Angular analysis of the $B^0 \to K^{*0} e^- e^+$ decay in the high dilepton invariant mass

An indirect search for New Physics

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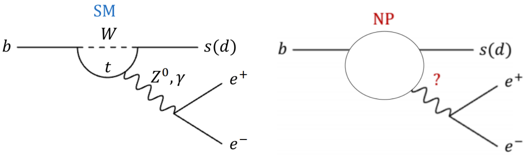
LHCb

CHIARO SCURO

Motivation: Indirect Search for New Physics

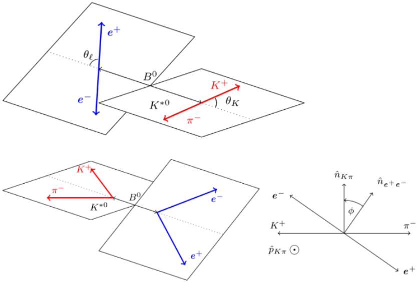
- Many open question with the SM $\rightarrow$ The SM is not complete
- This motivates the search for New Physics (NP)
- My decay: $B^0 \rightarrow K^{*0}e^+e^-$ is a FCNC $b \rightarrow s$ transition forbidden at tree level in SM
- Only allowed on loop level or box $\rightarrow$ *Highly suppressed by the SM* ($\mathcal{B} \approx 10^{-6}$)
- Virtual particles probed are much higher than the b quark... (W)
- $\rightarrow$ New particles can enter the loop and modify physics observables (Branching fraction, angular observables...)



Sensitive to TeV scale NP contribution

Goal of the analysis

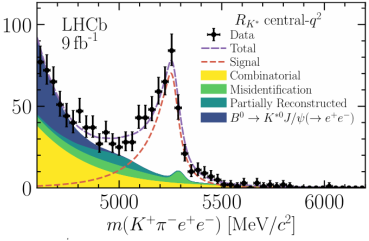
- Reconstructed mass of B^0 meson: $m(K^{*0}e^+e^-)$
- The $B^0 \to K^{*0}e^+e^-$ decay is described by θ_l, θ_K, ϕ

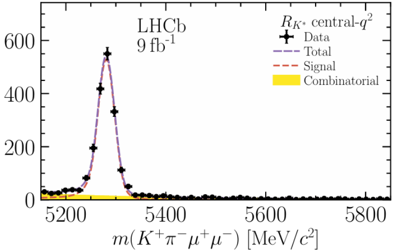


- Goal of the analysis:
  Through a fit to θ_l, θ_K, ϕ , measure **certain angular observables**
- Compare with SM predictions: NP?

Challenges of electrons at LHCb

- Electrons emit a lot of bremsstrahlung radiation when interacting with the detector making it hard to reconstruct electrons and have more background
- Dealing with electrons is extremely hard but not impossible...
- A lot of research has been done on muonic decay (cleaner channel)
- We want to use the electronic channel





https://arxiv.org/abs/2212.09153

Results

Mass models

- The reconstructed mass $m(K^{*0}e^+e^-)$ distribution is fitted for background samples and signal

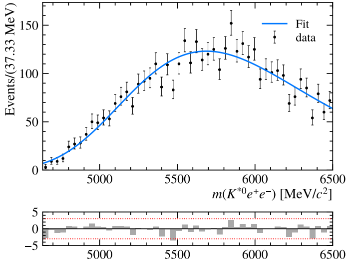


Figure: Combinatorial background

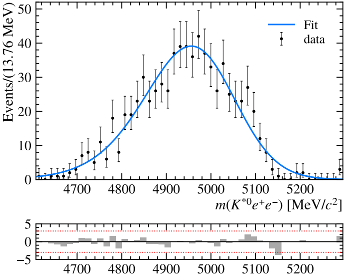


Figure: Partially reconstructed

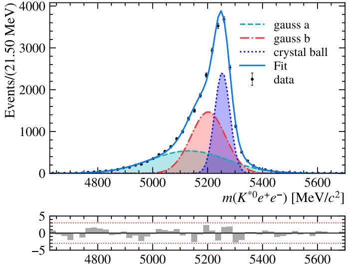


Figure: Monte Carlo Signal

Angular models

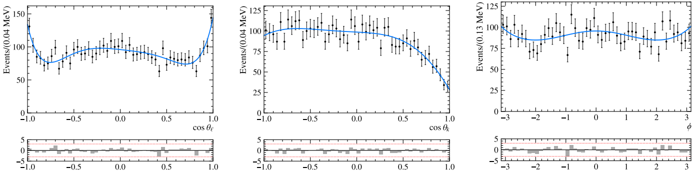


Figure: $B^0 \to K^{*0} e^{\pm} e^{\pm}$ background

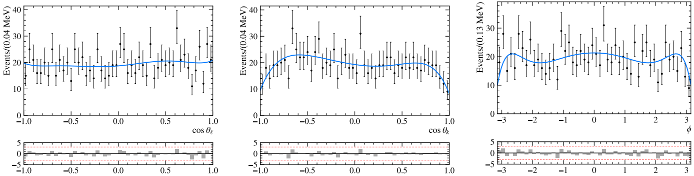


Figure: $B^+ \to K^+[\pi^+]\pi^- e^+ e^-$ background

Angular acceptance of phasespace MC

- $B^0 \to K^{*0}e^+e^-$ MC sample generated with **flat angular distributions** (i.e. *Phasespace MC*) is used to model the experimental selection and detection effects $\to$ *Acceptance*
- $\text{Corrections} = \frac{1}{f(\cos\theta_l)f(\cos\theta_k)f(\phi)}$ $\to$ used to correct for all acceptance effects in our data

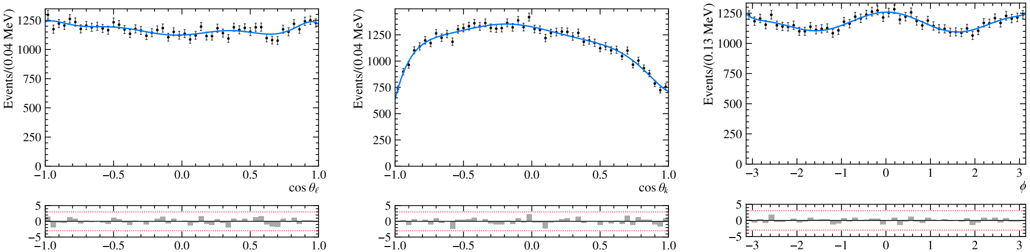


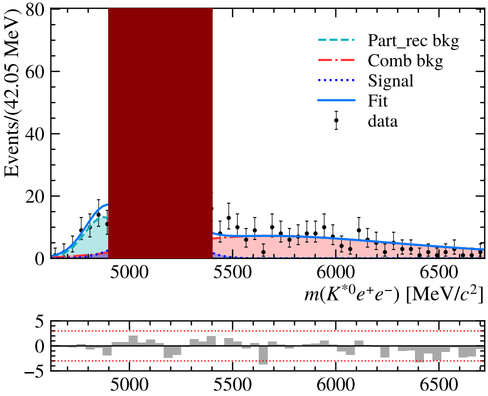
Figure: Fit of $B^0 \to K^{*0}e^+e^-$ phasespace MC angular distributions

Blinded fit to $m(K^{*0}e^+e^-)$

- Fit to the $m(K^{*0}e^-e^+)$ spectrum in $B^0 \to K^{*0}e^-e^+$ **data**
- The signal region $[4900, 5400]$ MeV and its yield are blinded throughout the analysis (to avoid bias)

- Further background studies need to be conducted to model them well(especially the combinatorial)

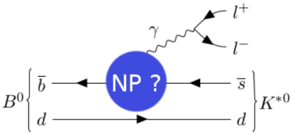
$N_{comb.}$	225 ± 17
N_{part_rec}	74 ± 11
$N_{sig.}$	blinded (predicted $\approx 127 \pm 15$)



Summary and prospects

- The $B^0 \to K^{*0}e^+e^-$ decay includes a $b \to sll$ transition where New Physics contributions can appear

- Currently performing an angular analysis of $B^0 \to K^{*0}e^+e^-$ and compare angular observables to SM predictions.

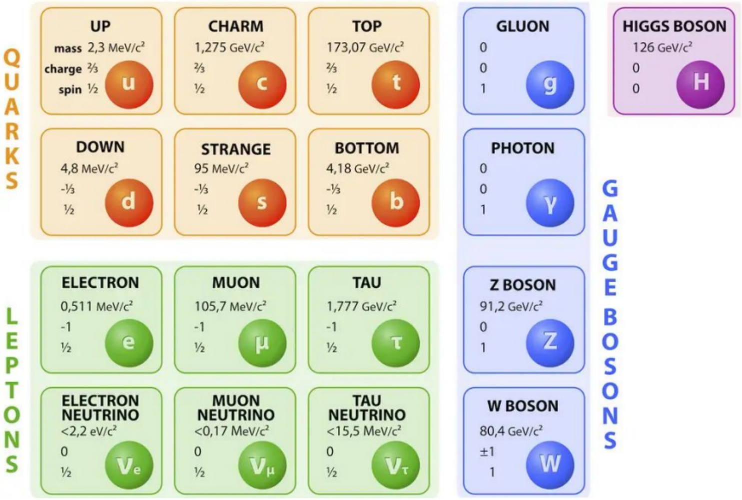


- As future work we aim to do toy studies: produce high statistics pseudoexperiments to confirm the robustness of our analysis

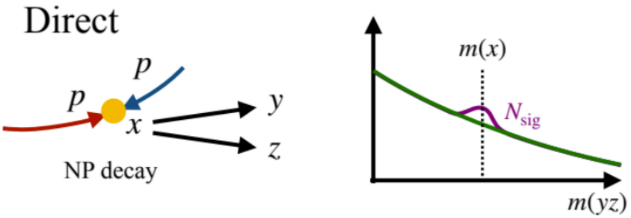
Thank you for your attention!

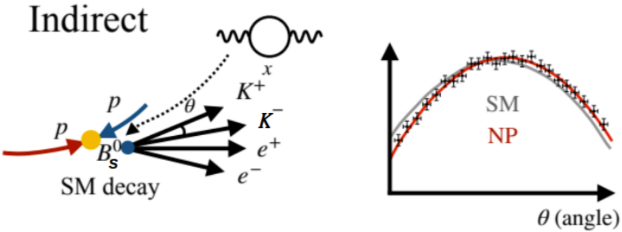
Backup

The Standard Model (SM)



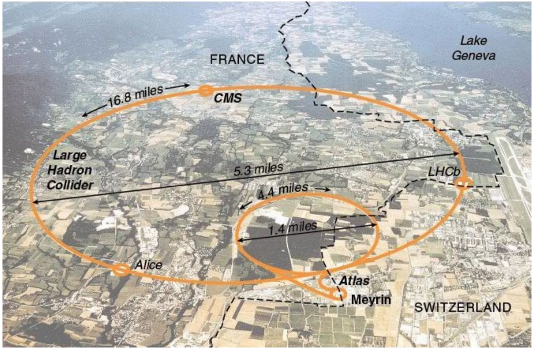
How to Search for New Physics (NP)?



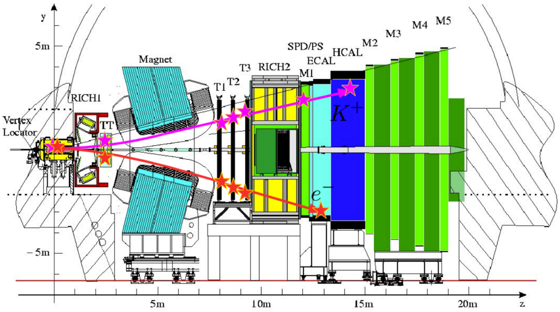


Large Hadron Collider (LHC)

- 27 km circular particle collider at CERN
- Proton-proton collision
- 4 beam collision points:
  - ATLAS
  - ALICE
  - CMS
  - LHCb
- CoM energy $13\,\mathrm{TeV}$ per collision

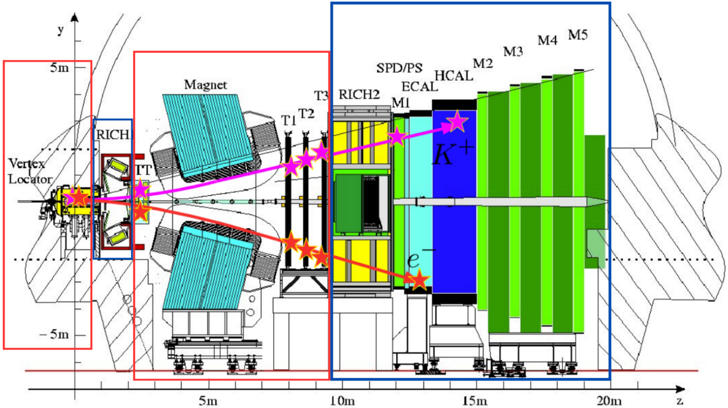


Large Hadron Collider beauty (LHCb)



- Beauty (bottom) and charm quark dedicated experiment
- Composed of several subdetectors

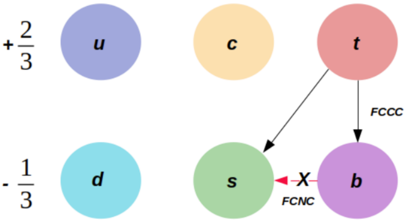
Large Hadron Collider beauty (LHCb)



- Detect position and momentum of particle
- Particle identification (PID) (and calorimeters)

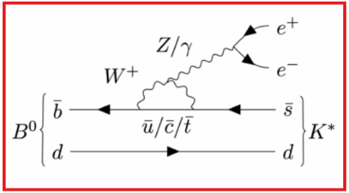
Rare Beauty-Quark Decays

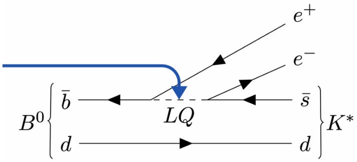
- A change in quark flavor with a charge change ($t \to s$)
  - Allowed at tree level in the SM
- A change in quark flavor without charge change ($b \to s$)
  - Forbidden at tree level in the SM $\to$ Happens through loop or box diagrams
- $b \to s$ transition is our interest
- Very suppressed (Branching fraction $\sim 10^{-6}$)



My decay: the $B^0 \to K^{*0} e^+ e^-$ decay

- Particles involved:
  - B^0: $\bar{b}d$
  - K^{*0}: $\bar{s}d \to K^+ \pi^-$
  - Electrons
- Involves $b \to s$ transition
- Decay proceeds by weak interaction (W)
- "Rare" decay: low probability of occurring ($\mathcal{B} \approx 10^{-6}$)
- Heavily studied at LHCb
- Sensitive to New Physics (NP)
- Internship: Angular analysis of $B^0 \to K^{*0} e^+ e^-$





Goal of the analysis

$$
\begin{aligned}
p(\theta_l, \theta_k, \phi) = \frac{9}{32\pi} \Bigg[& \frac{3}{4}(1 - F_L) \sin^2\theta_k + F_L \cos^2\theta_k \\
& + \frac{1}{4}(1 - F_L) \sin^2\theta_k \cos 2\theta_l - \boxed{F_L} \cos^2\theta_k \cos 2\theta_l \\
& + \boxed{S_3} \sin^2\theta_k \sin^2\theta_l \cos(2\phi) + \boxed{S_4} \sin 2\theta_k \sin 2\theta_l \cos(\phi) \\
& + \boxed{S_5} \sin 2\theta_k \sin\theta_l \cos(\phi) + \frac{4}{3} \boxed{A_{FB}} \sin^2\theta_k \cos\theta_l \\
& + \boxed{S_7} \sin 2\theta_k \sin\theta_l \sin(\phi) + \boxed{S_8} \sin 2\theta_k \sin 2\theta_l \sin(\phi) \\
& + \boxed{S_9} \sin^2\theta_k \sin^2\theta_l \sin(2\phi) \Bigg]
\end{aligned}
$$

Motivation of the high q^2

- Dilepton invariant mass: $q^2 = (p^{\mu}_{e^-} + p^{\mu}_{e^+})^2 = m^2_{e^+e^-}$
- Different resonant particles shown in the figure as a function of q^2
- High q^2 region is above the $\psi(2S)$ resonance

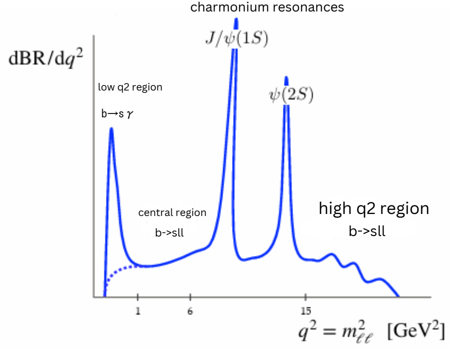


Figure: q^2 dependence on branching ratio of $B^0 \to K^{*0} l^+ l^-$

Samples and Selections

Data and Simulation Samples

The Signal: $B^0 \to K^{*0} e^+ e^-$ decay

- 6 years of data collected by the LHCb detector $(2011 - 2012, 2015 - 2018)$
- A dedicated simulation sample is used to describe its physical behaviour inside the LHCb detector

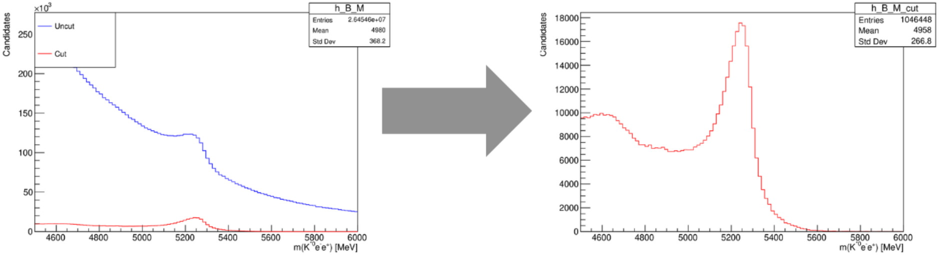
Background sources

1. Combinatorial background: random association of K^+, π^-, e^+, and e^- tracks of the pp collisions. **Same sign sample** $B^0 \to K^{*0} e^\pm e^\pm$ of the reconstructed data is used to model its physical behaviour.
2. Partially reconstructed background $B^+ \to K^+ [\pi^+] \pi^- e^+ e^-$: where the π^+ is not reconstructed by LHCb. A dedicated MC sample is used to simulate it

Offline selection criteria

A series of selections employed to enhance signal purity and suppress background contributions

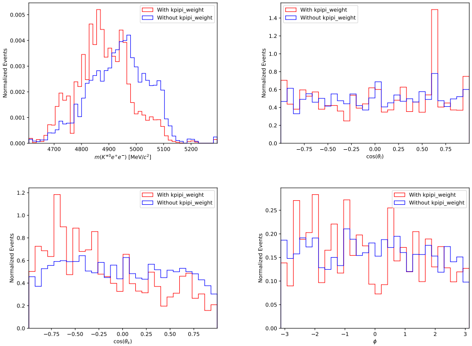
$$m(K^+\pi^-e^+e^-) \text{ should be } \sim m(B^0) = 5280\,\text{MeV}$$



Before selections **After selections**

Correction of Partially reconstructed simulation

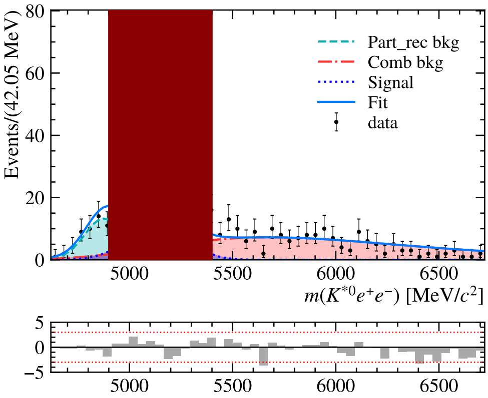
- $B^+ \to K^+[\pi^+]\pi^- e^+ e^-$: 5-body decay, quite complex
- Decay can proceed through number of resonances (e.g. $B^+ \to K_1^+(\to K^+[\pi^+]\pi^-)e^+e^-$)
- Simulation does **not** account for the sub-resonances: alters kinematic variables
- A **correction** applied to the mass and angles to correct for them



Blinded fit to $m(K^{*0}e^+e^-)$ at high q^2

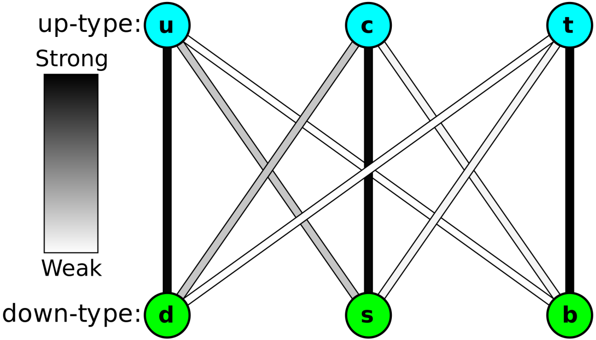
$$
\begin{aligned}
\mathrm{PDF}_{\mathrm{tot}} = N_{\mathrm{comb.}} \times PDF_{\mathrm{comb.}} \\
+ N_{\mathrm{sig.}} \times PDF_{\mathrm{sig.}} \\
+ N_{part\_rec} \times PDF_{\mathrm{part\_rec.}}
\end{aligned}
$$

$N_{\mathrm{comb.}}$	225 ± 17
N_{part_rec}	74 ± 11
$N_{\mathrm{sig.}}$	blinded (predicted ≈ 120)



CKM Matrix

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97373 \pm 0.00031 & 0.2243 \pm 0.0008 & 0.00382 \pm 0.00020 \\ 0.221 \pm 0.004 & 0.975 \pm 0.006 & 0.0408 \pm 0.0014 \\ 0.0086 \pm 0.0002 & 0.0415 \pm 0.0009 & 1.014 \pm 0.029 \end{bmatrix}.$$



kpipi

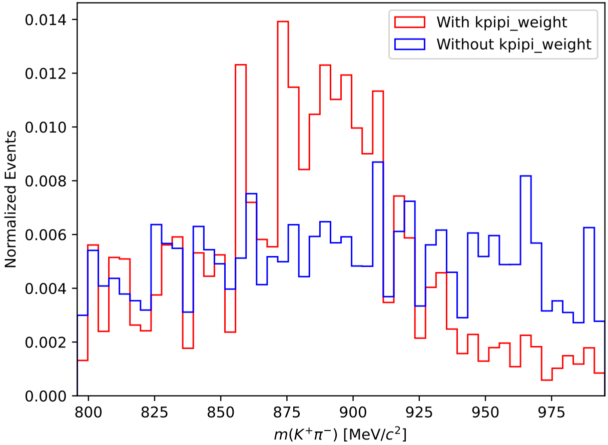


Figure: Impact of Kpipi weight on the $m(K^+\pi^-)$ distribution

PDFS

$$f(x;\mu,\sigma,\alpha_L,n_L,\alpha_R,n_R,\mu_1,\sigma_1,\mu_2,\sigma_2) = \begin{cases} A_L\cdot(B_L-\frac{x-\mu}{\sigma})^{-n_L}, & \text{for } \frac{x-\mu}{\sigma} < -\alpha_L \\ \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right), & \text{for } -\alpha_L < \frac{x-\mu}{\sigma} < \alpha_R \\ A_R\cdot(B_R+\frac{x-\mu}{\sigma})^{-n_R}, & \text{for } \frac{x-\mu}{\sigma} > \alpha_R \end{cases}$$

$$A_{L/R} = \left(\frac{n_{L/R}}{|\alpha_{L/R}|}\right)^{n_{L/R}} \cdot \exp\left(-\frac{|\alpha_{L/R}|^2}{2}\right)$$

$$B_{L/R} = \frac{n_{L/R}}{|\alpha_{L/R}|} - |\alpha_{L/R}|$$

ExpStep

$$f(x;\alpha,\beta,\sigma) = \frac{e^{(x-\alpha)}}{\left[1+(2^{\beta}-1)\,e^{-\frac{x-\alpha}{\sigma}}\right]^{\frac{1}{\beta}}}$$

Chebyshev Polynomials

- Chebyshev polynomials of the first kind, $T_n(x)$, are defined by the recurrence relation:

$$T_0(x) = 1, \quad T_1(x) = x, \quad T_{n+1}(x) = 2xT_n(x) - T_{n-1}(x)$$

- The 4th Chebyshev polynomial:

$$T_4(x) = 8x^4 - 8x^2 + 1$$

- The 6th Chebyshev polynomial:

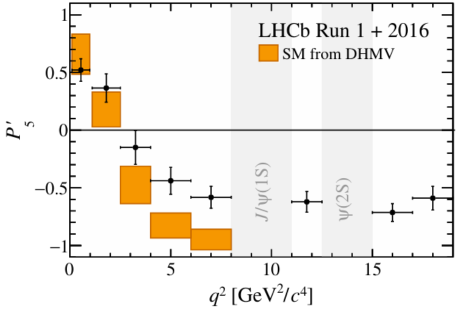
$$T_6(x) = 32x^6 - 48x^4 + 18x^2 - 1$$

$K\pi\pi$ Reweighing

- Simulated $B^+ \to K^+[\pi^+]\pi^- e^+ e^-$ samples do not match observed collision data because of the absence of subresonant contributions (e.g. $B^+ \to K_1^+(\to K^+[\pi^+]\pi^-)e^+e^-)$.
- A Boosted Decision Tree (BDT) reweighter will be trained on $m(K^+\pi^-)$, $m(\pi^+\pi^-)$, and $m(K^+\pi^+\pi^-)$ distributions from $B^+ \to K^+\pi^+\pi^-\mu^+\mu^-$ collision data simulation at the generator level
- Event-by-event *weights* will be produced and applied to the simulated $B^+ \to K^+[\pi^+]\pi^- e^+ e^-$ samples
- The reweighing **will** be done using the mass and the three angles combined

Why study angular distributions?

- Angular distributions give access to angular observables from the SM
- Any deviation from the SM could indicate NP!
- Recent results: **tensions with the SM are present in angular observables in** $B^0 \to K^{*0}\mu^+\mu^-$ shown in the figure



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

Simulation Corrections

Correction of Simulation

- A complex correction process is used to correct the simulation to make it match to the experimental data.
- This correction is encapsulated in a single correction, called *simulation weight*. We want to see if it has an effect on the angular distributions.

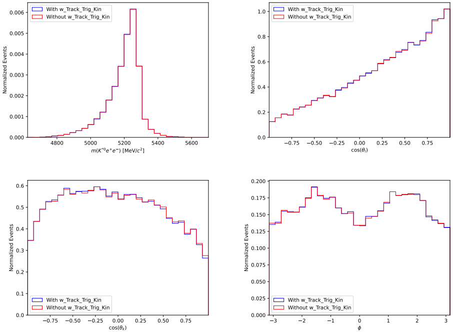


Figure: Impact of the MC correction on the $B^0 \to K^{*0}e^-e^+$ MC Signal events.

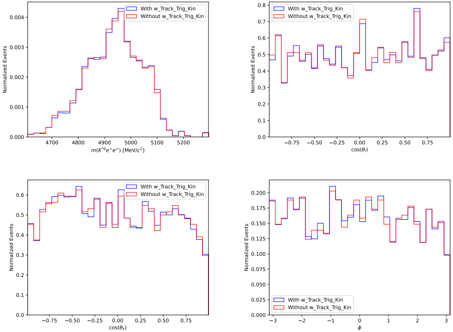


Figure: Impact of the MC correction on the $B^+ \to K^+\pi^+\pi^-e^+e^-$ MC Partially reconstructed events.

Angular fit of MC signal

Observable	Value	Error
F_L	0.254642	$\pm\ 0.003837$
S_3	-0.170871	$\pm\ 0.00583$
S_4	-0.27655	$\pm\ 0.004033$
S_5	-0.295446	$\pm\ 0.004151$
A_{FB}	0.435869	$\pm\ 0.004083$
S_6	0.009395	$\pm\ 0.00613$
S_7	-0.0042186	$\pm\ 0.0061225$
S_8	-0.0065145	$\pm\ 0.0061638$