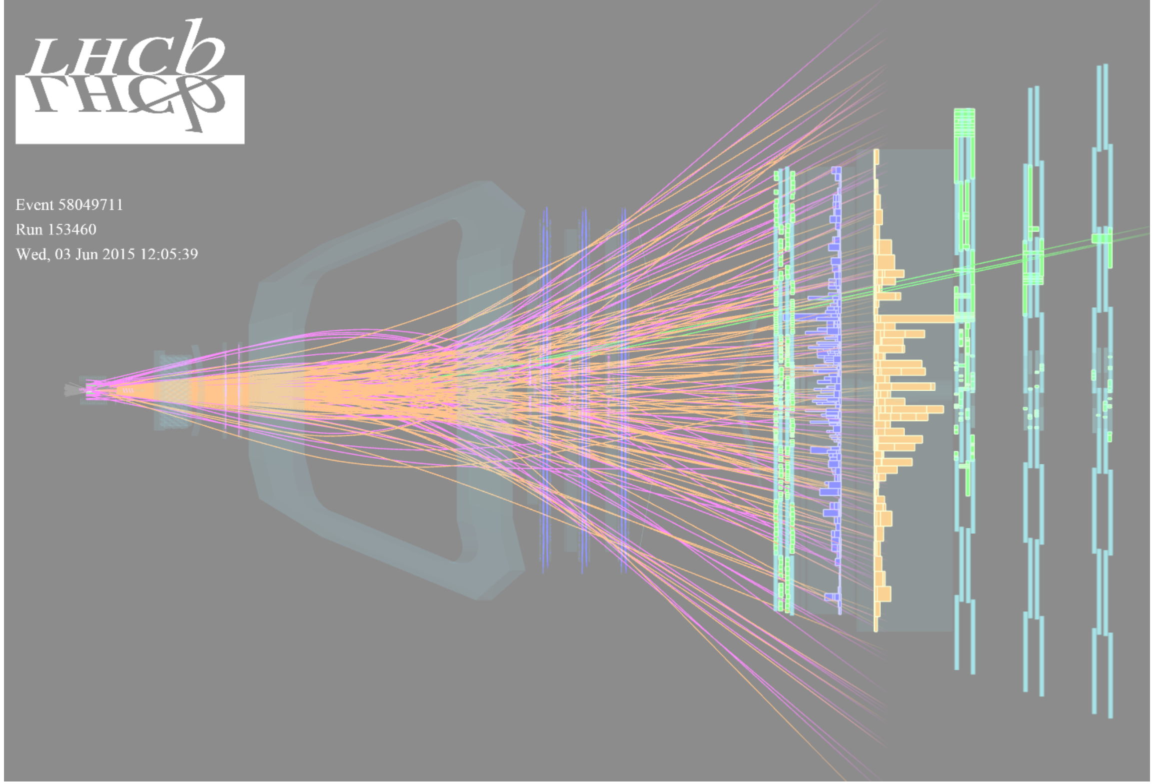

Highlights from the LHCb experiment

Pheno 2020, May 4 – 6, 2020

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on behalf of the LHCb collaboration
Physik Institut, University of Zurich
University of Zurich UZH

LHCb detector

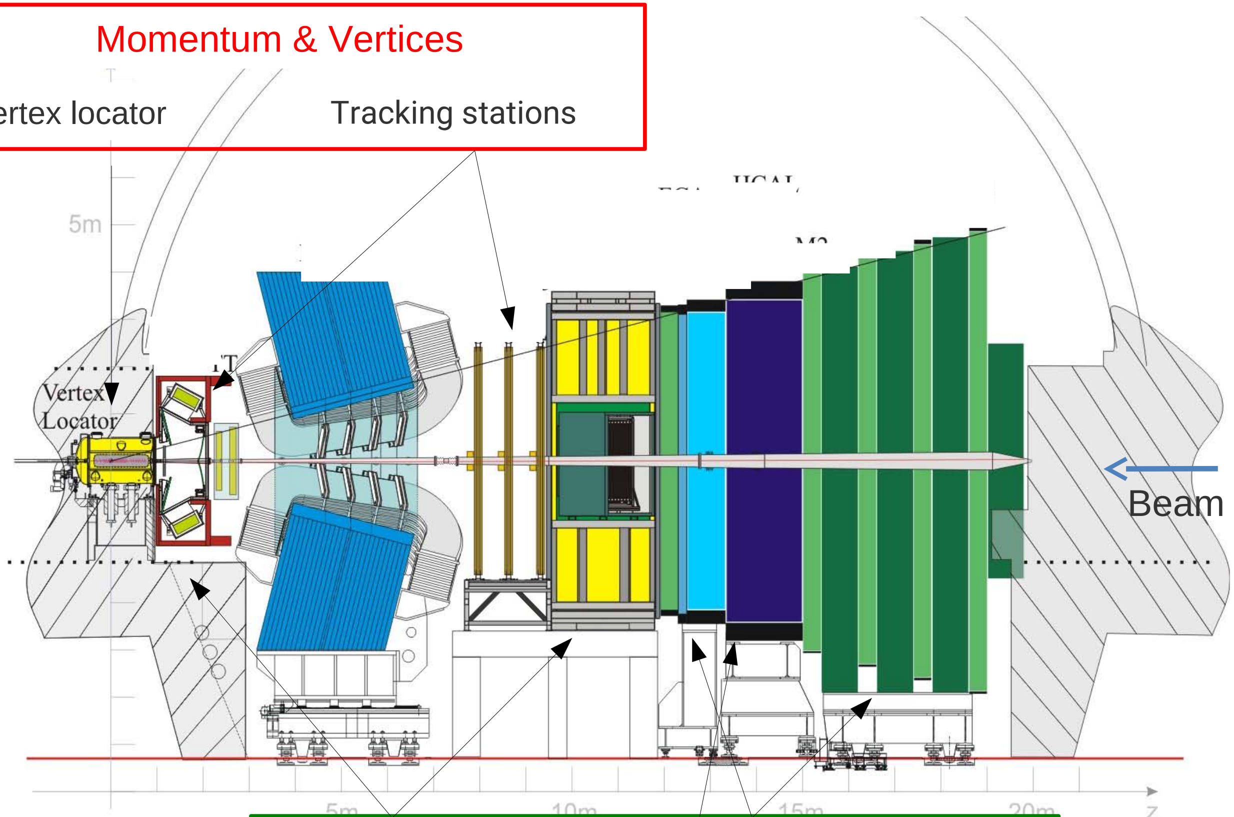
[Int. J. Mod. Phys. A30 (2015)1530022]

forward arm spectrometer for precision measurements (2<η<5)

Momentum & Vertices

Vertex locator   Tracking stations

Beam 1



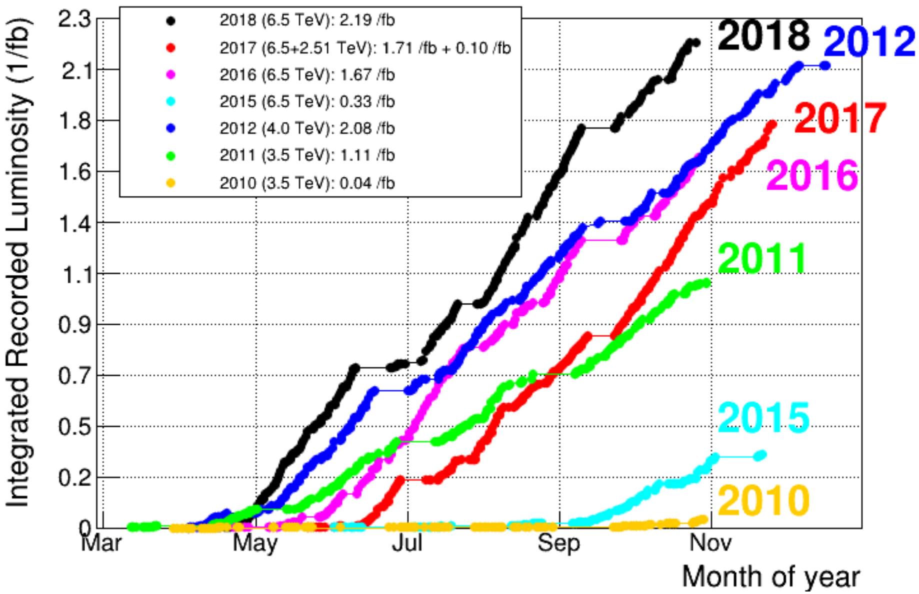
Beam 2

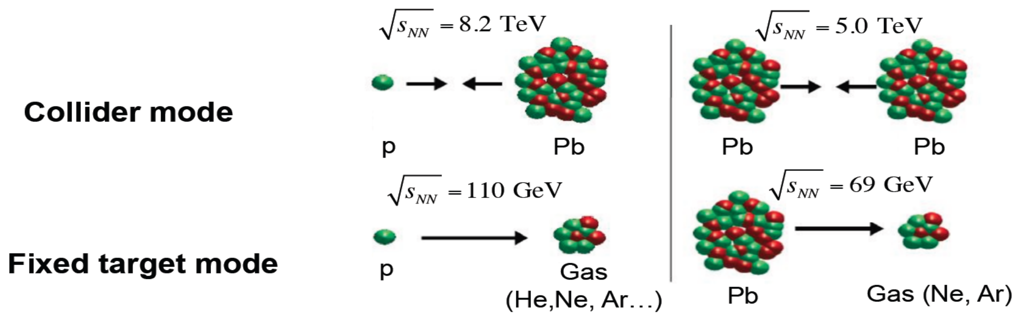
RICH detectors   Calorimeters   Muon stations

Particle ID

- good vertex and impact parameter resolution ($\sigma(IP)= 15 \pm 29/p_T$ μm)
- excellent momentum resolution ($\sigma(m_B) \sim 25$ MeV/c^2 for 2-body decays)
- excellent particle ID (μ ID 97% for ($\pi \rightarrow \mu$) misID of 1-3%)
- stable running conditions
  stable trigger
  constant μ
- trigger on small p_T and low mass objects
- real time analysis
  alignment and calibration fully automated

LHCb dataset





LHCb has recorded about 9 fb^{-1} of pp collisions

1 fb^{-1} @ 7 TeV
2 fb^{-1} @ 8 TeV – Run 1
6 fb^{-1} @ 13 TeV – Run 2

plus various datasets of proton-lead, lead-lead collisions
as well as fixed target datasets: pNe, pHe, pAr, PbAr

LHCb – a multipurpose detector in the forward region

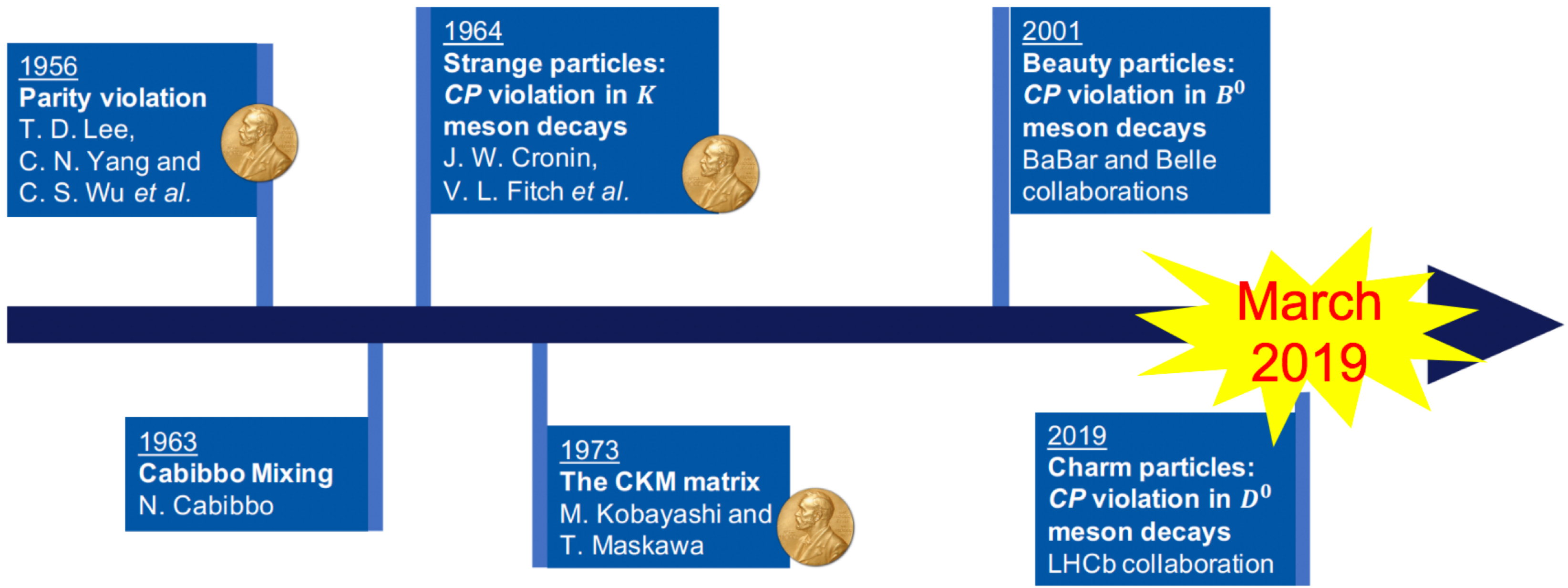
- Indirect searches for New Physics at the multi-TeV scale
  decays of beauty and charm hadron
  CP violation
- Understanding the details of QCD
  Heavy flavour production, pentaquark states,
  double heavy states, top physics, jets …
- Quark gluon plasma, cold nuclear effects in heavy ion collisions
  Heavy flavour production in p-Pb collisions, fixed target collisions

Outline

charm | beauty | spectroscopy | heavy ion fixed target | upgrade

- Observation of CP violation in charm [Phys. Rev. Lett. 122 (2019) 211803]
- A_Γ in $D^0 \rightarrow K^+K^-$, $\pi^+\pi^-$ [Phys. Rev. D101 (2020) 012005]
- Oscillations of charm mesons [Phys. Rev. Lett 122 (2019) 231802]
- Searches for 25 rare and forbidden decays of D^+ and D^+_s mesons [LHCb-PAPER-2020-007]

History of CP violation

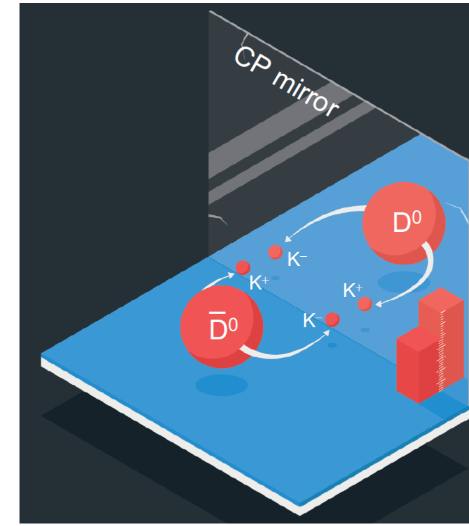


- CPV in Kaons and B mesons is well established – both are down type quarks
- charm hadrons contain an up-type quark
- SM predicts it to be at 10^{-3} - 10^{-4} level
- LHCb is a charm factory, with billions of charm decays produced

Observation of CP violation in charm

[Phys. Rev. Lett. 122 (2019) 211803]

charm decays allow CP violation to be probed in the up-sector
→ complementary to studies in K and B systems



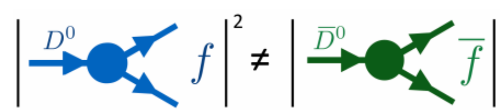
expected to be very small in the SM (10^{-3} - 10^{-4} level),
but theory predictions are not very precise (large long distance effects)

time dependent CP asymmetries

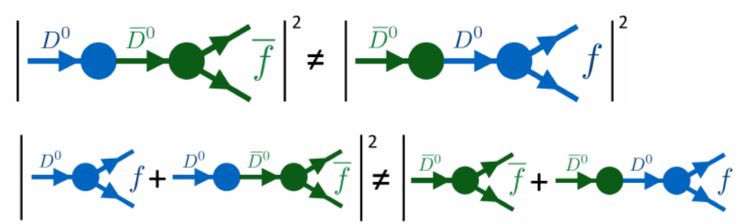
$$A_{CP}(f;t) = \frac{\Gamma(D^0(t) \to f) - \Gamma(\overline{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\overline{D}^0(t) \to f)}$$

sensitive to

- direct CP-violation (a_{CP}^{dir})



- indirect CP-violation (a_{CP}^{indir})
  (CP-violation in mixing or in the
  interference between mixing and decay)



Observation of CP violation in charm

[Phys. Rev. Lett. 122 (2019) 211803]

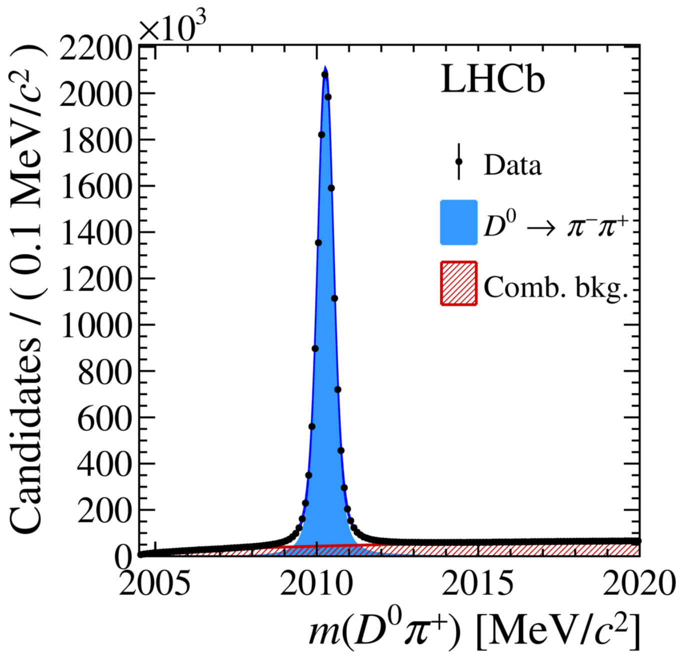
full Run 2 data 5.9 fb^{-1}
count how many D^0 and anti-D^0 decay into $\pi^+\pi^-$ and K^+K^-
should be equal if matter = antimatter

we measure raw asymmetry:

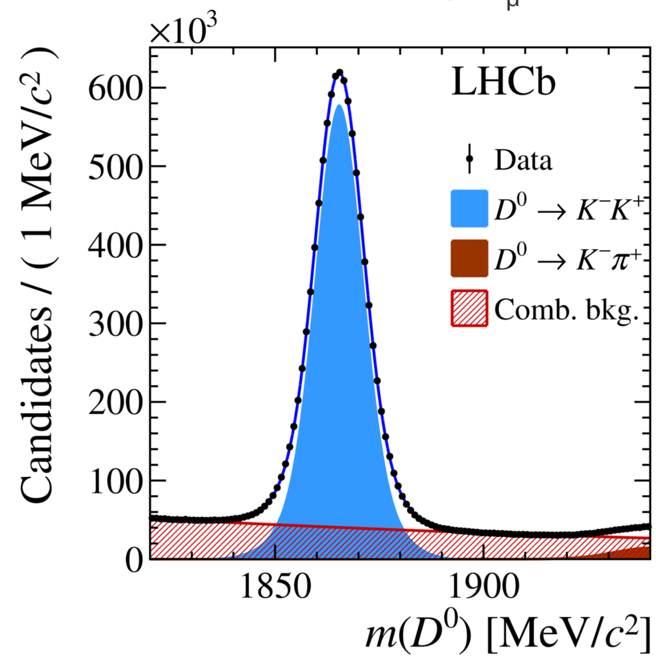
$$A^{Raw}(f) = \frac{N(D^0 \to f) - N(\bar{D}^0 \to f)}{N(D^0 \to f) + N(\bar{D}^0 \to f)}$$

initial flavour of D meson tagged by

charge of π in prompt decays
$D^* \to D^0\pi^+$



muon charge in secondary production
$\bar{B} \to D^0\mu^-\bar{\nu}_\mu X$



Observation of CP violation in charm

[Phys. Rev. Lett. 122 (2019) 211803]

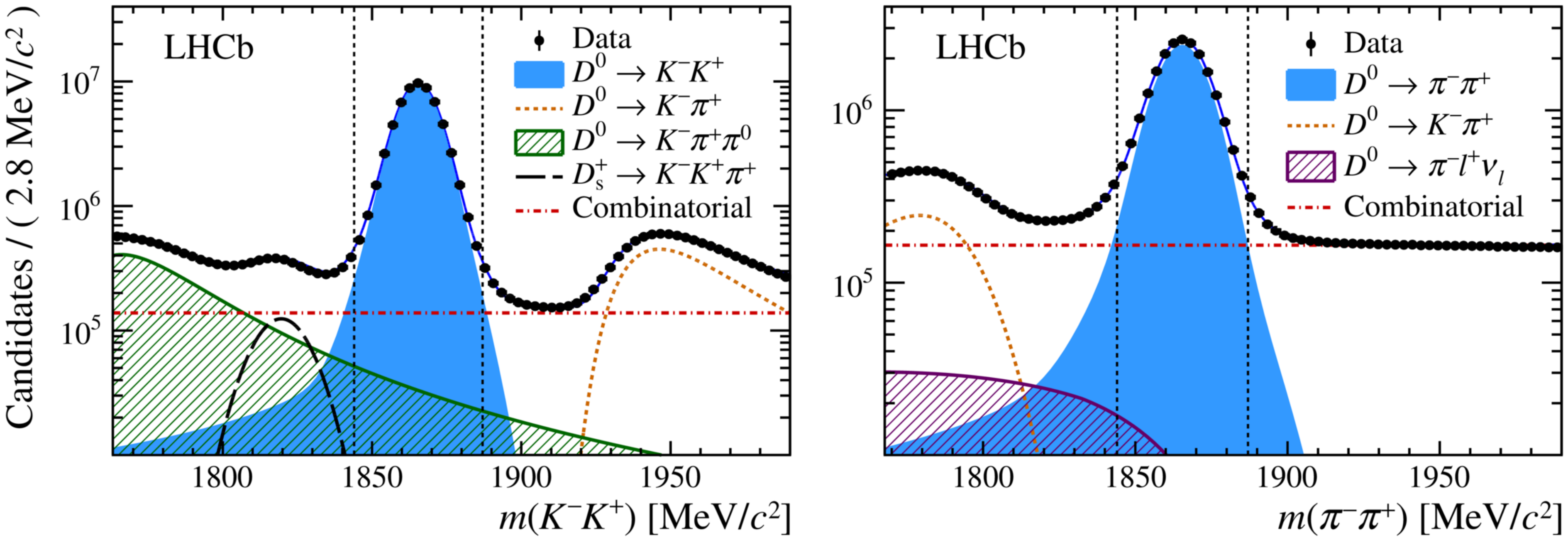
$$A^{Raw}(f) \simeq A^{CP}(f) + A^{Det}(f) + A^{Det}(\pi,\mu) + A^{Pr}(D^*,B)$$

A^{CP}: CP asymmetry

$A^{det}(f)$ and $A^{det}(\pi,\mu)$: D^0 detection asymmetry, $A^{pr}(D^*,B)$: D^*,B production asymmetry
detector and production asymmetries difficult to control at the level of $10^{-3} – 10^{-4}$!

→ difference in raw asymmetries: many systematic uncertainties cancel at first order

$$\Delta A^{CP} = A^{Raw}(K^- K^+) - A^{Raw}(\pi^- \pi^+) = A^{CP}(K^- K^+) - A^{CP}(\pi^- \pi^+)$$



Observation of CP violation in charm

[Phys. Rev. Lett. 122 (2019) 211803]

Run 2 result:

ΔA_{CP} =(-18.2 ± 3.2 (stat) ± 0.9 (syst))10^{-4} π-tag

ΔA_{CP} =(-9 ± 8 (stat) ± 5 (syst))10^{-4} μ-tag

compatible with previous LHCb result and world average

combination with Run 1 result

ΔA_{CP} =(-15.4 ± 2.9)10^{-4}

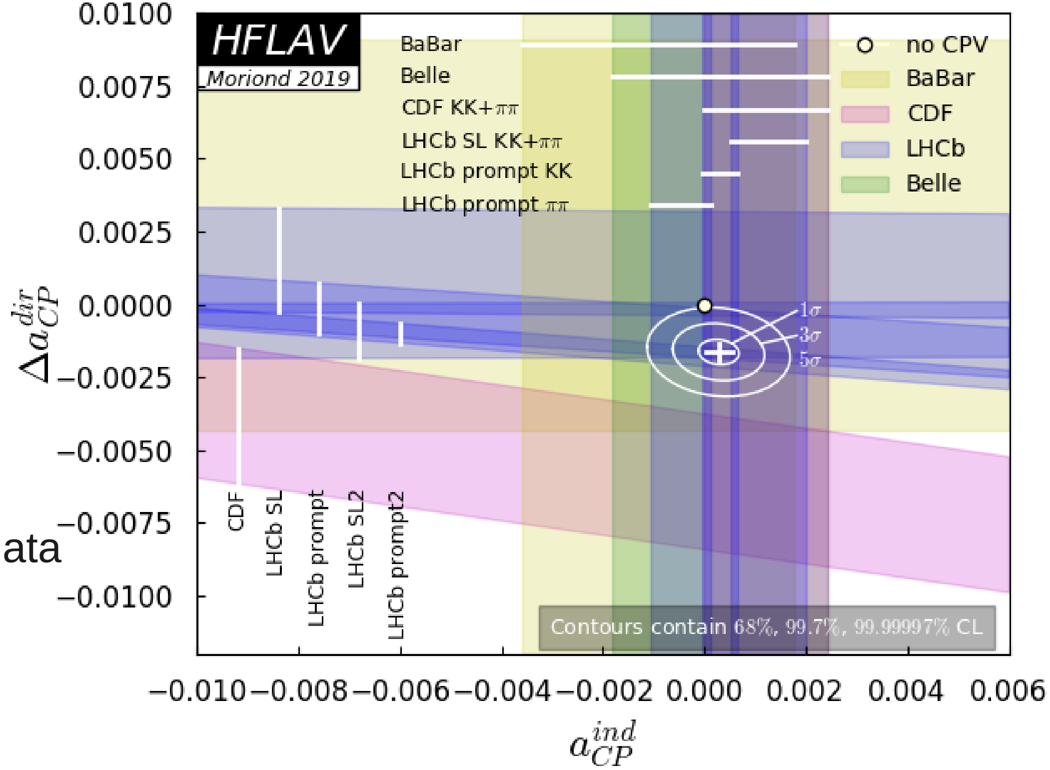
→ 5.3 σ difference from 0

→ roughly compatible with SM predictions

uncertainties of SM predictions larger than data

using LHCb input on indirect CP violation:

$$\Delta a_{CP}^{dir} = (-15.7 \pm 2.9) \times 10^{-4}$$



→ new window opened to investigate matter-antimatter asymmetry

Measurement of CPV parameter A_Γ in $D^0 \to K^+K^-$, $\pi^+\pi^-$

[Phys. Rev. D101 (2020) 012005]

A_Γ probes CPV in mixing and interference

$$A_{CP}(f,t) \approx A_{CP}^{decay} - A_\Gamma(f)\frac{\langle t\rangle_f}{\tau_D^0}$$

SM predictions: ≈ 3 x 10^{-5} [arXiv:1812.07638]

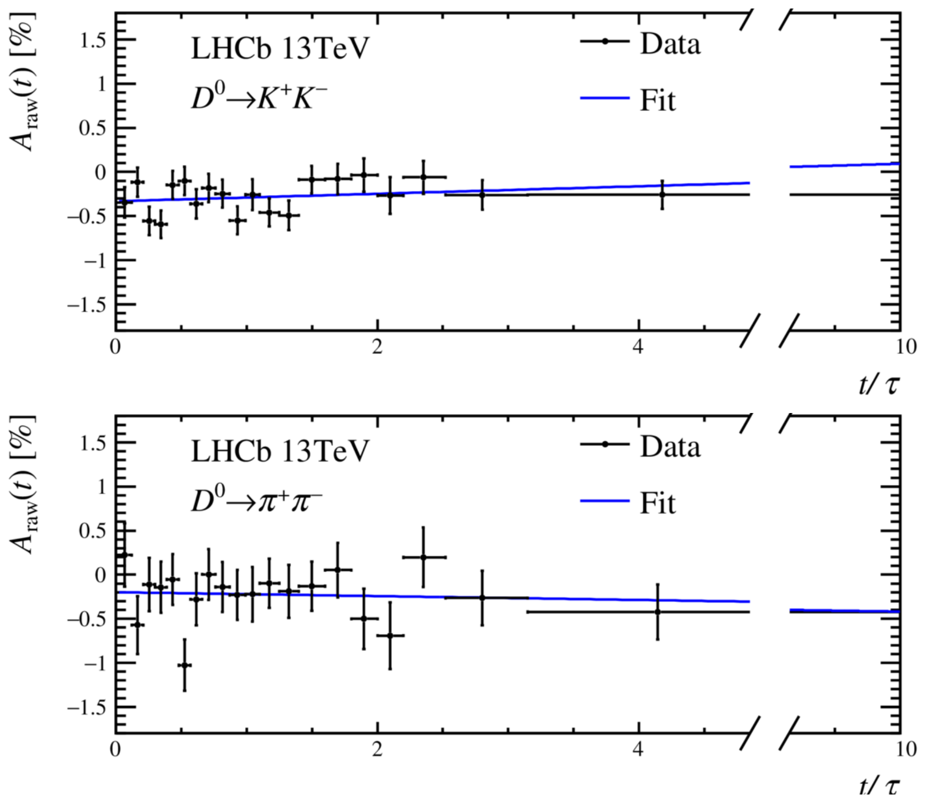
A_Γ required input to measure direct CPV Δa_{CP} in decay from ΔA_{CP}

→ measure time dependent CP asymmetry in $D^0 \to \pi^+\pi^-$ and K^+K^- decays:

$$A_\Gamma(K^+K^-) = (-4.3 \pm 3.6 \pm 0.5)10^{-4}$$
$$A_\Gamma(\pi^+\pi^-) = (2.2 \pm 7.0 \pm 0.8)10^{-4}$$

combined with previous LHCb result

$$A_\Gamma = (-2.9 \pm 2.0 \pm 0.6)10^{-4}$$



no indication for CPV in mixing or interference

analysis based on 2 fb^{-1} Run 2 data, statistically limited, still 4 fb^{-1} to be analysed
→ need Upgrade II to reach sensitivity of SM

Oscillations of charm mesons in $D^0 \to K_S^0\pi^-\pi^+$

[Phys. Rev. Lett 122 (2019) 231802]

neutral flavoured mesons can oscillate between their particle and antiparticle states

→ the physical mass eigenstates are linear combinations of the weak eigenstates

$$|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\overline{D}^0\rangle$$

with masses m_1 and m_2 and decay widths Γ_1+Γ_2

mixing parameters $x_{CP} \equiv (m_1-m_2)c^2/\Gamma$ and

$y_{CP} \equiv (\Gamma_1-\Gamma_2)/\Gamma$ $(\Gamma=(\Gamma_1+\Gamma_2)/2)$

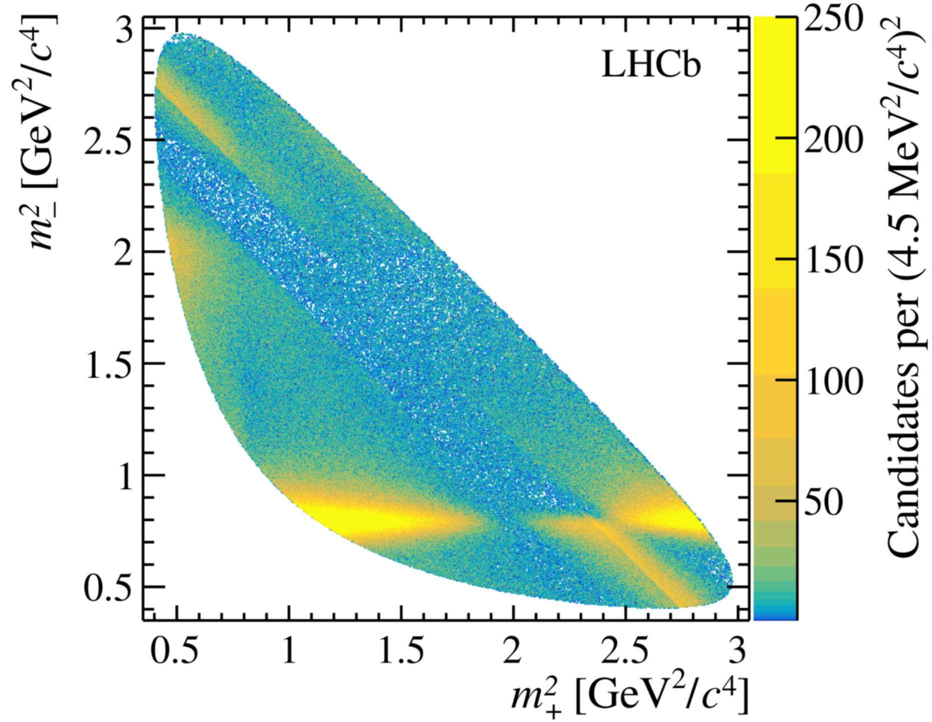
x_{CP} determines the oscillation rate

x_{CP} is very small for charm mesons but can be enhanced by the presence of new particles beyond the SM

LHCb Run 1, decay: $D^0 \to K_S^0\pi^-\pi^+$

yields: prompt 1.3M, secondary 1M candidates

decay-time-integrated distribution of background-subtracted $D^0 \to K_S^0\pi^+\pi^-$ candidates



Oscillations of charm mesons in $D^0 \rightarrow K_S^0 \pi^- \pi^+$

[Phys. Rev. Lett 122 (2019) 231802]

model independent approach (bin-flip method) [arXiv:1811.01032]

allowing for CPV mixing or interference

→ most precise determination of CP averaged normalized mass difference $x=(m_1-m_2)c^2/\Gamma$ by a single experiment

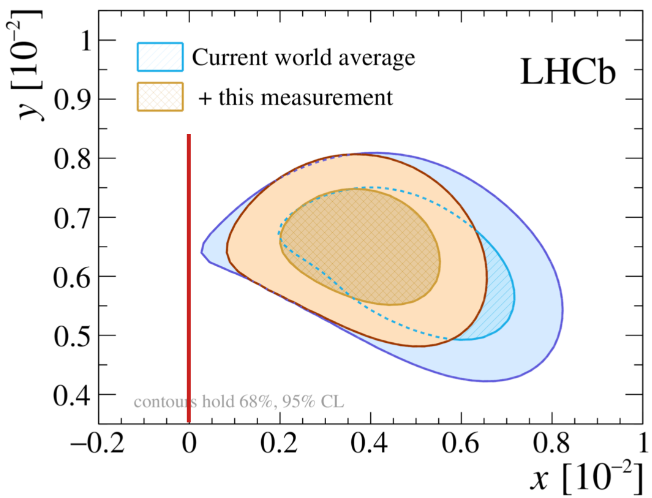
$x_{CP} = [2.7 \pm 1.6 \pm 0.4] \times 10^{-3}$

$y_{CP} = [7.4 \pm 3.6 \pm 1.1] \times 10^{-3}$

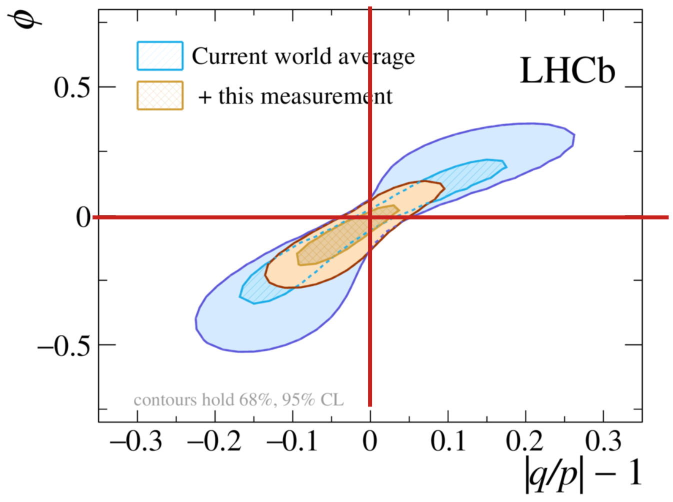
if CP symmetry in mixing and interference is conserved:
$x_{CP} = x$, $y_{CP} = y$

new world average provides first evidence of mass difference between the neutral charm mesons:

$$x_{CP} = (3.9^{+1.1}_{-1.2}) \times 10^{-3}$$



CPV parameters

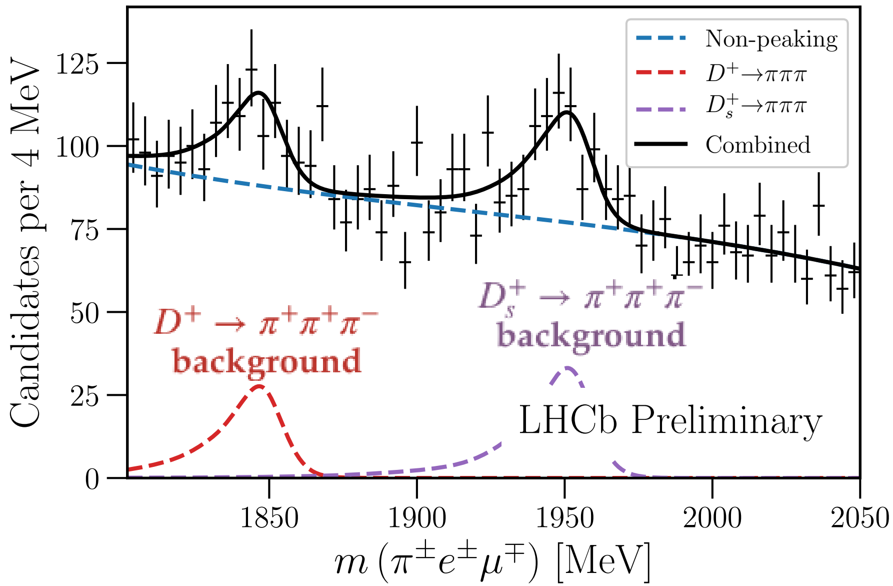


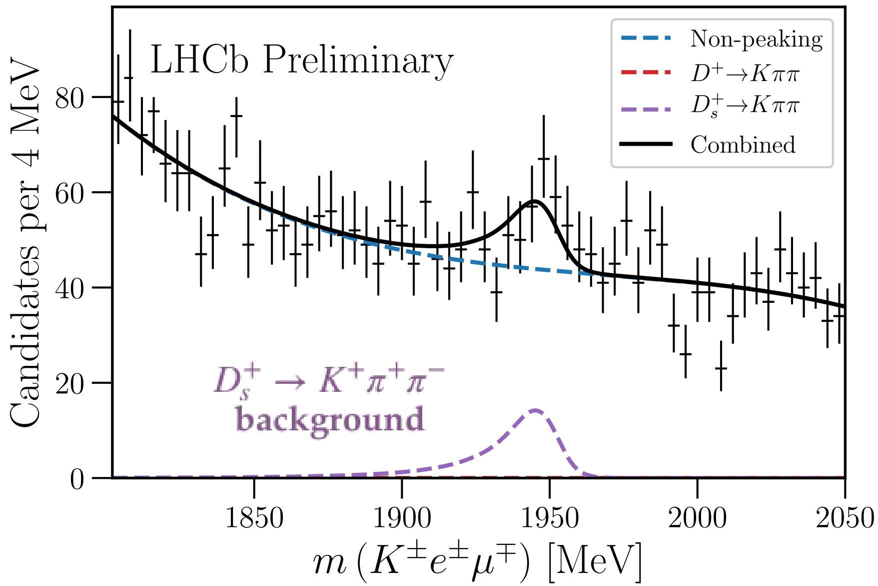
Searches for 25 rare and forbidden decays of D^+ and D^+_s mesons

New!

- four rare charm decays $D^+ \to \pi^+\ell^+\ell^-$ and $D_s^+ \to K^+\ell^+\ell^-$ (ℓ = e, μ)
  $c \to u\ell\ell$ and weak annihilation diagrams, dominated by light resonances (η, ρ, ω, φ)
- four weak-annihilation decays $D^+ \to K^+\ell^+\ell^-$ and $D_s^+ \to \pi^+\ell^+\ell^-$
- eight $D_{(s)}^+ \to h^+\ell^+\ell^{-\prime}$ LFV modes (h = π, K)
- nine $D_{(s)}^+ \to h^-\ell^+\ell^+$ and $D_{(s)}^+ \to h^-\ell^+\ell^{+\prime}$ LNV modes

Normalised and calibrated with $D_{(s)}^+ \to \pi^+\varphi$, all channels well described by background-only





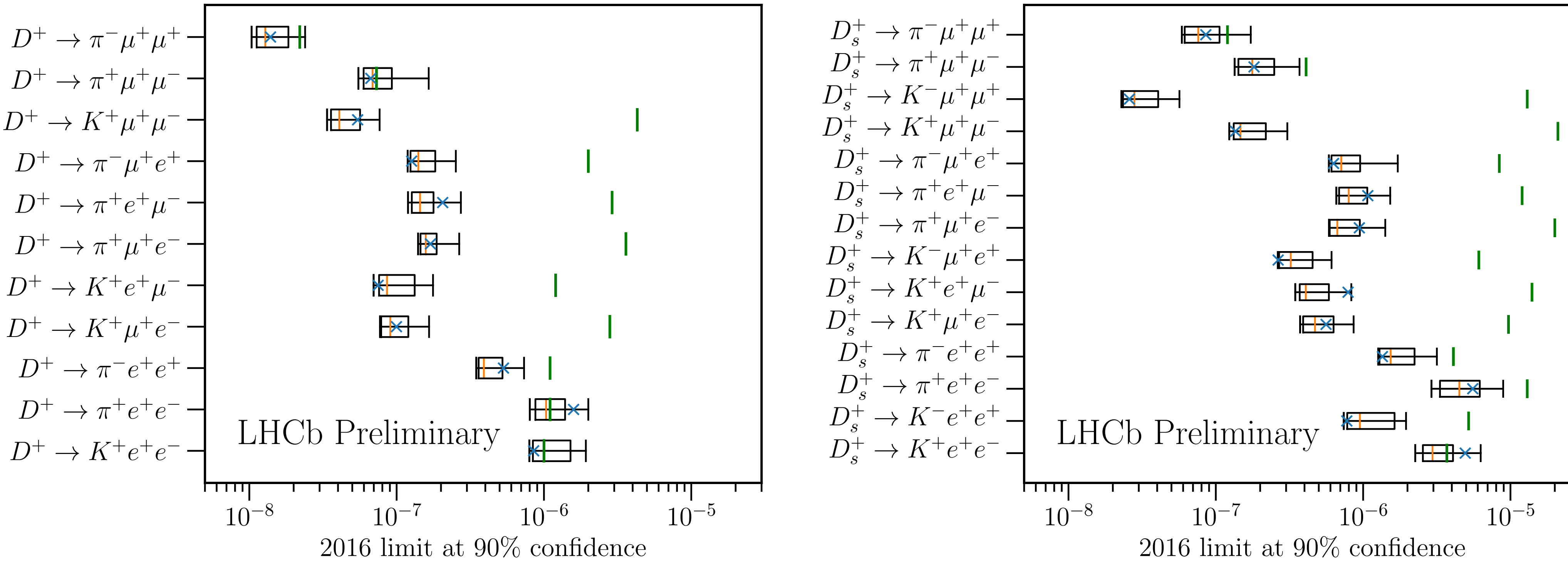
Searches for 25 rare and forbidden decays of D^+ and D^+_s mesons

[LHCb-PAPER-2020-007]

New!

All the limits (@90% CL) are shown in the backup
→ 23 best limits
2017-18 dataset yet to be analysed

expected median, with ± 1σ, ± 2σ intervals
x observed limit
prev. world's best limit (BaBar / CLEO/ LHCb)



Precision in beauty

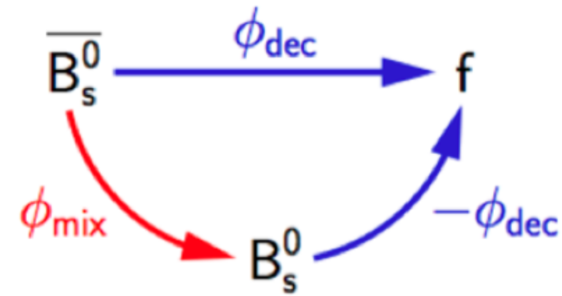
cp violation | **rare decays** | spectroscopy | heavy ion fixed target | upgrade

- B_s mixing phase Φ_s [Phys. Lett. B797 (2019) 134789, Eur. Phys. J. C 79 (2019) 706]
- New measurement of R(K) [Phys. Rev. Lett. 122 (2019) 191801] and R(pK) [arXiv:1912.08139]
- Angular analysis of rare decay $B^0 \rightarrow K^{*0}[K^+\pi^-]\mu^+\mu^-$ [http://arxiv.org/pdf/2003.04831]
- Search for Lepton flavour violating decays [Phys. Rev. Lett. 123 (2019) 211801, Phys. Rev. Lett.123 (2019) 241802, arXiv:2003.04352]

B_s mixing phase Φ_s from $B_s \to J/\psi\, KK$ and $B_s \to J/\psi\pi\pi$

[Phys. Lett. B797 (2019) 134789]
[Eur. Phys. J. C 79 (2019) 706]

measure the phase difference between the two processes



SM prediction $\Phi_s = -36.8^{+9.6}_{-6.8}$ mrad (CKM Fitter)
highly sensitive to NP contributions

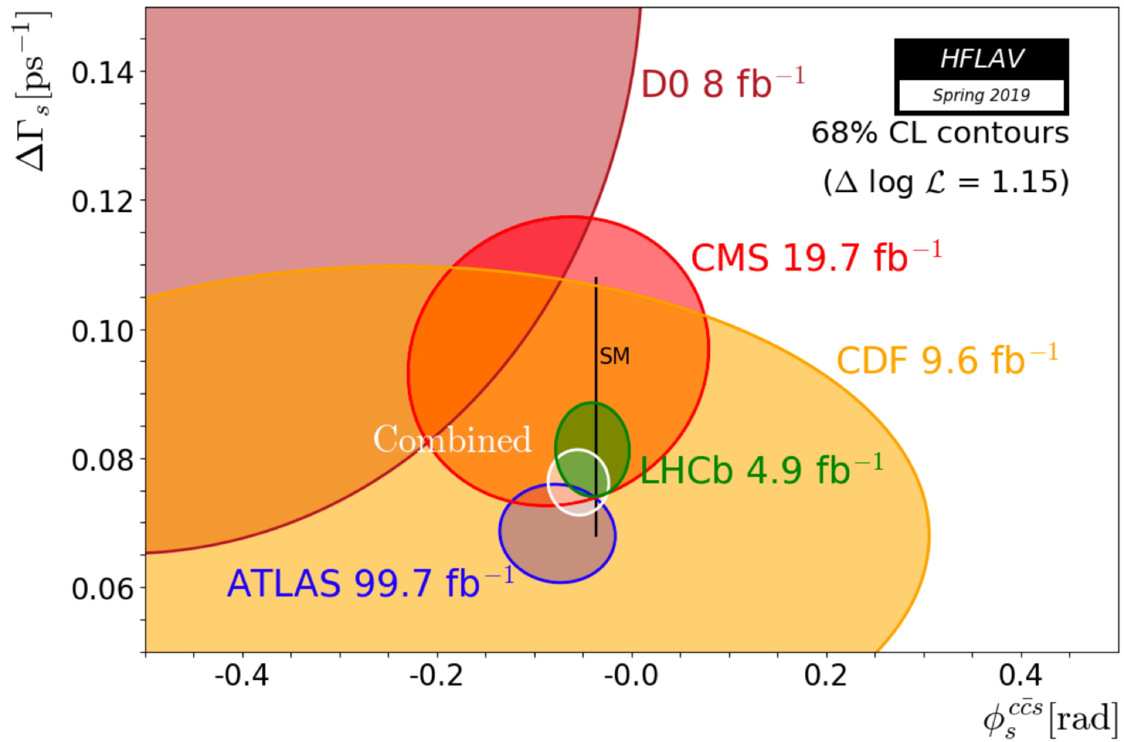
LHCb uses two channels:
$B_s \to J/\psi\, KK$ and $B_s \to J/\psi\pi\pi$

high yield, clean signature
→ very high precision measurements

flavour tagging from decay of other b hadron in the event
analysis part of Run 2 (2 fb^{-1})

combined with Run 1
Φ_s = (-41 ± 25) mrad
(still 4 fb^{-1} not analysed)

HFLAV combination:
Φ_s = (-55 ± 21) mrad

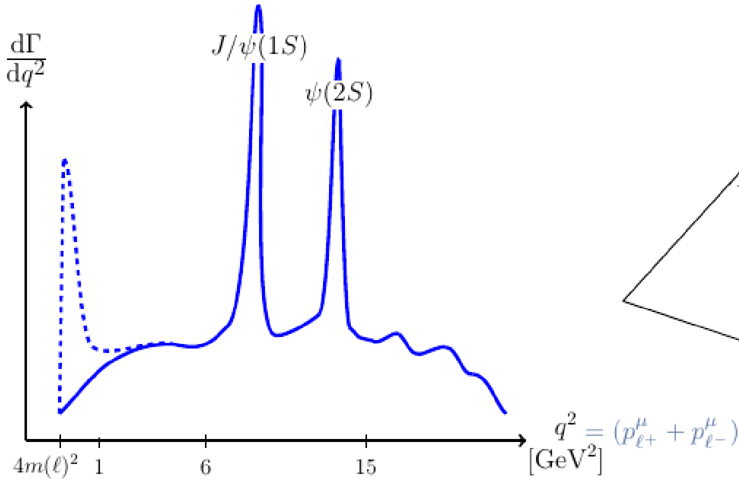


Rare decays as a test for new physics

excellent probe to look at new physics in rare decays as new heavy particles can enter at loop and/or tree level

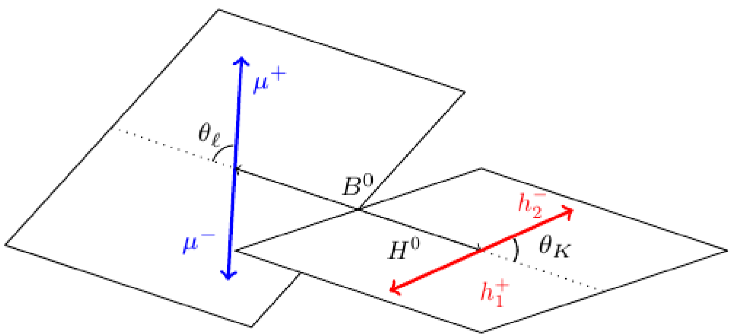
FCNC decays b→sℓℓ transitions forbidden at tree-level in the SM → BR 10^{-7} – 10^{-6}
coherent set of discrepancies wrt the SM

branching fractions



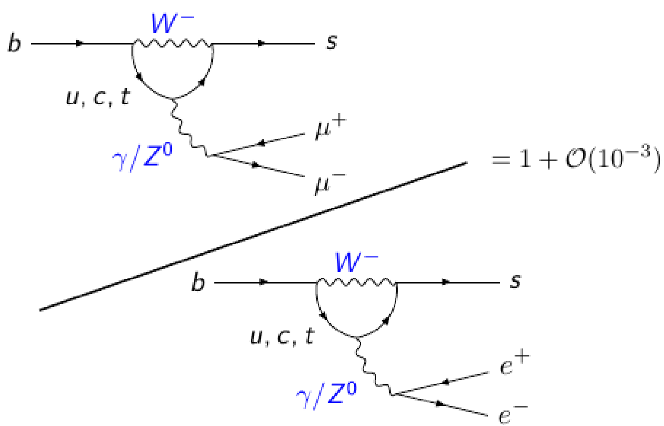
[JHEP 06 (2014) 133] B → K*μμ
[JHEP 06 (2015) 115] Λ_b→Λμμ
[JHEP 04 (2017) 142] B→Kπμμ, B→K*μμ
[JHEP 09 (2015) 179] B_s→ϕμμ
[JHEP 09 (2018) 146] Λ_b→Λμμ

angular distributions



[JHEP 02 (2016) 104] B → K*μμ
[JHEP 06 (2014) 133] B → $K^{(*)}$μμ
[JHEP 09 (2018) 146] Λ_b→Λμμ
[arXiv:2003.04831] B → K*μμ

test of LFU



[PRL 113 (2014) 151601] B^+→Kℓℓ
[JHEP 08 (2017) 055] B^0→K*ℓℓ
[PRL 122 (2019) 191801] B^+→Kℓℓ
[arXiv:1912.08139] Λ_b→pKℓℓ

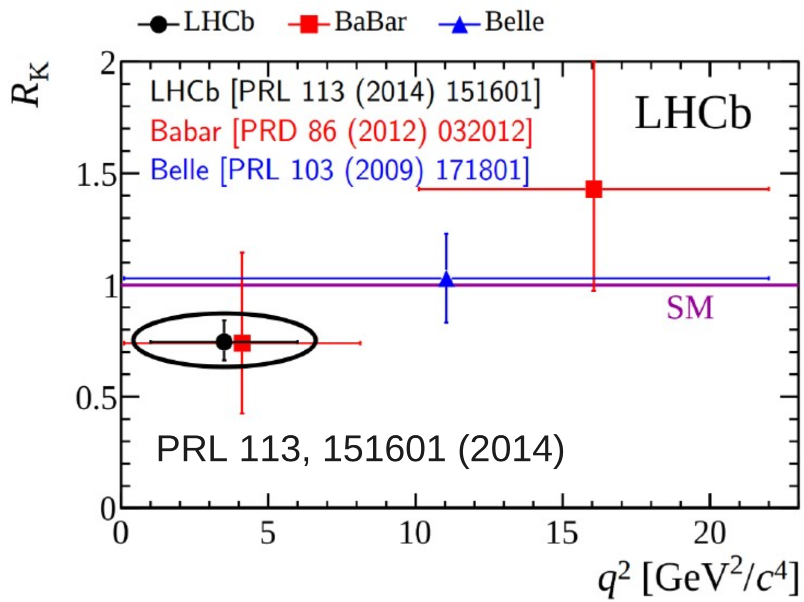
Test of lepton universality: R(K) and R(K*)

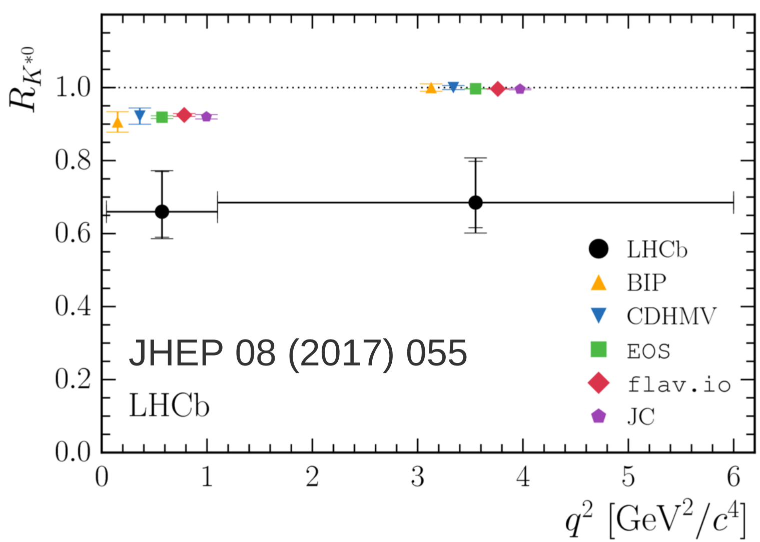
theoretically clean

$$R\left(K^{(*)}\right)=\frac{BR\left(B\rightarrow K^{(*)}\mu\mu\right)}{BR\left(B\rightarrow K^{(*)}ee\right)}=1\pm\underbrace{O\left(10^{-3}\right)}_{\text{neglect lepton mass}}\pm\underbrace{O\left(10^{-2}\right)}_{\text{QED}}$$

[EPJ C76 (2016) 8, 440]

Run 1 result: results for R(K) and R(K*)





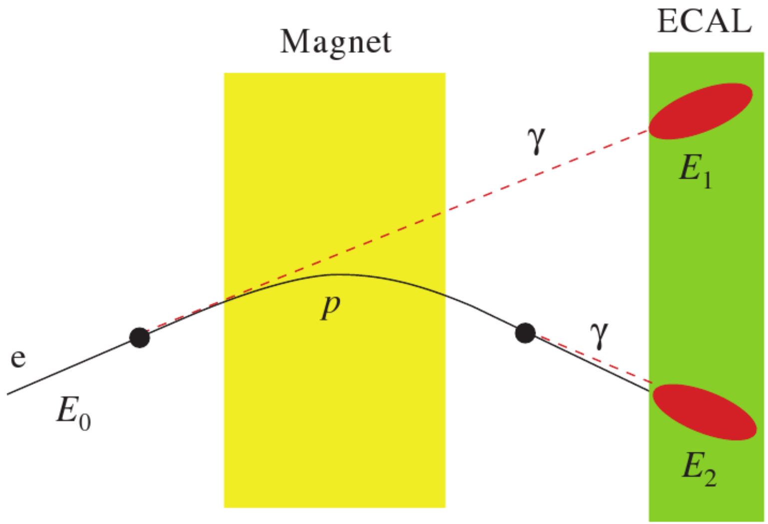
New measurement of R(K)

[Phys. Rev. Lett. 122 (2019) 191801]

new measurement re-analysing Run 1 data and adding ~2 fb^{-1} of Run 2 data
measure R as a double ratio to reduce systematic effects
due to differences between electrons and muons

$$R(K)=\frac{BR(B\to K\mu\mu)}{BR(B\to K J/\psi(\to\mu\mu))}\frac{BR(B\to K J/\psi(\to ee))}{BR(B\to K ee)}$$

but electrons are difficult to measure at LHCb: trigger, Bremsstrahlung ...



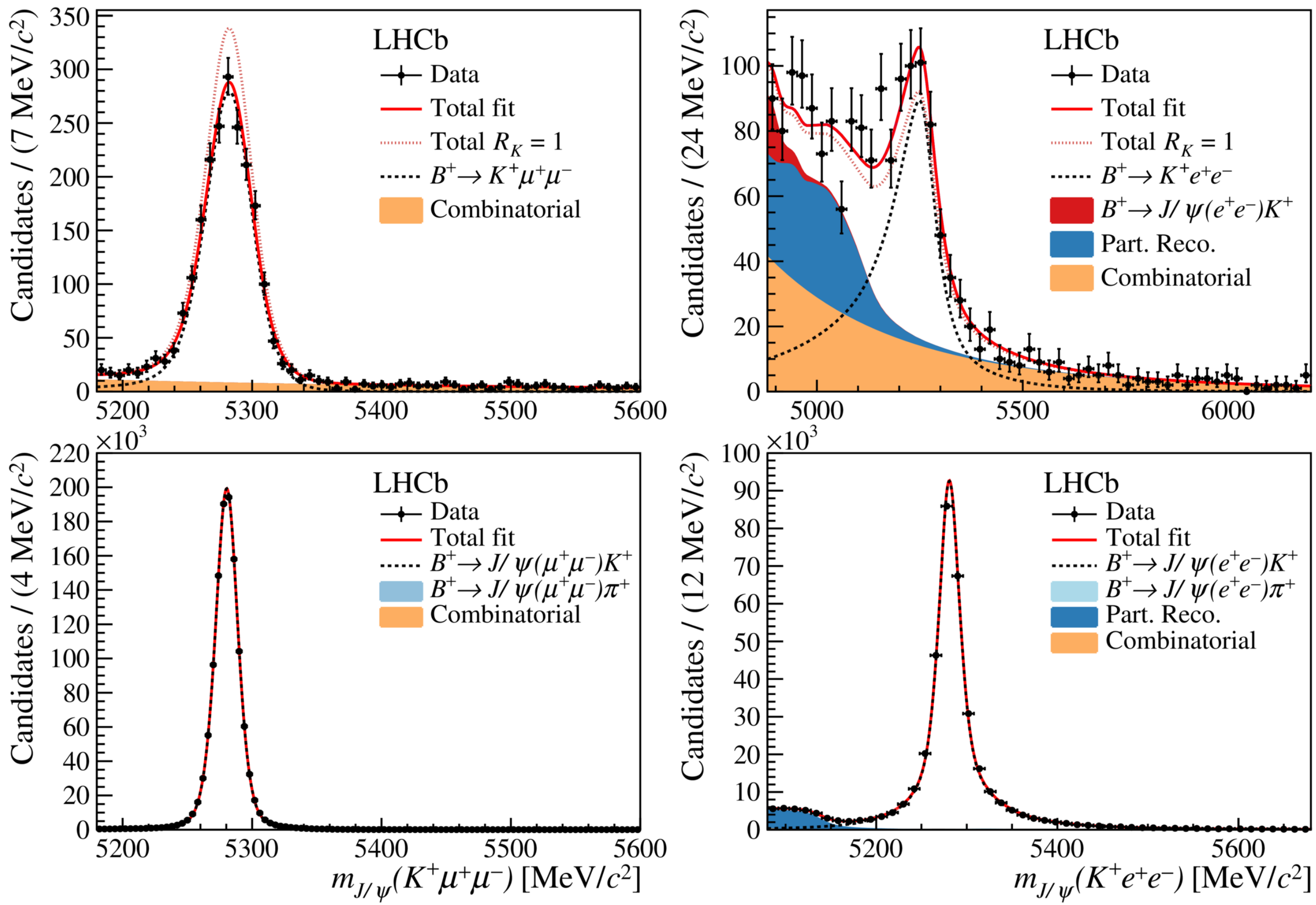
[Phys. Rev. Lett. 122 (2019) 191801]

Yield from simultaneous (muon or electron) fit of M(Kℓℓ) to the J/ψ and non-resonant channels

$$R(K) = \frac{BR(B\to K\mu\mu)}{BR(B\to K J/\psi(\to\mu\mu))}\,\frac{BR(B\to K J/\psi(\to ee))}{BR(B\to K ee)}$$

Signal

Normalisation



New measurement of R(K)

[Phys. Rev. Lett. 122 (2019) 191801]

$$R(K) = 0.846^{+0.060}_{-0.054}(\mathrm{stat})^{+0.016}_{-0.014}(\mathrm{syst})$$

2.5 σ away from the SM prediction
→ better precision
central value closer to the SM

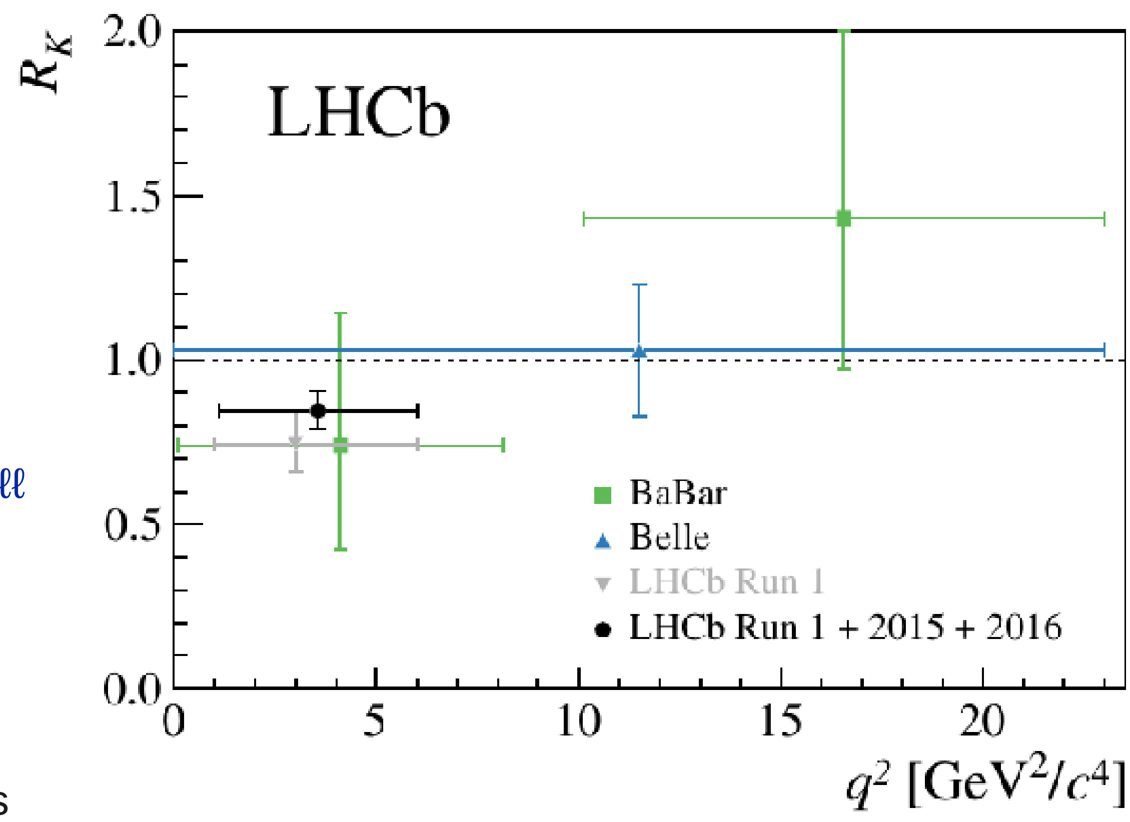
→ need more data:
inclusion of 2017+2018
data will double the statistics

[arXiv:1912.08139]
first test of LU with b baryons: $\Lambda_b \to pK\ell\ell$

$$R(pK) = 0.86^{+0.14}_{-0.11} \pm 0.05$$

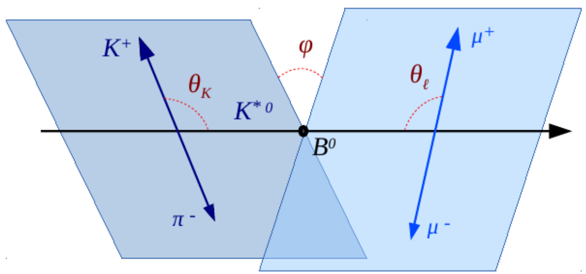
compatible with unity within one σ

other measurements in preparation
update of R(K*), other decay channels



Angular analysis of rare decay $B^0 \to K^{*0}[K^+\pi^-]\mu^+\mu^-$

[JHEP 02 (2016) 104]



Measure B → K*μμ decay rate as a function of q^2 and three helicity angles (Φ,θ_K,θ_l)

→ large set of variables with reduced theory uncertainties

$$\frac{d^4\bar{\Gamma}[B^0\to K^{*0}\mu^+\mu^-]}{dq^2\,d\vec{\Omega}} = \frac{9}{32\pi}\sum_i \bar{I}_i(q^2) f_i(\vec{\Omega})$$

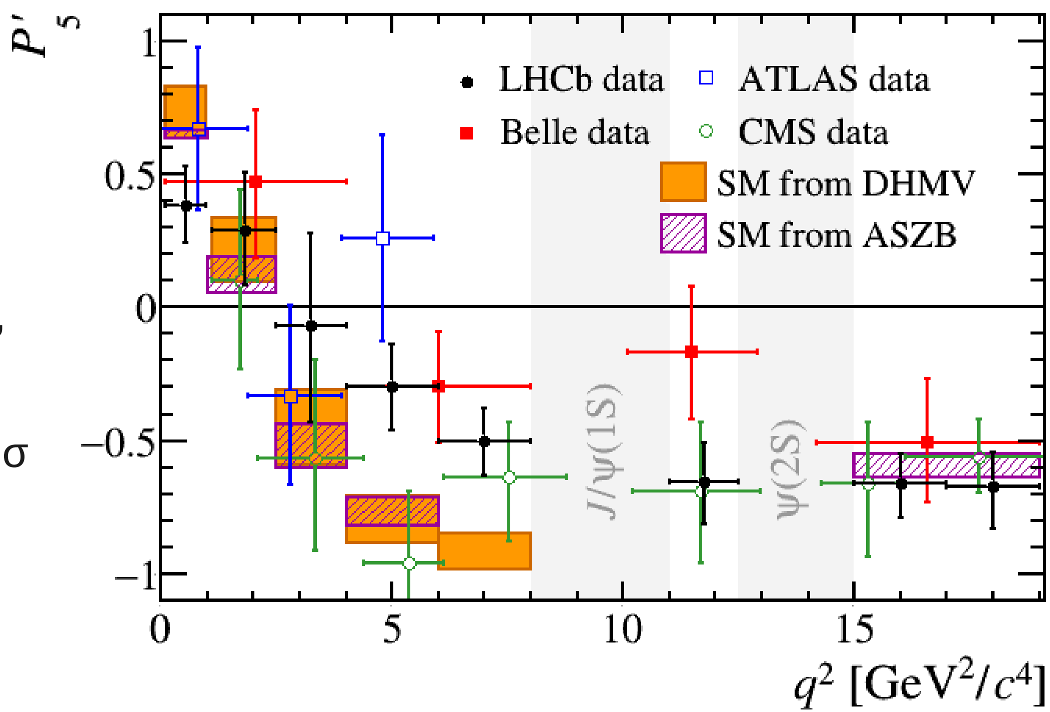
I_i: angular coefficients

f_i: angular functions

Construct optimized angular variables where form factors cancel at first order → P_5'

Observe tension with SM predictions by 3.4 σ

Limited understanding of the effects of long-distance non-perturbative QCD effects (charm-loops)



updated measurement of P_5' with Run 1 + 2016 data

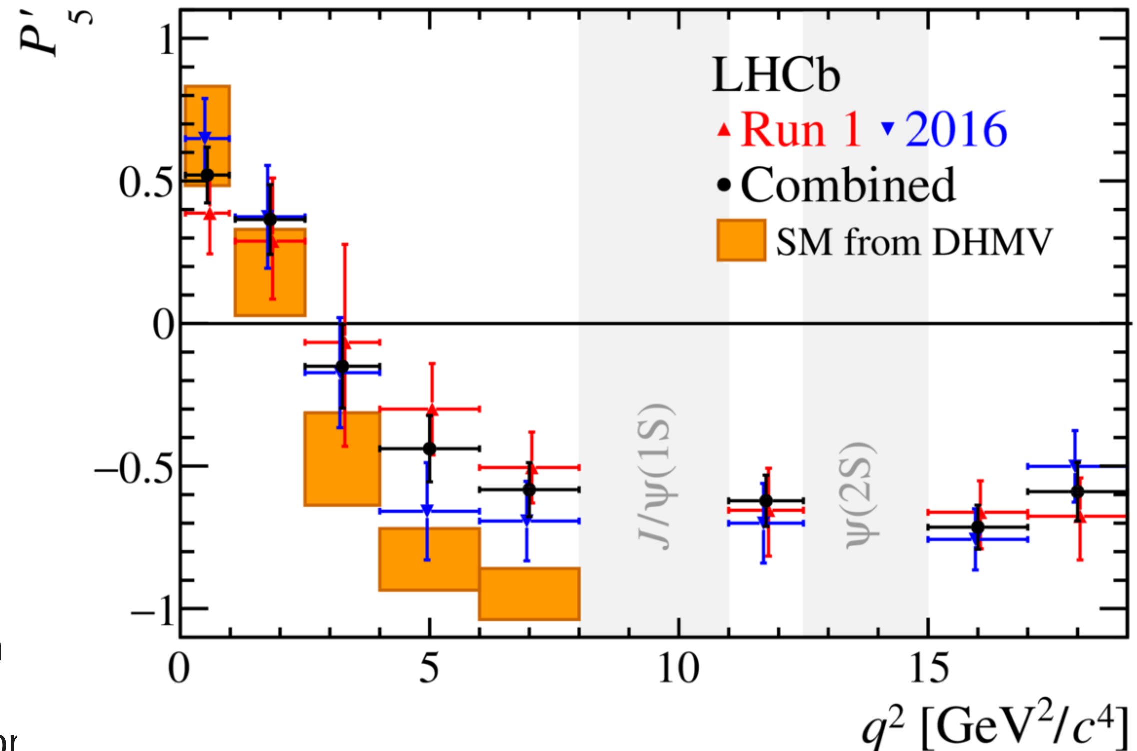
- $4 < q^2 < 6$ GeV^2 → 2.5 σ above the SM
- $6 < q^2 < 8$ GeV^2 → 2.9 σ above the SM

slightly reduced local tension in P_5'

the exact significance of the discrepancy depends on the nuisance parameters chosen and q^2 bins fitted

since previous analysis:
theory uncertainties associated with form factors have decreased
Parameterisation of sub-leading correctior is now more conservative

update with full Run 2 ongoing



Disclaimer: 2016 data is used for illustratory purposes only and contains no systematic uncertainties or bias and coverage corrections

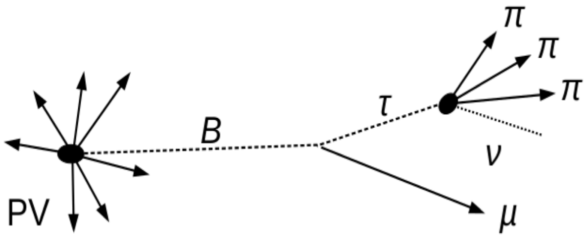
Search for lepton flavour violating decay $B^0_{(s)} \to \tau\mu$

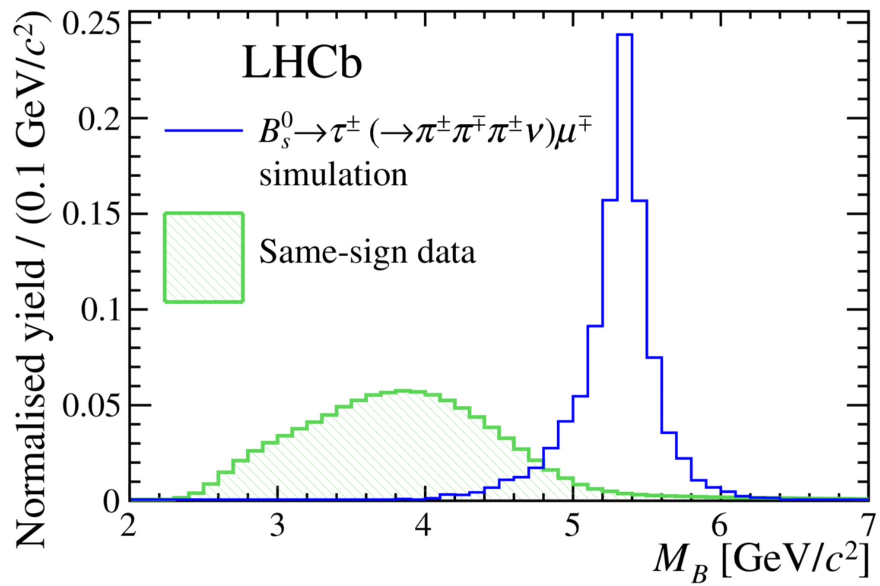
[Phys. Rev. Lett. 123 (2019) 211801]

search for lepton-flavour violating decays $B^0_{(s)} \to \tau^\pm\mu^\mp$

BR in SM highly suppressed: $\sim 10^{-54}$

can be strongly enhanced in NP models:
up to $O(10^{-8} - 10^{-5})$
τ reconstruction: three prong





Mode	Limit	90% CL	95% CL
$B_s^0 \to \tau^\pm\mu^\mp$	Observed	3.4×10^{-5}	4.2×10^{-5}
	Expected	3.9×10^{-5}	4.7×10^{-5}
$B^0 \to \tau^\pm\mu^\mp$	Observed	1.2×10^{-5}	1.4×10^{-5}
	Expected	1.6×10^{-5}	1.9×10^{-5}

first limits

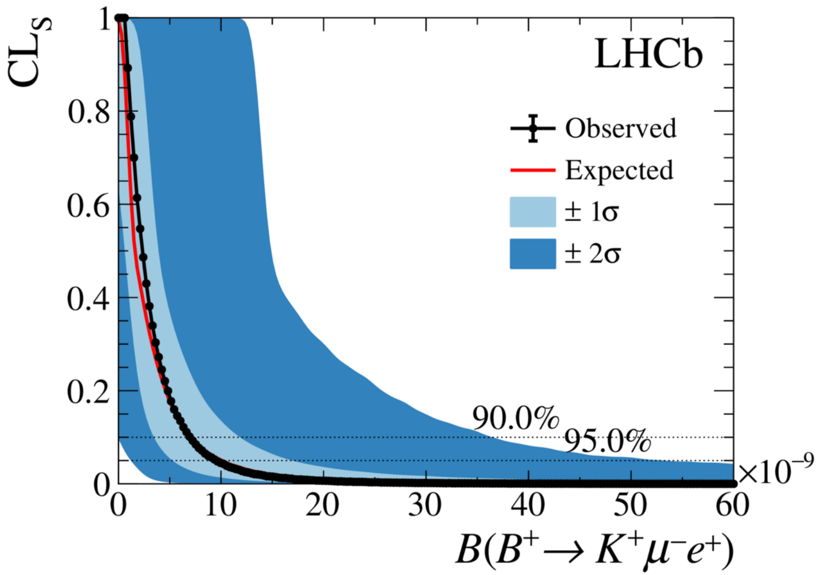
best limits

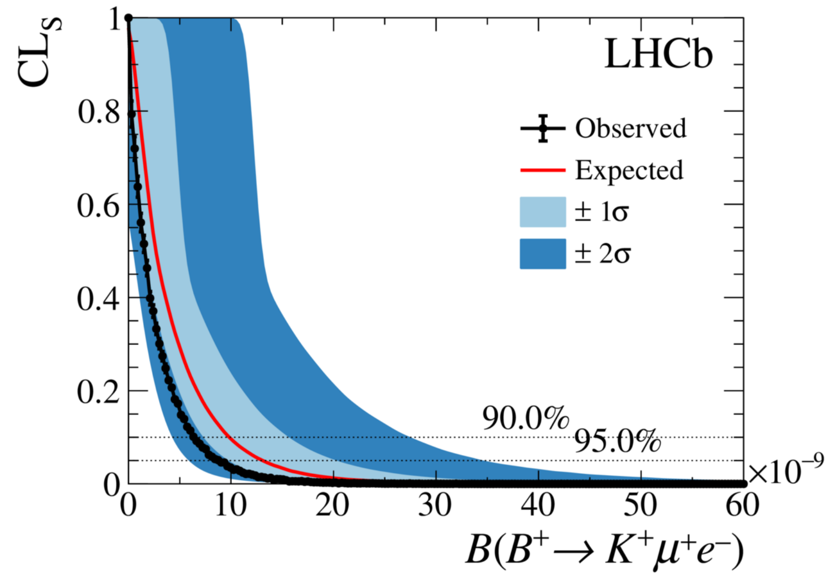
Search for lepton flavour violating decay $B^+ \to K^+\mu^\pm e^\mp$

[Phys. Rev. Lett.123 (2019) 241802]

NP models including leptoquarks, extended gauge boson models or CP violation in the neutrino sector predict branching fractions $10^{-8} - 10^{-10}$

search in full Run 1 dataset, no signal observed





	90% C. L.	95% C. L.
$\mathcal{B}(\ B^+ \to K^+\mu^-e^+\ )/10^{-9}$	7.0	9.5
$\mathcal{B}(\ B^+ \to K^+\mu^+e^-\ )/10^{-9}$	6.4	8.8

limits improved by more than one order of magnitude

New: search for LFV decay $B^+ \to K^+\mu^-\tau^+$ in $B^{*0}_{s2} \to B^+K^-$

$B(B^+ \to K^+\mu^-\tau^+) < 3.9\times10^{-5}$ @90% CL – comparable to the world-best limit [arXiv:2003.04352]

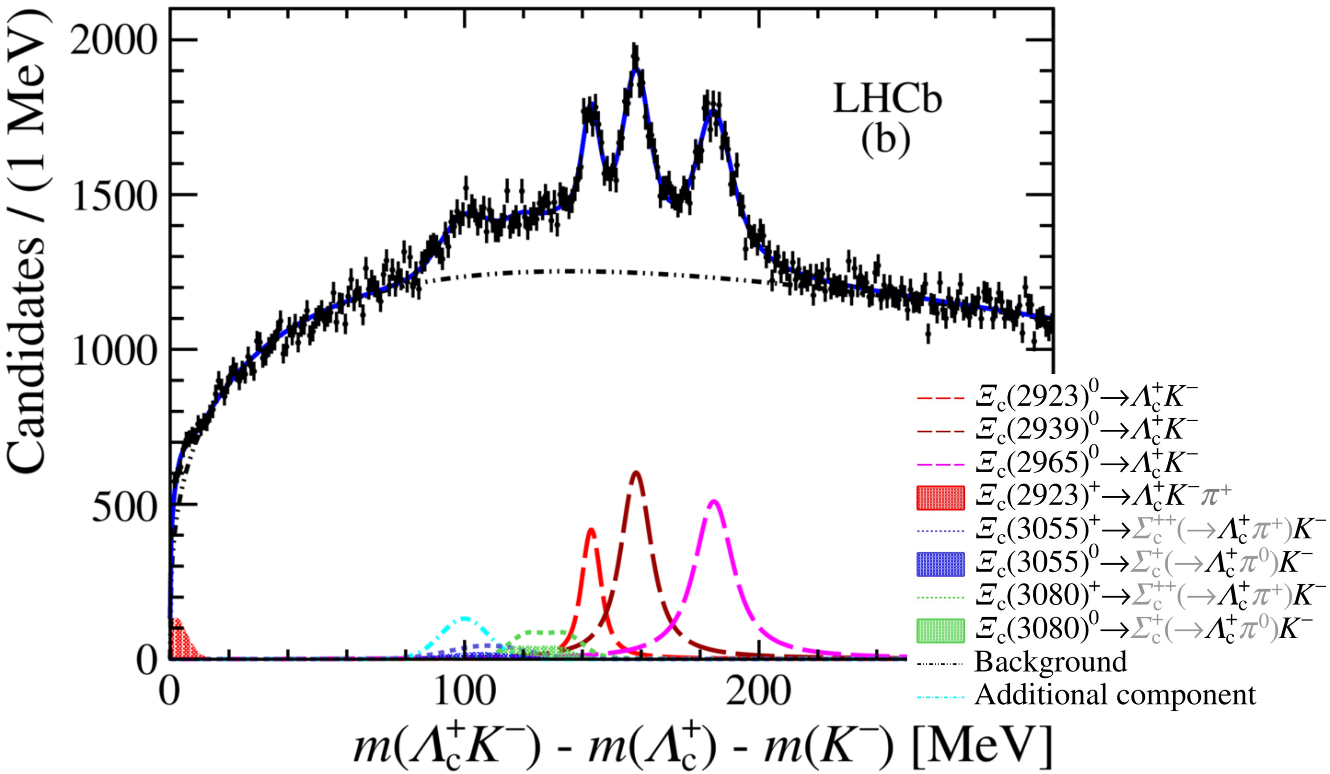
- Observation of new Ξ^0_c baryons decaying to $\Lambda^+_c K^-$ [arXiv:2003.13649]
- Excited Ω^-_b states [Phys. Rev. Lett. 124 (2020) 082002]
- Observation of new pentaquark states [Phys. Rev. Lett. 122 (2019) 222001]

Observation of new Ξ^0_c baryons decaying to $\Lambda^+_c K^-$

[arXiv:2003.13649]

5.6 fb^{-1} @ 13 TeV

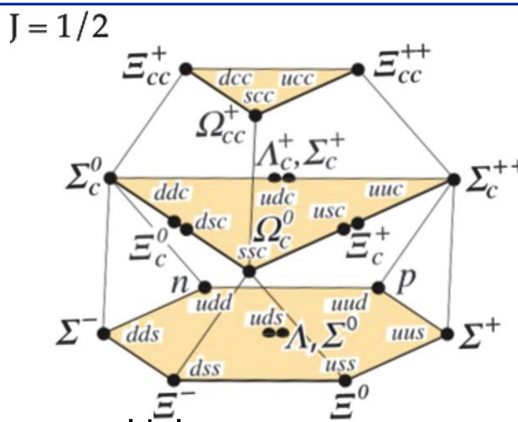
large theoretical interest in study of baryons with a heavy quark



$m(\Xi_c(2923)^0)$ =
2923.04 ± 0.25 ± 0.20 ± 0.14 MeV
Γ=7.1 ± 0.8 ± 1.8 MeV

$m(\Xi_c(2939)^0)$ =
2938.55 ± 0.21 ± 0.17 ± 0.14 MeV
Γ=10.2 ± 0.8 ± 1.1 MeV

$m(\Xi_c(2965)^0)$ =
2964.88 ± 0.26 ± 0.14 ± 0.14 MeV
Γ=14.1 ± 0.9 ± 1.3 MeV



Mass difference to excited $\mathbf{\Omega_c}$ states ≈ 125 MeV, comparable to
m($\mathbf{\Omega_c}$(2770)- m(Ξ_c(2645)) ≈ m(Ξ_c(2645)) - m(Σ_c(2520)) ≈ 125 MeV
→ measurements of spin-parities needed to confirm whether they belong to the same flavour multiplets

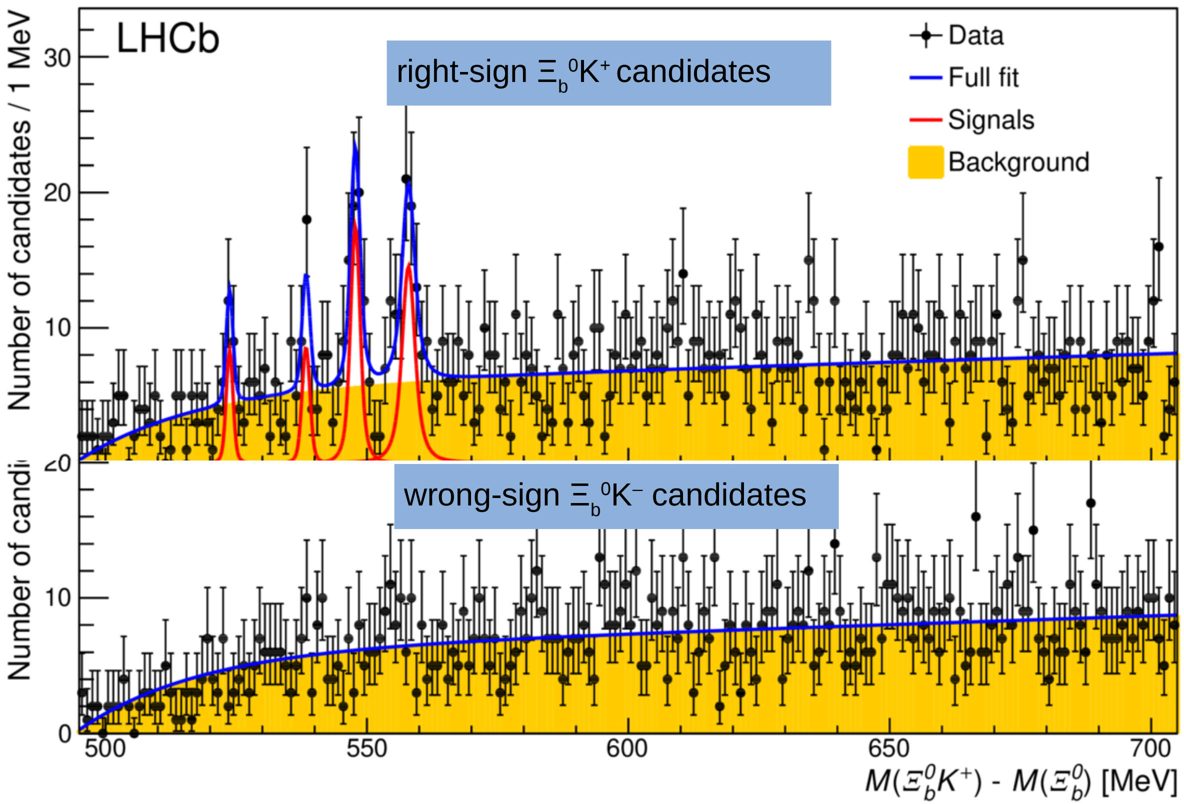
First observation of excited Ω_b^- states

[Phys. Rev. Lett. 124 (2020) 082002]

full Run 1+ Run 2 dataset

pure sample of $\Xi_b^0 \rightarrow \Xi_c^+ \pi^-$ ($\Xi_c^+ \rightarrow pK^-\pi^+$), combine Ξ_b^0 with a kaon

→ four narrow states interpreted as excited states of Ω_b^-



$m(\Omega_b(6316)^-)$ =
6315.64 ± 0.31 ± 0.07 ± 0.50 MeV

$m(\Omega_b(6330)^-)$ =
6330.30 ± 0.28 ± 0.07 ± 0.50 MeV

$m(\Omega_b(6340)^-)$ =
6339.71 ± 0.26 ± 0.05 ± 0.50 MeV

$m(\Omega_b(6350)^-)$ =
6349.88 ± 0.35 ± 0.05 ± 0.50 MeV

uncertainties: stat., syst., $m(\Xi_b^0)$

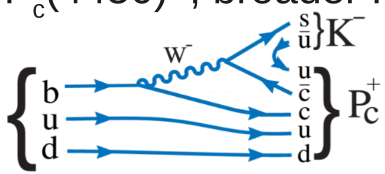
local significance: 3.6 – 7.2σ
global significance: 2.1 – 6.2σ

Observation of new pentaquark states

[Phys. Rev. Lett. 115 (2015) 072001]

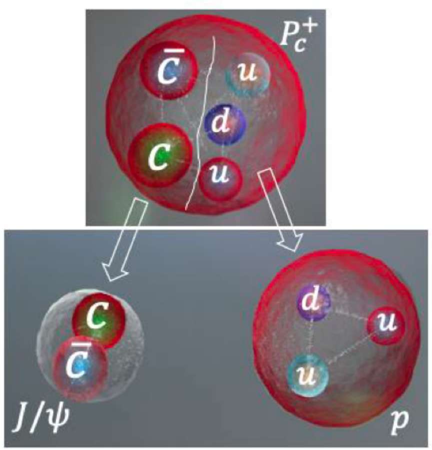
first pentaquarks observed by LHCb four years ago using $\Lambda_b \rightarrow J/\psi K p$

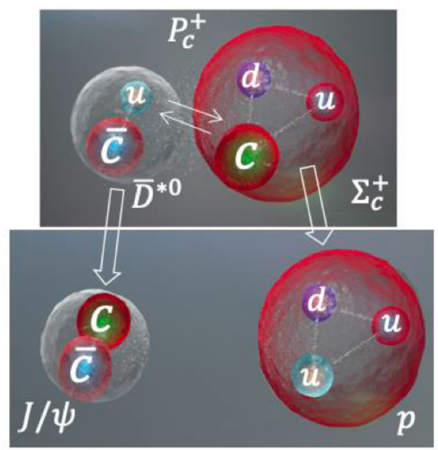
→ narrow $P_c(4450)^+$, broader $P_c(4380)^+$

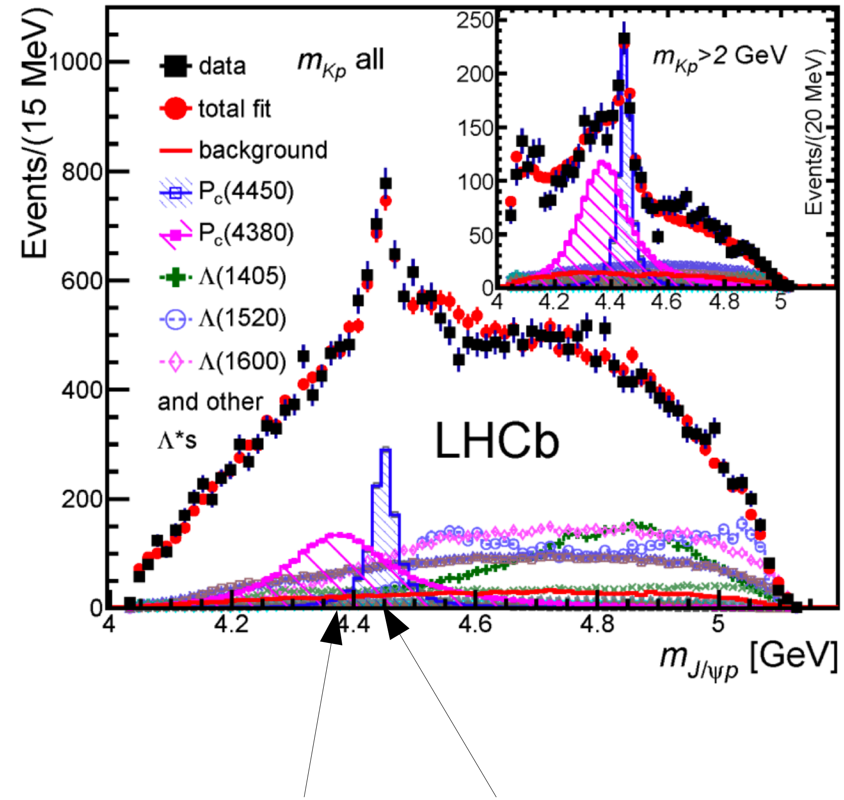


large theoretical interest in understanding the nature of the new states

tightly bound vs loosely bound molecular states







$P_c(4380)^+$ $P_c(4450)^+$

Observation of new pentaquark states

[Phys. Rev. Lett. 122 (2019) 222001]

Update with full Run 2 statistics, 246’000 candidates

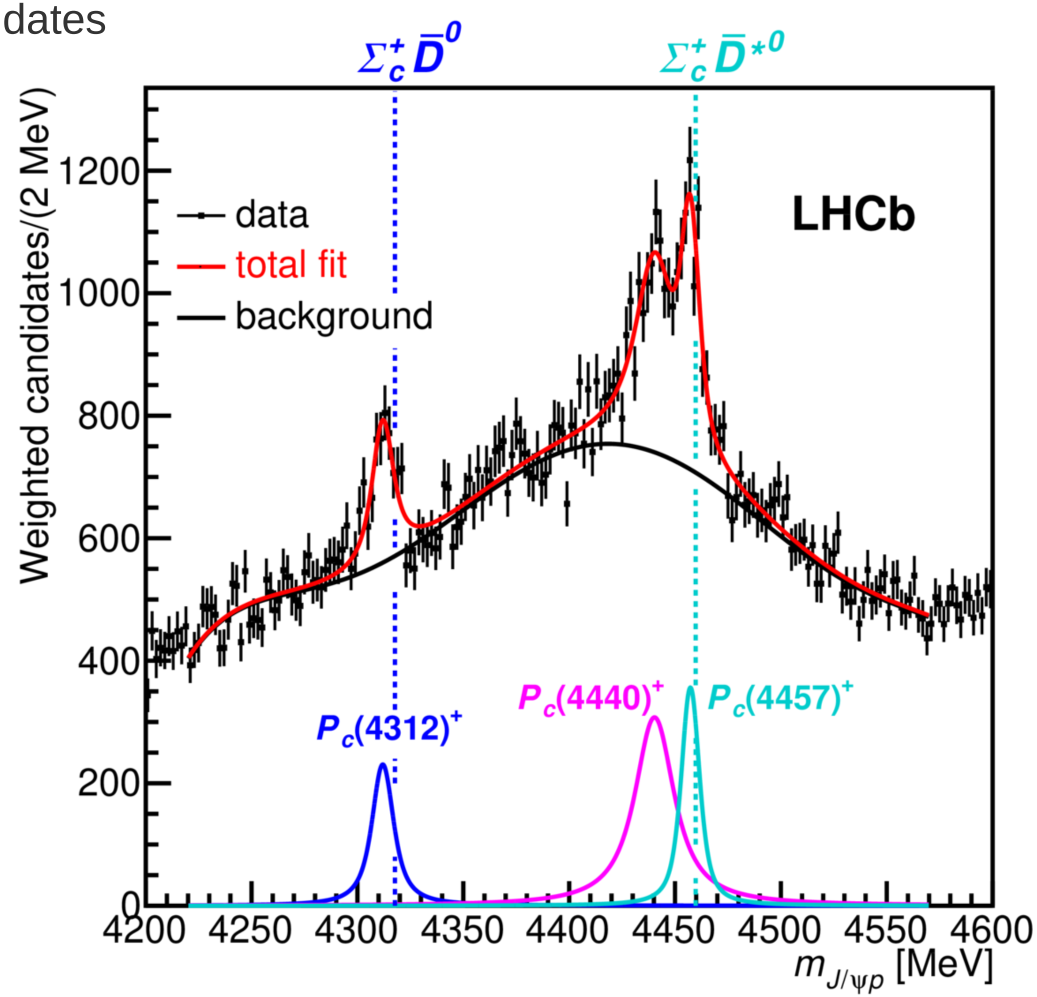
→ new peak at $P_c(4312)^+$ (7.3σ)

→ broad $P_c(4450)^+$ resolved as two narrow states (5.4σ): $P_c(4440)^+$ and $P_c(4457)^+$

minimal quark content duucc

narrow and close to $\Sigma_c^+D^0$ and $\Sigma_c^+D^{*0}$ ([duc][uc]) mass threshold

→ extremely important result to shed light on the nature of these exotic states



charm | beauty | spectroscopy | heavy ion fixed target | upgrade

• charm production in fixed target collisions [PRL 122 (2019) 132002]

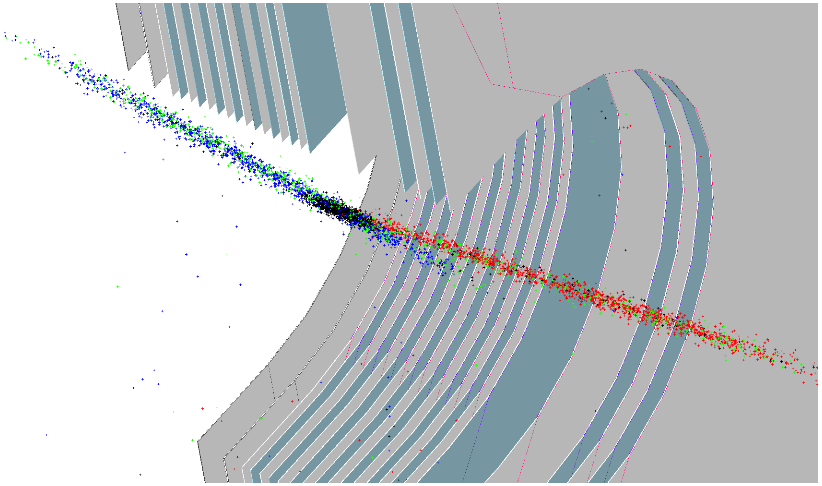
Charm production in fixed target collisions

[PRL 122 (2019) 132002]

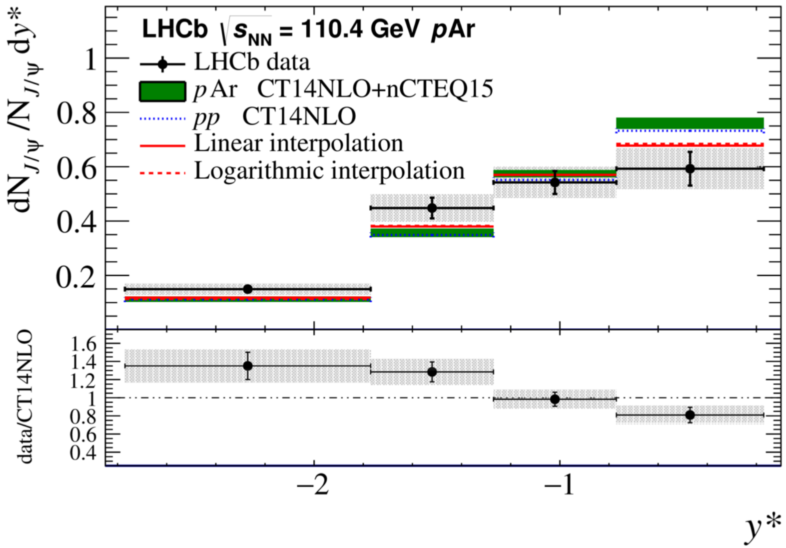
Unique opportunity for measurements in fixed target mode

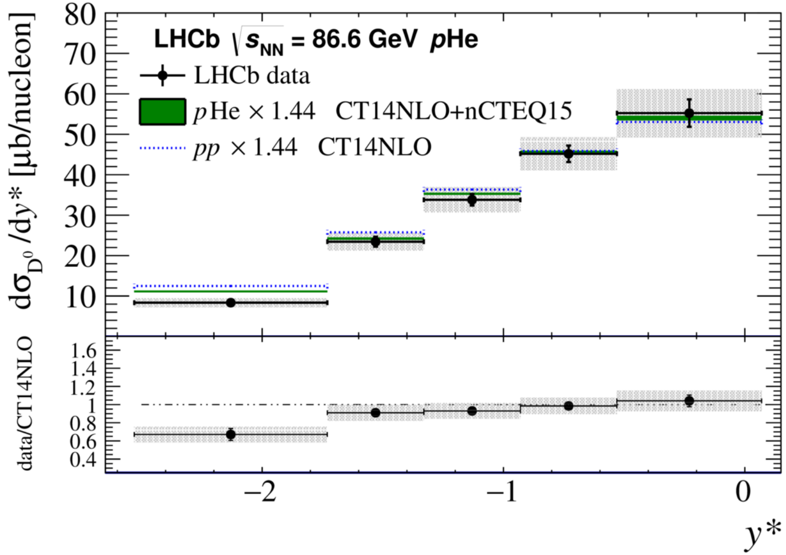
first measurement of charm production (J/ψ and D^0) in pAr @110.4 GeV and pHe @86.6 GeV

→ sensitive to large Bjorken-x, up to x=0.37 for D^0



D^0 good agreement in rapidity shapes
→ no evidence for significant contribution of valence-like intrinsic charm at high x



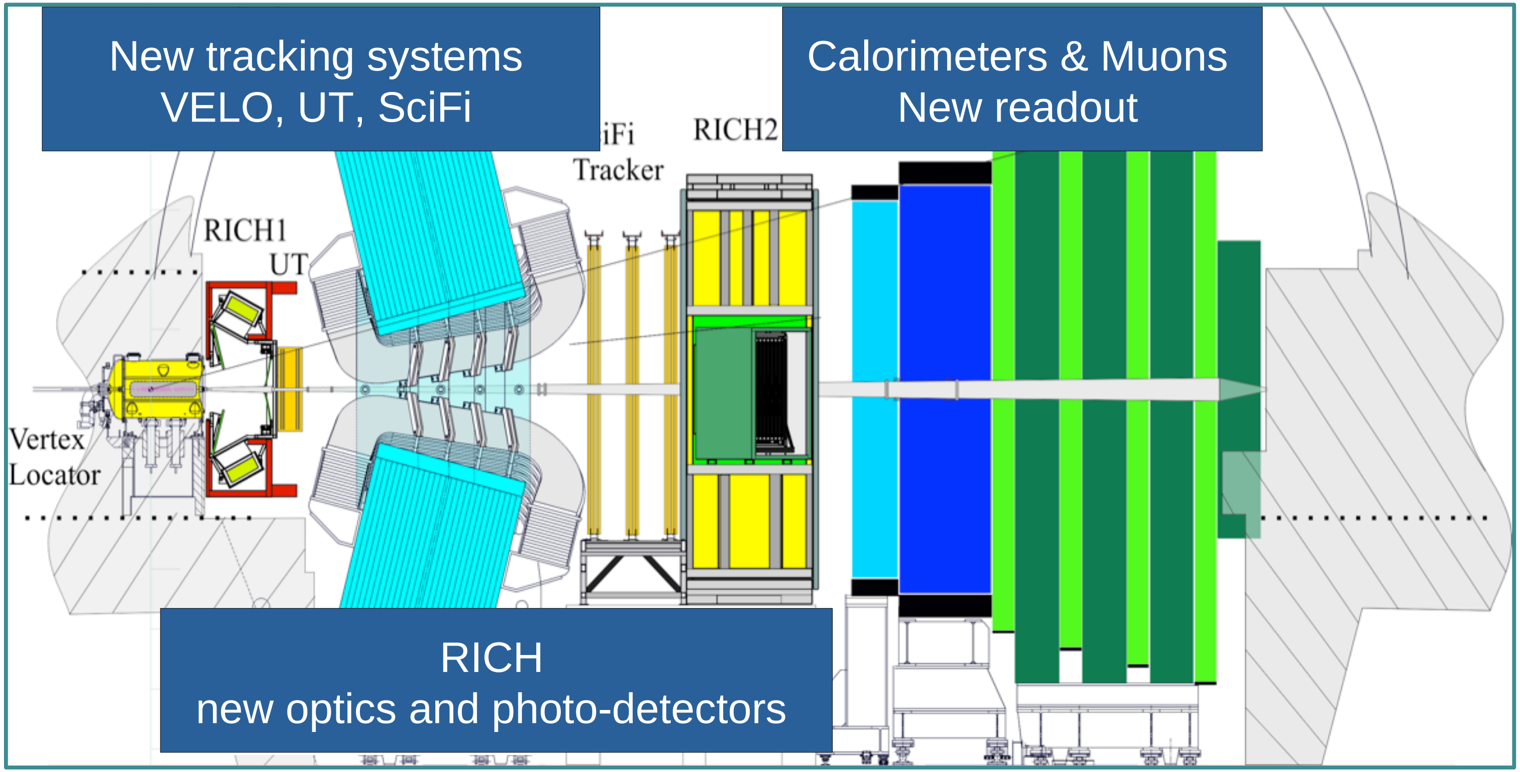


LHCb is transforming

charm | beauty | heavy ion fixed target | spectroscopy | upgrade

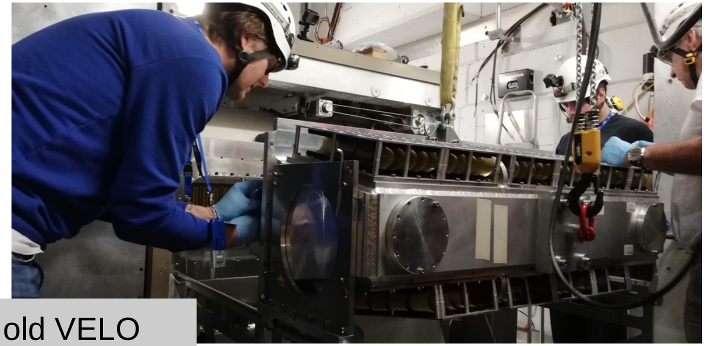
LHCb upgrade – upgrade I

Going on right now!
remove the hardware trigger → all detectors read out at 30 MHz



→ this will be a new detector at LHCb

LHCb upgrade – work in progress

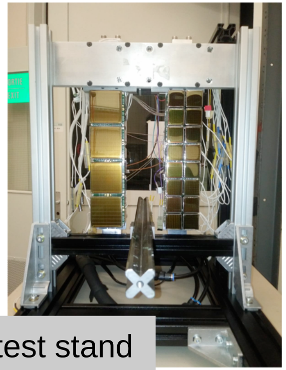


remove old VELO

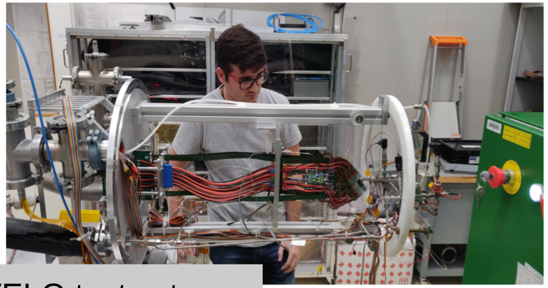
remove beampipe

dismantling muon station

UT stave



RICH test stand

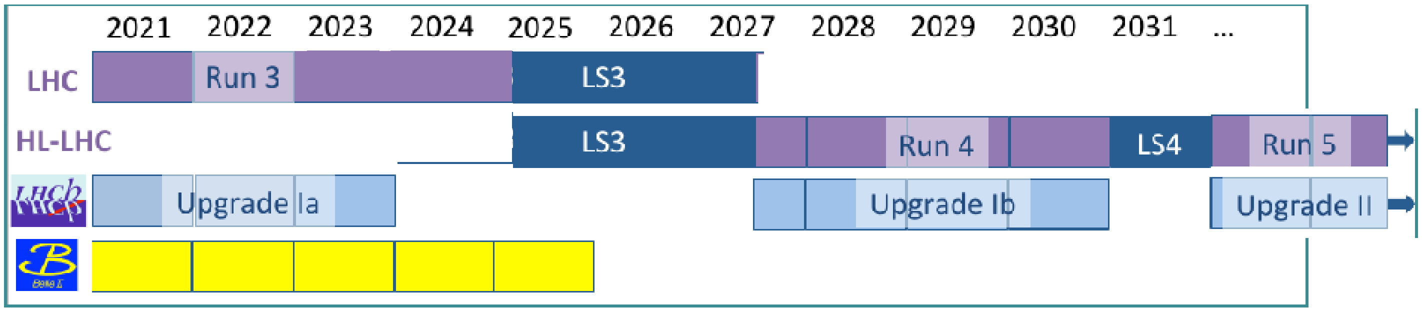


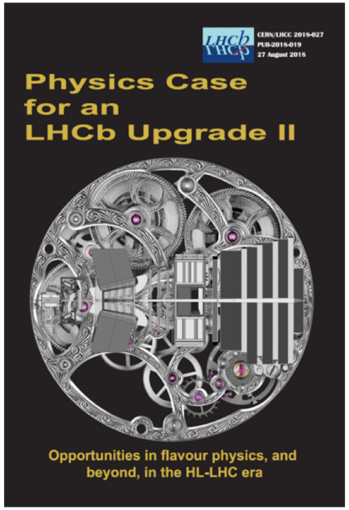
VELO test setup

VELO RF boxes

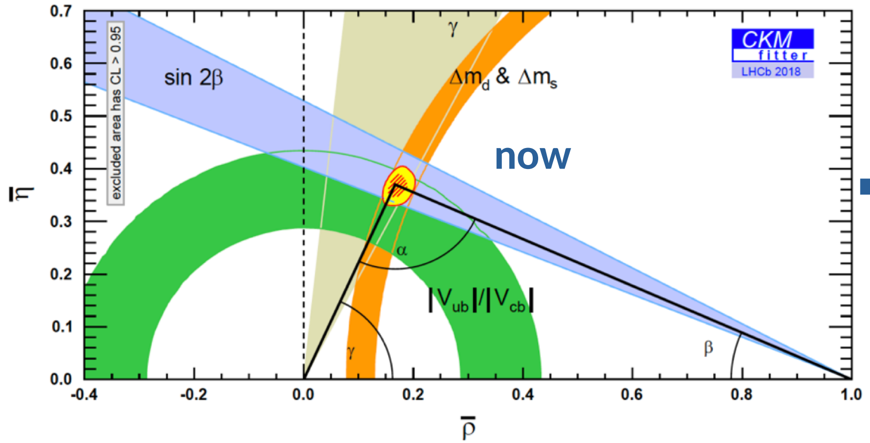
Event builder prototype

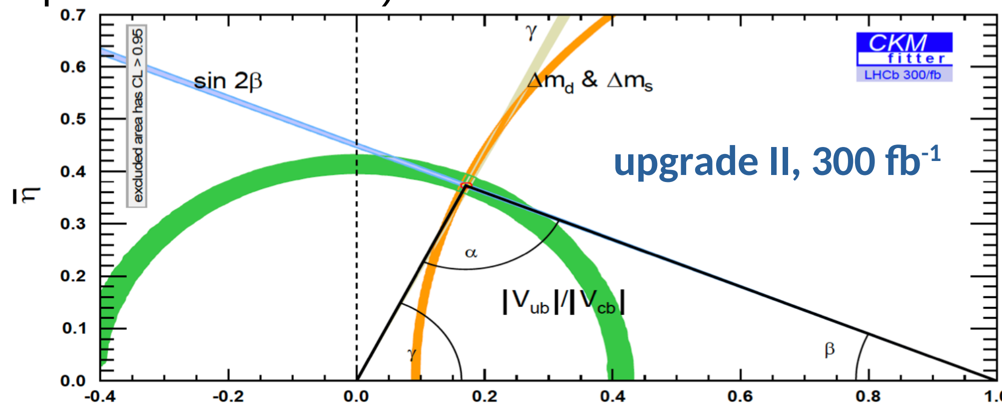
And looking further – upgrade II





- Aim to collect > 300 fb^{-1} at L = $2x10^{34}$, x10 with respect to Upgrade I
- Consolidate in LS3, major upgrade in LS4
- Expression of Interest issued in 2017, feasibility study [CERN-ACC-NOTE-2018-0038]
- Physics case document released [CERN-LHCC-2018-027]
- Green light from LHCC to proceed to TDRs (expected ~late 2020)



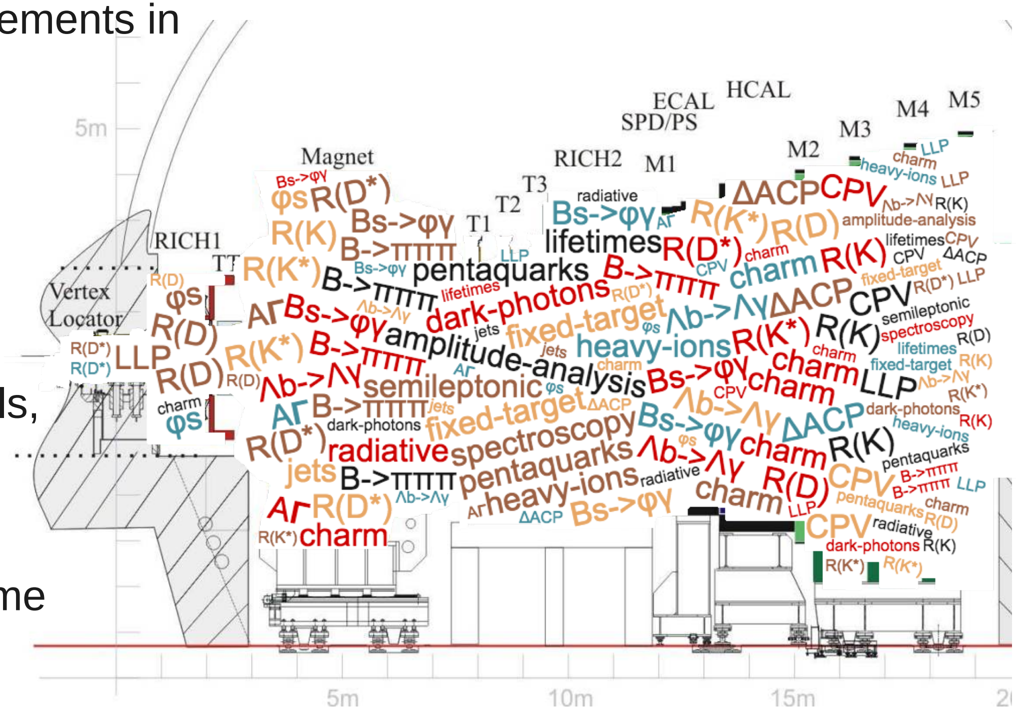


Conclusion and outlook

Plenty of interesting results still coming from LHCb Run1-2
LHCb upgrade opens the door to many improvements in precision, so interesting times are ahead!

LHCb has a bright future

- Tensions on lepton flavour universality will be clear in a few years
- Sensitivity to NP in many interesting channels, more will open with upgraded detector
- Precision measurements of SM parameters
- Heavy Ion and fixed target physics programme has much to add



See also parallel talks:

- Titus Mombacher : Search for rare B decays with the LHCb experiment (Tue, 14:15)
- Aravindhan Venkateswaran: First measurements of isospin amplitudes in Λ_b and Ξ_b decays (Tue, 14:30)

Backup

improvement relative to the world's best limits prior to this work

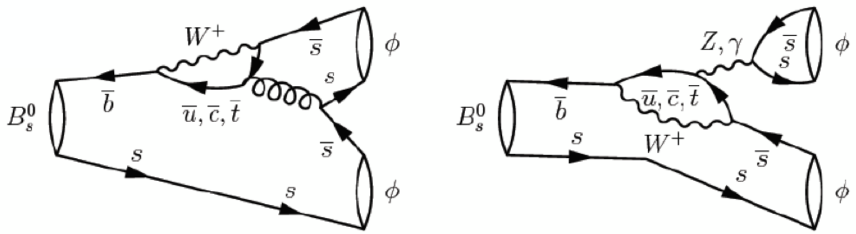
Decay	Branching fraction upper limit $[10^{-9}]$				Improvement	
	D^+		D^+_s			
	90 % CL	95 % CL	90 % CL	95 % CL	D^+	D^+_s
$D^+_{(s)} \to \pi^+\mu^+\mu^-$	67	74	180	210	1.1	2.3
$D^+_{(s)} \to \pi^-\mu^+\mu^+$	14	16	86	96	1.6	1.4
$D^+_{(s)} \to K^+\mu^+\mu^-$	54	61	140	160	79.0	150.0
$D^+_{(s)} \to K^-\mu^+\mu^+$	-	-	26	30	-	500.0
$D^+_{(s)} \to \pi^+e^+\mu^-$	210	230	1100	1200	14.0	11.0
$D^+_{(s)} \to \pi^+\mu^+e^-$	220	220	940	1100	16.0	21.0
$D^+_{(s)} \to \pi^-\mu^+e^+$	130	150	630	710	16.0	13.0
$D^+_{(s)} \to K^+e^+\mu^-$	75	83	790	880	16.0	18.0
$D^+_{(s)} \to K^+\mu^+e^-$	100	110	560	640	28.0	17.0
$D^+_{(s)} \to K^-\mu^+e^+$	-	-	260	320	-	23.0
$D^+_{(s)} \to \pi^+e^+e^-$	1600	1800	5500	6400	0.7	2.3
$D^+_{(s)} \to \pi^-e^+e^+$	530	600	1400	1600	2.1	3.0
$D^+_{(s)} \to K^+e^+e^-$	850	1000	4900	5500	1.2	0.8
$D^+_{(s)} \to K^-e^+e^+$	-	-	770	840	-	6.7

Measurement of CP violation in $B_s \rightarrow \Phi\Phi$

[JHEP 12 (2019) 155]

enhanced sensitivity to NP since decay is dominated by b→ sss penguin loop

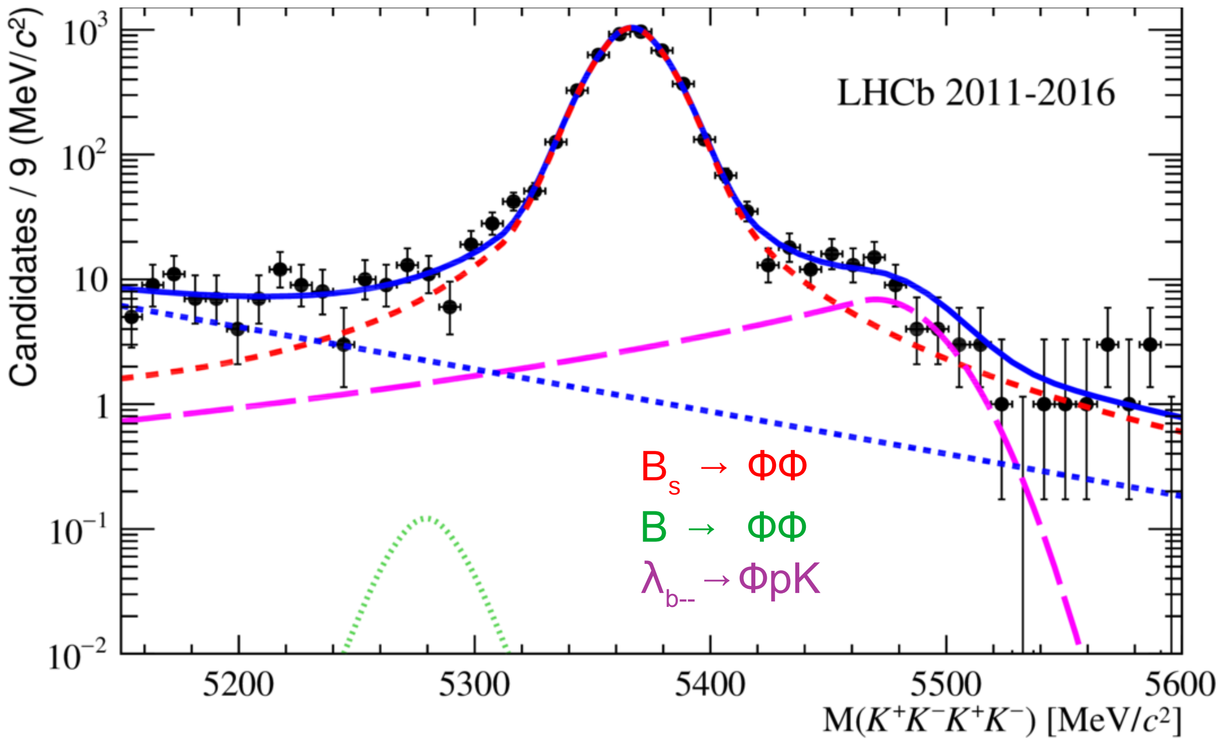
SM prediction $|\Phi_s^{sss}| < 20$ mrad
[arXiv:0810.0249 Phys.Rev.D80:114026,2009]



time dependent angular analysis, Run 1 + 2 fb^{-1} Run 2

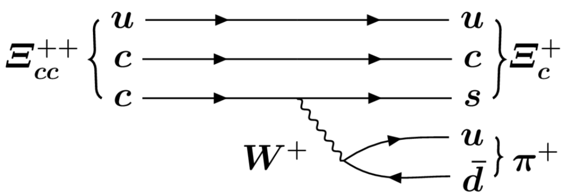
$\Phi_s^{sss} = -73 \pm 115 \pm 27$ mrad

$|\lambda| = -0.99 \pm 0.05 \pm 0.01$



Doubly charmed baryons

[Chin. Phys. C44 (2020) 022001]
[JHEP 02 (2020) 049]



ground states: Ξ_{cc}^{++} (ccu), Ξ_{cc}^{+} (ccd) and Ω_{cc}^{+} (ccs)

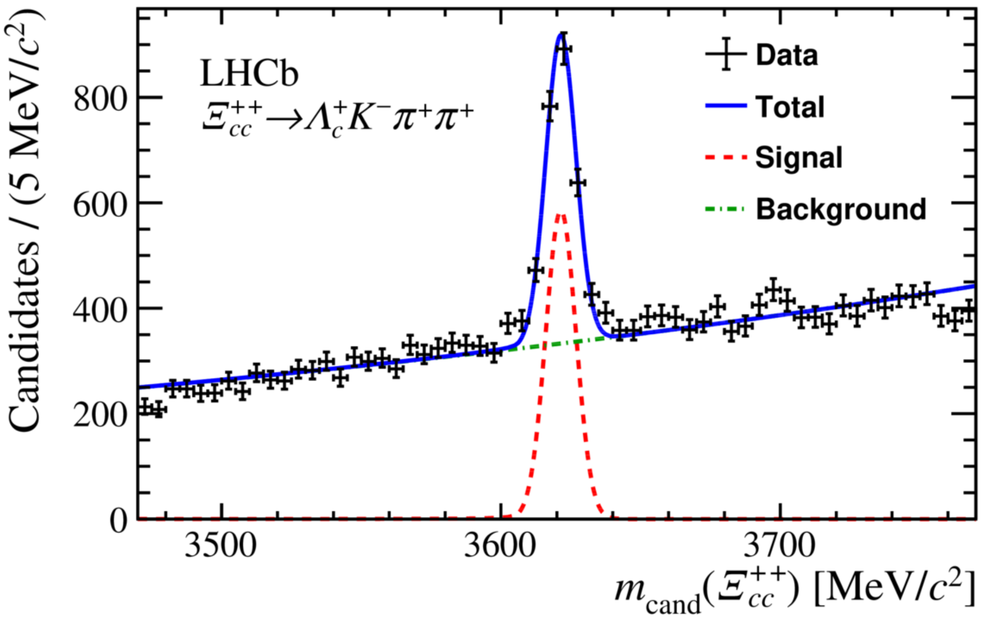
only Ξ_{cc}^{++} discovered so far, search ongoing for Ξ_{cc}^{+} and Ω_{cc}^{+}

first observed by LHCb in decay:

$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ and $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ [Phys. Rev. Lett. 121 162002 (2018)]

new analysis @ 13 TeV:

- production cross-section times the BF of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ relative to the prompt Λ_c^+ production cross-section:
  $(2.22 \pm 0.27 \pm 0.29) \times 10^{-4}$
  ($4 < p_T < 15$ GeV/c and $2.0 < y < 4.5$)

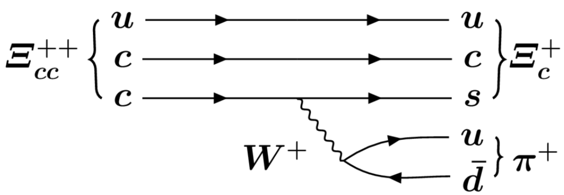


- precise mass measurement
  326 ± 37 candidates
  decay modes: $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$, $\Xi_{cc}^{++} \to \Lambda_c^+ K$

$M(\Xi_{cc}^{++}) = 3621.55 \pm 0.23(\text{stat}) \pm 0.30\,(\text{syst})$ MeV/c^2

Doubly charmed baryons

ground states: Ξ_{cc}^{++} (ccu), Ξ_{cc}^{+} (ccd) and Ω_{cc}^{+} (ccs)
only Ξ_{cc}^{++} discovered so far, search ongoing for Ξ_{cc}^{+} and Ω_{cc}^{+}



first observed by LHCb in decay:
$\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+}$ and $\Xi_{cc}^{++} \to \Lambda_c^{+} K^{-} \pi^{+} \pi^{+}$ [Phys. Rev. Lett. 121 162002 (2018)]

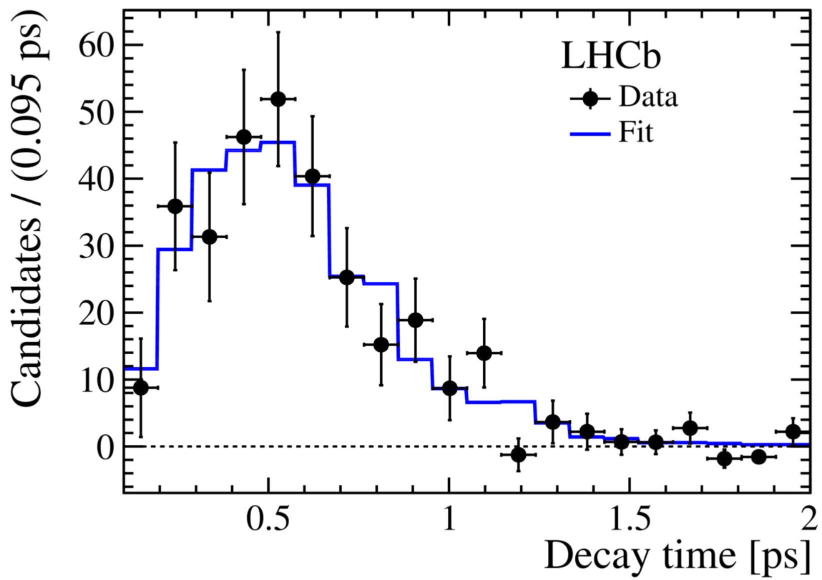
weakly decaying: $\tau(\Xi_{cc}^{++}) = 0.256{+0.024 \atop -0.022}\text{(stat)} \pm 0.014\text{(syst) ps}$ [PRL 121 (2018) 052002]
no signal found for: $\Xi_{cc}^{++} \to D^{+}(\to K^{-}\pi^{+}\pi^{+})\, pK^{-}\pi^{+}$ [JHEP 10 (2019) 124]

new analysis @ 13 TeV:

- production cross-section times the BF of $\Xi_{cc}^{++} \to \Lambda_c^{+} K^{-} \pi^{+} \pi^{+}$ relative to the prompt Λ_c^{+} production cross-section:

  $(2.22 \pm 0.27 \pm 0.29) \times 10^{-4}$
  ($4 < p_T < 15$ GeV/c and $2.0 < y < 4.5$)

- precise mass measurement

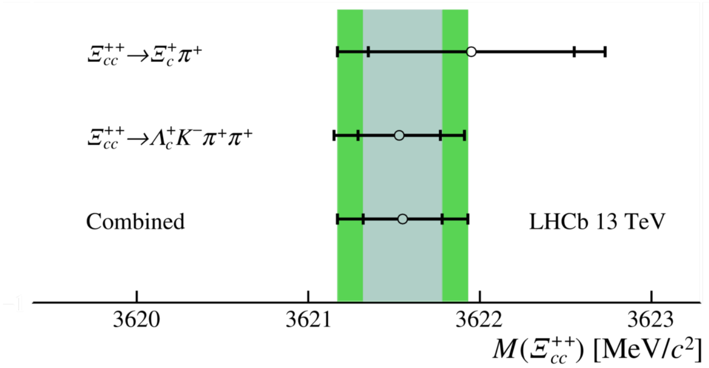


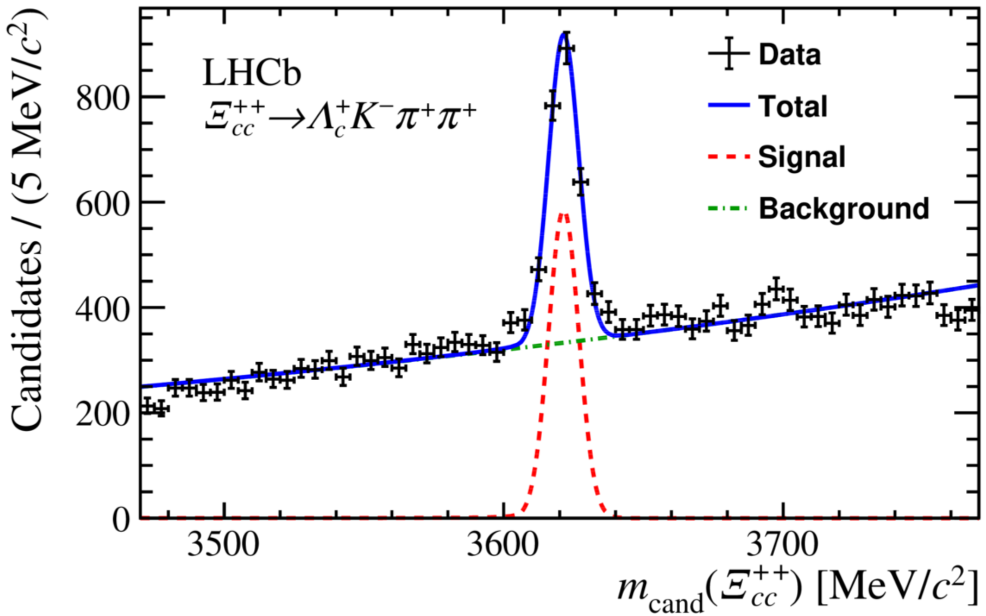
Doubly charmed baryons

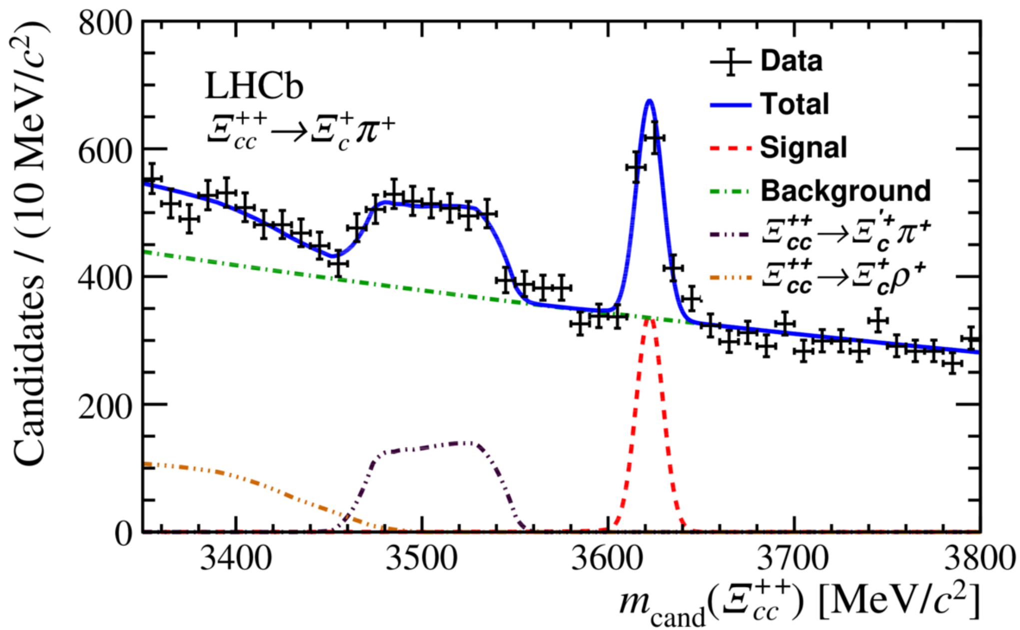
new analysis @ 13 TeV 326 ± 37 candidates
decay modes: $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$, $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$

$M(\Xi_{cc}^{++})$ = 3621.55 ± 0.23(stat) ± 0.30 (syst) MeV/c²

dominated by the result for the $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ mode







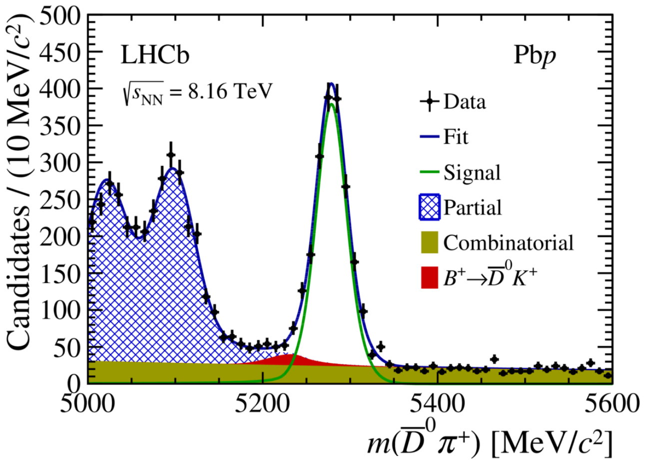
b-hadron production in proton-lead collisions

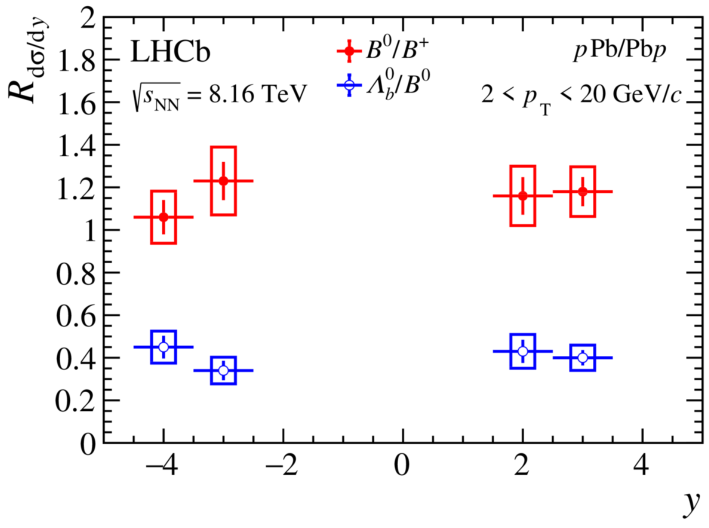
[Phys. Rev. D99 052011 (2019)]

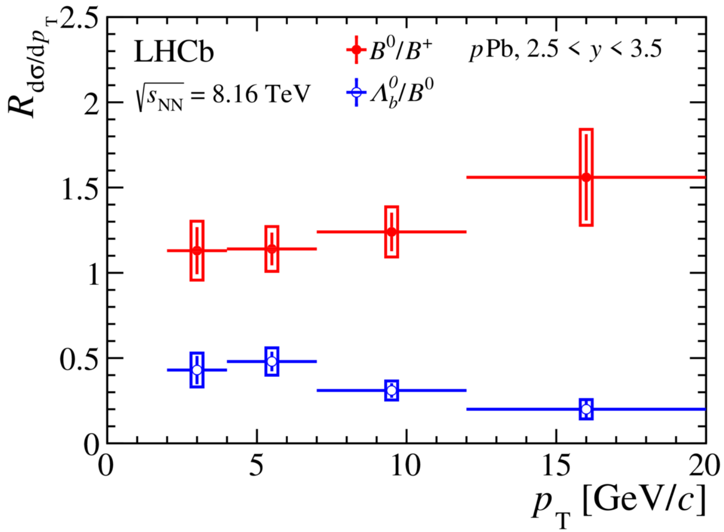
Production of B^0, B^+ and Λ_b in proton-lead cm enery 8.16 TeV with exclusive decay modes

→ first measurement of beauty hadron production at p_T< mass of the hadrons in the forward region

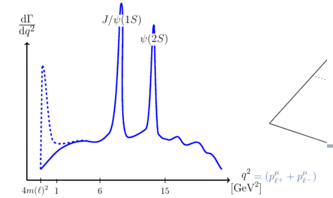
→ input for fits of the nuclear PDFs
→ fragmentation models in nuclear environment



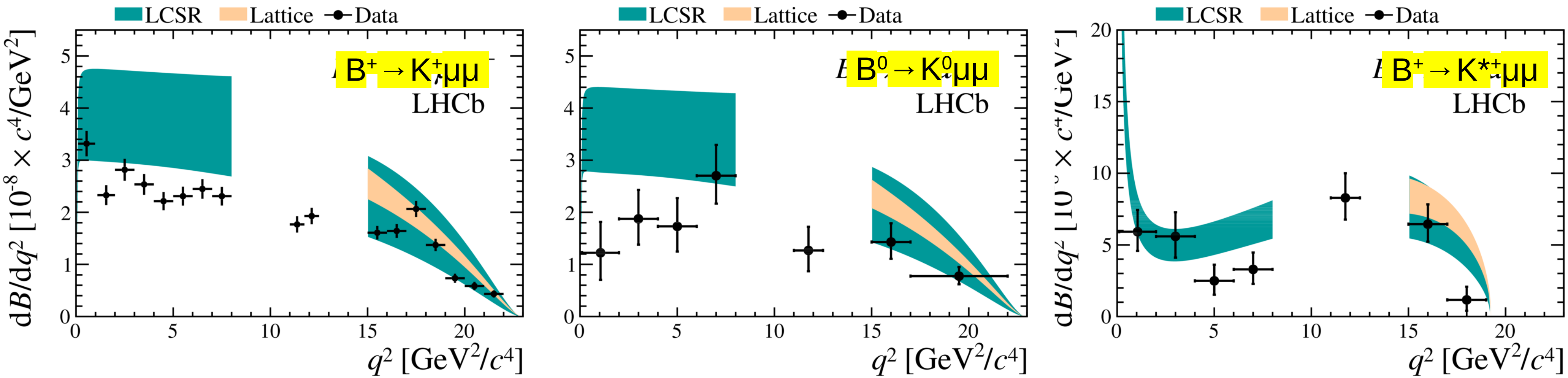




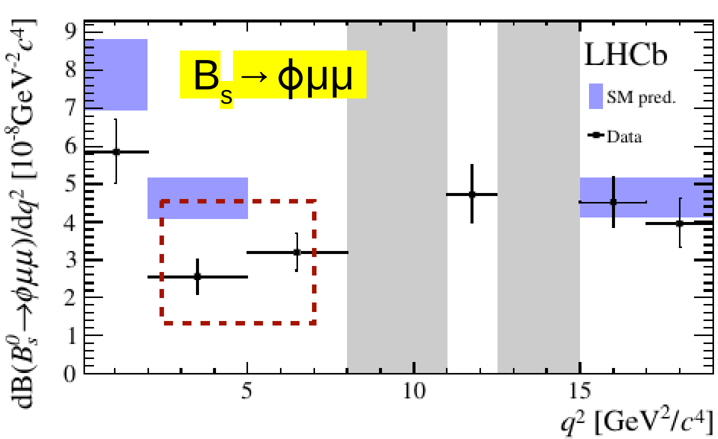
LHCb b → sμμ decay rates



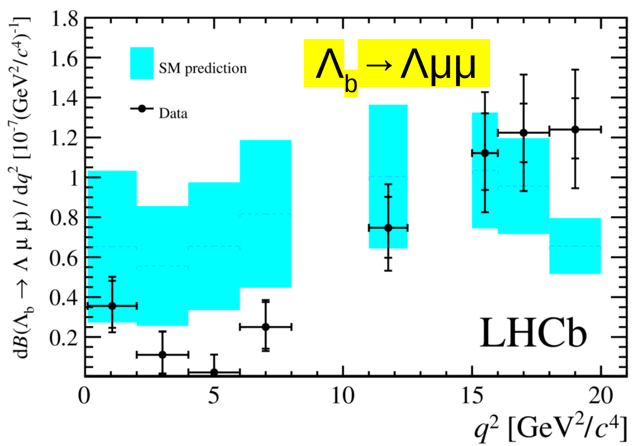
[JHEP 06 (2014) 133]



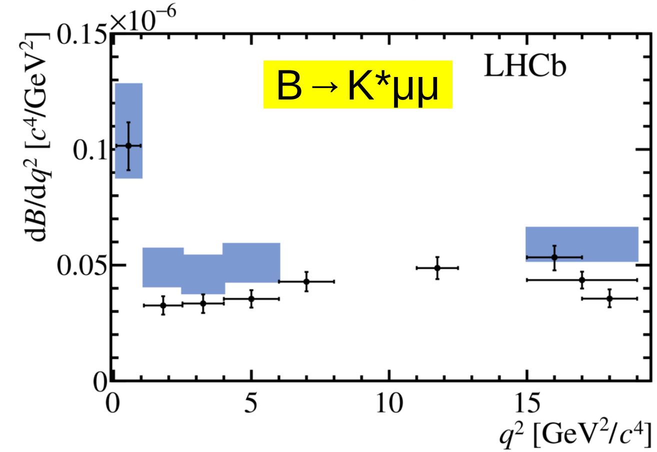
JHEP 09 (2015) 179



[JHEP 06 (2015) 115]



JHEP 04 (2017) 142]



$b \to s\ell\ell$ decay rates systematically below the SM predictions

Test of lepton flavour universality

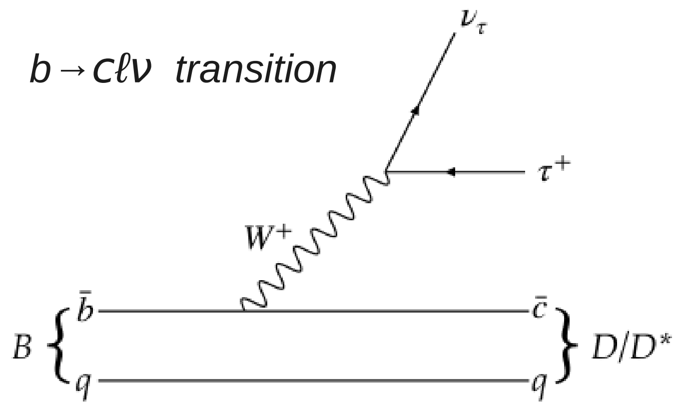
test of LFU in various B decays with leptons in the final state

Charged current (Semileptonic decays)

tree-level decays $b \to c\ell\nu$
BR of of few %, precise prediction in SM

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

$b \to c\ell\nu$ transition



Neutral currents (Rare decays)

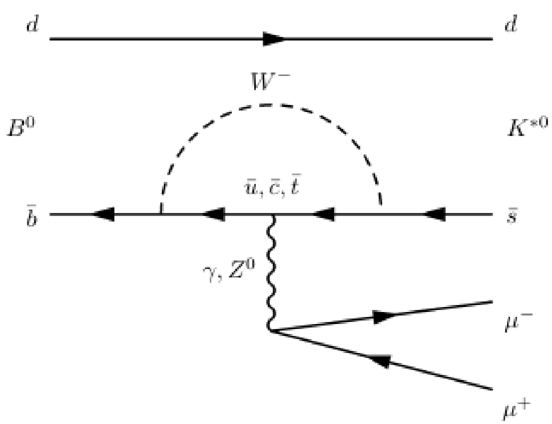
$b \to s\ell\ell$
forbidden at tree-level in the SM
→ FCNC only at loop level → BR $10^{-7} \div 10^{-6}$

theoretically clean

$$R(K^{(*)}) = \frac{BR(B \to K^{(*)} \mu\mu)}{BR(B \to K^{(*)} ee)} = 1 \pm \underbrace{O(10^{-3})}_{\text{neglect lepton mass}} \pm \underbrace{O(10^{-2})}_{\text{QED}}$$

EPJ C76 (2016) 8, 440

$b \to s\ell\ell$ transition



Multiplicity dependence of $X_{c1}(3872)/\psi(2S)$

[LHCB-CONF-2019-005]

$X_{c1}(3872)/\psi(2S)$ ratio versus multiplicity measured at $\sqrt{s}$ = 8 TeV helps to understand the nature of the exotic state

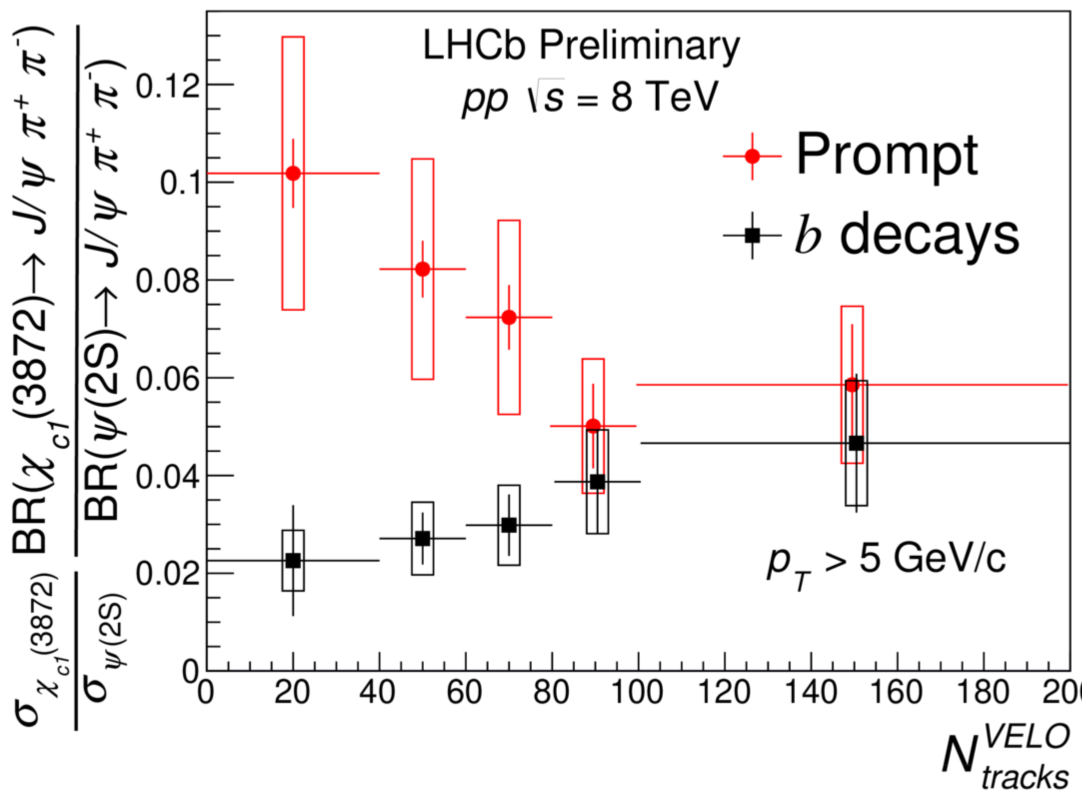
→ no significant variation is observed

for the non-prompt component

→ hint of a relative suppression for prompt component

consistent with the interpretation of the $\chi_{c1}(3872)$ as a weakly bound state such as a D^0D^{*0} hadronic molecule

baseline for a future analysis in proton-lead collisions



New measurement of R(K)

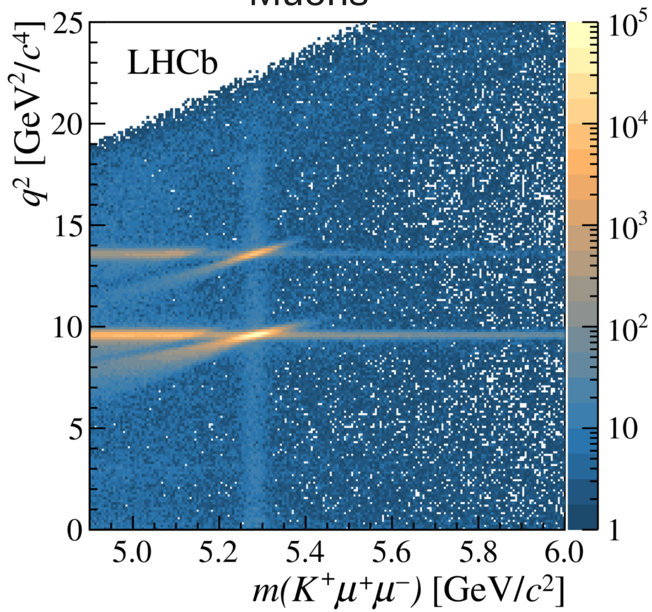
[Phys. Rev. Lett. 122 (2019) 191801]

measure R as a double ratio to reduce systematic effects
due to differences between electrons and muons

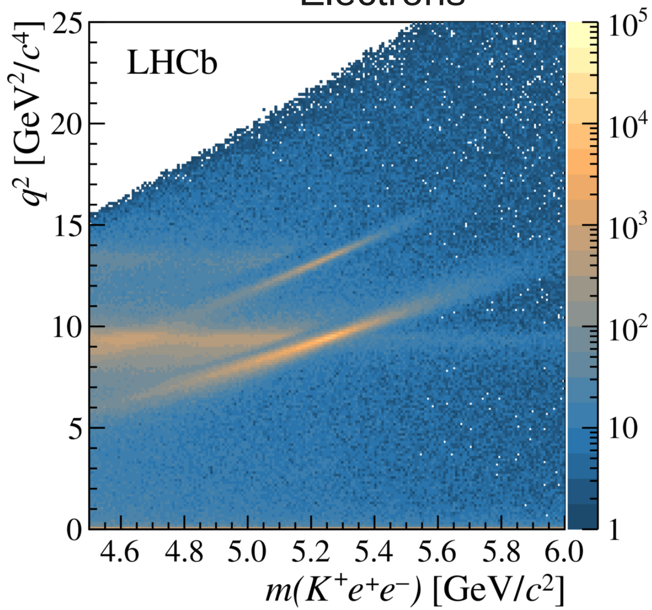
$$R(K)=\frac{BR(B\rightarrow K\mu\mu)}{BR(B\rightarrow K J/\psi(\rightarrow\mu\mu))}\frac{BR(B\rightarrow K J/\psi(\rightarrow ee))}{BR(B\rightarrow K ee)}$$

but electrons are difficult to measure at LHCb: trigger, Bremsstrahlung …

Muons



Electrons

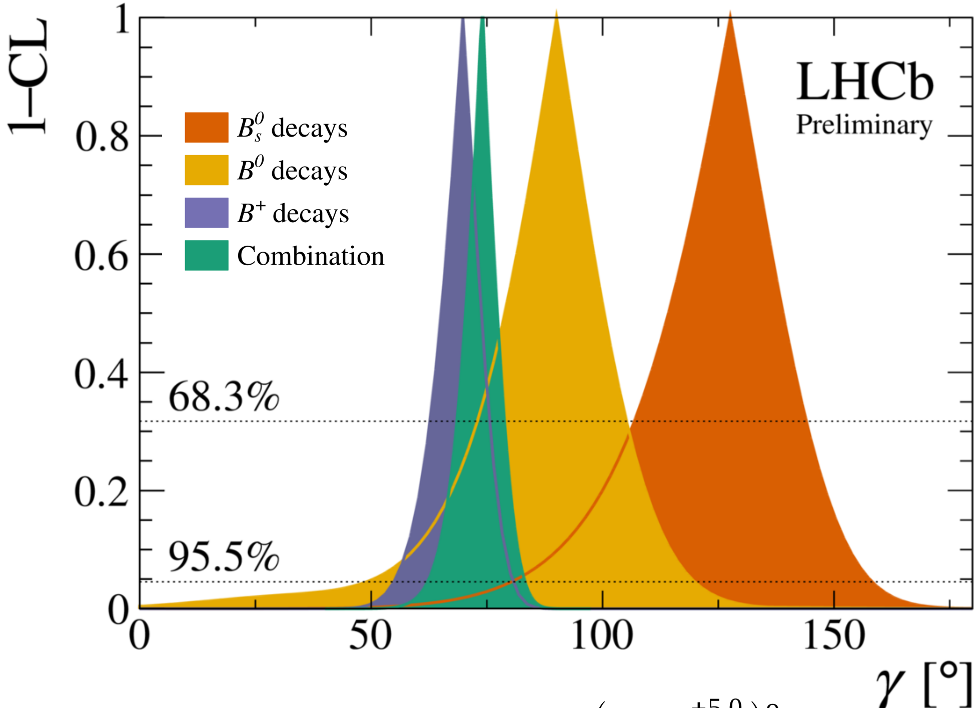


Combination of γ measurements

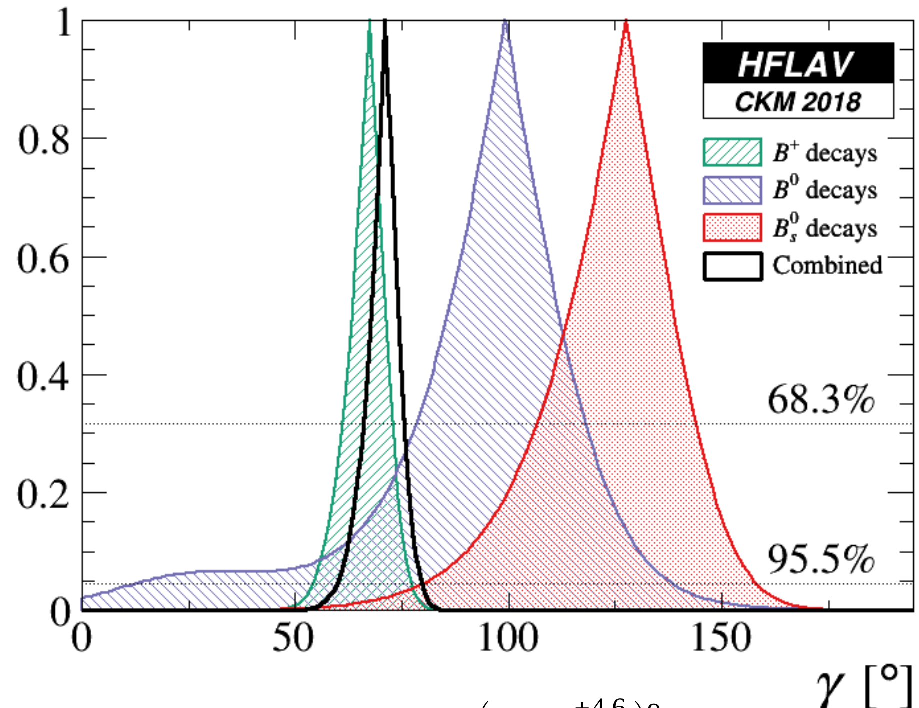
LHCb: new measurement in $B^0 \rightarrow DK^{*0}$ ($D \rightarrow K\pi$, KK, $\pi\pi$) [arXiv:1906.08350]

tension (2σ) between B^+ and B_s^0 results

tension (2σ) between direct measurements and indirect constraints from UT



$$\gamma = (74.0^{+5.0}_{-5.8})^{o}$$



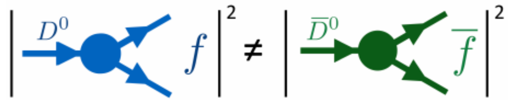
$$\gamma = (71.1^{+4.6}_{-5.3})^{o}$$

from UT (CKM fitter) $\gamma = (65.8^{+1.0}_{-1.7})^{o}$

Observation of CP violation in charm

[Phys. Rev. Lett. 122 (2019) 211803]

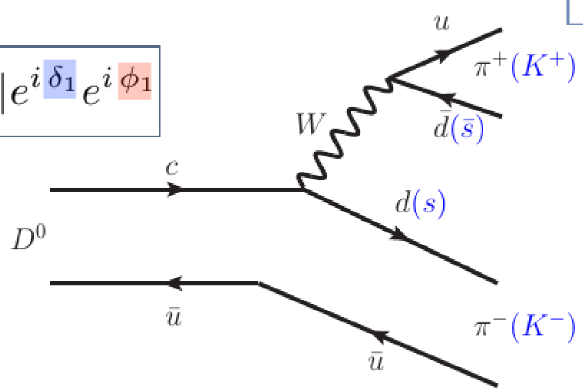
Difference in decay rates



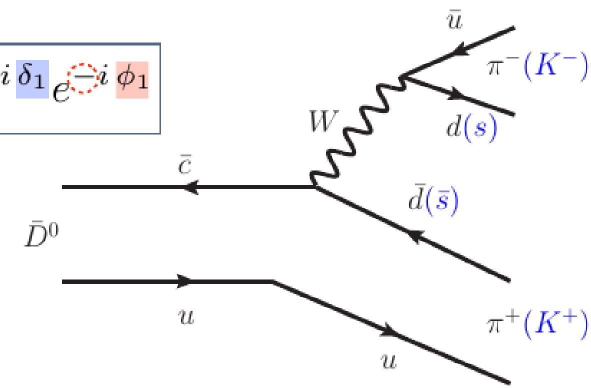
requires two amplitudes with different strong and weak phases

Tree diagram (A_T)

$|A_T|e^{i\,\delta_1}e^{i\,\phi_1}$

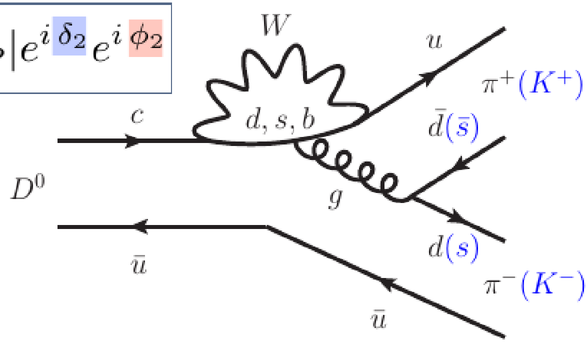


$|A_T|e^{i\,\delta_1}e^{-i\,\phi_1}$

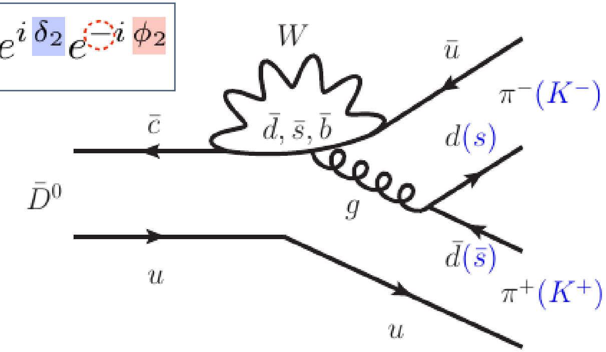


Penguin diagram (A_P)

$|A_P|e^{i\,\delta_2}e^{i\,\phi_2}$



$|A_P|e^{i\,\delta_2}e^{-i\,\phi_2}$



New combination of γ measurements

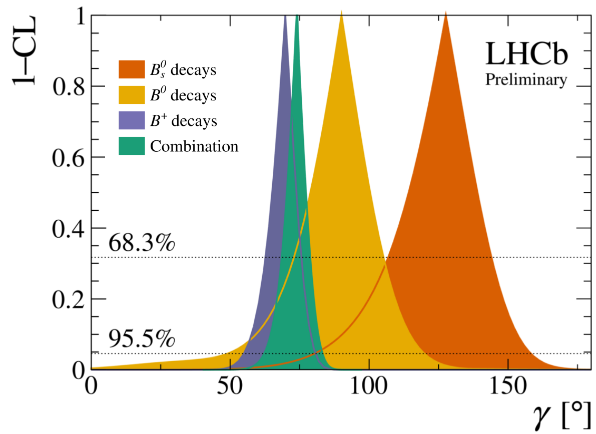
[LHCb-CONF-2018-002]

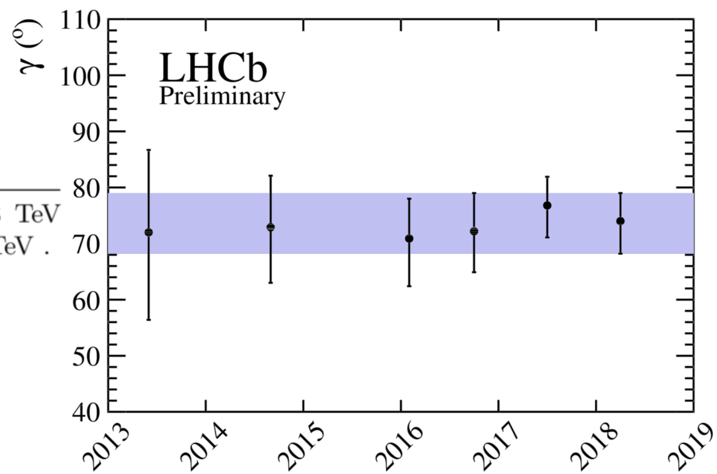
Combination of many tree level determinations

Using frquentist treatment

B decay	D decay	Method	Ref.	Dataset†	Status since last combination [3]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[16]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[17]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[18]	Run 2	New
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	[19]	Run 1	As before
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[20]	Run 1 & 2	Updated results
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1 & 2	New
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[22]	Run 1	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[23]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[24]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	TD	[25]	Run 1	Updated results
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^+\pi^-\pi^+$	TD	[26]	Run 1	New

† Run 1 corresponds to an integrated luminosity of 3 fb^{-1} taken at centre-of-mass energies of 7 and 8 TeV . Run 2 corresponds to an integrated luminosity of 2 fb^{-1} taken at a centre-of-mass energy of 13 TeV .





Run 2 measurements with 2 fb^{-1} (4 fb^{-1} yet to be included)

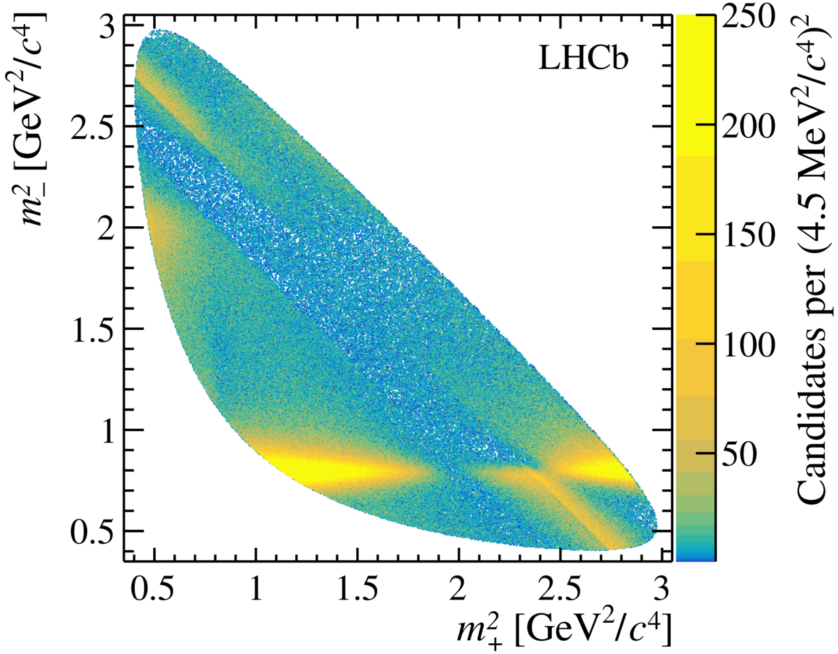
$$\gamma = (74.0^{+5.0}_{-5.8})^{\circ}$$

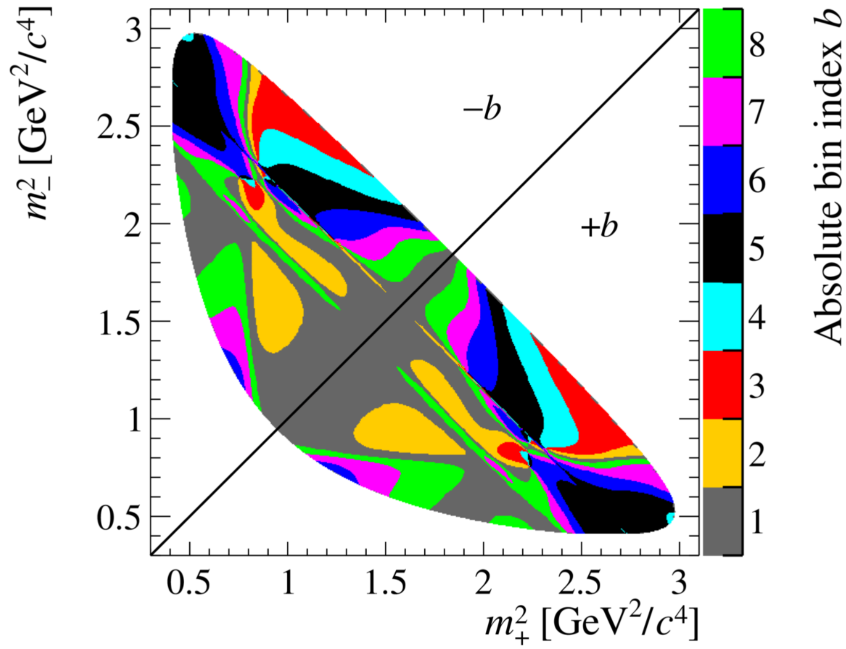
Oscillations of charm mesons in $D^0 \to K_S^0\pi^-\pi^+$

[Phys. Rev. Lett 122 (2019) 231802]

Model independent approach (bin-flip method)
Data is binned in Dalitz coordinates
binning scheme: approximately constant strong-phase differences

measure the yield ratio $R^{\pm}_{bj}$ between −b and b in bins of decay time





Phys. Rev. D99 (2019) 012007, arXiv:1811.01032l