Measurement of direct CPV in charm decays at LHCb

Federico Betti on behalf of the LHCb collaboration

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Istituto Nazionale di Fisica Nucleare
Sezione di Bologna

Outline

- Introduction on CP in charm
- Strategy to measure A_{CP}
- ΔA_{CP} status
- A_{CP} in $D^0 \to K_s^0 K_s^0$
- A_{CP} in $D^0 \to h^+ h^- \mu^+ \mu^-$
- Conclusions
- Will not cover CPV in charmed baryons → see talk by Carla Gobel on Thursday morning

CP Violation in Charm

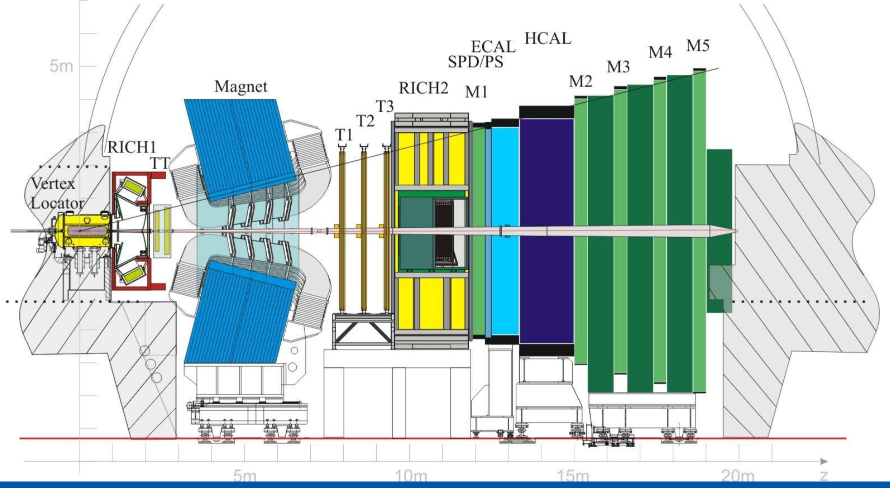
- Only way to probe CP violation in **up-type** quark decays
- **Complementary** to K and B mesons
- Difficult to calculate SM predictions, but small CP asymmetry is expected ($\sim \mathbf{10^{-3}}$) ➔ hints of **NP** if higher values are observed
- CPV in charm sector **not observed** yet

Charm at LHCb

- Large $c\bar{c}$ production cross section
$\sigma(pp \to c\bar{c}X)_{\sqrt{s}=13\ \mathrm{TeV}} = (2369 \pm 3 \pm 152 \pm 118)\ \mu\mathrm{b}$
- About ~790M $D^0 \to K^-\pi^+$ collected by LHCb between 2011 and 2016
- LHCb detector:
  - Excellent **IP** resolution ($\sim 13\ \mu\mathrm{m}$ on the transverse plane)
  - Very good **momentum** resolution ($\delta p/p \sim 0.5\% - 0.8\%$)

JHEP 05 (2017) 074

$$\sigma(pp \to D^0 X) = 2072 \pm 2 \pm 124\ \mu\mathrm{b}$$
$$\sigma(pp \to D^+ X) = 834 \pm 2 \pm 78\ \mu\mathrm{b}$$
$$\sigma(pp \to D_s^+ X) = 353 \pm 9 \pm 76\ \mu\mathrm{b}$$
$$\sigma(pp \to D^{*+} X) = 784 \pm 4 \pm 87\ \mu\mathrm{b}$$



Direct CP Asymmetry

$$A_{CP}(f) = \frac{\Gamma(M \to f) - \Gamma(\overline{M} \to \overline{f})}{\Gamma(M \to f) + \Gamma(\overline{M} \to \overline{f})} = \frac{1 - |\overline{A}_{\overline{f}}/A_f|^2}{1 + |\overline{A}_{\overline{f}}/A_f|^2}$$

- In D^0 **singly-Cabibbo-suppressed** decay into CP eigenstates f:

$$A_{CP}(f) = A_{CP}^{\text{dir}}(f) + A_{CP}^{\text{mix}} + A_{CP}^{\text{int}} = A_{CP}^{\text{dir}}(f) + A_{CP}^{\text{ind}}$$

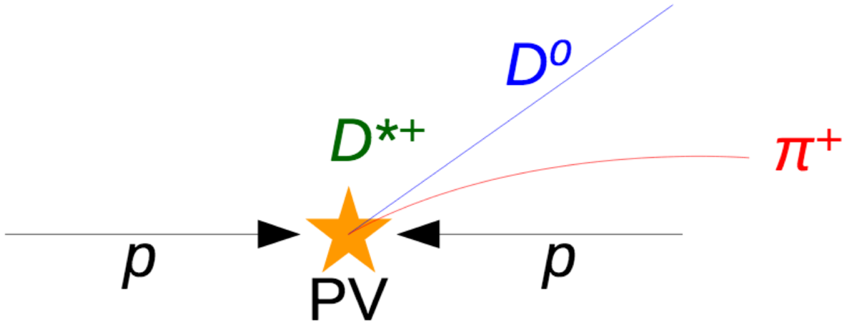
- Effect of **direct** CPV can be isolated (e.g. for h^+h^-):

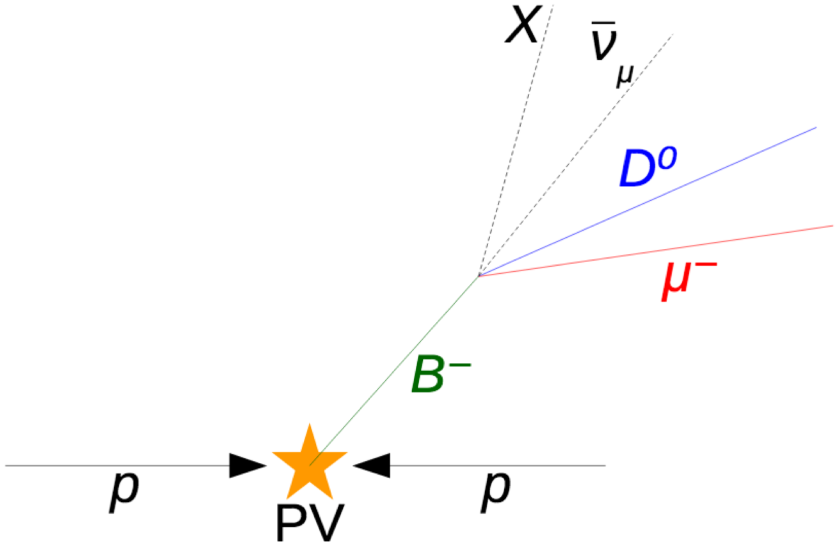
$$\Delta A_{CP} = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) = A_{CP}^{\text{dir}}(K^+K^-) - A_{CP}^{\text{dir}}(\pi^+\pi^-)$$

Flavour Tagging

- Look at the **charge** of the accompanying particle
- **Prompt** charm: $D^{*\pm} \to D^0\pi^\pm$
  - D^0 points to PV
  - Decay time acceptance
- **Semileptonic** charm: $B \to D^0\mu^\pm X$
  - D^0 does not point to PV
  - Access all D^0 decay times
  - Lower yield
- Possible to use **double tag**

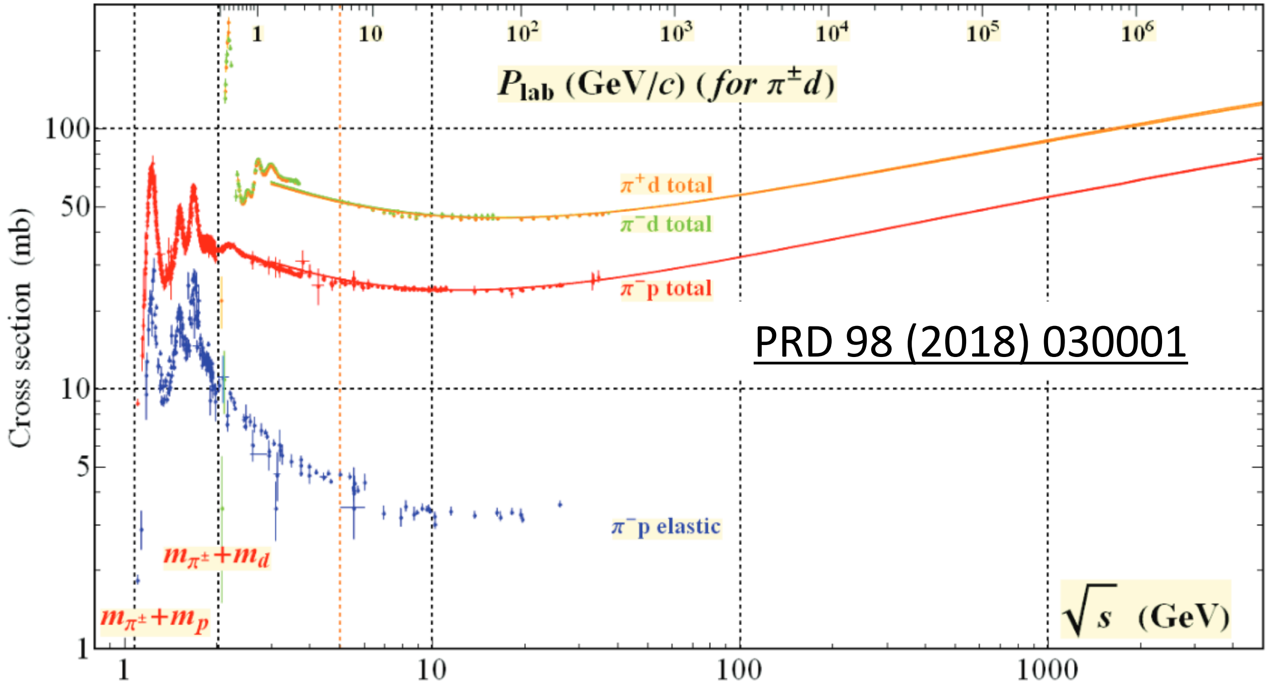
$$B \to D^{*\pm}(D^0\pi^\pm)\mu^\pm X$$





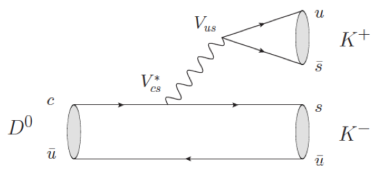
Detection Asymmetry

- **Asymmetry** in π^+ and π^- (or μ^+ and μ^-) detection
- Different **interaction** of matter and antimatter with detector
- **Detector** is not perfectly symmetric
- LHCb can reverse **magnet polarity** to keep geometric-induced asymmetries under control



PRD 98 (2018) 030001

Experimental Strategy – Prompt Tag



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

$D^{*+} \to D^0(\to K^+K^-)\pi_s^+$ | $D^{*+} \to D^0(\to \pi^+\pi^-)\pi_s^+$

True up to $\mathcal{O}(10^{-6})$

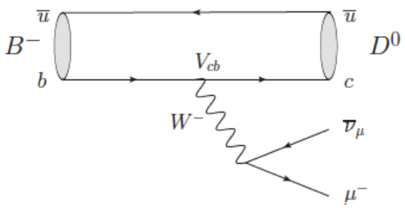
$$A_{\text{raw}}(f) \simeq A_{CP}(f) + A_{\text{D}}(f) + A_{\text{D}}(\pi_s) + A_{\text{P}}(D^{*+})$$

- $A_{CP}(f)$: Physical *CP* asymmetry
- $A_{\text{D}}(f)$: D^0 detection asymmetry ➔ equal to 0, since K^-K^+ and $\pi^-\pi^+$ are symmetric final states
- $A_{\text{D}}(\pi_s)$: π_s detection asymmetry → Independent on the final state
- $A_{\text{P}}(D^{*+})$: D^* production asymmetry → Independent on the final state

If the **kinematics** of the two decay modes are equal

$$\Rightarrow A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) = A_{\text{raw}}(K^-K^+) - A_{\text{raw}}(\pi^-\pi^+)$$

Experimental Strategy – SL Tag



$B \to D^0(\to K^+K^-)\mu^-X$	$B \to D^0(\to \pi^+\pi^-)\mu^-X$

True up to $\mathcal{O}(10^{-6})$

$$A_{\rm raw}(f) \simeq A_{CP}(f) + A_{\rm D}(f) + A_D(\mu^-) + A_P(B)$$

- $A_{CP}(f)$: Physical *CP* asymmetry
- $A_{\rm D}(f)$: D^0 detection asymmetry ➔ equal to 0, since K^-K^+ and $\pi^-\pi^+$ are symmetric final states
- $A_D(\mu^-)$: μ^- detection asymmetry → Independent on the final state
- $A_P(B)$: B production asymmetry → Independent on the final state

If the **kinematics** of the two decay modes are equal

$$\Rightarrow A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) = A_{\rm raw}(K^-K^+) - A_{\rm raw}(\pi^-\pi^+)$$

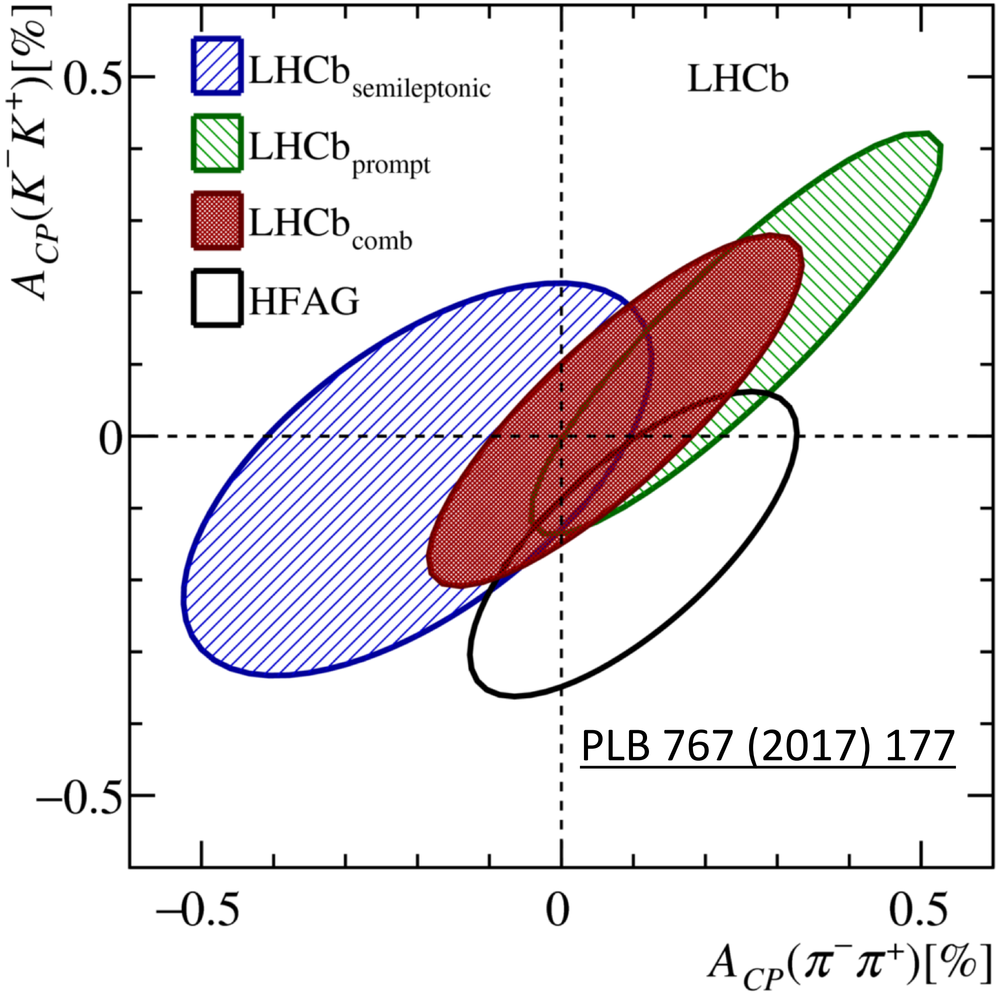
ΔA_{CP} Status

Experiment	ΔA_{CP}	
CDF	$(+62 \pm 21 \pm 10) \times 10^{-4}$	PRL 109 (2012) 111801
BaBar	$(+24 \pm 62 \pm 26) \times 10^{-4}$	PRL 100 (2008) 061803
Belle	$(-87 \pm 41 \pm 6) \times 10^{-4}$	PLB 670 (2008) 190
LHCb (3.0 fb^{-1}, muon-tagged)	$(+14 \pm 16 \pm 8) \times 10^{-4}$	JHEP 07 (2014) 041
LHCb (3.0 fb^{-1}, pion-tagged)	$(-10 \pm 8 \pm 3) \times 10^{-4}$	PRL 116 (2016) 191601

- Most **precise** measurements performed by LHCb
- **Run 2** analysis ongoing
- With the full Run 2 the statistical uncertainty is expected to decrease by a factor 2.4 ($\sim \mathbf{3.5 \times 10^{-4}}$)

$A_{CP}(K^+K^-)$ and $A_{CP}(\pi^+\pi^-)$

- LHCb is able to measure also **individual** asymmetries
- Needs **Cabibbo-favoured** decays as calibration samples



PLB 767 (2017) 177

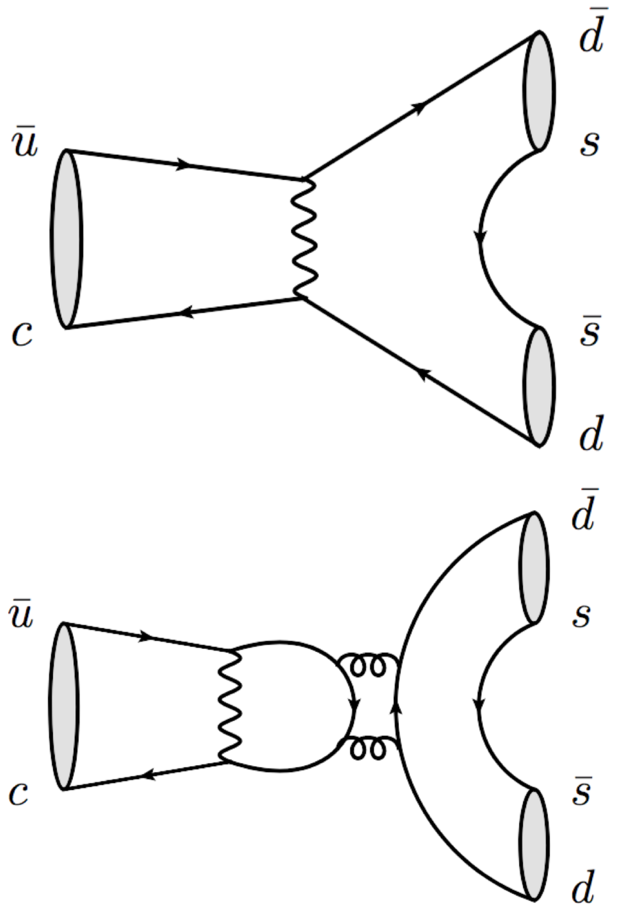
A_{CP} in $D^0 \to K_S^0 K_S^0$

A_{CP} in $D^0 \to K_S^0 K_S^0$ - Motivations

- Tree-level **exchange** and **penguin** annihiliation diagrams contribute to $D^0 \to K_S^0 K_S^0$
- $A_{CP}(K_S^0 K_S^0) < 1.1\% \ (95\% \text{C.L.})$ → any higher measured value would point to **New Physics** PRD 92 (2015) 054036

$A_{CP}(K_S^0 K_S^0)$ [%]	Collaboration	Reference
-23 ± 19	CLEO	PRD 63 (2001) 071101
$-2.9 \pm 5.2 \pm 2.2$	LHCb – Run 1	JHEP 10 (2015) 055
$-0.02 \pm 1.53 \pm 0.02 \pm 0.17$	Belle	PRL 119 (2017) 171801

Most precise measurement



A_{CP} in $D^0 \to K_S^0 K_S^0$ - Strategy

LHCb-PAPER-2018-012
arXiv:1806.01642
submitted to JHEP

- Reconstruct $D^* \to D^0\pi$, use $\boldsymbol{\pi}$ **to tag** D^0 flavour
- Fit $\boldsymbol{\Delta m = m(D^*) - m(D^0)}$ to extract number of D^0 and $\bar{D}^0$

$$A_{raw}(K_S^0 K_S^0) = A_{CP}(K_S^0 K_S^0) + A_P(D^*) + A_D(\pi_{tag})$$

- Use **calibration** channel $D^0 \to K^+K^-$

$$\Delta A_{CP} = A_{raw}(K_S^0 K_S^0) - A_{raw}(K^+K^-) = A_{CP}(K_S^0 K_S^0) - A_{CP}(K^+K^-)$$

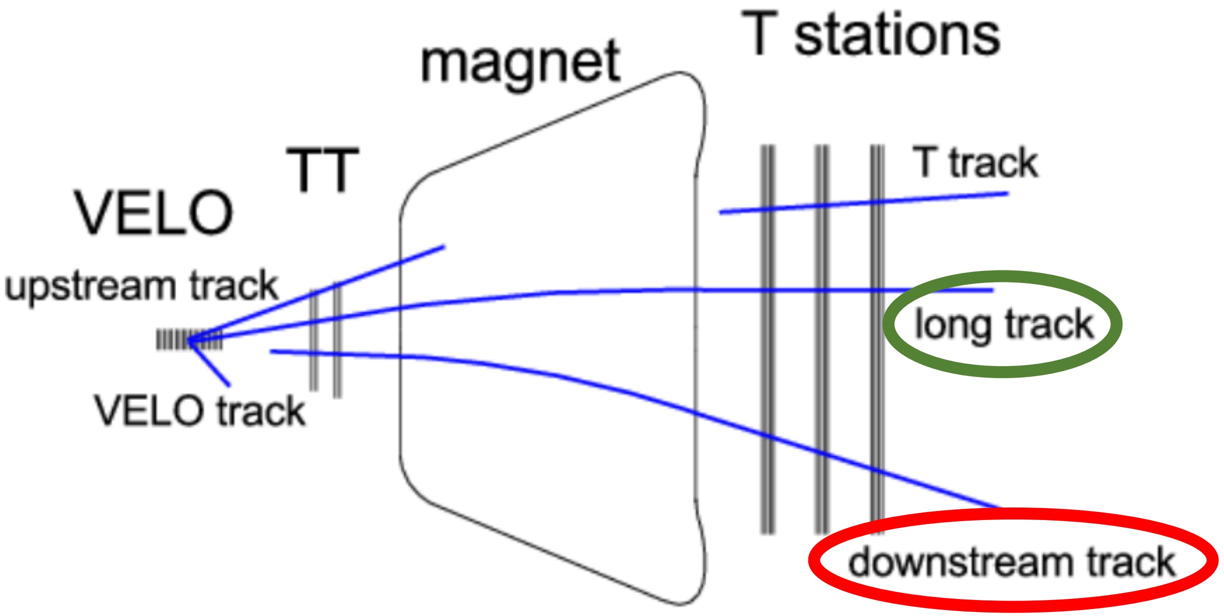
$$\Longrightarrow \boldsymbol{A_{CP}(K_S^0 K_S^0) = \Delta A_{CP} + A_{CP}(K^+K^-)}$$

- $A_{CP}(K^+K^-) = (0.04 \pm 0.12 \pm 0.10)\%$ measured by LHCb PLB 767 (2017) 177

A_{CP} in $D^0 \to K_S^0 K_S^0$ - Data Sample

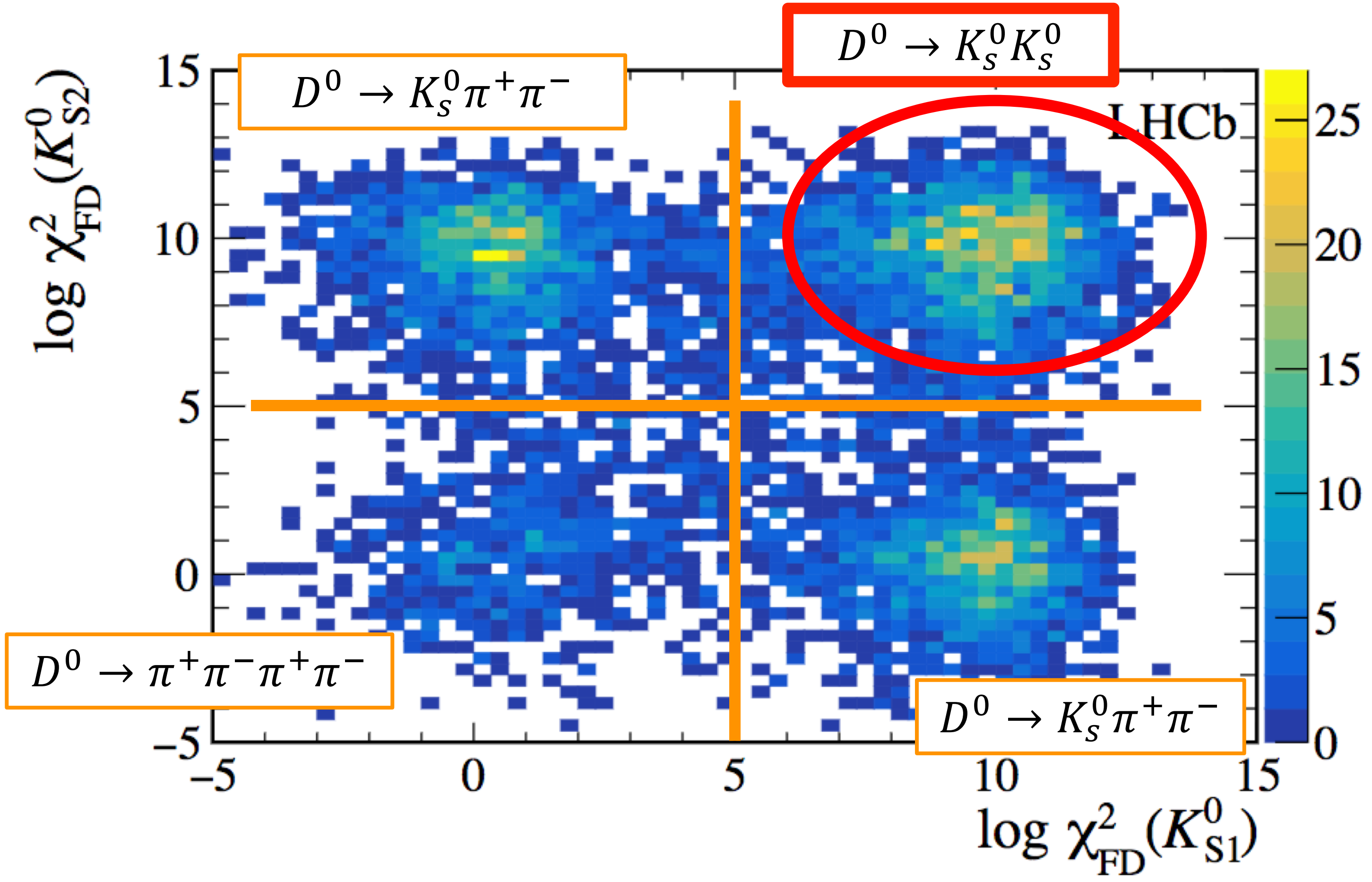
LHCb-PAPER-2018-012
arXiv:1806.01642
submitted to JHEP

- 2015+2016 data → $\mathbf{2.0\ fb^{-1}}$
- Two independent samples:
  1. **LD**: one K_S^0 is reconstructed from **long** tracks and the other from **downstream** tracks
  2. **LL**: both K_S^0 are reconstructed from **long** tracks
- Different **resolution** between the two samples



A_{CP} in $D^0 \to K_s^0 K_s^0$ - Data Sample

- Important **background** due to $D^0 \to K_s^0 \pi^+\pi^-$ and $D^0 \to \pi^+\pi^-\pi^+\pi^-$
- Selection on LL: $[\log \chi^2_{FD}(K^0_{s1}) - 10]^2 + [\log \chi^2_{FD}(K^0_{s2}) - 10]^2 < 16$
- Selection on LD: $\log \chi^2_{FD}(K^0_{sL}) > 2.5$



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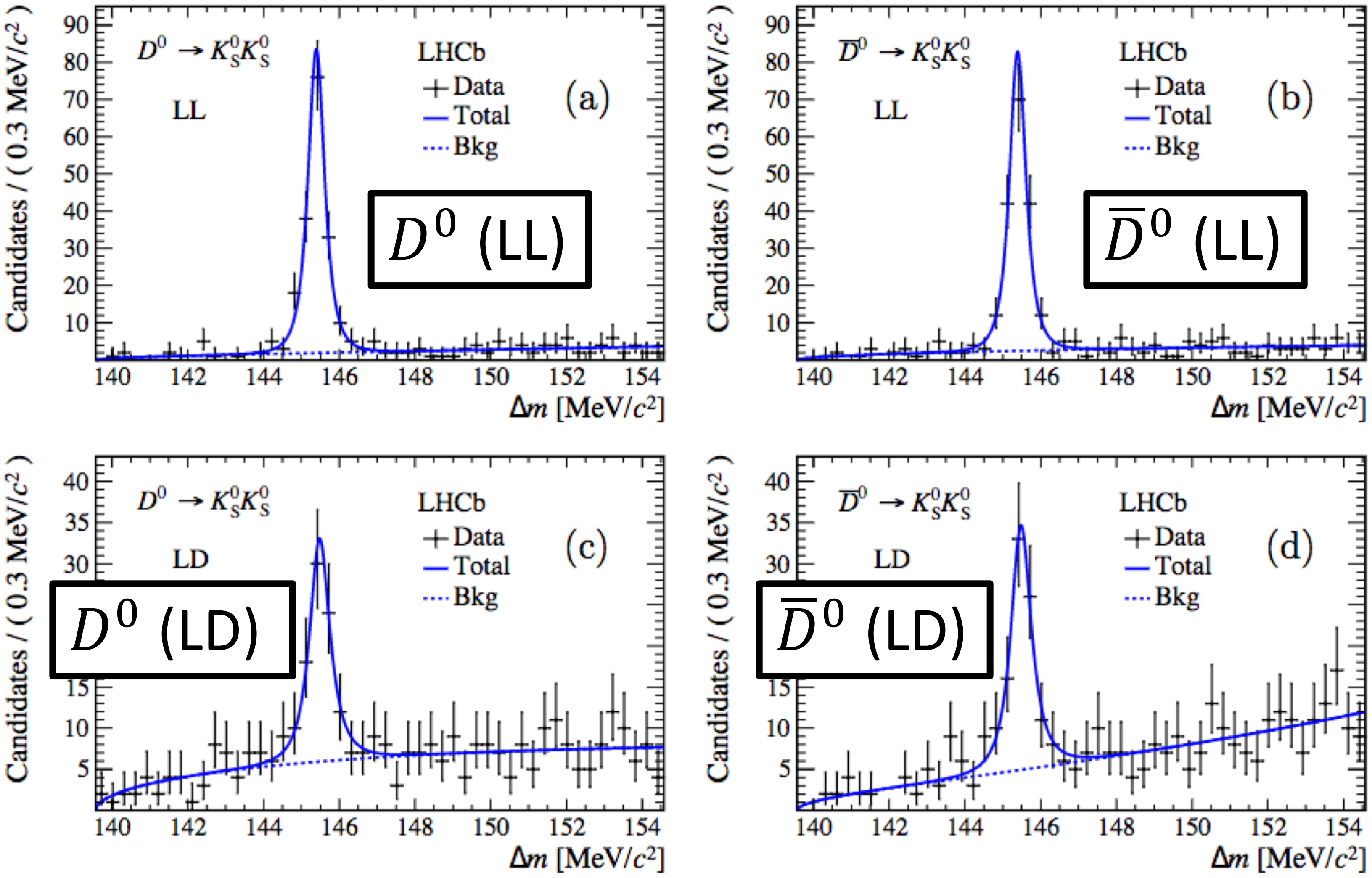
A_{CP} in $D^0 \to K_S^0 K_S^0$ - Fit

- Simultaneous fit to $\boldsymbol{\Delta m}$ in D^0 and $\bar{D}^0$ samples (sharing A_{raw})
- **Signal**: Johnson S_U
- **Background**: exponential × threshold factor
- LL yield: 759 ± 32
- LD yield: 308 ± 26



LHCb-PAPER-2018-012
arXiv:1806.01642 submitted to JHEP

A_{CP} in $D^0 \rightarrow K_S^0 K_S^0$ - Results

LHCb-PAPER-2018-012
arXiv:1806.01642
submitted to JHEP

- Results from this analysis:

$$A_{CP}(LL) = (6.7 \pm 3.8 \pm 0.9)\%$$
$$A_{CP}(LD) = (-5.3 \pm 7.4 \pm 1.3)\%$$
$$\Rightarrow \boldsymbol{A_{CP}(K_S^0 K_S^0) = (4.2 \pm 3.4 \pm 1.0)\%}$$

- Main **systematic** uncertainty due to fit model
- Combining with **Run 1**:

$$\boldsymbol{A_{CP}(K_S^0 K_S^0) = (2.0 \pm 2.9 \pm 1.0)\%}$$

- Consistent with **no-CPV** hypothesis
- **Compatible** with previous measurements

A_{CP} in $D^0 \to h^+h^-\mu^+\mu^-$

A_{CP} in $D^0 \to h^+h^-\mu^+\mu^-$

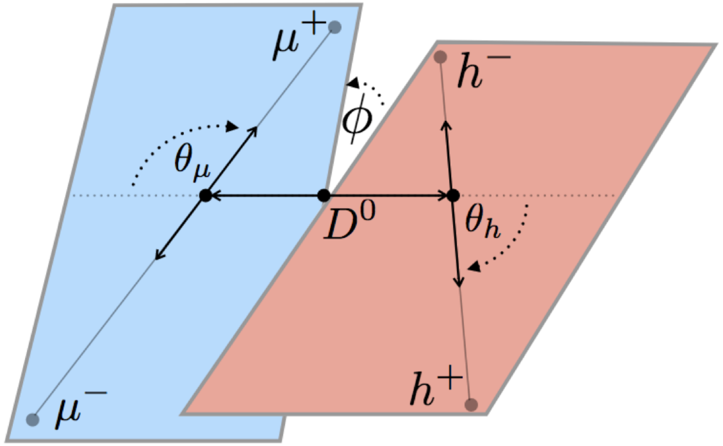
See talk by Chris Burr on Tuesday morning (WG3)

- **Rare** decay
- CP asymmetry predicted to be below 5×10^{-3} → large as $\mathcal{O}(1\%)$ if NP is present

$$A_{raw}(h^+h^-\mu^+\mu^-) - A_{raw}(K^+K^-) = A_{CP}(h^+h^-\mu^+\mu^-) - A_{CP}(K^+K^-)$$

$$\Rightarrow \boldsymbol{A_{CP}(h^+h^-\mu^+\mu^-) = A_{raw}(h^+h^-\mu^+\mu^-) - A_{raw}(K^+K^-) + A_{CP}(K^+K^-)}$$

- Forward-backward and triple-product asymmetries are measured as well



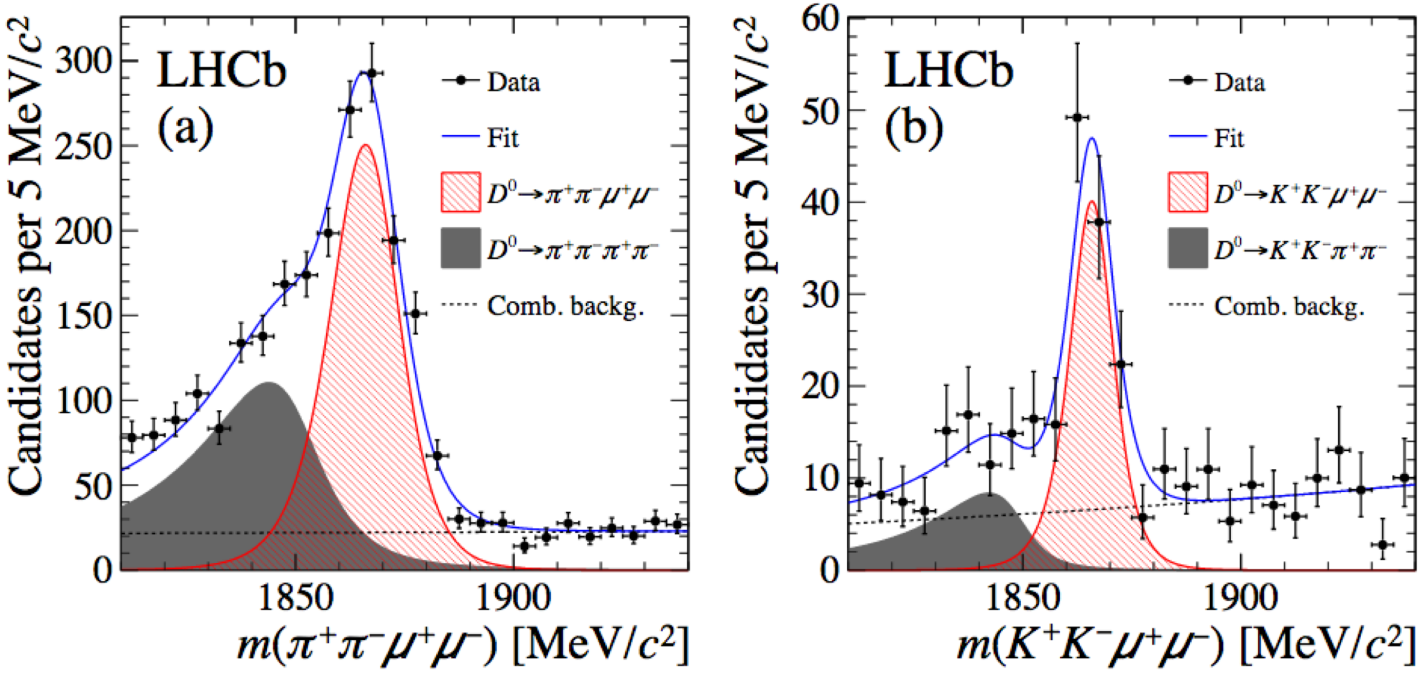
PRL 121 (2018) 091801

A_{CP} in $D^0 \to h^+h^-\mu^+\mu^-$

See talk by Chris Burr on Tuesday morning (WG3)

- Simultaneous fit to $\boldsymbol{m(h^+h^-\mu^+\mu^-)}$ to samples split by π_{tag} charge, $\cos\theta_\mu$, $\sin 2\phi$ (sharing asymmetries)
- ~1000 signal $D^0 \to \pi^+\pi^-\mu^+\mu^-$
- ~100 signal $D^0 \to K^+K^-\mu^+\mu^-$

PRL 121 (2018) 091801



With $5.0\ \mathrm{fb}^{-1}$:

$$A_{CP}(\pi^+\pi^-\mu^+\mu^-) = (4.9 \pm 3.8 \pm 0.7)\%$$

$$A_{CP}(K^+K^-\mu^+\mu^-) = (0 \pm 11 \pm 2)\%$$

Future prospects

- Expected stat uncertainty of $A_{CP}(K_S^0 K_S^0)$:
  - $\sim 1\%$ with Run 1 + Run 2
  - $\sim 0.12\%$ including also Upgrade
- Expected stat uncertainty of ΔA_{CP} LHCB-PUB-2018-009
  - $\sim 0.03\%$ with Run 1 + Run 2
  - $\sim 0.01\%$ including also Upgrade

Conclusions

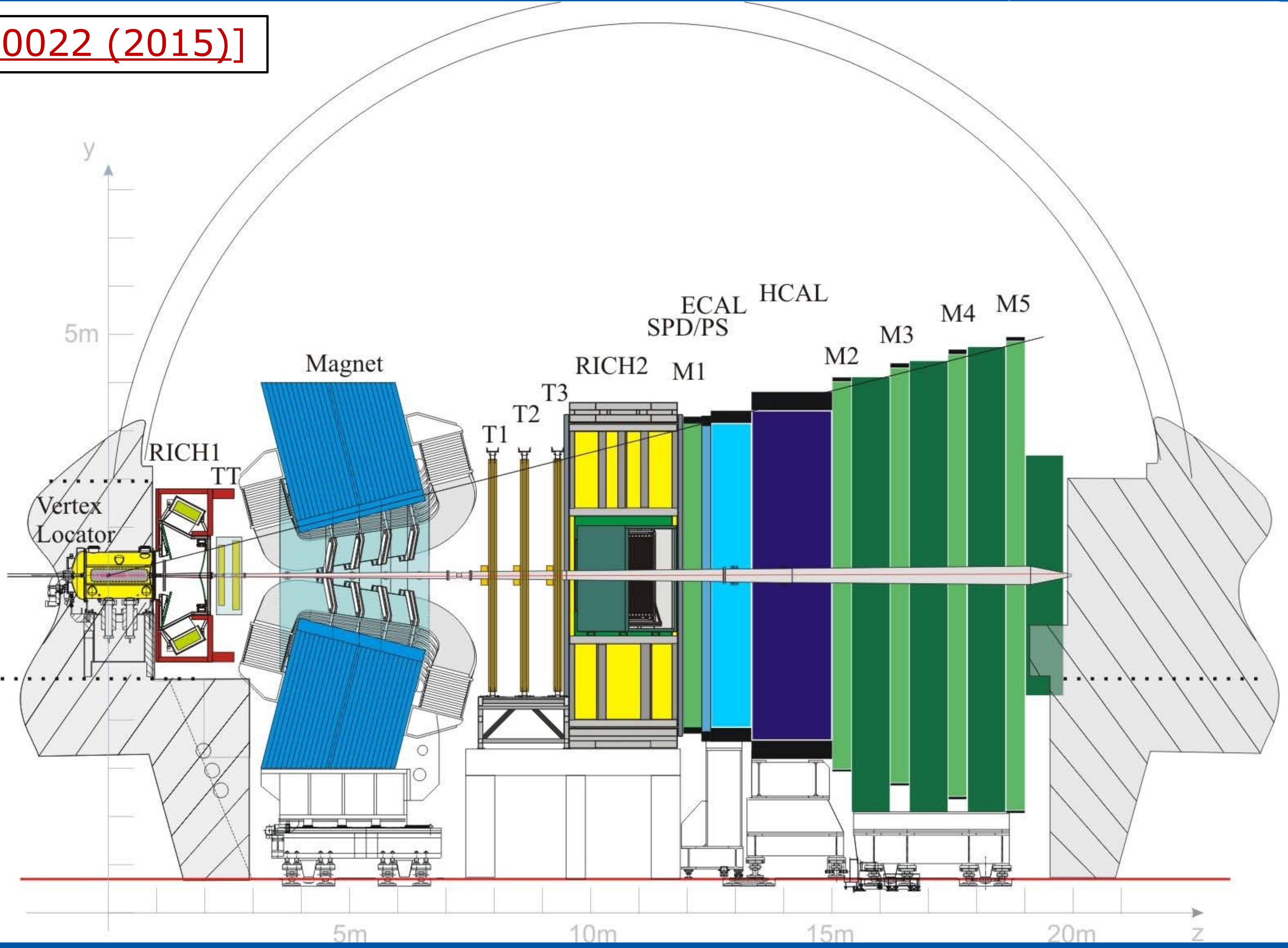
- New measurement of $A_{CP}(K_s^0 K_s^0)$ compatible with previous measurements
- First measurement of $A_{CP}(h^+h^-\mu^+\mu^-)$
- Still **no CPV** in charm
- LHCb is reaching the **precision** needed to observe CPV in charm
- Stay tuned for new results with **Run 2** data

Backup slides

The LHCb detector

[Int. J. Mod. Phys. A 30, 1530022 (2015)]

- Single arm spectrometer in $2 < \eta < 5$ range
- Excellent **vertex** resolution ($13\ \mu m$ in transverse plane for primary vertex)
- Excellent **IP** resolution ($\sim 13\ \mu m$ on the transverse plane)
- Very good **momentum** resolution ($\delta p/p \sim 0.5\% - 0.8\%$)
- Excellent **PID** capabilities
- Very good **trigger** efficiency ($\sim 90\%$)



$A_{CP}(D^0 \to K_S^0 K_S^0)$ - Systematics

Source	$\Delta\mathcal{A}^{CP}$(LL)	$\Delta\mathcal{A}^{CP}$(LD)
Fit procedure	5	10
$K_S^0\pi^+\pi^-$ background	4	5
Secondaries	2	3
Wrong $\pi_{tag}^{\pm}$ charge	–	–
Trigger selection	5	5
K^+K^- fit procedure	2	2
Residual detection asymmetry	2	2
Total	9	13