Update on the angular analysis of $B^0 \to K^{*0} e^+ e^-$ decay

Zhenzi Wang

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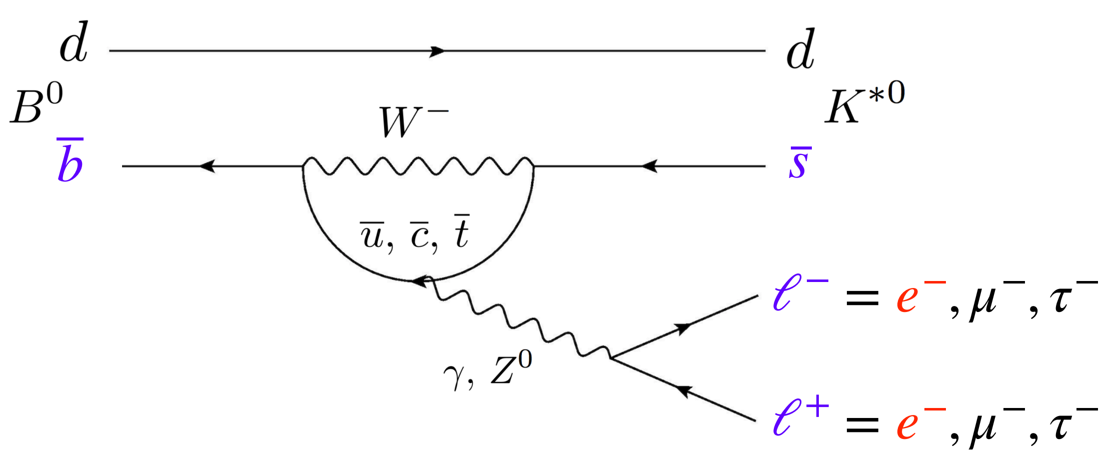
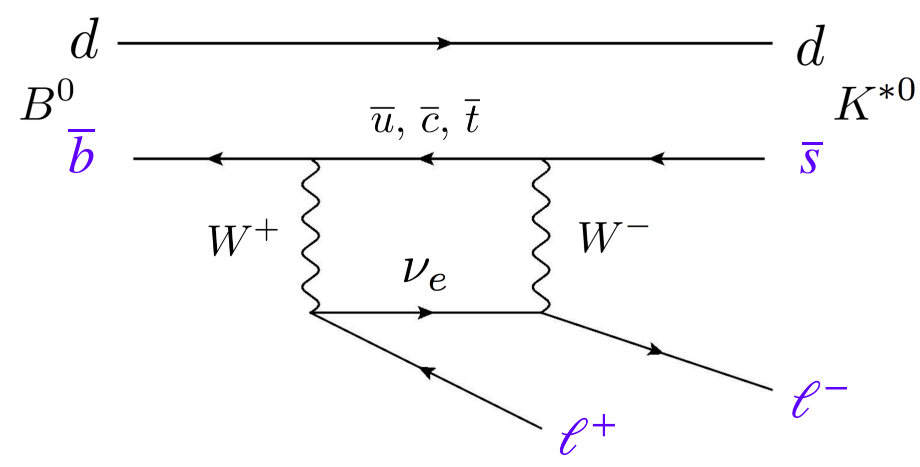
Swiss National Science Foundation

University of Zurich[UZH]

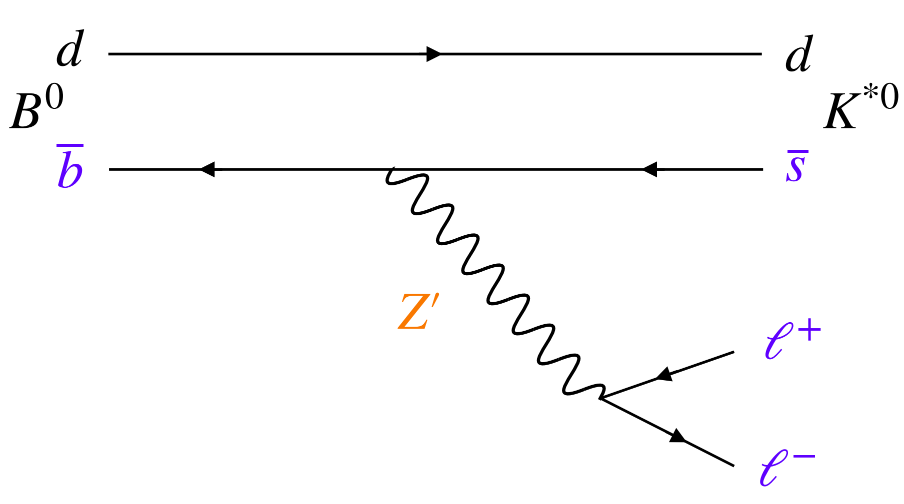
A rare and interesting decay

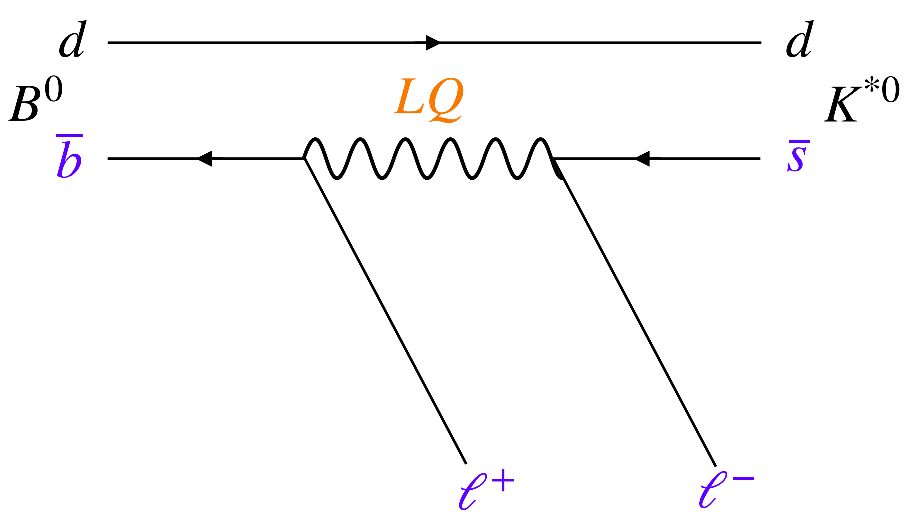
- $B^0 \to K^{*0}(\to K^+\pi^-)e^+e^-$ is a flavour changing neutral current decay that features an underlying $b \to s\ell^+\ell^-$ process





- Decay is forbidden at tree-level in the Standard Model (SM), and sensitive to new physics (NP) effects

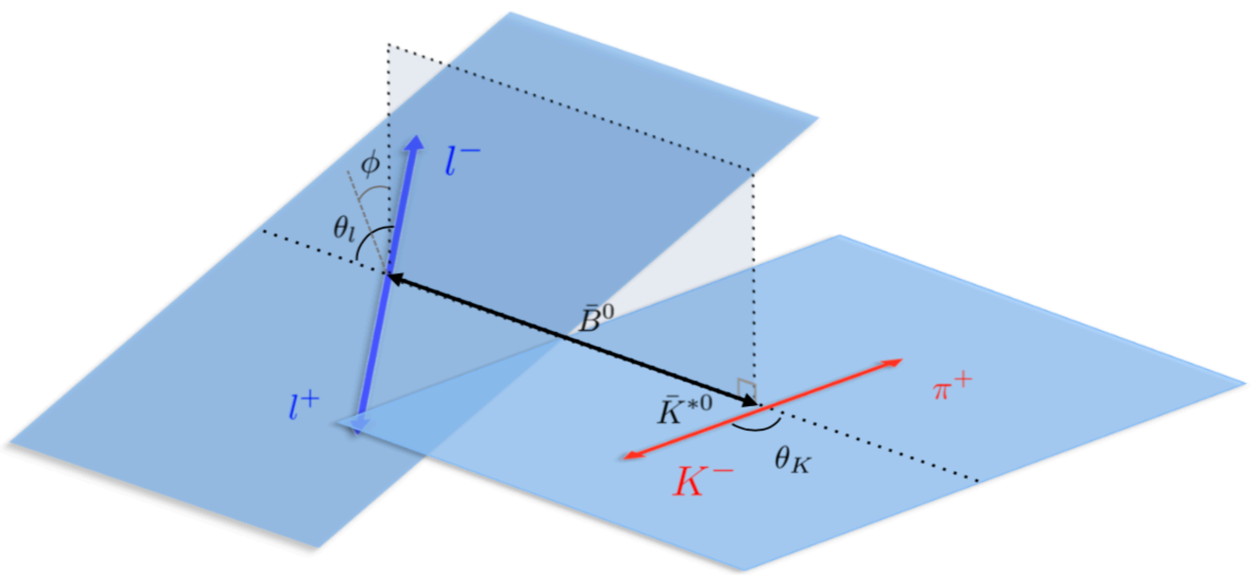




Differential decay rate

- Distribution of final state particles of $B^0 \to K^{*0}(\to K^+\pi^-)e^+e^-$ can be described by three angles: $\cos\theta_\ell$, $\cos\theta_K$, ϕ

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\vec{\Omega}} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K - F_L\cos^2\theta_K\cos 2\theta_\ell$$
$$+S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + \frac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_\ell$$
$$+S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi$$
$$+S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$



F_L — K^{*0} longitudinal polarisation fraction

A_{FB} — forward-backward asymmetry of the dilepton system

- F_L, A_{FB}, S_i — angular observable that are sensitive to the underlying physics
- P_i' — optimised observables with reduced theoretical uncertainties, e.g.

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

The (in)famous P'_5

2013: first measurement of P'_5 of $B^0 \to K^{*0}\mu^+\mu^-$ revealed tension with SM [1]

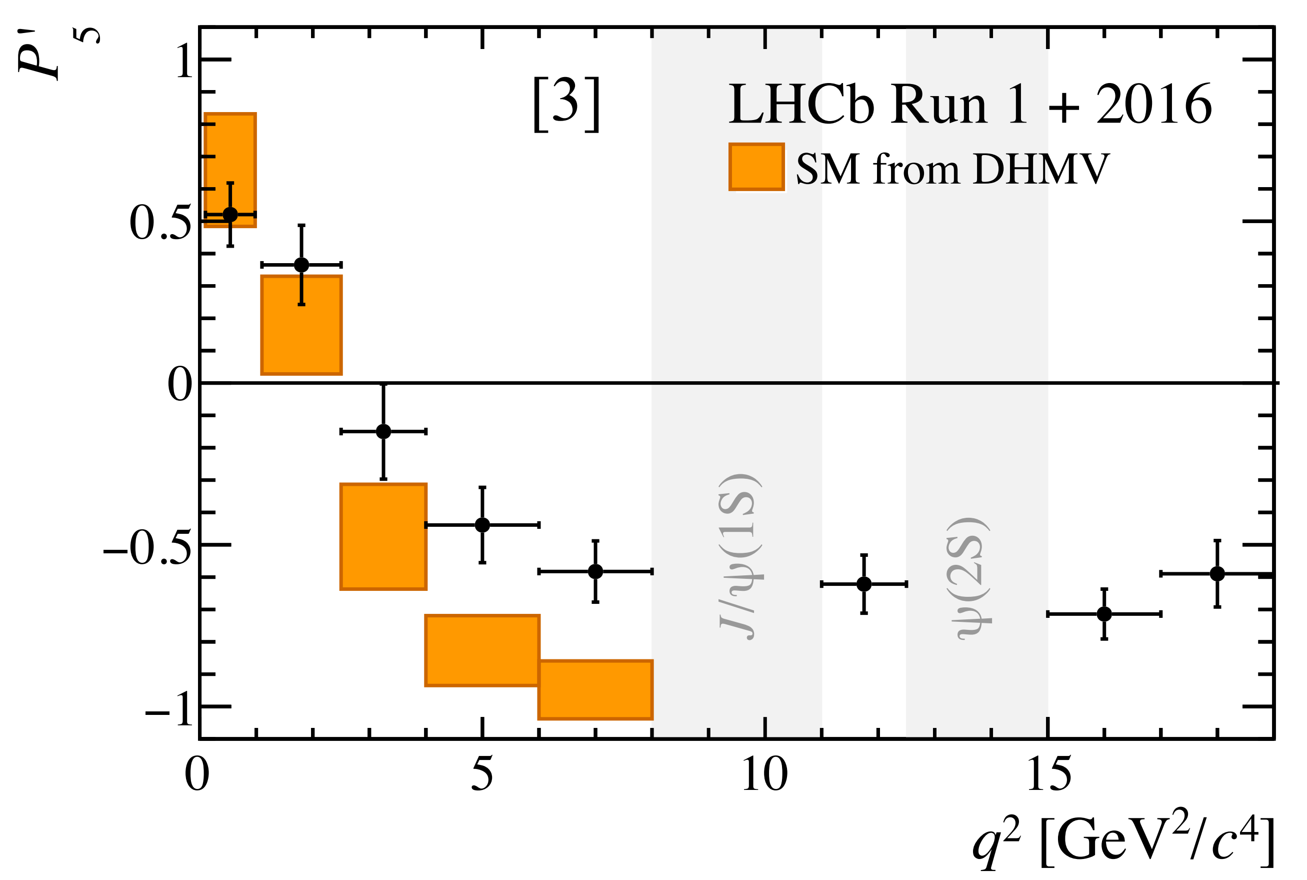
2015: measurement with larger statistics (2011+2012) — tension persists [2]

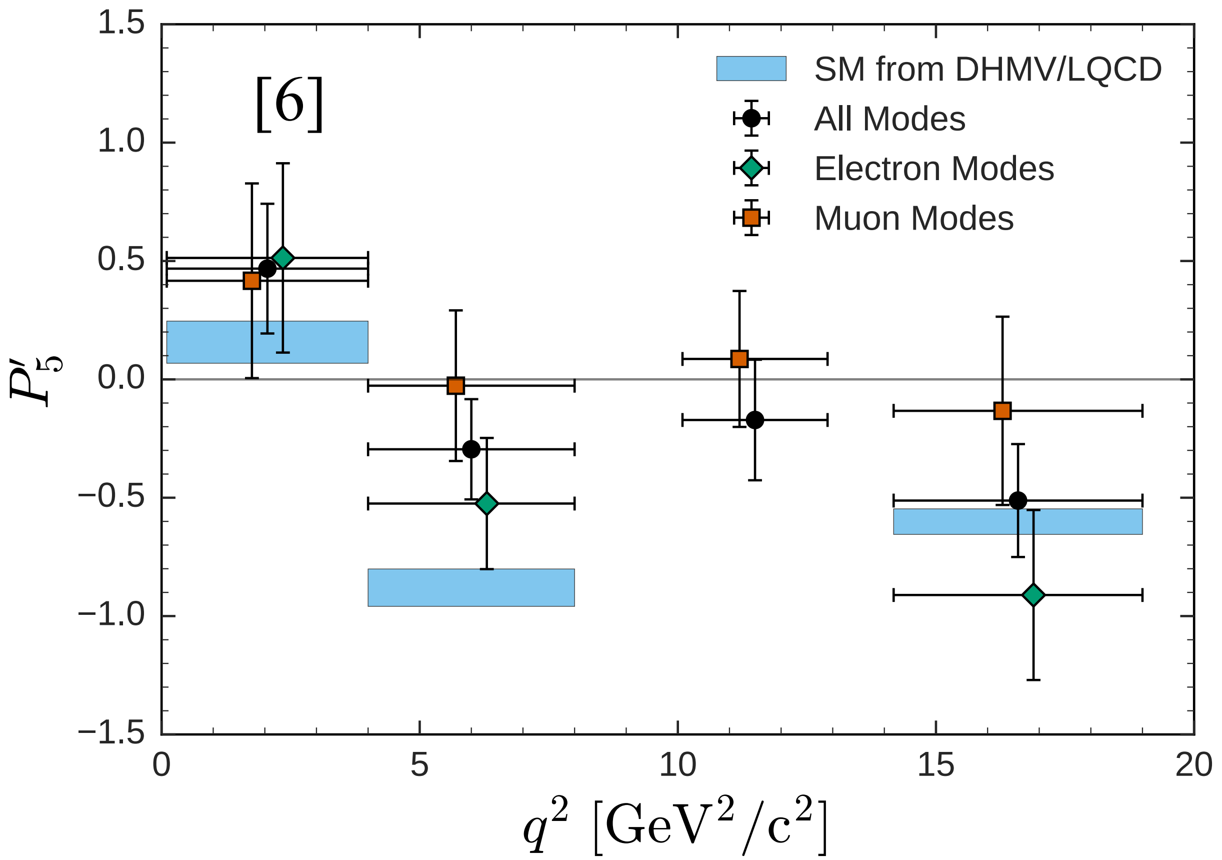
2020: most recent update with the addition of 2016 data — situation largely unchanged [3]

Lepton flavour universality (LFU) tests, such as R_{K*}, continue to hint at deviation from SM

$$R_{K*} = \frac{\mathscr{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathscr{B}(B^0 \to K^{*0}e^+e^-)} \quad [4]$$

What about angular observables of $B^0 \to K^{*0}e^+e^-$?



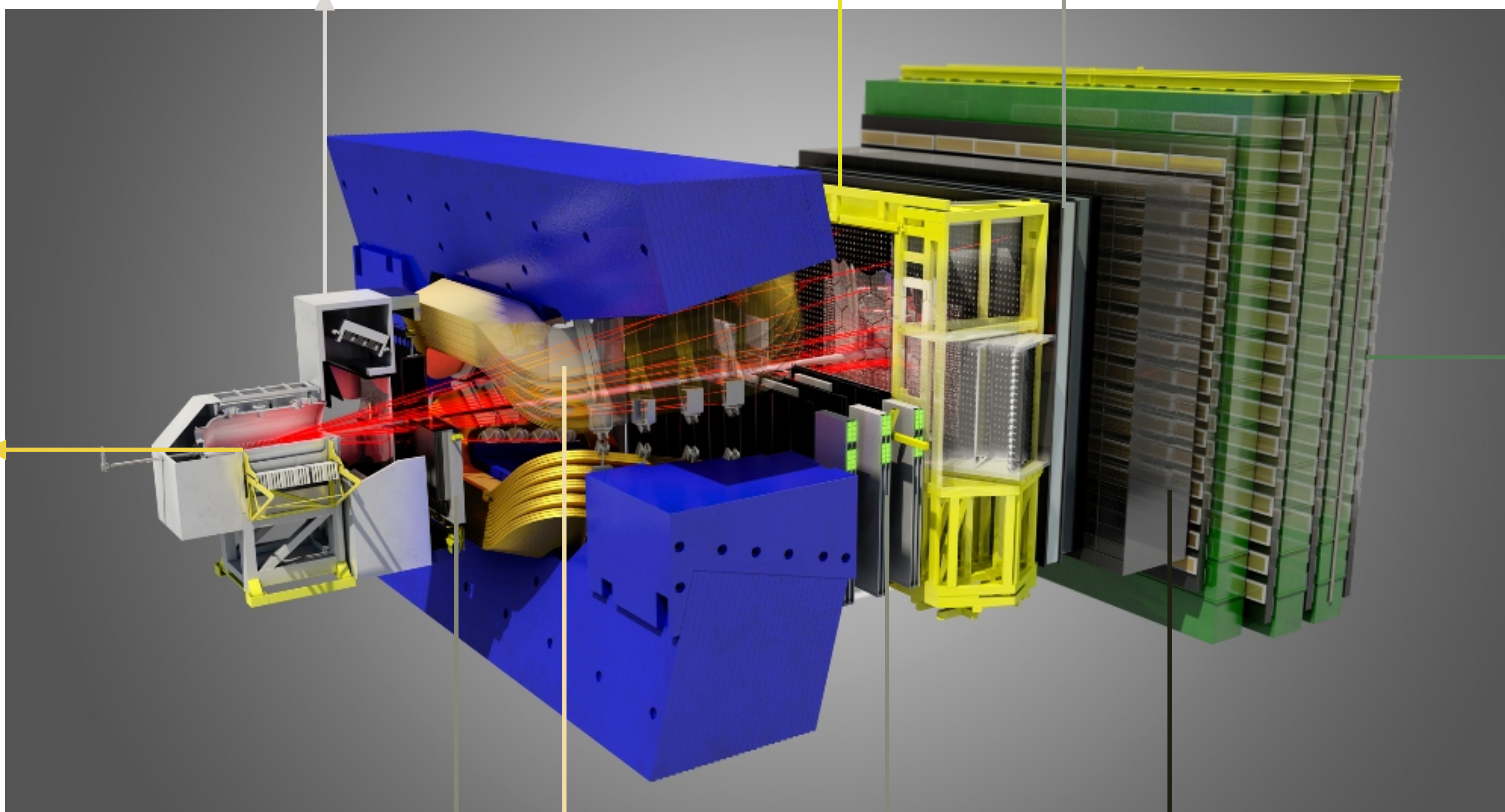


- The LHCb is a specialised detector dedicated to the study of b/c-hadron decays
- Aim: search for NP indirectly

RICH 1
- charged particle identification

RICH 2
(PID)

SPD/PS/ECAL
- Electron energy measurement
- Particle identification ($e/\gamma/h$)



Vertex locator (VELO)
- Precise vertex reconstruction

Muon stations

Magnet

UT (tracking)

TT (tracking)

HCAL
- h energy measurement, trigger, PID

- $B^0 \to K^{*0} e^+ e^-$ angular analysis is more challenging than that of $B^0 \to K^{*0} \mu^+ \mu^-$
- Experimentally, muons and electrons are very different
- Muons leave clear signatures and are relatively easy to reconstruct
- Electron reconstruction is more difficult due to large bremsstrahlung losses

✗ Decreased resolution: more background in signal region

✗ Decreased trigger efficiency: lower statistics

Compensation strategies

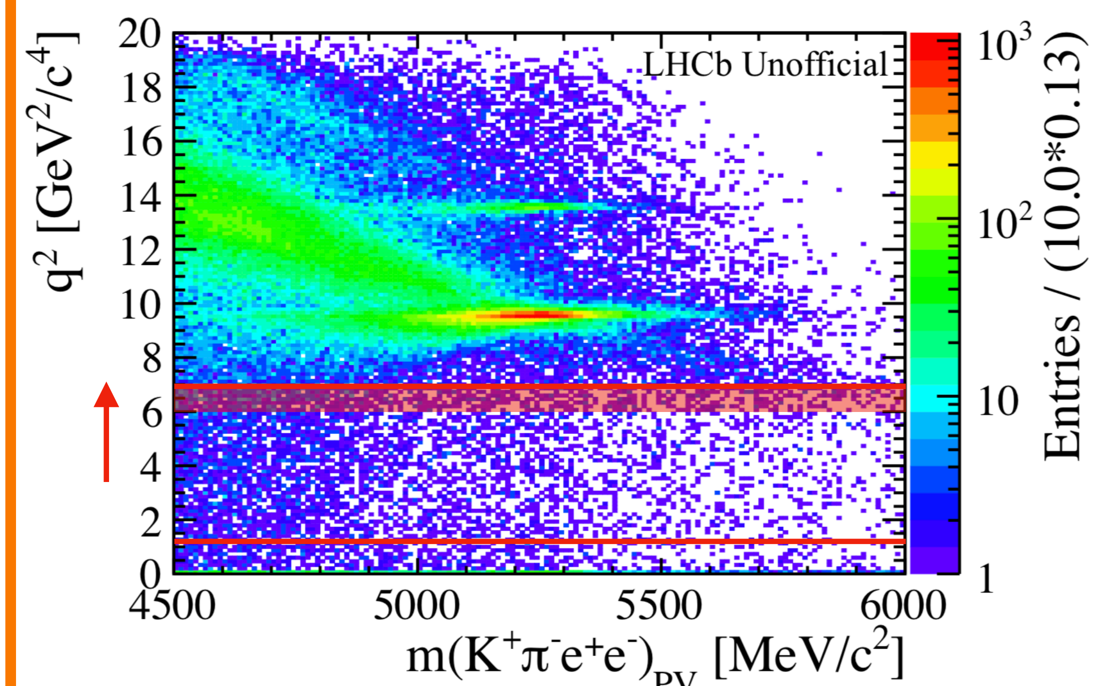
Simplify PDF

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2 d\vec{\Omega}} = \frac{9}{8\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_L)P_1\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + \sqrt{F_L(1-F_L)}\,P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi\Big]$$

$$\phi \to -\phi \;\text{ if } \phi < 0$$

$$\theta_\ell \to \pi - \theta_\ell \;\text{ if } \theta_\ell > \frac{\pi}{2}$$

Increase statistics

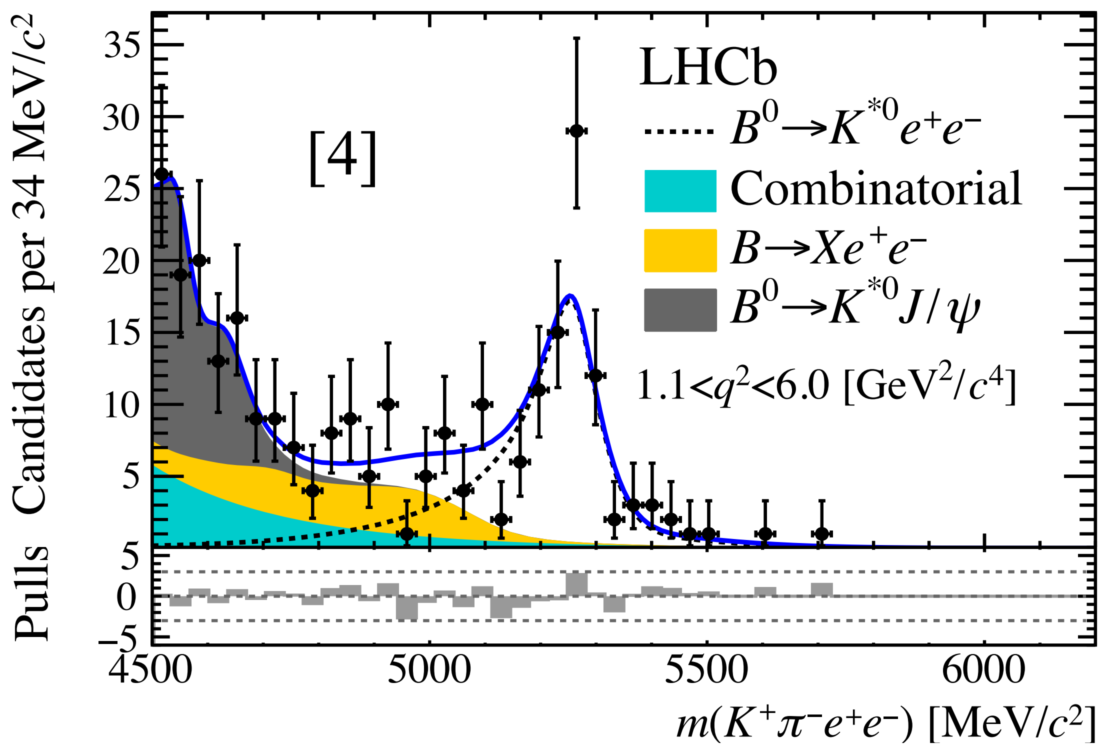


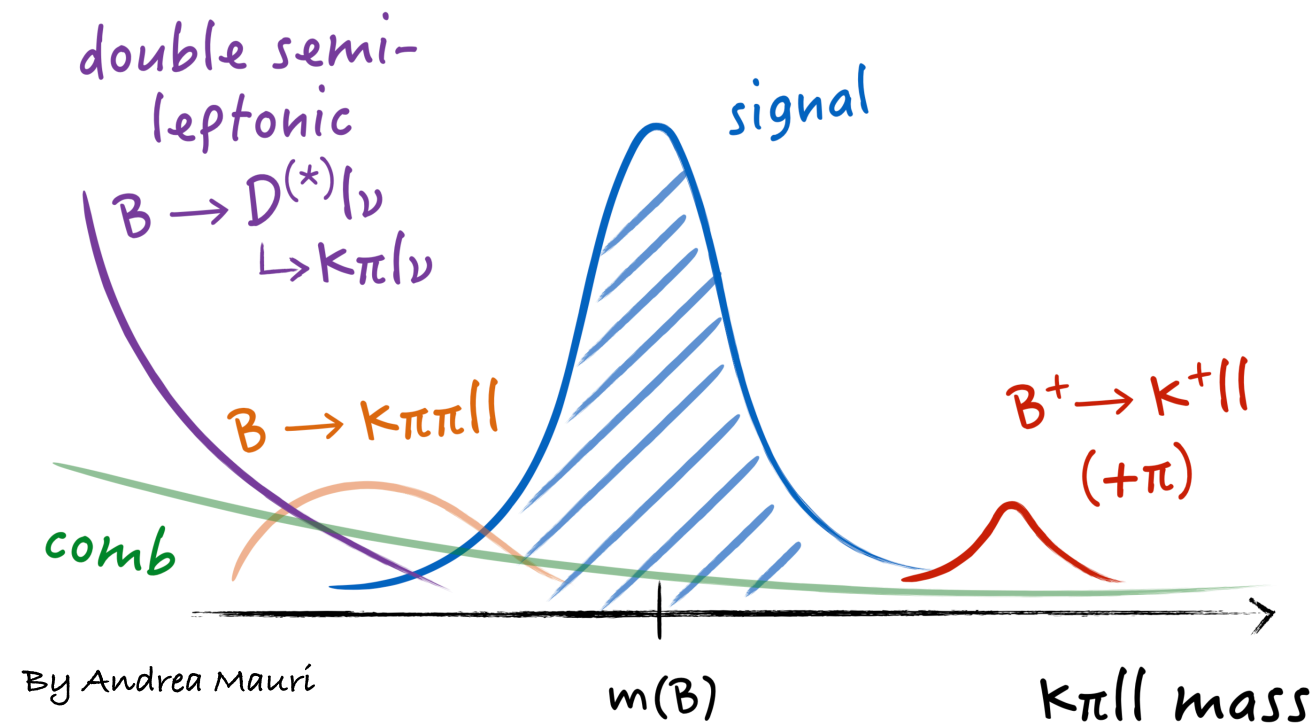
Some changes to the analysis strategy and progress have been made since the last presentation, the main ones include:

To cover today…

- Model double semi-leptonic background (instead of cut)
- Strategy change: fix combinatorial background angular parameters
- Cross-check with $B^0 \to K^{*0}(\to K^+\pi^-)J/\psi(\to e^+e^-)$
- Updated sensitivity studies
- First systematics studies

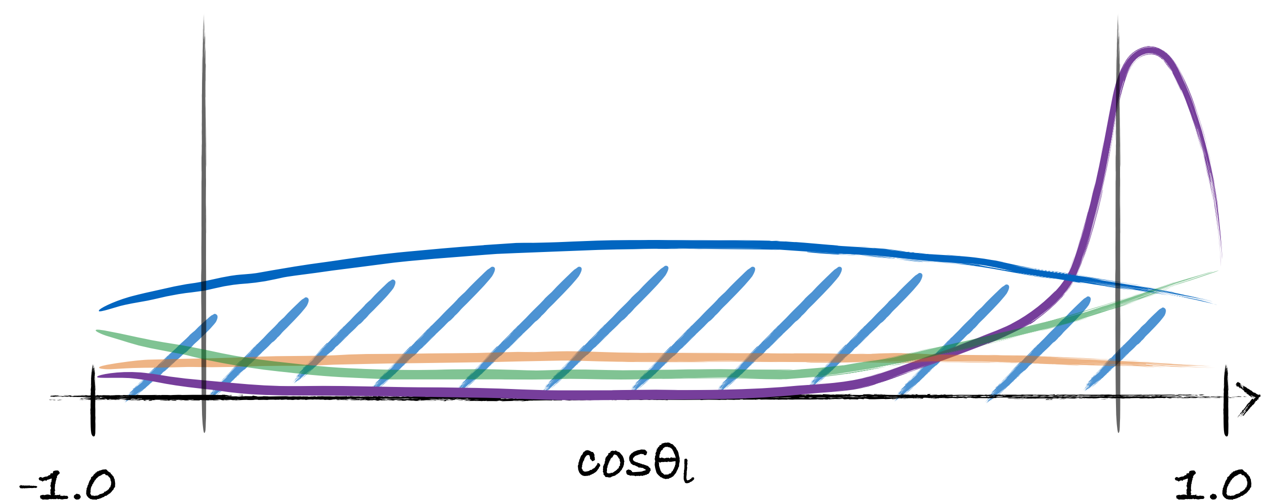
Angular observables to be extracted via unbinned maximum likelihood fit to mass + angles





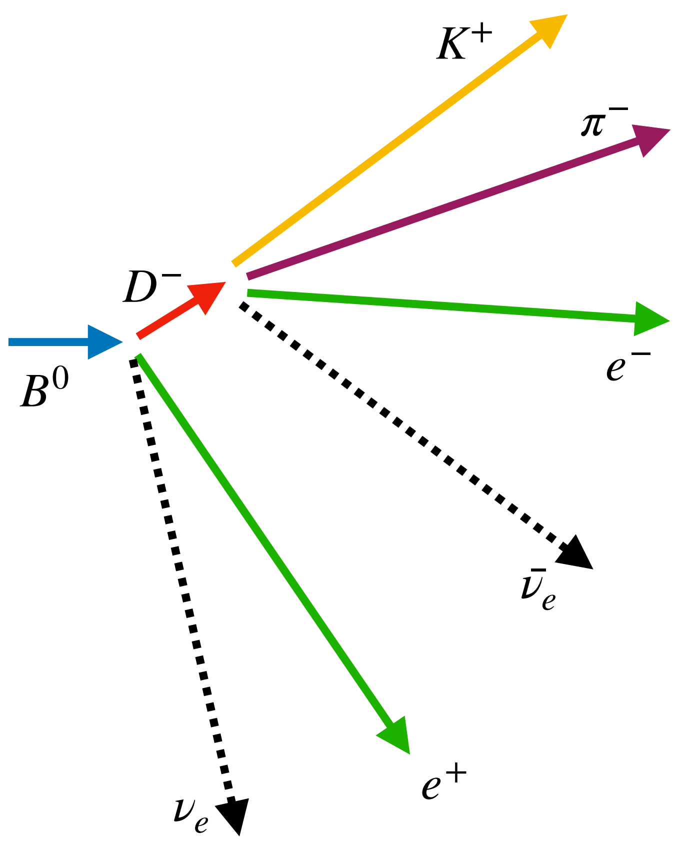
Background components include:

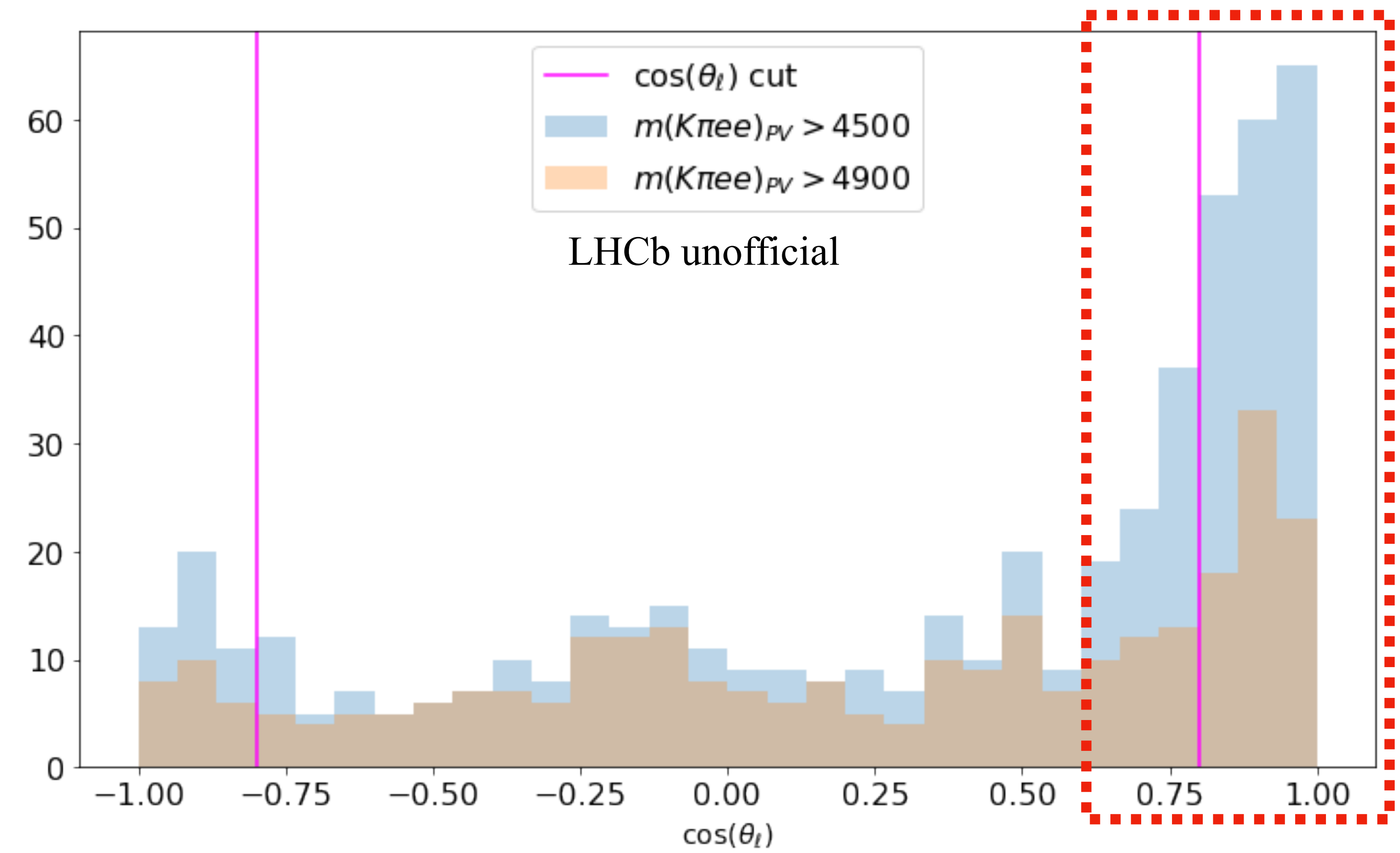
- Double semi-leptonic
- $B^+ \to K^+ e^+ e^-$ — vetoed
- Partially reconstructed
- Combinatorial



and $\cos\theta_K$, ϕ

- Double semi-leptonic background — e.g. $B^0 \to D^-(\to K^{*0}e^-\bar{\nu}_e)\, e^+\nu_e$ as signal
- Decay has large branching fraction compared to signal ($\mathcal{O}10^{-4}$)
- Due to energy loss from undetected neutrinos these events will resemble combinatorial background in the mass distribution
- However they distort the shapes of angular distributions, in particular that of $\cos\theta_\ell$

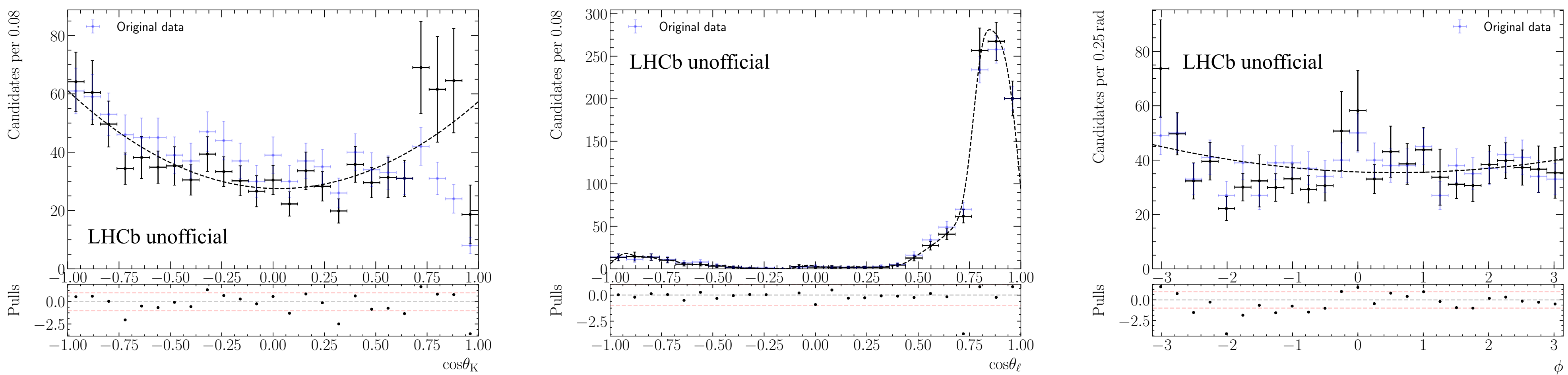




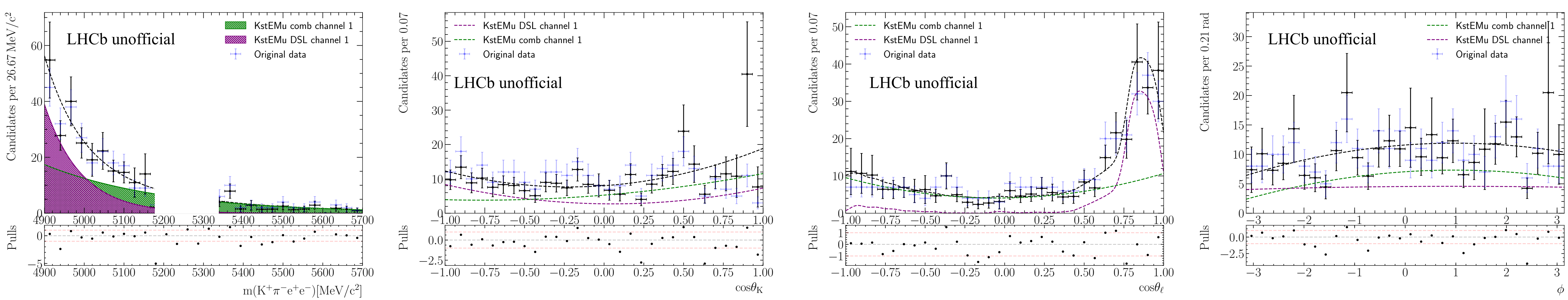
- Original strategy: apply $|\cos\theta_\ell| < 0.8$ cut

- Model using $K\pi e\mu$ data (LFV — no signal, mostly combinatorial and DSL events e.g. $B^0 \to D^-(\to K^{*0}e^-\bar{\nu}_e)\mu^+\nu_\mu$)
- Obtain angular shape of DSL and combinatorial together in a two-step procedure:

Step 1: fit 'pure' DSL sample (MVA>0.9985 (tight!), $4500 < m_{B^0} < 5200\,\mathrm{MeV/c^2}$)

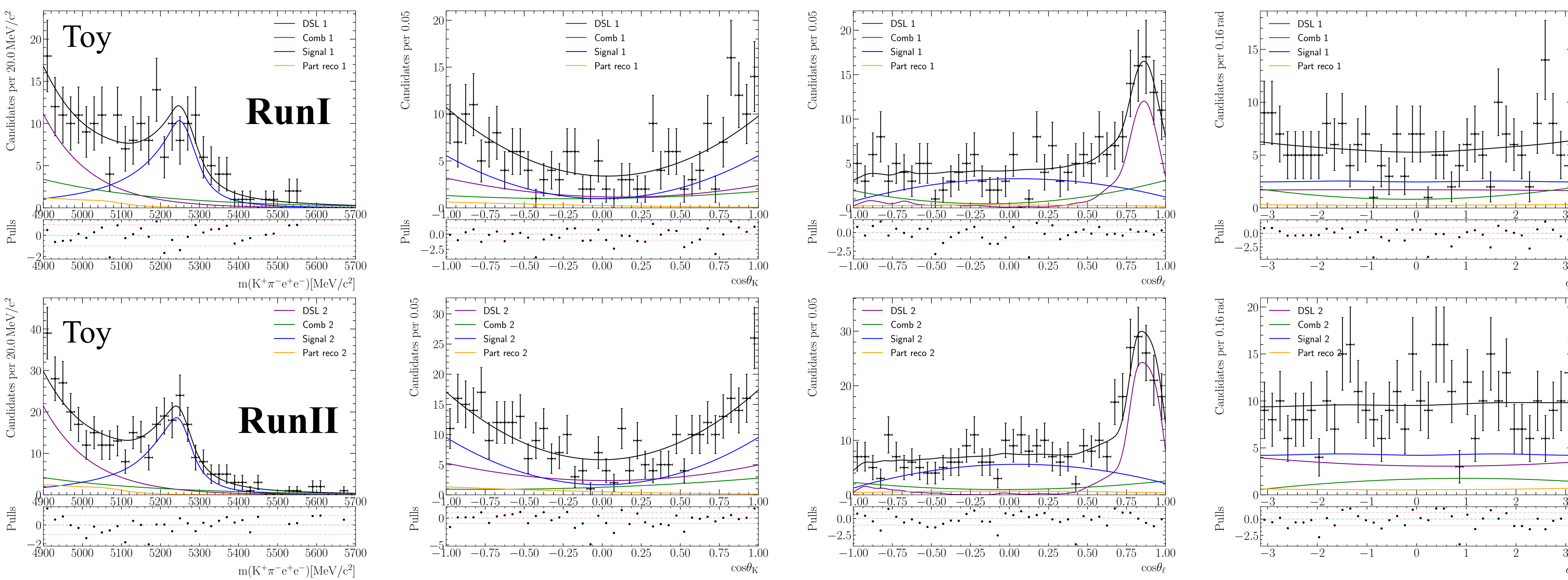


Step 2: fixing DSL angular shape, obtain slope and combinatorial shape + slope from fit to independent sample (0.99<MVA<0.9985, $4900 < m_{B^0} < 5700\,\mathrm{MeV/c^2}$)



- Toy studies: obtain expected sensitivities; determine if the combinatorial angular parameters should be allowed to vary ('float')
- ~2000 toys generated with realistic studies from data fits, using updated model

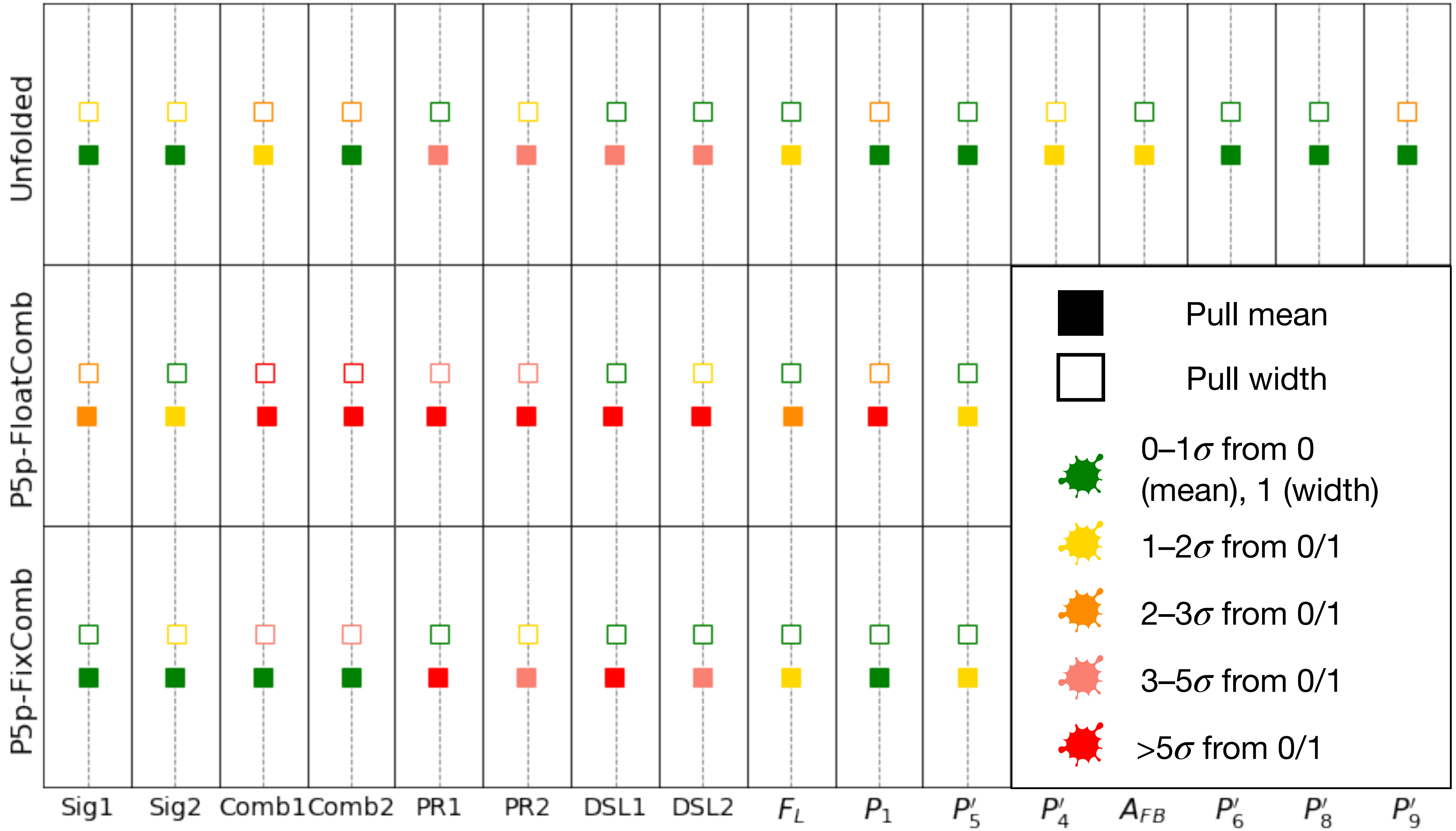
Component	Mass	Vary in fit	Angles	Vary in fit
Signal	Crystal Ball	N	Angular PDF	Y
Combinatorial	Exponential	Y	Chebyshev	??
Partially reconstructed	Non-parametric	N	Chebyshev	N
DSL	Exponential	N	Chebyshev + non-parametric	N



Estimations of convergence rate

- Folded, floating (combinatorial angular parameters) — around 50-60%
- Folded, fixed => ~98%
- Unfolded, fixed => ~98%

Summary of pulls



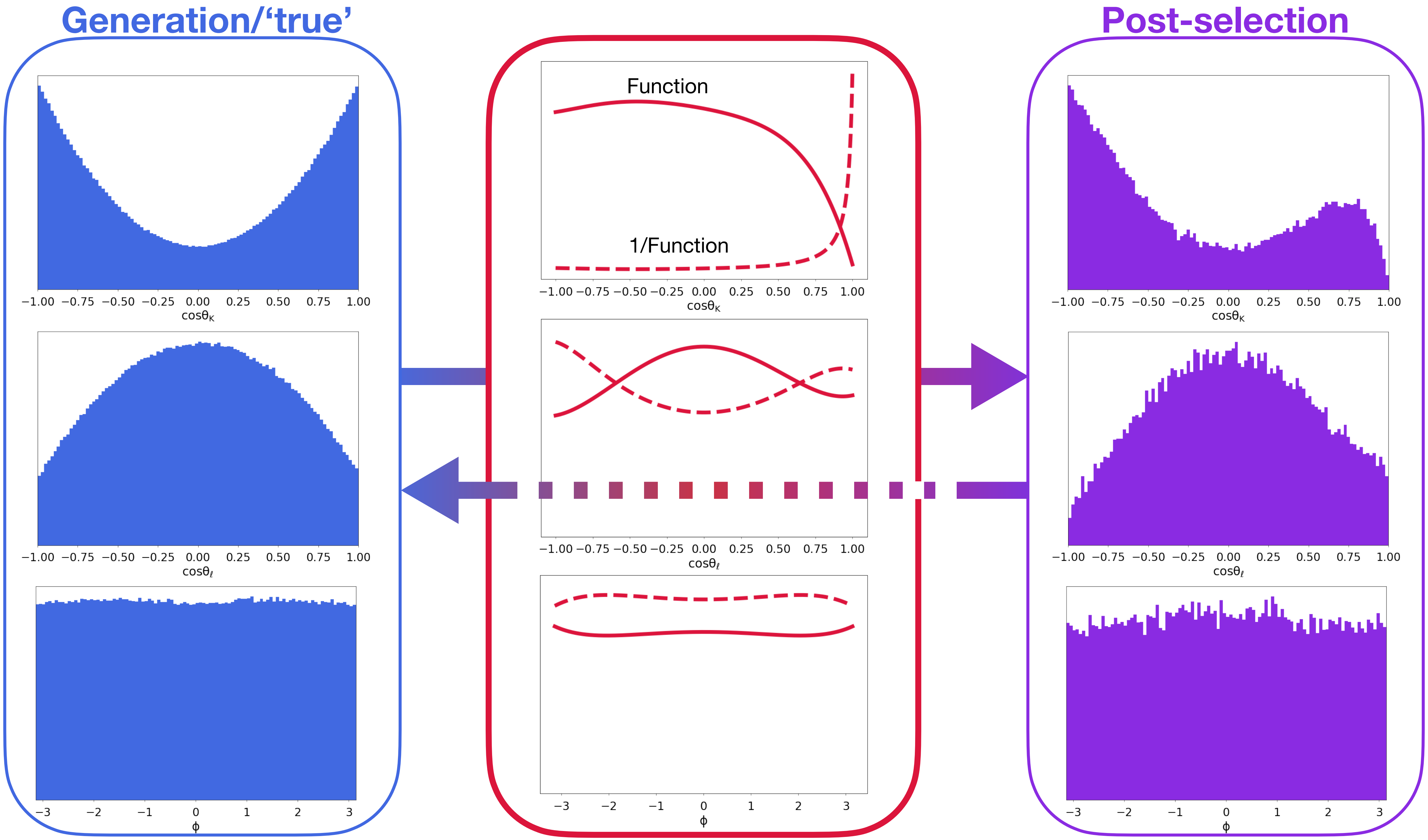
Sensitivity to observables (width of parameter distributions)

Observable	Unfolded, fixed	Folded, floating	Folded, fixed
F_L *	0.051+/-0.001	0.062+/-0.001	0.052+/-0.001
P_1 *	0.533+/-0.008	0.58+/-0.01	0.503+/-0.009
P_2	0.131+/-0.002	0.169+/-0.004	0.135+/-0.002
P_3	0.274+/-0.004	0.289+/-0.006	0.261+/-0.004
P'_4	0.196+/-0.003	0.221+/-0.005	0.204+/-0.004
P'_5	0.181+/-0.003	0.198+/-0.004	0.180+/-0.003
P'_6	0.177+/-0.003	0.196+/-0.004	0.182+/-0.003
P'_8	0.193+/-0.003	0.209+/-0.005	0.194+/-0.004

- When most backgrounds parameters are fixed, the advantage of folding is reduced…
- Current nominal choice: no folding, fixed combinatorial

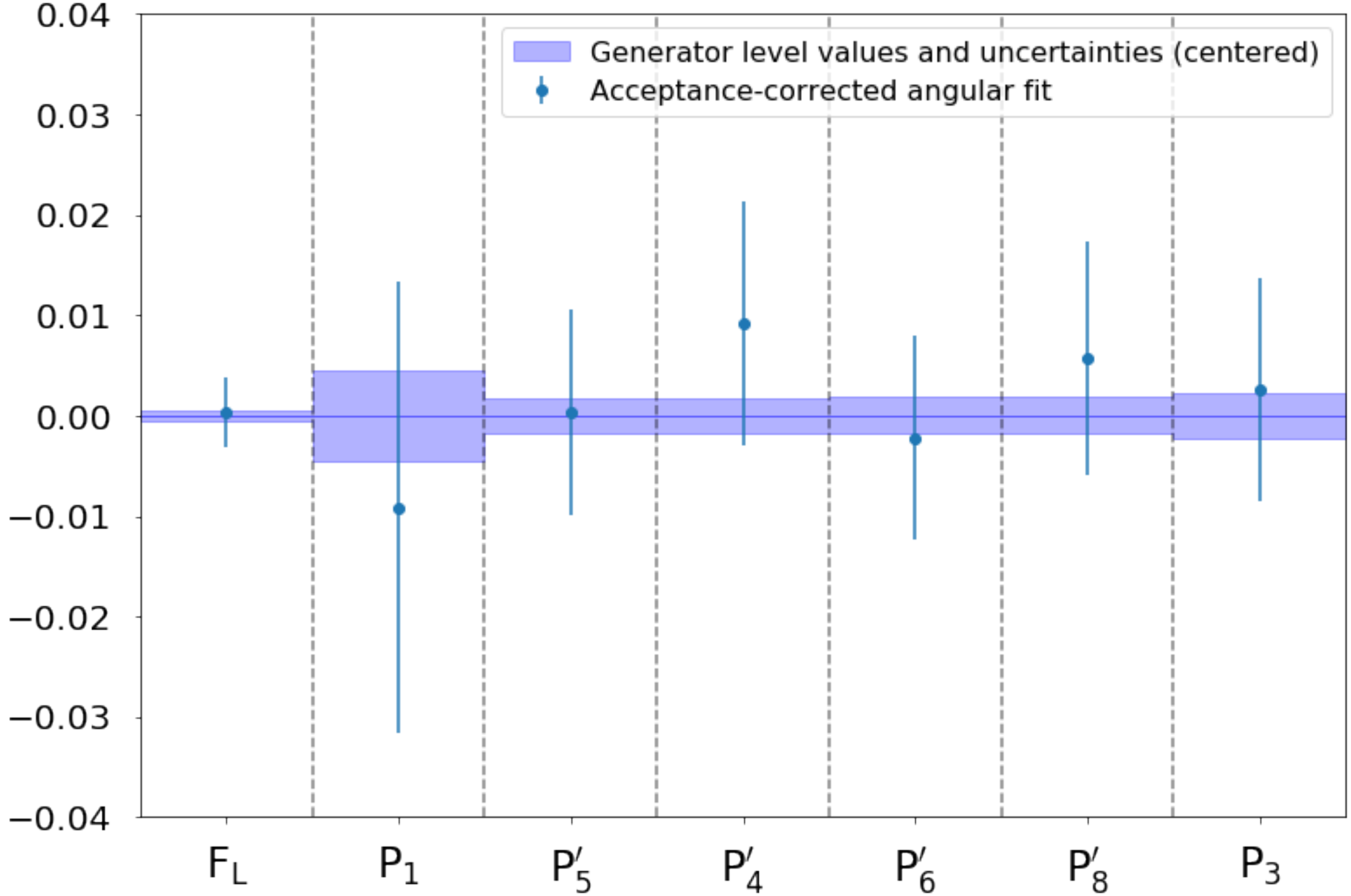
*present in multiple folds — lowest value displayed

Acceptance — a function that encodes the effects of reconstruction and selection (+resolution)



- Parametrise in 4d ($\cos\theta_K, \cos\theta_\ell, \phi, q^2$) using Legendre polynomials

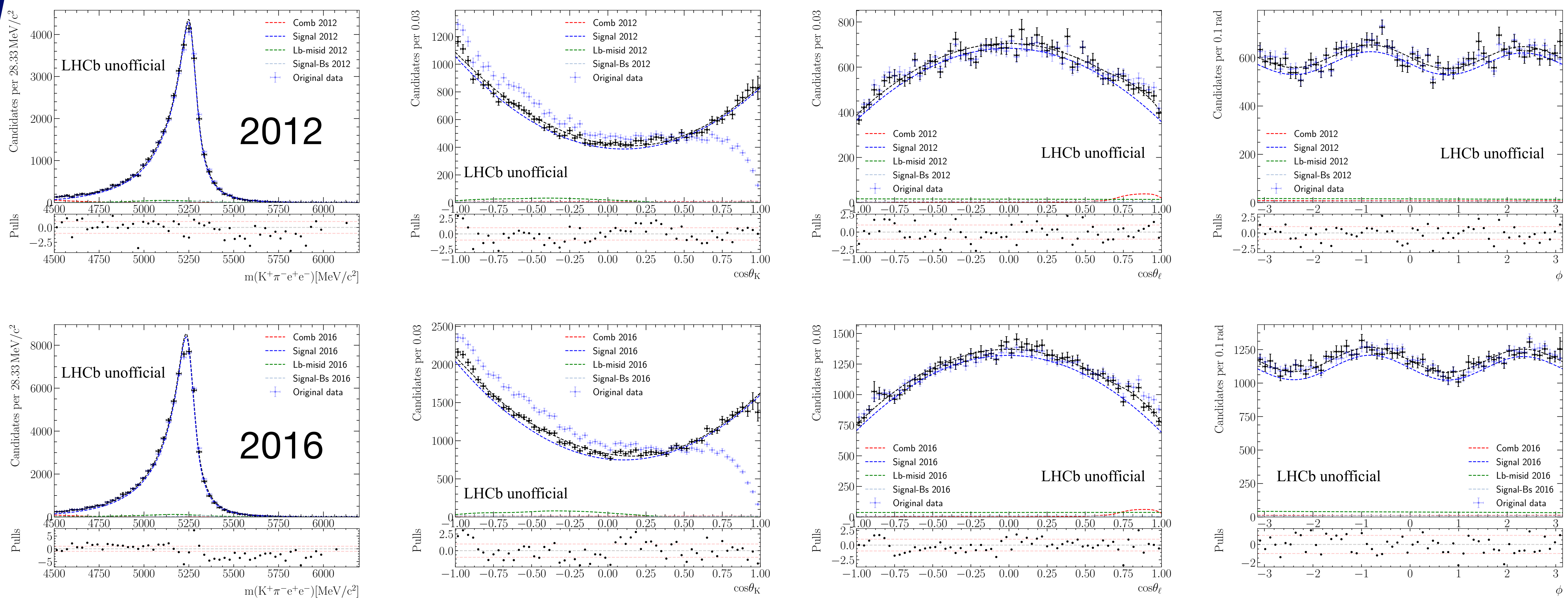
Basic check: retrieval of generator level angular observable values from acceptance corrected (weighted) post selection sample



Order of Legendre polynomials still under consideration, but in general performance is good

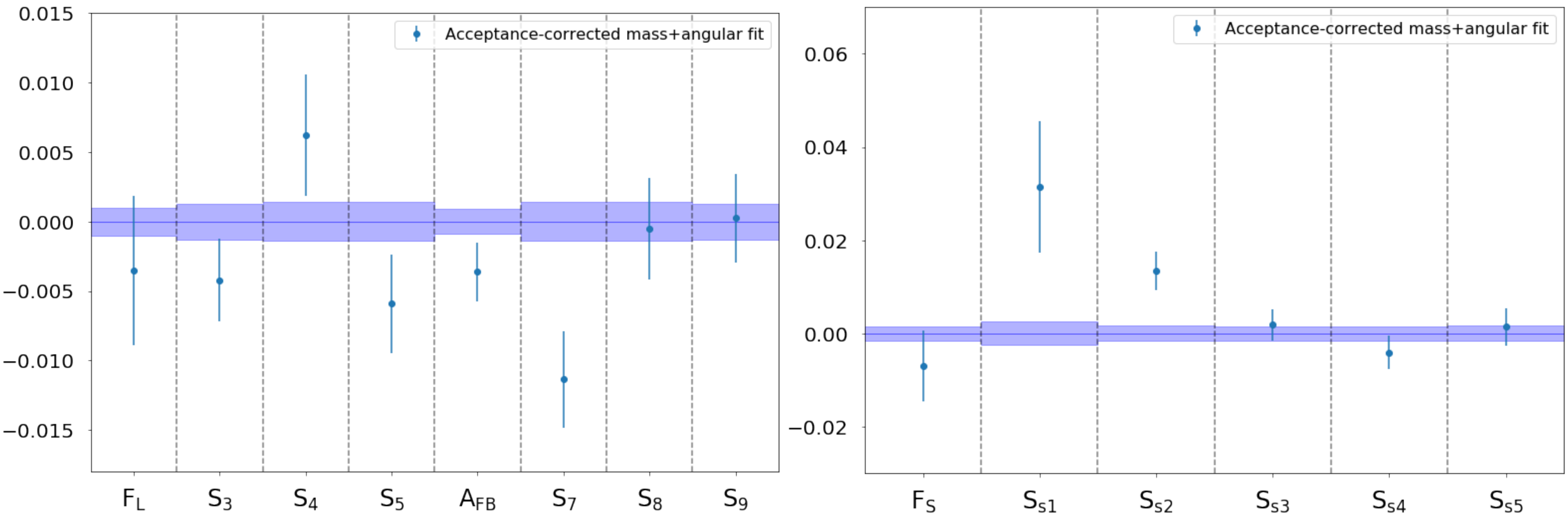
Control mode $B^0 \to K^{*0}J/\psi(\to e^+e^-)$ can be used to further check acceptance strategy

- Tree-level decay (not $b \to s\ell^+\ell^-$), large statistics (~$400 \times$ signal yield!)

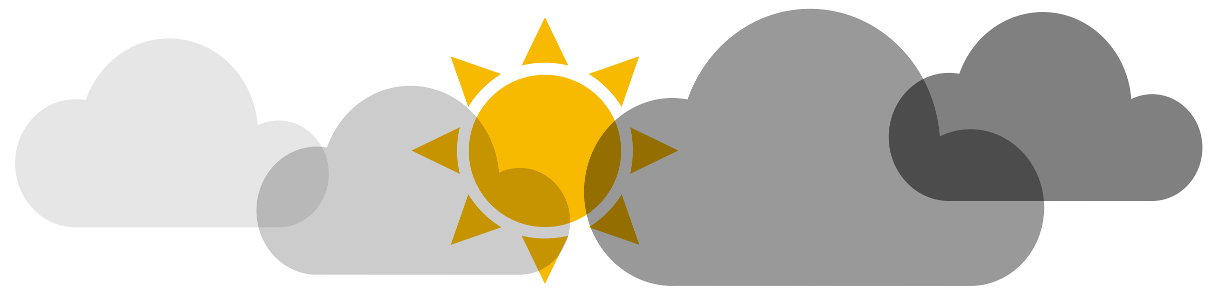


- Backgrounds components: combinatorial, DSL, $\Lambda_b^0 \to pKJ/\psi(\to e^+e^-)$ with $p \to \pi$ misidentification
- Dip at the edge of $\cos\theta_K$ is related to difficulties in modelling $\cos\theta_K$ acceptance near +1

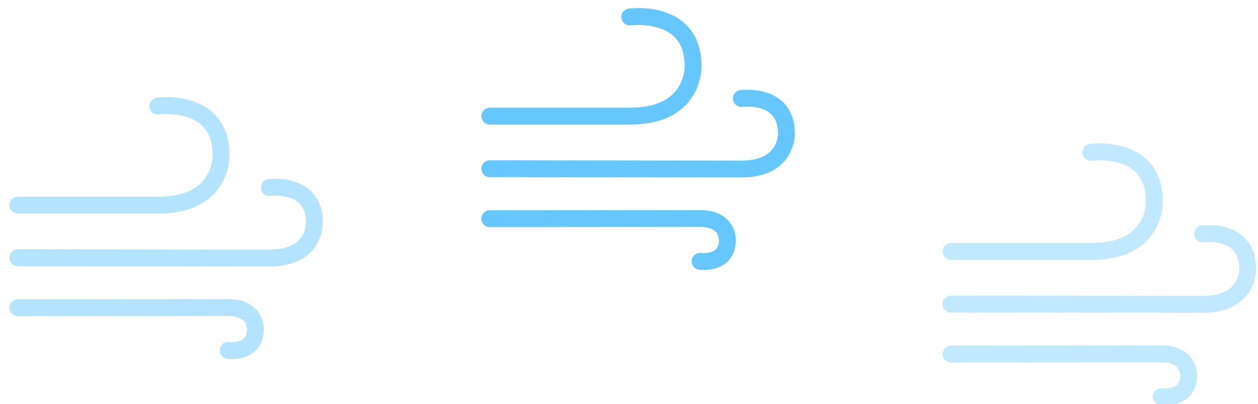
Control mode $B^0 \to K^{*0} J/\psi(\to e^+e^-)$ fit results (centred around values obtained for $B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-)$ as part of the $B^0 \to K^{*0}\mu^+\mu^-$ cross-check)



- Compare with independent external data fit results from the $B^0 \to K^{*0}\mu^+\mu^-$ analysis (different acceptance, fit model etc.)
- Agreement good for key observables of interest
- Still work in progress (e.g. background fractions need updating)



- Analysis strategy has been updated since last year:
  - Model (instead of cut) contribution from double semi-leptonic background
  - Use full $\cos\theta_\ell$ region (enabled by above)
  - Fix all background angular shapes and use unfolded signal pdf
- Now the focus is on:
  - Finalising details/decisions
  - Assessing systematics (lots of toys!)
  - Completing cross-checks and additional measurements (control mode, folded fits, $q^2 \in [1.1, 6.0]\,\mathrm{GeV}^2/c^4$, reduced $\cos\theta_\ell$ region…)
- Internal note writing is in progress
- Hopefully will start the LHCb review process soon



References

[1] $B^0 \to K^{*0}\mu^+\mu^-$ 1 fb^{-1} analysis: the LHCb collaboration, R. Aaij et al. Measurement of Form-Factor-Independent Observables in the Decay $B^0 \to K^{*0}\mu^+\mu^-$. Phys. Rev. Lett., 111:191801, 2013.

[2] $B^0 \to K^{*0}\mu^+\mu^-$ 3 fb^{-1} analysis: the LHCb collaboration, Aaij, R., Abellán Beteta, C. et al. J. High Energ. Phys. (2016) 2016: 104. https://doi.org/10.1007/JHEP02(2016)104

[3] $B^0 \to K^{*0}\mu^+\mu^-$ 4.7 fb^{-1} analysis: the LHCb collaboration, R. Aaij and et al. Measurement of CP-Averaged Observables in the $B^0 \to K^{*0}\mu^+\mu^-$ Decay. Physical Review Letters, 125(1), Jul 2020.

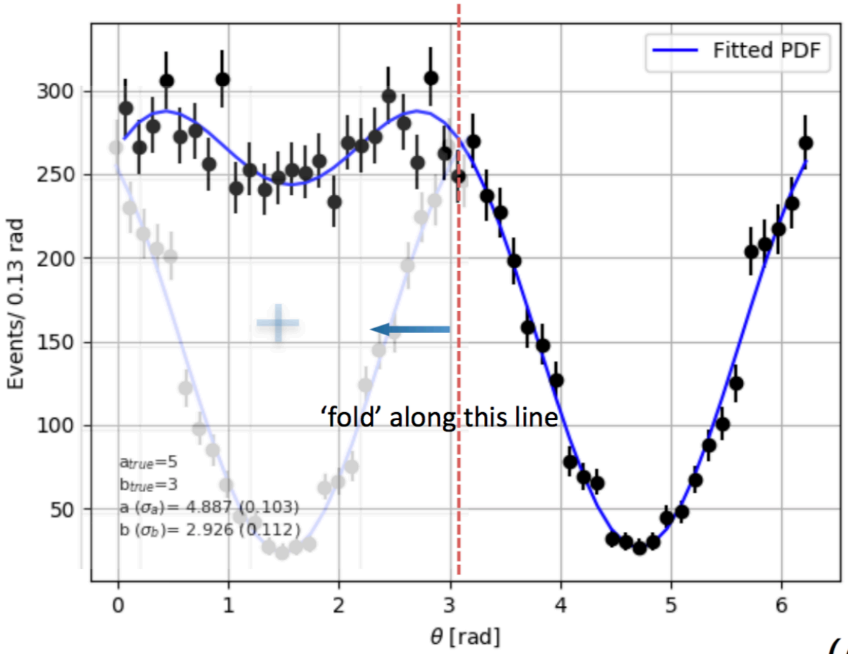
[4] R_{K*} 3 fb^{-1} analysis: The LHCb collaboration, Aaij, R., Adeva, B. et al. J. High Energ. Phys. (2017) 2017: 55. https://doi.org/10.1007/JHEP08(2017)055

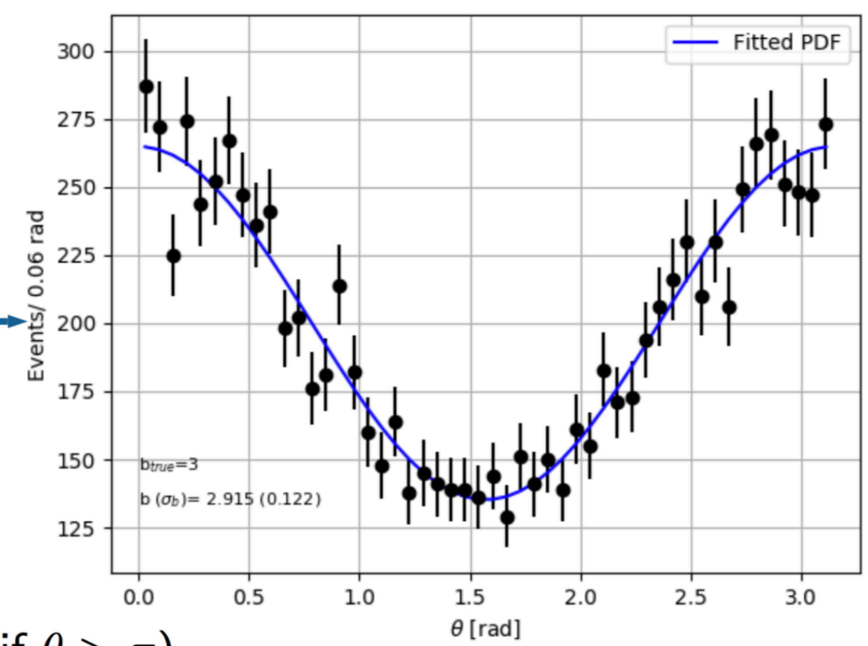
[5] Belle muon/electron P_5': S. Wehle *et al.* (Belle Collaboration), Phys. Rev. Lett. 118, 111801 – Published 13 March 2017

Backup

Electron strategy: folding

- For electron channel ‘fold’ signal PDF to reduce impact of low statistics, e.g. for P'_5





$(\theta \to -(\theta - 2\pi) \text{ if } \theta > \pi)$

$$f(\theta) = \frac{1}{18\pi}\left(\mathrm{a}\sin\theta + \mathrm{b}\cos 2\theta + 9\right) \longrightarrow f(\theta)_{\mathrm{fold}} = \frac{1}{9\pi}\left(\mathrm{b}\cos 2\theta + 9\right)$$

✔ Reduced number of observables to be determined in fit

$$\phi \to -\phi \quad \text{if } \phi < 0$$

$$\theta_\ell \to \pi - \theta_\ell \quad \text{if } \theta_\ell > \frac{\pi}{2}$$

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2 d\vec{\Omega}} = \frac{9}{8\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_L)P_1\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + \sqrt{F_L(1-F_L)}\,P'_5\sin 2\theta_K\sin\theta_\ell\cos\phi\Big]$$

Acceptance parametrisation

Acceptance is parametrised in 4d ($\cos\theta_K, \cos\theta_\ell, \phi, q^2$) using Legendre polynomials, the coefficients of which are obtained via method of moments

$$\epsilon(cos\theta_\ell, cos\theta_K\, \phi, q^2) = \sum_{klmn} c_{k,l,m,n}\, L_k(cos\theta_\ell)\, L_l(cos\theta_K)\, L_m(\phi)\, L_n(q^2)$$

L_i — Legendre polynomials of order i

$c_{k,l,m,n}$ — coefficients from moments analysis

Obtain $c_{k,l,m,n}$ through a calculation:

$$c_{k,l,m,n} = (\frac{2k+1}{2})(\frac{2l+1}{2})(\frac{2m+1}{2})(\frac{2n+1}{2})\frac{1}{N}\sum_{i=1}^{N} L_k(\cos\theta_{\ell i})L_l(\cos\theta_{Ki})L_m(\phi_i)L_n(q_i^2)$$

N — Number of events (sum is over all events in sample used for parametrisation)

Samples used: $B^0 \to K^{*0}e^+e^-$ generator level, and post selection simulation (two parameterisations)

Acceptance parametrisation — control mode check

- Control mode $B^0 \to K^{*0} J/\psi(\to e^+e^-)$ can be used to further check acceptance strategy
- Tree-level decay (not $b \to s\ell^+\ell^-$), large statistics (~400 × signal yield!)
- Measure angular observables in the same way… with a Ss-small twist

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\vec{\Omega}}\Bigg|_{\mathrm{S+P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K - F_L\cos^2\theta_K\cos2\theta_\ell$$
$$+S_3\sin^2\theta_K\sin^2\theta_\ell\cos2\phi + S_4\sin2\theta_K\sin2\theta_\ell\cos\phi$$
$$+S_5\sin2\theta_K\sin\theta_\ell\cos\phi + \tfrac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_\ell$$
$$+S_7\sin2\theta_K\sin\theta_\ell\sin\phi + S_8\sin2\theta_K\sin2\theta_\ell\sin\phi$$
$$+S_9\sin^2\theta_K\sin^2\theta_\ell\sin2\phi\Big]$$

- ‘P-wave’ => $K^+\pi^-$ from $K^{*0}(892)$ (spin-1)
- ‘S-wave’ => nonresonant $K^+\pi^-$, $K^+\pi^-$ from spin-0 K^{*0} …
- S-wave is a kind of ‘inseparable’ background
- Contribution neglected in rare mode fit (lack of sensitivity)

$$+\frac{3}{16\pi}\Big[F_S\sin^2\theta_l$$ → S-wave fraction

$$+S_{S1}\sin^2\theta_l\cos\theta_K$$
$$+S_{S2}\sin2\theta_l\sin\theta_K\cos\phi$$
$$+S_{S3}\sin\theta_l\sin\theta_K\cos\phi$$
$$+S_{S4}\sin\theta_l\sin\theta_K\sin\phi$$
$$+S_{S5}\sin2\theta_l\sin\theta_K\sin\phi\Big]$$

S-P interference terms