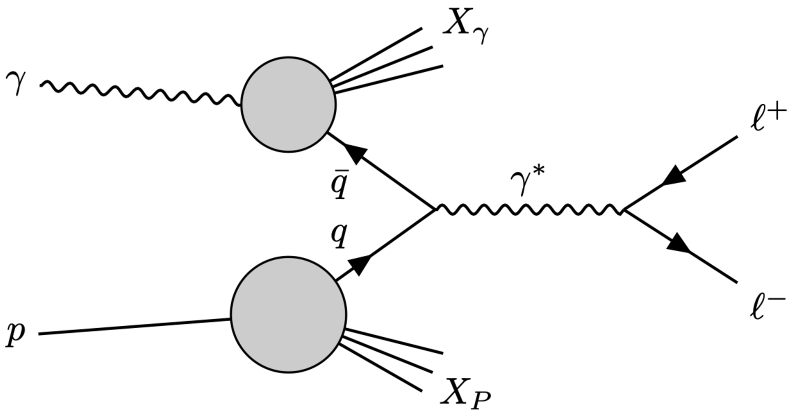
DRELL-YAN AT THE ELECTRON-ION COLLIDER



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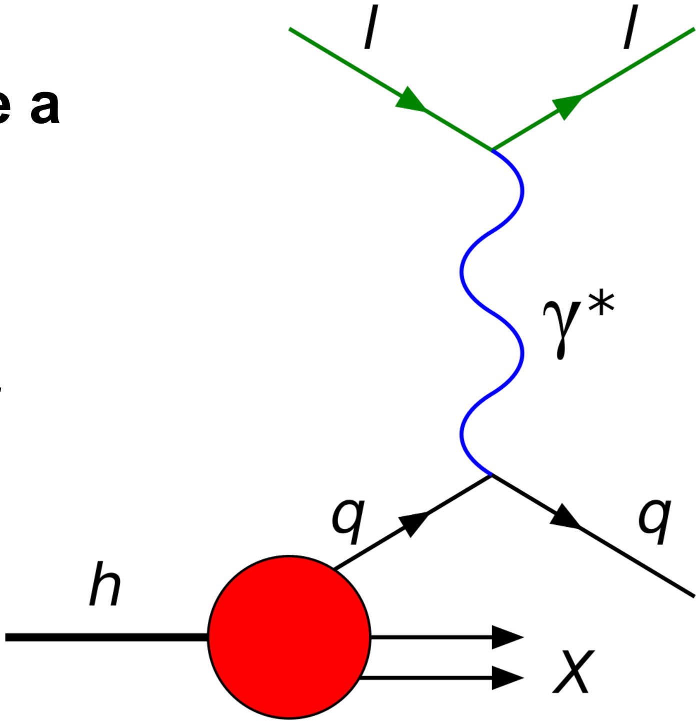
EICUG ECR Meeting
July 11, 2026

PARTON DISTRIBUTION FUNCTIONS

- When we scatter "deeply" on a hadron, **how likely are we to strike a parton with a given momentum?**

- How many quarks of flavor *i* carry longitudinal momentum fraction *x* of the hadron?
  - —What about the *transverse* momentum?

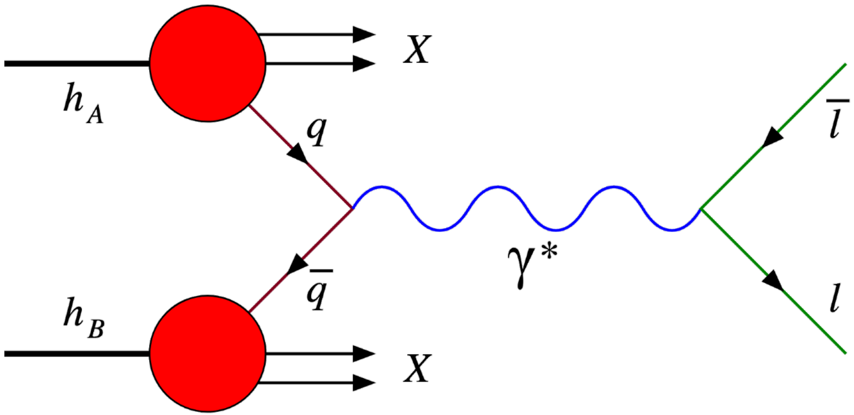


DRELL-YAN PROCESS

- Production of a **pair of leptons** in hadron+hadron scattering

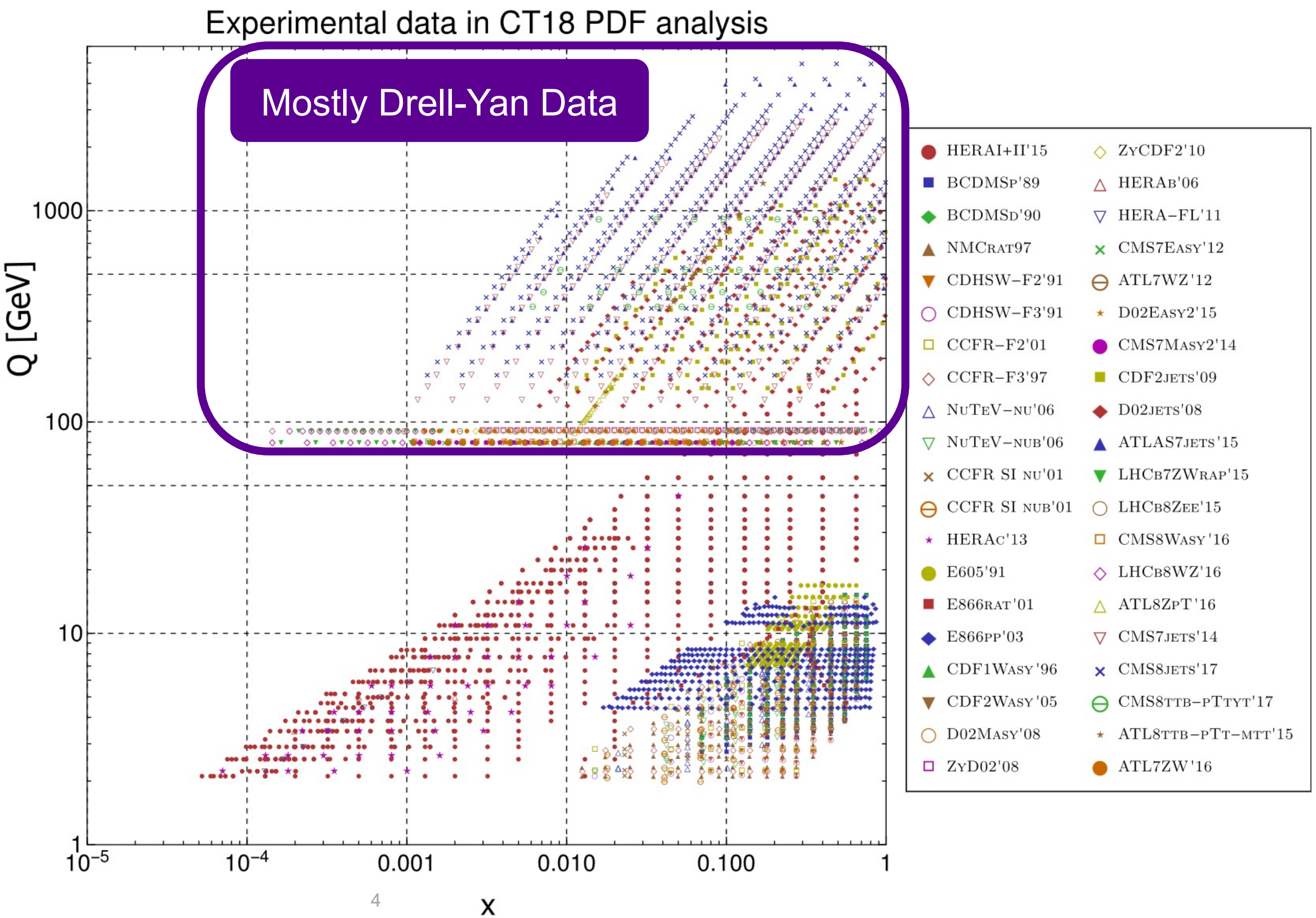
- At leading order arises from **annihilation of q and $\bar{q}$**

- $\ell^+\ell^-$ mass and angle constrain the **two** values of quark momenta
  - Hard scale **Q²** (virtuality of *produced* γ^*) from the $\ell^+\ell^-$ invariant mass



DRELL-YAN PROCESS - PDFS

- Drell-Yan is a powerful tool for understanding **parton distribution functions!**
- Many hadron colliders with many datapoints at very high energies
- But! Some ambiguity from colliding two **a priori unknown** distributions together

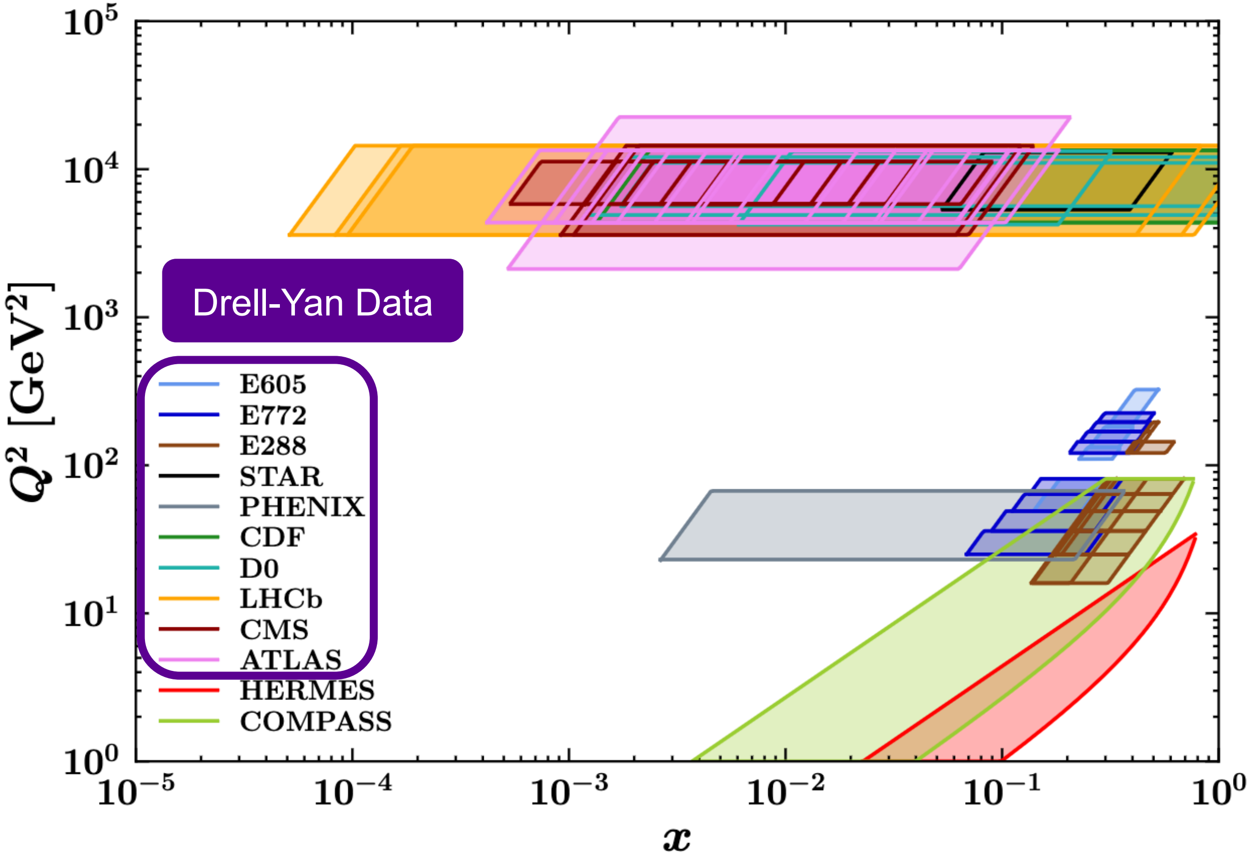


DRELL-YAN PROCESS - TMDPDFS

- Transverse momentum of the lepton pair tells you about the **transverse momentum of the quarks** in the proton!

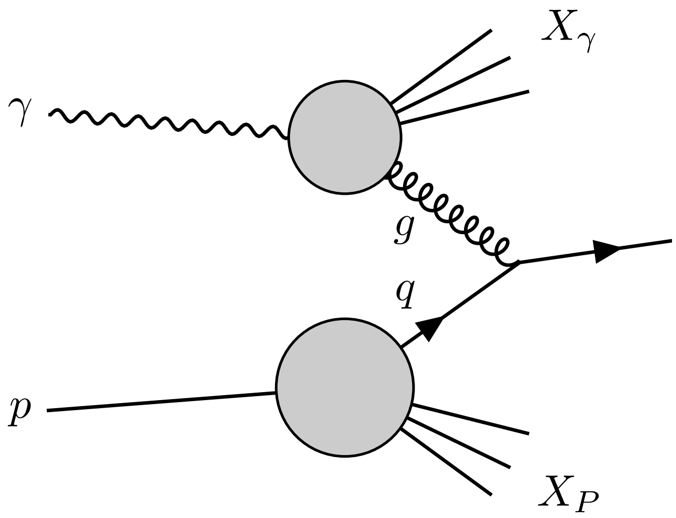
- Most of the data in existing fits of the TMDPDFs is Drell-Yan
  - EIC will contribute very precise semi-inclusive DIS data

- But can the EIC also provide Drell-Yan???



PHOTOPRODUCTION

- Electron beams can be used as a source of:
  - **Real photons (Q = 0),**
  - **Quasi-real photons (Q ~ 0),**
  - **Virtual photons (Q > 0)**



- Generally, we call it **“photoproduction”** if the photon is **real** or **quasi-real**
  - In contrast to “electroproduction”, which is used when the electron scattering angle is not negligible

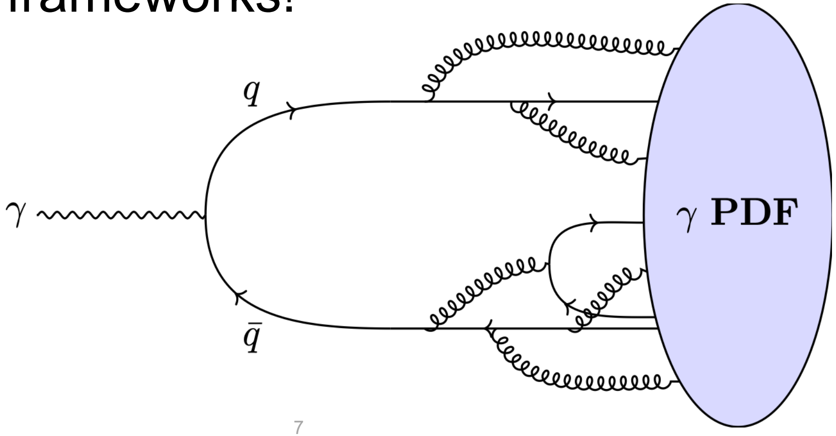
PHOTON STRUCTURE?

- Photon is the **only gauge boson we have easy access to in the lab**

- **At high energy, the photon can act as a source of partons!**
  - From this, one defines the **Photon PDF***

- **Simplest possible PDF**, partially perturbatively calculable → can be useful to test PDF/TMD frameworks!

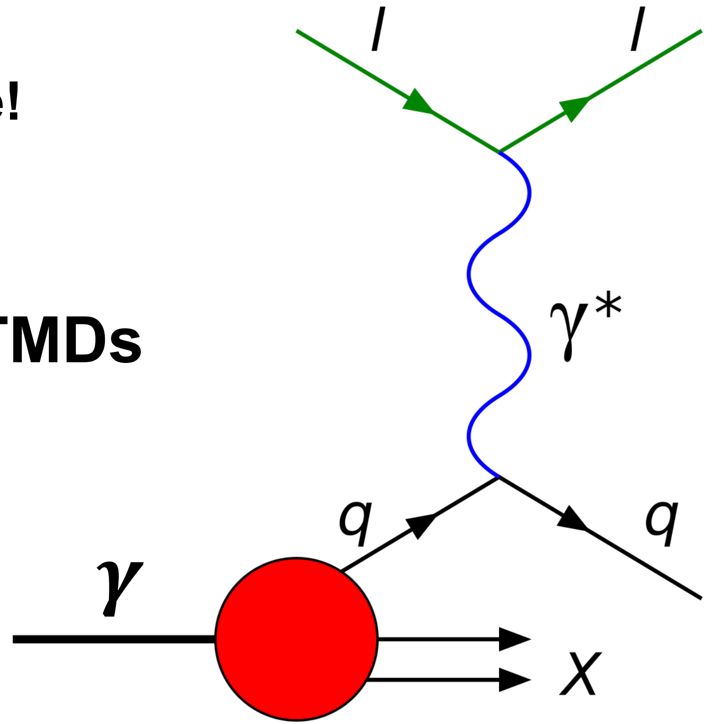
*Not to be confused with the PDF for photons inside of protons (which is also called the photon PDF…)



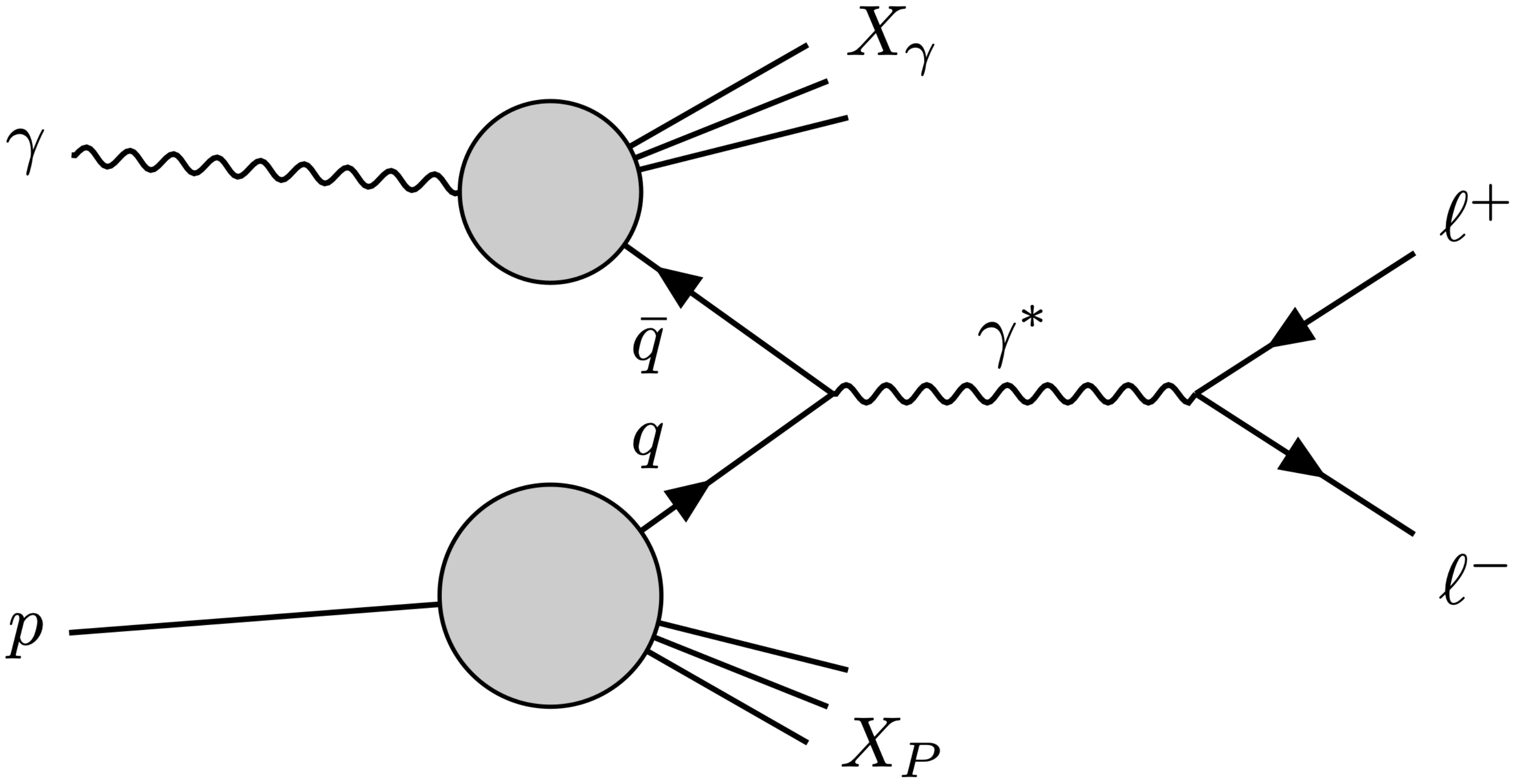
PHOTON STRUCTURE- STATE OF THE ART

- Photon PDF fits mostly to LEP data, via "DIS on the photon" process
  - **Photon PDF uncertainties are huge!**

- No constraints at all on **photon TMDs**



PHOTOPRODUCTION DRELL-YAN



DRELL-YAN PROCESS

- Can reconstruct the Bjorken x of the $q/\bar{q}$ (at leading order) via:

$$x_\gamma \simeq \frac{M_{\ell\ell}}{\sqrt{s_{\gamma p}}} e^{+y_{\ell\ell}}, \qquad x_p \simeq \frac{M_{\ell\ell}}{\sqrt{s_{\gamma p}}} e^{-y_{\ell\ell}}$$

  — $M_{\ell\ell}$ is the invariant mass of the lepton pair,
  — The lepton pair rapidity $y_{\ell\ell}$ is defined in the photon+proton center-of-mass frame

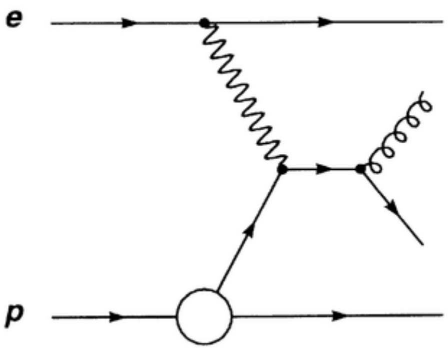
- So, all we need to reconstruct the Bjorken x of the parton in the photon:
  — Invariant mass of the lepton pair **(Easy)**
  — Rapidity of the lepton pair in the γ+p center-of-mass frame **(Not so easy)**
  — Center-of-mass energy of the γ+p collision **(Not so easy)**

ASIDE: RESOLVED OR DIRECT?

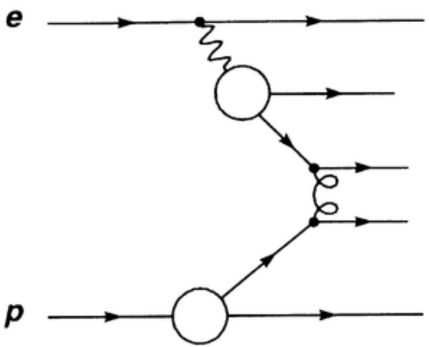
- "Resolved" photoproduction corresponds to the case where $x_\gamma < 1$
  - **Drell-Yan is always resolved!**

$$x_\gamma \simeq \frac{M_{\ell\ell}}{\sqrt{s_{\gamma p}}} e^{+y_{\ell\ell}}$$

- "Direct" photoproduction has $x_\gamma = 1$



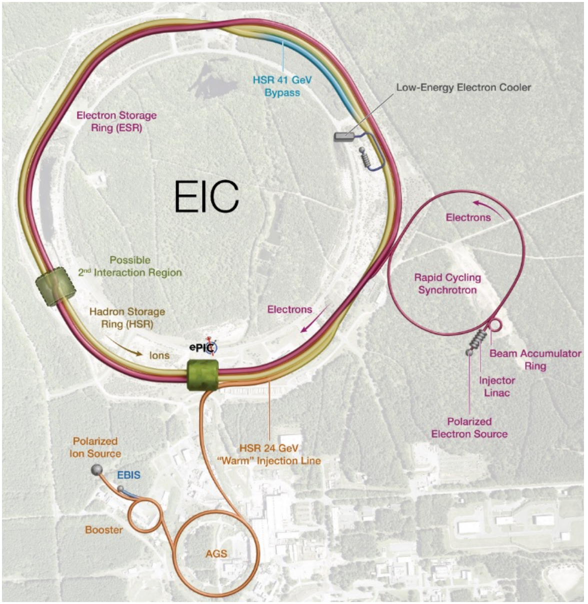
Direct photoproduction



Resolved photoproduction

DRELL-YAN AT THE EIC

- EIC is the **ideal machine** for photoproduction Drell-Yan
  - —**High luminosity** for a small cross section
  - —Detector acceptance **$|\eta| \leq 3.5$** with **excellent lepton identification**
  - —**Low-Q^2 tagger** provides direct measurement of γp center-of-mass energy
  - —**Highly polarized** proton beam
    - Enables target-spin asymmetry measurements!



PHOTOPRODUCTION IN SHERPA

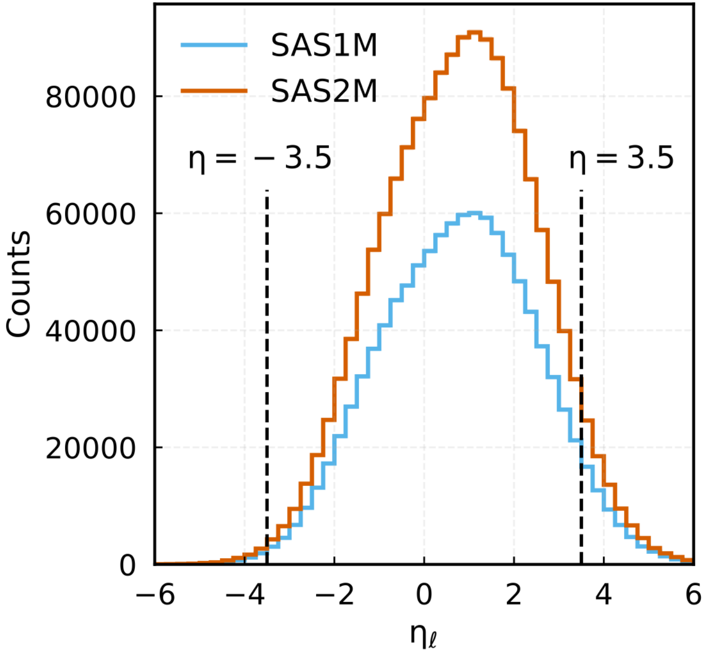
- Authors of **SHERPA** event generator recently extended added photoproduction!
  - Essentially the **only modern general-purpose event generator that handles photoproduction**
  - Can rigorously calculate γp DY cross section in pQCD & generate full events

Resolved photons in SHERPA

Stefan Höche[1,a], **Frank Krauss**[2,b], **Peter Meinzinger**[2,c]

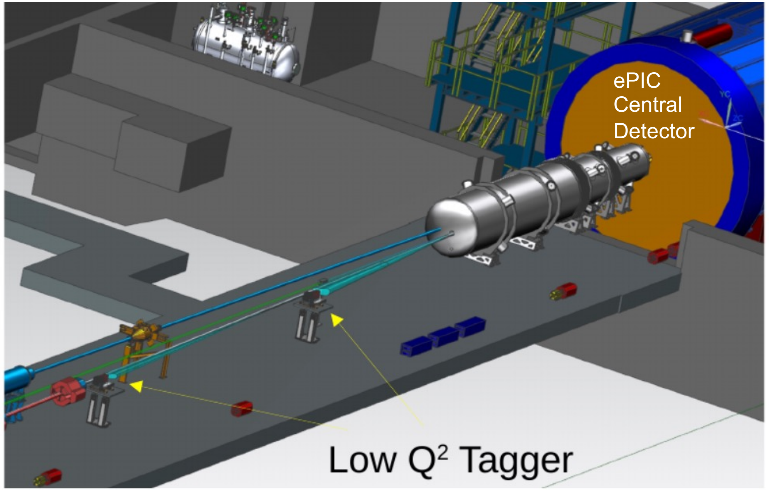
[1] Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[2] Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LE, UK

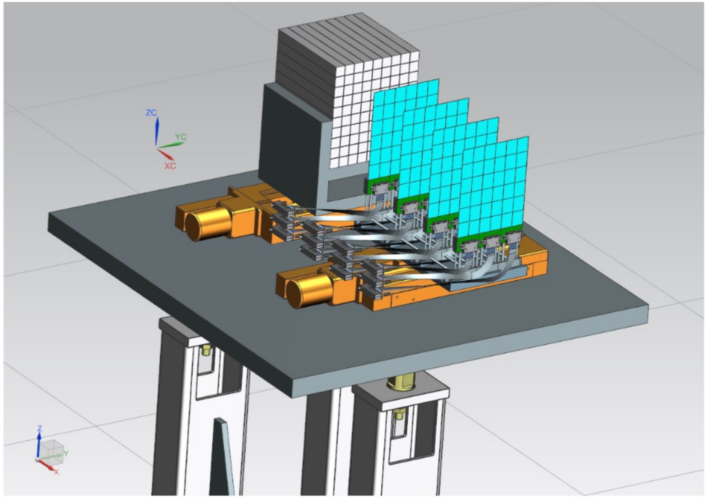
- **Photon PDFs compared**
  - SAS1M photon PDF: **5.4 pb**
  - SAS2M photon PDF: **8.1 pb**
  - **50% difference in DY cross section!**



- γp Drell-Yan cross section is **highly sensitive to photon PDF!**

LOW Q^2 TAGGER





- Detector located in the "far-backward" (electron-going) region
- Photon energy is $1 - E_{e'}$
  - Photon kinematics are known when $E_{e'}$ is reconstructed in **Low-Q^2 tagger**

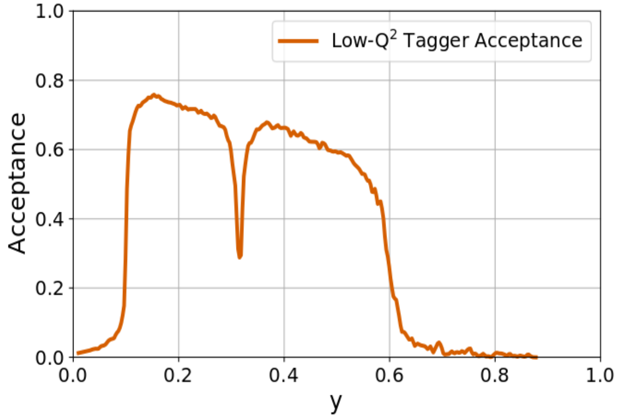
KINEMATICS

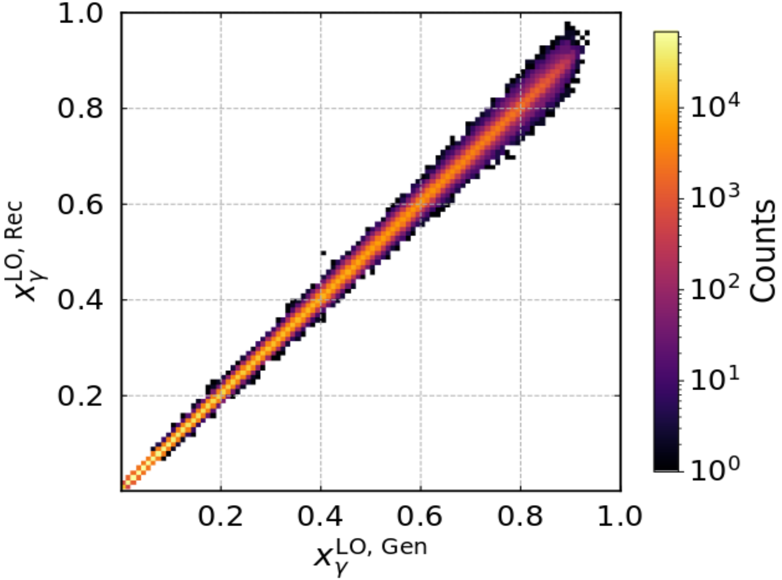
- To reconstruct Bjorken x, need to measure $s_{\gamma p}, M_{\ell\ell}$, and $y_{\ell\ell}$

$$x_\gamma \simeq \frac{M_{\ell\ell}}{\sqrt{s_{\gamma p}}} e^{-y_{\ell\ell}}, \qquad x_p \simeq \frac{M_{\ell\ell}}{\sqrt{s_{\gamma p}}} e^{+y_{\ell\ell}}$$

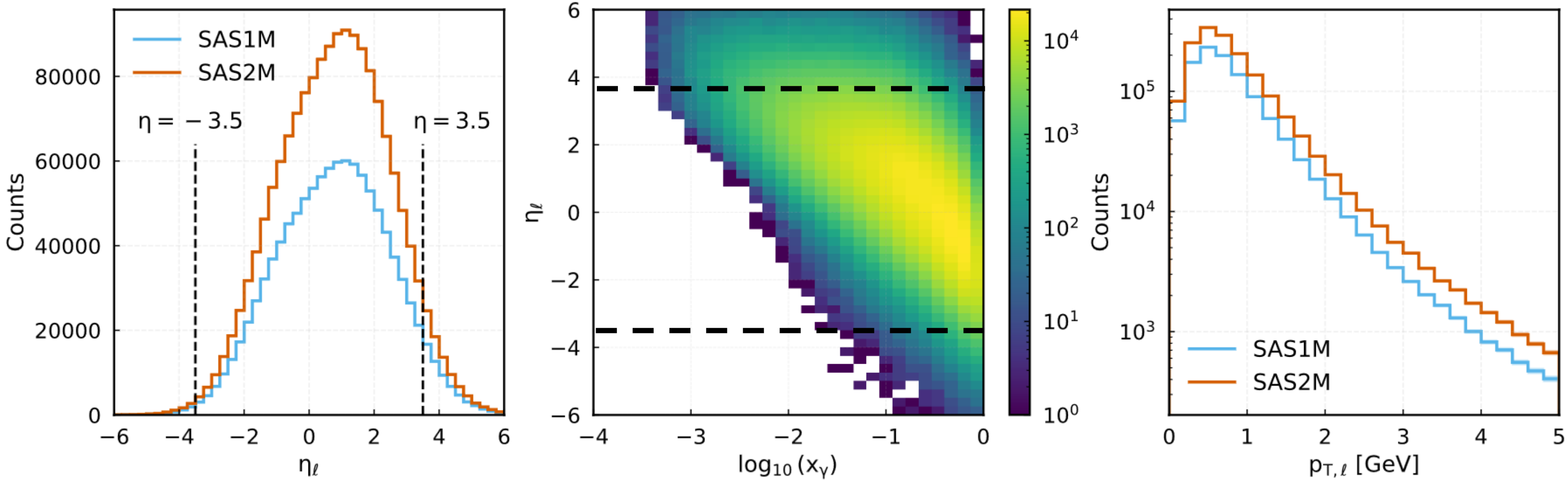
- Low Q^2 tagger gives good resolution on the photon energy, **crucial to reconstruct $s_{\gamma p}$**

- Since $M_{\ell\ell}$ and $y_{\ell\ell}$ come from tracking of only two particles, **resolution on x_γ ends up looking very good!**





LEPTON KINEMATICS

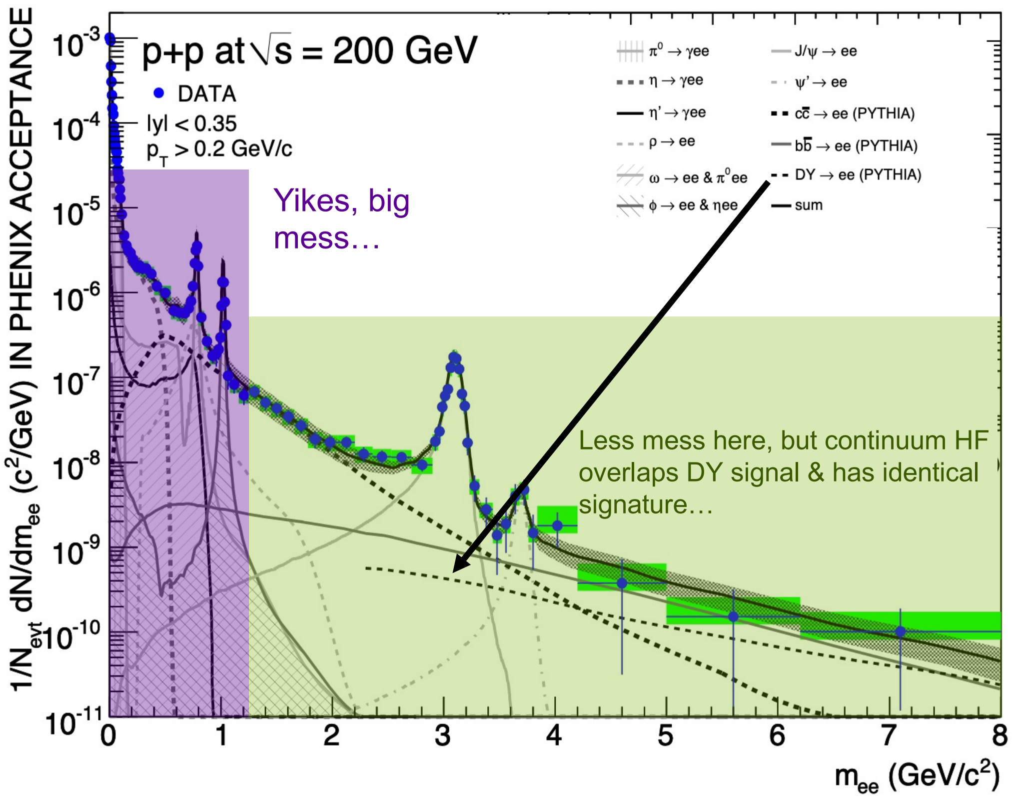


BACKGROUNDS

- Most difficult part of accessing Drell-Yan is **continuum $\ell^+\ell^-$ background**
  - Just because we see two leptons, doesn't mean it's Drell-Yan!
  - No peak to fit, backgrounds have to be suppressed the hard way

- **Biggest roadblock for an EIC measurement!**

PHENIX p+p Data



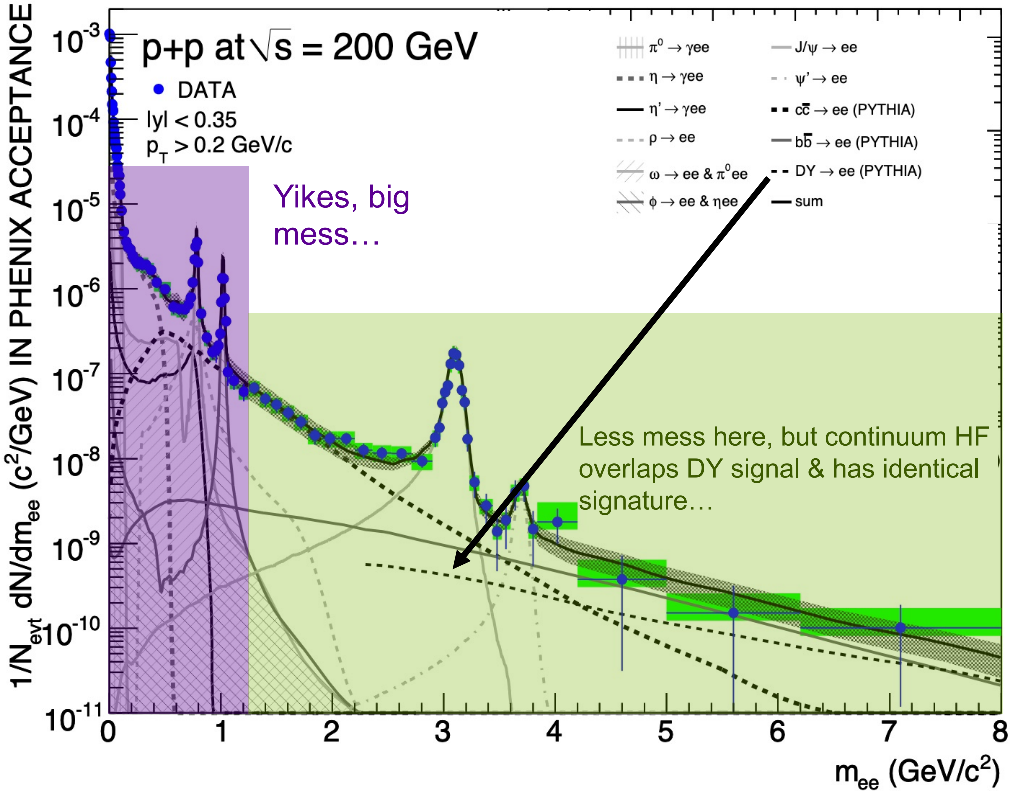
BACKGROUNDS

- Major contribution expected from **semi-leptonic decays of open heavy flavor**
  - I.e., two D-mesons produced from a $g \rightarrow c\bar{c}$, and both D mesons decay to one lepton + X

D^+ DECAY MODES	Fraction (Γ_i/Γ)
Inclusive modes	
e^+ semileptonic	(16.07 ± 0.30) %
μ^+ anything	(17.6 ± 3.2) %

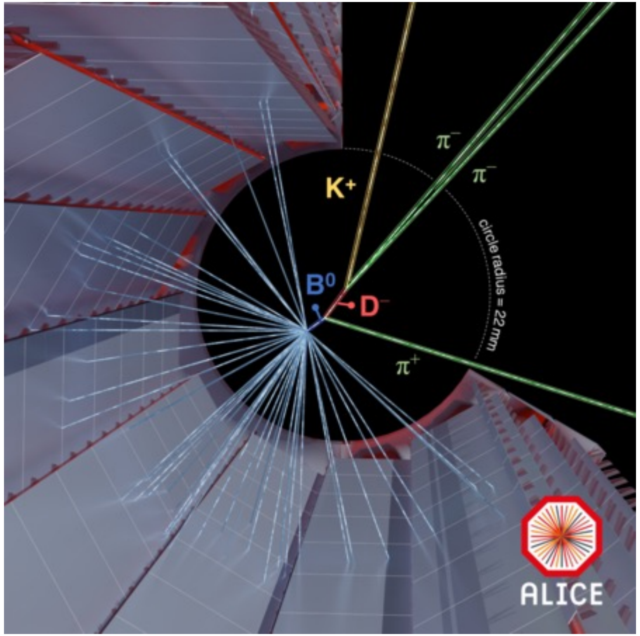
- In principle the HF background can be measured + subtracted
  - Precise vertexing will help! Demonstrated by ALICE

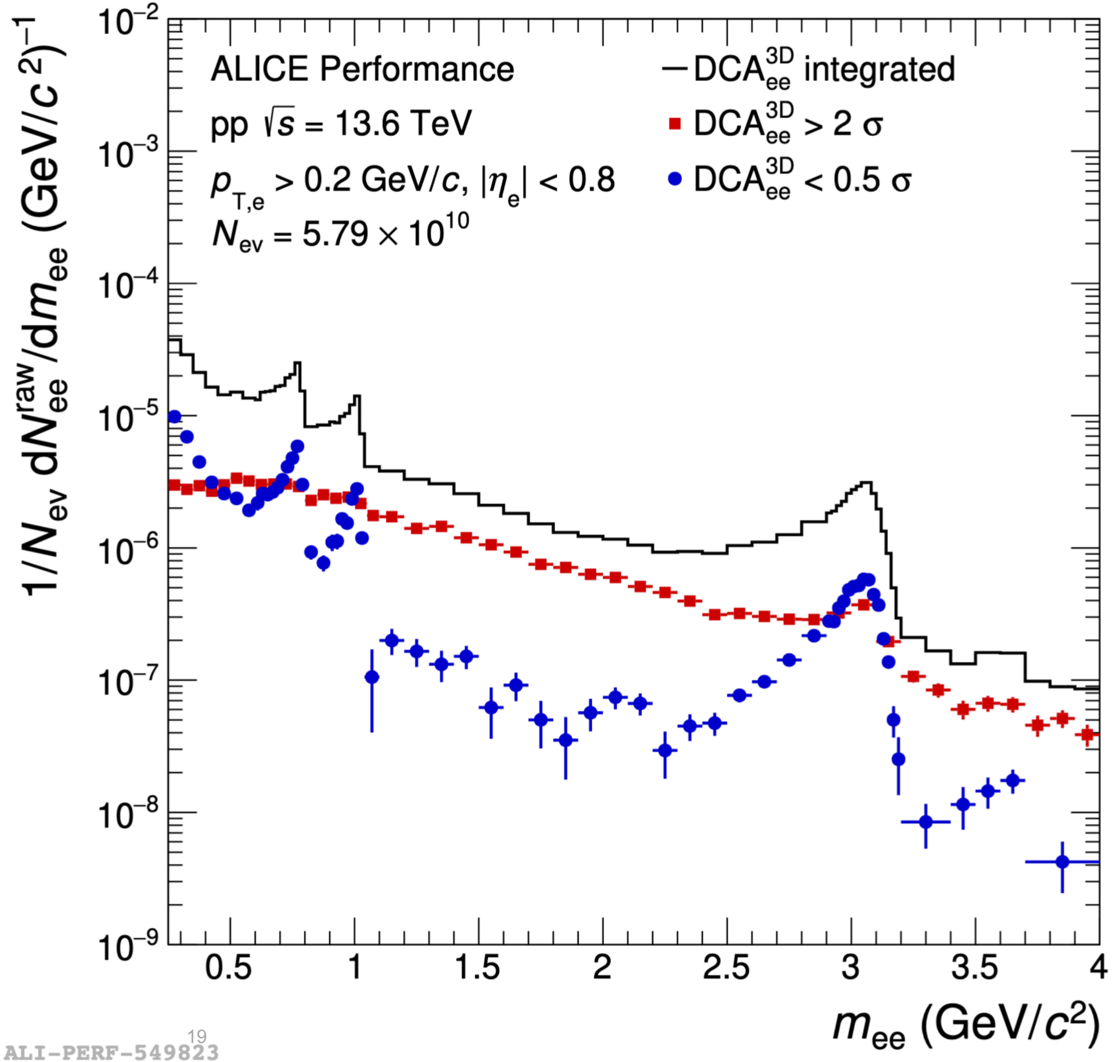
PHENIX p+p Data



BACKGROUNDS

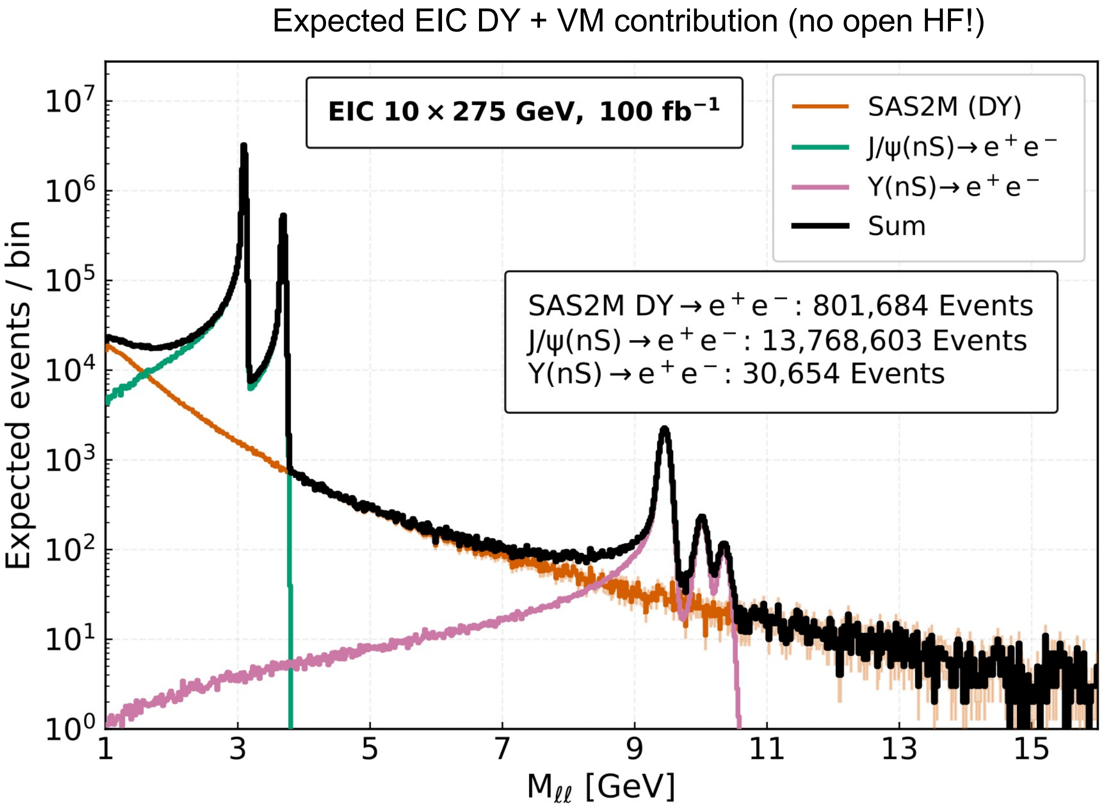
- Factor ~ 50 suppression of open heavy flavor achieved in ALICE by cutting out displaced vertices!
  - **EIC can do better!**



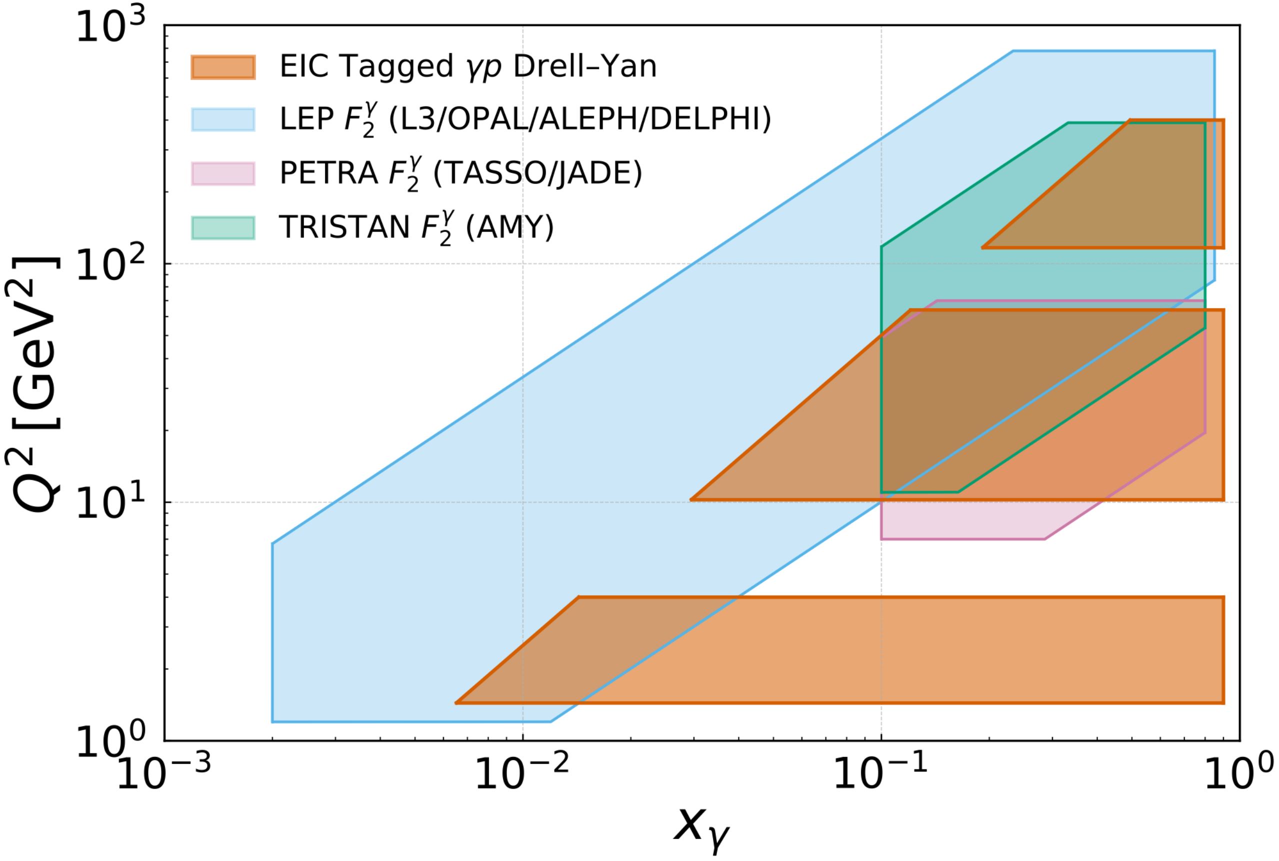


EXPECTED DRELL-YAN SPECTRUM IN EPIC

- Applied realistic ePIC detector resolutions and acceptances
- Vector mesons dominate certain regions of $M_{\ell\ell}$
  - How large this region is will depend on detector resolutions
- Large range seems dominated by Drell-Yan with ePIC resolutions



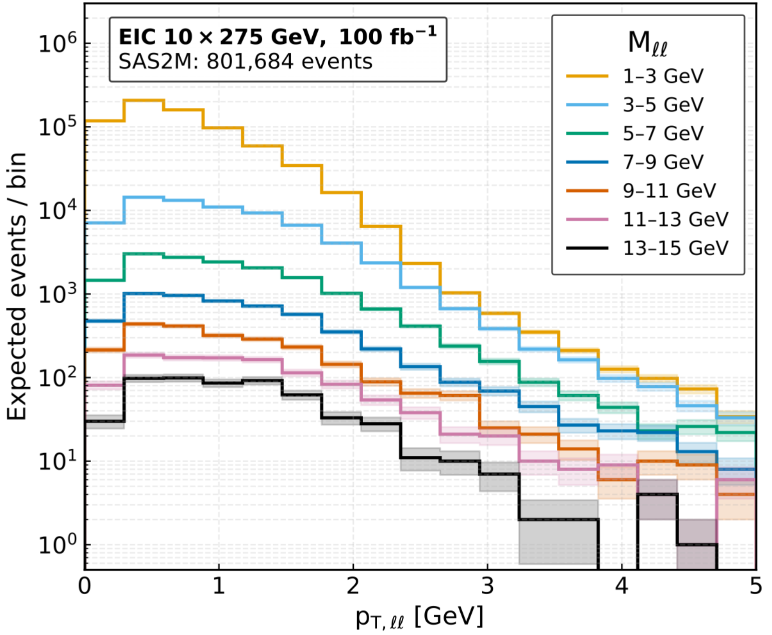
KINEMATIC REACH



PHOTON TMDS

- Once we know the proton TMDs well from EIC SIDIS data, can tease out the **Photon TMDs**
  - $p_{T\,\ell\ell}$ accesses photon ⊗ proton **TMDs**
  - Ideal for testing TMD framework!

Good statistics and resolution on $p_{T\,\ell\ell}$!



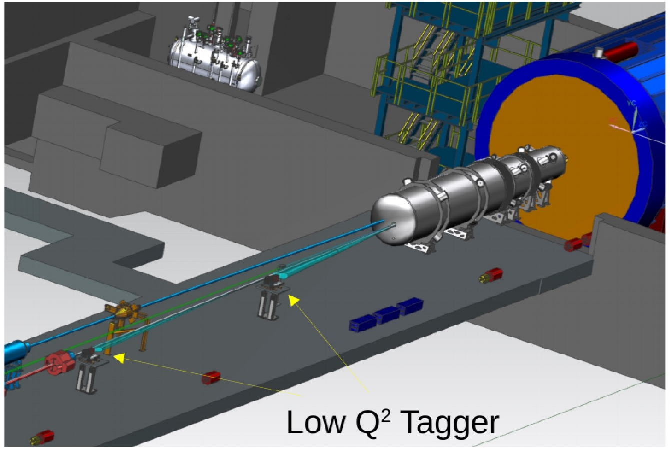
DRELL-YAN IN PHOTOPRODUCTION

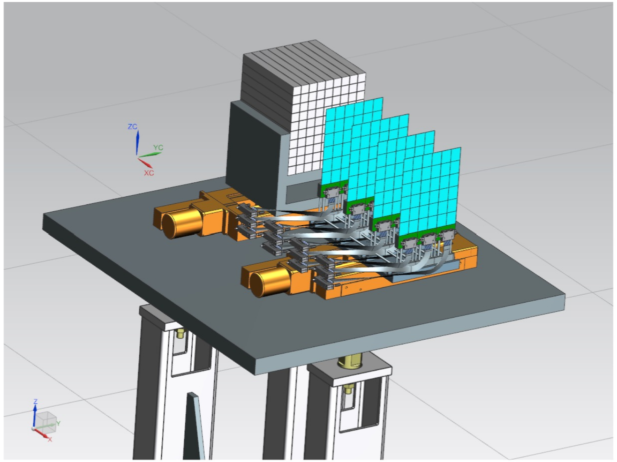
- **First-ever measurement of Drell-Yan in photoproduction** seems possible at the EIC
  - O(10^5) DY pairs in 100 fb^{-1} at 10x275 GeV;
  - Can measure multi-differential in $M_{\ell\ell}$, $y_{\ell\ell}$, $p_{T\,\ell\ell}$
  - Different photon PDFs predict factor 2 different cross sections

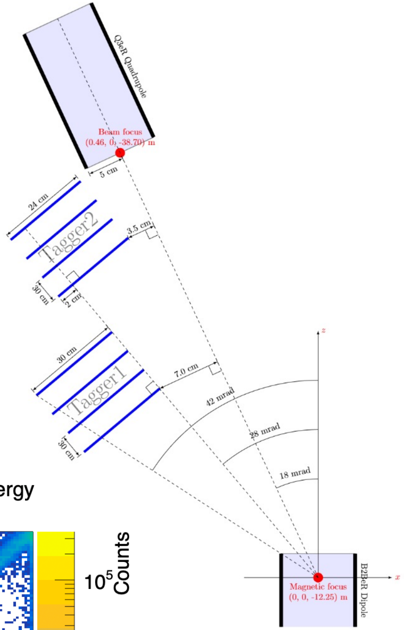
- **Drell-Yan at the EIC is a promising physics channel to elucidate the partonic structure of the photon!**

Full paper is available: ArXiv:2512.14690 & in PRD
Started out as a curiosity, ended up as a paper!
Explore your ideas!

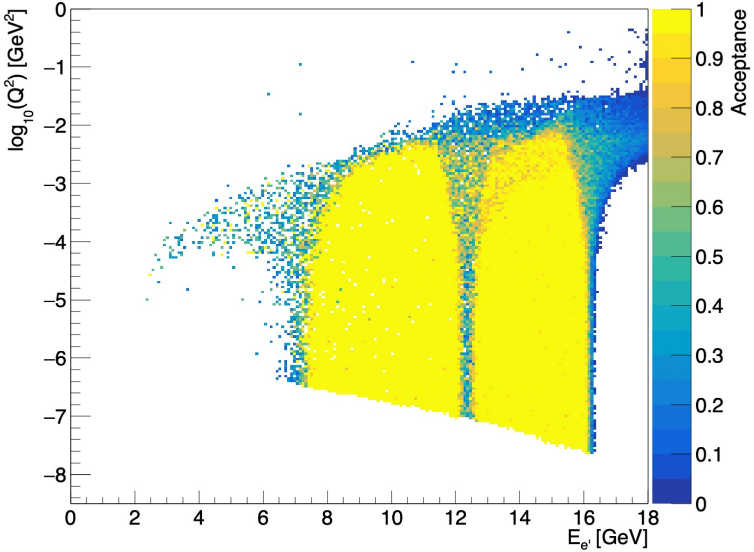
BACKUP



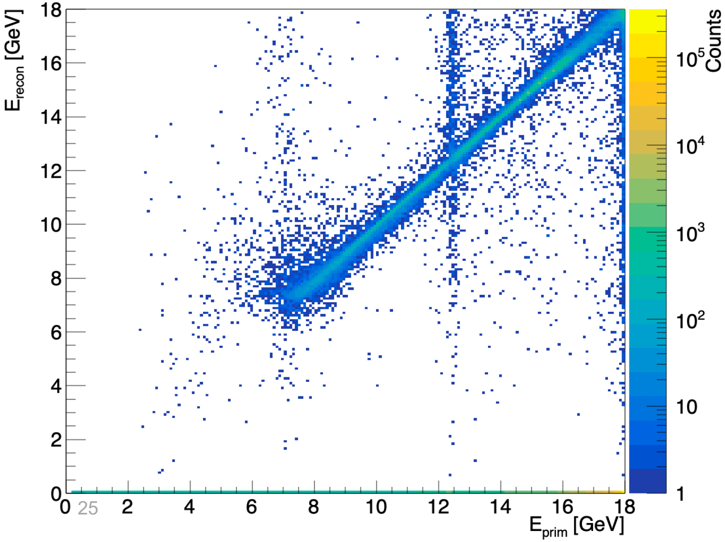




Acceptance as a function of scattered electron energy and reaction $\log_{10}(Q^2)$



Reconstructed electron energy vs. primary electron energy

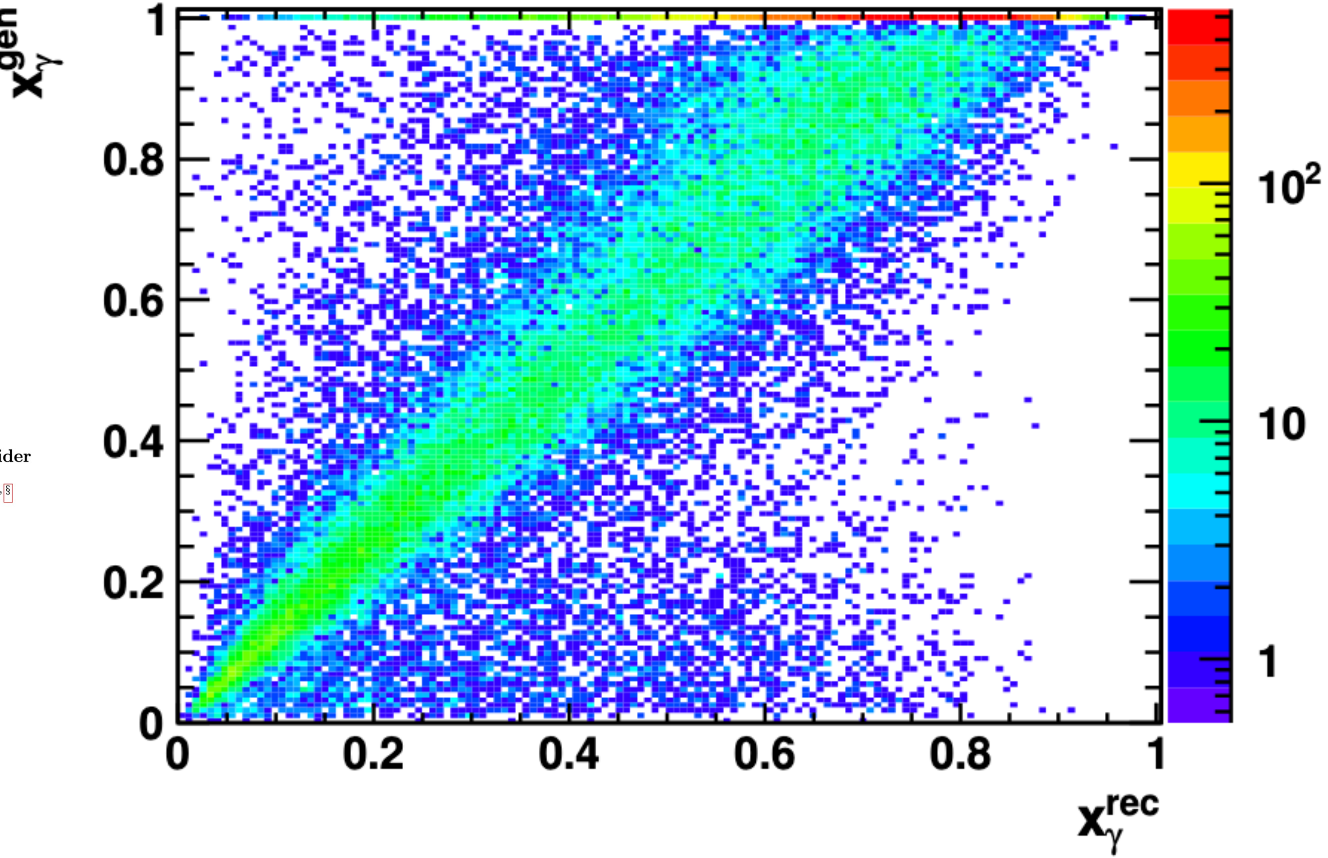


Photon structure studied at an Electron Ion Collider

X. Chu,[1,2,*] E.C. Aschenauer,[2,†] J.H. Lee,[2,‡] and L. Zheng[1,§]

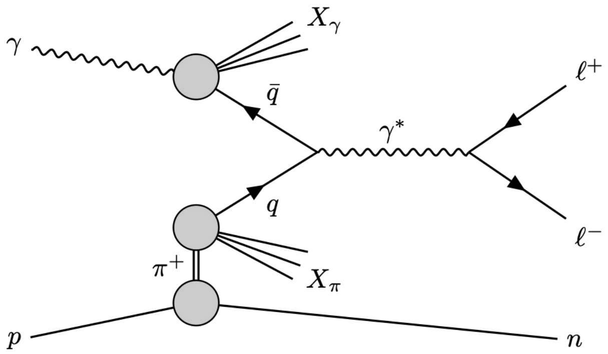
[1] *Key Laboratory of Quark and Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan 430079, China*

[2] *Physics Department, Brookhaven National Laboratory, Upton, NY 11973, U.S.A.*



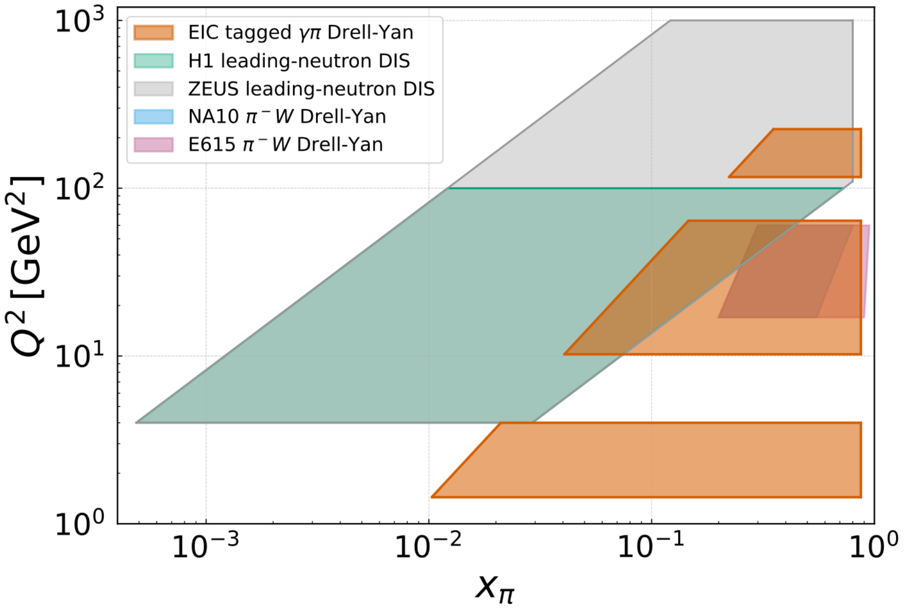
Di-jet x_γ resolution

$\gamma\pi$ DRELL-YAN



- **Leading-neutron "$\gamma\pi$" DY**
  - —Leading neutron in ZDC, $x_L \geq 0.8$
  - —~10k DY events in 100 fb^{-1}
  - — $\sigma_{x_L} \sim$ 2–3%

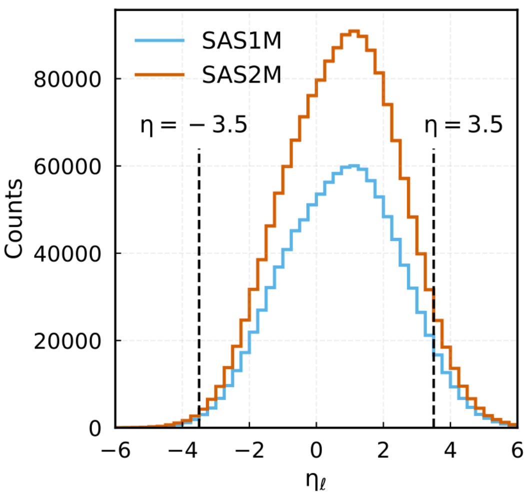
- **Kinematic reach**
  - —$\sqrt{s_{\gamma\pi}} \sim$ 7–36 GeV
  - —Overlaps NA10, E615 π-DY data
  - —First $\gamma\pi$ DY measurement!

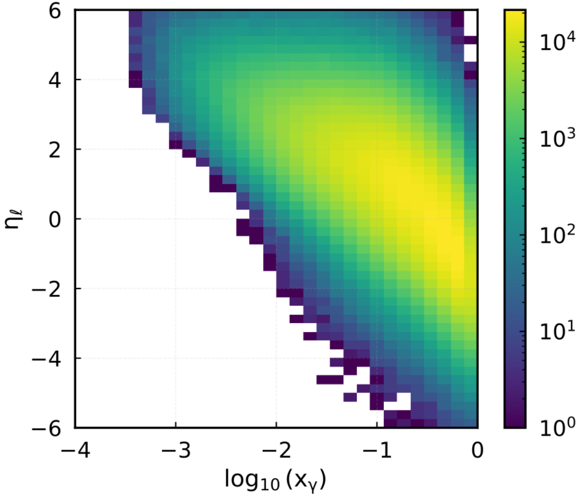


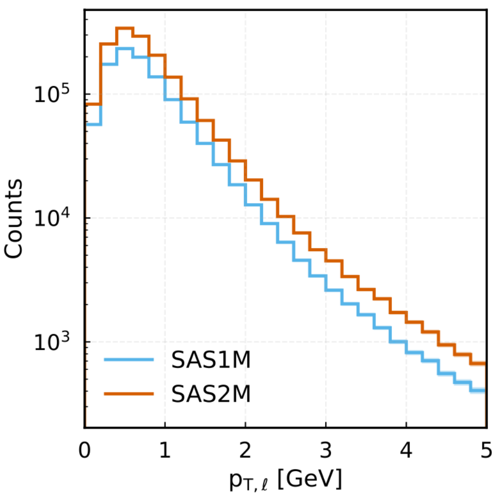
We simulate the signal process of $\gamma p \to l^+l^- + X$ for the EIC configuration of 10 GeV electrons on 275 GeV protons (henceforth denoted as 10x275) using SHERPA 3.0.1 [71] with the NLO resolved photoproduction model described in Ref. [67]. The 10x275 beam energy configuration is chosen because it offers the highest luminosity. The design luminosity for the 10x275 configuration is 100 fb^{-1} per year, around a factor of 7 higher than 18x275. In the SHERPA simulation, the initial-state photon is sourced from the electron via the Weizsäcker-Williams equivalent photon approximation. Q^2_{max} is set to 1 GeV^2 and the initial-state photons are assumed to be collinear to the electron beam. The matrix elements for the hard scattering process $q\bar{q} \to \ell^+\ell^-$ are handled by Amegic [72], Comix [73, 74], and OpenLoops [75]. The direct photoproduction contribution to dilepton production is not included. The parton distributions of the photon are the SaSg PDFs of Refs. [76] and [34], while the proton PDF is NNPDF 3.1 [77] at NNLO and the strong coupling constant was set to $\alpha_s = 0.118$. Multi-parton interactions, which have been observed to play a non-negligible role in photoproduction [78, 79], are included in the SHERPA model. Additional information on the various components of the simulations can be found in Refs. [80–88].

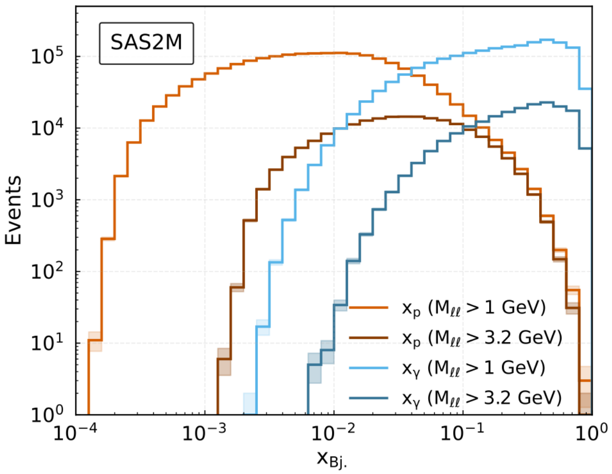
Based on these ingredients, SHERPA is able to numerically evaluate the cross section and perform scale variations to understand the uncertainty on the prediction. In Ref. [67], the SHERPA authors demonstrate the good agreement between their predictions and the HERA data as well as the large uncertainty engendered by the photon PDF.

For production of Drell–Yan dimuon pairs at the 10x275 beam energy with $M_{\ell\ell} > 1$ GeV, SHERPA with the SAS1M photon PDF set predicts a total cross section of $5.43^{+1.34}_{-1.25}$ pb, while the same setup with the SAS2M photon PDF predicts a total cross section of $8.10^{+0.47}_{-1.13}$ pb. The uncertainties provided on the SHERPA cross sections are the extrema of a 7-point scale variation. SAS2M was shown to be a better fit to world data on F_2^γ in Ref. [35], producing a $\chi^2/\text{ndf} = 1.01$ compared to the $\chi^2/\text{ndf} = 1.50$ of SAS1M. The significant difference in predicted cross sections between the two PDF sets highlights the large uncertainty in the photon PDF, as well as the high constraining power of the Drell–Yan process. The SAS1M PDF set employs a starting scale of $Q_0^2 = 0.36$ GeV^2, while SAS2M uses a starting scale of $Q_0^2 = 4$ GeV^2. Both sets use the $\overline{\text{MS}}$ renormalization scheme [34, 35, 76]. The discrepancy between the two sets does not go away at higher $Q^2 = M^2_{\ell\ell}$, as can be seen from Fig. 6. The differences in the derived photon structure function F_2^γ are around 30% between the two PDF sets [35]. These cross sections are more or less consistent with other estimates in the literature, namely those of Refs. [55, 58, 60, 63, 64]. The cross section for the 18x275 beam energy in SHERPA is around 50% higher than for 10x275.


SAS1M
SAS2M
η = − 3.5
η = 3.5
Counts
η_ℓ


η_ℓ
$\log_{10}(x_\gamma)$


Counts
SAS1M
SAS2M
$p_{T,\ell}$ [GeV]


SAS2M
Events
x_p ($M_{\ell\ell} > 1$ GeV)
x_p ($M_{\ell\ell} > 3.2$ GeV)
x_γ ($M_{\ell\ell} > 1$ GeV)
x_γ ($M_{\ell\ell} > 3.2$ GeV)
$x_{Bj.}$

INTERFERENCE IN DIRECT PHOTOPRODUCTION

Probing the Nucleon's Transversity and the Photon's Distribution Amplitude in Lepton Pair Photoproduction

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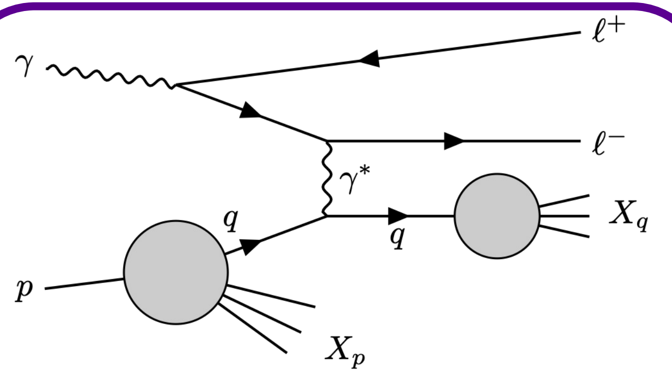
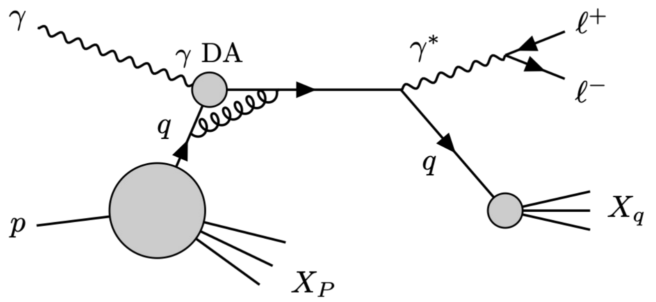
(Received 8 May 2009; published 14 August 2009)

- Interference between Bethe-Heitler and direct Drell-Yan can also be utilized
  - Similar to BH x DVCS interference

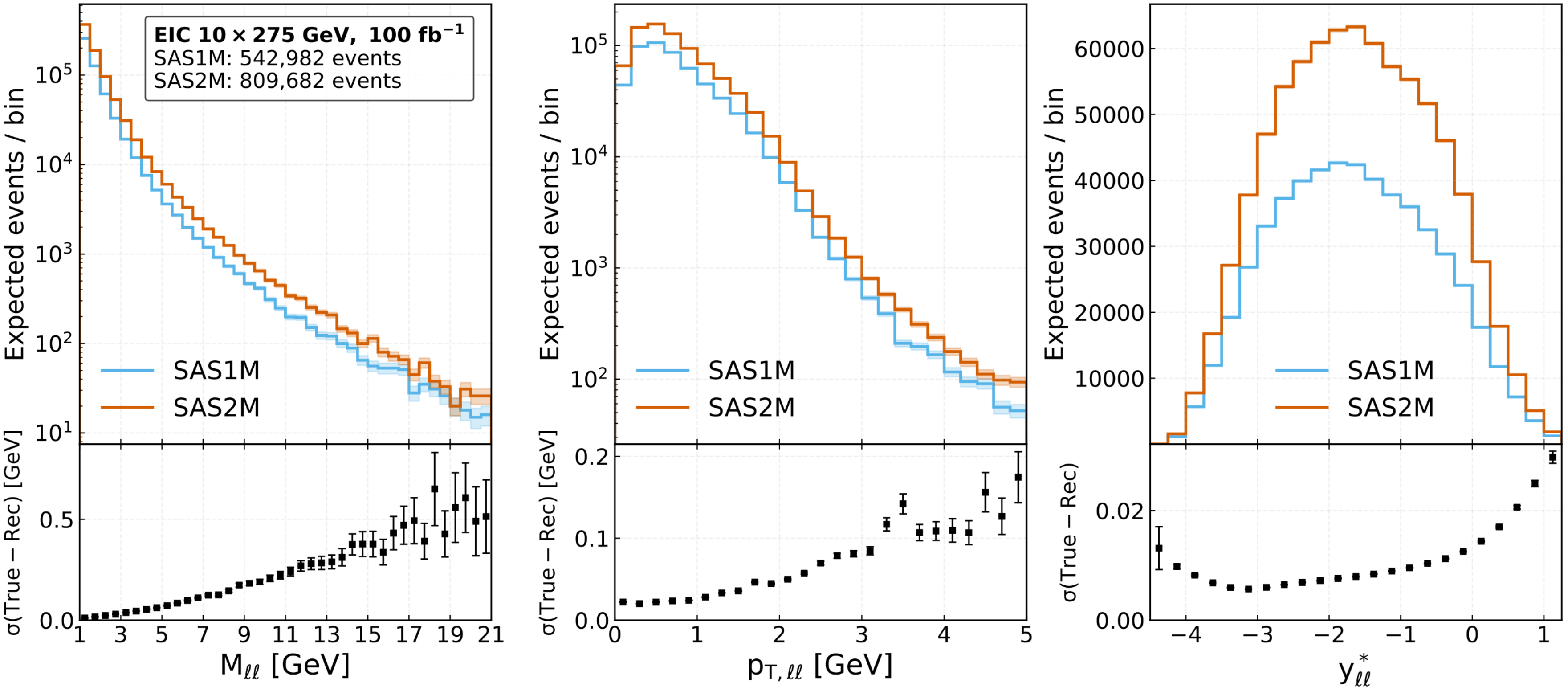
- **Transversity access**
  - Transverse spin asymmetry $\propto \phi_\gamma \cdot h_q^1$
    - ϕ_γ is the photon distribution amplitude
    - h_q^1 is the nucleon transversity distribution
  - **No fragmentation functions needed –** important cross-check for SIDIS measurements
  - e^+e^- vs $\mu^+\mu^-$ comparison useful



Bethe-Heitler Process



Drell-Yan process


EIC 10 × 275 GeV, 100 fb^{-1}
SAS1M: 542,982 events
SAS2M: 809,682 events
SAS1M
SAS2M
Expected events / bin
σ(True − Rec) [GeV]
$M_{\ell\ell}$ [GeV]
$p_{T,\ell\ell}$ [GeV]
σ(True − Rec)
$y^*_{\ell\ell}$