Measurements of CPV and mixing in charm decays

Rencontres de Physique de la Vallée d'Aoste

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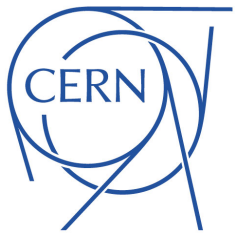
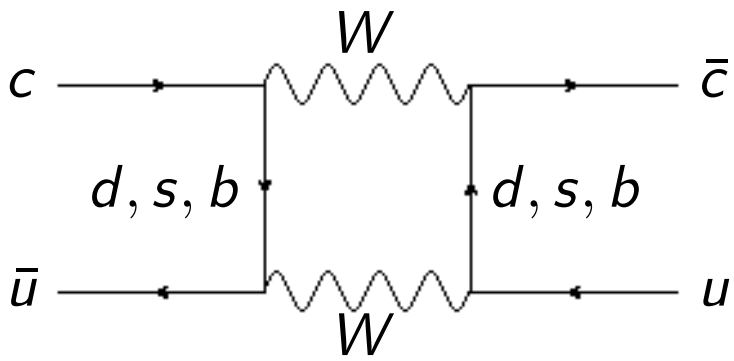


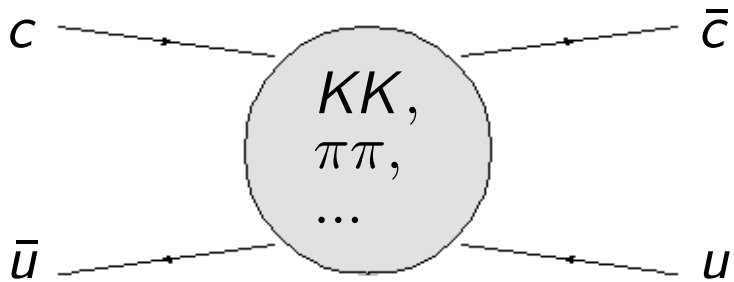
Outline

1. Introduction
2. Measurement of A_Γ in $D^0 \to hh$
3. Search for CPV in $D^0 \to \pi^-\pi^+\pi^0$
4. Conclusions

Why study charm physics?

- Up-type quark: unique probe of NP in the flavour sector, complementary to studies in K and B systems
- Precision CKM physics in the B sectors needs input from charm
- Small mixing and CPV in the SM due to GIM mechanism and CKM suppression





- Long-distance contributions are non-negligible, precise theoretical predictions are difficult, charm is more a discovery tool (but lattice QCD may one day help?)

Neutral D mesons

Produced as flavour D^0 and $\bar{D}^0$ eigenstates, decay as mass eigenstates D_1 and D_2

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

$$\left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}$$

$$|D_1\rangle = p\,|D^0\rangle + q\,|\bar{D}^0\rangle$$
$$|D_2\rangle = p\,|D^0\rangle - q\,|\bar{D}^0\rangle$$

$$|q|^2 + |p|^2 = 1$$

Mixing occurs if $\Delta M = M_1 - M_2 \neq 0$ or $\Delta\Gamma = \Gamma_1 - \Gamma_2 \neq 0$

Mixing parameters

$$x = \frac{\Delta M}{\Gamma}, \quad y = \frac{\Delta\Gamma}{2\Gamma} \qquad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

INDIRECT CPV

DIRECT CPV
Different decay amplitudes for D^0 and $\bar{D}^0$

$$A_f = \langle f|H|D^0\rangle \quad \bar{A}_{\bar{f}} = \langle \bar{f}|H|\bar{D}^0\rangle \quad \left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1$$

CPV IN MIXING
Different mixing rates $D^0 \to \bar{D}^0$ and $\bar{D}^0 \to D^0$

$$\left|\frac{q}{p}\right| \neq 1$$

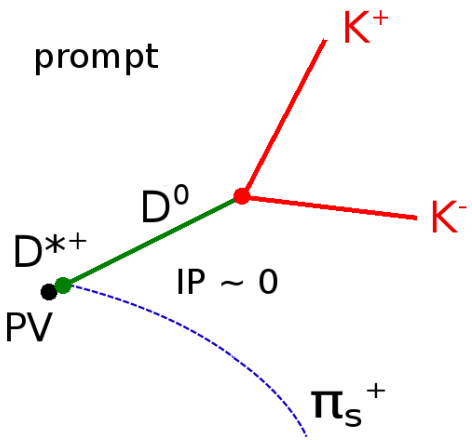
CPV IN INTERFERENCE
between mixing and decay

$$\phi = \arg\left(\frac{q\bar{A}_f}{pA_f}\right)$$

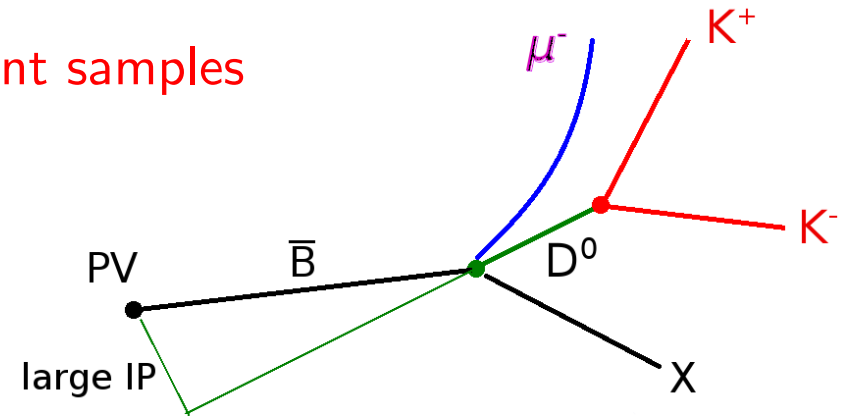
Precision on q/p and ϕ is driven by the knowledge of x and y

Charm physics at LHCb

- Unprecedented charm yields at LHC produced world best measurements:
  - Mixing and CPV in $D^0 \to K\pi$ [PRL 111 (2013) 251801]
  - Direct CPV with ΔA_{CP} [JHEP 07 (2014) 041, LHCb-CONF-2013-003]
  - Indirect CPV in A_Γ [PRL 112 (2014) 041801] (only 2011 data!)
  - CP violation searches in multibody decays
    [PLB 726 (2013) 623, PLB 728 (2014) 585, JHEP 10 (2014) 005 ...]
- Still statistically dominated in core measurements
- Experimentally we can tag D flavour at production:

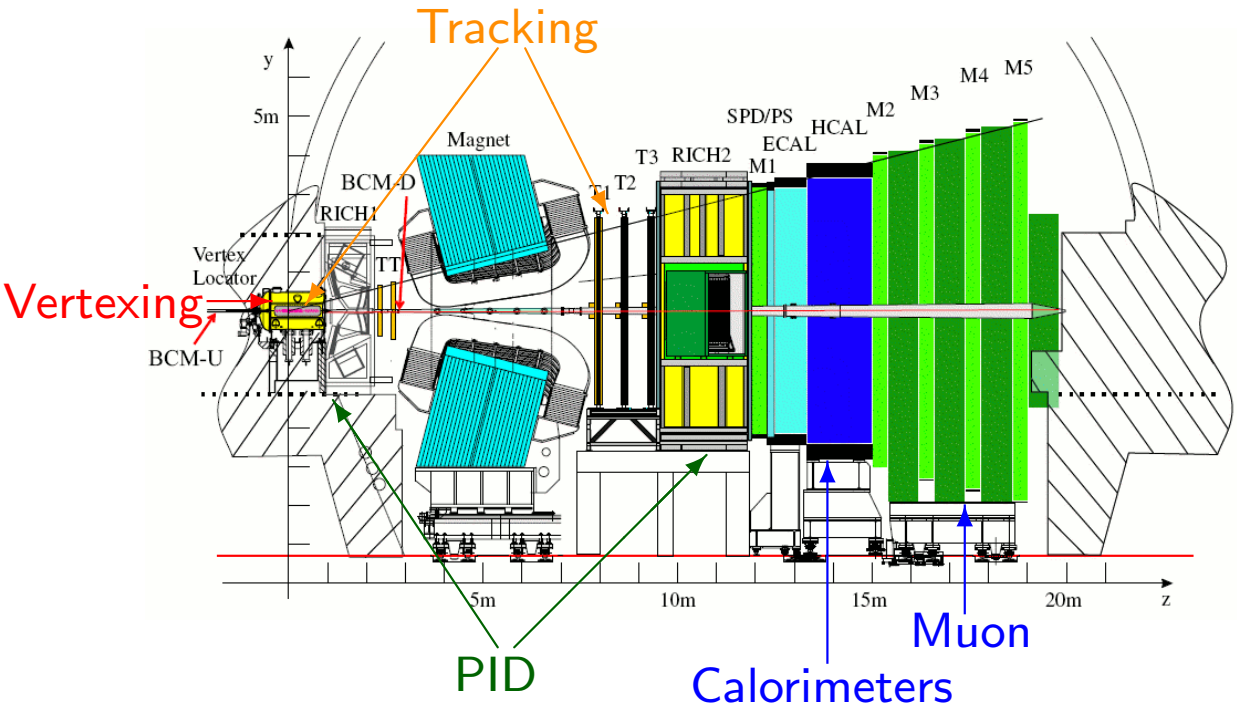


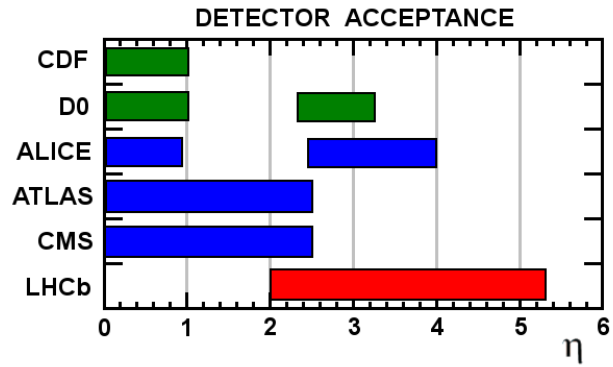
Independent samples



Current LHCb detector [JINST 3 (2008) S080005]

LHCb proved itself to be a forward general purpose detector at the LHC:





- Performance:
  - $\Delta p/p = 0.35\% - 0.55\%$
  - Mass resolution$= 10 - 25\,\mathrm{MeV/c^2}$
  - Impact parameter resolution: $20\,\mu\mathrm{m}$ for high-p_T tracks
  - ECAL $\sigma(E)/E = 10\%(E/\mathrm{GeV})^{-1/2} \oplus 1\%$
  - Excellent particle ID thanks with RICH detectors (2-100 GeV/c^2)

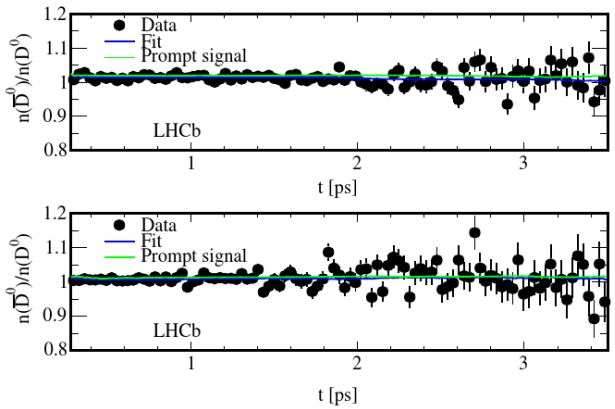
Measurement of A_Γ in $D^0 \to hh$ [PRL 112 (2014) 041801]

- Asymmetry in the effective lifetime between D^0 and $\bar{D}^0$

$$A_\Gamma = \frac{\tau^{eff}_{\bar{D}^0} - \tau^{eff}_{D^0}}{\tau^{eff}_{\bar{D}^0} + \tau^{eff}_{D^0}} \approx \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y \cos\phi - \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x \sin\phi$$

- Almost clean measurement of indirect CPV
- World best determination from LHCb using prompt sample with $1\,\mathrm{fb}^{-1}$

$$R(t) \approx \frac{N_{\bar{D}^0}}{N_{D^0}} \left(1 + \frac{2A_\Gamma}{\tau_{KK}} t\right) \frac{1 - e^{-\Delta t/\tau_{D^0}}}{1 - e^{-\Delta t/\tau_{\bar{D}^0}}}$$

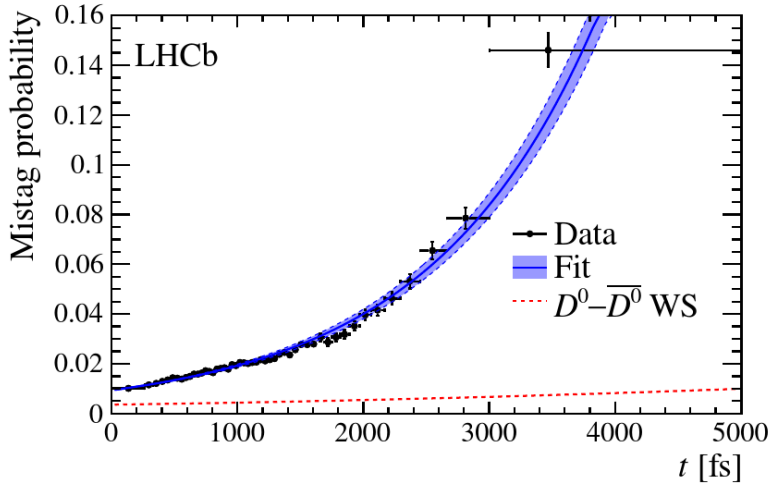


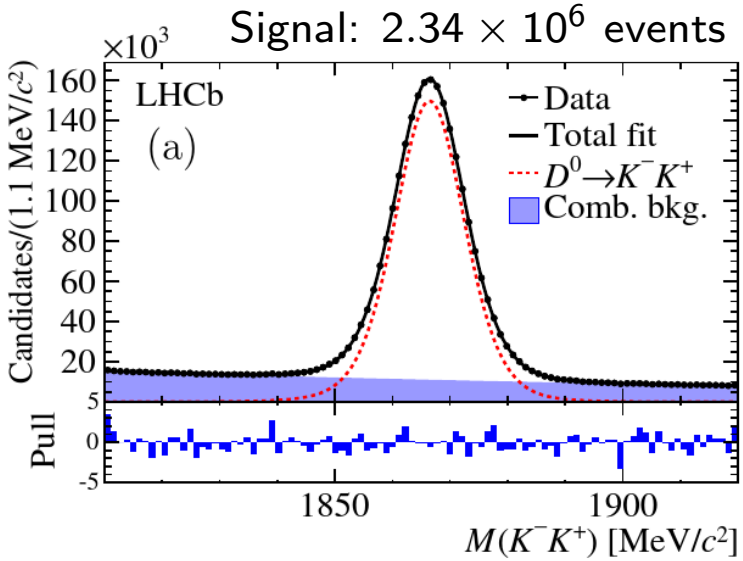
$$A_\Gamma(KK) = (-0.035 \pm 0.062_{stat} \pm 0.012_{syst})\%$$

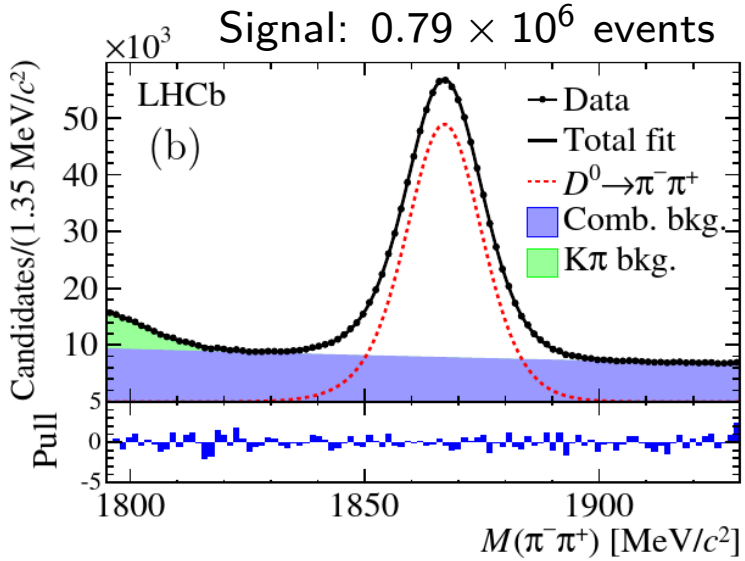
$$A_\Gamma(\pi\pi) = (0.033 \pm 0.106_{stat} \pm 0.014_{syst})\%$$

Measurement of A_Γ in $D^0 \to hh$ [arXiv:1501.06777 , sub. to JHEP]

- Latest LHCb measurement using D^0 from semi-leptonic B decays
- Full Run1 dataset, $3\,\mathrm{fb}^{-1}$
- Mistag asymmetry dominant systematic, $D^0 \to K^-\pi^+$ used as control channel







Measurement of A_Γ in $D^0 \to hh$ [arXiv:1501.06777 , sub. to JHEP]

- Fit the time evolution of the asymmetry

$$A_{CP}(t) \approx A_0 - A_\Gamma \frac{t}{\tau}$$

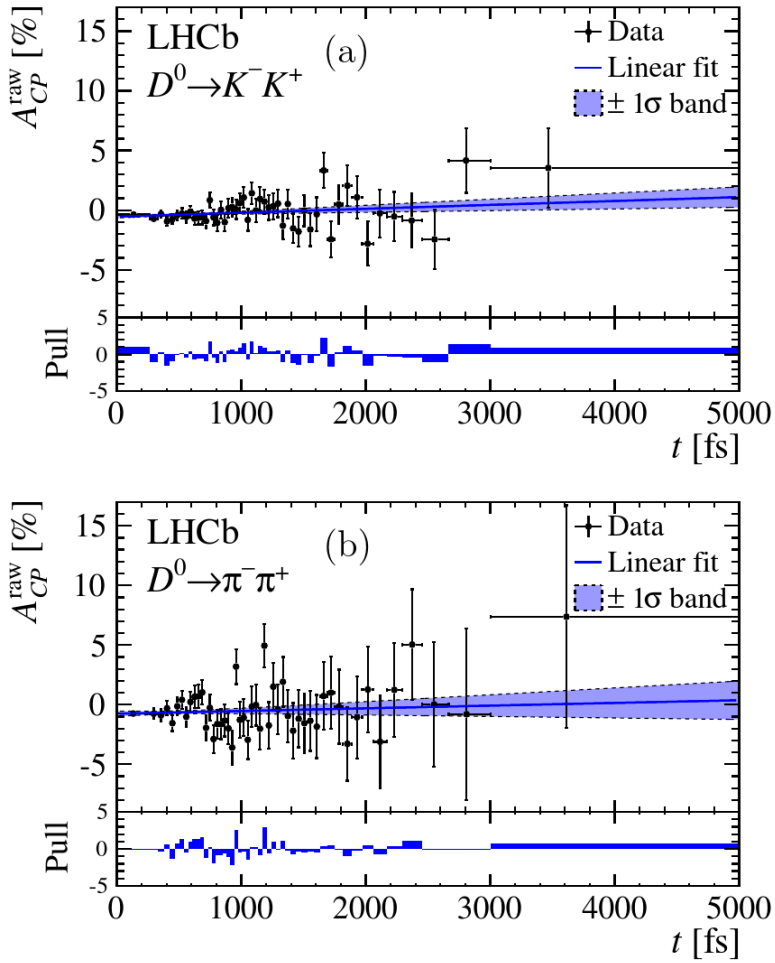
$$A_\Gamma(KK) = (-0.134 \pm 0.077_{stat}{}^{+0.026}_{-0.034})\%$$

$$A_\Gamma(\pi\pi) = (-0.092 \pm 0.145_{stat}{}^{+0.025}_{-0.033})\%$$

- Assuming indirect CPV is universal

$$A_\Gamma = (-0.125 \pm 0.073)\%$$

- In agreement with previous measurements and consistent with no indirect CPV in D^0 decays



Measurement of A_Γ in $D^0 \to hh$ [arXiv:1501.06777 , sub. to JHEP]

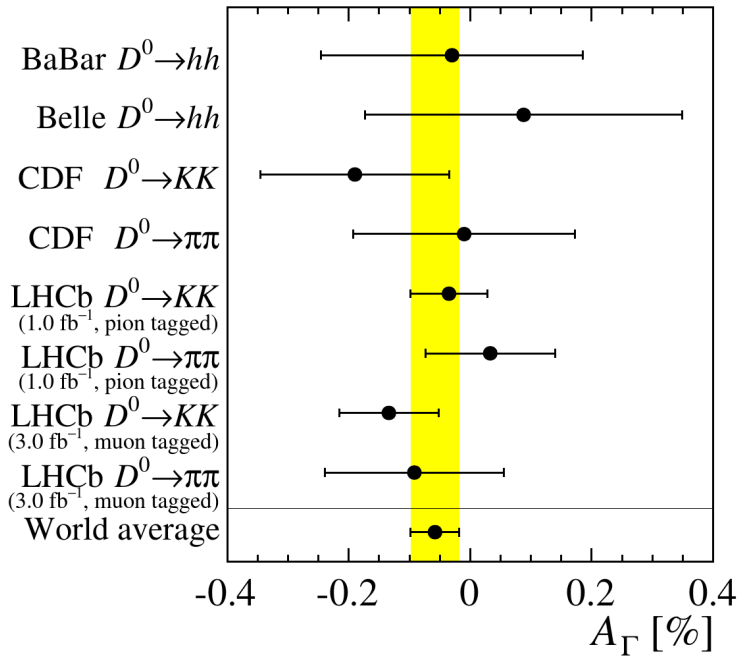
- Combining LHCb prompt and semileptonic results

$$A_\Gamma(KK) = (-0.072 \pm 0.050)\%$$

$$A_\Gamma(\pi\pi) = (-0.010 \pm 0.087)\%$$

- If universal indirect CPV: $A_\Gamma = (-0.056 \pm 0.044)\%$
- Combining also with Belle [arXiv:1212.3478], BaBar [PRD87 (2013) 012004], and CDF [PRD90 (2014) 111103]

$$A_\Gamma = (-0.058 \pm 0.040)\%$$

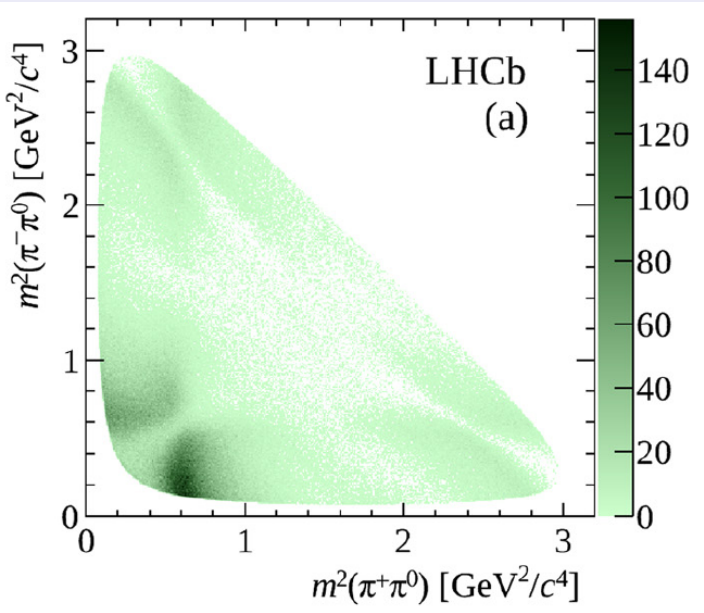


Search for CPV in $D^0 \to \pi^-\pi^+\pi^0$ [Phys. Lett. B 740 (2015) 158]

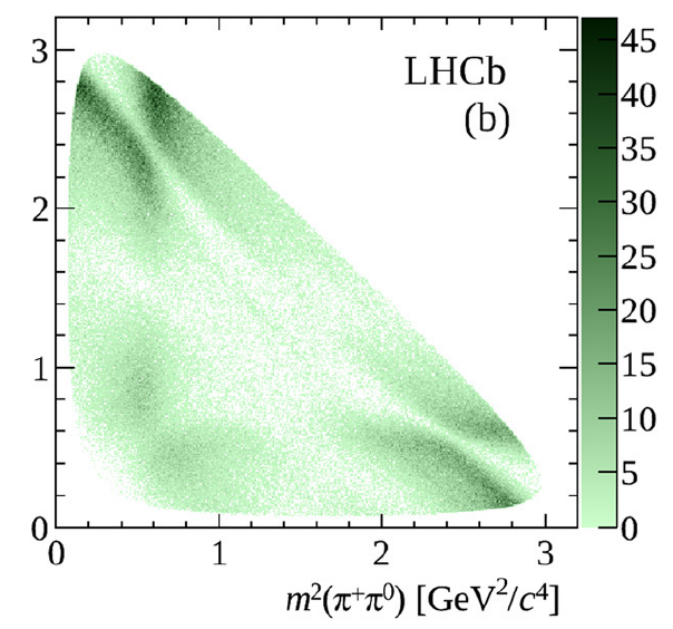
Time integrated CP asymmetry search in $D^0 \to \pi^-\pi^+\pi^0$ using the "energy test" method [Phys. Rev. D, 84 (2011), p. 054015]

- First CPV analysis with π^0s in LHCb

Resolved π^0, two ECAL clusters, better mass resolution, low p_T
416×10^3 events, purity: 82%



Merged π^0, single ECAL cluster, worse mass resolution, high p_T
247×10^3 events, purity: 91%



Search for CPV in $D^0 \to \pi^-\pi^+\pi^0$ [Phys. Lett. B 740 (2015) 158]

- Model independent and unbinned method to search for local CP asymmetry in the Dalitz plane [Phys. Rev. D, 84 (2011), p. 054015]
- Define test statistic T, which depends on the distance between pair of events in the Dalitz plane $\overrightarrow{\Delta x_{ij}}$

$$T = \underbrace{\frac{1}{n(n-1)}\sum_{i,j>i}^{n}\psi(\overrightarrow{\Delta x_{ij}})}_{\text{i,j are } D^0 \text{ tagged events}} + \underbrace{\frac{1}{\bar{n}(\bar{n}-1)}\sum_{i,j>i}^{\bar{n}}\psi(\overrightarrow{\Delta x_{ij}})}_{\text{i,j are } \bar{D}^0 \text{ tagged events}} - \underbrace{\frac{1}{n\bar{n}}\sum_{i,j}^{n,\bar{n}}\psi(\overrightarrow{\Delta x_{ij}})}_{\text{i(j) is a } D^0(\bar{D}^0) \text{ tagged event}}$$

- $\overrightarrow{\Delta x_{ij}} = (m^{2,j}_{12} - m^{2,i}_{12}, m^{2,j}_{23} - m^{2,i}_{23}, m^{2,j}_{13} - m^{2,i}_{13})$, does not depend on the choice of axes in the Dalitz plane
- $\psi(\overrightarrow{\Delta x_{ij}}) = \exp \overrightarrow{\Delta x^2_{ij}}/2\sigma^2$ is the metric used in the analysis

Search for CPV in $D^0 \to \pi^-\pi^+\pi^0$ [Phys. Lett. B 740 (2015) 158]

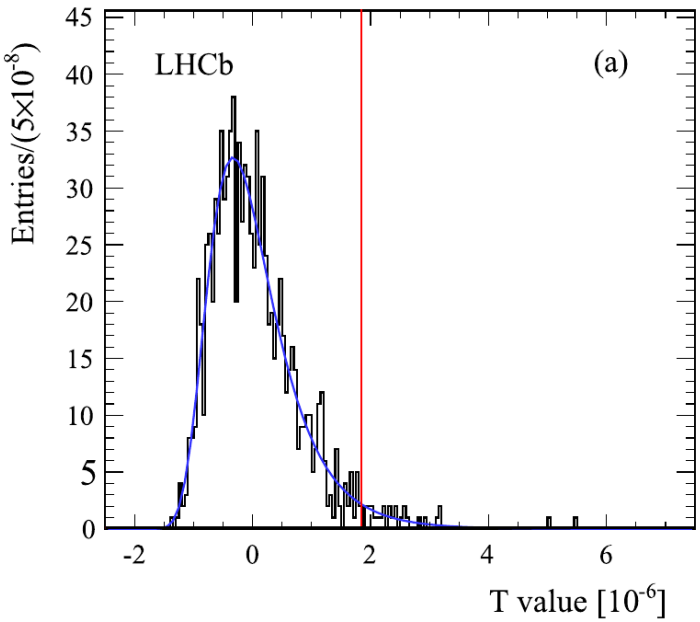
- Distribution of T for no-CPV hypothesis is determined by doing permutations randomly assigning the D^0 flavour
- It can be verified that the T distribution follows the Generalised Extreme Value (GEV) function

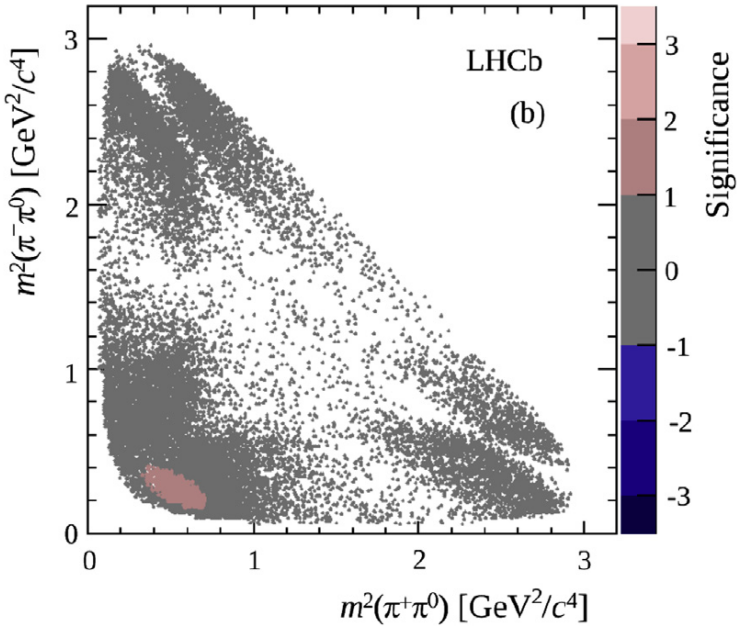
$$f(T;\mu,\delta,\xi) = N\left[1+\xi\left(\frac{T-\mu}{\delta}\right)\right]^{(-1/\xi)-1} \exp-\left[1+\xi\left(\frac{T-\mu}{\delta}\right)\right]^{-1/\xi}$$

- Local asymmetries can be looked at by defining for each event in the Dalitz plane

$$T_i = \frac{1}{2n(n-1)}\sum_{j\neq i}^{n}\psi_{ij} - \frac{1}{n\bar{n}}\sum_{j\neq i}^{\bar{n}}\psi_{ij}$$

Search for CPV in $D^0 \to \pi^-\pi^+\pi^0$ [Phys. Lett. B 740 (2015) 158]





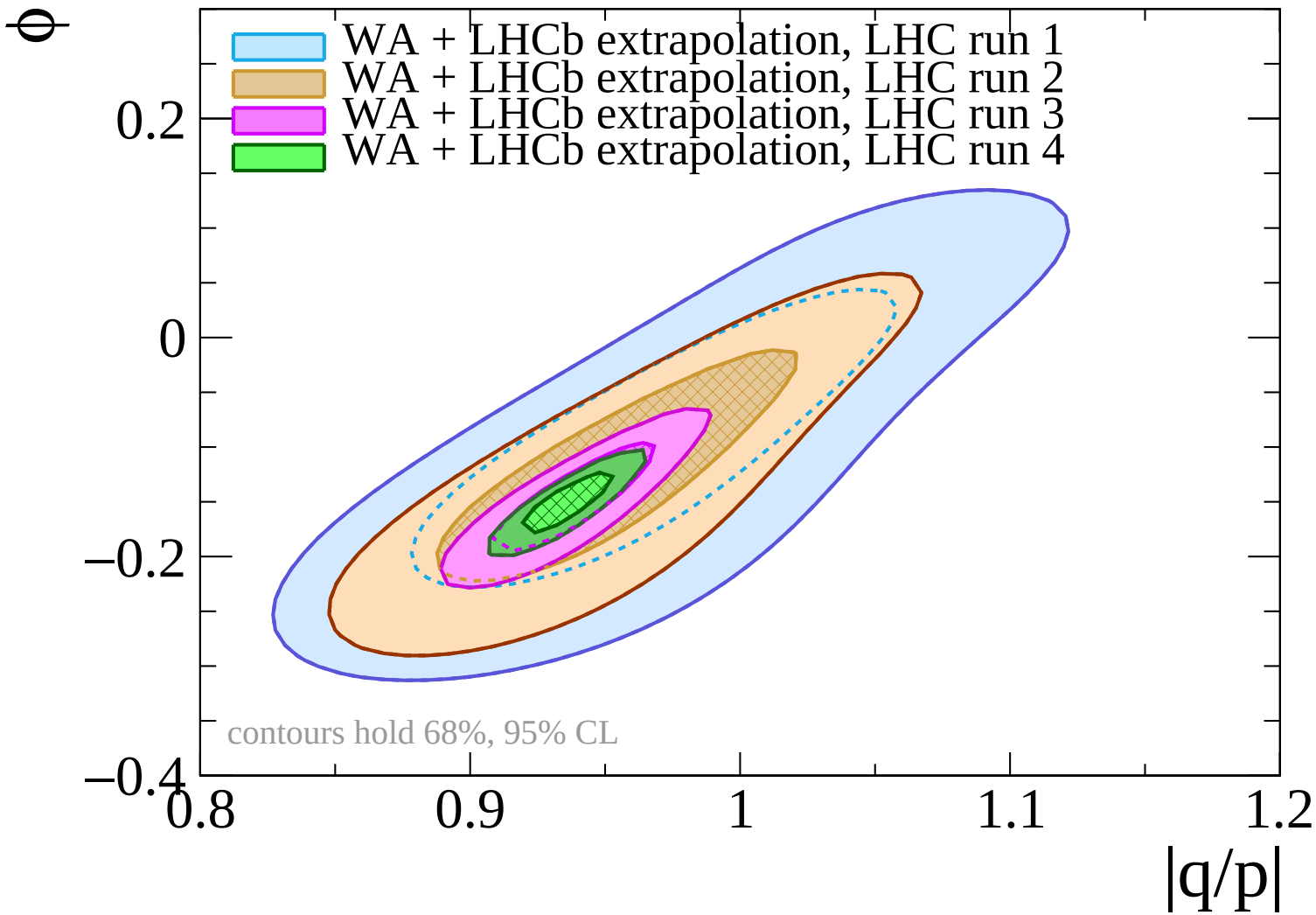
Consistent with CP conservation

p-value : $(2.6 \pm 0.5) \times 10^{-2}$

Local positive asymmetry exceeding 1σ significance in the region dominated by the ρ^+

Prospects for CP violation in charm at LHCb

courtesy of M. Gersabeck



Conclusions

- Charm physics is a unique probe of NP
- Precious input to charm physics from LHCb
- Precision measurements thanks to $\mathcal{O}(1M)$ samples
- Still more to come in Run 1
- Excellent prospects for Run2 and Upgrade
- Stay tuned!