Towards establishing NP in the amplitude analysis of $B^0 \to K^{*0} \ell^+ \ell^-$

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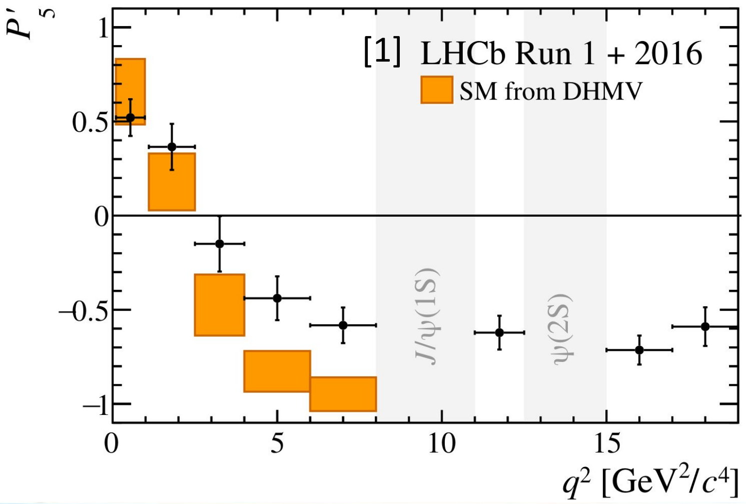
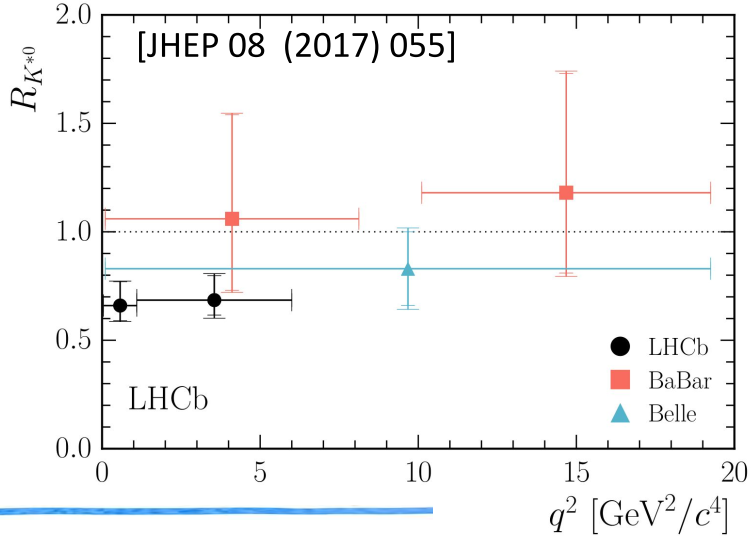
Anomalies in rare B decays

- Recent measurements confirmed some of the anomalies already observed in $B^0 \to K^{0*}\ell\ell$ and $B^+ \to K^+\ell\ell$ decays
- FCNC can only occur at loop-level, therefore could be sensitive to NP at higher energy scales





[1] https://doi.org/10.1103/PhysRevLett.125.011802

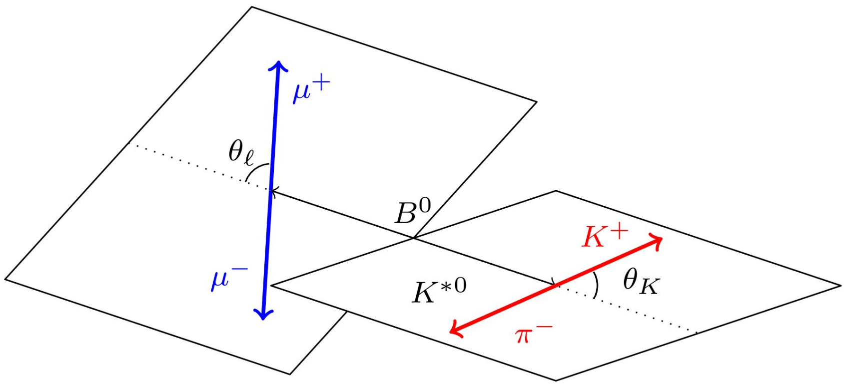
The $B^0 \to K^{*0}\ell^+\ell^-$ amplitude

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

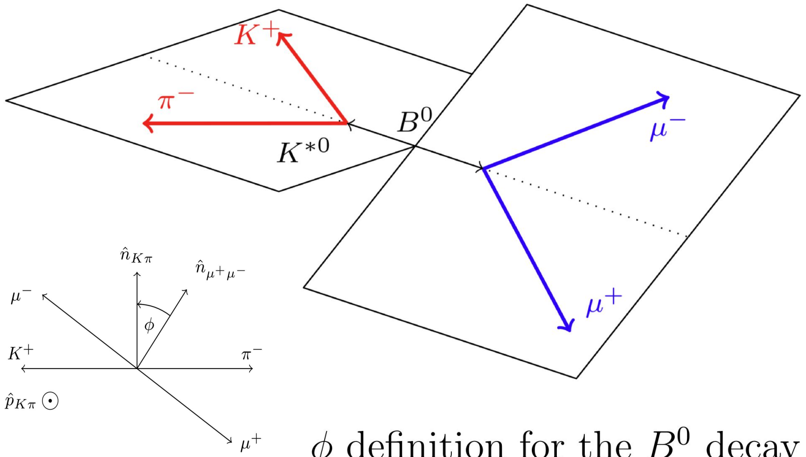
WC, *short distance* physics

local operators, *long distance* physics

$$\frac{8\pi}{3}\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_K\, d\phi} = (J_{1c} + J_{2c}\cos 2\theta_l + J_{6c}\cos\theta_l)\cos^2\theta_K$$
$$+ (J_{1s} + J_{2s}\cos 2\theta_l + J_{6s}\cos\theta_l)\sin^2\theta_K$$
$$+ (J_3\cos 2\phi + J_9\sin 2\phi)\sin^2\theta_K\sin^2\theta_l$$
$$+ (J_4\cos\phi + J_8\sin\phi)\sin 2\theta_K\sin 2\theta_l$$
$$+ (J_5\cos\phi + J_7\sin\phi)\sin 2\theta_K\sin\theta_l$$



θ_K and θ_ℓ definitions for the B^0 decay



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$$\mathcal{A}_\lambda^{(\ell)L,R} = \mathcal{N}_\lambda^{(\ell)}\left\{(C_9^{(\ell)} \mp C_{10}^{(\ell)})\mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2}\left[C_7^{(\ell)}\mathcal{F}_\lambda^T(q^2) - 16\pi^2\frac{M_B}{m_b}\mathcal{H}_\lambda(q^2)\right]\right\}$$

Normalization factor

Form factor (LFU)

Non-local hadronic matrix element (LFU)

The $B^0 \to K^{*0}\ell^+\ell^-$ amplitude

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WC, *short distance* physics

local operators, *long distance* physics

The measured Wilson's coefficients can be shifted from SM due to:

1. **NP contributions**
2. **NLH matrix element pollution**

$$C_i \to \tilde{C}_i = C_i^{SM} + C_i^{(\ell)NP} + C_i^{\mathcal{H}}$$

$$\mathcal{A}_\lambda^{(\ell)L,R} = \mathcal{N}_\lambda^{(\ell)} \left\{ (C_9^{(\ell)} \mp C_{10}^{(\ell)}) \mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2} \left[C_7^{(\ell)} \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

Normalization factor

Form factor (LFU)

Non-local hadronic matrix element (LFU)

Isolating NP through LFU

$$C_i \to \tilde{C}_i = C_i^{SM} + C_i^{(\ell)NP} + C_i^{\mathcal{H}}$$

Need to break the degeneracy to access NP

Retrive the "clean" NP contributions in the Wilson coefficients measuring the LFU test:

$$\boxed{\Delta C_i = \widetilde{C}_i^{(\mu)} - \widetilde{C}_i^{(e)} = C_i^{(\mu)NP} - C_i^{(e)NP}}$$

Isolating NP through LFU

Need to bre
degeneracy

Retrive the
coefficients

Our analysis aims to:

- provide a direct fit to the ΔC_i by including BR and angular information
- remove the NLH contribution by focussing on LFU quantities

$$\Delta C_i = \widetilde{C}_i^{(\mu)} - \widetilde{C}_i^{(e)} = C_i^{(\mu)NP} - C_i^{(e)NP}$$

Analysis strategy

Perform an **unbinned extended** ML fit to the decay channels $B^0 \to K^{*0}\mu^+\mu^-$ and $B^0 \to K^{*0}e^+e^-$.

- Extract $C_9, C_{10}, \Delta C_9, \Delta C_{10}$ from electrons and muons
- Amplitude and all the remaining parameters are treated as nuisance and shared between electrons and muons
- NLH matrix element parametrized as

$$\mathcal{H}_\lambda = \frac{1 - z z^*_{J/\psi}}{z - z_{J/\psi}} \cdot \frac{1 - z z^*_{\psi(2S)}}{z - z_{\psi(2S)}} \cdot \left[\sum_{k=0}^{K} \alpha_k^{(\lambda)} z^k\right] \mathcal{F}_\lambda$$

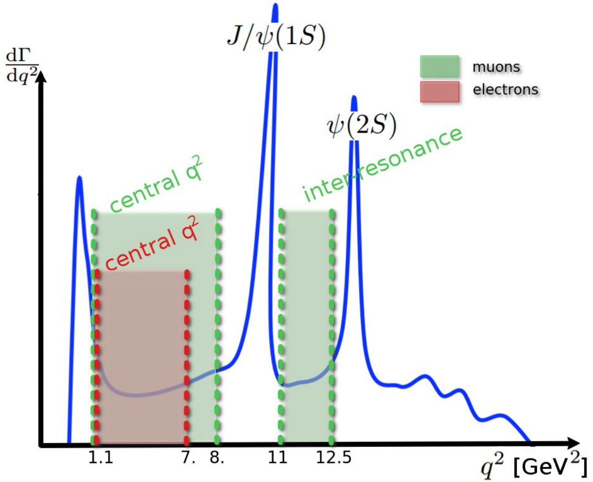
Analysis strategy

- **unbinned** in $\cos\theta_K, \cos\theta_L, \phi, q^2, m_B, m_{K\pi}$

observables in the amplitude

constrain background

constrain S-wave



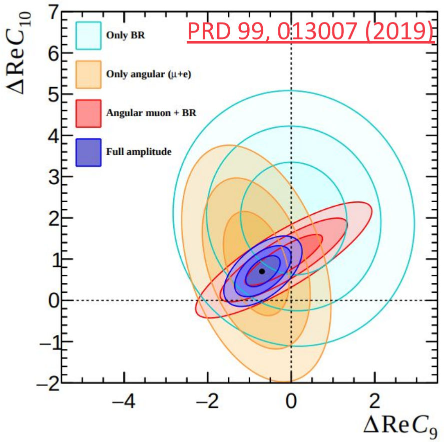
- **extended**

The observed yield adds an additional constraint

$$\lambda_{sig} \propto \frac{\tau_B}{\hbar} \int_{q^2 \in Q_i} \frac{d\Gamma}{dq^2} dq^2$$

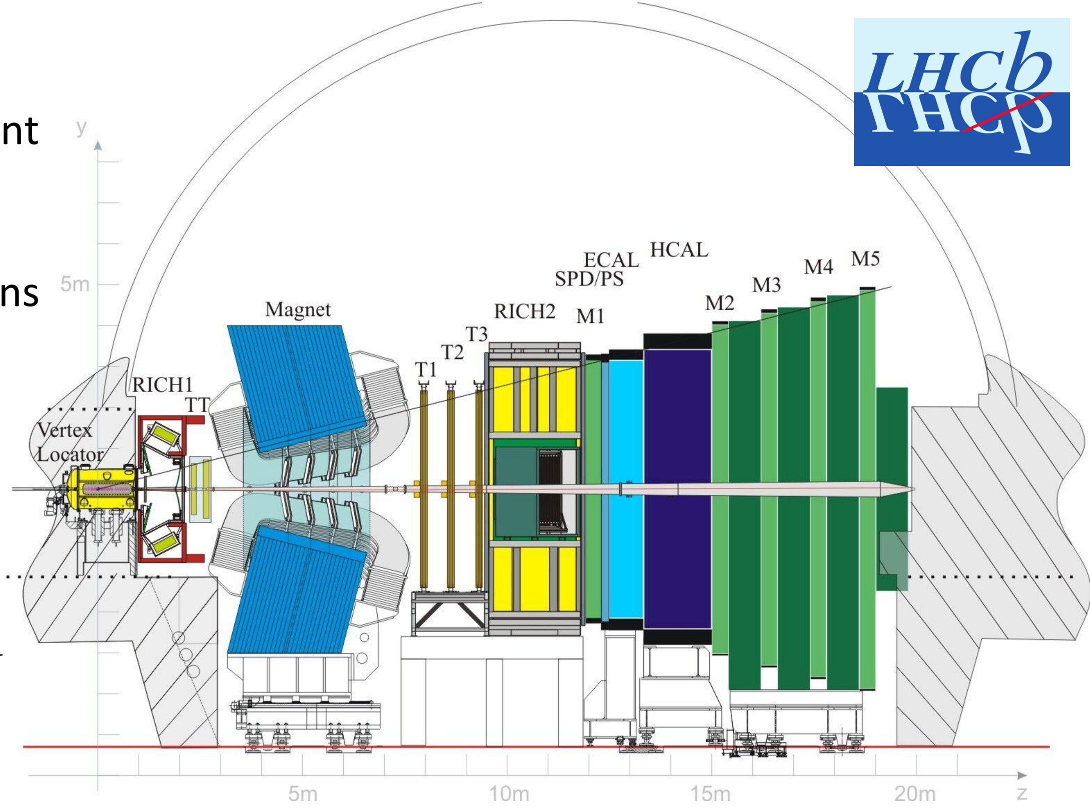
depends on Wilson coefficients

increases sensitivity!



Data samples

- Dataset collected at LHCb experiment @ CERN
- Forward single-arm spectrometer specialized in the physics of B mesons thanks to:
    - vertex resolution
    - tracking and momentum resolution
    - particle identification



- 3 fb^{-1} pp collisions at $\sqrt{s} = 7, 8$ TeV between 2011-12
- 2 fb^{-1} at $\sqrt{s} = 13$ TeV between 2015-16

Selection and main differences

Channels are selected similarly by requiring:

- four tracks in the final state of good quality coming from displaced vertex
- information from PID compatible with decay hypothesis
- mass from K and π within 100 MeV from K^{*0} mass

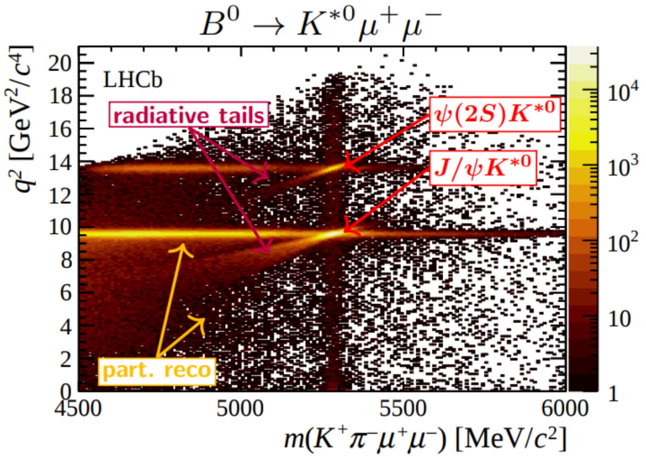
Two main differences:

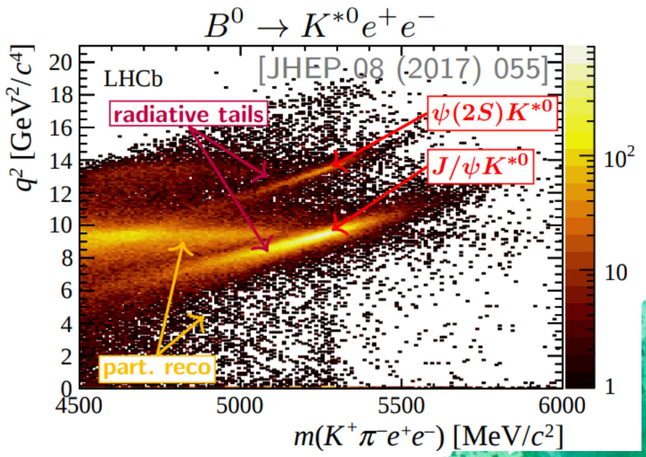
- Bremsstrahlung: electrons lose more energy than muons

  very different momentum resolution

- Trigger efficiency: muons are triggered more efficiently than electrons

  roughly x5 more muons than electrons

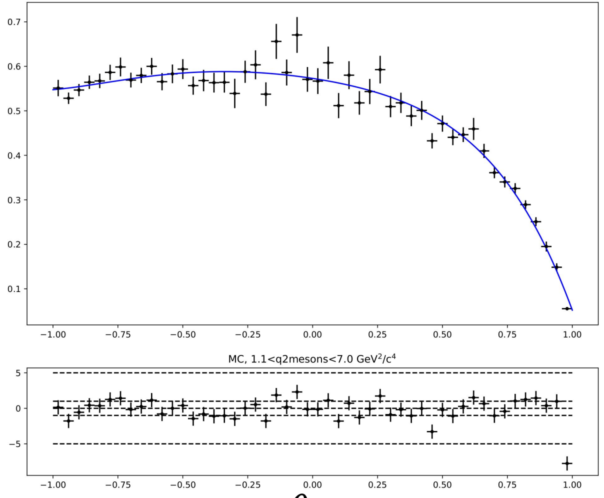




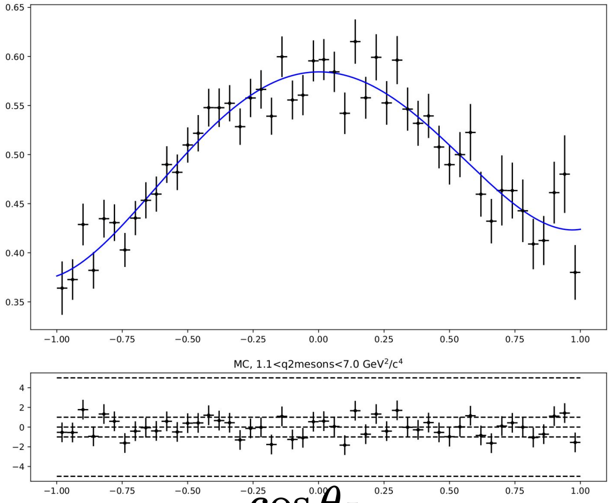
Describing the effect of the detector

The distortion introduced by the reconstruction and the selection of our dataset can be studied with the help of simulation.

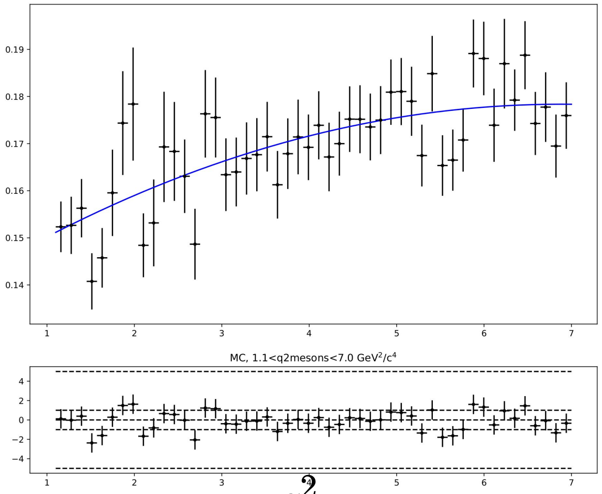
It can be described as a function of the variables of interest and used in the fit together with the signal pdf.



$\cos\theta_K$



$\cos\theta_L$



q^2

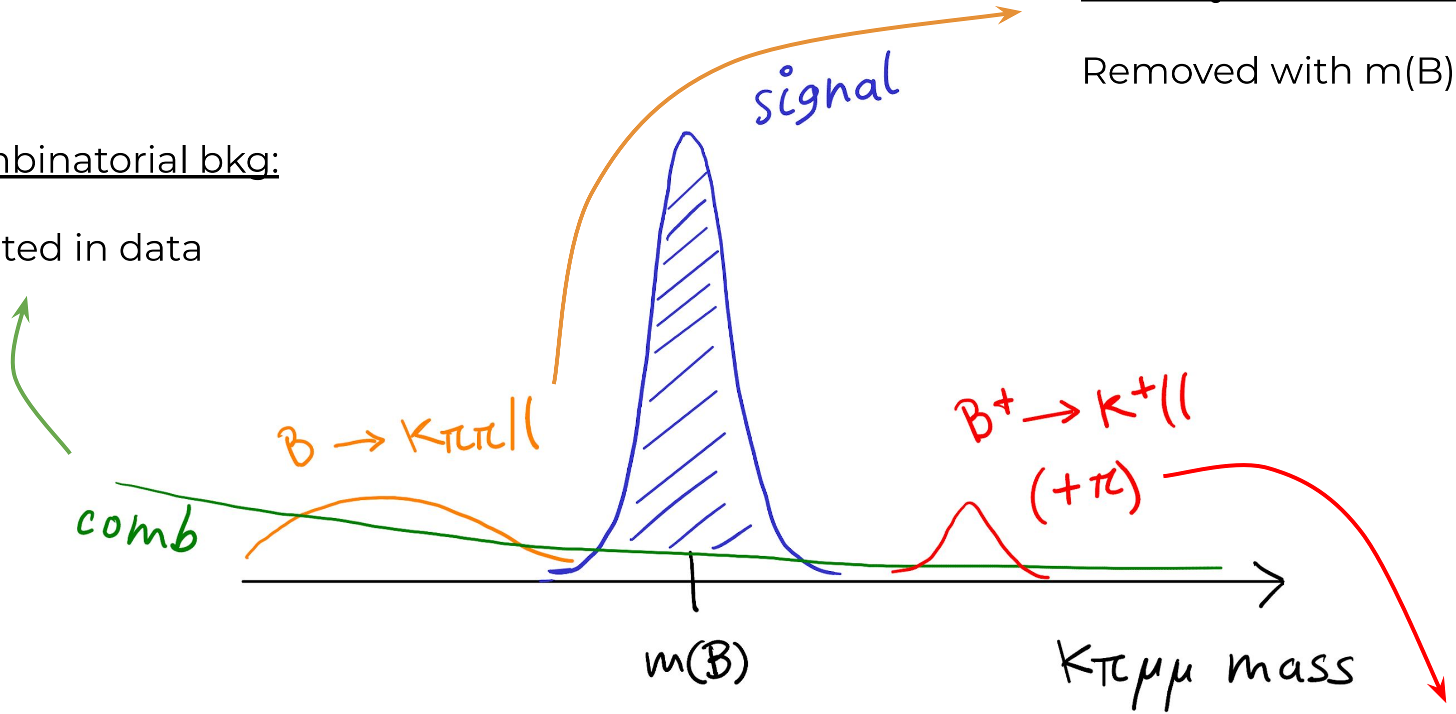
Backgrounds in $B^0 \to K^{*0}\mu^+\mu^-$

Partially reconstructed bkg:

Removed with m(B) cut

Combinatorial bkg:

Floated in data

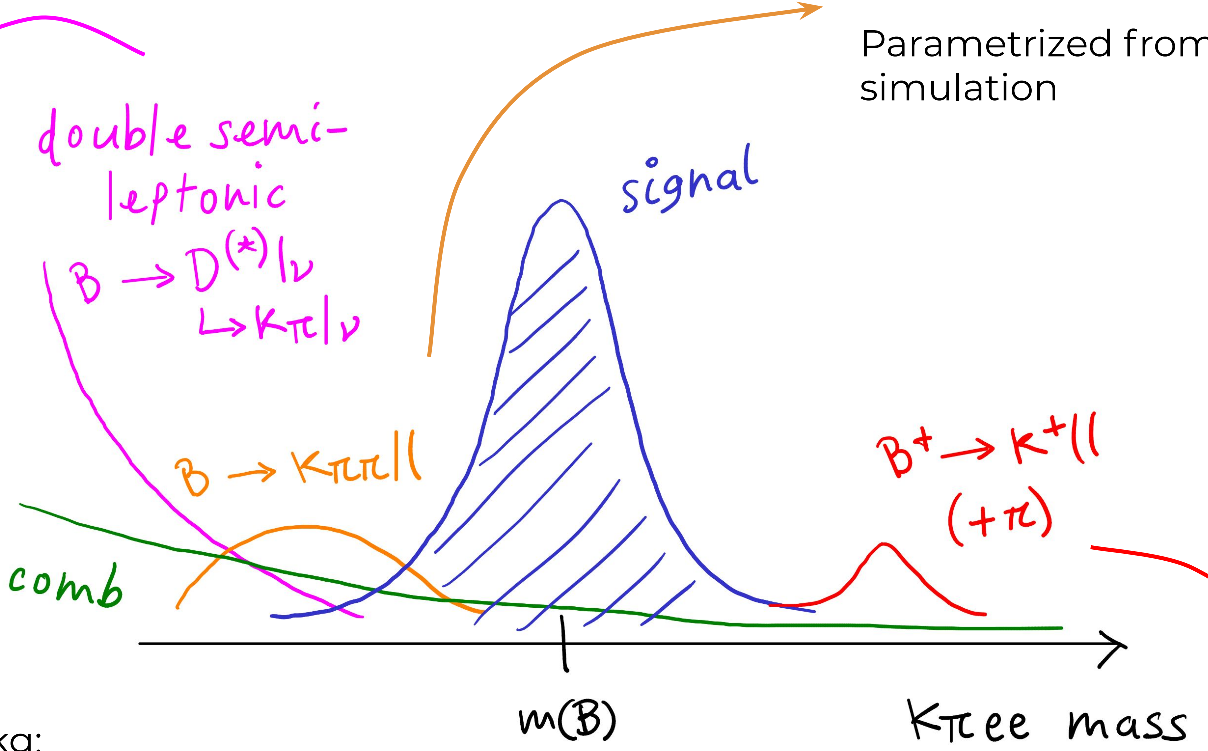


Removed with veto:

$$max(m_{K^+\ell\ell}, m_{(\pi^+\to K^+)\ell\ell}) < 5100 \text{ MeV/c}^2$$

Backgrounds in $B^0 \rightarrow K^{*0} e^+ e^-$

Parametrized from
control region
Simulation used
for systematics



Partially reconstructed bkg:

Parametrized from
simulation

Combinatorial bkg:

Floated in data

Removed with veto:

$max(m_{K^+\ell\ell}, m_{(\pi^+\rightarrow K^+)\ell\ell}) < 5100\ \mathrm{MeV/c}^2$

Toy studies - sensitivity

A simplified sensitivity study of the measurement has been performed with 200 toys:

- **Signal** for muons and electrons:
  - $C_9\,, C_{10}\,, \Delta C_9\,, \Delta C_{10}$
  - Form factors K*(892) and CKM parameters (gaussian constraint)
  - charm-loop parametrization
  - generated in $\Delta C_9 = -1.4$ scenario

- **Combinatorial** in electrons: slope of exponential, angular parameters and yield

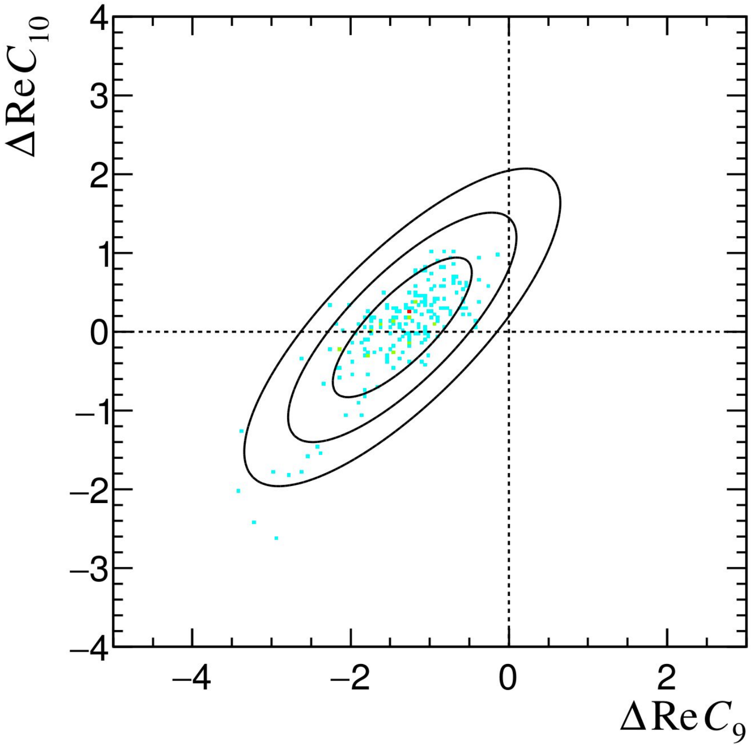
- **DSL background** in electrons: yield only

- **Partially reconstructed** background in electrons: yield only

The **statistic** considered is the one corresponding to **Run1+2015+2016** and **no S-wave** contribution in either muons or electrons has been considered here.

Toy studies - sensitivity for $\Delta C_9 = -1.4$

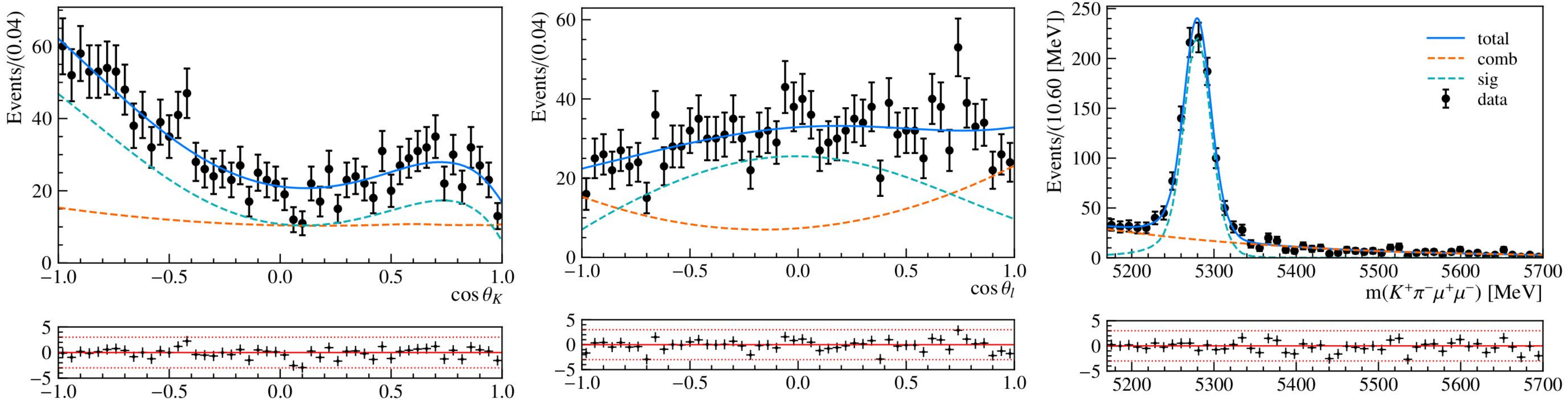
	ΔC_9	$\sigma_{\Delta C_9}$	ΔC_{10}	$\sigma_{\Delta C_{10}}$	ρ	σ_{LFU}
Full $\cos\theta_L$	-1.46 ± 0.04	0.62 ± 0.03	-0.17 ± 0.05	0.701 ± 0.035	0.84 ± 0.02	3.5



Fit to $B^0 \to K^{*0}\mu^+\mu^-$ data

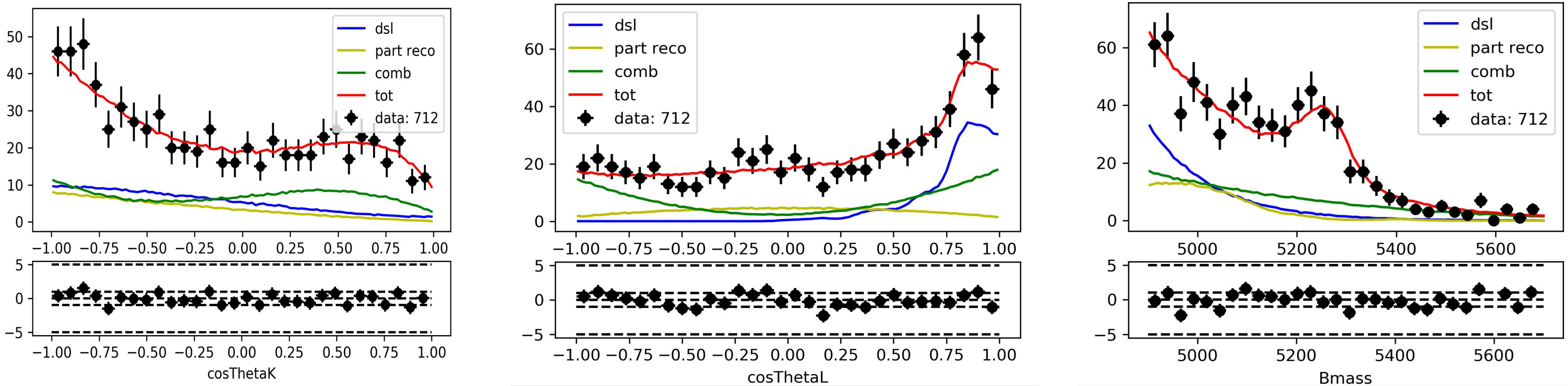
- The fit is in its final form and is currently already used for an amplitude analysis performed only in the muon channel

- Signal PDF includes a P and S-wave component to account for non-resonant $K\pi$ contribution



Fit to $B^0 \to K^{*0} e^+ e^-$ data

- Most of the machinery is common to the muon mode
- Main difference is in reduced statistics and additional backgrounds
- A full blind fit to data has not yet been performed but a simplified version is available for production of realistic toys



An important cross-check

BR is used as constraint on number of expected signal events for muons and electrons

$$\lambda_{sig} \propto \frac{\tau_B}{\hbar} \int_{q^2 \in Q_i} \frac{d\Gamma}{dq^2} dq^2$$

depends on Wilson coefficients

close relationship with $R_{K^{*0}}$ measurement.

A standard cross-check is to verify that:

$$r_{J/\Psi} = \frac{N_{B^0 \to K^* J/\Psi(\to \mu\mu)}}{\epsilon_{B^0 \to K^* J/\Psi(\to \mu\mu)}} \cdot \frac{\epsilon_{B^0 \to K^* J/\Psi(\to \mu\mu)}}{N_{B^0 \to K^* J/\Psi(\to \mu\mu)}} = 1$$

Cross-check requires detailed correction of different aspects of the simulation and is currently on-going. Feasibility has been already shown by previous analysis.

Summary

An unbinned amplitude analysis of $B^0 \to K^{*0} \ell^- \ell^+$, as proposed here, tests the *non-LFU* nature of NP in this class of decays, regardless of the "charm-loop" contribution.

This is possible due to the full sharing of the amplitude by the two, except for the Wilson coefficients!

Final remarks

- The analysis is in an advanced state, with few but important cross-checks to be done

- Next work focus on validation and pre-unblinding procedure, together with the estimation of the most important systematics

Backup