Overview of LHCb results

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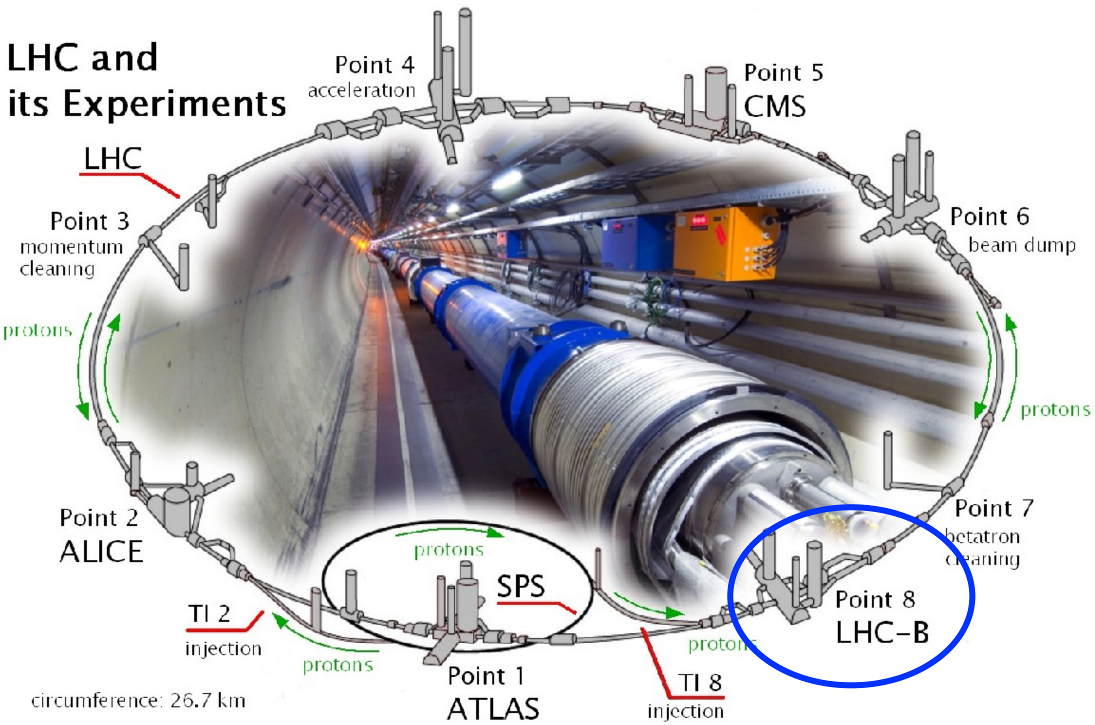
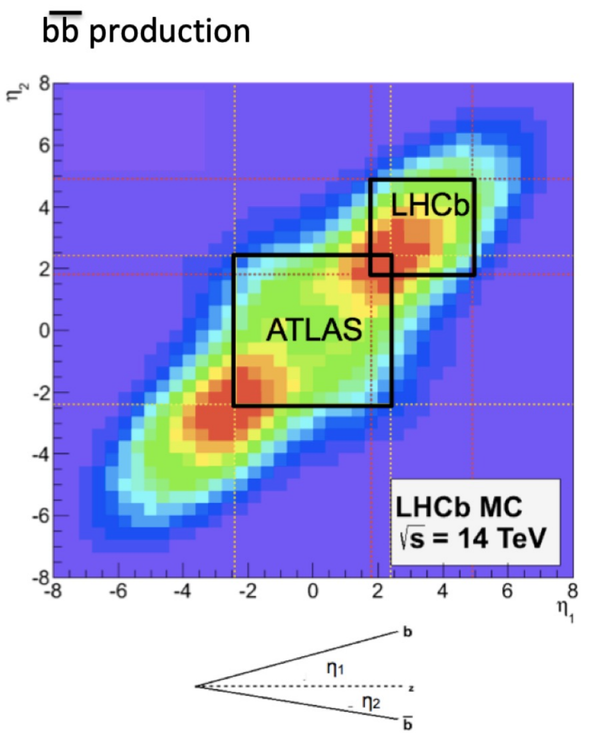
The LHCb experiment

- The LHCb experiment is one of the four large experiments at the LHC, dedicated to heavy flavor physics
  - ✓ LHC has the largest production cross-sections of b- and c-hadrons ever
    - $\sigma(b\bar{b}) \approx 500\ \mu b^{-1}$ @ 13 TeV & $\sigma(c\bar{c}) \approx 20\times\sigma(b\bar{b})$ in pp collisions
  - ✓ A great variety of b and c hadron species are accessible
  - ✗ Too many additional tracks

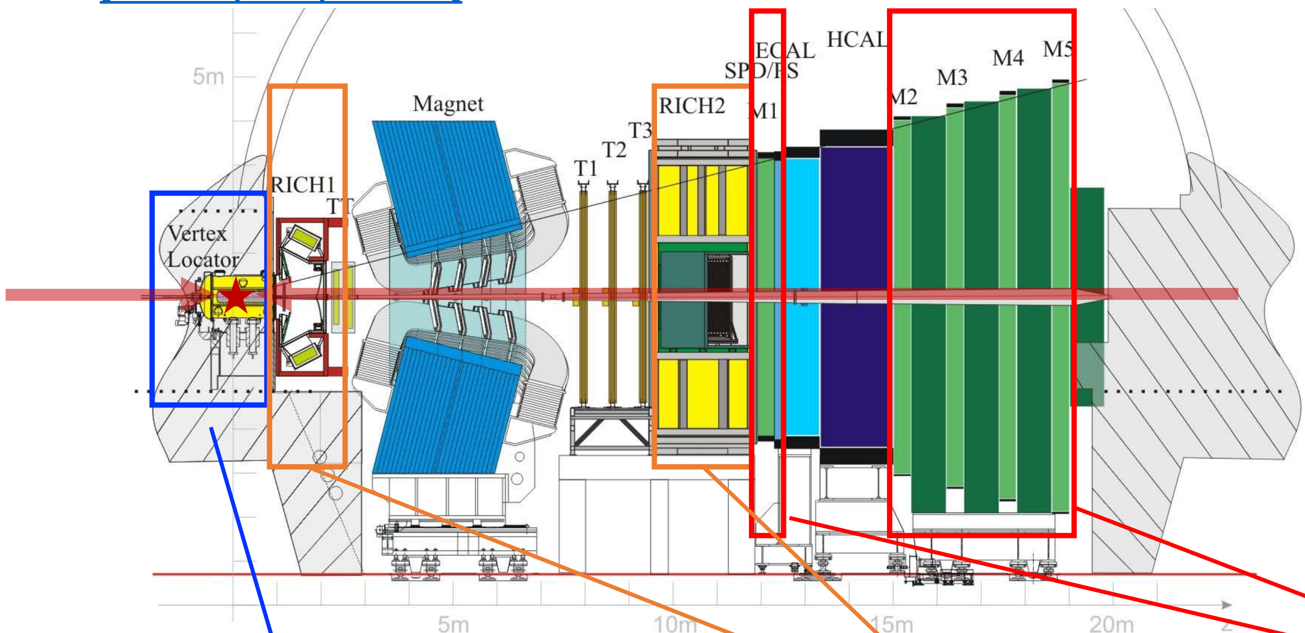




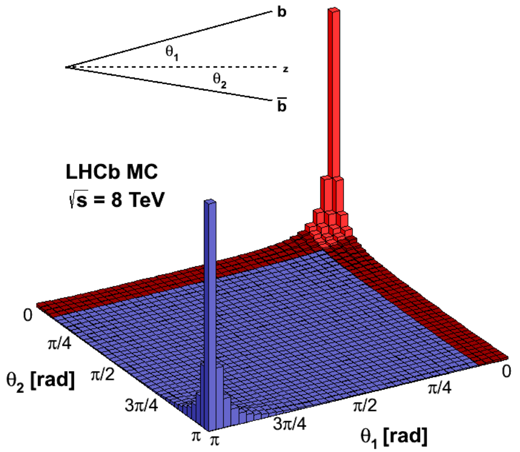
The LHCb detector in Run 1 & 2

- ➢LHCb is a single-arm forward region spectrometer covering $2 < \eta < 5$, with excellent ***vertexing***, ***tracking*** and ***particle identification (PID)*** performance

[JINST 3 (2008) S08005]



2.4% 4π angle
$\Rightarrow 25\%$ $b\bar{b}$



Vertex Locator: high precision; capable of separating b/c hadron production and decay vertices

$\sigma_{\mathrm{PV},x/y}{\sim}10$ μm, $\sigma_{\mathrm{PV},z}{\sim}60$ μm

RICHs: efficient identification of pions, kaons and protons

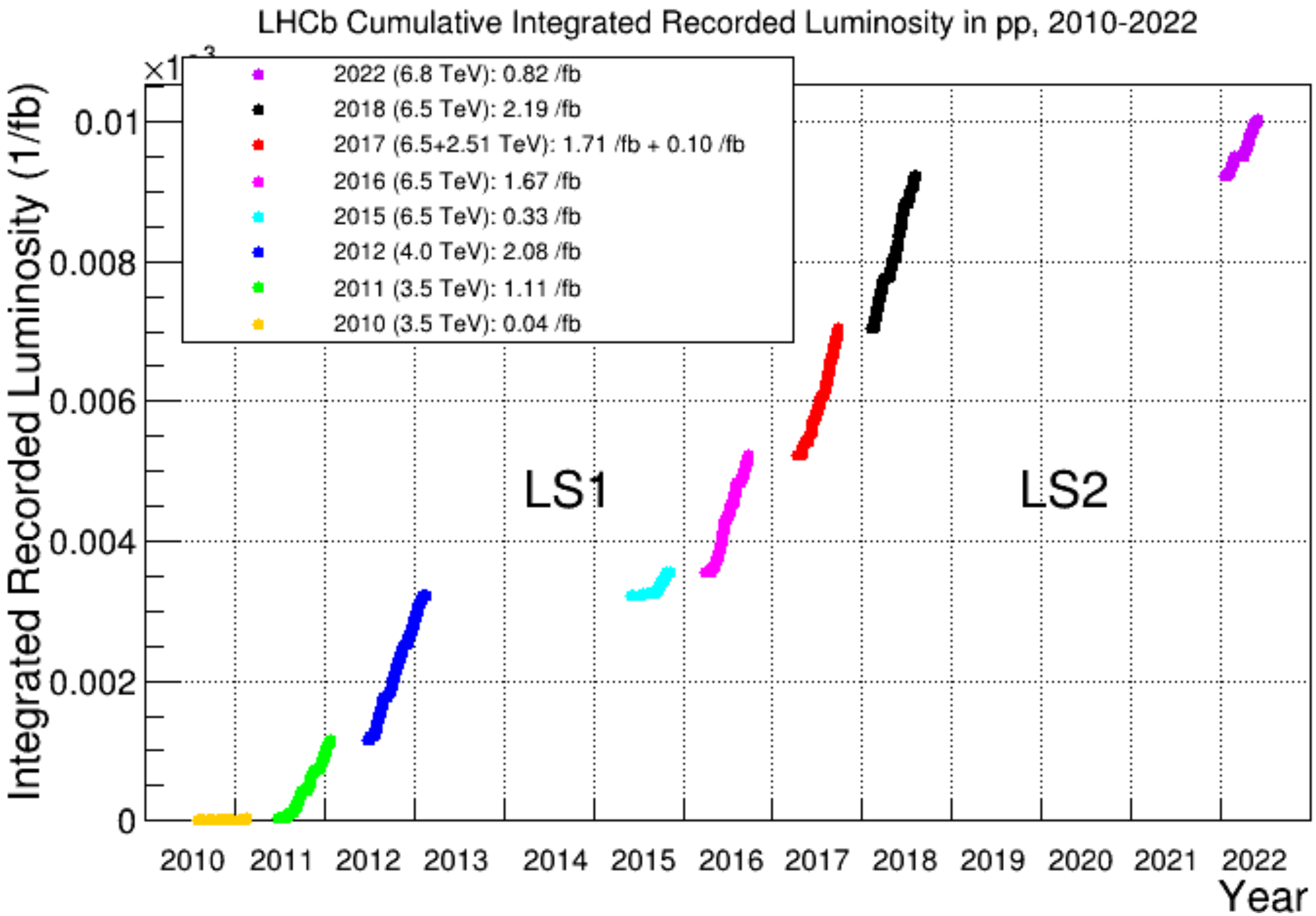
$\varepsilon(K \to K){\sim}95\%$
@ misID rate $(\pi \to K){\sim}5\%$

Muon system (M1-M5): efficient muon identification and trigger

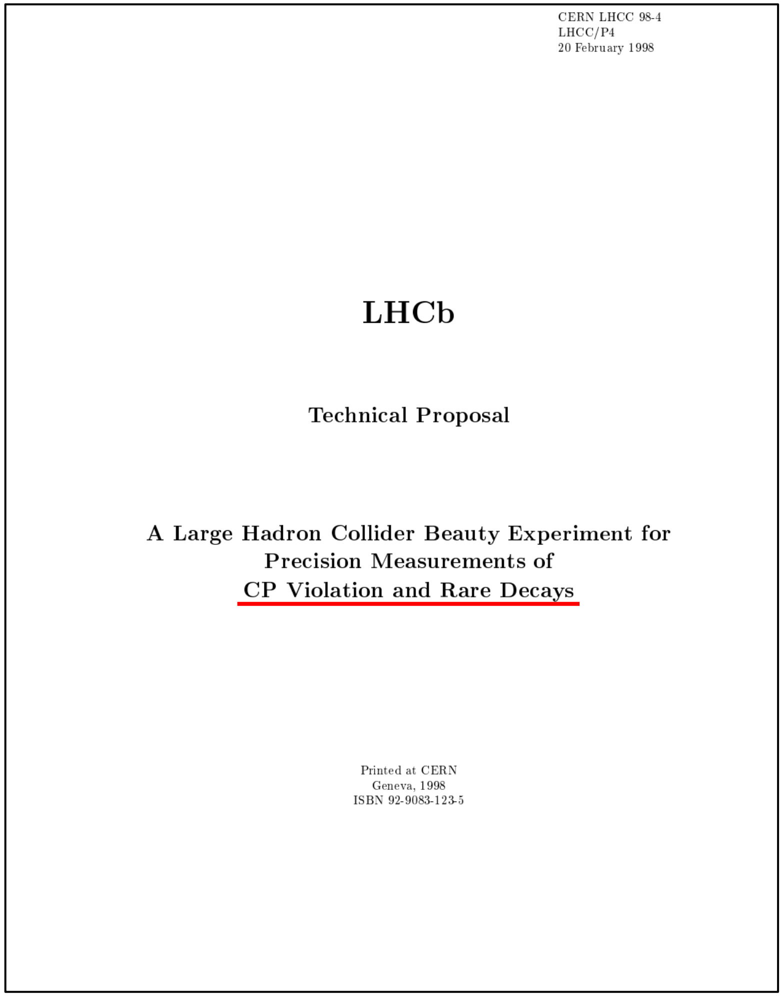
$\varepsilon(\mu \to \mu){\sim}97\%$
@ misID rate $(\pi \to \mu){\sim}1-3\%$

LHCb data taking

- Run 1 (2011-2012): $\mathcal{L}_{\text{int}} = 1\ \text{fb}^{-1}$ @ 7 TeV & 2 fb^{-1} @ 8 TeV
- Run 2 (2015-2018): $\mathcal{L}_{\text{int}} = 6\ \text{fb}^{-1}$ @ 13 TeV
- Run 3: emerging now @ 13.6 TeV



LHCb physics scheme


CERN LHCC 98-4
LHCC/P4
20 February 1998

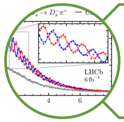
LHCb

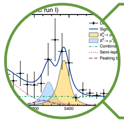
Technical Proposal

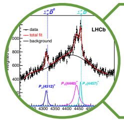
A Large Hadron Collider Beauty Experiment for
Precision Measurements of
CP Violation and Rare Decays

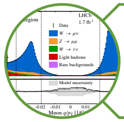
Printed at CERN
Geneva, 1998
ISBN 92-9083-123-5

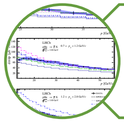
- LHCb has become a general purpose detector nowadays

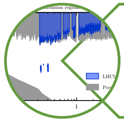

CP violation


Rare decays

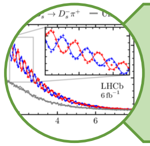

Spectroscopy


Electroweak

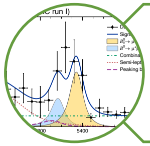

Heavy ions & fixed target


Dark sector ...

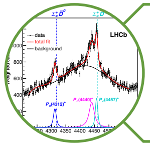
Outline



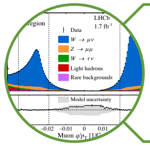
CP violation



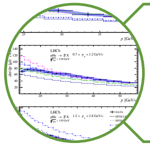
Rare decays



Spectroscopy



Electroweak

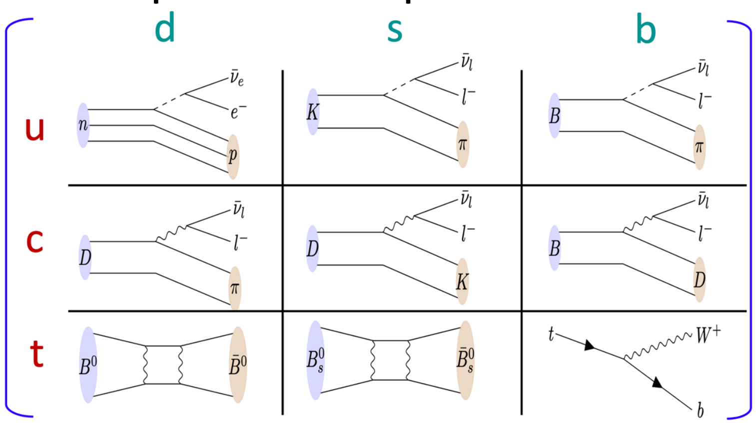


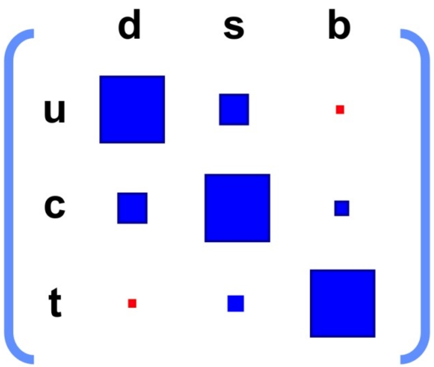
Heavy ions & fixed target

- Disclaimer: this talk cannot cover all the recent results; you can refer to https://lhcbproject.web.cern.ch/Publications/LHCbProjectPublic/Summary_all.html for a full list of LHCb publications

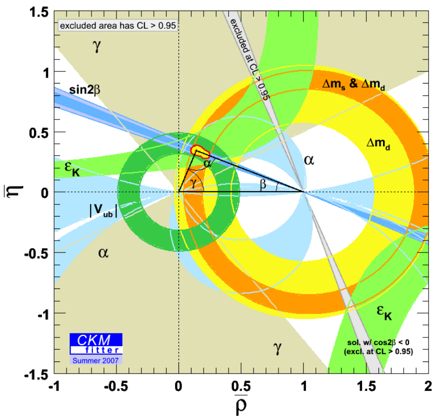
CKM matrix

- In the SM, the CKM phase is responsible for CPV in quark sector

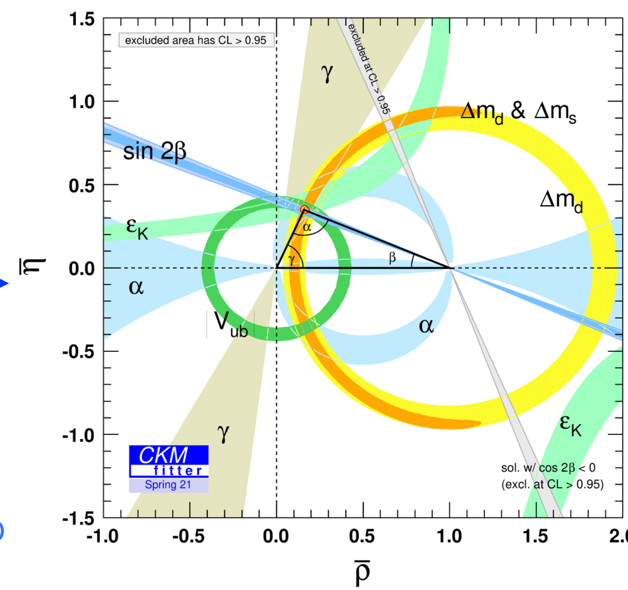
$V_{CKM} =$ 



- Decays of heavy-flavored hadrons are the best laboratory to
  - ✓Overconstrain the CKM unitarity triangle as a precision test of the SM
  - ✓Search for new sources of CPV ⇒ New Physics



LHCb plays an important role!

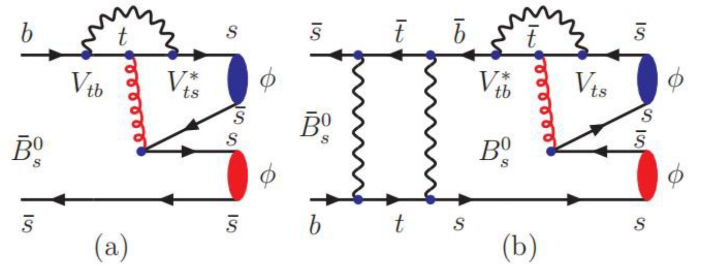


CKMfitter Group (J. Charles *et al.*), Eur. Phys. J. C41, 1-131 (2005) [hep-ph/0406184], updated results and plots available at: http://ckmfitter.in2p3.fr

CPV in $B_s^0 \to \phi\phi$

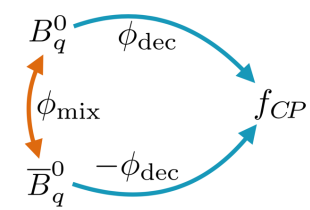
Kechen Li, Wenbin Qian, Yuehong Xie

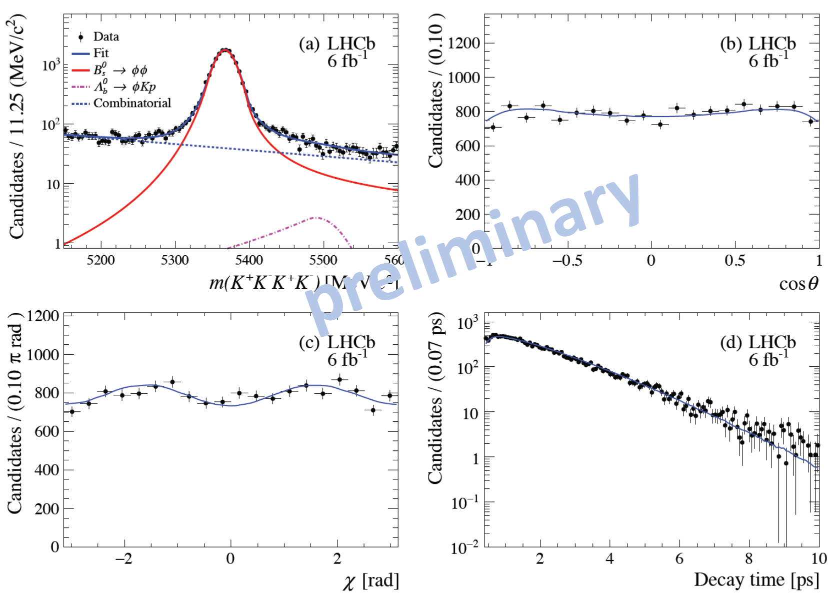
- $B_s^0 \to \phi\phi$ is a benchmark channel to study CPV in FCNC, highly sensitive to NP
- CPV in $B_s^0 \to \phi\phi$ comes from interference of decay and mixing; characterized by
  - ✓ CP violating phase: $\phi_s^{s\bar{s}s} = \phi_{\text{mix}} - 2\phi_{\text{dec}}$
  - ✓ Direct CP violation parameter: $|\lambda| = |(q/p)(\bar{A}_f/A_f)|$



parameters in time-dependent angular distribution

$$\frac{d^4\Gamma(t,\vec{\Omega})}{dt\,d\vec{\Omega}} \propto \sum_{k=1}^{6} h_k(t) f_k(\vec{\Omega})$$





- Run 2 (6 fb^{-1}) result:

$$\phi_s^{s\bar{s}s} = -0.042 \pm 0.075 \pm 0.009 \text{ rad}$$
$$|\lambda| = 1.004 \pm 0.030 \pm 0.009$$

- ✓ Consistent with SM prediction
- ✓ Show no evidence of polarization dependence
- ✓ Combined with Run 1 result, yielding the most precise study of time-dependent CPV in penguin-dominated B meson decay

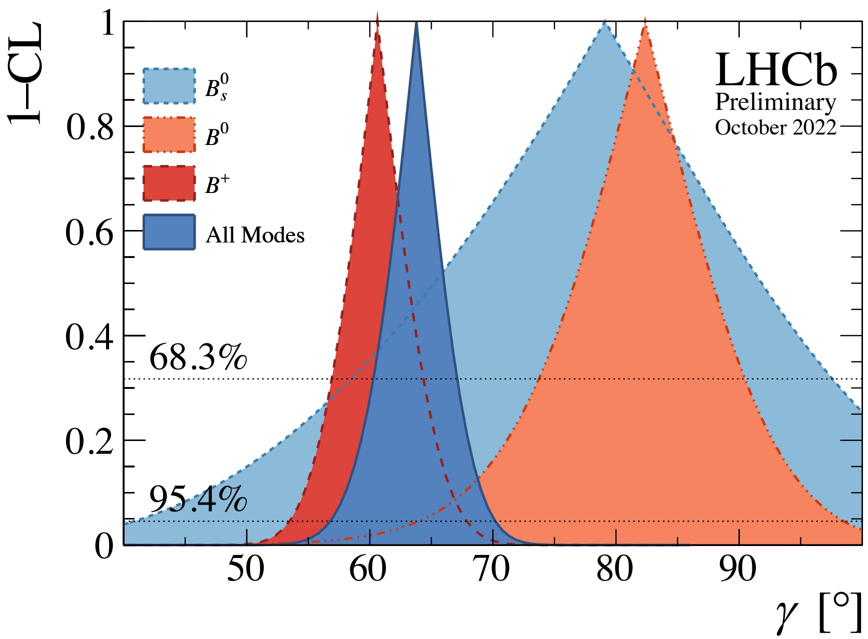
$$\phi_s^{s\bar{s}s} = -0.074 \pm 0.069 \text{ rad}$$
$$|\lambda| = 1.009 \pm 0.030$$

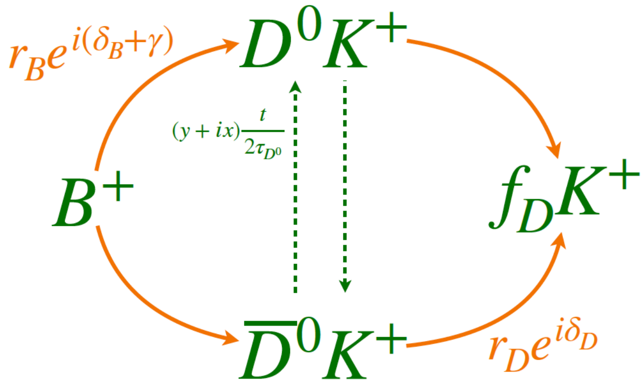
[LHCb-PAPER-2023-001]
In preparation

Direct measurement of γ

[LHCb-CONF-2022-003]

- $\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$
  - ✓ Measured in tree-level decays sensitive to interference between $b \to cW$ and $b \to uW$ transition amplitudes
- Golden modes: $B^\pm \to DK^\pm$
- γ combination at LHCb:





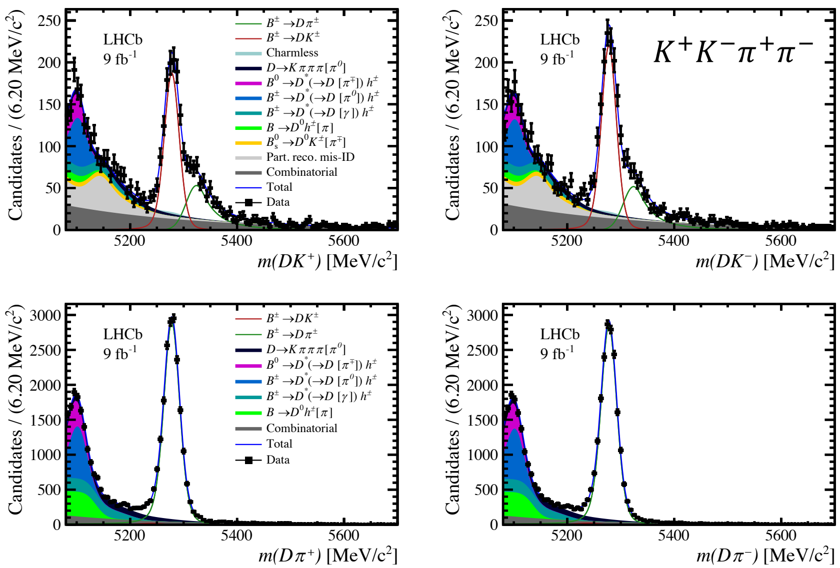
$\gamma = (63.8^{+3.5}_{-3.7})^\circ$

- ✓ The most precise determination from a single experiment
- ✓ Compatible with indirect determinations (fit from CKM triangle):
  - $\gamma = (65.5^{+1.1}_{-2.7})^\circ$ by CKMfitter
  - $\gamma = (65.8 \pm 2.2)^\circ$ by UTFit

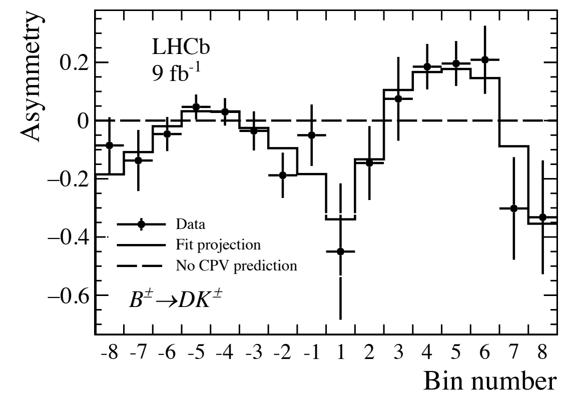
γ with $B^\pm \to [h^+h^-\pi^+\pi^-]_D h'^\pm$

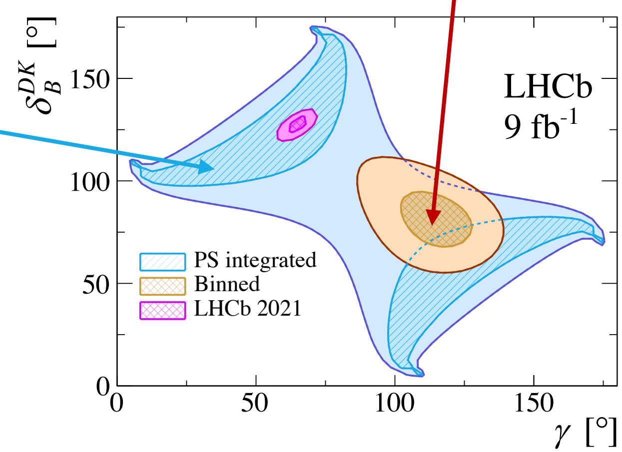
- First study of CPV in $B^\pm \to [K^+K^-\pi^+\pi^-]_D h^\pm, h = K, \pi$ [arXiv: 2301.10328]
- Full 9 fb^{-1} Run 1+2 dataset used

✓ Phase-space integrated analysis for both $K^+K^-\pi^+\pi^-$ and $\pi^+\pi^-\pi^+\pi^-$



✓ Binned analysis for $K^+K^-\pi^+\pi^-$: optimized sensitivity to local CP asymmetries

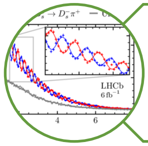




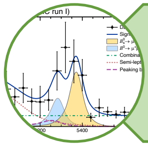
- Binned result: $\gamma = (116^{+12}_{-14})^\circ$

✓ **Precision will improve** when direct measurement of charm-decay parameters by BESIII become available

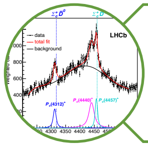
Outline



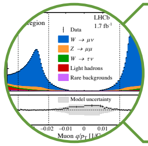
CP violation



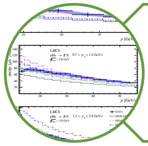
Rare decays



Spectroscopy



Electroweak

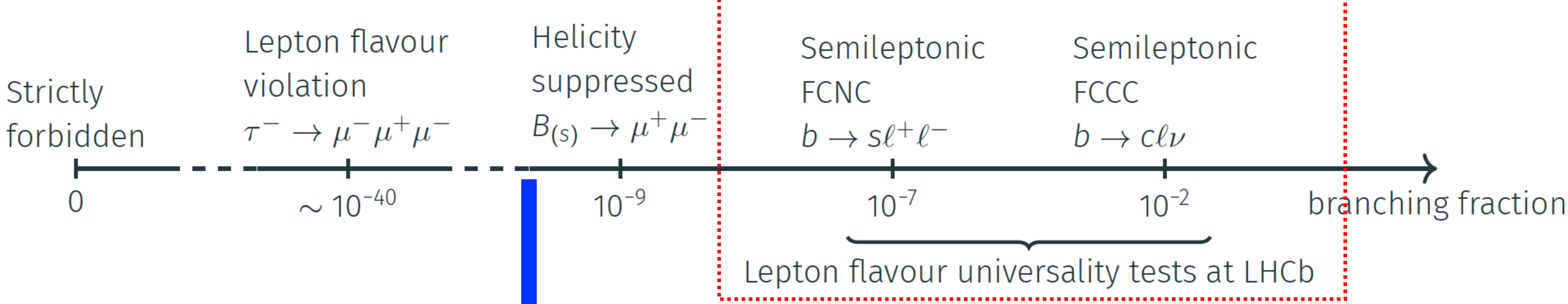


Heavy ions & fixed target

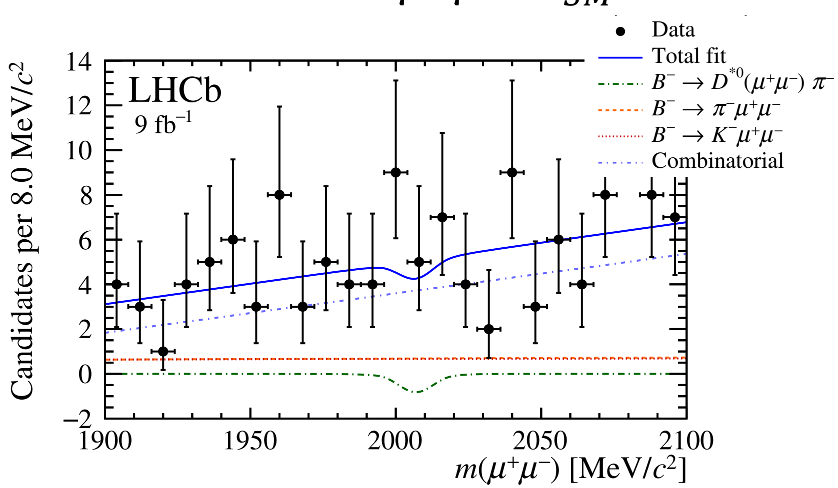
Rare decays

- ➢ Rare decays are sensitive to New Physics contributions

Credit: Alex Seuthe

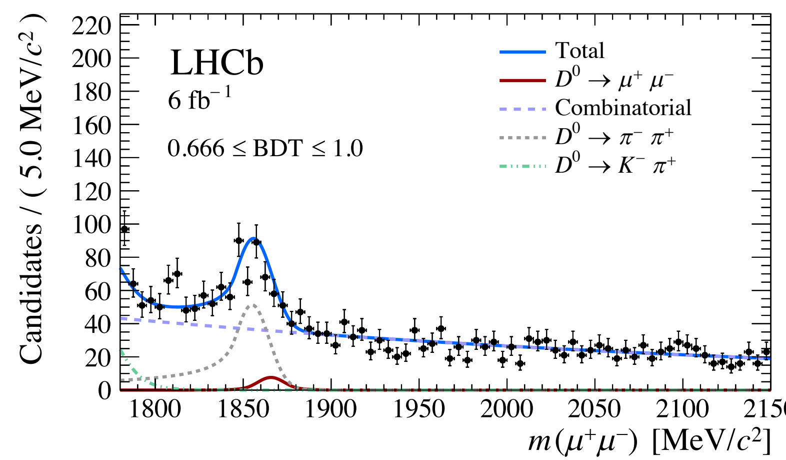


✓ Search for $D^{*0} \to \mu^+\mu^-$: $\mathcal{B}_{SM} \lesssim 10^{-19}$



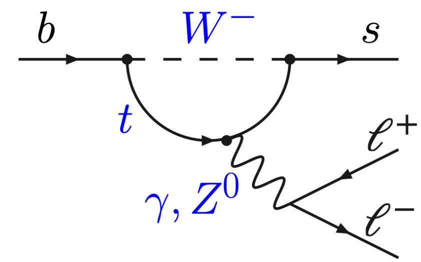
Most stringent limit on $D^{*0} \to l^+l^-$:
$\mathcal{B}(D^{*0} \to \mu^+\mu^-) < 2.6(3.4){\times}10^{-8}$
@ 90(95)% CL **[arXiv: 2304.01981]**

✓ Search for $D^0 \to \mu^+\mu^-$: $\mathcal{B}_{SM} \simeq 10^{-13}$

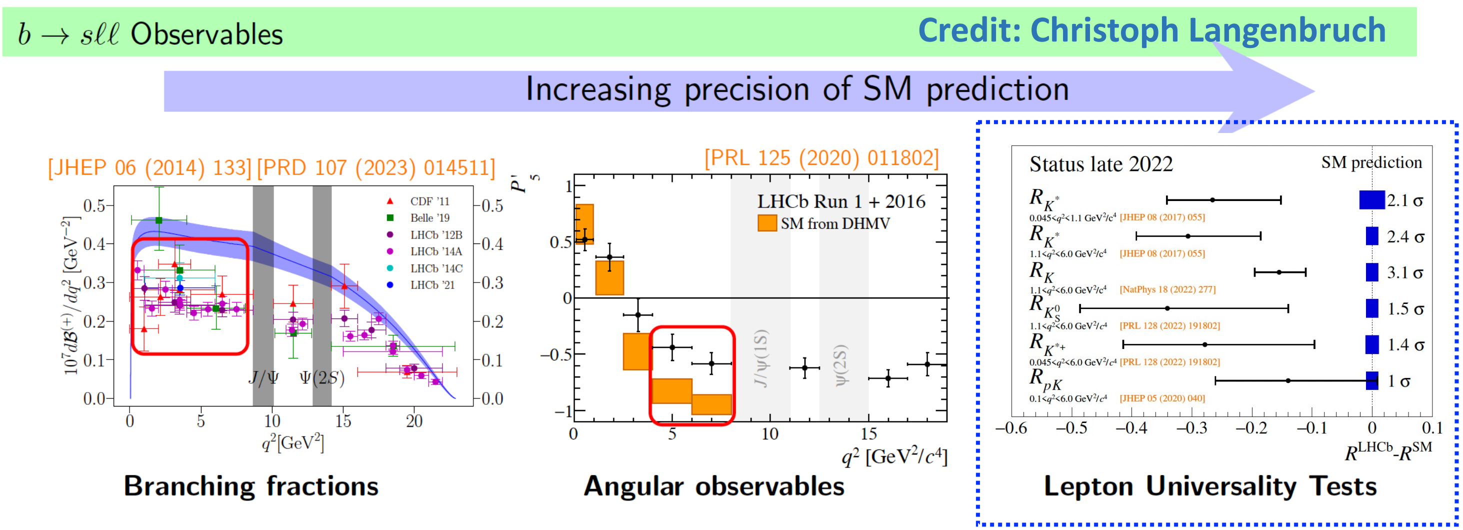


Most stringent limit of FCNC in charm sector:
$\mathcal{B}(D^0 \to \mu^+\mu^-) < 2.94(3.25){\times}10^{-9}$
@ 90(95)% CL **[arXiv: 2212.11203]**

LFU test with $b \to s l^+ l^-$



- $b \to s l^+ l^-$ was among the major design goals of LHCb
  - ✓Rare (loop suppressed) ⇒ good sensitivity to NP
  - ✓No neutrino involved ⇒ experimentally friendly



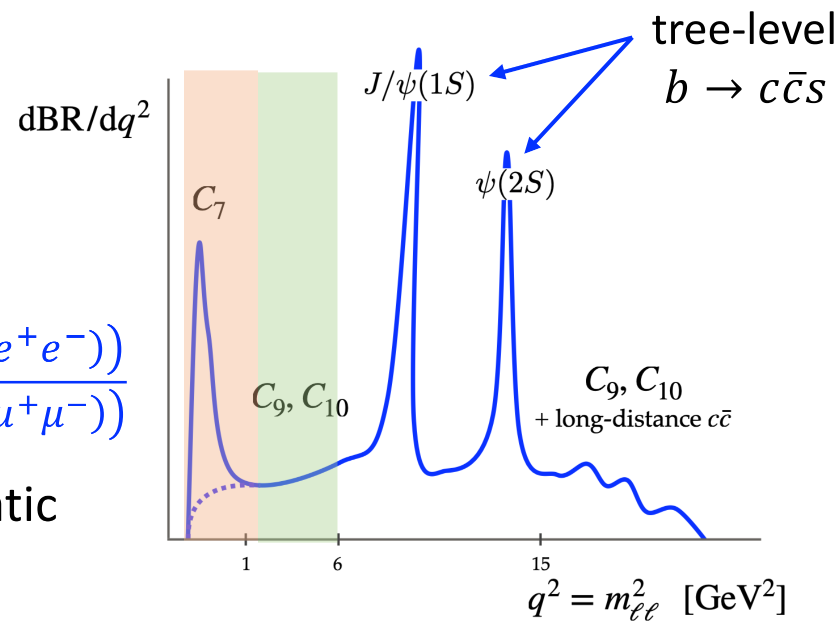
- LFU test observable:

$$R_{K,K^*} = \frac{\mathcal{B}\left(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-\right)}{\mathcal{B}\left(B^{(+,0)} \to K^{(+,*0)}e^+e^-\right)}$$

  - ✓In SM, difference from unity originates solely from lepton mass difference
  - ✓Uncertainty from QED corrections $\mathcal{O}(1\%)$
  - ✓Hadronic uncertainties cancel in the ratio

Measurement of R_K and R_{K^*}

- Simultaneous test of R_K and R_{K^*} in low-q^2: $0.1 < q^2 < 1.1\ \mathrm{GeV}^2/c^4$ and central-q^2: $1.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4$ with full 9 fb^{-1} LHCb dataset

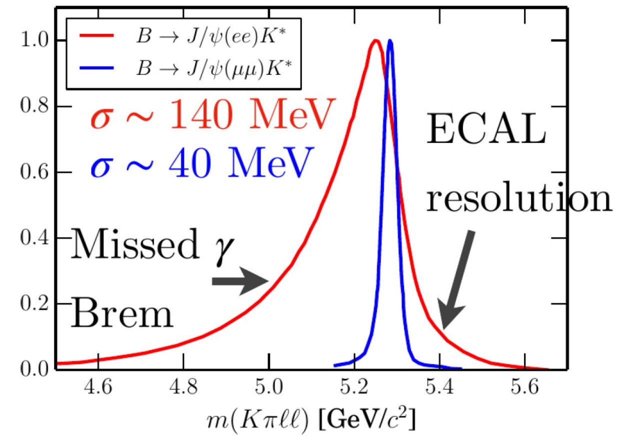


- Strategy: measure double ratio

$$R_K = \frac{\mathcal{B}(B^{+,0} \to K^{+,*0}\mu^+\mu^-)}{\mathcal{B}(B^{+,0} \to K^{+,*0}e^+e^-)} \times \frac{\mathcal{B}\left(B^{+,0} \to K^{+,*0}J/\psi(\to e^+e^-)\right)}{\mathcal{B}\left(B^{+,0} \to K^{+,*0}J/\psi(\to \mu^+\mu^-)\right)}$$

  - ✓ to maximize the cancellation of systematic effects in efficiencies

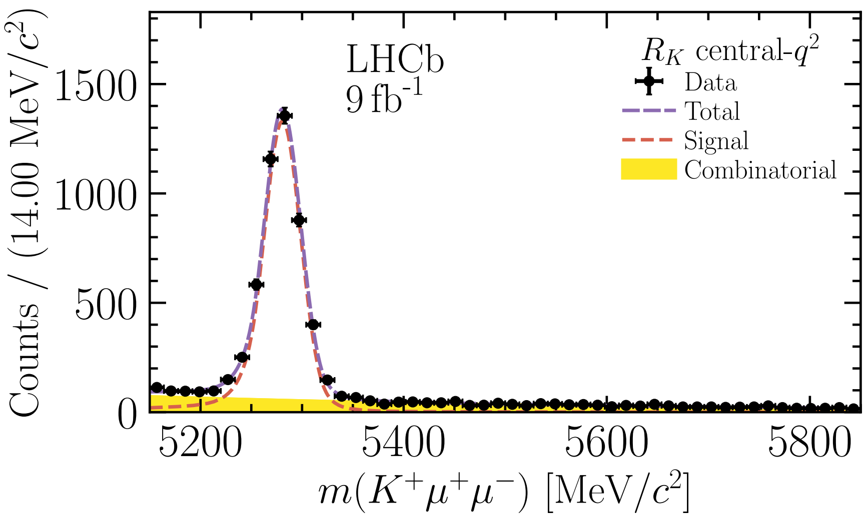
- Main challenge: the e/μ differences in detector response
  - ✓ Lower hardware-level trigger efficiency for e
  - ✓ Strong bremsstrahlung emission of e
  - ✓ e PID harder and slower than μ
  - ⇒ electron mode: lower efficiency & worse resolution & higher bkg. contamination

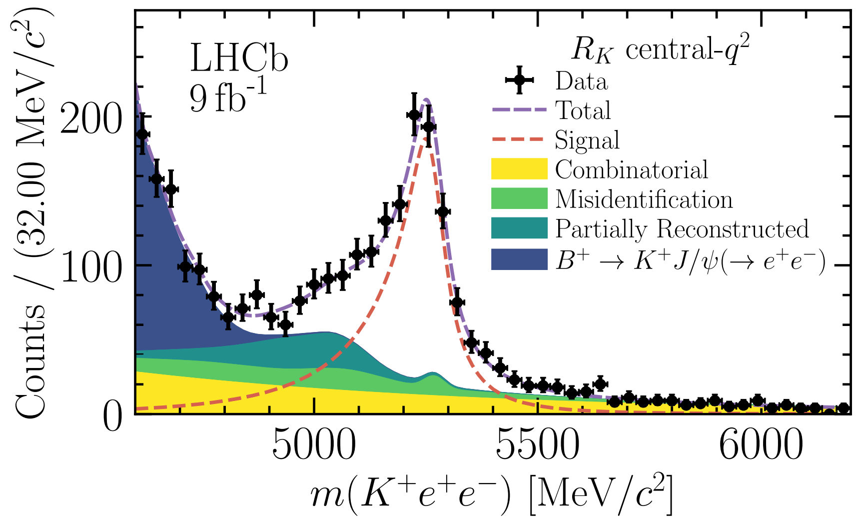


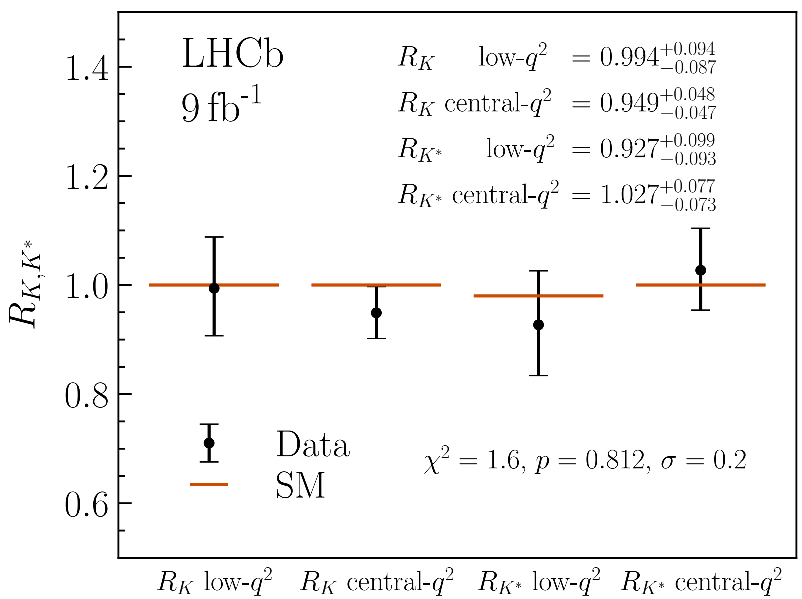
- Vast efforts to calibrate efficiencies and model bkg.

R_K and R_{K^*} results

[arXiv: 2212.09152]
[arXiv: 2212.09153]







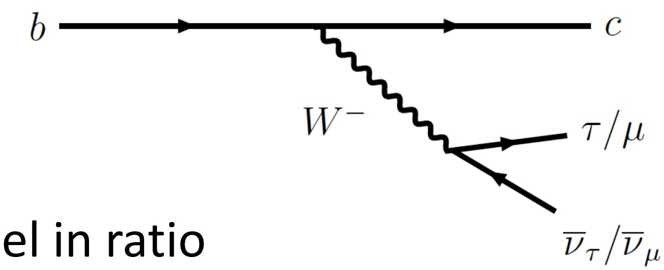
$$\text{low-}q^2 \begin{cases} R_K = 0.994\ ^{+0.090}_{-0.082}\,(\text{stat})\,^{+0.029}_{-0.027}\,(\text{syst}) \\ R_{K^*} = 0.927\ ^{+0.093}_{-0.087}\,(\text{stat})\,^{+0.036}_{-0.035}\,(\text{syst}) \end{cases}$$

$$\text{central-}q^2 \begin{cases} R_K = 0.949\ ^{+0.042}_{-0.041}\,(\text{stat})\,^{+0.022}_{-0.022}\,(\text{syst}) \\ R_{K^*} = 1.027\ ^{+0.072}_{-0.068}\,(\text{stat})\,^{+0.027}_{-0.026}\,(\text{syst}) \end{cases}$$

- ✓ R_K and R_{K^*} consistent with SM at 0.2σ
- ✓ Measurement statistically dominated
- ✓ Most precise LFU test with $b \to s l^+ l^-$ so far
- ✓ Measurement supersedes previous LHCb results

LFU test with $b \to cl\nu$

- LFU test observable:



$$R_{H_c} = \frac{\mathcal{B}(H_b \to H_c \tau \nu_\tau)}{\mathcal{B}(H_b \to H_c \mu \nu_\mu)}$$

✓ Common hadronic form factor uncertainties cancel in ratio

✓ Large statistics thanks to large b-hadron production and BF

✗ Missing neutrinos

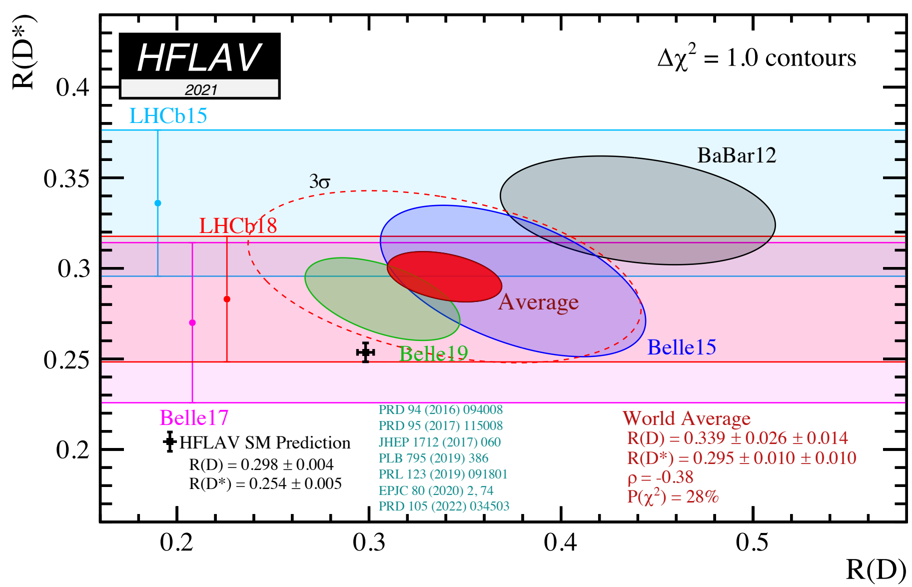
✗ Large partially reconstructed background

- Before Dec 2022:
  3.3σ tension wrt SM

- Two τ decay modes:

✓ Muonic: $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$

✓ Hadronic: $\tau^- \to \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau$



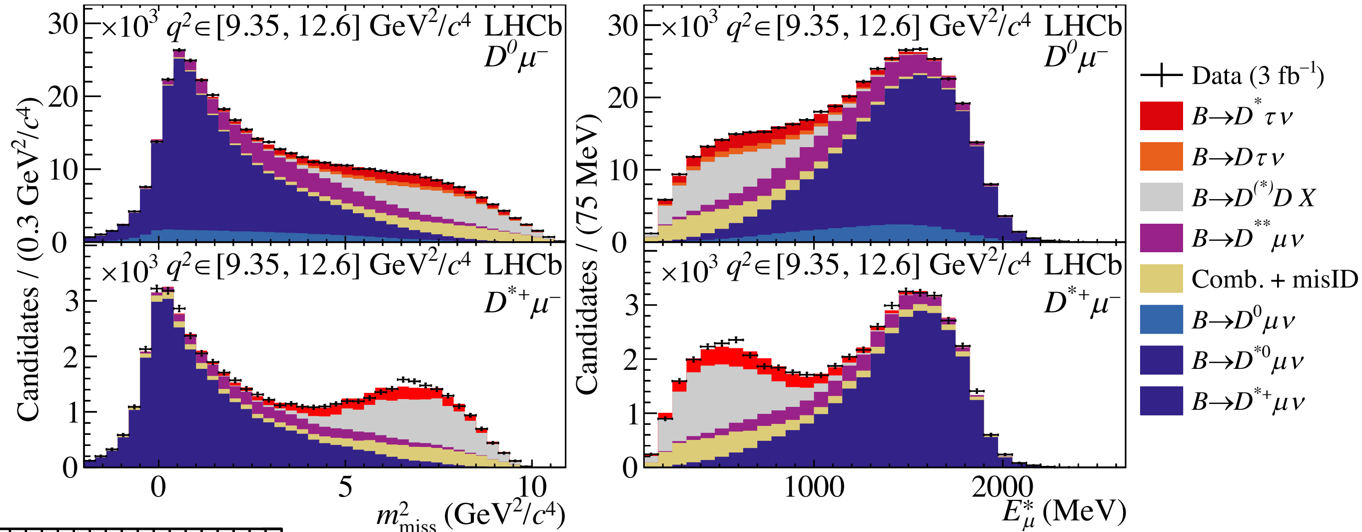
$R(D)$ and $R(D^*)$ with muonic τ decay

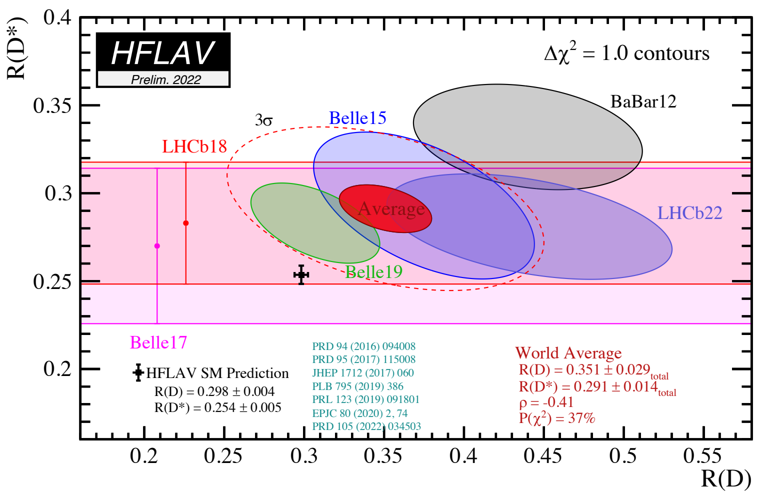
- 3 fb^{-1} Run 1 dataset used (supersedes old results) [arXiv:2302.02886]
  - ✓ $R(D)$: $B^- \to D^0\tau^-\bar{\nu}_\tau$
  - ✓ $R(D^*)$: $B^- \to D^{*0}\tau^-\bar{\nu}_\tau$ and $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$

Keys:

✓Discriminating variables to separate muon and tau modes

✓Model of each component





$$R(D^0) = 0.441 \pm 0.060 \pm 0.066$$
$$R(D^*) = 0.281 \pm 0.018 \pm 0.024$$
$$\rho = -0.43$$

- ✓ 1.9σ agreement with SM
- ✓ New average: slightly lower $R(D^*)$ & higher $R(D)$
- ✓ World Average wrt SM: $3.3\sigma \to 3.5\sigma$

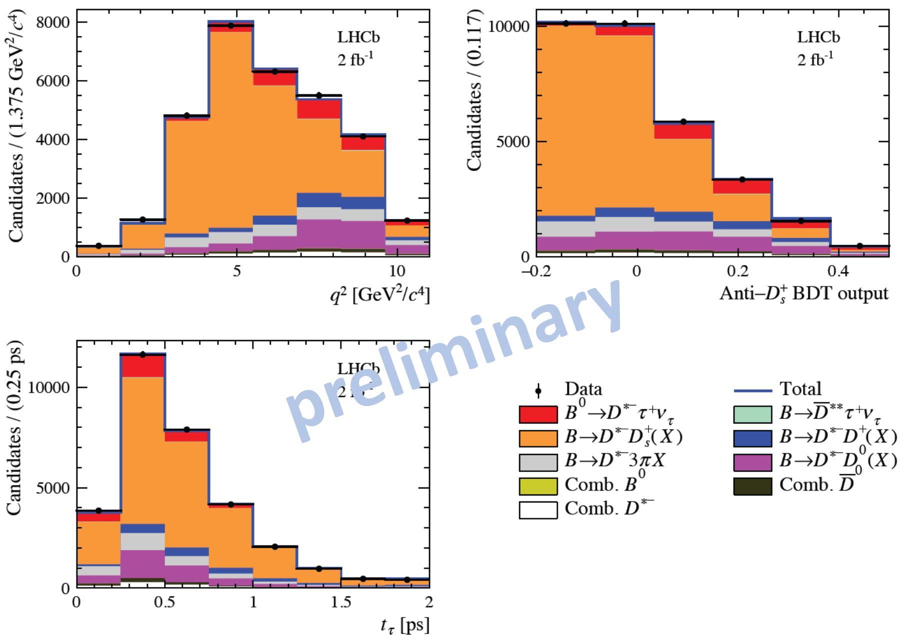
$R(D^*)$ with hadronic τ decay

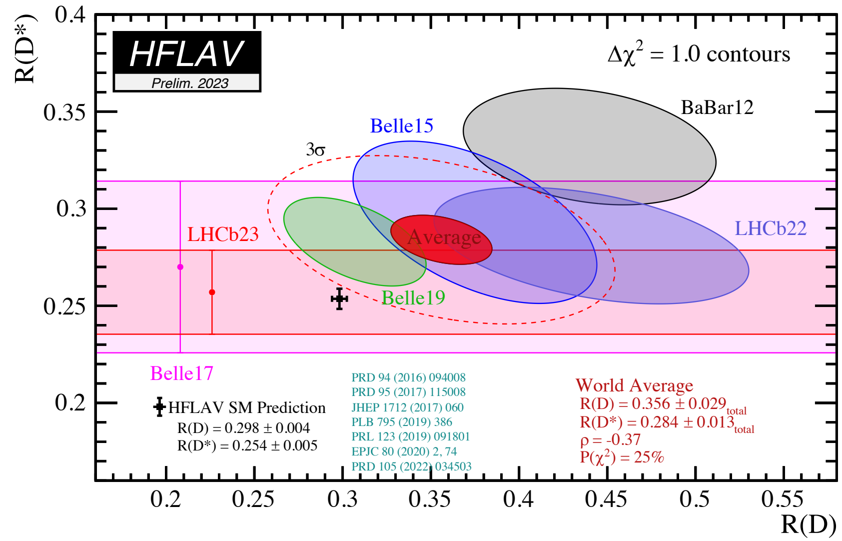
- 2 fb^{-1} Run 2 data from 2015-2016 used

$$\mathcal{R}(D^{*-}) = \mathcal{K}(D^{*-}) \frac{\mathcal{B}(B^0 \to D^{*-}3\pi)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

measure — external input

$$\mathcal{K}(D^{*-}) \equiv \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)}$$

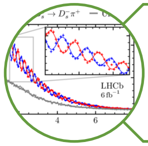


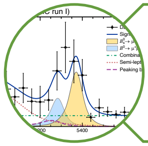


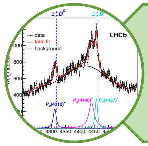
- ✓ To combine with Run 1 result gives $R(D^*) = 0.257 \pm 0.012 \pm 0.014 \pm 0.012(\text{ext})$
- ✓ Compatible with SM expectation
- ✓ Agreement between World Average and SM: $3.5\sigma \to 3.2\sigma$

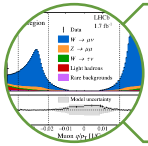
[LHCb-PAPER-2022-052]
In preparation

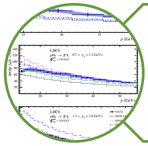
Outline


CP violation


Rare decays

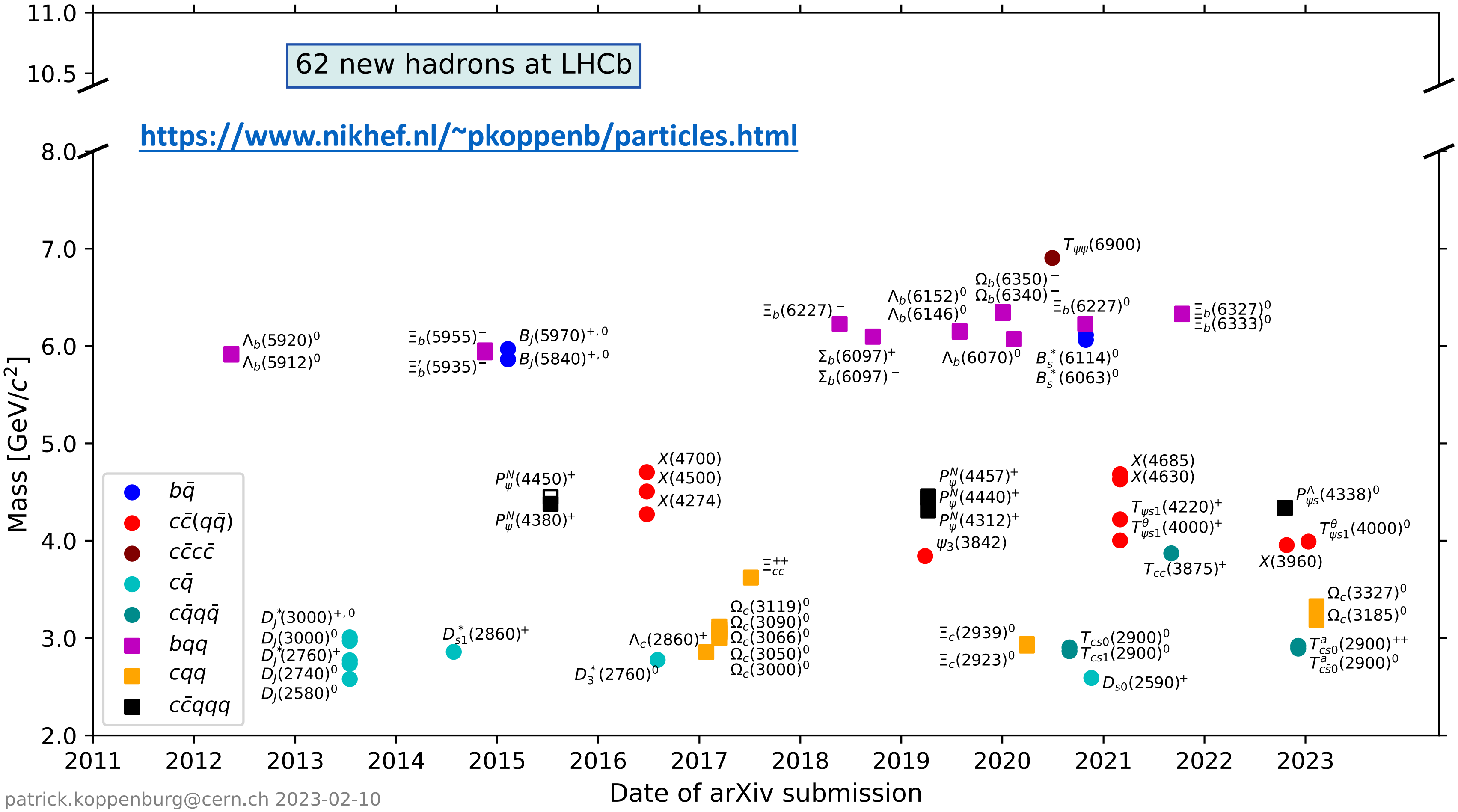

Spectroscopy


Electroweak


Heavy ions & fixed target

New hadrons at LHCb

➢Hadron spectroscopy provides primary tests and inputs to QCD models



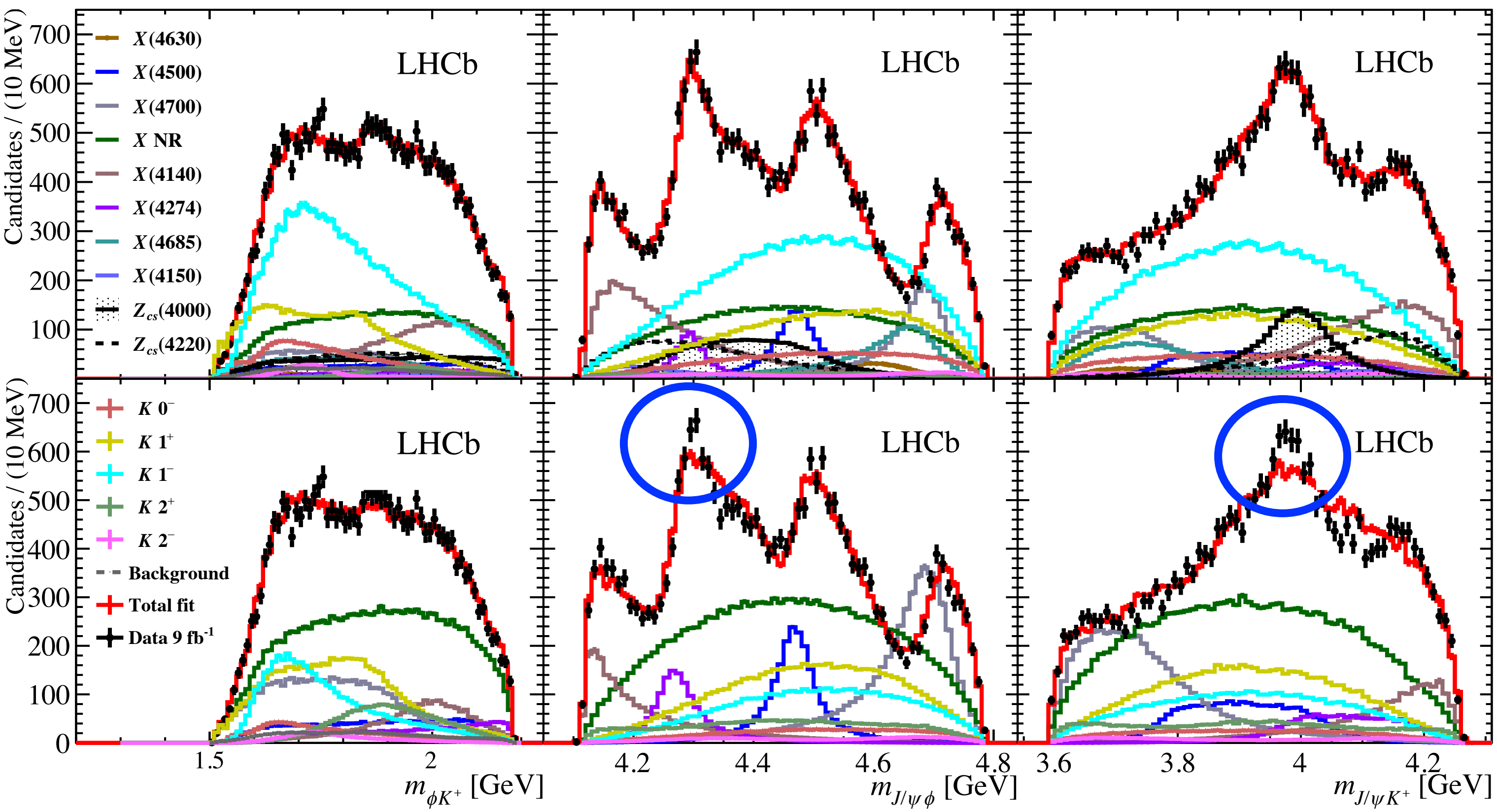
- Following "Exotic hadron naming convention" proposed by LHCb recently

[arXiv: 2206.15233]

$T_{\psi s1}^{\theta}(4000)^{+}$ in $B^{+} \to J/\psi\phi K^{+}$

Zehua Xu, Liming Zhang

[PRL 127 (2021) 082001]



Updated model

Run 1 model

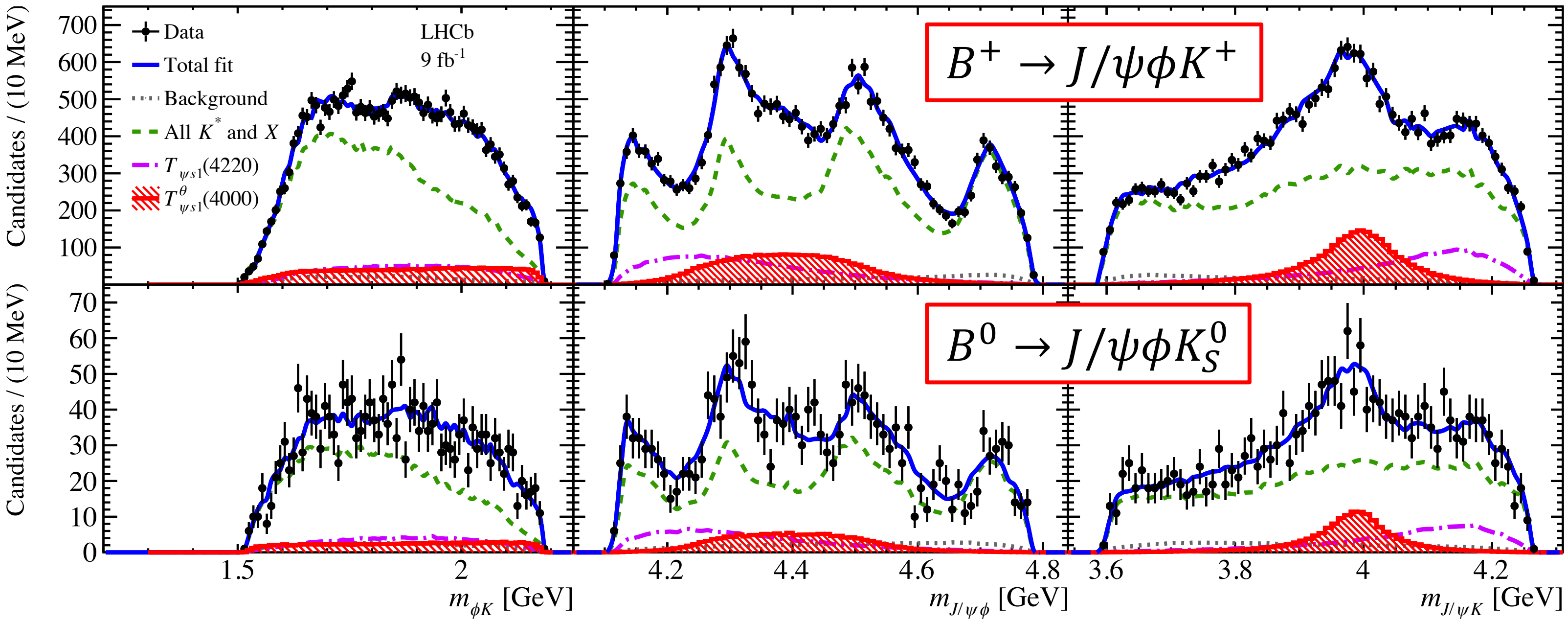
- $Z_{cs}(4000)$ (i.e. $T_{\psi s1}^{\theta}(4000)^{+}$) was observed with significance $> 10\ \sigma$
- J^P of $Z_{cs}(4000)$ was firmly determined to be 1^{+}

Evidence of $T_{\psi s1}^{\theta}(4000)^0$ in $B^0 \to J/\psi\phi K_S^0$

Zhihong Shen, Liming Zhang

- $B^0 \to J/\psi\phi K_S^0$ and $B^+ \to J/\psi\phi K^+$ are related by isospin symmetry
- Joint amplitude fit performed assuming isospin symmetry except for $T_{\psi s1}^{\theta}(4000)^0$, with significance of 4σ (5.4σ under isospin assumption)

[arXiv: 2301.04899]



$$M(T_{\psi s1}^{\theta}(4000)^0) = 3991\,^{+12}_{-10}\,^{+\ 9}_{-17}\ \text{MeV}$$
$$\Gamma(T_{\psi s1}^{\theta}(4000)^0) = 105\,^{+29}_{-25}\,^{+17}_{-23}\ \text{MeV}$$

$$\Delta M = -12\,^{+11}_{-10}\,^{+6}_{-4}\ \text{MeV}$$

- $T_{\psi s1}^{\theta}(4000)^0$ and $T_{\psi s1}^{\theta}(4000)^+$ are likely to be isospin partners

Study of $B^0 \to \bar{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$

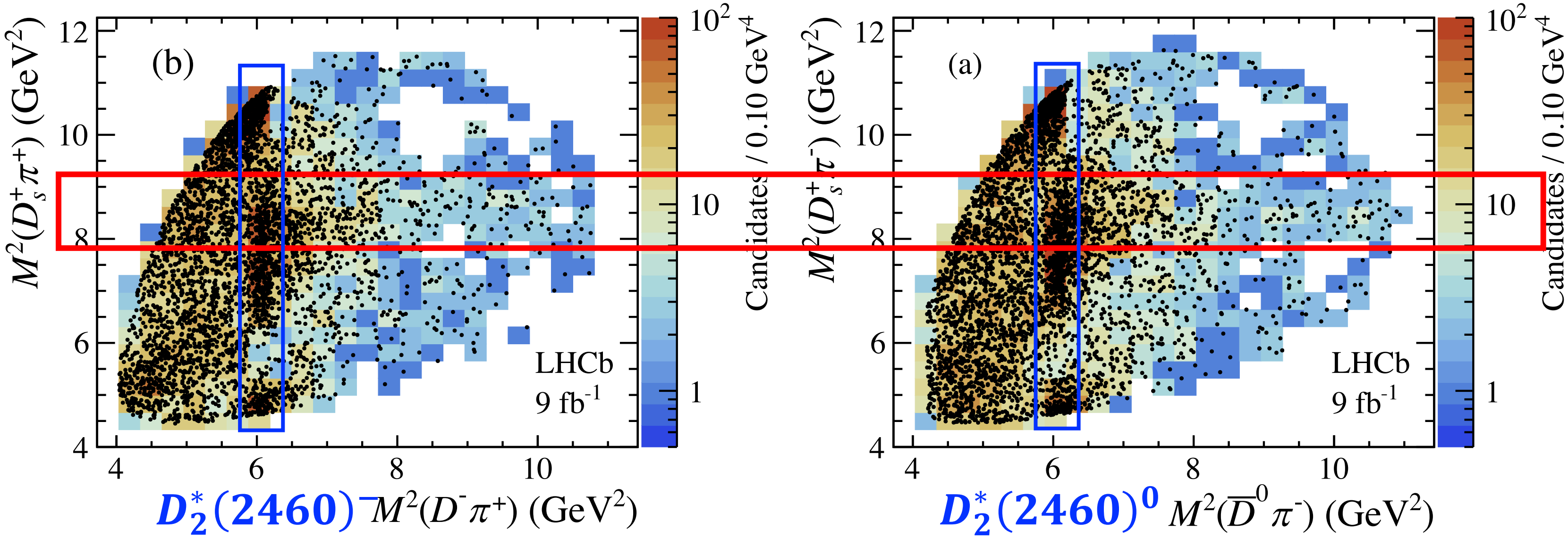
[arXiv: 2212.02716]

Ruiting Ma, Yinrui Liu

- Full 9 fb^{-1} Run1+Run2 LHCb data

⇒ 4420 $B^0 \to \bar{D}^0 D_s^+ \pi^-$ candidates with signal purity of 90.7%

3940 $B^+ \to D^- D_s^+ \pi^+$ candidates with signal purity of 95.2%



✓ Faint horizontal band at $M^2(D_s^+\pi) \approx 8.5\ \text{GeV}^2$ indicating $T_{c\bar{s}}$ candidates

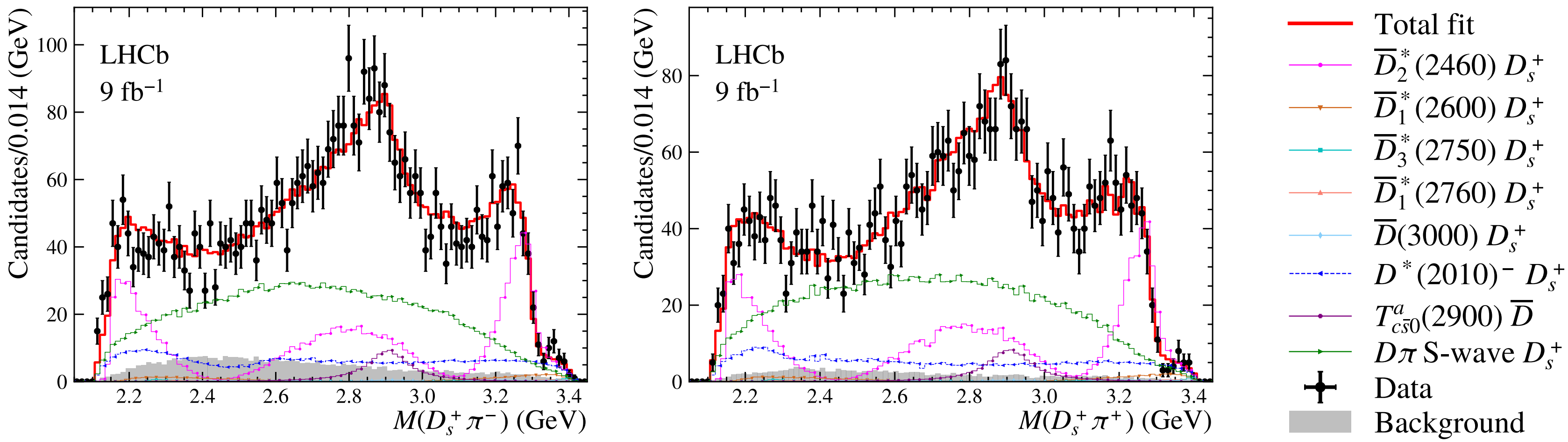
⇒ Joint amplitude analysis where amplitudes of the two decays are related through isospin symmetry

Observation of $T^{a}_{c\bar{s}0}(2900)^{0/++}$

Ruiting Ma,
Yinrui Liu

[arXiv: 2212.02716]

- Fit with two $D_s^+\pi$ states sharing resonance parameters



- $T^{a}_{c\bar{s}0}(2900)^{0} \rightarrow D_s^+\pi^-$ & $T^{a}_{c\bar{s}0}(2900)^{++} \rightarrow D_s^+\pi^+$ significance $> 9\sigma$
  - ✓A second 1^- $D_s^+\pi$ state yields significance of only 1.3σ
  - ✓Additional $D\pi, D_s^+\pi, DD_s^+$ resonances disfavored
- $J^P = 0^+$ favored over other spin-parity by more than 7.5σ

$$M = 2.908 \pm 0.011 \pm 0.020\ \text{GeV}$$

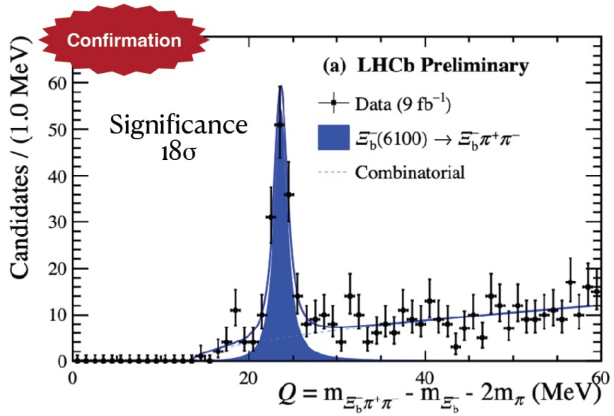
$$\Gamma = 0.136 \pm 0.023 \pm 0.011\ \text{GeV}$$

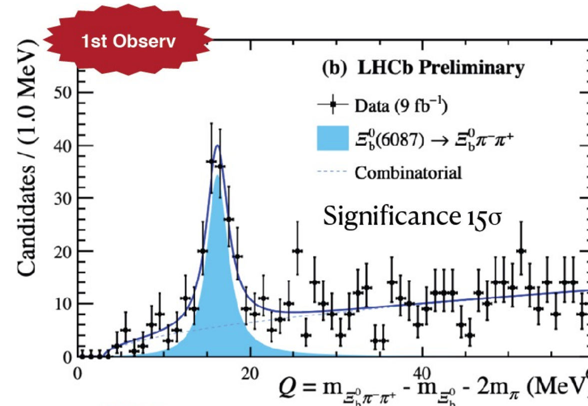
- Flavor partner of $T_{cs0}(2900)^0 \rightarrow D^-K^+$? Multiplets to be revealed in the future

Observation of $\Xi_b^{-/0**} \to \Xi_b^{-/0}\pi^+\pi^-$

- $\Xi_b^-\pi^+\pi^-$ with $\Xi_b^- \to \Xi_c^0[pK^-K^+\pi^+]\pi^-$ and $\Xi_b^- \to \Xi_c^0[pK^-K^+\pi^+]\pi^-\pi^+\pi^-$: an LHCb record of 9 tracks!
- $\Xi_b^0\pi^+\pi^-$ with $\Xi_b^0 \to \Xi_c^+[pK^-\pi^+]\pi^-$ and $\Xi_b^0 \to \Xi_c^+[pK^-\pi^+]\pi^-\pi^+\pi^-$

[PRL 126 (2021) 252003] by CMS

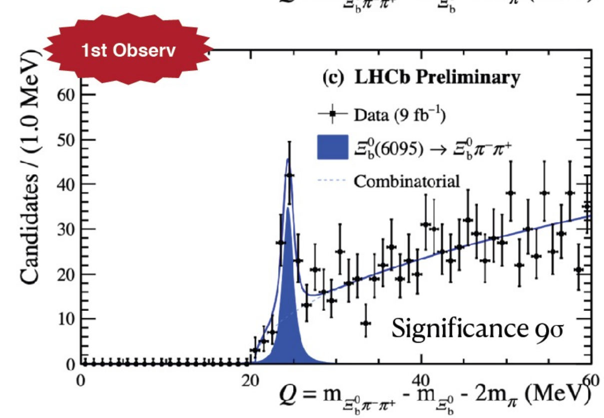




	Value [MeV]
Q_0 ($\Xi_b^-(6100)$)	$23.60 \pm 0.11 \pm 0.02$
Γ ($\Xi_b^-(6100)$)	$0.94 \pm 0.30 \pm 0.08$
m_0 ($\Xi_b^-(6100)$)	$6099.74 \pm 0.11 \pm 0.02 \pm 0.6$ (Ξ_b^-)
Q_0 ($\Xi_b^0(6087)$)	$16.20 \pm 0.20 \pm 0.06$
Γ ($\Xi_b^0(6087)$)	$2.43 \pm 0.51 \pm 0.10$
m_0 ($\Xi_b^0(6087)$)	$6087.24 \pm 0.20 \pm 0.06 \pm 0.5$ (Ξ_b^0)
Q_0 ($\Xi_b^0(6095)$)	$24.32 \pm 0.15 \pm 0.03$
Γ ($\Xi_b^0(6095)$)	$0.50 \pm 0.33 \pm 0.11$
m_0 ($\Xi_b^0(6095)$)	$6095.36 \pm 0.15 \pm 0.03 \pm 0.5$ (Ξ_b^0)

Confirmation

1st Observ



✓ Consistent with naïve expectation for 1P states

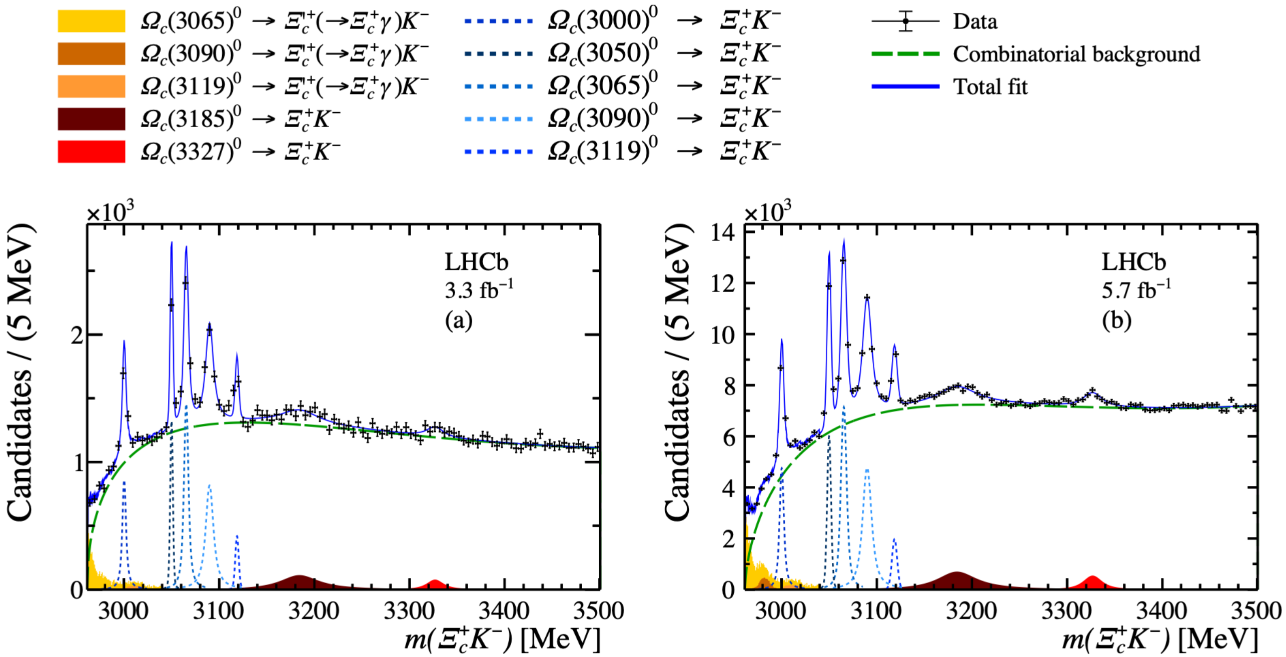
[LHCb-PAPER-2023-008] in preparation

Observation of new $\Omega_c^0 \to \Xi_c^+ K^-$

Zhihao Xu, Jibo He

[arXiv: 2302.04733]

➢Using full 9 fb^{-1} Run1+Run2 LHCb data

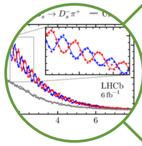


Resonance	m (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.44 \pm 0.07\ ^{+0.07}_{-0.13} \pm 0.23$	$3.83 \pm 0.23\ ^{+1.59}_{-0.29}$
$\Omega_c(3050)^0$	$3050.18 \pm 0.04\ ^{+0.06}_{-0.07} \pm 0.23$	$0.67 \pm 0.17\ ^{+0.64}_{-0.72}$
		$< 1.8\,\text{MeV}, 95\%$ C.L.
$\Omega_c(3065)^0$	$3065.63 \pm 0.06\ ^{+0.06}_{-0.06} \pm 0.23$	$3.79 \pm 0.20\ ^{+0.38}_{-0.47}$
$\Omega_c(3090)^0$	$3090.16 \pm 0.11\ ^{+0.06}_{-0.10} \pm 0.23$	$8.48 \pm 0.44\ ^{+0.61}_{-1.62}$
$\Omega_c(3119)^0$	$3118.98 \pm 0.12\ ^{+0.09}_{-0.23} \pm 0.23$	$0.60 \pm 0.63\ ^{+0.90}_{-1.05}$
		$< 2.5\,\text{MeV}, 95\%$ C.L.
$\Omega_c(3185)^0$	$3185.1 \pm 1.7\ ^{+7.4}_{-0.9} \pm 0.2$	$50 \pm 7\ ^{+10}_{-20}$
$\Omega_c(3327)^0$	$3327.1 \pm 1.2\ ^{+0.1}_{-1.3} \pm 0.2$	$20 \pm 5\ ^{+13}_{-1}$

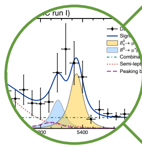
✓Most precise mass and width measurement

✓Two new states:

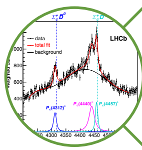
Outline



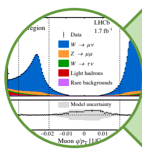
CP violation



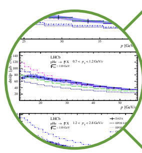
Rare decays



Spectroscopy



Electroweak



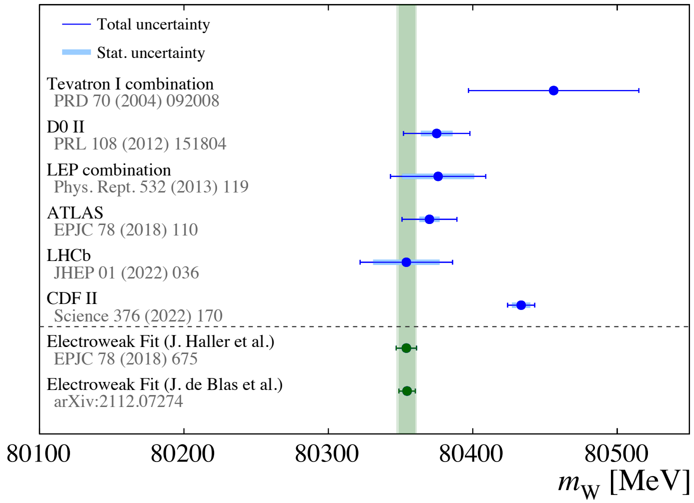
Heavy ions & fixed target

W mass

- m_W is directly related to EW symmetry breaking in SM

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta)$$

α: fine structure constant
Δ: loop corrections



[JHEP 01 (2022) 036]

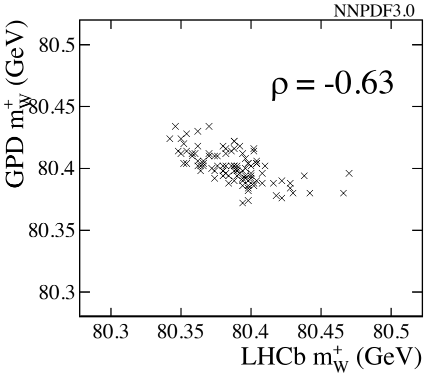
- 1.7 fb^{-1} (~1/3 of Run 2 data) result:

$$m_W = 80354 \pm 23 \pm 10 \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}$$

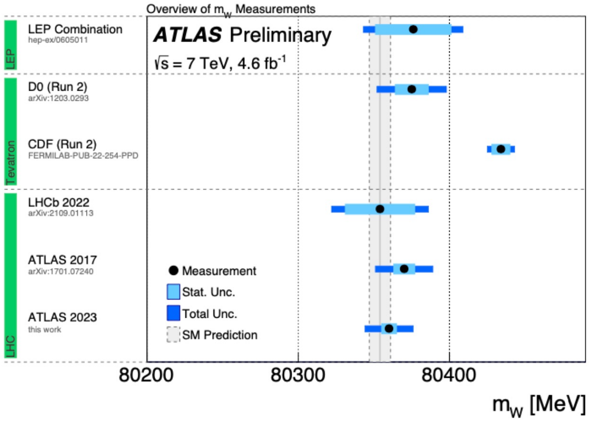
- ✓ Full Run 2 data ⇒ stat. uncertainty ~ 14 MeV
- ✓ Targeting an overall precision of ~ 20 MeV with all data and efforts to reduce syst. uncertainty

- ✓ PDF uncertainty at LHCb anticorrelated to that of GPD (ATLAS&CMS) ⇒ LHC experiments can achieve a sensitivity close to the global EW fit (80354 ± 7 MeV)
- ✓ Efforts ongoing for m_W combination

[EPJ C75 (2015) 601]



[link to Moriond talk]



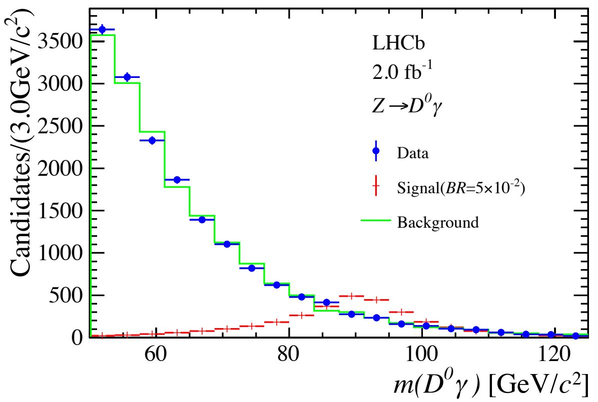
Rare W and Z decays

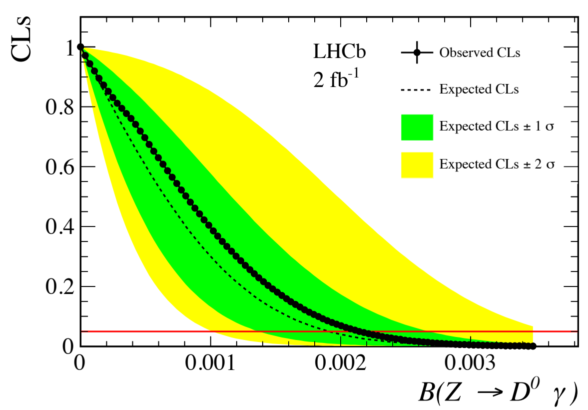
Qundong Han,
Hang Yin

- Hadronic-radiative W and Z decays can provide stringent tests of QCD factorization formalism
- 2 fb^{-1} of Run 2 data used

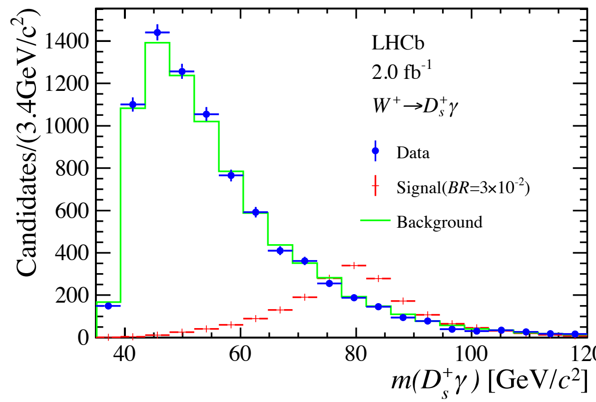
[arXiv: 2212.07120]

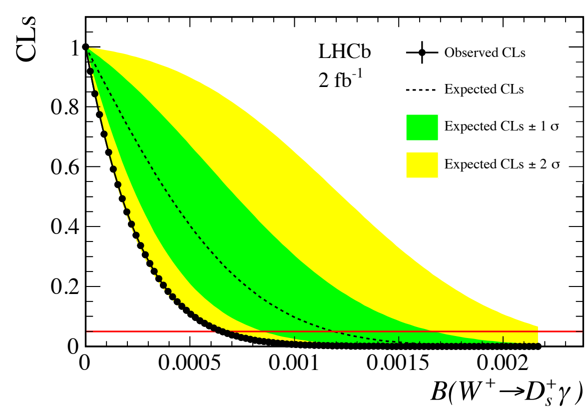
✓ First search of $Z \to D^0\gamma$:
$\mathcal{B} < 2.1\times10^{-3}$ @ 95% CL

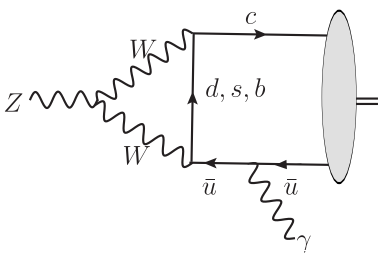


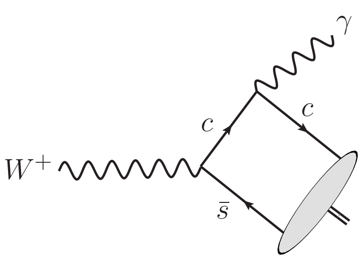


✓ Best limit on $W^+ \to D_s^+\gamma$:
$\mathcal{B} < 6.5\times10^{-4}$ @ 95% CL

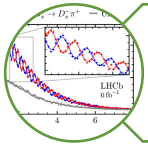




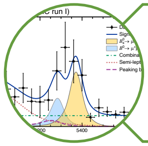




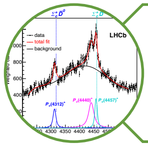
Outline



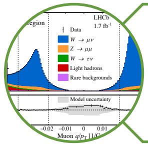
CP violation



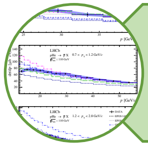
Rare decays



Spectroscopy



Electroweak

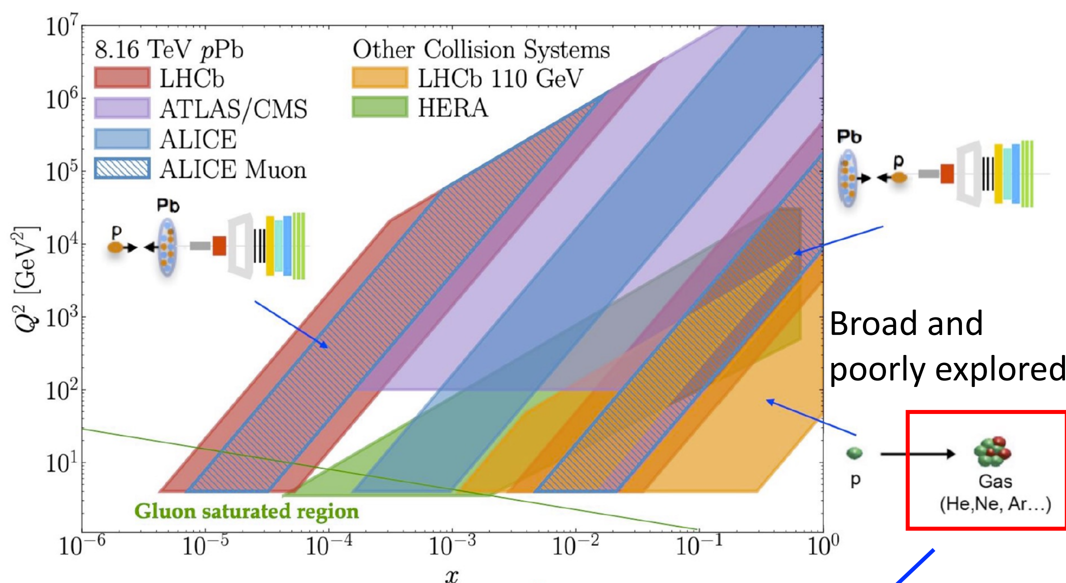


Heavy ions & fixed target

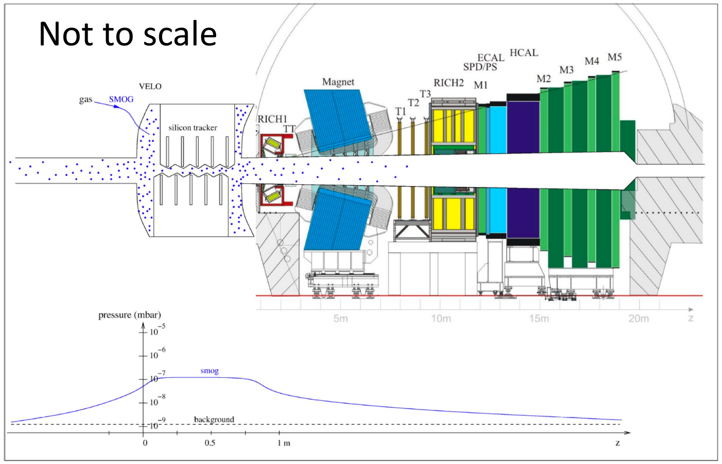
Heavy-ion physics at LHCb

- LHCb covers complementary kinematic regions to other experiments
- Unique role as highest-energy fixed-target experiment ever
- A broad physics scheme
  - ✓ Hadronization in hot and cold nuclear matter
  - ✓ Probes for quark-gluon plasma (QGP)
  - ✓ Constrain nPDF
  - ✓ Cosmic ray and astro-particle physics
  - ✓ Ultra-peripheral collisions (UPC)
  - ✓ Exotic production
  - ✓ …….

$Q^2 \sim m^2 + p_T^2$



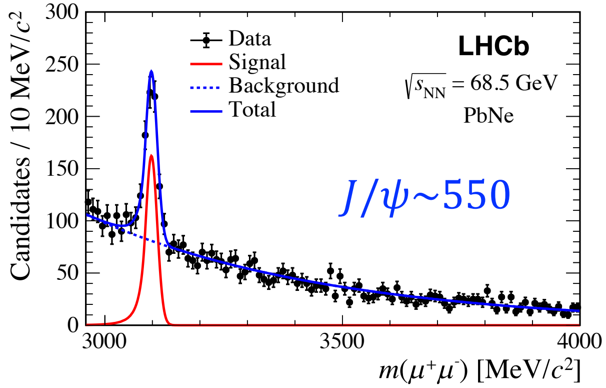
$x \sim \frac{Q}{\sqrt{s_{NN}}} e^{-\eta}$

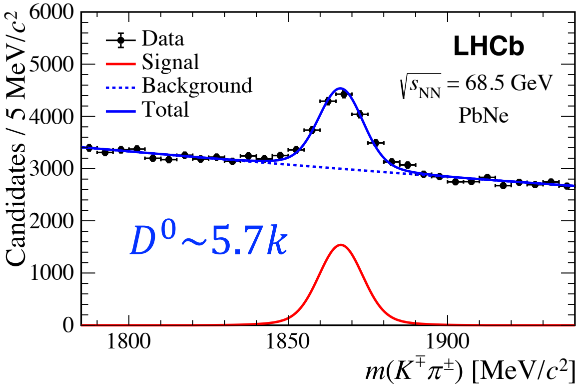


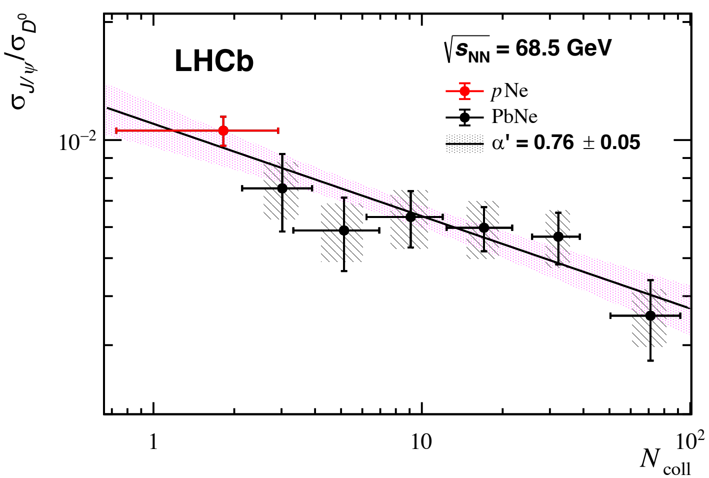
J/ψ and D^0 production in PbNe

[arXiv: 2211.11652]

- The first measurement in fixed-target nucleus-nucleus collision at the LHC!
- Lead ion beam with 2.5 TeV per nucleon + gaseous neon at rest $\Rightarrow \sqrt{s_{NN}} = 68.5$ GeV
- Search for potential formation of QGP through J/ψ suppression; D^0 is a proxy for the overall $c\bar{c}$ production





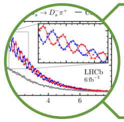


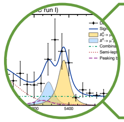
- ✓ J/ψ production is affected by additional nuclear effects wrt D^0
- ✓ $\sigma(J/\psi)/\sigma(D^0)$ vs. N_{coll} slope agrees with measurements from proton-nucleus collisions by NA50 $\Rightarrow$ no anomalous J/ψ suppression indicating QGP is observed

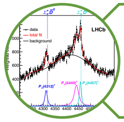
[PLB 410 (1997) 337]

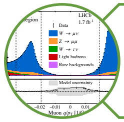
Summary

- ➢LHCb keeps making important contributions to a rich physics program
- ➢There are many more interesting results not covered in this talk: [LHCb publications]


CP violation


Rare decays


Spectroscopy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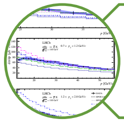
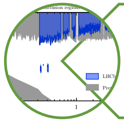
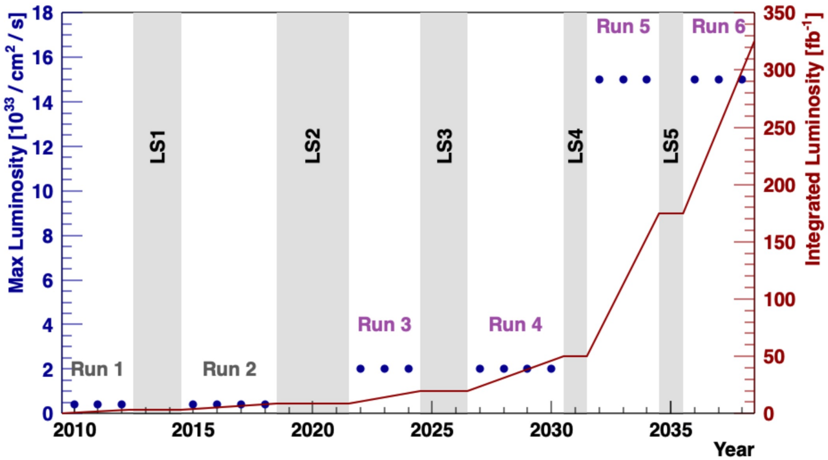

Heavy ions & fixed target


Dark sector ...



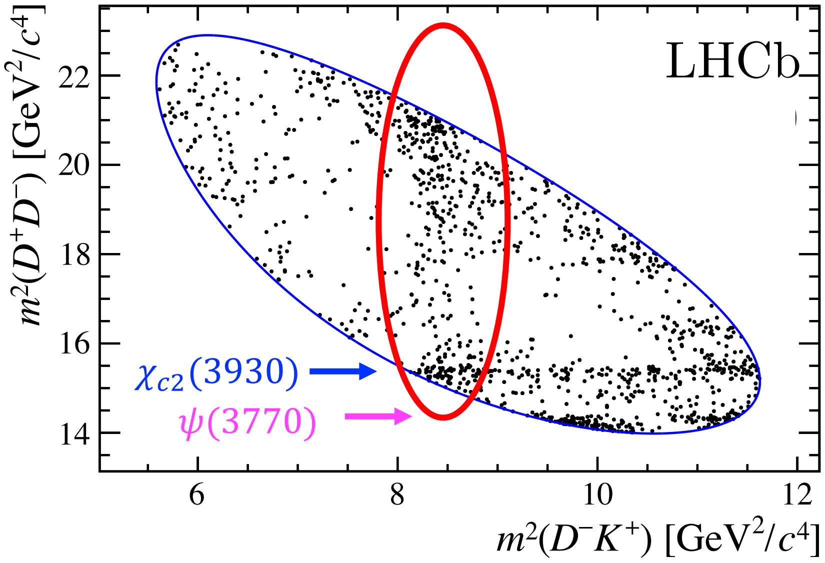
More exciting results are to come!

Back up

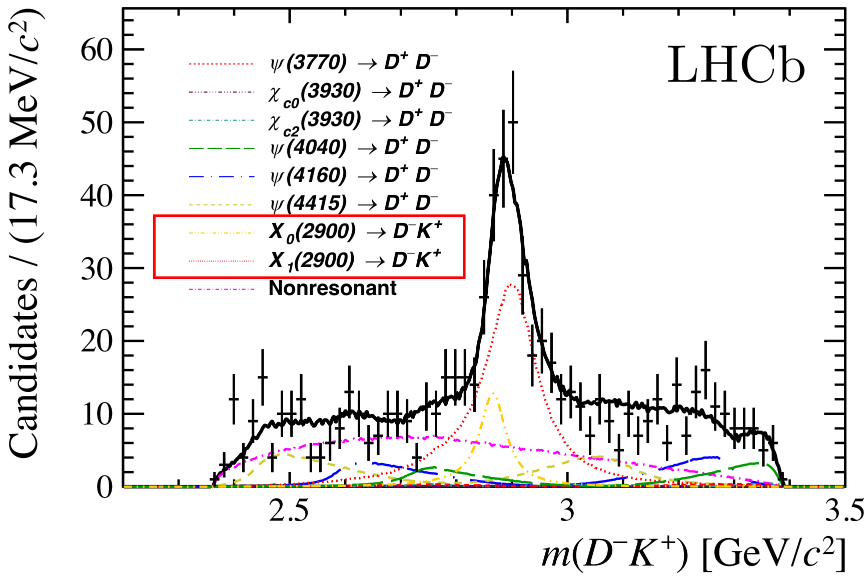
T_{cs} in $B^+ \to D^+D^-K^+$

[PRL 125 (2020) 242001]
[PR D102 (2020) 112003]

➢ Resonant structures observed in the D^-K^+ system from an amplitude analysis of the $B^+ \to D^+D^-K^+$ decay



$m(D^+D^-) > 4$ GeV$/c^2$



$$X_0(2900): \quad M = 2.866 \pm 0.007 \pm 0.002\,\mathrm{GeV}/c^2, \quad \Gamma = 57 \pm 12 \pm 4\,\mathrm{MeV}$$
$$X_1(2900): \quad M = 2.904 \pm 0.005 \pm 0.001\,\mathrm{GeV}/c^2, \quad \Gamma = 110 \pm 11 \pm 4\,\mathrm{MeV}$$

➢ First discovery of open-charm tetraquarks with four different flavors $[cs\bar{u}\bar{d}]$!

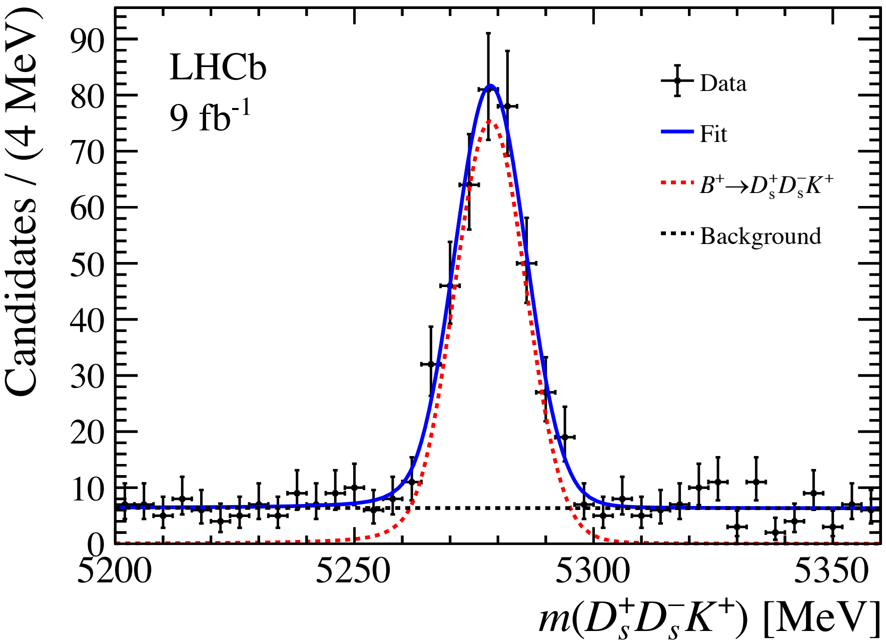
➢ The observation motivates study of $B \to \bar{D}D_s\pi$

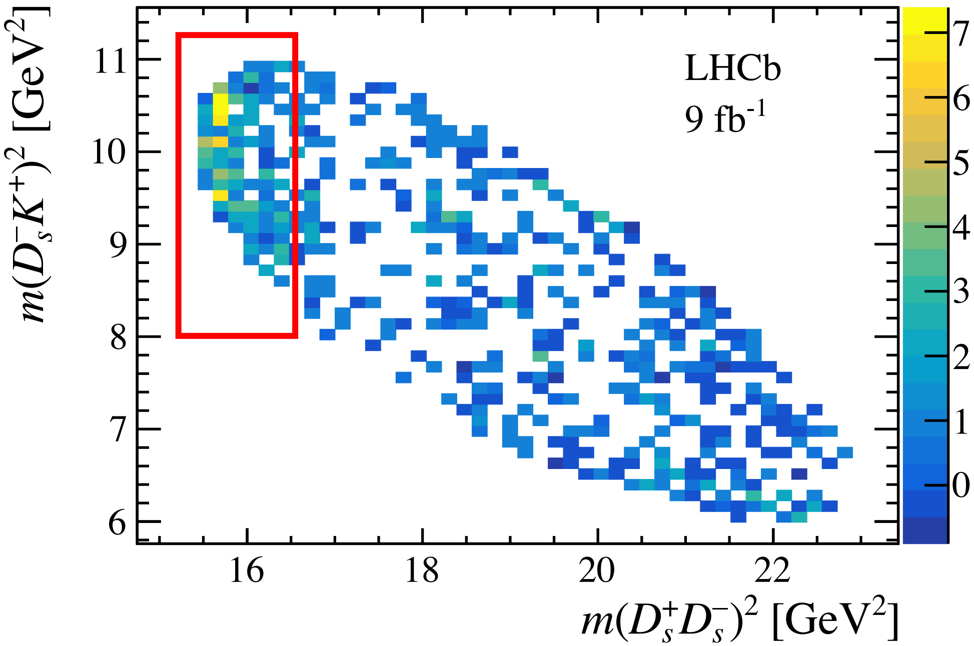
Observation of $B^+ \to D_s^+ D_s^- K^+$

[arXiv: 2211.05034]
[arXiv: 2210.15153]

- Full 9 fb^{-1} Run1+Run2 LHCb data

Chen Chen, Hongrong Qi, Liming Zhang





$N_{\text{sig}} = 360 \pm 22$
Purity: 84%

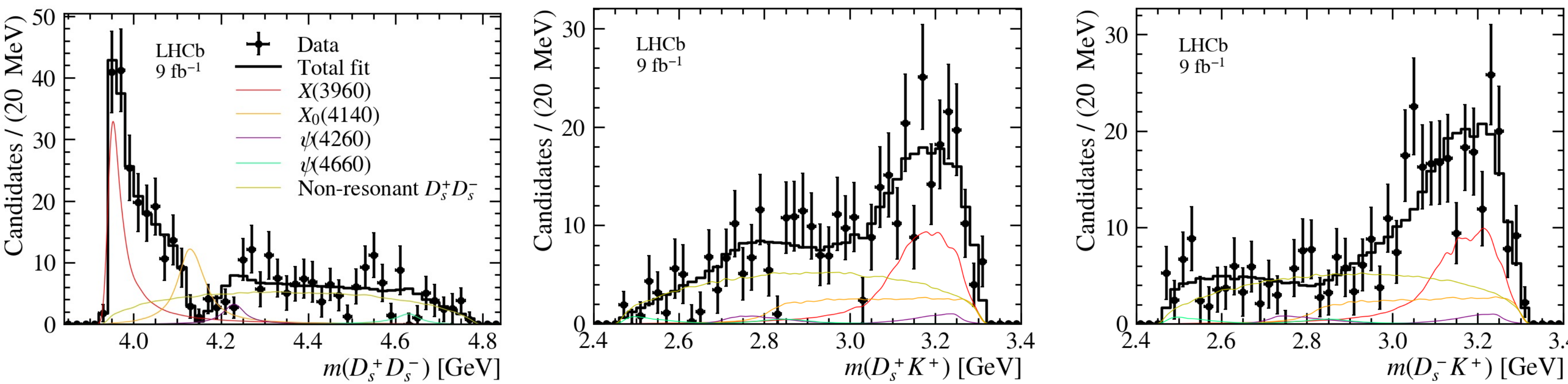
✓Near-threshold enhancement in $m(D_s^+ D_s^-)$
$\Rightarrow$ amplitude analysis

Observation of $X(3960) \to D_s^+ D_s^-$

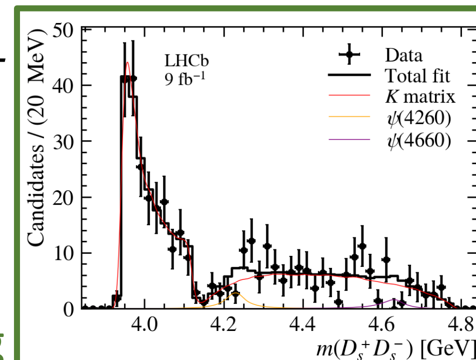
[arXiv: 2211.05034]
[arXiv: 2210.15153]

- Baseline model well describes data
  - ✓ 0^{++}: $X(3960)$ (14.3σ), $X_0(4140)$ (3.9σ), Non-resonant
  - ✓ 1^{--}: $\psi(4260), \psi(4660)$

Chen Chen, Hongrong Qi, Liming Zhang



- **$X(3960)$**: threshold enhancement
  - ✓ $J^{PC} = 0^{++}$ preferred over 1^{--} and 2^{++} by 9.3σ and 12.3σ
- **$X_0(4140)$**: dip at $\sim$4.14 GeV via interference
  - ✓ $J^{PC} = 0^{++}$ preferred over 1^{--} and 2^{++} by 3.5σ and 4.2σ
  - ✓ the dip can also be described by $J/\psi\phi \to D_s^+ D_s^-$ scattering



$X(3960)$ and $\chi_{c0}(3930)$

Chen Chen, Hongrong Qi, Liming Zhang

[arXiv: 2211.05034]
[arXiv: 2210.15153]

	M [MeV]	Γ [MeV]	J^{PC}
$X(3960)$	$3955 \pm 6 \pm 12$	$48 \pm 17 \pm 10$	0^{++}
$\chi_{c0}(3930)$	3924 ± 2	17 ± 5	

- Same particle?

$\mathcal{FF}$: Fit fraction

$$\frac{\Gamma(X \to D^+D^-)}{\Gamma(X \to D_s^+D_s^-)} = \frac{\mathcal{B}(B^+ \to D^+D^-K^+)\times\mathcal{FF}^X_{B^+\to D^+D^-K^+}}{\mathcal{B}(B^+ \to D_s^+D_s^-K^+)\times\mathcal{FF}^X_{B^+\to D_s^+D_s^-K^+}} = 0.29 \pm 0.09 \pm 0.10 \pm 0.08$$

  - ✓Creation of $s\bar{s}$ from vacuum is suppressed wrt $u\bar{u}$ or $d\bar{d}$
  - ✓$X \to D_s^+D_s^-$ has smaller phase-space factor than $X \to D^+D^-$
  - $\Rightarrow$ X has an exotic nature! Candidate for $c\bar{c}s\bar{s}$

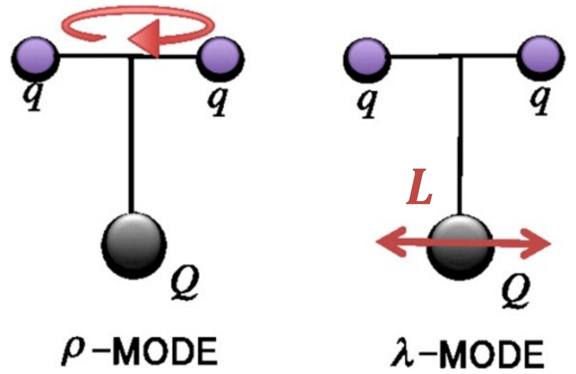
- Different particles?
  - ✓No obvious candidate within conventional charmonium multiplets for them; likely to be exotic

History of Ξ_c^{**}

➢Heavy quark-light diquark $Q[qq]$ model is widely used to describe Qqq systems

✓λ-mode: low-lying states well established ✓ρ-mode: no firm assignment yet

	$J^P_{[qq]} = 0^+$	$J^P_{[qq]} = 1^+$
$L = 0$	$\left(\frac{1}{2}\right)^+$	$\left(\frac{1}{2}\right)^+, \left(\frac{3}{2}\right)^+$
$L = 1$	$\left(\frac{1}{2}\right)^-, \left(\frac{3}{2}\right)^-$	$\left(\frac{1}{2}\right)^-, \left(\frac{3}{2}\right)^-, \left(\frac{1}{2}\right)^-, \left(\frac{3}{2}\right)^-, \left(\frac{5}{2}\right)^-$
$L = 2$	$\left(\frac{3}{2}\right)^+, \left(\frac{5}{2}\right)^+$	……



[PRD 92 (2015) 114029]

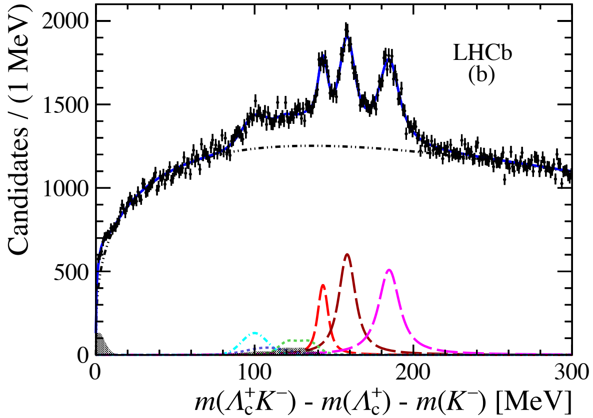
[PRD 77 (2008) 031101] [EPJC 78 (2018) 252] [EPJC 78 (2018) 928]

➢$\Xi_c(2930)^{0/+}$ seen by BaBar and Belle in $B \to \Lambda_c^+ \overline{\Lambda}_c^- K$

➢Prompt $\Lambda_c^+ K^-$ studied at LHCb

✓ $\Xi_c(2930)^0$ resolved into $\Xi_c(2923)^0 + \Xi_c(2939)^0$

✓Peak at ~2880 MeV but suffer from feed-down



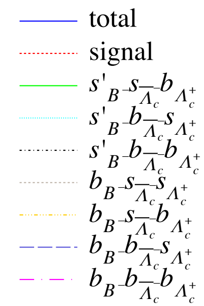
[PRL 124 (2020) 222001]

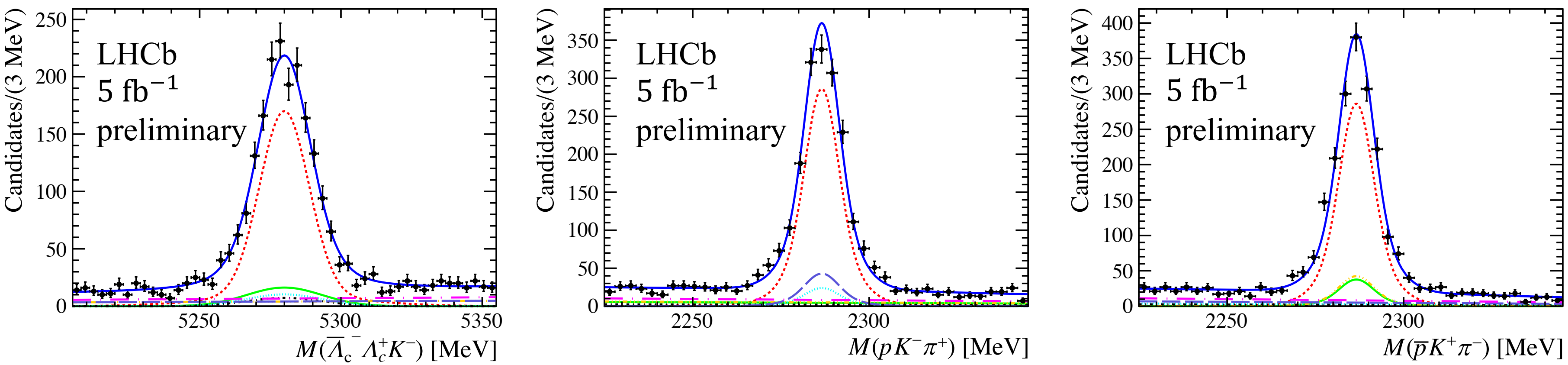
Study of $B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-$

[arXiv: 2211.00812]

Yiming Li, Yu Lu

- $B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-$ provides opportunities for
  - ✓ Search for $\Xi_c^{0**} \to \Lambda_c^+ K^-$ with lower background level & feed-down contribution in prompt $\Lambda_c^+ K^-$ spectrum will not present
  - ✓ Search for possible exotics in $\Lambda_c^+ \overline{\Lambda}_c^-$ and $\overline{\Lambda}_c^- K^-$ systems
- 5 fb^{-1} LHCb data at $\sqrt{s} = 13$ TeV used
- Signals extracted using $(m_{B^-}, m_{\Lambda_c^+}, m_{\overline{\Lambda}_c^-})$ 3D fit: $N_{\mathrm{sig}} = 1365 \pm 42$





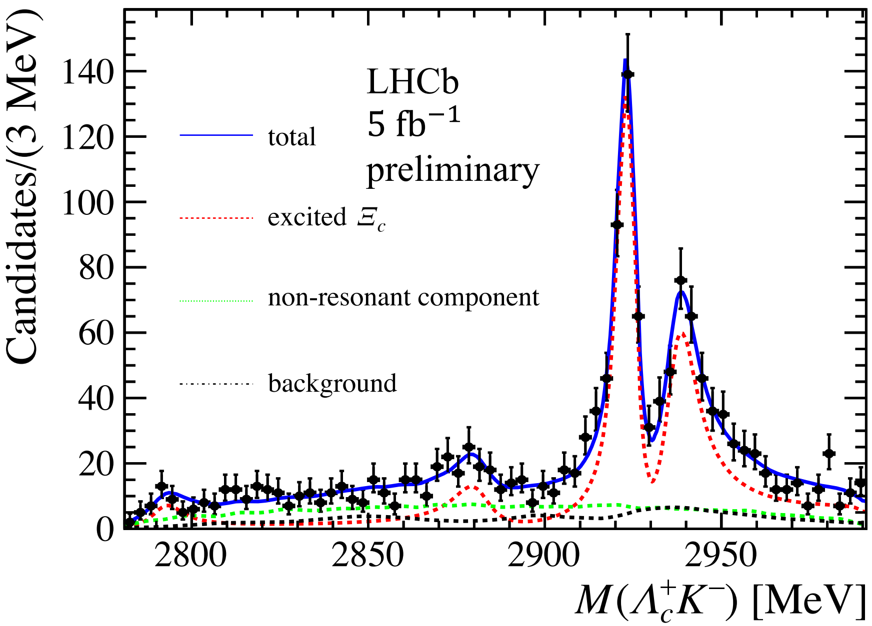
$$\frac{\mathcal{B}(B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-)}{\mathcal{B}(B^- \to D^+ D^- K^-)} = 2.36 \pm 0.11 \pm 0.22 \pm 0.25(\mathcal{B})$$

$\Lambda_c^+ K^-$ mass spectrum

[arXiv: 2211.00812]

Yiming Li, Yu Lu

- $\Xi_c(2790)^0, \Xi_c(2880)^0, \Xi_c(2923)^0, \Xi_c(2939)^0$ included in the nominal fit
  - ✓ $J^P = 1/2^-$ (known), $1/2^-, 3/2^-, 3/2^-$ (1P $J^P_{[qq]} = 1^+$ multiplets; alternatives studied in systematics); interference considered
  - ✓ $\Xi_c(2790)^0$: $3.7\sigma \Rightarrow$ evidence of new decay mode
  - ✓ $\Xi_c(2880)^0$: $3.8\sigma \Rightarrow$ evidence of a new state
  - ✓ $\Xi_c(2923)^0, \Xi_c(2939)^0$: confirm prompt $\Lambda_c^+ K^-$ observation
- No significant structure in $M(\overline{\Lambda}_c^- K^-)$ and $M(\Lambda_c^+ \overline{\Lambda}_c^-)$



$$M(\Xi_c(2880)^0) = 2881.8 \pm 3.1 \pm 8.5 \text{ MeV}$$
$$\Gamma(\Xi_c(2880)^0) = 12.4 \pm 5.3 \pm 5.8 \text{ MeV}$$

$$M(\Xi_c(2923)^0) = 2924.5 \pm 0.4 \pm 1.1 \text{ MeV}$$
$$\Gamma(\Xi_c(2923)^0) = 4.8 \pm 0.9 \pm 1.5 \text{ MeV}$$

$$M(\Xi_c(2939)^0) = 2938.5 \pm 0.9 \pm 2.3 \text{ MeV}$$
$$\Gamma(\Xi_c(2939)^0) = 11.0 \pm 1.9 \pm 7.5 \text{ MeV}$$

Interpretation of $\Xi_b^{-/0**} \to \Xi_b^{-/0}\pi^+\pi^-$

	$J^P_{[qq]} = 0^+$	$J^P_{[qq]} = 1^+$
$L = 0$	$(1/2)^+$ $\Xi_b^{0,-}$	$(1/2)^+, (3/2)^+$ $\Xi_b'(5935)^-, \Xi_b(5955)^- \to \Xi_b^0\pi^-$ $\Xi_b(5945)^0 \to \Xi_b^-\pi^+$
$L = 1$	$(1/2)^-, (3/2)^-$ $(3/2)^- \to \Xi_b^*(3/2+)\pi$ $(1/2)^- \to \Xi_b'(1/2+)\pi$	……

	Value [MeV]
$Q_0\ (\Xi_b^-(6100))$	$23.60 \pm 0.11 \pm 0.02$
$\Gamma\ (\Xi_b^-(6100))$	$0.94 \pm 0.30 \pm 0.08$
$m_0\ (\Xi_b^-(6100))$	$6099.74 \pm 0.11 \pm 0.02\ \pm 0.6\ (\Xi_b^-)$
$Q_0\ (\Xi_b^0(6087))$	$16.20 \pm 0.20 \pm 0.06$
$\Gamma\ (\Xi_b^0(6087))$	$2.43 \pm 0.51 \pm 0.10$
$m_0\ (\Xi_b^0(6087))$	$6087.24 \pm 0.20 \pm 0.06\ \pm 0.5\ (\Xi_b^0)$
$Q_0\ (\Xi_b^0(6095))$	$24.32 \pm 0.15 \pm 0.03$
$\Gamma\ (\Xi_b^0(6095))$	$0.50 \pm 0.33 \pm 0.11$
$m_0\ (\Xi_b^0(6095))$	$6095.36 \pm 0.15 \pm 0.03\ \pm 0.5\ (\Xi_b^0)$
$Q_0\ (\Xi_b^{*0})$	$15.80 \pm 0.02 \pm 0.01$
$\Gamma\ (\Xi_b^{*0})$	$0.87 \pm 0.06 \pm 0.05$
$m_0\ (\Xi_b^{*0})$	$5952.37 \pm 0.02 \pm 0.01\ \pm 0.6\ (\Xi_b^-)$
$Q_0\ (\Xi_b^{\prime -})$	$3.66 \pm 0.01 \pm 0.00$
$\Gamma\ (\Xi_b^{\prime -})$	$0.03 \pm 0.01 \pm 0.03$
$m_0\ (\Xi_b^{\prime -})$	$5935.13 \pm 0.01 \pm 0.00\ \pm 0.5\ (\Xi_b^0)$
$Q_0\ (\Xi_b^{*-})$	$24.27 \pm 0.03 \pm 0.01$
$\Gamma\ (\Xi_b^{*-})$	$1.43 \pm 0.08 \pm 0.08$
$m_0\ (\Xi_b^{*-})$	$5955.74 \pm 0.03 \pm 0.01\ \pm 0.5\ (\Xi_b^0)$

Confirmation

1st Observ

Improvements

[LHCb-PAPER-2023-008]
in preparation

*Neutral 1S $(1^+, 1/2^+)$ not seen because it is highly likely below $\Xi_b^-\pi^+$ threshold thus decaying 100% to $\Xi_b^0\pi^0$ or $\Xi_b^0\gamma$
*Charged 1P $(0^+, 3/2^-)$ observed by CMS [PRL 126 (2021) 252003]

✓ Results consistent with naïve expectation for 1P $J^P_{[qq]} = 0^+$ $(1/2)^-, (3/2)^-$ doublet

*Charged 1P $(0^+, 1/2^-)$ not seen because it mainly decays to the missing neutral 1S $(1^+, 1/2^+)$