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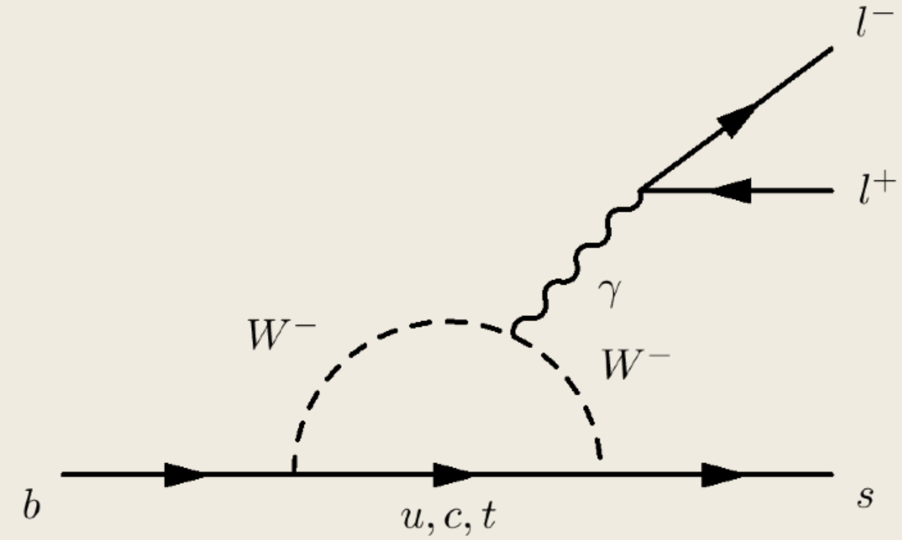
Angular analysis of the rare decay $B_s^0 \to \phi e^+ e^-$ at LHCb

IOP Joint APP, HEPP and NP Annual Conference

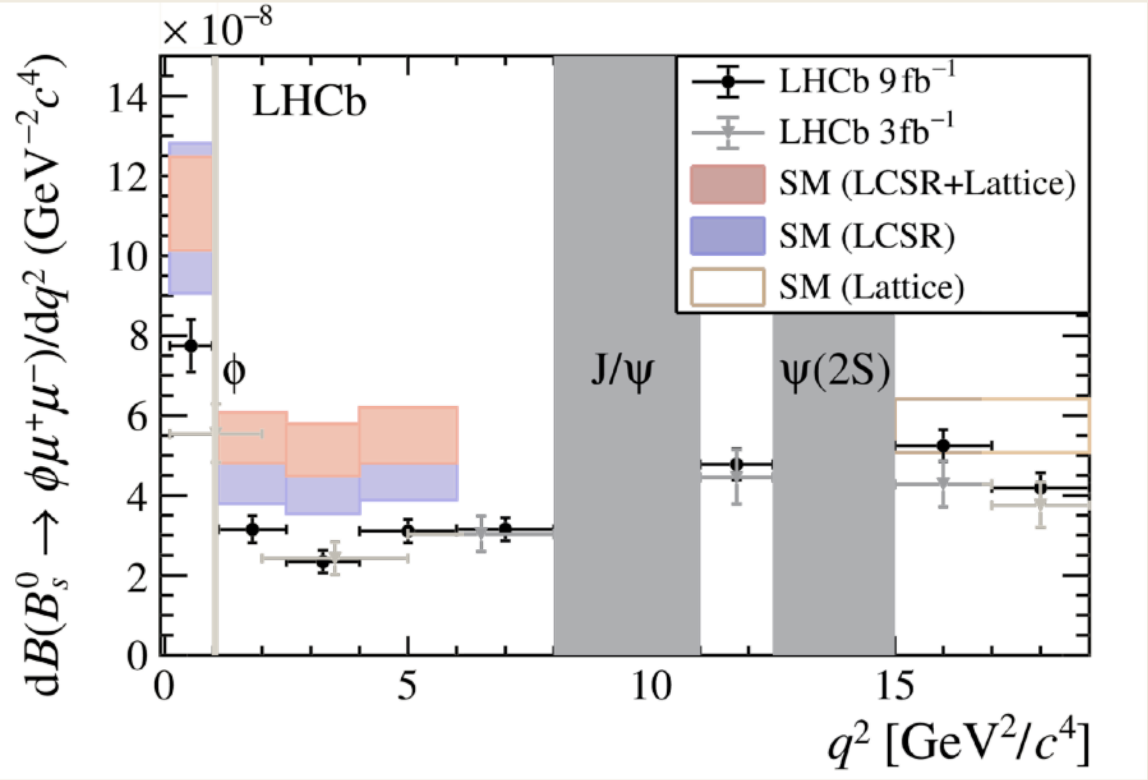
Liverpool, 8th-11th April 2024

Introduction

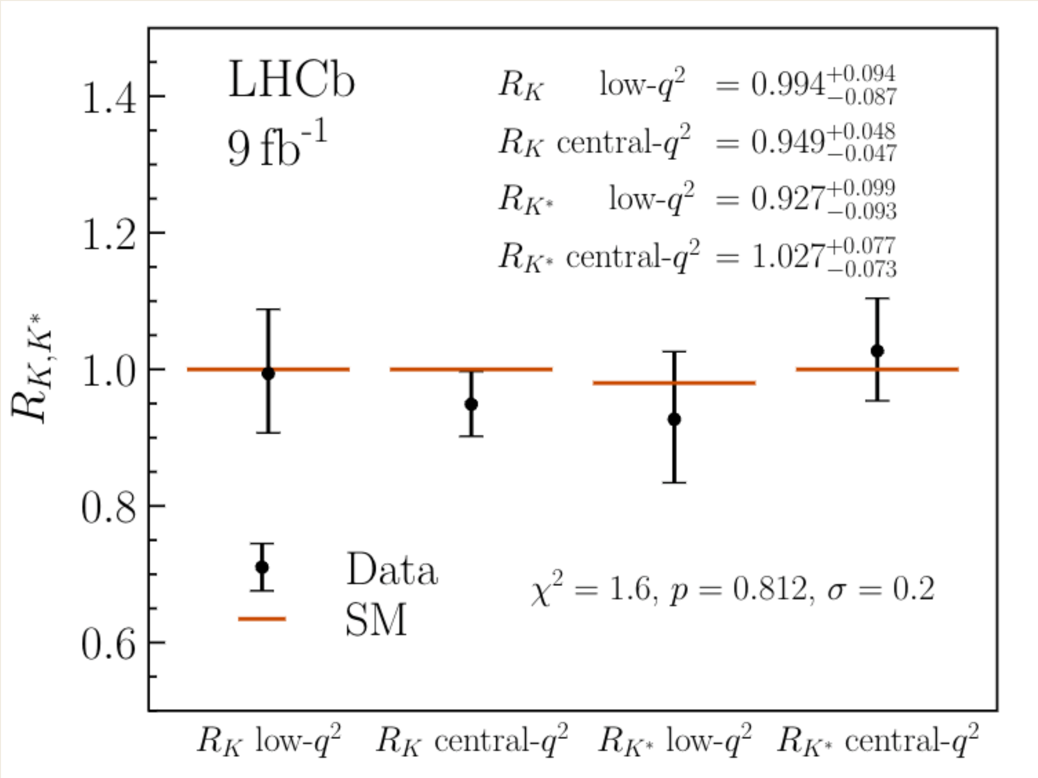
- Involves $b \to s\ell\ell$ transition, suppressed ($\mathcal{B} < 10^{-6}$), only at loop level in the SM.
- Sensitive to New Physics (NP) mediators.
- Discrepancies observed in $b \to s\mu\mu$.
- $b \to see$ **transitions still largely unexplored**, with unique SM tests (LFUV).



Measurement of $\mathrm{d}\Gamma(B_s^0 \to \phi\mu\mu)/\mathrm{d}q^2 \sim 3\sigma$ deviation from SM.



Measurement of LFU ratio R_{K,K^*}, compatible with SM.



JHEP 11 (2021) 043

Phys. Rev. Lett. 131 (2023) 051803
Phys. Rev. D 108 (2023) 032002

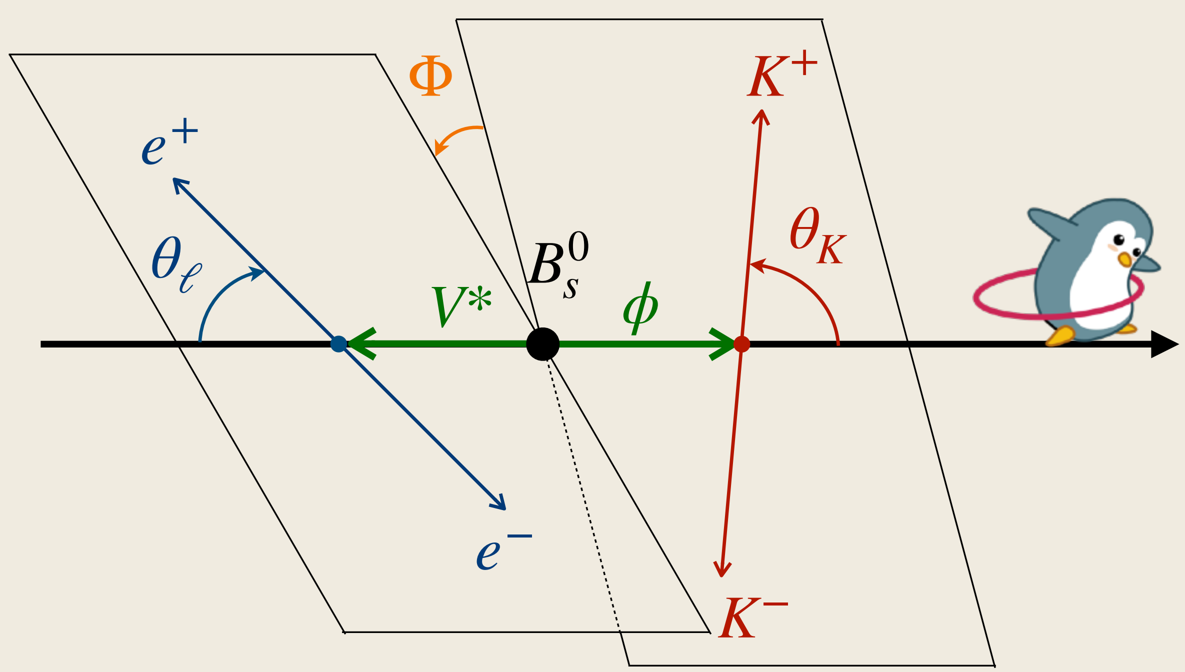
Theoretical background

- Angular distribution of $B \to V\ell\ell$ decay is expressed in terms of **three decay angles** [1].

Angular coefficient
(encodes decay amplitudes)

$$\frac{d\Gamma}{dq^2 d\cos\theta_K d\cos\theta_e d\Phi} = \sum_i J_i(q^2) \quad f_i(\cos\theta_K, \cos\theta_e, \Phi)$$

Angular function
(encodes spin structure)



- **Decay mode not flavour specific.** We can only access the CP average:

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d(\Gamma+\bar{\Gamma})}{dq^2 d\cos\theta_K d\cos\theta_e d\Phi} =$$

$$\frac{9}{32\pi}\Bigg[\frac{3}{4}(1-F_L)\sin^2\theta_K(1+\frac{1}{3}\cos 2\theta_e)$$

$$+ F_L\cos^2\theta_K(1-\cos 2\theta_e) + S_3\sin^2\theta_K\sin^2\theta_e\cos 2\Phi$$

$$+ S_4\sin 2\theta_K\sin 2\theta_e\cos\Phi + A_5\sin 2\theta_K\sin\theta_e\cos\Phi$$

$$+ A_6\sin^2\theta_K\cos\theta_e \qquad + S_7\sin 2\theta_K\sin\theta_e\sin\Phi$$

$$+ A_8\sin^2\theta_K\sin 2\theta_e\sin\Phi \quad + A_9\sin^2\theta_K\sin^2\theta_e\sin 2\Phi\Bigg]$$

and measure S_i , $A_i^{(*)}$ observables.

(*) symmetric or antisymmetric under CP.

[1] JHEP 04 (2015) 045

Analysis strategy

- $B_s^0 \to \phi e^+ e^-$ **unobserved**, branching fraction $\mathscr{B} \sim 10^{-7}$ [1].

- With $f_s/f_d \simeq 0.25$ [2], **low expected yields.**

q^2 [GeV$^2/c^4$]	$[0.1, 1.1]$	$[1.1, 6.0]$	$[15, 19]$
$N(B_s^0 \to \phi e^+ e^-)$	42.2	83.6	62.4

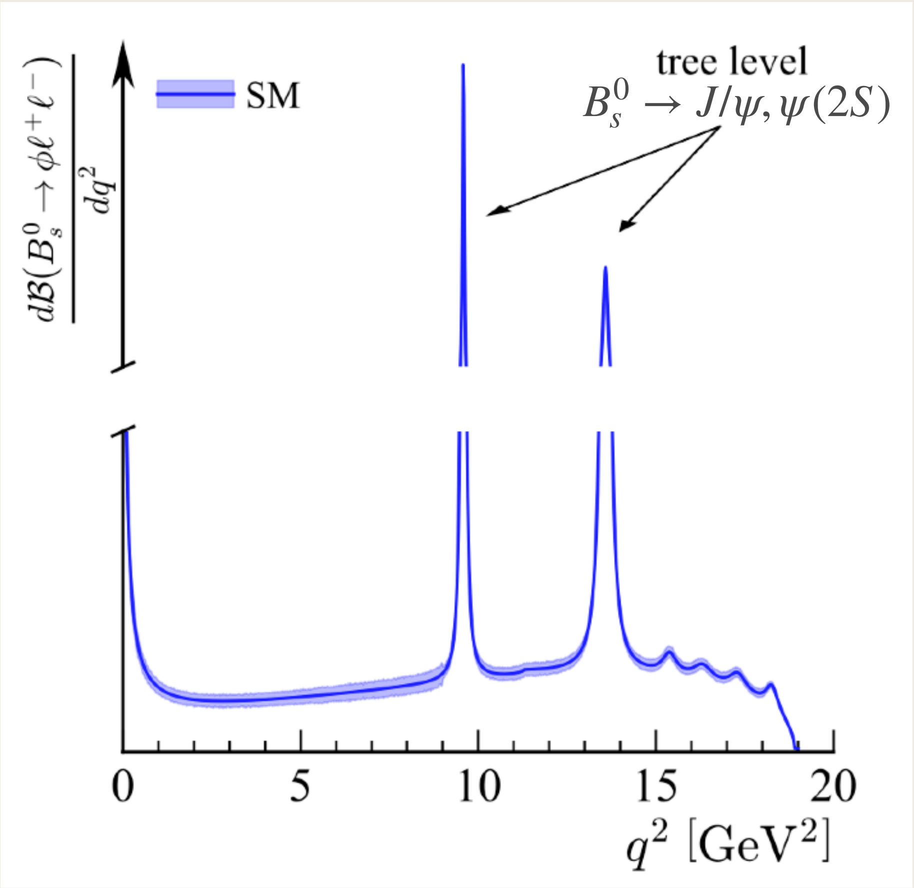
Expected signal yields for Run 1 and Run 2 in the three q^2 regions.

- **Fit angular projections** $(\cos\theta_K, \cos\theta_e)$, Φ

  $\Longrightarrow$**Measure** F_L , S_3 , A_6 A_9 **in bins of** q^2**:**

$q^2 \equiv m^2(e^+e^-) \in [0.1,1.1], [1.1,6.0], [15,19]$ GeV$^2/c^4$

Low Central High



Differential branching fraction of $B_s^0 \to \phi\ell\ell$ decays, computed with the Flavio package.

- Use of $J/\psi, \psi(2S)$ modes for cross checks.

- Analysis performed in parallel with BR measurement / LFU test R_ϕ.

[1] Particle Data Group, assuming Lepton Flavour Universality.

[2] Phys. Rev. D 104 (2021) 032005

Candidate selection

PRESELECTION

- **Exclusive hardware trigger categories** firing independent of signal / on signal lepton.
- Higher level trigger selection based on decay topology:
  - Looks for a displaced vertex.
  - At least 3 tracks.
- Soft cuts on B meson mass, impact parameter, particle kinematics.

OFFLINE SELECTION

- 12 MeV/c^2 window on $\phi \to KK$, **shields from partially reconstructed decays.**
- Tight electron PID.
- Background vetoes for hadron-lepton "swaps" from B^0, B_s^0, Λ_b.
- BDT trained to reduce combinatorial background.
  - Trained on kinematics and reconstruction quality.
  - Cut optimised on $S = \dfrac{N_S}{\sqrt{N_S + N_B}}$

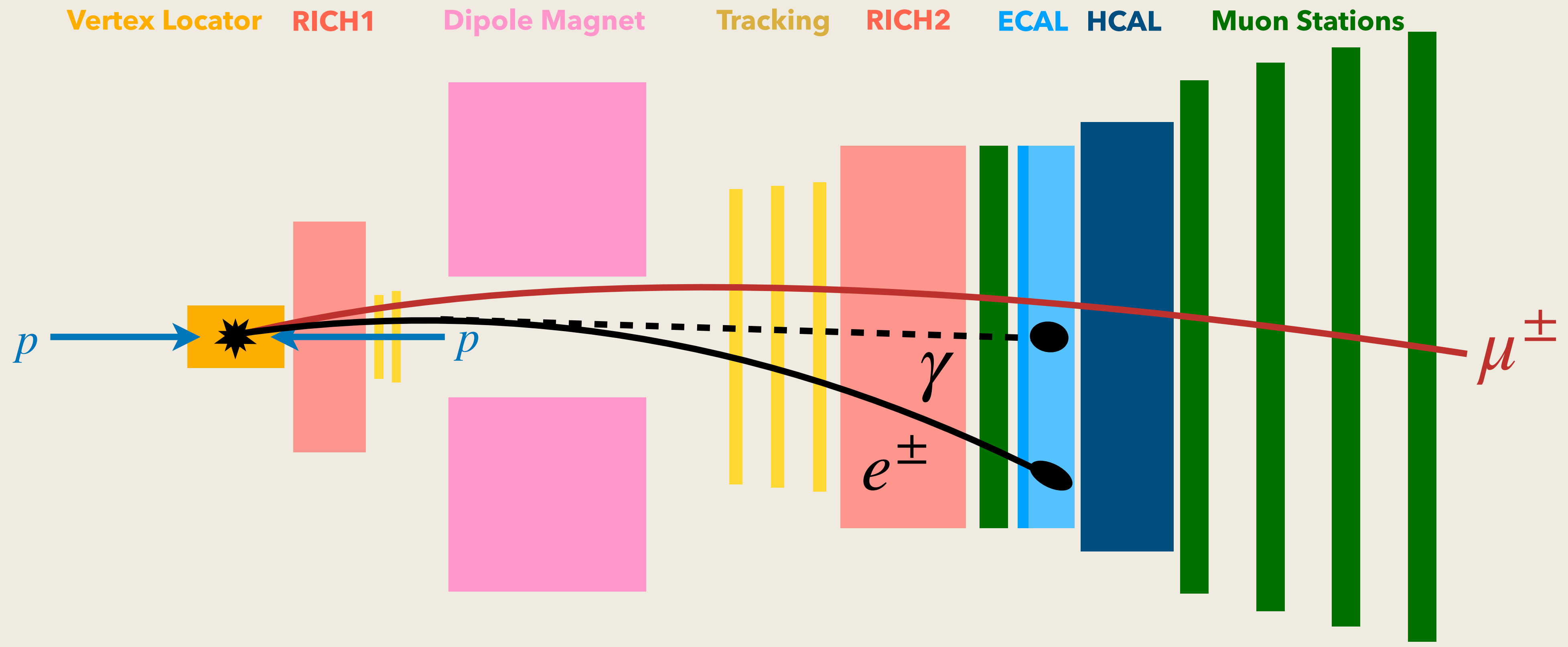
Electron reconstruction challenges

Muons

- Clear signature in Muon Stations, highly penetrating $\Longrightarrow$ high PID efficiency.
- Negligible bremsstrahlung $\Longrightarrow$ excellent momentum resolution.

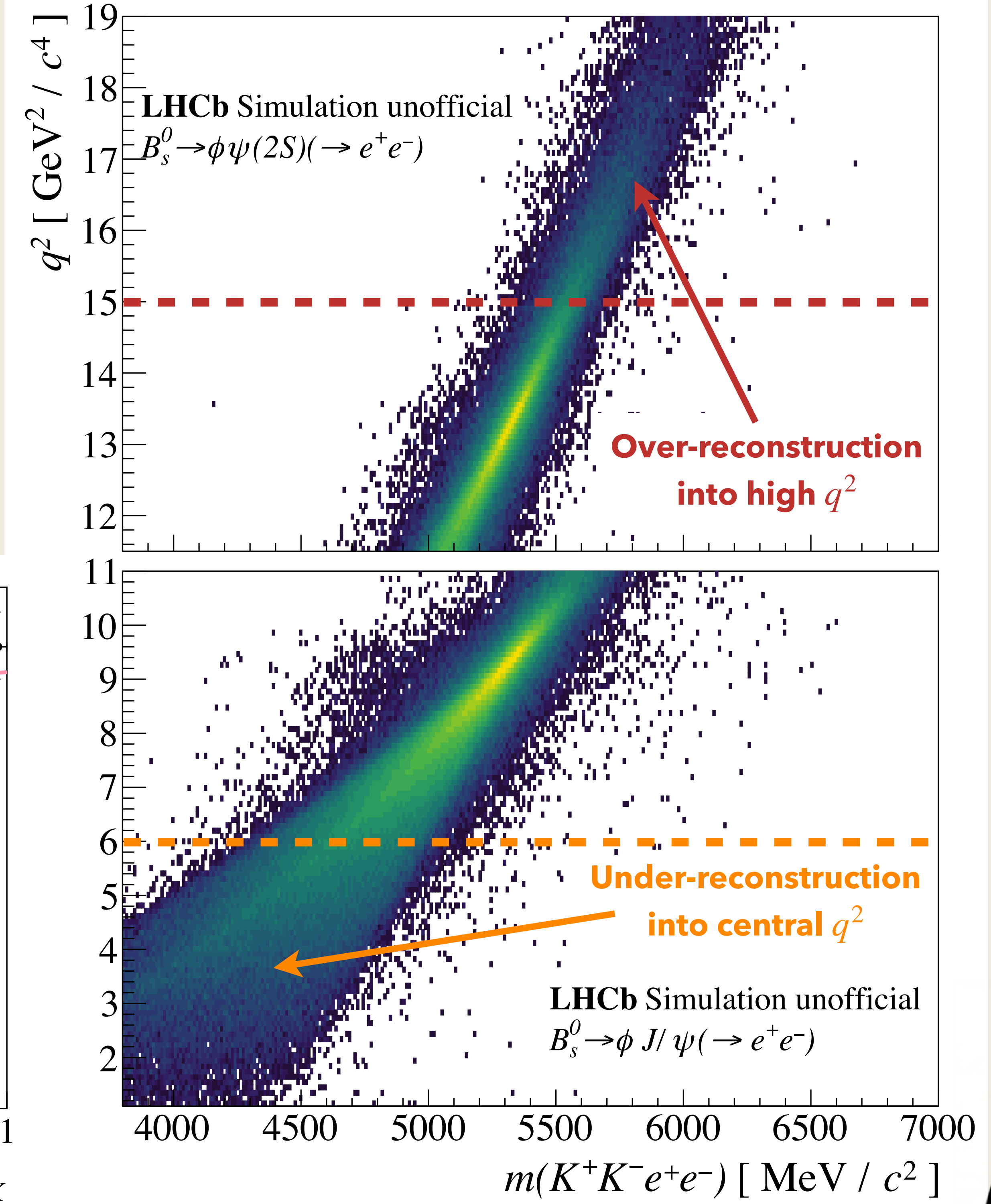
Electrons

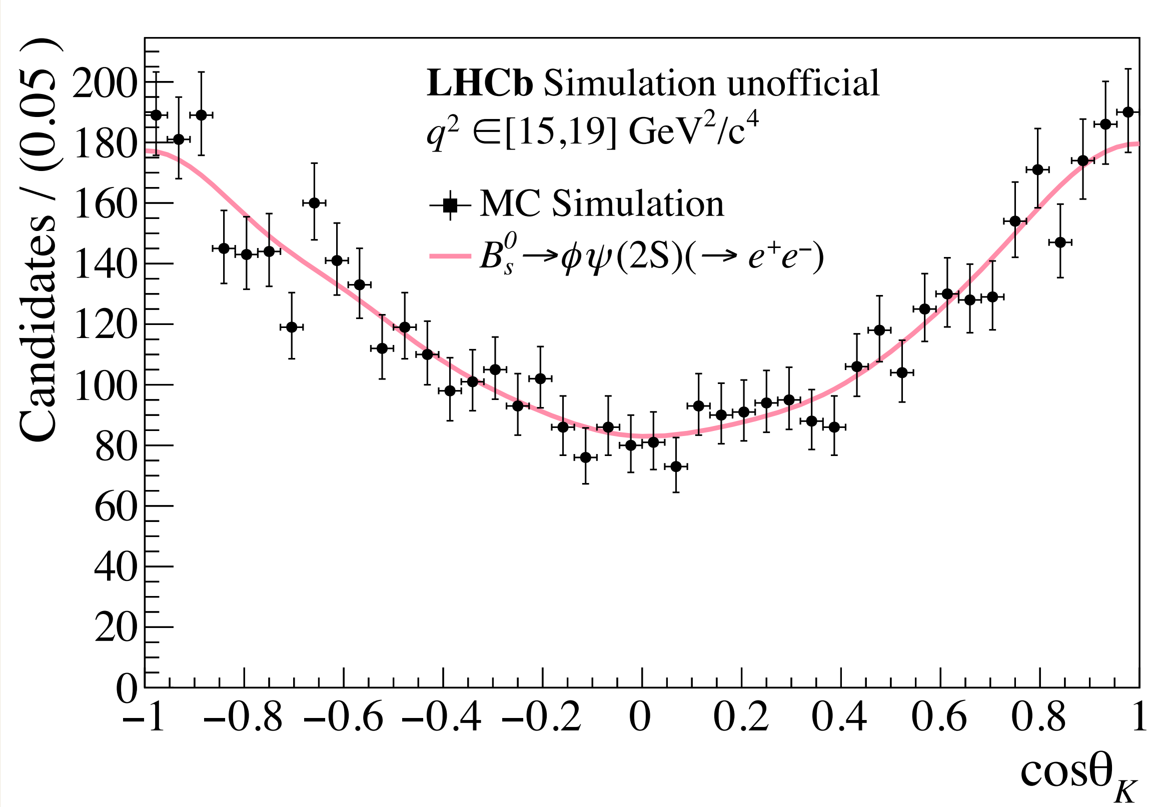
- **Higher misidentification rates:**
  - RICH $e^{\pm}, h^{\pm}$ separation harder at high p.
  - High L0 trigger E_T threshold.
- Bremsstrahlung recovery $\Longrightarrow$ **improves momentum resolution.**



Background contamination

- **Leakage from resonant modes.**
    - With bremsstrahlung recovery $\Longrightarrow q^2$ bin migration.
- Effect modelled in simulation.



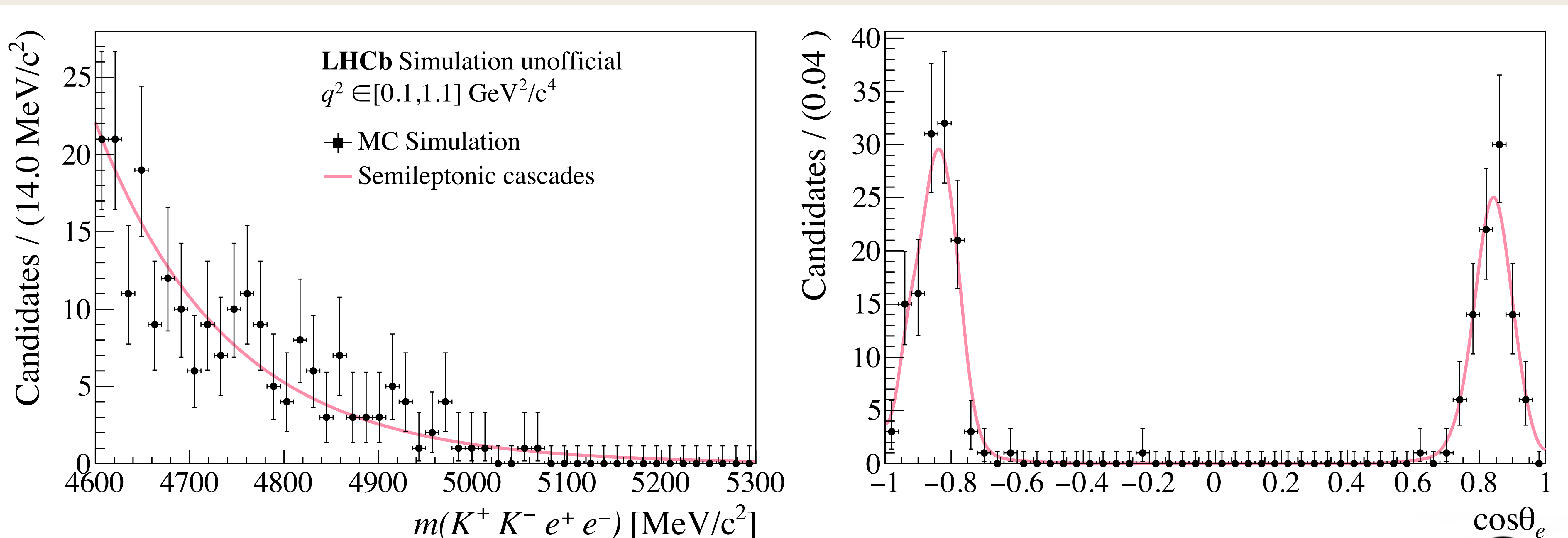


Background contamination

- **Semileptonic double-cascades.**

  $B_s^0 \to D_s^{(*)-} e^+ \nu_e$ with $D_s^{(*)-} \to \phi e^- \bar{\nu}_e (\gamma)$.

- Same final state, irreducible.
- Modelled in simulation.

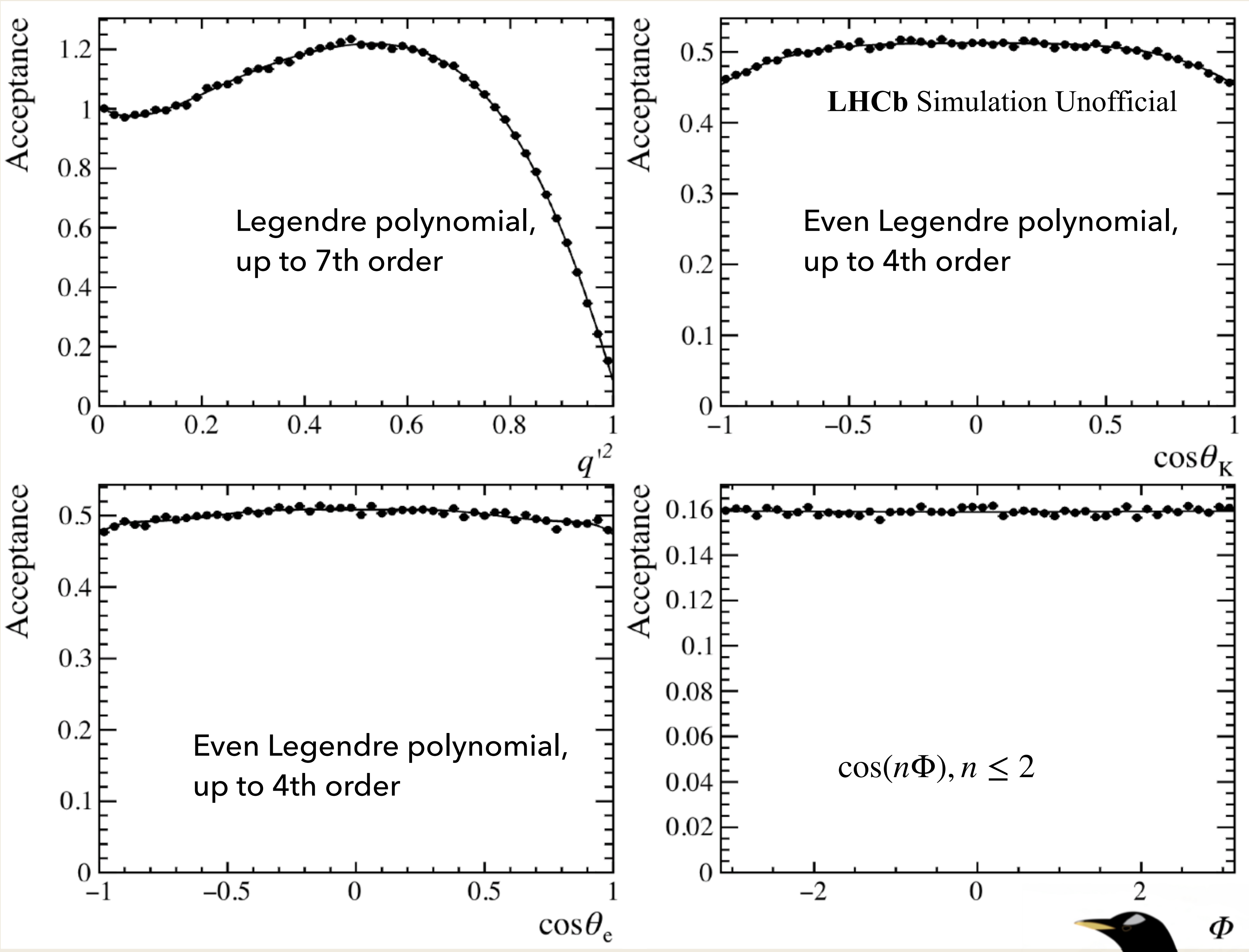


Acceptance modelling

- **Warping effect (acceptance)** from reconstruction process.

$$\Downarrow$$

- Generate events **flat in angles and q^2** and run through full selection.
- Extract C_{klmn} from fully corrected simulation [1].



$$\varepsilon(q^2, \cos\theta_K, \cos\theta_e, \Phi) = \sum_{klmn} C_{klmn} \cdot P_k(q^2) \cdot P_l(\cos\theta_K) \cdot P_m(\cos\theta_e) \cdot \cos(n\Phi)$$

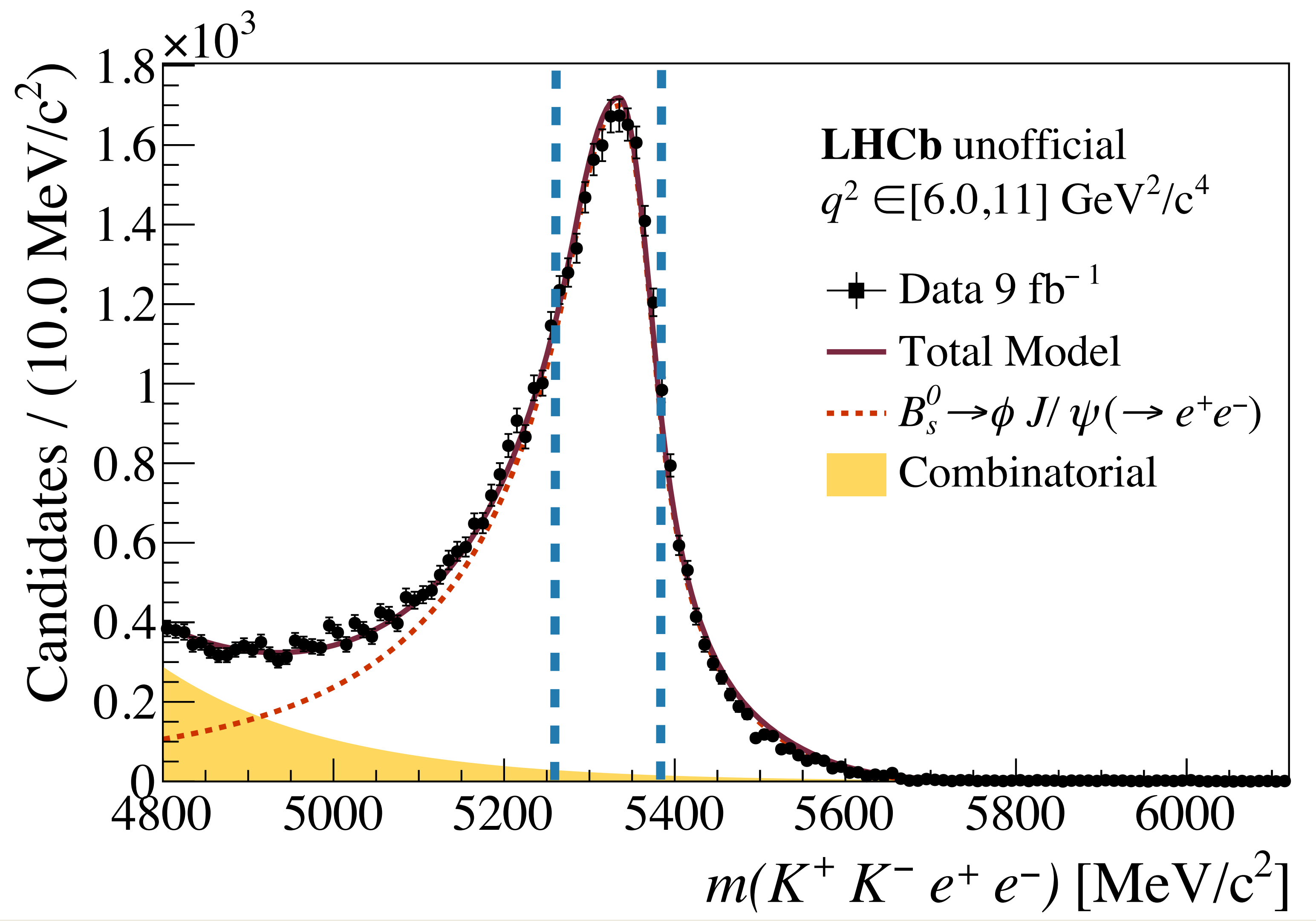
[1] JHEP 11 (2021) 043

Resonant mode fit

- Large sample of $B_s^0 \to J/\psi\phi$ available.

  $\Longrightarrow$ **Cross check fit** with published LHCb analyses [1,2].

- **Perform angular fits** around the peak for the highest signal-to-background ratio.



Around 17.5k signal events (300 combinatorial events) in region $m(K^+K^-e^+e^-) \in [5260,5380]$ MeV/c^2

[1] Eur. Phys. J. C81 (2021) 1026

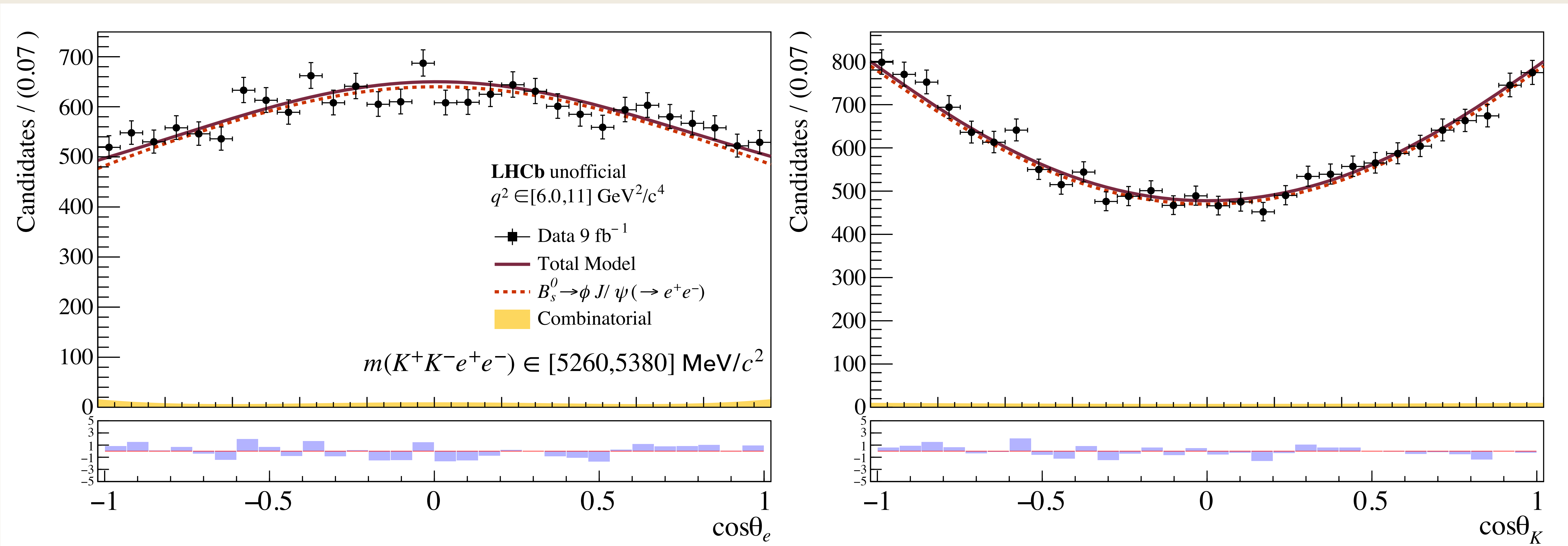
[2] Phys. Rev. Lett. 132 (2024) 051802

Resonant mode fit

- **Fit performs well**, some small issues are being investigated.

$\vec{\Omega} = (\cos\theta_K, \cos\theta_e)$ or Φ $\quad$ $\vec{\lambda}$ = nuisance parameters

$\vec{\Theta} = (F_L, A_6')$ or (S_3, A_9) $\quad$ $f_i = \dfrac{N_i}{N_{evts}}$



Physics PDF ⋆ Mass model

$$\mathrm{PDF}(\vec{\Omega}, m \mid q^2, \vec{\Theta}, \vec{\lambda}) = \left(1 - \sum_{i\in\{bkg\}} f_i\right) \cdot \boxed{\varepsilon(\vec{\Omega} \mid q^2)} \cdot \boxed{\mathrm{pdf}_{sig}(\vec{\Omega}, m \mid \vec{\Theta}, \vec{\lambda})} + \sum_{i\in\{bkg\}} f_i \cdot \boxed{\mathrm{pdf}_i(\vec{\Omega}, m \mid \vec{\lambda}_{bkg,i})}$$

Angular acceptance integrated over q^2bin

Background pdf captures acceptance effects


Photo Credit: www.photo.antarctica.ac.uk

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Conclusions

- $b \to see$ transitions offer a **mostly unexplored environment** to look for NP.
- Electron reconstruction at LHCb brings additional challenges, which can be tackled.
- Two LHCb analyses on-going in parallel to:
  - Report the observation of $B_s^0 \to \phi ee$.
  - Perform its first angular analysis.
- **Angular analysis of $B_s^0 \to \phi ee$ is in an advanced state.**

TO-DO
  - Complete validation on resonant modes.
  - Test robustness of fit strategy with pseudo-experiments.
  - Compute systematic uncertainties.

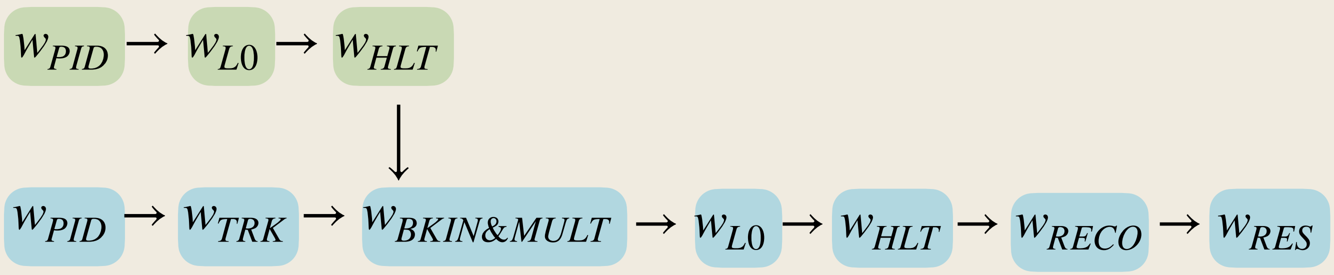
LHCb

WARWICK
THE UNIVERSITY OF WARWICK

Backup

Simulation Corrections

- Iterative correction chain first employed in (R_K, R_{K^*}) measurement [1,2].
- Corrections to:
  - Particle Identification (**PID**).
  - Tracking (**TRK**).
  - Trigger (**HLT**, **L0**).
  - B kinematics, event multiplicity (**BKIN&MULT**).
  - Vertex reconstruction (**RECO**).
  - q^2 smearing (**RES**).



[1] *Phys. Rev. Lett. 131 (2023) 051803*

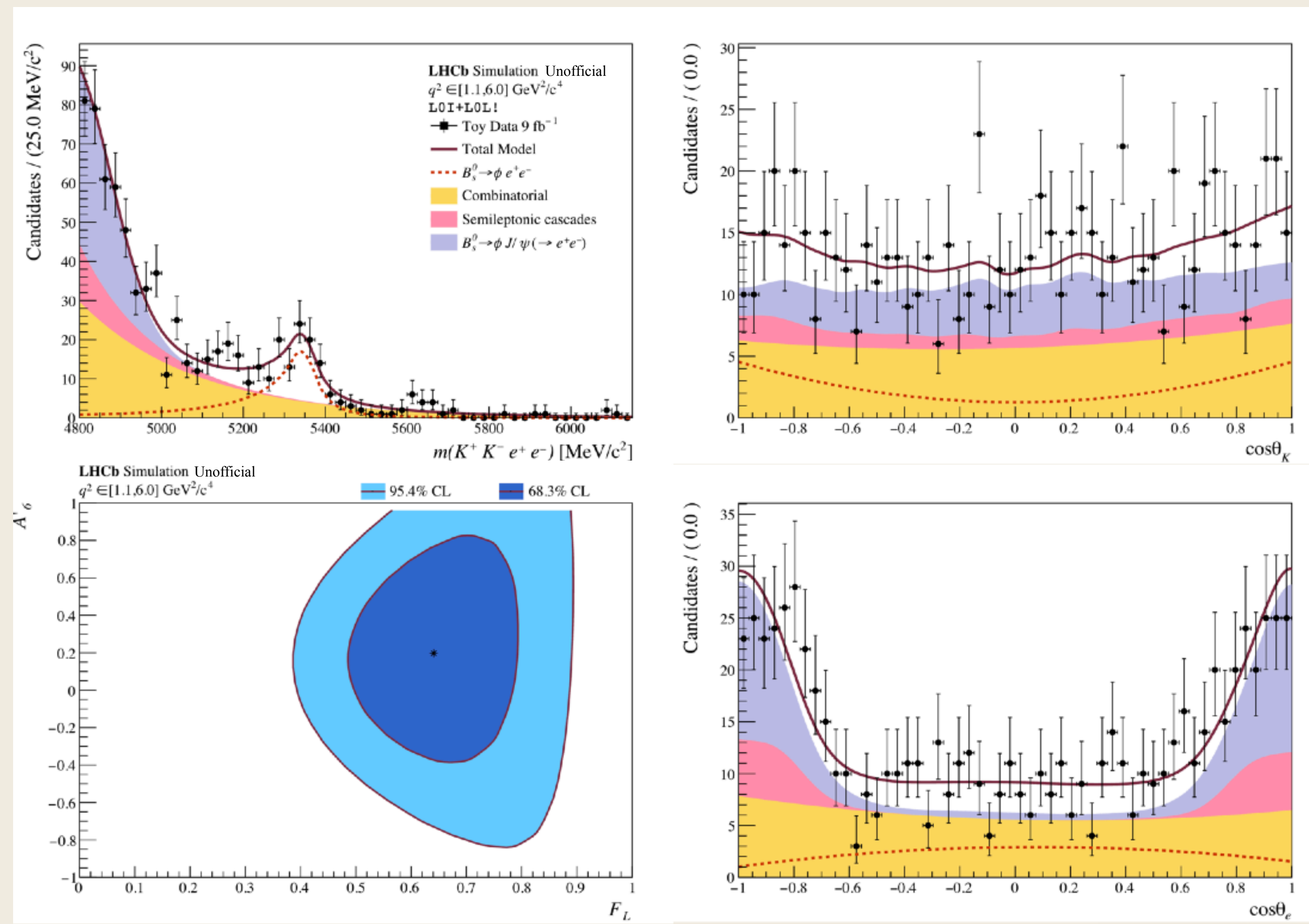
[2] *Phys. Rev. D 108 (2023) 032002*

Preliminary toy studies

- Semileptonic and leakage background yields constrained to expected value.
- Combinatorial generated assuming flat.
- Large fraction of toys end up at **limit of physical parameter space**.

$\Longrightarrow$ Will use **Feldman-Cousins prescription** to recover correct coverage intervals.

Toy generated with $F_L = 0.715,\ A_6 = 0.006$ (from LHCb-PAPER-2021-022).



Angular fit strategy

$\vec{\Omega} = (\cos\theta_K, \cos\theta_e)$ or Φ

$\vec{\Theta} = (F_L, A_6')$ or (S_3, A_9)

$\vec{\lambda} =$ nuisance parameters

$f_i = \frac{N_i}{N_{evts}}$

- Extended maximum likelihood fit in each q^2 bin:

Physics PDF

$$\text{PDF}(\vec{\Omega}, m \,|\, q^2, \vec{\Theta}, \vec{\lambda}) = \left(1 - \sum_{i\in\{bkg\}} f_i\right) \cdot \varepsilon(\vec{\Omega}\,|\,q^2) \cdot \text{pdf}_{sig}(\vec{\Omega}\,|\,\vec{\Theta}) \cdot \text{pdf}_{sig}(m\,|\,\vec{\lambda}_{sig}) + \sum_{i\in\{bkg\}} f_i \cdot \text{pdf}_i(\vec{\Omega}, m\,|\,\vec{\lambda}_{bkg,i})$$

Angular acceptance integrated over q^2bin

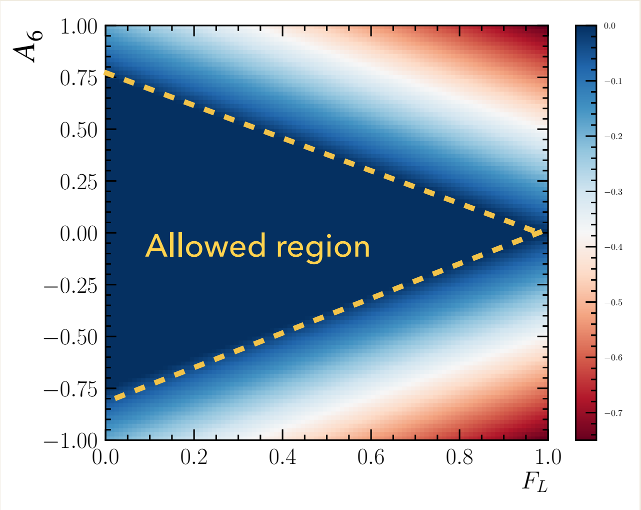
Background pdf captures acceptance effects

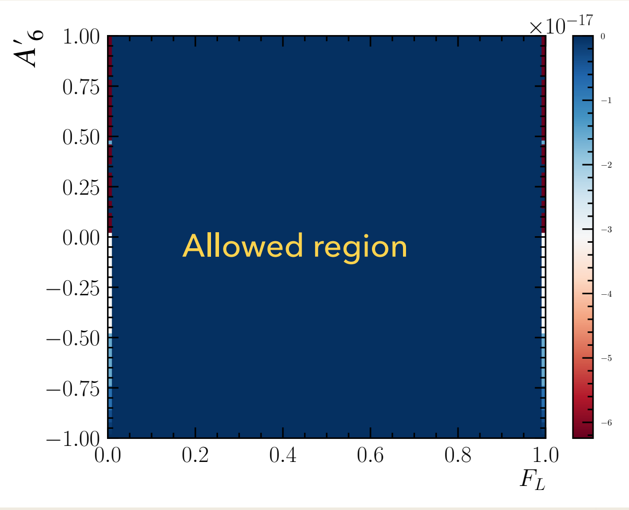
- For $\vec{\Omega} = (\cos\theta_K, \cos\theta_e)$ parametrise:

$$A_6 = \frac{3}{4}(1 - F_L)A_6'$$

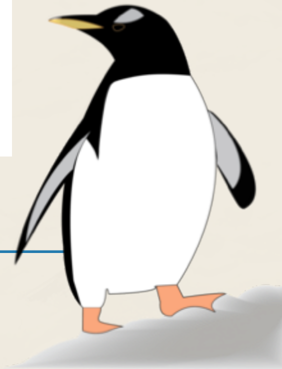
F_L, A_6' independent parameters.

$\Longrightarrow$ fit handles better parameter boundaries.





Triangular physical boundary → Square physical boundary



Handling the acceptance in the fit (1)

- The angular signal pdf is constructed as

$$\text{PDF}(\vec{\Omega}\,|\,q^2, \vec{\Theta}) = \varepsilon(\vec{\Omega}\,|\,q^2) \cdot \text{pdf}_{sig}(\vec{\Omega}\,|\,\vec{\Theta})$$

$\vec{\Omega} = (\cos\theta_K, \cos\theta_e)$ or Φ

$\vec{\Theta} = (F_L, A_6')$ or (S_3, A_9)

- The full acceptance:

$$\varepsilon(\cos\theta_K, \cos\theta_e, \Phi, q^2) = \sum_{klmn} C_{klmn} \cdot P_k(q^2) \cdot P_l(\cos\theta_K) \cdot P_m(\cos\theta_e) \cdot \cos(n\Phi)$$

- How to account for the q^2 dependence?

➡Integrate over bin

$$C_{lmn} \equiv \frac{1}{q'^2_{max} - q'^2_{min}} \sum_k C_{klmn} \int_{q'^2_{min}}^{q'^2_{max}} P_k(q'^2)\mathrm{d}q'^2$$

➡Fix the bin centre

$$C_{lmn} \equiv \sum_k C_{klmn} P_k(q'^2 = q'^2_{centre})$$

Handling the acceptance in the fit (2)

- The angular signal pdf is constructed as

$$\mathrm{PDF}(\vec{\Omega}\,|\,q^2, \vec{\Theta}) = \varepsilon(\vec{\Omega}\,|\,q^2)\cdot \mathrm{pdf}_{sig}(\vec{\Omega}\,|\,\vec{\Theta})$$

$\vec{\Omega} = (\cos\theta_K, \cos\theta_e)$ or Φ

$\vec{\Theta} = (F_L, A_6')$ or (S_3, A_9)

- The full acceptance:

$$\varepsilon(\cos\theta_K, \cos\theta_e, \Phi, q^2) = \sum_{klmn} C_{klmn}\cdot P_k(q^2)\cdot P_l(\cos\theta_K)\cdot P_m(\cos\theta_e)\cdot \cos(n\Phi)$$

- How to do the projections properly? It can be shown that, e.g. if $\vec{\Omega} = (\cos\theta_K, \cos\theta_e)$

$$\mathrm{PDF}(\cos\theta_K, \cos\theta_e\,|\,q^2, \vec{\Theta}) =$$

$$\varepsilon(\cos\theta_K, \cos\theta_e\,|\,q^2)\cdot \mathrm{pdf}_{sig}(\cos\theta_K, \cos\theta_e\,|\,\vec{\Theta})$$

Acceptance projection — Physics PDF projection

$$+\sum_{lm}\sum_{n\neq 0} C_{lmn}\cdot I_n(\cos\theta_K, \cos\theta_e)\cdot P_l(\cos\theta_K)\cdot P_m(\cos\theta_e)$$

Residual integrals over Φ

Small contribution, can assign systematic

$$\varepsilon(\cos\theta_K, \cos\theta_e\,|\,q^2) = \sum_{lm} C_{lm0} P_l(\cos\theta_K)\cdot P_m(\cos\theta_e)$$

$$I_n(\cos\theta_K, \cos\theta_e) = \int_{-\pi}^{\pi} \mathrm{pdf}_{sig}(cos\theta_K, \cos\theta_e, \Phi\,|\,\vec{\Theta})\cdot \cos(n\Phi)\mathrm{d}\Phi$$