Measurement of f_L and $\mathcal{CP}$ asymmetries of the $B^0 \to \rho^0 K^*(892)^0$ decay at LHCb

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Outline

$\mathcal{CPV}$ and New Physics searches in the B system

$\mathcal{CPV}$ within the Standard Model

- It arises from a **single phase in the CKM matrix**

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$

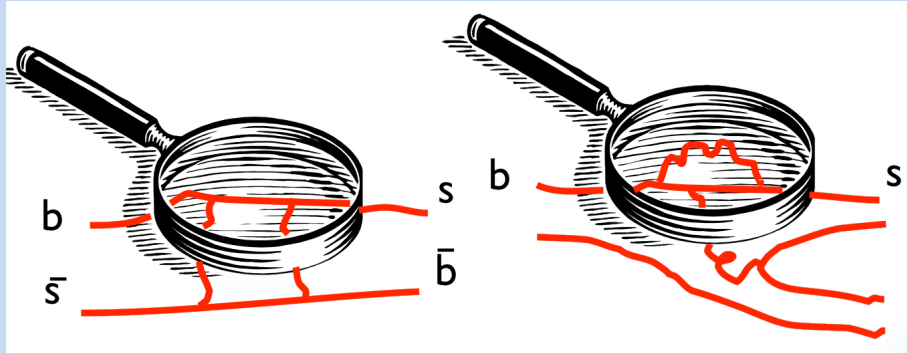
- The **SM fails to explain** the observed $\mathcal{CP}$ asymmetry of the Universe
  $\to$ **New Physics $\mathcal{CP}$V is expected**

Two main approaches for NP searches:

- **Direct** detection $\to$ ATLAS&CMS
  Limiting factor: **energy**
- **Indirect** searches $\to$ **LHCb**
  Limiting factor: **precision**

$\mathcal{CPV}$ within the B physics framework

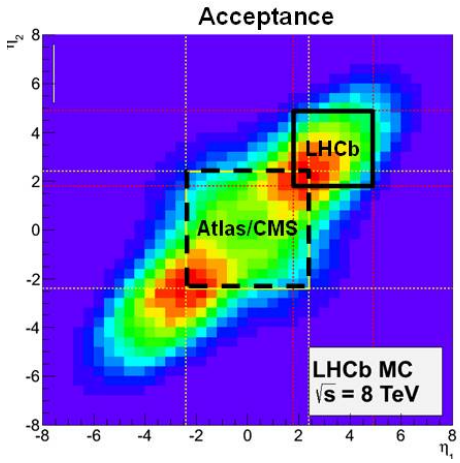
- in the **mixing**: $B^0/\bar{B}^0 \to f$
- in the **decay**: $\mathcal{A}(B \to f) \neq \bar{\mathcal{A}}(\bar{B} \to \bar{f})$
- from the **interference** between the two

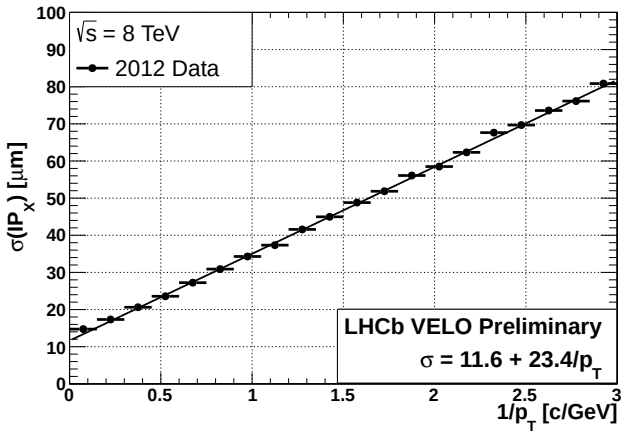


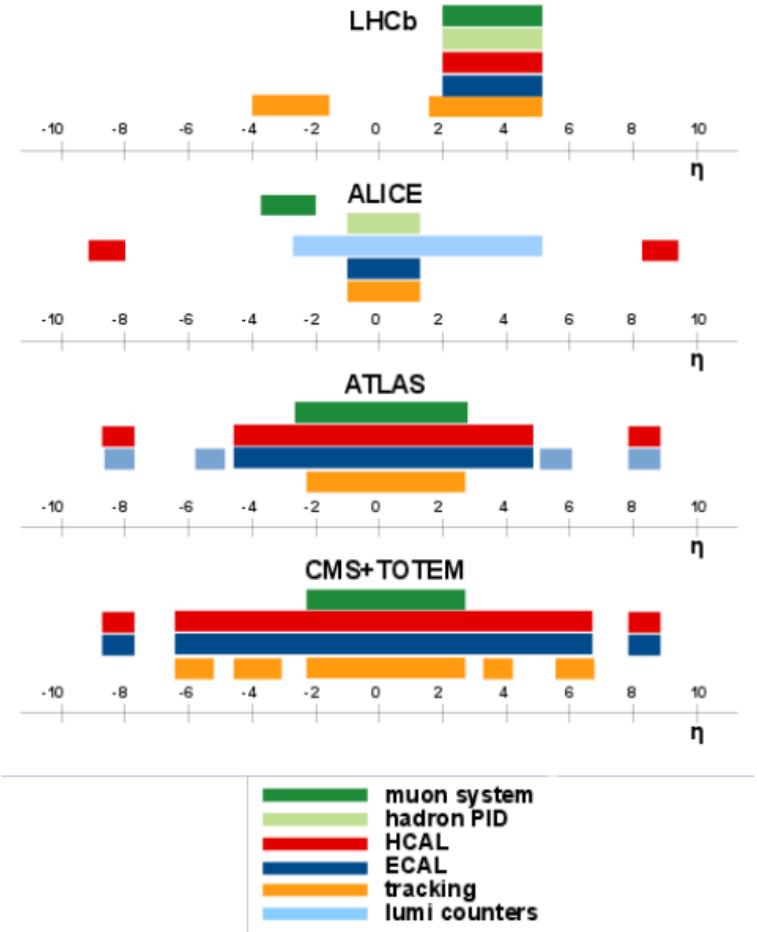
Flavour physics at the LHC

Hadronic environment means:

- $\sigma_{b\bar{b}} \sim 300\mu b \to > 10^{13} b\bar{b}$ pairs
- Large **track multiplicity**: **excellent vertexing** and **triggering** are key features of the detector
- At LHC energies, $b\bar{b}$ pairs are highly **boosted**



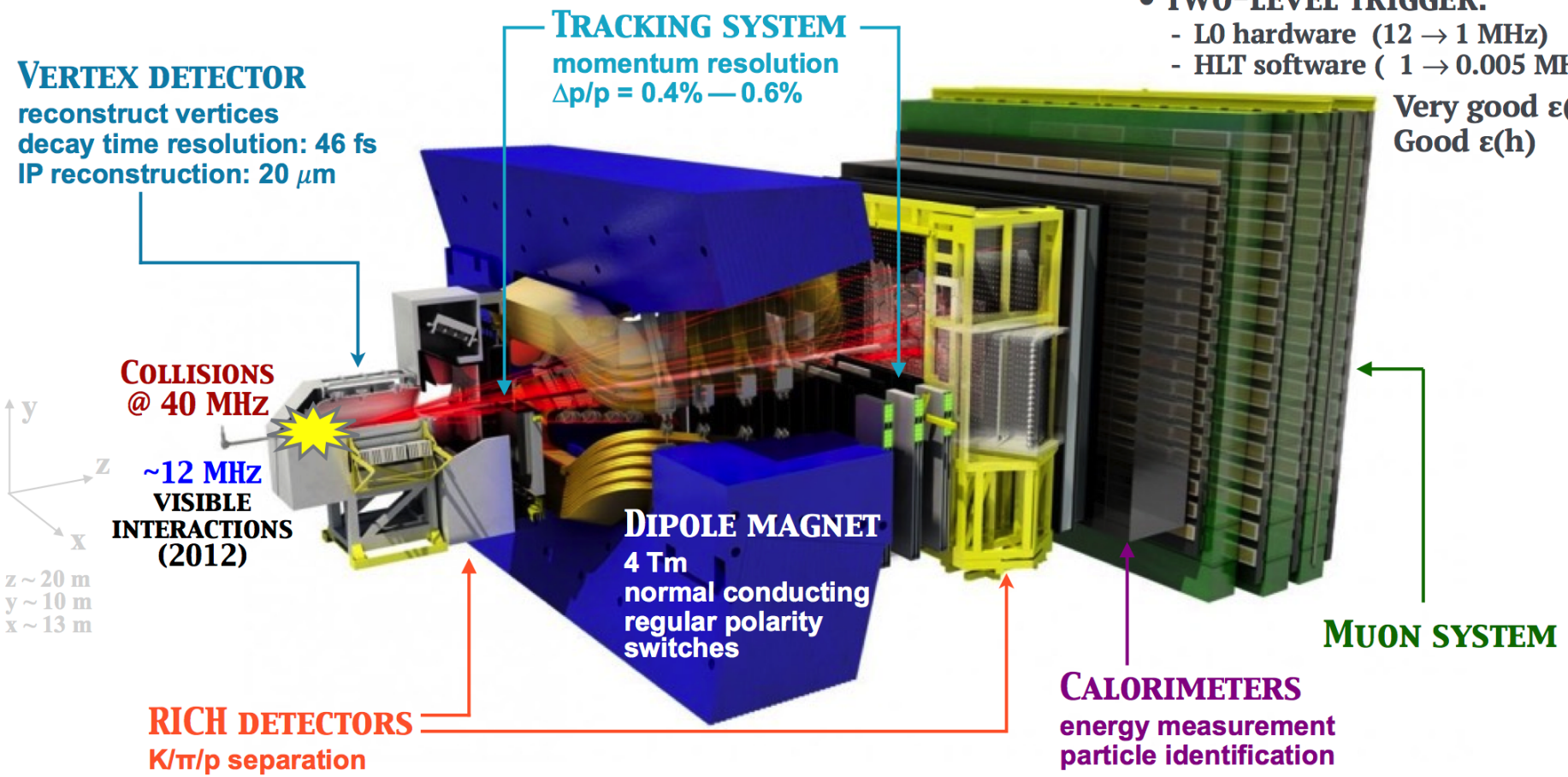




LHCb: specific design for a B physics programme

- Single-arm forward spectrometer
- VErtex LOcator gets **8.2 mm** to the beam
- Very good PID, $\vec{p}$ and position resolution
- Possibility to reverse magnet polarity

The LHCb detector

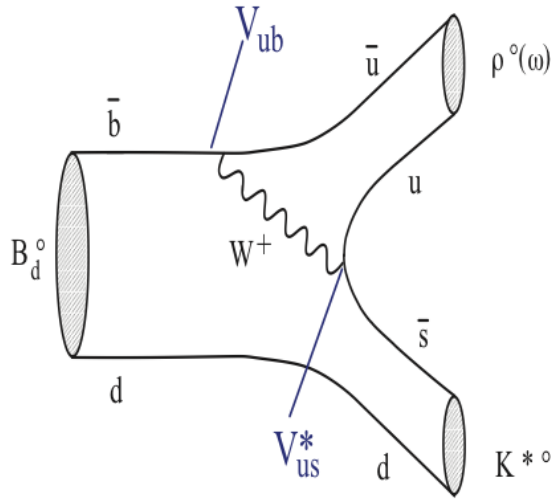


The $B^0 \to \rho^0 K^*(892)^0$ decay

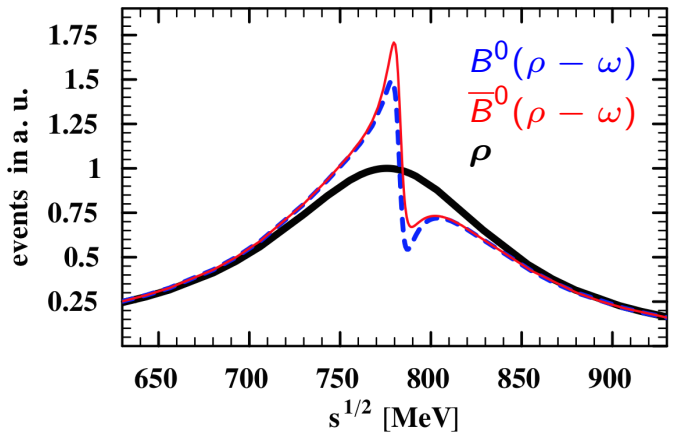
Charmless B^0 **meson** decay into two **vector** resonnances: $\mathbf{B^0 \to \rho^0(\pi^+\pi^-)K^*(892)^0(K^+\pi^-)}$

- **Proceeds either via**:
  - ◇ A **doubly Cabibbo suppressed tree**
  - ◇ A **gluonic b → s penguin**

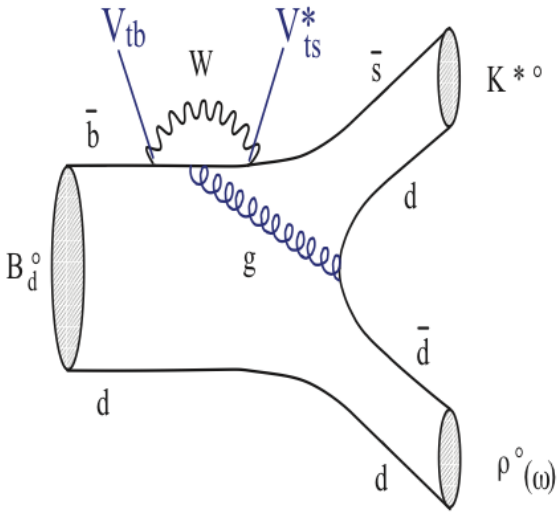
  → similar amplitudes! (good for a_{CP} search)



- **Self-tagged** decay: $\begin{cases} B^0 \to (\pi^+\pi^-)(K^+\pi^-) \\ \overline{B}^0 \to (\pi^-\pi^+)(K^-\pi^+) \end{cases}$
- **Vector** resonances → **additional** $\mathcal{CP}$ violating **observables**
- $\rho - \omega$ interplay may enhance $\mathcal{CP}$ violating effects!



M. Gronau, J. Zupan
arXiv:hep-ph/0502139



Angular analysis: formalism

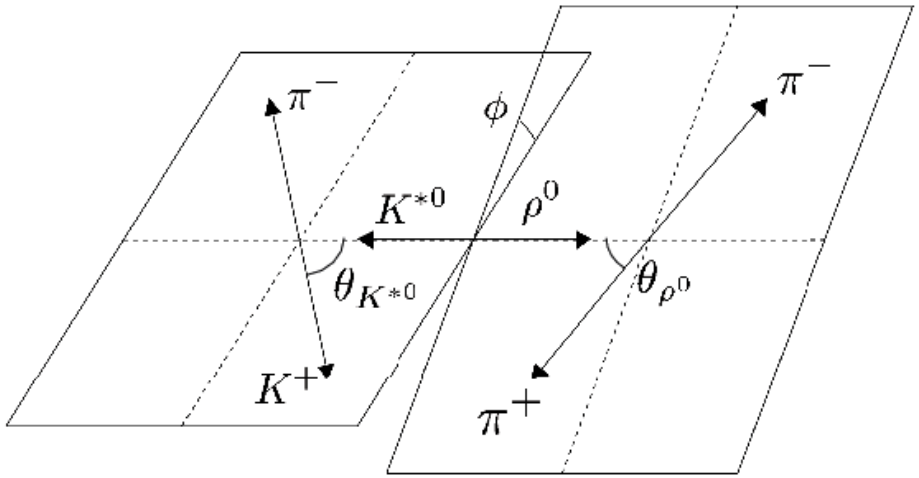
B $\to$ (p_1p_2)(p_3p_4) decays

Can be **fully described** in terms of:

- **Three helicity angles**: θ_1, θ_2, ϕ
- **Two invariant masses**: $m_{(p_1p_2)}, m_{(p_3p_4)}$

Hence, the **decay rate** (Φ_4 is the phase space):

$$d^5\Gamma \propto \Phi_4(m_1, m_2)|\mathcal{A}_T(\theta_1, \theta_2, \phi, m_1, m_2)|^2$$



A **B $\to$ VV final state is an admixture of three amplitudes**
$\to$ three allowed **spin configurations**: CP-odd $S_{VV} = 1$ and CP-even $S_{VV} = 0, 2$:

$$J_B = 0 \text{ Angular Momentum Conservation } \Rightarrow \mathrm{J_{VV}} = 0, \text{ thus } \mathrm{S_{VV}} = \mathrm{L_{VV}}$$

Generalising to N amplitudes and taking into account the **masses** and **angles** factorisation:

$$\mathbf{d^5\Gamma \propto \Phi_4 \left|\sum_{i=1}^{N} A_i \cdot g_i(cos(\theta_1), cos(\theta_2), \phi) \cdot M_i(m_1, m_2)\right|^2 \propto \Phi_4 \sum_{i,j=1}^{N} (A_i \cdot g_i \cdot M_i)(A_j \cdot g_j \cdot M_j)^*}$$

An amplitude analysis disentangles the final state!

$A_i \to$ **physical parameters** | $g_i(\theta_1, \theta_2, \phi) \to$ **spherical harm.** | $M_i(m_1, m_2) \to$ **mass prop.**

Observables (I)

Polarization fraction measurement

Polarization fractions are defined as $\mathbf{f_i} = \frac{|\mathbf{A_i}|^2}{\sum_\lambda |\mathbf{A_\lambda}|^2}$

Aiming to contribute to solve the $B \to VV$ puzzle: **expectation was** $\mathbf{f_L} \gg \mathbf{f_{||}}, \mathbf{f_\perp}$
... but pure penguins decay modes ($B_s \to K^*(892)^0 \bar{K}^*(892)^0$, $B^0 \to \phi K^0(892)^0$, etc) do not agree with it.

Direct $\mathcal{CP}$ asymmetry

The decay amplitude can be written as: $\mathcal{A} = \langle K^* \rho^0(\omega)|H^T|B\rangle + \langle K^* \rho^0(\omega)|H^P|B\rangle$

Which leads to the definition of:

$$\mathbf{a_{CP}^{dir}} = \frac{|\mathcal{A}|^2 - |\bar{\mathcal{A}}|^2}{|\mathcal{A}|^2 + |\bar{\mathcal{A}}|^2} = \frac{\mathbf{-2r\sin\delta\sin\phi}}{\mathbf{1+r^2+2r\cos\delta\cos\phi}}$$

Where, **within the SM framework**:

$$\phi = arg[(V_{tb}V_{ts}^*)/(V_{ub}V_{us}^*)] \Rightarrow \mathbf{\sin\phi = \sin\gamma_{CKM}}$$

Observables (II)

True and fake triple product definition

Scalar triple products of three-momentum or spin vectors are **odd under T reversal** due to either:

(TP^{True}) **T-violating** ($\to \mathcal{CP}$-violating) **phase**

(TP^{Fake}) $\mathcal{CP}$-conserving phase from **final state interactions**

Construction:

- $\vec{n}_{12}$ and $\vec{n}_{34}$ unit vectors normal to the V resonnances decay planes
- Helicity angle ϕ
- $(\vec{\mathbf{n}}_{12} \times \vec{\mathbf{n}}_{34})_z = \mathbf{sin}\phi$ and $\mathbf{sin2}\phi = \mathbf{2}(\vec{\mathbf{n}}_{12} \cdot \vec{\mathbf{n}}_{34})(\vec{\mathbf{n}}_{12} \times \vec{\mathbf{n}}_{34})_z$ are **T-odd**

$$\mathcal{A}_T(sin2\phi) = \frac{N(sin(2\phi{>}0) - N(sin(2\phi{<}0)}{N(sin(2\phi{>}0) + N(sin(2\phi{<}0)}$$

Triple products in the $\mathbf{B^0 \to \rho^0 K^*(892)^0}$

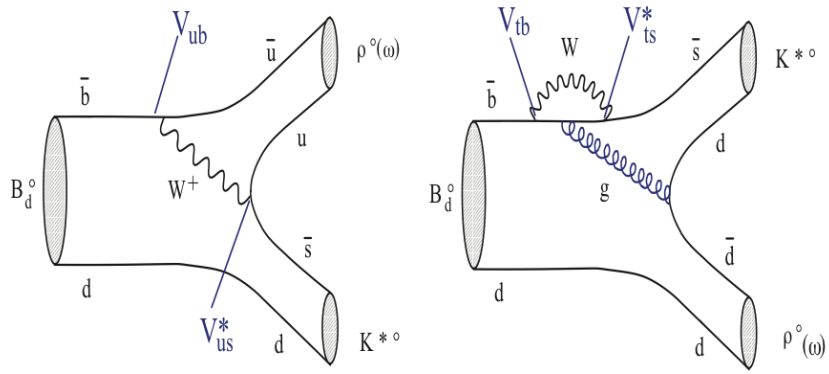
The angular analysis disentagles the physical amplitudes according to their angular dependence. T-odd terms arise from the combinations including $\mathbf{A}_\perp^{\rho \mathbf{K}^*}$ or $\mathbf{A}_\perp^{\omega \mathbf{K}^*}$

$$TP^{True} \propto \mathrm{Im}(A_\perp A_\lambda^* - \overline{A}_\perp \overline{A}_\lambda^*) \qquad TP^{Fake} \propto \mathrm{Im}(A_\perp A_\lambda^* + \overline{A}_\perp \overline{A}_\lambda^*) \qquad \lambda = 0, ||$$

Analysis strategy

Main physics goals: $B^0 \to \rho^0 K^*(892)^0$

Measure $\mathbf{a_{CP}^{dir}}$, $\mathbf{f_L}$ and the accesible **TPs**.



Main analysis steps:

1. **Event selection**: trigger+topology+PID.
2. **Four-body mass spectrum**: isolate $B^0 \to (K^+\pi^-)(\pi^+\pi^-)$ events.
3. **Amplitude analysis**: disentangle $\mathcal{CP}$ eigenstates, as well as $B \to VV, VS, SV, SS$ waves.
4. **Fit the data**: account for acceptance effects, build fitting PDF.
5. **Systematical uncertainties study**

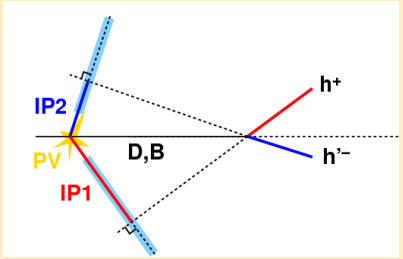
Selection summary

Event **selection** is performed in three steps:

Stripping + loose preselection cuts

Geometry of B decays is preselected using soft cuts on the p_T,IP and a good track quality is required.

Soft PID cuts allow to **reconstruct ρ^0** and **$K^*(892)^0$ candidates.**

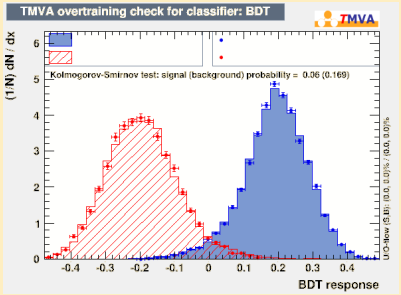


Multivariate analysis

A **BDT** is used reduce the **combinatorial background**.

Charm decays are rejected by eliminating their phase space.

Tighter PID cuts on $\pi^{\pm}$ and $K^{\pm}$ are applied and $\mu^{\pm}$ are vetoed.

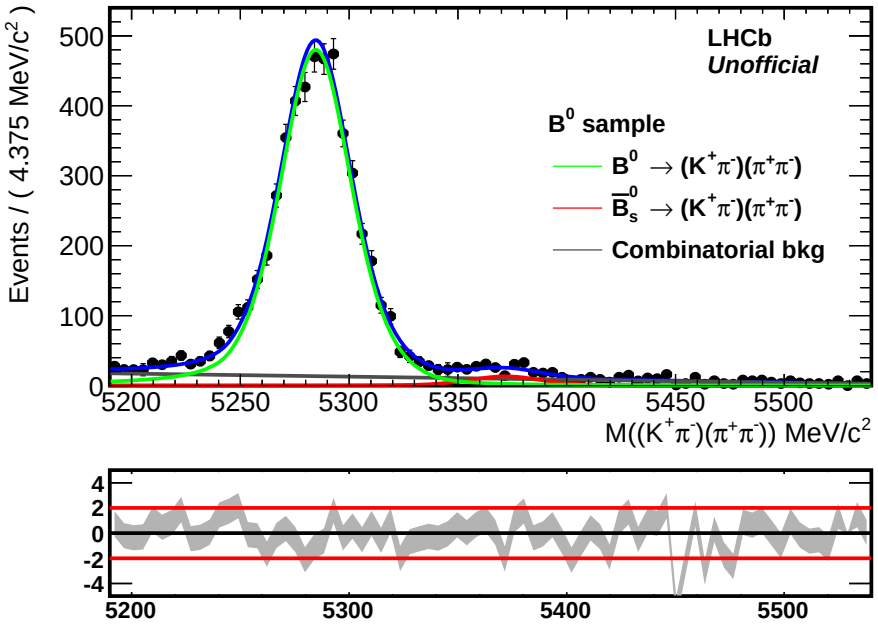


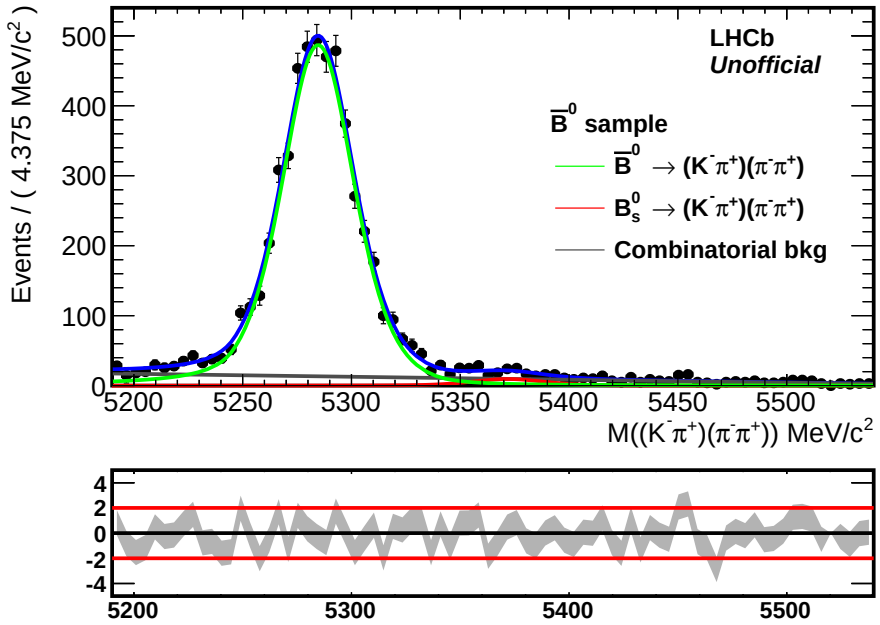
s-Weights&Injection of simulated events

Obtain a **background substracted** sample via **s-Weights**$\to$ $M(K\pi\pi\pi)$ spectrum.

The **topologically similar** $B_s \to K^*(892)^0 \bar{K}^*(892)^0$ decay is cancelled by **injecting simulated** $(K^+\pi^-)(K^-\pi^+)$ events.

4-body mass fit





Yields				
	2011		2012	
	B^0	$\bar{B}^0$	B^0	$\bar{B}^0$
$N_{B^0 \to \rho^0 K^*(892)^0}$	2102 ± 51	2076 ± 51	4871 ± 76	4972 ± 77
$N_{B_s \to \rho^0 K^*(892)^0}$	71 ± 14	22± 10	144 ± 19	89 ± 18
N_{Comb}	451 ± 28	451 ± 28	839 ± 37	839 ± 37

Background substraction

- $B_s \to (K^+\pi^-)(K^-\pi^+)$: inject simulated events
- Comb: s-Weights

Angular analysis: considered amplitudes

A PDF taking into account **8 different decay channels and 12 amplitudes** has been built

Mass propagators

- $\boldsymbol{\rho^0}$: Gounaris-Sakurai
- $\boldsymbol{\omega, K^*(892)^0}$: relativistic spin-1 Breit-Wigners
- $\mathbf{f^0(500)}$: spin-0 Breit-Wigner/Bugg
- $\mathbf{f^0(980)}$: Flattè
- $\mathbf{(K\pi)_0}$: Lass

i	Type	A_i	$g_i(\theta_1, \theta_2, \phi)$	$M_i(m_1, m_2)$
1		$A^0_{\rho K^*}$	$cos\theta_1 cos\theta_2$	$M_\rho(m_1)M_{K^*}(m_2)$
2	$V_1 V$	$A^{\|\|}_{\rho K^*}$	$\frac{1}{\sqrt{2}} sin\theta_1 sin\theta_2 cos\phi$	$M_\rho(m_1)M_{K^*}(m_2)$
3		$A^{\perp}_{\rho K^*}$	$\frac{i}{\sqrt{2}} sin\theta_1 sin\theta_2 sin\phi$	$M_\rho(m_1)M_{K^*}(m_2)$
4		$A^0_{\omega K^*}$	$cos\theta_1 cos\theta_2$	$M_\omega(m_1)M_{K^*}(m_2)$
5	$V_2 V$	$A^{\|\|}_{\omega K^*}$	$\frac{1}{\sqrt{2}} sin\theta_1 sin\theta_2 cos\phi$	$M_\omega(m_1)M_{K^*}(m_2)$
6		$A^{\perp}_{\omega K^*}$	$\frac{i}{\sqrt{2}} sin\theta_1 sin\theta_2 sin\phi$	$M_\omega(m_1)M_{K^*}(m_2)$
7	$V_1 S$	$A^0_{\rho(K\pi)}$	$\frac{1}{\sqrt{3}} cos\theta_1$	$M_\rho(m_1)M_{(K\pi)}(m_2)$
8	$V_2 S$	$A^0_{\omega(K\pi)}$	$\frac{1}{\sqrt{3}} cos\theta_1$	$M_\omega(m_1)M_{(K\pi)}(m_2)$
9	$S_1 V$	$A^0_{f_0(500)K^*}$	$\frac{1}{\sqrt{3}} cos\theta_2$	$M_{f_0(500)}(m_1)M_{K^*}(m_2)$
10	$S_2 V$	$A^0_{f_0(980)K^*}$	$\frac{1}{\sqrt{3}} cos\theta_2$	$M_{f_0(980)}(m_1)M_{K^*}(m_2)$
11	$S_1 S$	$A^0_{f_0(500)(K\pi)}$	$\frac{1}{3}$	$M_{f_0(500)}(m_1)M_{(K\pi)}(m_2)$
12	$S_2 S$	$A^0_{f_0(980)(K\pi)}$	$\frac{1}{3}$	$M_{f_0(980)}(m_1)M_{(K\pi)}(m_2)$

Account for the $\bar{B}$ decay: $A_i \to \eta_i \bar{A}_i$; with η_i the $\mathcal{CP}$ eigenvalue for each amplitude:

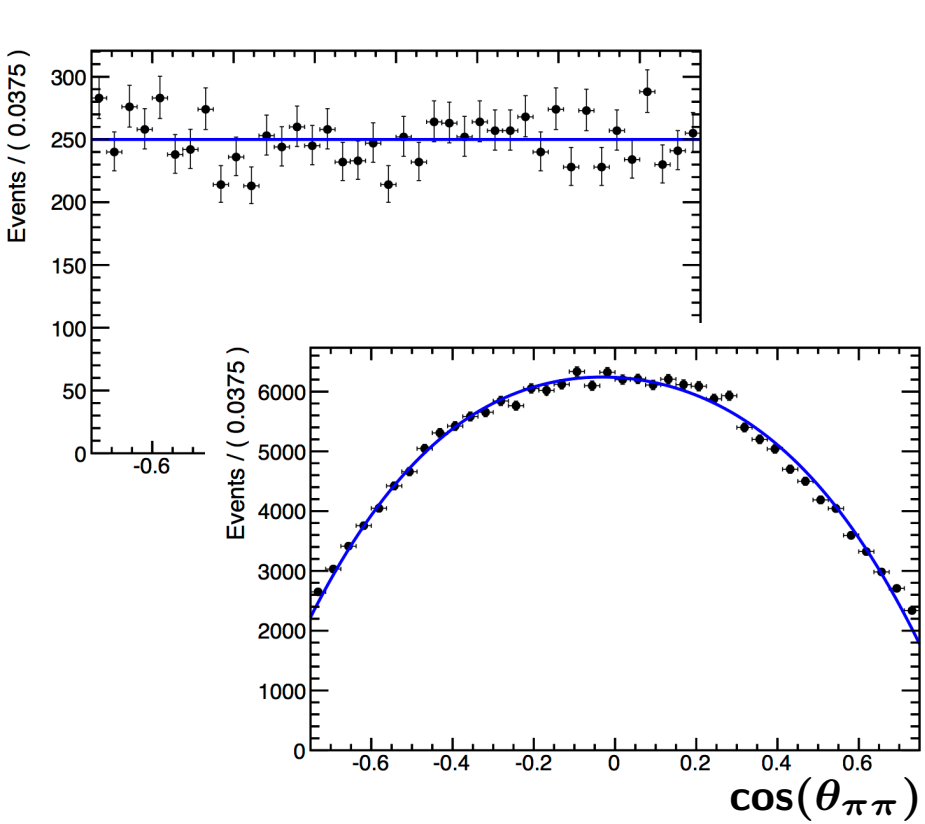
$$\eta_{\mathcal{A}_i} = 1 \text{ except for } \eta_{\mathcal{A}_\perp} = -1$$

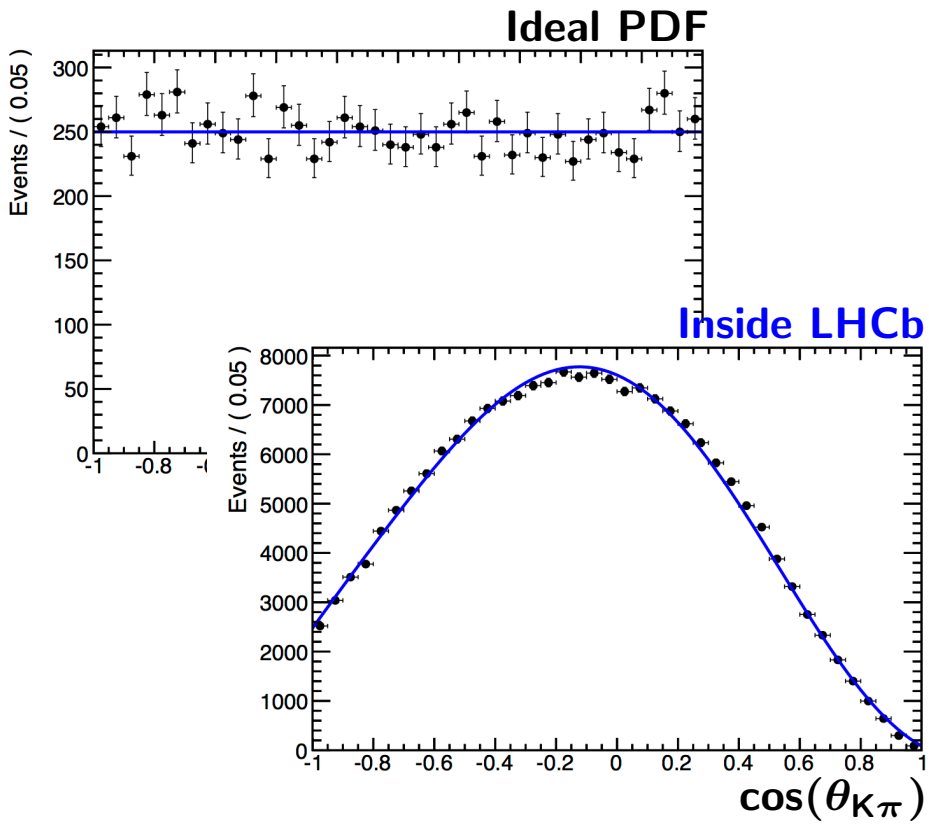
Detector acceptance effects

Selection requeriments + detector geometry affect the angular distributions

- Fitting only requires the **integrated acceptance → normalization weights**
- Model **visualisation requires a parametric function**:

$$\varepsilon(\theta) = 1 + a \cdot cos\theta + b \cdot cos^2\theta + c \cdot cos^3\theta + d \cdot cos^4\theta$$
$$\varepsilon(\phi) = \varepsilon(m) = 1$$

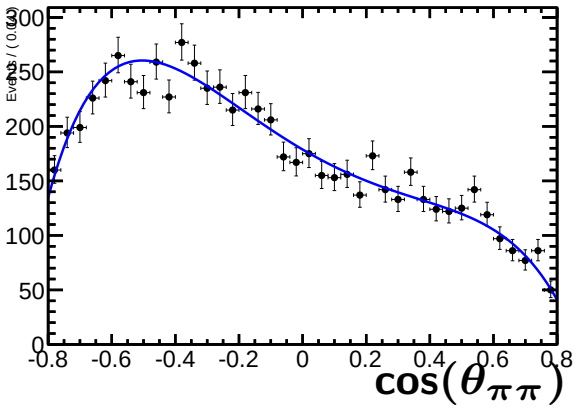


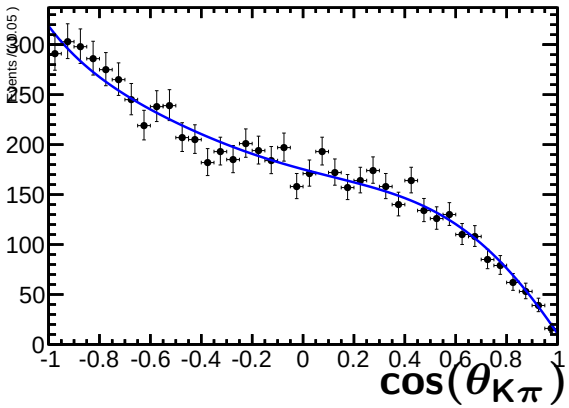


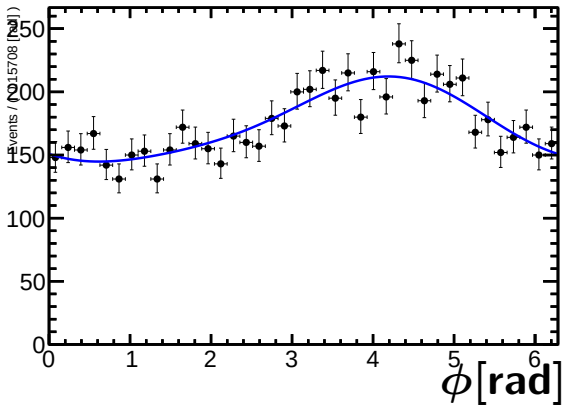
ToyMC studies

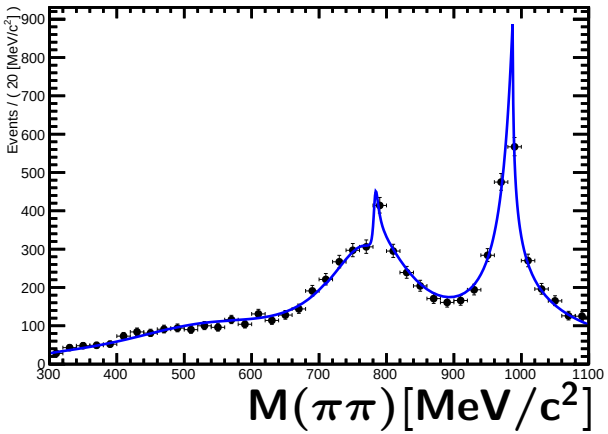
Remarks: ToyMC with N ∼real signal yield

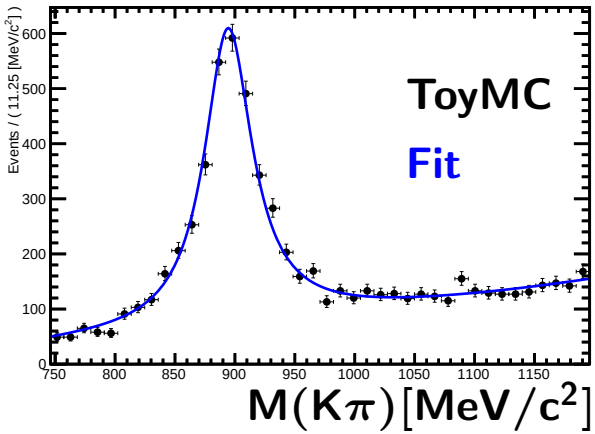
- **Statistical uncertainty** on $\mathbf{f_L}$ is $\sim 1\%$ using the whole data sample
- A_i extracted from a preliminary fit to real data (not allowing for $\mathcal{CP}$ violation)
- Fit **converges** without problems and **recovers generation values**











Conclusions

1. **Amplitude analyses** of **B → VV** decays are a **powerful method** to search for new sources of ***CP* violation.**

2. With the **statistics** achieved by **LHCb** during the Run-1, many of these analyses have become **feasible** and **high precision measurements are being perfomed**

3. The $\mathbf{B^0 \to \rho^0 K^*(892)^0}$ channel was found to be a good candidate to perform such a study:
   - ◇ tree diagram **doubly Cabibbo suppressed**
   - ◇ **Self-tagged** with four **charged hadrons** in the final state→ **high selection efficiency**
   - ◇ Final data sample has ∼ **14000** $(K^{\pm}\pi^{\mp})(\pi^{\pm}\pi^{\mp})$ **events**

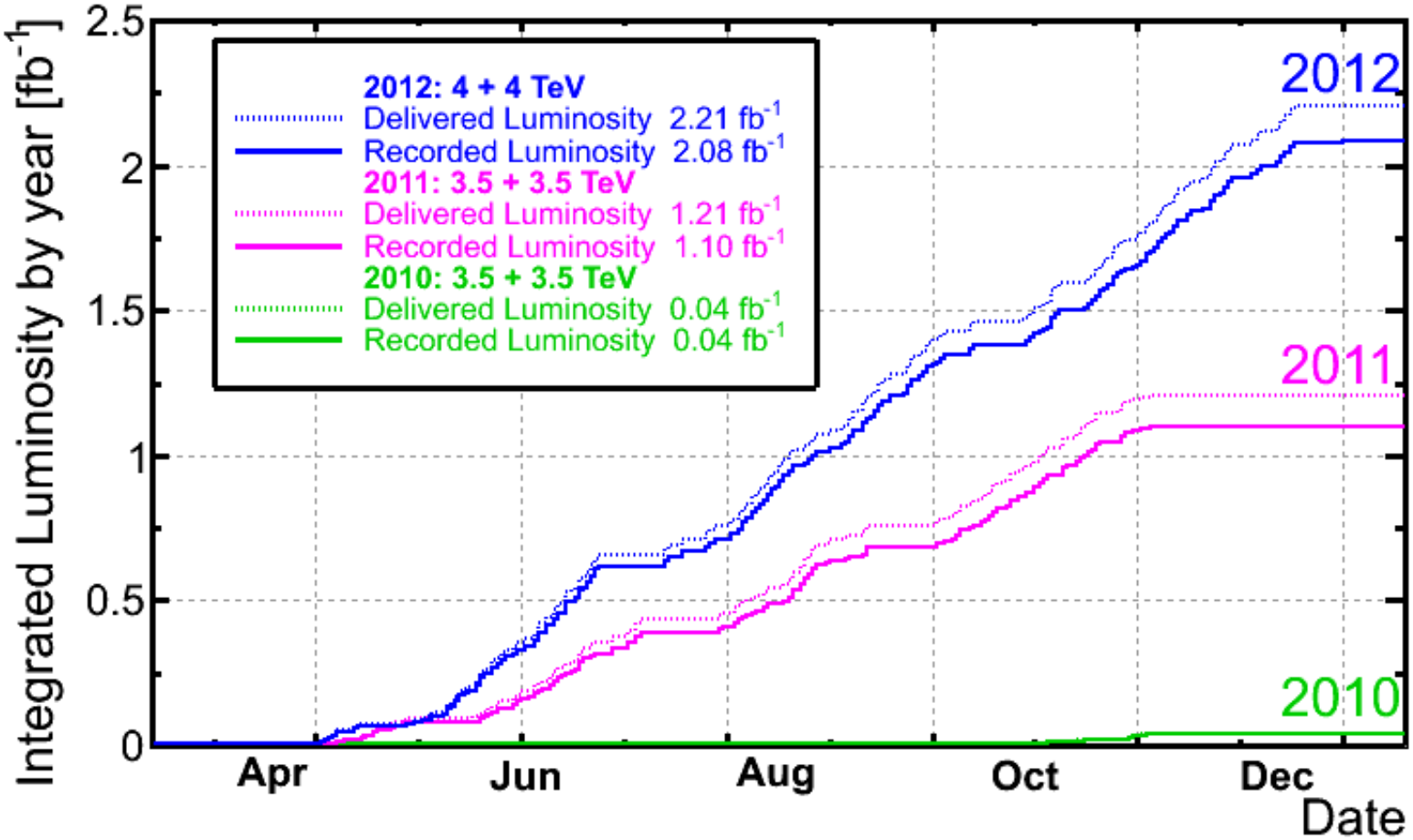
4. The analysis work well advanced and **final results are expected soon.**

Thank you for your attention!

...questions

Backup slides

LHCb Recorded Luminosity



Angular analysis: acceptance effects

- Selection requeriments or the detector geometry may affect the angular distributions → this acceptance depends on all the kinematic variables → **unknown**
- **However** the acceptance does **not depend on the physical parameters** appearing in the model → the **normalisation weights** technique takes advantage of this situation:

$$\sum_{j=1}^{n} \frac{\partial}{\partial \lambda_j} ln\mathcal{L} = \sum_{j=1}^{n} \frac{\partial}{\partial \lambda_j} \sum_e ln \frac{\mathcal{P}(X_e;\lambda_i)\varepsilon(X_e)}{\int \mathcal{P}(X;\lambda_i)\varepsilon(X)d^5X} =$$

$$= \sum_{j=1}^{n} \frac{\partial}{\partial \lambda_j} \sum_e ln \frac{\mathcal{P}(X_e;\lambda_i)}{\int \mathcal{P}(X;\lambda_i)\varepsilon(X)d^5X} = 0$$

- ◇ Only the integrated acceptance is needed in the fit ∼ counting events in a fully Monte Carlo generated sample.
- ◇ However, visualisation requires integration in only 4 variables: the acceptance is assumed to factorize as:

$$\varepsilon(X) \sim \varepsilon_1(\theta_1) \cdot \varepsilon_2(\theta_2) \cdot \varepsilon_3(\phi) \cdot \varepsilon_4(m_1) \cdot \varepsilon_5(m_2).$$

Angular analysis: normalisation weights

The normalisation weights are defined such that:

$$\int \Phi_4 \sum_{i,j=1}^{12} (A_i \cdot g_i \cdot M_i)(A_j \cdot g_j \cdot M_j)^* \varepsilon(X) d^5X = \sum_{i,j=1}^{12} A_i A_j^* w_{ij}$$

However: $\sum_{i,j=1}^{12} \to$ 78 complex numbers$\to$ 156 real parameters $\equiv$ 156 integrals (approximated by sums) performed with the events in the MC sample $\to$ with current MC, very poor statistics
First approach: use the factorised acceptance (visualisation) also for fitting: $\sim$ neglect correlations between variables.

Angular analysis: simultaneous fit parametrisation

Account for direct $\mathcal{CP}$ violation: parametrisation in terms of **mean** values and their **asymmetry** $B/\bar{B}$:

$$|A^i_{mean}|^2 = \frac{1}{2}(|A^i_B|^2 + |A^i_{\bar{B}}|^2), \qquad |A^i_{asym}|^2 = \frac{|A^i_B|^2 - |A^i_{\bar{B}}|^2}{|A^i_B|^2 + |A^i_{\bar{B}}|^2}$$

$$\delta^i_{mean} = \frac{1}{2}(\delta^i_B + \delta^i_{\bar{B}}), \qquad \delta^i_{cp} = \frac{1}{2}(\delta^i_B - \delta^i_{\bar{B}})$$

Thus:

$$|A^i_{B(\bar{B})}|^2 = |A^i_{mean}|^2 \cdot (1 + (-)|A^i_{asym}|^2), \qquad \delta^i_{B(\bar{B})} = \delta^i_{mean} + (-)\delta^i_{cp}.$$

Since the amplitudes always appear in terms like $A_i A^*_j$ only their **phase difference** can be measured $\to \delta^{0(\rho K^*)}_{mean} = 0$ is the **reference phase**. Thus, the fit is insentitive to $\delta^{0(\rho K^*)}_{cp}$, and this phase needs to be fixed too.

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It is convenient to reparametrize the $B \to \omega K^*$ decay amplitudes such that:

$$\omega_{frac} = \frac{|A^0_{\omega K^*}|^2 + |A^{||}_{\omega K^*}|^2 + |A^{\perp}_{\omega K^*}|^2}{|A^0_{\rho K^*}|^2 + |A^{||}_{\rho K^*}|^2 + |A^{\perp}_{\rho K^*}|^2} \xrightarrow[norm]{} |A^0_{\omega K^*}|^2 + |A^{||}_{\omega K^*}|^2 + |A^{\perp}_{\omega K^*}|^2$$

Thus:

$$f^{\lambda}_{\omega} = \frac{|A^{\lambda}_{\omega K^*}|^2}{|A^0_{\omega K^*}|^2 + |A^{||}_{\omega K^*}|^2 + |A^{\perp}_{\omega K^*}|^2} = \frac{|A^{\lambda}_{\omega K^*}|^2}{\omega_{frac}}$$

Being:

$$|A^{\lambda}_{\omega}|^2 = f^{\lambda}_{\omega} \cdot \omega_{frac}$$