Mixing and CP violation in charm decays at LHCb

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On behalf of the LHCb collaboration

EPS -HEP Conference
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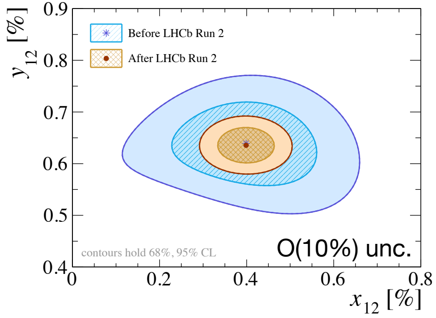
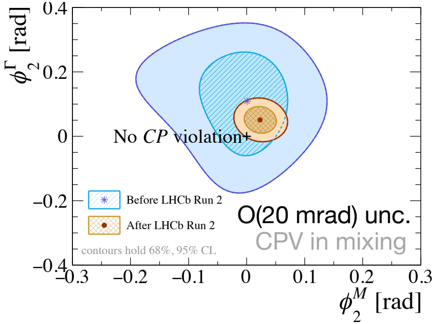
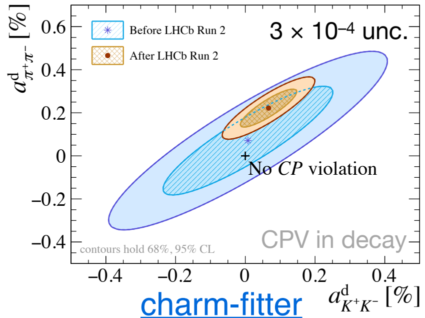
Current Experimental knowledge

- Charm is the only up-type quark with observable mixing and CPV effects. Unique window into fundamental physics, possible path to new dynamics
- Experimentally more difficult than bottom and strange quarks
  - Smaller effects, requires large statistics and tight control of systematics.
- First evidence of charm mixing in 2007, first CPV observation in 2019
  - Mixing parameters known at 10% level
  - Single observation of CPV in decay: $\Delta A_{CP}(K^+K^- - \pi^+\pi^-)$ PRL 122, 211803
    - Known at ~20%
  - No CPV yet seen in Mixing
    - Phase measured at ~20 mrad level
- **A lot to measure and discover in this field !**

LHCb ideally suited for this investigation
 - has been the leading contributor to current knowledge (see plots)







charm-fitter

LHCb features for charm physics

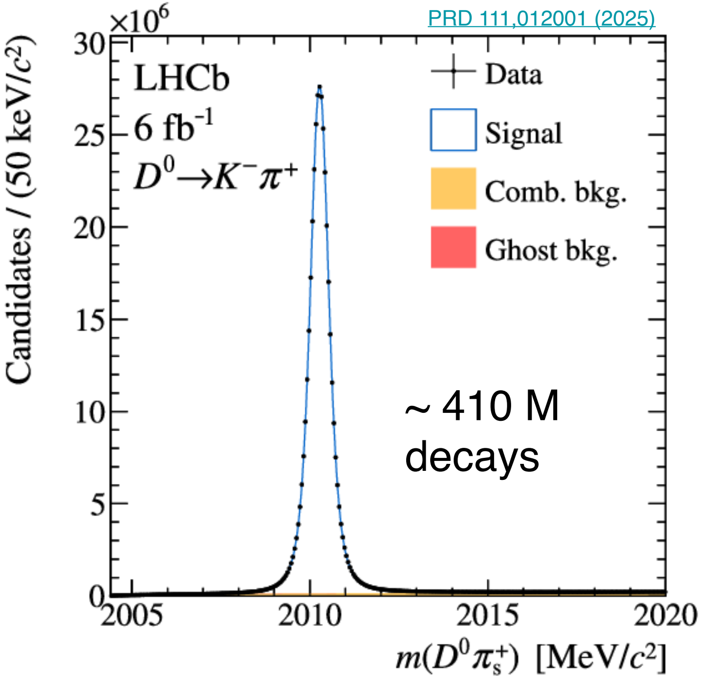
Int.J.Mod.Phys.A 30 (2015) 07, 1530022

A heavy-flavor targeted experiment at the LHC

- Huge production $\sigma(pp \to \textit{charm } X) \times L_{\text{inst}}$ (Run 2) ~**1 MHz**
- **Forward geometry** covers large acceptance in small area
- Focus on **tracking**
  - **Mass and vertexing resolution**
  - disentangle signal from background
  - Measure decay times
- High-performance **particle identification**
  → separate and distinguish decay modes
- Complex trigger capability, focused on detailed tracking

→ O(Billion) cleanly reconstructed charm decays

PRD 111,012001 (2025)



~ 410 M decays

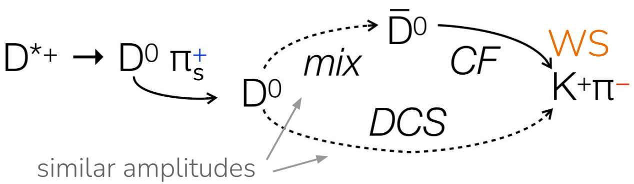
Mixing + CPV in $D^0 \to K\pi$ - full Run 2

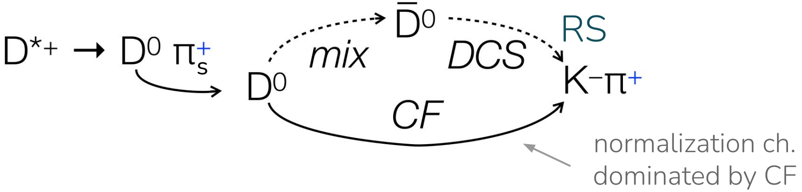
PRD 111,012001 (2025)
JHEP03(2025)149

Measure ratio between:

- $D^{*+} \to D^0(\to K^+\pi^-)\pi^+$ → Wrong Sign (WS)
- $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ → Right Sign (RS)

$$R^+_{K\pi}(t) \equiv \frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(\overline{D}^0(t) \to K^+\pi^-)} \qquad R^-_{K\pi}(t) \equiv \frac{\Gamma(\overline{D}^0(t) \to K^-\pi^+)}{\Gamma(D^0(t) \to K^-\pi^+)}$$



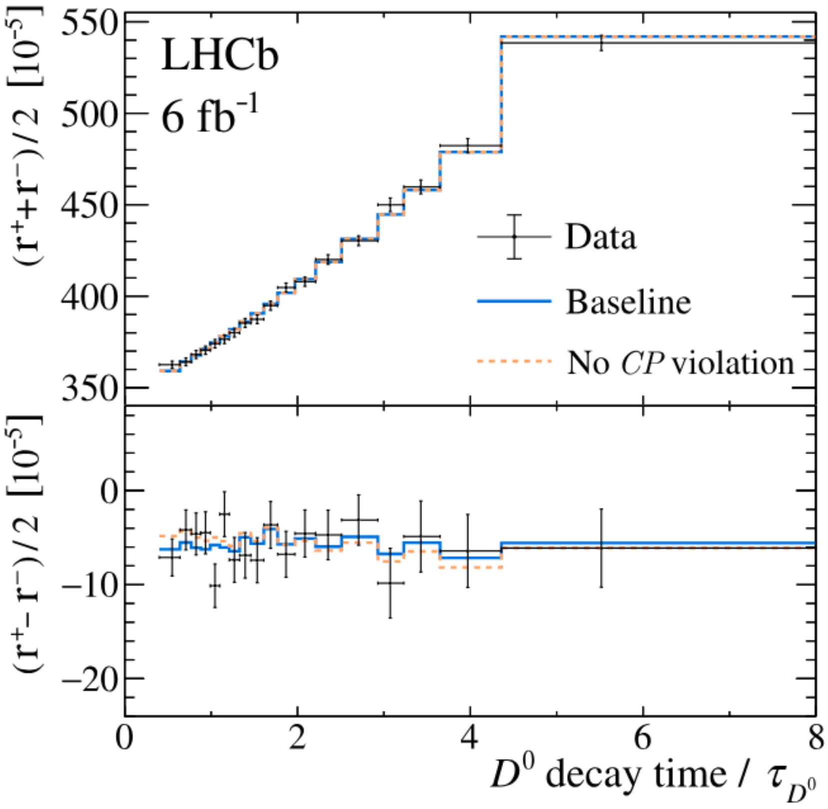


$$R^\pm_{K\pi}(t) \approx R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}(c_{K\pi} \pm \Delta c_{K\pi})\, t + (c'_{K\pi} \pm \Delta c'_{K\pi})\, t^2$$

CPV parameters

Results of 'prompt' analysis

PRD 111,012001 (2025)

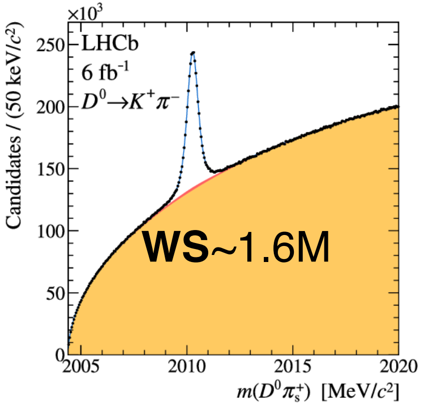


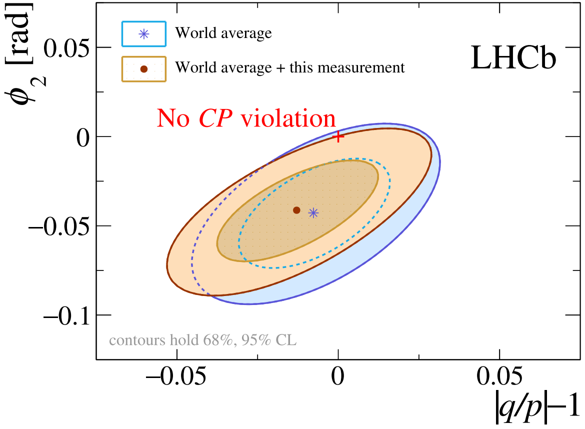
WA resolution improved 60%

$R_{K\pi}$	$(343.1 \pm 2.0) \times 10^{-5}$
$c_{K\pi}$	$(51.4 \pm 3.5) \times 10^{-4}$
$c'_{K\pi}$	$(13.1 \pm 3.7) \times 10^{-6}$
$A_{K\pi}$	$(-7.1 \pm 6.0) \times 10^{-3}$
$\Delta c_{K\pi}$	$(3.0 \pm 3.6) \times 10^{-4}$
$\Delta c'_{K\pi}$	$(-1.9 \pm 3.8) \times 10^{-6}$

First evidence of t^2 term

Still no CP-violation



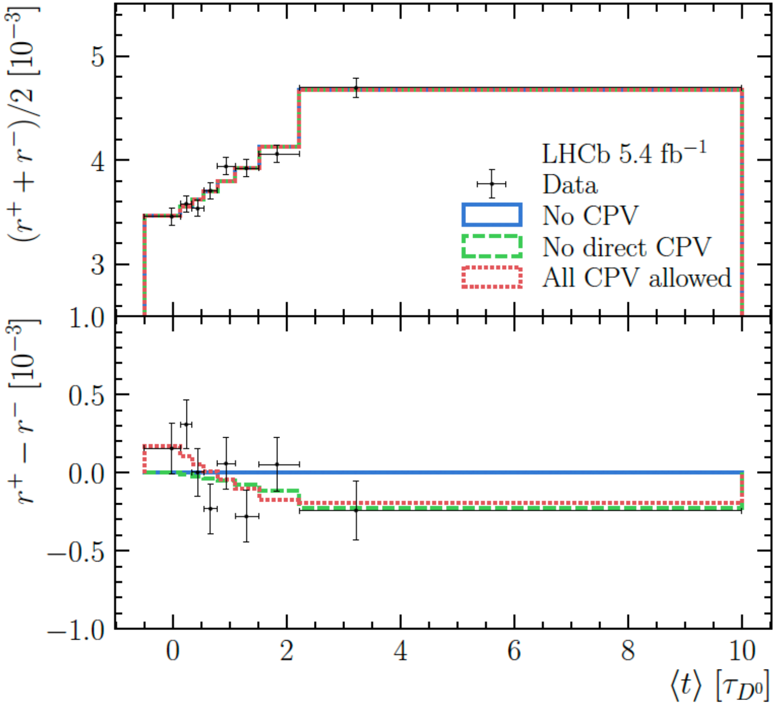


Results of double-tagged analysis

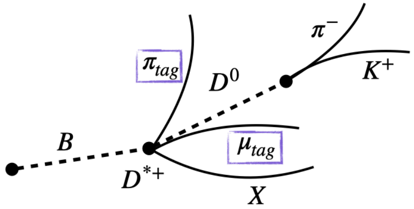
JHEP03(2025)149

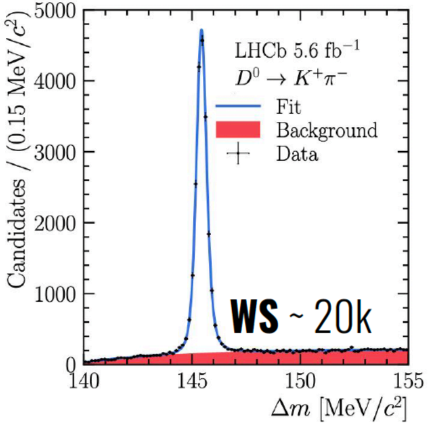
- Much smaller, but much cleaner WS sample and lower decay times

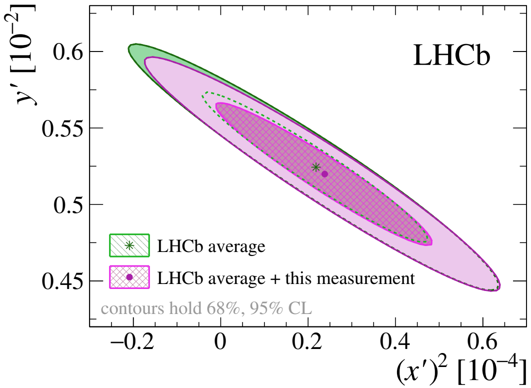
→ Compatible results, resolutions further improved ~5%



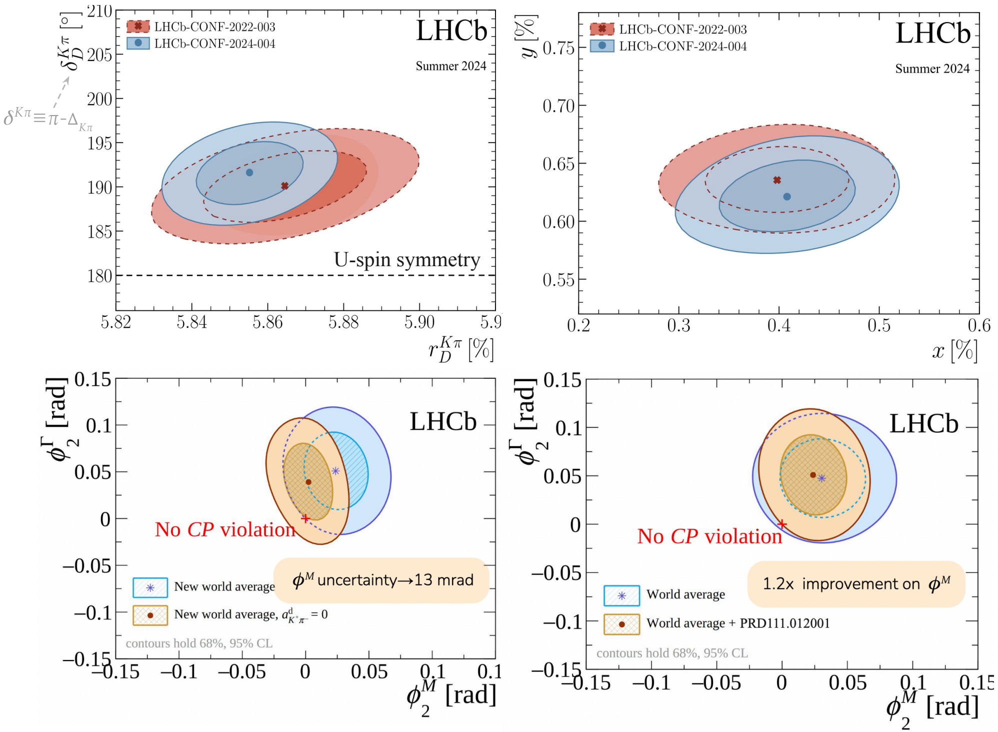
$R_{K\pi}$	$(347.2 \pm 5.8) \times 10^{-5}$
$c_{K\pi}$	$(5.8 \pm 1.6) \times 10^{-3}$
$c'_{K\pi}$	$(0.9 \pm 2.6) \times 10^{-5}$
$A_{K\pi}$	$(2.3 \pm 1.7) \times 10^{-2}$
$\Delta c_{K\pi}$	$(-2.3 \pm 1.6) \times 10^{-3}$
$\Delta c'_{K\pi}$	$(2.1 \pm 2.6) \times 10^{-5}$







Impact on charm mixing/CPV parameters



Overall fit to extract physics parameters from experimental observables [charm-fitter]

Mixing:

$$c_{K\pi} \simeq y_{12}\cos\phi^\Gamma_{K\pi}\cos\delta_{K\pi} - x_{12}\cos\phi^M_{K\pi}\sin\delta_{K\pi}$$

$$c'_{K\pi} \simeq \frac{1}{4}\left(x_{12}^2 + y_{12}^2\right)$$

CPV:

$$\mathcal{A}_{K\pi} = a^d_{WS} + a^d_{RS}$$

$$\Delta c_{K\pi} \simeq x_{12}\phi^M_{K\pi}\cos\delta_{K\pi} + y_{12}\phi^\Gamma_{K\pi}\sin\delta_{K\pi}$$

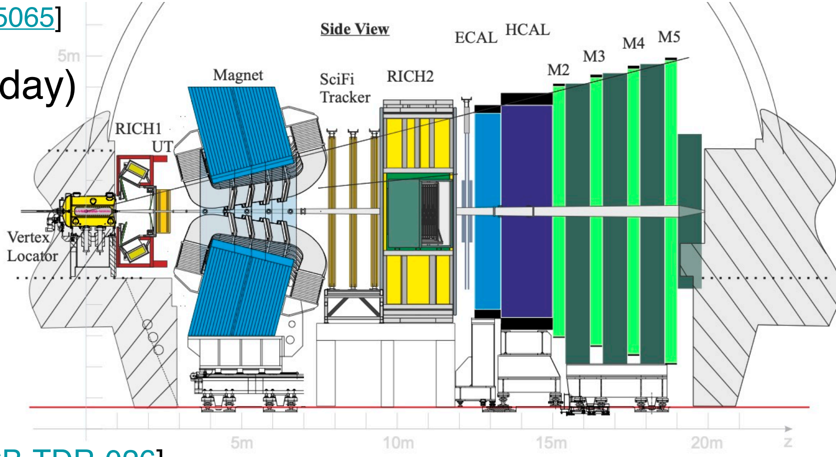
$$\Delta c'_{K\pi} \simeq \frac{1}{2}x_{12}y_{12}\left(\phi^M_{K\pi} - \phi^\Gamma_{K\pi}\right)$$

*Strong phase $\delta_{K\pi}$ takes advantage of external inputs

LHCb-CONF-2024-004 (LHCb internal combination, most precise) PRD 86, 112001 EPJC 82, 1009 https://arxiv.org/abs/2506.07906 https://arxiv.org/abs/2506.07907

The LHCb Upgrades (I & II)

- Facts proved the LHCb approach was right: precision tracking, PID, smart trigger, large B/W
    - But it is necessary to walk that path further to achieve the desirable precision on charm
- LHCb has been fully rebuilt for Run 3 (x5 Lumi) [JINST 19, P05065]
    - All-new tracking/PID (see talk by G. Cavallero later today)
    - Full reconstruction of every LHC collision @30MHz
        - Allows smarter selections using full information
        - See talk by D. Von Bruch yesterday



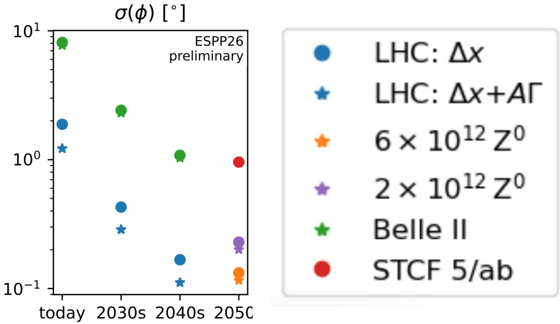
- Even more advances planned for U2 (Run 5, L ~10^{34}) [LHCB-TDR-026]
    - High granularity, hit timing, mostly-silicon tracker, upgraded PID...
    - Largest DAQ dataflow in HEP (~200Tb/s)

LHCb's Long-term aims in charm CPV/mix

Charm mixing&CPV prominently appear in LHCb future program

Input to ESPPU #81
"Discovery potential of LHCb Upgrade II" arXiv:2503.23087

A 10x gain in precision
A long-term physics legacy !
[Flavour WG report, Venice, 23/6/25]



Observable	Current LHCb (up to $9\,\mathrm{fb}^{-1}$)	Upgrade I ($23\,\mathrm{fb}^{-1}$)	Upgrade I ($50\,\mathrm{fb}^{-1}$)	Upgrade II ($300\,\mathrm{fb}^{-1}$)
CKM tests				
γ ($B \to DK$, *etc.*)	$2.8°$	$1.3°$	$0.8°$	$0.3°$
ϕ_s ($B_s^0 \to J/\psi\phi$)	20 mrad	12 mrad	8 mrad	3 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	3%	2%	1%
Charm				
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5}	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare decays				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—	—	—	0.2
$A_{\mathrm{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	0.060	0.043	0.016
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	0.148	0.097	0.038

An ambitious goal. Today a first step towards it

Today's feature:

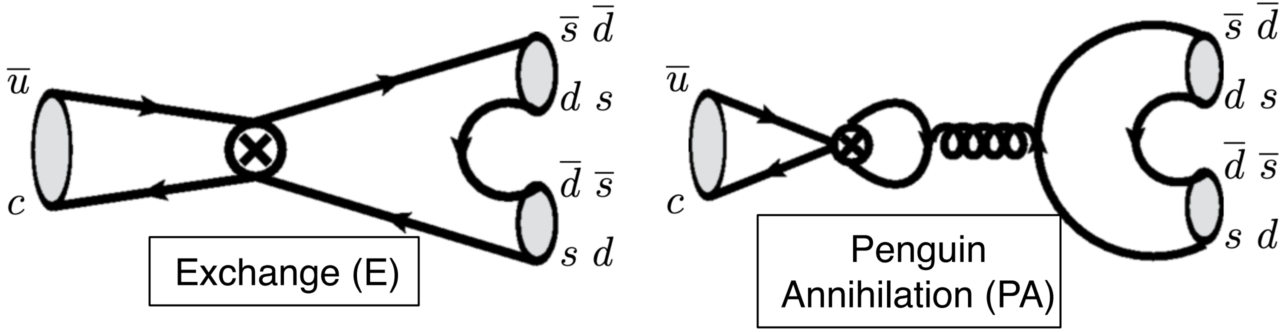
First CPV measurement with the Upgraded LHCb

(first LHCb result with 2024 data)

Paper in preparation: LHCB-PAPER-2025-036

$A_{\mathrm{CP}}(D^0 \to K_S^0 K_S^0)$

- $D^0 \to K_S^0 K_S^0$ is another 2-body decay into pseudo-scalar particles, just as $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$
    - Interesting to look for another possibly non-zero ACP parameter, additional to $\Delta A_{\mathrm{CP}}(K^+K^- - \pi^+\pi^-)$
- Similarity is only on the surface: it is sensitive to a different set of fundamental processes, being dominated by Penguin-Annihilation and Exchange PRD 92 (2015) 054036 PRD 92 (2015) 014004



- Smaller BR (vanishes in SU(3)$_F$ limit) but A_{CP} might be enhanced, potentially up to O(**1%**)
- Conversely, some theory fits to data constrain the E contribution and predict small $A_{\mathrm{CP}} \simeq 0.35 \cdot A_{\mathrm{CP}}(\pi^+\pi^-)$ (PRD 99(2019)113001).

Interesting to see what picture emerges, and how well it fits with SM.

Experimental status of $A_{CP}(D^0 \to K_S^0 K_S^0)$

CLEO: PRD 63, 071101

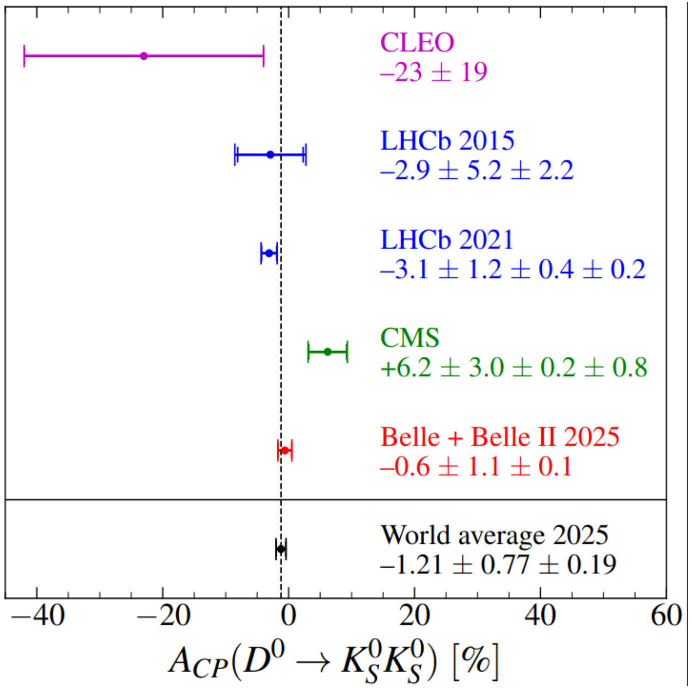
LHCb Run 1 JHEP 10, 055

LHCb Run 2 PRD 104, L031102

CMS with b-parking sample: EPJC s10052-024-13244

Belle + Belle II combined result ArXiv:2504.15881

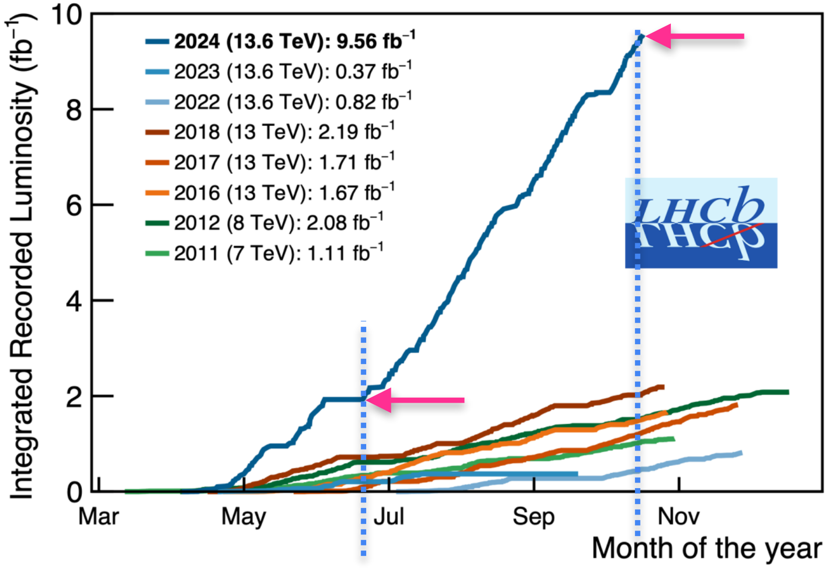
charm-fitter



- WA a bit away from zero, resolution below percent
- Some tension between results (PDG assigns S=2.0)
- Interest in further results

Data sample for the new measurement

- In 2024, LHCb collected more data than in all previous years combined
- Sample used here is 6.2 fb-1 of best quality, all-detector data, final trigger configuration, design luminosity or close to it (L = 2*10^{33}, μ = ~5)
- ~Same lumi of the Run 2 analysis

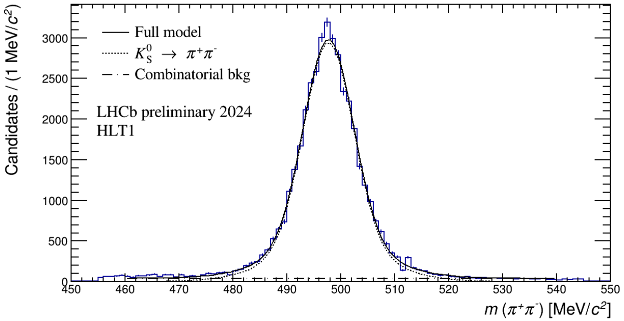


Data block	$\int \mathcal{L} dt$ [fb^{-1}]
1	1.12
2	0.58
3	0.65
4	0.72
5	1.09
6	0.90
7	0.68
8	0.42
Total	6.19

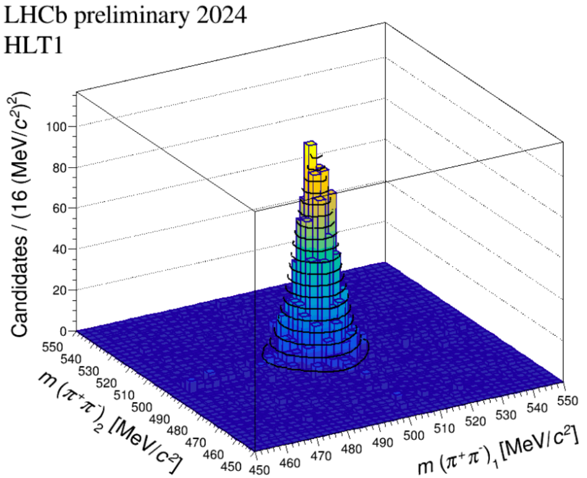
- **Split into 8 subsamples** by running conditions
- Each block analyzed separately
- **A_{CP} results combined at the end**

Trigger selection

- Long-lived particles like K_S^0 are challenging at LHCb
- Evolution of approach:
    - Run1: trigger on CALO energy
    - Run2: 1-track generic trigger after CALO
- **Run 3 (now)**: K_S^0 at very first trigger level (software, no L0)
    - No other LHC experiment does this
    - Requires building all track-pair combinations at 30 MHz
    - Plus, even a Ks-pair trigger ! (not used here)
- Not just more efficiency, but:
    - Get a $K_S^0\pi^+\pi^-$ reference sample from same trigger: *best possible calibration of spurious asymmetries*

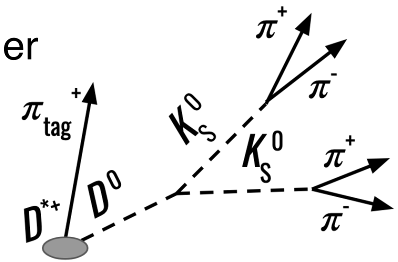


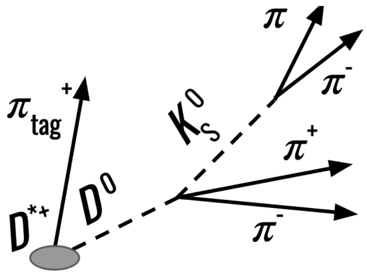
LHCB-FIGURE-2024-013



Methodology of 2024 measurement

- Some ingredients identical to Run-2 analysis [PRD 104, L031102]:
  - Tag D^0 flavor with $D^{*+} \to D^0 \pi^+$ decays
  - Exploit both prompt and secondary candidates as signal
  - 3D fit to Δm and two $m(K_S^0)$ to extract A^{CP} from D^0/anti-D^0 asymmetry
  - Correct for **production+detection** asymmetries by reweighting individual candidates with weights extracted from a calibration mode via a kNN algorithm
  - Split each sample in two bins of purity according to a multivariate classifier
- Novelties of the Run-3 analysis: LHCB-PAPER-2025-036(in preparation)
  - Calibrate with $\boldsymbol{D^0 \to K_S^0 \pi^+ \pi^-}$ instead of $\boldsymbol{D^0 \to K^+ K^-}$
    - same final particles as signal (5 pions),
    - same HLT1 trigger as signal. Closely similar HLT2 trigger.
  - Restrict to 'easiest' categories of events for faster result
    - Only K_S^0 decaying inside VErtex LOcator (VELO) (HLT1 trigger)
    - Only PV-compatible candidates
    - This will be revisited for final Run 3 results with full data sample

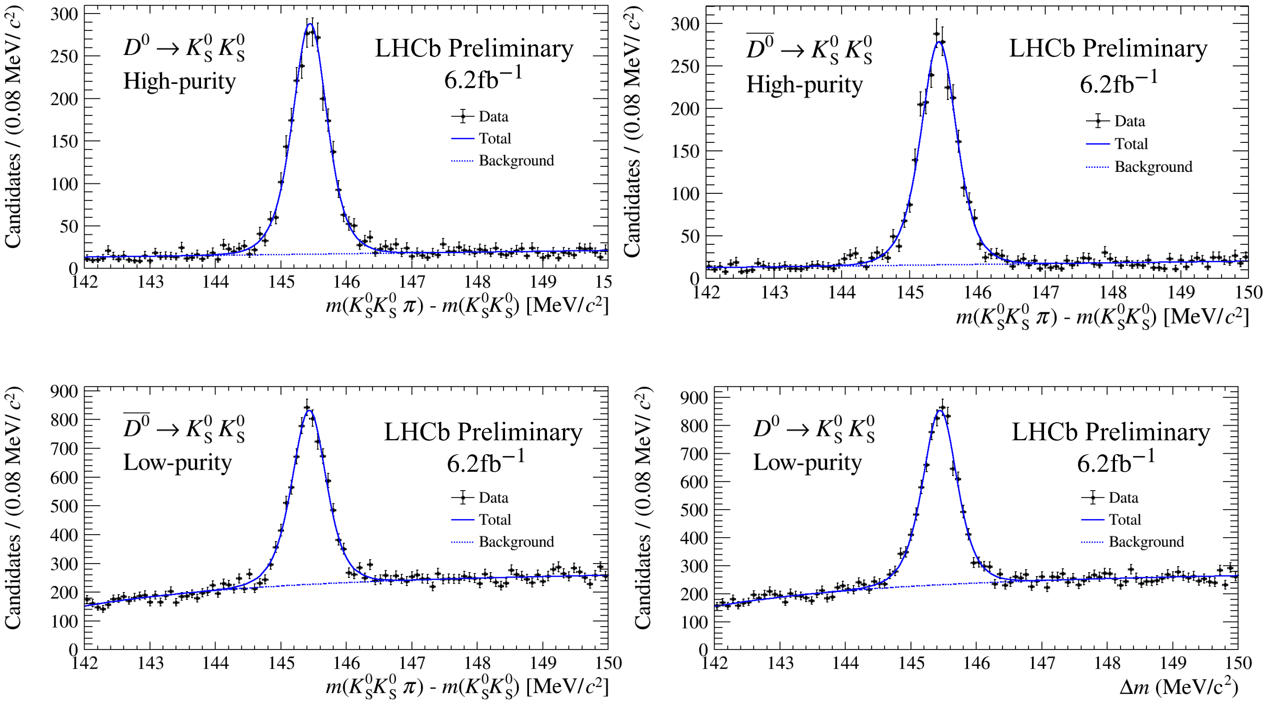




Signals after offline selections

LHCB-PAPER-2025-036
(in preparation)

- Cumulative plots, adding together all data blocks (fitted separately)



- Total signal yield:
  N = **15,676 ± 229**
- Largest existing D*-tag sample
  - LHCb Run2 ~ 8,000
  - Belle ~ 4,900
  - Belle II ~ 2,200
  - CMS ~ 2,000

  (Belle/II also has a 19k non-D* sample, but with much more background)
- LHCb Run2: 5,400 candidates in same category in 6fb-1

→Factor of x3 efficiency gain (effect of the new trigger) ***and*** collected in much shorter time.

Collect decays at a rate ~15x LHCb Run 2

A^{CP} results

LHCB-PAPER-2025-036
(in preparation)

Data block	Yield	$\mathcal{A}^{CP}$ [%]
1	2915 ± 85	0.3 ± 2.4
2	1385 ± 55	-0.3 ± 3.4
3	1639 ± 56	0.8 ± 3.2
4	1534 ± 75	5.5 ± 3.4
5	3149 ± 94	0.0 ± 2.4
6	2544 ± 77	4.6 ± 2.6
7	1599 ± 67	1.7 ± 3.3
8	911 ± 54	5.6 ± 4.3
Total	$\mathbf{15676 \pm 229}$	$\mathbf{1.86 \pm 1.04}$

LHCb Preliminary

- Results for each block, calibrated and averaged over Low Purity and High Purity bins. All compatible.
- Average effect of calibration is +1.35 % shift
  - Corrections decreases χ^2: **12.7** → **9.4** (17 DOF)
    → Confirms it is working properly
- Global average yields the result (statistical error only):

$$A_{CP}(D^0 \to K_S^0 K_S^0) = (1.86 \pm 1.04)\%$$

World's best statistical precision

- Better than Run 2 precision (1.2%) with just few months of Run 3 data ***and*** only one sub-category of events:
  - no Downstream Ks candidates, no PV-incompatible candidates
- Corresponding Run 2 sample had 1.6 % resolution

Systematic uncertainties

Leading systematic effects:

1. Fit model
   - A^{CP} sensitivity to model of signal *pdf* → **0.27%**
2. Cancellation of spurious charge asymmetries
   → Statistical fluctuations of calibration sample → **0.24%**
   → Choice of *k* in kNN-based charge calibration → **0.20%**
3. K^0 material effects contribution to $A^{raw}(D^0 \to K_S^0 \pi^+ \pi^-)$ (negligible)
   → precisely measured in Run 2 detector, expected small
   → remeasured in current $K_S^0 \pi^+ \pi$ sample: **< 0.05%** for Long K_S^0

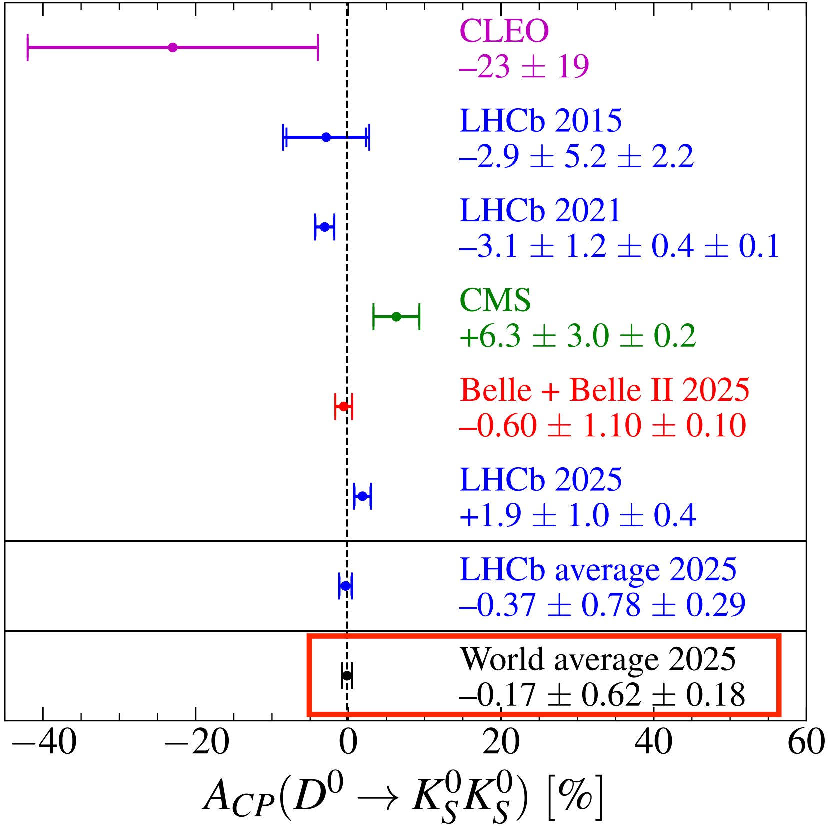
Total combined systematics → **0.41%**

LHCB-PAPER-2025-036
(in preparation)

Final result

$A_{CP}(D^0 \to K_S^0 K_S^0)$ = (1.86±1.04±0.41)%

- Compatible with no CPV
- Compatible with previous WA
- Marginal agreement (~1%) with previous LHCb results (2.9σ from Run 2, that was -2.5σ from zero)
  - Global LHCb average: (-0.37 ± 0.78 ± 0.29)%
- Brings back WA to full agreement with zero CPV
  - And statistical resolution down to **0.62%**
- Expect significant further improvement with complete Run 3 sample (23 fb^{-1} expected)
- Will enter an interesting region of sensitivity



Conclusions

- LHCb the leading laboratory for Charm CPV and Mixing
- Today first Run 3 result: time-integrated $A_{\rm CP}(D^0 \to K_S^0 K_S^0)$
  - Improve on Run 2 result from just year 2024 data
  - Still statistics-dominated
    - Most of systematics is statistical in nature anyway
- This is just the beginning - expect to see:
  - More data
  - More channels
  - More upgrades...

BACKUP

Mixing parameterization

$$i\frac{\partial}{\partial t}\begin{pmatrix} M^0(t) \\ \overline{M}^0(t) \end{pmatrix} = \left[\begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}\right]\begin{pmatrix} M^0(t) \\ \overline{M}^0(t) \end{pmatrix}$$

$$x_{12} \equiv \frac{2|M_{12}|}{\Gamma} \simeq \frac{\Delta m}{\Gamma}, \qquad y_{12} \equiv \frac{|\Gamma_{12}|}{\Gamma} \simeq \frac{\Delta\Gamma}{2\Gamma}$$

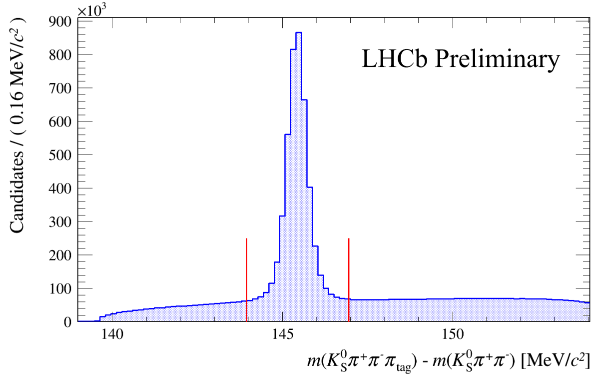
$$\phi_2^M \sim \arg\left(M_{12}\right), \qquad \phi_2^\Gamma \sim \arg\left(\Gamma_{12}\right)$$

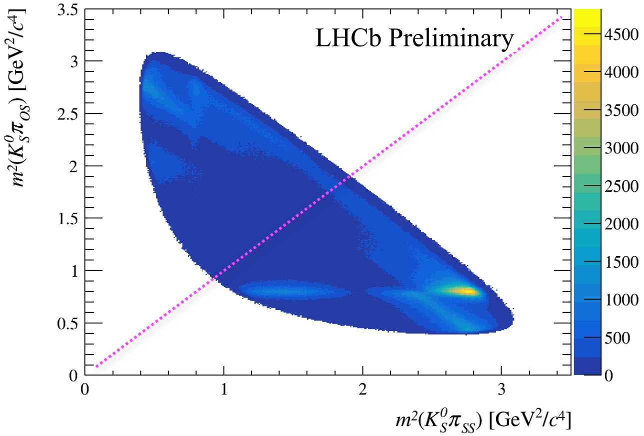
Calibration channel sample

LHCB-PAPER-2025-036
(in preparation)

- Different from $K_S^0\pi^+\pi^-$ sample of other LHCb analyses
- Triggered on the K_S^0
- Dedicated selection without IP/$\chi_{IP}^2(\pi)$ cuts on pions, to preserve similarity to signal sample.

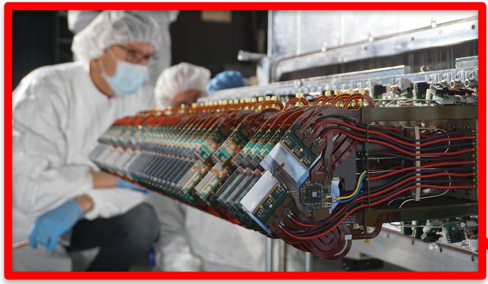
- **Yield ~750** $D^0\rightarrow K_S^0\pi^+\pi^-$/pb^{-1} vs **2.5** $D^0\rightarrow K_S^0 K_S^0$/pb^{-1} **S/B ~ 10**
  → large enough for calibration
- However, $K_S^0\pi^+\pi^-$ has non-trivial Dalitz distribution
  - Pion pair not charge-symmetric
  - Need preliminary re-weight to symmetrize pion pair





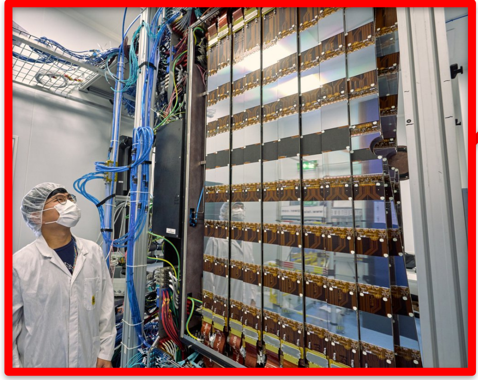
The LHCb Upgrade I

New silicon-pixel (55 × 55 μm) vertex tracker

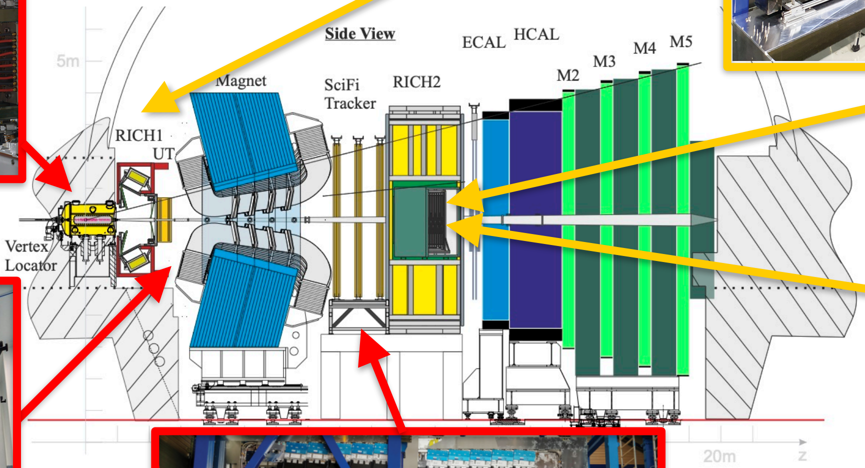


VELO

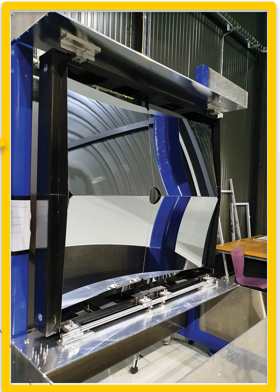
New silicon-strip tracker



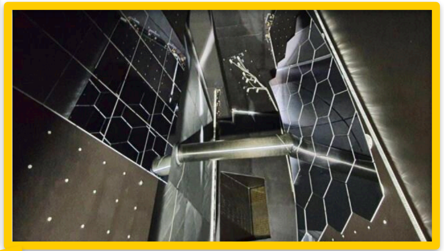
UT



RICH1



New photodetectors & optics



RICH2

New scintillating-fibre tracker

SciFi

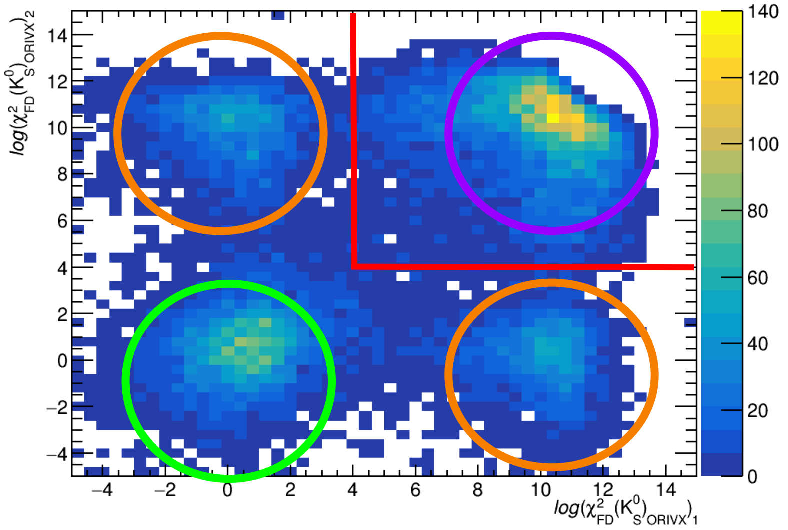
JINST 19 (2024) 05, P05065

Removal of $D^0 \to K_S^0\pi\pi$ background

$D^0 \to K_S^0\pi^+\pi^-$ decay is also a background to signal sample:

- peaks in Δm - similarly as $D^0 \to K_S^0 K_S^0$
- disentangled in the 3D fit

$D^0 \to K_S^0 K_S^0$



Preliminary rejection to improve statistical precision
→ cut on K_S^0 flight-distance significance from D^0 vtx

Cut optimized to minimize σ_S/S during Run 2 analysis
→ **keep Run 2 selection** - no difference expected

Applied selection → $\log(\chi_{FD}^2(K_S^0)_{1,2}) > 4$

$D^0 \to \pi^+\pi^-\pi^+\pi^-$
+ combinatorics

$D^0 \to K_S^0\pi^+\pi^-$