Direct CPV studies at LHCb

Eva Gersabeck
on behalf of the LHCb collaboration

BESIII-LHCb joint workshop, Beijing, February 2018

Outline

- CP violation basics and charm
- Direct CPV searches in
  - two-body $D^0 \to h^+h^-$ charm decays
  - other two- or three-body charm decays
  - multi-body charm decays
- Conclusions and prospects

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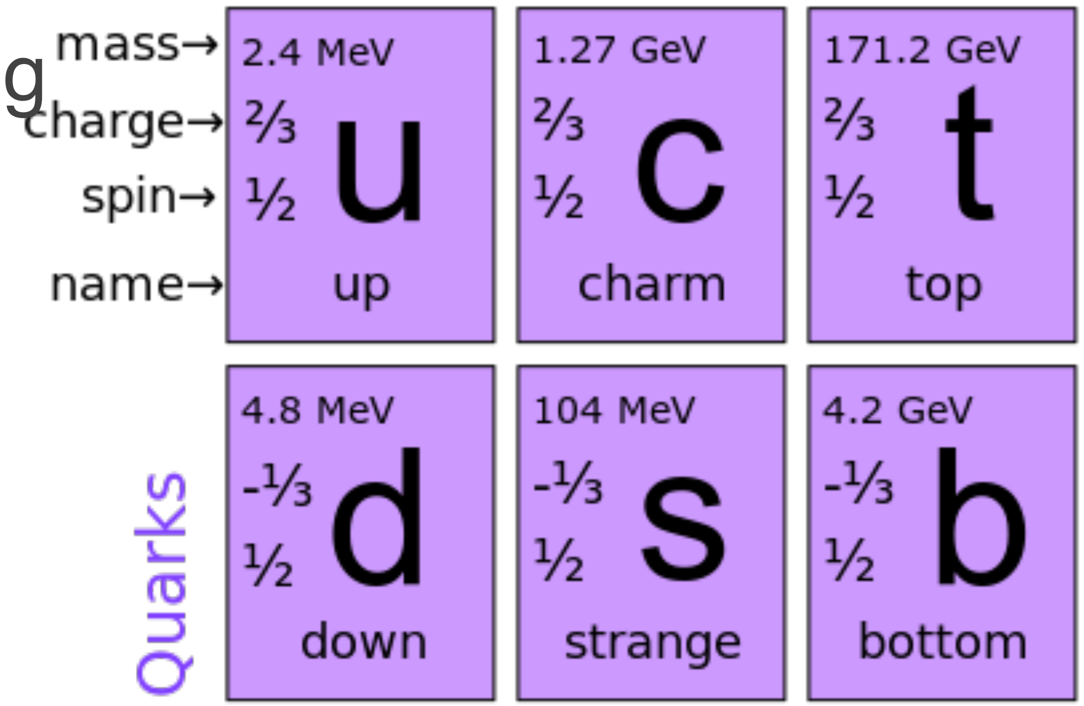
CP violation in the up and down sectors

- CP symmetry applies to processes invariant under the combined transformation of
  - charge conjugation (C): exchange of particle and anti-particle
  - and parity (P): spatial inversion
- CP symmetry conserved in the strong and the EM interaction
- CPV discovered in weak decays of strange and beauty mesons containing quarks from the down sector
- What about the up-sector?



Charm

- Charm is unique: only bound up-type quark system where mixing and CP violation can occur

No CP violation at first order: imaginary part of V_{cd} very small

$$V_{CKM} \approx \begin{array}{c} \\ \\ \end{array}\begin{array}{cccc} d & s & b & \\ \left(\begin{matrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda - iA^2\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\hat{\rho}-i\hat{\eta}) & -A\lambda^2 - iA\lambda^4\eta & 1 \end{matrix}\right) & & & \begin{matrix} u \\ c \\ t \end{matrix} \end{array}$$

- Making precise SM predictions in the D-meson sector is difficult
  - Perturbative QCD valid at energies >> 1 GeV
  - Chiral perturbation theory valid between 0.1 GeV and 1GeV
  - D^0 mass = 1.864 GeV

Types of CPV

The symmetry under CP transformation can be violated in different ways: Present if λ_f is not equal to 1

$$\lambda_f \equiv \frac{q\bar{A}_{\bar{f}}}{pA_f} = -\eta_{CP}\left|\frac{q}{p}\right|\left|\frac{\bar{A}_f}{A_f}\right| e^{i\phi}$$

$$|\bar{A}_{\bar{f}}/A_f| \neq 1$$

direct CPV
depends on the decay mode

$$|q/p| \neq 1$$

CPV in mixing
The transition probability of particles to anti-particles compared to the reverse process differs.

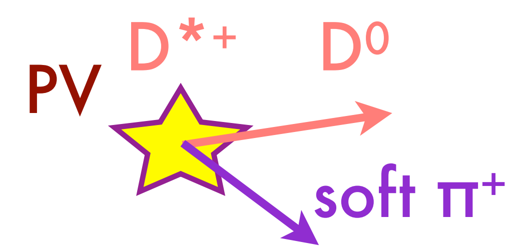
CPV in the interference
φ, the CP-violating relative phase between q/p and $\bar{A}_{\bar{f}}/A_f$, is non-zero

The indirect CP violation is independent of the decay mode.

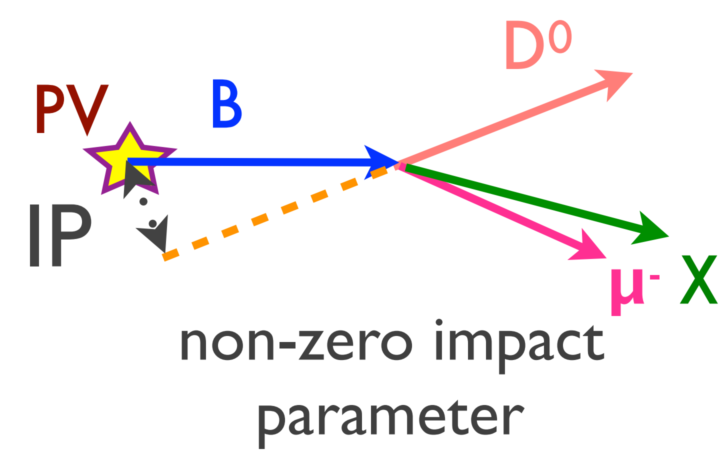
It involves neutral particles

Flavour tagging at LHCb

Prompt charm:
D points to primary vertex
Daughters of D don't in general



Secondary charm:
D doesn't point to PV



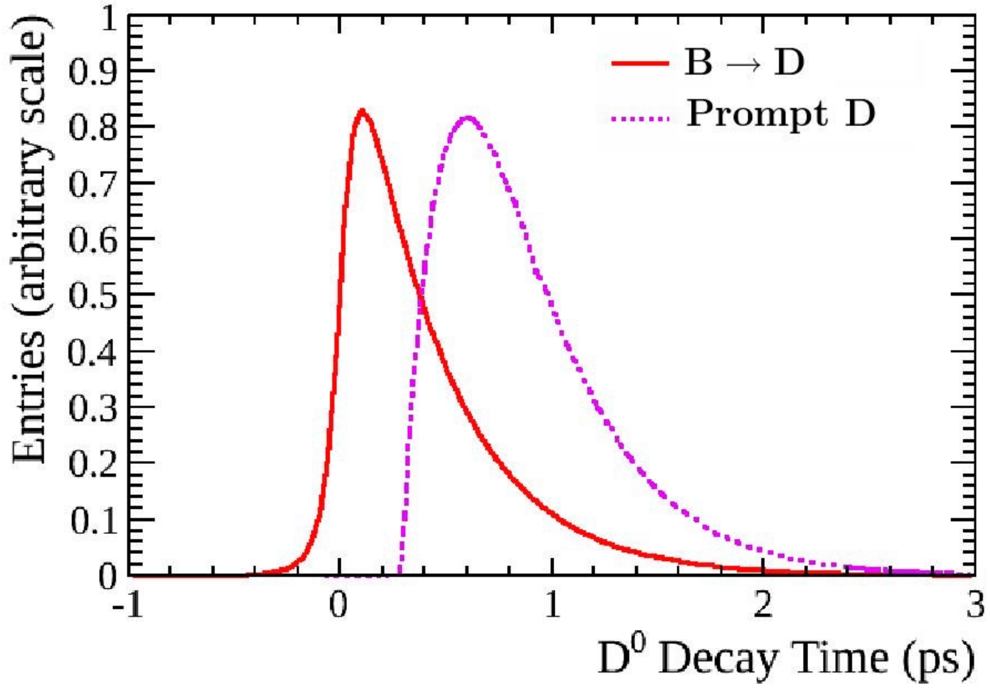
If $B \to D^{*\pm}(\to D^0\pi^\pm)\mu^\mp\nu$:
doubly-tagged decays

The flavour of the initial state $\left(D^0, \bar{D}^0\right)$ is tagged by the charge of the **soft pion** or the **muon**

Prompt vs secondary decays

- prompt charm:
  - high yield (3x)
  - access only to high D^0 decay times
  - small impact parameter
  - smaller flight distance
- secondary charm:
  - high trigger efficiency
  - access to all D^0 decay times
  - large impact parameter
  - larger flight distance
- Most direct CPV searches presented today use prompt decays, full Run 1 data sample (3 fb^{-1}), unless specified

Convolution of (decay time x time resolution) and acceptance



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The CP asymmetries

Measure the time integrated asymmetry in the SCS decays $D^0 \to hh$ decays (h=K or π)

$$\boxed{A_{CP}(f) = \frac{\Gamma\left(D^0 \to f\right) - \Gamma\left(\bar{D}^0 \to \bar{f}\right)}{\Gamma\left(D^0 \to f\right) + \Gamma\left(\bar{D}^0 \to \bar{f}\right)}}$$

But A_{CP} this is not what we measure. We measure

$$A_{raw}(f) = \frac{N\left(D^{*+} \to D^0(f)\pi_s^+\right) - N\left(D^{*-} \to \bar{D}^0(\bar{f})\pi_s^-\right)}{N\left(D^{*+} \to D^0(f)\pi_s^+\right) + N\left(D^{*-} \to \bar{D}^0(\bar{f})\pi_s^-\right)}$$

$f = \bar{f} = K^+K^-$
or
$f = \bar{f} = \pi^+\pi^-$

where N(X) refers to the number of reconstructed events of decay X after background subtraction

We measure the physical CP asymmetry plus asymmetries due to detection effects and production

$$A_{raw} = A_{CP} + A_{production} + A_{detection}$$

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LHCb

The observable ΔA_{CP}

Main experimental challenge: separate the CP asymmetry from the nuisance asymmetries ~O(1%)

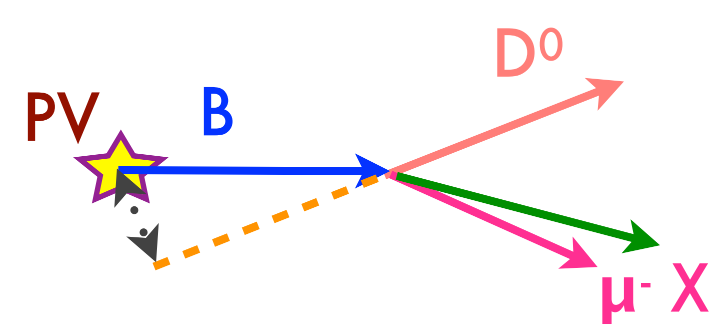
$$A_{raw} = A_{CP} + A_{production} + A_{detection}$$

if we take the raw asymmetry difference: experimentally more robust and enhanced sensitivity to CP violation

$$\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

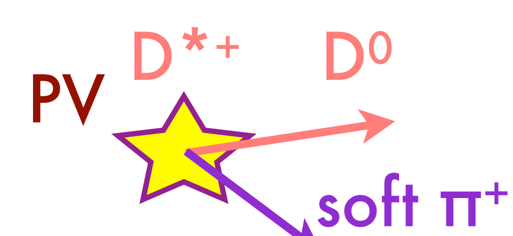
ΔA_{CP} muon-tagged = (+0.14 ± 0.16 ± 0.08)%

JHEP 1407 (2014) 041



ΔA_{CP} prompt = (-0.10 ± 0.08 ± 0.03) %

Phys. Rev. Lett. 116, 191601 (2016)



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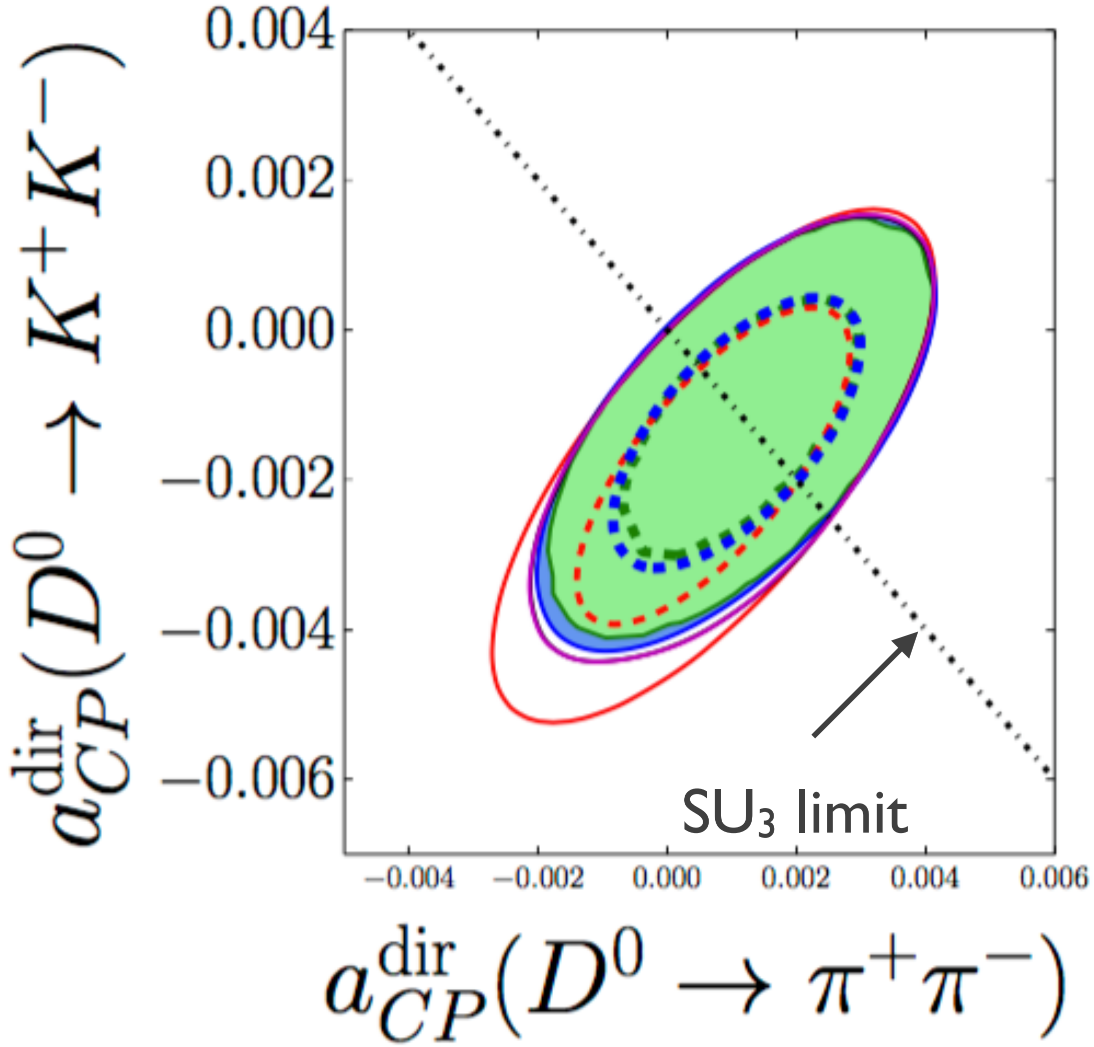
Theoretical expectations for the asymmetries



- $a_{CP}^{dir} < 10^{-2}$ within the SM
- Enhancements up to 1 order of magnitude possible in some BSM models
- Sum rules link several experimental observables
- Branching ratios are essential for the CP asymmetry sum rules:
  - the sum rule coefficients in front of the CP asymmetries are topologies which are constrained by the branching ratios

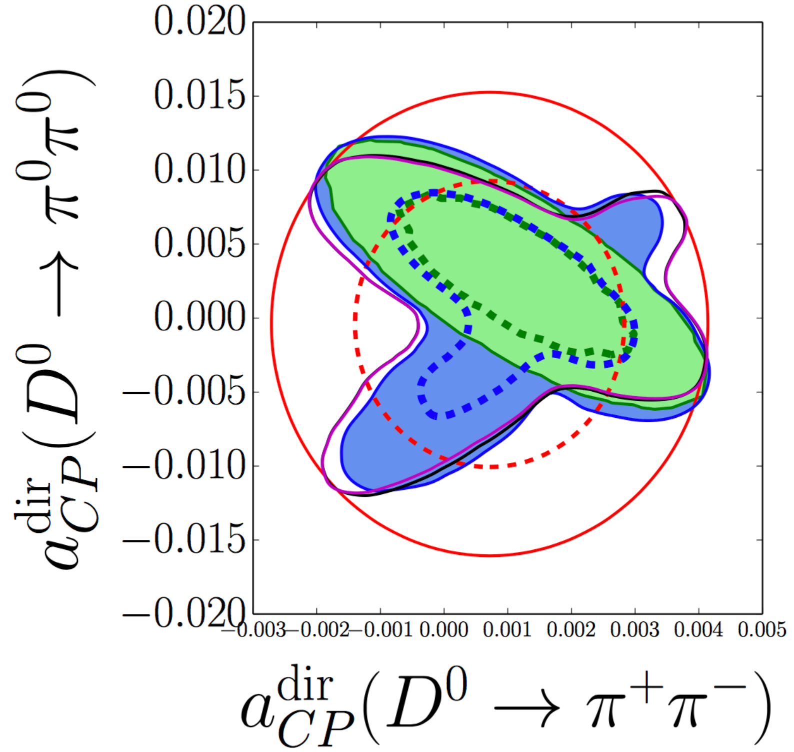
Global fit of D→hh branching ratios to topological amplitudes including linear $SU(3)_F$ breaking and 1/Nc-counting

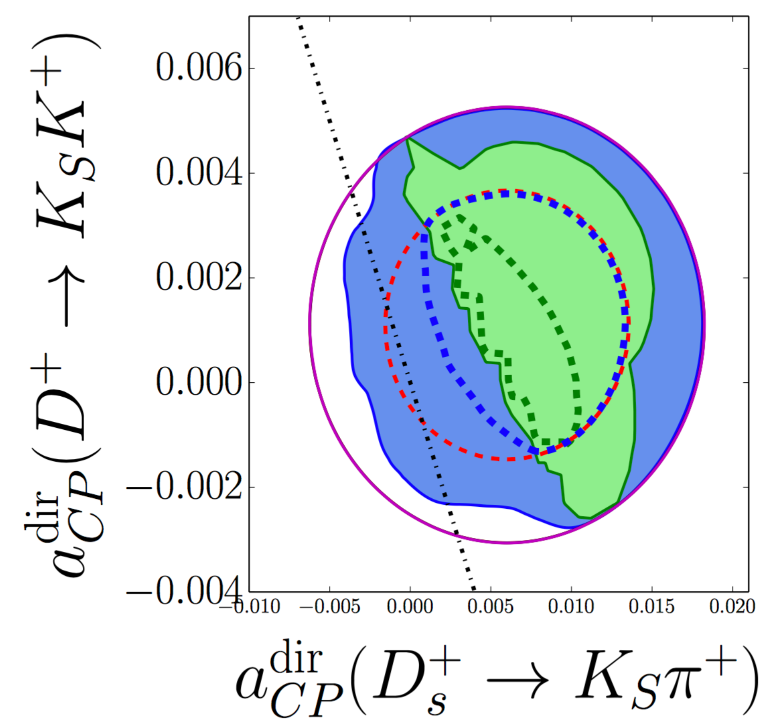
Müller, Nieste, Schacht, Phys. Rev. Lett. 115, 251802 (2015)

Theoretical expectations

- The SM prediction for the CP asymmetries based on the sum rule with **current** data is shown in blue.
- The SM prediction for the CP asymmetries based on the sum rule with **future** data is shown in green (all errors scaled by a factor 1/sqrt(50)).
- For the green ellipse no improvement in the CP asymmetries is assumed, in order to show the effect of improved branching ratios only.
- With better branching ratios one can eliminate one of the two overlapping solutions.

Müller, Nieste, Schacht, Phys. Rev. Lett. 115, 251802 (2015)





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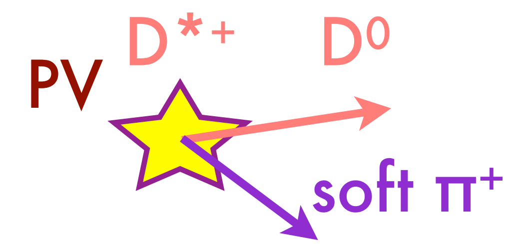
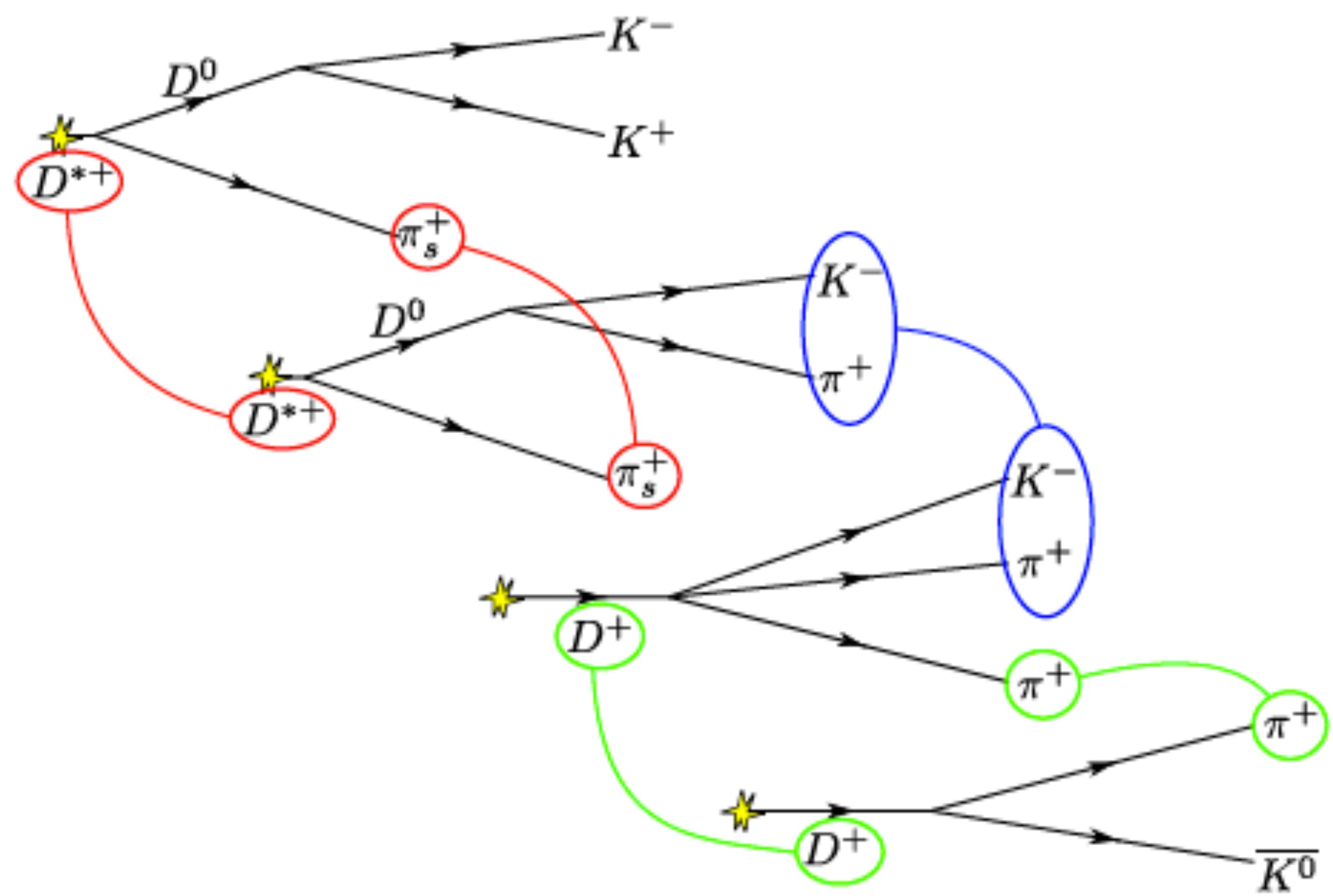
Experimental strategy for measuring the individual asymmetries: use CF decay control channels

$$A_{raw}(K^+K^-) = A_{cp}(K^+K^-) + A_D(\pi_s) + A_P(D^{*+})$$





$$\rightarrow A_{cp}(K^+K^-) = A_{raw}(K^+K^-) - A_{raw}(K^-\pi^+) + A_{raw}(K^-\pi^+\pi^+) - A_{raw}(\overline{K}^0\pi^+) + A_D(\overline{K}^0)$$

Combination with the prompt ΔA_{CP} measurement

$\Delta A_{CP} = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \approx \Delta a_{CP}^{dir}(1+y_{CP}\langle t\rangle/\tau) + a_{CP}^{ind}\Delta\langle t\rangle/\tau$

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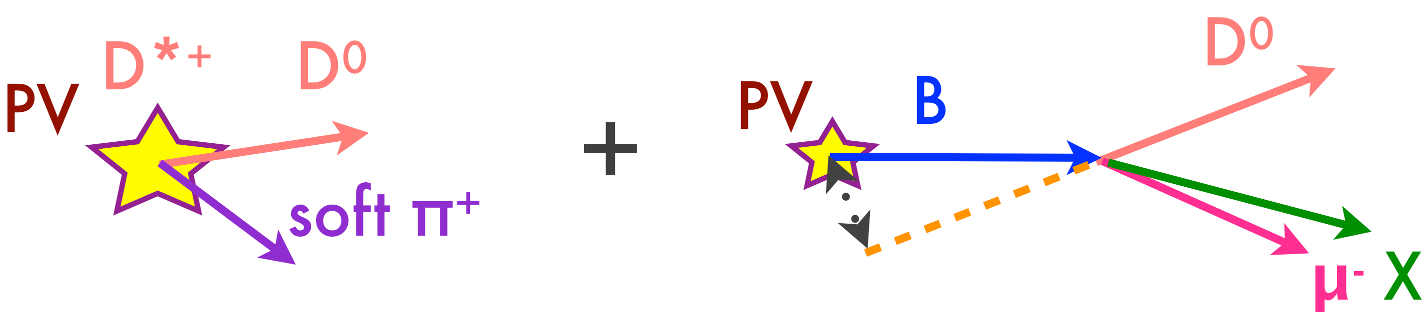
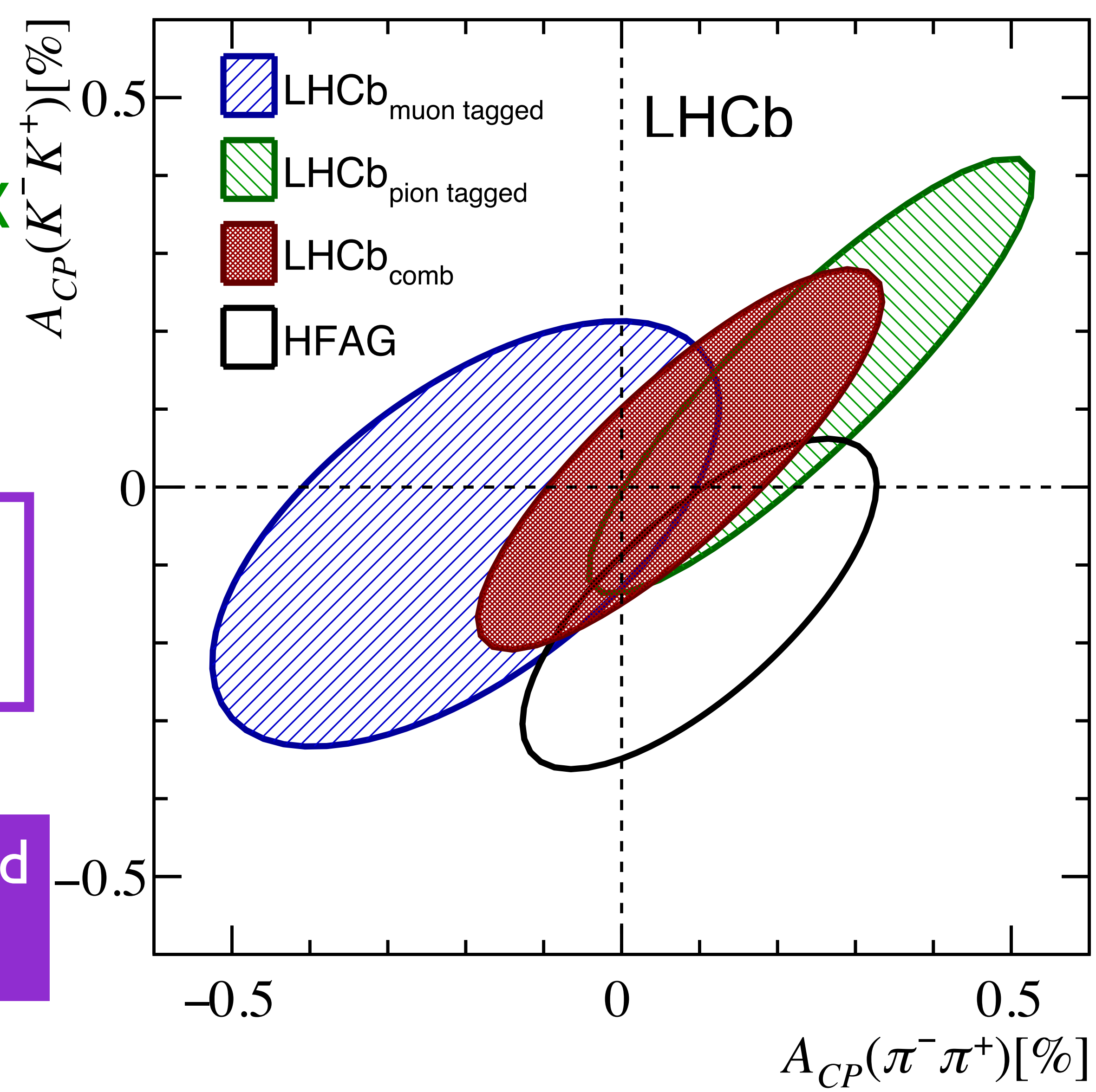
$A_{CP}(h^-h^+)$ results with LHCb Run 1 data



Phys. Lett. B 767 177-187



Combination of the prompt and secondary results

$A_{CP}^{comb}(K^-K^+)$ = (0.04 ± 0.12(stat) ± 0.10(syst))%
$A_{CP}^{comb}(\pi^-\pi^+)$ = (0.07 ± 0.14(stat) ± 0.11(syst))%

Most precise measurement of charm time-integrated CP asymmetry

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Desirable input from BESIII

- Improved D→hh branching fraction ratios for improving the theory predictions
  - $\Gamma(D^0 \to K^+K^-)/\Gamma(D^0 \to \pi^+\pi^-) = 2.760 \pm 0.040 \pm 0.034$ (CDF, 7334 events): LHCb can do this
  - $\Gamma(D^0 \to K^+K^-)/\Gamma_{total} = 4.08 \pm 0.08 \pm 0.09$ (CLEO, 4746 events)
  - $\Gamma(D^0 \to \pi^0\pi^0)/\Gamma_{total} = 8.24 \pm 0.21 \pm 0.30$ (BESIII, 6k)👍

BESIII BR preliminary results @CHARM'16

Mode	N^{net}_{signal}	ϵ (%)	$\mathcal{B}\pm$(stat)$\pm$(sys)	$\mathcal{B}_{PDG}$
$\pi^+\pi^-$	21105 ± 249	66.03 ± 0.25	$(1.505 \pm 0.018 \pm 0.031) \times 10^{-3}$	$(1.421 \pm 0.025) \times 10^{-3}$
K^+K^-	56438 ± 273	62.82 ± 0.32	$(4.229 \pm 0.020 \pm 0.087) \times 10^{-3}$	$(4.01 \pm 0.07) \times 10^{-3}$
$K^-\pi^+$	537745 ± 767	64.98 ± 0.09	$(3.896 \pm 0.006 \pm 0.073)$ %	(3.93 ± 0.04) %
$K^0_S\pi^0$	66539 ± 302	38.06 ± 0.17	$(1.236 \pm 0.006 \pm 0.032)$ %	(1.20 ± 0.04) %
$K^0_S\eta$	9532 ± 126	31.96 ± 0.14	$(5.149 \pm 0.068 \pm 0.134) \times 10^{-3}$	$(4.85 \pm 0.30) \times 10^{-3}$
$K^0_S\eta'$	3007 ± 61	12.66 ± 0.08	$(9.562 \pm 0.197 \pm 0.379) \times 10^{-3}$	$(9.5 \pm 0.5) \times 10^{-3}$
$\pi^0\pi^+$	10108 ± 267	48.98 ± 0.34	$(1.259 \pm 0.033 \pm 0.025) \times 10^{-3}$	$(1.24 \pm 0.06) \times 10^{-3}$
π^0K^+	1834 ± 168	51.52 ± 0.42	$(2.171 \pm 0.198 \pm 0.060) \times 10^{-4}$	$(1.89 \pm 0.25) \times 10^{-4}$
$\eta\pi^+$	11636 ± 215	46.96 ± 0.25	$(3.790 \pm 0.070 \pm 0.075) \times 10^{-3}$	$(3.66 \pm 0.22) \times 10^{-3}$
ηK^+	439 ± 72	48.21 ± 0.31	$(1.393 \pm 0.228 \pm 0.124) \times 10^{-4}$	$(1.12 \pm 0.18) \times 10^{-4}$
$\eta'\pi^+$	3088 ± 83	21.49 ± 0.18	$(5.122 \pm 0.140 \pm 0.210) \times 10^{-3}$	$(4.84 \pm 0.31) \times 10^{-3}$
$\eta'K^+$	87 ± 25	22.39 ± 0.22	$(1.377 \pm 0.428 \pm 0.202) \times 10^{-4}$	$(1.83 \pm 0.23) \times 10^{-4}$
$K^0_S\pi^+$	93884 ± 352	51.38 ± 0.18	$(1.591 \pm 0.006 \pm 0.033) \times 10^{-2}$	$(1.53 \pm 0.06) \times 10^{-2}$
$K^0_SK^+$	17704 ± 151	48.45 ± 0.14	$(3.183 \pm 0.028 \pm 0.065) \times 10^{-3}$	$(2.95 \pm 0.15) \times 10^{-3}$

- CP violation in SCS $D^0 \to h^-h^+$ decays:
  - A_{CP} measurements assume that CP violation in the Cabibbo-favoured decays is negligible
  - How precise can BESIII measure the A_{CP} in CF decays?
  - $A_{CP}(D^0 \to K^-\pi^+) = (0.3 \pm 0.3 \pm 0.6)\%$ (CLEO)
  - $A_{CP}(D^+ \to K_S\pi^+) = (-1.1 \pm 0.6 \pm 0.2)\%$ (CLEO), $= (-0.363 \pm 0.094 \pm 0.067)\%$* (BELLE) (neutral kaon contribution not subtracted)
  - $A_{CP}(D^0 \to K^-\pi^+\pi^+) = (-0.16 \pm 0.15 \pm 0.09)\%$ (D0), $= (-0.3 \pm 0.2 \pm 0.4)\%$ (CLEO)

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CP asymmetries in $D^0 \to h^+h^-$ from theoretical point of view

Feldman, Nandi, Soni
JHEP 1206 (2012) 007

- Many other SCS decay modes involving penguins suggested: $D^+ \to K^+\bar{K}^{*0}, K^{*+}\bar{K}^{*0}$; $D^+ \to \phi\pi^+$, $\rho^0\pi^+$, $\pi^+\pi^0(\eta')$; $Ds^+ \to \phi K^+(\eta')$, $K^0(K^{*0})^+$ and many more.
  - same operators in the weak effective Hamiltonian as $D^0 \to \pi^+\pi^-$, K^+K^-
- Could be expected to yield direct CP asymmetries of similar magnitude.
- One can constrain direct CP violation in tree-level decays such as $D^+ \to \bar{K}^0(\bar{K}^{*0})\pi^+$, $Ds^+ \to \phi\pi^+$, $D^+ \to \eta'\pi^+$ etc. in order to test against NP contributions in charged flavour transitions.

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CP violation in SCS $D^+ \to K_S K^+$ and $D_s^+ \to K_S \pi^+$ decays

$$A_{raw}(f) = A_{CP}(f) + A_{CP/\mathrm{int}}\left(K^0 / \bar{K}^0\right) + A_D\left(h^+\right) + A_P\left(D_{(s)}^+\right)$$

$h^+ = K^+$ or π^+

Cancel production and detection asymmetries:

control channel CF $D_S^+ \to \Phi\pi^+$, $D_S^+ \to K_S K^+$ and $D^+ \to K_S \pi^+$ decays

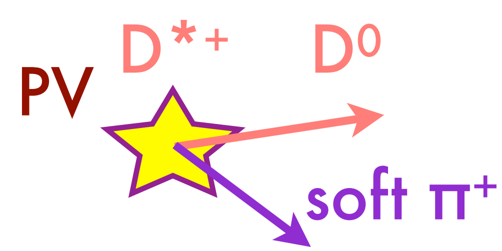
$A_{CP/\mathrm{int}}(K^0)$: small effect from CPV

Only K^0 decays with short times used

JHEP 1410 (2014) 25

$$\mathcal{A}_{CP}^{D^\pm \to K_S^0 K^\pm} = (+0.03 \pm 0.17 \pm 0.14)\%$$

~1M



$$\mathcal{A}_{CP}^{D_s^\pm \to K_S^0 \pi^\pm} = (+0.38 \pm 0.46 \pm 0.17)\%.$$

~120k

Most precise measurement of these quantities

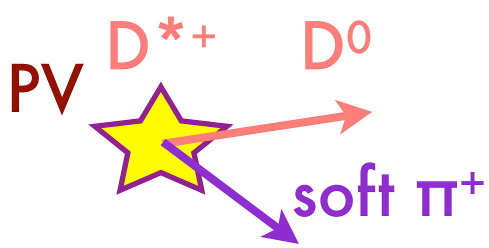
$$\mathcal{A}_{CP}^{D^\pm \to K_S^0 K^\pm} + \mathcal{A}_{CP}^{D_s^\pm \to K_S^0 \pi^\pm} = (+0.41 \pm 0.49 \pm 0.26)\%.$$

No indication for CPV

CP violation in $D^0 \to K_S K_S$

Hiller, Jung, Schacht, *Phys.Rev. D87 (2013) 1, 014024*

$$\frac{a_{CP}^{\mathrm{dir}}(D^0 \to K^0 \bar{K}^0)}{a_{CP}^{\mathrm{dir}}(D^0 \to K^+ K^-)} \sim \sqrt{\frac{BR(D^0 \to K^+ K^-)}{BR(D^0 \to K^0 \bar{K}^0)}} \sim 3,$$



$\boxed{A_{CP} = (-2.9 \pm 5.2 \pm 2.2)\%}$ no CPV

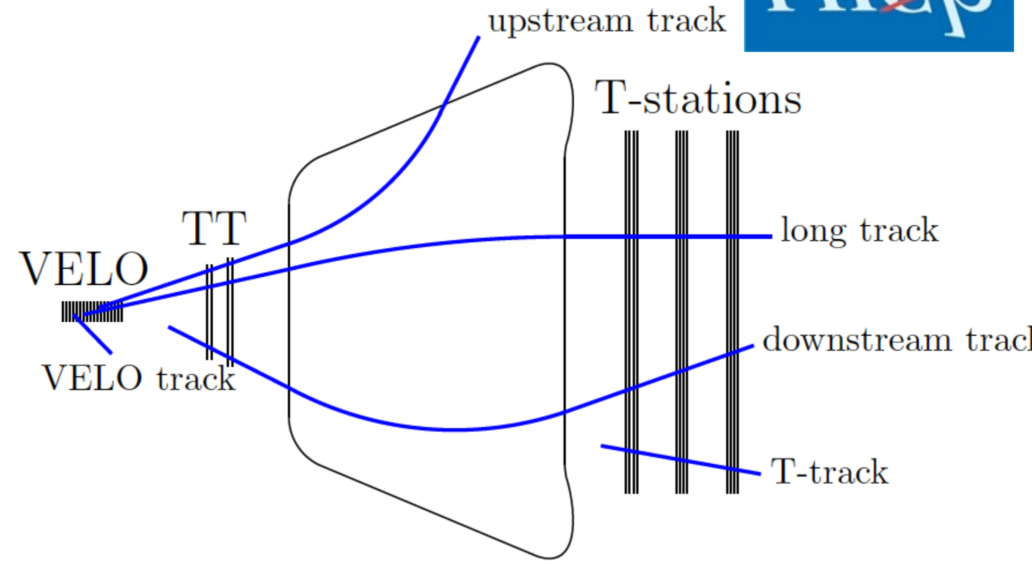
Nierste, Schacht, *Phys. Rev. D 92, 054036 (2015)*

$$|a_{CP}^{\mathrm{dir}}(D^0 \to K_S K_S)| \leq 1.1\% \ (95\% \text{ C.L.})$$

Belle's result is more precise

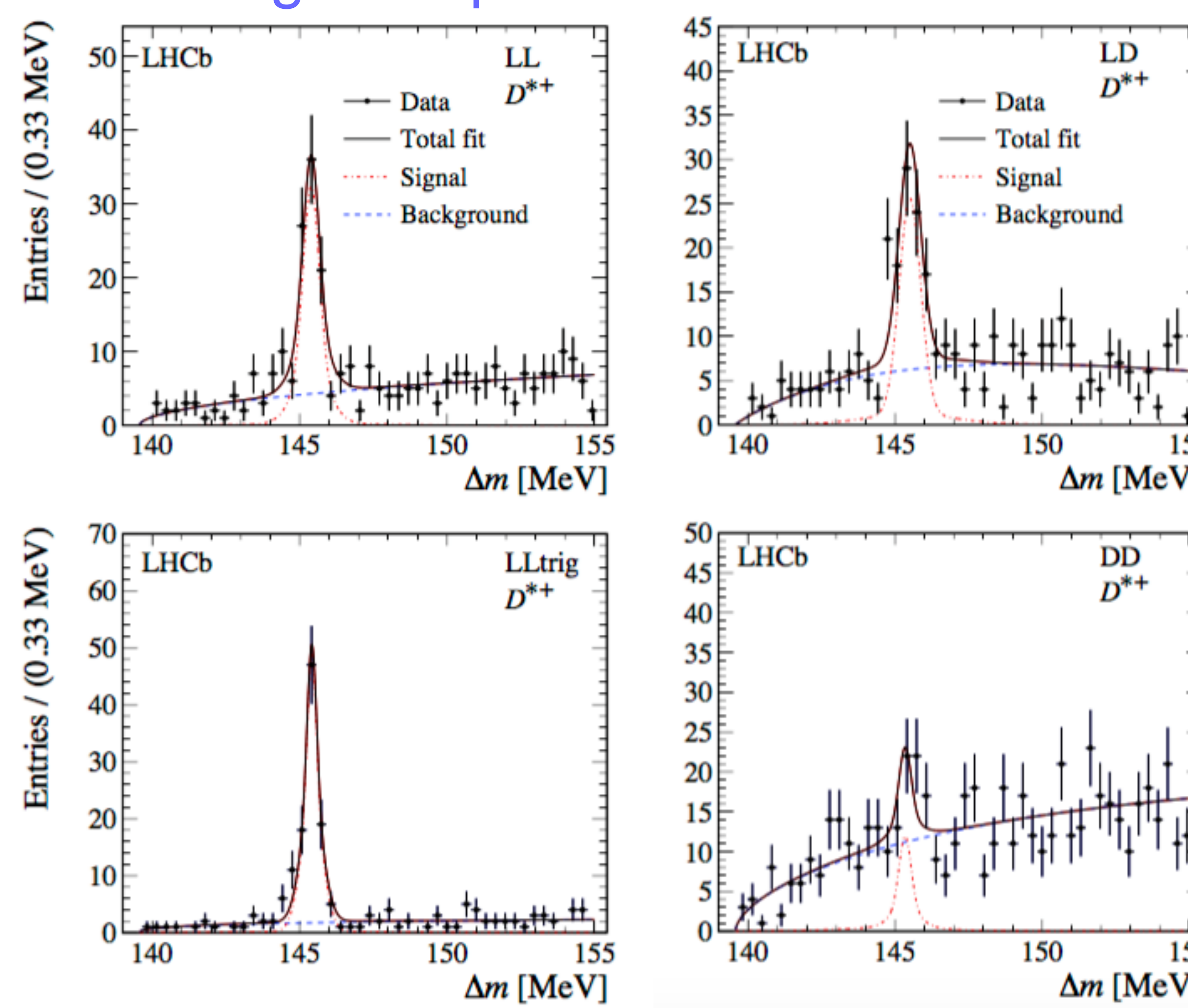
$A_{CP} = (-0.02 \pm 1.53 \pm 0.17)\%$

CONF-1609 ArXiv 1609.06393



Experimentally challenging:

2 long lived particles

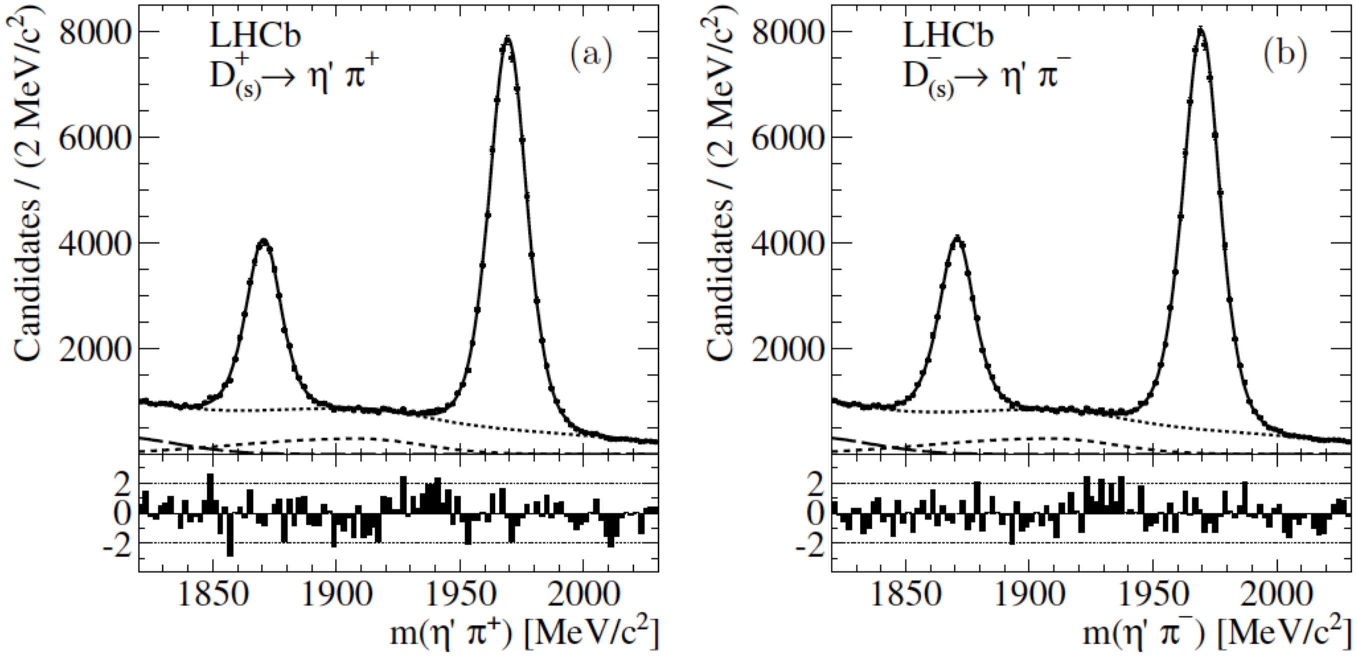


~ 600 events

JHEP 10 (2015) 055

Direct CPV search in $D^+_{(s)} \to \eta'\pi^+$

Phys. Lett. B 771 (2017) 21-30



63k $D^\pm$ and 152k $D^\pm_s$

Usual strategy: Subtract detector asymmetries using control channels

Signal $D^+_{(S)} \to \eta'\pi^+$ with $\eta' \to \pi^+\pi^-\gamma$
Control $D^+ \to K_S\pi^+$ with $K_S \to \pi^+\pi^-$
or $D^+_S \to \phi\pi$ with $\phi \to K^+K^-$

$$A_{CP}(D^+ \to \eta'\pi^+) \equiv A_{raw}(D^+ \to \eta'\pi^+) - A_{raw}(D^+ \to K_S\pi^+) + A_{CP}(D^+ \to K^0_S\pi^+) + A_{mix}(K^0_S)$$

$$A_{CP}(D^+_s \to \eta'\pi^+) \equiv A_{raw}(D^+_s \to \eta'\pi^+) - A_{raw}(D^+_s \to \phi\pi^+) + A_{CP}(D^+_s \to \phi\pi^+)$$

Fit m($\eta'\pi^\pm$) to extract raw asymmetry

Control channel asymmetry

External input (D0, Belle)

Consistent with CP conservation

$$A_{CP}(D^\pm \to \eta'\pi^\pm) = (-0.61 \pm 0.72 \pm 0.55 \pm 0.12)\ \%$$
$$A_{CP}(D^\pm_s \to \eta'\pi^\pm) = (-0.82 \pm 0.36 \pm 0.24 \pm 0.27)\ \%$$

More precise input from BESIII?

Most precise measurements to date of these variables

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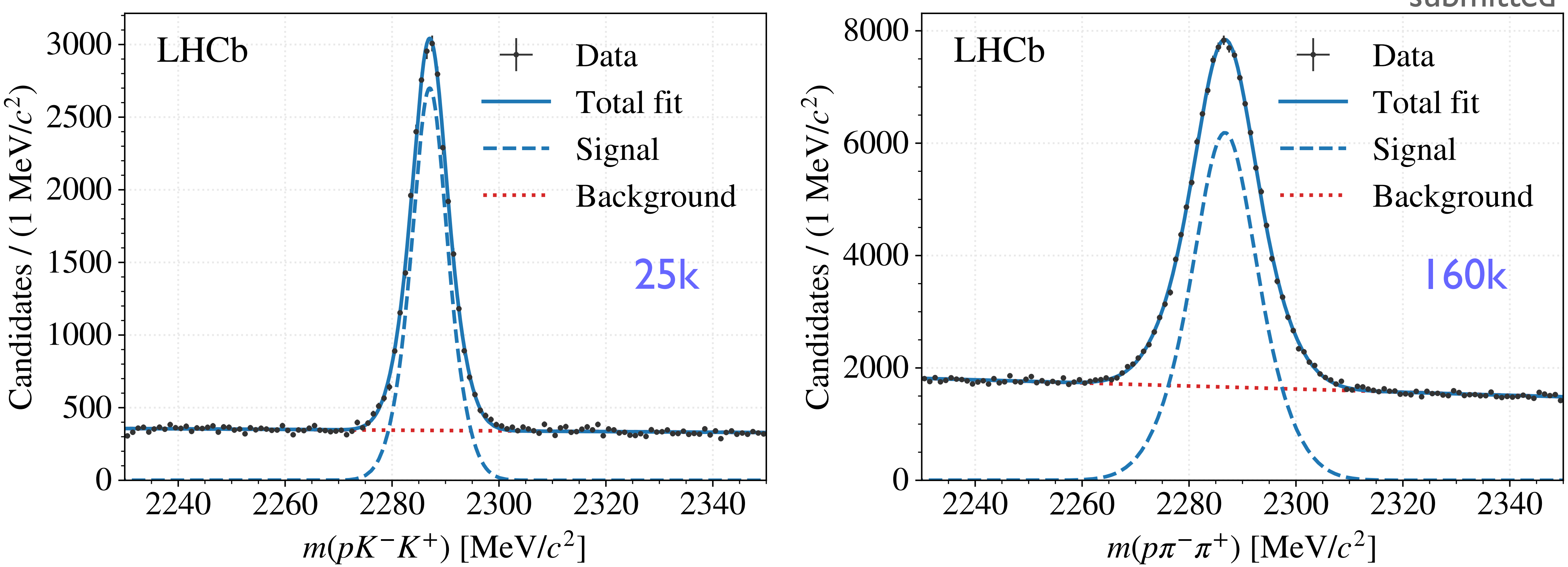
First measurement of CPV parameters in three-body Λ_c decays

- Little theoretical understanding of the dynamics of $\Lambda_c \to phh$ decays; no CPV prediction
- Run I (2011-2012, 3 fb^{-1}) data used
- Reconstructed as part of $\Lambda_b \to \Lambda_c \mu X$ decays in order to reduce prompt background
- Measurement of ΔA_{CP} in order to cancel production and detection asymmetry $\Lambda_c \to pKK$
- 6 dimensional kinematical reweighting (Λ_b, p, μ)
- $\Delta A_{CP} \approx A_{CP}(\Lambda_c \to pK^-K^+) - A_{CP}(\Lambda_c \to p\pi^-\pi^+) = (0.30 \pm 0.91 \pm 0.61)$ %

LHCb-PAPER-2017-044
arXiv:1712.07051
submitted to JHEP



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Desirable input from BESIII

- Improved $D \to K_S K_S$ branching fraction ratios,
    - $\Gamma(D^0 \to K^0 K^0)/\Gamma_{total}$ = 1.67±0.11±0.11 (BESIII, 576 events)👍
    - (*theory paper 2013; BESIII paper 2017)
- CP violation in SCS $D^+_{(s)} \to K^0 h^+$ decays:
    - Assuming that CP violation in the Cabibbo-favoured decays is negligible
    - How precise can BESIII measure the A_{CP} in CF decays?
        - $A_{CP}(D_S^+ \to K_S K^+)$ = (-0.05 ± 0.23 ± 0.24)% (BABAR)
        - $A_{CP}(D^+ \to K_S \pi^+)$ = (-1.1±0.6±0.2)% (CLEO), = (-0.363 ± 0.094 ± 0.067)%* (BELLE) (*neutral kaon contribution not subtracted)
        - $A_{CP}(D_S^+ \to \phi \pi^+)$ = (-0.38±0.26±0.08)% (D0)
- CP violation in $D^+_{(s)} \to \eta' \pi^+$
    - How precise can BESIII measure the A_{CP} in CF decays?
        - $A_{CP}(D^+ \to K_S \pi^+)$, $A_{CP}(D_S^+ \to \phi \pi^+)$
- Further sum rules input:
    - $\Gamma(D^+ \to K_S K^+)/\Gamma_{total}$ =3.14±0.09±0.08 (CLEO, 1971 events); (CHARM'16 =3.06±0.09±0.10 BESIII)
    - $\Gamma(D_S^+ \to K_S \pi^+)/\Gamma_{total}$ =8.5±0.7±0.2 (CLEO, 393 events);

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Multi-body decays and local asymmetries

- Many ways to reach multi-body final states through intermediate resonances

- Local asymmetries potentially larger than the phase space integrated ones

Discover CPV

- Model-independent:
  Look for asymmetries in regions of phase space by “counting”
  - binned (χ^2 difference method)
  - unbinned (Energy test, kNN)

Stat. Comp. Simul. 75, Issue 2 109-119 (2004),
Nucl. Instrum. Methods A537, 626-636 (2005)

Origin of CPV

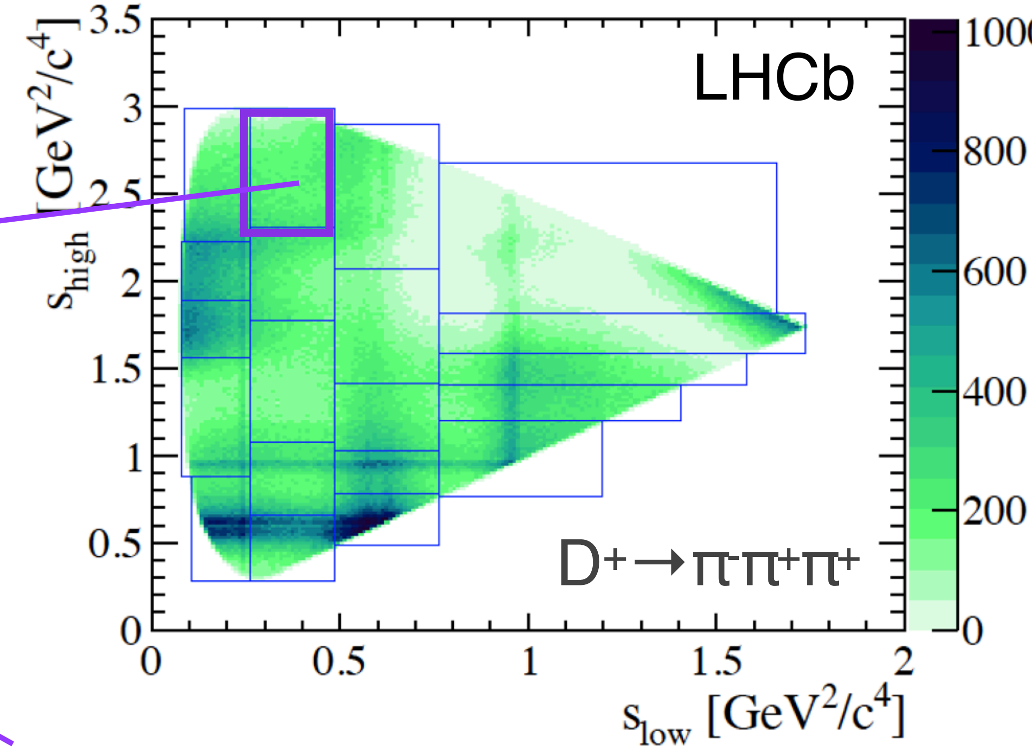
- Model-dependent:
  Fit all contributing amplitudes and look for differences in fit parameters

Binned method (χ² difference method)

asymmetry significance

$$\mathcal{S}^i_{CP} = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}}$$

$$\alpha = \frac{N_{\text{tot}}(D^+)}{N_{\text{tot}}(D^-)}$$



removes sensitivity to global asymmetries

$$\chi^2 = \sum(\mathcal{S}^i_{CP})^2$$

p-value for no CPV hypothesis

- $D^+ \to \pi^-\pi^+\pi^+$ decays(1 fb^{-1}): sensitive to 1°-10° differences in phase and 1-10% in magnitude *Phys.Lett. B728 (2014) 585–595,*
  p-values for no-CPV hypothesis> 50%
- $D^0 \to 4\pi/KK\pi\pi$ decays (1 fb^{-1}): sensitive to 10° differences in phase and 10% in magnitude *Phys.Lett. B726 (2013) 623–633*
  p-values for no-CPV hypothesis are 9.1% for $KK\pi\pi$ and 41% for 4π

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LHCb

Unbinned method: Energy test

Energy test: unbinned sample comparison used to assign p-value for hypothesis of identical distributions (= no CPV)

Test statistic $$T \approx \frac{1}{n(n-1)} \sum_{i,j>i}^{n} \psi(\Delta\vec{x}_{ij}) + \frac{1}{\bar{n}(\bar{n}-1)} \sum_{i,j>i}^{\bar{n}} \psi(\Delta\vec{x}_{ij}) - \frac{1}{n\bar{n}} \sum_{i,j}^{n,\bar{n}} \psi(\Delta\vec{x}_{ij}).$$

- Compare average pair-wise distance in Dalitz plot between: all D^0 events; all $\bar{D}^0$ events; all D^0 to $\bar{D}^0$ events
  - no CP violation → T≈0
  - CP asymmetry → T > 0
- For 4-body decays, introduce triple product C_T as parity sensitive variable
- Analyse different flavours and signs of C_T regions

$$C_T = \vec{p}(\pi_3)\cdot[\vec{p}(\pi_1)\times\vec{p}(\pi_2)]$$

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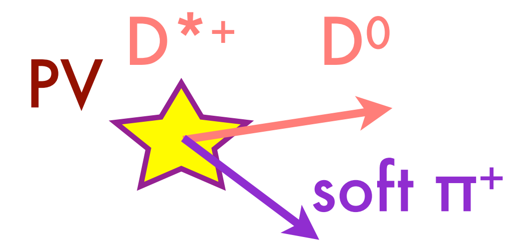


Energy test at LHCb

- $D^0 \to \pi^-\pi^+\pi^0$ decays (2 fb^{-1}) ~660k

First application of the method

Phys.Lett.B740 (2015) 158-167

Resonance (A, ϕ)	p-value (fit)	upper limit
ρ^0 $(+3\%, +0°)$	$1.1^{+2.4}_{-1.1} \times 10^{-2}$	4.0×10^{-2}
ρ^0 $(+0\%, +3°)$	$1.5^{+1.7}_{-1.4} \times 10^{-3}$	3.8×10^{-3}
ρ^+ $(+2\%, +0°)$	$5.0^{+8.8}_{-3.8} \times 10^{-6}$	1.8×10^{-5}
ρ^+ $(+0\%, +1°)$	$6.3^{+5.5}_{-3.3} \times 10^{-4}$	1.4×10^{-3}
ρ^- $(+2\%, +0°)$	$2.0^{+1.3}_{-0.9} \times 10^{-3}$	3.9×10^{-3}
ρ^- $(+0\%, +1.5°)$	$8.9^{+22}_{-6.7} \times 10^{-7}$	4.2×10^{-6}

p-value = (2.6±0.5)%

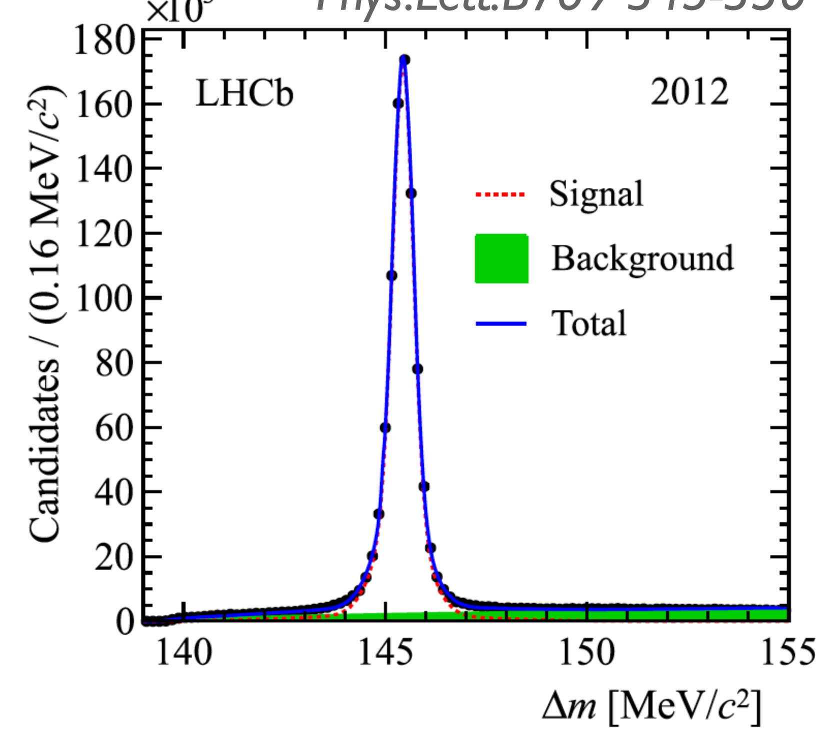
Results consistent with no CP violation

- $D^0 \to \pi^-\pi^+\pi^-\pi^+$ decays (3 fb^{-1}) ~1M

Phys.Lett.B769 345-356

R (partial wave) $(\Delta A, \Delta\phi)$	p-value (fit)
$a_1 \to \rho^0\pi$ (S) $(5\%, 0°)$	$2.6^{+3.4}_{-1.7} \times 10^{-4}$
$a_1 \to \rho^0\pi$ (S) $(0\%, 3°)$	$1.2^{+3.6}_{-1.2} \times 10^{-6}$
$\rho^0\rho^0$ (D) $(5\%, 0°)$	$3.8^{+2.9}_{-1.9} \times 10^{-3}$
$\rho^0\rho^0$ (D) $(0\%, 4°)$	$9.6^{+24}_{-7.2} \times 10^{-6}$
$\rho^0\rho^0$ (P) $(4\%, 0°)$	$3.0^{+1.2}_{-0.9} \times 10^{-3}$
$\rho^0\rho^0$ (P) $(0\%, 3°)$	$9.8^{+4.4}_{-3.8} \times 10^{-4}$

Phys.Lett.B769 345-356



Direct CPV searches in $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ decays

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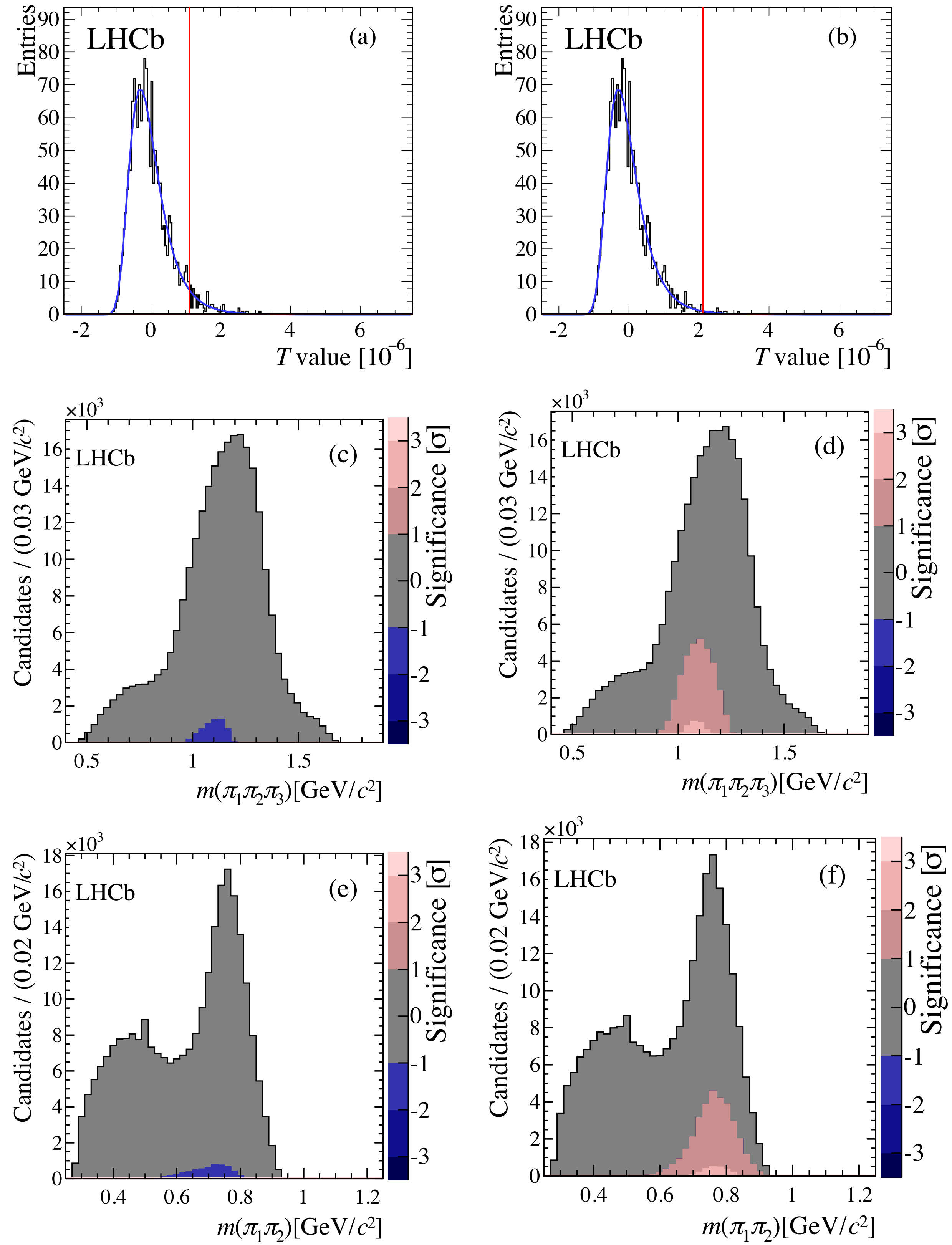
Phys.Lett.B769 345-356

P-even

p-value:
(4.6±0.5)%

P-odd

p-value:
(0.6±0.2)%
2.7σ



P-even test consistent with *CP symmetry*

P-odd test only marginally consistent with no-*CPV* hypothesis

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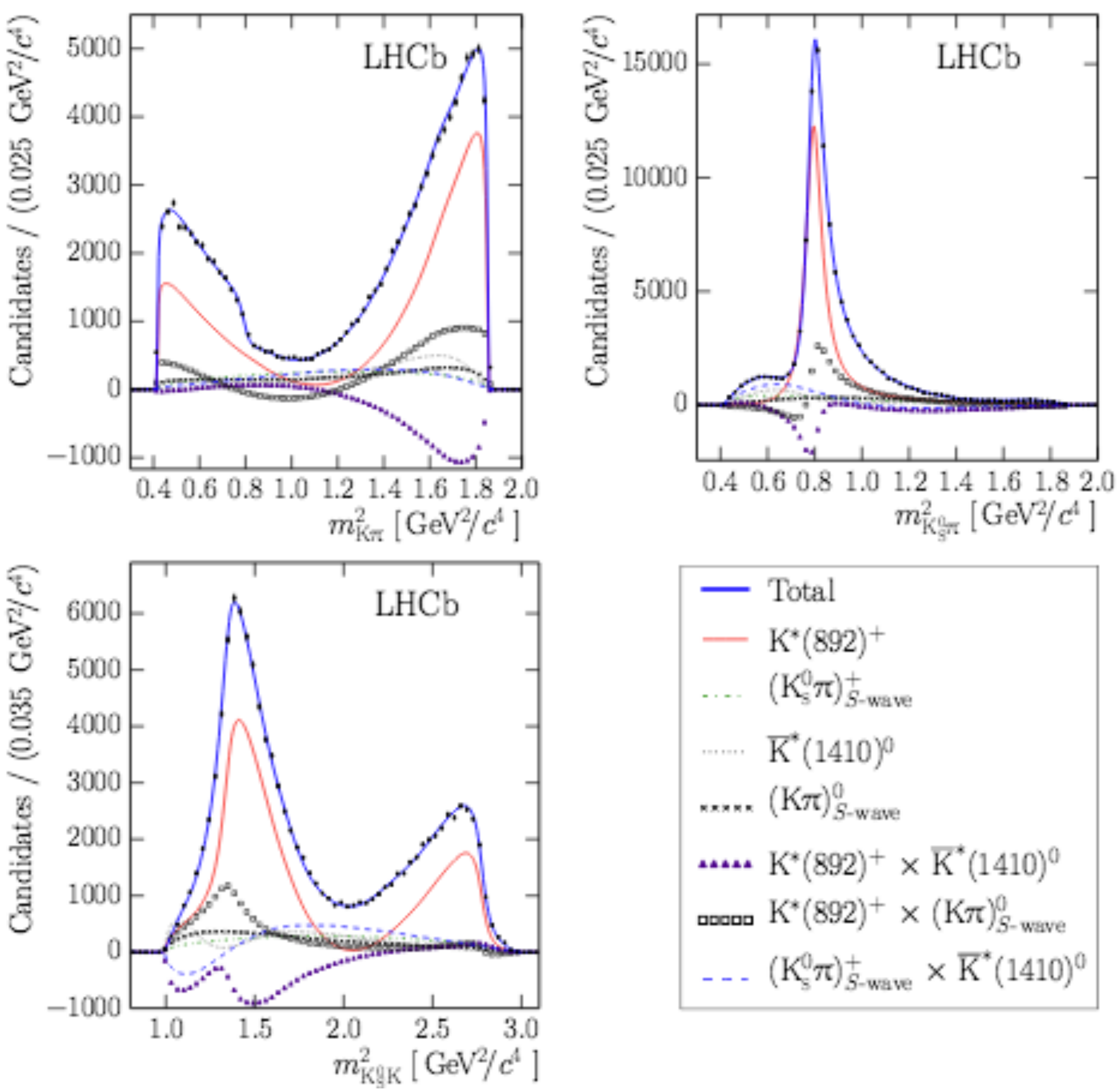
Model dependent searches

Searches for time-integrated CPV effects in the resonant structure of $D^0 \to K_S K \pi$

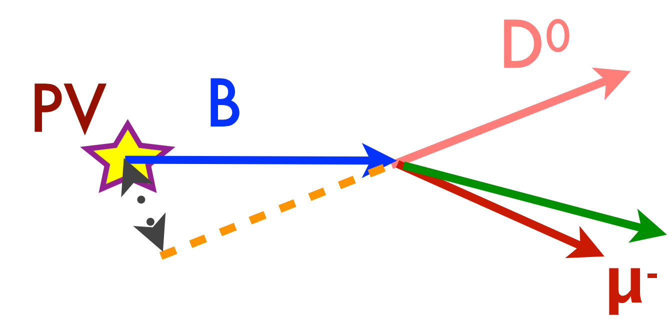
$D^0 \to K_S K^- \pi^+$ (favoured)



Phys. Rev. D 93, 052018 (2016)

- 116k $D^0 \to K_S K^- \pi^+$; 76k $D^0 \to K_S K^+ \pi^-$ (2011+2012)
- Full amplitude analysis
- Fit the amplitudes separately for D^0 and $\bar{D}^0$ events
- CPV in the resonance amplitude $a_R \to a_R(1 \pm \Delta a_R)$; the phase $\Phi_R \to \Phi_R \pm \Delta\Phi_R$
- Results consistent with no CP violation

Multibody decays (phase-space integrated approach)
CP violation in $D^0 \to KK\pi\pi$ (3 fb^{-1})



~171k decays

Using triple product of final state particle momenta

$$C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}) \qquad \overline{C}_T \equiv \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})$$

Define triple product asymmetries

$$A_T \equiv \frac{\Gamma_{D^0}(C_T > 0) - \Gamma_{D^0}(C_T < 0)}{\Gamma_{D^0}(C_T > 0) + \Gamma_{D^0}(C_T < 0)}, \qquad \overline{A}_T \equiv \frac{\Gamma_{\overline{D}^0}(-\overline{C}_T > 0) - \Gamma_{\overline{D}^0}(-\overline{C}_T < 0)}{\Gamma_{\overline{D}^0}(-\overline{C}_T > 0) + \Gamma_{\overline{D}^0}(-\overline{C}_T < 0)},$$

$$a_{CP}^{T\text{-odd}} \equiv \frac{1}{2}(A_T - \overline{A}_T)$$

Triple product asymmetries ~sinϕ cosδ

More careful consideration given in Durieux, Grossman
Phys. Rev. D 92, 076013 (2015)

JHEP 1410 (2014) 005

All production and detection effects cancel
All final states interactions cancel

$\boxed{a^{T\text{-odd}}_{CP} = (0.18 \pm 0.29 \pm 0.04)\%}$

No indication of CPV

Desirable input from BESIII

- Improved amplitude models for multibody decays:
  - used to test the sensitivity of the model independent techniques

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Outline

- CP violation basics and charm
- Direct CPV searches in
  - two-body $D^0 \to h^+h^-$ charm decays
  - other two- or three-body charm decays
  - multi-body charm decays
- Conclusions and prospects

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Conclusions

- Latest precision direct CP violation searches in the charm sector at LHCb presented
- CPV in charm not yet observed: All searches consistent with no direct CPV - some only marginally
- Sub-permile precision reached in direct CPV searches
- The key measurements are still statistically limited; systematics reduces with statistics
- BESIII measurements can help improve some SM theoretical expectations
- A precise measurement of the A_{CP} in CF channels could be used as external input instead of assumptions
- Improved models of multibody decays with BESIII data can be used to test sensitivities for model independent direct CPV searches

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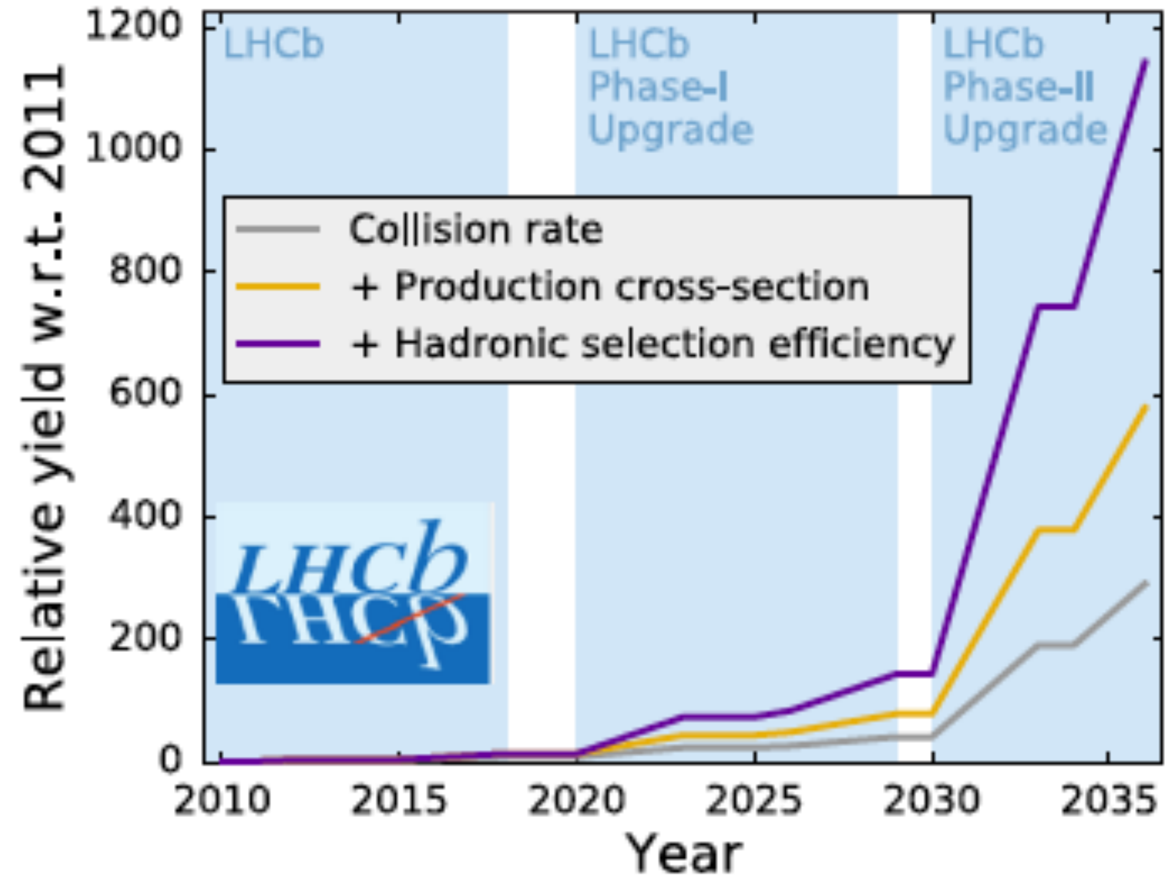
What comes next?

- LHCb Run II analyses ongoing
- Factor two gain in statistics seen with Run II LHCb data due to trigger optimisation and the higher cross-sections @13TeV
- and even more with the upgraded LHCb experiment is expected



Run1	Run2	Run3	Run4	Run5
3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}

Δa_{CP}: uncertainty 10^{-4} at 50 fb^{-1}

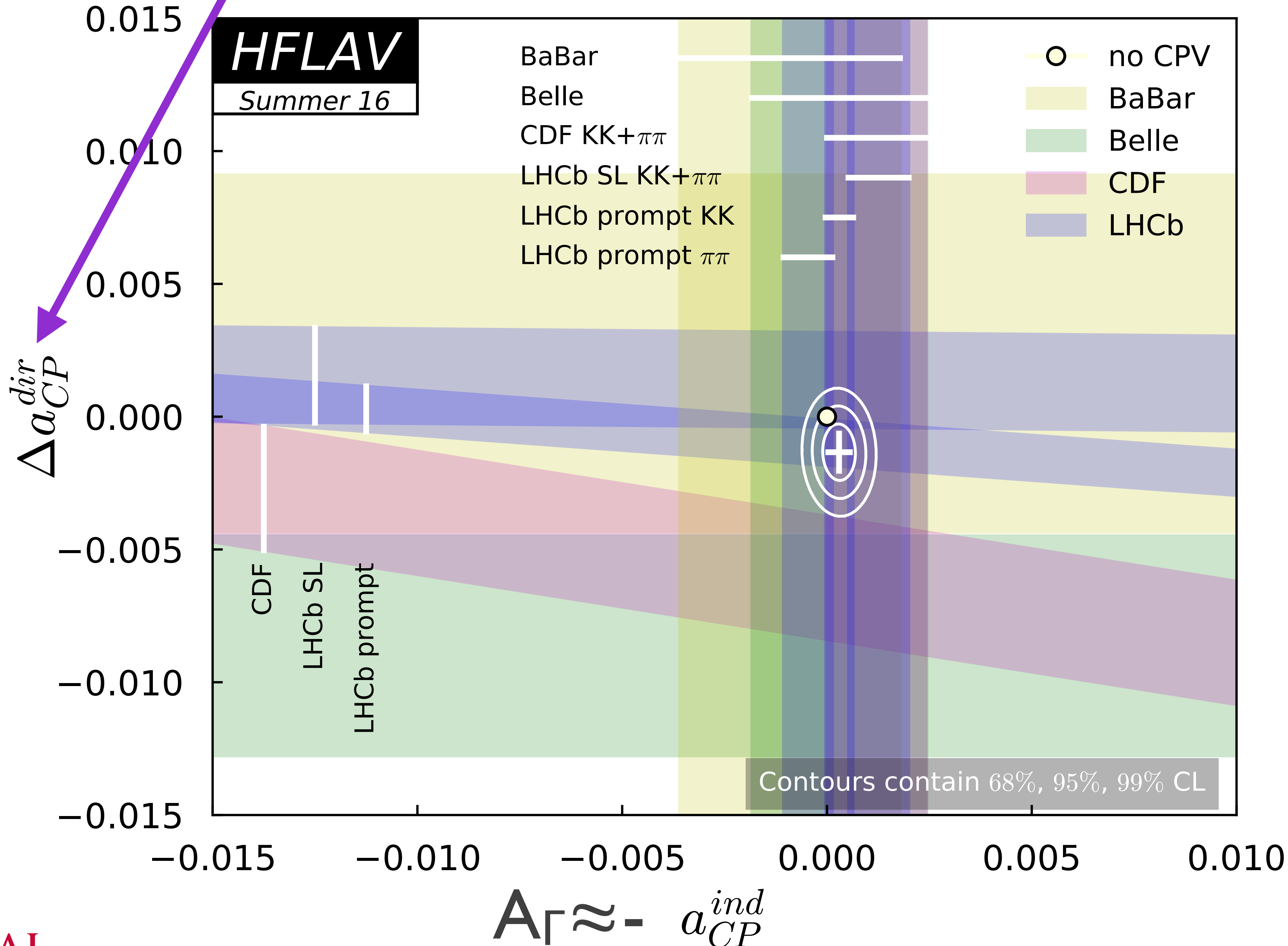
upgrade; gain more data by removing the L0 thresholds

BACKUP

HFLAV averages including the latest results

Mostly a measure of direct CPV

$$\Delta A_{CP} \equiv A_{CP}(KK) - A_{CP}(\pi\pi)$$
$$\approx \Delta a_{CP}^{dir}\left(1 + y_{CP}\,\overline{\langle t\rangle}/\tau\right) + a_{CP}^{ind}\,\Delta\langle t\rangle/\tau$$



Compatible with no-CPV in the charm sector at 9.3% CL

$a_{CP}^{ind} = (0.030 \pm 0.026)\%$
$\Delta a_{CP}^{dir} = (-0.134 \pm 0.070)\%$

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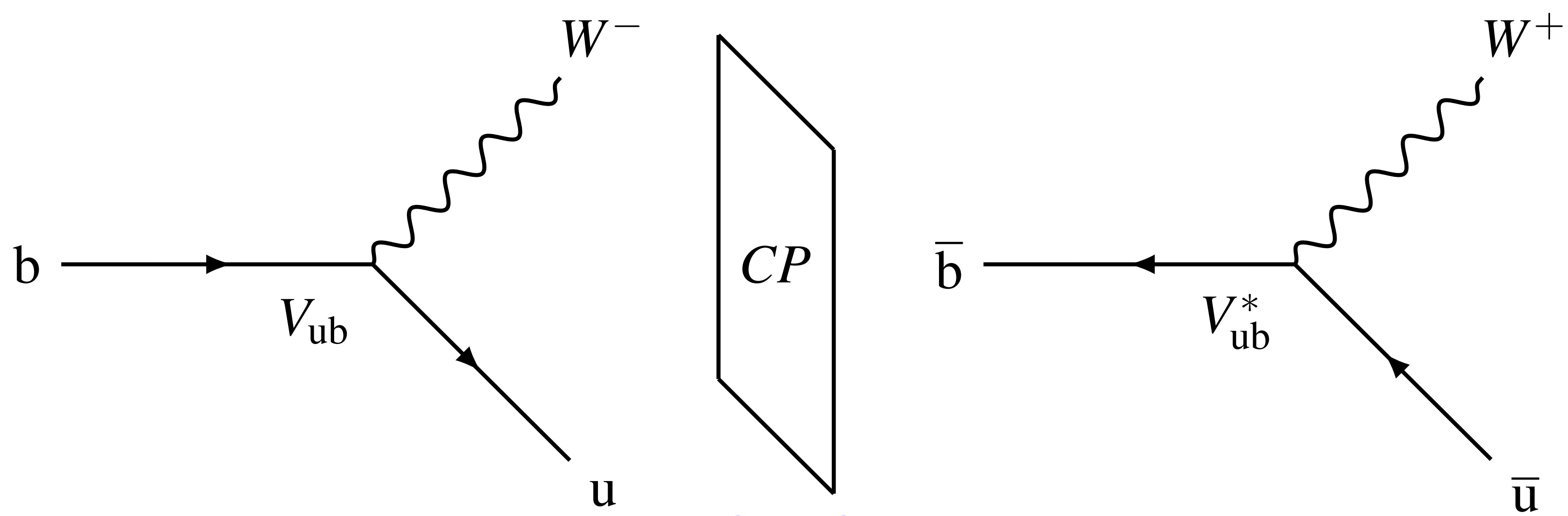
CP violation

CP symmetry applies to processes invariant under the combined transformation of

charge conjugation (C): exchange of particle and anti-particle

and parity (P): spatial inversion



CP violation discovered in 1964 in weak interactions of neutral Kaon decays by Cronin and Fitch

CP symmetry conserved in the strong and the EM interaction

The symmetry under CP transformation can be violated in different ways

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Direct CPV

- Condition for direct CPV: $|A/\bar{A}| \neq 1$
- Need A and $\bar{A}$ to consist of (at least) two parts: with different weak (φ) and strong (δ) phases
- Divide amplitudes into leading and sub-leading parts:

$$A(D \to f) = C(1 + re^{i(\delta+\phi)})$$
$$\bar{A}(\bar{D} \to \bar{f}) = C(1 + re^{i(\delta-\phi)})$$

- C is the leading amplitude
- r is the ratio of sub-leading over leading amplitude

- CP violation requires difference in strong (δ) and weak phase (ϕ):
$$a_{CP} \equiv (|A|^2 - |\bar{A}|^2)/(|A|^2 + |\bar{A}|^2) = 2\,r \sin(\delta) \sin(\phi)$$

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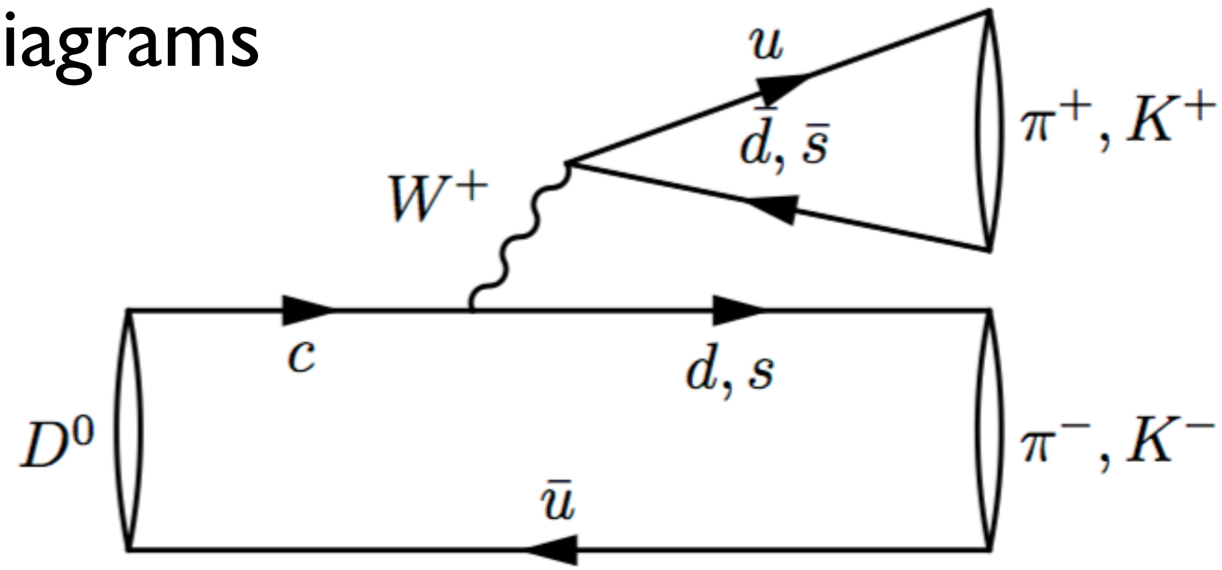
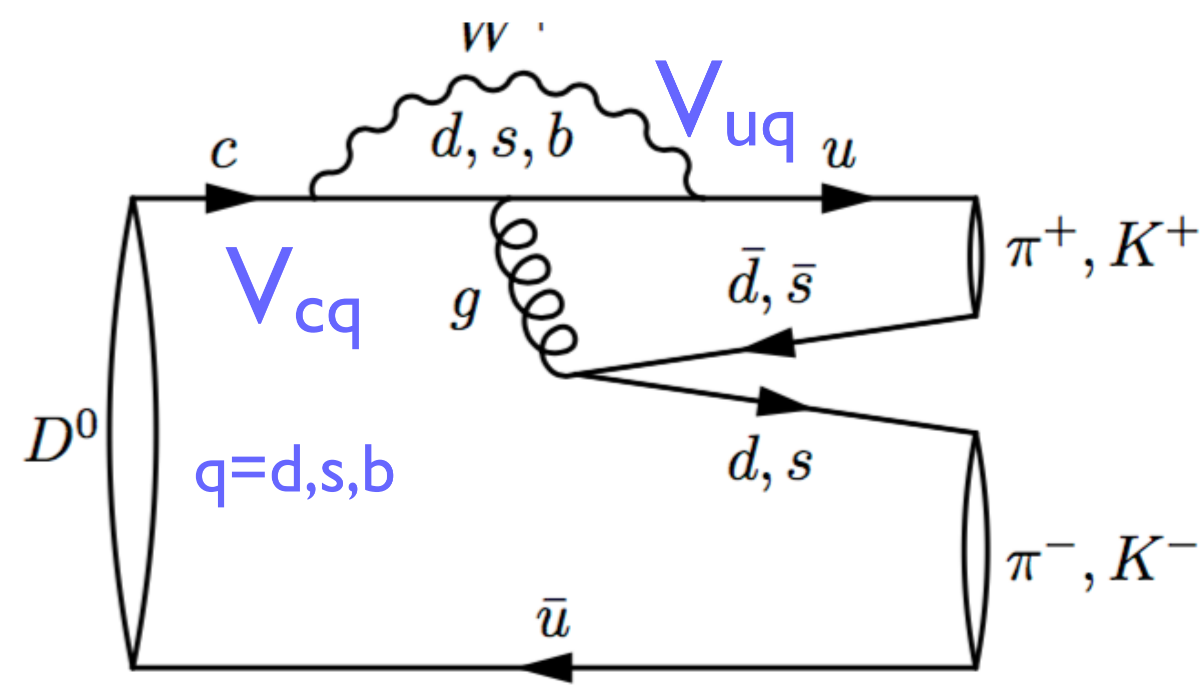
CPV in decay: SCS $D^0 \to h^+h^-$ decays

Often realised by "tree" and "penguin" diagrams



Tree-level weak decay amplitude.

- involves the CKM matrix elements
  - V_{us} and V_{cs} for $D^0 \to K^+K^-$
  - V_{ud} and V_{cd} for $D^0 \to \pi^+\pi^-$



One-loop amplitude ("penguin")

- b-loop involves $V_{ub} V_{cb}^*$: tiny
- s and d loops: similar magnitude, opposite sign

$V_{us} \approx -V_{cd} \approx 0.22$ gives the Cabbibo suppression

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The observable ΔA_{CP}

$$A_{CP}(f) \approx a_{CP}^{\text{dir}}(f)\left(1+\frac{\langle t(f)\rangle}{\tau}y_{CP}\right)+\frac{\langle t(f)\rangle}{\tau}a_{CP}^{\text{ind}}$$ where $y_{CP} \equiv \frac{\Gamma_{CP\pm}}{\Gamma}-1$

$$\boxed{\begin{aligned}\Delta A_{CP} &\equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)\\ &\approx \Delta a_{CP}^{\text{dir}}\left(1+\frac{\overline{\langle t\rangle}}{\tau}y_{CP}\right)+\frac{\Delta\langle t\rangle}{\tau}a_{CP}^{\text{ind}}\end{aligned}}$$

- Mostly a measure of direct CPV
- The indirect CPV is expected to cancel but a small amount could be present due to the different decay time acceptance of the two decays
- ΔA_{CP} is more sensitive to direct CPV but if non-zero, the individual asymmetries are needed to find the source of direct CPV

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What to expect?

Individual asymmetries are expected to have opposite sign due to CKM structure

$$A(\overline{D}^0 \to \pi^+\pi^-, K^+K^-) = \mp\tfrac{1}{2}\left(V_{cs}V_{us}^* - V_{cd}V_{ud}^*\right)(T \pm \delta S) - V_{cb}V_{ub}^*\left(P \mp \tfrac{1}{2}\delta P\right),$$

Direct CP violation depends on the decay mode: can be different for different final states

Expect non-zero $\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi)$ result in presence of direct CP violation

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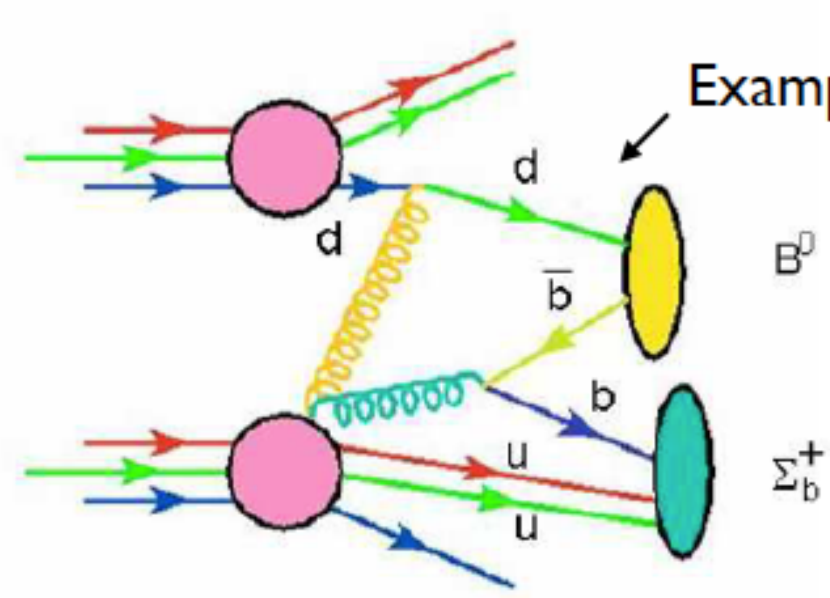
Production asymmetries

Production rates of B^0 and $\bar{B}^0$ (or D^0 and $\bar{D}^0$) are not the same

gluon fusion, quarks combine with valence quark from the beam protons, valence quark scattering, etc.



Example mechanism

Expected to be around 1%

$$a_P = \frac{\sigma(pp \to \bar{B}) - \sigma(pp \to B)}{\sigma(pp \to \bar{B}) + \sigma(pp \to B)}$$

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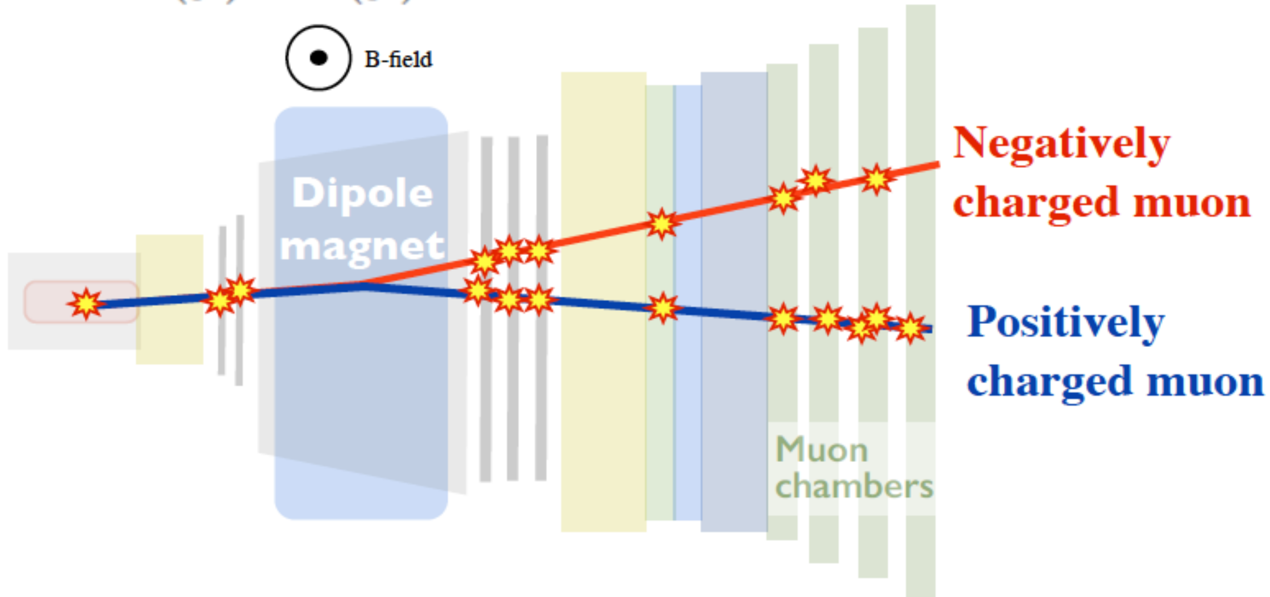
Detection asymmetries (1)

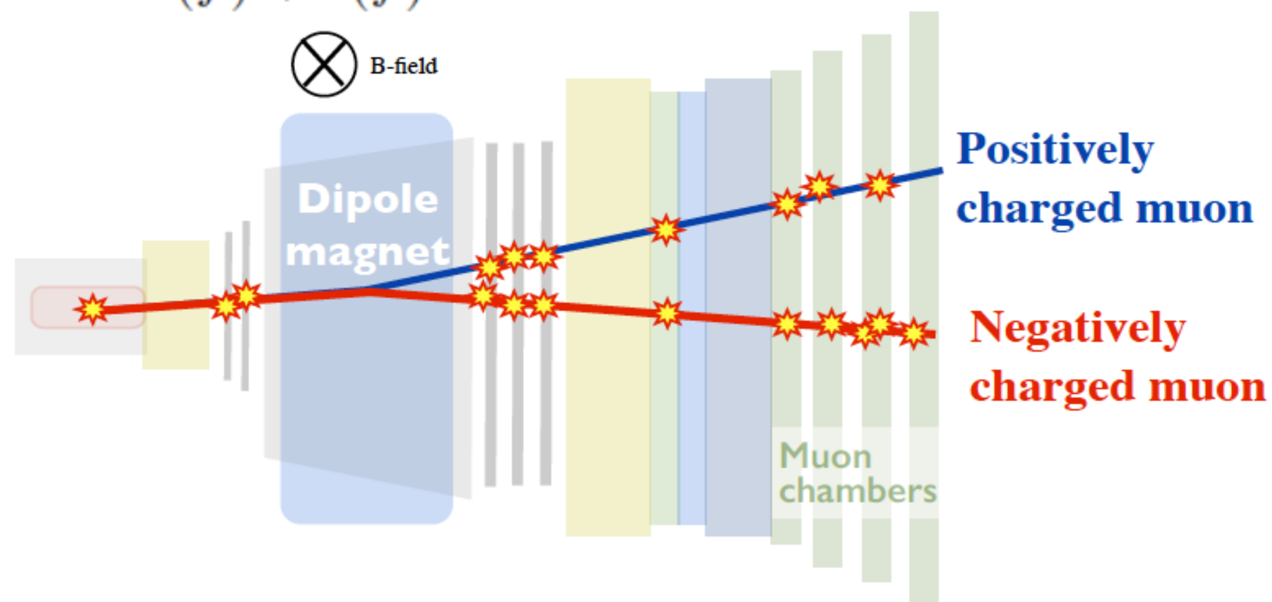
- Detector asymmetries

$$A_D = \frac{\varepsilon(f) - \varepsilon(\overline{f})}{\varepsilon(f) + \varepsilon(\overline{f})}$$



$$A_D = \frac{\varepsilon(f) - \varepsilon(\overline{f})}{\varepsilon(f) + \varepsilon(\overline{f})}$$

Reversed magnet polarity

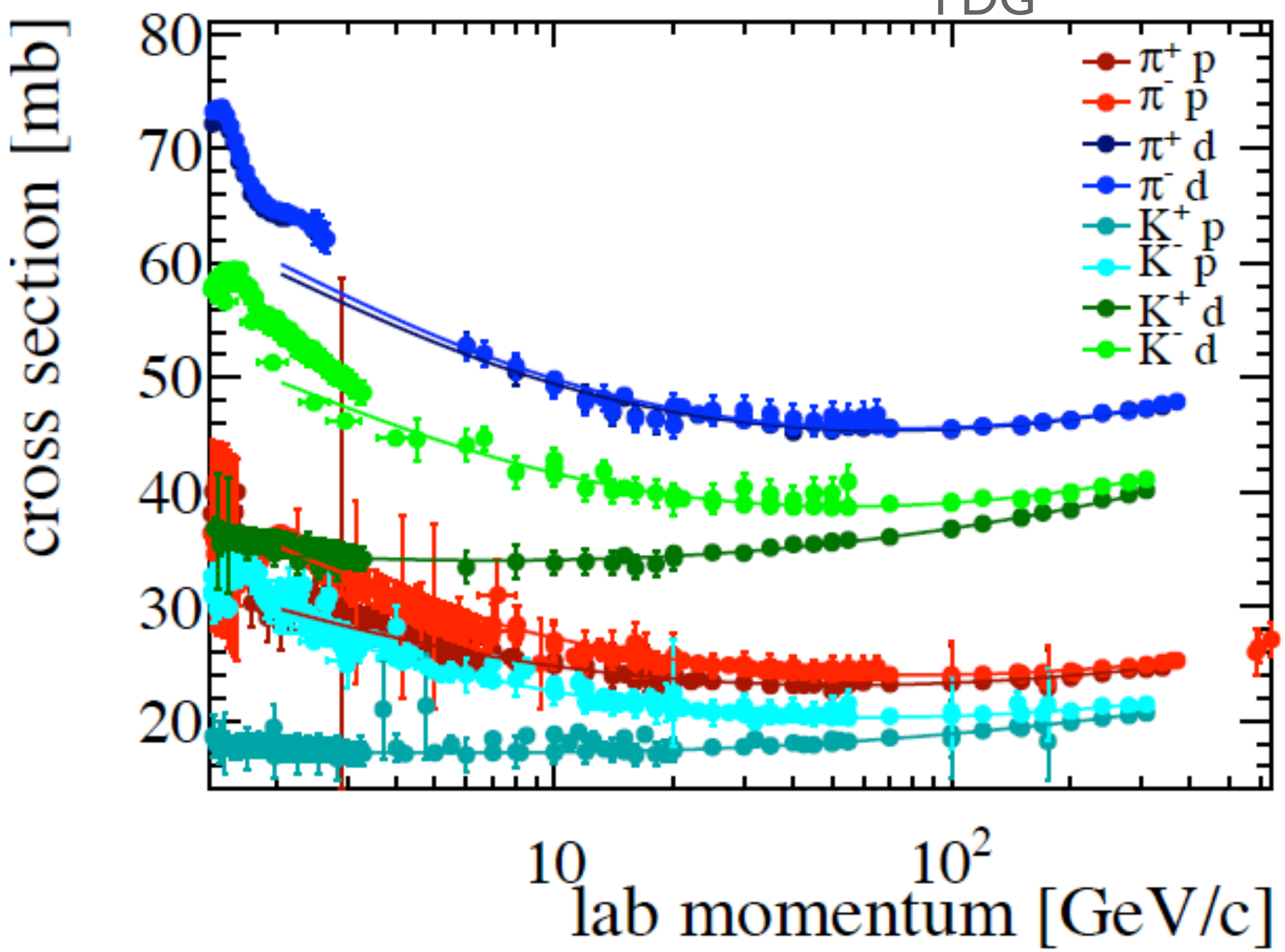


- Cancel left-right asymmetries by swapping dipole field
- But do not rely only on it (detectors move, alignment changes etc.)

Detection asymmetries (2)

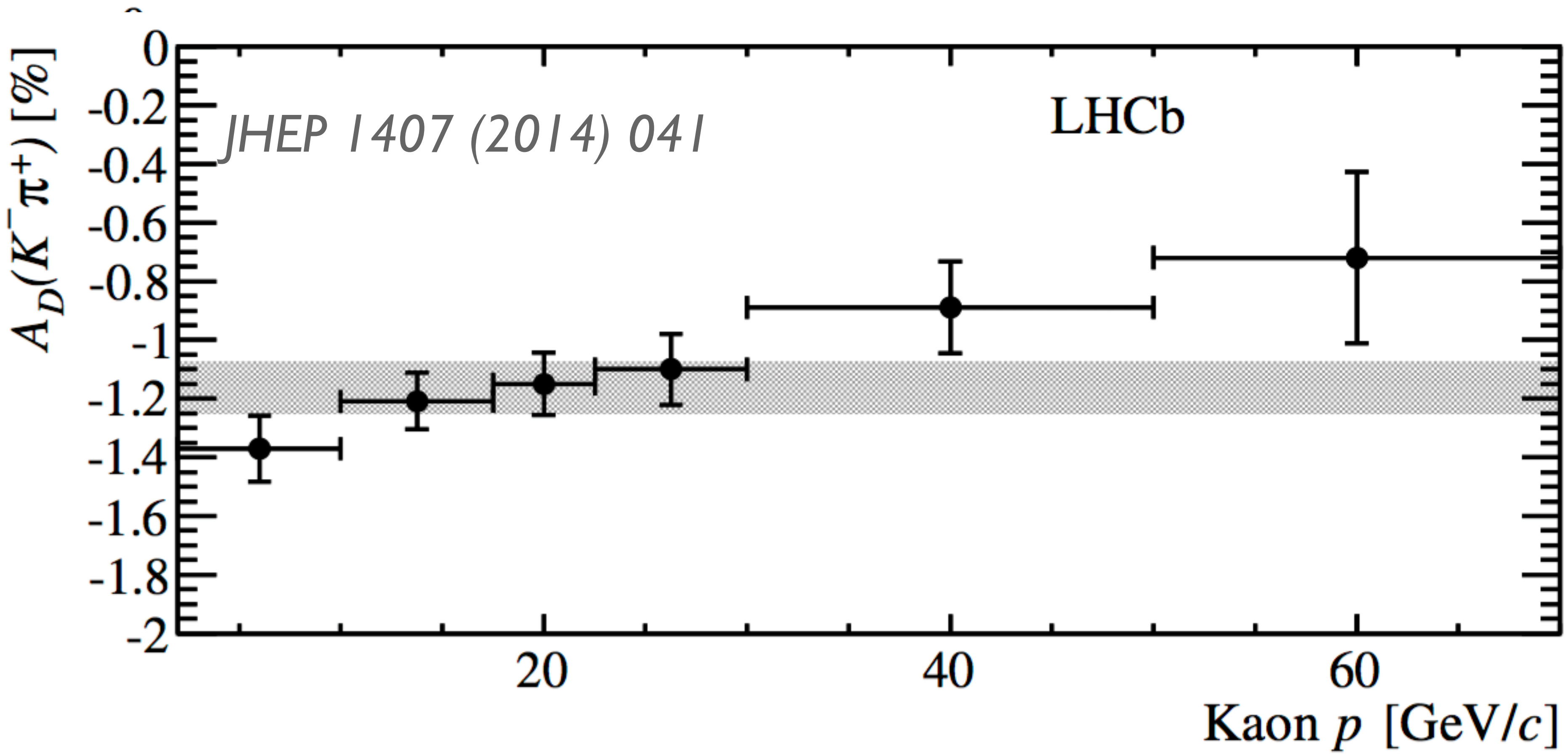
- Interaction asymmetries: e.g. K⁺ cross-section for interaction with matter differs from K⁻ cross-section

PDG



Cancellation of nuisance asymmetries

The detection asymmetries as well as the production asymmetries depend on the kinematics of the decay



A_D, A_P (~1%) cancel to 1st order but if the decays are kinematically very different there would be a residual nuisance asymmetry: equalise the KK and ππ kinematical distributions by re-weighting

Direct CPV search in $D^+_{(s)} \to \eta' \pi^+$

Bin in $\eta(\pi)$, $p_T(\pi)$ to improve cancellation of detector asymmetries

- Main challenge: Background modelling. Main physics BG from $D_{(s)}^+ \to \pi^+(\phi \to \pi^+\pi^-\pi^0)$
- Also gives largest systematic uncertainty
- Statistically limited
- Additional uncertainty from external A_{CP}(control) inputs

arXiv:1701.01871 submitted to PLB

Source	$\delta[\Delta\mathcal{A}_{CP}(D^\pm)]$	$\delta[\Delta\mathcal{A}_{CP}(D_s^\pm)]$
Non-prompt charm	0.03	0.03
Trigger	0.09	0.09
Background model	0.50	0.19
Fit procedure	0.16	0.09
Sideband subtraction	0.03	0.02
K^0 asymmetry	0.08	–
$D^\pm_{(s)}$ production asymmetry	0.07	0.02
Total	0.55	0.24

$$\mathcal{A}_{CP}(D^\pm \to \eta'\pi^\pm) = (-0.61 \pm 0.72 \pm 0.55 \pm 0.12)\,\%$$
$$\mathcal{A}_{CP}(D_s^\pm \to \eta'\pi^\pm) = (-0.82 \pm 0.36 \pm 0.24 \pm 0.27)\,\%$$

Consistent with CP conservation

Most precise measurements to date of these variables

Multi-body decays and local asymmetries

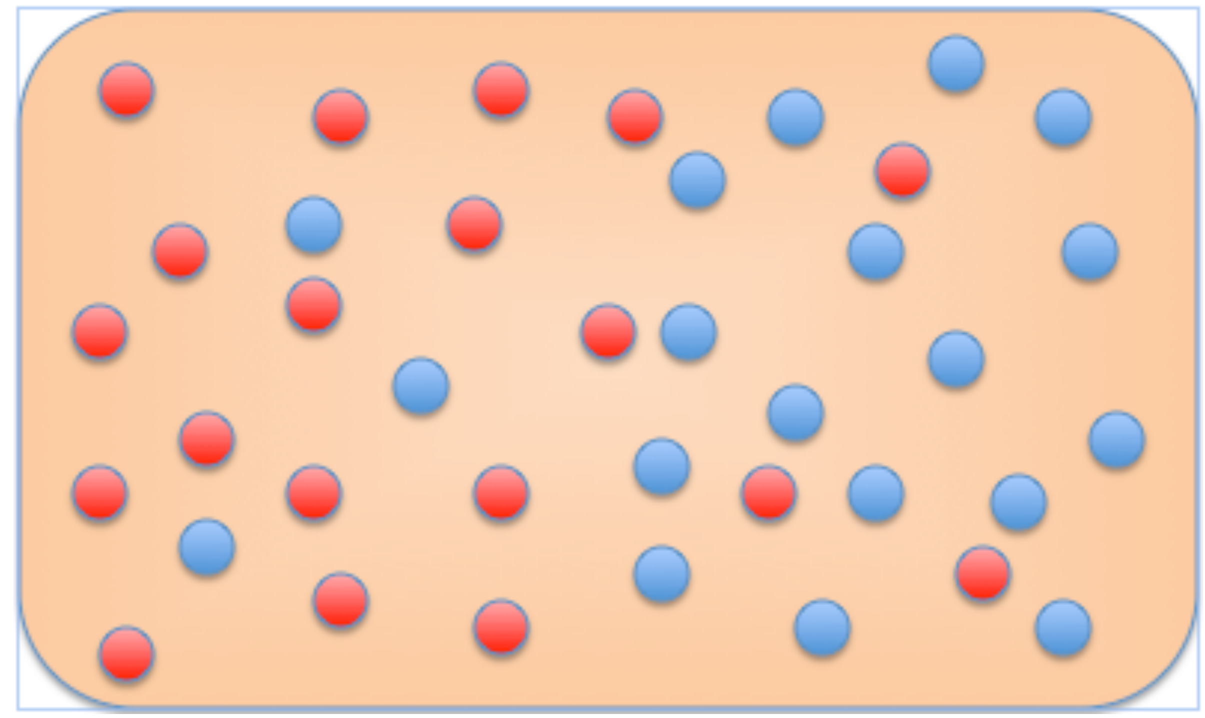
- Many ways to reach multi-body final states through intermediate resonances
- Resonances interfere and can carry different strong phases: Superb playground for CP violation

Local asymmetries

- potentially larger than the phase space integrated ones
- may change sign across the phase space
- additional information about the dynamics

Energy test

- Compare two distributions statistically
- Idea comes from the calculation of electric potential energy



+q and −q equally distributed,
electric potential energy = 0

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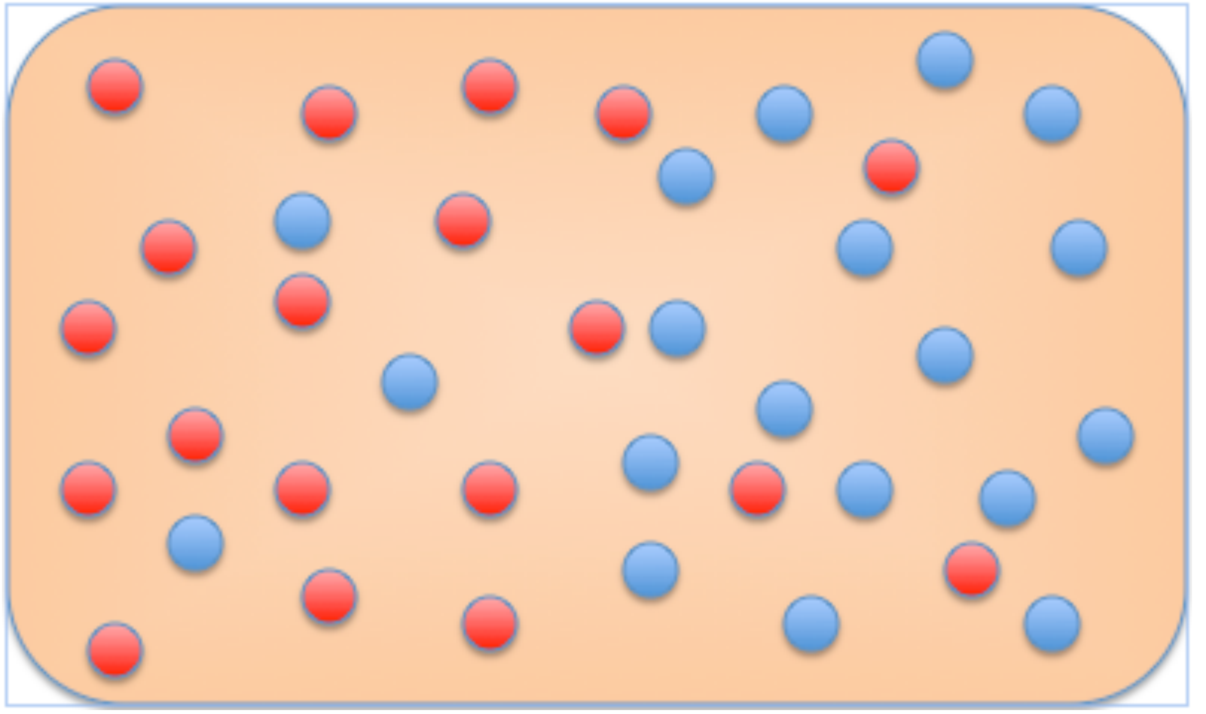
Energy test

- Compare two distributions statistically
- Idea comes from the calculation of electric potential energy



+q and −q equally distributed,
electric potential energy = 0

+q and −q distributions different,
electric potential energy > 0

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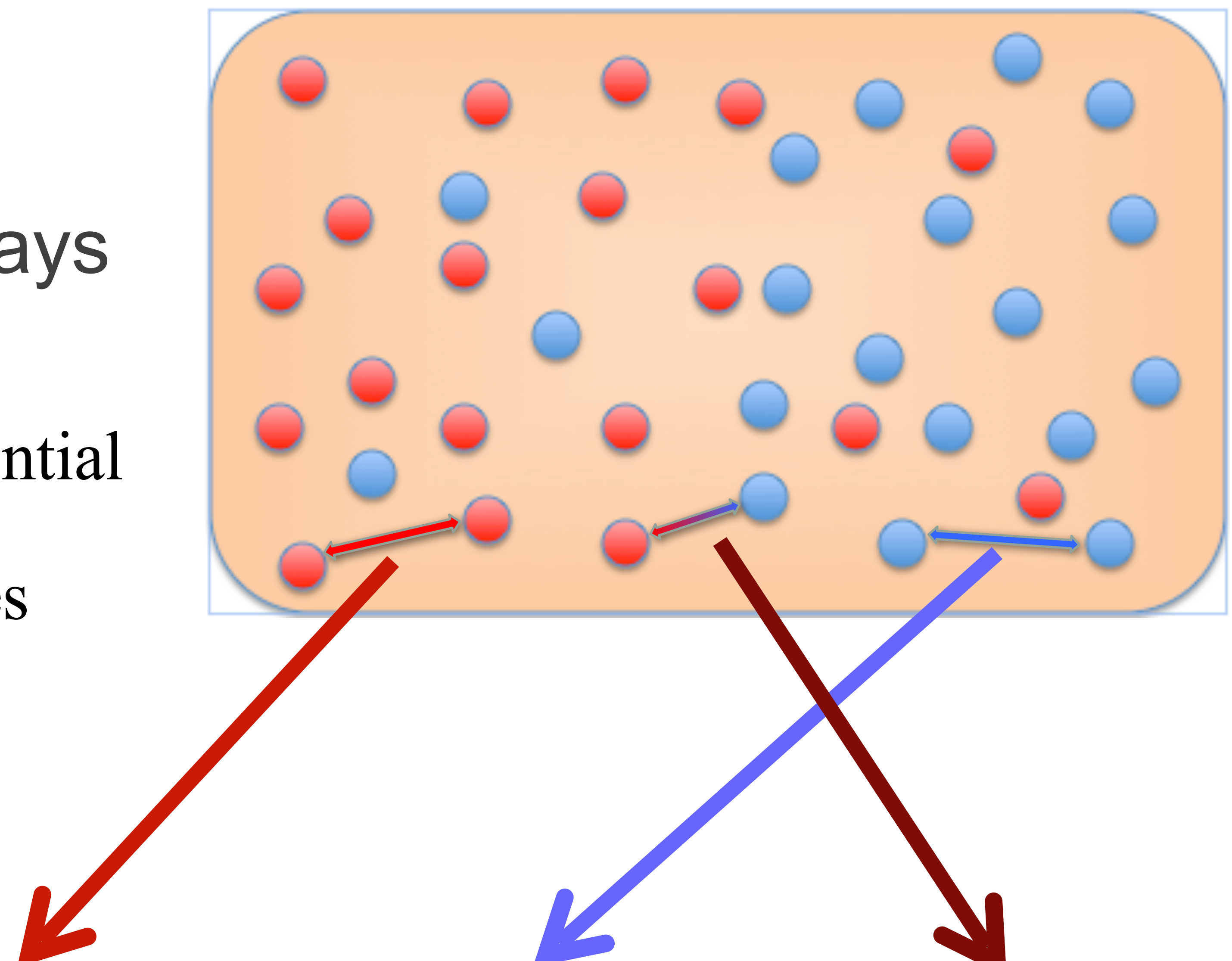
Energy test

System → phase space

+q /−q → opposite flavoured decays



$\psi(d_{ij}) = e^{-d_{ij}/2\delta^2}$: interaction potential

$n, \bar{n}$: number of $D^0, \overline{D}^0$ candidates

d_{ij} : distance in phase space

δ - tunable parameter:
effectively, radius in the phase space in which a local asymmetry is measured

D^0-D^0 $\overline{D}^0$-$\overline{D}^0$ D^0-$\overline{D}^0$

Test statistic: $T = \frac{1}{n(n-1)} \sum_{i,j>i}^{n} \psi(d_{ij}) + \frac{1}{\bar{n}(\bar{n}-1)} \sum_{i,j>i}^{\bar{n}} \psi(d_{ij}) - \frac{1}{n\bar{n}} \sum_{i,j}^{n,\bar{n}} \psi(d_{ij})$

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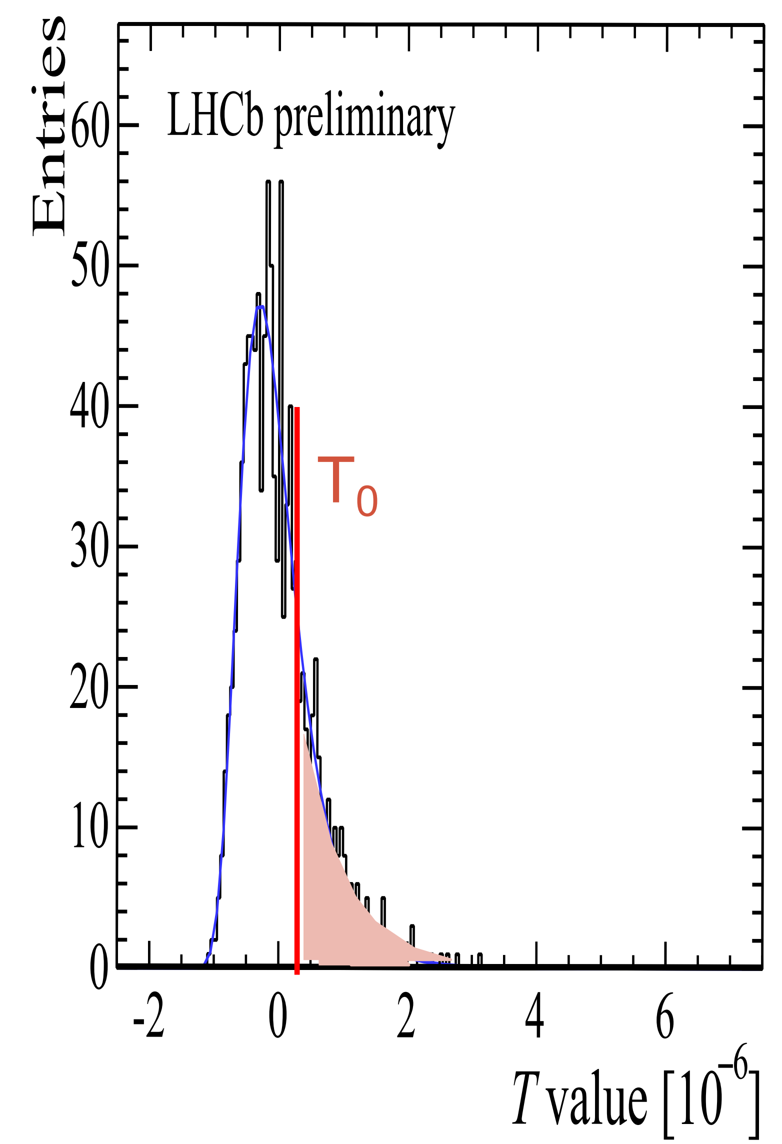
Energy test p-value

Phys. Lett. B 769 345-356

- Calculate p-value for no CPV hypothesis
- Compare T-value from tested sample (T_0) with T-values from no-*CPV* samples
- No-*CPV* sample from permutation of data: randomly assign flavour tags
- p-value: fraction of permutation T-values above T_0



Large *p*-value, no-*CPV*

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New *P*-odd observables

- In decays to four or more pseudo-scalars, there is the possibility of using *P*-parity-odd observables for *CP* violation searches
- Four-body-decay kinematics cannot be described unambiguously using only invariant-mass-squared variables, as these are all parity even
- Introduce triple product C_T as parity sensitive variable

$$C_T = \vec{p}(\pi_3) \cdot [\vec{p}(\pi_1) \times \vec{p}(\pi_2)]$$

- Analyse different flavours and signs of C_T regions

Detection / tracking / production asymmetries

- Cancellations occur due to method
- Verified with a control sample of Cabibbo-favoured $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ decays
  - Split into ten sub-samples equal in size to signal mode
  - Sensitive with neither *P*-even nor *P*-odd tests
- *p*-value distributions for reference sample

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Sensitivity tests with Monte Carlo

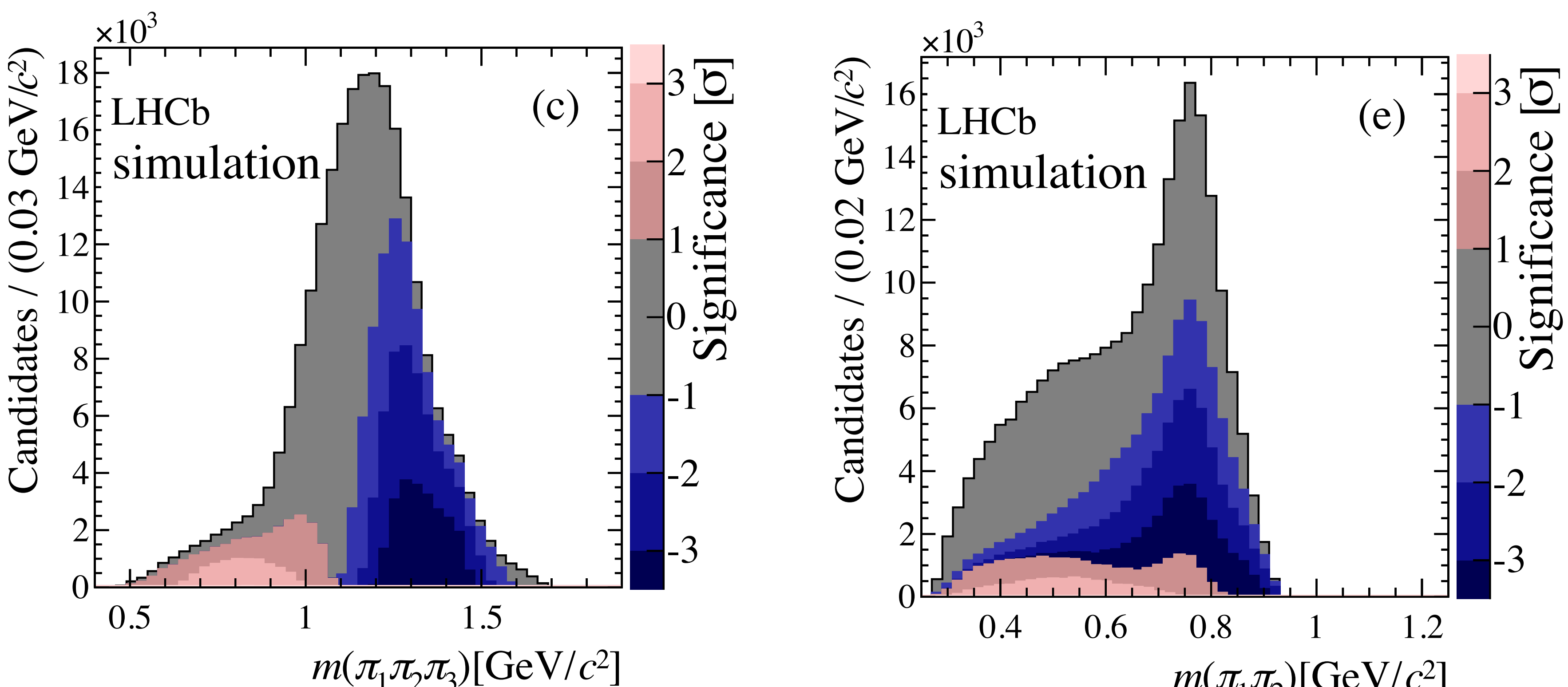
Phys. Lett. B 769 345-356

- Performed for both *P*-even and *P*-odd tests
- Insert *CP* violation to simulated samples*, apply energy test, determine the sensitivity
- Visualise significance of asymmetries by assigning per-event T-values
- Highlight those >1,2,3σ positive in pink, negative in blue

R (partial wave) $(\Delta A, \Delta\phi)$	p-value (fit)
$a_1 \to \rho^0\pi$ (S) $(5\%, 0°)$	$2.6^{+3.4}_{-1.7} \times 10^{-4}$
$a_1 \to \rho^0\pi$ (S) $(0\%, 3°)$	$1.2^{+3.6}_{-1.2} \times 10^{-6}$
ρ^0 ρ^0 (D) $(5\%, 0°)$	$3.8^{+2.9}_{-1.9} \times 10^{-3}$
ρ^0 ρ^0 (D) $(0\%, 4°)$	$9.6^{+24}_{-7.2} \times 10^{-6}$
ρ^0 ρ^0 (P) $(4\%, 0°)$	$3.0^{+1.2}_{-0.9} \times 10^{-3}$
ρ^0 ρ^0 (P) $(0\%, 3°)$	$9.8^{+4.4}_{-3.8} \times 10^{-4}$

P-even

P-odd



Example:
3° phase difference in $D^0 \to a_1(1260)^+\pi^-$ Amplitude
(*P*-even test)

*Amplitude model taken from P. d'Argent, N. Skidmore … E.Gersabeck et al. arXiv:1703.08505

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Results for CPV searches in the $D^0 \to K_S K \pi$

- In the CPV searches the resonance amplitude $a_R \to a_R(1 \pm \Delta a_R)$; the phase $\Phi_R \to \Phi_R \pm \Delta\Phi_R$

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

	Δa_R	$\Delta\Phi_R$
$K^*(892)^+$	0.0 (fixed)	0.0 (fixed)
$K^*(1410)^+$	$0.07 \pm 0.06 \pm 0.04$	$3.9 \pm 3.5 \pm 1.9$
$(K^0_S\pi)^+_{S\text{-wave}}$	$0.02 \pm 0.08 \pm 0.07$	$2.0 \pm 1.7 \pm 0.0$
$\overline{K}^*(892)^0$	$-0.046 \pm 0.031 \pm 0.005$	$1.2 \pm 1.6 \pm 0.3$
$\overline{K}^*(1410)^0$	$0.006 \pm 0.034 \pm 0.017$	$2 \pm 5 \pm 5$
$(K\pi)^0_{S\text{-wave}}$	$0.05 \pm 0.04 \pm 0.02$	$0.4 \pm 1.6 \pm 0.6$
$a_2(1320)^-$	$-0.25 \pm 0.14 \pm 0.01$	$2 \pm 9 \pm 3$
$a_0(1450)^-$	$-0.01 \pm 0.14 \pm 0.12$	$0 \pm 5 \pm 4$
$\rho(1450)^-$	$0.06 \pm 0.13 \pm 0.11$	$-13 \pm 10 \pm 9$

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

	Δa_R	$\Delta\Phi_R$
$K^*(892)^-$	0.0 (fixed)	0.0 (fixed)
$K^*(1410)^-$	$0.05 \pm 0.12 \pm 0.08$	$-6 \pm 4 \pm 3$
$(K^0_S\pi)^-_{S\text{-wave}}$	$0.10 \pm 0.25 \pm 0.24$	$-7.7 \pm 3.4 \pm 0.0$
$K^*(892)^0$	$-0.010 \pm 0.024 \pm 0.001$	$-1.4 \pm 2.9 \pm 2.2$
$K^*(1410)^0$	$0.10 \pm 0.10 \pm 0.09$	$-1 \pm 9 \pm 8$
$(K\pi)^0_{S\text{-wave}}$	$-0.07 \pm 0.06 \pm 0.05$	$-2 \pm 4 \pm 4$
$a_0(980)^+$	$0.06 \pm 0.04 \pm 0.01$	$-3 \pm 5 \pm 2$
$a_0(1450)^+$	$-0.11 \pm 0.10 \pm 0.04$	$10 \pm 8 \pm 5$
$\rho(1700)^+$	$-0.03 \pm 0.13 \pm 0.09$	$4 \pm 6 \pm 2$

No CPV

Phys. Rev. D 93, 052018 (2016)

Triple product observables in multi-body decays

Triple product observables in theory

Different sensitivity to CPV

CP asymmetries $\sim \sin\varphi \sin\delta$

Triple product asymmetries $\sim \sin\varphi \cos\delta$

More careful consideration given in Durieux, Grossman
Phys. Rev. D 92, 076013 (2015)

Unlike total rate asymmetries between CP-conjugate processes, their sensitivity to small differences in CP-violating phases is not conditioned by the presence of CP-conserving strong phase differences.

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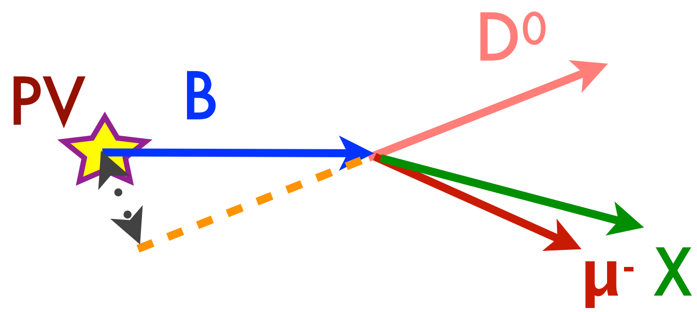
CP violation in $D^0 \to KK\pi\pi$



Analysis based on the full Run I statistics
Using secondary charm

Using triple product of final state particle momenta

$$C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}) \qquad \overline{C}_T \equiv \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})$$

Define tripple product asymmetries

$$A_T \equiv \frac{\Gamma_{D^0}(C_T > 0) - \Gamma_{D^0}(C_T < 0)}{\Gamma_{D^0}(C_T > 0) + \Gamma_{D^0}(C_T < 0)}, \qquad \overline{A}_T \equiv \frac{\Gamma_{\overline{D}^0}(-\overline{C}_T > 0) - \Gamma_{\overline{D}^0}(-\overline{C}_T < 0)}{\Gamma_{\overline{D}^0}(-\overline{C}_T > 0) + \Gamma_{\overline{D}^0}(-\overline{C}_T < 0)},$$

$$a_{CP}^{T\text{-odd}} \equiv \frac{1}{2}(A_T - \overline{A}_T)$$

All final states interactions cancel
All production and detection effects cancel

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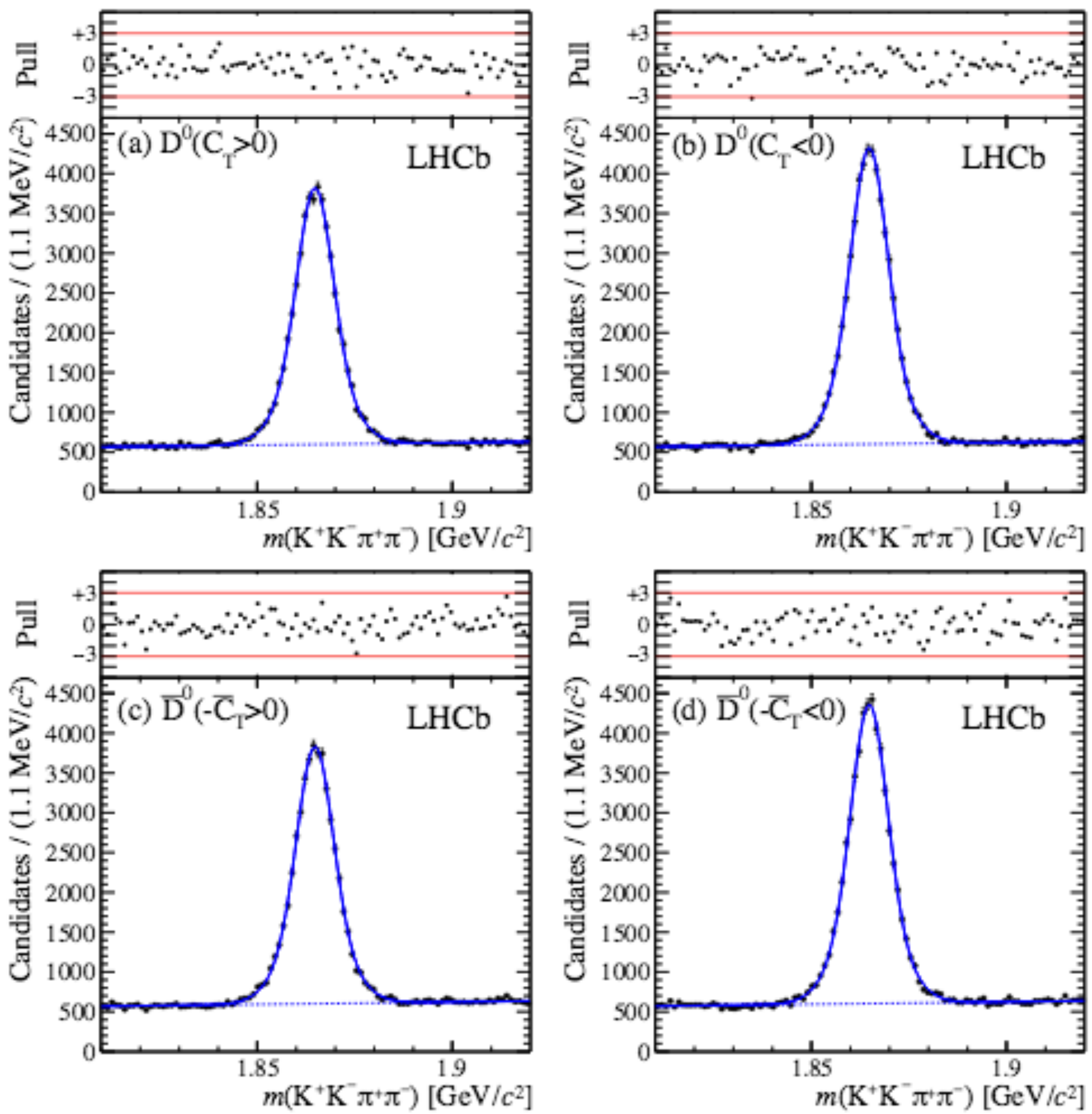
JHEP 1410 (2014) 005

CP violation in $D^0 \to KK\pi\pi$



~171k decays

Integrated over the phase-space

$a^{T\text{-odd}}_{CP} = (0.18 \pm 0.29 \pm 0.04)\%$

additionally: measurements in bins of decay time and phase space regions

No indication of CPV

Previous measurements by
FOCUS: $(1.0 \pm 5.7 \pm 3.7)\%$ PLB622 (2005) 239-248
BaBar: $(0.10 \pm 0.51 \pm 0.44)\%$ PRD81(2010) 111103

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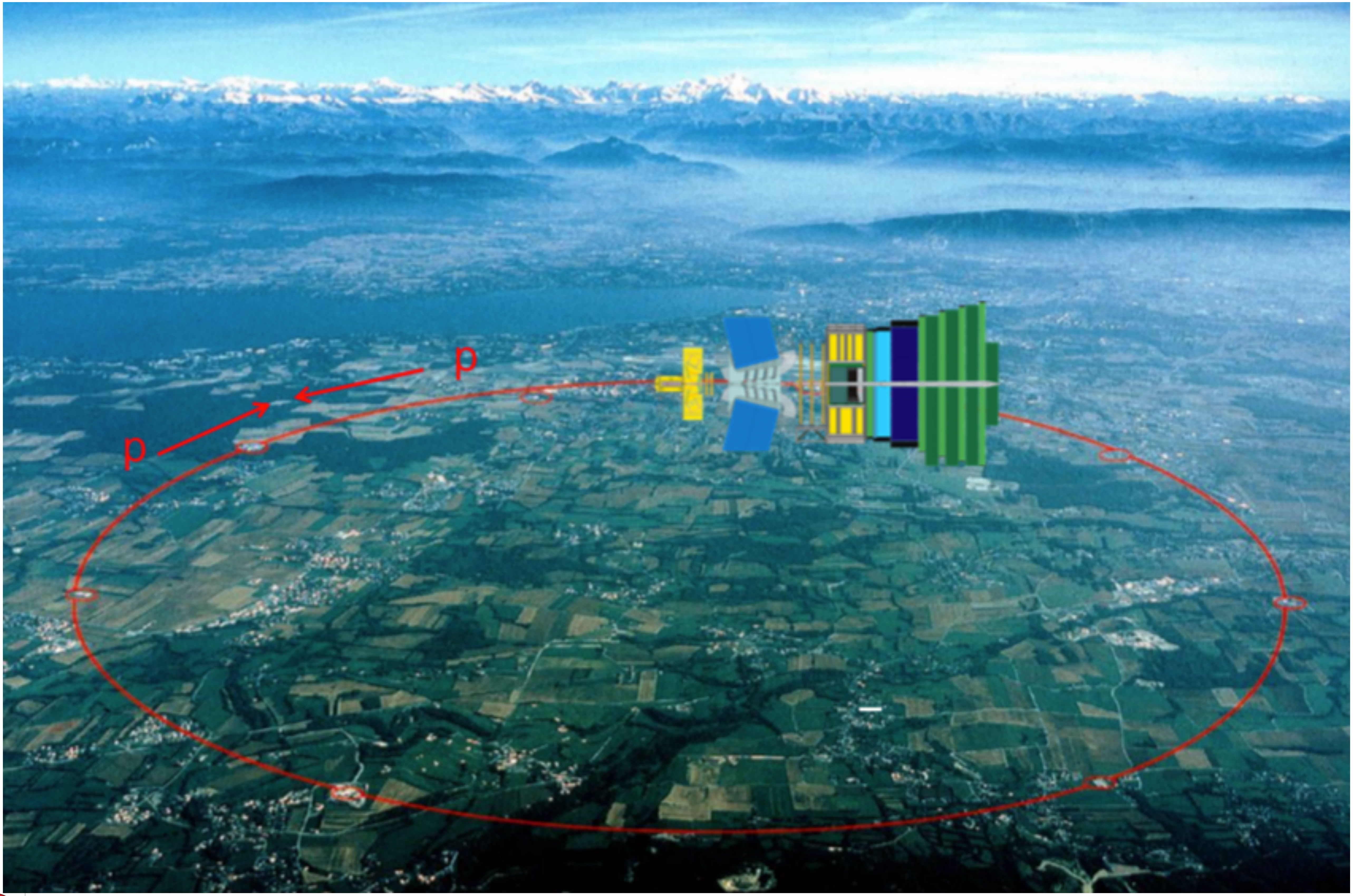
Improved trigger strategies for Run11

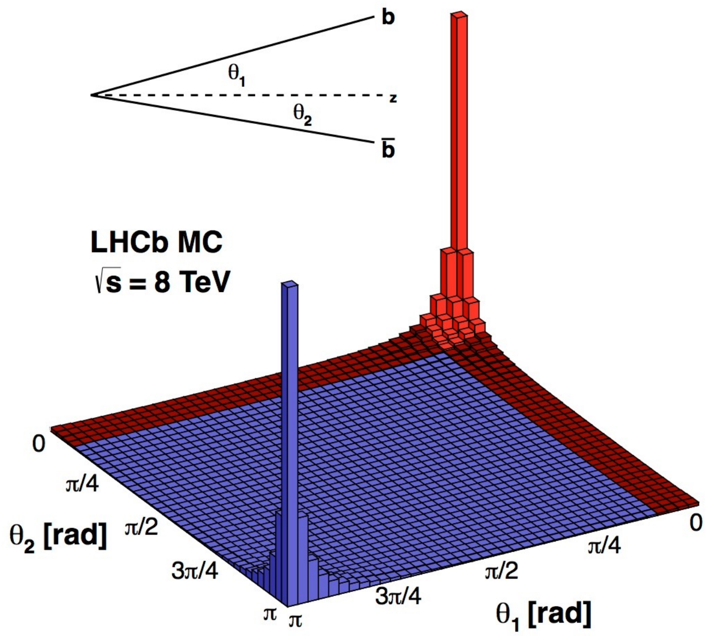
- Turbo stream of the trigger:
  - Data are ready for analysis directly after the trigger
  - Smaller size of raw events: reduce pre-scaling
- More efficient exclusive charm triggers
  - Split high level trigger in 2 stages: gain CPU power
  - Events from lower trigger levels can be buffered on disk while performing real-time alignment and calibration
  - Improved speed of the algorithms

LHC & LHCb



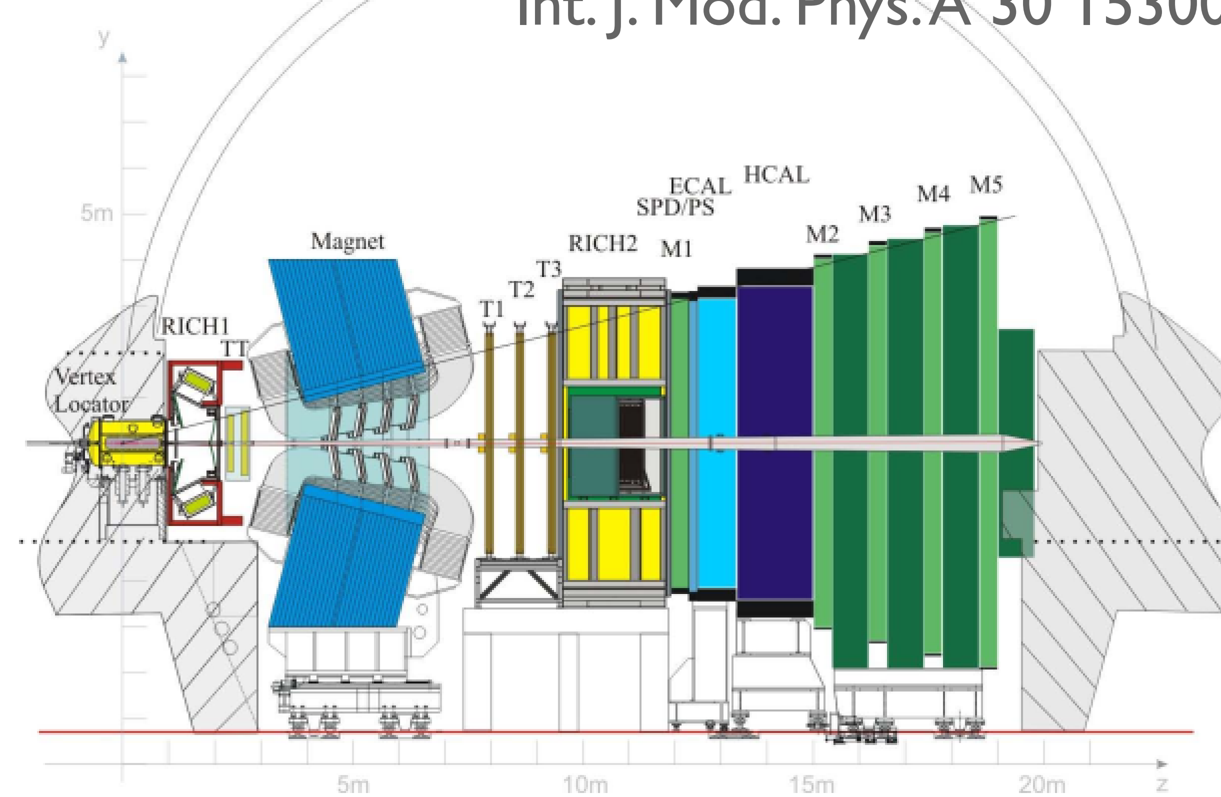
Forward spectrometer at LHC

LHCb is optimised for heavy flavour physics



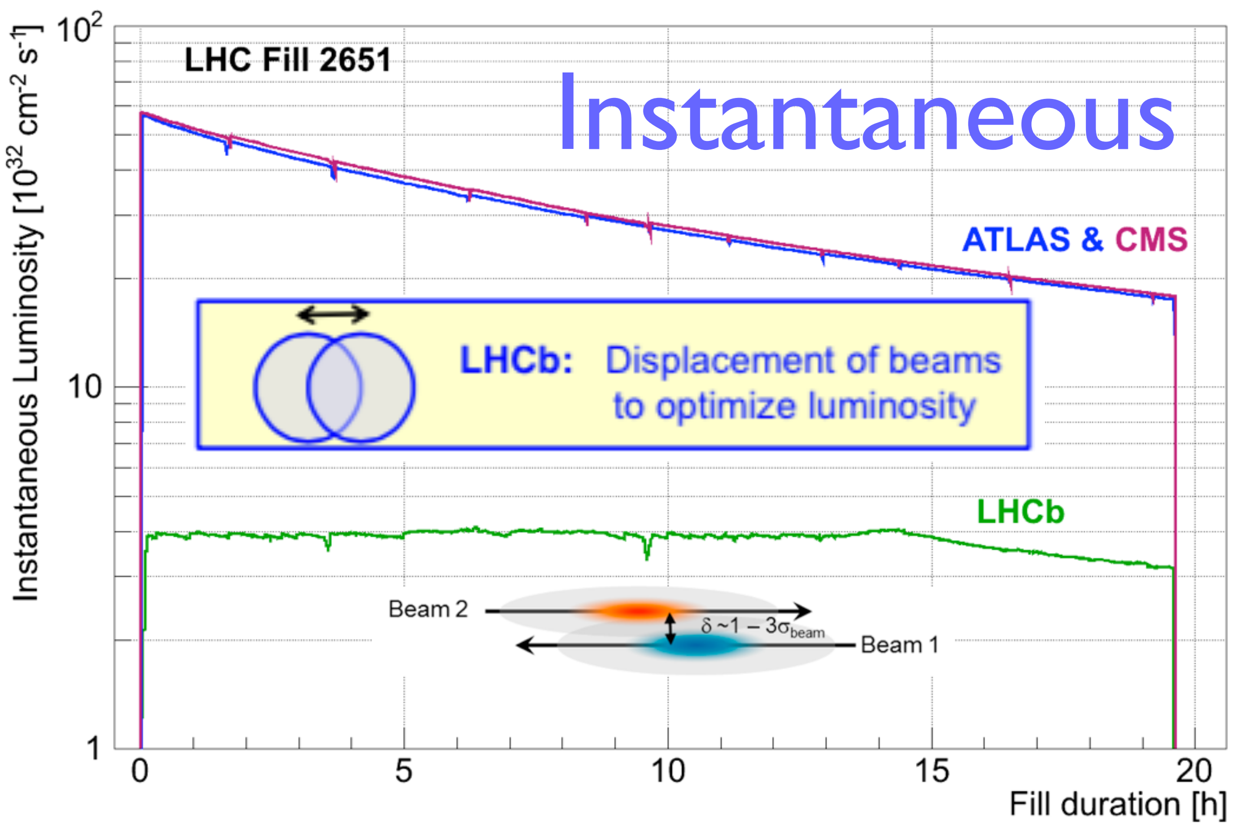
$b\bar{b}$ (and $c\bar{c}$) production angles strongly correlated: heavily boosted in the forward or backward direction

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

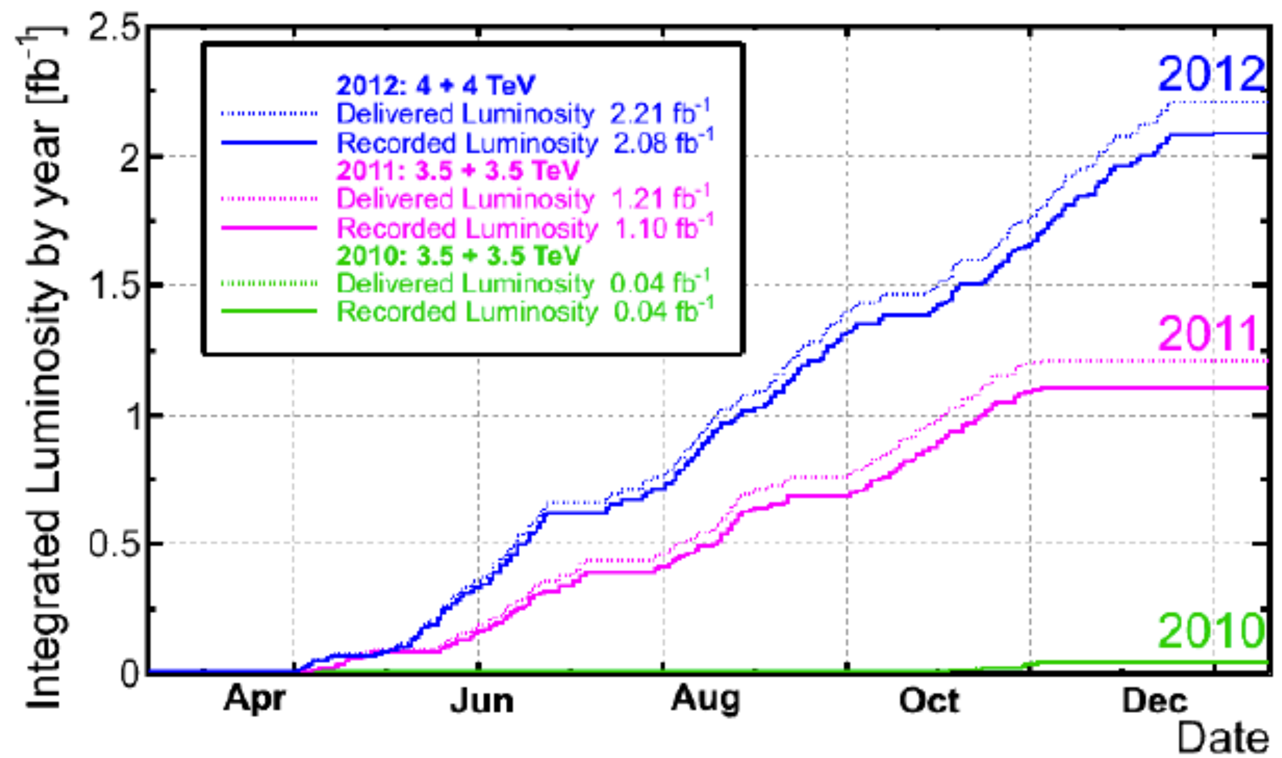


- Forward acceptance $2<\eta<5$
- Precise vertex reconstruction
- Precise & efficient tracking
- Excellent decay time resolution ~$0.1\tau_D$
- Hadron identification: RICHes
- Dipole magnet with reversible polarity

Run 1 performance



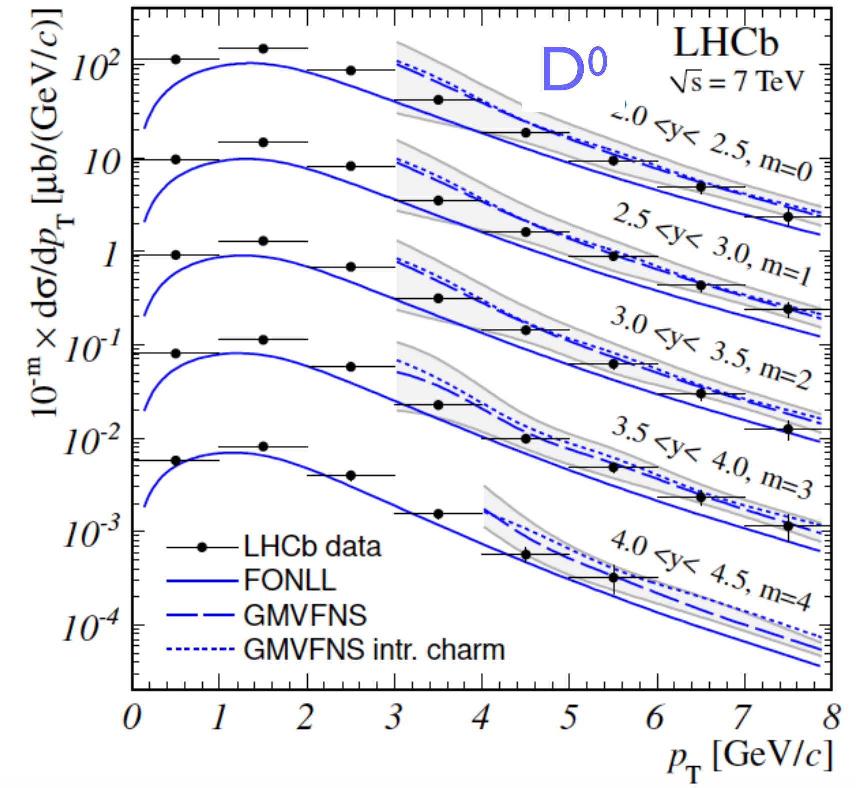
Luminosity levelling unlike ATLAS and CMS: uniform operating conditions



Charm production cross-sections @ 7TeV in LHCb acceptance

All c species produced at LHCb

$$\sigma(D^0) = 1661 \pm 129\,\mu b$$
$$\sigma(D^+) = 645 \pm 74\,\mu b$$
$$\sigma(D^{*+}) = 677 \pm 83\,\mu b$$
$$\sigma(D_s^+) = 197 \pm 31\,\mu b$$
$$\sigma(\Lambda_c^+) = 233 \pm 77\,\mu b$$



- Cross section for cc̄ in LHCb acceptance

$$\boxed{\sigma(c\bar{c})_{p_T<8\,\text{GeV}/c,\,2.0<y<4.5} = 1419 \pm 12\,(\text{stat}) \pm 116\,(\text{syst}) \pm 65\,(\text{frag})\,\mu b}$$

2010 data
Nucl.Phys. B871 (2013) 1-20

  - ~5×10^{12} D^0 mesons produced in LHCb acceptance in run1
- Huge statistics of prompt and secondary charm: worlds' best sensitivity to very small CP asymmetries