Data Analysis of Drell-Yan Process in the CMS Experiment at the LHC

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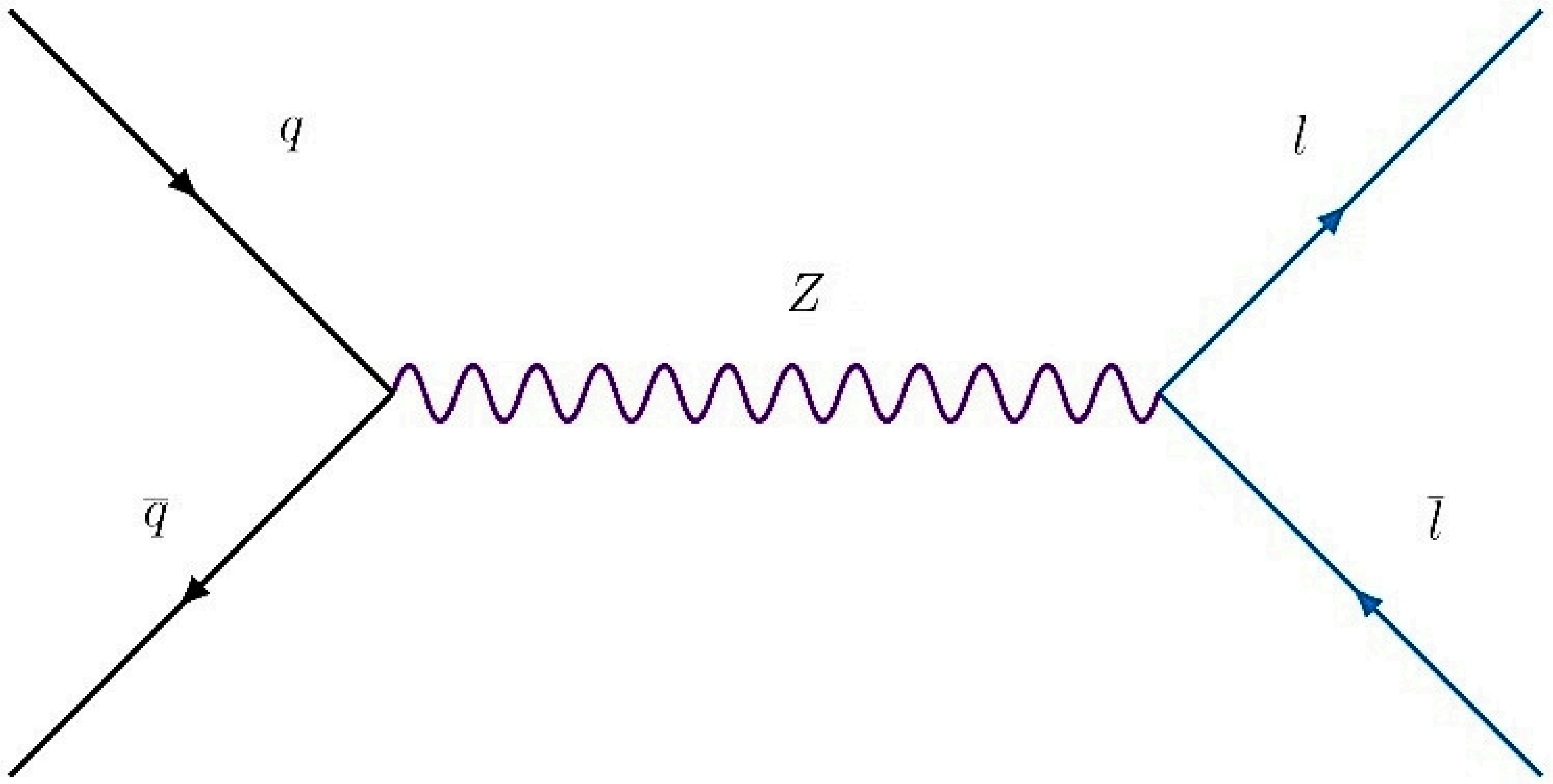
Introduction: Drell-Yan process

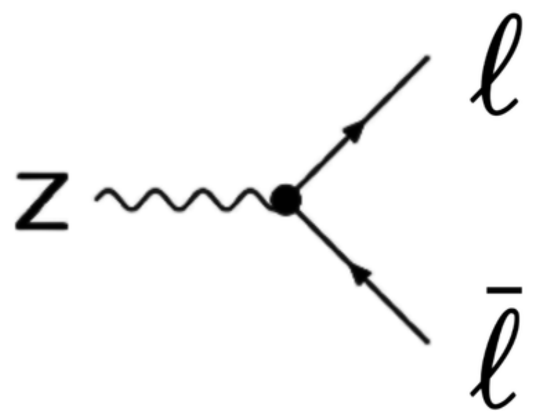
It takes place when a quark of one hadron and an antiquark of another hadron annihilate, creating a Z boson which then decays into a lepton-antilepton pair.



$$q\bar{q} \to Z \to \ell\bar{\ell}$$

Introduction: Z-boson

- The Z boson decays into lepton-antilepton pairs with a branching ratio of approximately 10%.
- In our case, the lepton-antilepton pair of interest is an “electron-positron” pair.
- This electron(positron) pair will thus act as our signal in this analysis.
- The invariant mass of the lepton pair is calculated and created a peak near the Z-boson mass region ($\simeq 91.2GeV$).



Introduction: Z-boson

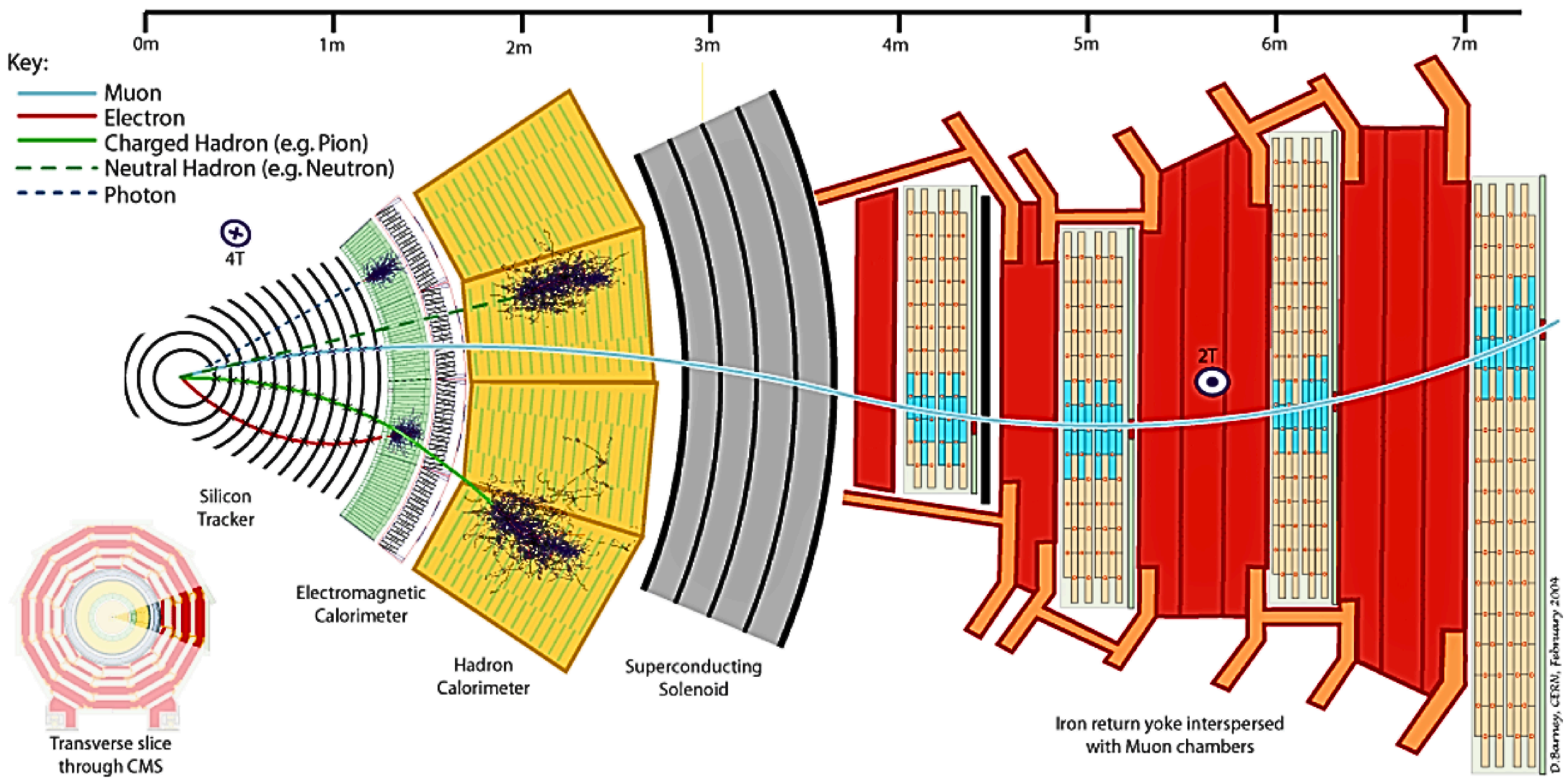
- The decay of Z-boson is not as straightforward. Given below are the branching ratio of of Z.

	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	(3.363 ± 0.004) %
Γ_2	$\mu^+\mu^-$	(3.366 ± 0.007) %
Γ_3	$\tau^+\tau^-$	(3.367 ± 0.008) %
Γ_4	hadrons	(69.91 ± 0.06) %
Γ_5	invisible	(20.00 ± 0.06) %

- Since we now have the signal we can use a detector to detect it and do our analysis.

The Compact Muon Solenoid

- It is located at one of the LHC's interaction points, known as Point 5, in an underground cavern near Cessy.
- The CMS detector at the LHC measures 28.7 meters in length, has a 15-meter radius, and weighs approximately 14,000 tonnes.



Transverse view of the CMS detector

CMS: Coordinate system

- Particle momentum is divided into longitudinal (p_z) and transverse (p_T) components.

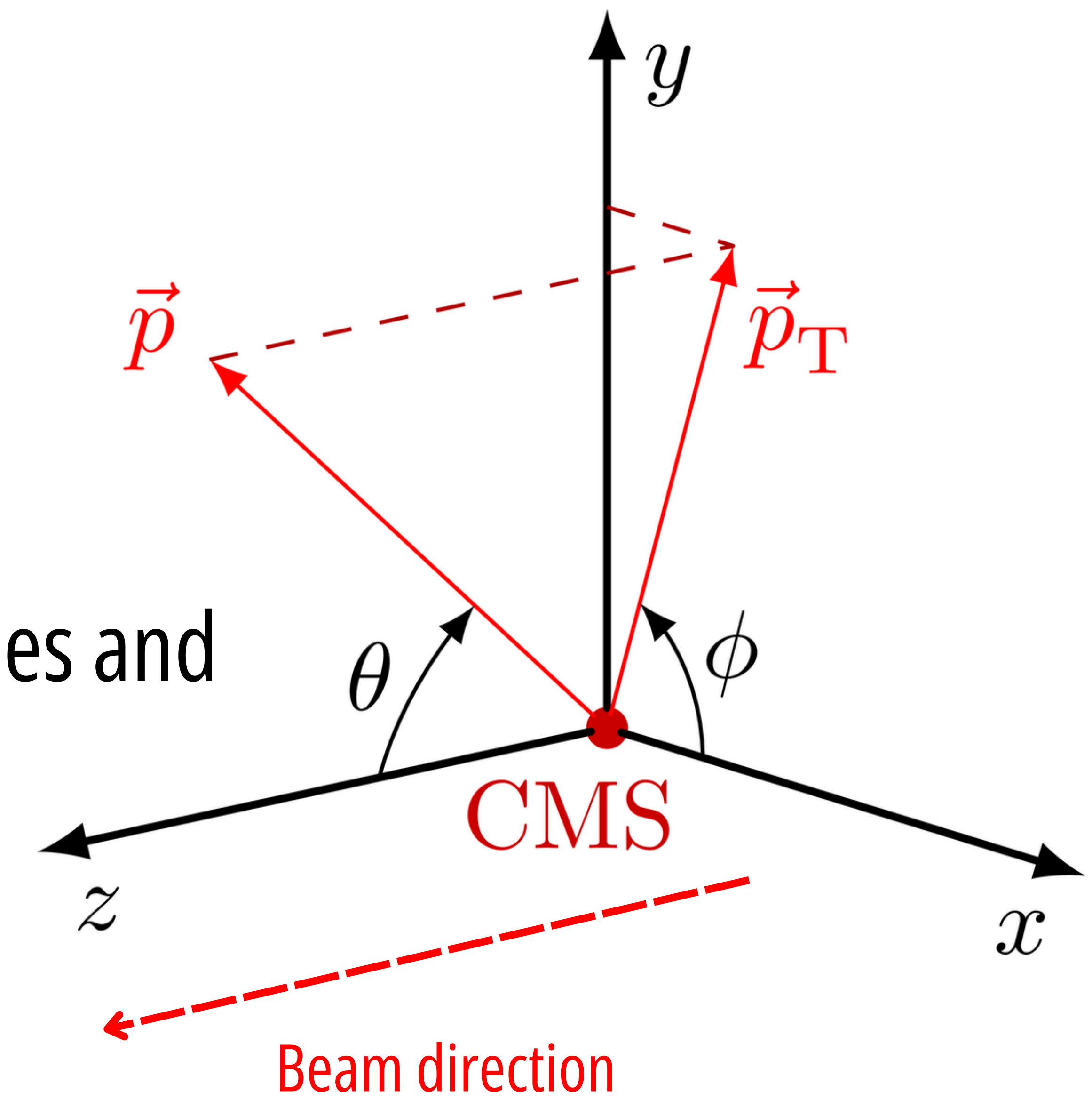
$$p_T = \sqrt{p_x^2 \ + \ p_y^2}$$

- Pseudorapidity (η) approximates rapidity for high-energy particles and is given by dependent only on the polar angle θ.

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

- Rapidity is defined as,

$$y = \frac{1}{2} \times ln\frac{E+p_z}{E-p_z}$$

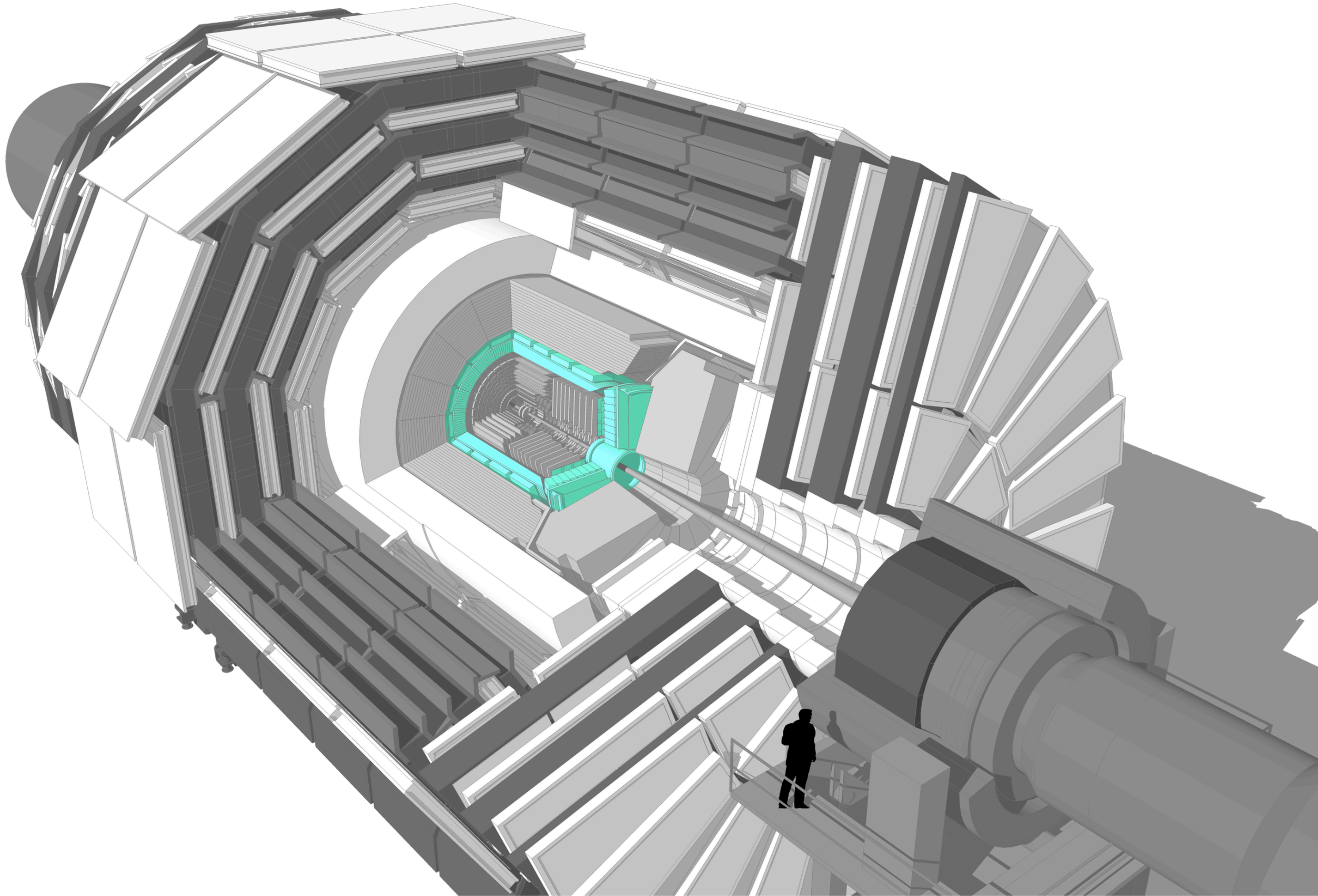


CMS: Electromagnetic Calorimeter

- Crucial for studying electrons, positrons, and photons.
- Made of 61,200 lead tungstate ($PbWO_4$) crystals in the barrel and 7,324 crystals in each endcap.

Why $PbWO_4$?

- High density (8.28 g/cm^3)
- Short radiation length (0.89 cm)
- Small Moliere radius (2.2 cm)
- Fast Decay: 80% light emitted in 25 ns.



CMS: Electromagnetic Calorimeter

Electromagnetic shower

An ElectroMagnetic shower is a cascade of secondary electrons/positrons and photons initiated by the interaction with matter of an incoming of electron/positron or photon.

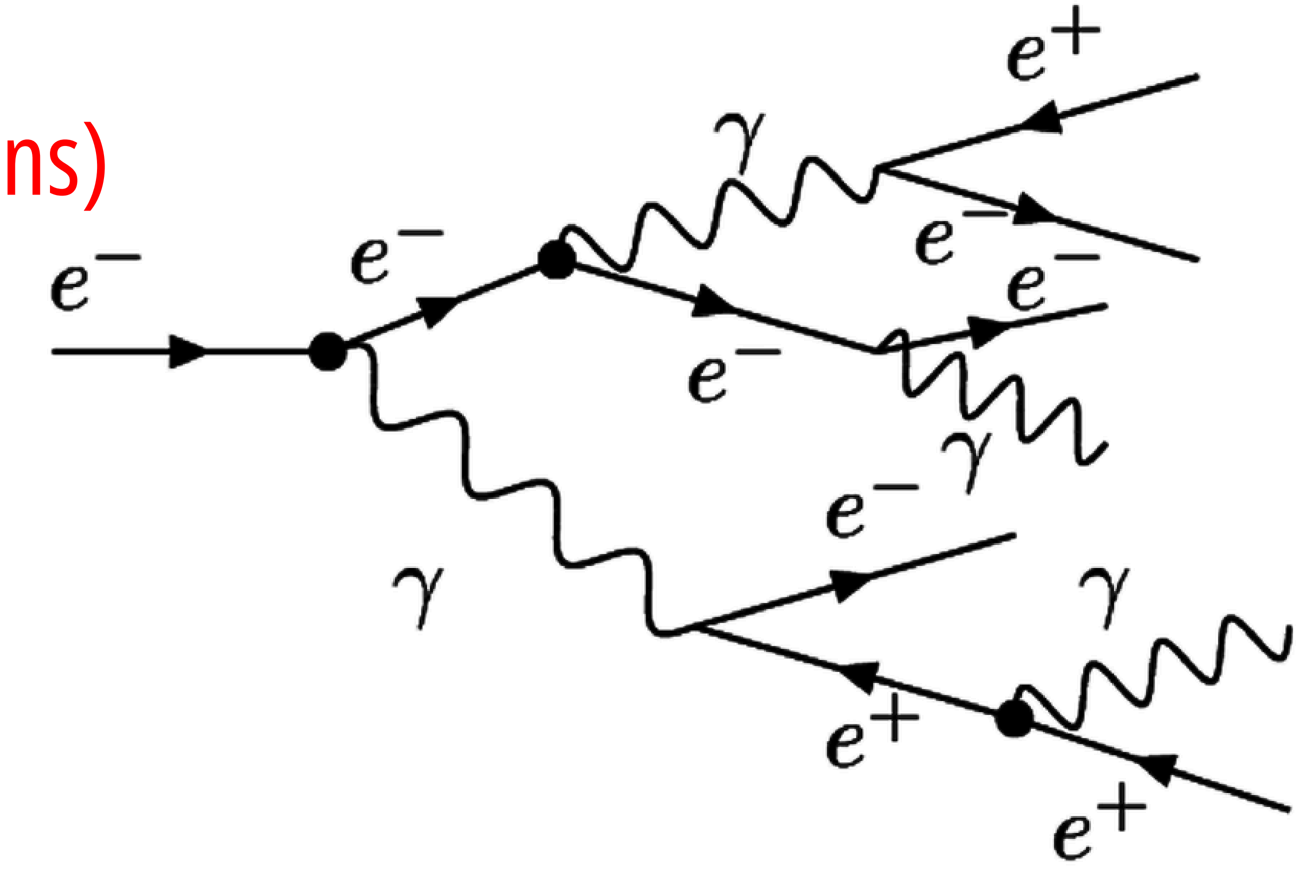
The main energy loss mechanism are:

- Ionization
- *Bremsstrahlung*

for electrons(positrons)

- Compton scattering
- *Pair production*
- Photo-electric effect

for photons



Data Analysis

- The analysis uses data from the CERN Open Data Portal.
- The primary signal is the Drell-Yan production of electron-positron pairs (e^+e^-) with an invariant mass greater than 50 GeV, modeled using the DYToLL M-50 Monte Carlo sample.
- Background processes are modeled with Monte Carlo simulations, including:
  - $t\bar{t} \to (bW^+)(\bar{b}W^-) \to (b\ell^+\nu_\ell)(\bar{b}\ell'^-\bar{\nu}_{\ell'})$
  - $W^+W^- \to (\ell^+\nu_\ell)(\ell'^-\bar{\nu}_{\ell'})$
  - $W^\pm Z \to (\ell^+\nu_\ell)(\ell'^+\ell'^-)$
  - $ZZ \to (\ell^+\ell^-)(\ell'^+\ell'^-)$
  - $t\bar{t} \to (bW^+)(\bar{b}W^-) \to (b\ell^+\nu_\ell)(\bar{b}q\bar{q}')$
- The study aims to isolate the Drell-Yan signal while accurately accounting for background contributions.

Data Analysis: Selection cuts

We will impose certain selection "cuts" to our data so that only events of our interest (electrons and positrons) can be filtered out.

Criterion	**Description**
Lepton Multiplicity	Exactly two leptons in the event
Transverse Momentum (p_T)	Leading lepton: $p_T > 25\,\text{GeV}$, Subleading lepton: $p_T > 20\,\text{GeV}$
Pseudorapidity ($\lvert\eta\rvert$)	Both leptons must satisfy $\lvert\eta\rvert < 2.5$
Lepton Pair Charge	Oppositely charged lepton pair (e^+e^-)
Invariant Mass ($m_{\ell\ell}$)	$60\,\text{GeV} < m_{\ell\ell} < 120\,\text{GeV}$

Data Analysis: Variables

The analysis is performed using the ROOT CERN framework.

Key quantities to be plotted include:

- Transverse Momentum (pT):

The momentum of lepton in the transverse(x-y) plane.

$$p_T = \sqrt{p_x^2 + p_y^2}$$

- Pseudorapidity(η):

A coordinate that describes the angle of a particle relative to the beamline. It is related to the polar angle (θ) of the particle's trajectory.

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

Data Analysis: Variables

- Invariant Mass of the Di-Electron Pair:

For two electrons, it represents the combined mass of the system in the center-of-mass frame, given by:

$$M_{\ell\ell} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$$

- Transverse Momentum of the Di-Electron Pair:

The transverse momentum measures the momentum of the pair in the plane perpendicular to the beam direction. For the di-electron system, it's calculated as:

$$p_{T\ell\ell} = \sqrt{(p_x^1 + p_x^2)^2 + (p_y^1 + p_y^2)^2}$$

Data Analysis: Variables

- Azimuthal Angle Difference Between the Two Electrons :

This is the difference in azimuthal angles (ɸ) of the two electrons in the transverse plane. The azimuthal angle is defined as the angle of the momentum vector relative to the x-axis:

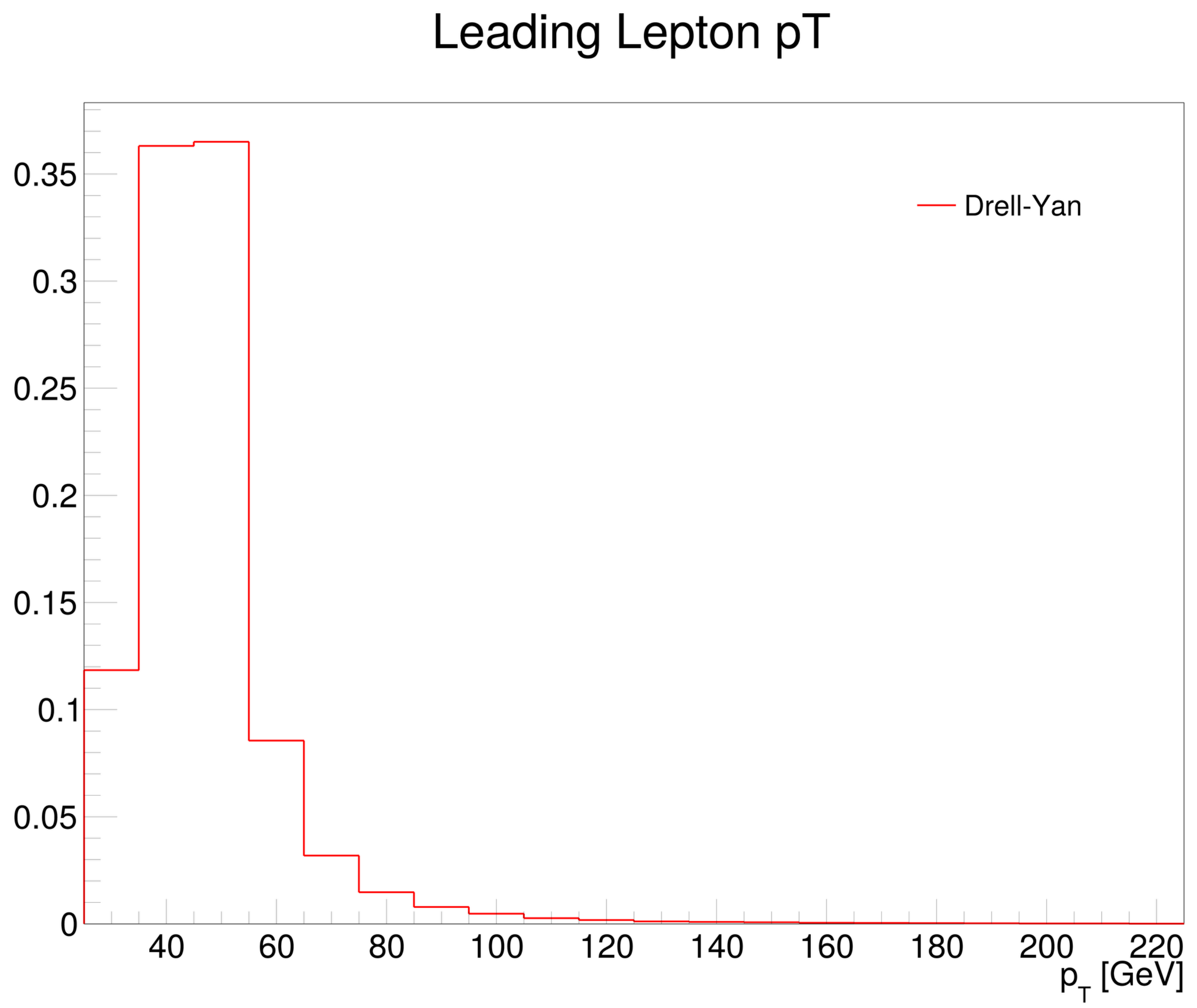
$$\Delta\phi_{\ell\ell} = |\phi_1 - \phi_2| \qquad\qquad \phi_i = tan^{-1}\left(\frac{p_y i}{p_x i}\right)$$

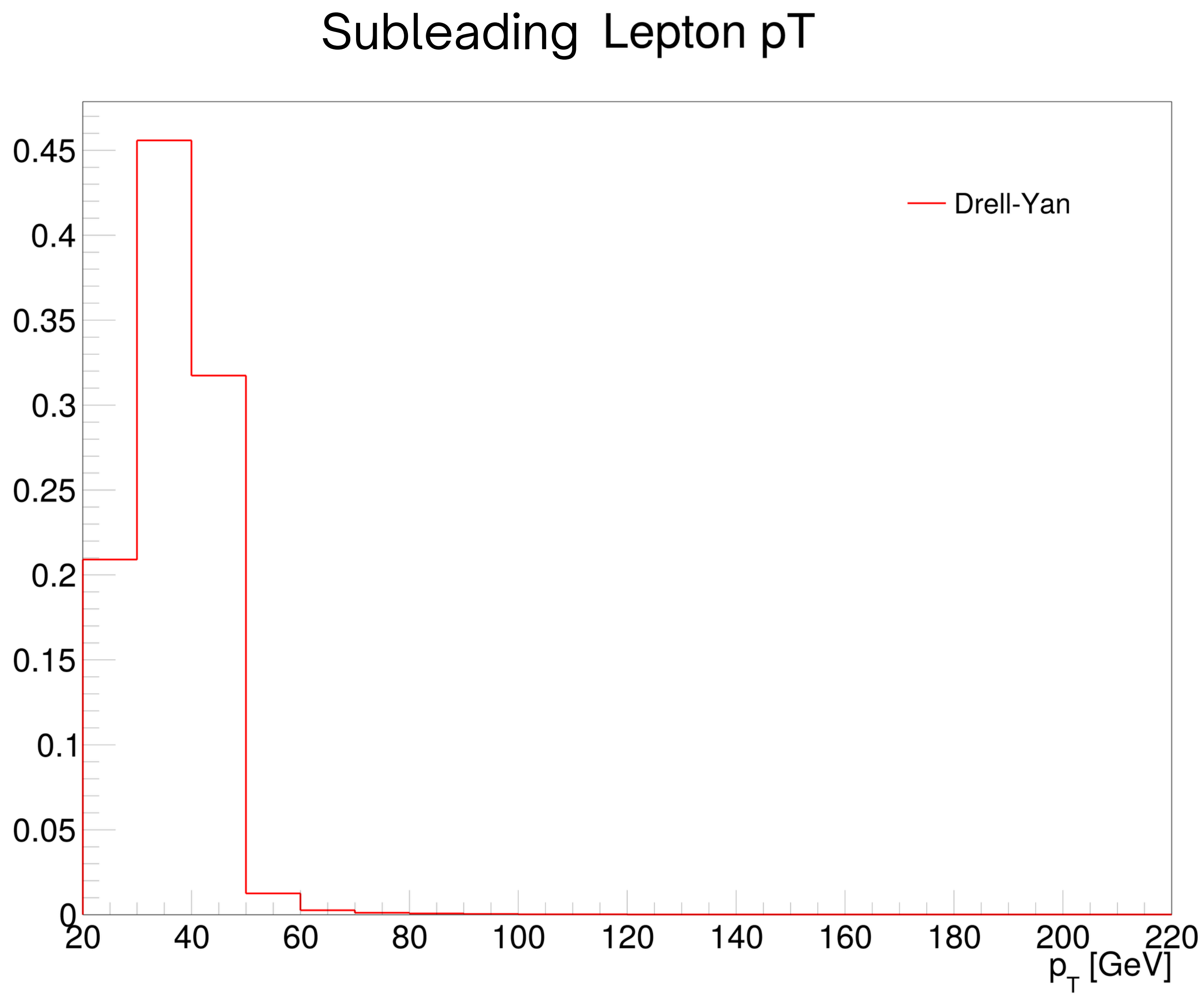
- Missing Transverse Energy (MET):

MET represents the transverse momentum imbalance in an event, indicating the presence of invisible particles like neutrinos.

Data Analysis: Plots without backgrounds

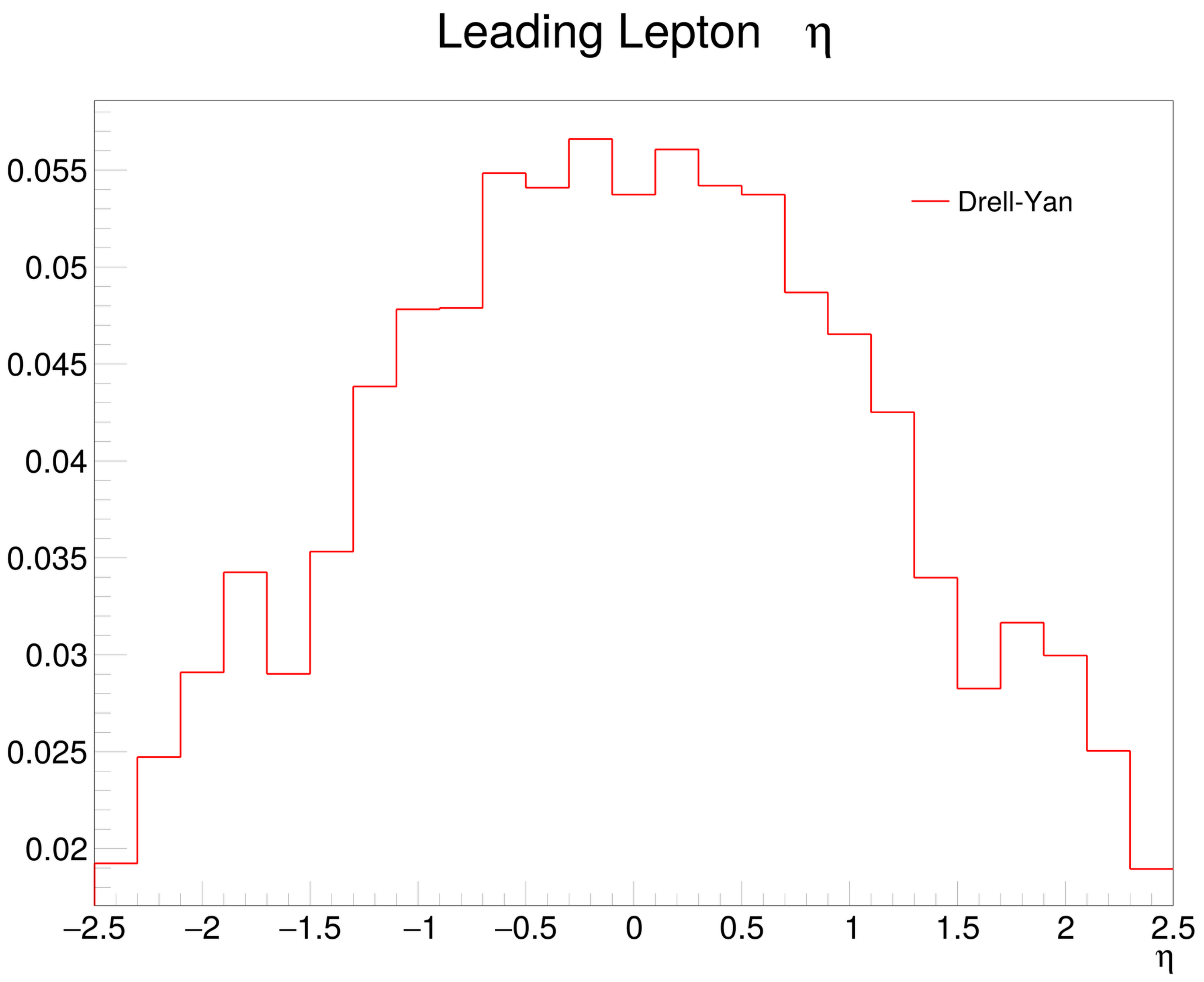
Drell-Yan $(Z \rightarrow e^+e^-)$ Plots

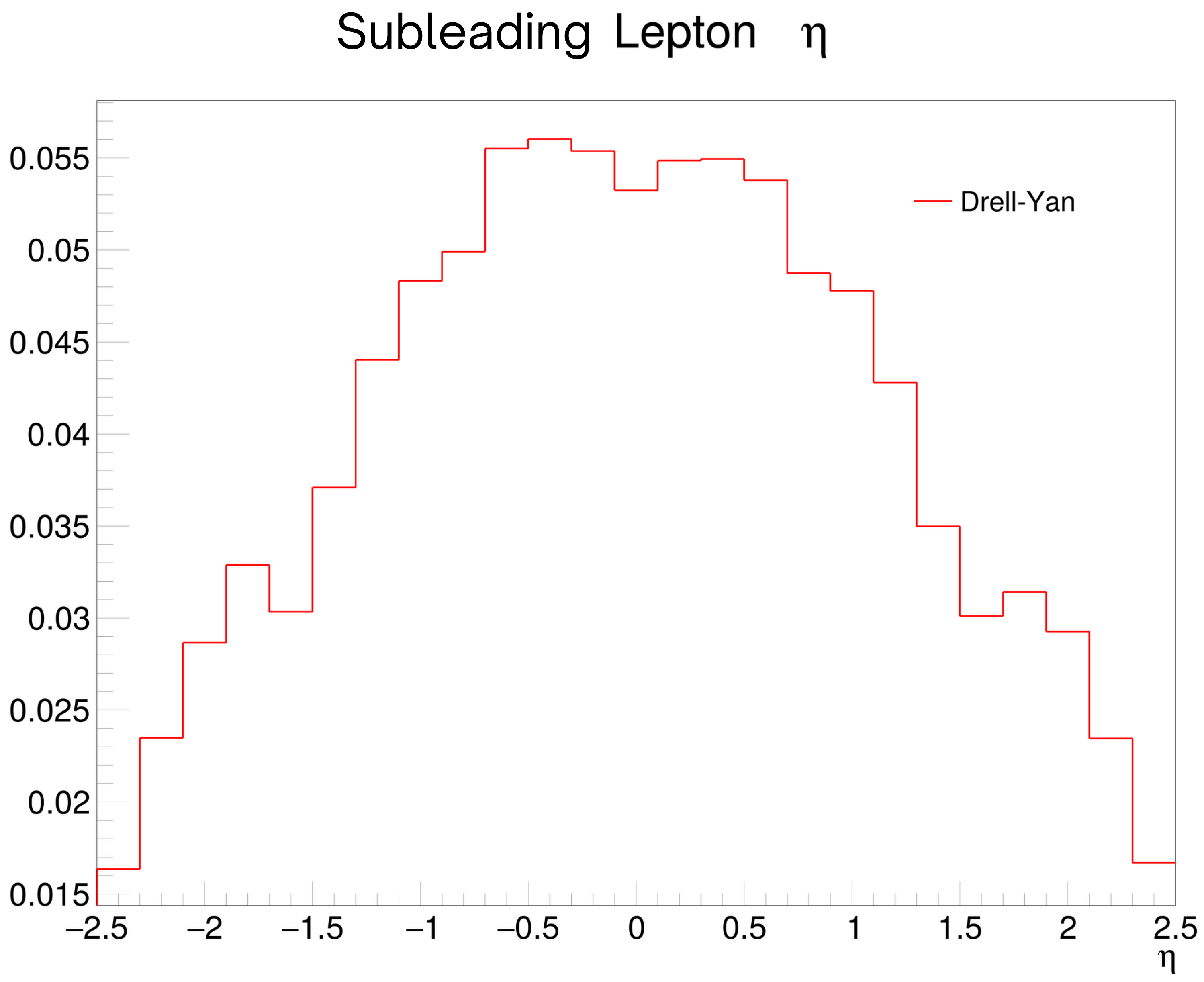




Data Analysis: Plots without backgrounds

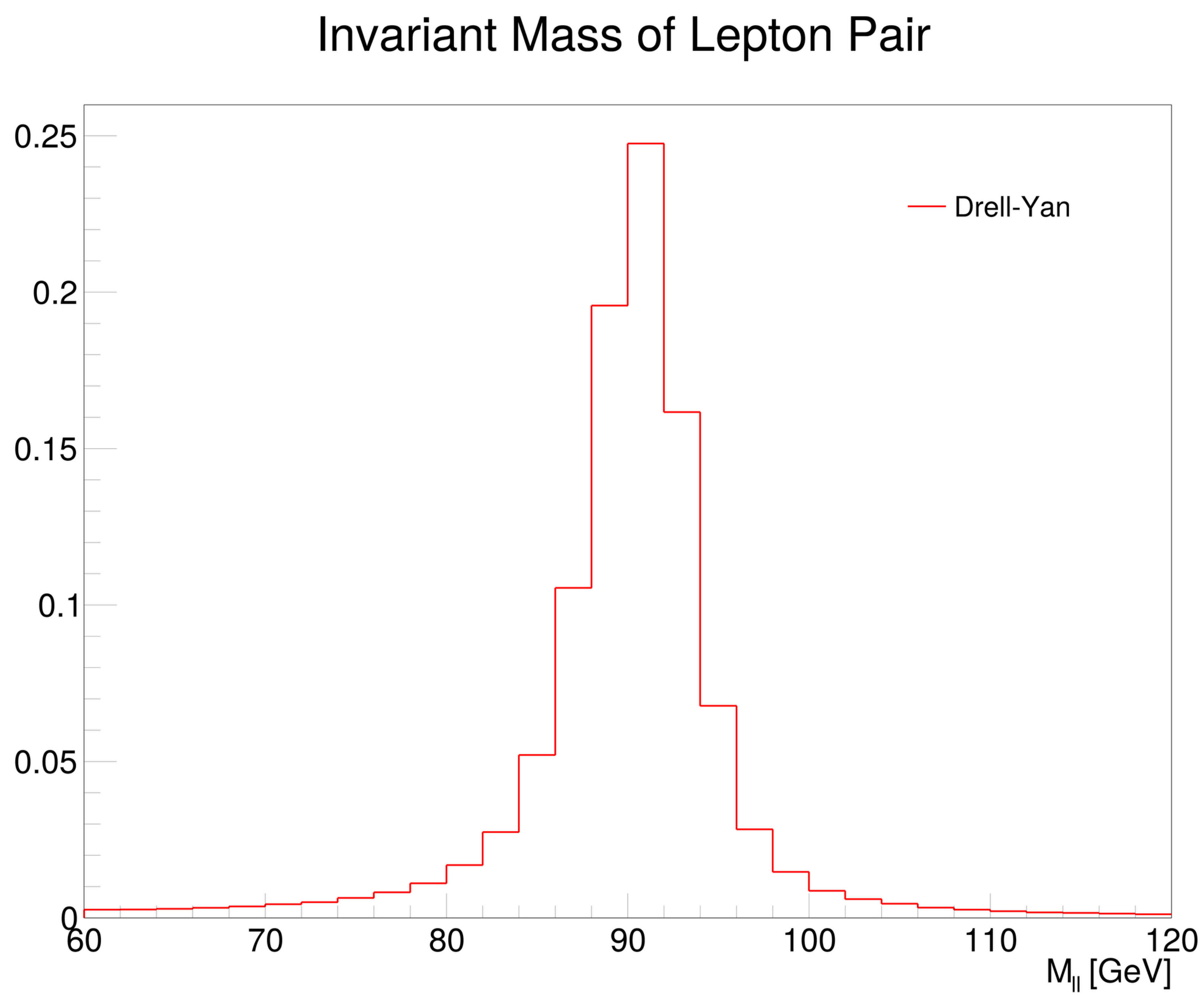
Drell-Yan $(Z \to e^+e^-)$ Plots





Data Analysis: Plots without backgrounds

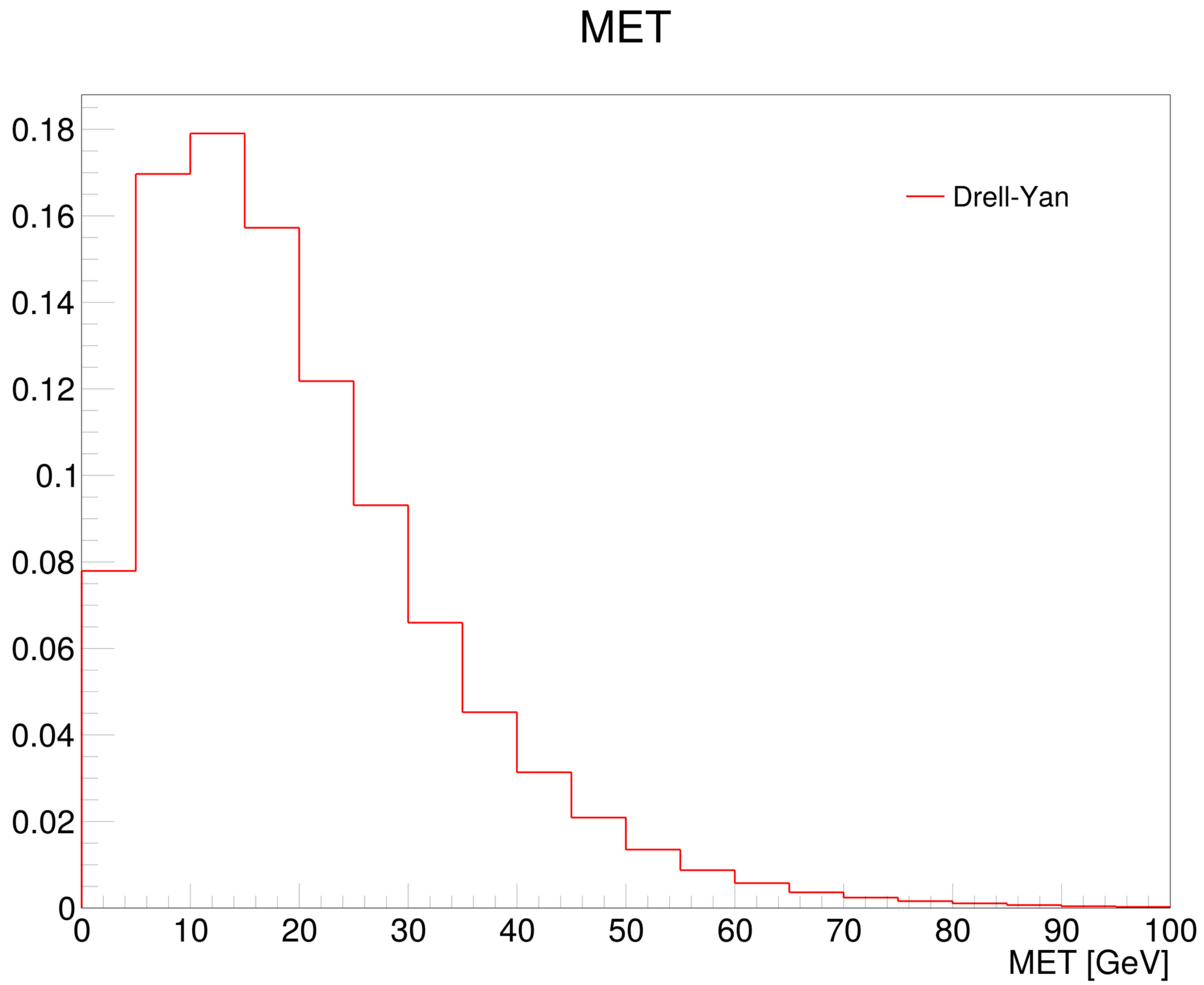
Drell-Yan ($Z \to e^+e^-$) Plots



- Centred around 91 GeV, which is the mass of the Z-boson.

Data Analysis: Plots without backgrounds

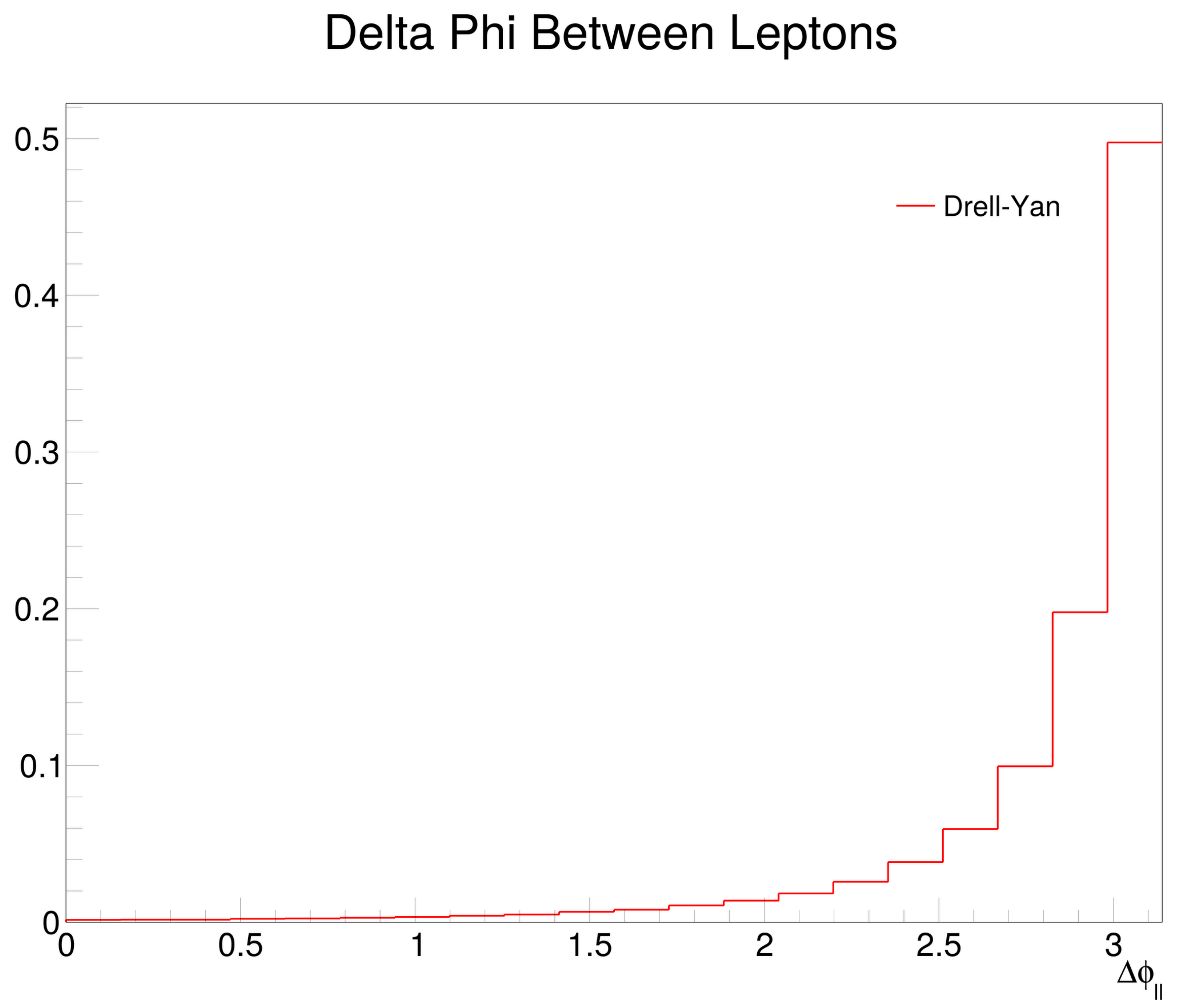
Drell-Yan ($Z \rightarrow e^{+}e^{-}$) Plots



- In Drell-Yan events, a lepton-antilepton pair is produced via an intermediate Z-boson, with no neutrinos in the final state.
- Ideally, MET should be close to zero because all visible particles are detected, and no invisible particles (like neutrinos) carry away energy.
- Detector resolution: Imperfect measurement of lepton momenta can lead to artificial MET.

Data Analysis: Plots without backgrounds

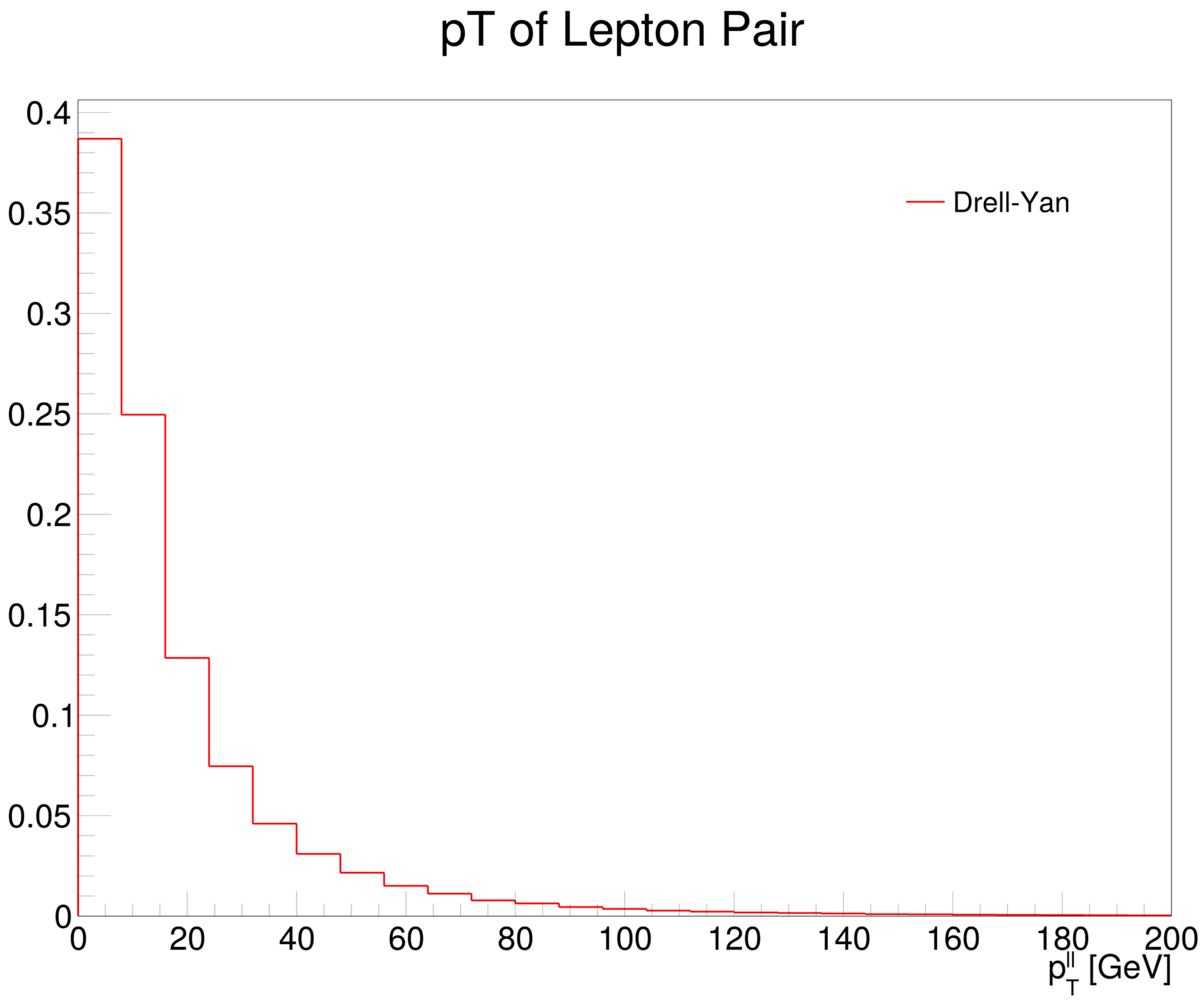
Drell-Yan ($Z \to e^+e^-$) Plots



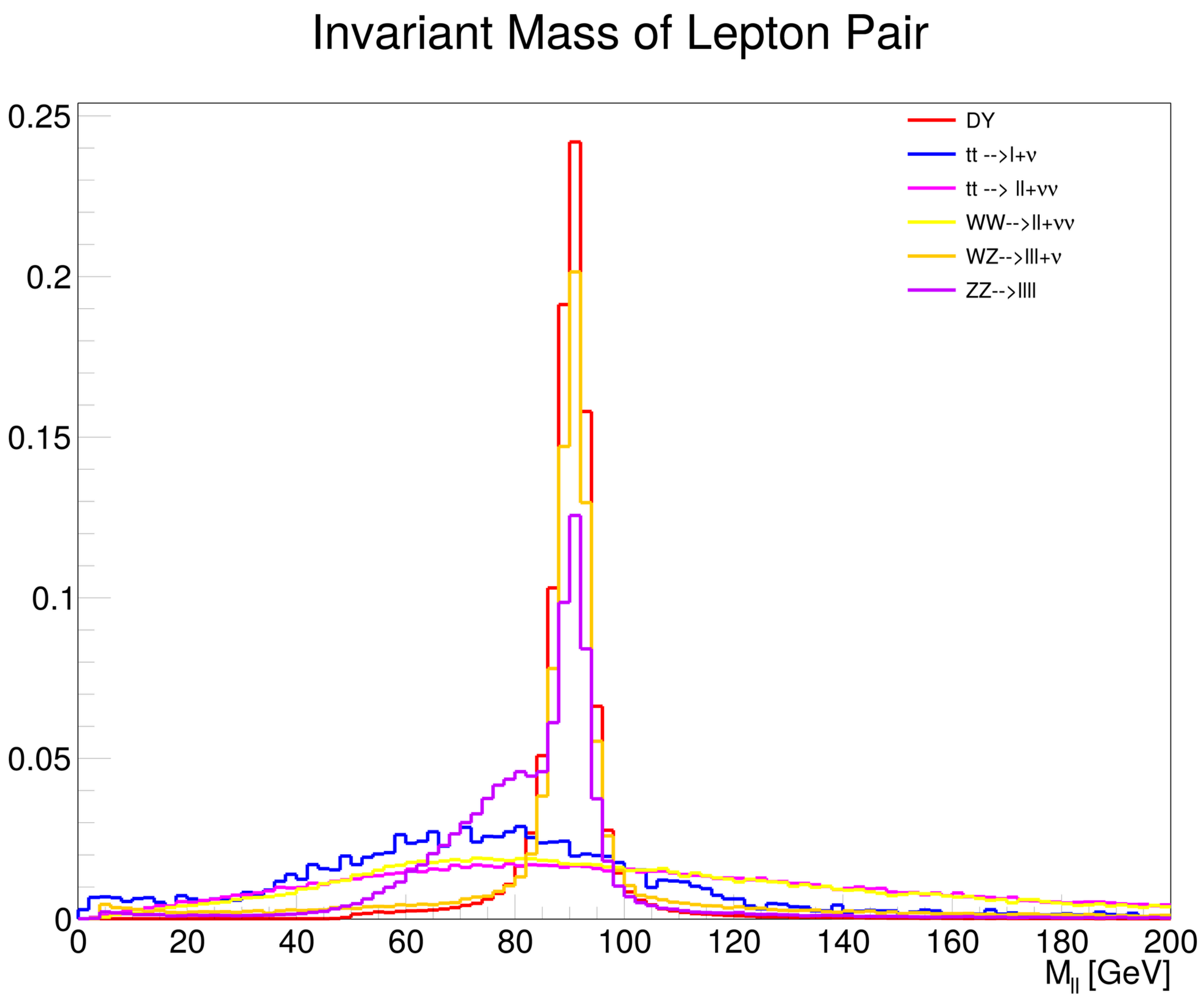
- $\Delta\phi$ provides information about the relative directions of the leptons in the transverse plane.
- The leptons are often produced back-to-back in the transverse plane (opposite directions).

Data Analysis: Plots without backgrounds

Drell-Yan $(Z \to e^+e^-)$ Plots

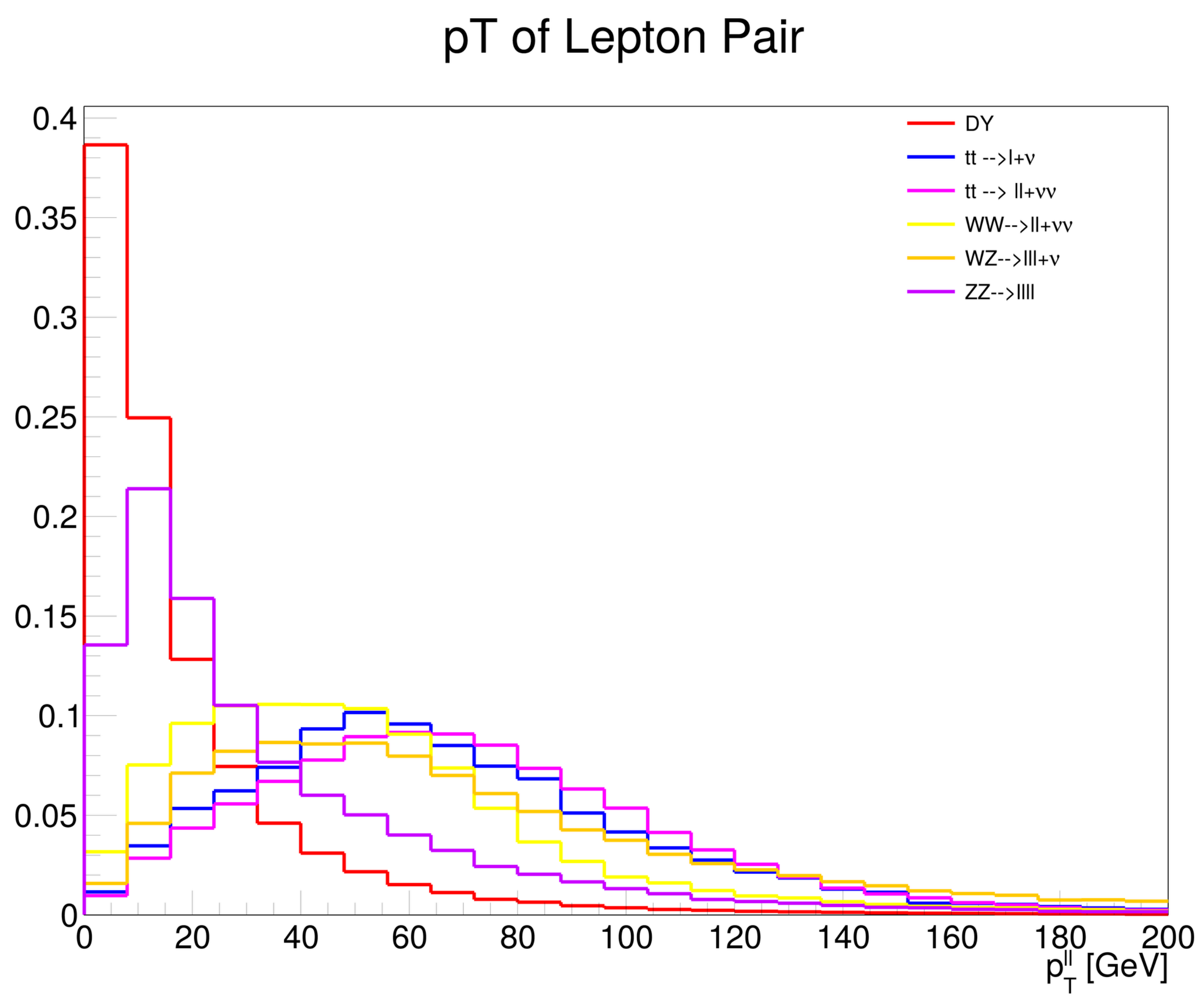


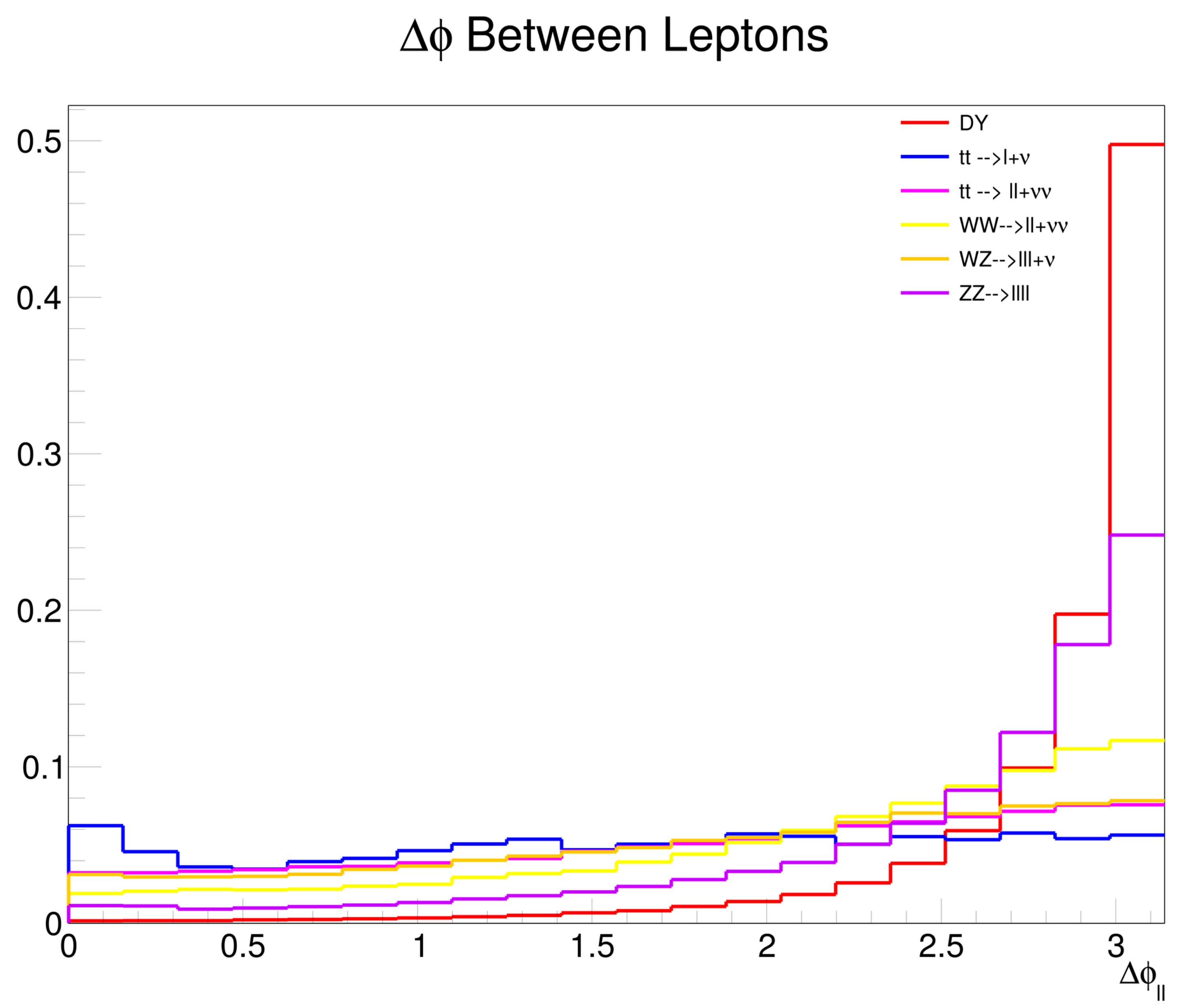
Data Analysis: Plots with backgrounds



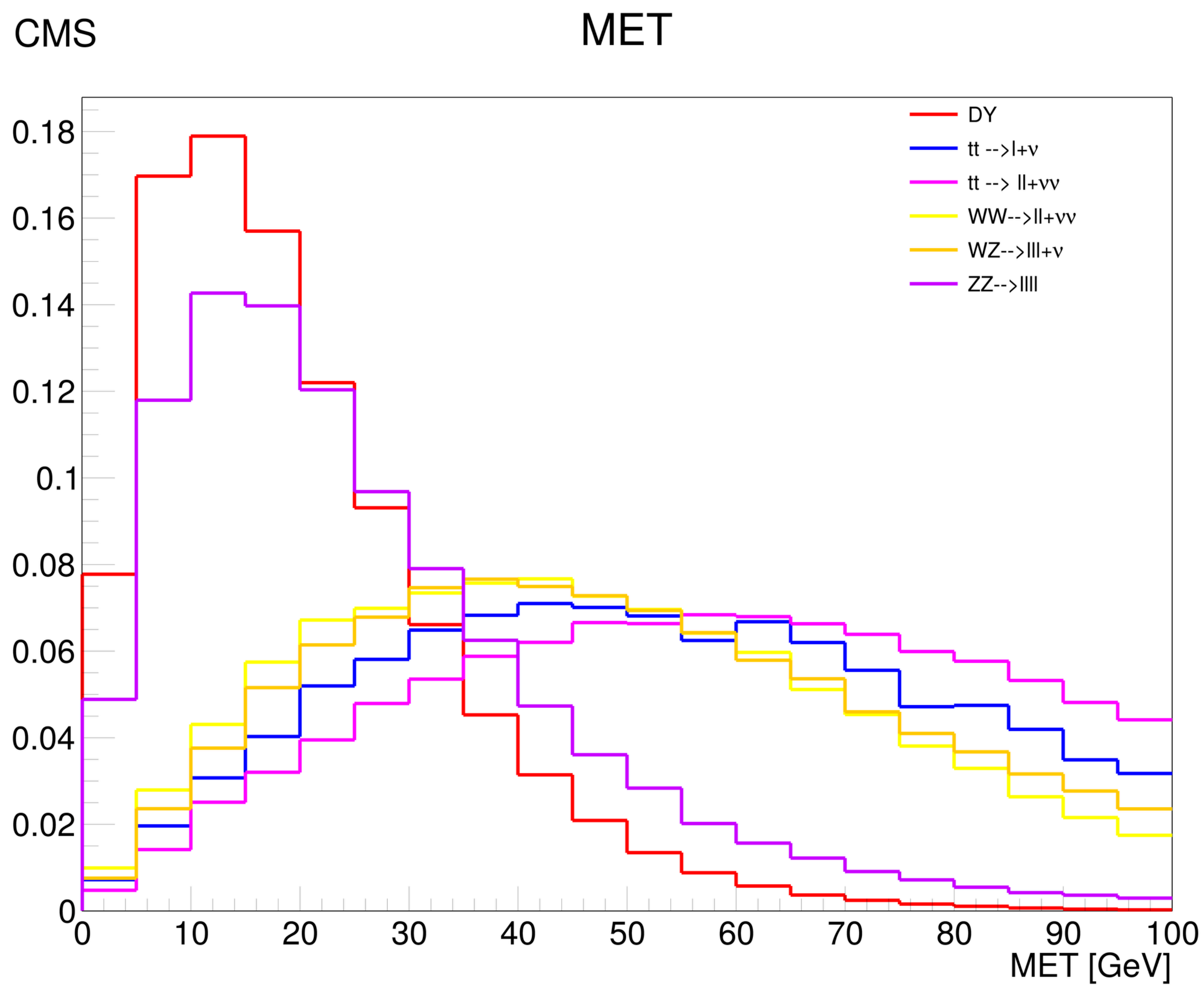
- Signals coming from Z bosons are centered around 91 GeV.
- This information can be exploited while developing selection techniques.

Data Analysis: Plots with backgrounds



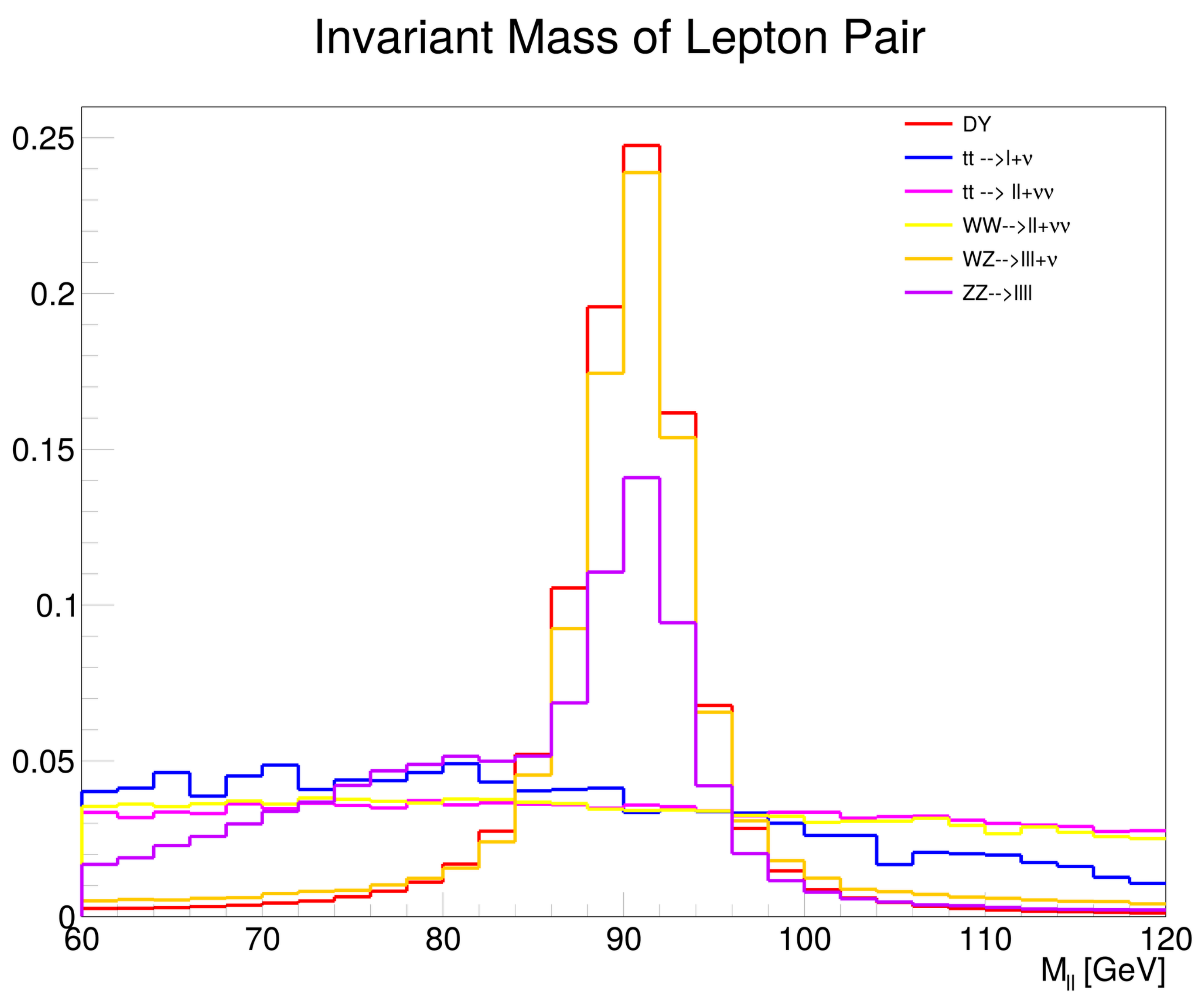


Data Analysis: Plots with backgrounds

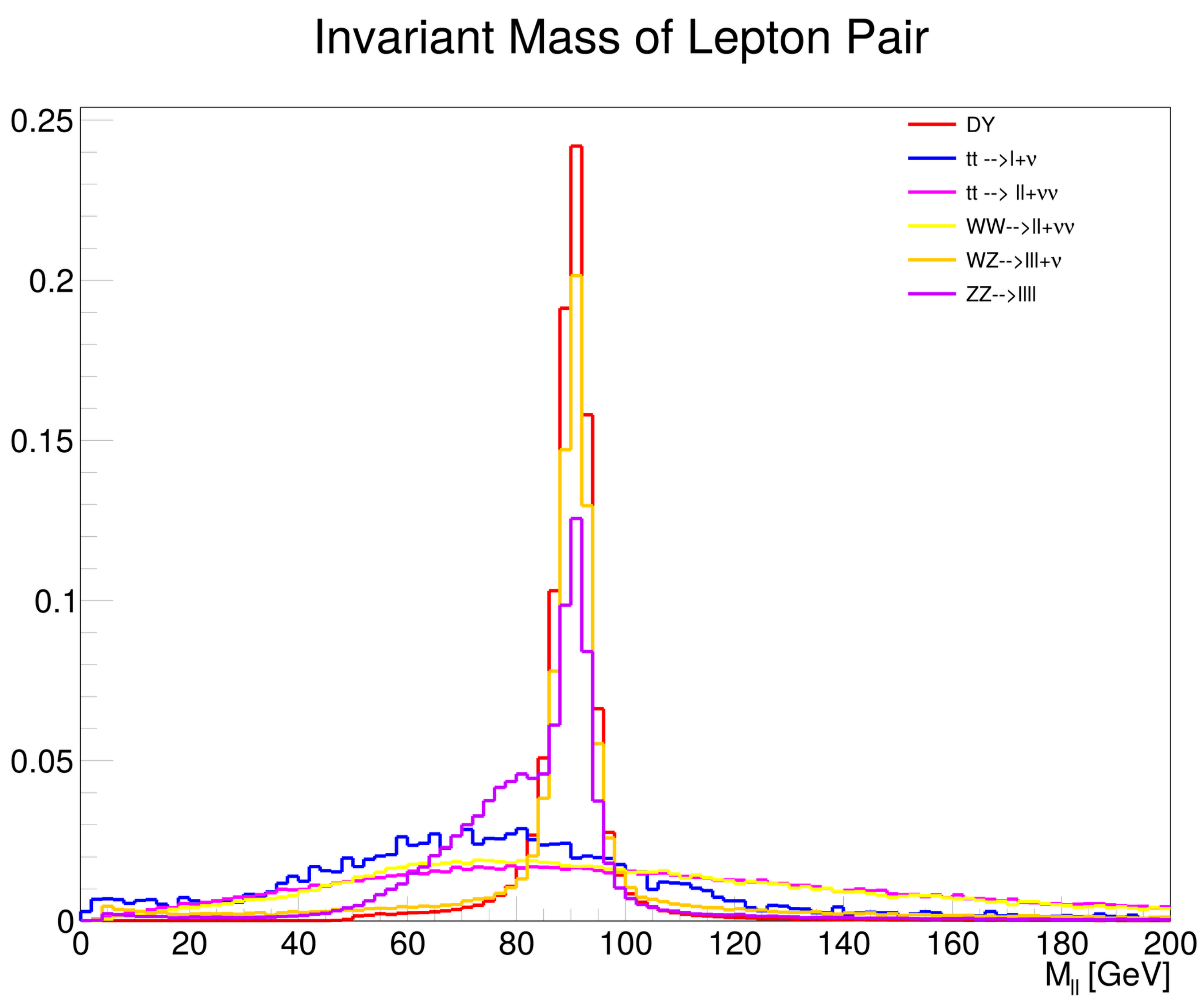


- The distinct behavior of the Drell-Yan signal offers valuable insights into the nature of the signal, aiding in the development of effective selection techniques.

Data Analysis: Plots with backgrounds



(a) Invariant mass, $M_{\ell\ell}$ of the lepton pair with cuts 60 GeV $< M_{\ell\ell} <$ 120 GeV .



(b) Invariant mass, $M_{\ell\ell}$ of the lepton pair without cuts.

Summary and Outlook

- We explored the Drell-Yan process without diving too deep into theoretical details.

- Using CMS Open Data (MC simulation), we analyzed key kinematic distributions of the Drell-Yan process ($Z \rightarrow e^+e^-$), including transverse momentum, pseudorapidity (η), and dilepton invariant mass, etc. We highlighted the characteristic features of the Drell-Yan process and examined the influence of background processes on these distributions.

- In the forthcoming semester, we will focus on developing selection criteria to refine our analysis and improve the signal-to-background ratio.

Thank you for your time!