Angular analysis of $B_d \to K\pi\mu\mu$ and $\Lambda_b \to pK\mu\mu$ using a moments approach

Biplab Dey

work w/

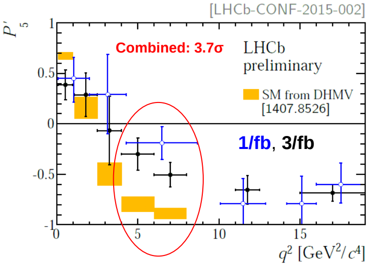
(D. Marangotto, N. Neri (Milano) & E. Bowen, N. Serra (UZH))

INFN Istituto Nazionale di Fisica Nucleare

Sezione di Milano

Motivation for angular analyses

- Lesson from P_5': anomalies can show up in hitherto unexpected places.



- Angular observables being interference terms have more sensitivity than rates. Good bet for NP hunting.

Moments idea – introduction

- Very simple idea. Re-write rate in an orthonormal basis:

$$\frac{d\Gamma}{d\Omega} = \sum_i f_i(\Omega) \times \Gamma_i.$$

- Orthonormal angular basis: $\int f_i(\Omega) f_j(\Omega) d\Omega = \delta_{ij}$.
- Weighting each event by $f_i(\Omega)$ projects out the $\langle\Gamma_i\rangle$'s.
- All your observables can now be *solved* out from the Γ_i.
- Completely equivalent to doing a likelihood fit, as long as you extract the covariance matrix correctly.
- Can be quite non-trivial in the presence of background, and efficiency calculations. See discussion Sec. C in 1505.02873.

Moments idea: why it is a good idea

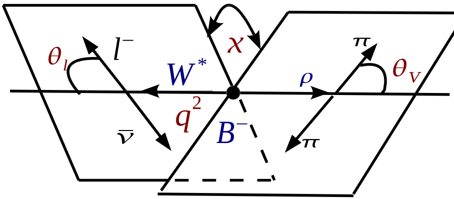
- Two main thrusts here:

1. Very stable against low statistics. No fit bias, start values, etc. No enternal input – it is what it is.

2. In many/most situations with higher waves, the observables turn out to be related. Hard problem to understand what constitutes a minimal set of independent parameters to float in likelihood fit. MOM is completely impervious to this.

$B_d \to K\pi\mu\mu$ and friends

- $b \to X(\to h_1 h_2)\ell_1\ell_2$ topology: $\Phi \in \{m_X, q^2, \theta_\ell, \theta_V, \chi\}$



- Wide window in the m_X spectrum.
- Higher waves in the dihadron system $\Rightarrow$ more observables to play around with.

Example: $\bar{B} \to J/\psi K^- \pi^+$

- The orthonormal basis is constructed out of $Y_l^m \equiv Y_l^m(\theta_\ell, \chi)$ and $P_l^m \equiv \sqrt{2\pi} Y_l^m(\theta_V, 0)$.
- 7 complex amplitudes, $\{S, H_{0,\|,\perp}, D_{0,\|,\perp}\}$, or 13 real numbers.
- 28 Γ_i moments/observables. A few examples:

i	$f_i(\Omega)$	$\Gamma_i^{\rm tr}$
1	$P_0^0 Y_0^0$	$\left[\lvert H_0\rvert^2 + \lvert H_\|\rvert^2 + \lvert H_\perp\rvert^2 + \lvert S\rvert^2 + \lvert D_0\rvert^2 + \lvert D_\|\rvert^2 + \lvert D_\perp\rvert^2\right]$
2	$P_1^0 Y_0^0$	$2\left[\frac{2}{\sqrt{5}} Re(H_0 D_0^*) + Re(S H_0^*) + \sqrt{\frac{3}{5}} Re(H_\| D_\|^* + H_\perp D_\perp^*)\right]$
5	$P_4^0 Y_0^0$	$\frac{2}{7}\left[-2(\lvert D_\|\rvert^2 + \lvert D_\perp\rvert^2) + 3\lvert D_0\rvert^2\right]$
28	$P_4^0 \sqrt{2}\, Im(Y_2^2)$	$-\frac{4}{7}\sqrt{\frac{3}{5}}\, Im(D_\perp D_\|^*)$

Example: $\bar{B} \to J/\psi K^- \pi^+$ (cntd.)

- Interesting things are now solvable for (no fitting):

$$
\begin{aligned}
|D_0|^2 &= \frac{7}{9}\left(\frac{\Gamma_5}{2} - \sqrt{5}\Gamma_{10}\right) \\
|D_{||}|^2 &= \frac{7}{4}\left(\sqrt{\frac{5}{3}}\Gamma_{23} - \frac{1}{3}\left(\sqrt{5}\Gamma_{10} + \Gamma_5\right)\right) \\
|D_{\perp}|^2 &= \frac{7}{4}\left(-\sqrt{\frac{5}{3}}\Gamma_{23} - \frac{1}{3}\left(\sqrt{5}\Gamma_{10} + \Gamma_5\right)\right)
\end{aligned}
$$

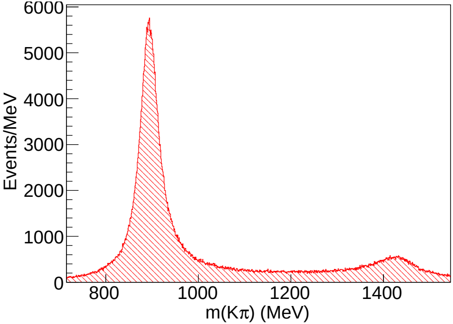
- However, many things missing. Like, $(|H_0|^2 + |S|^2)$ always occur together. So F_S (S-wave fraction) "might" not be extractable.

Goodness of model estimation

- $d\Gamma/d\Omega = \sum_i f_i(\Omega)\Gamma_i$ *is* the model. PHSP MC weighted by this model should match data in all distributions.
- Eg.: in $B_d \to \psi(2S)K\pi$, I can look at $m(\psi(2S)\pi)$ spectrum for the $Z(4430)$.
- As long as enough number of waves are included, the moments model extracts the maximal information content in the angular distributions.
- However, we have outgoing spinors (proton/muon) whose spins we average over.
- This results in "dilution" of information present in the angular distributions.

$B_d \to J/\psi K\pi$:

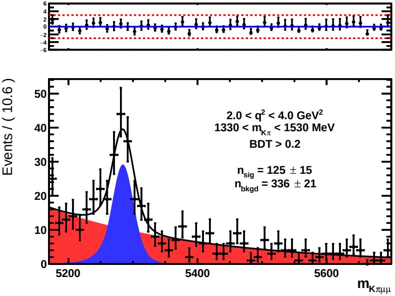
- Mass-indpendent analysis in 36 $m(K\pi)$ bins. Expected yield is 556638 till $m(K\pi) < 1530$ MeV.



- Moments till $J = 4$ being calculated.

$B_d \to K\pi\mu\mu$:

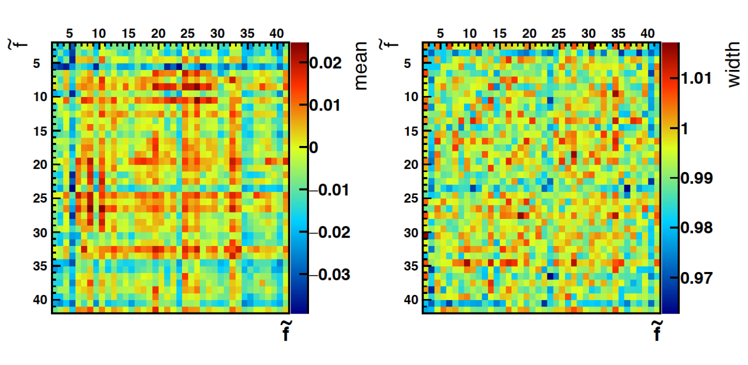
- Around 380 events in $q^2 \in [0.1, 6]$ GeV^2, $|m(K\pi) - 1430| < 100$ MeV.



- $\{q^2, \mathrm{m(K\pi)}\}$ binning and coverage being discussed.

Ongoing toy studies ($B_d \to K\pi\mu\mu$)

- Interesting observables (like P_5') are often combinations of the Γ_i moments. Full covariance matrix is critical.
- Pulls on $\Gamma_{ij} \equiv (\Gamma_i + \Gamma_j)$ efficienctly validates Cov_{ij}.



Why is LHCb's $J/\psi K\pi$ important

- Long-standing confusion: in $D^+ \to \rho^0 \ell^- \overline{\nu}_\ell$, CLEO/BESIII/FOCUS does not mention how the charge-conjugation should be done (affects *BABAR*'s $\rho\ell\nu$). Follow $\pi^+(\pi^-)$ in $D^+(D^-)$?
- I also have a $\chi \to \pi + \chi$ flip with Belle's $Z(4430)$ Appendix.
- Either case above would mean incorrect angular expression.
- Detailed cross-checks (also with B and $\bar{B}$ separately) absolutely *necessary*.
- Moments formalism immediately extends to $B_s \to KK\mu\mu$ in wide $m(KK)$ range ($f_2(1525)$ seen).

Extending the formalism to the spin-$\frac{1}{2}$ Λ_b case

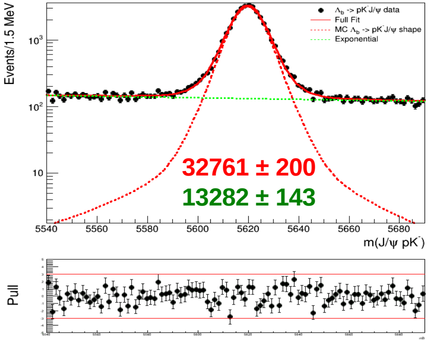
- Mass-independent moments version of $\Lambda_b \to J/\psi pK$ (P_c^+ analysis) could be a good cross-check.
- *Very* poorly known Λ^*: P_c analysis quotes a good fraction of $\Lambda(1405)$, when $\Lambda(1405) \to N\text{-}\overline{K}$ is not even listed in the PDG.
- Experimental hints towards double-pole structure in $\Lambda(1405)$.
- Moments can handle low statistics, so we can do fine $m(pK)$ bins.
- In each $m(pK)$ bin, include moments for J^P waves till $\frac{11}{2}^{\pm}$.
- "Mass-independent" approach. No lineshape assumptions.

Moments for $\Lambda_b \to h_1 h_2 \mu\mu$

- Hard problem: Λ_b polarization + Rarita-Schwinger J^P spinors for Λ^*.
- Start with spin-$\frac{1}{2}$ $\Lambda(1115)$: $\Lambda_b \to J/\psi \Lambda$.
- Four complex amplitudes, fully reconstructable from 5-D angular distribution (Lednicky). LHCb's 1/fb Λ_b polarization analysis used the integrated version.
- $\Lambda(1115) \to p\pi$ is self-analyzing, but hadronic $\Lambda^* \to pK$ are not. Might not access to full amplitudes.
- Long term plan:
  - Re-derive Lednicky's expression from Korner's formalism in $\Lambda(1115)$ case.
  - Extend to $\frac{11}{2}^{\pm}$ $\Lambda^* \to pK$. NR dimuon gets further $\{V, A\}$ amplitudes.

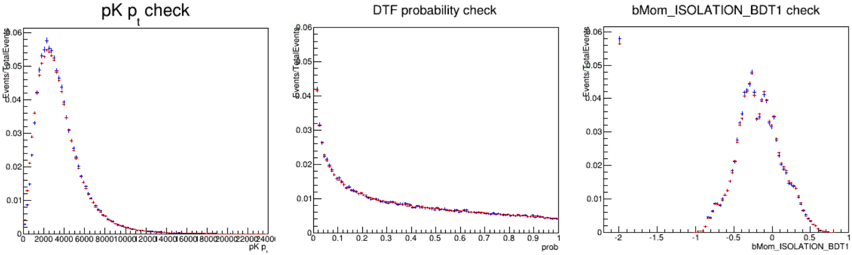
Ongoing $\Lambda_b \to pK\mu\mu$ data analysis (DM, BD, NN)

- Simple counting: $\Delta\mathcal{A}_{CP}$, $A_{FB}^{\ell,h}$ and T-odd correlations.
- $\Lambda_b \to J/\psi pK$ as proxy w/o J/ψ mass-constrained.
- After BDT cut, purity is ~ 0.712, lower than P_c, but yield consistent.



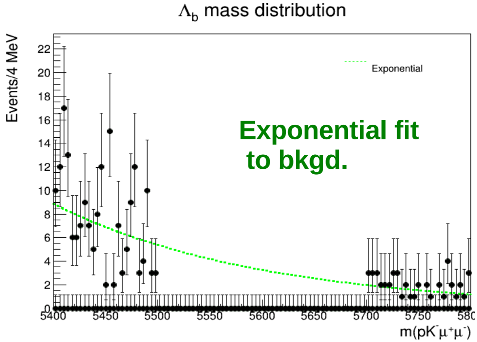
$\Lambda_b \to pK\mu\mu$: MC reweighting

- MC reweighted in nTracks, 2-d $\{p_T(\Lambda_b), p(\Lambda_b)\}$, $p(P)$, $p(K)\}$. PID re-weighting from PIDCalib.
- sWeighted $J/\psi pK$ data used to derive weights.
- Good agreement between Data and MC after re-weighting.



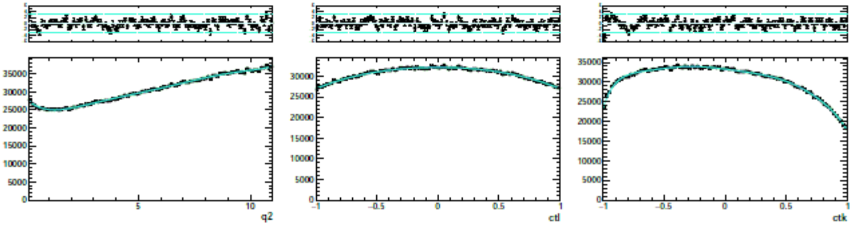
$\Lambda_b \to pK\mu\mu$: preliminary expected yield

- $n_{\rm sig}$ from Mott-Roberts model. $n_{\rm bkgd}$ from sideband fit.
- Optimal BDT cut: significance $\sim$ 14. $n_{\rm sig} \sim$ 310.



5-d efficiency parameterization

- Both $K\pi\mu\mu$ and $pK\mu\mu$ will use 5-d efficiency $\epsilon(\phi)$, $\phi \in \{q^2, \mathrm{m_X}, \cos\theta_{\mathrm{V}}, \cos\theta_\ell, \chi\}$.
- Mature tool: $\epsilon(\phi)$ expanded in Legendre polynomials.
- Subsequent event-by-event reweighting of data by $1/\epsilon(\phi)$.



Publication strategy

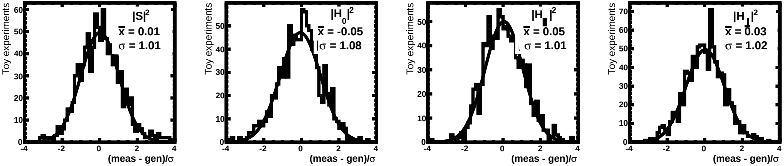
1. $B_d \to J/\psi K\pi$: mass-independent moments till spin $J = 4$ in K^{*J} in 36 $m(K\pi)$ bins.
2. Provide the full set of moments + covariance matrix in each $m(K\pi)$ bin. By far the most comprehensive world data till $m(K\pi) < 1530$ MeV.
3. $B_d \to K\pi\mu\mu$: similar set of results in the higher $m(K\pi)$ region (first observation!). Exact $\{q^2, m(K\pi)\}$ bins under discussion.
4. $\Lambda \to pK\mu\mu$: integrated $m(pK)$ bin (first observation!). May be one low q^2 and one high q^2 bin: $A_{FB}^{\ell,h}$.

On-going work and immediate to-do

- Both NR modes: improved $c\bar{c}$-vetoing using DTF refitting.
- $K\pi\mu\mu$: include F- and G-wave moments. Toys.
- $pK\mu\mu$: switch to ProbNN from DLL. Problems with proton PID. Toys.
- Calculate the full set of moments for $\Lambda_b \to pK\mu\mu$.
- ANA-Notes under development.

Classic case: $B \to \rho \ell \nu$ in BABAR

- $B^- \to \pi^+ \pi^- \ell^- \overline{\nu}_\ell$ in BABAR with $S + P$ waves under the ρ.
- *Highly* statistics limited. Long-standing effor to pull out the S-wave (affects $|V_{ub}|$).



- *Without the moments method, pulling out F_S is semi-impossible.* Full moments paper in the pipeline.