Sensitivity Studies to Intrinsic Charm in Z + c-jet Events

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Abstract

This study explored the sensitivity of intrinsic charm (IC) component in proton structure by analyzing the production of Z ($\rightarrow e^{+}e^{-}$) boson in association with charm jet ($c\!-\!jet$). Monte Carlo simulations with the $CT14nnlo$, $BHPS1$, $BHPS2$, and $BHPS3$ models were used to assess the influence of IC on key observables such as c-jet transverse momentum, c-jet x_F, and Z-boson rapidity. The analysis was conducted by comparing two selections: one requiring both electrons to be produced with central pseudo-rapidity ($|\eta| < 2.5$) and the other requiring one electron with central pseudo-rapidity and the other with forward pseudo-rapidity ($2.5 < |\eta| < 4.5$).

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1 Introduction

For over forty years, the study of intrinsic charm (IC) within protons has captivated physicists. Traditionally, we understand protons as being primarily composed of up (u) and down (d) quarks, forming $< uud|$. However, the IC hypothesis suggests that charm-anticharm ($c\bar{c}$) quark pairs may be intrinsic components of the protons structure. This challenges the conventional view, which holds that charm quarks are produced solely through perturbative quantum chromodynamics processes [1].

Recent experimental data from the LHCb collaboration has suggested that intrinsic charm could indeed play a significant role in proton structure [2]. This potential discovery has the capacity to reshape our understanding of protons and high-energy particle interactions. Given the implications for theoretical models and experimental techniques, it is crucial that we investigate the influence of IC on particle processes in detail.

2 Methodology

In this study, I aim to examine the sensitivity of intrinsic charm in high-energy physics by analyzing the production of Z ($\rightarrow e^+e^-$) bosons in association with charm jets ($c - jet$). Simulation of Z ($\rightarrow e^+e^-$) + c-jets processes were produced with MadGraph FxFx Monte Carlo generator. By reweighting the nominal sample, several models of IC were generated:

- $CTI4nnlo(noIC)$: assumes no intrinsic charm in the proton.

- $BHPS1$: incorporates intrinsic charm with c-quarks transporting an average fraction of $< x_c >= 0.6\%$ of the proton momentum.

- $BHPS2$: incorporates intrinsic charm with c-quarks transporting an average fraction of $< x_c >= 2.1\%$ of the proton momentum.

- $BHPS3$: more realistic scenario based on CT18NNLO Parton Distribution Function.

The analysis focuses on events containing a Z-boson and at least one c-jet. The electron decay channel of the Z-boson was considered, where two selections for the electrons are compared: one with two central electrons ($|\eta| < 2.5$) and one with one electron central and the other forward ($2.5 < |\eta| < 4.5$). Here, η is the pseudo-rapidity, defined as

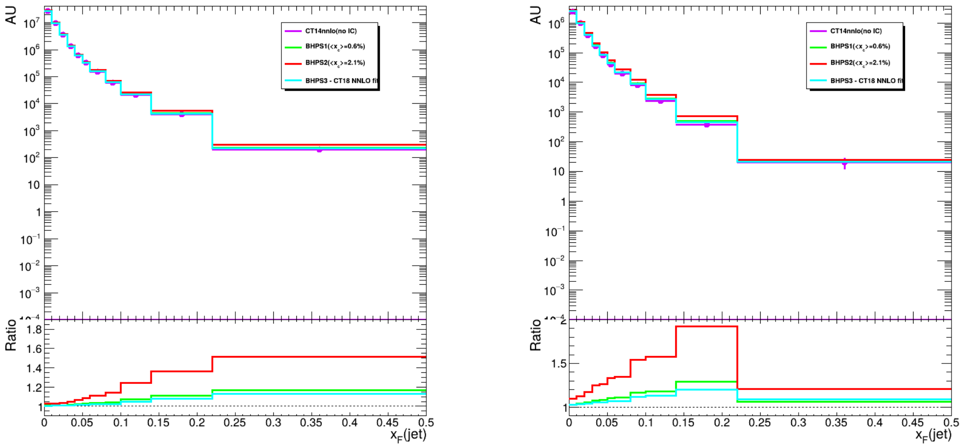
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right],$$

where θ is the polar angle of the particle with respect to the beamline. Pseudo-rapidity is used to describe the angular distribution of particles and is a useful approximation of rapidity in high-energy physics. To evaluate the impact of IC and determine whether forward electron channels present a viable method for probing its existence, I compared the different models by analyzing several kinematic distributions;

- c-jet transverse momentum: the component of c-jet momentum perpendicular to the beam axis.
- Z-boson rapidity: a measure that combines a particle's energy and momentum along the beam axis. The rapidity y is defined as $y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$, where E is the energy of the particle and p_z is the momentum along the beam axis.
- c-jet x_F: the ratio of c-jet longitudinal momentum to the centre of mass energy ($\sqrt{s}$).

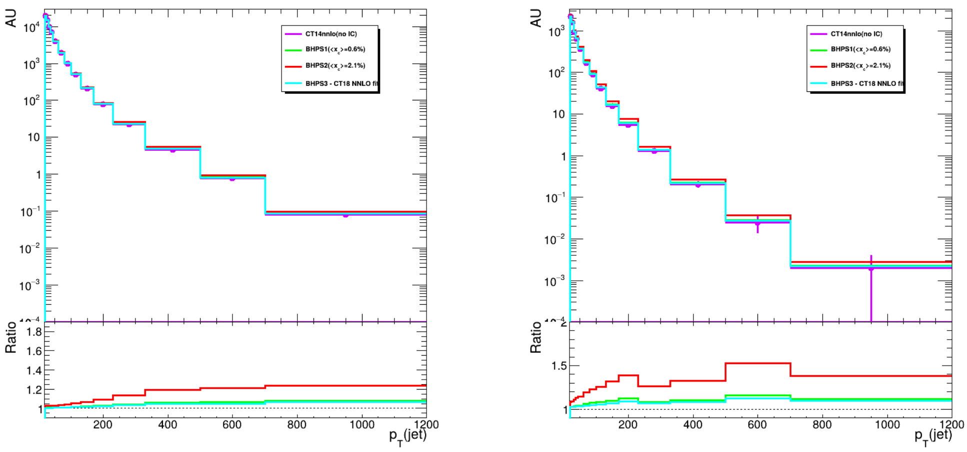
These comparisons were designed to explore the sensitivity of different kinematic regions to the presence of IC. This research not only addresses scientific curiosity but also has broader implications for particle physics, potentially leading to a revised understanding of fundamental particles and interactions. By addressing these questions, this study contributes to ongoing effort to refine our knowledge of proton structure and high-energy particle dynamics.

3 Results in Central-Forward Electron Channel



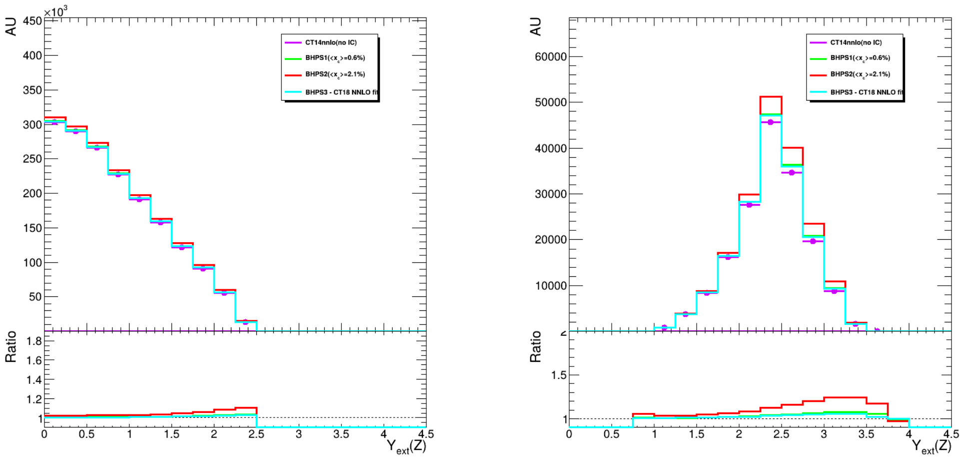
(a) **(b)**

Figure 1: Distribution of simulated $Z(\rightarrow e^+e^-)$ + c-jets events (a) requiring two electrons with central pseudo-rapidity ($|\eta| < 2.5$) and (b) requiring one electron with central pseudo-rapidity and one with forward pseudo-rapidity ($2.5 < |\eta| < 4.5$). Different models are compared as a function of the x_F variable. The lower panel shows the ratio of the three models that allow the IC component to the prediction with no intrinsic charm.



(a) **(b)**

Figure 2: Distribution of simulated $Z(\rightarrow e^+e^-)$ + c-jets events (a) requiring two electrons with central pseudo-rapidity ($|\eta| < 2.5$) and (b) requiring one electron with central pseudo-rapidity and one with forward pseudo-rapidity ($2.5 < |\eta| < 4.5$). Different models are compared as a function of the p_T variable. The lower panel shows the ratio of the three models that allow the IC component to the prediction with no intrinsic charm.



(a) **(b)**

Figure 3: Distribution of simulated $Z(\to e^+e^-)$ + c-jets events (a) requiring two electrons with central pseudo-rapidity $(|\eta| < 2.5)$ and (b) requiring one electron with central pseudo-rapidity and one with forward pseudo-rapidity $(2.5 < |\eta| < 4.5)$. Different models are compared as a function of the $Y(Z)$ variable. The lower panel shows the ratio of the three models that allow the IC component to the prediction with no intrinsic charm.

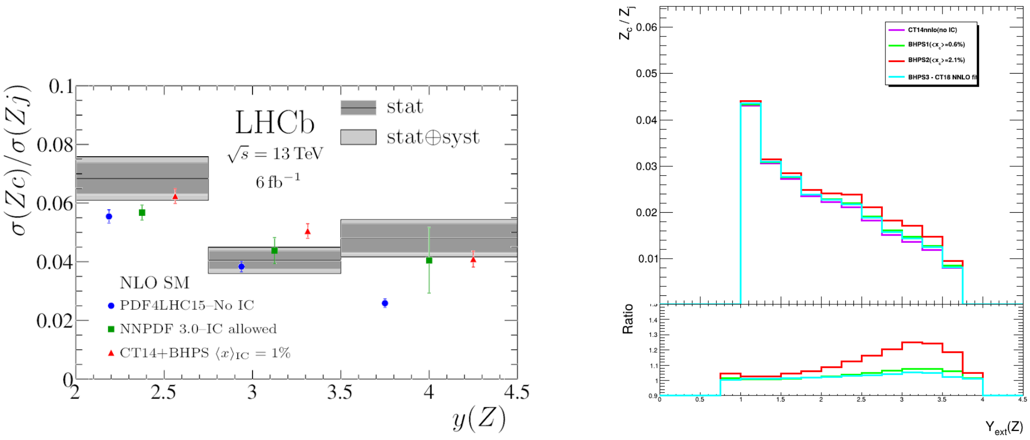
In this Section the results obtained by comparing the two selections on electrons are compared. Figure 1 shows the comparison of several models of IC charm for the c-jet x_F. It can be observed that models with IC increase the population of events of approximately $50-60\%$ at $x_F = 0.22$ with respect to the baseline, represented by the model without IC (see Figure 1(a)). Figure 1(b) refers to the central+forward selection, where the increase is more pronounced, ranging from $80-90\%$ at $x_F = 0.22$.

The same observation can be drawn when analysing the c-jet p_T observable in Figure 2. In particular, in the central region (Figure 2(a)) models with IC enhance the production at high p_T $(p_T \sim 700GeV)$ by about $20-30\%$ with respect to the no-IC hypothesis. In the central+forward region displayed in Figure 2(b), the increase with respect to no-IC model reaches $50-60\%$ at $p_T \sim 700GeV$.

Figure 3 shows the same comparison for the Z-boson Y. in the central selection shown in Figure 3(a), the addition of IC increases the population at $Y \sim 2.5$ by $10-15\%$, as expected since both electrons are required to be within $|\eta| < 2.5$. When extending the electron pseudo-rapidity in $2.5 < |\eta| < 4.5$ (see Figure 3(b)), the contribution of IC models increase at Z boson $Y \sim 3.5$ by $40-50\%$ with respect to the no-IC hypothesis.

Summarizing, the central+forward kinematic region enhances the sensitivity to IC, this is because the IC is expected to carry a large fraction of the proton momentum and thus to be pronounced with higher p_T and Y.

4 Ratio Result



(a) **(b)**

Figure 4: (a) Measurement of the Z + c-jet over Z + jets cross section ratio as a function of the Z-boson rapidity by the LHCb collaboration [2]. (b) Ratio of simulated Z + c-jet over Z + jets reconstructed events in the central+forward selection for different models of IC as a function of the Z-boson rapidity.

To further evaluate these findings, a comparison was made with the LHCb measurement on Z + c-jets production. LHCb result in Figure 4(a) shows that moving to higher rapidity of the Z-boson, the measured data seem to support the hypothesis of IC while discarding the hypothesis of no-IC. The preliminary study shown in Figure 4(b) from simulations support that the sensitivity to IC indeed increase for forward regions, a region never explored by ATLAS for the Z + c-jet process. This comparison provides compelling support for the hypothesis that intrinsic charm significantly increases $Z+c$-jet production, reinforcing the validity of the IC hypothesis.

5 Conclusion

This study offers significant insights into the sensitivity of intrinsic charm (IC) within proton structure through an analysis of $Z+c$-jets events. Monte Carlo simulations demonstrated that the presence of IC could substantially enhance $Z + c$-jet production rates, particularly in forward regions. The effect on forward electrons was observed to be twice as significant as that of the central electrons, suggesting that forward electron channels may be especially promising for the existence of IC.

However, additional research is necessary to further validate these results and explore the broader implications for high-energy physics. Among the needed improvement to this study would be the analysis of real data and the detail study of the effect of the statistical and systematic uncertainty (for example the efficiency in reconstructing c-jets) to give an estimate of the significance to IC. Confirming the existence of intrinsic charm could profoundly impact our understanding of proton structure and various particle interactions prompting a reevaluation of theoretical models.

References

[1] S.J. Brodsky, P. Hoyer, C. Peterson, and N. Sakai, *The intrinsic charm of the proton*, Phys. Lett. 93B, 451 (1980).

[2] The LHCb Collaboration, *Study of Z Bosons Produced in Association with Charm in the Forward Region*, Phys. Rev. Lett. 128, 082001 (2022).