W Helicity Measurement at LHCb
2023 US LHC Users Association

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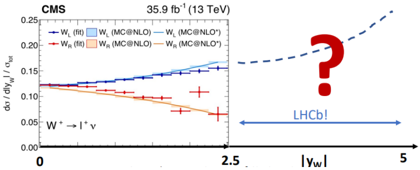
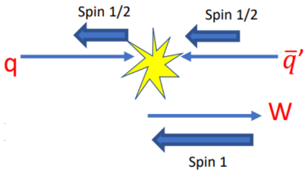
Motivation

- Measurement of the W helicity distribution is an important test of SM prediction, with sensitivity to presence of BSM physics.
- LHCb detector allows for a unique access to measure these values out to where the expected left-handed fraction is highest





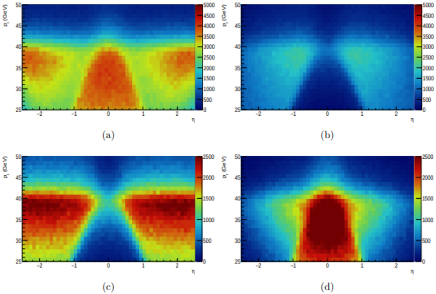
→ Expectation: Going to more forward $|y_W|$ will move towards a purely left-handed state

→ Challenge: LHCb lepton acceptance will sculpt the distribution

Inspiration

- Manca and Rolandi show that different helicity states have different muon $p_T - \eta$ distributions

$W^{+}_{L,R}$



$W^{-}_{L,R}$

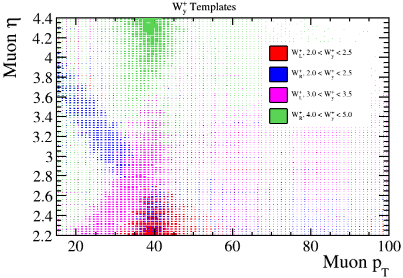
Goal: Build a 2-D template(s) (p_T^μ, η^μ) to fit to the data 2-D distribution to determine the fraction of W boson helicity states.

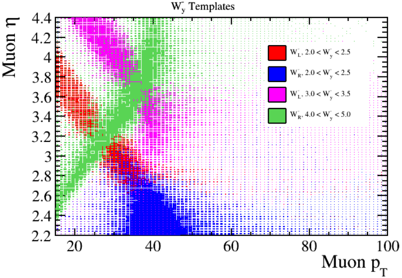
Process: Use $cos\theta^*$ to reweight to pure helicity states, using reconstructed muon kinematics as templates

y_W-Binned Templates – Probe W Kinematics With Observable Quantities

The W-helicity fraction as a function of the y_W can be extracted by building templates for each y_W bin

→ **Templates are still in muon kinematics :**



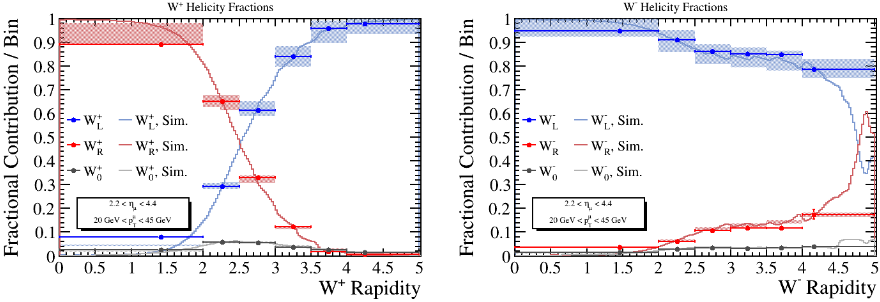


Choosing 6 bins of y_W leads to 6×3 templates for each W charge

- y^W bins: [0, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0]

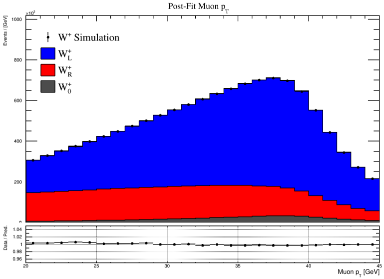
Fits: MC-Only Fits

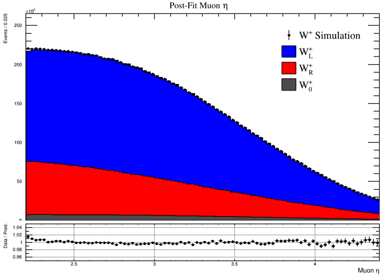
- Simultaneous fit of each of the 6 x 3 templates made, extracting fraction from overall yield post-fit
  - W_0 fraction is fixed to expected values per bin
- Target data is taken as the $p_T^\mu - \eta_\mu$ distribution from Pythia simulation

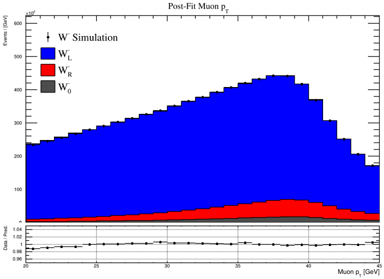


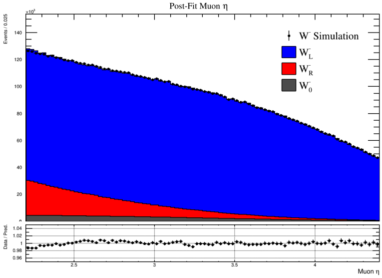
- Nominal fit results are compared to expected values from simulation

Post-Fit Kinematics







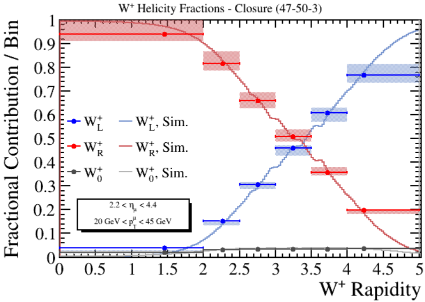


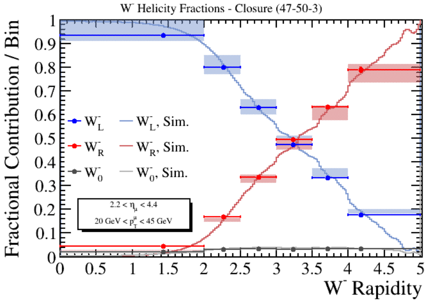
Constructed Closure Test

A closure test is performed by creating a pseudo-data template from the *W* 4π samples reweighted to known helicity fractions

- The procedure is done the same way the templates are made $\rightarrow$ $cos\theta^*$ **Reweighting!**

$\rightarrow$ Many values checked!





Very good agreement to the expectation is observed
$\rightarrow$ If data is different, our fit will know!

Conclusions and Things to Come

→ **Conclusions:**

- LHCb has a unique opportunity to measure helicity states of very forward W bosons produced at LHC
- Closure test has been performed making use of pseudo-data sample of known helicity fractions
  - Extremely good agreement with expectation; Templates will find what the data is telling us!

→ **Takeaway:**

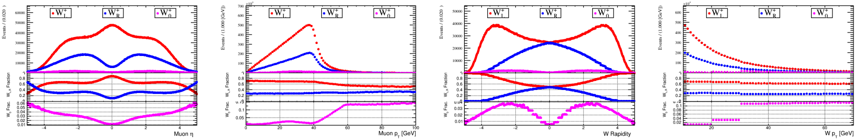
- LHCb detector provides a unique area of coverage to study EW physics at the most extreme phase-spaces at the LHC

BACKUP

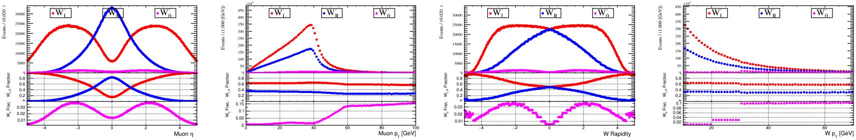
Kinematic Control Study

- The weights extracted for different helicity states can be applied to any kinematic distribution to study the shapes of each state
- Kinematic comparisons after the reweighting procedure of signifcant $W^{\pm}$ and $\mu^{\pm}$ kinematics:

W^{+}



W^{-}

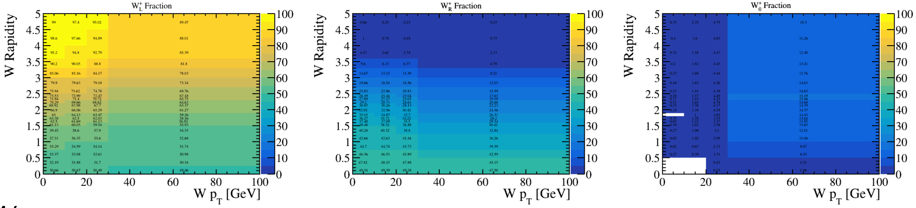


$\rightarrow$ "Expected fractions" as a function of η_{μ} saved for statistical analysis

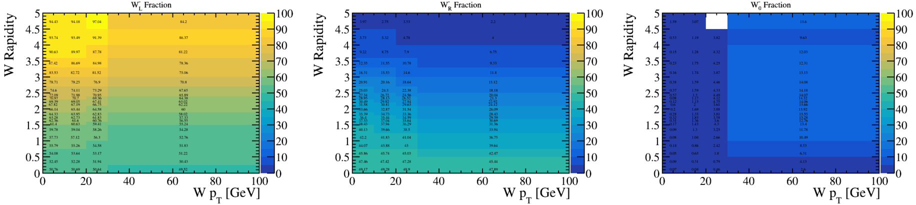
Differential Truth Normalization Extraction

- $cos\theta^*$ fits performed in different p_T^W and y^W bins used to extract the normalization to be applied → Big Difference in bins! → Calculate differential weights!
  - p_T^W bins: [0, 10, 20, 30, 100]
  - y^W bins: [0, 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.6, 1.7, 1.8, 1.9, 2.1, 2.2, 2.3, 2.4, 2.5, 2.7, 3.0, 3.3, 3.6, 4.0, 4.5, 5.0]

W^+



W^-

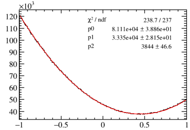


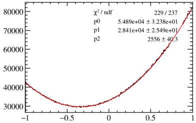
Template Construction Plan

- Challenge: Build these templates of pure right, left, and longitudinal states without having the helicity information from generators

$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^{*}\mathrm{d}p_{\mathrm{T}}^{\mathrm{W}}\mathrm{d}y_{\mathrm{W}}} = \frac{3}{8}(1 \mp \cos\theta^{*})^{2} f_{\mathrm{L}}^{\left(p_{\mathrm{T}}^{\mathrm{W}}, y_{\mathrm{W}}\right)} + \frac{3}{8}(1 \pm \cos\theta^{*})^{2} f_{\mathrm{R}}^{\left(p_{\mathrm{T}}^{\mathrm{W}}, y_{\mathrm{W}}\right)} + \frac{3}{4}\sin^{2}\theta^{*} f_{0}^{\left(p_{\mathrm{T}}^{\mathrm{W}}, y_{\mathrm{W}}\right)},$$

The helicity fractions can be obtained using the theory-produce functional equation

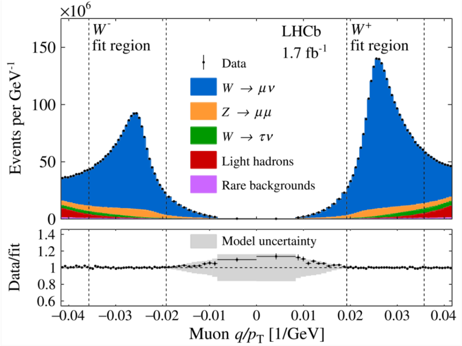




- A purely (L, R, 0)-state W boson can be extracted in the case of all all other fractions $\rightarrow$ 0
- Allows possibility to reweight the sample to a specific W helicity state (or what one should look like) by reweighting $cos\theta^{*}$
- After the weights are extracted and applied, we can then use these to gain the 2-D templates of a pure W_{LR0} boson.

Background Consideration

- Background estimate will consist of using the same processes as the W-mass measurement, with the majority of backgrounds fixed to SM estimate
- Fixed backgrounds will be included in the fit as fixed templates similar to W_0

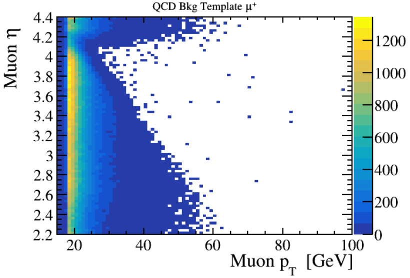


- Prompt hadron background (mostly pion and kaons) is left floating and will be included in the template fit as an additional template
- Studies to be performed prior to unblinding to ensure no degeneracy between prompt hadron and $W^{\pm}_{L,R}$ shapes

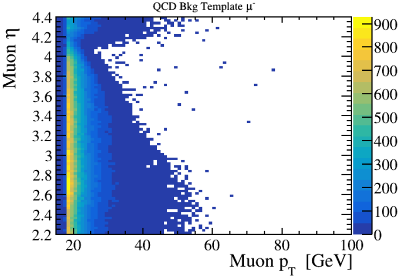
Background Consideration: Prompt Hadron (QCD Bkg.)

- To ensure no significant degeneracy between the prompt hadron background and the $W^{\pm}_{L,R}$ templates, a comparison of the p_T^{μ} is made in the η_μ fit bins

W^+



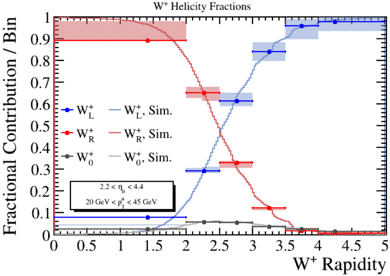
W^-

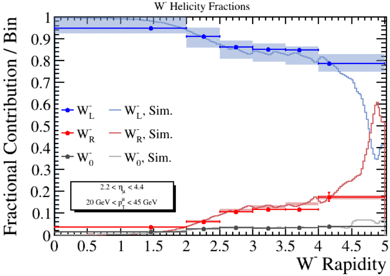


→ Note: Clear differences in shapes observed from $W^{\pm}_{L,R,0}$ templates → Fit will differentiate well!

Fits: MC-Only Fits

- To simplify the fit behavior, W_0 fraction is to be extracted from the control plots using the "expected" fraction for each individual y_W bin.
  - The rate of the longitudinal template is fixed, the fraction is then floating in each y_W bin, dependant on left and right-handed yields
- Target data is taken as the $p_T^{\mu} - \eta_{\mu}$ distribution from Pythia simulation until unblinding.



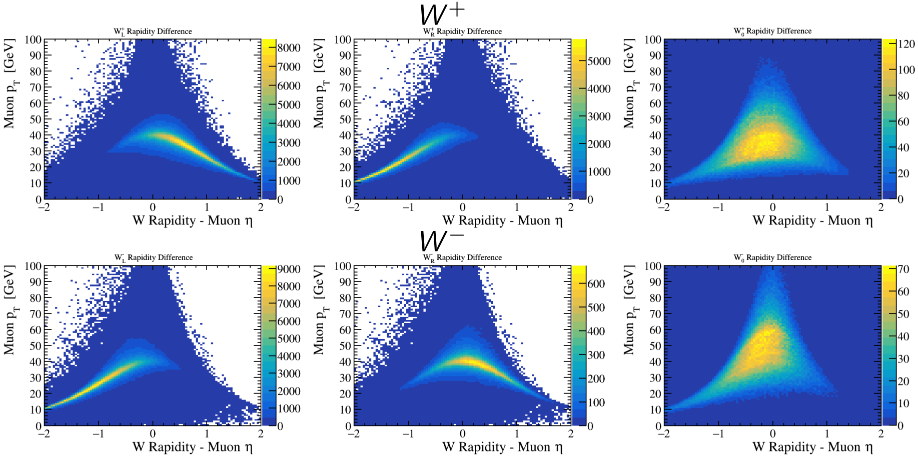


- Nominal fit results are compared to expected values (curves) taken from simulation. Integrated values plus 5% error (hashed) allow for direct validation of the fit result to the simulation expectation
- Strong agreement is seen between fit results and expectation

Fits: That Doesn't Look Like What We Expect?

Expected values of the W-helicity fractions do not follow the similar expected trend of "higher rapidity, more left-handed"

→ **Why? Fiducial Selection and Correlations**



Building a Closure Test

Ideally, a closure test could be performed to a test data-set with a known helicity fraction. Due to the limitation of the MC generation, we cannot directly extract the helicity values from a generated sample. However...

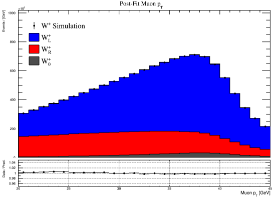
→ What can we do:

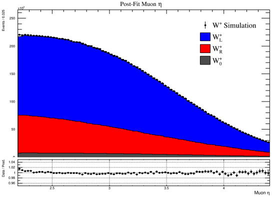
- Create a pseudo-data sample using the reweighting procedure previously used to produce the control plots samples, following the steps:
  1. Predefine a flat distribution of helicity fractions for each individual W-kinematic bin
  2. Calculate the $cos\theta^*$ weight for each of the helicity states, including the above normalization
  3. Fill closure target data event by event, with weight as $\Sigma_{Weights}$
- Use the baseline templates as fit inputs, making use of the pseudo-data sample as the target
- Evaluate the results, comparing to the produced y_W"expected" values for a given helicity fraction definition

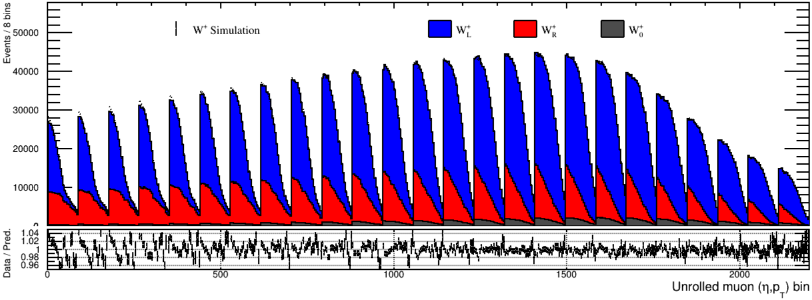
Post-Fit Kinematics – W^+

Post-fit distributions of the unrolled fit templates (bottom) and the summed muon kinematics (right)

Very good agreement in both the unrolled and summed distributions



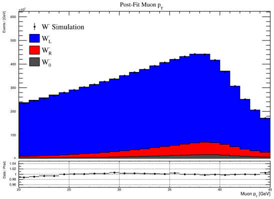


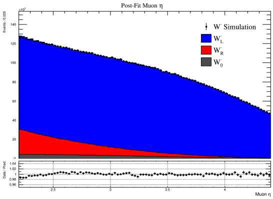


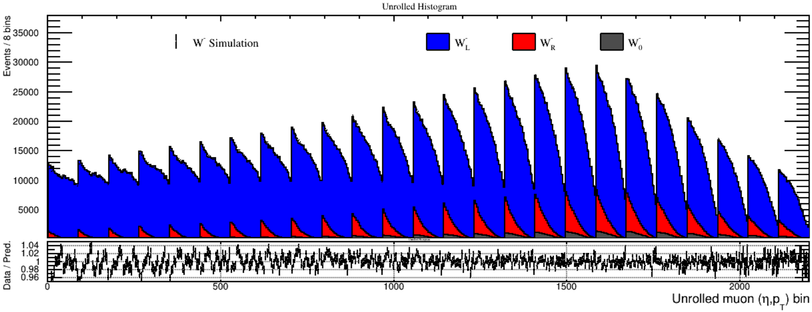
Post-Fit Kinematics – W^-

Post-fit distributions of the unrolled fit templates (bottom) and the summed muon kinematics (right)

Very good agreement in both the unrolled and summed distributions







Systematic Uncertainty Plans – Big Picture

General plan is to follow closely the systematics used in the W-mass measurement due to the same data-set and selections.

Below gives an overview of planned systematics, and their expected impact

→ **Detector Effects (Experimental):**

- Momentum scale and resolution (medium)
- Muon ID, trigger, and tracking efficiencies (low-insignificant)
- Isolation efficiency (low-insignificant)
- QCD background (insignificant)

→ **Modelling Effects (Theoretical):**

- Matrix-element (hard scatter) uncertainty (medium-high)
- Scale uncertainty (higher order corrections) (medium-high)
- PDF uncertainties (Choice and relative unc.) (high-leading)

→ Initial plan is to report all uncertainties as uncorrelated and summed in quadrature