Prospects for DDVCS measurements

IJCLab - Orsay

BY:
Juan Sebastian Alvarado
Mostafa Hoballah
Eric Voutier

Towards improved hadron tomography with hard exclusive reactions

August 4th 2024, Trento

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INTRODUCTION

GPDs

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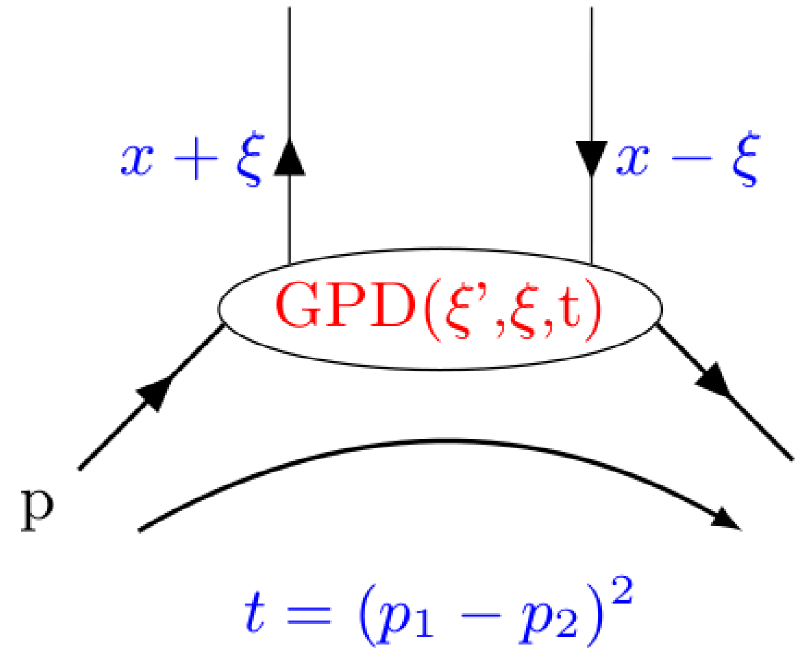
Motivation

1 INTRODUCTION

Generalized Parton Distributions (GPDs) allows to access the 3D structure of nucleons

- They correlate the transverse position and longitudinal momentum of partons in the nucleon.
  - spatial distribution of partons
  - mechanical properties of hadrons
  - hadron's spin decomposition
- To measure GPDs we require deep exclusive processes
- They enter the cross-section through Compton Form Factors (CFFs).
- For a spin 1/2 particle there are four chiral-even GPDs

$$\mathcal{F}(\xi, t) \equiv \mathcal{P} \int_{-1}^{1} dx\, F(x, \xi, t) \left(\frac{1}{x - \xi + i\epsilon} \pm \frac{1}{x + \xi + i\epsilon} \right).$$



GPDs: $H^q, E^q, \widetilde{H}^q, \widetilde{E}^q(x, \xi, t)$

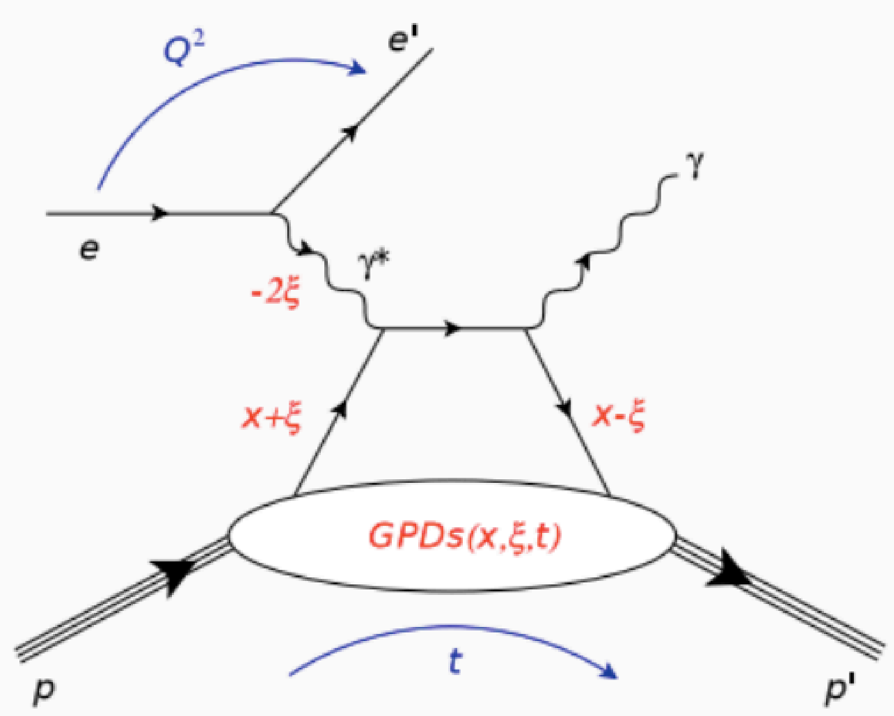
1

Two golden channels for GPD measurements are DVCS and DDVCS

K. Deja, V. Martinez-Fernandez et al. Phys. Rev. D 107.9 (2023), p. 094035.

See Victor's talk !

$ep \rightarrow ep\gamma$



Deeply Virtual Compton Scattering (DVCS)

$$\mathcal{H}(\xi,\xi,t) = \sum_q e_q^2 \left\{ \mathcal{P}\int_{-1}^{1} dx\, H^q(x,\xi,t)\left[\frac{1}{x-\xi}+\frac{1}{x+\xi}\right] - i\pi\left[H^q(\xi,\xi,t)-H^q(-\xi,\xi,t)\right]\right\}$$

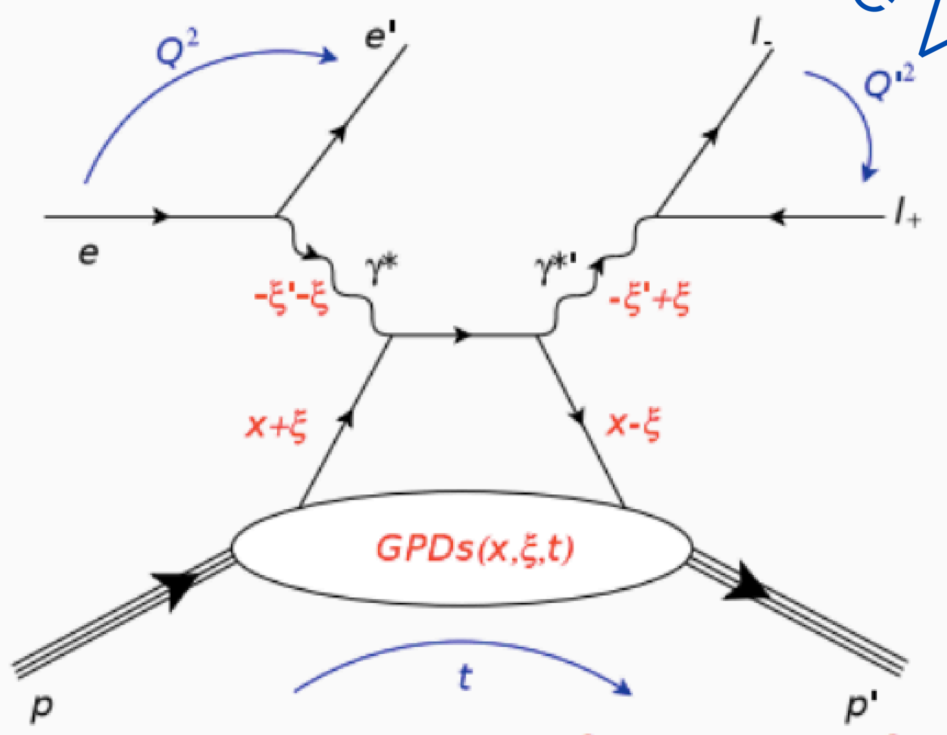
PROS:

- Direct GPD measurement from Im(CFF).

CONS:

- GPD measurements only at $x = \pm\xi$.

$ep \rightarrow epl^- l^+$



Double DVCS (DDVCS)

$$\mathcal{H}(\xi',\xi,t) = \sum_q e_q^2 \left\{ \mathcal{P}\int_{-1}^{1} dx\, H^q(x,\xi,t)\left[\frac{1}{x-\xi'}+\frac{1}{x+\xi'}\right] - i\pi\left[H^q(\xi',\xi,t)-H^q(-\xi',\xi,t)\right]\right\}$$

PROS:

- GPD measurement at $\xi' \neq \xi$ values.
- Generalizes the results of DVCS and TCS.

CONS:

- Smaller cross section.

1 INTRODUCTION

We consider a muon pair in the final state, polarized electron/positron beams and a polarized proton target.

- At JLab (12 GeV beam energy):
  - A muon detector is planned (SoLID collaboration)
  - A positron beam is planned (PEPPo, Ce+BAF and JLab positron working group)
- At EIC (140 GeV CoM energy):
  - Positron beams may exist
  - Muon detection might be possible
- We consider the following experimental observables*:
  - Beam Spin Asymmetry (BSA) A_{LU}
  - Target Spin Asymmetry (TSA) A_{UL}
  - Double Spin Asymmetry (DSA) A_{LL}
  - Beam Charge Asymmetry (BCA) A_{UU}^{C}

Jefferson Lab Experiment LOI12-16-004
Jefferson Lab Experiment LOI12-23-012

A. Accardi et al. Eur. Phys. J. A 57 (2021), p. 261,
J. Grames et al. arXiv preprint arXiv:2309.15581 (2023)

A. Accardi et al. In: The European Physical Journal A 52 (2016), pp. 1–100.

*defined with the cross-section integrated over muon angles

1 INTRODUCTION

Such observables have the following CFF dependence

$$A_{LU} \propto \sin(\phi)\Im\left((F_1\mathcal{H} - kF_2\mathcal{E}) + \xi'(F_1+F_2)\tilde{\mathcal{H}}\right)$$

$$A_{UU}^{C} \propto \cos(\phi)\Re\left(\frac{\xi'}{\xi}(F_1\mathcal{H} - kF_2\mathcal{E}) + \xi(F_1+F_2)\tilde{\mathcal{H}}\right)$$

$$A_{UL} \propto \sin(\phi)\Im\left(F_1\tilde{\mathcal{H}} + \xi'(F_1+F_2)\left(\mathcal{H} + \frac{\xi}{1+\xi}\mathcal{E}\right) - \xi\left(\frac{\xi}{1+\xi}F_1 + kF_2\right)\tilde{\mathcal{E}}\right)$$

$$A_{LL} \propto A + B\cos(\phi)$$

$$A \propto \Re\left(\xi(F_1+F_2)\left(\mathcal{H} + \frac{\xi}{1+\xi}\mathcal{E}\right) + F_1\tilde{\mathcal{H}} - \xi\left(\frac{\xi}{1+\xi}F_1 + kF_2\right)\tilde{\mathcal{E}}\right)$$

$$B \propto \Re\left(\xi(F_1+F_2)\left(\mathcal{H} + \frac{\xi}{1+\xi}\mathcal{E}\right) + \frac{\xi'}{\xi}F_1\tilde{\mathcal{H}} - \xi'\left(\frac{\xi}{1+\xi}F_1 + kF_2\right)\tilde{\mathcal{E}}\right)$$

A. V. Belitsky et al. In: Physical Review D 68.11 (2003), p. 116005

- A_{LU} and A_{UU}^{C} are GPD H dominated.
- A_{UL} is GPD $\widetilde{H}$ dominated.
- Due to the ξ' dependence, the coefficients in A_{LL} no longer have the same CFF dependence. Likewise for A_{LU} and A_{UU}^{C}

1 INTRODUCTION

To model GPDs, the models used for evaluations are:

- VGG: Orsay's code.
  For a review see M. Guidal et al. Rep. Prog. Phys. 76.6 (2013): 066202.
- GK19: Latest model from PARTONS (B. Berthou et al. Eur. Phys. J. C 78 (2018): 1-19.)
  S. Goloskokov et al. Eur. Phys. J. C 50 (2007), pp. 829–842.
- KM10, KM15: Models from Gepard (https://gepard.phy.hr)
  K. Kumerički and D. Mueller. Nuc. Phys. B 841.1-2 (2010), pp. 1–58.
- AFKM12: KM model adaptation for EIC kinematics
  E. Aschenauer et al. JHEP 2013.9 (2013), pp. 1–59

→ Extended for DDVCS computations

The main goal of this study is to:

- Quantify the GPD dependence of the DDVCS observables within a reasonable kinematic window.
- Look for kinematic regions where models can be discriminated.
- Give preliminary projections for DDVCS measurements within the JLab and EIC experimental configurations.

2

MEASUREMENTS AT JLAB KINEMATICS

The CLAS12 spectrometer

The SoLID spectrometer

The 22 GeV case

2

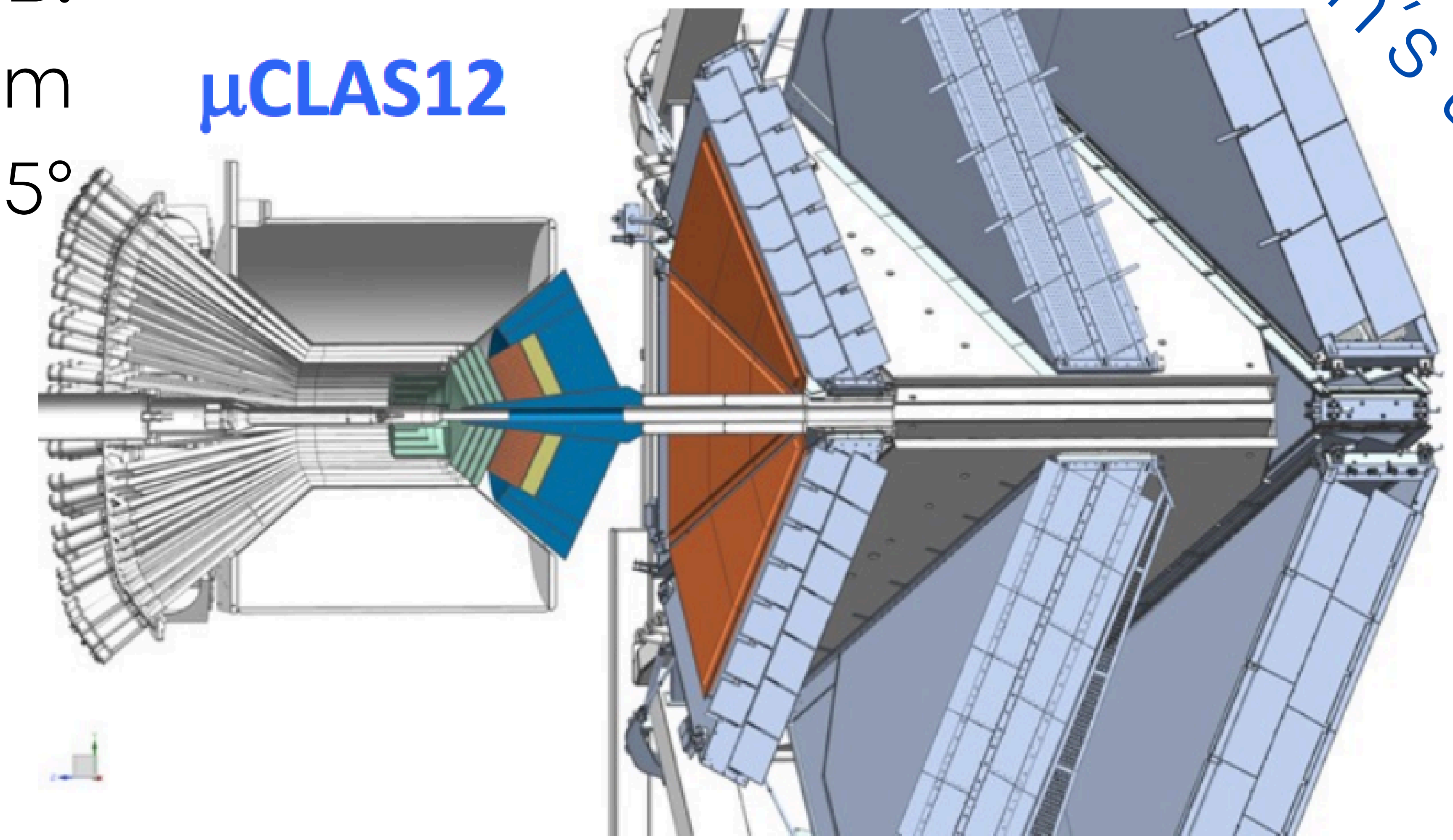
MEASUREMENTS AT JLAB

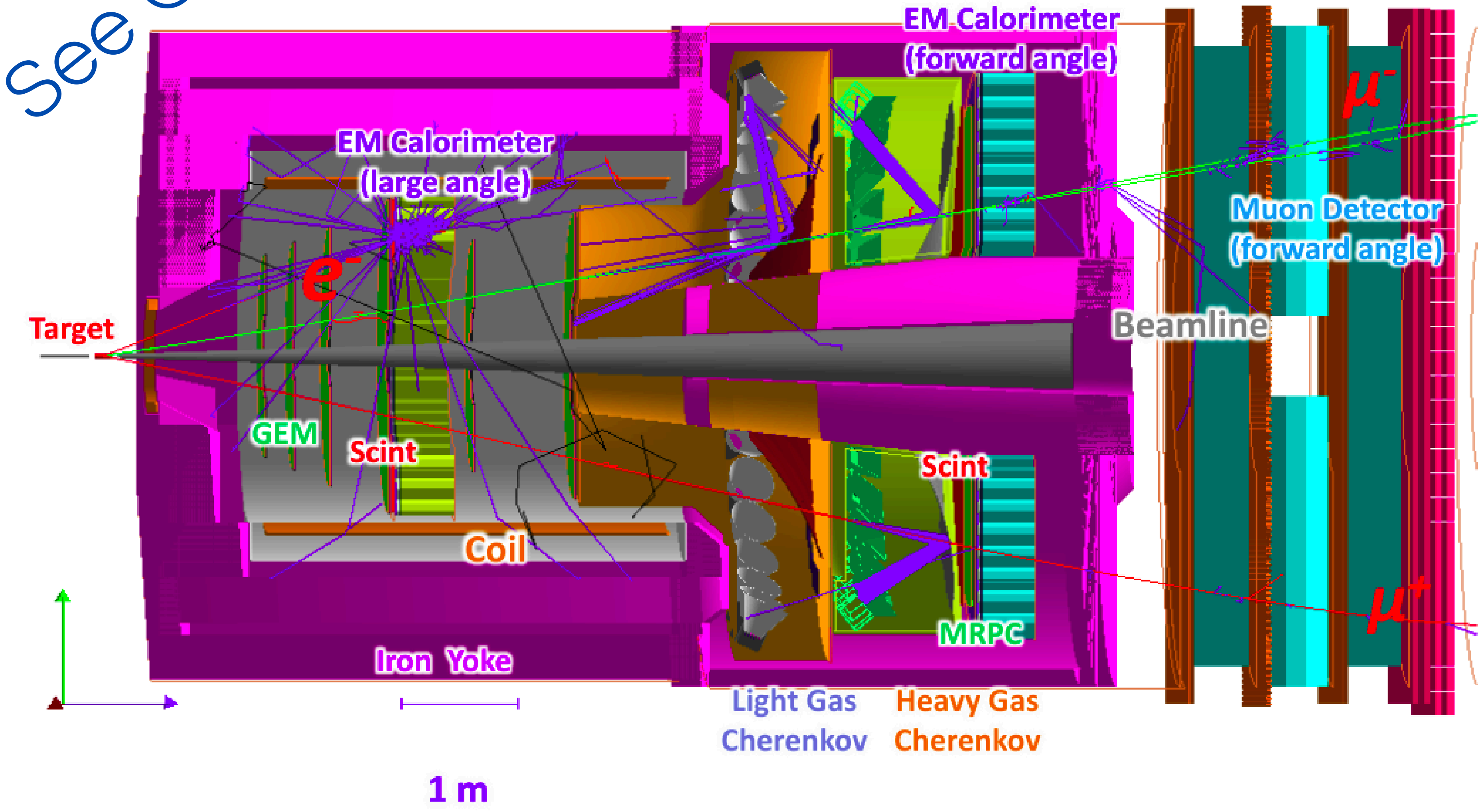
See Stepan's talk!

Upgraded CLAS12 spectrometer at Hall B:

- acceptance of charged particles from 7° to 35°

See Garth's talk !

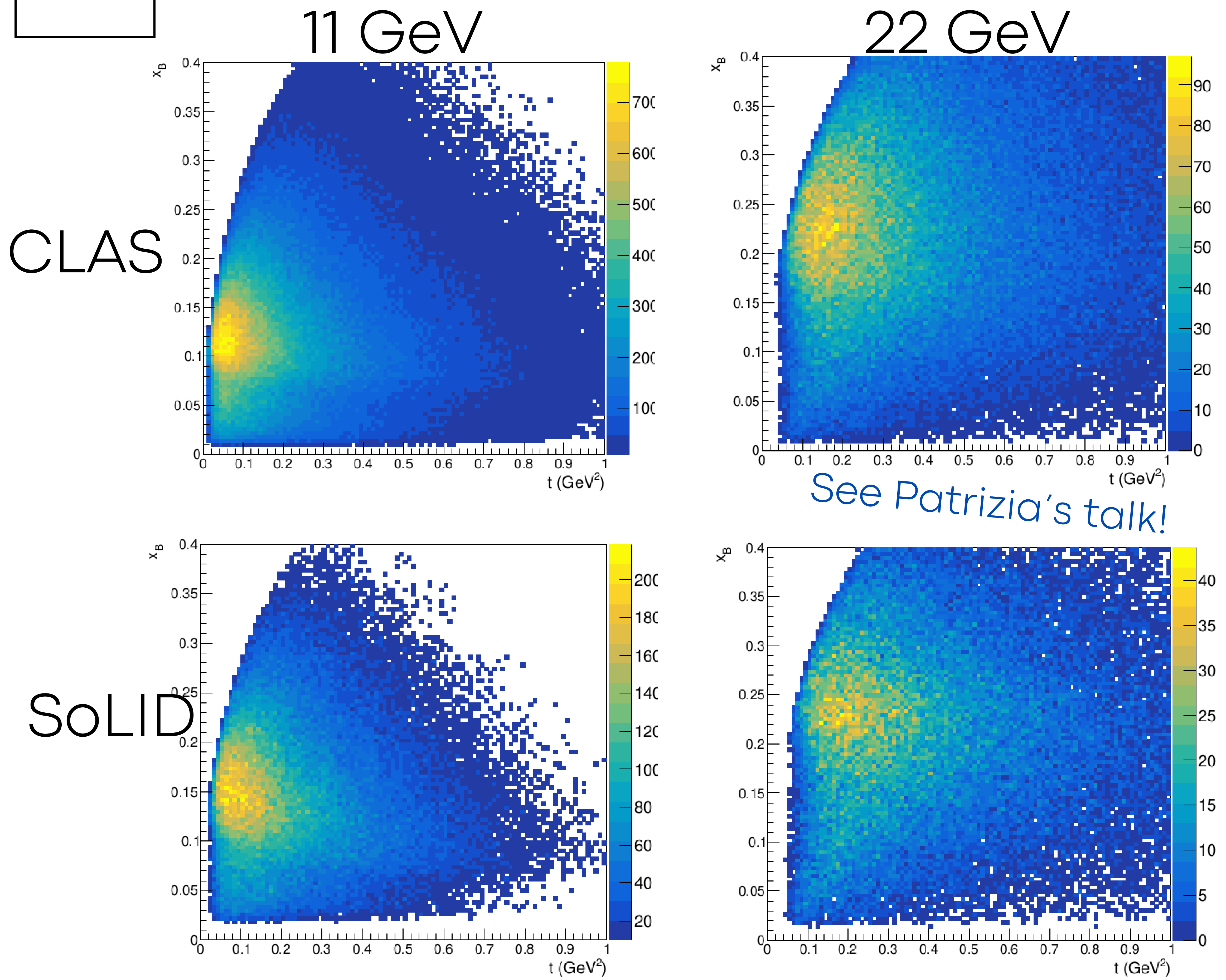




SoLID spectrometer at Hall A

- acceptance of muons from 7° to 50°
- acceptance of scattered electron from 7° to 35°

MEASUREMENTS AT JLAB



The kinematic reach for DDVCS was studied in the LOI12-16-004 for CLAS and LOI12-15-005 for SoLID.

In both cases, the detectors are designed to support a luminosity of

$$\mathcal{L} = 10^{37}\mathrm{cm}^{-2}\mathrm{s} - 1$$

(although SoLID can go up to 10^{39})

They would allow measurements at small t and

$$0.1 < x_B < 0.3$$

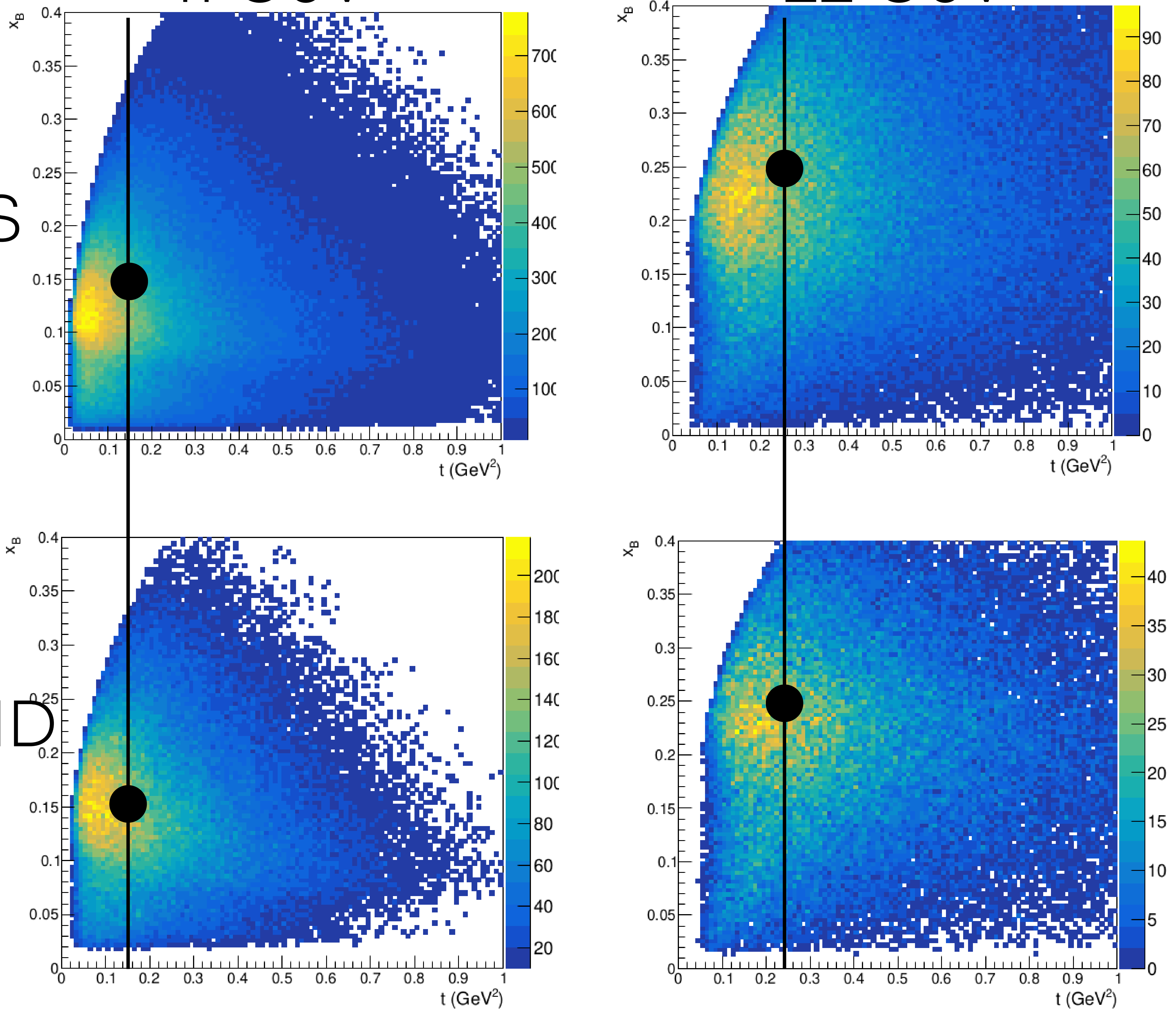
2

MEASUREMENTS AT JLAB

11 GeV 22 GeV

CLAS

SoLID



We perform an exploration of the DDVCS observables at:

- t=-0.15 GeV^2 and xB=0.15 @ 11 GeV
- t=-0.25 GeV^2 and xB=0.25 @ 22 GeV

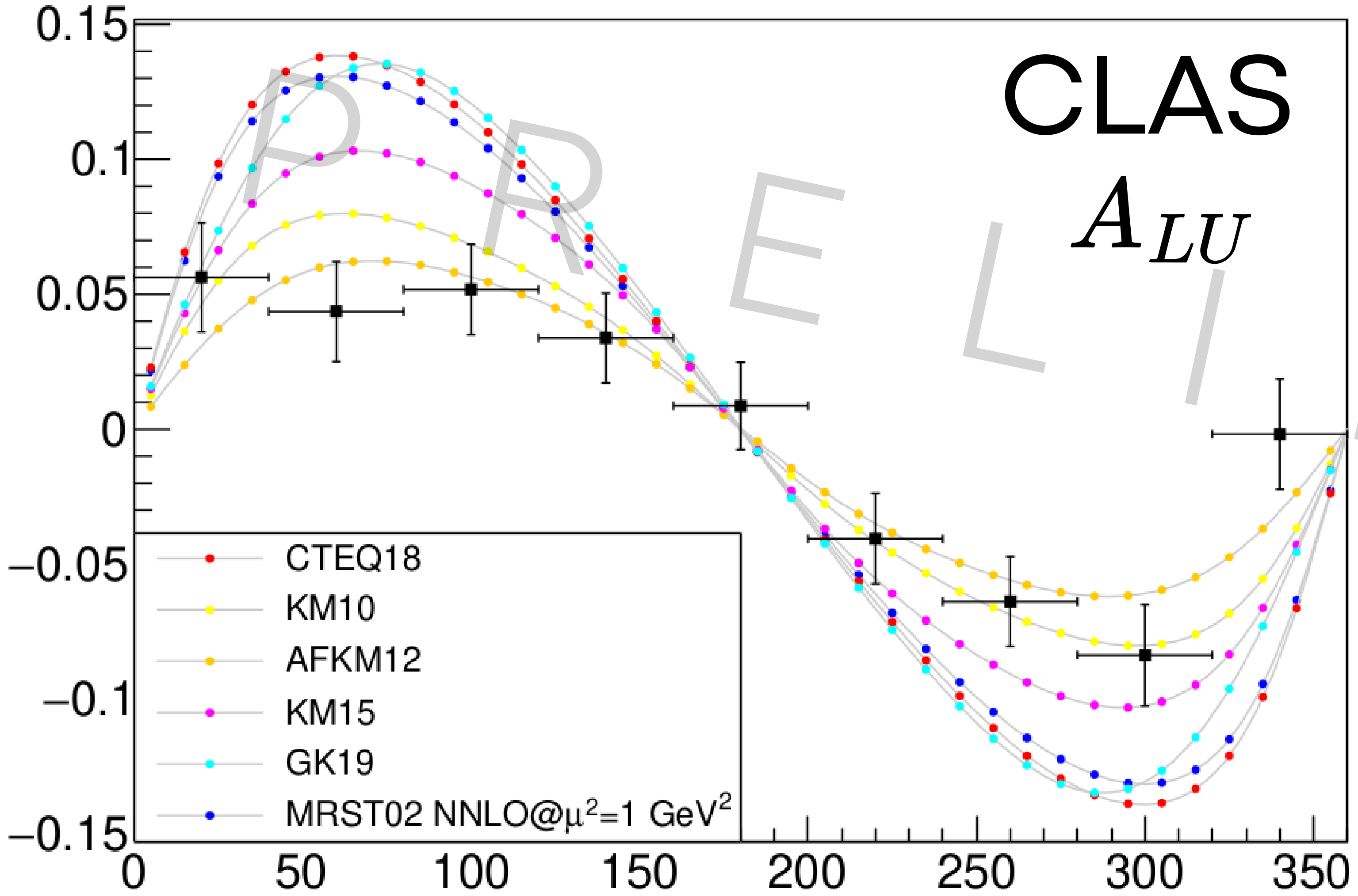
While Q^2 and Q'^2 are explored in the allowed kinematic range:

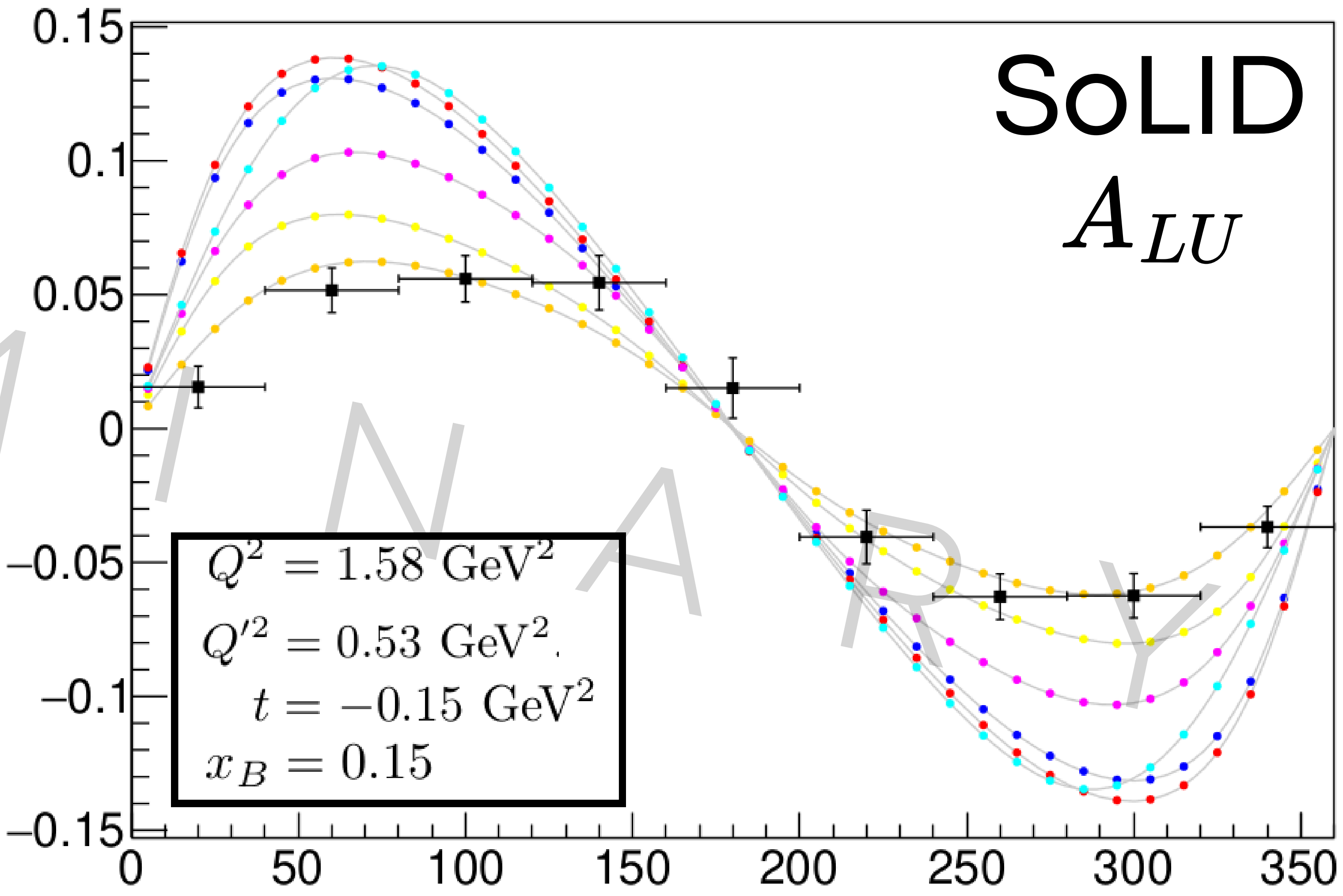
$$0 < Q^2 < 2Mx_BE$$

$$4m_\mu^2 < Q'^2$$

2

MEASUREMENTS AT JLAB





At 11 GeV, measurements are possible within **100** days of beam time

Bins widths are given by:

- $\Delta Q^2 = 1\ \mathrm{GeV}^2$,
- $\Delta Q'^2 = 1\ \mathrm{GeV}^2$,
- $\Delta t = 0.05\ \mathrm{GeV}^2$,
- $\Delta x_B = 0.1$.

Statistics from EpIC and detector acceptance

E. C. Aschenauer, et al. Eur. Phys. J C 82.9 (2022): 1-12.

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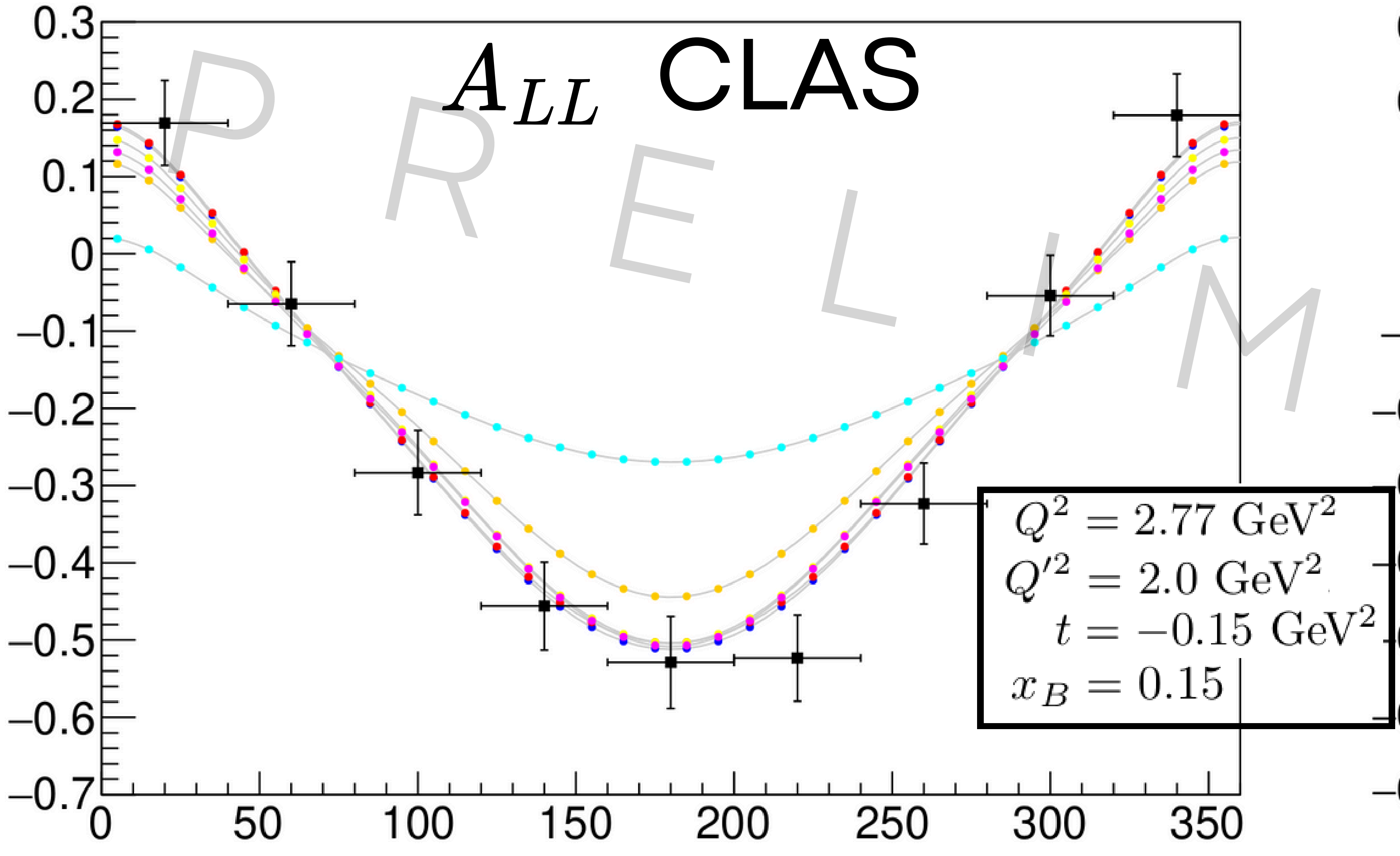
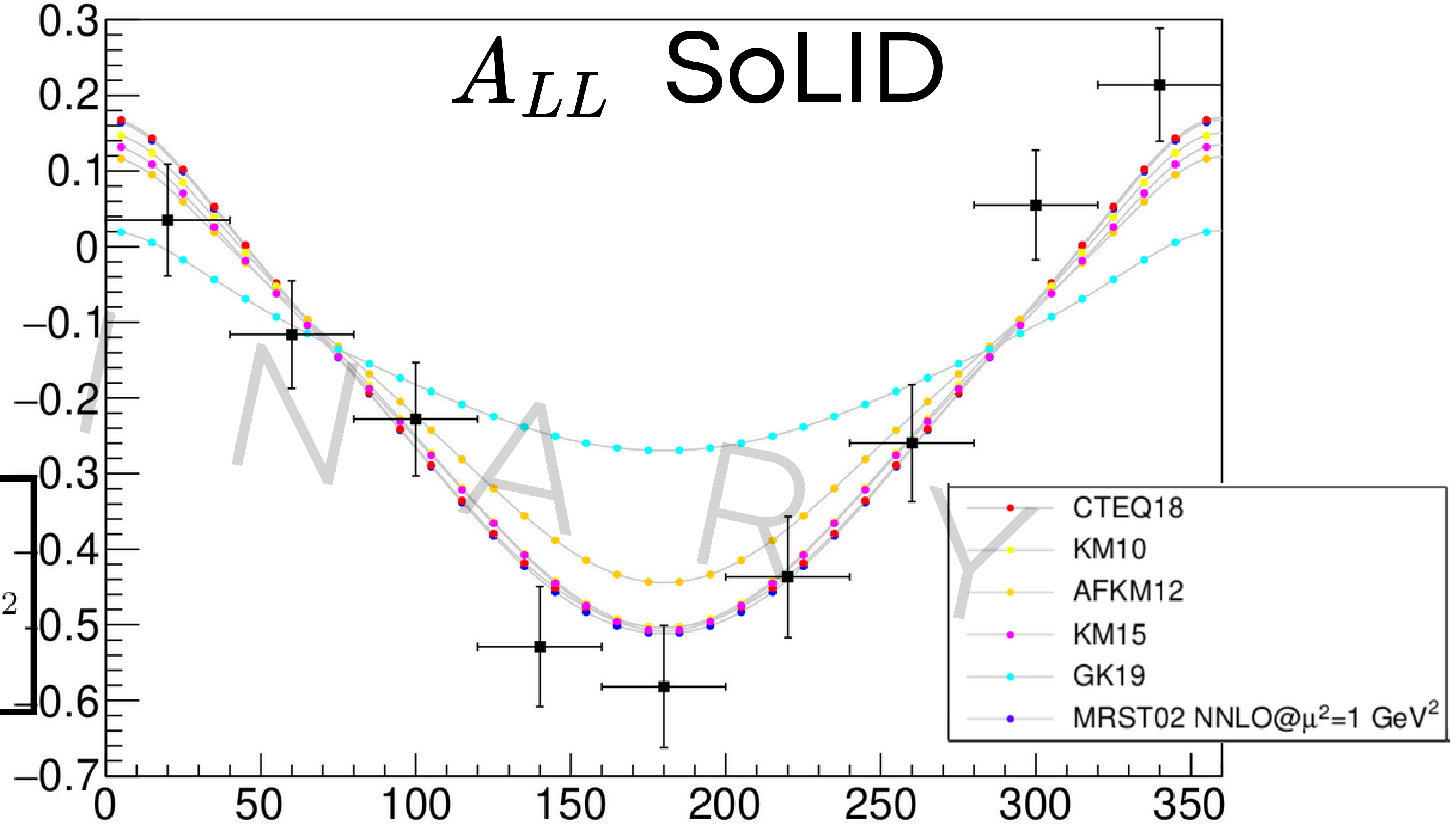
MEASUREMENTS AT JLAB





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Here we assume a polarized NH3 target

Statistics from EpIC and detector acceptance

E. C. Aschenauer, et al. Eur. Phys. J C 82.9 (2022): 1-12.

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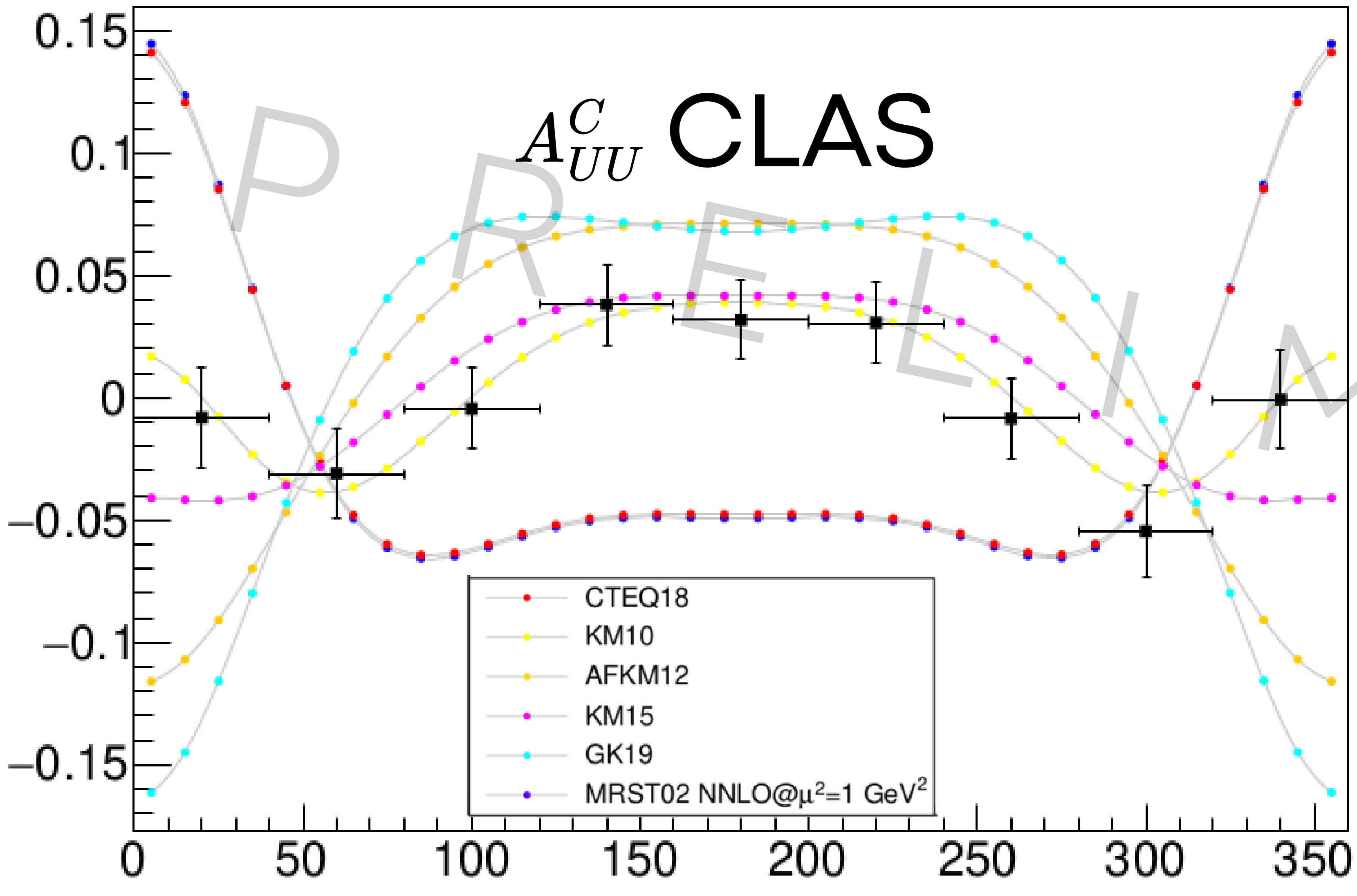
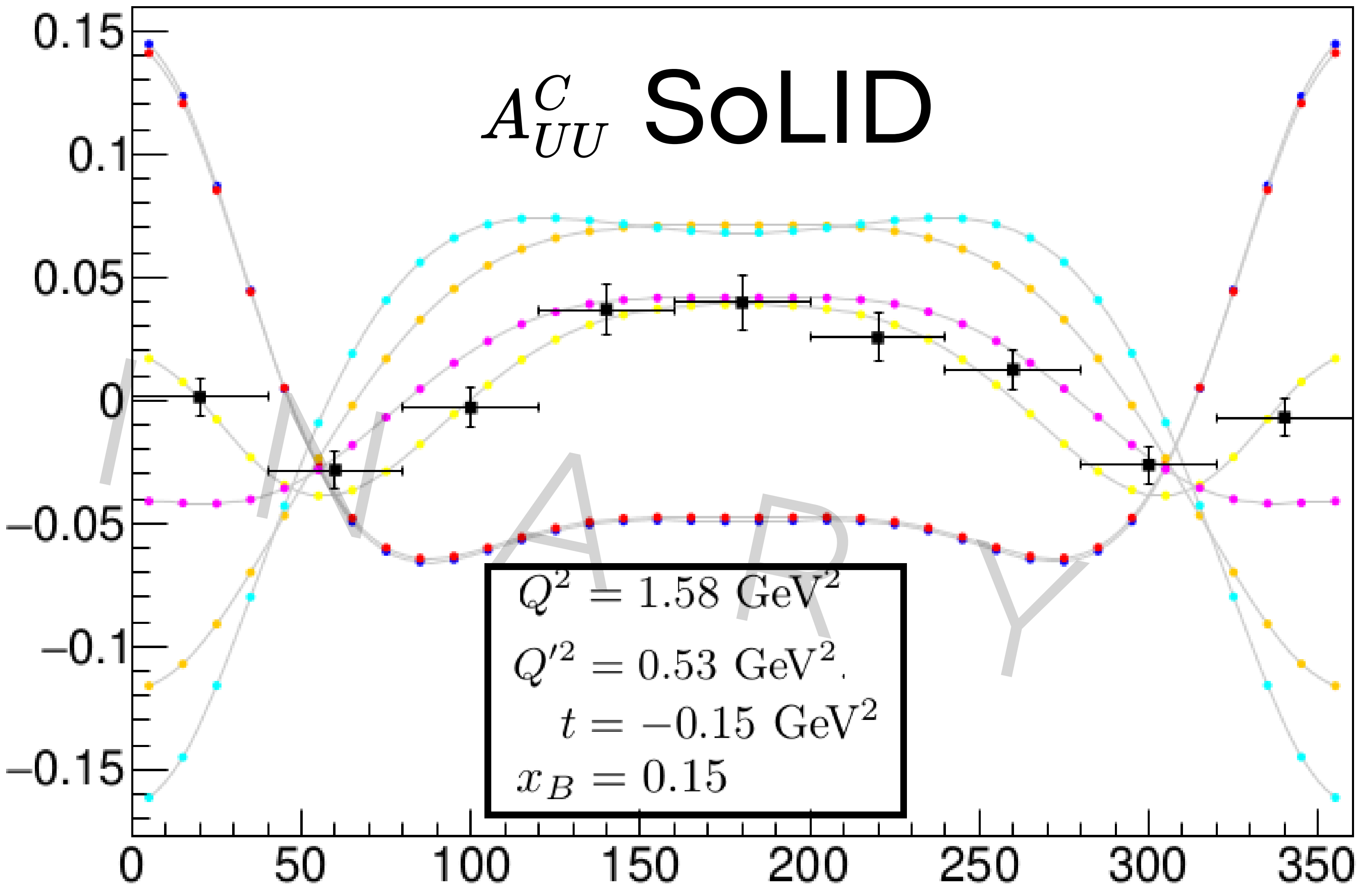
MEASUREMENTS AT JLAB





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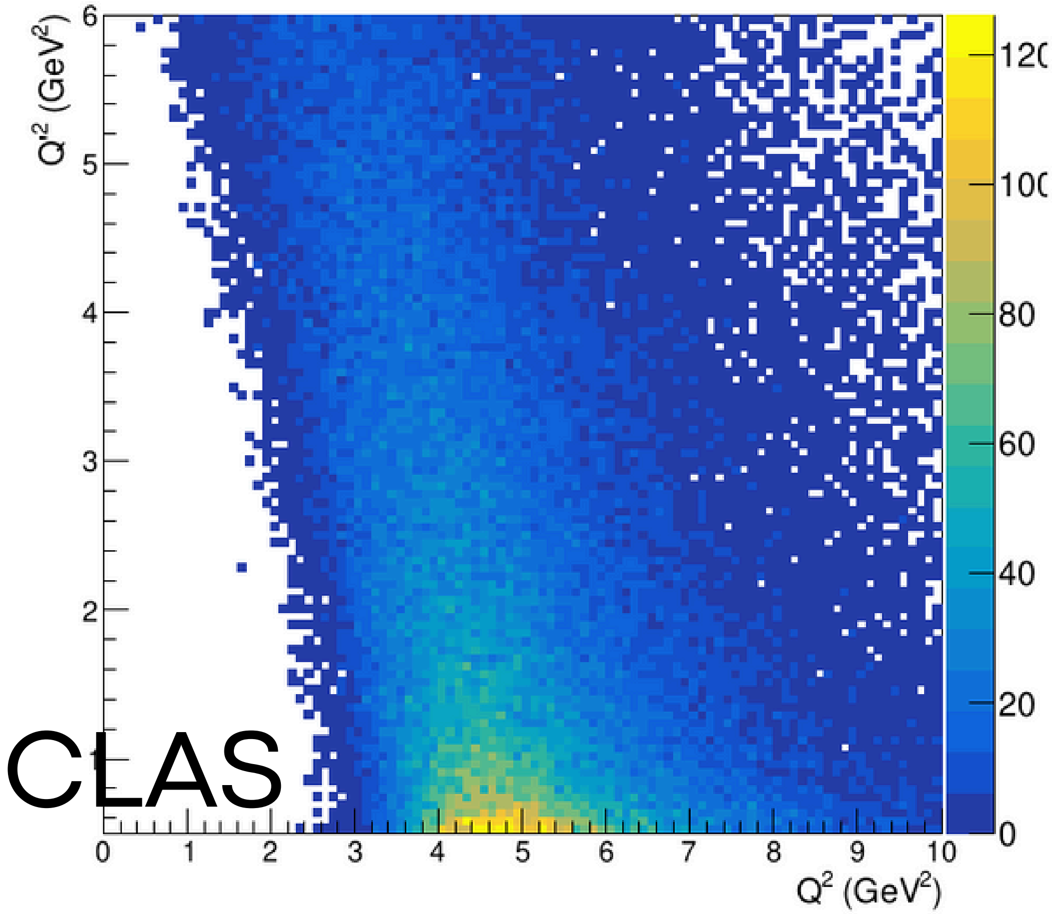
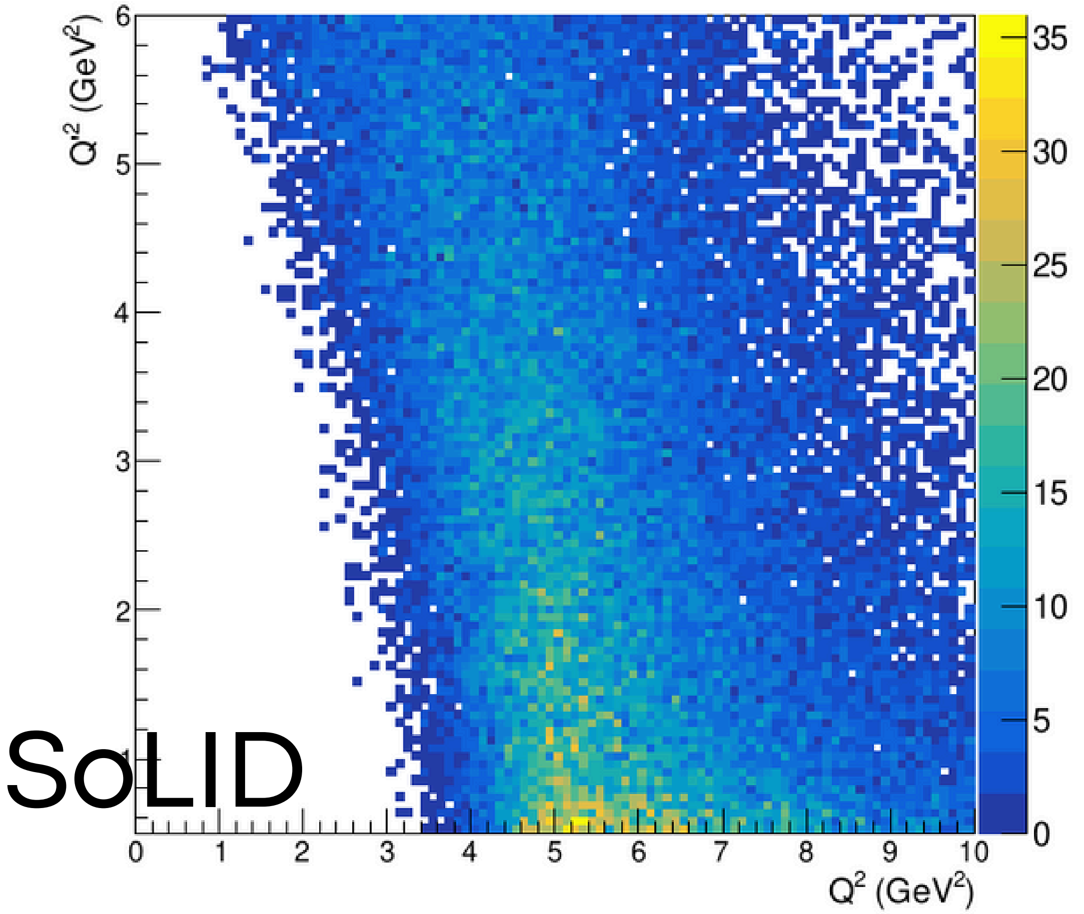
Statistics from EpIC and detector acceptance

E. C. Aschenauer, et al. Eur. Phys. J C 82.9 (2022): 1-12.

MEASUREMENTS AT JLAB

At 22 GeV we are restricted to larger values in Q^2 due to electron acceptance



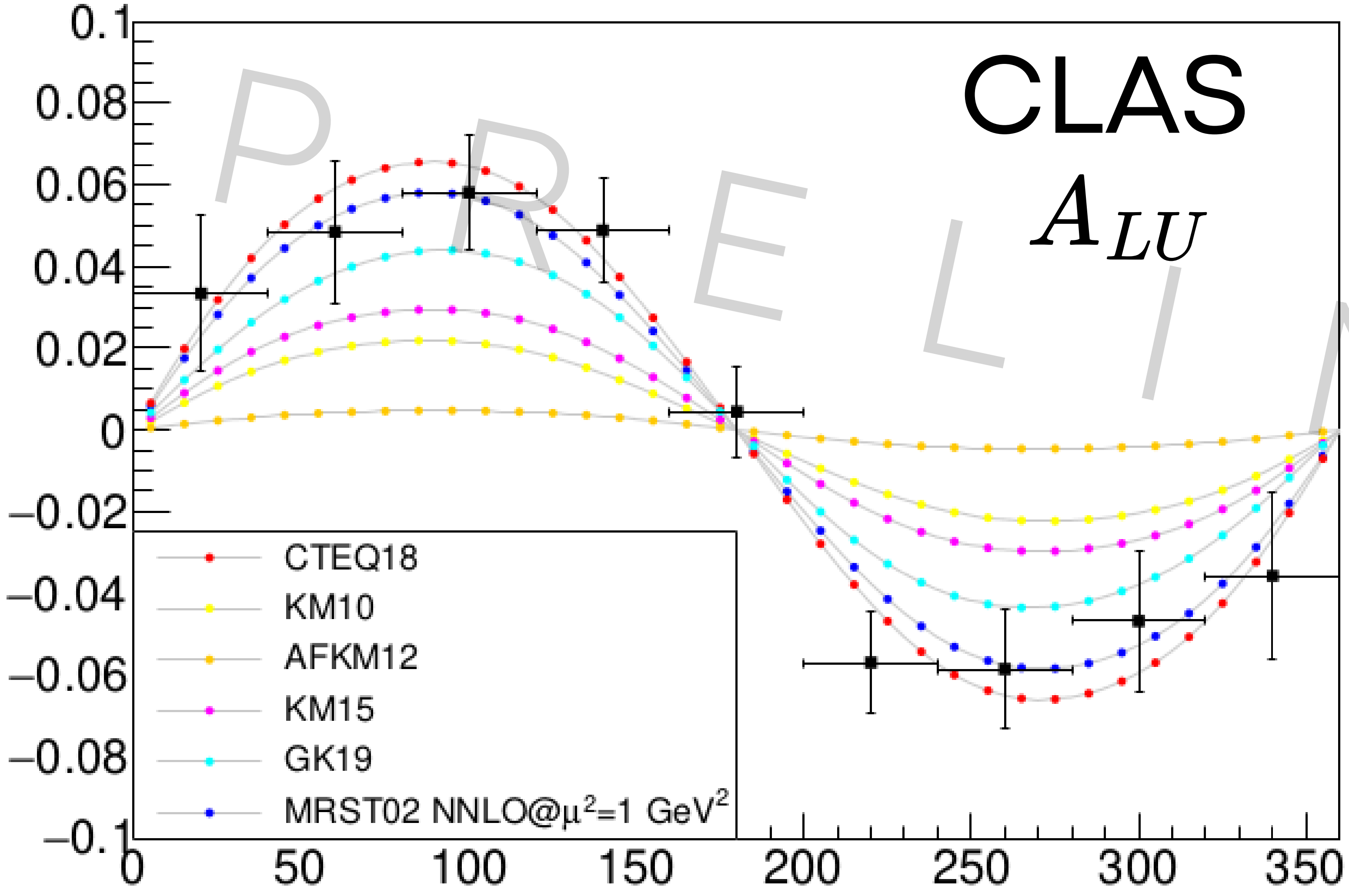


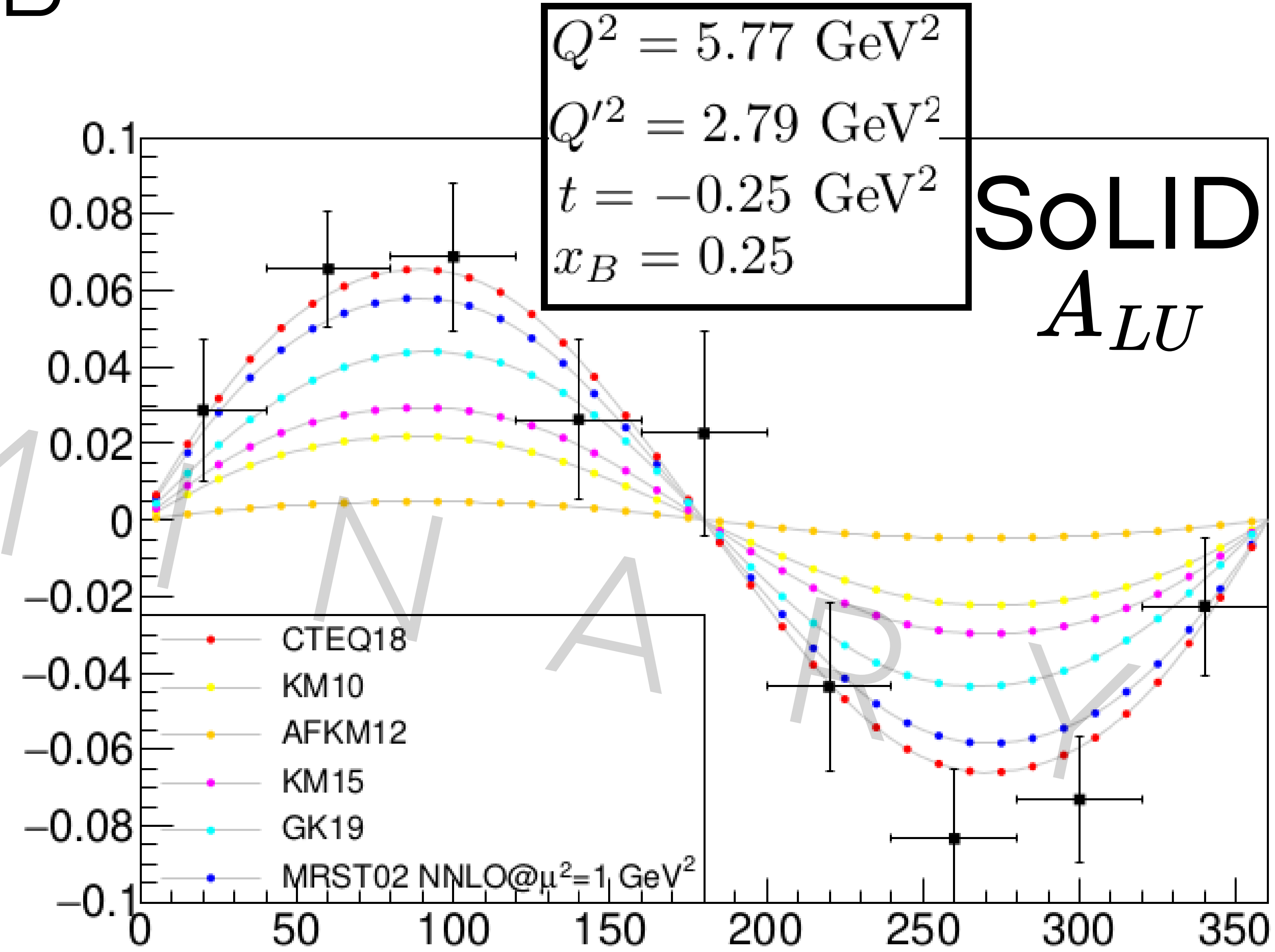
To compensate the smaller cross-section and explore regions of relative large Q'^2 we need to consider larger bins.

Let us consider the case of a single bin in t and xB :

$$t > -0.4\ \mathrm{GeV}^2$$
$$x_B < 0.4$$

MEASUREMENTS AT JLAB





At 22 GeV, measurements are possible within **200** days of beam time

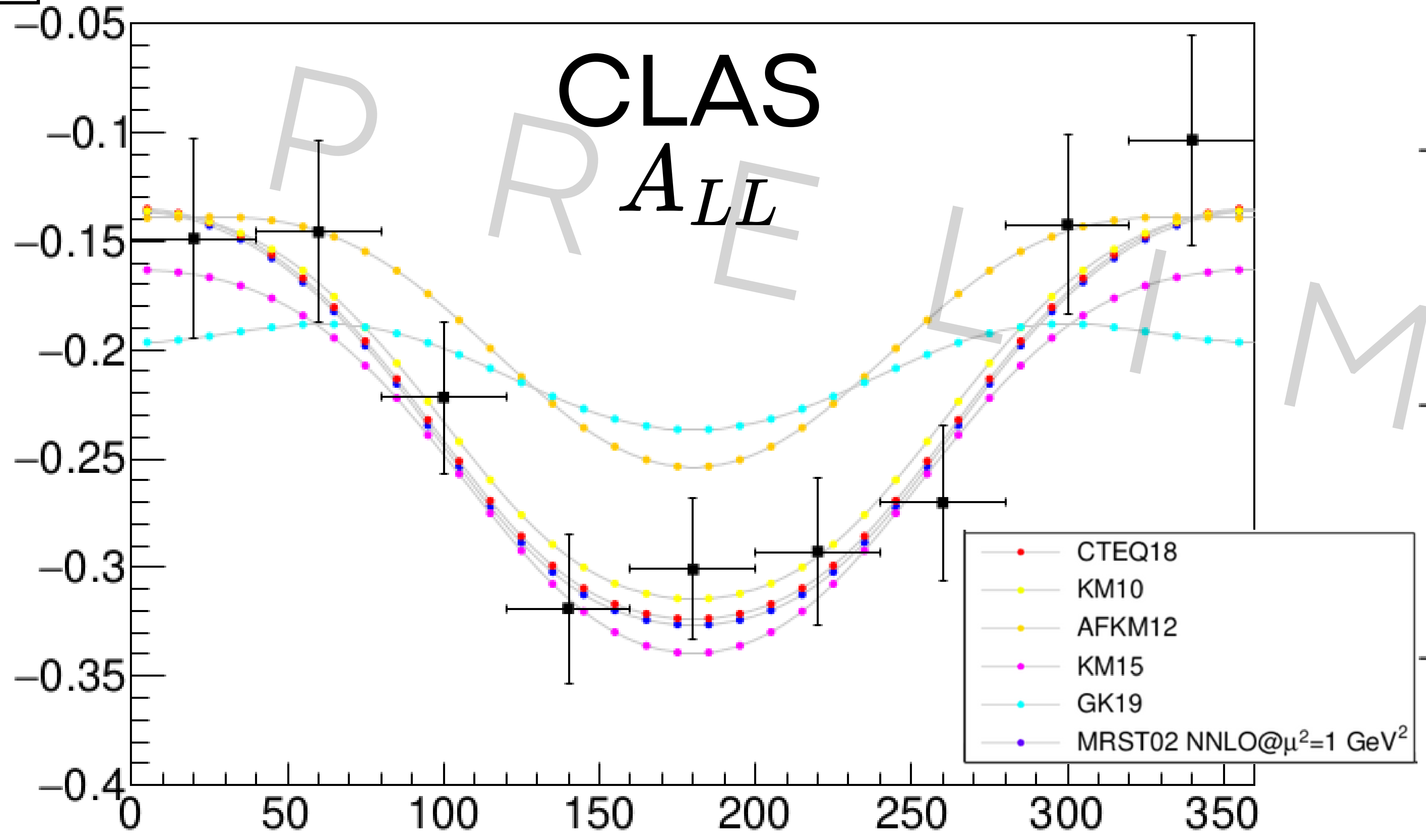
Bins widths are given by:

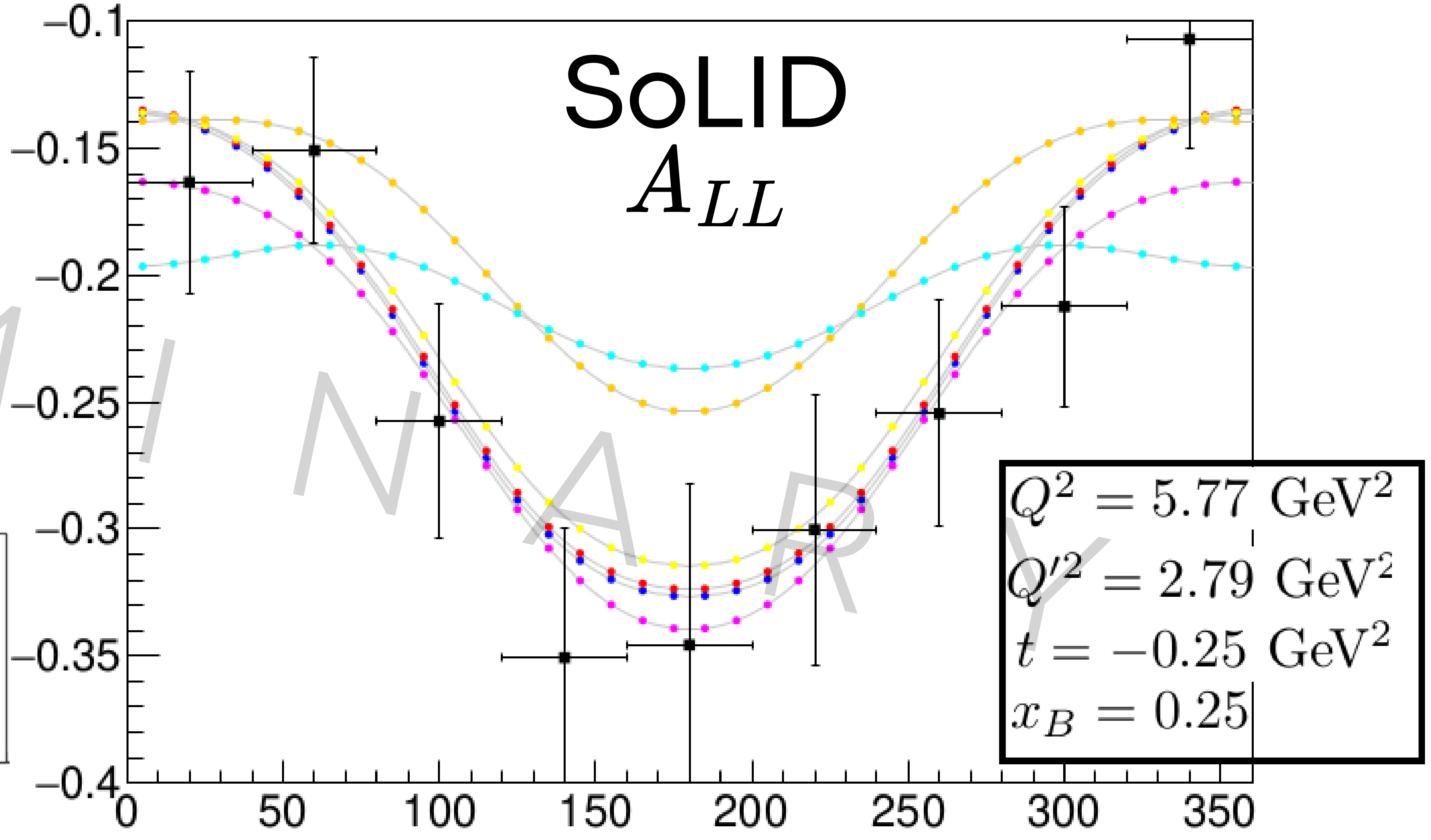
- $\Delta Q^2 = 1$ GeV^2,
- $\Delta Q'^2 = 1$ GeV^2,
- $t > -0.4$ GeV^2

Statistics from EpIC and detector acceptance

E. C. Aschenauer, et al. Eur. Phys. J C 82.9 (2022): 1-12.

MEASUREMENTS AT JLAB





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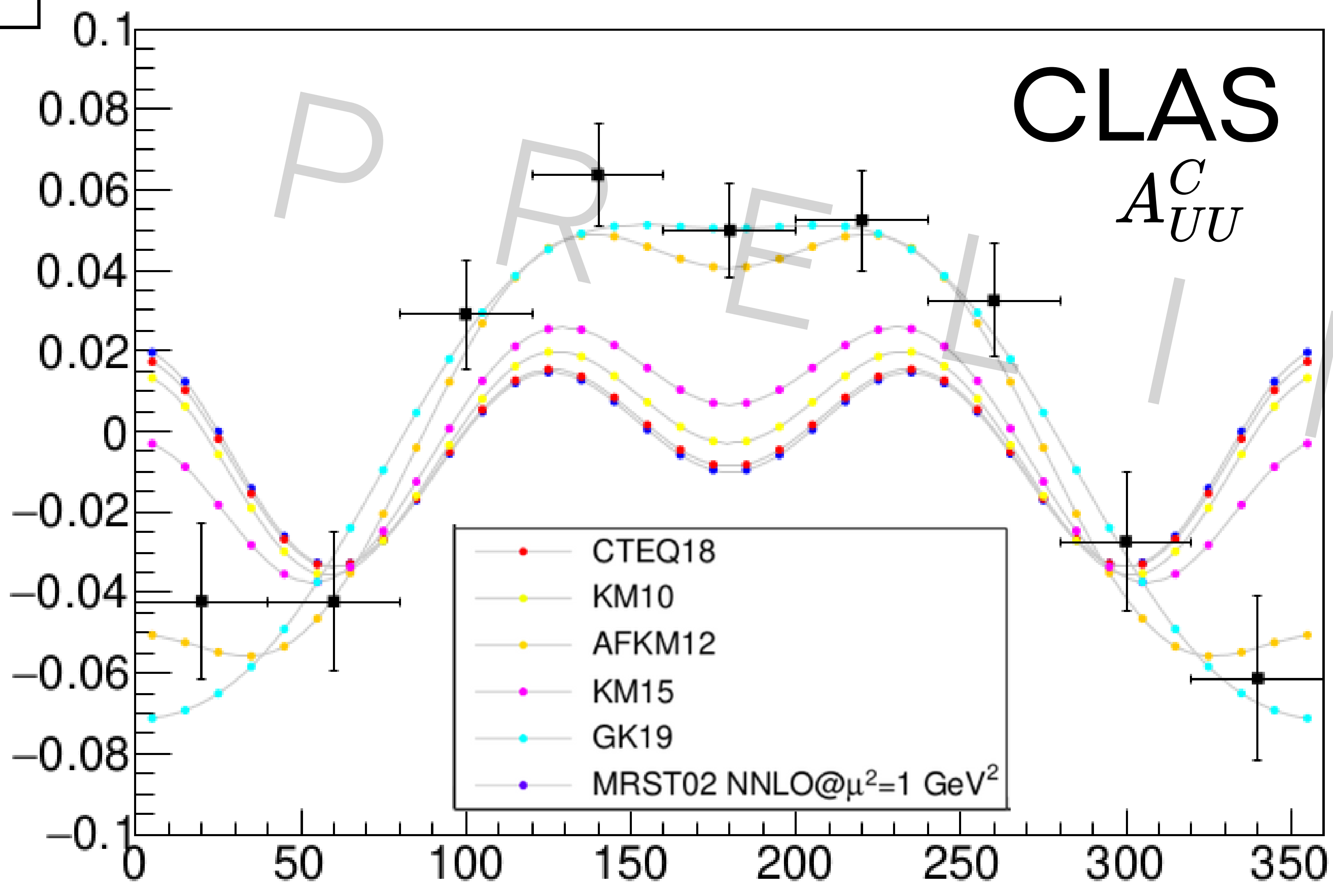
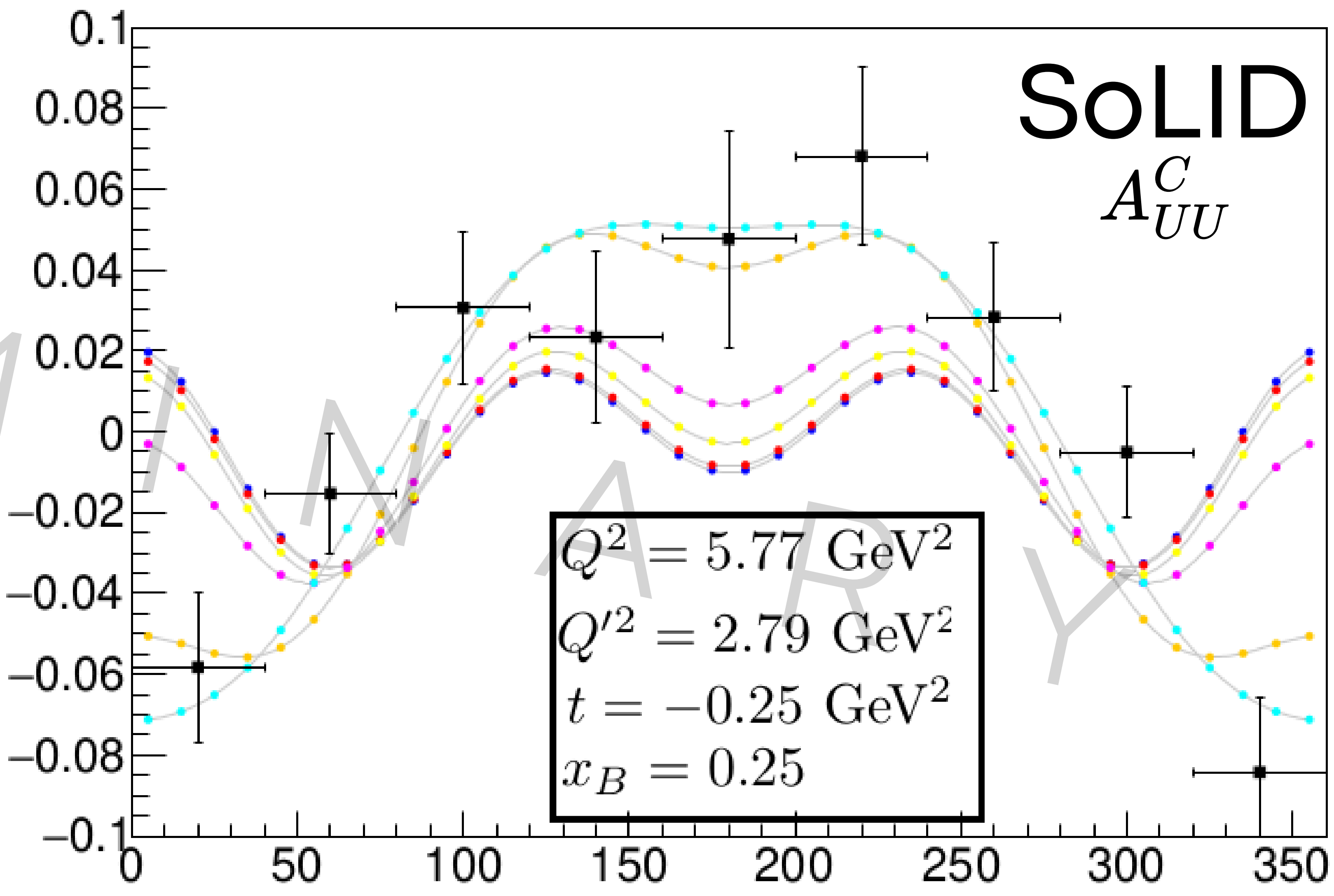
Here we assume a polarized NH3 target

Statistics from EpIC and detector acceptance

E. C. Aschenauer, et al. Eur. Phys. J C 82.9 (2022): 1-12.

MEASUREMENTS AT JLAB





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Statistics from EpIC and detector acceptance

E. C. Aschenauer, et al. Eur. Phys. J C 82.9 (2022): 1-12.

3

SENSITIVITY AT EIC KINEMATICS

3

MEASUREMENTS AT EIC

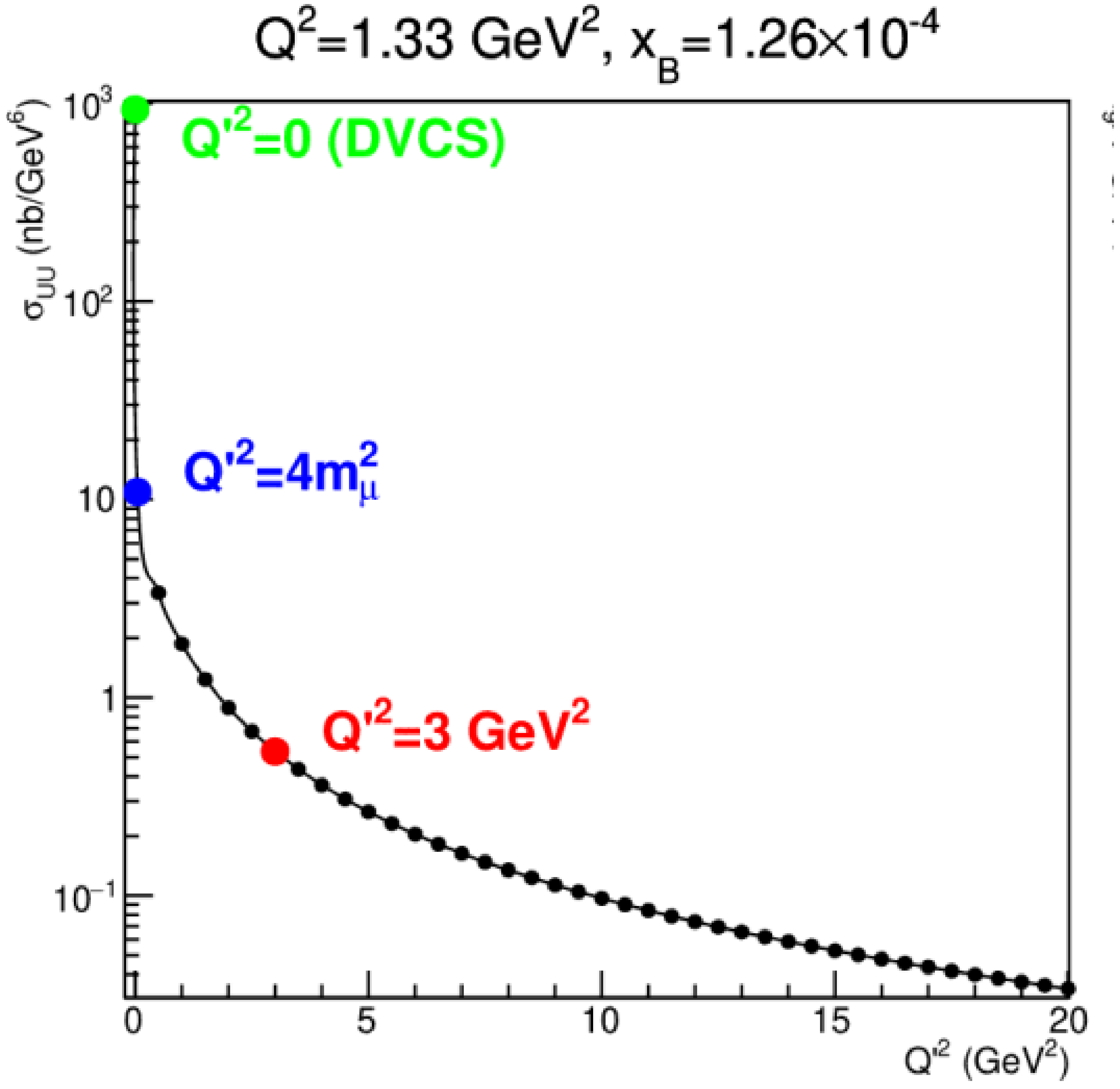
More details on Charlotte's talk

At EIC we expect:

- Maximum CoM energy of 140 GeV, allowing measurements up to $x_B \sim 10^{-4}$
- $\mathcal{L} = 10\ \mathrm{fb}^{-1}\mathrm{year}^{-1} < \mathcal{L}_{\mathrm{JLab}}$

The DDVCS cross section drops quickly with Q^2 and Q'^2.

Thus, we require measurements at relatively small Q^2 and Q'^2 values to compensate the smaller luminosity.



3 MEASUREMENTS AT EIC

- At large center of mass energies, we can access smaller xB values.

- As $x_B \to 0, \xi(\xi') \to 0$ as well. Then, the experimental observables simplify to:

$$A_{LU} \propto \sin(\phi)\Im\left(\quad (F_1\mathcal{H} - kF_2\mathcal{E})\right)$$

$$A_{UU}^{C} \propto \cos(\phi)\Re\left(\frac{\xi'}{\xi}(F_1\mathcal{H} - kF_2\mathcal{E})\right)$$

$$A_{UL} \propto \sin(\phi)\Im\left(F_1\tilde{\mathcal{H}}\right)$$

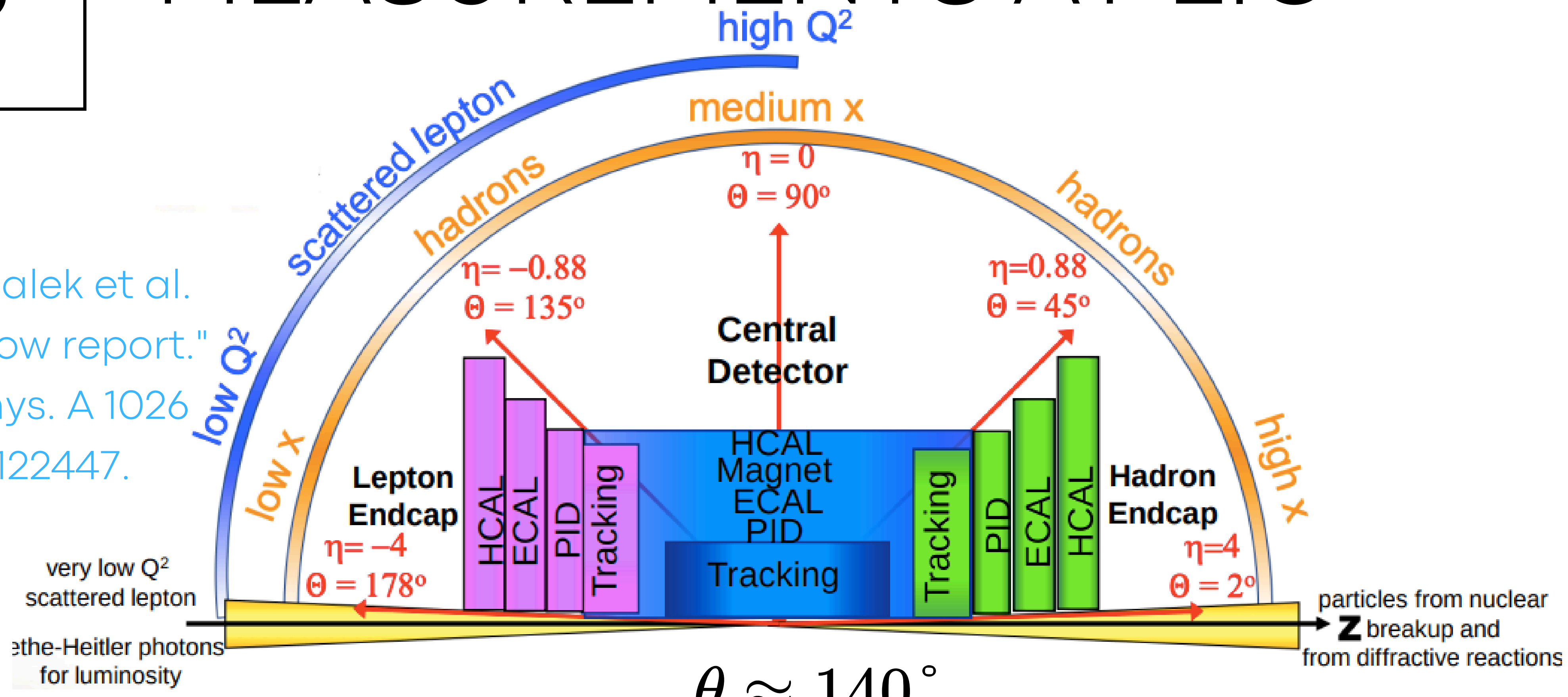
$$A_{LL} \propto A + B\cos(\phi)$$

  - $A, B \propto \Re(F_1\tilde{\mathcal{H}})$

Allowing then cleaner measurements of GPDs.

However, only A_{LU} and A_{UU}^{C} have amplitudes above 1% on the explored region

MEASUREMENTS AT EIC

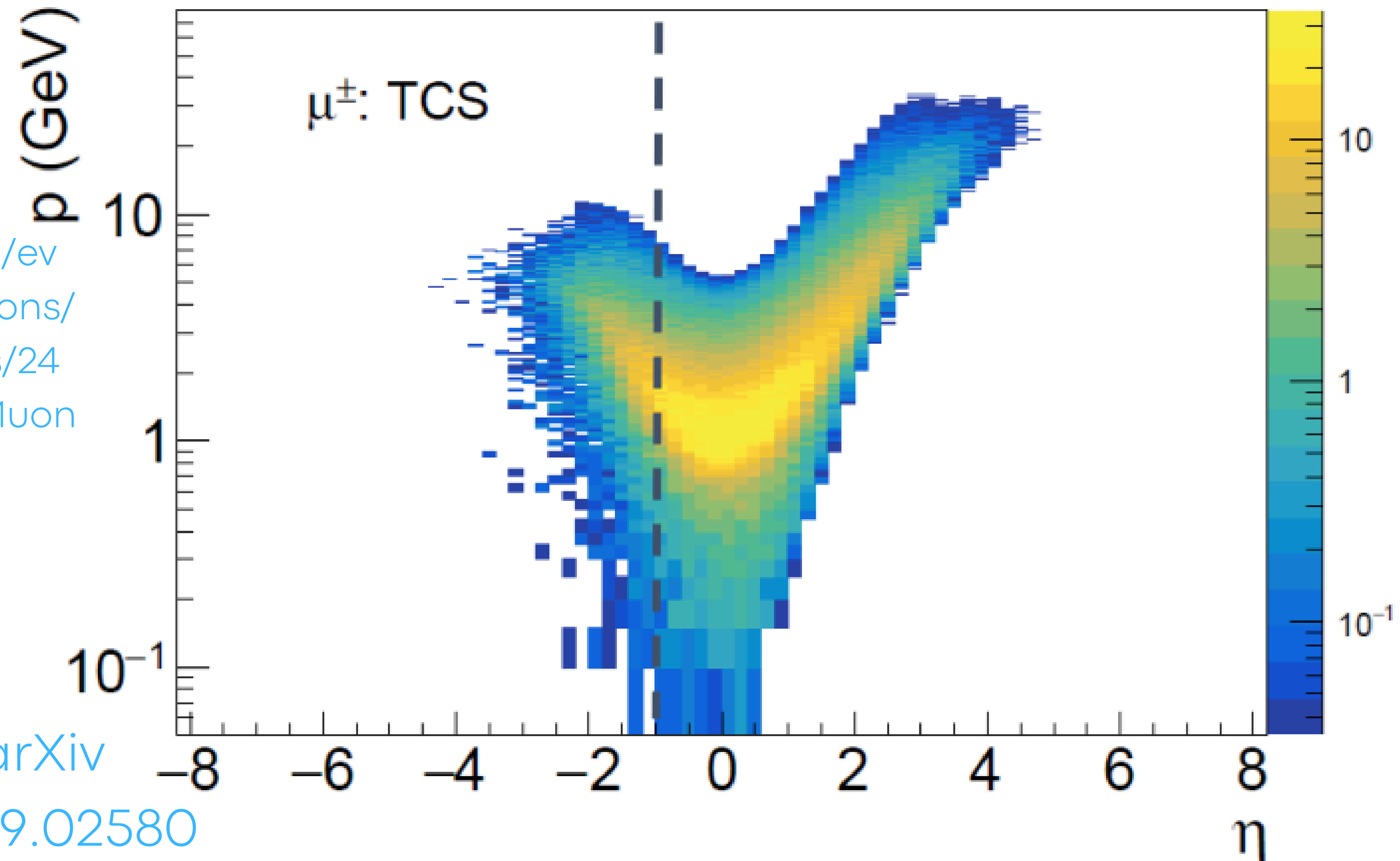


R. A. Khalek et al. EIC yellow report." Nuc. Phys. A 1026 (2022): 122447.

$\theta \approx 140^\circ$

η<-1: potential muon chamber upgrade

η>-1: ECCE muon ID coverage with EMCal + HCal



https://indico.cern.ch/event/1152971/contributions/4841393/attachments/2430661/4162119/ECCE_Muons.pdf

J. K. Adkins et al. arXiv preprint arXiv:2209.02580

We generated DDVCS events using the EpIC generator considering

- Electrons @ 18 GeV
- Protons @ 275 GeV

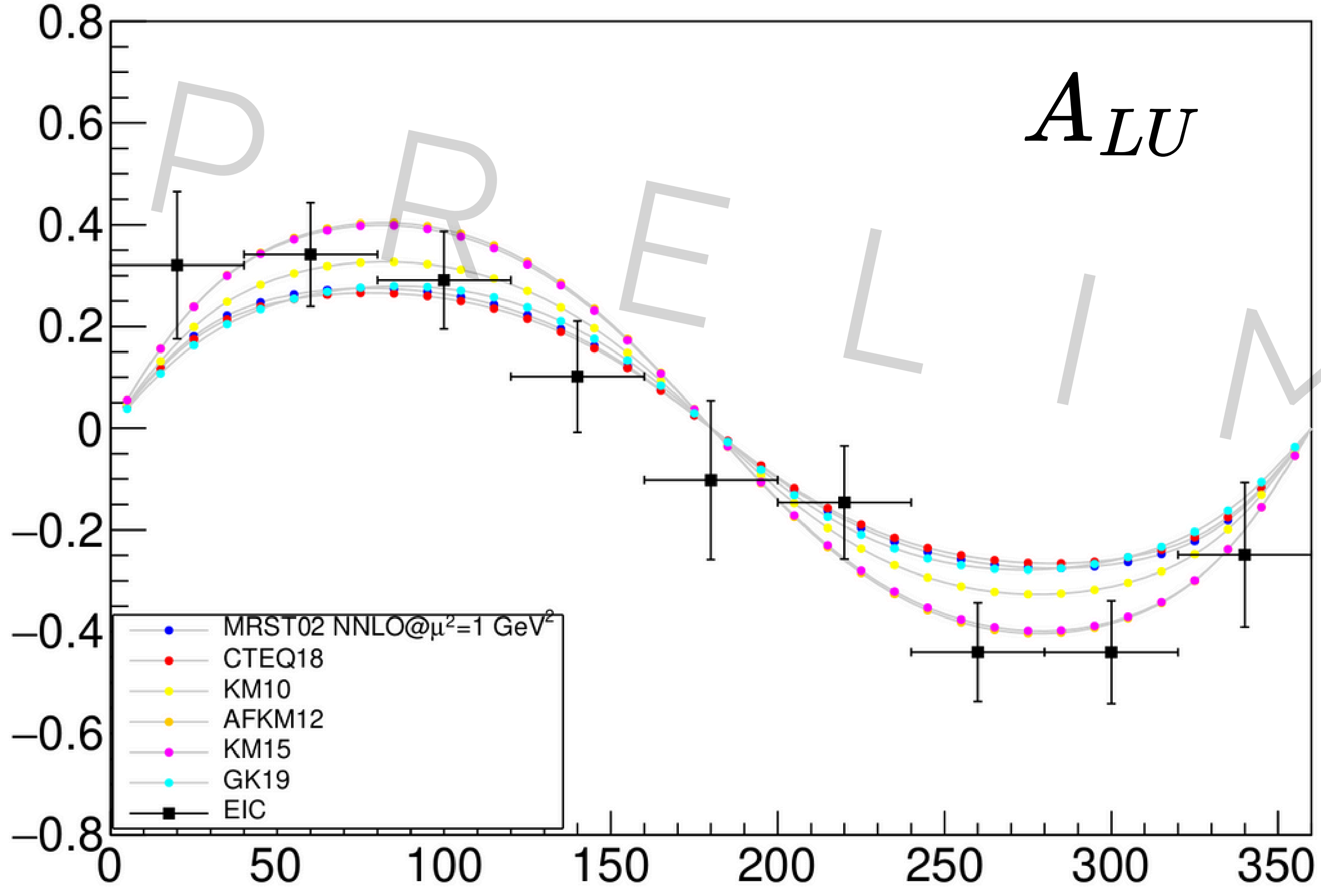
Then, we assumme muon detection of

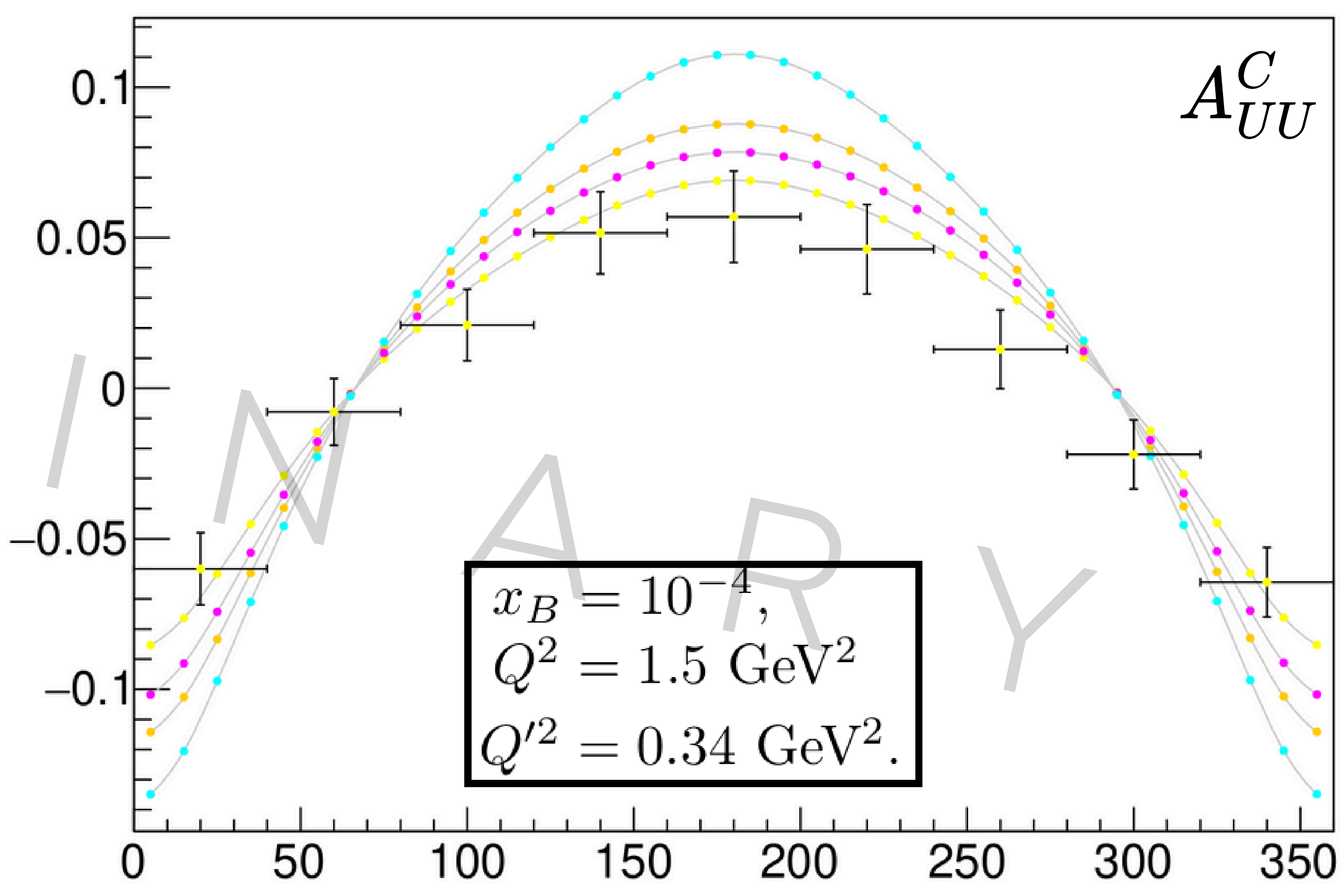
- muons in the range 2°-140°
- everything else in the range 2°-178°

Finally, we explored the region:

$$0.5 < Q^2(\text{GeV}^2) < 3$$
$$4m_\mu^2 < Q'^2(\text{GeV}^2) < 3$$
$$t = -0.025\ \text{GeV}^2$$
$$x_B = 10^{-4}$$

3 MEASUREMENTS AT EIC





At EIC, measurements are possible within **1** year of beam time

Bins widths are given by:

$$\Delta Q^2 = 1\ \mathrm{GeV}^2$$
$$\Delta Q'^2 = 1\ \mathrm{GeV}^2$$
$$\Delta x_B = 0.5 \times 10^{-4}$$
$$\Delta t = 0.025\ \mathrm{GeV}^2$$

Statistics from EpIC and detector acceptance

4 SUMMARY

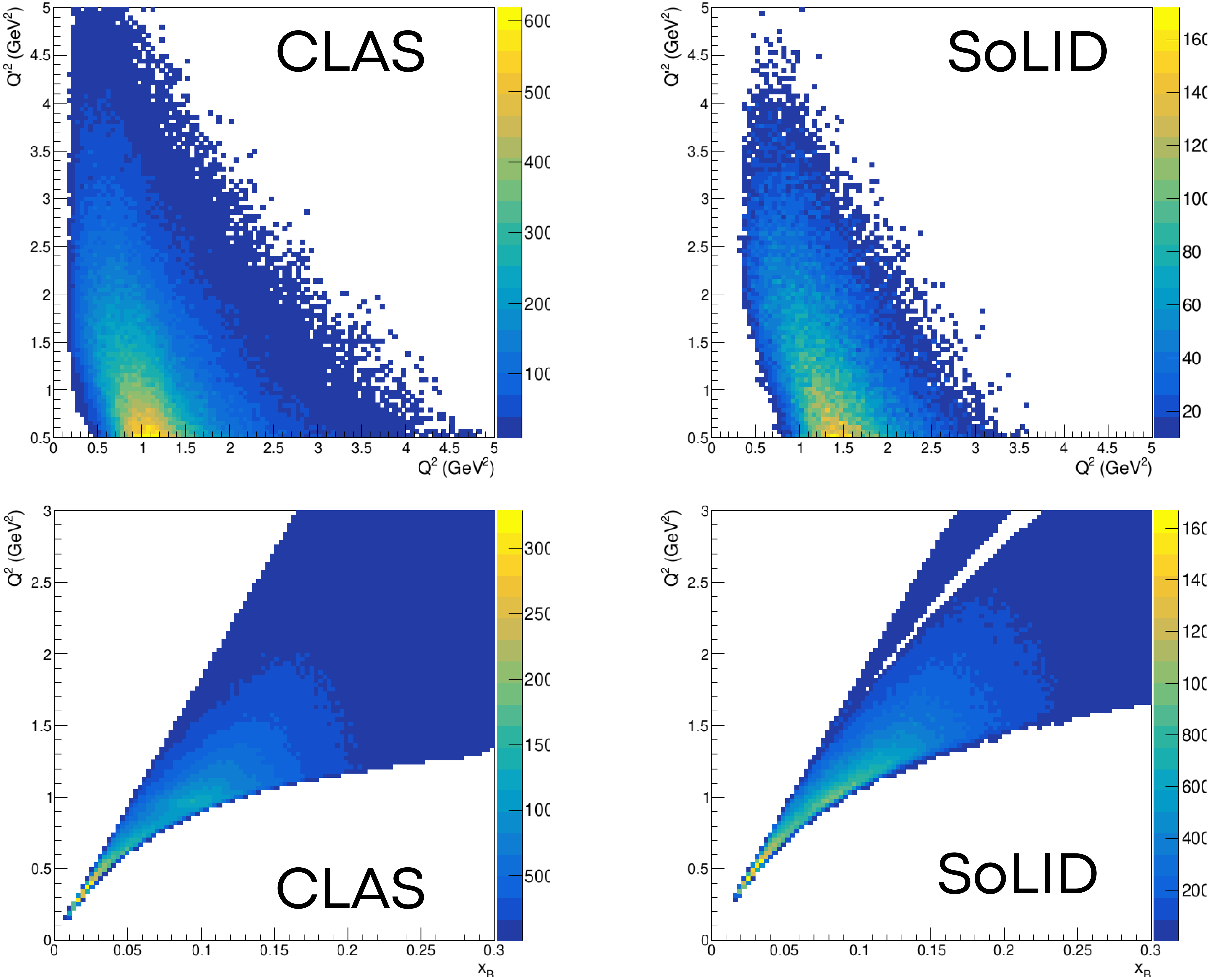
- DDVCS is a golden channel for GPD studies as it allows to explore them at independent $\xi' \neq \xi$ values
- At JLab:
  - measurements of DDVCS observables can be achieved within
    - 100 days with a 11 GeV beam.
    - 200 days with a 22 GeV beam and large bins.
  - A 22 GeV beam would allow measurements at larger Q^2 and Q'^2 values.
  - DDVCS observables show an important model sensitivity
- At EIC:
  - Measurements of BSA and BCA can be achieved within 1 year of data taking

THANKS

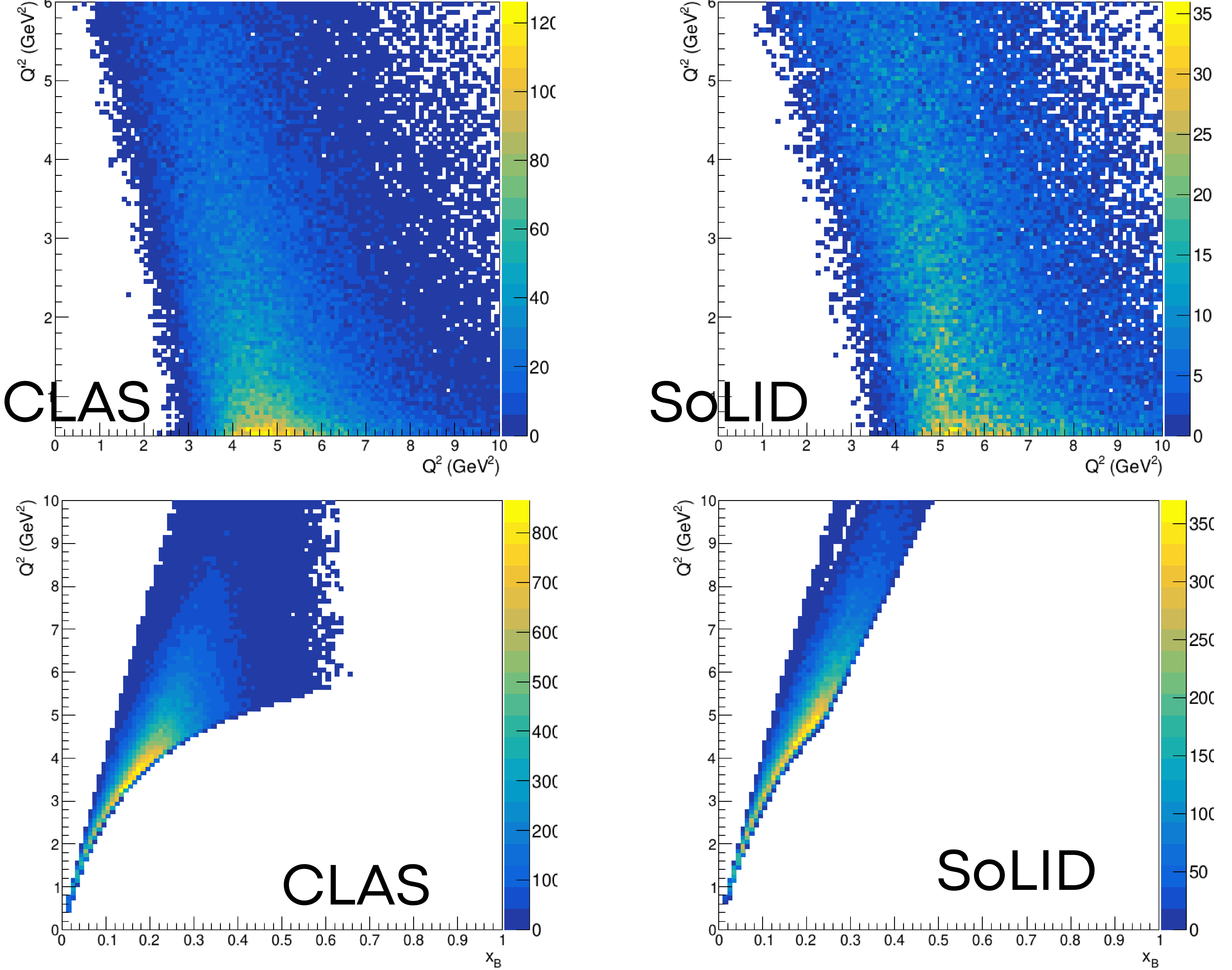
(5)

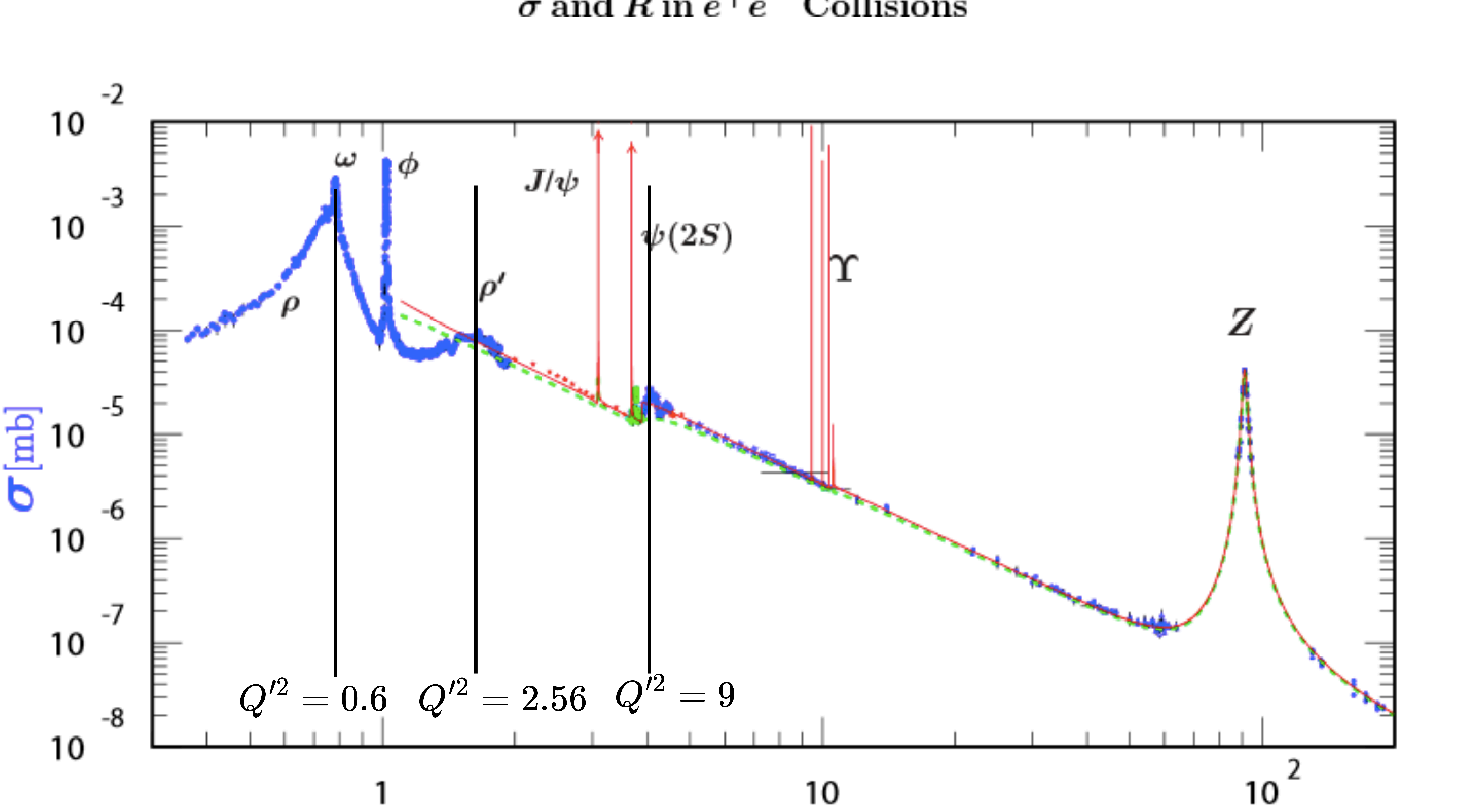
BACK UP

11 GeV



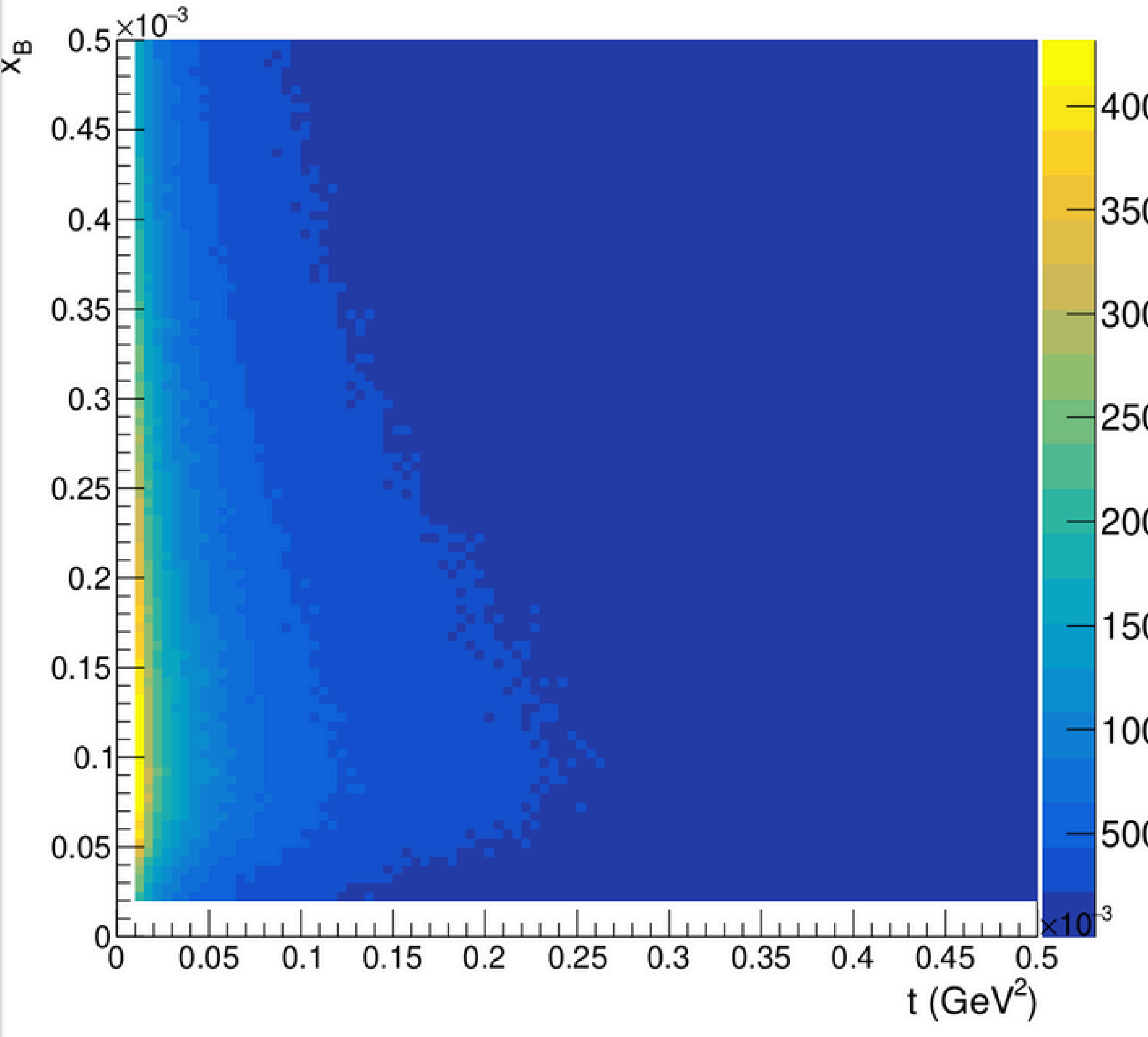
22 GeV

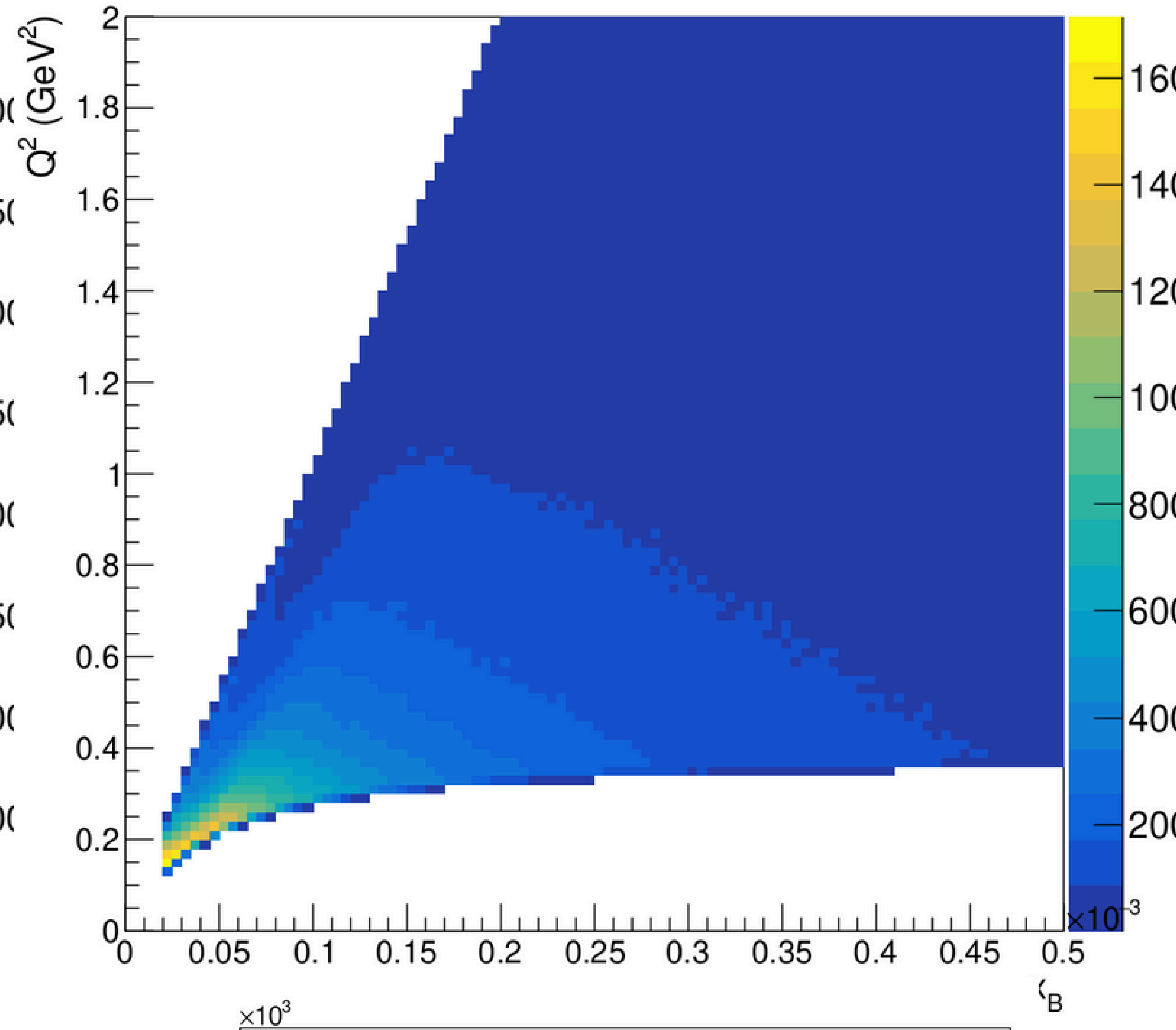


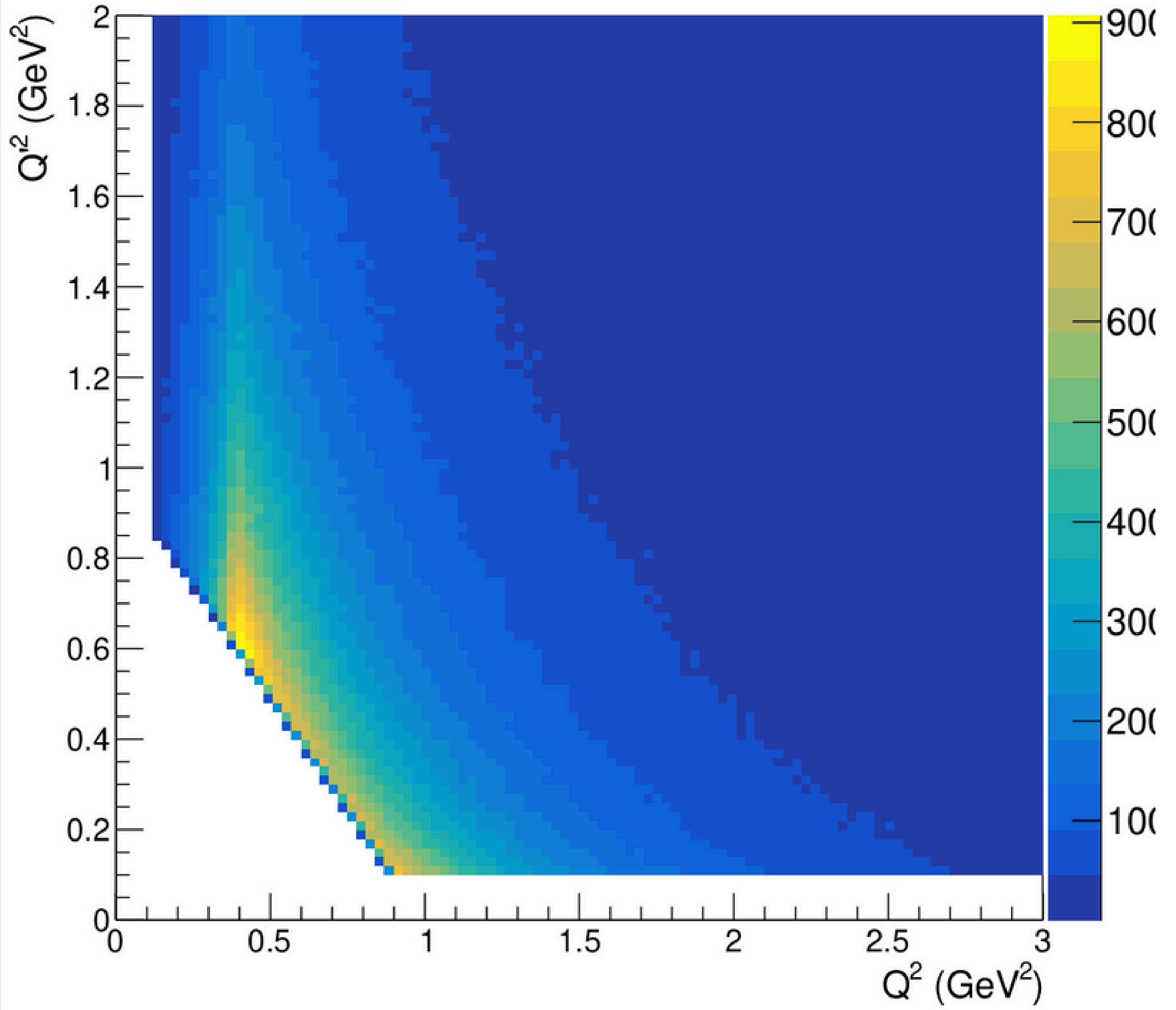


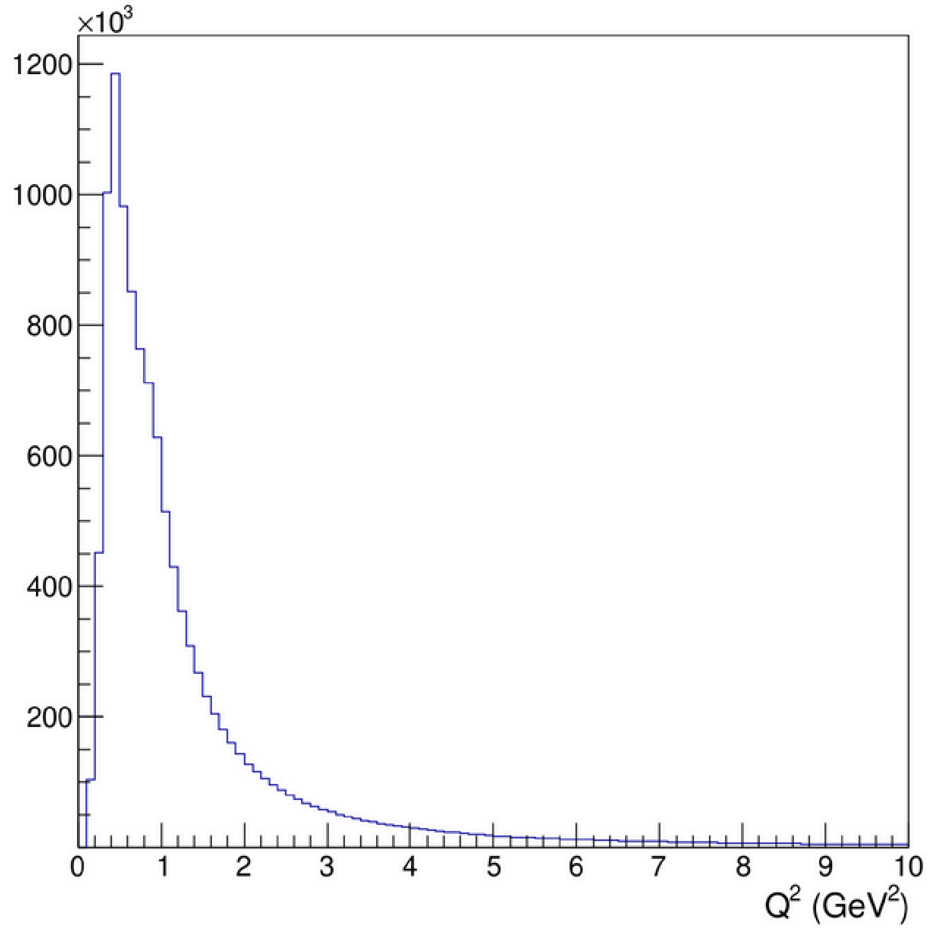
https://i.sstatic.net/WxIiO.png

Kinematic distributions EIC case









IMAGINARY PART

VALENCE QUARK GPD CONTRIBUTION

For DVCS, GPD H is modeled on the cross-over line using the DD representation:

K. Kumerički and D. Mueller. Nuclear Physics B 841.1-2 (2010): 1-58.

taken at an "input scale" of $Q^2 = 2\,\mathrm{GeV}^2$. We model the GPD on the cross-over line using the DD representation (23),

$$F(x,x,t) = \frac{2}{1+x}\int_0^1 du\, f\left(\frac{ux}{1+x}, \frac{1-2u+x}{1+x}, t\right) , \tag{106}$$

and take the t-dependence from the quark spectator model [88]. This suggests the following functional form:

$$H(x,x,t) = \frac{n\,r}{1+x}\left(\frac{2x}{1+x}\right)^{-\alpha(t)}\left(\frac{1-x}{1+x}\right)^{b}\frac{1}{\left(1-\frac{1-x}{1+x}\frac{t}{M^2}\right)^{p}} . \tag{107}$$

r is an skewness ratio related to an hypergeometric function.

Its value is given instead by small xB fits

It suggest that:

- There is an analytically integrable DD
- If I can find such DD, I can generalize it.

IMAGINARY PART

VALENCE QUARK GPD CONTRIBUTION

Let us see how the DVCS results might be obtained

1. Consider the DD profile

$$h(y,z,t=0) = \frac{\Gamma(3/2+b)}{\Gamma(1/2)\Gamma(1+b)} \frac{q(y)}{1-y} \left(1 - \frac{z^2}{(1-y)^2}\right)^b .$$

2. The t dependence is taken from the spectator model

D. S. Hwang and D. Mueller. Physics Letters B 660.4 (2008): 350-359.

$$q(y) \to q(y,t) \propto y^{-\alpha}(1-y)^3 \text{ and a factor } \sim \left(1 - \frac{t}{M^2}\right)^{-p}$$

Then

```
h[y_, z_] := (y^-α * (1 - y)^β)/(1 - y) * (1/((-(1-y)^2 - ((1-y)^2 - z^2)*k)/(-(1-y)^2)))^p * (1 - z^2/(1 - y)^2)^b;
```

IMAGINARY PART

VALENCE QUARK GPD CONTRIBUTION

3. Variable change $y = \frac{x+1}{2}u$
   Exact integration can be achieved by taking only linear terms on ‘u’.

$$2^{2b-\alpha}\left(-\frac{u(-1+x)}{1+x}\right)^{b}\left(\frac{u\,x}{1+x}\right)^{-\alpha}\left(\frac{1}{1+\frac{4ku(-1+x)}{1+x}}\right)^{p}$$

4. It now matches the definition of an Hypergeometric function

$$\mathrm{B}(b,c-b)\,{}_2F_1(a,b;c;z)=\int_0^1 x^{b-1}(1-x)^{c-b-1}(1-zx)^{-a}\,dx \qquad \Re(c)>\Re(b)>0, \qquad c-b-1=0$$

5. As a result, we obtain the H(x,x,t) functional dependence, times an hypergeometric function (say ‘r’).

$$H(x,x,t)=\frac{n\,r}{1+x}\left(\frac{2x}{1+x}\right)^{-\alpha(t)}\left(\frac{1-x}{1+x}\right)^{b}\frac{1}{\left(1-\frac{1-x}{1+x}\frac{t}{M^2}\right)^{p}}.$$

IMAGINARY PART

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Now I re-compute the integral for the general case:

$$H(x,\xi,t) = \frac{nr\vartheta}{\vartheta+x}\frac{1+\vartheta}{2}\left(\frac{(1+\vartheta)x}{\vartheta+x}\right)^{-\alpha(t)}\left(\frac{\vartheta^2(1+\vartheta)}{2}\frac{1-x}{\vartheta+x}\right)^{b}\frac{1}{\left(1-(1-\vartheta^2)\frac{t}{M^2}-\frac{\vartheta^2(1+\vartheta)}{2}\frac{(1-x)}{\vartheta+x}\frac{t}{M^2}\right)^{p}}$$

And it has the correct $\vartheta \to 1$ limit

$$H(x,x,t) = \frac{n\,r}{1+x}\left(\frac{2x}{1+x}\right)^{-\alpha(t)}\left(\frac{1-x}{1+x}\right)^{b}\frac{1}{\left(1-\frac{1-x}{1+x}\frac{t}{M^2}\right)^{p}}\,.$$