CP violation searches in the charm sector at LHCb

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on behalf of the LHCb collaboration

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Outline

- CP violation
- LHCb & its performance during Run I
- Run I results
    - Indirect CPV searches in $D^0 \rightarrow h^+h^-$
    - Direct CPV searches in $D^0 \rightarrow h^+h^-$
    - Complementary CPV searches in other two- and multi-body decays
- Prospects for Run II and the LHCb upgrade

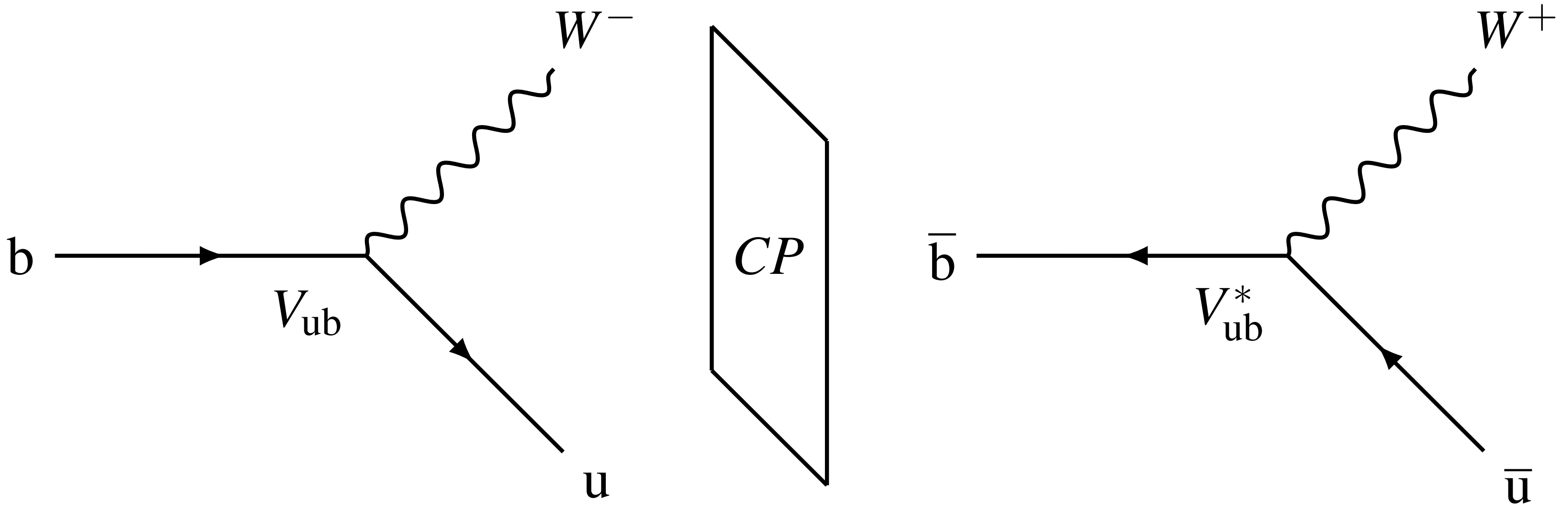
CP violation

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

Types of CPV: direct CPV

The decay rate of a particle to a final state f, A_f, is different to the rate of the anti-particle decay to the CP conjugate final state $\bar{f}$, $\bar{A}_{\bar{f}}$.

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

Direct CPV occurs for non-zero Ad

$$A_d \equiv (|A_f|^2 - |\bar{A}_f|^2)/(|A_f|^2 + |\bar{A}_f|^2)$$

This type of CPV depends on decay mode.

Types of CPV: indirect CPV

CPV in mixing (involves neutral particles)

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

$$P(M^0(t) \to \overline{M}^0) \neq P(\overline{M}^0(t) \to M^0)$$

Occurs if: $|q/p| \neq 1$

Where p,q - complex coefficients relating the mass and the flavour eigenstates

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle$$

Types of CPV: indirect CPV

CPV in interference (mixing and decay amplitudes can interfere)

Present if the imaginary part of λ_f is non-zero

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

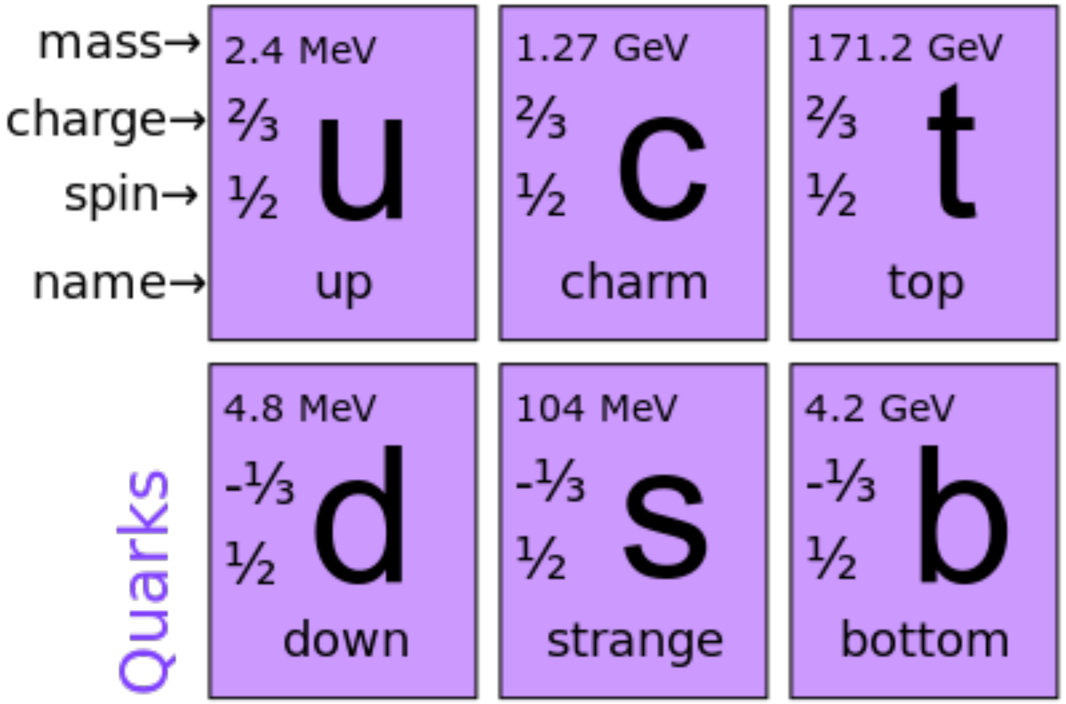
φ is the CP violating relative phase between q/p and $\bar{A}_{\bar{f}}/A_f$

It involves neutral particles

The indirect CP violation is independent of the decay mode.

CPV in K,B,D mesons

- Discovered in decays of strange and beauty mesons containing quarks from the down sector
- What about the up-sector?



Charm

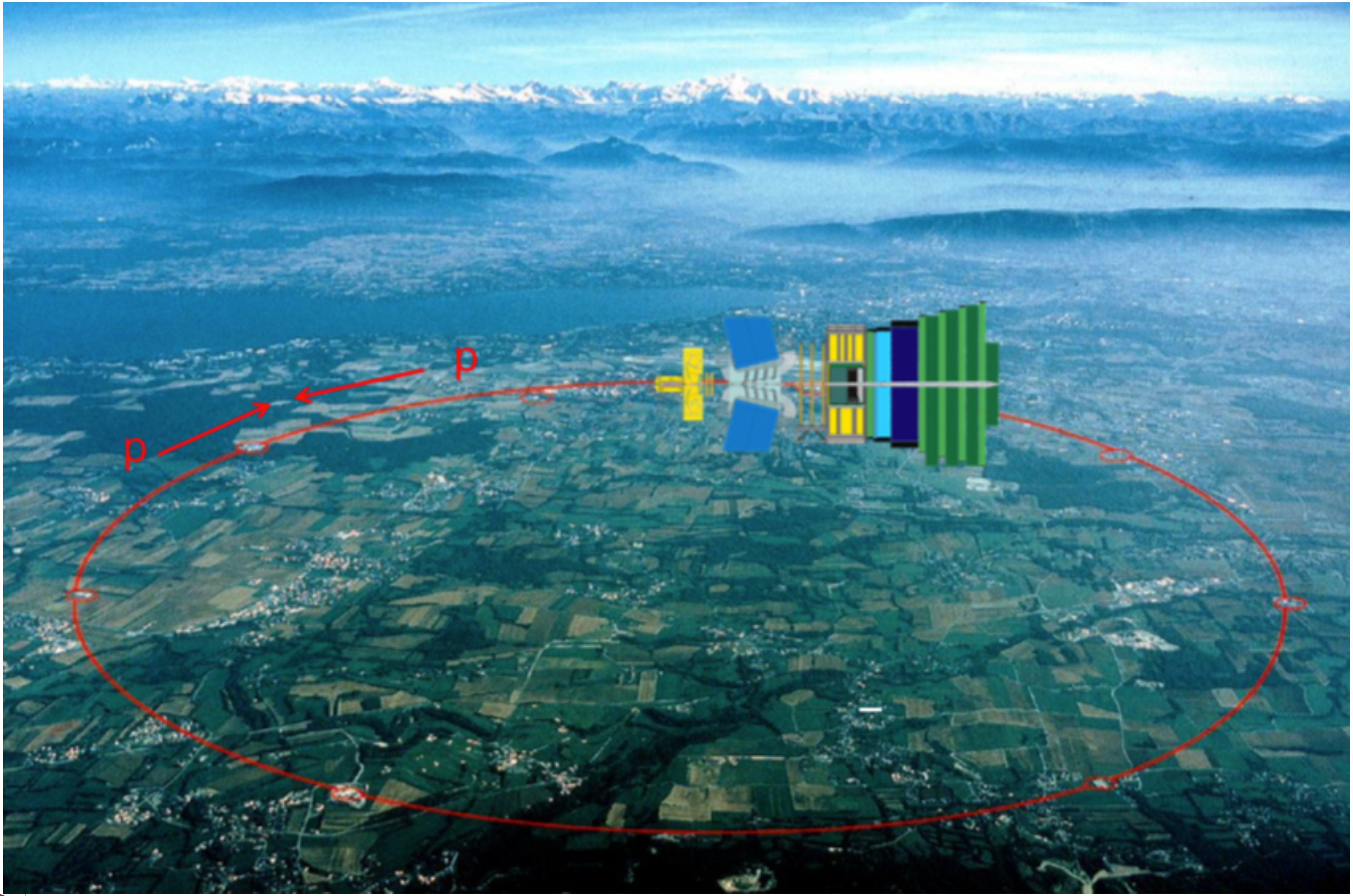
- Charm is unique: only bound up-type quark system where mixing and CP violation can occur

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

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

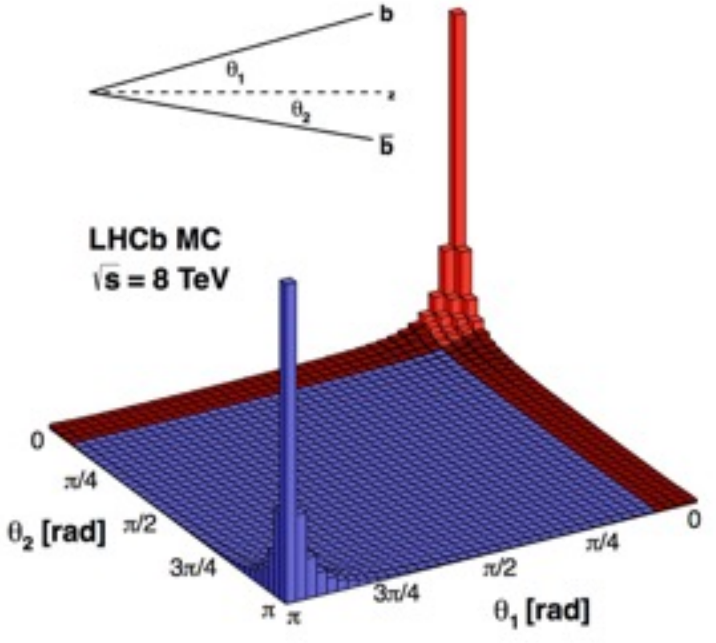
- Making precise SM predictions in the D-meson sector is difficult
  - Perturbative QCD valid at energies >> 1 GeV
  - Chiral perturbation theory valid between 0.1 GeV and 1 GeV
  - D^0 mass = 1.864 GeV

LHC & LHCb



Forward spectrometer at LHC

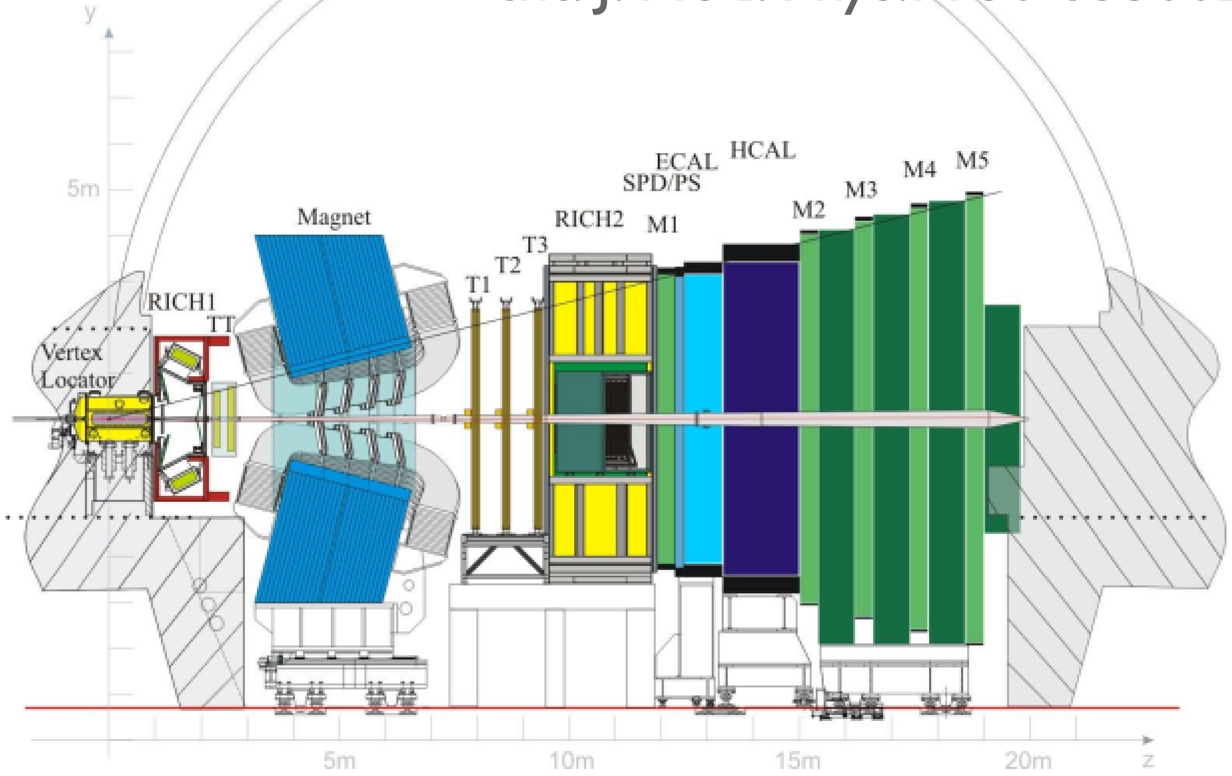
LHCb is optimised for heavy flavour physics



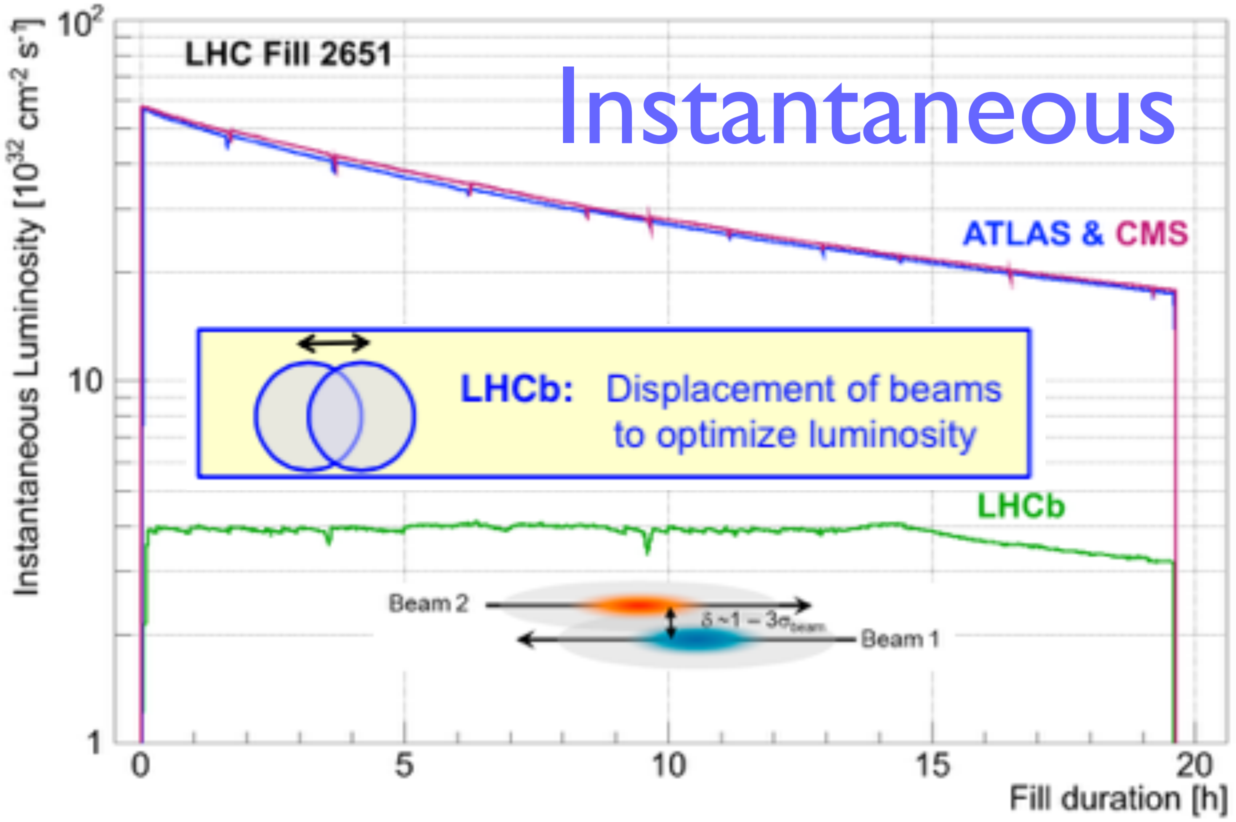
$b\bar{b}$ (and $c\bar{c}$) production angles strongly correlated: heavily boosted in the forward or backward direction

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

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



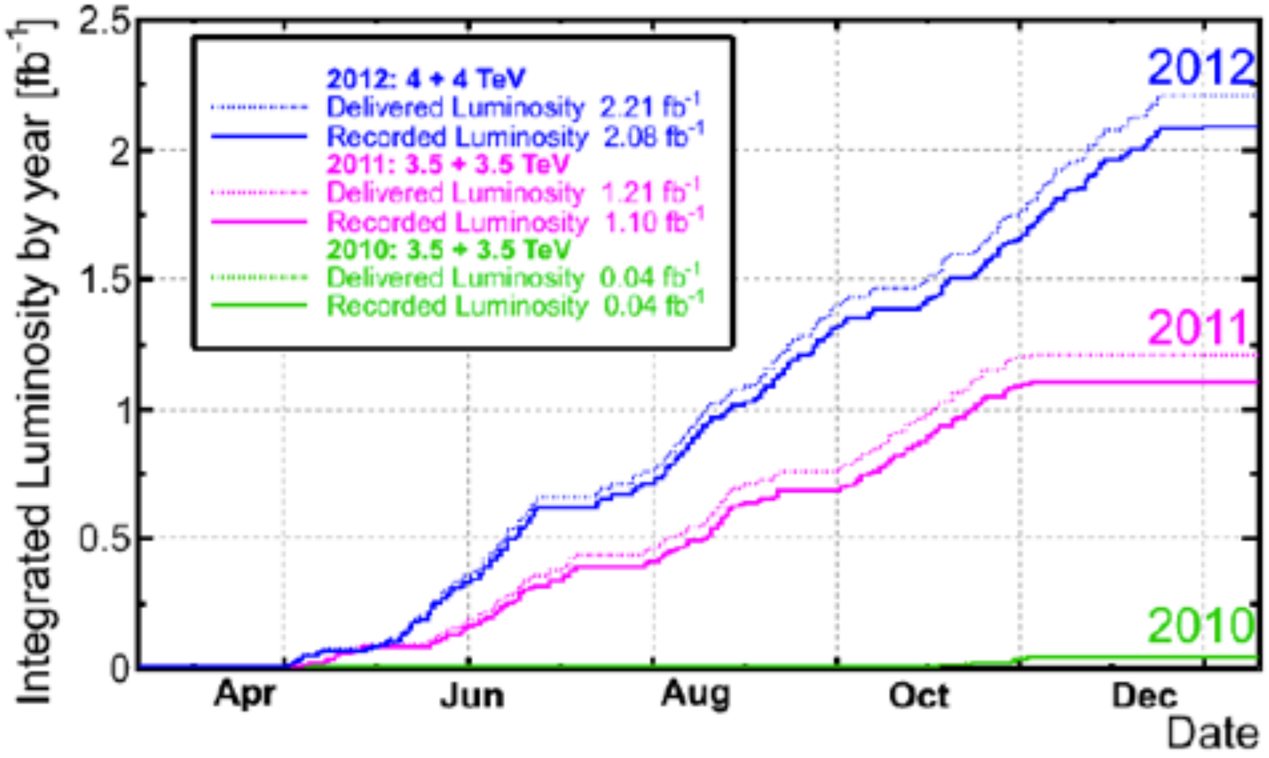
Run 1 performance



Instantaneous

Luminosity levelling unlike ATLAS and CMS: uniform operating conditions

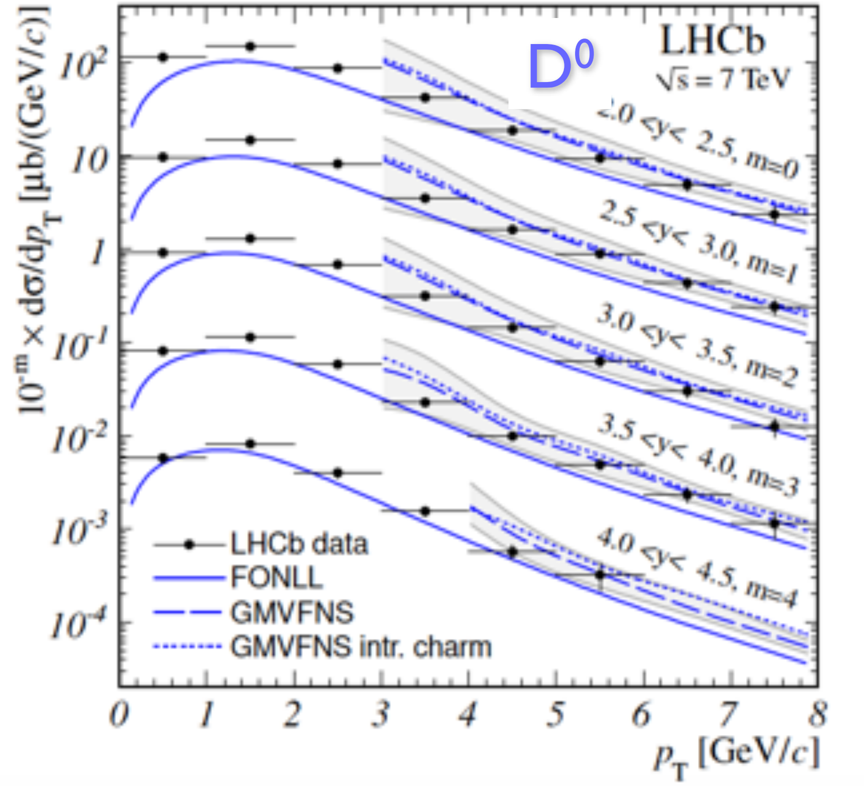
- In total:
  - 2010: 37 pb^{-1} @ 7 TeV
  - 2011: 1 fb^{-1} @ 7 TeV
  - 2012: 2 fb^{-1} @ 8 TeV



Charm production cross-sections @ 7TeV in LHCb acceptance

All c species produced at LHCb

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



- Cross section for $c\bar{c}$ in LHCb acceptance

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

2010 data

Nucl.Phys. B871 (2013) 1-20

  - ~5x10^{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

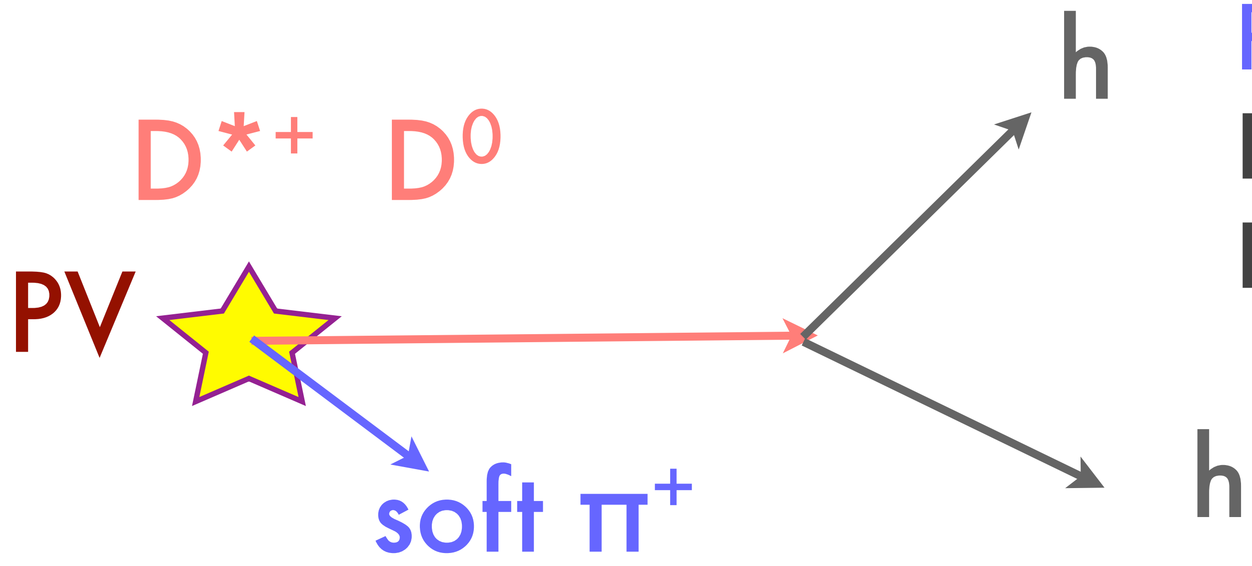
The CP asymmetries

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

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

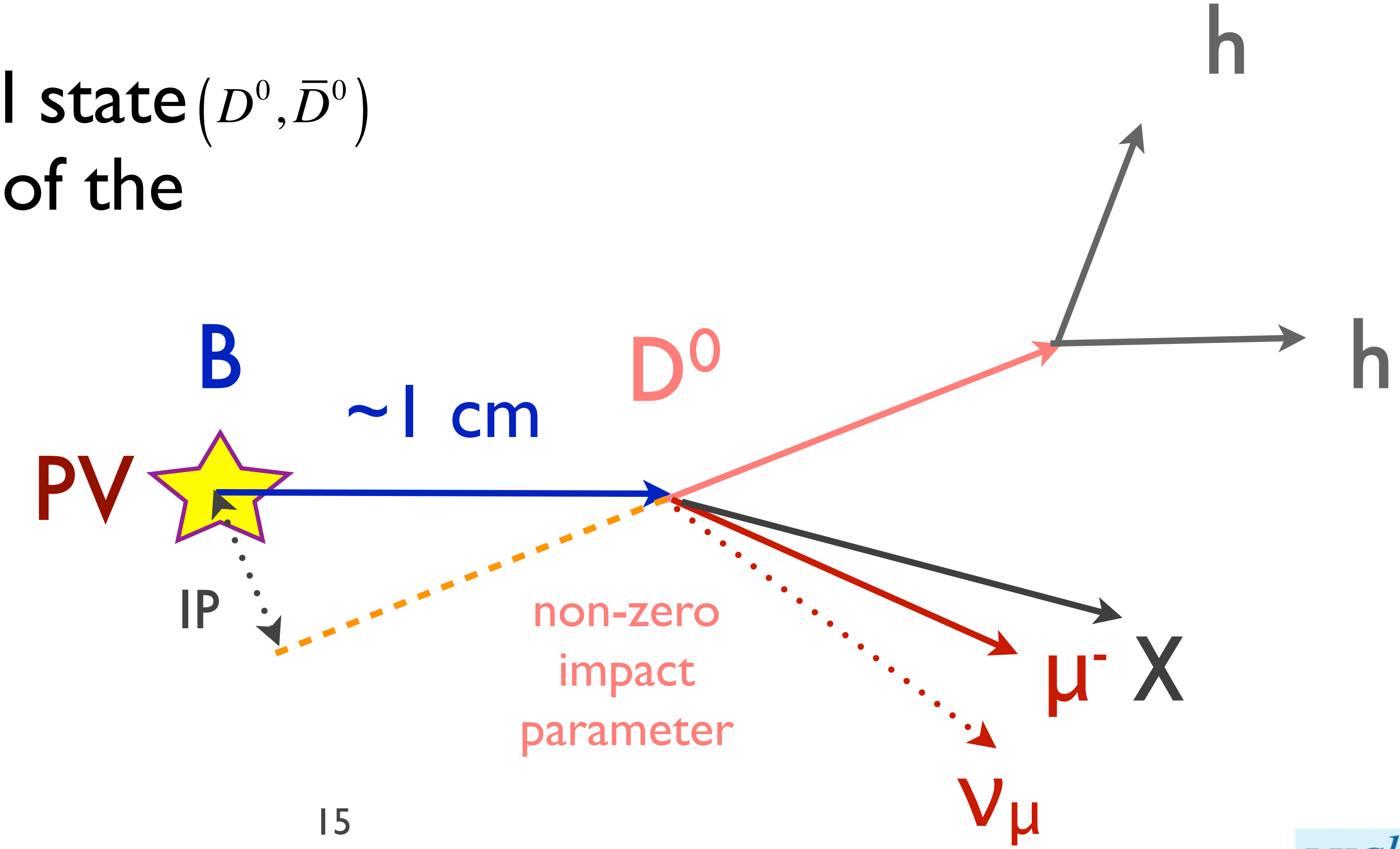
How do we identify the flavour of the neutral D mesons?

D^0 flavour tagging: prompt and secondary charm



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

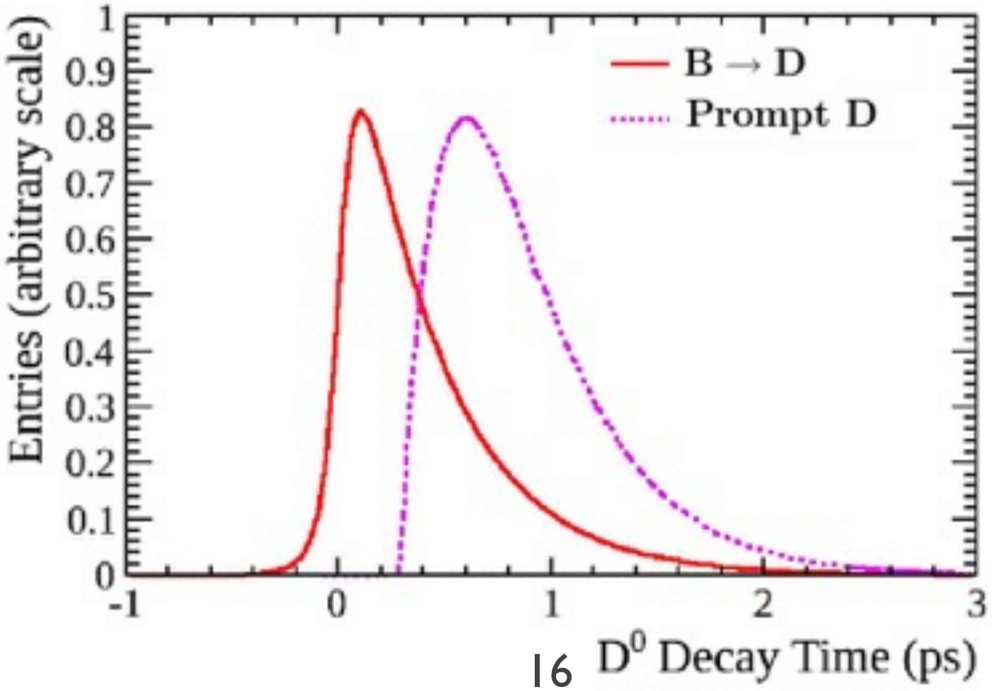
The flavour of the initial state $(D^0, \bar{D}^0)$ is tagged by the charge of the **soft pion** or the **muon**



Secondary charm:
D doesn't point to PV

Prompt vs secondary decays

- Reconstructed prompt D^0 decays ≈ 3x muon - tagged D^0 decays
- Small IP parameter for prompt decays; larger for muon-tagged decays
- Smaller flight distance for prompt decays; larger for the muon-tagged decays
- Different decay-time acceptances



Convolution of (decay time x time resolution) and acceptance

Indirect CPV in charm

A_Γ: Indirect CPV in $D^0 \rightarrow h^+h^-$ decays

Comprises CPV in mixing and in the interference

$$A_\Gamma \approx A_M\, y \cos\phi + x \sin\phi \equiv -a_{CP}^{ind}$$

(Neglecting direct CPV: $A_d\, y \cos\phi$)

$$A_M = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}$$

CPV phase $\phi = \beta_c \approx 0.35°$ (theory) : tiny

mixing parameters $y \equiv \Delta\Gamma/(2\Gamma)$ $\quad x \equiv \Delta m/\Gamma$

$$\Delta\Gamma \equiv \Gamma_2 - \Gamma_1 \qquad \Delta m \equiv m_2 - m_1$$

Time dependent: Measure asymmetries of effective lifetimes of decays to CP eigenstates

$$A_\Gamma \equiv [\tau(\bar{D}^0 \rightarrow h^+ h^-) - \tau(D^0 \rightarrow h^+ h^-)] / [\tau(\bar{D}^0 \rightarrow h^+ h^-) + \tau(D^0 \rightarrow h^+ h^-)]$$

Universal: does not depend on the decay mode

A_Γ predictions

SM predicts $A_\Gamma < 10^{-4}$

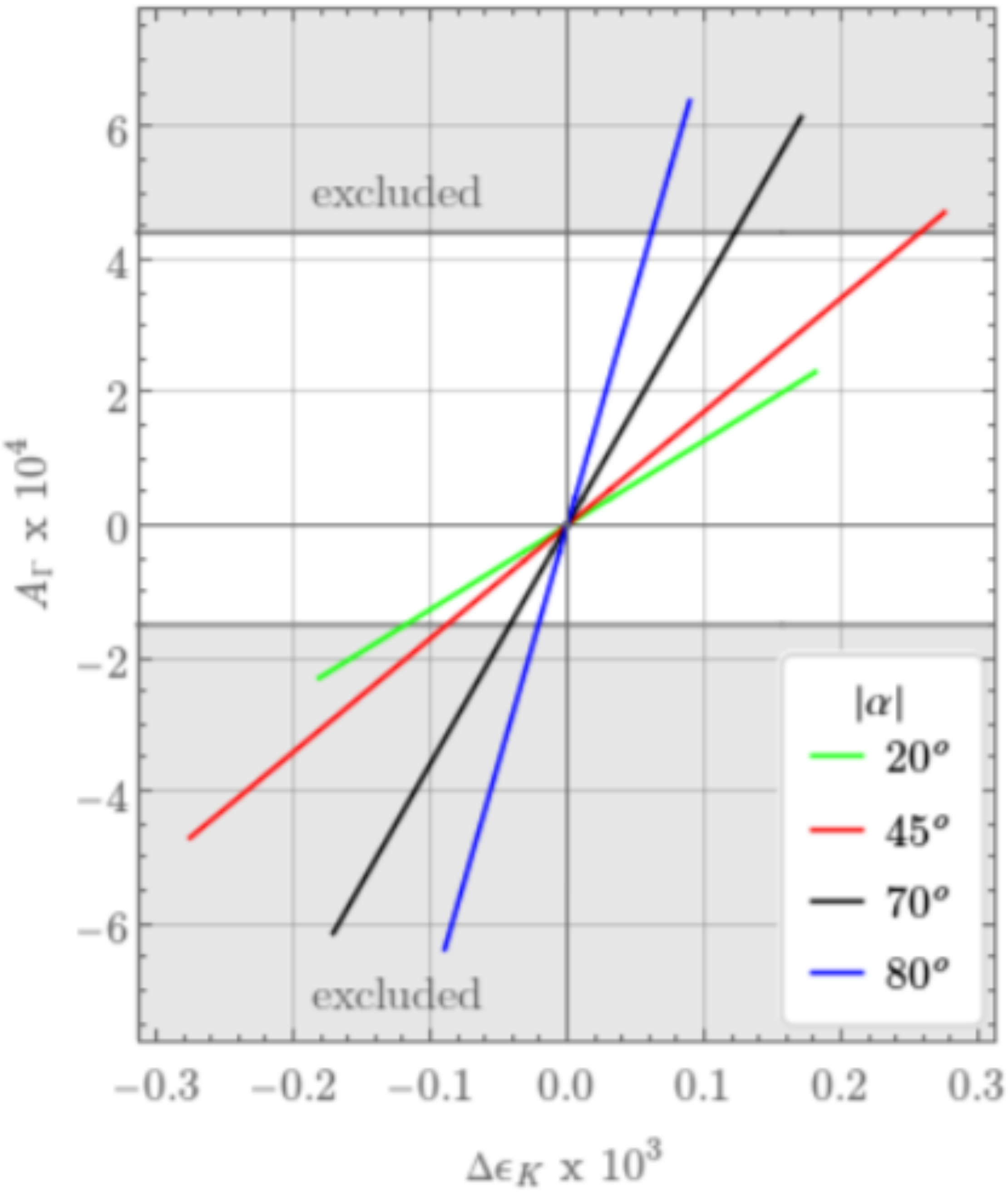
Phys.Rev. D80 (2009) 076008, JHEP 1106 (2011) 089

Enhancements up to 1 order of magnitude are possible in BSM models

Large A_Γ or final state dependence will indicate NP

Phenomenology of SUSY alignment models

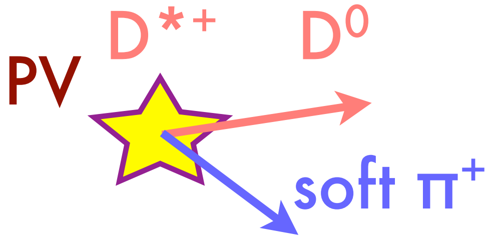
correlations between CP observables in K^0 and D^0 system



Ghosh, Paradisi, Perez, Spada
arXiv:1512.03962

Indirect CP violation in prompt $D^0 \rightarrow h^+h^-$ ($1 fb^{-1}$)

Measurements use prompt $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$ decays ($1\ fb^{-1}$)



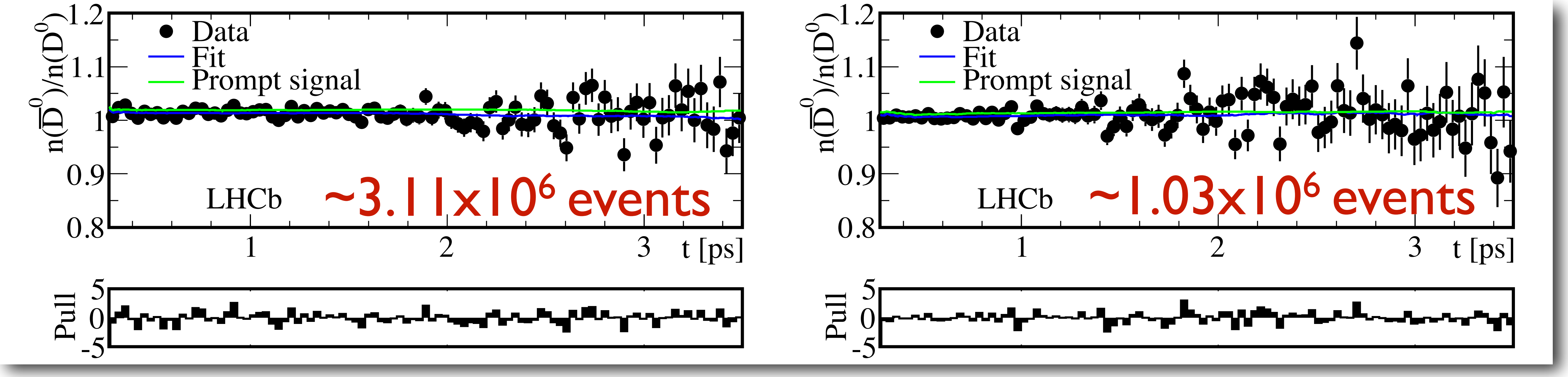
Fit the asymmetries between the decay times

$A_\Gamma(KK) = (-0.35 \pm 0.62 \pm 0.12) \times 10^{-3}$

$A_\Gamma(\pi\pi) = (0.33 \pm 1.06 \pm 0.14) \times 10^{-3}$

Most precise measurement of charm CP asymmetries

PRL 112 (2014) 041801

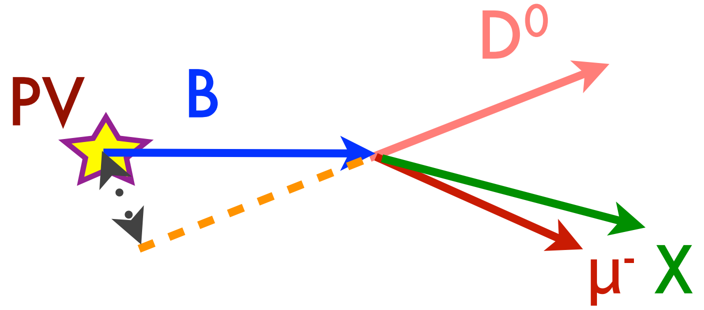


$\sim 3.11 \times 10^6$ events

$\sim 1.03 \times 10^6$ events

ratio of $D^0/\overline{D}^0$ data and fit models

Indirect CPV in muon-tagged $D^0 \to h^+h^-$ ($3fb^{-1}$)



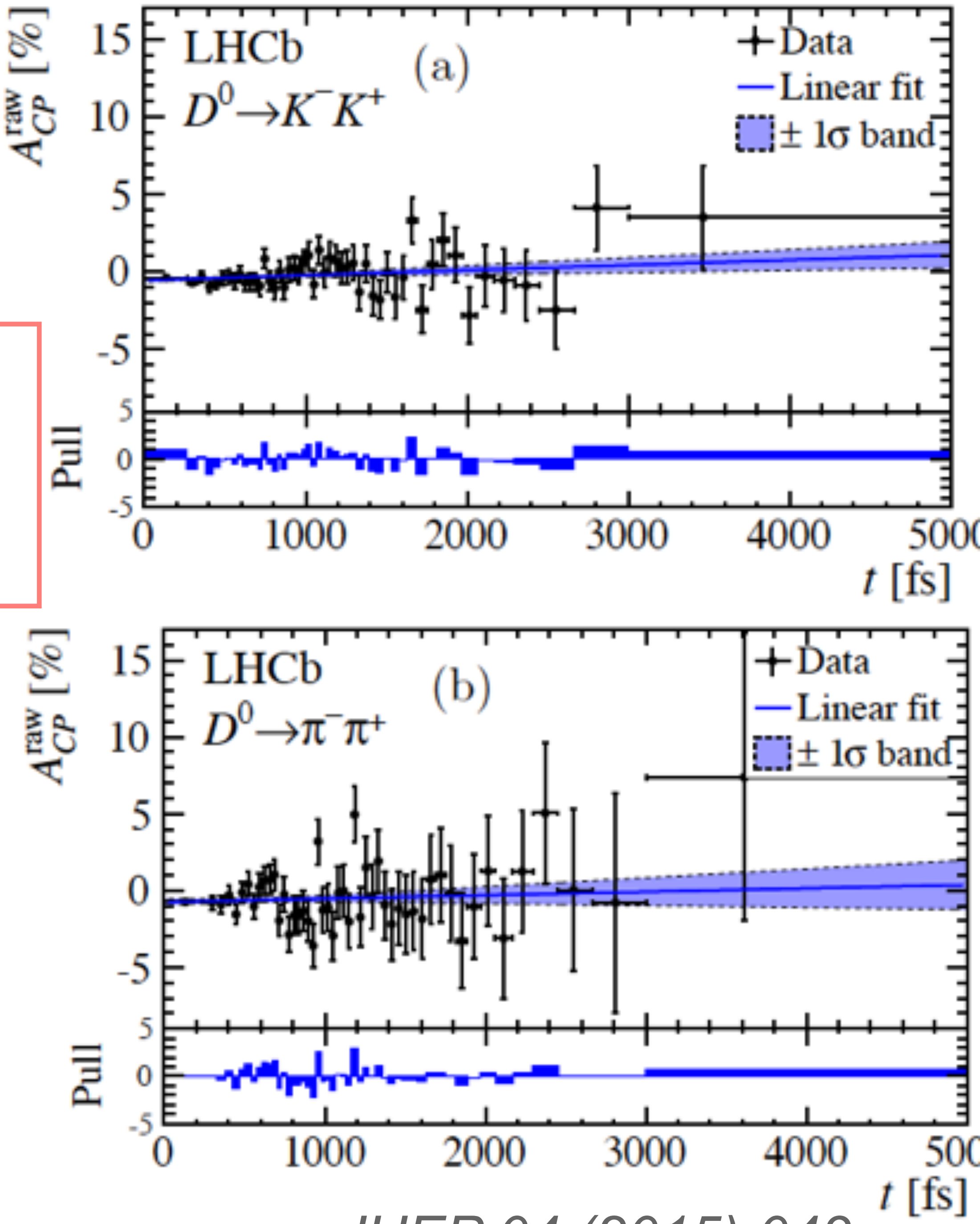
Fit the time dependent CP asymmetry to extract A_Γ

$$A_{raw}(t) = A_{CP}^{dir} - A_\Gamma\, t/\tau + A_P + A_d$$

$$\boxed{\begin{aligned} A_\Gamma(KK) &= (-1.34 \pm 0.77\ {}^{+0.26}_{-0.34}) \times 10^{-3} \\ A_\Gamma(\pi\pi) &= (-0.92 \pm 1.45\ {}^{+0.25}_{-0.33}) \times 10^{-3} \end{aligned}}$$

Prompt and secondary charm results are uncorrelated

Using both tagging techniques improves decay time coverage



JHEP 04 (2015) 043

Direct CPV searches in two-body charm decays

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:

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

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

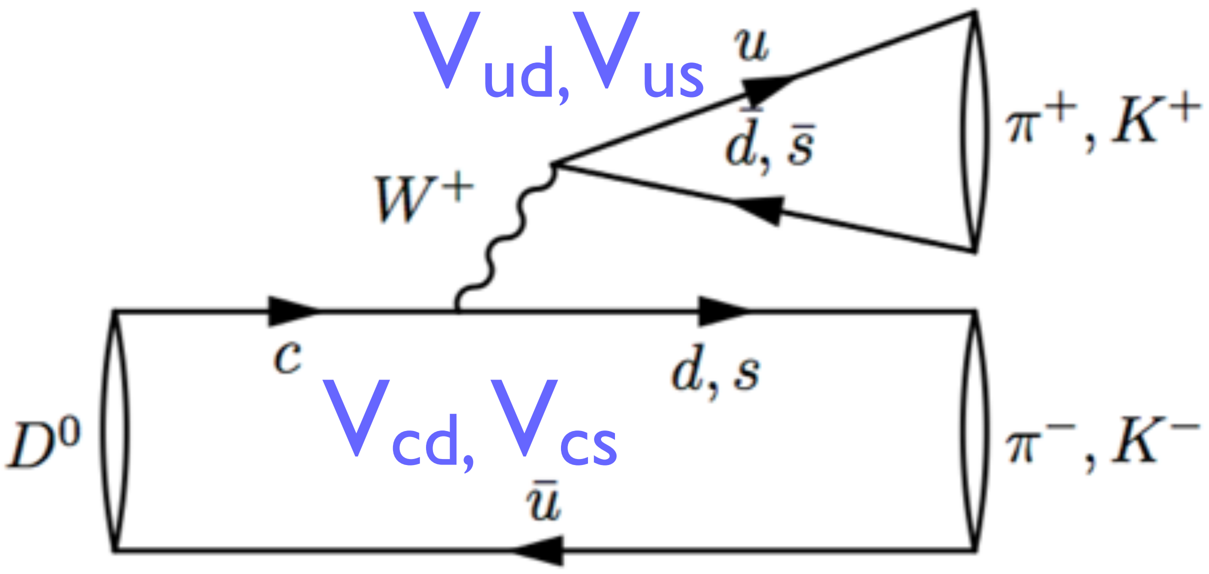
- CP violation requires difference in strong (δ) and weak phase (ϕ):
  $a_{CP} \equiv (\,|A|^2-|\bar{A}|^{2)})/(|A|^2+|\bar{A}|^2) = 2\,r\,\sin(\delta)\,\sin(\phi)$

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

Often realised by “tree” and “penguin” diagrams

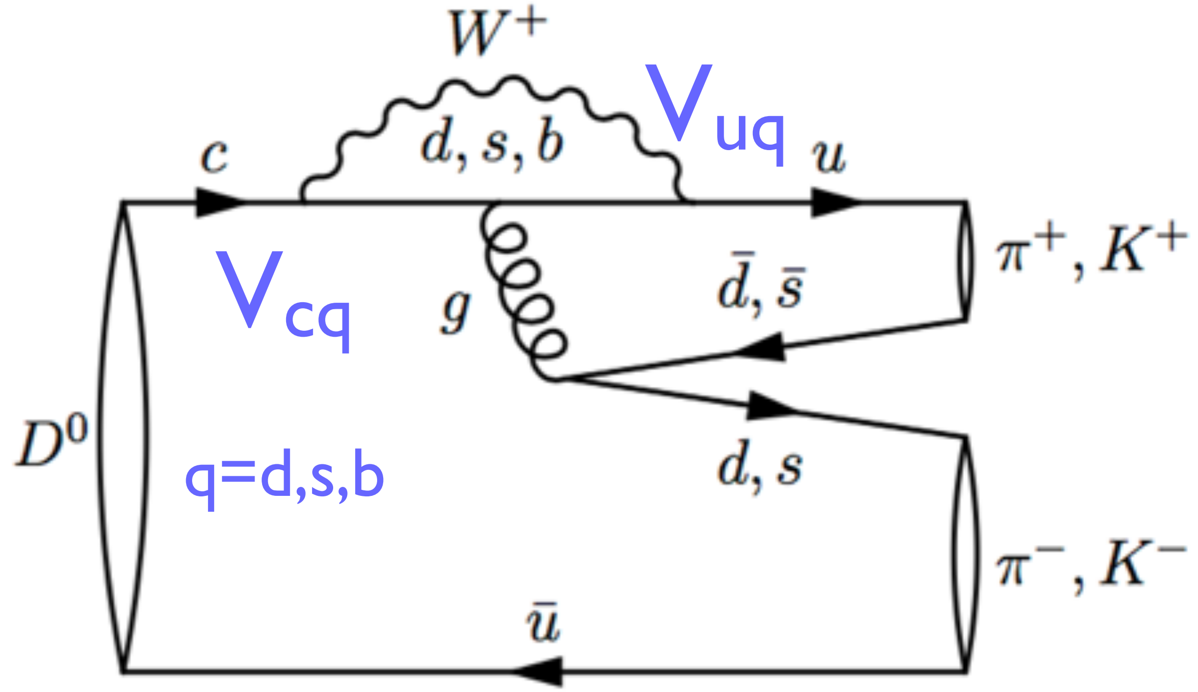
Tree-level weak decay amplitude.

- 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

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

ΔA

$$A_{CP}(f) \approx a_{CP}^{\text{dir}}(f)\left(1 + \frac{\langle t(f)\rangle}{\tau}\, y_{CP}\right) + \frac{\langle t(f)\rangle}{\tau}\, a_{CP}^{\text{ind}}$$

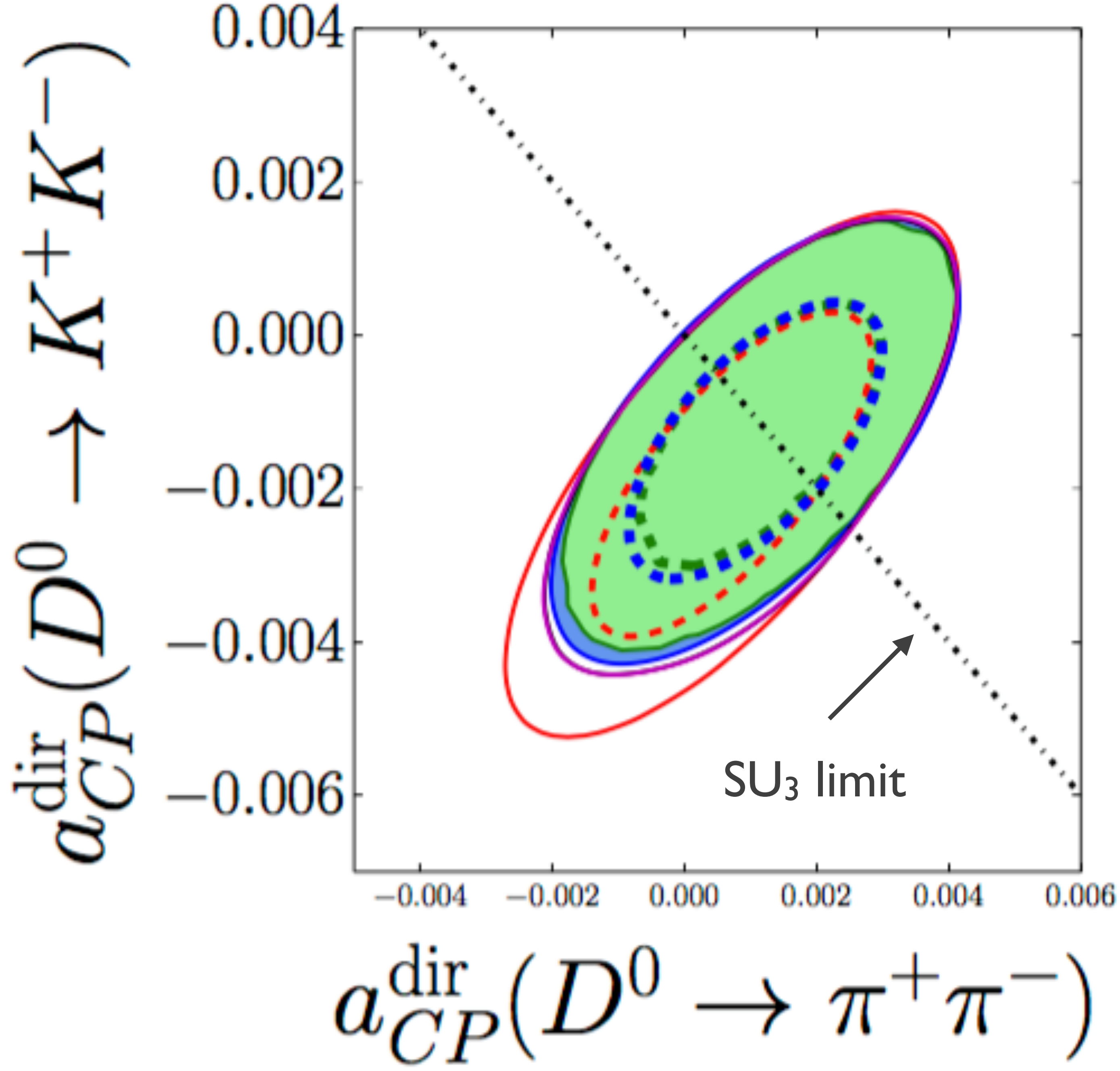
where $y_{CP} \equiv \frac{\Gamma_{CP\pm}}{\Gamma} - 1$

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

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

Theoretical expectations



$a_{CP}^{\mathrm{dir}} < 10^{-2}$ within the SM

Enhancements up to 1 order of magnitude possible in some BSM models

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)

The CP asymmetries

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

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

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

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

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

or

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

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

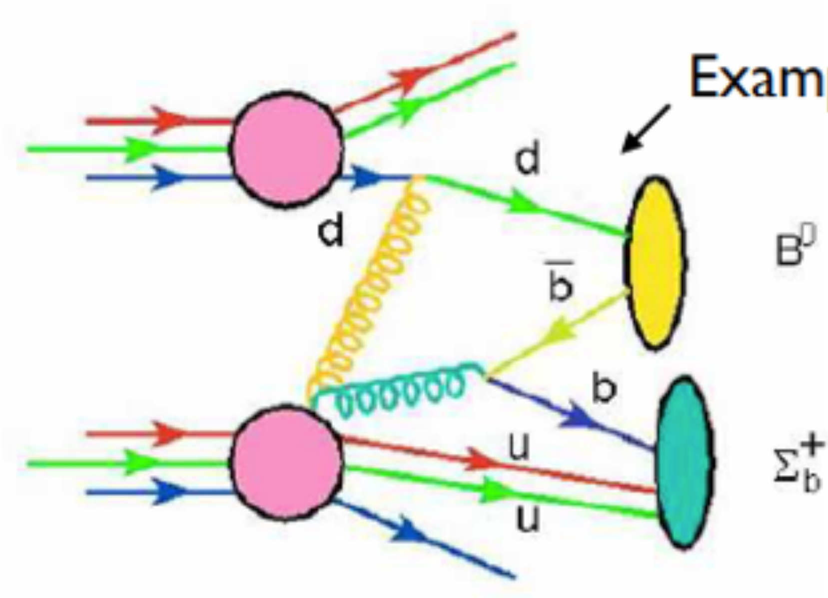
We measure the physical CP asymmetry plus asymmetries due to detection effects and production

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

Production asymmetries

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

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



Example mechanism

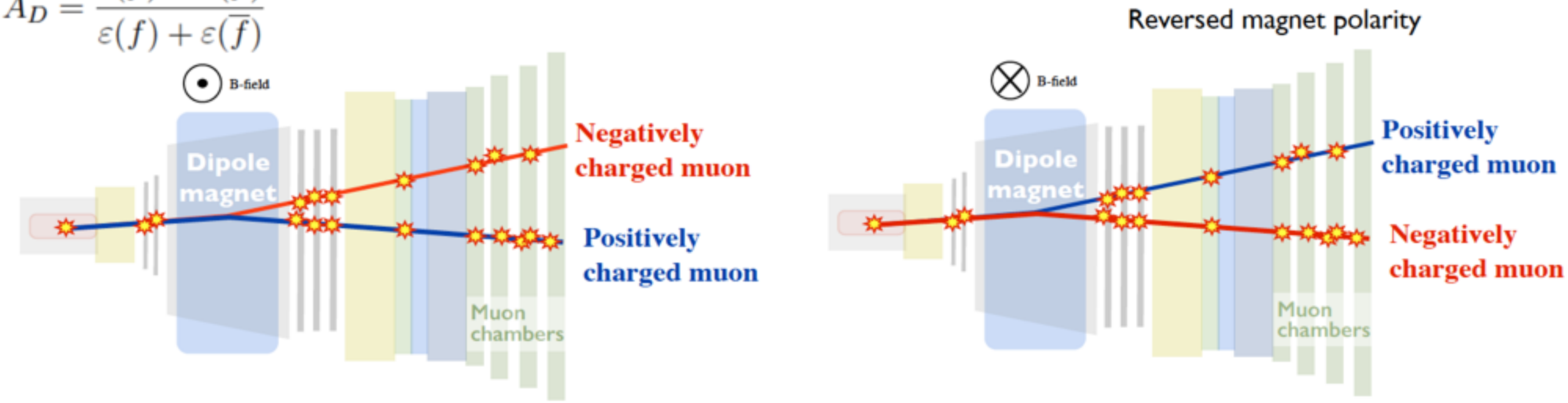
Expected to be around 1%

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

Detection asymmetries (1)

- Detector asymmetries

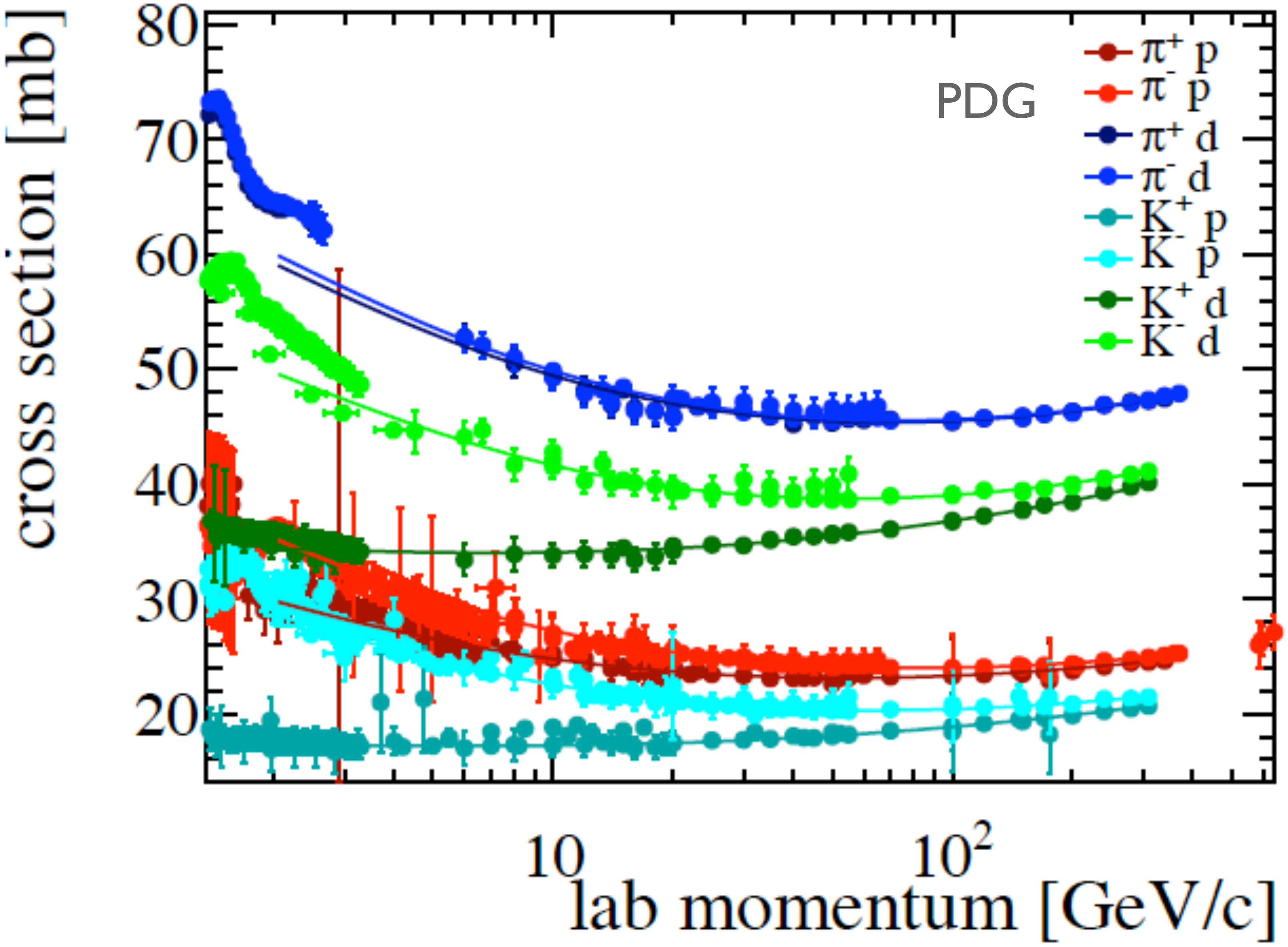
$$A_D = \frac{\varepsilon(f) - \varepsilon(\overline{f})}{\varepsilon(f) + \varepsilon(\overline{f})}$$



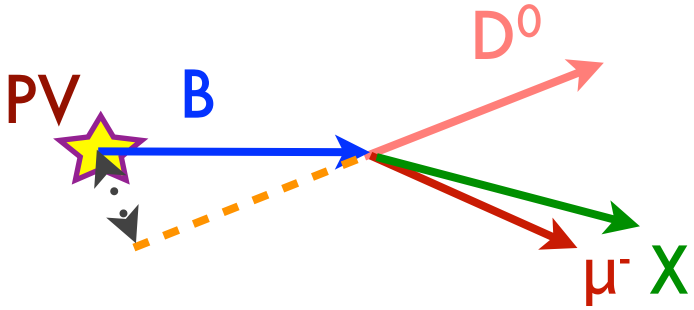
  - Cancel left-right asymmetries by swapping dipole field
  - But do not rely only on it (detectors move, alignment changes etc.)

Detection asymmetries (11)

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



Muon-tagged ΔA_{CP}



$$A_{raw} = A_{CP} + A_{production}(B) + A_{detection}(\mu)$$

ΔA_{CP}

Main experimental challenge: separate the asymmetries

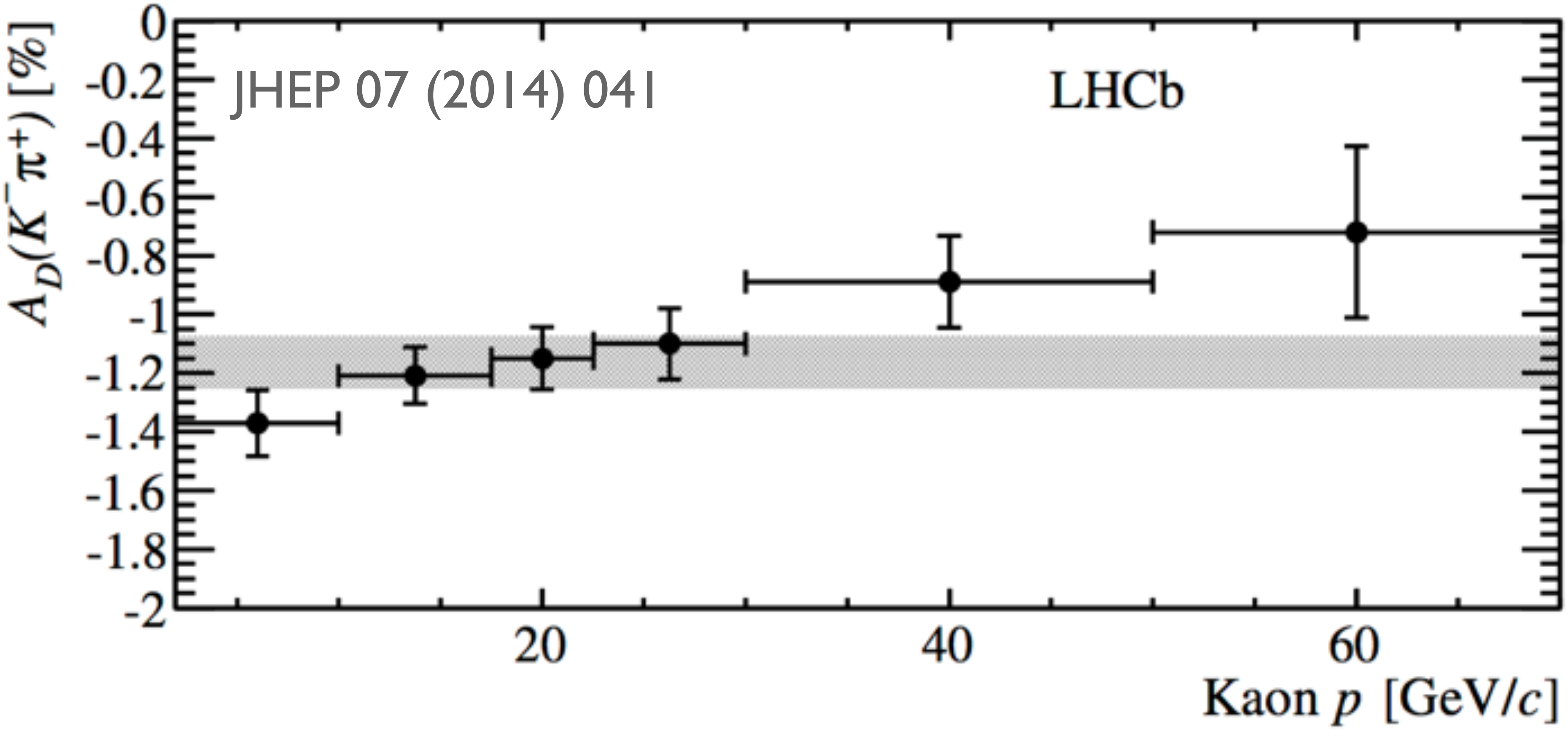
$$A_{raw} = A_{CP} + A_{production} + A_{detection}$$

if we take the raw asymmetry difference:
experimentally more robust

$$\Delta A_{CP} \equiv A_{raw}\left(KK\right) - A_{raw}\left(\pi\pi\right) \overset{1^{st}\text{ order}}{=} A_{CP}\left(KK\right) - A_{CP}\left(\pi\pi\right)$$

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

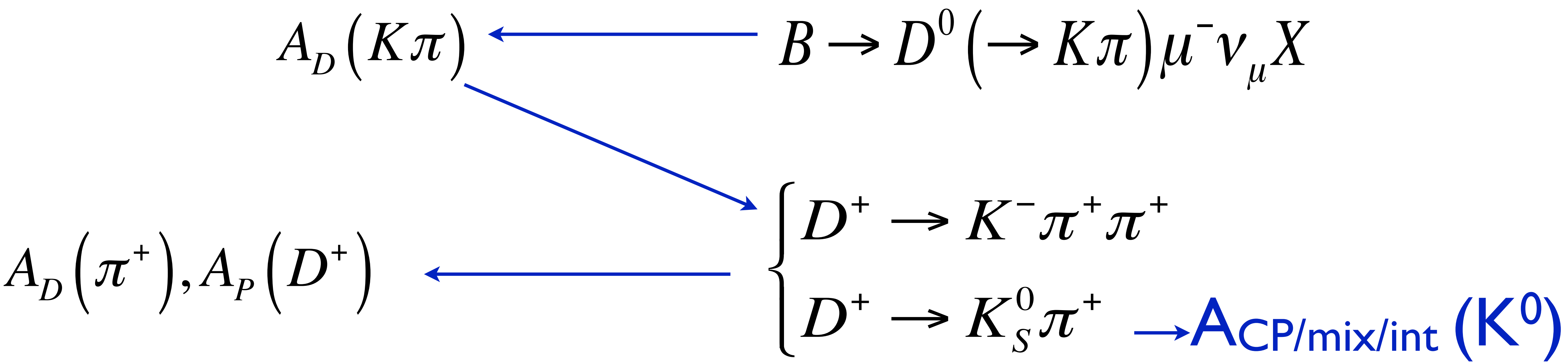
Challenge: Individual CP asymmetries

$$\boxed{\boxed{A_{CP}(KK)} = \boxed{A_{raw}(KK)} - \underbrace{A_D(\mu) - A_P(B)}}$$

want measure

Measure the nuisance asymmetries by using control modes with CF final states (= no CPV)

Additional asymmetries arising



$A_D(K\pi)$ ← $B \to D^0(\to K\pi)\mu^- \nu_\mu X$

$A_D(\pi^+), A_P(D^+)$ ← $\begin{cases} D^+ \to K^- \pi^+ \pi^+ \\ D^+ \to K^0_S \pi^+ \end{cases}$ → $A_{CP/mix/int}(K^0)$

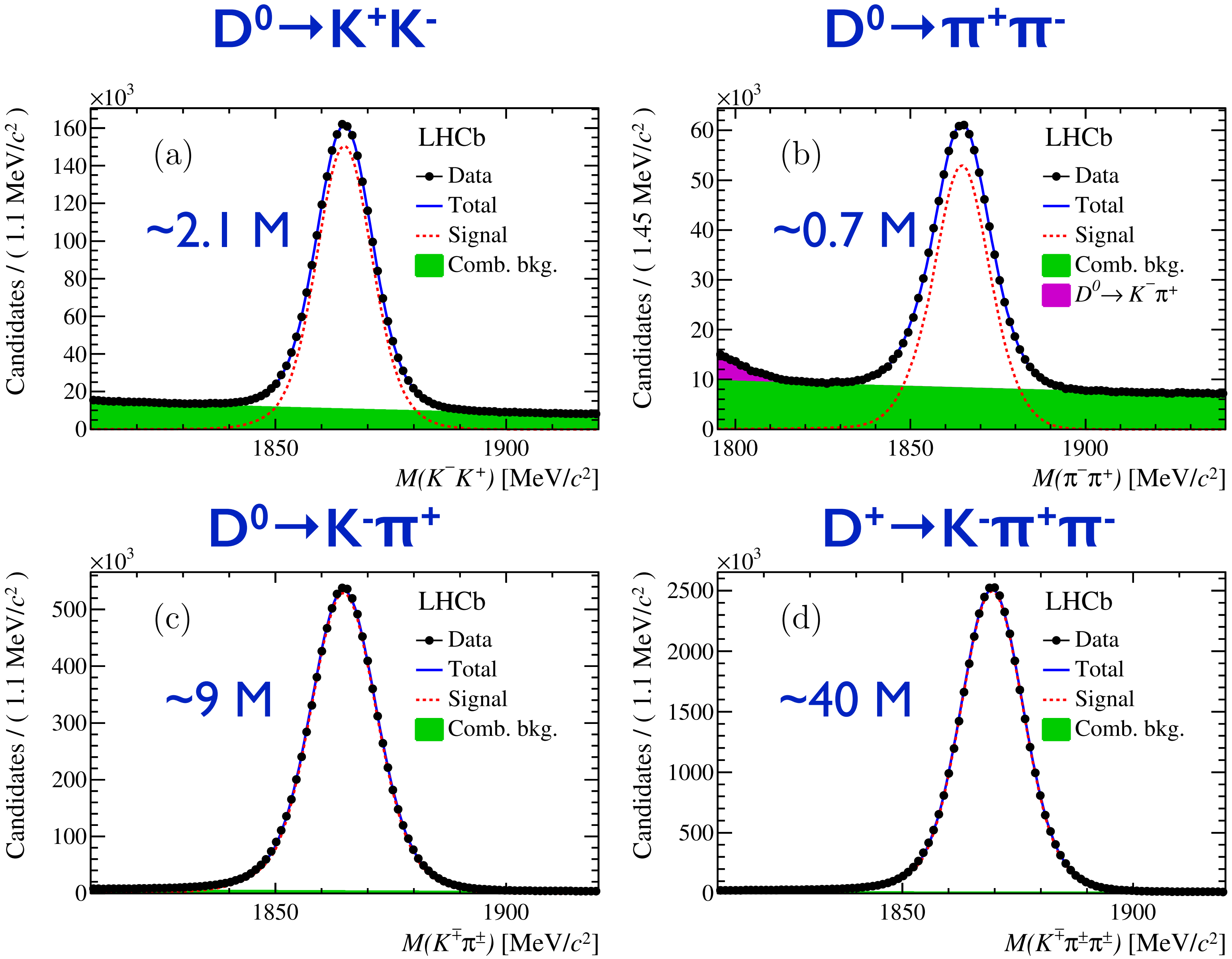
Careful treatment of kaon interactions with matter

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

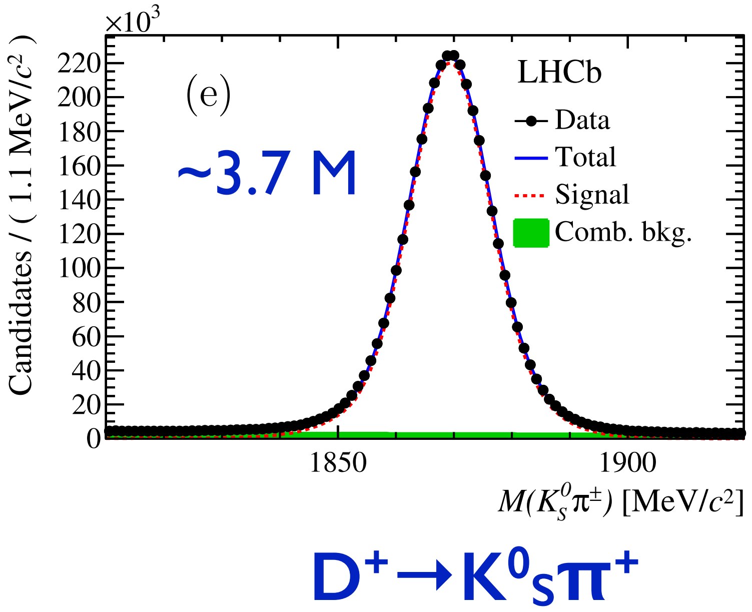
First measurement by LHCb of the two individual CP asymmetries

Yields

- Using 3 fb^{-1} data (2011 and 2012 data)
- 2011 and 2012 data and the up-down magnet polarities independently analysed



JHEP 1407 (2014) 041



World averages

$$\Delta A_{CP} = (+0.14 \pm 0.16\,(\text{stat}) \pm 0.08\,(\text{syst}))\%$$
$$A_{CP}(K^-K^+) = (-0.06 \pm 0.15\,(\text{stat}) \pm 0.10\,(\text{syst}))\%$$

Correlation ρ = 0.28

$$A_{CP}(\pi^-\pi^+) = (-0.20 \pm 0.19(\text{stat}) \pm 0.10(\text{syst}))\%$$

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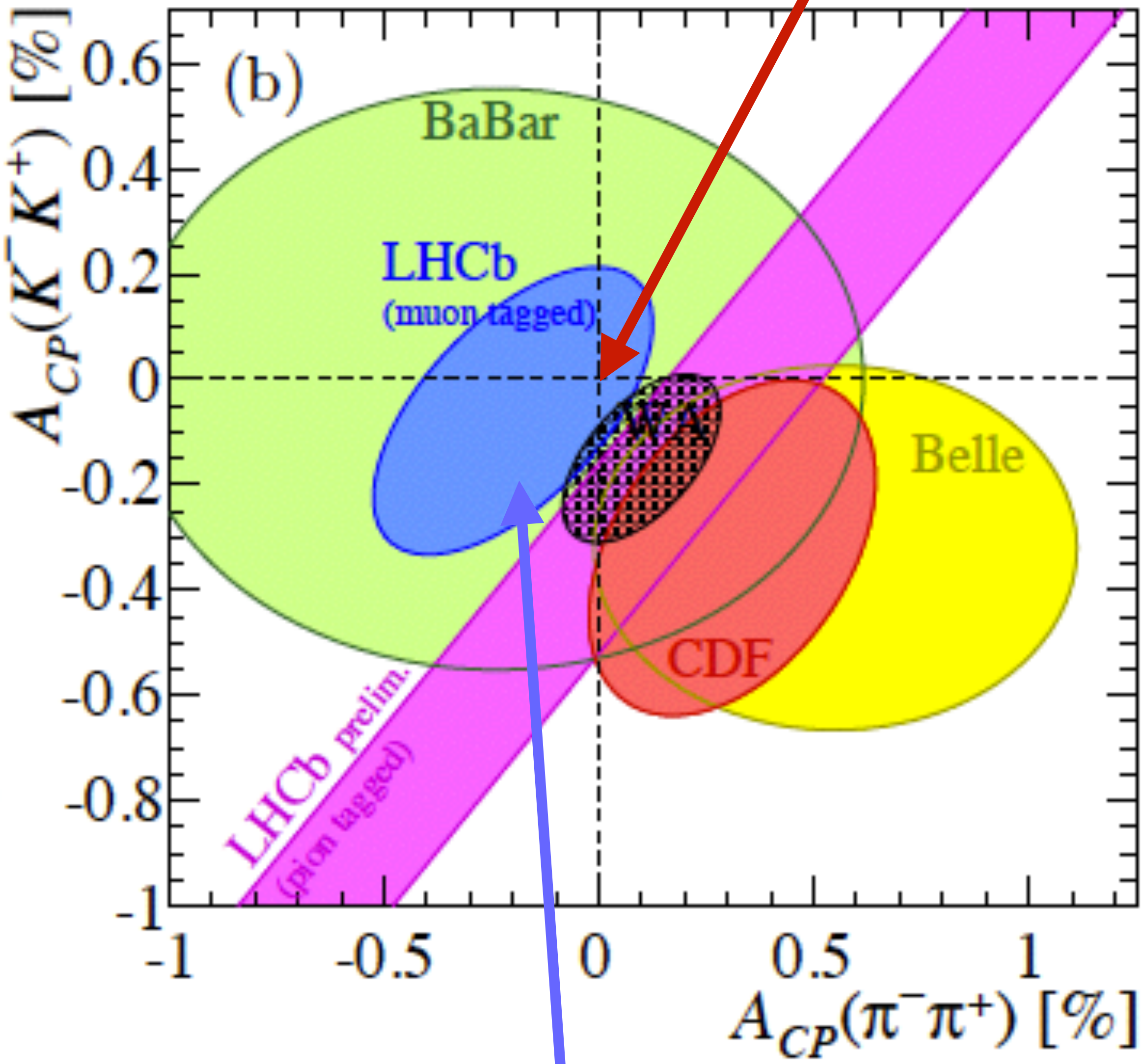
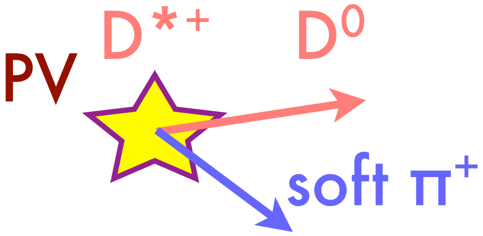
No CPV point



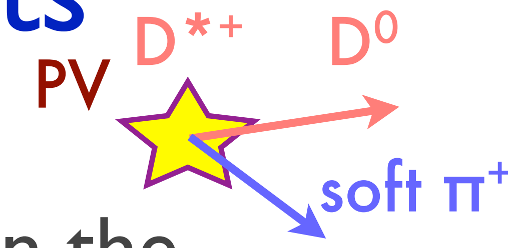
Most precise measurement of these individual asymmetries

Prompt ΔA_{CP}

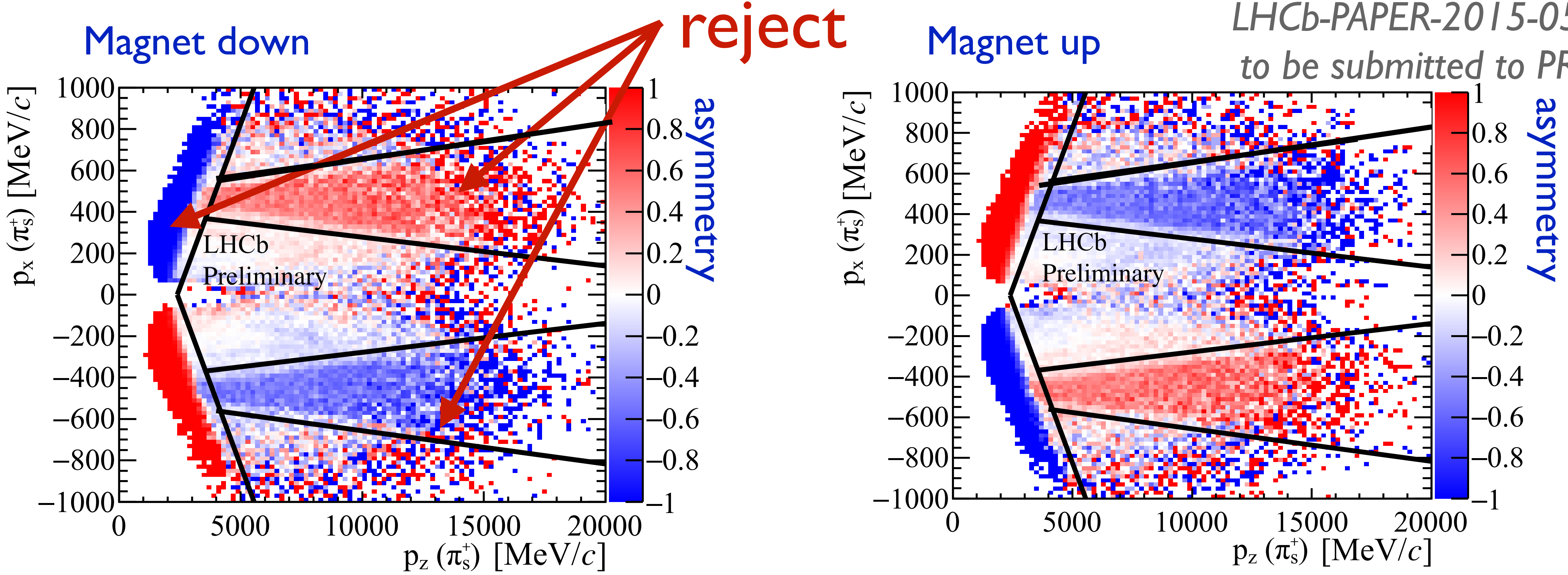


$$A_{raw} = A_{CP} + A_{production}(D^{*+}) + A_{detection}(\pi^{+})$$

Selection of prompt $D^0 \rightarrow h^+h^-$ events



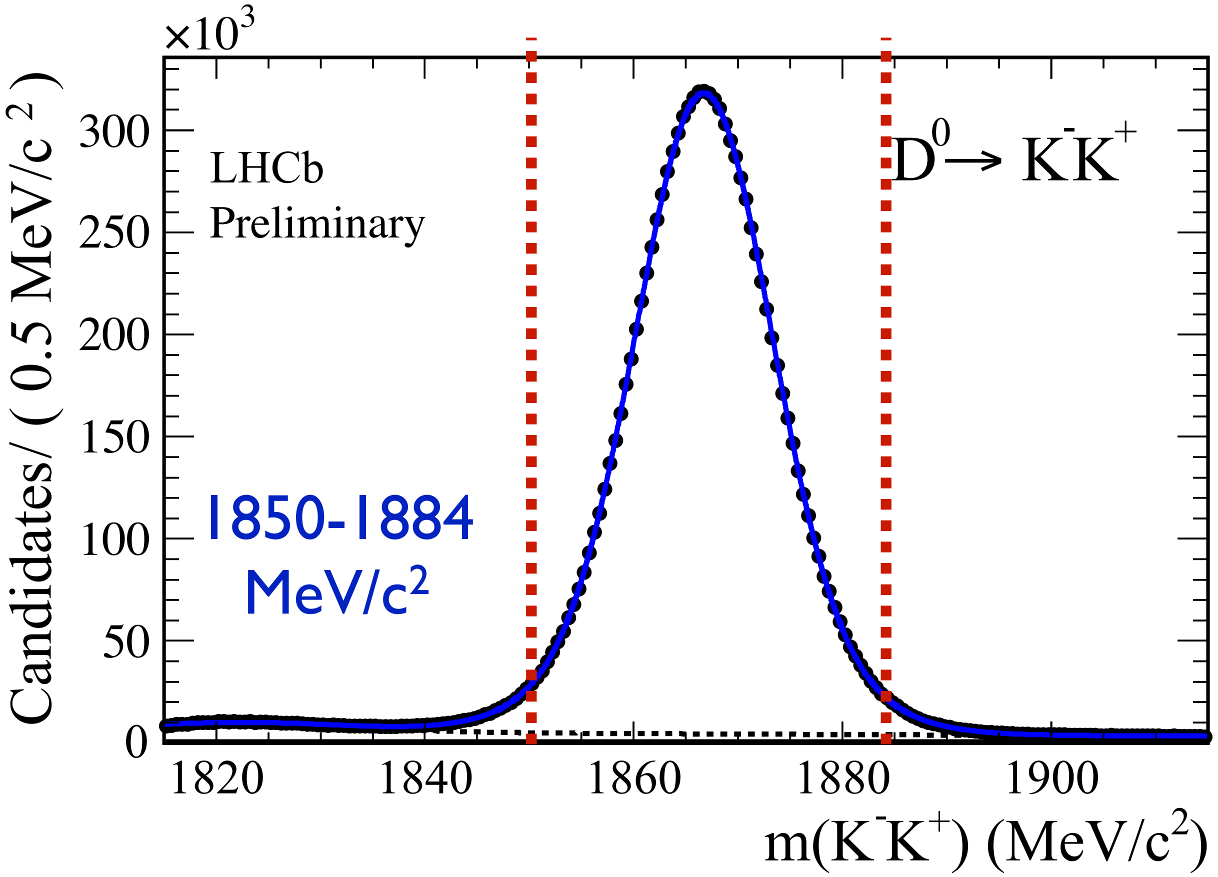
- Soft pions trajectories are bent in different directions in the horizontal bending plane depending on their charge
- Soft pions of one charge may easily escape the acceptance of the detector around the edges or the uninstrumented beam pipe
- Remove regions with large raw asymmetries in the soft pion reconstruction efficiency

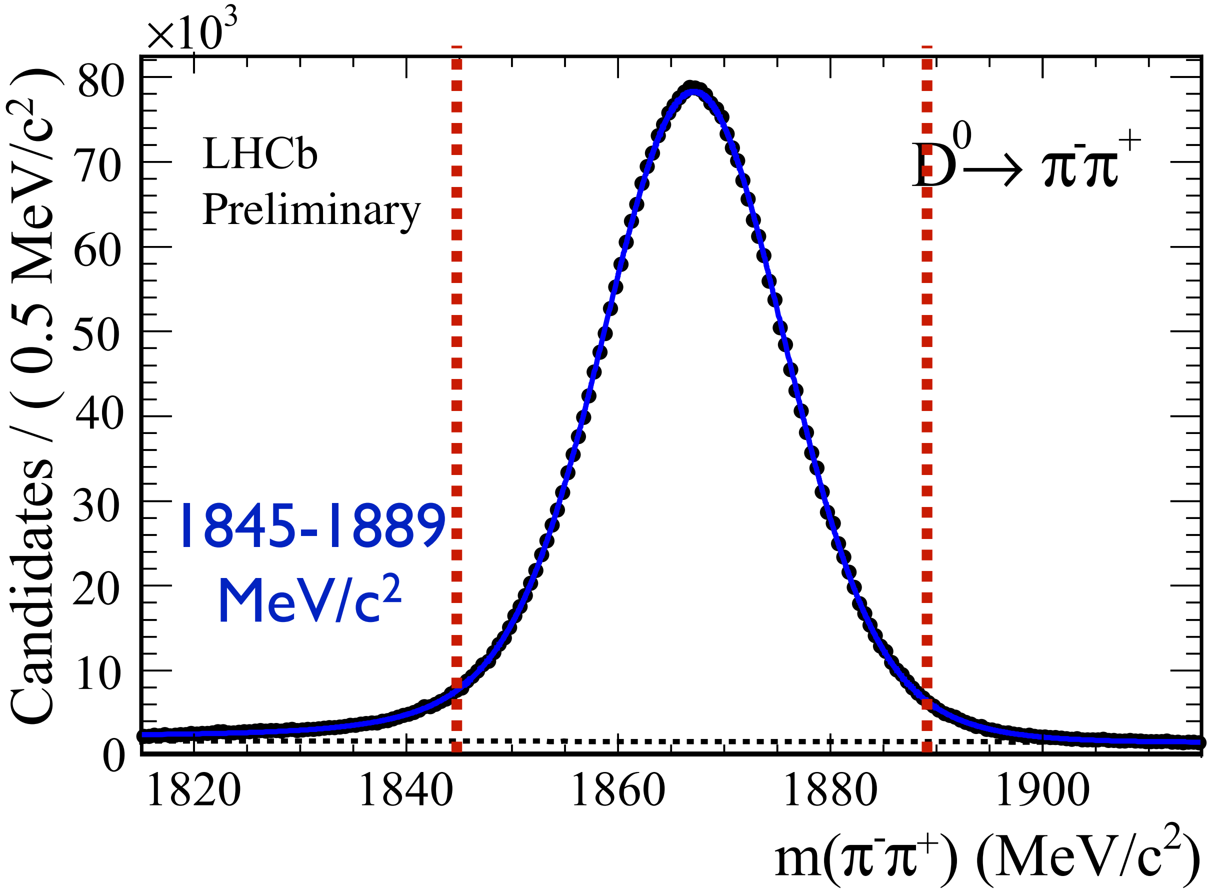


LHCb-PAPER-2015-055
to be submitted to PRL

Selection of prompt $D^0 \rightarrow h^+h^-$ events

- Tight cuts on K and **π** PID to suppress mis-ID backgrounds
- Cut on Mass D^0 to suppress multi-body decays





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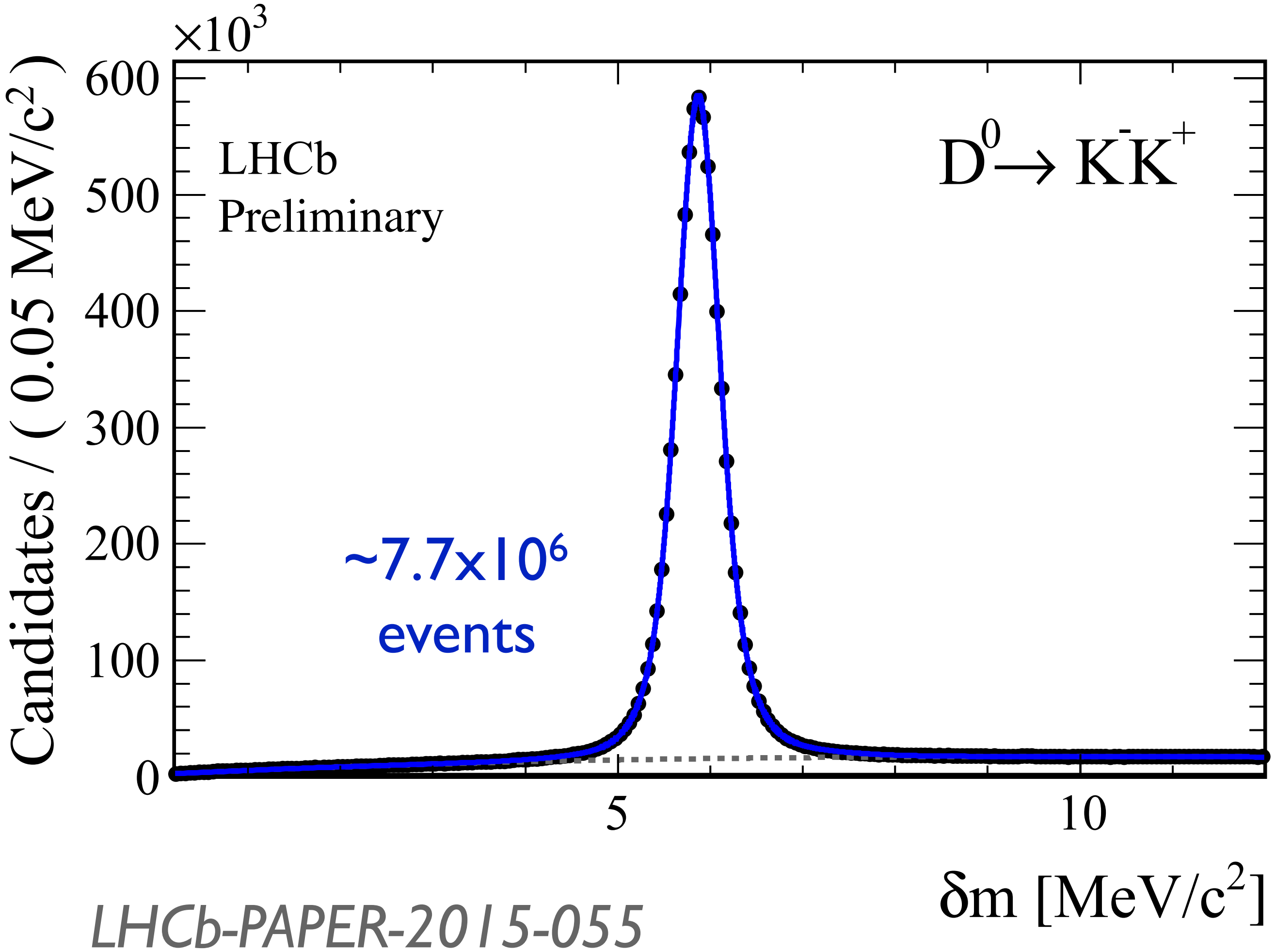
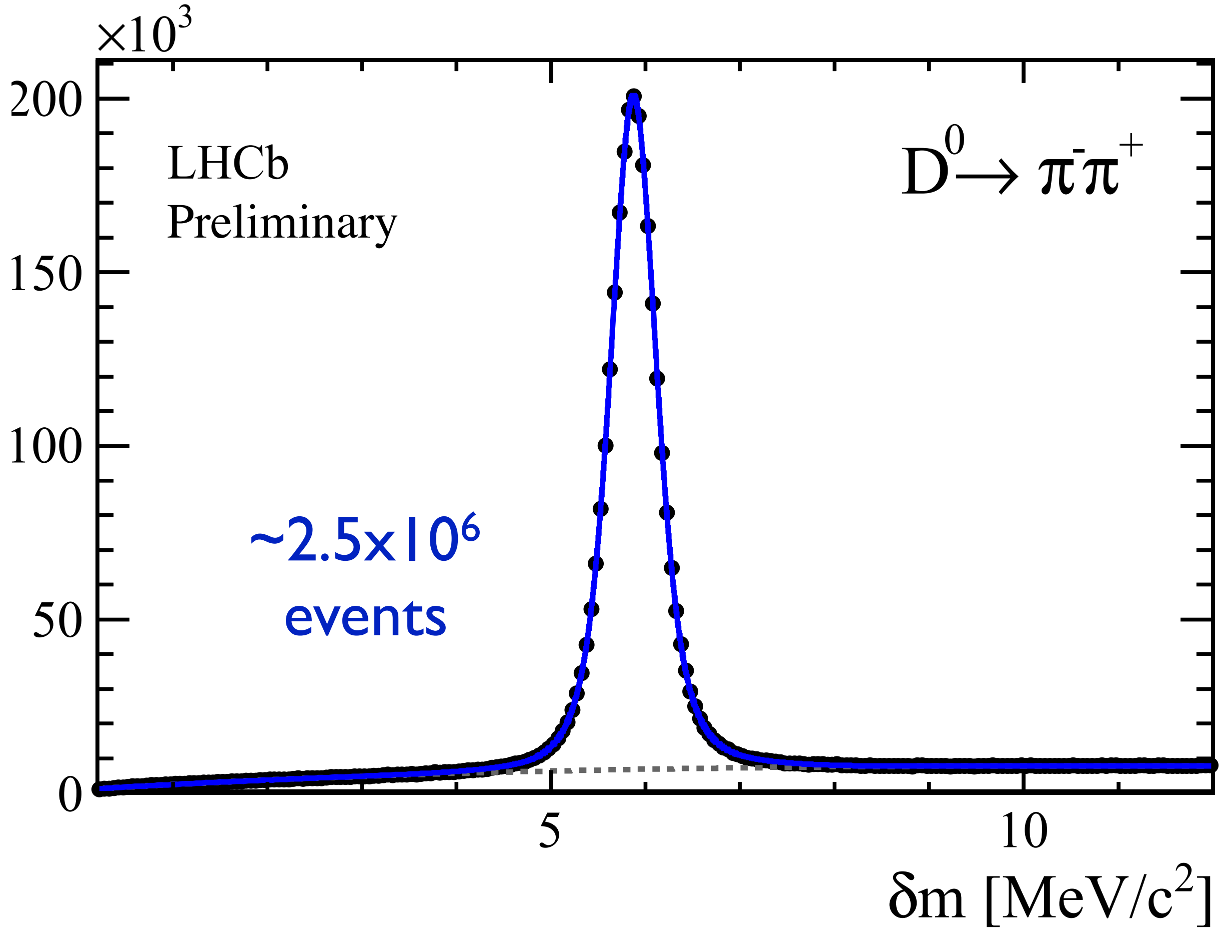
to be submitted to PRL

Selection & fit

- Cut on D^0 IPχ^2 to suppress secondary backgrounds
- Fit $\delta m = m(D^{*+}) - m(D^0)$



~7.7×10^6 events



~2.5×10^6 events

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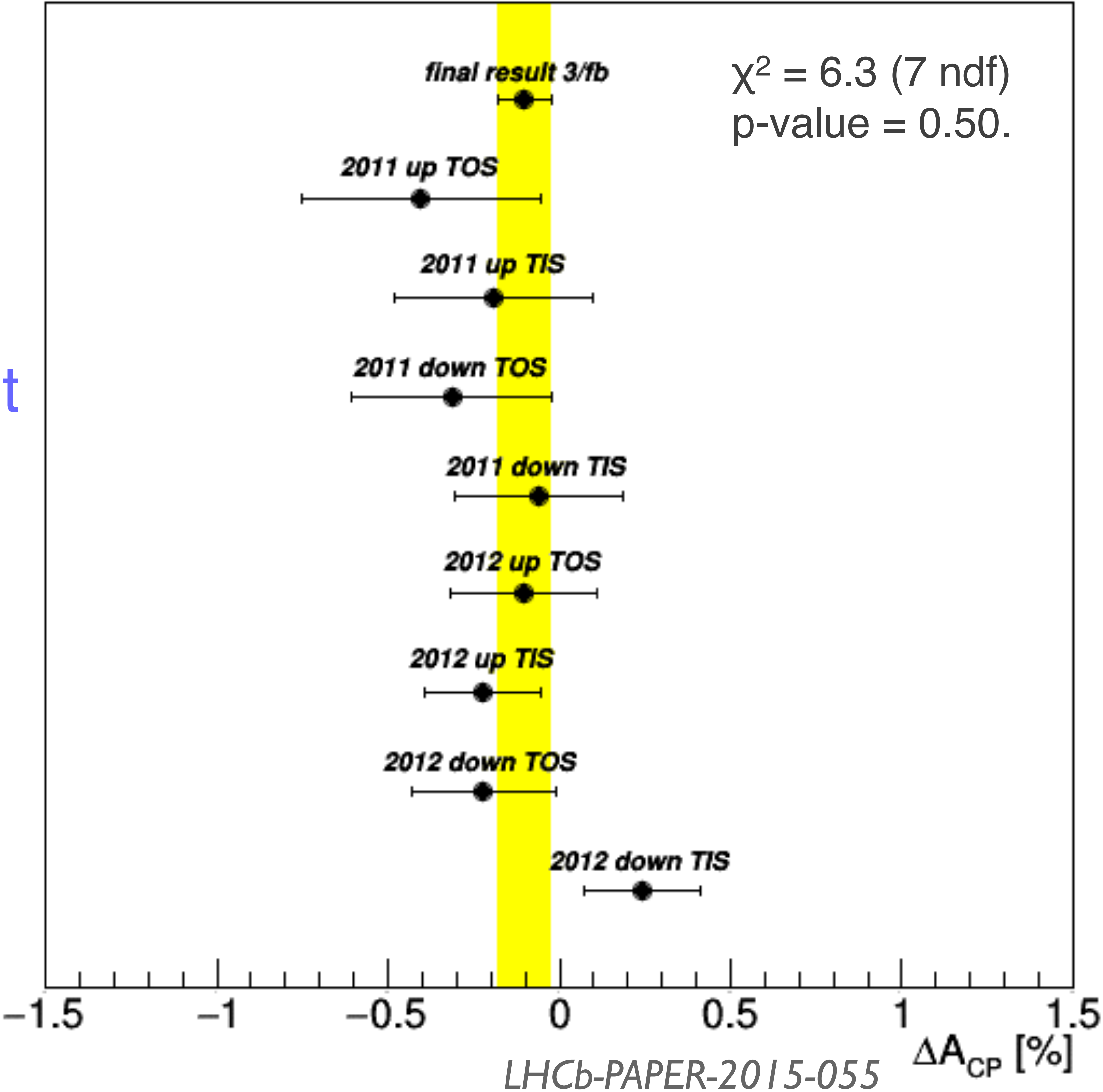
Results for the subsamples

Analysis done in 8 disjoint subsamples

Split by

- magnet polarity: test the cancellation of detector related effects
- year: different data taking conditions
- hardware-level trigger: different kinematics of the decays



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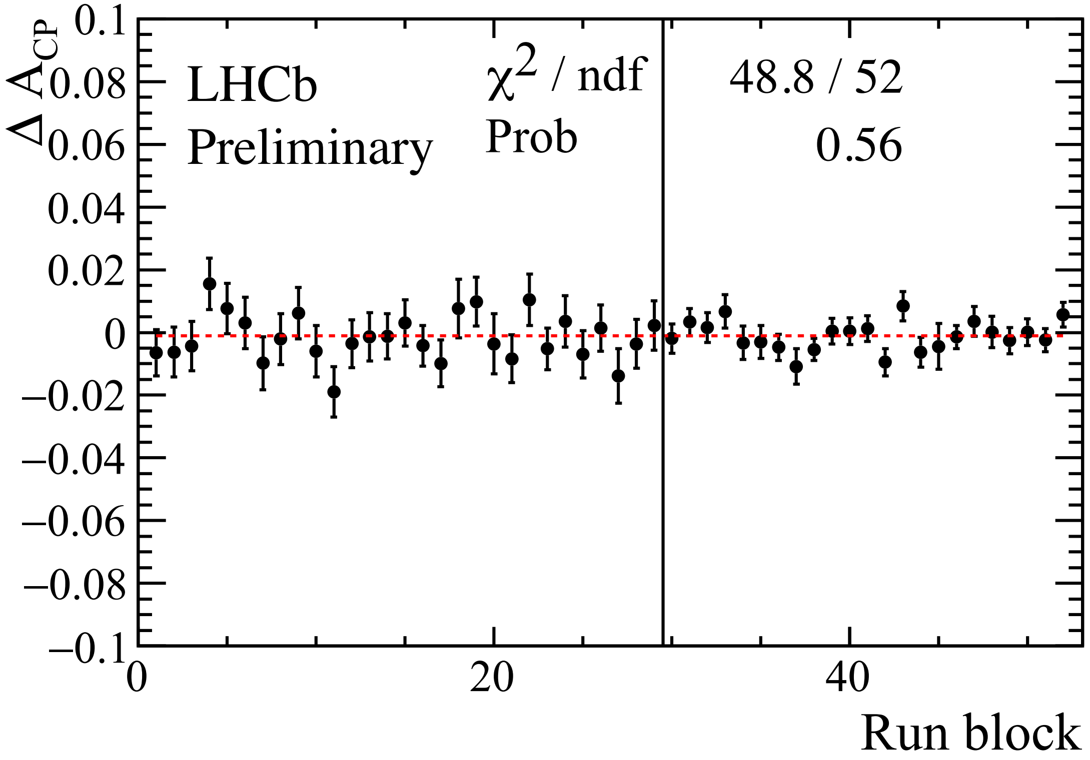
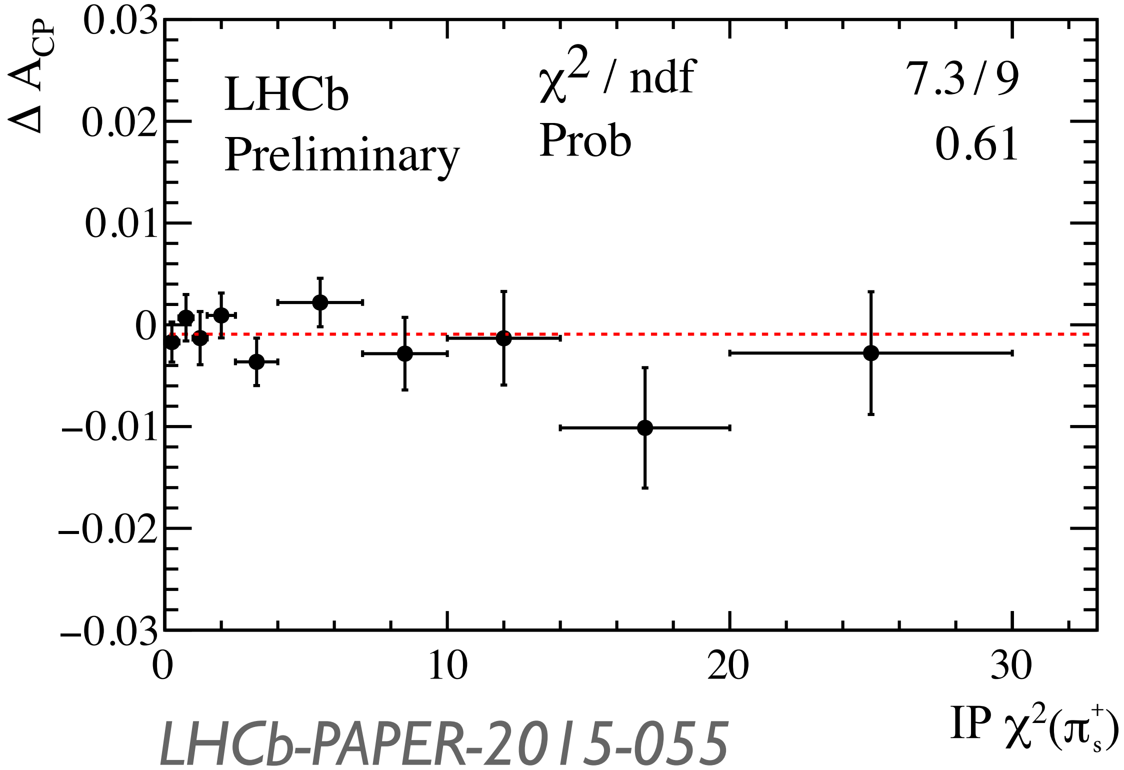
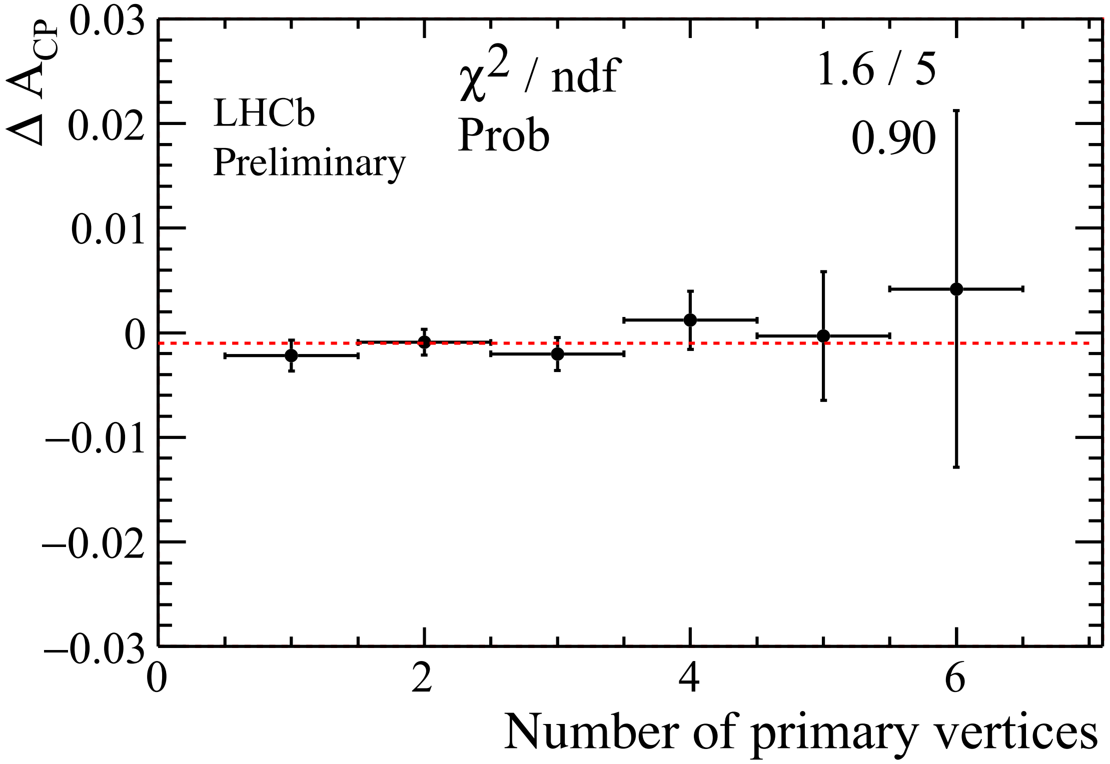
Stability checks



- Choice of the binning
- Time (i.e. run number) dependency
- Number of primary vertices
- Quality of the **D**$^{*+}$ vertex
- π_s kinematics
- **D**^{0} kinematics
- separation in phase space of the **D**^{0} and the π_s
- **D**^{0} mass (inside the signal region)
- PID cuts





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Systematic uncertainties

Source	uncertainty [%]
Fit Model	0.016
Multiple candidates	0.015
Peaking background	0.011
Reweighting	0.004
Fiducial cut	0.017
Secondaries	0.004
Total	0.030

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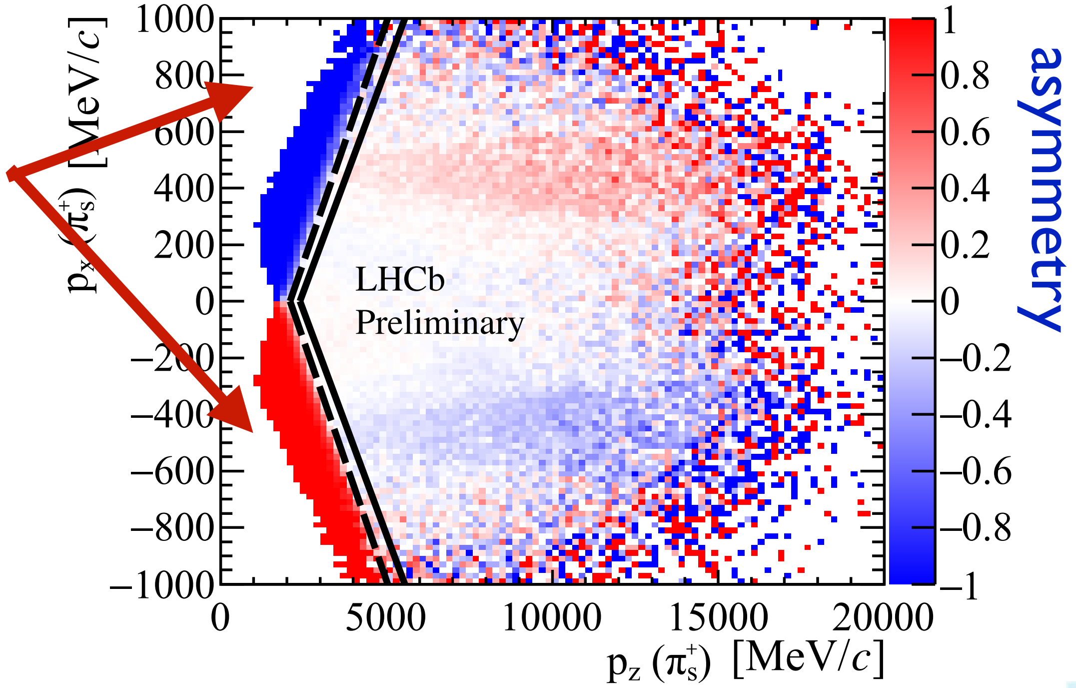
Test alternative signal and background models, extend fitting range

Exclude smaller edge & beam pipe regions; select events closer to the high-asymmetry regions

Reject randomly events with multiple candidates - keep only one candidate

Magnet down



The final result

The most precise measurement of a time-integrated CP asymmetry in the charm sector

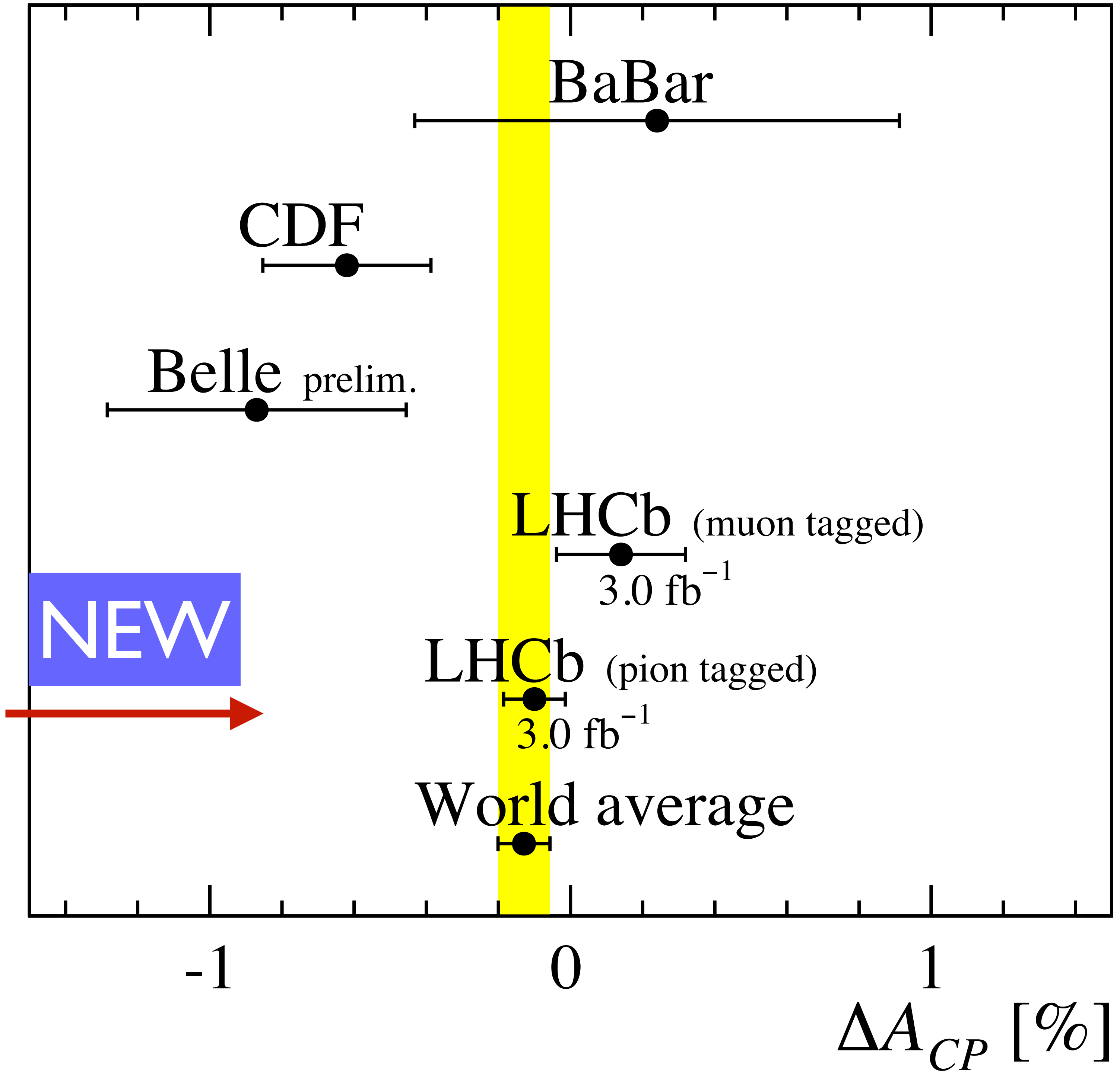
NEW *LHCb-PAPER-2015-055*
to be submitted to PRL

$\Delta A_{CP\ \mathrm{prompt}} = (-0.10 \pm 0.08(\mathrm{stat}) \pm 0.03(\mathrm{syst}))\%$

compatible with the muon-tagged result
$\Delta A_{CP\ \mathrm{sec}} = (+0.14 \pm 0.16(\mathrm{stat}) \pm 0.08(\mathrm{syst}))\%$ JHEP 07 (2014) 041

Both results are statistically and systematically uncorrelated

Current experimental status



Phys. Rev. Lett. **100**, 061803

Phys. Rev. Lett. **109**, 111801

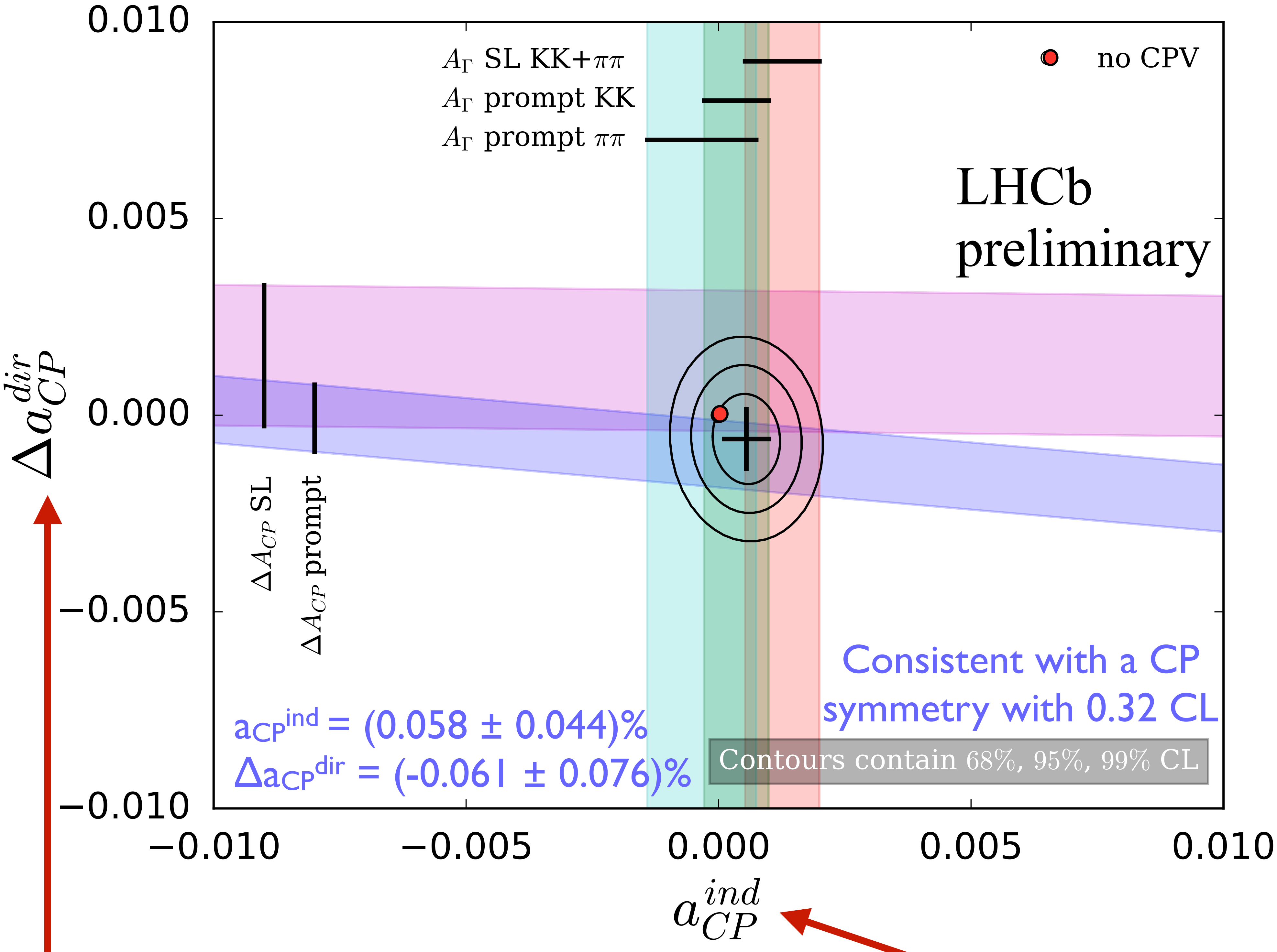
arXiv:1212.5320

JHEP 07 (2014) 041

LHCb-PAPER-2015-055
to be submitted to PRL

naive WA ignoring the indirect CPV contribution = -0.129 ± 0.072%

LHCb summary of the CPV searches in $D^0 \to h^+h^-$



$a_{CP}^{ind} = (0.058 \pm 0.044)\%$

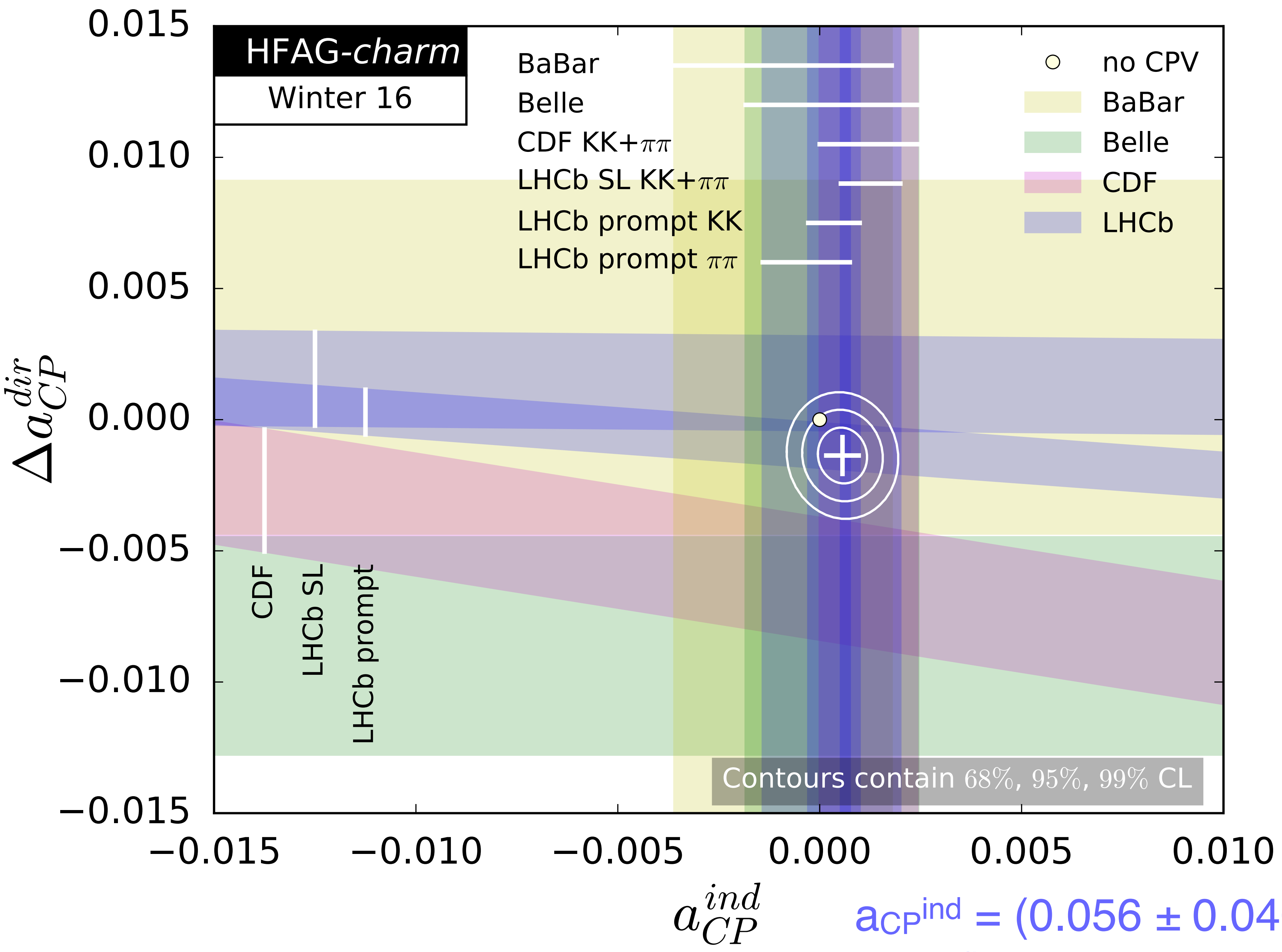
$\Delta a_{CP}^{dir} = (-0.061 \pm 0.076)\%$

Consistent with a CP symmetry with 0.32 CL

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

$$A_\Gamma \approx -a_{CP}^{ind}$$

HFAG averages including the latest results



$a_{CP}^{ind} = (0.056 \pm 0.040)\%$

$\Delta a_{CP}^{dir} = (-0.137 \pm 0.070)\%$

Compatible with no-CPV in the charm sector at 6.5% CL

Complementary searches in other 2 body decays

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

Feldman, Nandi, Soni
JHEP 1206 (2012) 007

- Modes like $D^+ \to \varphi\pi^+$, $D_s \to \varphi K^+$, which are induced by the 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 $D^+ \to \overline{K}^0(\overline{K}^{*0})\pi^+$, $D_s \to \varphi\pi^+$ etc. in order to test against NP contributions in charged flavour transitions.

CP violation in SCS $D^{+}_{(s)} \to K^0_S h^+$ 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 $D^{+}_{(s)} \to \Phi h^+$

$A_{CP/\mathrm{int}}(K^0)$: small effect from CPV, only K^0 decays with short times used

JHEP 1410 (2014) 25

$$\boxed{A_{CP}^{D^\pm \to K^0_S K^\pm} = (+0.03 \pm 0.17 \pm 0.14)\%}$$

$$\boxed{A_{CP}^{D^\pm_s \to K^0_S \pi^\pm} = (+0.38 \pm 0.46 \pm 0.17)\%.}$$

Most precise measurement of these quantities: dominating in the current WA

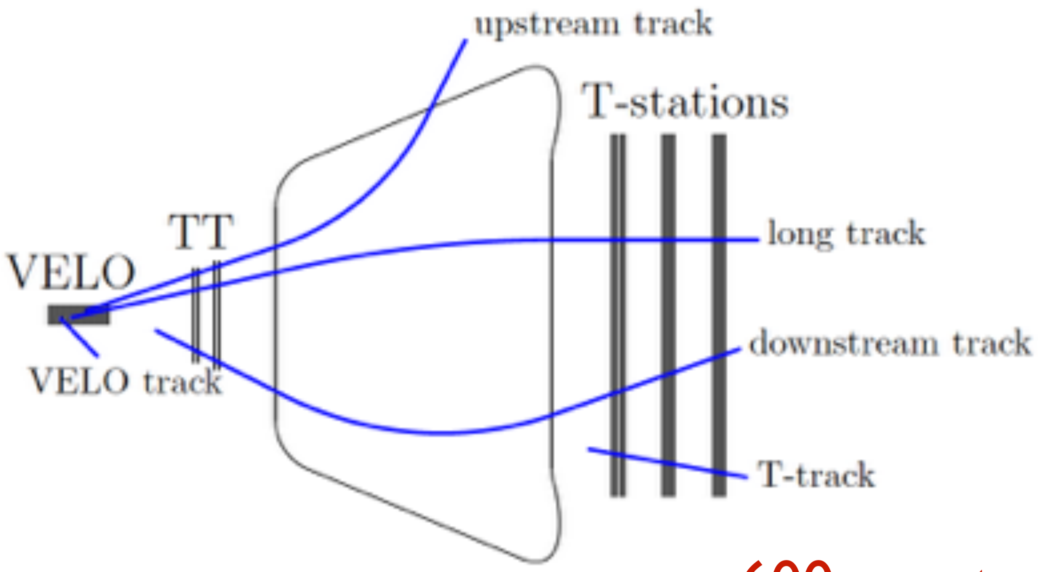
$$\boxed{A_{CP}^{D^\pm \to K^0_S K^\pm} + A_{CP}^{D^\pm_s \to K^0_S \pi^\pm} = (+0.41 \pm 0.49 \pm 0.26)\%.}$$

No indication for CPV

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

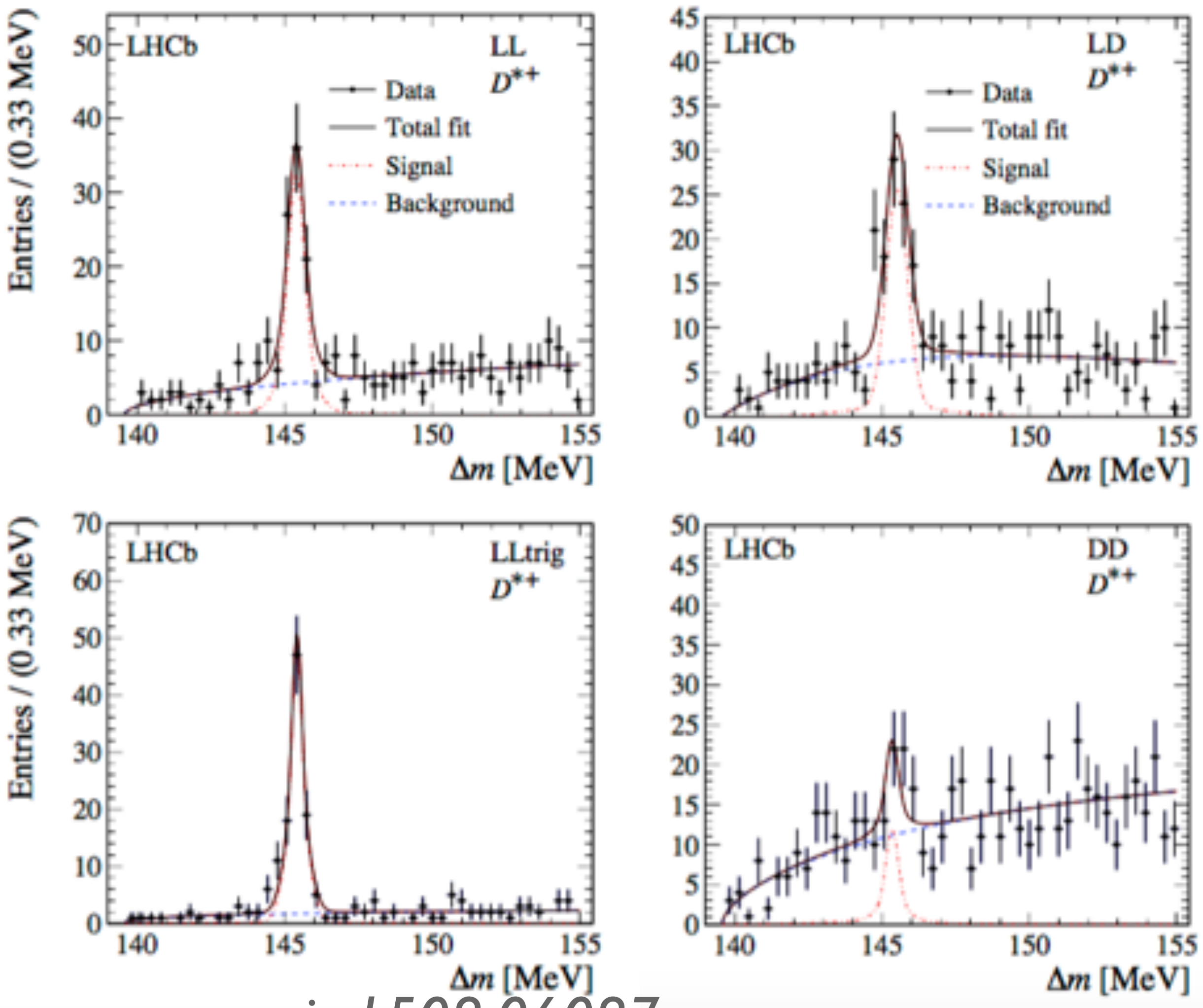
Hiller, Jung, Schacht,
Phys.Rev. D87 (2013) 1, 014024

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



- Using prompt D^0, 3 fb^{-1}
- Experimentally challenging: 2 long lived particles

~ 600 events



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

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

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

Only previous measurement from CLEO: $A_{CP}=(23\pm19)\%$
[PRD 63 (2001) 071101]

arxiv:1508.06087
accepted for publication in JHEP

Direct CPV searches in multi-body charm decays

Isospin decompositions of 2- and multi-body decays

Measurements in one mode can help constrain the theory uncertainties in other decays

Grossman, Kagan, Zupan,
Phys.Rev. D85 (2012) 114036

Decomposition of the amplitudes ignoring isospin breaking effects

$$\boxed{A_{\pi^+\pi^-} = \sqrt{2}\mathcal{A}_3 + \sqrt{2}\mathcal{A}_1,}$$

$$A_{\pi^0\pi^0} = 2\mathcal{A}_3 - \mathcal{A}_1,$$

$$A_{\pi^+\pi^0} = 3\mathcal{A}_3,$$

- Decompose the matrix elements in SM and NP contribution
- Test sum rules e.g.

$$\frac{1}{\sqrt{2}}(A_{\pi^+\pi^-} - \bar{A}_{\pi^-\pi^+}) \neq -(A_{\pi^0\pi^0} - \bar{A}_{\pi^0\pi^0})$$

One can build set of isospin sum rules for CP asymmetries in SCS D decays that can be used to discriminate SM and NP scenarios

$$\boxed{\begin{aligned} A_{\rho^+\pi^-} &= \mathcal{A}_3 + \mathcal{B}_3 + \frac{1}{\sqrt{2}}\mathcal{A}_1 + \mathcal{B}_1, \\ A_{\rho^0\pi^0} &= 2\mathcal{A}_3 - \mathcal{B}_1, \\ A_{\rho^-\pi^+} &= \mathcal{A}_3 - \mathcal{B}_3 - \frac{1}{\sqrt{2}}\mathcal{A}_1 + \mathcal{B}_1, \end{aligned}}$$

$$\boxed{A_{K^+\bar{K}^0\pi^-} = \mathcal{B}_1 - \mathcal{A}_1 + \mathcal{C}_3 + \mathcal{B}_3,}$$

$$A_{K^+K^-\pi^0} = \mathcal{B}_1' + \frac{1}{\sqrt{2}}\mathcal{A}_1 + \sqrt{2}\mathcal{C}_3 + \mathcal{B}_3',$$

$$A_{K^0\bar{K}^0\pi^0} = -\mathcal{B}_1' + \frac{1}{\sqrt{2}}\mathcal{A}_1 + \sqrt{2}\mathcal{C}_3 - \mathcal{B}_3',$$

$$\boxed{A_{K^0K^-\pi^+} = -\mathcal{B}_1 - \mathcal{A}_1 + \mathcal{C}_3 - \mathcal{B}_3,}$$

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

Local asymmetries searches techniques

Discover CPV

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

Phys.Lett. B728 (2014) 585–595,
Phys.Lett. B726 (2013) 623–633
PRD 84 (2011) 112008

Stat. Comp. Simul. 75, Issue 2 109-119 (2004),
Nucl. Instrum. Methods A537, 626-636 (2005),
Phys.Rev. D84 (2011) 054015.

Origin of CPV

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

Model independent searches

Binned (χ^2 difference method)

Phys.Lett. B728 (2014) 585–595,
Phys.Lett. B726 (2013) 623–633

- $D^+\to\pi^-\pi^+\pi^+$ decays($1\ \mathrm{fb}^{-1}$): sensitive to 1°-10° differences in phase and 1-10% in magnitude

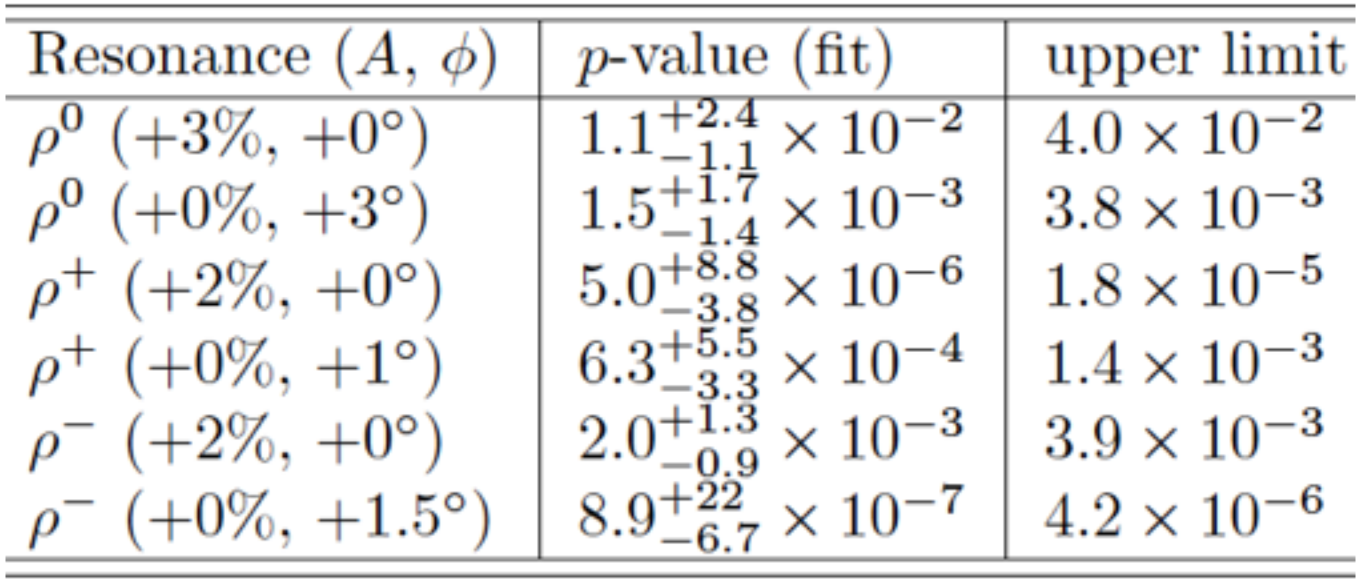
  p-values for no-CPV hypothesis> 50%
- $D^0\to 4\pi/KK\pi\pi$ decays ($1\ \mathrm{fb}^{-1}$): sensitive to 10° differences in phase and 10% in magnitude

  p-values for no-CPV hypothesis are 9.1% for $KK\pi\pi$ and 41% for 4π

Unbinned (Energy test)

PLB 740 (2015) 158-167

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



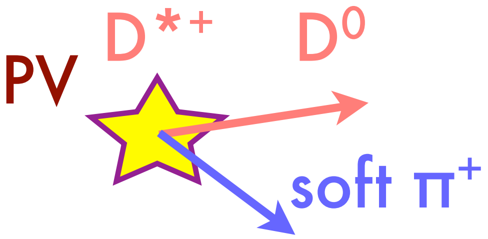
Resonance (A, ϕ)	p-value (fit)	upper limit
ρ^0 $(+3\%, +0°)$	$1.1^{+2.4}_{-1.1}\times10^{-2}$	4.0×10^{-2}
ρ^0 $(+0\%, +3°)$	$1.5^{+1.7}_{-1.4}\times10^{-3}$	3.8×10^{-3}
ρ^+ $(+2\%, +0°)$	$5.0^{+8.8}_{-3.8}\times10^{-6}$	1.8×10^{-5}
ρ^+ $(+0\%, +1°)$	$6.3^{+5.5}_{-3.3}\times10^{-4}$	1.4×10^{-3}
ρ^- $(+2\%, +0°)$	$2.0^{+1.3}_{-0.9}\times10^{-3}$	3.9×10^{-3}
ρ^- $(+0\%, +1.5°)$	$8.9^{+22}_{-6.7}\times10^{-7}$	4.2×10^{-6}

Better sensitivity than BaBar in general, but comparable for ρ^0 amplitude CPV

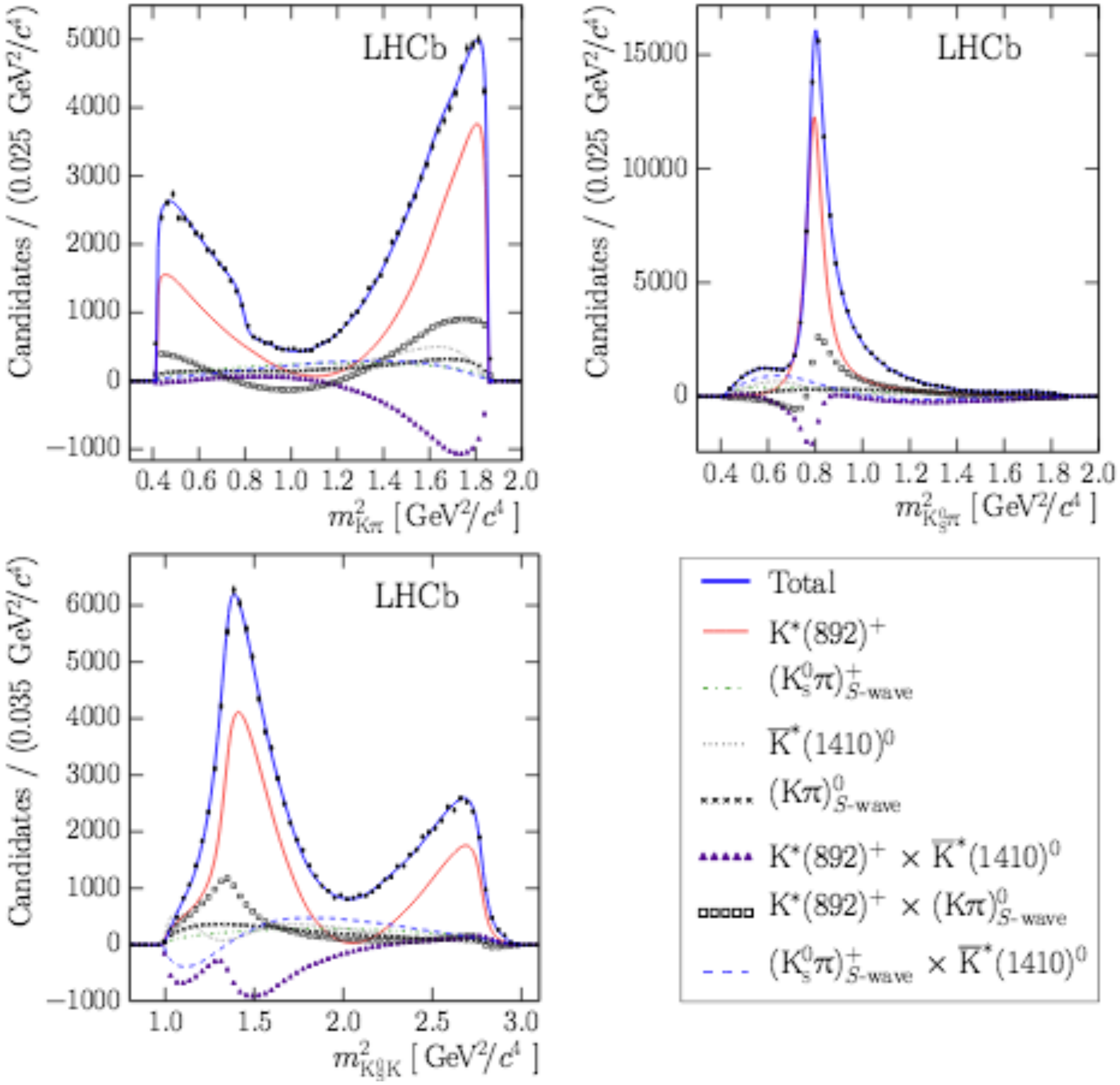
p-value = (2.6±0.5)%

Results consistent with no CP violation

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)



- Using full Run 1 statistics, prompt D^0
- 116k $D^0 \to K_S K^- \pi^+$; 76k $D^0 \to K_S K^+ \pi^-$
- Full amplitude analysis
- Fit the amplitudes separately for D^0 and $\overline{D}^0$ events

arXiv:1509.06628
submitted to PRD

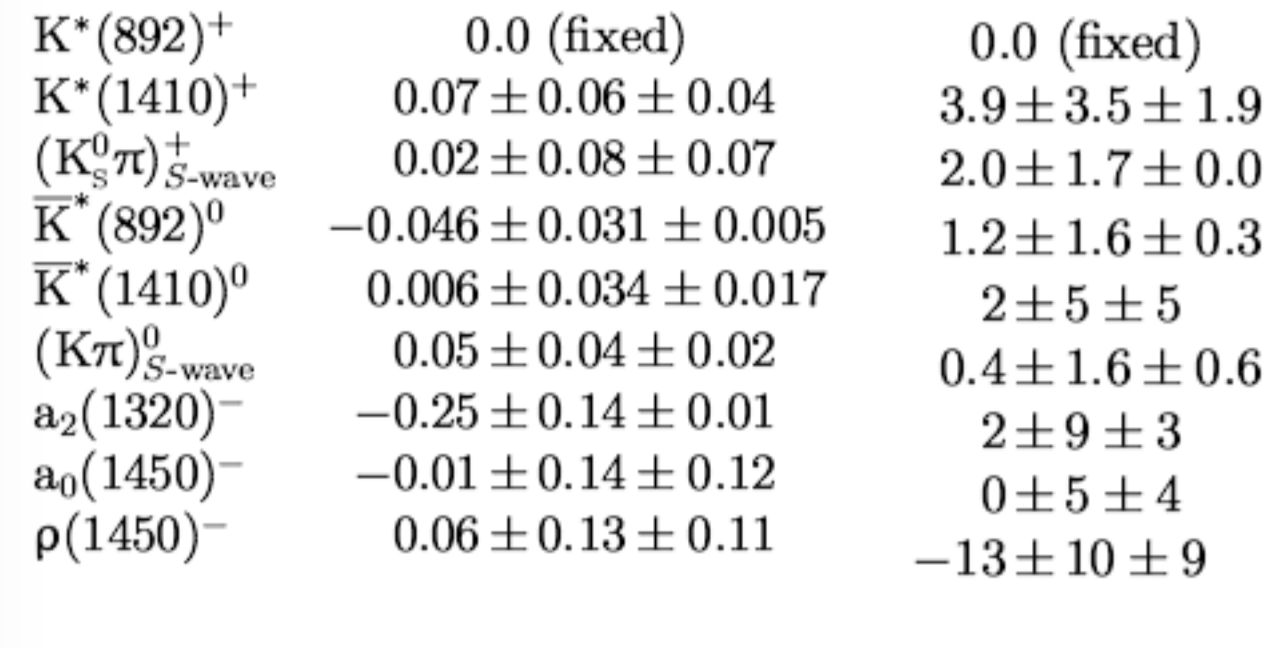
previous analysis of CLEO based on ~500 and ~300 events *PRD85, 092016 (2012)*

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

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

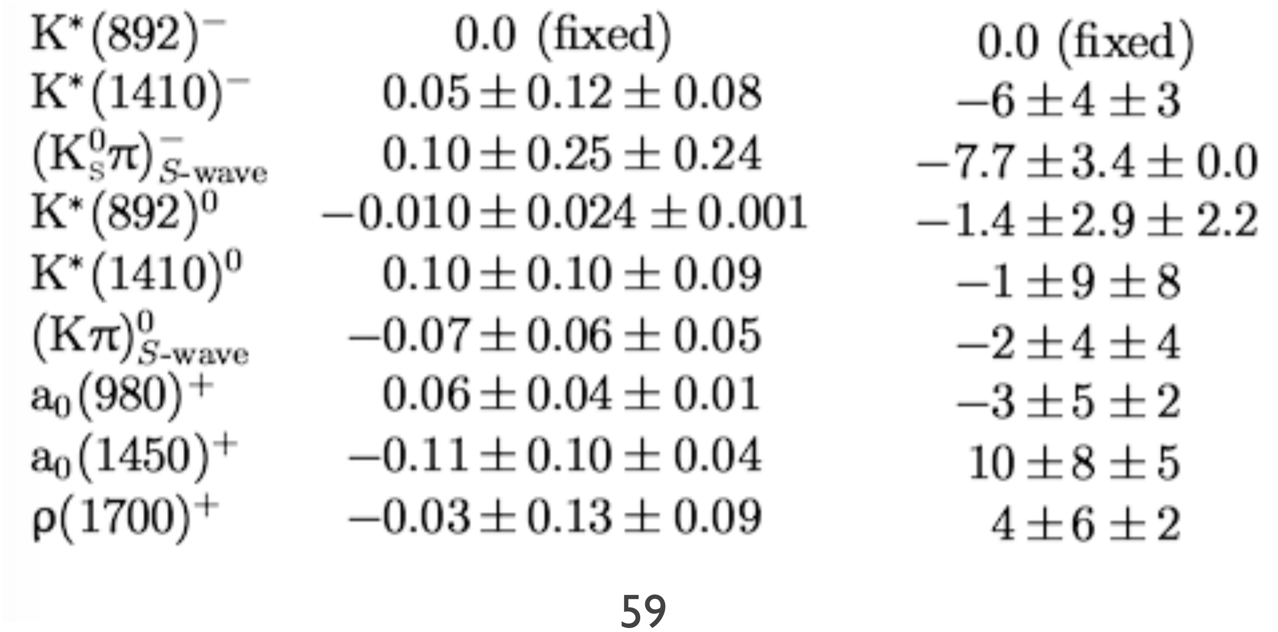
arXiv:1509.06628
submitted to PRD

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



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

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



	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

Triple product observables in multi-body decays

Triple product observables in theory

Different sensitivity to CPV

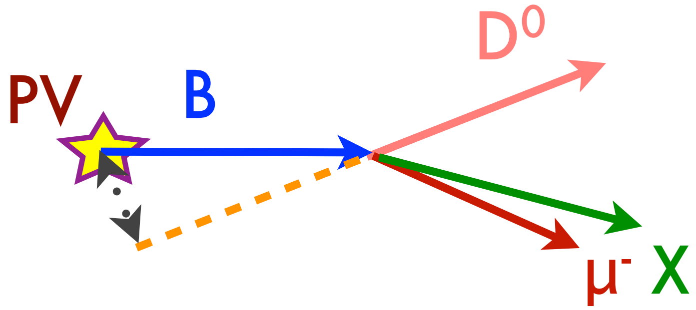
CP asymmetries $\sim \sin\varphi \sin\delta$

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.

CP violation in D⁰→KKππ



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

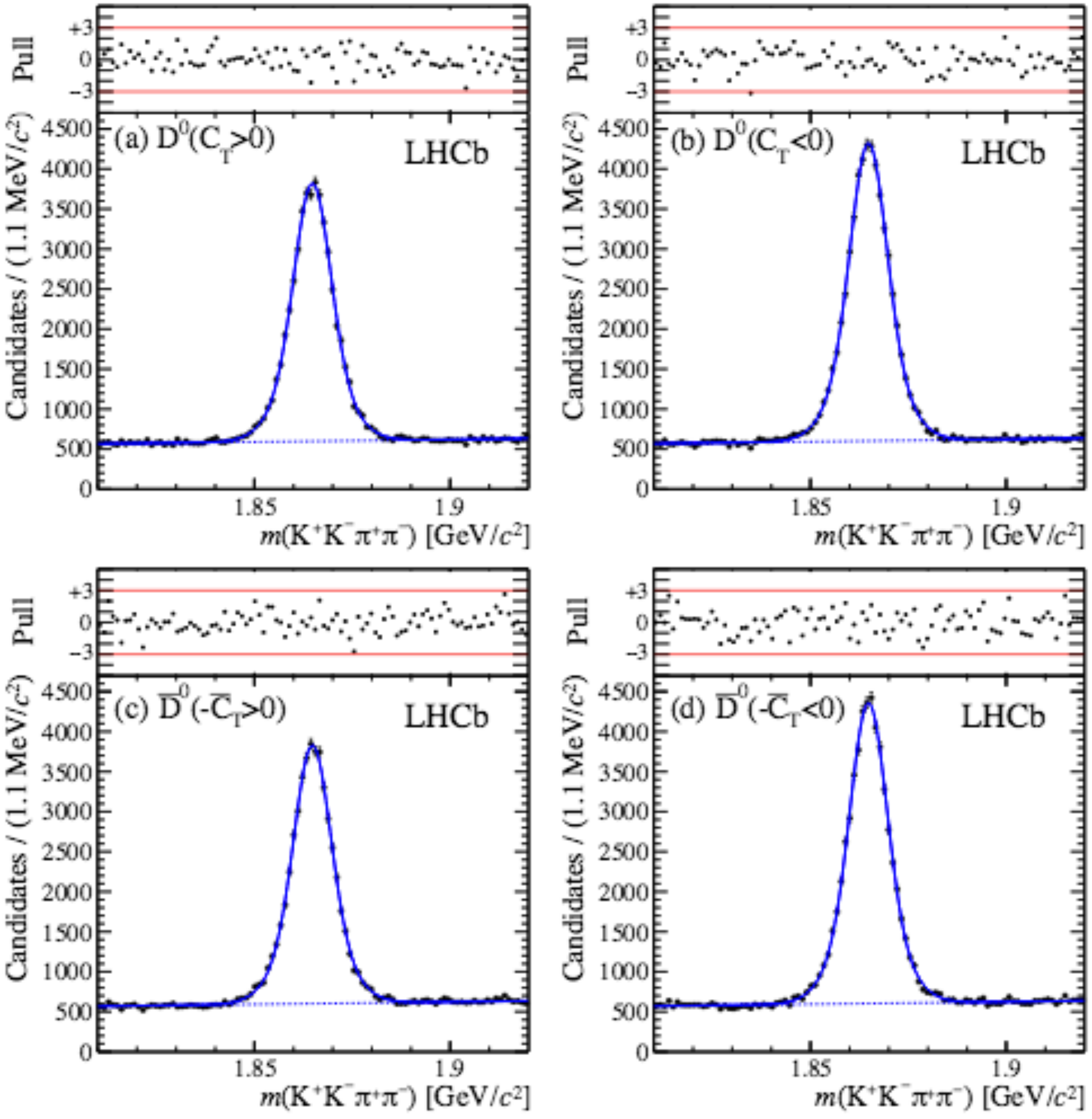
$$A_T \equiv \frac{\Gamma_{D^0}(C_T > 0) - \Gamma_{D^0}(C_T < 0)}{\Gamma_{D^0}(C_T > 0) + \Gamma_{D^0}(C_T < 0)}, \qquad \overline{A}_T \equiv \frac{\Gamma_{\overline{D}^0}(-\overline{C}_T > 0) - \Gamma_{\overline{D}^0}(-\overline{C}_T < 0)}{\Gamma_{\overline{D}^0}(-\overline{C}_T > 0) + \Gamma_{\overline{D}^0}(-\overline{C}_T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

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

All final states interactions cancel
All production and detection effects cancel

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

~171k decays



JHEP 1410 (2014) 005

Integrated over the phase-space

$$a^{T\text{-odd}}_{CP}=(0.18\pm0.29\pm0.04)\%$$

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

No indication of CPV

Previous measurements by
FOCUS: $(1.0\pm5.7\pm3.7)\%$ PLB622 (2005) 239-248
BaBar: $(0.10\pm0.51\pm0.44)\%$ PRD81(2010) 111103

but before that

Prospects
Run11 and beyond

Improved trigger strategies for Run I I

First full calibration and reconstruction of a HEP detector in real time
Barbara Storaci
Detector Seminar

- 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

Run 2 cross-sections & estimated integrated luminosity

- More data!!! Higher cross-sections in LHCb acceptance x2 @ 13TeV

$$\boxed{\sigma(pp \to c\bar{c}X) = 2944 \pm 3 \pm 183 \pm 156\,\mu\text{b},}$$

arxiv:1510.01707; submitted to JHEP

compare to Run 1 @ 7TeV

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

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

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

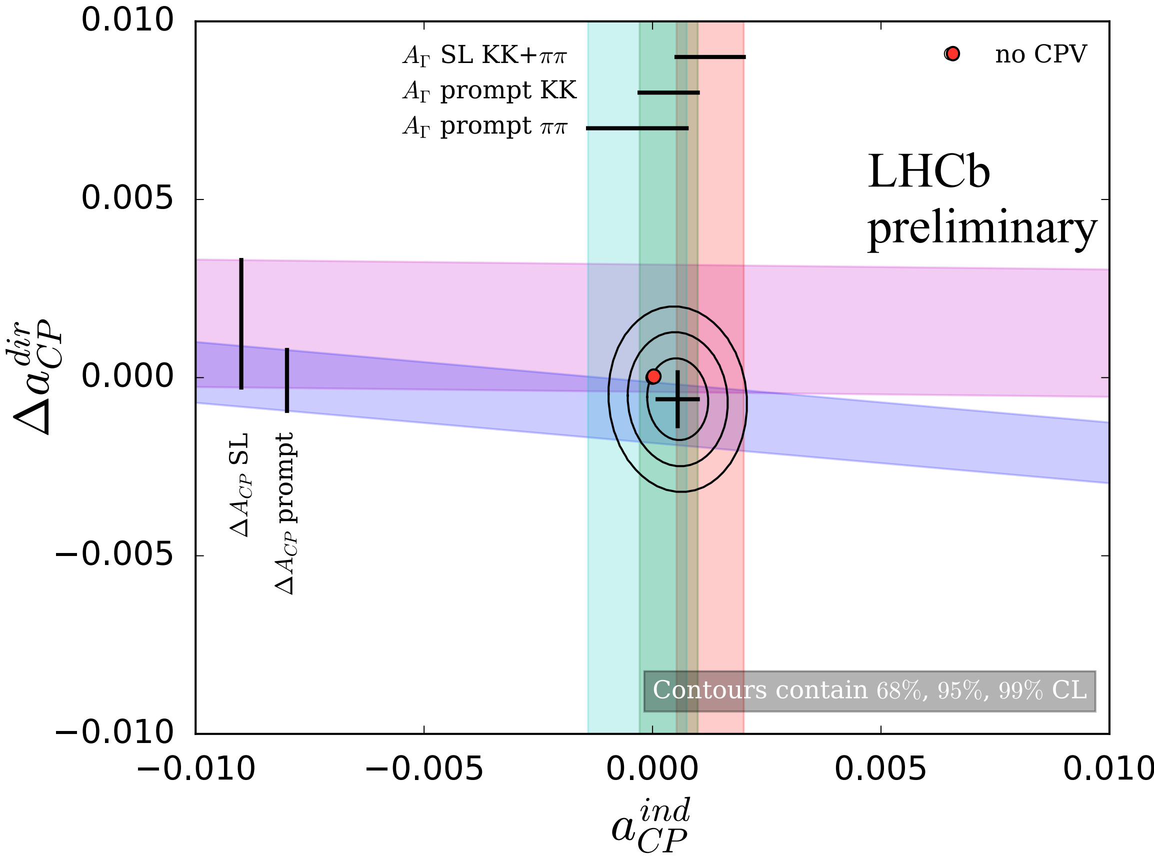
Δa_{CP}: uncertainty 10^{-4} at 50 fb^{-1}

upgrade; gain more data by removing the L0 thresholds

Conclusions

- Precision measurements in the charm sector at LHCb
  - CPV in charm not yet observed: All searches consistent with no direct or indirect CPV
- The key measurements are still statistically limited
- Several key LHCb Run I analyses still ongoing
- Improvements with Run II, and even more with the upgraded LHCb experiment

$\Delta A_{CP\ prompt} = (-0.10 \pm 0.08 \pm 0.03)$ %



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