

# Search for CPV in $B \rightarrow D^* \mu \bar{\nu}_\mu$ at LHCb

Vlad Dedu

Aix Marseille Univ, CNRS/IN2P3, CPPM, IPhU, Marseille, France

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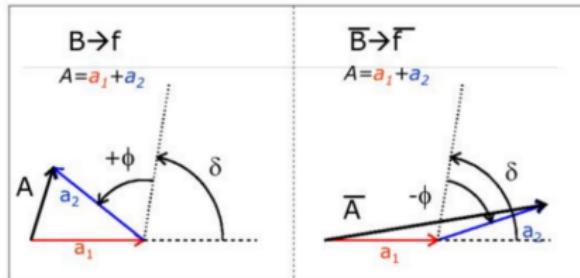


## Introduction - CPV in $b \rightarrow c\ell\nu$ decays

- Semileptonic decays are interesting probes of NP
- $(RD - RD^*)$  anomalies can be explained by different NP models in  $b \rightarrow c\ell\nu$
- This project: Search for CPV in  $B \rightarrow D^*\ell\nu$ , first analysis of CPV in a SL decay. Closely related to the angular analysis, but focus only on CPV terms.
- No CPV in SM in SL decays  $\rightarrow$  theoretically clean probe of NP.
- Sensitive to effects that could fake CP asymmetry
- Start with  $\mu$  instead of  $\tau$  channel: more statistics, easier analysis ( $\tau$  reconstruction is difficult). Although NP should couple more to  $\tau$  due to larger mass, same NP may affect  $\mu$ . Can still provide constraints for NP.

# Introduction - CP violation

- Search for Charge Parity Violation in  $B \rightarrow D^* \ell \nu$  ( $b \rightarrow c \ell \nu$ ) analysis



- In SM  $B^0 \rightarrow D^* \ell \bar{\nu}_\ell$  has only 1 amplitude  $\rightarrow$  **no CPV**
- NP amplitude will have different weak phase but no strong phase (QCD amplitudes are the same for SM and NP)  
 $\rightarrow$  **not enough for direct CPV**

Possible ways to obtain CPV in SL decays:

- Four-(or more)-body B decays: Triple product asymmetries
- Interference of decay amplitudes with overlapping resonances, i.e.  $B \rightarrow D^{**} \mu \nu$ , with  $D^{**} = D_0^*, D_1, D_2^*$

# Introduction - Effective Hamiltonian

- Effective field theory for  $b \rightarrow c \ell \bar{\nu}$  decays

$$\mathcal{H}_{\text{eff}}^{\text{NP}} = \frac{G_F V_{cb}}{\sqrt{2}} \sum_i g_i \mathcal{O}_i + \text{h.c.},$$

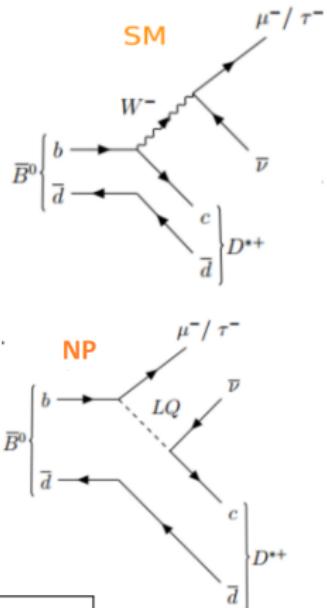
$$\mathcal{O}_S = \bar{c} b \ell (1 - \gamma_5) \nu$$

$$\mathcal{O}_P = \bar{c} \gamma_5 b \ell (1 - \gamma_5) \nu$$

$$\mathcal{O}_L = \bar{c} \gamma^\mu (1 - \gamma_5) b \ell \gamma_\mu (1 - \gamma_5) \nu$$

$$\mathcal{O}_R = \bar{c} \gamma^\mu (1 + \gamma_5) b \ell \gamma_\mu (1 - \gamma_5) \nu$$

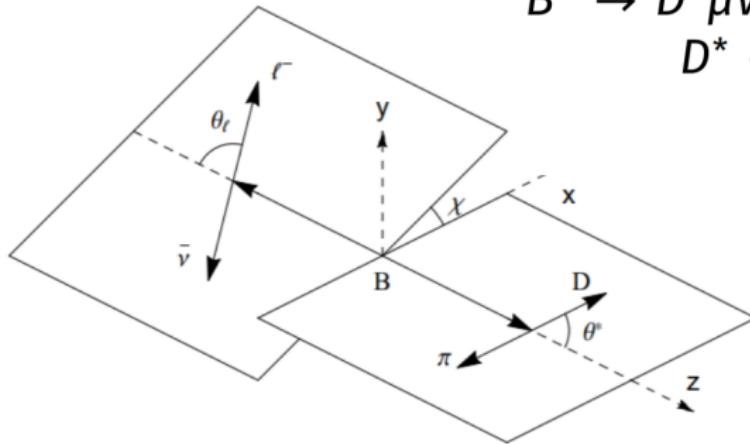
$$\mathcal{O}_T = \bar{c} \sigma^{\mu\nu} (1 - \gamma_5) b \ell \sigma_{\mu\nu} (1 - \gamma_5) \nu$$



- $SM : g_S = g_P = g_L = g_R = g_T = 0; \mathcal{H}_{\text{eff}}^{\text{SM}} \propto \mathcal{O}_L$
- Couplings  $g_L, g_R, g_S, g_P, g_T$  can be complex.

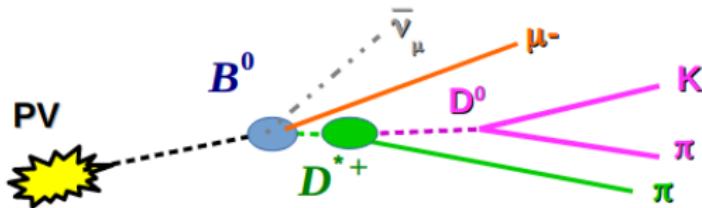
# Helicity angles

$$\begin{aligned}B^0 &\rightarrow D^* \mu \bar{\nu} \\D^* &\rightarrow D^0 \pi_s \\D^0 &\rightarrow K \pi\end{aligned}$$



- $B^0 \rightarrow D^*(\rightarrow D^0 \pi) \mu \bar{\nu}_\mu$  decay is described by 4 kinematic parameters:  
3 helicity angles ( $\theta_\ell, \theta_D, \chi$ ) and  $q^2$

# Neutrino reconstruction

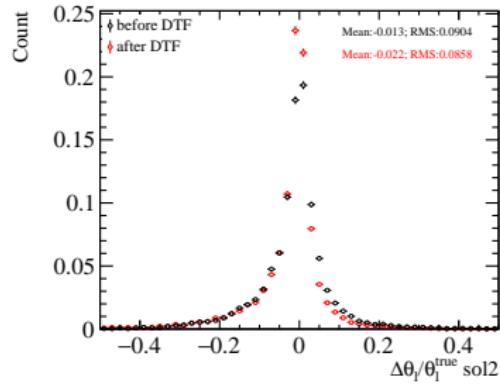
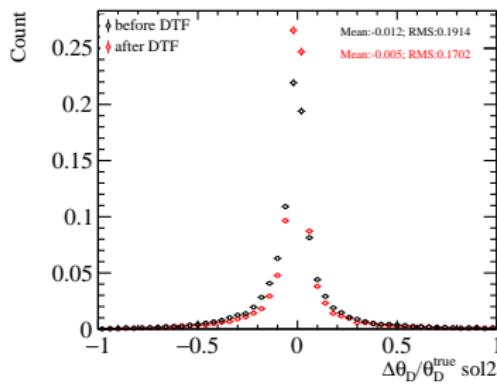
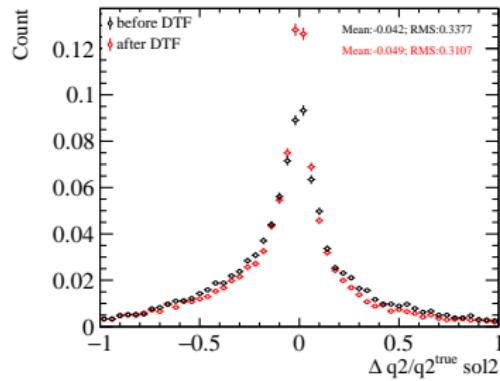
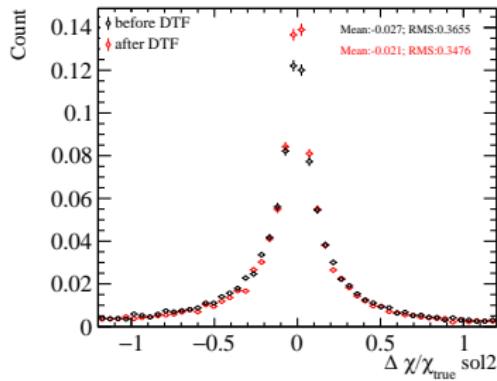


- Kinematic reco: Estimate  $B$ ,  $\nu$  momenta from decay topology using the  $B$  line of flight between PV and b-vertex [D. Hill et al]

$$|\vec{p}_{B^0}| = \frac{(m_Y^2 + m_{B^0}^2)|\vec{p}_Y| \cos \theta_{B^0,Y} \pm E_Y \sqrt{(m_{B^0}^2 - m_Y^2)^2 - 4m_{B^0}^2 |\vec{p}_Y|^2 \sin^2 \theta_{B^0,Y}}}{2(E_Y^2 - |\vec{p}_Y|^2 \cos^2 \theta_{B^0,Y})}$$

- Run full refit (DecayTreeFit) of the decay tree including all possible info: missing  $\nu$ , vertex, mass constraints
- Improve precision in reconstructing quantities of interest ( $\theta_L, \theta_D, \chi, q^2$ )

# Angle resolutions after DTF - simulation



# Triple products

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta^* d\chi} = \frac{3}{8\pi} \frac{G_F^2 |V_{cb}|^2 (q^2 - m_\ell^2)^2 |p_{D^*}|}{2^8 \pi^3 m_B^2 q^2} \\ \times \mathcal{B}(D^* \rightarrow D\pi) \left( N_1 + \frac{m_\ell}{\sqrt{q^2}} N_2 + \frac{m_\ell^2}{q^2} N_3 \right)$$

- Angular distribution derived from most general  $\mathcal{H}_{\text{eff}}^{NP}$  [D.London et al]
- NP couplings  $\rightarrow$  CPV terms (triple products)  $\propto \sin \chi$
- Same magnitude and sign for  $B0$  and  $\overline{B0}$

Not suppressed	Coupling	Angular Function
$\text{Im}(\mathcal{A}_\perp \mathcal{A}_0^*)$	$\text{Im}[(1 + g_L + g_R)(1 + g_L - g_R)^*]$	$-\sqrt{2} \sin 2\theta_\ell \sin 2\theta^* \sin \chi$
$\text{Im}(\mathcal{A}_\parallel \mathcal{A}_\perp^*)$	$\text{Im}[(1 + g_L - g_R)(1 + g_L + g_R)^*]$	$2 \sin^2 \theta_\ell \sin^2 \theta^* \sin 2\chi$
$\text{Im}(\mathcal{A}_{SP} \mathcal{A}_{\perp,T}^*)$	$\text{Im}(g_P g_T^*)$	$-8\sqrt{2} \sin \theta_\ell \sin 2\theta^* \sin \chi$
$\text{Im}(\mathcal{A}_0 \mathcal{A}_\parallel^*)$	$\text{Im}[(1 + g_L - g_R)(1 + g_L + g_R)^*]$	$-2\sqrt{2} \sin \theta_\ell \sin 2\theta^* \sin \chi$

- Exploit orthogonality of Fourier terms and perform Fourier transformation of scattered data to obtain coefficient
- We construct a set of 50 orthogonal terms (up to 2nd order harmonics)  $\rightarrow$  control terms

# Sensitivity study - HAMMER



[HAMMER website: paper,  
manual, git etc]

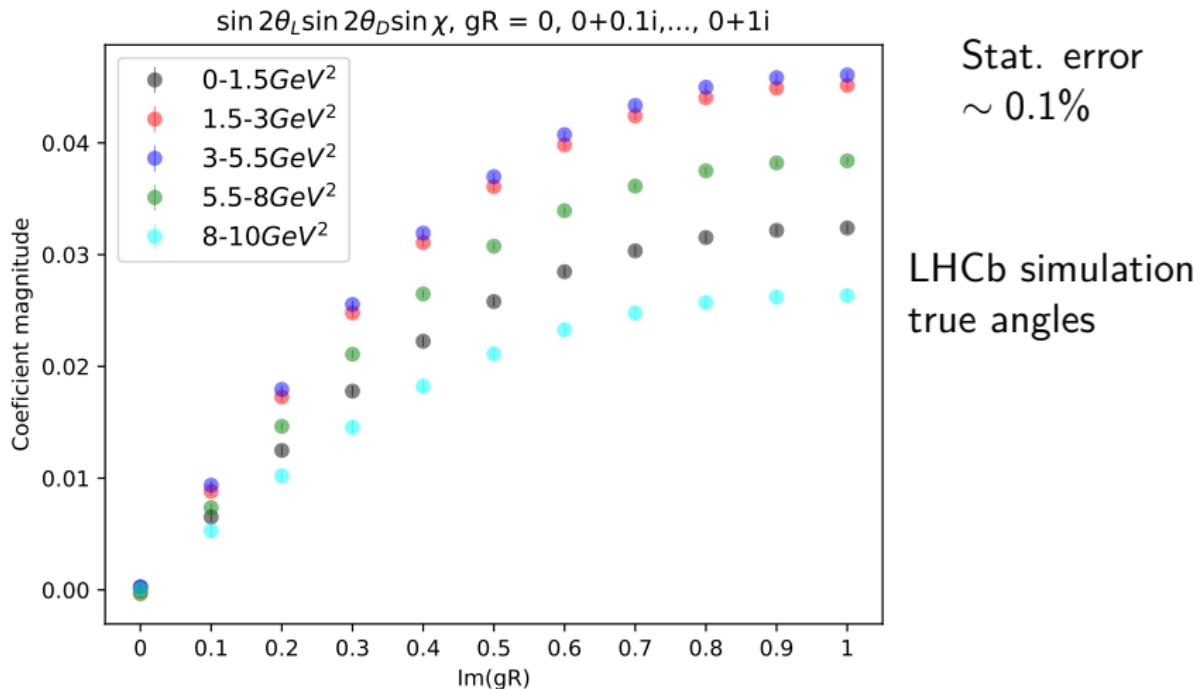
- "A fast and efficient means to reweight large MC samples to any desired NP, or to any description of the hadronic matrix elements"
- Set FF scheme (BLPR) and Wilson coefficients (complex) values

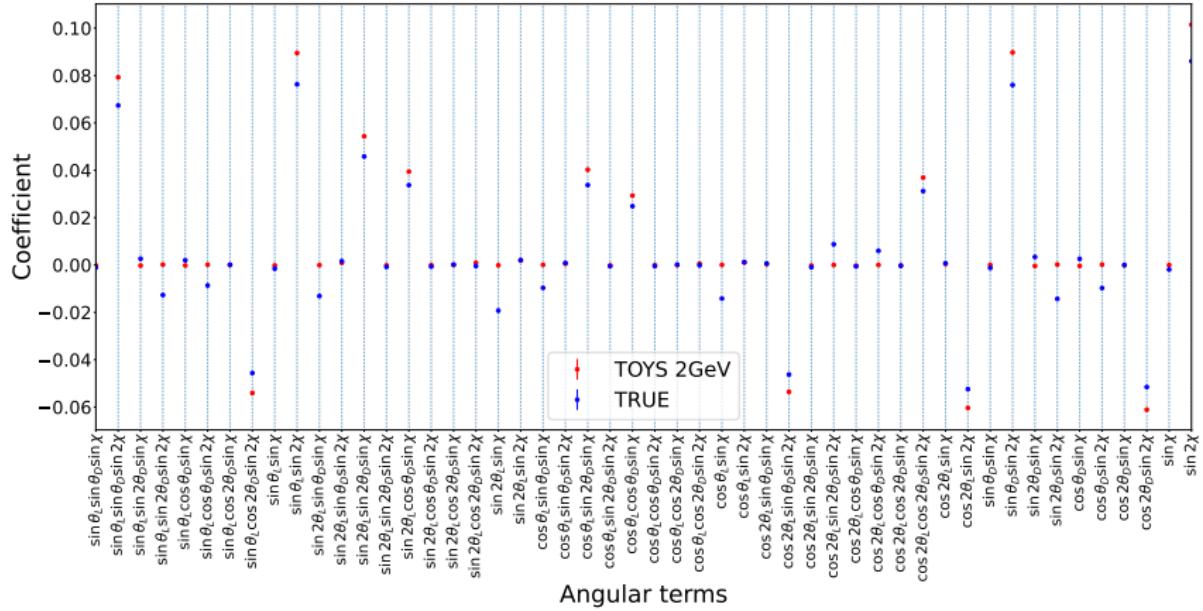
$$B \rightarrow (D^* \rightarrow D\pi)\ell\nu \quad | \quad \text{ISGW2}^*, \text{ BGL}^{*\ddagger}, \text{ CLN}^{*\ddagger}, \text{ BLPR}^\ddagger$$

- Calculate weight to NP scenario for each event based on true 4-momenta and particle IDs

# CPV terms. Sensitivity study with simulation

- Inject NP in MC with HAMMER (reweights each event based on NP:  $g_L, g_R, g_P, g_T \neq 0$ )





## Systematic uncertainties

We would need to control any systematics that could introduce "fake CP-asymmetry" at the 0.1% level

Non-zero  $\sin \chi$  terms: what does it practically mean?

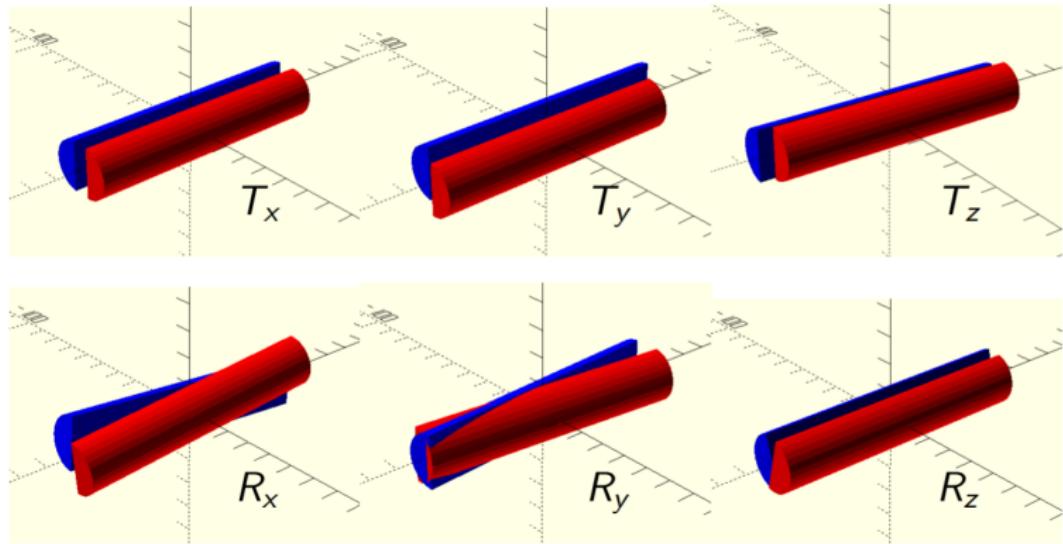
$\nu$  direction is reconstructed from topology of PV and secondary vertices.

- Term  $\propto \sin \chi$ : up-down asymmetry  $(N_{\uparrow} - N_{\downarrow})/N_{\text{tot}}$ .
- $\nu$  "up"  $\Leftrightarrow$  PV "below"  $D^0\pi^+\mu^-$  plane
- $\nu$  "down"  $\Leftrightarrow$  PV "above"  $D^0\pi^+\mu^-$  plane

What experimental effects can introduce non-zero "PV below-above" asymmetry?

- CPV in backgrounds
- **VELO misalignment**
- **Asymmetry of tracking efficiency**

## Systematic uncertainties - VELO misalignment



- Misalignments of VELO as a whole should not introduce bias in angles, but displacements of the two halves wrt each other can
- Expect  $T_y$  and  $R_x$  to show largest source of bias

# Misalignment in VELO

- VELO misalignment can affect the angles and introduce bias in CP asymmetry
- $\vec{\Theta} = \Theta_i \equiv (\theta_D, \theta_\ell, \chi, q^2)$ ,  $P(\vec{\Theta})$  is an angular term

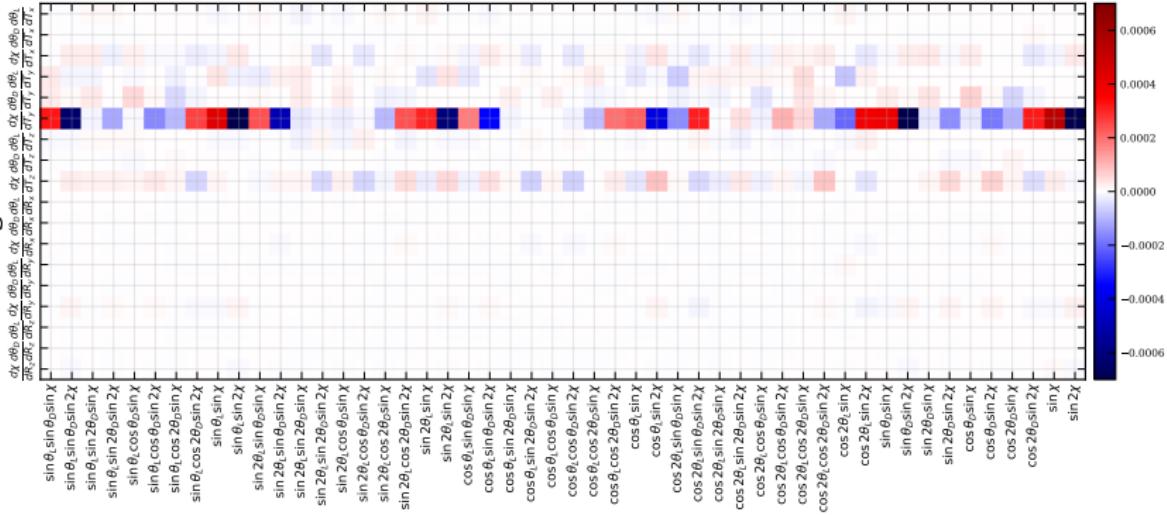
$$A_{CP} = \frac{1}{N} \sum_{\alpha=1}^N P(\vec{\Theta}_\alpha) = \langle P(\vec{\Theta}) \rangle$$

$$\delta A_{CP} = \sum_k \rho_k \left\langle \frac{\partial P}{\partial \Theta_i}(\vec{\Theta}) \frac{\partial \Theta_i}{\partial \rho_k}(\vec{\Theta}) \right\rangle$$

- Calculate partial derivative for each event ( $\alpha$ ) by introducing small displacement in tracks i.e.:

$$\theta'_{D,\alpha} = \theta_{D,\alpha} + \frac{\partial \theta_{D,\alpha}}{\partial \Delta x} \Delta x$$

## Angle bias



Angular terms

- Typical VELO alignment precision:  $1 \mu\text{m}$  for  $T_{x,y}$ ,  $3 \mu\text{m}$  for  $T_z$ ,  $3 \mu\text{rad}$  in  $R_{x,y}$ ,  $10 \mu\text{rad}$  in  $R_z$
- Largest source of bias is  $T_y$ , up to 0.05%
- Can use control terms to control misalignment systematics in a data-driven way

# Conclusions and outlook

## Conclusions:

- $B \rightarrow D^* \mu \nu$  : indirect CPV from angular distribution.
- MC study for sensitivity to CPV  $\rightarrow$  a few % with stat error  $\sim 0.1\%$
- Helicity angle resolution studies (10-20 % improvement with DTF)
- Systematic uncertainties - detector misalignments

## Outlook:

- Estimate all systematics: CPV in backgrounds and non-uniform detector efficiencies (similar approach as for misalignment)
- Look in data
- $\tau$  channel

## BACK-UP SLIDES

## Fourier transform method

- $P(\theta_\ell, \theta_D, \chi) = \sum_n C_n F_n(\theta_\ell, \theta_D, \chi)$ ,  $F_n$  are all orthogonal
- $C_k = \int P(\theta_\ell, \theta_D, \chi) F_k(\theta_\ell, \theta_D, \chi) d\theta_\ell d\theta_D d\chi$
- $P(\theta_\ell, \theta_D, \chi) = \frac{1}{n} \sum_{i=1}^n \delta(\theta_\ell - \theta_\ell^{(i)}) \delta(\theta_D - \theta_D^{(i)}) \delta(\chi - \chi^{(i)})$
- $C_k = \frac{1}{n} \sum_{i=1}^n F_k(\theta_\ell^{(i)}, \theta_D^{(i)}, \chi^{(i)})$
- Example:
- $F_k(\theta_\ell, \theta_D, \chi) = \sin 2\theta_\ell \sin 2\theta_D \sin \chi$
- $C_k = \frac{1}{n} \sum_{i=1}^n (\sin 2\theta_\ell^{(i)} \sin 2\theta_D^{(i)} \sin \chi^{(i)})$