YETI SL practical

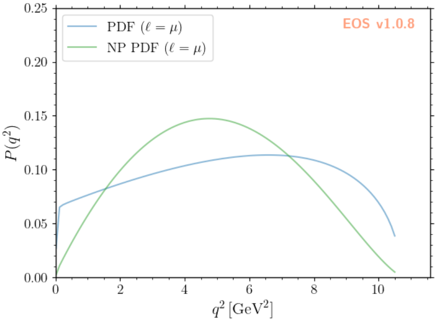
Durham

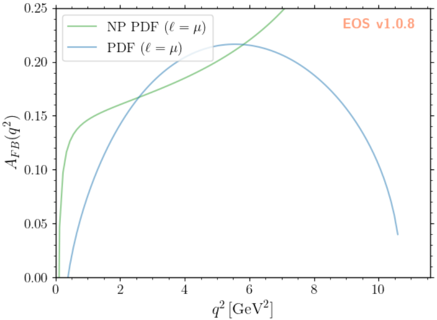
Mark Smith, Lucia Grillo

August 2023

You have been presented with some "data" and simulation to study the $B^0 \to D^{*-}\mu^+\nu_\mu$ SL decay:

- The "data" is a mixture of the signal decay and various backgrounds
- The signal in the data may include some NP - can we measure it? You have a choice:
  1. Find the q^2 distribution of the signal and compare with SM theory prediction
  2. Measure an angular observable - the lepton forward-backward asymmetry, A_{FB} - compare with SM theory prediction





Steps to follow

1. Look at the necessary kinematic variables in your data and MC - m_{corr}, q^2, $\cos\theta_\ell$, (`Manipulating_tuples.ipynb`)
   - You will need to calculate the corrected mass.
   - What is the resolution? Does the resolution depend on some characteristics of the B kinematics?
   - Plot signal and some backgrounds - how good is the separation in corrected mass?
2. Bin in your chosen variable of interest and fit m_{corr} to extract a signal yield in each bin, (`CorrectedMassFit.ipynb`, `config.yaml`, `YAML_writer.ipynb`)
   - If you choose to study the q^2 distribution you will need a few bins
   - If you measure A_{FB} you need two bins of $\cos\theta_\ell$
3. Unfold yields in each bin from reconstructed variable to true variable, (`Unfolding.ipynb`)
   - Extract the true q^2 distribution or A_{FB}
   - Compare with SM prediction - is your data SM?

Template fit

Binned likelihood: b bins, c components of the model:

$$\mathcal{L} = \prod_i^b \mathcal{P}(N^i_{\mathrm{exp}}|N^i_{\mathrm{obs}}) \qquad N^i_{\mathrm{exp}} = \sum_j^c \mu_j N_{j,i}$$

$N_{j,i}$ is expected no. of events of component j in bin i, μ_j is a scaling factor - **fit variables**. $\mathcal{P}$ is a Poisson.

The $N_{i,j}$ are taken from MC or data control samples - they have statistical uncertainty. Include in the fit likelihood (BB-lite [CPC 77, 2 (1993)]). Allow the total expected number N^i_{exp} to vary with a Gaussian ($\mathcal{G}$) of width $\sqrt{N^i_{\mathrm{exp}}}$

$$\mathcal{L} = \prod_i^b = \mathcal{P}(N^i_{\mathrm{fit}}|N^i_{\mathrm{obs}}) \cdot \mathcal{G}(N^i_{\mathrm{fit}}|N^i_{\mathrm{exp}})$$

So you have a scaling factor for each component and a nuisance parameter in each bin for the statistical uncertainty of the templates.

A_{FB}

The differential decay rate of $B^0 \to D^{*-}\mu^+\nu_\mu$ is completely described by 4 kinematic variables: q^2, $\cos\theta_\ell$, $\cos\theta_D$, χ. The rate is

$$\frac{d\Gamma}{dq^2 d\cos\theta_\ell, d\cos\theta_D d\chi} \sim \sum_{12} J_i(q^2) f_i(\cos\theta_\ell, \cos\theta_D, \chi),$$

where the 12 angular coefficients, J_i are q^2 dependent.
Simplify - average B^0 and $\overline{B}^0$, integrate over χ, $\cos\theta_D$, q^2 and normalise to the total rate $\hat{\Gamma}$:

$$\frac{1}{\hat{\Gamma}}\frac{d\hat{\Gamma}}{d\cos\theta_\ell} = \frac{1}{2} + \langle A_{FB}\rangle \cos\theta_\ell + \frac{1}{8}(1 - 3\langle F_L\rangle)(3\cos^2\theta_\ell - 1)$$

$\langle F_L\rangle$ and $\langle A_{FB}\rangle$ are q^2 *integrated observables*.
Now integrate twice more:

$$\int_{-1}^{0} \frac{1}{\hat{\Gamma}}\frac{d\hat{\Gamma}}{d\cos\theta_\ell} d\cos\theta_\ell = \frac{1}{2}(1 - A_{FB}) \qquad \int_{0}^{1} \frac{1}{\hat{\Gamma}}\frac{d\hat{\Gamma}}{d\cos\theta_\ell} d\cos\theta_\ell = \frac{1}{2}(1 + A_{FB})$$

So take two bins of $\cos\theta_\ell$, [-1,0] and [0,1] (it is a forward-backward asymmetry), find difference in yields and measure A_{FB}

Backgrounds

- Combinatorial - random combinations of tracks. Data control sample
- Mis-identified particles - Usually use data control samples - could use MC
- Feed-down
  - Higher excited charm states that decay to $D^{*-}\pi$, i.e. $D_1(2420)^- \to D^{*-}\pi^0$. Not well measured. Use MC.
- Double charm
  - Decays to $D^{*-}H_c$, where H_c is some charm hadron that decays $H_c \to \mu^+\nu_\mu X$. Use MC.
- SL decays to τ^+, with $\tau^+ \to \mu^+\nu_\mu\overline{\nu}_\tau$. Use MC.
- Fake D^{*-}
  - Usually a combination of real D^0 with a random π^-. Remove with cut on $\Delta m = m(D^{*-}) - m(D^0)$

Have we made any approximations or assumptions?

Yes!

- Integrating over angles to reduce the number of observables to measure only works if the experimental efficiency is flat in the variables you integrate over
  - If not flat then angular functions $f_i(\cos\theta_\ell, \cos\theta_D\chi)$ do not integrate to 0. Neglecting them can lead to biases
  - Similarly integrating q^2 is only viable if your q^2 efficiency is flat - otherwise you may end up with a bias
- How many bins?
  - Ideally have more bins of q^2- more sensitive to the shape variations, i.e A_{FB} at low q^2.
  - Narrower bins make the unfolding less reliable - more bin migration across multiple bins.
  - Narrower bins can make the $m_{\rm corr}$ fit unstable with fewer events in each
  - It is a trade-off - could be optimised
- Could NP (also FFs) affect your discriminating fit variables?
  - $m_{\rm corr}$ is in general agnostic to the physics model - width dominated by experimental resolution
  - $B^0 \to D^{*-}\tau^+\nu_\tau$ analyses fit more kinematic variables - assuming SM for the templates could lead to a bias. Need to introduce FF variations.

What you will not do

- Data/MC corrections
  - pythia, trigger, tracking efficiency, PID calibration etc
- Validate background models
  - Fit many control regions
- Mis-ID unfolding
- Isolation