Physics at LHCb

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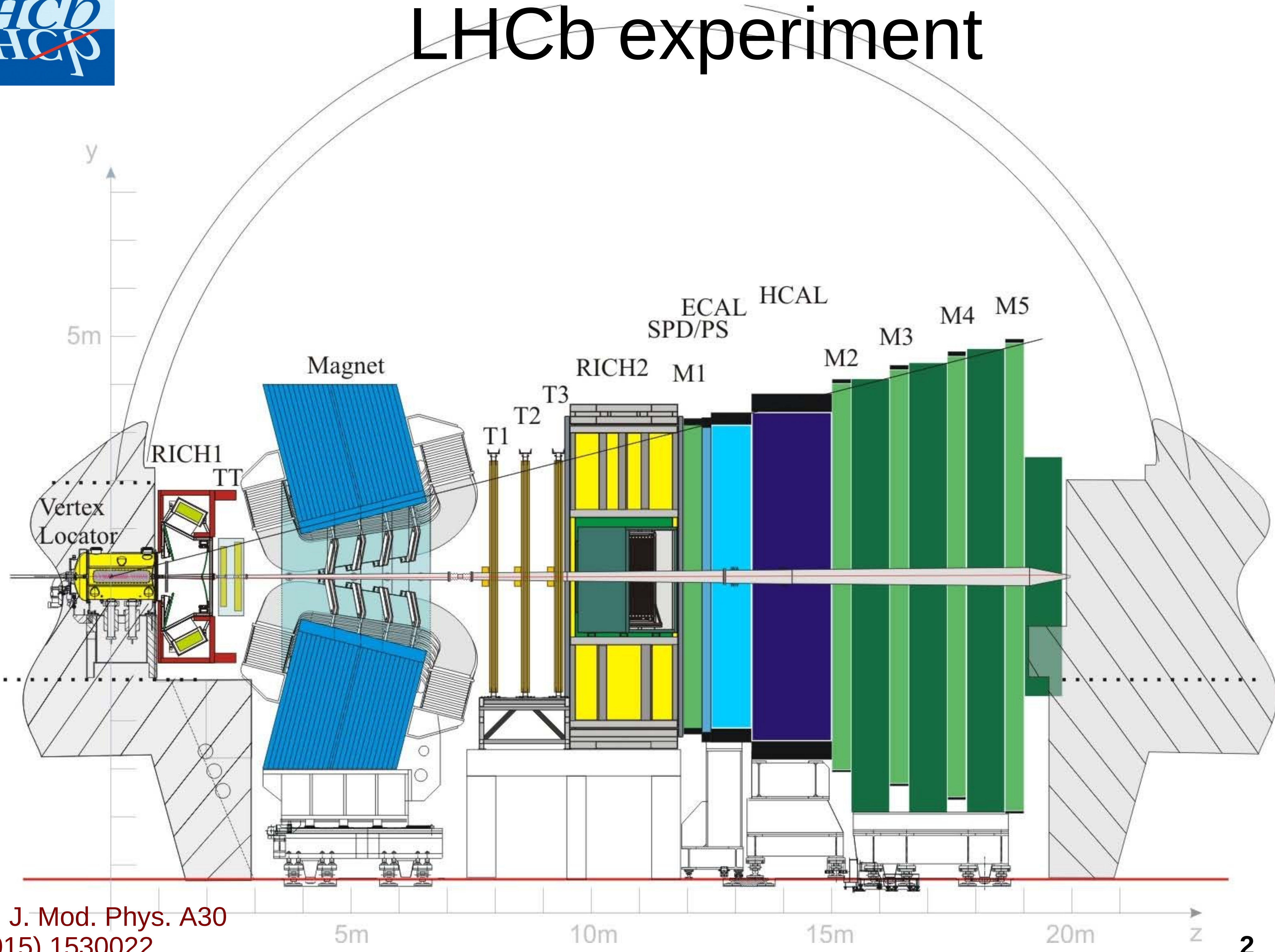
on behalf of the LHCb Collaboration

Budker INP & Novosibirsk University

Outline:

- LHCb detector & data taking
- ~~Lepton flavour universality & CP violation~~
- Rare decays
- Spectroscopy
- Soft QCD
- LHCb upgrade
- Summary

LHCb experiment

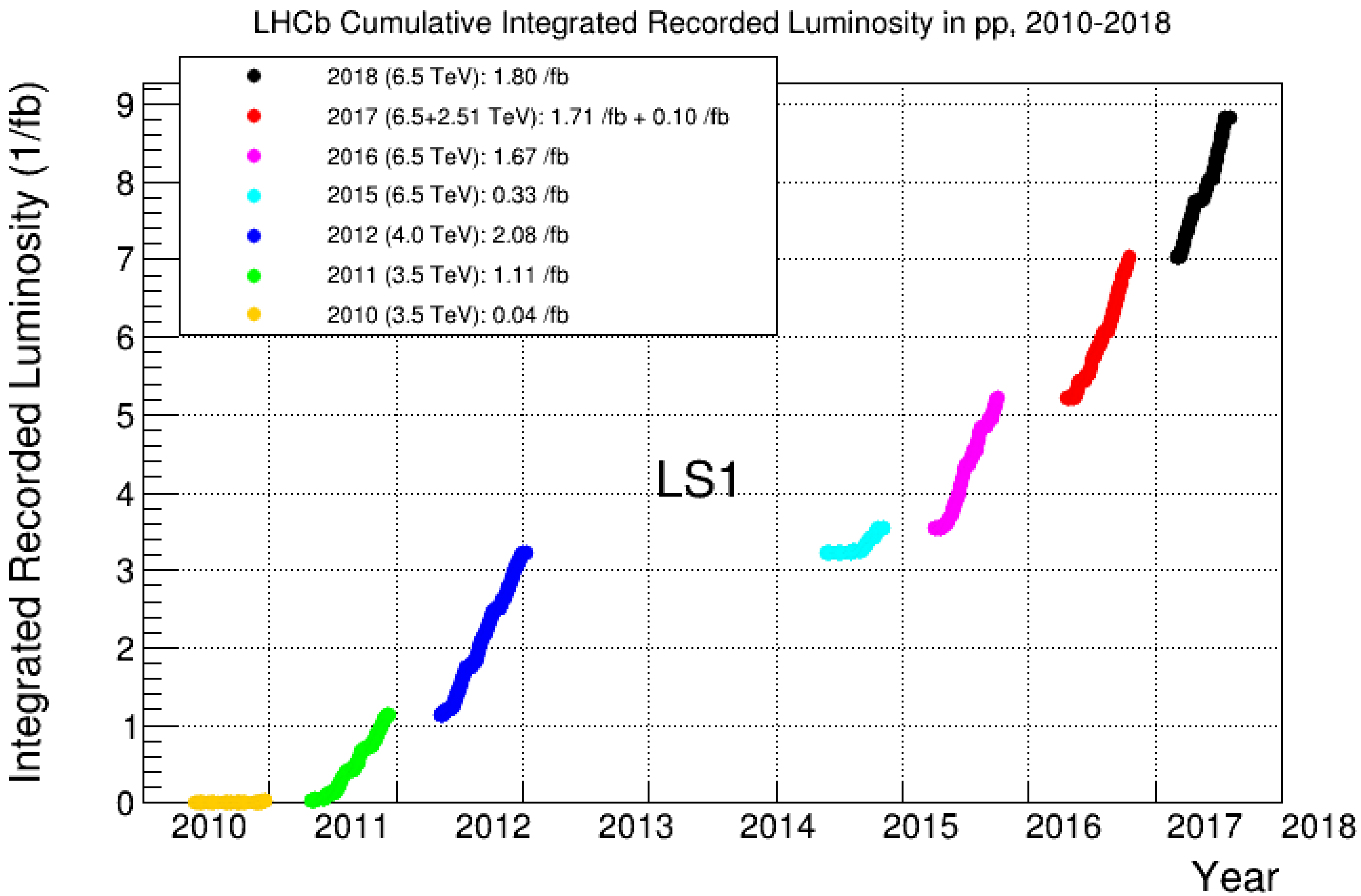


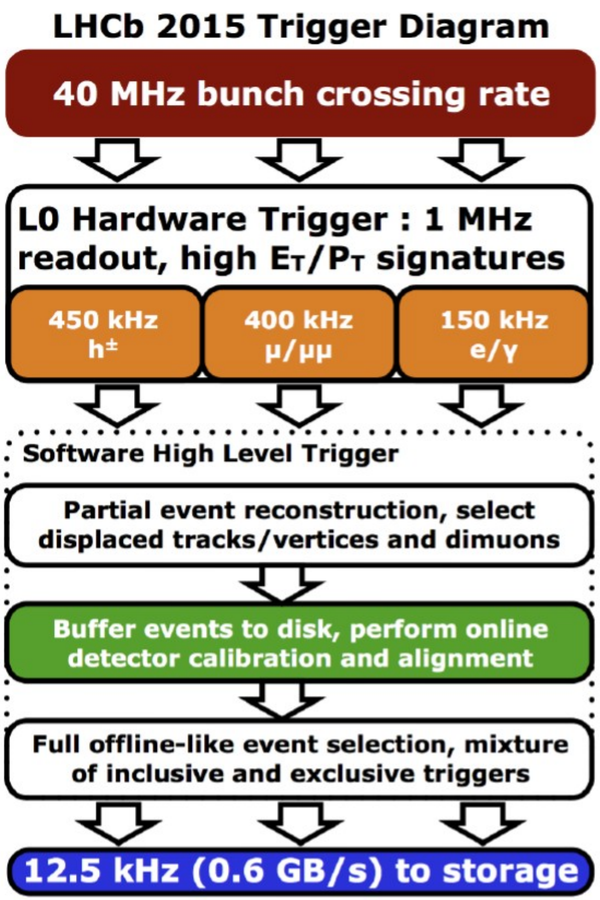
Int. J. Mod. Phys. A30 (2015) 1530022

LHCb performance

Acceptance: $2 < \eta < 5$

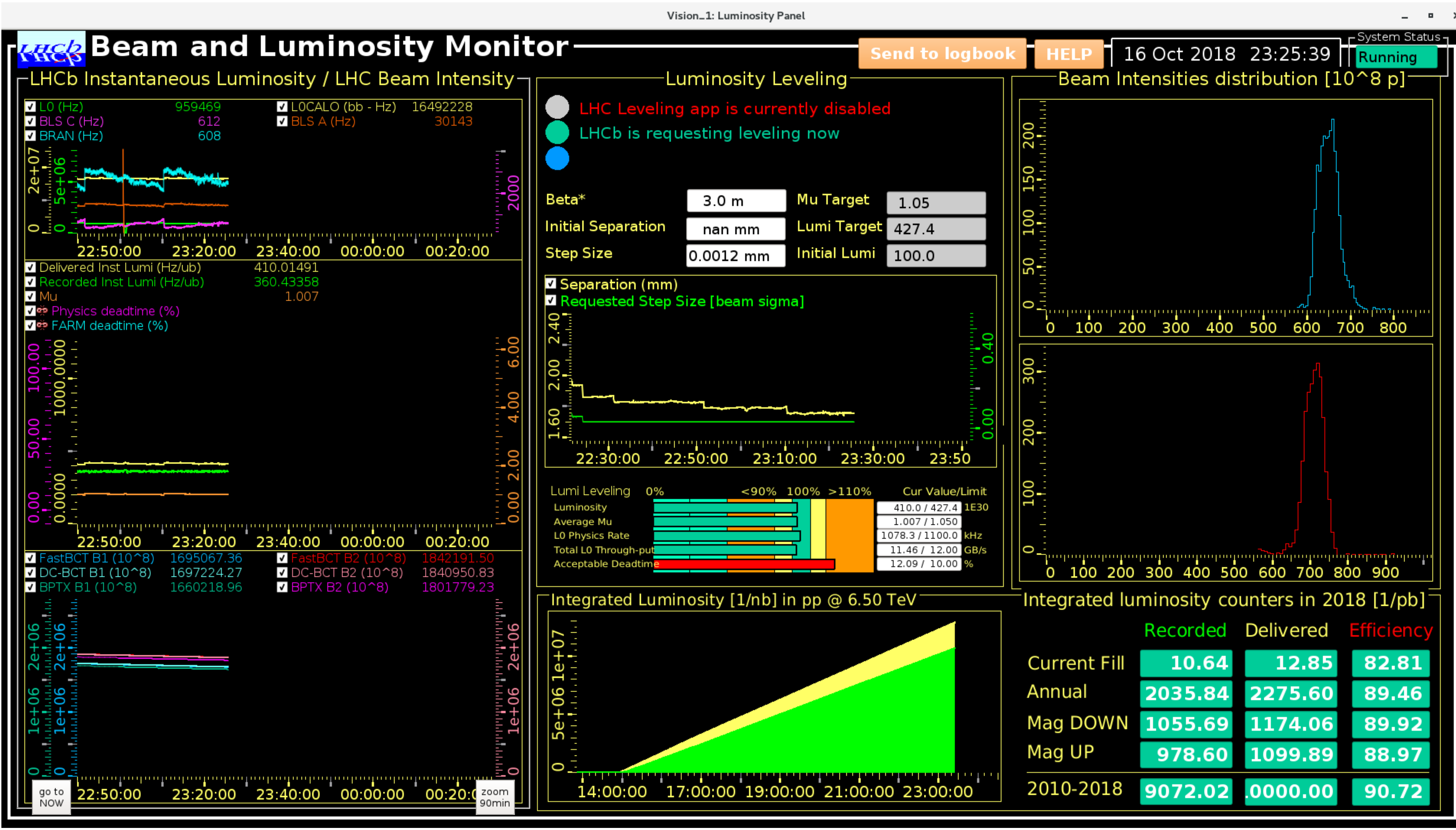
- Momentum resolution: 0.4 – 0.6% at 5 – 100 GeV
- Muon ID efficiency: 97 % with 1-3 % $\pi \rightarrow \mu$ mis-ID probability
- Electron ID efficiency: 90% with 4% $h \rightarrow e$ mis-ID probability
- Kaon ID efficiency: 95% with 5 % $\pi \rightarrow K$ mis-ID probability





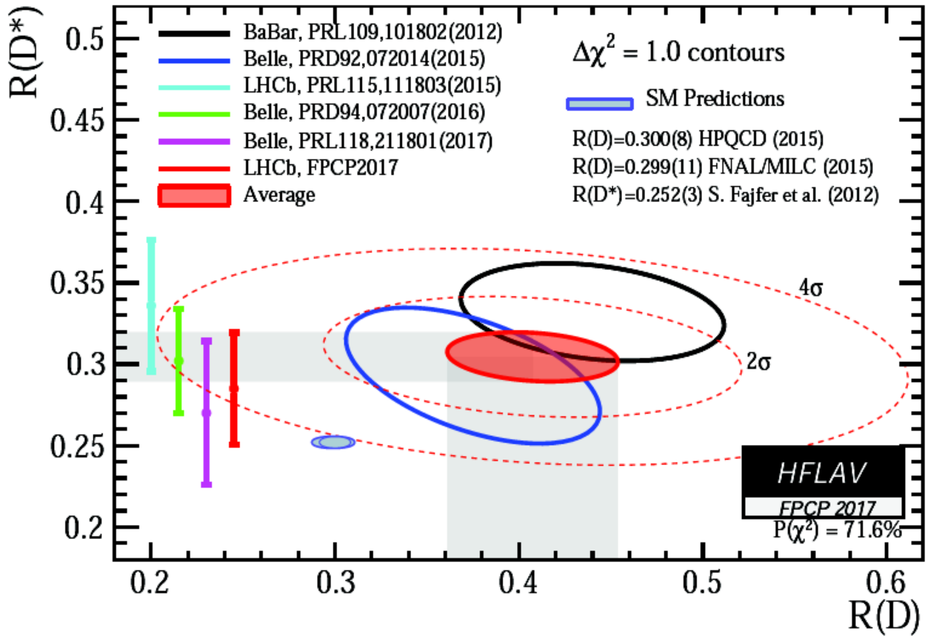
1) Commun. 208 35 -42
2) Int. J. Mod. Phys. A 30 (2015) 153022

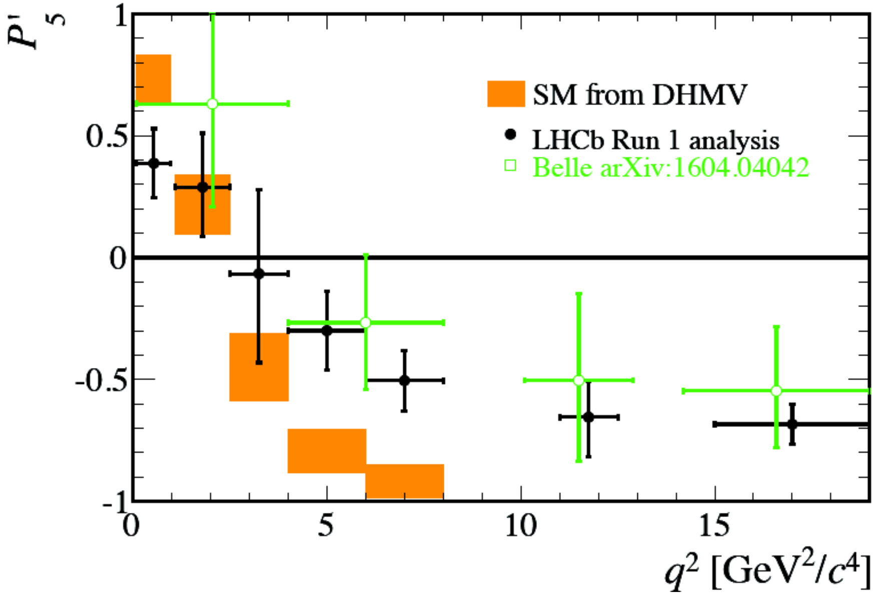
10 fb^{-1} delivered!

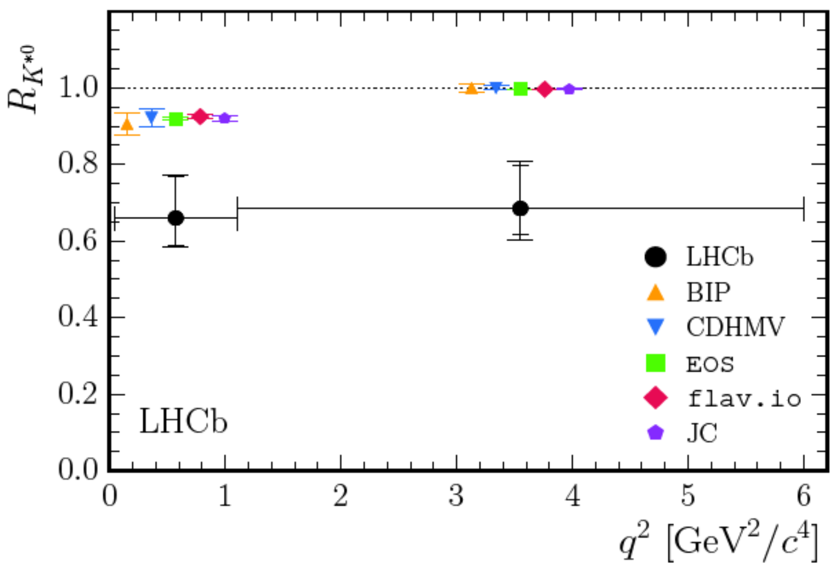


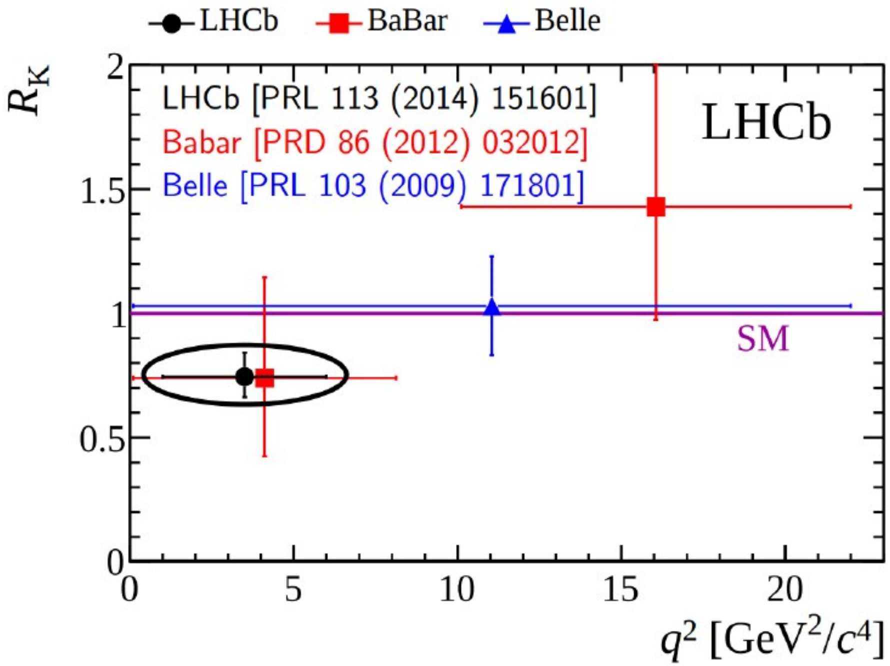
LFV results

Please see dedicated talk



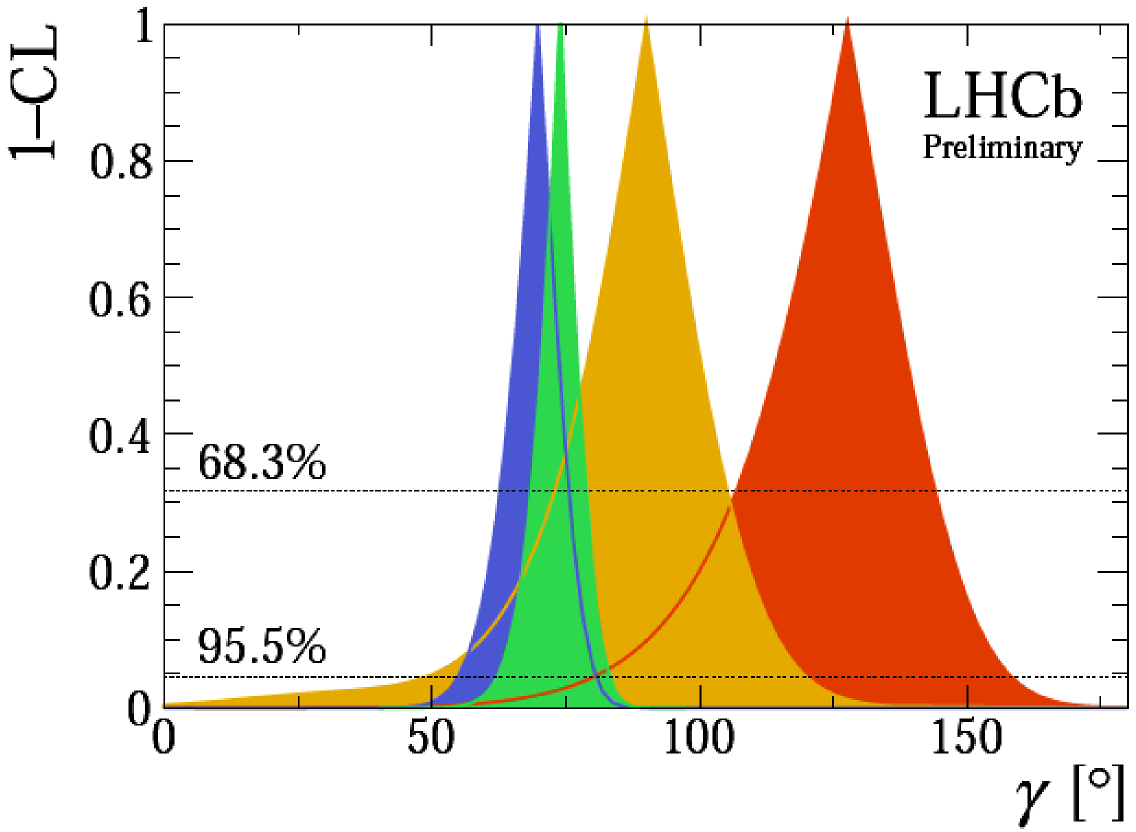


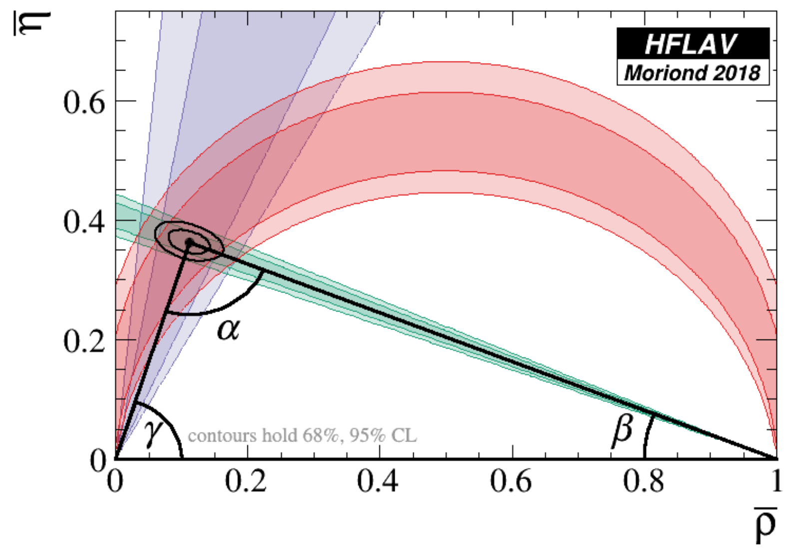


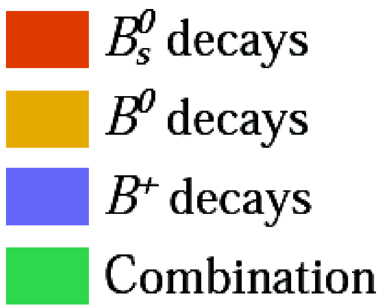


CPV results

Please see dedicated talk

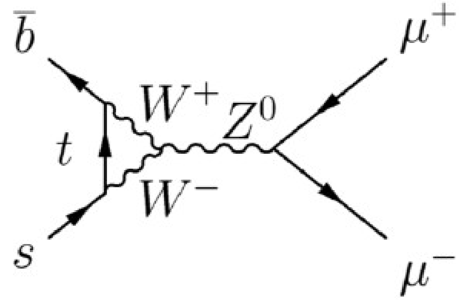


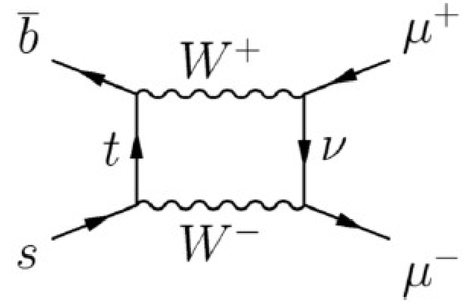




$$\gamma = (74.0\,^{+5.0}_{-5.8})^\circ$$

LHCb CONF 2018-002


$\bar{b}$
W^+
Z^0
μ^+
t
W^-
s
μ^-


$\bar{b}$
W^+
μ^+
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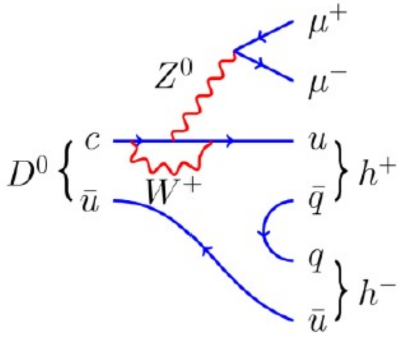
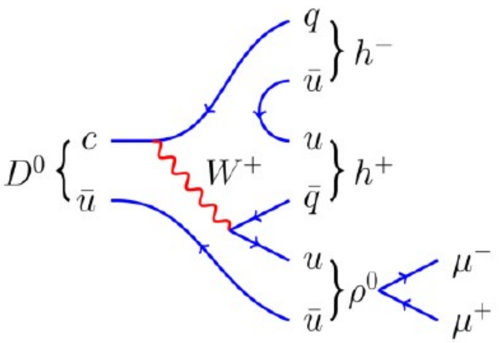
ν
s
W^-
μ^-


μ^+
Z^0
μ^-
D^0
c
$\bar{u}$
W^+
u
$\bar{q}$
h^+
q
$\bar{u}$
h^-


q
$\bar{u}$
h^-
D^0
c
$\bar{u}$
W^+
u
$\bar{q}$
h^+
u
$\bar{u}$
ρ^0
μ^-
μ^+

Rare decays

Evidence for $B_s^0 \to K^{*0}\mu^+\mu^-$

JHEP 07 (2018) 020

$$\mathcal{B}(B_s^0 \to \overline{K}^{*0}\mu^+\mu^-) = (2.9 \pm 1.0 \pm 0.2 \pm 0.3(\mathrm{norm})) \times 10^{-8}$$

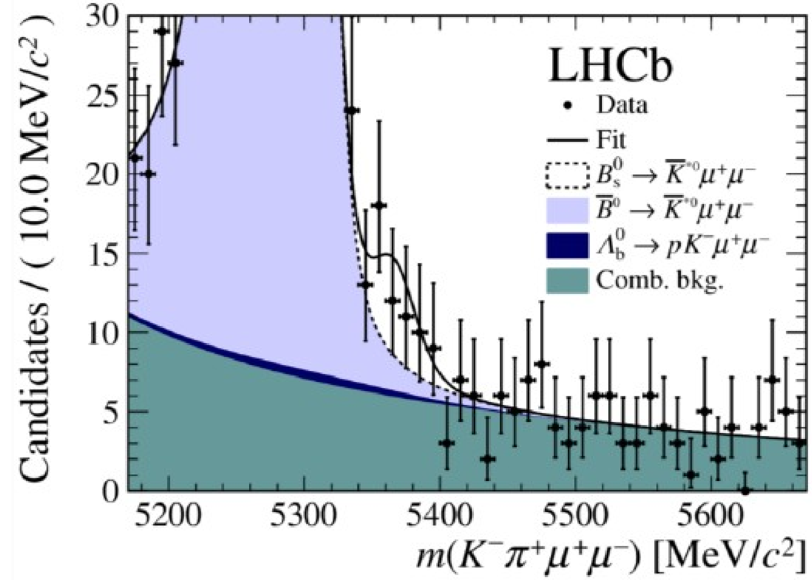
- Proceed by b→d FCNC
- SM expectation $B(B_s^0 \to K^{*0}\mu^+\mu^-) \sim 10^{-8}$
- Sensitive to physics beyond the SM
- Complementary to b→s FCNC studies

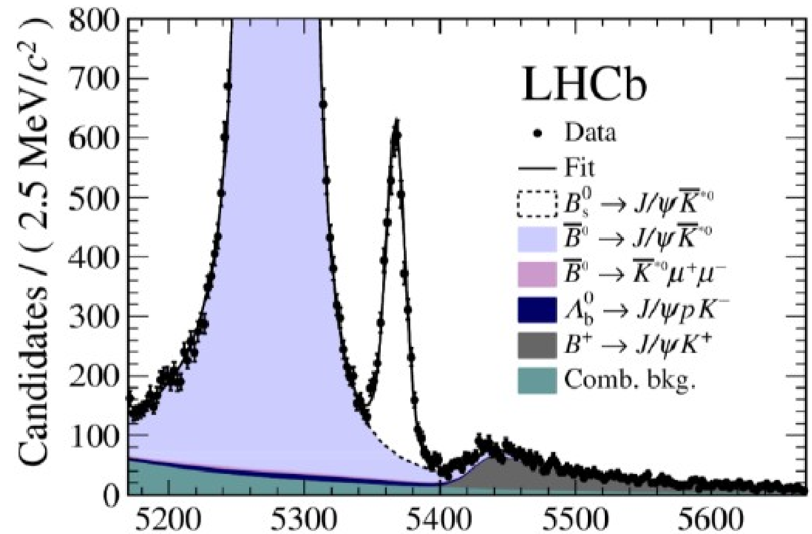
$$\mathcal{B}(B_s^0 \to \overline{K}^{*0}\mu^+\mu^-) = \mathcal{B}(\overline{B}^0 \to J/\psi \overline{K}^{*0}) \times \mathcal{B}(J/\psi \to \mu^+\mu^-) \times \frac{f_d}{f_s} \frac{N(B_s^0 \to \overline{K}^{*0}\mu^+\mu^-)}{\varepsilon(B_s^0 \to \overline{K}^{*0}\mu^+\mu^-)} \frac{\varepsilon(\overline{B}^0 \to J/\psi \overline{K}^{*0})}{N(\overline{B}^0 \to J/\psi \overline{K}^{*0})}$$

- Simultaneous unbinned ML fit to the $m(K^-\pi^+\mu^+\mu^-)$ in eight bins [4 NN bins] x [Run 1 : Run2]
- Signal yield is 38 ± 12 (3.4 σ significance)

  $q^2 \in [0.1 : 19]$ GeV^2/c^4 excluding J/ψ and $\psi(2S)$

$$\frac{\mathcal{B}(B_s^0 \to \overline{K}^{*0}\mu^+\mu^-)}{\mathcal{B}(B_s^0 \to J/\psi \overline{K}^{*0}) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)} = (1.4 \pm 0.4 \pm 0.1 \pm 0.1) \times 10^{-2}$$

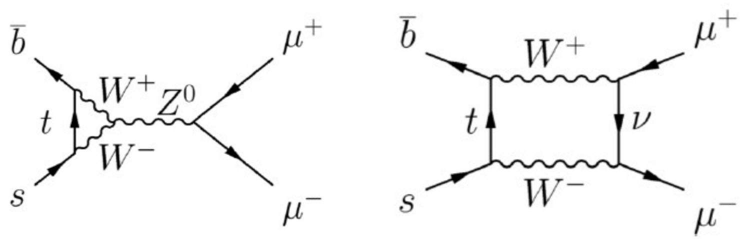




Dataset:
1.0 fb^{-1} @ √s=7 TeV
2.0 fb^{-1} @ √s=8 TeV
1.6 fb^{-1} @ √s=13TeV

$B_{(s)} \rightarrow \mu^+\mu^-$

PRL 118 (2017) 191801



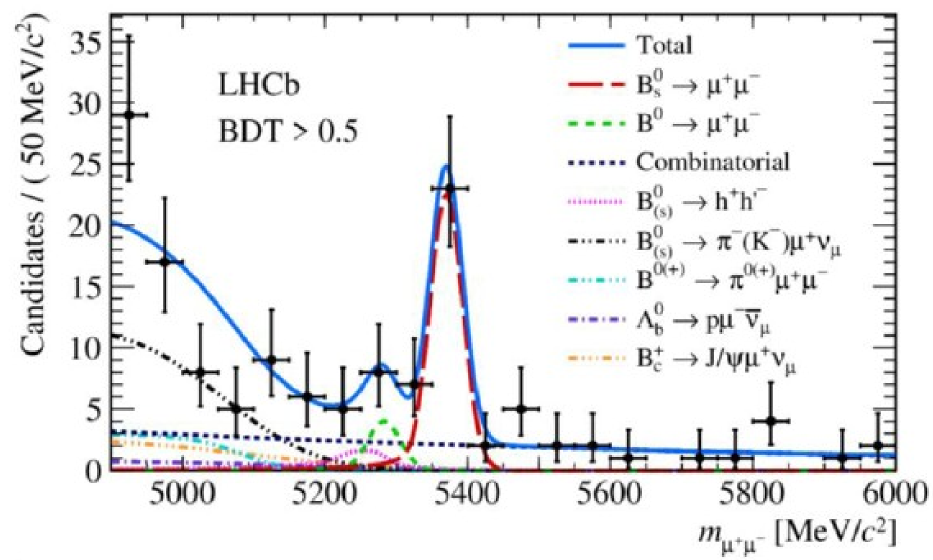
- SM expectations [PRL 112 (2014) 101801]:

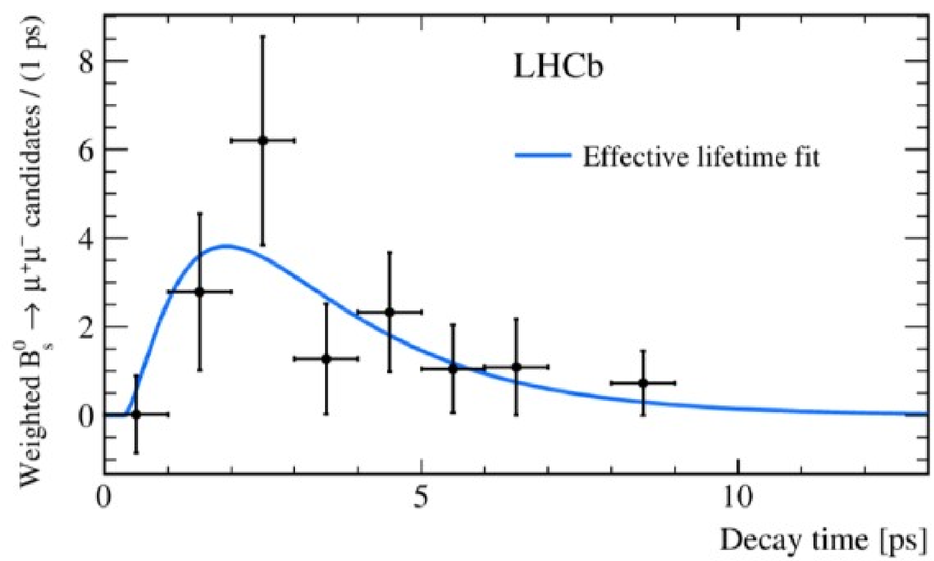
$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

- Very sensitive to physics beyond the SM
- Only heavy B_s^0 decays to $\mu^+\mu^-$ in SM. Measurement of decay time can disentangle contributions from the two states.
- The results:

$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$
$$\tau(B_s^0 \rightarrow \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$$
$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 3.4 \times 10^{-10} \text{ @ } 95\% \text{ C.L.}$$

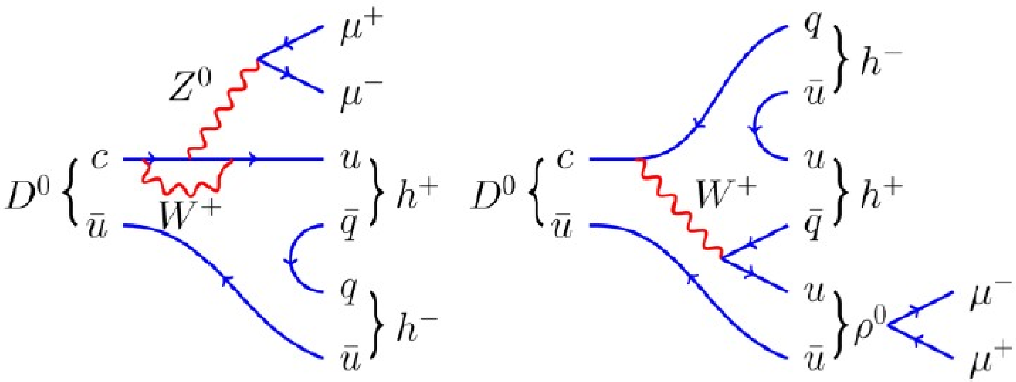
World average (HFLAV): $\tau(B_s^0) = 1.510 \pm 0.005$ ps





Dataset:
1.0 fb^{-1} @ $\sqrt{s}$=7 TeV
2.0 fb^{-1} @ $\sqrt{s}$=8 TeV
1.4 fb^{-1} @ $\sqrt{s}$=13TeV

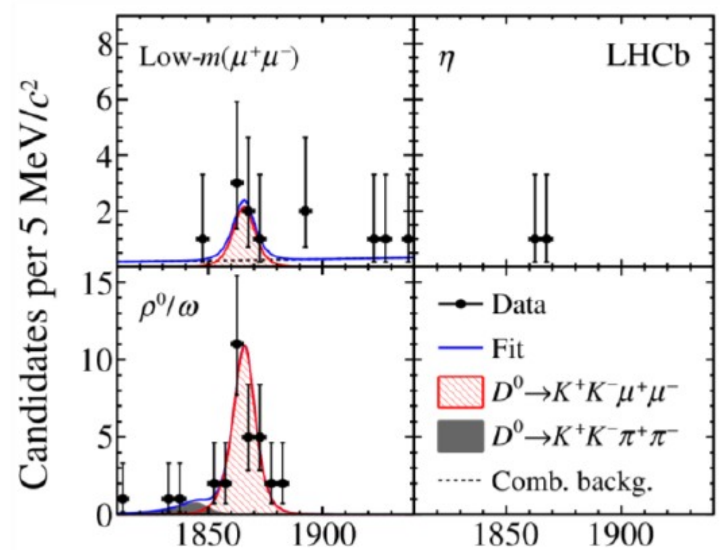
Observation of $D^0 \to h^+h^- \mu^+\mu^-$

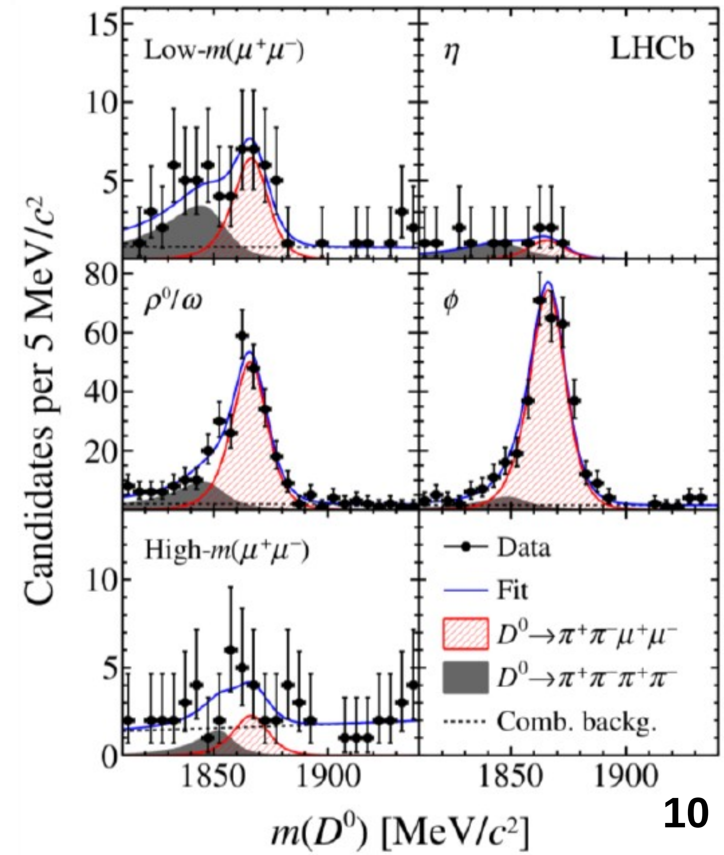


Normalization BF

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}$$
$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}$$

- Rarest charm decay ever observed
- Short distance FCNC $c \to u\mu^+\mu^-$ gives B ~ 10^{-9}
- Search for CP violation and angular asymmetry: [arXiv 1806.10793] → not significant, need more statistics



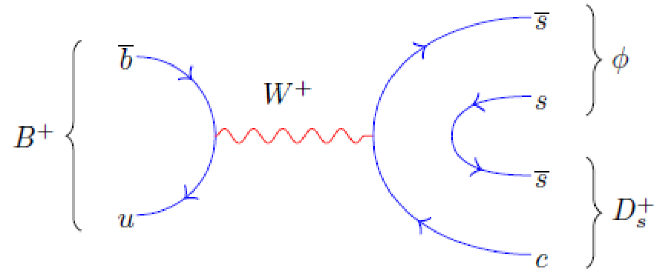


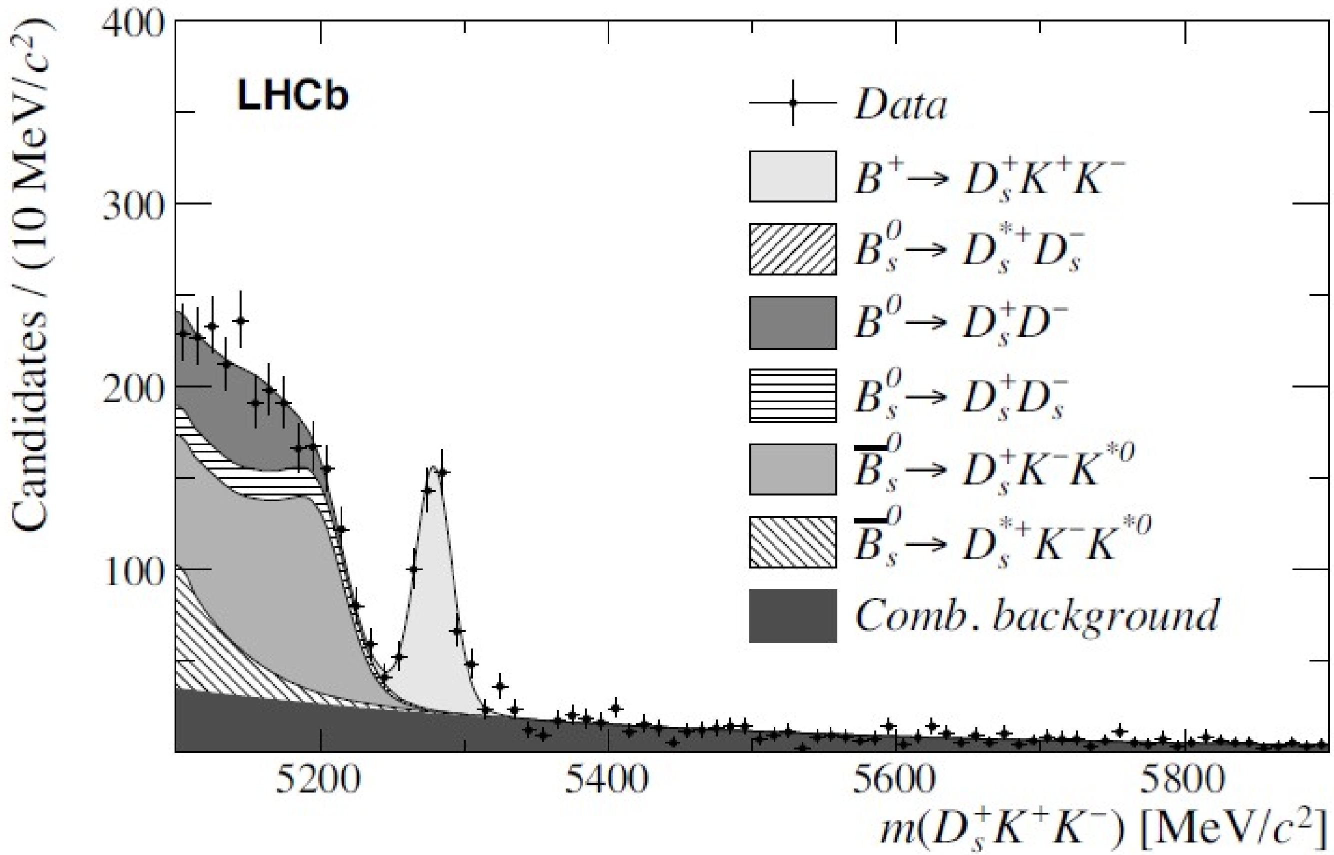
PRL 119 (2017) 181805

Dataset:
2.0 fb^{-1} @ √s=8 TeV

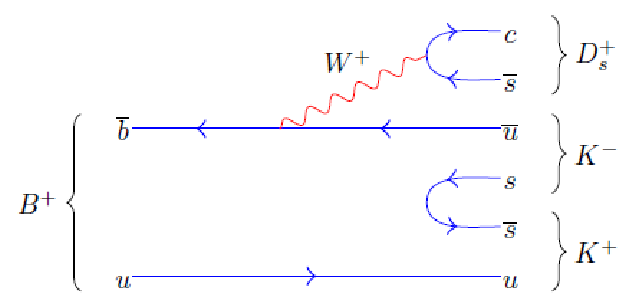
Search for $B^+ \to D_s^+ \phi$

- Pure annihilation decay
- Normalize to $B^+ \to D_s^+ D^0[K^+K^-]$





3-body $B^+ \to D_s^+ K^+ K^-$

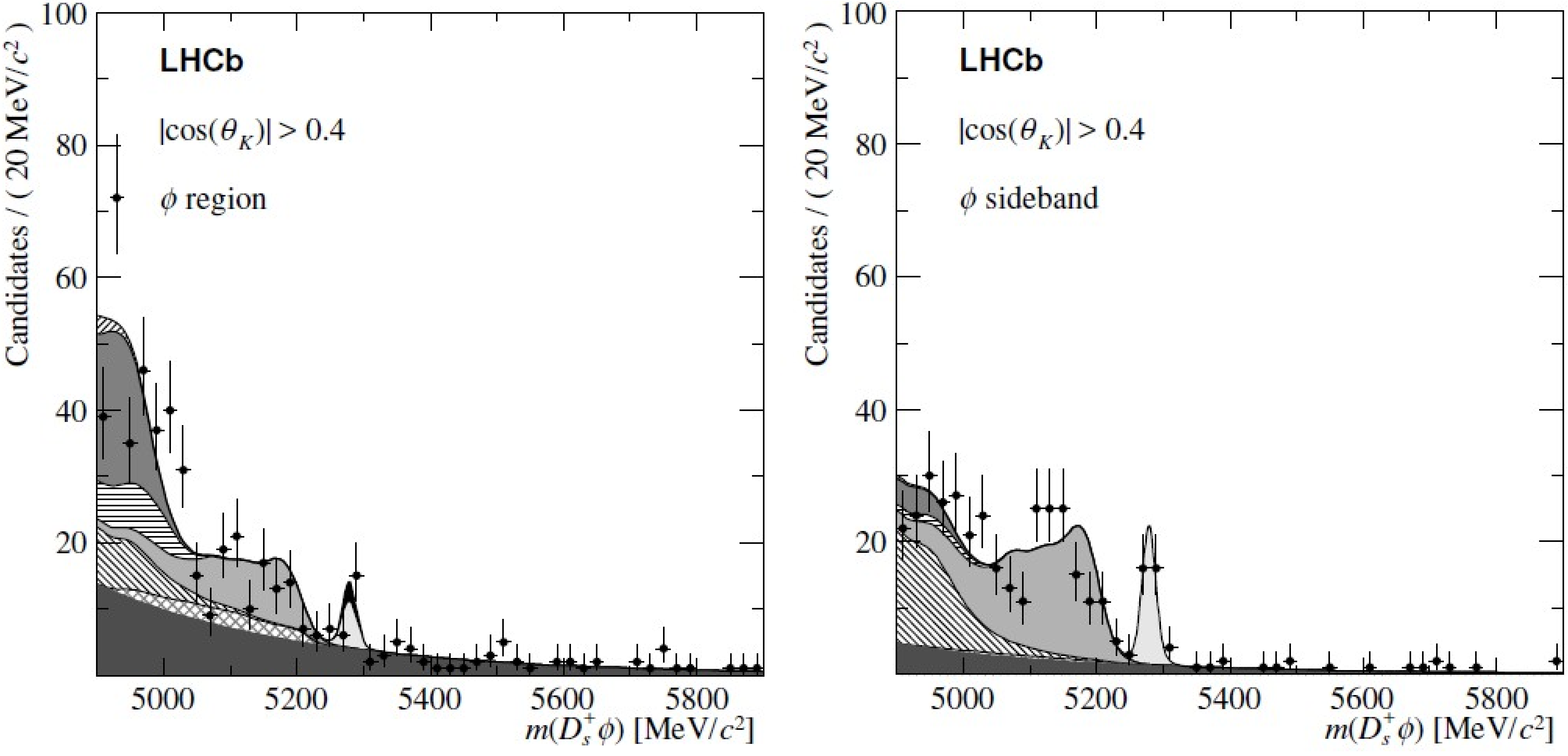


$$\mathcal{B}(B^+ \to D_s^+ K^+ K^-) = (7.1 \pm 0.5 \pm 0.6 \pm 0.7) \times 10^{-6}$$

Dataset:
1.0 fb^{-1} @ $\sqrt{s}$=7 TeV
2.0 fb^{-1} @ $\sqrt{s}$=8 TeV
1.8 fb^{-1} @ $\sqrt{s}$=13TeV

JHEP 01 (2018) 131

Search for $B^+ \to D_s^+ \phi$



$$N(B^+ \to D_s^+\phi) = 5.3 \pm 6.7$$

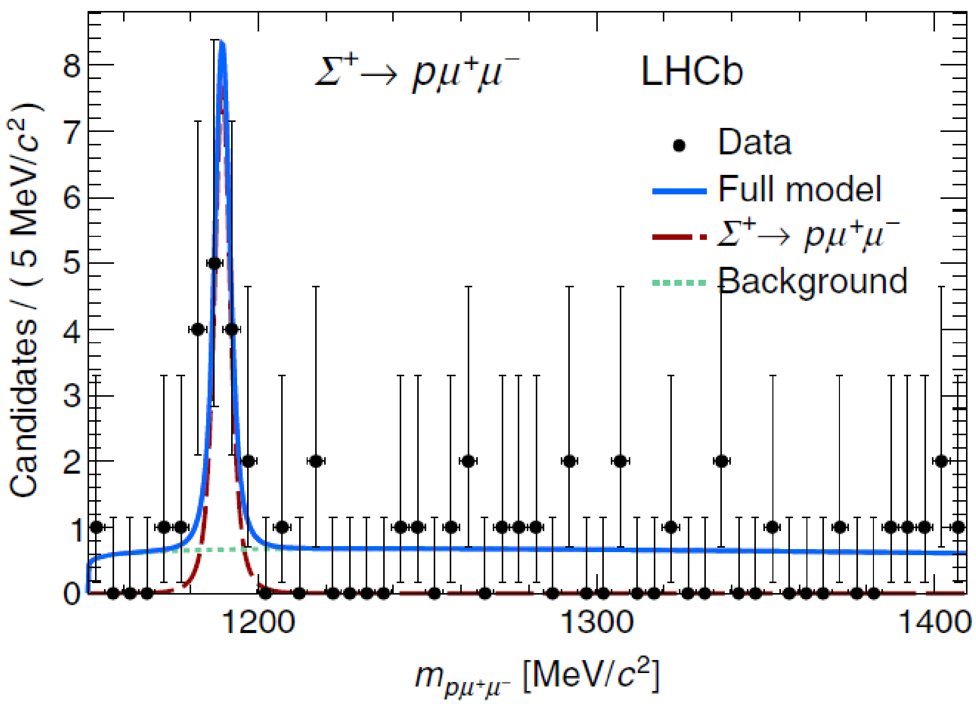
$$\mathcal{B}(B^+ \to D_s^+\phi) < 4.9 \times 10^{-7}$$

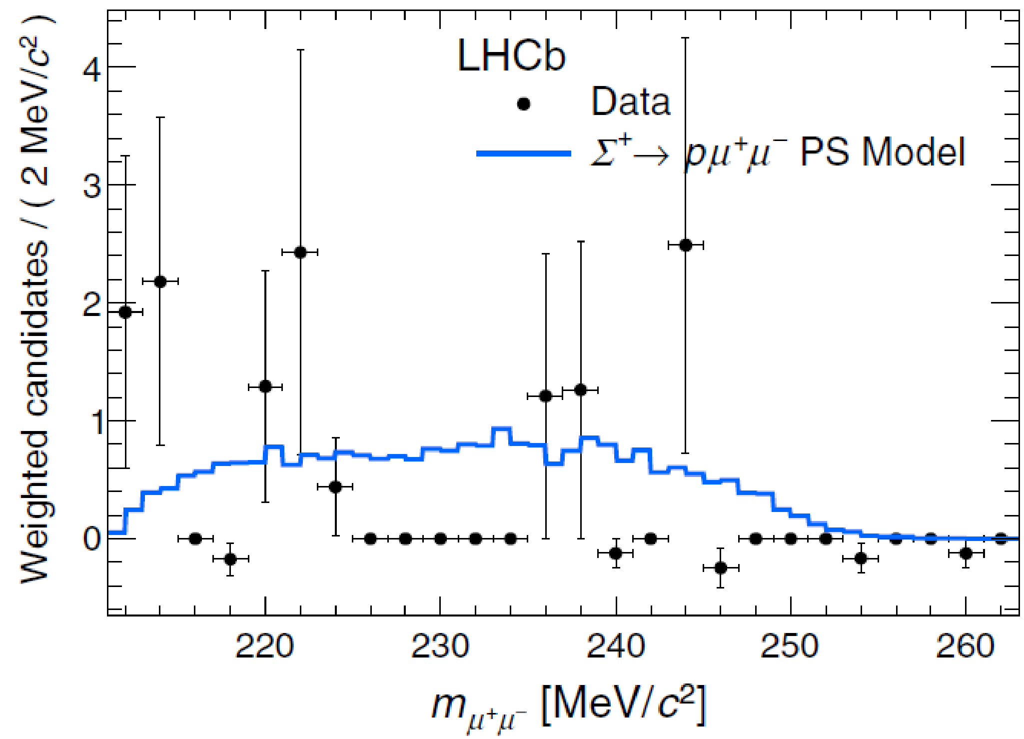
Dataset:
1.0 fb^{-1} @ $\sqrt{s}$=7 TeV
2.0 fb^{-1} @ $\sqrt{s}$=8 TeV
1.8 fb^{-1} @ $\sqrt{s}$=13TeV

JHEP 01 (2018) 131

First evidence for $\Sigma^+ \rightarrow p\mu^+\mu^-$

- FCNC s→dll transition
- BR in SM: (1.6-9.0) 10^{-8} [He,Tandean, Valencia, PRD 05] dominated by long distance contributions





$$\mathcal{B}(\Sigma^+ \rightarrow p\mu^+\mu^-) = (2.2^{+1.8}_{-1.3}) \times 10^{-8}$$

4.1 σ significance

No significant structure observed in $\mu^+\mu^-$ invariant mass distribution

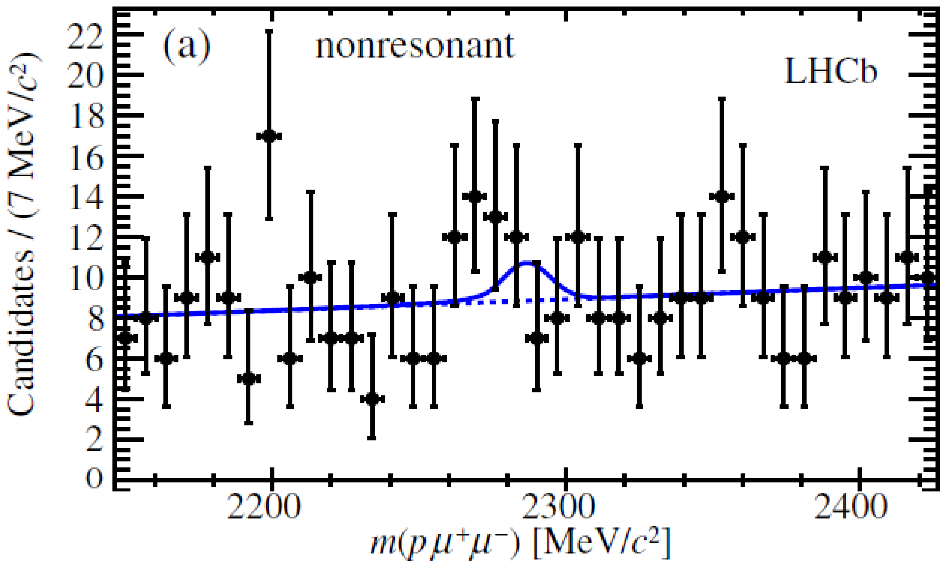
Dataset:
1.0 fb^{-1} @ √s=7 TeV
2.0 fb^{-1} @ √s=8 TeV

PRL 120 (2018) 221803

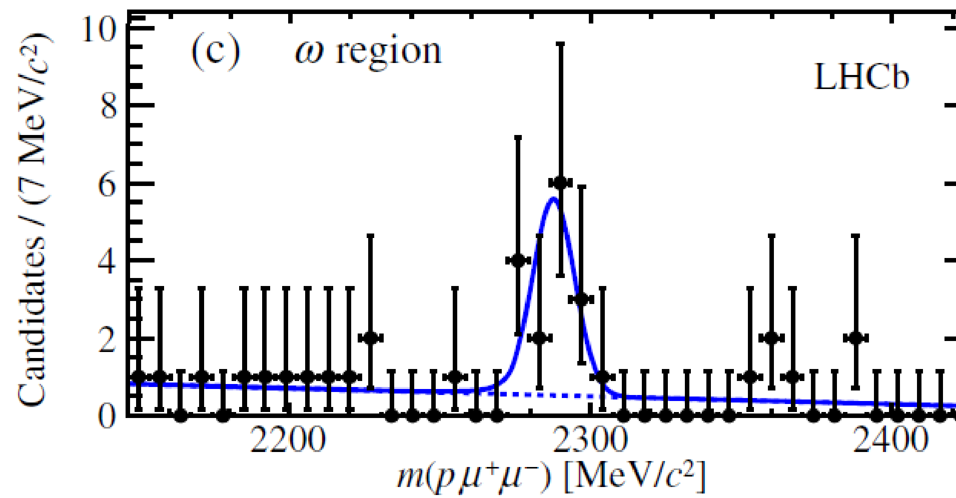
First evidence for $\Lambda_c^+ \to p\,\omega[\mu^+\mu^-]$

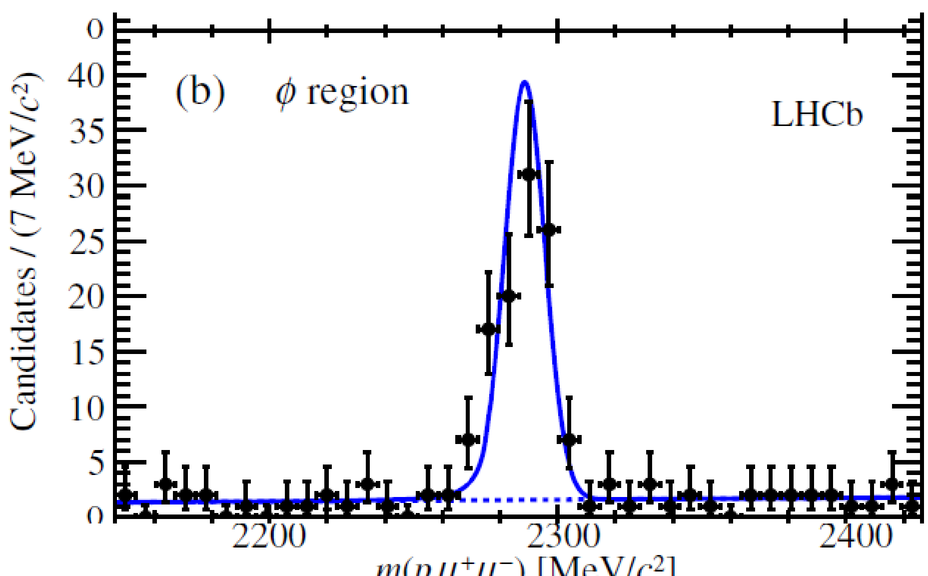
PRD 97 (2018) 091101

- FCNC $c \to ull$ transition
- Short distance BR in SM ~10^{-9} , long distance (via $V \to \mu^+\mu^-$) BR up to 10^{-6}



$B(\Lambda_c^+ \to p\mu^+\mu^-) < 7.7\ 10^{-8}$ at 90% CL





$B(\Lambda_c^+ \to p\omega) = (9.4 \pm 3.2 \pm 1.0 \pm 2.0)\ 10^{-4}$

Dataset:
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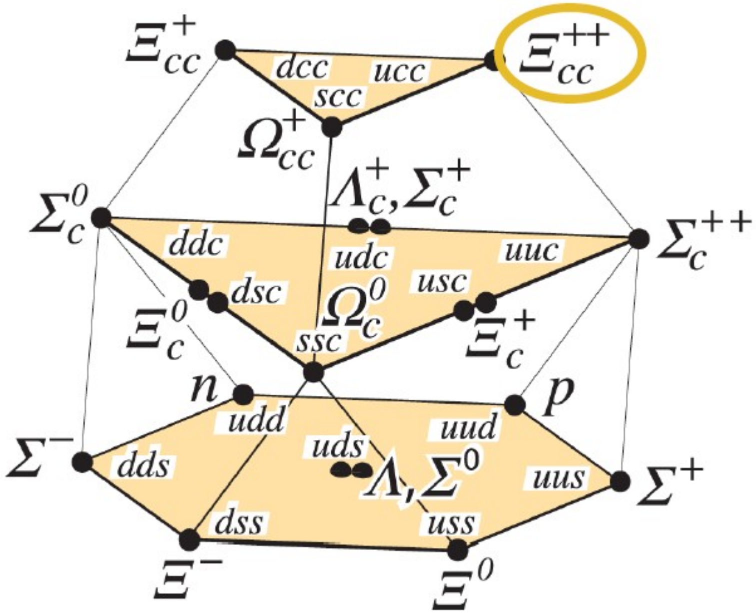
$2.0\ fb^{-1}$ @ $\sqrt{s}$=8 TeV

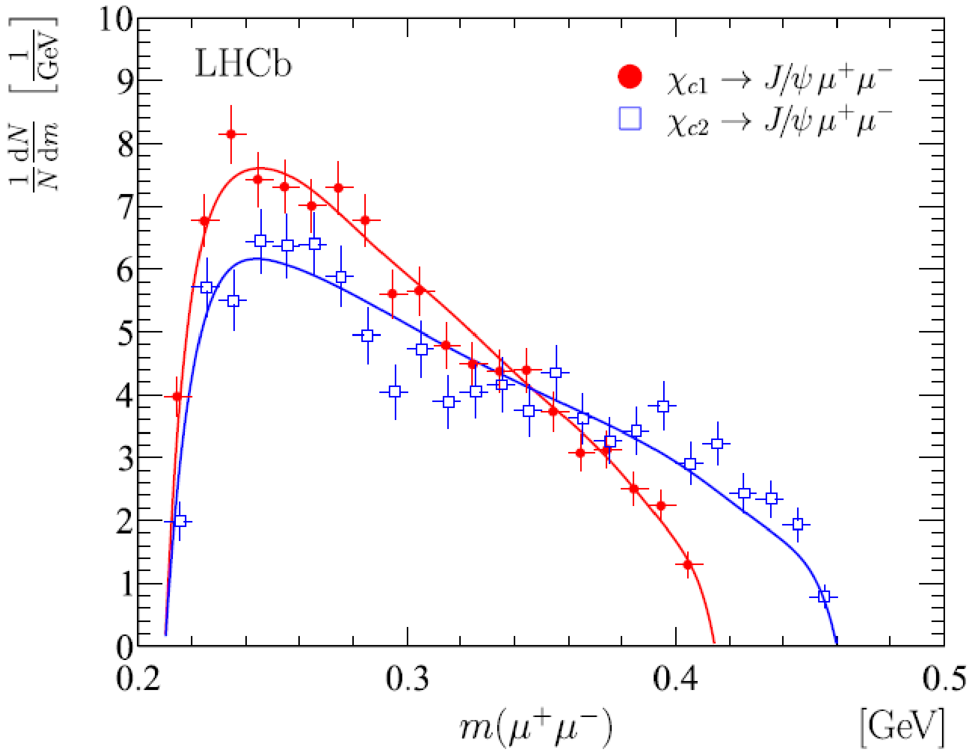


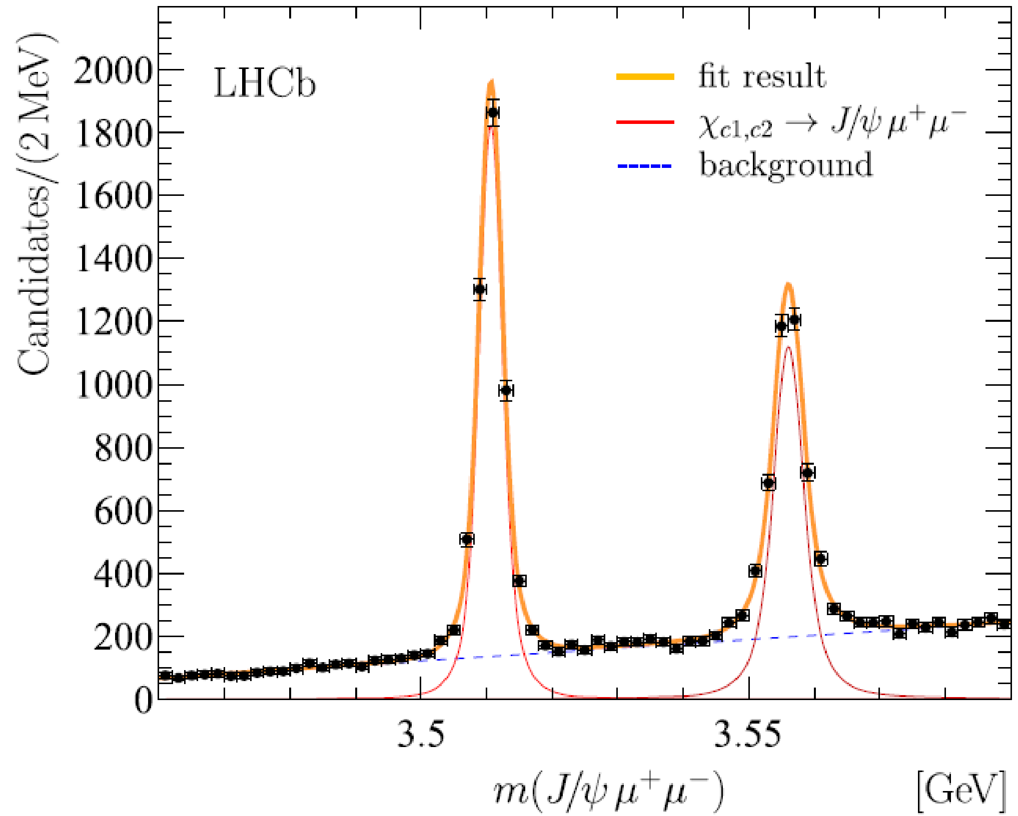
Spectroscopy

$\chi_{c1,2} \to J/\psi\ \mu^+\mu^-$

PRL 119 (2017) 221801

- Follows observation of $\chi_{c1,2} \to J/\psi\ \mu^+\mu^-$ at BESIII [PRL 118 (2017) 101802]
- Clear 4μ signature
- Probes low p_T $\chi_{c1,2}$





Dataset:
1.0 fb^{-1} @ $\sqrt{s}$=7 TeV
2.0 fb^{-1} @ $\sqrt{s}$=8 TeV
1.9 fb^{-1} @ $\sqrt{s}$=13TeV

$M(\chi_{c1}) = 3510.71 \pm 0.04 \pm 0.09$ MeV/c^2

$M(\chi_{c2}) = 3556.10 \pm 0.06 \pm 0.11$ MeV/c^2

$M(\chi_{c2}) - M(\chi_{c1}) = 45.39 \pm 0.07 \pm 0.3$ MeV/c^2

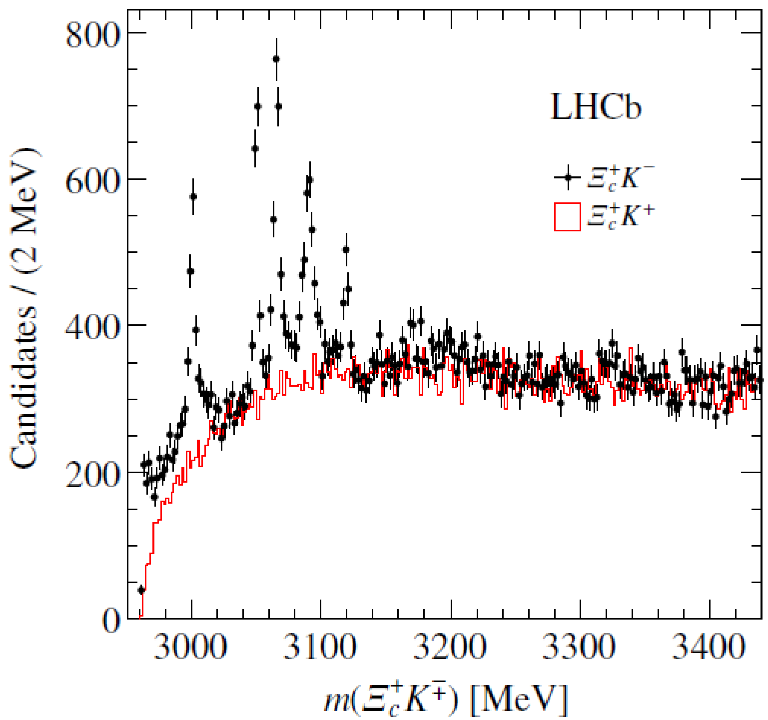
$\Gamma(\chi_{c2}) = 2.10 \pm 0.20 \pm 0.02$ MeV

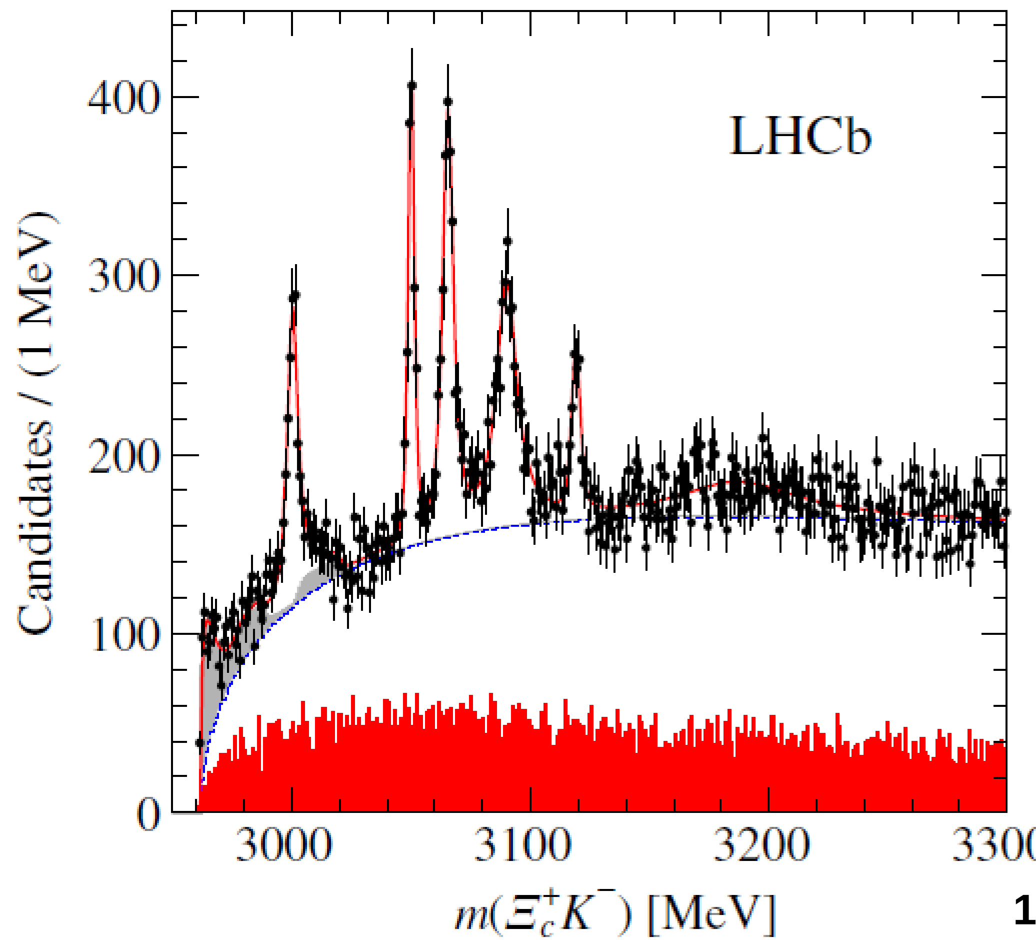
Compatible with previous measurements

Observation of five narrow Ω_c^0 states

PRL 118 (2017) 182001

- Ω_c^0 family corresponds to css quark content
- Two ground states were known: Ω_c^0 $J^P=1^+$ and $\Omega_c^0(2770)$ $J^P=3/2^+$ [PLB 672 (2009) 1]
- Study spectrum of $[\Xi_c^+ \rightarrow pK^-\pi^+]K^+$
- Spin-parity analysis is in progress



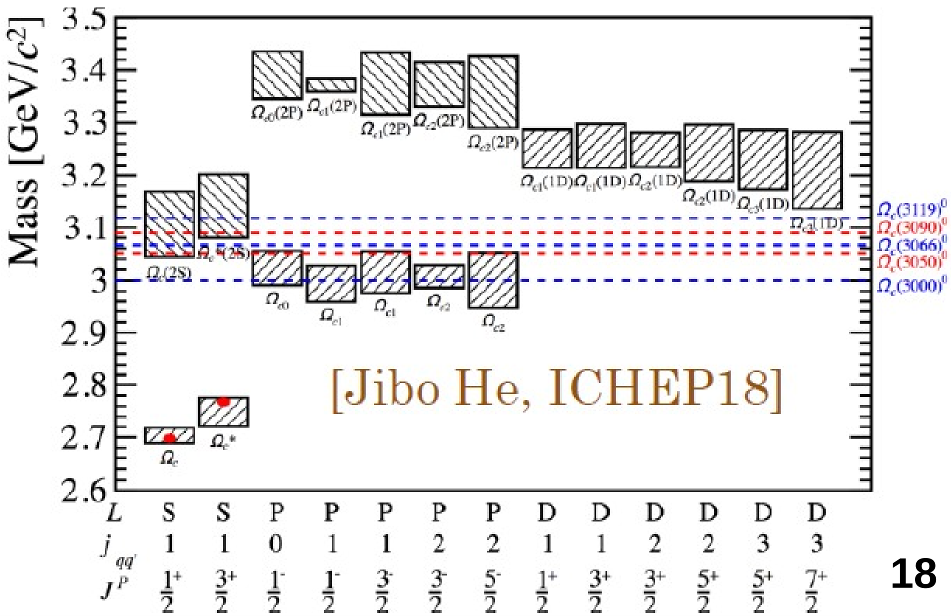


Dataset:
1.0 fb^{-1} @ $\sqrt{s}$=7 TeV
2.0 fb^{-1} @ $\sqrt{s}$=8 TeV
0.3 fb^{-1} @ $\sqrt{s}$=13TeV

Ω_c^0 states properties

Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		<1.2 MeV, 95% C.L.		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		<2.6 MeV, 95% C.L.		
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	
$\Omega_c(3066)^0_{\rm fd}$			$700 \pm 40 \pm 140$	
$\Omega_c(3090)^0_{\rm fd}$			$220 \pm 60 \pm 90$	
$\Omega_c(3119)^0_{\rm fd}$			$190 \pm 70 \pm 20$	

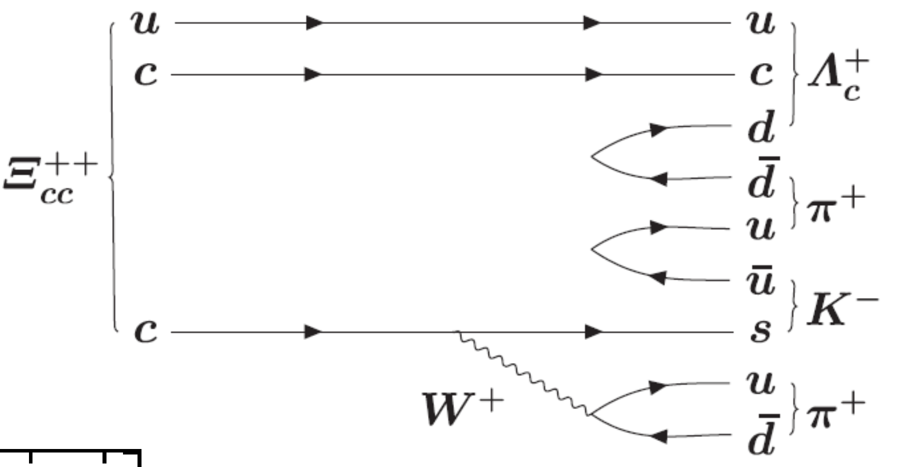
Four states have been confirmed by Belle [PRD 97 (2018) 051102]

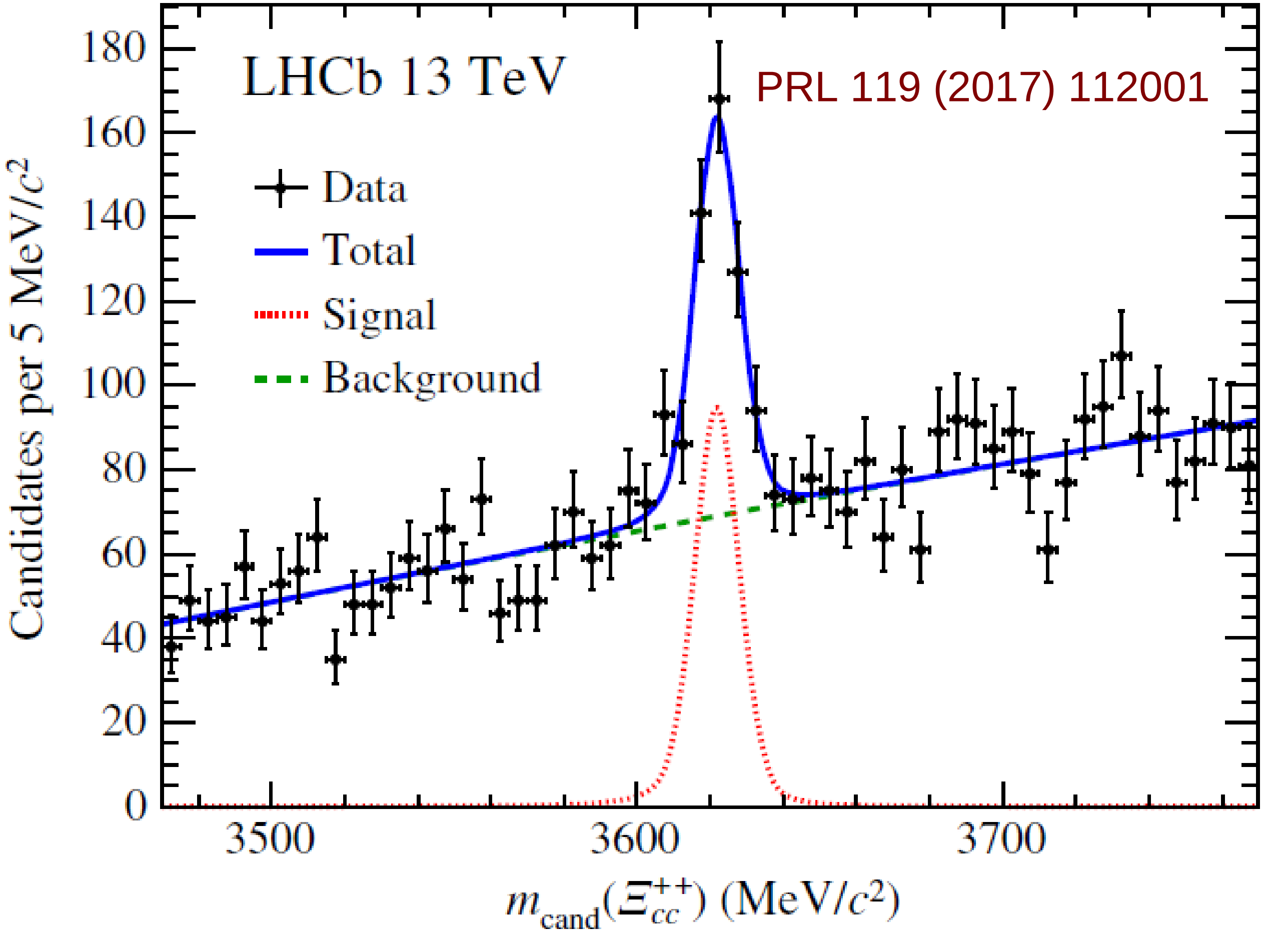


PRL 118 (2017) 182001

Study of doubly charmed baryon Ξ_{cc}^{++}

- Using decay $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$
- $\Delta M = 1334.94 \pm 0.72 \pm 0.27$ MeV/c^2
- $M(\Xi_{cc}^{++}) = 3621.40 \pm 0.72 \pm 0.27 \pm 0.14$ MeV/c^2





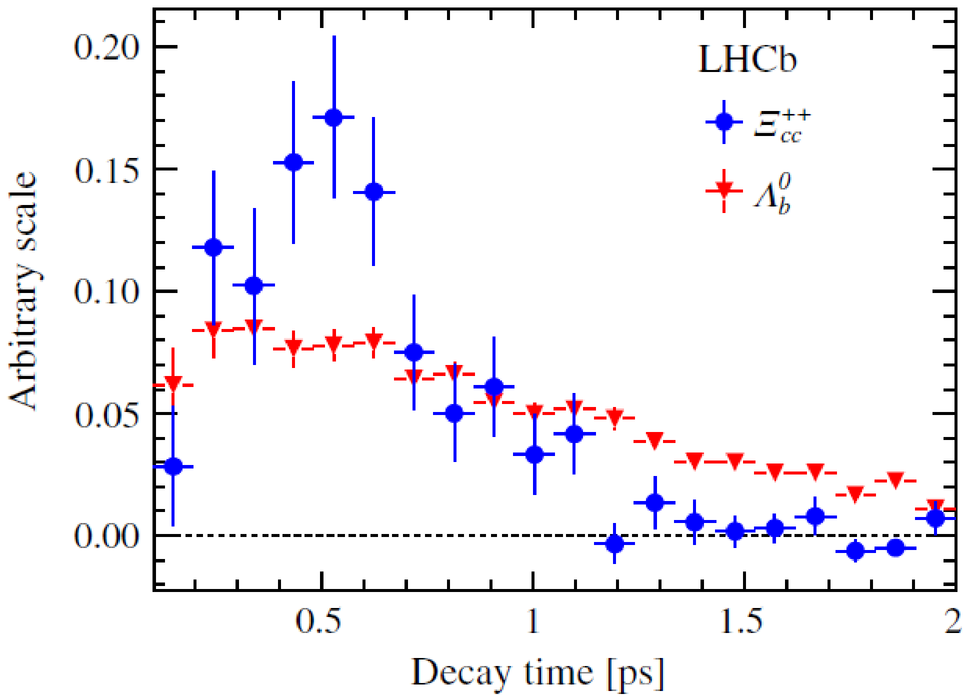
PRL 119 (2017) 112001

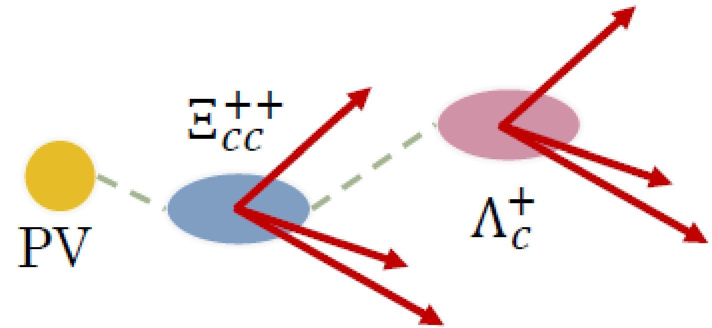
Dataset:
1.0 fb^{-1} @ $\sqrt{s}$=7 TeV
2.0 fb^{-1} @ $\sqrt{s}$=8 TeV
1.7 fb^{-1} @ $\sqrt{s}$=13TeV

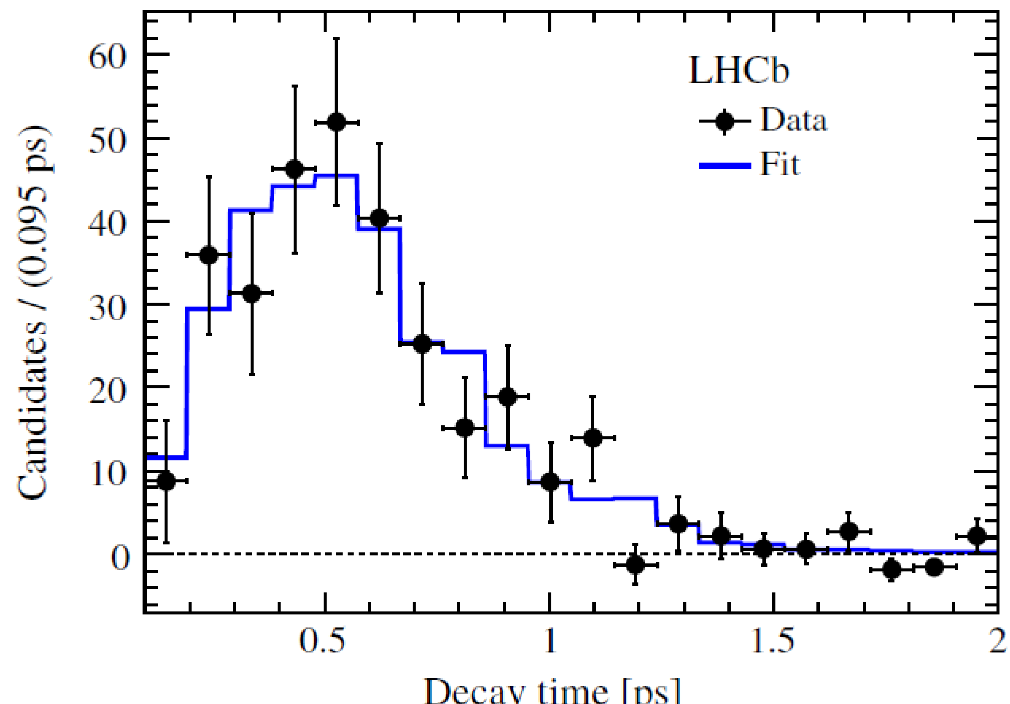
PRL 121 (2018) 052002

Measurement of Ξ_{cc}^{++} lifetime

- Decay time relative to $\Lambda_b^0[\Lambda_c^+\pi^-\pi^+\pi^-]$
- Decay time resolution is 63 (32) ps for Ξ_{cc}^{++} (Λ_b^0)







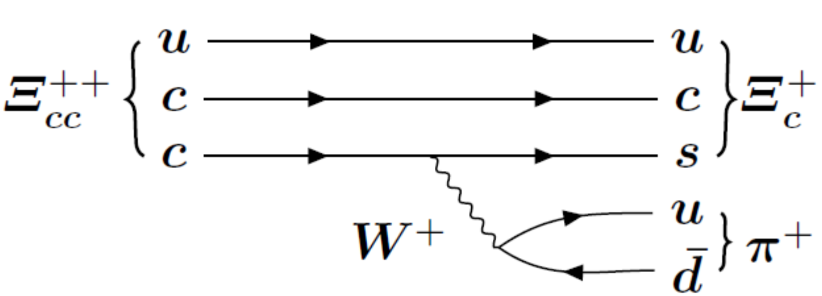
$$\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022}(\text{stat}) \pm 0.014(\text{syst})\ \text{ps}$$

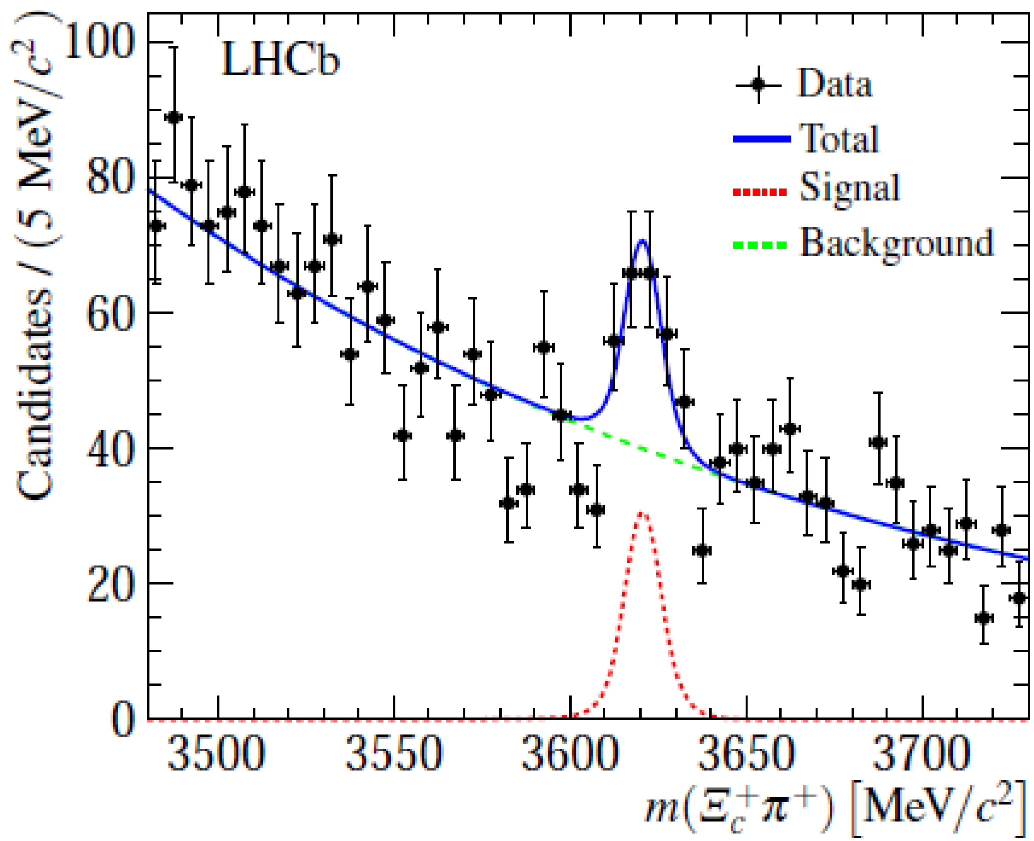
Confirmation of weak decay of Ξ_{cc}^{++}

Dataset:
1.0 fb^{-1} @ $\sqrt{s}$=7 TeV
2.0 fb^{-1} @ $\sqrt{s}$=8 TeV
1.7 fb^{-1} @ $\sqrt{s}$=13TeV

PRL 121 (2018) 052002

First observation of decay $\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{-}$





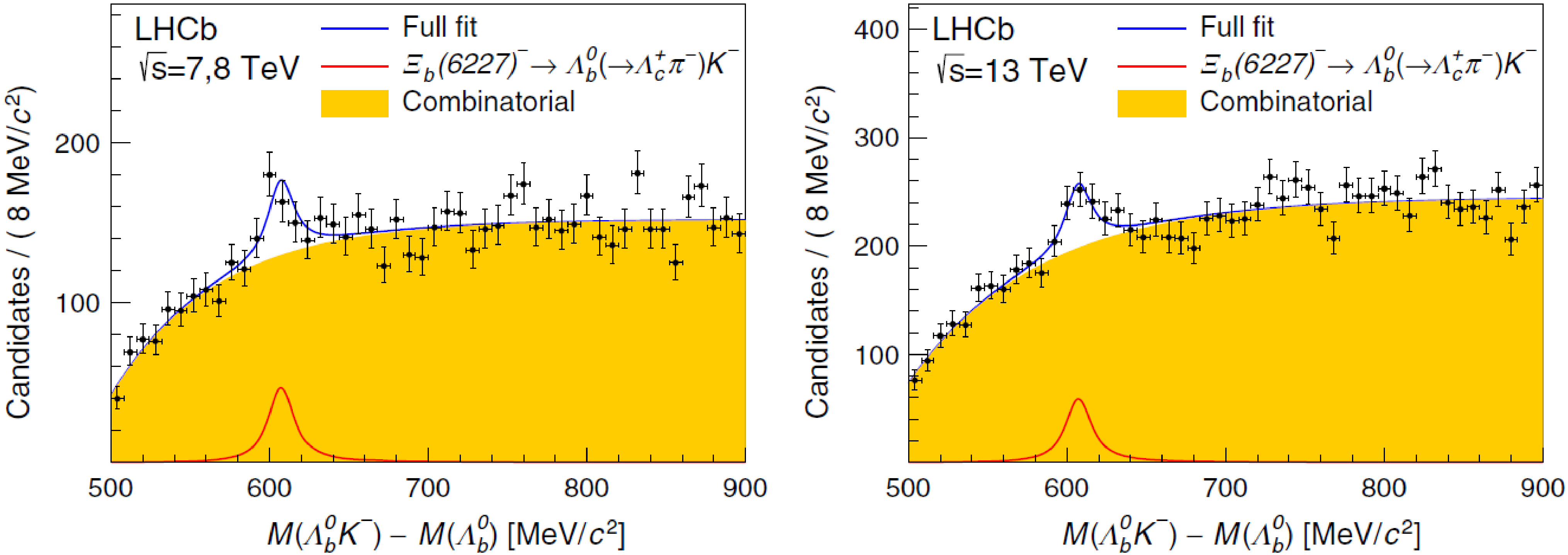
$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+\pi^+) \times \mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+) \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = 0.035 \pm 0.009\,(\text{stat}) \pm 0.003\,(\text{syst})$$

Dataset:
1.0 fb^{-1} @ $\sqrt{s}$=7 TeV
2.0 fb^{-1} @ $\sqrt{s}$=8 TeV
1.7 fb^{-1} @ $\sqrt{s}$=13TeV

PRL 121 (2018) 162002

Observation of Ξ_b^-

Hadronic channel $\Xi_b(6227)^- \rightarrow [\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-]K^-$



$M[\Xi_b(6227)^-] = 6226.9 \pm 2.0 \pm 0.3 \pm 0.2$ MeV/c^2

$\Gamma[\Xi_b(6227)^-] = 18.1 \pm 5.4 \pm 1.8$ MeV

Dataset:
1.0 fb^{-1} @ √s=7 TeV
2.0 fb^{-1} @ √s=8 TeV
1.5 fb^{-1} @ √s=13TeV

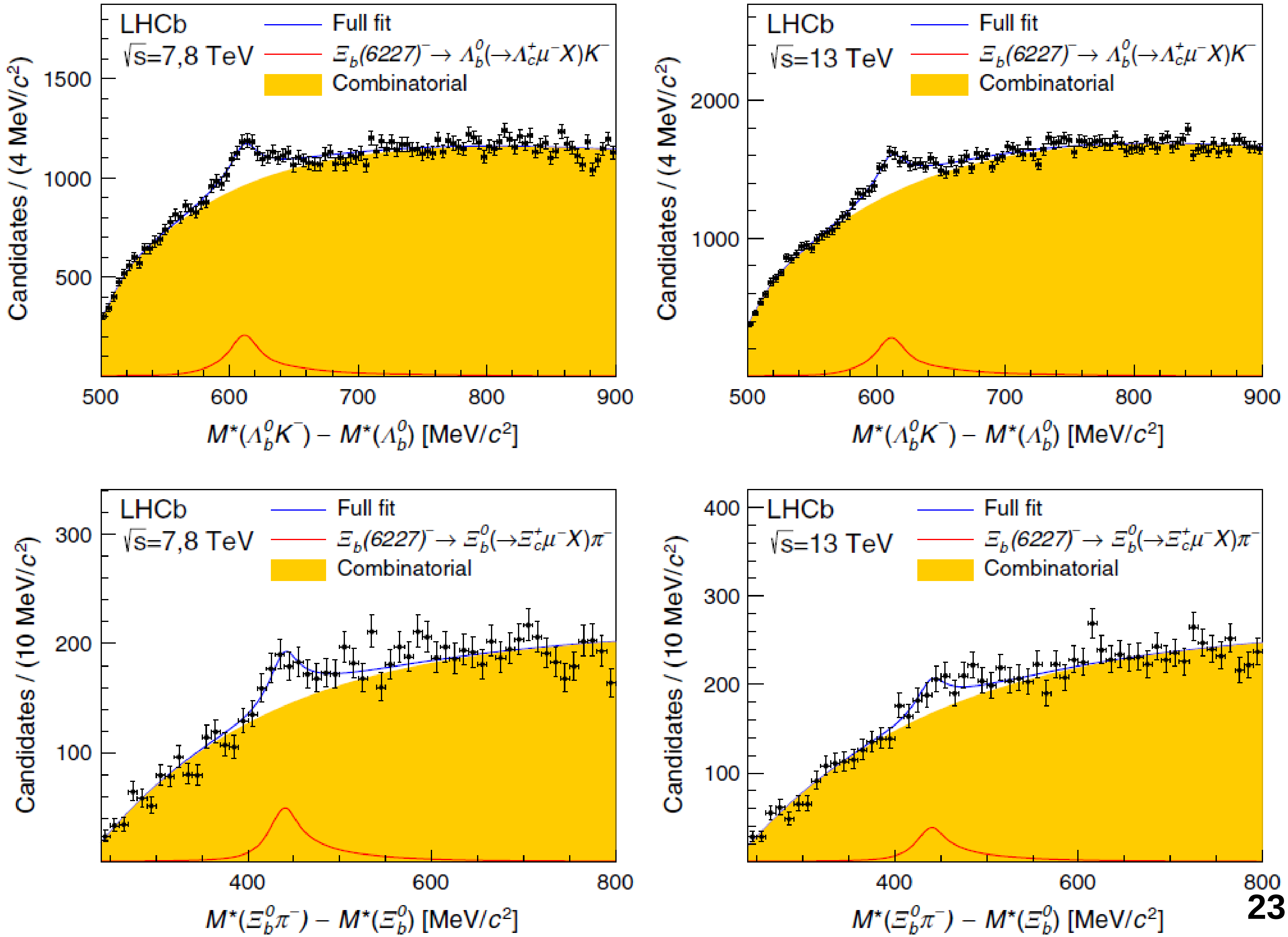
PRL 121 (2018) 072002

Observation of Ξ_b^-

Semileptonic channels: $\Xi_b(6227)^- \to [\Lambda_b^0 \to \Lambda_c^+ \mu^- X]K^-$ and $[\Xi_b \to \Xi_c^+ \mu^- X]\pi^-$

Larger samples (about 25σ significance) but with missing mass. Relative production rates are reported. Consistent with strong decay of radially or orbitally excited state (1P Ξ_b).

PRL 121 (2018) 072002

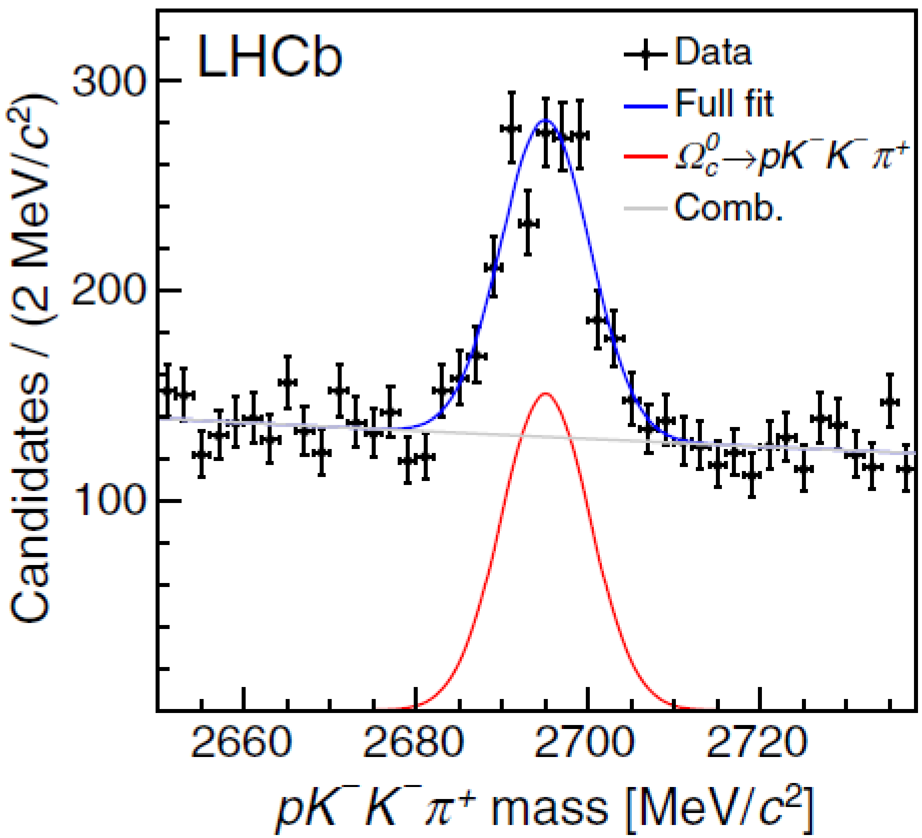


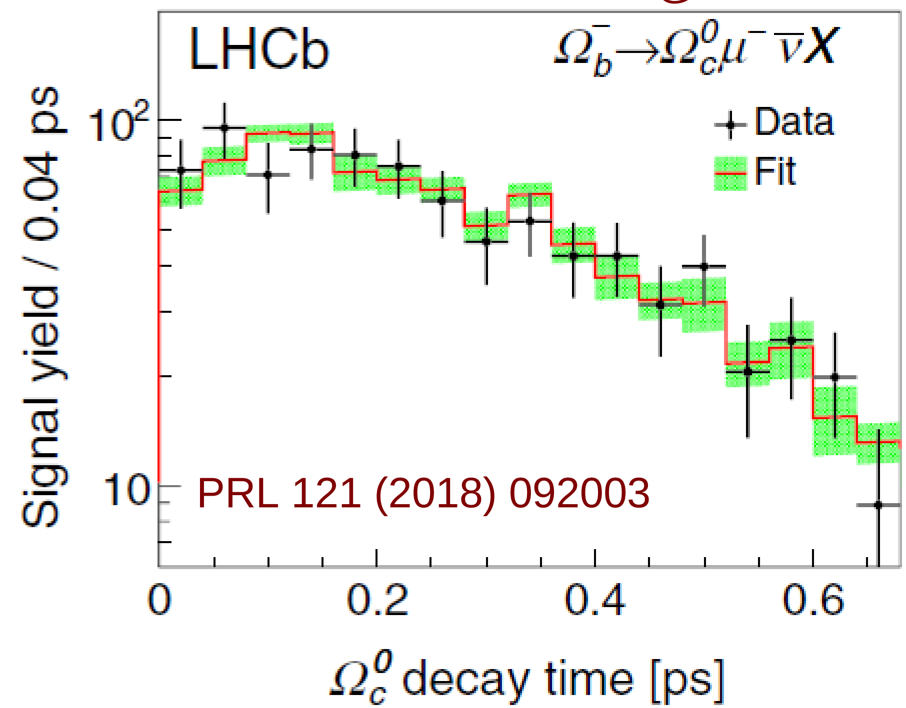
Dataset:
1.0 fb^{-1} @ √s=7 TeV
2.0 fb^{-1} @ √s=8 TeV
1.5 fb^{-1} @ √s=13TeV

Measurement of Ω_c^0 lifetime

- Useful for testing higher order effects in heavy quark expansion (HQE)
- Using $\Omega_c^0 \to pK^-\pi^+\pi^-$ decays obtained from $\Omega_b^- \to \Omega_c^0 \mu^-\bar{\nu}X$
- $B^+ \to D^+ \mu^-\bar{\nu}X$ decays used as a normalization channel

Dataset:
1.0 fb^{-1} @ $\sqrt{s}$=7 TeV
2.0 fb^{-1} @ $\sqrt{s}$=8 TeV

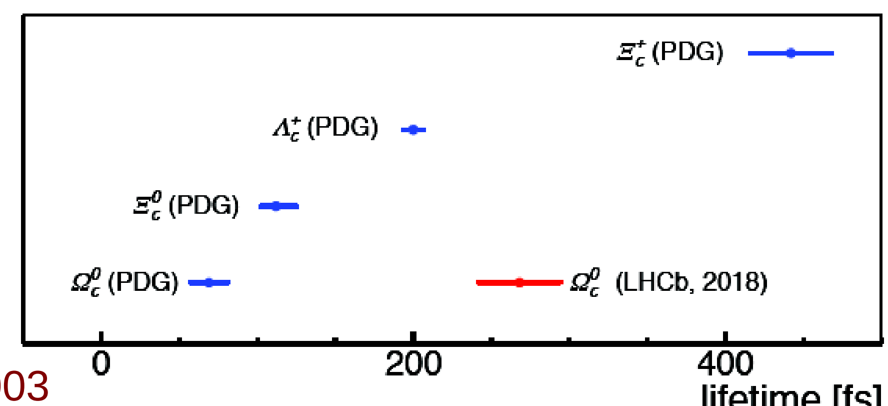




$$\frac{\tau_{\Omega_c^0}}{\tau_{D^+}} = 0.258 \pm 0.023 \pm 0.010$$

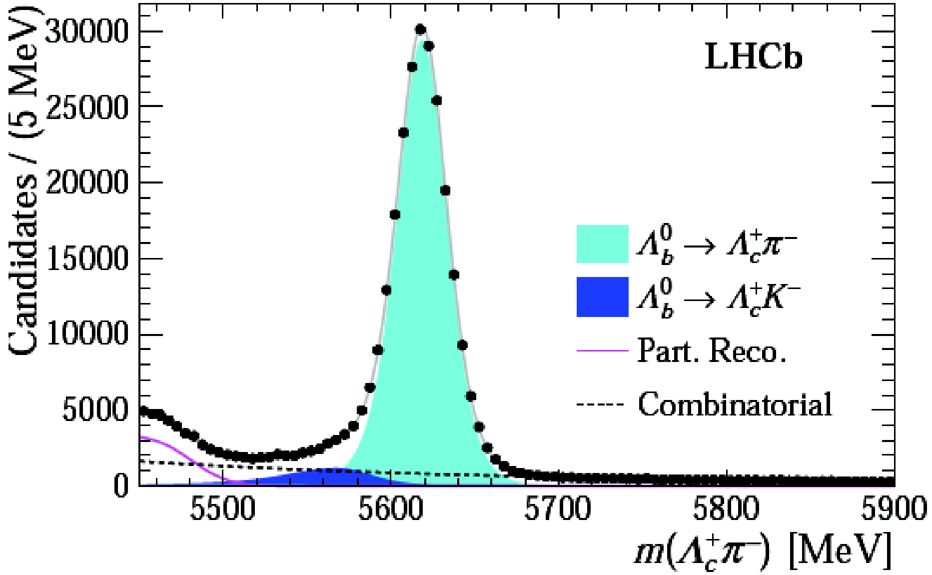
$$\tau_{\Omega_c^0} = 268 \pm 24 \pm 10 \pm 2 \text{ fs},$$

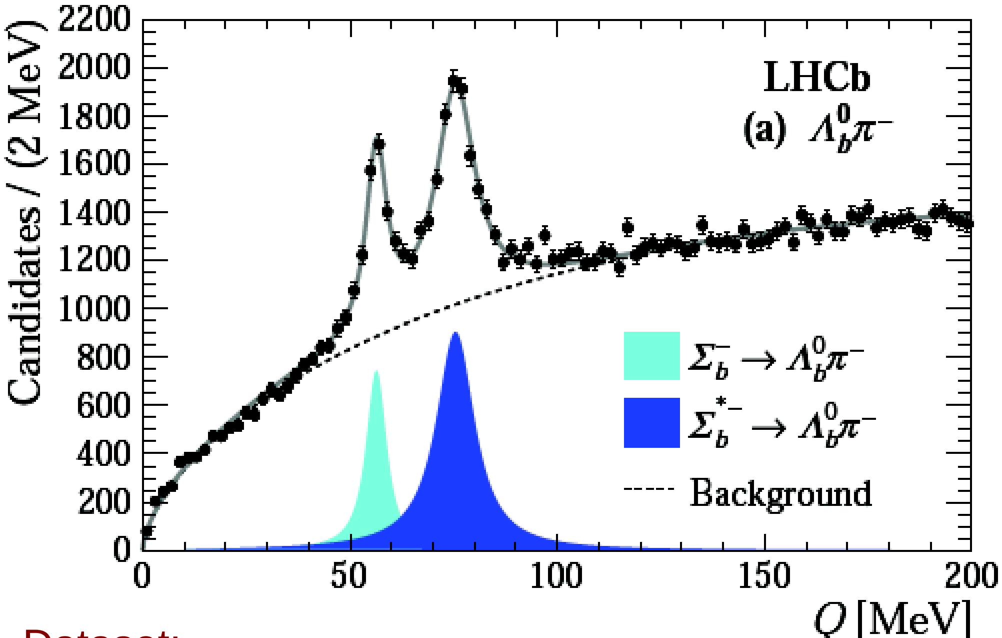
PRL 121 (2018) 092003

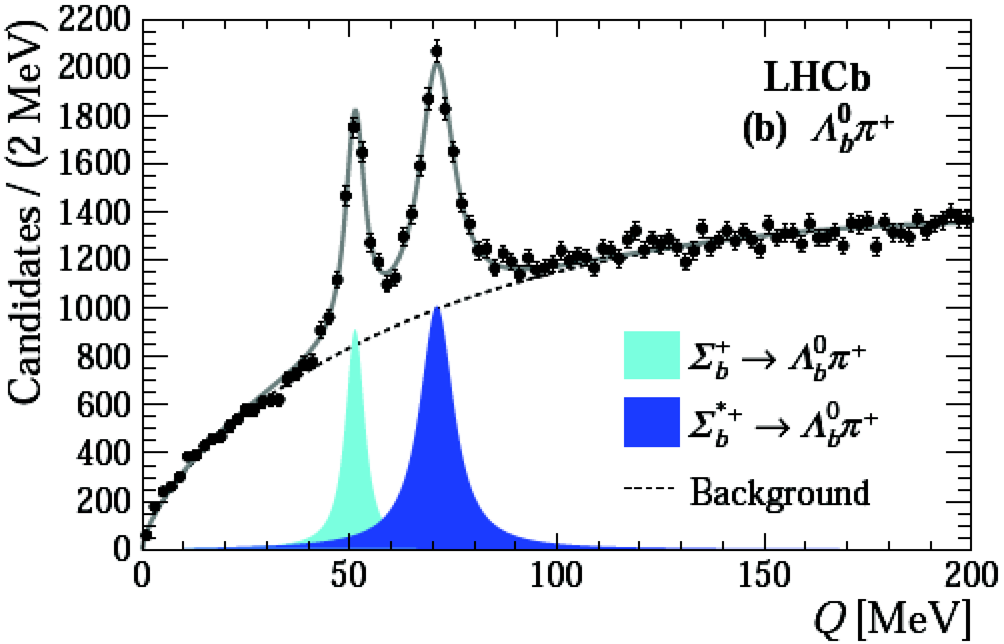


Study $\Lambda_b^0\pi^\pm$ system

- Study of the $\Lambda_b^0\pi^\pm$ system using $\Lambda_b^0[\rightarrow\Lambda_c^+\pi^-]$ baryons combined with a prompt pion with $p_T(\pi) > 200$ MeV/c
- $Q = m(\Lambda_b^0\pi^\pm)-m(\Lambda_b^0)-m(\pi^\pm) < 200$ MeV/c^2
- Measurement of $\Sigma^\pm$ and $\Sigma^{*\pm}$ baryon properties with ~5 times improved precision in comparison with CDF results





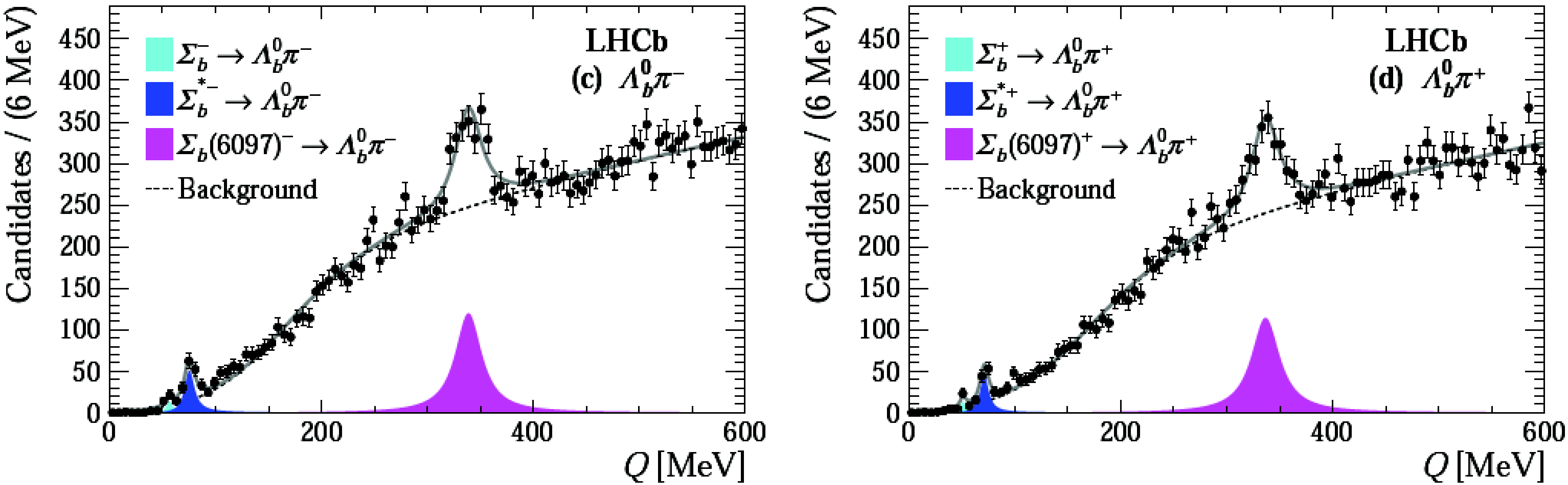


Dataset:
1.0 fb^{-1} @ $\sqrt{s}$=7 TeV
2.0 fb^{-1} @ $\sqrt{s}$=8 TeV

arXiv:1809.07752

Observation of two new resonances in $\Lambda_b^0\pi^\pm$

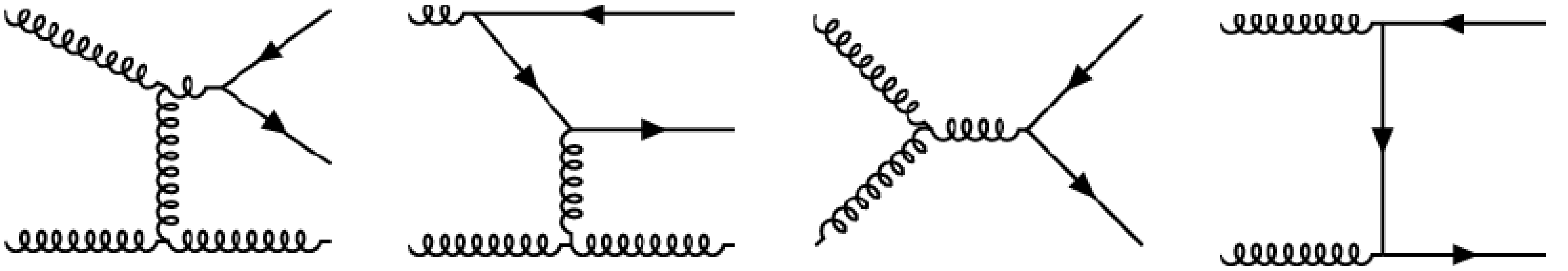
- Extend study to region with Q < 600 MeV/c^2
- $p_T(\pi)$> 1000 MeV/c used to suppress combinatorial background
- Peaks with local significance more than 12σ have been observed



Quantity	Value [MeV]
$m(\Sigma_b(6097)^-)$	$6098.0 \pm 1.7 \pm 0.5$
$m(\Sigma_b(6097)^+)$	$6095.8 \pm 1.7 \pm 0.4$
$\Gamma(\Sigma_b(6097)^-)$	$28.9 \pm 4.2 \pm 0.9$
$\Gamma(\Sigma_b(6097)^+)$	$31.0 \pm 5.5 \pm 0.7$

Dataset:
1.0 fb^{-1} @ $\sqrt{s}$=7 TeV
2.0 fb^{-1} @ $\sqrt{s}$=8 TeV

arXiv:1809.07752

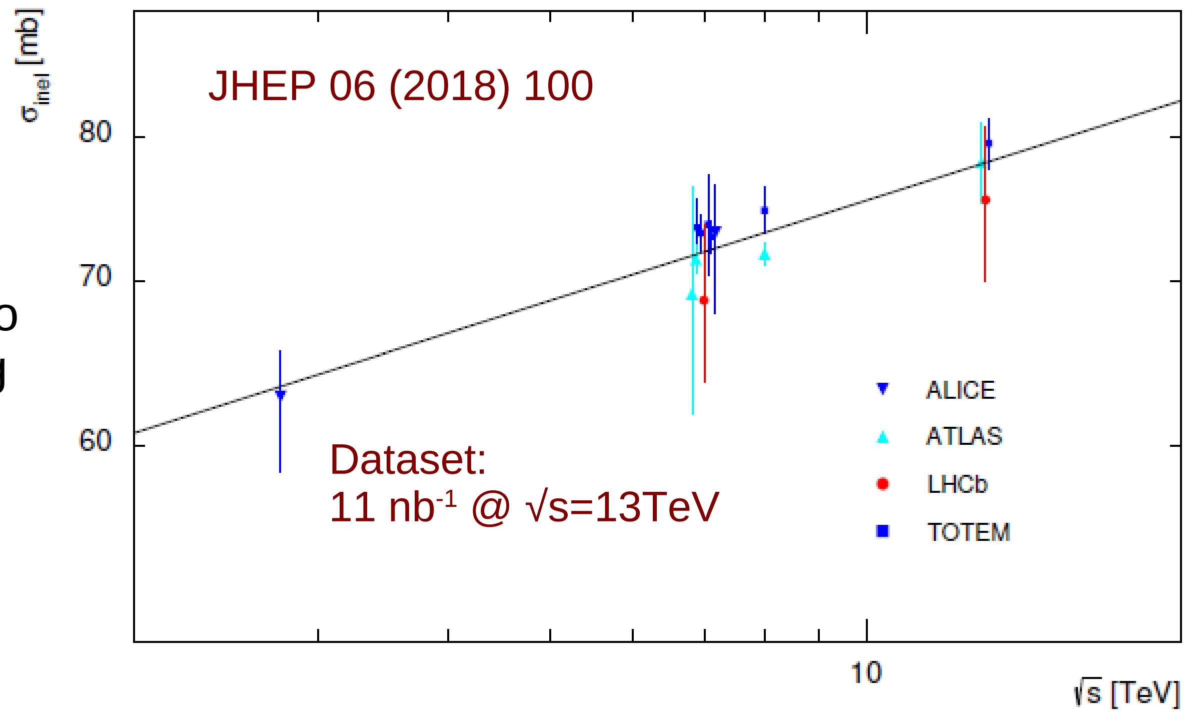


Soft QCD

Inelastic *pp* cross-section at 13 TeV

A fiducial cross section σ_{acc}

- At least one prompt, long-lived charged particle with p > 2 GeV/c
- Unbiased triggers: random events
- Leading bunches in LHC bunch-trains to avoid background from previous crossing

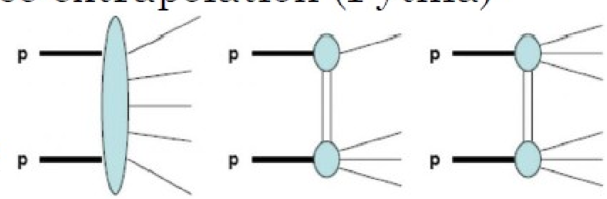


Measure fraction of non-empty events

$$\sigma_{acc} = \frac{(\mu - \mu_{bkg})N_{evt}}{\mathcal{L}}$$

$$\sigma_{acc} = 62.2 \pm 0.2(\text{syst}) \pm 2.5(\text{lumi}) \text{ mb @ 13 TeV}$$

- The full phase-space extrapolation (Pythia)
  - Non-diffractive
  - Single-diffractive
  - Double-diffractive



$$\sigma_{inel} = 75.4 \pm 3.0(\text{expt}) \pm 4.5(\text{extrap}) \text{ mb @ 13 TeV}$$

- μ = -ln(p_0) is the average number of interactions in event
- p_0 is the fraction of empty events
- μ_{bkg}/μ < 1%
- Correction to detector inefficiency and wrongly reconstructed tracks

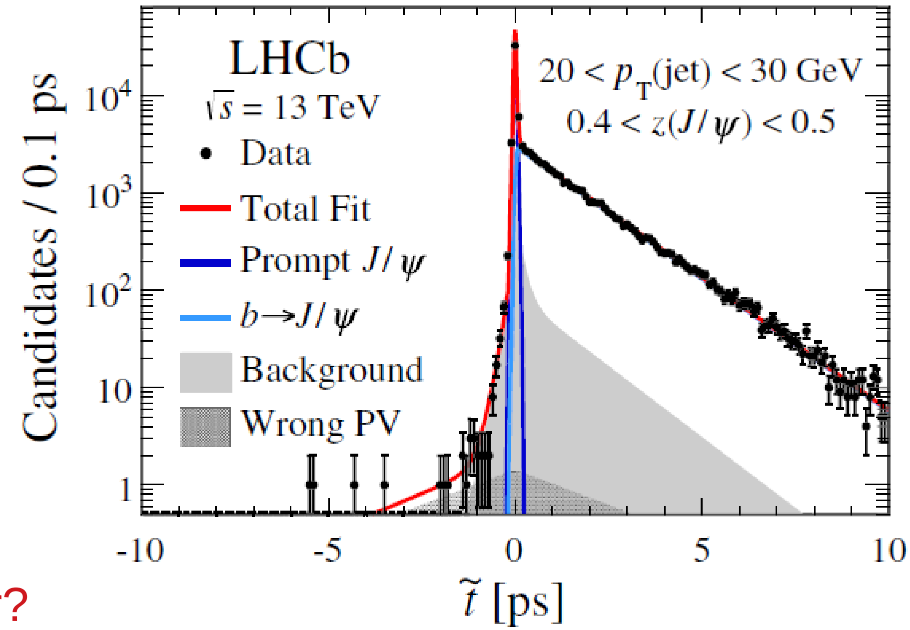
J/ψ production in jets

PRL 118 (2017) 192001

The J/ψ in-jets polarization puzzle: NRQCD predicts large transverse polarization that is not seen in data.

Measure J/ψ isolation: $$z(J/\psi) \equiv \frac{p_T(J/\psi)}{p_T(\text{jet})}$$

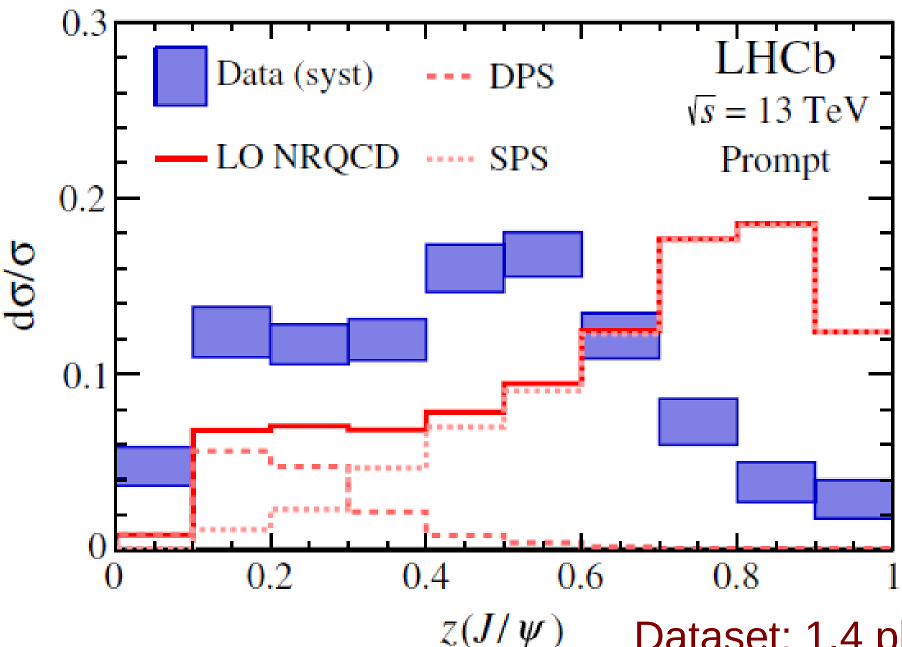
- $p_T(\text{jet}) > 20\ \text{GeV}/c^2$
- $2.5 < \eta(\text{jet}) < 4.0,\ 2.0 < \eta(J/\psi) < 4.5$
- $p_T(\mu) > 0.5\ \text{GeV}/c^2,\ p(\mu) > 5\ \text{GeV}/c^2$

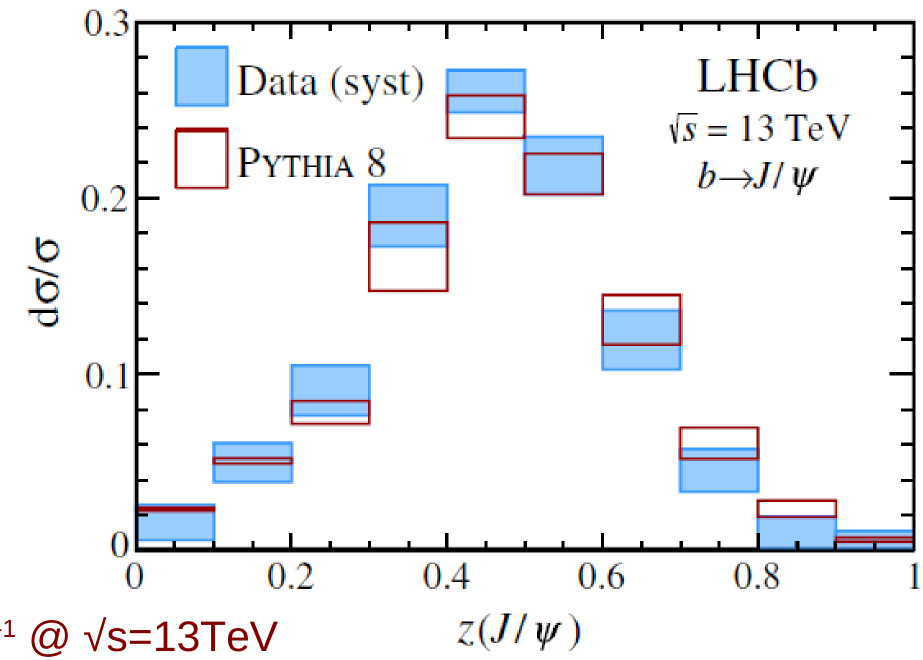


Separate prompt and b production using pseudo-time

Prompt J/ψ are much less isolated than predicted.

High p_T J/ψ predominately produced in parton shower?





Dataset: 1.4 pb^{-1} @ √s=13TeV

Kinematic $b\bar{b}$ correlations

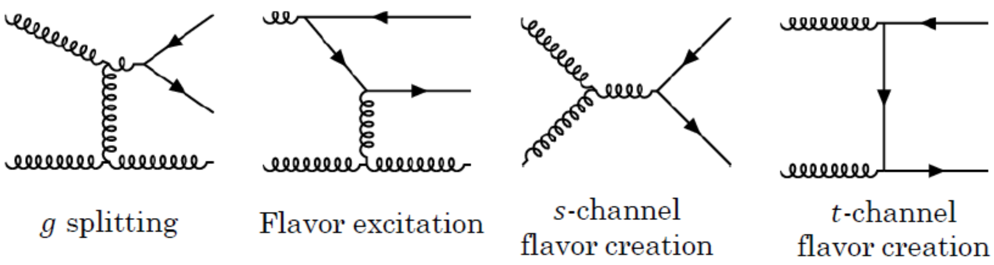
JHEP 11 (2017) 030

$b\bar{b}$ correlations probe production mechanism

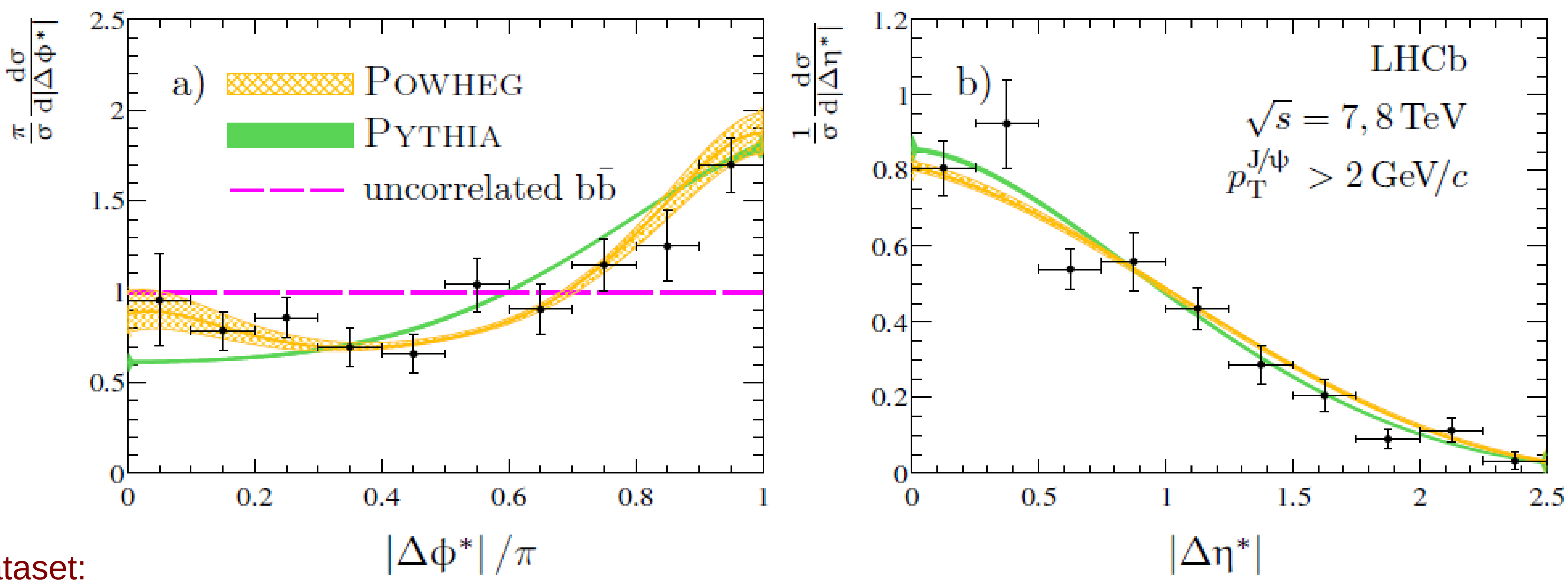
Inclusive reconstruction using b → J/ψ X decays

Two J/ψ candidates:

- $2 < p_T < 25$ GeV/c
- $2 < \eta < 4.5$
- Displaced vertices from same PV



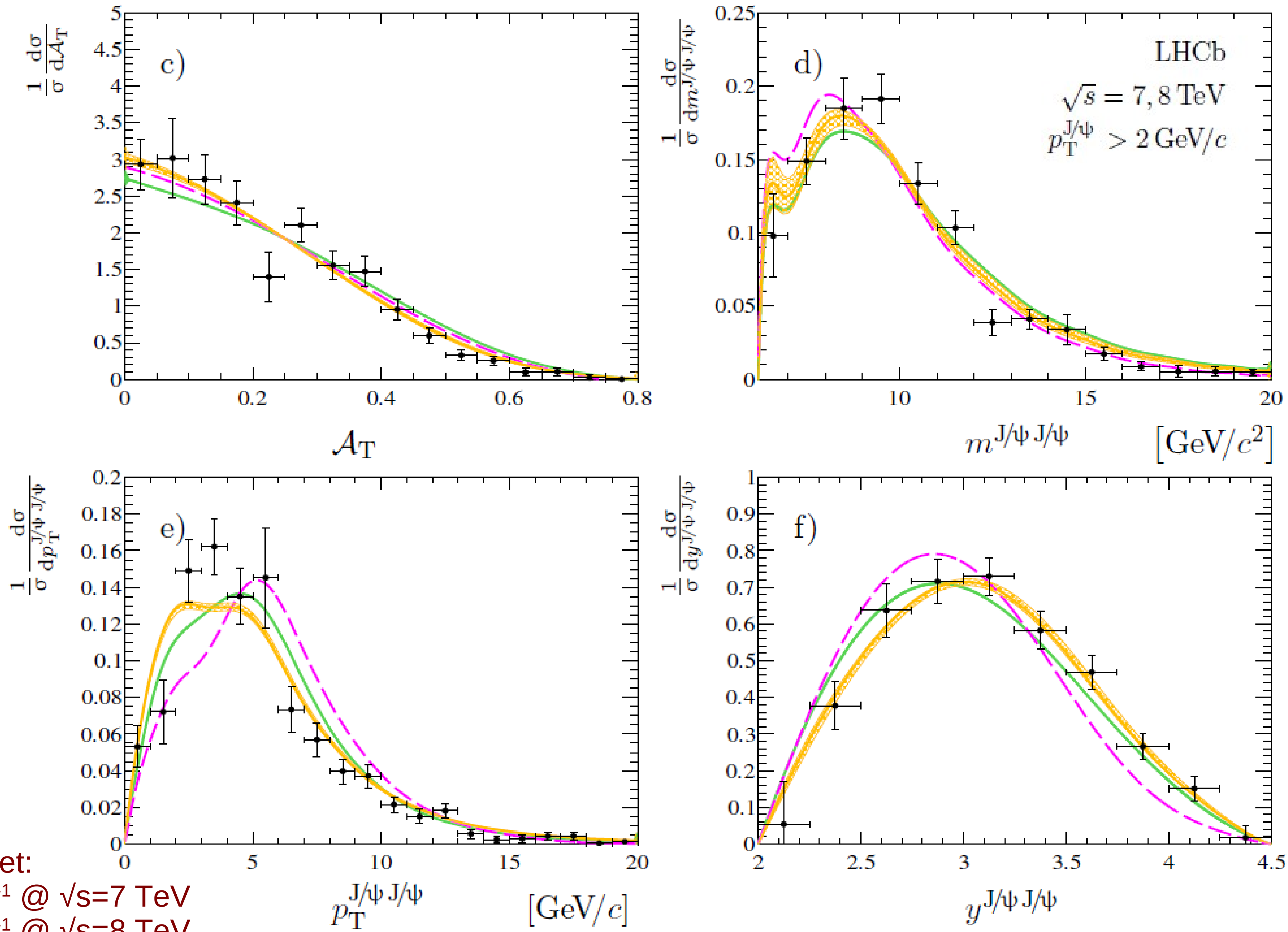
Differential cross section



Dataset:
1.0 fb^{-1} @ √s=7 TeV
2.0 fb^{-1} @ √s=8 TeV

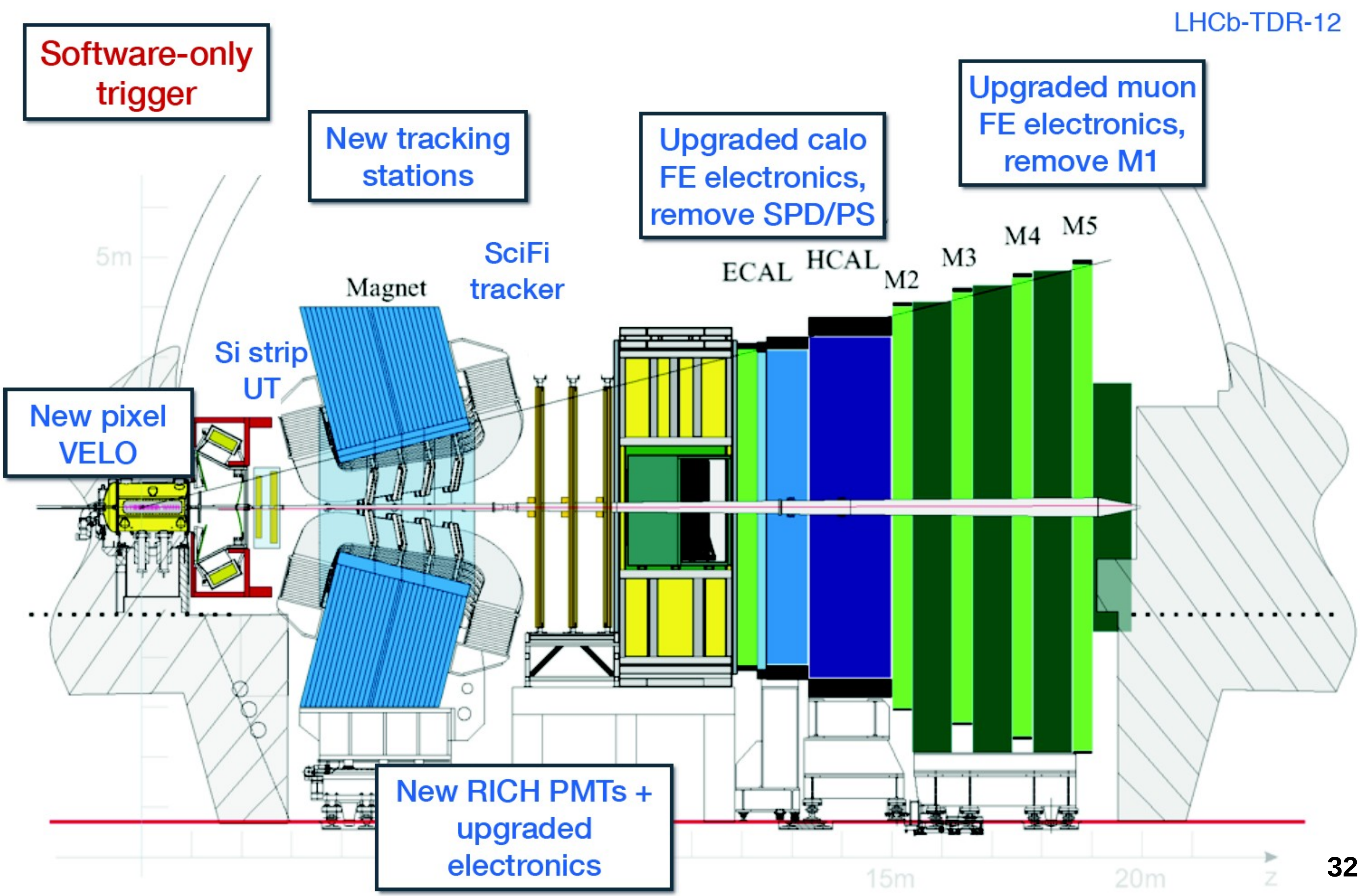
Kinematic $b\bar{b}$ correlations

JHEP 11 (2017) 030

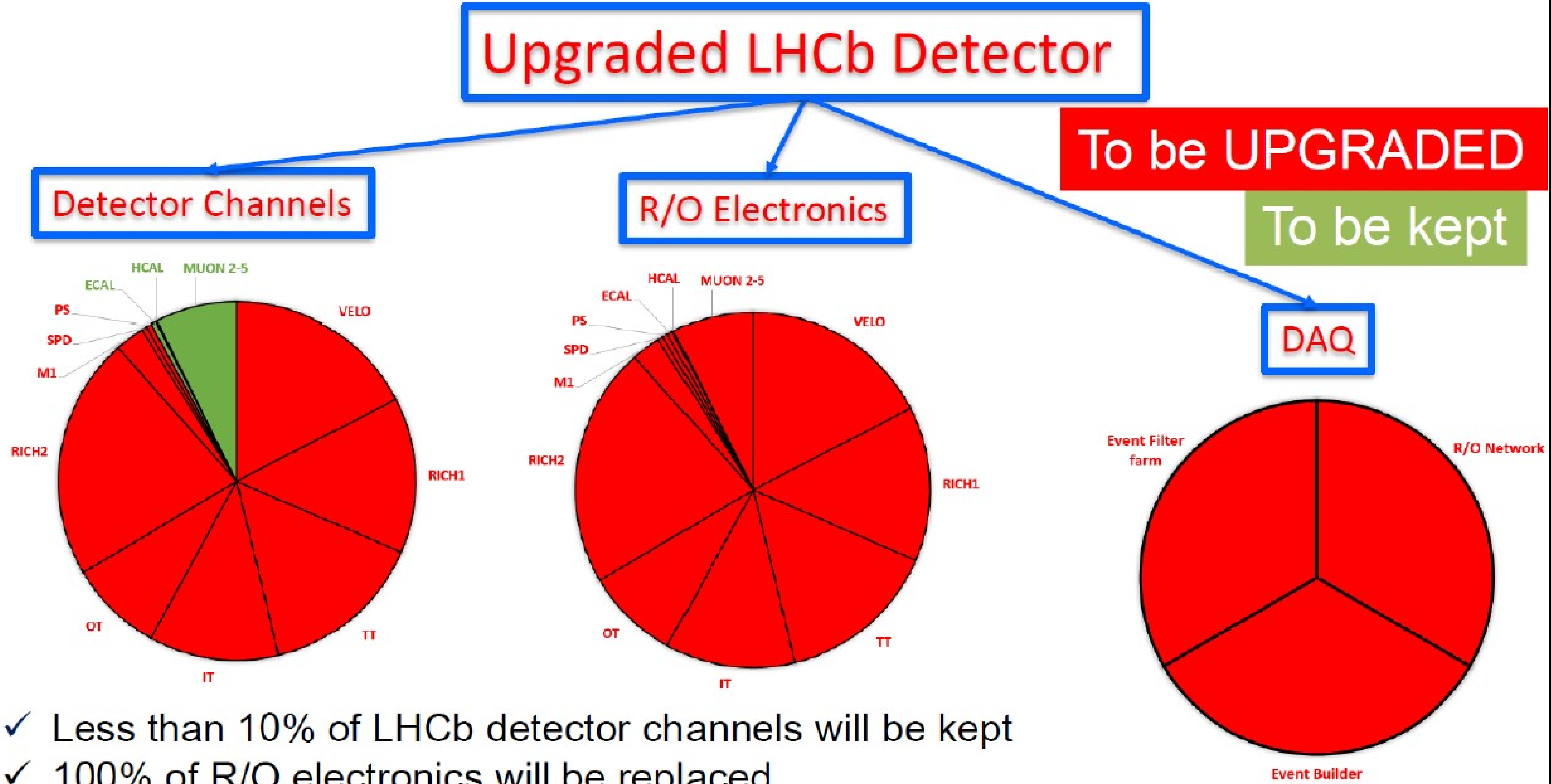


Dataset:
1.0 fb^{-1} @ √s=7 TeV
2.0 fb^{-1} @ √s=8 TeV

LHCb upgrade



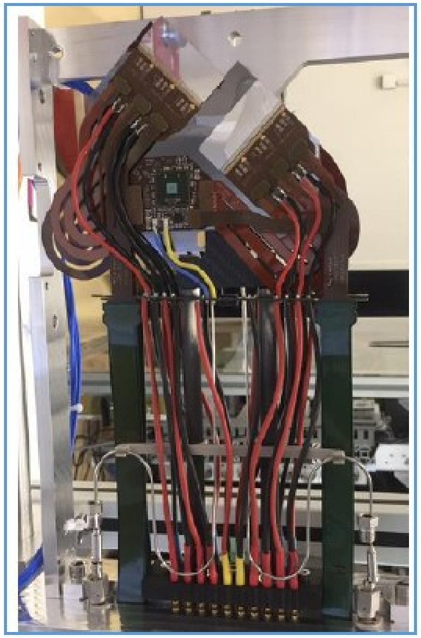
LHCb upgrade



- ✓ Less than 10% of LHCb detector channels will be kept
- ✓ 100% of R/O electronics will be replaced
- ✓ NEW DAQ system and DATA CENTER

LHCb upgrade

Velo module



UT sensor

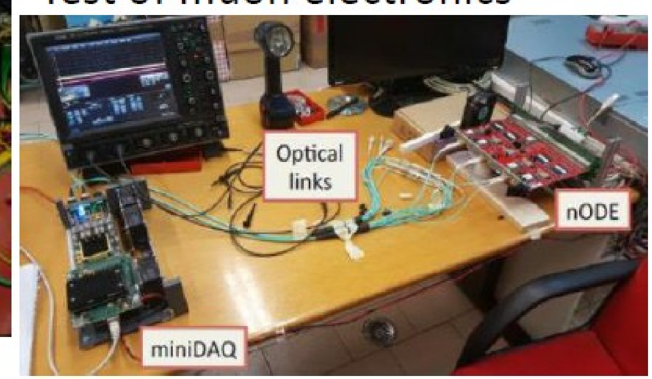
RICH MAMPT under test

SciFi Module

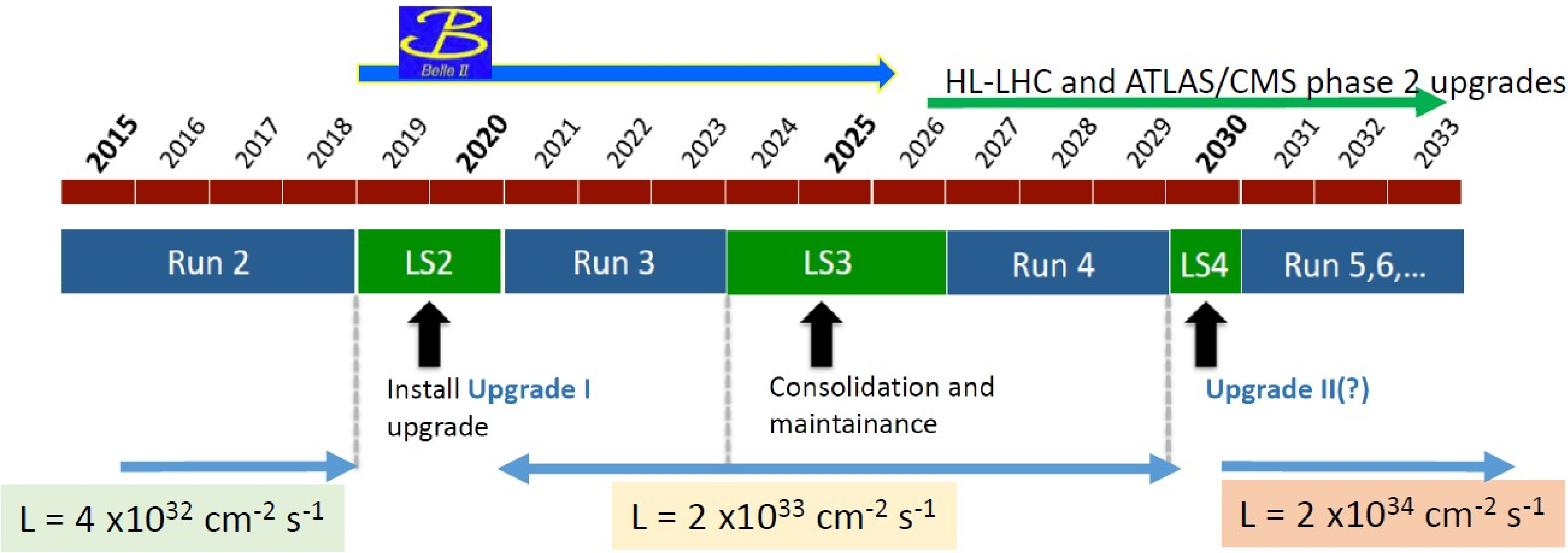
UT staves constructions

Calorimter electorncis

Test of muon electronics



LHCb upgrade II



Major detector upgrade in LS4 (2030)

- Expression of Interest [CERN-LHCC-2017-003]
- Aim to run at 10 x Upgrade I luminosity and collect 300 fb^{-1}
- Challenging conditions for flavour physics (number of visible interactions ~50)
- Physics case document: CERN-LHCC-2018-027
- LHCb may be the only large-scale flavour physics experiment to run in HL-LHC era

Conclusion

- LHCb operating well in the final few months of data-taking in Run 2
- New and more complex analyses constantly being added to physics program.
- Less than half on Run 2 statistics is used in presented results. We expect significant improvement after processing all collected data.
- Preparation for LHCb Upgrade I proceeding well.
- Most of key measurement will be still limited by statistics before HL-LHC era (Upgrade II ~2030?)

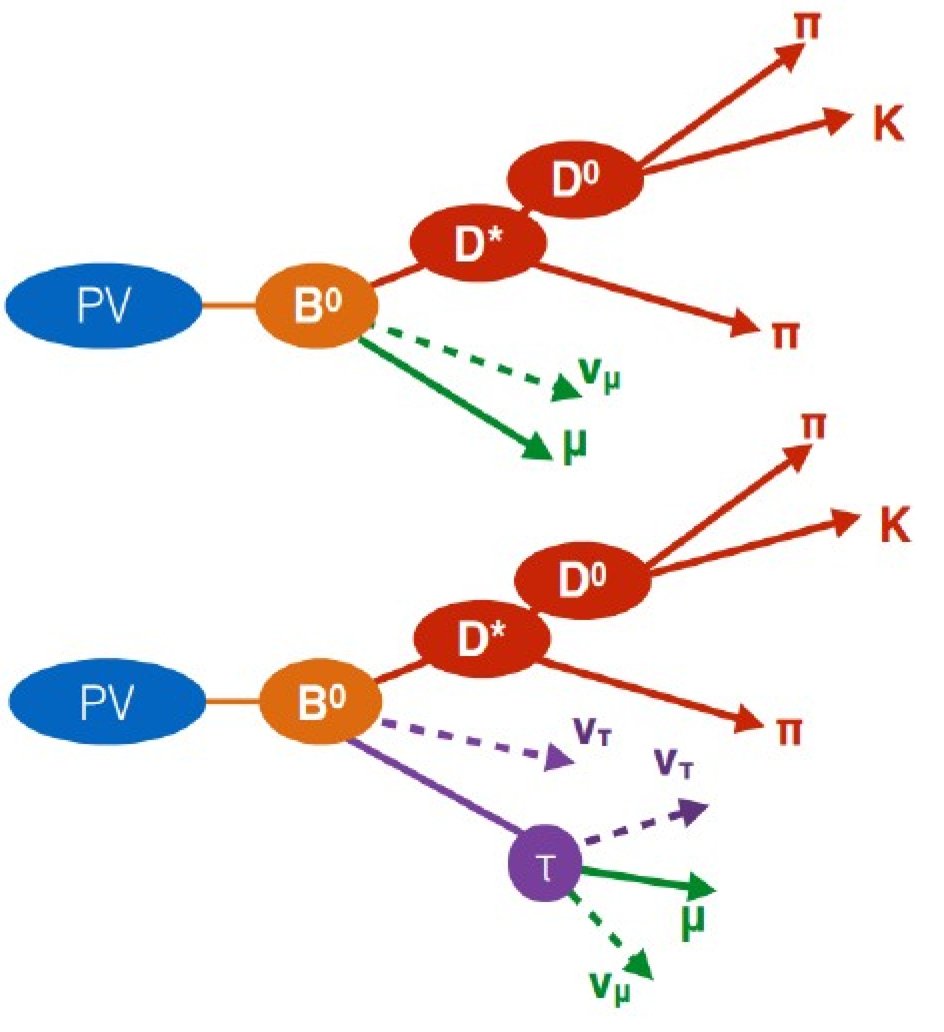
Backup

R_{D*} in muonic channels

- τ reconstructed by $\tau^- \rightarrow \mu^- \nu_\tau \bar{\nu}_\mu$
- Both channels have the same final state ($K\pi\pi\mu$)

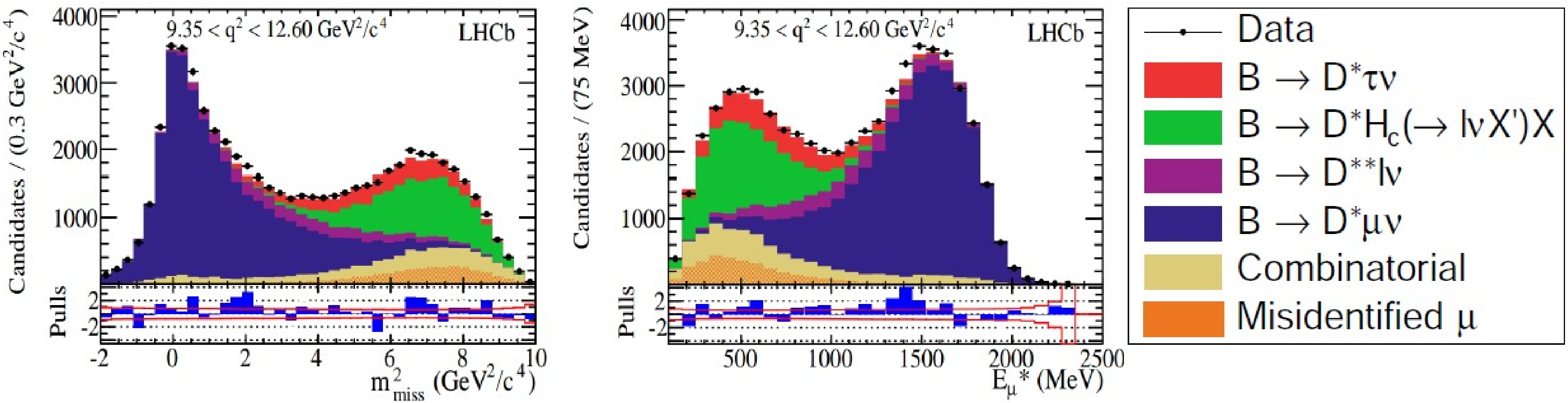
- Separation using difference in kinematics:
  - E^*_μ, E_μ in $\bar{B}^0$ rest frame
  - $M^2_{miss} = (p_{B0}-p_{D*}-p_\mu)^2$
  - $q^2 = (p_{B0}-p_{D*})^2$

- Approximate p_{B0} using
  - $\bar{B}^0$ flight direction
  - $(p_{B0})_z = m_B/m_{reco}\ (p_{reco})_z$



R_{D^*} in muonic channels

- Yields are extracted with a 3D binned ML fit in E^*_m, m^2_{miss} , q^2
- Templates for the signal, normalization and backgrounds are obtained on MC and checked against control samples



- $R_{D^*} = 0.336 \pm 0.027$ (stat) ± 0.030 (syst) 2σ above SM
- Main background: Partially reconstructed and mis-ID decays
- Main systematic: Size of the simulated sample

Phys. Rev. Lett. 115, 111803 (2015)

R_{D^*} in hadronic τ decays

τ reconstructed by $\tau^- \rightarrow \pi^-\pi^-\pi^+ \nu_\tau$ independent from R_{D^*} muonic

$$R_{D^*} = \underbrace{\frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)}}_{\text{measured ratio } \mathcal{K}(\mathrm{D}^{*-})} \cdot \underbrace{\frac{\mathcal{B}(B^0 \to D^{*-}3\pi)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}}_{\text{external inputs}}$$

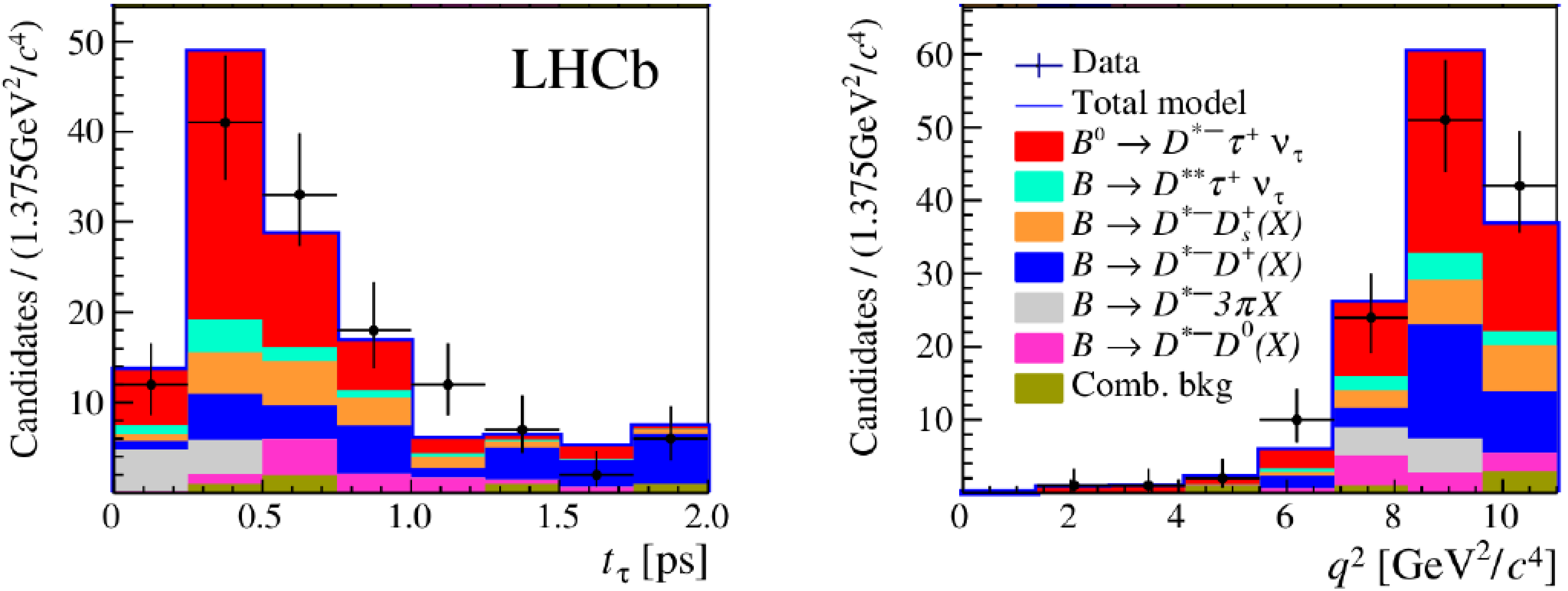
~4% precision (BABAR, Belle, LHCb)

~2% precision, HFLAV

- Partial cancellation of experimental systematic uncertainties
- Main background:
  - $B^0 \rightarrow D^*\pi\pi\pi X$, suppressed with τ decay time, t_τ
  - $B \rightarrow DD_{(s)}X$, suppressed with BDT

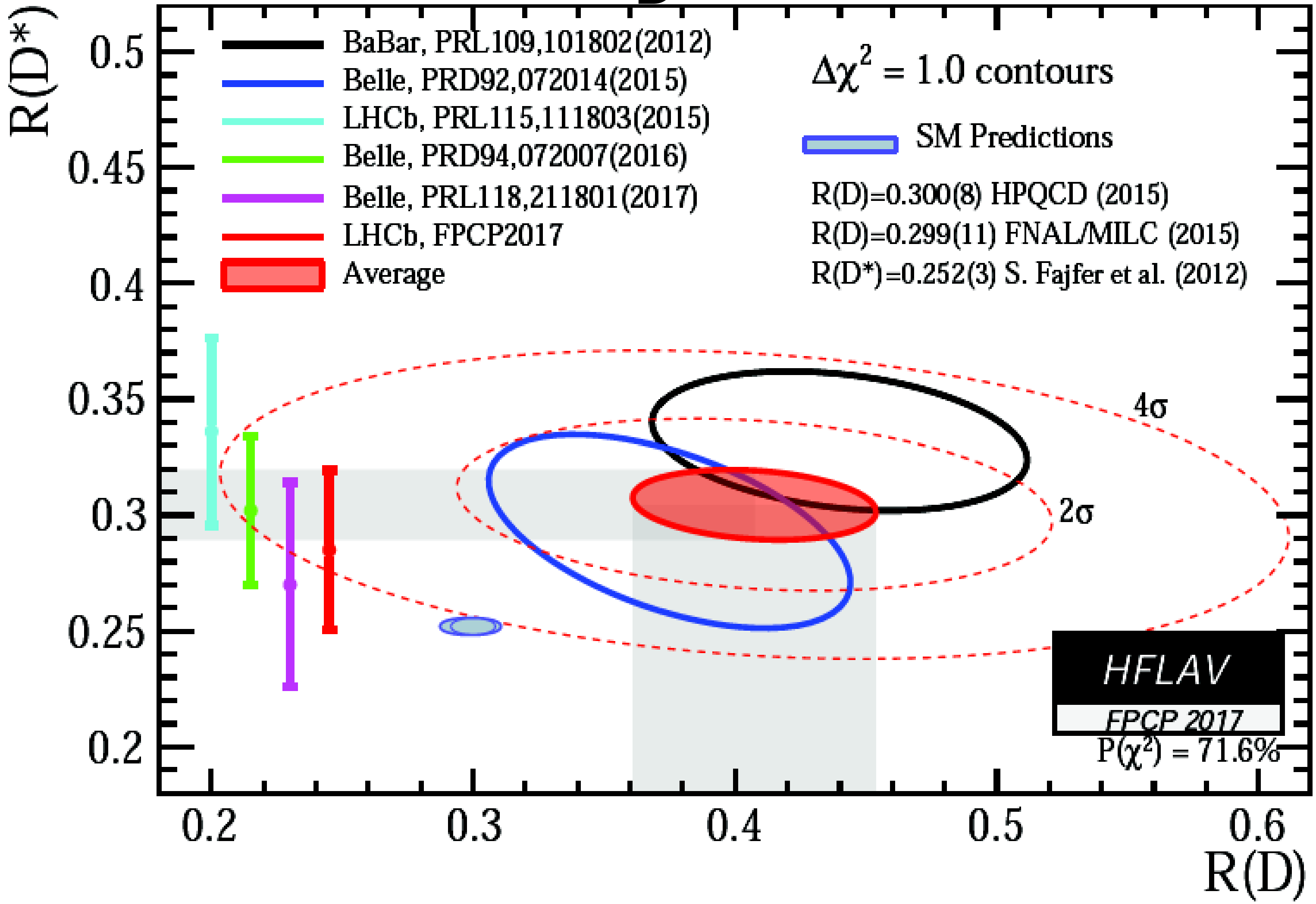
R_{D*} in hadronic τ decays

- Yields are extracted by a binned ML fit on q^2, BDT and t_τ



- R_{D*} = 0.291 ±0.019 (stat) ± 0.026 (syst) ± 0.013 (ext)
  1σ above SM
  Phys. Rev. Lett. 120, 181802 (2018)
- Main systematic: Size of the simulated sample
- LHCb average: R_{D*} = 0.310 ± 0.016 (stat) ± 0.022 (syst)
  2.2σ above SM

R_{D^*} results



- Measurements of R_D and R_{D*} are consistent with each other
- Combined result is 3.8σ above SM prediction
- Tension is slightly reduced in a recent SM update [JHEP 11 (2017) 061]

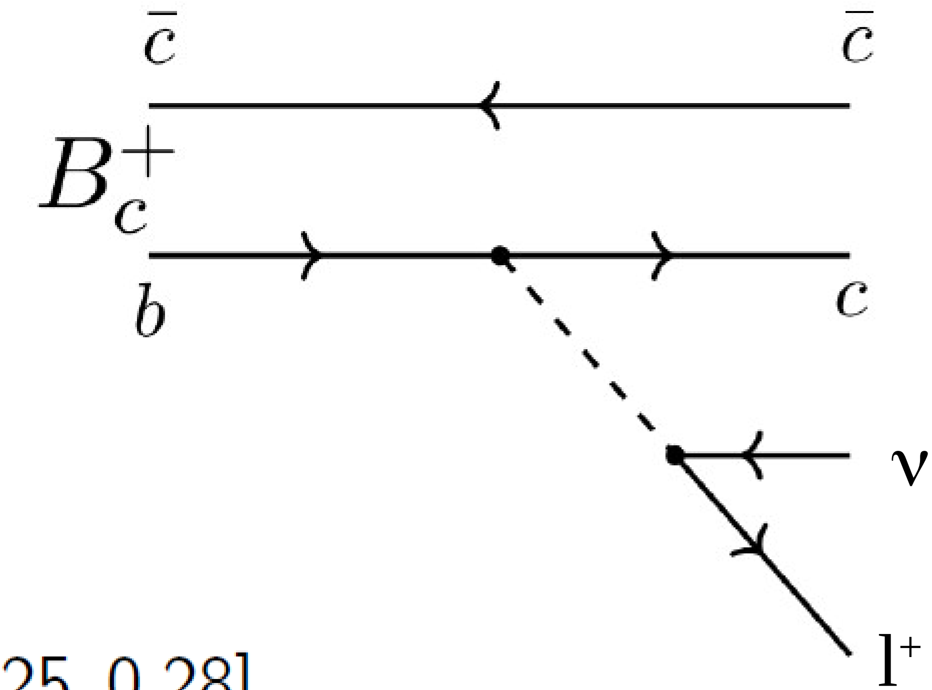
SM prediction of $R_{J/\psi}$

Test of LFU in $b \to c\ell\nu$ decays

with a different spectator quark

using large B^+_c sample available

at LHCb



$$R_{J/\psi} \equiv \frac{\mathcal{B}(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)} \overset{\text{SM}}{\in} [0.25, 0.28]$$

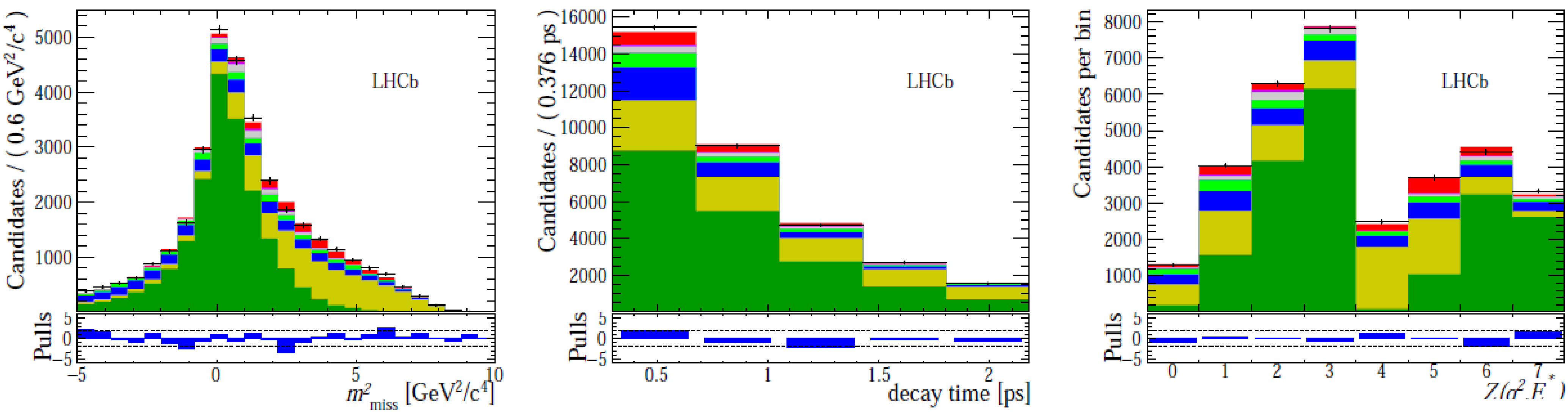
Interval is due to form factor uncertainty [PLB 452 (1999) 129] [arXiv:hep-ph/0211021] [PRD 73 (2006) 054024] [PRD 74 (2006) 074008]

Lattice calculation is in progress

$R_{J/\psi}$ results

τ reconstructed by $\tau^- \rightarrow \mu^- \nu_\tau \bar{\nu}_\mu$

Analysis strategy as in R_{D*} + t_τ as 4th discriminating variable



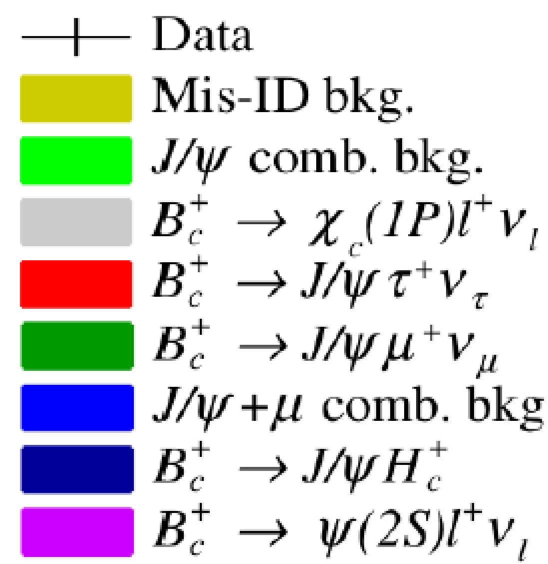
Main backgrounds: B $\rightarrow$ J/ψ + mis-ID hadron

Systematic: MC sample, $B^+_c \rightarrow J/\psi$ form factors

$R_{J/\psi}$ = 0.71 ± 0.17(stat) ± 0.18(syst)

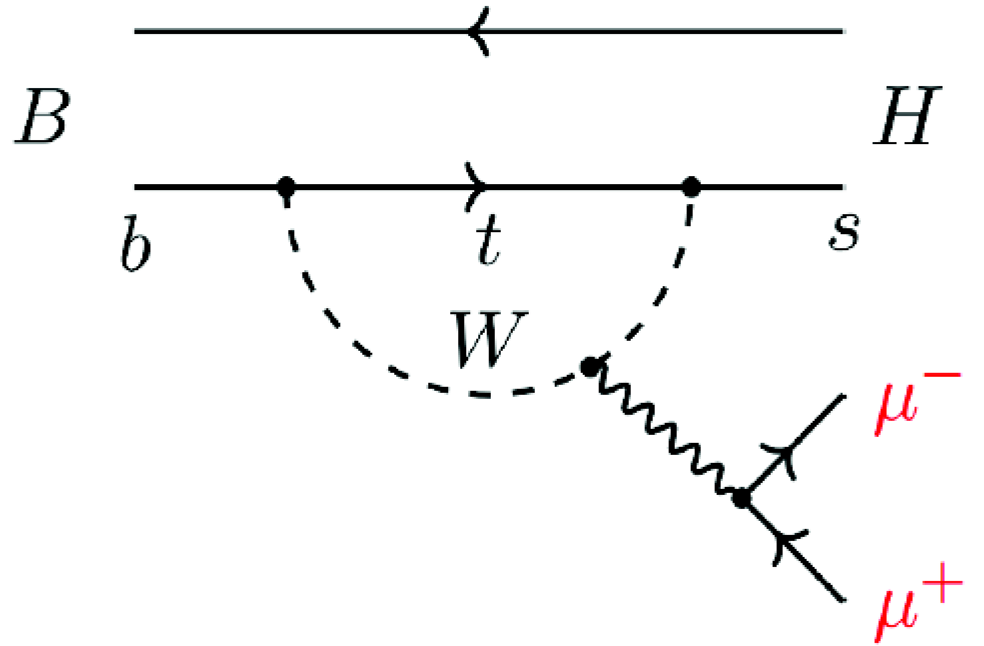
Phys.Lett. B783 (2018) 178

First evidence (3σ) of $B^+_c \rightarrow J/\psi\ \tau^+\ \nu_\tau$



LFU tests in b → sℓℓ

b → sℓ⁺ℓ⁻ are FCNC processes that can only occur at loop-level in SM

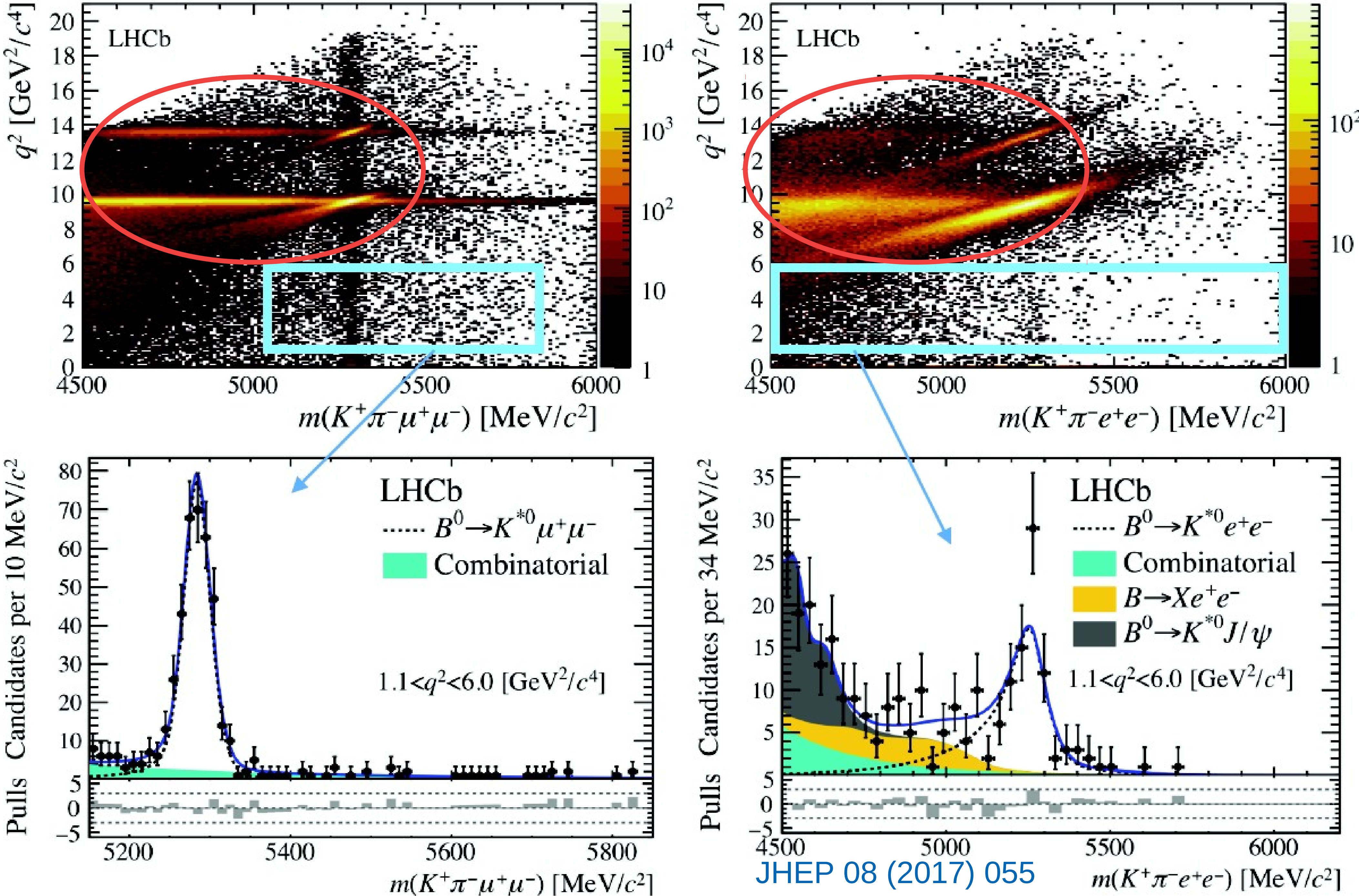


$$R_H \equiv \frac{\mathcal{B}(B\to H\,\mu^+\mu^-)}{\mathcal{B}(B\to H\,e^+e^-)} \overset{\text{SM}}{=} 1 \pm \underbrace{\mathcal{O}(10^{-3})}_{\text{neglect } m_\ell} \pm \underbrace{\mathcal{O}(10^{-2})}_{\text{QED effects}}$$ [EPJC76(2016)8,440]

Use double ratio to reduce systematic effects:

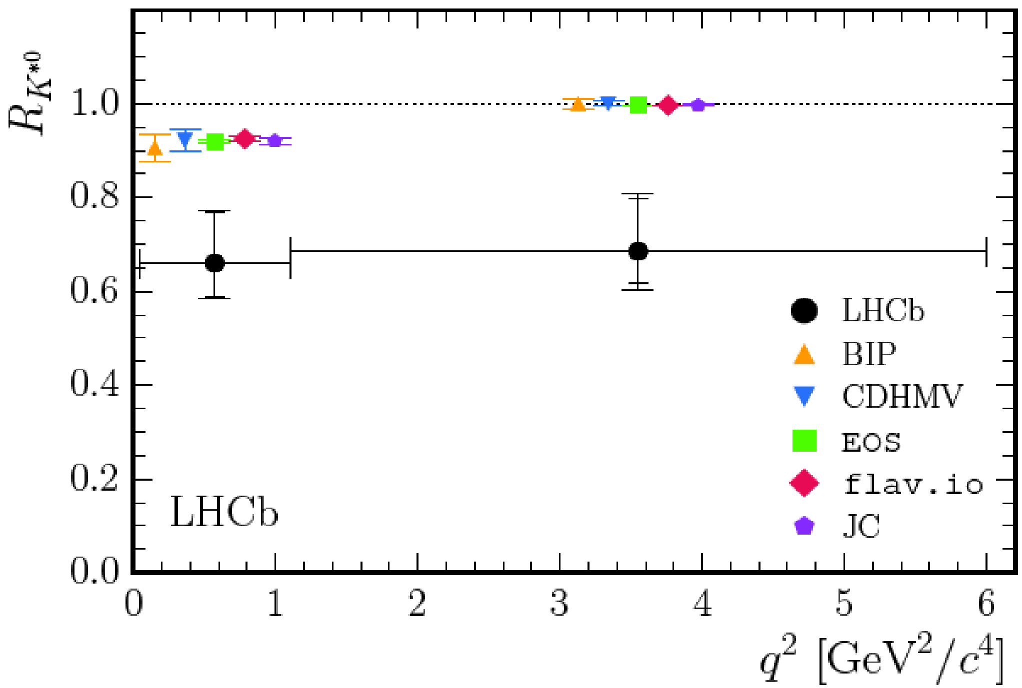
$$R_H \equiv \frac{\mathcal{B}(B \to H\,\mu^+\mu^-)}{\mathcal{B}(B \to H\ (J/\psi \to \mu^+\mu^-))} \cdot \frac{\mathcal{B}(B \to H\ (J/\psi \to e^+e^-))}{\mathcal{B}(B \to H\,e^+e^-)}$$

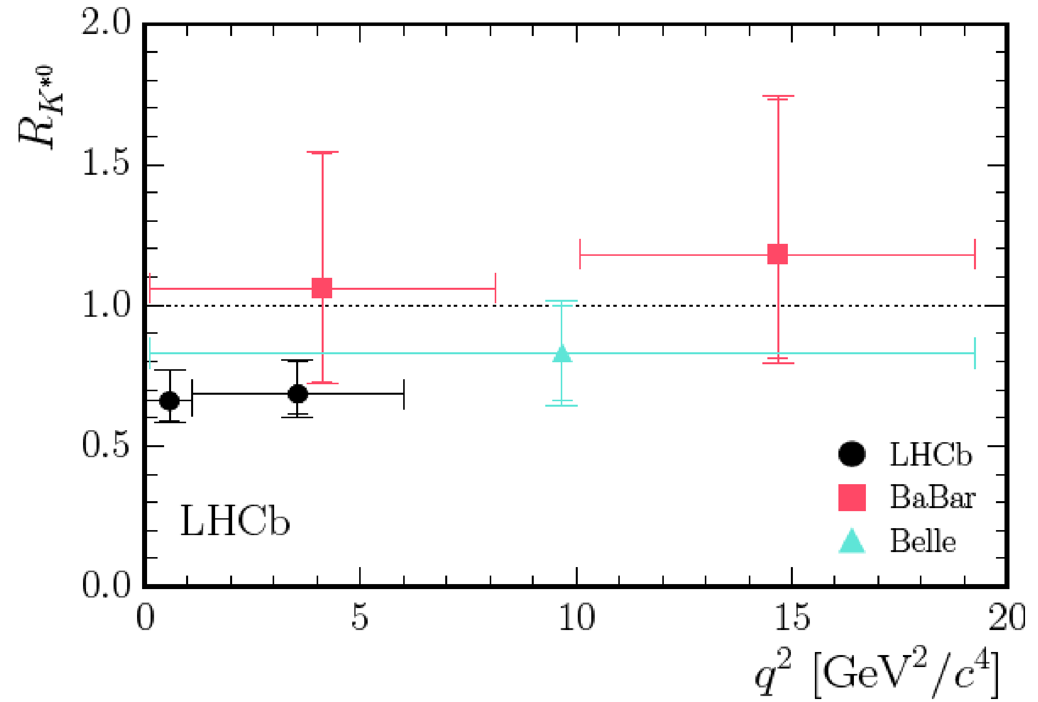
Measurement of R_{K^*}



JHEP 08 (2017) 055

R_{K^*} results





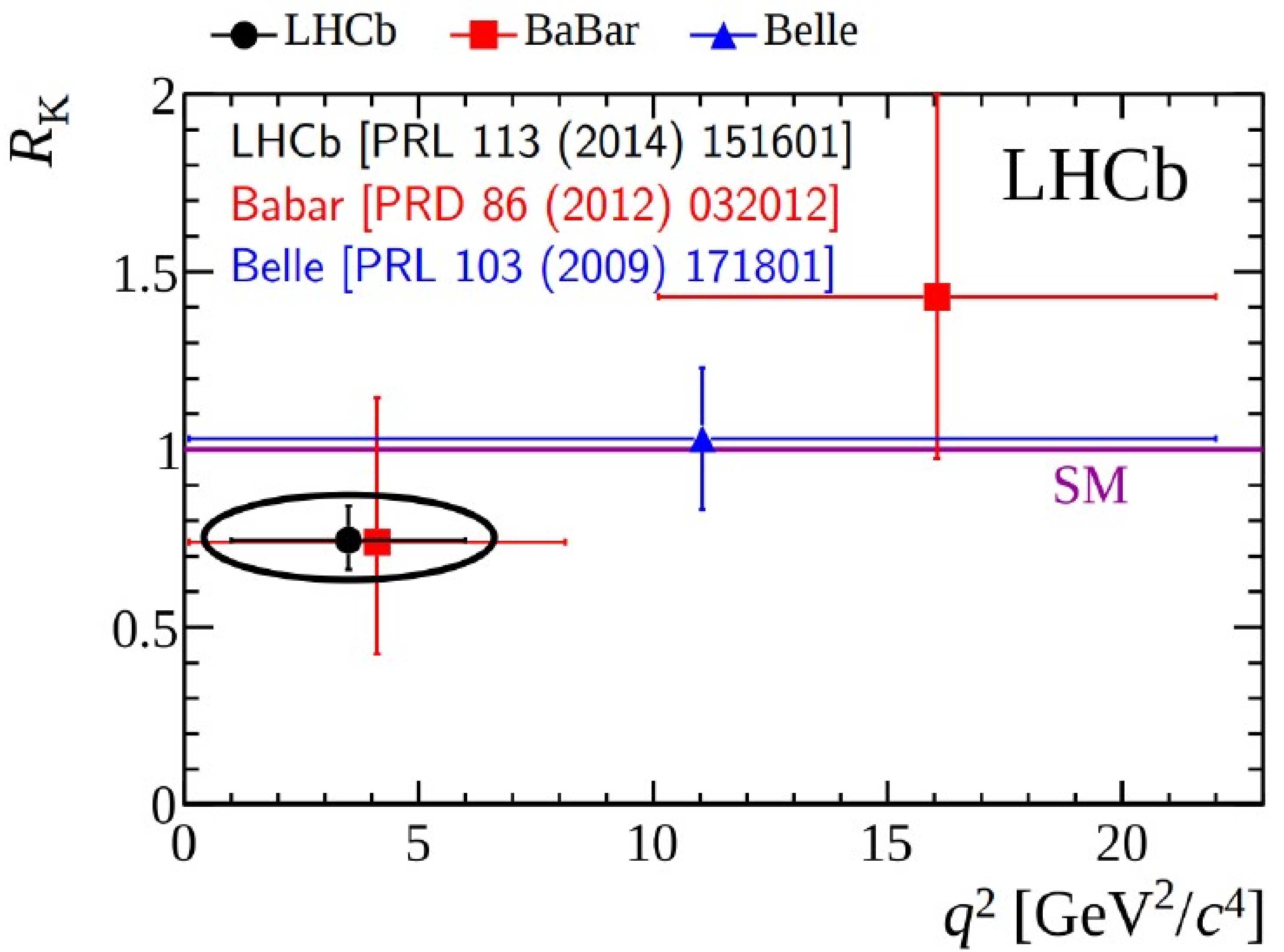
$$R_{K^*} = \begin{cases} 0.66^{+0.11}_{-0.07}(\text{stat}) \pm 0.03(\text{syst}), & \text{at low } q^2 \ (\sim 2.2\sigma \text{ below SM}) \\ 0.69^{+0.11}_{-0.07}(\text{stat}) \pm 0.05(\text{syst}), & \text{at central } q^2 \ (\sim 2.4\sigma \text{ below SM}) \end{cases}$$

JHEP 08 (2017) 055

- Most precise measurement to date
- Compatible with BaBar and Belle
- Statistically limited by the electron sample

BIP [EPJC 76 (2016) 440]
CDHMV [JHEP 04 (2017) 016]
EOS [PRD 95 (2017) 035029]
flav.io [EPJC 77 (2017) 377]
JC [PRD 93 (2016) 014028]
BaBar [PRD 86 (2012) 032012]
Belle [PRL 103 (2009) 171801]

R_K results

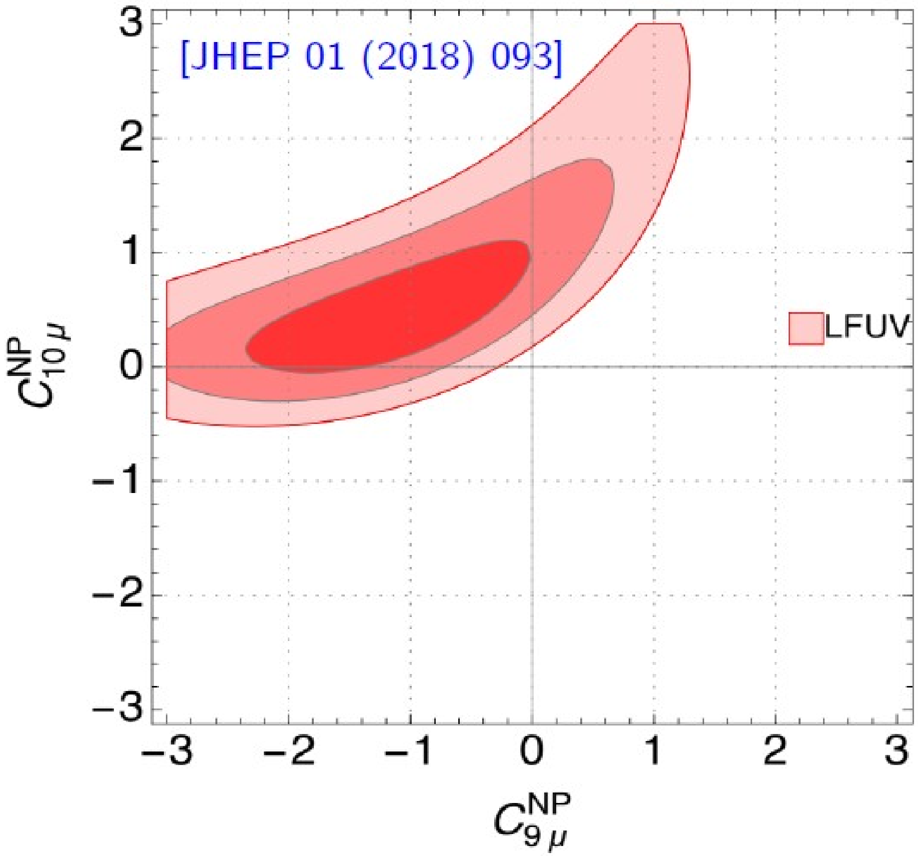


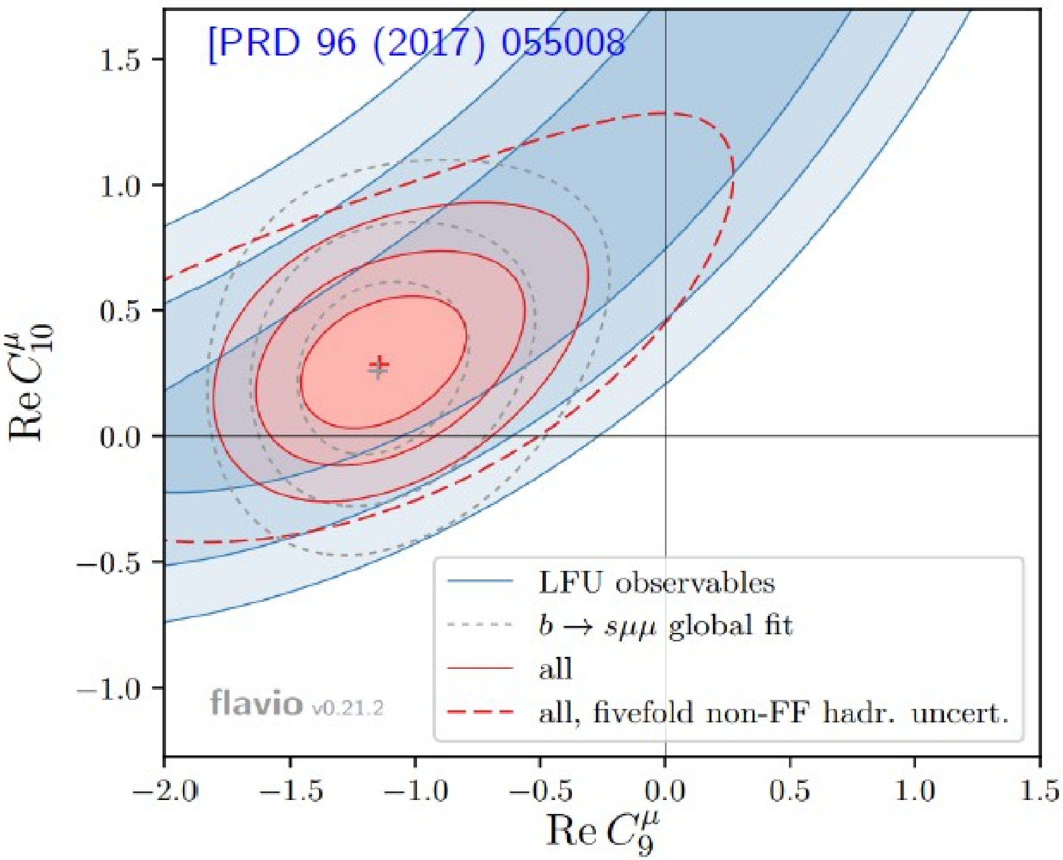
Phys. Rev. Lett. 113, 151601 (2014)

$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)}$$ in central q^2 region $[1,6]\mathrm{GeV}^2/c^4$

$$R_K = 0.745^{+0.090}_{-0.074}(\mathrm{stat}) \pm 0.036(\mathrm{syst}) \sim 2.6\sigma \text{ below SM}$$

$R_{K(*)}$ combination



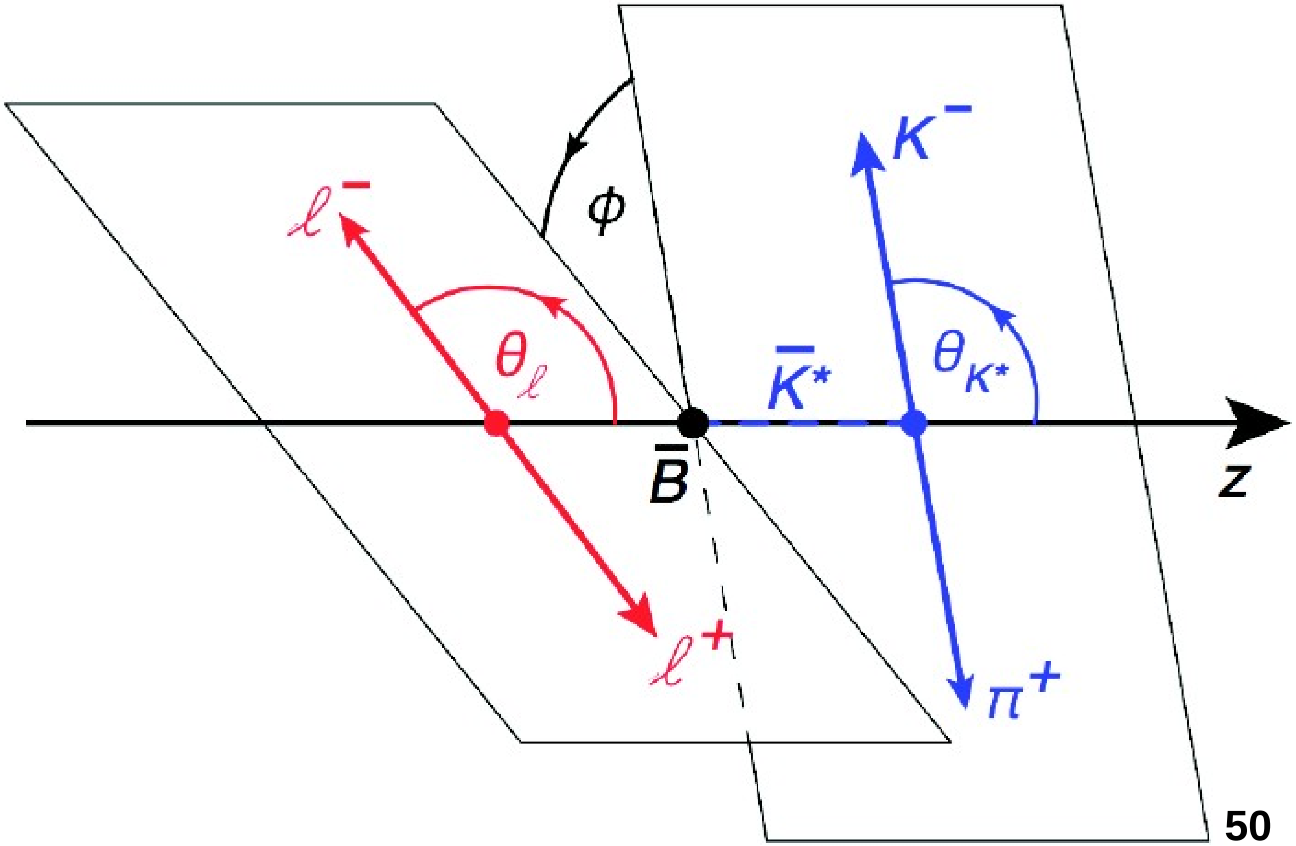


- Combination of R_{K^*} , R_K and [PRL 118 (2017) 111801] is ~4σ from SM
- $b \to s\mu^+\mu^-$ BR and angular obs. are in agreement with LFU tests
- Considered together the tension with SM further increases

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

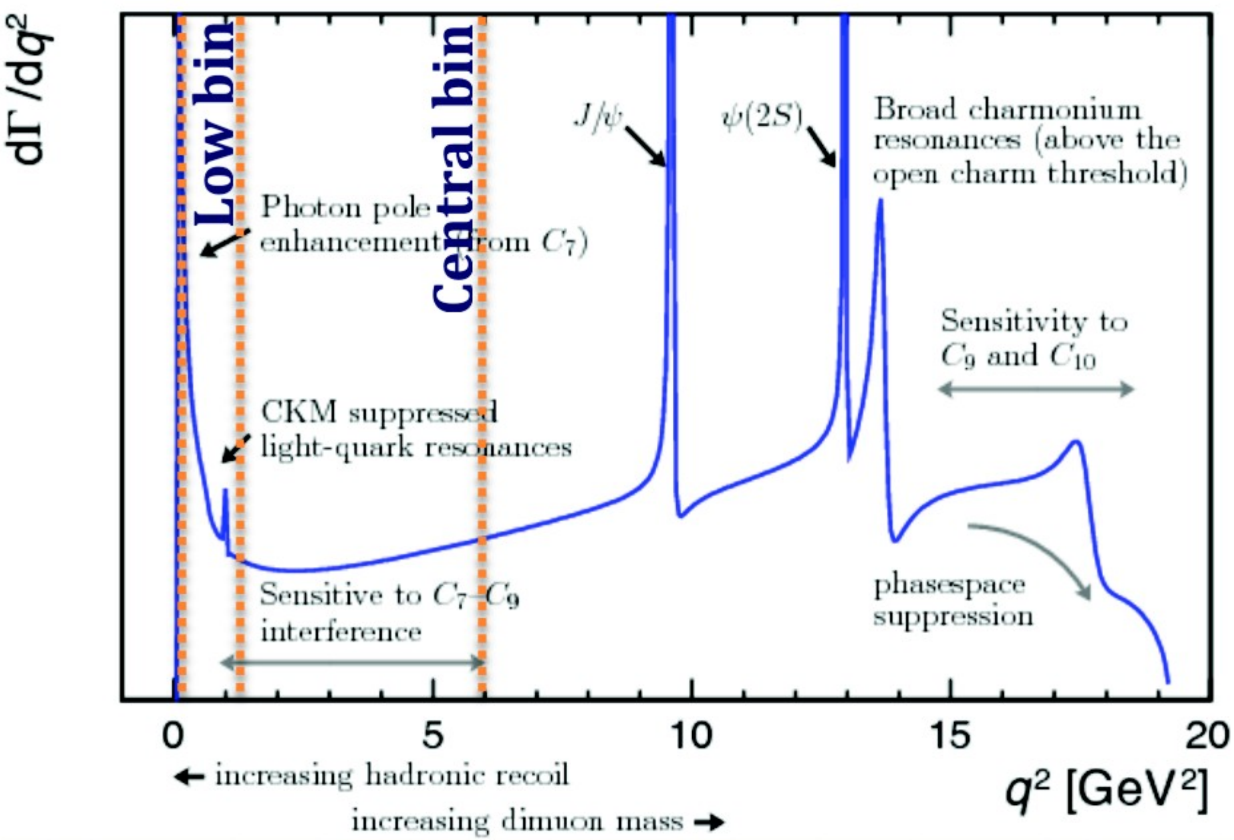
NP models which explain the observed discrepancies in the measurement of R(K(*)) w.r.t SM predictions, foresee anomalous behaviors also in the angular distribution of the decay $B^0 \rightarrow K^{*0}\mu^+\mu^-$

Decay amplitude can be described using q^2 and three angles: θ_l, θ_K, ϕ:



Decay amplitude of $B^0 \to K^{*0}\mu^+\mu^-$

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{d\vec{\Omega}dq^2} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_k + F_L\cos^2\theta_k + \tfrac{1}{4}(1-F_L)\sin^2\theta_k\cos 2\theta_\ell - F_L\cos^2\theta_k\cos 2\theta_\ell + S_3\sin^2\theta_k\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_k\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_k\sin\theta_\ell\cos\phi + \tfrac{4}{3}A_{FB}\sin^2\theta_k\cos\theta_\ell + S_7\sin 2\theta_k\sin\theta_\ell\sin\phi + S_8\sin 2\theta_k\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_k\sin^2\theta_\ell\sin 2\phi\Big],$$



The P_5' anomaly

- Angular observable: $P_5' \equiv S_5/\sqrt{F_L(1-F_L)}$

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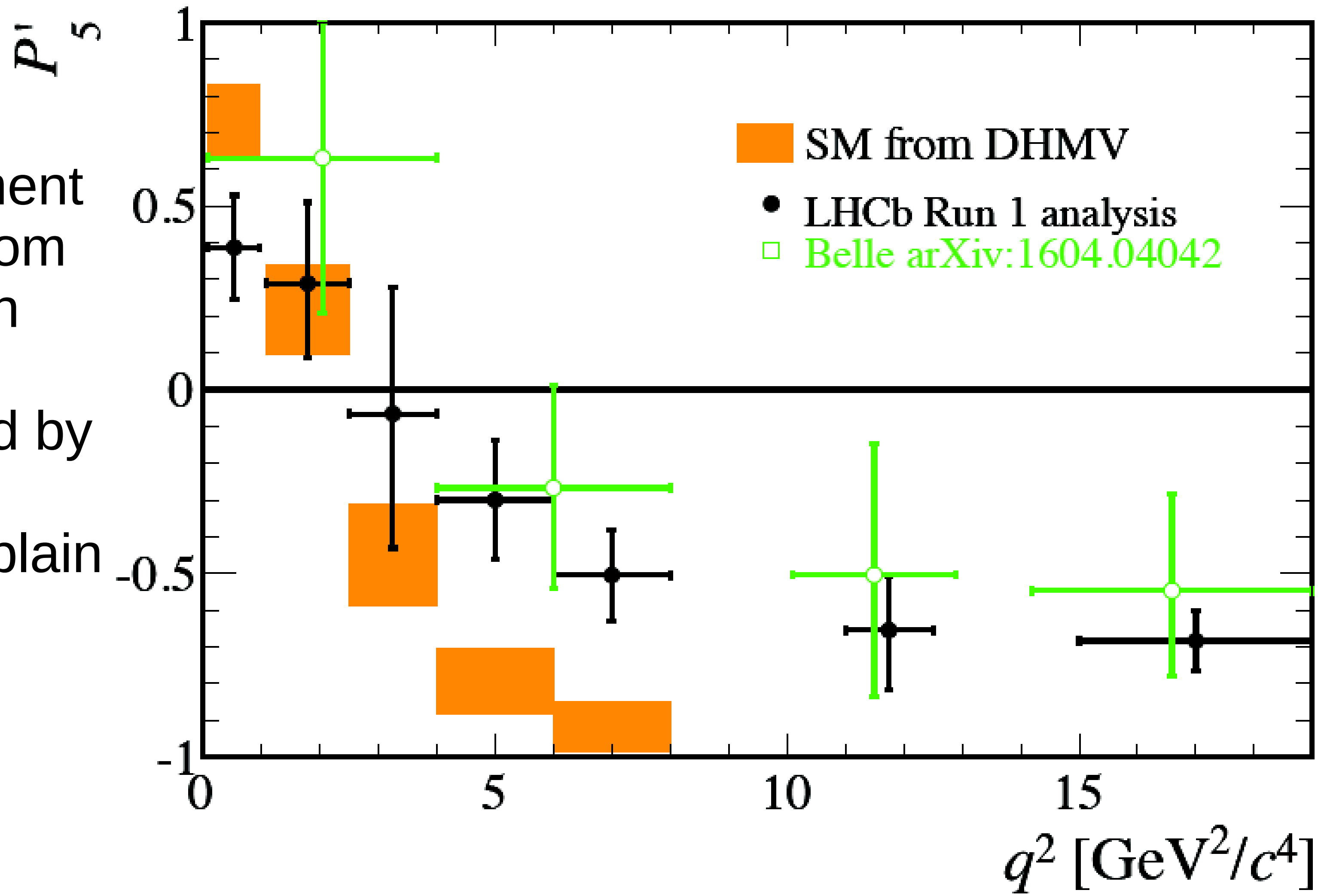
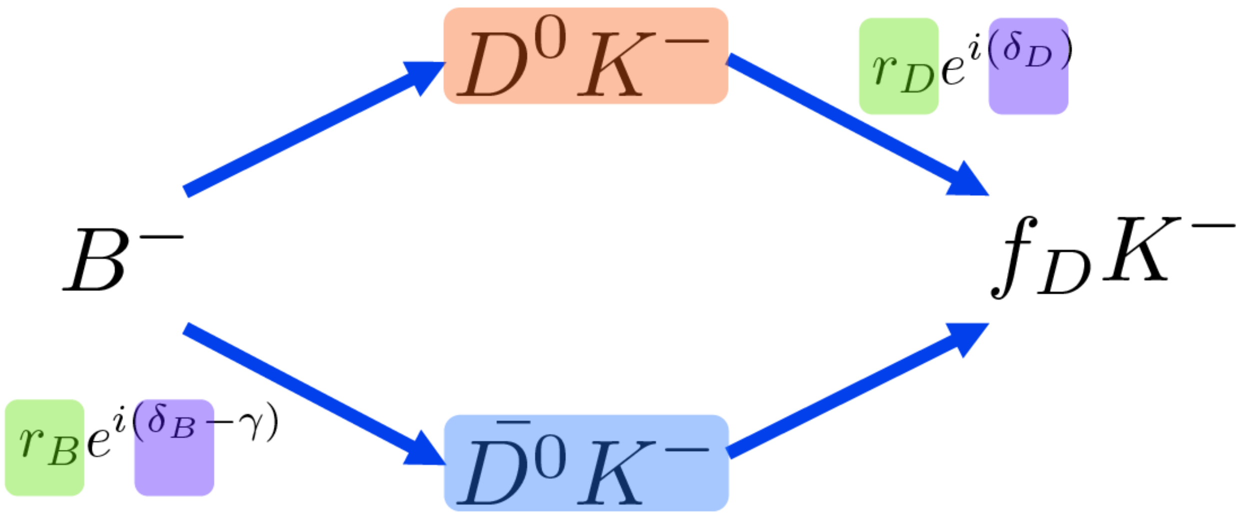
- LHCb measurement differs by 3.4σ from the SM prediction

- Can be explained by
 - SM charm-loop effects (cannot explain tension in R_{K*})
 - New Physics

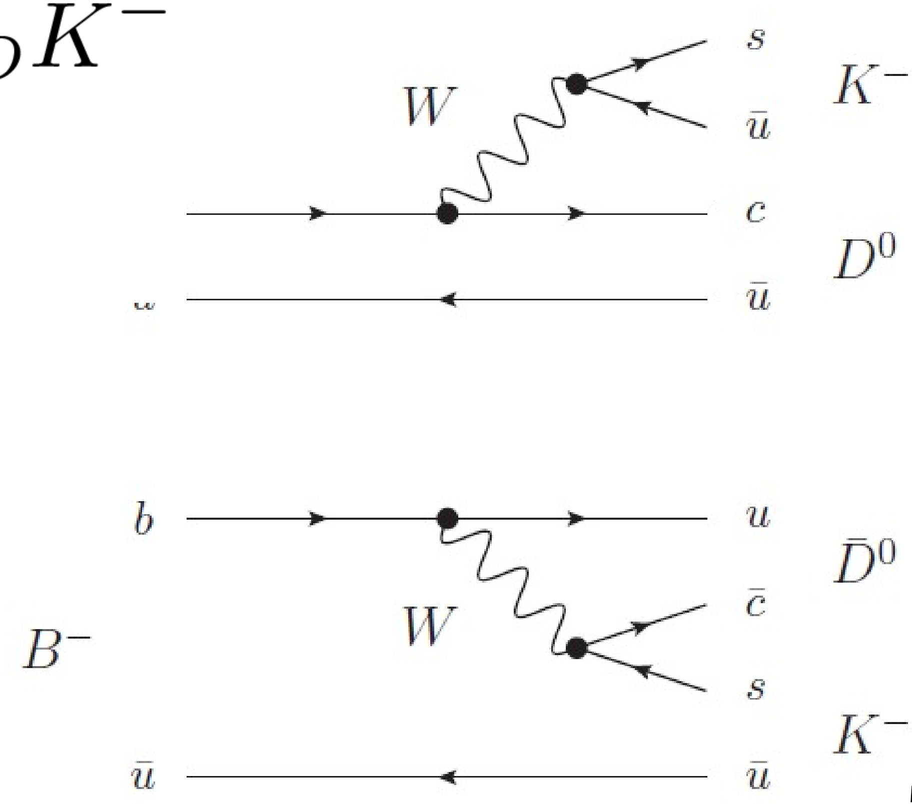


How to measure γ

Two amplitudes $b \to cW(\bar{u}s)$ $[B^- \to D^0 K^-]$ and $b \to uW(\bar{c}s)$ $[B^- \to \bar{D}^0 K^-]$ give same final state when both D and $\bar{D}$ decay to a common final state. No penguin contribution ⇒ theoretically clean.



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



- Amplitude ratios: r_B, r_D
- Strong phases: δ_B, δ_D

Experimental methods

- GLW (Gronau, London, Wyler) [1991]: $D \to K^+K^-, \pi^+\pi^-$

$$A_{CP} = \frac{\Gamma(B^- \to D_{CP} K^-) - \Gamma(B^+ \to D_{CP} K^+)}{\Gamma(B^- \to D_{CP} K^-) + \Gamma(B^+ \to D_{CP} K^+)} = \frac{2 r_B \sin(\delta_B + \delta_D) \sin\gamma}{1 + r_B^2 + 2 r_B \cos(\delta_B + \delta_D) \cos\gamma}$$

- ADS (Atwood, Dunietz, Soni) [1997,2001]: $D \to K^+\pi^-$

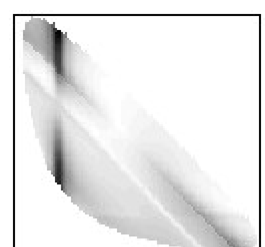
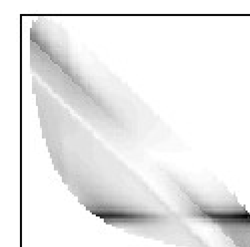
$$A_{CP} = \frac{\Gamma(B^- \to [K^+\pi^-] K^-) - \Gamma(B^+ \to [K^-\pi^+] K^+)}{\Gamma(B^- \to [K^+\pi^-] K^-) + \Gamma(B^+ \to [K^-\pi^+] K^+)} = \frac{2 r_B r_D \sin(\delta_B + \delta_D) \sin\gamma}{r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D) \cos\gamma}$$

- GGSZ (Giri, Grossman, Soer, Zupan) [2003]: $D \to K^0_S\pi^+\pi^-$

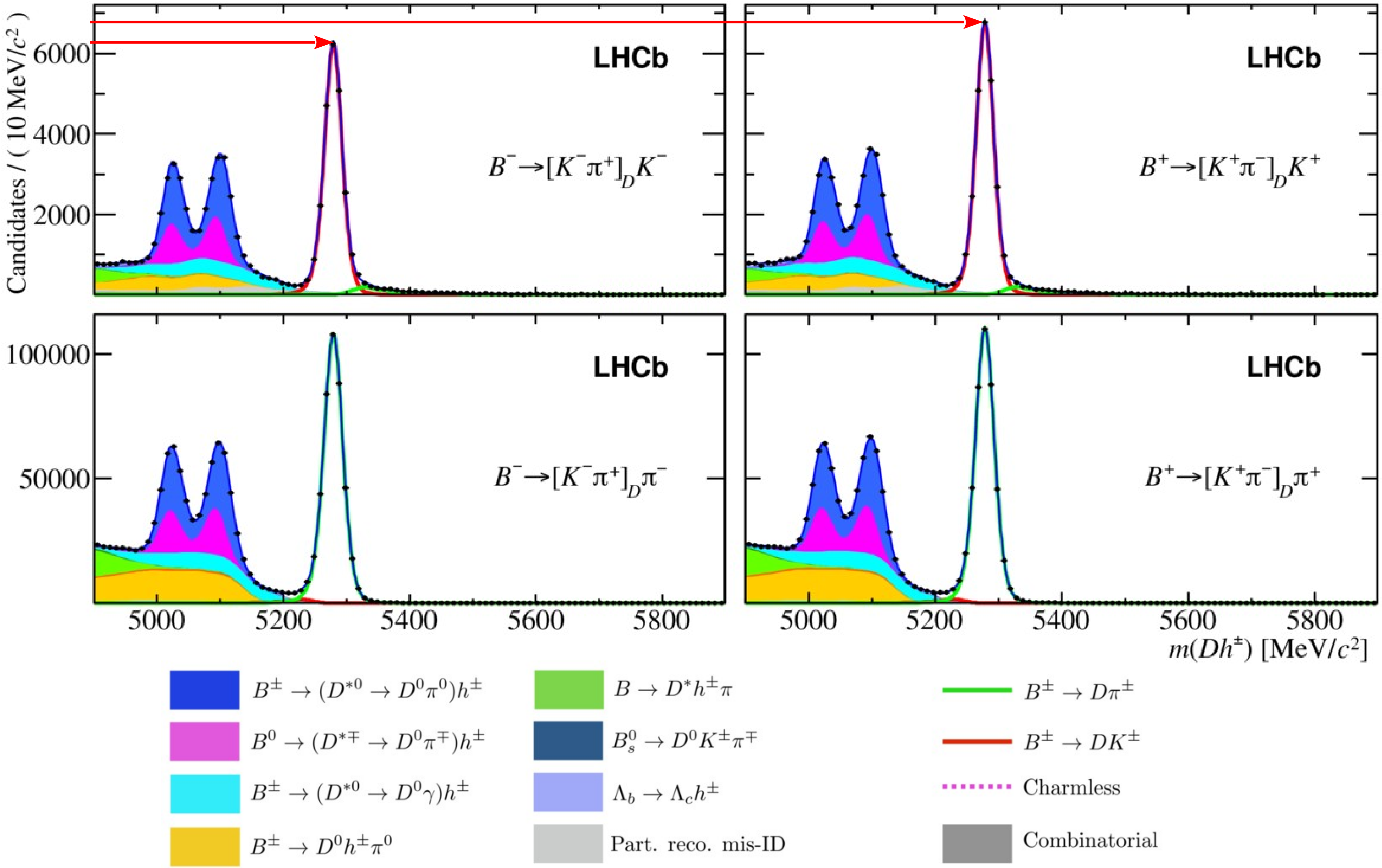
Dalitz plot $D \to K_S^0\pi^+\pi^-$ $\quad d\sigma(m_+^2, m_-^2) \sim |A|^2 dm_+^2\, dm_-^2$, $\quad m_\pm^2 = m^2(K_S^0\pi^\pm)$,

D^0 amplitude: $A_D(m_+^2, m_-^2)$, $\overline{D}^0$ amplitude: $\overline{A}_D(m_-^2, m_+^2)$

Amplitude of $D \to K_S^0\pi^+\pi^-$ from $B^+ \to DK^+$:

$A_D(m_+^2, m_-^2) + r_B e^{i\delta B + i\gamma} A_D(m_-^2, m_+^2)$ $=$  $+ r_B e^{i\delta_B + i\gamma}$ 

ADS: $B^{\pm} \to D^{(*)}K^{\pm}$ and $B^{\pm} \to D^{(*)}\pi^{\pm}$



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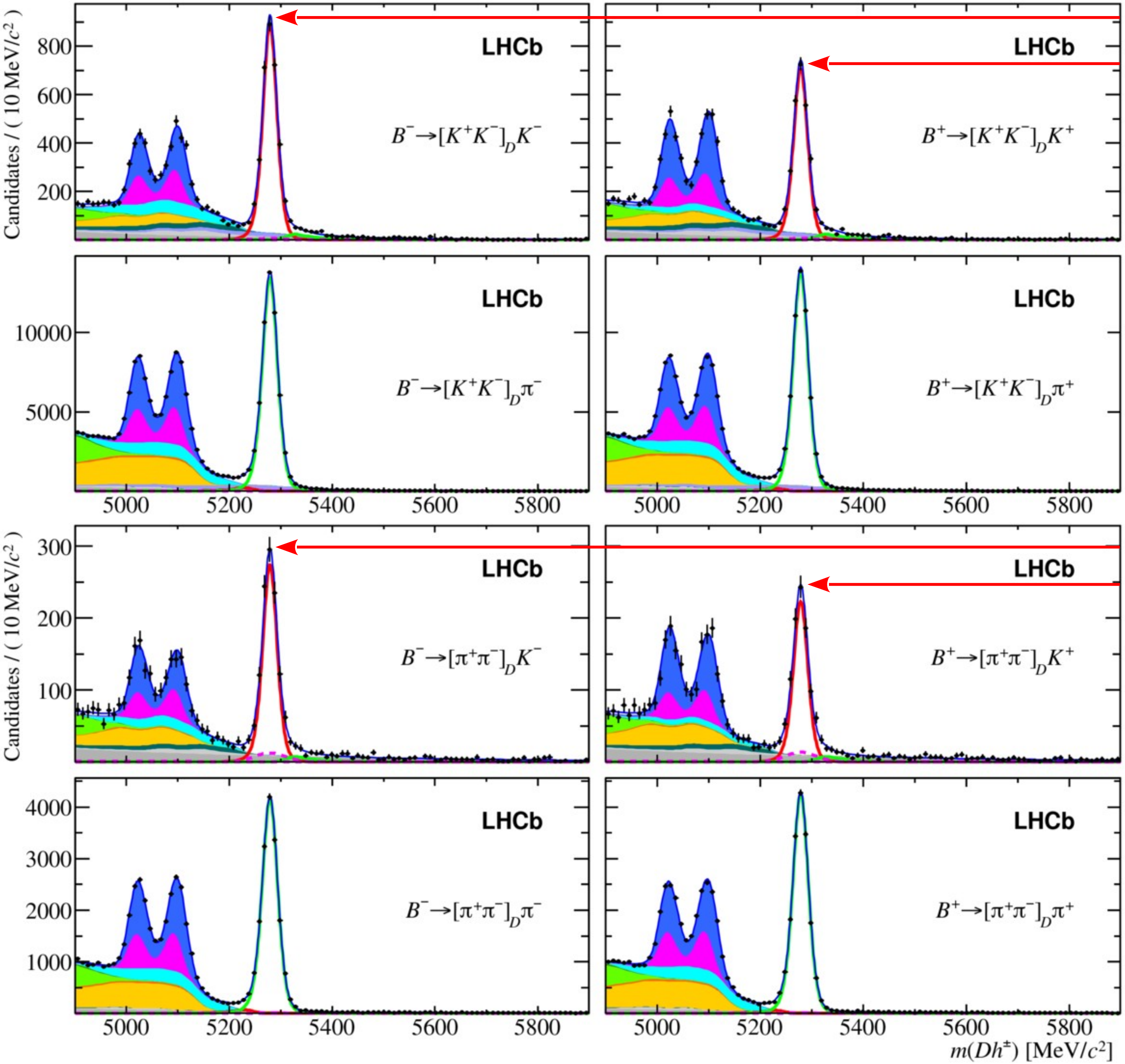
GLW: $B^{\pm} \to D^{(*)}K^{\pm}$ and $B^{\pm} \to D^{(*)}\pi^{\pm}$



Dataset:
1.0 fb^{-1} @ $\sqrt{s}$=7 TeV
2.0 fb^{-1} @ $\sqrt{s}$=8 TeV
2.0 fb^{-1} @ $\sqrt{s}$=13TeV

$A = A_{CP} + A_{det} + A_{prod}$

$R_{CP} = 0.989 \pm 0.013 \pm 0.010$

$A_{CP} = +0.124 \pm 0.012 \pm 0.002$

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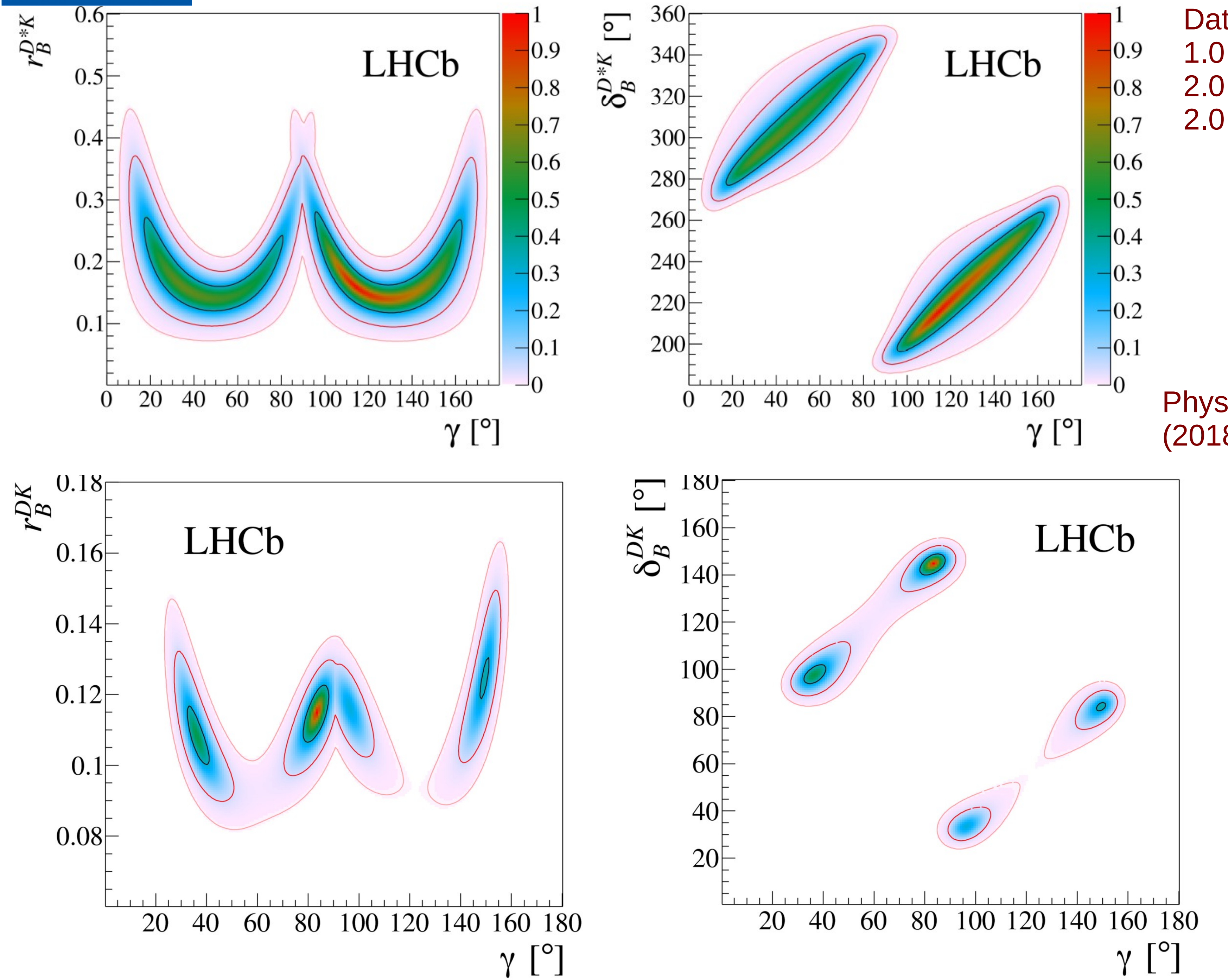
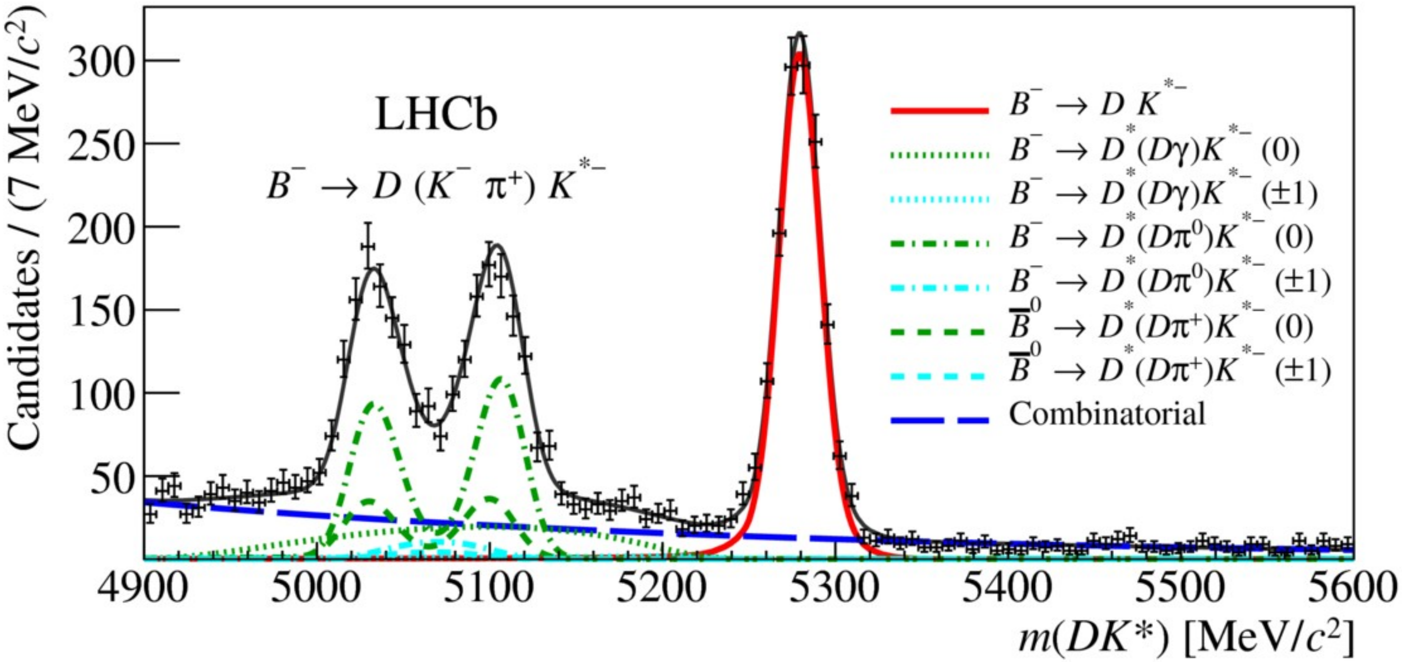
Results: $B^\pm \to D^{(*)}K^\pm$ and $B^\pm \to D^{(*)}\pi^\pm$

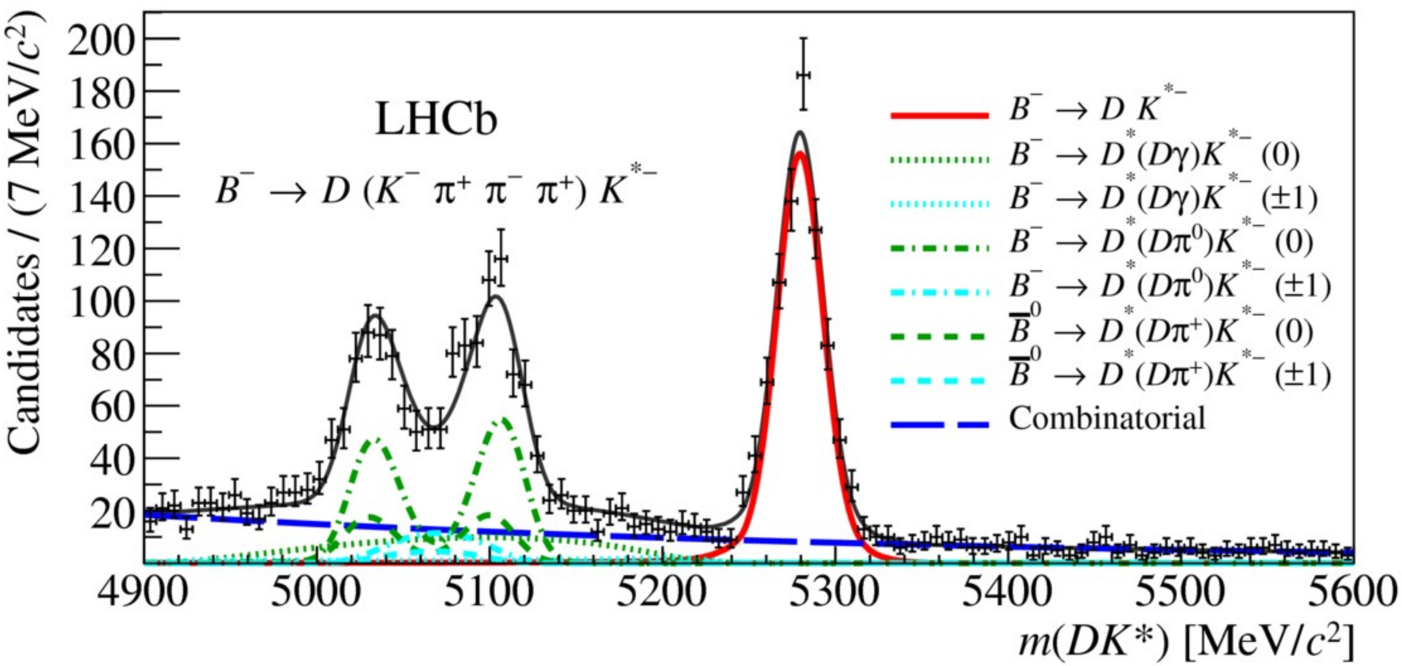


Dataset:
1.0 fb^{-1} @ √s=7 TeV
2.0 fb^{-1} @ √s=8 TeV
2.0 fb^{-1} @ √s=13TeV

Physics Letters B 777 (2018) 16-30

$B^\pm \to DK^{*\pm}$





Dataset:
1.0 fb^{-1} @ $\sqrt{s}$=7 TeV
2.0 fb^{-1} @ $\sqrt{s}$=8 TeV
1.8 fb^{-1} @ $\sqrt{s}$=13TeV

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ADS: $B^{\pm} \rightarrow DK^{*\pm}$

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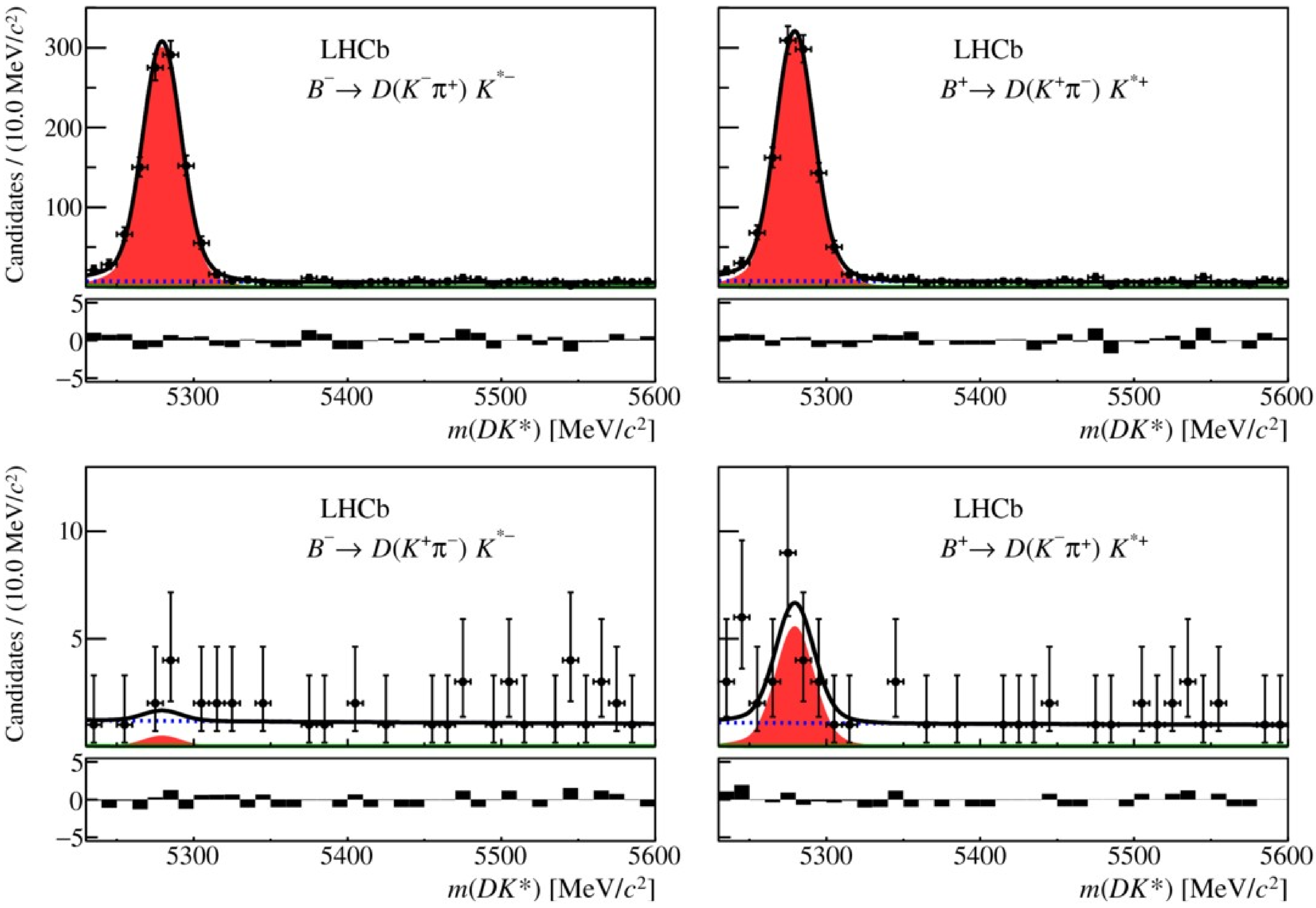

GLW: $B^{\pm} \rightarrow DK^{*\pm}$

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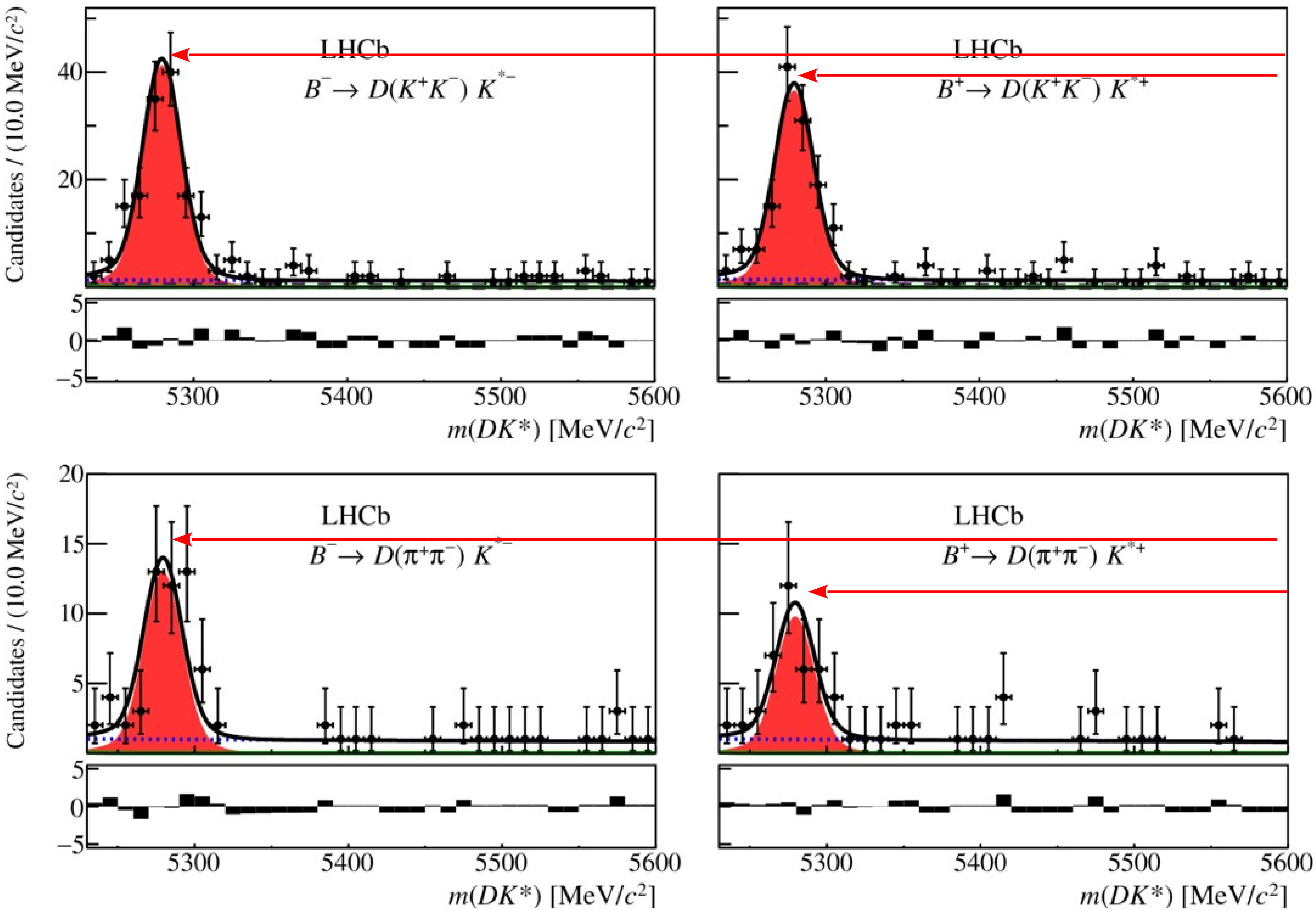

Results: $B^{\pm} \to DK^{*\pm}$

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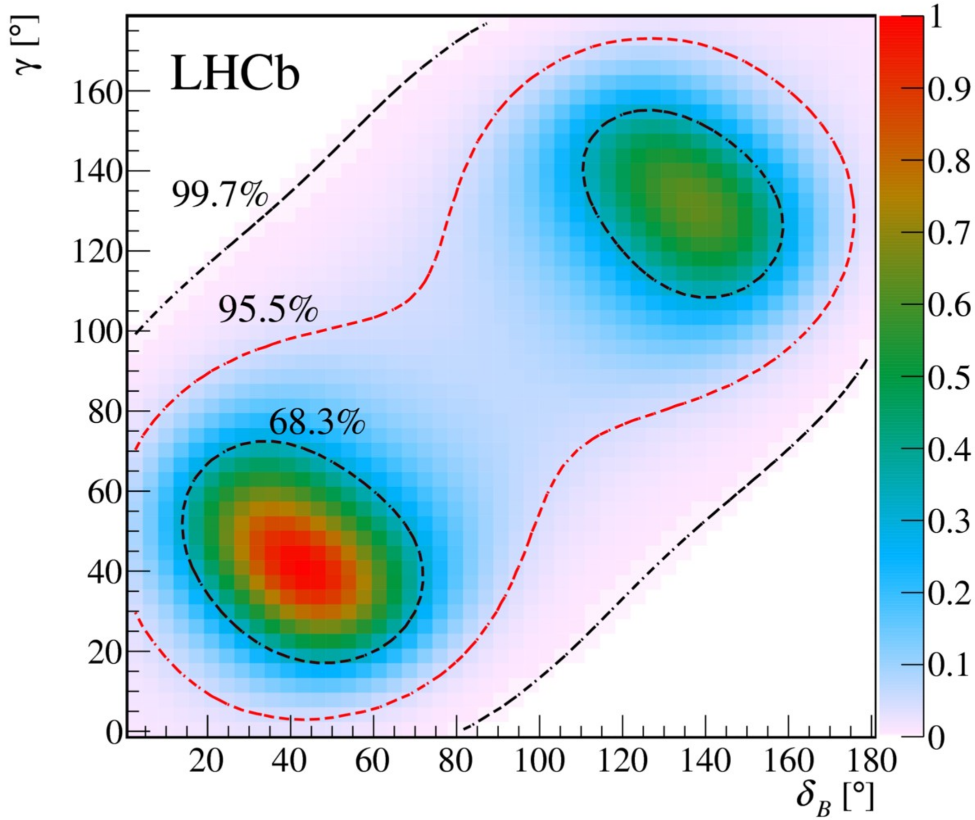
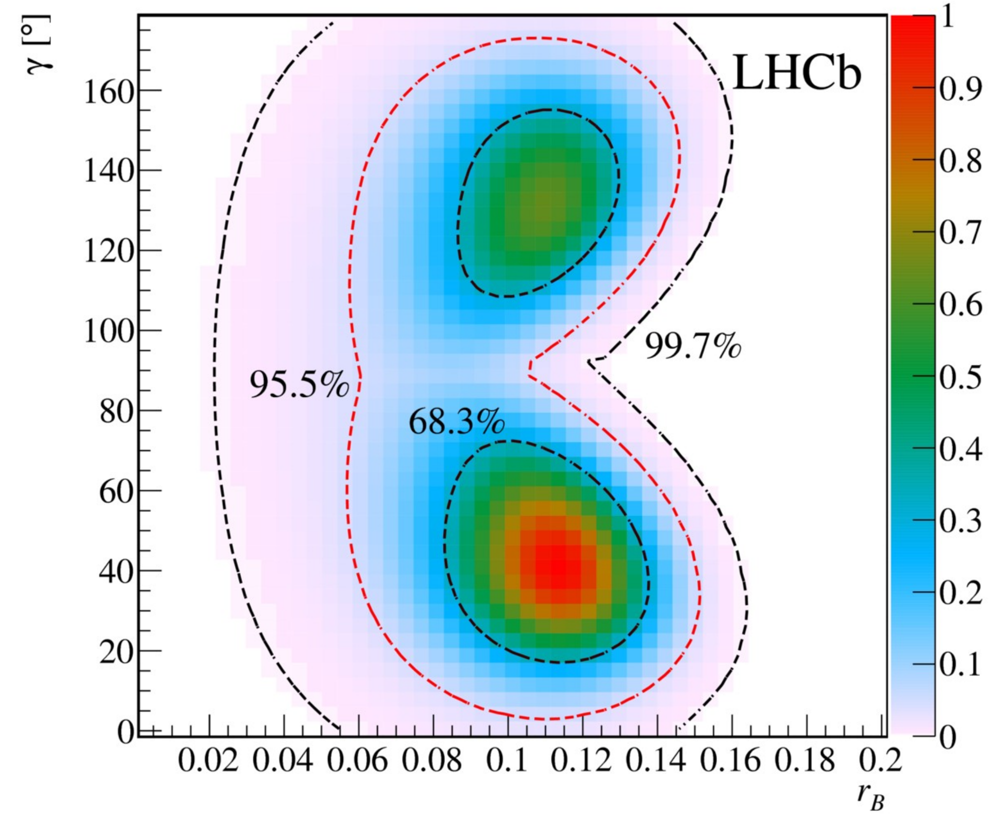




$R_{CP+} = 1.18 \pm 0.08 \pm 0.02$

$A_{CP+} = +0.08 \pm 0.06 \pm 0.01$

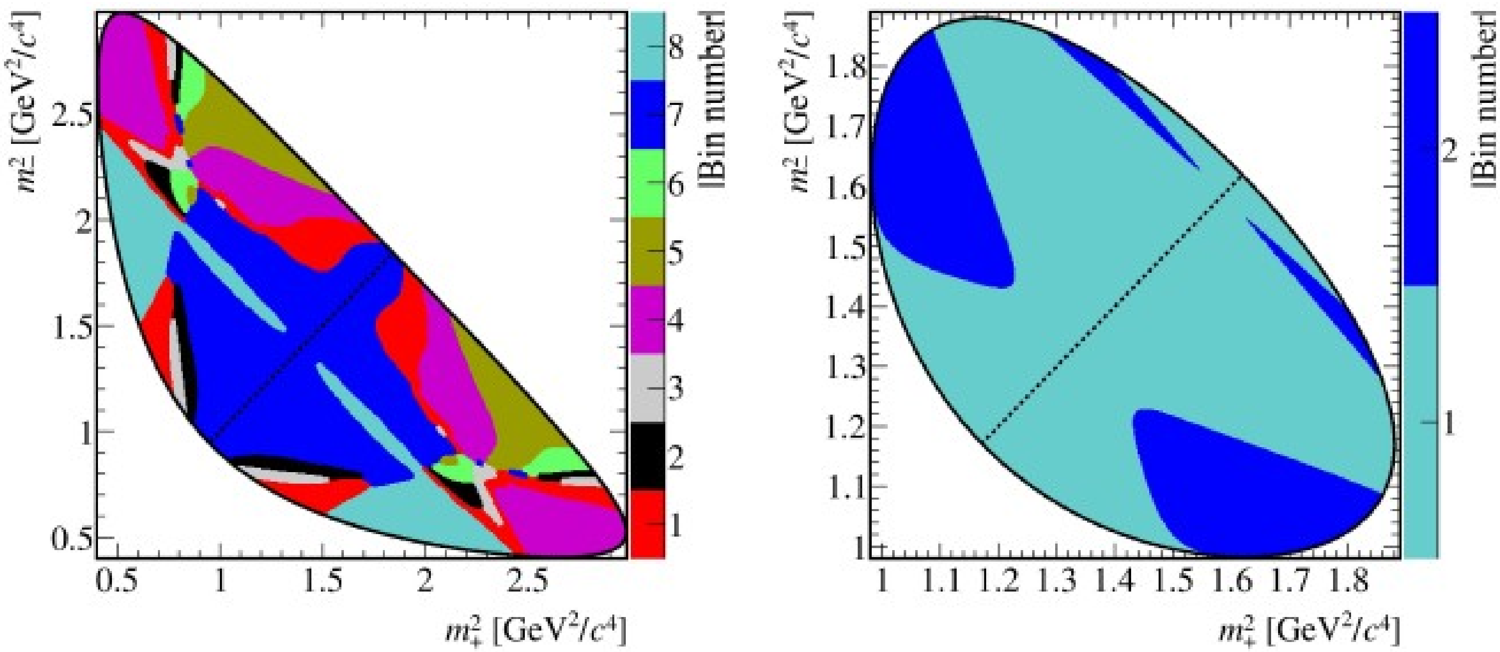
$R^{k\pi}_{ADS} = 0.0011 \pm 0.004 \pm 0.001$

$A^{k\pi}_{ADS} = -0.81 \pm 0.17 \pm 0.04$

$R^{k\pi\pi\pi}_{ADS} = 0.0011 \pm 0.005 \pm 0.003$

$A^{k\pi\pi\pi}_{ADS} = -0.45 \pm 0.21 \pm 0.14$

GGSZ method



Dataset:
1.0 fb^{-1} @ √s=7 TeV
2.0 fb^{-1} @ √s=8 TeV
2.0 fb^{-1} @ √s=13TeV

$x_\pm \equiv r_B \cos(\delta_B \pm \gamma)$ and $y_\pm = r_B \sin(\delta_B \pm \gamma)$

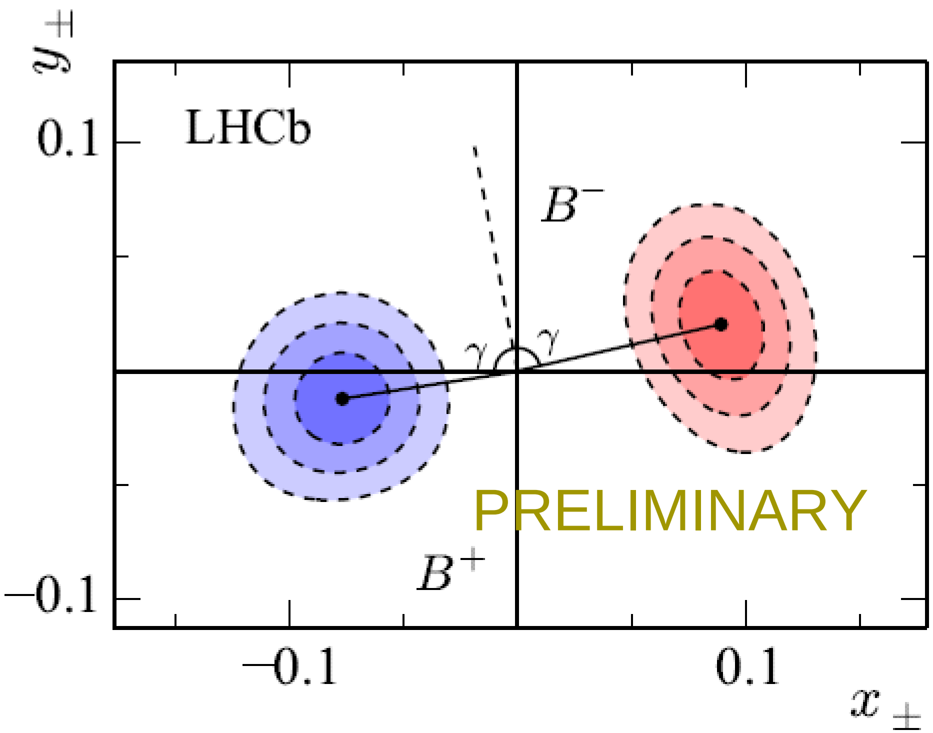
$$N_{\pm i}^{+} = h_{B^+}\left[F_{\mp i} + (x_+^2 + y_+^2)F_{\pm i} + 2\sqrt{F_i F_{-i}}(x_+ c_{\pm i} - y_+ s_{\pm i})\right]$$
$$N_{\pm i}^{-} = h_{B^-}\left[F_{\pm i} + (x_-^2 + y_-^2)F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_- c_{\pm i} + y_- s_{\pm i})\right]$$

$$F_i = \frac{\int_i dm_-^2\, dm_+^2\, |A_D(m_-^2, m_+^2)|^2\, \eta(m_-^2, m_+^2)}{\sum_j \int_j dm_-^2\, dm_+^2\, |A_D(m_-^2, m_+^2)|^2\, \eta(m_-^2, m_+^2)}$$

$$\overset{(-)}{B} \to D^{*\pm}\mu^{\mp}\overset{(-)}{\nu}_\mu,\ D^{*\pm} \to \overset{(-)}{D}\pi^{\pm},\ \overset{(-)}{D} \to K_S^0 h^+ h^-$$

LHCb paper 2018-017

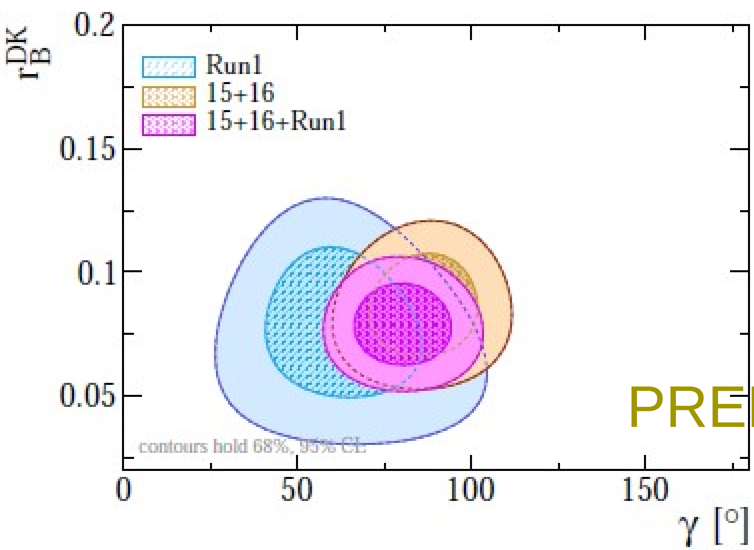
GGSZ results

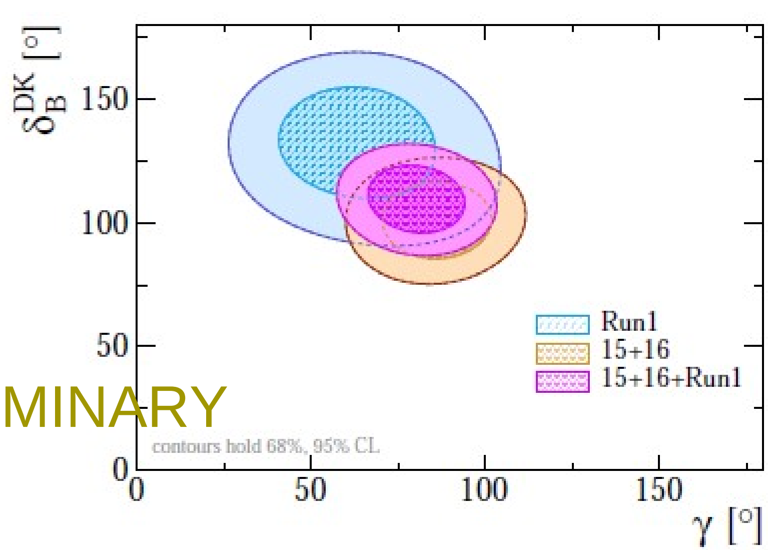


$$x_- = (\;\;9.0 \pm 1.7 \pm 0.7 \pm 0.4) \times 10^{-2},$$
$$y_- = (\;\;2.1 \pm 2.2 \pm 0.5 \pm 1.1) \times 10^{-2},$$
$$x_+ = (-7.7 \pm 1.9 \pm 0.7 \pm 0.4) \times 10^{-2},$$
$$y_+ = (-1.0 \pm 1.9 \pm 0.4 \pm 0.9) \times 10^{-2},$$

PRELIMINARY

$$\gamma = 87^\circ\,{}^{+11^\circ}_{-12^\circ}\,({}^{+22^\circ}_{-23^\circ}),$$
$$r_B = 0.087^{+0.013}_{-0.014}({}^{+0.025}_{-0.027}),$$
$$\delta_B = 101^\circ\,{}^{+11^\circ}_{-11^\circ}\,({}^{+22^\circ}_{-23^\circ}).$$



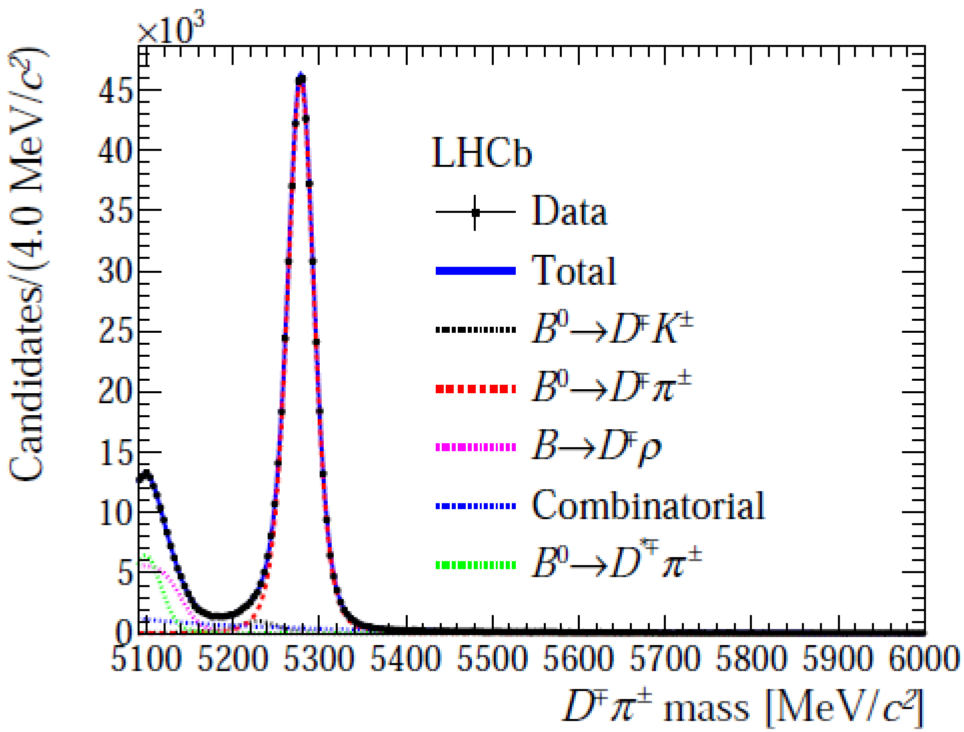


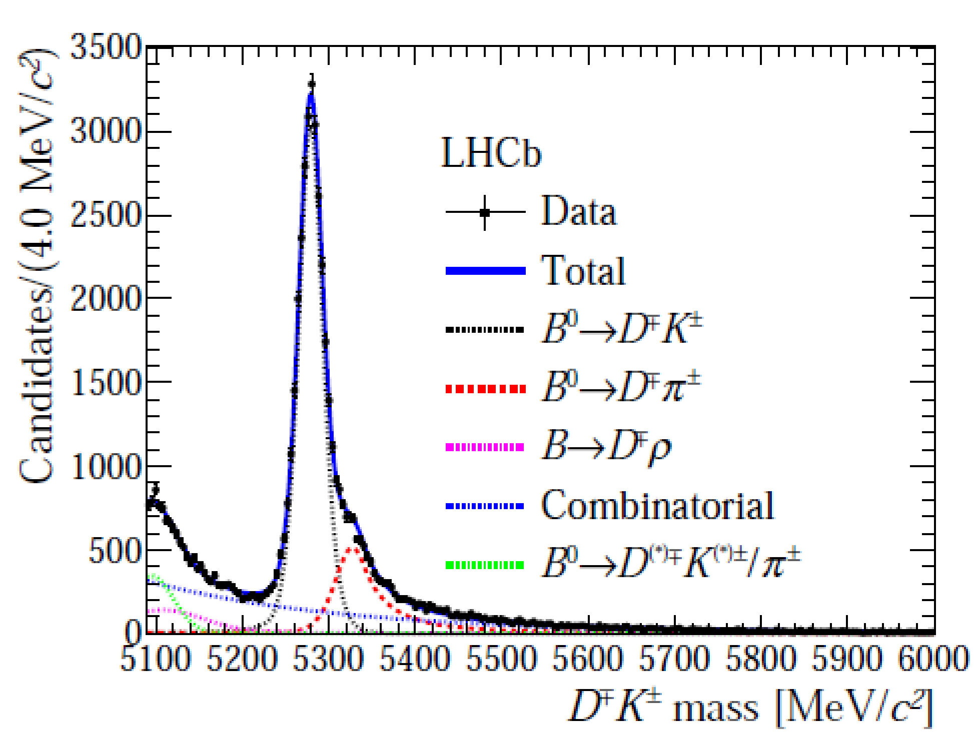
LHCb paper 2018-017

Measurement of CP violation in $B^0 \to D^{\mp}\pi^{\pm}$

$$\Gamma_{B^0\to f}(t) \propto e^{-\Gamma t}\left[1 + C_f\cos(\Delta m\, t) - S_f\sin(\Delta m\, t)\right] ,$$
$$\Gamma_{B^0\to \bar{f}}(t) \propto e^{-\Gamma t}\left[1 + C_{\bar{f}}\cos(\Delta m\, t) - S_{\bar{f}}\sin(\Delta m\, t)\right] ,$$

$$C_f = \frac{1 - r_{D\pi}^2}{1 + r_{D\pi}^2} = -C_{\bar{f}} ,$$
$$S_f = -\frac{2r_{D\pi}\sin\left[\delta - (2\beta + \gamma)\right]}{1 + r_{D\pi}^2} ,$$
$$S_{\bar{f}} = \frac{2r_{D\pi}\sin\left[\delta + (2\beta + \gamma)\right]}{1 + r_{D\pi}^2} ,$$



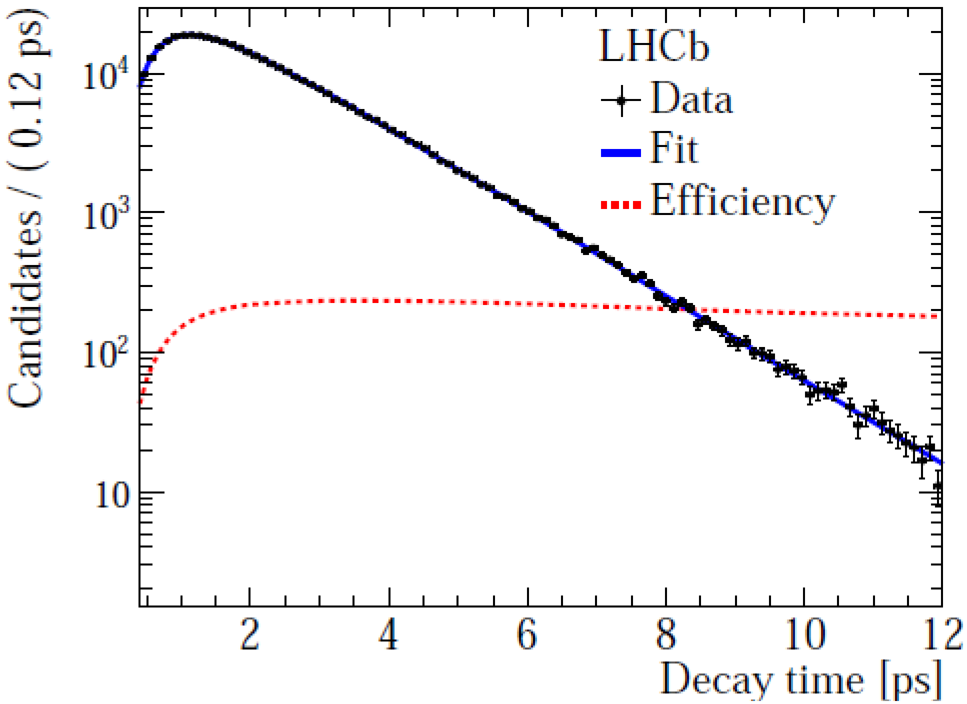


Dataset:
1.0 fb^{-1} @ $\sqrt{s}$=7 TeV
2.0 fb^{-1} @ $\sqrt{s}$=8 TeV

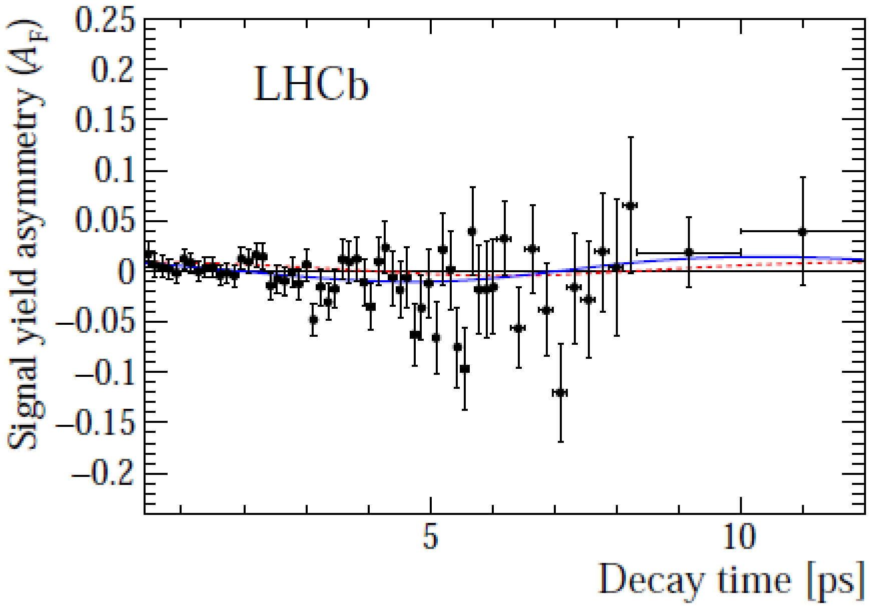
arXiv:1805.03448

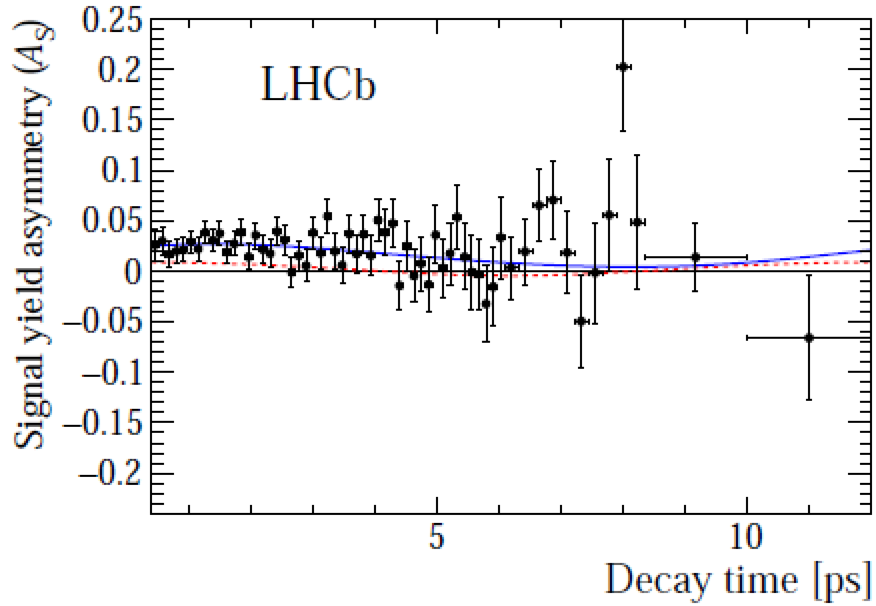
Measurement of CP violation in $B^0 \to D^{\mp}\pi^{\pm}$

arXiv:1805.03448

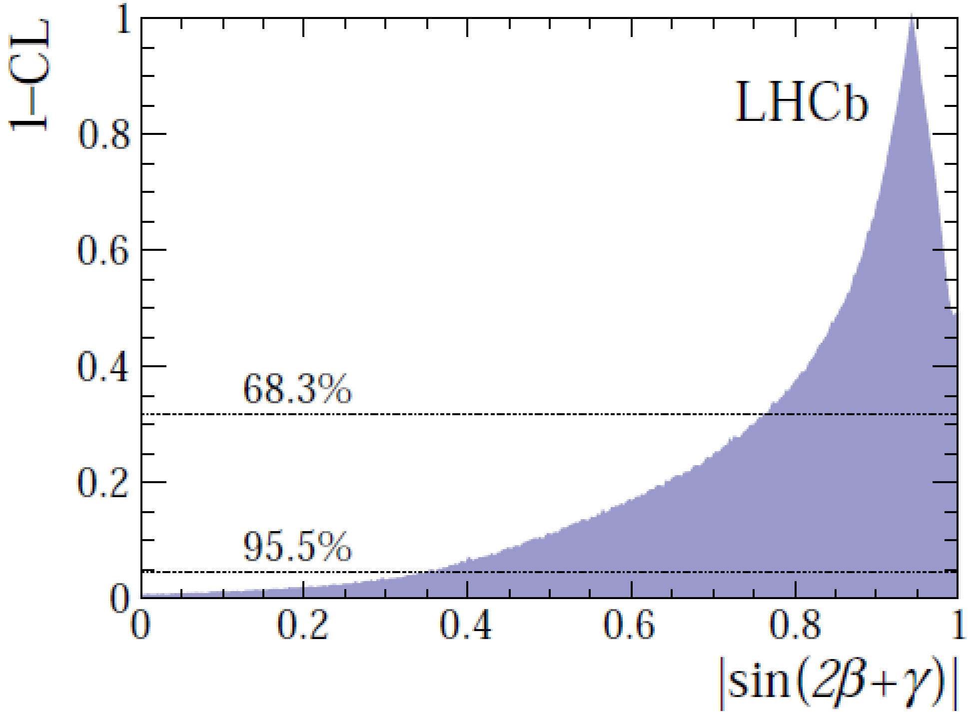


$$S_f = 0.058 \pm 0.020\,(\text{stat}) \pm 0.011\,(\text{syst}),$$
$$S_{\bar{f}} = 0.038 \pm 0.020\,(\text{stat}) \pm 0.007\,(\text{syst}),$$



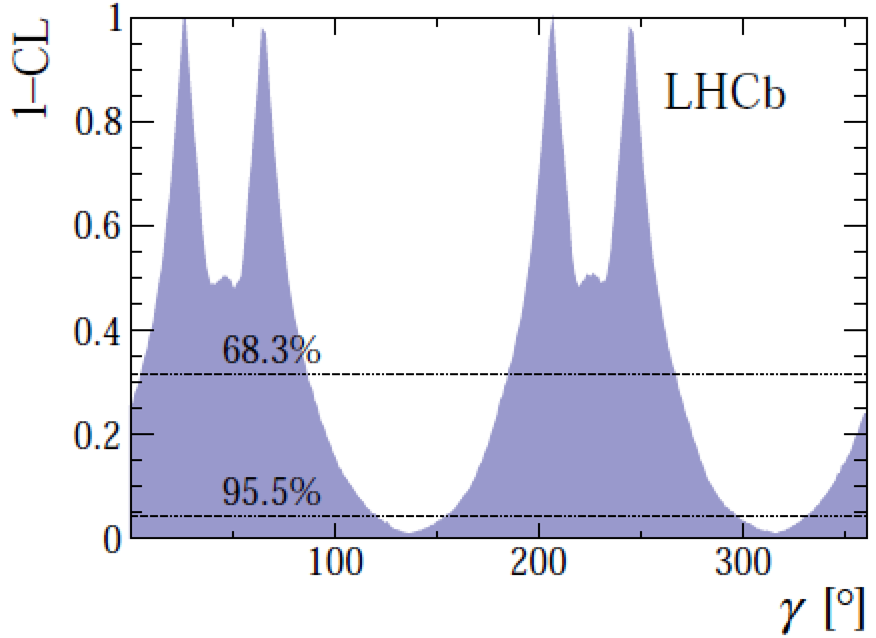


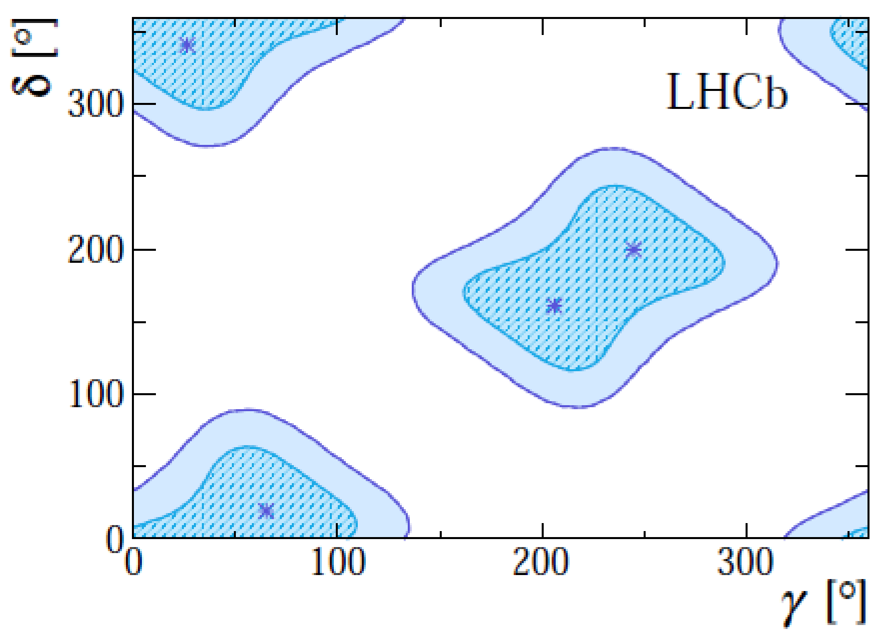
Measurement of CP violation in $B^0 \to D^{\mp}\pi^{\pm}$



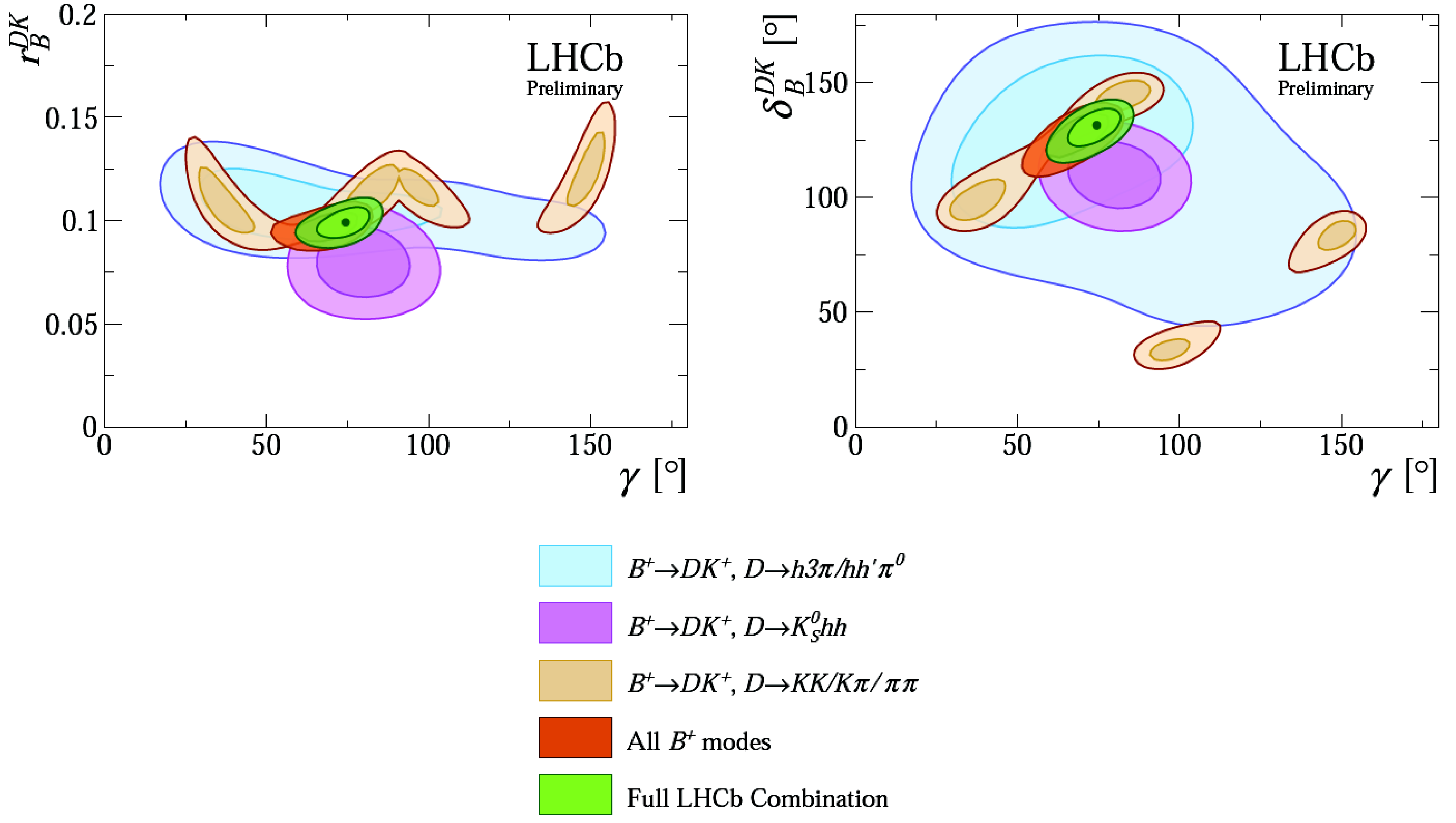
arXiv:1805.03448

$$|\sin(2\beta+\gamma)| \in [0.77, 1.0]\,,$$
$$\gamma \in [5, 86]^\circ \cup [185, 266]^\circ\,,$$
$$\delta \in [-41, 41]^\circ \cup [140, 220]^\circ\,,$$



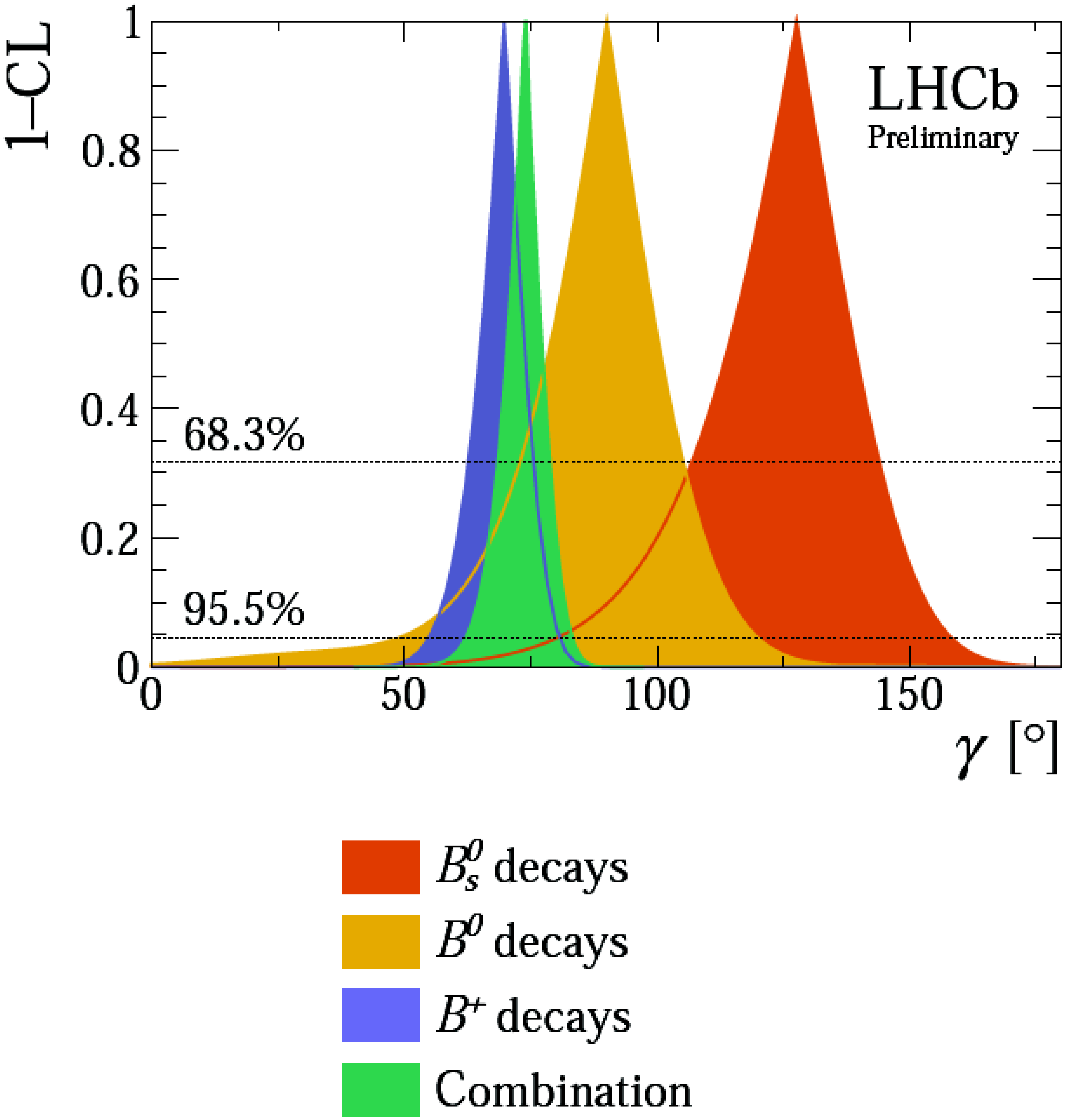


γ combination



LHCb CONF 2018-002

γ combination



$B_s^0 \rightarrow D_s^{\mp} K^{\pm}$ time-dep

$B^0 \rightarrow DK^{*0}$
$B^0 \rightarrow DK^{+}\pi^{-}$
$B^0 \rightarrow D^{\mp}\pi^{\pm}$ time-dep

$B^+ \rightarrow DK^+$
$B^+ \rightarrow D^*K^+$
$B^+ \rightarrow DK^{*+}$
$B^+ \rightarrow DK^+\pi^+\pi^-$

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

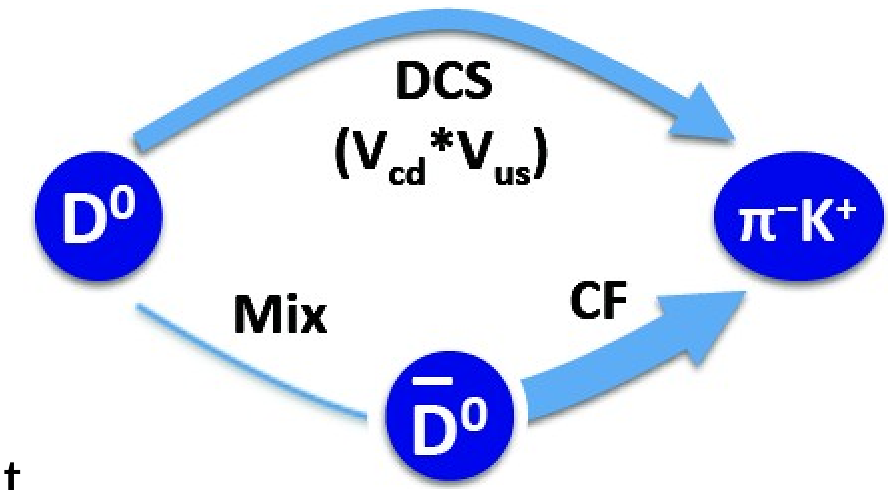
LHCb CONF 2018-002

D^0-$\overline{D}^0$ mixing and CP violation in $D^0 \to K^+\pi^-$

Right-sign (RS) $D^0 \to K^-\pi^+$ is dominated by CF decay

Wrong-sign (WS) $D^0 \to K^+\pi^-$

has two sources:



Mixing amplitude is time-dependent

Ratio $R(t) = \Gamma_{WS}(t)/\Gamma_{RS}(t)$ depends on x and y:

$$R(t) = R_D + \sqrt{R_D}\, y' \left(\frac{t}{\tau}\right) + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2$$

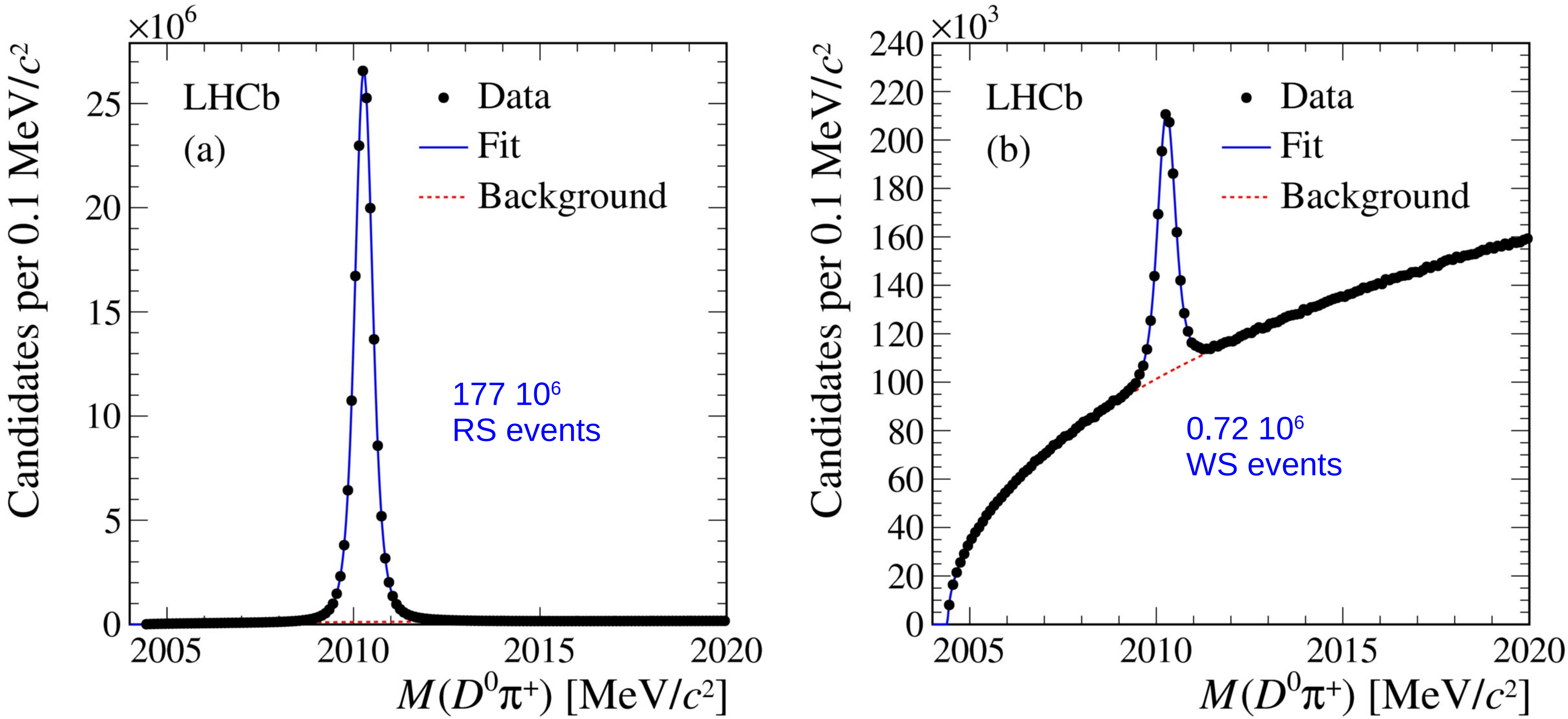
$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

$$R^{\pm}(t) = R_D^{\pm} + \sqrt{R_D^{\pm}}\, y'^{\pm} \left(\frac{t}{\tau}\right) + \frac{x'^{\pm 2} + y'^{\pm 2}}{4} \left(\frac{t}{\tau}\right)^2$$

ICPV: $x'^+ \neq x'^-$
and/or $y'^+ \neq y'^-$

DCPV: $R_D^+ \neq R_D^-$

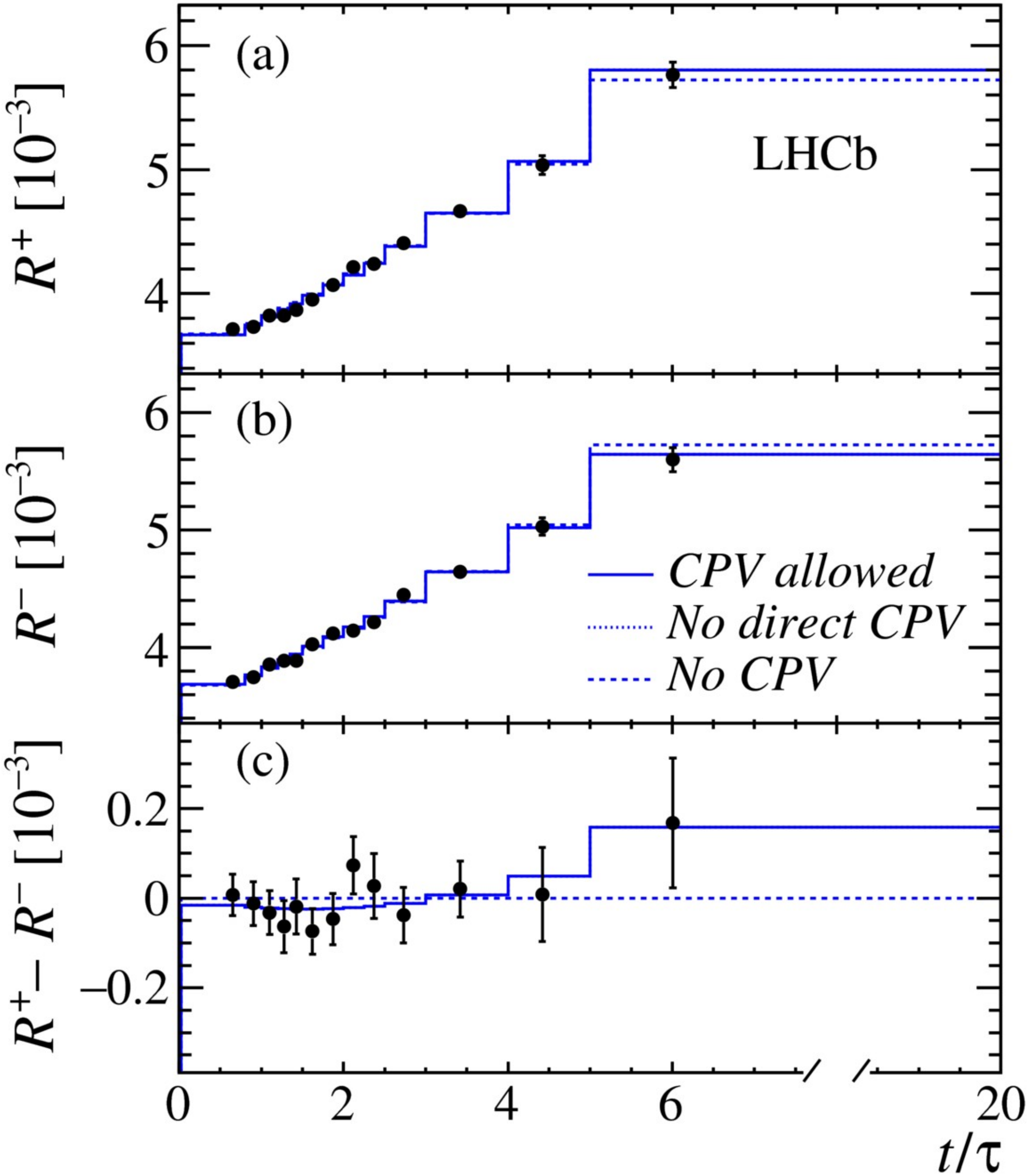
D^0-$\bar{D}^0$ mixing and CP violation by $D^0 \to K^+\pi^-$

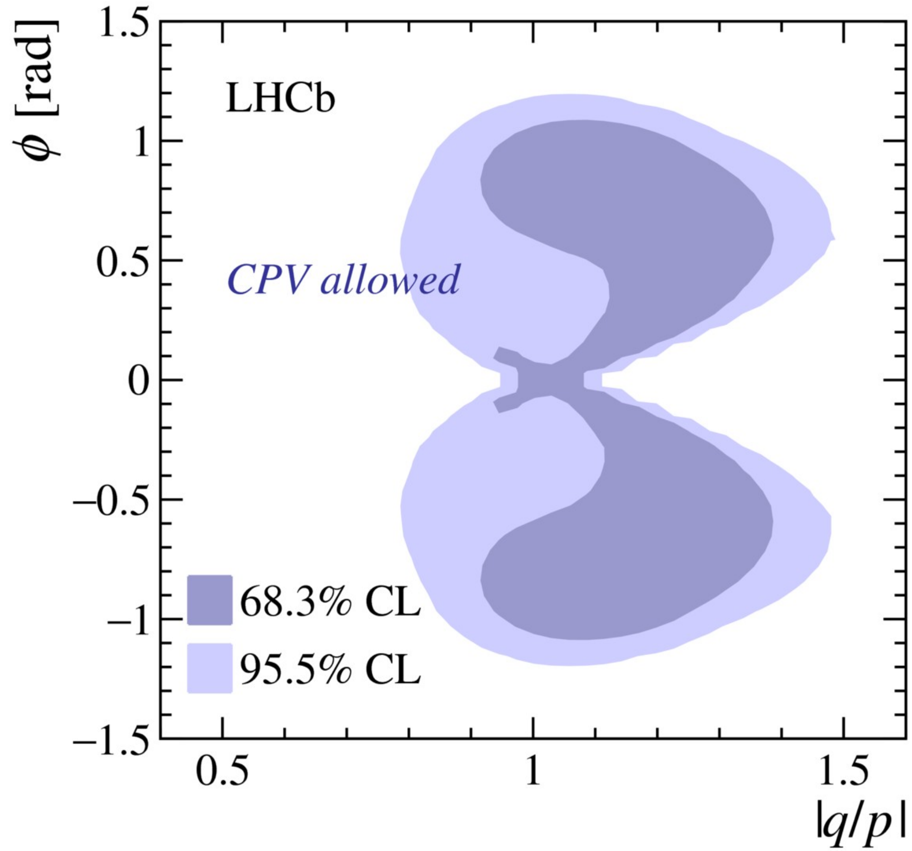


Dataset:
1.0 fb^{-1} @ $\sqrt{s}$=7 TeV
2.0 fb^{-1} @ $\sqrt{s}$=8 TeV
2.0 fb^{-1} @ $\sqrt{s}$=13TeV

Phys Rev D97, 031101 (2018)

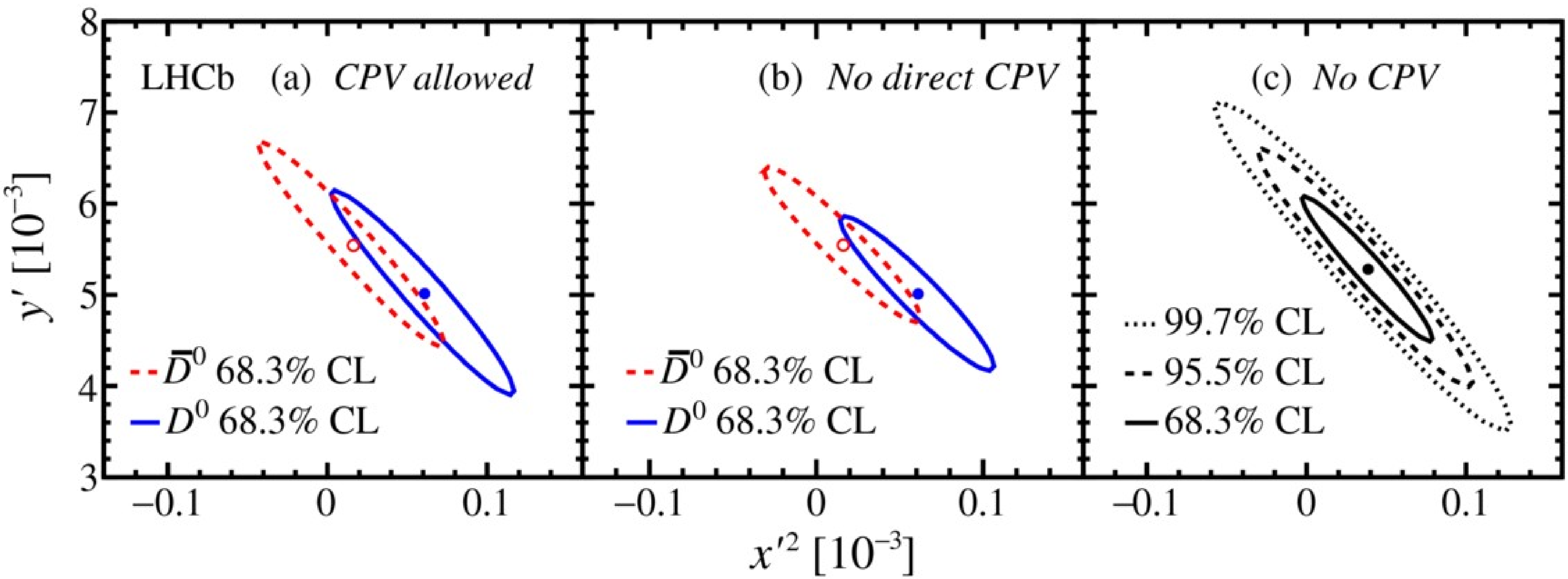
D^0-$\overline{D}^0$ mixing and CP violation by $D^0 \to K^+\pi^-$





Phys Rev D97, 031101 (2018)

D^0-$\overline{D}^0$ mixing and CP violation by $D^0 \to K^+\pi^-$



$R_D^+ = 3.454 \pm 0.040 \pm 0.020$
$y`^+ = 5.01 \pm 0.64 \pm 0.38$
$(x`^+)^2 = 0.061 \pm 0.032 \pm 0.019$
$R_D^- = 3.454 \pm 0.040 \pm 0.020$
$y`^- = 5.54 \pm 0.64 \pm 0.38$
$(x`^-)^2 = 0.016 \pm 0.033 \pm 0.020$

$R_D = 3.454 \pm 0.028 \pm 0.014$
$y`^+ = 5.01 \pm 0.48 \pm 0.29$
$(x`^+)^2 = 0.061 \pm 0.026 \pm 0.016$
$y`^- = 5.54 \pm 0.48 \pm 0.29$
$(x`^-)^2 = 0.016 \pm 0.026 \pm 0.016$

$R_D = 3.454 \pm 0.028 \pm 0.014$
$y` = 5.28 \pm 0.45 \pm 0.27$
$x`^2 = 0.039 \pm 0.023 \pm 0.014$

$A_D = (-0.1 \pm 9.1)\times 10^{-3}$

Phys Rev D97, 031101 (2018)