CMS: Diffractive production of W/Z bosons or jets in association with a forward proton using low-pileup data at 13 TeV

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Abstract

This work investigates the diffractive production of W and Z bosons, or high-pT jets, in association with a forward-tagged proton using low-pileup proton-proton collision data at $\sqrt{s}$ = 13 TeV, collected by the CMS experiment at the LHC. Diffractive events, characterized by the presence of an intact proton, are studied by analyzing the rapidity distributions of final state leptons or jets. These distributions are sensitive to the kinematic differences between events with and without a tagged proton. By applying statistical analysis to the dataset, we aim to quantify the significance of these differences and provide the first observation of single diffractive W and Z boson production at this energy scale. The study offers crucial insights into the dynamics of diffractive processes and contributes to refining theoretical models, such as pomeron exchange, that describe hard diffraction in quantum chromodynamics (QCD). Preliminary results indicate the presence of diffractive processes, with potential implications for the understanding of proton structure and the modeling of forward physics at the LHC.

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Introduction

Diffractive processes in high-energy proton-proton (pp) collisions offer unique insights into the non-perturbative regime of quantum chromodynamics (QCD), the theory governing strong interactions. In such processes, one or both protons involved in the collision emerge intact, or with minimal momentum loss, leading to the formation of large rapidity gaps between the forward proton and the central hard-scattering system. These events are mediated by colorless exchanges, most commonly through pomerons or photons, which preserve the proton's integrity. Understanding diffractive events is critical for improving models of particle interactions, particularly in forward physics, where phenomena such as pomeron exchange dominate.

This project focuses on the diffractive production of W and Z bosons or high-pT jets, in association with a tagged proton, using low-pileup (PU) pp collision data at $\sqrt{s} = 13$ TeV, recorded by the CMS-TOTEM Precision Proton Spectrometer (CT-PPS). The dataset, collected during the 2017 low-PU run, offers an optimal environment to reduce background from overlapping interactions, enhancing the sensitivity to diffractive processes.

The key variable under study is the rapidity distribution of final state particles, specifically leptons or jets, which provides a clear signature of the event kinematics. A forward-tagged proton induces an asymmetry in these distributions, reflecting the unique dynamics of diffractive events. By comparing the rapidity distributions of events with tagged protons to those without, this work aims to quantify the occurrence of diffractive processes and determine the fraction of such events in the inclusive production of W, Z, and jets.

Preliminary studies suggest a possible first observation of single diffractive W boson production at 13 TeV, marking a significant advancement in the study of hard diffraction. These results will contribute to refining QCD-based theoretical models, such as those incorporating pomeron exchange, and provide valuable information on proton structure and diffractive cross-sections. Ultimately, this work aims to enhance our understanding of diffractive processes, offering new perspectives on both forward and central physics at the LHC.

1. Project Development and Student Involvement

The project began with my participation in the lectures and workshops provided by the Summer Student Programme, which covered key concepts in particle physics and data analysis. Following this, I familiarized myself with the ROOT software framework, essential for analyzing high-energy physics data. Through meetings with my supervisors, I gained an understanding of the project's objectives and methodologies. During these meetings, I received guidance and feedback, along with specific daily and weekly tasks to complete. This approach allowed me to progressively develop the necessary skills and knowledge to contribute effectively to the project.

2. Key Concepts

2.1 Diffraction in High-Energy Physics

Diffraction processes help understand proton behavior during collisions at the LHC. These events involve protons emerging intact or slightly deflected, with minimal energy exchange. They are crucial for probing Quantum Chromodynamics (QCD) aspects of particle interactions.

2.2 W Boson Production in Proton-Proton Collisions

2.2.1 Types of W Bosons:

(1) W^+ boson produced in $u+\bar{d}$ interactions.

(2) W^- boson produced in $d+\bar{u}$ interactions.

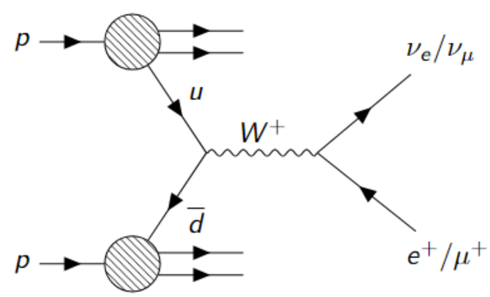


Figure 1. W^+ boson produced in $u+\bar{d}$ interactions.

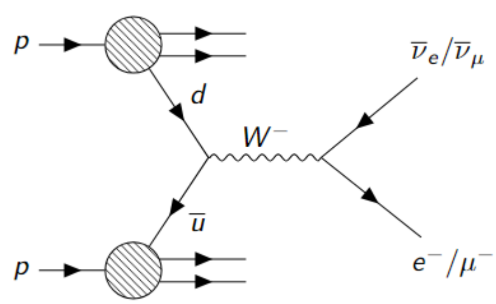


Figure 2. W^- boson produced in $d+\bar{u}$ interactions.

2.2.2 Proton Composition and W Boson Production:

- u quarks are more abundant in protons than d quarks.
- Leads to a higher likelihood of W^+ boson production over W^-.

2.2.3 Hard Diffraction and Pomeron Exchange

Hard Diffraction: A process where protons remain intact or lose little momentum. It is characterized by a colorless exchange, leading to large rapidity gaps.

Pomeron Exchange: A hypothetical object exchanged between protons, composed mainly of gluons and sea quarks.

2.2.4 W/Z Boson Production via Pomeron Exchange

Pomeron exchange plays a significant role in W and Z boson production through quark interactions, modifying the dynamics of this process. This exchange mechanism can influence the favorability of W^+ production, depending on the partonic content involved in the interactions. As a result, understanding Pomeron exchange is crucial for accurately predicting the outcomes of high-energy particle collisions and the subsequent production rates of these fundamental bosons.

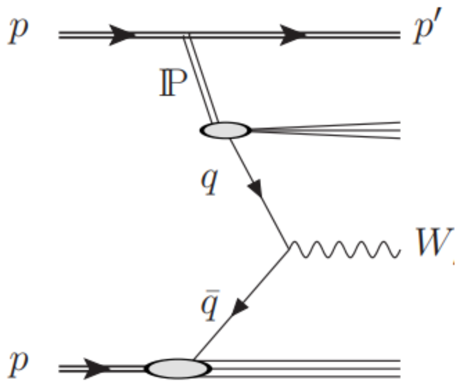


Figure 3. Production of a forward proton in association with a W/Z boson via Pomeron exchange.

2.2.5 Bjorken-x Distributions in the Context of Diffractive W Boson Production

The Bjorken-x (x_{bj}) variable plays a pivotal role in understanding partonic interactions in proton-proton collisions, especially in the context of diffractive processes. In this analysis, the x_{bj} distribution is calculated using the formula:

$$x_{bj} = \frac{(E_{lep} + E_{neutrino} \pm P_{Z_{lep}} \pm P_{Z_{neutrino}})}{13000}$$

where:

- E_{lep} and $P_{Z_{lep}}$ refer to the energy and longitudinal momentum of the charged lepton (from the W boson decay),
- $E_{neutrino}$ and $P_{Z_{neutrino}}$ are the corresponding energy and longitudinal momentum of the neutrino,
- 13000 GeV is the center-of-mass energy of the collisions at the LHC.

2.2.6 Connection to Diffractive Production of W Bosons

In diffractive production of W bosons, a proton remains intact or slightly dissociated, and is observed in the forward region of the detector. This process often leads to a large rapidity gap and a distinct energy transfer pattern compared to inclusive production. As a result, the available energy for the partonic interaction within the proton is reduced, leading to unique characteristics in the x_{bj} distribution.

Key features of diffractive W boson production that influence x_{bj}:

- **Lower values of x_{bj}**: In diffractive events, the proton typically retains a significant portion of its energy, resulting in partonic interactions that occur at lower momentum fractions. Therefore, diffractive processes are expected to contribute primarily at lower values of x_{bj}.
- **Tagged Forward Proton**: These events would exhibit distinct kinematic features compared to inclusive production, with potentially lower x_{bj} values due to the reduced available partonic energy.
- **Quark vs. Gluon Dominance**: Diffractive production often involves quark-antiquark interactions, and the partonic distributions involved in diffractive processes may lead to different asymmetry patterns between W+ and W- boson production at low x_{bj}.

2.2.7 x_{bj} Asymmetry between W+ and W-

The asymmetry between the x_{bj} distributions for W+ and W- production is an important observable in this study.This asymmetry can shed light on the different partonic distributions responsible for producing W+ and W- bosons, and it can also reveal specific features of diffractive versus non-diffractive events.

- **In inclusive W boson production**, the partonic distributions of the proton (primarily consisting of up and down quarks) dominate the process. This is reflected in the x_{bj} asymmetry between W+ and W- production, as the proton's quark content influences the relative production rates of W+ (from $u\bar{d}$) and W- (from $d\bar{u}$) bosons.
- **In diffractive W boson production**, the rapidity distribution of the final-state particles (leptons from W decays) may shift, leading to different x_{bj} distributions compared to inclusive production. Events with a tagged forward proton are expected to show unique characteristics in both the x_{bj} distribution and the asymmetry between W+ and W- production.

2.3 Data and Selection Criteria

The data used in this analysis can be found at the following location: `/eos/cms/store/cmst3/group/top/low_mu_data/nano_output_23_01_10/mc`

2.3.1 Selection Criteria:

The general selection criteria applied consists of:

- `nano_LepPT > 20`
- `nano_WMT > 50`
- `nano_LepID == 4`
- `nano_LepIso`
- `abs(nano_LepEta) < 2.4`

Proton Tagged:

- For proton tagged in +z direction: `nano_xip > 0`
- For proton tagged in -z direction: `nano_xin > 0`

2.3.2 Branches and Their Meanings

In the directory `/eos/cms/store/cmst3/group/top/low_mu_data/nano_output_23_01_10/mc`, one can find the following branches: nGenProton, GenProton_px, GenProton_py, GenProton_pz, nano_nProtons, nano_ProXi, nano_xip, nano_xin, nano_WMT, nano_WPT, nano_nLeptons, nano_LepPT, nano_LepEta, nano_LepIso, nano_LepDxy, nano_LepDz, nano_LepQ, nano_nJets, nano_JetPT, nano_JetEta, nano_JetPhi, MET_pt, MET_phi, and MET_sumEt.

nGenProton
Number of generated protons

GenProton_px
Proton momentum component p_x

GenProton_py
Proton momentum component p_y

GenProton_pz
Proton momentum component p_z

nano_nProtons
Number of protons

nano_ProXi
Proton ξ

nano_xip
Proton ξ_p

nano_xin
Proton ξ_n

nano_WMT
W Transverse Mass

nano_WPT
W Transverse Momentum p_T

nano_nLeptons
Number of leptons

nano_LepPT
Lepton Transverse Momentum p_T

nano_LepEta
Lepton Pseudorapidity η

nano_LepIso
Lepton Isolation

nano_LepDxy
Lepton transverse impact parameter d_{xy}

nano_LepDz
Lepton longitudinal impact parameter d_z

nano_LepQ
Lepton Charge

nano_nJets
Number of jets

nano_JetPT
Jet Transverse Momentum p_T

nano_JetEta
Jet Pseudorapidity η

nano_JetPhi
Jet Azimuthal Angle ϕ

MET_pt
MET Transverse Momentum p_T

MET_phi
MET Azimuthal Angle ϕ

MET_sumEt
MET Scalar Sum of E_T

3. Results and Discussion

3.1 Histograms of Generated Proton Momentum (p_x) and (p_y)

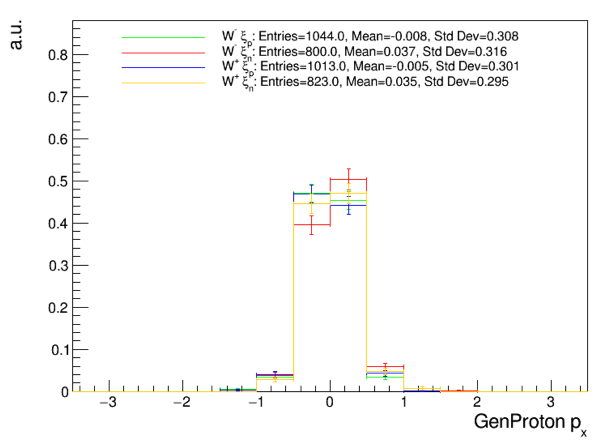


Figure 4. Histogram of generated proton momentum along the x-axis for different W boson production processes.

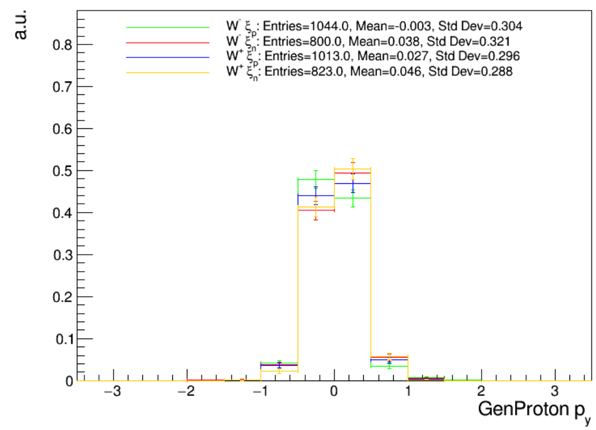


Figure 5. Histogram of generated proton momentum along the y-axis for different W boson production processes.

Observations: Both p_x and p_y components of the proton's momentum show slight variations across W boson production processes, with small biases and similar spreads. These differences might highlight underlying asymmetries or biases related to the dynamics of W boson production and proton tagging.

3.2 Histogram of Generated Proton Momentum (p_z)

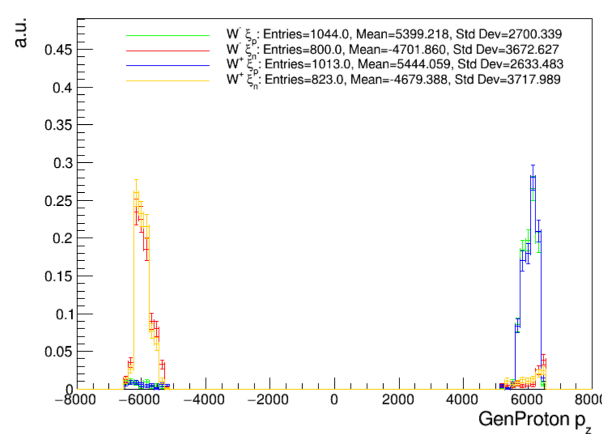
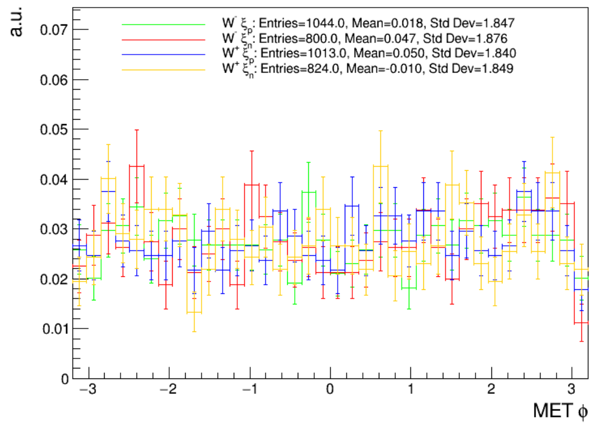


Figure 6. Histogram of generated proton momentum along the z-axis for different W boson production processes.

Observations: This plot reveals a strong correlation between the proton's momentum direction (p_z) and the sign of the W boson charge and proton tagging variable (ξ_p or ξ_n). Protons tagged with ξ_p tend to have a positive p_z, while those tagged with ξ_n have a negative p_z. The differences in standard deviations suggest that protons in the -z direction exhibit more variability in their momentum compared to those in the +z direction. This observation could be important for understanding the underlying dynamics of the proton-proton collisions and W boson production.

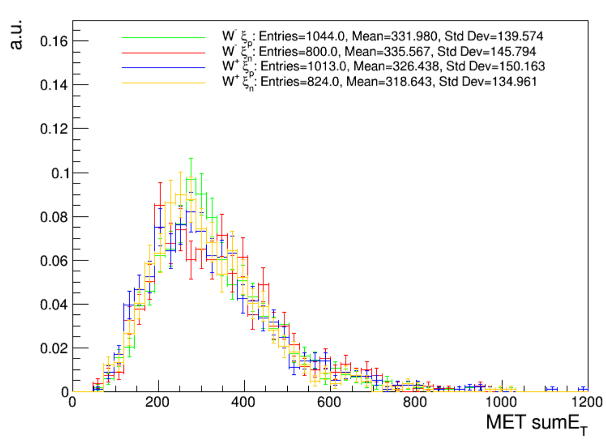
3.3 Histogram of the azimuthal angle (Φ) of the missing transverse energy (MET)



Observations:

- The ϕ distribution for MET appears to be fairly uniform across all four cases. This suggests that there is no preferred direction in the transverse plane for the MET, which is consistent with isotropic emission in the transverse plane.
- There are slight fluctuations in the distribution, but they are generally within the error bars, indicating that these deviations are statistically insignificant.
- The mean values of the ϕ distributions are close to zero, which indicates that, on average, the MET is symmetrically distributed around the origin in the transverse plane.

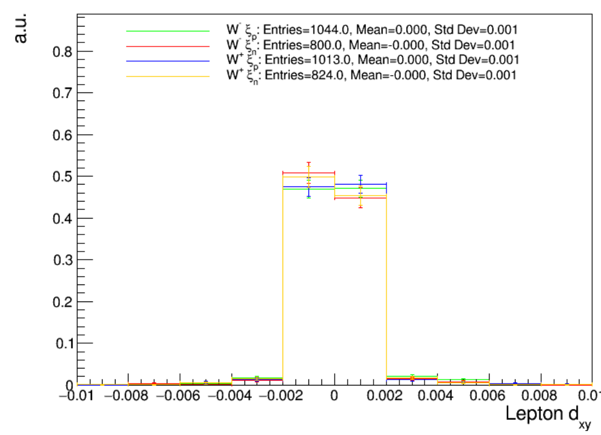
3.4 Histogram of the total MET



Observations:

- All four distributions have a similar shape, with a peak around the 200-400 GeV range.
- The distributions for W^- (green and red) and W^+ (blue and orange/yellow) are similar in shape but slightly differ in their means and standard deviations. The mean values for both ξ_p and ξ_n are slightly higher for W^- events compared to W^+ events, though the difference is not large.

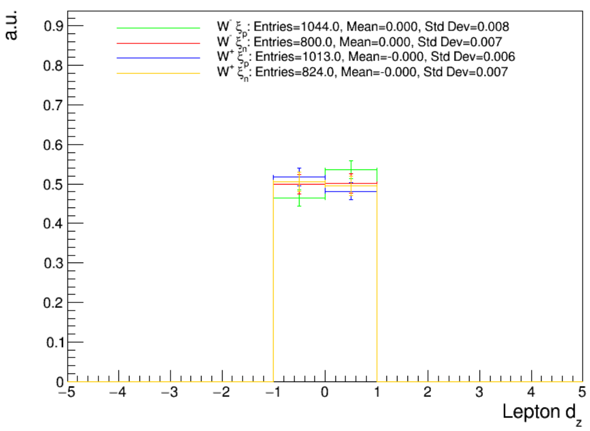
3.5 Histogram of the transverse impact parameter (d_{xy}) of the lepton for events with proton tagging (ξ_p or ξ_n)



Observations:

- The d_{xy} distribution is centered around zero, as expected for leptons originating from primary vertices.
- Any differences between the distributions are minimal, which is expected since the d_{xy} parameter is primarily influenced by the detector resolution and the primary vertex location, not by the production mechanism of the W boson.
- Given that the d_{xy} distribution is so tightly constrained around zero with minimal variations, it suggests that the transverse impact parameter of the lepton is not significantly affected by whether the event is diffractive or non-diffractive.

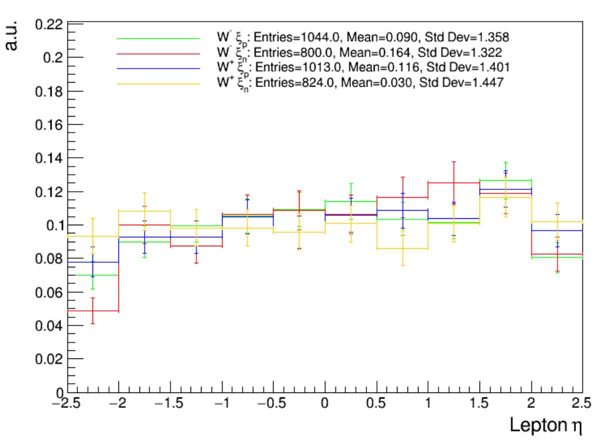
3.6 Histogram of the longitudinal impact parameter (d_z) of the lepton for events with proton tagging (ξ_p or ξ_n)



Observations:

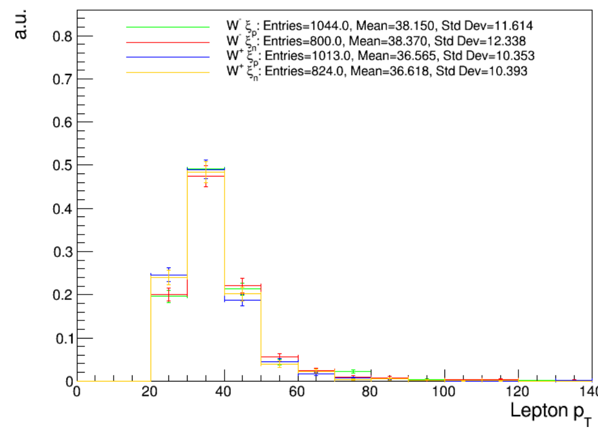
- The d_z distribution, like the d_{xy} distribution, primarily reflects the accuracy of vertex reconstruction and track measurements. It doesn't offer direct insight into whether the W boson production is diffractive. The small differences observed in the d_z distributions across different categories are not likely to be directly related to the diffractive production of W bosons but rather due to minor variations in event reconstruction and detector performance.

3.7 Histogram of the pseudorapidity of the lepton



Observations: The plot shows that the η distributions for W^- and W^+ events are generally similar, but with slight differences, especially in the mean and standard deviation values.

3.8 Histogram of the transverse momentum (pT) of leptons originating from W boson decays



Observations:

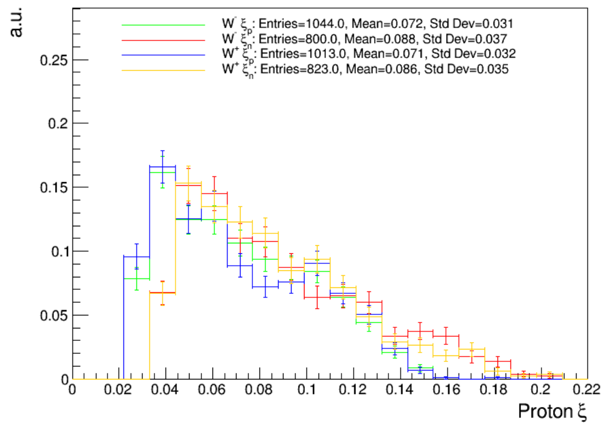
- The pT distribution shows a peak around 30-40 GeV, which is typical for leptons from W boson decays. This is consistent with the fact that the W boson has a mass of around 80 GeV, and the leptons from W decays typically carry a substantial fraction of the W boson's energy.

- The distributions for W^+ and W^- leptons are quite similar, with only slight differences in their mean pT values. The W^- distributions have a slightly higher mean pT, but the difference is small.

- The standard deviations of the distributions are also very close, indicating similar spread in the pT of leptons for both W^+ and W^-.

- The small differences in mean pT and standard deviation between the different proton tagging categories (ξ_p vs ξ_n) suggest that the tagging does not introduce significant kinematic biases. This could imply that the proton tagging variables ξ_p and ξ_n are more influenced by the forward part of the event (e.g., the remnants of the proton) rather than the hard scatter producing the W boson.

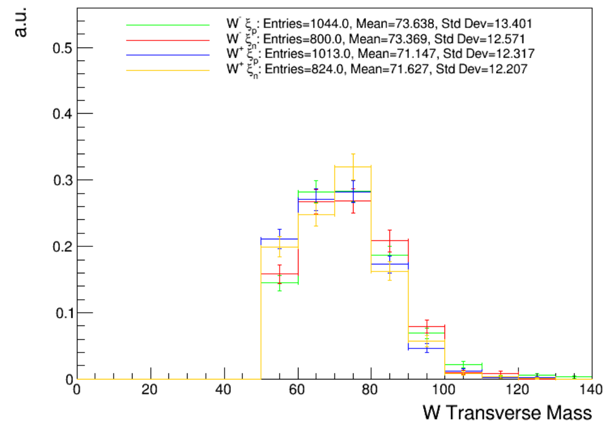
3.9 Histogram of the proton's fractional momentum loss (ξ)



Observations:

- In diffractive events, ξ tends to be small because the proton remains intact and only a small fraction of its momentum is transferred to the produced particles.
- There is a noticeable population of events with low ξ values ($\xi < 0.05$). These are characteristic of diffractive events where the proton is only slightly deflected and loses a minimal amount of momentum.
- The different W charge and ξ tagging categories show subtle differences, particularly at higher ξ values, but overall the shapes are quite similar, with most events concentrated at lower ξ.
- The mean ξ values range from about 0.071 to 0.088, which suggests that most events are not purely diffractive but might include a mix of diffractive and non-diffractive processes.
- The concentration of events at low ξ supports the presence of diffractive production in the data. Diffractive W boson production would indeed lead to events where the proton retains most of its momentum, resulting in small ξ values.
- The tail at higher ξ values indicates the presence of non-diffractive processes, where the proton loses a more significant fraction of its momentum, or the proton breaks up altogether. This is expected in standard W production mechanisms.

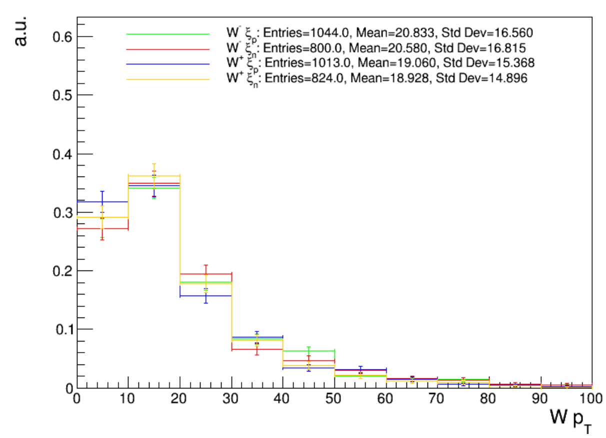
3.10 Histogram of the W boson's transverse mass



Observations:

- The slight differences in the mean values and standard deviations suggest that the transverse mass distributions for W^- and W^+ events are similar but not identical.
- The histograms suggest that the transverse mass distributions for events with forward-tagged protons (ξ_p) and backward-tagged protons (ξ_n) are quite similar, but there are slight differences in the number of events and the shape of the distributions.

3.11 Histogram of the transverse momentum (pT) of W boson decays



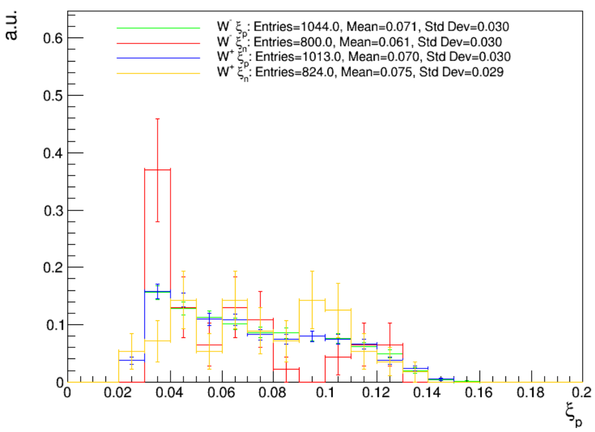
Observations:

- The distributions across all categories are similar in shape. This suggests that the transverse momentum distribution of W bosons is not significantly different whether the proton is tagged in the forward or backward direction.

- The mean transverse momentum is slightly higher for W^- than for W^+.

- Similar to the previous plot, this analysis likely explores whether diffractive production impacts the transverse momentum distribution of W bosons. If diffractive processes had a distinct signature in p_T, we might expect a more pronounced difference between the ξ_p and ξ_n tagged distributions or between W^+ and W^-.

3.12 Histogram of the fractional momentum loss of a proton in the negative rapidity direction



Observations:

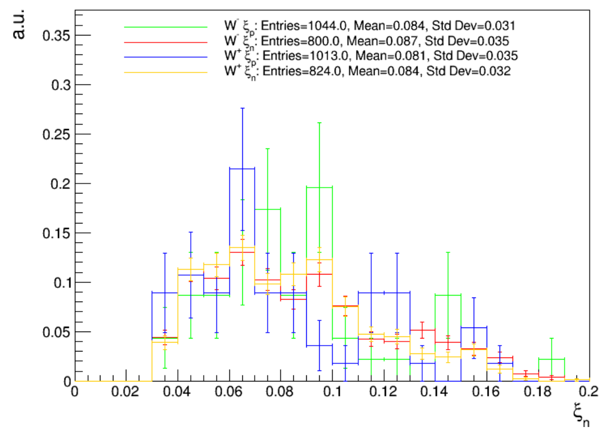
- The distribution of ξ_n provides information about the momentum loss of the proton in the direction opposite to the beam (negative rapidity direction) during the W boson production process.

- The four categories show similar shapes in their ξ_n distributions but with slight differences in the mean and spread (standard deviation).

- In diffractive events, one expects the proton to lose only a small fraction of its momentum, leading to low values of ξ_n. The fact that most of the ξ_n values are small (below 0.2) supports the interpretation that these could be diffractive events, where the proton remains intact with only a small momentum loss.

- The presence of small values could also be correlated with the presence of a rapidity gap.

3.13 Histogram of the fractional momentum loss of a proton in the positive rapidity direction

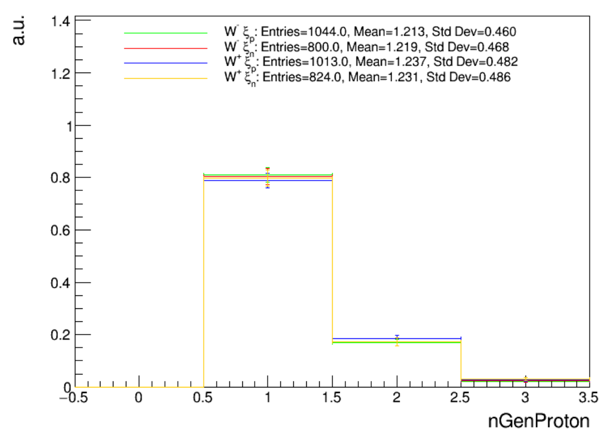


Observations:

- The distributions seem to have different shapes, particularly at lower values of ξ, which is the result of the non-symmetrical acceptance for the detectors at $+200$m and -200 m.

- If the production mechanism for W^- and W^+ differs in the diffractive process, this could be reflected in the slight differences in the mean ξ_p.

3.14 Histogram of the variable "nGenProton" for W^- and W^+ events



Observations:

- The variable "nGenProton" represents the number of generated protons in the event that satisfy certain criteria, such as being within a particular momentum range.

- The distributions for W^- and W^+ events are quite similar, with minor differences in the mean values and standard deviations. This suggests that the proton generation in these events is relatively consistent across the different types of W boson events.

- The distributions for W^- and W^+ events are quite similar, with minor differences in the mean values and standard deviations. This suggests that the proton generation in these events is relatively consistent across the different types of W boson events.

4. Lorentz Vector Construction from Event Data

To construct the Lorentz vectors for the lepton, neutrino, and W boson using the event data from tree branches and the method `getNeuEta`, the following steps are required:

4.1 Lorentz Vector Fundamentals

A Lorentz vector $P^\mu = (E, \mathbf{p})$ consists of energy E and three-momentum $\mathbf{p} = (p_x, p_y, p_z)$. For a particle with mass m, the relation between energy and momentum is:

$$E = \sqrt{p_x^2 + p_y^2 + p_z^2 + m^2}$$

For massless particles such as neutrinos, energy simplifies to:

$$E = |\mathbf{p}| = \sqrt{p_x^2 + p_y^2 + p_z^2}$$

4.2 Lepton Lorentz Vector

The lepton's Lorentz vector can be constructed using its transverse momentum (`nano_LepPT`), pseudorapidity (`nano_LepEta`), and azimuthal angle (`nano_LepPhi`). The components of the three-momentum $\mathbf{p}$ are given by:

$$p_x = p_T \cos(\phi), \quad p_y = p_T \sin(\phi), \quad p_z = p_T \sinh(\eta)$$

where p_T is the transverse momentum and ϕ is the azimuthal angle.

The energy E can be computed as:

$$E = \sqrt{p_T^2 \cosh^2(\eta) + m^2}$$

where m is the mass of the lepton (e.g., the muon or electron mass).

4.3 Neutrino Lorentz Vector

The neutrino's transverse momentum p_T is given by the missing transverse energy (MET, `nano_WPT`), and its azimuthal angle is $\phi_\nu = \text{MET}_\phi$. The pseudorapidity η_ν is calculated using the `getNeuEta` method.

The `getNeuEta` function solves a quadratic equation to compute the possible values for η_ν. Here is a simplified version of the function:

```
def getNeuEta(self):
    phil = self.pl3.Phi()
    etal = self.pl3.Eta()
    ptl = self.pl3.Pt()
    phinu = self.met.Phi()
    ptnu = self.met.Pt()

    muVal = (80.385)**2 / 2. + ptl * ptnu *
        cos(phil - phinu)
    disc = (muVal**2 * sinh(etal)**2 - (ptl**2 *
        cosh(etal)**2) * ptnu**2)

    if disc >= 0:
        sqrt_disc = sqrt(disc)
        etanuUp = asinh((muVal + sqrt_disc) /
            (ptl * ptnu))
        etanuDn = asinh((muVal - sqrt_disc) /
            (ptl * ptnu))
        return etanuUp, etanuDn
    else:
        return None, None
```

This method returns two possible solutions for η_ν, which can be used to construct the neutrino's Lorentz vector.

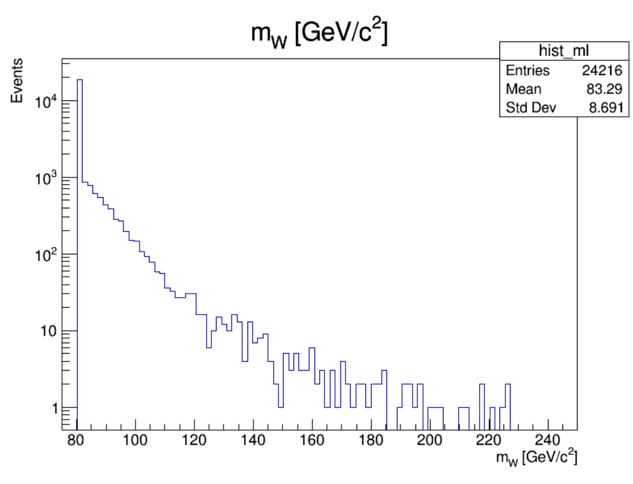
4.4 W Boson Lorentz Vector

The W boson is reconstructed by summing the lepton and neutrino Lorentz vectors:

$$P_W^\mu = P_{\text{lepton}}^\mu + P_{\text{neutrino}}^\mu$$

This sum gives the full Lorentz vector of the W boson.

4.5 Invariant mass distribution of the W^- boson (m_{W^-})



Observations: The histogram shows the invariant mass distribution of the W boson (denoted m_{W^-}), which is reconstructed from events where a single lepton and missing transverse energy (MET) are detected.

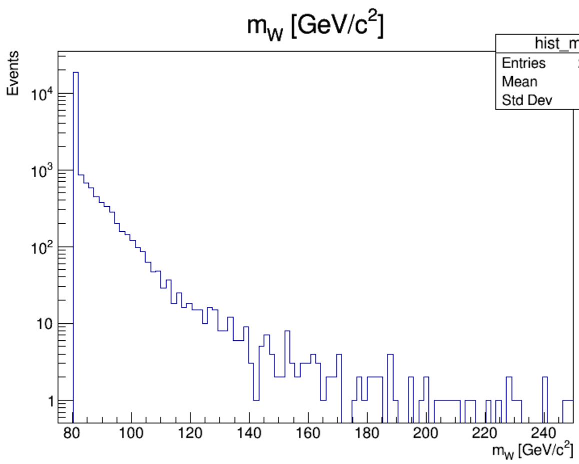
- The y-axis uses a logarithmic scale, which is why the event counts decrease rapidly but remain visible even for low-probability events.

- The peak of the histogram is close to 80-85 GeV/c^2, which aligns with the known mass of the W boson ($\sim$ 80.385 GeV/c^2).
- This peak corresponds to correctly reconstructed W^- bosons from events where a lepton and missing transverse energy are observed, consistent with a W^- decay.

High-Mass Tail: The tail extending to higher masses (above 100 GeV/c^2) could be due to:

- **Detector Resolution and Smearing:** Imperfect reconstruction of the lepton and neutrino momenta can lead to overestimated invariant mass values.
- **Background Processes:** Other processes that mimic W boson production, or events where additional particles contribute to the apparent mass.
- **Final State Radiation:** The lepton might emit additional radiation (e.g., a photon), altering the momentum calculation.

4.6 Invariant mass distribution of the W^+ boson (m_{W^+})



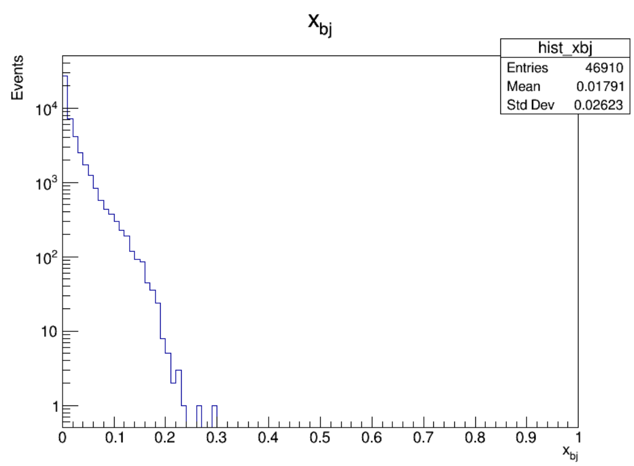
Observations:

- The histogram represents W^+ boson events, reconstructed from decays where a positively charged lepton (like e^+ or μ^+) and missing transverse energy (from a neutrino) are detected.
- The fact that the shape and characteristics of this histogram are very similar to the W^- case supports the notion that the W bosons are being correctly reconstructed regardless of their charge.

4.7 Comparing W^+ and W^- Histograms:

- **Peak Position:** The peak for both W^+ and W^- histograms is near the expected W boson mass of approximately 80.4 GeV/c^2. This consistency is expected since both W^+ and W^- bosons should have the same mass.
- **Mean Values:** The mean of the W^+ distribution is slightly lower than the W^- distribution. This could be due to statistical fluctuations, differences in detector acceptance or reconstruction efficiency, or other minor experimental effects.
- **Tail Distribution:** The high-mass tail (above 100 GeV/c^2) appears to be similar in both cases, which suggests that the same processes, like detector resolution effects and background events, affect both W^+ and W^- boson reconstructions similarly.

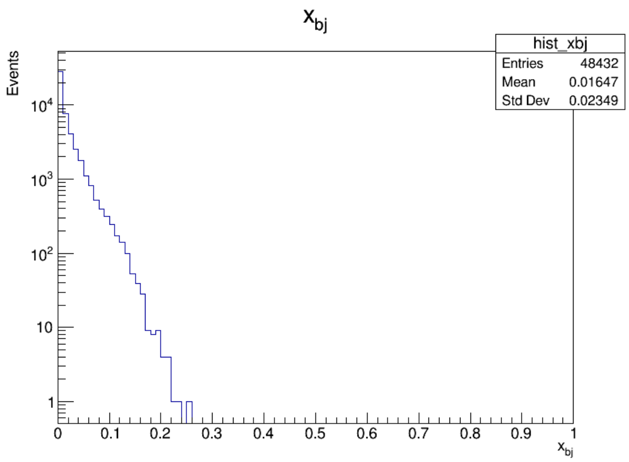
4.8 Histogram of the Bjorken scaling variable x_{bj} for W^+ boson production



Observations:

- The steep rise at low x_{bj} values indicates that the majority of interactions involve partons carrying a small fraction of the proton's momentum.
- The tail extending up to $x_{bj} \approx 0.3$ suggests that interactions involving higher momentum fractions are much less frequent. These higher momentum partons are typically the proton's valence quarks.

4.9 Histogram of the Bjorken scaling variable x_{bj} for W^- boson production



This second histogram shows the Bjorken scaling variable, x_{bj}, for W^- boson production. The features are similar to the previous graph (W^+ production), but there are slight differences in the statistical results.

Observations:

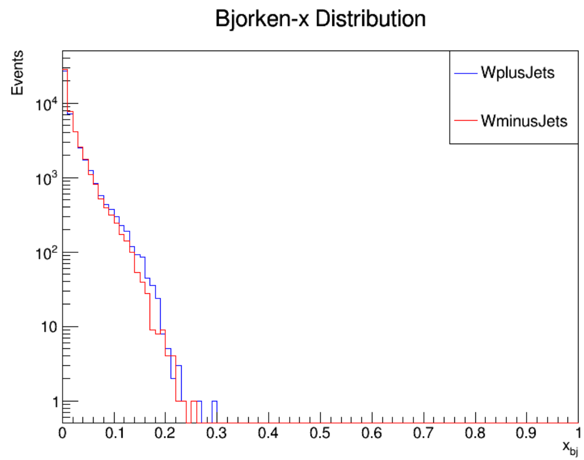
- **Lower Mean**: The mean x_{bj} for W^- production is marginally lower than that for W^+, suggesting that partons in W^- production typically carry slightly less momentum.

- **Fewer High x_{bj} Events**: The W^- distribution seems to taper off more rapidly than the W^+ distribution, with fewer events at higher x_{bj} values (e.g., around 0.2 or higher). This could reflect differences in the dynamics of W^+ vs. W^- production, possibly due to differences in the parton distribution functions (PDFs) for quarks and antiquarks.

This histogram reflects the distribution of x_{bj} for W^- boson production. The lower mean and narrower distribution, compared to W^+ production, may indicate subtle differences in the underlying partonic structure of the proton when producing W^- bosons. This is consistent with the fact that W^+ and W^- bosons are produced through different initial quark interactions: W^+ production is typically dominated by $u\bar{d}$ interactions, while W^- production is dominated by $d\bar{u}$ interactions.

The overall shape, featuring a large number of low-x_{bj} events and fewer high-x_{bj} events, is typical for proton-proton collisions, where most of the momentum is carried by soft partons.

4.10 Bjorken-x Distribution for WplusJets and WminusJets Events



The histogram shows the Bjorken-x (x_{bj}) distribution for events in both the WplusJets (blue) and WminusJets (red) samples. This distribution is created by reconstructing events with a W boson decaying into a lepton and a neutrino, and then calculating the x_{bj} variable, which is related to the momentum fraction carried by the partons in the proton-proton collisions.

4.10.1 Key Observations

Low x_{bj} (0.0 to ∼0.1):

- This region has the highest event counts for both Wplus and Wminus events, as expected from parton distribution functions, where low-x gluons dominate proton-proton collisions at 13 TeV.

- However, WplusJets events seem to dominate slightly in this region.

Mid-range x_{bj} (∼0.1 to 0.3):

- As x_{bj} increases, both distributions fall rapidly, but Wplus still remains slightly more frequent than Wminus.

- This reflects the partonic structure of the proton and the asymmetry between quarks and antiquarks.

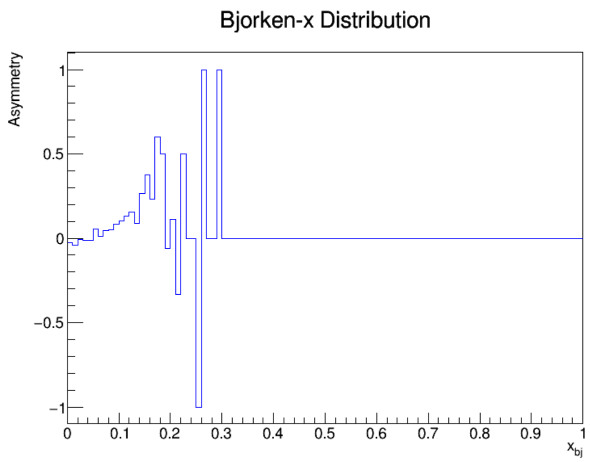
High x_{bj} (∼0.3 to 1.0):

- The number of events becomes very small, and there is little to no significant difference between Wplus and Wminus.

4.11 Asymmetry

The subtle differences between Wplus and Wminus distributions are crucial for calculating the asymmetry.

4.11.1 Asymmetry in Bjorken-x Distribution



The y-axis is labeled Asymmetry, which is calculated as:

$$A(x_{\text{bj}}) = \frac{N_{W^+} - N_{W^-}}{N_{W^+} + N_{W^-}}$$

where N_{W^+} is the number of Wplus events and N_{W^-} is the number of Wminus events in each bin of x_{bj}.

4.11.2 Key Features

Low x_{bj} (0 to 0.15):

- In this region, the asymmetry starts at zero and gradually rises to positive values, indicating that there are more WplusJets events than WminusJets events in this x_{bj} range.
- The positive asymmetry here is consistent with the fact that the up quark content of the proton, which is involved in W^+ production, is larger than the down quark content, which is involved in W^- production.

Mid x_{bj} (0.15 to 0.3):

- There are significant fluctuations in the asymmetry, with spikes both in the positive and negative direction. These large variations could be due to statistical fluctuations from low event counts in certain x_{bj} bins. In this range, the number of events is lower, leading to larger uncertainties.
- The spikes indicate that, at certain x_{bj} values, the dominance switches between Wplus and Wminus events, though this might not have physical significance and could be due to binning or statistical noise.

High x_{bj} (Above 0.3):

- The asymmetry stabilizes and approaches zero for x_{bj} values above 0.3. This indicates that the number of Wplus and Wminus events becomes nearly equal at high x_{bj}, which is expected as both processes are driven by high-momentum partons where the difference in quark and antiquark distributions becomes less pronounced.

Fluctuations:

- The asymmetry plot shows notable fluctuations around $x_{\text{bj}} = 0.2 - 0.3$, where the asymmetry sharply changes between positive and negative values. These could be artifacts of low statistics, or they might suggest regions where there are sharp changes in the production mechanisms of W^+ and W^- bosons.

5. Conclusion

The analysis conducted in this study focused on the diffractive production of W bosons in association with a forward-tagged proton using low-pileup data collected by the CMS experiment at 13 TeV. Several key observations were made from the results:

- **Proton Momentum:** The histograms of the proton's momentum components (p_x, p_y, and p_z) showed slight asymmetries and variations, suggesting underlying differences in the dynamics of W boson production. Notably, protons tagged in the positive rapidity direction exhibited different momentum characteristics compared to those in the negative direction, hinting at potential correlations between proton tagging and W boson charge.
- **Bjorken-x Distribution:** The analysis of the Bjorken-x distribution revealed that at lower x_{bj} values, a slight asymmetry between W^+ and W^- production, with more events involving W^+ at lower x_{bj}.

In this study, the **Z bosons were not covered** due to time constraints within the project. This limitation leaves room for future work to expand on the study of diffractive Z boson production.

Finally, the data used in this study were part of the **official next-to-leading order (NLO) Monte Carlo simulations**. It is important to note that these are **non-diffractive events**, meaning all protons observed are **pileup protons**. Further studies will be required to explore diffractive processes in these contexts and calculate their respective cross-sections.

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