Recent Results from LHCb

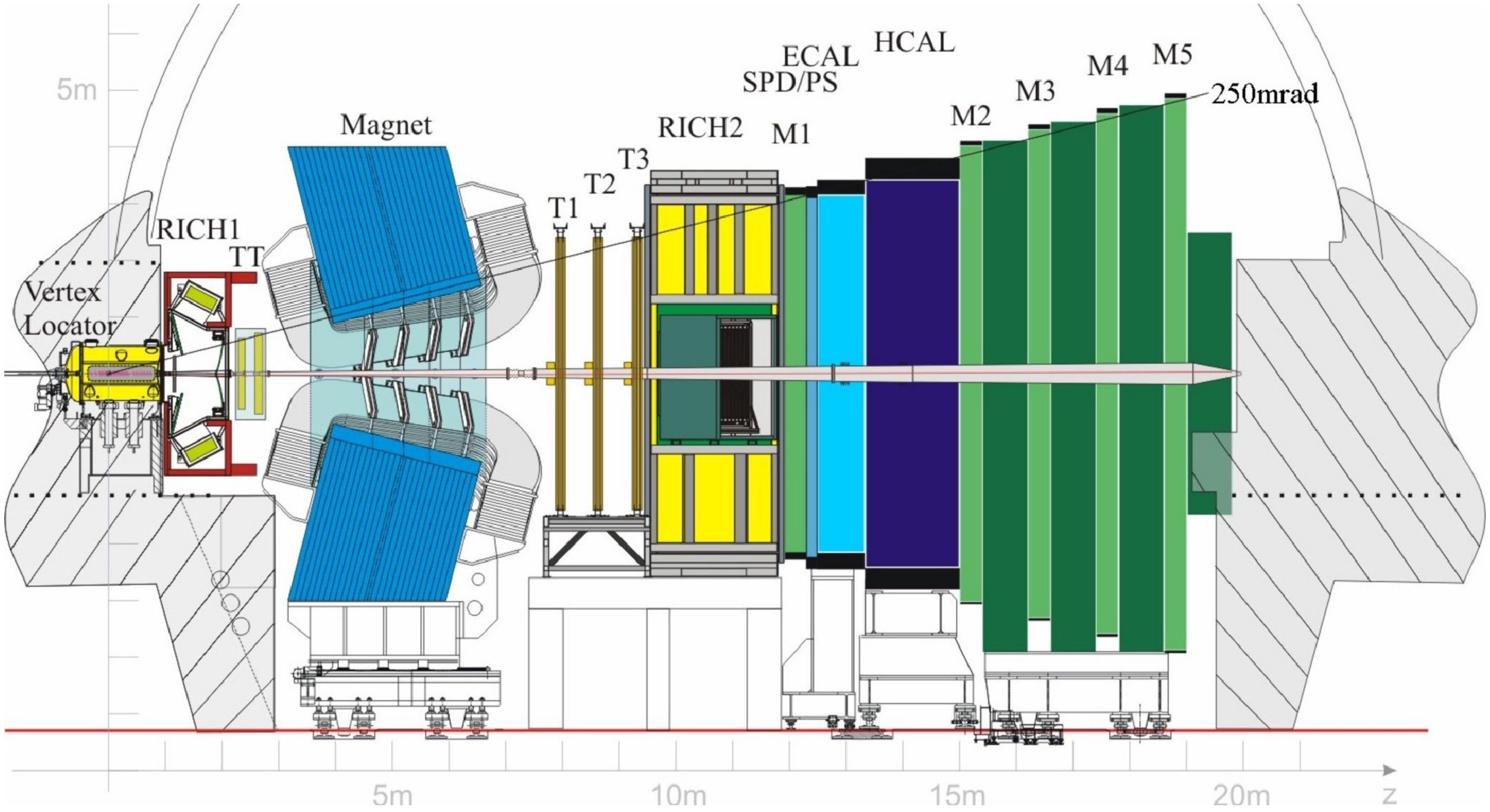
Conor Henderson
University of Cincinnati
On behalf of the LHCb Collaboration

2023 Phenomenology Symposium
8-10 May 2023

Outline

- Introduction to LHCb detector
- Recent results:
  - Measurement of CKM angle gamma
  - CP Violation in D mesons
  - Tests of Lepton Flavor Universality
  - Exotic hadrons: First observation of doubly-charged tetraquark
- LHCb Detector Upgrade for Run 3

The LHCb Detector for LHC Run 2



- Forward spectrometer: $2<\eta<5$
- Dipole magnet with 4 Tm integrated field
- Momentum resolution: 0.5% up to 1.0% at p=200 GeV
- Impact parameter resolution: $(15 + 29/p_T)$ µm [p_T in GeV]

Cabibbo-Kobayashi-Maskawa (CKM) Matrix & Unitarity

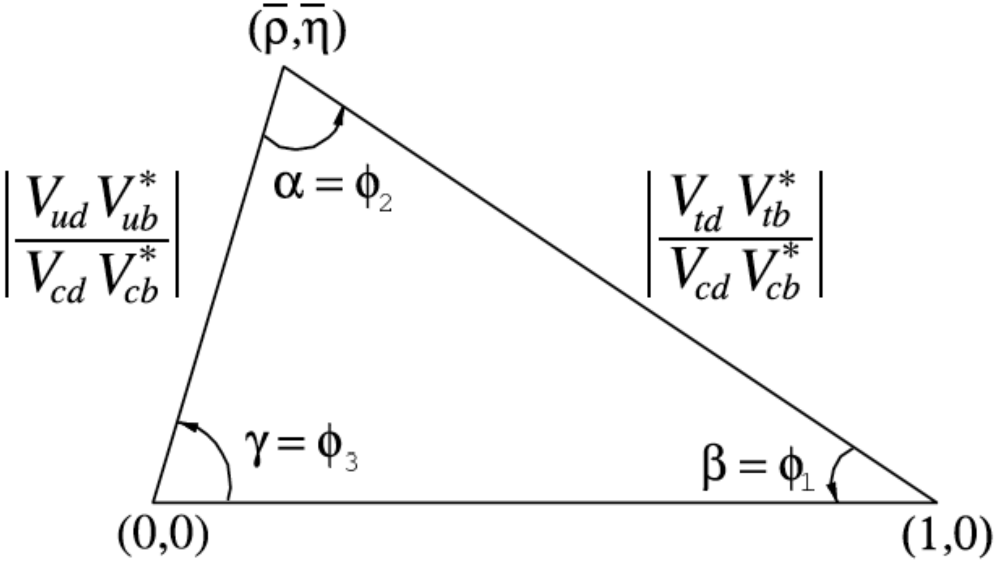
- Quark mixing in SM described by 3x3 complex unitary CKM matrix :

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Can be parametrized by 3 mixing angles and 1 CP-violating phase
- CKM matrix unitarity can be represented by triangle in complex plane:
- Convention:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \quad \Longrightarrow$$

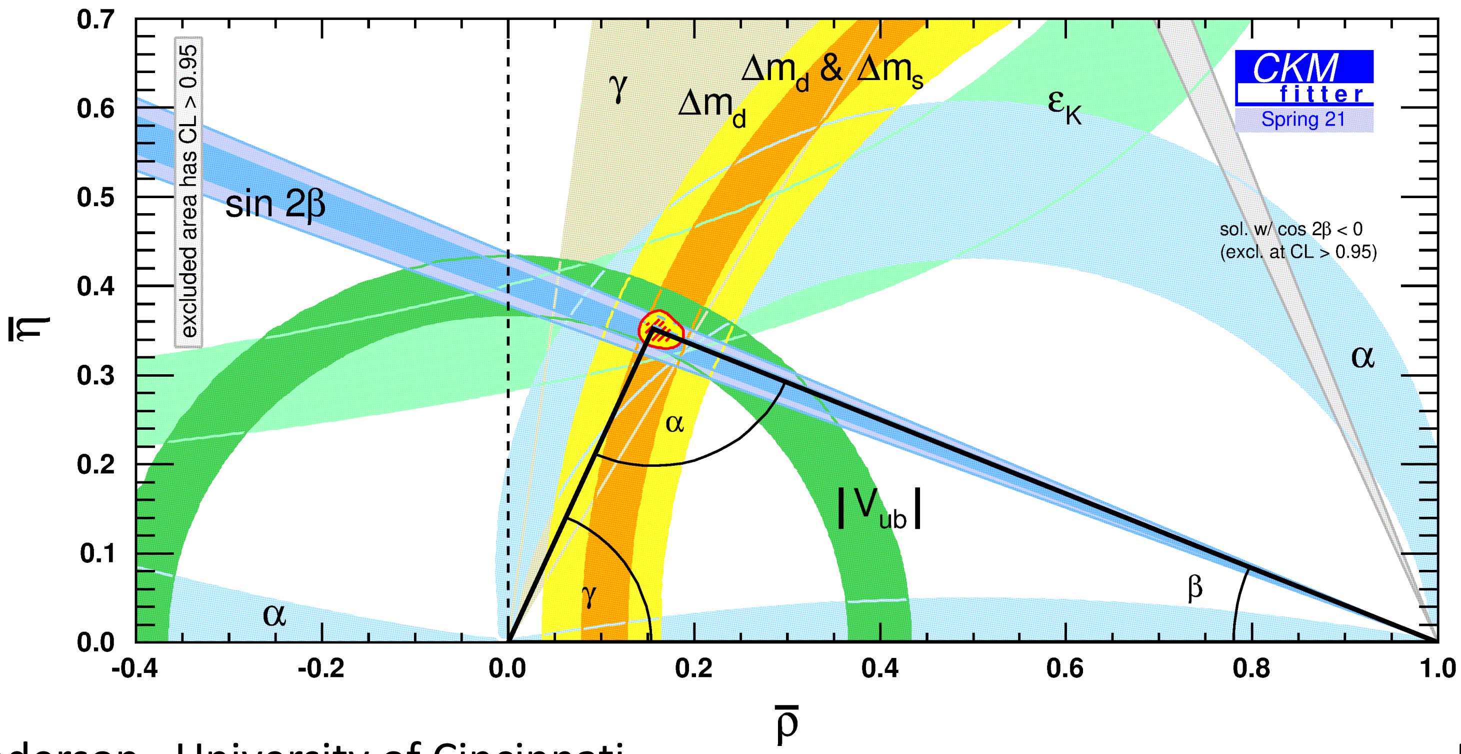
(divide by $V_{cd}V_{cb}^*$)



- Goal: overconstrain Unitarity Triangle by measurements of sides and angles

Measurement of CKM Angle γ

- CKM angle γ is only one which does not depend on top-couplings, hence can be determined from tree-level B processes, with small theory uncertainty
- Direct measurements of γ consistent with but have larger uncertainty than value inferred from global fits assuming Unitarity



Measurement of CKM γ from $B^{\pm} \to D[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]h^{\pm}$ Decays

- Consider $B^{\pm} \to DK^{\pm}$ and $D \to K^{\pm}\pi^{\mp}\pi^{\mp}\pi^{\pm}$ (D is D^0 or $\bar{D}^0$)
- Decay rates relate to γ and other factors:

$$\Gamma_{B^{\pm}\to D[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]K^{\pm}} \propto r_{K3\pi}^2 + (r_B^K)^2 + 2r_{K3\pi}r_B^K \underline{R_{K3\pi}} \cos(\delta_B^K + \underline{\delta_{K3\pi}} \pm \gamma)$$

$$\Gamma_{B^{\pm}\to D[K^{\pm}\pi^{\mp}\pi^{\mp}\pi^{\pm}]K^{\pm}} \propto 1 + (r_{K3\pi}^2 r_B^K)^2 + 2r_{K3\pi}r_B^K \underline{R_{K3\pi}} \cos(\delta_B^K - \underline{\delta_{K3\pi}} \pm \gamma)$$

- Sensitivity of measured decay rates to γ depends on relative magnitude of other factors => strategy: divide D->K3π phase space into regions to enhance sensitivity to γ

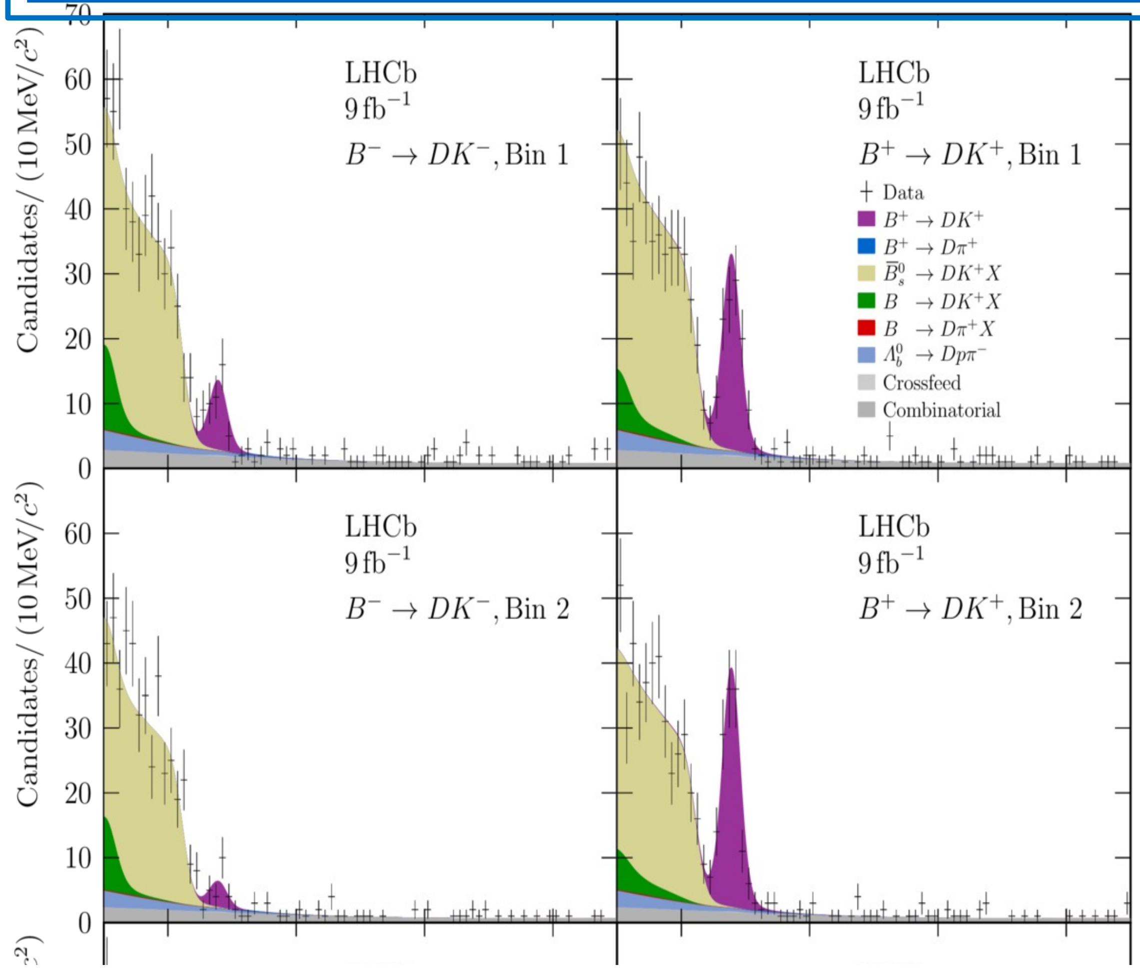
Measurement of CKM γ from $B^{\pm} \to D[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]h^{\pm}$ Decays

LHCb PAPER-2022-017, arXiv:2209.03692

- Signal yields extracted from mass fits in 4 phase space bins
- Determine hadronic params and γ:

$$\gamma = \left(54.8 \,^{+6.0}_{-5.8} \,^{+0.6}_{-0.6} \,^{+6.7}_{-4.3}\right)^{\circ},$$

- One of the most precise determinations from a single D-decay mode

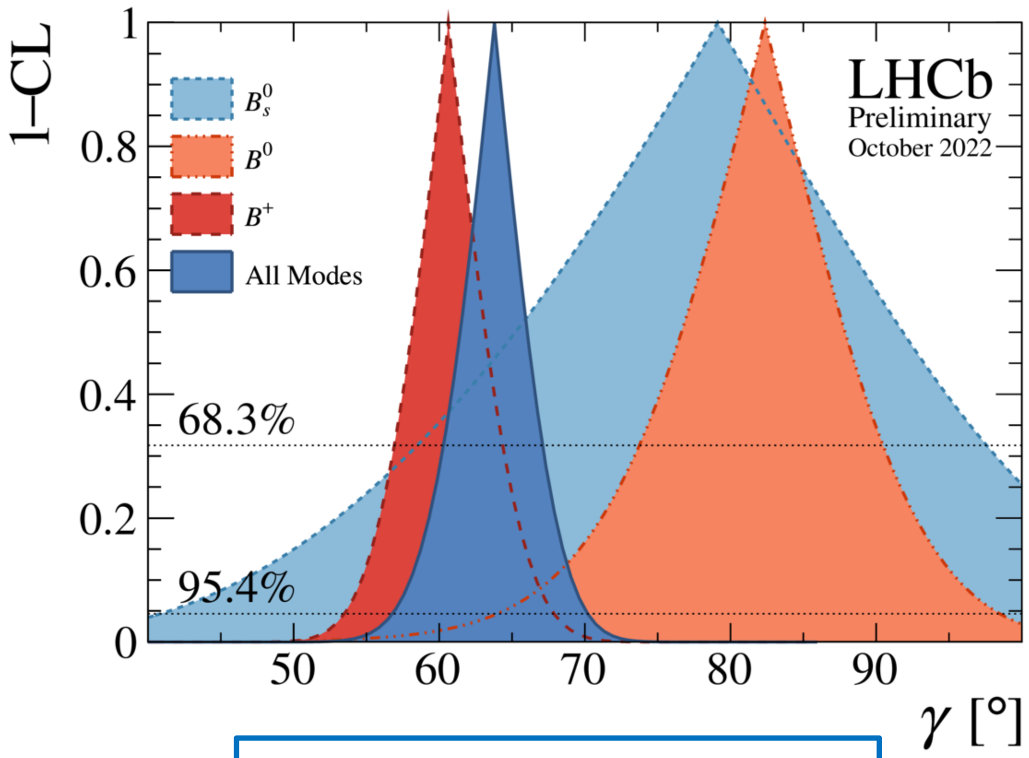


Combined Determination of CKM γ

- Combine LHCb CKM γ measurements from 16 different decay channels for $B^{\pm}, B^0, B_s^0$
- Combined result: $\gamma = (63.8^{+3.5}_{-3.7})^o$

(Still dominated by stat. uncertainty)

- Agrees with global CKM fits: 65.5 ± 1.2º (CKMFitter 2021)



LHCb CONF-2022-03

Charge-Parity Violation (CPV)

- Violation of Charge-Parity (CP) symmetry required to explain matter-antimatter asymmetry of universe
- In SM, CPV arises from complex phase in CKM matrix
- CPV observed in neutral K and B meson decays, and most recently in D mesons (LHCb 2019, arXiv:1903.08726)
- Motivates further study to understand nature of CPV in D system

Measurement of the time-integrated CP asymmetry in $D^0 \to K^- K^+$ decays

- Time-integrated *CP asymmetry* for $D^0/\overline{D}^0$ decays to final state $f = K^+K^-$:

$$\mathcal{A}_{CP}(f) \equiv \frac{\int \mathrm{d}t\, \epsilon(t) \left[\Gamma(D^0 \to f)(t) - \Gamma(\overline{D}^0 \to f)(t)\right]}{\int \mathrm{d}t\, \epsilon(t) \left[\Gamma(D^0 \to f)(t) + \Gamma(\overline{D}^0 \to f)(t)\right]},$$

where ε(t) is reco eff as function of D^0 decay time

- $D^0/\overline{D}^0$ from $D^{*+} \to D^0\pi^+$(and charge conjug.); pion charge can tag $D^0/\overline{D}^0$
- *Measured* asymmetry: $$A(K^-K^+) \equiv \frac{N(D^{*+} \to D^0\pi^+) - N(D^{*-} \to \overline{D}^0\pi^-)}{N(D^{*+} \to D^0\pi^+) + N(D^{*-} \to \overline{D}^0\pi^-)},$$
- But has contributions from *production* (A_P) and *instrumental* asymmetries (A_D):

$$A(K^-K^+) \approx \mathcal{A}_{CP}(K^-K^+) + A_{\mathrm{P}}(D^{*+}) + A_{\mathrm{D}}(\pi^+_{\mathrm{tag}}),$$

  – estimate and remove by considering related Cabibbo-favored (no CP asym.) decays with similar production and instrumental asym.

LHCb PAPER-2022-024, arXiv:2209.03179

Measurement of the time-integrated CP asymmetry in $D^0 \to K^- K^+$ decays

- Obtain result: $$\mathcal{A}_{CP}(K^-K^+) = [6.8 \pm 5.4\,(\text{stat}) \pm 1.6\,(\text{syst})] \times 10^{-4},$$
- CP violation in final state f has *direct* (a^d_f) + *mixing* components: $$\mathcal{A}_{CP}(f) \approx a^d_f + \frac{\langle t \rangle_f}{\tau_D} \cdot \Delta Y_f,$$

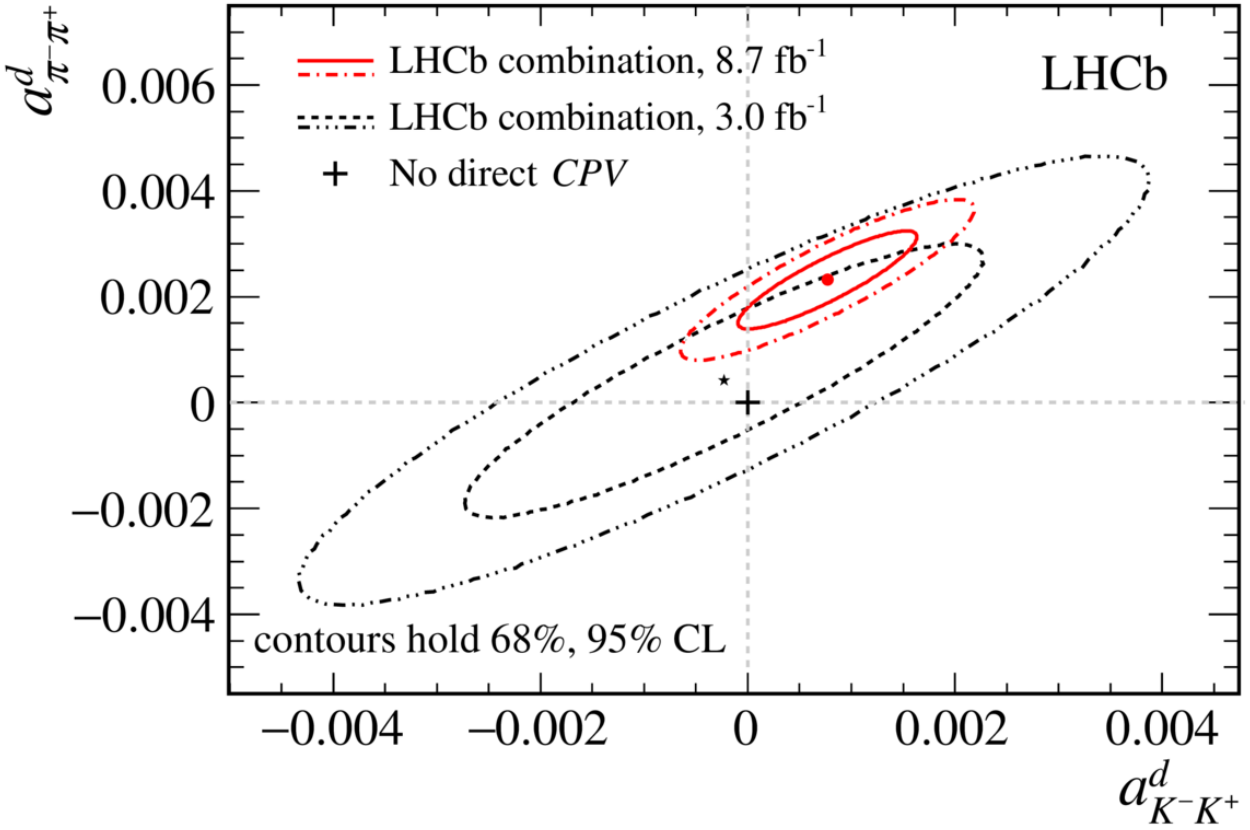
where $\langle t \rangle_f$ is mean decay time of D^0 mesons in the sample, τ_D is D^0 lifetime, and ΔY represents interference between mixing and decay (assumed equal for f=K^+K^- and f=$\pi^+\pi^-$)

Measurement of the time-integrated CP asymmetry in $D^0 \to K^- K^+$ decays

- Combine this result with other LHCb measurements and D^0 data to obtain:

$$a^d_{K^-K^+} = (\ 7.7 \pm 5.7) \times 10^{-4},$$
$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4},$$

- Deviate from zero by 1.4 and 3.8 σ for $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ respectively
- First evidence for direct CP violation in a specific D^0 decay



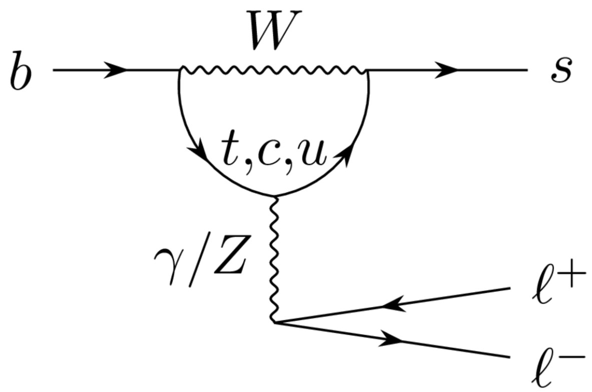
LHCb PAPER-2022-024, arXiv:2209.03179

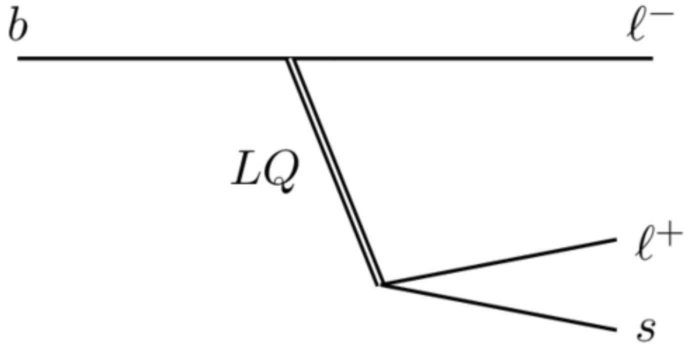
Tests of Lepton Flavor Universality

- Although not protected by a known symmetry of the SM, Lepton Flavor Universality (LFU) observed experimentally to high degree in W/Z decays; violation of LFU could indicate beyond-SM physics
- Two recent LHCb results from LFU tests:
  - $b \to s\ell^+\ell^-$ (ℓ = e,μ)
  - $b \to c\ell\upsilon$ (ℓ = τ,μ)

Test of Lepton Universality in $b \to s\ell^+\ell^-$ Decays

- SM $b \to s\ell^+\ell^-$ decays via Penguin diagrams; BSM possible with eg Leptoquark or Z'
- LHCb: study $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^{*0}\ell^+\ell^-$
- Measure double-ratios with *resonant* $J/\psi \to \ell^+\ell^-$ to cancel detector efficiencies:

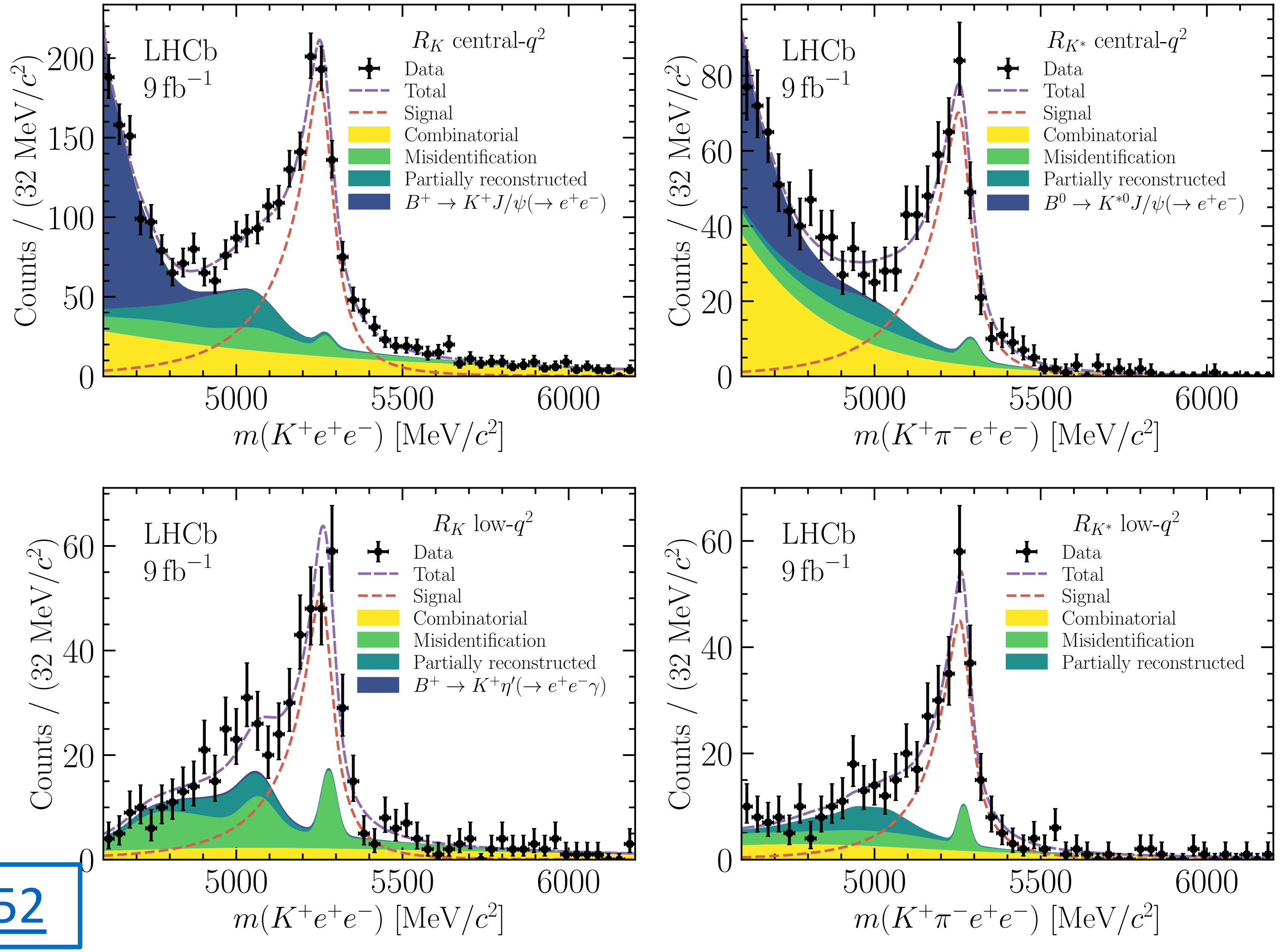




$$R_{(K,K^*)} \equiv \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}e^+e^-)}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(\to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

Test of Lepton Universality in $b \to s\ell^+\ell^-$ Decays

- Stringent particle ID and multivariate selections applied to reduce bkg from hadronic and partially-reconstructed B decays
- Good description of data obtained

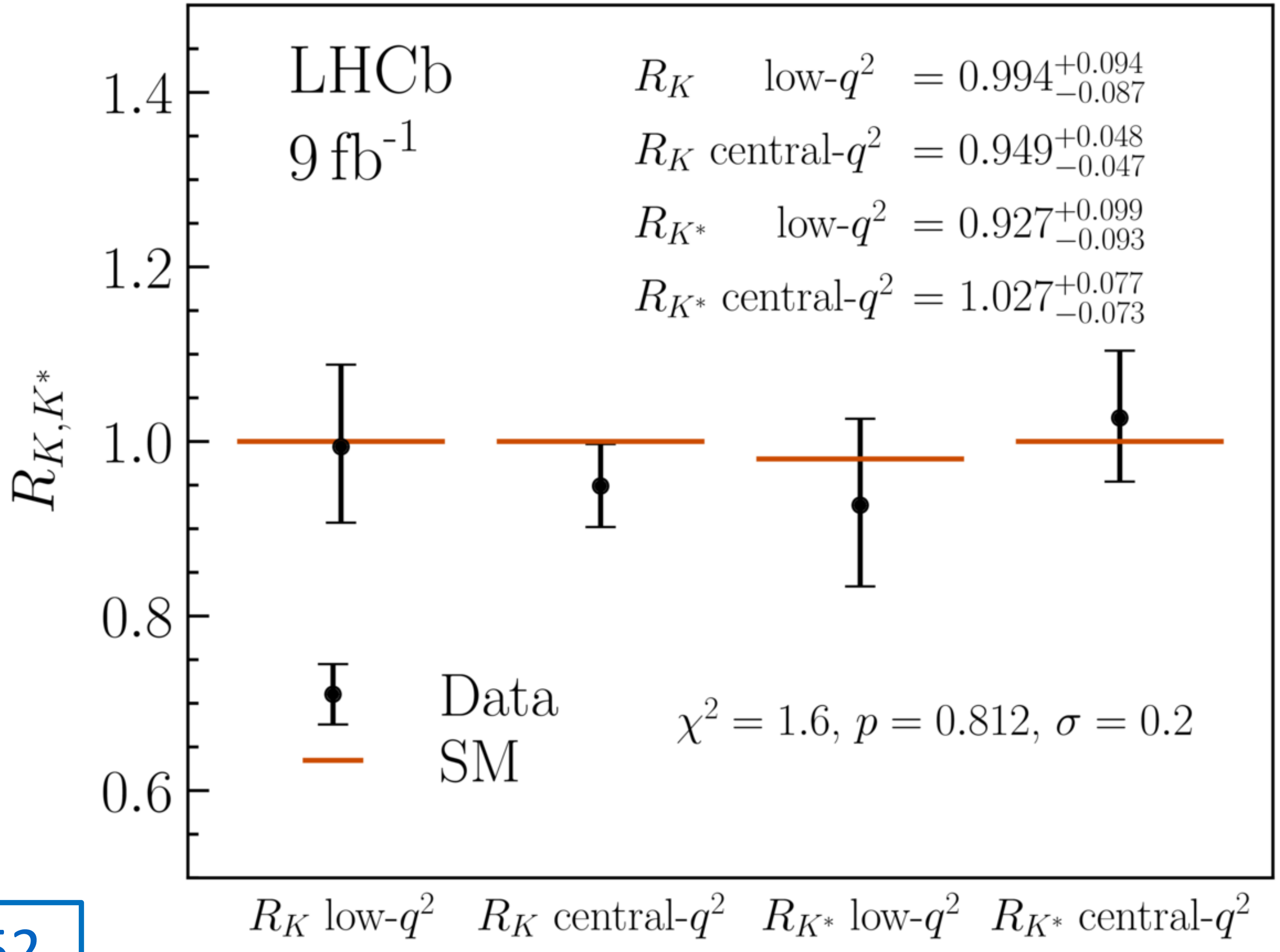


[LHCb PAPER-2022-046, arXiv:2212.09152]

Test of Lepton Universality in $b \to s\ell^+\ell^-$ Decays

- R_K and R_{K*} in regions of q^2 = dilepton invariant mass:
- These results are in agreement with SM predictions and supersede previous LHCb measurements

LHCb PAPER-2022-046, arXiv:2212.09152



Measurement of the Ratios of Branching Fractions $\mathcal{R}(D^*)$ and $\mathcal{R}(D^0)$

- Test Lepton Flavor Universality (LFU) in $b \to c$ semileptonic decays by measuring ratios:

$$\mathcal{R}(D^*) \equiv \mathcal{B}(\bar{B} \to D^* \tau^- \bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^* \mu^- \bar{\nu}_\mu)$$

$$\mathcal{R}(D^0) \equiv \mathcal{B}(B^- \to D^0 \tau^- \bar{\nu}_\tau)/\mathcal{B}(B^- \to D^0 \mu^- \bar{\nu}_\mu)$$

- World average from multiple experiments (BaBar, Belle, LHCb) has tended to show excess of tau decays relative to SM expectation

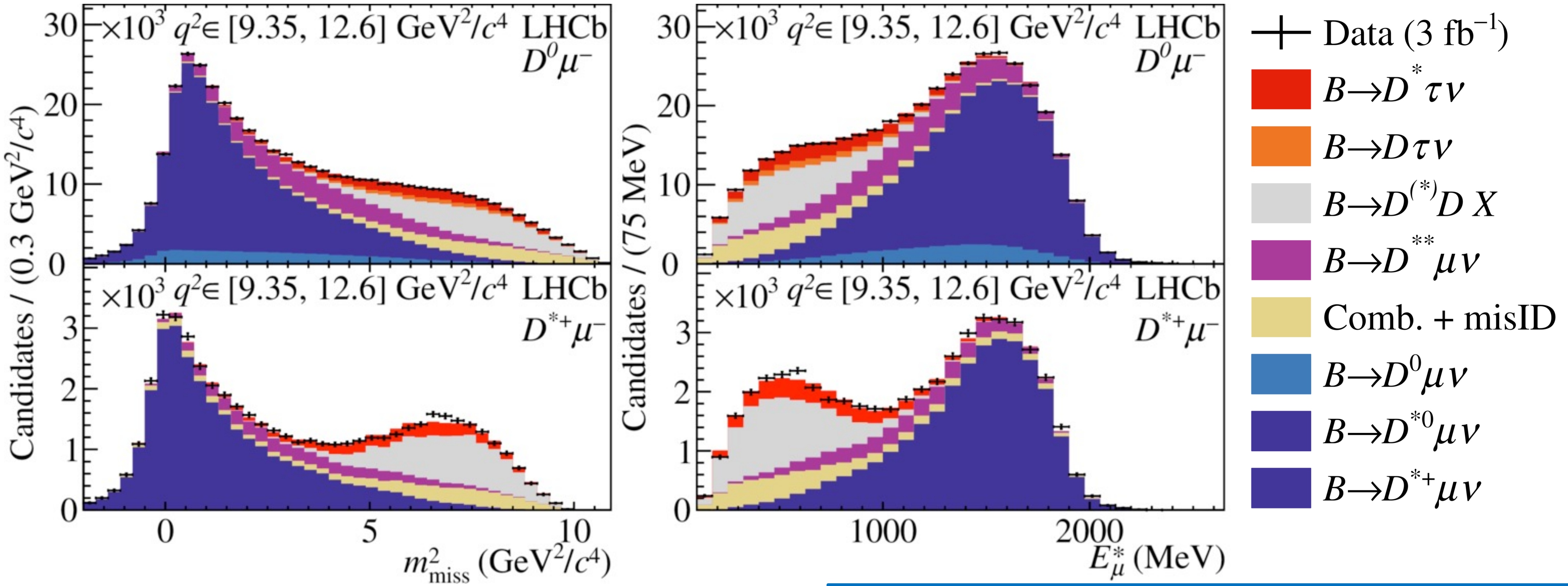
Measurement of the Ratios of Branching Fractions $\mathcal{R}(D^*)$ and $\mathcal{R}(D^0)$

- Dataset = 3 fb^{-1} from Run 1 at 7 & 8 TeV; final states $D^0\mu^-$ and $D^{*+}\mu^-$
- Combination of signal decays, backgrounds from other (partially reconstructed) decays, mis-ID etc; fit data to model of multidimensional templates (data-derived, or from simulation validated against data); simultaneous analysis helps constrain common parameters in fit model
- Kinematic variables in B candidate rest frame used:

  missing mass, $m_{miss}^2 = (p_B - pD - p_\mu)^2$ and muon energy, E_μ^*

Measurement of the Ratios of Branching Fractions $\mathcal{R}(D^*)$ and $\mathcal{R}(D^0)$

- Obtain a very good description of the data:



LHCb PAPER-2022-039, arXiv:2302.02886

Measurement of the Ratios of Branching Fractions $\mathcal{R}(D^*)$ and $\mathcal{R}(D^0)$

- Results:

$$\mathcal{R}(D^*) = 0.281 \pm 0.018\ (\textit{stat.}) \pm 0.024\ (\textit{syst.})$$

$$\mathcal{R}(D^0) = 0.441 \pm 0.060\ (\textit{stat.}) \pm 0.066\ (\textit{syst.})$$

- First measurement of $\mathcal{R}(D^0)$ at a hadron collider
- Results consistent with current expt. averages; 1.9σ deviation from LFU SM predictions

LHCb PAPER-2022-039, arXiv:2302.02886

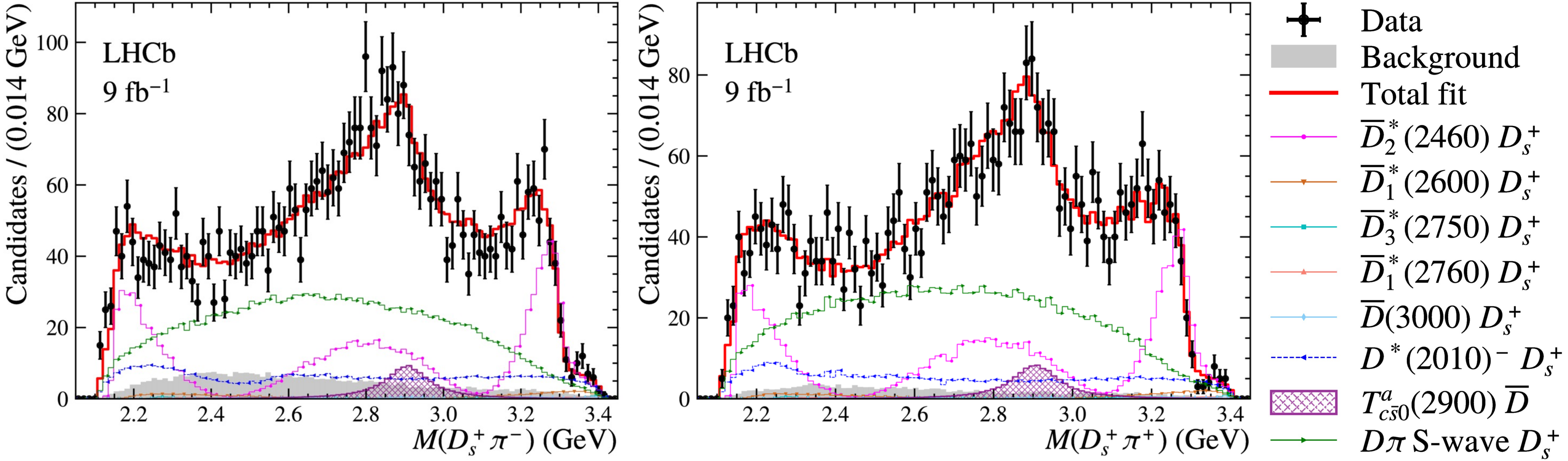
First Observation of Doubly-Charged Tetraquark

- *Exotic hadrons*: non-minimal meson/baryon states eg $q\bar{q}q\bar{q}$ 'tetraquark'
- Search for a '4-flavor' doubly-charged $[c\bar{s}u\bar{d}]$ tetraquark (and isospin partner) as $D_s^+\pi^\pm$ resonances in $B^0 \to \bar{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays
- Only expected resonant backgrounds from known excited $\bar{D}^*$states

LHCb PAPER-2022-026, arXiv:2212.02716

First Observation of Doubly-Charged Tetraquark

- $M(D_s\pi)$ shows evidence for peaks attributed to tetraquark states:



LHCb PAPER-2022-026, arXiv:2212.02716

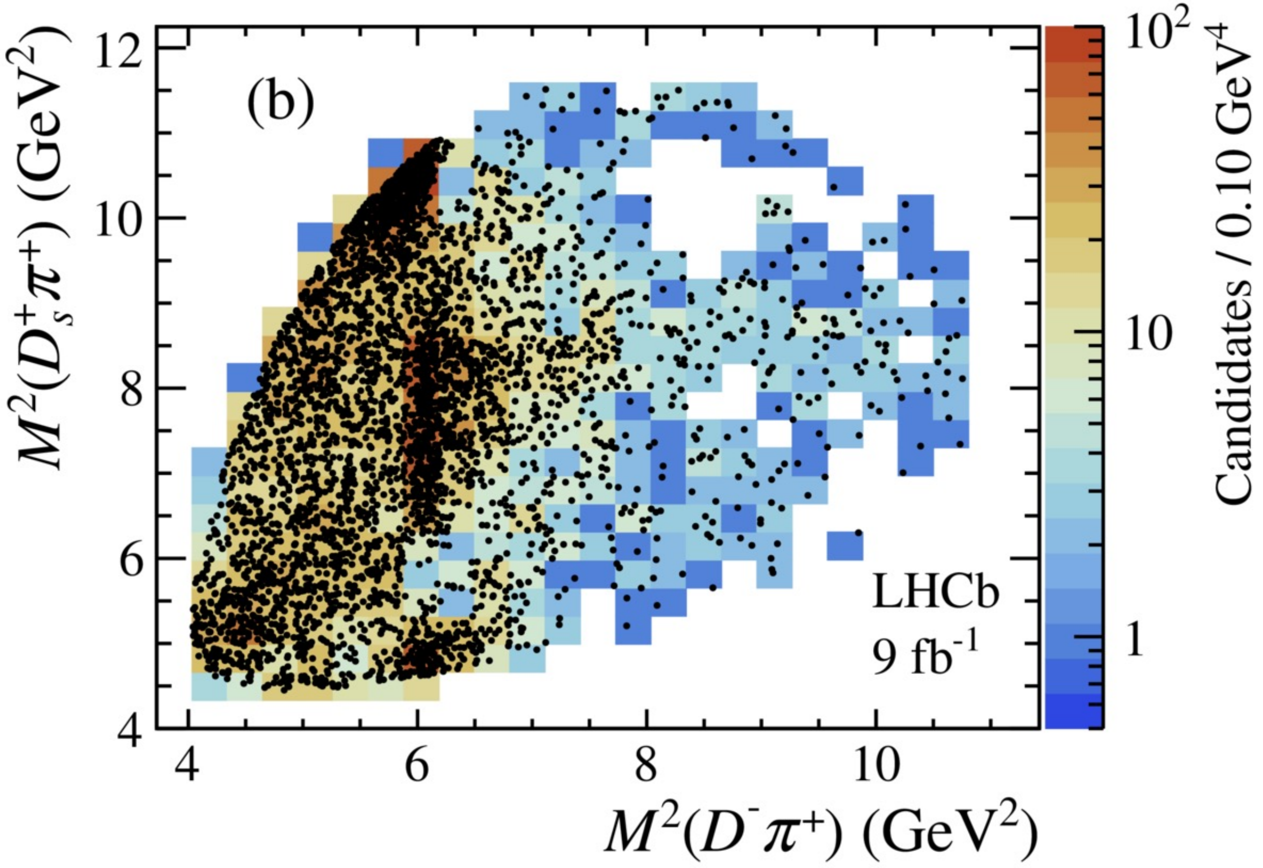
First Observation of Doubly-Charged Tetraquark

- Full amplitude analysis:
- Extract common mass M and width Γ for $[c\bar{s}u\bar{d}]$ and $[c\bar{s}\bar{u}d]$ tetraquark states:

  M = 2.908 ± 0.011 ± 0.020 GeV

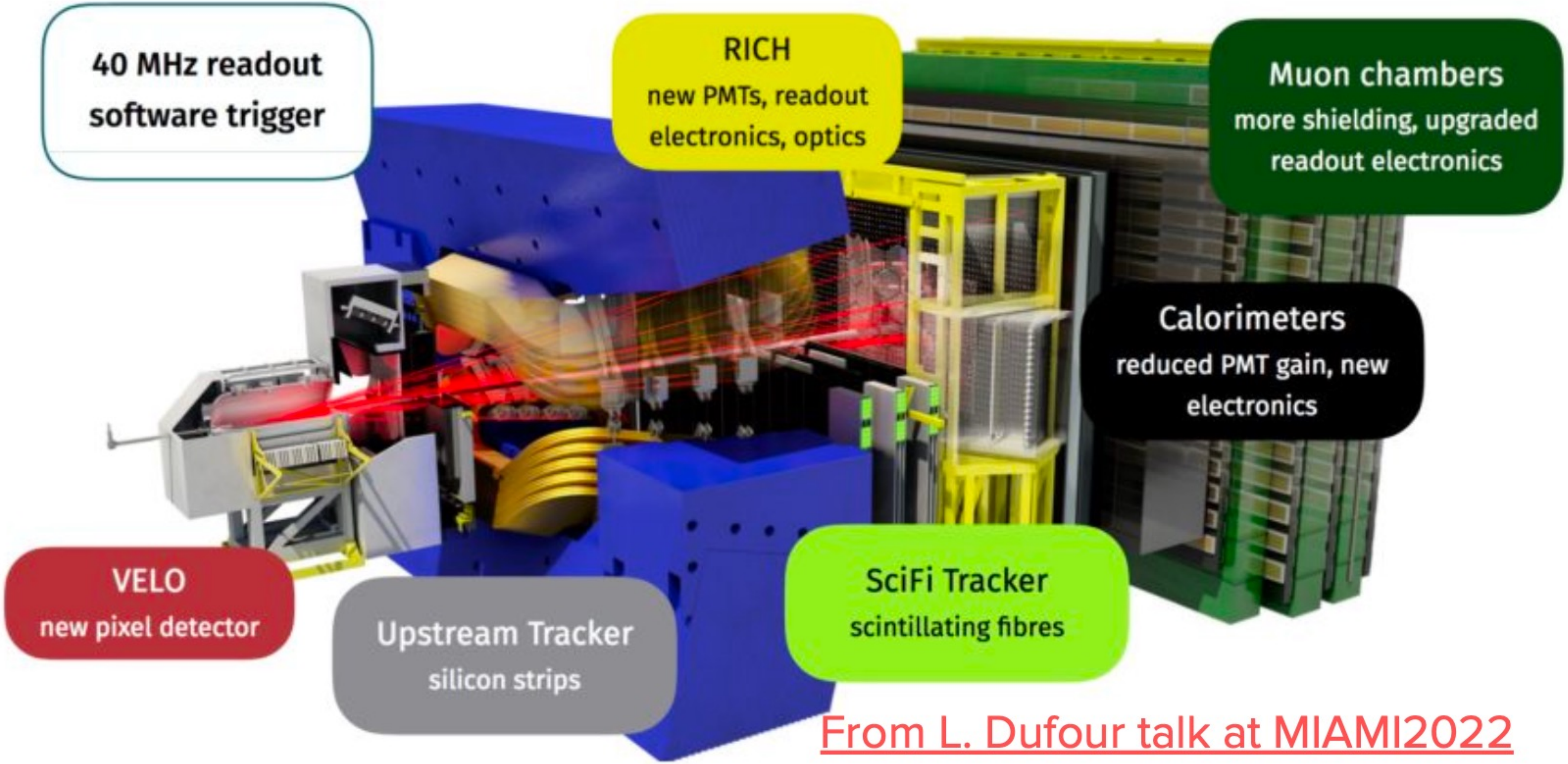
  Γ = 0.134 ± 0.023 ± 0.011GeV

- Significance of observation: >9σ
- Spin-parity: best likelihood for 0+



LHCb PAPER-2022-026, arXiv:2212.02716

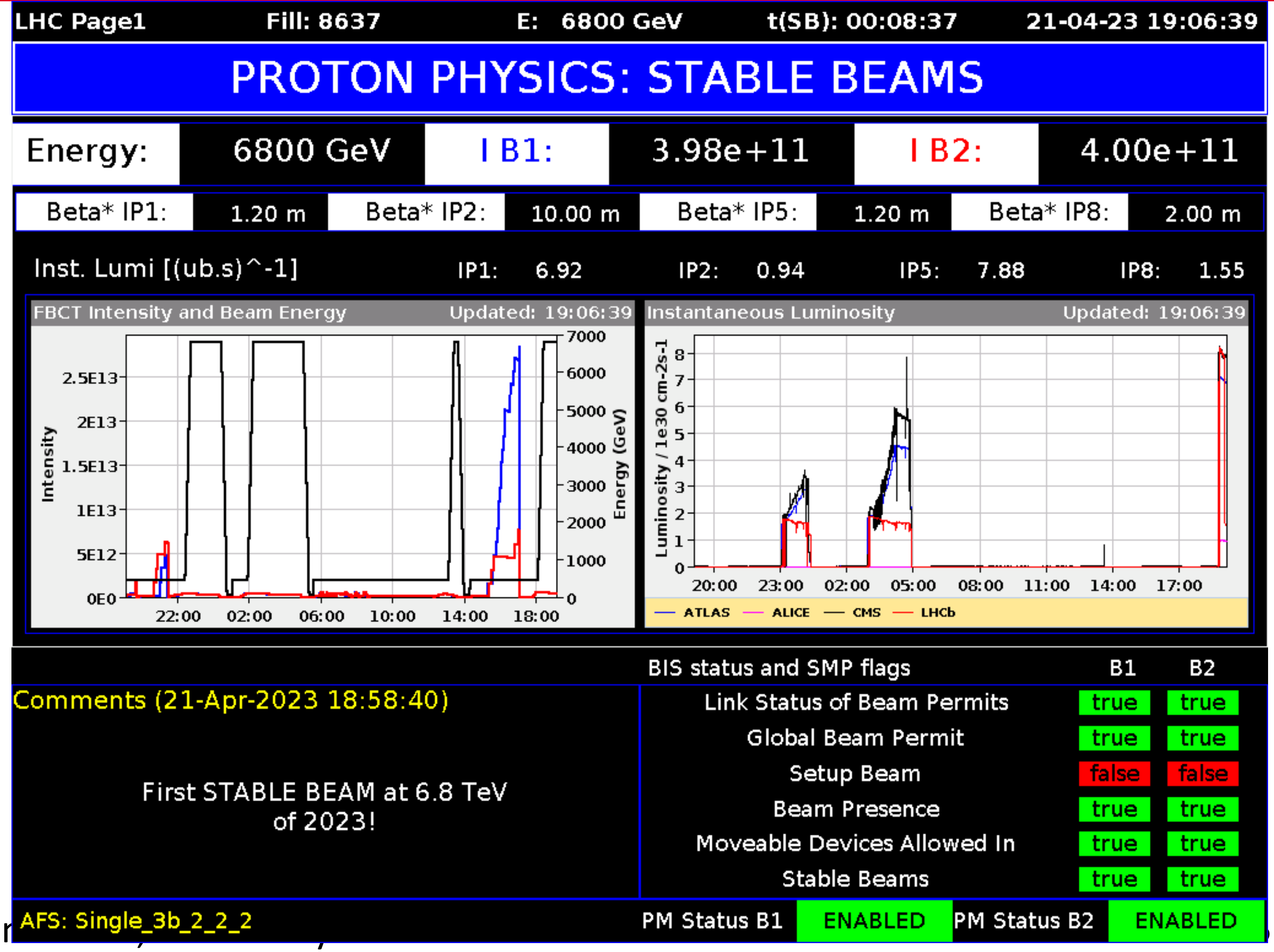
LHCb Detector Upgrade for Run 3



From L. Dufour talk at MIAMI2022

LHC Run 3

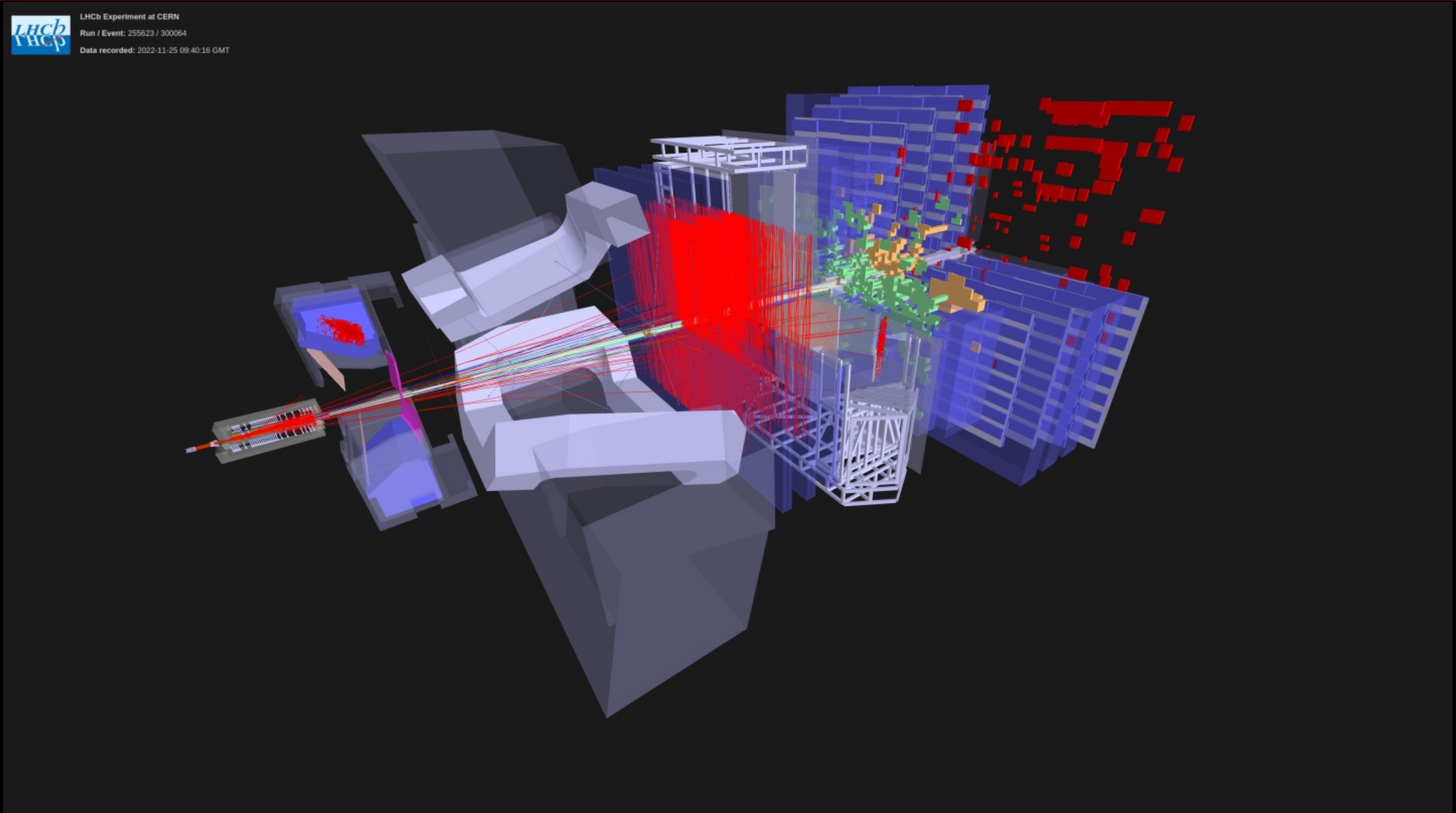
- LHC Run3: collision energy increased to 13.6 TeV
- Expecting first physics running in 2023 very soon



Summary

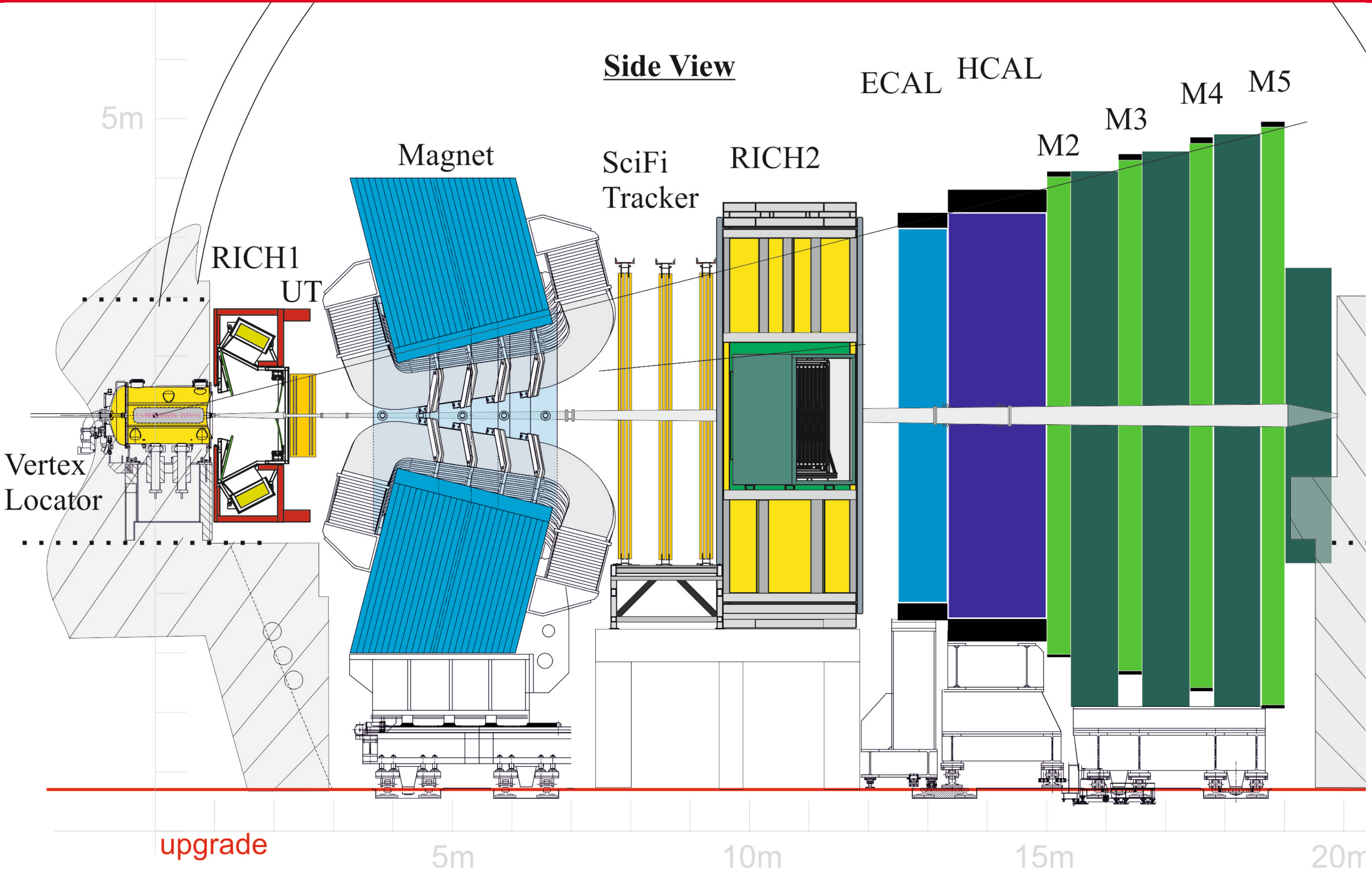
- We presented recent LHCb results on:
  - Measurement of CKM angle gamma
  - First evidence for direct CP violation in neutral D meson decays
  - Tests of lepton flavor universality
  - Observation of first doubly-charged tetraquark
- LHCb detector upgraded for Run 3 – we look forward to more exciting results!
- All LHCb public results:
  https://lhcbproject.web.cern.ch/Publications/LHCbProjectPublic/Summary_all.html

Run 3 Event Display: 13.6 TeV p-p collision



Backup

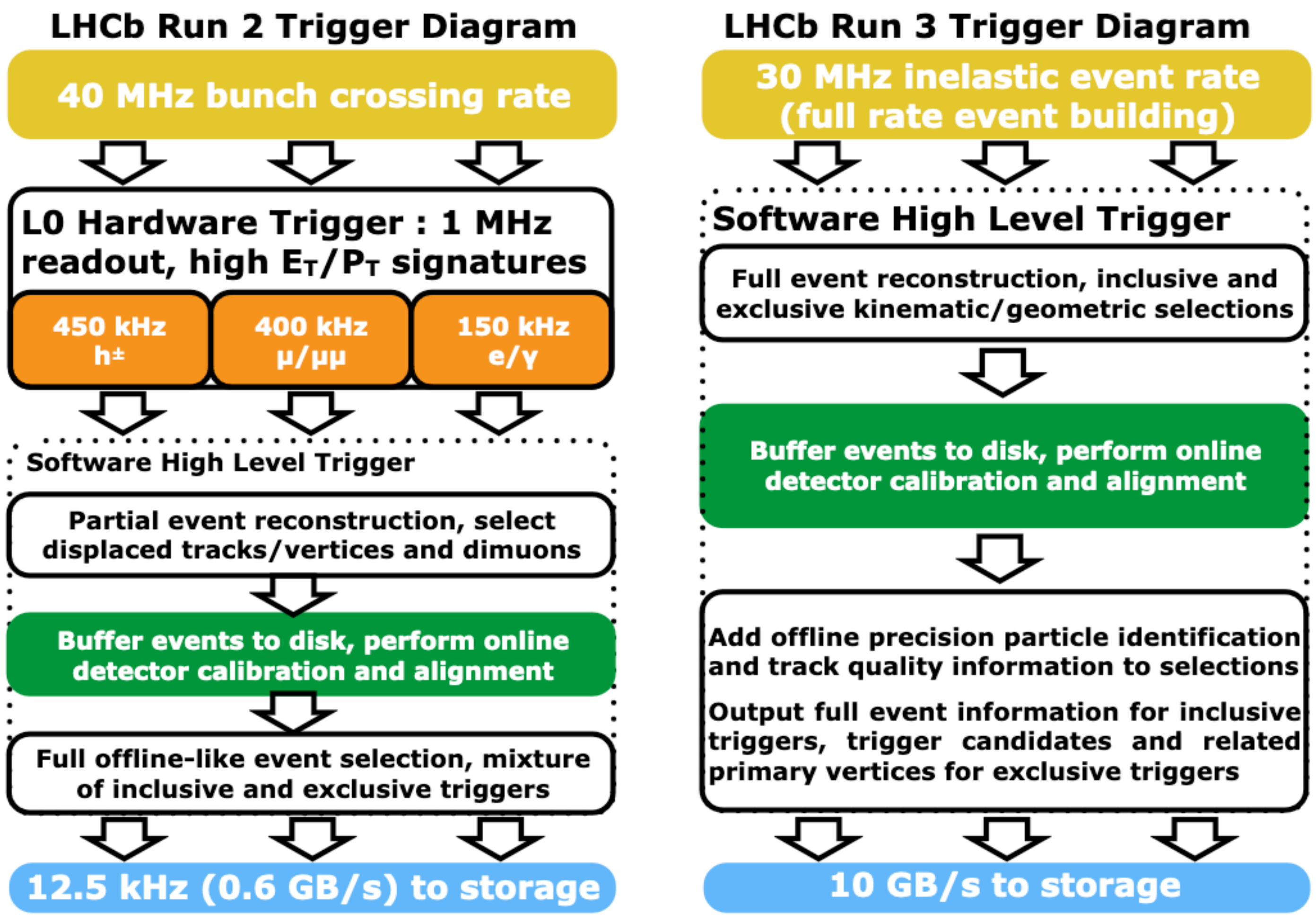
LHCb Detector Upgrade for Run 3



- Run3 detector

Trigger Upgrade - Real Time Analysis

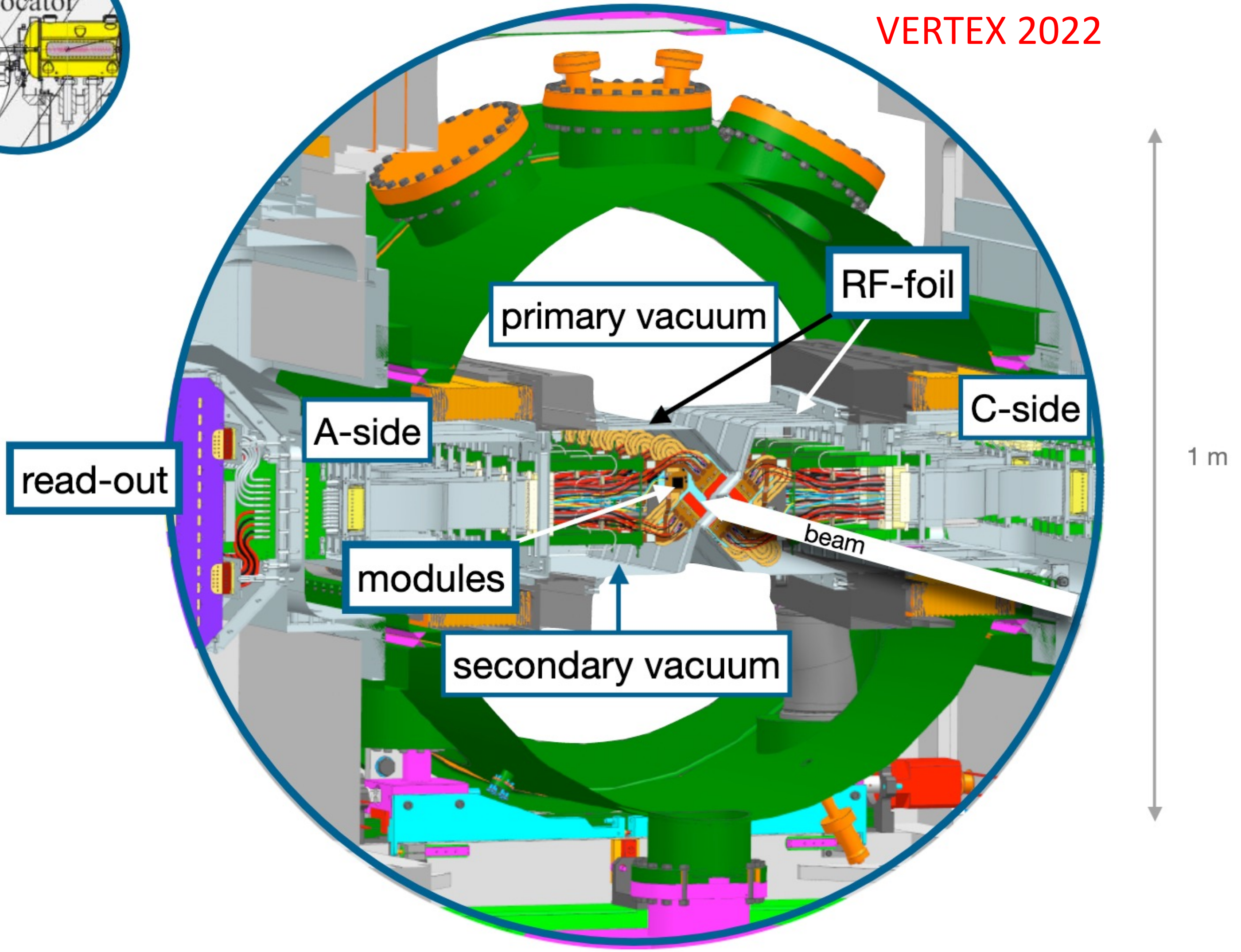
- Full software trigger with detector readout at 30 MHz (non-empty bunch rate)
- First HLT stage implemented in GPUs



Vertex Locator (VELO) Upgrade

- 26 layers of 50x50 μm^2 Si pixels
- Bring closer to beampipe (5 mm); reduce material budget before first hit
- Aim to significantly improve impact parameter resolution for low momentum particles

V Lukashenko, VERTEX 2022



Upstream Tracker

Real Time Analysis

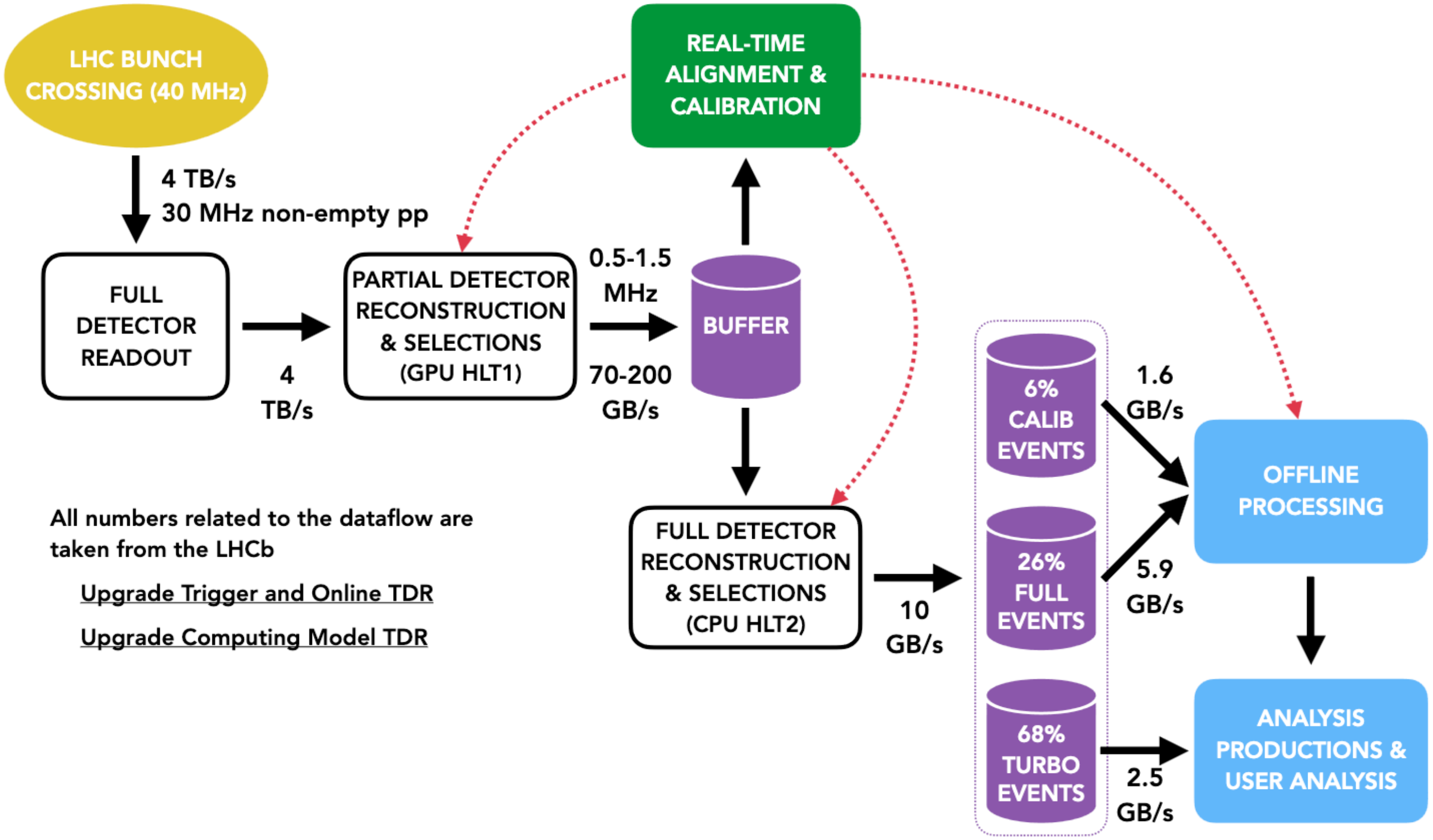
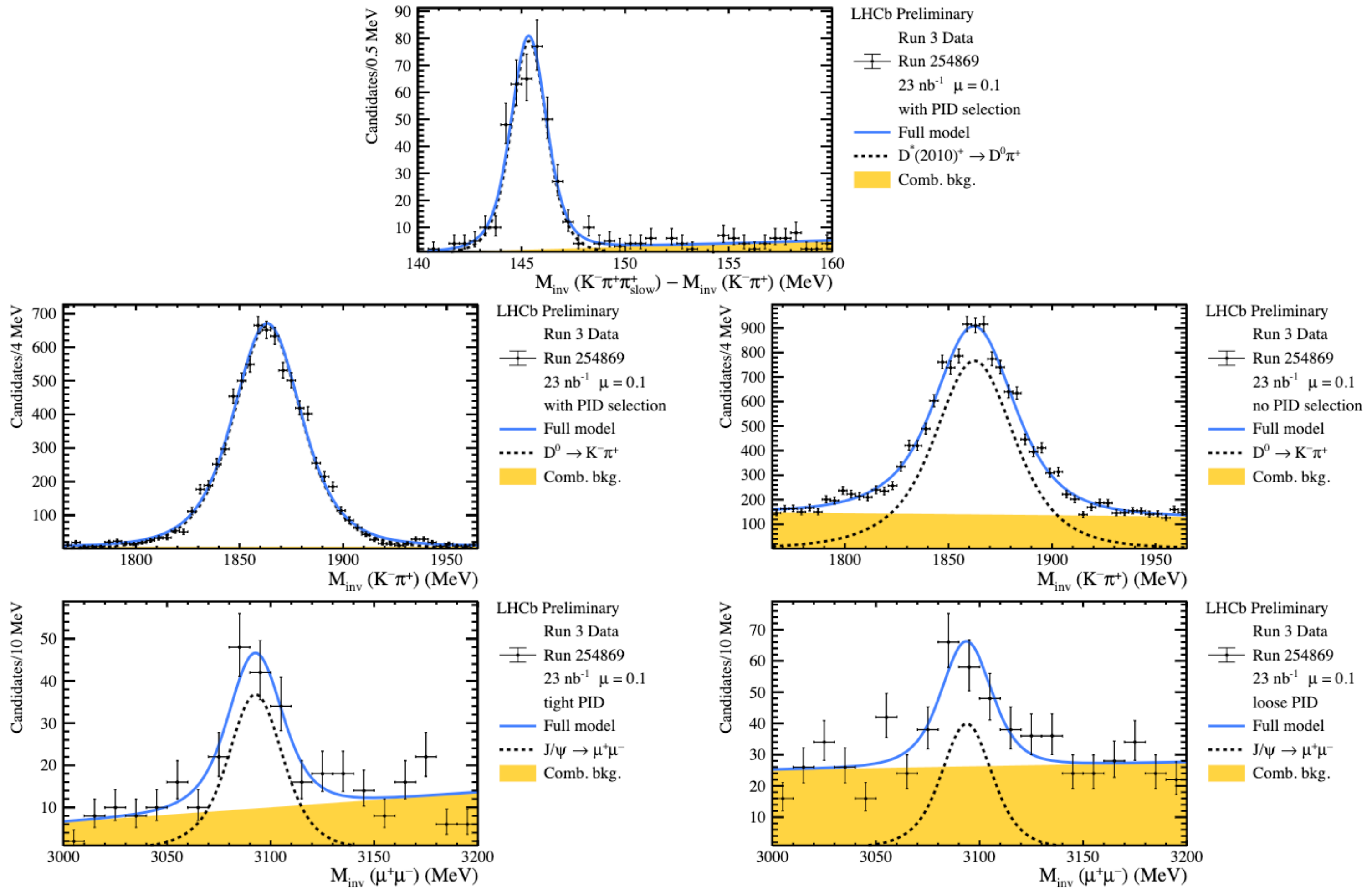


Figure 1: LHCb upgrade dataflow focusing on the real-time aspects.

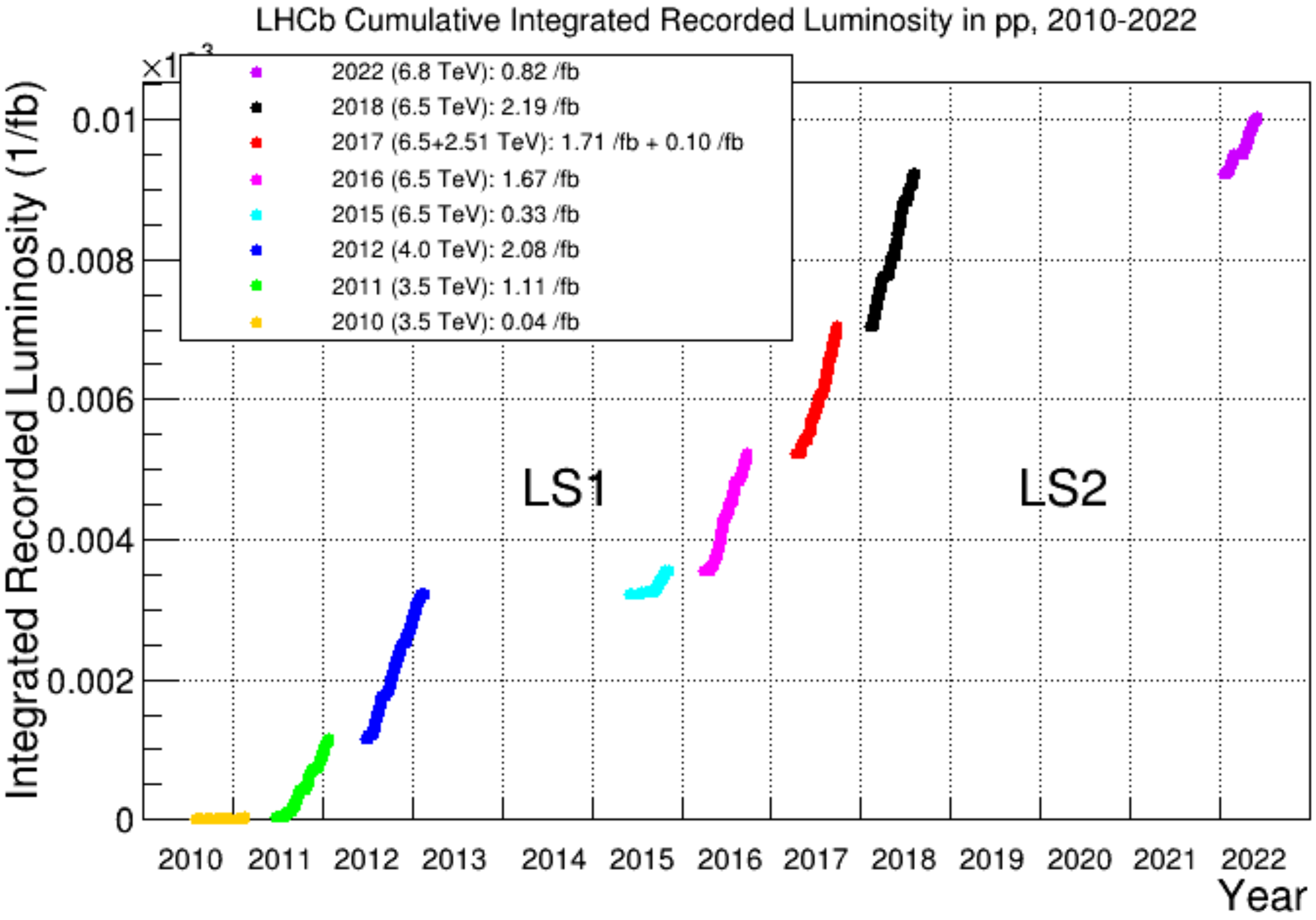
Run 3 Mass Plots

- LHCb Figure 023-002
- D*
- D0 to Kpi
- J/psi to mumu



LHCb Luminosity

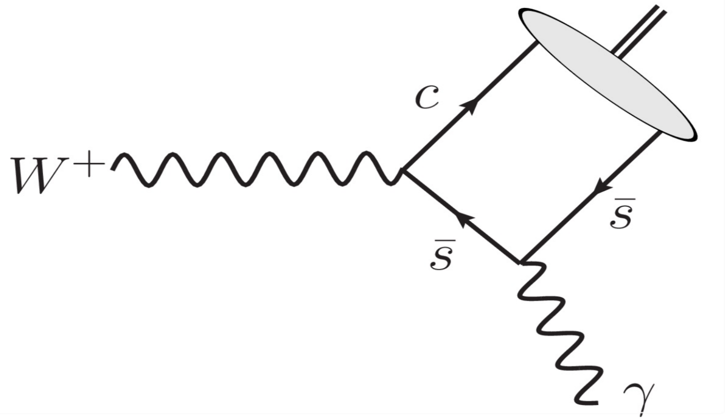
- LHCb Cumulative Luminosity

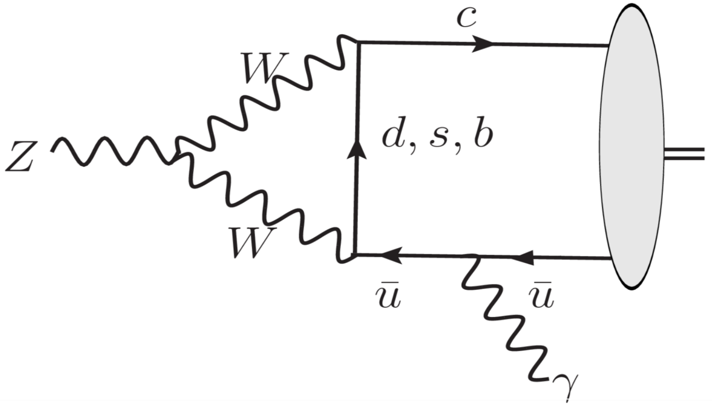


Search for rare decays $W^+ \to D_s^+\gamma$, $Z \to D^0\gamma$

- Radiative hadronic W/Z decays very rare in SM
- Search for $W^+ \to D_s^+\gamma$, $Z \to D^0\gamma$ (2018 data)
- Reconstruct $D_s \to KK\pi$, $D^0 \to K\pi$
- Consider *Pseudomass* of meson M and photon:

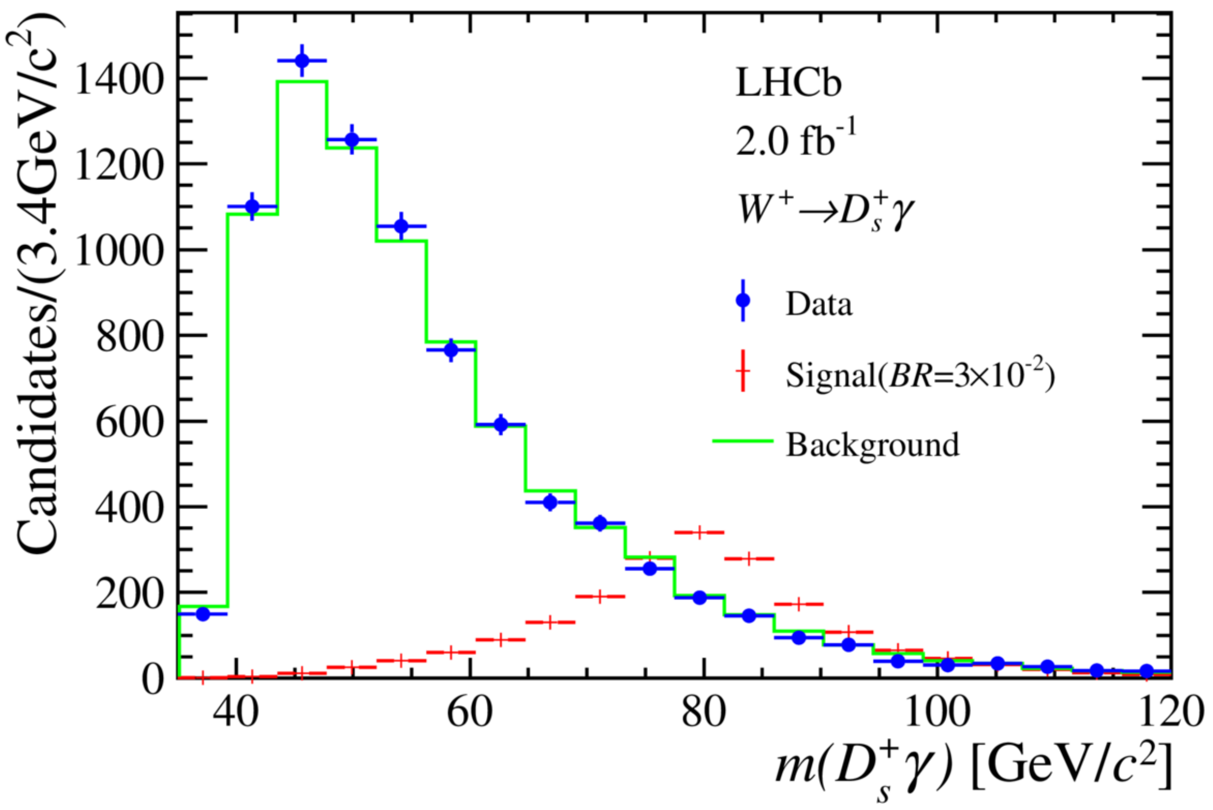
$$m(M\gamma) = \sqrt{2p^M p_T^M \frac{p^\gamma}{p_T^\gamma}(1-\cos\theta)},$$





Search for rare decays $W^+ \to D_s^+\gamma$, $Z \to D^0\gamma$

LHCb PAPER-2022-033, arXiv:2212.07120

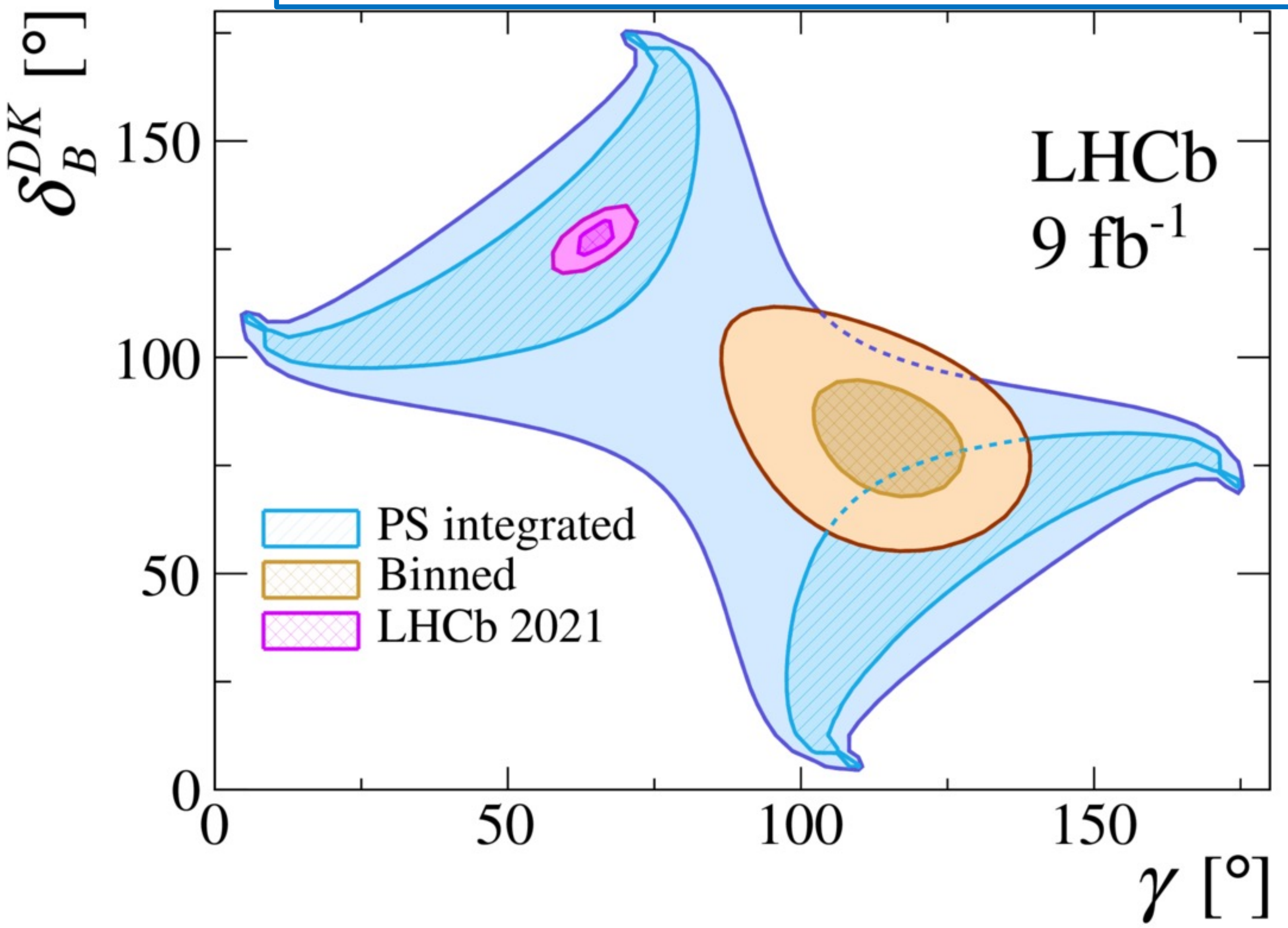


- Data-driven background from sidebands in meson mass
- No excess seen in data
- $\mathcal{B}(W^+ \to D_s^+\gamma) < 6.5$ e-4 (95% CL); strongest limit to date
- $\mathcal{B}(Z \to D^0\gamma) < 2.1$ e-3 (95% CL); first reported search

A study of *CP* violation in the decays $B^\pm \to [K^+K^-\pi^+\pi^-]_D h^\pm$ ($h = K, \pi$) and $B^\pm \to [\pi^+\pi^-\pi^+\pi^-]_D h^\pm$

[LHCb PAPER-2022-037, arXiv:2301.10328]

- Needed external input for charm decay parameters
- Obtained $\gamma = (116^{+12}_{-14})^o$
- (Sub. Jan 2023, so not included in 2022 Combo)



Measurement of CKM γ from $B^{\pm} \to D[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]h^{\pm}$ Decays

- Coherence:

The coherence factor $R_{K3\pi}$ and the average strong-phase difference $\delta_{K3\pi}$ are defined by

$$R_{K3\pi}e^{i\delta_{K3\pi}} \equiv (A_{D^0}A_{\bar{D}^0})^{-1}\int \mathrm{d}\psi \mathcal{A}_{\bar{D}^0}(\psi)\mathcal{A}^*_{D^0}(\psi), \quad (2)$$

- Phase space binning:

The scheme used in this paper was proposed in Ref. [17] and splits the decays into four bins using the *normalised strong-phase difference*, defined as

$$\tilde{\delta}_{K3\pi}(\psi) \equiv \arg\left(\mathcal{A}_{\bar{D}^0}(\psi)\mathcal{A}^*_{D^0}(\psi)\right) - \arg\left(\int \mathrm{d}\psi' \mathcal{A}_{D^0}(\psi')\mathcal{A}^*_{\bar{D}^0}(\psi')\right), \quad (4)$$

Bin	Limits ($\tilde{\delta}_{K3\pi}$)	$R^i_{K3\pi}$	$\delta^i_{K3\pi}$
1	$-180^\circ < \tilde{\delta}_{K3\pi} \leq -39^\circ$	$0.66^{+0.18}_{-0.21}$	$(117^{+14}_{-19})^\circ$
2	$-39^\circ < \tilde{\delta}_{K3\pi} \leq 0^\circ$	$0.85^{+0.14}_{-0.21}$	$(145^{+23}_{-14})^\circ$
3	$0^\circ < \tilde{\delta}_{K3\pi} \leq 43^\circ$	$0.78^{+0.12}_{-0.12}$	$(160^{+19}_{-20})^\circ$
4	$43^\circ < \tilde{\delta}_{K3\pi} \leq 180^\circ$	$0.25^{+0.16}_{-0.25}$	$(288^{+15}_{-29})^\circ$

LHCb PAPER-2022-017, arXiv:2209.03692

Measurement of CKM γ from $B^{\pm} \to D[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]h^{\pm}$ Decays

The observables used to determine γ and related hadronic parameters are the ratios of rates of OS-to-LS $B^{\pm} \to Dh^{\pm}$ decays in each phase-space bin. These observables are given in the ith bin by

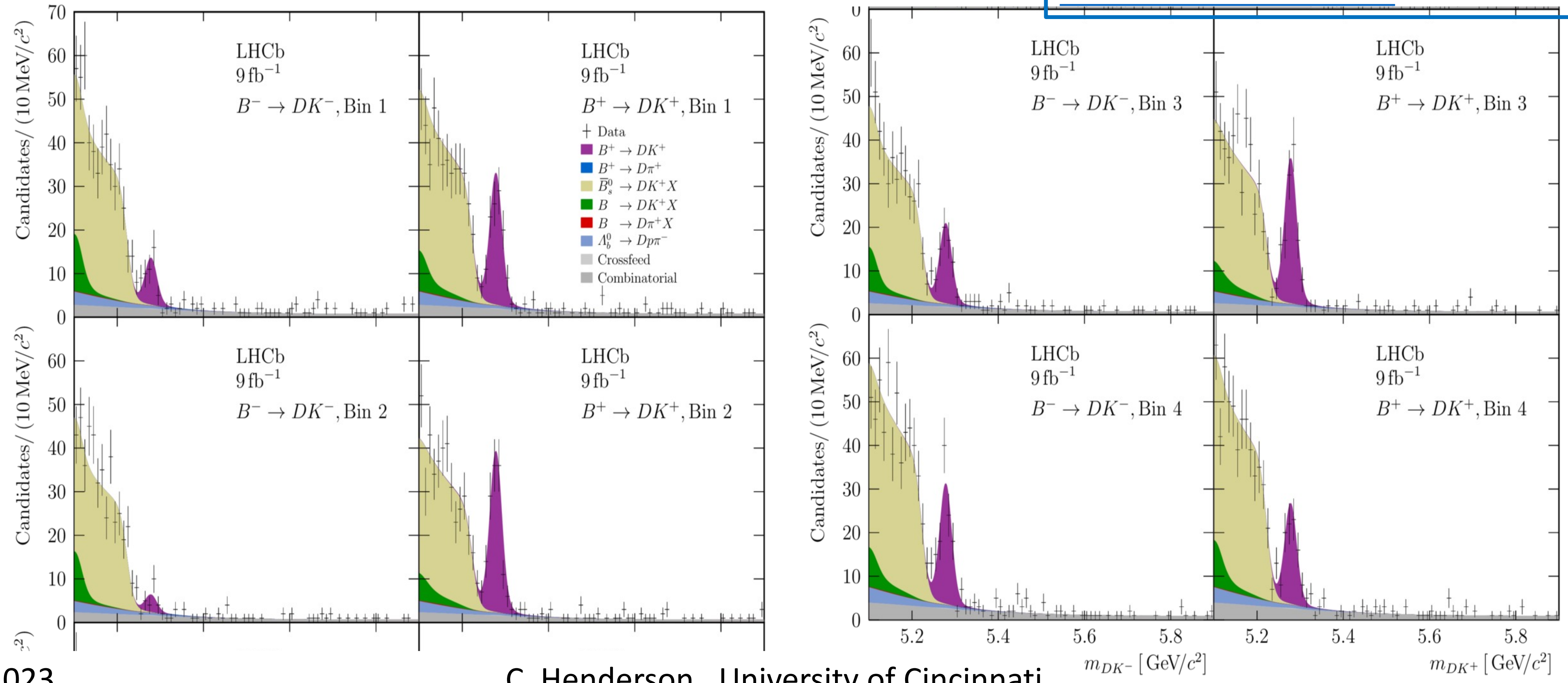
$$\begin{aligned}\mathcal{R}^i_{h^{\pm}} = \Big(&(r^i_{K3\pi})^2 + (r^h_B)^2 + 2r^i_{K3\pi}r^h_B R^i_{K3\pi}\cos(\delta^h_B + \delta^i_{K3\pi} \pm \gamma) \\ &- r^i_{K3\pi}R^i_{K3\pi}\left(y\cos\delta^i_{K3\pi} - x\sin\delta^i_{K3\pi}\right) + \frac{1}{2}\left(x^2+y^2\right) \\ &- r^h_B\left(y\cos(\delta^h_B \pm \gamma) + x\sin(\delta^h_B \pm \gamma)\right)\Big) \\ &\Big/ \Big(1 + (r^h_B)^2(r^i_{K3\pi})^2 + 2r^i_{K3\pi}R^i_{K3\pi}r^h_B\cos(\delta^h_B - \delta^i_{K3\pi} \pm \gamma)\Big),\end{aligned} \qquad (5)$$

where the average ratio of D-decay amplitudes is denoted by $r^i_{K3\pi}$. The effects of charm mixing are now included, in contrast with Eq. 1. This is governed by the parameters x and y, both of which are smaller than 1% [15, 22].

Measurement of CKM γ from $B^{\pm} \to D[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]h^{\pm}$ Decays

LHCb PAPER-2022-017, arXiv:2209.03692

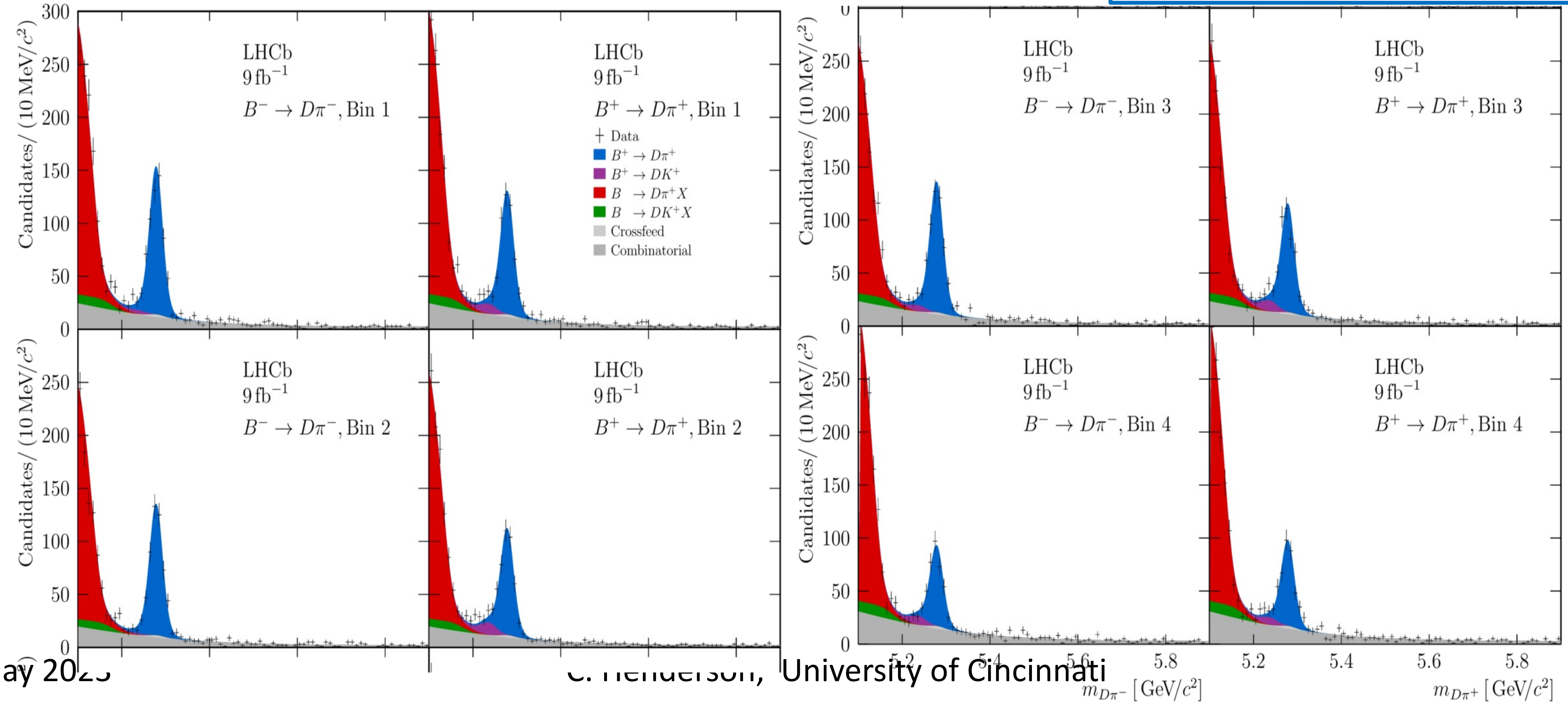
- B->DK Mass fits in phase space bins



Measurement of CKM γ from $B^{\pm} \to D[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]h^{\pm}$ Decays

[LHCb PAPER-2022-017, arXiv:2209.03692]

- B->Dpi mass fits in phase space bins



Combined Determination of CKM γ and Mixing/CPV Parameters in Charm Sector

Abstract

A combination of measurements sensitive to the *CP* violation angle γ of the Cabibbo–Kobayashi–Maskawa unitarity triangle, to the charm mixing parameters that describe oscillations between D^0 and $\overline{D}^0$ mesons, and to *CP* asymmetries in the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays is performed. All relevant beauty and charm results obtained with the data collected with the LHCb detector at CERN's Large Hadron Collider to date are included. The charm mixing parameters are determined to be $x = (0.398\,^{+0.050}_{-0.049})\%$ and $y = (0.636\,^{+0.020}_{-0.019})\%$, the magnitude and phase of *CP* violation in charm mixing to be $|q/p| = (0.995\,^{+0.015}_{-0.016})$ and $\phi = (2.5 \pm 1.2)^\circ$, and the *CP* asymmetries in decay to be $a^{\rm d}_{K^+K^-} = (9.0 \pm 5.7) \times 10^{-4}$ and $a^{\rm d}_{\pi^+\pi^-} = (24.0 \pm 6.2) \times 10^{-4}$, with a correlation of $\rho = 0.88$. The angle γ is found to be $(63.8\,^{+3.5}_{-3.7})^\circ$ and is the most precise determination from a single experiment.

Combined Determination of CKM γ and Mixing/CPV Parameters in Charm Sector

- Updated LHCb combination for CKM γ (and mixing/CPV params. in charm sector)
- Measurements used in the combination:

B decay	D decay	Ref.	Dataset
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[29]	Run 1&2
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[30]	Run 1
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$	[18]	Run 1&2
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[19]	Run 1&2
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[31]	Run 1&2
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[32]	Run 1&2
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[29]	Run 1&2
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[33]	Run 1&2(*)
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]	Run 1&2(*)
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[34]	Run 1
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[35]	Run 1&2(*)
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[35]	Run 1&2(*)
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[36]	Run 1
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[37]	Run 1
$B^0_s \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	[38]	Run 1
$B^0_s \to D_s^\mp K^\pm\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	[39]	Run 1&2

Combined Determination of CKM γ and Mixing/CPV Parameters in Charm Sector

Table 4: Confidence intervals and best-fit values for γ when splitting the combination inputs by initial B meson species, computed using the Feldman-Cousins *Plugin* method [63].

Species	Value [°]	68.3% CL		95.4% CL	
		Uncertainty	Interval	Uncertainty	Interval
B^+	60.6	$^{+4.0}_{-3.8}$	[56.8, 64.6]	$^{+7.8}_{-7.5}$	[53.1, 68.4]
B^0	82.0	$^{+8.1}_{-8.8}$	[73.2, 90.1]	$^{+17}_{-18}$	[64, 99]
B^0_s	79	$^{+21}_{-24}$	[55, 100]	$^{+51}_{-47}$	[32, 130]

Table 5: Confidence intervals and best-fit values for γ when splitting the combination inputs by time-dependent and time-integrated methods.

Method	Value [°]	68.3% CL		95.4% CL	
		Uncertainty	Interval	Uncertainty	Interval
Time-dependent	79	$^{+21}_{-23}$	[56, 100]	$^{+51}_{-48}$	[31, 130]
Time-integrated	63.3	$^{+3.7}_{-3.9}$	[59.4, 67.0]	$^{+7.1}_{-7.8}$	[55.5, 70.4]

Combined Determination of CKM γ and Mixing/CPV Parameters in Charm Sector

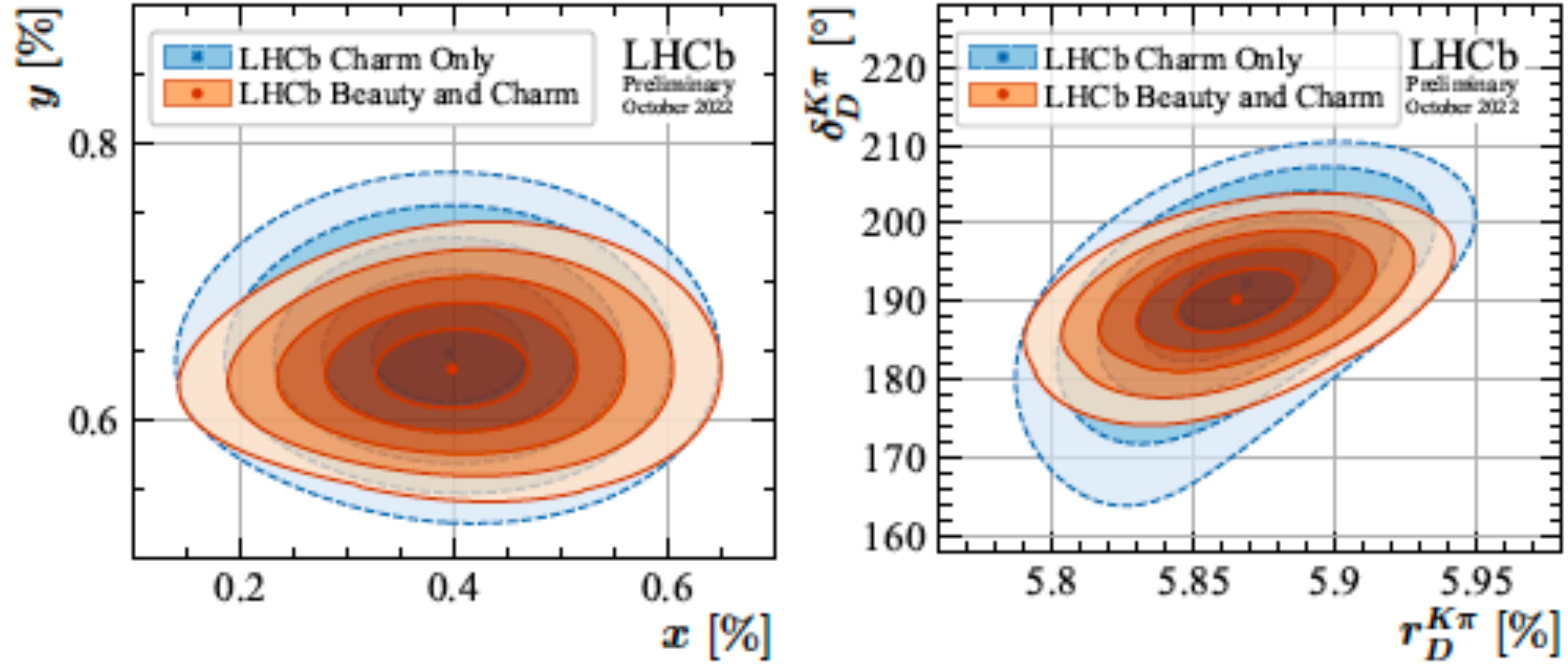


Figure 2: Two dimensional profile likelihood contours for (left) the charm mixing parameters x and y, and (right) the $r_D^{K\pi}$ and $\delta_D^{K\pi}$ parameters. The blue contours (dashed) show the charm only inputs, the orange (solid) contours show the result of this combination. Contours are drawn out to 5σ and contain 68.3%, 95.4%, 99.7%, *etc.* of the distribution.

Combined Determination of CKM γ and Mixing/CPV Parameters in Charm Sector

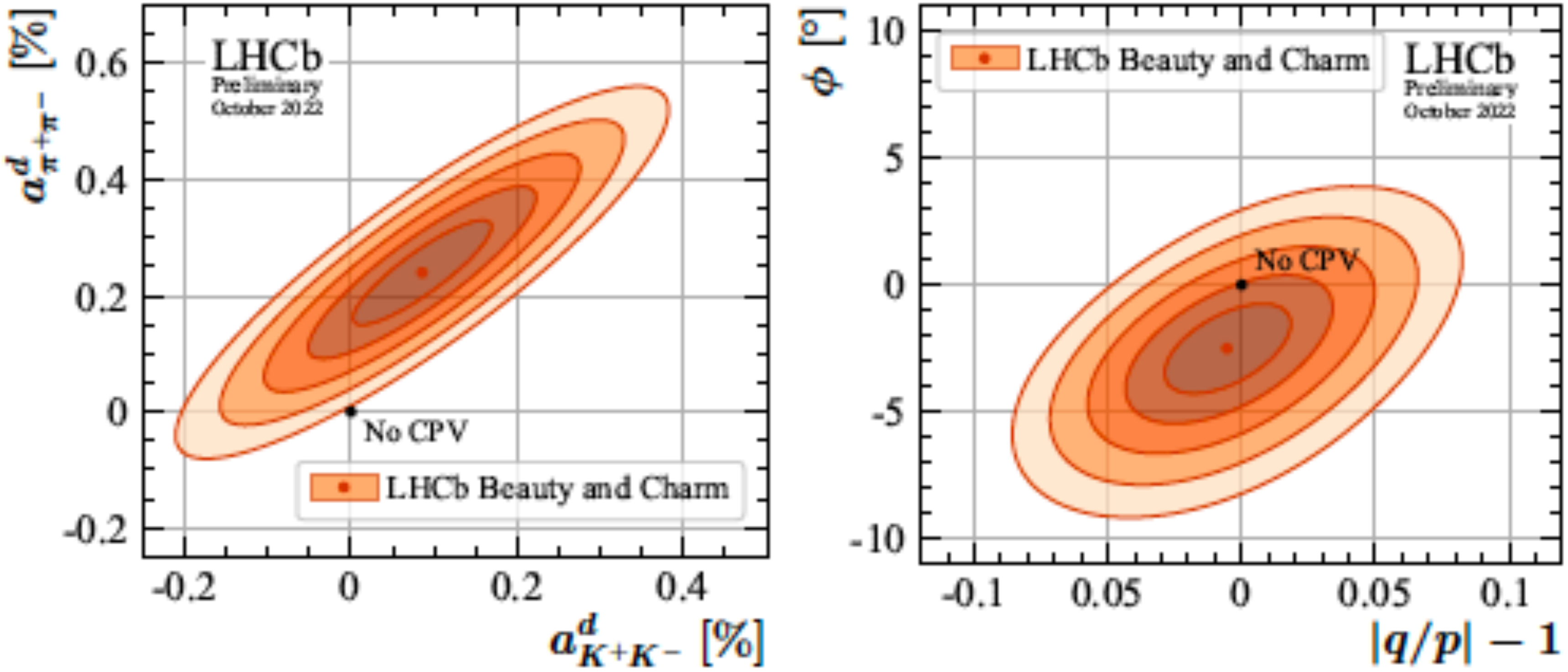


Figure 3: Two dimensional profile likelihood contours for (left) the *CP* asymmetries in the decay of the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ channels, and (right) the $|q/p|$ and ϕ parameters. The orange contours show the result of this combination, contours for the charm only inputs are indistinguishable so are not shown. Contours are drawn out to 5σ and contain 68.3%, 95.4%, 99.7%, *etc.* of the distribution.

Combined Determination of CKM γ and Mixing/CPV Parameters in Charm Sector

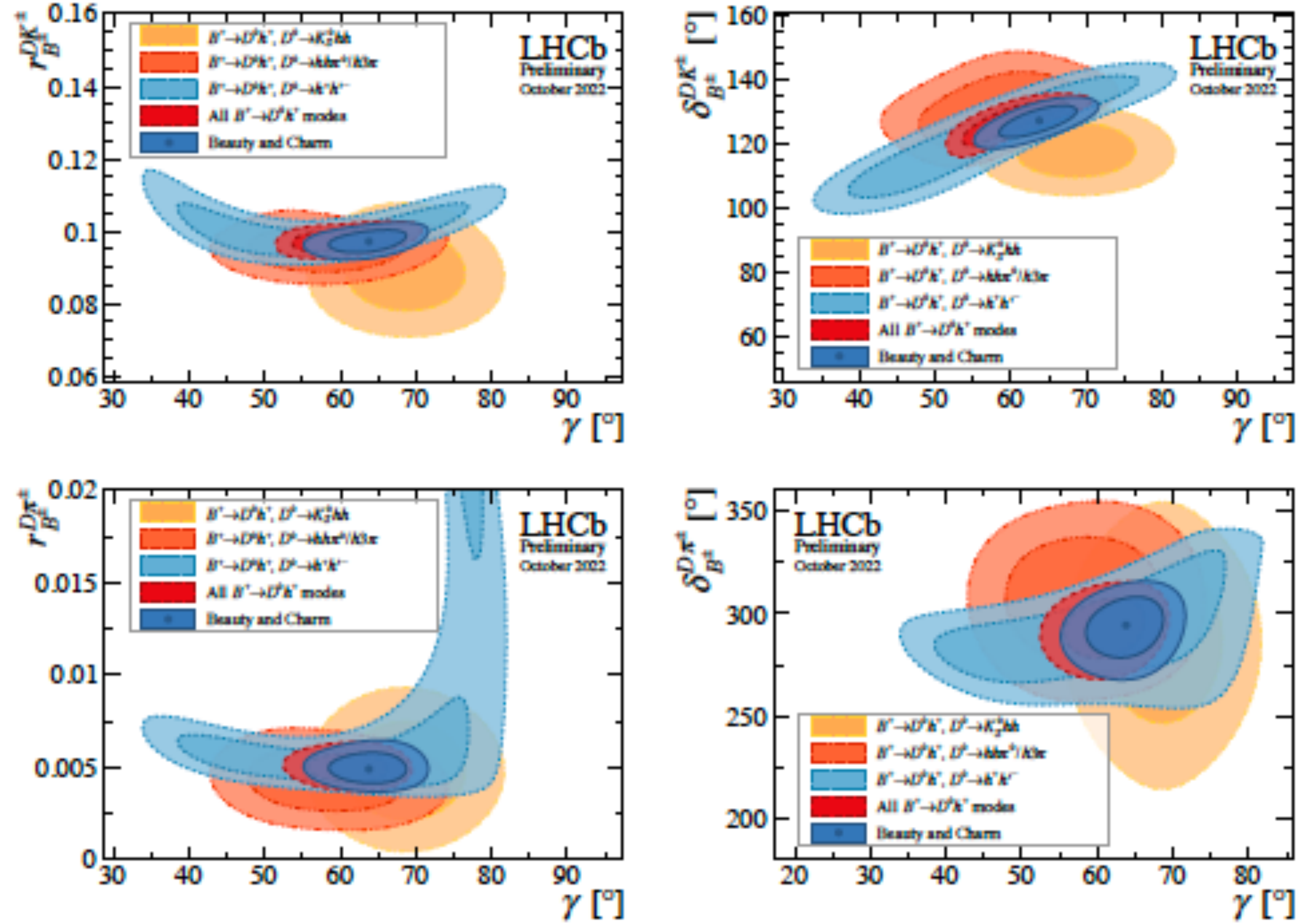


Figure 4: Profile likelihood contours for the components which contribute towards the γ part of the combination, showing the breakdown of sensitivity amongst different sub-combinations of

Combined Determination of CKM γ and Mixing/CPV Parameters in Charm Sector

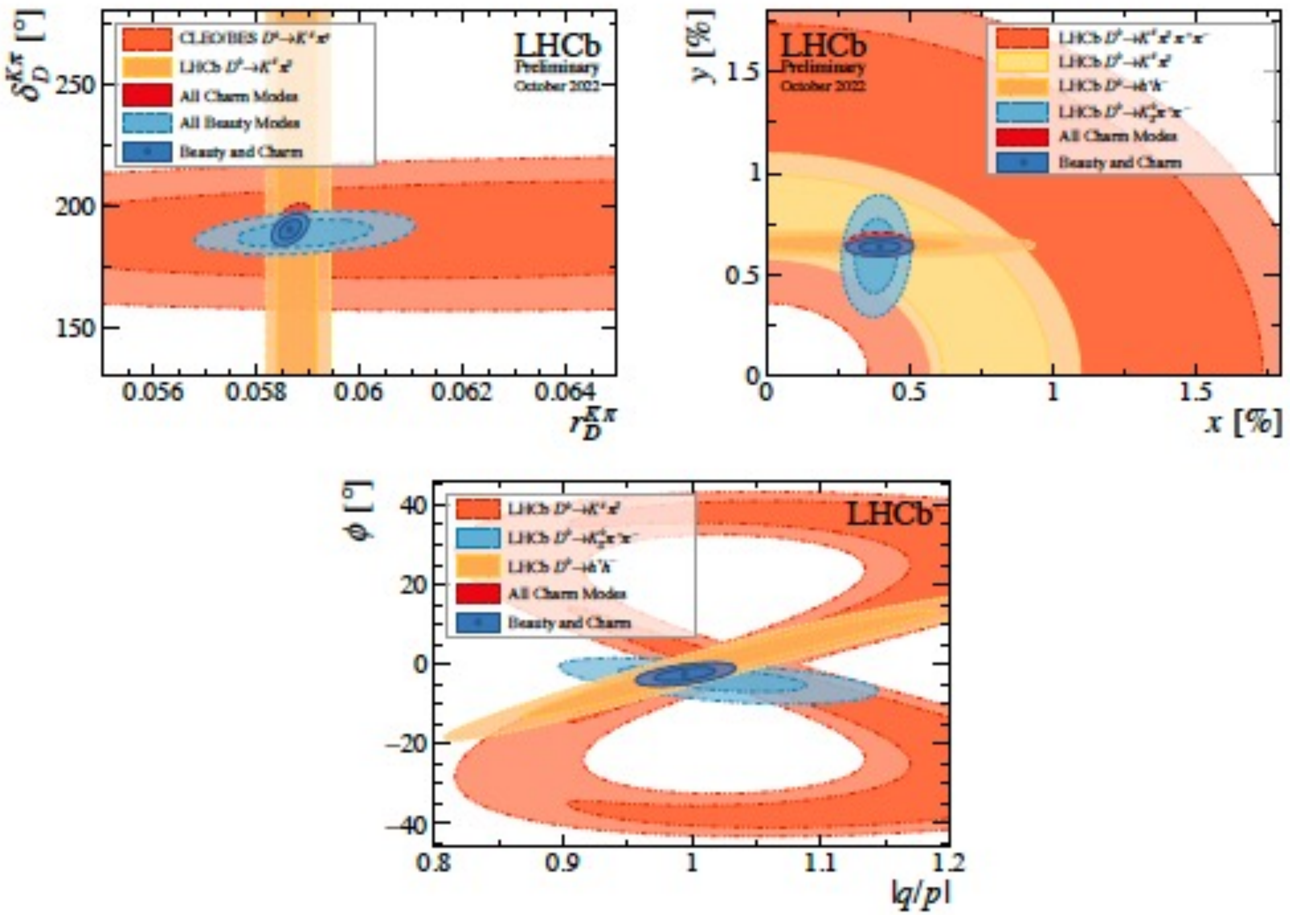


Figure 5: Profile likelihood contours for the charm decay and mixing parameters, showing the breakdown of sensitivity amongst different sub-combinations of modes. The contours indicate the 68.3% and 95.4% confidence regions.

Measurement of the time-integrated CP asymmetry in $D^0 \rightarrow K^-K^+$ decays

The time-integrated CP asymmetry in the Cabibbo-suppressed decay $D^0 \rightarrow K^-K^+$ is measured using proton-proton collision data, corresponding to an integrated luminosity of $5.7\,\text{fb}^{-1}$ collected at a center-of-mass energy of 13 TeV with the LHCb detector. The D^0 mesons are required to originate from promptly produced $D^{*+} \rightarrow D^0\pi^+$ decays and the charge of the companion pion is used to determine the flavor of the charm meson at production. The time-integrated CP asymmetry is measured to be

$$\mathcal{A}_{CP}(K^-K^+) = [6.8 \pm 5.4\,(\text{stat}) \pm 1.6\,(\text{syst})] \times 10^{-4}.$$

The direct CP asymmetries in $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$ decays, $a^d_{K^-K^+}$ and $a^d_{\pi^-\pi^+}$, are derived by combining $\mathcal{A}_{CP}(K^-K^+)$ with the time-integrated CP asymmetry difference, $\Delta\mathcal{A}_{CP} = \mathcal{A}_{CP}(K^-K^+) - \mathcal{A}_{CP}(\pi^-\pi^+)$, giving

$$\begin{aligned} a^d_{K^-K^+} &= (\ 7.7 \pm 5.7) \times 10^{-4}, \\ a^d_{\pi^-\pi^+} &= (23.2 \pm 6.1) \times 10^{-4}, \end{aligned}$$

with a correlation coefficient corresponding to $\rho = 0.88$. The compatibility of these results with CP symmetry is 1.4 and 3.8 standard deviations for $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$ decays, respectively. This is the first evidence for direct CP violation in a specific D^0 decay.

LHCb PAPER-2022-024, arXiv:2209.03179

Measurement of the time-integrated CP asymmetry in $D^0 \to K^- K^+$ decays

- 'Calib' procedure:

The contributions from the production and instrumental asymmetries, referred to as nuisance asymmetries, are estimated and removed through two calibration procedures denoted as C_{D^+} and $C_{D_s^+}$, using a set of promptly produced D^+ and D_s^+ meson decays. Namely, the C_{D^+} procedure uses $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$, $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to \overline{K}^0\pi^+$ decays; while the $C_{D_s^+}$ procedure uses $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$, $D_s^+ \to \phi(\to K^-K^+)\pi^+$ and $D_s^+ \to \overline{K}^0 K^+$ decays.

$$
\begin{aligned}
A(K^-\pi^+) &\approx A_{\mathrm{P}}(D^{*+}) - A_{\mathrm{D}}(K^+) + A_{\mathrm{D}}(\pi^+) + A_{\mathrm{D}}(\pi^+_{\mathrm{tag}}),\\
A(K^-\pi^+\pi^+) &\approx A_{\mathrm{P}}(D^+) - A_{\mathrm{D}}(K^+) + A_{\mathrm{D}}(\pi^+_1) + A_{\mathrm{D}}(\pi^+_2),\\
A(\overline{K}^0\pi^+) &\approx A_{\mathrm{P}}(D^+) + A(\overline{K}^0) + A_{\mathrm{D}}(\pi^+),\\
A(\phi\pi^+) &\approx A_{\mathrm{P}}(D_s^+) + A_{\mathrm{D}}(\pi^+),\\
A(\overline{K}^0K^+) &\approx A_{\mathrm{P}}(D_s^+) + A(\overline{K}^0) + A_{\mathrm{D}}(K^+).
\end{aligned}
$$

$$
\begin{aligned}
\mathrm{C}_{D^+} &: \mathcal{A}_{CP}(K^-K^+) = A(K^-K^+) - A(K^-\pi^+) + A(K^-\pi^+\pi^+) - A(\overline{K}^0\pi^+) + A(\overline{K}^0),\\
\mathrm{C}_{D_s^+} &: \mathcal{A}_{CP}(K^-K^+) = A(K^-K^+) - A(K^-\pi^+) + A(\phi\pi^+) - A(\overline{K}^0K^+) + A(\overline{K}^0).
\end{aligned}
$$

$$
\begin{aligned}
\mathrm{C}_{D^+} &: \mathcal{A}_{CP}(K^-K^+) = [13.6 \pm 8.8\,(\mathrm{stat}) \pm 1.6\,(\mathrm{syst})] \times 10^{-4},\\
\mathrm{C}_{D_s^+} &: \mathcal{A}_{CP}(K^-K^+) = [\;2.8 \pm 6.7\,(\mathrm{stat}) \pm 2.0\,(\mathrm{syst})] \times 10^{-4},
\end{aligned}
$$

Measurement of the time-integrated CP asymmetry in $D^0 \to K^- K^+$ decays

$$a^d_{K^-K^+} = (\ 7.7 \pm 5.7) \times 10^{-4},$$
$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4},$$

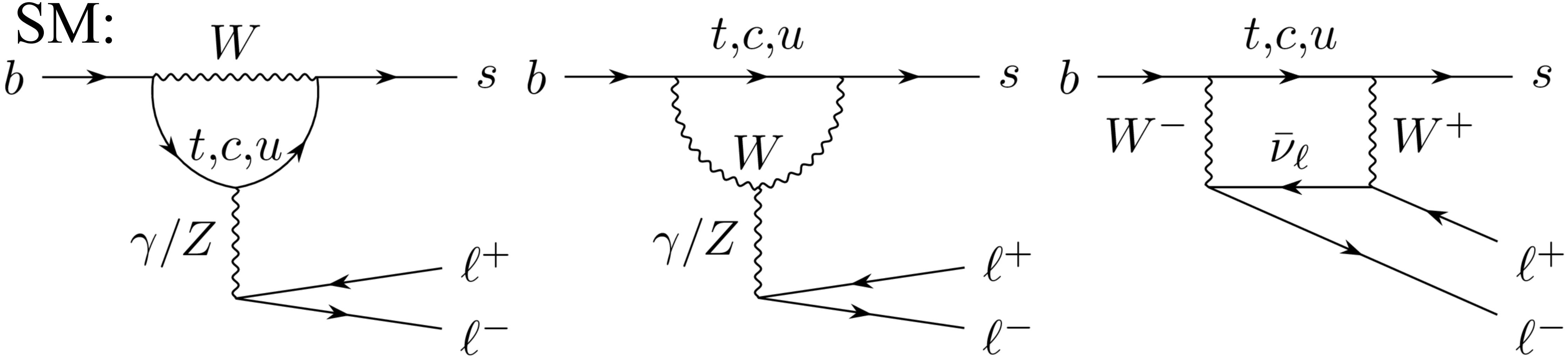
where the uncertainties include systematic and statistical contributions with a correlation coefficient of 0.88. Figure 2 shows the central values and the confidence regions in the $(a^d_{K^-K^+}, a^d_{\pi^-\pi^+})$ plane for this combination and the one realized with data collected between 2010 and 2012 [49,54,56,58,59]. The two combinations are based on an integrated luminosity of 8.7 fb^{-1} and 3.0 fb^{-1}, respectively.

The direct CP asymmetries deviate from zero by 1.4 and 3.8 standard deviations for $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays, respectively. This is the first evidence for direct CP violation in the $D^0 \to \pi^-\pi^+$ decay. U-spin symmetry implies $a^d_{K^-K^+} + a^d_{\pi^-\pi^+} = 0$ [60]. A value of $a^d_{K^-K^+} + a^d_{\pi^-\pi^+} = (30.8 \pm 11.4) \times 10^{-4}$ has been found, corresponding to a departure from U-spin symmetry of 2.7 standard deviations.

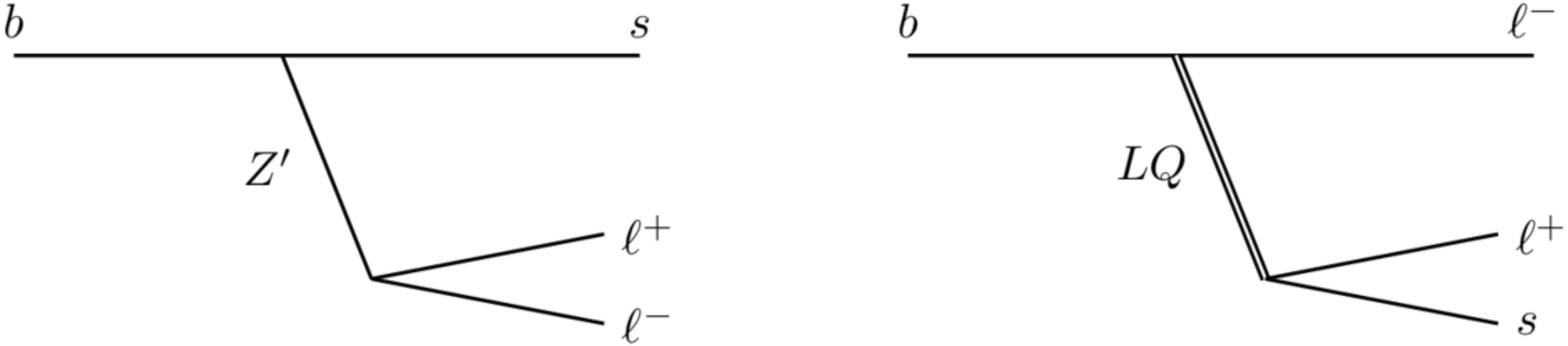
In summary, this Letter reports the most precise measurement of the time-integrated CP asymmetry in the $D^0 \to K^-K^+$ decay to date. A combination with the previous LHCb measurements shows the first evidence of direct CP asymmetry in an individual charm meson decay. These results will help to clarify the theoretical understanding of

Test of Lepton Universality in $b \to s\ell^+\ell^-$ Decays

- SM:



- BSM:



Test of Lepton Universality in $b \to s\ell^+\ell^-$ Decays

- Definitions of $R(K,K^*)$:

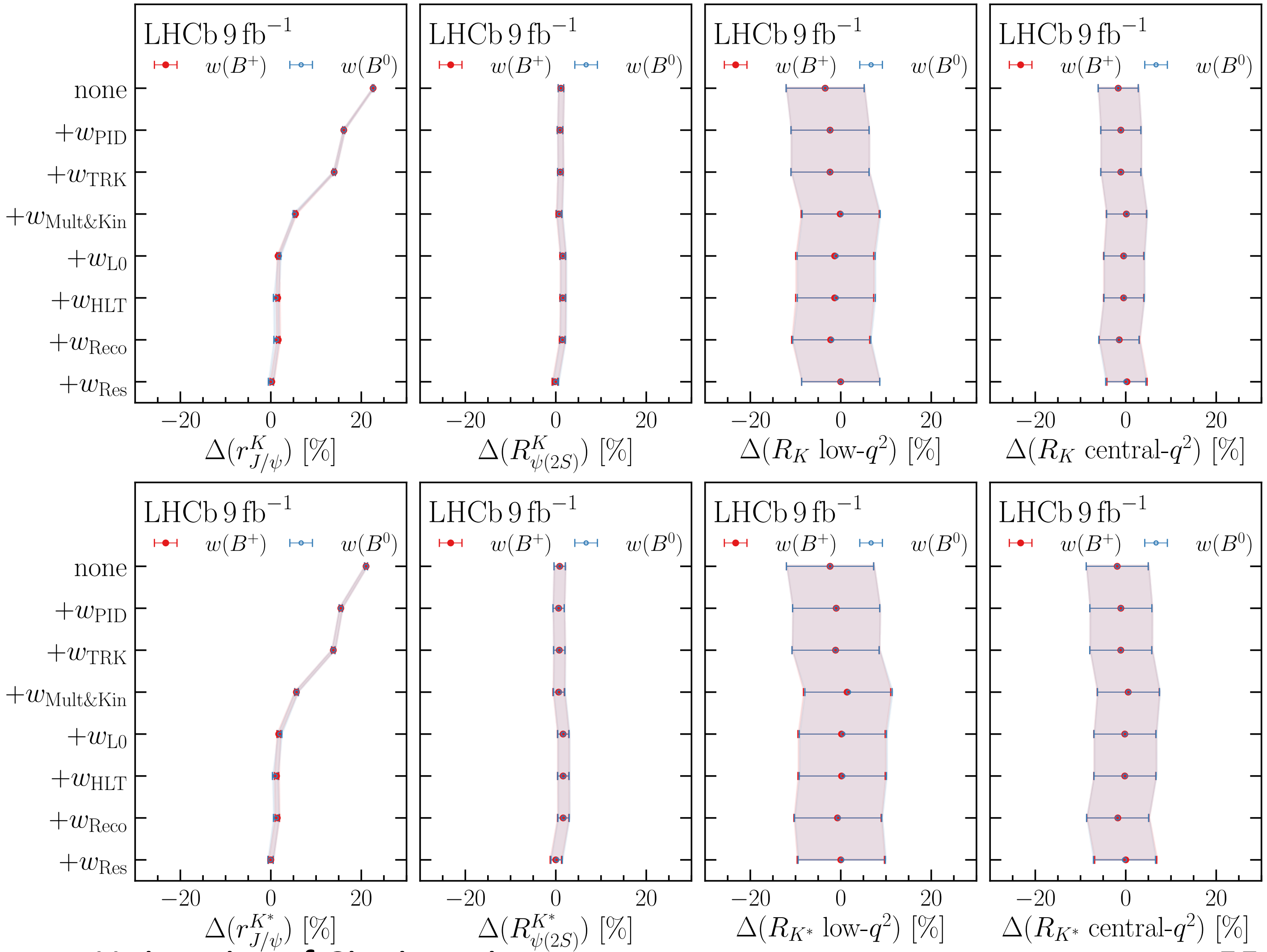
$$R_{(K,K^*)}(q_a^2, q_b^2) = \frac{\displaystyle\int_{q_a^2}^{q_b^2} \frac{\mathrm{d}\Gamma(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\displaystyle\int_{q_a^2}^{q_b^2} \frac{\mathrm{d}\Gamma(B^{(+,0)} \to K^{(+,*0)}e^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2}$$

- Double-ratios to cancel detector eff:

$$R_{(K,K^*)} \equiv \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}e^+e^-)}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(\to e^+e^-))}$$

Test of Lepton Universality in $b \to s\ell^+\ell^-$ Decays

- Evolution of eff-corrected ratios as function of corrections applied to simulated data
- (For double-ratios, impact of calib chain less than few %)



Test of Lepton Universality in $b \to s\ell^+\ell^-$ Decays

- Results (in regions of q^2 = dilepton invariant mass):

low- q^2 R_K	central- q^2 R_K	low- q^2 R_{K^*}	central- q^2 R_{K^*}
$0.994\,^{+0.090}_{-0.082}\,^{+0.029}_{-0.027}$	$0.949\,^{+0.042}_{-0.041}\,^{+0.022}_{-0.022}$	$0.927\,^{+0.093}_{-0.087}\,^{+0.036}_{-0.035}$	$1.027\,^{+0.072}_{-0.068}\,^{+0.027}_{-0.026}$

- SM predictions (Flavio package):

	R_K low-q^2	R_K central-q^2	R_{K^*} low-q^2	R_{K^*} central-q^2
SM prediction	0.9936	1.0007	0.9832	0.9964
SM uncertainty	0.0003	0.0003	0.0014	0.0006

- The results are in agreement with SM predictions and supersede previous LHCb measurements

LHCb PAPER-2022-046, arXiv:2212.09152

Test of Lepton Universality in $b \to s\ell^+\ell^-$ Decays

Systematic uncertainties associated with efficiencies are evaluated by varying the assumptions made when calibrating the simulated samples. The biggest uncertainty of this type is the stability of the $r^K_{J/\psi}$ and $r^{K^*}_{J/\psi}$ ratios as a function of different kinematic and geometric variables associated with these decays. The overall systematic uncertainties for efficiencies are below 1% in all cases except R_{K^*} low-q^2 where they are 2%. Systematic uncertainties associated with the modeling of nonresonant decay form factors, which affect the efficiencies, are evaluated using simulation and found to be negligible for B^+ decays and around 1% for B^0 decays. Systematic uncertainties associated with the modeling of the invariant mass distributions are dominated by the data-driven modeling of misidentified backgrounds, and are 2.0–2.5% depending on the LU observable in question. Although larger than the systematic uncertainties assigned in the previous LHCb analyses [29, 32], these are significantly smaller than the statistical uncertainties associated with each of the four LU observables.

LHCb PAPER-2022-046, arXiv:2212.09152

Test of Lepton Universality in $b \to s\ell^+\ell^-$ Decays

- Difference to previous R(K,K*) measurements:

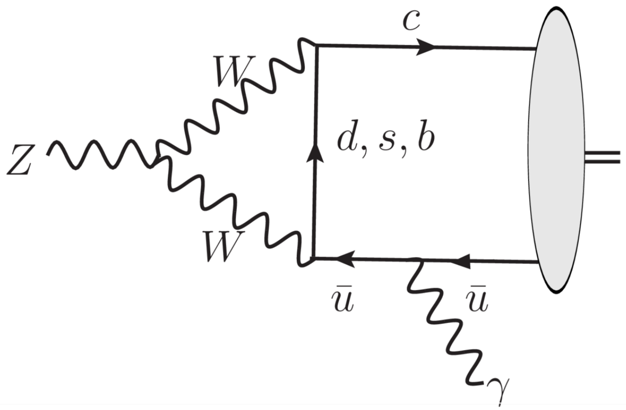
The results presented here differ from previous LHCb measurements of R_K [32] and R_{K^*} [29]. For R_K central-q^2, the difference is partly due to the use of tighter electron identification criteria and partly due to the modeling of the residual misidentified hadronic backgrounds; statistical fluctuations make a smaller contribution to the difference since the same data are used as in Ref. [32]. The systematic shift due to misidentified hadronic backgrounds consists of components related to the tighter PID working point (0.064) and the treatment of the residual component in the fit (0.038). The statistical component of the difference has been evaluated using pseudoexperiments and found to have a Gaussian distribution of width 0.033.

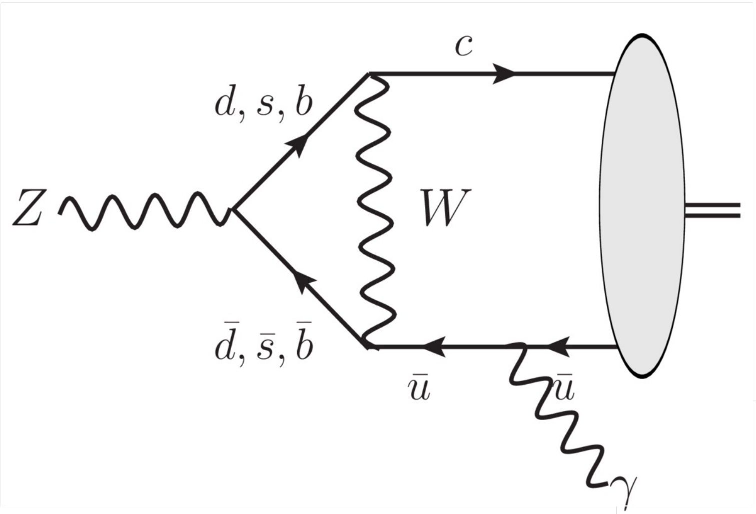
LHCb PAPER-2022-046, arXiv:2212.09152

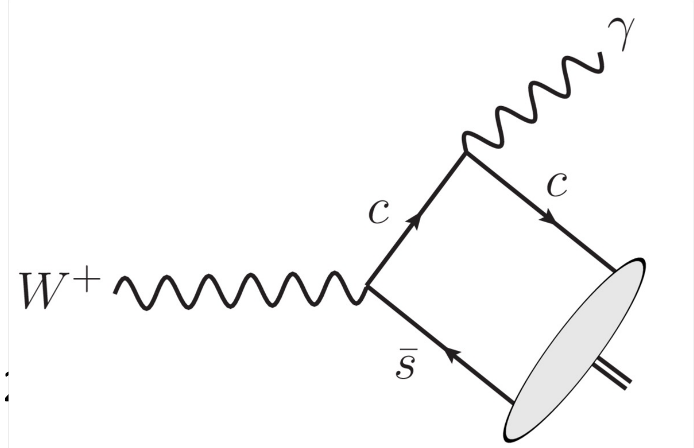
Measurement of the Ratios of Branching Fractions $\mathcal{R}(D^*)$ and $\mathcal{R}(D^0)$

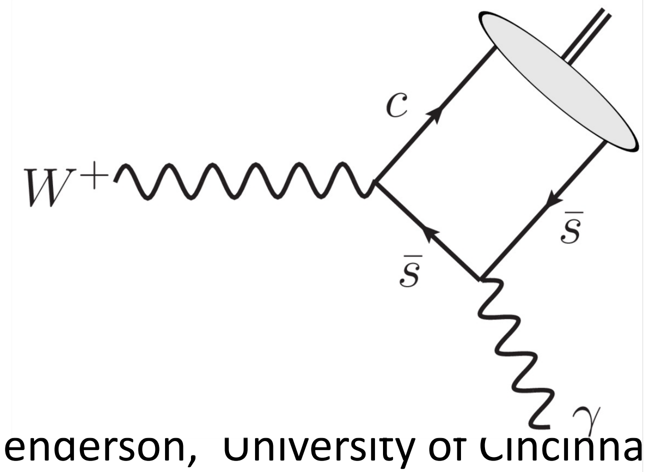
Internal fit uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	Correlation
Statistical uncertainty	1.8	6.0	−0.49
Simulated sample size	1.5	4.5	
$B \to D^{(*)}DX$ template shape	0.8	3.2	
$\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell$ form-factors	0.7	2.1	
$\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu$ form-factors	0.8	1.2	
$\mathcal{B}\ (\overline{B} \to D^* D_s^-(\to \tau^-\overline{\nu}_\tau)X)$	0.3	1.2	
MisID template	0.1	0.8	
$\mathcal{B}\ (\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)$	0.5	0.5	
Combinatorial	< 0.1	0.1	
Resolution	< 0.1	0.1	
Additional model uncertainty	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	
$B \to D^{(*)}DX$ model uncertainty	0.6	0.7	
$\overline{B}_s^0 \to D_s^{**}\mu^-\overline{\nu}_\mu$ model uncertainty	0.6	2.4	
Data/simulation corrections	0.4	0.8	
Coulomb correction to $\mathcal{R}(D^{*+})/\mathcal{R}(D^{*0})$	0.2	0.3	
MisID template unfolding	0.7	1.2	
Baryonic backgrounds	0.7	1.2	
Normalization uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	
Data/simulation corrections	$0.4 \times \mathcal{R}(D^*)$	$0.6 \times \mathcal{R}(D^0)$	
$\tau^- \to \mu^-\nu\overline{\nu}$ branching fraction	$0.2 \times \mathcal{R}(D^*)$	$0.2 \times \mathcal{R}(D^0)$	
Total systematic uncertainty	2.4	6.6	−0.39
Total uncertainty	3.0	8.9	−0.43

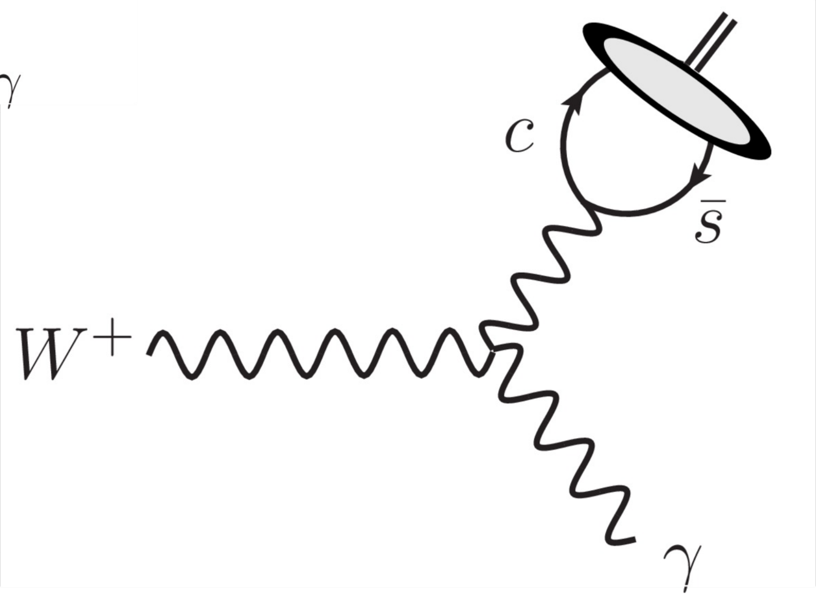
Search for rare decays W+→ $D_s^+\gamma$, Z → $D^0\gamma$





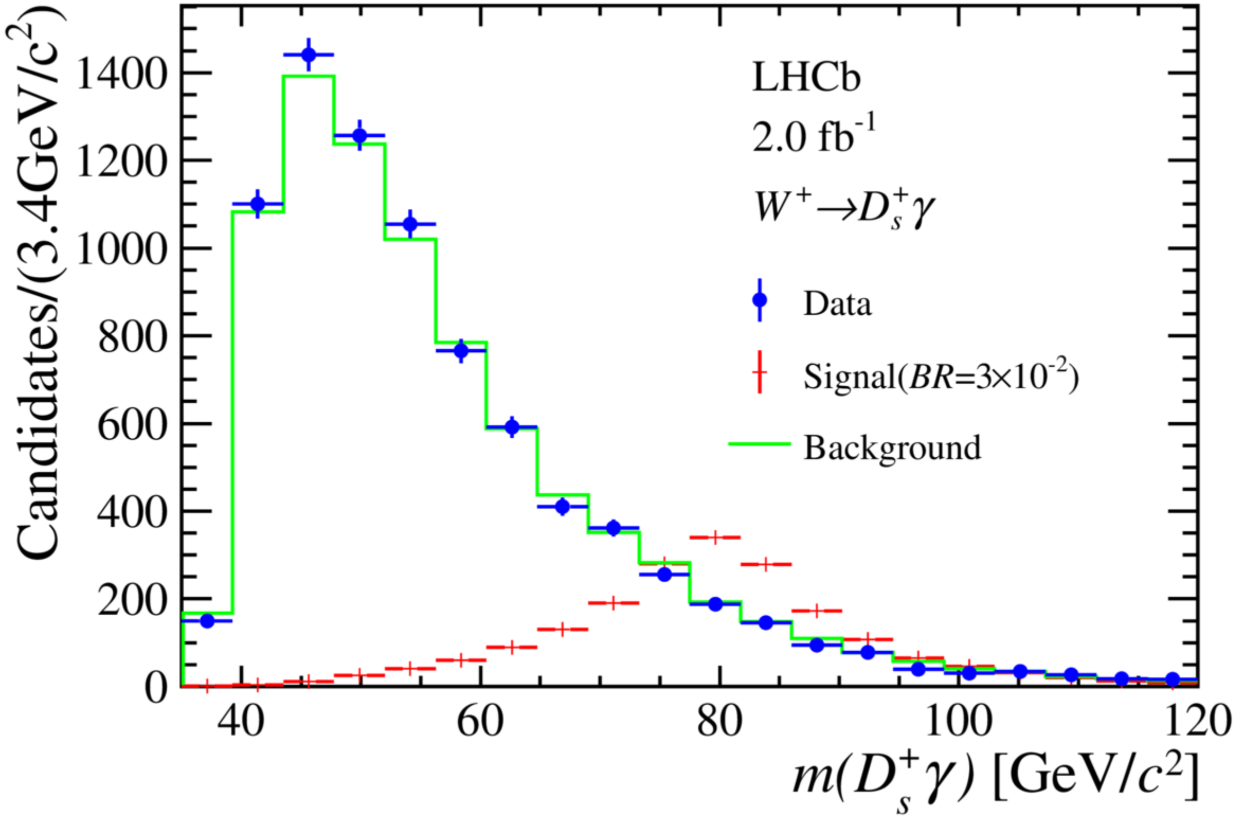


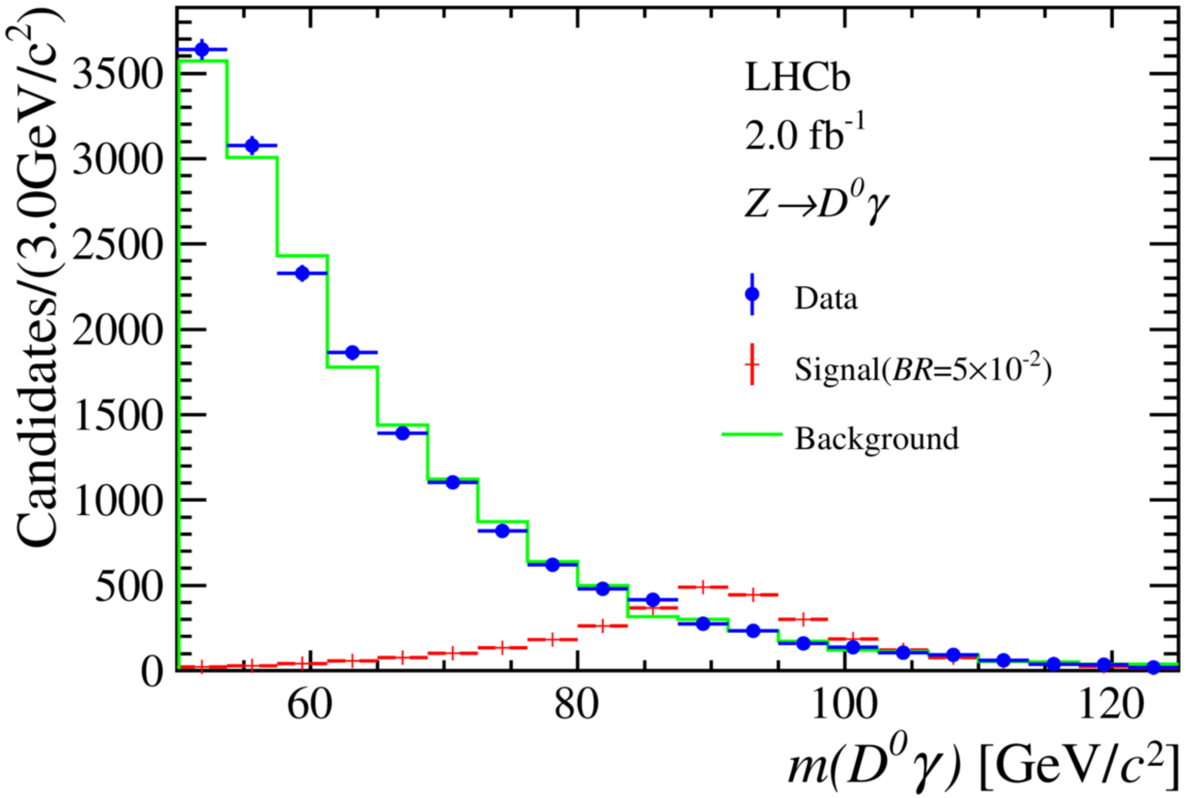




Search for rare decays $W^+ \to D_s^+\gamma$, $Z \to D^0\gamma$

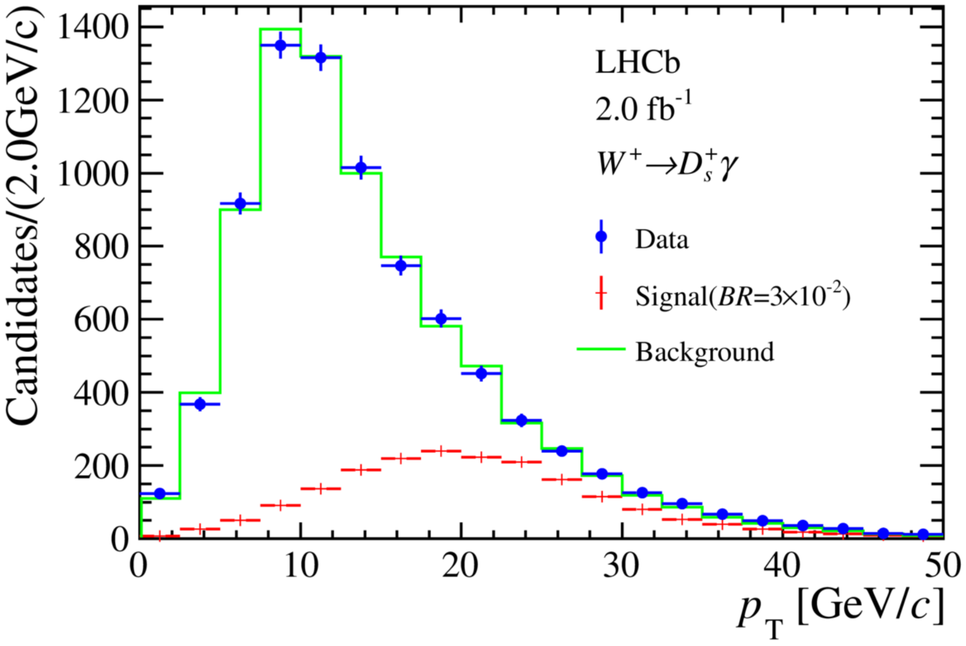
- Pseudomass distributions:

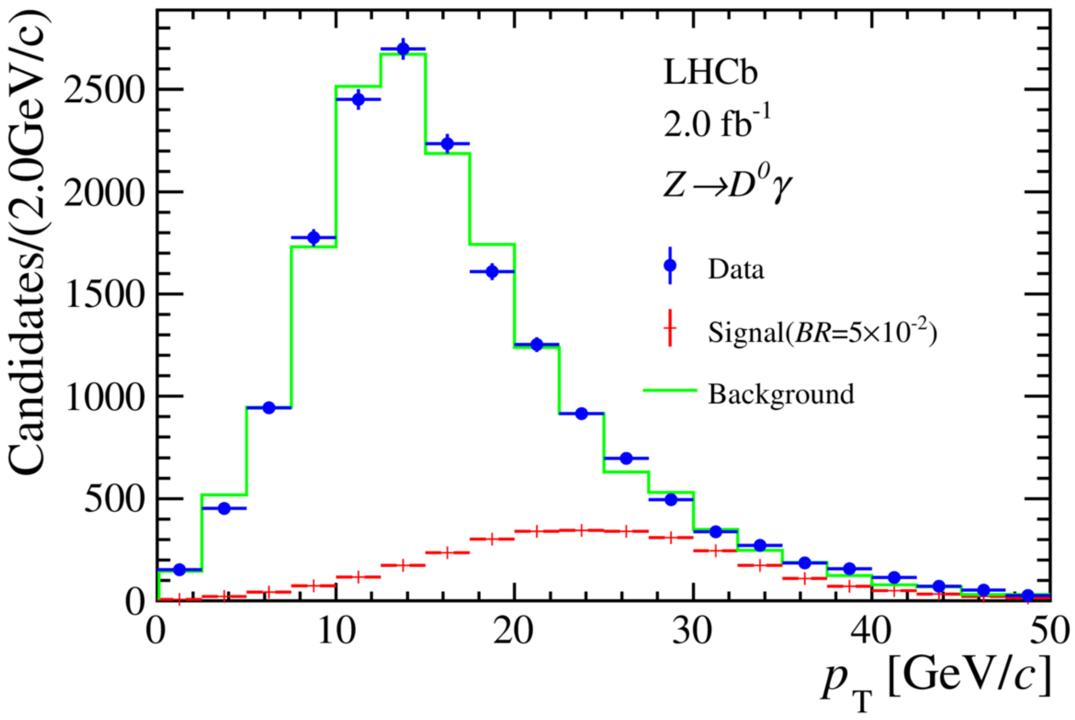




Search for rare decays W+→ $D_s^+\gamma$, Z → $D^0\gamma$

- pT distributions:





Search for rare decays $W^+ \to D_s^+\gamma$, $Z \to D^0\gamma$

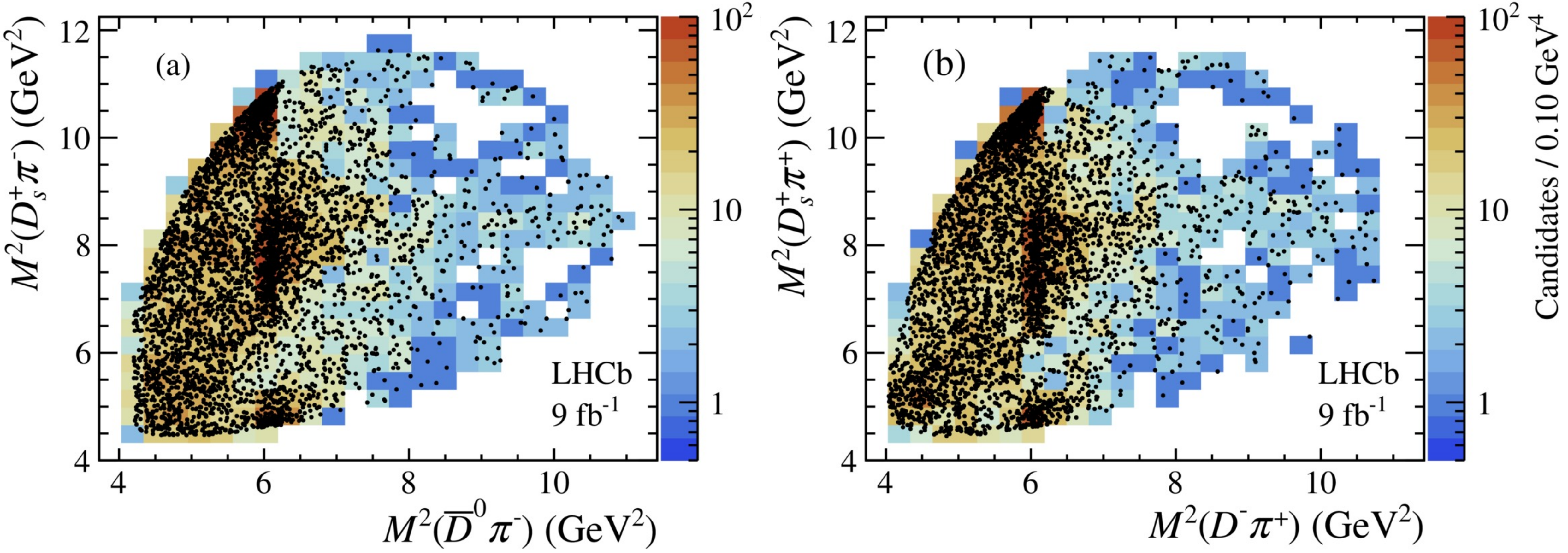
- Systematic uncertainties:

Source	$Z \to D^0\gamma$ (%)	$W^+ \to D_s^+\gamma$ (%)
Meson BF	0.76	1.86
Normalization	0.96	3.08
Dalitz	-	0.24
MC sample size	0.11	0.09
PID	0.09	0.17
Photon ID	2.32	0.95
Calorimeter saturation	3.00	3.10
Background	0.36	0.08
Acceptance	0.18	0.21
PV association	0.57	0.29
Resolution	0.20	0.09
Total	4.04	4.86

First Observation of Doubly-Charged Tetraquark

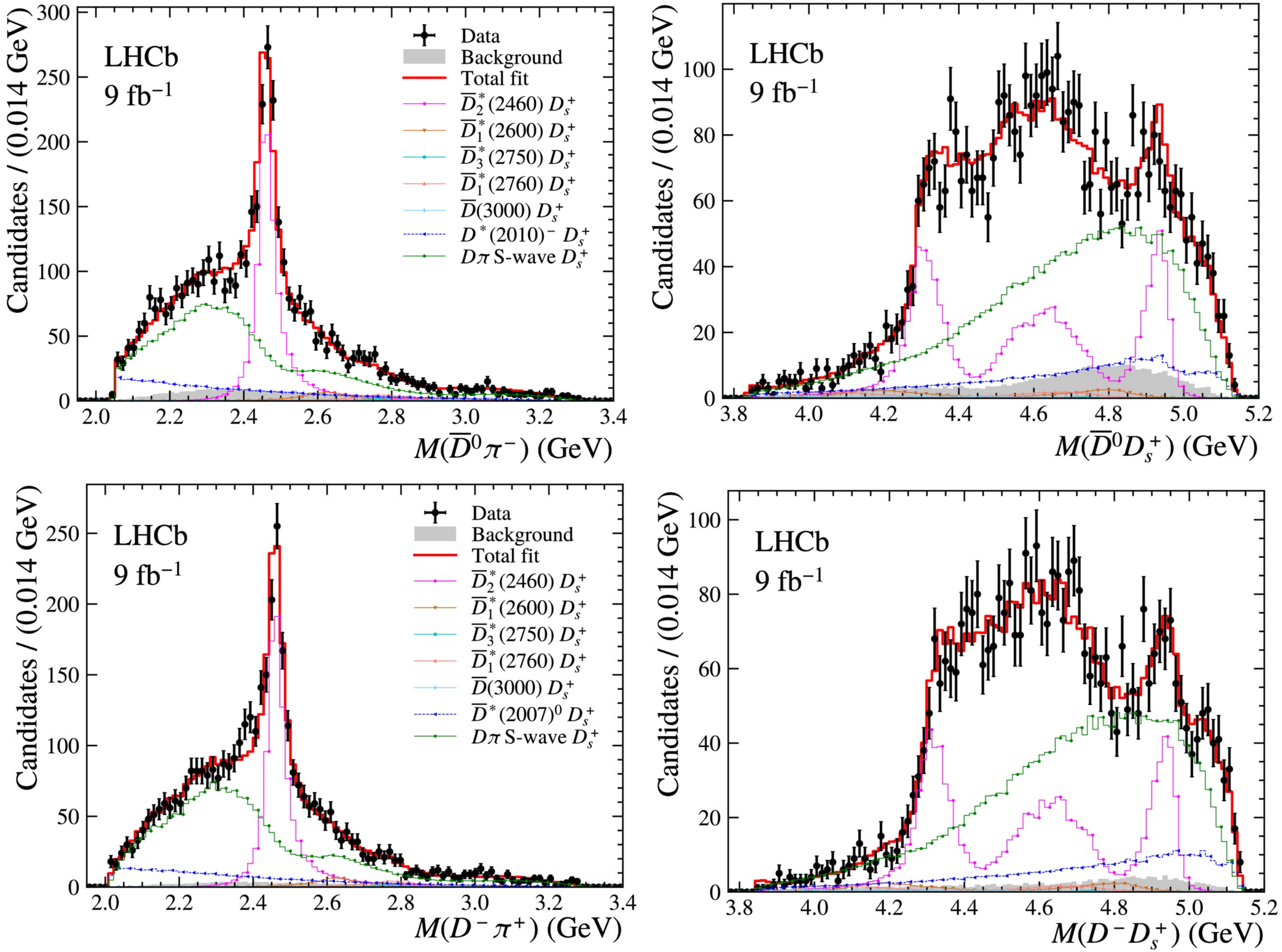
- Dalitz plots:

LHCb PAPER-2022-026, arXiv:2212.02716



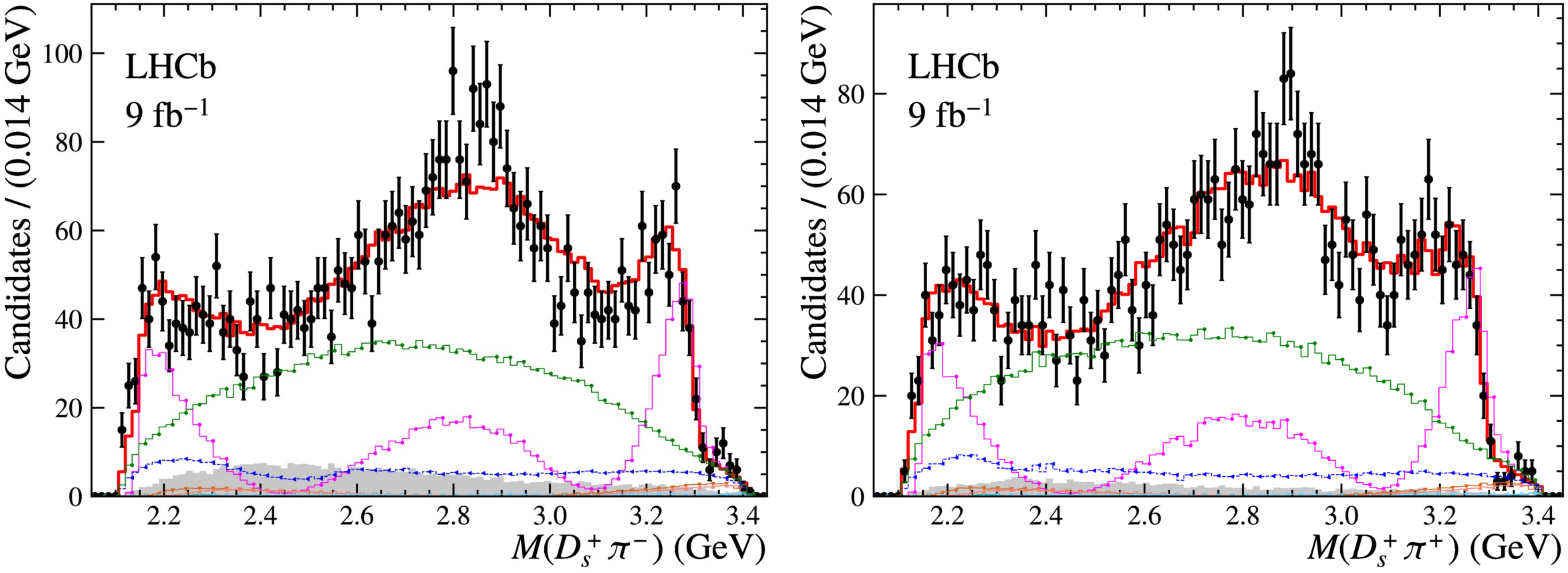
First Observation of Doubly-Charged Tetraquark

- Invariant mass from non-Dspi combos: well described by bkg



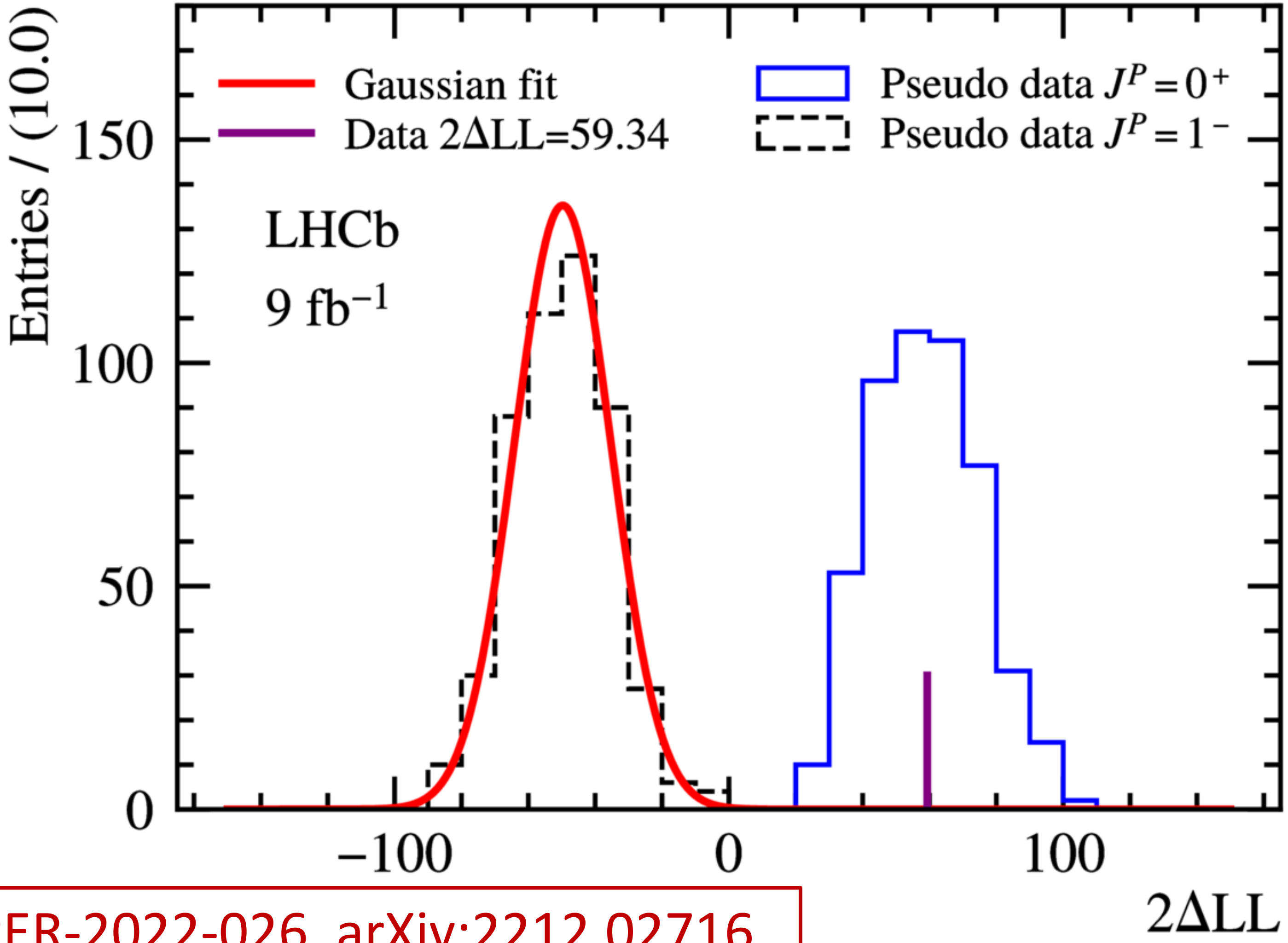
First Observation of Doubly-Charged Tetraquark

- M(Dspi) in absence of tetraquarks:



First Observation of Doubly-Charged Tetraquark

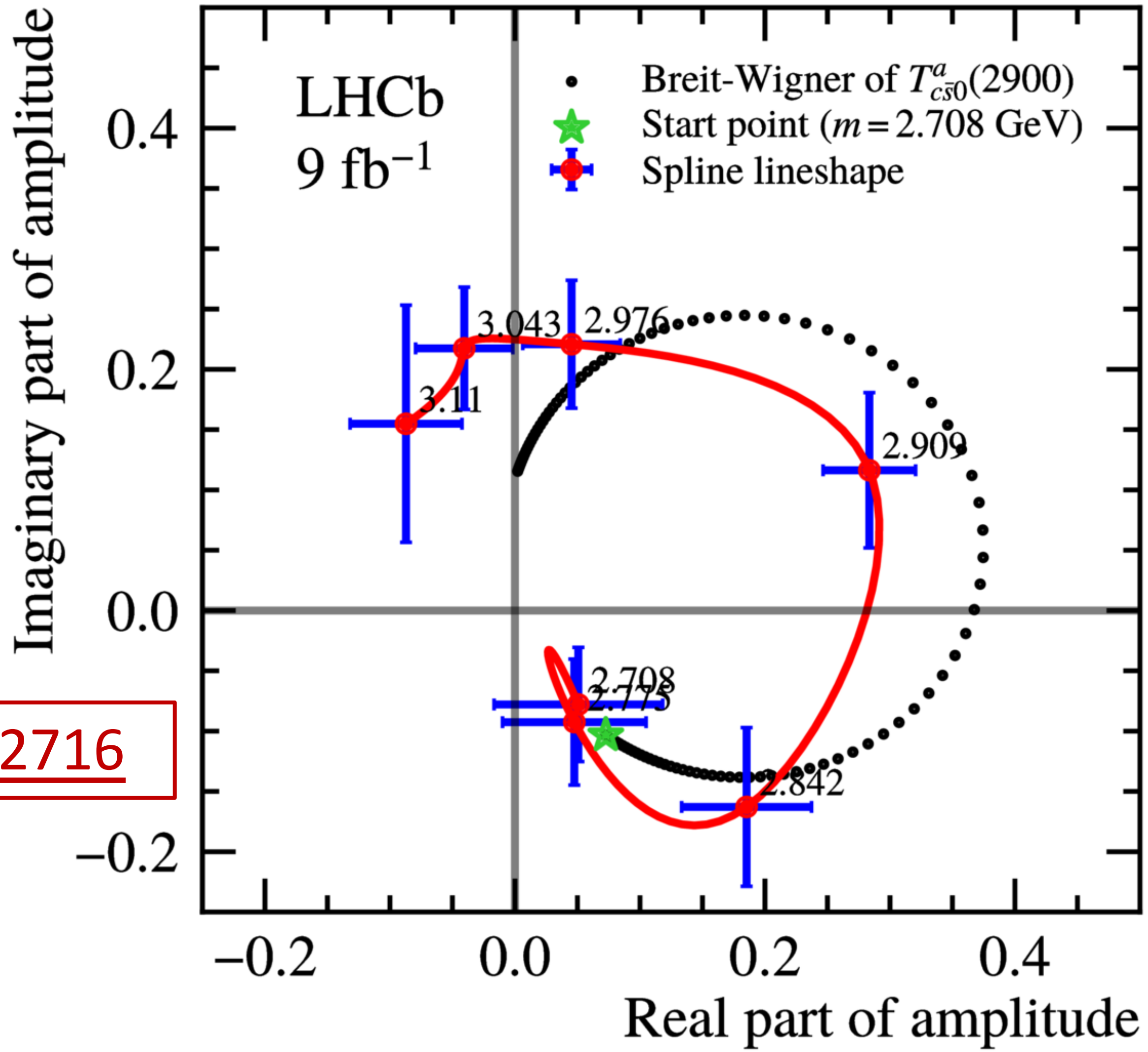
- Spin analysis:



LHCb PAPER-2022-026, arXiv:2212.02716

First Observation of Doubly-Charged Tetraquark

- Argand diagram:

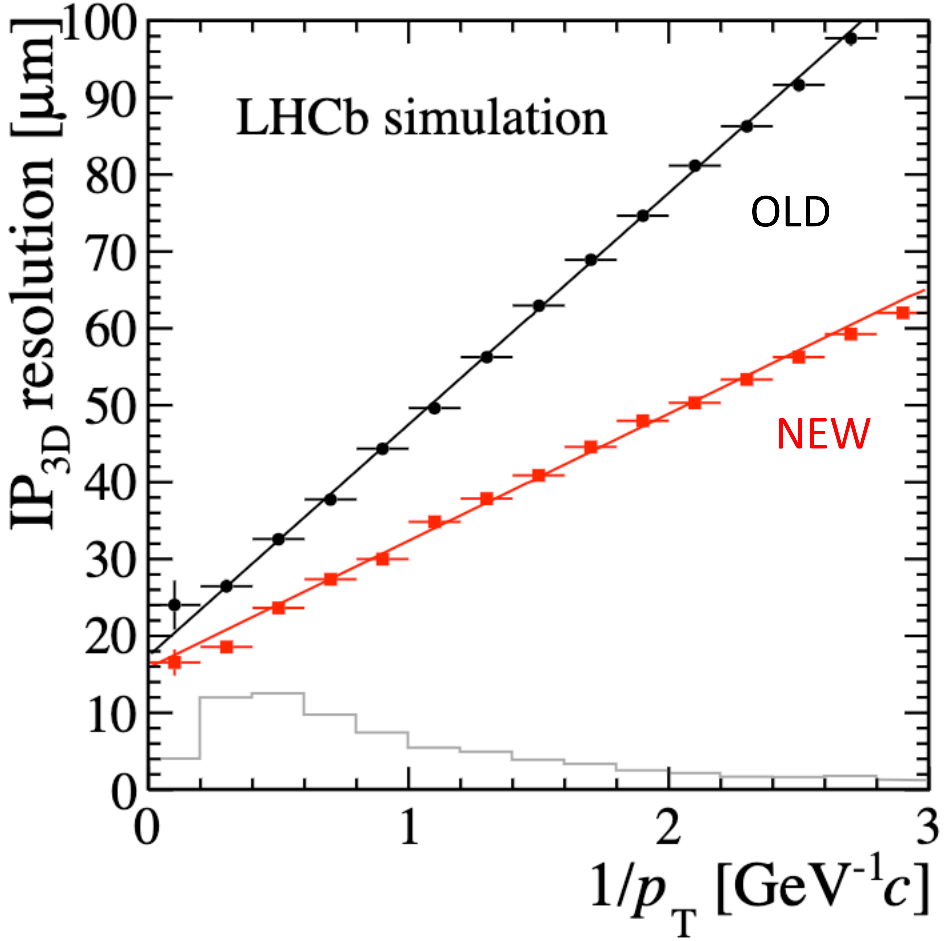


LHCb PAPER-2022-026, arXiv:2212.02716

VELO Upgraded IP Resolution

- Simulation of 3D Impact Parameter resolution expected for new VELO (red) compared to old (Black)

[VELO TDR (LHCb-TDR-013), Fig 31]



Cabibbo-Kobayashi-Maskawa (CKM) Matrix

- Quark mixing in SM described by 3x3 complex unitary CKM matrix :

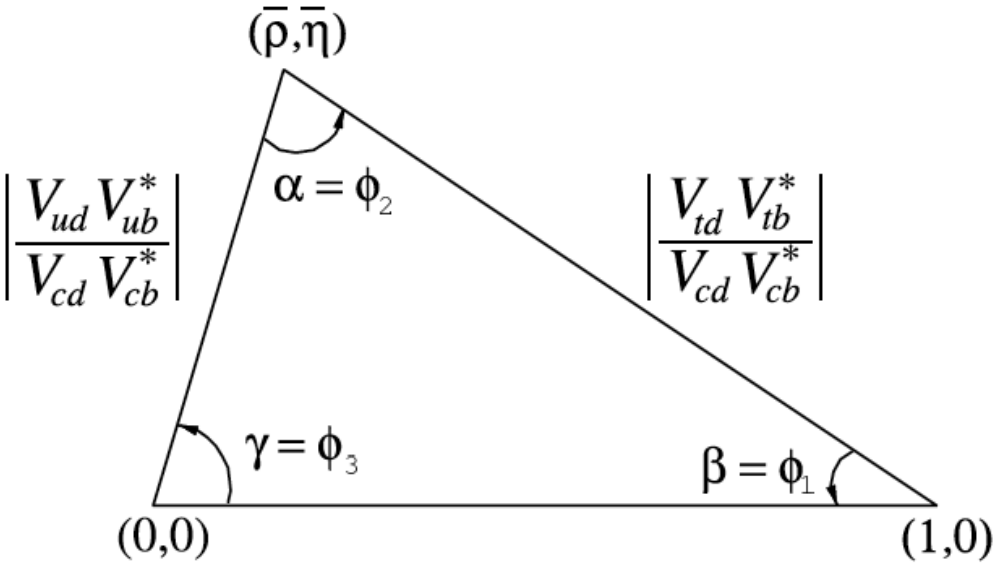
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Can be parametrized by 3 mixing angles and 1 CP-violating phase (or Wolfenstein param.: λ,A,ρ,η)

CKM Unitarity Triangle

- CKM matrix unitarity can be represented by triangle in complex plane
- Conventional to use: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$, divide all sides by $V_{cd}V_{cb}^*$

$\Longrightarrow$



- Goal: overconstrain Unitarity Triangle by measurements of sides and angles