LHCb at LHC: recent results and search for new physics

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- INFN – Florence and CERN

Colloquium – Firenze 19/10/2017

Outline

- The LHCb experiment
- LHCb operations and performance in 2017
- Selected physics results
  - ★ Include some new results
- The LHCb upgrade
- Conclusions and outlook

The LHCb experiment

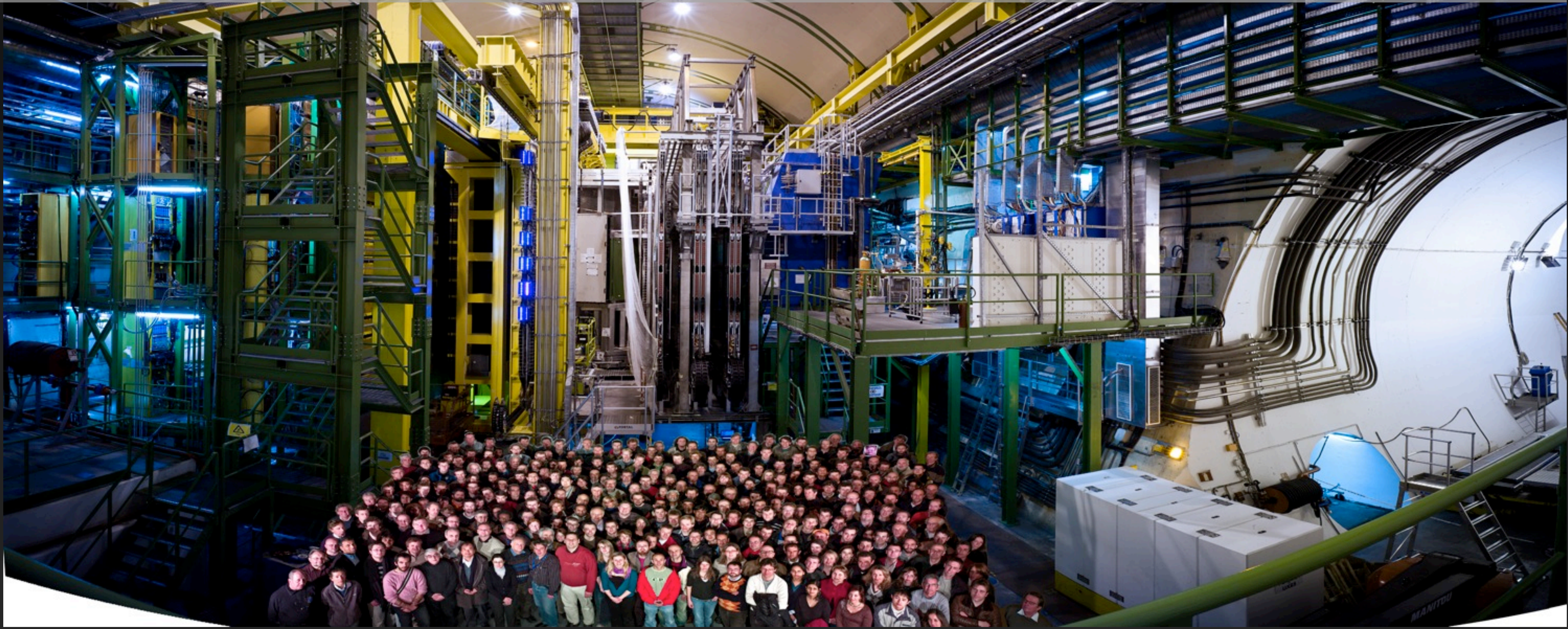
A general purpose experiment in the forward region

LHCb: Large Hadron Collider beauty experiment

1200 members from 72 institutes in 16 countries

Designed to study CPV and new physics in rare b and c decays

Nowadays a general purpose experiment for physics in forward region



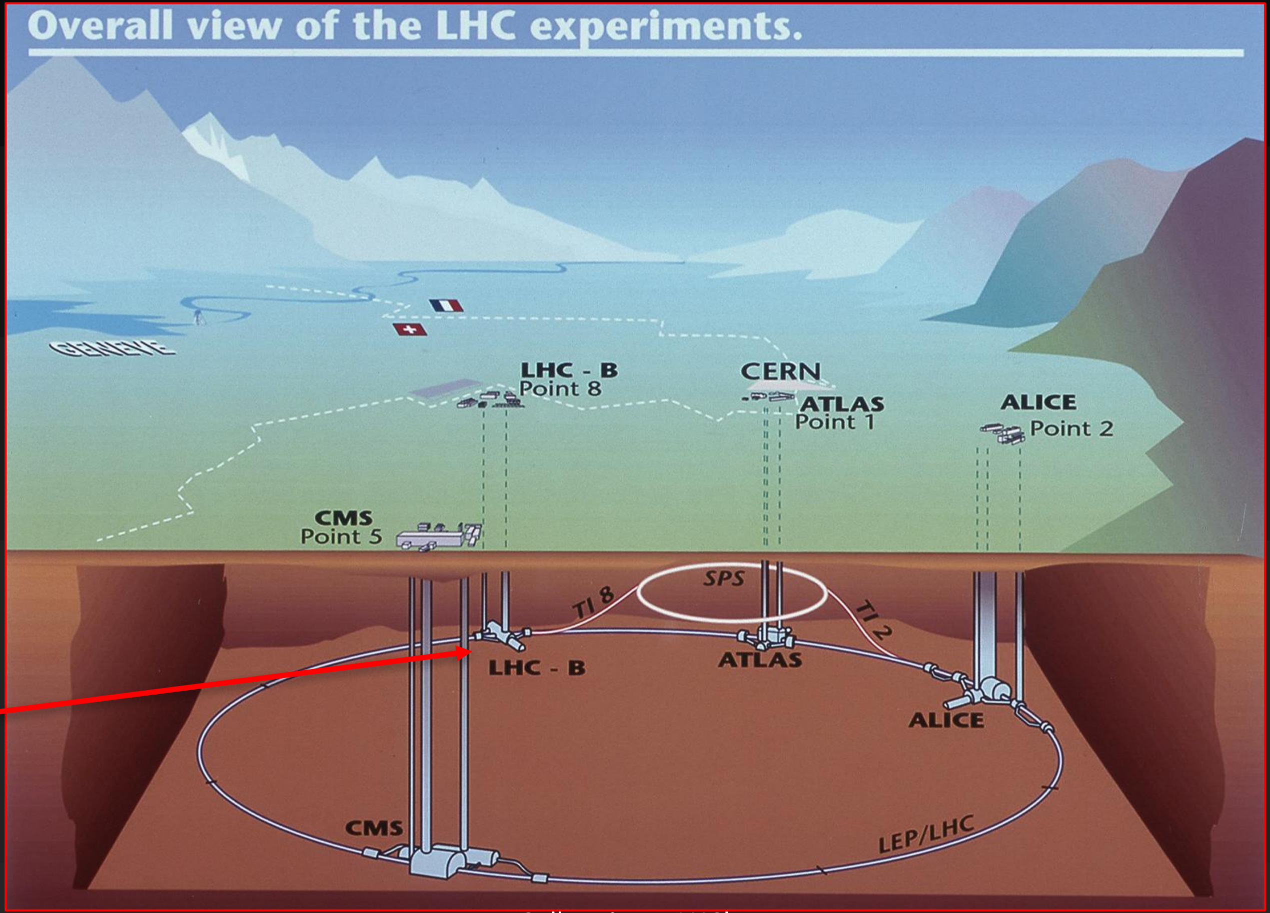
LHCb @ Firenze

- Small group but very active !
  - ★ Giacomo Graziani, group leader – working group convener, fixed target physics, muon ID
  - ★ Lucio Anderlini – working group convener, spectroscopy, quark production, particle ID
  - ★ Andrea Bizzeti – operations
  - ★ Saverio Mariani – undergraduate student – fixed target physics
  - ★ GP
  - ★ Michele Veltri – operations

- Built ~1/5 of the wire chambers for the muon detector
- Leading role in a number of diverse analysis and physics tools domains

- R&D project for 3D diamond sensors with timing capabilities for a vertex detector in a future very high luminosity flavor experiment (Call GR5, PI: Silvio Sciortino)

LHCb: Large Hadron Collider beauty experiment



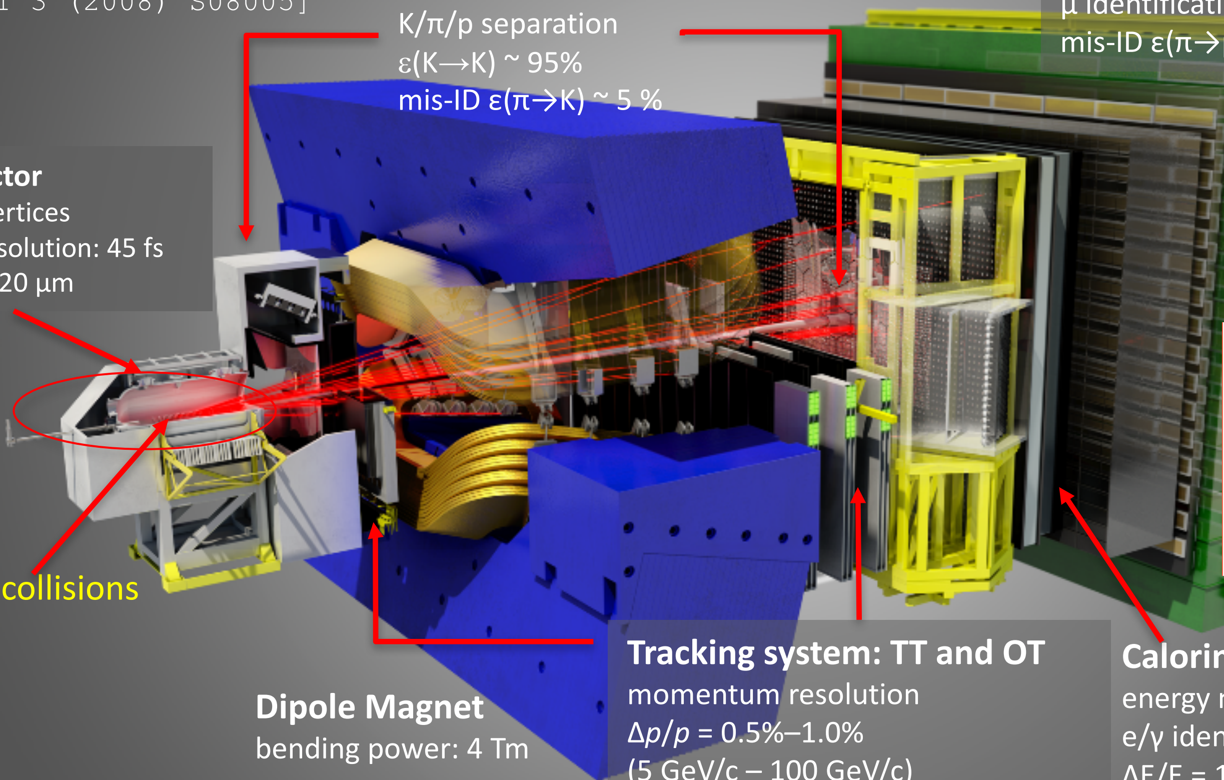
LHCb: a forward one arm spectrometer

[IJMPA 30 (2015) 1530022]
[JINST 3 (2008) S08005]

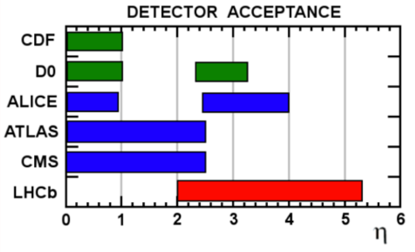
RICH detectors
K/π/p separation
ε(K→K) ~ 95%
mis-ID ε(π→K) ~ 5 %

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

Vertex Detector
reconstruct vertices
decay time resolution: 45 fs
IP resolution: 20 μm



pp collisions

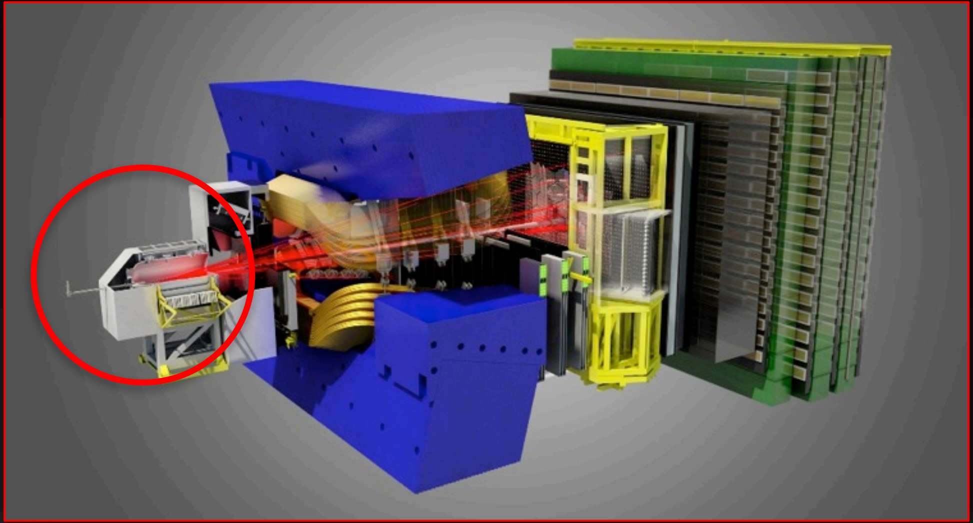


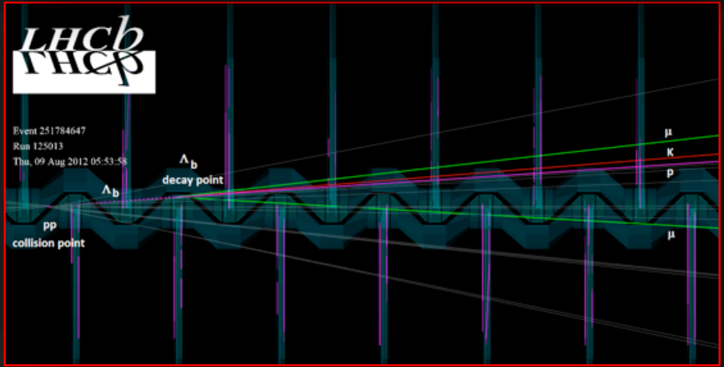
Dipole Magnet
bending power: 4 Tm

Tracking system: TT and OT
momentum resolution
$\Delta p/p$ = 0.5%–1.0%
(5 GeV/c – 100 GeV/c)

Calorimeters (ECAL, HCAL)
energy measurement
e/γ identification
$\Delta E/E = 1\% \oplus 10\%/\sqrt{E(\mathrm{GeV})}$

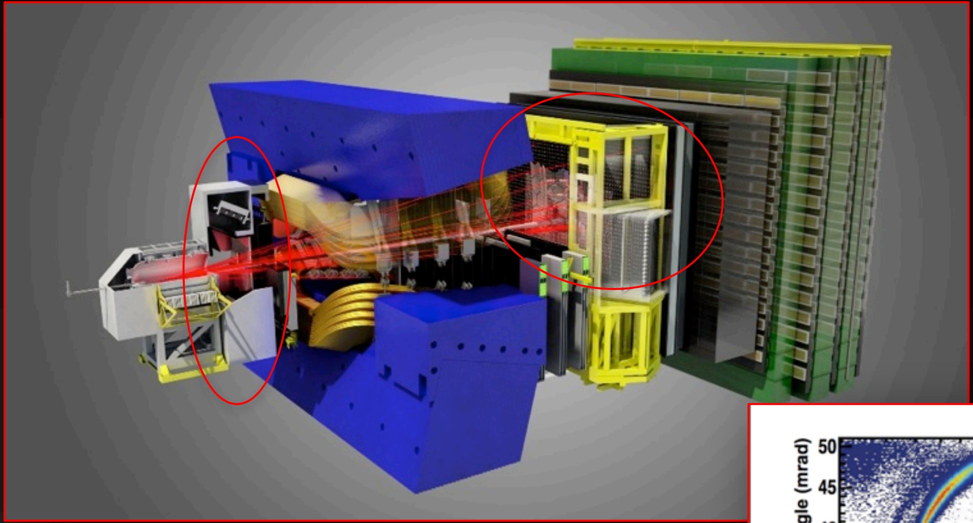
LHCb: Vertex detector (VELO)

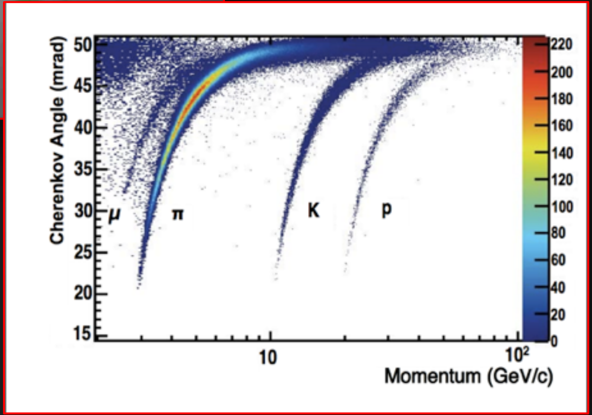


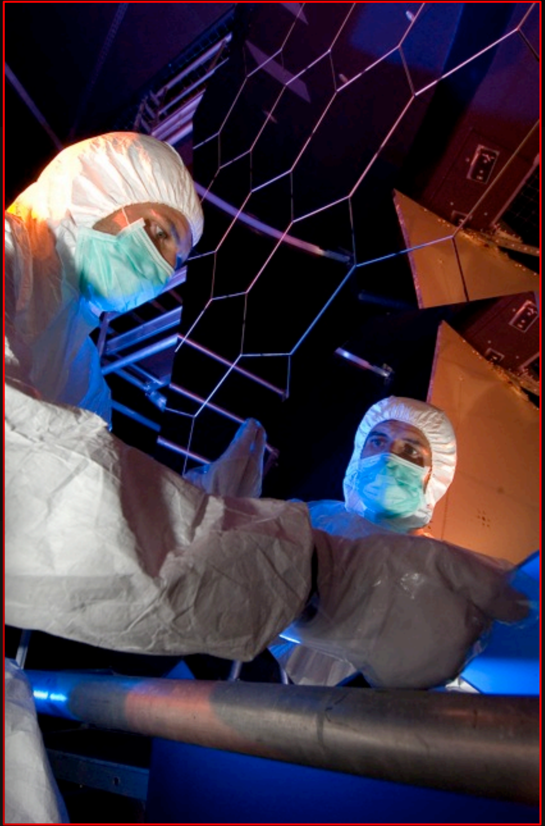


- The VELO is a silicon strip detector around the interaction point.
- Reconstruction of primary and secondary vertices
- 8 mm from LHC beam!

LHCb: Cherenkov detectors (RICH)

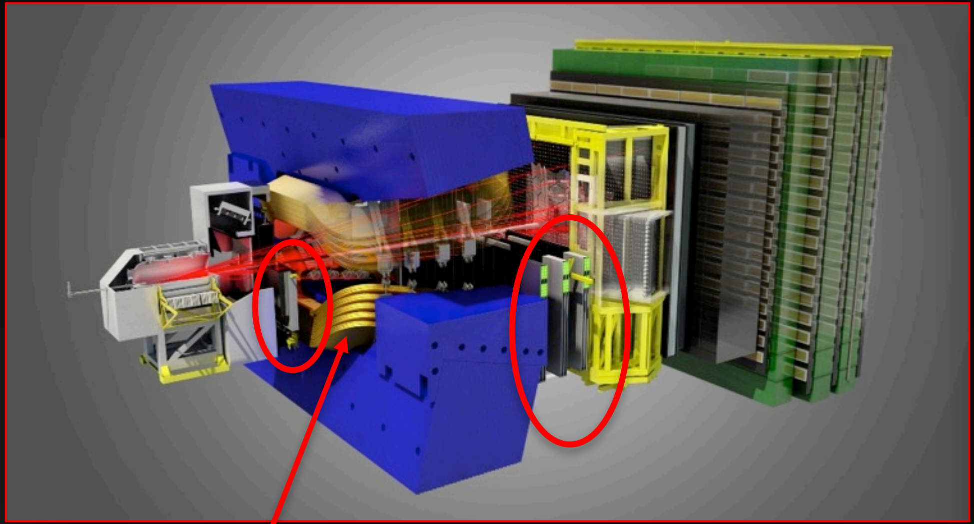


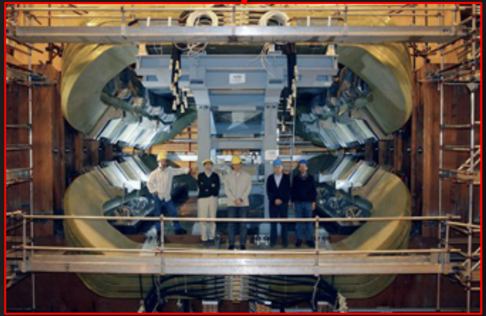




- Two ‘RICH’ detectors provide hadron identification from ~2 to 100 GeV/c

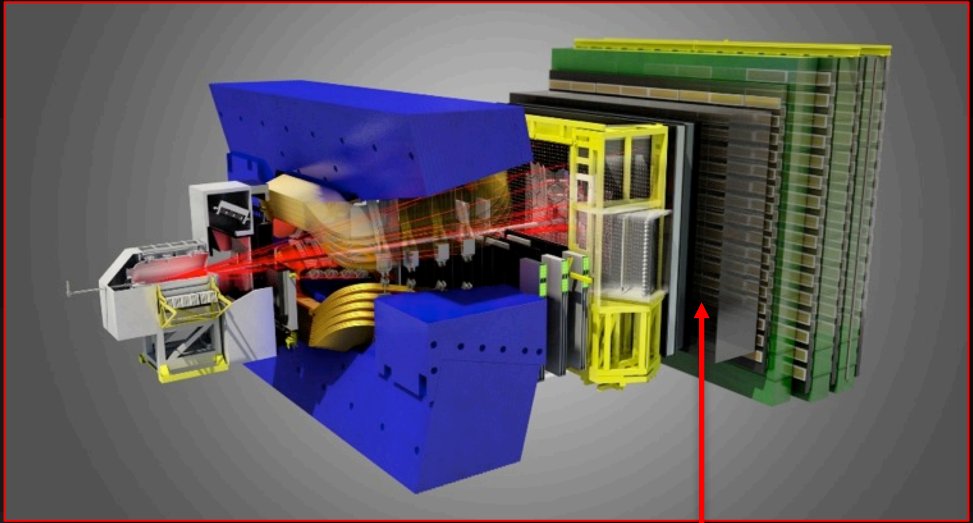
LHCb: Tracking System

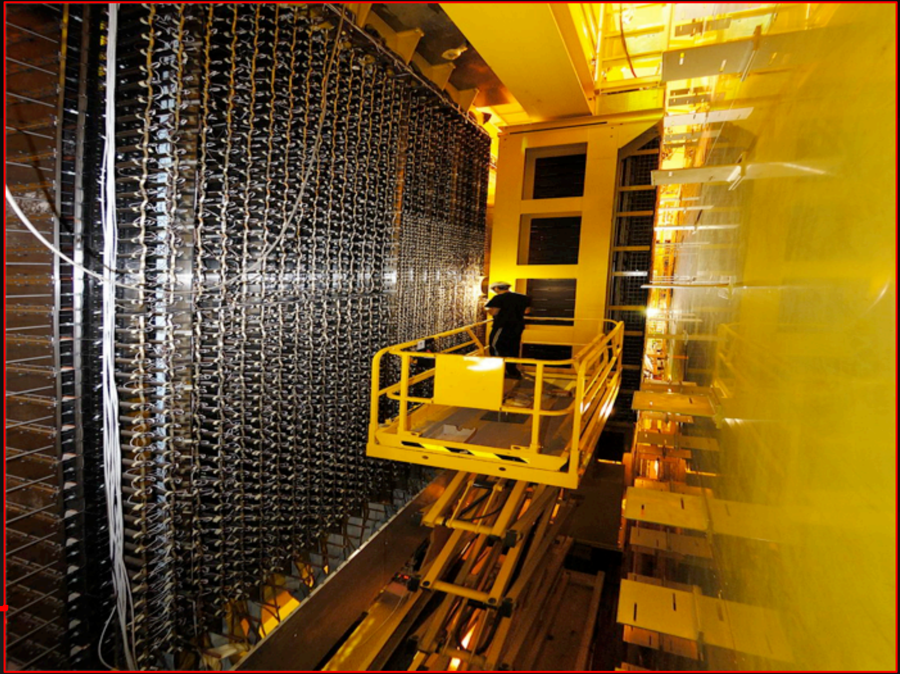




- 4Tm dipole magnet
- Silicon tracking stations upstream the magnet
- Straw tubes stations downstream the magnet
- momentum resolution 0.4-0.6 % (for $5 < p < 100$ GeV)

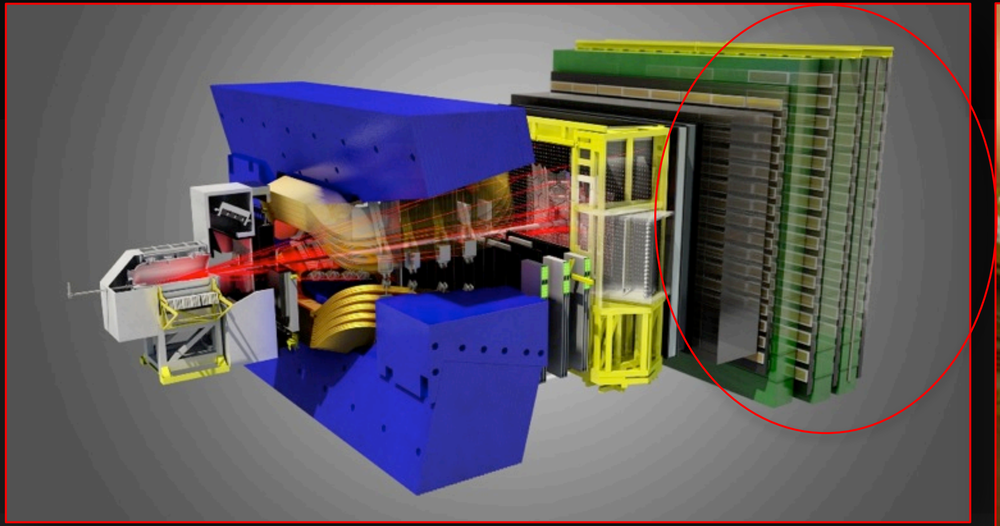
LHCb: Calorimeter System





- Electromagnetic (ECAL) and hadronic (HCAL) calorimeters
- Provide information to L0 trigger
- Energy reconstruction and identification of photons, electrons, hadrons

LHCb: Muon System



- 5 stations with MWPC and GEM
- Provide information to L0 trigger
- Muon identification

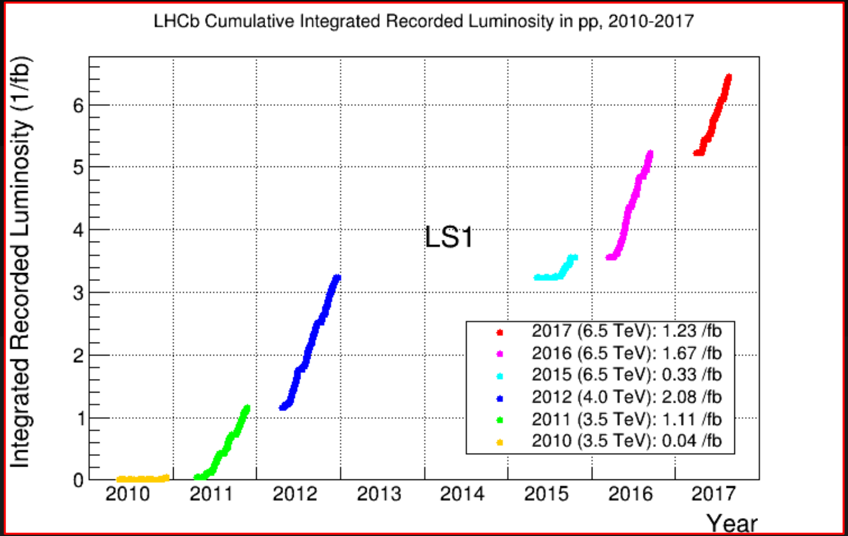
2017 LHCb run

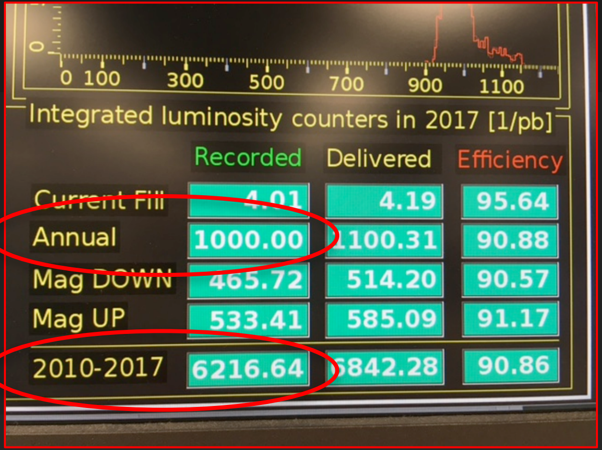
LHCb operations and performance

Detector operations

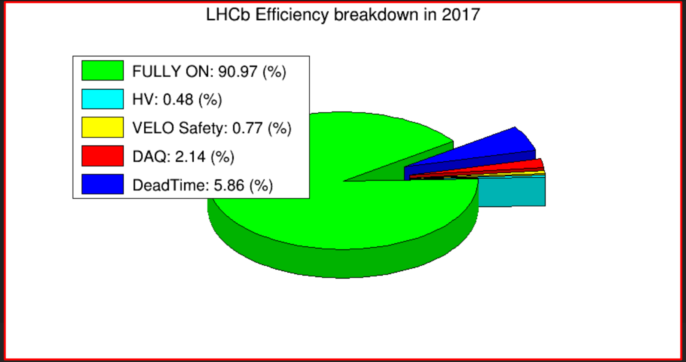
- Reached 6 fb^{-1}
- x2 integrated luminosity wrt run 1
- x3 number of B decays ($\sigma_{bb}^{(run\ 2)} \sim 2 \times \sigma_{bb}^{(run\ 1)}$)

- LHCb running very smoothly, DAQ efficiency ~91%
  - ★ Close to the achievable maximum (~7% irreducible deadtime)



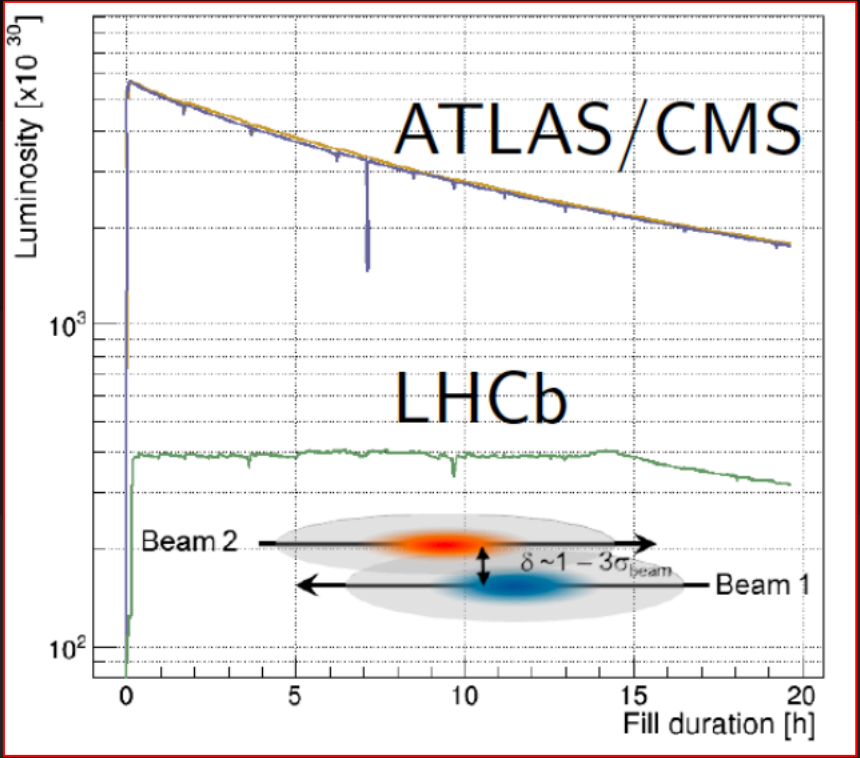


Units in pb^{-1}



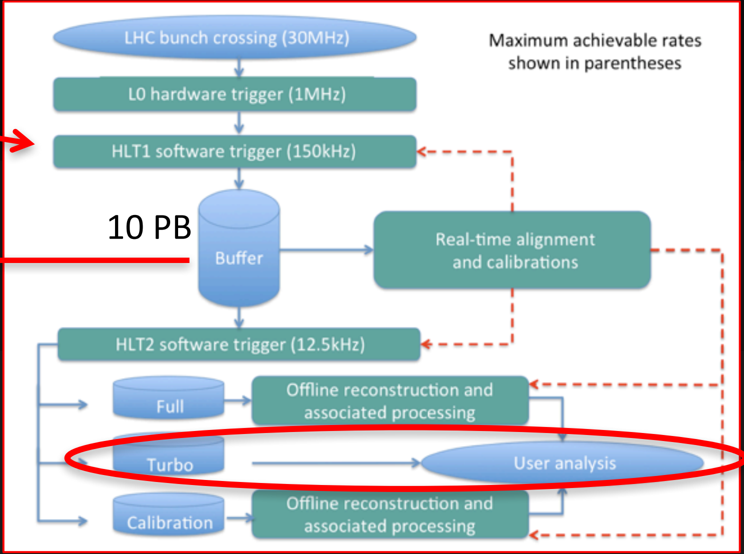
LHCb running conditions

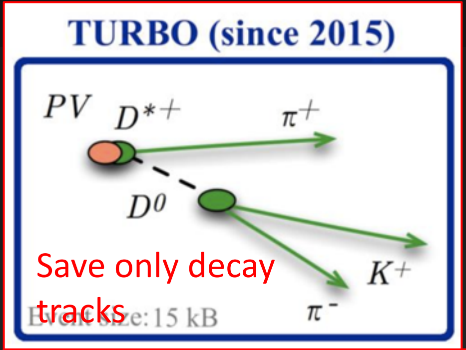
- LHCb is running in very special conditions
- Luminosity is "levelled" i.e. is kept constant throughout the fill by adjusting the beam focusing and ovelap
- Very uniform data taking conditions
- Maximize integrated luminosity

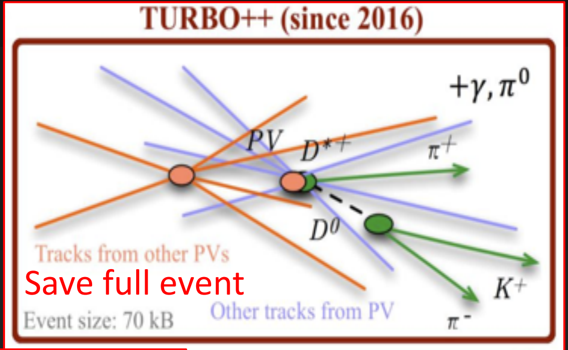


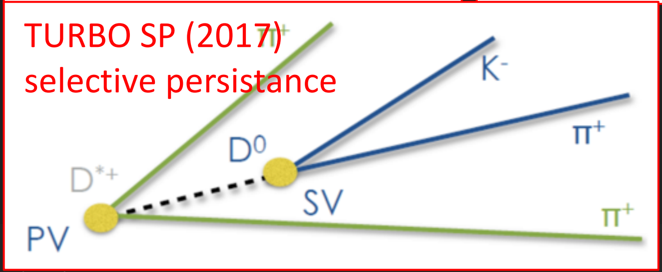
Split HLT and TURBO stream

- HLT split in two stages
- A new concept: TURBO stream
  - ★ An anticipation of the upgrade trigger
  - ★ Selected data saved in a format ready for the analysis no offline reconstruction

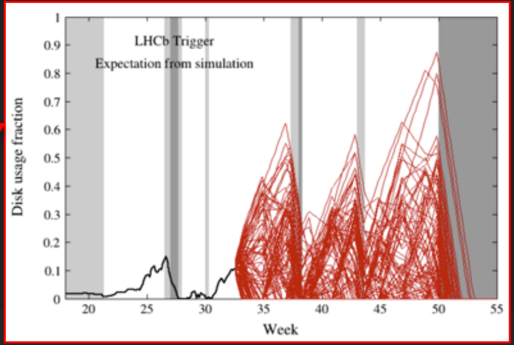








- To avoid filling the buffer two HLT1 configurations: tight, loose
- Simulations for buffer filling predictions



A trigger for dark matter

Search for dark photons from TURBO stream data

Search for dark photons

[new]

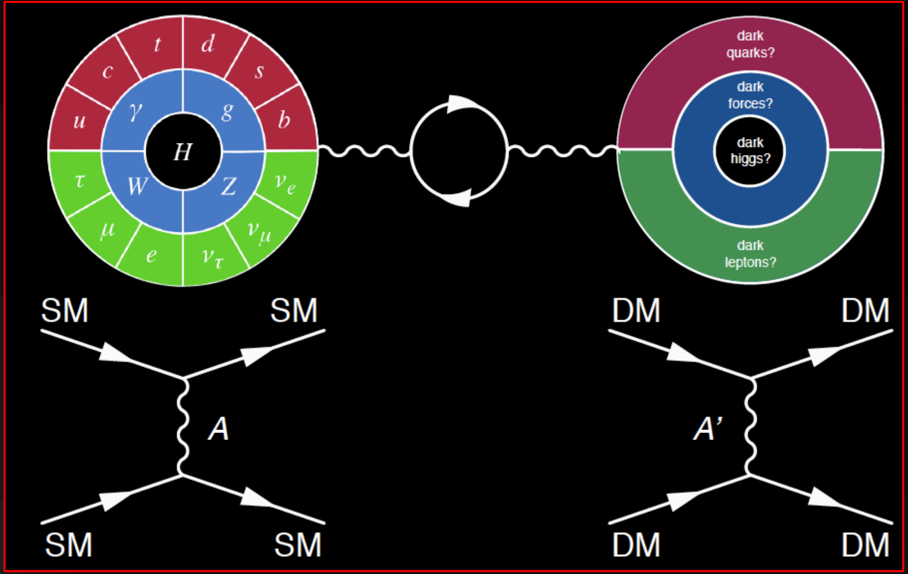
[LHCb-PAPER-2017-038]

- As a possible explanation for dark matter, a "dark sector" is postulated, with fields not interacting directly with SM fields.

- Dark fields interact with SM fileds through the lagrangian kinetic terms with a mixing strength ε.

- Dark vector fields A' are called "dark photons" and they weakly couple to SM electromagnetic current with a coupling $e\varepsilon$ where $10^{-6} < \varepsilon < 10^{-2}$ depending on the models

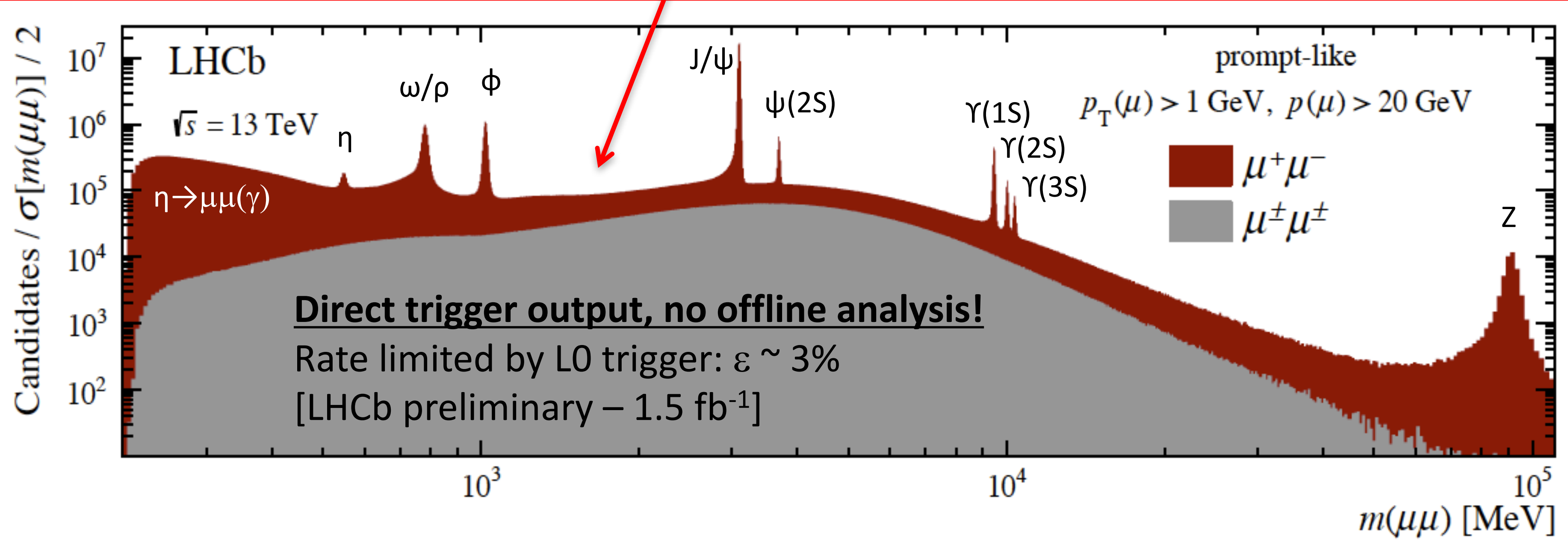
- This mixing provides a "portal" for production and detection of A' via SM particles ("visible dark photons")



Search for dark photons: $A' \to \mu^+\mu^-$

[LHCb-PAPER-2017-038]

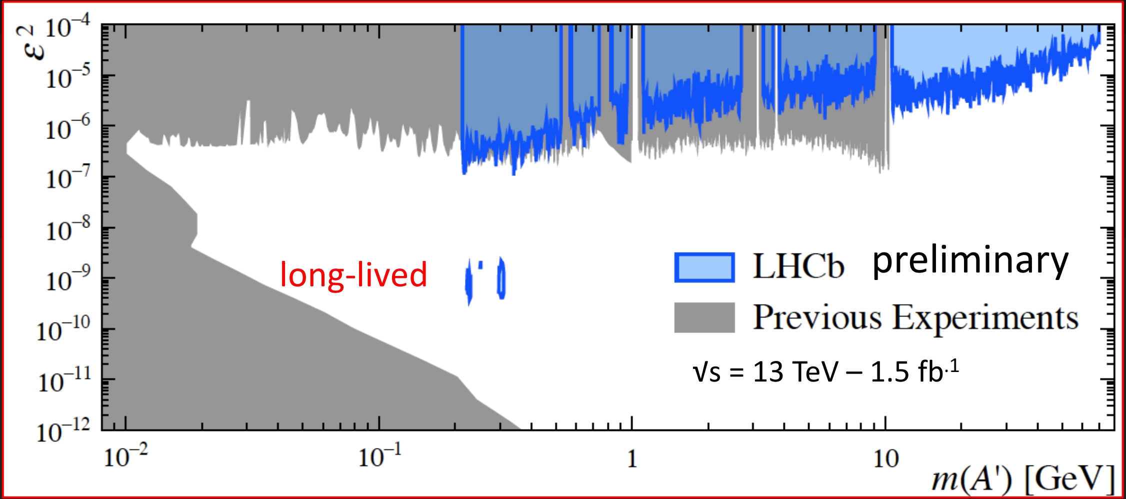
- A promising channel to detect dark photons is $A' \to \mu^+\mu^-$
- The signal yield can be directly inferred from $\gamma^* \to \mu^+\mu^-$: fully data driven analysis
- At LHCb: search for $A' \to \mu^+\mu^-$ in run 2 data (1.5 fb^{-1})
- Dedicated trigger in the TURBO stream



Search for dark photons: $A' \to \mu^+\mu^-$

[LHCb-PAPER-2017-038]

- Two signatures searched:
  - ★ Prompt decays (compatible with coming from primary vertex): $m_{\mu\mu} < 70$ GeV
  - ★ Long leaved: 214 < m(A') < 350 MeV
- No signal found → exclusion plot



- LHCb has sensitivity at the level of B-factories in the low mass region
- Most stringent constraints for 10.6 < m(A') < 70 GeV
- First exclusion limits to long-lived dark photons at a non-beam-dump experiment
- Main limitation from L0: ε ~ 3%
- Huge increase in sensitivity expected in run 3 thanks to the fully software trigger (no L0)

Quest for precision

Measurements of CKM matrix prameters

- *A new measurement of sin2β*
- *Measurement of the B_s mixing phase ϕ_s*
- *A new measurement of CKM angle γ*

The CKM matrix and the weak force

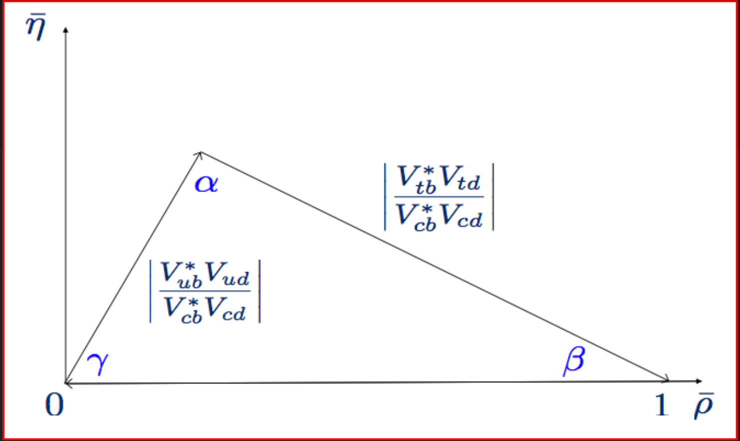
- Arises from the Yukawa terms for quarks in the SM lagrangian
- Connects u- and d- type quarks via the weak force
- Each element related to a transition probability, $|V_{ij}|^2$

- 3X3 unitary matrix is parameterised by three rotation angles and one complex phase

- Phase changes sign under the CP operator
  In SM, this phase is the single source of quark sector CP violation

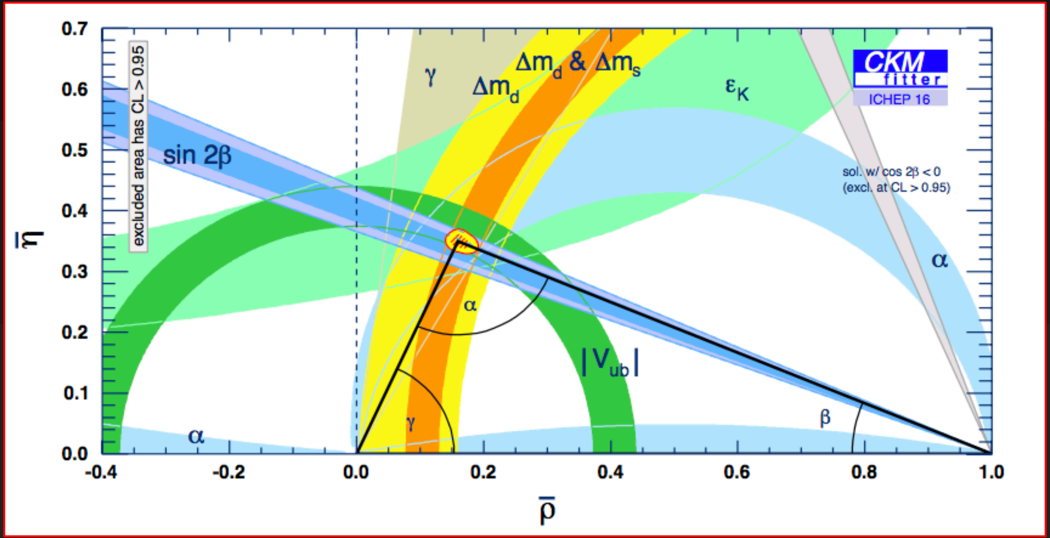
- Unitarity conditions lead to the Unitarity Triangle grafical representation

$$V_{\mathrm{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$



Is the Unitarity Triangle actually a triangle?

- Global CKM fits performed using information from many measurements that over-constraint the UT
  - ★ If the triangle does not “close” it is a clear sign of something beyond the SM
- Measuring β and γ is an important part of this process



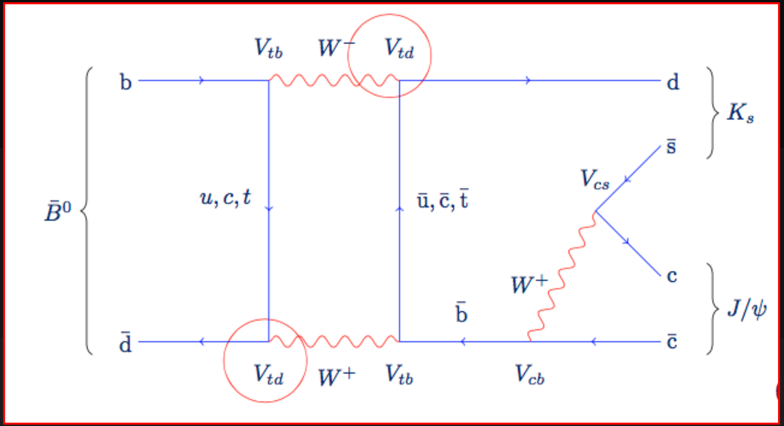
Let’s explore β first as an example

$$\alpha = \arg\left[-\frac{V_{td}V_{tb}^{*}}{V_{ud}V_{ub}^{*}}\right] \quad \beta = \arg\left[-\frac{V_{cd}V_{cb}^{*}}{V_{td}V_{tb}^{*}}\right] \quad \gamma = \arg\left[-\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right]$$

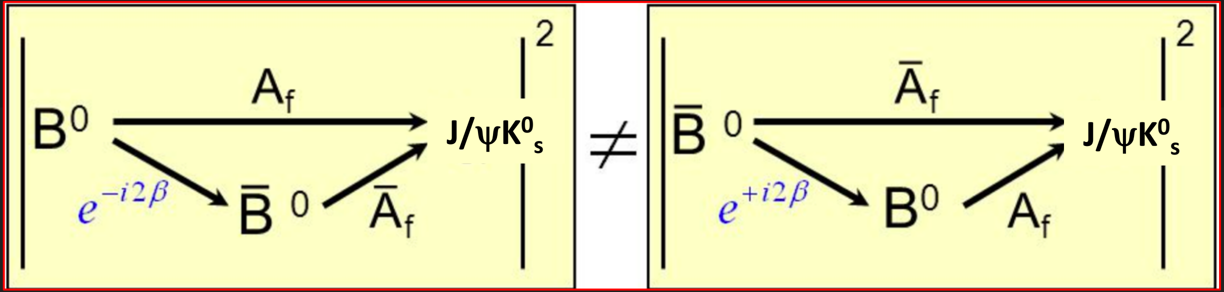
Measurement of β

- To measure β need to access V_{tb} and V_{td}
- A good place to look is the B^0-$\overline{B}^0$ mixing

- CP violation arises in interference in mixing
- Involves a box diagram
- It may include NP contributions



- Requires a time-dependent analysis and flavour tagging (to distinguish initial state B^0 and $\overline{B}^0$)

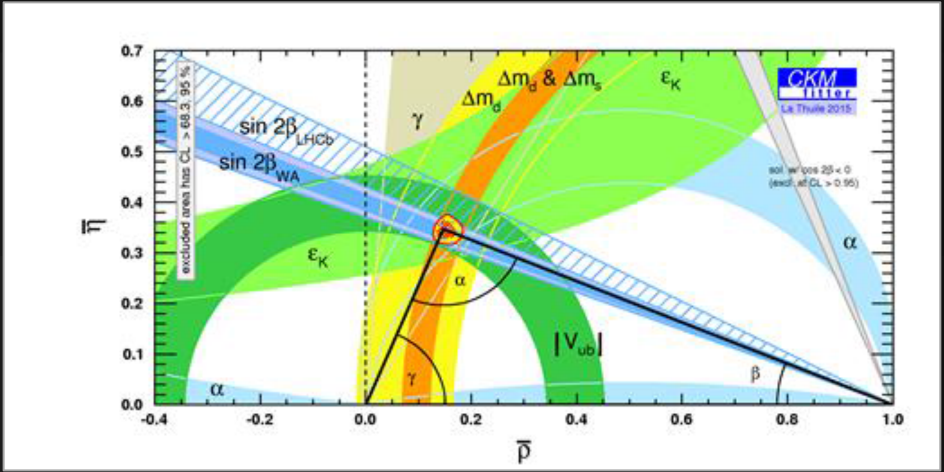


$$A_{CP}(t) = \frac{S\sin(\Delta m t) - C\cos(\Delta m t)}{\cosh(\Delta\Gamma t/2) + A_{\Delta\Gamma}\sinh(\Delta\Gamma t/2)} \overset{\Delta\Gamma=0}{\approx} S\sin(\Delta m t) - C\cos(\Delta m t)$$

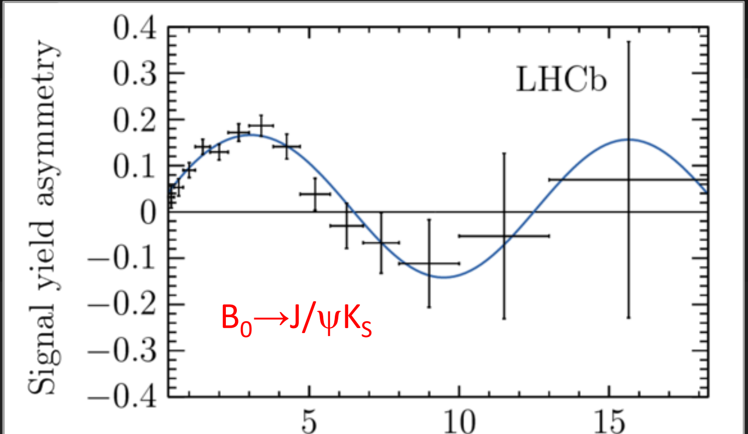
$$S_{J/\psi K^0_S} \approx \sin 2\beta$$

Unitarity Triangle: sin2β

- Measurement of β is the legacy of the *B*-factories: probably one of the most beautiful measurements in particle physics!
- This measurement requires time-dependent measurement and flavour tagging, which is trickier at a hadron collider than at an e^+e^- machine



Precision obtained by LHCb with $B_0 \rightarrow J/\psi K_S$ is very similar to that of the *B*-factories.



[PRL 115 (2015) 031601]

$\sin 2\beta_{eff} = 0.731 \pm 0.035\ (\text{stat}) \pm 0.020(\text{syst})$

(BaBar stat error = 0.036, Belle stat error = 0.029)

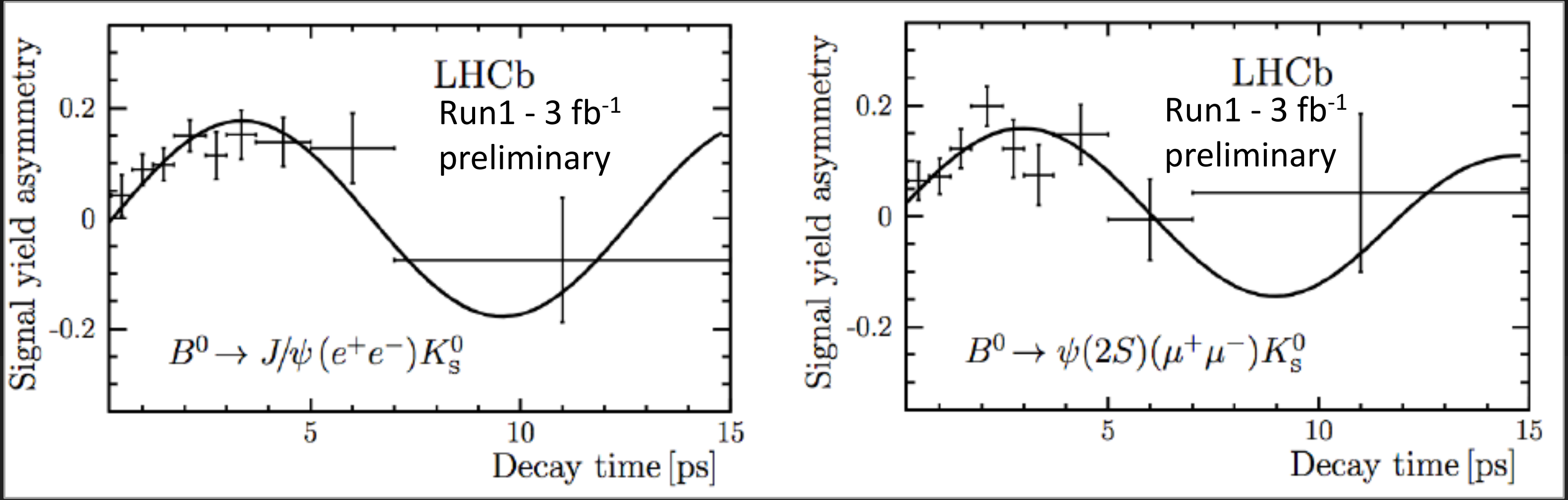
New measurement of sin2β

[LHCb-PAPER-2017-029]

- Decay-time-dependent CP violation in $B^0 \to J/\psi(e^+e^-)K^0_S$ and $B^0 \to \psi(2S)(\mu^+\mu^-)K^0_S$

$$A_{CP}(t) = \frac{S\sin(\Delta m t) - C\cos(\Delta m t)}{\cosh(\Delta\Gamma t/2) + A_{\Delta\Gamma}\sinh(\Delta\Gamma t/2)} \overset{\Delta\Gamma=0}{\approx} S\sin(\Delta m t) - C\cos(\Delta m t)$$

$$S_{J/\psi K^0_S} \approx \sin 2\beta$$



$$C = 0.12^{+0.07}_{-0.07}\,(\text{stat}) + 0.02\,(\text{syst})$$
$$S = 0.83^{+0.07}_{-0.08}\,(\text{stat}) + 0.01\,(\text{syst})$$

$$C = -0.05^{+0.10}_{-0.10}\,(\text{stat}) + 0.01\,(\text{syst})$$
$$S = 0.84^{+0.10}_{-0.10}\,(\text{stat}) + 0.01\,(\text{syst})$$

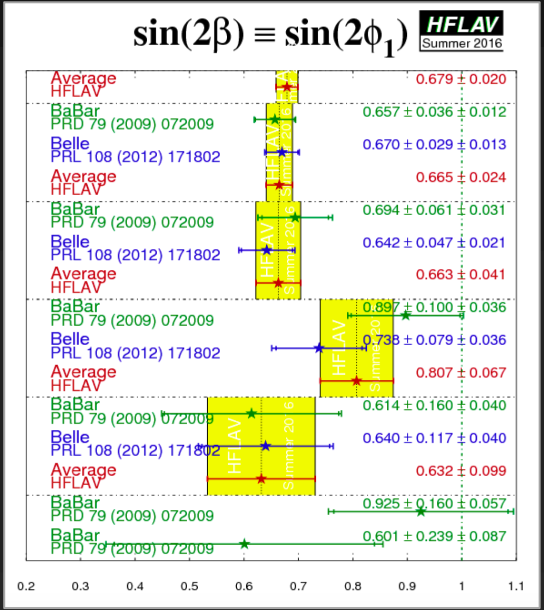
New measurement of sin2β

- Average of LHCb measurements from Run 1

$$C(B^0 \to [c\bar{c}]K^0_S) = -0.017 \pm 0.029$$
$$S(B^0 \to [c\bar{c}]K^0_S) = 0.760 \pm 0.034$$

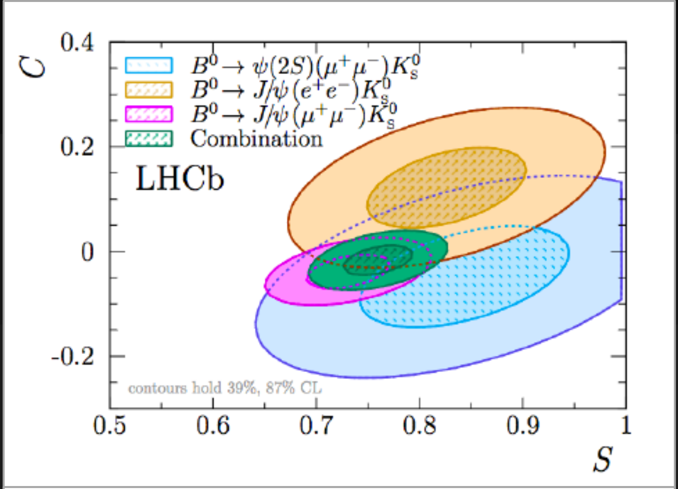
- Slight tension with the average from B factories on sin2β, at the2σ level

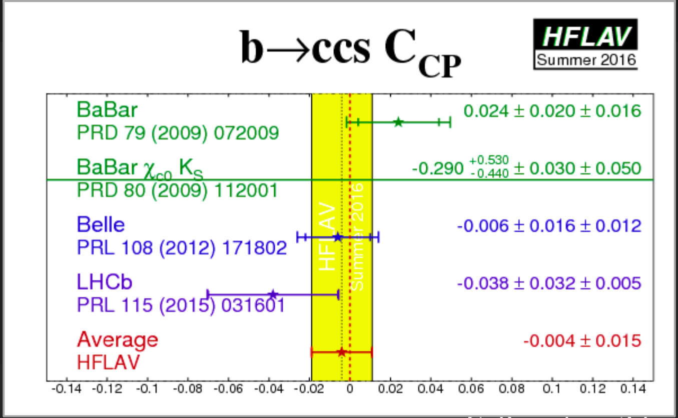
[LHCb-PAPER-2017-029]



Further investigations with Run2 data are needed

sin2β from B factories:
0.679±0.020

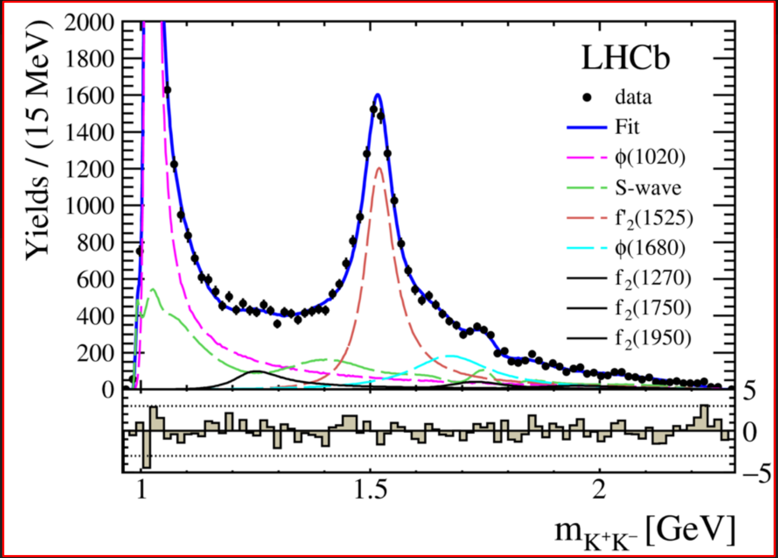


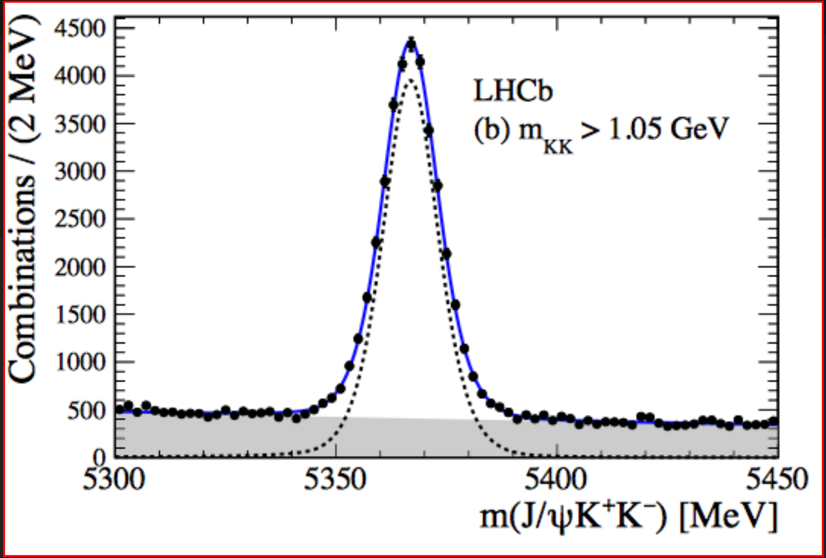


B_s mixing phase: legacy ϕ_s result from Run 1

JHEP 08 (2017) 037

- LHCb measured ϕ_s from Run-1 with $B_s \to J/\psi KK$ (and $B_s \to J/\psi \pi\pi$) already some time ago
  - ★ but the measurement only included the KK system around the $\phi(1020)$ mass
- There is non negligible statistics for $m_{KK} > 1.05$ GeV/c^2





B_s mixing phase: legacy ϕ_s result from Run 1

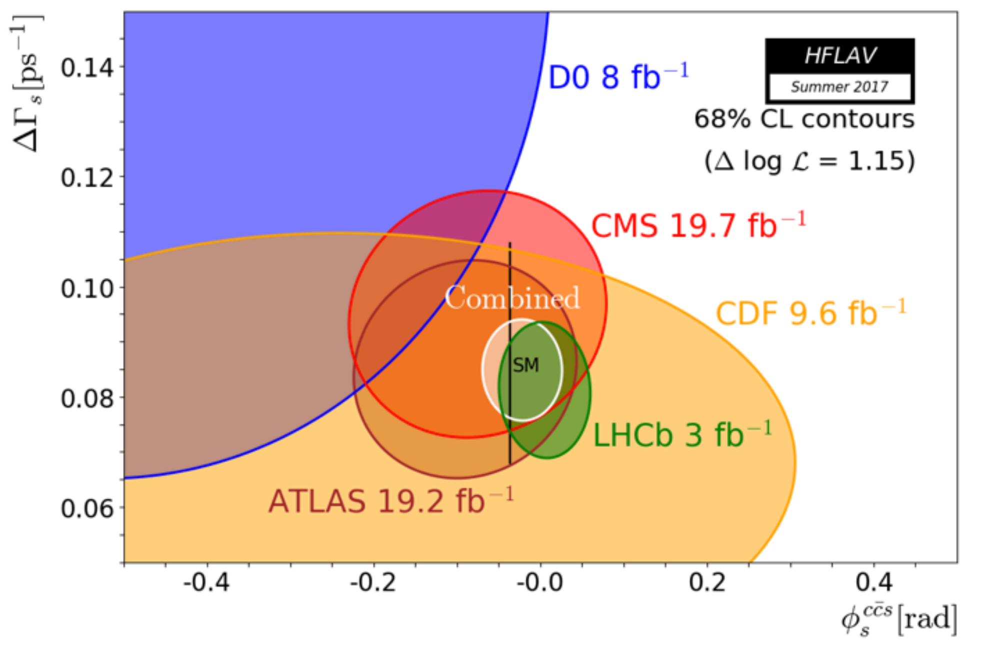
- Quite challenging, as a decay- time dependent amplitude analysis is involved
- Results for m_{KK}>1.05 GeV/c^2

$$\begin{aligned}\phi_s &= 119 \pm 107 \pm 34\,\text{mrad},\\ |\lambda| &= 0.994 \pm 0.018 \pm 0.006,\\ \Gamma_s &= 0.650 \pm 0.006 \pm 0.004\,\text{ps}^{-1},\\ \Delta\Gamma_s &= 0.066 \pm 0.018 \pm 0.010\,\text{ps}^{-1}.\end{aligned}$$

- And averaging with low KK mass

$$\begin{aligned}\phi_s &= -25 \pm 45 \pm 8\,\text{mrad},\\ |\lambda| &= 0.978 \pm 0.013 \pm 0.003,\\ \Gamma_s &= 0.6588 \pm 0.0022 \pm 0.0015\,\text{ps}^{-1},\\ \Delta\Gamma_s &= 0.0813 \pm 0.0073 \pm 0.0036\,\text{ps}^{-1}.\end{aligned}$$

- Finally, including also $B_s \to J/\psi\pi\pi$



$$\phi_s = 1 \pm 37\,\text{mrad and } |\lambda| = 0.973 \pm 0.013$$

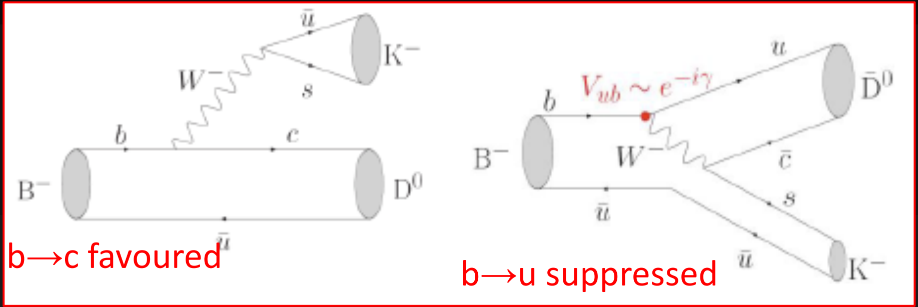
JHEP 08 (2017) 037

Now working on the update with Run-2 data

Unitarity Triangle: the angle γ

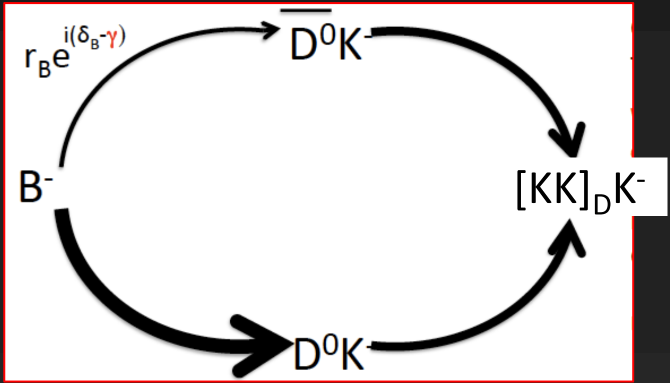
- A precise measurement of the angle γ is one of the flagship measurements of LHCb

$$\gamma = -\arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$



- Tree-level decays: strategy very clean and the results are unpolluted by New Physics
- Provides a SM benchmark against which other measurements can be compared

- Many D^0 decays can be exploited: Kπ, KK, Kπππ...



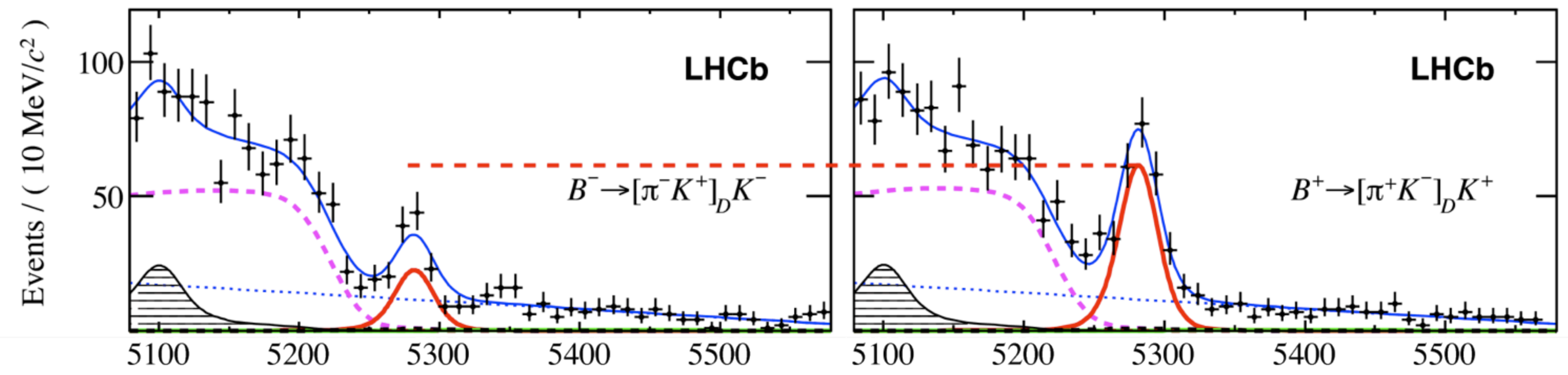
e.g. “GLW” method with decay to CP eigenstates

$$\frac{N(B^-)-N(B^+)}{N(B^-)+N(B^+)} = A_{CP+} = \frac{1}{R_{CP+}} 2r_B \sin(\delta_B)\sin(\gamma)$$

$$\frac{N(B\to[KK]_D K)\times\Gamma(D\to K\pi)}{N(B\to[K\pi]_D K)\times\Gamma(D\to KK)} = R_{CP+} = 1+r_B^2+2r_B\cos(\delta_B)\cos(\gamma)$$

Unitarity Triangle: the angle γ

- High precision obtained through the combination of many complementary methods and channels, including some rare decays (e.g. the "ADS" $B^{\pm} \to (K^{\mp}\pi^{\pm})_D K^{\pm}$ mode (BR ~ 10^{-7}))…



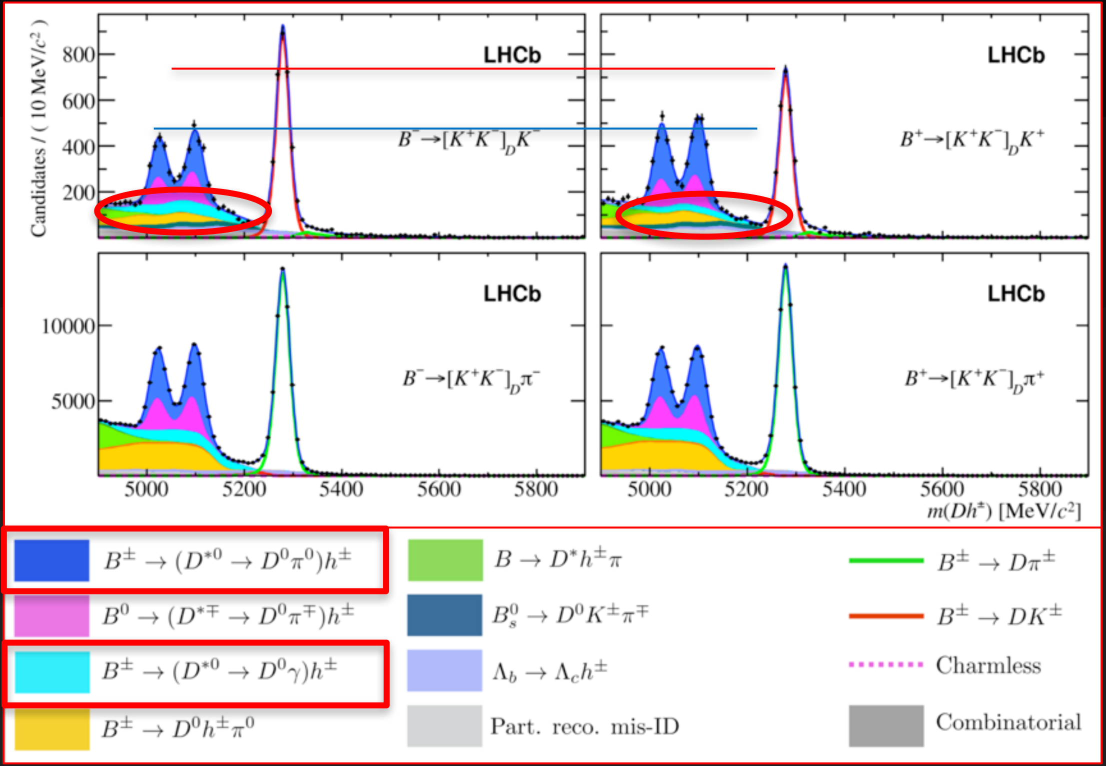
[PLB 760 (2016) 117]

This CP asymmetry carries ultra-clean, easy to interpret, information on γ!

CKM angle γ: a new measurement with run 2 data

[arXiv:1708.06370]

- LHCb performed a new measurement using all run 1 data plus the first 1.5 fb^{-1} from run-2 exploiting the decay $B^{\pm} \to (D^{*} \to D\pi^{0} / \gamma) K^{\pm}$
- Use partially reconstructed D^{*}
- The sensitivity to γ is through $D^{0} \to K^{+}K^{-}$ $D^{0} \to \pi^{+}\pi^{-}$ decays to CP eigenstates (GLW method)
- $D^{*} \to D\pi^{0}$ and $D^{*} \to D\gamma$ give opposite sign CP asymmetries



CKM angle γ: LHCb combination

[arXiv:1708.06370]

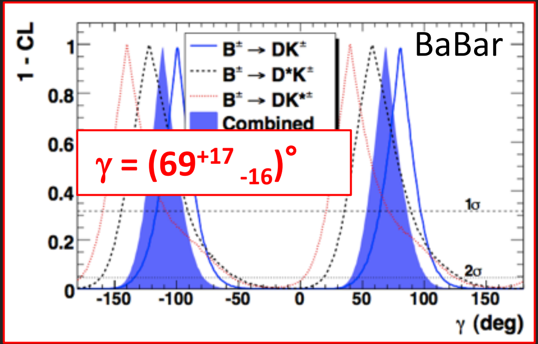
- Angle γ can be measured with a large number of different independent methodes
- Recent additions to the LHCb combination:

• $B^\pm \to D^0 K^{*\pm}$ ADS/GLW [LHCb-CONF-2016-014]	NEW	
• $B^\pm \to D^{*0} K^{*\pm}$ GLW [LHCb-PAPER-2017-021]	NEW	
• $B_s^0 \to D_s^\mp K^\pm$ TD [LHCb-CONF-2016-015]	$1\ fb^{-1} \to 3\ fb^{-1}$	
• $B^\pm \to D^0 K^\pm$ GLW [LHCb-PAPER-2017-021]	$3\ fb^{-1} \to 5\ fb^{-1}$	

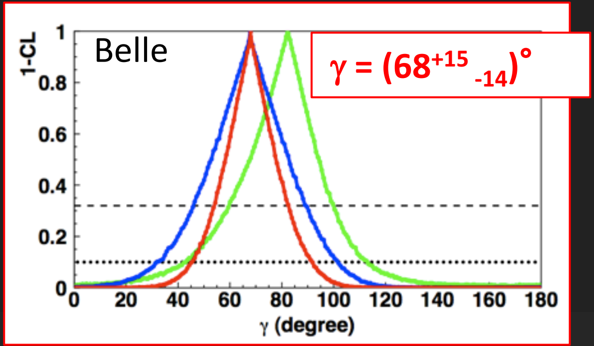
- Significantly more precise than previous results from the B-factories and undergoing continuous improvements:
- Is γ the least well known CKM angle ?

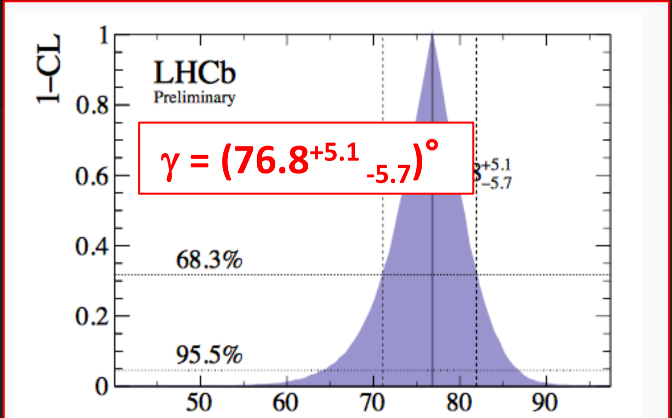
cfr $\alpha = (88.8 \pm 2.3)^\circ$ [CKMfitter ICHEP 2016]

[Phys. Rev. D87 (2013) 052015]



[arXiv:1301.2033]

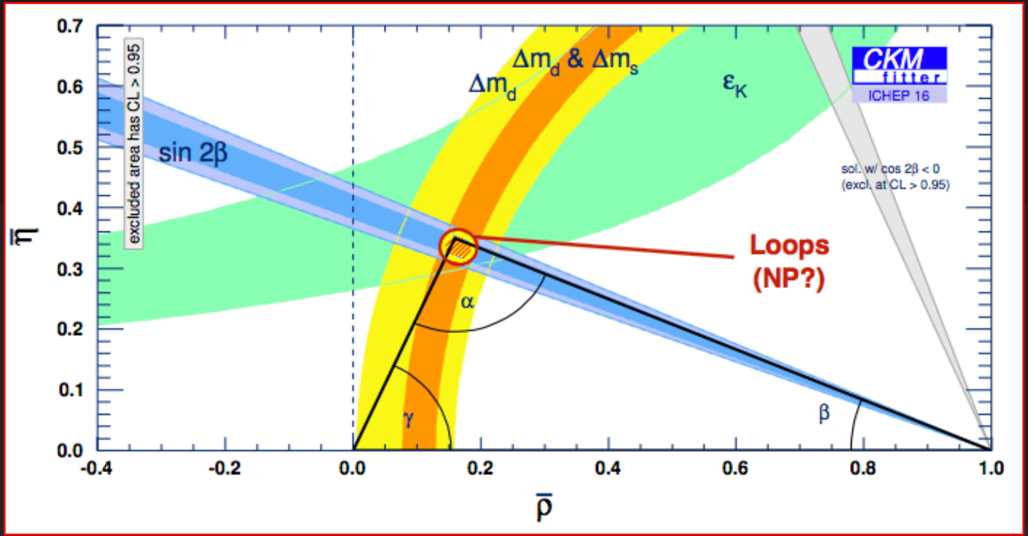




[LHCb-CONF-2017-004]

The global picture

- Main idea: compare γ measured in tree level decays with the value inferred from indirect global fits
- Loop processes, which give β, Δm_s and Δm_d, are NP sensitive
- Indirect γ precision ~ 2° - limited by QCD theory uncertainty in Δm_s and Δm_d [MILC]
- We must strive to push tree level measurement of γ below this limit
- Does the Unitarity Triangle close?



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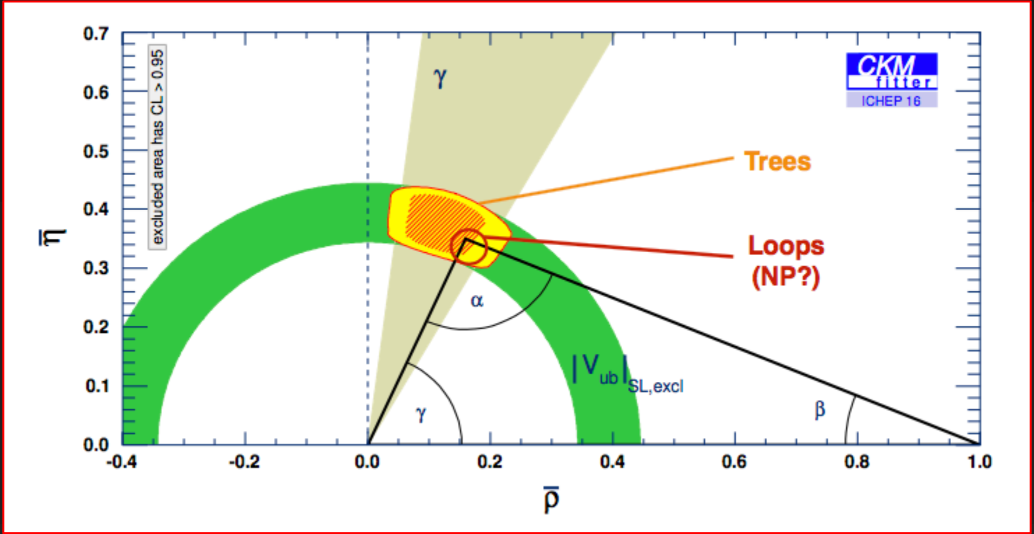
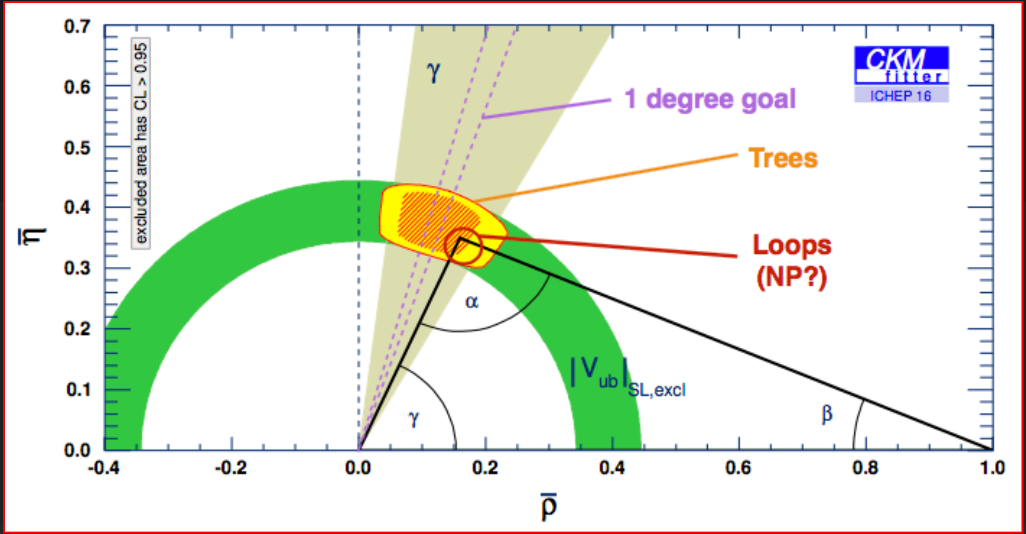


The global picture

- Main idea: compare γ measured in tree level decays with the value inferred from indirect global fits
- Loop processes, which give β, Δm_s and Δm_d, are NP sensitive
- Indirect γ precision ~ 2° - limited by QCD theory uncertainty in Δm_s and Δm_d [MILC]
- <1° precision expected with upgraded LHCb; Belle II will also enter in the game
- Does the Unitarity Triangle close?



Is Nature blind to lepton flavour?

Tests for lepton flavour universality in B decays

- *Semitauonic B decays – $R(D^*)$, $R(J/\psi)$*
- *$b \to s l^+ l^-$ FCNC decays – $R(K^{(*)})$*

Tests of lepton universality

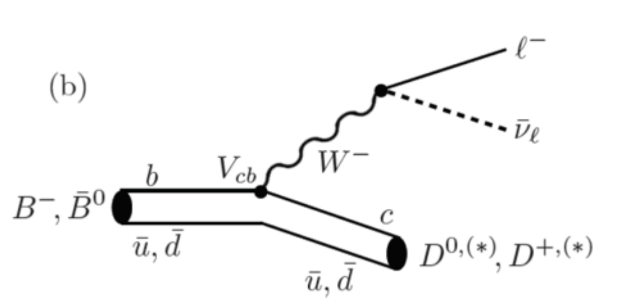
- In SM the coupling of gauge bosons with leptons is universal
- Lepton flavour universality can be checked in several B meson decays involving leptons in the final state

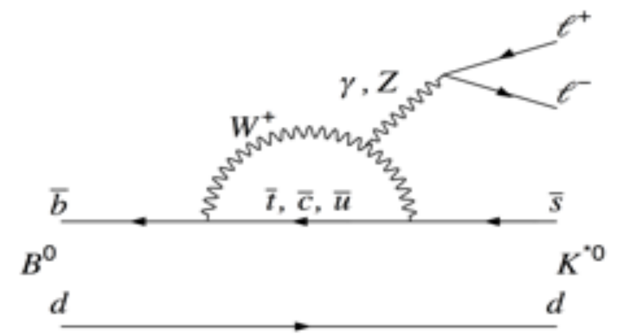
- Two main classes of decays have been studied:
  - ★ Semileptonic $B^0 \to D^{(*)-} l^+ \nu$ - tree level decay
  - ★ $b \to s l^+ l^-$ decays e.g. $B^0 \to K^{*0} l^+ l^-$ - FCNC decays

- Observables:

$$R(D^*) = \frac{BF(B \to D^* \tau \nu)}{BF(B \to D^* \mu \nu)} \overset{SM}{=} 0.252 \pm 0.003$$

$$R(K^{(*)}) = BF(B \to K^{(*)} \mu^+ \mu^-)/BF(B \to K^{(*)} e^+ e^-) \overset{SM}{\sim} 1$$





Tests of lepton universality: semitauonic decays - $R(D^*)$

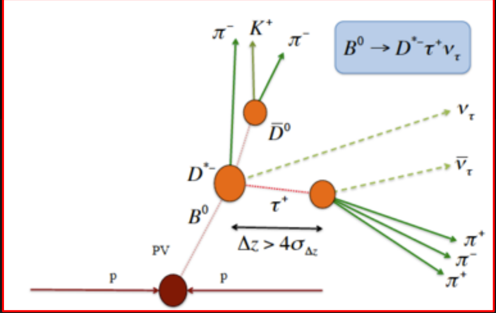
[arXiv:1708.08856]

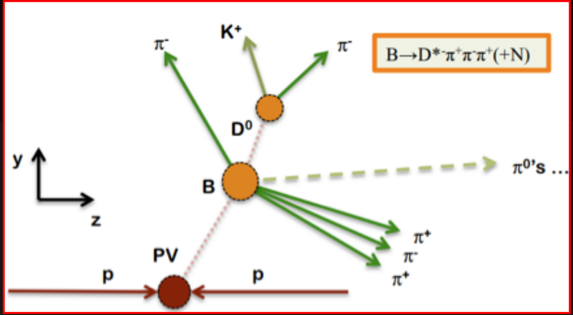
- Latest measurement from LHCb look at final states $\tau\to\pi^+\pi^-\pi^+\nu$
- Normalisation done through a very similar known final state

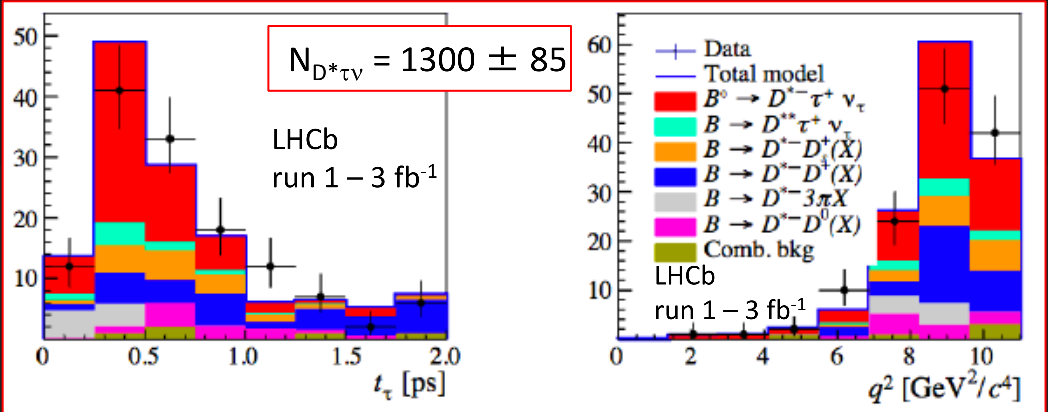
$$R(D^*) = K_{had}(D^*)\times\frac{BR(B^0\to D^{*-}\pi^+\pi^-\pi^+)}{BR(B^0\to D^{*-}\mu^+\nu_\mu)}$$

$$K_{had}(D^*) = \frac{BR(B^0\to D^{*-}\tau^+\nu_\tau)}{BR(B^0\to D^{*-}\pi^+\pi^-\pi^+)}$$

- Kinematical constraints used to close the decay
- Three-dimensional fit in decay time, q^2 and BDT output



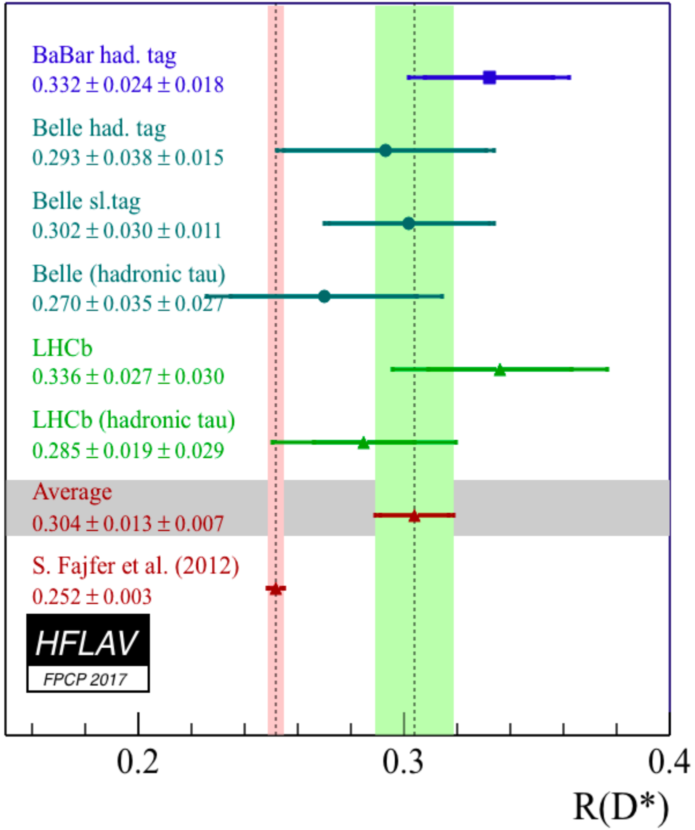


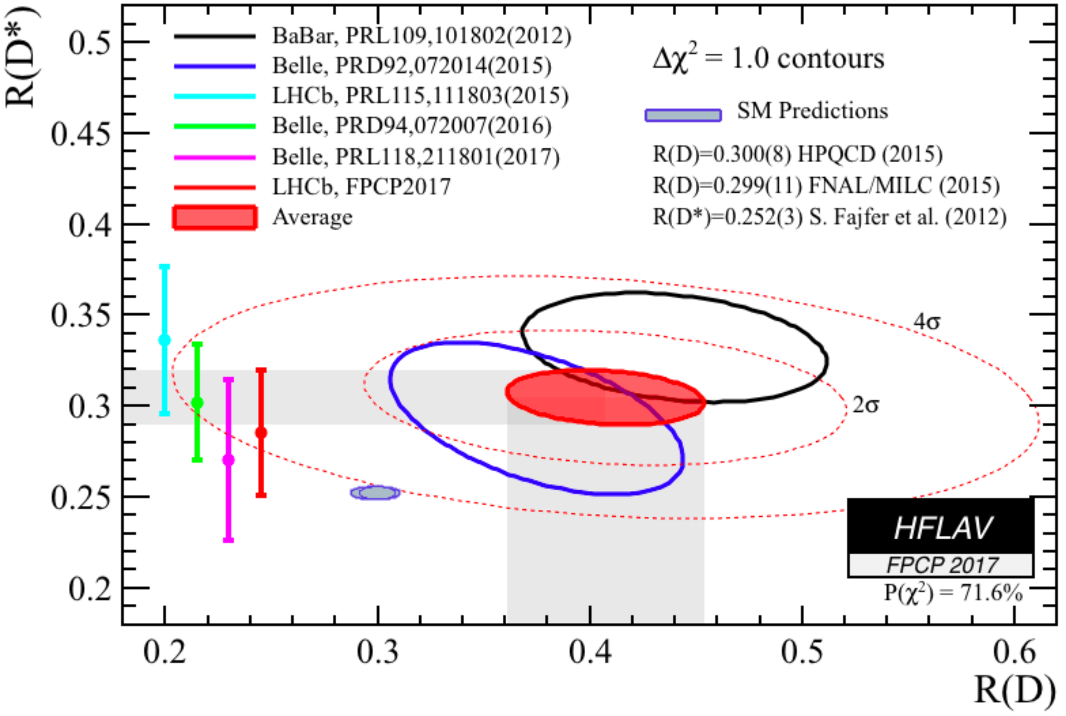


$BR(B^0\to D^*\tau\nu) = (1.39 \pm 0.09 \pm 0.12 \pm 0.06)\%$

Tests of lepton universality: semitauonic decays - R(D*)

[arXiv:1708.08856]





Results are internally consistent and 4σ from SM prediction

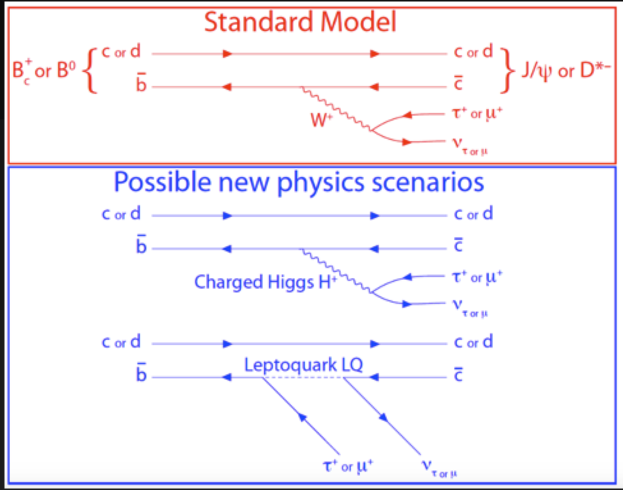
Tests of lepton universality – a new tool: B_c [new]

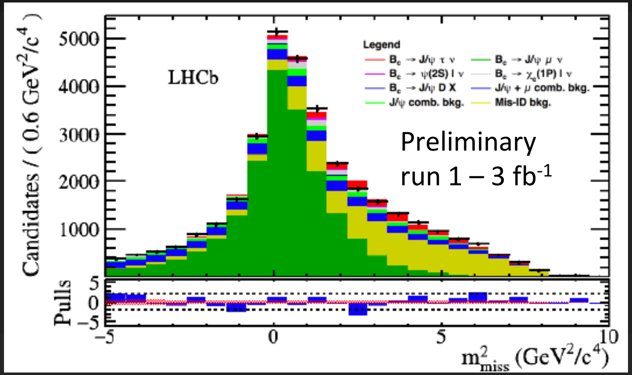
[LHCb-PAPER-2017-035]

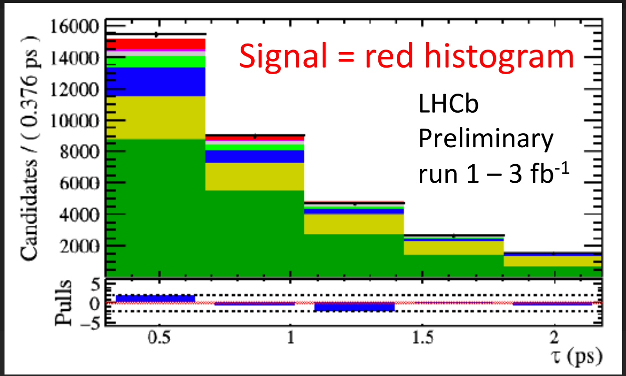
- Test of lepton universality using semitauonic B_c decays.
- Generalization of R(D) to the B_c sector:

$R(J/\psi) = BF(Bc \to J/\psi\tau\nu)/BF(B_c \to J/\psi\mu\nu)$

- Theoretical prediction still more uncertain due to the need of precise form factor calculations: in the range 0.25-0.28
- Ongoing LQCD efforts will lead to a more precise estimate
- The analysis makes use of the muonic τ decay

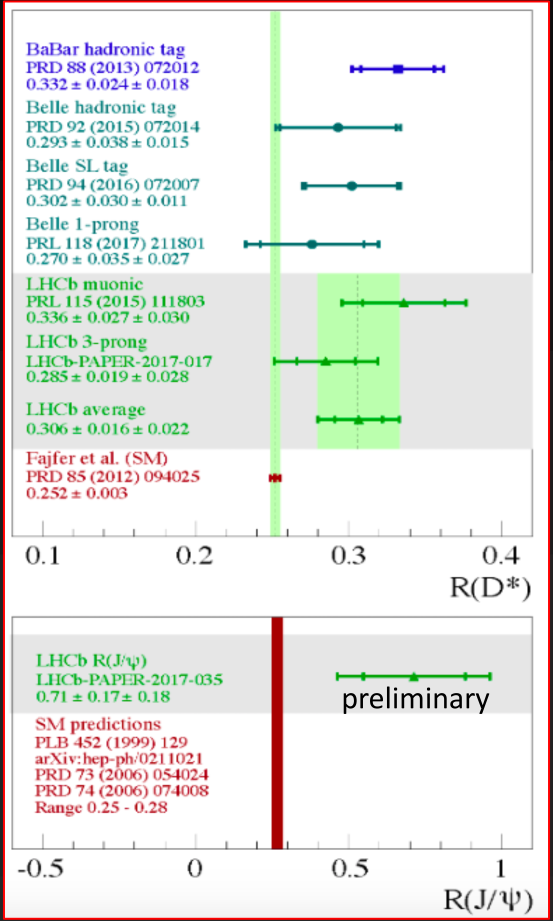






Tests of lepton universality – a new tool: B_c

[LHCb-PAPER-2017-035]



- $R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$
  about 2σ from the SM
- Intriguingly, again a measurement above the SM prediction…

- Excellent prospects for the future
- Form-factor related systematics will be reduced by LQCD

- Only LHCb can perform this measurement!

Tests of lepton universality: R(K) and R(K*)

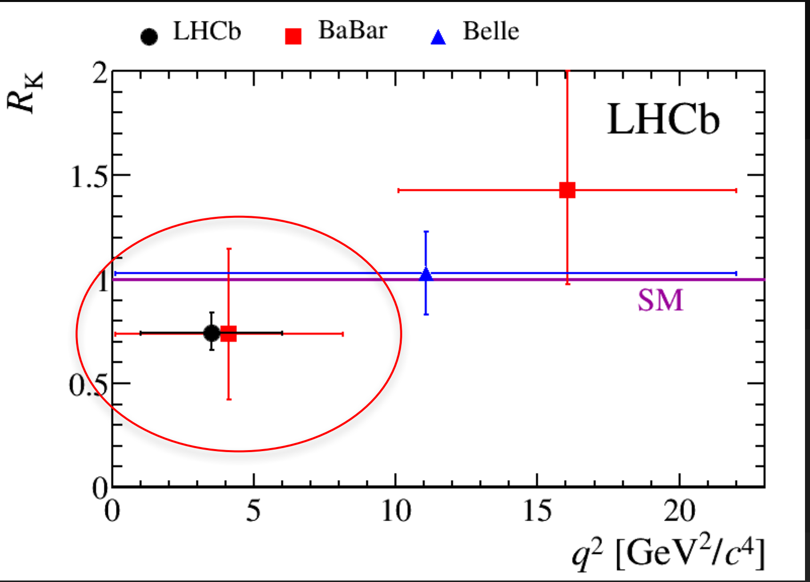
- LHCb measured in 2014 the LFU test ratio

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

$$1 < q^2 < 6\,\mathrm{GeV}^2/c^4$$

- The result was found to deviate from the Standard Model expectation by 2.6 standard deviations

- Since then a campaign started to make similar measurements with different decay modes



Tests of lepton universality: R(K) and R(K*)

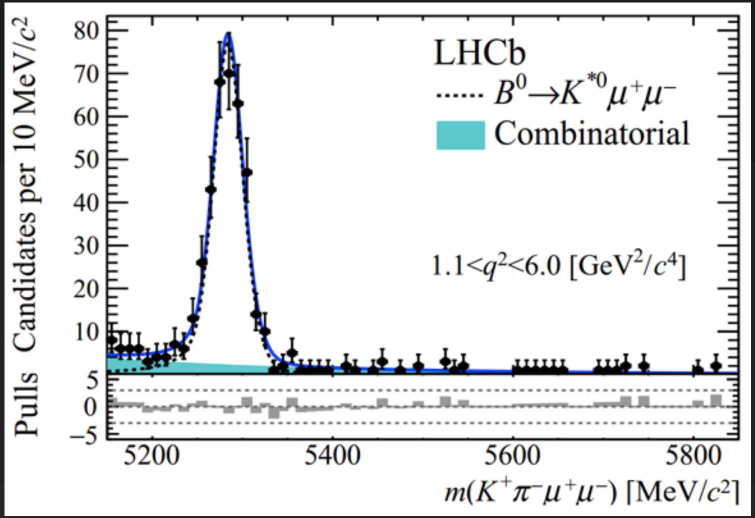
[JHEP 08 (2017) 055]

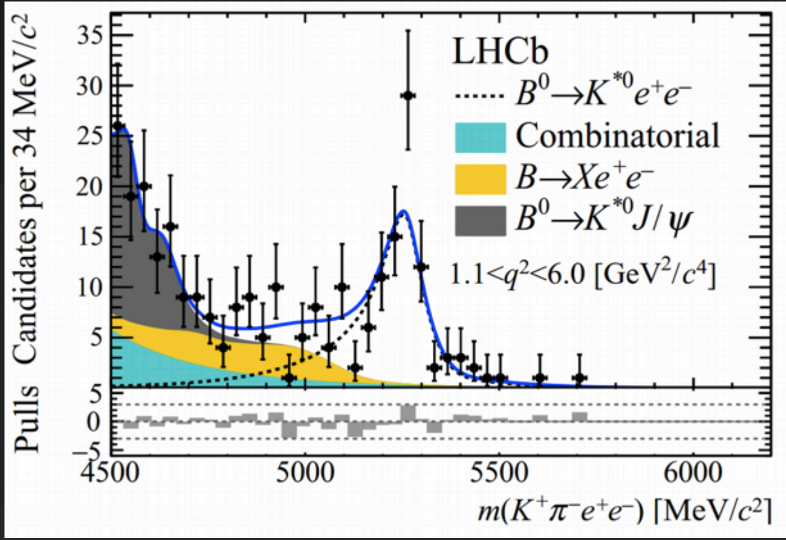
Test the LFU in electroweak penguin decays (e.g. the class of FCNC decays $b \to s l^+ l^-$)

- For example, study the double ratio R(K*):

$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

Should be ~1 in the SM
1st order systematics in efficiency cancel in double ration– robust !



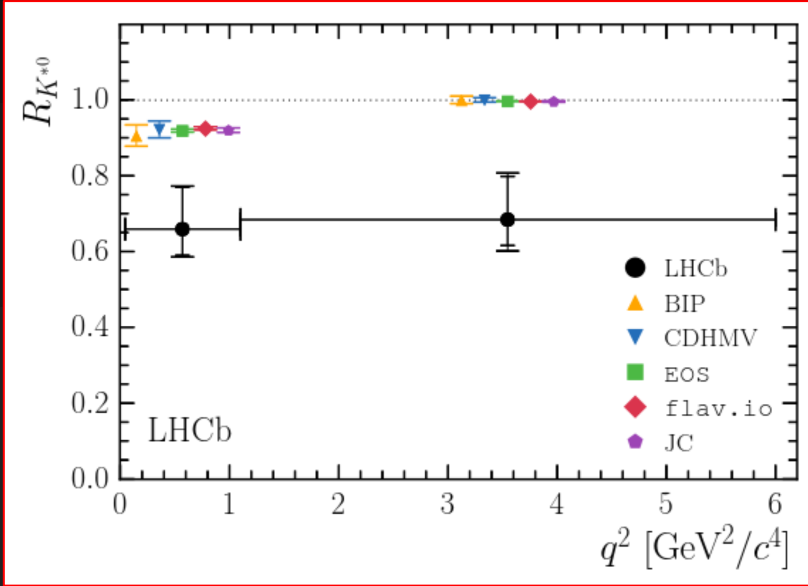


Tests of lepton universality: R(K) and R(K^*)

Test the LFU in electroweak penguin decays (e.g. the class of FCNC decays $b \to s l^+ l^-$)

- Results for R(K*):

[JHEP 08 (2017) 055]



2.1 – 2.3 standard deviations from the Standard Model

$$R_{K^{*0}} = \begin{cases} 0.66\,^{+\,0.11}_{-\,0.07}\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst}) & \text{for } 0.045 < q^2 < 1.1\ \mathrm{GeV}^2/c^4 \\ 0.69\,^{+\,0.11}_{-\,0.07}\,(\mathrm{stat}) \pm 0.05\,(\mathrm{syst}) & \text{for } 1.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4 \end{cases}$$

2.4 – 2.5 standard deviations from the Standard Model

- Too early to claim anything. Updates expected for the winter conferences
- Other channels being explored:
  - $B_s \to \phi l^+ l^-$ [≡ R(ϕ)]
  - $\Lambda_b \to pK l^+ l^-$ [≡ R(pK)]
  - ....

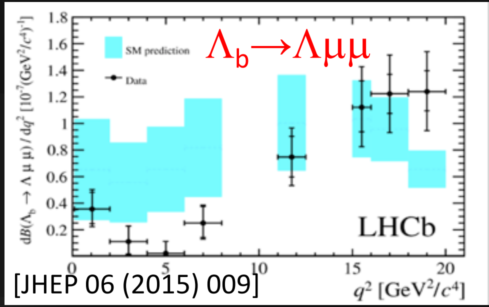
A picture with multiple tensions

Study of $b \to s l^+ l^-$ decays

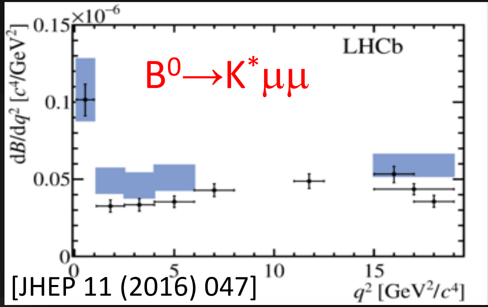
A complex picture with multiple tensions

In electroweak penguin decays (e.g. the class of FCNC decays $b \to s l^+ l^-$) there are many more tensions:

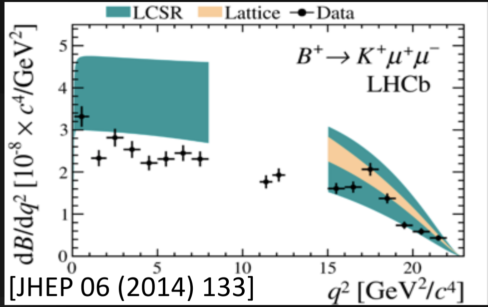
- Branching fractions: intriguingly consistent tendency for differential x-sections to be smaller than prediction at low q^2



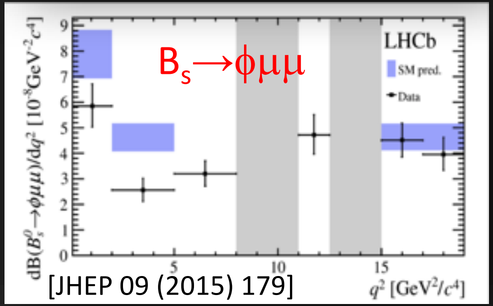
[JHEP 06 (2015) 009]



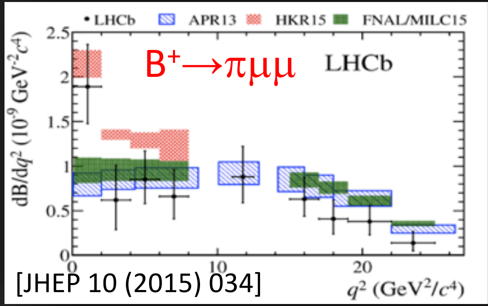
[JHEP 11 (2016) 047]



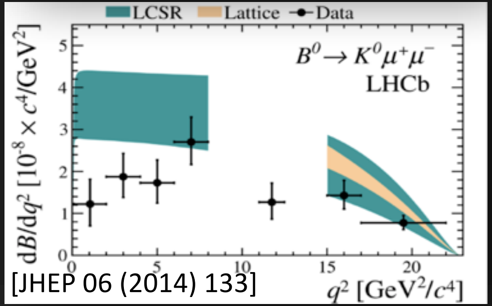
[JHEP 06 (2014) 133]



[JHEP 09 (2015) 179]



[JHEP 10 (2015) 034]



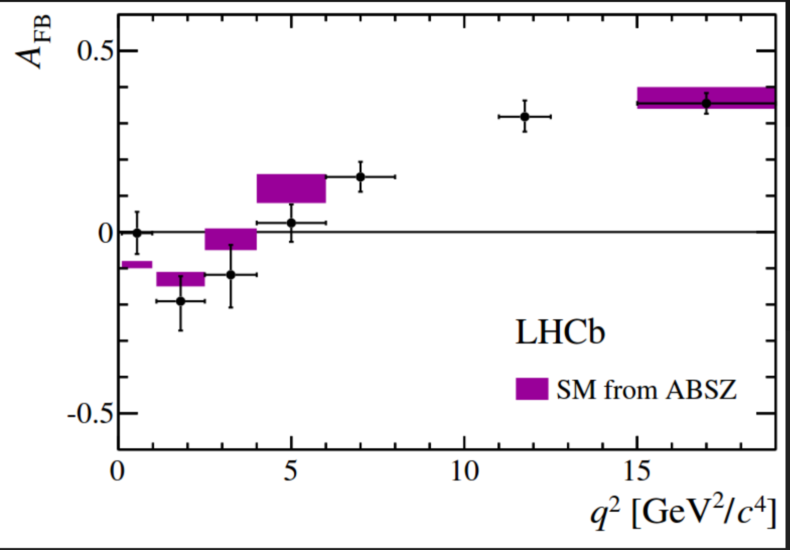
[JHEP 06 (2014) 133]

A complex picture with multiple tensions

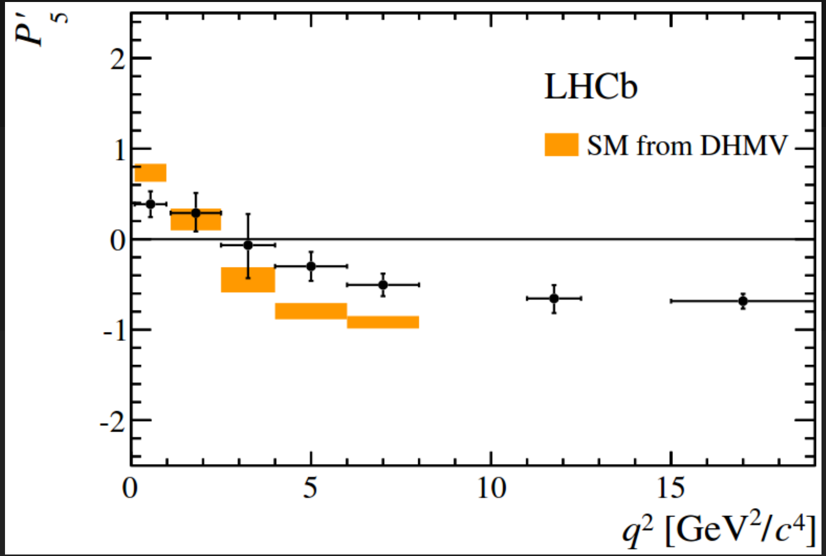
In electroweak penguin decays (e.g. the class of FCNC decays $b \to s l^+ l^-$) there are many more tensions:

- Angular observables

[JHEP 02 (2016) 104]



[JHEP 02 (2016) 104]



- A whole set of results with slight deviations from theory: more statistics will tell us if this is genuine new physics

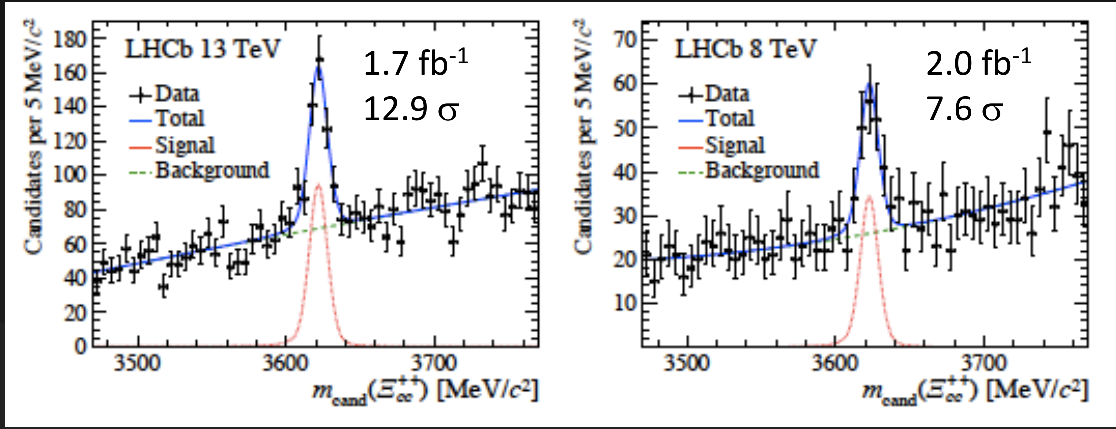
A benchmark for QCD: spectroscopy

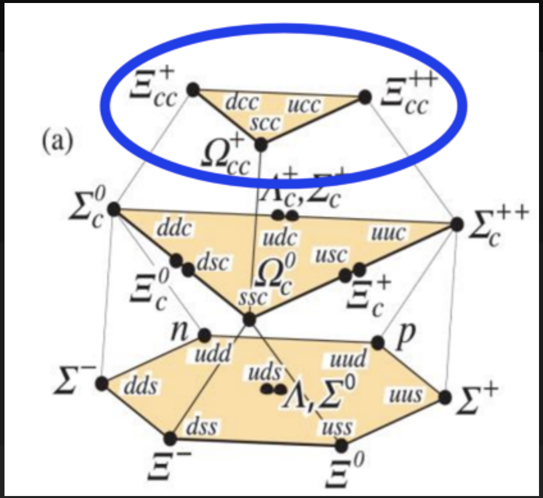
New results from heavy hadron spectroscopy

Observation of Ξ_{cc}^{++}

[Physical Review Letters 119 (2017) 112001]

- Doubly charmed baryons predicted by quark model
- Observation of Ξ_{cc}^{+} claimed by SELEX [Phys. Lett. B 628 (2005) 18-24]
- No evidence observed by BaBar, FOCUS, Belle and LHCb
- Search in LHCb for $\Xi_{cc}^{++} \rightarrow \Lambda_c^{+} K^{-} \pi^{+} \pi^{+}$

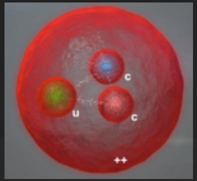


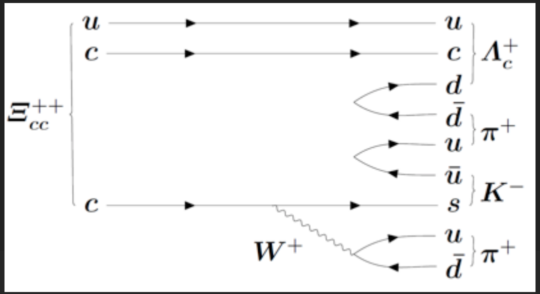


- Combined yield: 426 ± 39
- The mass is measured with the 2016 sample
- M(Ξ_{cc}^{++}) = 3621 ± 0.72 (stat) ± 0.31 (syst) MeV/c2

Lattice QCD calculations m(Ξ_{cc}^{++}) = (3606 ± 11 ± 8) MeV/c^2

[arXiv: 1704.02647]

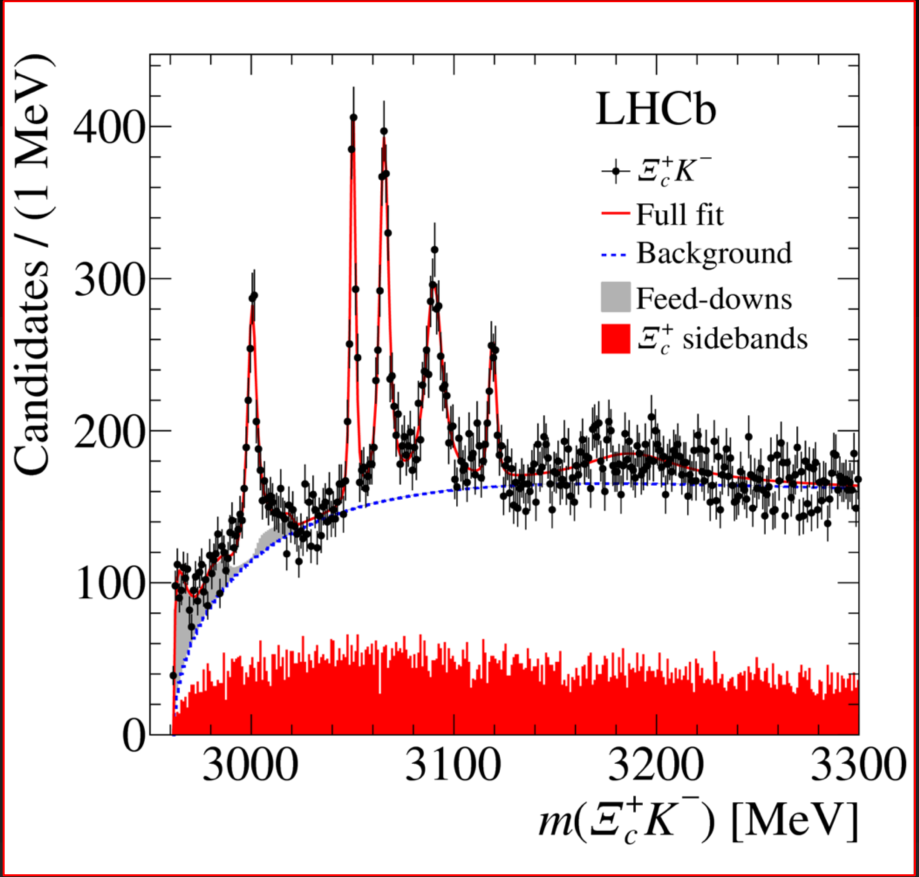




Observation of five excited Ω_c states

[Phys. Rev. Lett. 118 (2017) 182001]

- Only Ω_c ground states ($J_P = 1/2^+$ and $3/2^+$) were known till now
- Searh for Ξ_c ($\rightarrow pK^-\pi^+$) combined with opposite sign kaons
- 5 new narrow states observed in one shot!
- Most likely a record for the number of narrow states found in a single analysis



LHC: a machine for precision physics

Precise measurement of χ_{c1} and χ_{c2} resonance parameters

Precise measurement of $\chi_{c1,c2}$ resonance parameters [new]

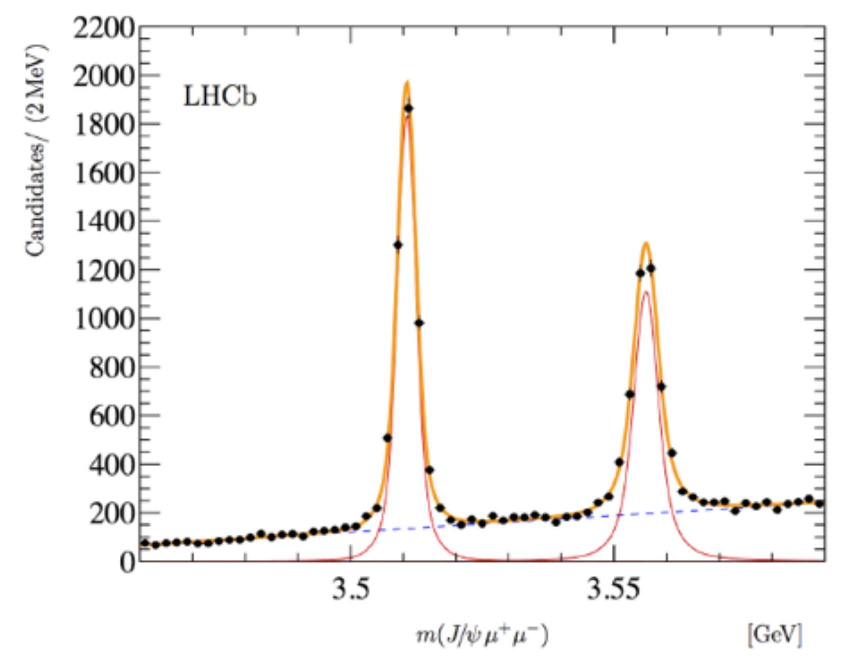
[arXiv:1709.04247]

- LHCb observed for the first time the Dalitz decays $\chi_{c1,c2} \rightarrow J/\psi\mu^+\mu^-$

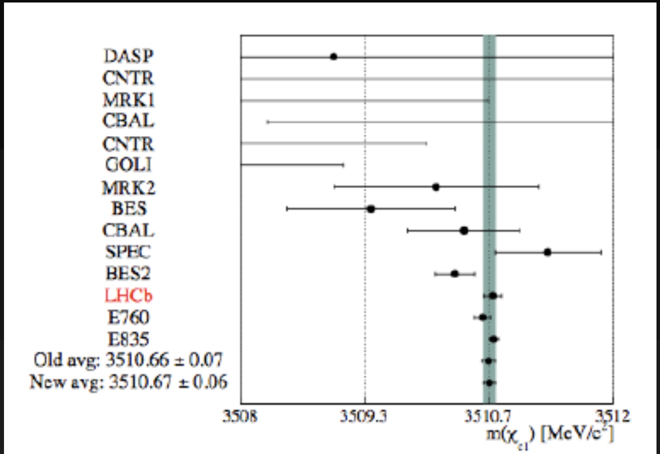
- Used full run 1 and run 2 (TURBO) datasets
- Mass resolution enough to measure the natural width of χ_{c2}

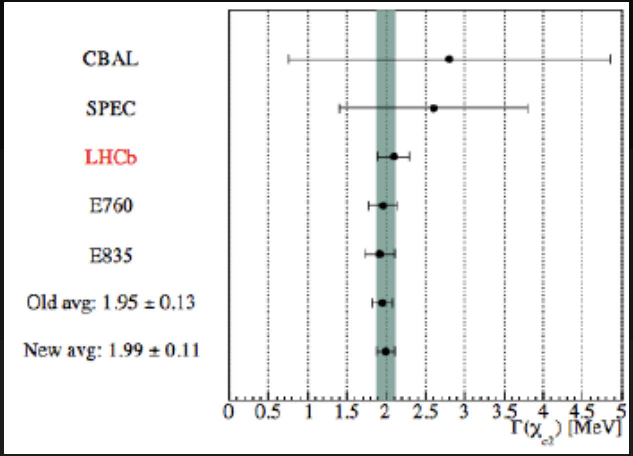
$$m(\chi_{c1}) = 3510.71 \pm 0.04\,(\text{stat}) \pm 0.09\,(\text{syst})\ \text{MeV}/c^2,$$
$$m(\chi_{c2}) = 3556.10 \pm 0.06\,(\text{stat}) \pm 0.11\,(\text{syst})\ \text{MeV}/c^2,$$
$$m(\chi_{c2}) - m(\chi_{c1}) = 45.39 \pm 0.07\,(\text{stat}) \pm 0.03\,(\text{syst})\ \text{MeV}/c^2$$

$$\Gamma(\chi_{c2}) = 2.10 \pm 0.20\,(\text{stat}) \pm 0.02\,(\text{syst})\ \text{MeV}.$$



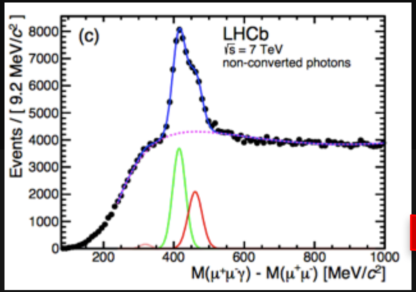
Precise measurement of χ_{c1} and χ_{c2} resonance parameters



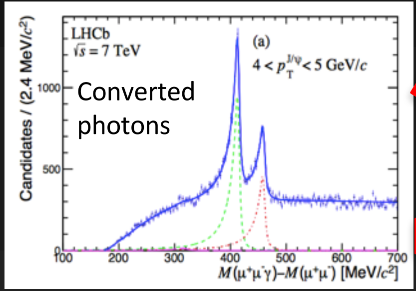


[arXiv:1709.04247]

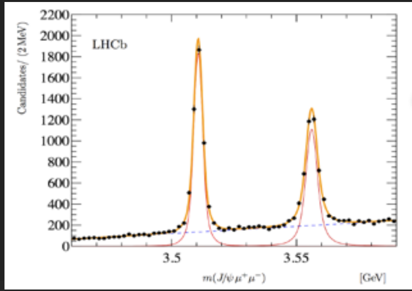
LHCb-PAPER-2011-030



LHCb-PAPER-2013-028



[arXiv:1709.04247]



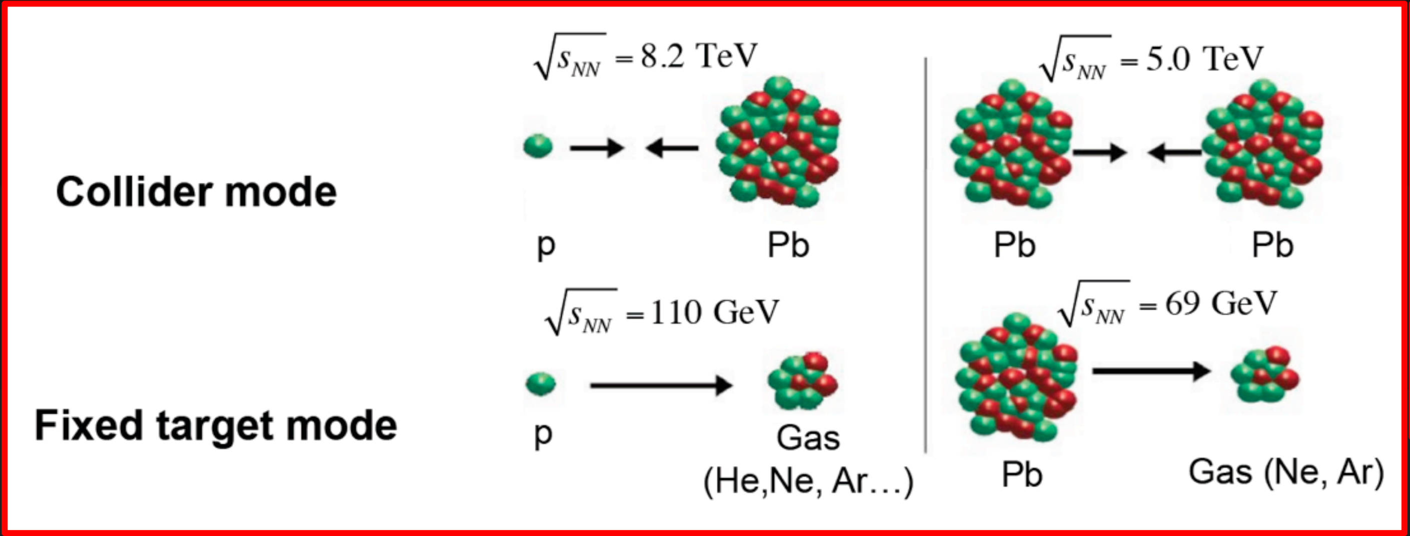
- LHCb measurement at the same level of precision of dedicated experiment E760/E835, based on p-pbar resonance scanning
- Major breakthrough in χ_c spectroscopy!
  - ★ Next step is measuring BF x production rate and ratio of BFs
- Lots of opportunities
  - ★ extend studies to X(3872), χ_c^0, χ_b states

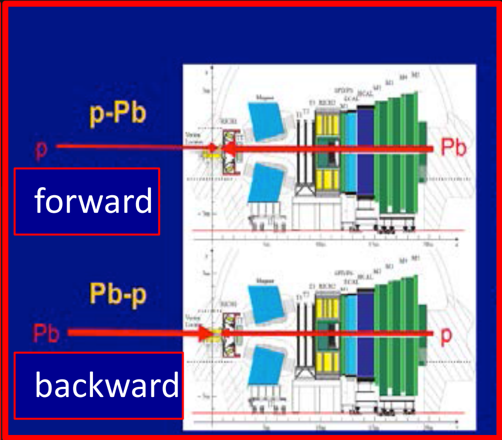
Not only flavour

Heavy ion and fixed target physics

Heavy ion operation modes

- LHCb can operate in collider mode, fixed target mode or both in parallel!





- Collider mode: forward/backward coverage
  Fixed target mode: central and backward coverage with $\sqrt{s_{NN}}$ between SPS and RHIC

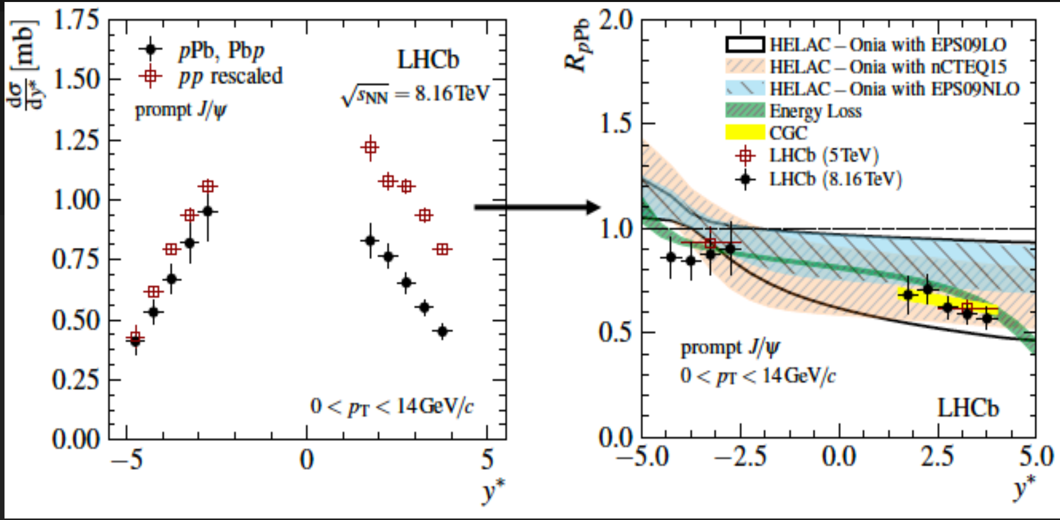
J/ψ producton in pPb collisions at √s = 8 TeV

[arXiv:1706.07122]

- Nuclear effects are seen in the comparison with pp collisions and in the comparison of pPb with Pbp.
- Use nuclear modification factors and forward-backward asymmetries as observables:

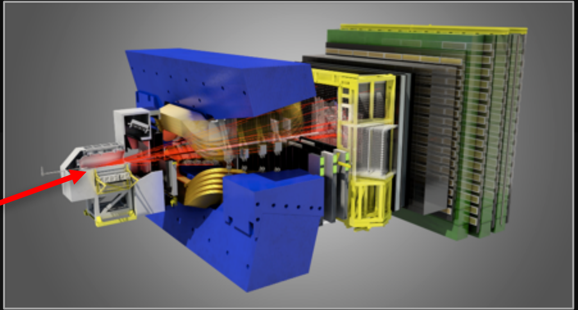
$$R_{pPb}(p_T, y^*) \equiv \frac{1}{A}\frac{d^2\sigma_{pPb}(p_T, y^*)/dp_T dy^*}{d^2\sigma_{pp}(p_T, y^*)/dp_T dy^*}$$ and $$R_{FB}(p_T, y^*) \equiv \frac{d^2\sigma_{pPb}(p_T, +y^*)/dp_T dy^*}{d^2\sigma_{pPb}(p_T, -y^*)/dp_T dy^*}$$

- Analysis made using candidates selected via the TURBO stream
- First heavy ion physics LHC paper with 2016 pPb run data!
- Suppression clearly visible in the forward region
- Good agreement with theoretical models especially color glass condensate and energy loss

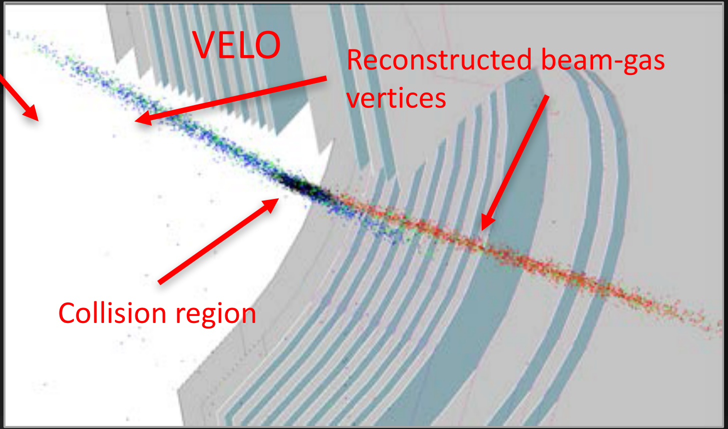


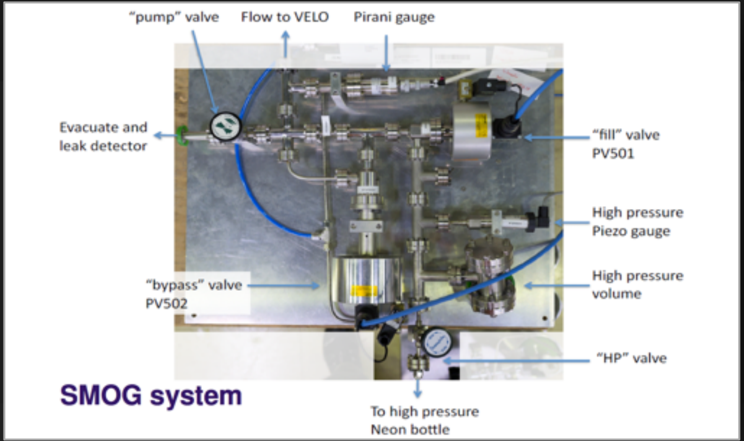
Fixed target physics with LHCb

- LHCb has a “fixed-target like” geometry
- Very well suited for. . . fixed target physics!
- The System for Measuring Overlap with Gas (SMOG) allows to inject small amount of noble gas (He, Ne, Ar, . . .) inside the LHC beam around (20 m) the LHCb collision region
- Expected pressure 2 x10^{-7} mbar
- Originally designed to measure the luminosity

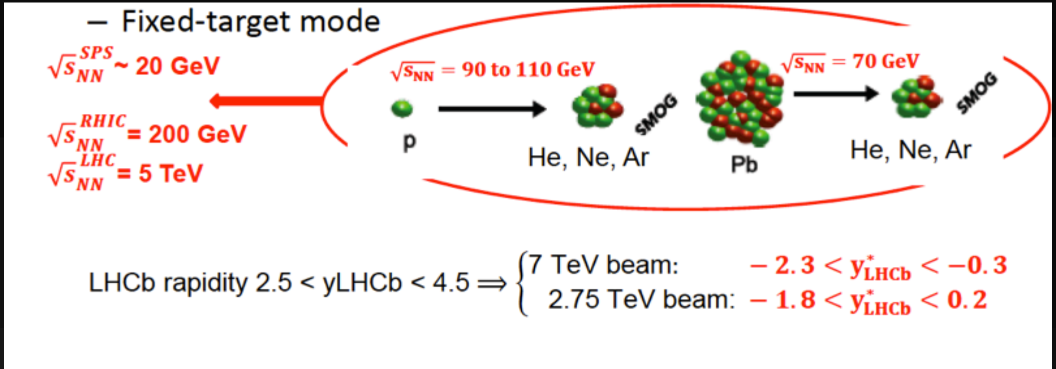


Imaging of beams with gas collisions



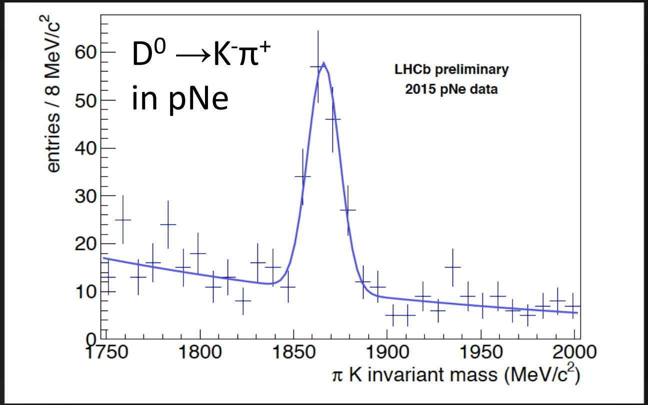


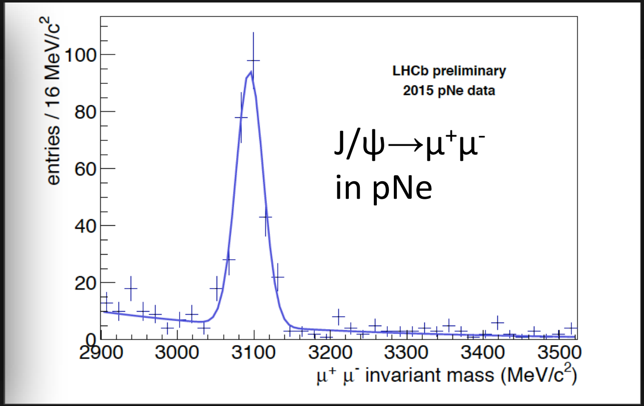
Fixed target physics with LHCb



- Collisions at energies unique to LHCb
- Energies between SPS and RHIC
- Probes the negative rapidity region

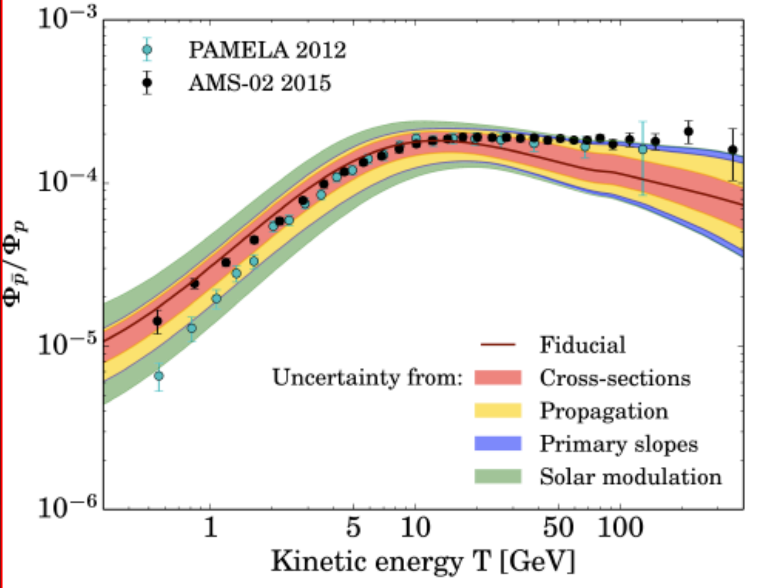
- COSMIC RAY PHYSICS @ LHCb:
  pHe collisions will provide $\sigma(pHe \rightarrow \bar{p}\,X)$ crucial for the interpretation of major cosmic ray physics results





Cosmic ray physics at LHCb: p+He→anti-p+X

- The recent AMS02 results provide unprecedented accuracy for measurement of anti-p/p ratio in cosmic rays at high energies [PRL 117, 091103 (2016)]
- Hint for a possible excess, and milder energy dependence than expected
- Prediction for anti-p/p ratio from spallation of primary cosmic rays on interstellar medium (H and He) is presently limited by uncertainties on anti-p production cross-sections, particularly for p-He
- No previous measurement of anti-p production in p-He, predictions from soft QCD models vary within a factor 2



Giesen et al., JCAP 1509, 023 (2015)

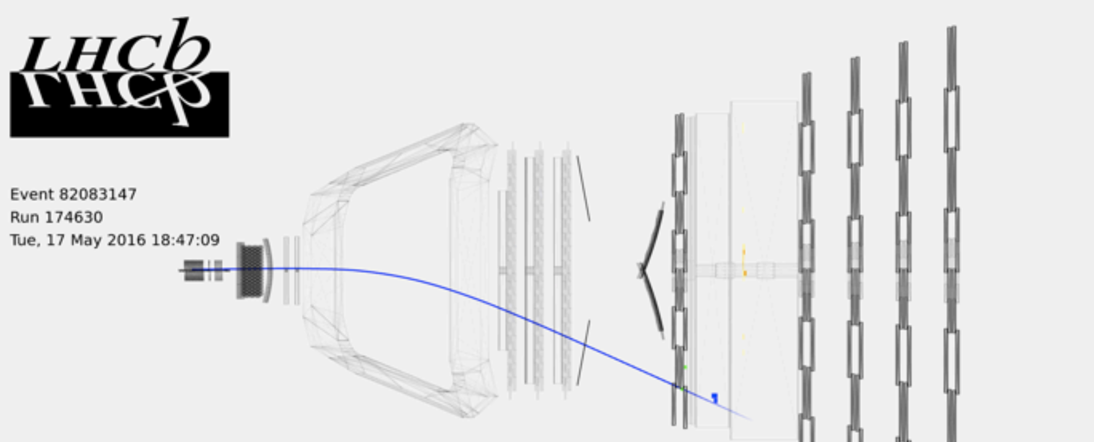
- The LHC energy scale and LHCb+SMOG are very well suited to perform this measurement

Cosmic ray physics at LHCb: p+He→anti-p+X

- LHCb took p-He collision data in May 2016, with proton energy 6.5 TeV, $\sqrt{s_{NN}}$ = 110 GeV
- Anti-protons are identified using the RICH detectors
- The luminosity is measured using elastic scattering of protons on atomic electrons
  - ★ Fully elastic regime in the LHCb acceptance
  - ★ Very well known theoretically

- A luminosity measurement at the 10% level can be obtained (main uncertainty: gas contamination !)

- $\mathcal{L} = 0.443 \pm 0.011 \pm 0.027\ nb^{-1}$



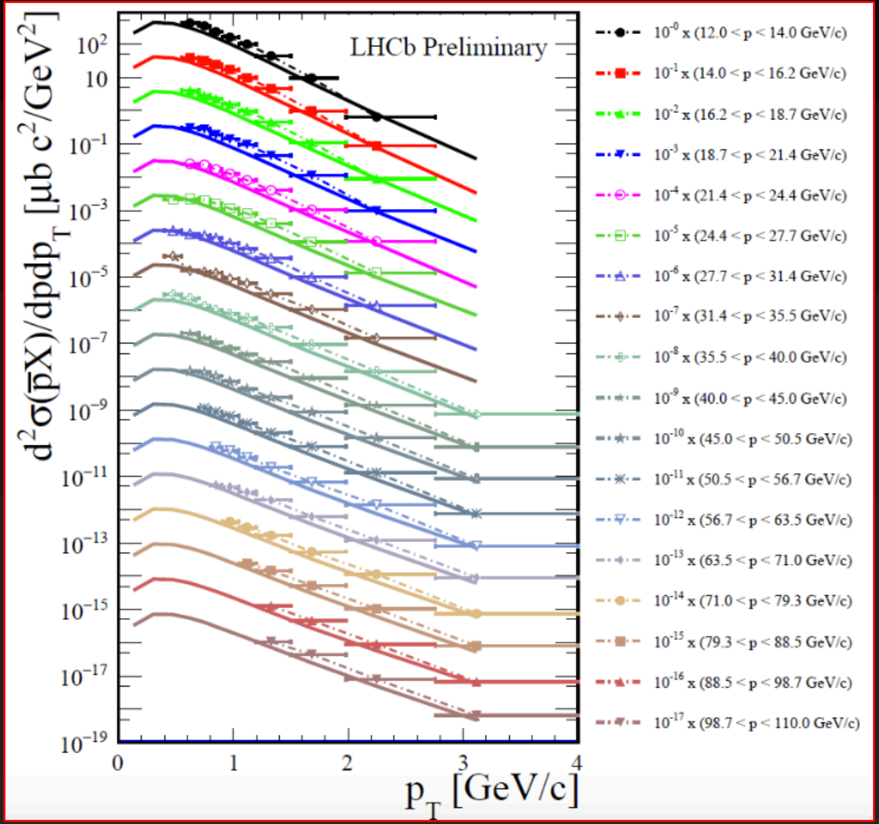
Single electron event in LHCb

Cosmic ray physics at LHCb: p+He→anti-p+X

- Antiproton cross section measured with 10% precision
  - ★ The measurement is larger by 1.5 with respect to EPOS LHC

- Now waiting for theoretical interpretation
- Additional production measurements are also important
  - ★ antiprotons from Λ
  - ★ anti-deuterium
  - ★ anti-He
  - ★ Positrons
  - ★ Prompt photons

- Rich programme to develop!



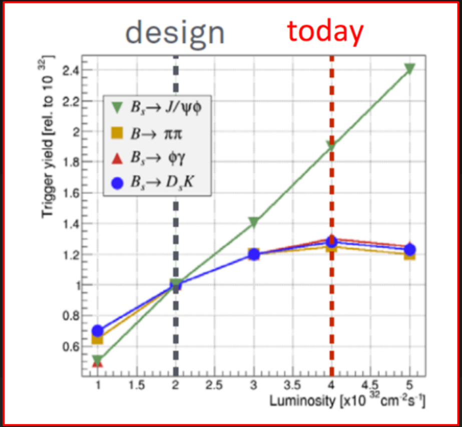
The LHCb upgrade

The LHCb upgrade

- An LHCb Upgrade is scheduled, with installation in 2019-2020 (LHC LS2) and first data-taking in Run 3 (2021-2023). The motivation is to take increased advantage of the huge rate of heavy-flavour production at the LHC.

1. Full software trigger
   - Allows effective operation at higher luminosity
   - Improved efficiency in hadronic modes
2. Raise operational luminosity by factor five to 2 x $10^{33}cm^{-2}s^{-1}$

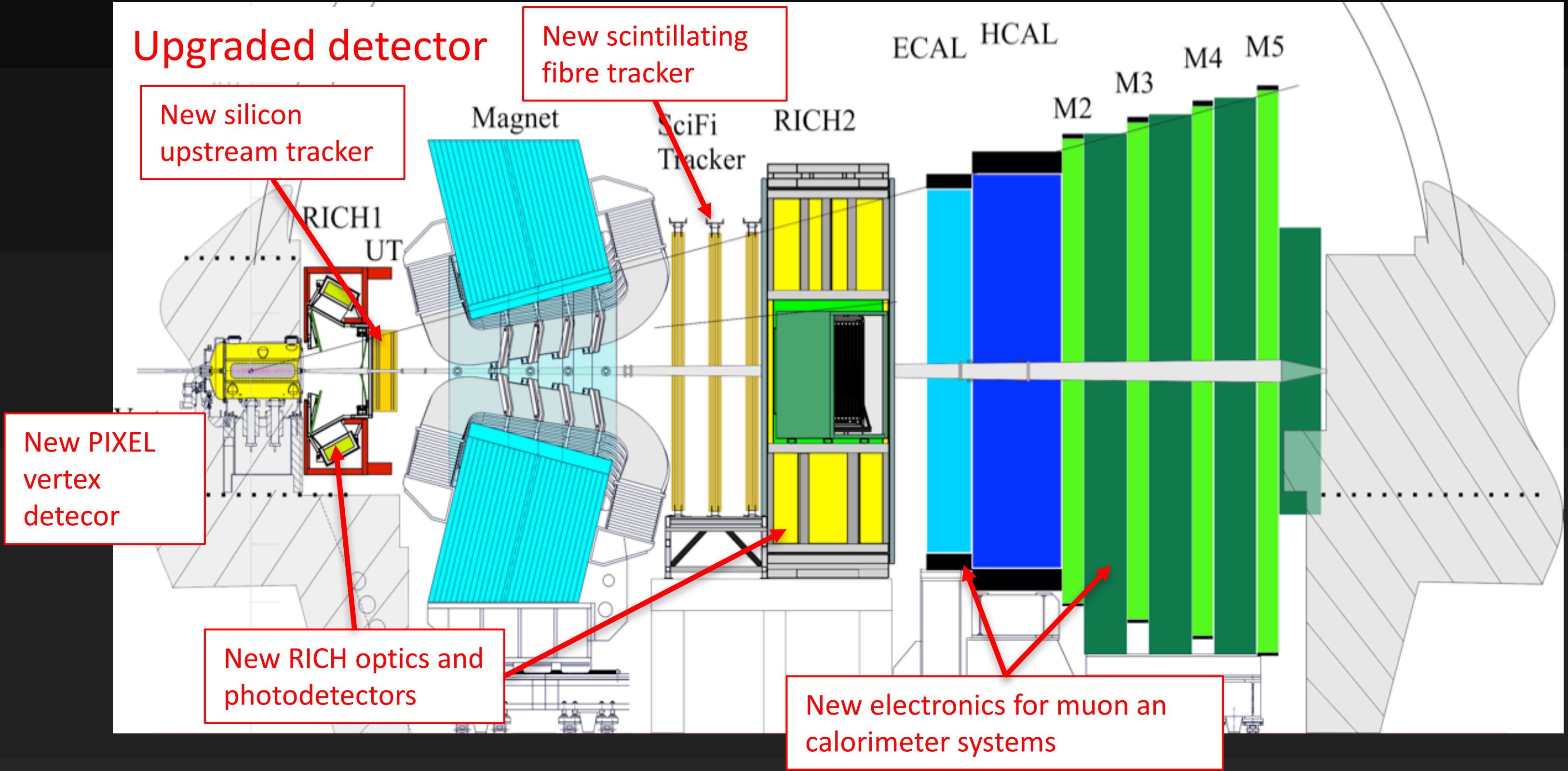
- Necessitates redesign of several sub-detectors and overhaul of readout



- Huge increase in precision, in many cases to the theoretical limit, and the ability to perform studies beyond the reach of the current detector.
- Flexible trigger and unique acceptance also opens up opportunities in other topics apart from flavour (‘a general purpose detector in the forward region’)

The LHCb upgrade in a snapshot

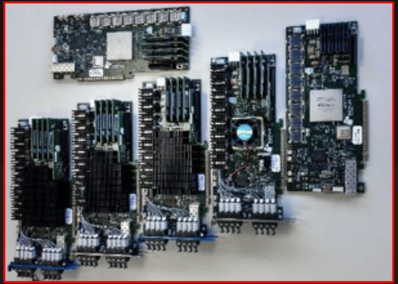
All sub-detectors read out at 40 MHz for a **fully software trigger**



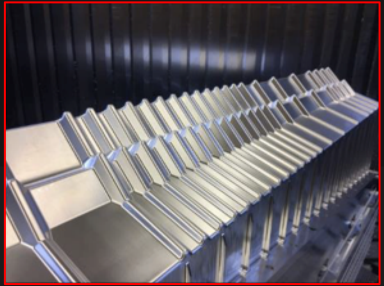
Status of upgrade

- Construction well advanced, aim at installation in 2019

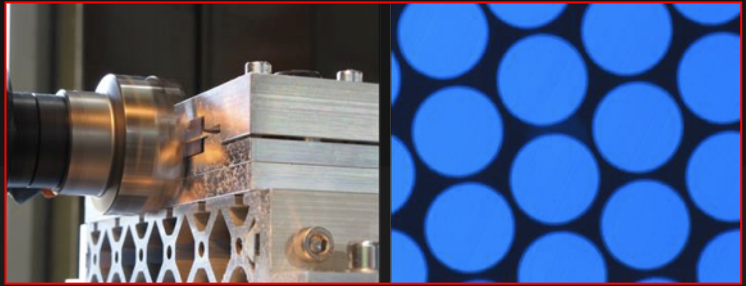
Prototypes of DAQ board (PCIe40)

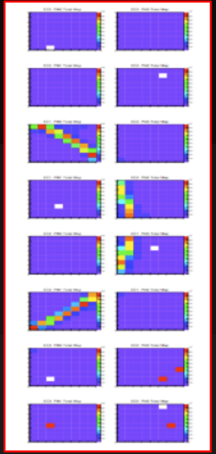


VELO RF-foil (250 um thick machined aluminum foil)

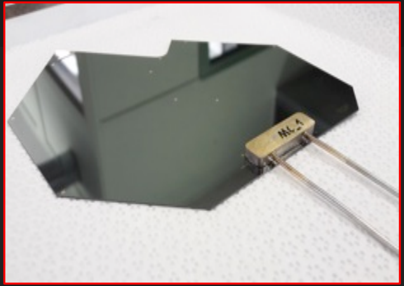


Machining and light scan of the scintillating fiber mats for the fibre tracker

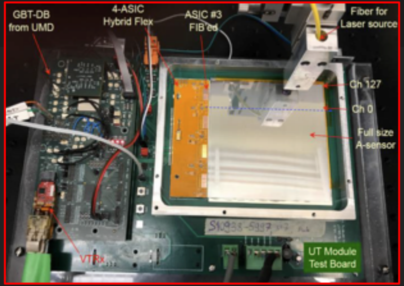




Cherenkov ring from a full RICH MaPMT module

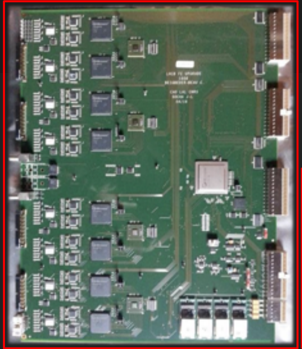


Si μchannel cooling plate for VELO with soldered connector



Upstream Tracker silicon sensor module under test

First scintillating fibre modules arriving at CERN



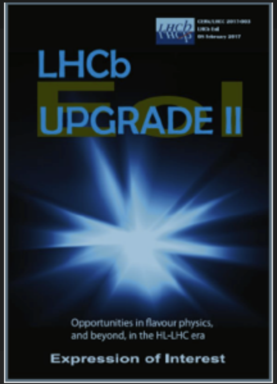
Calorimeter front-end board

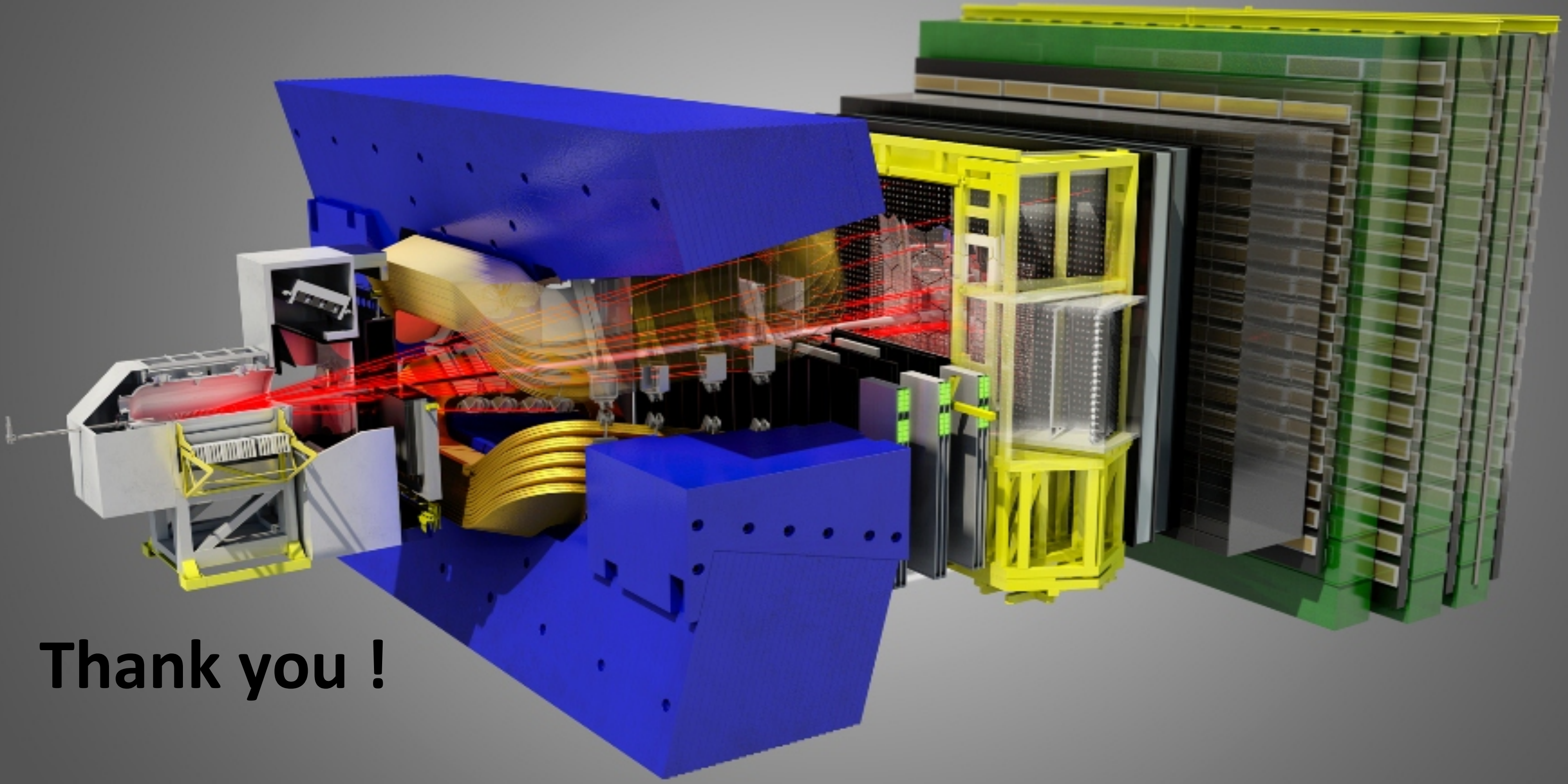
Muon system readout ASIC

Conclusions and outlook

Conclusions and outlook

- LHCb is providing a wealth of excellent physics results
- Not only flavour physics: LHCb is definitely a general purpose experiment in the forward region
  - ★ Electroweak physics, heavy ions, fixed target programme
- Some very intriguing results
  - ★ Are they statistical fluctuations ? Updates expected for the winter conference !
- Preparing a fully upgraded detector for run 3
- Looking into the far future: Expression of Interest for future upgrades
  - ★ Recently INFN GR5 call awarded to Florence (+ others) to develop 3D diamond diamond sensors with high timing resolution





Thank you !