Imperial College London

Determination of hadronic resonance contributions to the $B^0 \to K^{*0}\mu^+\mu^-$ transition

Malte Hecker, on behalf of the LHCb collaboration

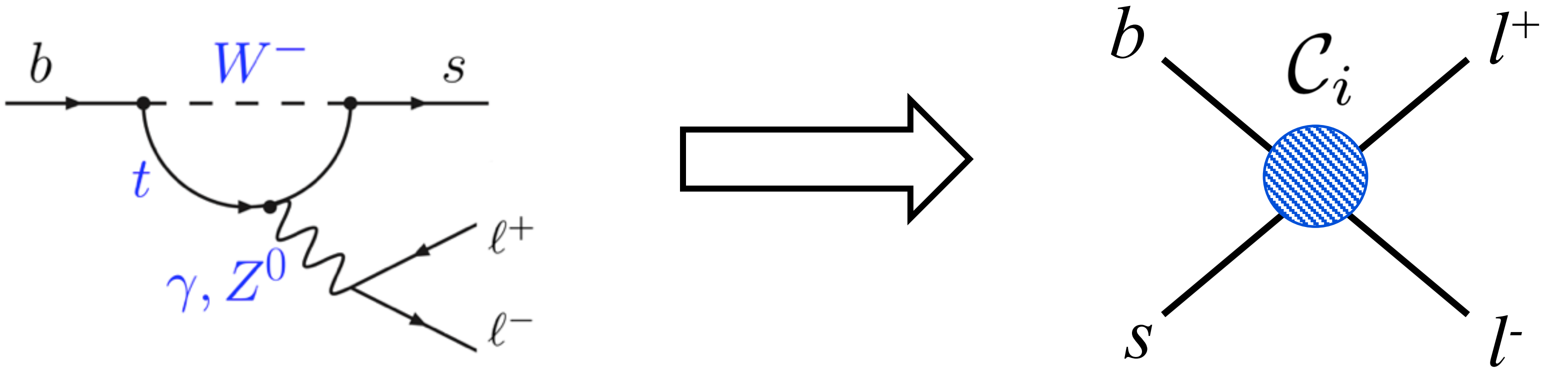
IoP joint HEPP and APP Annual Conference 2019
9th of April 2019

Effective field theory

- b->sll processes can be described with effective Hamiltonian:

$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i$$

- Particles heavier than B-meson are absorbed into Wilson Coefficients

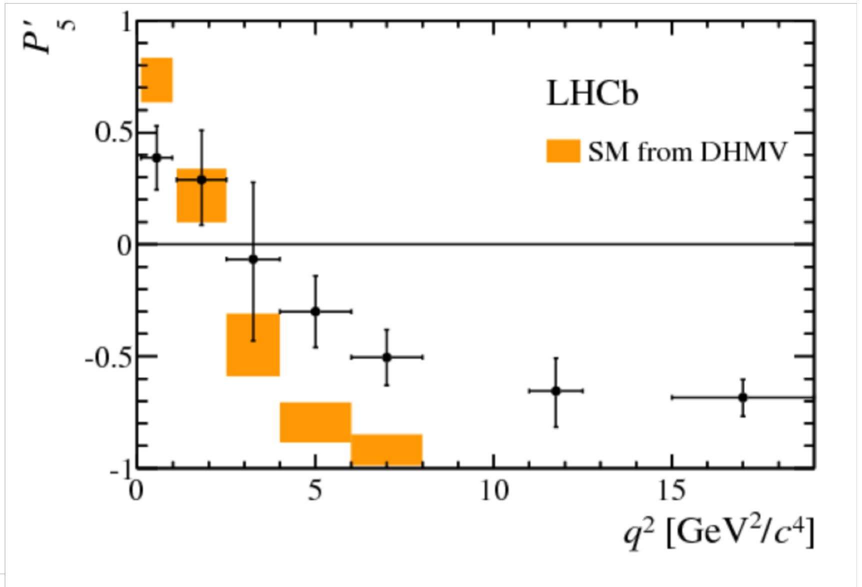


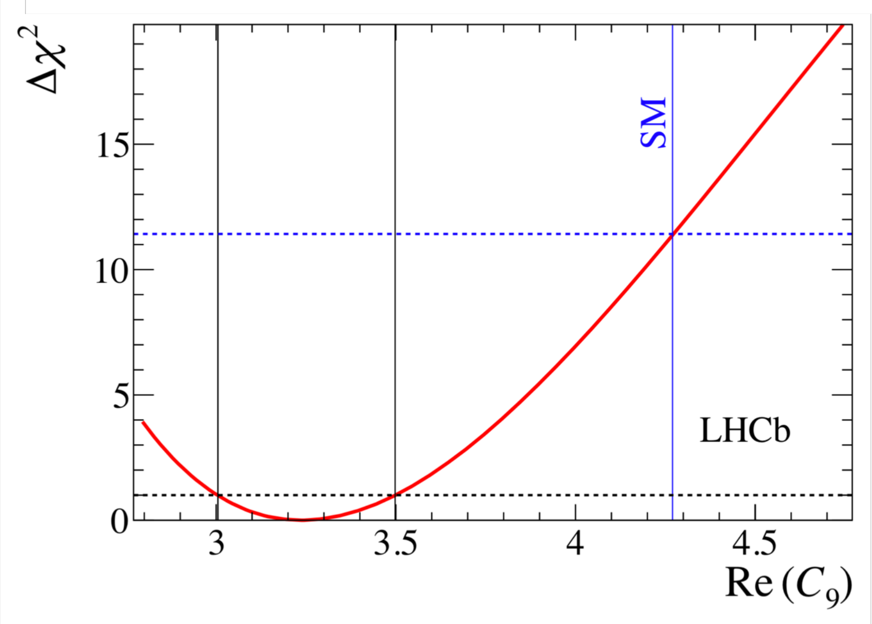
- $B^0 \rightarrow K^{*0}\mu^+\mu^-$ sensitive to:
  - C_7 – photon coupling
  - C_9 – vector coupling
  - C_{10} – axial vector coupling

- NP can modify the values of Wilson Coefficients: $\mathcal{C}_i^{\mathrm{NP}} = \mathcal{C}_i - \mathcal{C}_i^{\mathrm{SM}}$

Angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay

- Decay fully described by 3 helicity angles and squared inv. mass of muon pair (q^2)
- Angular distributions depend on Wilson coefficients → Can be influenced by NP
- Measurement of angular observables (e.g. P'_5) in bins of q^2 show deviation from SM at level of 3.4 standard deviations
- *"These differences could be explained by an unexpectedly large hadronic effect that changes the SM predictions."*





LHCb collaboration, JHEP 1602 (2016) 104

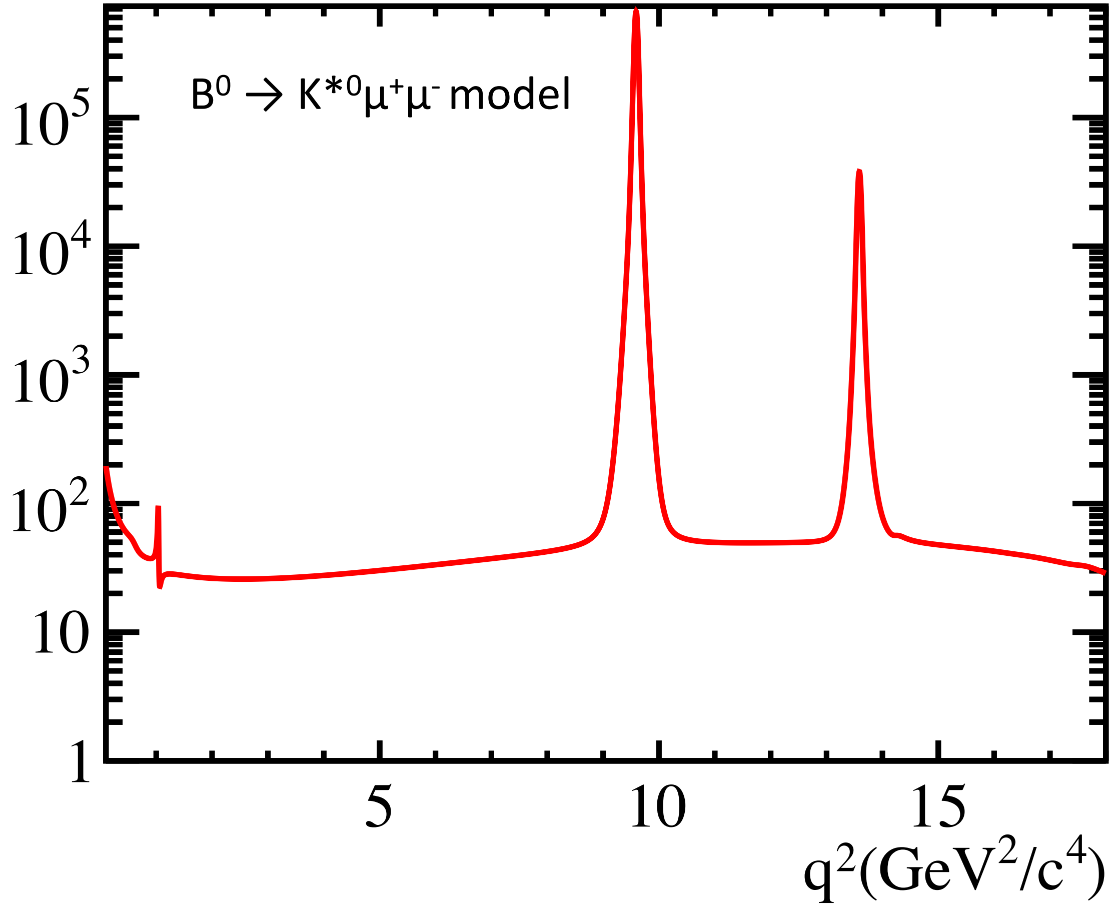
Hadronic contributions

- Several decays involving *vector resonances* (e.g. $B^0 \to J/\Psi(\to \mu^+\mu^-)K^{*0}$) give same final state as $B^0 \to K^{*0}\mu^+\mu^-$

- Interference of these $b \to sq\bar{q}(\to l^+l^-)$ processes with the $b \to sl^+l^-$ FCNC can mimic NP effect on C_9

- Ongoing discussion whether the amount of interference under good control in the SM calculations

➢ Perform measurement of the interference by fitting for both penguin and resonant amplitudes



The model

angular coefficients   angular terms

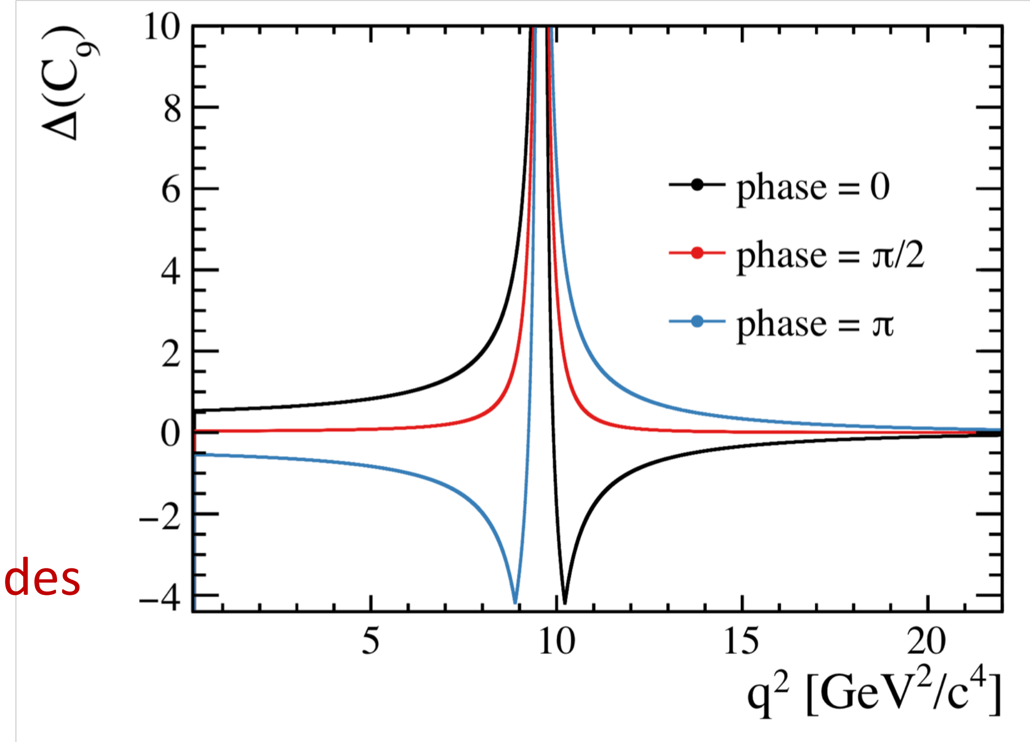
$$\frac{\mathrm{d}^4\Gamma[B^0 \to K^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_i \boxed{J_i(q^2)}\boxed{f_i(\cos\theta_l, \cos\theta_K, \phi)}$$

- $J_i(q^2)$ are bilinear combinations of decay amplitudes (depend on Wilson Coefficients and Form Factors)
- Fitting directly for amplitude parameters while including empirical model for resonance contributions:

$$\mathcal{C}_{9,\lambda}^{\mathrm{eff}}(q^2) = \mathcal{C}_9 + \sum_j \boxed{\|n_j\|\, e^{i\delta_j}}\boxed{\mathrm{BW}_j(q^2)}$$

BW Amplitudes

Magnitude and phase for each resonance relative to the penguin

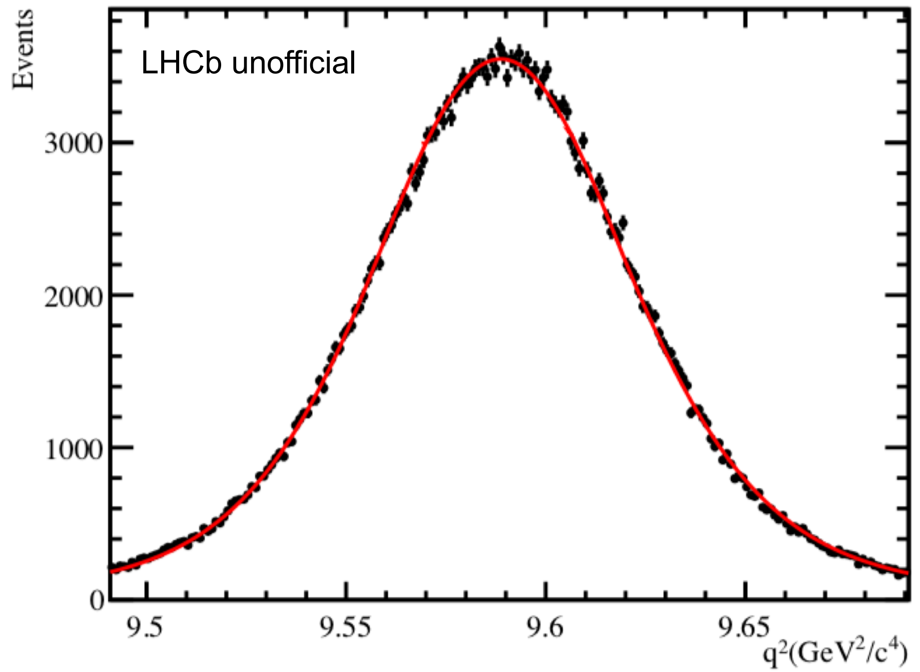


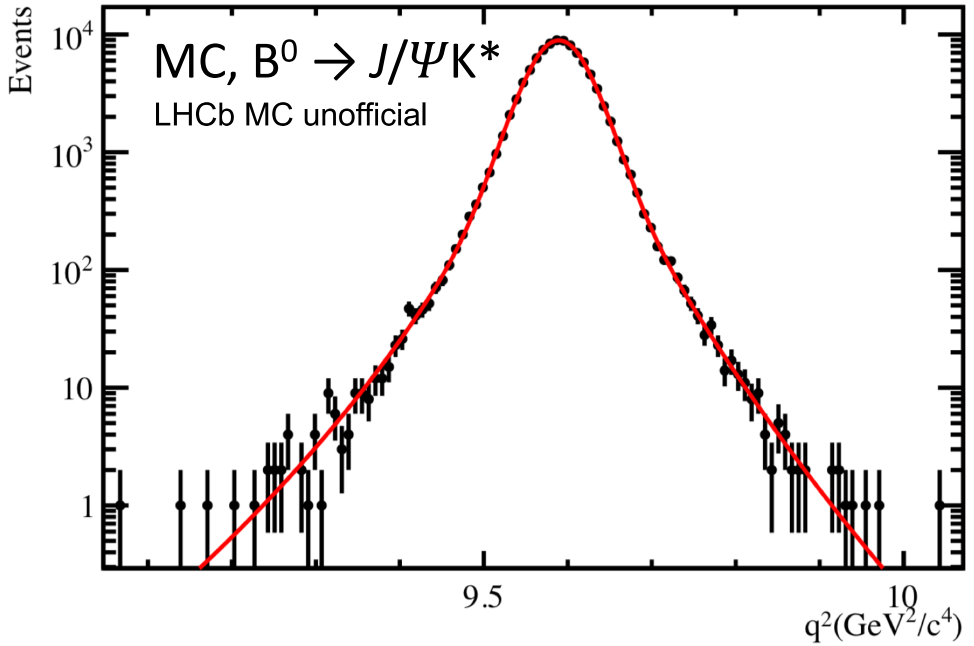
- Resonances included in our analysis: J/Ψ, $\Psi(2S)$, $\rho(770)$, $\varphi(1020)$, $\Psi(3770)$, $\Psi(4040)$ and $\Psi(4160)$

Resolution in q^2

- Using kinematic fit with B^0 mass constraint to improve resolution of final state particles
- For J/Ψ, $\Psi(2S)$, $\varphi(1020)$ observed peaks much wider than internal width of the resonances
- Convolve signal model with resolution model (double sided crystal ball plus Gaussian) to fit data
- Resolution parameters determined in data
- Resolution model verified in MC

Data, $B^0 \to K^*\mu^+\mu^-$, J/Ψ core region





Background Fit Strategy

GOAL

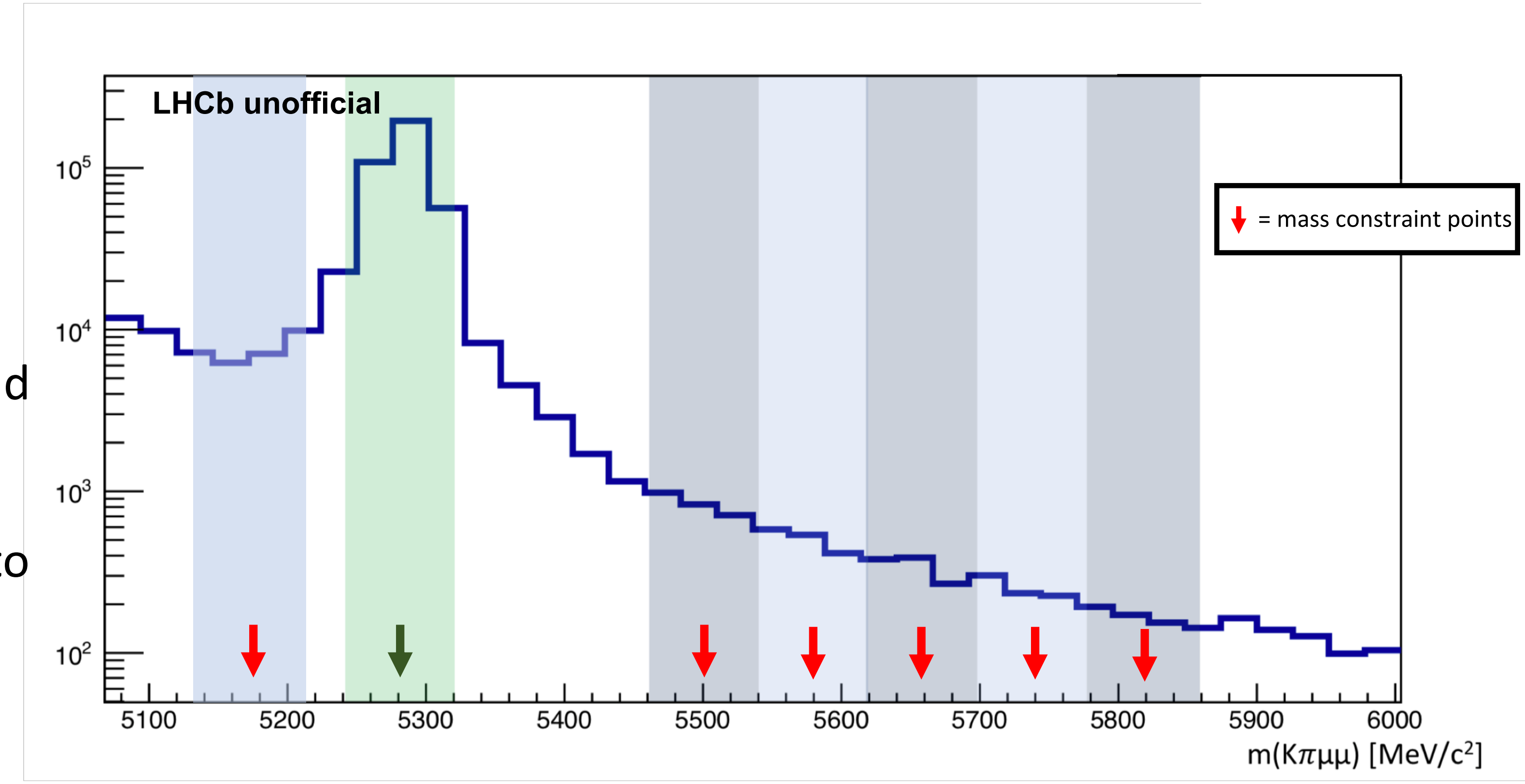
Determine a parameterization of the background in the **signal region.**

PROBLEM

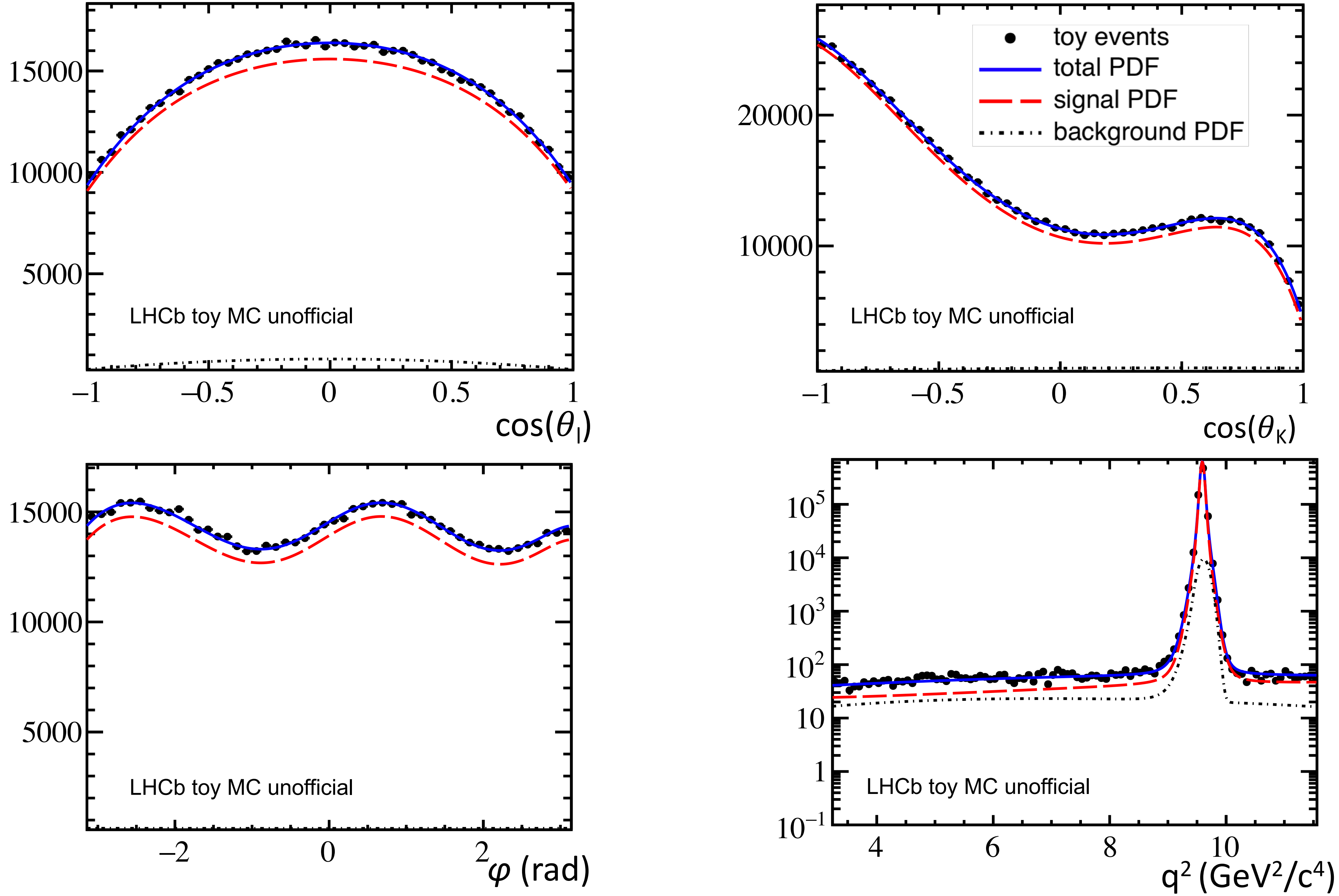
B^0 mass constraint distorts the distributions of the background and introduces a **dependence of the background shape on the width of the B^0 window**

SOLUTION

- Split up sideband into several regions
- Mass constrain events to the centre of respective region.
- Perform simultaneous fit to all sideband regions
- Interpolate background parameters into signal region – allowing for linear mass dependence of all parameters



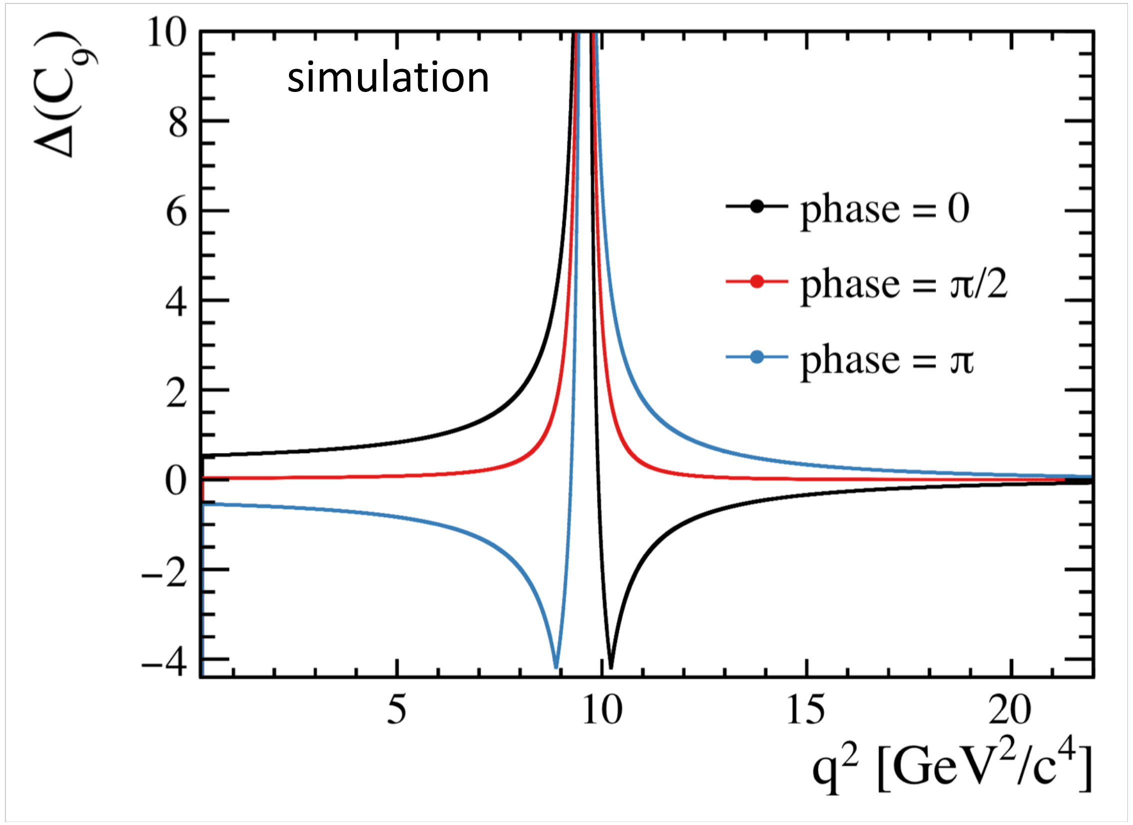
Projections of Toy Fits - Signal + Background: J/Ψ region



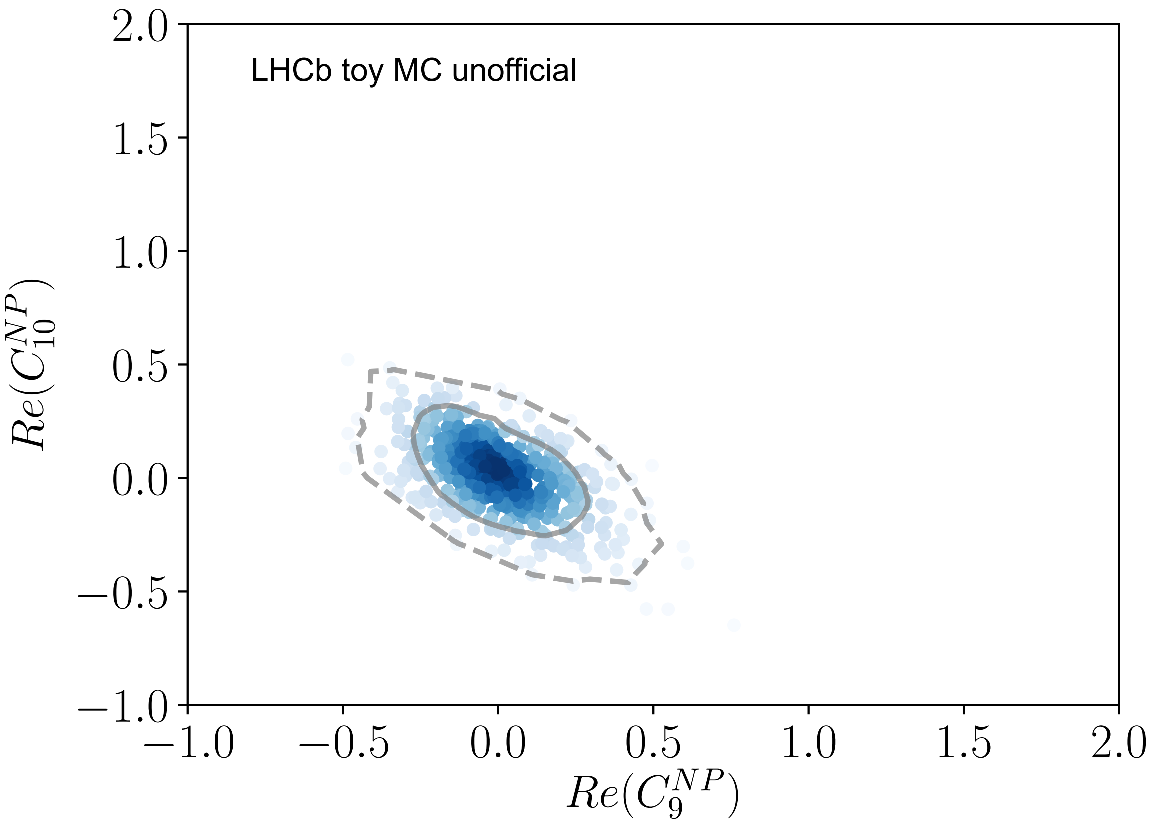
Sensitivity to phases and Wilson Coefficients

Require ~0.1 rad precision on the phases

to ascertain role from non-local effects



Expected Sensitivity



- Not yet including background effects
- Form Factors floated within existing constraints
- Statistical precision with run1+run2:
  - ~ 5% for Wilson Coefficients
  - ~ 0.01 rad for the phases

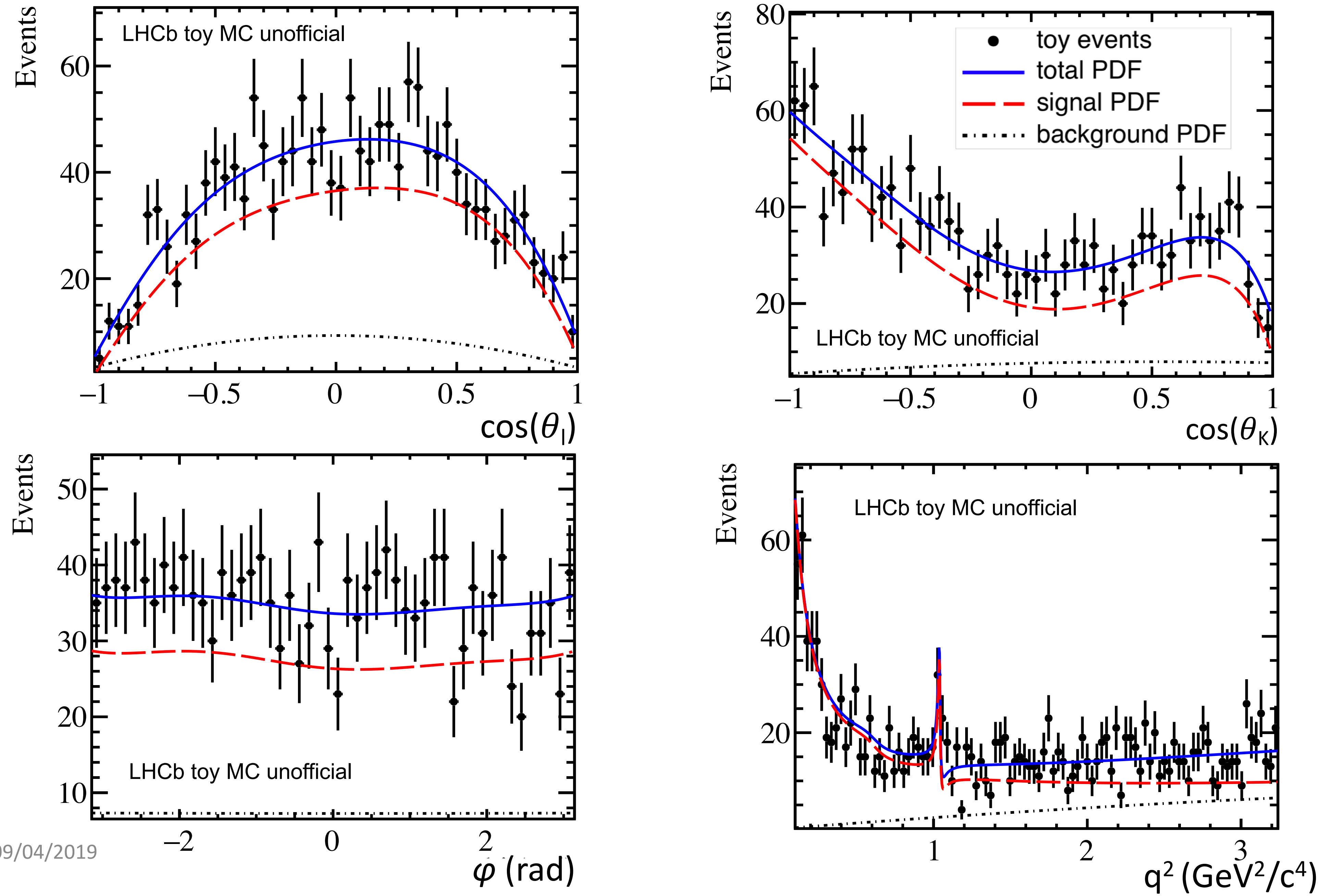
- High sensitivity to Wilson Coefficients due to use of full q^2 spectrum and unbinned fit
- Sensitivity to phases far better than required to ascertain role of non-local effects

Conclusion

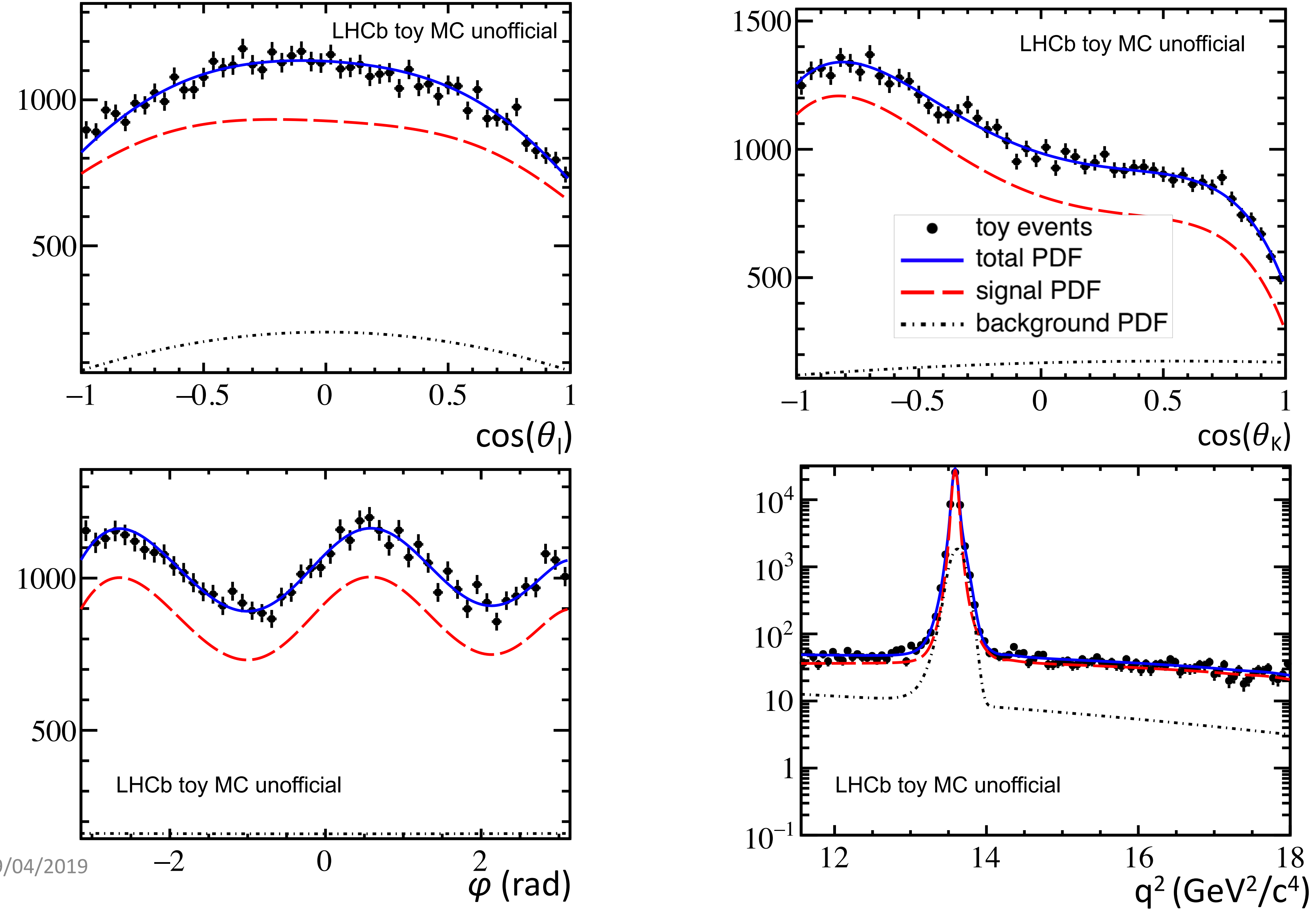
- Crucial to understand hadronic effects in $B^0 \to K^{*0}\mu^+\mu^-$ to interpret the observed discrepancies with the Standard Model
- Empirical model to determine Wilson Coefficients and the level of hadronic interference in unbinned fit to full q^2 spectrum of $B^0 \to K^{*0}\mu^+\mu^-$
- Kinematic fit with B^0 mass constraint to improve the crucial q^2 resolution. This has implications for background fit
- Very promising sensitivity to C_9, C_{10} and the phases

Backup

Projections of Toy Fits - Signal + Background: **φ region**



Projections of Toy Fits - Signal + Background: $\Psi(2S)$ region



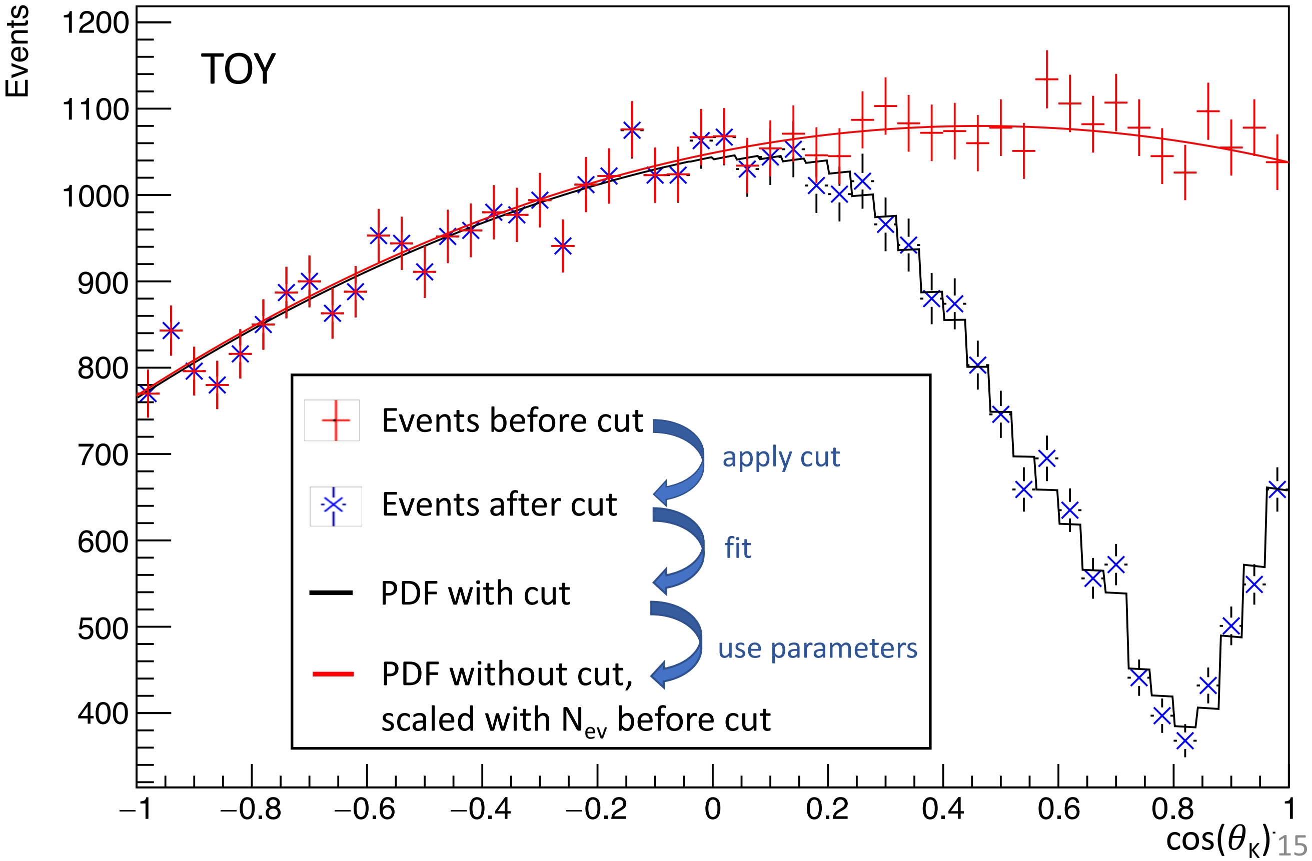
The effect of the Kμμ veto

- To reject background events from $B^+ \to K^+\mu\mu$ (plus random π^-) in our $K^+\pi^-\mu\mu$-sample we use a veto:

  Remove all events with: **(5220 < m(Kμμ) < 5340) MeV/c2** and m(Kπμμ) > 5380 MeV/c

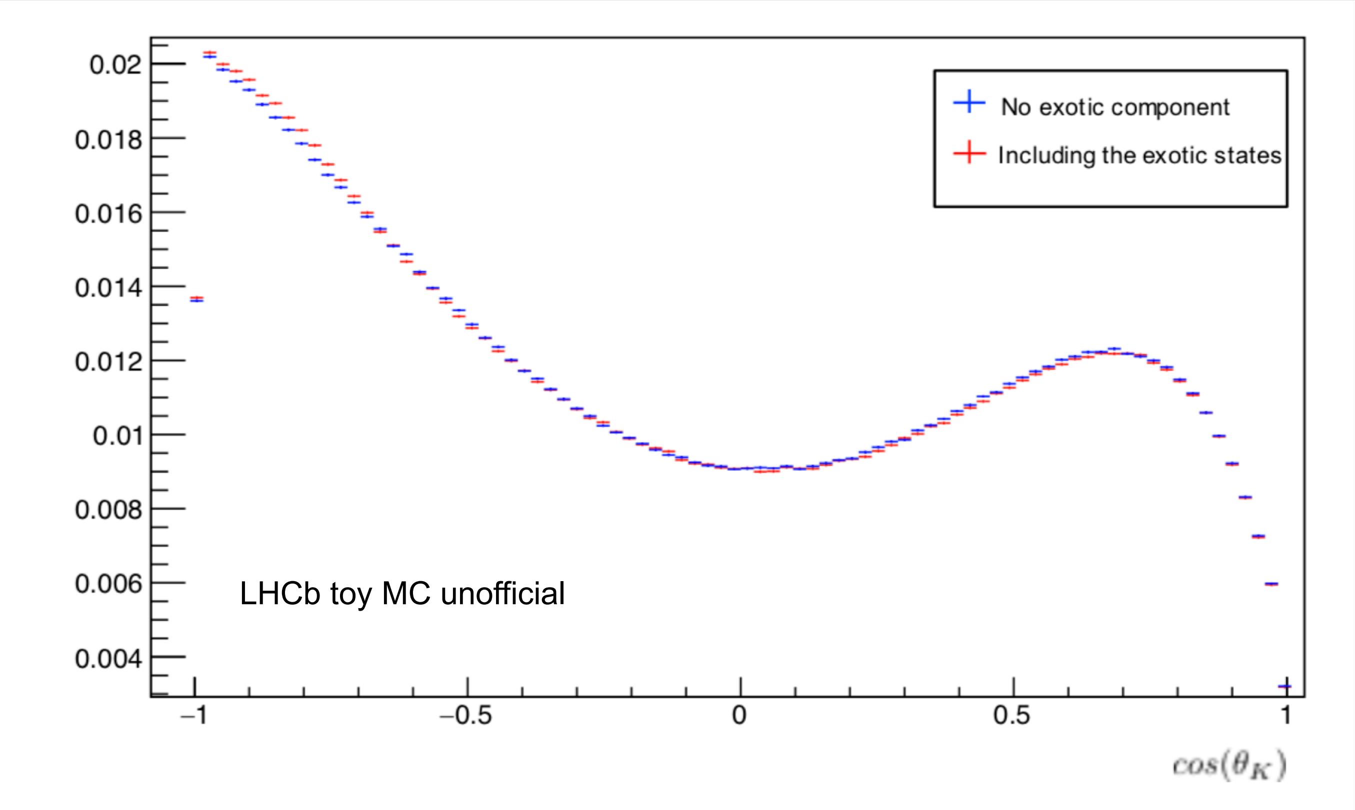
- This causes a gap in the the $\cos(\theta_K)$, q^2, and m(Kπμμ) phase space which can cause biases in the sideband fit

- By adjusting the normalisation of the PDF we can recover the correct background parameters



Z(4430) and Z(4200)

- Charmonium-like states with a quark content of $|c\bar{c}ud\rangle$
- Decaying to Ψ(2S)π or J/Ψπ



The model (Blake et al., Eur.Phys.J. C78 (2018) no.6 453)

The differential decay rate of $B^0 \rightarrow K^{*0}\mu^+\mu^-$ transitions depends on 6 complex amplitudes $A_{\parallel}^{L,R}$, $A_{\perp}^{L,R}$, $A_{0}^{L,R}$

$$\mathcal{A}_0^{\mathrm{L,R}}(q^2) = -8N\frac{m_B m_{K^*}}{\sqrt{q^2}}\left\{(C_9 \mp C_{10})A_{12}(q^2) + \frac{m_b}{m_B + m_{K^*}}C_7 T_{23}(q^2) + \mathcal{G}_0(q^2)\right\}$$

$$\mathcal{A}_\parallel^{\mathrm{L,R}}(q^2) = -N\sqrt{2}(m_B^2 - m_{K^*}^2)\left\{(C_9 \mp C_{10})\frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2}C_7 T_2(q^2) + \mathcal{G}_\parallel(q^2)\right\}$$

$$\mathcal{A}_\perp^{\mathrm{L,R}}(q^2) = N\sqrt{2\lambda}\left\{(C_9 \mp C_{10})\frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}C_7 T_1(q^2) + \mathcal{G}_\perp(q^2)\right\},$$

Wilson Coefficients | Form Factors | Non-local hadronic contributions

Form Factors modelled with parameters obtained from combination of Light Cone Sum Rules and Lattice QCD

$$F^i(q^2) = \frac{1}{1 - q^2/m_{R_i}^2}\sum_{k=0}^{2}\alpha_k^i[z(q^2) - z(0)]^k$$

Straub et al, JHEP08 (2016) 098

Modelling non-local hadronic contributions

$$\mathcal{G}_0 = \frac{m_b}{m_B + m_{K^*}} T_{23}(q^2) \zeta^0 e^{i\omega^0} + A_{12}(q^2) \sum_j \eta_j^0 e^{i\theta_j^0} A_j^{\text{res}}(q^2),$$

$$\mathcal{G}_{\parallel} = \frac{2m_b}{q^2} T_2(q^2) \zeta^{\parallel} e^{i\omega^{\parallel}} + \frac{A_1(q^2)}{m_B - m_{K^*}} \sum_j \eta_j^{\parallel} e^{i\theta_j^{\parallel}} A_j^{\text{res}}(q^2),$$

$$\mathcal{G}_{\perp} = \frac{2m_b}{q^2} T_1(q^2) \zeta^{\perp} e^{i\omega^{\perp}} + \frac{V(q^2)}{m_B + m_{K^*}} \sum_j \eta_j^{\perp} e^{i\theta_j^{\perp}} A_j^{\text{res}}(q^2),$$

Magnitude and phase of non-local contribution to dipole form factor

Sum over all resonances

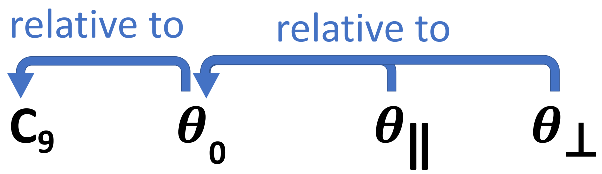
Magnitude and phase for each resonance

BW Amplitudes

- Resonances included in our analysis: J/Ψ, $\Psi(2S)$, $\rho(770)$, $\varphi(1020)$, $\Psi(3770)$, $\Psi(4040)$ and $\Psi(4160)$

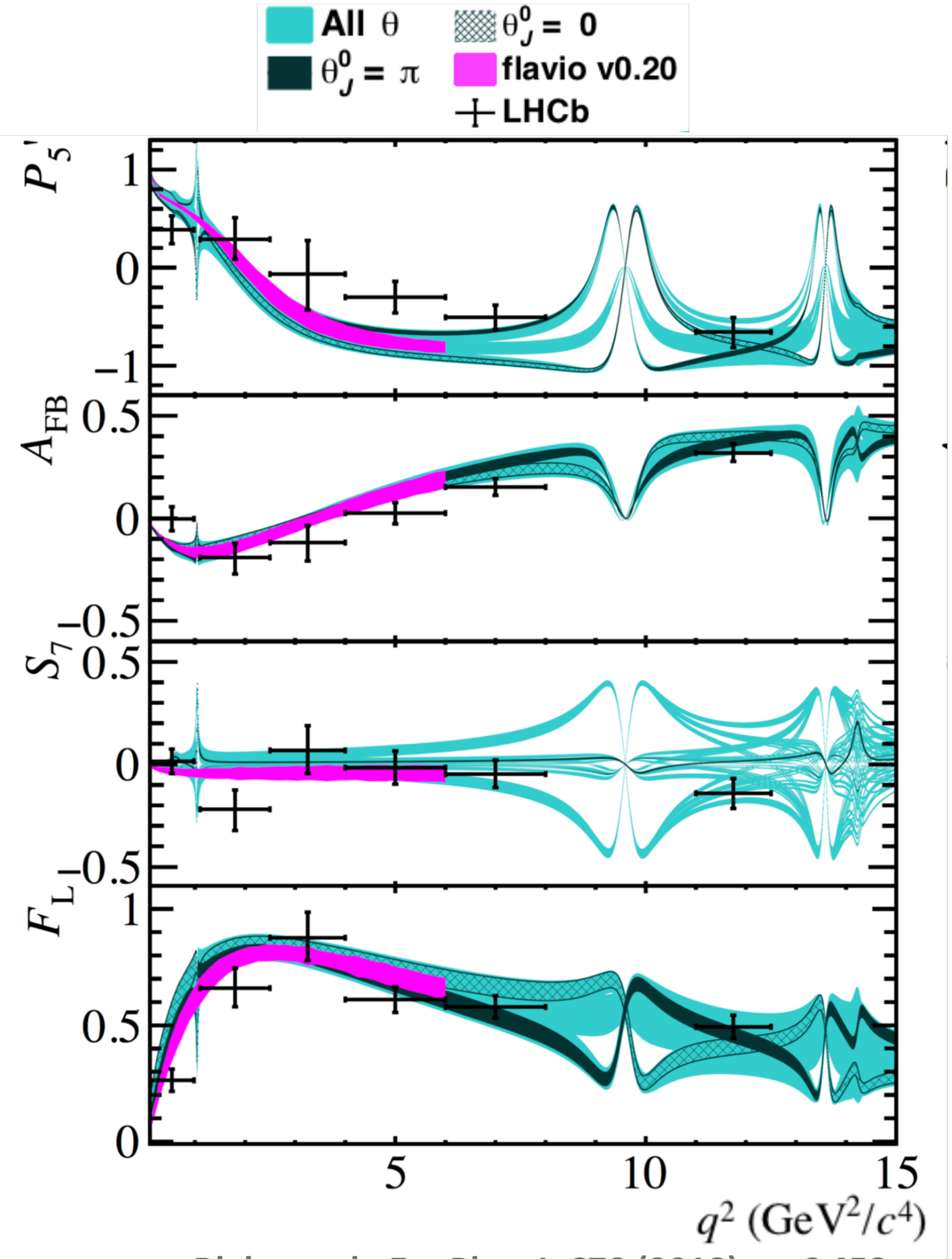
- BF of $B^0 \rightarrow K^{*0}\mu^+\mu^-$ is implicitly included in the model through the magnitudes of the resonances which are measured relative to the penguin

Comparison to other models



Three phases for every resonance: C_9 θ_0 $\theta_{\parallel}$ $\theta_{\perp}$

- Amplitude analyses of $B \to VK^*$ (for J/Ψ, $\Psi(2S)$, $\varphi(1020)$, $\rho(770)$) decays from LHCb, Belle and BaBar constrain sizes of the magnitudes $\eta_{0,\parallel,\perp}$ and the relative phases $\theta_{\parallel,\perp}$
- **The phase θ_0 (relative to the penguin) of each resonance is completely unknown**
- Fixing the relative phases and varying the unknown phases θ_0, can predict angular observables and compare to data and other models
- In the fit to data also include contribution from S-wave amplitudes for both short-distance and non-local components



Blake et al., Eur.Phys.J. C78 (2018) no.6 453