Recent highlights from the LHCb experiment and future prospects

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Content

- The LHCb Experiment

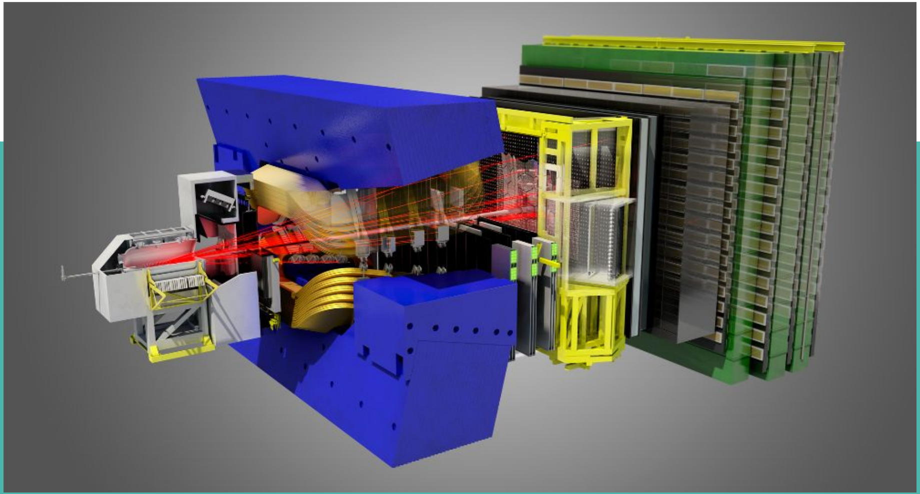
- Recent results
  - Rare decays of b-hadrons
  - Spectroscopy
  - CPV

- Future prospects

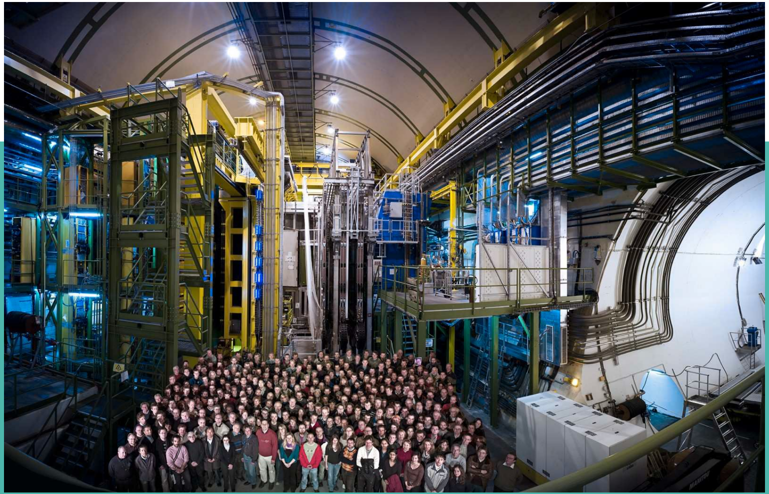
Disclaimer: no time to cover everything, selected topics reflect my personal bias

The LHCb experiment

LHCb: Large Hadron Collider Beauty experiment



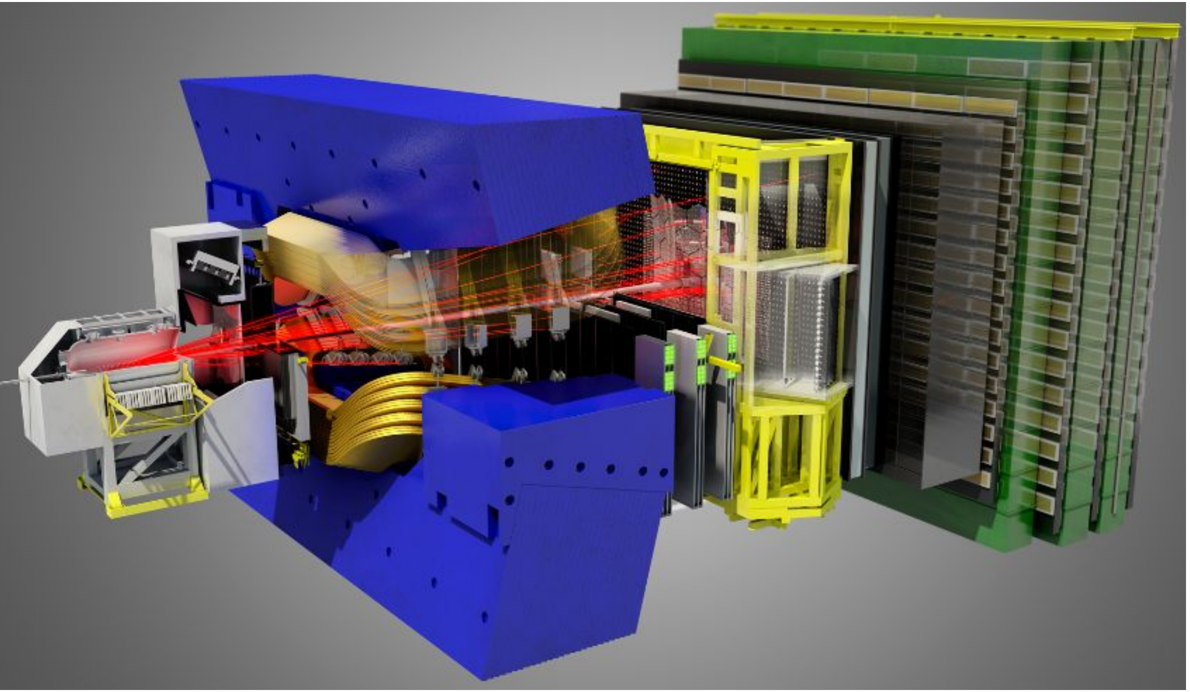
- Precision measurements heavy flavor physics
- Core physics: CPV and rare decays
- Much more: spectroscopy, QCD, heavy ions…



- > 900 authors and > 40 nationalities
- 87 institutes from 18 countries

JINST 3 (2008) S08005

Experimental setup



$\Delta p / p = 0.5 - 1.0\%$
$\Delta IP = (15 + 29/p_T[GeV])\ \mu m$

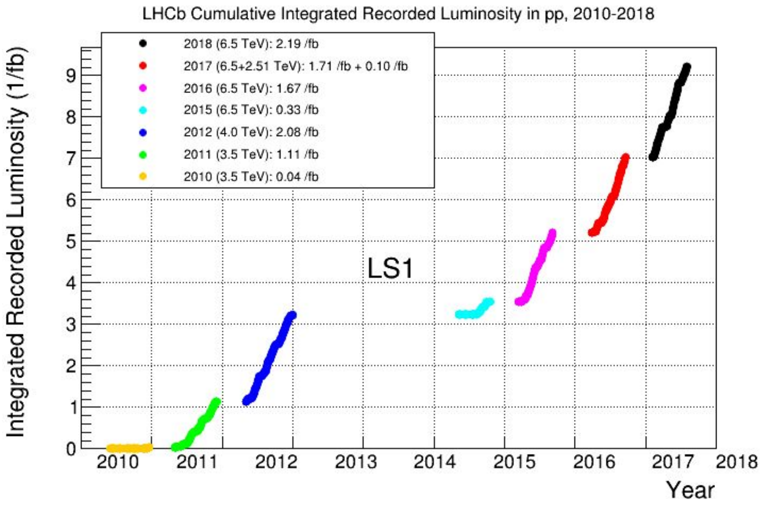
$\Delta E/E_{ECAL} = 1\% + 10\% / \sqrt{(E[GeV])}$

Electron ID ~90% for ~5% e→h mis-id probability

Kaon ID ~ 95 % for ~ 5 % π→K mis-id probability

Muon ID ~ 97% for 1-3% π→μ mis-id probability

LHCb dataset



Total recorded luminosity ~9 fb^{-1}:

- Run 1 (2010-2012) ~ 3 fb^{-1}
- Run 2 (2015-2018) ~ 6 fb^{-1}

$\sigma^{13TeV}(pp \to B^{\pm}X)/\sigma^{7TeV}(pp \to B^{\pm}X)$ = 2.02 ± 0.02 ± 0.12
[JHEP 1712 (2017) 026] → almost x4 b-hadrons in Run 2

All b-hadron species!

- B_s: $\frac{f_s}{f_d+f_u} = 0.122 \pm 0.006$ *
- Λ_b: $\frac{f_{\Lambda_b}}{f_d+f_u} = 0.259 \pm 0.018$

average over $p_T \in [4, 25]$ GeV and $\eta \in [2, 5]$
in pp collisions at 13 TeV [PRD100(2019)031102]
and more: Ξ_b, Ω_b, B_c, B^* ...

*combination of LHCb results ongoing

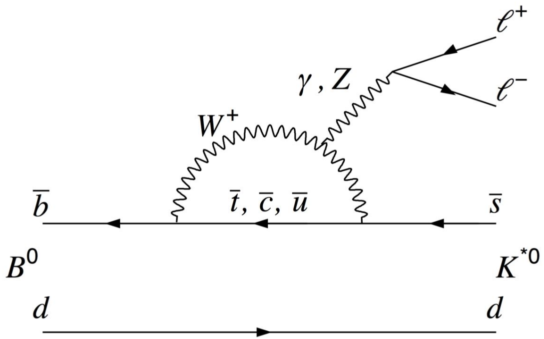
Recent LHCb results

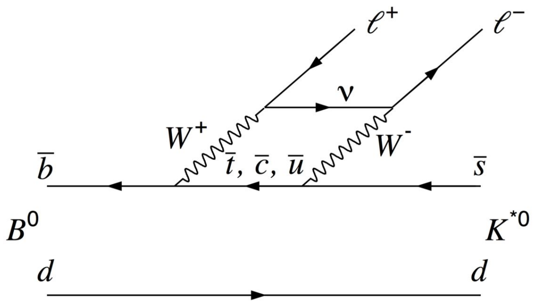
Recent LHCb results

Rare decays of b-hadrons

Rare b-hadron decays

- FCNC sensitive to indirect effects of New Physics (NP) in loops
  - branching fractions (BR), angular distributions, etc.
- Access to much larger scales than direct searches





Effective Hamiltonian approach

Model independent description in effective field theory [Buchalla et al.]:

$$H_{eff} \propto V_{tb} V_{ts}^* \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

O_i = 4-fermion operators, C_i = short distance, computed perturbatively

Form factors needed to describe hadronization process

$$O_7^{(\prime)} \propto (\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$$

$$O_9^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{l}\gamma_\mu l)$$

$$O_{10}^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{l}\gamma_\mu \gamma_5 l)$$

$$O_S^{(\prime)} \propto (\bar{s}P_{L(R)}b)(\bar{l}\,l)$$

$$O_P^{(\prime)} \propto (\bar{s}P_{L(R)}b)(\bar{l}\gamma_5 l)$$

Wilson coefficients

Transition	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
$b \to s\gamma$	X			
$b \to \ell^+\ell^-$			X	X
$b \to s\ell^+\ell^-$	X	X	X	

Effective Hamiltonian

b → sll sensitivity to Wilson coefficients varies with dilepton invariant mass, q^2

→ measurements performed in various bins and combined in global fits

Wilson coefficients

Transition	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
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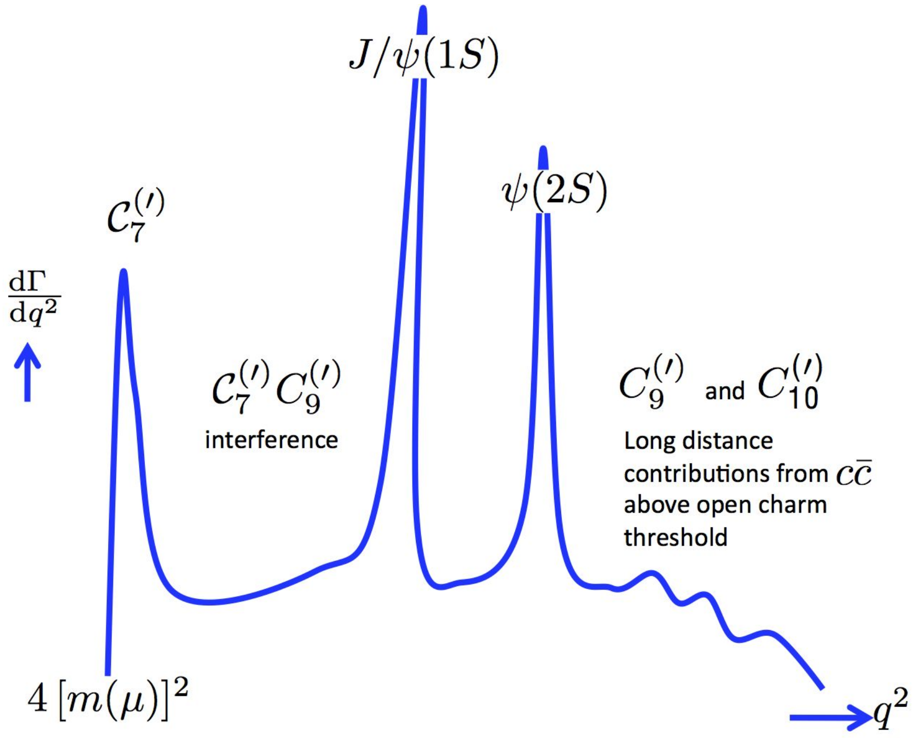
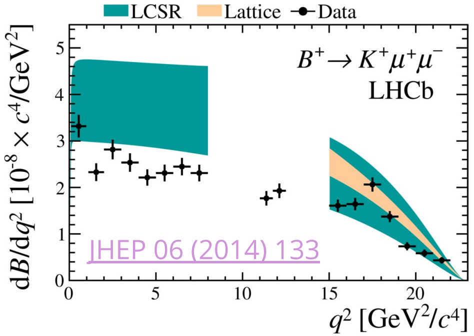
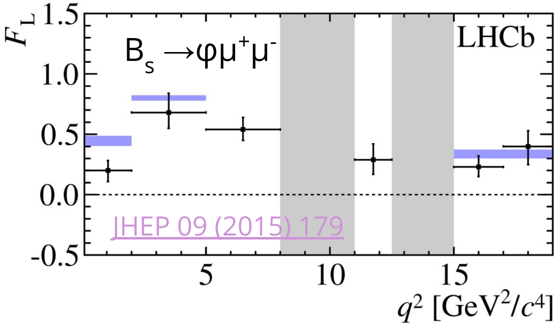
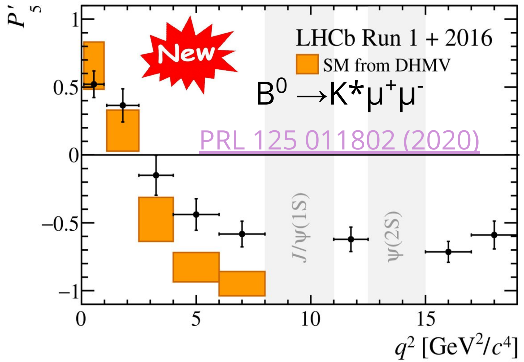


Intriguing deviations in rare b decays

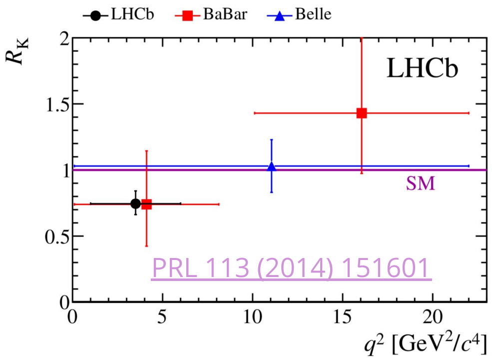
Differential BR and angular distributions

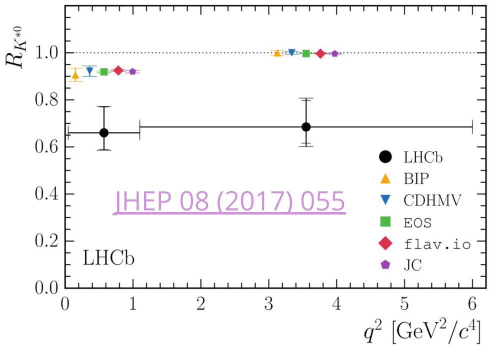


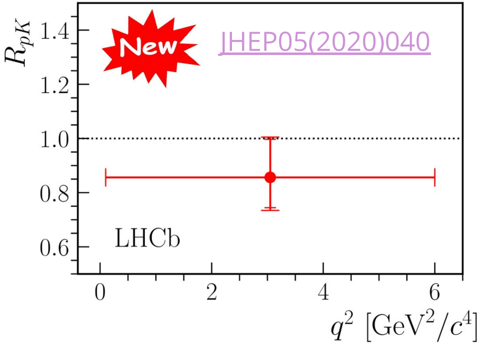




Lepton Flavour Universality (LFU) tests

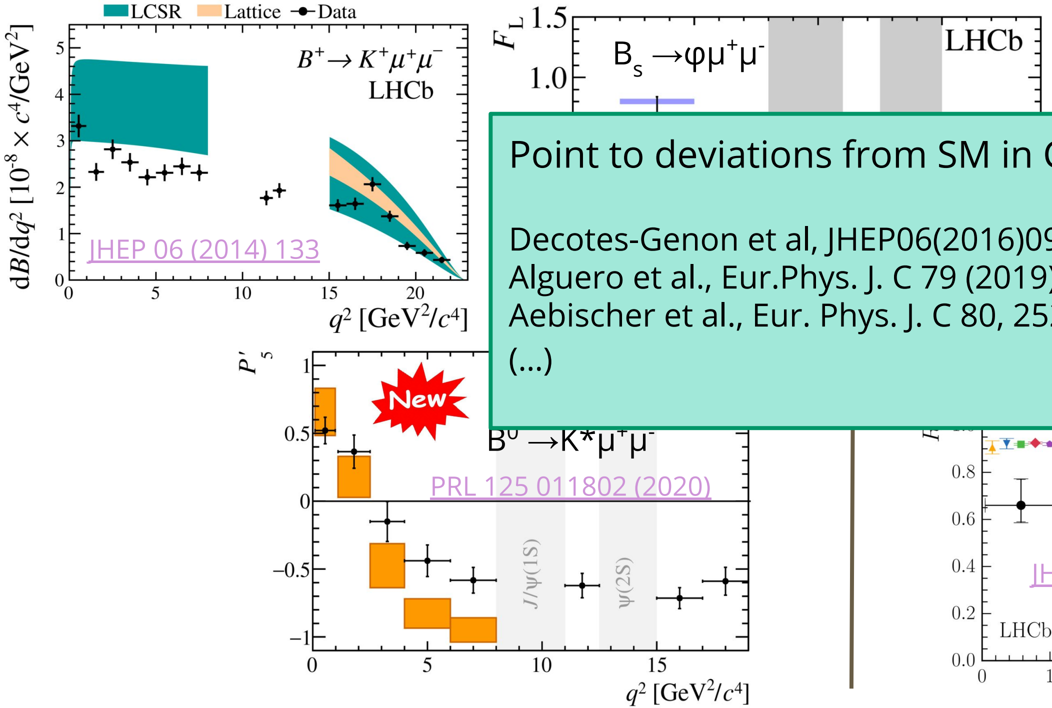




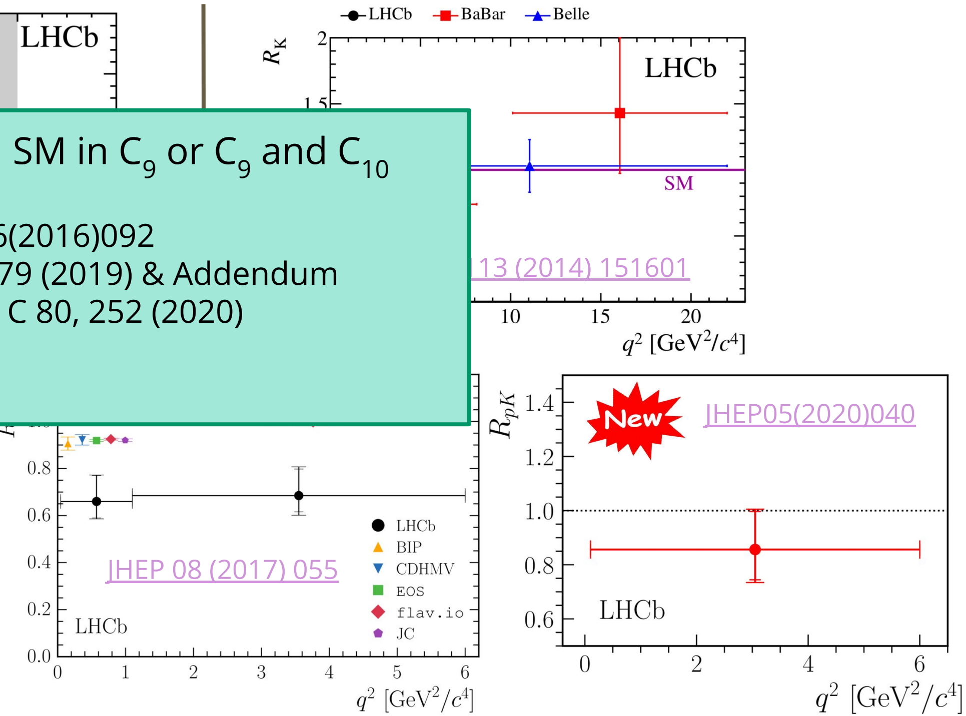


Intriguing deviations in rare b decays

Differential BR and angular distributions



Lepton Flavour Universality (LFU) tests



Point to deviations from SM in C_9 or C_9 and C_{10}

Decotes-Genon et al, JHEP06(2016)092
Alguero et al., Eur.Phys. J. C 79 (2019) & Addendum
Aebischer et al., Eur. Phys. J. C 80, 252 (2020)
(…)

LFU tests

In the SM:

$$R_H = \frac{BR(B \to H\mu^+\mu^-)}{BR(B \to He^+e^-)} = 1$$

Experimentally:

$$R_H = \boxed{\frac{N(B \to H\mu^+\mu^-)}{N(B \to He^+e^-)}} \times \boxed{\frac{\epsilon(B \to He^+e^-)}{\epsilon(B \to H\mu^+\mu^-)}}$$

from mass fit

from MC and calibration samples

Exploit the well tested LFU in J/ψ modes

$$r_{J/\psi} = \frac{BR(B \to HJ/\psi(\mu^+\mu^-))}{BR(B \to HJ/\psi(e^+e^-))} = 1$$

- as stringent cross-check
- to build double ratio → cancel systematic effects

$$R_H = \frac{\dfrac{N(B \to H\mu^+\mu^-)}{N(B \to HJ/\psi(\mu^+\mu^-))}}{\dfrac{N(B \to He^+e^-)}{N(B \to HJ/\psi(e^+e^-))}} \times \frac{\dfrac{\epsilon(B \to He^+e^-)}{\epsilon(B \to HJ/\psi(e^+e^-))}}{\dfrac{\epsilon(B \to H\mu^+\mu^-)}{\epsilon(B \to HJ/\psi(\mu^+\mu^-))}}$$

LFU tests: R_{pK}

In the SM:

Exploit the well tested LFU in J/ψ modes

$$R_{pK}^{-1} = \frac{\mathcal{B}(\Lambda_b^0 \to pK^- e^+ e^-)}{\mathcal{B}(\Lambda_b^0 \to pK^- J/\psi(\to e^+e^-))} \Bigg/ \frac{\mathcal{B}(\Lambda_b^0 \to pK^- \mu^+ \mu^-)}{\mathcal{B}(\Lambda_b^0 \to pK^- J/\psi(\to \mu^+\mu^-))}$$

measured at LHCb using Run 1 + 2016 data

Experin

R_H

from mass fit

from MC and calibration samples

$$R_H = \frac{\frac{N(B\to H\mu^+\mu^-)}{N(B\to HJ/\psi(\mu^+\mu^-))}}{\frac{N(B\to He^+e^-)}{N(B\to HJ/\psi(e^+e^-))}} \times \frac{\frac{\epsilon(B\to He^+e^-)}{\epsilon(B\to HJ/\psi(e^+e^-))}}{\frac{\epsilon(B\to H\mu^+\mu^-)}{\epsilon(B\to HJ/\psi(\mu^+\mu^-))}}$$

Electrons at LHCb

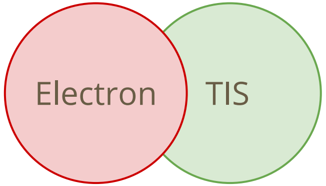
Hardware trigger

Larger ECAL occupancy → tighter thresholds for electrons:

- e p_T > 2700/2400 MeV in 2012/2016
- μ p_T > 1700/1800 MeV in 2012/2016

[LHCb-PUB-2014-046, 2019 JINST 14 P04013]

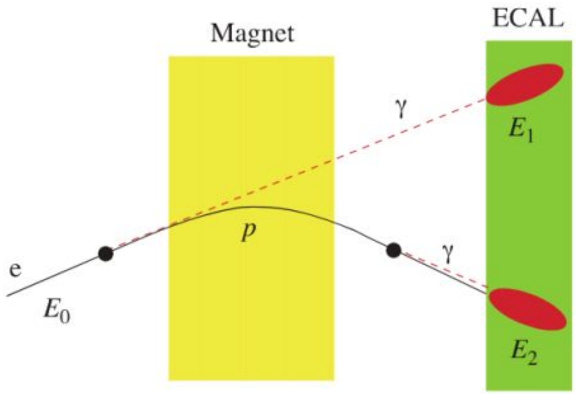
Include events triggered independently of the signal (TIS)



Interaction with detector material

Electrons radiate much more Bremsstrahlung

Recovery procedure in place



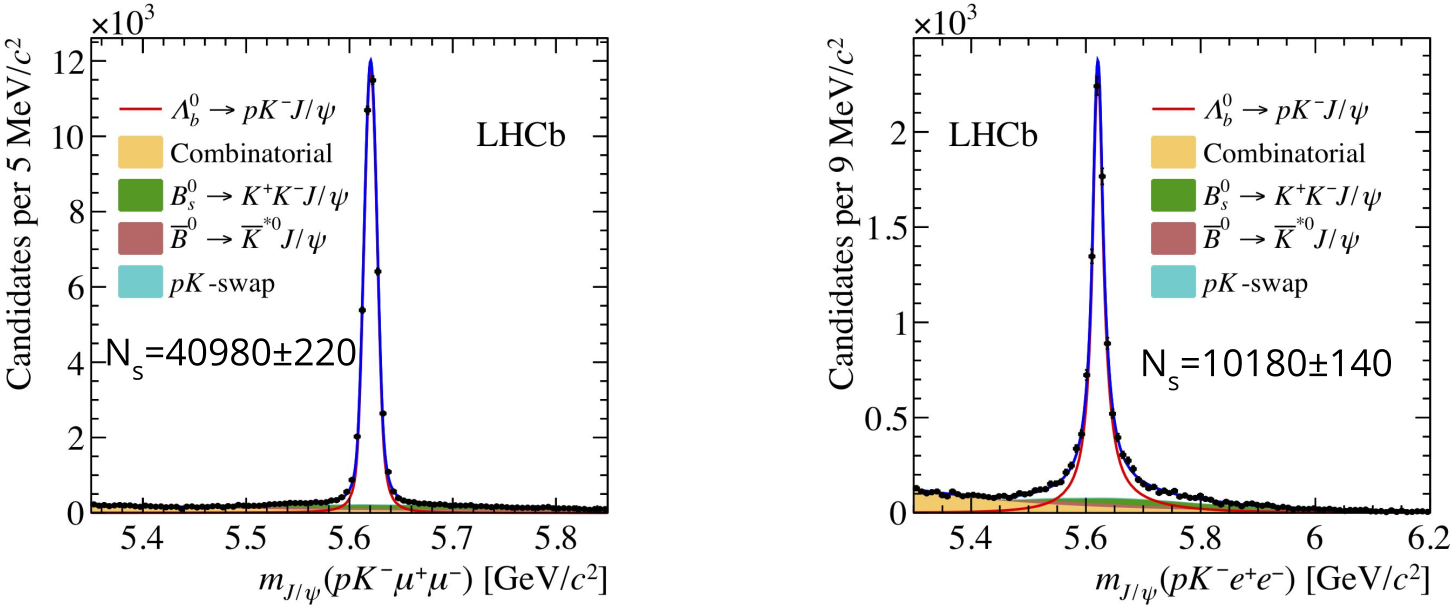
- miss some photons and add fake ones
- ECAL resolution worse than tracking

→ worse mass resolution for electron modes

R_{pK}: $r_{J/\psi}$ cross-check

JHEP05(2020)040

Constrain m(ee/μμ) to known J/ψ mass → better mass resolution

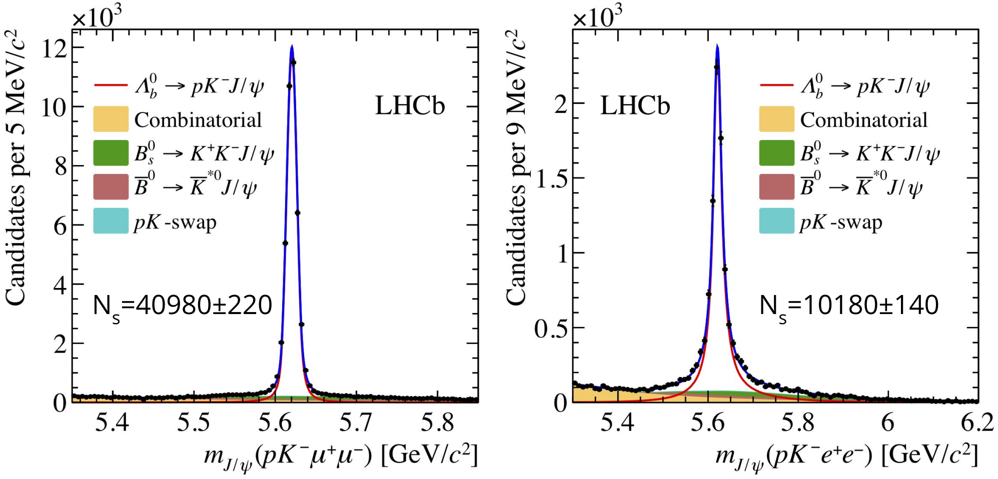


JHEP05(2020)040

R_{pK}: $r_{J/\psi}$ cross-check

Efficiency cross-check: single ratio $r_{J/\psi}$ known to be LU

$$r^{-1}_{J/\psi} = \frac{N(\Lambda_b^0 \to pK^- J/\psi(\to e^+e^-))}{N(\Lambda_b^0 \to pK^- J/\psi(\to \mu^+\mu^-))} \times \frac{\epsilon(\Lambda_b^0 \to pK^- J/\psi(\to \mu^+\mu^-))}{\epsilon(\Lambda_b^0 \to pK^- J/\psi(\to e^+e^-))}$$



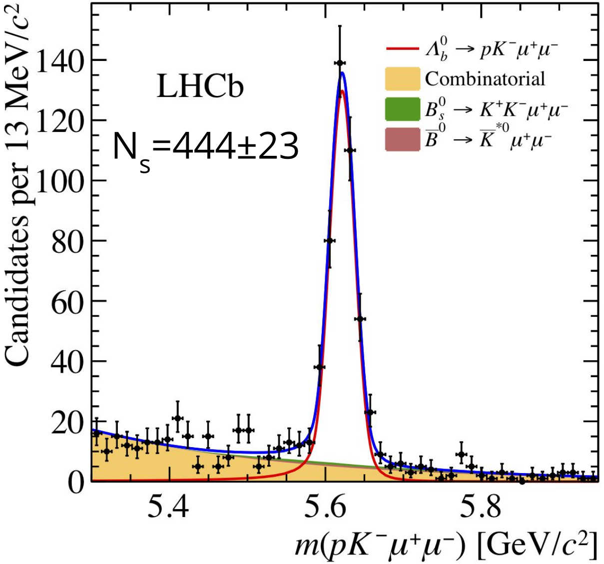
$r^{-1}_{J/\psi} = 0.96 \pm 0.05$

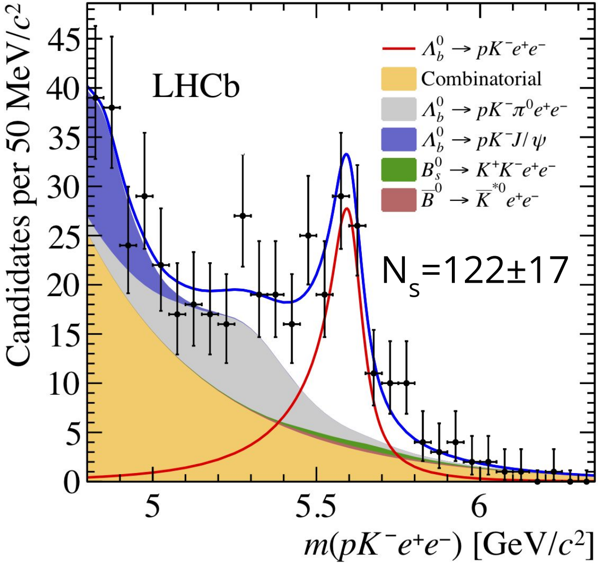
including stat. and syst.

Rare modes

JHEP05(2020)040

Mass constraint not possible → larger mass ranges, degradation for electrons





R_{pK} results

JHEP05(2020)040

Putting all together

$$R_{pK} = \frac{\frac{N(\Lambda_b \to pK^- \mu^+ \mu^-)}{N(\Lambda_b \to pK^- J/\psi(\mu^+ \mu^-))}}{\frac{N(\Lambda_b \to pK^- e^+ e^-)}{N(\Lambda_b \to pK^- J/\psi(e^+ e^-))}} \times \frac{\frac{\epsilon(\Lambda_b \to pK^- e^+ e^-)}{\epsilon(\Lambda_b \to pK^- J/\psi(e^+ e^-))}}{\frac{\epsilon(\Lambda_b \to pK^- \mu^+ \mu^-)}{\epsilon(\Lambda_b \to pK^- J/\psi(\mu^+ \mu^-))}}$$

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

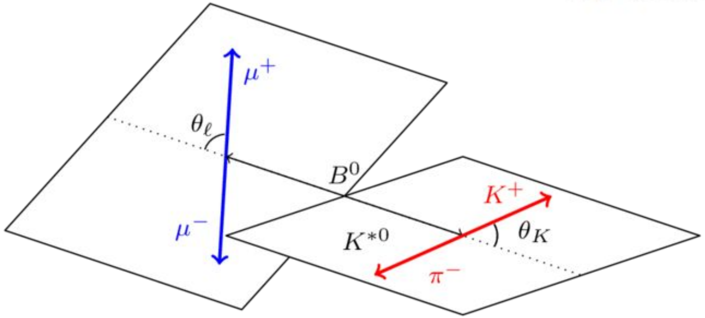
compatible with SM within 1σ but same trend as R_K and R_{K*}

$$\mathcal{B}(\Lambda_b^0 \to pK^-\mu^+\mu^-)\big|_{0.1<q^2<6\,\mathrm{GeV}^2/c^4} = \left(2.65 \pm 0.14 \pm 0.12 \pm 0.29\,^{+\,0.38}_{-\,0.23}\right) \times 10^{-7}$$

$$\mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)\big|_{0.1<q^2<6\,\mathrm{GeV}^2/c^4} = \left(3.1 \pm 0.4 \pm 0.2 \pm 0.3\,^{+\,0.4}_{-\,0.3}\right) \times 10^{-7}$$

Angular analysis of $B \longrightarrow K^*ll$

Full decay width of 4-body decay described by 3 angles + dilepton mass (q^2)



$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[I_1^s \sin^2\theta_K + I_1^c \cos^2\theta_K + I_2^s \sin^2\theta_K \cos 2\theta_\ell + I_2^c \cos^2\theta_K \cos 2\theta_\ell + I_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + I_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi + I_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + I_6 \sin^2\theta_K \cos\theta_\ell + I_7 \sin 2\theta_K \sin\theta_\ell \sin\phi + I_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + I_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big],$$

Rich angular distribution: 11 angular terms (I_i) -- combination of helicity amplitudes, related to Wilson coefficients

Angular observables

- CP-averages and asymmetries:

$$S_i = (I_i + \bar{I}_i) \Big/ \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2}\right) \qquad A_i = (I_i - \bar{I}_i) \Big/ \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2}\right)$$

- "Physical" observables:
    - $F_L = S_{1c}$: fraction of longitudinally polarised K^*
    - $A_{FB} = ¾ S_{6s}$: forward-backward asymmetry of the dimuon system

- Optimised observables: form-factor uncertainties cancel at first order

$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_{\mathrm{L}}(1 - F_{\mathrm{L}})}}$$

Angular fit to data

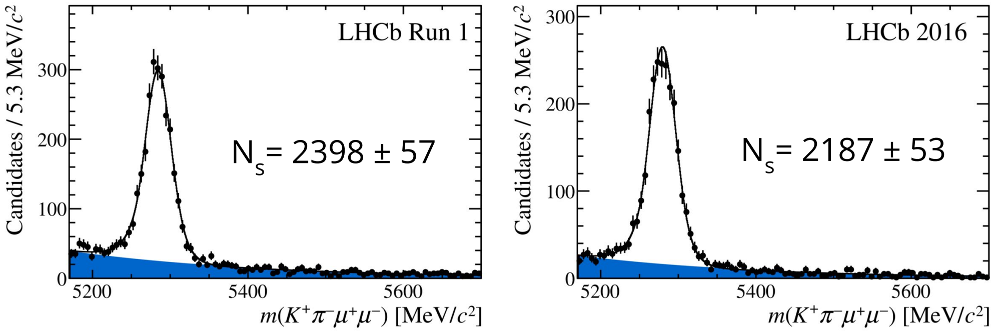
- acceptance: impact of detector geometry, trigger, reconstruction and selection on angular distribution → shape from calibrated simulation
- 4D fit of mass and 3 angles: signal is separated from background through invariant mass

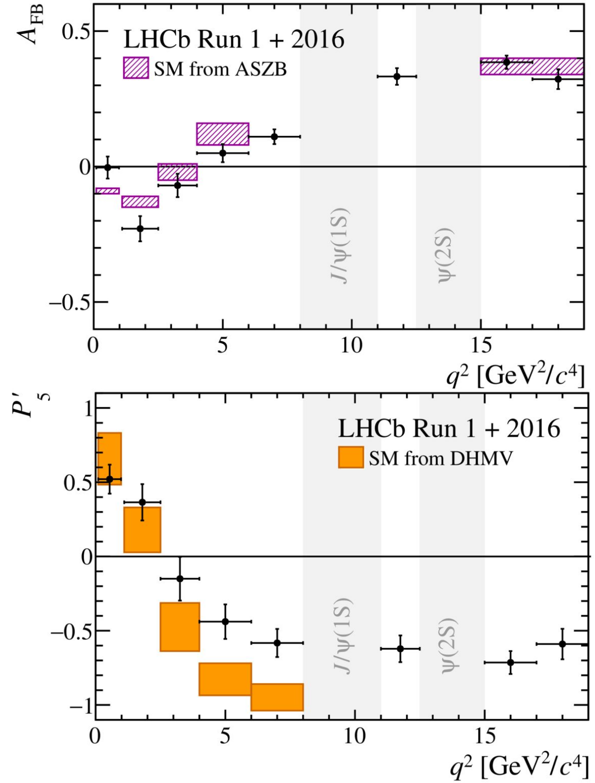
$$PDF = \boxed{\epsilon(cos\theta_K, cos\theta_l, \phi, q^2)} \times \boxed{d\Gamma(cos\theta_K, cos\theta_l, \phi, m; I_i)}$$

- fit performed in each q^2 bin
- fit also $m(K^+\pi^-)$ to separate P-wave $K^*(892)$ from S-wave non-resonant component

Angular analysis of $B^0 \rightarrow K^{*}\mu^{+}\mu^{-}$

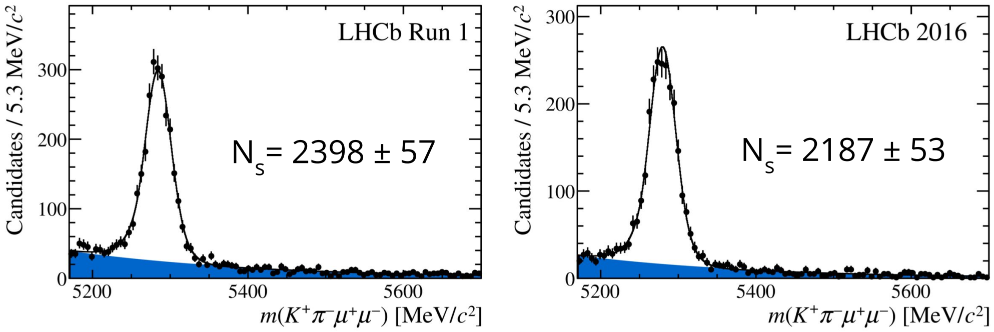
Measure CP-averaged and optimised observables with Run 1 + 2016 data

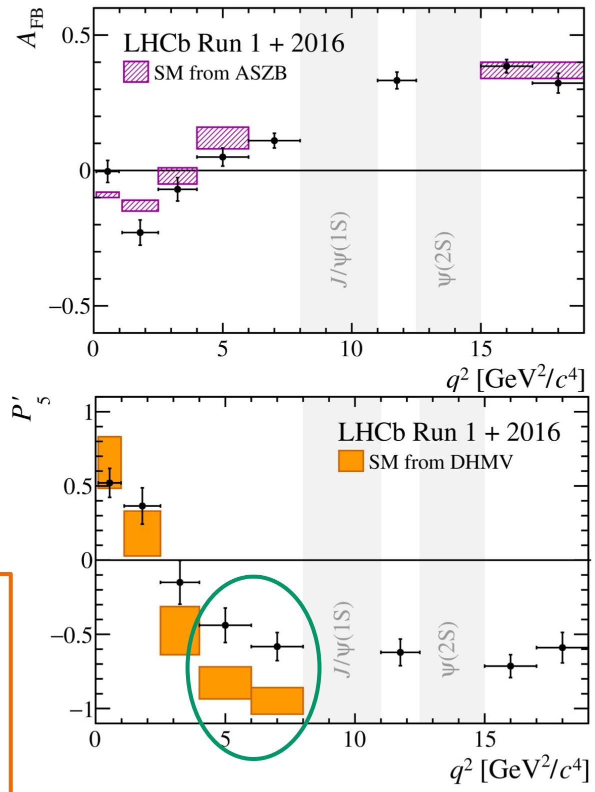




Angular analysis of $B^0 \to K^* \mu^+ \mu^-$

Measure CP-averaged and optimised observables with Run 1 + 2016 data

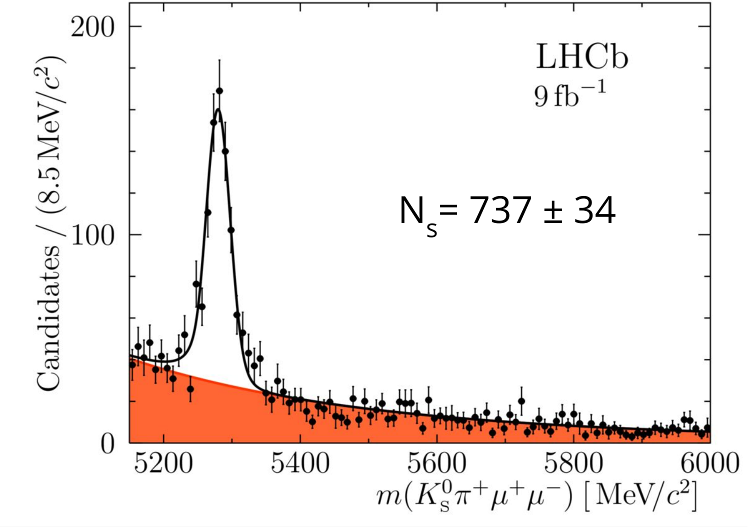




Local discrepancy of 2.5 and 2.9σ in P'_5
Global tension of 3.3σ with the SM using Flavio
best fit at $\Delta Re(C_9)$ = -0.99

Angular analysis of $B^+ \rightarrow K^{*+}\mu^+\mu^-$

Use full LHCb dataset (9 fb^{-1}) and $K^{*+} \rightarrow K_s \pi^+$ decay to measure CP-averaged and optimised observables



Cannot determine all observables simultaneously → apply folding to simplify angular expression

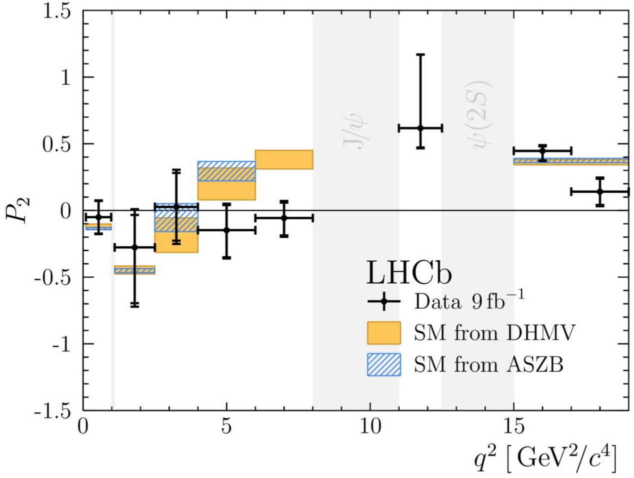
Five folds used to extract all observables, eg:

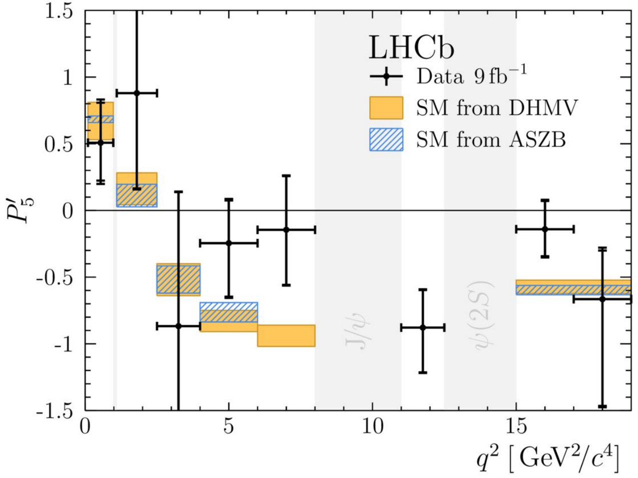
$\Phi \rightarrow \Phi + \pi$ for $\Phi < 0$
sinΦ, cosΦ terms cancel out

$$P'_5, S_5: \begin{cases} \phi \rightarrow -\phi & \text{for } \phi < 0 \\ \theta_\ell \rightarrow \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2, \end{cases}$$

Angular analysis of $B^+ \to K^{*+}\mu^+\mu^-$

Local discrepancy of 3σ in P_2 (A_{FB}), same trend in P_2 and P'_5 as for B^0 mode



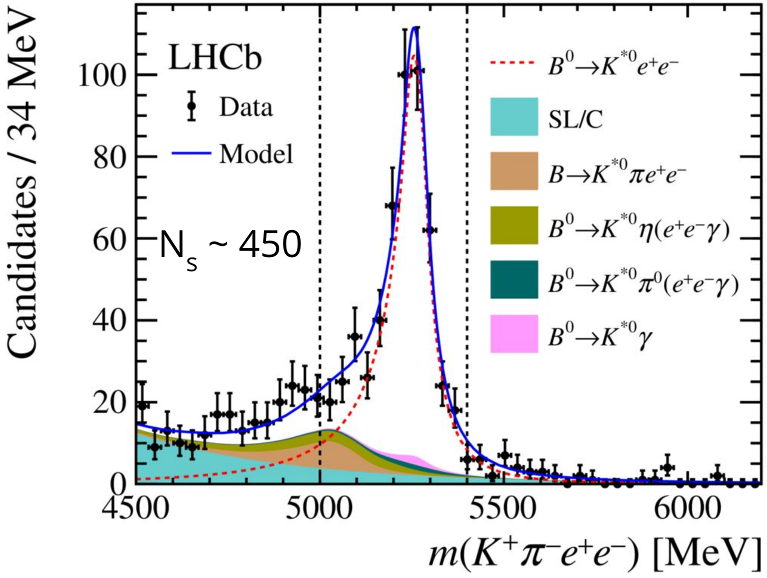


Global tension of 3.1σ with the SM using Flavio
best fit at $\Delta Re(C_9) = -1.9$

Angular analysis of $B^0 \to K^* e^+ e^-$ at low q^2

JHEP 12 (2020) 081

Use full LHCb data (9 fb^{-1}) in $q^2 \in [0.0008, 0.257]$ GeV^2/c^4 to test virtual photon contribution (C_7)



Fold Φ to simplify expression, keeping angular observables of interest. Historical variables used:

- F_L
- $A_T^{Re} = 2P_2$ - related to A_{FB}

} small at low q^2

- $A_T^{(2)} = P_1$
- $A_T^{Im} = -2P_3^{CP}$

$$A_T^{(2)}(q^2 \to 0) = \frac{2\mathcal{R}e(C_7 C_7'^*)}{|C_7|^2 + |C_7'|^2}$$

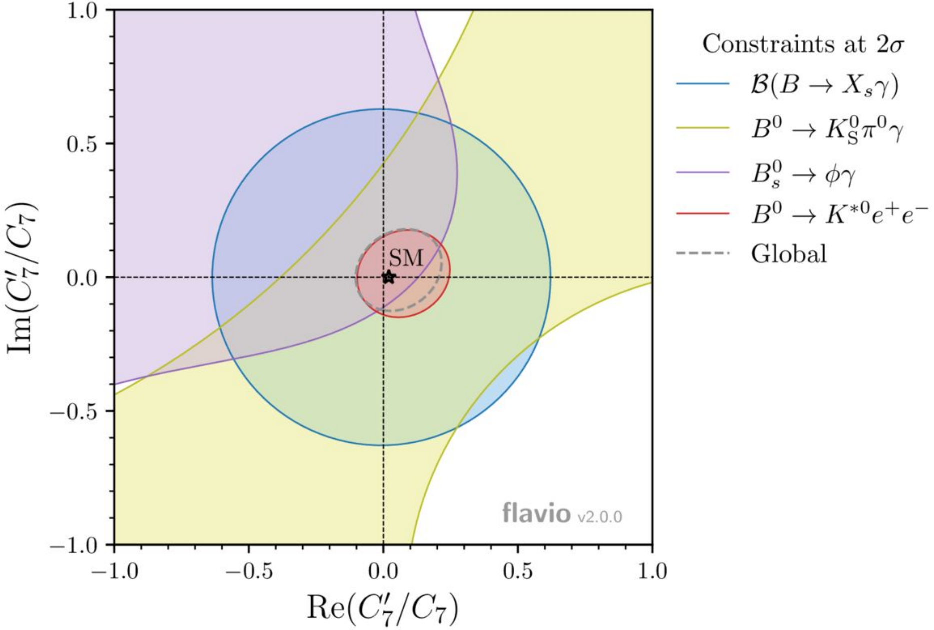
$$A_T^{Im}(q^2 \to 0) = \frac{2\mathcal{I}m(C_7 C_7'^*)}{|C_7|^2 + |C_7'|^2}$$

Angular analysis of $B^0 \longrightarrow K^{*}e^{+}e^{-}$ at low q^2

JHEP 12 (2020) 081

Word-best constraints on C'_7 achieved:

$$
\begin{aligned}
F_{\mathrm{L}} &= 0.044 \pm 0.026 \pm 0.014, \\
A_{\mathrm{T}}^{\mathrm{Re}} &= -0.06 \pm 0.08 \pm 0.02, \\
A_{\mathrm{T}}^{(2)} &= +0.11 \pm 0.10 \pm 0.02, \\
A_{\mathrm{T}}^{\mathrm{Im}} &= +0.02 \pm 0.10 \pm 0.01,
\end{aligned}
$$



Very good agreement with SM

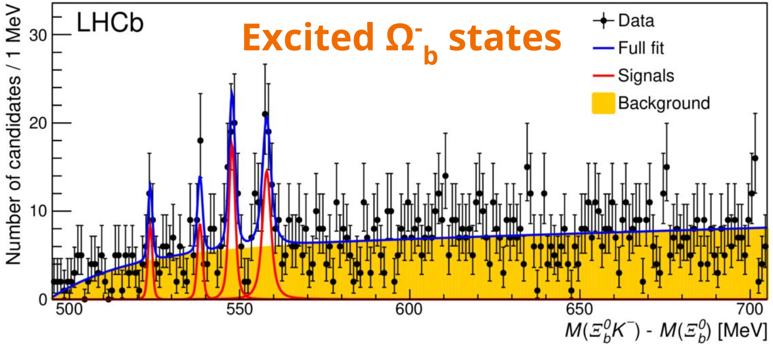
Recent LHCb results

Spectroscopy

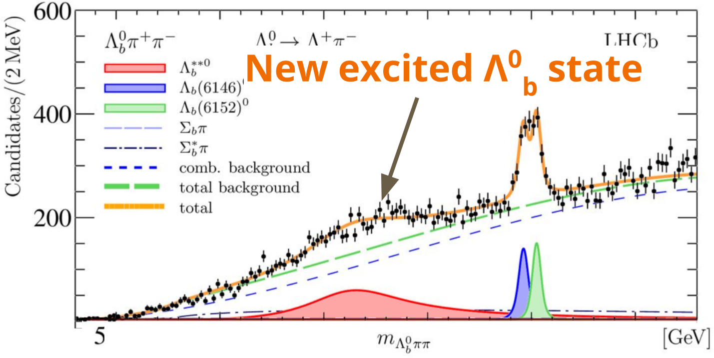
A b-hadron factory

All in 2020

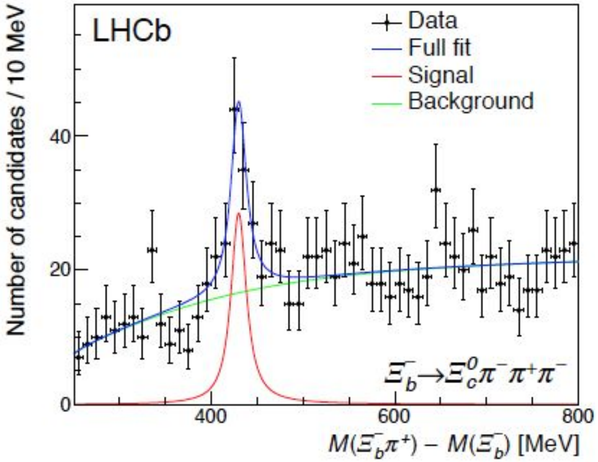
PRL 124 (2020) 082002



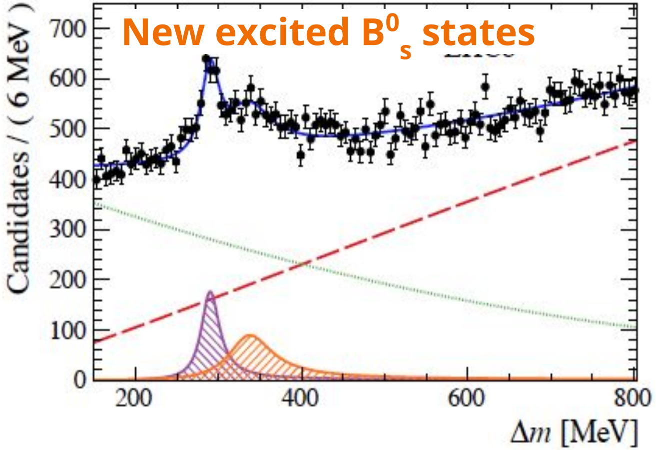
JHEP 06 (2020) 136



PRD103 (2021) 012004



arXiv:2010.15931

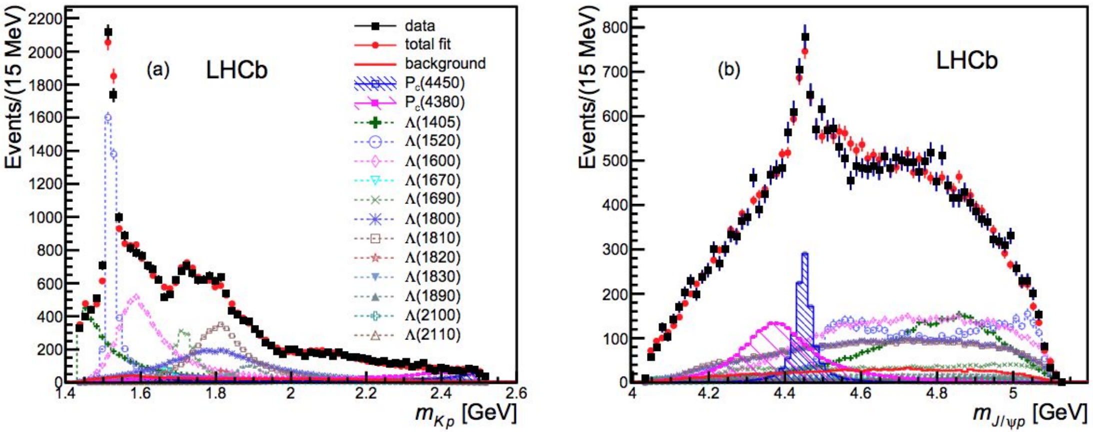


Exotic hadrons

Quark model allows states with >3 quarks, eg qq**qq** (tetra) or qqqq**q** (penta)

- χ_{c1}(3872) [Belle, 2003]: resonance-like structure in $J/\psi\pi^+\pi^-$
  - soon confirmed by BaBar
- P_c [LHCb, 2015]: resonance-like structures in pJ/ψ

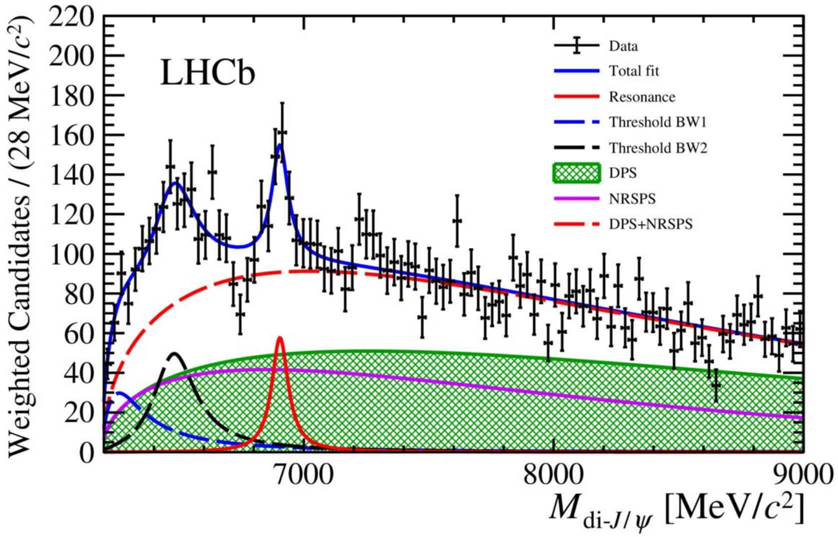
Phys.Rev.Lett.115 072001



4 charm-quark states in di-J/ψ spectrum

SCIENCE BULLETIN 65 (2020) 032

Study di-J/ψ spectrum using full LHCb dataset (9 fb^{-1})

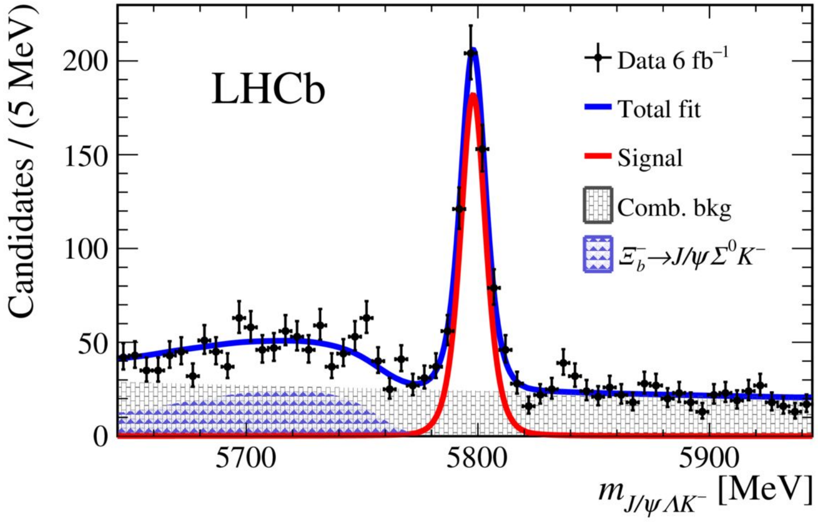


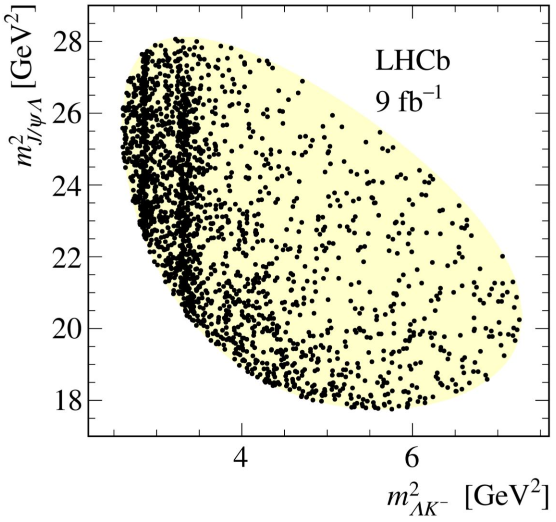
- Narrow structure ~6.9 GeV, X(6900), matching shape of a resonance
- **Broader structure** just above di-J/ψ threshold
- Deviation from nonresonant di-J/ψ production > 5σ in [6.2, 7.4] GeV
  - 4 charm-quark states predicted in this region

$J/\psi\Lambda$ structure in $\Xi_b^- \to J/\psi\Lambda K^-$

arXiv:2012.10380

Using full LHCb dataset, study $\Xi_b^- \to J/\psi\Lambda K^-$ where P_{cs} states are predicted



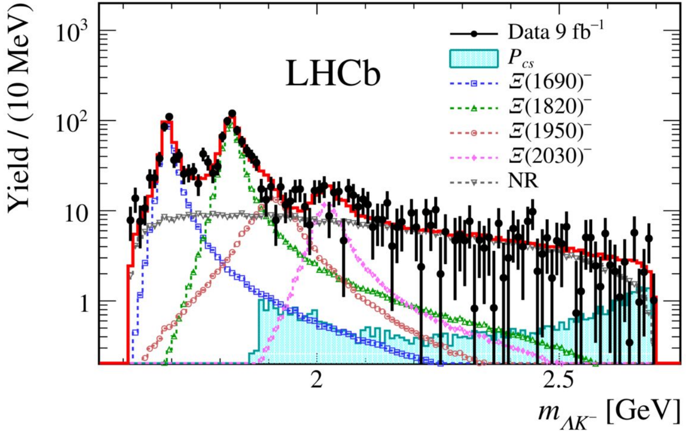


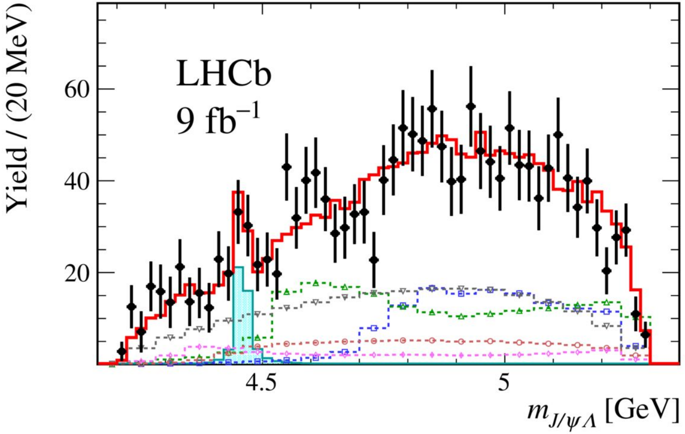
J/ψΛ structure in $\Xi_b^- \to J/\psi\Lambda K^-$

arXiv:2012.10380

Full amplitude analysis: extra contribution to J/ψΛ is preferred at 3.1σ

State	M_0 [MeV]	Γ_0 [MeV]
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$





Also, improved determination of Ξ(1690)⁻ and Ξ(1820)⁻ mass and width

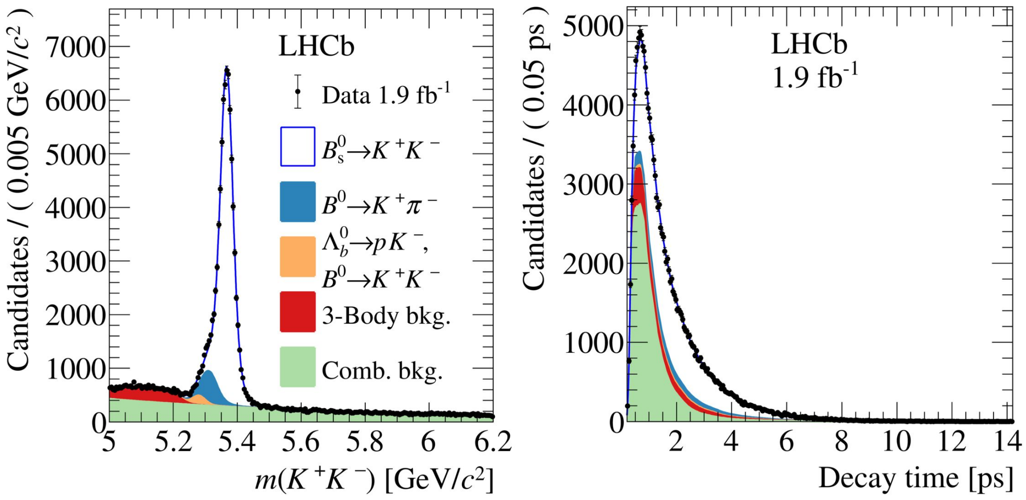
Recent LHCb results

CPV

CPV in $B_{(s)} \to h^+h^-$ decays

arXiv:2012.05319

Study time-dependent CPV in $B_{(s)}\to\pi^+\pi^-$ (K^+K^-) and integrated CPV in $B_{(s)}\to K^\pm\pi^\mp$ using part of Run 2 data: simultaneous fit to control cross-feeds



Final CP-eigenstates: interference between decay and mixing → CPV

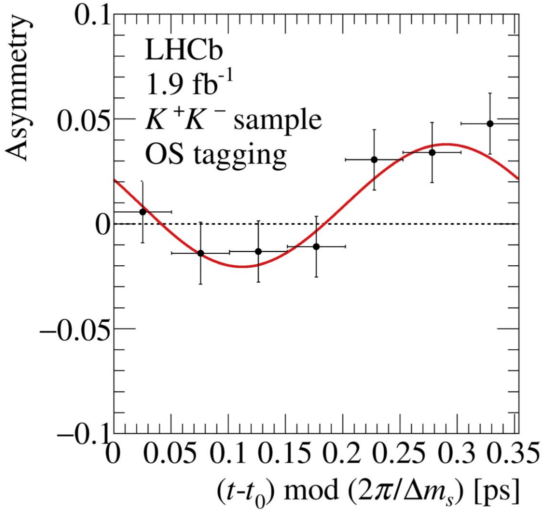
Critical ingredients:

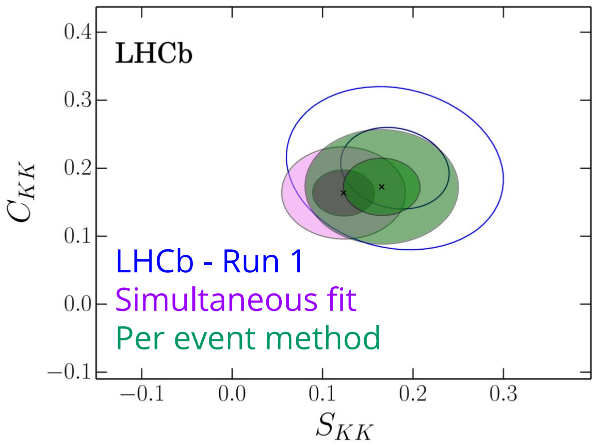
- determination of B flavour
- good decay time resolution

arXiv:2012.05319

TD-CPV in $B_s \longrightarrow K^+K^-$ decays

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f \cos(\Delta m_{d,s} t) + S_f \sin(\Delta m_{d,s} t)}{\cosh\left(\frac{\Delta\Gamma_{d,s}}{2} t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d,s}}{2} t\right)}$$





$$C_{KK} = 0.164 \pm 0.034 \pm 0.014,$$
$$S_{KK} = 0.123 \pm 0.034 \pm 0.015,$$
$$\mathcal{A}_{KK}^{\Delta\Gamma} = -0.83 \pm 0.05 \pm 0.09,$$

arXiv:2012.05319

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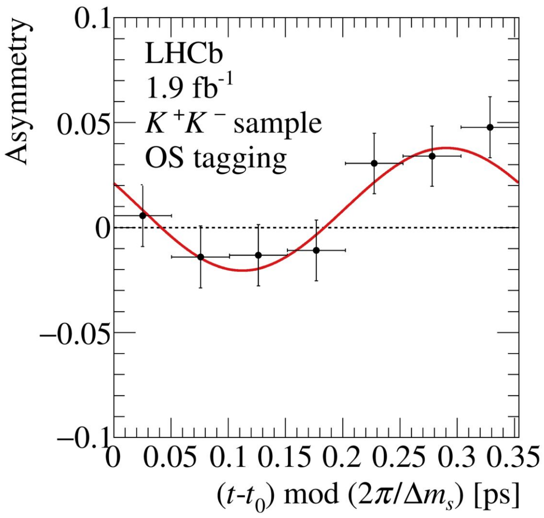

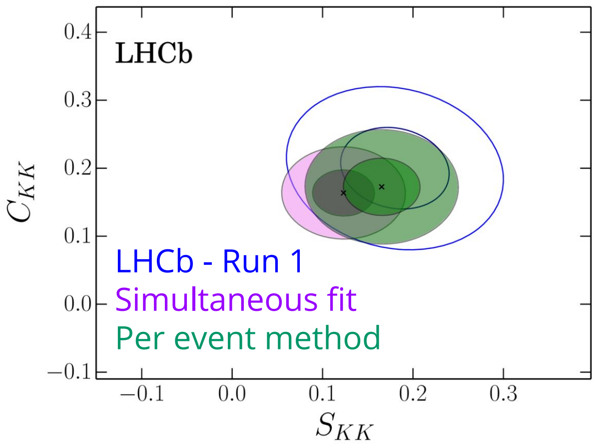

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$$S_{KK} = 0.123 \pm 0.034 \pm 0.015,$$
$$\mathcal{A}^{\Delta\Gamma}_{KK} = -0.83 \pm 0.05 \pm 0.09,$$

Compatible with Run 1 results

CPV >6σ from combination:

$$C_{KK} = 0.172 \pm 0.031,$$
$$S_{KK} = 0.139 \pm 0.032,$$
$$\mathcal{A}^{\Delta\Gamma}_{KK} = -0.897 \pm 0.087$$

The Kπ puzzle in B → Kπ decays

Direct CPV measured in whole family of B → Kπ decays, with amplitudes related by isospin symmetry in SM: $B^0 \to K^+\pi^-$, $B^+ \to K^+\pi^0$, $B^0 \to K^0\pi^0$ and $B^+ \to K^0\pi^+$

However:

$$\left.\begin{aligned} A_{CP}(B^0 \to K^+\pi^-) &= -0.084 \pm 0.004 \\ A_{CP}(B^+ \to K^+\pi^0) &= -0.044 \pm 0.021 \end{aligned}\right\} \text{not equal at } 5.5\sigma$$

New results on $B^0 \to K^+\pi^-$ from previous analysis, next step: $B^+ \to K^+\pi^0$

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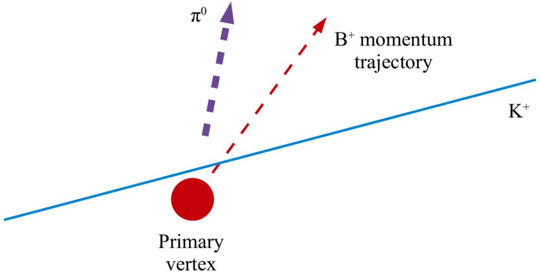
not equal at 5.5σ

New results on $B^0 \to K^+\pi^-$ from previous analysis, next step: $B^+ \to K^+\pi^0$

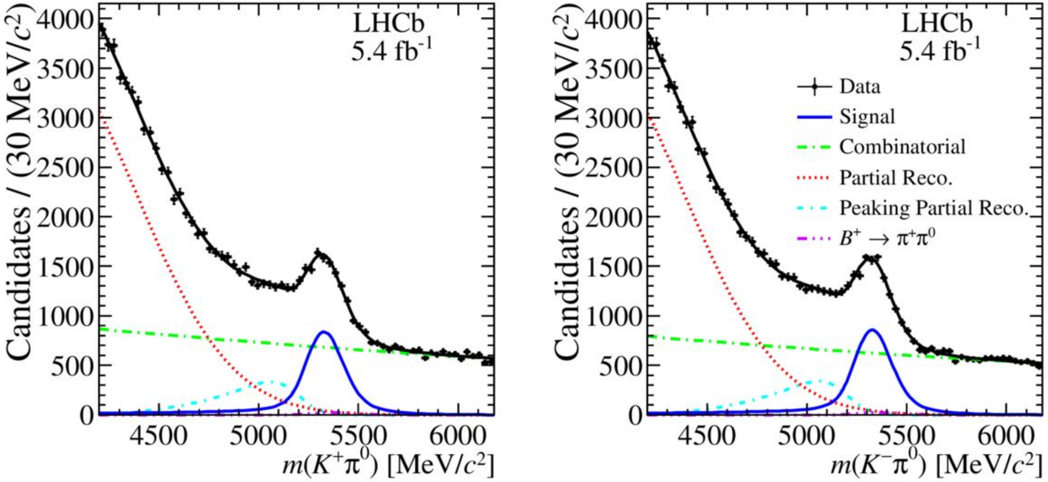
Challenge: B^+ decay vertex cannot be reconstructed in this decay



arXiv:2012.05319

CPV in $B^+ \to K^+\pi^0$

Use 2016 - 2018 LHCb sample (dedicated trigger needed) and highly optimised selection to fight large backgrounds



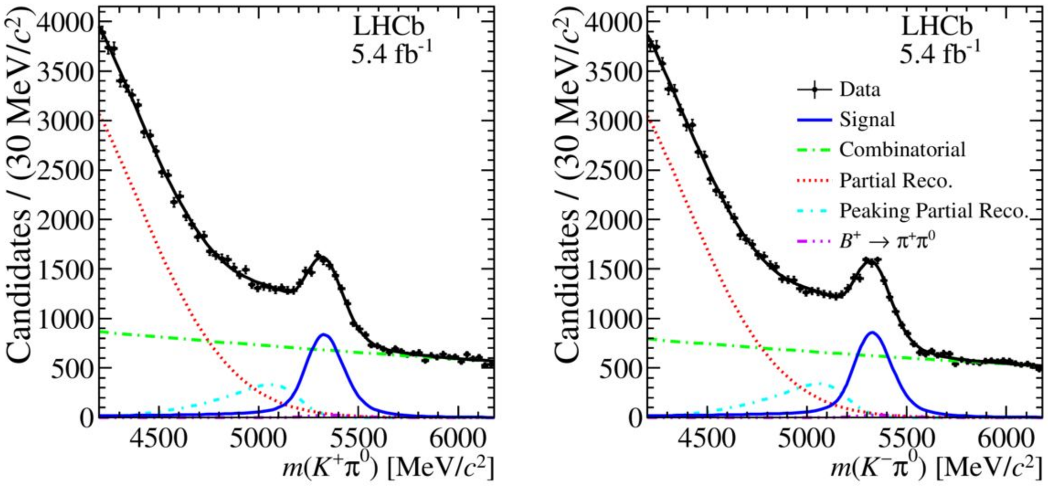
$$A_{CP}(B^+ \to K^+\pi^0) = 0.025 \pm 0.015 \pm 0.006 \pm 0.003,$$

More precise than word average!

CPV in $B^+ \to K^+\pi^0$

arXiv:2012.05319

Use 2016 - 2018 LHCb sample (dedicated trigger needed) and highly optimised selection to fight large backgrounds



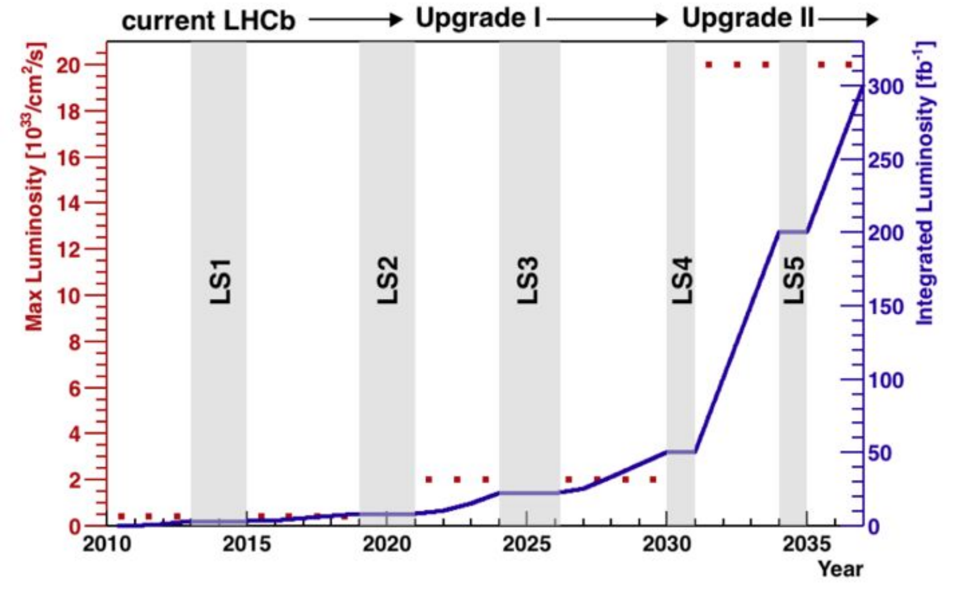
Using new word average:

$\Delta CP(K\pi) \neq 0$ at $>8\sigma$

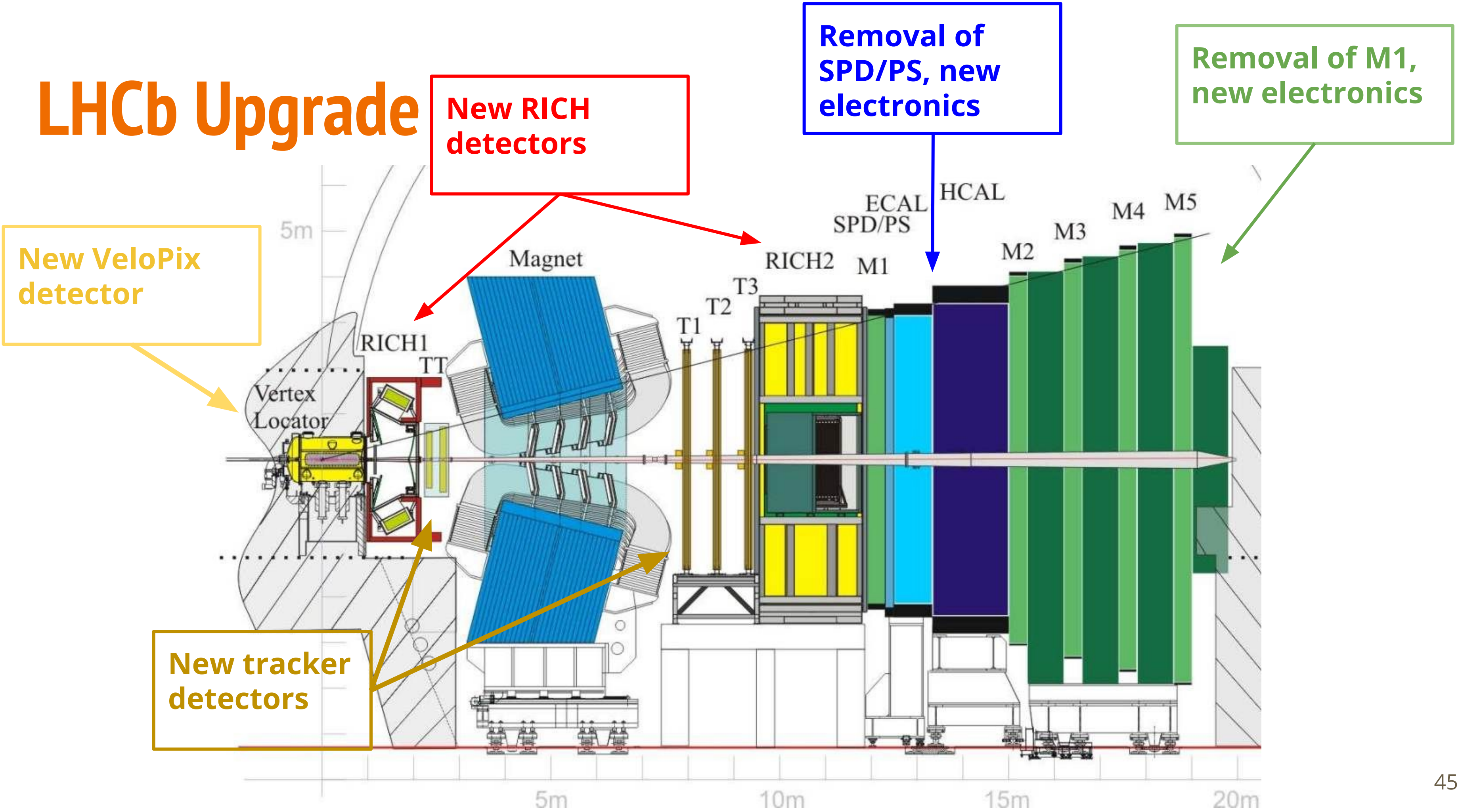
$$A_{CP}(B^+ \to K^+\pi^0) = 0.025 \pm 0.015 \pm 0.006 \pm 0.003,$$

More precise than word average!

Future prospects



LHCb Upgrade



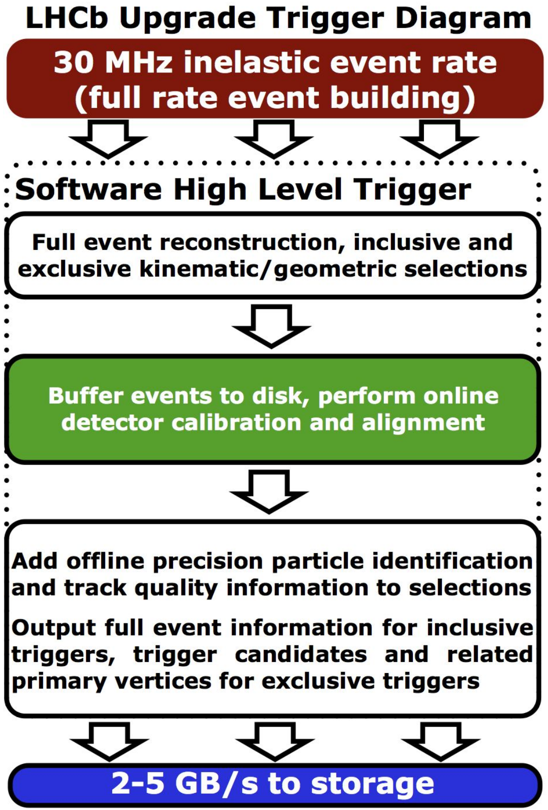
Trigger in Run 3 and beyond

Remove limitations of hardware trigger:

- remove tight p_T and E_T requirements
- x2 yields for fully hadronic decays

First level software trigger in GPUs:

- increase complexity of tracking algorithms
- better performance at higher throughput

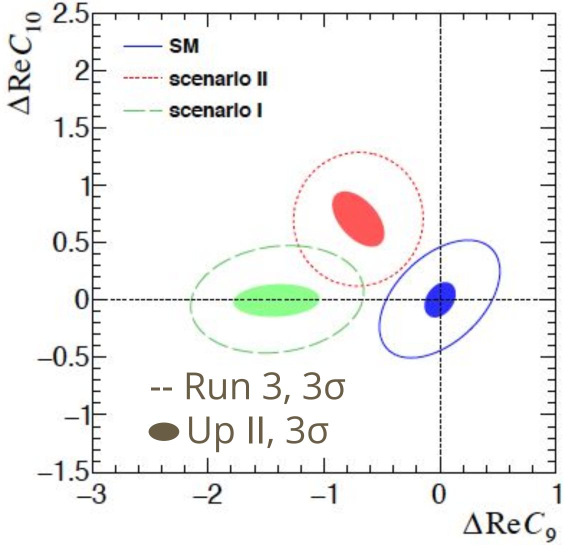


arXiv:1808.08865

Prospects for Rare Decays

- update measurements with full Run 1+2 dataset
  - full Run 2 dataset: ~4 times number of b's in Run 1
- study LU and angular observables in new modes
  - muon modes well established in several b → sll decays

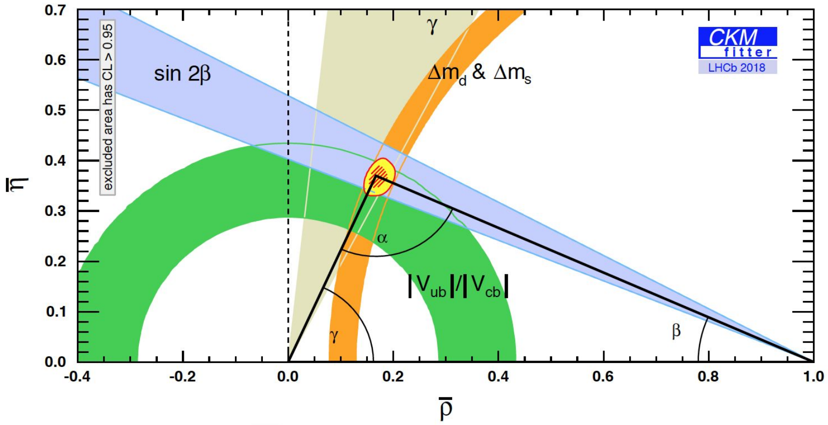
		Run 3	Run 4	Upgrade II
R_X precision	$9\,\text{fb}^{-1}$	$23\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$
R_K	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	0.052	0.031	0.020	0.008
R_ϕ	0.130	0.076	0.050	0.020
R_{pK}	0.105	0.061	0.041	0.016
R_π	0.302	0.176	0.117	0.047

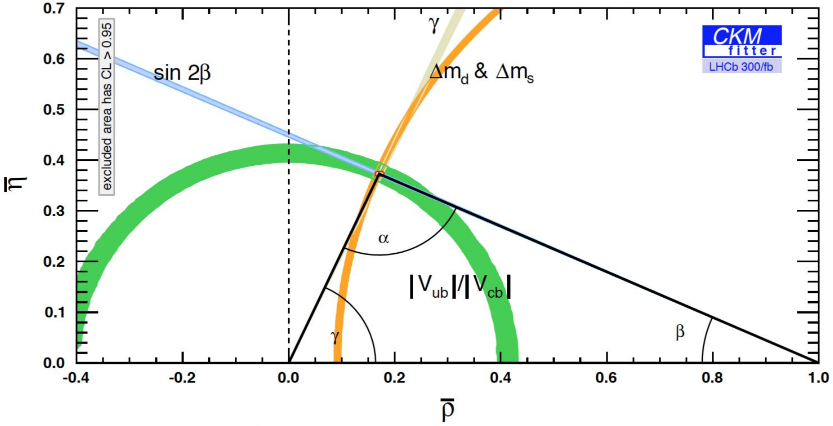


arXiv:1808.08865

Prospects for CKM measurements

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
$a_{\rm sl}^s$	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\|V_{ub}\|/\|V_{cb}\|$	6% [201]	3%	1%	1%	–

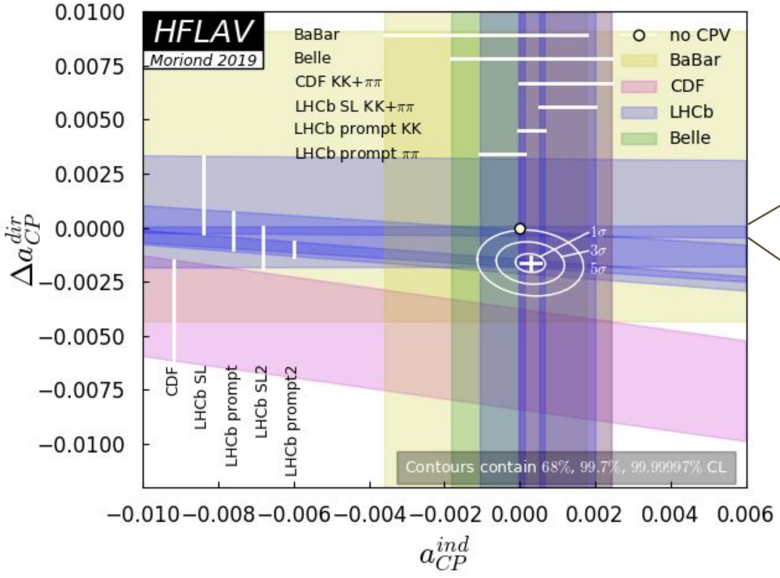


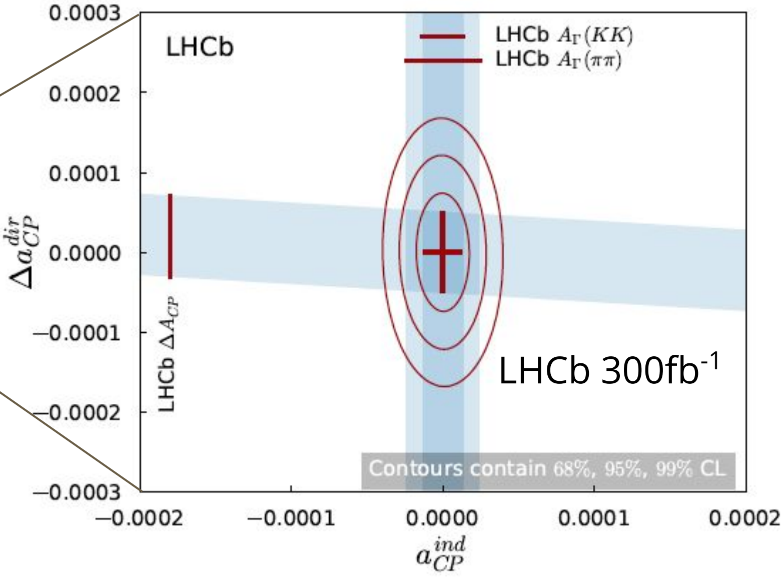


arXiv:1808.08865

Prospects for Charm physics

Large benefit from fully software trigger





Conclusions

LHCb is not only a b-factory (huge production of $B^{0/+}$, B_s, Λ_b...) but also a general purpose detector in the forward region

Wealth of new results this year and more to come soon:

- intriguing deviations from SM in RD might be hints for NP
- bunch of new conventional and exotic hadrons discovered
- probing CPV at unprecedented precision

LHCb is being (will be) upgraded to collect x30 larger dataset in Run 3-5

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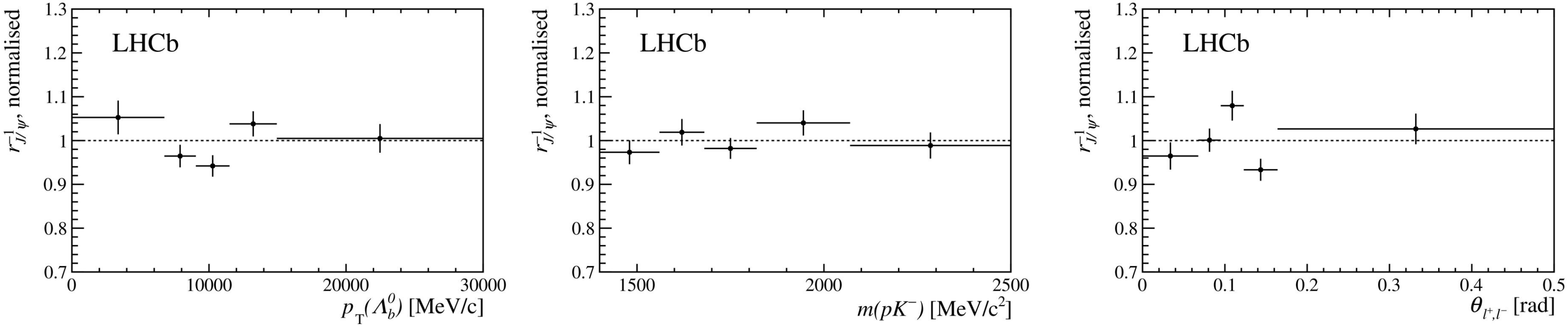
Stay tuned!

BACK-UP

R_{pK}: $r_{J/\psi}$ cross-check

Efficiency depends on lab-frame variables → check $r_{J/\psi}$ as a function of them

$$r^{-1}_{J/\psi} = \frac{N(\Lambda^0_b \to pK^- J/\psi(\to e^+e^-))}{N(\Lambda^0_b \to pK^- J/\psi(\to \mu^+\mu^-))} \times \frac{\epsilon(\Lambda^0_b \to pK^- J/\psi(\to \mu^+\mu^-))}{\epsilon(\Lambda^0_b \to pK^- J/\psi(\to e^+e^-))}$$



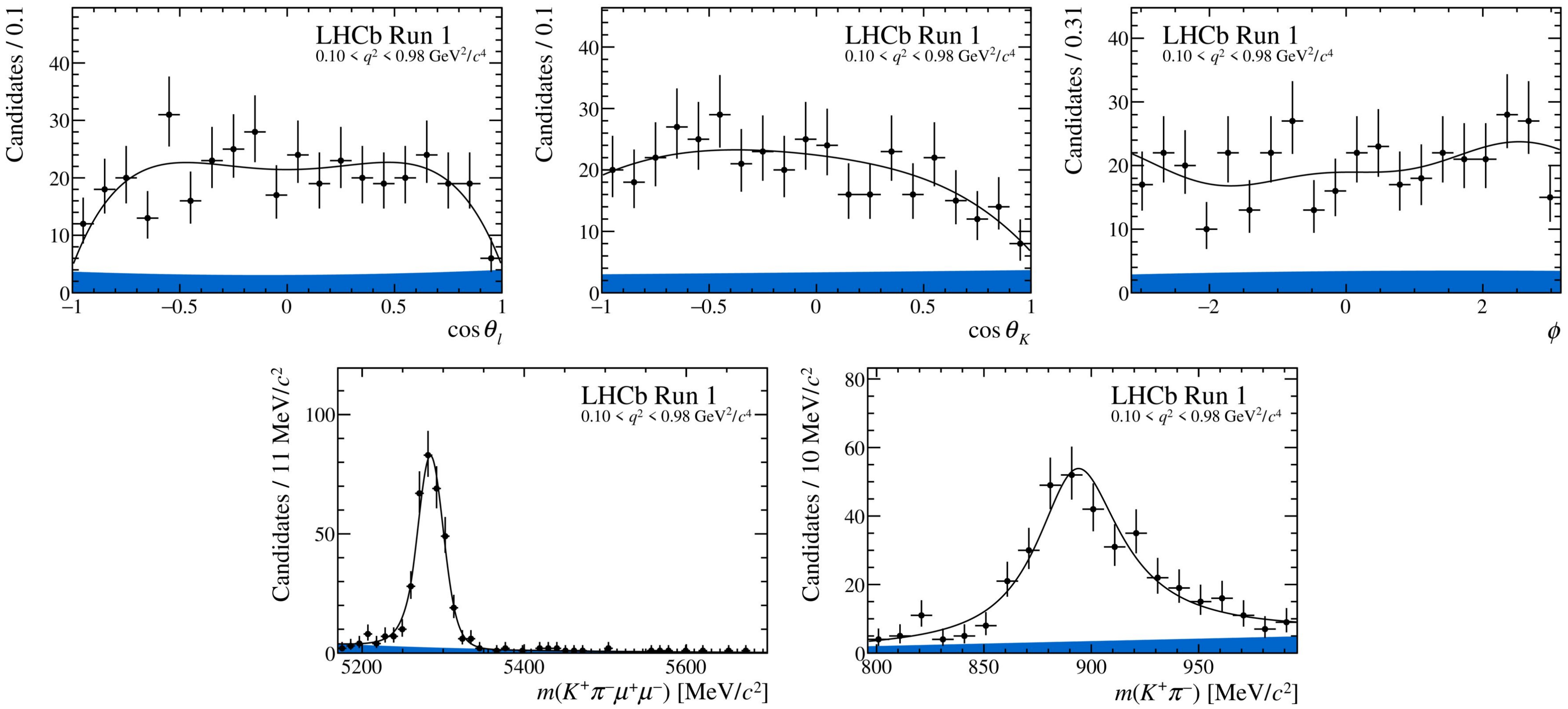
Flat on kinematic and topological variables

Systematic uncertainties

R^{-1}_{pK} measurement statistically dominated, main systematic uncertainties:

- Fit model (5.2%): partially reconstructed background shape in $\Lambda_b \to pK^- ee$
  - nominal: $\Lambda_b \to pK^{*-} ee$, $K^{*-} \to K^- \pi^0$; alternative: nonresonant $\Lambda_b \to pK^- \pi^0 ee$ decay
- Normalisation mode (~3.5%): uncertainties on yields and efficiencies
- Decay model (1.9%): alternative corrections from $\Lambda_b \to pK^- \mu\mu$ data
- Others: other corrections to simulation, m_{corr} cut efficiency, q^2 migration

$B^0 \to K^*\mu^+\mu^-$: fit projections lowest q^2 bin



$B^+ \longrightarrow K^{*+}\mu^+\mu^-$: angular folding

folding 0:

$$\phi \rightarrow \phi + \pi \qquad \text{for } \phi < 0$$

folding 1:

$$\begin{aligned} \phi &\rightarrow -\phi && \text{for } \phi < 0 \\ \phi &\rightarrow \pi - \phi && \text{for } \cos\theta_L < 0 \\ \cos\theta_L &\rightarrow -\cos\theta_L && \text{for } \cos\theta_L < 0 \end{aligned}$$

folding 2:

$$\begin{aligned} \phi &\rightarrow -\phi && \text{for } \phi < 0 \\ \cos\theta_L &\rightarrow -\cos\theta_L && \text{for } \cos\theta_L < 0 \end{aligned}$$

folding 3:

$$\begin{aligned} \cos\theta_L &\rightarrow -\cos\theta_L && \text{for } \cos\theta_L < 0 \\ \phi &\rightarrow \pi - \phi && \text{for } \phi > \frac{\pi}{2} \\ \phi &\rightarrow -\pi - \phi && \text{for } \phi < -\frac{\pi}{2} \end{aligned}$$

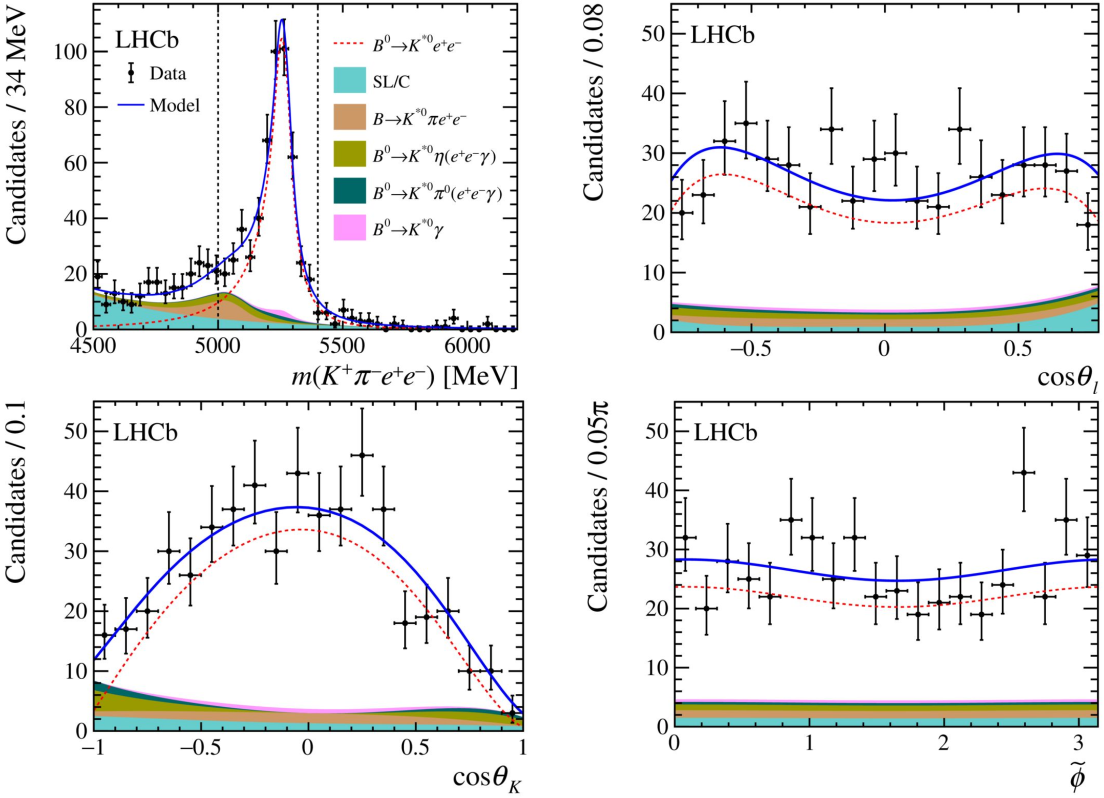
folding 4:

$$\begin{aligned} \cos\theta_L &\rightarrow -\cos\theta_L && \text{for } \cos\theta_L < 0 \\ \phi &\rightarrow \pi - \phi && \text{for } \phi > \frac{\pi}{2} \\ \phi &\rightarrow -\pi - \phi && \text{for } \phi < -\frac{\pi}{2} \\ \cos\theta_K &\rightarrow -\cos\theta_K && \text{for } \cos\theta_L < 0 \end{aligned}$$

55

$B^0 \to K^{*}e^{+}e^{-}$ at low q^2: fit projections

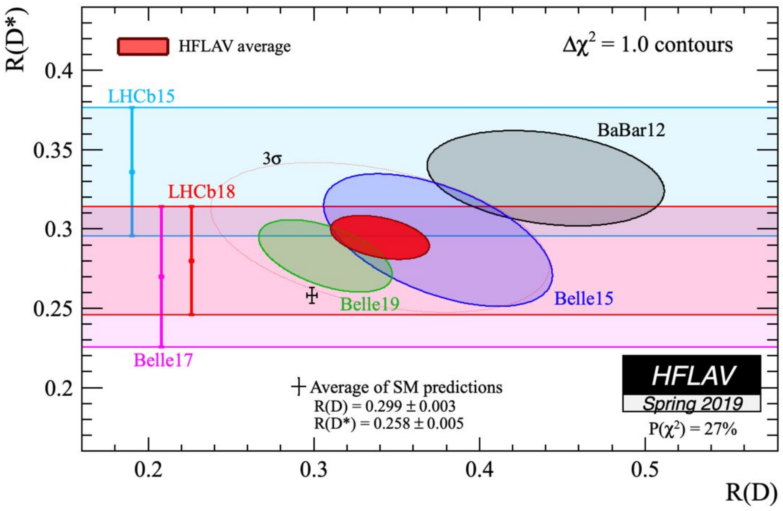
JHEP 12 (2020) 081

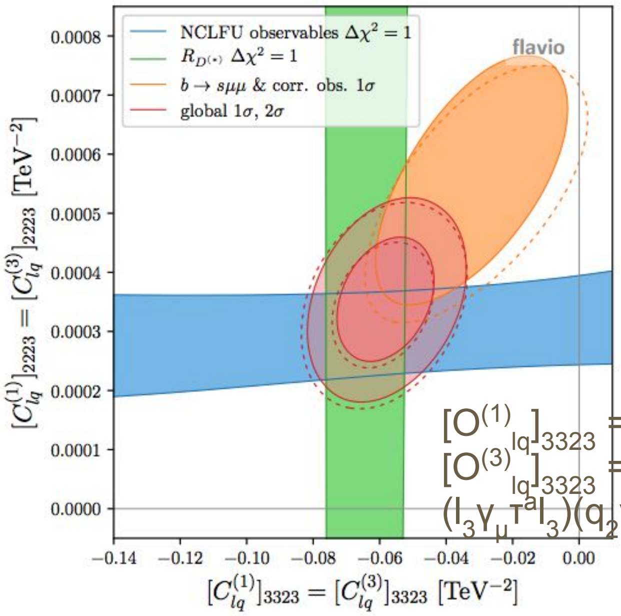


Compatibility with other b anomalies

Hints for NP also in $b \to c l \nu$ LU ratios $R(D^{(*)})$ by Belle, BaBar and LHCb at 3σ

Common explanation to $b \to s l l$ anomalies is possible!





P. Stangl

Similar conclusions
Aebischera et al.
Alguero et al.
Arbey et al.

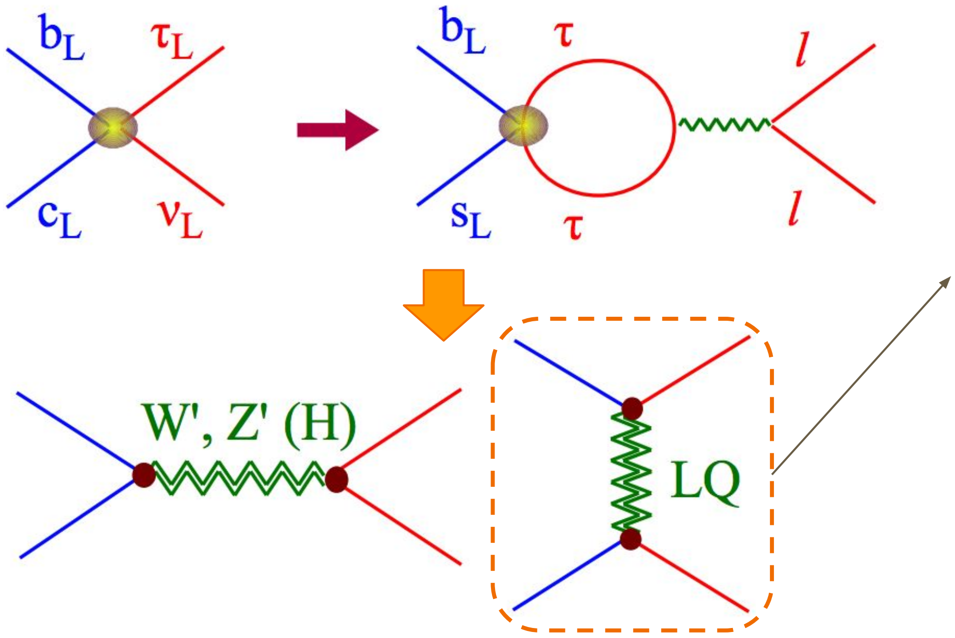
$[O^{(1)}_{lq}]_{3323} = (\bar{l}_3\gamma_\mu l_3)(\bar{q}_2\gamma_\mu q_3)$

$[O^{(3)}_{lq}]_{3323} = (\bar{l}_3\gamma_\mu\tau^a l_3)(\bar{q}_2\gamma_\mu\tau^a q_3)$

NP models in the market

G. Isidori @Beyond the flavour anomalies

To explain b → sll and b → clν simultaneously:

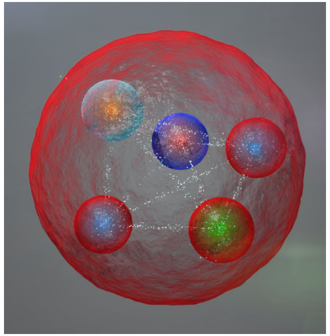


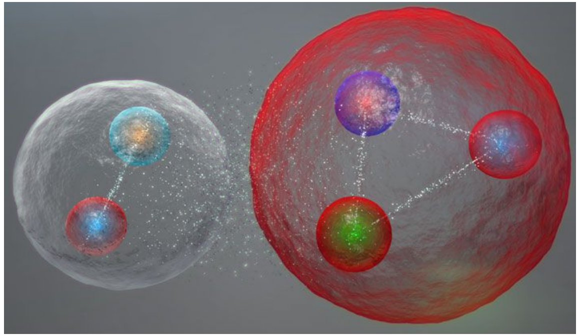
Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_1	✗*	✓	✗*
R_2	✗*	✓	✗
$\widetilde{R}_2$	✗	✗	✗
S_3	✓	✗	✗
U_1	✓	✓	✓
U_3	✓	✗	✗

Angelescu et al.

[Phys.Rev.Lett.122 222001](https://doi.org/10.1103/PhysRevLett.122.222001)

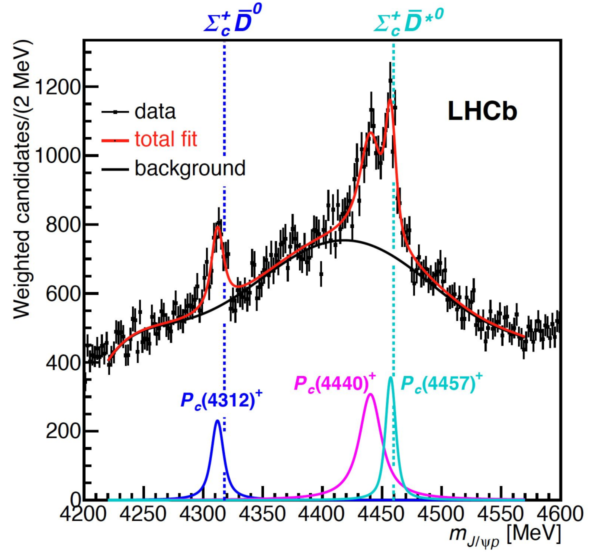
P_c nature





5 quark states:

- tight combination?
- di-quark + tri-quark bound state?



di-J/ψ candidates

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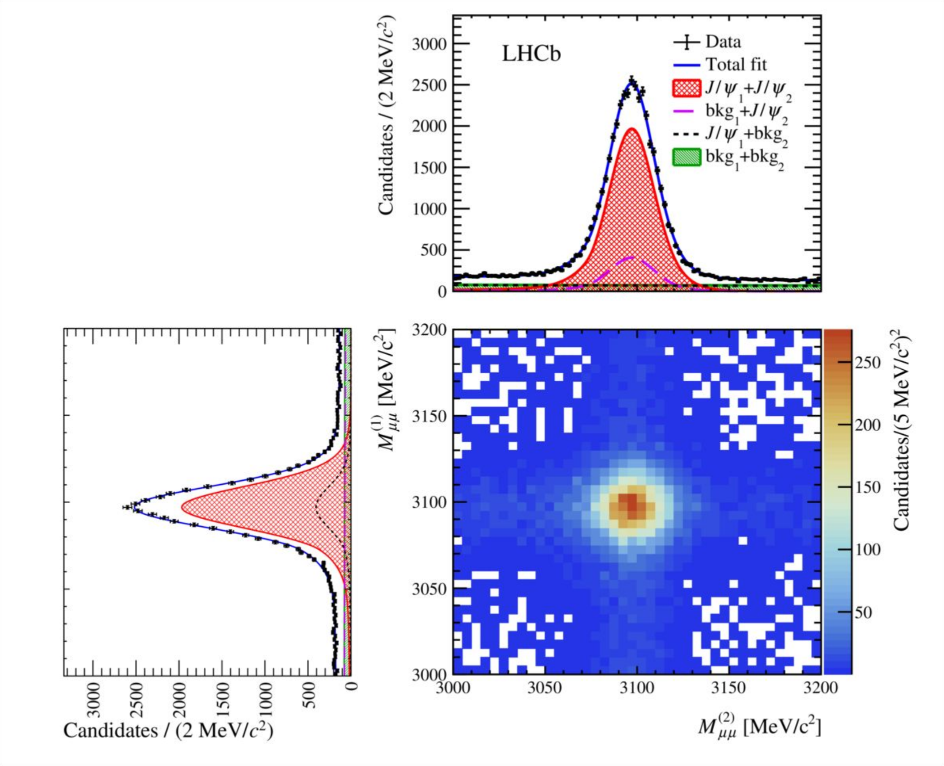
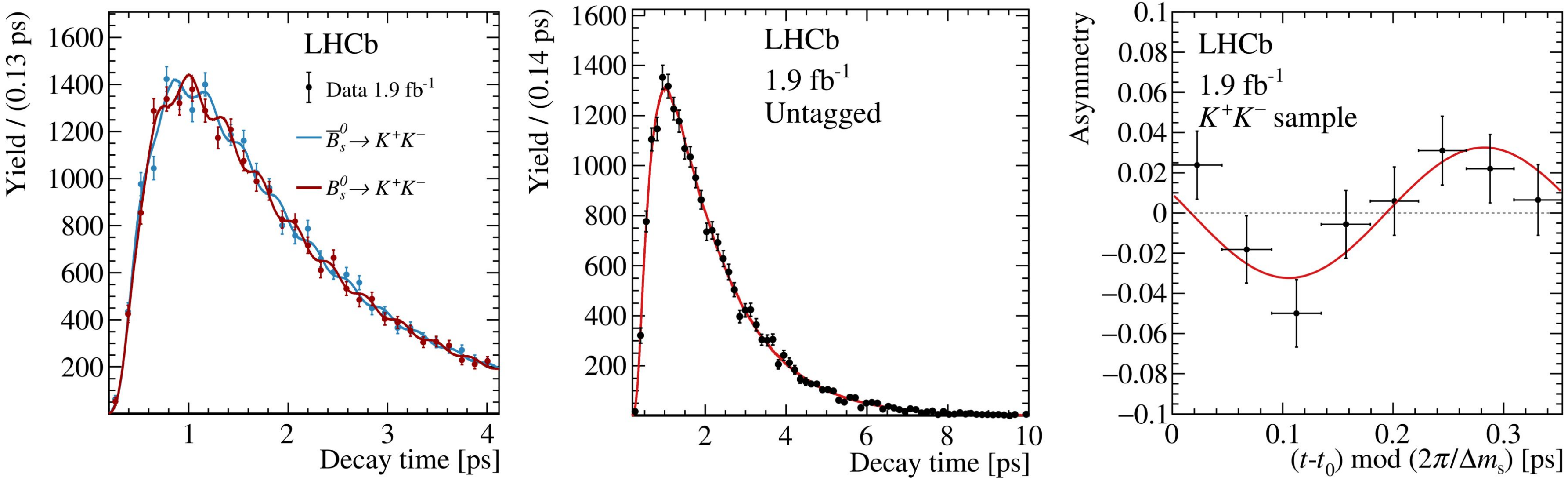


arXiv:2012.05319

CPV in $B_s \to K^+K^-$: per-candidate method



CPV in $B \to \pi^+\pi^-$ decays

arXiv:2012.05319