Measurement of CP violation in the Charm System

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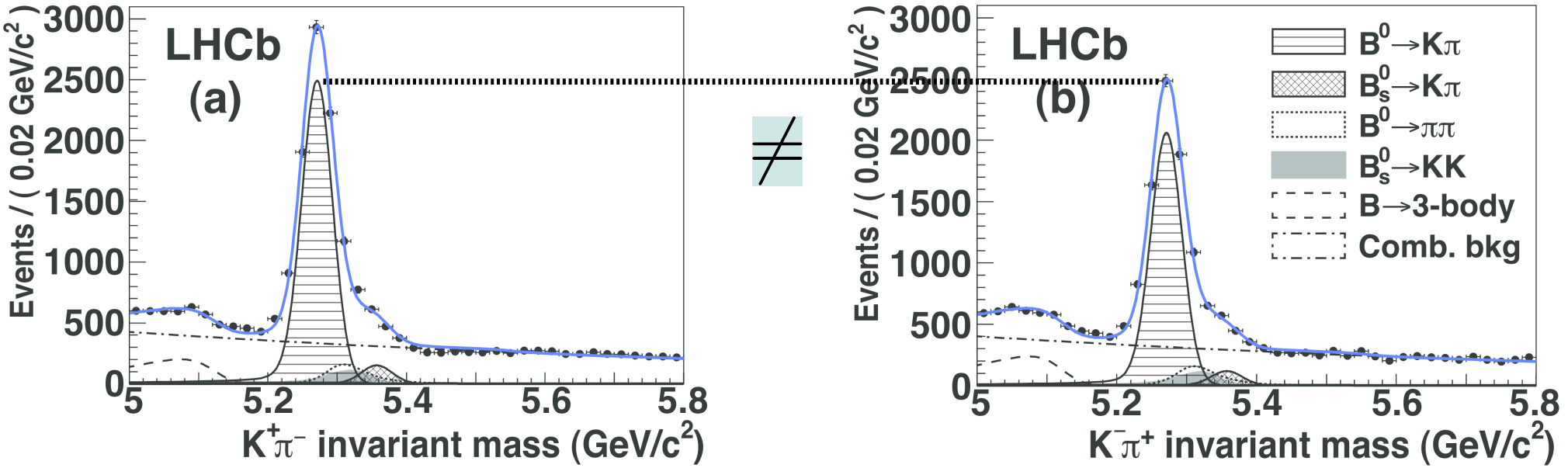
What is CP violation?

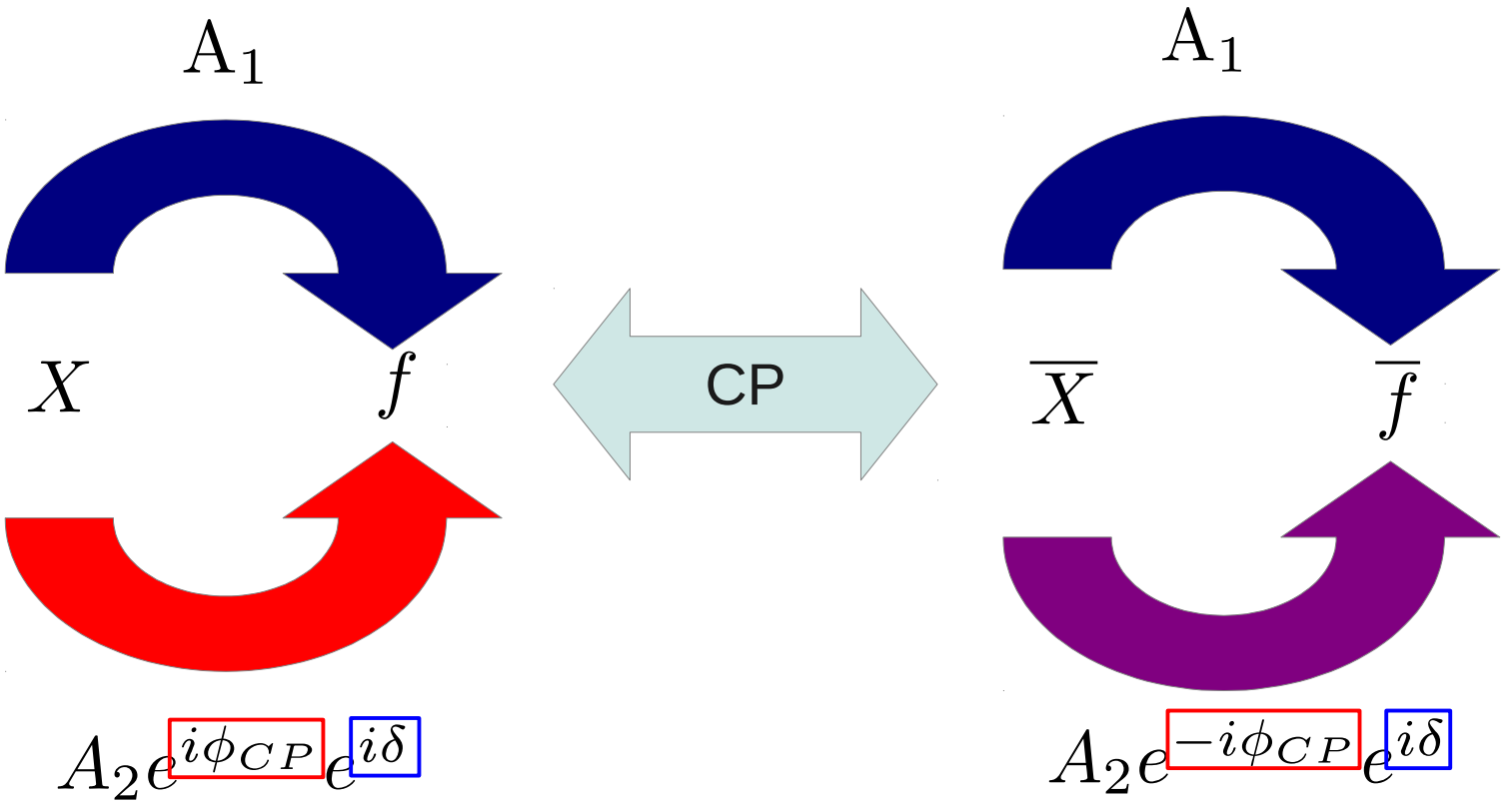
- C = charge conjugation, P = space inversion

$$X \to f \quad \Leftrightarrow \text{CP} \Leftrightarrow \quad \overline{X} \to \overline{f}$$

$$B^0 \to K^+\pi^- \qquad \overline{B}^0 \to K^-\pi^+$$



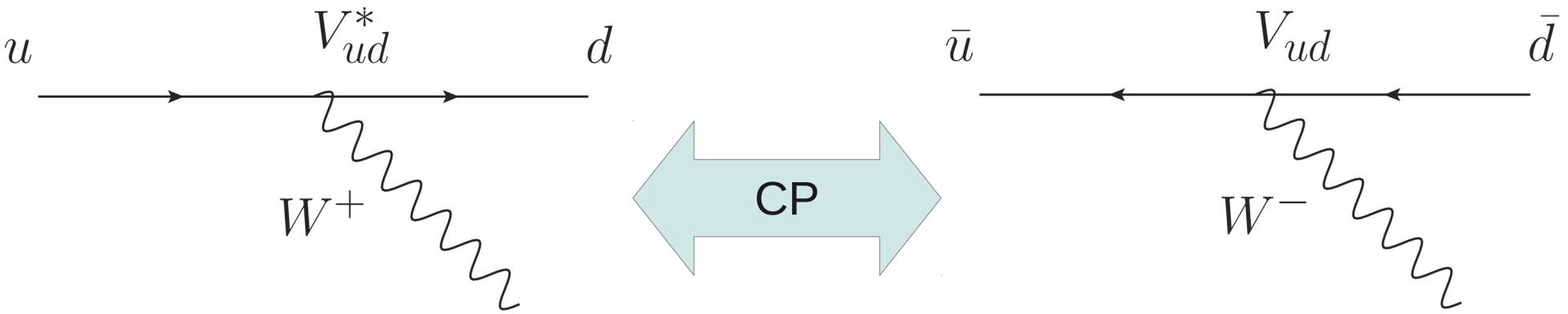
How do you get CP violation?



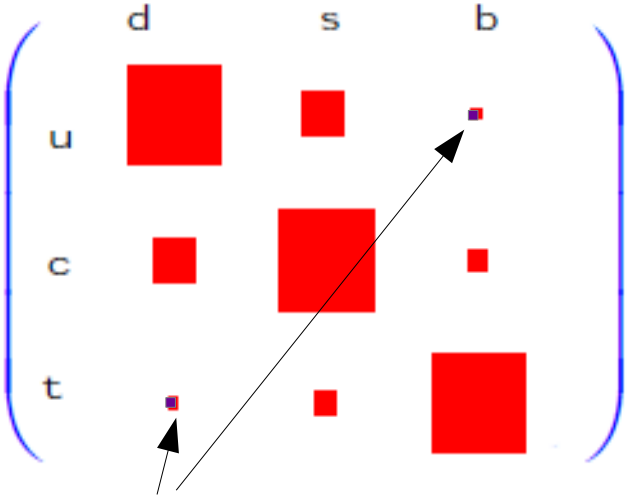
$$|A|^2 = |A_1 + A_2 e^{i\phi_{CP}} e^{i\delta}|^2 \qquad |\overline{A}|^2 = |A_1 + A_2 e^{-i\phi_{CP}} e^{i\delta}|^2$$

$$\text{CP asymmetry} \propto |A|^2 - |\overline{A}|^2 = 4|A_1||A_2| \sin\phi_{CP} \sin\delta$$

CKM matrix describes transition between quarks



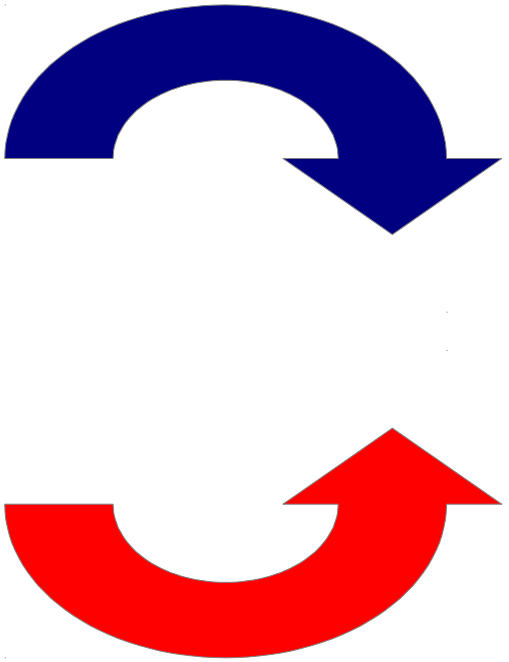
$$\mathrm{V_{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} =$$



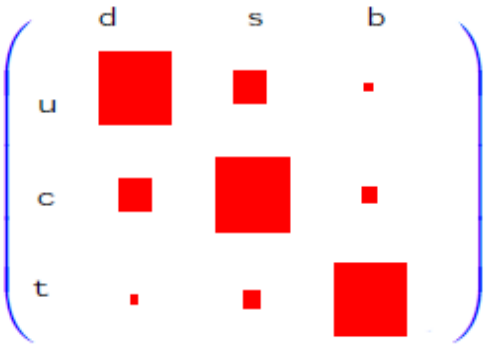
Largest imaginary part

CP violation in charm decays

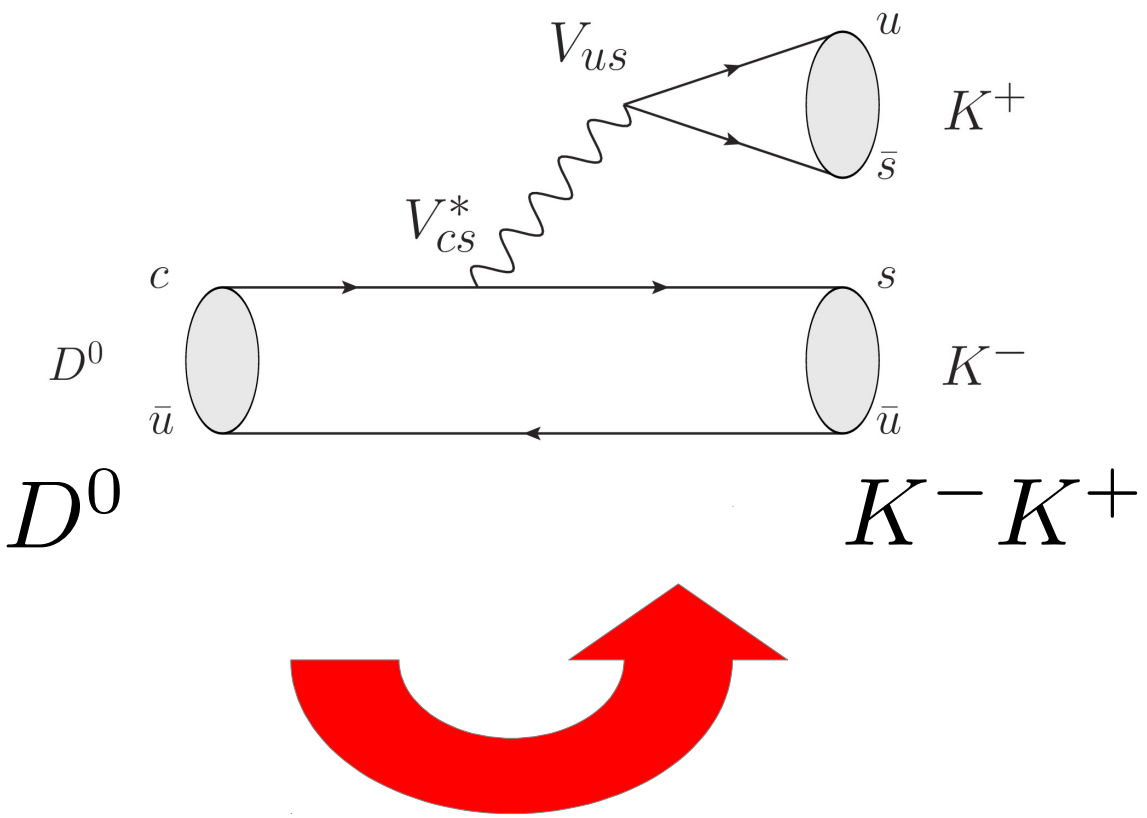
D^0

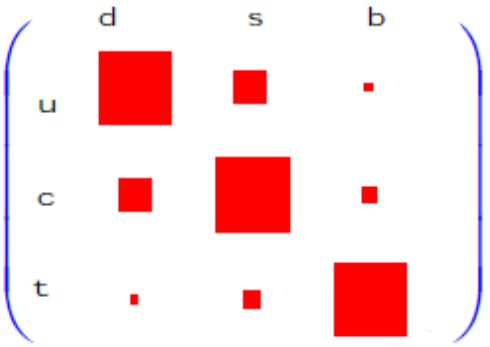


$K^- K^+$

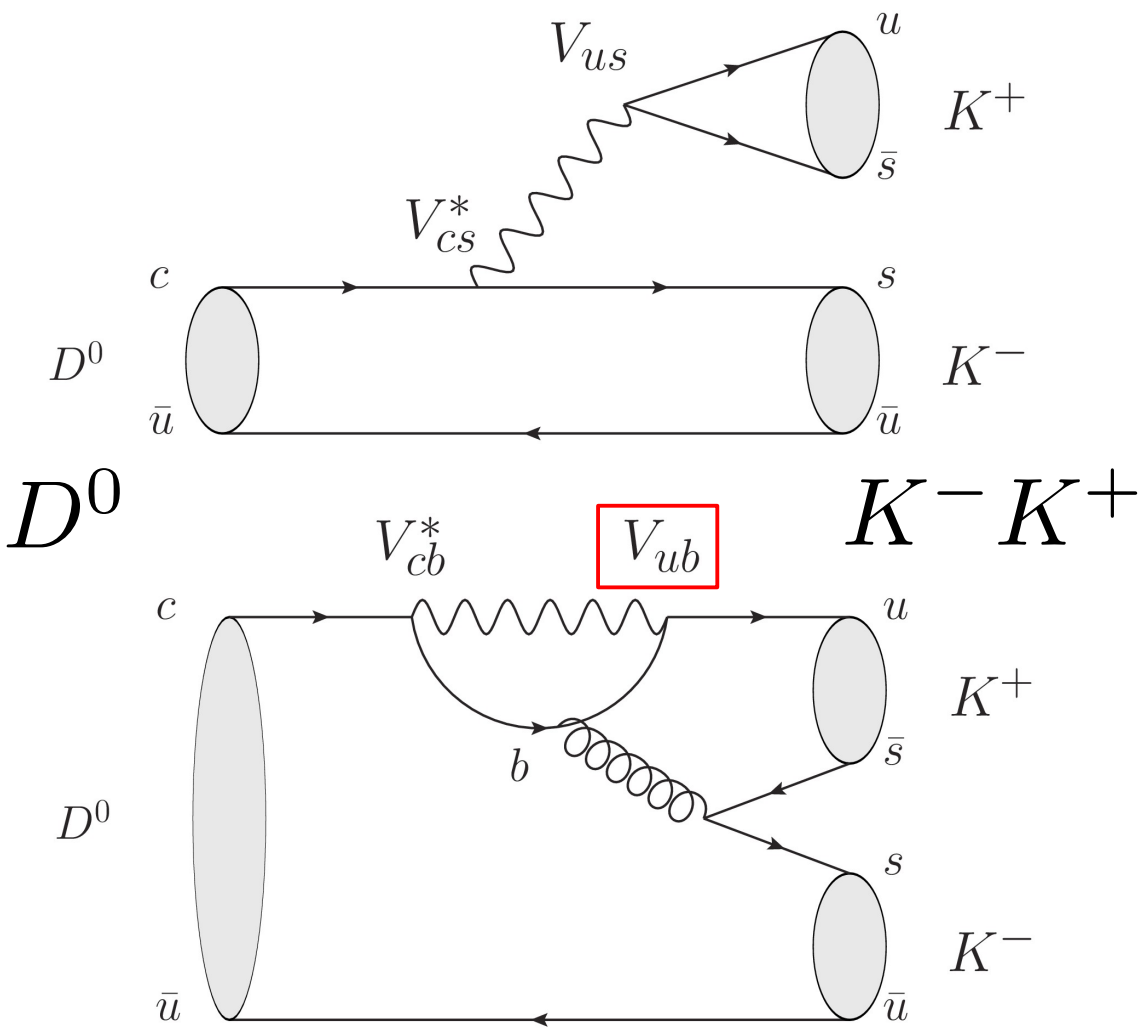


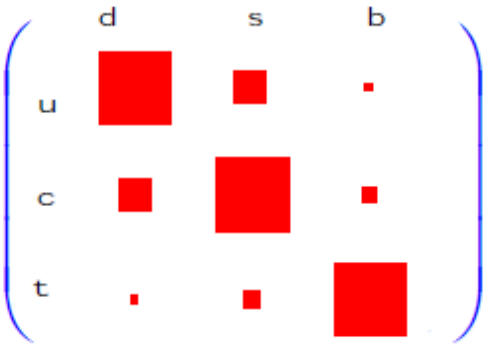
CP violation in charm decays





CP violation in charm decays

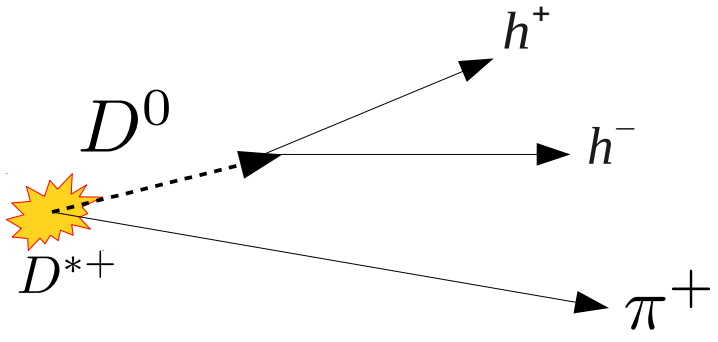


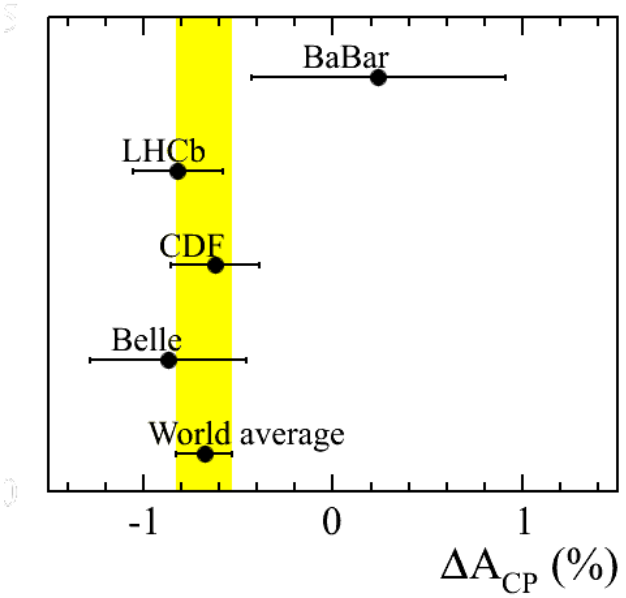


Theory: $A_{CP}(f) = \frac{N(D^0 \to f) - N(\bar{D}^0 \to f)}{N(D^0 \to f) + N(\bar{D}^0 \to f)} \lesssim \mathcal{O}(0.1\ \%)$

CP measurements in $D^0 \to h^- h^+,\ h = K \text{ or } \pi$, by LHCb

Prompt produced Charm





$$\Delta a_{\mathrm{CP,dir}} = (-0.678 \pm 0.147)\%$$

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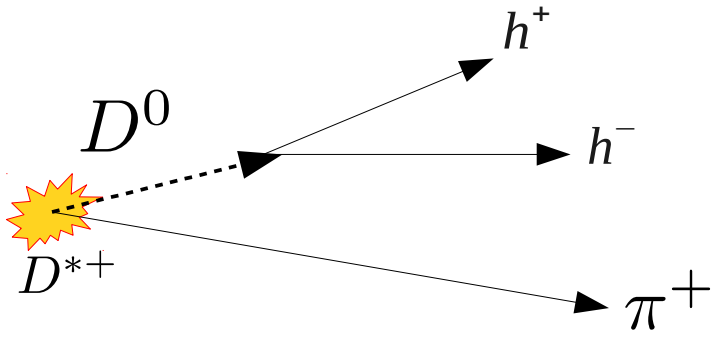
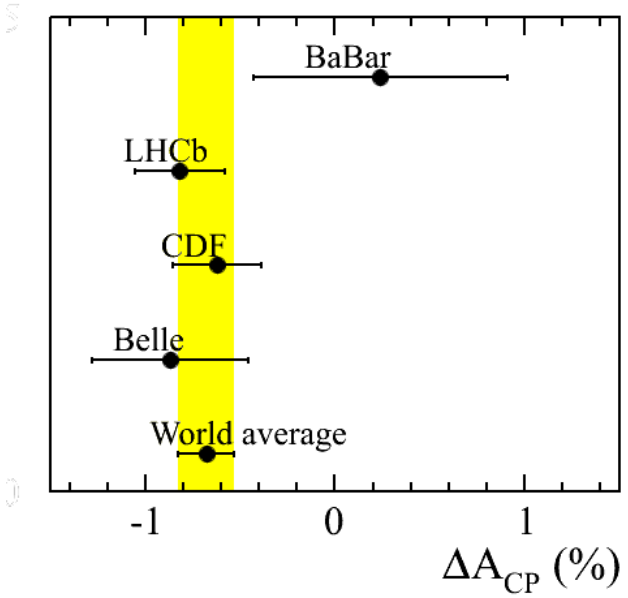
Prompt produced Charm





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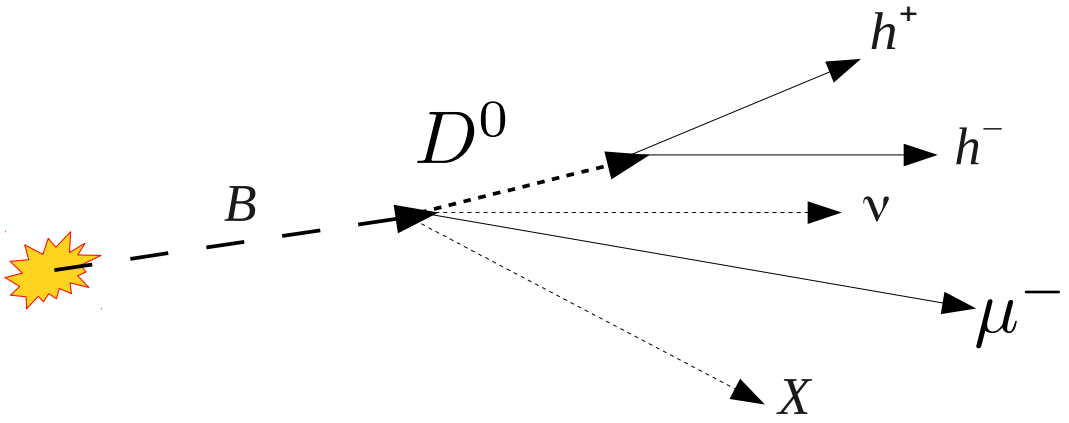
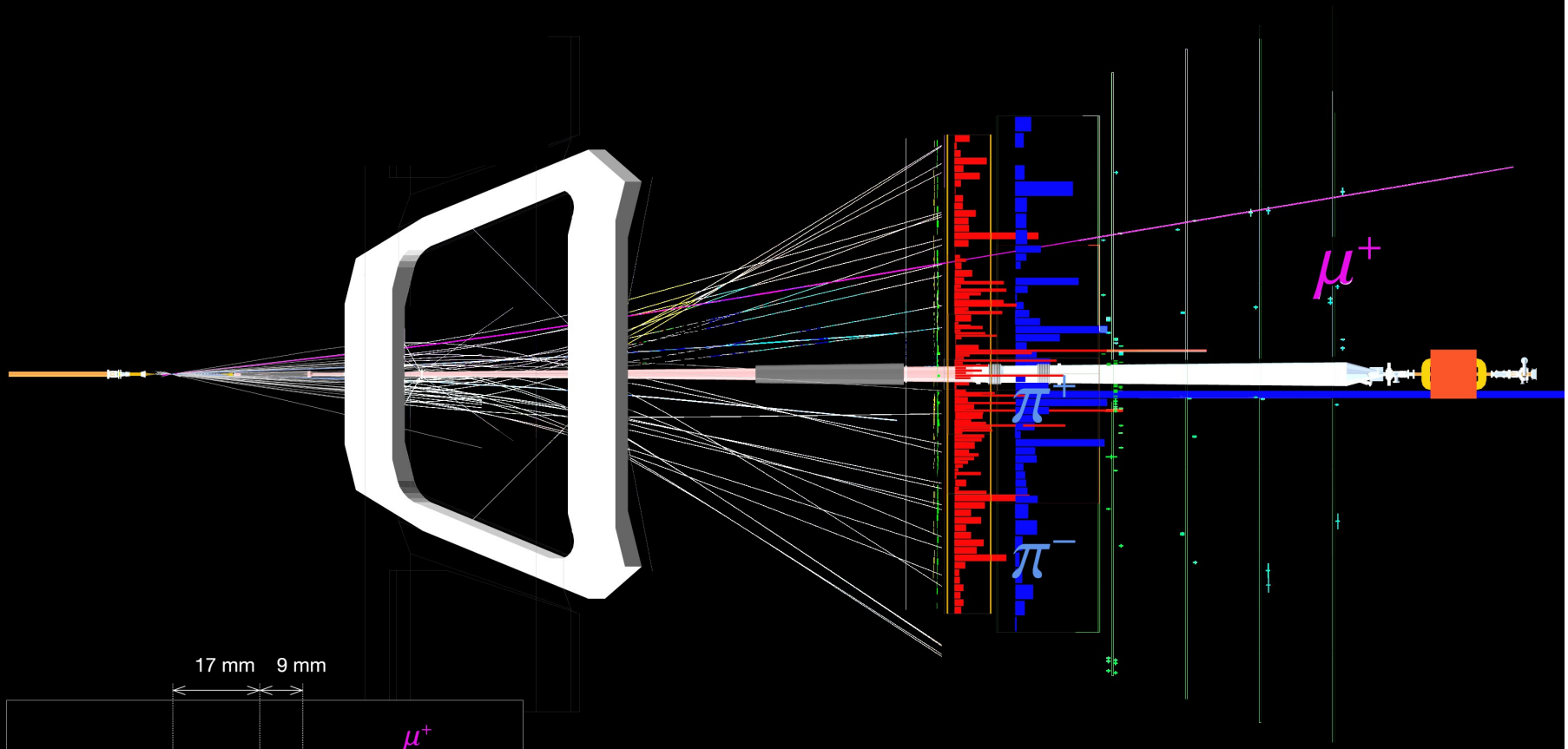
Semileptonic B decays

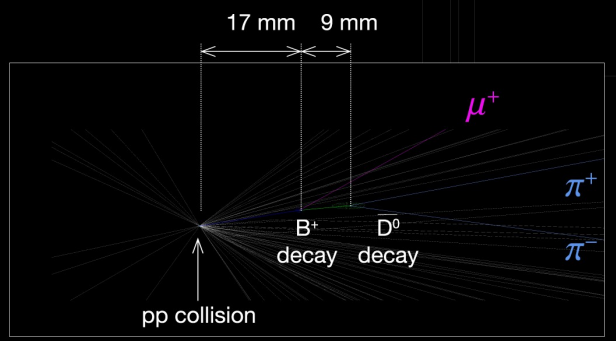


- Important cross-check analysis
- Different detection signature

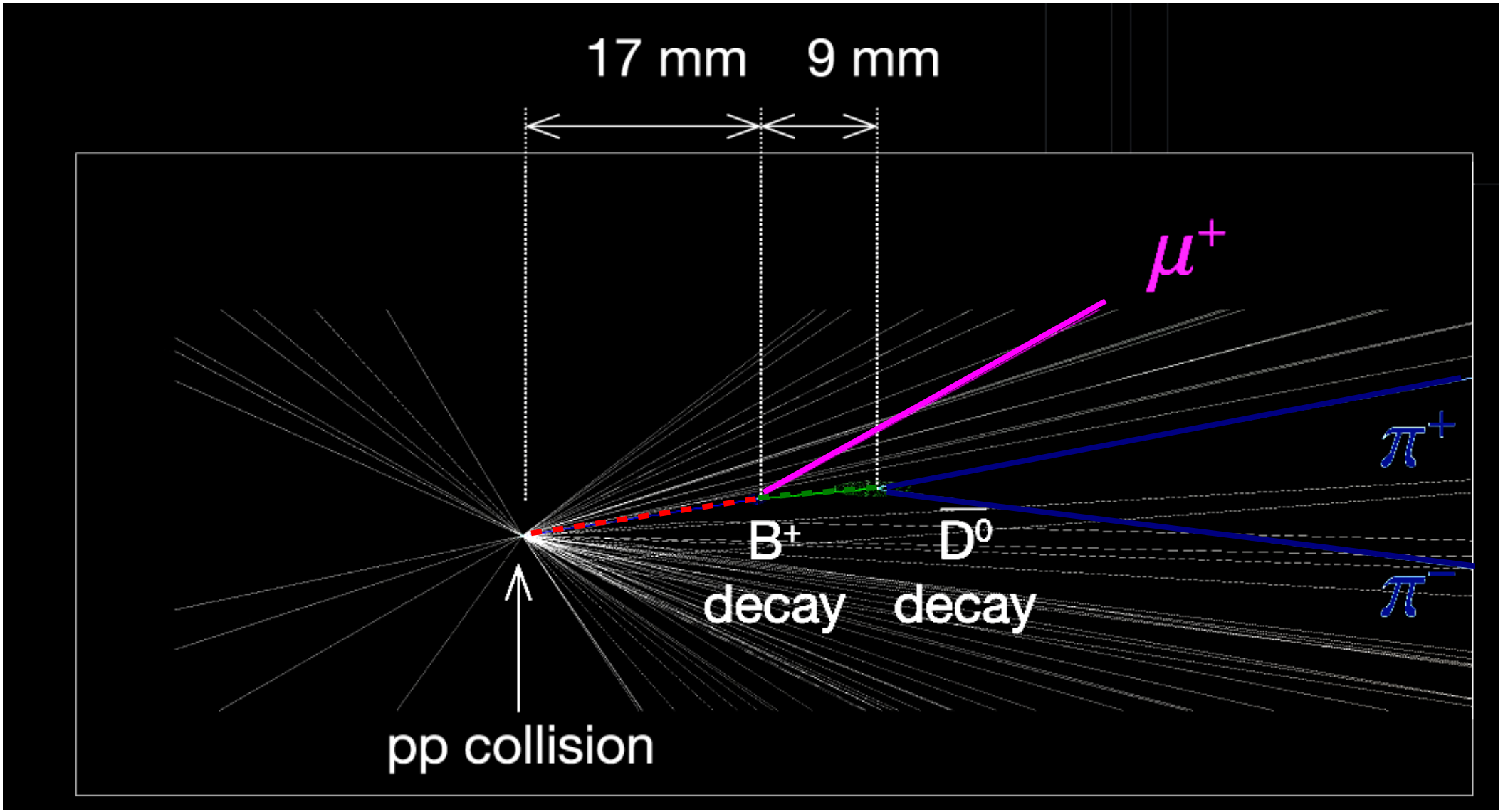
My analysis

$$B^+ \longrightarrow \overline{D^0}\,\mu^+(\nu)$$
$$\downarrow$$
$$\pi^+\pi^-$$



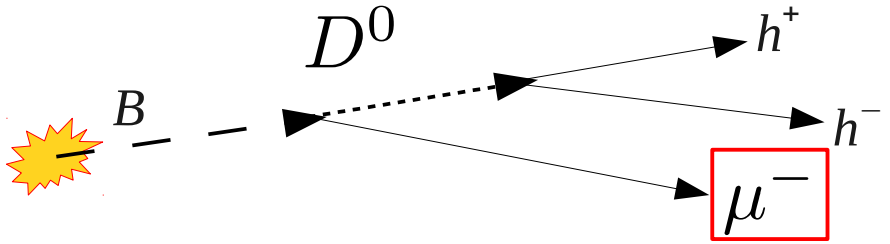


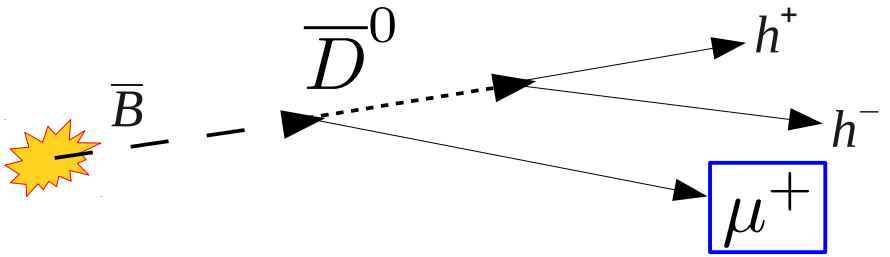
Only well reconstructed tracks with $p_T > 500$ MeV

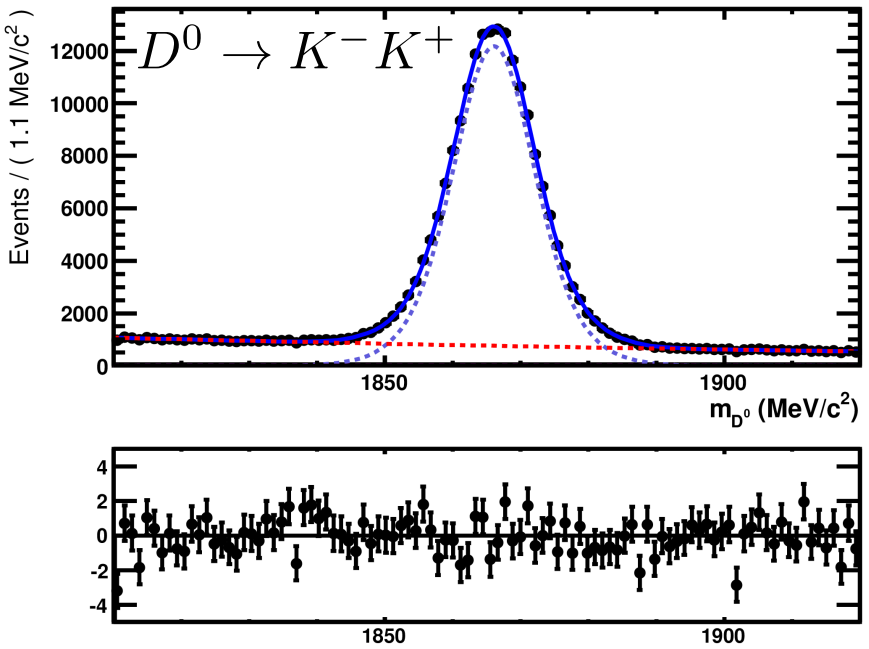

17 mm
9 mm
μ^+
π^+
π^-
B^+
decay
$\overline{D}^0$
decay
pp collision

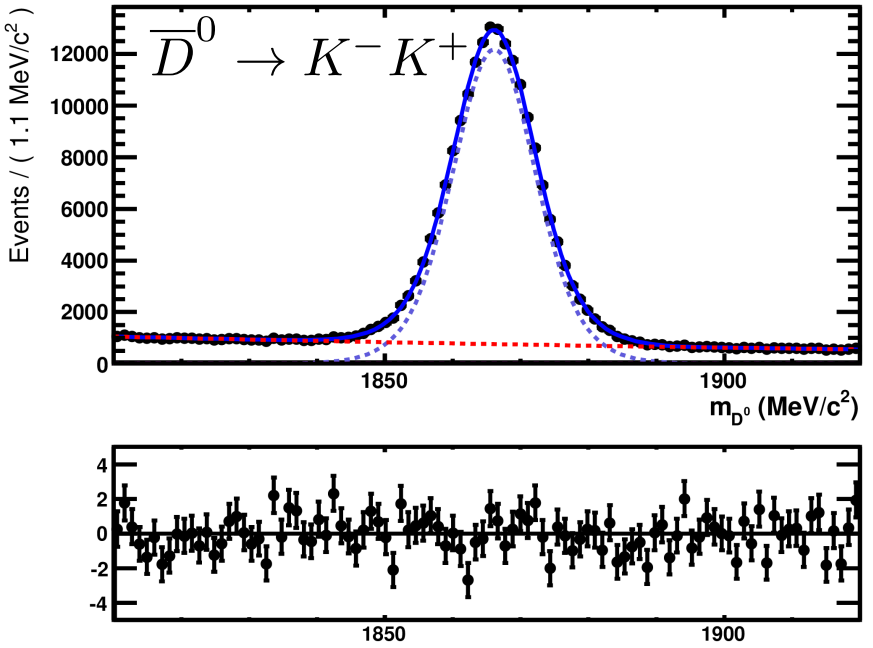
How to determine an asymmetry?

$$A_{raw}(f) = \frac{N(f,\mu^-) - N(f,\mu^+)}{N(f,\mu^-) + N(f,\mu^+)}$$









Measured quantities: $\mathrm{A}_{raw}(f)$ and ΔA_{CP}

Measured asymmetry:

$$\mathrm{A}_{raw}(f) = \frac{N(f,\mu^-) - N(f,\mu^+)}{N(f,\mu^-) + N(f,\mu^+)}$$

$$f = K^+K^-, \pi^+\pi^-$$

$$A_{raw}(f) = A_{CP}(f) + A_D(\mu) + A_P(B)$$

CP Asymmetry

Detection asymmetry

Production asymmetry

All of order 1% or below.

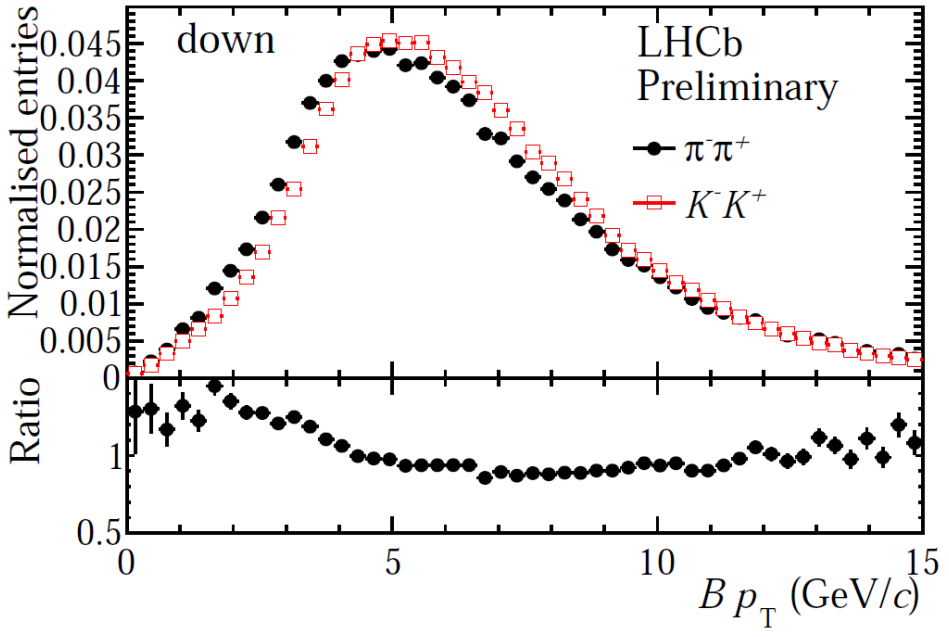
Experimentally more robust:

$$\begin{aligned} \Delta A_{CP} &= A_{raw}(K^+K^-) - A_{raw}(\pi^+\pi^-) \\ &= A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \end{aligned}$$

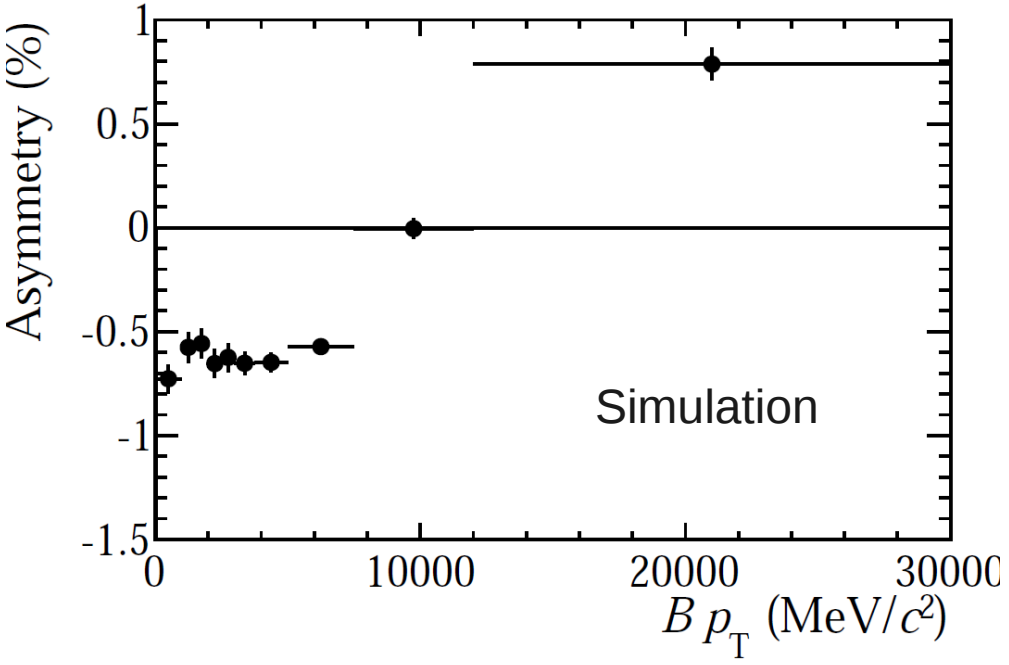
Assumption: Detector- and production asymmetry cancel.

Production and detection asymmetries

- Assumption: Cancellation of production and detection asymmetry in difference
- Production and detection asymmetry depend on kinematics



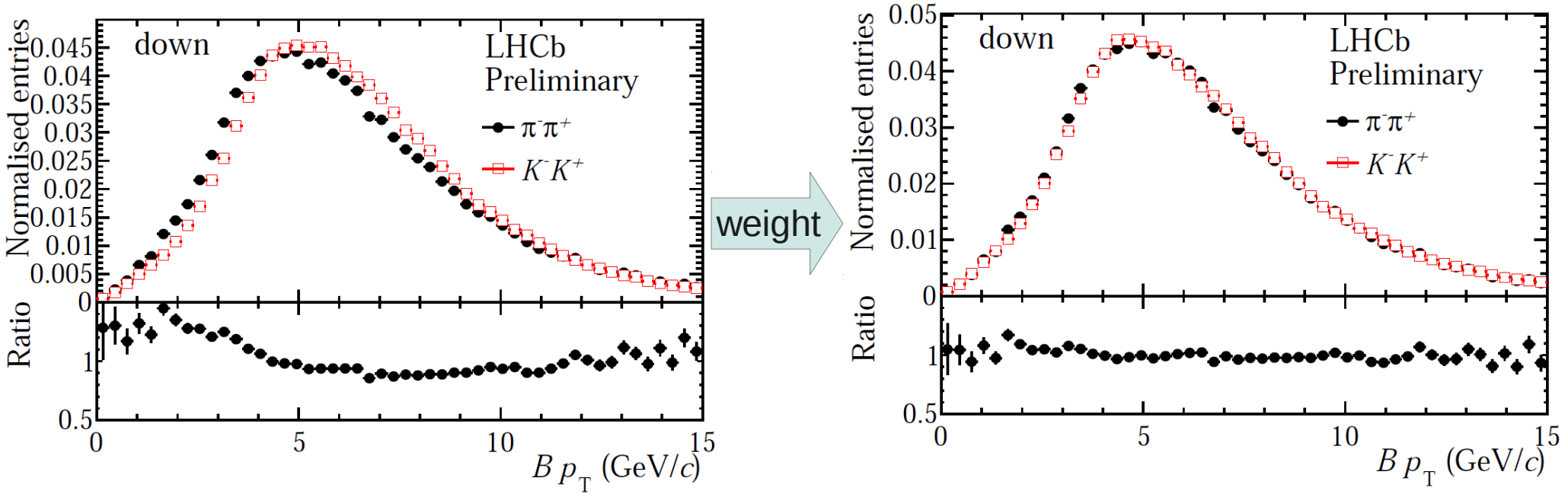
Production asymmetry:



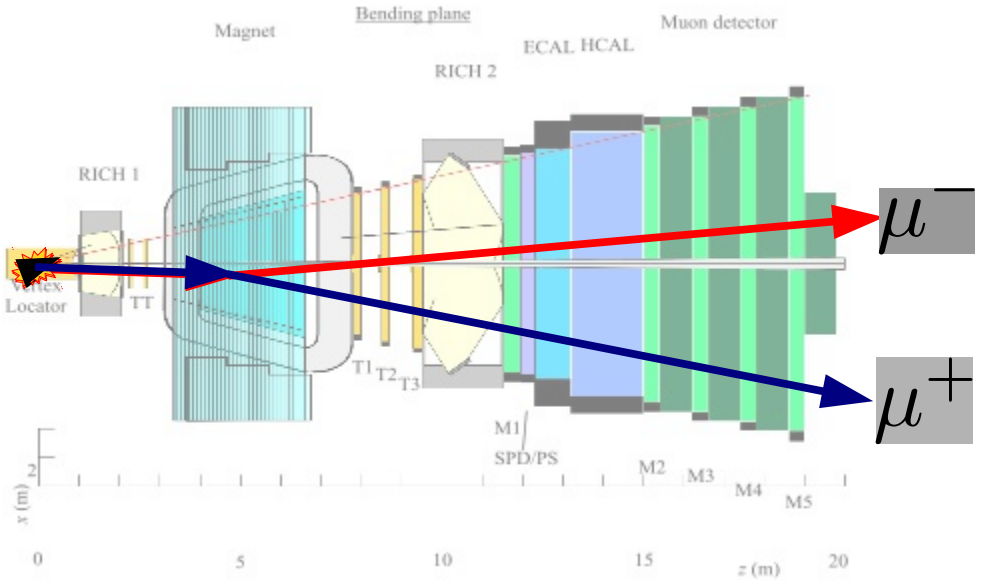
Production and detection asymmetries

- Assumption: Cancellation of production and detection asymmetry in difference
- Production and detection asymmetry depend on kinematics
- Assign weights to events to match kinematics

  → Ensures cancellation of asymmetries

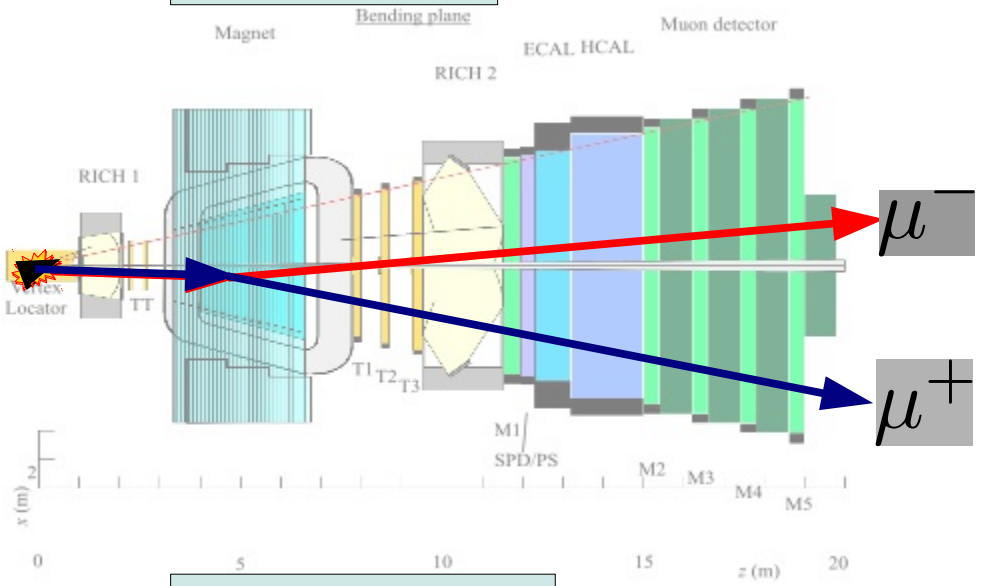


Controlling detection asymmetries

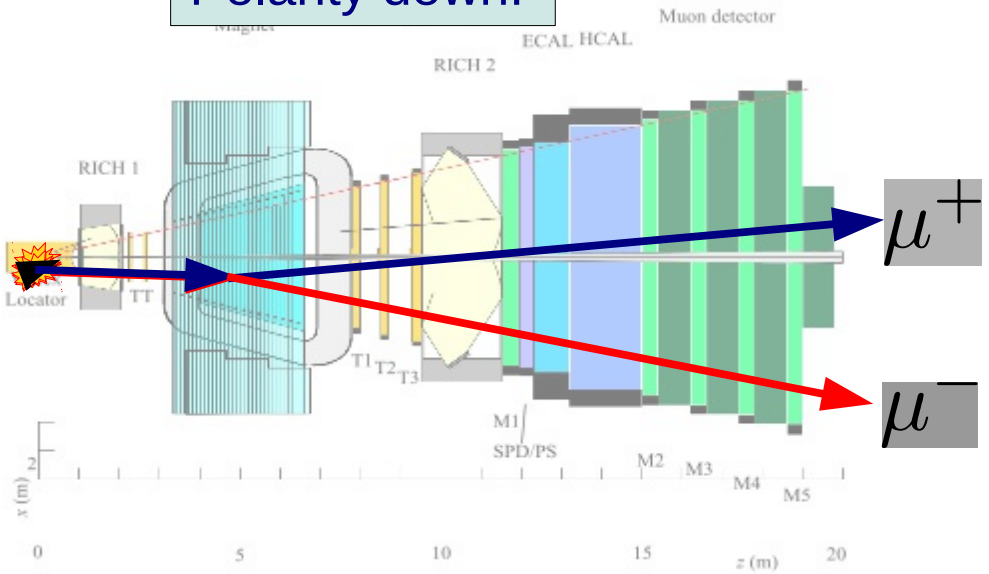


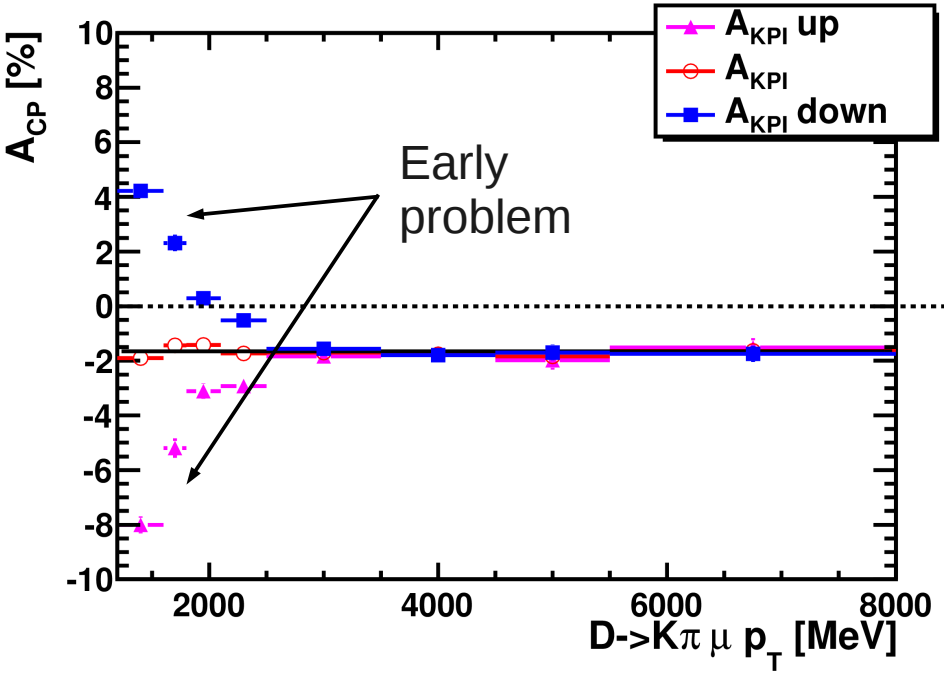
Controlling detection asymmetries

Polarity up:



Polarity down:





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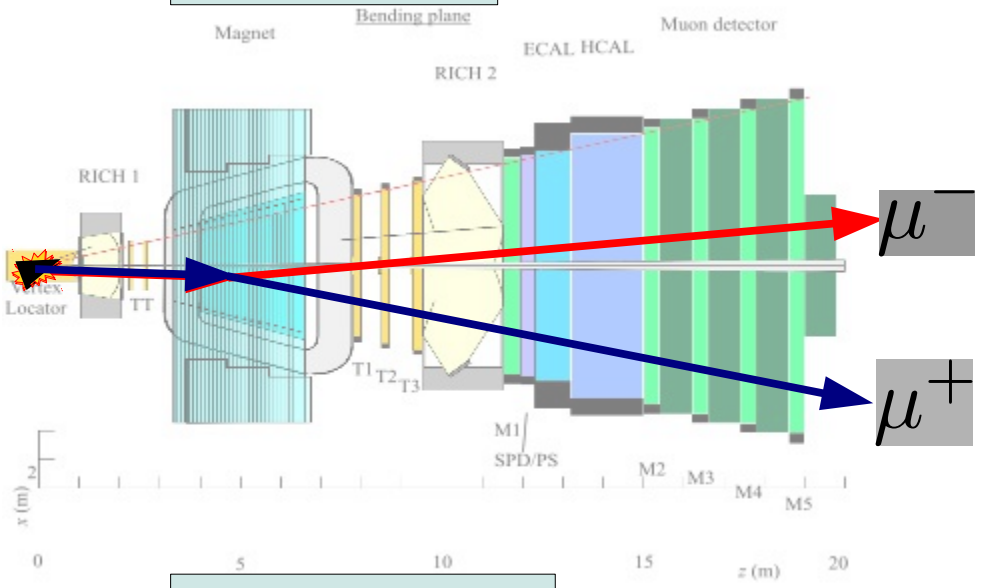
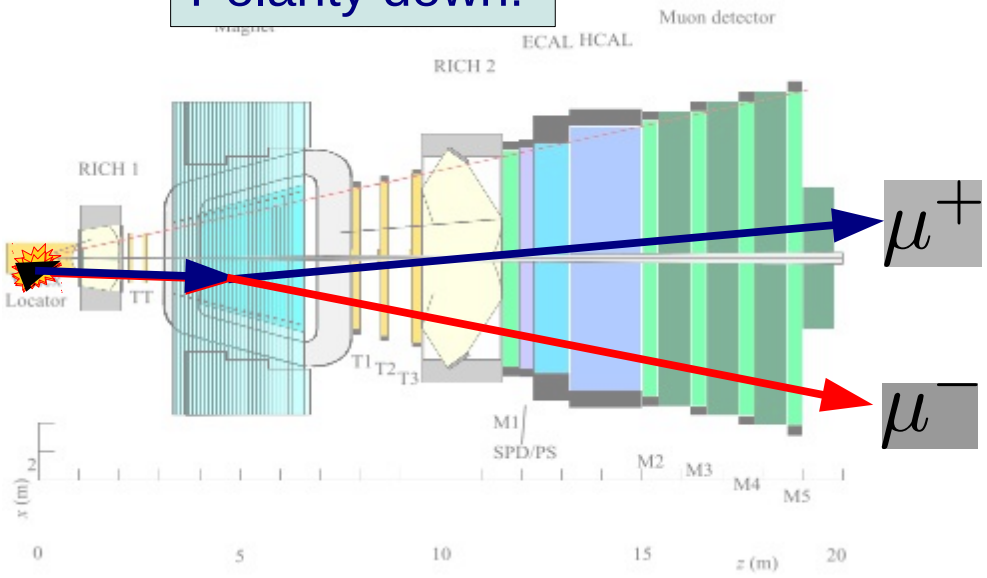
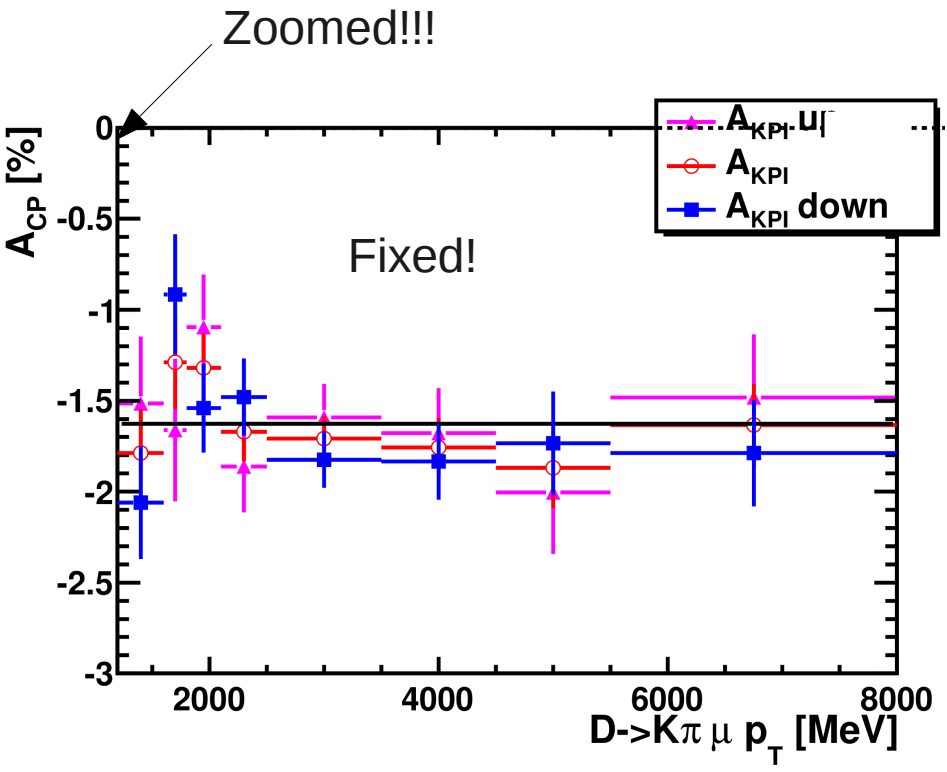


Polarity down:

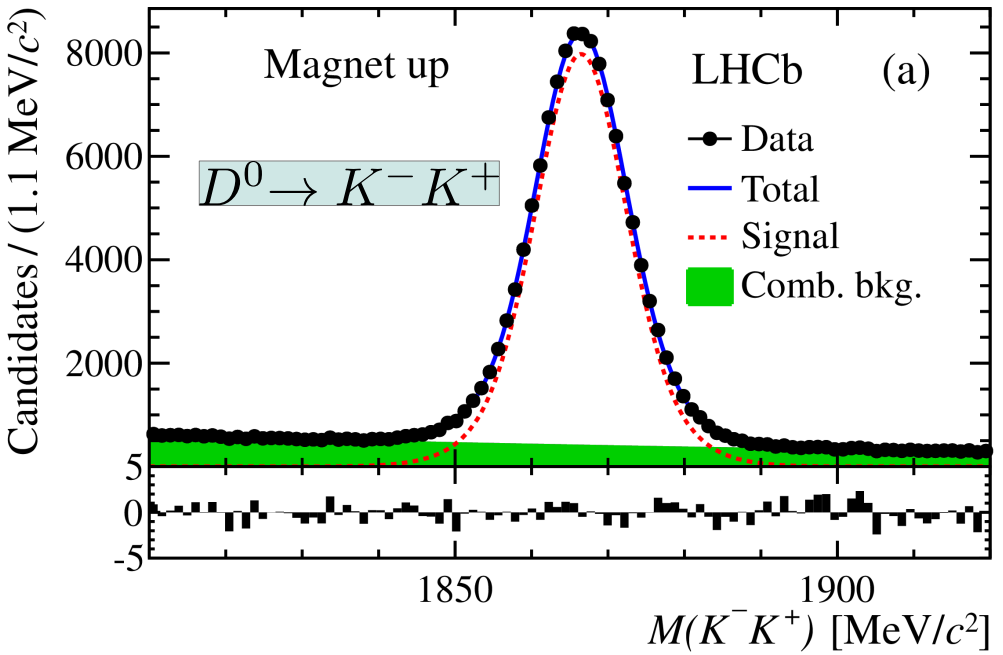


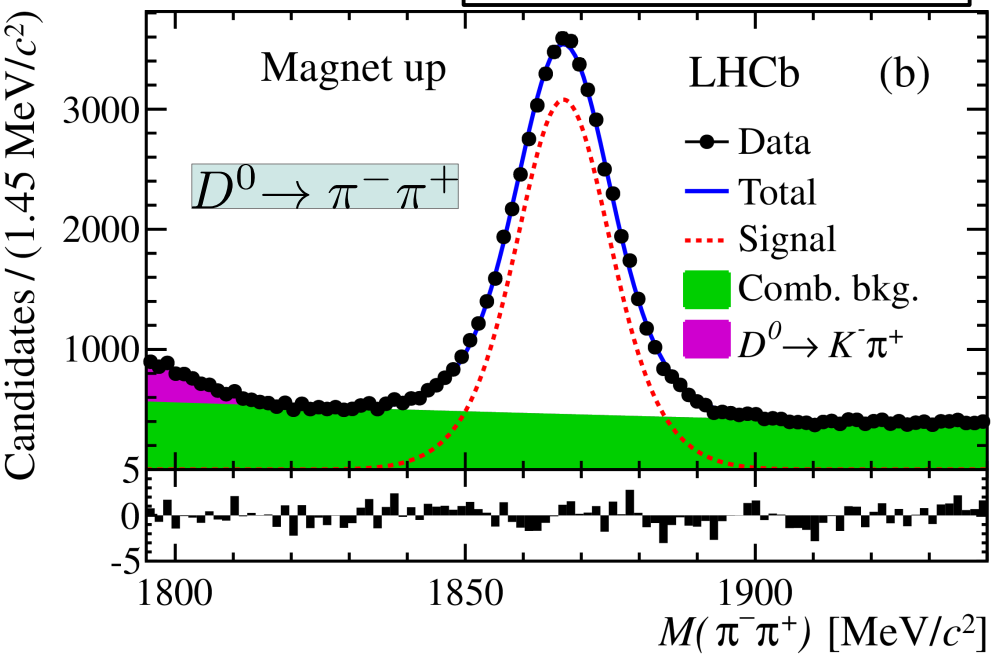


Results

- About 0.6 million D→KK and 0.2 million D→ππ candidates

LHCb-PAPER-2013-003





Numbers in %	Magnet up	Magnet down	Mean
$A_{\rm raw}(K^-K^+)$	-0.39 ± 0.23	-0.20 ± 0.19	-0.29 ± 0.15
$A_{\rm raw}(\pi^-\pi^+)$	-1.25 ± 0.40	-0.29 ± 0.34	-0.77 ± 0.26
ΔA_{CP}	0.86 ± 0.46	0.09 ± 0.39	0.48 ± 0.30

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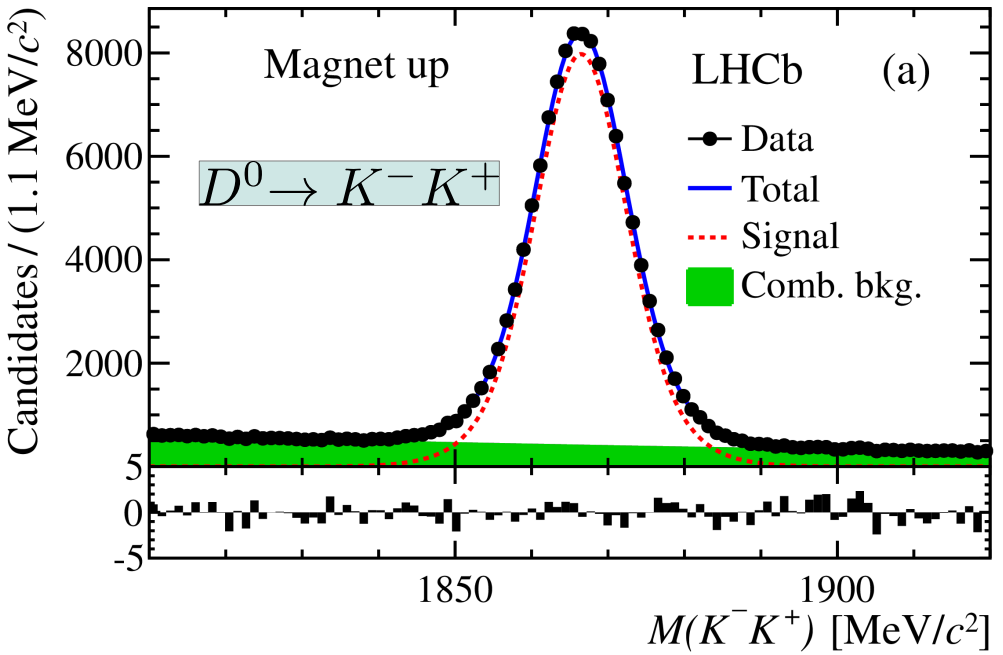

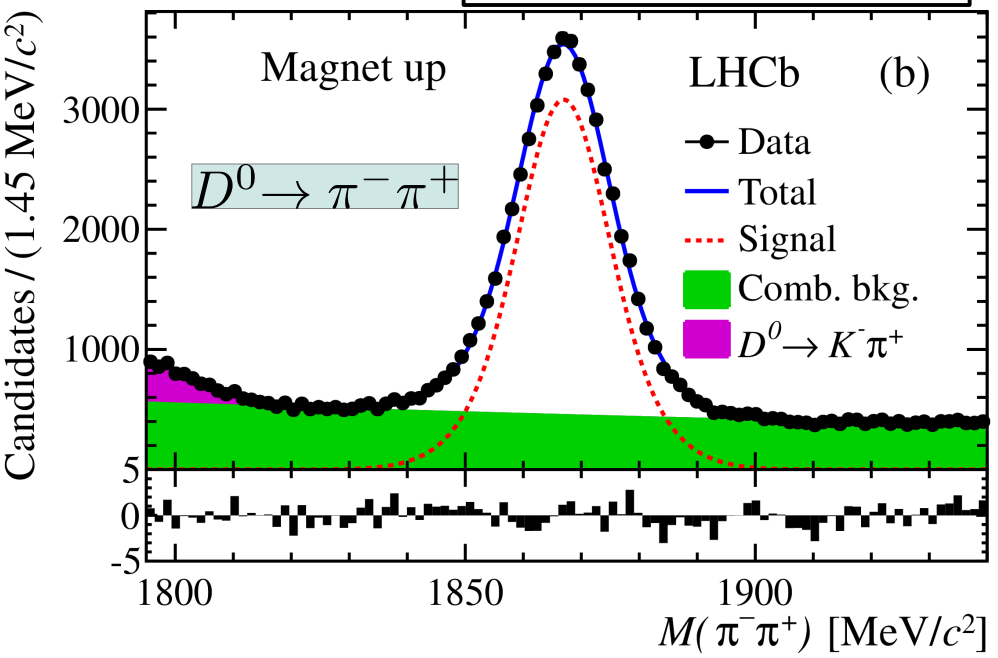

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Status of CP violation in Charm decays

LHCb-PAPER-2013-003

LHCb-CONF-2013-003

Semileptonic: $\Delta A_{CP} = (+0.49 \pm 0.30(stat.) \pm 0.14(syst.))\ \%$

New prompt: (preliminary)

$\Delta A_{CP} = (-0.34 \pm 0.15(stat.) \pm 0.10(syst.))\ \%$

$\Delta A_{CP,LHCb} = (-0.15 \pm 0.16)\ \%$

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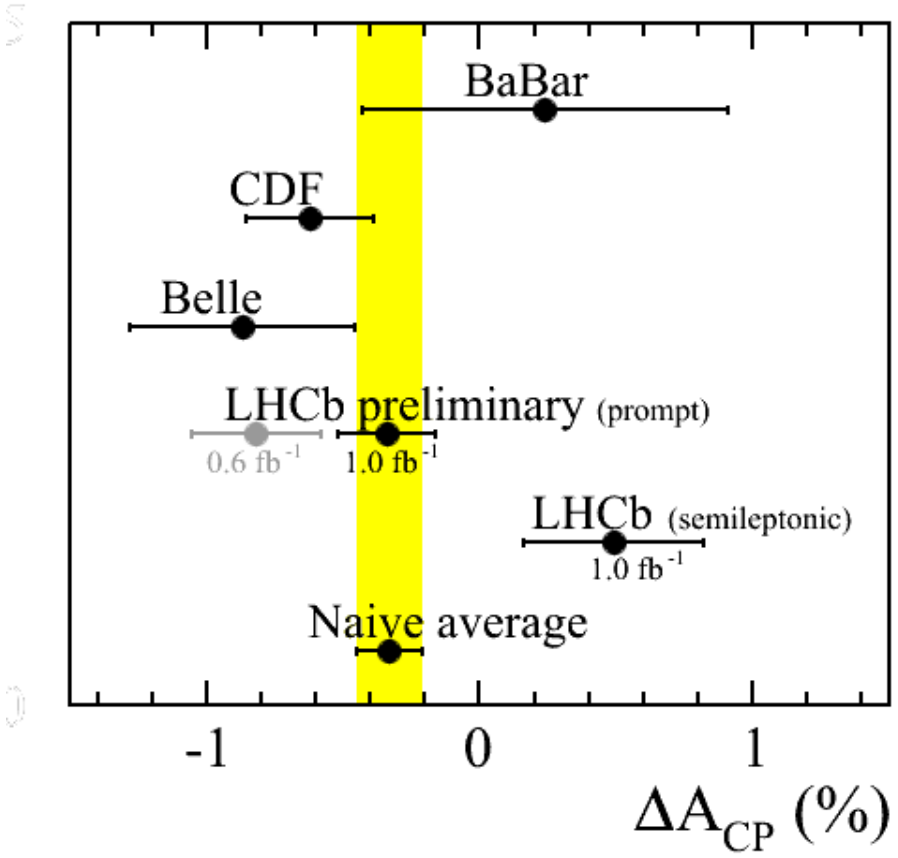

$\Delta a_{\mathrm{CP,dir}} = -0.329 \pm 0.121\%$

(HFAG average)

Outlook: Measuring individual asymmetries

$$\text{Theory}: \ \mathrm{A_{CP}}(\mathrm{K^+K^-}) \approx -\mathrm{A_{CP}}(\pi^+\pi^-)$$

$$A_{raw}(f) = A_{CP}(f) + \boxed{A_D(\mu) + A_P(B)} \qquad f = K^+K^-, \pi^+\pi^-$$

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$$A_{raw}(f) = A_{CP}(f) + A_D(\mu) + A_P(B) \qquad f = K^+K^-, \pi^+\pi^-$$

use CKM favoured decay $D^0 \to K^-\pi^+$ / $\overline{D}^0 \to K^+\pi^-$

$$A_{raw}(K^\mp\pi^\pm) = A_D(\mu) + A_P(B) + A_D(K^\mp\pi^\pm)$$

Expected to be about 1%

Conclusion

- The LHCb experiment performed two independent analyses on the 2011 data set.

Semileptonic: $\Delta A_{CP} = (+0.49 \pm 0.30(stat.) \pm 0.14(syst.))\ \%$

LHCb-PAPER-2013-003, arXiv:1303.2614

Prompt: (preliminary) $\Delta A_{CP} = (-0.34 \pm 0.15(stat.) \pm 0.10(syst.))\ \%$

LHCb-CONF-2013-003, available on CDS

- LHCb does not confirm evidence of CP violation in Charm decays.

$$\Delta A_{CP,LHCb} = (-0.15 \pm 0.16)\ \%$$ (naive average)

~3 fb^{-1} on tape.

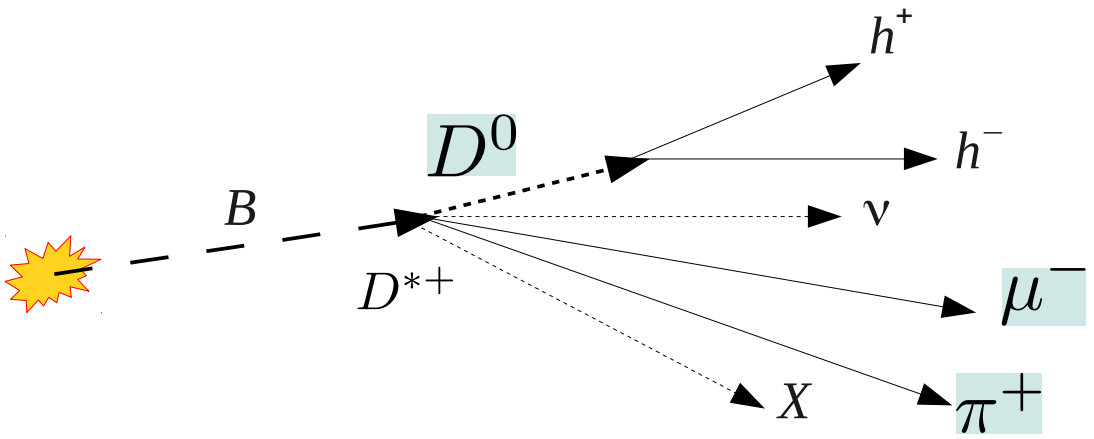
Looking forward to analysing 2012 data.

Determination of mistag rate in semileptonic decays

- Random combination of real D with random muon fakes decay
- Mistag rate ($\bar{\omega}$) dilutes asymmetry
- Different mistag rates for D and $\bar{D}$ possible ($\Delta\omega$)

$$\mathrm{A}_{raw}^{\mathrm{corr}}(f) = (1 - 2\bar{\omega})\ A_{raw} - \Delta\omega$$

- Determination in D* and muon doubly-tagged subsample and flavour specific decay $D^0 \to K^-\pi^+$



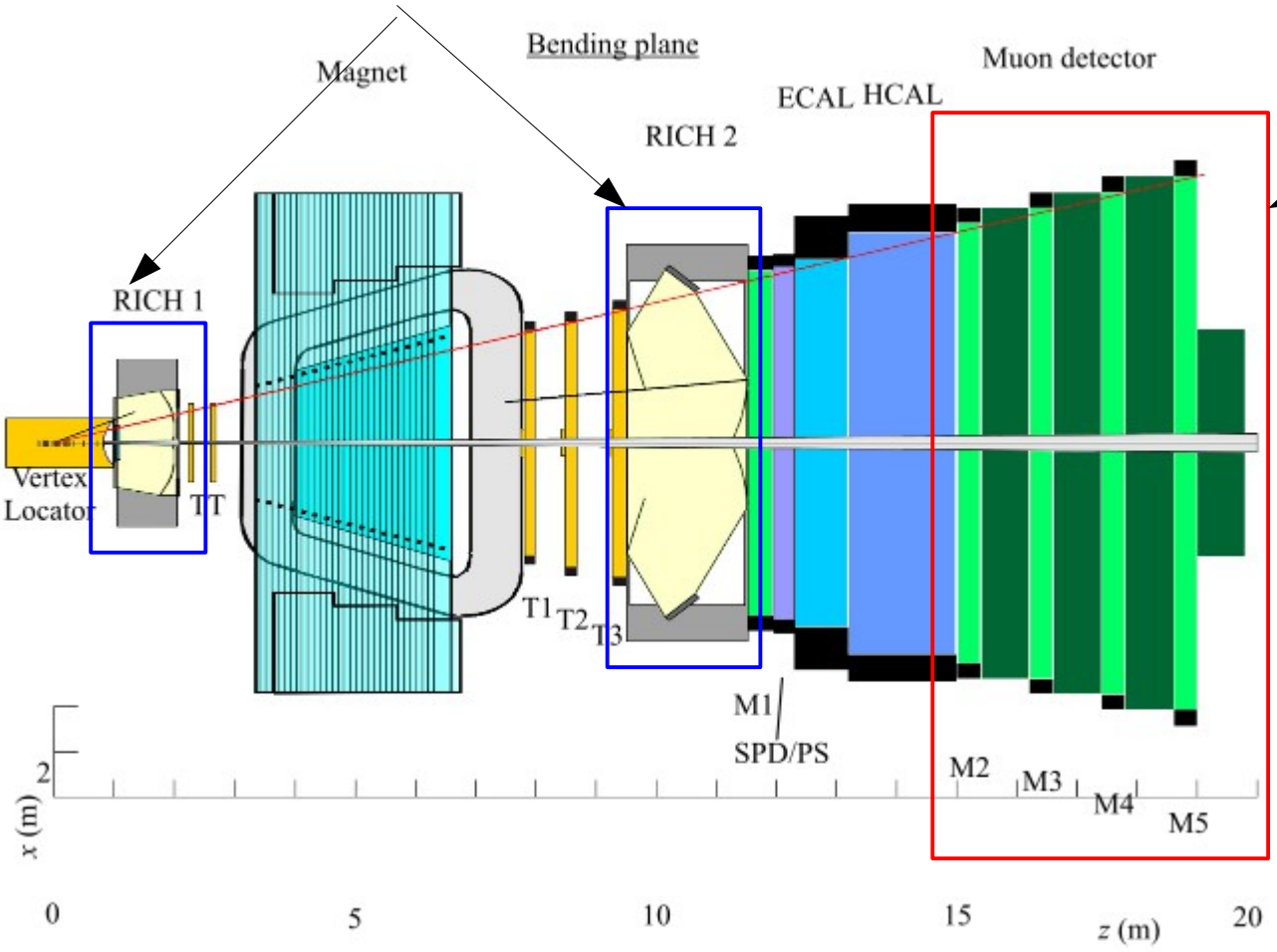
$$\bar{\omega} = (0.982 \pm 0.012)\%$$
$$\Delta\omega = (0.006 \pm 0.021)\%$$

The LHCb experiment

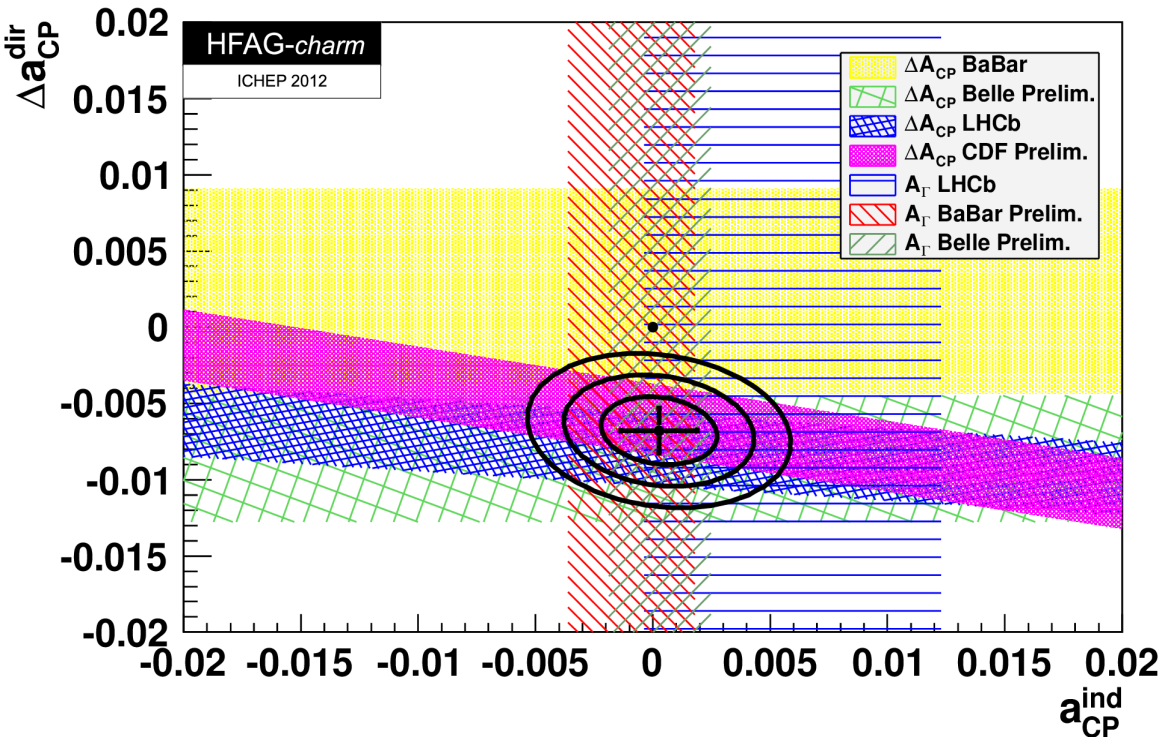
- Collected 1 fb^{-1} in 2011 and 2 fb^{-1} in 2012
  → Huge b (26 10^{10}) and c (59 10^{11}) samples

Kaon and Pion separation

Muon identification



Experimental status of CP violation in February 2013



experiment	$\Delta A_{CP}[\%]$
BaBar [1]	$0.24 \pm 0.62\ (stat.) \pm 0.26\ (syst.)$
Belle [2]	$-0.87 \pm 0.42\ (stat.) \pm 0.06\ (syst.)$
LHCb [3]	$-0.82 \pm 0.21\ (stat.) \pm 0.11\ (syst.)$
CDF [4]	$-0.62 \pm 0.21\ (stat.) \pm 0.10\ (syst.)$
Avg.	-0.678 ± 0.147

4.6 σ evidence for CP violation

Main systematic uncertainties

- Semileptonic analysis
  - Low decay time backgrounds
  - Weighting procedure
  - Fit model

Source of uncertainty	Absolute uncertainty
Production asymmetry:	
Difference in b-hadron mixture	0.02%
Difference in B decay time acceptance	0.02%
Production and detection asymmetry:	
Different weighting	0.05%
Background from real D^0 mesons:	
Mistag asymmetry	0.02%
Background from fake D^0 mesons:	
D^0 mass fit model	0.05%
Low-lifetime background in $D^0 \to \pi^-\pi^+$	0.11%
Λ_c^+ background in $D^0 \to K^-K^+$	0.03%
Quadratic sum	0.14%

Kaon detection asymmetry

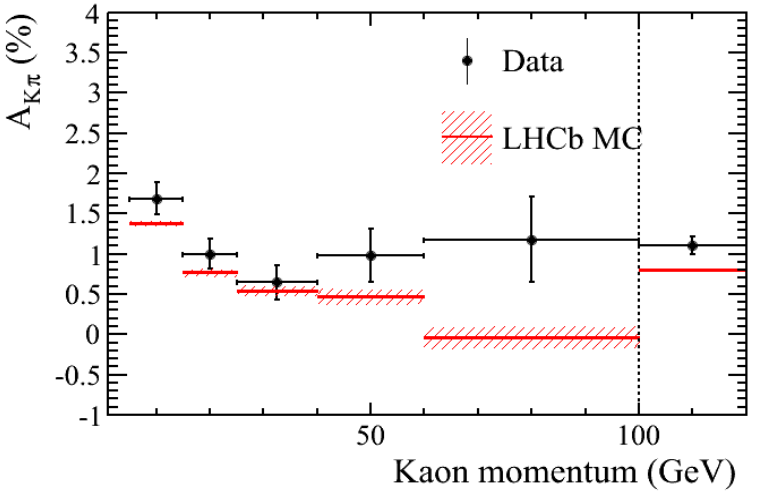
- Idea: Take prompt, Cabibbo favoured D→Kπ π and D→Ks π

$$A_{raw}(K\pi\pi) = A_D(K\pi) + A_D(\pi) + A_P(D)$$

$$A_{raw}(K_s\pi) = A_D(\pi) + A_P(D)$$

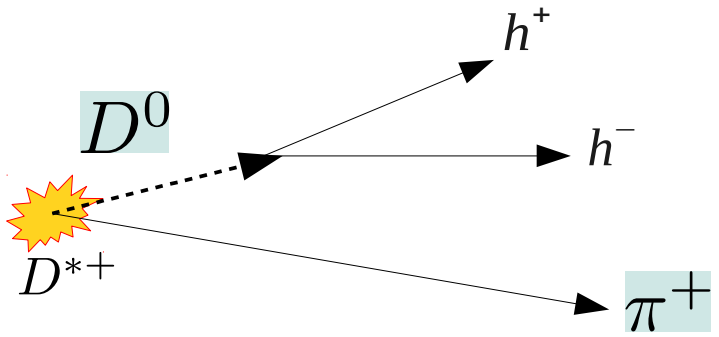
Not fully true

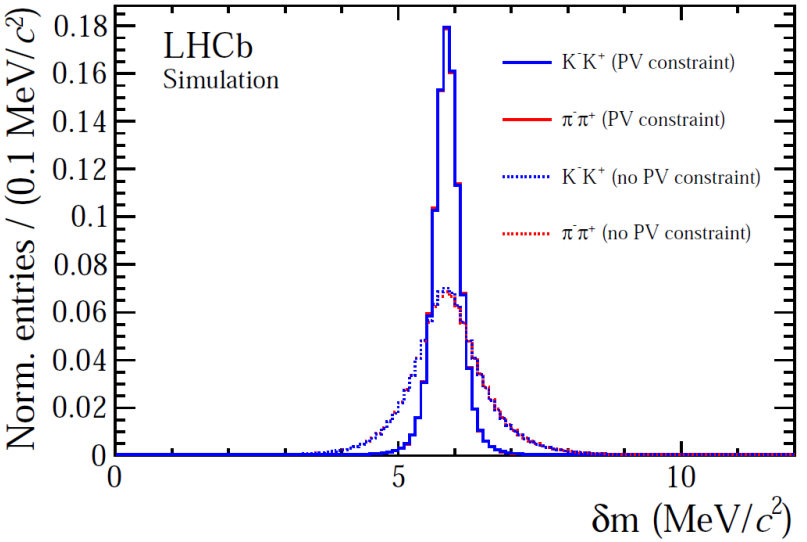
$$A_{raw}(K\pi\pi) - A_{raw}(K_s\pi) = A_D(K\pi)$$



Differences from the previous prompt result

- Prompt ΔA_{cp} shifted from -0.82 ± 0.21 % to -0.34 ± 0.15 %
- Change of result understood and compatible with statistical fluctuations
- New reconstruction on 0.6 fb^{-1} → better particle ID for D children
  - Removed and added events → on overlapping events, same result
- Increased data set, 0.6 fb^{-1} → 1 fb^{-1}
  - 0.4 fb^{-1} additional data with lower but compatible asymmetry
- Improved mass resolution due to additional constraint in vertex fit





LHCb-CONF-2013-003 in preparation

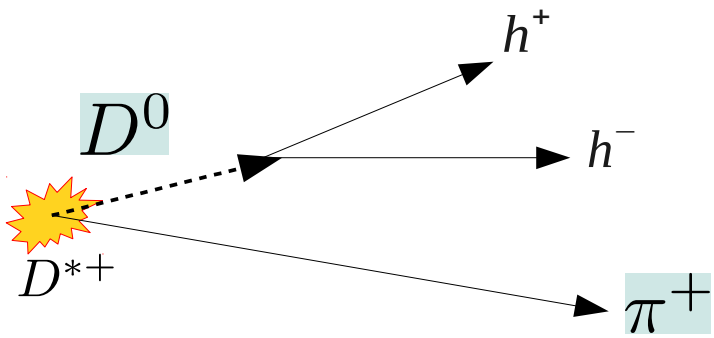
Changes to previous published result – data sample

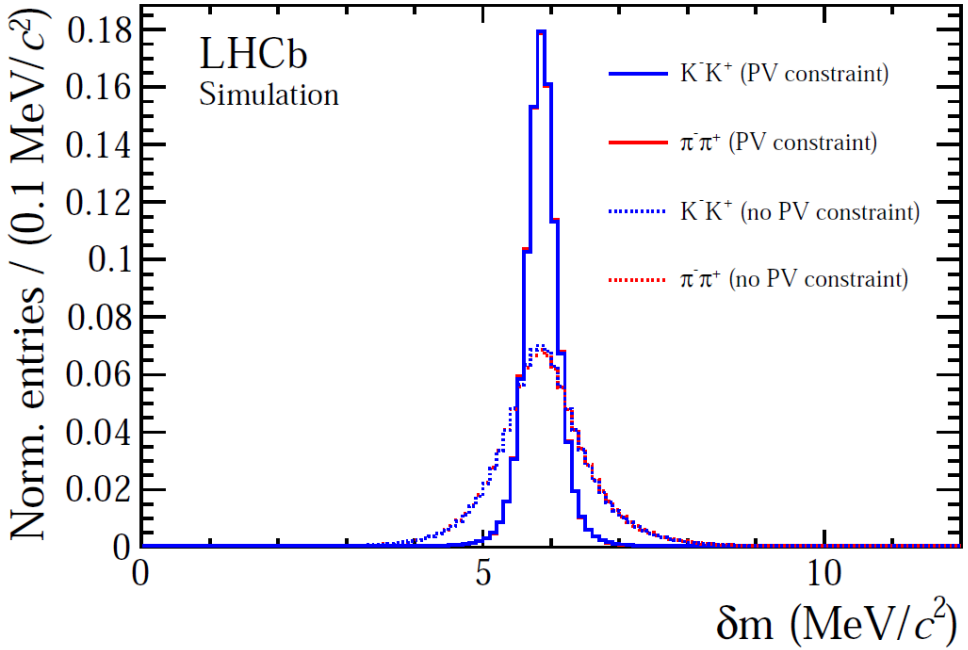
- Prompt ΔA_{cp} shifted from -0.82 ± 0.21 % to -0.34 ± 0.15 %
  - Larger data sample (0.6 → 1.0 fb^{-1})
  - Better reconstruction and calibrations applied
  - Changed analysis procedure (next slide)
- 0.6 fb^{-1} analysed before
  - 15 / 14 % of KK/ππ not selected anymore
    → same ΔA_{cp}
  - 17 / 34 % of KK/ππ additionally selected
    → ΔA_{cp} = (-0.55 ± 0.21) % on 0.6 fb^{-1}
- Extra 0.4 fb^{-1} → ΔA_{cp} = (-0.28 ± 0.26) %
- Combined ΔA_{cp} = (-0.45 ± 0.17) %

→ Consistency between all independent subsamples

LHCb-CONF-2013-003 in preparation

Changes to previous published result – analysis procedure





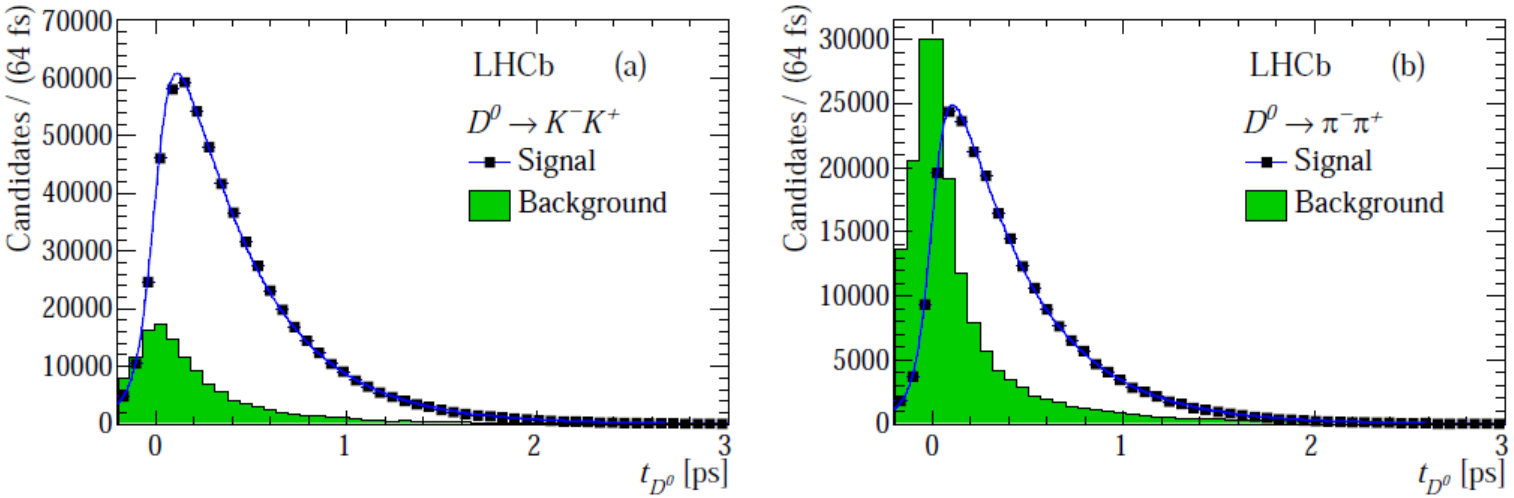
- New: slow pion constraint to PV in vertex fit
- Additional information → improved mass resolution of factor 2.5
  - Better background rejection, better sensitivity
- ΔA_{cp} = (-0.34 ± 0.15) %
- Toy studies show expected variation of 0.05 %
  - Possible correlation with IP cut → already systematic of 0.08% assigned

Sensitivity to indirect CP violation (SL analysis)

- Small contribution due to time dependent CP violation

$$\Delta A_{CP} \approx \Delta a_{CP}^{\mathrm{dir}} \left(1 + y\cos\phi\frac{\overline{\langle t\rangle}}{\tau}\right) + \left(a_{CP}^{\mathrm{ind}} + \overline{a_{CP}^{\mathrm{dir}}} y\cos\phi\right)\frac{\Delta\langle t\rangle}{\tau}$$

- <t> and Δ<t> describe effective lifetime measured in D→KK und D→ππ
  - Different lifetime acceptances
  - Fit of effective lifetime and acceptance in both decay channels



→ Sensitivity to indirect CP violation ~2 % (SL), ~10 % (prompt)

Results: Semileptonic analysis

- Unweighted

Table 1: Unweighted raw asymmetries (in %) for the $D^0 \to \pi^-\pi^+$, $D^0 \to K^-K^+$ and $D^0 \to K^-\pi^+$ decays for the two magnet polarities. The mean value is the arithmetic average over the two polarities. The uncertainties are statistical only.

	Magnet up	Magnet down	Mean
$A_{\rm raw}^{\rm unweighted}(K^-K^+)$	-0.33 ± 0.23	-0.22 ± 0.19	-0.28 ± 0.15
$A_{\rm raw}^{\rm unweighted}(\pi^-\pi^+)$	-1.18 ± 0.40	-0.35 ± 0.34	-0.77 ± 0.26
$\Delta A_{CP}^{\rm unweighted}$	0.85 ± 0.46	0.13 ± 0.39	0.49 ± 0.30
$A_{\rm raw}^{\rm unweighted}(K^-\pi^+)$	-1.64 ± 0.10	-1.60 ± 0.08	-1.62 ± 0.06

- Weighted

Table 2: Weighted raw asymmetries (in %) for the $D^0 \to \pi^-\pi^+$ and $D^0 \to K^-K^+$ decays for the two magnet polarities. The mean value is the arithmetic average over the two polarities. The uncertainties are statistical only.

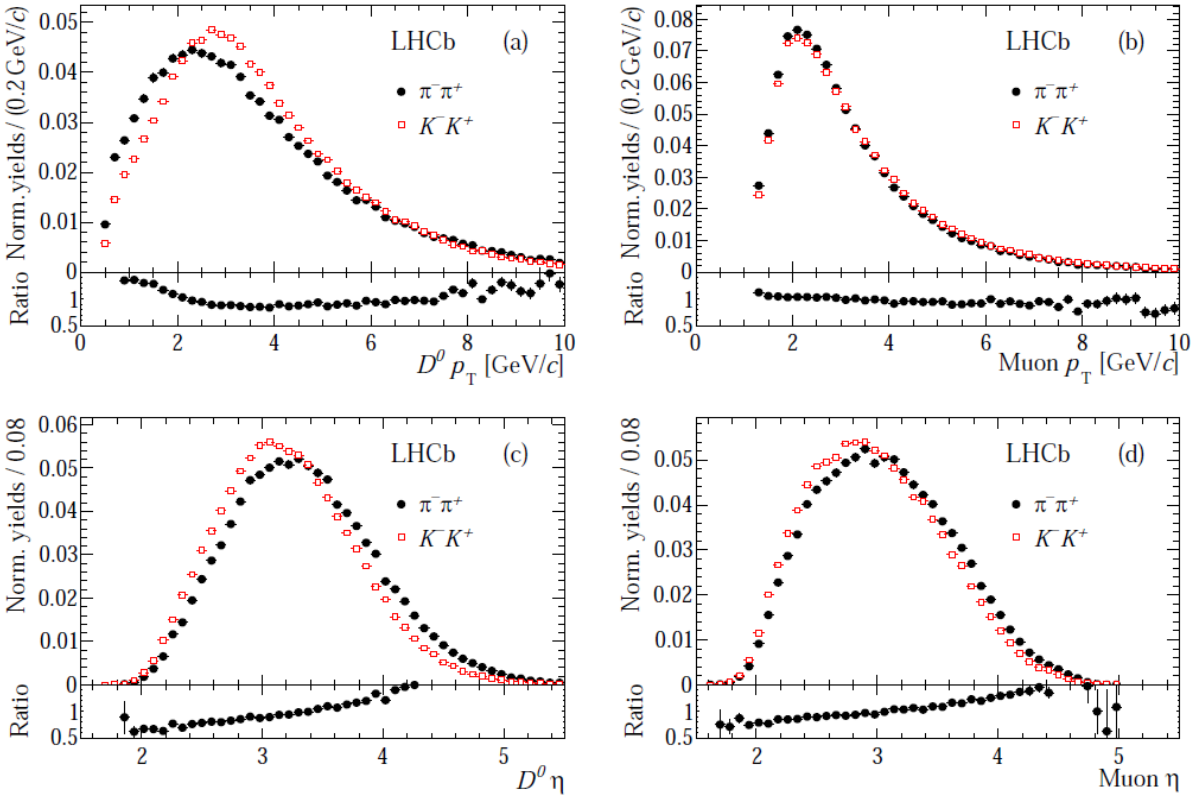
	Magnet up	Magnet down	Mean
$A_{\rm raw}(K^-K^+)$	-0.39 ± 0.23	-0.20 ± 0.19	-0.29 ± 0.15
$A_{\rm raw}(\pi^-\pi^+)$	-1.25 ± 0.40	-0.29 ± 0.34	-0.77 ± 0.26
ΔA_{CP}	0.86 ± 0.46	0.09 ± 0.39	0.48 ± 0.30

- Up and down compatible also in individual asymmetries

Kinematical weighting (semileptonic decays)

- Production- and detector asymmetries depend on D and muon kinematics
- Different kinematics due to different particle identification cuts
- Assign weights to $D \to KK$ and $D \to \pi\pi$ to match kinematics.
  → Same production- and detector asymmetries

Before:



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After: