Flavour physics at LHCb

Selected results

Sergey Barsuk, IJCLab Orsay
on behalf of the LHCb collaboration

- Flavour physics and LHCb detector
- Examples of recent measurements
  - B meson lifetimes
  - Heavy flavour spectroscopy
  - CPV angle γ
  - CPV in b-baryons
  - CPV in charm sector
  - Rare b → s/d $\ell^+\ell^-$ decays
  - D^0 and $\Upsilon(nS)$ production in heavy-ion collisions
- Outlook

Marc Chagall, Over the town

New Opportunities for Particle Physics 2026
Beijing, August 14-16

Flavour physics: Cabibbo theory and absence of FCNC

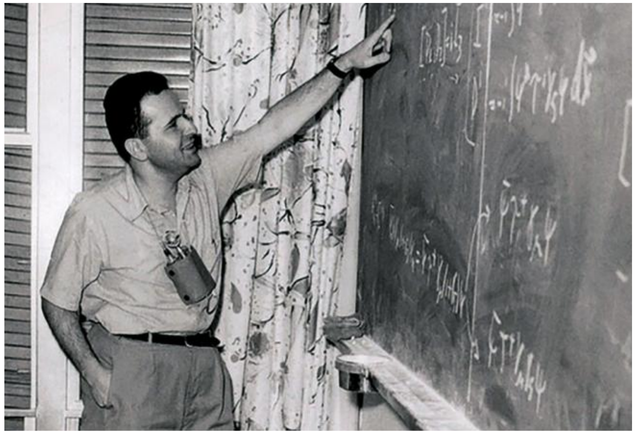
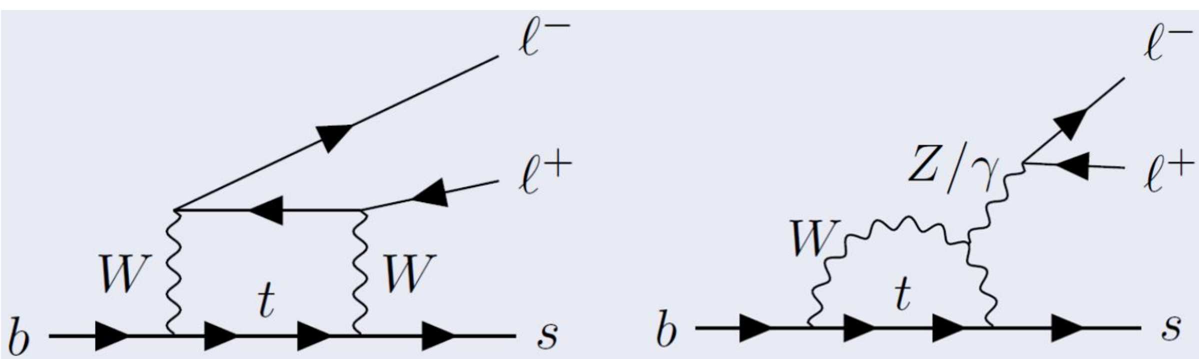


Photo credit: *Monica Pepe-Altarelli, Cabibbo's family*

- ❑ Simultaneous analysis of leptonic and semi-leptonic decays
- ❑ Cabibbo rotation angle: **link between weak and mass eigenstates**

Photo credit: https://indico-tdli.sjtu.edu.cn/event/30/images/9-GIM_2011.JPG

- ❑ **GIM mechanism** to explain the **absence of FCNC** at tree level
- ❑ Prediction of charm quark



- ❑ Universality of weak neutral current
- ❑ Non-universality of weak charged current

- ❑ **Flavour physics probes new physics energy scales >> 1 TeV** via loop-mediated processes

- Standard Model (SM) describes the quarks mixing via 3X3 unitary (complex) **CKM matrix**

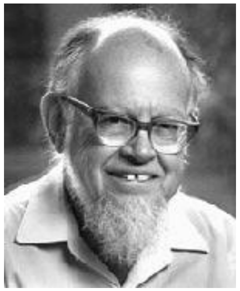


Photo credit: CMU

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{array}{cc} & \begin{array}{ccc} d & s & b \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \end{array}$$

- Search for physics beyond SM indirectly, via decays mediated by loops, **rare decays**

- **CP-parity violation** (CPV) is successfully (so far) accommodated in all flavor species **via a single complex phase**, intimately linked to the number of generations
- Experimentally discovered in strange, **charm and beauty sectors.** Suppressed for charm as codified via CKM matrix elements and GIM mechanism

Photo credit: KEK

- Powerful consistency checks, e.g. via **unitarity triangles**

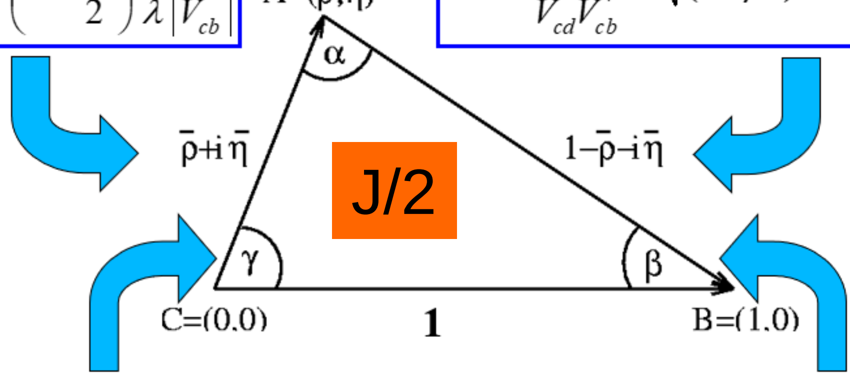
- Powerful consistency checks, e.g. via **unitarity triangles**

$$\overline{AC} = \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} = \sqrt{\bar{\rho}^2+\bar{\eta}^2} = \left(1-\frac{\lambda^2}{2}\right)\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|$$

(b→u transitions)

$$\overline{AB} = \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = \sqrt{(1-\bar{\rho})^2+\bar{\eta}^2} = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{cb}}\right| \sim \frac{1}{\lambda}\left|\frac{V_{td}}{V_{ts}}\right|$$

(B mixing)



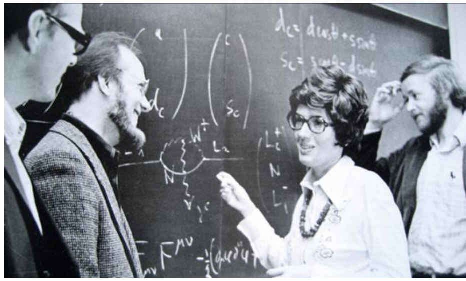


Photo credit: NORDITA

$$\boxed{\gamma = \arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) = \operatorname{atan}\left(\frac{\bar{\eta}}{\bar{\rho}}\right)}$$

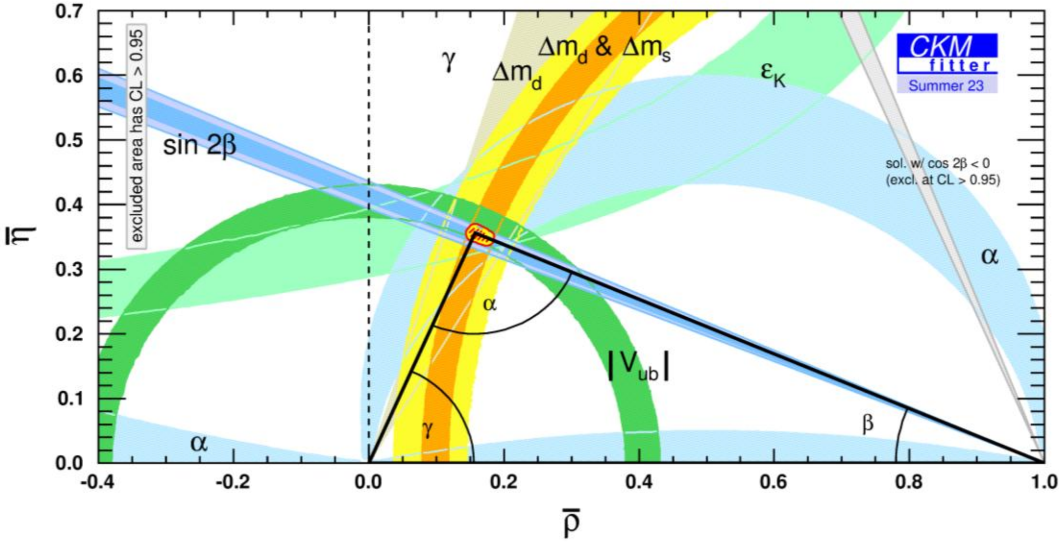
(b→u phase)

$$\beta = \arg\left(\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right) = \operatorname{atan}\left(\frac{\bar{\eta}}{(1-\bar{\rho})}\right)$$

(B mixing phase)

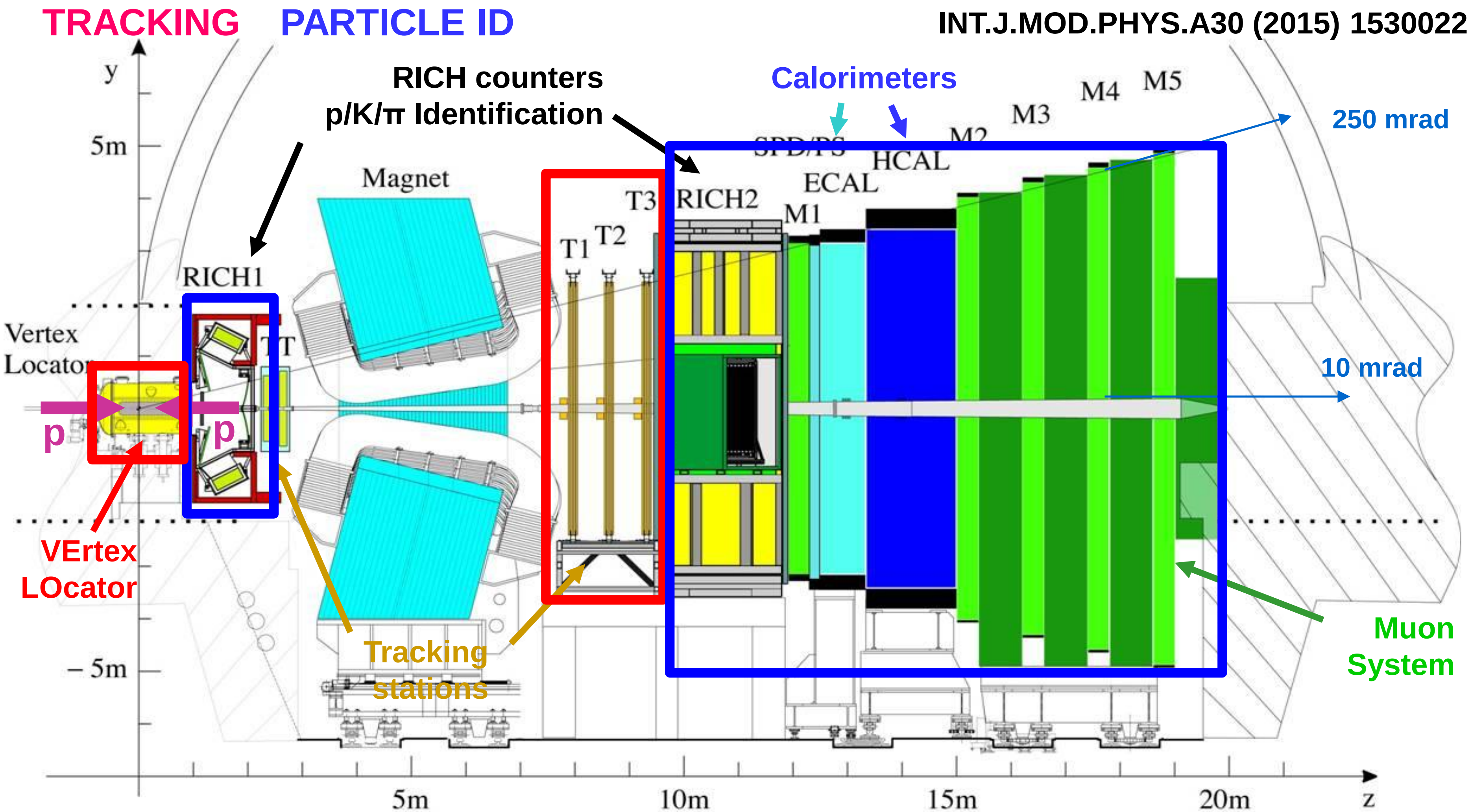
$$\alpha + \beta + \gamma = \pi$$

- Over-constrain UT, check that UT closes
- Compare measurements involving CPV (angles) to decay-probability measurements (sides)
- Compare CPV in tree-mediated processes to CPV in processes involving loops



LHCb – single-arm forward spectrometer, 10-250 mrad (V), 10-300 mrad (H)

INT.J.MOD.PHYS.A30 (2015) 1530022



Vertex reconstruction: VELO

Kinematics: Magnet, Tracker, Calorimeters

PID: RICHs, Calorimeters, Muon

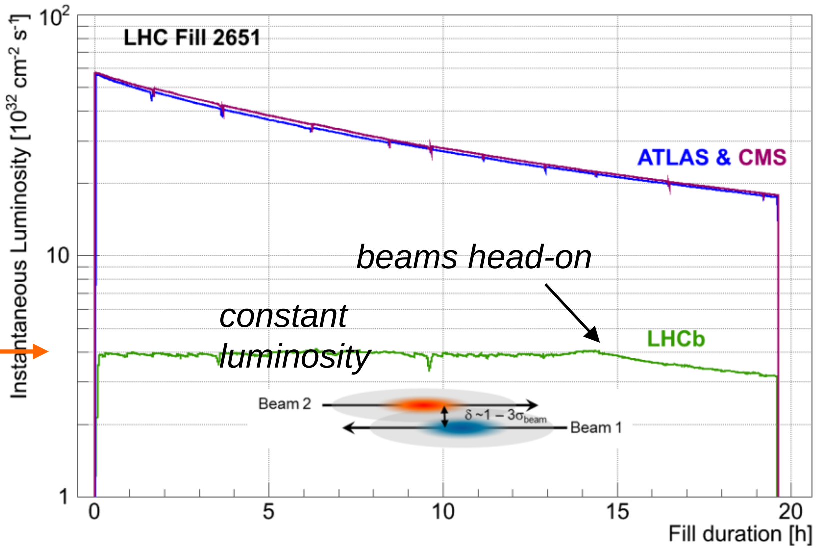
Trigger: Muon, Calorimeters, Tracker

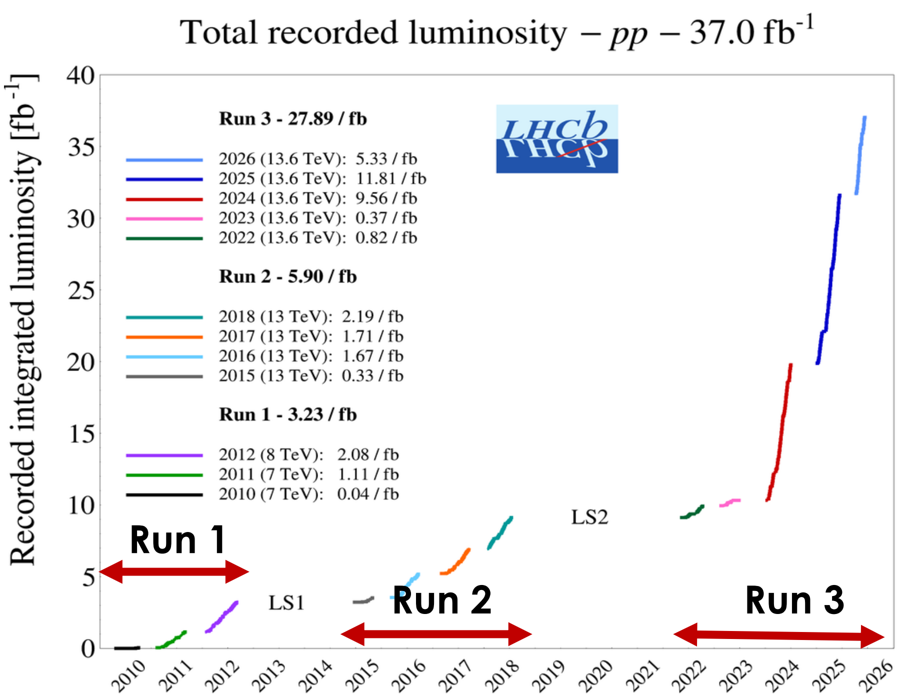
- **Heavy flavour production** at LHC: **prolific, forward peaked & correlated**
- LHCb **~4% of solid angle**, but **~40% of HF production x-section**

- **Excellent performance of LHC and LHCb**

- Luminosity leveling for LHCb

LHCb luminosity levelling



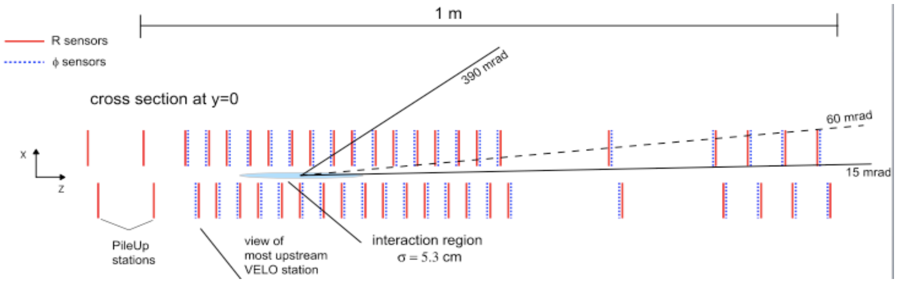


- ***pp* collisions**: $\sqrt{s}$ = 7, 8, 13, 13.6 TeV
- At $\sqrt{s}$ = 13 TeV:
  $\sigma(b\bar{b}) \approx 0.5$ mb, $\sigma(c\bar{c}) \approx 20\times\sigma(b\bar{b})$
- LHCb integrated luminosity : ∫Ldt ~ 37 fb^{-1}

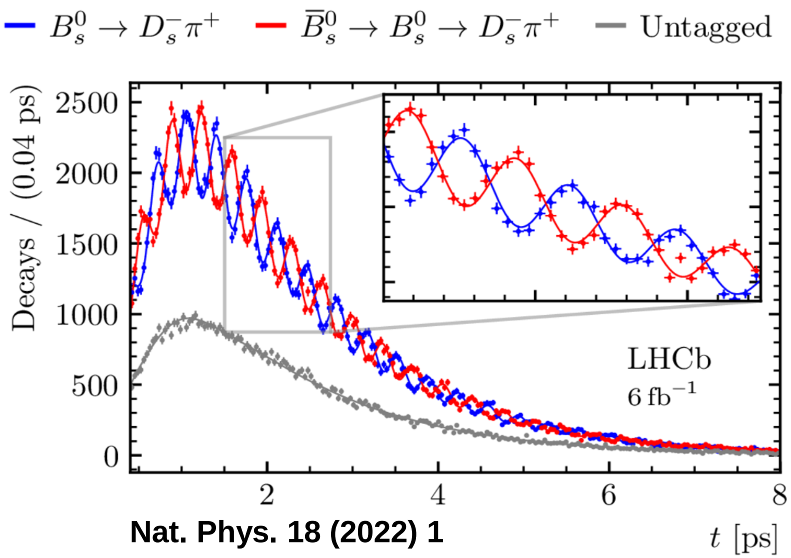
- **Heavy ion collisions**
- *Dedicated slide later*

JINST 8 (2013) P08002, JINST 9 (2014) P09007

- 88 semi-circular **microstrip Si sensors**
- Double-sided, **R and φ** layout
- 300 μm thick n-on-n sensors, strip pitches from 40 to 120 μm
- **First active strip at 8 mm from beam axis**



- Excellent **spatial resolution**, down to 4 μm for single tracks
- Precise **impact parameter** measurement,
  $\sigma_{IP} = 11.6 + 23.4/pT$ [μm]
- Precise **primary vertex** reconstruction,
  $\sigma_{x,y}$ = 13 μm, σ_z = 69 μm for vertex of 25 tracks
- Excellent **proper time** resolution
- **Vertex resolution** allows to resolve fast (x~27) $B_s\bar{B}_s$ oscillations

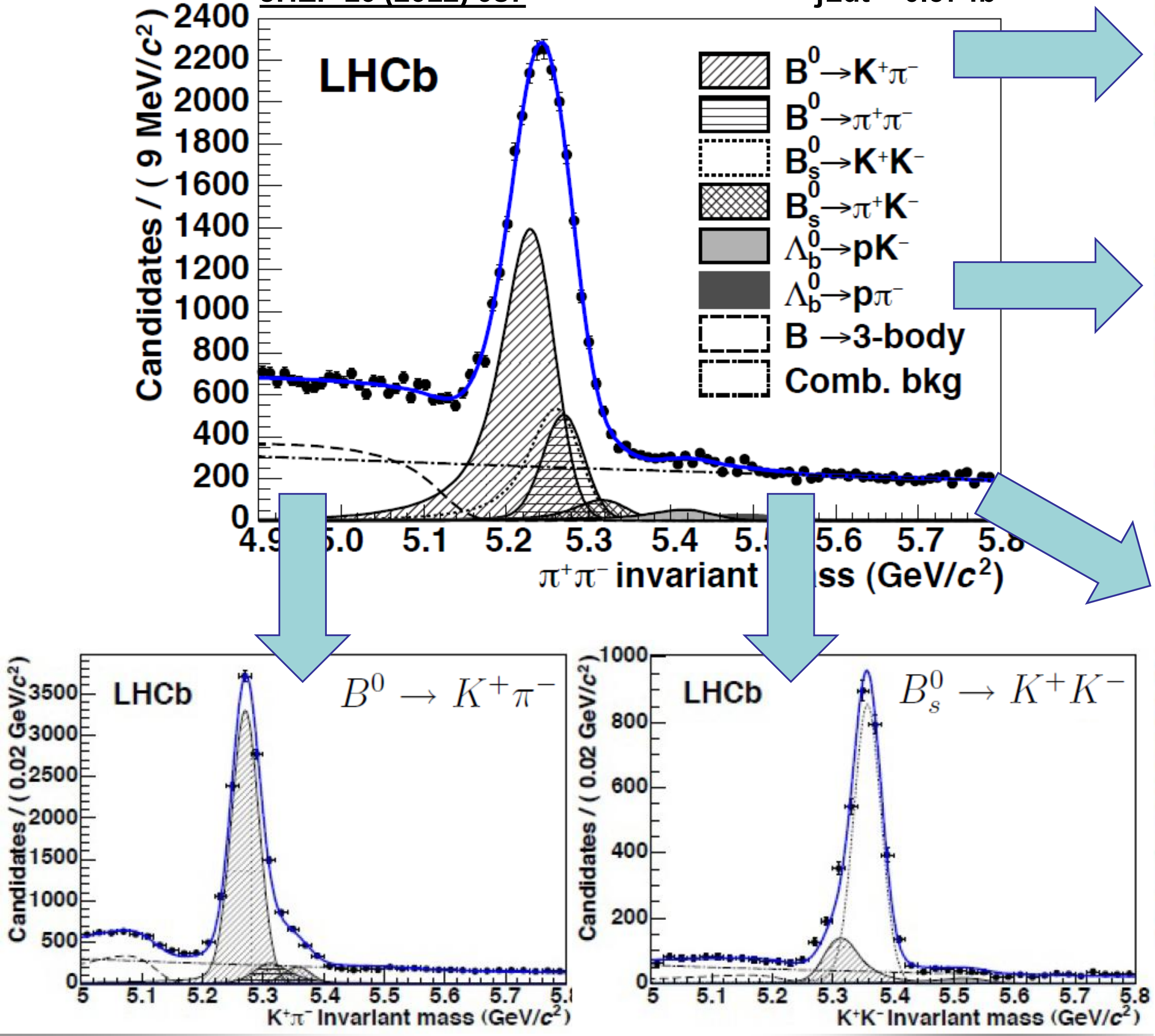


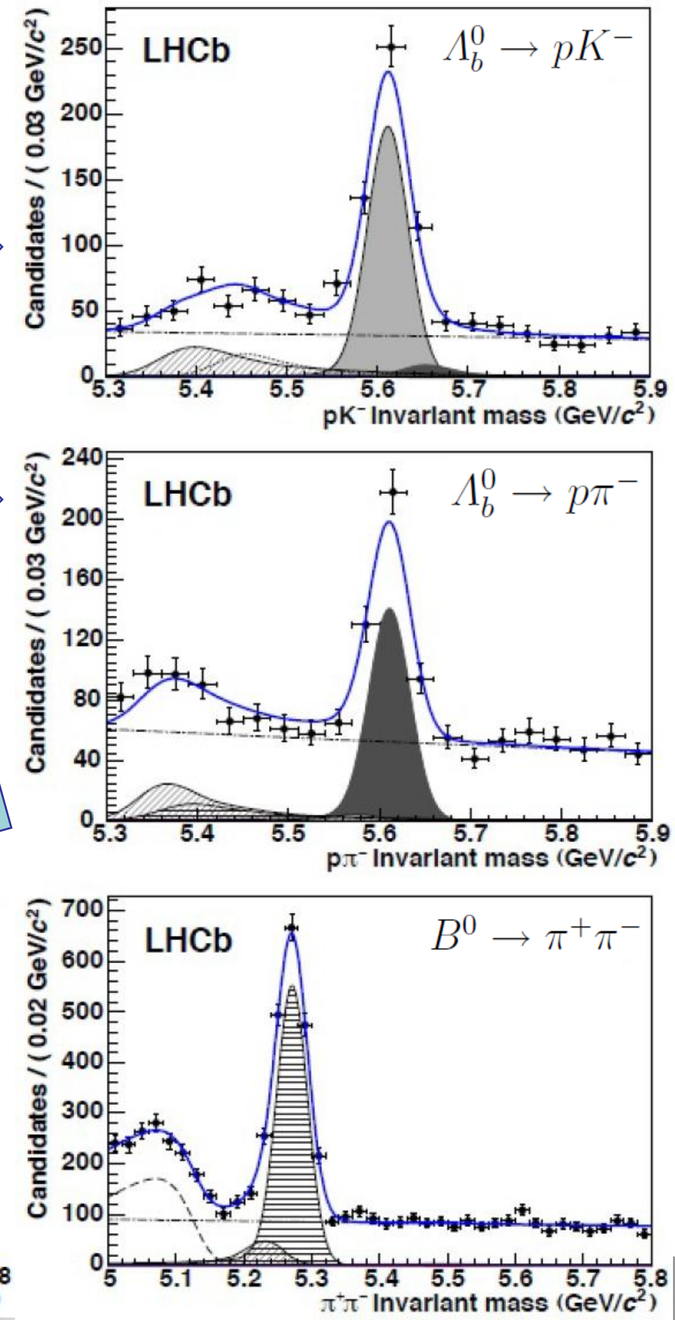
Nat. Phys. 18 (2022) 1

Charged hadron ID in LHCb: Cherenkov light detectors

- ❑ **2 Ring Imaging Cherenkov Detectors**
- ❑ Charged hadron ID, **charmless 2-body b-hadron decays**

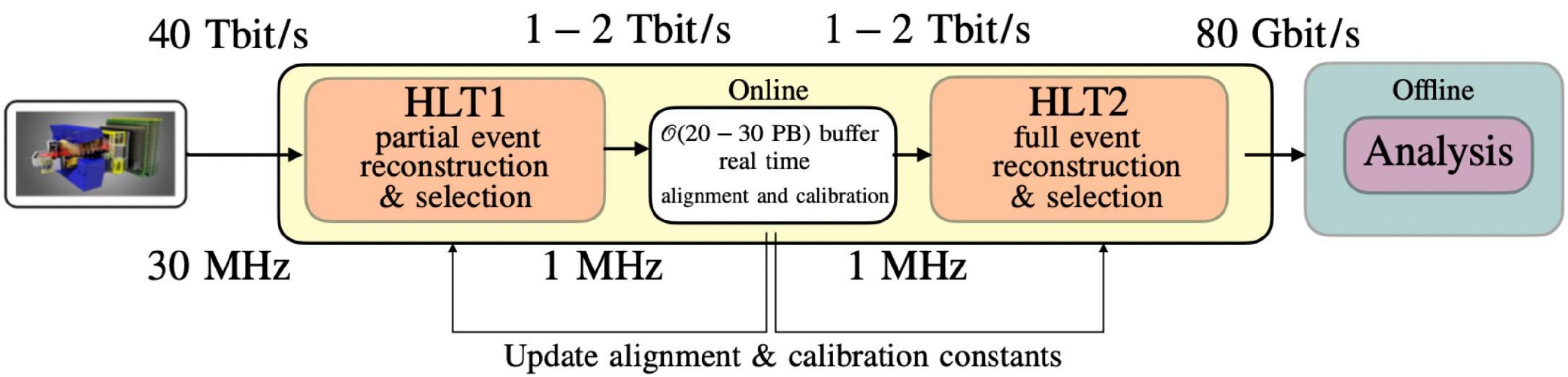
JHEP 10 (2012) 037 $\int L dt \sim 0.37\ fb^{-1}$





LHCb Upgrade I

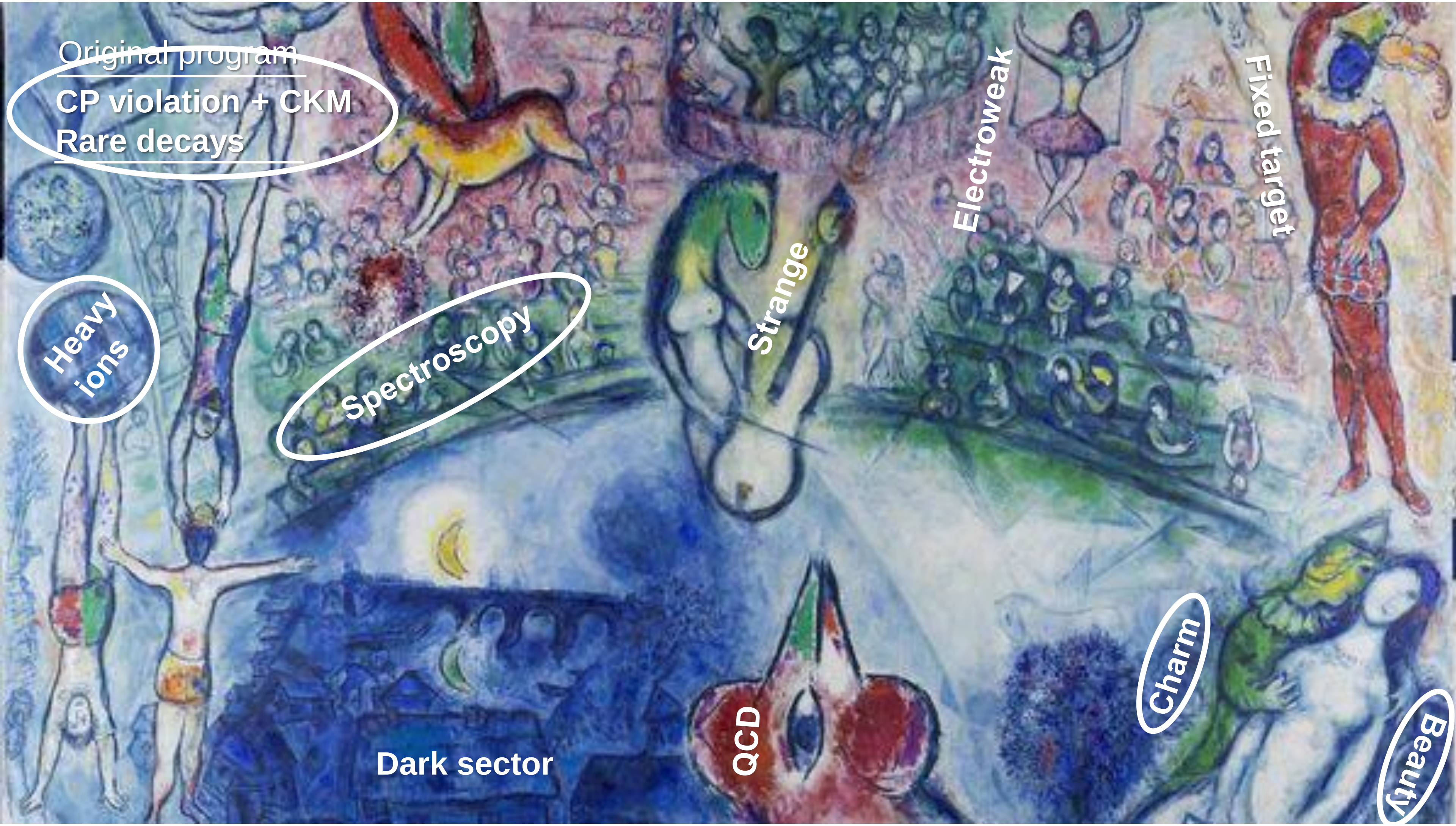
- LHCb upgrade I for runs 3 and 4
- **VELO** new design **with pixels**
- **Upstream tracker** with silicon strips, **main tracker** with scintillating fibers
- **RICH** photodetectors MAPMTs
- New dedicated **luminometer**
- SMOG2 **gas target** integrated in VELO
- All subdetectors readout at 40 MHz for a **fully software trigger using GPUs**
- Can run at 5 x higher luminosity



- 30 MHz of inelastic collisions reduced to ~1 MHz by the HLT1 (tracking/vertexing and muon ID) running on **GPUs**
- **Highest throughput of any HEP experiment**
- Many measurements directly profit from higher statistical precision (about x3 with run 3 only)

Marc Chagall, La triomphe de la musique

Examples of the physics results



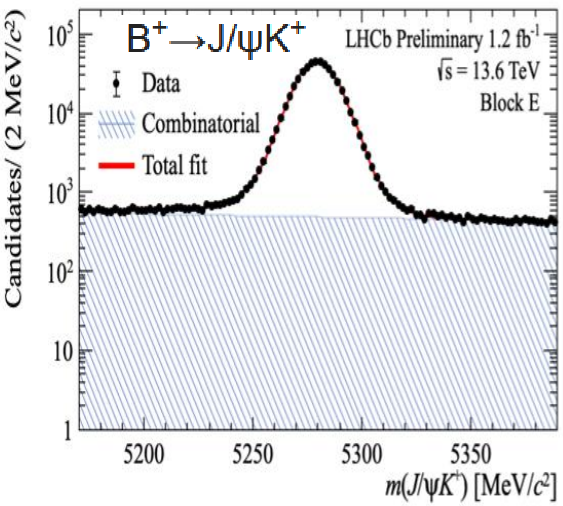
Marc Chagall, La triomphe de la musique

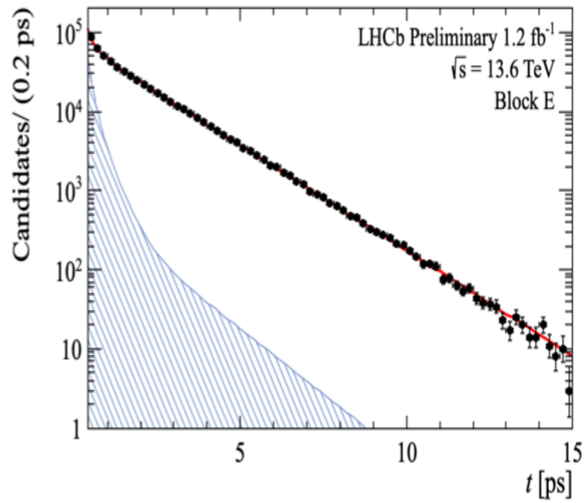
Beauty: new precision studies

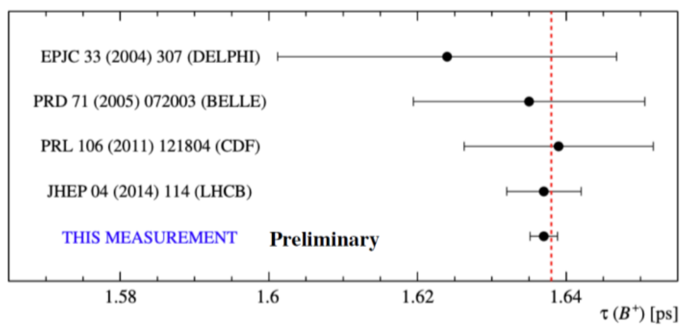
First results using run 3 data

LHCb-PAPER-2026-039, in preparation
LHCb-PAPER-2026-040, in preparation
Run 3 data

- **(Effective) lifetimes of B^0 and B$^+$** mesons via $B^0 \to J/\psi K^*(892)^0$ and $B^+ \to J/\psi K^+$ decays
- Tests of the Heavy Quark Expansion (HQE)
- 2D maximum likelihood fit to invariant mass and decay-time distribution



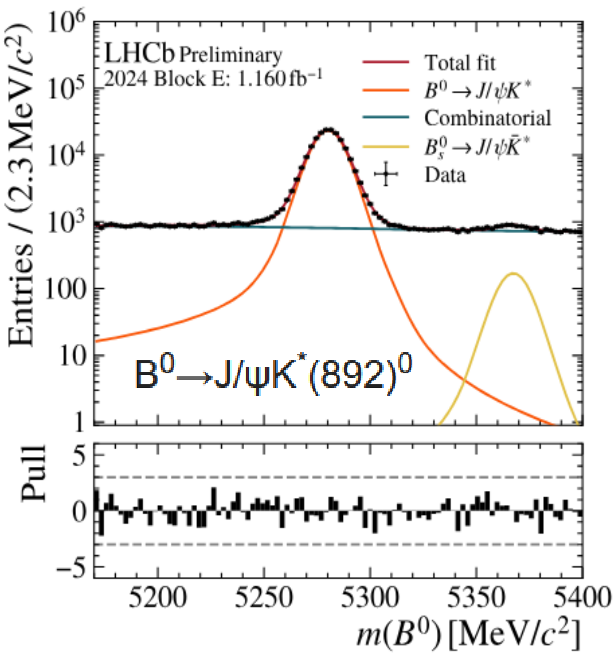


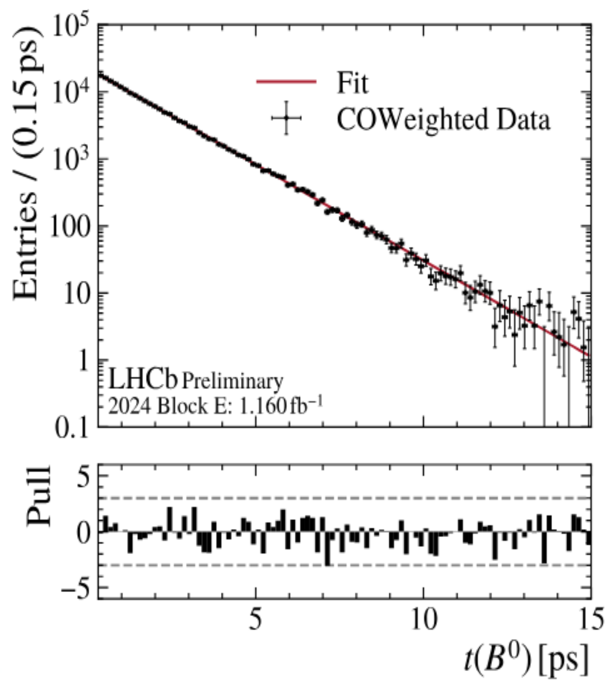


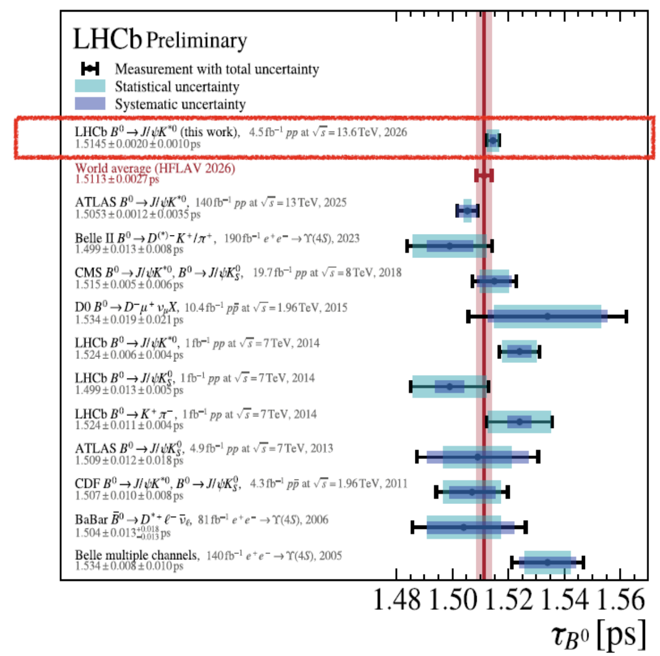
- **Most precise measurement** to date: $\tau(B^+) = 1.6370 \pm 0.0014 \pm 0.0014$ ps
- Agreement with HFLAV and previous LHCb Run 1 result

LHCb-PAPER-2026-039, in preparation
LHCb-PAPER-2026-040, in preparation
Run 3 data

- **(Effective) lifetimes of B^0 and B^+** mesons via $B^0 \to J/\psi K^*(892)^0$ and $B^+ \to J/\psi K^+$ decays
- Tests of the Heavy Quark Expansion (HQE)
- Unbinned maximum likelihood fit to the mass distribution
- COWs to account for possible correlations **Dembinski, Kenzie, Langenbruch, Schmelling NIMA 1040 (2022) 167270**



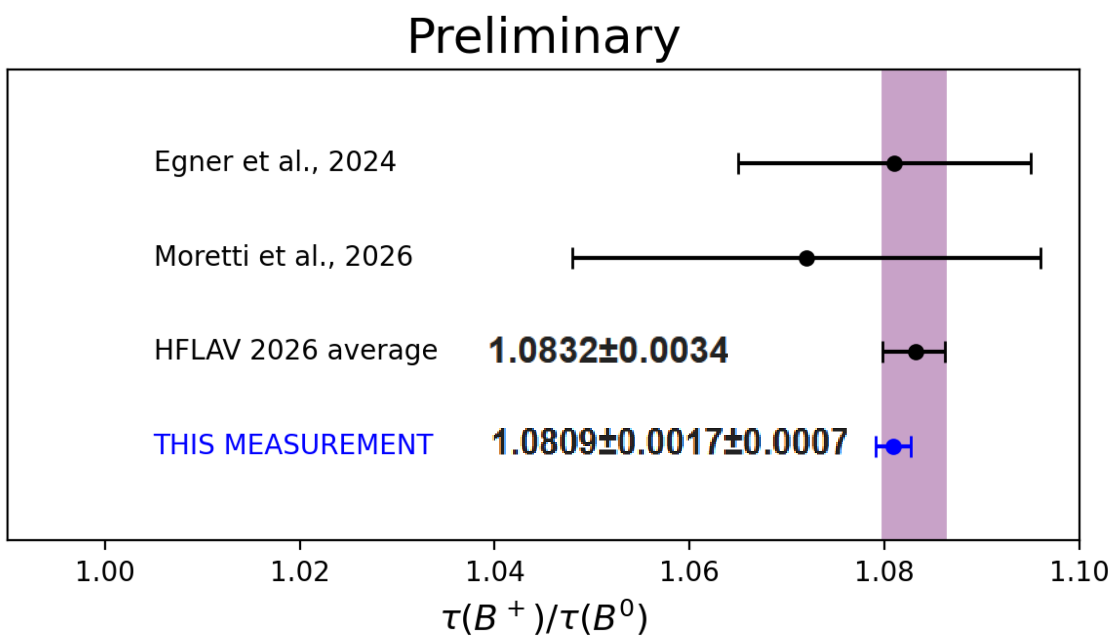




- **Most precise measurement** to date: $\tau(B^0) = 1.5145 \pm 0.0020 \pm 0.0010$ ps
- Agreement with HFLAV and previous LHCb Run 1 result

LHCb-PAPER-2026-039, in preparation
LHCb-PAPER-2026-040, in preparation
Run 3 data

- **(Effective) lifetimes of B^0 and B^+** mesons via $B^0 \to J/\psi K^*(892)^0$ and $B^+ \to J/\psi K^+$ decays
- Tests of the Heavy Quark Expansion (HQE)
- More reliable **theory prediction on the ratio**



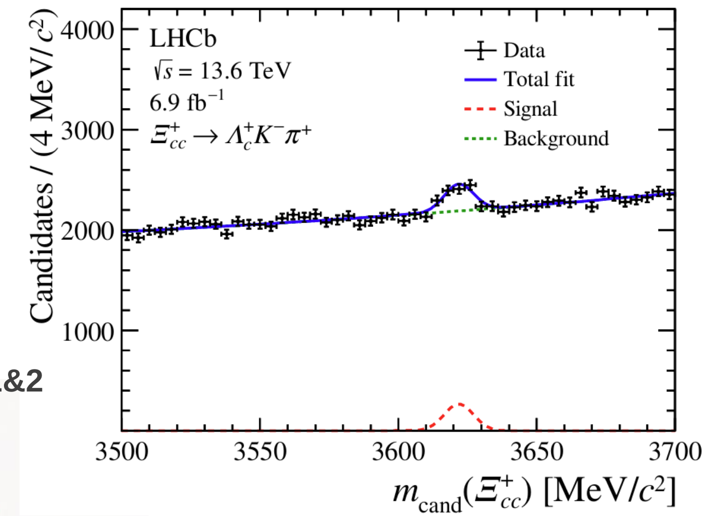
- **Most precise measurement** to date: 1.0809±0.0017±0.0007
- Precision on ratio ~ 2 x 10^{-3}
- Agreement with HFLAV and previous LHCb Run 1 result

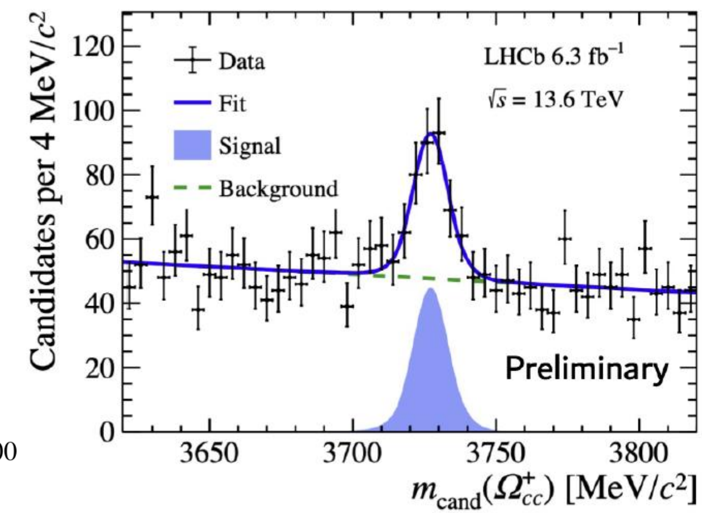
Heavy flavour spectroscopy

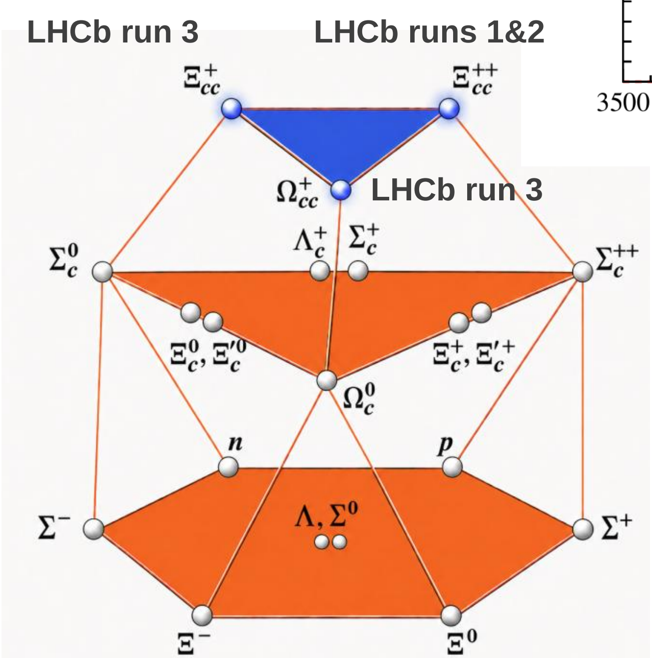
First results using run 3 data

PRL 137 (2026) 2, 021902
LHCb-PAPER-2026-022, in preparation

- First **new hadrons discovered with Run 3** data
- Observation in $\Xi_{cc}^{+} \to \Lambda_c^{+}(pK^{-}\pi^{+})K^{-}\pi^{+}$ (ccd) and $\Omega_{cc}^{+} \to \Omega_c^{0}(\to pK^{-}K^{-}\pi^{+})\pi^{+}$ (ccs)
- Yield per fb^{-1} improved factor ~4 thanks to improved fully-software trigger



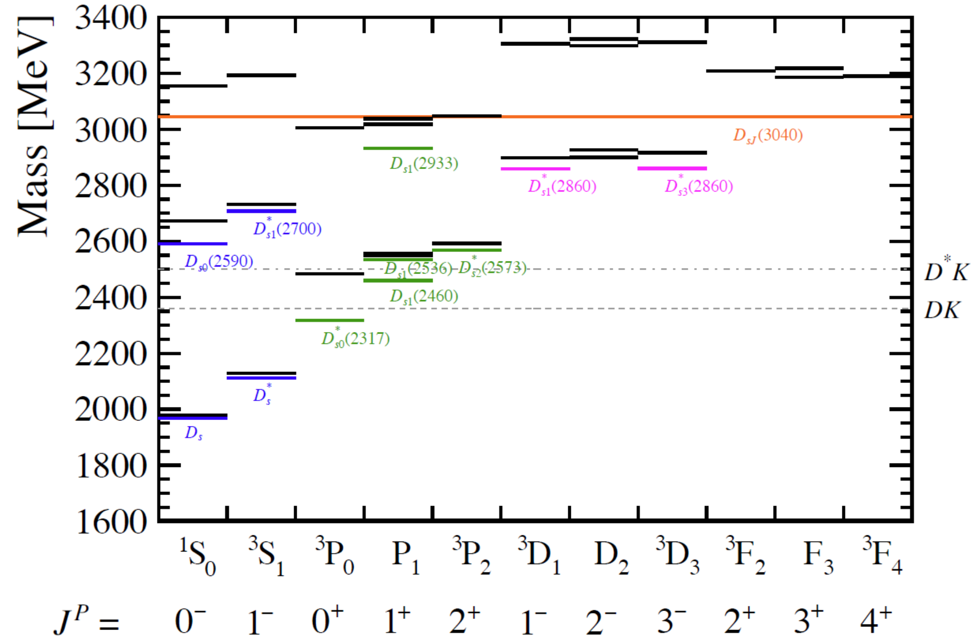




$$M(\Xi_{cc}^{+}) = 3619.97 \pm 0.83 \pm 0.26\,^{+1.90}_{-1.30}\ \text{MeV}/c^2$$

- All members of the spin-1/2 20-plet of ground-state baryons established
- Future interesting probes of charm hadronization

- **$D^*_{s0}(2317)^+$ and $D_{s1}(2460)^+$** observed in 2003 with unexpected properties
  - → Masses below prediction
  - → Isospin-violating decay to $D_s^{(*)+}\,\pi^0$
- Interpretations
- **Non-conventional internal structure**
  - → Tetraquark multiplet; part of a lower excitation multiplet; molecule
- **Broken chiral symmetry**
  - → $D^*_{s0}(2317)^+$: 0^+ chiral partner of the 0^- ground state D_s^+
  - → Spontaneous breaking of chiral symmetry → universal mass splitting, 349 MeV in charm
- *Does it exist in b-sector ?*



Tang et al, Commun. Theor. Phys. 75 (2023) 055203

Maiani, Polosa and Riquer, PRD 110 (2024) 034014

LHCb collab., Sci. Bull. 70 (2025) 1432

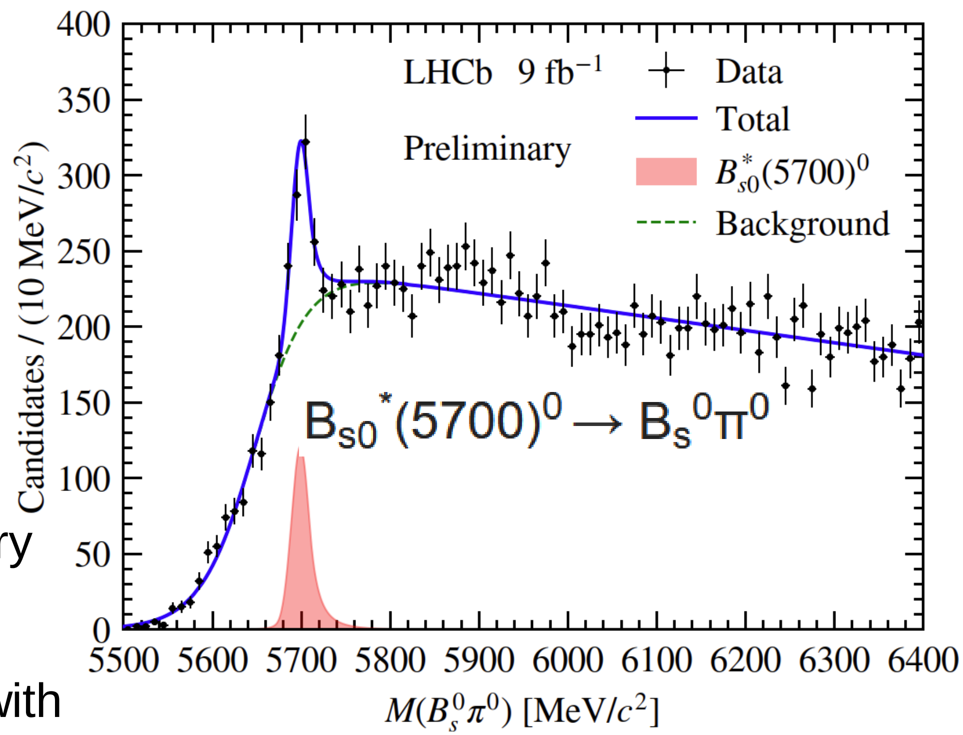
Observation of a narrow beauty-strange state

LHCb-PAPER-2026-021, in preparation

- Reconstruct $B_s^0\pi^0$ combinations using decays $B_s^0 \to D_s^-\pi^+$, $B_s^0 \to J/\psi\varphi$ and $B_s^0 \to D_s^-\pi^+\pi^+\pi^-$
- $B_{s0}^*(5700)^0$ peak consistently visible in all decay modes
- *First LHCb analysis with prompt π^0*

$$m = 5698.9 \pm 1.5 \pm 0.6 \pm 0.1\ \text{MeV}$$

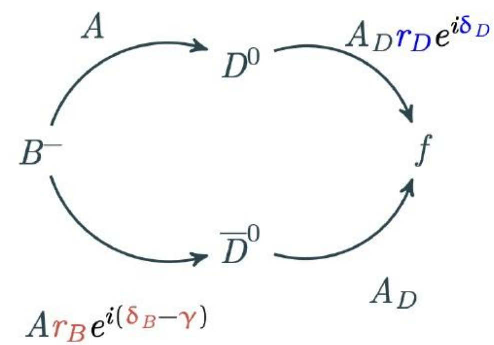
$$\Gamma < 9.8\ (11.8)\ \text{MeV at } 90\ (95)\ \%\ \text{CL}$$

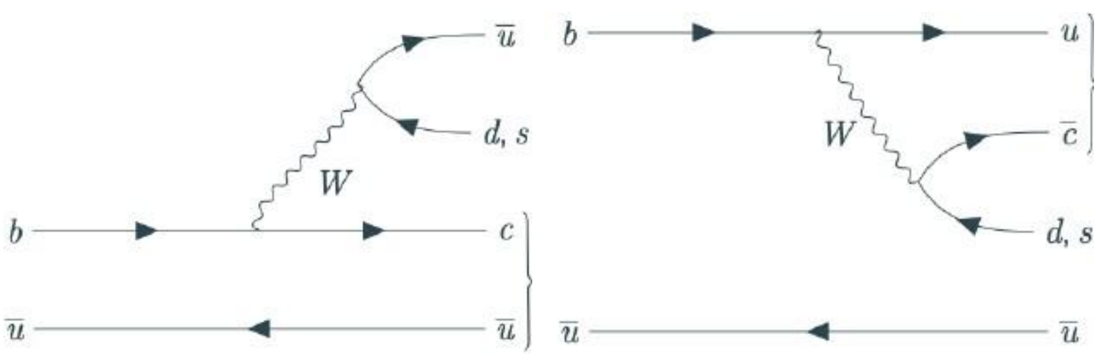


- **Mass ~130 MeV below QM prediction**
- Consistent with
  - Predictions from chiral doubling theory
  - Mass splitting in charm sector
- M, Γ and decay channel also consistent with
  - The first single-beauty hadron molecule
  - Feed-down from a new $B_{s1}^0 \to (B_s^{*0} \to B_s^0\gamma)\pi^0$, which provides equivalent experimental support for the theory paradigm
- **Consistent anomaly across both charm and beauty sectors**
- **Major input for QCD**: fundamental symmetry or new form of hadronic matter

CP-violation: angle γ

- At LHCb, benefit from large statistics using **tree-dominated processes**
- Tree-level decays, theoretically clean ($\delta\gamma \sim 10^{-7}$)
- Complementary methods, dependent on combinations of favored and suppressed B and D decays
- **Multi-body D decays** are used in combination with input on **strong phases from independent measurements** (BESIII, CLEO3)
- Final states accessible to both D and $\overline{\text{D}}$ to examine **interference between b → c and b → u transitions**



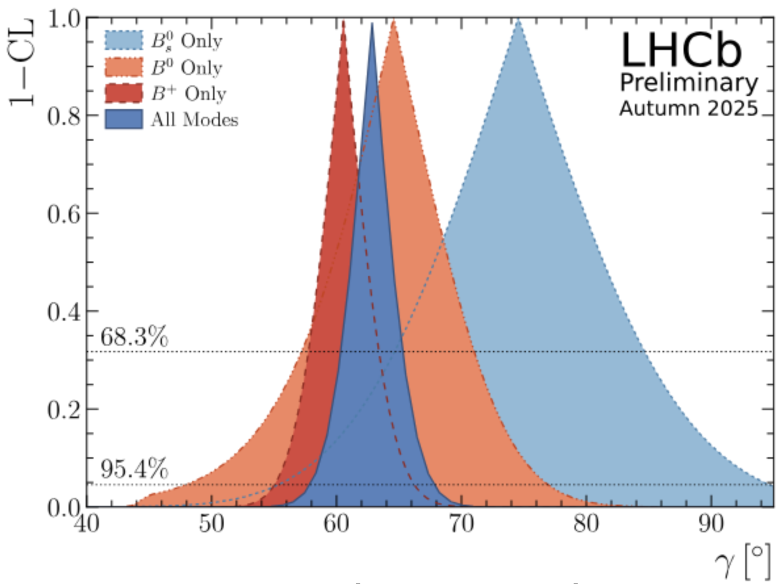


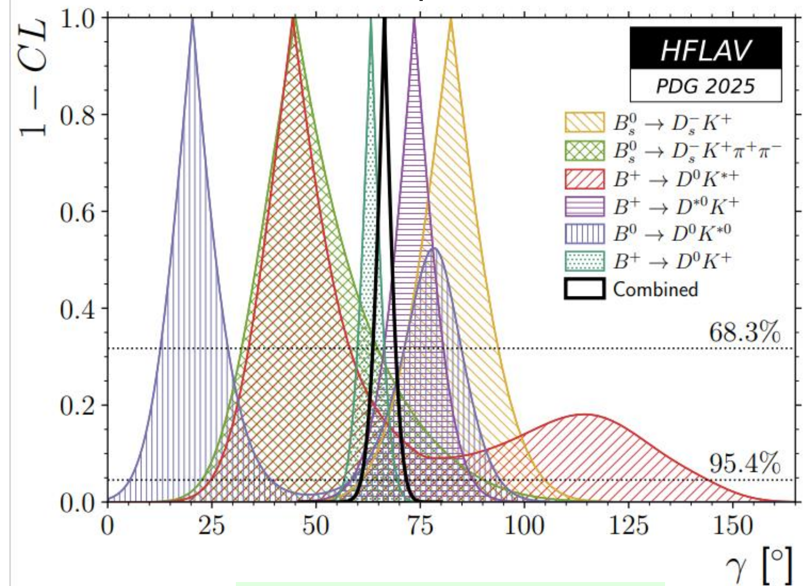
$$|A(B^-)|^2 \propto A_D^2 + r_B^2 A_{\bar{D}}^2 + 2A_D A_{\bar{D}} r_B \cos(\delta_B - \gamma)$$

$$|A(B^+)|^2 \propto A_D^2 + r_B^2 A_{\bar{D}}^2 + 2A_D A_{\bar{D}} r_B \cos(\delta_B + \gamma)$$

- Combination of **LHCb measurements of the CKM angle *γ* and charm mixing** parameters

https://hflav.web.cern.ch/





$\gamma = (62.8 \pm 2.6)^\circ$

$$\gamma \equiv \phi_3 = (66.4^{+2.7}_{-2.8})^\circ$$

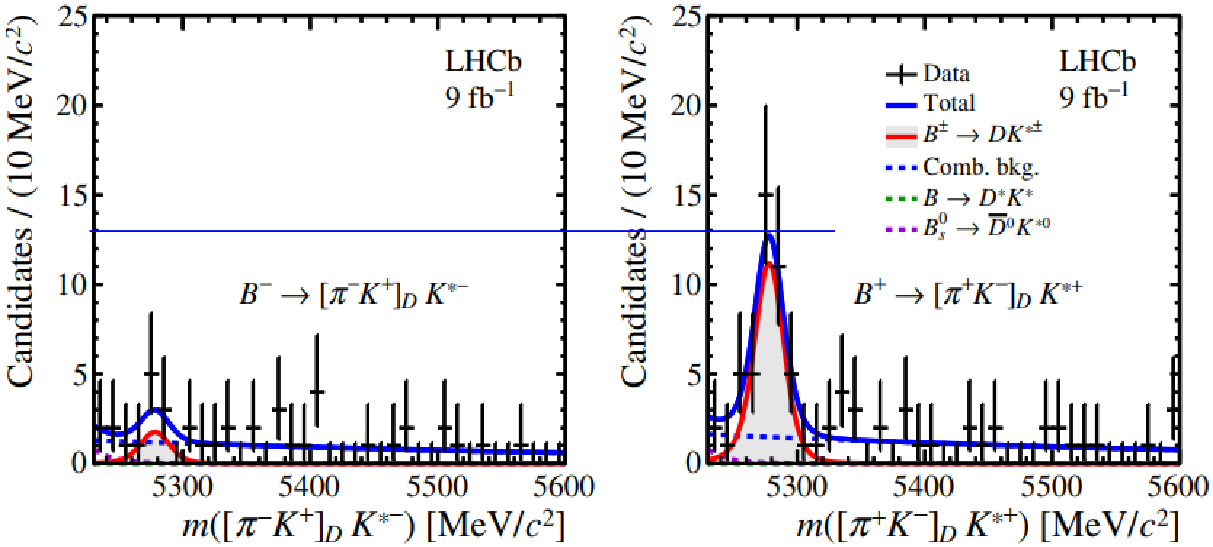
LHCb-CONF-2025-003

- The **most precise determination of γ from a single experiment** to date

CKM fitter: $\gamma_{\text{indirect}} = \left(66.3\,^{+\,0.7}_{-\,1.9}\right)^\circ$ **http://ckmfitter.in2p3.fr/**

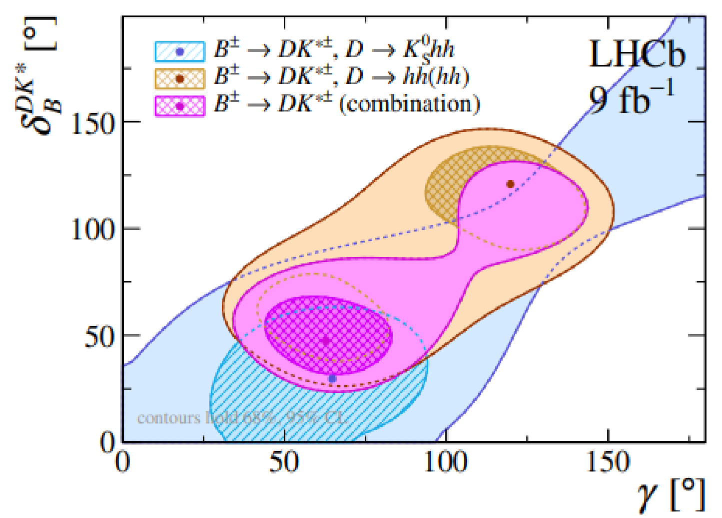
JHEP 02 (2025) 113

- Simultaneous measurement of γ using **2-, 3- and 4-body D^0 ($\overline{D}^0$) decays**



D decay mode	B^-	B^+	Purity (%)
$K\pi$	2656 ± 55	2844 ± 57	94
KK	366 ± 20	274 ± 18	90
$\pi\pi$	121 ± 13	63 ± 10	69
πK	5 ± 4	35 ± 7	58
$K\pi\pi\pi$	1665 ± 44	1783 ± 45	93
$\pi\pi\pi\pi$	160 ± 14	149 ± 14	77
$\pi K\pi\pi$	13 ± 5	18 ± 5	58
$K_S^0\pi\pi$	279 ± 18	268 ± 18	85
$K_S^0 KK$	29 ± 6	40 ± 7	86

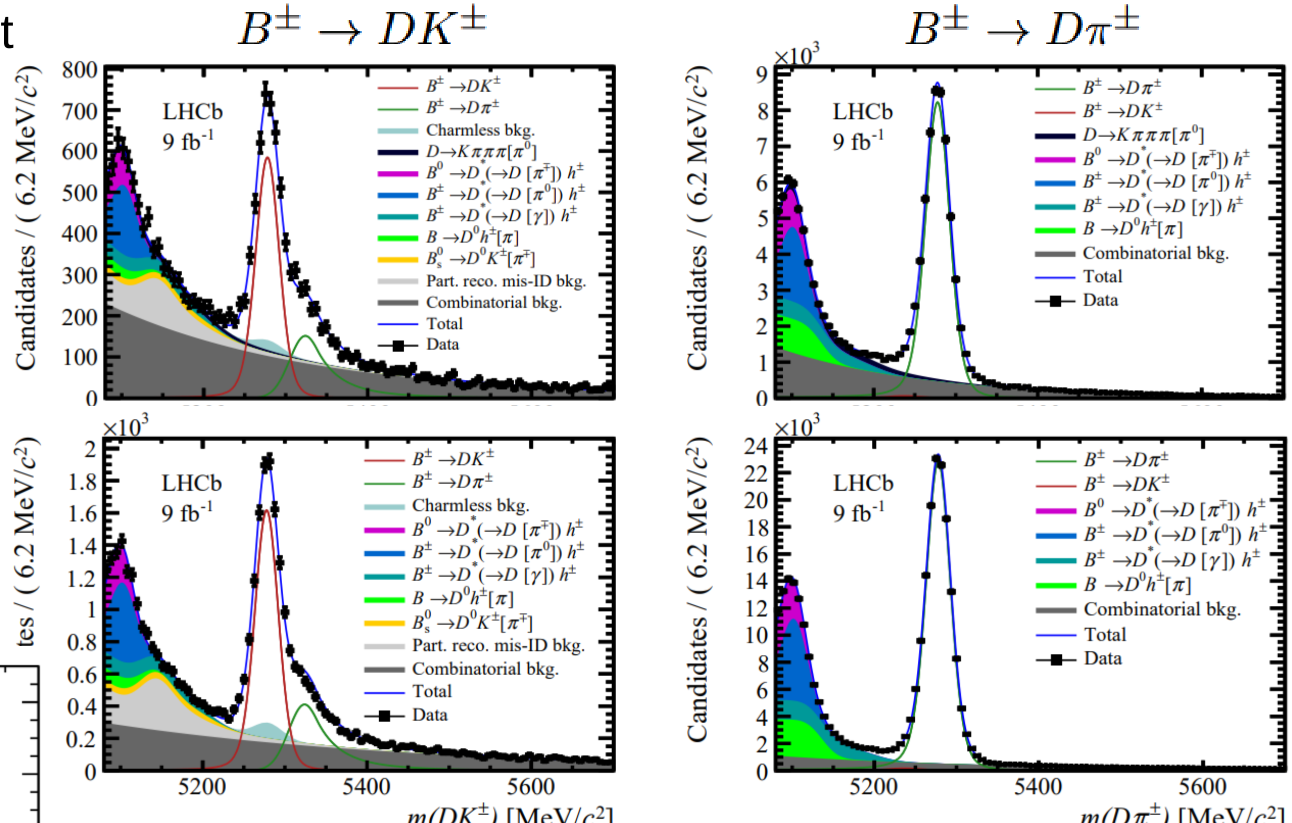
- **First observation of DCSD** $B^{\pm} \rightarrow [\pi^{\pm} K^{\mp}]_D K^{*\pm}$ and $B^{\pm} \rightarrow [\pi^{\pm} K^{\mp} \pi^{\pm} \pi^{\mp}]_D K^{*\pm}$
- CP fit to 2- and 4- body decays, and for the first time at LHCb to 3-body decays with Dalitz input from CLEO3 and BESIII
- CKM angle γ: $\boxed{\gamma = (63 \pm 13)^\circ}$



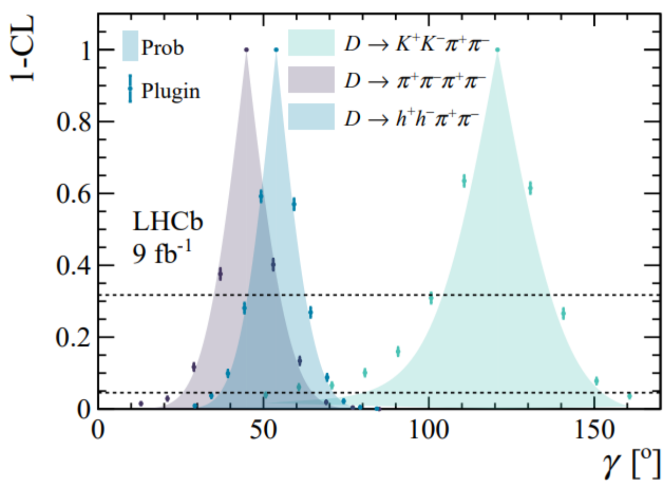
JHEP 01 (2026) 062

- **Model-independent** measurement of CKM angle γ in $B^{\pm} \rightarrow [K^+K^-\pi^+\pi^-]_D h^{\pm}$ and $B^{\pm} \rightarrow [\pi^+\pi^-\pi^+\pi^-]_D h^{\pm}$ where D = D^0 or $\bar{D}^0$
- Strong phase in **phase-space bins of the D^0 and $\bar{D}^0$ decays** from BESIII measurement

PRD 112 (2025) 012015



$$\boxed{\gamma = (53.9^{+9.5}_{-8.9})^{\circ}}$$



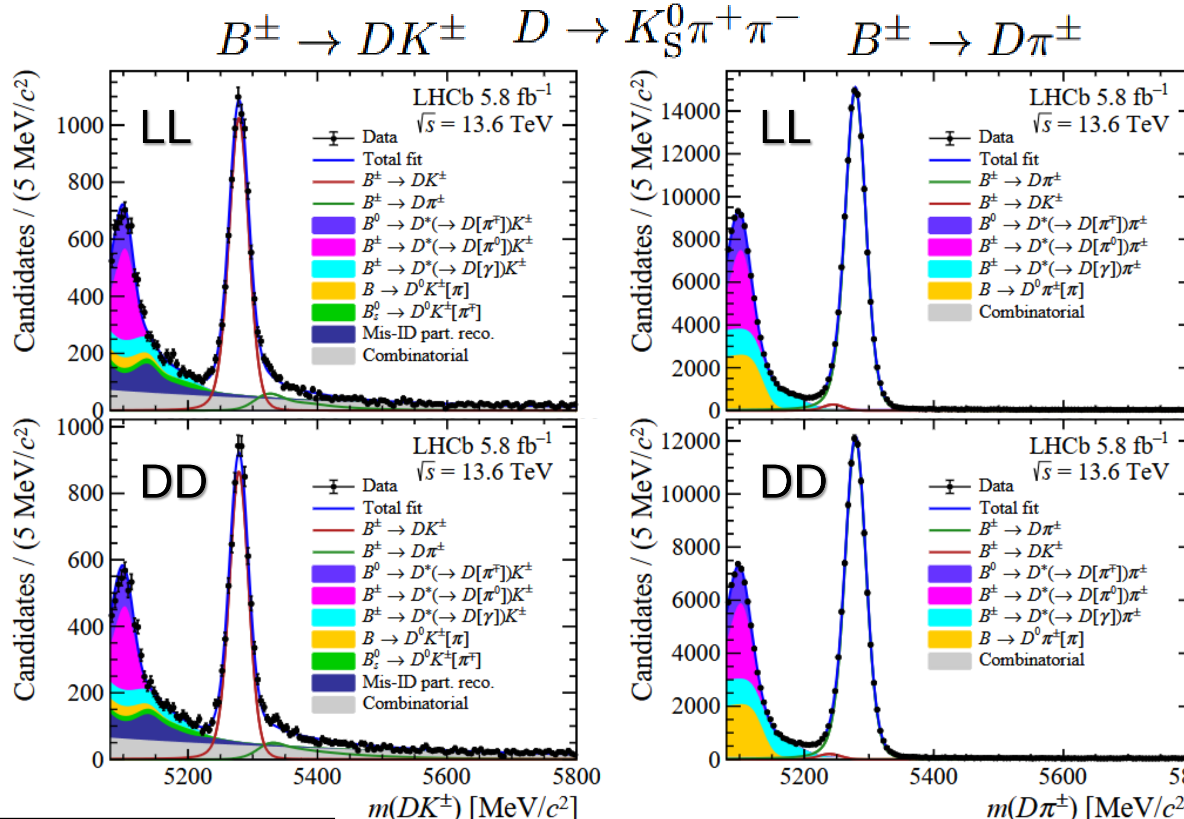
- Combined with the phase-space integrated measurement

$$\boxed{\gamma = (52.6^{+8.5}_{-6.4})^{\circ}}$$

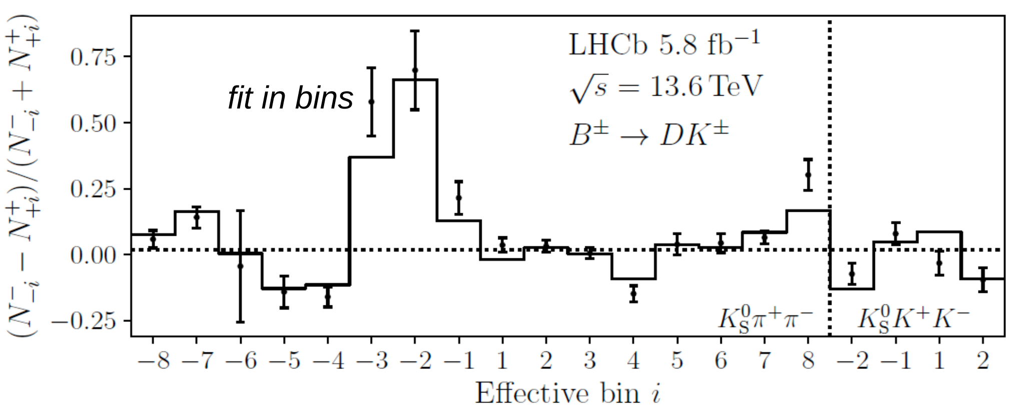
EPJC 84 (2023) 547

JHEP 08 (2026) 037

- *First CKM angle γ result from the upgraded LHCb detector*
- $K_S \rightarrow \pi^+\pi^-$ reconstruction: Long (LL) / Downstream (DD) categories, i.e. with π tracks in VELO / beyond



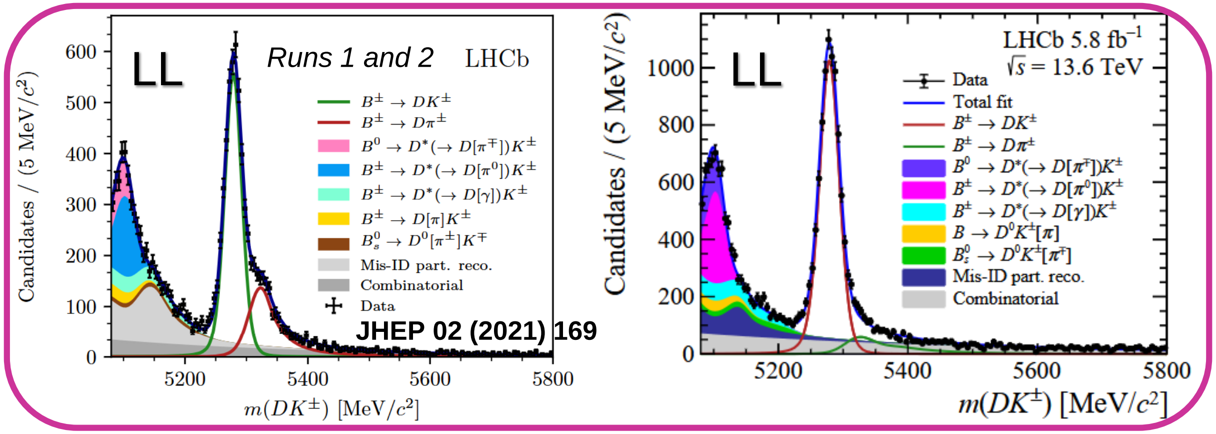
- Global mass fits
- Analysis in **optimized bins of the D-decay Dalitz plot**



- Data well-described
- Measurements of the strong-phase parameters from BESIII for $D \rightarrow K_S\pi^+\pi^-$ and BESIII and CLEO for $D \rightarrow K_SK^+K^-$

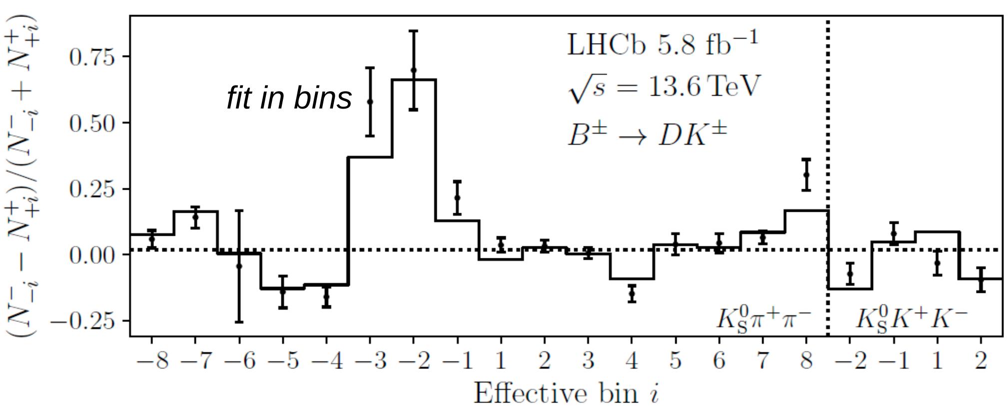
- *First CKM angle γ result from the upgraded LHCb detector* **JHEP 08 (2026) 037**
- $K_S \to \pi^+\pi^-$ reconstruction: Long (LL) / Downstream (DD) categories, i.e. with π tracks in VELO / beyond

$B^\pm \to DK^\pm$



LL+DD: Run 1+2 ~12500 events vs. Run 3 - 2024 ~13800 events

- Analysis in **optimized bins of the D-decay Dalitz plot**



- Data well-described
- Measurements of the strong-phase parameters from BESIII for $D \to K_S\pi^+\pi^-$ and BESIII and CLEO for $D \to K_S K^+K^-$

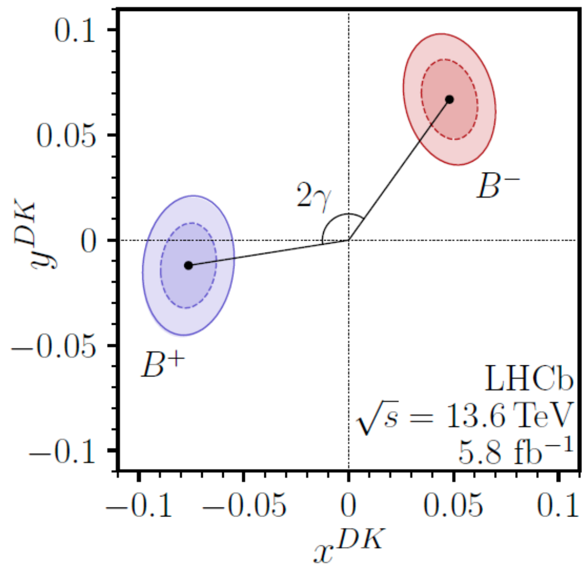
JHEP 08 (2026) 037

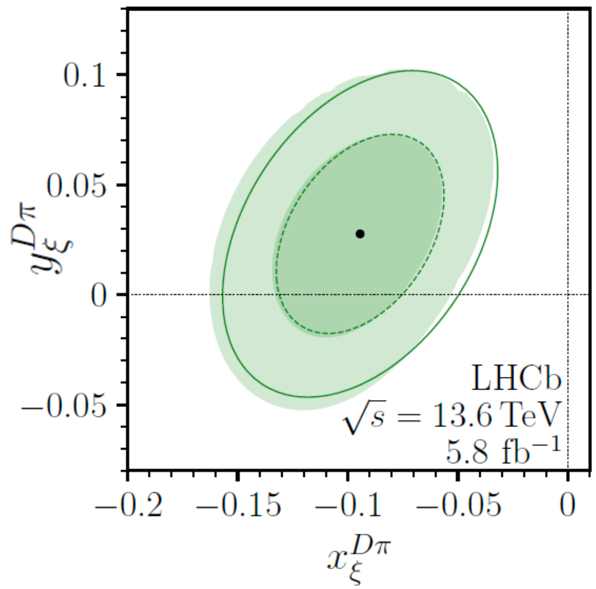
- Measurement observables

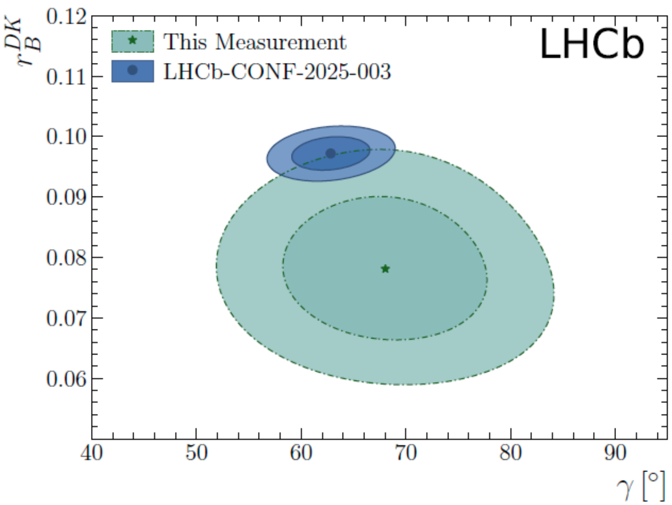
$$x_\pm^{DK} \equiv r_B^{DK} \cos(\delta_B^{DK} \pm \gamma)$$
$$y_\pm^{DK} \equiv r_B^{DK} \sin(\delta_B^{DK} \pm \gamma)$$

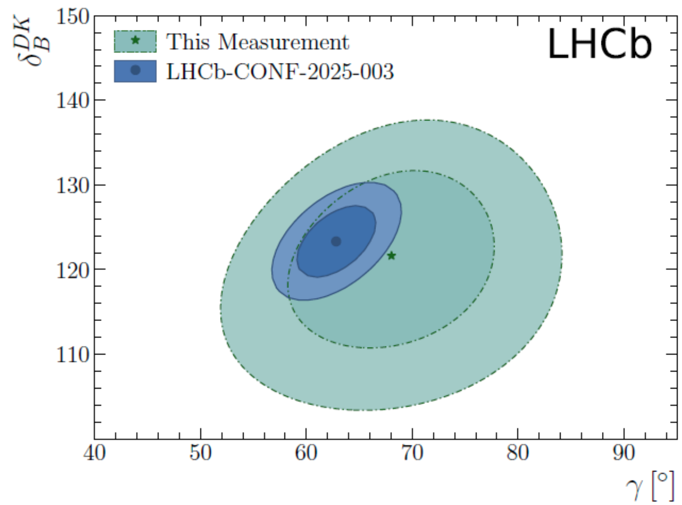
$$\xi^{D\pi} = \left(\frac{r_B^{D\pi}}{r_B^{DK}}\right) \exp\left(i\delta_B^{D\pi} - i\delta_B^{DK}\right)$$

$$x_\pm^{D\pi} = x_\xi^{D\pi} x_\pm^{DK} - y_\xi^{D\pi} y_\pm^{DK}$$
$$y_\pm^{D\pi} = x_\xi^{D\pi} y_\pm^{DK} + y_\xi^{D\pi} x_\pm^{DK}$$









$$\gamma = (68.1 \pm 6.7)^\circ,$$
$$r_B^{DK} = 0.0781^{+0.0078}_{-0.0079},$$
$$\delta_B^{DK} = (121.5^{+6.9}_{-7.4})^\circ,$$
$$r_B^{D\pi} = 0.0073^{+0.0016}_{-0.0015},$$
$$\delta_B^{D\pi} = (286^{+20}_{-23})^\circ$$

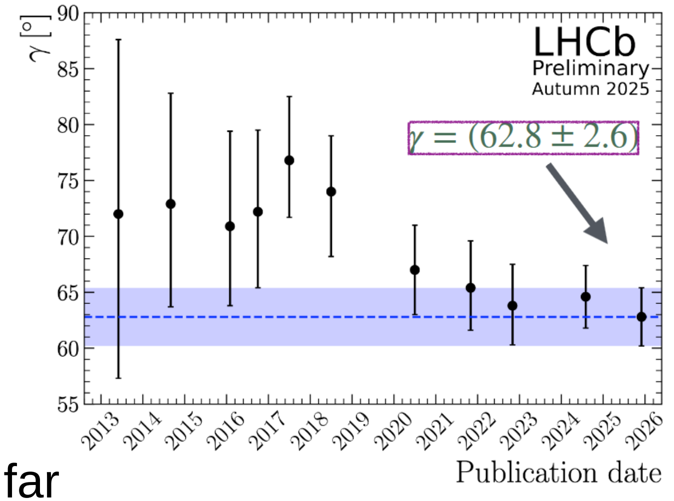
- **New independent measurement, in agreement with the Runs 1+2 combination**

- Overall outstanding **improvement of the precision**

$$A = 0.826^{+0.016}_{-0.015} \quad \lambda = 0.22501 \pm 0.00068$$

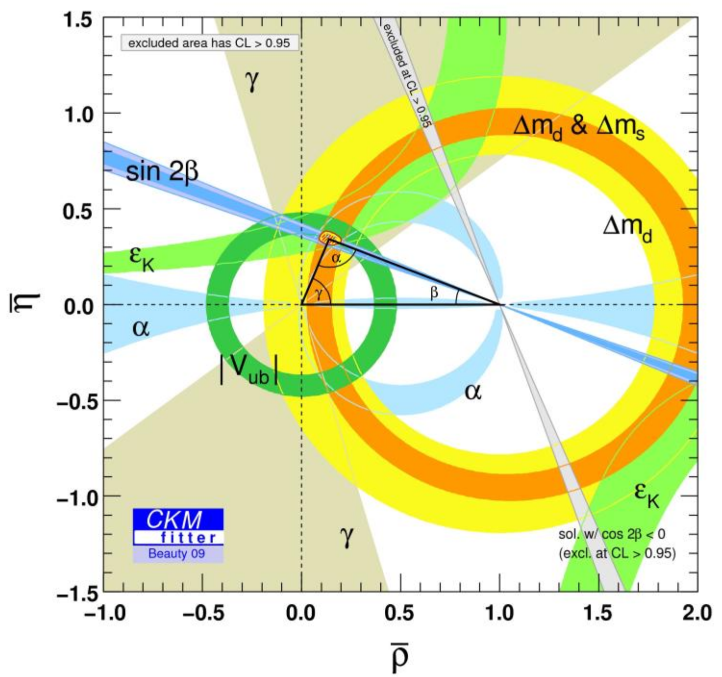
$$\bar{\rho} = 0.1591 \pm 0.0094 \quad \bar{\eta} = 0.3523^{+0.0073}_{-0.0071}$$

$$\alpha + \beta + \gamma = (172 \pm 5)^{\circ}$$

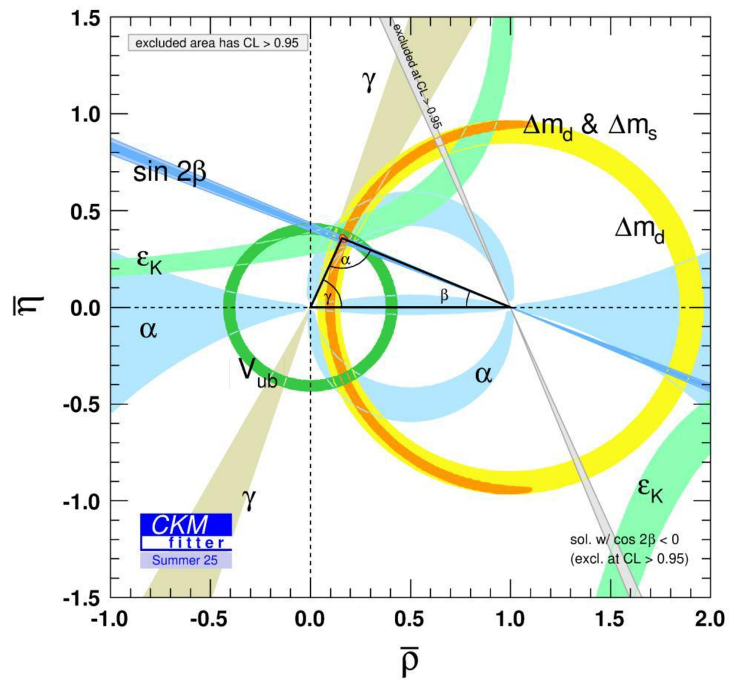


- The **UT apex position** η known to 1.4% precision
- All available measurements of different observables, including amplitude and phase measurements, give so far **consistent picture** and point to the same UT triangle apex

Before LHC (CKM fitter, 2009)



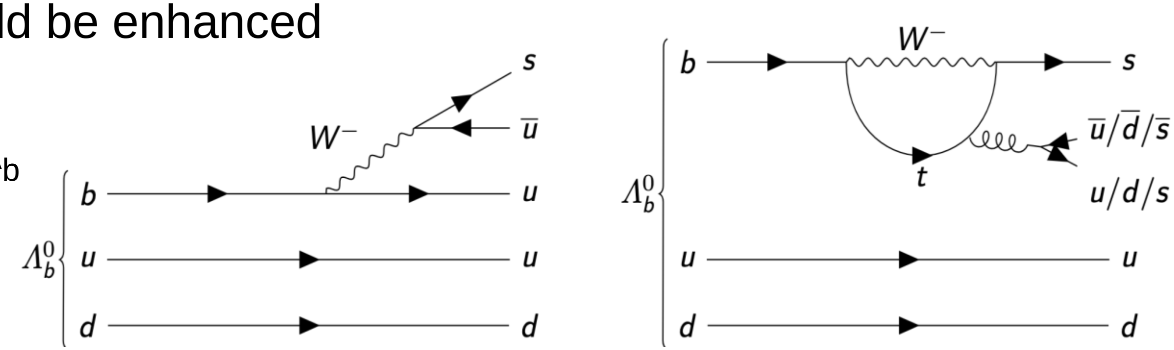
Now (CKM fitter, 2025)

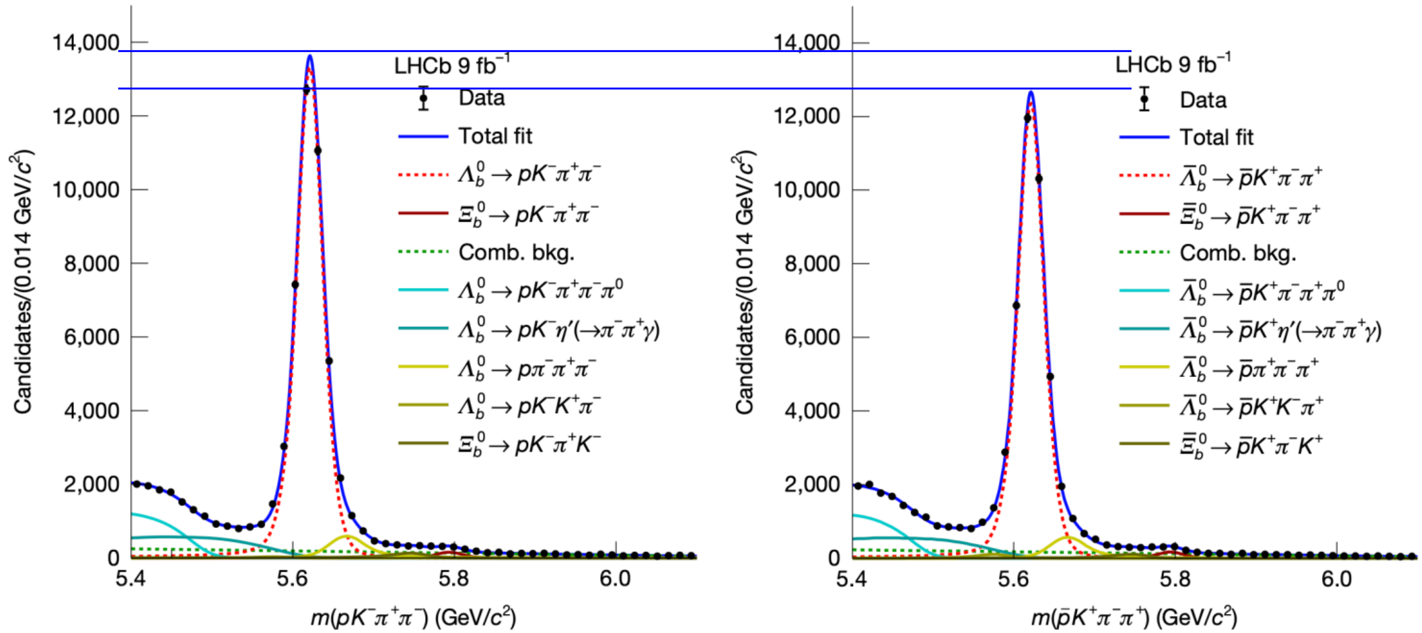


CP-violation in baryons

Nature 643 (2025) 1223

- **$\Lambda_b \to pK^-\pi^+\pi^-$ decay**: CPV may arise from tree and penguin interference, could be enhanced by intermediate resonances
- Clean sample of 80K Λ_b and $\overline{\Lambda}_b$





- **Phase-space integrated CP asymmetry** after accounting for biases from production and detection (~1%) measured in the $\Lambda_b \to \Lambda_c(pK^-\pi^+)\pi^-$ control channel

A_{CP} **= 2.45 ± 0.46 ± 0.10 %**, 5.2σ from zero

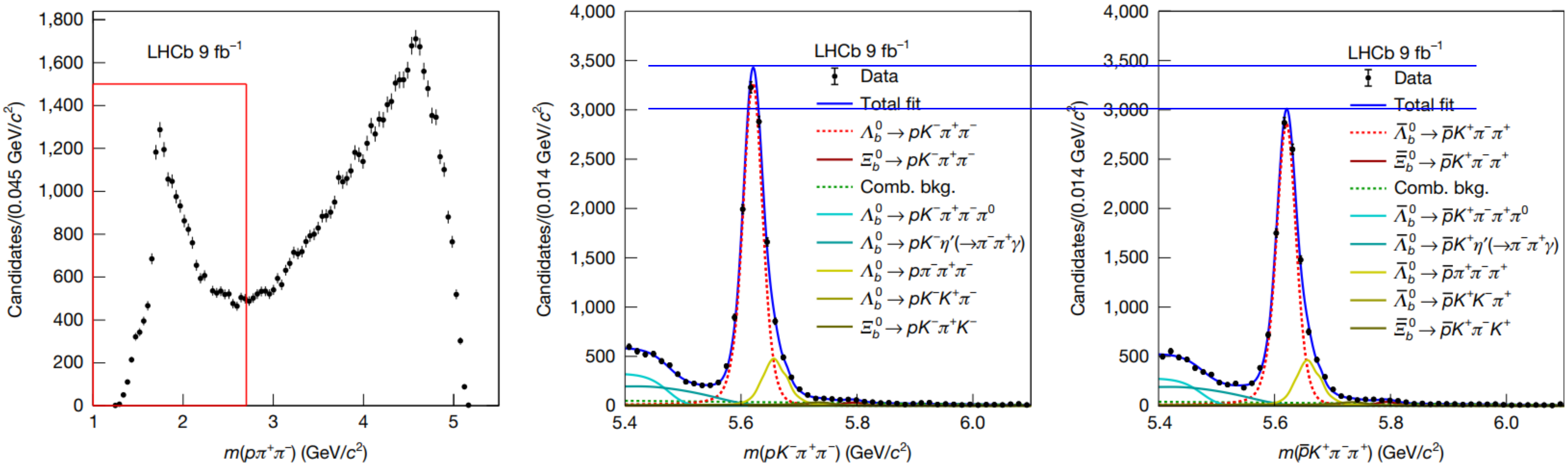
First observation of CPV in baryons

- **Asymmetry in regions of phase space**, dominated by various resonances and decay topologies

Nature 643 (2025) 1223

Decay topology	Mass region (GeV/c^2)	$\mathcal{A}_{CP}$
$\Lambda_b^0 \to (pK^-)(\pi^+\pi^-)$	$m_{pK^-} < 2.2$ $m_{\pi^+\pi^-} < 1.1$	$(5.24 \pm 1.29 \pm 0.21)\%$
$\Lambda_b^0 \to (p\pi^-)(K^-\pi^+)$	$m_{p\pi^-} < 1.7$ $m_{\pi^+K^-} \in [0.8, 1.0] \cup [1.1, 1.6]$	$(2.73 \pm 0.82 \pm 0.14)\%$
$\Lambda_b^0 \to (p\pi^-\pi^+)K^-$	$m_{p\pi^-\pi^+} < 2.7$	$(5.39 \pm 0.86 \pm 0.10)\%$
$\Lambda_b^0 \to (K^-\pi^+\pi^-)p$	$m_{K^-\pi^+\pi^-} < 2.0$	$(2.01 \pm 1.16 \pm 0.30)\%$

- 6σ from zero →



- Suggests that **intermediate resonances** are important to initiate the **CP asymmetry**

CP-violation in charm sector

- Mixing and CPV studies at LHCb
- Precision measurements require an excellent control of the systematic uncertainties

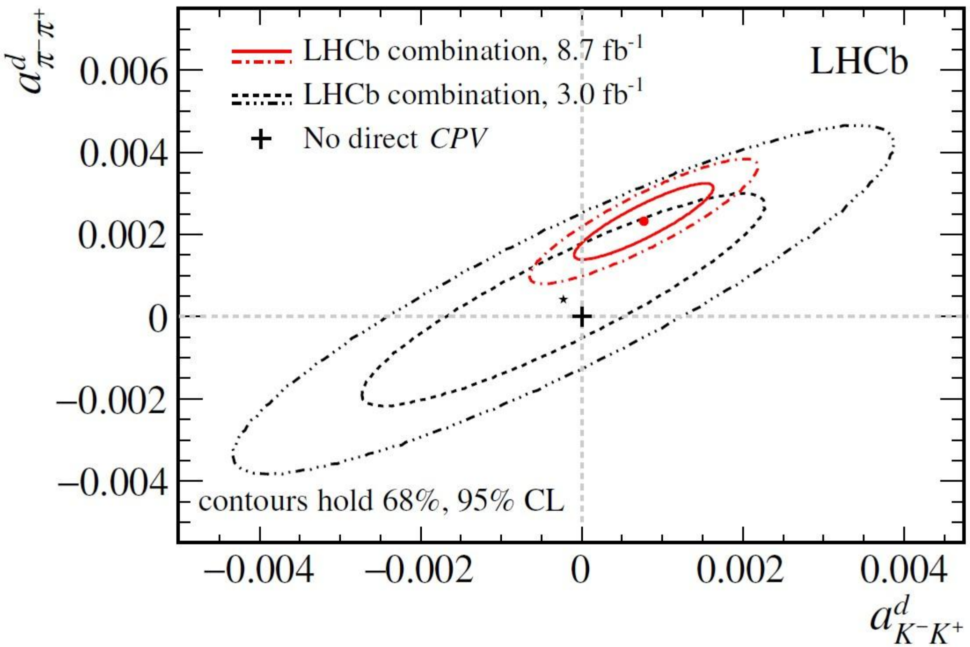
- **First observation of CPV in charm sector**

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) = (-15.4 \pm 2.9) \times 10^{-4}$$

PRL 122 (2019) 211803

PRL 131 (2023) 091802

$$\mathcal{A}^{CP}(f) \approx a_f^d + \frac{\langle t \rangle_f}{\tau_D} \cdot \Delta Y_f$$

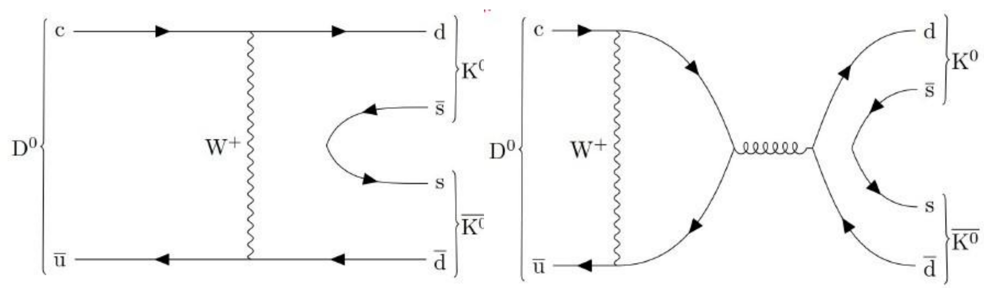


- Evidence of **direct CPV in $D^0 \rightarrow \pi^+\pi^-$** individual charm meson decay

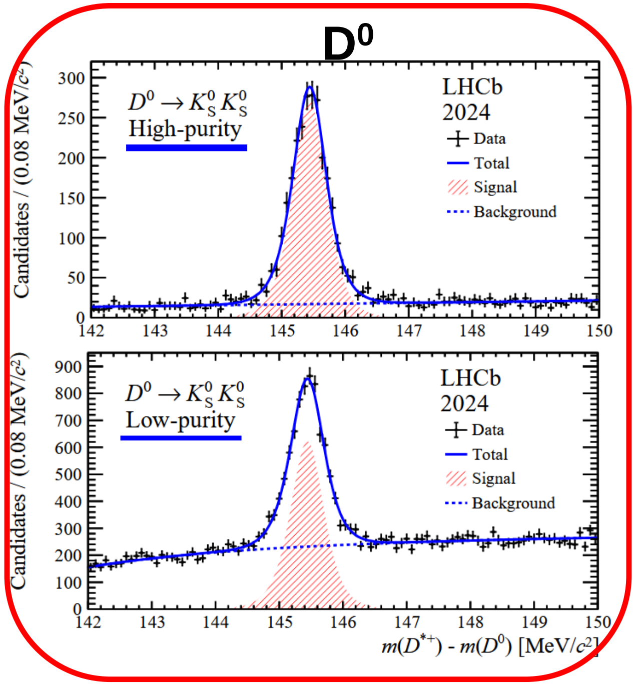
CPV in $D^0 \to K_S K_S$ with run 3 data

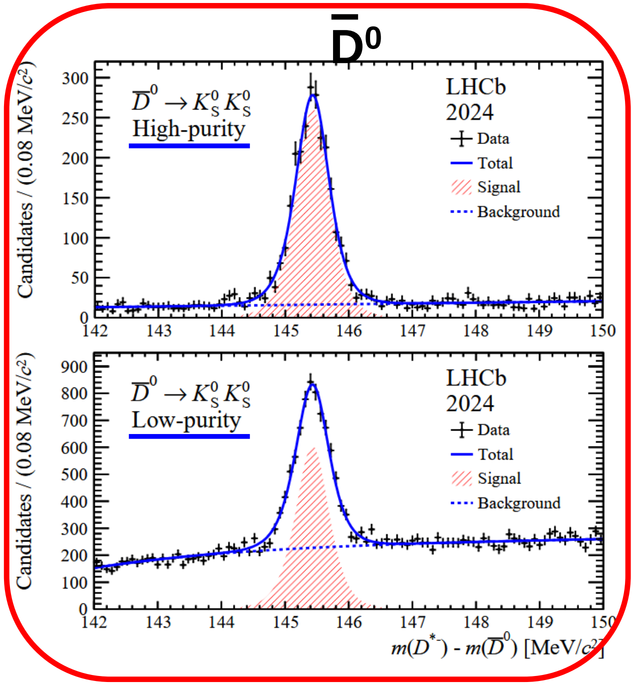
- CPV in the up-type quark sector

JHEP 02 (2026) 253, JHEP 06 (2026) 282

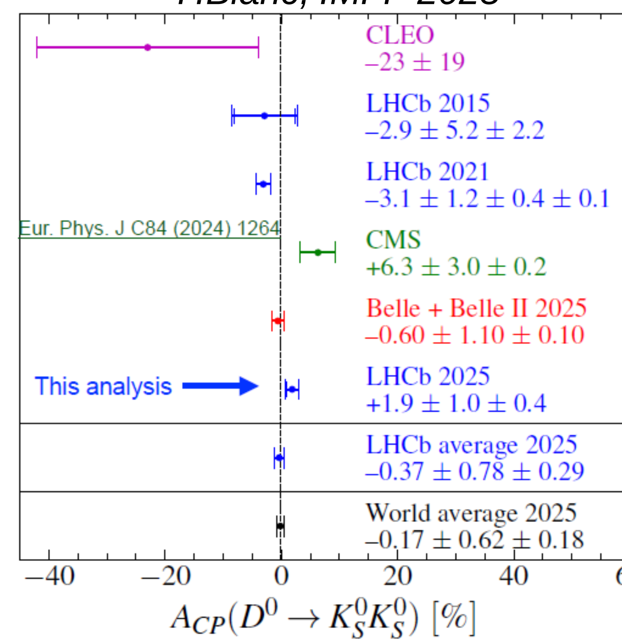


- D^0 and $\bar{D}^0$ **tagged by accompanying pion** $D^{*+} \to D^0\pi^+$
- **$D^0 \to K_S\pi^+\pi^-$** used as **control mode**, tagged with the same method as the signal
- Two categories with different purities according to a MVA classifier





F.Blanc, IMFP 2025

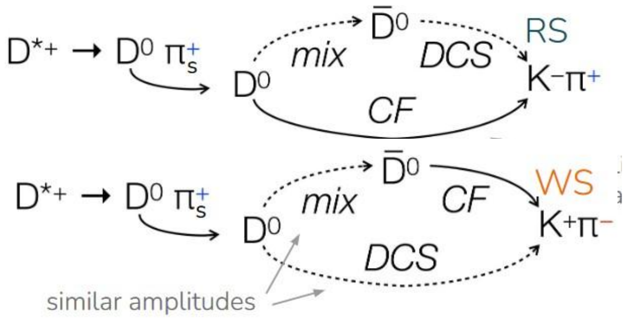


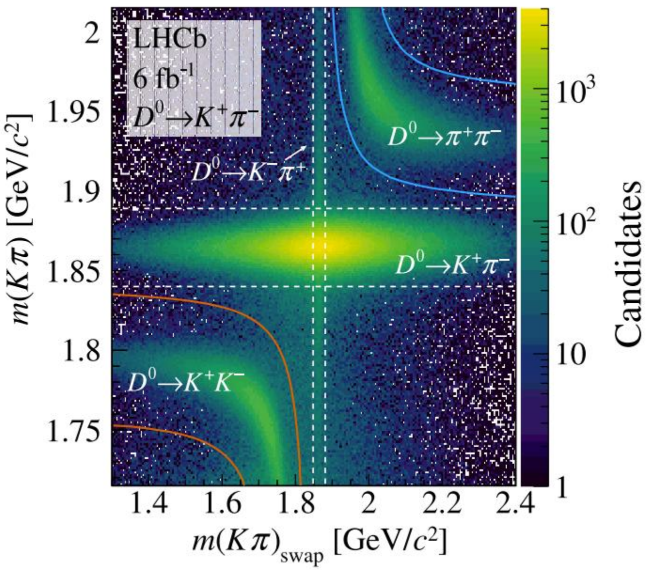
$$\boxed{\mathcal{A}^{CP}(K^0_S K^0_S) = (1.86 \pm 1.04 \pm 0.41)\%}$$

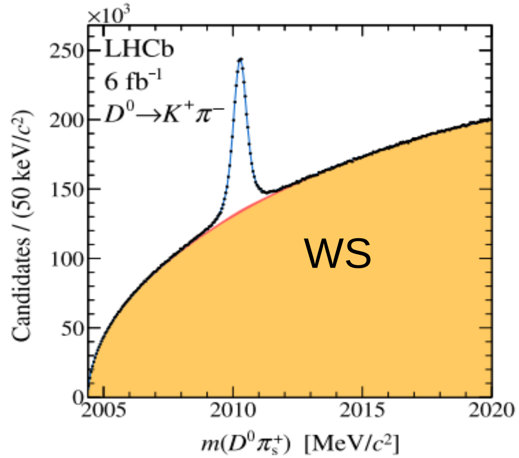
Most precise single measurement of this quantity to date

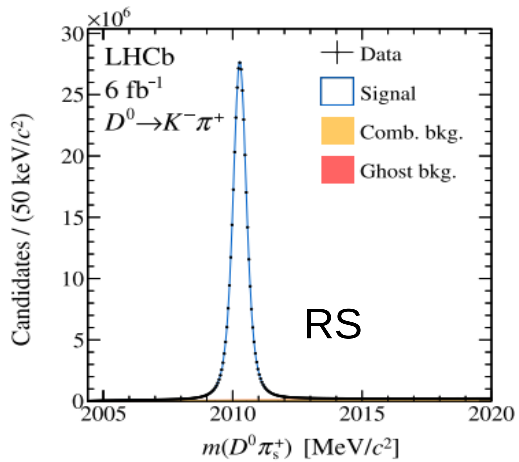
PRD 111 (2025) 012001

- **Mixing and CPV** parameters with right sign (RS) and wrong sign (WS) $D^0 \to K^+\pi^-$ decays tagged with **prompt** D* decays

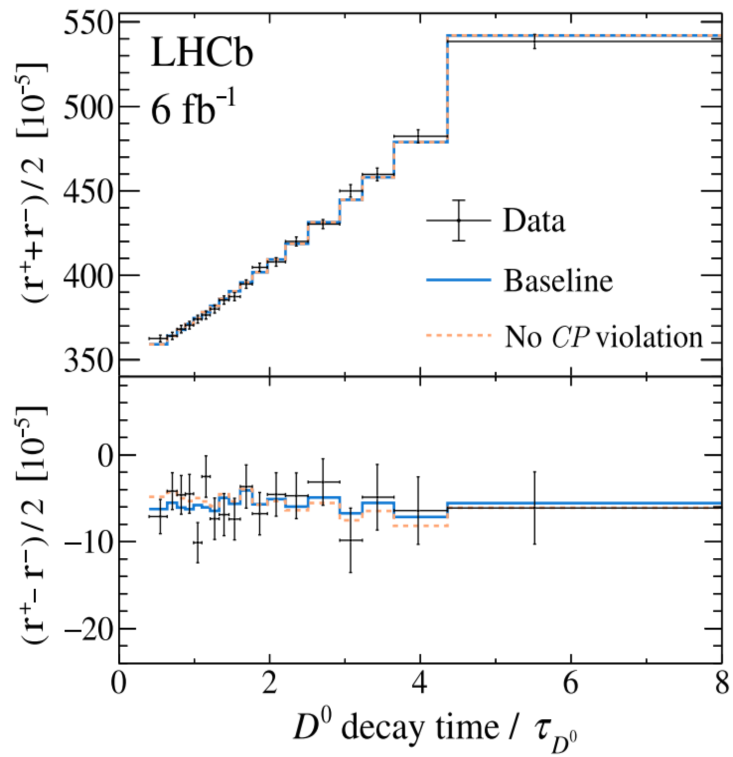








Mixing and CPV in $D^0 \to K\pi$



- Most precise results for mixing and CPV parameters
- **No evidence for CPV neither in decays, mixing nor interference**

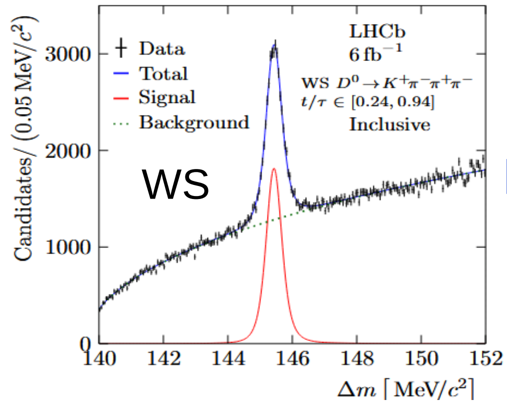
JHEP 12 (2025) 153

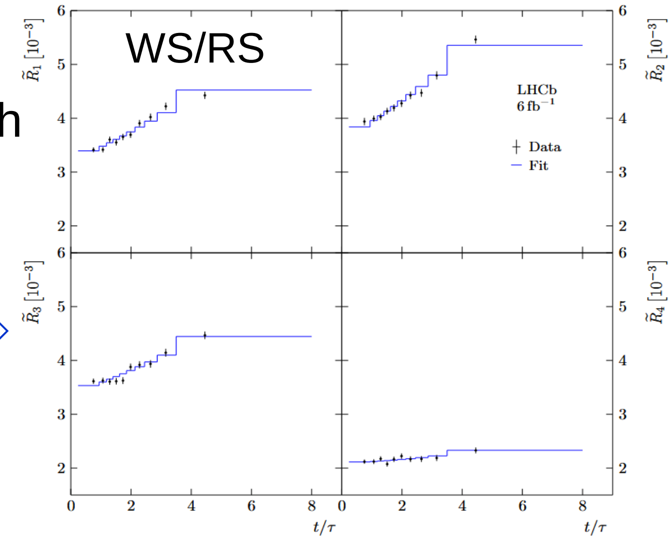
- **Mixing and CPV** with right (RS) and wrong sign (WS) $D^0 \to K^+\pi^-\pi^+\pi^-$ decays, PS binned measurement
- Same binning as for angle γ with $B \to D^0(\to K^+\pi^-\pi^+\pi^-)h$

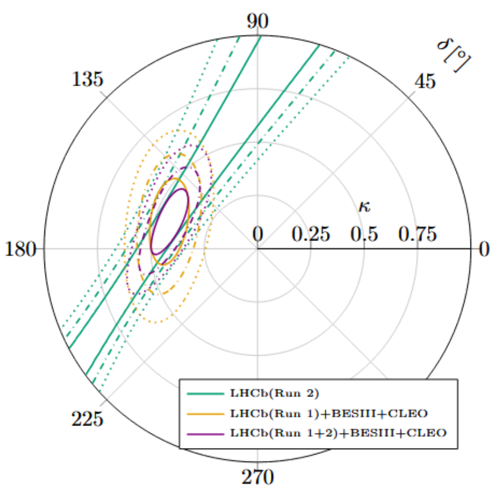
$$R(t) \equiv \frac{\Gamma[D^0 \to K^+\pi^-\pi^+\pi^-](t)}{\Gamma[D^0 \to K^-\pi^+\pi^-\pi^+](t)} \approx$$

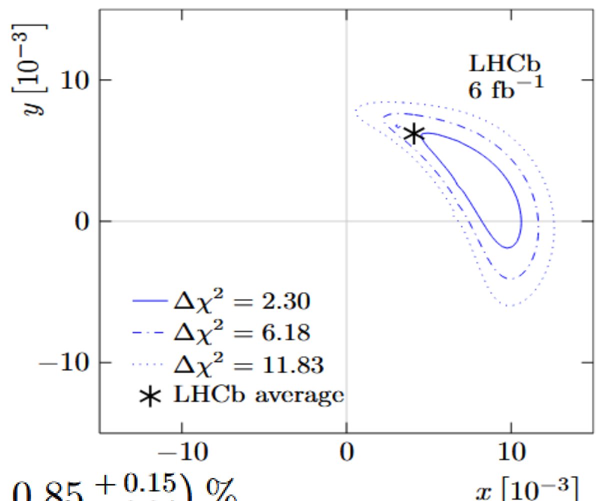
$$\approx r^2 - r\kappa y' \frac{t}{\tau} + \frac{x^2+y^2}{4}\left(\frac{t}{\tau}\right)^2$$

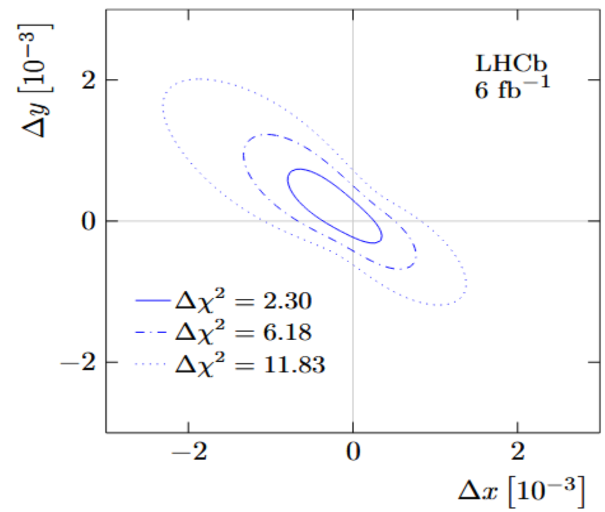
$$\kappa e^{i\delta} \equiv \langle\cos\delta_l\rangle + i\langle\sin\delta_l\rangle$$











$$r = (5.49 \pm 0.02) \times 10^{-2}$$
$$\kappa = 0.430\,^{+0.043}_{-0.039},$$
$$\delta = (163.3\,^{+13.8}_{-14.8})^\circ,$$

$$x = (\ 0.85\,^{+0.15}_{-0.24})\,\%,$$
$$y = (\ 0.21\,^{+0.29}_{-0.27})\,\%,$$
$$\Delta x = (-0.02 \pm 0.04)\,\%$$
$$\Delta y = (\ 0.02\,^{+0.04}_{-0.03})\,\%.$$

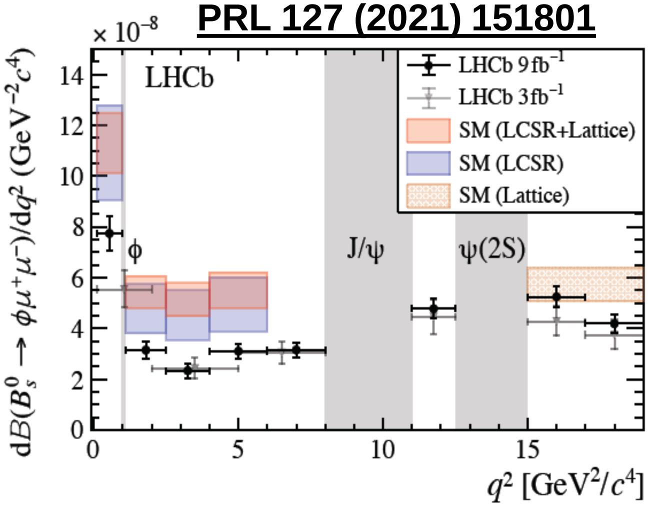
- Results in agreement with other LHCb measurements
- Consistent with **CP symmetry**

Rare b-hadron decays

- Many **observables to test SM**
- Affected by **SM corrections**: Form Factors and/or cc loops

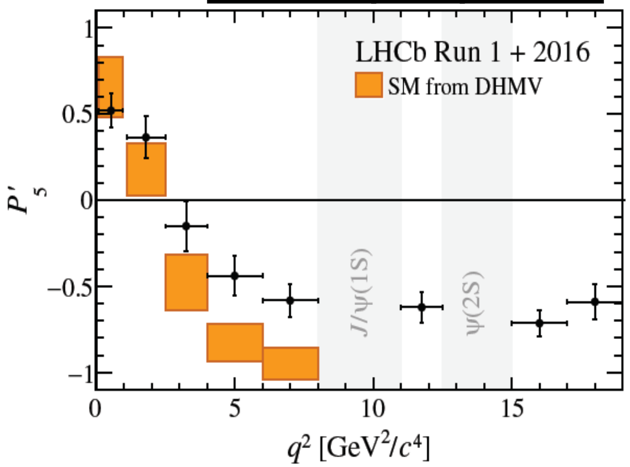
Branching fractions

PRL 127 (2021) 151801



Angular analyses

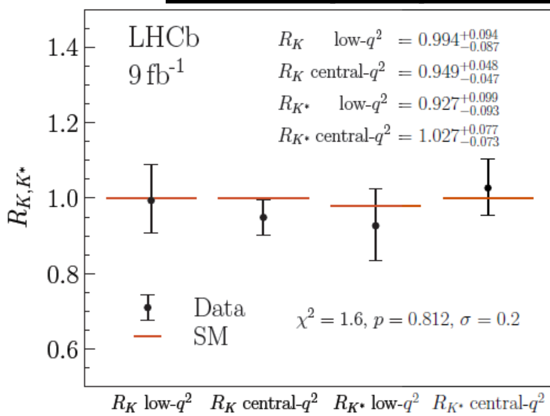
PRL 125 (2020) 011802

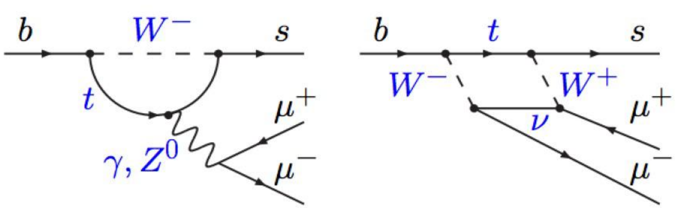


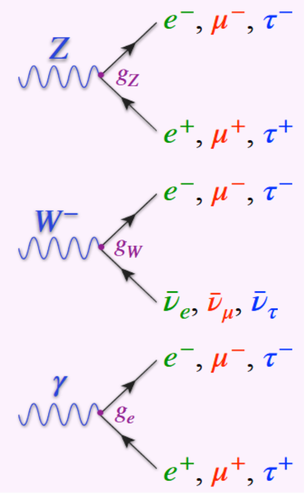
Lepton Flavour Universality

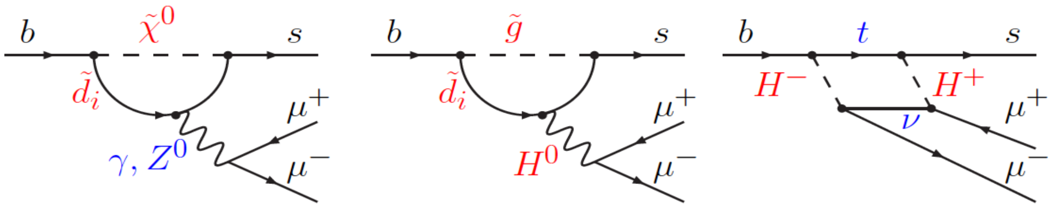
LFU tests

PRL 127 (2021) 151801





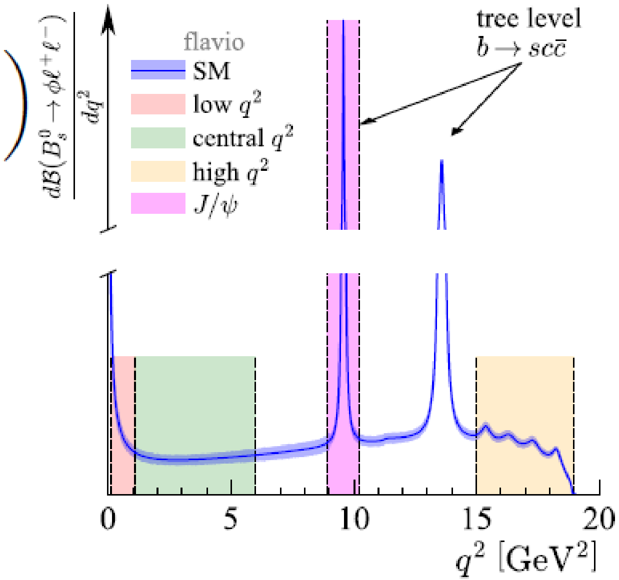


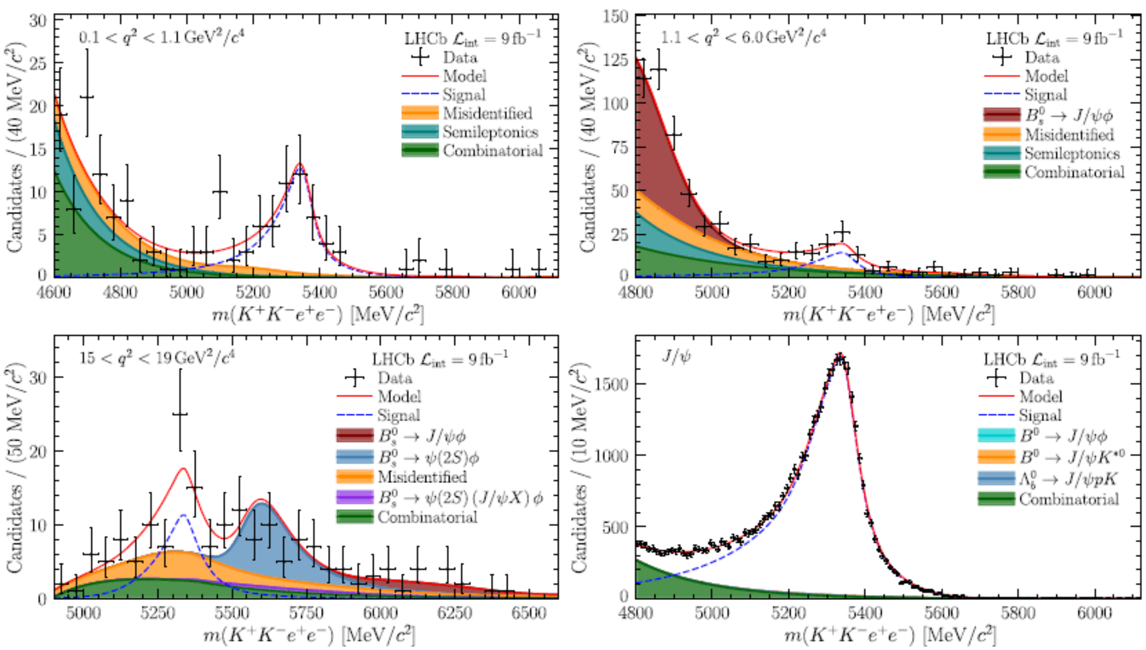


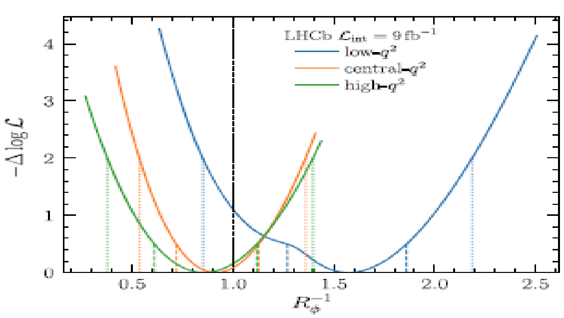
PRL 134 (2025) 121803

- Test of LFU in $B^0_s \to \phi\ell^+\ell^-$, theoretically clean
- Measure R_ϕ in **three q^2 bins** (first time: $15 < q^2 < 19$ GeV^2/c^4)
- **Double ratio** to cancel systematic effects

$$R_\phi = \left(\frac{\mathcal{B}(B^0_s \to \phi\mu^+\mu^-)}{\mathcal{B}(B^0_s \to J/\psi(\to \mu^+\mu^-)\phi)}\right) \Big/ \left(\frac{\mathcal{B}(B^0_s \to \phi e^+e^-)}{\mathcal{B}(B^0_s \to J/\psi(\to e^+e^-)\phi)}\right)$$





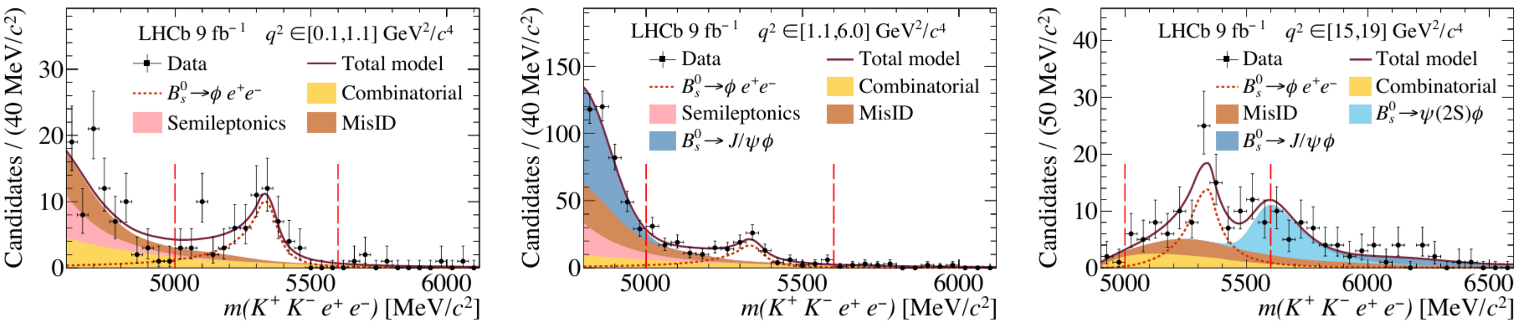


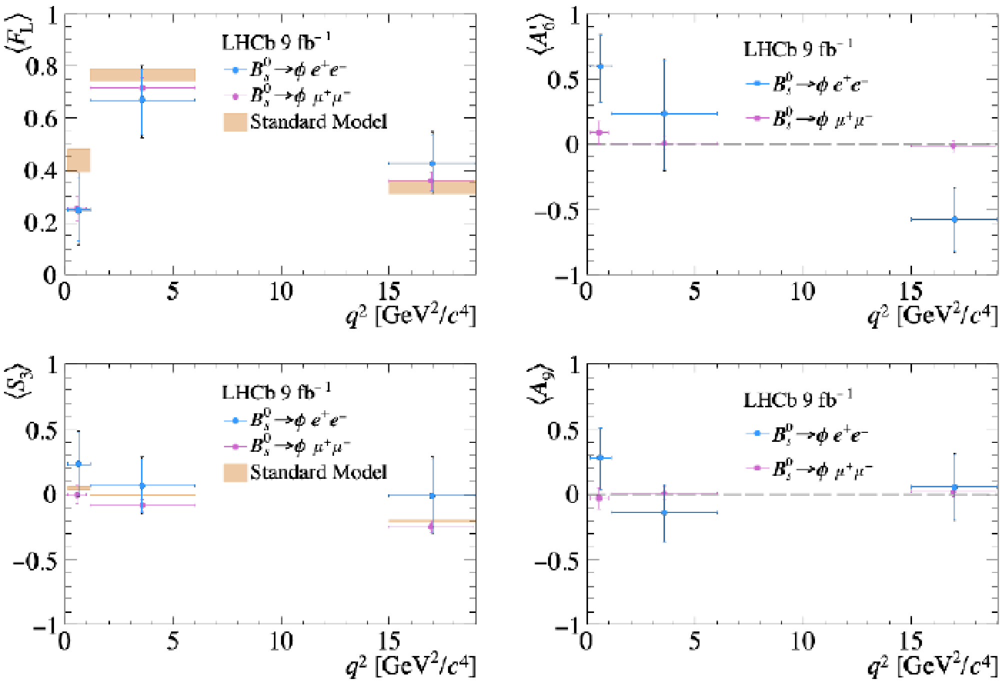
q^2 [GeV$^2/c^4$]	R_ϕ^{-1}
$0.1 < q^2 < 1.1$	$1.57\,^{+0.28}_{-0.25} \pm 0.05$
$1.1 < q^2 < 6.0$	$0.91\,^{+0.20}_{-0.19} \pm 0.05$
$15.0 < q^2 < 19.0$	$0.85\,^{+0.24}_{-0.23} \pm 0.10$

- **Observation of $B^0_s \to \phi e^+e^-$**
- **Ratios consistent with LFU**

- Angular analysis of the decay $B_s \to \phi e^+e^-$ in **three q^2 regions**

JHEP 07 (2025) 069





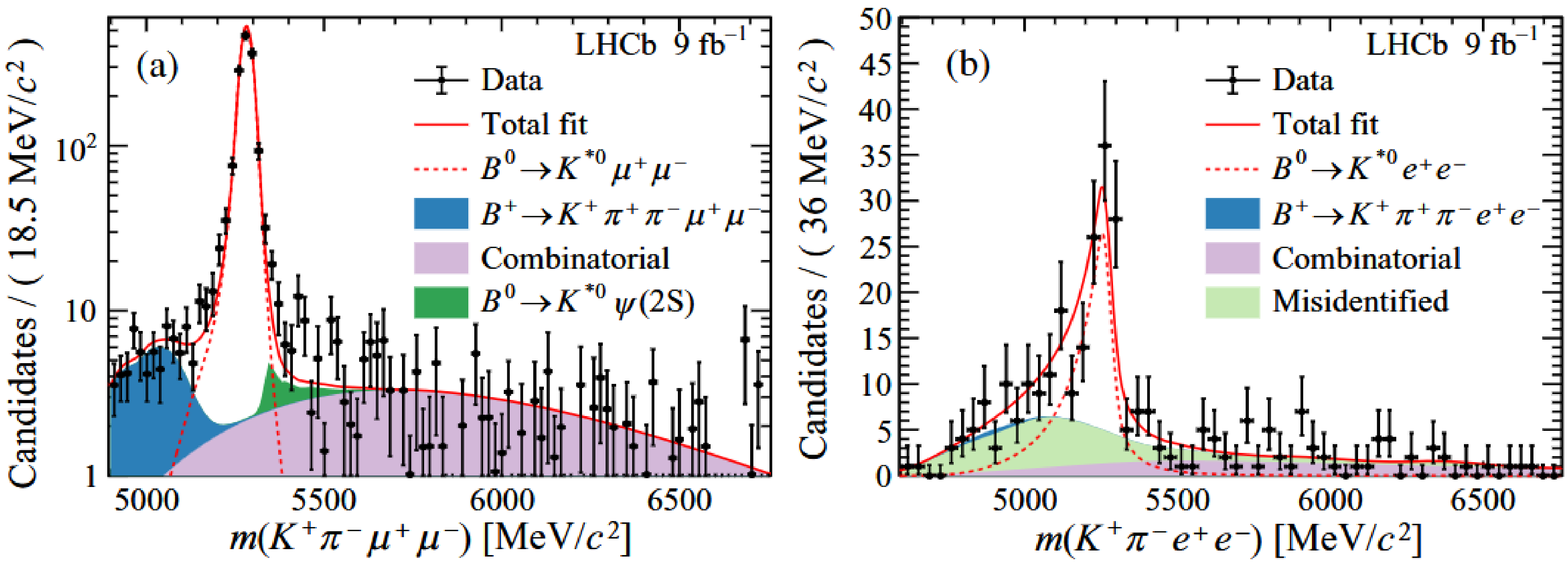
- Compatible with the muon channel analysis and with SM
- Limited signal sample size (Runs 1+2)
- No flavour tagging: CP averaged and decay-time-integrated fit
- Folding of different projections, fit in q^2 and either of ($\cos\theta_K$, $\cos\theta_e$) or ϕ

- **Consistent global picture**
- **Anomalies in the muon modes** to be understood

- Test of LFU in $\mathbf{B^0 \to K^{*0}\ell^+\ell^-}$, theoretically clean

PRL 137 (2026) 051803

- Measure R_{K^*} in the q^2 bin $\mathbf{q^2 > 14\ GeV^2/c^4}$
- **Double ratio** to cancel systematic effects

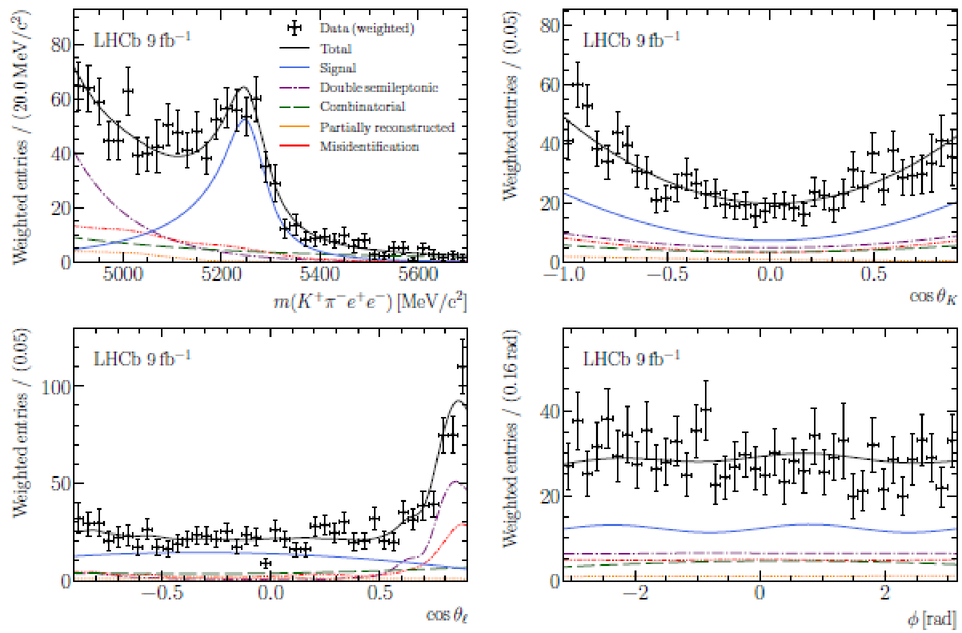


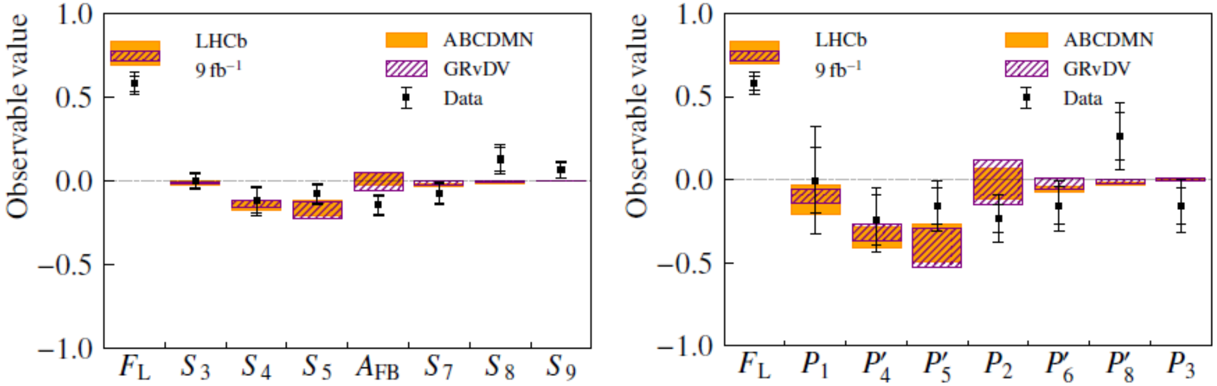
$$R_{K^{*0}} = 1.08^{+0.14}_{-0.12}(\text{stat}) \pm 0.07(\text{syst})$$

- First measurement at hadron collider in high q^2 bin
- Consistent and 3 x more precise then previous Belle result
- Consistent with LFU

JHEP 06 (2025) 140

- Angular analysis of the decay $B^0 \to K^{*0}e^+e^-$
- Analysis performed in central **q^2 region $1.1 < q^2 < 6.0$ GeV^2/c^4**

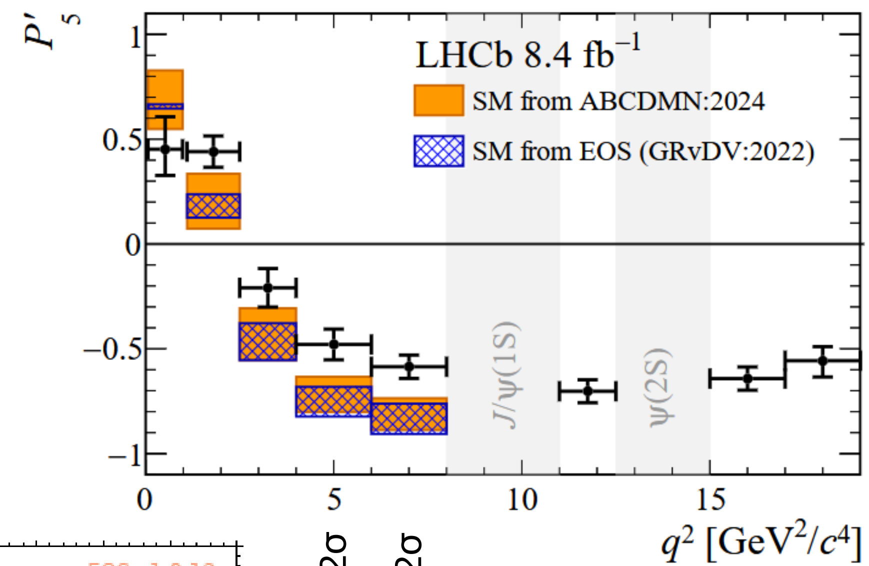




- **No significant disagreement with SM**
- No evidence for LFU violations when analyzing electron and muon modes together

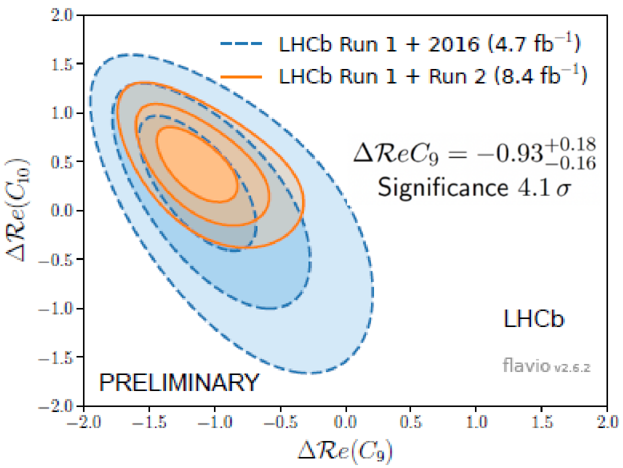
PRL 137 (2026) 2, 021802

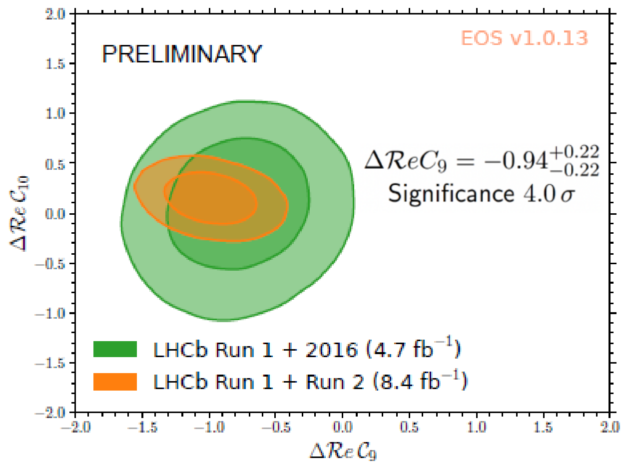
- Binned angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$
- Improved selection, more observables (CPV, BF)
- Include **finer q^2 binning**
- Take into account effects of lepton masses



discrepancy > 2σ

discrepancy > 2σ



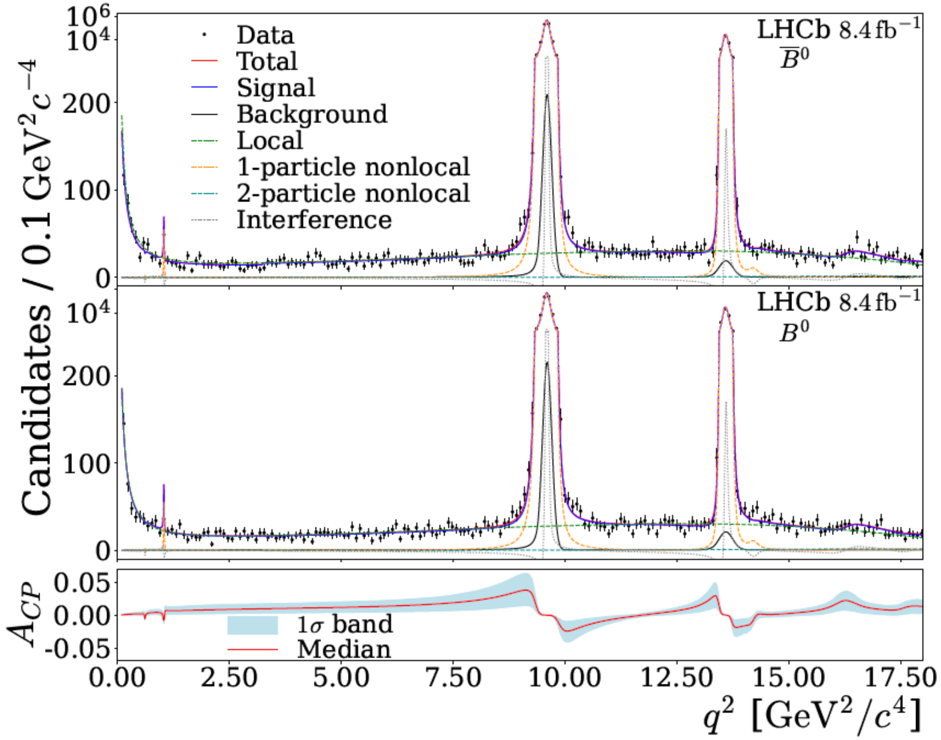


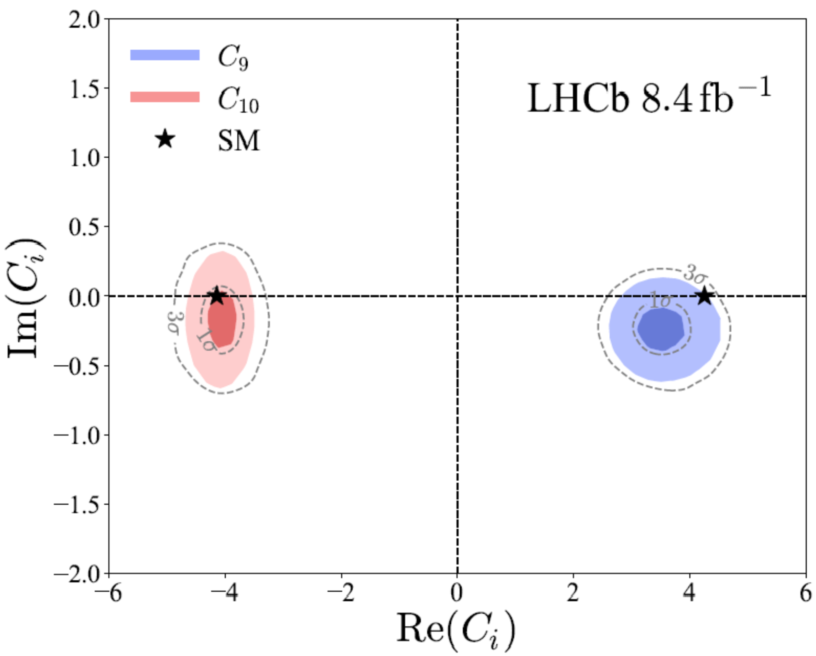
- Excellent **agreement with previous results**
- Confirms previous **tension with SM** predictions

CPV of local and nonlocal amplitudes in $B^0 \to K^{*0}\mu^+\mu^-$

arXiv:2605.07582

- Unbinned, full-q^2 analysis of local and nonlocal amplitudes
  JHEP 09 (2024) 026 **ibid.** **05 (2025) 208**
- Fit **nonlocal contributions with data** instead of external inputs, still model-dependent
- Consider B^0 and $\bar{B}^0$ separately
- Probes a new set of CPV couplings

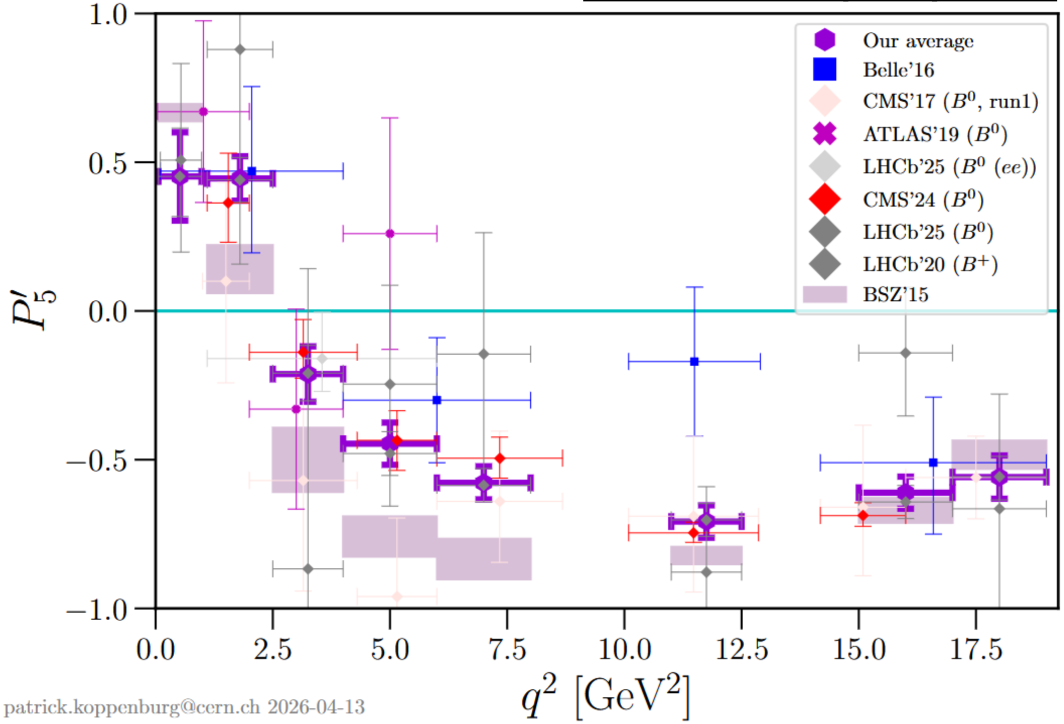




- **No significant CPV observed**
- Sensitivity to CPV observables, including Im(C_9) and Im(C_{10}), improved by an order of magnitude
- First analysis **sensitive to CPV in FCNC** decays at a **level similar to SM expectations**

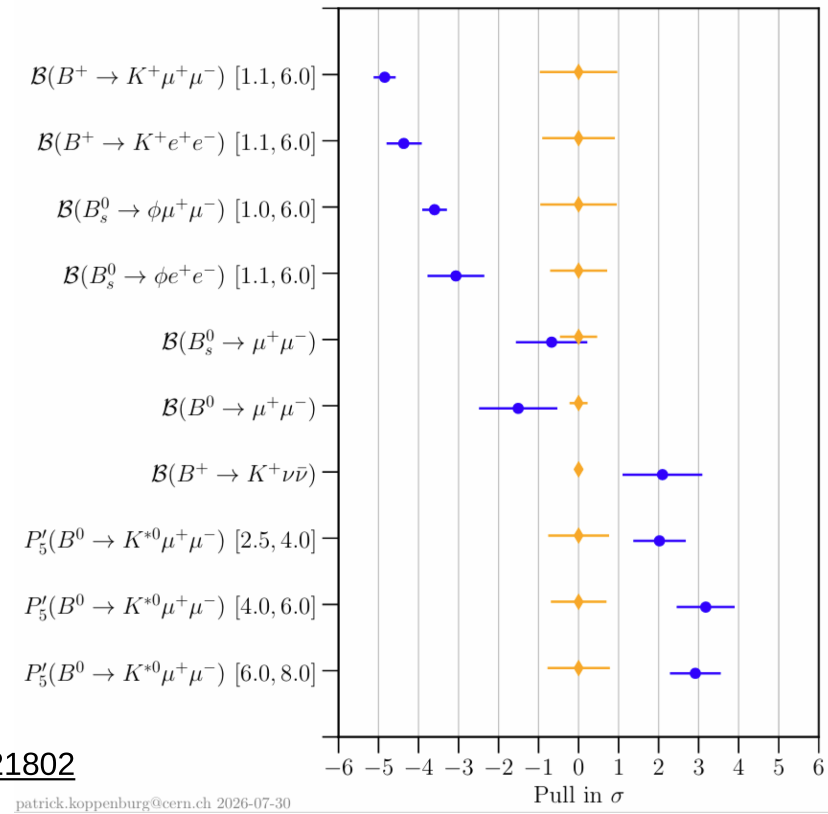
- Summary of P_5' measurements in q^2 bins

EPJ Plus 141 (2026) 4, 443



- Deviations of BRs with dileptons from SM predictions

https://www.koppenburg.ch/anomalies.html

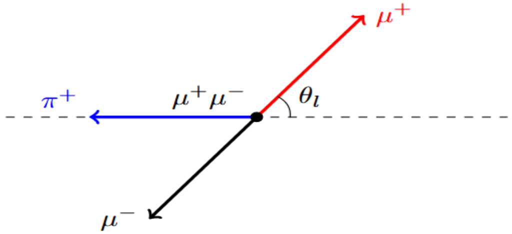


LHCb: PRL 126 (2021) 161802, JHEP 06 (2025) 140, PRL 137 (2026) 2, 021802
Belle: PRL 118 (2017) 111801
CMS: PLB 781 (2018) 517, PLB 864 (2025) 139406
ATLAS: JHEP 10 (2018) 047
Theory: Algueró et al., EPJC 83 (2023) 648,
Descotes-Genon, Hofer, Matias, Virto, JHEP 12 (2014) 125

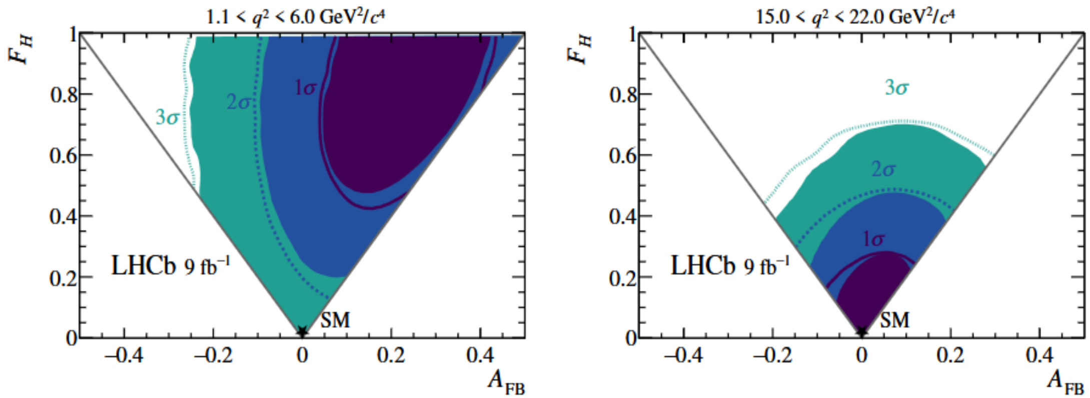
- Confirms previous **tension with SM** predictions
- Important to quantify, with larger data samples, the effect evolution with q^2

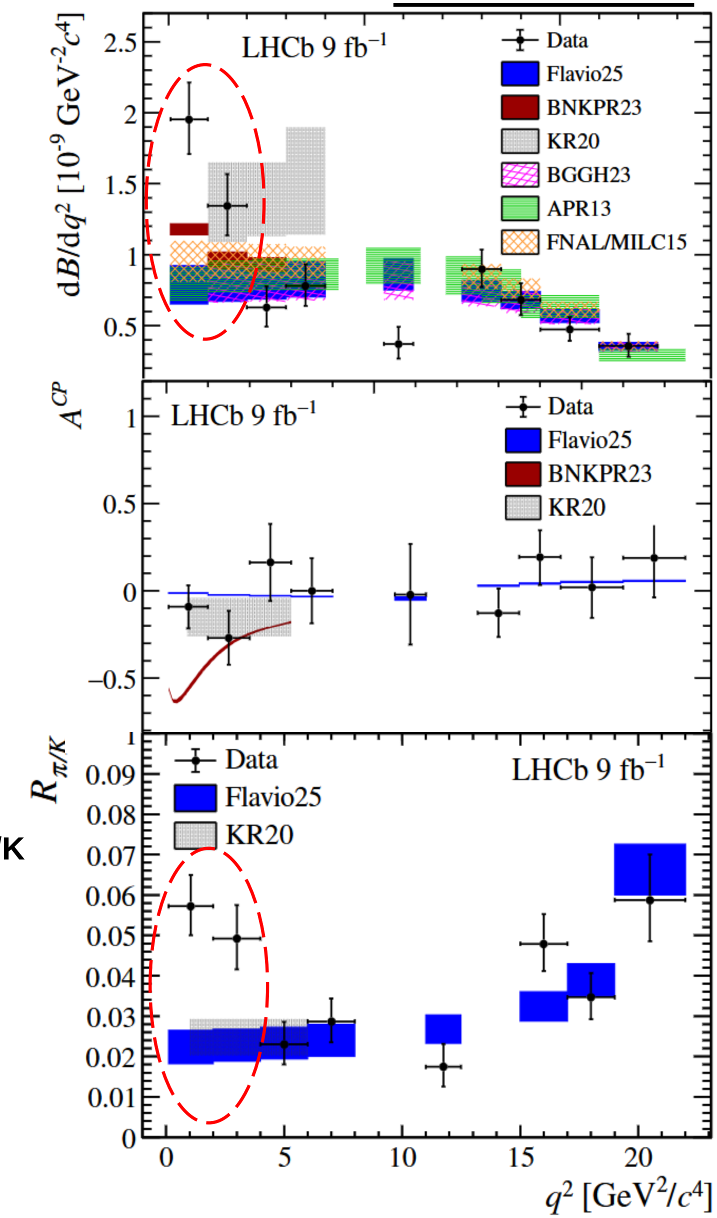
arXiv:2604.21987
arXiv:2606.23646

- **$B^+ \to \pi^+\mu^+\mu^-$: b → d** FCNC, BR ~ O(10^{-8}) in SM
- Angular analysis



$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_l} = \frac{3}{4}(1-F_H)(1-\cos^2\theta_l) + \frac{F_H}{2} + A_{\mathrm{FB}}\cos\theta_l$$





- **First differential measurement** of BR, **CPV** and **$R_{\pi/K}$**

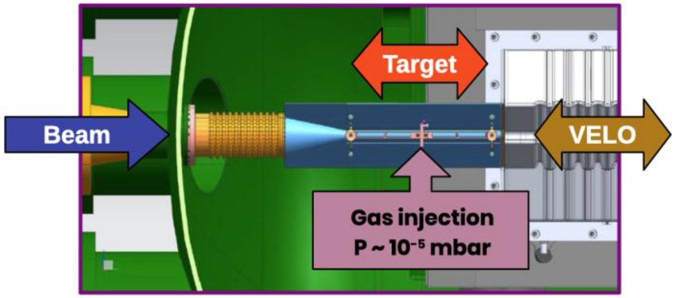
$$\mathcal{A}^{CP} \equiv \frac{\left\langle\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}\right\rangle_{\pi^-} - \left\langle\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}\right\rangle_{\pi^+}}{\left\langle\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}\right\rangle_{\pi^-} + \left\langle\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}\right\rangle_{\pi^+}}, \quad R_{\pi/K} \equiv \frac{\left\langle\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}\right\rangle_{\pi^-} + \left\langle\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}\right\rangle_{\pi^+}}{\left\langle\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}\right\rangle_{K^-} + \left\langle\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}\right\rangle_{K^+}}$$

- From the q^2 region 2-6 GeV²/c⁴ $|V_{td}/V_{ts}| = 0.241^{+0.030}_{-0.027}$
- Localised deviations from SM up to 3σ

Heavy ions

Heavy flavours in heavy-ion collisions

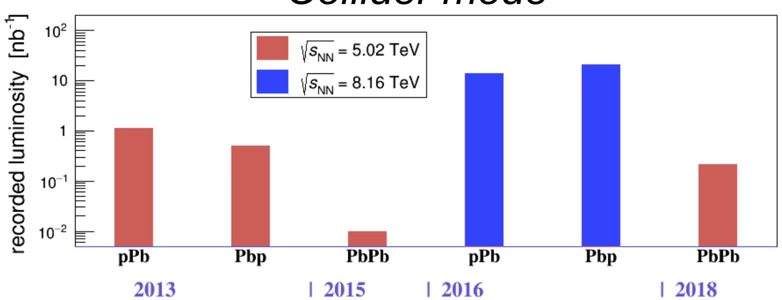
- Upgraded tracking system → improved performance at higher occupancies (PbPb)
- **SMOG2: fixed-target system upgraded in Run 3**
- Increased luminosity, simultaneous data-taking with collider mode
- **Rich Run 3 data-taking heavy-ion campaign**: 2 nb^{-1} of PbPb (x 10 of Run 2)
- Unique samples taken in 2026: pXe@113 GeV; pH_2, pD_2, pHe@44 GeV; pp@2.4 TeV; $PbCH_4$, PbHe@70.9 GeV



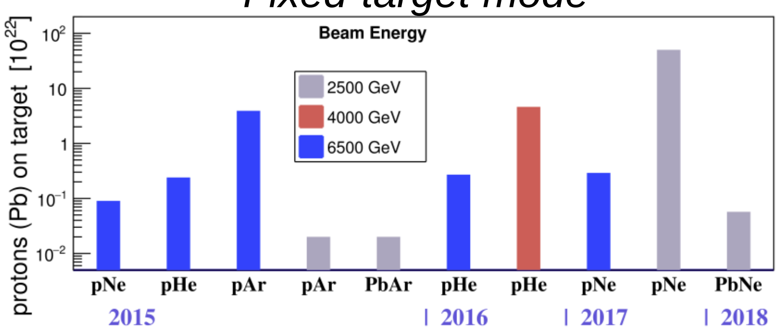
Phys.Rev.Accel.Beams 27 (2024) 11, 111001

Runs 1&2 (2010-2018)

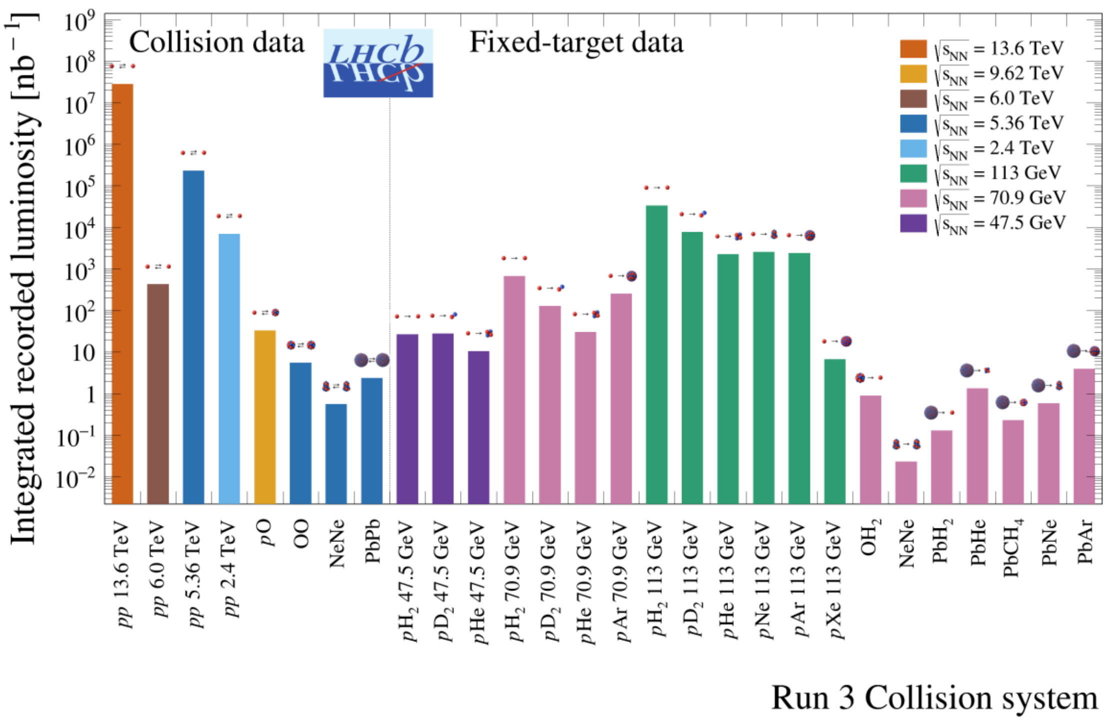
Collider mode



Fixed-target mode



Run 3 (2022-2026)

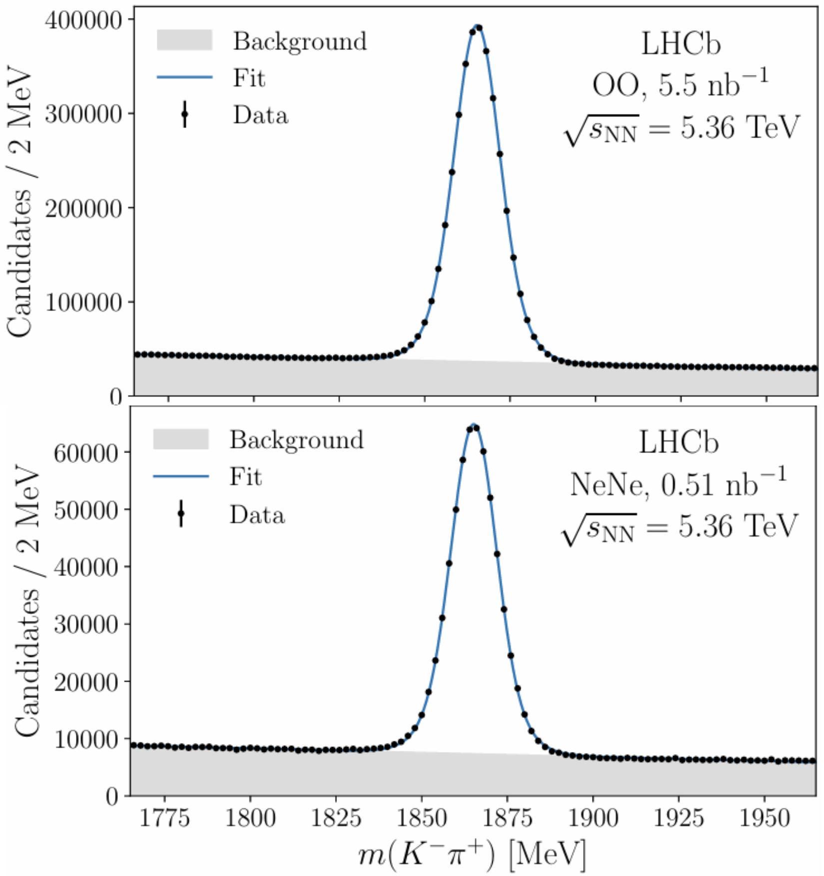


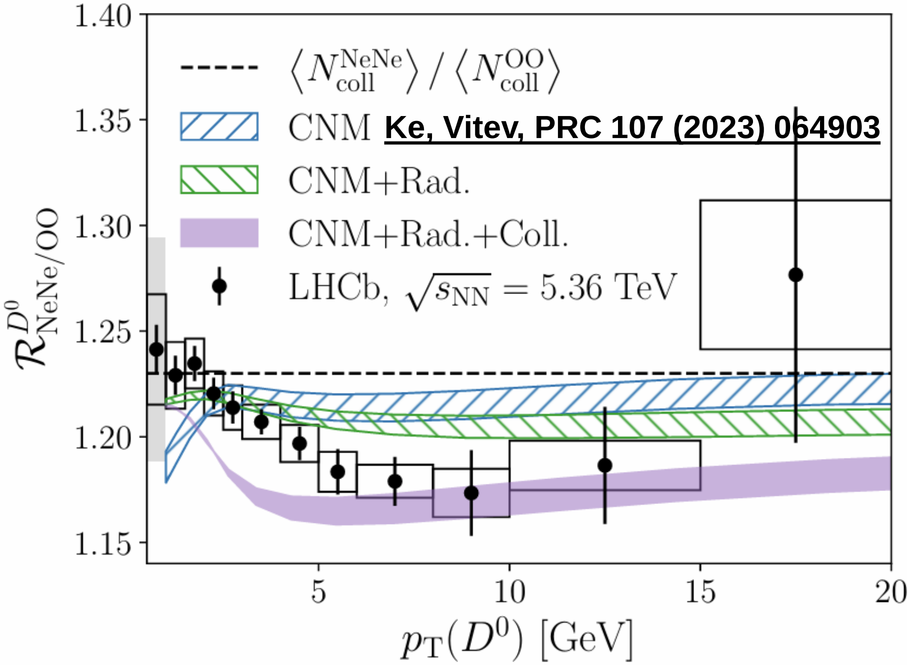
D^0 meson production in NeNe and OO collisions

arXiv:2605.27273

- First study of charm production in light-ion collisions at the LHC
- Study **onset of QGP production with increasing nucleus size**
- NeNe collisions expected to produce a slightly larger volume of QGP than OO collisions
  → larger energy loss effects
- Clean sample, 2025 light ion run

$$\mathcal{R}^{D^0}_{\mathrm{NeNe/OO}} \equiv \frac{\mathrm{d}N^{\mathrm{NeNe}}_{D^0}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N^{\mathrm{OO}}_{D^0}/\mathrm{d}p_{\mathrm{T}}} \frac{N^{\mathrm{OO}}_{\mathrm{inel}}}{N^{\mathrm{NeNe}}_{\mathrm{inel}}}$$



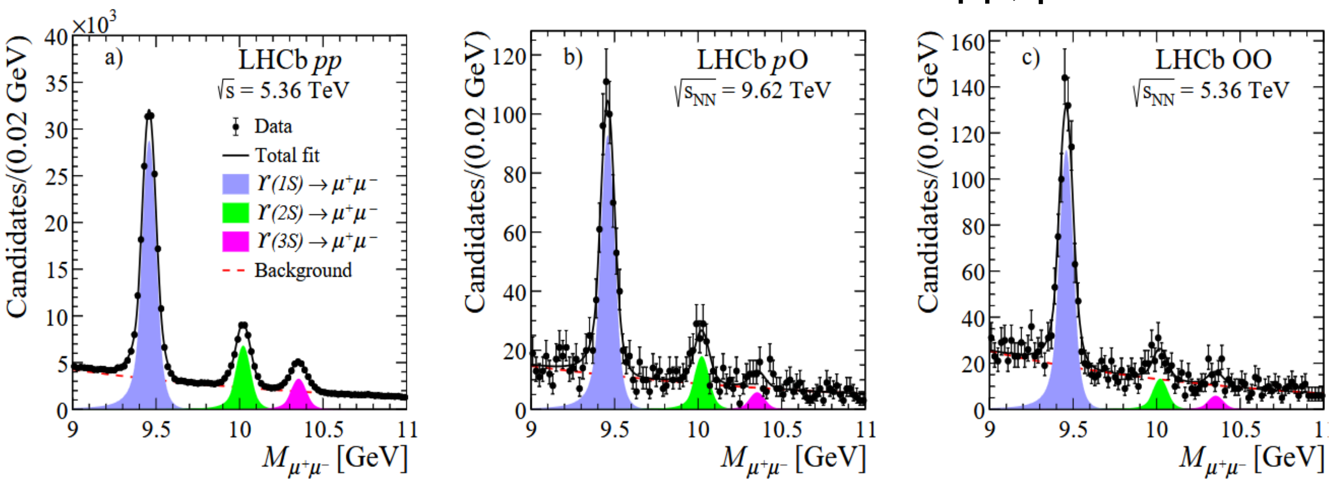


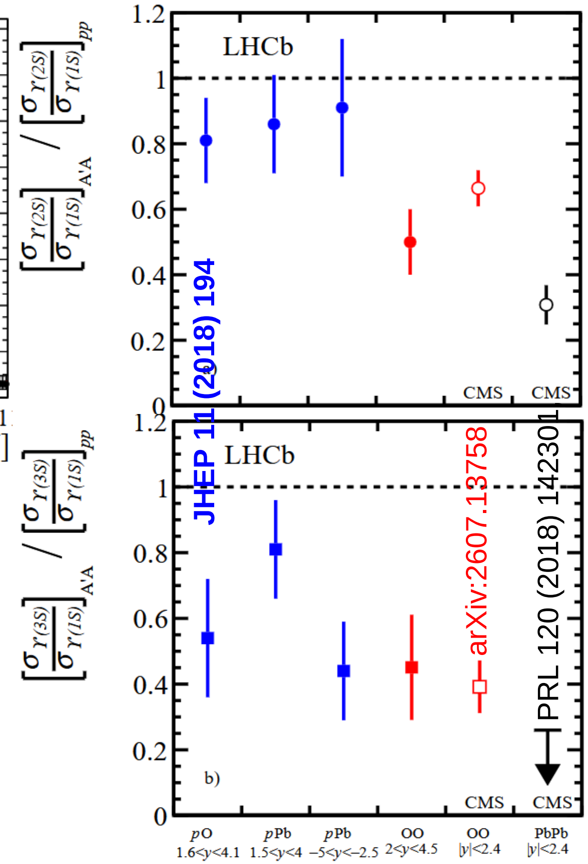
- Evidence for gradual **increase of QGP-like effects with collision size** in light-ion collisions
- Constraints on heavy quark diffusion and energy loss in the produced medium

Υ(nS) production in pO and OO collisions

arXiv:2608.00182

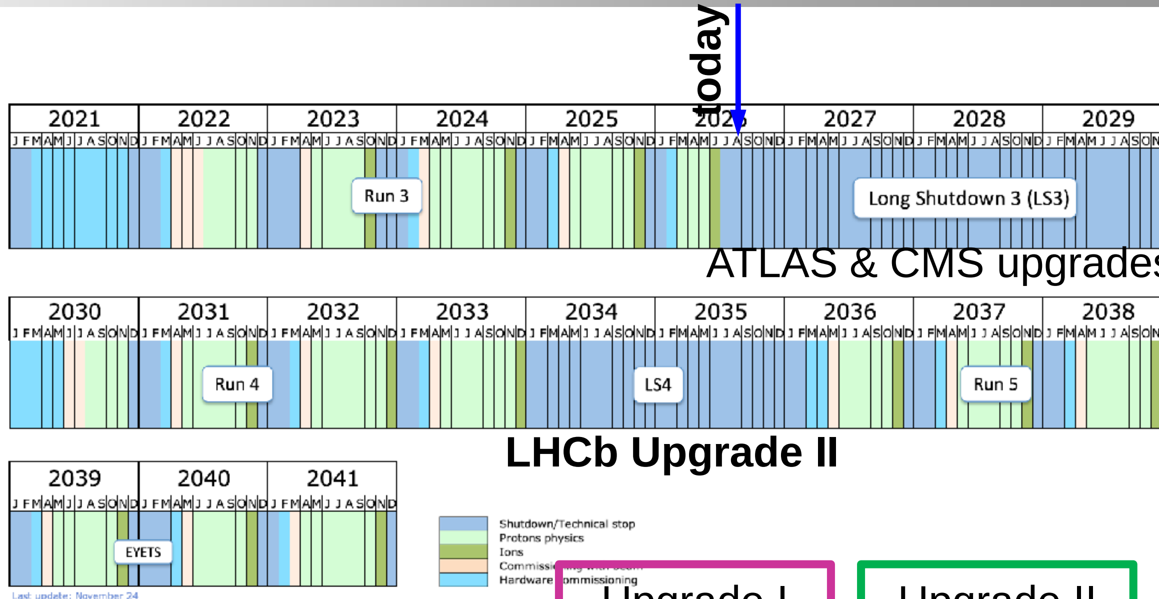
- ❑ Clean Υ(1S), Υ(2S) and Υ(3S) signals in Run 3 data
  → pp, pO and OO collisions



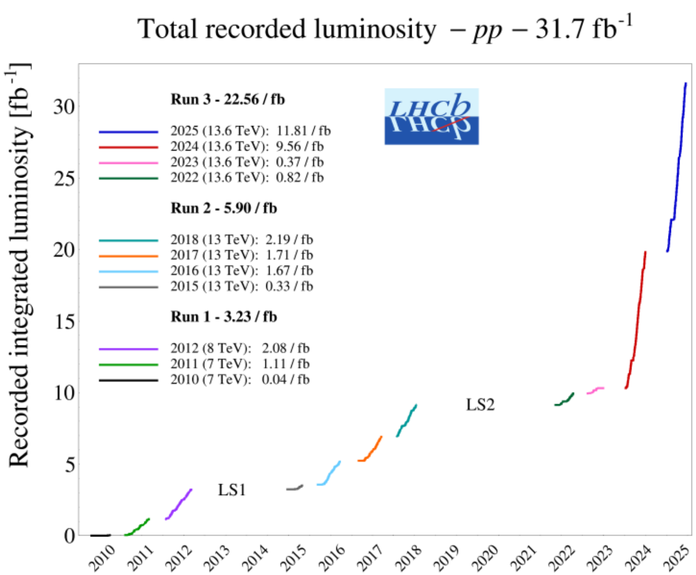


- ❑ Υ(nS) suppression: signature of QGP formation
- ❑ Double ratios excited-to-ground state with pp
  → cancel initial-state effects
- ❑ pO, pPb, Pbp – reference for Cold Nuclear Matter effects
- ❑ x2 **suppression of Υ(2S)/Υ(1S) production in OO collisions** relative to pp,
  4.8σ difference – similar to PbPb collisions and larger than pO ➔ not CNM alone
- ❑ **Suppression of Υ(3S)/Υ(1S) production in pO and OO collisions** relative to pp
  → interpreted as interplay of CNM and QGP
- ❑ **Evidence consistent with formation of QGP in OO collisions**

- LHCb and LHC timeline

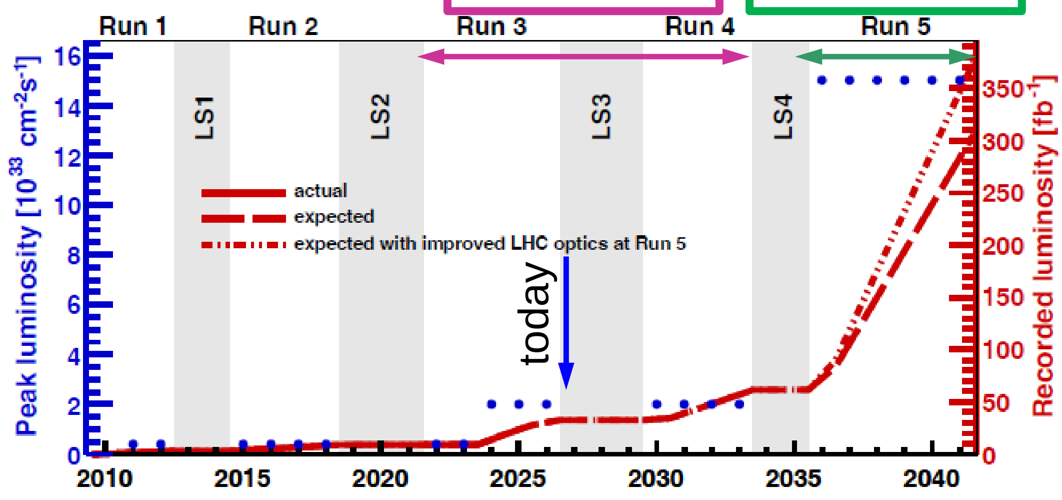


- **LHCb Runs 3+4**
  - Higher pile-up + software trigger
  - Collect 50 fb-1 by 2033



Upgrade I

Upgrade II

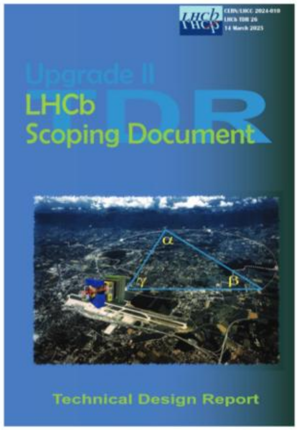


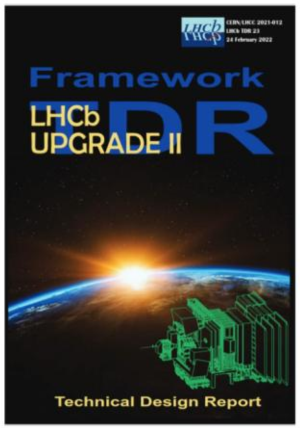
$\mathcal{L} = 4 \times 10^{32}\ \mathrm{cm^{-2}s^{-1}}$ 1.1 visible interactions / crossing **8 fb^{-1}** collected	$\mathcal{L} = 2 \times 10^{33}\ \mathrm{cm^{-2}s^{-1}}$ 5.5 visible interactions / crossing **50 fb^{-1}** collected	$\mathcal{L} = 2 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ 55 visible interactions / crossing **300 fb^{-1}** collected

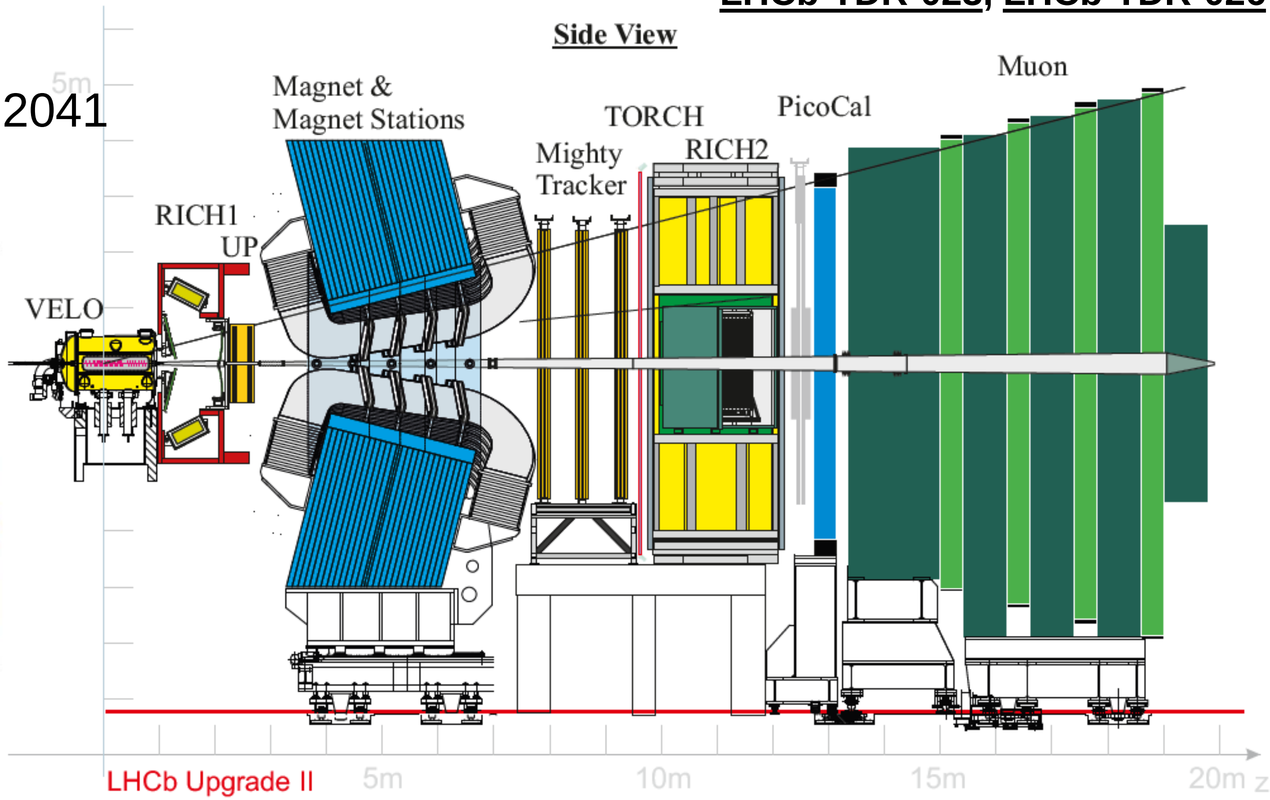
- **LHCb Upgrade II** in LS4
  - Collect > 300 fb-1 by 2041

LHCb-TDR-023, LHCb-TDR-026

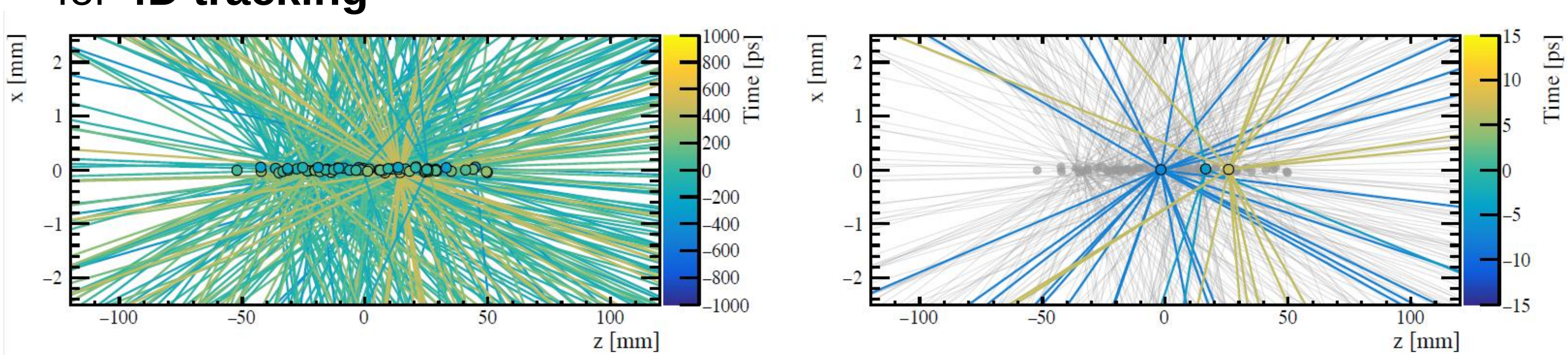
- ❑ **LHCb Upgrade II** in LS4
  - ❑ Collect > 300 fb-1 by 2041
  - ❑ Pile-up of 28 – 42







- ❑ Timing capabilities for **4D tracking**

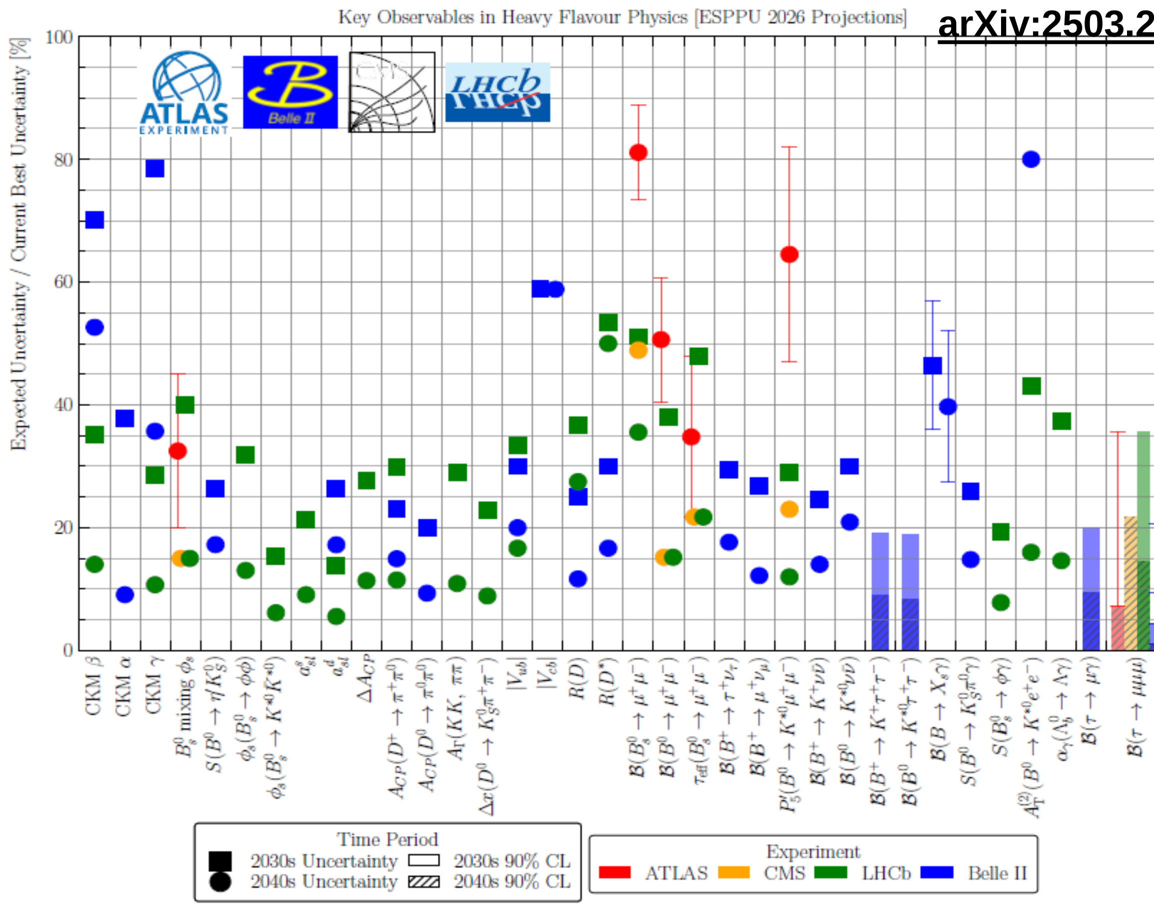


- ❑ New vertex, tracking, PID, and CALO detector, and upgraded MUON detector

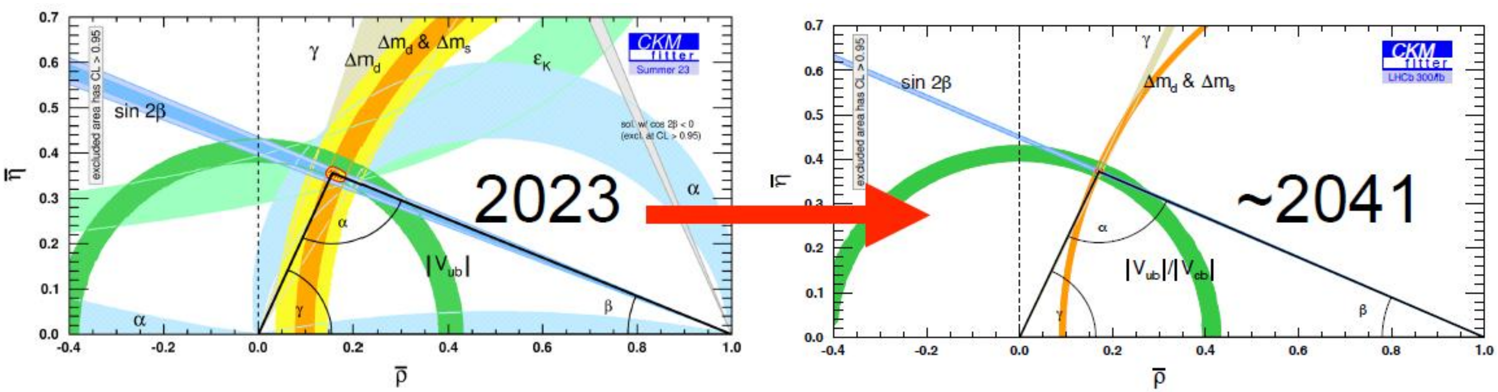
Projections for key measurement in HF physics

- Projections by ATLAS, Belle II, CMS, LHCb for the EPPSU 2024–2026
- Complementarity between the experiments
- Collective **improvement of about an order of magnitude on most observables** by 2040s

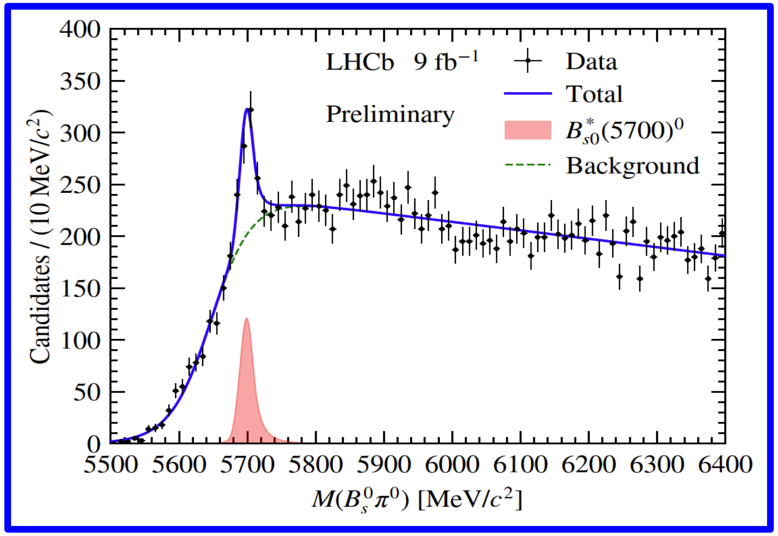
arXiv:2503.24346



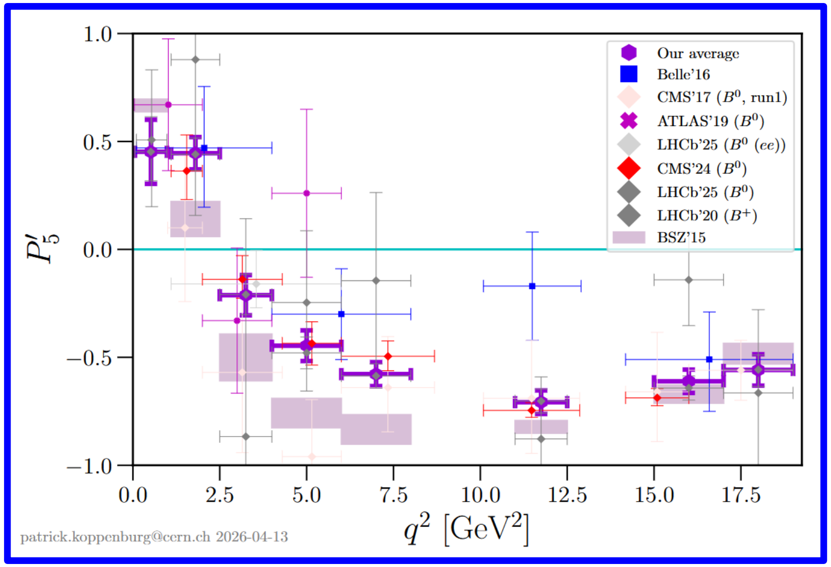
- LHCb results will be **dominant** for many of the key measurements



- ❑ **Rich flavour physics program** of LHCb
- ❑ Successful operation, good quality data – both **proton and heavy ion collisions**
- ❑ **Majority of results consistent with the SM**
- ❑ Bigger / better **dataset, precision, sensitivities**
- ❑ We know there is **more physics than** provided by the **SM**. Some **tensions** motivate strong students to join the quest



- ❑ Many interesting analyses ongoing, new opportunities with **LHCb Upgrade II**



Marc Chagall, Entre paix et guerre

- ❑ *Possible effects beyond the SM attacked via **direct and indirect searches**. Key role of LHCb in flavour physics*

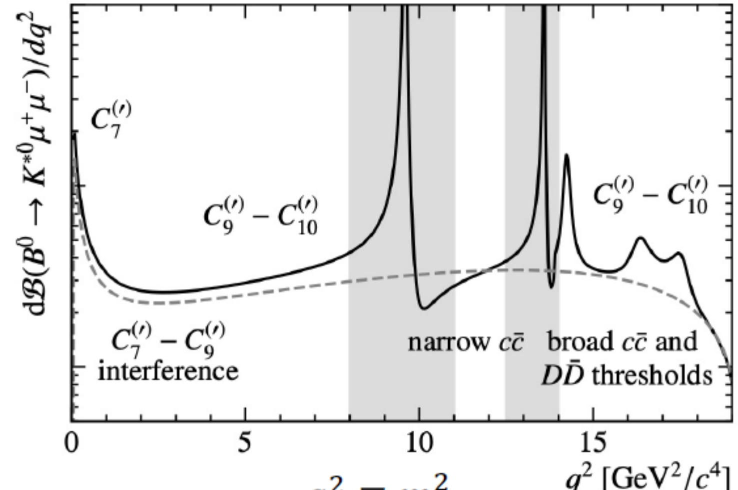
Backup

Effective field theory

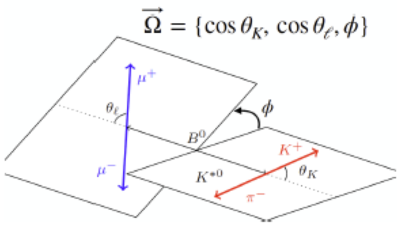
$$\mathcal{H}_{\mathrm{WET}} = \frac{-4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i \boxed{\mathcal{C}_i^{(\prime)}(\mu)} \mathcal{O}_i^{(\prime)}(\mu)$$

$b \to s l^+ l^-$ probes Wilson coefficients C_7, C_9, C_{10}

New physics modifies C_i or introduces new terms



$q^2 \equiv m^2_{l^+l^-}$



Angular distribution for $B^0 \to K^* l^+ l^-$ decay (CP averaged):

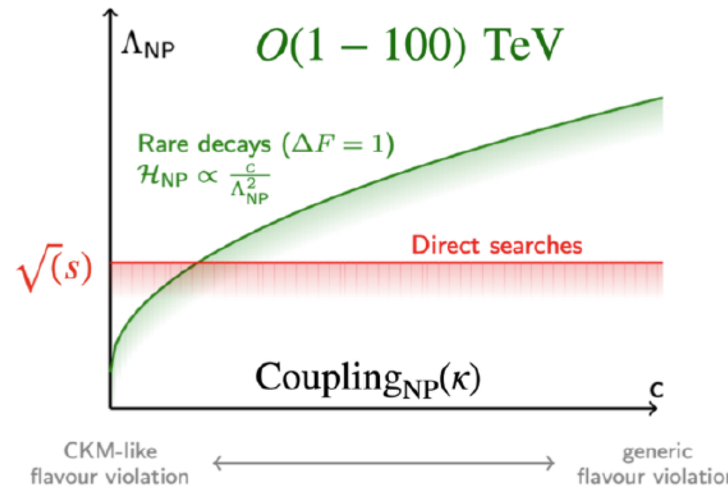
$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{dq^2 d\vec{\Omega}}\bigg|_P = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\frac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi + S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

F_L: longitudinal polarization, A_{FB} forward-backward asymmetry

Cleaner observables: $P_i' = S_i\sqrt{F_L(1-F_L)}$

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda}\sum_{i=1}^{N_5} C_i^{(5)} O_i^{(5)} + \frac{1}{\underbrace{\Lambda^2}_{\text{NP scale}}}\sum_{i=1}^{N_6} \underbrace{C_i^{(6)}}_{\text{unknown Wilson coefficients}} \underbrace{O_i^{(6)}}_{\text{higher-dimensional operators}} + \mathscr{O}\left(\frac{E^3}{\Lambda^3}\right)$$

- **Standard Model as an effective field theory (SMEFT)**
  - Constraint (*any*) new-BSM from lower energy processes
  - ***Rare b-decays:*** **indirect probes of NP**
- **In practice, with rare and flavour studies**
  - *Measurements → indirect constraints on* C_i
  - Constraints used to lower bound Λ_{NP} on a variety of BSM models



Wilson coefficient		Operator
γ-penguin[1]	$\mathcal{C}_7^{(\prime)}$	$\frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$
ew. penguin	$\mathcal{C}_9^{(\prime)}$	$\frac{e^2}{g^2}(\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\mu}\gamma^\mu\mu)$
	$\mathcal{C}_{10}^{(\prime)}$	$\frac{e^2}{g^2}(\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\mu}\gamma^\mu\gamma_5\mu)$
scalar	$\mathcal{C}_S^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b(\bar{s}P_{R(L)}b)(\bar{\mu}\mu)$
pseudoscalar	$\mathcal{C}_P^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b(\bar{s}P_{R(L)}b)(\bar{\mu}\gamma_5\mu)$

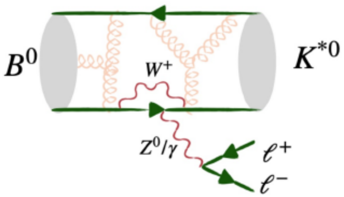
$b \to s\gamma$

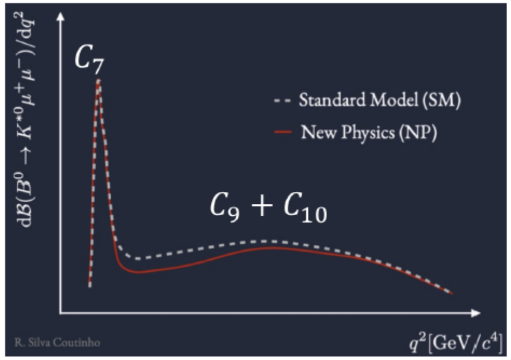
$b \to s\ell\ell$

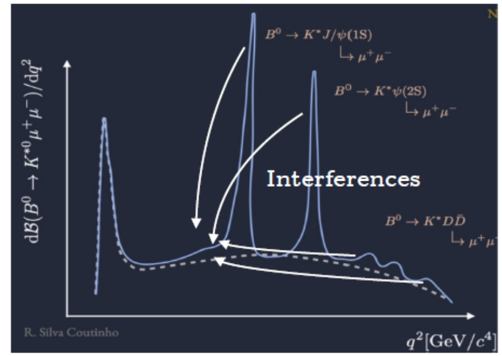
$B_s^0 \to \mu^+\mu^-$

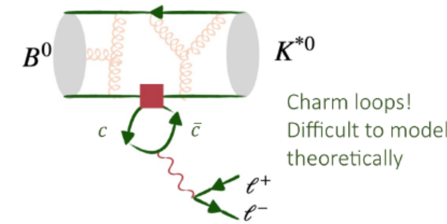
from R. Quagliani

Local-amplitudes $C_9^{\mathrm{eff}} = C_9^{SM} + C_9^{NP} + Y_{c\bar{c}}(q^2)$ Non-local amplitudes









Optimistic (example LQ model)

- LQ with enhanced coupling to 3rd generation leptons
  - Generates anomalies in b→see & b→sμμ via radiative effects even if LFU holds
- LQ model can explain at the same time also the tensions in RD/RD* in b→clν
- Motivate search of enhanced $B \to K^*\tau\tau$

Pessimistic

- Non-local large contribution from $b \to c\bar{c}s$ can mimic the observed shift in C_9
- **What can we do with existing data to convince ourself this is not the case?**

from R. Quagliani

LFU in $B^+ \to K^+\pi^+\pi^-\ell^+\ell^-$ decays

- Test of LFU in $B^+ \to K^+\pi^+\pi^-\ell^+\ell^-$, theoretically clean
- Measure $R_{K\pi\pi}$ in one **q^2 bin $1.1 < q^2 < 7$ GeV^2/c^4**
- **Double ratio** to cancel systematic effects

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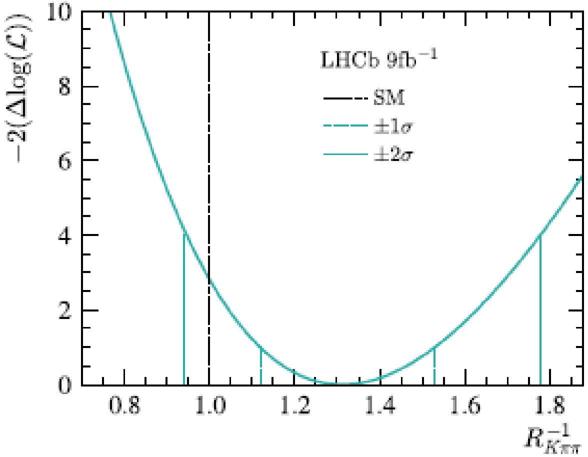

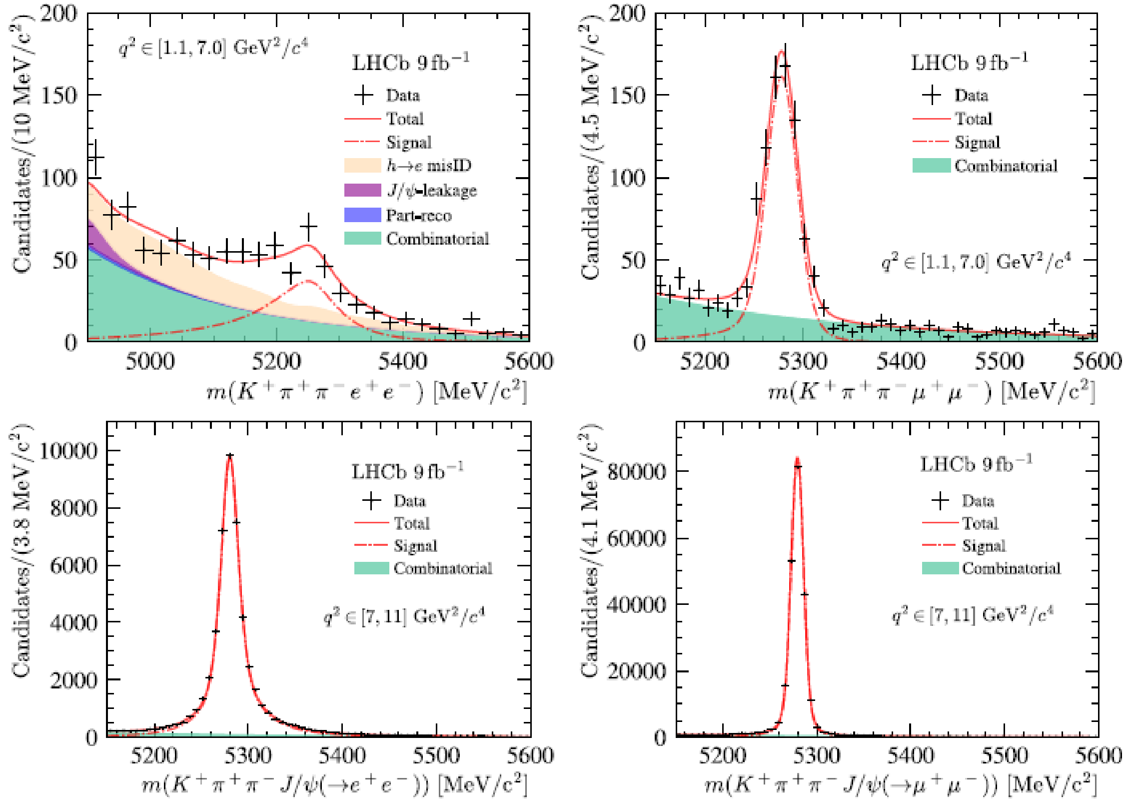

$$R^{-1}_{K\pi\pi} = 1.31^{+0.18}_{-0.17}(\text{stat})^{+0.12}_{-0.09}(\text{syst})$$

- **Observation of $B^+ \to K^+\pi^+\pi^-e^+e^-$**
- **Ratios consistent with LFU**