Accessing the proton structure using the exclusive dilepton final state:
from CLAS12 to the EIC second detector

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clas
Jefferson Lab

Outline of the talk

I Motivations for the measurement of dilepton final state at CLAS12 and the EIC

II Accessing GPDs using the dilepton final state with the CLAS12 experiment
- Timelike Compton scattering
- J/ψ photoproduction
- Double Deeply Virtual Compton Scattering

What have we learned ?

III Applications and projections for a second EIC detector

Lessons learned

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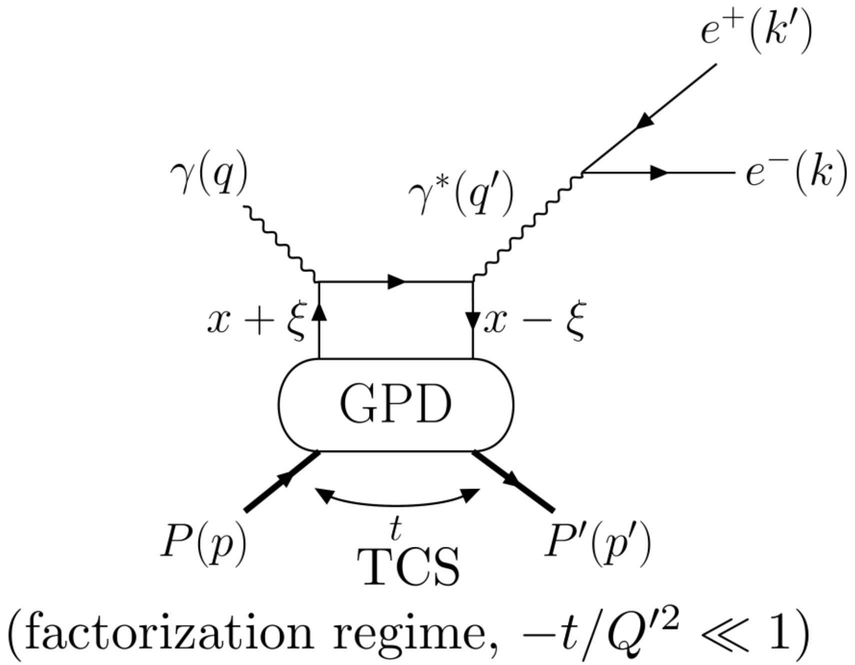
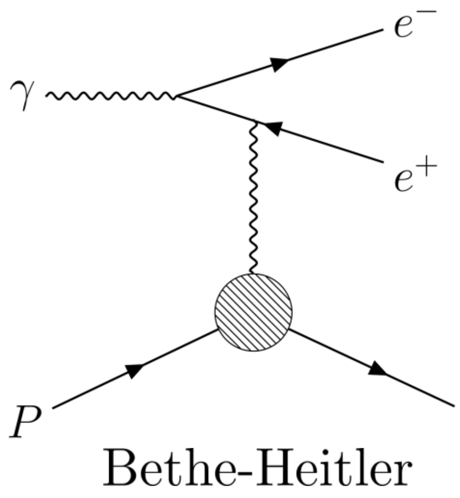
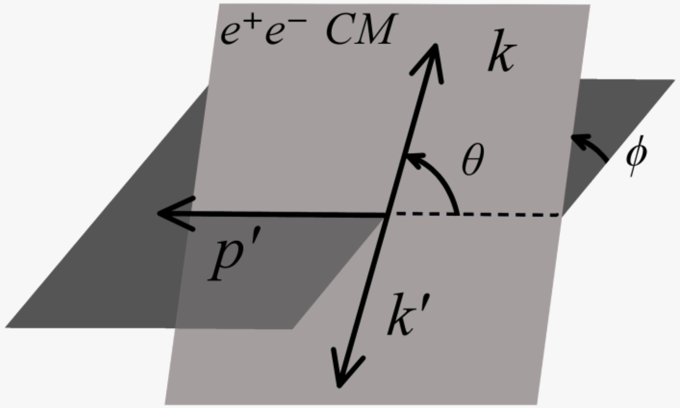
Timelike Compton Scattering

DVCS: $ep \to e'p'\gamma$ TCS: $\gamma p \to e^+e^-p'$







$$-t = (p-p')^2$$
$$Q'^2 = (k+k')^2$$
$$L = [(q-k)^2 - m_l^2][(q-k')^2 - m_l^2]$$
$$L_0 = (Q'^2 \sin^2\theta)/4$$

- BH cross section only depends on electromagnetic FFs.
- At JLab, energies the BH cross section is expected to be larger than the TCS one. We aimed at measuring the interference cross section between BH and TCS.

TCS interference cross-section formulae, CFFs and GFFs

TCS unpolarized cross-section

Formulae and notations of Berger, Diehl, Pire, Eur.Phys.J.C23:675-689,2002

$$\frac{d^4\sigma_{INT}}{dQ'^2 dt d\Omega} \propto \frac{L_0}{L}\left[\cos(\phi)\frac{1+\cos^2(\theta)}{\sin(\theta)}\mathrm{Re}\mathcal{H} + \ldots\right]$$

Compton Form Factors (CFFs)

$$\mathcal{H} = \int_{-1}^{1} dx H(x,\xi,t)\left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right)$$

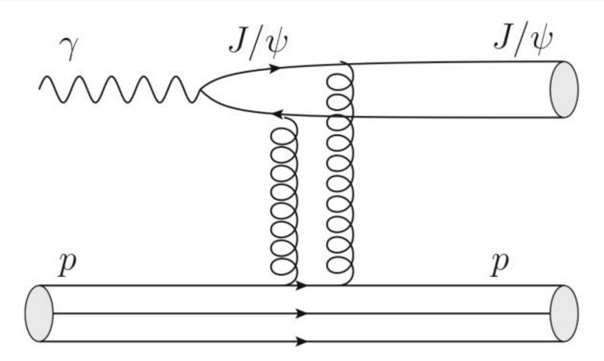
Dispersion relation and link to GFFs

- Angular dependence of the TCS cross-section gives access to the real part of $\mathcal{H}$.
- This quantity is not well constrained by existing DVCS data (accessed in cross-section mostly).
- $\mathrm{Re}(\mathcal{H})$ is related to the GFFs D, itself related to the mechanical properties of the nucleon:

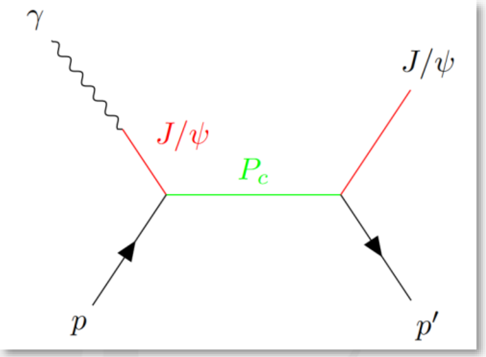
$$\mathrm{Re}\mathcal{H}(\xi,t) = \mathcal{P}\int_{-1}^{1} dx \left(\frac{1}{\xi - x} - \frac{1}{\xi + x}\right)\mathrm{Im}\mathcal{H}(\xi,t) + \Delta(t) \longrightarrow \Delta(t) \propto D^Q(t) \propto \int d^3\mathbf{r}\; p(r)\frac{j_0(r\sqrt{-t})}{t}$$

J/ψ photoproduction

- Probe the gluon content of the proton (under 2-gluon exchange assumption and no open-charm contributions discussed in the next slide)



- The t-dependence of the cross-section allow to access gluon Gravitational Form Factors (GFFs), mass radius of the nucleon (under 2-gluon exchange assumption and no open-charm contributions, see back-up).
- Model-dependent limit on the branching ratio of the Pc pentaquark.



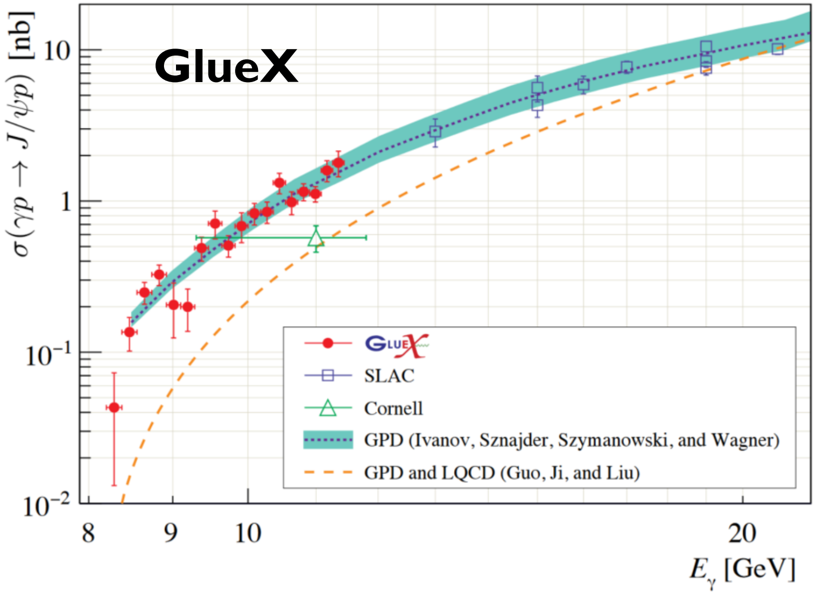


Figure in, Measurement of the J/ψ photoproduction cross section over the full near-threshold kinematic region, S. Adhikari *et al.* (GlueX Collaboration) arXiv:2304.03845

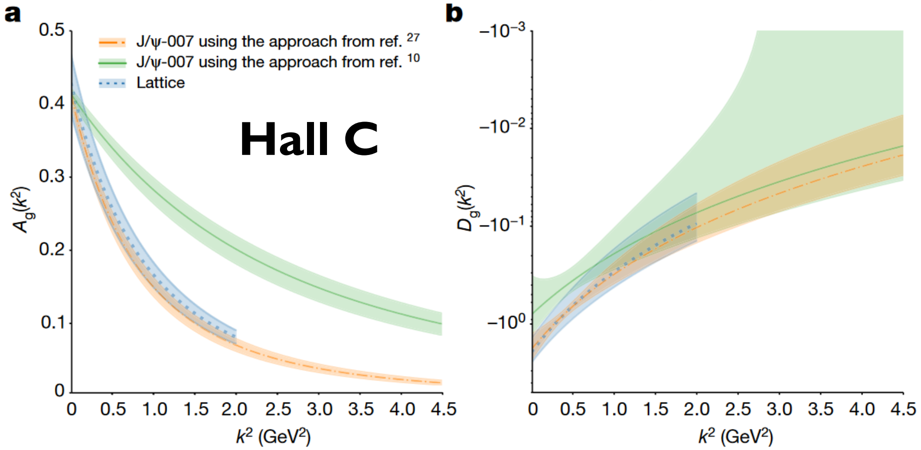
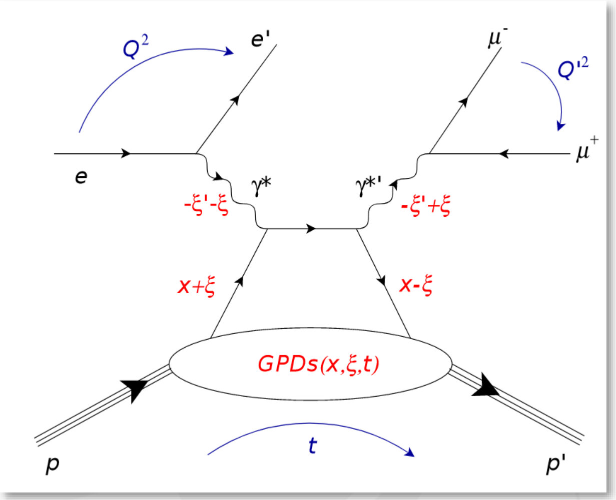


Figure in Duran, B., Meziani, ZE., Joosten, S. *et al.* Determining the gluonic gravitational form factors of the proton. *Nature* 615, 813–816 (2023)

Double DVCS measurement

$$ep \to e'\mu^+\mu^- p$$

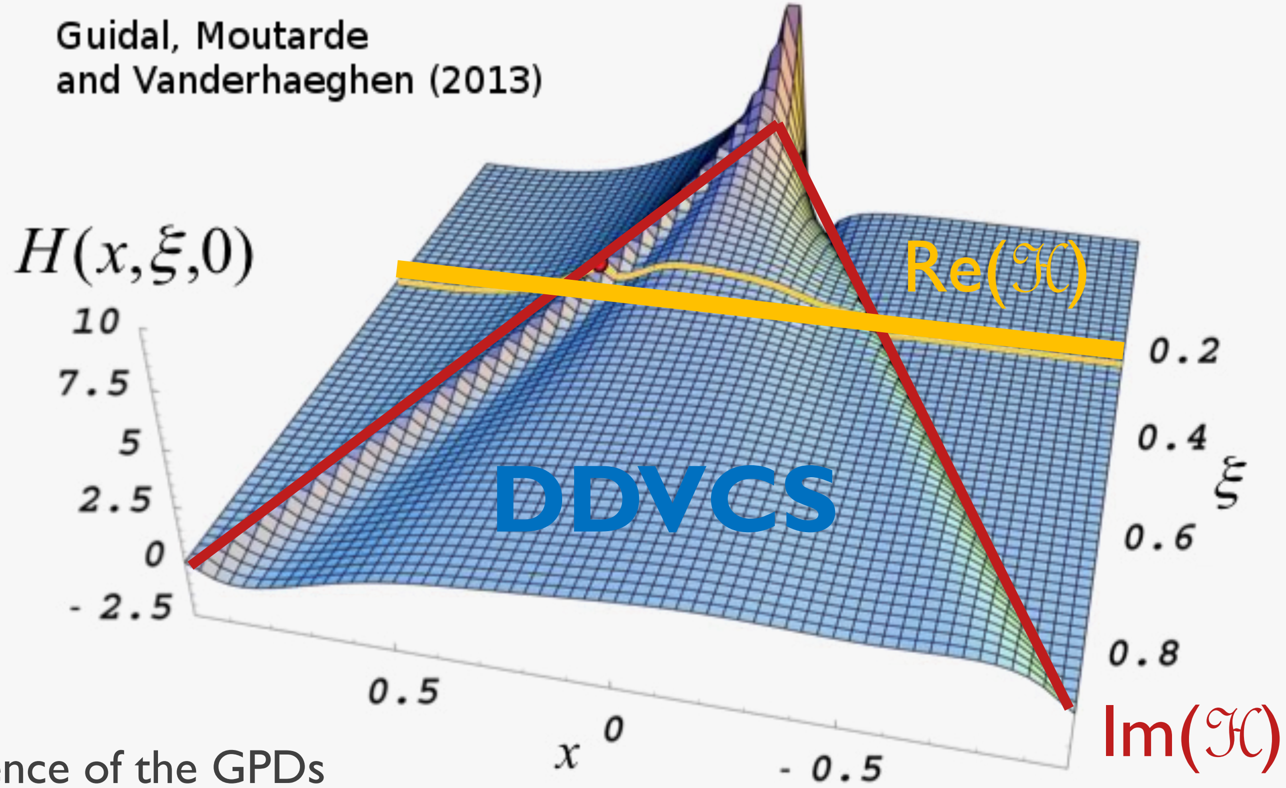
Capturing the complete kinematic dependence of GPDs



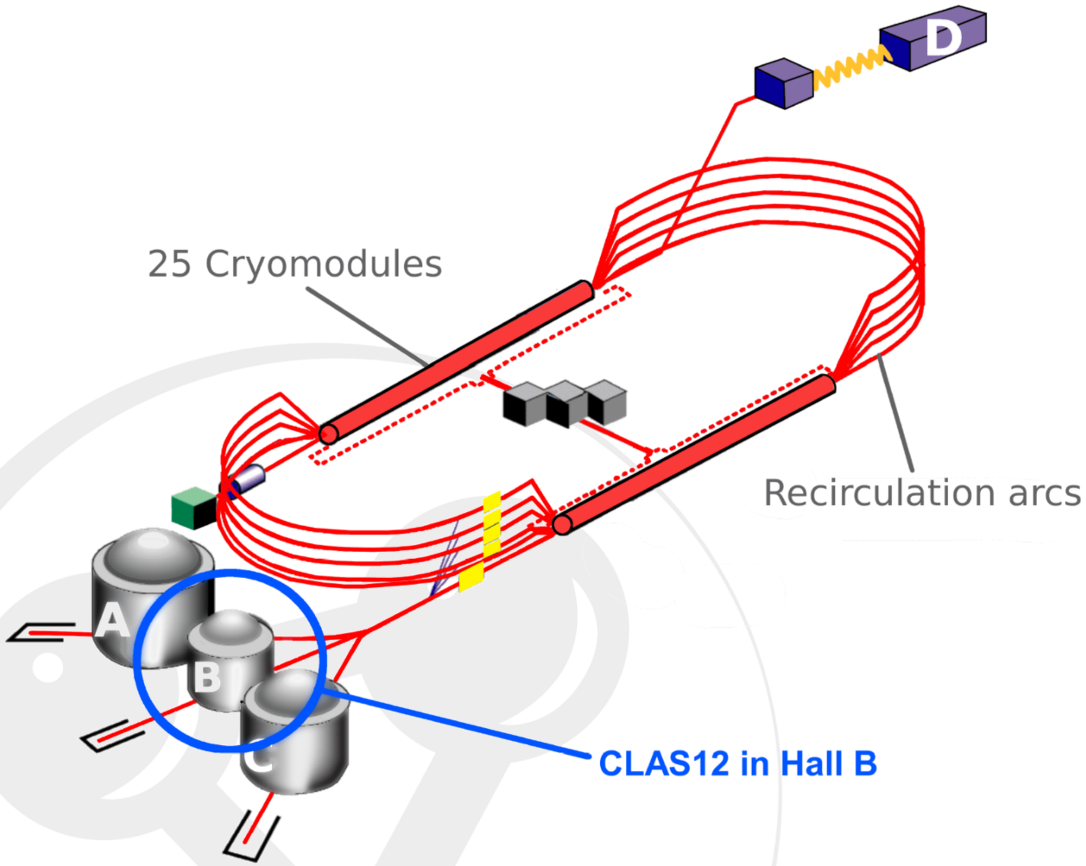
$$\mathcal{H}(\xi',\xi,t) = \int_{-1}^{1} dx H(x,\xi,t)\left(\frac{1}{\xi'-x-i\epsilon} - \frac{1}{\xi'+x-i\epsilon}\right)$$

$$Im\mathcal{H}(\xi',\xi,t) \propto H(\xi',\xi,t) - H(-\xi',\xi,t)$$

→ Allow to completely map the kinematic dependence of the GPDs



The CLAS12 experiment at Jefferson Lab

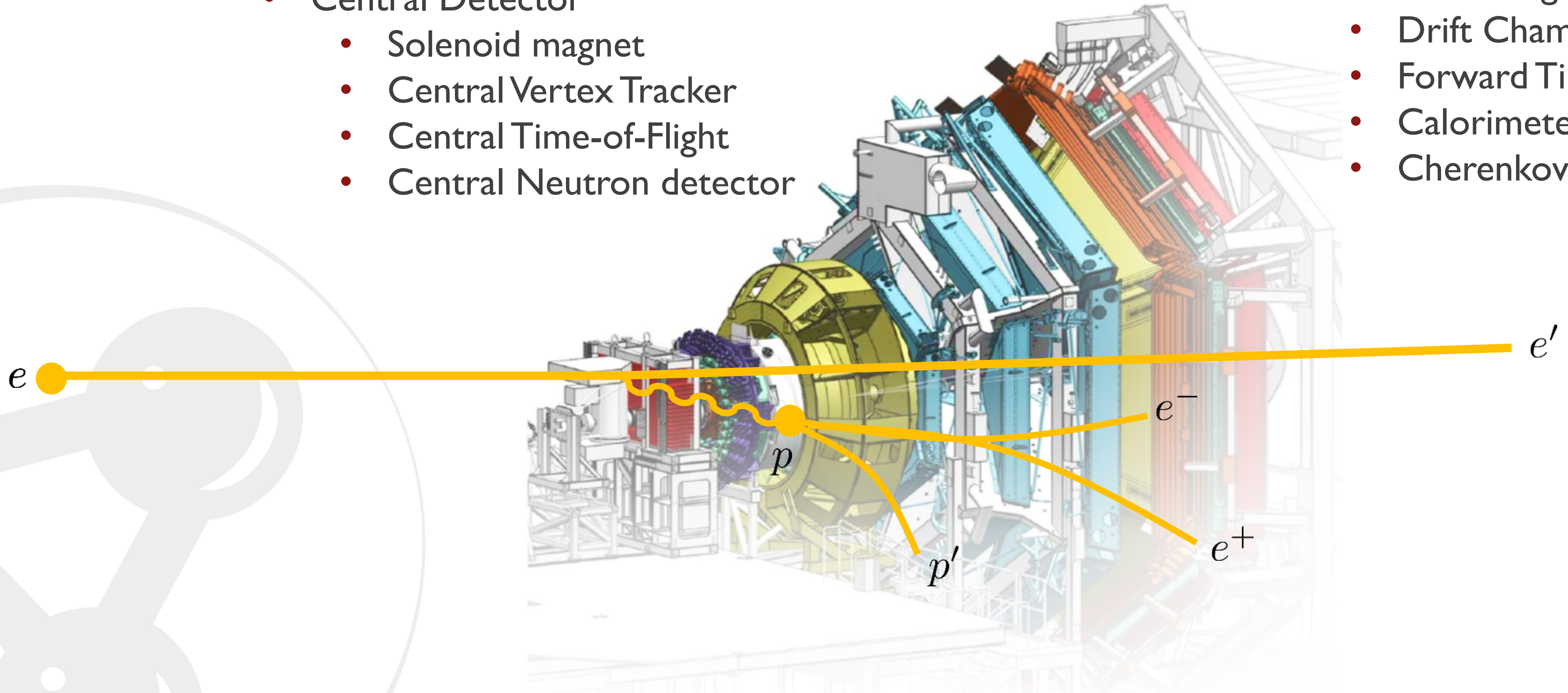


- The Continuous Electron Beam Accelerator Facility provides a quasi-continuous beam of polarized electron, up to 12 GeV.
- Build around two anti-parallel linacs, with recirculation arcs on both ends. The maximum energy is reached after 6 pass through the linacs.
- 4 experimental halls: A,B,C and D
  A. C. Small acceptance but large luminosity
  B. Housing CLAS12, a large acceptance detector
  D. Tagged photon beam, dedicated to spectroscopy

CLAS12 in action

- Central Detector
  - Solenoid magnet
  - Central Vertex Tracker
  - Central Time-of-Flight
  - Central Neutron detector

- Forward Detector (6 sectors)
  - Torus magnet
  - Drift Chambers
  - Forward Time-of-Flight
  - Calorimeters
  - Cherenkov counters



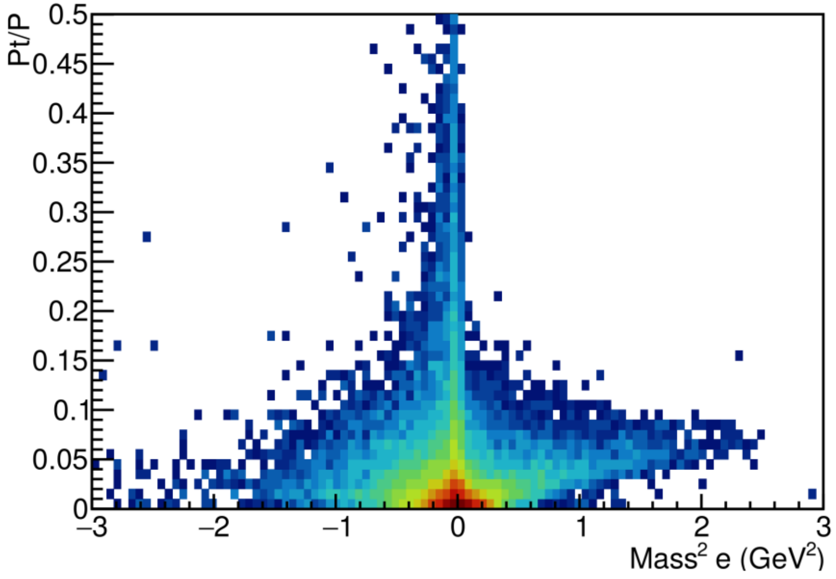
(Quasi-)Photoproduction events selection

1) CLAS12 PID + Positron NN PID

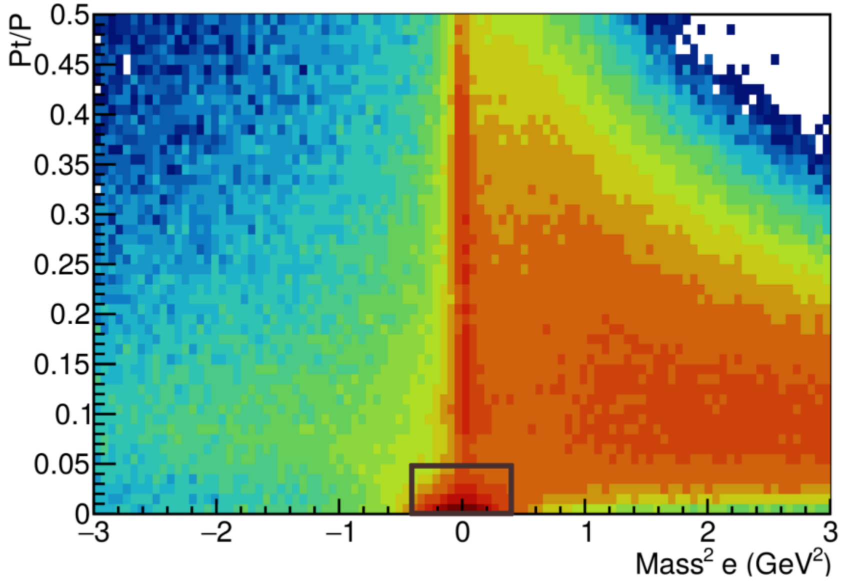
$$ep \rightarrow (e')\gamma p \rightarrow (X)e^+e^-p'$$

$p_X = p_{beam} + p_p - p_{e^+} - p_{e^+} - p_{p'}$ → 2) $|M_X^2| < 0.4GeV^2$ → 3) $\frac{Pt_X}{P_X} < 0.05$ $\rightarrow Q^2 < 0.1$ GeV^2

Simulation



Data



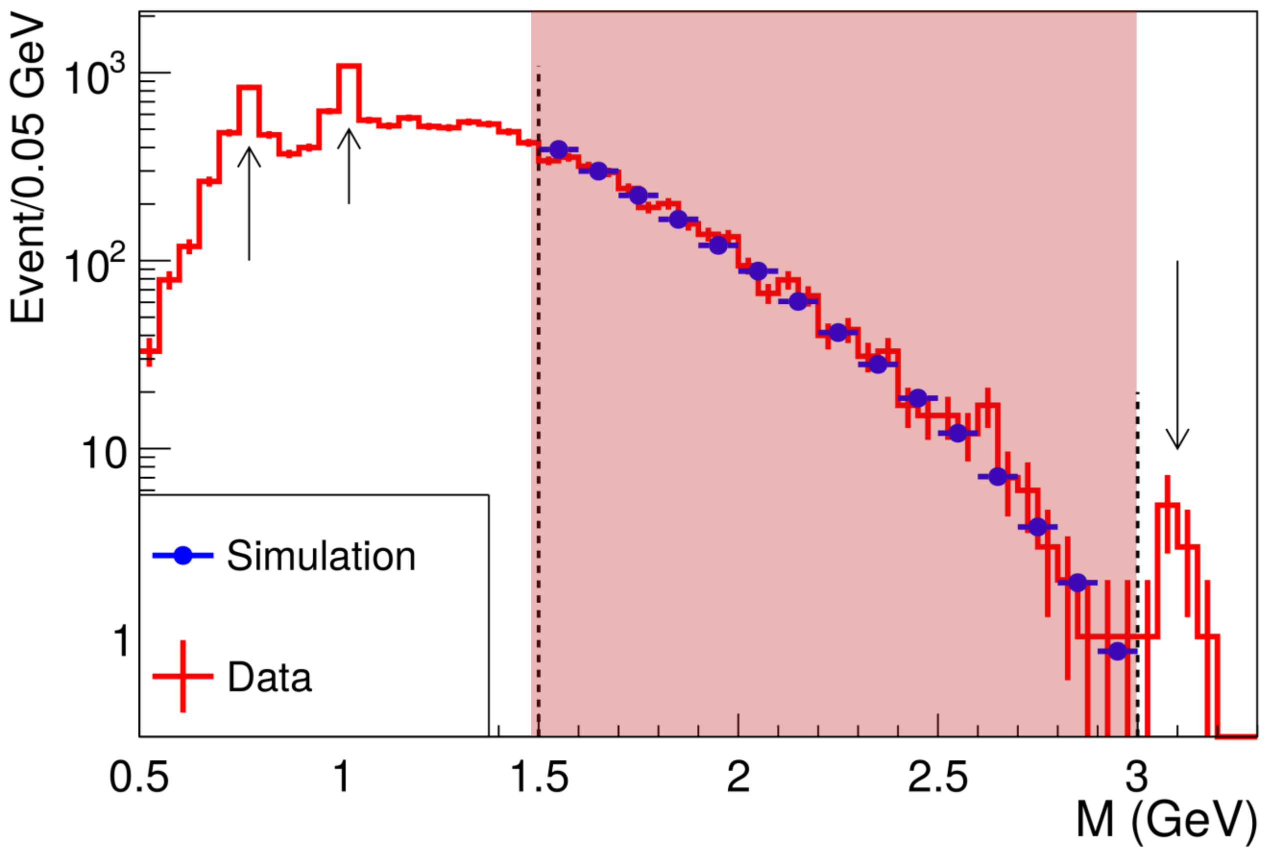
The CLAS12 dilepton invariant mass spectrum

- Data taken in Fall 2018
- 10.6 GeV beam on Liquid H_2 target
- Accumulated charge: 37mC or 48 fb^{-1}

- Vector mesons peaks are visible in data: ω (770), ρ (782), ϕ (1020) and J/ψ (3096).
- Data/simulation are matching at the 15% level, up to an overall normalization factor.
- No clear contribution of higher mass vector meson production (ρ (1450), ρ (1700)).

Phase-space for the TCS analysis

$$0.15 \text{ GeV}^2 < -t < 0.8 \text{ GeV}^2$$
$$1.5 \text{ GeV} < M_{e^+e^-} < 3 \text{ GeV}$$
$$4 \text{ GeV} < E_\gamma < 10.6 \text{ GeV}$$



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The TCS Forward/Backward asymmetry

Observable definition

$$A_{FB}(\theta_0,\phi_0) = \frac{d\sigma(\theta_0,\phi_0) - d\sigma(180^\circ-\theta_0, 180^\circ+\phi_0)}{d\sigma(\theta_0,\phi_0) + d\sigma(180^\circ-\theta_0, 180^\circ+\phi_0)}$$

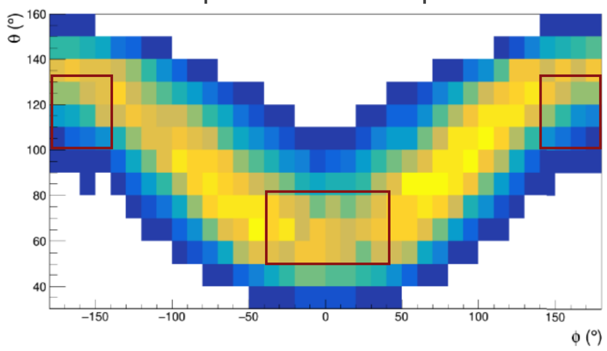
$$\propto \frac{\frac{L_0}{L}\cos\phi_0 \frac{(1+\cos^2\theta_0)}{\sin(\theta_0)} \mathrm{Re}\tilde{M}^{--}}{d\sigma_{BH}(\theta_0,\phi_0) + d\sigma_{BH}(180^\circ-\theta_0, 180^\circ+\phi_0)}$$

- Integration over the forward angular bin :

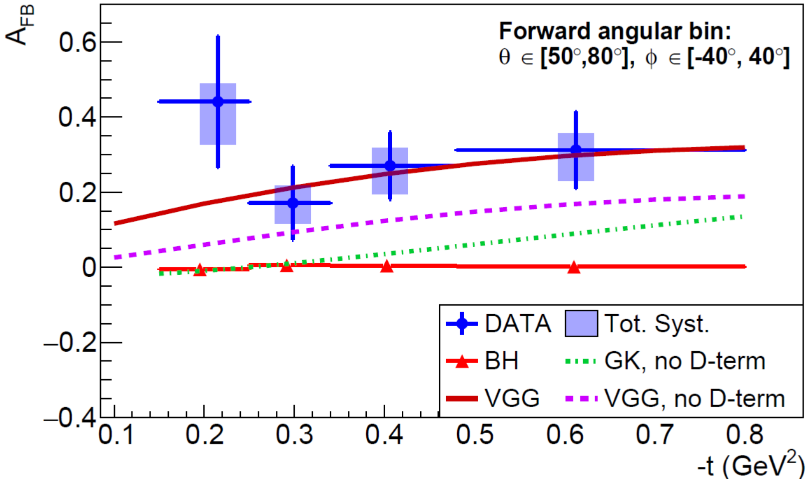
  $\theta \in [50^\circ, 80^\circ]$ and $\phi \in [-40^\circ, 40^\circ]$

- The measured asymmetry is non-zero: **evidence of signal** beyond pure BH contribution

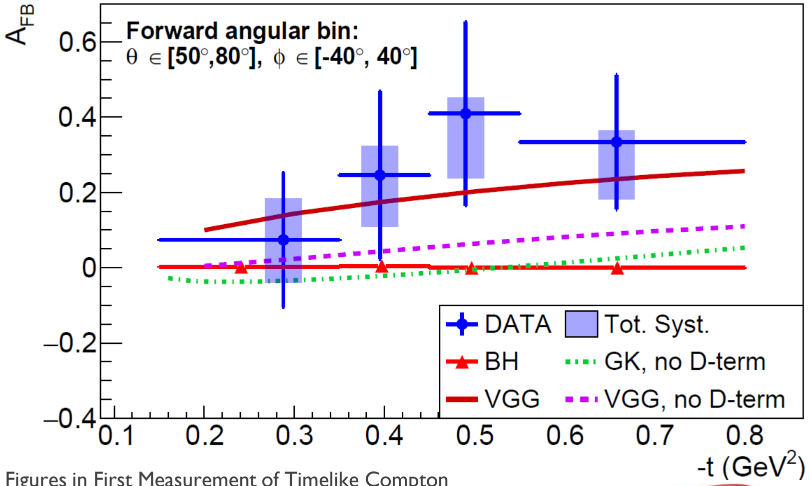
CLAS12 acceptance for the dilepton final state



$< M >= 1.8$ GeV; $< E_\gamma >= 7.24$ GeV



$< M >= 2.25$ GeV; $< E_\gamma >= 8.13$ GeV



Figures in First Measurement of Timelike Compton Scattering, P. Chatagnon *et al.* (CLAS Collaboration), Phys. Rev. Lett. 127, 262501 (2021)

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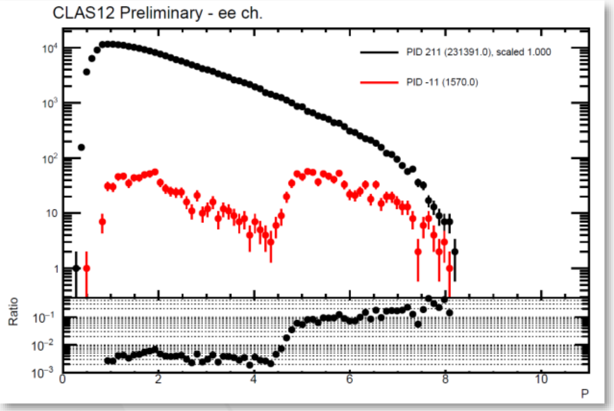
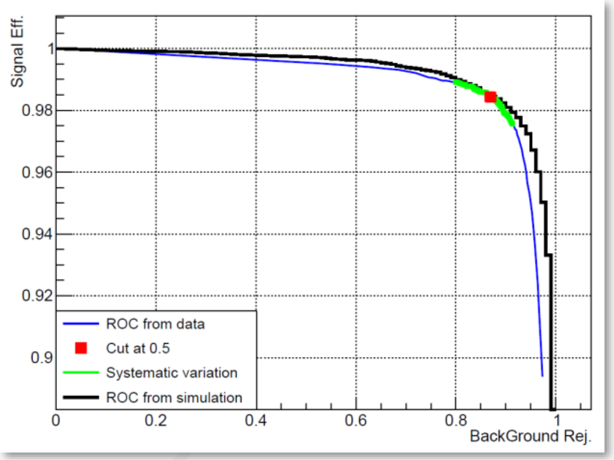
What we have learned so far ?

Lepton PID

- Main background: ep→ eπ⁺(π⁻)p
- CLAS12 relies on a Cherenkov counter and Calorimeters for lepton/pion separation
- In the momentum region where the Cherenkov counter is not useful, we have developed a ML approach

$ep \to ep\pi^+\pi^-$ VS $ep \to epe^+\pi^-$





Angular coverage

- Necessary to measure the forward/backward asymmetry

Momentum resolution

- Necessary to ensure (quasi-)exclusivity using missing mass/momentum technics

Proton detection & low-Q2 tagger

- At most one missing particle

Importance of muon detection

- For the DDVCS case, it allows to fully reconstruct the kinematic variables in the absence of a resonance.
- For electro-production events

Simulation setup

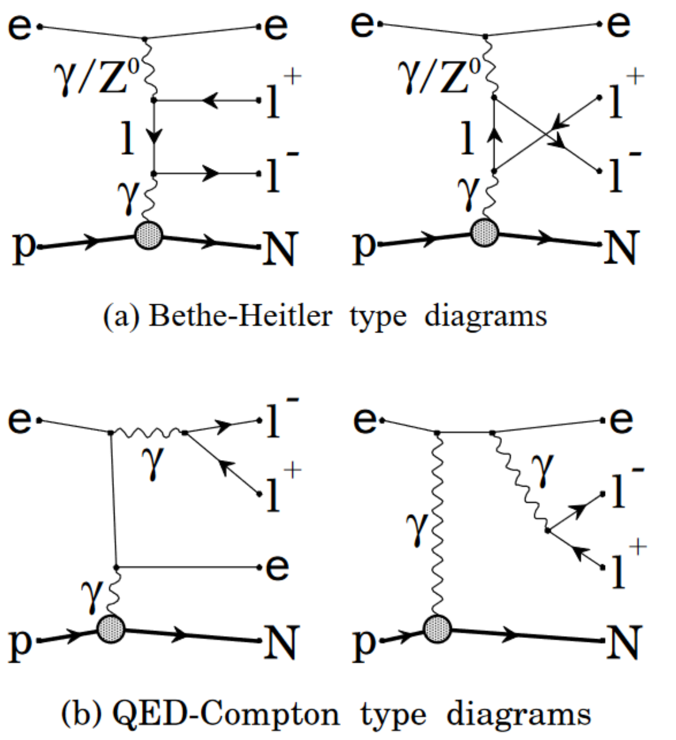
Generator

- Grape, generator developed for HERA
  Tetsuo Abe, GRAPE-Dilepton (Version 1.1): A generator for dilepton production in ep collisions, Computer Physics Communications (2001)
- Included all relevant Bethe-Heitler and Z diagrams
- Final state interference included

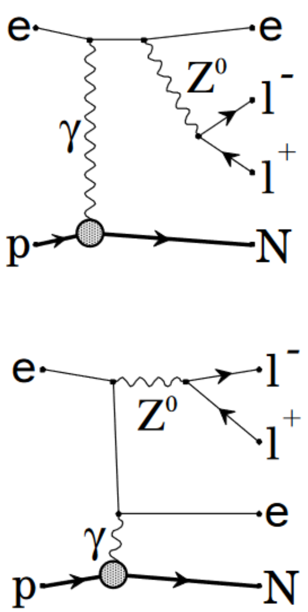
Beam configurations and kinematic limits

- Beam energy: 10 GeV electron, 275 GeV proton
- Only Bethe-Heitler diagrams included
- Muon in the final state (avoid ambiguities of the two electrons final state, while keeping *almost* the same kinematics)
- Muon polar angle above 3 degree (η~3.5)

Included



Not included



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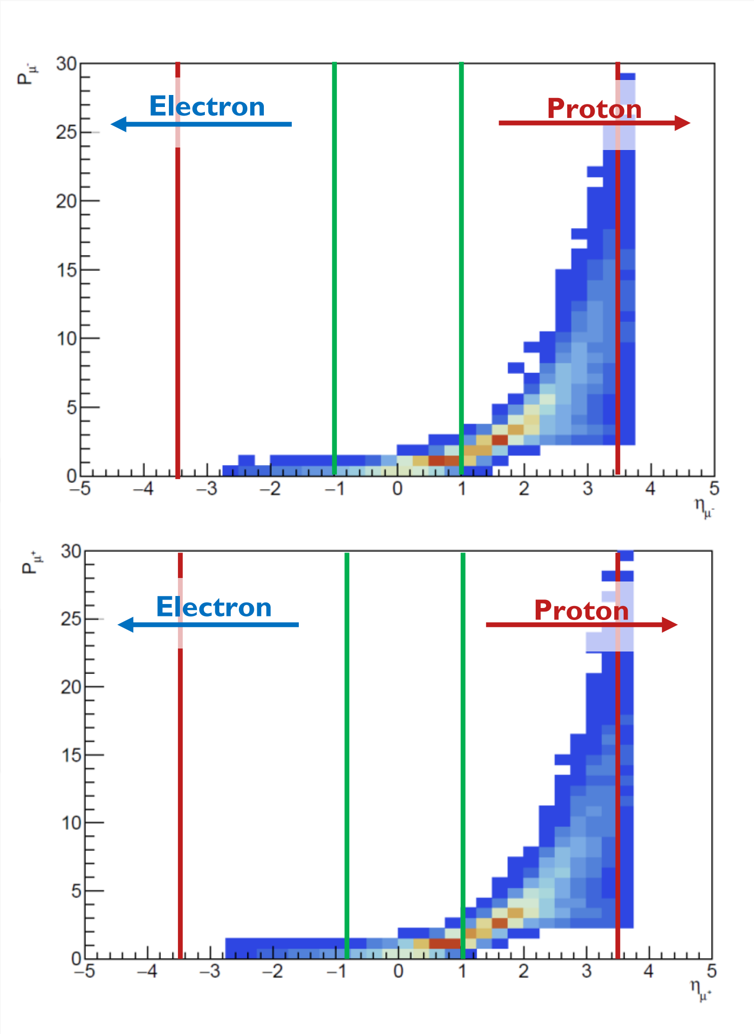
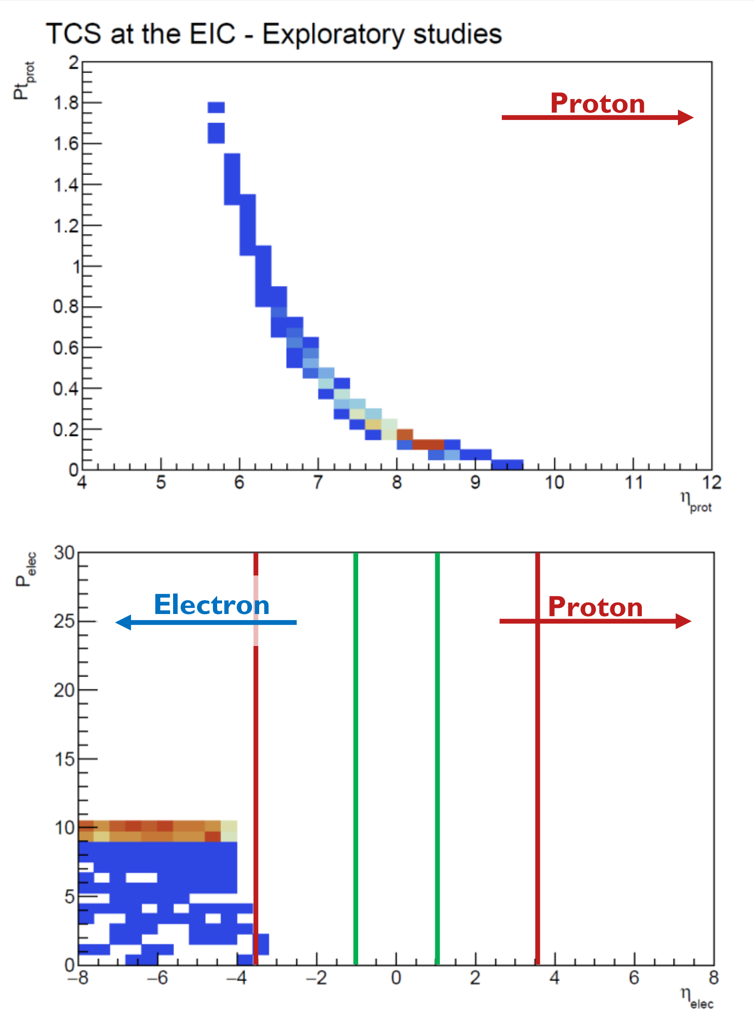
TCS at the second EIC detector

Pair kinematics



Beam remnants kinematics



Simulation setup

- 2 GeV < M_{ll} < 3 GeV & Q^2 < 0.1 GeV
- $Pt_{Lept.}$ > 0.1 GeV & $P_{lept.}$ > 0.5 GeV
- xL_{Proton} < 99%

Ideal setup

- Lepton identification on both hadron and lepton side (Pion/electron separation is essential).
- Lepton identification from 0.5 to 3 GeV in barrel, up to ~20 GeV in hadron endcap.
- Scattered proton detection necessary, if scattered electron reconstructed as missing particle.

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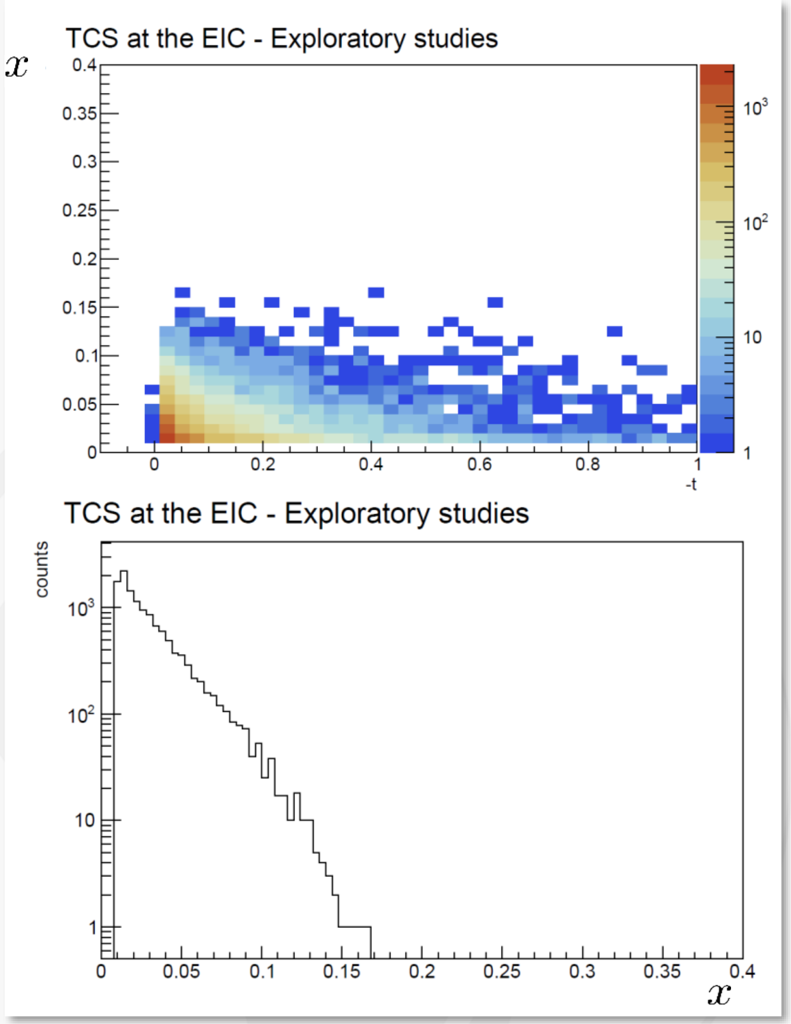
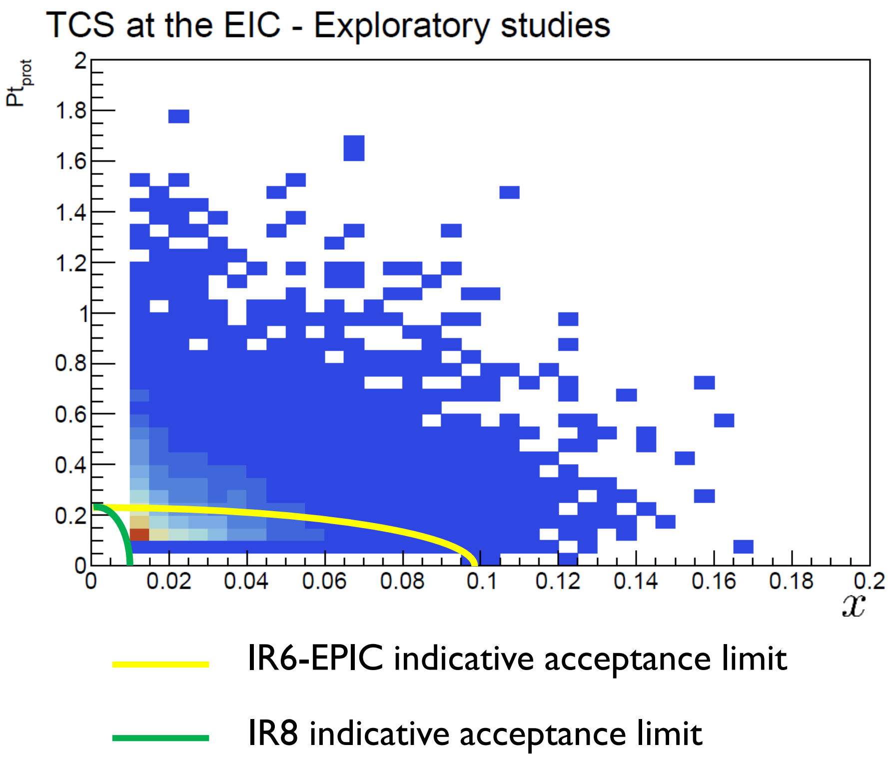
TCS at the second EIC detector: Focus on the proton detector

Proton kinematics



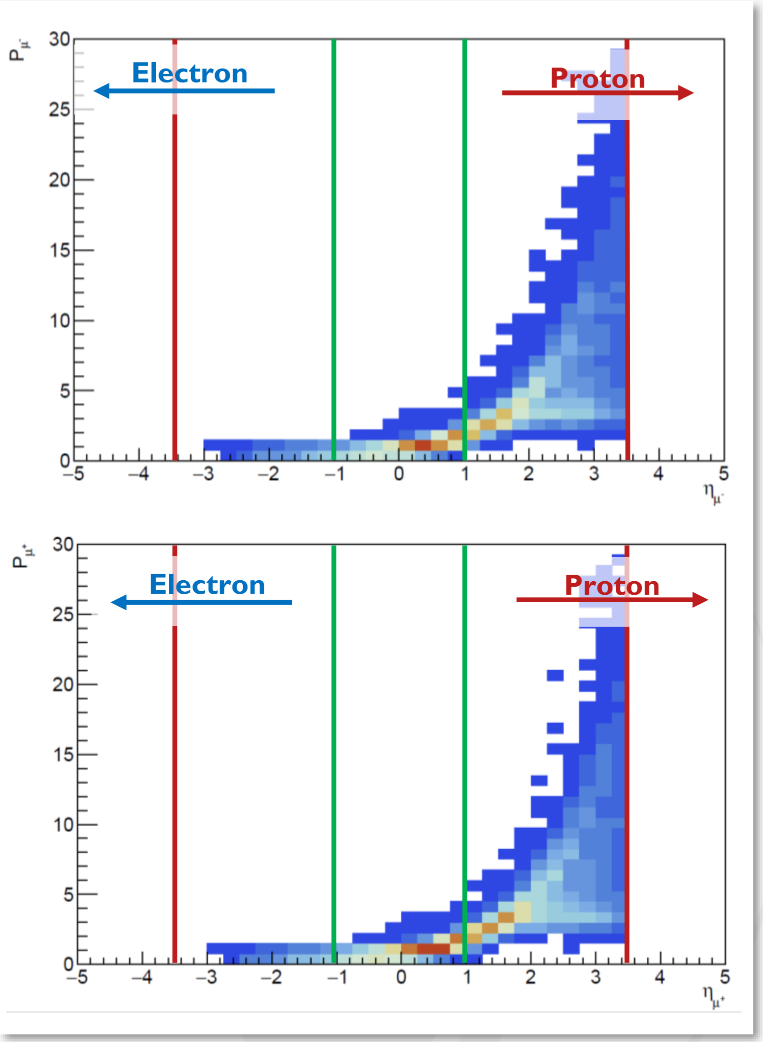


Ideal setup for proton detection

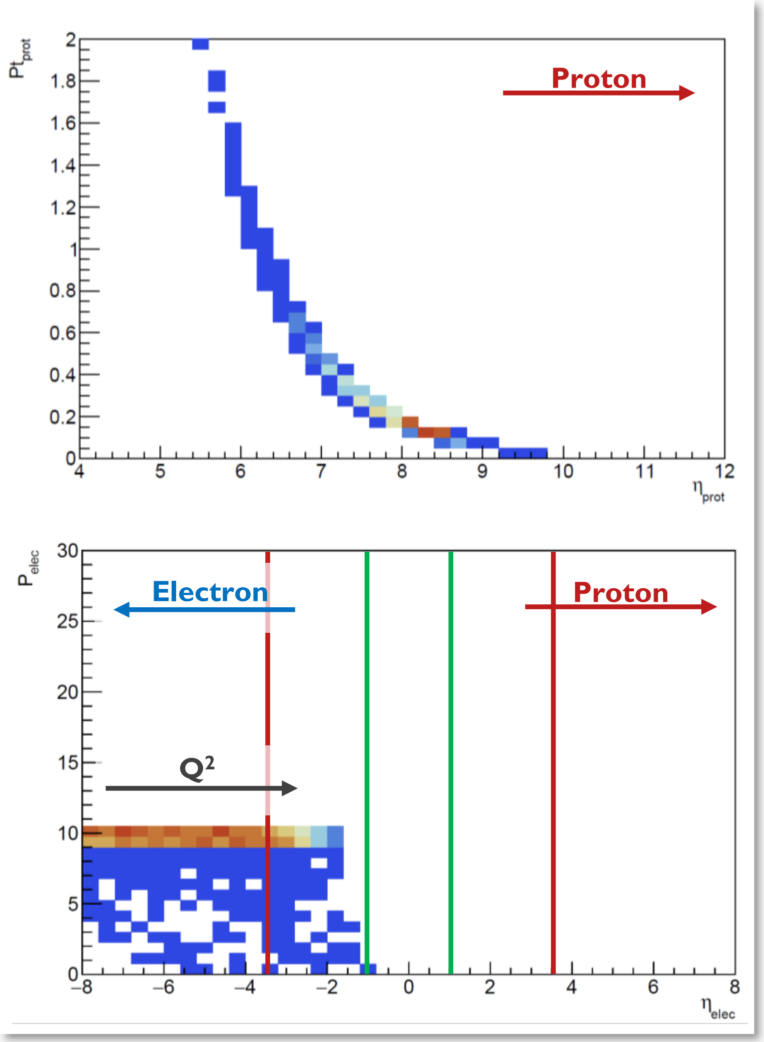
- Most event have a proton carrying a large fraction of the initial momentum and small Pt
- $1\% < x < 5\% \sim 15\%$
- At least $P_t > 0.1 GeV$

Electro-production of J/ψ and DDVCS at the second EIC detector

Pair kinematics



Beam remnants kinematics



Simulation setup

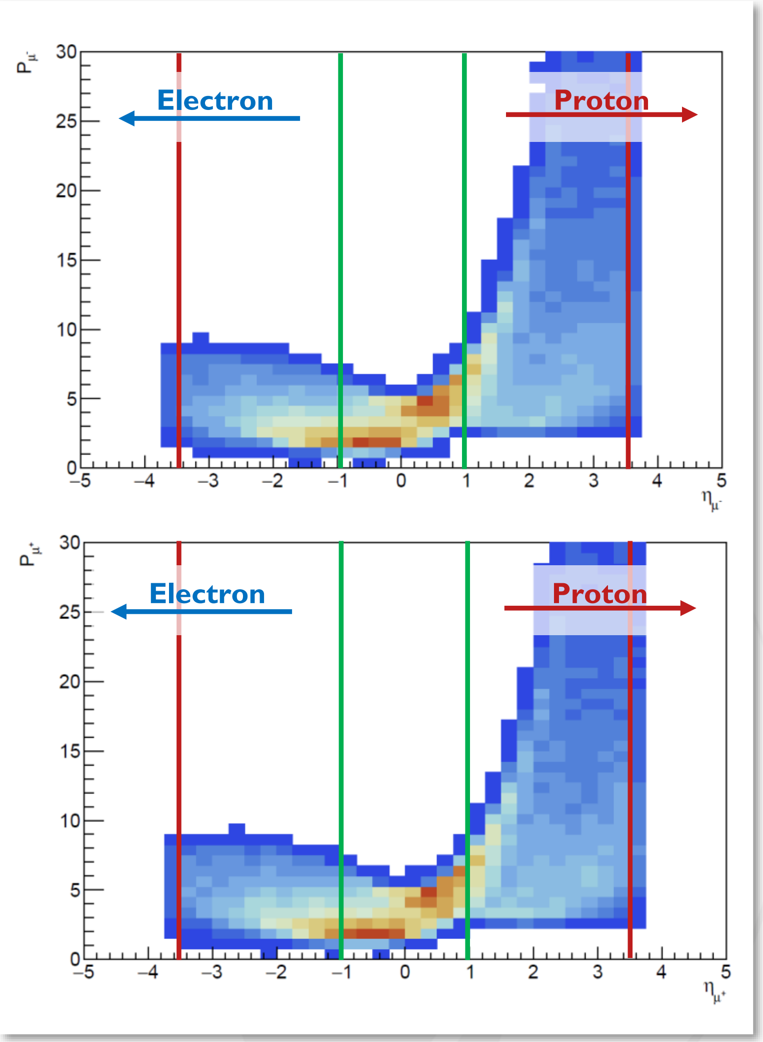
- 2.5 GeV < M_{ll} < 3.5 GeV
- $Pt_{Lept.}$ > 0.1 GeV & $P_{lept.}$ > 0.5 GeV
- xL_{Proton} < 99%

Ideal setup

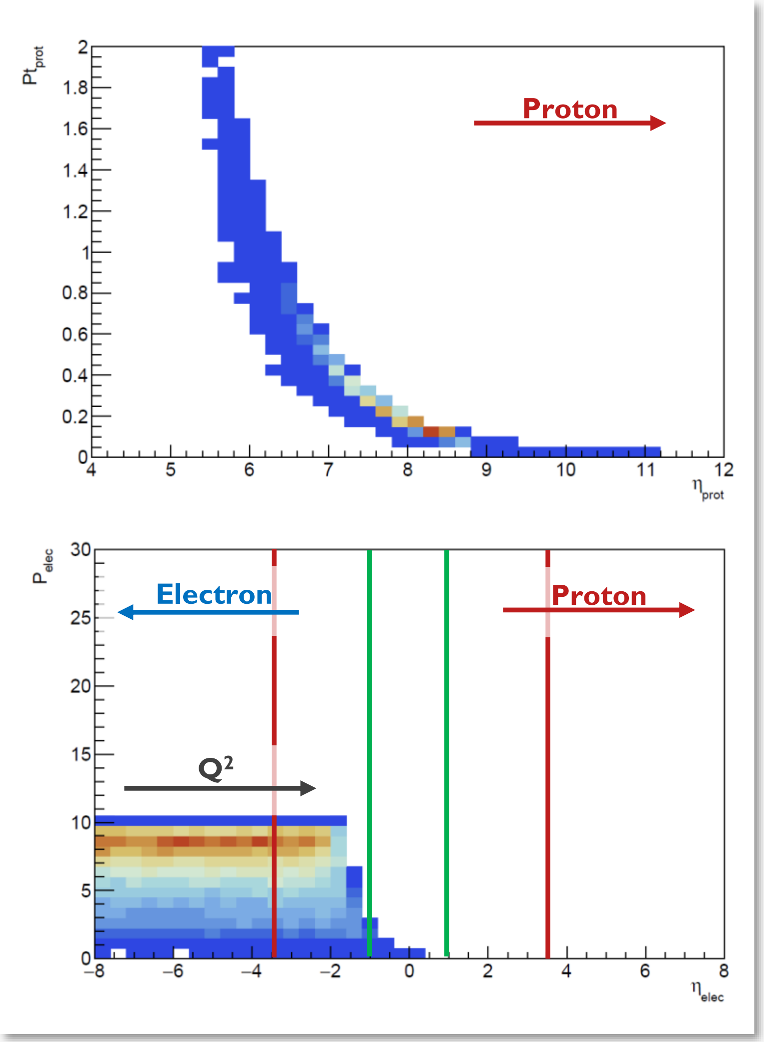
- Lepton (electrons and muons) identification on both side.
- Lepton identification from 0.5 to 4 GeV in barrel, up to ~20 GeV in hadron endcap.
- Scattered proton detection necessary
- Scattered electron detection both on the lepton side and in low-Q^2 tagger

Electro-production of Upsilon at the second EIC detector

Pair kinematics



Beam remnants kinematics



Simulation setup

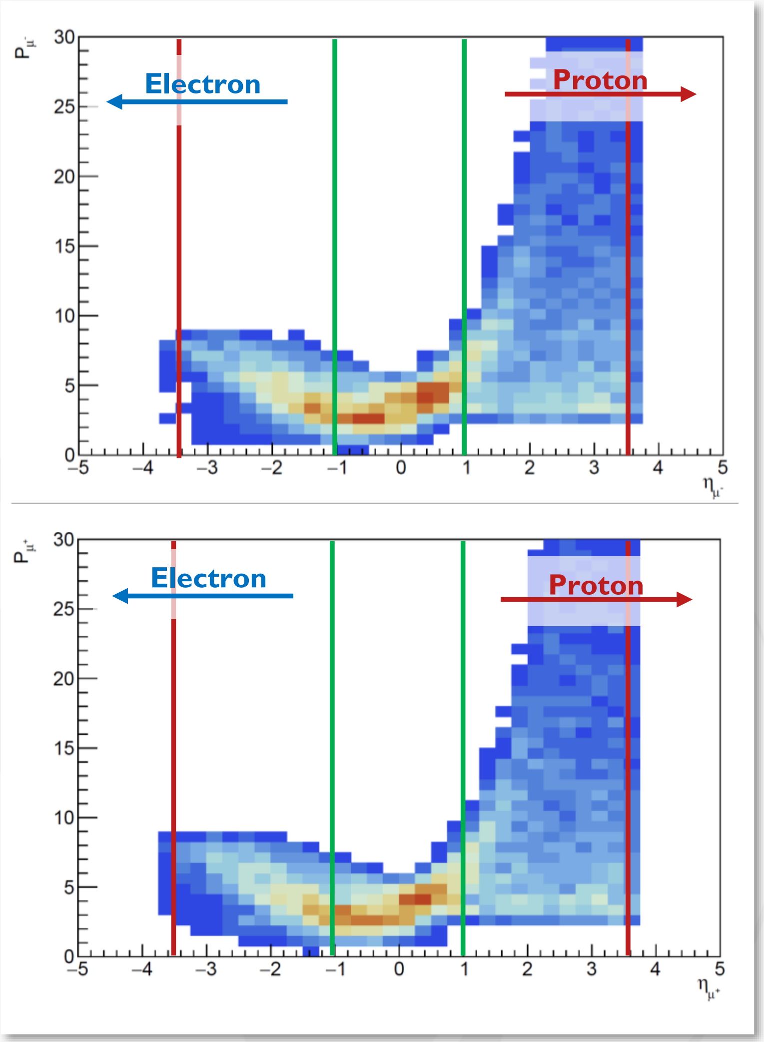
- 9.4 GeV < M_{ll} < 9.6 GeV
- $Pt_{Lept.}$ > 0.1 GeV & $P_{lept.}$ > 0.5 GeV
- xL_{Proton} < 99%

Ideal setup

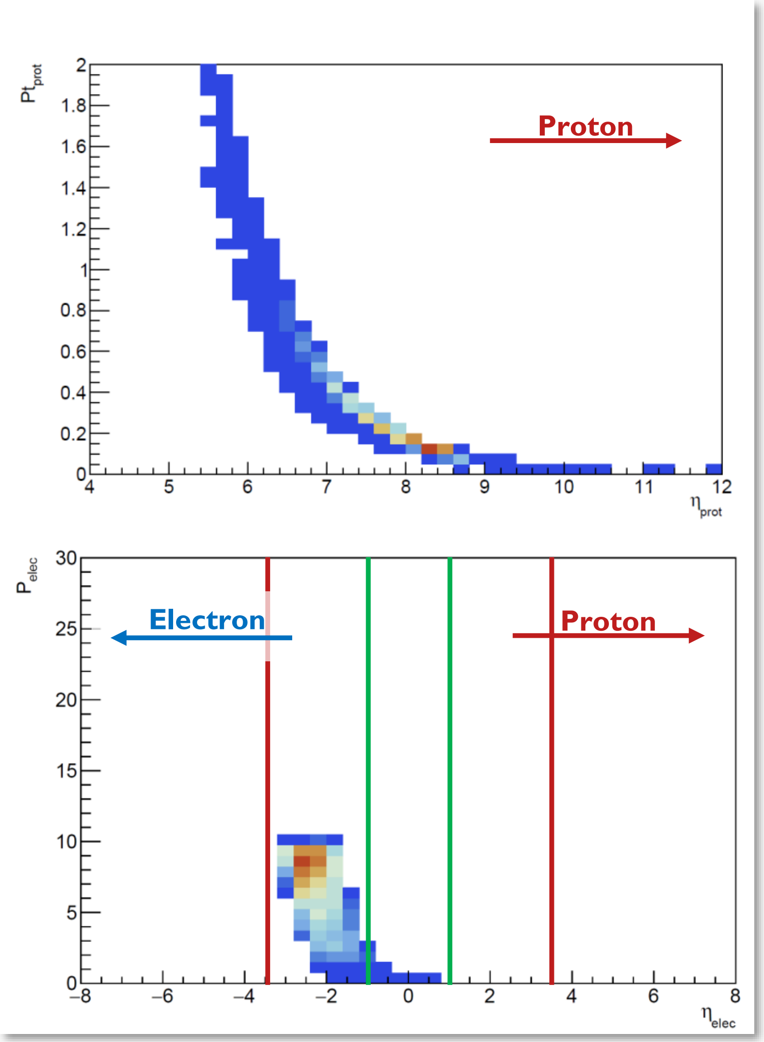
- Muon identification needed
- Muon identification on both side from 0.5 to 8 GeV in barrel, and up to ~30 GeV in hadron endcap.
- Scattered proton detection necessary
- Scattered electron detection both on the lepton side and in low-Q^2 tagger

Electro-production of Upsilon at the second EIC detector

Pair kinematics



Beam remnants kinematics



Simulation setup

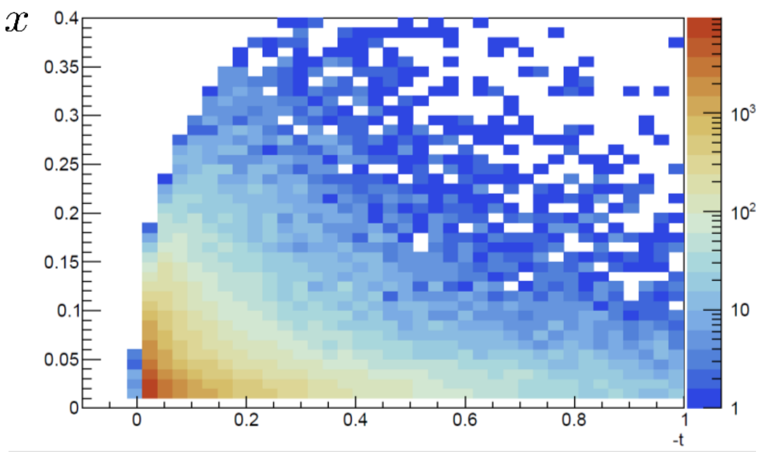
- 9.4 GeV < M_{ll} < 9.6 GeV & Q^2 > 1.0 GeV
- $Pt_{Lept.}$ > 0.1 GeV & $P_{lept.}$ > 0.5 GeV
- xL_{Proton} < 99%

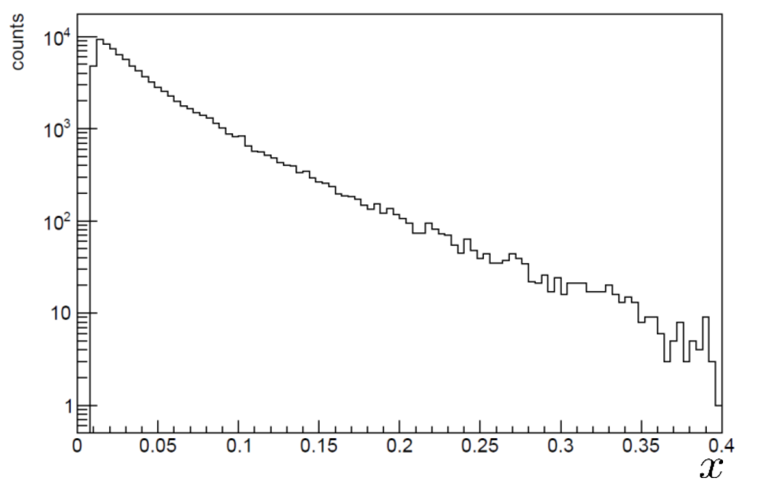
Ideal setup

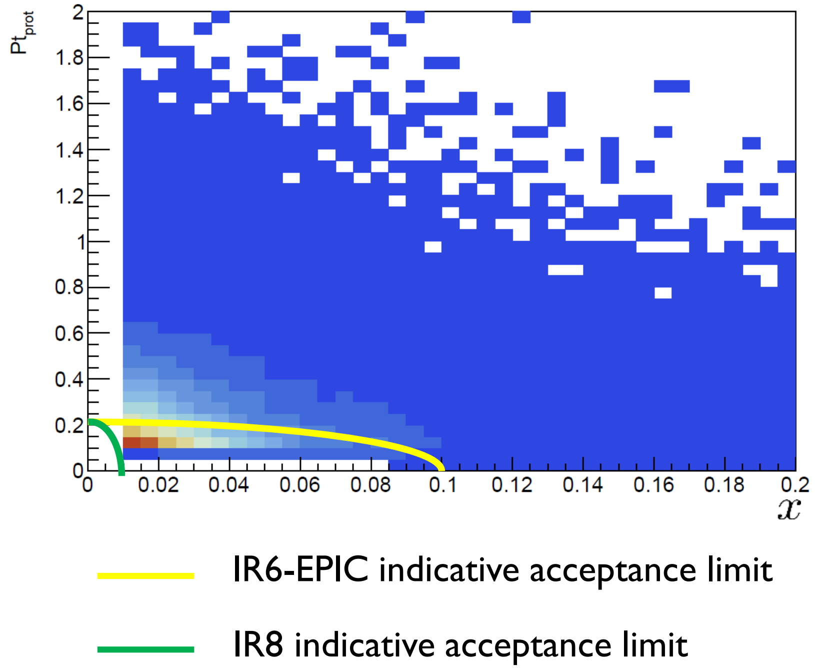
- Muon detection seems essential to distinguished final state negative leptons

Electro-production of Upsilon at the second EIC detector: Focus on the proton

Proton kinematics







Ideal setup for proton detection

- $1\% < x < 20 \sim 40\%$
- At least $P_t > 0.1GeV$

Observables and focus on the TCS FB asymmetry

Polarized observables

- Rather straightforward with EIC polarized beams

FB asymmetry

- Positive asymmetry at JLab energies.
- Expected to become negative at small ξ .

$$A_{FB}(\theta_0,\phi_0) = \frac{d\sigma(\theta_0,\phi_0) - d\sigma(180^\circ-\theta_0, 180^\circ+\phi_0)}{d\sigma(\theta_0,\phi_0) + d\sigma(180^\circ-\theta_0, 180^\circ+\phi_0)}$$
$$\propto \frac{\frac{L_0}{L}\cos\phi_0 \frac{(1+\cos^2\theta_0)}{\sin(\theta_0)} \mathrm{Re}\tilde{M}^{--}}{d\sigma_{BH}(\theta_0,\phi_0) + d\sigma_{BH}(180^\circ-\theta_0, 180^\circ+\phi_0)}$$

Figure in Timelike and spacelike hard exclusive reactions
D. Müller, B. Pire, L. Szymanowski, and J. Wagner
Phys. Rev. D 86, 031502(R), 2012

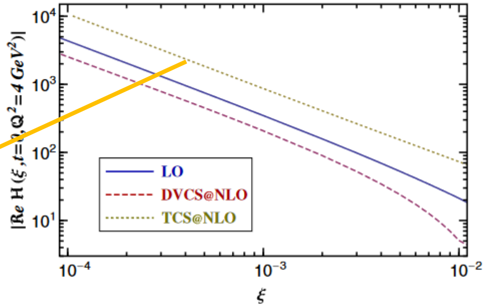
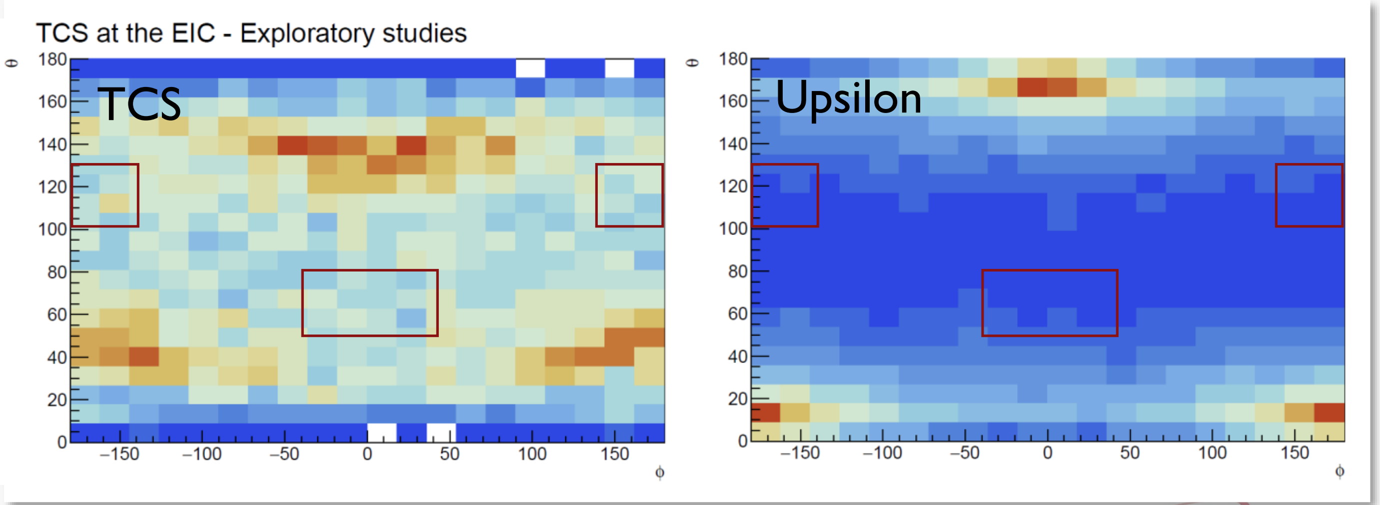


FIG. 2 (color online). The real part of CFF $\mathcal{H}$ vs ξ with $\mu^2 = Q^2 = 4$ GeV^2 and $t = 0$ at LO (solid curve) and NLO for DVCS (dashed curve). For TCS at NLO its negative value is shown as the dotted curve.

Angular coverage

- In CLAS12, the angular coverage is the limiting factor to calculate the forward/backward asymmetry
- Pseudo-rapidity coverage down to 3.5 allow to cover most of the angular phase space



Summary and take-aways

- The dilepton final state allows to access fundamental properties of the nucleon (GPDs, GFFs).
- Rich experimental program with the CLAS12 detector, already producing some important results.
- Along the way, we have learn some important lesson that could be applied for a second detector at the EIC.
- Proton detection is essential to perform exclusive dilepton measurements. A second detector could provide ideal momentum reach.
- Muon detector would greatly improve the physics case and seem essential for some key measurements.