FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

University of Zurich[UZH]

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

Zhenzi Wang

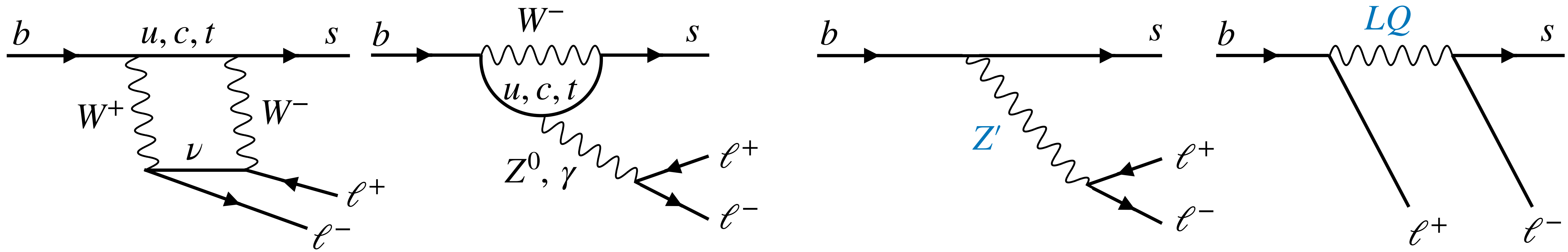
Annual Meeting of the Swiss Physical Society

June 28, 2022

Université de Fribourg

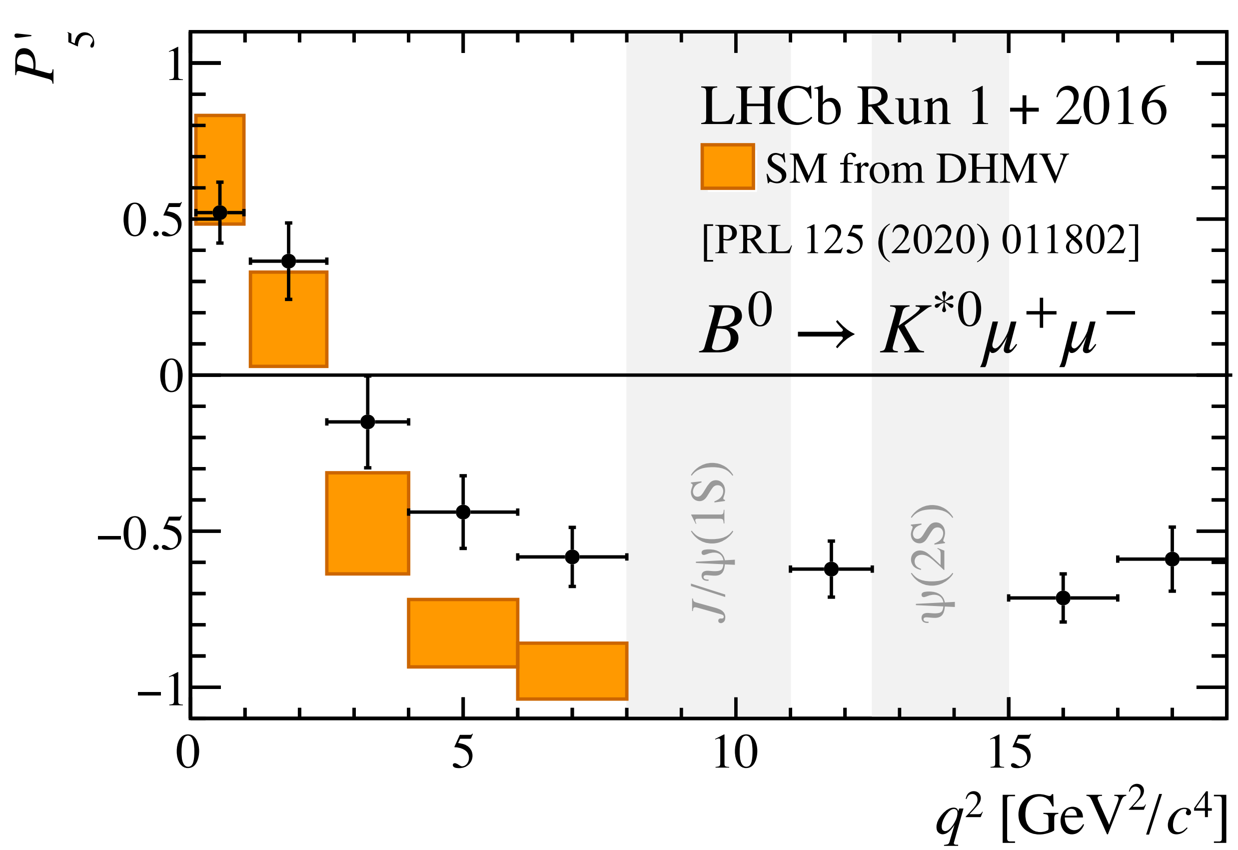
Motivation

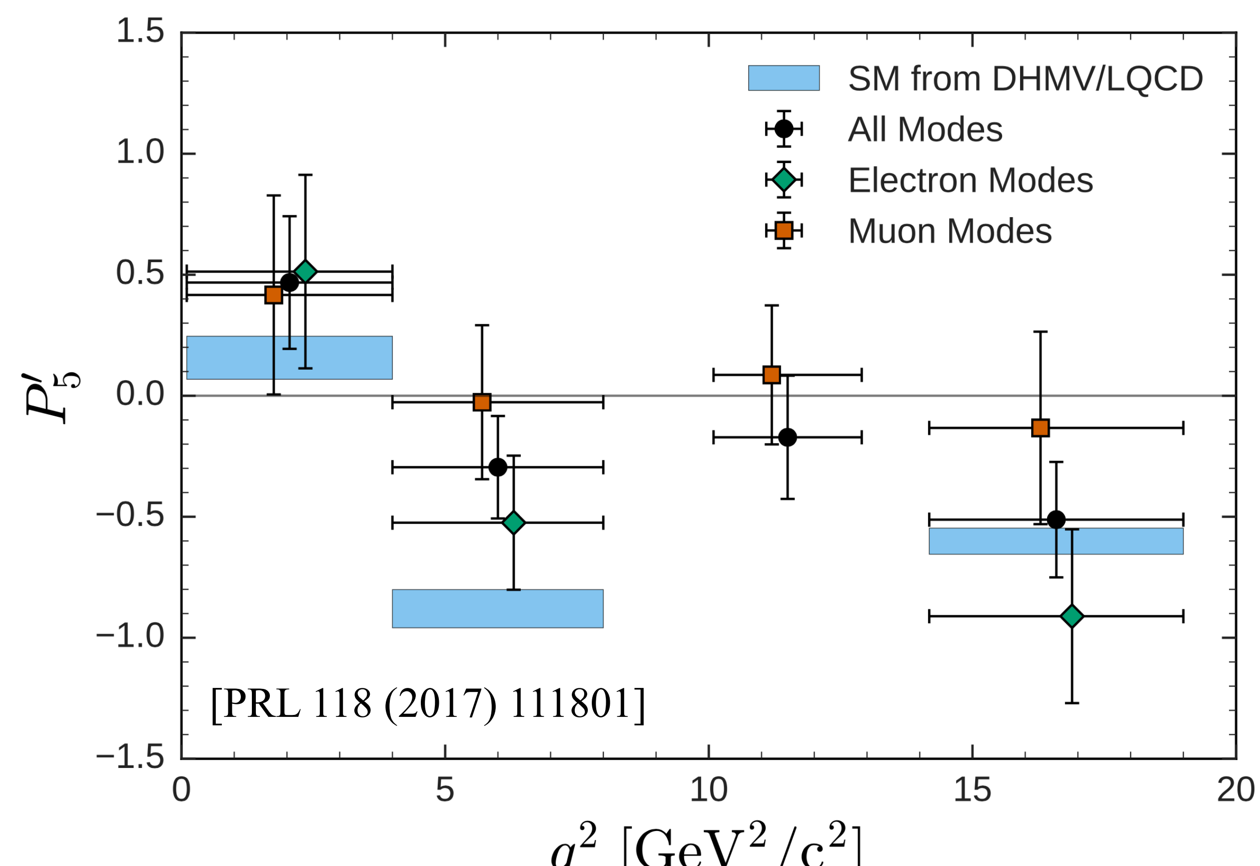
- Rare decays of b-hadrons are flavour changing neutral current decays that only occur at loop level in the Standard Model (SM) — sensitive to NP



- Tension with the SM in e.g. P'_5 of $B^0 \to K^{*0}\mu^+\mu^-$ — NP (~~LFU~~?) or QCD effects?

→ $B^0 \to K^{*0}e^+e^-$ can help!

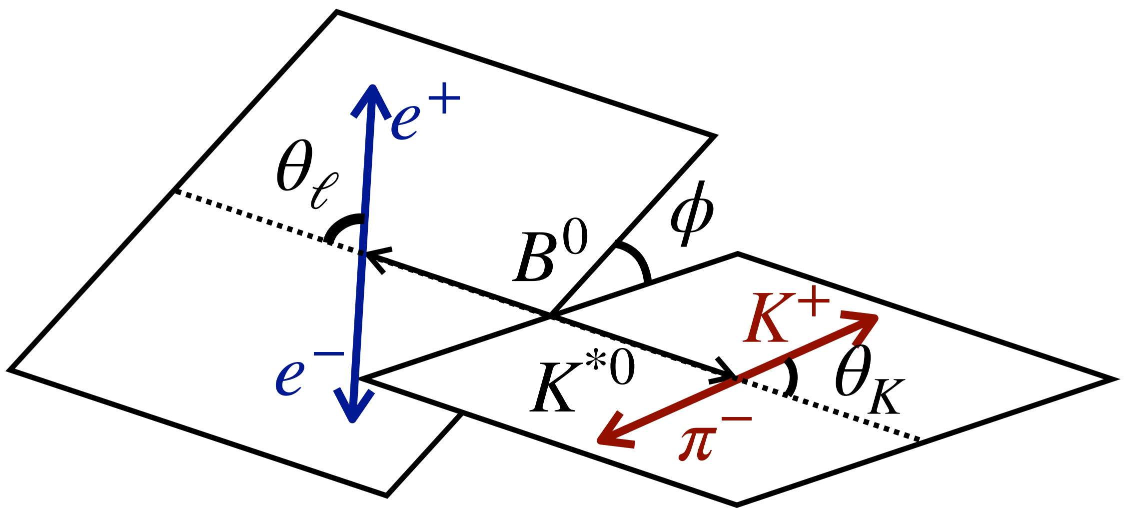




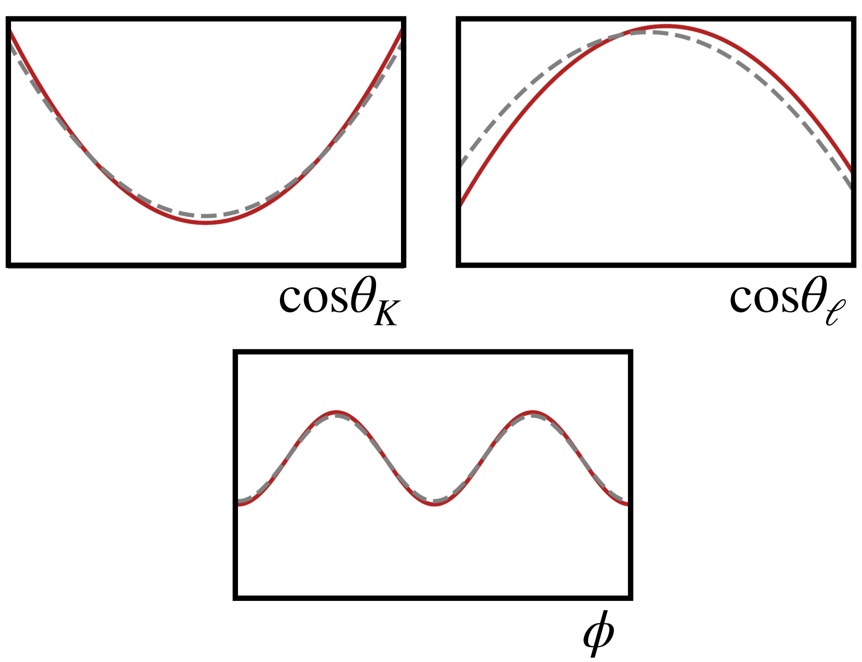
Analysis overview

- Distribution of the final state particles of $B^0 \to K^{*0} e^+ e^-$ can be described by three angles, $\cos\theta_K$, $\cos\theta_\ell$ and ϕ, and $q^2 = m_{ee}^2$

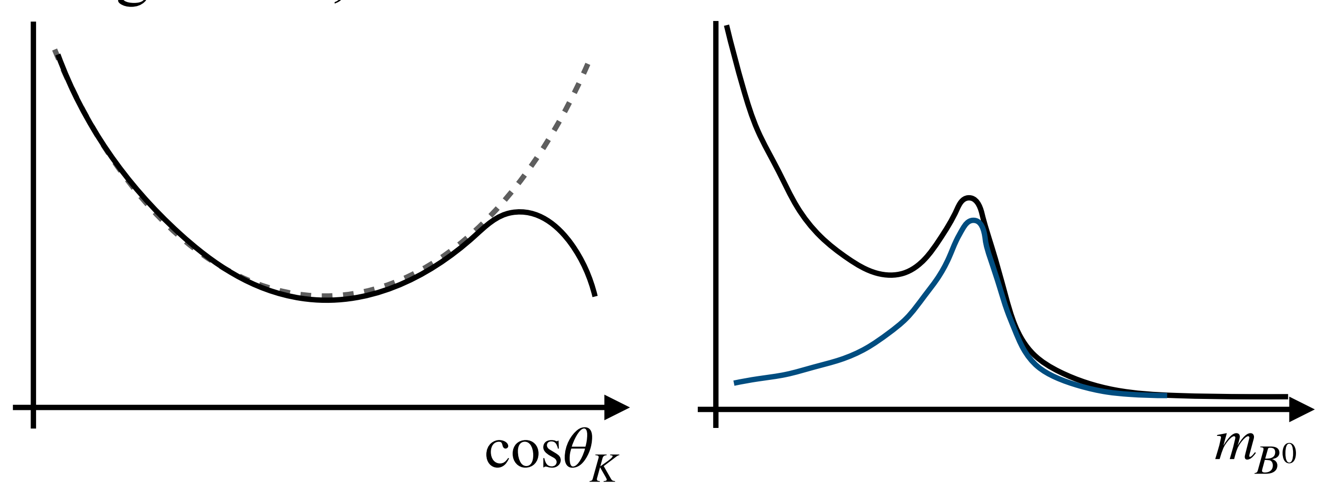
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin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



also e.g. $P_5' = \dfrac{S_5}{\sqrt{F_L(1-F_L)}}$ [JHEP, 05 (2013) 137]

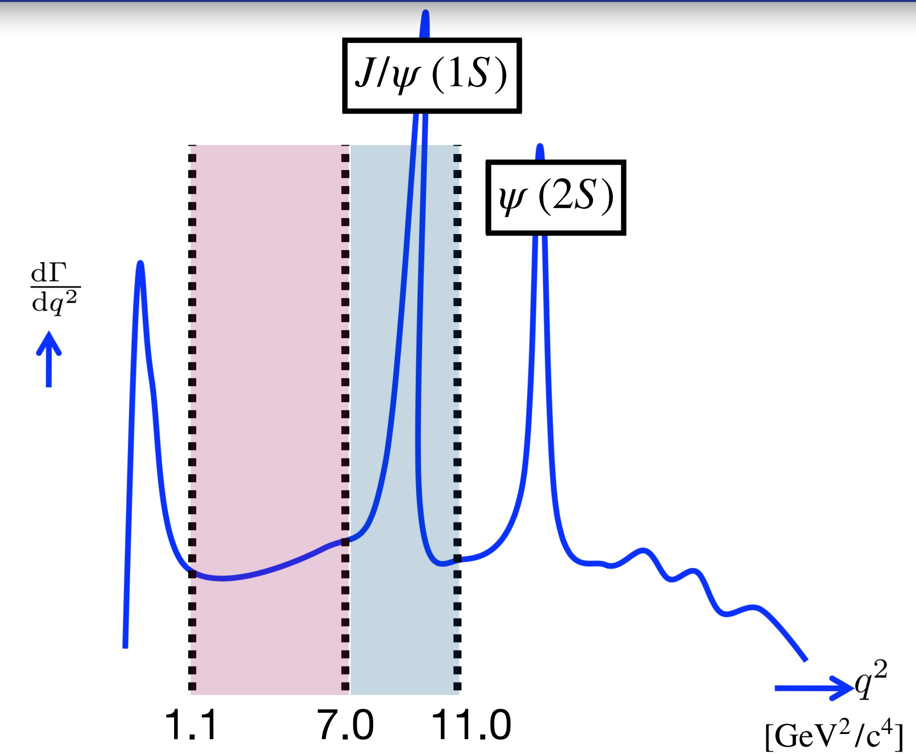


- **Complications**: acceptance + resolution, backgrounds, statistics

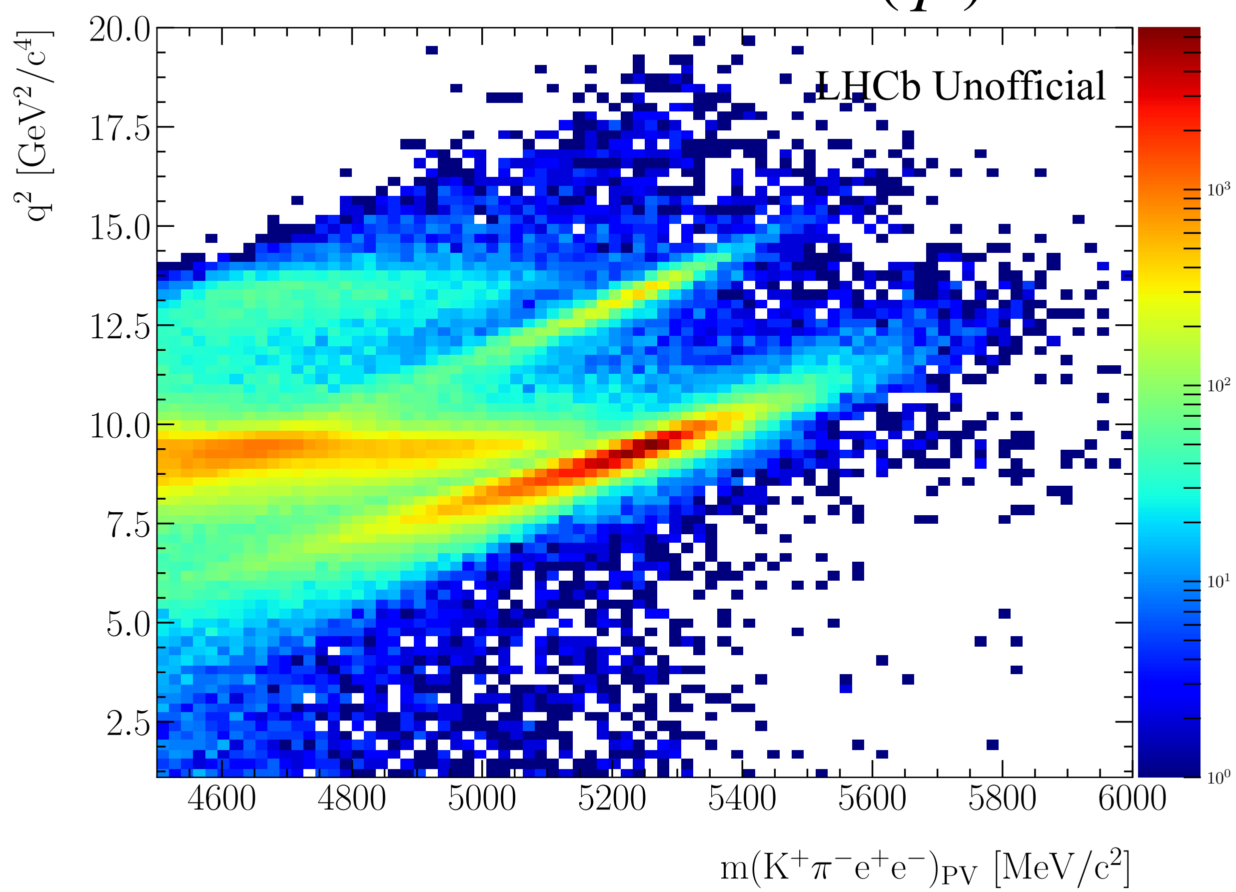


Analysis strategy

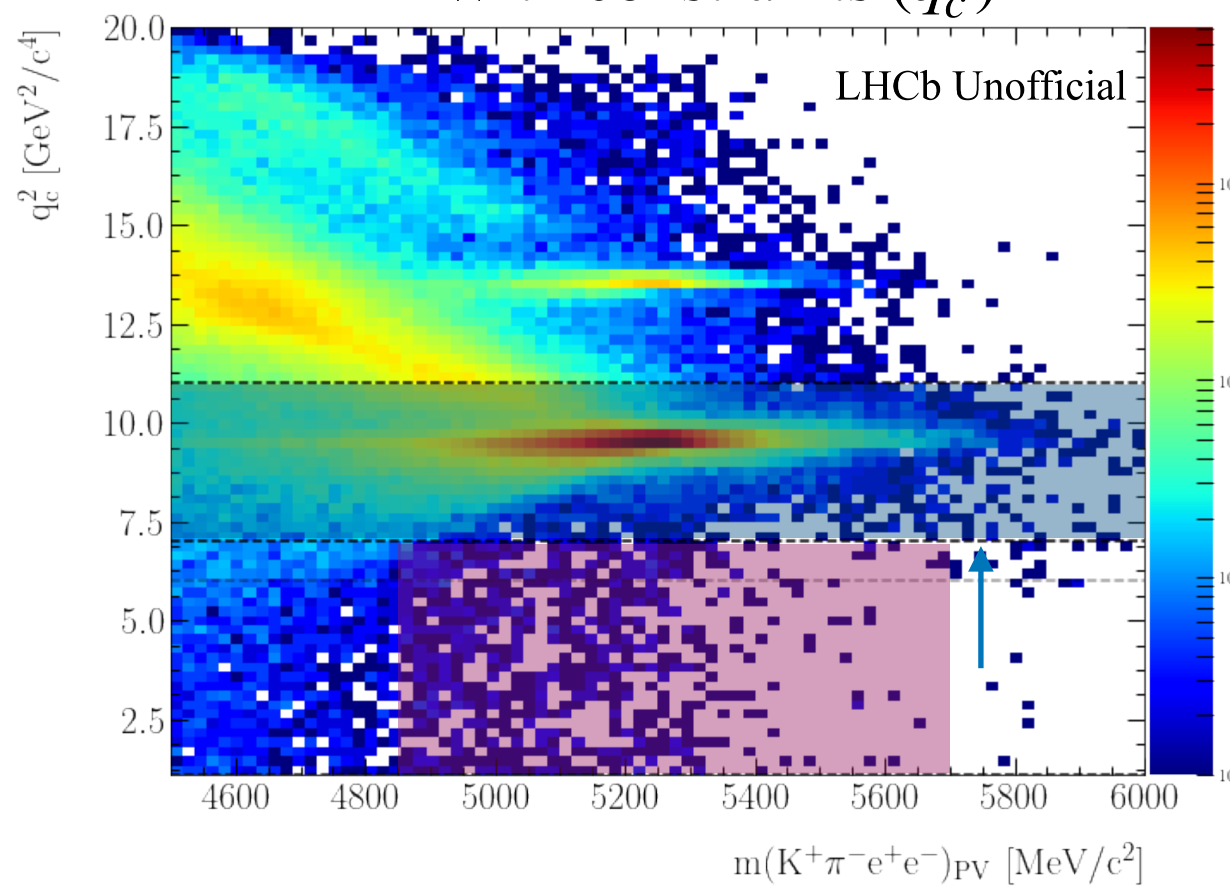
- Full Run 1 and Run 2 data
- Use q^2 calculated with B^0 PV and mass constraint (q_c^2)
- Measure in two bins of q_c^2
  - 1.1–6.0 GeV^2/c^4
  - 1.1–7.0 GeV^2/c^4 [feasible with q_c^2]
- Measure: S_i, $P_i^{(\prime)}$, $\Delta S_i = S_i^{\mu} - S_i^{e}$, $\Delta P_i^{(\prime)} = P_i^{(\prime)\mu} - P_i^{(\prime)e}$
- Use $B^0 \to K^{*0} J/\psi(\to e^+e^-)$ as control mode



Without constraints (q^2)

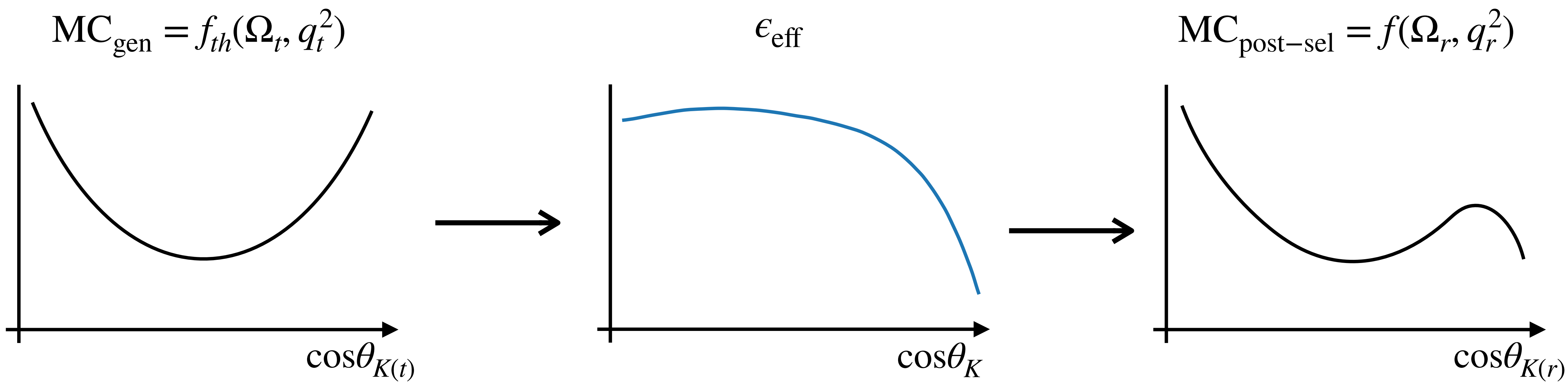


With constraints (q_c^2)



- Differential decay rate pdf does not describe angular distribution in data due to: FSR, acceptance and resolution effects
- If simulation (MC) can be trusted, then function that encodes the effective correction can be obtained via

$$\epsilon_{\rm eff} = {\rm MC}_{\rm post-sel}/{\rm MC}_{\rm gen}$$

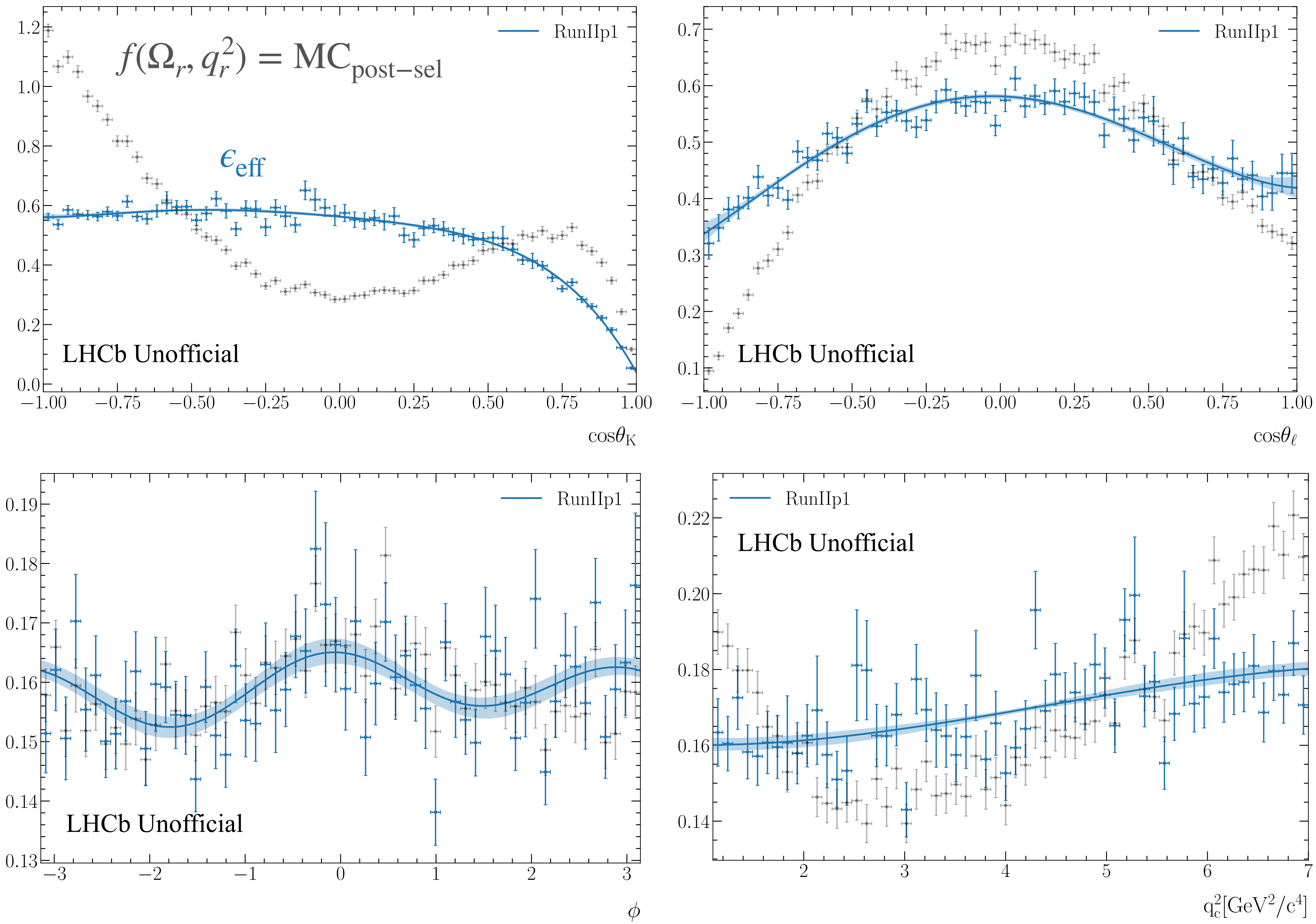


- Parametrisation of $\epsilon_{\rm eff}$ made in 4d without factorisation using Legendre polynomials and Fourier terms (Fourier more suitable for ϕ due to its periodic nature)

$$\epsilon_{\rm eff}(\cos\theta_\ell, \cos\theta_K\, \phi, q_c^2) = \sum_{klmn} c_{klmn}\, L_k(\cos\theta_\ell)\, L_l(\cos\theta_K)\, F_m(\phi)\, L_n(q_c^2)$$

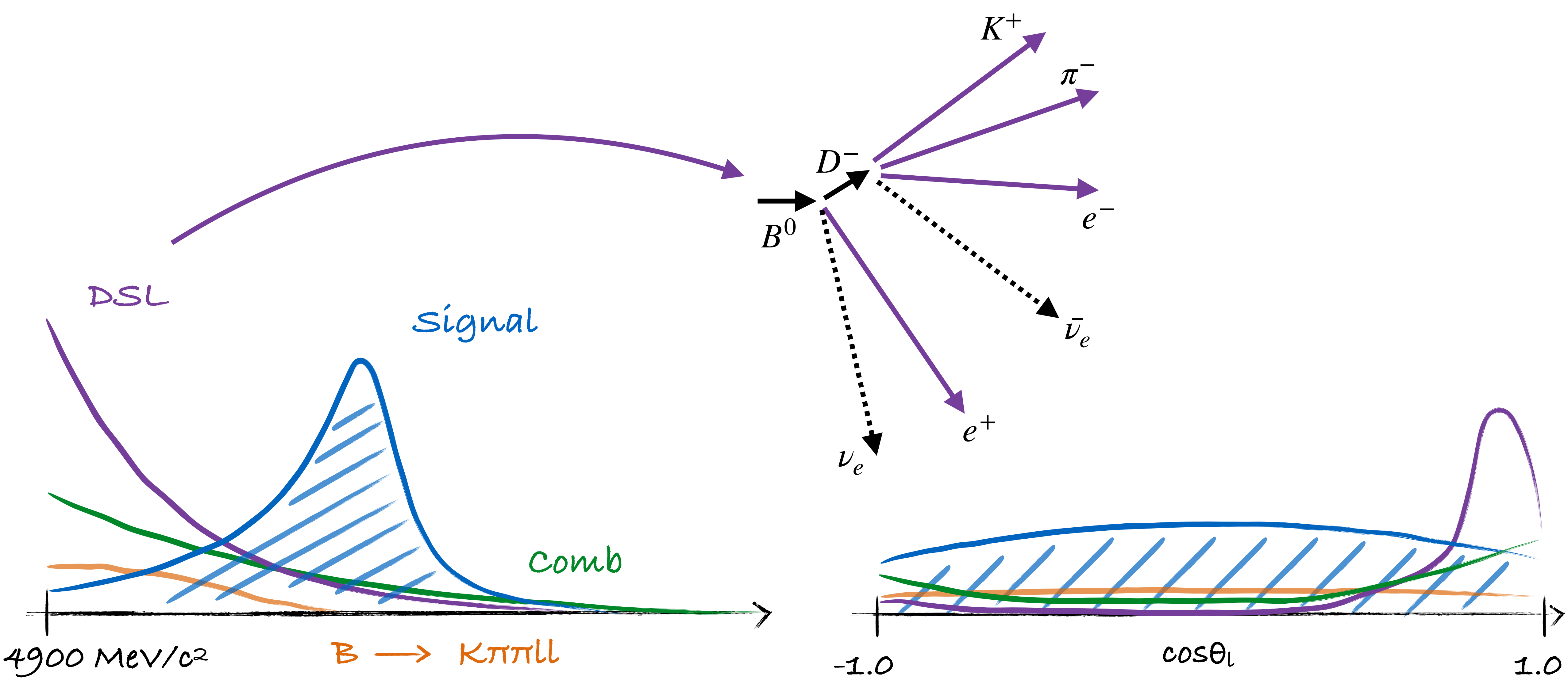
Acceptance example

- Effective acceptance function obtained from $B^0 \to K^{*0}e^+e^-$ simulation:



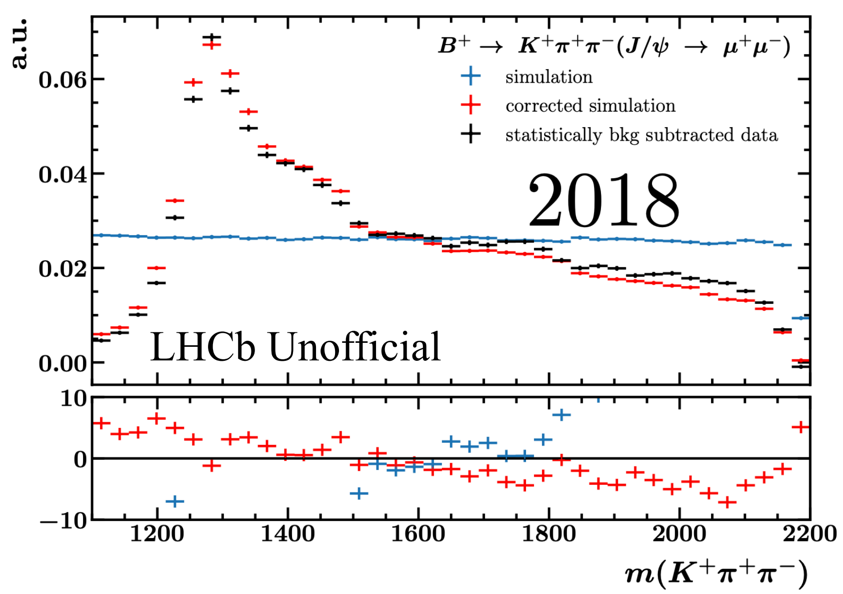
Background components

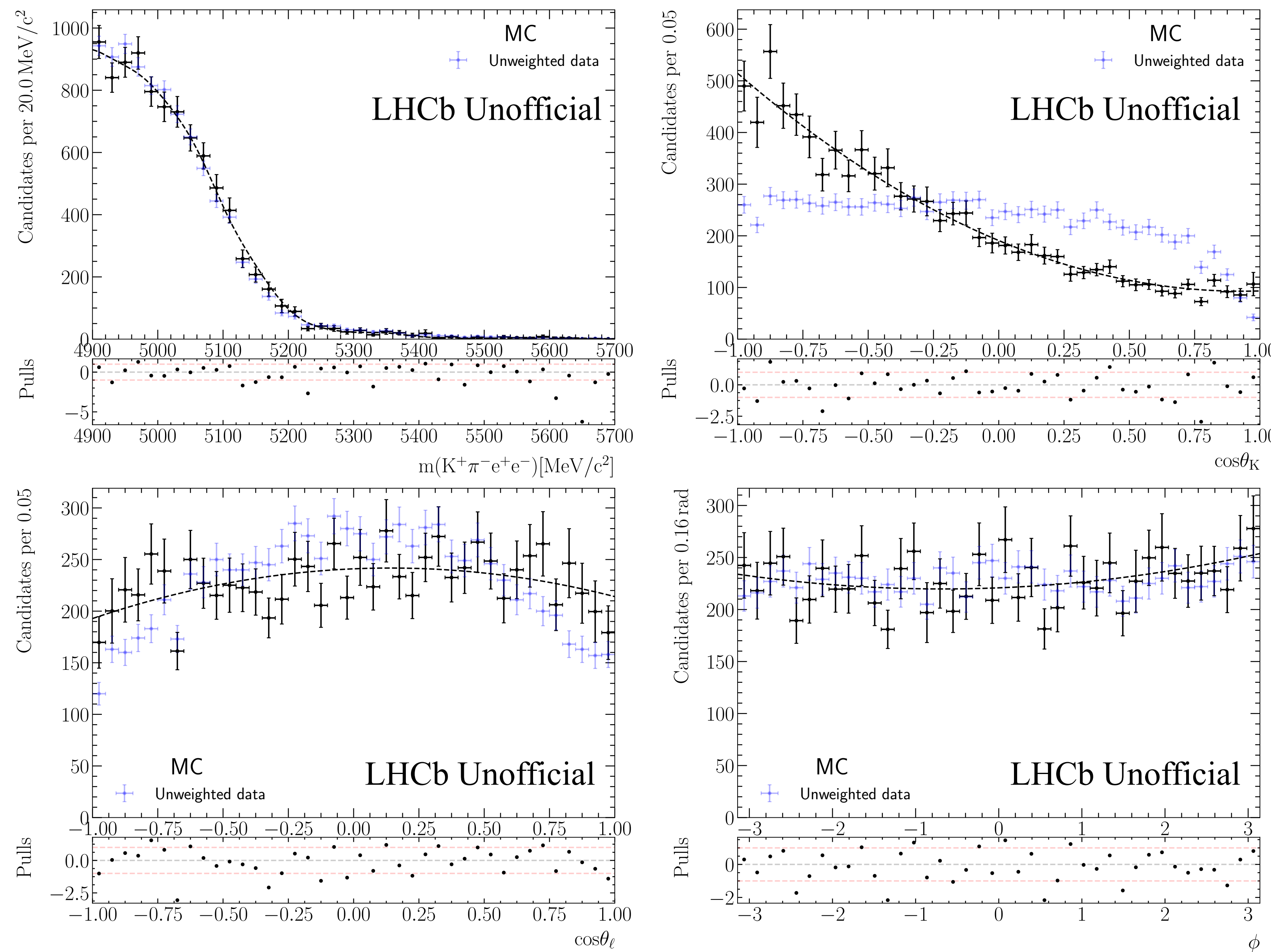
- Backgrounds modelled in the fit:
  - Partially reconstructed, e.g. $B \to (K_1/K_2 \to (K^{*0} \to K^+\pi^-)\pi)\, e^+e^-$
  - Double semi-leptonic (DSL), e.g. $B^0 \to D^-(\to K^{*0}e^-\bar{\nu}_e)\, e^+\nu_e$
  - Combinatorial



Partially reconstructed background

- Hadronic system difficult to model from simulation
- Use $B^+ \to K_1^+(\to K^+\pi^+\pi^-)e^+e^-$ simulation generated flat in $m(K^\pm\pi^\mp\pi^\pm)$ reweighed to resemble background subtracted data from $B^+ \to K^+\pi^+\pi^-(J/\psi \to \mu^+\mu^-)$
- KDE for mass modelling; Chebyshev polynomials up to 2nd order used for angles

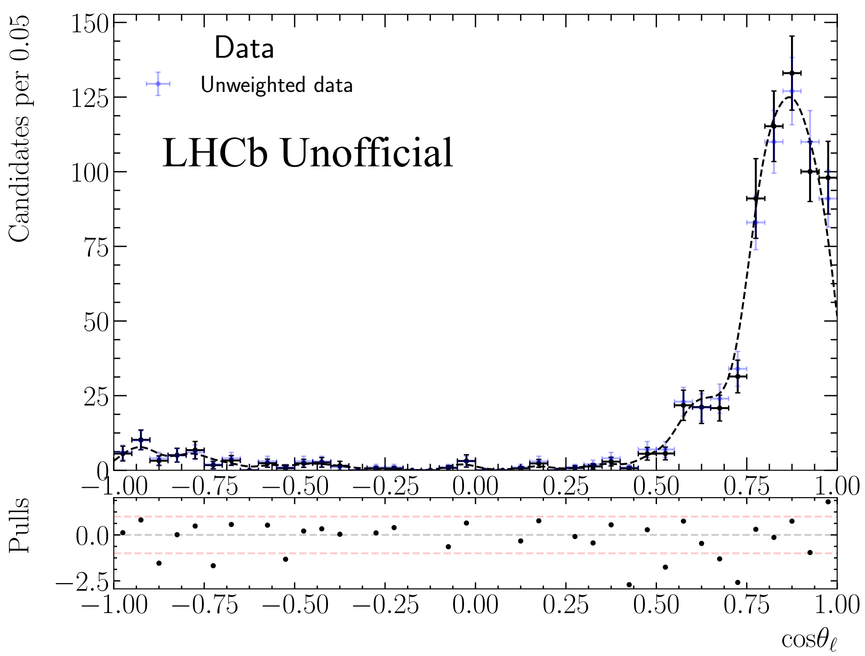




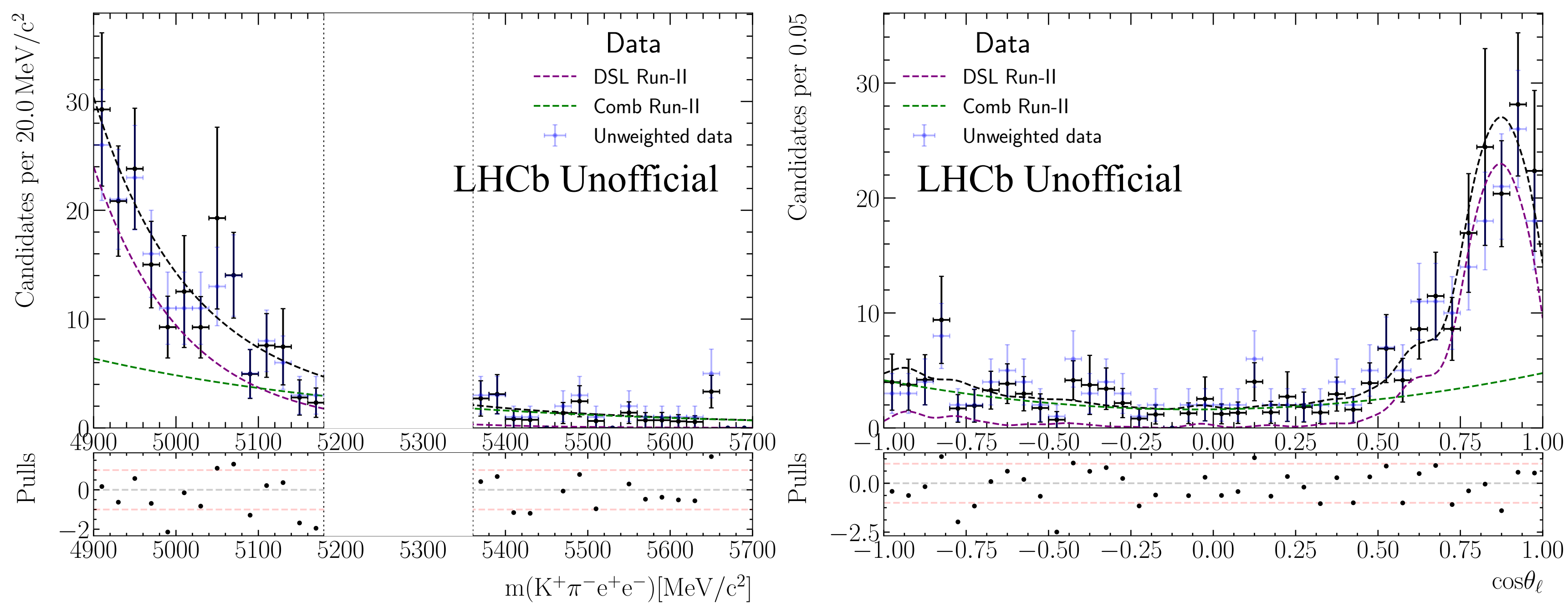
DSL and combinatorial

- Reconstruction of e.g. $B^0 \to D^-(\to K^{*0} e^- \bar{\nu}_e)\, e^+ \nu_e$ as signal
- Challenging to simulate due to presence of multiple modes and partly combinatorial contributions — use data-driven approach
- Extract models for DSL (effective) and combinatorial using LFV $K^+\pi^-e^+\mu^-$ sample
  - Step 1: obtain DSL angular model
  - Step 2: fix DSL angular shape from Step 1, obtain slope of DSL mass distribution as well as combinatorial slope and angular parameters

1



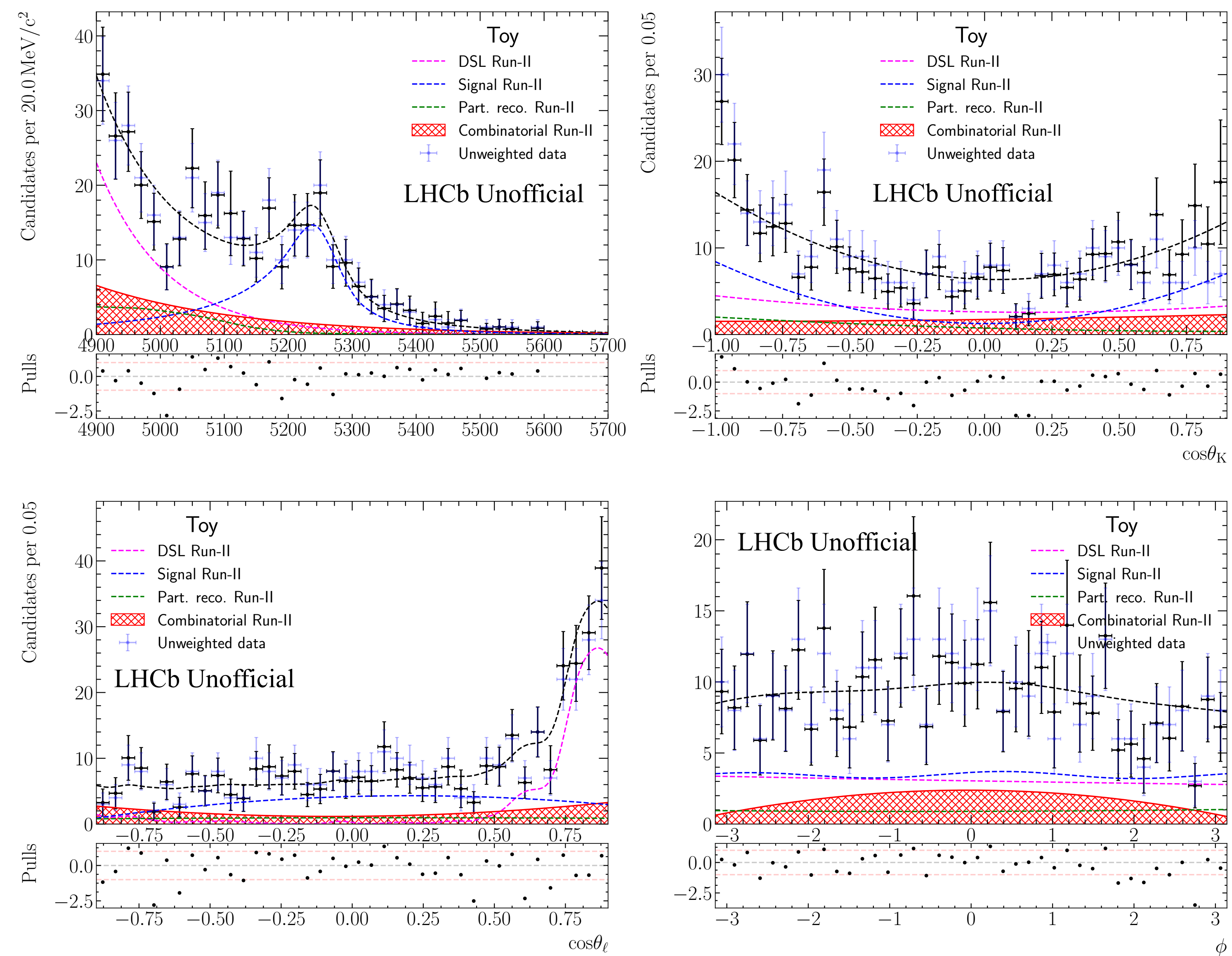
2



Realistic pseudoexperiments

- Generate toys for sensitivity studies including effective acceptance
- Use component yields obtained from simplified data fit ($N_{\text{sig}} = \mathcal{O}(600)$)
- Fit in reduced phase-space region

Example toy fit



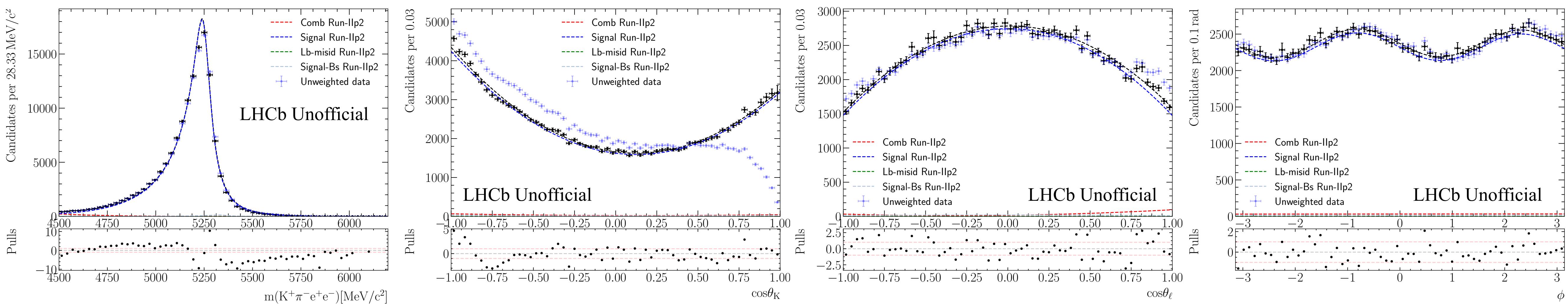
Expected sensitivities

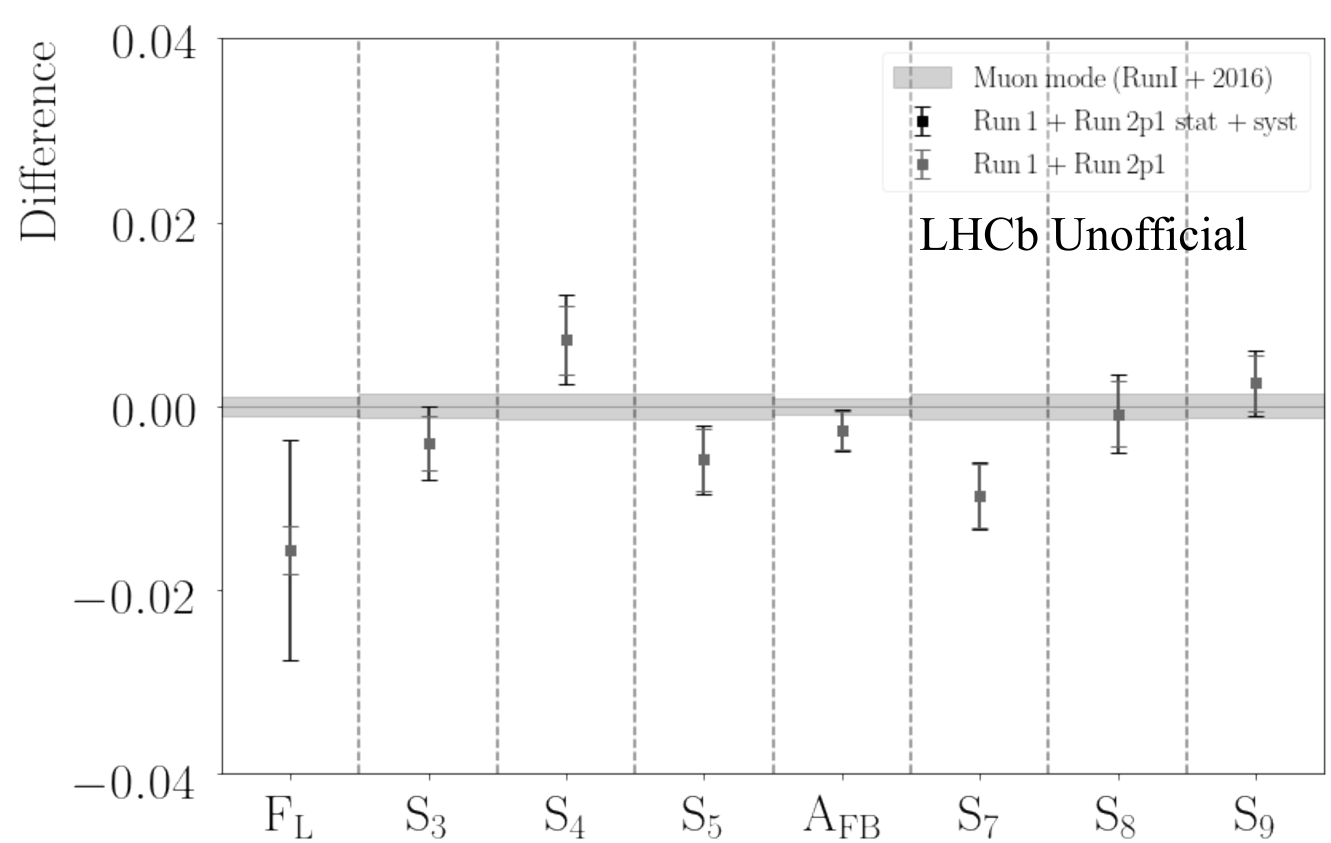
	$1.1 < q_c^2 < 7.0$	$1.1 < q_c^2 < 6.0$
F_L	0.0404 ± 0.0009	0.0458 ± 0.0010
P_1	0.295 ± 0.006	0.380 ± 0.008
P_4'	0.1354 ± 0.0029	0.164 ± 0.004
P_5'	0.1206 ± 0.0026	0.1436 ± 0.0032
P_2	0.1024 ± 0.0022	0.1334 ± 0.0030
P_6'	0.1178 ± 0.0025	0.1410 ± 0.0031
P_8'	0.1400 ± 0.0030	0.167 ± 0.004
P_3	0.1478 ± 0.0032	0.187 ± 0.004

- For $1.1 < q^2 < 6.0\,\text{GeV}^2/c^4$
  - $B^0 \to K^{*0}e^+e^-$ $\sigma_{\text{stat}}^{P_5'e} = 0.14$
  - $B^0 \to K^{*0}\mu^+\mu^-$ $\sigma_{\text{stat+syst}}^{P_5'\mu} = 0.07$ (Run 1 + 2016) [PRL 125 (2020) 011802]

Control mode validation

- Check angular fit strategy using control mode of $B^0 \to K^{*0}(\to K^+\pi^-)J/\psi(\to e^+e^-)$
- Compare against observable values of $B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-)$
- Main source of systematic uncertainty: simulation correction strategy





Summary and status

- Angular analysis of $B^0 \to K^{*0}(\to K^+\pi^-)e^+e^-$ decays can help clarify the nature of the anomalies in $b \to s\mu^+\mu^-$ (e.g. $B^0 \to K^{*0}\mu^+\mu^-$)
- Added more data since last presentation (2021), now use full Run 1 and Run 2 statistics ($N_{\rm sig} = \mathcal{O}(600)$)
- Analysis under collaboration review — performed many checks, but more to go…
- Pending: systematic uncertainties, cross-checks
- Old timeline (2021) too optimistic — currently aiming for publication next year

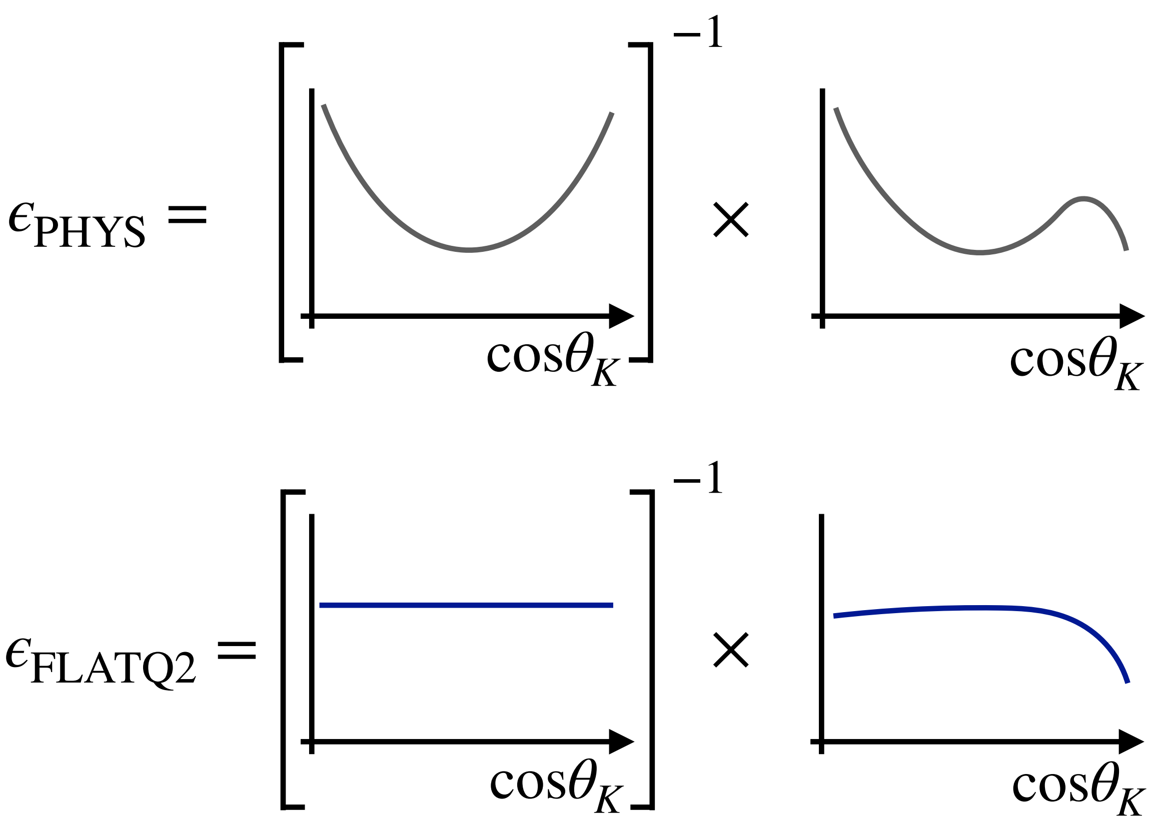
Backup

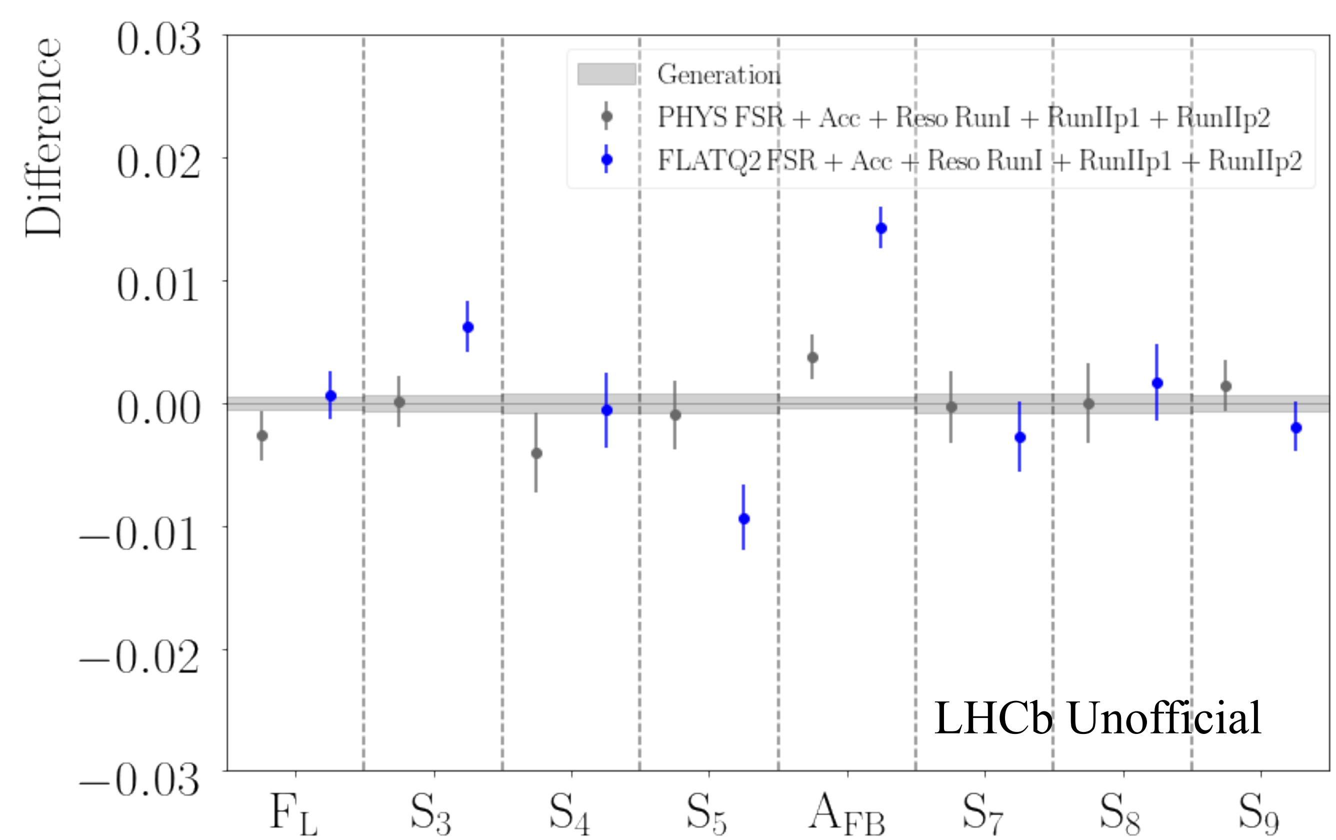
Acceptance simulation choice

- The parametrisation is made in 4d without factorisation using Legendre and Fourier terms:

$$\epsilon_{\text{eff}}(\cos\theta_\ell, \cos\theta_K\, \phi, q_c^2) = \sum_{klmn} c_{klmn}\, L_k(\cos\theta_\ell)\, L_l(\cos\theta_K)\, F_m(\phi)\, L_n(q_c^2)$$

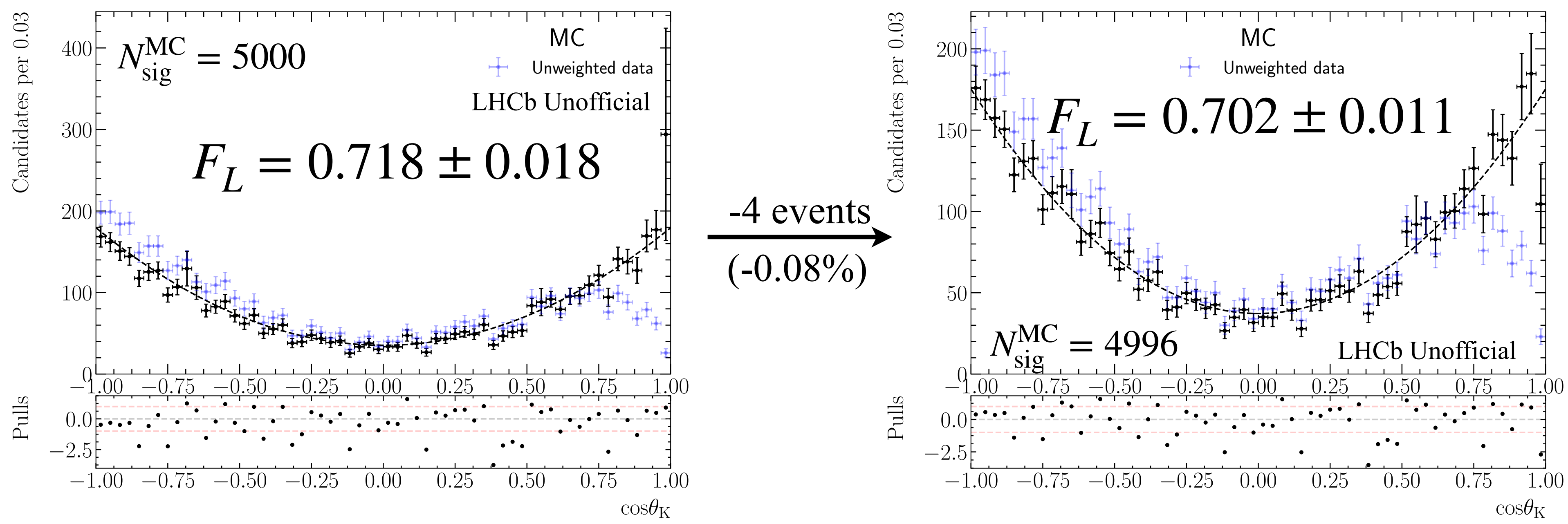
- Use effective ‘acceptance’ function: parametrise acceptance + FSR + resolution together
- Cost of approach: dependent on underlying physics of the simulation
  - Uniform (‘FLATQ2’) MC != physics MC



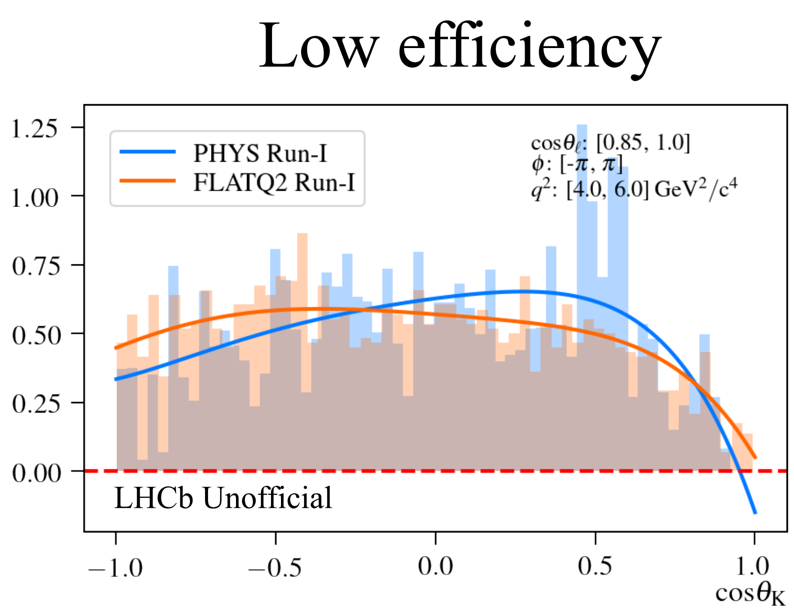


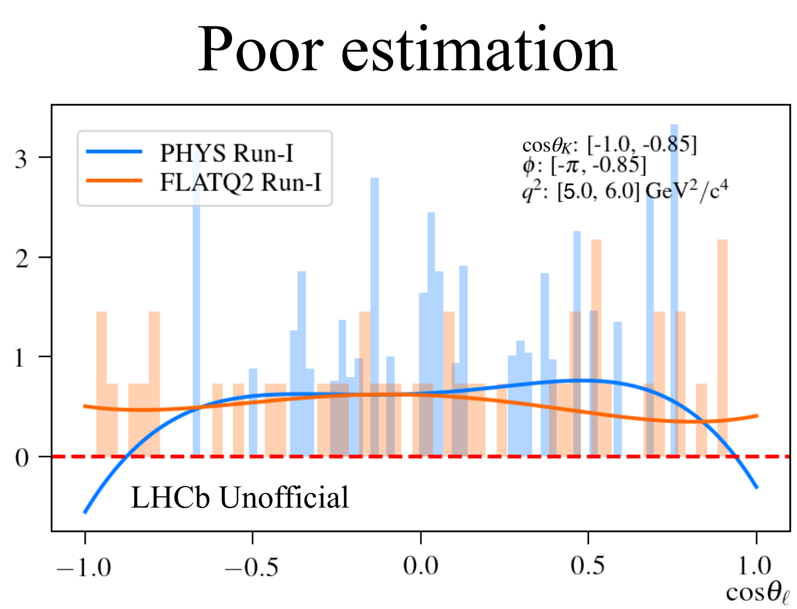
Pathological acceptance weights

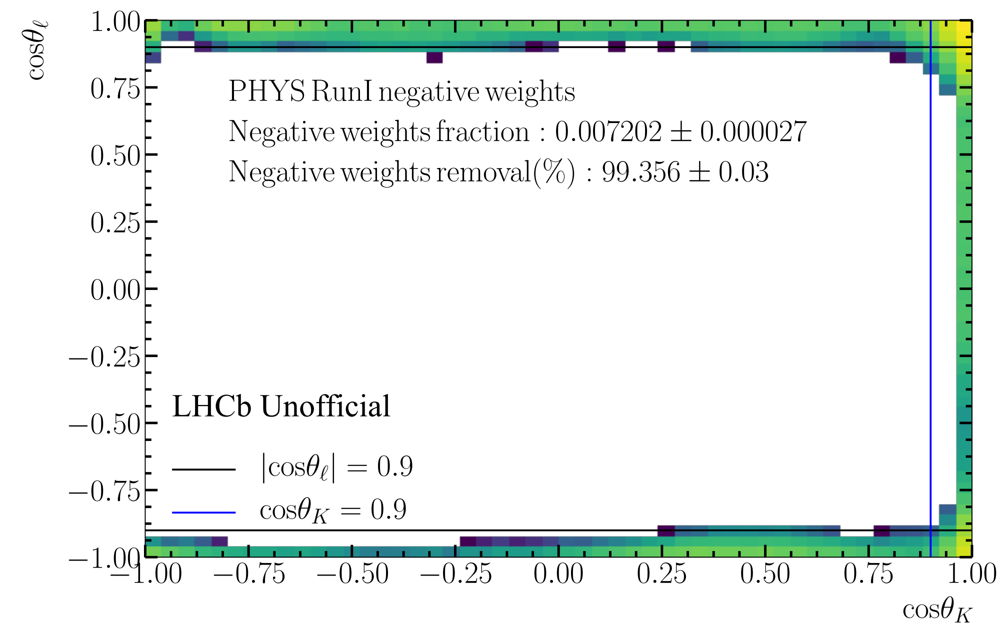
- The parametrisation of ϵ_{eff} from physics MC with underpopulated regions, and the application of ϵ_{eff} to small samples can lead to pathological behaviour, e.g.



- Affected region well defined — cut of: $|\cos\theta_\ell| < 0.9$ & $\cos\theta_K < 0.9$ significantly reduces instances of negative/large weights



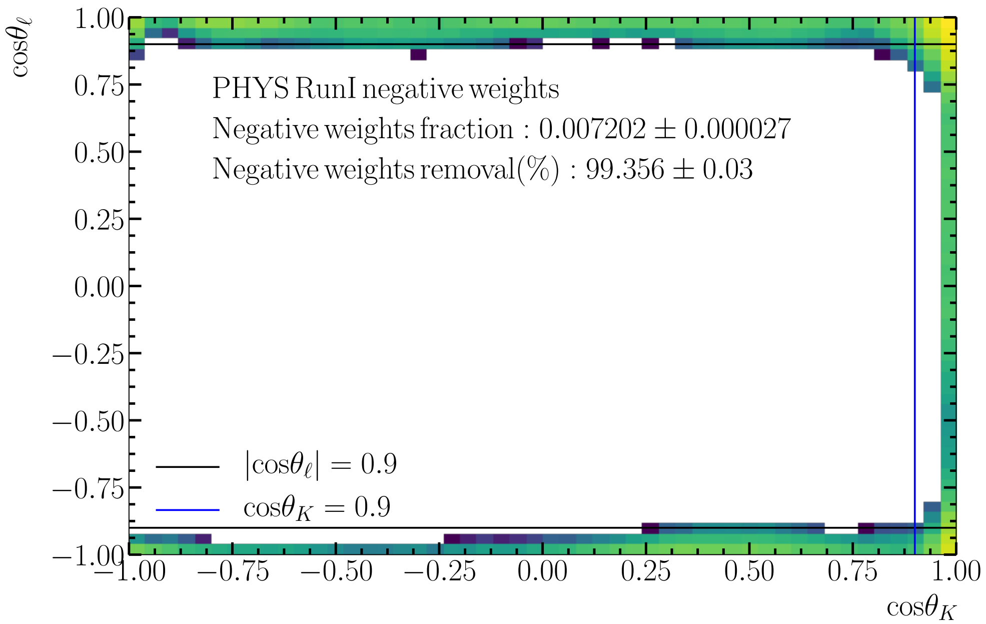




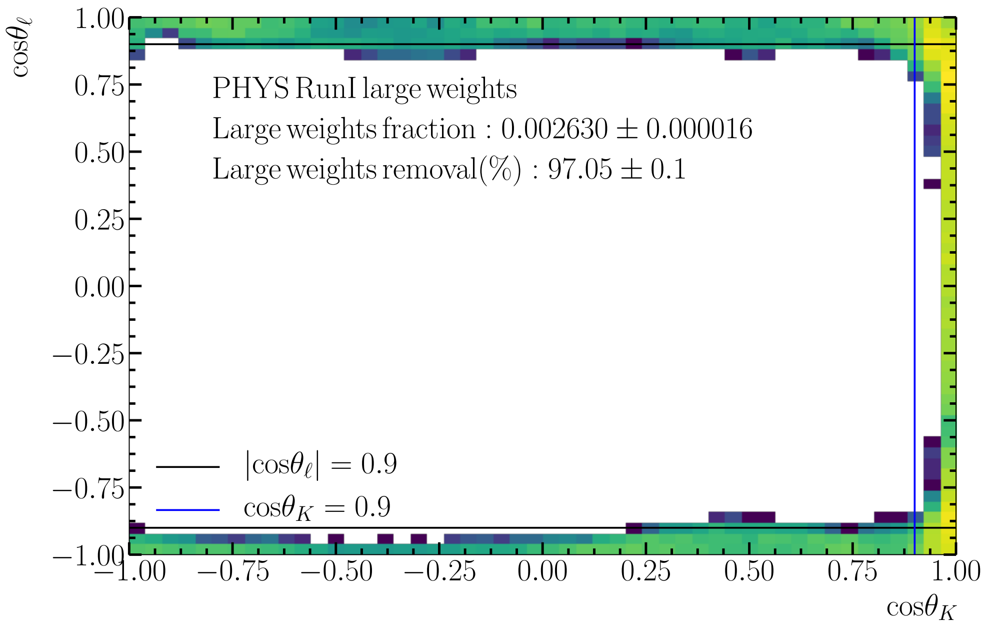
Acceptance strategy revision

Revision of nominal acceptance choice

- Low efficiency regions are typically located near the edges of $\cos\theta_\ell$ and $\cos\theta_K = 1$
- Simple cut of: $|\cos\theta_\ell| < 0.9$ & $\cos\theta_K < 0.9$ significantly reduces instances of negative/large weights and lead to FLATQ2-like behaviour in pseudoexperiment studies



Without cut



With cut

	Sensitivity	Pull mean	Pull width
F_L	0.0418 ± 0.0011	-0.30 ± 0.04	1.041 ± 0.028
P_1	0.289 ± 0.008	0.07 ± 0.04	1.007 ± 0.027
P'_4	0.1348 ± 0.0035	0.02 ± 0.04	1.010 ± 0.027
P'_5	0.1202 ± 0.0028	0.11 ± 0.04	1.027 ± 0.028
P_2	0.0935 ± 0.0025	0.15 ± 0.04	1.048 ± 0.028
P'_6	0.1173 ± 0.0032	-0.01 ± 0.04	1.006 ± 0.027
P'_8	0.141 ± 0.004	0.01 ± 0.04	1.028 ± 0.028
P_3	0.143 ± 0.004	-0.03 ± 0.04	1.002 ± 0.027

	Sensitivity	Pull mean	Pull width
F_L	0.0389 ± 0.0011	-0.17 ± 0.04	1.000 ± 0.028
P_1	0.291 ± 0.008	0.08 ± 0.04	1.002 ± 0.028
P'_4	0.136 ± 0.004	0.01 ± 0.04	1.002 ± 0.028
P'_5	0.1223 ± 0.0034	0.04 ± 0.04	1.044 ± 0.029
P_2	0.1006 ± 0.0028	0.01 ± 0.04	1.028 ± 0.028
P'_6	0.1184 ± 0.0033	-0.00 ± 0.04	1.011 ± 0.028
P'_8	0.138 ± 0.004	0.02 ± 0.04	0.988 ± 0.027
P_3	0.145 ± 0.004	-0.04 ± 0.04	1.007 ± 0.028

Updated sensitivity studies

- Updated pseudoexperiments are produced with the updated PHYS acceptances and the following yields:

Component	Run 1	Run 2p1	Run 2p2
Signal	114	170	342
Combinatorial	75	53	104
Partially reconstructed	23	35	24
DSL	94	141	164

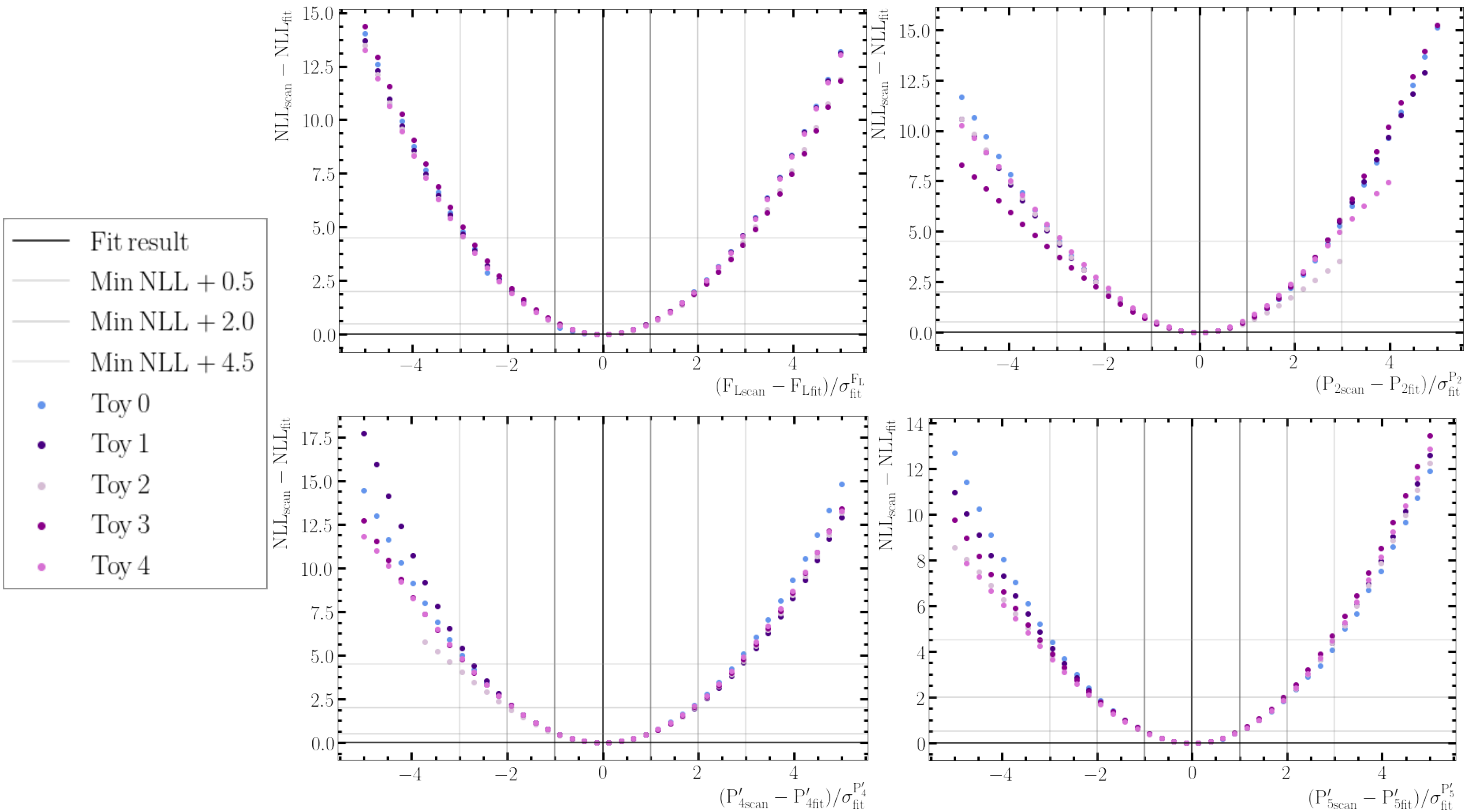
- Around 1000 pesudoexperiments are fitted with the cut of $|\cos\theta_\ell| < 0.9$ & $\cos\theta_K < 0.9$:

$1.1 < q_c^2 < 7.0$, SM	Sensitivity	Pull mean	Pull width
F_L	0.0403 ± 0.0009	-0.163 ± 0.032	1.027 ± 0.023
S_3	0.0376 ± 0.0008	0.036 ± 0.032	1.031 ± 0.023
S_4	0.0589 ± 0.0013	0.017 ± 0.032	1.017 ± 0.022
S_5	0.0499 ± 0.0011	0.015 ± 0.032	1.039 ± 0.023
A_{FB}	0.0379 ± 0.0008	0.071 ± 0.032	1.017 ± 0.022
S_7	0.0509 ± 0.0011	-0.027 ± 0.031	1.003 ± 0.022
S_8	0.0602 ± 0.0013	0.015 ± 0.031	0.993 ± 0.022
S_9	0.0378 ± 0.0008	0.002 ± 0.032	1.025 ± 0.023
F_L	0.0404 ± 0.0009	-0.156 ± 0.032	1.035 ± 0.022
P_1	0.295 ± 0.006	0.031 ± 0.031	1.021 ± 0.022
P_4'	0.1354 ± 0.0029	0.024 ± 0.031	1.001 ± 0.022
P_5'	0.1206 ± 0.0026	0.060 ± 0.031	1.033 ± 0.022
P_2	0.1024 ± 0.0022	0.046 ± 0.031	1.022 ± 0.022
P_6'	0.1178 ± 0.0025	-0.020 ± 0.031	1.005 ± 0.022
P_8'	0.1400 ± 0.0030	0.014 ± 0.030	0.995 ± 0.021
P_3	0.1478 ± 0.0032	-0.003 ± 0.031	1.010 ± 0.022

$1.1 < q_c^2 < 6.0$, SM	Sensitivity	Pull mean	Pull width
F_L	0.0453 ± 0.0010	-0.148 ± 0.033	1.021 ± 0.023
S_3	0.0424 ± 0.0010	0.028 ± 0.033	1.046 ± 0.024
S_4	0.0681 ± 0.0016	-0.019 ± 0.033	1.035 ± 0.024
S_5	0.0559 ± 0.0013	0.018 ± 0.033	1.032 ± 0.024
A_{FB}	0.0427 ± 0.0010	0.052 ± 0.033	1.021 ± 0.023
S_7	0.0588 ± 0.0013	-0.043 ± 0.033	1.034 ± 0.024
S_8	0.0690 ± 0.0016	0.012 ± 0.033	1.011 ± 0.023
S_9	0.0418 ± 0.0010	-0.008 ± 0.033	1.031 ± 0.024
F_L	0.0458 ± 0.0010	-0.152 ± 0.033	1.049 ± 0.023
P_1	0.380 ± 0.008	0.022 ± 0.032	1.013 ± 0.023
P_4'	0.164 ± 0.004	0.008 ± 0.033	1.011 ± 0.023
P_5'	0.1436 ± 0.0032	0.057 ± 0.032	1.022 ± 0.023
P_2	0.1334 ± 0.0030	0.052 ± 0.032	0.999 ± 0.022
P_6'	0.1410 ± 0.0031	-0.042 ± 0.032	1.020 ± 0.023
P_8'	0.167 ± 0.004	0.009 ± 0.032	1.000 ± 0.022
P_3	0.187 ± 0.004	-0.002 ± 0.032	1.000 ± 0.022

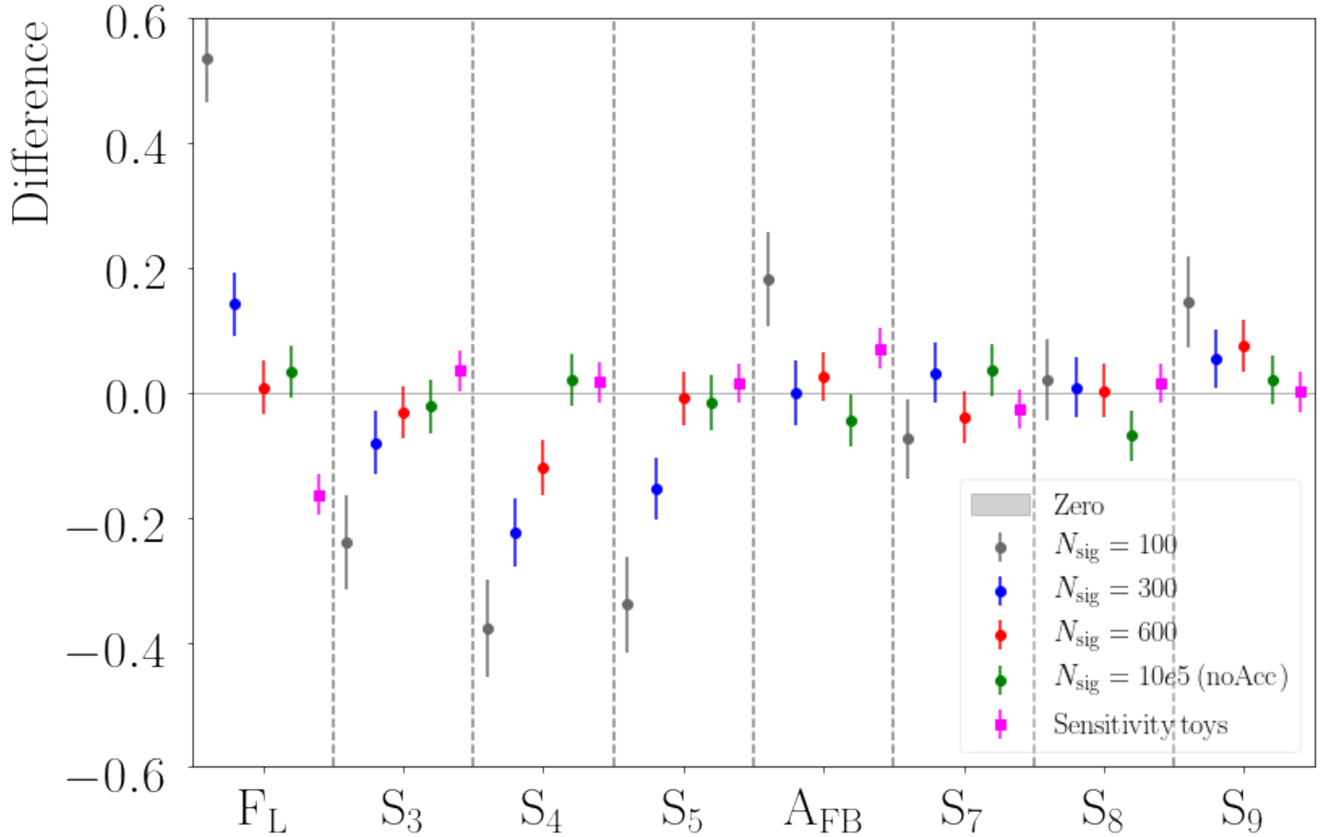
Likelihood scans

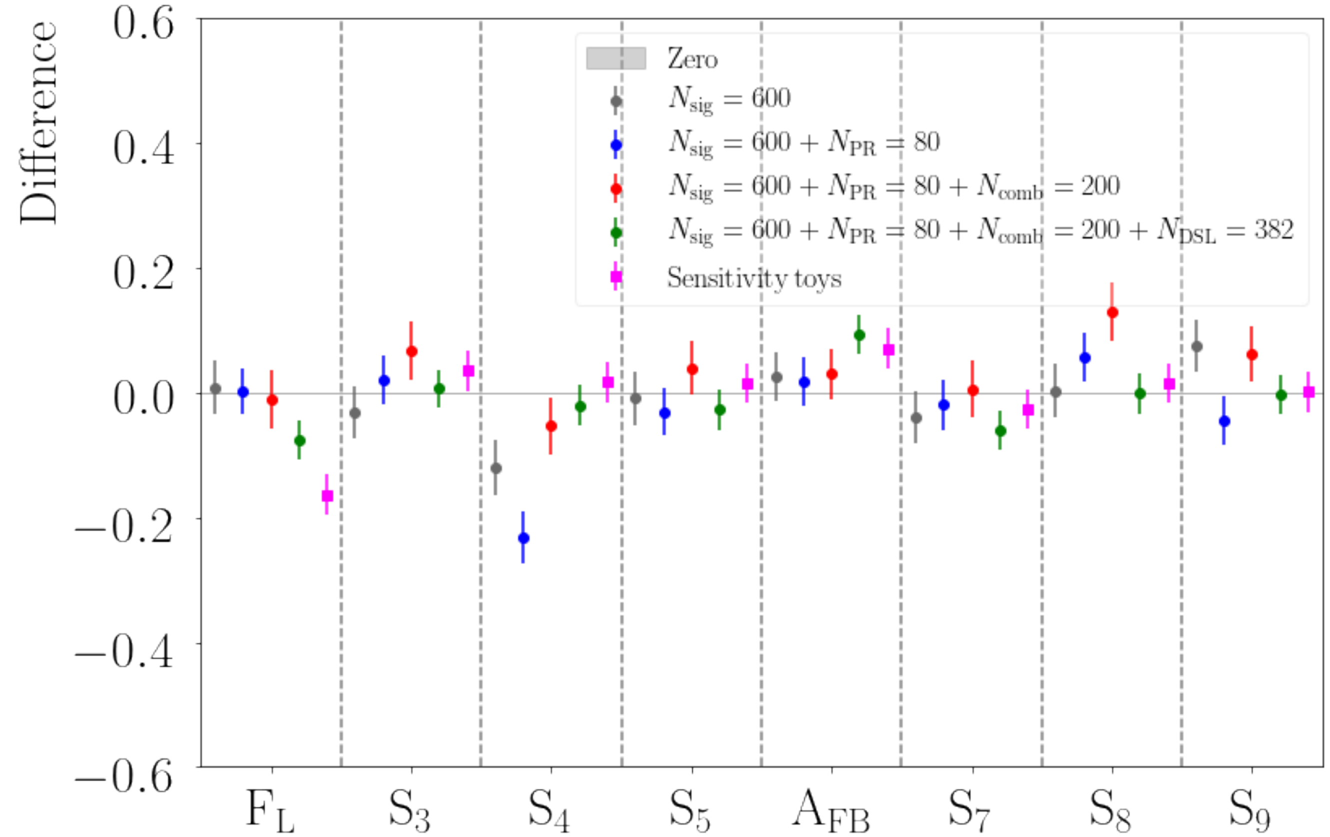
- Performed likelihood scans in 1d for five SM pseudoexperiments by repeating the fit with the value of a given observable fixed to a range of values about the best-fit result:



Toy behaviour

- Investigated possible causes of F_L, A_{FB} toy biases
- F_L, A_{FB} bias may be due to physical boundary of signal pdf, but in this case signal-only toys do not show the same effect

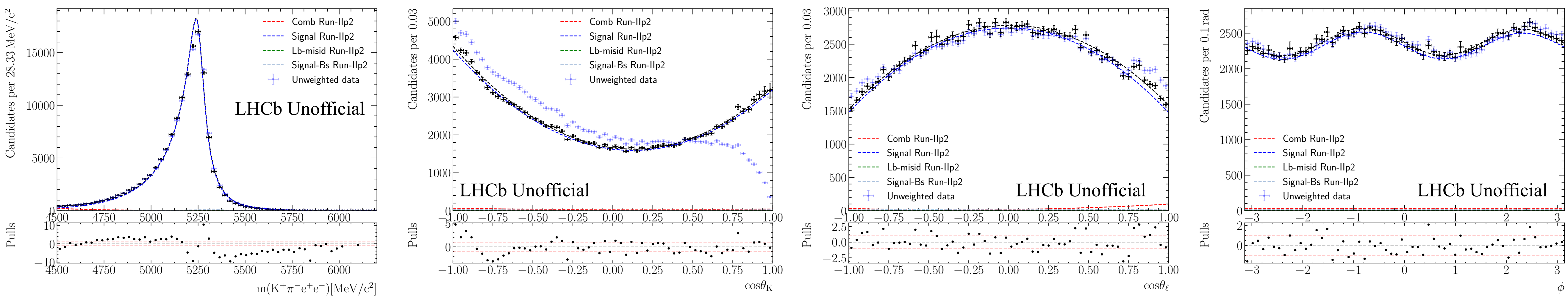


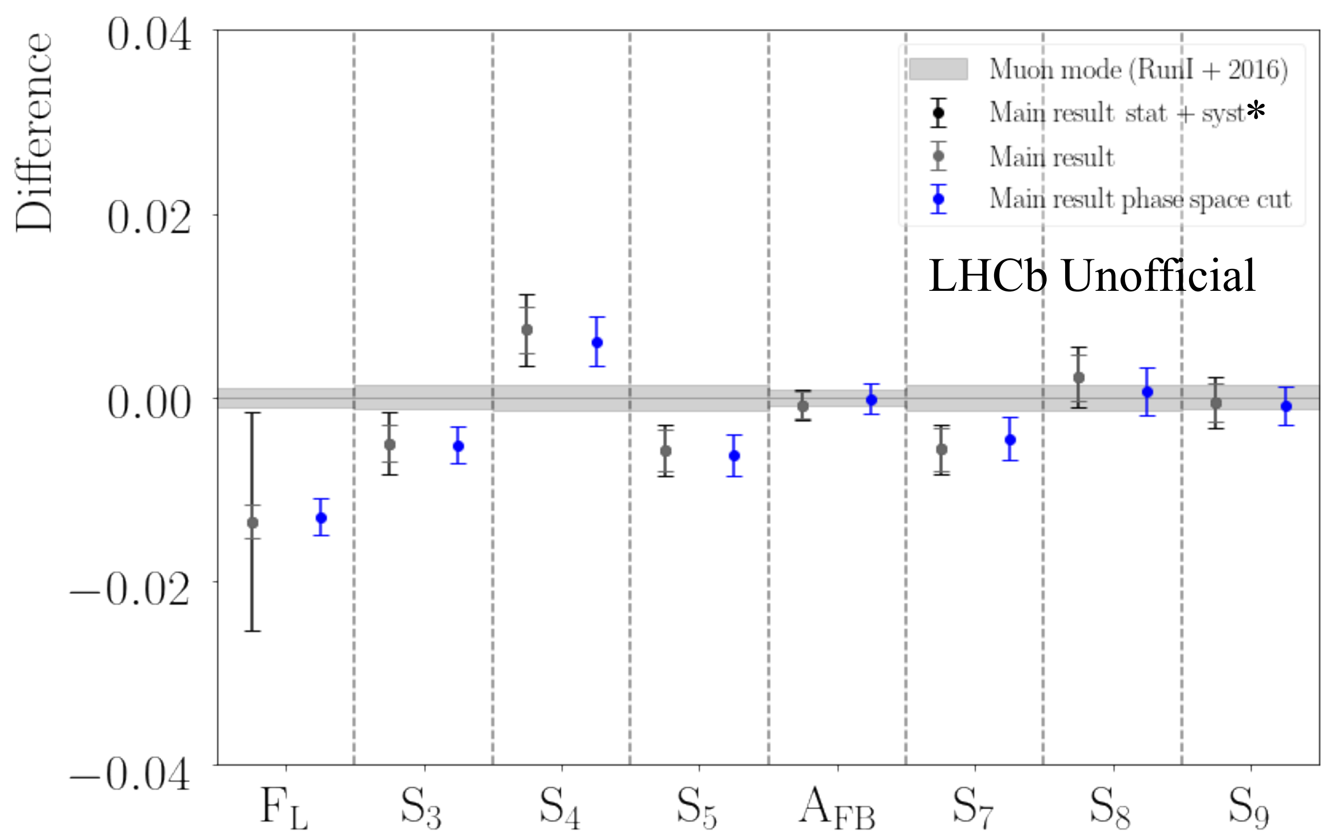


- Instead they seem to be related to signal-background separation, and likely depends on the background shape
- Plan to take into account as systematic uncertainty (rather than corrections)

Control mode fit updates

- 2017-2018 data added, fit made with/without phase-space cut
- Compare against observable values of $B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-)$ [LHCb-ANA-2017-055]
- Main source of systematic uncertainty: simulation correction strategy





*Updated systematics assessment (+2017 and 2018) pending