LHCb experiment - selected results and prospects

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NOI seminar

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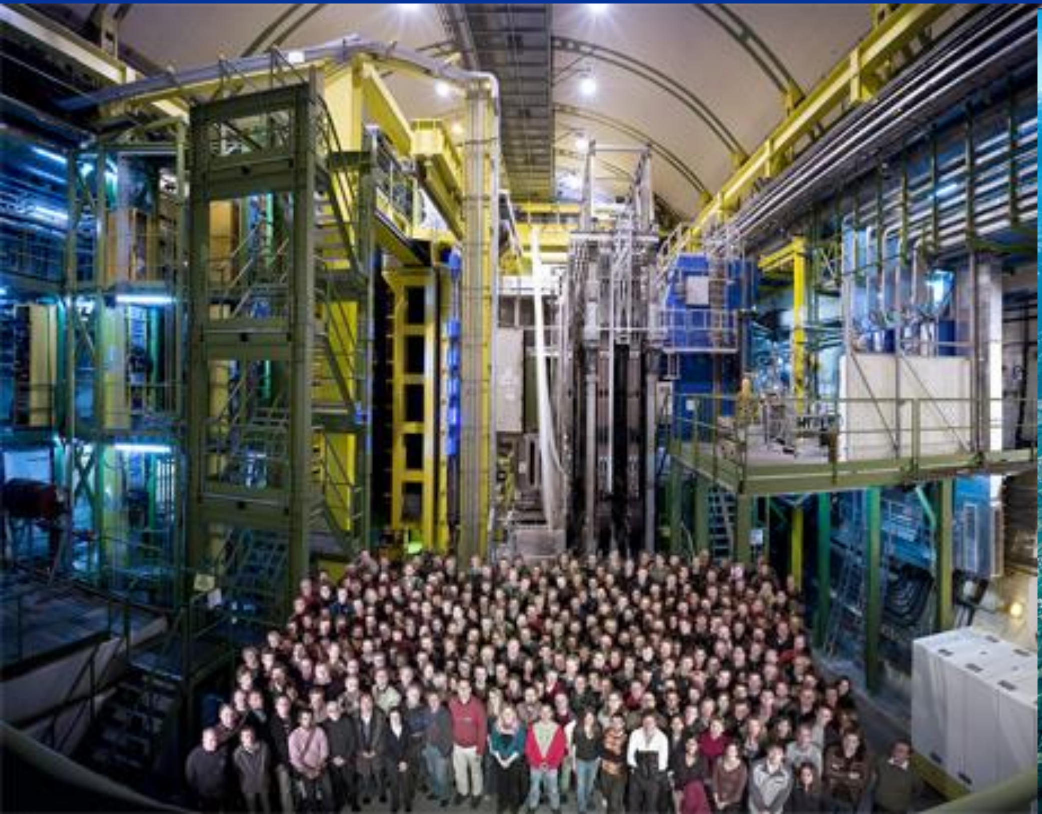
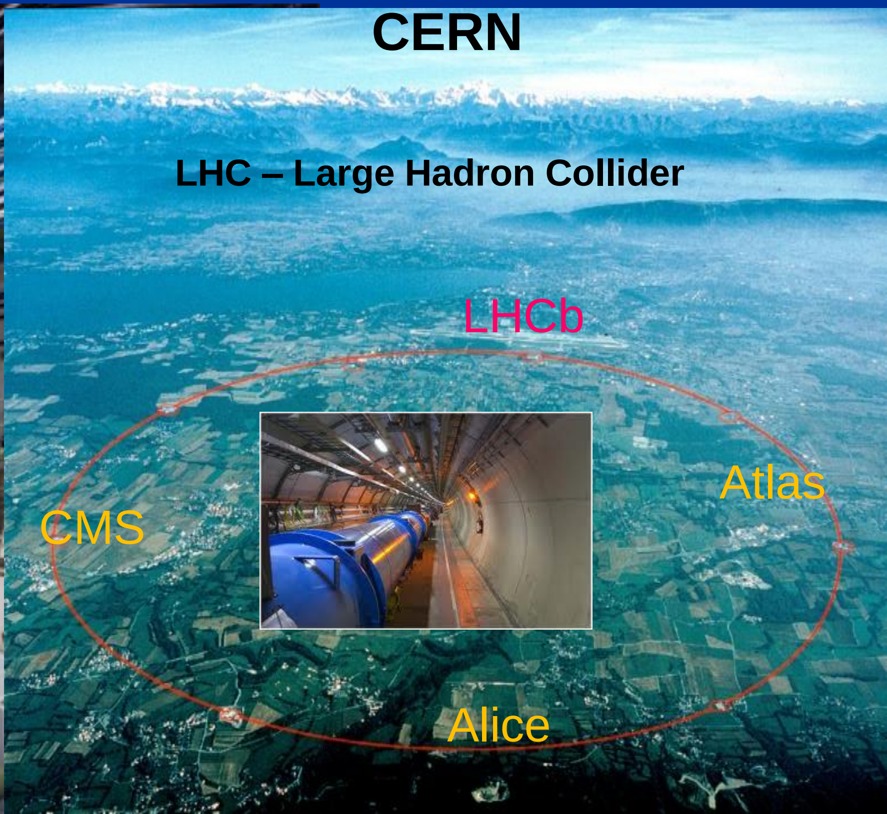


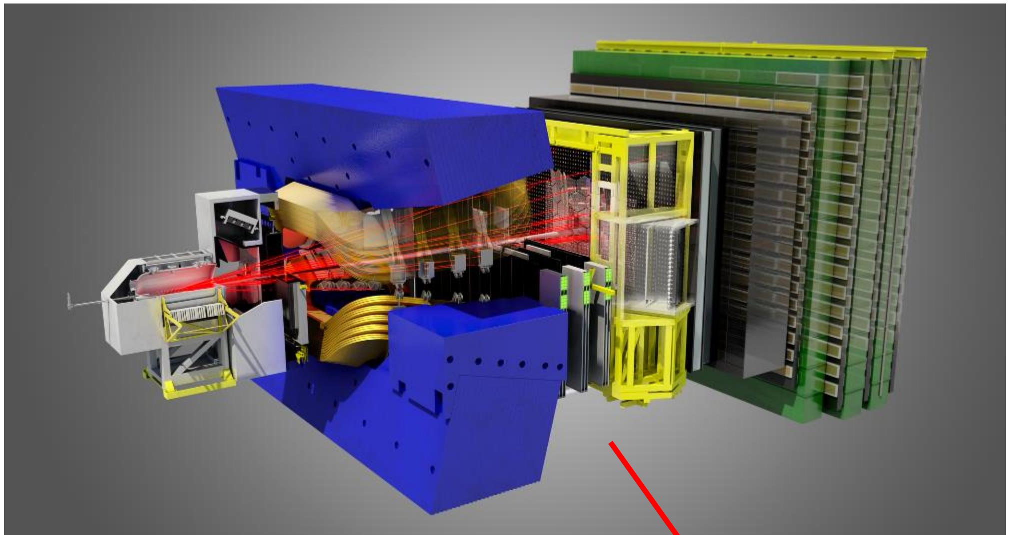


Outline

- LHCb experiment
- Selected measurements from Run1 & Run2
- Detector upgrades and prospects
- Summary

LHCb experiment

A dedicated LHC Collider Beauty Experiment for precision measurements of CP-violation and searches for New Physics.



High cross-section of heavy-quark production

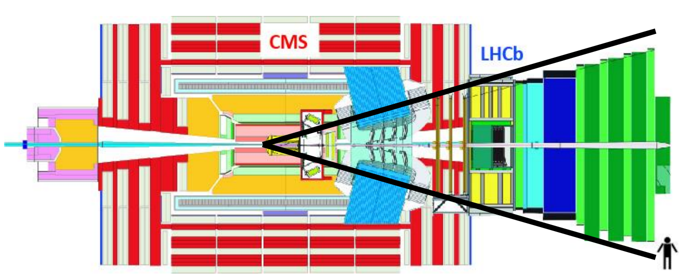
Excellent decay time resolution

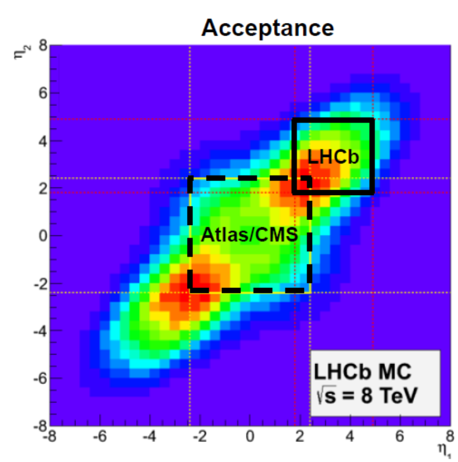
Excellent particle identification

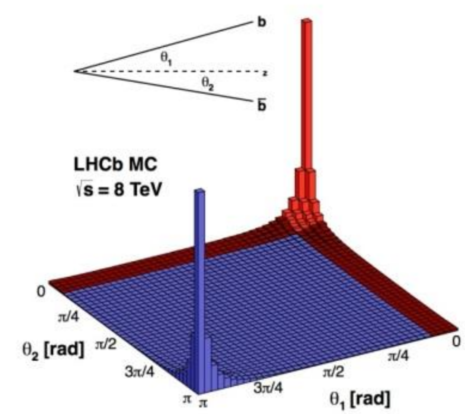
Excellent momentum resolution

Fully instrumented in $2 < \eta < 5$

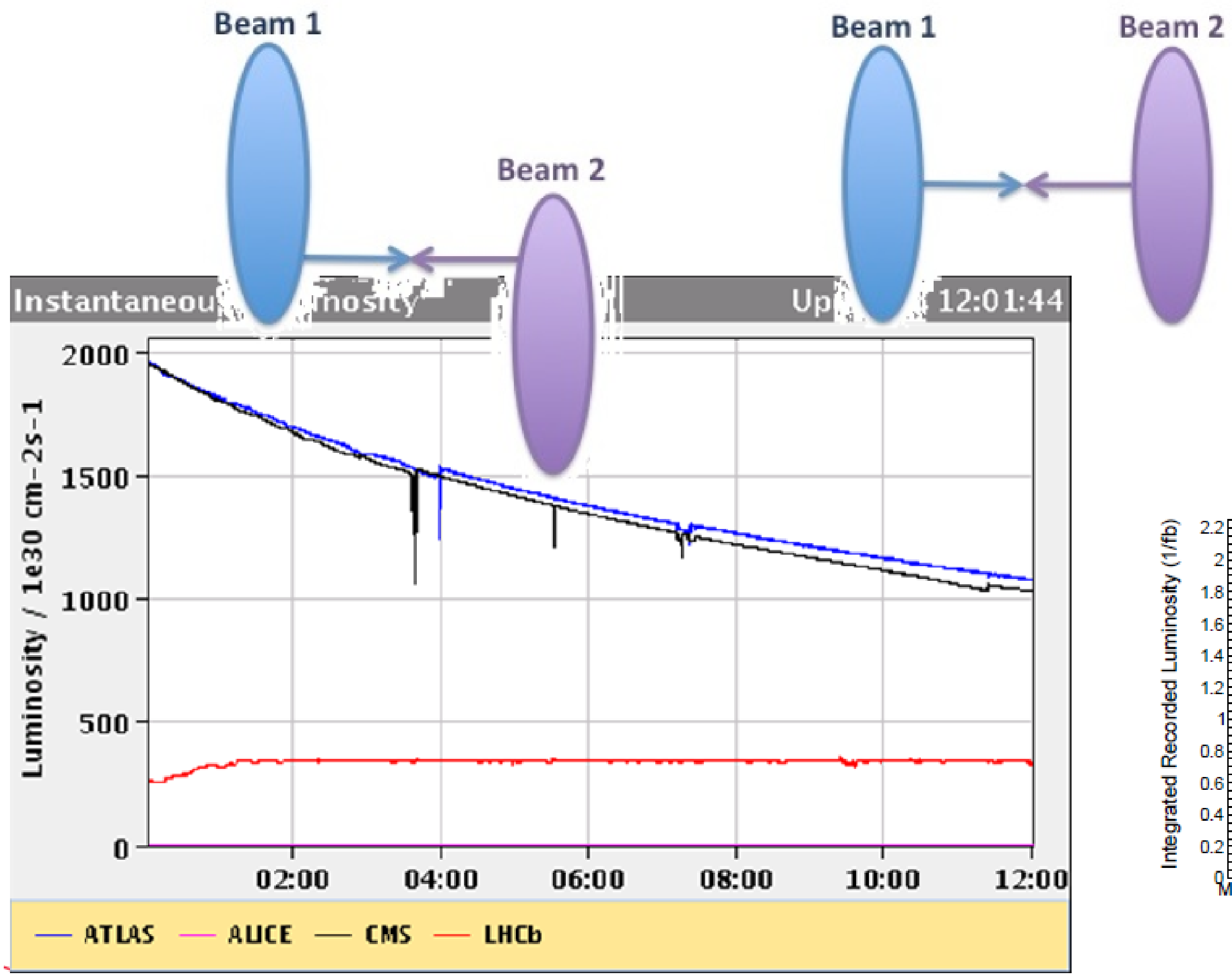
LHCb high PT ~ few GeV



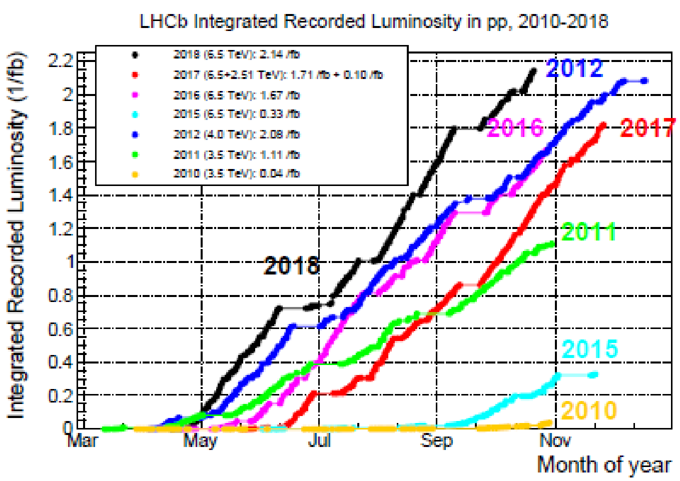




Luminosity leveling



Beams are offset in real time to keep a constant luminosity



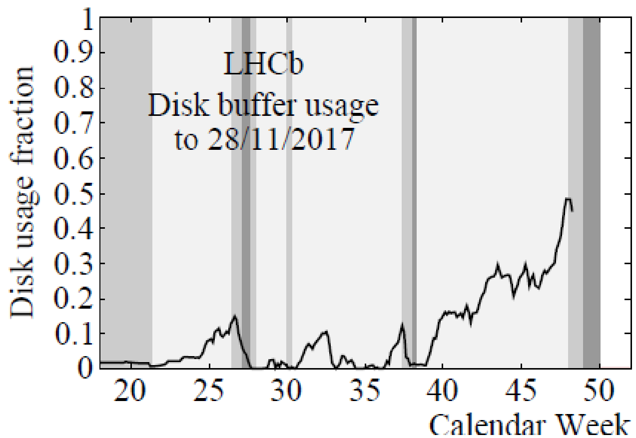
Trigger - Run 2

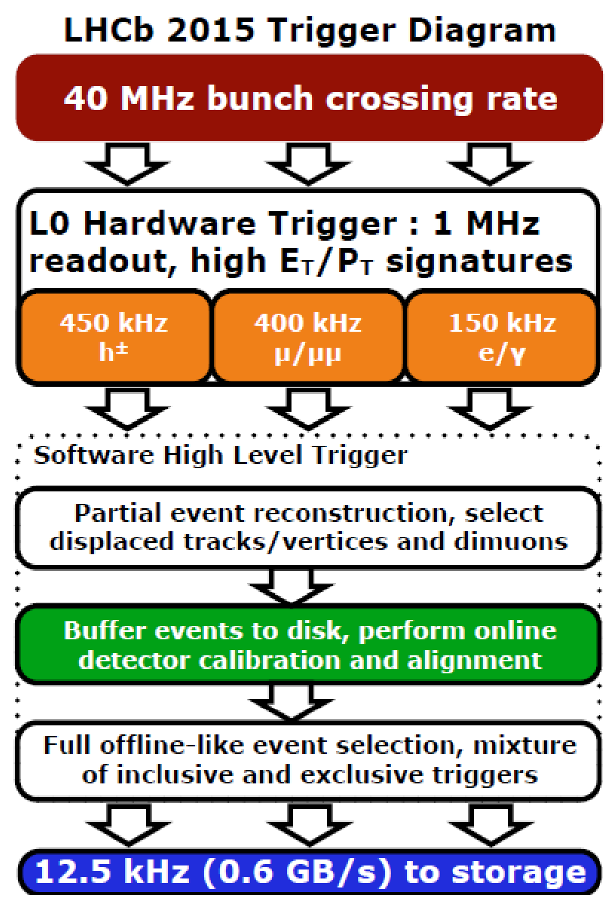
Offline storage (WLCG grid) limits the measurement sensitivity (statistics)

Turbo Stream – offline selection at online phase → large charm samples in Run2

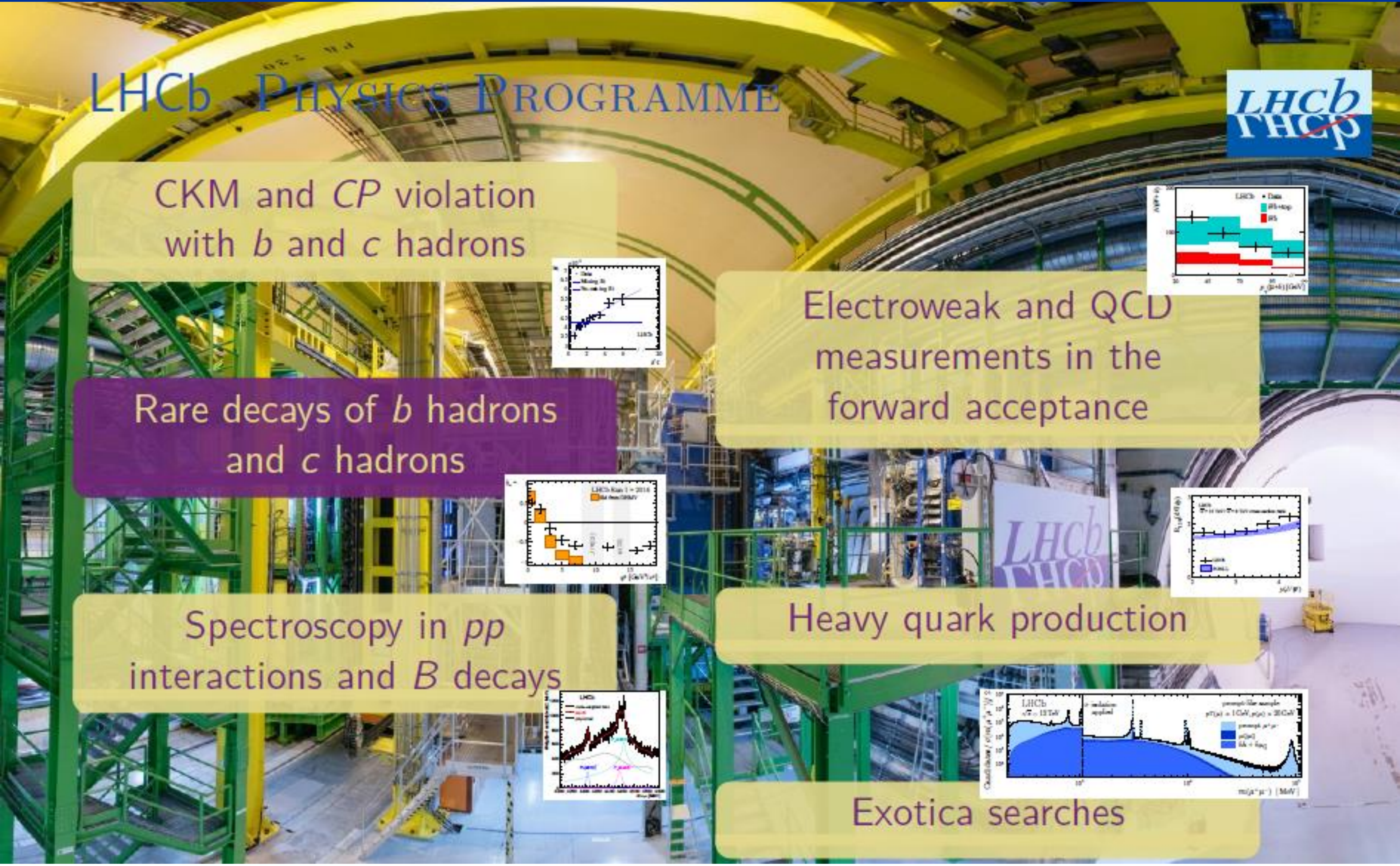
Events are buffered on disk (10 PB) while calibrations are being run.

- → Offline-quality trigger objects available for analysis.
- Disk → more CPU. The full reconstruction can also be run during LHC downtime.



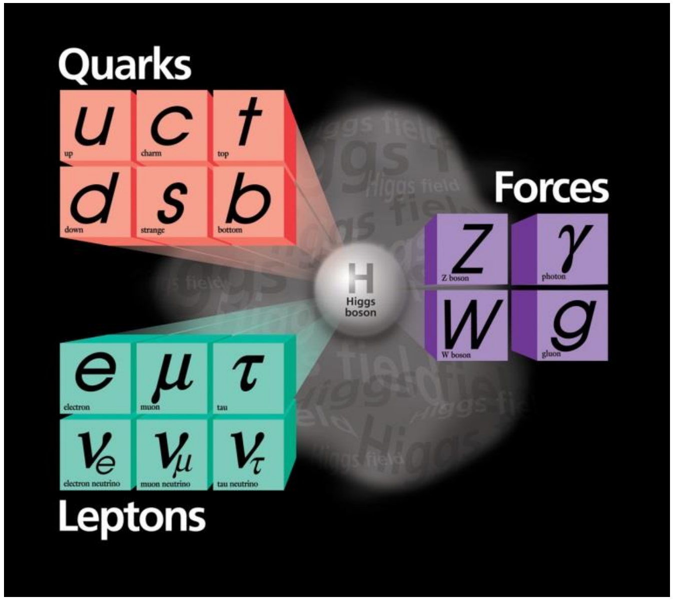


LHCb physics programme



Standard Model

Extremely successful theory of fundamental interactions,



- 1 fundamental scalar
- 2 types of fermions
- 3 generations
- 4 fermions/generation
- 3 types of interactions
- 4 bozons

but:

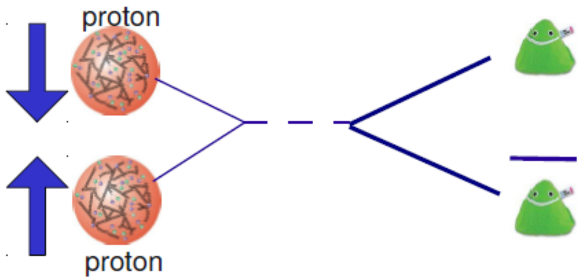
Matter-antimatter asymmetry in the Universe?
Structure of 3 generations, origin of neutrino masses?
What is the nature of dark matter?

New Physics beyond SM needed.

Two ways to search for New Physics

Direct observations

Probe up to ~4 TeV

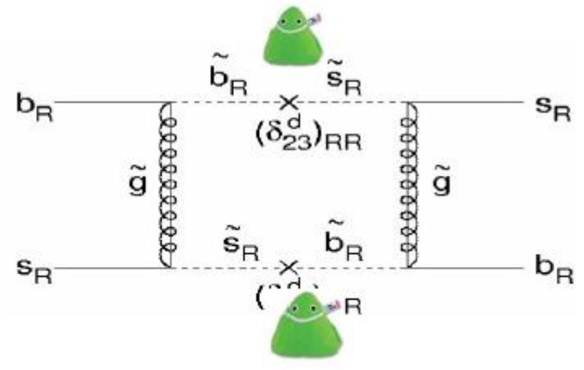


Direct production of new objects at √s =14 TeV

Probe up to ~50 TeV

LHCb approach

Indirect searches



Precision measurements of well predicted observables in SM , in particular these with small values, makes us sensitive to higher mass scale.

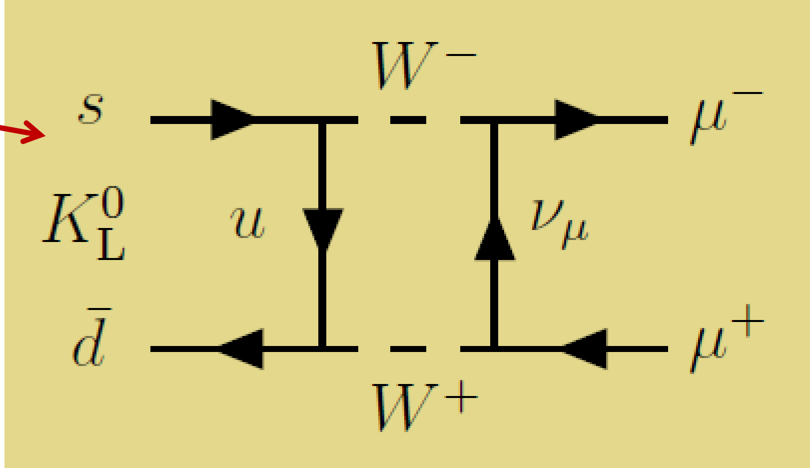
Examples of indirect discoveries:

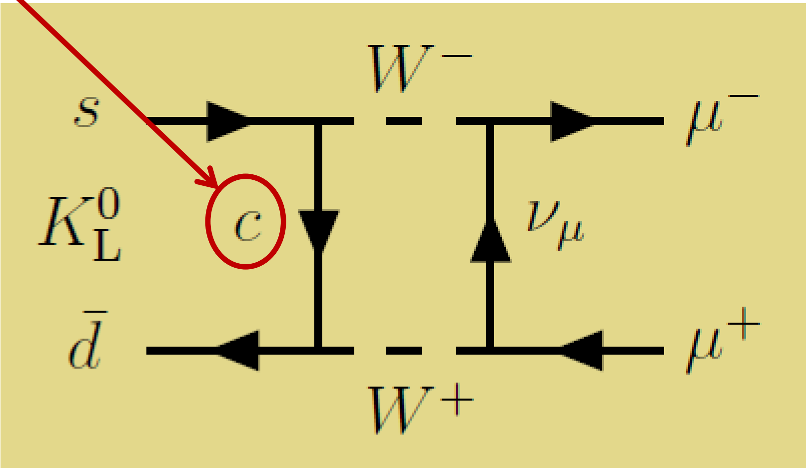
- Prediction of third generation of quarks (***b*,*t***) to introduce CPV in SM
- ***c*** and ***t*** quarks first „seen” in FCNC processes in *K* and *B* mesons
- (ν+N→ν+N) seen in 1973; direct ***Z*** observation 10 years later

The GIM mechanizm

- $K^0_L \to \mu^+\mu^-$ was not observed though expected
  - Now $\mathcal{B}$ is measured to be $(6.84 \pm 0.11) \cdot 10^{-9}$ [Ambrose et, al, 2000]

➜ Led to the postulation of the c quark "GIM mechanism" in 1970 [Glashow, Iliopoulos and Maiani, PRD 2 (1970) 1285] (also [Bjorken, Glashow, PL 11 (1964) 255])





indirect observation of a particle

The GIM mechanizm

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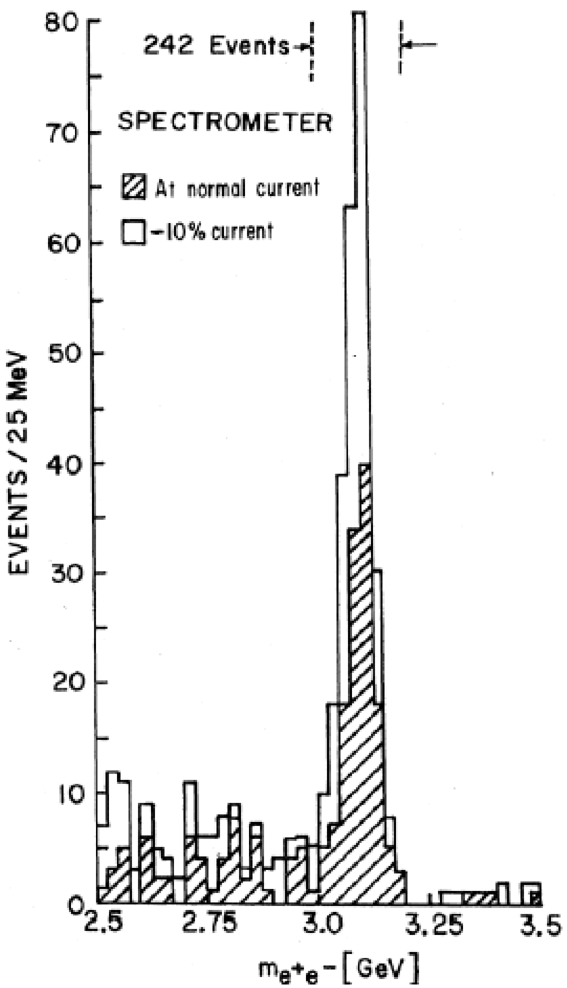
➜ c quark eventually observed in 1974 [Richter et al., PRL 33 (1974) 1406], [Ting et al., PRL 33 (1974) 1404]

direct observation of a particle

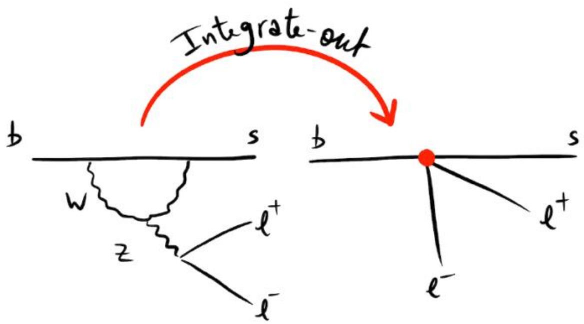


Indirect measurements - precision

- 3 ingredients needed
  - Precise SM prediction
  - Good experimental precision
  - If possible precise BSM prediction

Effective Field Theory (EFT) approach

Example: $b \to sll$ transition



Effective-Hamiltonian approach

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} \frac{e^2}{16\pi^2} V_{tb} V_{ts}^* \sum_i C_i O_i + \text{h.c.}$$

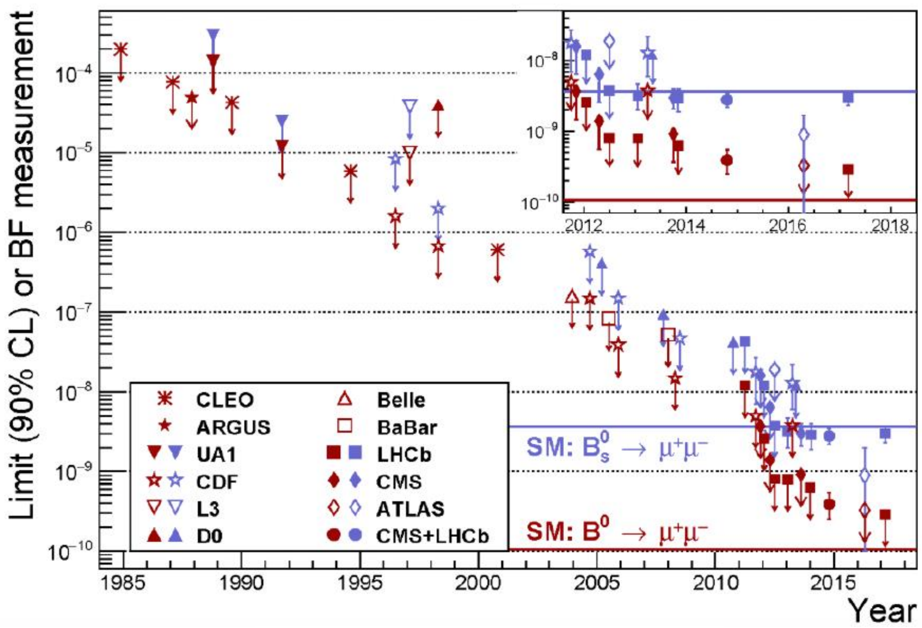
coupling constants
(Wilson coefficients)
NP entres here

Local interaction terms (operators)

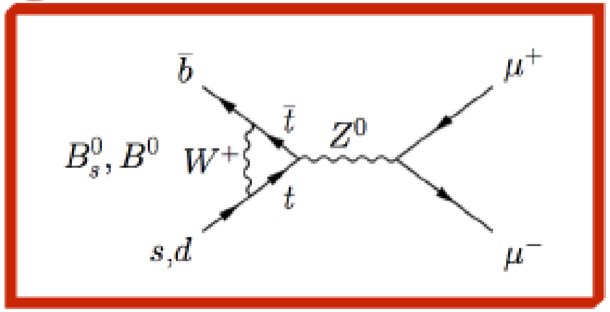
Analog of Fermi Theory for weak decays.
Information on the electroweak-scale physics is encoded in the values of C_i.

Very rare decay - $B^0_{(s)} \to \mu\mu$

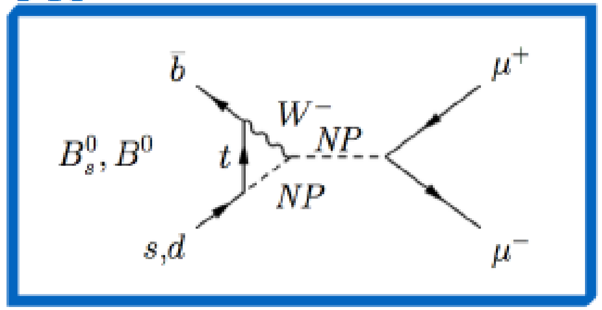
- Highly suppressed in the SM FCNC + CKM + helicity
- Possible tree level BSM contributions → very sensitive
- Ratio between B_s and B^0 highly constrains MFV
- Leptonic decay (no hadronic uncertainties) → Very well predicted



SM



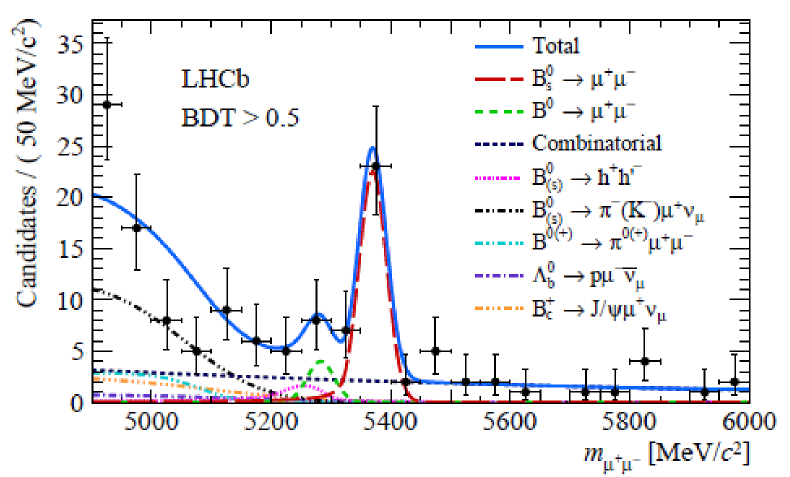
NP

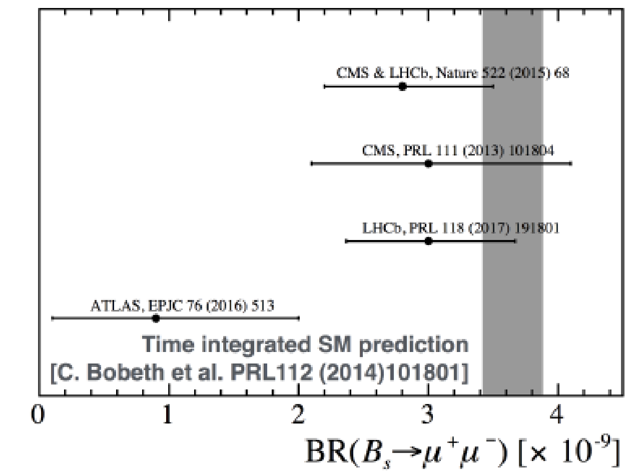


Very rare decays - $B^0_{(s)} \to \mu\mu$

- Recent LHCb analysis using Run 1 and 2 data ($3\text{fb}^{-1} + 1.4\text{fb}^{-1}$) provided the first single experiment observation of $B_s^0 \to \mu^+\mu^-$ at 7.8σ
- $B_s \to \mu^+\mu^-$ is the rarest b hadron decay ever observed

LHCb $$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 3.0 \pm 0.6(\text{stat})^{+0.3}_{-0.2}(\text{syst}) \times 10^{-9}$$





- Results for $B_s^0 \to \mu^+\mu^-$ are consistent with SM expectations
- $\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$ a the 95% CL

ATLAS + CMS + LHCb combination:

$$\mathscr{B}\left(B_s^0 \to \mu^+\mu^-\right) = \left(2.69^{+0.37}_{-0.35}\right) \times 10^{-9}$$
$$\mathscr{B}\left(B^0 \to \mu^+\mu^-\right) < 1.9 \times 10^{-10} \text{ at } 95\% \text{ CL}$$

Latest BR predictions have precision at 4-5% level:

$$\mathscr{B}\left(B_s^0 \to \mu^+\mu^-\right) = \left(3.66 \pm 0.14\right) \times 10^{-9}$$
$$\mathscr{B}\left(B^0 \to \mu^+\mu^-\right) = \left(1.03 \pm 0.05\right) \times 10^{-10}$$

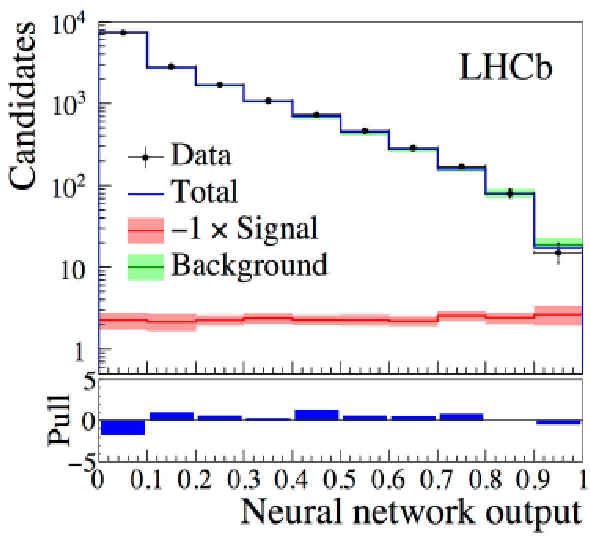
SM

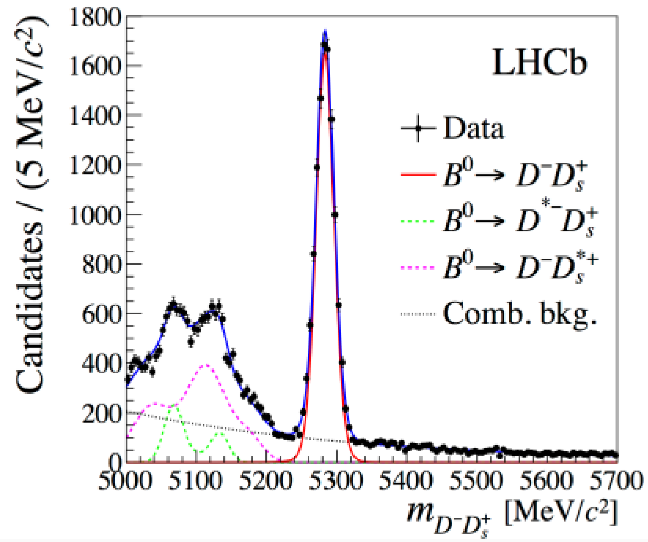
Beneke et al JHEP 10 (2019) 232

$B_s \to \tau^+\tau^-$

- Can be used to study LFU when combined with $B_s \to \mu\mu$
- Less helicity suppression → higher BR ~10^{-7} vs 10^{-9}
- Reconstructed using $\tau \to 3\pi\nu$. Challenging due to the neutrinos.
- Normalised with respect to $B^0 \to D^+(K^-\pi^+\pi^+)D^-(K^-K^+\pi^+)$
- As there is no peak the MVA output is fitted

[PRL 118 (2017) 251802]



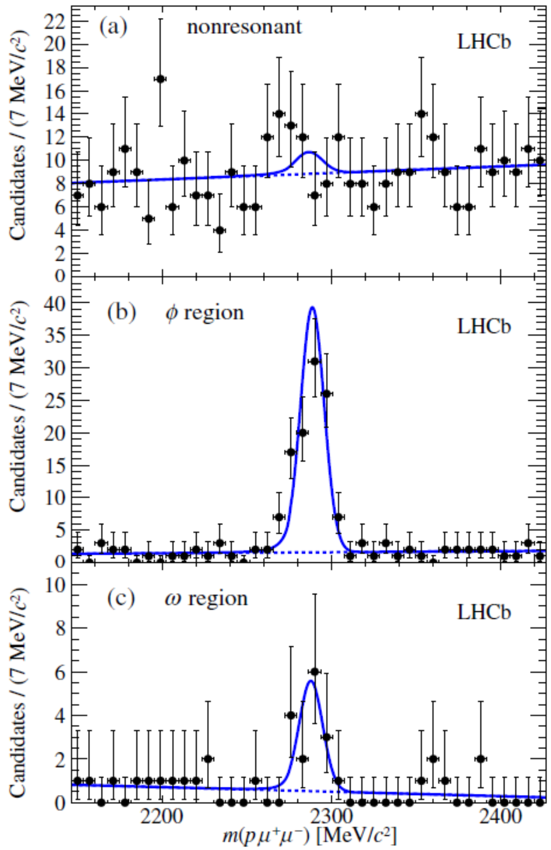


First measurement!

- LHCb sets limits on:
  - $\mathcal{B}(B_s^0 \to \tau^+\tau^-) < 6.8 \times 10^{-3}$(@95%$CL$) First limit on $B_s \to \tau^+\tau^-$
  - $\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3}$(@95%$CL$) Best limit on $B \to \tau^+\tau^-$

Search for $\Lambda^+_c \to p\mu^+\mu^-$ decay

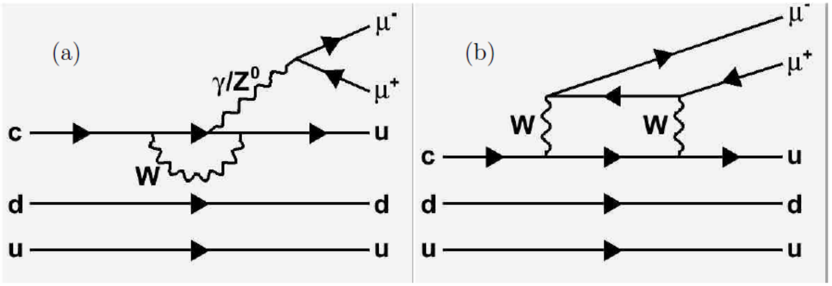
$\Lambda^+_c \to p\mu^+\mu^-$: FCNC, highly suppressed decay



Signal
$\Lambda_c^+ \to p\mu^+\mu^-$

Normalization
$\Lambda_c^+ \to p\phi$

New
$\Lambda_c^+ \to p\omega$



SM BF($\Lambda^+_c \to p\mu^+\mu^-$):

~10^{-9}: short distance $c \to u l^+ l^-$

~10^{-6}: possible enhancement of long distant contribution.

Experimental status (2017):

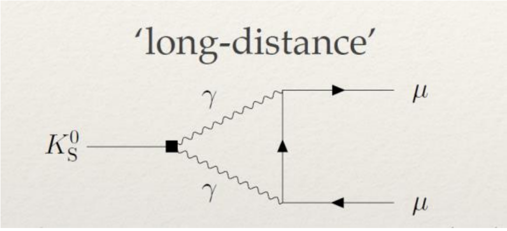
BABAR: arXiv:1107.4465

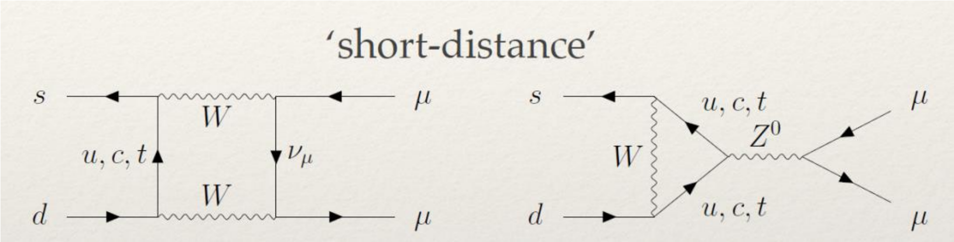
BF($\Lambda^+_c \to p\mu^+\mu^-$) < $4.4 \cdot 10^{-5}$ at 90 % CL

LHCb, UL improved by 2 orders of magnitude

$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 7.7(9.6) \times 10^{-8} \quad \text{at } 90\%(95\%) \text{ C.L.}$$

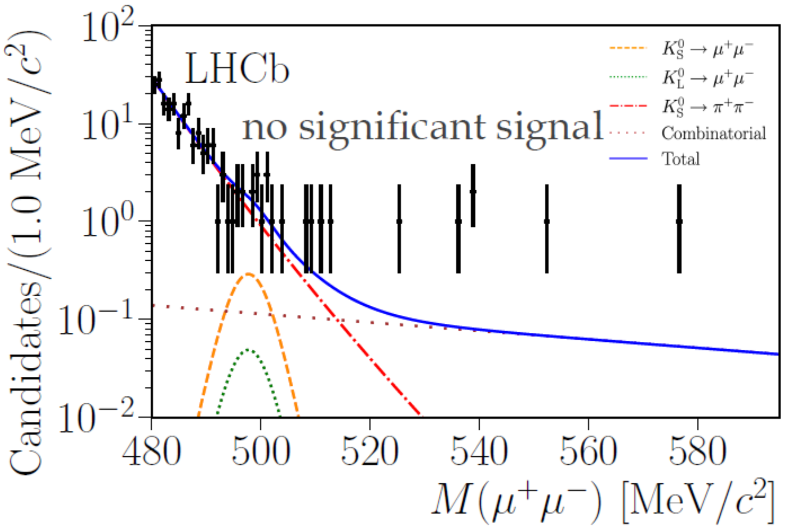
Very rare decays - $K^0_s \to \mu\mu$

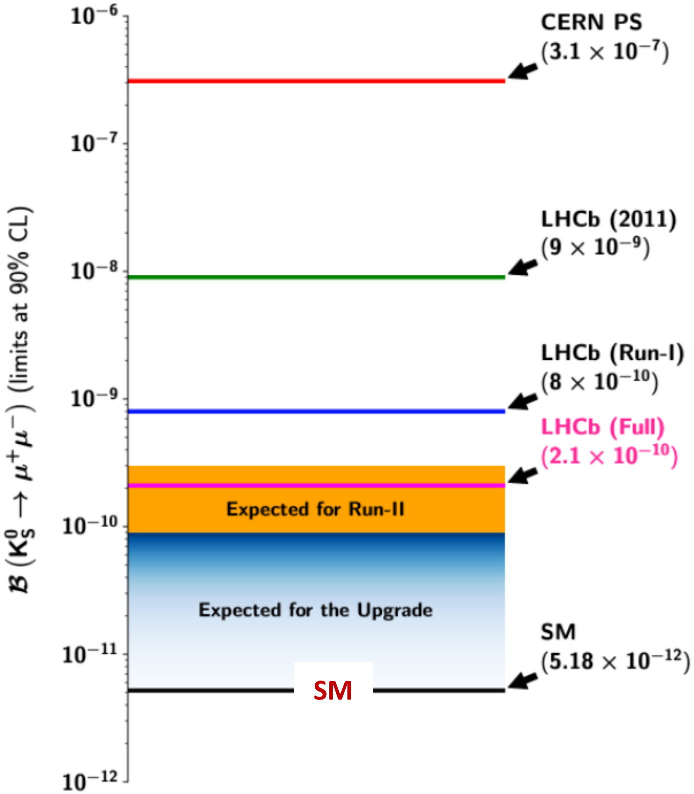




Normalised to $K_S \to \pi^+\pi^-$

$K_S \to \pi^+\pi^-$ also is a dominant misidentification background: branching fraction is more than *ten orders of magnitude* larger!

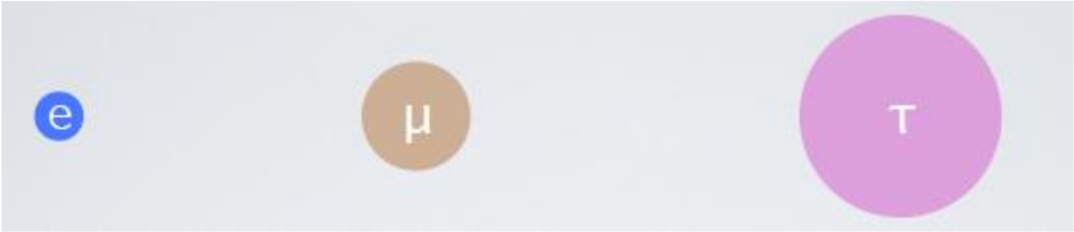




Lepton universality

Charged leptons (*e,μ,τ*) may appear the same due to accidental symmetry.

120 years ago electron and proton seemed to be the same except for mass.
Only long wavelength „microscope" was available →unable to see structure.



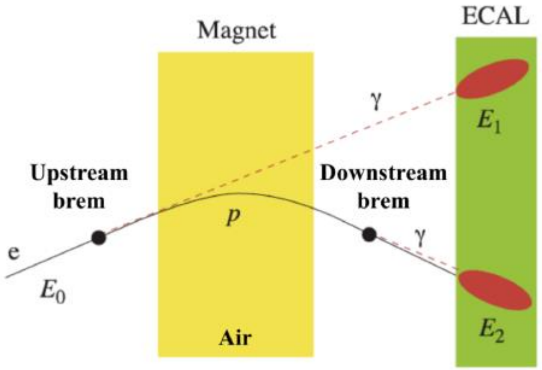
Similar situation for leptons now? They differ in mass only?
Perhaps they are different. We need better microscope.

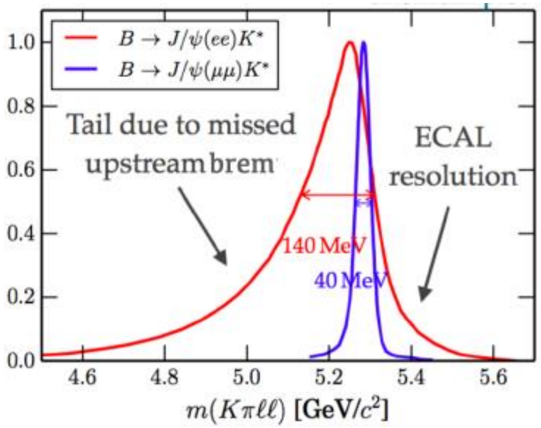
Lepton universality - R_K

$$R_H \equiv \frac{\int \frac{d\Gamma(B\to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int \frac{d\Gamma(B\to He^+e^-)}{dq^2}\, dq^2}$$

$q^2 = m^2(ll)$, $l = \mu, e^{\pm}$

$$R_{K^+} = \frac{\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathcal{B}(B^+\to K^+e^+e^-)}$$



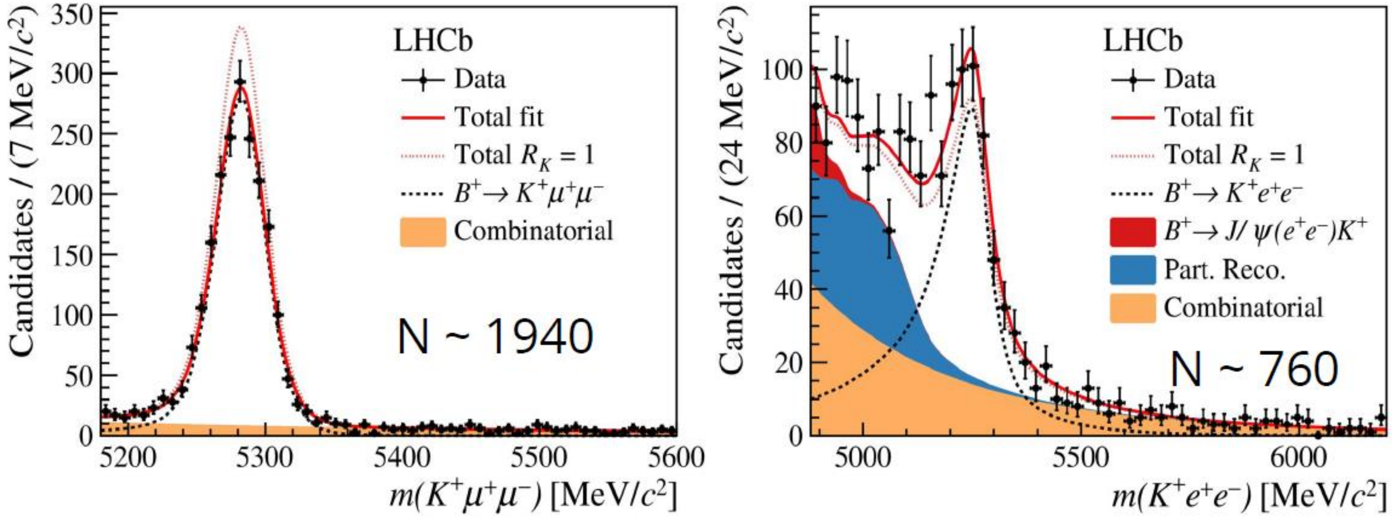


Detection of electron and muon differ significantly.

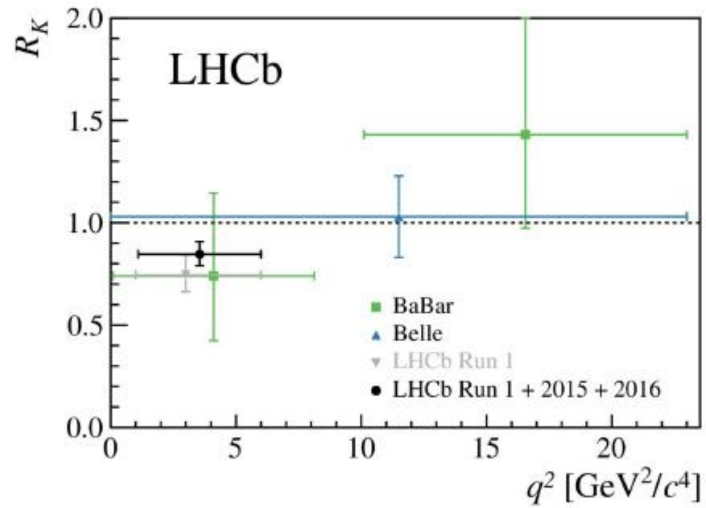
To cancel most experimental systematics, measure double ratio of rare mode with resonant J/ψ mode:

$$R_{K^+} = \frac{\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathcal{B}(B^+\to K^+e^+e^-)} \frac{\mathcal{B}(B^+\to K^+J/\psi(\to e^+e^-))}{\mathcal{B}(B^+\to K^+J/\psi(\to \mu^+\mu^-))}$$

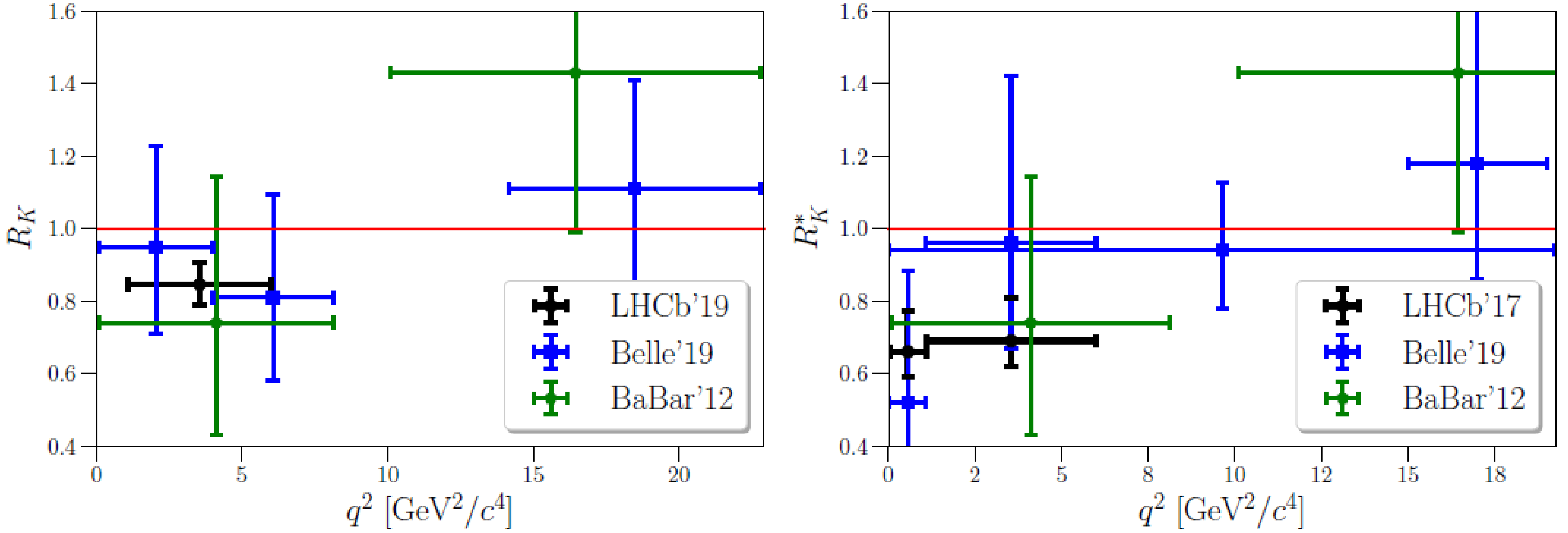
R_K



$$R_K = 0.846^{+0.060+0.016}_{-0.054-0.014}$$



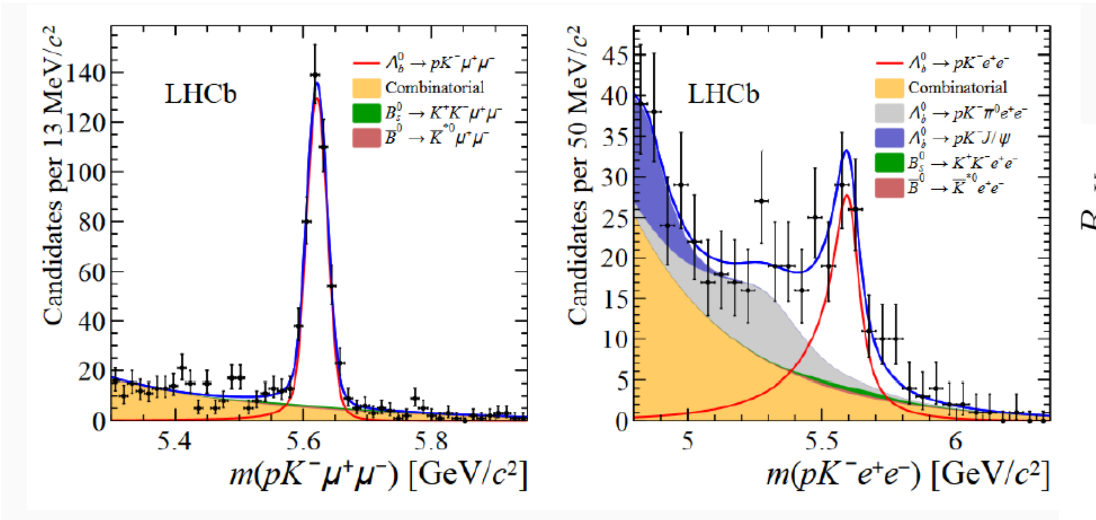
R_K & R_{K*} present status

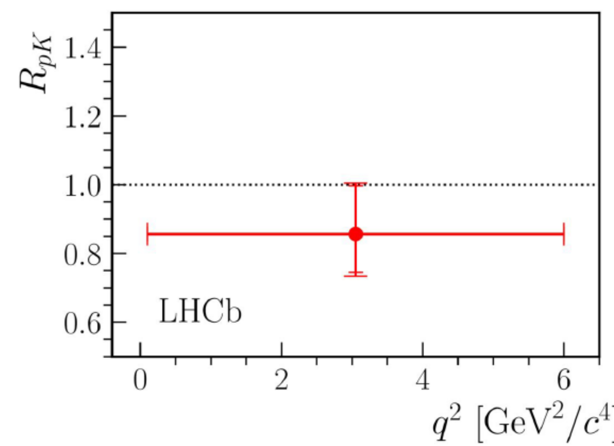


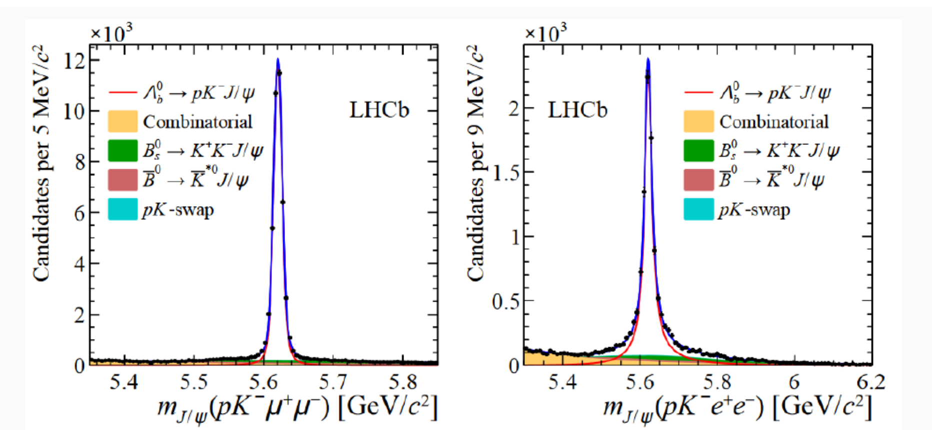
LHCb [JHEP 08 (2017) 055] [PRL 122 (2019) 191801]. Belle [arXiv:1904.02440] [arXiv:1908.01848]. BaBar [PRD 86 (2012) 032012].

$\Lambda_b \to pKll$ - R_{pK}

$N(\Lambda_b \to pK^- \mu\mu) = 444 \pm 23$ $N(\Lambda_b \to pK^- ee) = 122 \pm 17$



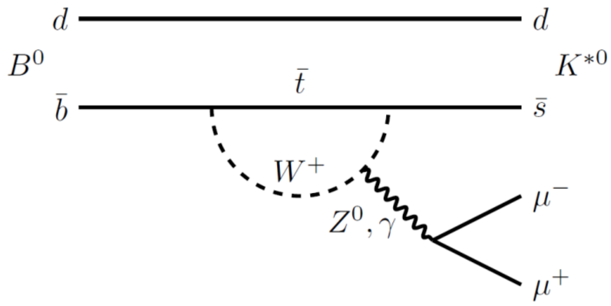


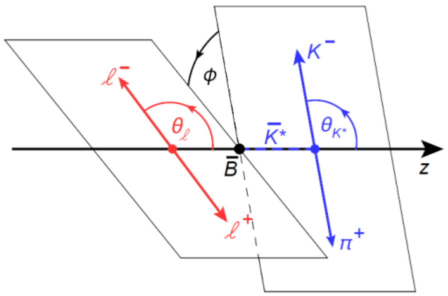


Input for double ratio, decay via J/ψ

$$R_{pK}\big|_{0.1<q^2<6\,\mathrm{GeV}^2/c^4} = 0.86^{+0.14}_{-0.11} \pm 0.05$$

$B^0 \to K^*\mu\mu$





$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

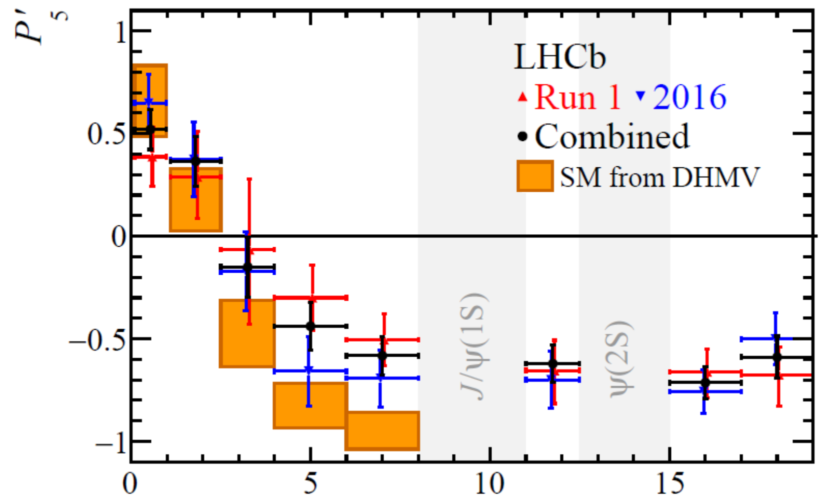
Decay described by 3 angles (θ_l, θ_K, ϕ) and $q^2=m^2_{\mu\mu}$

Rich set of observables.
Possibility to construct variables with cancellation of hadronic effects.

$$P'_5 = \frac{S_5}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}$$

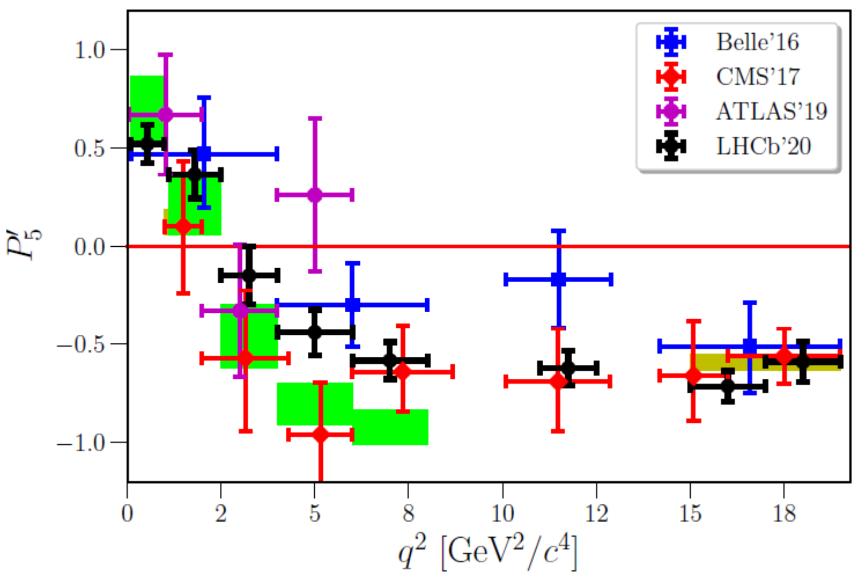
$B^0 \to K^* \mu\mu$

LHCb measurements



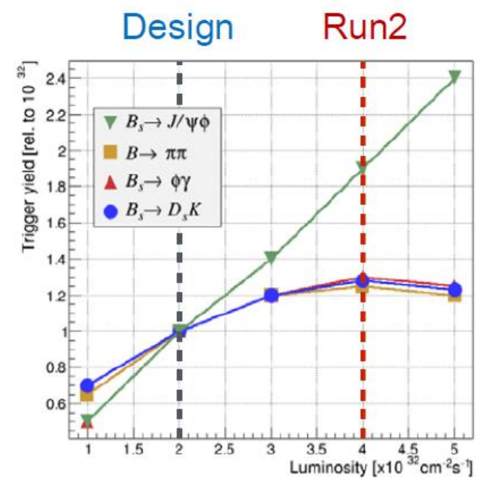
DHMV: [Descotes-Genon, Hofer, Matias, Virto, JHEP 12 (2014) 125]
[Khodjamirian, Mannel, Pivovarov, Wang, JHEP 09 (2010) 089]

Belle, ATLAS, CMS, LHCb



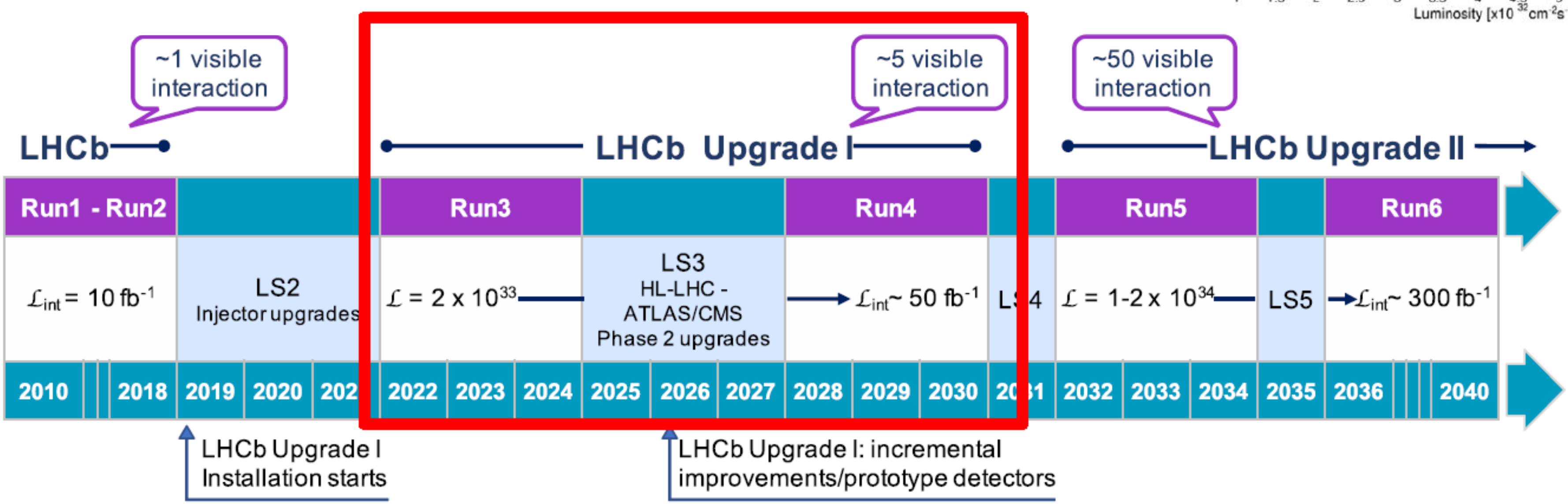
It seems that set of (consistent) anomalies are observed in LHCb and other HEP experiments. So far below of the level of 5σ threshold to claim NP discovery.

Detector upgrade



A lot of valuable measurements in Run1 & Run2

- No significant signs of New Physics but anomalies observed
- More precision needed
- Remove limitations from hardware trigger.

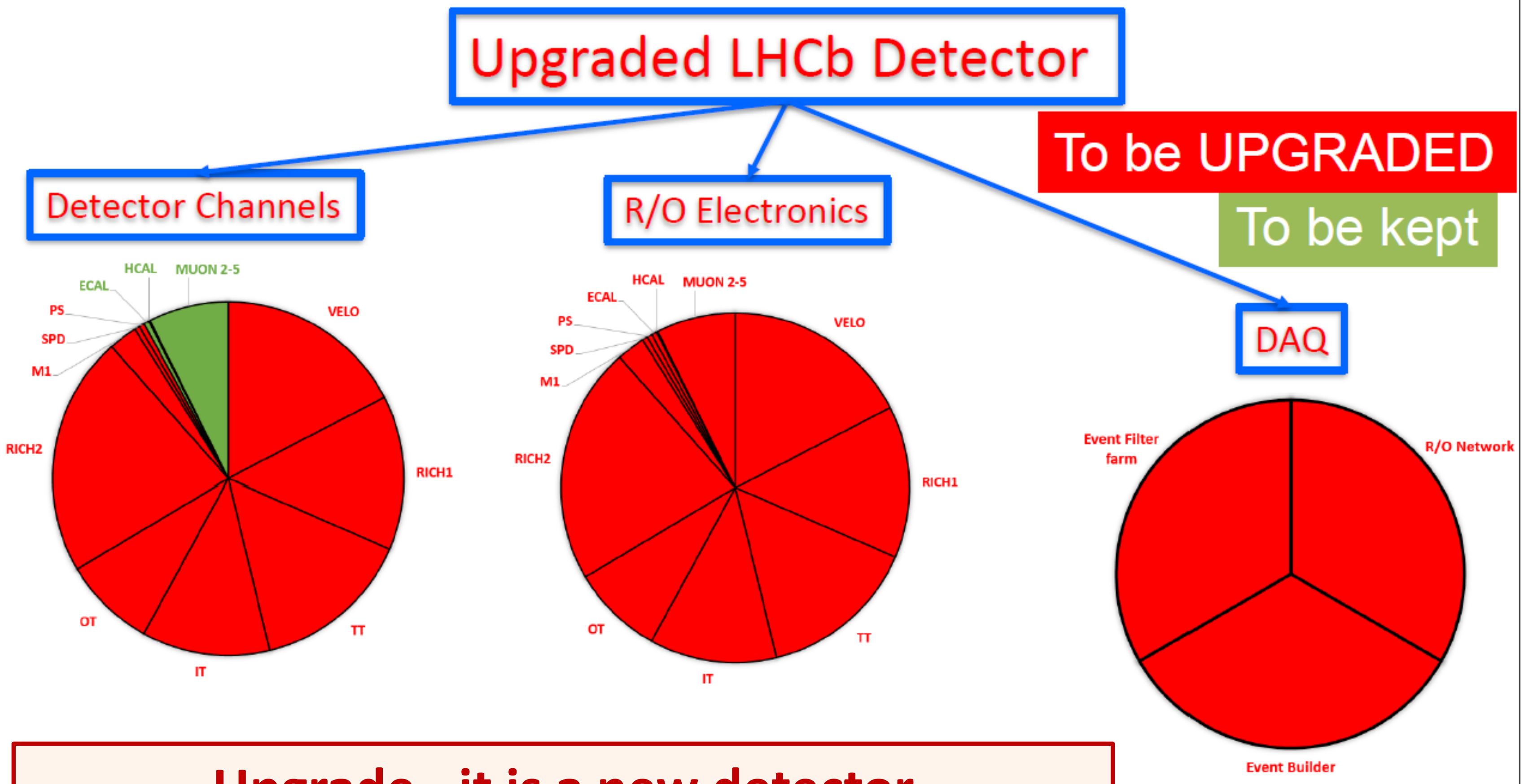


LHCb Phase-I upgrade ongoing now during LS2 for Run3 and Run4

- full software trigger and readout all detectors at 40MHz
- replace tracking detectors + PID + VELO and $\mathcal{L} \sim 2 \times 10^{33}$ sec^{-1} cm^{-2}
- Consolidate PID, tracking and ECAL during LS3

Detector upgrade

CERN-LHCC-2012-007



Upgrade - it is a new detector

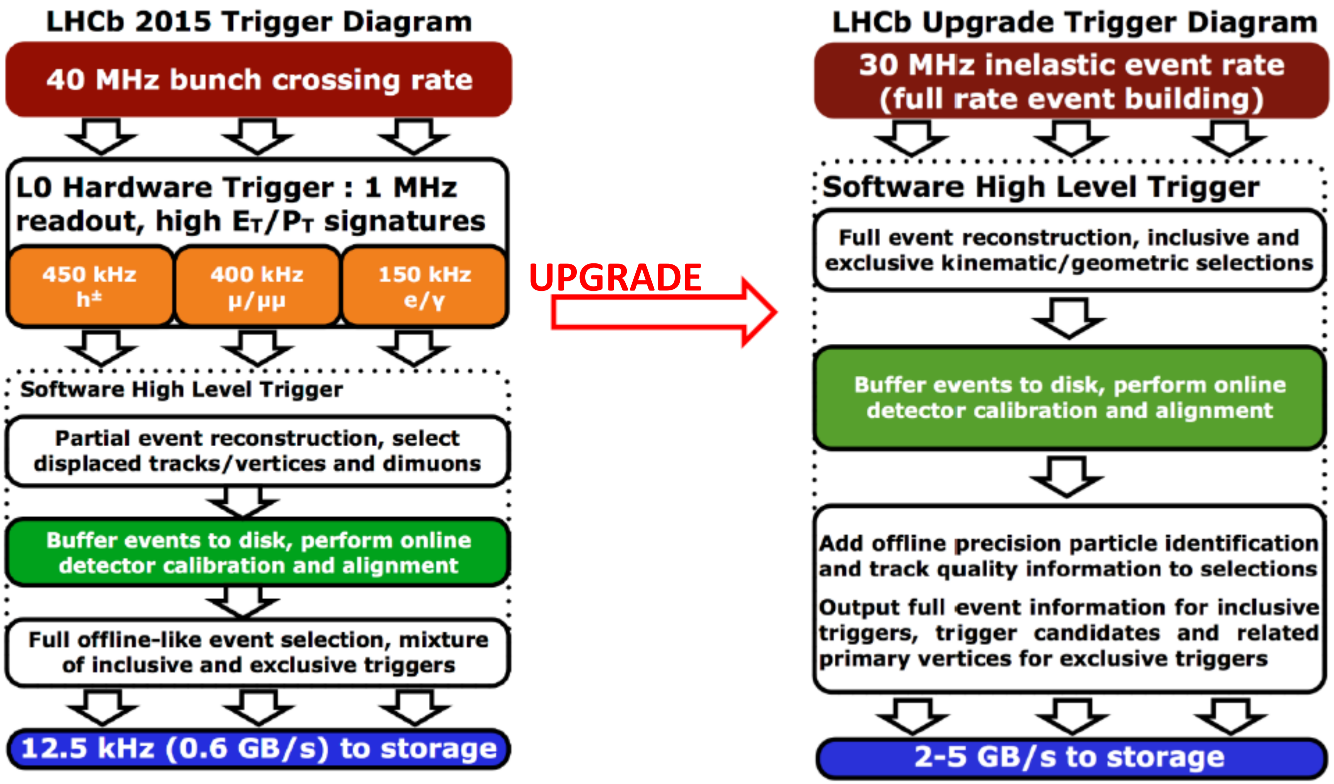
Upgraded trigger

Remove L0 (hardware) trigger

- full readout at 40 MHz (30 MHz of inelatsic events)

Online reconstruction with offline quality.

- **online alignment and calibration (buffer events to disks)**
- **offline-like selection at online phase**
- **raw data not kept**



LHCb upgrades - prospects

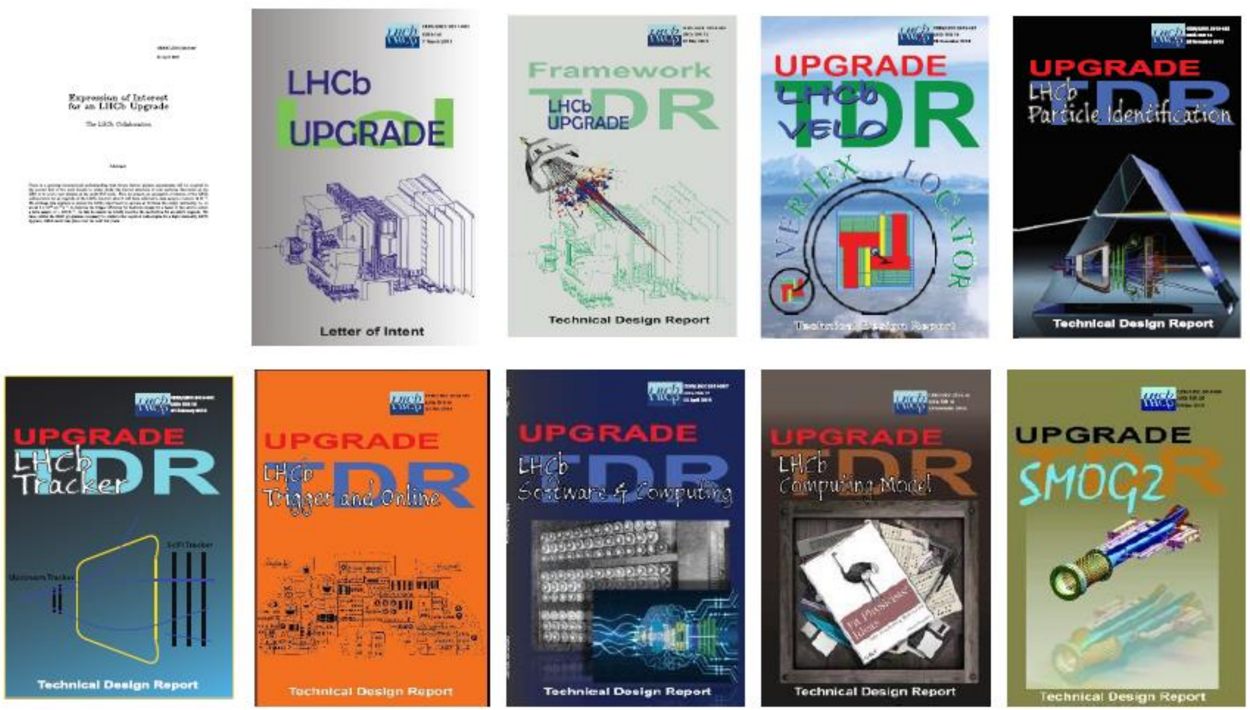
arXiv:1808.08865v4

Belle II sensitivities taken from „*The Belle II Physics Book*”

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Summary

- **Precise measurements of flavour observables provide a powerful probe for New Physics effects.**
- **LHCb performed many valuable measurements, most compatible with SM but a few tensions are observed.**
- **Upgrae I is ongoning. A factor of 5 increase in statistics expected in Run3 and 4.**



Backup

$D^0 \to \mu\mu$

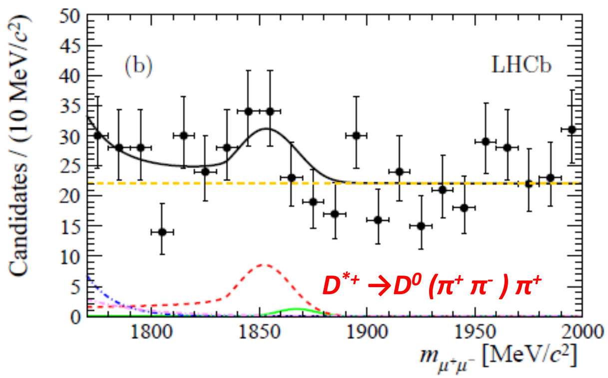
- FCNC has been extensively studied in the strange and beauty sectors
- In the charm sector short-distance contribution highly suppressed by the GIM < 10^{-18}
- $D^0 \to \mu\mu$ dominated by the long-distance contribution to the two-photon intermediate state ~10^{-5}

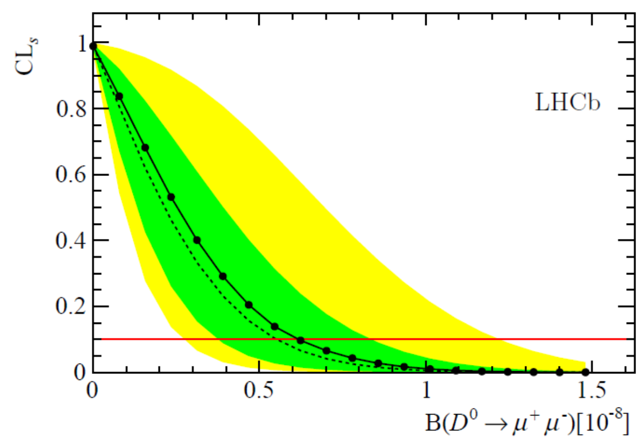
$$\mathcal{B}(D^0 \to \mu^+\mu^-) \simeq 2.7 \times 10^{-5} \mathcal{B}(D^0 \to \gamma\gamma)$$

Long distance SM limit > 6 x 10^{-11}

Best exp limit from Belle $\mathcal{B}(D^0 \to \mu^+\mu^-) < 1.4 \cdot 10^{-7}$
Phys. Rev. D81 (2010) 0911

LHCb



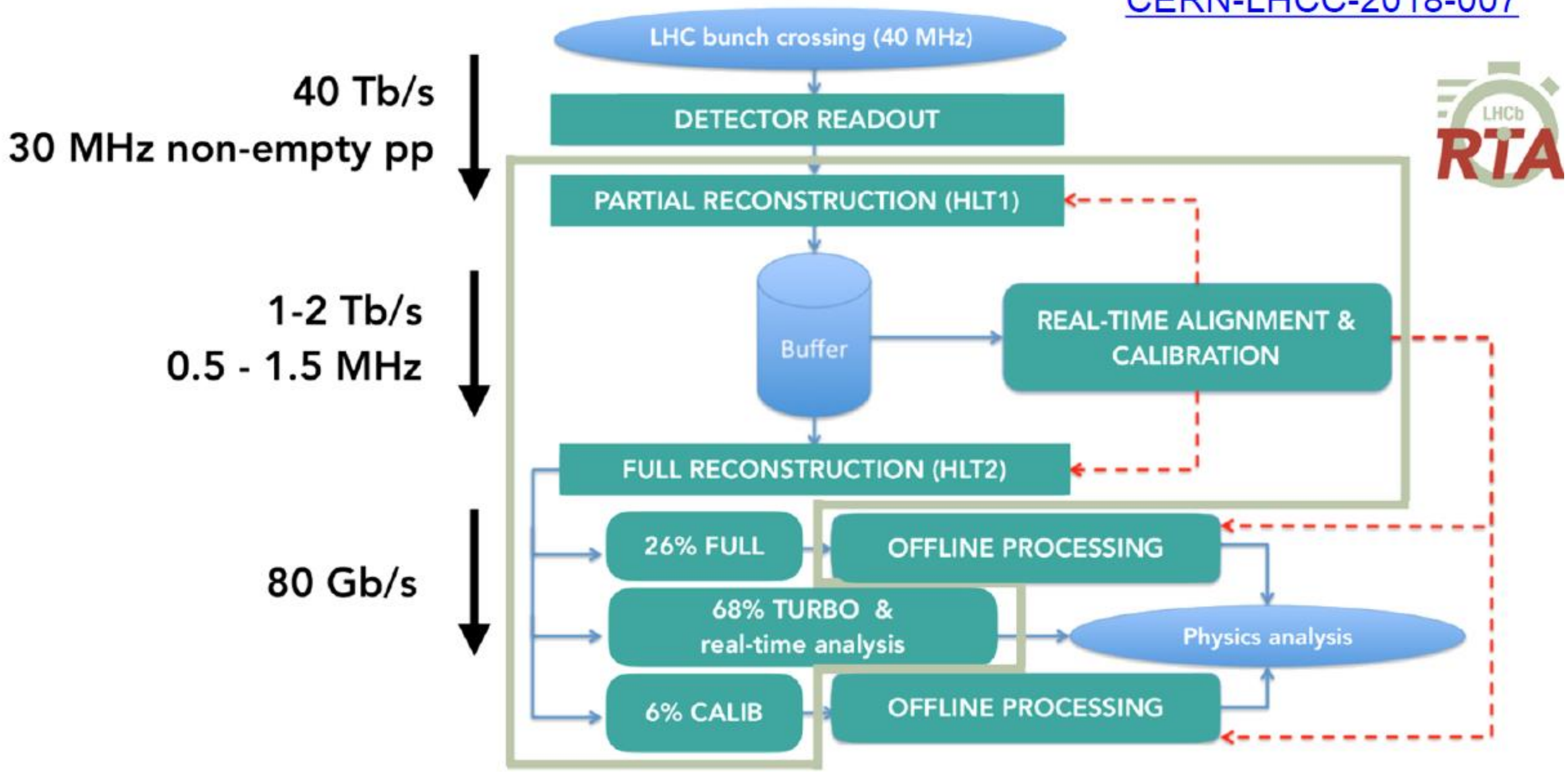


$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2\ (7.6) \times 10^{-9} \text{ at } 90\%\ (95\%) \text{ CL.}$$

[Phys. Lett. B 725]

Data processing and trigger

CERN-LHCC-2018-007



- HLT1 reconstruction in GPUs
- Offline reconstruction in HLT2
- TURBO model for exclusive selections

Comput. Phys. Commun. **208** 35-42
Run 2: 2019 *JINST* **14** P04013
GPU: Comput Softw Big Sci 4, 7 (2020)
TURBO: 2019 *JINST* **14** P04006