Testing the lepton PDFs of the proton at lepton-proton colliders

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Based on arxiv:2408.12644

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MuC Meeting BY THE LAKE
Northwestern Technological Instititute, Evaston, IL

Sep 18, 2024

Lepton PDFs

- At zeroth order in perturbation theory the lepton carries all the momentum of the beam

- At high energies, collinear radiation emitted by splitting of the initial state must be taken into account.

Weizsiieker, Kopenhagen

https://doi.org/10.1007/BF01333110

Williams

https://doi.org/10.1103/PhysRev.45.729

- The case of collinear photon emission from an electron gives the

  Equivalent Photon Approximation (EPA):

  given by the Weizsacker-Williams spectrum

$$f_{\gamma,l}(x) \approx Q_\ell^2 \frac{\alpha}{2\pi} P_{\gamma,\ell}(x) \ln \frac{E^2}{m_\ell^2}$$

Splitting func: $P_{\gamma,\ell}(x) = \frac{1+(1-x)^2}{x}$

the probability of the lepton to emit a photon with a fraction x of its longitudinal momentum.

- These radiated photons can furthermore provide other fermion parton content to the colliding lepton

  via the $\gamma \to f\bar{f}$ splitting function $P_{f,\gamma}(z_f) = 1 - 2z_f + 2z_f^2$

  $z_f \longrightarrow$ the fraction of momentum of the fermion with respect to the photon.

- The EPA has been generalized to describe EW gauge bosons in high-energy collisions, in what is now known as

  Effective Vector Approximation (EVA)

Lepton PDFs

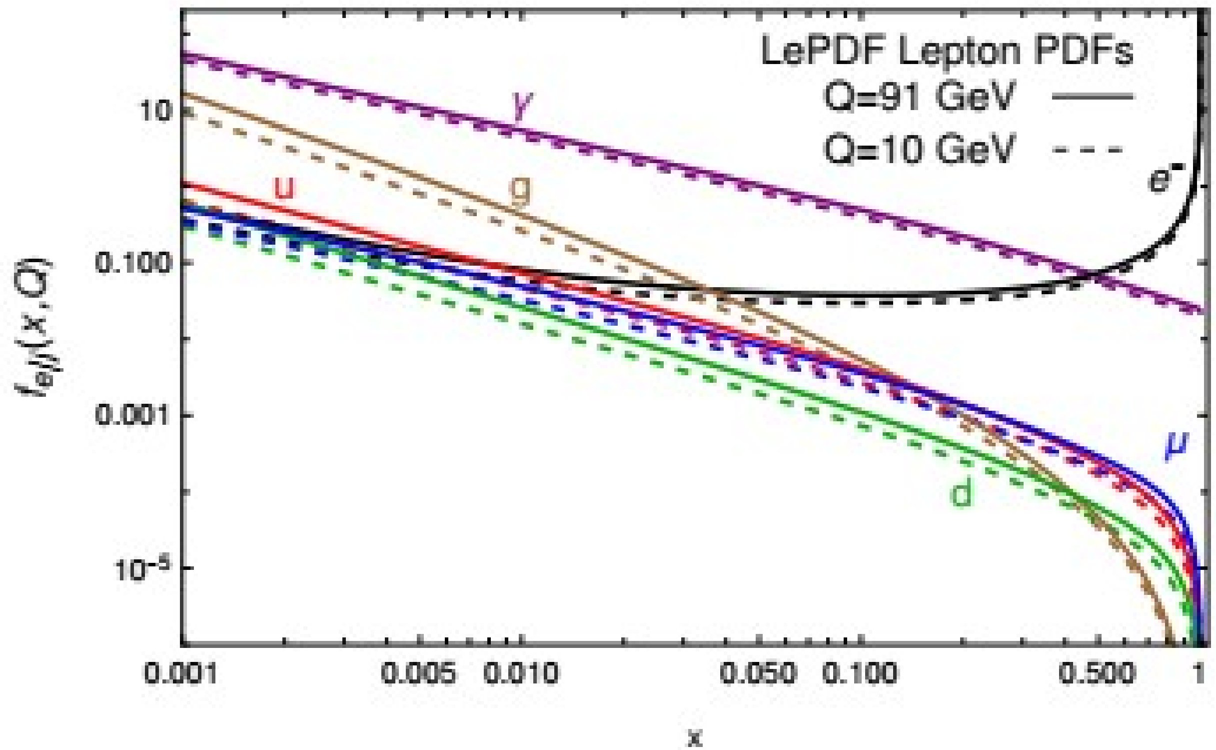
- This previous description becomes inadequate at some high scale

At high energies $E >> m_\ell$ the collinear logarithmic term can become sizeable and needs to be resummed for reliable predictions.

→ Leads to solving QED analog of Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equations

Generalization of Parton Distribution Functions (PDFs) for charged leptons

- Recently, it has been computed for electron and muons



Garosi, et al.

https://arxiv.org/abs/2303.16964

Han, et al.

https://arxiv.org/abs/2007.14300

https://arxiv.org/abs/2103.09844

https://arxiv.org/abs/1607.03210

Lepton PDFs of proton

hep-ph/9412286
hep-ph/0403200
hep-ph/0411040

- A similar description applies to the QED interactions within the proton.

When estimating proton PDFs involving QED-induced processes, hadronization effects lead to a modification of the logarithmic factor to $\ln(\mu_F^2/\Lambda^2)$

$\mu_F \to$ factorization scale

$\Lambda \to$ typical hadronic scale

arXiv:2005.06477
Buonocore, et al.

- In a pure QCD model, protons consist of valence quarks, with abundant soft and collinear QCD radiation.

Order of quark and gluon PDFs $(\alpha_S L)^n$, $L = \ln(\mu_F/\Lambda)$

If $L \sim 1/\alpha_S$, all the contributions becomes relevant

Notes:

- DGLAP equations account for perturbative evolution (renormalization scale dependence).
- Non-perturbative initial conditions (momentum fraction dependence) are extracted through global fits to DIS and collider data

- Naive expection from power counting that the lepton density in the proton very small $f_\ell \sim \alpha^2 f_q$

But it could be large due to large logarithimic factors

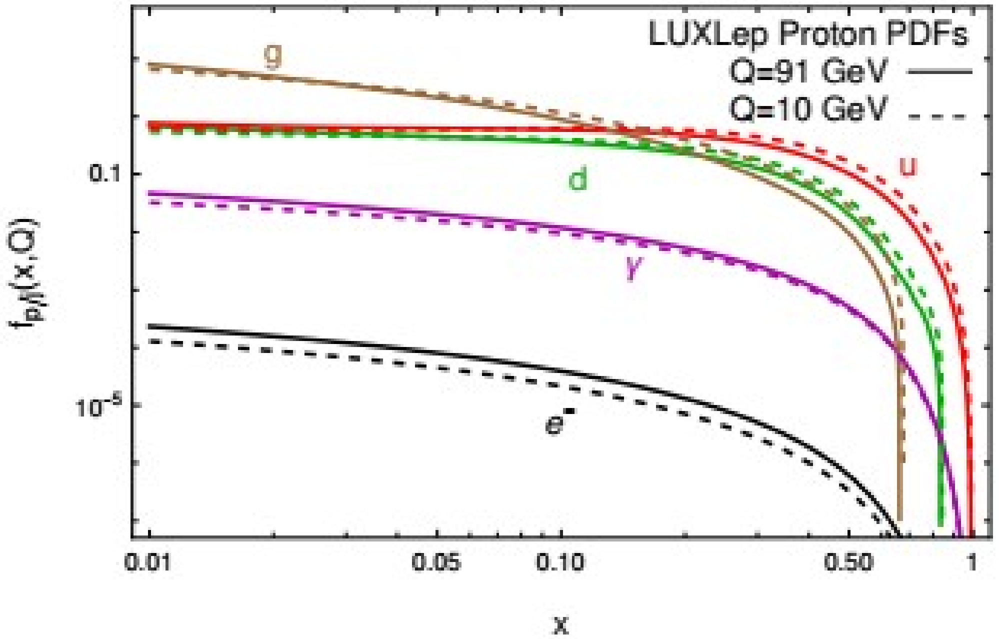
Buonocore, et al.

Power counting schemes

- quark and gluon PDF $(\alpha_S L)^n\,,\ L = \ln(\mu_F/\Lambda)$
- The photon PDF is reduced by a factor of αL (collinear-enhanced term)at the LO compared to the quark PDF.

$$\alpha \sim \alpha_s^2 \qquad L \sim 1/\alpha_s \qquad \to \alpha L \sim \alpha_s$$

- Similarly, leptons will be suppressed by a factor of $(\alpha L)^2 \sim \alpha_s^2$ at the LO
  - So, $f_{p/q}$ and $f_{p/g} \sim (\alpha_s L)^n \sim \mathcal{O}(1)$ $\quad f_{p/\gamma} \sim \alpha_s \quad f_{p/\ell} \sim \alpha_s^2 C_\ell \quad C_\ell = 3/20$



- Recently, the lepton PDFs of proton has been computed by Buonocore, et al.

arXiv:2005.06477

- One can think of the LHC as a lepton collider with varying energy.
  (not in terms of backgrounds)

Claim:

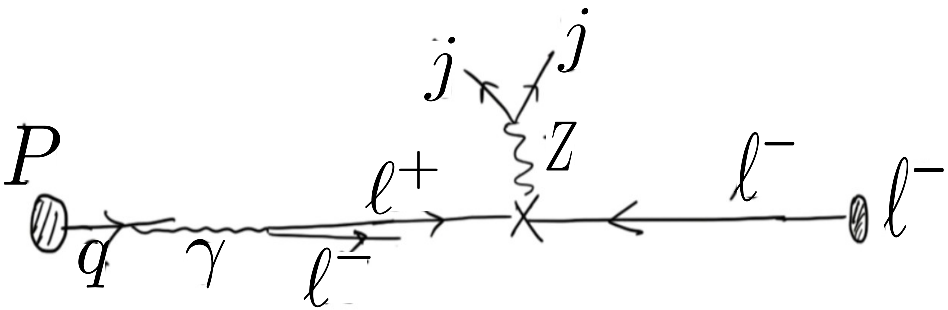
- The LHC can probe lepto-philic Z' up to 600 GeV, leptoquarks and doubly charged scalars up to 2.5--3 TeV with order-one couplings at high luminosity

Resonant Z-boson production at proton-lepton colliders:

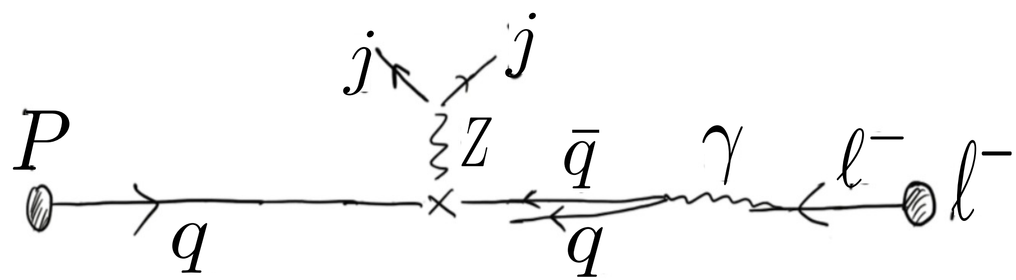
- For HERA and EIC , e^+ from P and the e^- from e^- collides and produce Z-boson

For MUIC, the same process would take place involving μ instead of electron

- Another processes: involving quarks coming from the colliding proton and lepton beams



Lepton-initiated process



quark-initiated process

PDF formalism is crucial as leptons and quarks originating from photons are in the collinear regime.

- Cross-sections in pe colliders: $f_{p/i} \otimes f_{e/j} \otimes \hat{\sigma}_{ji}$ → $\text{hard scattering between partons } i \text{ from the } p \text{ and } j \text{ from the } e^-$

PDFs

- $\text{For}, e^+e^- \to Z \quad \hat{\sigma}_{e^+e^-} \sim \alpha/\hat{s} \sim \alpha_s^2/\hat{s}, \quad \hat{s} \sim m_z^2,$ Lepton-initaited process $\longrightarrow \alpha_s^4 C_\ell / m_Z^2$
- $\text{For}, q\bar{q} \to Z \quad f_{e/\gamma} \sim \alpha L' \sim \alpha_s, \; f_{e/q} \sim (\alpha L')^2 C_q \sim \alpha_s^2 C_q \quad L' = \log(\mu_f^2/m_e^2), \; C_q \sim 3Q_q^2/20$

quark-initaited process $\longrightarrow \alpha_s^4 (C_u + C_d)/m_Z^2$

- Why Focus on a Lepton-Proton Collider Instead of a Hadron-Hadron Collider Like the LHC?

- Lepton involving process $p(\ell^{\pm})p(\ell^{\mp}) \to Z$ cannot be tested at hadron colliders, as the quark initiated processes $p(q)p(\bar{q}) \to Z$ dominate.

- Making the Proton-Lepton collider a unique machine to study lepton initiated Z-resonant production and test the lepton PDFs of proton.

- There is a need to distinguish lepton-initiated processes from quark-initiated processes at the proton-lepton colliders.

- Useful variable: $E - P_z \equiv \sum_i (E^i - P_z^i)$

Sum runs over all detected particles

$P_z \to$ momentum along the Z-direction

$E \to$ Energy

Kinematics:

Energies of the colliding partons

- Resonance featurs the relation: $4E_1 E_2 \sim m_Z^2$

$$\rightarrow 4E_{e^-/e^-}E_{p/e^+} \sim m_Z^2$$

$$x_{e^-/e^-}E_e \qquad\qquad x_{p/e^+}E_p$$

- Electron PDFs of electron peaks at $x_{e^-/e^-} \simeq 1$ (at the LO, its a Dirac-Delta func)

- The largest contribution to the resonant Z-production cross section from the lepton-initiated process occurs for

$$x_{p/e^+} = \frac{m_Z^2}{4E_e E_p}$$

- The lepton-initiated process mostly occurs for a fixed value of x_{p/e^+} ,

  while for the quark-initiated process, a range of $x_{e^-/q}$ and $x_{p/q}$ exists for which significant contributions

HERA:

[arXiv:0911.0884]

Operated from 1992 to 2007

Electrons or positrons colliding with protons

Proton ~ 920 GeV and Electrons ~ 27.5 GeV → $E_{p/e^+} \sim 75\,\mathrm{GeV}$, $x_{p/e^+} \sim 0.082$

Integrated luminosity: 500 pb^{-1} per collider experiment (H1 and ZEUS)

$$x_{p/e^+} = \frac{m_Z^2}{4E_eE_p}$$

Lepton-initiated Z production

EIC:

[arXiv:1212.1701, 2103.05419]

Proton ~ 250 GeV and Electrons ~ 20 GeV → $E_{p/e^+} \sim 103.5\,\mathrm{GeV}$, $x_{p/e^+} \sim 0.412$

Integrated luminosity: 10-100 fb^{-1} (expected)

MUIC:

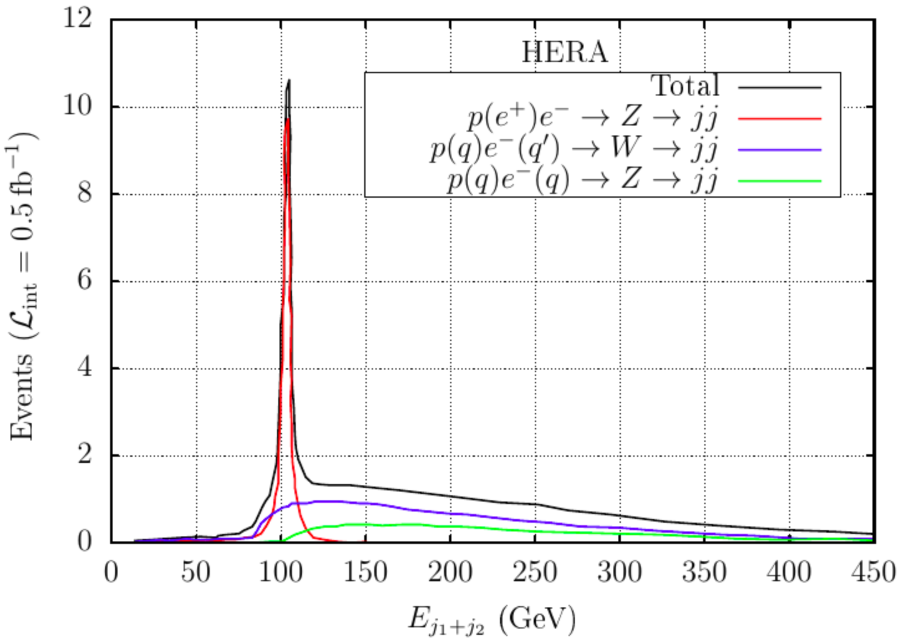
(proposed) [arXiv:2107.02073, 2203.06258]

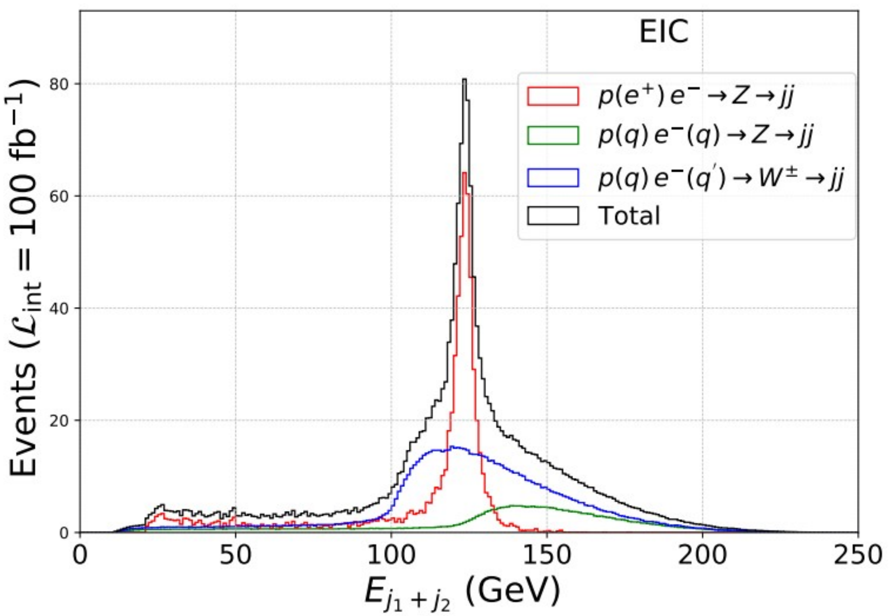
Proton ~ 275 GeV and Muons ~ 1 TeV → $E_{p/\mu^+} \sim 2\,\mathrm{GeV}$, $x_{p/\mu^+} \sim 0.0073$

Integrated luminosity: 400 fb^{-1}

Energy sum of decaying objects coming from the produced Z-boson

Focus to the di-jet decay mode of Z

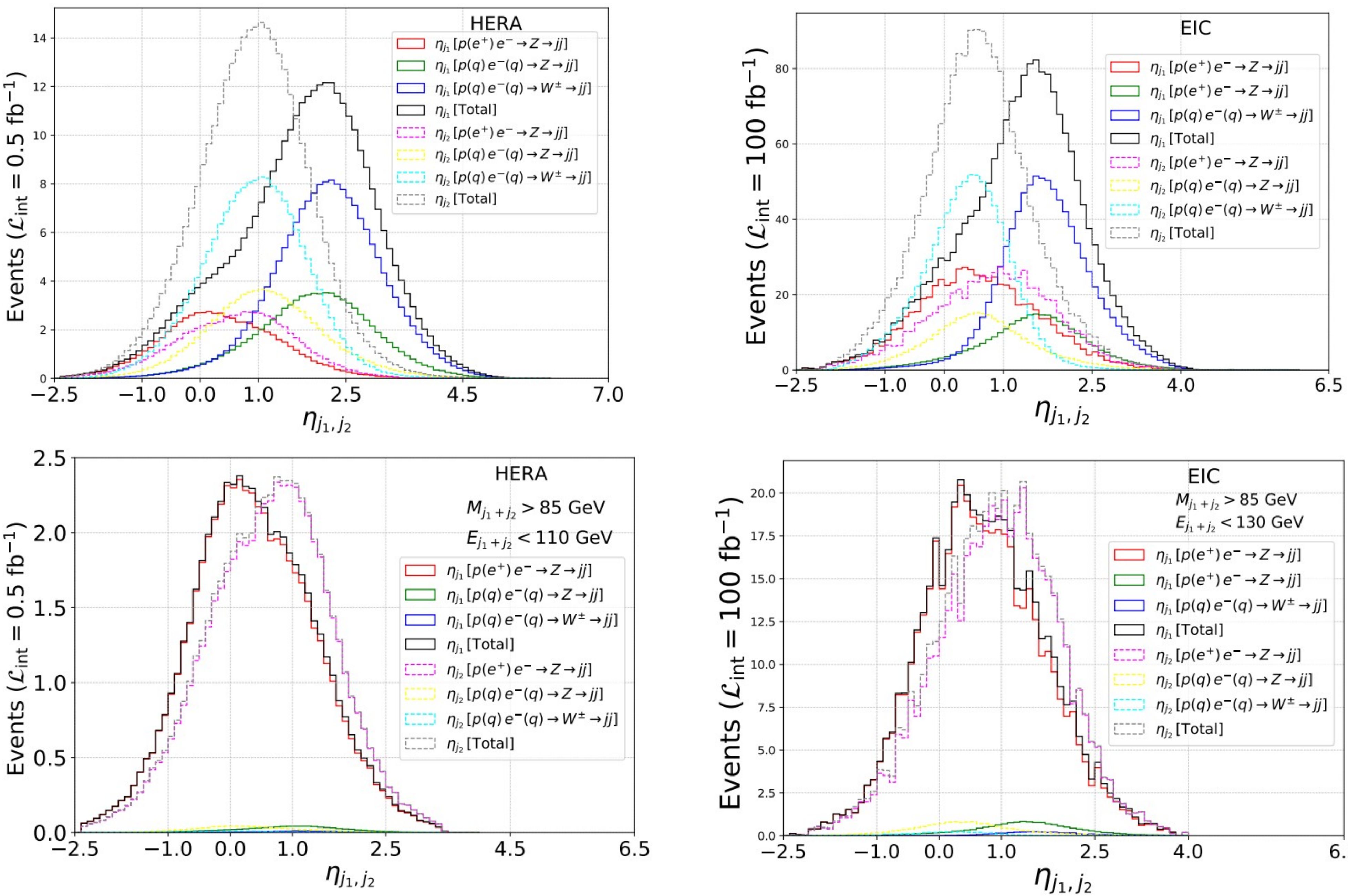




- These distributions suggest that the quark-initiated processes occur for a wide range of longituidinal momentum fraction of the quarks coming from the proton and the lepton.

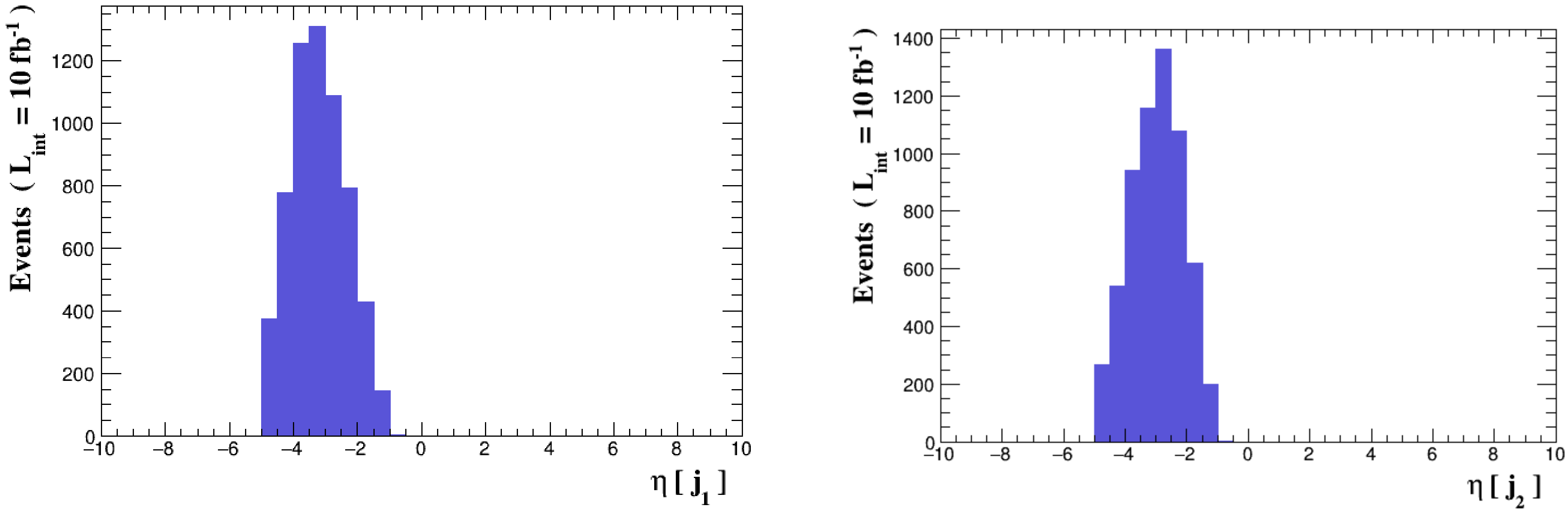
- Meanwhile, the lepton-initiated process occurs at approximately a fixed value of the longitudinal momentum fraction of the lepton originating from the proton.

η-distributions of the leading two jets



η -distributions of jets from Z, produced through the lepton-initited process at MuIC

$$P(\mu^+)\mu^- \to Z \to jj$$



- $E_\mu \sim 1\,\mathrm{TeV}$ $E_p \sim 275\,\mathrm{GeV}$
- $\to E_{p/\mu^+} \sim 2\,\mathrm{GeV}$

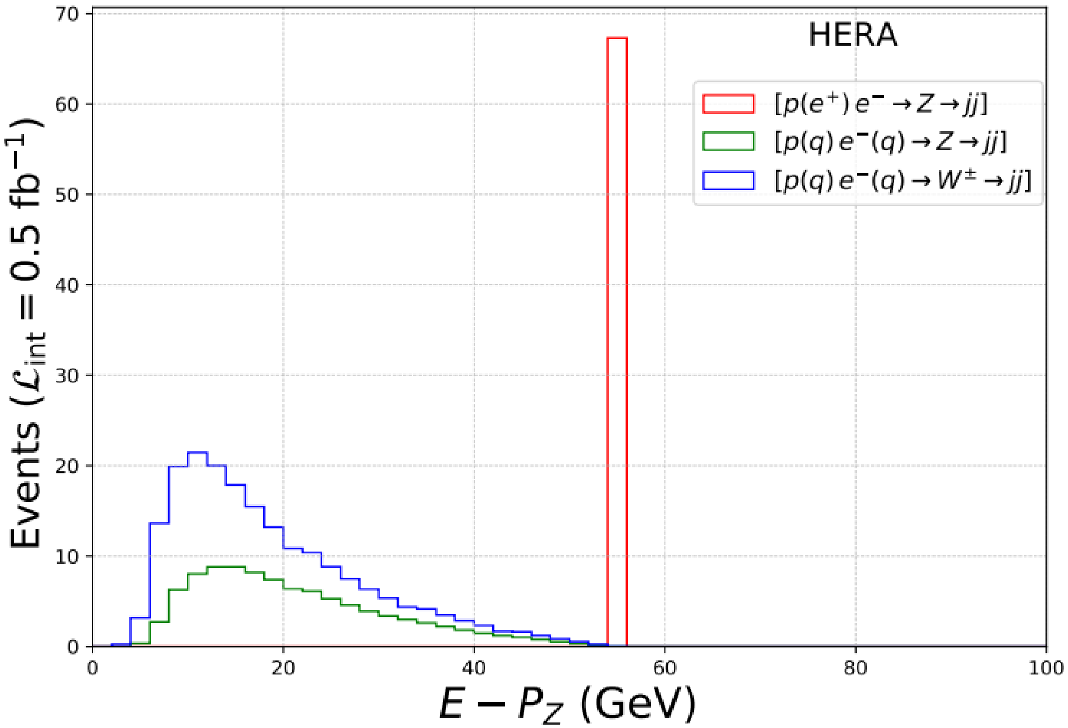
Dominant contribution to Z-production through lepton-initited process

- Decaying objects carry longituidinal boosts along the muon-beam direction ($-\hat{z}$-direction)

$$E - P_z \equiv \sum_i (E^i - P_z^i)$$

$P \rightarrow$ $\quad \leftarrow e^-$ $\quad \hat{z} \rightarrow$

sum runs over all detected particles



$E \rightarrow$ Energy

$P_z \rightarrow$ momentum along the z-direction

(proton beam direction)

- According to longitudinal momentum conservation this quantity should be equal to $2x_{e/j}E_e$

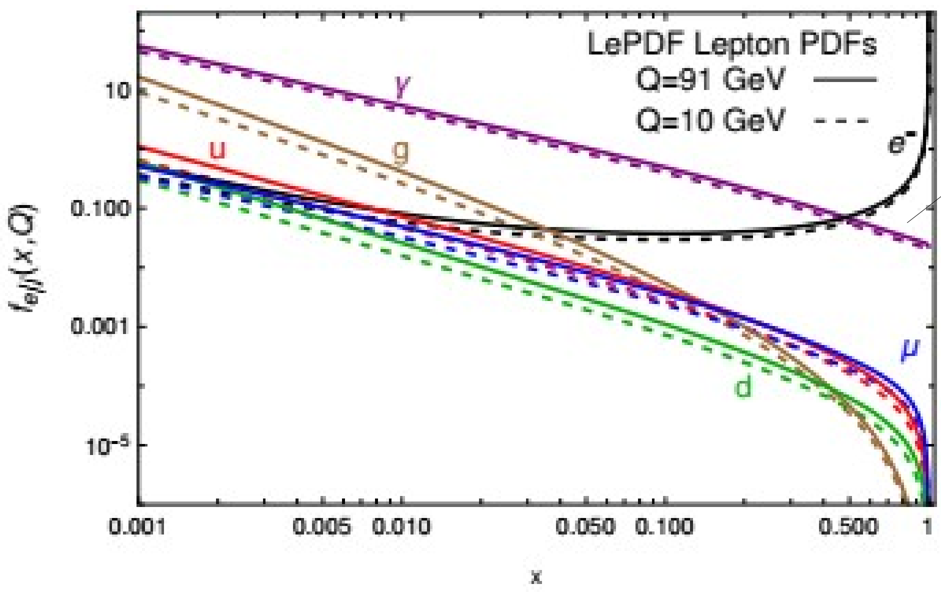
  $j \rightarrow$ colliding parton within the electron

- cut of $E - P_z$ close to $2E_e$ leads to enhancing the purely electron initiated process due to the almost Dirac delta-like behaviour of the electron PDFs of electron near $x_{e/e} \sim 1$
- kinematical distributions of the quark-initiated and photon-initiated processes predominantly peak at relatively small $x_{e^-/q}$ and $x_{e^-/\gamma}$ $\rightarrow$ significantly smaller $E - P_z$
- cut of $E - P_z$ close to $2E_e$ can seperate these two contributions

Other relevant SM processes:

- Di-jet production processes involving photon partons from the lepton beam and gluon/quark partons from the proton

- Selection cuts of $E - P_z > 52\,\mathrm{GeV}$ ⟶ Only processes with incoming photons or quarks from the electron carrying more than 26 GeV. i.e., $x_{e/\gamma}, x_{e/q} > 0.945$ contribute.



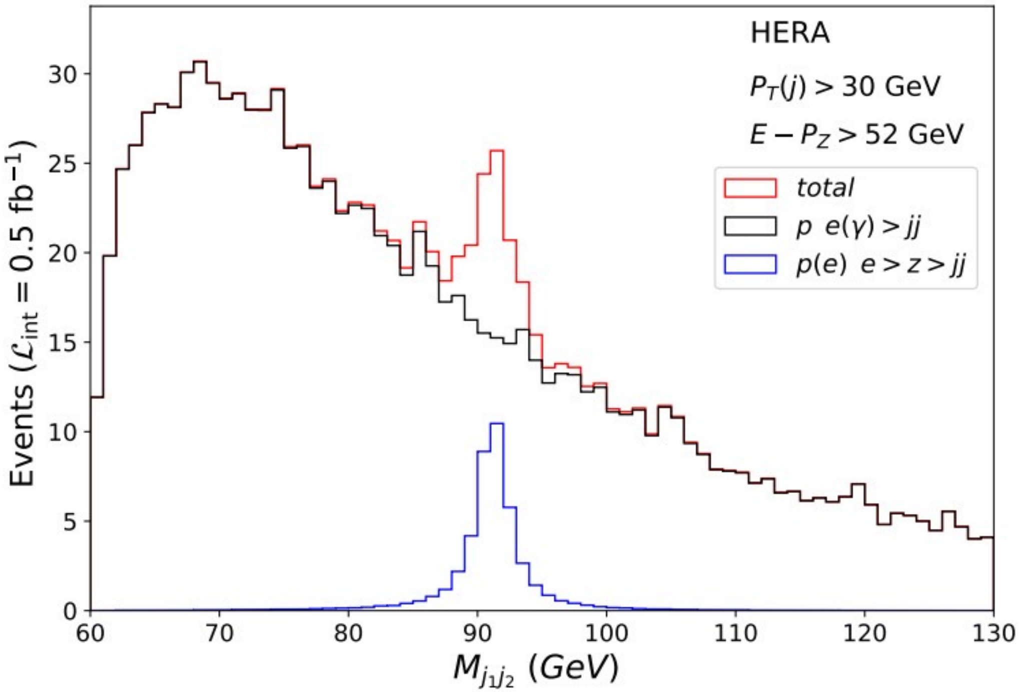
- Photon PDFs of the electron is not too small, even at relatively large x-values.
- Photon from electron involving processes dominate.

- A di-jet background with no lepton can arise from processes such as $pe^- \to je^-$,j j e^- and $je^-\gamma$ where the final state electron is misidentified as a jet.

  ⟶ Negligible number of events in the signal region considering 10^{-3} fake rate

- Other production processes are also suppressed.

$M_{j_1 j_2}$ distribution



- Perform a cut-based analysis

  selection cuts:
  - $E - P_Z > 52\,\text{GeV}$
  - $P_T(j) > 30\,\text{GeV}$
  - $|\eta(j)| < 2$
  - 5 GeV selection window of $M_{j_1 j_2}$ and $E_{j_1 j_2}$ around 91 GeV and 103 GeV, respectively

Applying the selection cuts

- Obtain 73 signal events and 267 background events considering the combined integrated luminosity of $0.98\ \text{fb}^{-1}$ of H1 and ZEUS detectors
- Signal significance of around 4.5σ at HERA
- Since our calculations are at LO in QCD and QED, and no showering, hadronization, or detector effects are included, it's better to extract the di-jet background from data by extrapolating from sidebands ---- similar to the approach used for the di-photon background in the Higgs discovery at the LHC.
- Similar analysis can be done in EIC. We obtain 4.3 σ signal significance there for the same process.
- Due to the larger luminosity at the EIC, leptonic decay modes (particularly involving muons) of the Z boson can be studied.

NLO corrections

There are virtual corrections at one-loop level and real corrections from radiation to the processes that we discuss.

For resonant Z production,

- NLO QED corrections can be obtained via the photon initiated processes:

$\gamma e^- \to Z e^-$ $\quad \hat{\sigma}_{\gamma e^-} \sim \alpha^2/m_Z^2 \sim \alpha_s^4/m_Z^2$ After convolution with the PDFs $\quad \sigma \sim \alpha_s^5 C_\ell/m_Z^2$

- Corrections from processes with virtual particles in a loop, as well as those with a final photon

$$e^+e^- \to Z\gamma \qquad \sigma \sim \alpha_s^6 C_\ell/m_Z^2$$

- NLO QCD corrections in $Z + j$ production

$gq \to Zq$ and $q\bar{q} \to Zg$ (initial quark or gluon coming from the colliding lepton) $\quad \sigma \sim \alpha_s^5/m_Z^2$

- The lepton-initiated resonant process has $x_{e^-/e^-} \simeq 1$, while the NLO QCD correction processes peak at low $x_{e^-/q,g}$
- A cut on $E - P_Z$ can reject these corrections.
- Finally, processes with a final photon:

$q\bar{q} \to Z\gamma$ are suppressed by α_s^2 compared with the resonant production.

Another possibility:

- Study of non-resonant di-leptonic final state

- Signal is dominated by photon mediated t/u and s-channel processes involving the lepton PDFs of the proton

- Concentrate on the $ee,\ e\mu$ and $\mu\mu$ final states. (interesting: same sign different flavor)

  - $E - P_Z$ of processes involing electron PDFs of electron beam peaks at $2E_e \sim 55$ GeV at HERA

$$\rightarrow e^- e^+,\ e^- e^-\ e^- \mu^\pm$$

$e^- \mu^\pm$: exclusively involves muon PDFs of proton

$e^- e^+$, $e^- e^-$: involves positron, electron PDFs of proton

- $e^- e^+,\ \mu^+ \mu^-$ final states can produce via the so-called photoproduction processes Involing photon PDFs of proton and electron.

  $E - P_Z$ would peak relatively smaller value

- One can compare with this with the existing data of HERA

Comparison with data

https://arxiv.org/pdf/0907.3627

Multi-Leptons at HERA ($0.94\ \mathrm{fb}^{-1}$)

Sample	Data	SM	Pair Production (GRAPE)	NC DIS + QEDC
ee	873	895 ± 57	724 ± 41	171 ± 28
$\mu\mu$	298	320 ± 36	320 ± 36	< 0.5
$e\mu$	173	167 ± 10	152 ± 9	15 ± 3
eee	116	119 ± 7	117 ± 6	< 4
$e\mu\mu$	140	147 ± 15	147 ± 15	< 0.5
$(\gamma\gamma)_e$	284	293 ± 18	289 ± 18	4 ± 1
$(\gamma\gamma)_\mu$	235	247 ± 26	247 ± 26	< 0.5

- Multi-Leptons HERA analysis

Selection cuts:

- at least two central leptons (electrons or muons) $(20^\circ < \theta < 150^\circ)$
- Leading lepton $P_T^\ell > 10\,\mathrm{GeV}$, other leptons $P_T^\ell > 5\,\mathrm{GeV}$
- Isolated leptons $\Delta R > 0.5$
- $E - P_Z < 45\,\mathrm{GeV}$ cut to isolate the di-leptonic $(e^+e^-, \mu^+\mu^-)$ events from photo-production regime.

Our results:

final state	ℓ-init	γ-init	γ-init$_{E-P_z>45\mathrm{GeV}}$
e^+e^-	216^{+34}_{-41}	560^{+54}_{-55}	70^{+7}_{-8}
e^-e^-	346^{+65}_{-64}	–	–
$\mu^+\mu^-$	12^{+2}_{-2}	430^{+41}_{-43}	54^{+5}_{-6}
$e^-\mu^-$	174^{+39}_{-32}	–	–

- The detector efficiencies for e and μ in the central region: e – 80% (HI) and 90% (ZEUS), μ – 90% (HI) and 55% (ZEUS).

- $0.005 \lesssim x_{p/e,\mu} \lesssim 0.03$ region contributes under these cuts

- Check cross-section uncertainties by varying the renormalization scale by a factor of 2 up and down.

  Obtain large uncertainty which reflects that our results are only accurate at LO.

Comparison with data

- We estimate more di-leptonic events than observed at HERA.
- Agreement in a few percent is found for ee and μμ events for $E - Pz > 45$ GeV region where lepton-initiated processes mostly dominates
- Our results show 632^{+105}_{-113} (ee) and 66^{+7}_{-8} $(\mu\mu)$ events vs. 418 (ee) and 63 $(\mu\mu)$ reported.
- Agreement is worse in the $e\mu$ channel, with 348^{+79}_{-64} events estimated vs. 173 observed.
- Overestimates are seen in photon-initiated di-lepton pair-production (The rate of this processes involves the photon PDFs of the electron and the proton.) with $E - P_z < 45$ GeV: 490^{+47}_{-47} (ee) and 376^{+36}_{-36} $(\mu\mu)$ events estimated vs. 284 (ee) and 235 $(\mu\mu)$ observed.

These discrepancies could originate from various factors:

- higher order corrections
- showering, hadronization → estimated numbers may drop to lower values
- proper detector simulation

- Alternatively, this may suggest an overestimation of lepton and photon PDFs in the proton.

Further theoretical and experimental analysis is needed to understand these discrepancies

EIC

- Like at HERA, di-leptonic final states from non-resonant processes can be studied at the EIC to test these PDFs.

- Lepton-initiated proceses:

$$E - P_Z \sim 2E_e \sim 40\,\text{GeV}$$

- Expected number of di-lepton events at EIC at the LO, considering the selection cuts of $P_T^\ell > 10$ GeV and $|\eta_\ell| < 2.0$ and setting the renormalization scale as P_T of the lepton. →

$$e^+e^- \to 15067$$
$$e^-e^- \to 23287$$
$$\mu^+\mu^- \to 730$$

- Additionally, same-flavor, opposite-charge di-lepton final states can arise from photo-production predominantly in the regions of $0.1 \lesssim x_{e^-/\gamma} \lesssim 1.0$ and $0.04 \lesssim x_{p/\gamma} \lesssim 0.2$, under the same phase space cuts

- 23900 e^+e^- total events at the LO under the same cuts, out of which 2780 events occur in the $E - P_Z > 35$ GeV region

  similar numbers for $\mu^+\mu^-$

- Once future data is available, a detailed study of these processes can be performed at the EIC to test the lepton PDFs of the proton

MuIC

- Proton ~ 275 GeV and Muons ~ 1 TeV   Integrated luminosity: 400 fb^{-1}
    - selection criteria: $P_T(\ell) > 5\,\mathrm{GeV},\ |\eta_\ell| < 2.5$

- $P\mu^- \to \mu^+\mu^-$ ~ 150 events

  $\to \mu^-\mu^-$ ~ 600 events

  $\to \mu^- e^\pm$ ~ 720 events

  $\to e^+e^-$ ~ 30 events

  All these events, $E - P_z$ peaks at $2\,\mathrm{TeV}$

- Furthermore,
  opposite-sign same-flavor di-lepton final states can be produced through photoproduction, involving the photon PDFs of the proton and muon, with $E - P_z$ peaking at relatively low values.

Consider rare SM signatures at hadron colliders like LHC

Non-resonant production of back-to-back same sign and/or different favour di-leptons

arXiv:2005.06477

Buonocore, et al.

- At the LO $p_{T,\ell} > 20\,\mathrm{GeV}, \quad |\eta| < 2.4, \quad \mu_F = p_{T,\ell}$

	$e^+\mu^-$	$e^+\tau^-$	$\mu^+\tau^-$	e^+e^+	$\mu^+\mu^+$	$\tau^+\tau^+$
$\sigma_{13\mathrm{TeV}}$ [fb]	$0.29^{+0.13}_{-0.10}$	$0.18^{+0.11}_{-0.08}$	$0.16^{+0.10}_{-0.07}$	$0.24^{+0.10}_{-0.08}$	$0.19^{+0.09}_{-0.07}$	$0.08^{+0.06}_{-0.04}$
$\sigma_{27\mathrm{TeV}}$ [fb]	$0.53^{+0.25}_{-0.18}$	$0.34^{+0.21}_{-0.15}$	$0.30^{+0.19}_{-0.14}$	$0.440^{+0.19}_{-0.14}$	$0.34^{+0.16}_{-0.12}$	$0.14^{+0.12}_{-0.07}$

- Number of events of such processes are estimated using the lepton PDFs of the proton

  Measurable number of events are expected at HL-LHC

- For example, at $3\mathrm{ab}^{-1}$ of data, $850\, e^+\mu^-$, $550 e^+\tau^-$ and $500\mu^+\tau^-$ events are expects at HL-LHC, considering these phase space cuts

- Analysis on this at HL-LHC can also verify the distributions of these leptonic PDFs of proton

- This could be even crucial for studying BSM scenarios, like flavor-violating scalars, as precise knowledge of the SM background is required.

Conclusions

- PDFs are key to hadron collider phenomenology, describing the momentum distribution of proton constituents.

- The lepton PDFs of the proton have been recently computed (LuxLep).

- This is crucial for LHC searches in BSM scenarios, including hadrophobic and leptophilic $Z^{'}$, doubly charged scalars, leptoquarks, flavor-violating leptophilic scalars, etc.

- We propose to validate the lepton content of the proton by analyzing both non-resonant di-lepton production and di-jets from resonantly produced Z boson,
  Using existing HERA data and future measurements from other lepton-proton colliders

  - For Z-resonant production, we propose conducting this study at pe colliders rather than at a hadron collider like the LHC.

  - Focus to di-jet decay modes of Z, due to large branching fractions

  - Feasible to study the leptonic decay modes of the Z boson, particularly in the di-muon final state, at the EIC

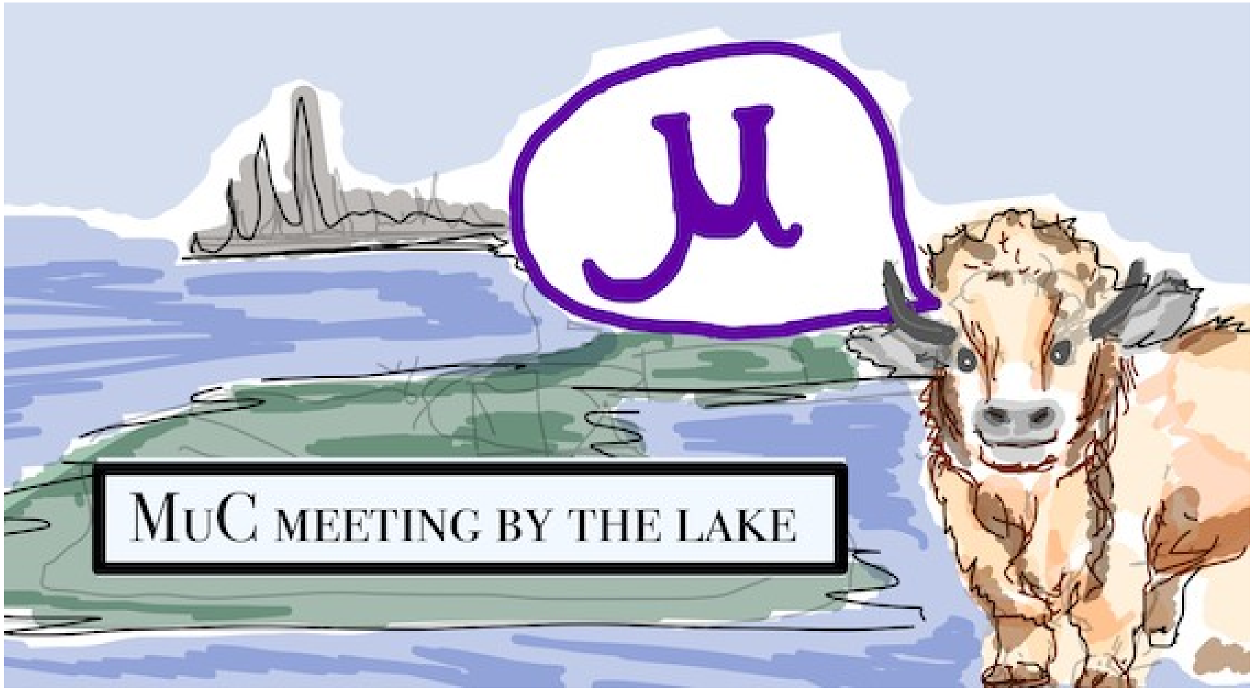
  - For non-resonant di-lepton final states, consider all flavor combinations and charge pairings.

  - These can explore a smaller $x_{p/e,\mu}$ region of the proton lepton PDFs compared to resonant Z-boson production.

  - Comparison with HERA data indicates a slight overestimation of di-lepton production rates bya few tens of percent.

  - A dedicated theoretical and experimental study could clarify these discrepancies.


THANK YOU!


μ
MuC meeting by the lake

Extra

NLO corrections in non-resonant dilepton processes

- For the non-resonant di-lepton production there are real corrections from photon emission of initial and final particles, with the same initial state as the leading processes, that are suppressed by α_s^2 compared with them.

- Di-lepton plus jet final states can be obtained from $\gamma q \longrightarrow \ell\ell q$, being suppressed by α_s only, compared with the leading processes.

- When considering the quark and gluon content of the electron one can also obtain di-lepton plus jet final states which are suppressed by α_s

- The kinematic distributions of processes initiated by partons of the electron, other than the electron itself, are peaked towards low values of $E - P_z$, thus the rates of these processes can be controlled by cuts on this variable.

- Virtual QED corrections are expected to be suppressed by α_s^2 compared with the real ones.

- A dedicated analysis containing these corrections, as well as parton showering, is needed for a precise calculation.