Highlights from the LHCb experiment

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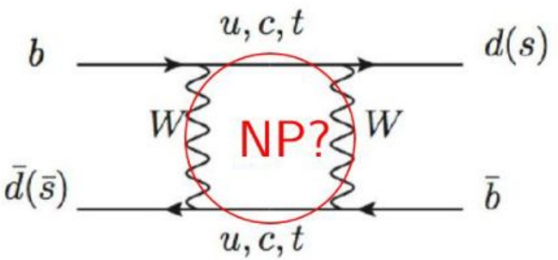
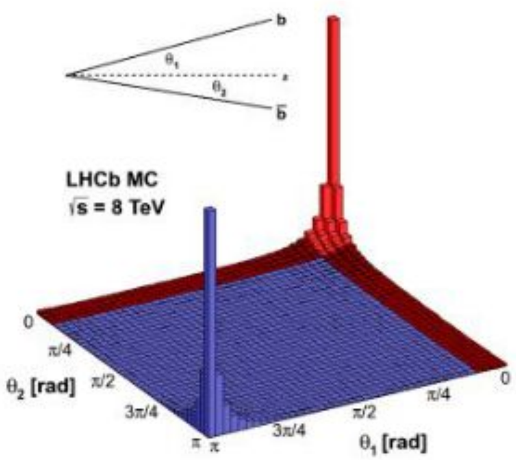
Introduction



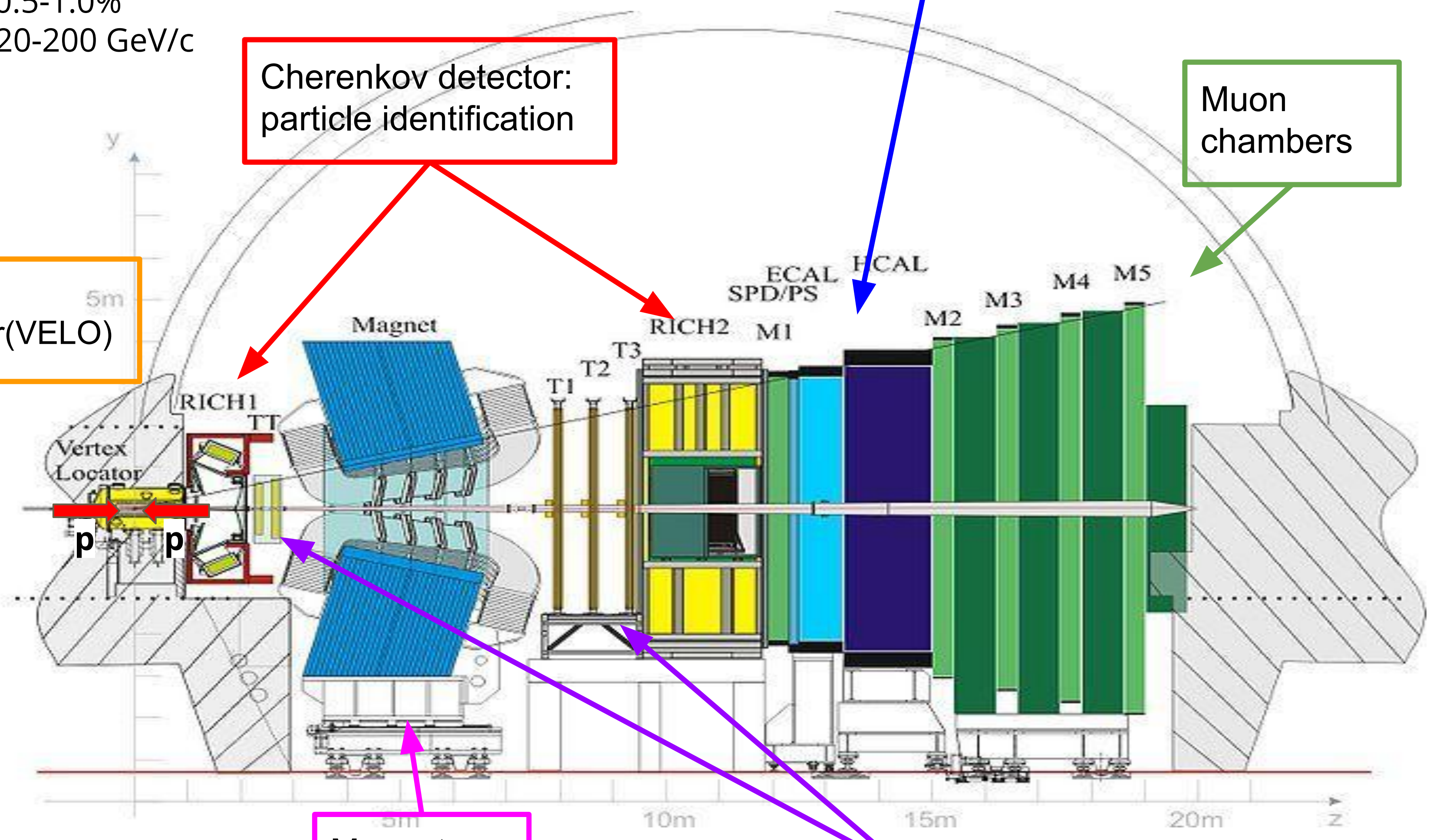
- Why 3 generations of fermions?
- Are there other sources of CPV violation?
- Precision measurements to test SM predictions
- Hadronic machines: large $b\bar{b}$ (and $c\bar{c}$) production cross section
  - $\rightarrow$ LHCb experiment: forward spectrometer with excellent vertexing, tracking and particle identification



The LHCb experiment

JINST 3 S08005 (2008), Int. J. Mod. Phys. A 30 (2015) 1530022

δp/p = 0.5-1.0%
for p = 20-200 GeV/c



Not only a flavour experiment

- LHCb has collected ~3 fb^{-1} of data in Run1 and ~6 fb^{-1} of data in Run2
- Designed to study B mesons decays, but rich physics program!

CP violation & CKM

Lepton universality tests

Hadornic spectroscopy

Rare decays

Dark sector

Fixed target

Heavy ions

Electroweak physics

Not only a flavour experiment

- LHCb has collected ~3 fb^{-1} of data in Run1 and ~6 fb^{-1} of data in Run2
- Designed to study B mesons decays, but rich physics program!

- **This talk:** selected measurements on flavour physics. See also:

  → Alice Biolchini, Lepton flavour universality tests in $b \to s\ell\ell$ decays at LHCb experiment

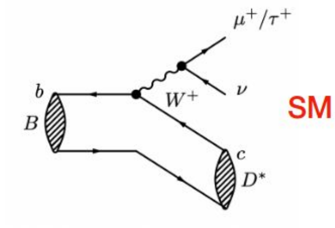
  → Camille Normand, $B_s \to \mu\mu\gamma$ decay in the high-$q2$ region

  → Lisa Fantini, Lepton number and lepton flavour violation searches in B decays at LHCb

Lepton flavour universality tests

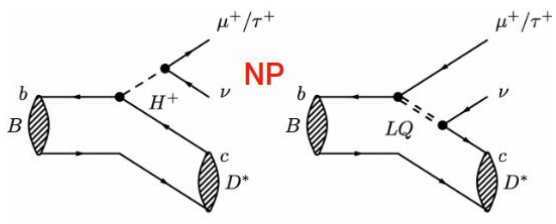
LFU tests in LHCb

- EW couplings to leptons “universal” (the only difference is the mass) in the SM
- Can be tested in
  - b → clν



$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau^+\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\mu^+\nu_\mu)}$$

Predicted with a ~1% precision in the SM

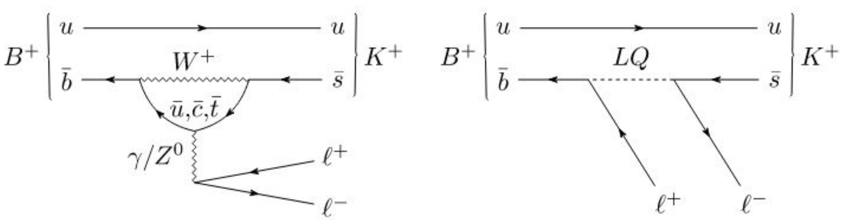


  - b→ sll

→ Covered in [Alice's talk](#) !

Sensitive to NP coupling to EW penguin

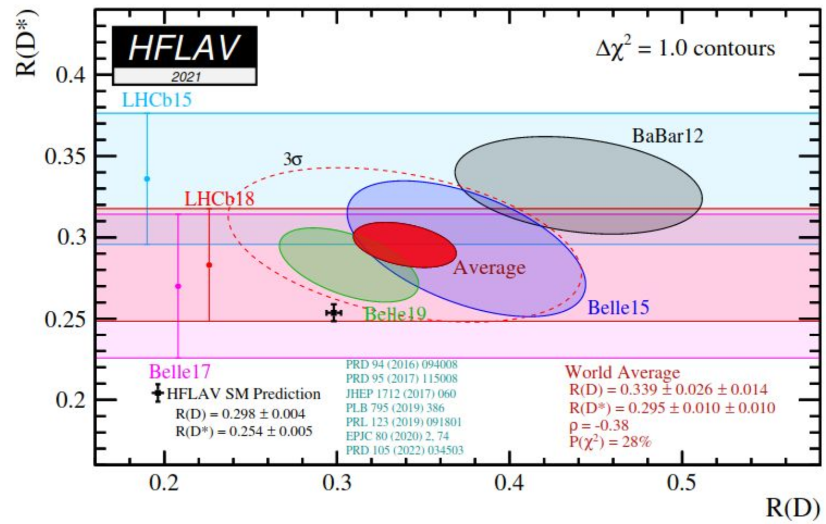
LFU tests theoretically clean



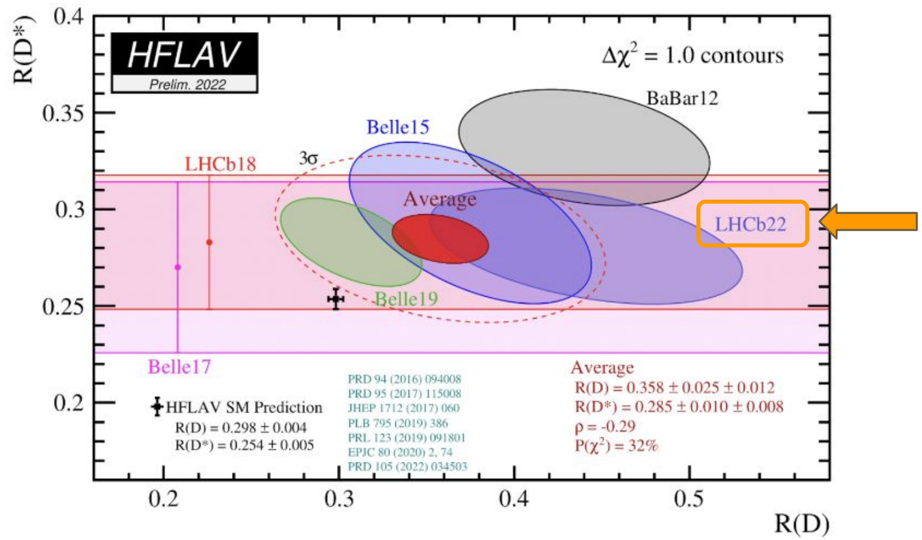
$$R_{\mathrm{H}}\left[q^2_{\mathrm{min}}, q^2_{\mathrm{max}}\right] = \frac{\int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} \mathrm{d}q^2 \frac{\mathrm{d}\Gamma(B\to H\mu^+\mu^-)}{\mathrm{d}q^2}}{\int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} \mathrm{d}q^2 \frac{\mathrm{d}\Gamma(B\to He^+e^-)}{\mathrm{d}q^2}}\ , \quad q^2 = m^2(\ell\ell)$$

$b \to c l \nu$

Until ~ 1 year ago:
longstanding 3.3σ effect



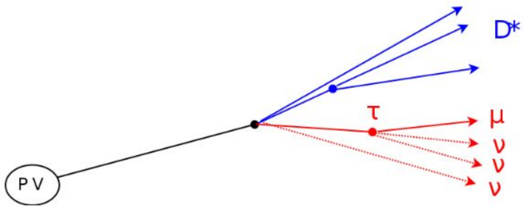
Recent update from LHCb!
→ 3.2σ effect

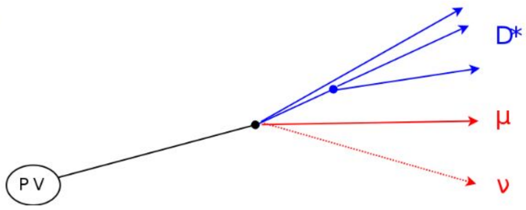


$R(D^{(*)})$

- First joint measurement of R(D) and R(D*) at a hadron collider
  - Run 1 (2011-2012) dataset
- Experimental challenge: neutrinos → no narrow peak to fit

$\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ $\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu$





- Strategy: make 3D template fits to q^2, missing mass and lepton energy distributions

$R(D^{(*)})$

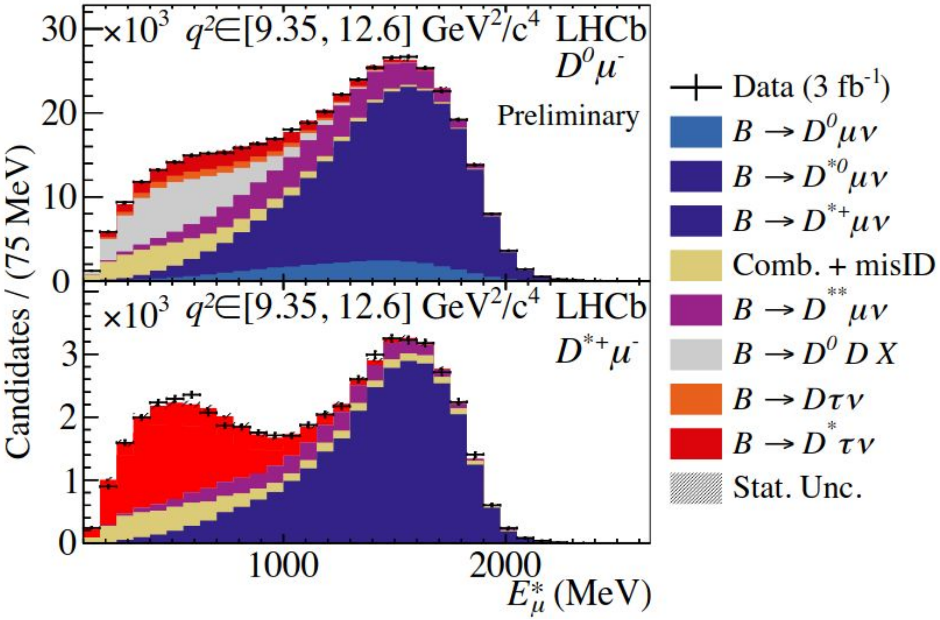
LHCb-PAPER-2022-039
arXiv:2302.02886

- Both precision measurement and inclusive analysis with high statistics
  - Understanding of background fundamental

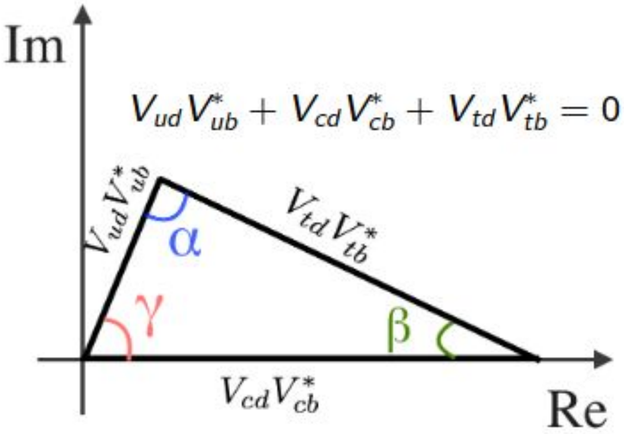
- Final result:

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

- Run 2 measurement ongoing



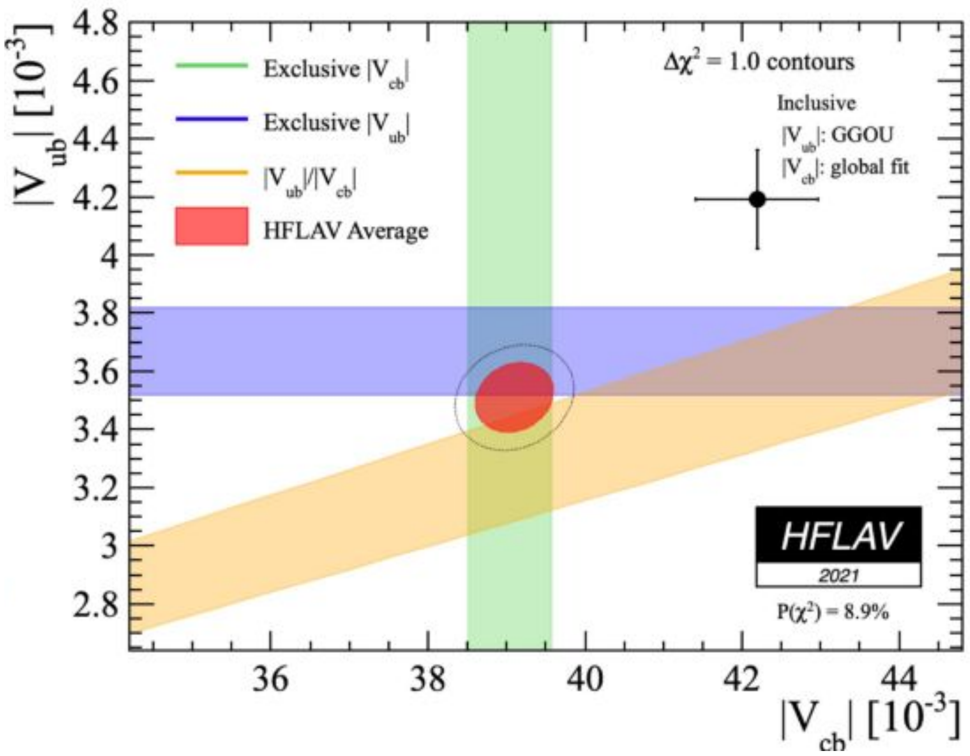
CKM metrology



$|V_{cb}|$ measurement

- Long-standings tension (~3σ) between inclusive and exclusive determinations

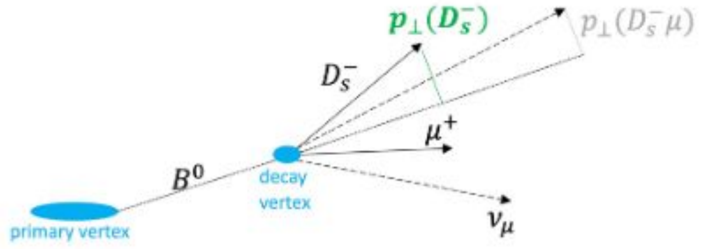
- At LHCb
  - $|V_{ub}| / |V_{cb}|$ using Λ^0_b decays
  - B^0_s system



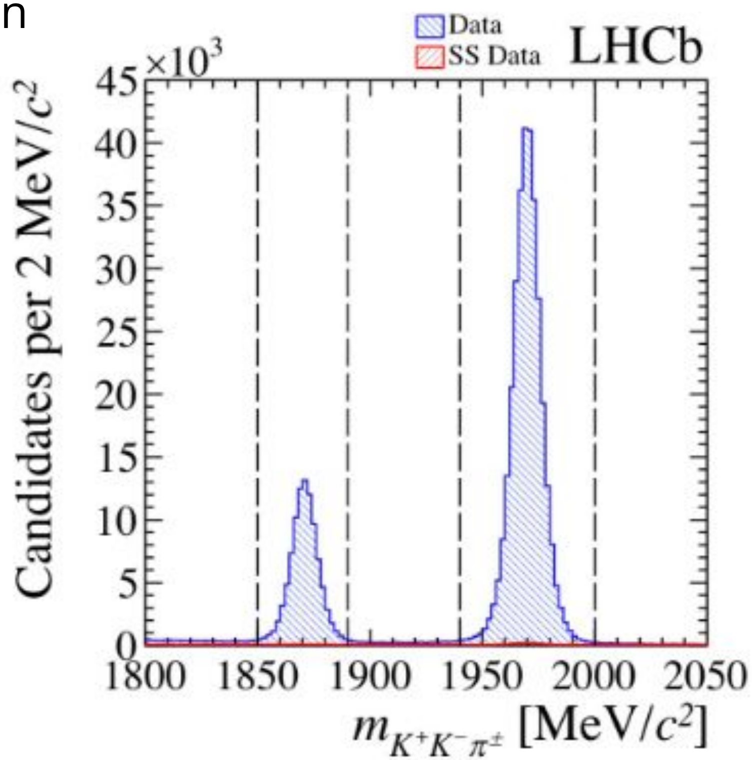
$|V_{cb}|$ via $B^0_s \to D^*_s \mu\nu$

PRD 101(2020) 072004

- 2011-2012 data, $B^0 \to D^*\mu\nu$ used as normalization
- Unreconstructed neutrino → 2D fit to
  - $p_\perp$, correlated with hadron recoil (preserves FF information)



  - $$m_{corr} \equiv \sqrt{m^2(D_s^-\mu^+) + p_\perp^2(D_s^-\mu^+)} + p_\perp(D_s^-\mu^+)$$



- → simultaneous extraction of $|V_{cb}|$ and FF

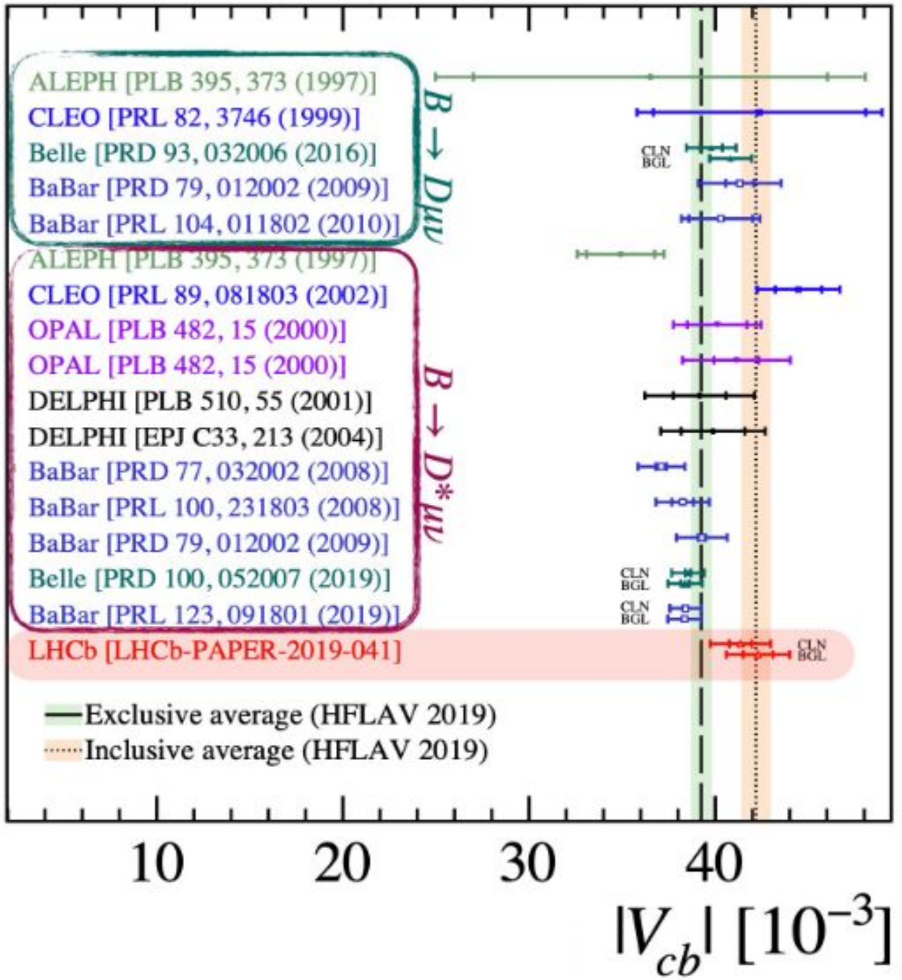
$|V_{cb}|$ via $B^0_s \to D^*_s \mu\nu$

PRD 101(2020) 072004

- Final result:

$$|V_{cb}|_{\mathrm{CLN}} = (41.6 \pm 0.6(\mathrm{stat}) \pm 0.9(\mathrm{syst}) \pm 1.2(\mathrm{ext})) \times 10^{-3}$$

$$|V_{cb}|_{\mathrm{BGL}} = (42.3 \pm 0.8(\mathrm{stat}) \pm 0.9(\mathrm{syst}) \pm 1.2(\mathrm{ext})) \times 10^{-3}$$

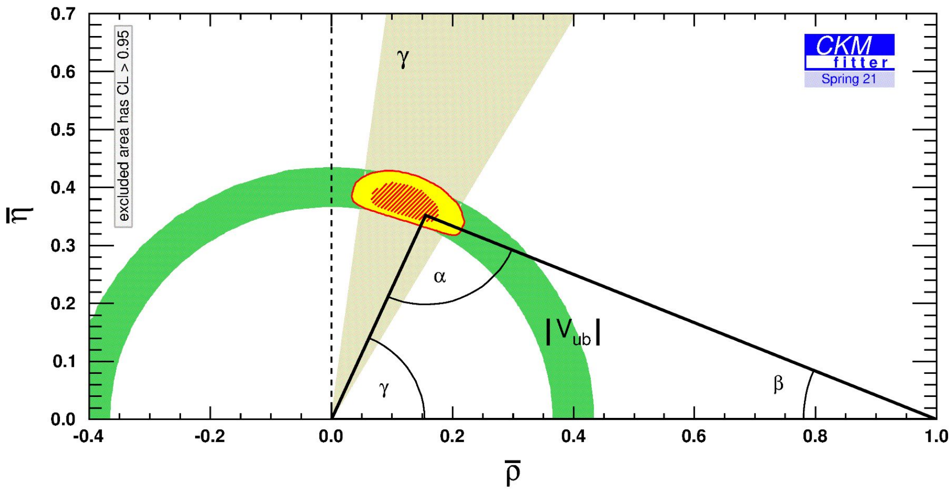


- Limited by external inputs → will benefit from LHCb Run 3 measurement on fs/fd and any update on $K^+K^-\pi^+$ resonance from Belle II

Measurement of γ angle

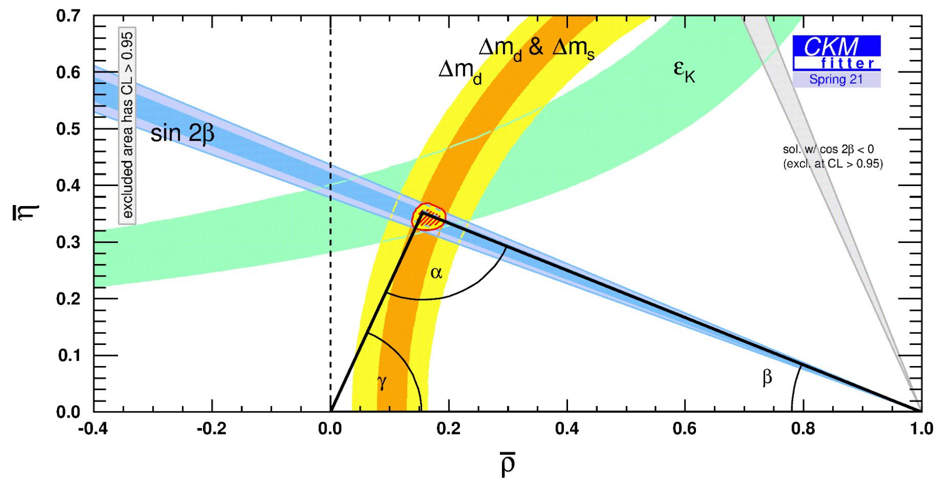
$$\gamma = -\arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

- Accessible studying processes involving only tree-level diagrams
  - Negligible theoretical uncertainty ($<10^{-7}$) JHEP 1401 (2014) 051
  - Comparison between direct and indirect determination, obtained using unitarity relation → sensitive to NP



$$\gamma = (66.2^{+3.3}_{-3.5})^\circ$$

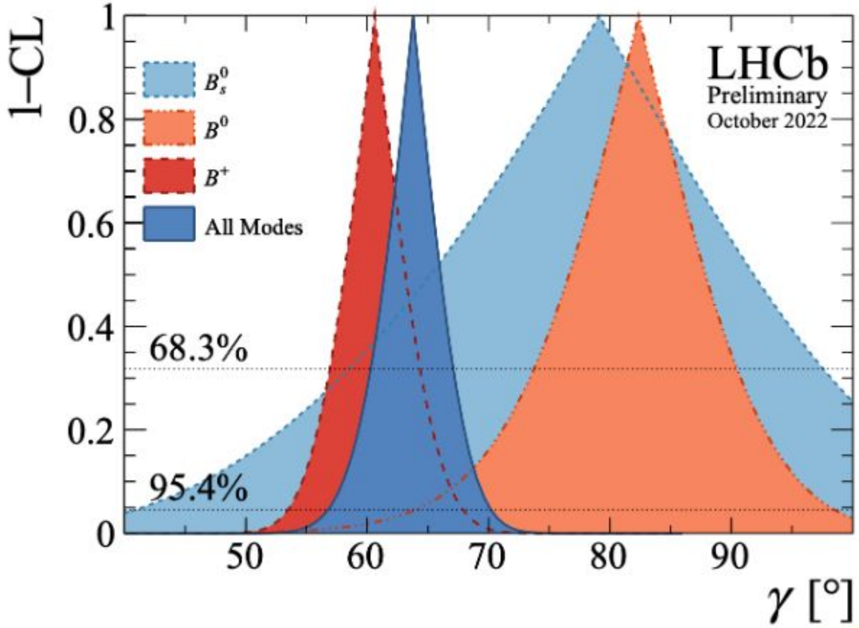
From HFLAV

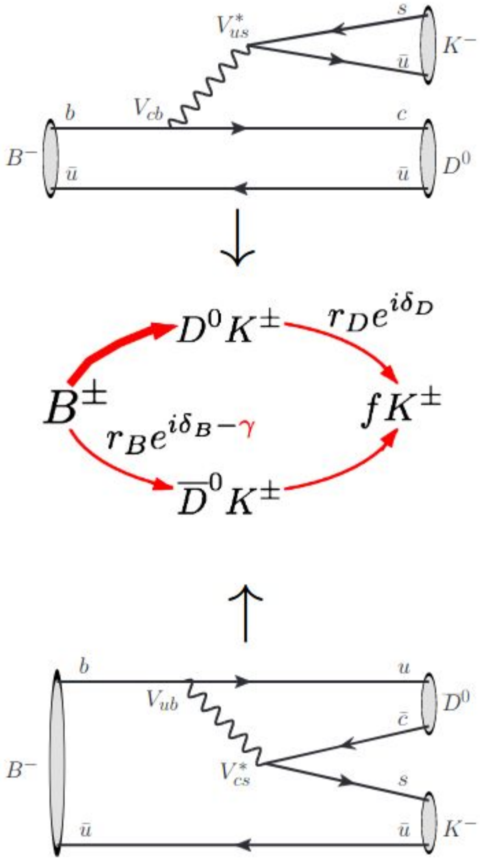


$$\gamma = (65.5^{+1.1}_{-2.7})^\circ$$

Measurement of γ angle

- Interference between b→cūs and b→ uc̄s transitions
- → occurs when D^0 and $\overline{D}^0$ decay to the same final state
  - ➢ CP eigenstates, e.g. $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$
  - ➢ CF or DCS decays, e.g. $D^0 \to K\pi$
  - ➢ self-conjugated 3-body final states,e.g. $D^0 \to K_S^0\pi^+\pi^-$



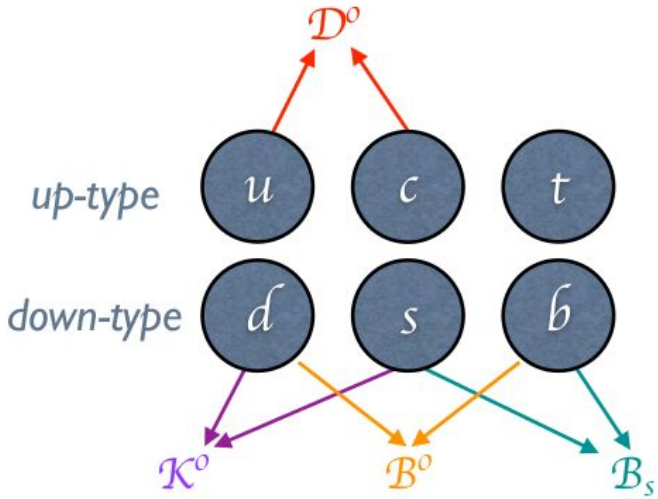


LHCb-CONF-2022-003

CPV in charm

The charm quark

- Charm transitions are a unique portal for obtaining a novel access to flavor dynamics
  - complementarity with K^0 and $B^0_{(S)}$
  - expected CPV in charm $\lesssim 10^{-3} \rightarrow$ difficult to observe it experimentally



- Theoretical predictions challenging:
  - non-perturbative QCD regime (mass *c*-mesons O(2 GeV))
  - $\rightarrow$ large uncertainties

First observation of CPV in charm

PRL 122 (2019) 211803

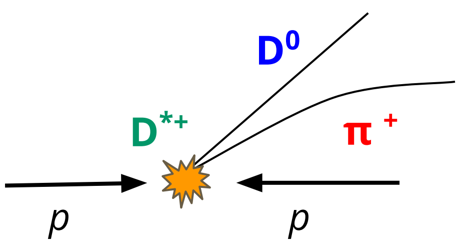
- Difference in CP asymmetries between $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$
  - Need to distinguish between D^0 and $\overline{D}^0$

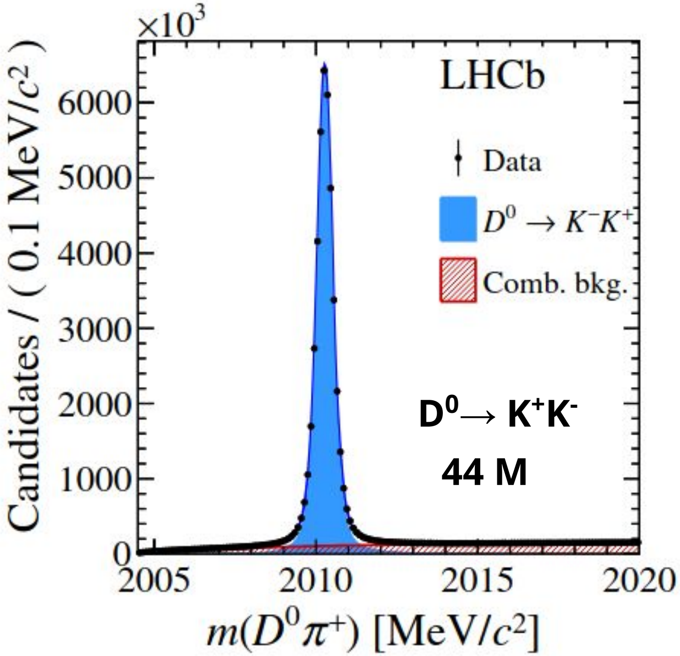
$$\mathcal{A}^{raw} \equiv \frac{N_{D^0} - N_{\bar{D}^0}}{N_{D^0} + N_{\bar{D}^0}}$$

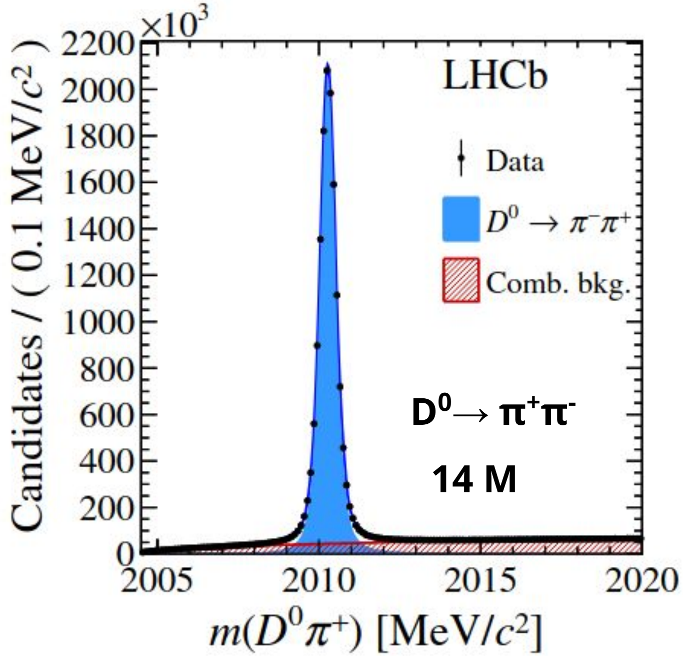
$$\mathcal{A}^{CP}(f) = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$

$$\mathcal{A}^{raw} \approx \mathcal{A}^{CP} + \mathcal{A}^{prod} + \mathcal{A}^{det}$$

$D^{*+} \to D^0 \pi^+$





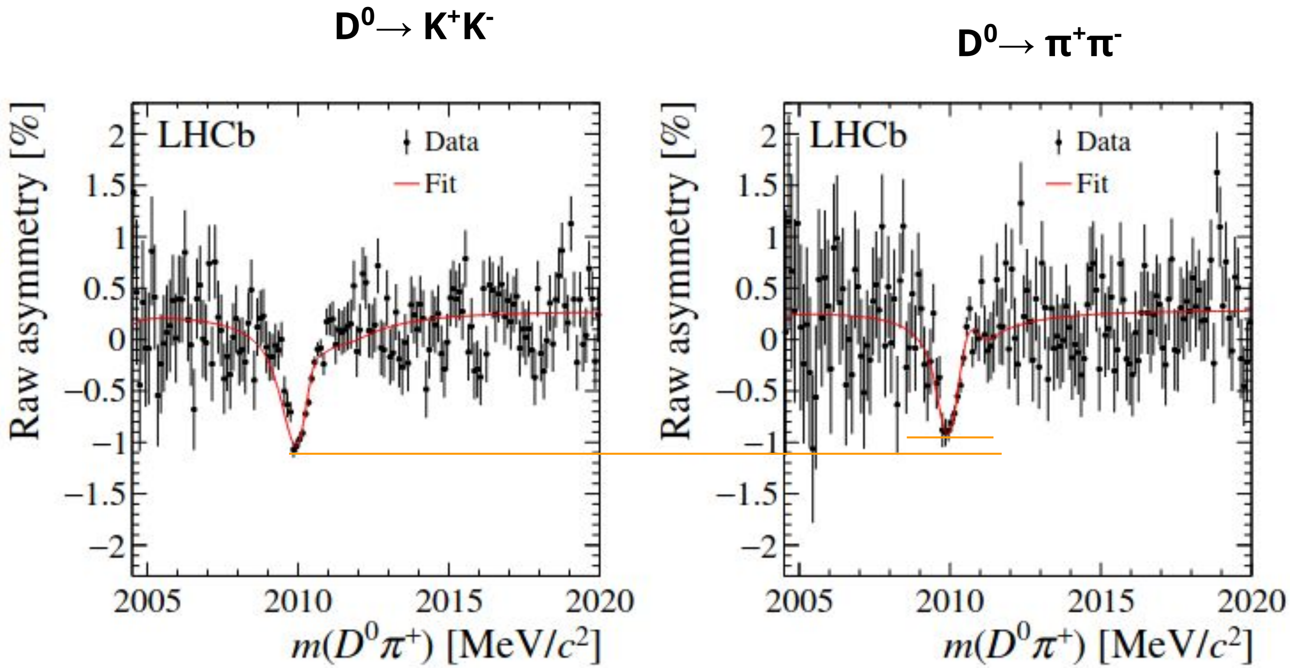


First observation of CPV in charm

PRL 122 (2019) 211803

$\Delta A^{CP} = (-15.4 \pm 2.9) \times 10^{-4}$

5.3 σ from zero

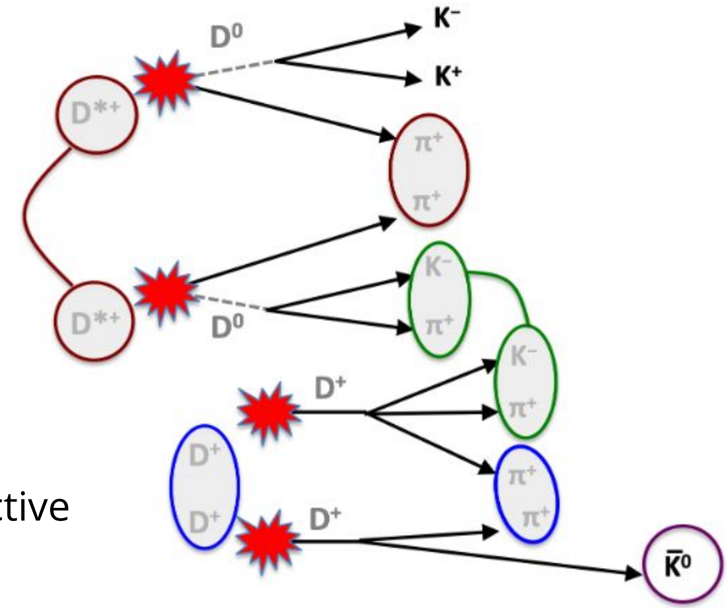


- SM or not?
- Large samples needed
- → LHCb: **10^6 $c\bar{c}$ pairs per second** in acceptance (Run 2)

$A^{CP}(D^0 \to K^+K^-)$

LHCb-PAPER-2022-024
arXiv:2209.03179

- New in Run 2: two independent ways to cancel nuisance asymmetries
  - $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D^+ \to \overline{K}^0\pi^+$
  - $D^0 \to K^-\pi^+$, $D_s^+ \to \Phi\pi^+$, $D_s^+ \to \overline{K}^0K^+$
  - ~40% improvement of σ_{stat}



- Main systematic uncertainties
  - Kinematic reweighting → reduces also effective yield
  - Knowledge of detector material → need accurate model in simulation and/or new data-driven approaches

A^{CP} $(D^0 \to K^+K^-)$

LHCb-PAPER-2022-024
arXiv:2209.03179

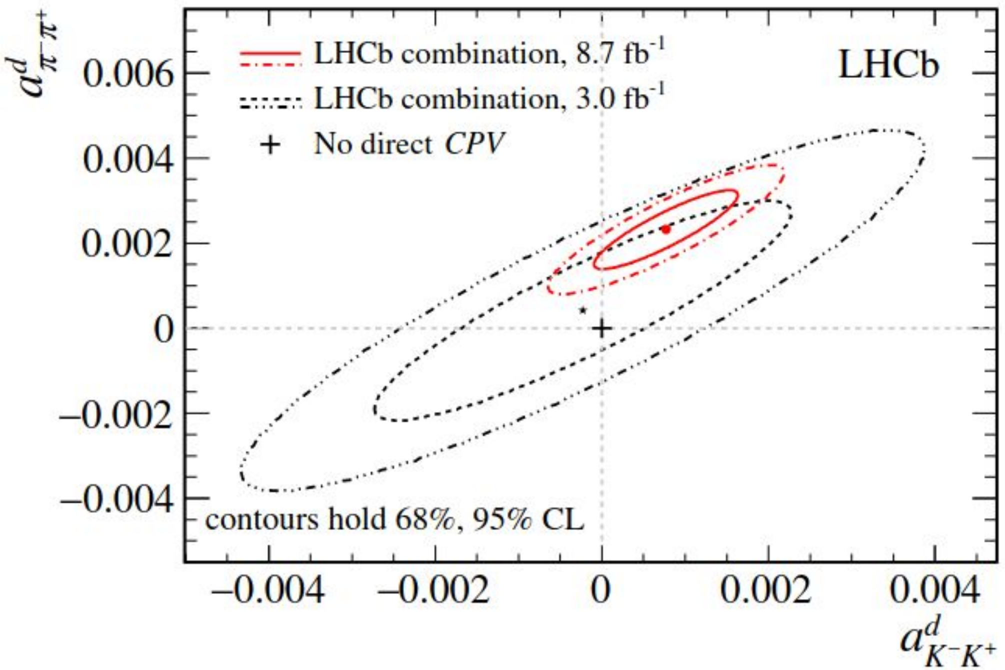
$A^{CP}(K^+K^-) = [6.8 \pm 5.4\ (stat) \pm 1.6\ (syst)] \times 10^{-4}$

CPV in decay

$A^{CP}(K^+K^-) = a^d_{KK} + \langle t \rangle_{KK}/\tau_{D0}\, \Delta Y$

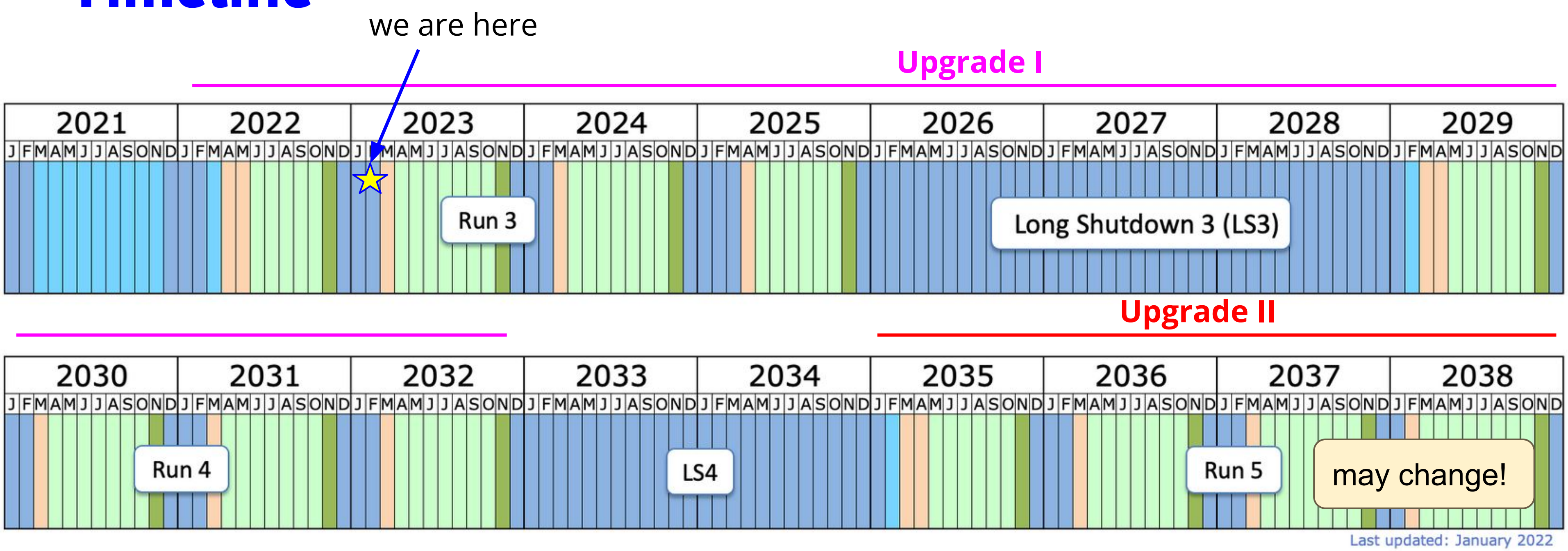
mixing-induced CPV

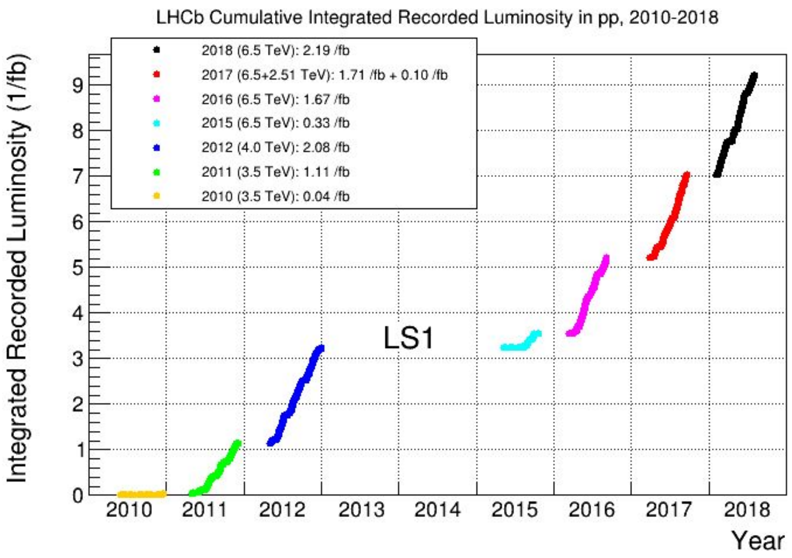
→ $\mathbf{a^d_{KK}} = (7.7 \pm 5.7) \times 10^{-4}$ $\mathbf{a^d_{\pi\pi}} = (23.2 \pm 6.1) \times 10^{-4}$ **3.8σ from 0**



Looking at the future

Timeline

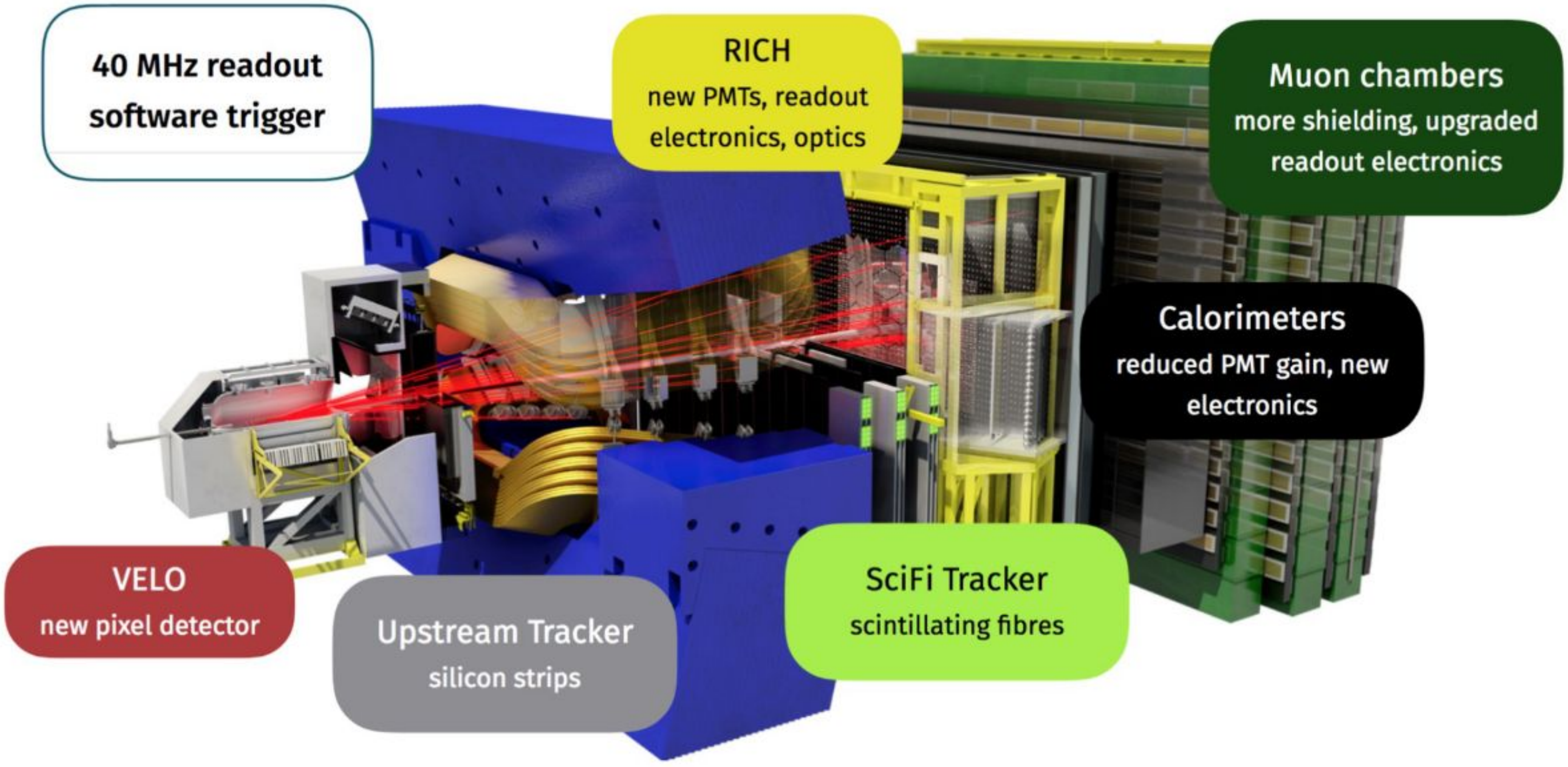




- Run 1+2
  - Integrated luminosity 9 fb^{-1}
- Upgrade I
  - Integrated luminosity ~41 fb^{-1}
- Upgrade II
  - Integrated luminosity ~250 fb^{-1}

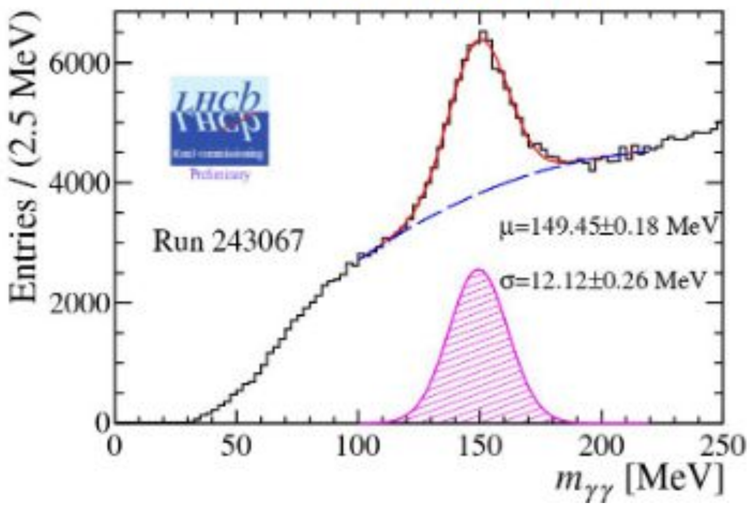
LHCb experiment in Run 3

- 5x increase in instantaneous luminosity
  - From ~1 PV per event, to ~ 5 PVs per event

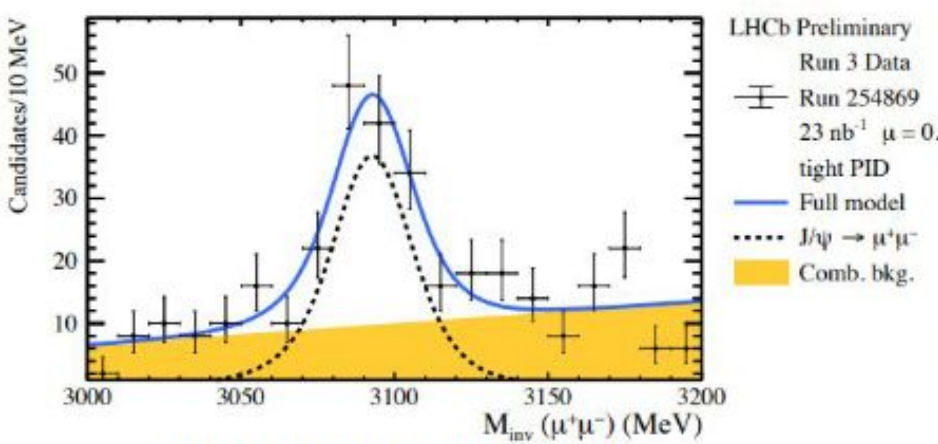


First mass peaks

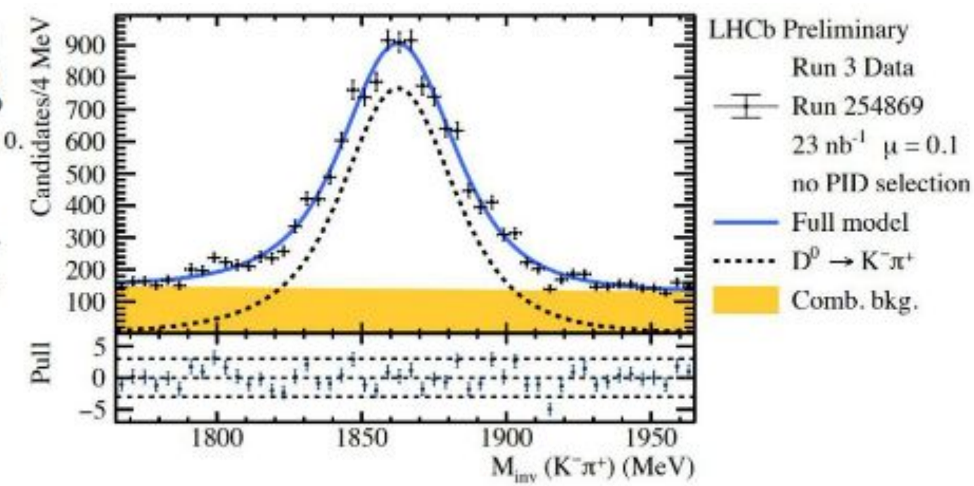
LHCb-FIGURE-2022-019



- Currently working hard on understanding new detector and improving calibration and alignment



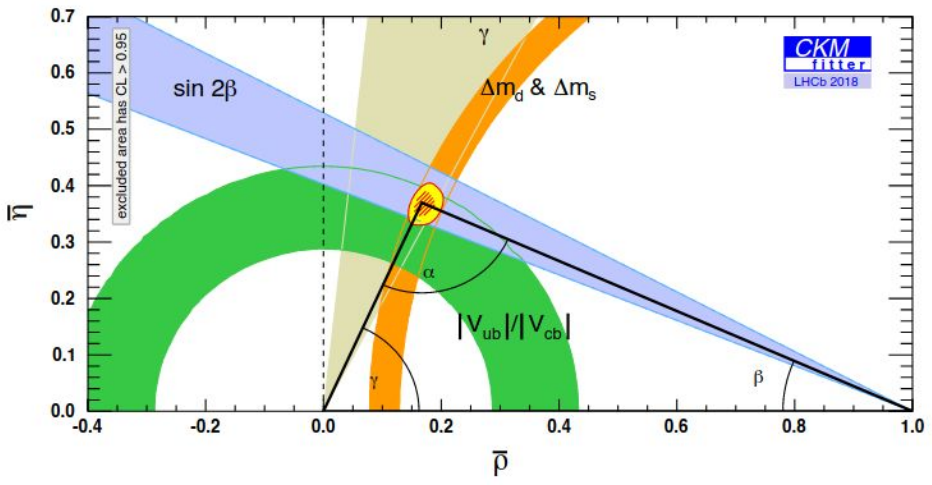
LHCb-FIGURE-2022-034

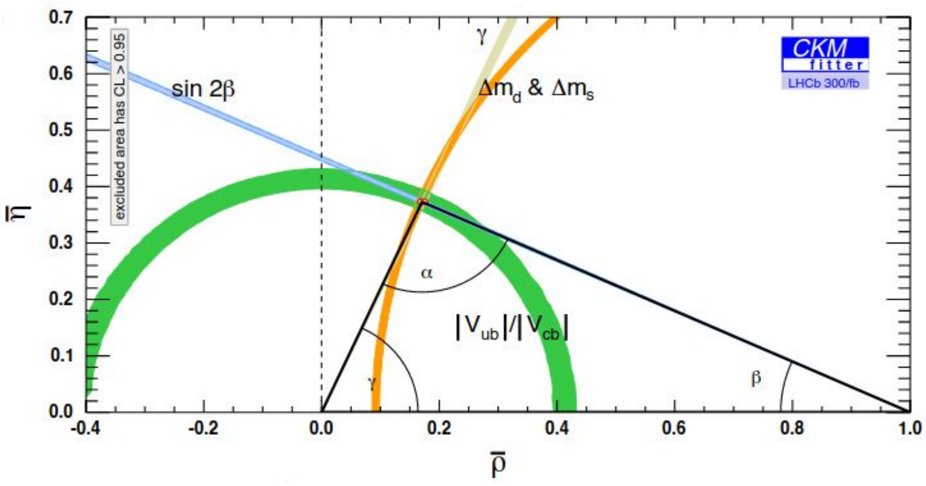


LHCb Upgrade II

LHCb-TDR-023

- Pile-up ~40, 200 Tb/s data produced
- To keep same performance, timing needed in some sub-detectors
  - R&D ongoing on new technologies





Final remarks

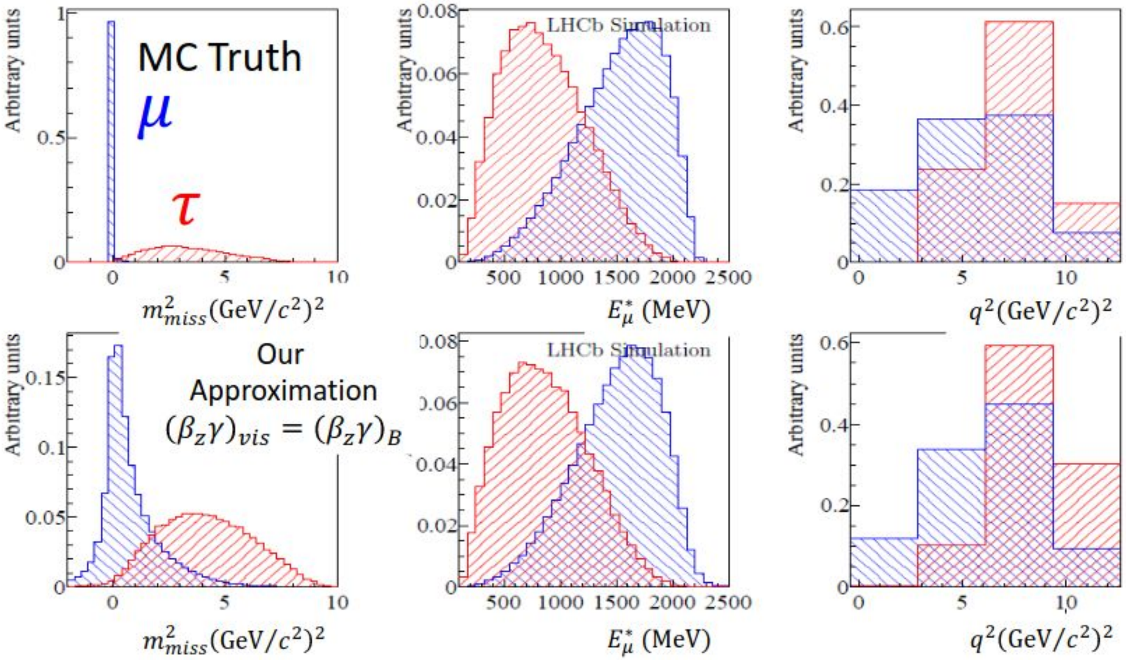
- LHCb is an ideal lab for measurements in flavour sector
  - Presented a selection of world leading results
  - Not covered today, but LHCb showed capabilities that go well beyond its design (e.g. heavy ions, EW physics)
- Now focusing on Run 3 to acquire a larger dataset
- Started R&D towards an even more capable detector

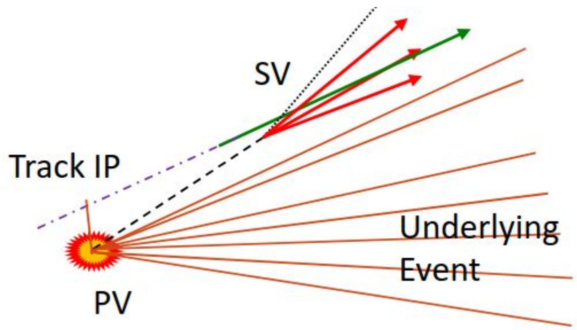
Backup slides

$R(D^{(*)})$

LHCb-PAPER-2022-039

❖ To solve for full B momentum: approximation + knowledge of PV-SV direction





Time-integrated CPV: methodology

- Difference of decay rate between two CP conjugate states

$$\mathcal{A}^{CP}(f) = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$

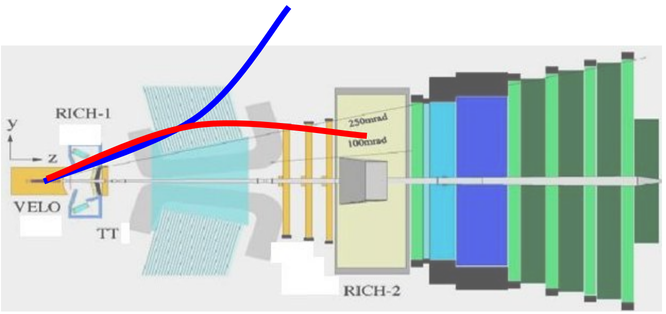
- Quantity measured

$$\mathcal{A}^{raw} \equiv \frac{N_D - N_{\bar{D}}}{N_D + N_{\bar{D}}}$$

Production asymmetry: initial state pp is not CP symmetric

$$\mathcal{A}^{raw} \approx \mathcal{A}^{CP} + \mathcal{A}^{prod} + \mathcal{A}^{det}$$

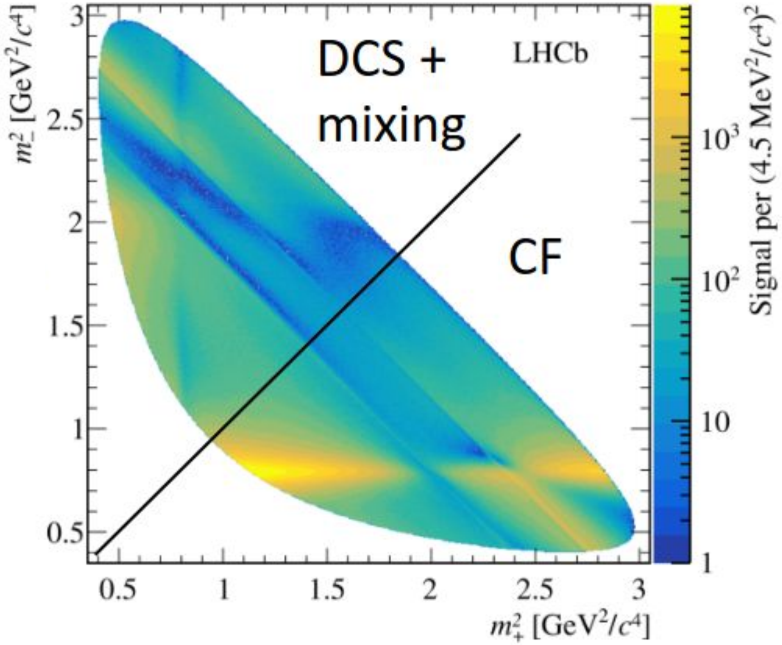
Asymmetric detector acceptance + material interaction different for particles/antiparticles

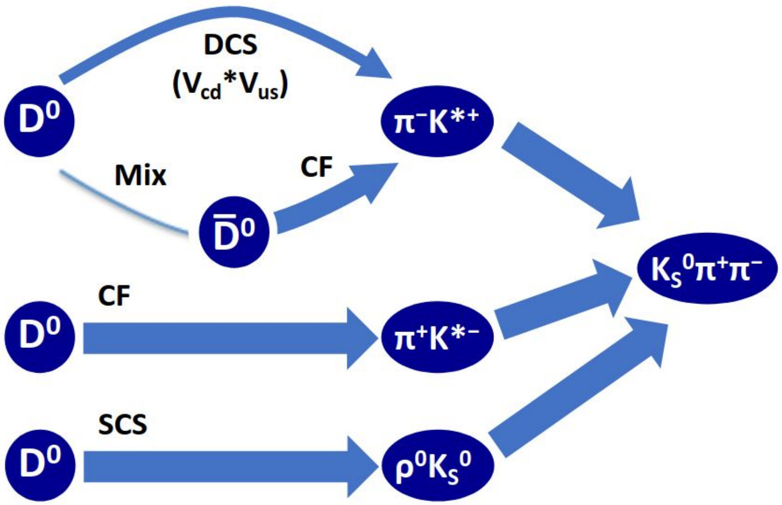


Mixing (and mixing-induced CPV) in $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

- Can directly measure alle four mixing and CPV parameters: $x=\Delta m/\Gamma$, $y=\Delta\Gamma/2\Gamma$, q/p, Φ
- Requires time and phase-space dependent analysis
- Model-independent “bin-flip” method
  - Strong phases constrained from CLEO and BESIII

PRL 127(2021)111801





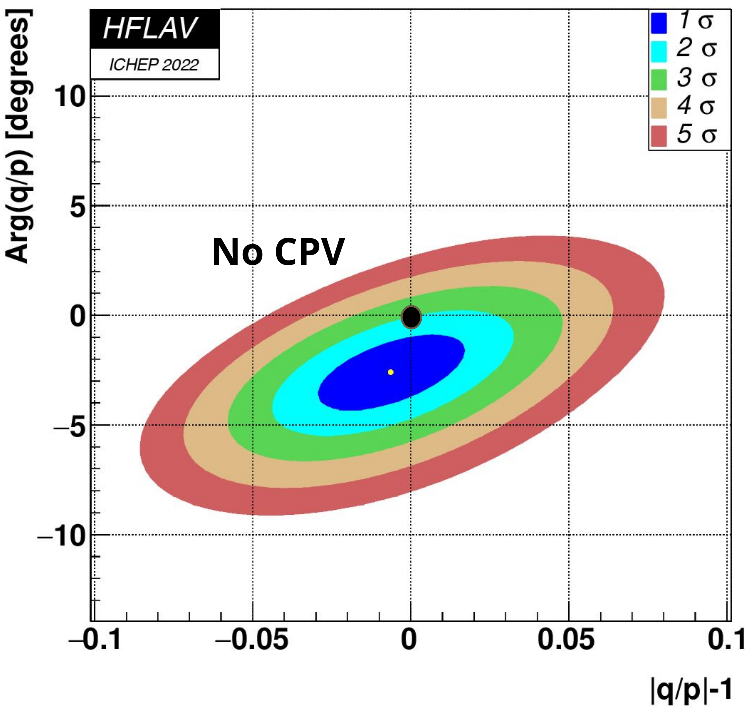
$\sigma_{stat} \sim 1.5\sigma_{syst}$

$x_{CP} = (3.97 \pm 0.46 \pm 0.29) \times 10^{-3}$

$y_{CP} = (4.59 \pm 1.20 \pm 0.85) \times 10^{-3}$

Prospects

Current status
(average on all available measurements)



Future prospects (only $D^0 \to K_S^0\pi^+\pi^-$)

Sample (lumi $\mathcal{L}$)	Tag	$\sigma(\lvert q/p\rvert)$	$\sigma(\phi)$
Run 1–3 (23 fb^{-1})	SL	0.036	2.5°
	Prompt	0.017	0.77°
Run 1–4 (50 fb^{-1})	SL	0.024	1.7°
	Prompt	0.011	0.48°
Run 1–5 (300 fb^{-1})	SL	0.009	0.69°
	Prompt	0.004	0.18°

Physics case for an LHCb Upgrade II