$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis using the full Run 1+2 sample
FSP Meeting

H. Jage, C. Langenbruch, L. Carus, E. Smith, T. Oeser

RWTH Aachen, Germany

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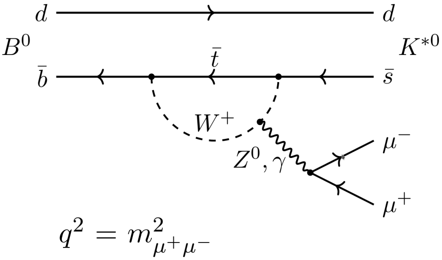
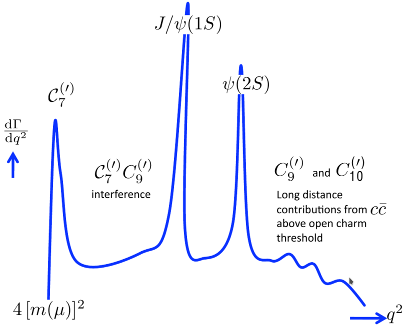
Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

Motivation





- B^0 decays via $b \to s$ flavour changing neutral current (FCNC)
- Forbidden in the SM at tree-level
- High sensitivity to New Physics due to high suppression in SM
- Probe Λ_{NP} up to $\mathcal{O}(100\ \text{TeV})$ [A. Buras, arxiv:1505.00618]
- Angular analysis gives access to set of q^2 dependent observables
  - Less affected by theoretical uncertainties than $\mathcal{B}$

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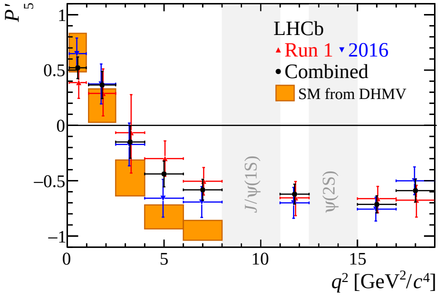
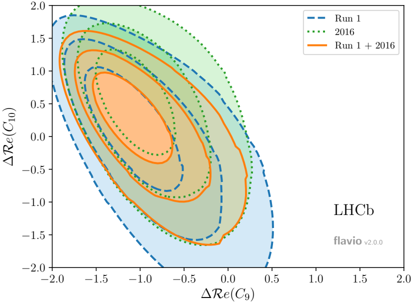
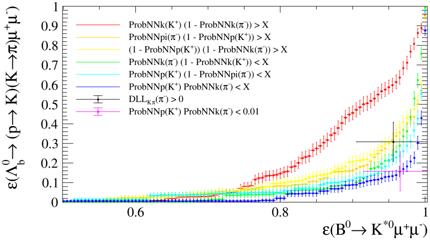
Motivation

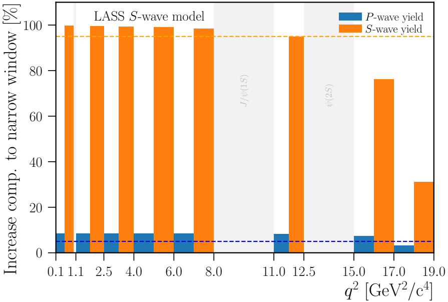




- Run 1+2016 result [PRL 125 (2020) 011802] published
- Very good agreement between Run 1 and 2016 data samples
- Global tension increased: $3.0\,\sigma$ (Run 1) $\rightarrow 3.3\,\sigma$ (Run 1 + 2016)
- Update to full Run2 dataset to clarify

Improved selection

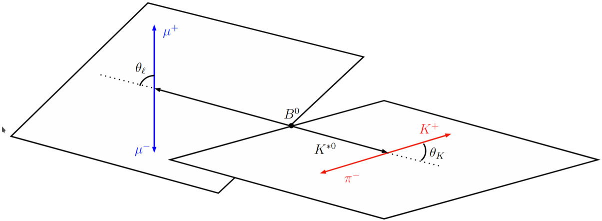


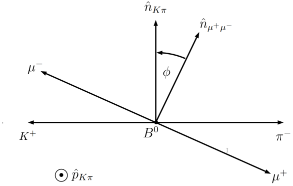


- LHCb data: Run1 and 2016-2018 (Integrated luminosity 8.8 fb^{-1})
- Improved selection → Increased efficiency and background rejection
  - Tuned PID selection → increased peaking background suppression
  - Improved combinatorial BDT → increased selection efficiency
- Allows to widen $m_{K\pi}$ window to $[745.9, 1095.9]\,\text{MeV}/c^2$

Angular Analysis

Angular description of the decay





- Decay fully described by three angles $\Omega = (\theta_l, \theta_K, \phi)$ + q^2 and $m_{K\pi}$
- $m_{K\pi}$ dependence now directly included into PDF as Breit-Wigners
- Previously: $m_{K\pi}$ shape fitted integrated over decay angles

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{\overset{\leftrightarrow}{\Gamma}}{d\vec{\Omega}\, dq^2\, dm_{K\pi}} = \frac{9}{32\pi}\Big[\frac{S_1^s \pm A_1^s}{2}\sin^2\theta_K + \frac{S_1^c \pm A_1^c}{2}\cos^2\theta_K + \big(\frac{S_2^s \pm A_2^s}{2}\sin^2\theta_K + \frac{S_2^c \pm A_2^c}{2}\cos^2\theta_K\big)\cos 2\theta_\ell$$
$$+ \frac{S_3 \pm A_3}{2}\sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + \frac{S_4 \pm A_4}{2}\sin 2\theta_K \sin 2\theta_\ell \cos\phi$$
$$+ \frac{S_5 \pm A_5}{2}\sin 2\theta_K \sin\theta_\ell \cos\phi + \big(\frac{S_6^s \pm A_6^s}{2}\sin^2\theta_K + \frac{S_6^c \pm A_6^c}{2}\cos^2\theta_K\big)\cos\theta_\ell$$
$$+ \frac{S_7 \pm A_7}{2}\sin 2\theta_K \sin\theta_\ell \sin\phi + \frac{S_8 \pm A_8}{2}\sin 2\theta_K \sin 2\theta_\ell \sin\phi$$
$$+ \frac{S_9 \pm A_9}{2}\sin^2\theta_K \sin^2\theta_\ell \sin 2\phi\Big] \times |\mathcal{BW}_{\mathcal{P}}(m_{K\pi})|^2$$

$$F_{\mathrm{L}} = -S_2^c$$
$$A_{FB} = \frac{3}{4}S_6^s$$

- S_i/A_i are CP-symmetries/asymmetries of angular observables

Angular description of the decay

- Aim to also publish observables from P/S-Wave interference terms

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\Big|_{\mathrm{P+S}} \frac{\mathrm{d}^5\overleftrightarrow{\Gamma}}{\mathrm{d}q^2\,\mathrm{d}m_{K\pi}\,\mathrm{dcos}\theta_\ell\,\mathrm{dcos}\theta_K\,\mathrm{d}\phi} = (1-F_{\mathrm{S}})\frac{9}{32\pi}\sum_{i\,\in\,\text{P-wave}} \tfrac{1}{2}(S_i \pm A_i) f_i(\cos\theta_\ell,\cos\theta_K,\phi)|\mathcal{BW}_{\mathrm{P}}(m_{K\pi})|^2$$
$$+\frac{3}{16\pi}\Big[\big(\tfrac{1}{2}(S_{10}\pm A_{10})+\tfrac{1}{2}(S_{12}\pm A_{12})\cos 2\theta_\ell\big)\times\big|\mathcal{BW}_{\mathrm{S}}(m_{K\pi})\big|^2$$
$$+\tfrac{1}{2}\cos\theta_K\,\big((S_{11}^{\mathrm{re}}\pm A_{11}^{\mathrm{re}})\times\mathrm{Re}[\mathcal{BW}_{\mathrm{S}}(m_{K\pi})\mathcal{BW}^*_{\mathrm{P}}(m_{K\pi})]-(S_{11}^{\mathrm{im}}\pm A_{11}^{\mathrm{im}})\times\mathrm{Im}[\mathcal{BW}_{\mathrm{S}}(m_{K\pi})\mathcal{BW}^*_{\mathrm{P}}(m_{K\pi})]\big)$$
$$+\tfrac{1}{2}\cos\theta_K\cos 2\theta_\ell\,\big((S_{13}^{\mathrm{re}}\pm A_{13}^{\mathrm{re}})\times\mathrm{Re}[\mathcal{BW}_{\mathrm{S}}(m_{K\pi})\mathcal{BW}^*_{\mathrm{P}}(m_{K\pi})]-(S_{13}^{\mathrm{im}}\pm A_{13}^{\mathrm{im}})\times\mathrm{Im}[\mathcal{BW}_{\mathrm{S}}(m_{K\pi})\mathcal{BW}^*_{\mathrm{P}}(m_{K\pi})]\big)$$
$$+\tfrac{1}{2}\sin\theta_K\sin 2\theta_\ell\cos\phi\,\big((S_{14}^{\mathrm{re}}\pm A_{14}^{\mathrm{re}})\times\mathrm{Re}[\mathcal{BW}_{\mathrm{S}}(m_{K\pi})\mathcal{BW}^*_{\mathrm{P}}(m_{K\pi})]-(S_{14}^{\mathrm{im}}\pm A_{14}^{\mathrm{im}})\times\mathrm{Im}[\mathcal{BW}_{\mathrm{S}}(m_{K\pi})\mathcal{BW}^*_{\mathrm{P}}(m_{K\pi})]\big)$$
$$+\tfrac{1}{2}\sin\theta_K\sin\theta_\ell\cos\phi\,\big((S_{15}^{\mathrm{re}}\pm A_{15}^{\mathrm{re}})\times\mathrm{Re}[\mathcal{BW}_{\mathrm{S}}(m_{K\pi})\mathcal{BW}^*_{\mathrm{P}}(m_{K\pi})]-(S_{15}^{\mathrm{im}}\pm A_{15}^{\mathrm{im}})\times\mathrm{Im}[\mathcal{BW}_{\mathrm{S}}(m_{K\pi})\mathcal{BW}^*_{\mathrm{P}}(m_{K\pi})]\big)$$
$$+\tfrac{1}{2}\sin\theta_K\sin\theta_\ell\sin\phi\,\big((S_{16}^{\mathrm{re}}\pm A_{16}^{\mathrm{re}})\times\mathrm{Im}[\mathcal{BW}_{\mathrm{S}}(m_{K\pi})\mathcal{BW}^*_{\mathrm{P}}(m_{K\pi})]+(S_{16}^{\mathrm{im}}\pm A_{16}^{\mathrm{im}})\times\mathrm{Re}[\mathcal{BW}_{\mathrm{S}}(m_{K\pi})\mathcal{BW}^*_{\mathrm{P}}(m_{K\pi})]\big)$$
$$+\tfrac{1}{2}\sin\theta_k\sin 2\theta_\ell\sin\phi\,\big((S_{17}^{\mathrm{re}}\pm A_{17}^{\mathrm{re}})\times\mathrm{Im}[\mathcal{BW}_{\mathrm{S}}(m_{K\pi})\mathcal{BW}^*_{\mathrm{P}}(m_{K\pi})]+(S_{17}^{\mathrm{im}}\pm A_{17}^{\mathrm{im}})\times\mathrm{Re}[\mathcal{BW}_{\mathrm{S}}(m_{K\pi})\mathcal{BW}^*_{\mathrm{P}}(m_{K\pi})]\big)\Big] \quad (1)$$

- Observables measured in bins of q^2

5D Acceptance correction

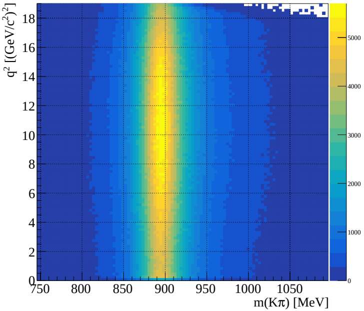
- Reconstruction and selection distort decay angles, q^2 and $m_{K\pi}$
- Acceptance shape parameterized using Legendre polynomials

$$\epsilon = \sum_{k,l,m,n,o} c_{klmno} P(cos(\theta_l), k) P(cos(\theta_K), l) P(\phi, m) P(q^2, n) P(m(K\pi), o)$$

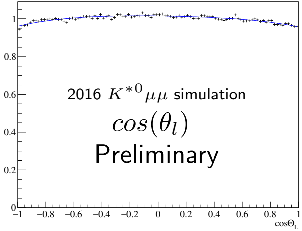
- c_{klmno} calculated with the method of moments

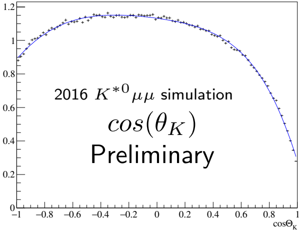
variable	order
$\cos(\theta_l)$	4
$\cos(\theta_K)$	5
ϕ	6
q^2	5
$m(K\pi)$	1

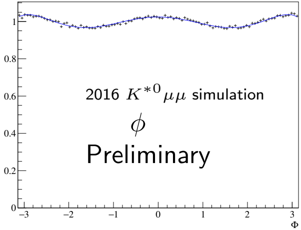
Table: Maximum orders of polynomials

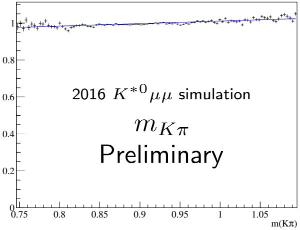


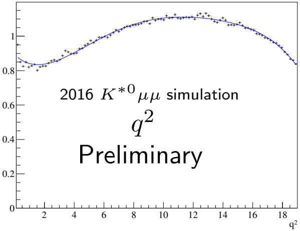
Acceptance projections on angles and q^2







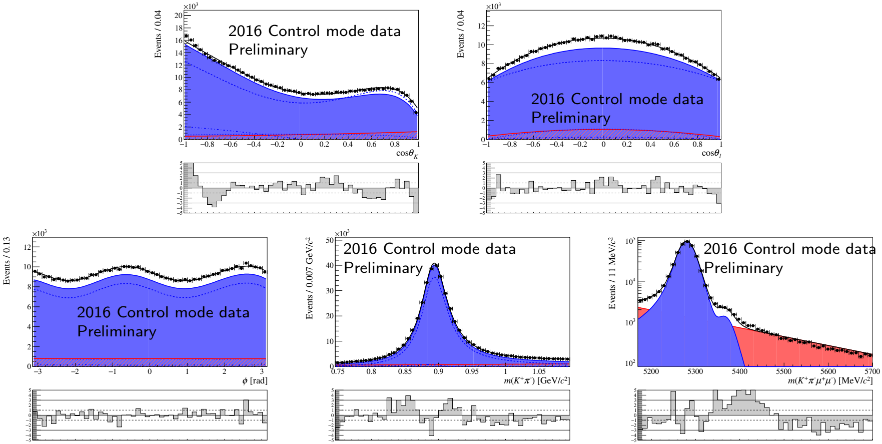




- Parameterization describes the acceptance shape well

Fit validation on $B^0 \to J/\psi\, K^{*0}$ control mode

- Validate acceptance on the control mode



- Overall good agreement of projection of 5D PDF on data
- Mismodelling in B-mass from residual $\Lambda_b^0 \to p\pi^-\mu^+\mu^-$ backgrounds
- Small discrepancy from exotica in $\cos\theta_K$, only effects control mode

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Comparison with previous analysis

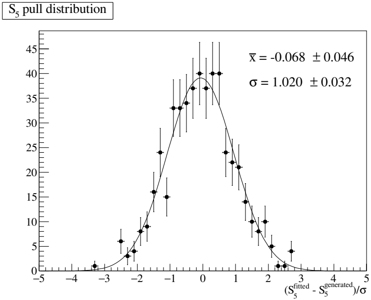
- Preliminary results for control mode fit

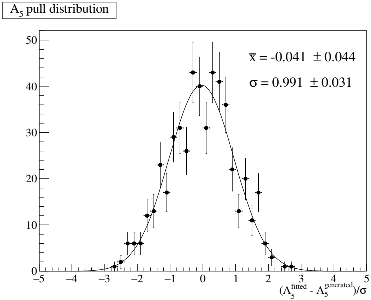
Parameter	Sim. fit	PhysRevD 88 052002
F_L	0.5642 ± 0.0006	0.572 ± 0.008
S_3	-0.0029 ± 0.0008	-0.013 ± 0.010
S_4	-0.2444 ± 0.0009	-0.250 ± 0.006
S_5	0.0017 ± 0.0009	0
A_{FB}	-0.0011 ± 0.0005	0
S_7	0.0008 ± 0.0009	0
S_8	-0.0500 ± 0.0009	-0.048 ± 0.007
S_9	-0.0851 ± 0.0008	-0.084 ± 0.006

- Good agreement with dedicated analysis [PhysRevD 88 052002]

New PDF and 5D acceptance validated on toys

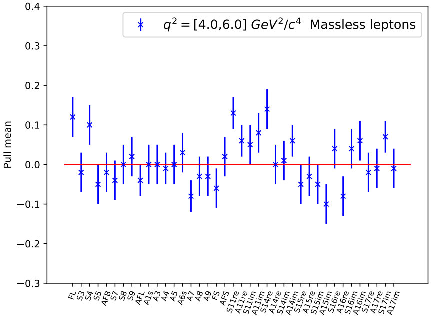
- Validate 5d fit and acceptance on sets of 500 toys for each q^2 bin
- Generated and fitted using expected signal yield for Run 1 + Run 2
- Ensure correct coverage of uncertainties / unbiased fit

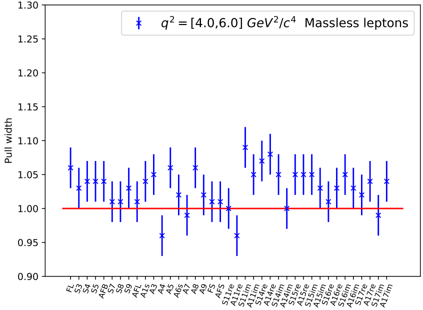




Bias and coverage

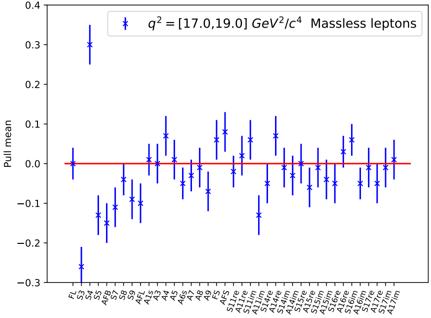
- Pull mean compatible with zero → no bias in this bin
- Pull width slightly above one → slight undercoverage

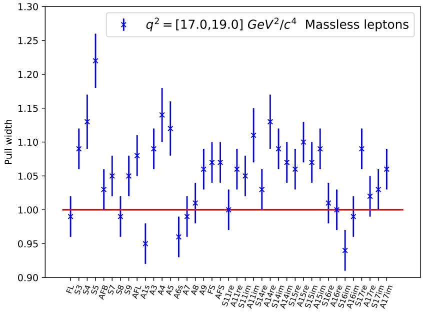




Bias and coverage

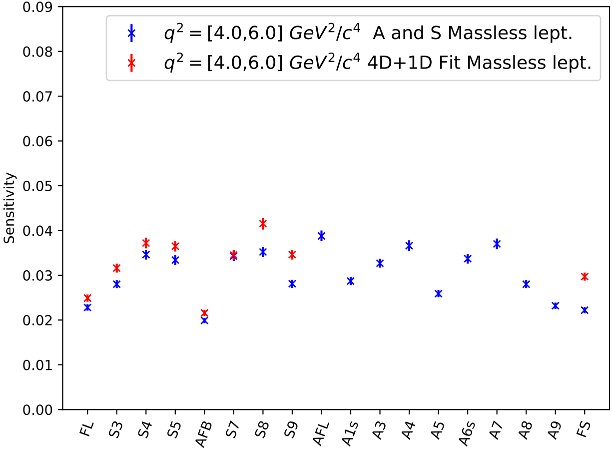
- Some bins show signs of bias/undercoverage
- Reasons: Low statistics/values close to physical boundaries
- Will employ coverage correction
  (Feldman-Cousins implemented as in [JHEP 02 (2016) 104])





Expected sensitivity

- Sensitivity with the new 5D PDF is improved compared to previous 4D+1D PDF[1] employed in [PRL 125 (2020) 011802]



[1]Evaluated using same yields/$m_{K\pi}$ range

Summary of preliminary systematic uncertainties

- Systematic uncertainties evaluated using high statistics toys
- Toys generated with alternative model/acceptance
- Fitted twice with nominal and alternative model
- Preliminary results with $4 - 20$ million events per q^2 bin
- Uncertainties on similar level compared to previous iteration

Source (Preliminary)	F_L	$S_1^c - S_9$	$A_{FL} - A_9$	$F_S - S_{17}^{\text{re/im}}$	$A_{FS} - A_{17}^{\text{re/im}}$
Acceptance stat. uncertainty	< 0.01	< 0.01	< 0.001	< 0.01	< 0.003
Acceptance polynomial order	< 0.015	< 0.015	< 0.001	< 0.02	< 0.001
Data-simulation differences	< 0.01	< 0.03	< 0.001	< 0.015	< 0.001
Acceptance variation with q^2	< 0.01	< 0.01	< 0.001	< 0.01	< 0.001
$m(K\pi)$ S-Wave model	< 0.01	< 0.015	< 0.001	< 0.015	< 0.003
Angular background model	< 0.01	< 0.01	< 0.001	< 0.01	< 0.001
$m(K\pi)$ background model	< 0.01	< 0.01	< 0.001	< 0.015	< 0.001
Peaking background	< 0.01	< 0.01	< 0.003	< 0.03	< 0.004
$m(K\pi\mu\mu)$ model	< 0.01	< 0.01	< 0.001	< 0.01	< 0.001

- Measurement still statistically dominated

Conclusions

- Significant improvement on the last analysis:
  - Improved selection
  - Wider $m_{K\pi}$window used, giving better sensitivity
  - $m_{K\pi}$dependence included into angular fit, improved sensitivity
  - Simultaneous fit of CP-symmetries and asymmetries
- Fit validation using $B^0 \to J/\psi K^{*0}$, good agreement with dedicated amplitude analysis
- Fit validation using toy studies, Feldmann Cousins will be used for coverage correction.
- Calculated most of the relevant systematic uncertainties

Backup

Angular coefficients I'_i and corresponding $f_i(\vec{\Omega})$

i	I'_i	f_i
$1s$	$\frac{3}{4}(\lvert A_\parallel^L\rvert^2 + \lvert A_\perp^L\rvert^2 + \lvert A_\parallel^R\rvert^2 + \lvert A_\perp^R\rvert^2) \times \lvert\mathcal{BW}_\mathrm{P}\rvert^2$	$\sin^2\theta_K$
$1c$	$(\lvert A_0^L\rvert^2 + \lvert A_0^R\rvert^2) \times \lvert\mathcal{BW}_\mathrm{P}\rvert^2$	$\cos^2\theta_K$
$2s$	$\frac{1}{4}(\lvert A_\parallel^L\rvert^2 + \lvert A_\perp^L\rvert^2 + \lvert A_\parallel^R\rvert^2 + \lvert A_\perp^R\rvert^2) \times \lvert\mathcal{BW}_\mathrm{P}\rvert^2$	$\sin^2\theta_K \cos 2\theta_\ell$
$2c$	$(-\lvert A_0^L\rvert^2 - \lvert A_0^R\rvert^2) \times \lvert\mathcal{BW}_\mathrm{P}\rvert^2$	$\cos^2\theta_K \cos 2\theta_\ell$
3	$\frac{1}{2}(\lvert A_\perp^L\rvert^2 - \lvert A_\parallel^L\rvert^2 + \lvert A_\perp^R\rvert^2 - \lvert A_\parallel^R\rvert^2) \times \lvert\mathcal{BW}_\mathrm{P}\rvert^2$	$\sin^2\theta_K \sin^2\theta_\ell \cos 2\phi$
4	$\sqrt{\frac{1}{2}}\,\mathrm{Re}[A_0^L A_\parallel^{L*} + A_0^R A_\parallel^{R*}] \times \lvert\mathcal{BW}_\mathrm{P}\rvert^2$	$\sin 2\theta_K \sin 2\theta_\ell \cos\phi$
5	$\sqrt{2}\,\mathrm{Re}[A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*}] \times \lvert\mathcal{BW}_\mathrm{P}\rvert^2$	$\sin 2\theta_K \sin\theta_\ell \cos\phi$
$6s$	$2\,\mathrm{Re}[A_\parallel^L A_\perp^{L*} - A_\parallel^R A_\perp^{R*}] \times \lvert\mathcal{BW}_\mathrm{P}\rvert^2$	$\sin^2\theta_K \cos\theta_\ell$
$6c$	0	$\cos^2\theta_K \cos\theta_\ell$
7	$\sqrt{2}\,\mathrm{Im}[A_0^L A_\parallel^{L*} - A_0^R A_\parallel^{R*}] \times \lvert\mathcal{BW}_\mathrm{P}\rvert^2$	$\sin 2\theta_K \sin\theta_\ell \sin\phi$
8	$\sqrt{\frac{1}{2}}\,\mathrm{Re}[A_0^L A_\perp^{L*} + A_0^R A_\perp^{R*}] \times \lvert\mathcal{BW}_\mathrm{P}\rvert^2$	$\sin 2\theta_K \sin 2\theta_\ell \sin\phi$
9	$\mathrm{Im}[A_\parallel^L A_\perp^{L*} + A_\parallel^R A_\perp^{R*}] \times \lvert\mathcal{BW}_\mathrm{P}\rvert^2$	$\sin^2\theta_K \sin^2\theta_\ell \sin 2\phi$
10	$\frac{1}{2}(\lvert A_\mathrm{S}^L\rvert^2 + \lvert A_\mathrm{S}^R\rvert^2) \times \lvert\mathcal{BW}_\mathrm{S}\rvert^2$	1
11	$\sqrt{3}\,\mathrm{Re}[(A_\mathrm{S}^L A_0^{L*} + A_\mathrm{S}^R A_0^{R*}) \times \mathcal{BW}_\mathrm{S}\mathcal{BW}_\mathrm{P}^*]$	$\cos\theta_K$
12	$-\frac{1}{2}(\lvert A_\mathrm{S}^L\rvert^2 + \lvert A_\mathrm{S}^R\rvert^2) \times \lvert\mathcal{BW}_\mathrm{S}\rvert^2$	$\cos 2\theta_\ell$
13	$-\sqrt{3}\,\mathrm{Re}[(A_\mathrm{S}^L A_0^{L*} + A_\mathrm{S}^R A_0^{R*}) \times \mathcal{BW}_\mathrm{S}\mathcal{BW}_\mathrm{P}^*]$	$\cos\theta_K \cos 2\theta_\ell$
14	$\sqrt{\frac{3}{2}}\,\mathrm{Re}[(A_\mathrm{S}^L A_\parallel^{L*} + A_\mathrm{S}^{\prime R} A_\parallel^{\prime R*}) \times \mathcal{BW}_\mathrm{S}\mathcal{BW}_\mathrm{P}^*]$	$\sin\theta_K \sin 2\theta_\ell \cos\phi$
15	$2\sqrt{\frac{3}{2}}\,\mathrm{Re}[(A_\mathrm{S}^L A_\perp^{L*} - A_\mathrm{S}^R A_\perp^{R*}) \times \mathcal{BW}_\mathrm{S}\mathcal{BW}_\mathrm{P}^*]$	$\sin\theta_K \sin\theta_\ell \cos\phi$
16	$2\sqrt{\frac{3}{2}}\,\mathrm{Im}[(A_\mathrm{S}^L A_\parallel^{L*} - A_\mathrm{S}^R A_\parallel^{R*}) \times \mathcal{BW}_\mathrm{S}\mathcal{BW}_\mathrm{P}^*]$	$\sin\theta_K \sin\theta_\ell \sin\phi$
17	$\sqrt{\frac{3}{2}}\,\mathrm{Im}[(A_\mathrm{S}^L A_\perp^{L*} + A_\mathrm{S}^R A_\perp^{R*}) \times \mathcal{BW}_\mathrm{S}\mathcal{BW}_\mathrm{P}^*]$	$\sin\theta_K \sin 2\theta_\ell \sin\phi$

The angular fit in [arxiv:2003.04831]

- "4D+1D fit": Fit of the decay angles $\vec{\Omega}$, m_B, and the $m_{K\pi}$ projection
- Reminder: P-wave (8 Observables)[2]

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

- Full PDF including P-wave and S-wave (6 add. Observables)[1]

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\Big|_{\mathrm{S+P}} = (1-F_{\mathrm{S}})\,\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\Big|_{\mathrm{P}}$$
$$+\frac{3}{16\pi}F_{\mathrm{S}}\sin^2\theta_l + \frac{9}{32\pi}(S_{11}+S_{13}\cos 2\theta_l)\cos\theta_K$$
$$+\frac{9}{32\pi}(S_{14}\sin 2\theta_l + S_{15}\sin\theta_l)\sin\theta_K\cos\phi$$
$$+\frac{9}{32\pi}(S_{16}\sin\theta_l + S_{17}\sin 2\theta_l)\sin\theta_K\sin\phi\,, \qquad (3)$$

- P-wave observables are scaled by $1-F_S$, reducing sensitivity
- Note the above expression are integrated over $m_{K\pi}$

[2] Definition of observables in terms of decay amplitudes in backup

$m_{K\pi}$ dependence in 4D+1D fit

- Exploit $m_{K\pi}$ distribution in a simultaneous fit to constrain F_S
- P-wave amplitude dependency on $m_{K\pi}$ given by BW[3]

$$\mathcal{A}_P(m_{K\pi}) = \sqrt{kp} \times B'_{L_B}(k,k_0,d)\left(\frac{k}{m_B}\right)^{L_B} \times B'_{L_{K^*}}(p,p_0,d)\left(\frac{p}{m_{K\pi}}\right)^{L_{K^*}} \times \frac{1}{m_{K^*}^2 - m_{K\pi}^2 - i m_{K^*}\Gamma(m_{K\pi})} \quad (4)$$

- S-wave amplitude parameterisation Isobar or LASS (below)^2

$$\mathcal{A}_S(m_{K\pi}) = \sqrt{kp} \times B'_{L_B}(k,k_0,d)\left(\frac{k}{m_B}\right)^{L_B} \times B'_{L_{K_0^*}}(p,p_0,d)\left(\frac{p}{m_{K\pi}}\right)^{L_{K_0^*}} \times \left(\frac{1}{\cot\delta_B - i} + e^{2i\delta_B}\frac{1}{\cot\delta_R - i}\right), \quad (5)$$

- The $m_{K\pi}$ projection is then (with $\xi_i = \int \epsilon f_i(\vec{\Omega})\mathrm{d}\vec{\Omega}$)

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{d}m_{K\pi}}\bigg|_{\mathrm{S+P}} = (1-F_S)\sum_{i=1}^{9}\tfrac{9}{32\pi}\xi_i S_i^{(s,c)}|\mathcal{A}'_P(m_{K\pi})|^2 + \tfrac{3}{16\pi}\Big[F_S\xi_{F_S}|\mathcal{A}'_S(m_{K\pi})|^2 + (S_{S1}\xi_{S1} + S_{S2}\xi_{S2} + S_{S3}\xi_{S3})\,\mathrm{Re}\left(\mathcal{A}'_S(m_{K\pi})\mathcal{A}^{*\prime}_P(m_{K\pi})\right) + (S_{S4}\xi_{S4} + S_{S5}\xi_{S5})\,\mathrm{Im}\left(\mathcal{A}'_S(m_{K\pi})\mathcal{A}^{*\prime}_P(m_{K\pi})\right)\Big] \quad (6)$$

[3] Note these need to be normalised correctly

Full 5D fit

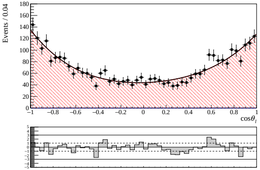
- Idea: Use the full 5D decay rate instead

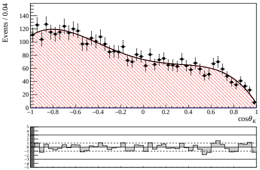
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^5(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}\mathrm{d}m_{K\pi}}\Big|_{\mathrm{S+P}} = (1-F_{\mathrm{S}})\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\Big|_{\mathrm{P}}|\mathcal{A}'_P(m_{K\pi})|^2$$
$$+\frac{3}{16\pi}F_{\mathrm{S}}\sin^2\theta_l\,|\mathcal{A}'_S(m_{K\pi})|^2$$
$$+\frac{9}{32\pi}(S_{11}+S_{13}\cos 2\theta_l)\cos\theta_K\,\mathrm{Re}(\mathcal{A}'_S(m_{K\pi})\mathcal{A}'^*_P(m_{K\pi}))$$
$$+\frac{9}{32\pi}(S_{14}\sin 2\theta_l+S_{15}\sin\theta_l)\sin\theta_K\cos\phi\,\mathrm{Re}(\mathcal{A}'_S(m_{K\pi})\mathcal{A}'^*_P(m_{K\pi}))$$
$$+\frac{9}{32\pi}(S_{16}\sin\theta_l+S_{17}\sin 2\theta_l)\sin\theta_K\sin\phi\,\mathrm{Im}(\mathcal{A}'_S(m_{K\pi})\mathcal{A}'^*_P(m_{K\pi})) \quad (7)$$

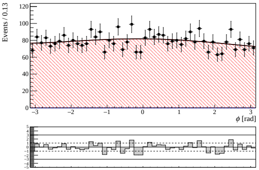
- Uses the available information in a more optimal way
- Allows for better control of S-wave, and S-wave/P-wave interference
- Reduces potential issues from physical F_S boundary
- Expect highest precision in wide $m_{K\pi}$ window

Angular background modeling

- Nominal background model: Second order Chebyshev polynomial
- Fit background from upper mass sideband with fourth order polynomial in different bins of q^2
  - BDT cut removed for increased statistics
- High statistics toys generated with alternative background model
- Fit twice with both background models

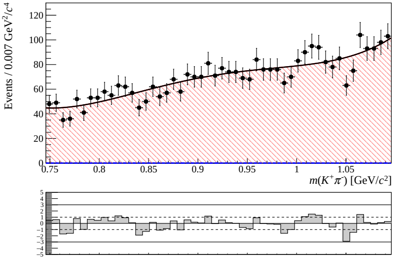


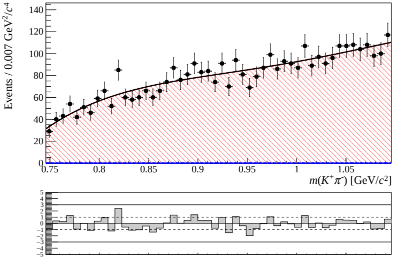




$m_{K\pi}$ shape: Combinatorial background

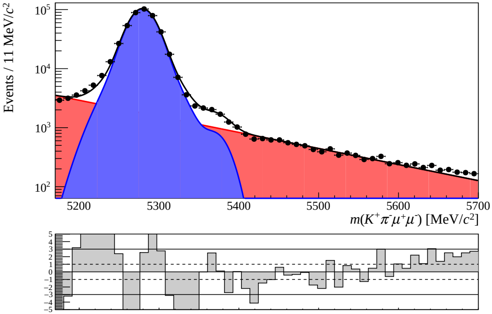
- Nominal background model: First order Chebyshev polynomial
- Fit background from upper mass sideband with fourth order polynomial in different bins of q^2
  - BDT cut removed for increased statistics
- High statistics toys generated with alternative background model
- Fit twice with both background models





Signal mass modeling

- Systematic for potential mismodeling of the $m(K\pi\mu\mu)$ signal shape
- Double Gaussian (below) used as alternative signal model
  - Parameters taken from fit to $B^0 \to J/\Psi K^{*0}$ events
- Produce high statistics toys with double Gaussian model
- Fit twice with both models



$m_{K\pi}$ shape: ISOBAR vs LASS

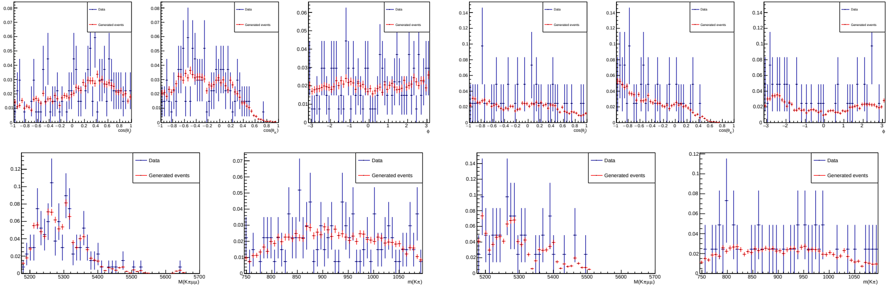
- Assign systematic to cover mismodeling of the S-Wave $m(K\pi)$ shape
- Alternative model: ISOBAR model

$$\mathcal{A}_{ISO}(m_{K\pi}) = |r_{f800}|e^{iarg\delta_{f800}}\mathcal{A}_{f800}(m_{K\pi}) + (1 - |r_{f800}|)\mathcal{A}_{K_0^{*0}(1430)}(m_{K\pi})$$

- Parameters taken from PDG or control mode fit
- High statistics toys generated with ISOBAR model
- Fit twice with LASS and ISOBAR model

Peaking backgrounds

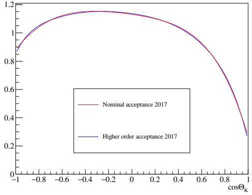
- Estimate effect of remaining peaking background on fit result
- Generate toy peaking background events using data
  - Select background events (blue) from data by inverting PID cuts
  - Model angular and mass distribution using kernel estimation (red)
- Inject background events into high statistics toys
- Could move to simulation for kernel estimation in the future

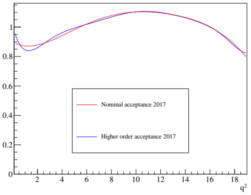


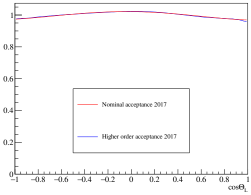
$B^0 \to J/\Psi(K^{*0} \to (K \leftrightarrow \pi))$ $\quad$ $\Lambda_b \to J/\Psi p K$

Maximum order of acceptance description

- Maximum order of acceptance description is limited
- Calculate acceptance increasing orders by 3 in all dimensions
- High statistics toys generated with alternative acceptance
- Fit twice with both acceptance functions
- Below: acceptance projection for $\cos\theta_K$, q^2 and $\cos\theta_\ell$, using nominal and higher orders







Acceptance variation in q^2

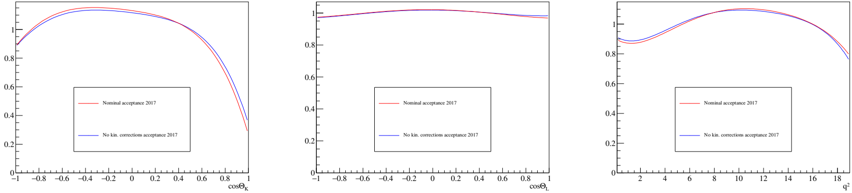
- Acceptance is evaluated at fixed point in narrow q^2 bins
- Evaluate acceptance at at different q^2 values
  - Mean of q^2 in each bin
  - Half way between bin center and upper/lower bin edge
- Produce high statistics toys with alternative acceptance values
- Fit twice with both acceptance settings (i.e. generate using evaluation point in either lower/upper half of bin)
- Select largest systematic for different q^2 values in each bin

Statistical uncertainty of angular acceptance

- Size of MC simulated samples is limited
- Estimate statistical effect by bootstrapping of simulation
- Generate high statistic toy using bootstrapped acceptance
- Fit twice with nominal and varied acceptance

Data-Simulation agreement

- Differences corrected using re-weighting of kinematic distribution
- Conservative systematic: Recalculate acceptance without kinematic corrections
- Generate high statistic toy using uncorrected acceptance
- Fit twice with both acceptances



- Ongoing studies:
  - Differences in momentum distributions of kaons and pions
  - Residual differences in PID distributions
  - L0 trigger corrections

5D Acceptance and $m_{K\pi}$

- 1D $m(K\pi)$ projection not completely flat
- $m(K\pi)$ acceptance effects do not fully factorize