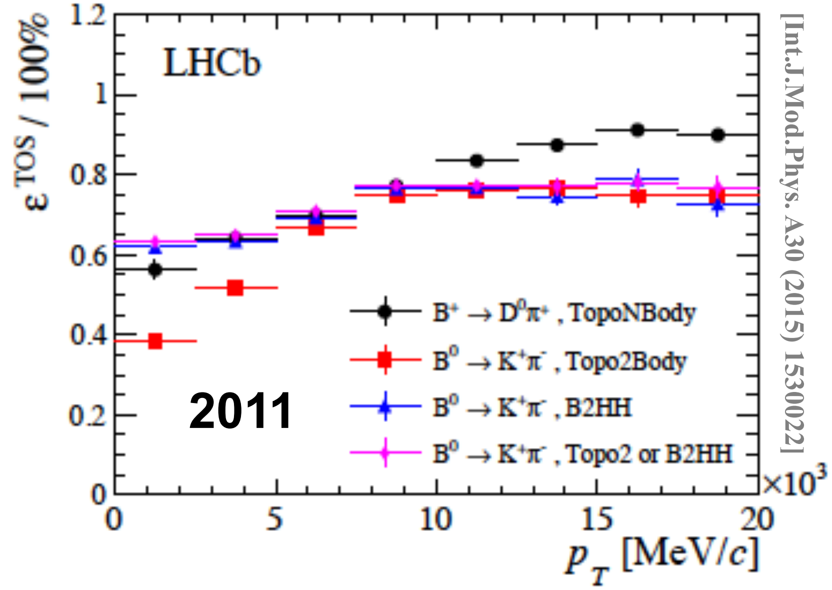
Exclusive beauty selections:
E.g. B→ φφ, B→ γγ

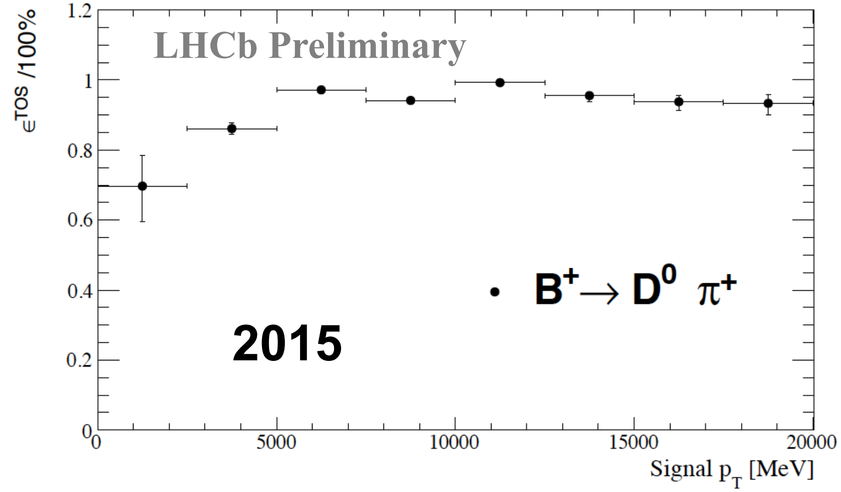


Charm selections
- Inclusive selection of $D^* \rightarrow (D^0 \rightarrow X)\pi+$
- Charmed baryons
- Final states with K0S
- 2,3,4,5-body final states

Electroweak bosons

Nearly 400 selections in total



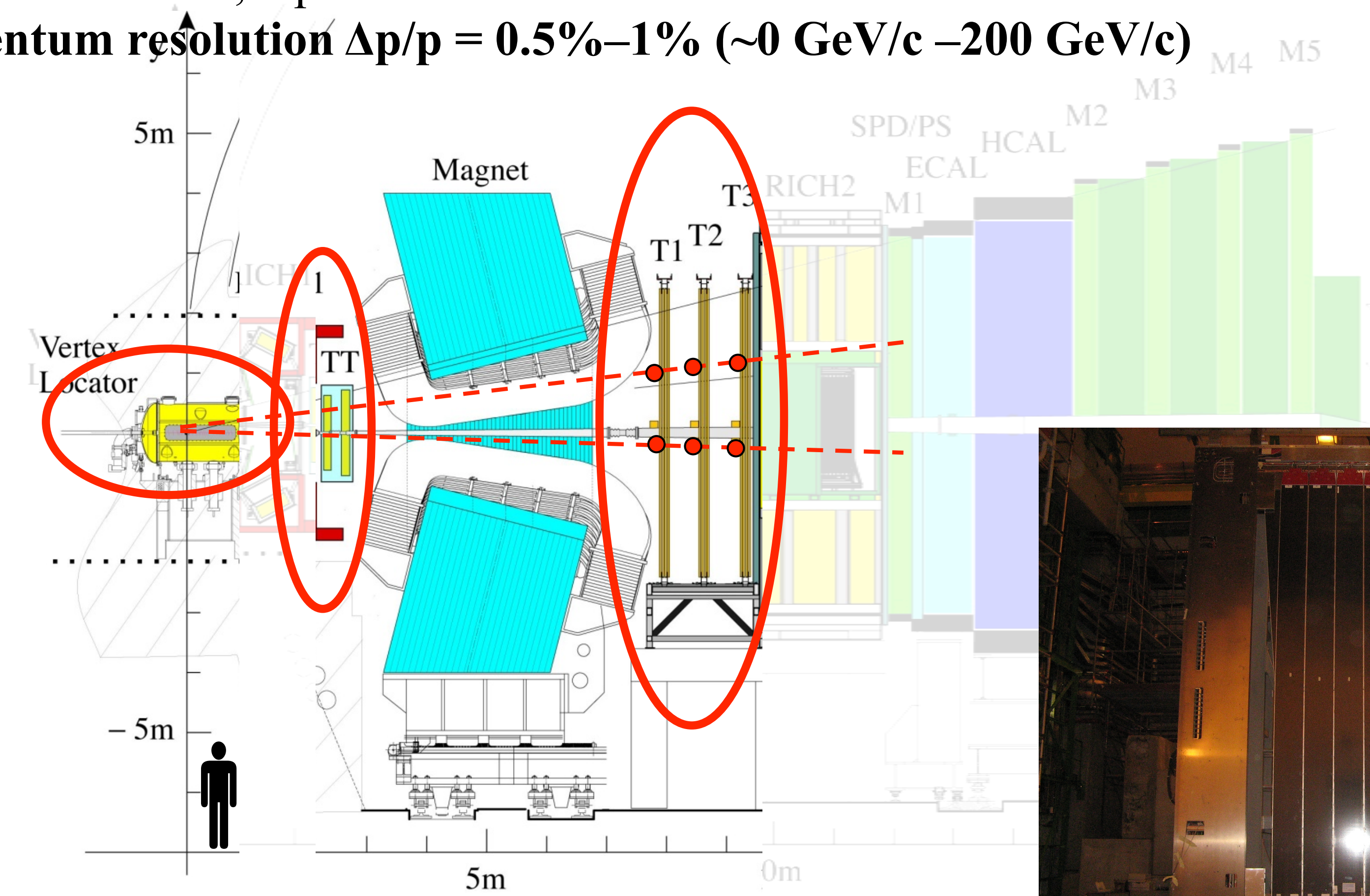


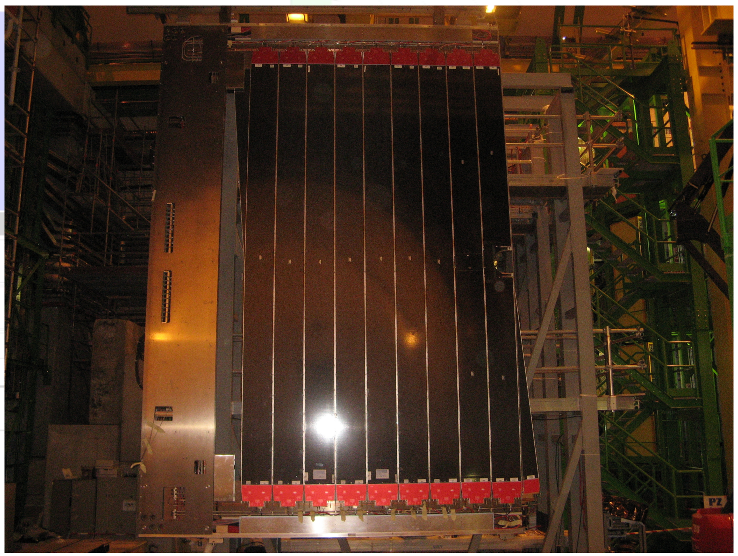
[e.g. HLT2 efficiency for inclusive b trigger: $B^+ \rightarrow D^0\pi^+$ increased from ~75% to >90%]

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

Tracking system

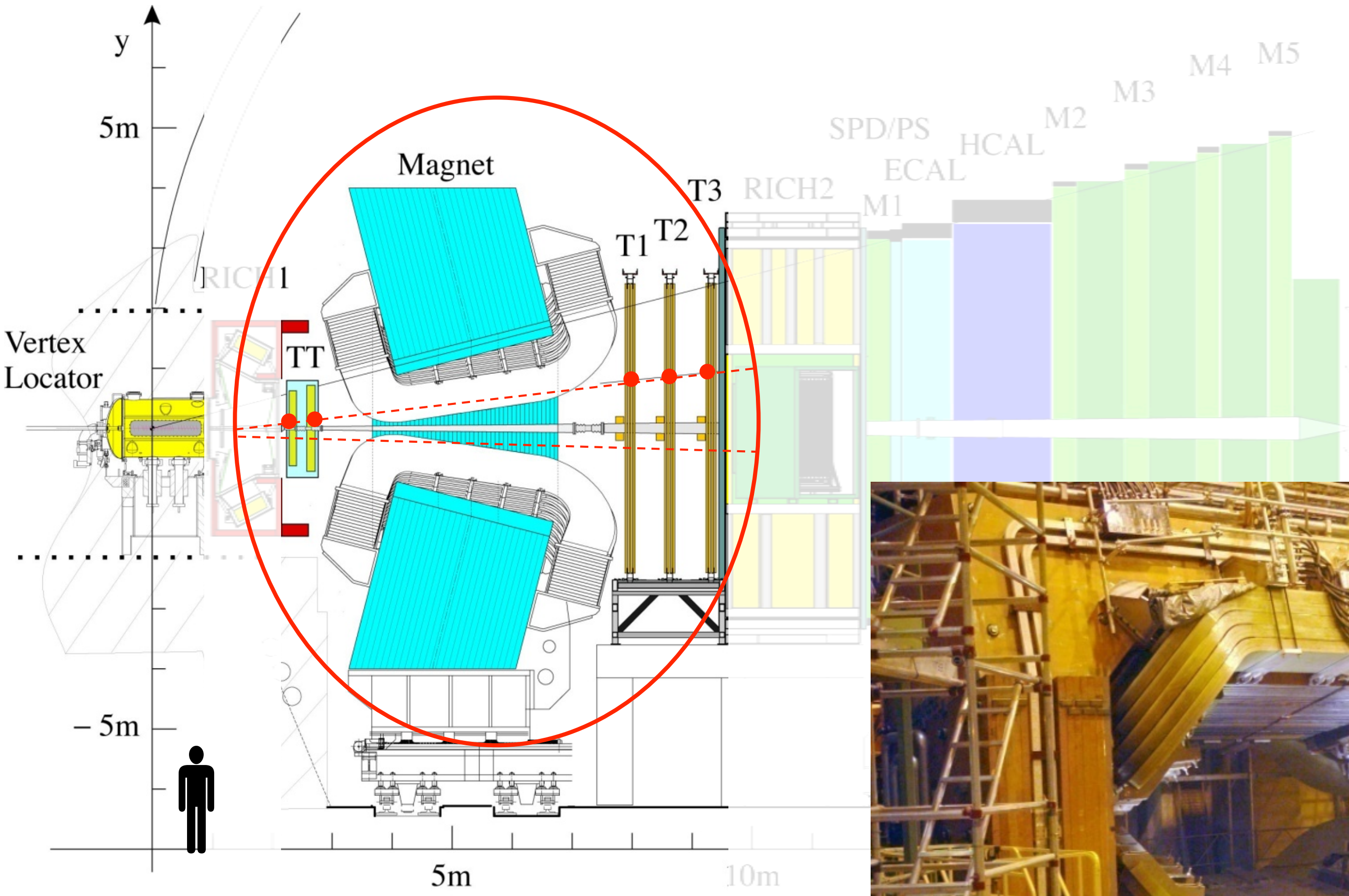
Tracker Turicensis (before the magnet): 4 plans of silicon μ-strip, 8 m^2.
Tracker (after the magnet)
 Inner (close to beam pipe): 3 stations, 4 plans of silicon μ-strip, 4.2 m^2.
 Outer: 3 stations, 4 plans of straw tubes
Momentum resolution $\Delta p/p$ = 0.5%–1% (~0 GeV/c –200 GeV/c)

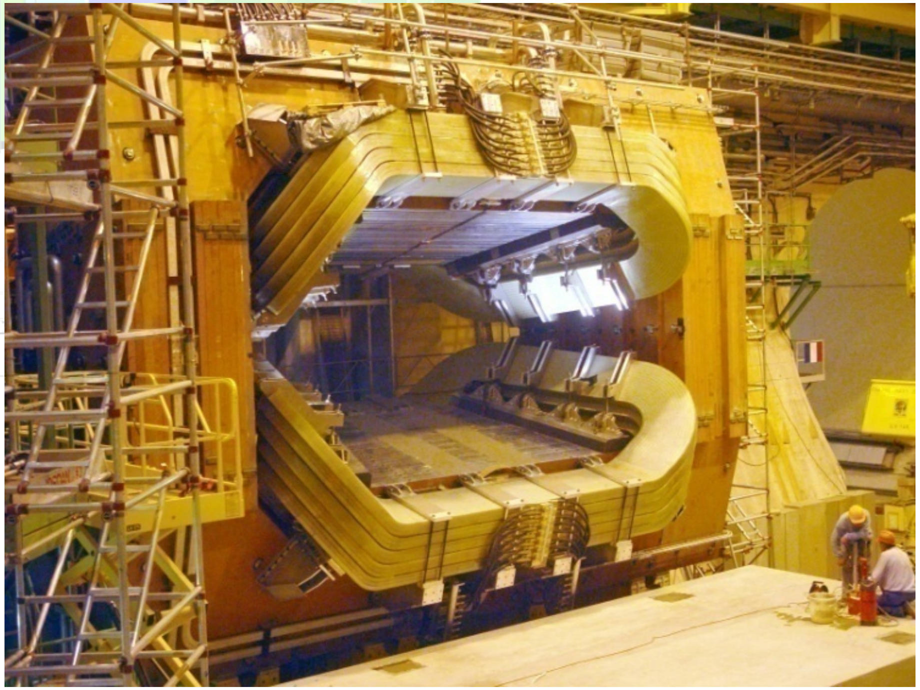




Magnet

Warm **dipole** magnet, bending power: 4 Tm
- Two triplets of magnets to compensate for its effect in LHC.



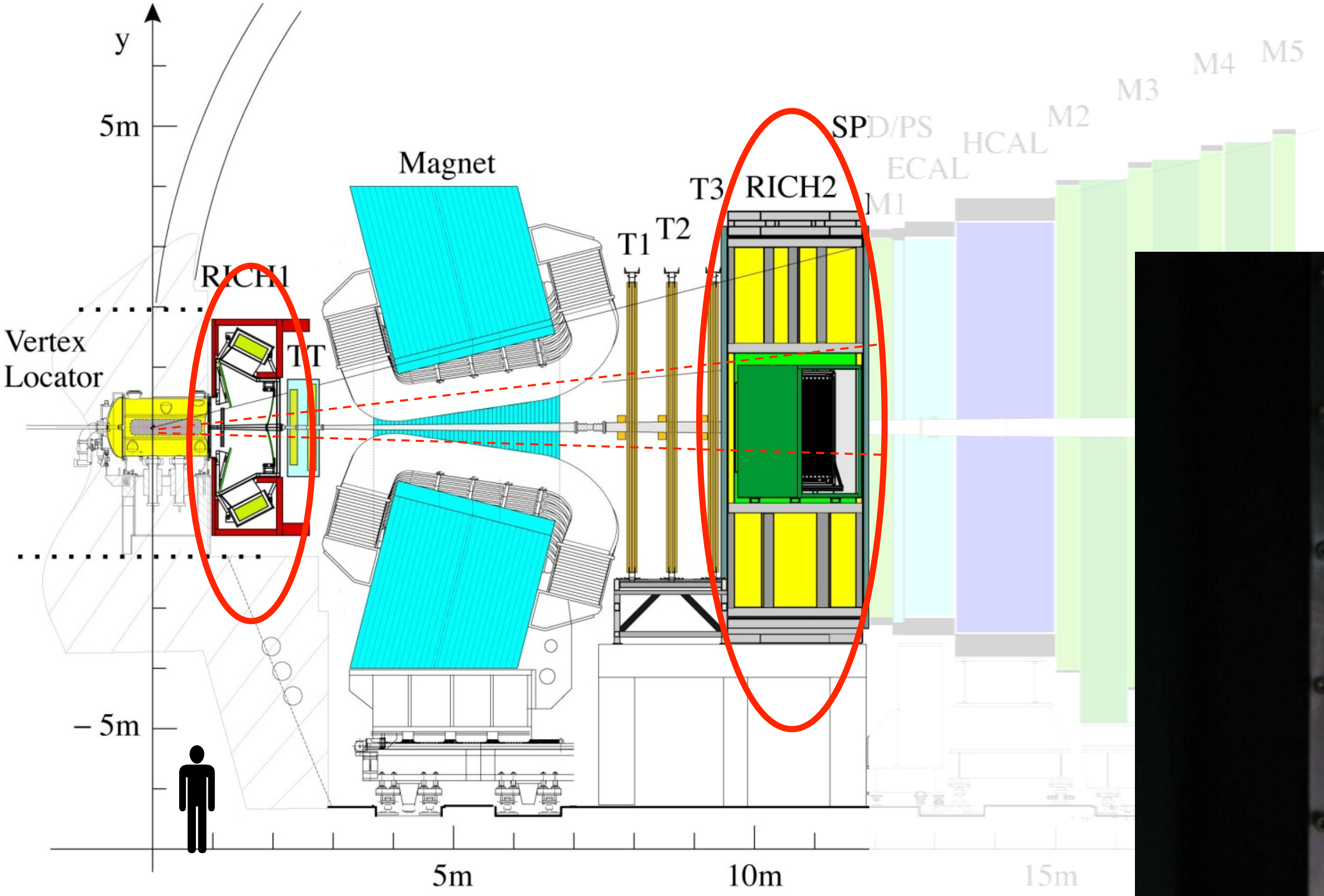


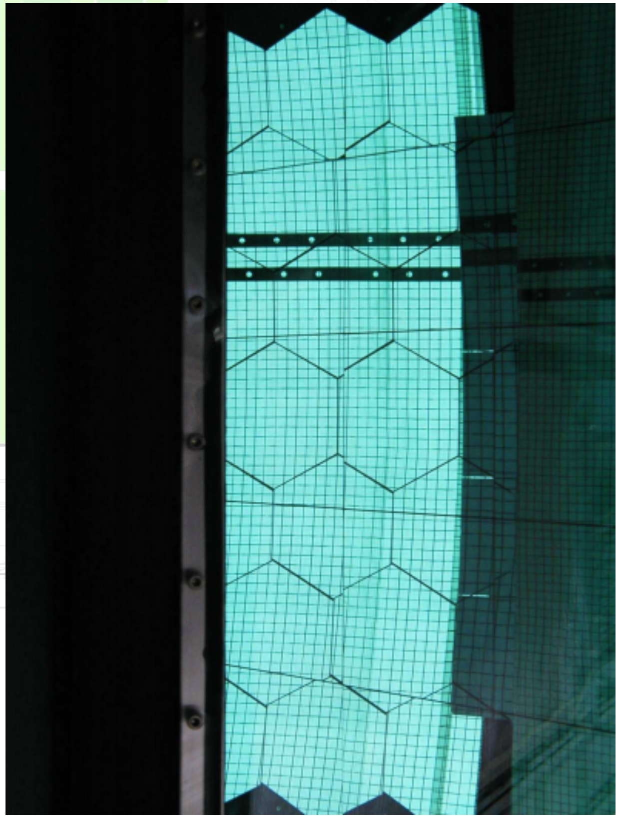
Weight: 1600 t
Power: 4200 kW
Cooling water = 150.000 l/h

[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

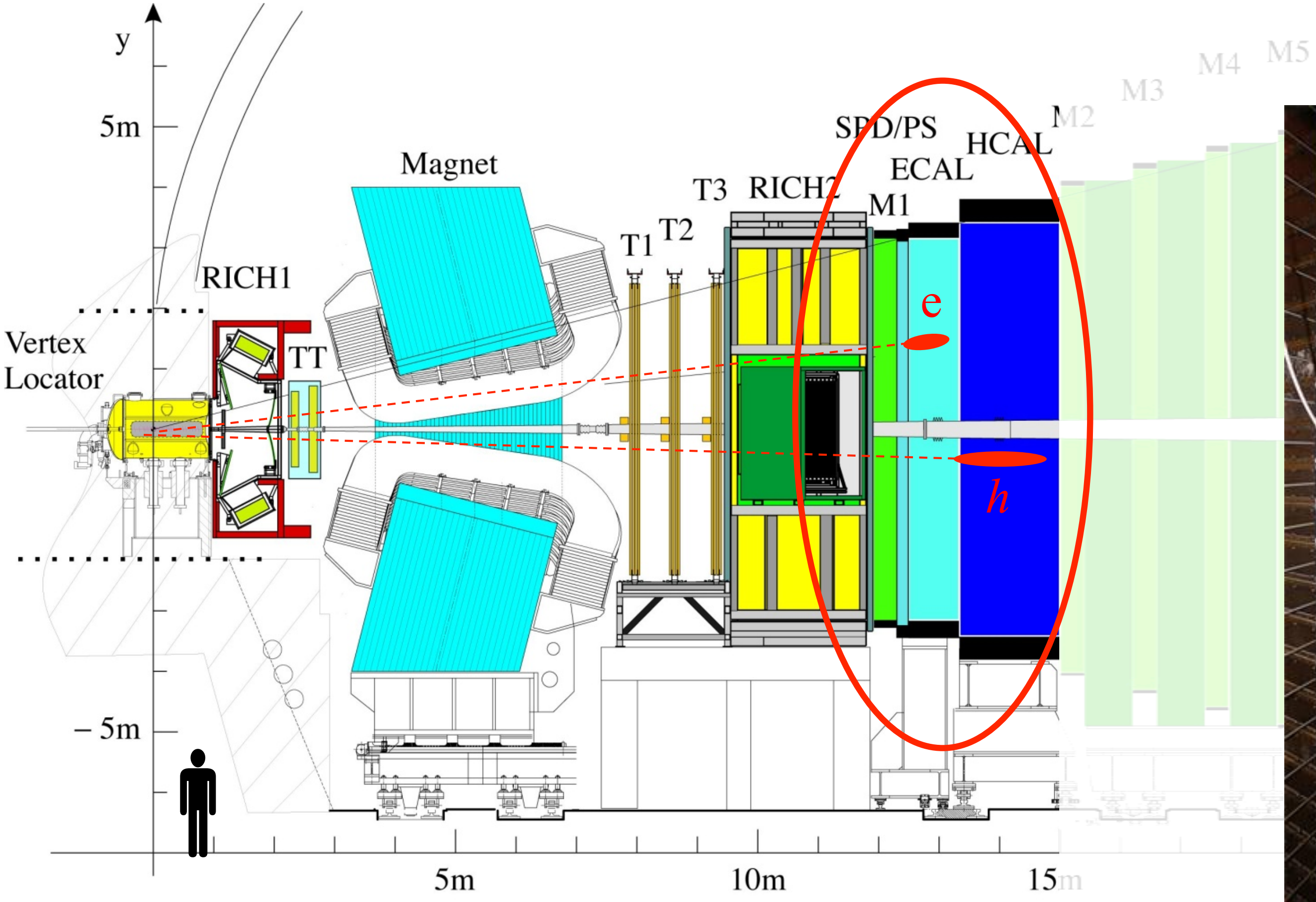


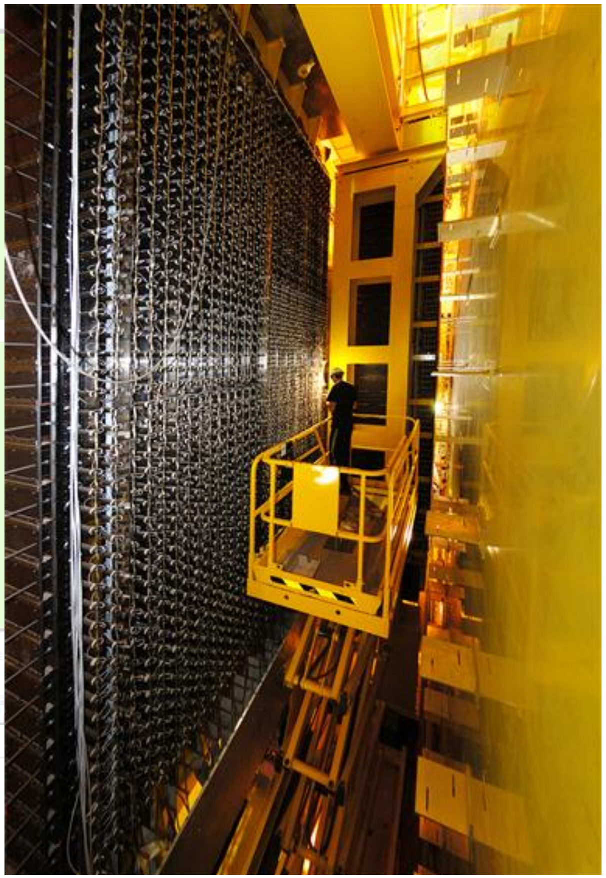


[LHCb Detector Performance Int.J.Mod.Phys. A30 (2015) 1530022]

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]





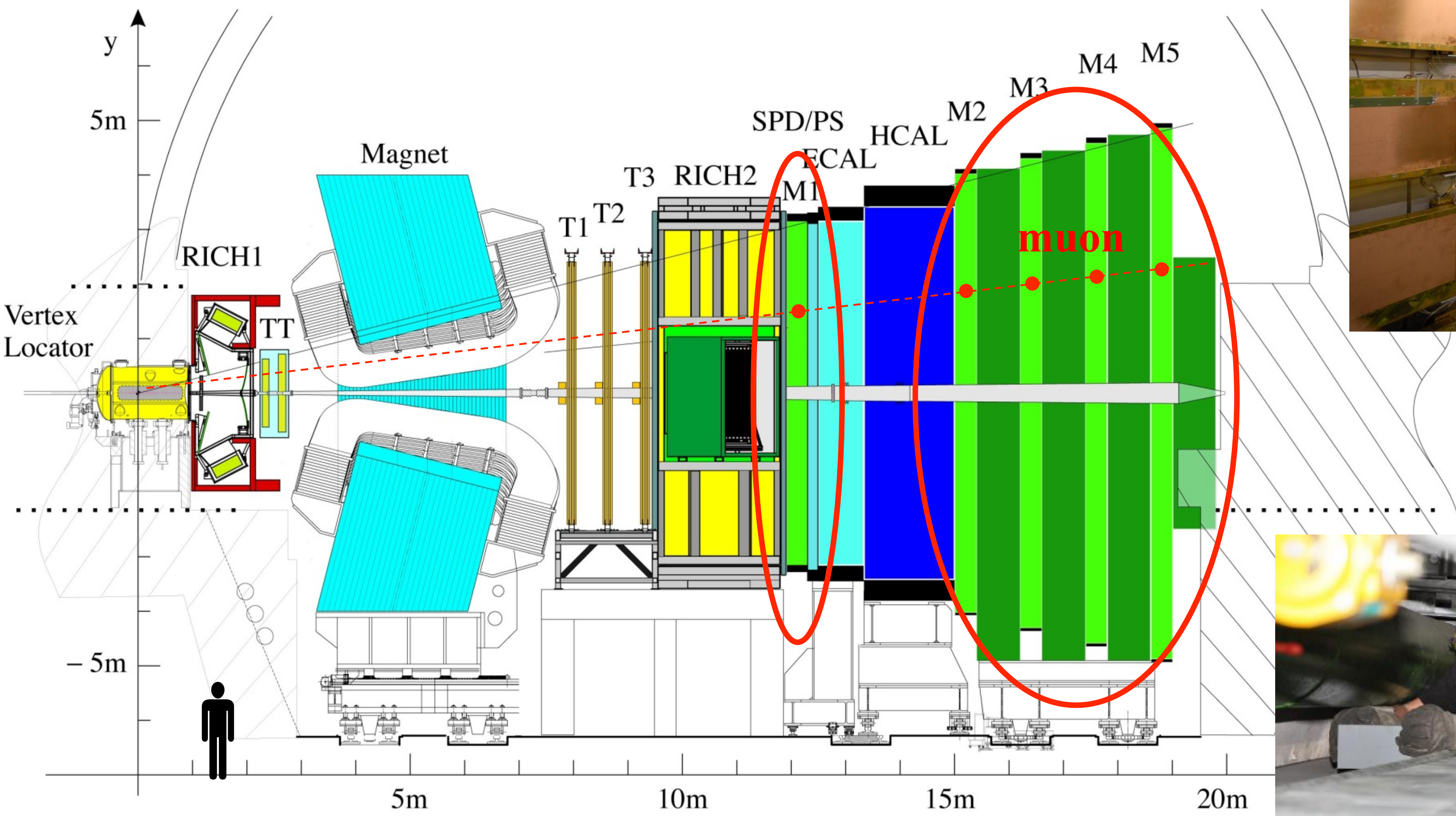
[Performance of the Muon Identification at LHCb JINST 8 (2013) P10020]
[Performance of the LHCb Muon system JINST 8 (2013) P02022]

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 %

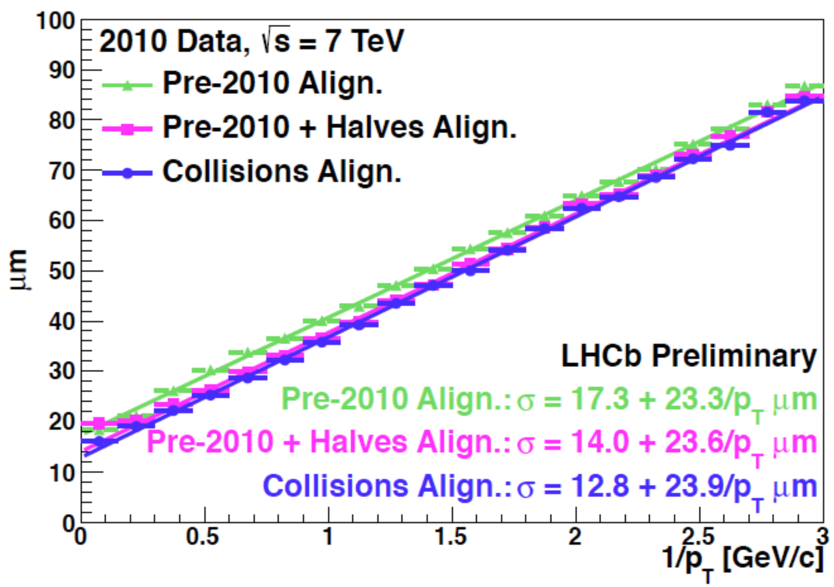
Used in the first level of the trigger [L0]

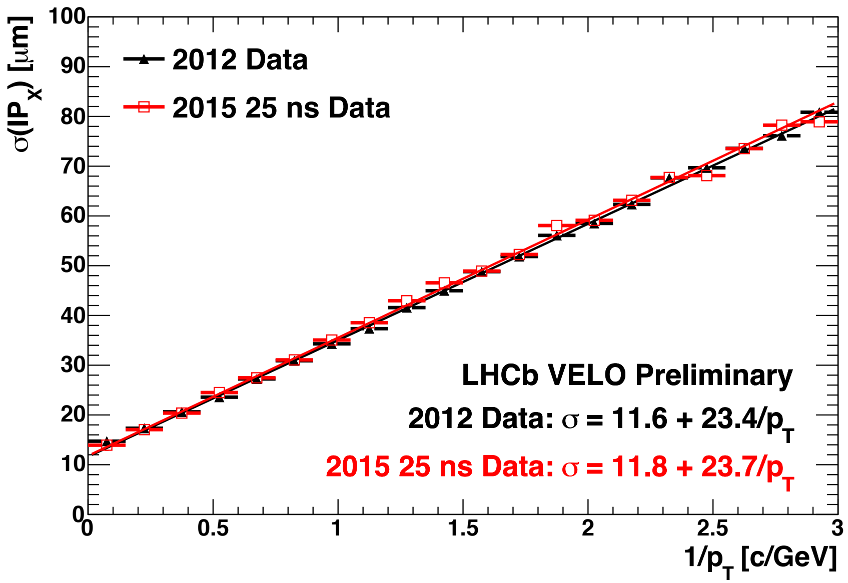


Alignment

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)



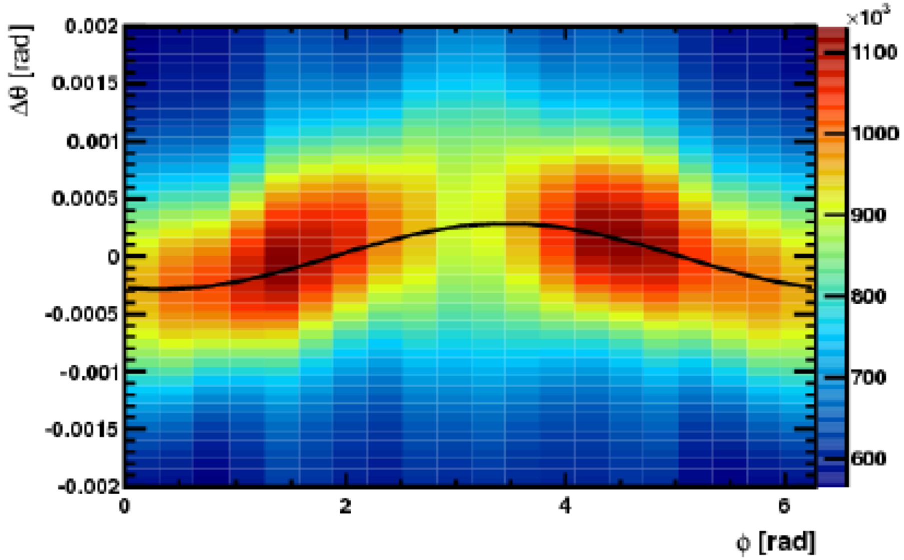


Alignment

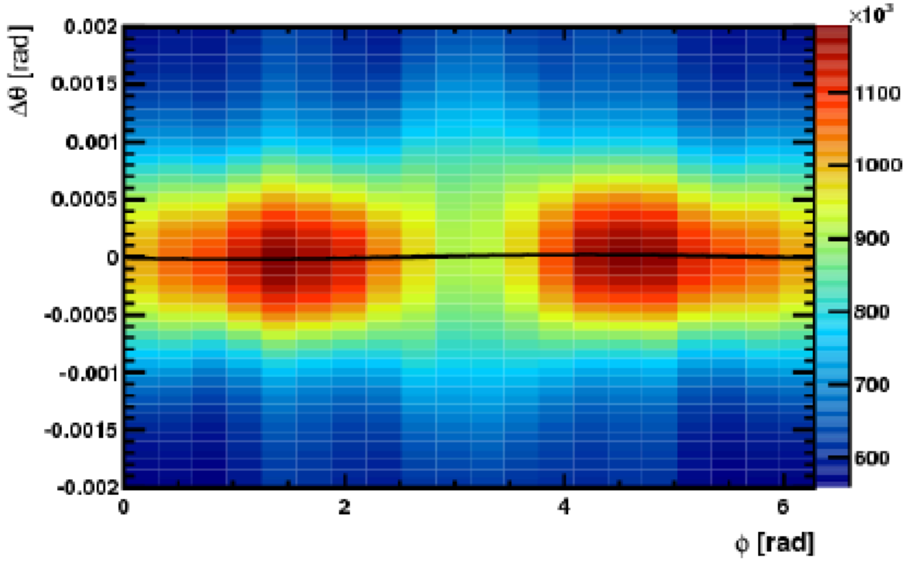
Alignments Run on the HLT-farm at the beginning of every fill;

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

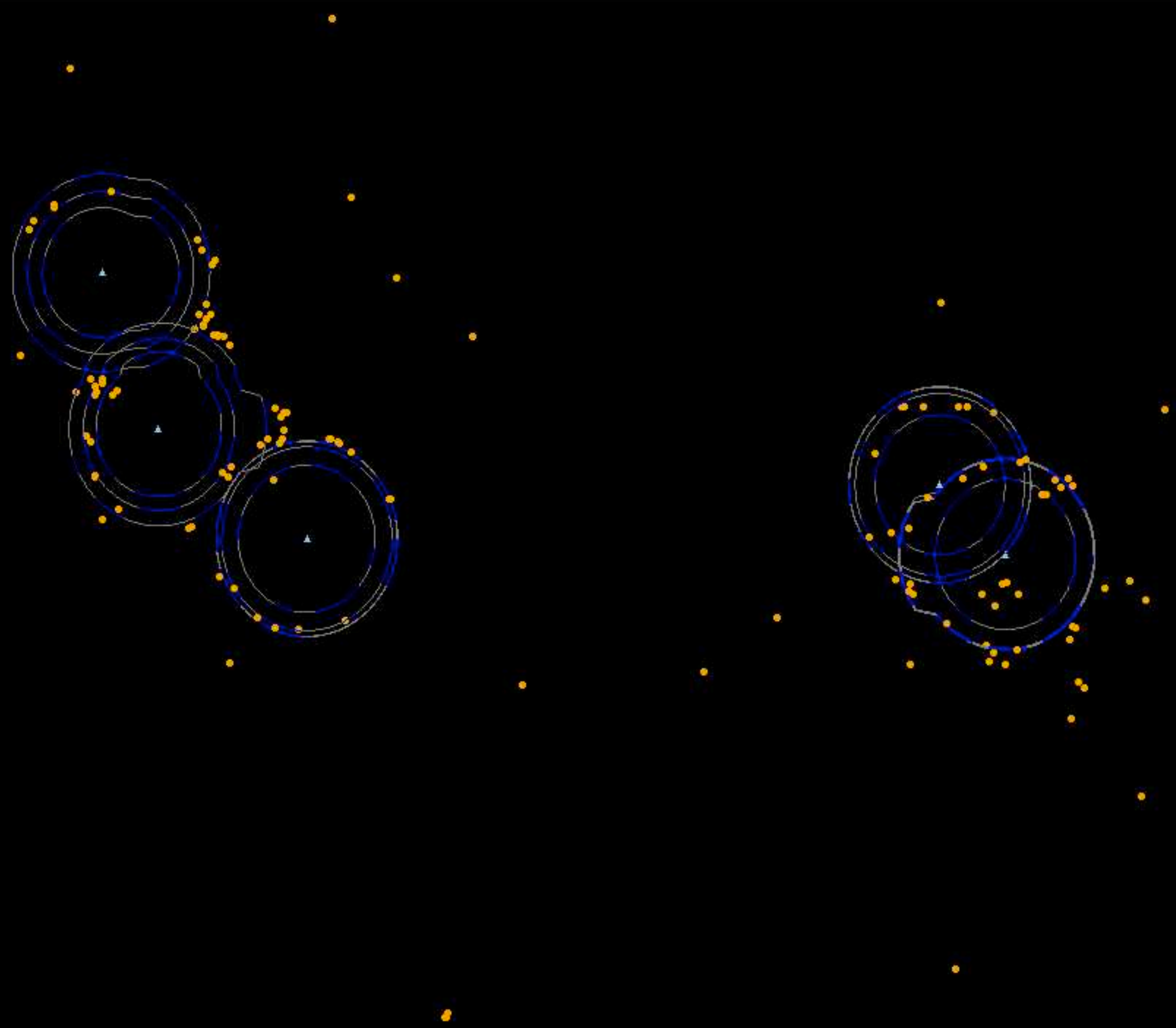
Before mirror alignment



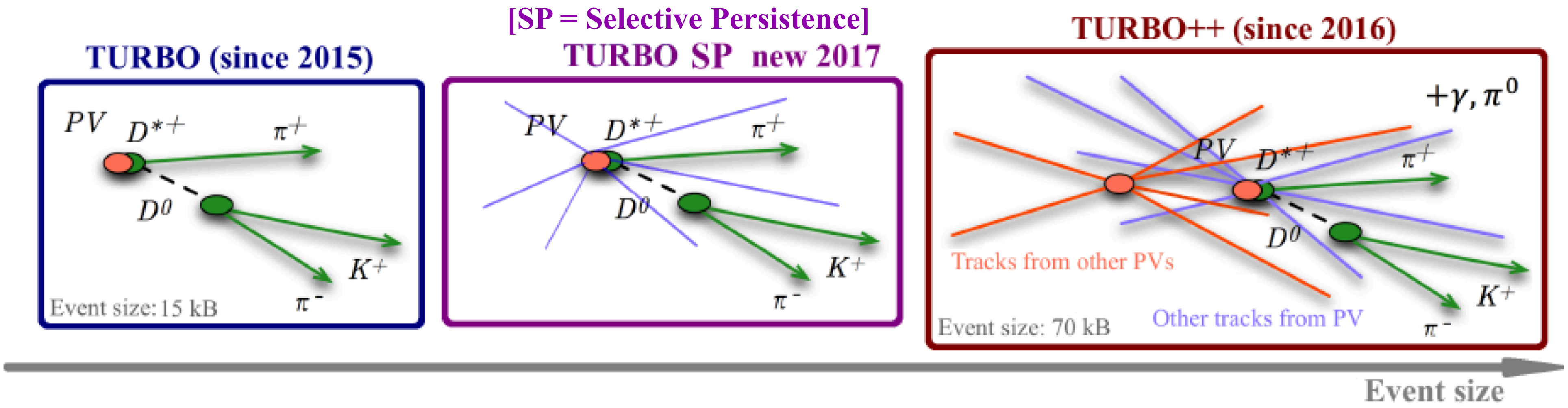
After mirror alignment



RICH



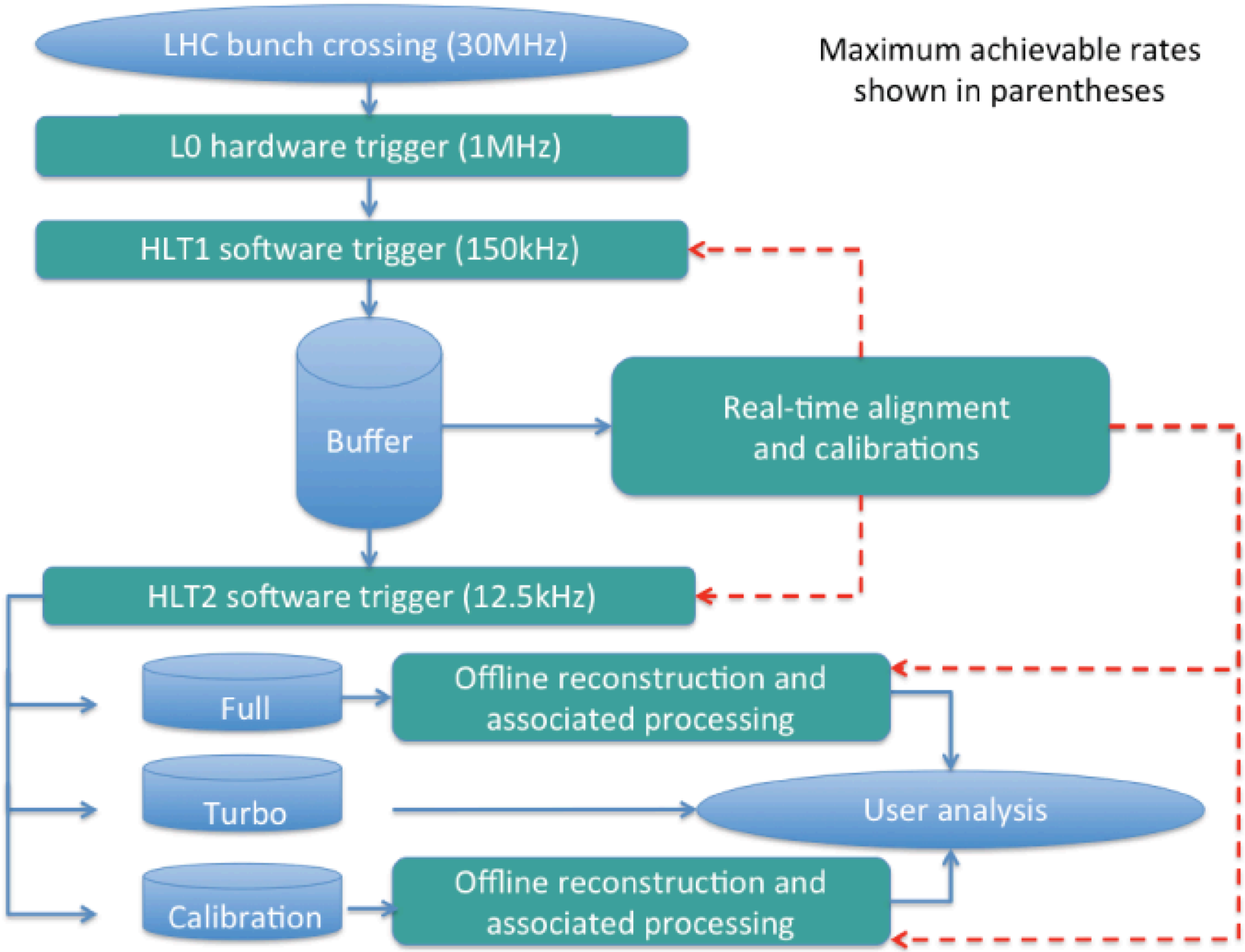
Is every part of the collision interesting?



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, ++)



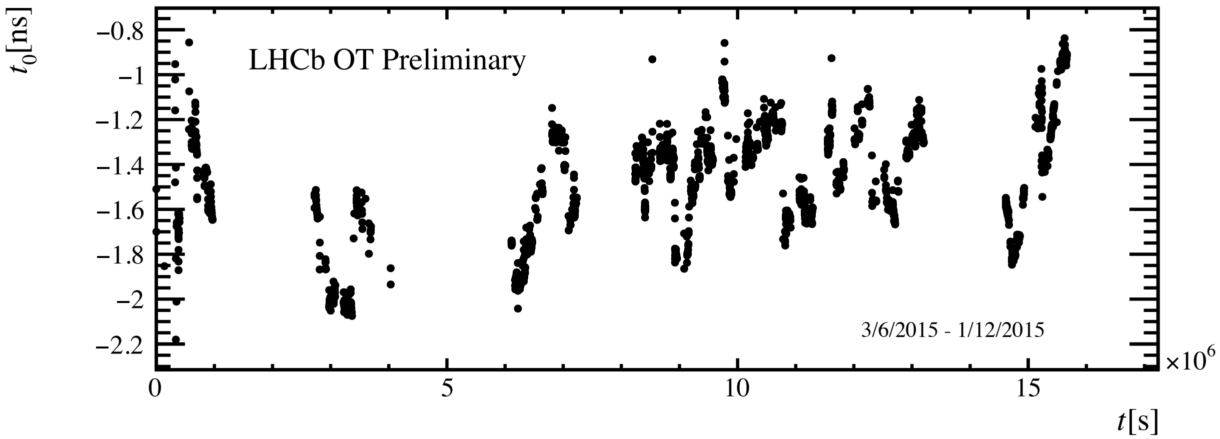
[Tesla : an application for real-time data analysis in High Energy Physics, 1604.05596v1]

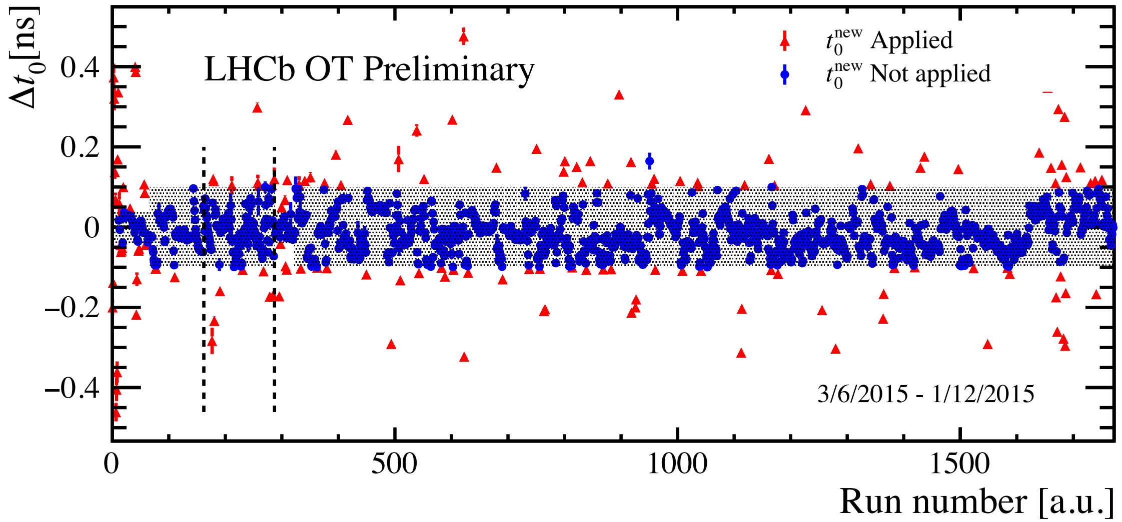
Real-time alignment and calibration: tasks

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*	

Calibration

Calibrations run on the monitoring histograms for ~every run:
 - **OT calibration**: global time alignment of the OT wrt LHC clock

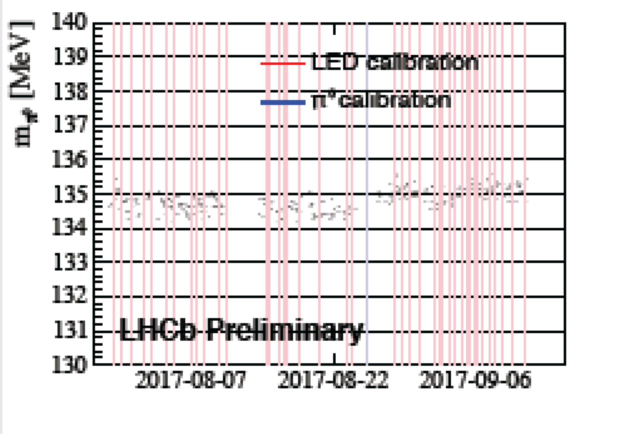




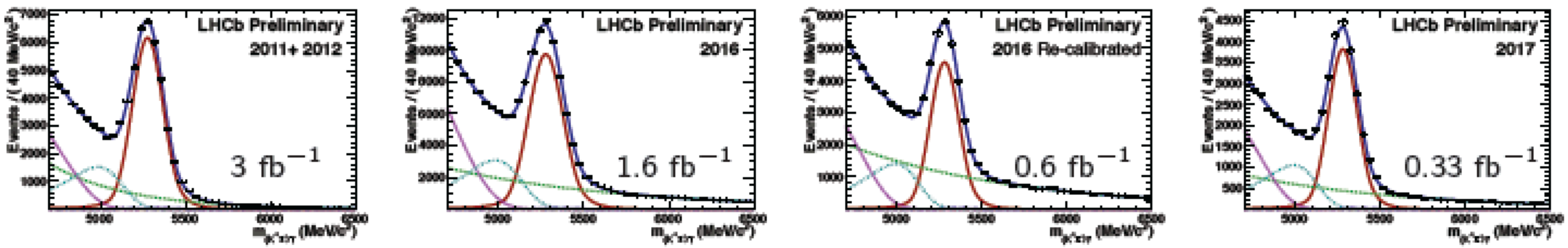
Calibration

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