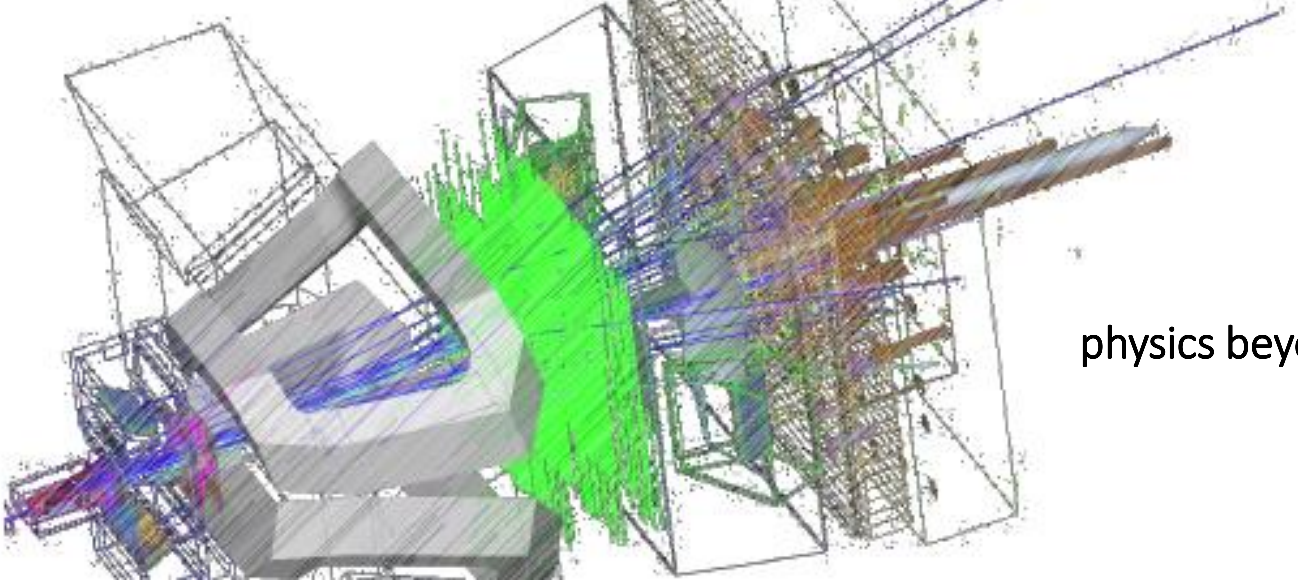
AGH University of Science and Technology

Bartłomiej Rachwał (AGH Kraków)
on behalf of LHCb collaboration

Recent results from the LHCb

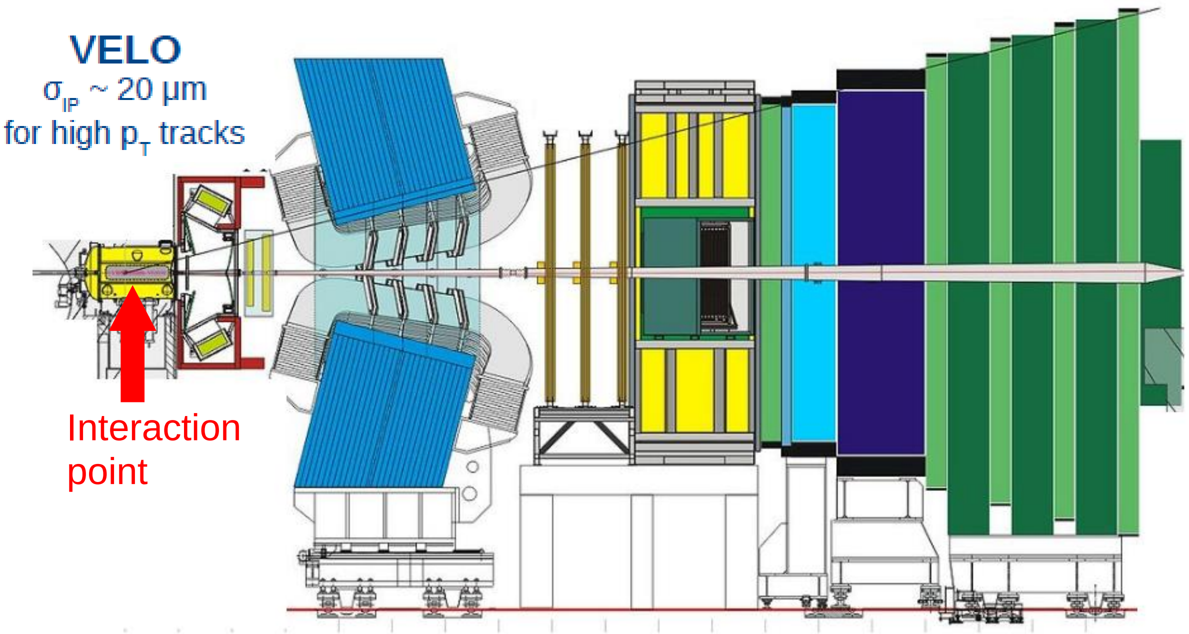


20th Planck Conference
physics beyond the Standard Model
22-27 May 2017
Warszawa, PL

- LHCb proved itself to be the Forward General-Purpose Detector at the LHC

- High cross-section of heavy-quark production
- Excellent particle identification
- Excellent decay time resolution
- Excellent momentum resolution

[JINST 3 (2008) S08005] [Int.J.Mod.Phys. A (2015) 1530022]



- LHCb specialises (mostly) in the 'indirect' approach where precise measurements of low energy phenomena tells us about unknown physics at higher energies;

Heavy flavour production

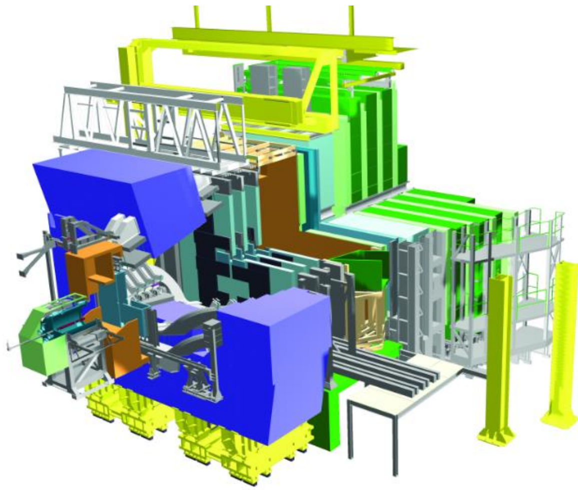
CKM and CPV with b and c hadrons

Rare decays of b and c hadrons

EW, QCD + Exotica in forward region

Spectroscopy in pp collisions and B decays

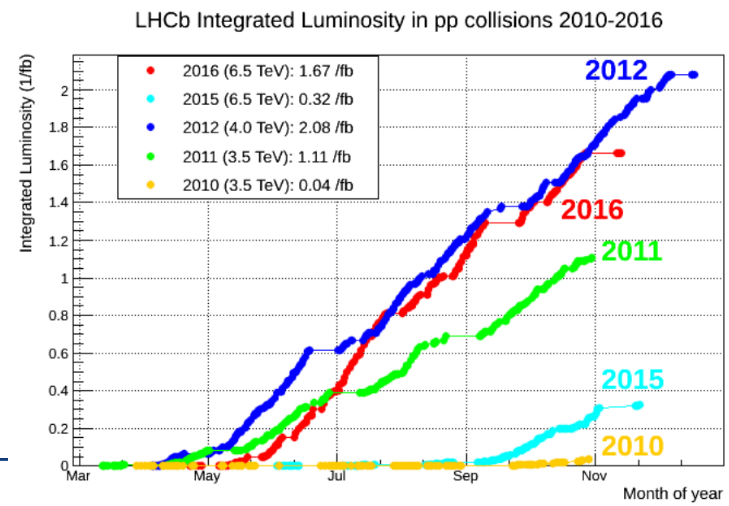
Ions and Fixed Targen



> 378 papers! Public results link

> 50 in 2016

> 20 in 2017



PRL 118, 052002 (2017)

$\sigma(pp \to b\bar{b}X)$

7TeV: $\approx 295\ \mu b$

13TeV: $\approx 600\ \mu b$

$\sigma(pp \to c\bar{c}X) \approx 20\ \times \sigma_{bb}$

Data

- $0.36\ fb^{-1}$ $\sqrt{s} = 7$ TeV (2010)
- $1\ fb^{-1}$ $\sqrt{s} = 7\ TeV$ (2011)
- $2\ fb^{-1}$ $\sqrt{s} = 8\ TeV$ (2012)
- $2\ fb^{-1}$ $\sqrt{s} = 13\ TeV$ (2015&2016)

Outlook

Heavy flavour production

CKM and CPV with b and c hadrons

Rare decays of b and c hadrons

EW, QCD + Exotica in forward region

Spectroscopy in pp collisions and B decays

Ions and Fixed Targen

- First ϕ_s measurement in $B_s \to J/\psi KK$ [arXiv:1704.08217]
- CPV in baryons [Nature Physics 13 (2017) 391]
- $B^0_{(s)} \to \mu^+\mu^-$ [PRL 118 (2017) no.19, 191801]
- $B^0_{(s)} \to \tau^+\tau^-$ [arXiv:1703.02508]
- $B^+ \to K^+\mu^+\mu^-$ [EPJ C77 (2017) no.3, 161]
- LU test with B decays:

  $R(K^{*0})$ [arXiv:1705.05802]

CP-violation

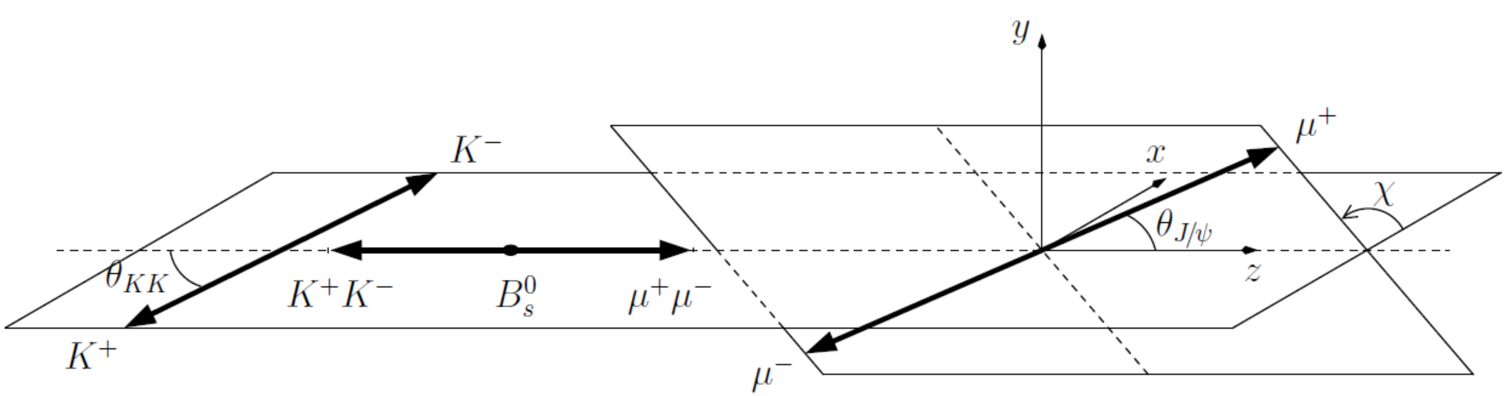
- The Standard Model prediction of the CP-violating phase in $b \to c\bar{c}$ transitions:

$$\phi_s^{SM} \equiv -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -36.5^{+1.3}_{-1.2}\ \mathrm{mrad}$$ [Phys. Rev. D91 (2015) 073007]

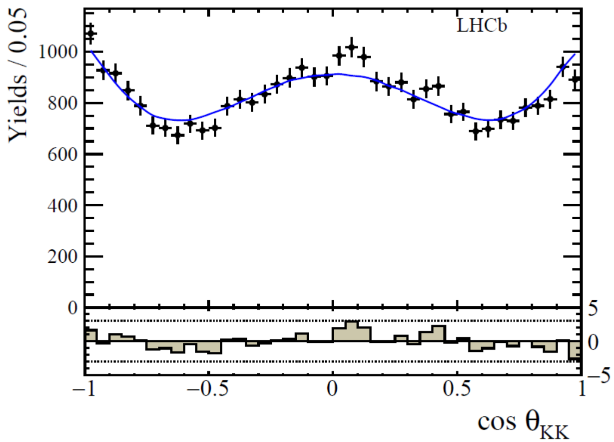
- The average of previous measurements (D0, LHCb, ATLAS, CMS):

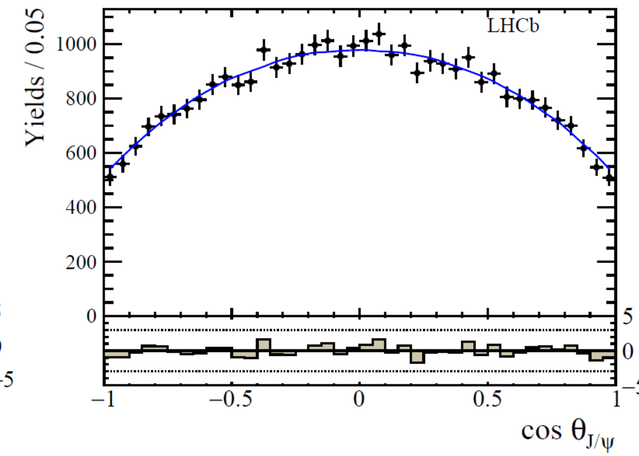
$$\phi_s = -30 \pm 33\ \mathrm{mrad}$$ [arXiv:1612.07233]

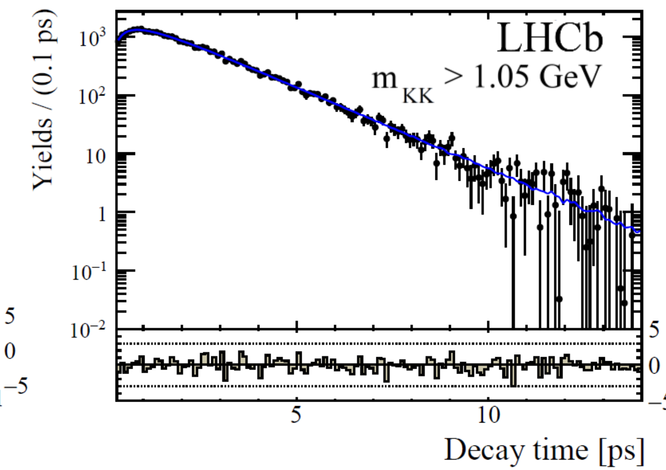
- The LHCb update :
  - ✓ Full Run 1 dataset;
  - ✓ The first measurement using $B_s \to J/\psi K^+ K^-$ decays with K^+K^- mas region above the $\phi(1020)$ meson;
  - ✓ The CP-even and CP-odd components in the decay fitted as functions of the B_s proper decay time and helicity angles



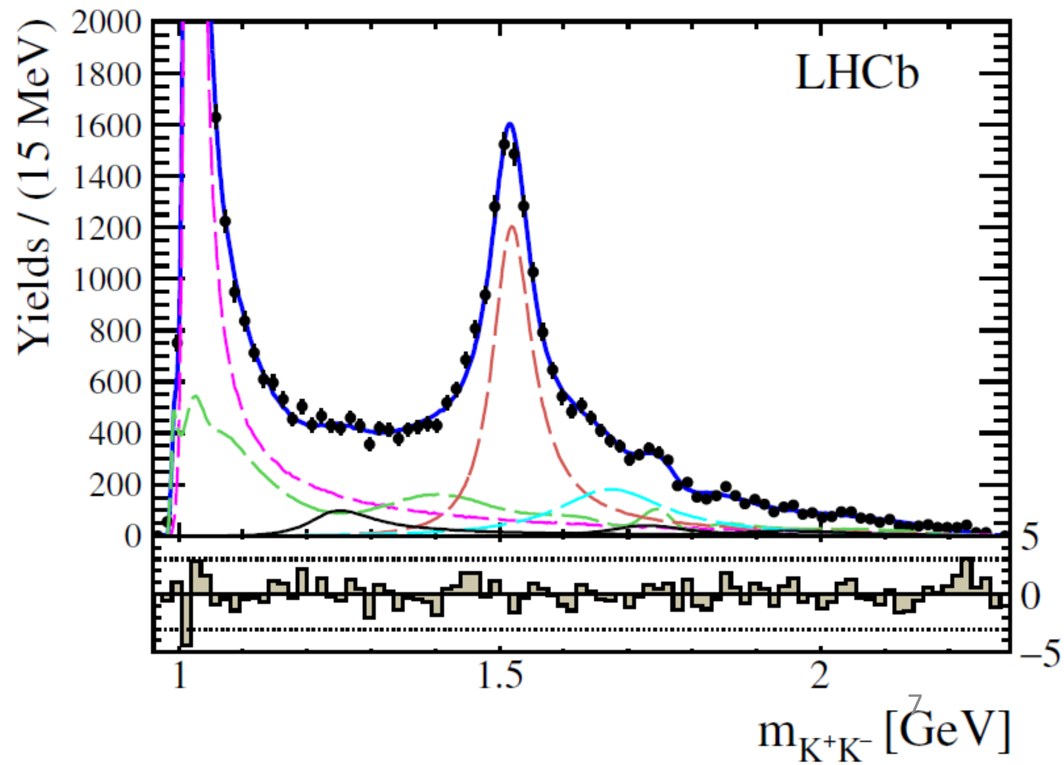
CPV | ϕ_s measurement in $B_s \to J/\psi K^+K^-$ [arXiv:1704.08217]



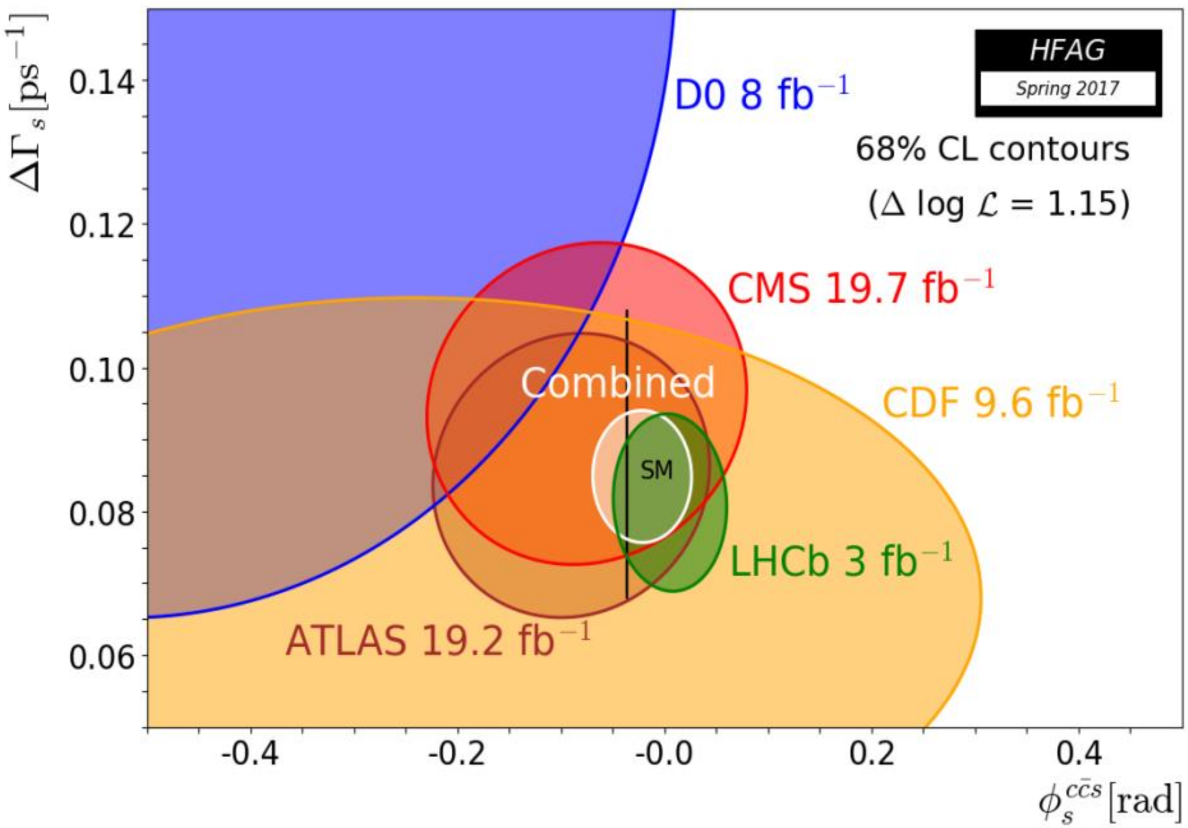




- Many resonances and a S-wave structure have been found:
  - $\phi(1020)$
  - $f_2(1270)$
  - $f_2'(1525)$
  - $\phi(1680)$
  - $f_2(1750)$
  - $f_2(1950)$
  - S-wave
- Results
  $\phi_s = 119 \pm 107 \pm 34$ mrad
- The LHCb combination
  $\phi_s = -25 \pm 45 \pm 8$ mrad



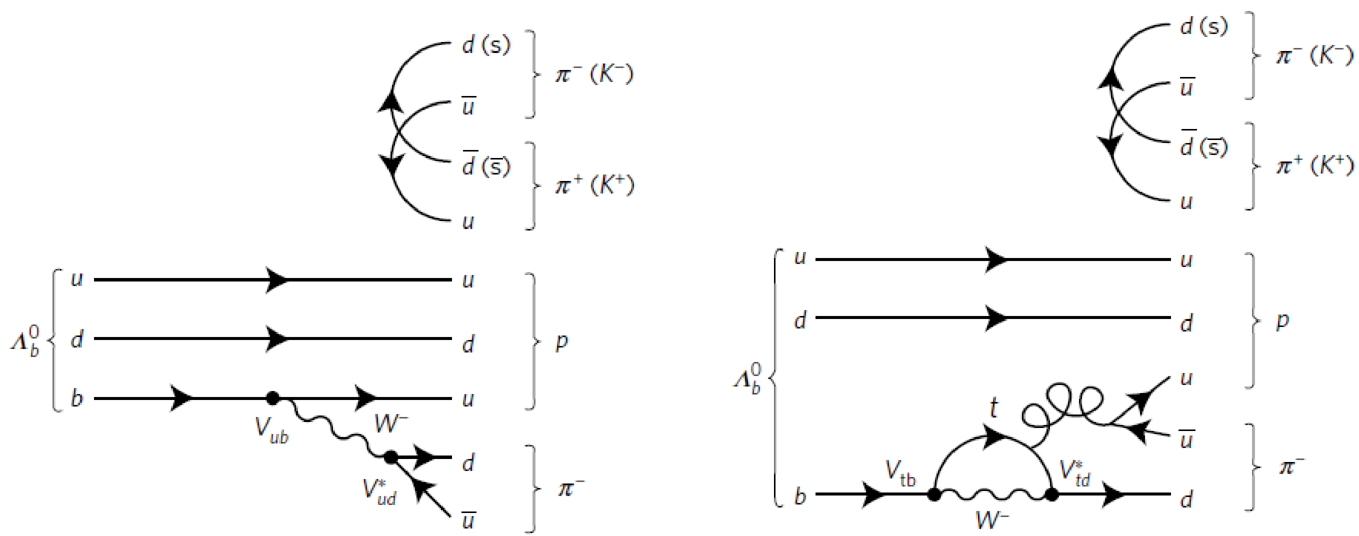
- The measurement of the CP-violating phase ϕ_s is in agreement with the SM prediction:



T. Gershon at Moriond EW

- CP violation has never been measured in baryons before, despite predictions from the SM that CP violation also exists in the baryon sector.

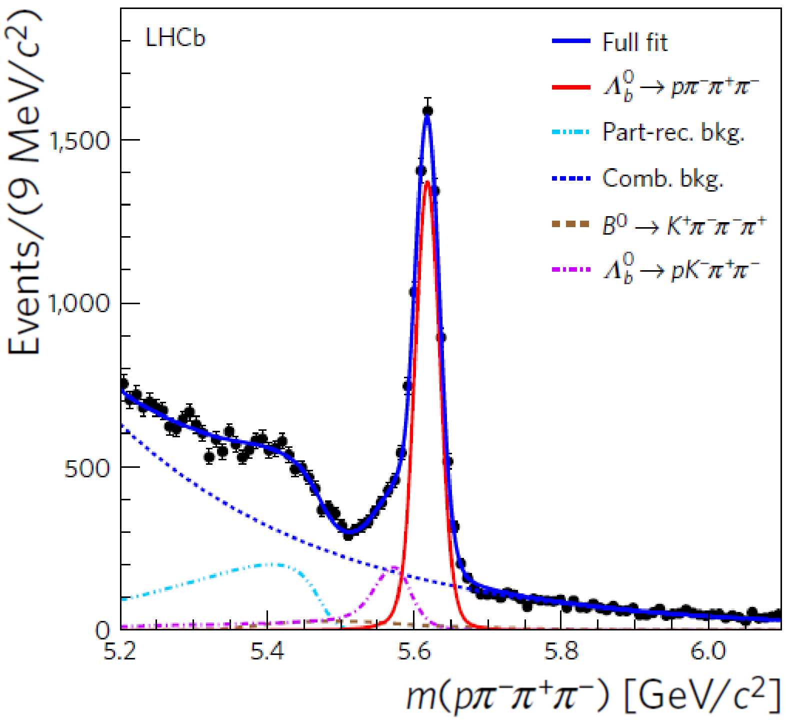
- LHCb search for CP-violating asymmetries in the decay angle distributions of $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$and $\Lambda_b^0 \to p\pi^-K^+K^-$ decays

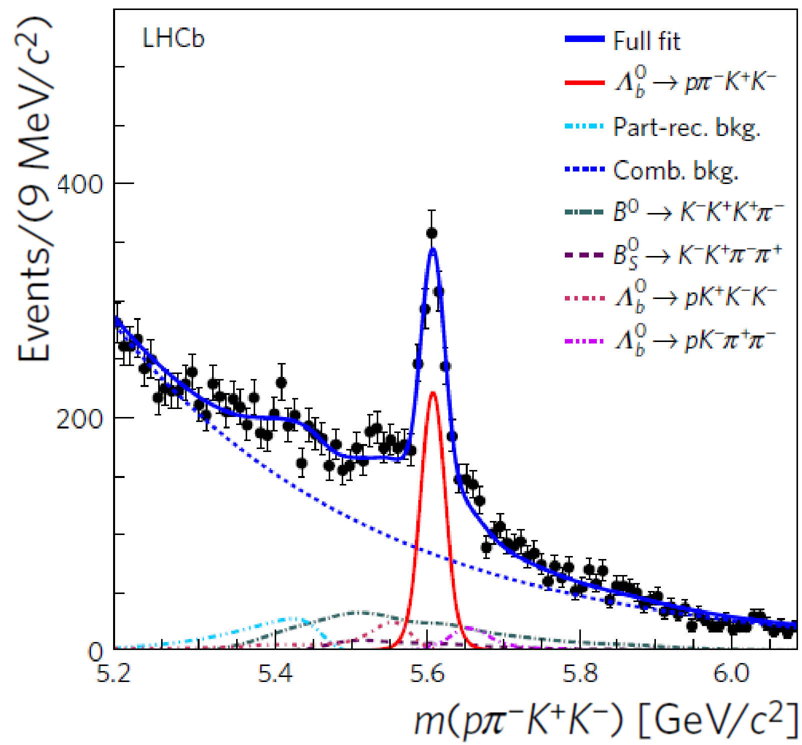


- The P- and CP- violating observables defind on assymetries, $A_{\hat{T}}$ built from scalar triple products

$$a_P^{\hat{T}\text{-odd}} = \frac{1}{2}\left(A_{\hat{T}} + \overline{A}_{\hat{T}}\right), \qquad a_{CP}^{\hat{T}\text{-odd}} = \frac{1}{2}\left(A_{\hat{T}} - \overline{A}_{\hat{T}}\right)$$

[Nature Physics 13 (2017) 391]





Signal yields obtained from fits to data:

$6{,}646 \pm 105$ $1{,}030 \pm 56$

* For $\Lambda_b^0 \to p\pi^-K^+K^-$ smaller purity and signal yield of the sample do not permit PV and CPV to be probed with the same precision as for $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

- Searches for localized P or CP violation

Scheme A

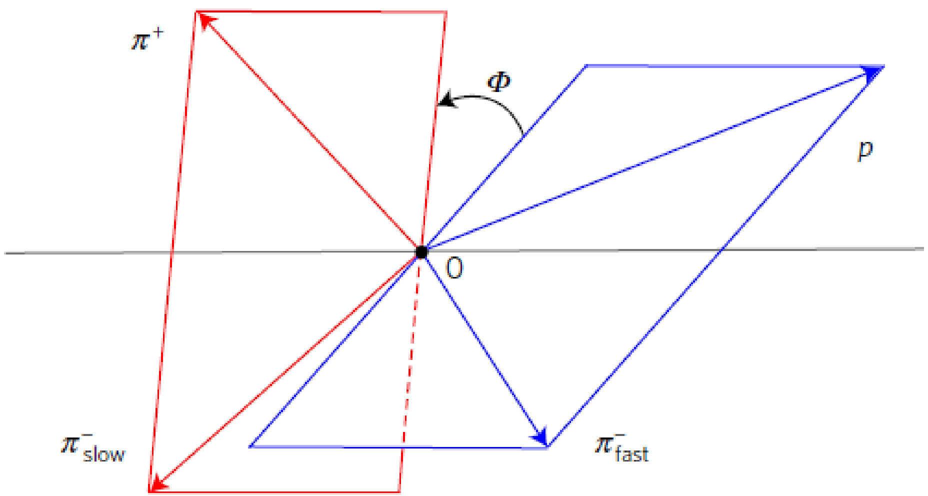
To isolate regions of phase space according to their dominant resonant contributions:

$$\Delta(1232)^{++} \to p\pi^{+}$$

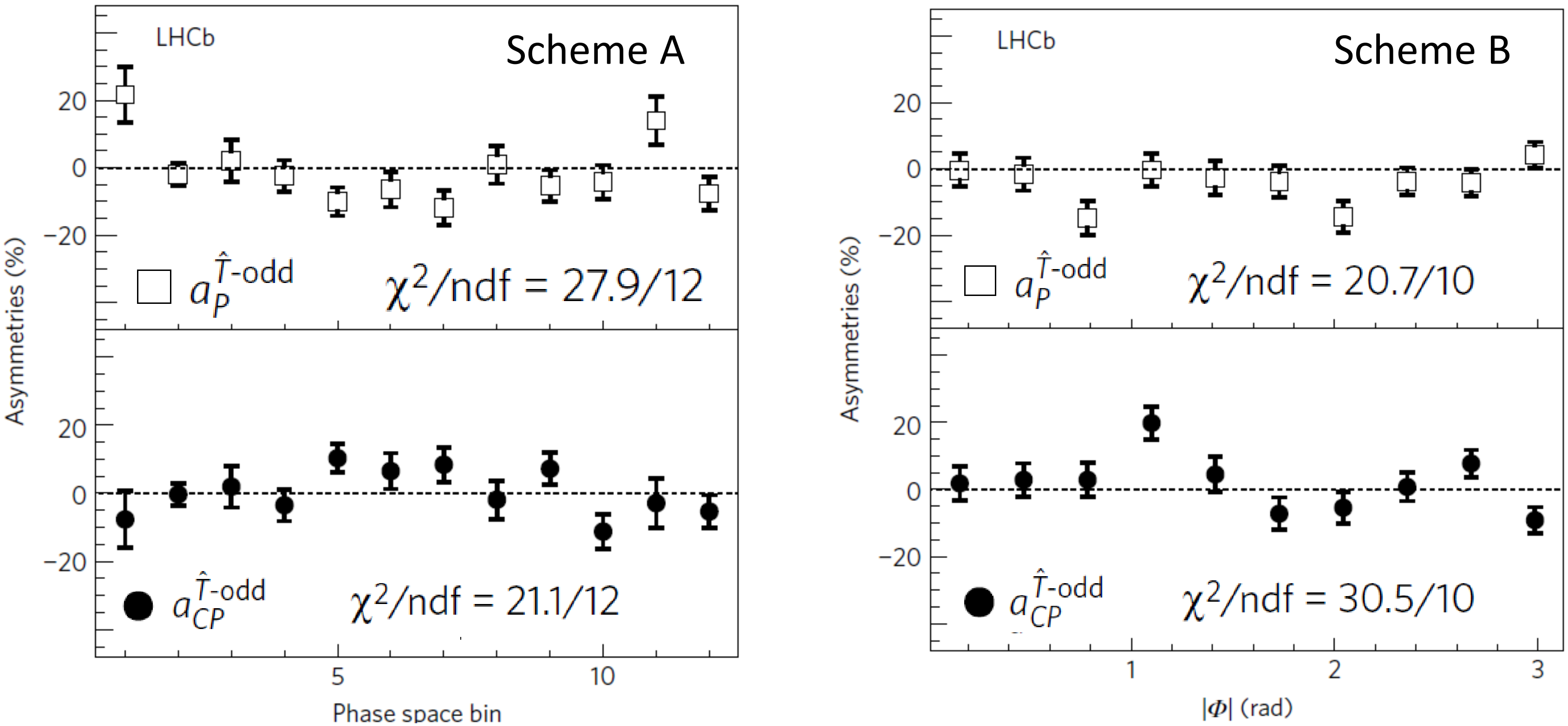
$$\rho(770)^{0} \to \pi^{+}\pi^{-}$$

Scheme B

To exploits in more detail the interference of contributions visible as a function of the angle between the decay planes



- Results for $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$



An overall deviation from no-CPV hypothesis: $3.3\ \sigma$

First hints of CP violation in baryons!!!

Rare decays

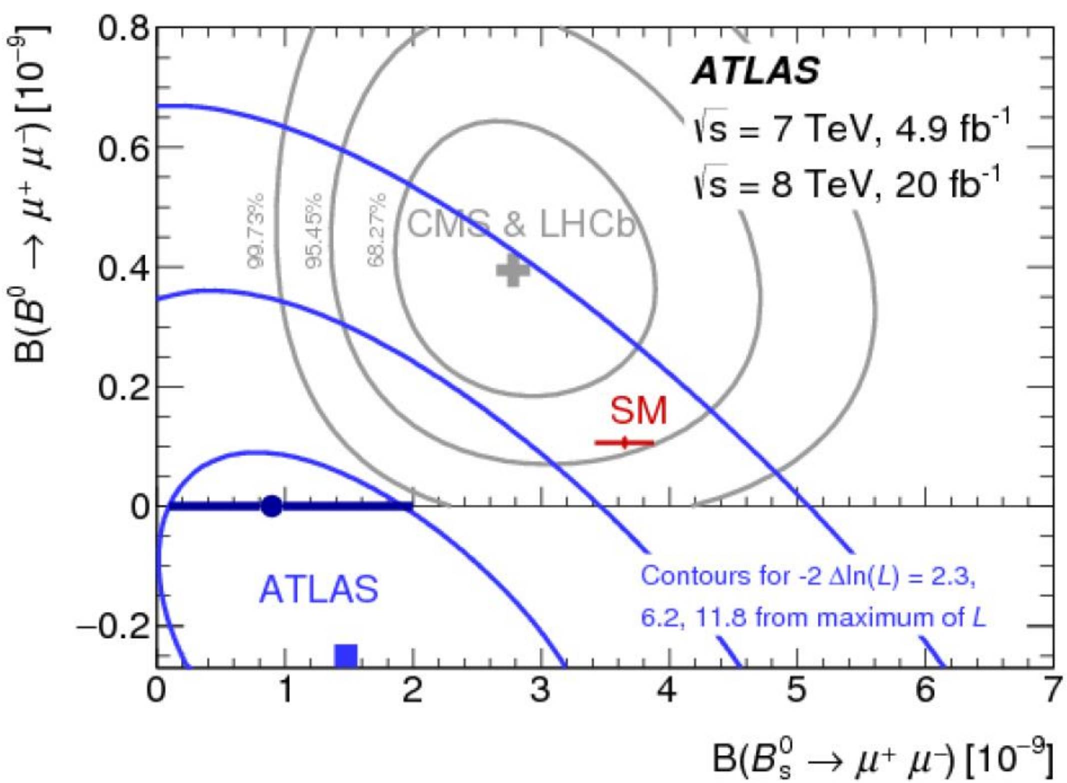
- Strategy: measure with presicion processes containing SM particles
- Very important to have SM predictions under theoretical control
- Some channels are very clean, only limiting factor is statistics

Rare decays | $B^0_{(s)} \to \mu^+\mu^-$

- Very accurate SM predictions [PRL 96 (2006) 241802]

$$\mathcal{B}(B^0 \to \mu^+\mu^-) \stackrel{\text{SM}}{=} (1.06 \pm 0.09) \times 10^{-10}$$
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) \stackrel{\text{SM}}{=} (3.66 \pm 0.23) \times 10^{-9}$$

- Summary previous measurements / current situation



ATLAS, [EPJC 76 (2016) 513]
CMS+LHCb, [Nature 522 (2015) 68]

LHCb update

- $3\mathrm{fb}^{-1}$ of Run1 + $1.4\mathrm{fb}^{-1}$ of Run2
- new signal isolation
- new BDT: 50% better bgd rejection
- improved PID: 50% less $B \to h^+h^-$

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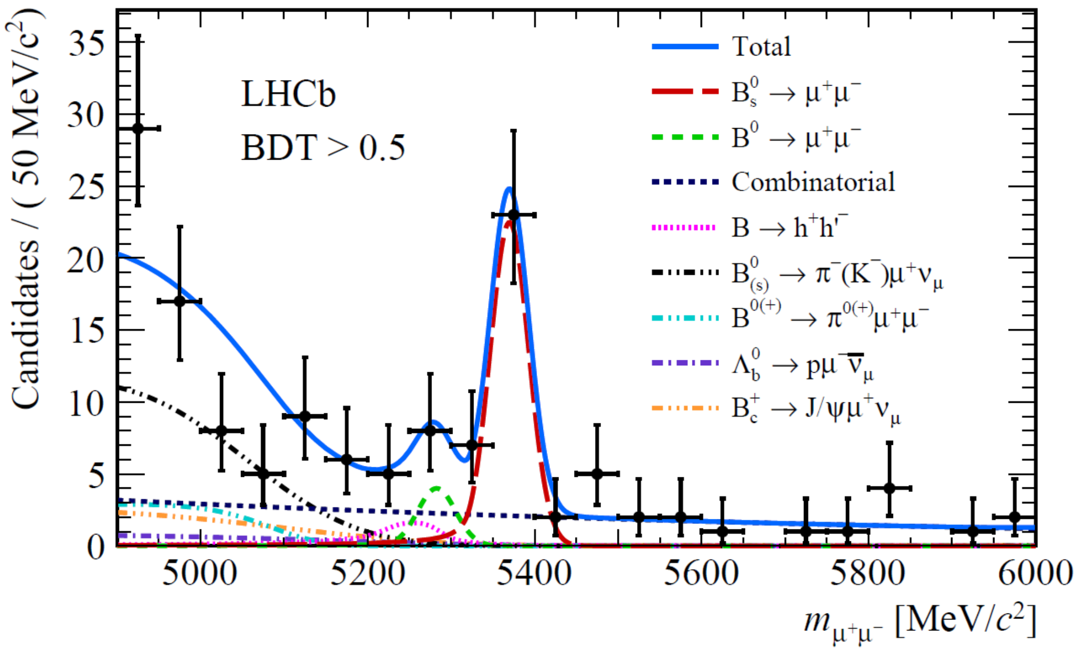


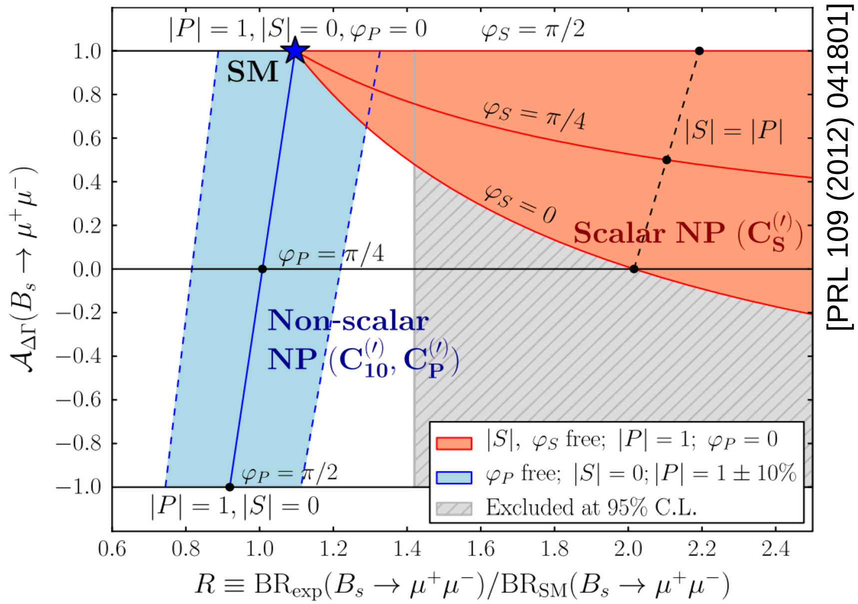
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \text{ at 95\% CL}$$

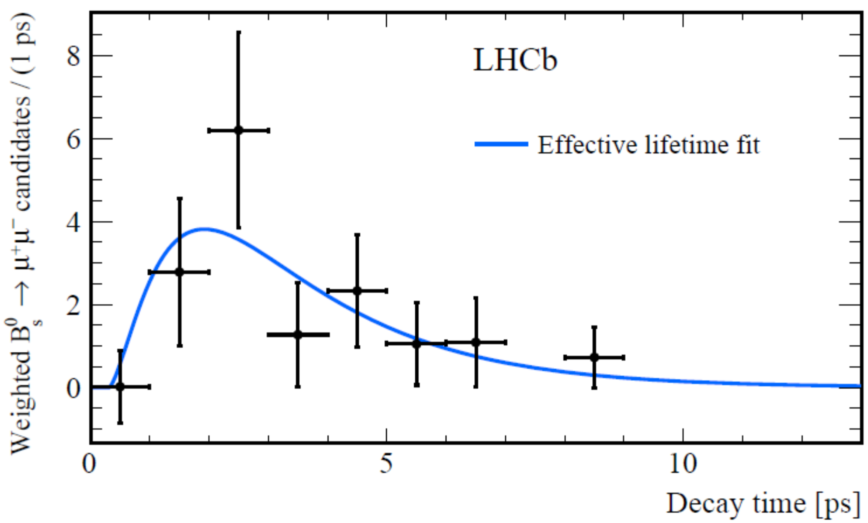
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,(\text{stat})\,^{+0.3}_{-0.2}\,(\text{syst})) \times 10^{-9} \qquad (7.8\sigma)$$

First single-experiment observation of the B_s mode !!!

⇒ New observable: effective lifetime

- Even if the BF is SM, the effective lifetime provides a probe to search for NP.
- The effective lifetime can be expressed in terms of $A_{\Delta\Gamma}^{\mu^+\mu^-}$ [PRL 109 (2012) 041801]





- For the first time, measurement of the effective lifetime

$$\boxed{\tau(B^0_s \to \mu^+\mu^-) = 2.04 \pm 0.44\,(\text{stat}) \pm 0.05\,(\text{syst})\ \text{ps}}$$

- The measurement consistency:

  SM: $A_{\Delta\Gamma}^{\mu^+\mu^-} = 1\ (1\sigma)$

  NP: $A_{\Delta\Gamma}^{\mu^+\mu^-} = -1\ (1.4\sigma)$

- The first step for future analyses of this kind.

- Theoretically, as clean as the muonic mode
- Experimentally much more challenging
- More abundant than the muon mode [PRL 112 (2014) 101801]

$$\mathcal{B}(B^0 \to \tau^+\tau^-) \stackrel{\text{SM}}{=} (2.22 \pm 0.19) \times 10^{-8}$$

$$\mathcal{B}(B^0_s \to \tau^+\tau^-) \stackrel{\text{SM}}{=} (7.73 \pm 0.49) \times 10^{-7}$$

- Will make for a very clean LFU test with muonic mode in the future
- Only existing limit on the B^0 mode from Babar [PRL 96 (2006) 241802]

$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 4.1 \times 10^{-3} \quad @\, 90\%\ \text{C.L.}$$

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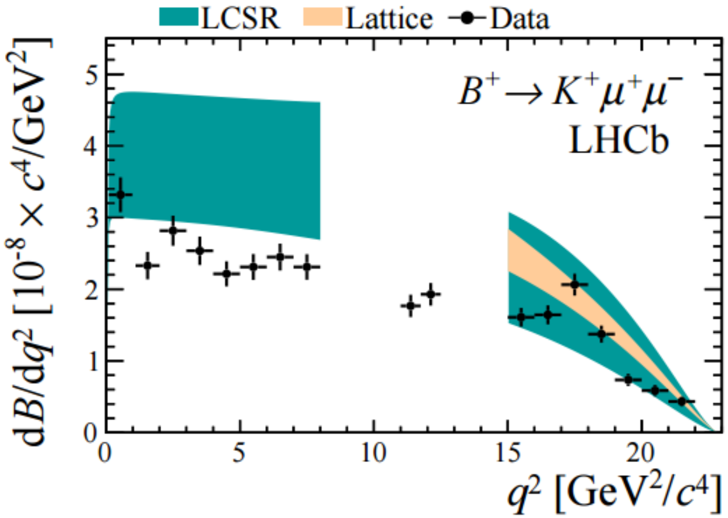
- Analysis of LHCb Run1 data, in hadronic tau decay via the resonances

$$\tau^- \to a_1(1260)^-\nu_\tau,\ a_1(1260)^- \to \rho(770)^0\pi^-$$
$$\mathcal{B}(\tau^\pm \to \pi^\pm\pi^\mp\pi^\pm\bar{\nu}_\tau) = (9.31 \pm 0.05)\%$$

- **World best limits** set for each mode (assuming no contributions from the other):

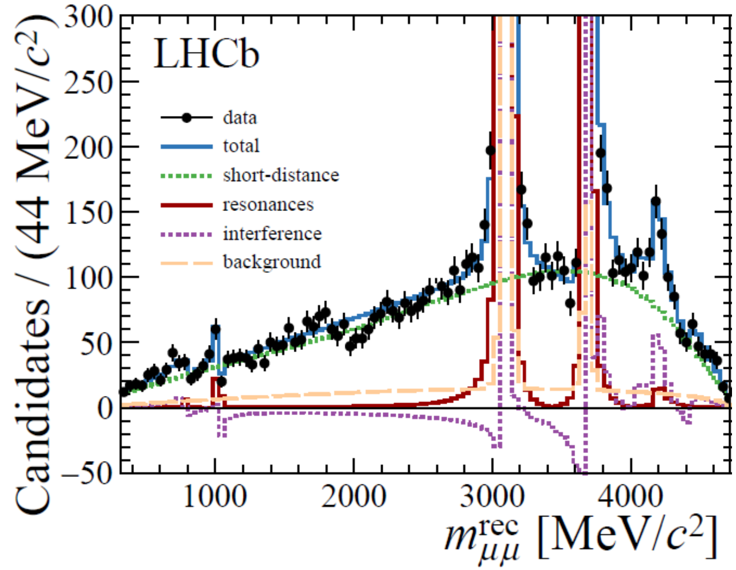
$$\boxed{\begin{aligned}\mathcal{B}(B^0_s \to \tau^+\tau^-) &< 6.8 \times 10^{-3} \text{ at } 95\%\ CL\\ \mathcal{B}(B^0 \to \tau^+\tau^-) &< 2.1 \times 10^{-3} \text{ at } 95\%\ CL\end{aligned}}$$

- The observed tensions in measurements where regions of dimuon mass around the J/ψ and $\psi(2S)$ resonances were excluded [JHEP 06 (2014) 133]



[JHEP 06 (2014) 133]

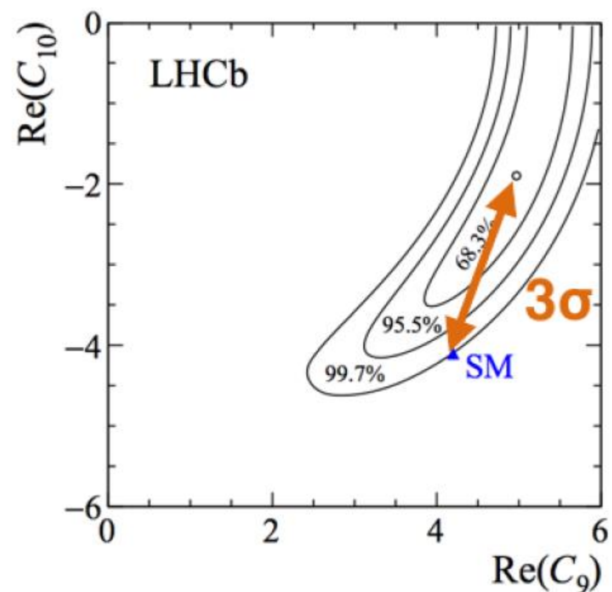
neg. neg.



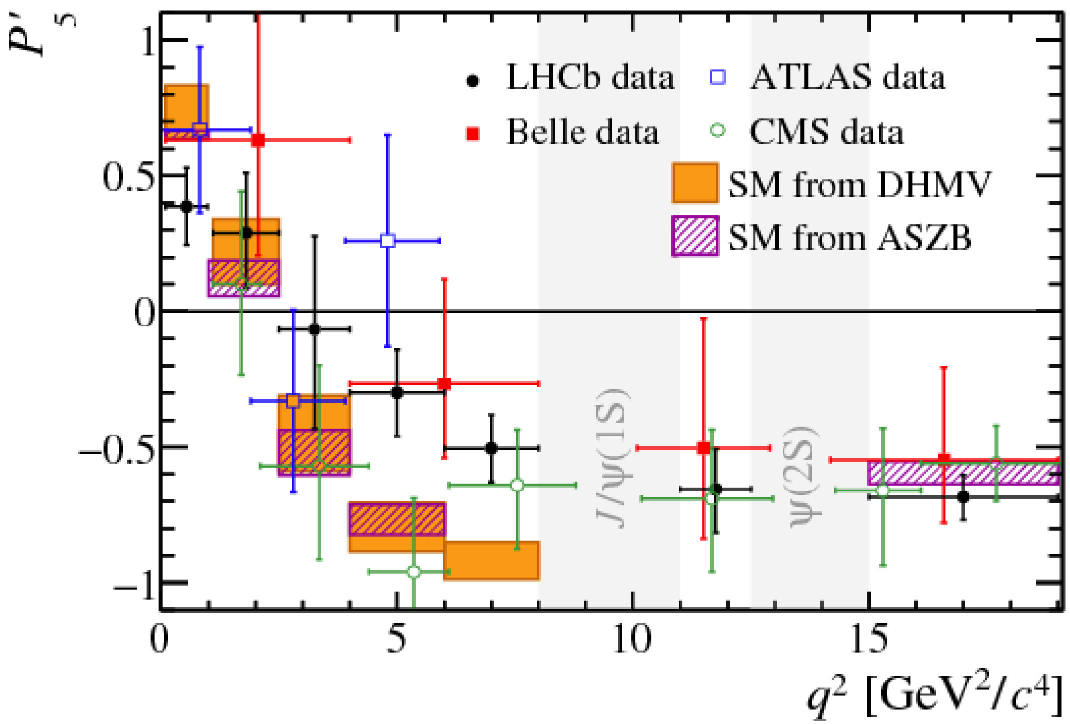
- The observed tensions in measurements where regions of dimuon mass around the J/ψ and $\psi(2S)$ resonances were excluded
- Analyse the $m(\mu\mu)$ spectrum of $B^+ \to K^+\mu^+\mu^-$ modeling all resonances:
  - Fits with different phase hypotheses for long-distance contributions
- The observed **BF is lower than the SM**, in agreement with previous analysis (same data)

$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (4.37 \pm 0.15\,(\text{stat}) \pm 0.23\,(\text{syst})) \times 10^{-7}$$

- Scan of Wilson coefficients disfavours the SM solution



- Lepton Flavour Universality tests with B decays – tension in the data coming from $B \to K^{*}\mu^{+}\mu^{-}$ angular observables



LHCb: JHEP 02 (2016) 104
Belle: BELLE-CONF-1603
ATLAS: ATLAS-CONF-2017-023
CMS: CMS-PAS-BPH-15-008

DHMV: JHEP 12(2014)125
ASZB: EPJC 75 (2015) 382

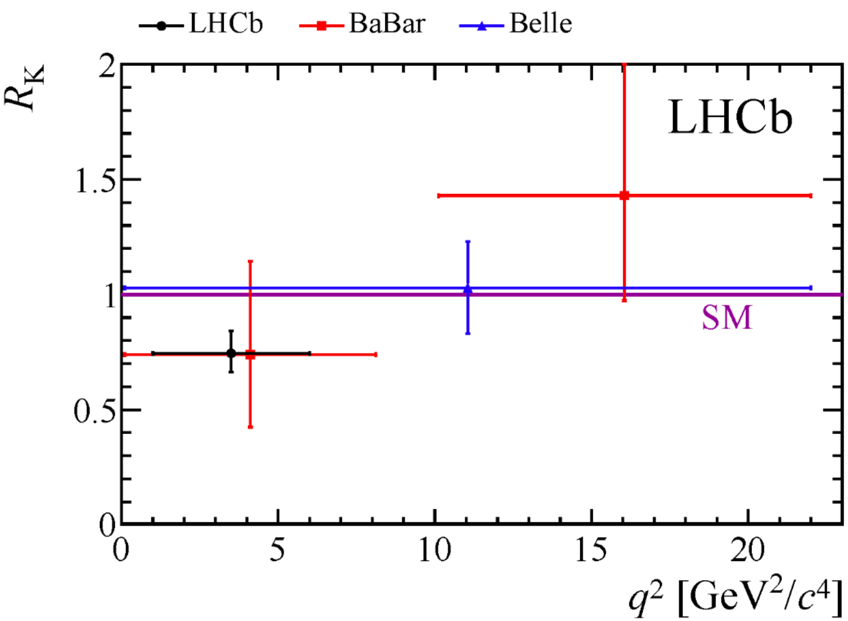
* Belle, ATLAS and CMS use angular folding, differences in observables, background treatment and control modes.

- Lepton Flavour Universality tests with B decays – tension in the data coming from $B \to K^{*}\mu^{+}\mu^{-}$ angular observables

- Violation of lepton universality

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

- $R(K)$ results



LHCb: PRL 113 (2014) 151601
BaBar: PRD 86 (2012) 032012
Belle: PRL 103 (2009) 171801

- LHCb : $0.745^{+0.090}_{-0.074} \pm 0.036$ in the $1 < q^2 < 6$ GeV^2/c^4, tension with the SM at 2.6σ

Submitted to JHEP last week!

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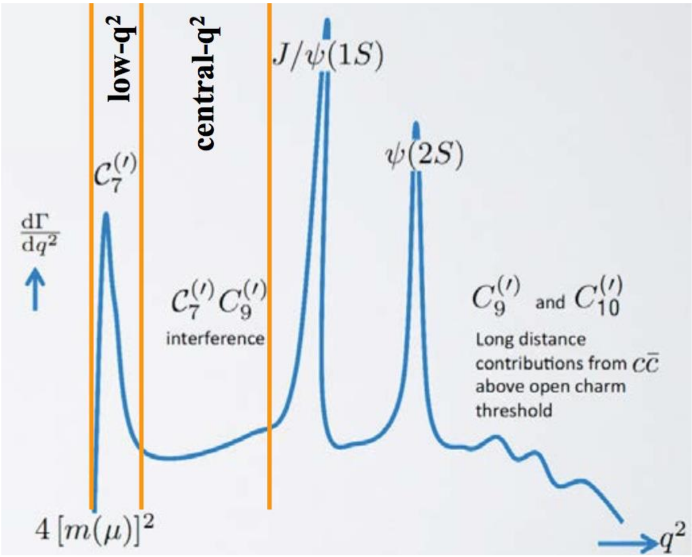
- $R(K)$ results

- $R(K^{*0})$ measurement
  - Using full Run 1 data
  - Double ratio to cancel systematics
  - Measuring in two bins of q^2:
    Low: 0.045-1.1 GeV/c2
    Central: 1.1-6   GeV/c2

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



Talk by S. Bifani, LHCb 18/04/2017

Submitted to JHEP last week!

- $R(K^{*0})$ measurement

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

Results compatibility with the SM expectations:

- low$-q^2$ bin 2.1 - 2.3 σ
- central-q^2 bin 2.4 - 2.5 σ

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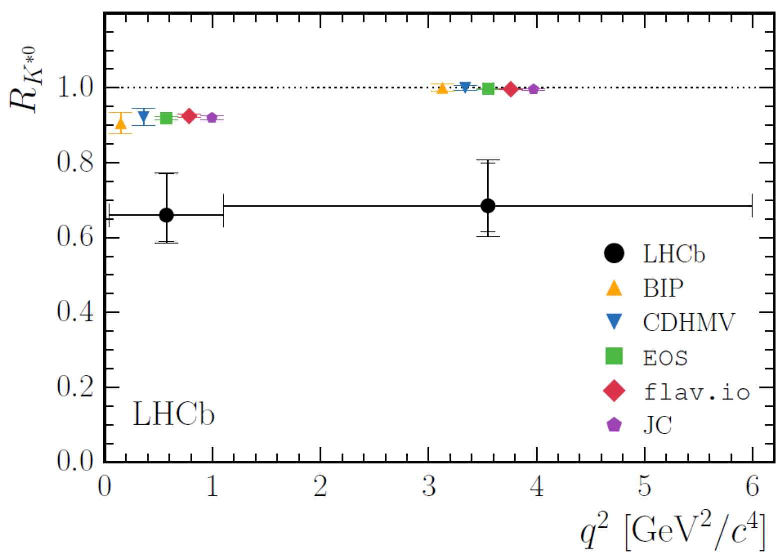
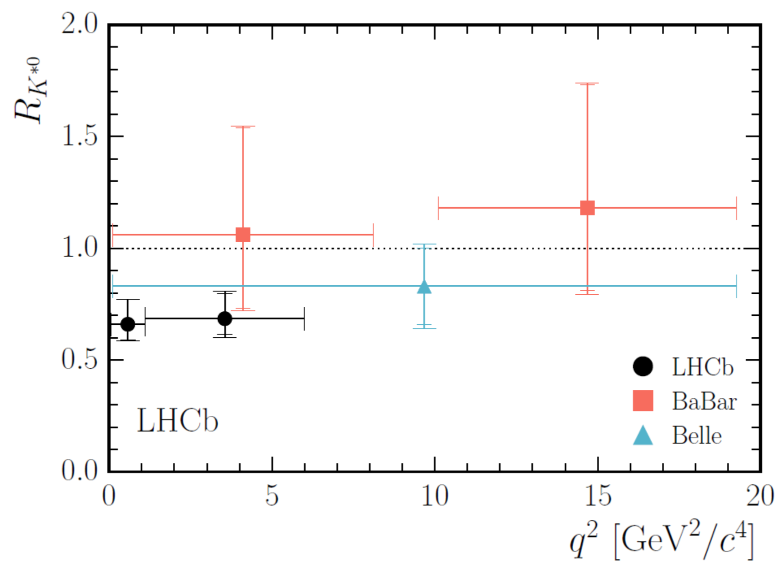
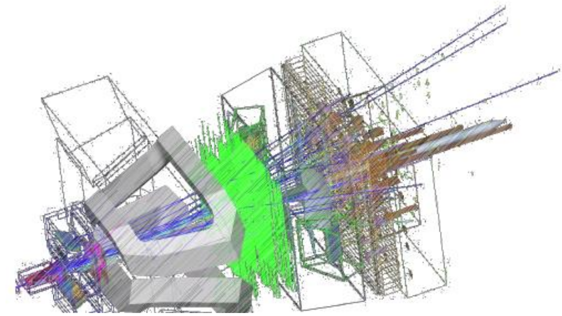






Conclusions

- LHCb has taken series of measurement in flavour physics
- CP violation results compatible with the SM
- First hints of CP violation in baryons
- Rare decays remain the source of tensions with the SM both in LFU tests and in global fits to Wilson coefficients
- First measurement of promising observable, the effective lifetime $B_s^0 \to \mu^+\mu^-$
- Many other recent results not covered here: [link]

Backup

dark matter
astroparticle
cosmic ray
gamma
non-thermal universe
neutrino
advanced technologies
dark universe
theory
alliance
research
astronomy
physics
big bang
nuclei
beyond
subatomic
helmholtz
supernova
galaxy
black hole
high energy
decay
universe
air shower
burst
collisions
luminosity
interacting
decoupling
electron
detectors
galactic
spectrum
experiment
SUSY
standard model
fundamental
discovery
messenger
field
interaction
million
atmosphere
secondary
fluorescence
telescope
source
density
mass
antiparticle
detection
cerenkov
underwater
space
explosion
measurement
crystal
unknown
GeV

- Fit results of the resonant structure.
  The three possible polarizations of the J/ψ generate longitudinal ($\mathbf{0}$), parallel (||) and perpendicular (⊥) transversity amplitudes.

Component	Fit fraction (%)	Transversity fraction (%)		
		0	$\parallel$	$\perp$
$\phi(1020)$	$70.5 \pm 0.6 \pm 1.2$	50.9 ± 0.4	23.1 ± 0.5	26.0 ± 0.6
$f_2(1270)$	$1.6 \pm 0.3 \pm 0.2$	76.9 ± 5.5	6.0 ± 4.2	17.1 ± 5.0
$f_2'(1525)$	$10.7 \pm 0.7 \pm 0.9$	46.8 ± 1.9	33.8 ± 2.3	19.4 ± 2.3
$\phi(1680)$	$4.0 \pm 0.3 \pm 0.3$	44.0 ± 3.9	32.7 ± 3.6	23.3 ± 3.6
$f_2(1750)$	$0.59\,^{+0.23}_{-0.16} \pm 0.21$	58.2 ± 13.9	31.7 ± 12.4	$10.1\,^{+16.8}_{-6.1}$
$f_2(1950)$	$0.44\,^{+0.15}_{-0.10} \pm 0.14$	$2.2\,^{+6.7}_{-1.5}$	38.3 ± 13.8	59.5 ± 14.2
S-wave	$10.69 \pm 0.12 \pm 0.57$	100	0	0

- Scalar triple products of final-state particle momenta in the Λ_b^0 centre-of-mass frame

$$C_{\widehat{T}} = \mathbf{p}_p \cdot (\mathbf{p}_{h_1^-} \times \mathbf{p}_{h_2^+}) \quad \overline{C}_{\widehat{T}} = \mathbf{p}_{\overline{p}} \cdot (\mathbf{p}_{h_1^+} \times \mathbf{p}_{h_2^-}) \text{ for } \overline{\Lambda}_b^0$$

- Assymetries definiotion

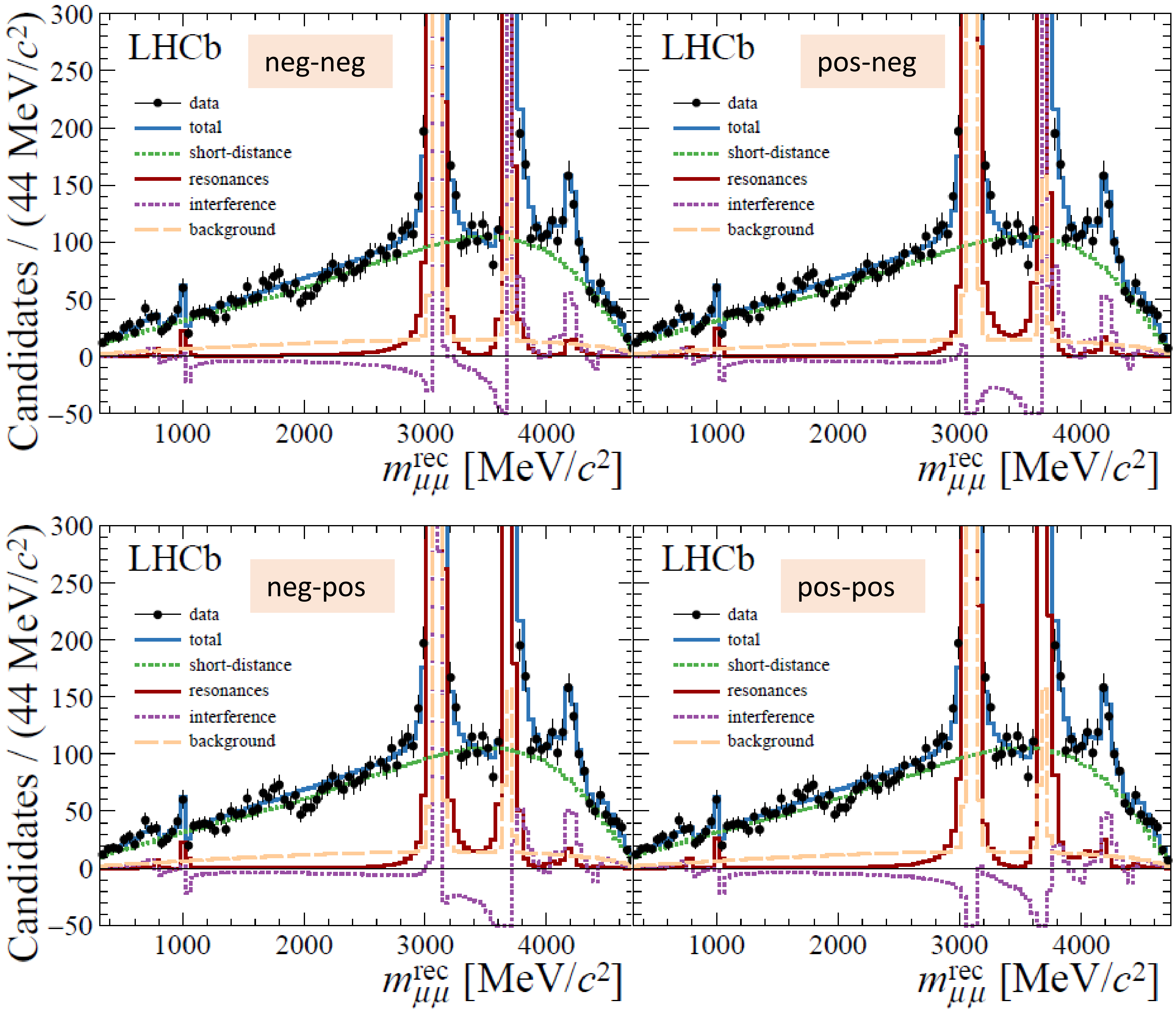
$$A_{\widehat{T}}(C_{\widehat{T}}) = \frac{N(C_{\widehat{T}} > 0) - N(C_{\widehat{T}} < 0)}{N(C_{\widehat{T}} > 0) + N(C_{\widehat{T}} < 0)}$$

$$\overline{A}_{\widehat{T}}(\overline{C}_{\widehat{T}}) = \frac{\overline{N}(-\overline{C}_{\widehat{T}} > 0) - \overline{N}(-\overline{C}_{\widehat{T}} < 0)}{\overline{N}(-\overline{C}_{\widehat{T}} > 0) + \overline{N}(-\overline{C}_{\widehat{T}} < 0)}$$

N and $\overline{N}$ are the numbers of Λ_b^0 and $\overline{\Lambda}_b^0$ decays

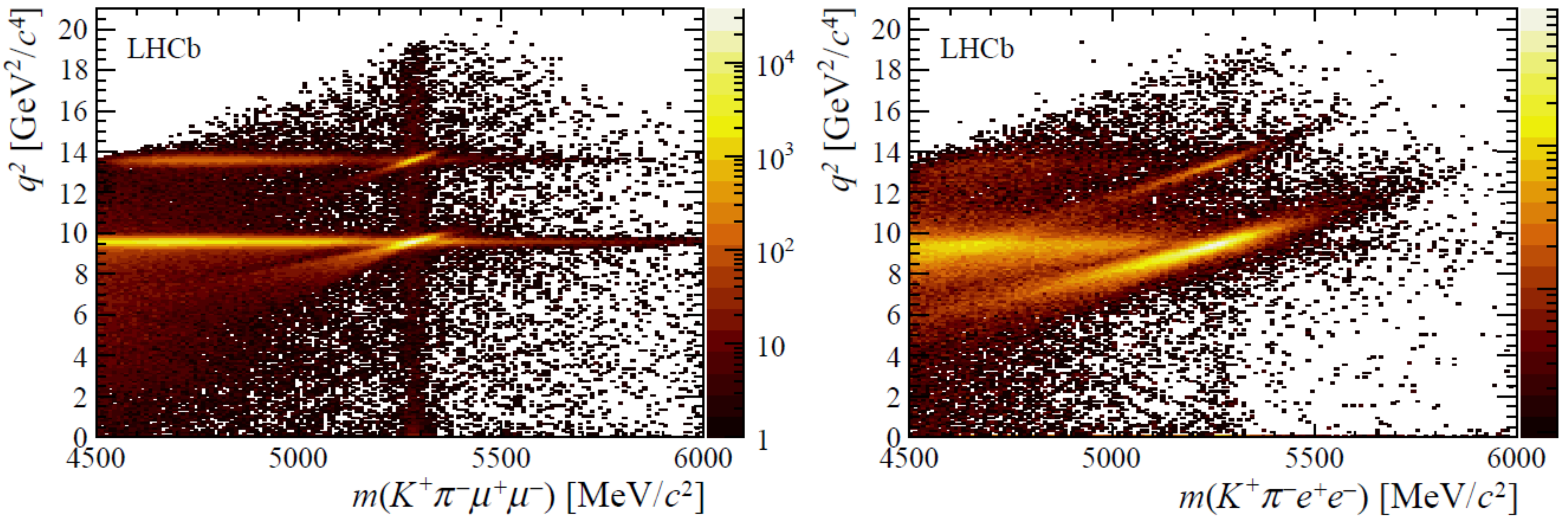
- The P- and CP-violating observables:

$$a_P^{\widehat{T}\text{-odd}} = \frac{1}{2}\left(A_{\widehat{T}} + \overline{A}_{\widehat{T}}\right) \qquad a_{CP}^{\widehat{T}\text{-odd}} = \frac{1}{2}\left(A_{\widehat{T}} - \overline{A}_{\widehat{T}}\right)$$


LHCb
neg-neg
data
total
short-distance
resonances
interference
background
LHCb
pos-neg
LHCb
neg-pos
LHCb
pos-pos
Candidates / (44 MeV/c^2)
$m_{\mu\mu}^{\rm rec}$ [MeV/c^2]
300
250
200
150
100
50
0
−50
1000
2000
3000
4000

Submitted to JHEP last week!

- Number of candidates for $B^0 \to K^{*0} l^+ l^-$ final states with muons and electrons



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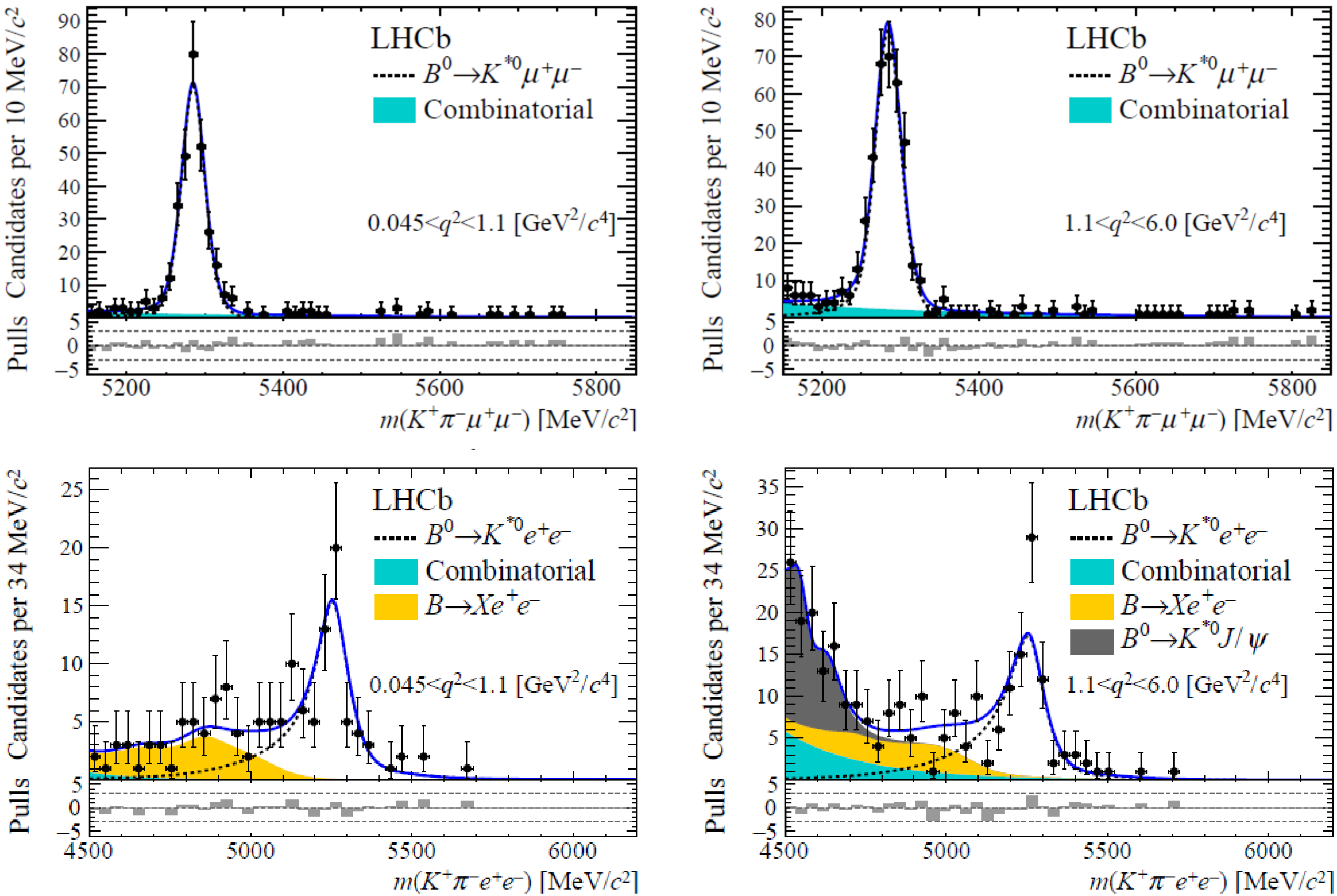

- Systematic uncertainties

	$\Delta R_{K^{*0}}/R_{K^{*0}}$ [%]					
	low-q^2			central-q^2		
Trigger category	L0E	L0H	L0I	L0E	L0H	L0I
Corrections to simulation	2.5	4.8	3.9	2.2	4.2	3.4
Trigger	0.1	1.2	0.1	0.2	0.8	0.2
PID	0.2	0.4	0.3	0.2	1.0	0.5
Kinematic selection	2.1	2.1	2.1	2.1	2.1	2.1
Residual background	–	–	–	5.0	5.0	5.0
Mass fits	1.4	2.1	2.5	2.0	0.9	1.0
Bin migration	1.0	1.0	1.0	1.6	1.6	1.6
$r_{J/\psi}$ ratio	1.6	1.4	1.7	0.7	2.1	0.7
Total	4.0	6.1	5.5	6.4	7.5	6.7