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

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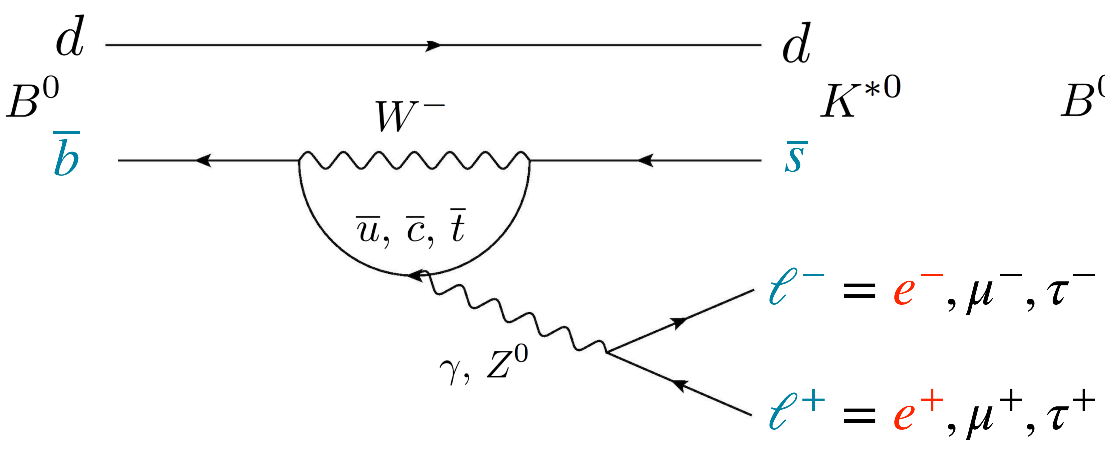
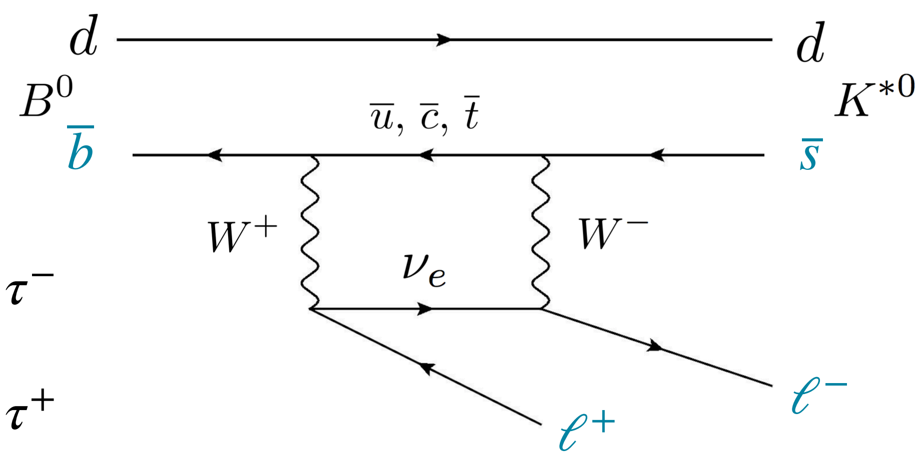
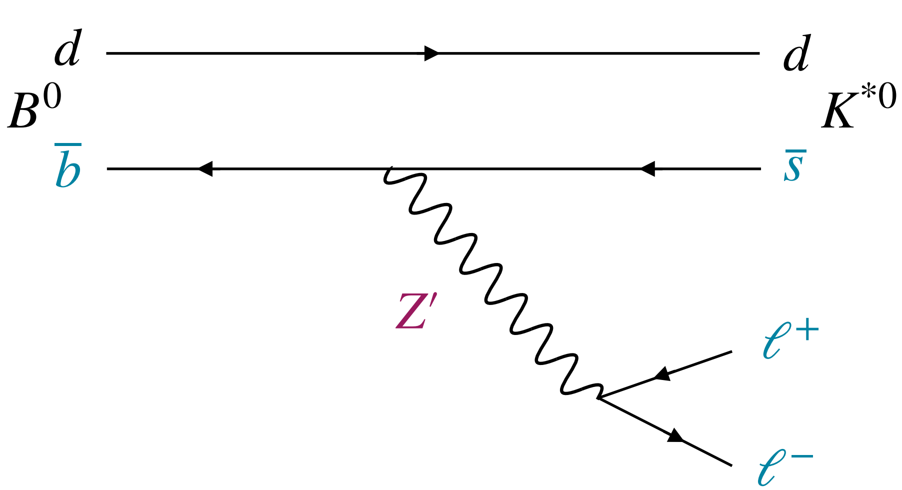
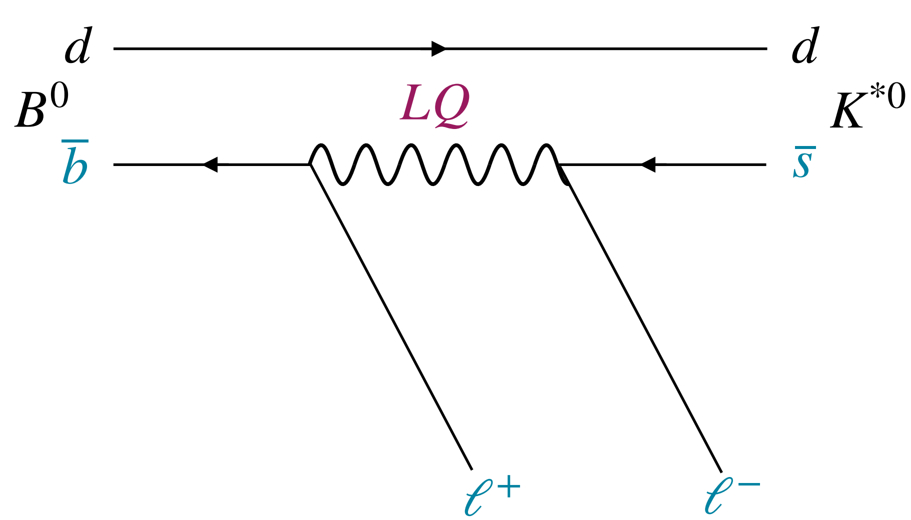
- $B^0 \to K^{*0}(\to K^+\pi^-)e^+e^-$ is a flavour changing neutral current decay that features an underlying $b \to s\ell^+\ell^-$ process





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

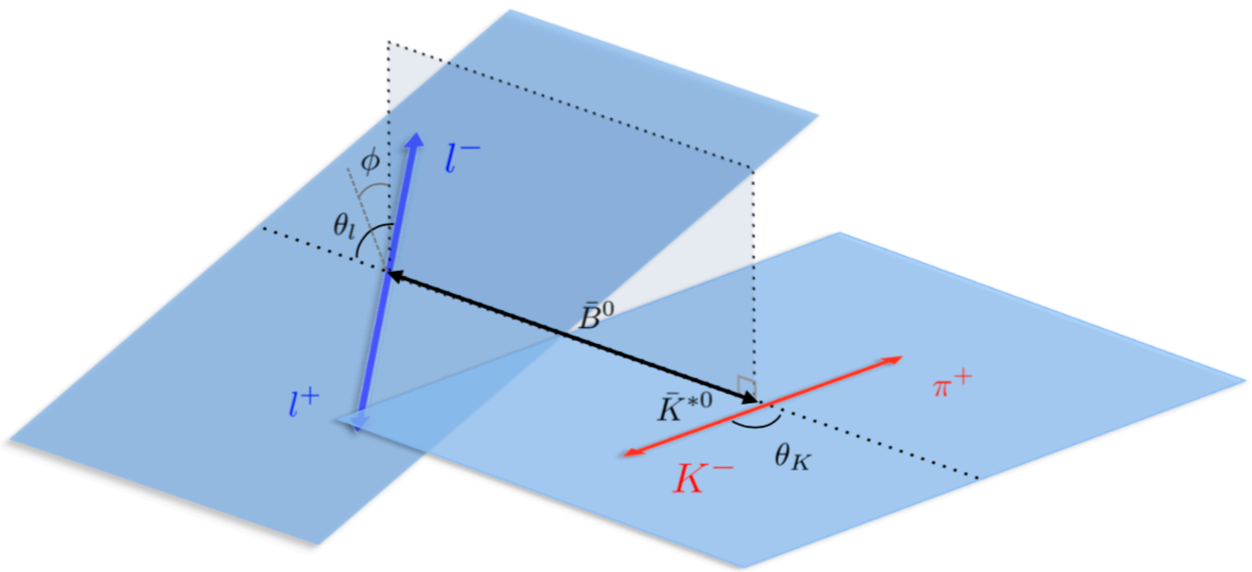




- Four-body final state, K^{*0} spin-1 — many observables

- 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

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



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.

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

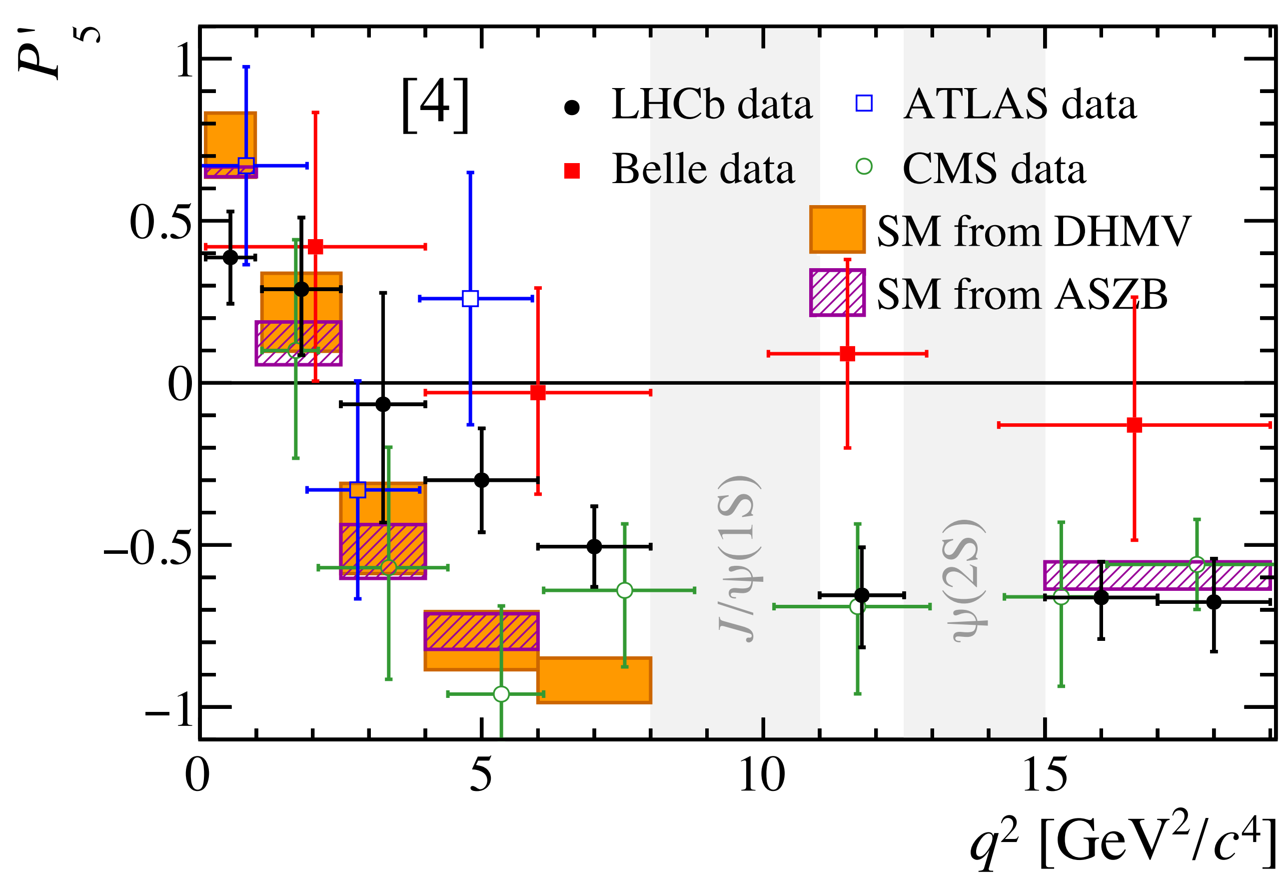
- 2013: measurement of angular observable P_5' of $B^0 \to K^{*0}\mu^+\mu^-$ revealed tension with SM [1]
- 2015: P_5' measurement with larger statistics (2011+2012) — tension persists [2]

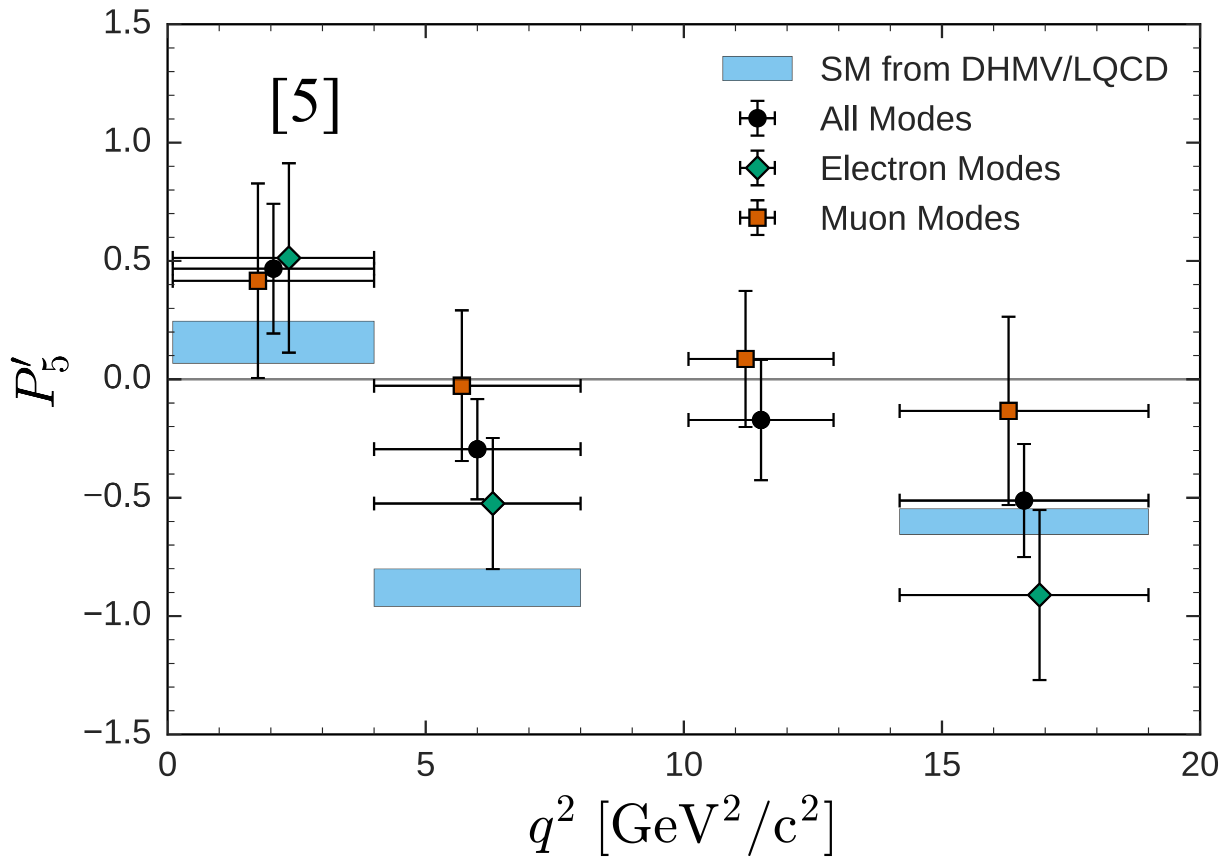
Meanwhile…

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

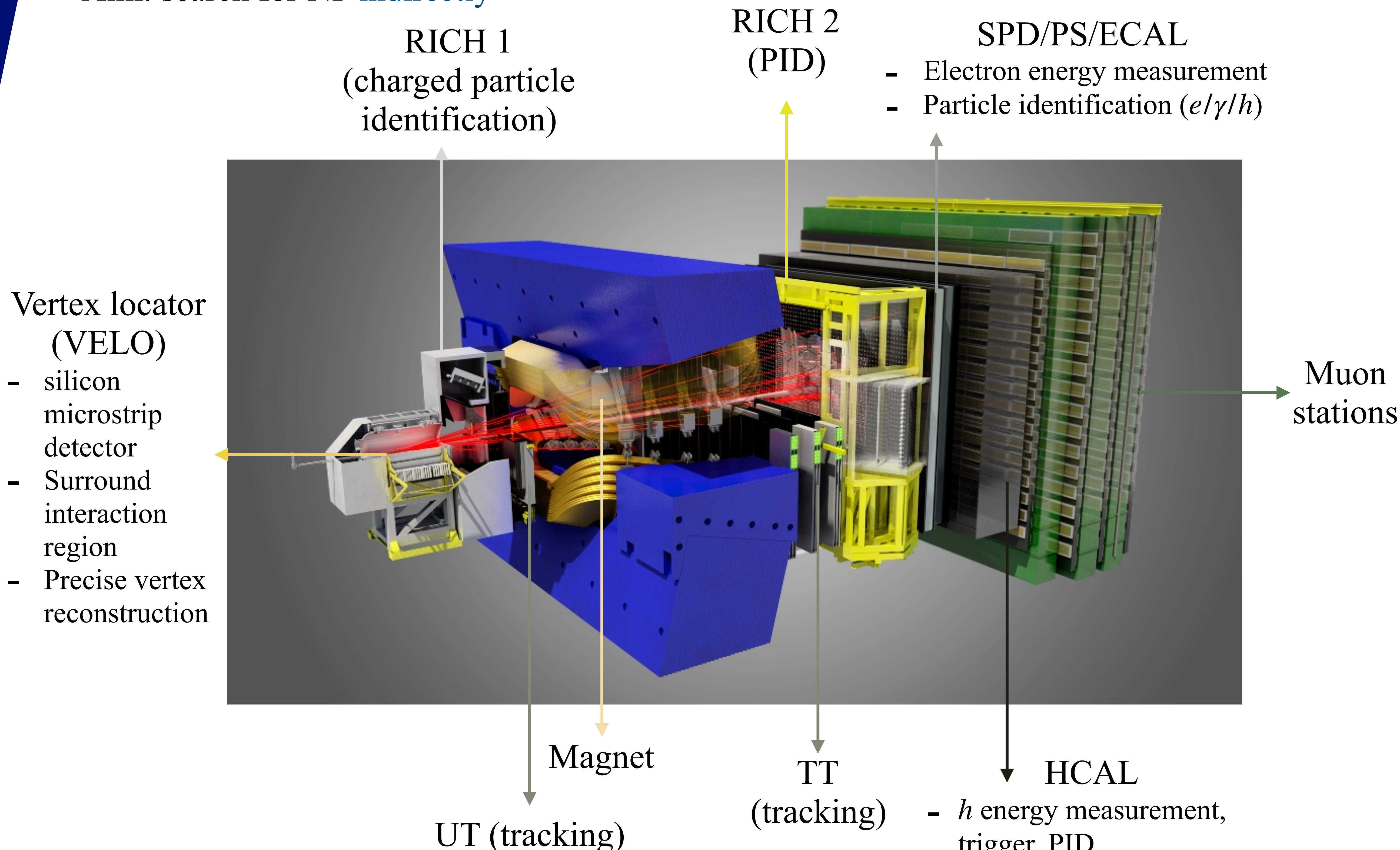
$$R(K^*) = \frac{\mathscr{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathscr{B}(B^0 \to K^{*0}e^+e^-)} \quad [3]$$

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





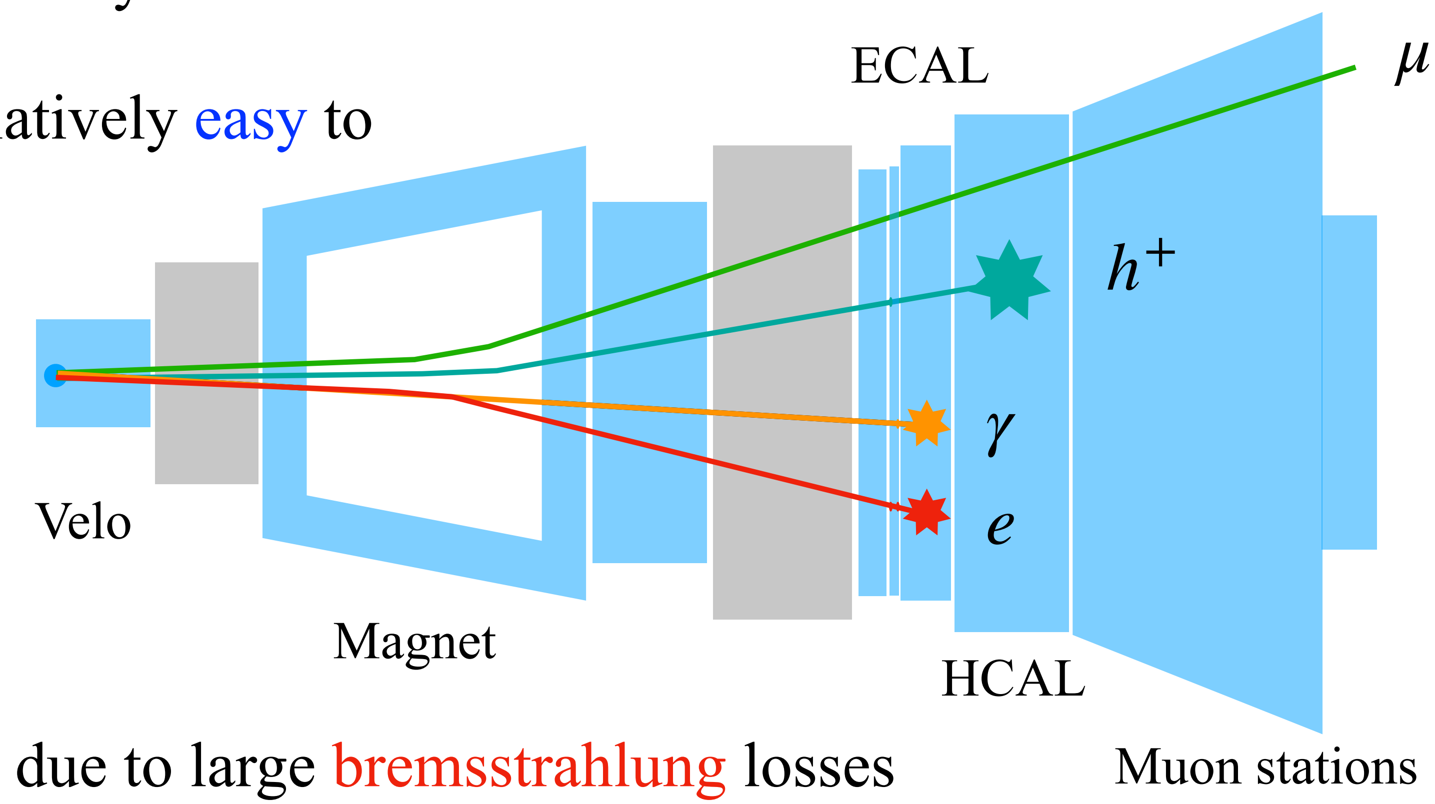
- The LHCb is a specialised detector dedicated to the study of b/c-hadron decays
- Aim: search for NP indirectly



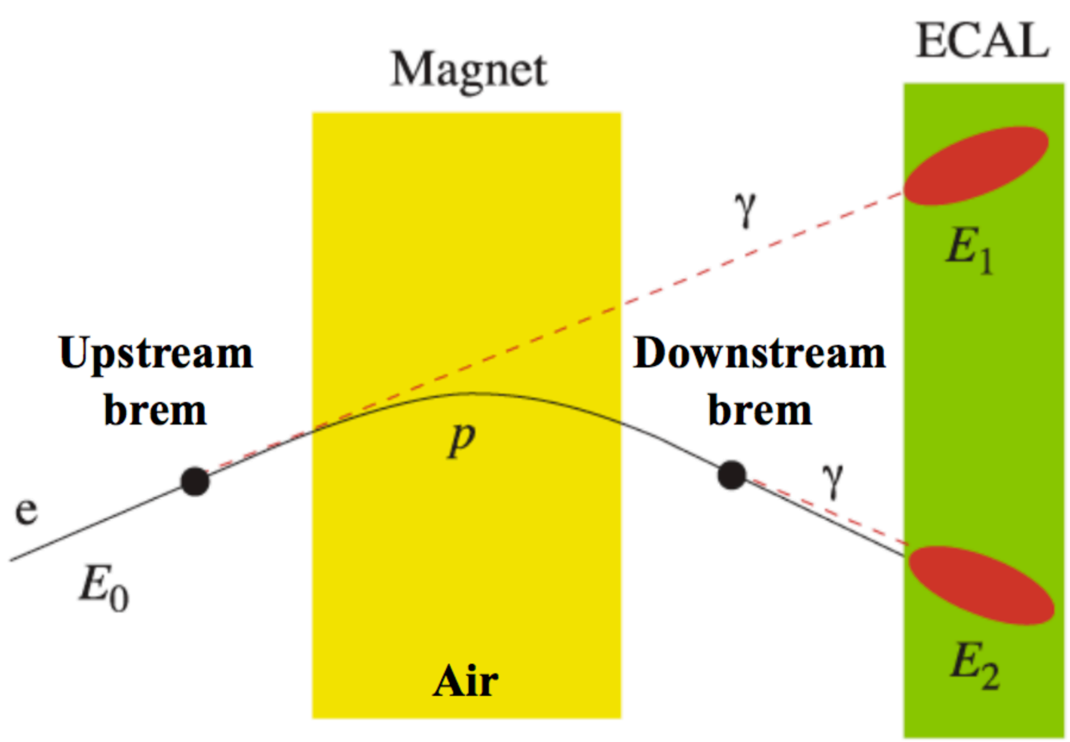
- $B^0 \to K^{*0}e^+e^-$ angular analysis is more challenging than that of $B^0 \to K^{*0}\mu^+\mu^-$
- Experimentally, muons and electrons are very different
- Muons leave clear signatures and are relatively easy to reconstruct

✓ dedicated muon stations for trigger/PID

✓ high tracking efficiency



- Electron reconstruction is more difficult due to large bremsstrahlung losses



✗ decreased mass and q^2 resolution

✗ lower trigger & PID performance

Electron mode: $\times 5$ lower efficiency than muon mode

Compensation strategies

- To (partially) compensate for reduced statistics, fold signal angular PDF

For P_5'

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2 d\vec{\Omega}} = \frac{9}{8\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos2\theta_\ell - F_L\cos^2\theta_K\cos2\theta_\ell + \frac{1}{2}(1-F_L)P_1\sin^2\theta_K\sin^2\theta_\ell\cos2\phi + \sqrt{F_L(1-F_L)}P_5'\sin2\theta_K\sin\theta_\ell\cos\phi\Big]$$

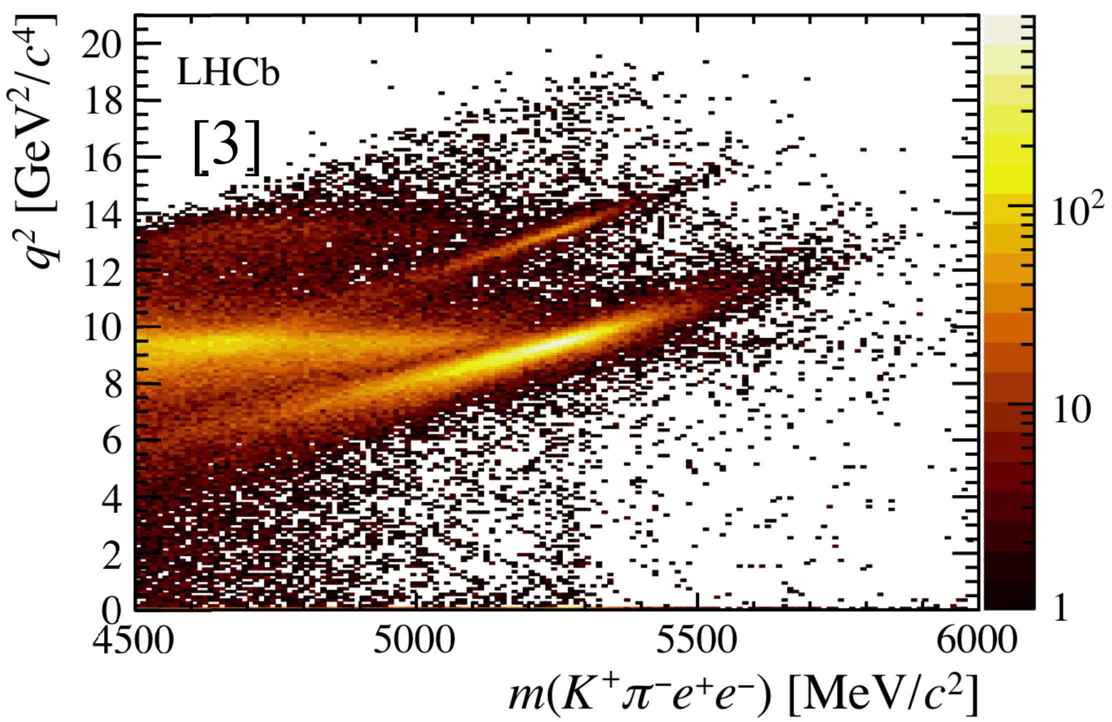
$$\phi \to -\phi \ \text{ if } \phi < 0$$

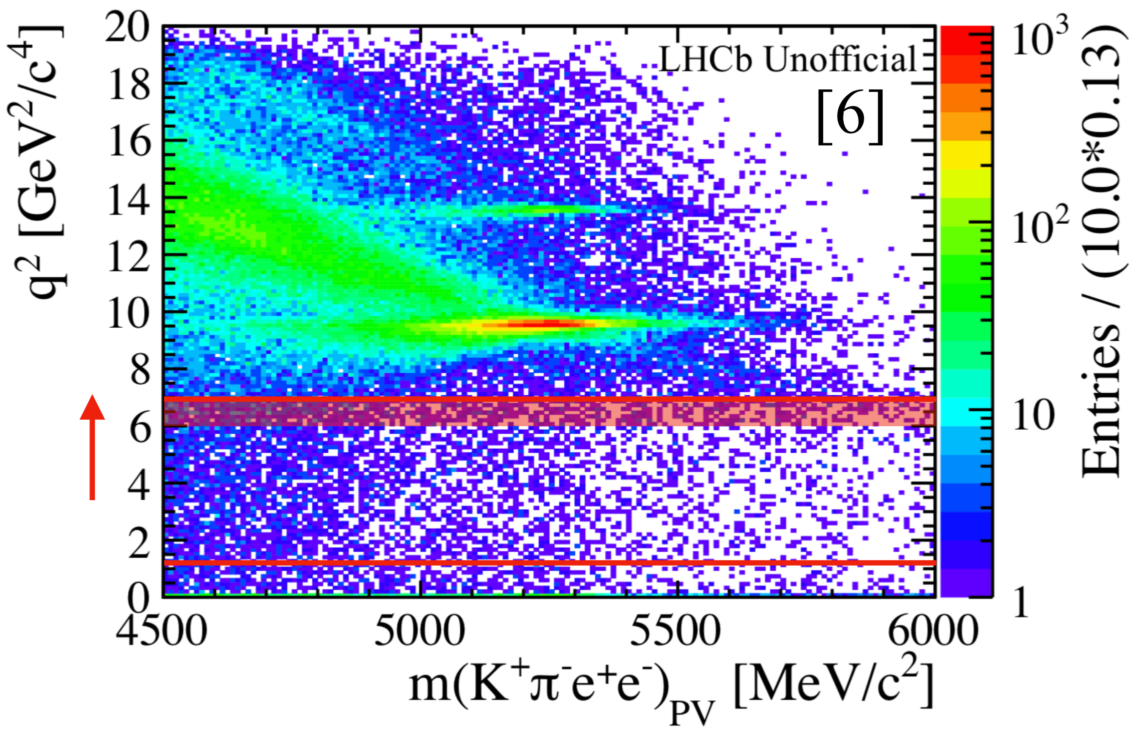
$$\theta_\ell \to \pi - \theta_\ell \ \text{ if } \theta_\ell > \frac{\pi}{2}$$

✔ Reduced number of observables to be determined in fit

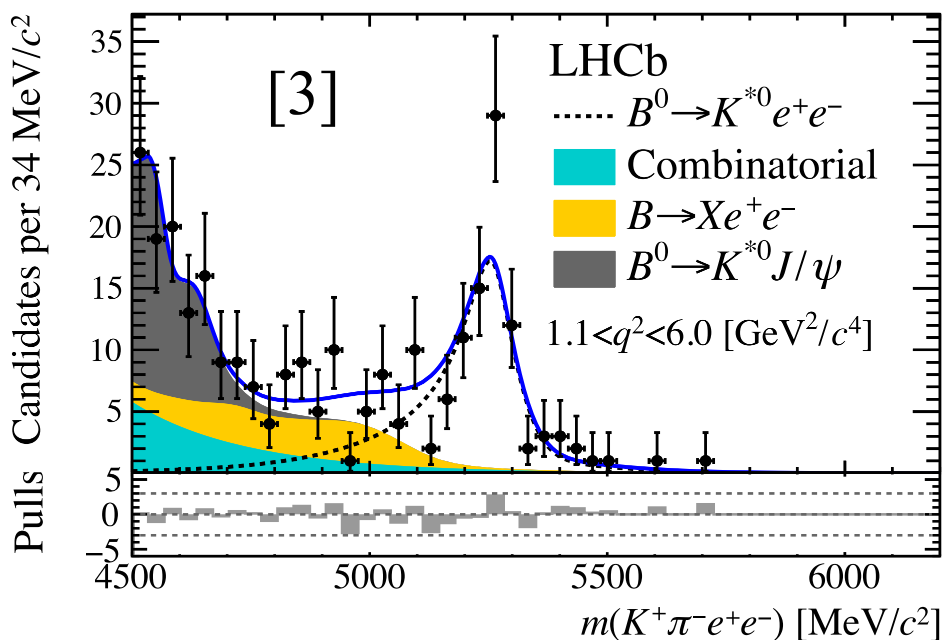
- Cutting on the q^2 with B^0 primary vertex and mass constraint allows for the extension of the analysis range up to 7.0 GeV^2/c^4

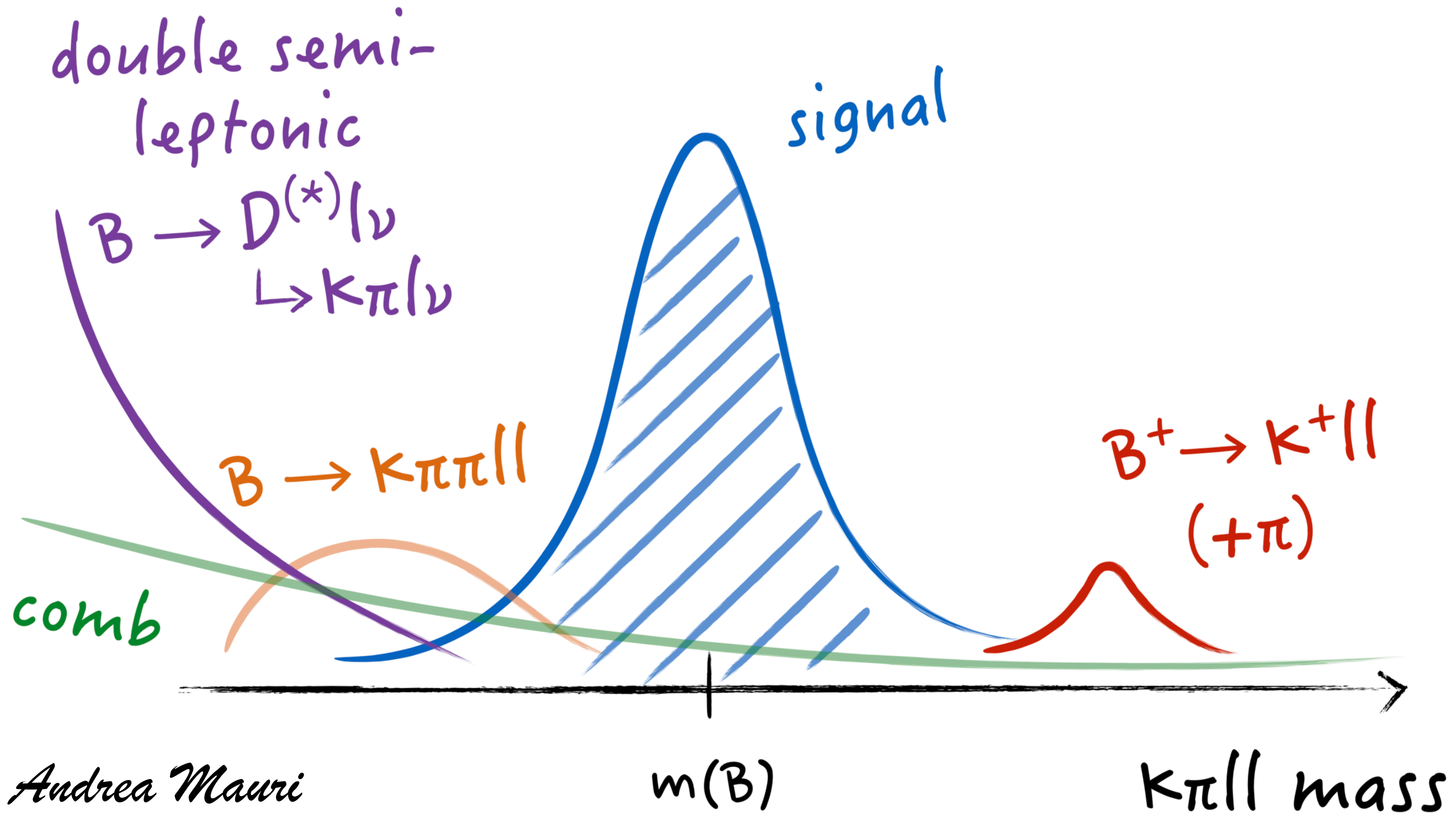
✔ Increase statistics without increasing background





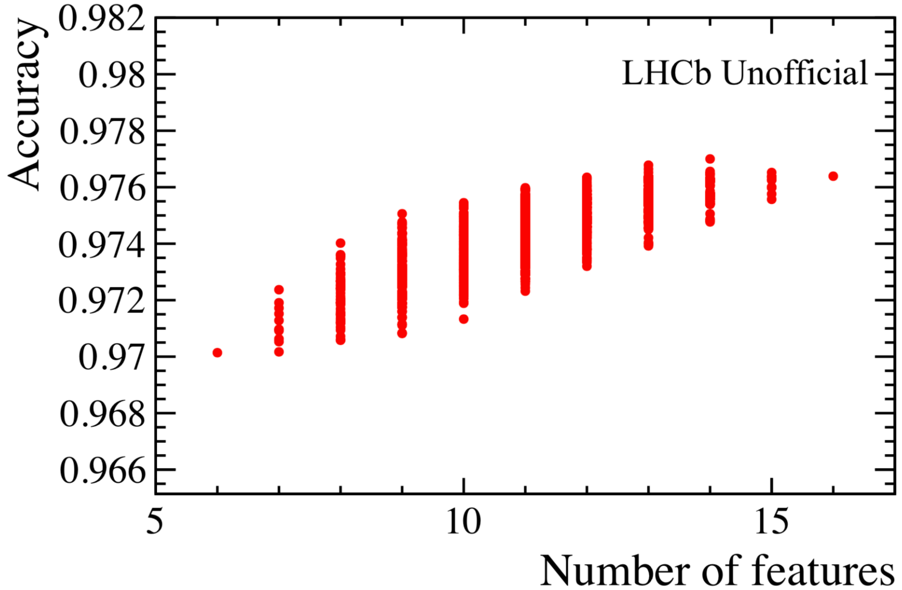
- Angular observables to be extracted via unbinned maximum likelihood fit to mass+angles

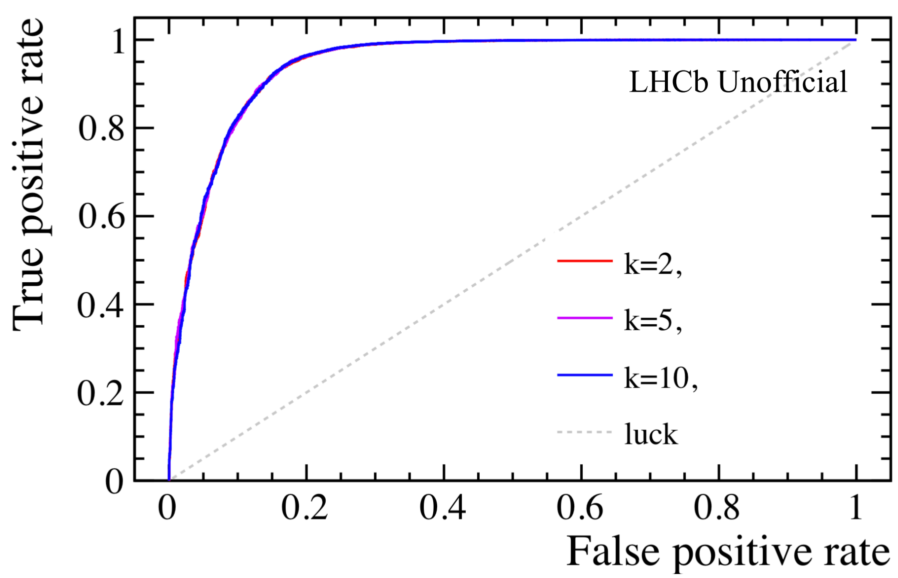


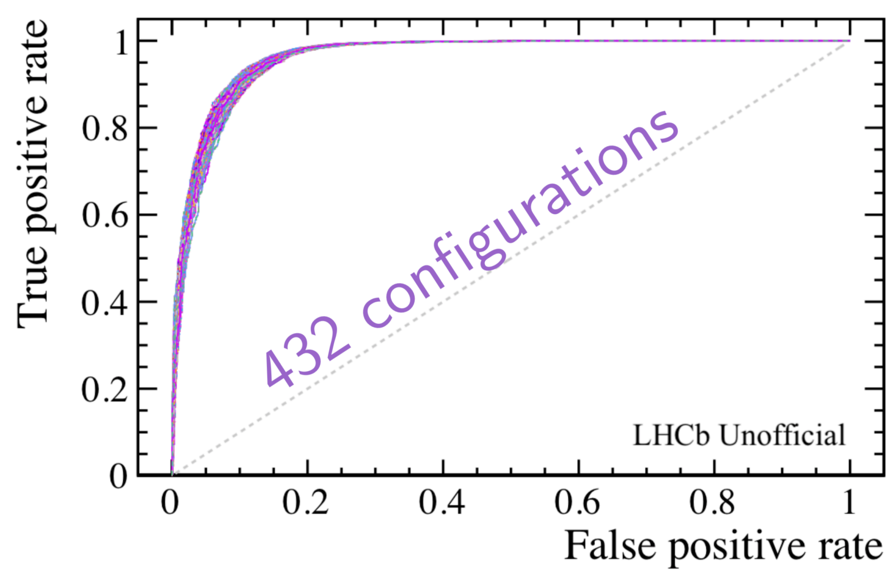


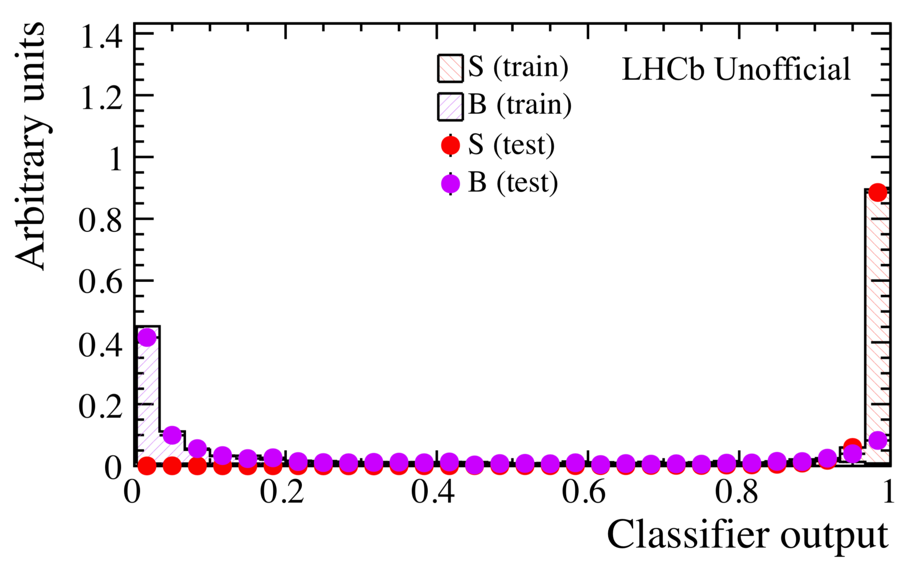
- Background components to be considered:
  - Double semi-leptonic — largely removed by cuts
  - $B^+ \to K^+ e^+ e^-$ — vetoed
  - Partially reconstructed — model
  - Combinatorial — reduced via multivariate analysis techniques, model remaining

- Combinatorial background: random combinations of b/c-hadron decay products
- Reduce using multivariate classifier (XGBoost)
  - Signal sample — $B^0 \to K^{*0}e^+e^-$ simulation
  - Background sample — data upper mass side-band
- Optimised for best set of hyper-parameters and input features
- Adopt K-folding approach to make full use of available training statistics (folds=10)









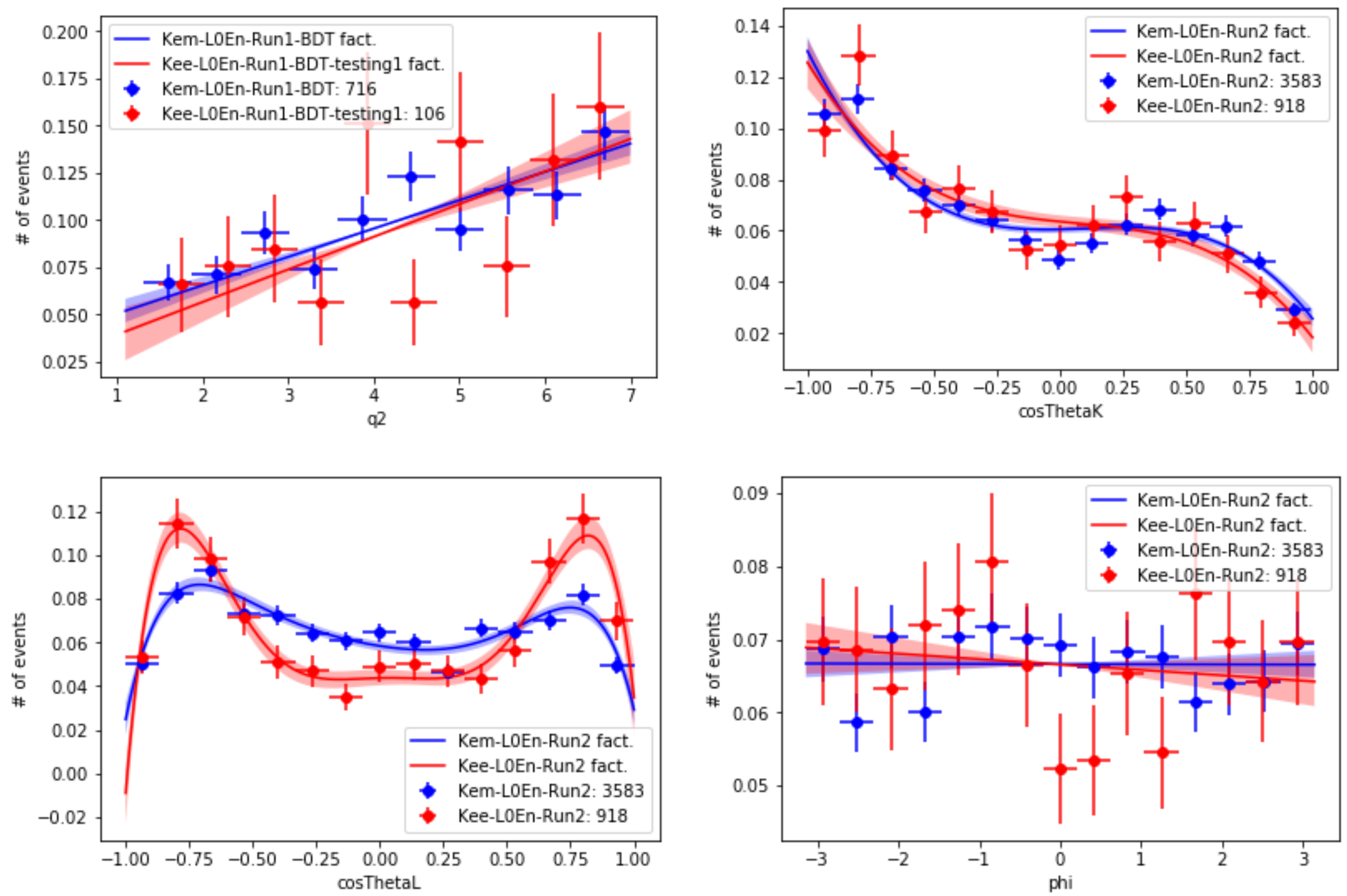
14 features: B^0 characteristics, kinematic, topological, vertex quality variables

Work by F.Lionetto [6]

- Remaining combinatorial background needs to be modelled
- Mass — exponential distribution
- Angles — model using Chebyshev polynomials, two options:
    - A. $K^{+}\pi^{-}e^{+}e^{-}$ data, upper mass side-band (default)
    - B. Lepton flavour violating $K^{+}\pi^{-}e^{+}\mu^{-}$ data

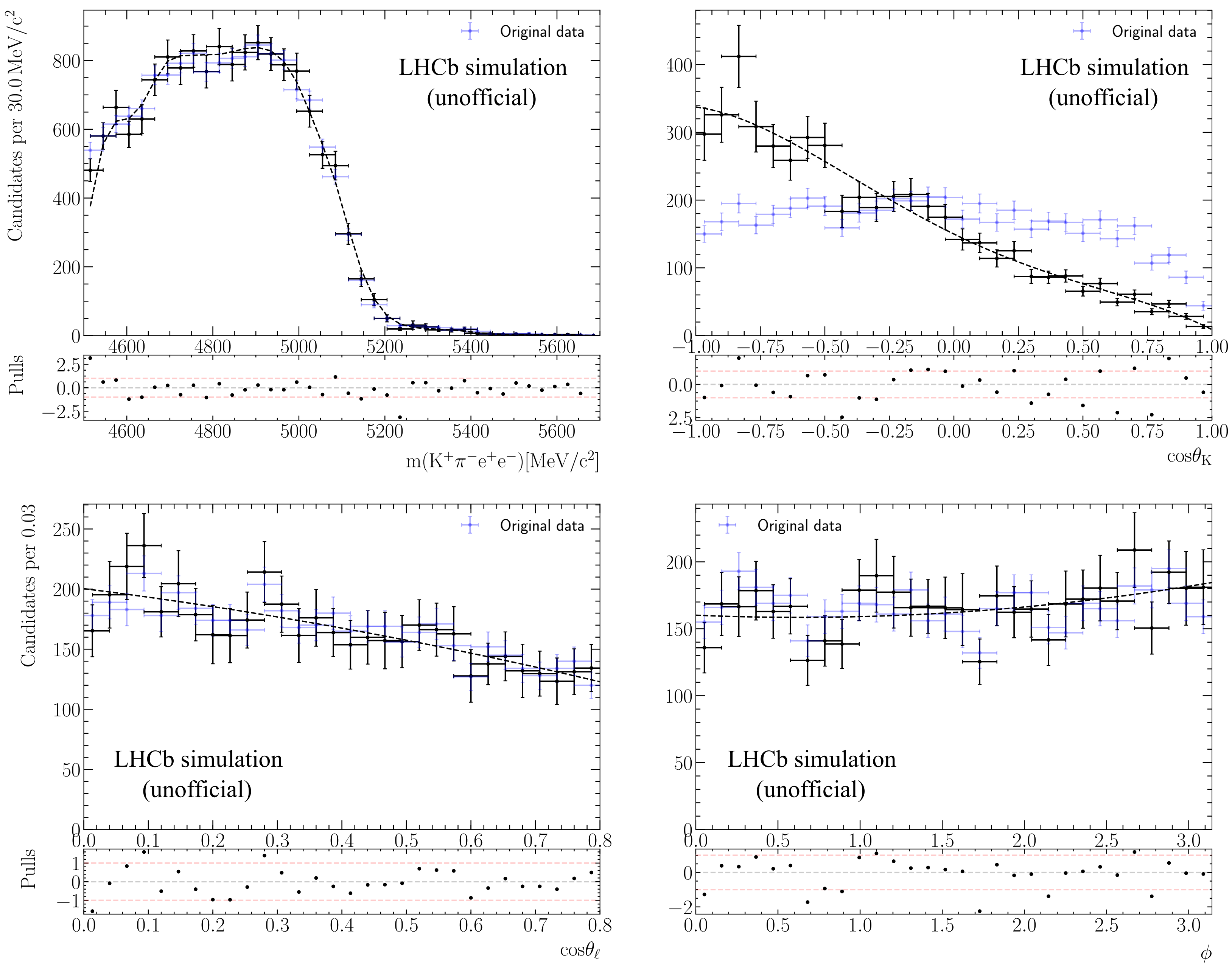
✔ larger statistics and mass range

✘ μe-ee differences

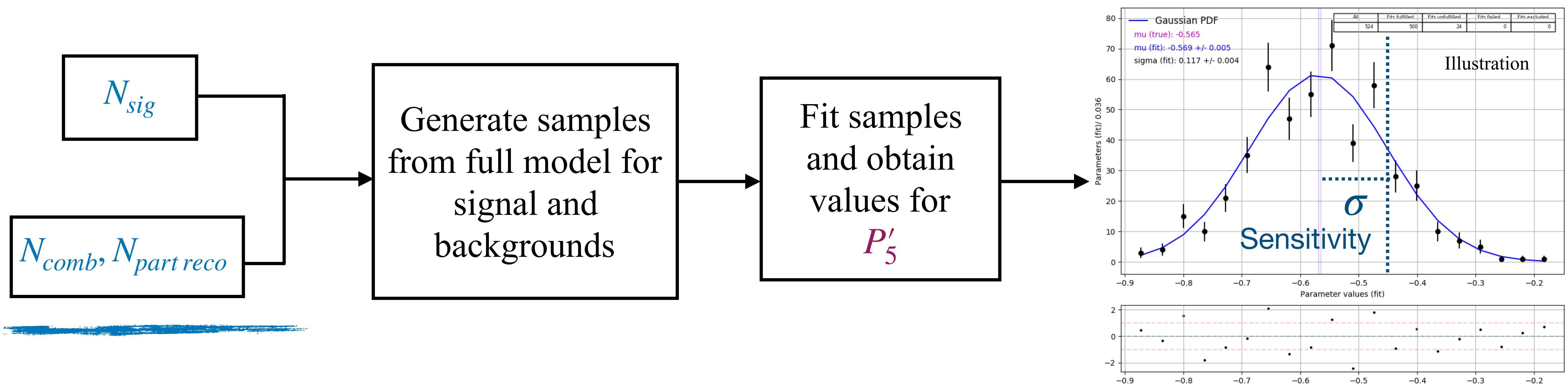


Work by:
M. Atzeni

- Partially reconstructed background — decays e.g. $B \to (K_1/K_2 \to (K^{*0} \to K^+\pi^-)\pi)\, e^+e^-$ that have been reconstructed with some particles missing
- Tend to lie in the lower mass region
- Model using $B^- \to K^+\pi^-\pi^-e^+e^-$ simulation (reconstructed missing one pion) with data-driven corrections based on $B^+ \to K^+\pi^+\pi^-(J/\psi \to e^+e^-)$



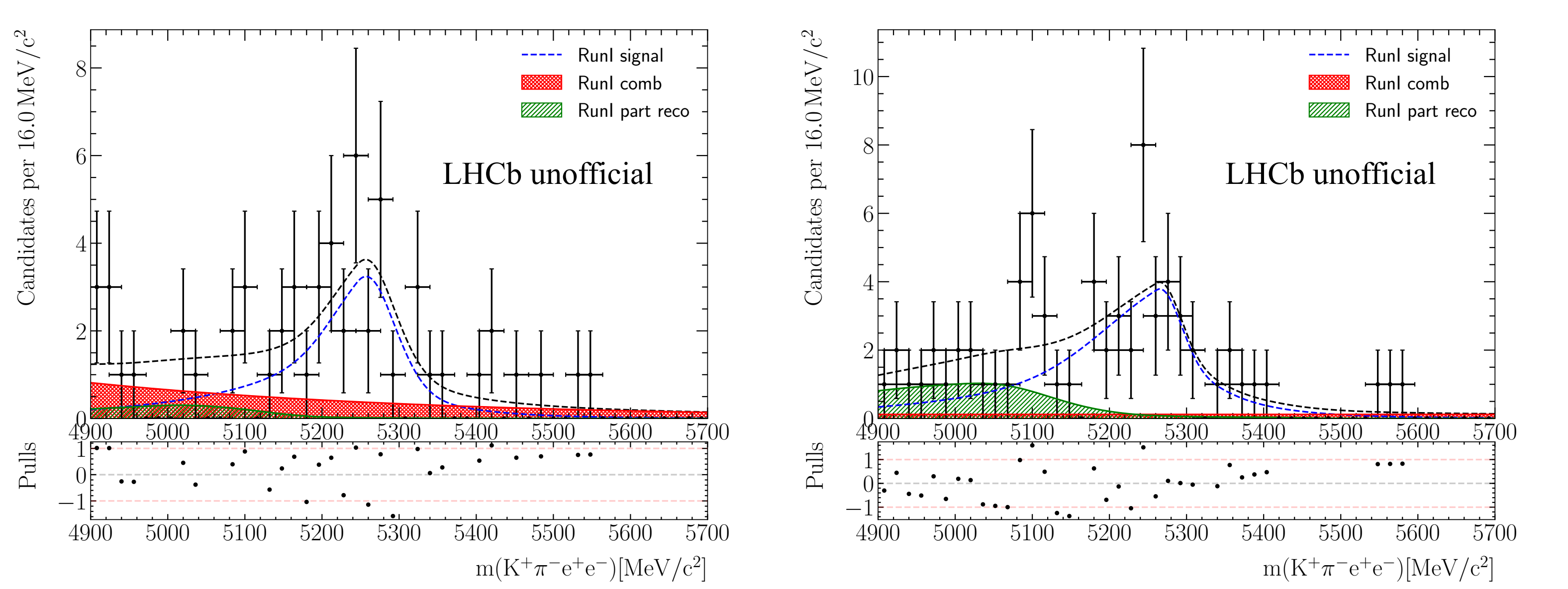
- Aim: optimise for multivariate classifier cut that gives the best P_5' sensitivity
- Procedure: for different threshold values, generate and fit to toy-simulation samples (angles+mass)
  - Signal => physics and simulation
  - Backgrounds => models for partially reconstructed/combinatorial components

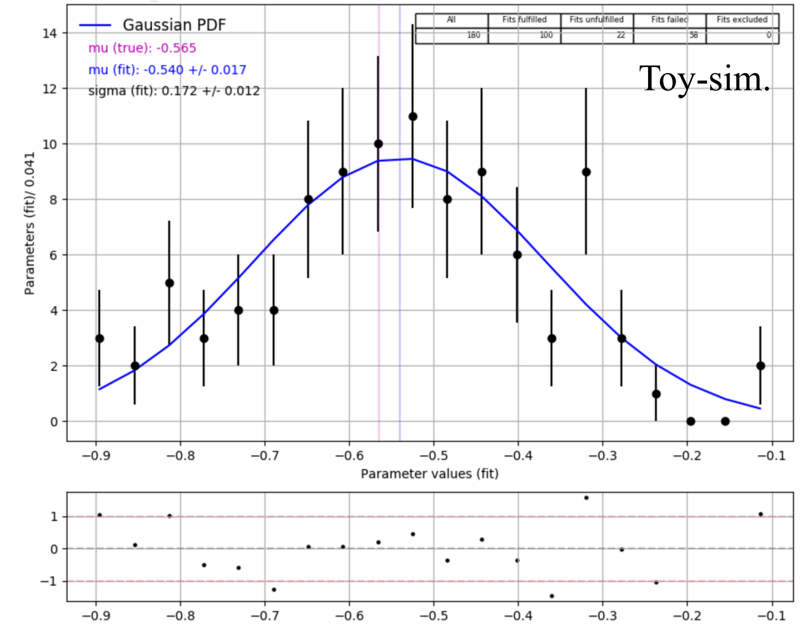


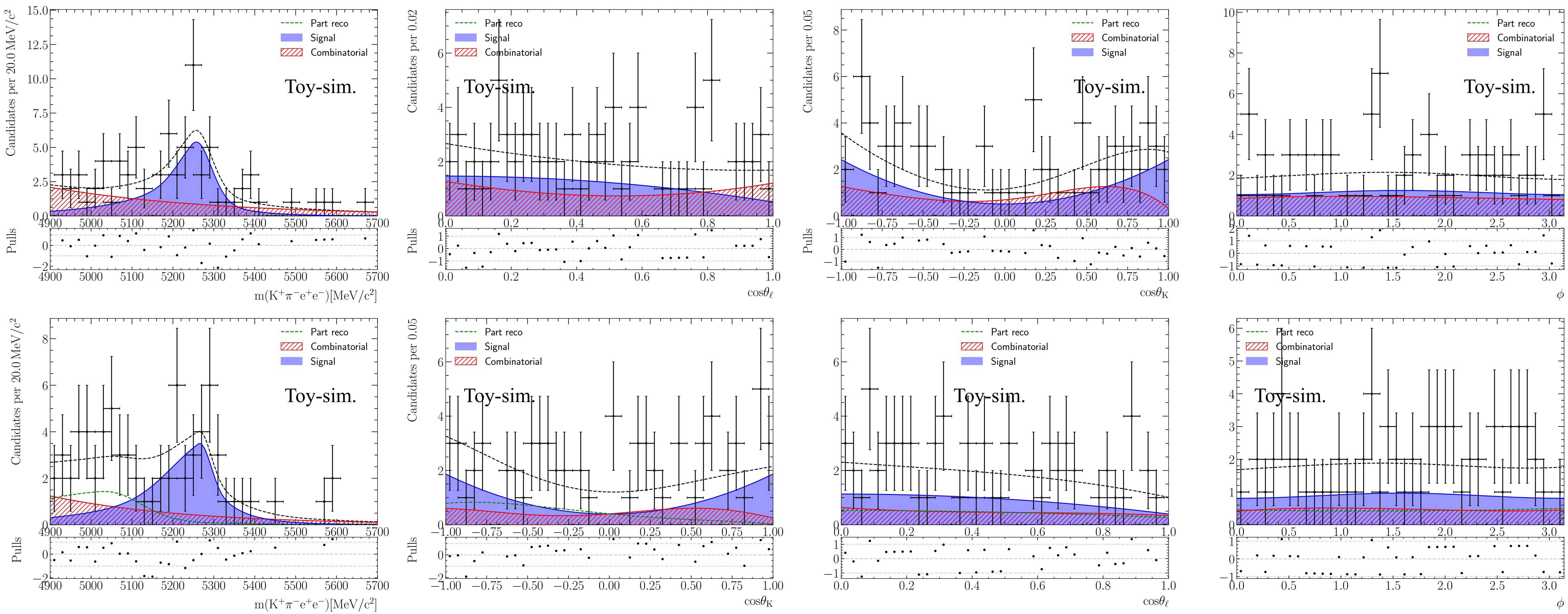
- Required input: yields
  - Obtain $N_{comb}, N_{part\ reco}$ by making mass fits to data
  - Obtain N_{sig} by scaling yield from reliable fit (e.g. tight cut/$B^0 \to K^{*0}(J/\psi \to e^+e^-)$) to current selection using ratio from $B^0 \to K^{*0}e^+e^-$ simulation

Multivariate classifier cut optimisation

Example for classifier output > 0.992 (Run 1)







Acceptance parametrisation

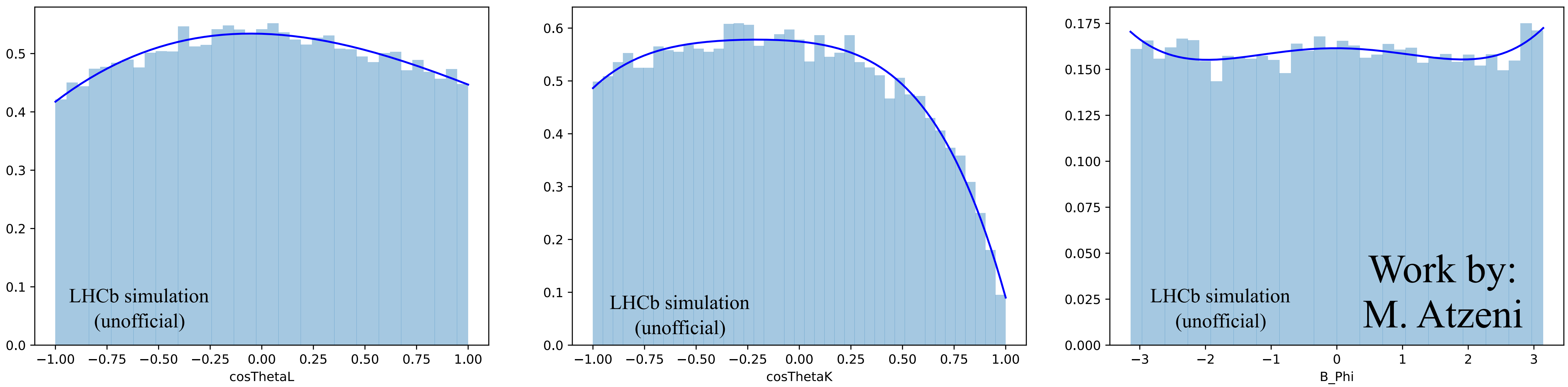
- The distributions of $\cos\theta_K, \cos\theta_\ell, \phi$ (and q^2) are distorted by reconstruction, triggering and selections — 'acceptance effect'
- Parametrise acceptance in four dimensions via:

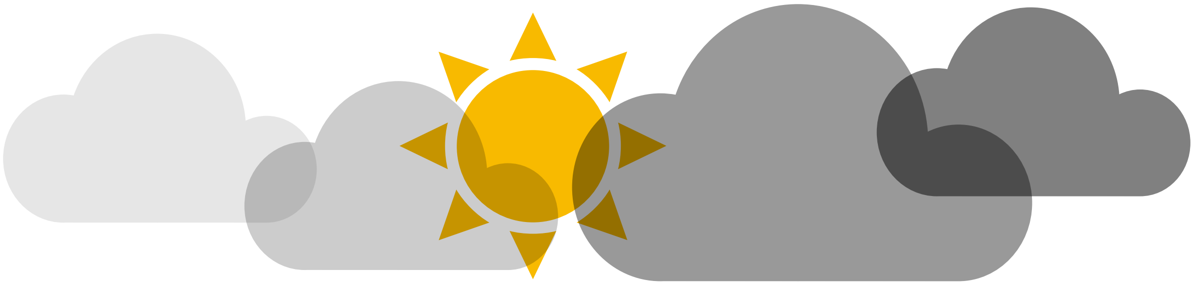
$$\epsilon(cos\theta_l, cos\theta_K\, \phi, q^2) = \sum_{ijmn} c_{ijmn}\, L_i(cos\theta_l)\, L_j(cos\theta_K)\, L_m(\phi)\, L_n(q^2)$$

L_i — Legendre polynomials of order i $\qquad$ c_{ijmn} — coefficients from moments analysis

- Two options for the parametrisation of $B^0 \to K^{*0} e^+ e^-$ simulation:
  A. Pre- and post-selection (physics)
  B. Post-selection distributions (flat in $\cos\theta_K, \cos\theta_\ell, \phi, q^2$) <= preferred method

Example for case B





- Analysis in advanced stage
- main focus currently on classifier output cut optimisation
- Many details to work on:
  - Combinatorial background: $K^+\pi^-e^+\mu^-$ vs $K^+\pi^-e^+e^-$
  - Incorporation of acceptance weights
  - Dangerous background checks (after full selection)
  - Cross-checks with similar analyses
  - Systematic uncertainties
- Still some ground to cover, but will (hopefully) move towards some concrete results by the end of the year

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] 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

[4] P_5' multi-collaborations plot: ATLAS, ATLAS-CONF-2017- 023, Apr 2017; CMS, CMS-PAS-BPH-15-008, 2017; Belle, S. Wehle et al. Phys. Rev. Lett., 118:111801, Mar 2017; LHCb, R. Aaij et al. JHEP, 02:104, 2016.

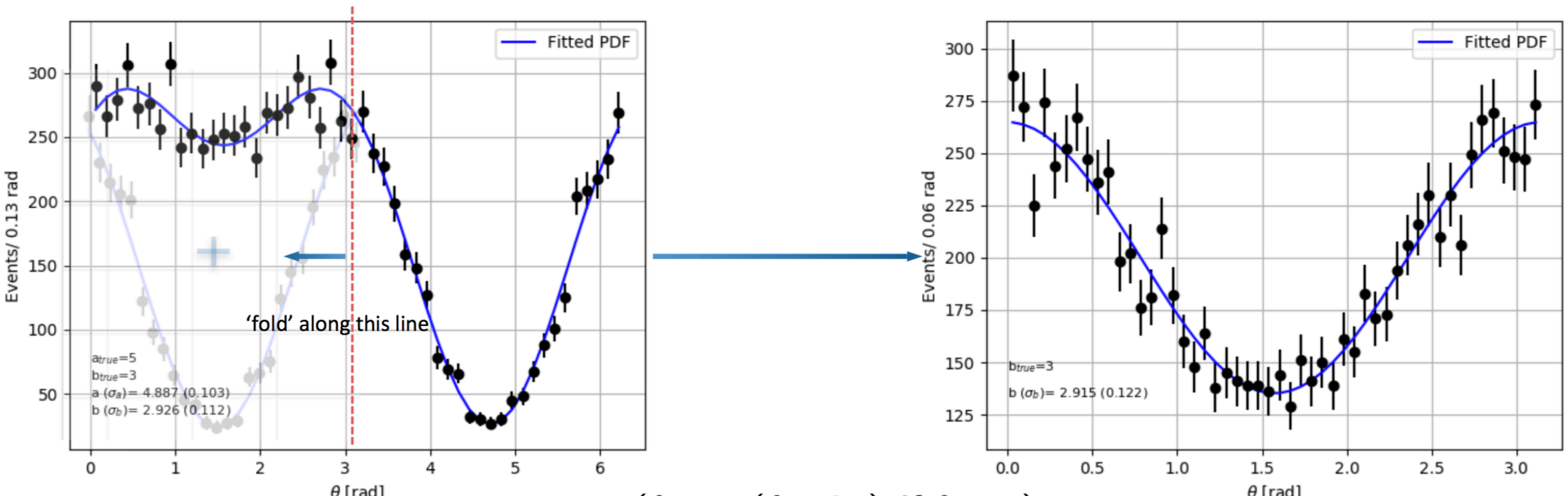
[5] Belle muon/electron P_5': S. Wehle *et al.* (Belle Collaboration), Phys. Rev. Lett. 118, 111801 – Published 13 March 2017

[6] Federica Lionetto. Measurement of Angular Observables of $B^0 \to K^{*0}\mu^+\mu^-$ and $B^0 \to K^{*0}e^+e^-$ Decays and the Upgrade of LHCb, Feb 2018. Presented 22 Mar 2018.

Backup

Electron strategy: folding

- For electron channel 'fold' signal PDF to reduce impact of low statistics, e.g. for P_5'



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

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

✔ Reduced number of observables to be determined in fit

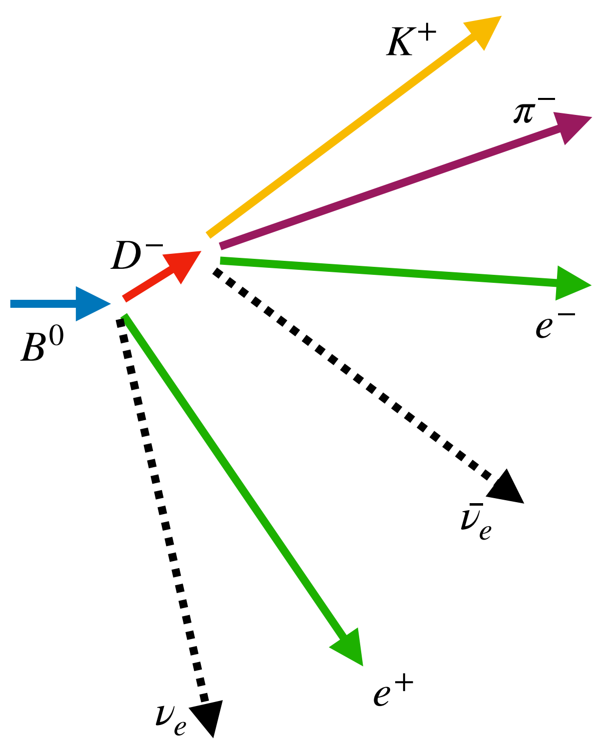
$$\phi \to -\phi \;\text{ if } \phi < 0$$

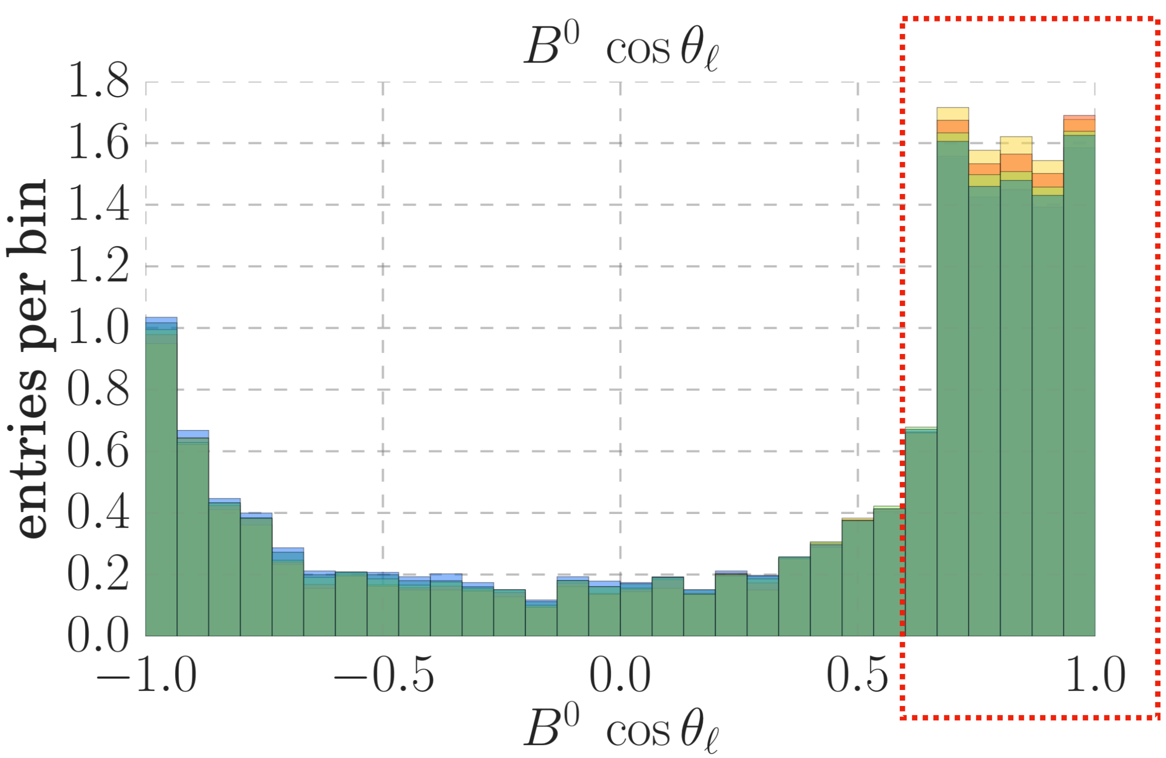
$$\theta_\ell \to \pi - \theta_\ell \;\text{ if } \theta_\ell > \frac{\pi}{2}$$

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

Double semi-leptonic background overview

- From reconstruction of 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
- However they distort the shapes of angular distributions, in particular that of $\cos\theta_\ell$ ($e^{-/+}$ from $D^{-/+}$ softer, so always have $\cos\theta_\ell$ close to one as $e^{+/-}$ is in direction the of $B^0/\overline{B}^0$ in the dilepton rest frame)





Double semi-leptonic background cut I

- 'Fashionable' methods of removal
  - Cut on $\cos\theta_\ell$ ($\cos\theta_\ell < 0.8$): DSL efficiency ~12%, signal efficiency ~95%
  - Cut on $K\pi e$ mass ($m(K\pi e) > 1900\,\mathrm{MeV/c^2}$): DSL efficiency ~0.5%, signal efficiency ~93%
- Problem => these cuts make $\cos\theta_\ell$ distribution asymmetric
- Possible solution — make symmetric cut in $\cos\theta_\ell$ ($|\cos\theta_\ell| < 0.8$) with signal and DSL efficiencies of ~91% and ~12%, respectively
- Or search for alternative methods…

Impact of $m(K\pi e)$ cut on signal MC $\cos\theta_\ell$ distribution