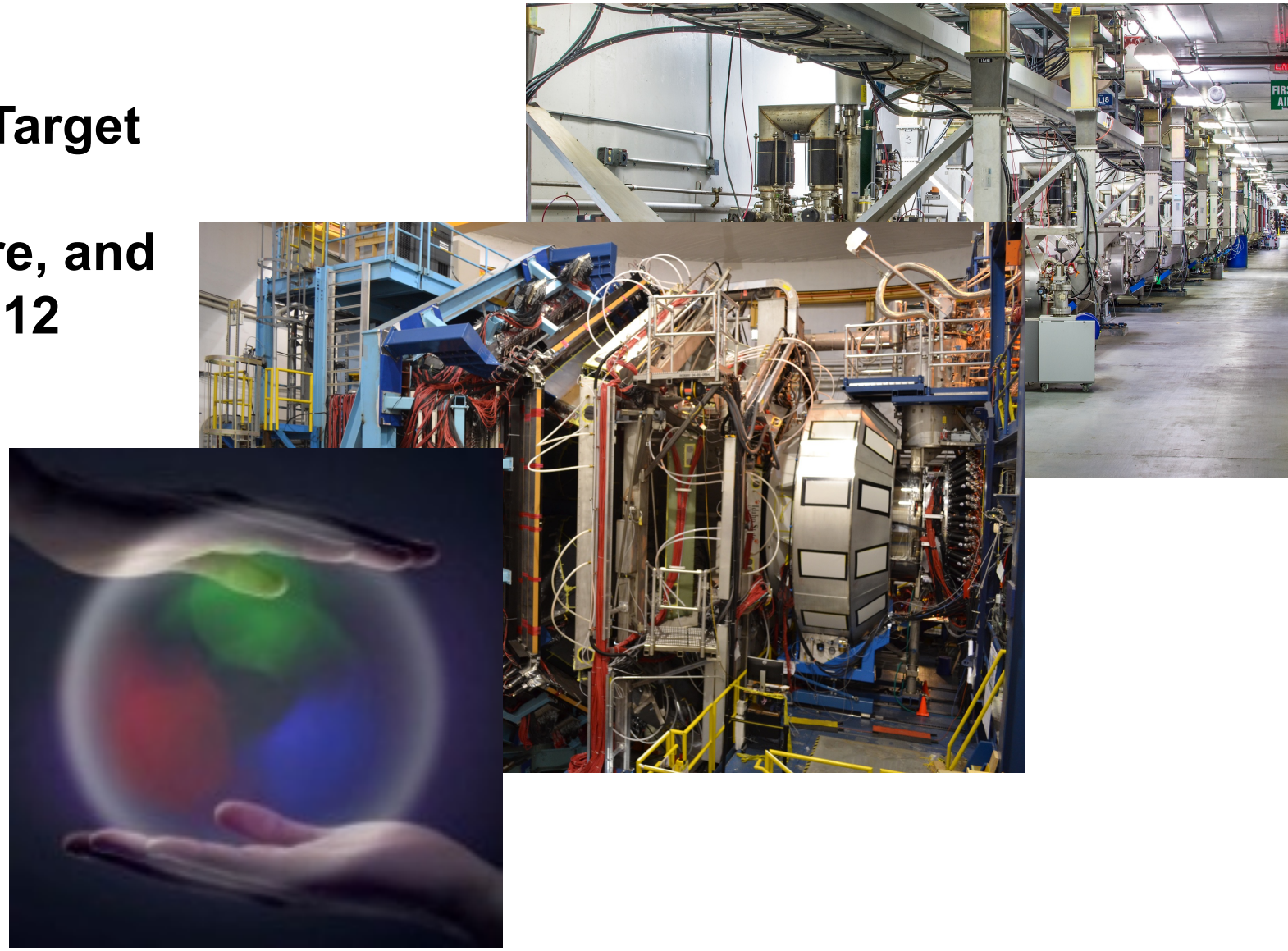
HALL B RUN GROUP A (RG-A) (POL. E ON UNPOL. H)

11 GeV Polarized Electrons on Unpolarized Liquid-Hydrogen Target to Study Proton Structure, 3D Imaging, Gravitational Structure, and Gluonic Excitations with CLAS12



Latifa Elouadrhiri
For RG-A and the CLAS Collaboration

PAC52, Jefferson Lab
July 10, 2024

OUTLINE

- RG-A science program
- New information with scientific importance since the original proposal - some highlights
- The experiments
- Data analysis and required beam time
- Summary

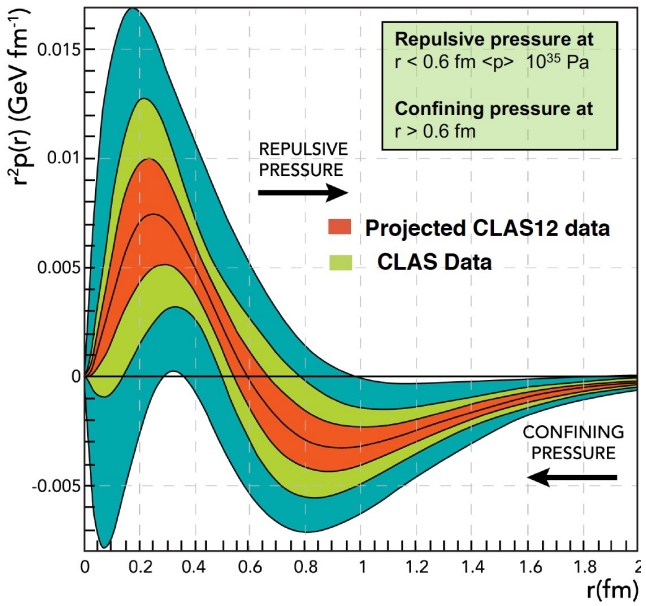
RG-A Science Program

The CLAS12 RG-A experiments were meticulously designed to conduct complementary measurements to investigate proton structure in both ground and excited states, 3D imaging, and gluonic excitations. Their primary mission is to comprehend how the constituents of protons are bound together by the strong force.

RG-A is composed of 13 experiments driven by an international collaboration grouped in 5 categories:

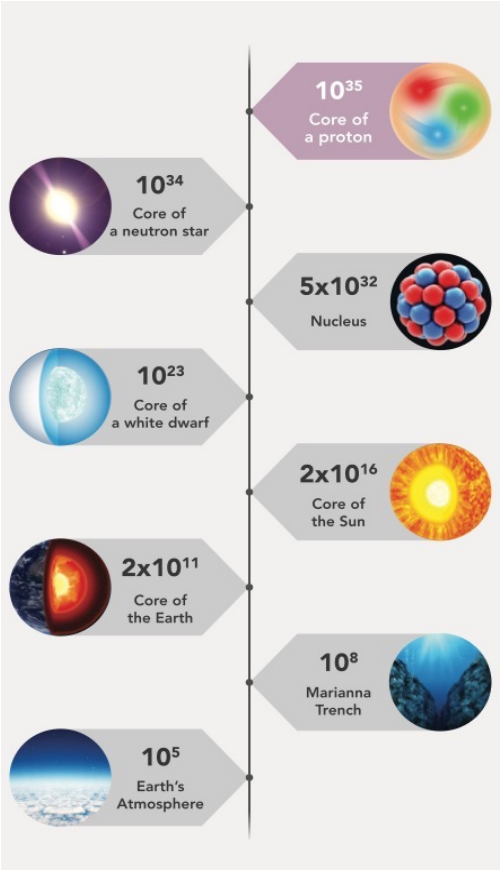
1. Deep Exclusive Processes (E12-06-119, E12-06-108 and E12-12-00): Study of Generalized Parton Distributions (GPDs), (2 +1)-D imaging of the proton and the study of its gravitational and mechanical structure
2. Quasi-real photo-production (E12-12-001 and E12-12-001A): Study of Time-like Compton Scattering and J/ψ photoproduction
3. Deep inclusive & SIDIS (E12-06-112, E12-06-112A and E12-06-112B): Study of the Transverse Momentum Distributions (TMDs) and the 3D structure in momentum space
4. Nucleon structure (E12-09-003, E12-06-108A, E12-06-108B): Study of nucleon resonance structure in broad range in Q^2
5. MesonX program (E12-11-005 and E12-11-005A): Study of meson spectroscopy in search for hybrid mesons including strangeness Program

New Information with Scientific Importance – Highlights – 2023 LRP

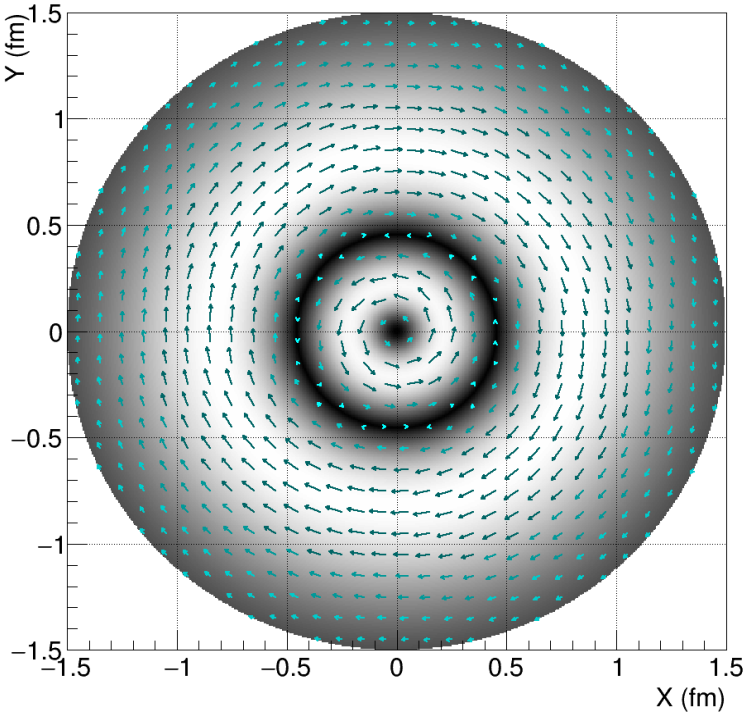


V.D. Burkert, L. Elouadrhiri, F.X. Girod, Nature 557 (2018) 7705, 396

Peak pressure in objects on earth, the sun, and the universe



Tangential stress force inside the proton changes direction near r ~ 0.45 fm
Peak : 38,000 N (4 metric tons)



Burkert, V.D., *et al.*, Colloquium: Gravitational form factors of the proton. *Reviews of Modern Physics* **95**, 041002 (2023)

Pierre Chatagnon
JLab – Post-doc

This breakthrough has paved the way for a completely groundbreaking approach to unraveling the intricate structure of the proton.

New Information with Scientific Importance – Highlights

CEBAF Large Acceptance Spectrometer

Precision meson photo-production data led to the discovery of several new states and the full establishment of poorly known states, in the mass range up to 2200 MeV.

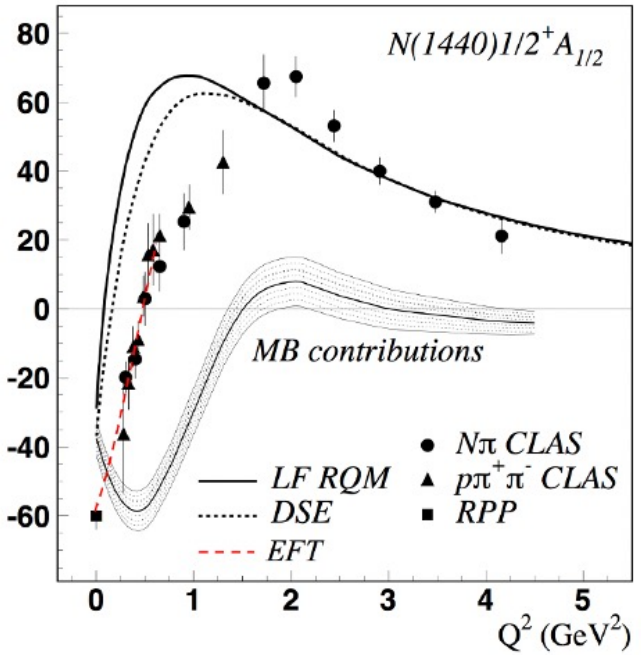
State N((mass)J^P	PDG 2010	PDG 2018
N(1710)1/2$^+$	***	****
N(1880)1/2$^+$		***
N(2100)1/2$^+$	*	***
N(1895)1/2$^-$		****
N(1900)3/2$^+$	**	****
N(1875)3/2$^-$		***
N(2120)3/2$^-$		***
N(2060)5/2$^-$		***
Δ(1600)3/2$^+$	***	****
Δ(1900)1/2$^-$	**	***
Δ(2200)7/2$^-$	*	***

**** - existence is certain
*** - existence is likely
** - evidence of existence is fair
* - evidence of existence is poor

http://pdg.lbl.gov/2019/reviews/rpp2018-rev-n-delta-resonances.pdf

THE QUEST FOR MISSING RESONANCES

CLAS12 will allow the extension of this program to high Q^2



V.B., C. Roberts, Rev.Mod.Phys. 91 (2019) no.1, 011003

***LF RQM**: I. Aznauryan, V.B. arXiv:1603.06692*
***DSE:** J. Segovia, C.D. Roberts et al., PRC94 (2016) 042201*
***EFT:** T. Bauer, S. Scherer, L. Tiator, PRC90 (2014) 015201*

➔ Non-quark contributions are significant at $Q^2 < 2.0$ GeV^2. The behavior at $Q^2 < 0.5$ can be modeled in EFT.

➔ The 1st radial excitation of the q^3 core emerges as the probe penetrates the MB cloud

"Nature" of the Roper – is consistent with the 1st radial excitation of its quark core surrounded by a meson-baryon "cloud".

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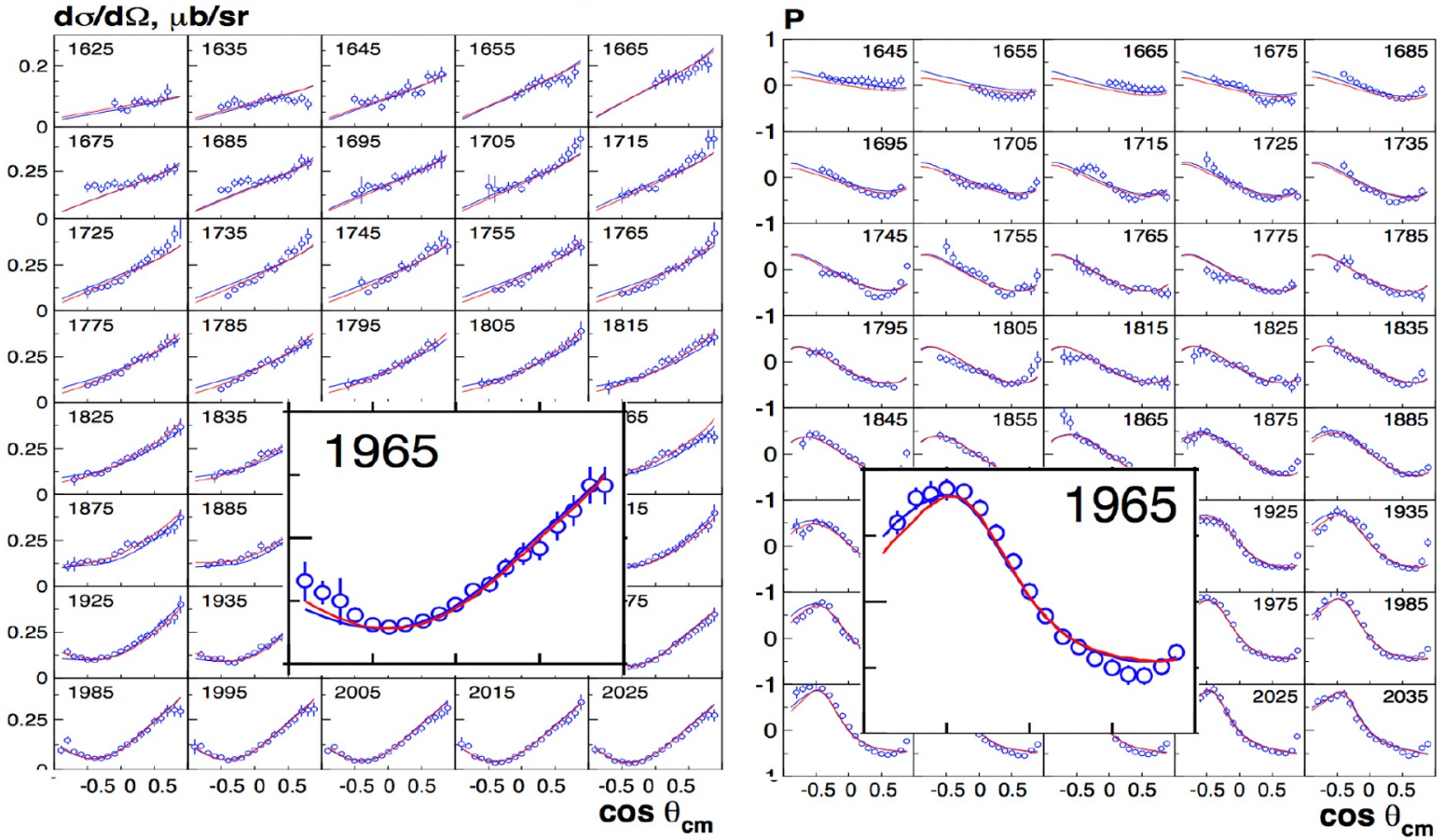
New Information with Scientific Importance – Highlights

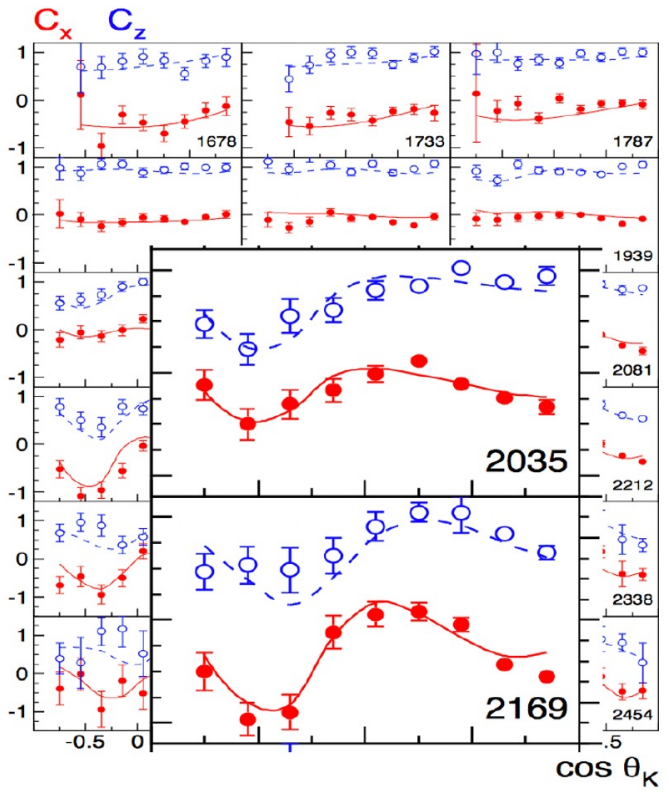
Hyperon photoproduction $\gamma p \rightarrow K^+\Lambda \rightarrow K^+ p\pi^-$

Fit by BnGa group *A.V. Anisovich et al, EPJ A48, 15 (2012)*



M. Mc Cracken et al.(CLAS), Phys.RevC81,025201,2010

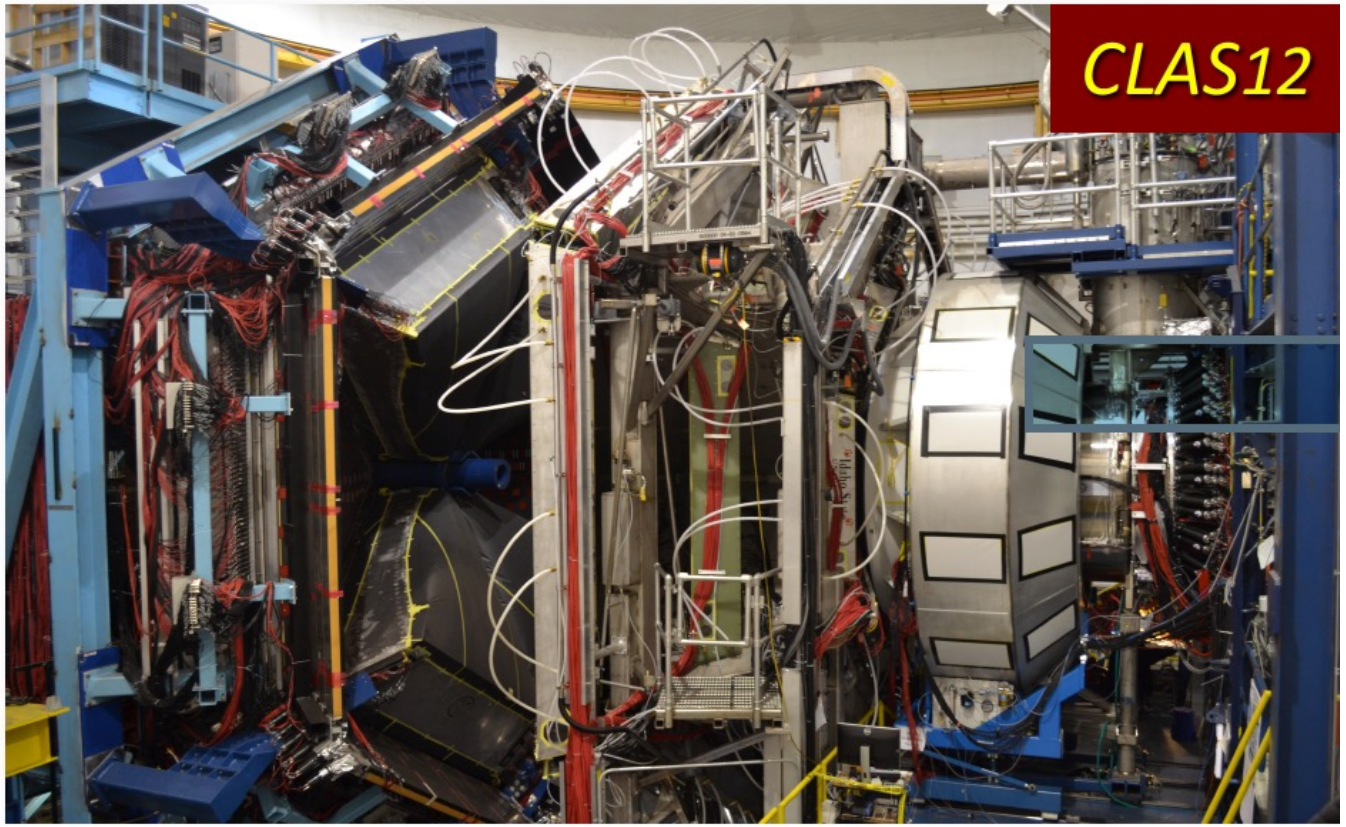
γ->Λ Polarization transfer



D. Bradford et al. (CLAS), Phys.Rev. C75, 035205, 2007

RG-A Experiment

- RG-A has acquired data in three separate running periods, spring 2018, fall 2018, and spring 2019, with the collected beam time amounting to roughly half of the full approved RG-A beam time. The first period included detector commissioning.
- **To fully realize the goals of the RG-A science program, the full statistics of the approved beam time is required.**

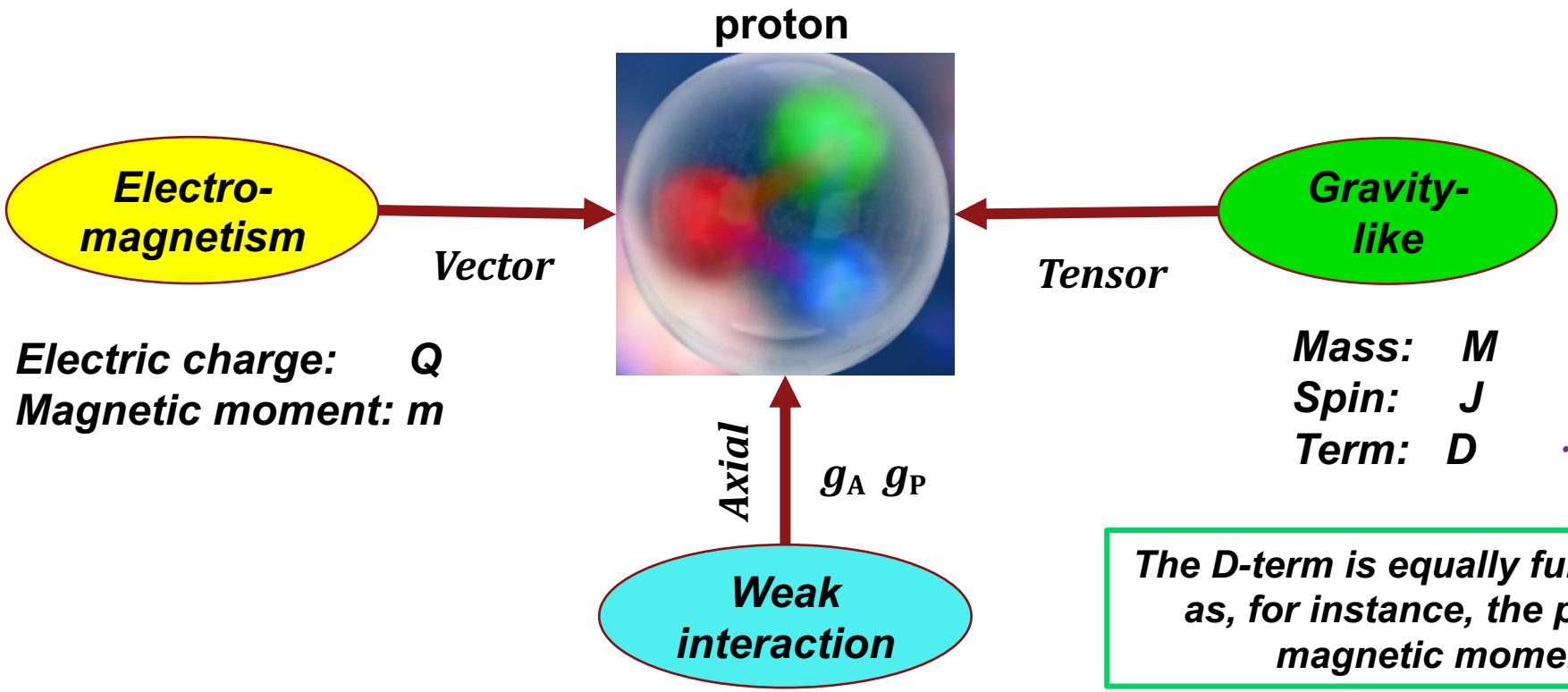


The experimental setup and configuration overall remain unchanged; however, with the new beam time, we will benefit from optimized parameters for efficient detector operation, resulting in improved resolution and the ability to run at a higher beam current.

Probing Gravitational Properties of the Strong Interaction

The proton has been studied in its electromagnetic and weak properties.

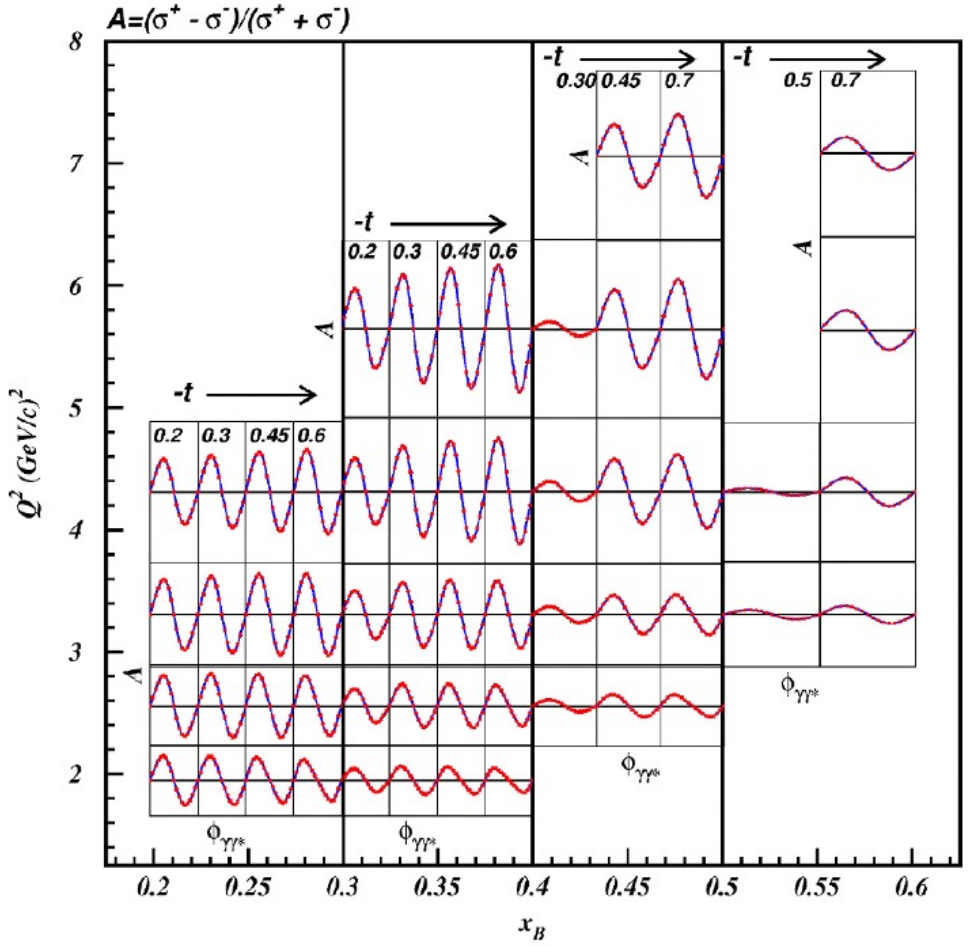
If we could use *gravity* to probe the structure of the proton, what would we learn?

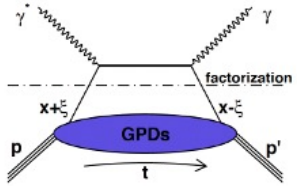


DVCS Experiment – Projections

80 days @ $\mathcal{L} = 10^{35}$ cm^{-2}s^{-1} with 85% polarized beam

$A_{LU} \propto F_1\mathcal{H} + \xi G_M\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}$

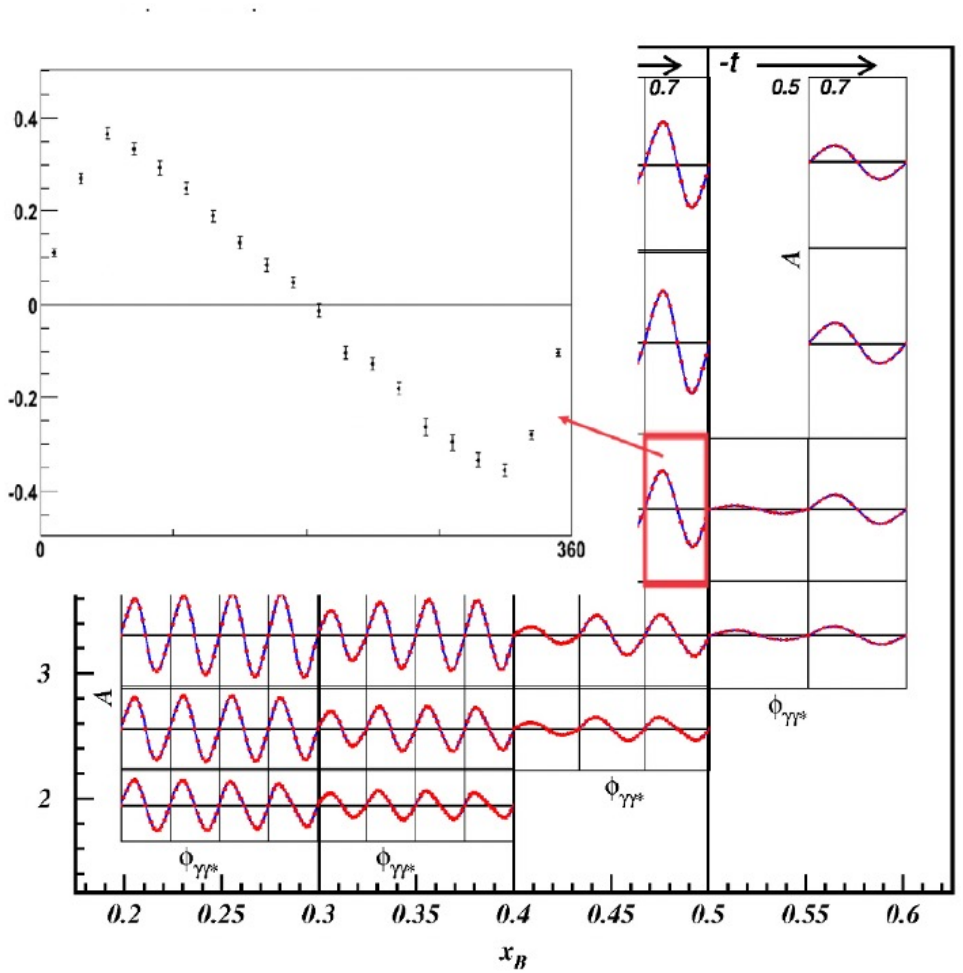




Projections for CLAS12

Statistical uncertainties :
from 1 % (low Q^2)
to 10 % (high Q^2)

Unprecedented statistics
over the full ϕ range
up to high $x = 0.6$

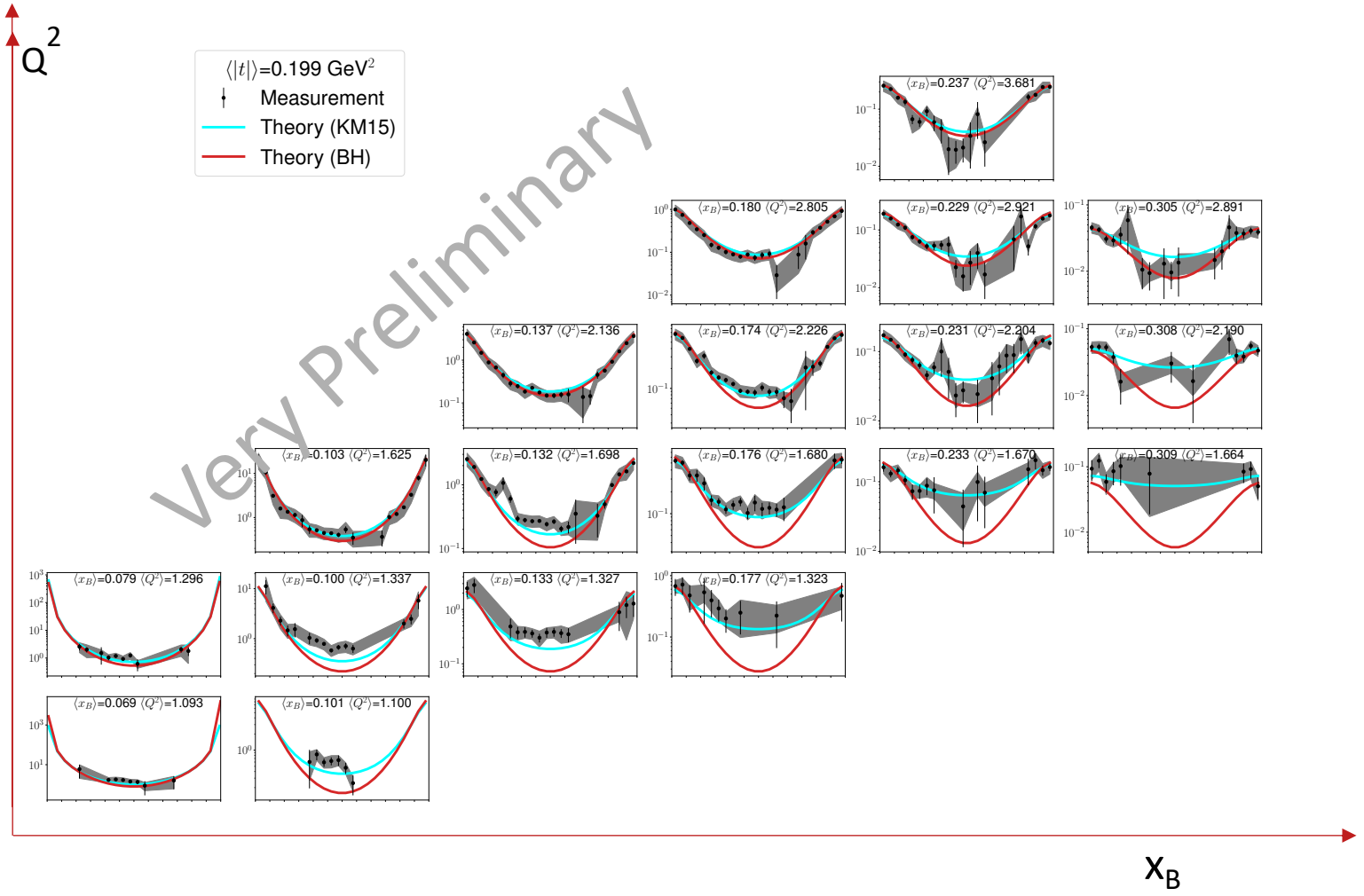


DVCS Experiment Preliminary Results

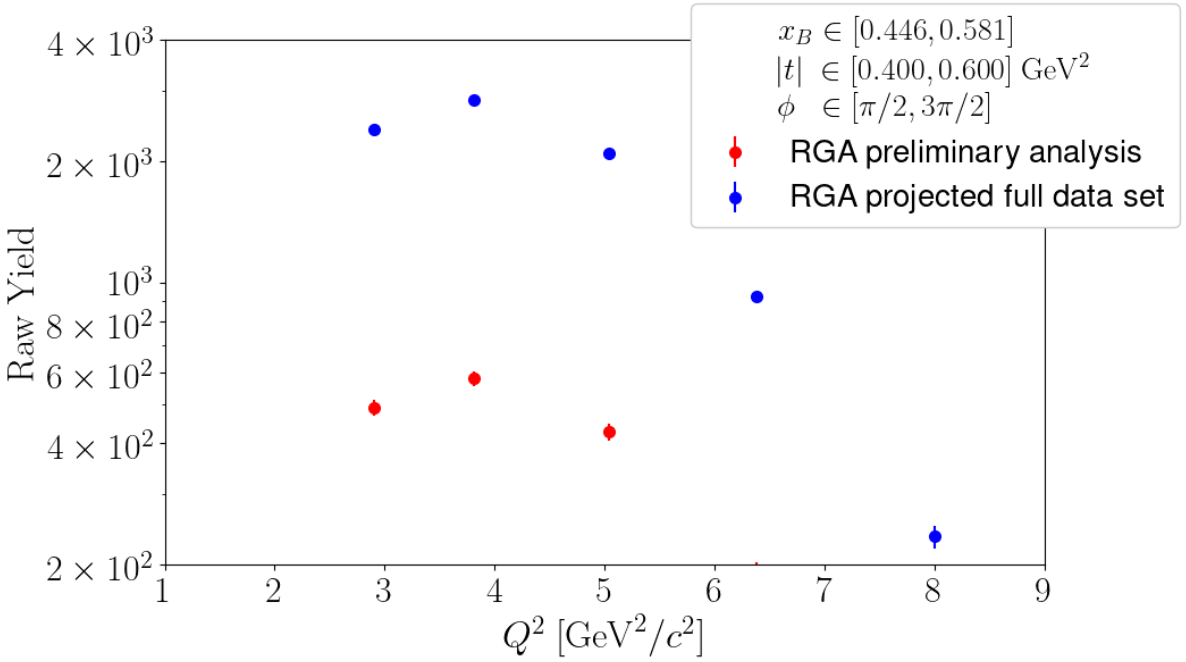
- First DVCS cross section analysis well on track, tremendous effort to improve tracking resolution, control of the systematics such as a sizable π^0 contamination in high-x_B bins and fine-tuning of selection cuts to maximize the signal/background ratio. Publication in preparation .

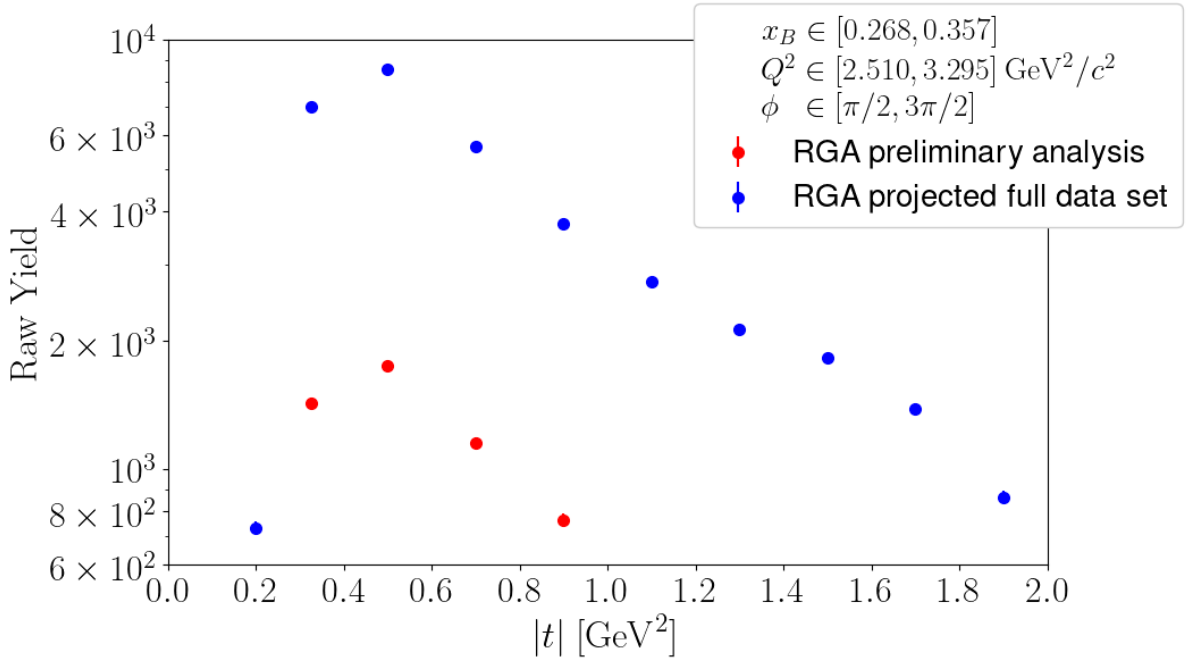
- **RG- A DVCS program with its large phase space coverage and the expected full statistics is a cornerstone of the worldwide effort (Hall A-C, COMPASS, EIC).**

- **Full statistics is required for the multi-dimensional binning in all kinematical variables.**



DVCS Experiment Projected Results





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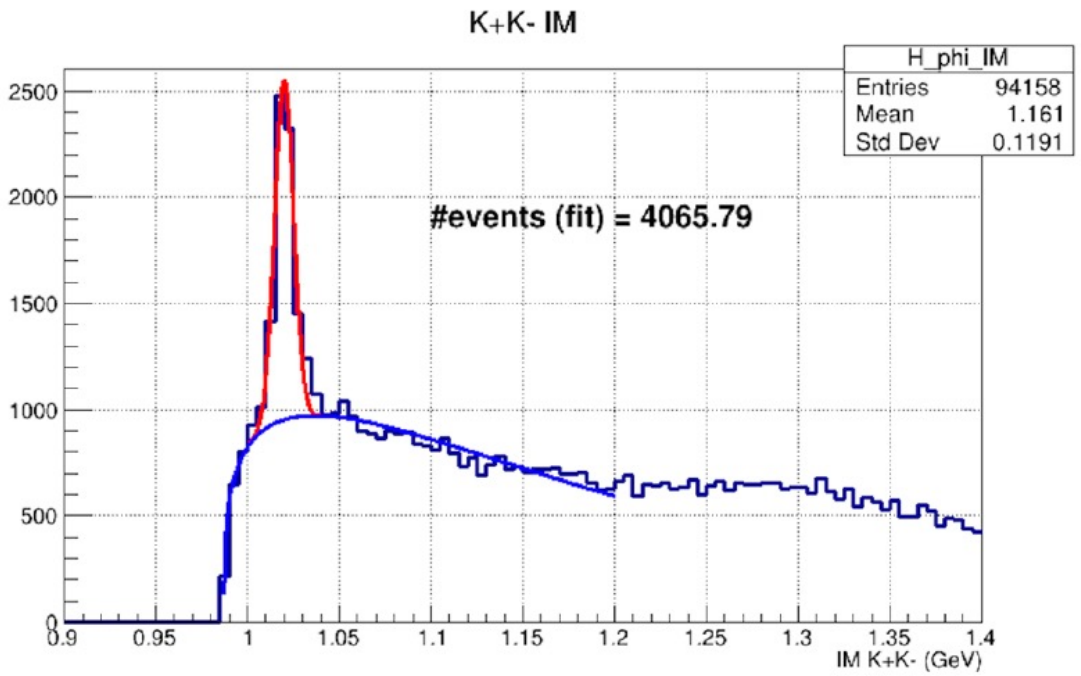
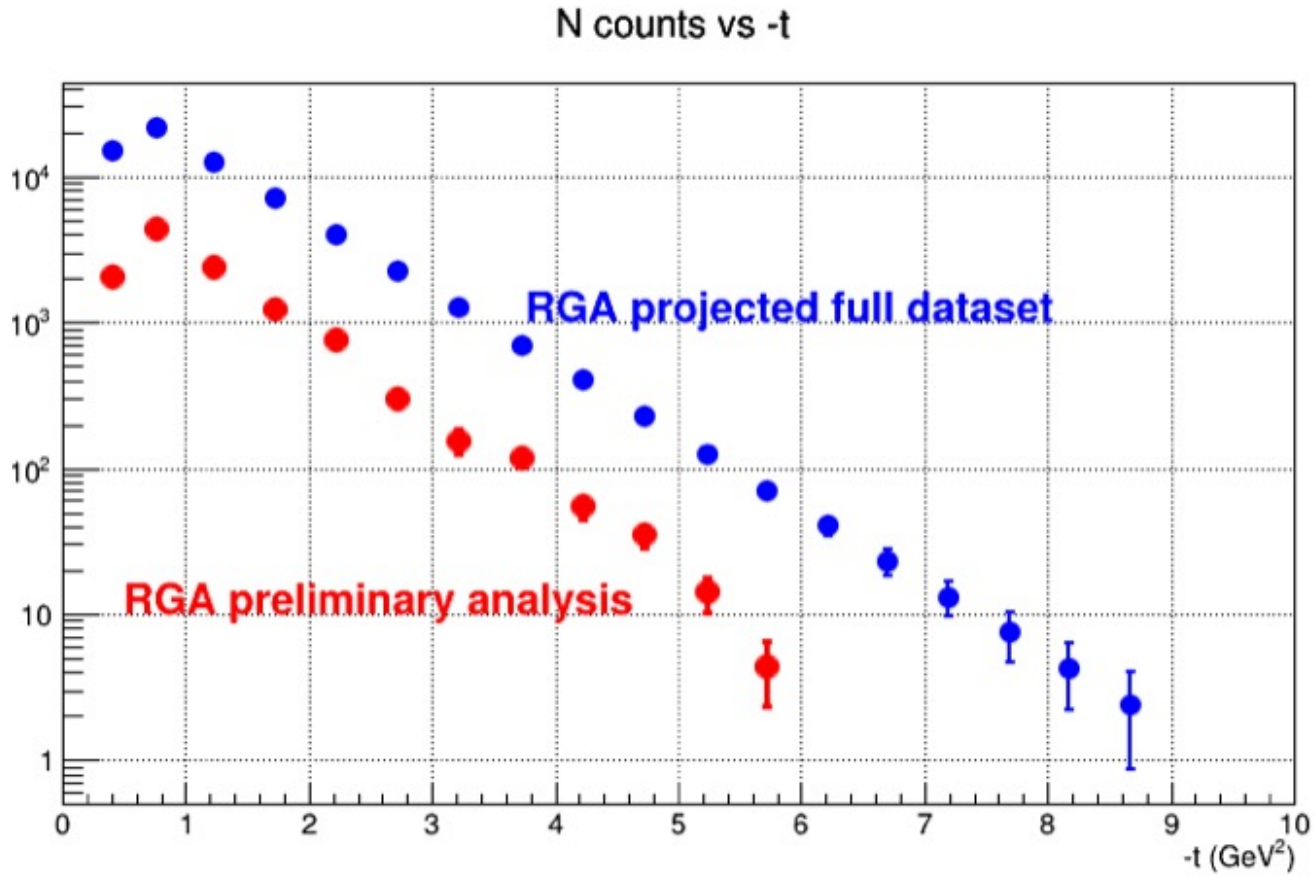
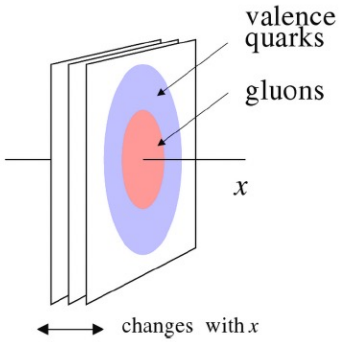
Exclusive ϕ Meson







Exclusive ϕ meson production offers a unique opportunity to probe the gluon spatial distribution and derive the gluon radius.

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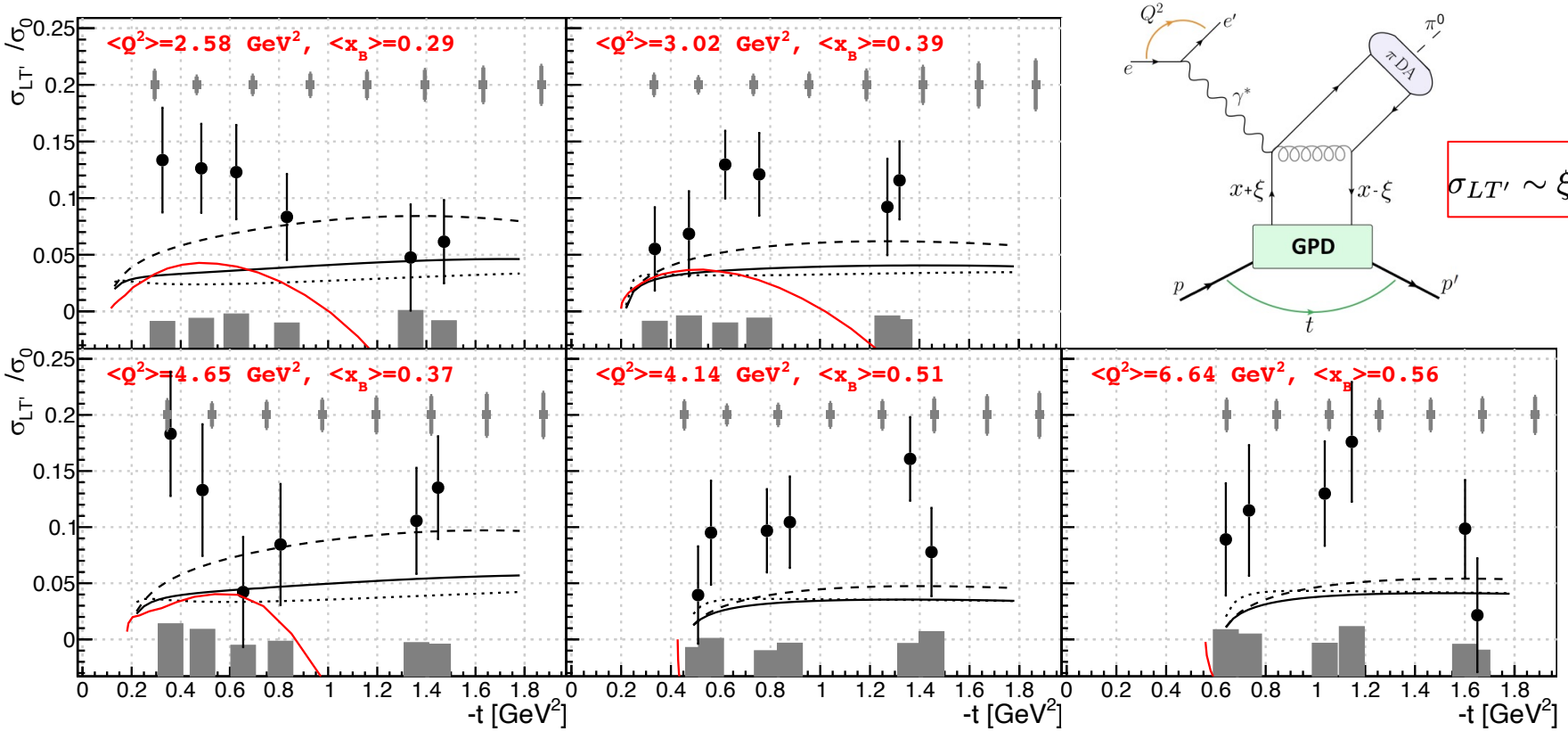
Beam Spin Asymmetry of π^0 Exclusive Production



$$\sigma_{LT'} \sim \xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m} Im\left[\langle \bar{E}_T\rangle^* \langle \tilde{H}\rangle + \langle H_T\rangle^* \langle \tilde{E}\rangle\right]$$

The strongest uncertainty for the theoretical prediction is expected from the poorly known **GPD $E_T$bar** which plays a **dominant role** in the π^0 electroproduction. Multidimensional, high precision π^0 BSA and unpolarized cross section measurements are necessary to enable a better determination of the GPD $E_T$bar. This will improve our understanding of the nucleon's anomalous tensor magnetic moment $k_T^{u,d} = \int dx \bar{E}_T^{u,d}(x,\xi,t=0)$

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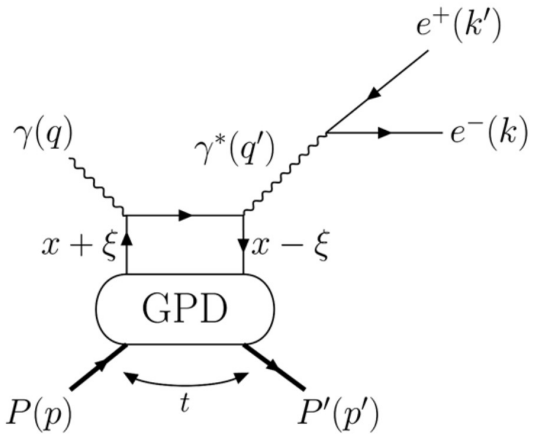
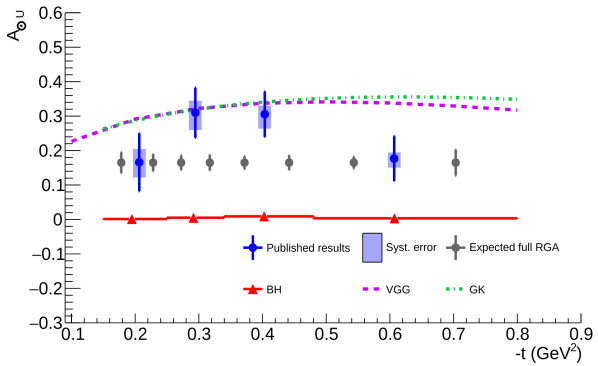
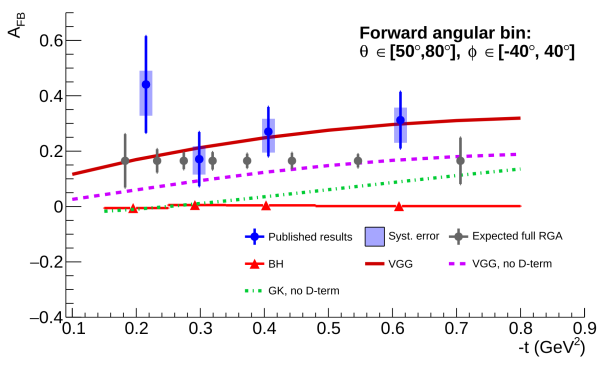
Timelike Compton Scattering



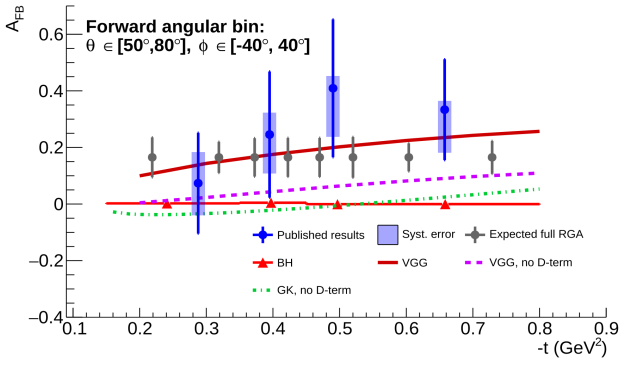
- Outgoing photon virtuality Q'^2 sets the hard scale.
- Photon polarization asymmetry measurement $A_{\odot U}$ allows access to the **Imaginary** part of Compton Form Factors (CFFs).
- Forward Backward asymmetry A_{FB} allows to access the **Real** part of CFFs.
- First TCS measurement is in favor of universalities of GPDs.
- TCS data are in better agreement with GPD model calculations that include the D-term.
- To have a more quantitative understanding on universality of GPDs, on the contribution of the D-term, and meaningfully contribute to the extraction of GPDs, more data points in **Q'^2** and **s** with smaller uncertainties are needed.
- In addition, a high precision A_{FB} measurements will be important inputs to currently ongoing efforts on extraction of Gravitational Form Factors (GFFs).



(a) $A_{\odot U}$ as a function of $-t$ at the averaged kinematic point $E_\gamma = 7.29 \pm 1.55$ GeV; $M = 1.8 \pm 0.26$ GeV.



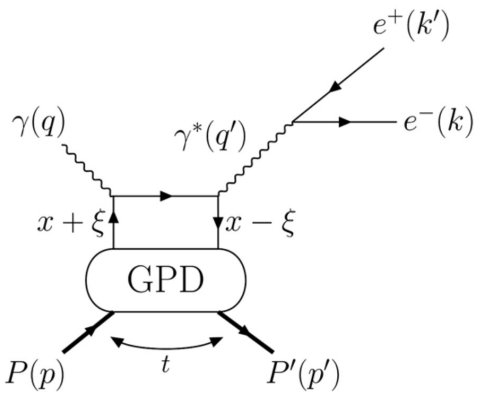
(b) A_{FB} as a function of $-t$ at the averaged kinematics $E_\gamma = 7.23 \pm 1.61$ GeV; $M = 1.81 \pm 0.26$ GeV.



(c) A_{FB} as a function of $-t$ at the averaged kinematics $E_\gamma = 8.13 \pm 1.23$ GeV; $M = 2.25 \pm 0.2$ GeV.

E12-12-001 and E12-12-001A

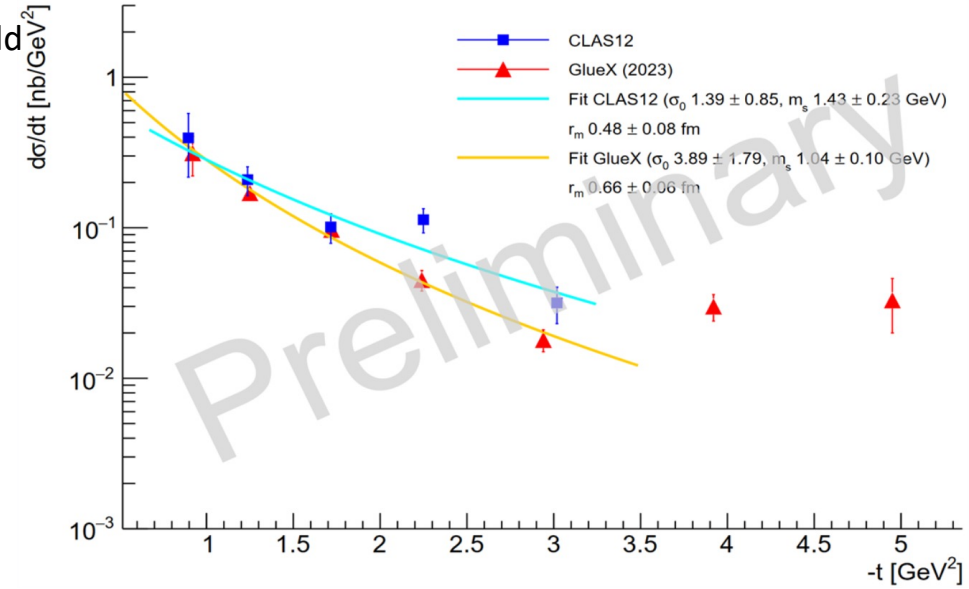
J/ψ Photoproduction



- J/ψ meson photoproduction near the production threshold allows access to the nucleons' gluonic GFFs.
- In particular the t-dependence of the differential cross-section is sensitive to the mass radius of the proton.

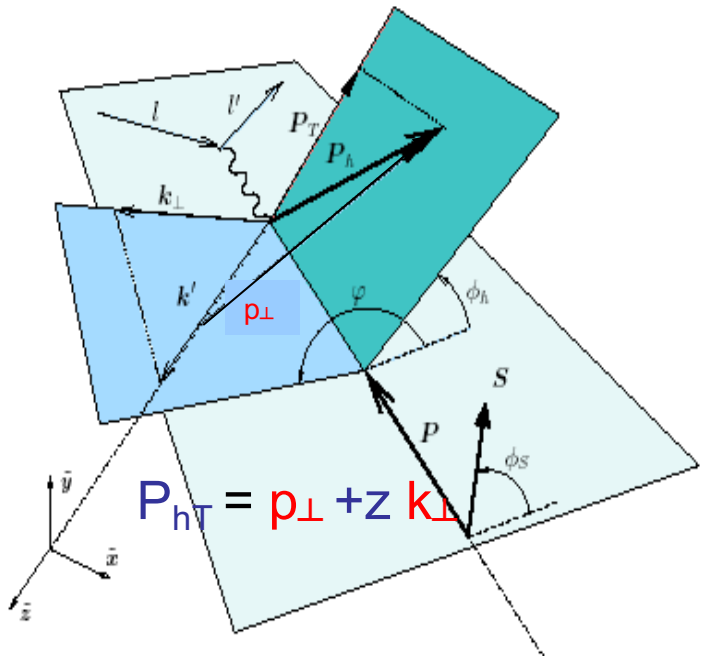
  Phys. Rev. D 104 (5 Sept. 2021), p. 054015

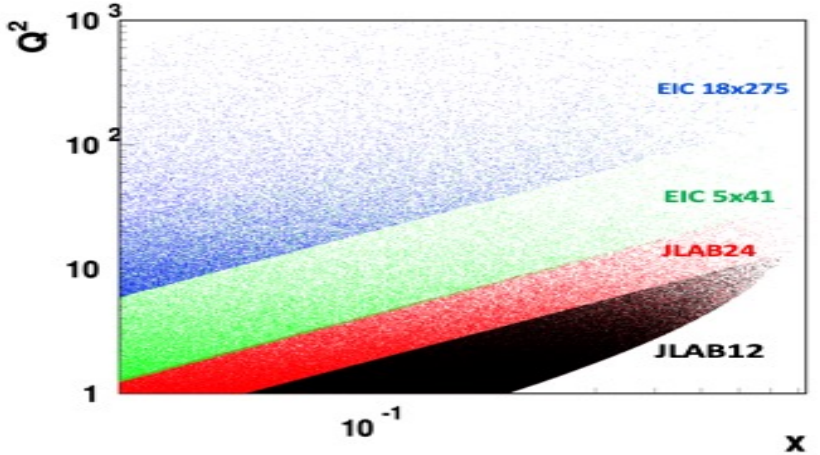
- Recently GlueX and Hall-C have released their results on near threshold production. GlueX observed flattening behavior at high -t.
- At small –t CLAS12 uncertainties are comparable w/ GlueX data.
- CLAS12 needs more data to independently verify the flattening behavior at high –t, and hence the applicability of the mass radius extraction formalism at high –t.

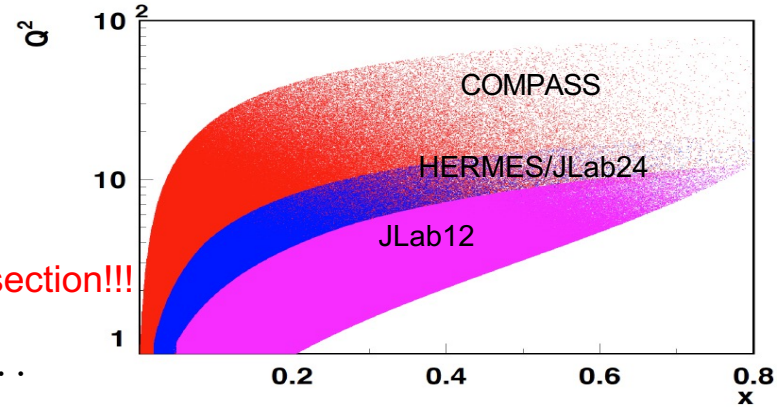


E12-12-001 and E12-12-001A

SIDIS Kinematic Coverage and Observables





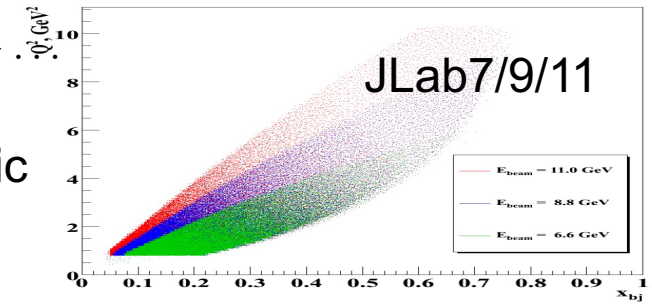


EIC

Experiments measure the full azimuthal dependence of the cross section!!!

$$\sigma \propto F_{UU} + P_b\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi}\sin\phi + P_t\epsilon F_{UL}^{\sin 2\phi}\sin 2\phi + \ldots$$

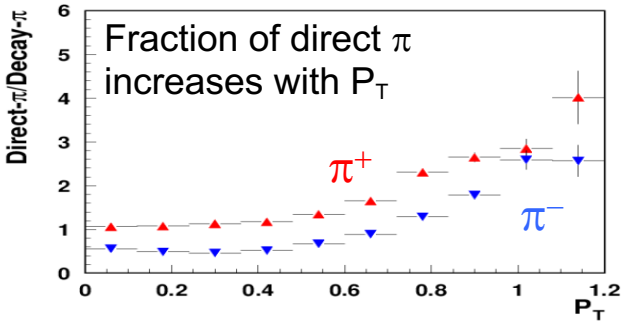
$$+\epsilon F_{UU,L} + |S_\perp|[F_{UT}^{\sin(\phi-\phi_S)}\sin(\phi-\phi_S) + \sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin\phi_S}\sin\phi_S] + \ldots$$

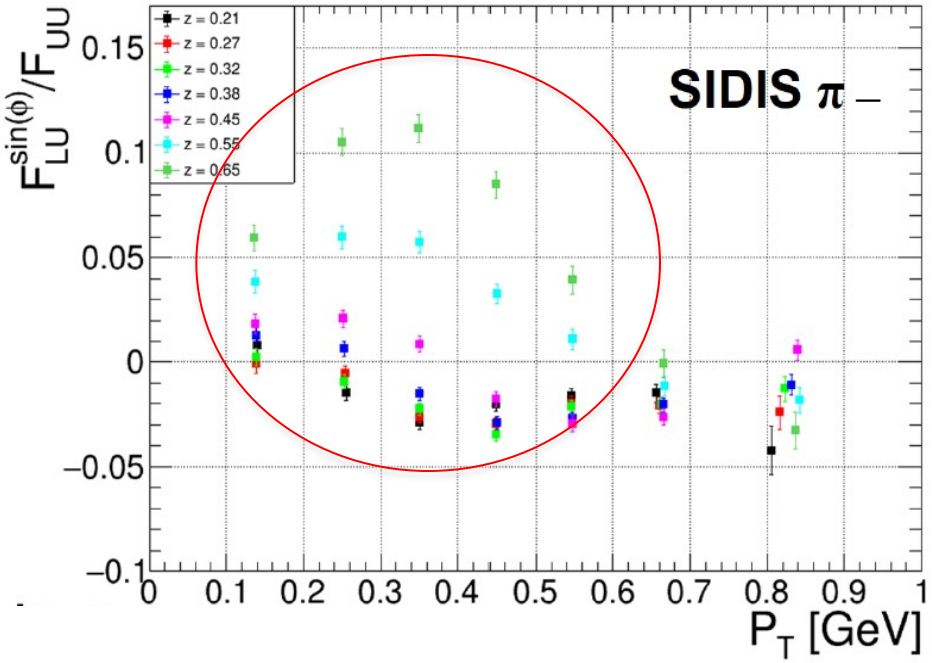


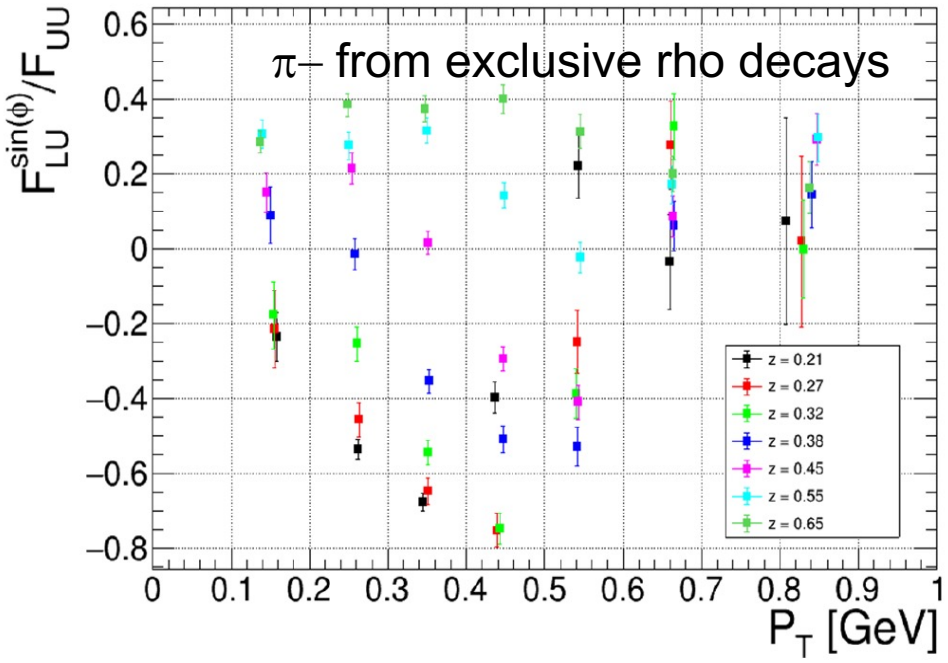
Studies of azimuthal modulations give access to underlying 3D partonic distributions

SIDIS SSAs

- Biggest contributions from exclusive rhos in low P_T, large z
- Large fractions of low-z pions from semi-inclusive VM decays





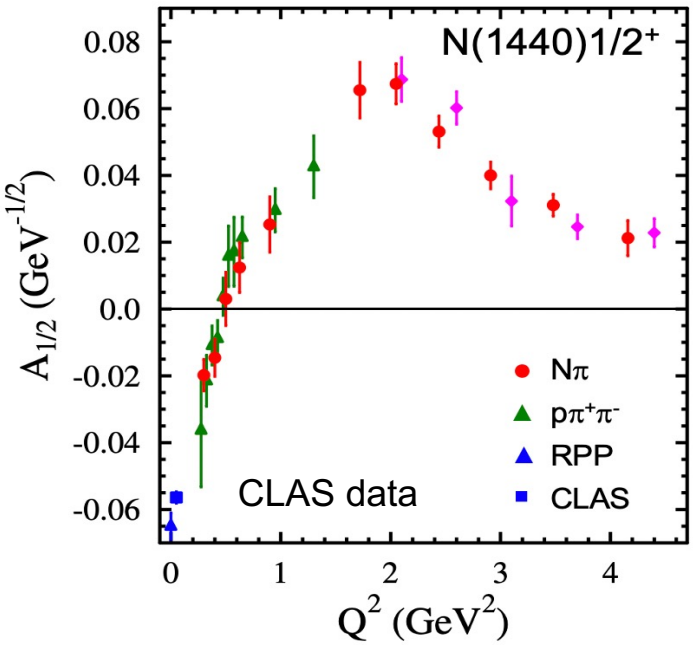


Interpretation of SSAs can be very challenging in certain kinematics
For low P_T the impact of rho can be critical even for small fractions

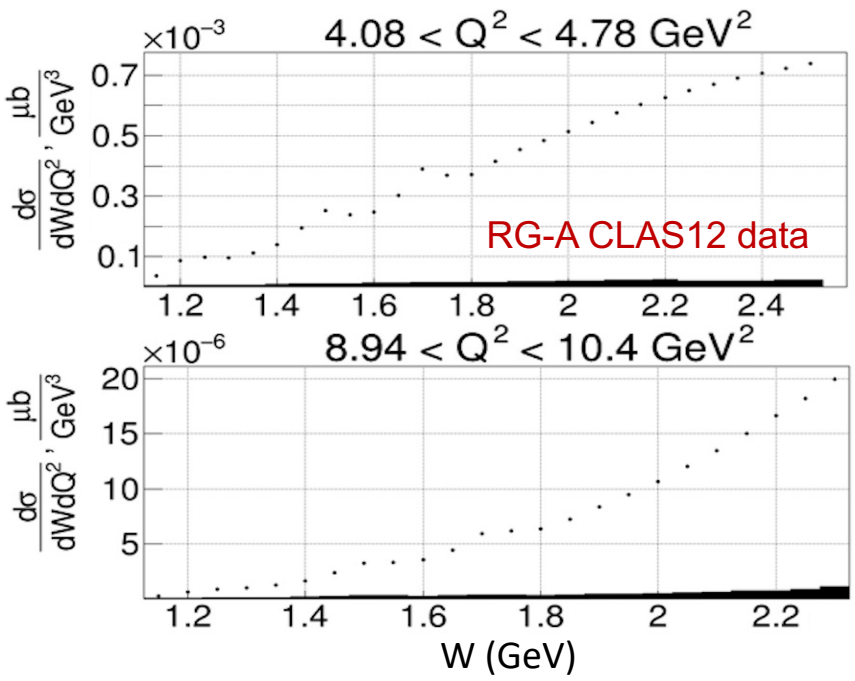
Nucleon Resonance Structure

N* structure studies through extraction of helicity amplitudes provide a unique source of information on many facets of the strong interaction at distances where the transition from the strongly coupled to pQCD regimes is expected.

Helicity Amplitude
Transverse Electrocouplings



Inclusive (e,e′X) Cross Section



Ref.: D.S. Carman, R.W. Gothe, V.I. Mokeev, and C.D. Roberts, Particles 6, 416 (2023)

- Resonance structures seen in W-dependence of inclusive (e,e′X) cross sections for Q^2 from 4−10 GeV^2 demonstrate the opportunity to extend the γ_vpN* electrocouplings for Q^2 up to 10 GeV^2.
- Inclusive cross sections from Ph.D. thesis of Valerii Klimenko (UConn) – now under CLAS analysis review; paper in progress.

- CLAS12 is the only facility in the world capable of determining the γ_vpN* electrocouplings of the most prominent N* states at the highest four-momentum transfers ever achieved, covering Q^2 from 2 to 10 GeV^2.
- Most meson electroproduction channels in the N* region will be extracted from RG-A data for Q^2<10 GeV^2. Consistent results on the γ_vpN* electrocouplings from these channels will confirm their credible extraction.

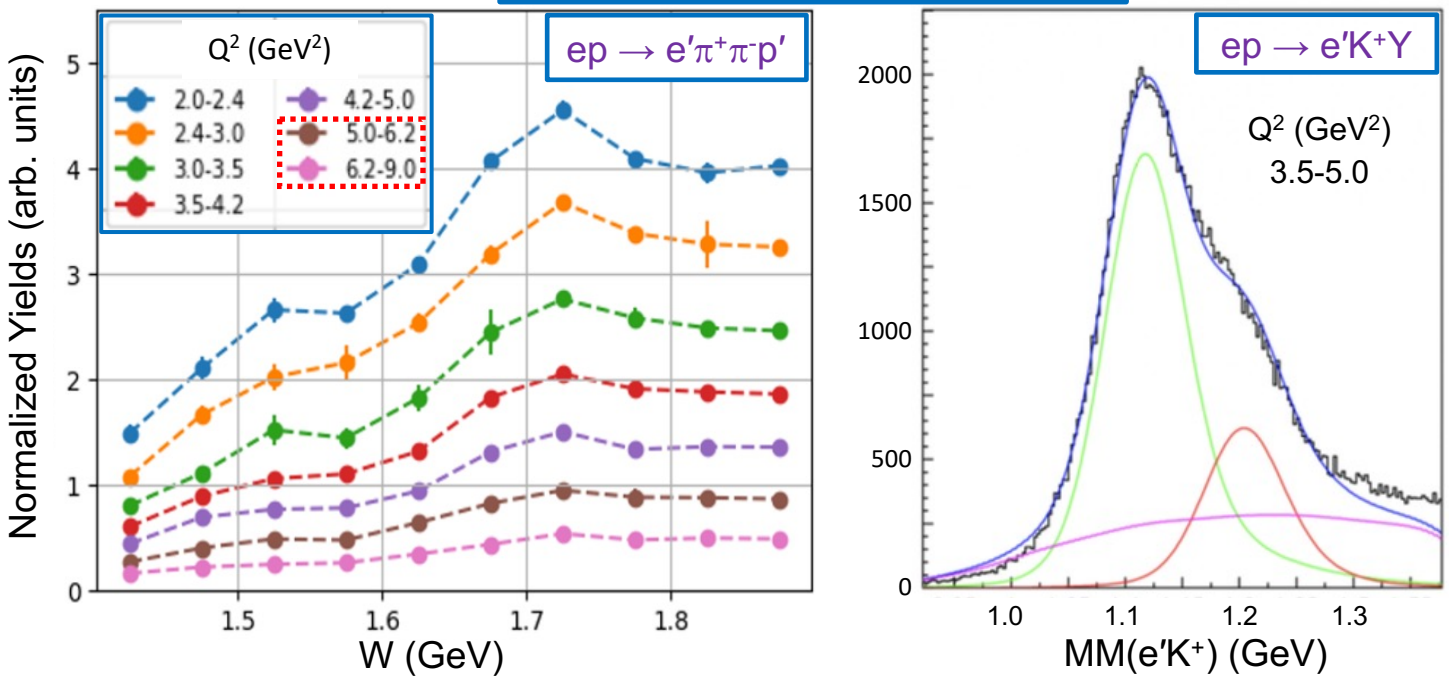
E12-06-108A, E12-09-113

Ref.: V.I. Mokeev *et al.*, PRC 108, 025204 (2023)

Nucleon Resonance Structure

Analyses of CLAS12 RG-A data aim for extraction of the $\gamma_v pN^*$ electrocouplings from πN, KY, and $\pi^+\pi^- p$ channels for $Q^2 < 10$ GeV^2, while the results from CLAS covered $Q^2 < 5$ GeV^2.

Yields from existing RG-A data



The existing RG-A F18 and Spr19 datasets:

- Allow determination of $\gamma_v pN^*$ electrocouplings only up to Q^2 = 6-7 GeV^2
- They do not allow separation of $K\Lambda$ and $K\Sigma$ channels, but CLAS12 upgrades since 2019 provide nearly a *factor of two* improvement in momentum resolution.

Reapproval of the remaining RG-A beam time will allow for:

- determination of the $\gamma_v pN^*$ electrocouplings up to Q^2 =10 GeV^2 with bin size $\Delta Q^2 \leq 1$ GeV^2
- removal of statistical limitations across multi-dimensional phase space for all exclusive channels and allow for the necessary fine binning for the final state kinematic variables
- separation of the $K\Lambda$ and $K\Sigma$ channels due to the now improved CLAS12 momentum resolution

E12-06-108A, E12-09-113

MesonEx with CLAS12 and the Forward Tagger

- Quasi-real photoproduction provides high flux of meson resonance production
- Tagging the photon with the Forward Tagger provides exclusive reactions
- Quasi-real photon has linear and circular polarization, essential for Partial Wave Analysis
- Many reactions possible, currently studying: $\pi^+\pi^-$; $\pi^+\pi^+\pi^-$; K^+K^-; $K^+K^-\pi^+$.
- Example distributions from $\pi^+\pi^+\pi^-$

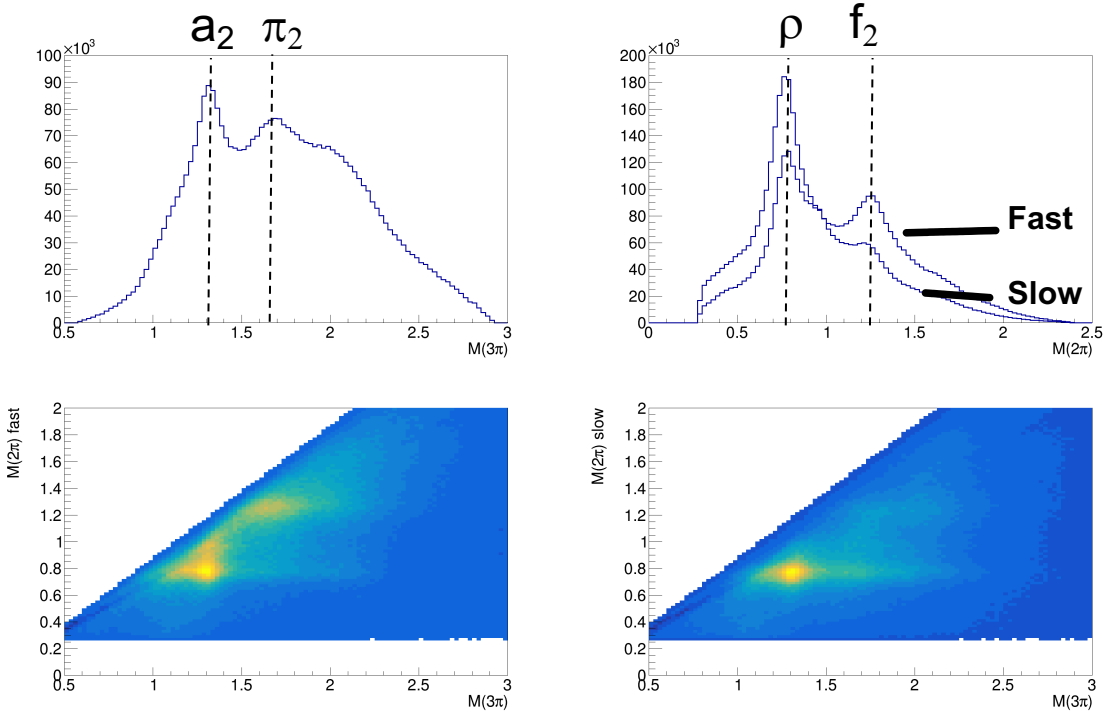


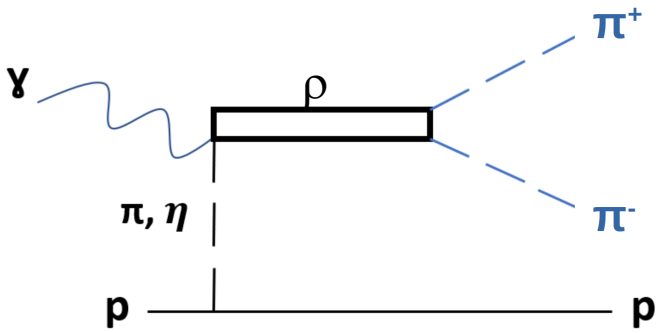
Fig. Mass distributions for $\pi^+\pi^+\pi^-$ final state.
Top Left : Total 3π mass distribution
Top Right : 2π mass distributions
Bottom : 2D, 2π versus 3π mass distributions
Left : Fast 2π mass. Right : Slow 2π mass

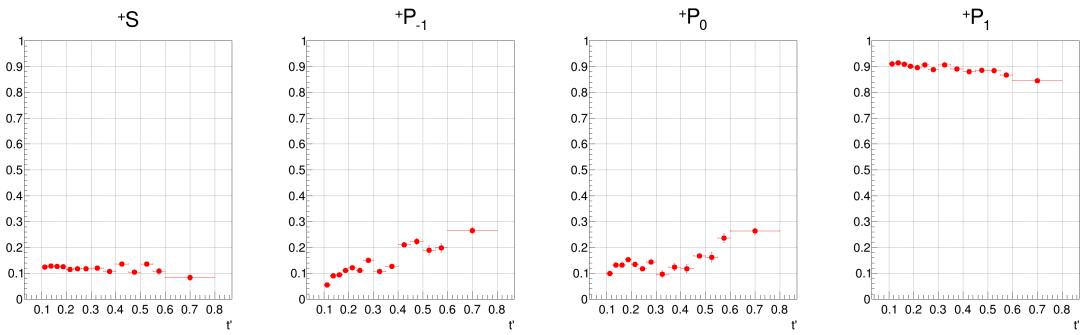
Visible 3π contributions from $a_2(1320)$ and $\pi_2(1670)$
2π contributions from ρ and $f_2(1270)$

Pass 2 data => factor 2 increase in statistics

MesonEx Partial Wave Analysis

- Amplitude analysis allows us to determine quantum numbers of contributing resonances
- Photoproduction reactions can generate resonances of all quantum numbers
  - ... including exotic hybrid mesons
- Photon polarization provides a means of filtering smaller contributions (reflectivity waves)
- PWA tools have been developed for fitting the reactions
- First results on $\pi^+\pi^-$ partial waves in the ρ resonance region below





Exotic waves possible in $\pi^+\pi^+\pi^-$ and $K^+K^-\pi^+$

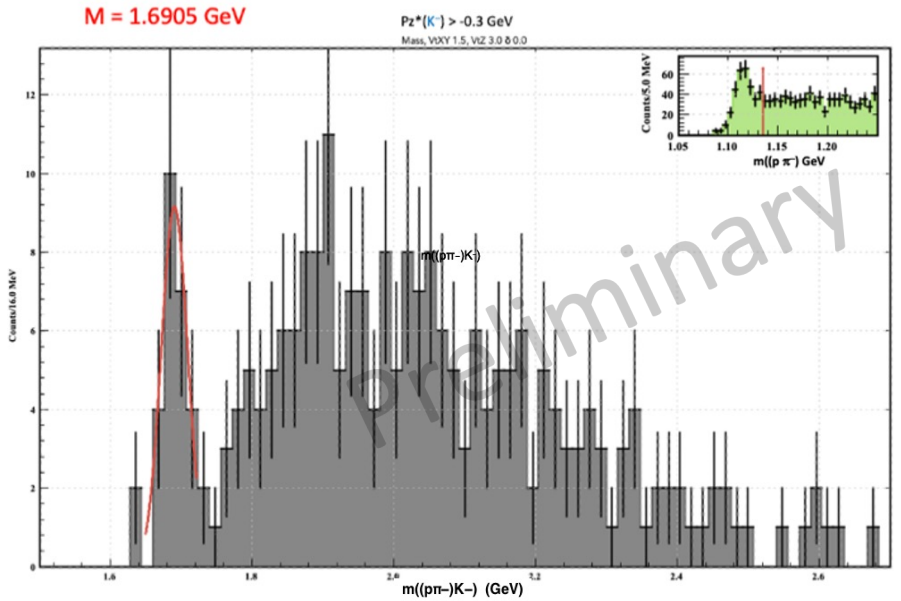
Fig. Magnitudes of contributing partial waves in the ρ resonance region. (S, P_{-1}, P_0, P_{+1})

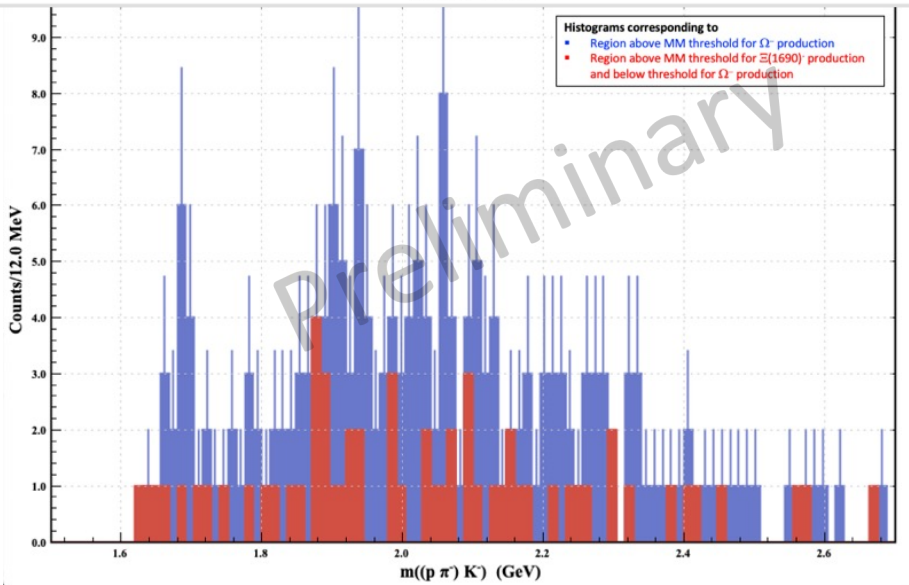
Preliminary result in good agreement with expectations from s-channel helicity conservation and pomeron exchange

Finishing the run-time will allow detailed analysis of the 3 meson final states

Very Strange Experiment: Search for the Ω^-

- Search for the Ω^- in the reaction ep → e′ΛK⁻(X), Λ → pπ⁻ using the RG-A fall 2018 and spring 2019 datasets.
  - Select events containing at least one proton, one negative pion, and one negative kaon.
  - Algorithm estimating the position of the Λ hyperon detached vertex used to improve the signal-to-background ratio.
- An excess of events in the expected Ω^- region is observed with a statistical significance close to 3s.
- Possible ambiguity for an observed signal in the expected Ω region: The $\Xi^-(1690)$ resonance also decays to ΛK⁻.
- MM threshold (0.85 GeV) for doubly strange $\Xi^-(1690)$ is lower than that for Ω^-. We compare m((pπ⁻)K⁻) spectra corresponding to $\Xi^-(1690)$ and Ω^- production thresholds to study possible contamination from $\Xi^-(1690)$ to the peak Ω^-.
- Need for more statistics to resolve ambiguity.





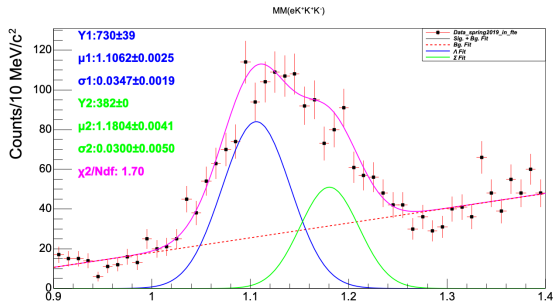
Within the remaining approved RG-A beam time, we expect to collect several times more statistics for this reaction.

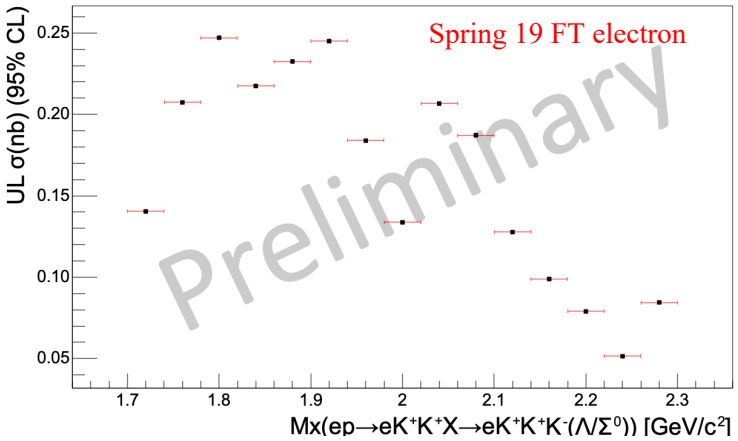
If the signal is confirmed, it will constitute the first observation of the Ω^- in electroproduction.

Very Strange Experiment: Cascade Hyperons

$ep \rightarrow epK^+K^+K^-(\Lambda, \Sigma^0)$

Missing Mass Distribution Using RG-A Spring 2019 Inbending FT-e



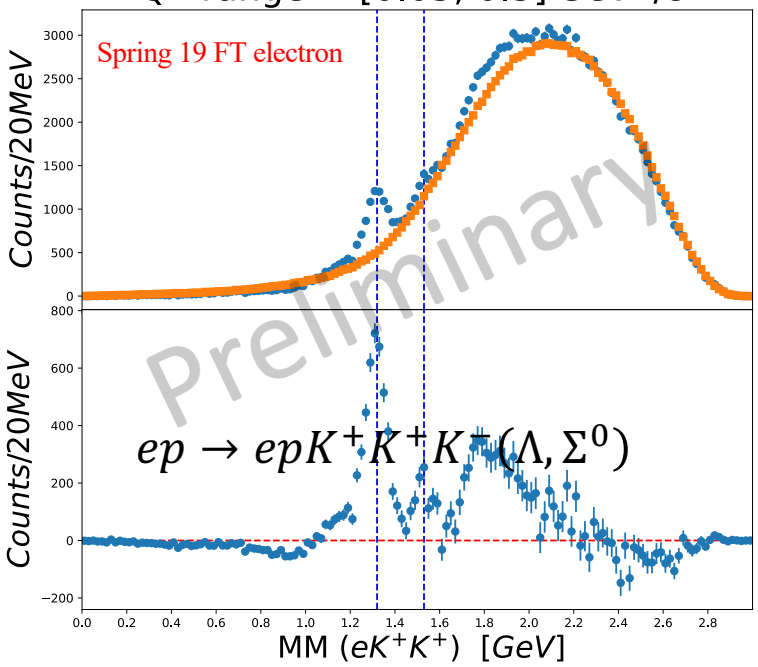


(b) Spring 2019 in FT-e Q^2 : $[0.03, 0.13]$ GeV^2.

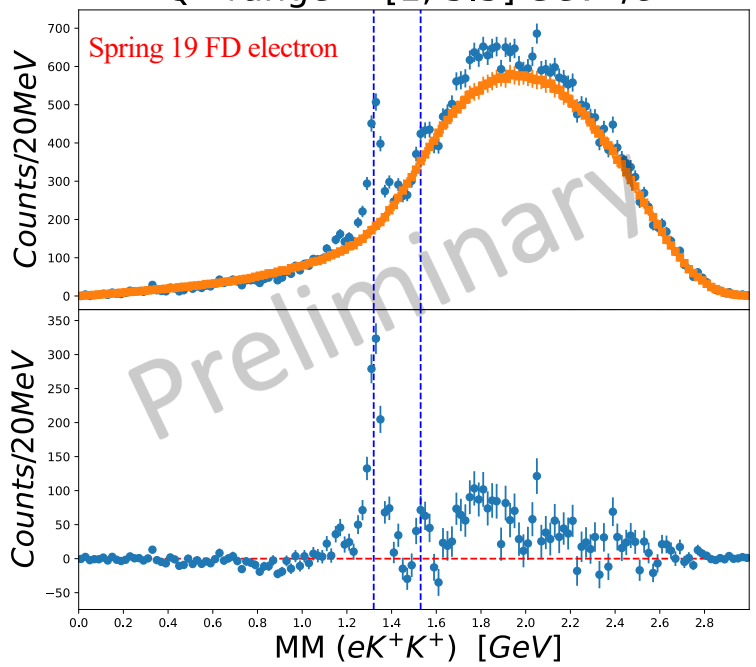
Preliminary results of the upper limit (<1 nb) for excited cascade cross sections were determined; Differential cross sections were also obtained.

$ep \rightarrow epK^+K^+\left(\Xi^{-(*)}\right)$

Q^2 range = [0.03, 0.3] GeV^2/c^2



Q^2 range = [1, 5.5] GeV^2/c^2



First-time measurement for cascade ground state cross sections in electroproduction
Background determined using mixed events techniques.

We expect to collect several times more statistics within the remaining approved RG-A beam time. This is critical for higher mass cascades. It will also allow us to measure decay branching and decay angular distributions necessary for determining the quantum numbers.

Summary and beam-time request

- The RG-A science program designed to address several of the most fundamental questions in hadronic physics.
- We have designed and optimized a sophisticated trigger system to enable the successful concurrent execution of all 13 experiments. The data processing and analysis of the 50% of RG-A data already recorded are in an advanced stage, resulting in several publications.

- **We request approval for the remaining 65 days necessary to fully achieve the objectives of the RG-A science program. The complete dataset is required to facilitate:**

  - A significant extension in Q^2 as promised by the CLAS12 and 12-GeV upgrade, to chart the transition from strong to perturbative QCD and high t range needed for high-level analysis and interpretation of the data.
  - Multi-dimensional analysis for the 3D imaging program and hadron structure.
  - Advanced amplitude analyses for hadron spectroscopy and structure.
  - Measurement of rare processes.
  - Potential for groundbreaking scientific discoveries.