Heavy flavour physics with LHCb

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On behalf of the LHCb collaboration

ICPPA – Москва 02/10/2017

Outline

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

2017 LHCb run

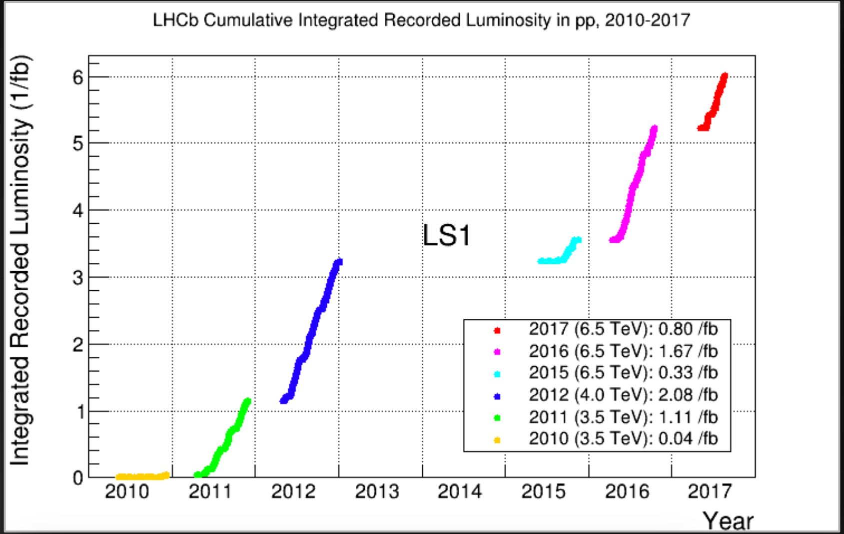
LHCb operations and performance

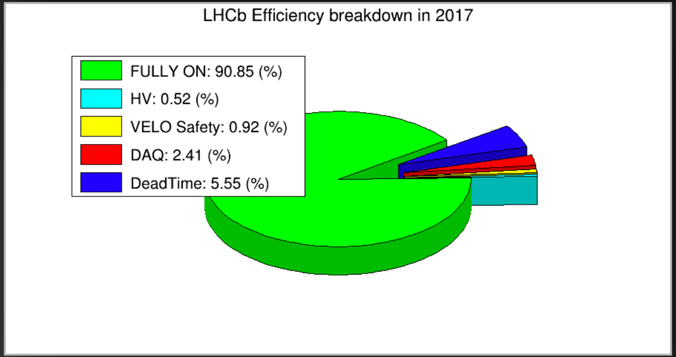
Detector operations

- During winter stop only minimal interventions
- Run restarted smoothly

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

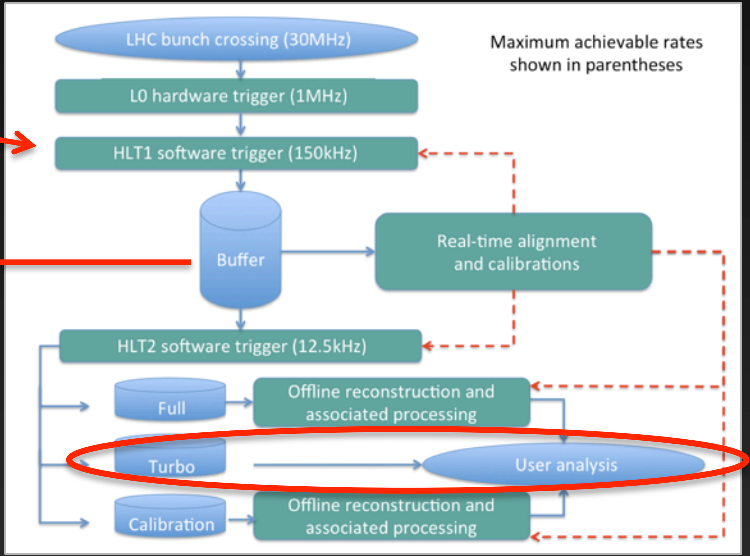
- LHCb running very smoothly, DAQ efficiency ~91%
  - ★ Close to the achievable maximum (~7% irreducible deadtime)

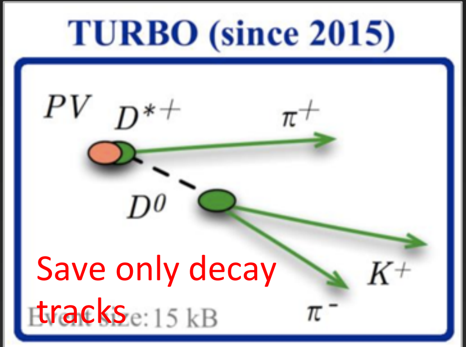


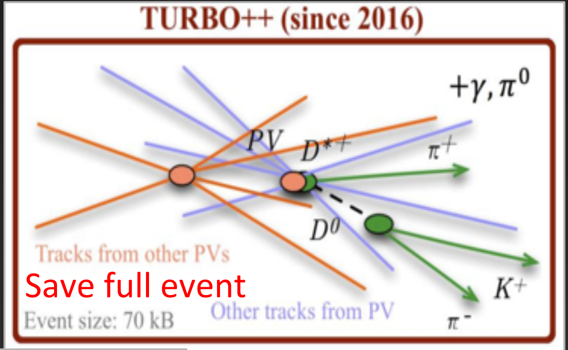


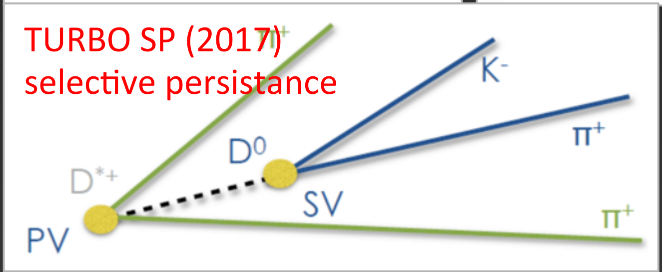
Split HLT and TURBO stream

- 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

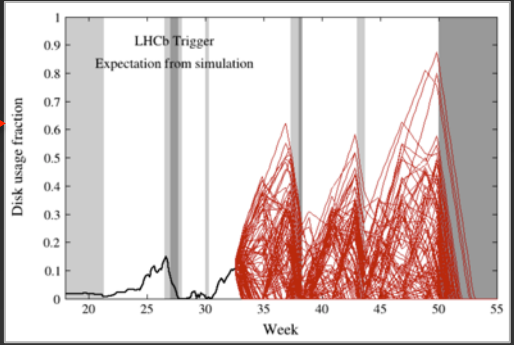








- To avoid filling the buffer two HLT1 configurations: tight, loose
- Simulations for buffer filling predictions

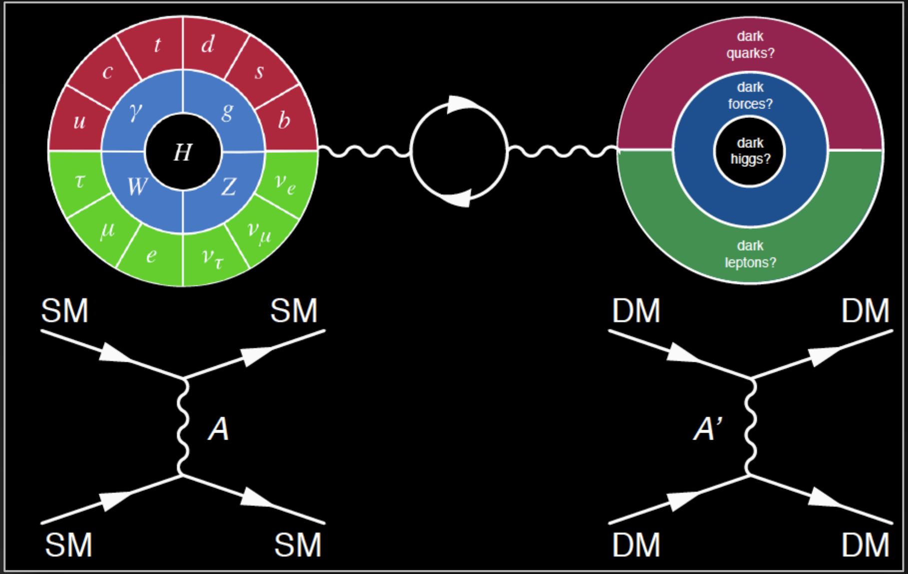


A trigger for dark matter

Search for dark photons from TURBO stream data

[LHCb-PAPER-2017-038]

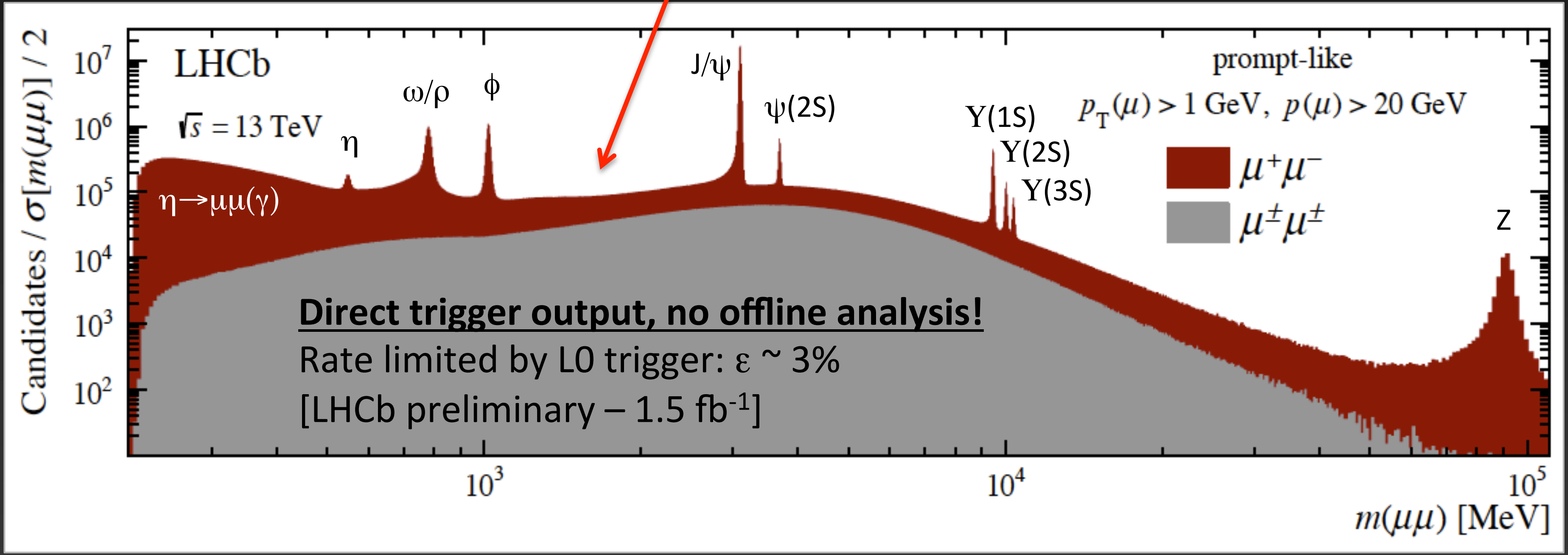
- As a possible explanation for dark matter, a "dark sector" is postulated, with fields not interacting directly with SM fields.
- Dark fields interact with SM fileds through the lagrangian kinetic terms with a mixing strength ε.
- Dark vector fields A' are called "dark photons" and they weakly couple 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]

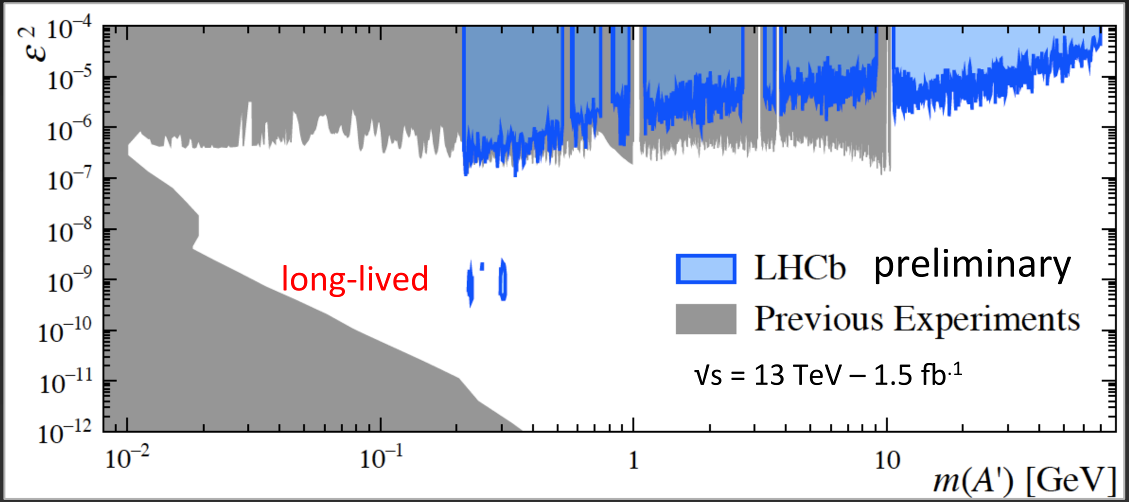
- A promising channel to detect dark photons is $A' \to \mu^+\mu^-$
- The signal yield can be directly inferred from $\gamma^* \to \mu^+\mu^-$: fully data driven analysis
- At LHCb: search for $A' \to \mu^+\mu^-$ in run 2 data (1.5 fb^{-1})
- Dedicated trigger in the TURBO stream



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

[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)

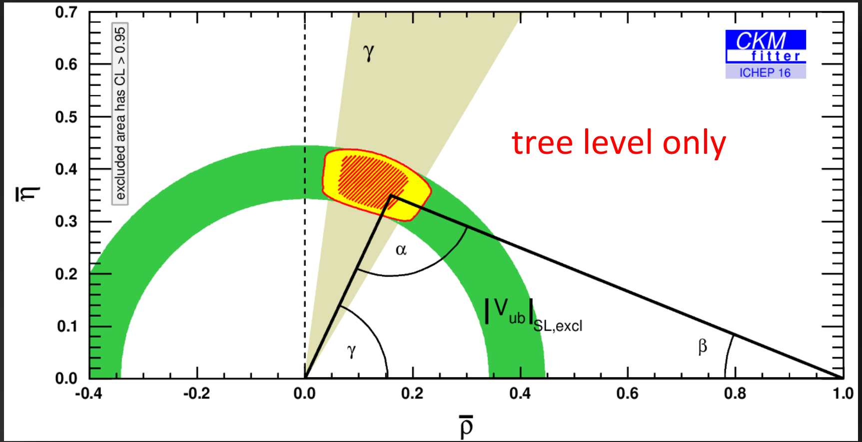
Quest for precision

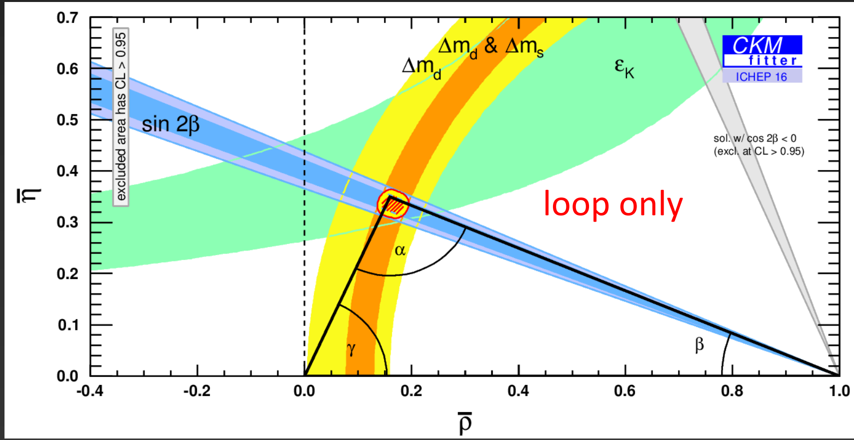
Measurements of CKM matrix prameters

- *A new measurement of CKM angle γ*
- *A new measurement of $\sin 2\beta$*

Improve SM parameters

- To enable a discovery of New Physics, we need to know the SM parameters with high precision.: e.g. CKM parameters!
- If there is no NP in flavour physics, the unitarity triangle should be the same in all measurements
- Comparing tree level decays and loop level decays is a way to look for inconsistency

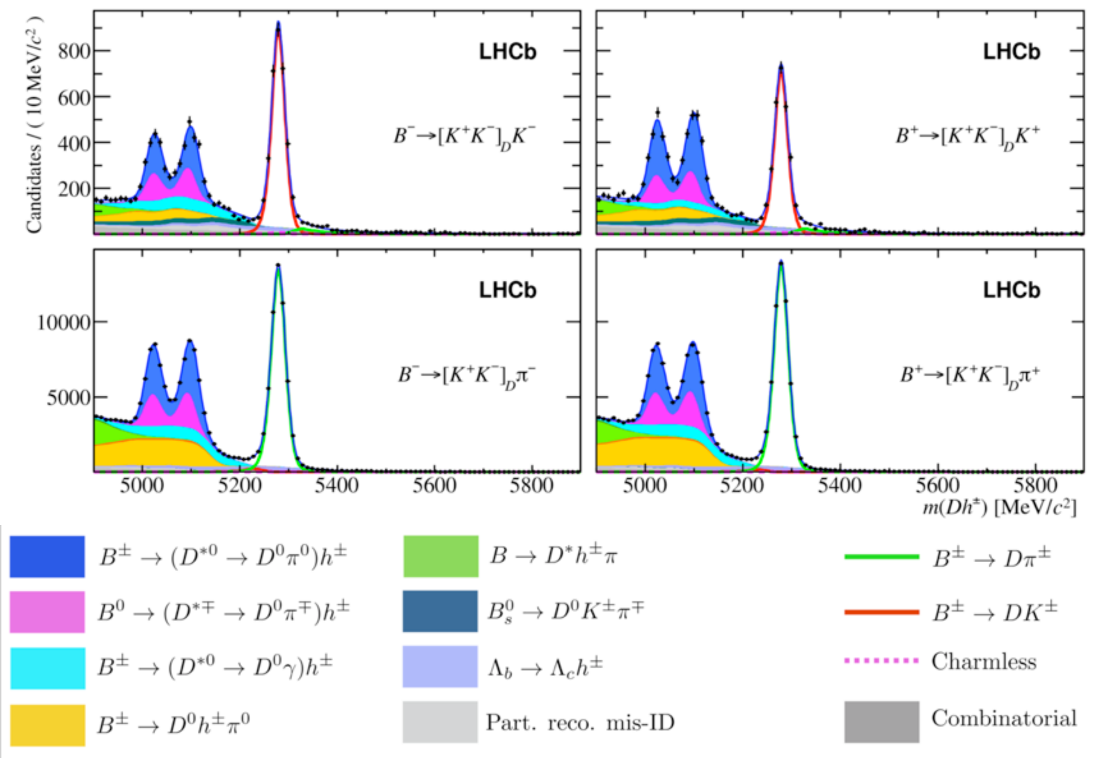




CKM angle γ: a new measurement with run 2 data

[arXiv:1708.06370]

- The CKM angle γ is best measured in interference between b⟶c and b⟶u tree level decays
- We 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)



CKM angle γ: LHCb combination

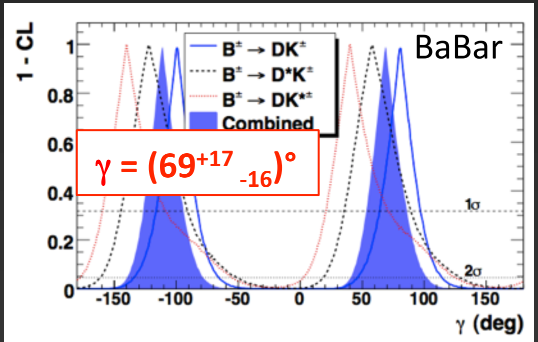
[arXiv:1708.06370]

- 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] $1\ \mathrm{fb}^{-1} \to 3\ \mathrm{fb}^{-1}$
  - $B^{\pm} \to D^{0} K^{\pm}$ GLW [LHCb-PAPER-2017-021] $3\ \mathrm{fb}^{-1} \to 5\ \mathrm{fb}^{-1}$

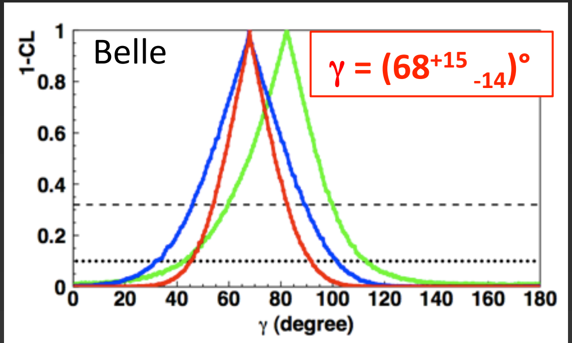
- Significantly more precise than previous results from the B-factories and undergoing continuous improvements:
- Is γ the least well known CKM angle ?

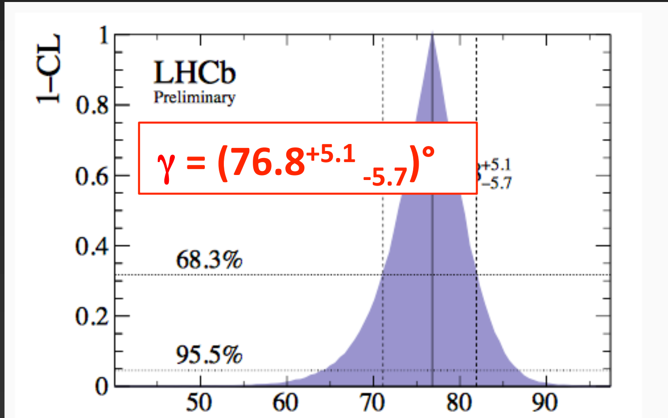
cfr $\alpha = (88.8 \pm 2.3)°$ [CKMfitter ICHEP 2016]

[Phys. Rev. D87 (2013) 052015]



[arXiv:1301.2033]





[LHCb-CONF-2017-004]

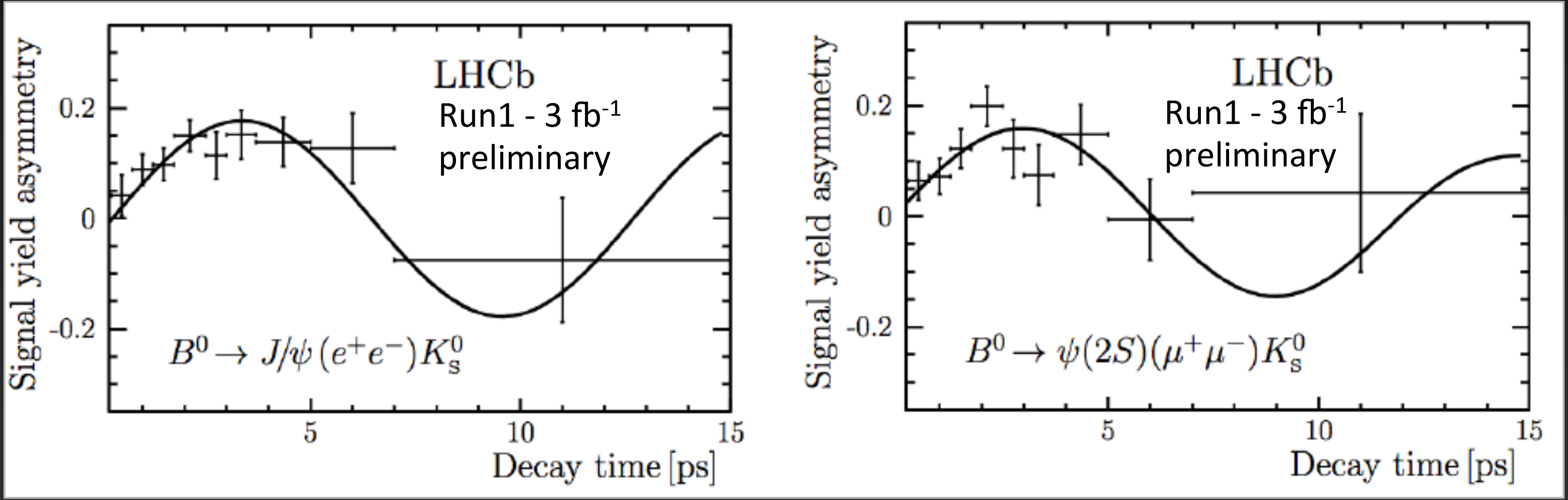
New measurement of sin2β

[LHCb-PAPER-2017-029]

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

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

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



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

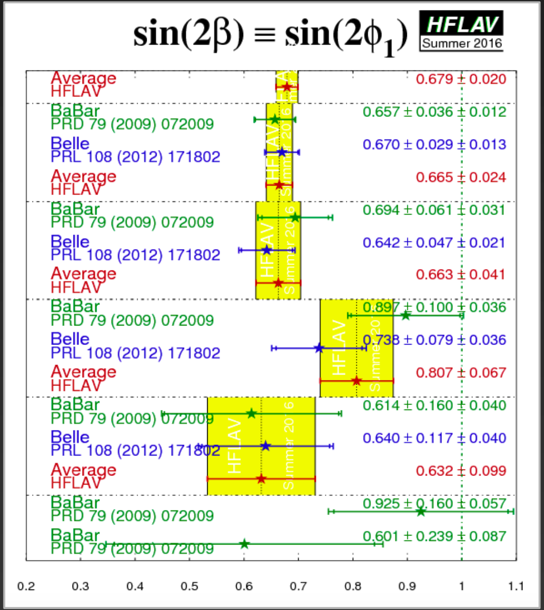
$$C = -0.05^{+0.10}_{-0.10}\ (\text{stat}) + 0.01\ (\text{syst})$$
$$S = 0.84^{+0.10}_{-0.10}\ (\text{stat}) + 0.01\ (\text{syst})$$

New measurement of sin2β

- Average of LHCb measurements from Run 1

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

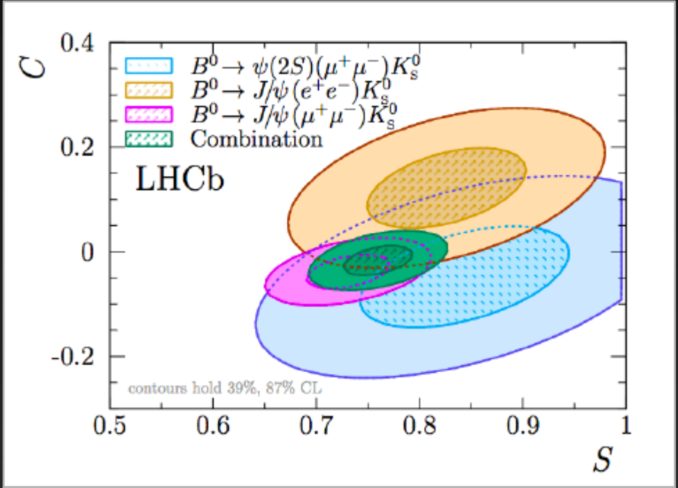
- Slight tension with the average from B factories on sin2β, at the2σ level

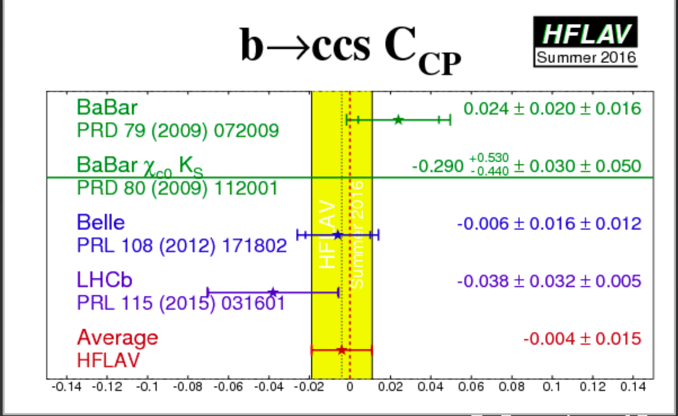


Further investigations with Run2 data are needed

sin2β from B factories:
0.679±0.020

[LHCb-PAPER-2017-029]





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

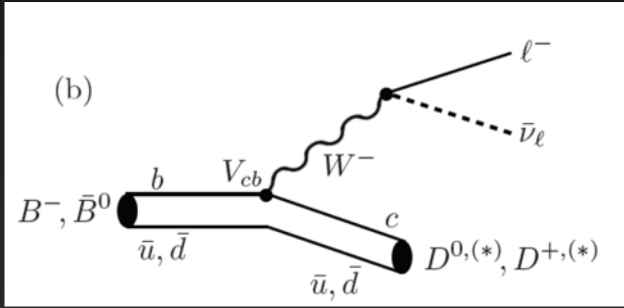
- Lepton flavour universality can be checked in several B meson decays involving leptons in the final state

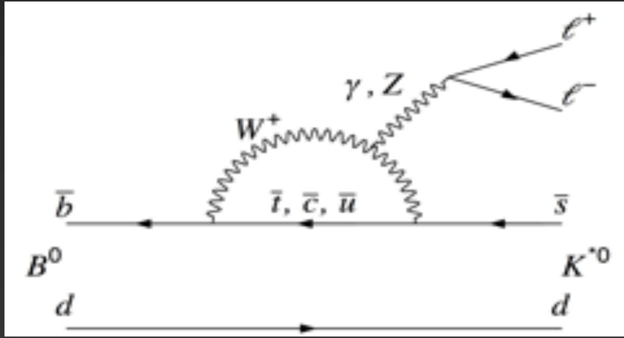
- Two main classes of decays have been studied:
  - ★ Semileptonic $B^0 \to D^{(*)-} l^+ \nu$ - tree level decay
  - ★ $b \to s l^+ l^-$ decays e.g. $B^0 \to K^{(*)0} l^+ l^-$ - FCNC decays

- Observables:

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

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





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

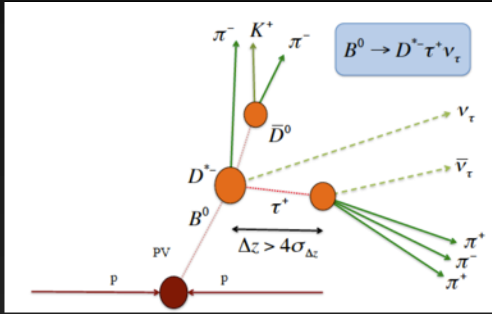
[arXiv:1708.08856]

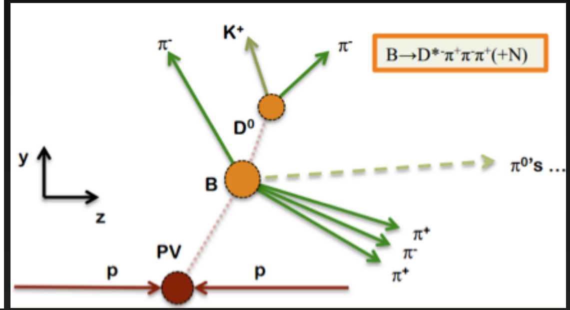
- Latest measurement from LHCb look at final states $\tau \to \pi^+ \pi^- \pi^+ \nu$
- Normalisation done through a very similar known final state

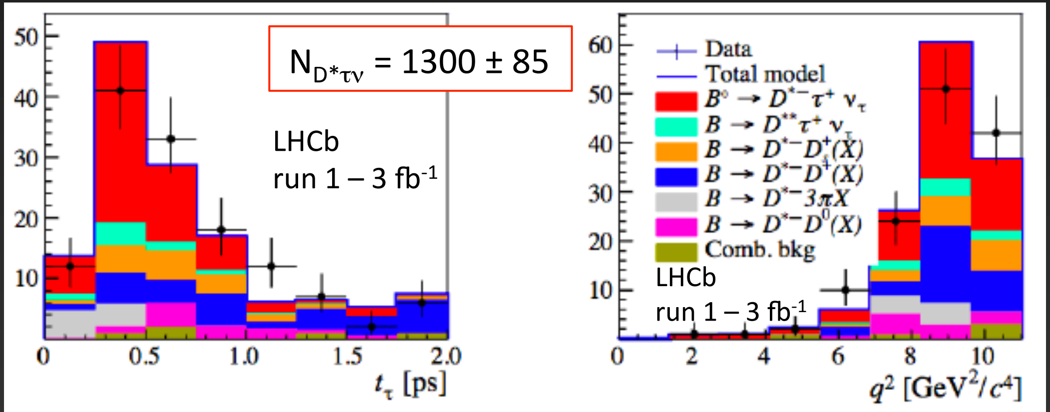
$$R(D^*) = K_{had}(D^*) \times \frac{BR(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}{BR(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

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

- Kinematical constraints used to close the decay
- Three-dimensional fit in decay time, q^2 and BDT output
- $BR(B^0 \to D^*\tau\nu) = (1.39 \pm 0.09 \pm 0.12 \pm 0.06)\%$

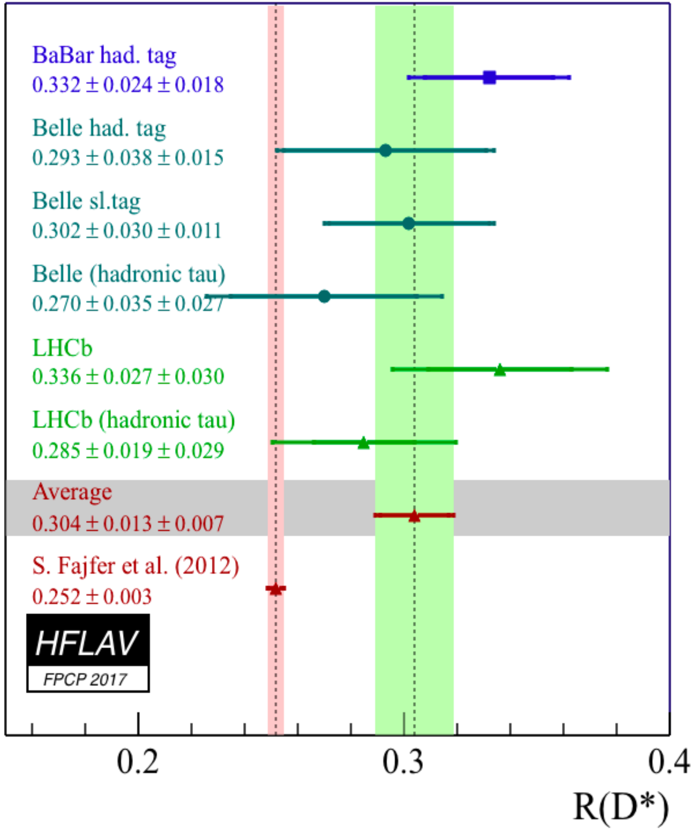


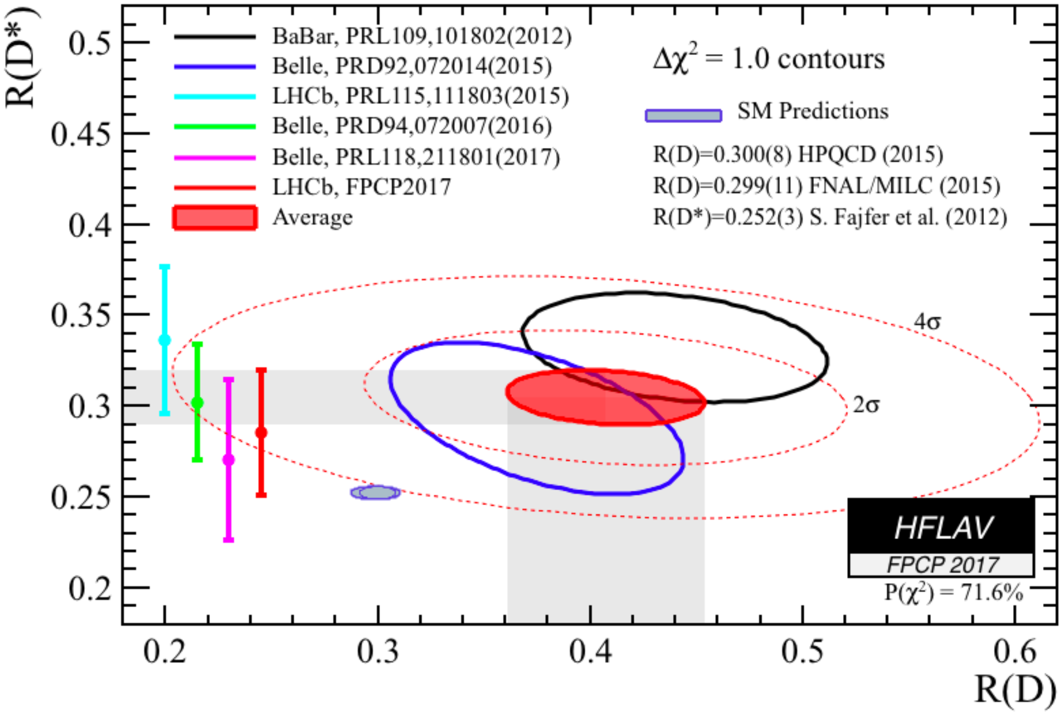




Tests of lepton universality: semitauonic decays - R(D*)

[arXiv:1708.08856]





Results are internally consistent and 4σ from SM prediction

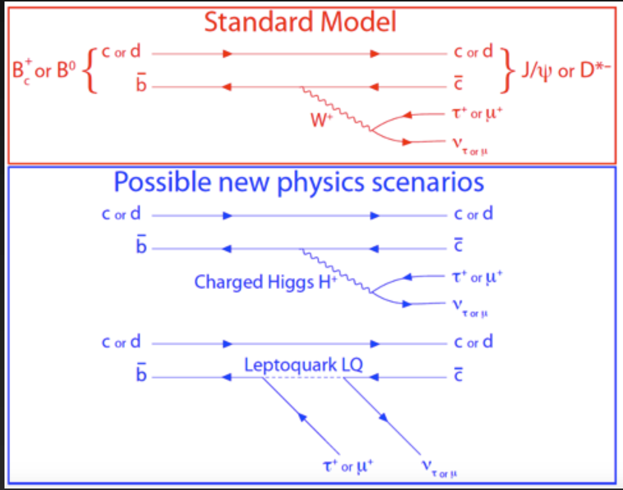
Tests of lepton universality – a new tool: B_c [new]

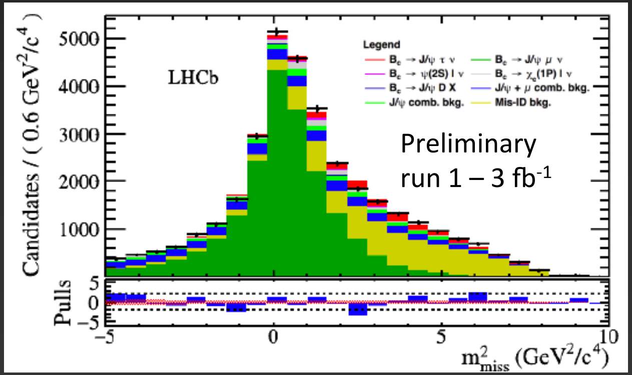
[LHCb-PAPER-2017-035]

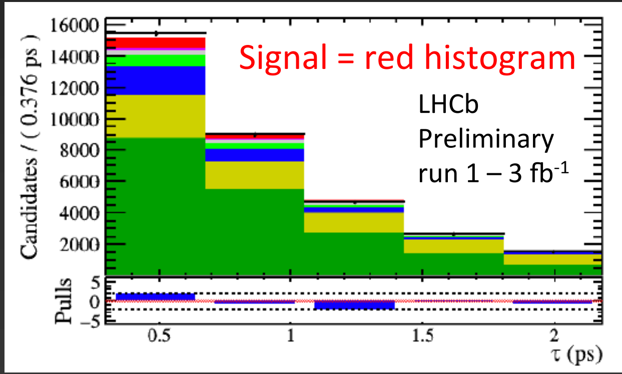
- Test of lepton universality using semitauonic B_c decays.
- Generalization of R(D) to the B_c sector:

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

- 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

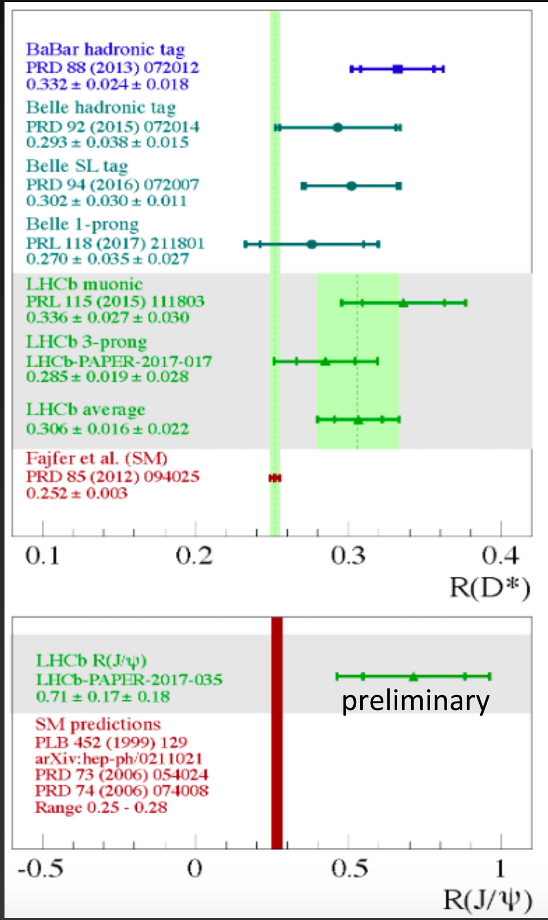






Tests of lepton universality – a new tool: B_c

[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
- Run 1 + Run 2 data will allow a finer binning in missing mass
- Form-factor related systematics will be reduced by LQCD

- Only LHCb can perform this measurement!

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

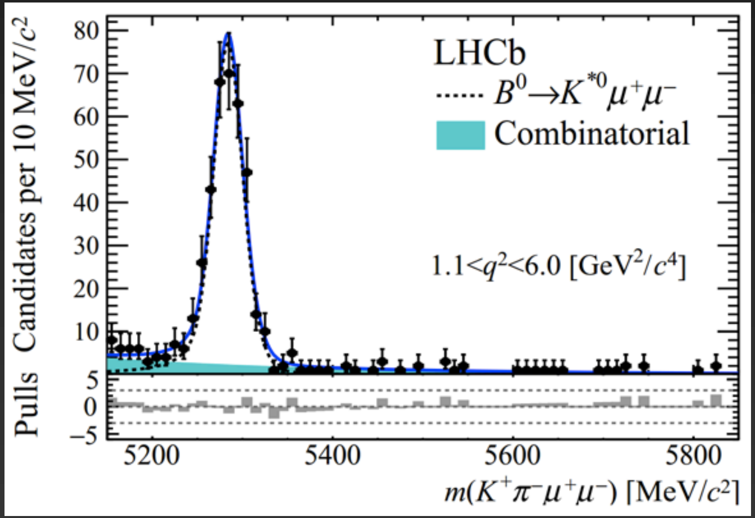
[JHEP 08 (2017) 055]

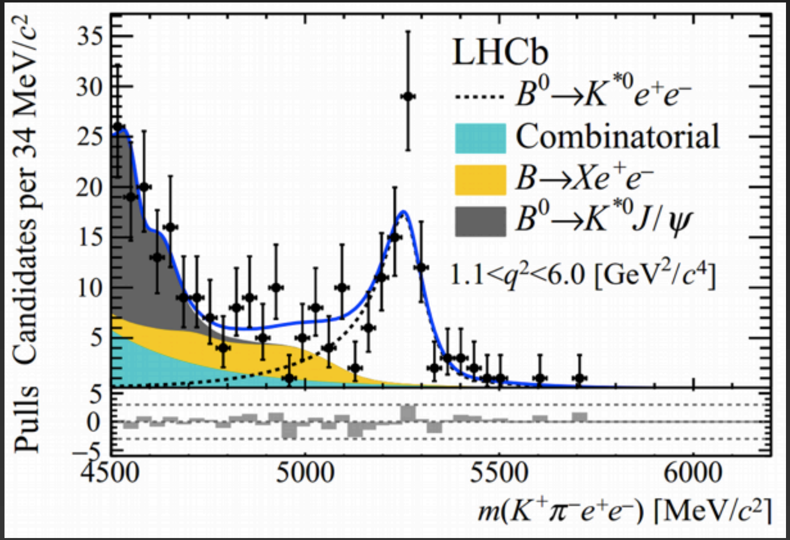
Test the LFU in electroweak penguin decays (e.g. the class of FCNC decays $b \to s l^+ l^-$)

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

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

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





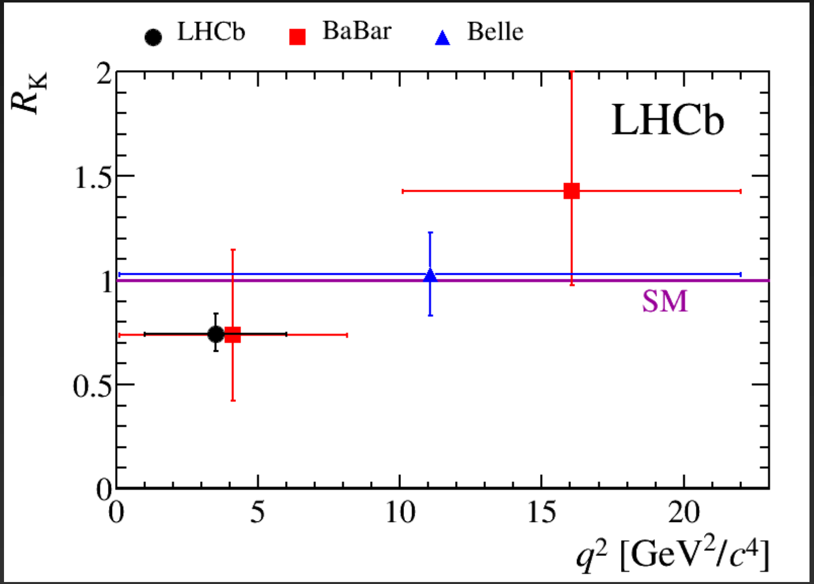
Tests of lepton universality: R(K) and R(K^*)

[JHEP 08 (2017) 055]

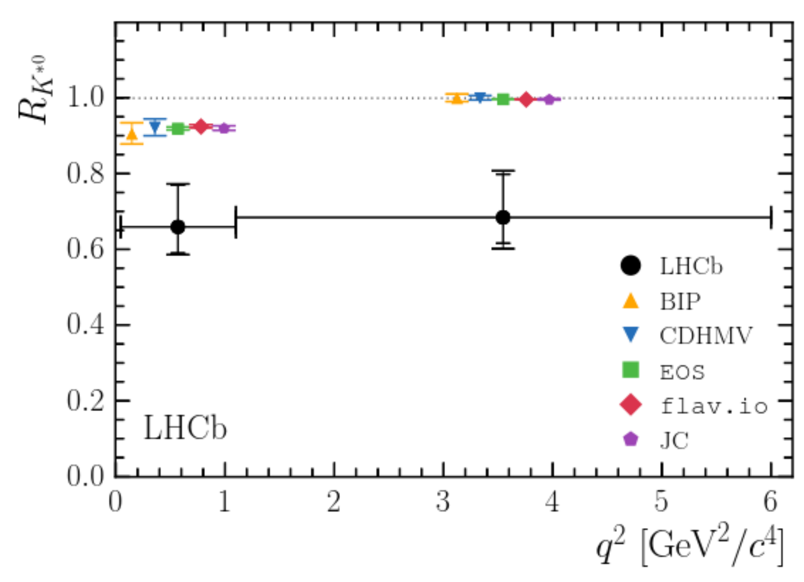
Test the LFU in electroweak penguin decays (e.g. the class of FCNC decays $b \to s l^+ l^-$)

- Results for R(K) and R(K*):

[Phys. Rev. Lett. 113 (2014) 151601]



[JHEP 08 (2017) 055]



~2-2.5 σ away from SM with potential to become 4-5 σ in few years

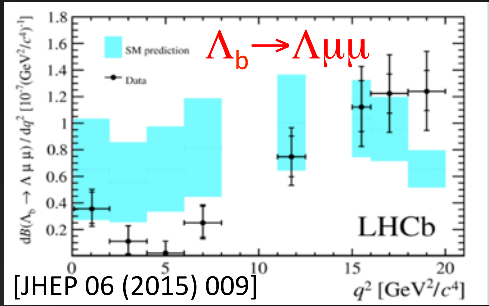
A picture with multiple tensions

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

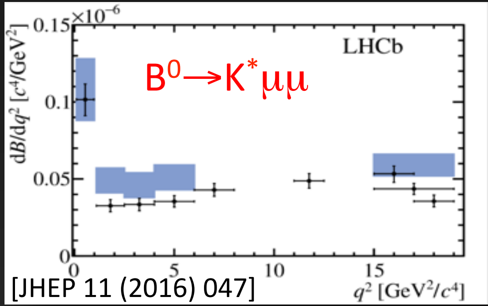
A complex picture with multiple tensions

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

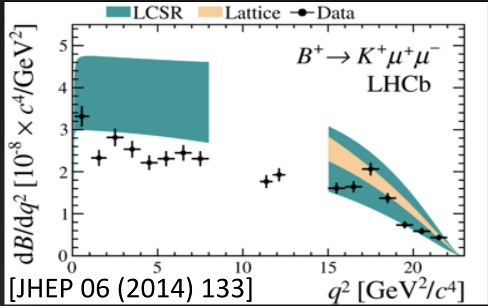
- Branching fractions: intriguingly consistent tendency for differential x-sections to be smaller than prediction at low q^2



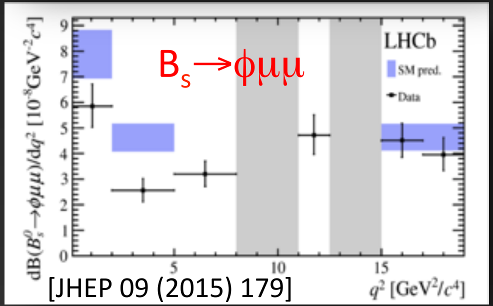
[JHEP 06 (2015) 009]



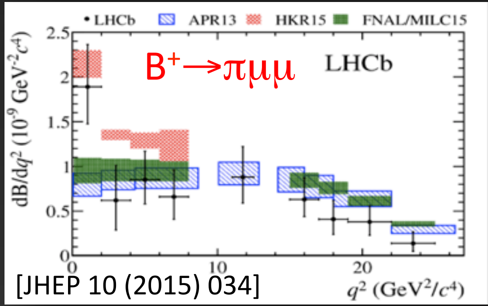
[JHEP 11 (2016) 047]



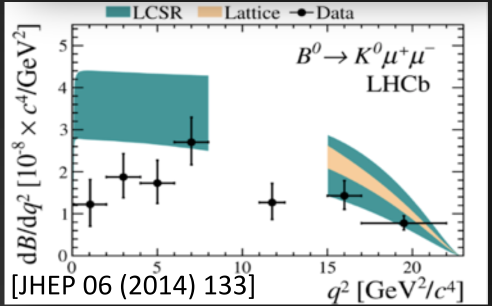
[JHEP 06 (2014) 133]



[JHEP 09 (2015) 179]



[JHEP 10 (2015) 034]



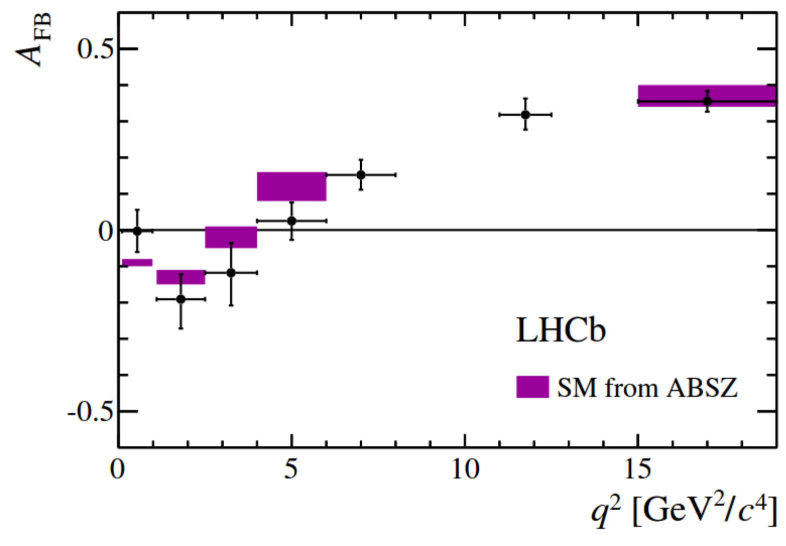
[JHEP 06 (2014) 133]

A complex picture with multiple tensions

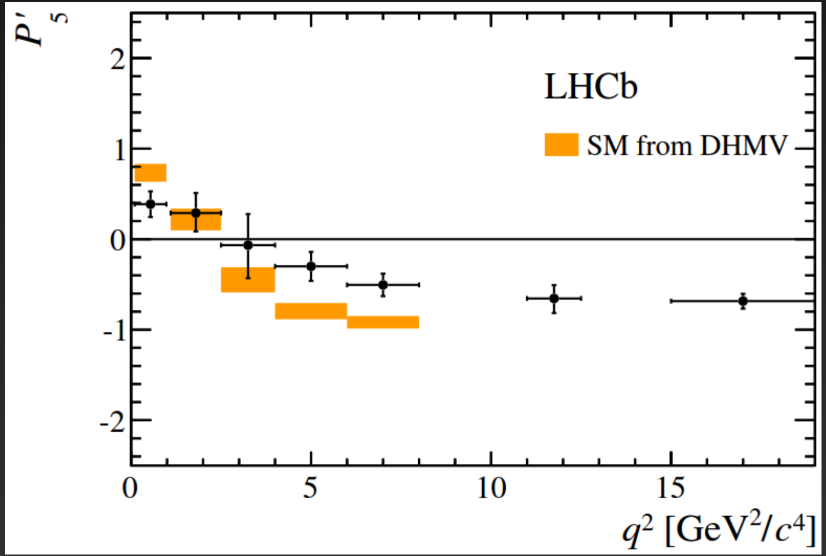
In electroweak penguin decays (e.g. the class of FCNC decays $b \to s l^+ l^-$) there are many more tensions:

- 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

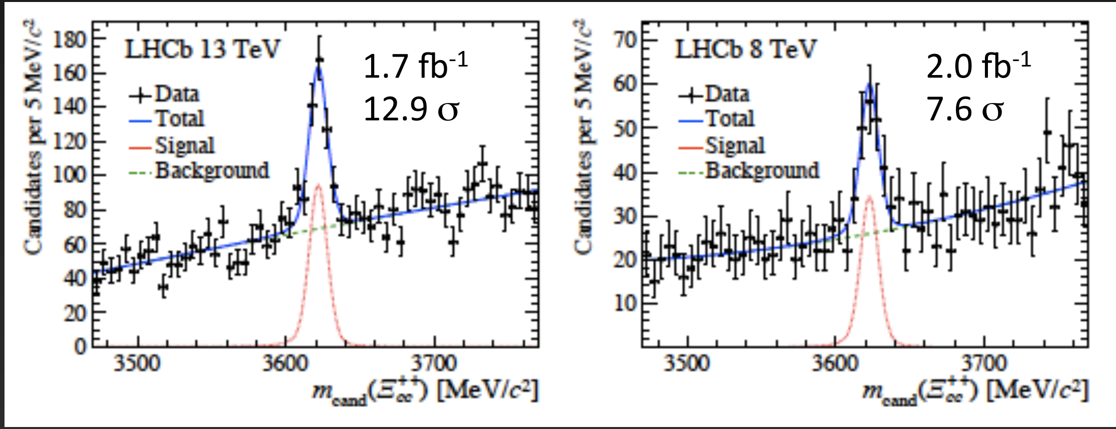
A benchmark for QCD: spectroscopy

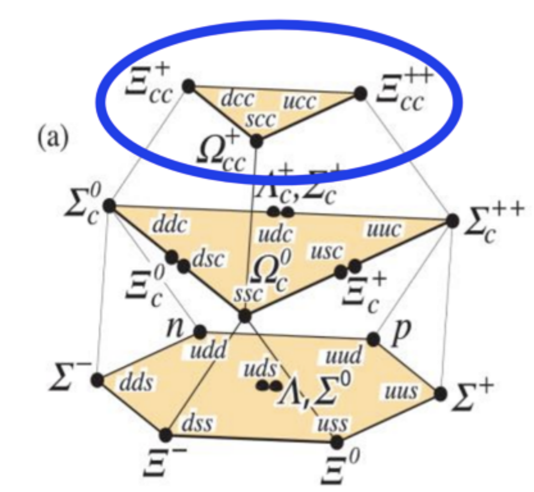
New results from heavy hadron spectroscopy

Observation of Ξ_{cc}^{++}

[Physical Review Letters 119 (2017) 112001]

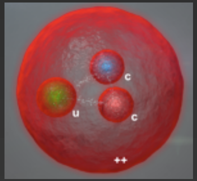
- Doubly charmed baryons predicted by quark model
- Observation of Ξ_{cc}^{+} claimed by SELEX [Phys. Lett. B 628 (2005) 18-24]
- No evidence observed by BaBar, FOCUS, Belle and LHCb
- Search in LHCb for $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$

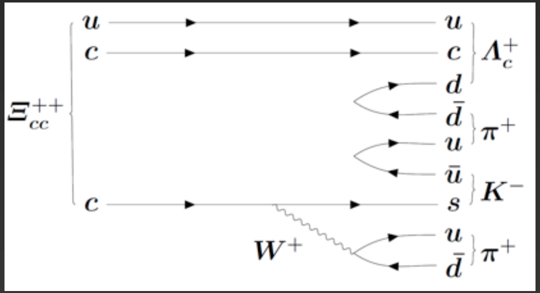




- Combined yield: 426 ± 39
- The mass is measured with the 2016 sample
- $M(\Xi_{cc}^{++}) = 3621 \pm 0.72$ (stat) ± 0.31 (syst) MeV/c2

Lattice QCD calculations $m(\Xi_{cc}^{++}) = (3606 \pm 11 \pm 8)$ MeV/c^2
[arXiv: 1704.02647]





LHC: a machine for precision physics

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

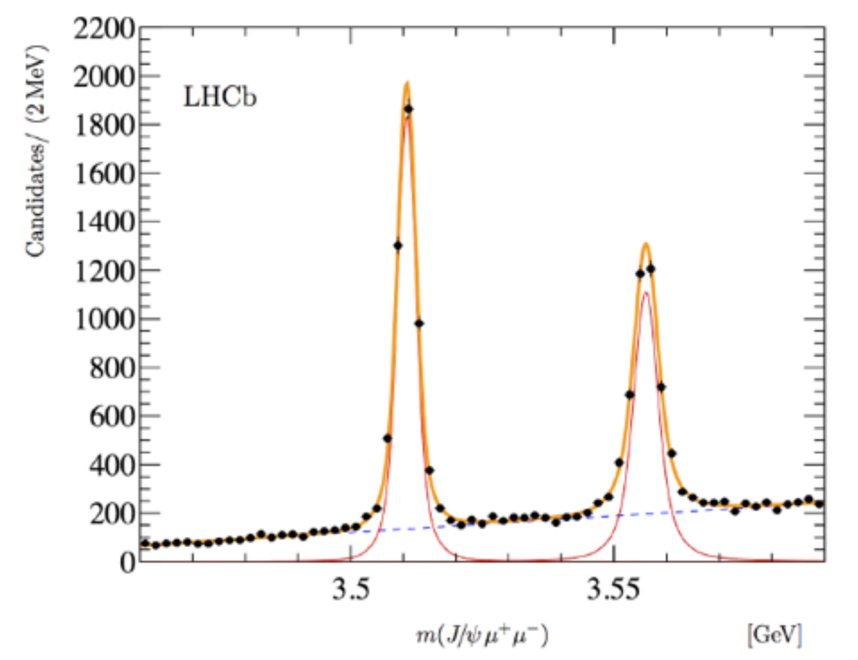
Precise measurement of $\chi_{c1,c2}$ resonance parameters [new]

[arXiv:1709.04247]

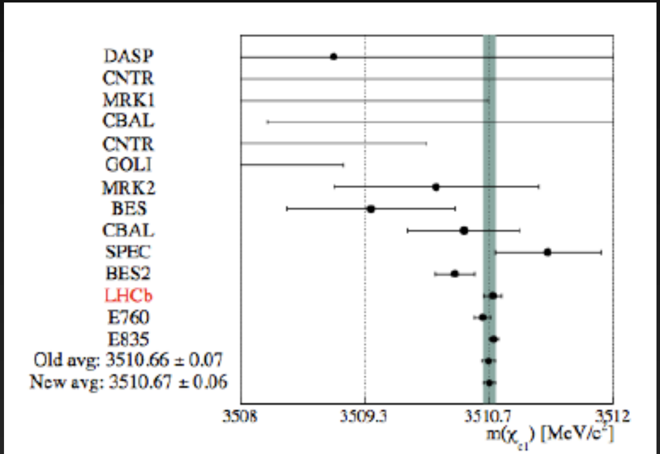
- LHCb observed for the first time the Dalitz decays $\chi_{c1,c2} \rightarrow J/\psi\mu^+\mu^-$
- Used full run 1 and run 2 (TURBO) datasets
- Mass resolution enough to measure the natural width of χ_{c2}

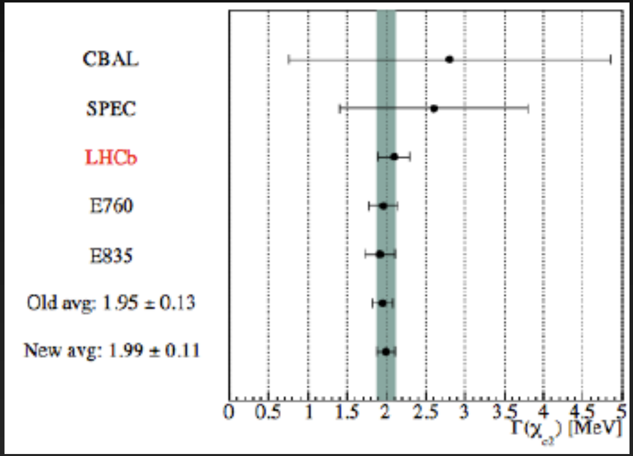
$$m(\chi_{c1}) = 3510.71 \pm 0.04\,(\text{stat}) \pm 0.09\,(\text{syst})\ \text{MeV}/c^2,$$
$$m(\chi_{c2}) = 3556.10 \pm 0.06\,(\text{stat}) \pm 0.11\,(\text{syst})\ \text{MeV}/c^2,$$
$$m(\chi_{c2}) - m(\chi_{c1}) = 45.39 \pm 0.07\,(\text{stat}) \pm 0.03\,(\text{syst})\ \text{MeV}/c^2$$

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



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



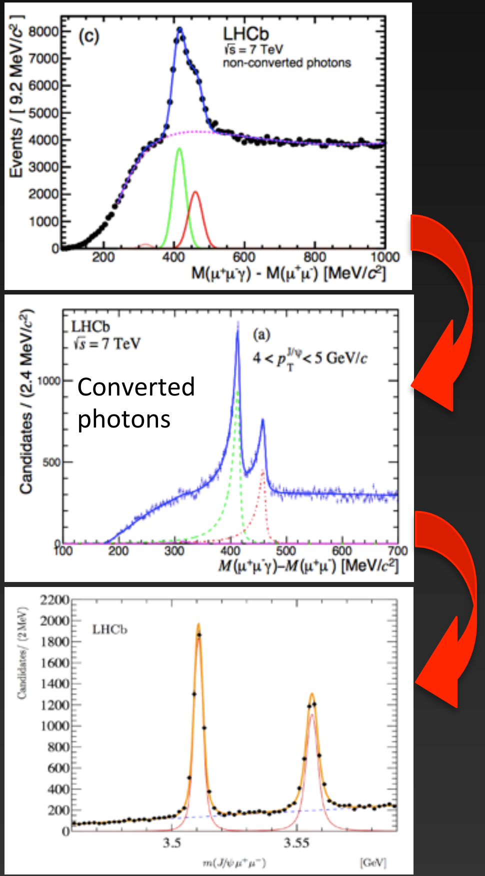


[arXiv:1709.04247]

LHCb-PAPER-2011-030

LHCb-PAPER-2013-028

[arXiv:1709.04247]



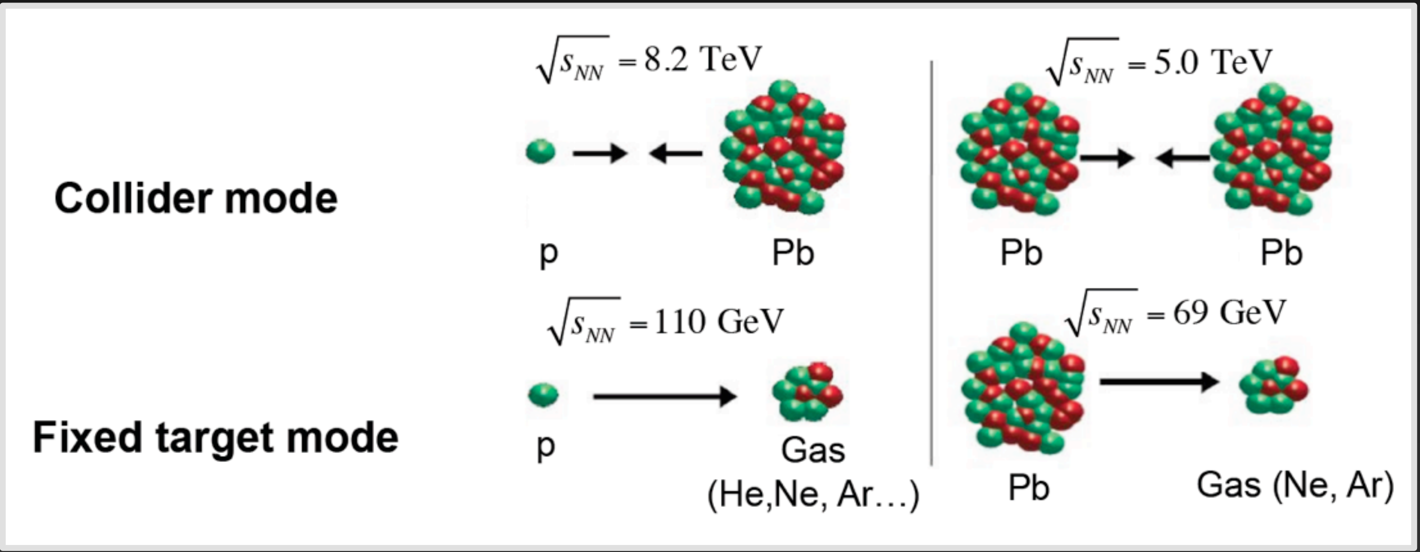
- LHCb measurement at the same level of precision of dedicated experiment E760/E835, based on p-pbar resonance scanning
- Major breakthrough in χ_c spectroscopy!
  - ★ Next step is measuring BF x production rate and ratio of BFs
- Lots of opportunities
  - ★ extend studies to X(3872), χ_c^0, χ_b states

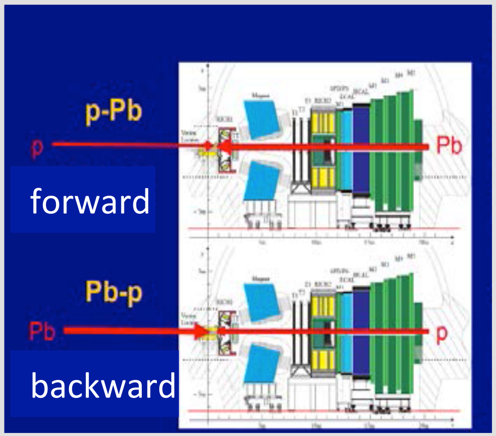
Not only flavour

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

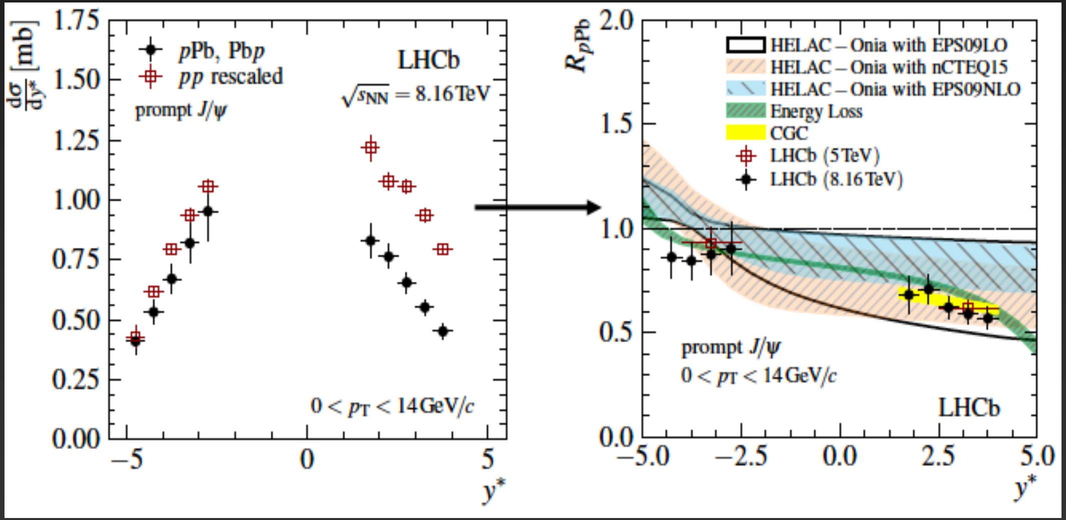
J/ψ producton in pPb collisions at $\sqrt{s}$ = 8 TeV

[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:

$$R_{p\mathrm{Pb}}(p_\mathrm{T}, y^*) \equiv \frac{1}{A}\frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_\mathrm{T}, y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{pp}(p_\mathrm{T}, y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*} \quad \text{and} \quad R_\mathrm{FB}(p_\mathrm{T}, y^*) \equiv \frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_\mathrm{T}, +y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_\mathrm{T}, -y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}$$

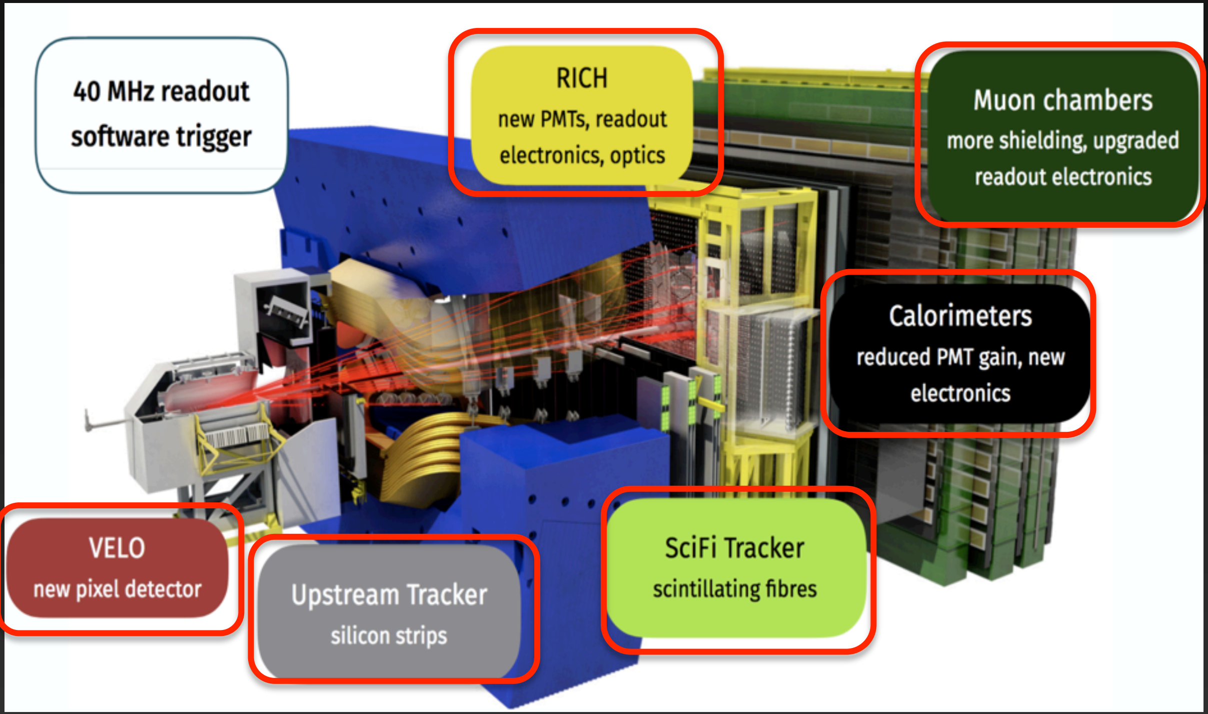
- Analysis made using candidates selected via the TURBO stream
- First heavy ion physics LHC paper with 2016 pPb run data!
- Suppression clearly visible in the forward region
- Good agreement with theoretical models especially color glass condensate and energy loss



The LHCb upgrade

The LHCb upgrade in a nutshell

- Run at higher luminosity:
  - ★ $2x10^{33}$ (x5 wrt to current LHCb)
- Fully software trigger – 30 MHz input rate
- New tracking detectors
- Upgraded PID detectors
- New front-end electronics
  - ★ Must be read out at 40 MHz

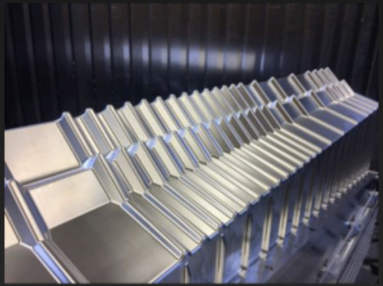


Status of upgrade

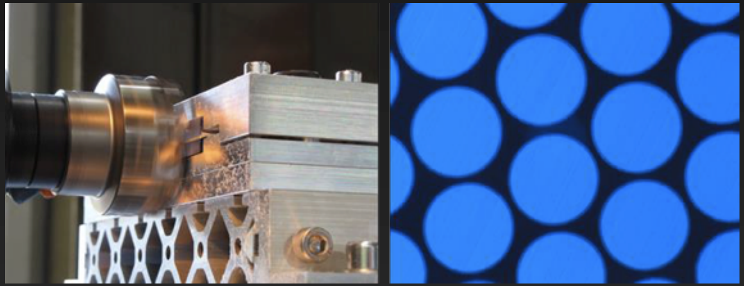
- Construction well advanced, aim at installation in 2019

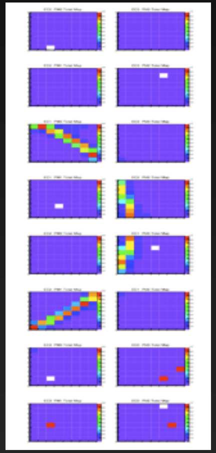
Prototypes of DAQ board (PCIe40)

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

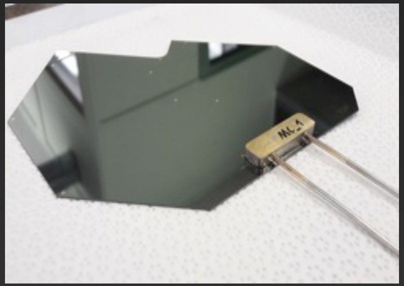


Machining and light scan of the scintillating fiber mats for the fibre tracker

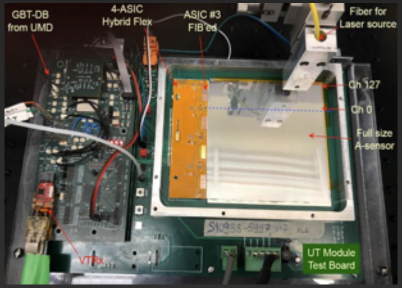




Cherenkov ring from a full RICH MaPMT module

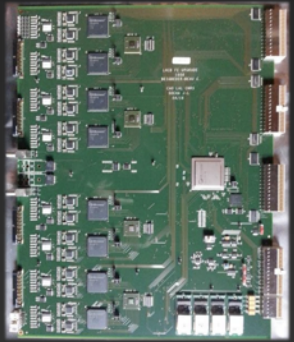


Si μchannel cooling plate for VELO with soldered connector



Upstream Tracker silicon sensor module under test

First scintillating fibre modules arriving at CERN



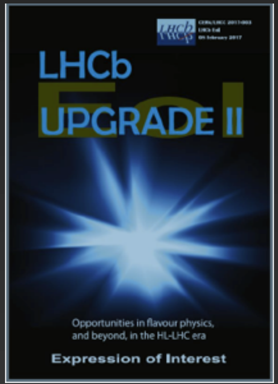
Calorimeter front-end board

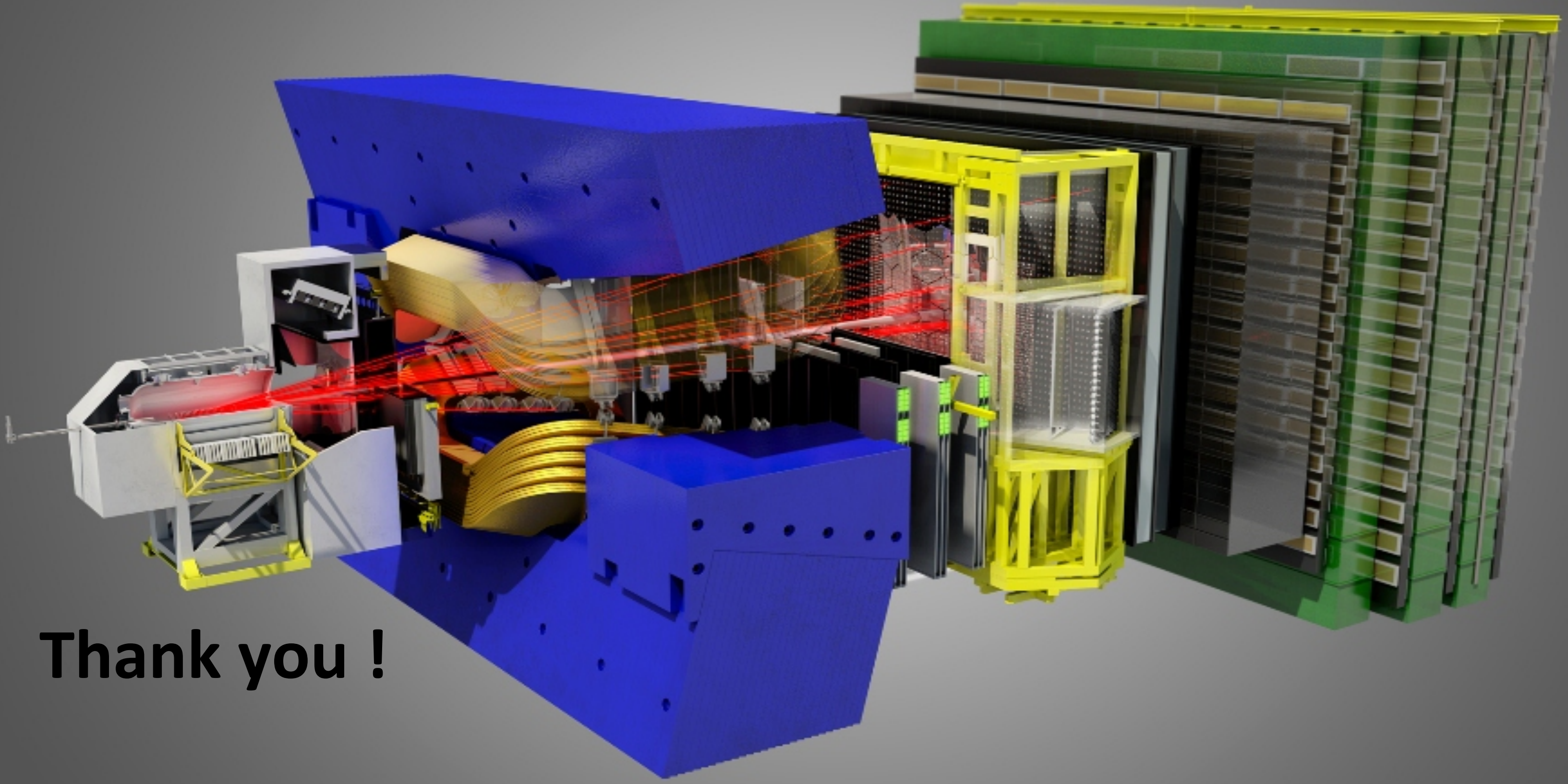
Muon system readout ASIC

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: Epression of Interest for future upgrades

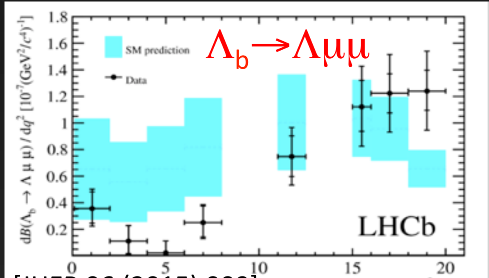




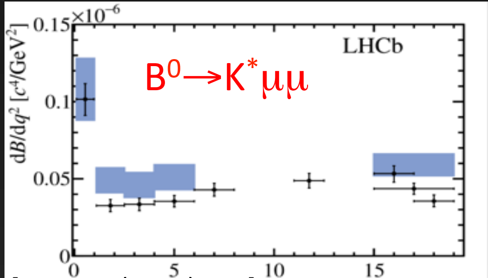
Thank you !

FCNCs - $b \rightarrow s\ell^+\ell^-$: differential branching fractions

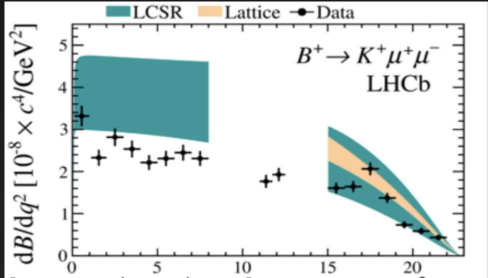
- P_5' is not the only funny thing going on in $b \rightarrow (s,d)l^+l^-$ decays.
- Consistent tendency for differential x-sections to be smaller than prediction at low q^2.
- Intriguing. But can there be larger theory uncertainties than currently estimated? …



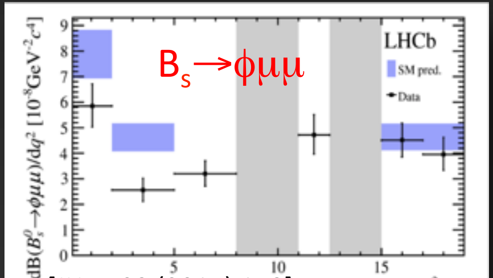
[JHEP 06 (2015) 009]



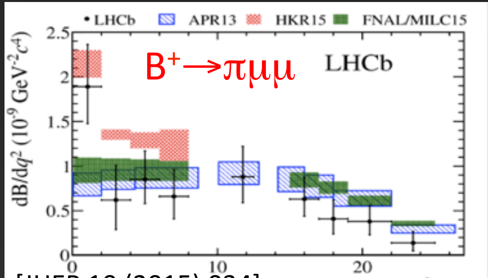
[JHEP 11 (2016) 047]



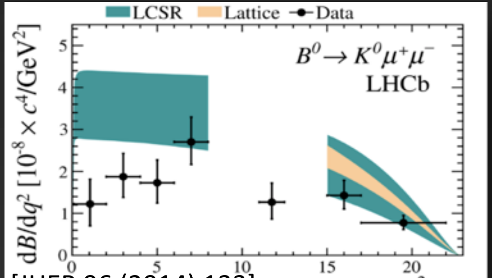
[JHEP 06 (2014) 133]



[JHEP 09 (2015) 179]



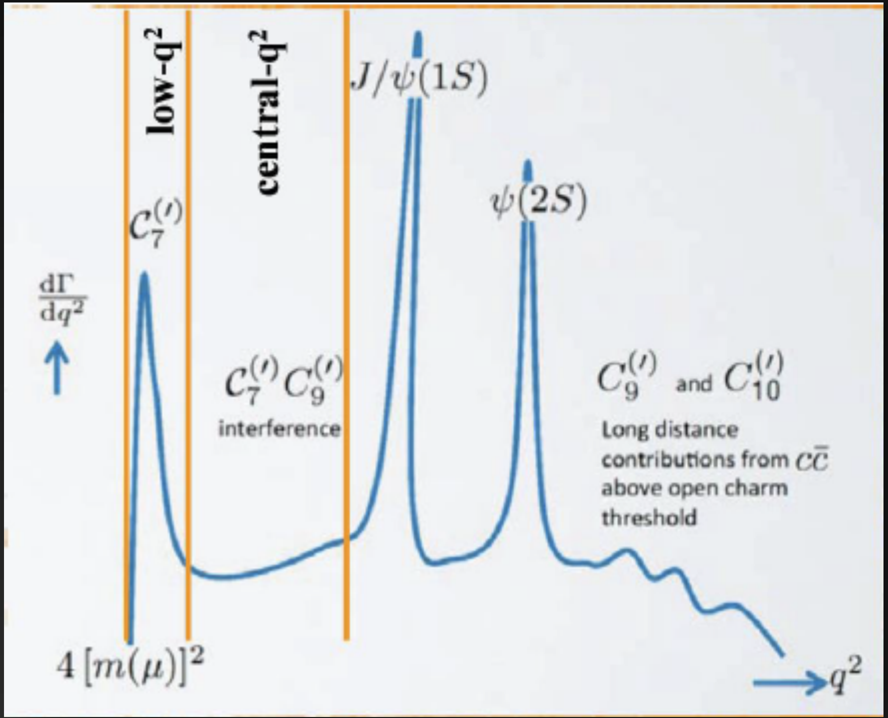
[JHEP 10 (2015) 034]



[JHEP 06 (2014) 133]

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

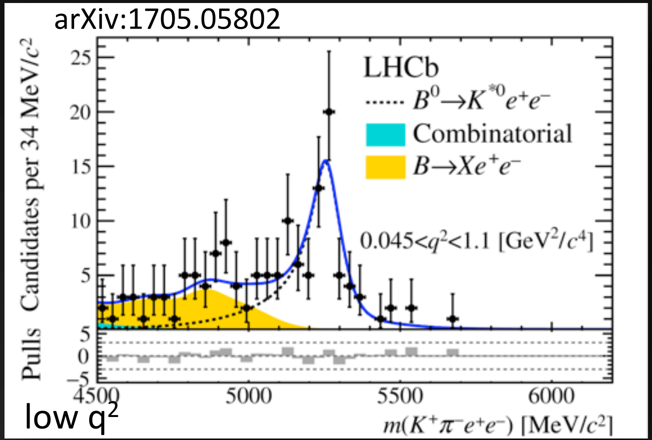
- Measurement performed in two q^2 regions:
  - ★ low: $0.045 < q^2 < 1.1$ GeV^2
  - ★ central: $1.1 < q^2 < 6.0$
- (high q^2 region, above resonances, is certainly of interest, but this presents different experimental challenges, and requires a separate analysis)

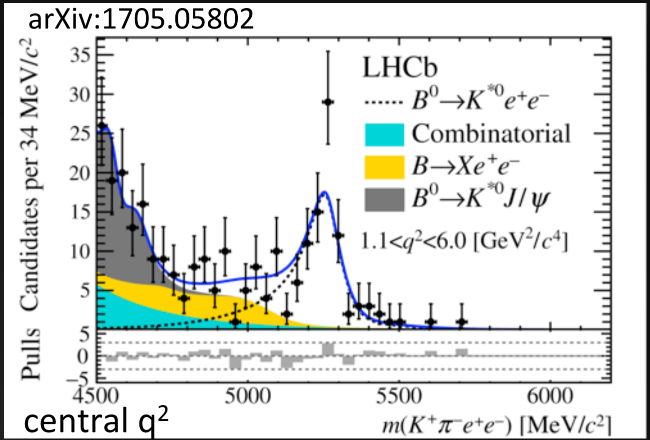


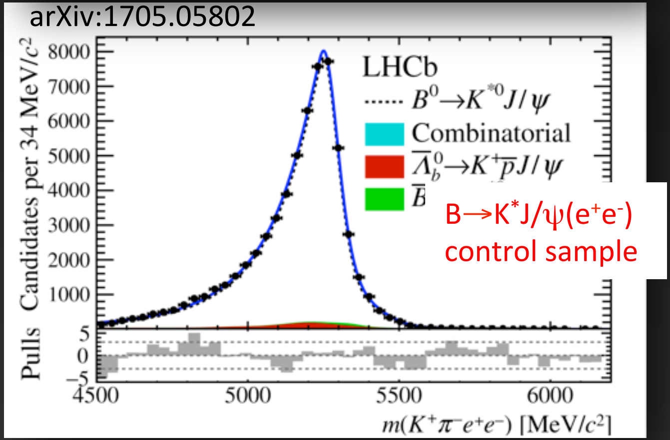
For $K^*e^+e^-$, three exclusive trigger categories are used, depending on whether triggered on electron(s) (L0E), K^* candidate(s) (L0H), or not on signal (TIS)

Tests of lepton universality: R(K*)

Mass spectra for the e^+e^- final state

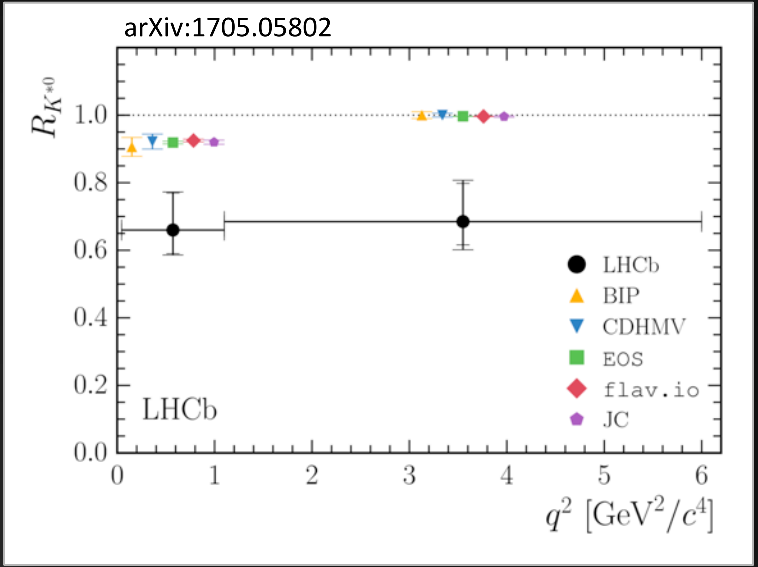






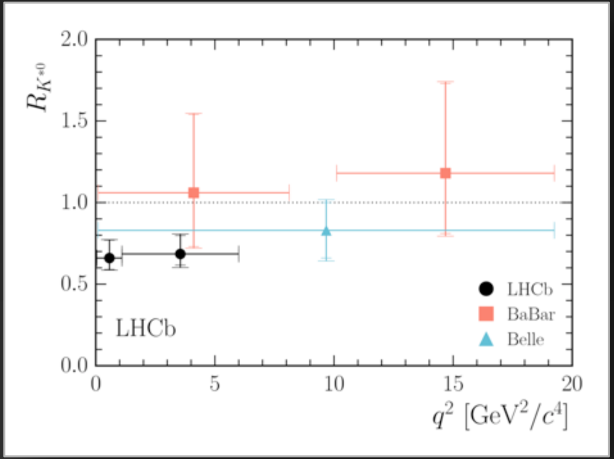
- Around 90 and 110 signal candidates in low-q^2 and central q^2, respectively.
- 58k in control channel
- Muon samples 3-5 times larger

Tests of lepton universality: R(K*)



	low- q^2	central- q^2
$R_{K^{*0}}$	$0.66\ ^{+\ 0.11}_{-\ 0.07} \pm 0.03$	$0.69\ ^{+\ 0.11}_{-\ 0.07} \pm 0.05$
95.4% CL	[0.52, 0.89]	[0.53, 0.94]
99.7% CL	[0.45, 1.04]	[0.46, 1.10]

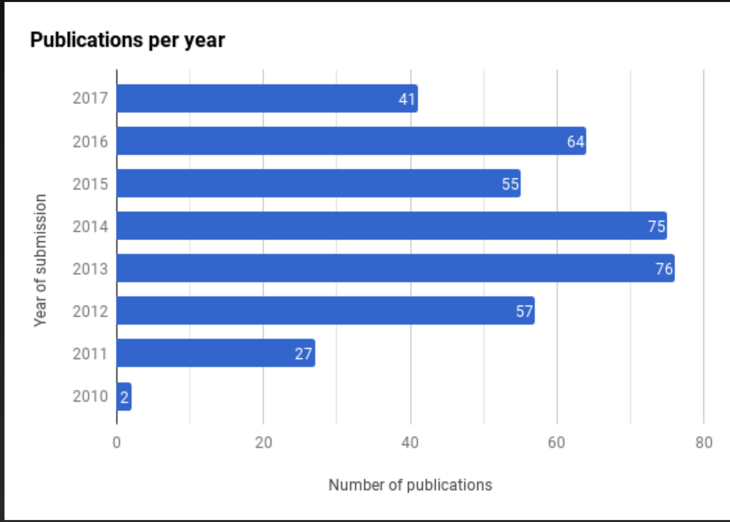
- 2.2-2.4σ and 2.4-2.5σ away from SM at low and central-q^2, respectively
- Tens of paper published immediately after the publication of results with many interpretations…



Selected physics results

Paper production

Physics: paper production



- 397 papers submitted
  - ★ 14 using Run-2 data
  - ★ 41 in 2017
  - ★ 9 other papers being processed within the Editorial Board
    - 3 using Run-2 data
- 35 further analyses under review
  - ★ 8 using Run-2 data