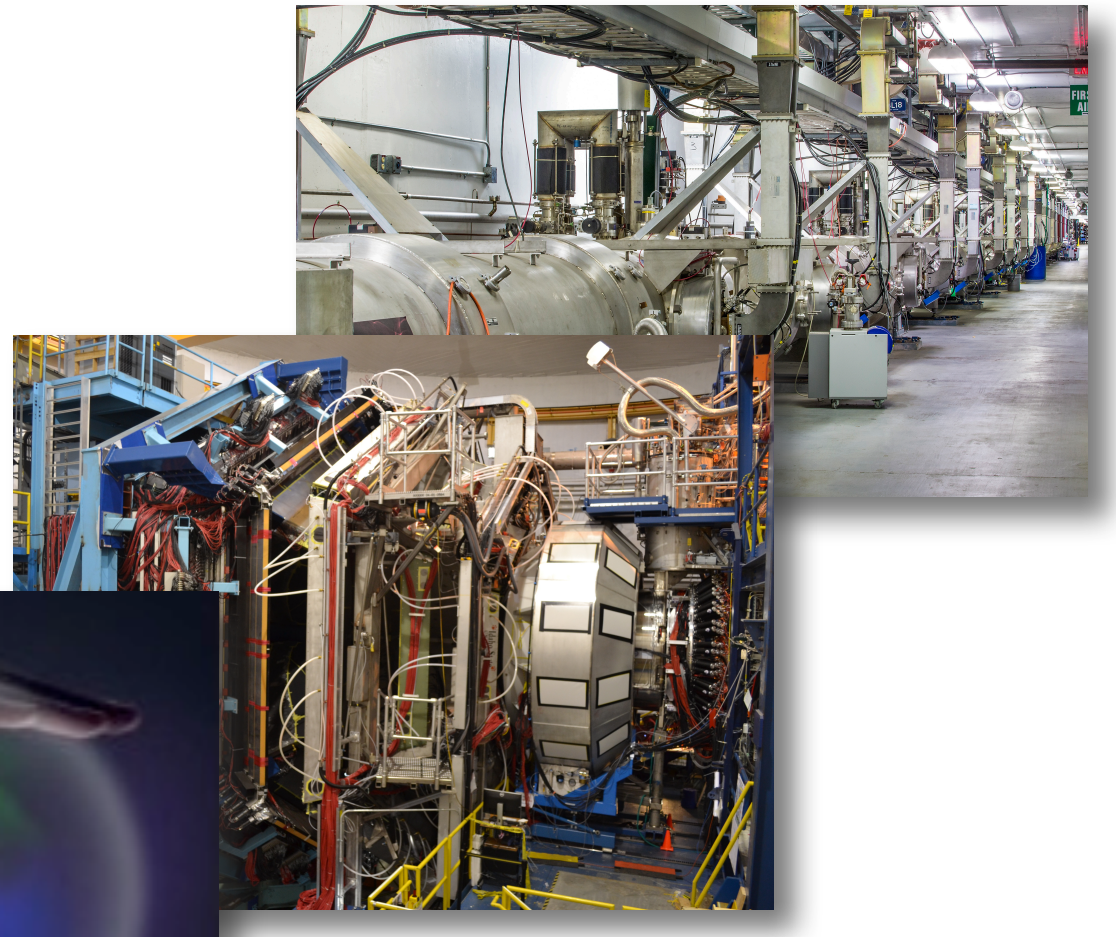
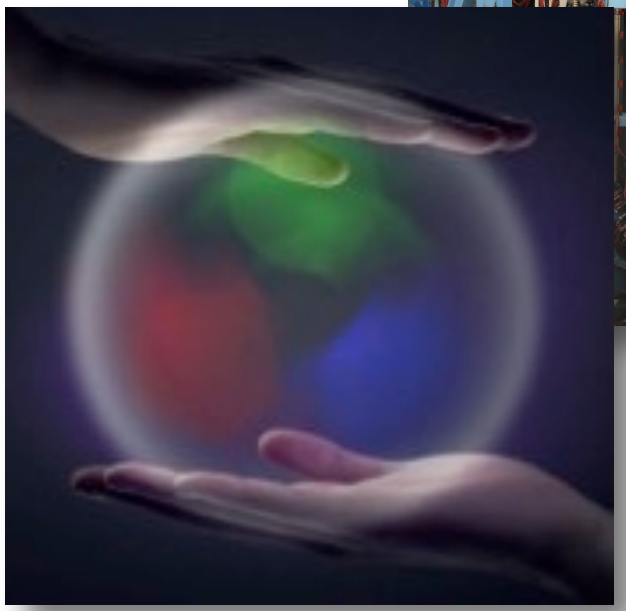
HALL B RUN GROUP A (RG-A) (POL. E ON UNPOL. H)

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





Latifa Elouadrhiri

For RG-A and the CLAS Collaboration

Jefferson Lab PAC 48

September 25, 2020

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

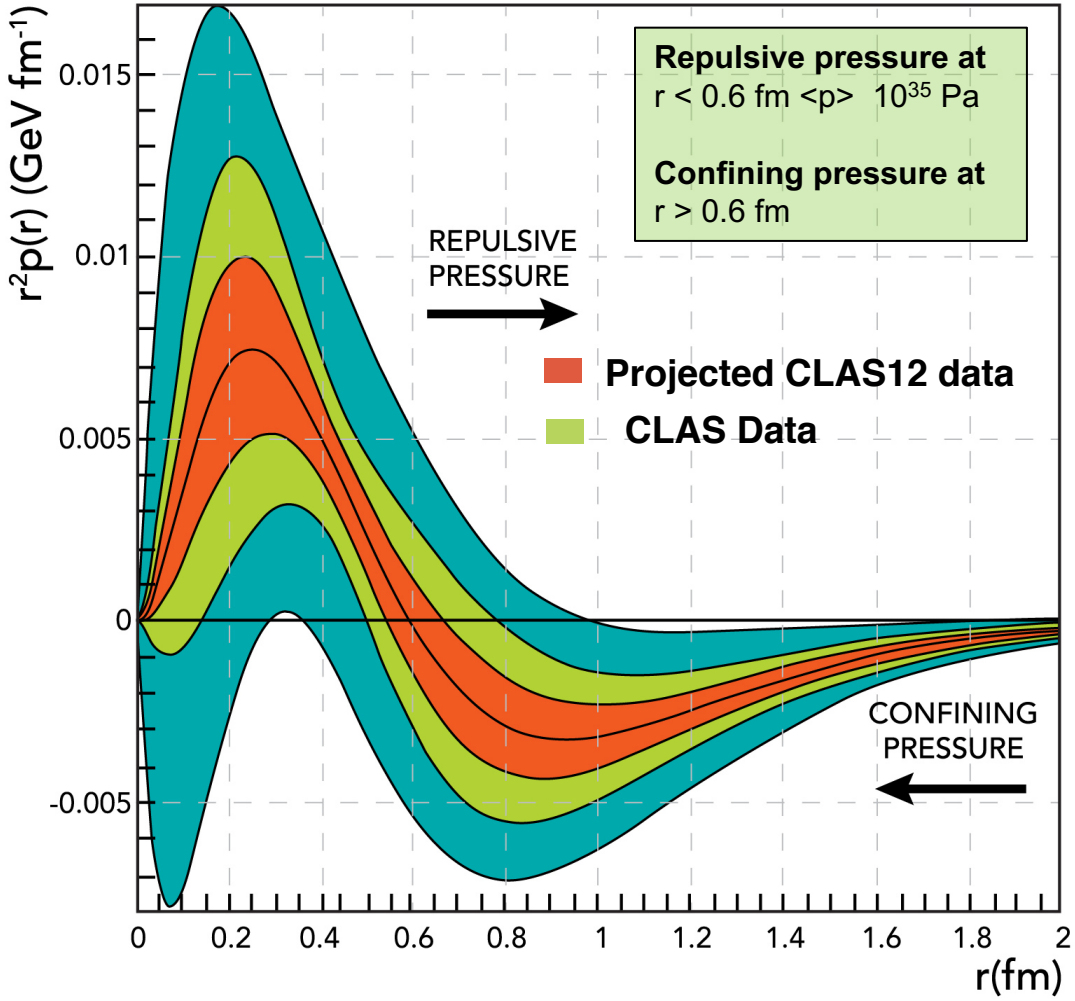
The CLAS12 RG-A experiments were designed to perform complementary measurements to study proton structure for both the ground and excited states, 3D imaging, and gluonic excitations with the core mission to understand the manner in which the constituents of protons are held together by the strong force and the emergence of the dominant part of hadron mass.

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. **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*
3. **Nucleon structure (E12-09-003, E12-06-108A, E12-06-108B)**: *Study of nucleon resonance structure at Q^2 from 2.0 to 12 GeV^2*
4. **Quasi-real photo-production (E12-12-001 and E12-12-001A):** *Study of J/ψ photoproduction, LHCb pentaquarks, and Time-like Compton Scattering*
5. **MesonX program (E12-11-005 and E12-11-005A)**: *Study of meson spectroscopy in search for hybrid mesons*

New information with scientific importance - highlights

THE PRESSURE DISTRIBUTION INSIDE THE PROTON

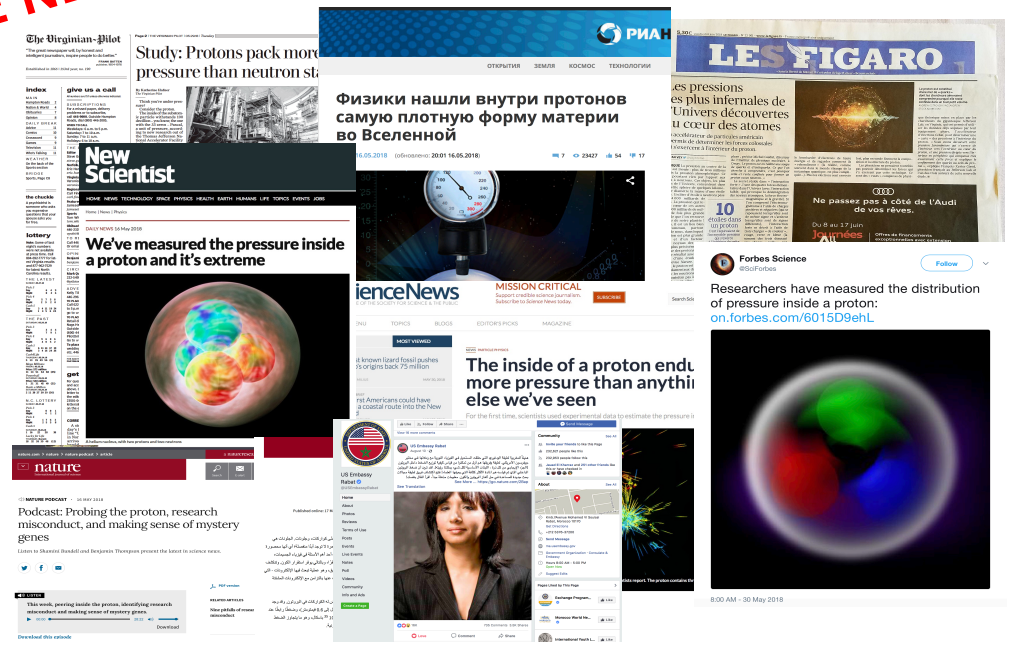


nature
International weekly journal of science

Nature 557 (2018) no.7705, 396-399

V. Burkert, L. Elouadrhiri, F.X. Girod

IN THE NEWS



This work opens up a new area of research on the fundamental gravitational properties of protons, neutrons, and nuclei, which can provide access to their physical radii, the internal shear forces acting on the quarks, and their pressure distributions

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New information with scientific importance - highlights

THE QUEST FOR MISSING RESONANCES

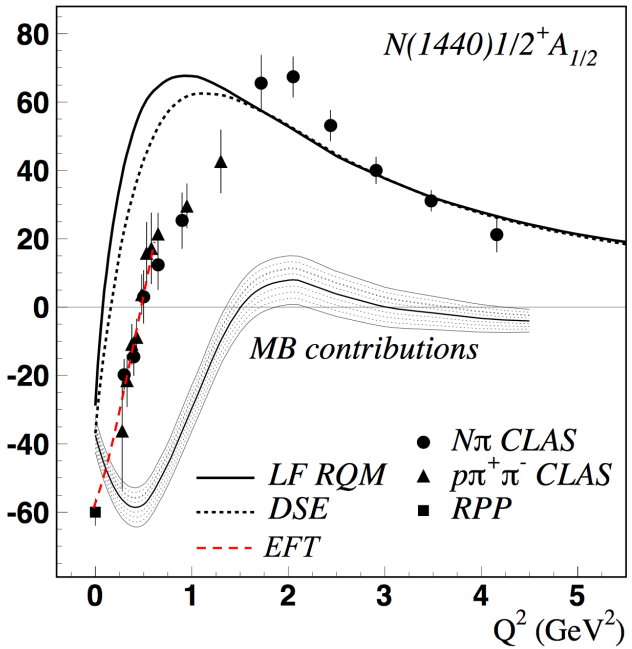
Precision meson photo-production data led to the discovery of several new states and the full establishment of poorly known states, in the mass range up to 2200 MeV.

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

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.

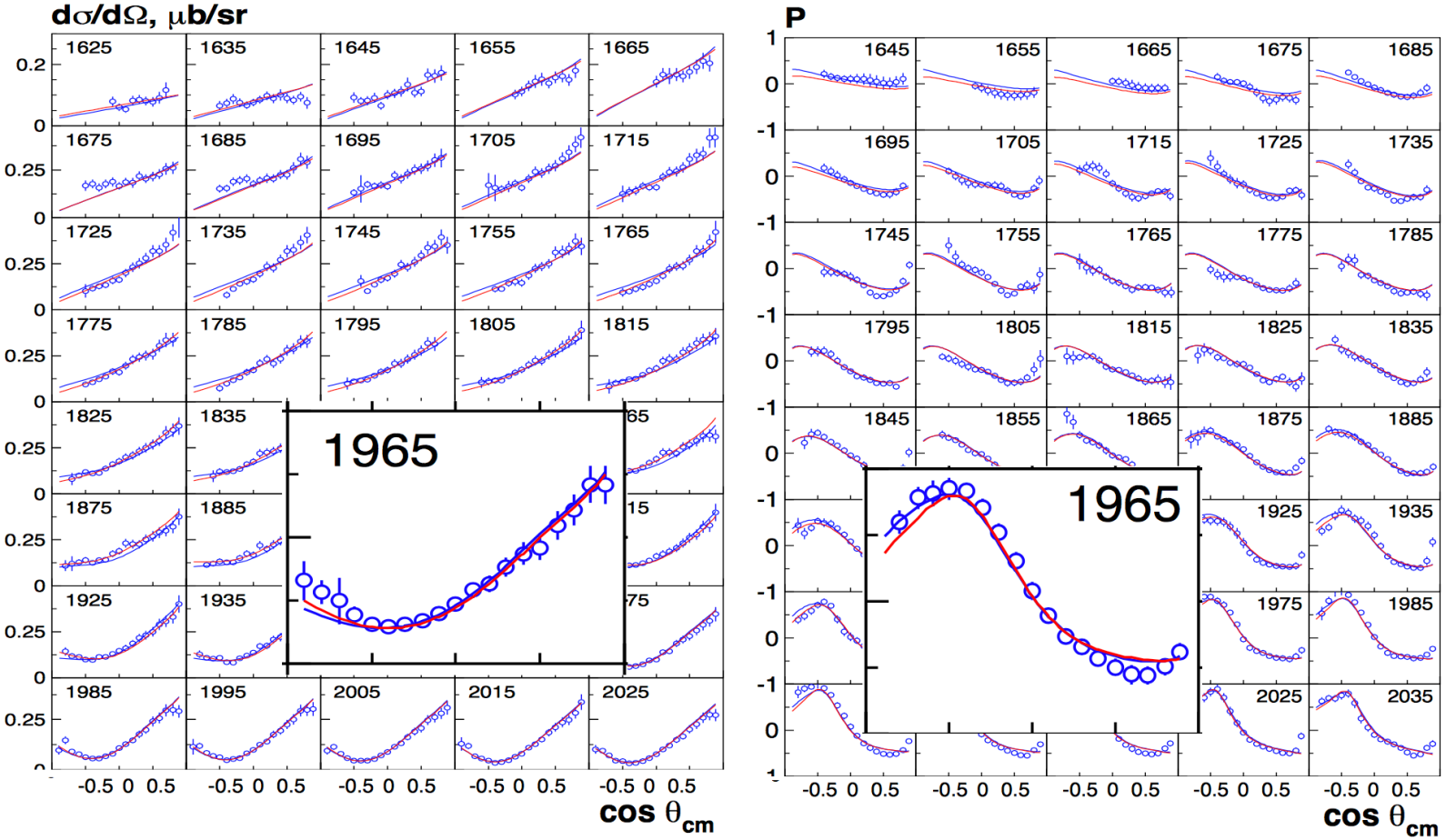
➔ The 1st radial excitation of the q^3 core emerges as the probe penetrates the MB cloud

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

NEW INFORMATION WITH SCIENTIFIC IMPORTANCE - HIGHLIGHTS

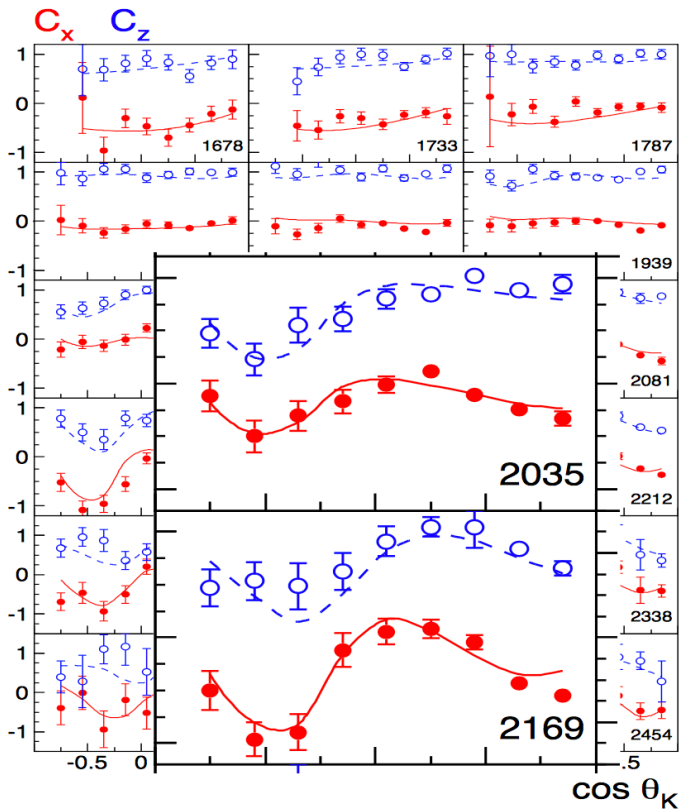
Hyperon photoproduction $\gamma p \rightarrow K^+\Lambda \rightarrow K^+ p\pi^-$

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

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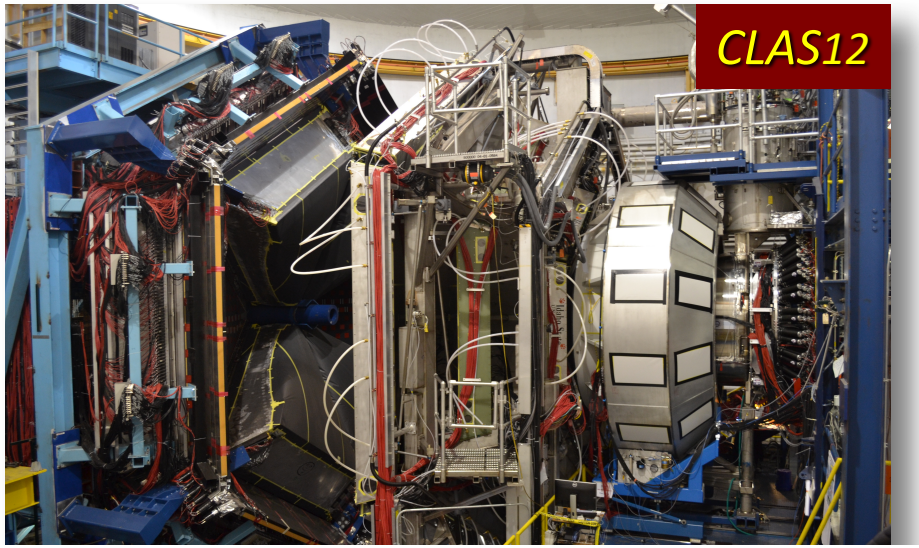
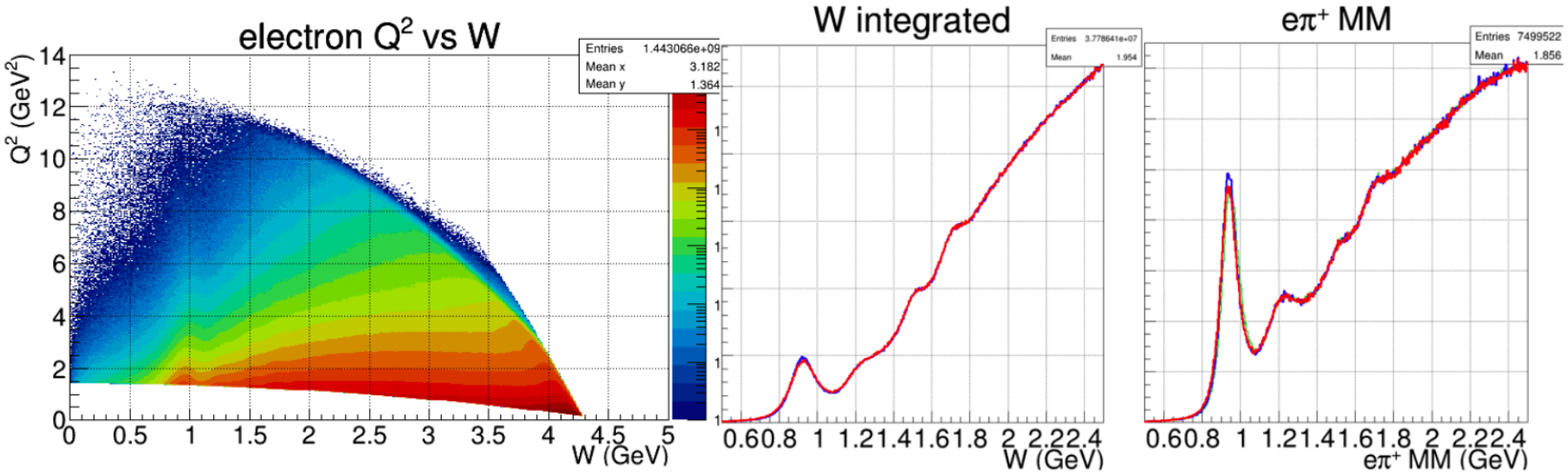
RG-A EXPERIMENT



RG-A has acquired data in three separate running periods, spring 2018 (126 mC), fall 2018 (99 mC), and spring 2019 (60 mC), with the collected charge amounting to roughly **half of the full approved RG-A beam time**. So far, the fall 2018 data set has been calibrated and processed for data analysis.

To fully realize the goals of the RG-A science program, the full statistics of the approved beam time is required.

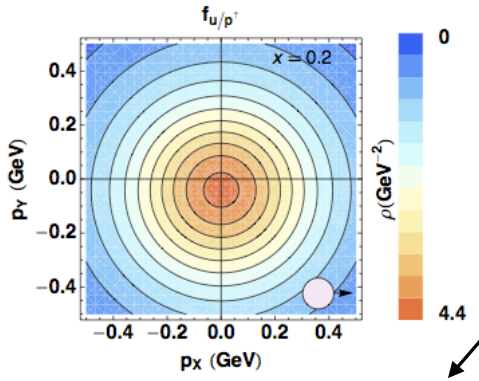


Published in: *Nucl. Instrum. Meth. A* 959, 163419 (2020)

Quantum phase-space distributions of quarks

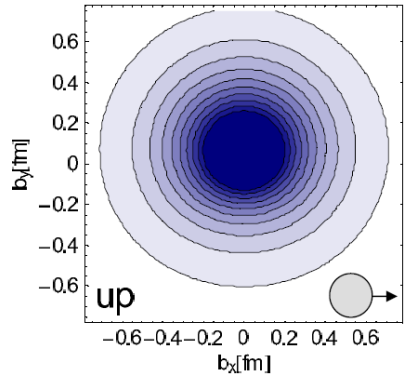
$W_p^q(x,k_T,r)$ "Mother" Wigner distributions

Probability to find a quark q in a nucleon P with a certain polarization in a position r and momentum k



d^3r d^2k_T

[Wigner (1932)] QM
[Belitsky, Ji, Yuan (04)] QFT (Breit frame)
[Lorce', BP (11)] QFT (light cone)



TMD PDFs: $f_p^u(x,k_T)$,...

GPDs: $H_p^u(x,\xi,t)$, ...

Semi-inclusive measurements
Momentum transfer to quark
Direct info about momentum distribution

d^2k_T $\xi=0, t=0$

Exclusive measurements
Momentum transfer to target
Direct info about spatial distribution

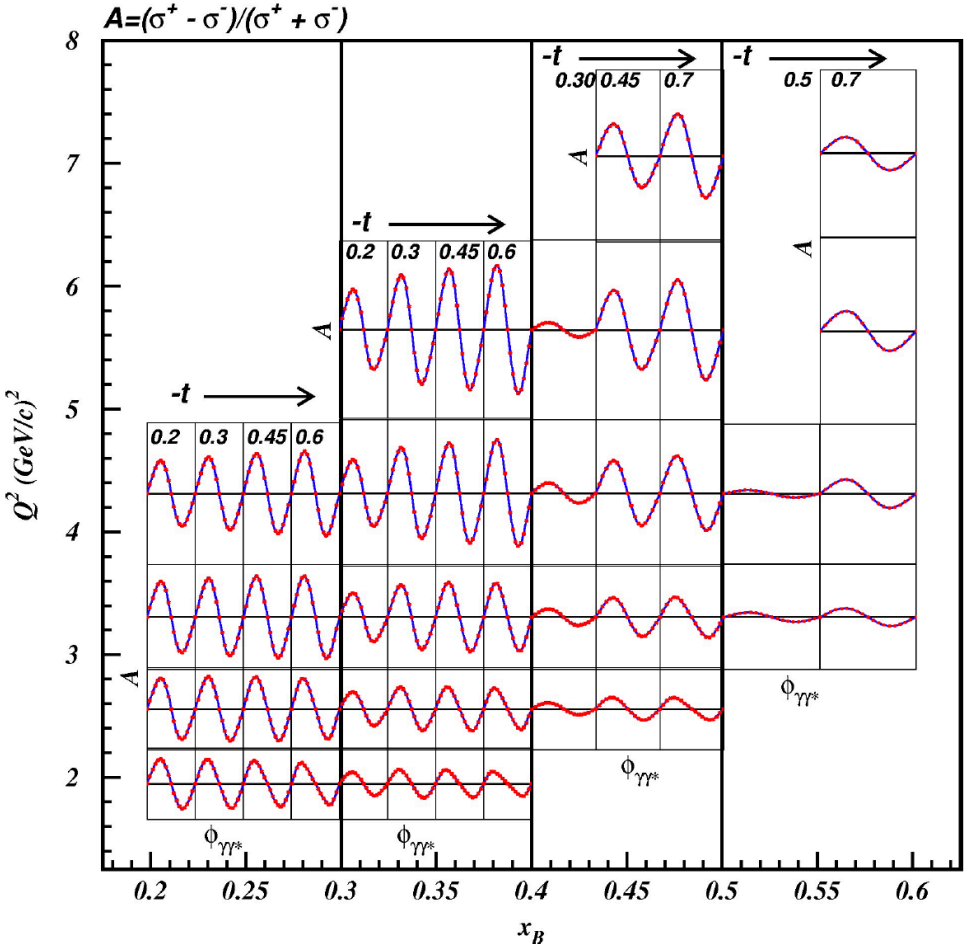
PDFs $f_p^u(x)$,...

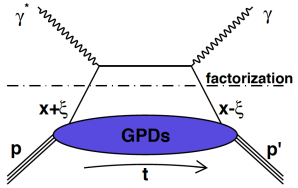
$$J_q = \frac{1}{2}\Delta\Sigma + L_q = \lim_{t\to 0}\int_{-1}^{1} dx\; x\left[H(x,\xi,t) + E(x,\xi,t)\right]$$

DVCS EXPERIMENT

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

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

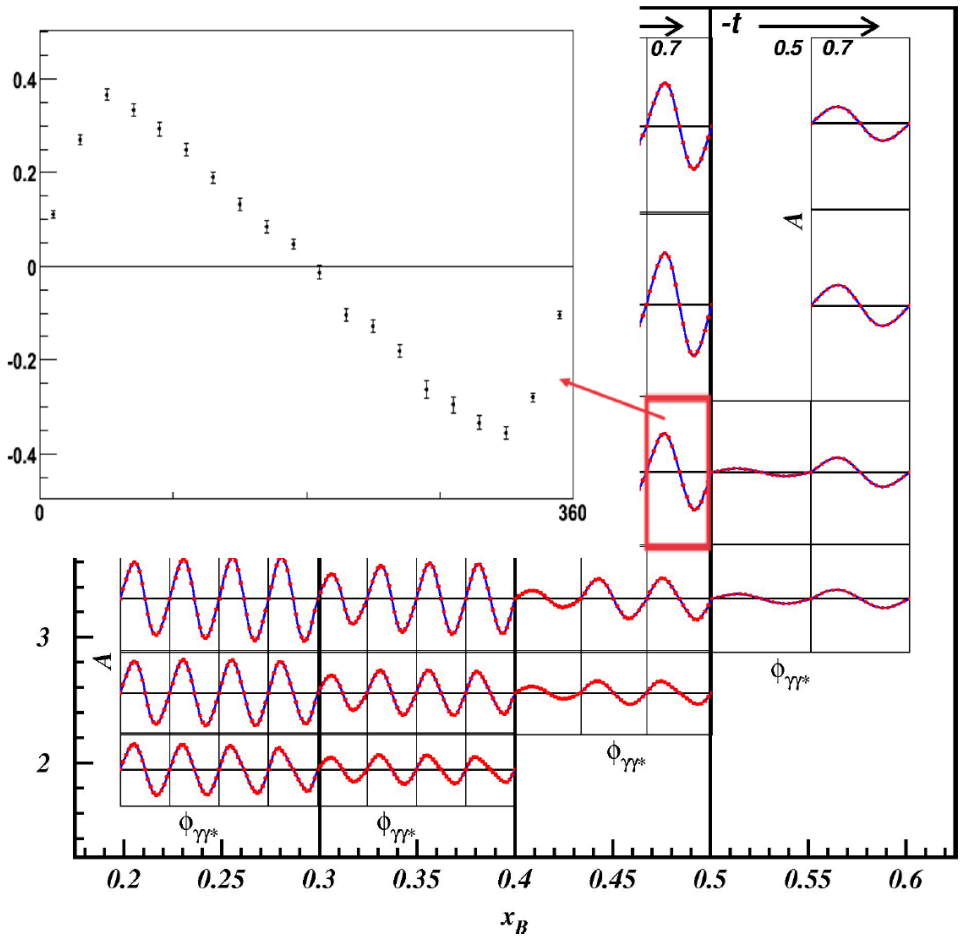




Projections for CLAS12

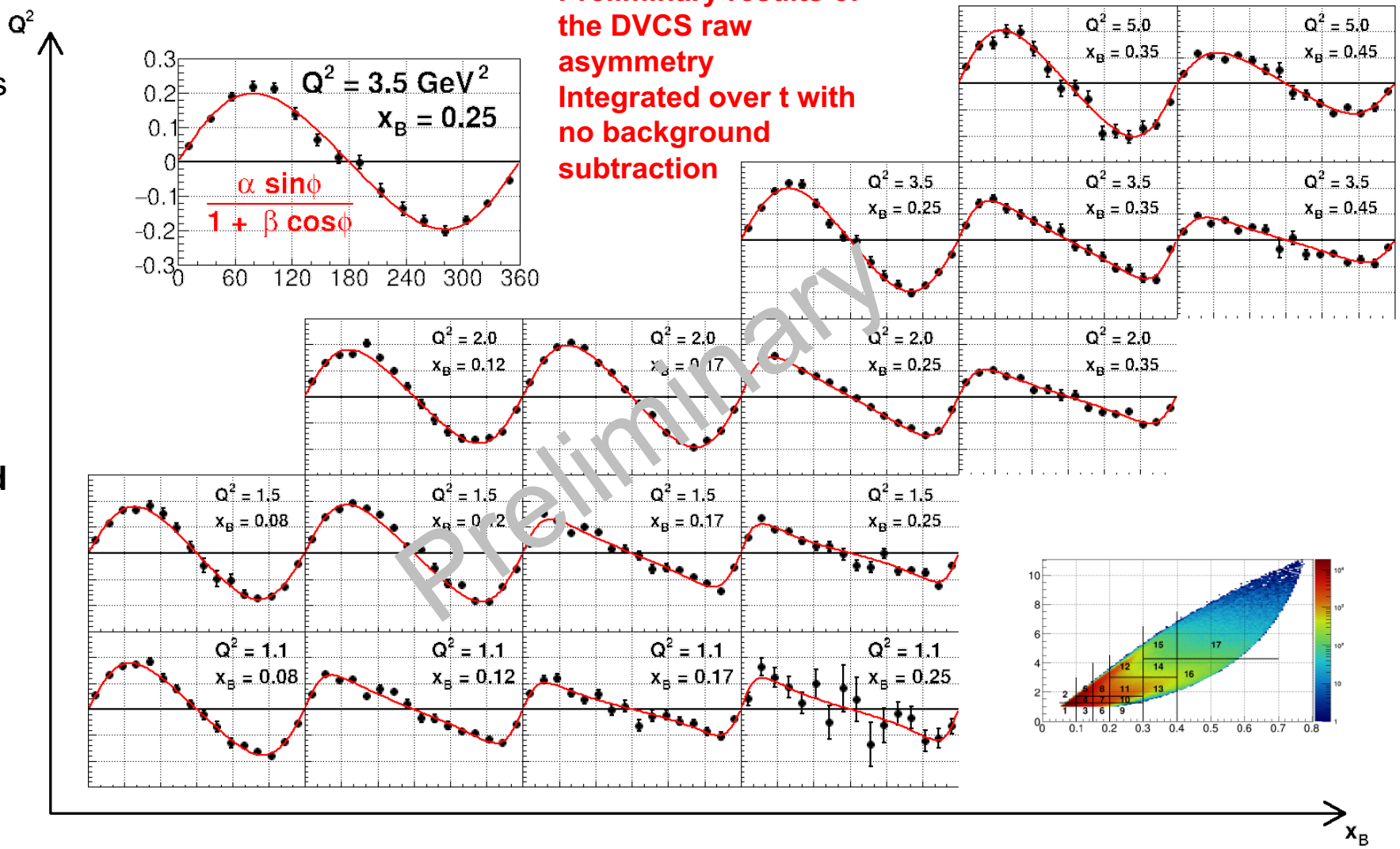
Statistical uncertainties :
from 1 % (low Q^2)
to 10 % (high Q^2)

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



RG – A PRELIMINARY DVCS BEAM SPIN ASYMMETRY

- Analysis well on track, tremendous effort to improve tracking resolution, control of the systematics such as a sizable pi0 contamination in high-x_B bins and fine-tuning of selection cuts to maximize the signal/background ratio
- **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.**



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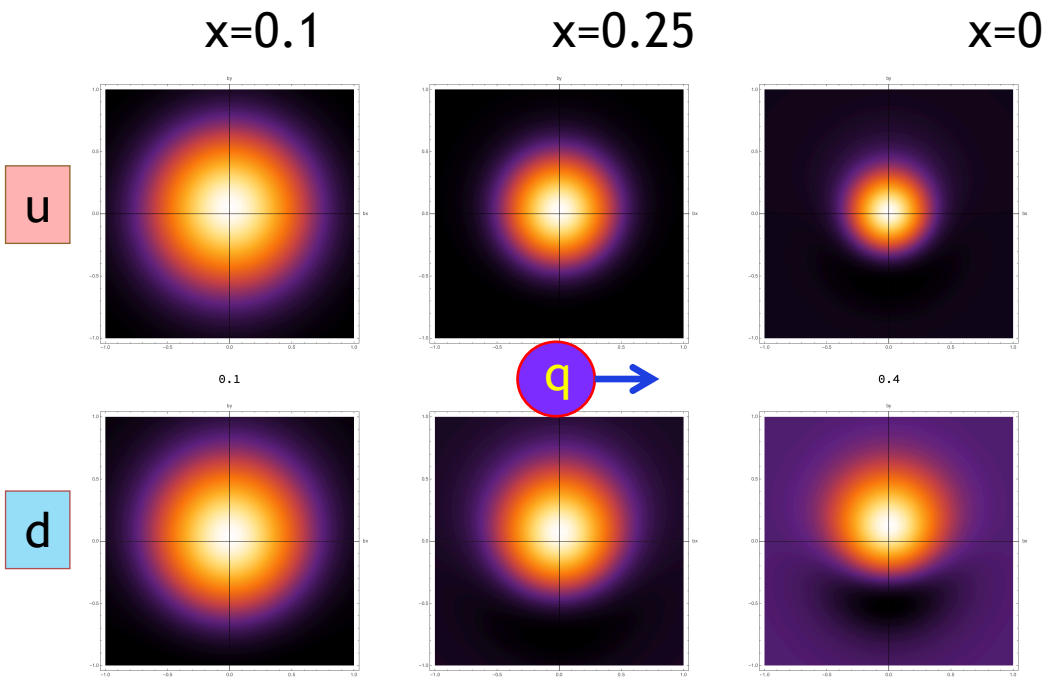
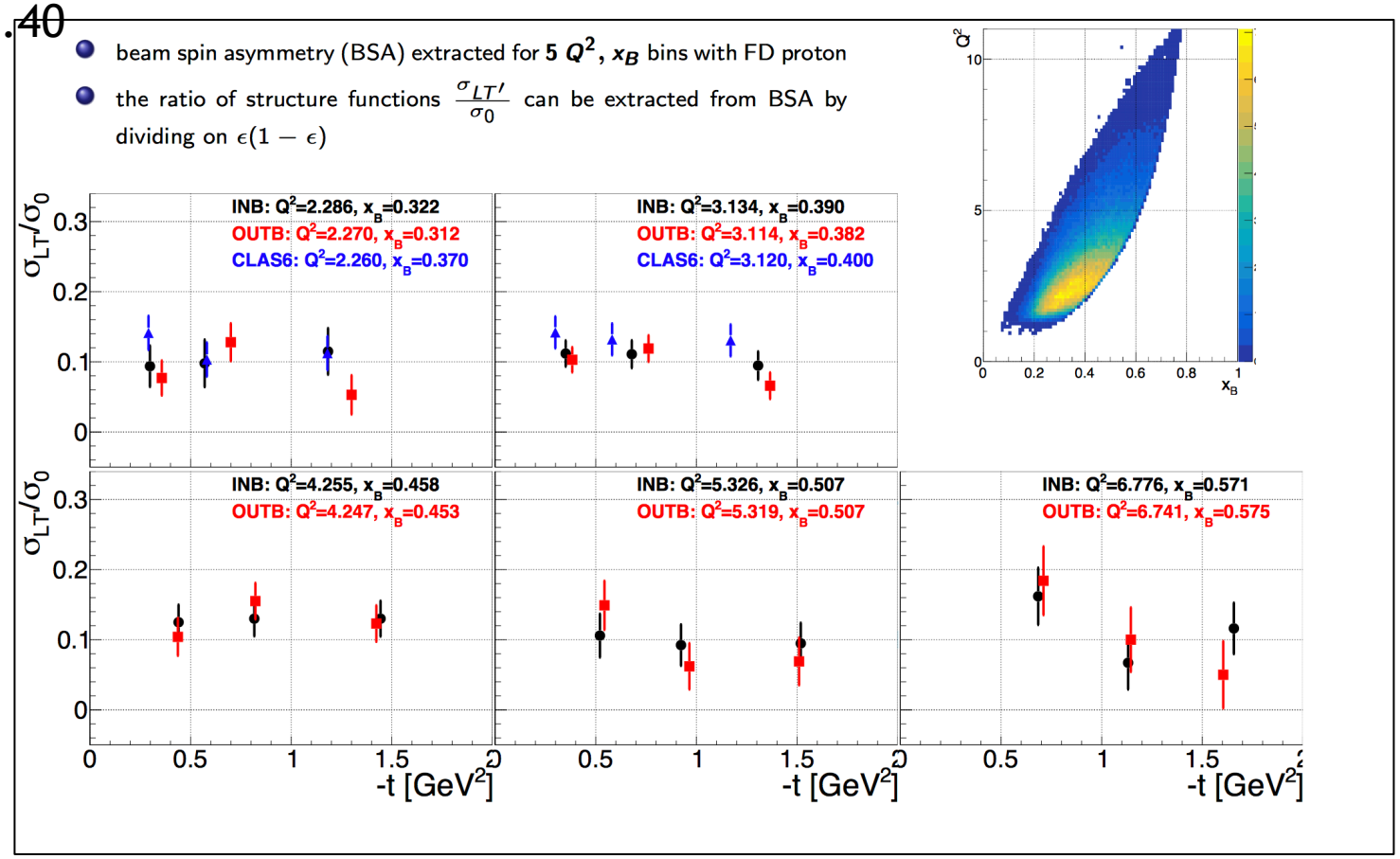


Polarized Quarks Transverse Densities in Unpolarized Proton from π^0 η production



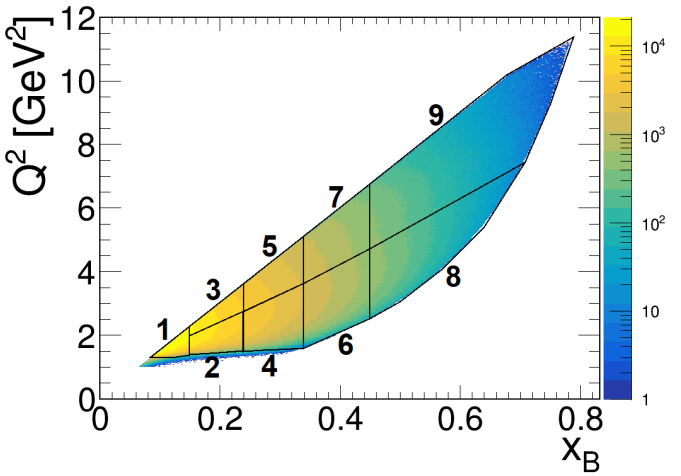
A first multidimensional, high precision study of SIDIS π^+ beam single spin asymmetry over a wide range of kinematics

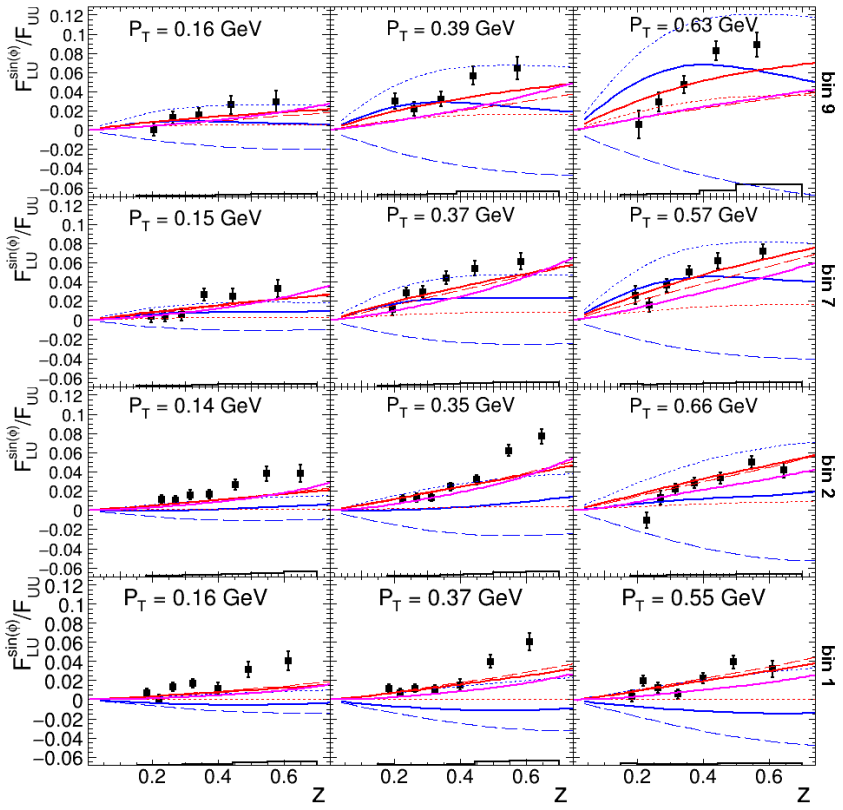
➔ SIDIS can probe the transverse momentum dependent parton structure

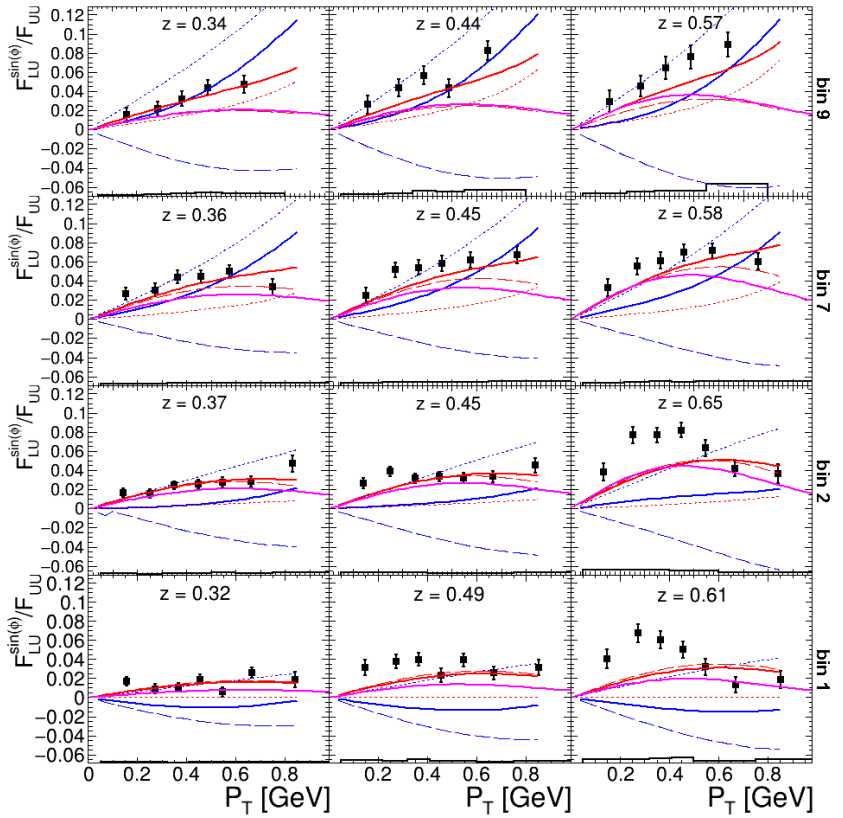
Previous experiments: Mostly only one dimensional studies

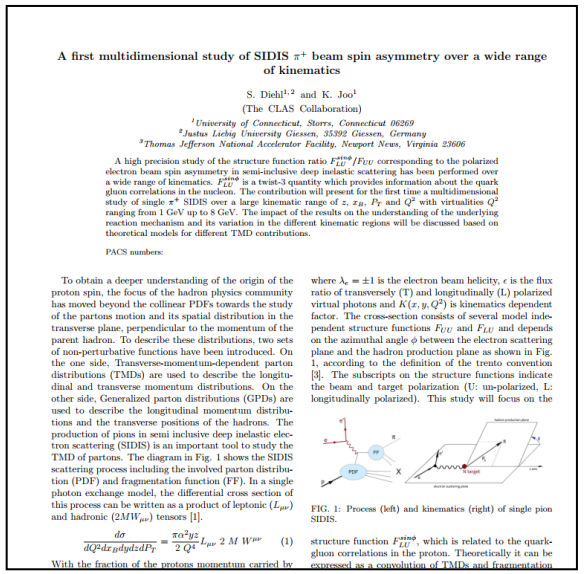
CLAS12: First fully differential study

➔ High precision CLAS12 data can help to distinguish between reaction models and to improve global fits of TMDs and FFs









A first multidimensional study of SIDIS π^+ beam spin asymmetry over a wide range of kinematics

S. Diehl[1,2] and K. Joo[1]

(The CLAS Collaboration)

[1]University of Connecticut, Storrs, Connecticut 06269
[2]Justus Liebig University Giessen, 35392 Giessen, Germany
[3]Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606

A high precision study of the structure function ratio $F_{LU}^{\sin\phi}/F_{UU}$ corresponding to the polarized electron beam spin asymmetry in semi-inclusive deep inelastic scattering has been performed over a wide range of kinematics. $F_{LU}^{\sin\phi}$ is a twist-3 quantity which provides information about the quark gluon correlations in the nucleon. The contribution will present for the first time a multidimensional study of single π^+ SIDIS over a large kinematic range of z, x_B, P_T and Q^2 with virtualities Q^2 ranging from 1 GeV up to 8 GeV. The impact of the results on the understanding of the underlying reaction mechanism and its variation in the different kinematic regions will be discussed based on theoretical models for different TMD contributions.

PACS numbers:

To obtain a deeper understanding of the origin of the proton spin, the focus of the hadron physics community has moved beyond the collinear PDFs towards the study of the partons motion and its spatial distribution in the transverse plane, perpendicular to the momentum of the parent hadron. To describe these distributions, two sets of non-perturbative functions have been introduced. On the one side, Transverse-momentum-dependent parton distributions (TMDs) are used to describe the longitudinal and transverse momentum distributions. On the other side, Generalized parton distributions (GPDs) are used to describe the longitudinal momentum distributions and the transverse positions of the hadrons. The production of pions in semi inclusive deep inelastic electron scattering (SIDIS) is an important tool to study the TMD of partons. The diagram in Fig. 1 shows the SIDIS scattering process including the involved parton distribution (PDF) and fragmentation function (FF). In a single photon exchange model, the differential cross section of this process can be written as a product of leptonic ($L_{\mu\nu}$) and hadronic ($2MW_{\mu\nu}$) tensors [1].

$$\frac{d\sigma}{dQ^2 dx_B dy d\varepsilon d\vec{P}_T} = \frac{\pi\alpha^2 y z}{2\,Q^4} L_{\mu\nu}\, 2\,M\, W^{\mu\nu} \quad (1)$$

With the fraction of the protons momentum carried by

where $\lambda_e = \pm 1$ is the electron beam helicity, ϵ is the flux ratio of transversely (T) and longitudinally (L) polarized virtual photons and $K(x, y, Q^2)$ is kinematics dependent factor. The cross-section consists of several model independent structure functions F_{UU} and F_{LU} and depends on the azimuthal angle ϕ between the electron scattering plane and the hadron production plane as shown in Fig. 1; according to the definition of the trento convention [3]. The subscripts on the structure functions indicate the beam and target polarization (U: un-polarized, L: longitudinally polarized). This study will focus on the

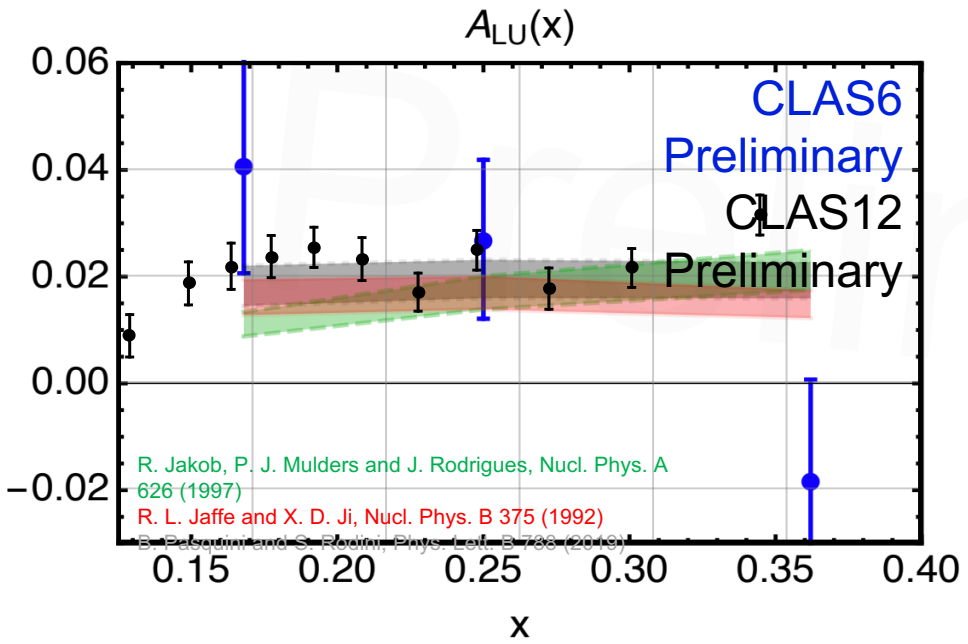
FIG. 1: Process (left) and kinematics (right) of single pion SIDIS.

structure function $F_{LU}^{\sin\phi}$, which is related to the quark-gluon correlations in the proton. Theoretically it can be expressed as a convolution of TMDs and fragmentation

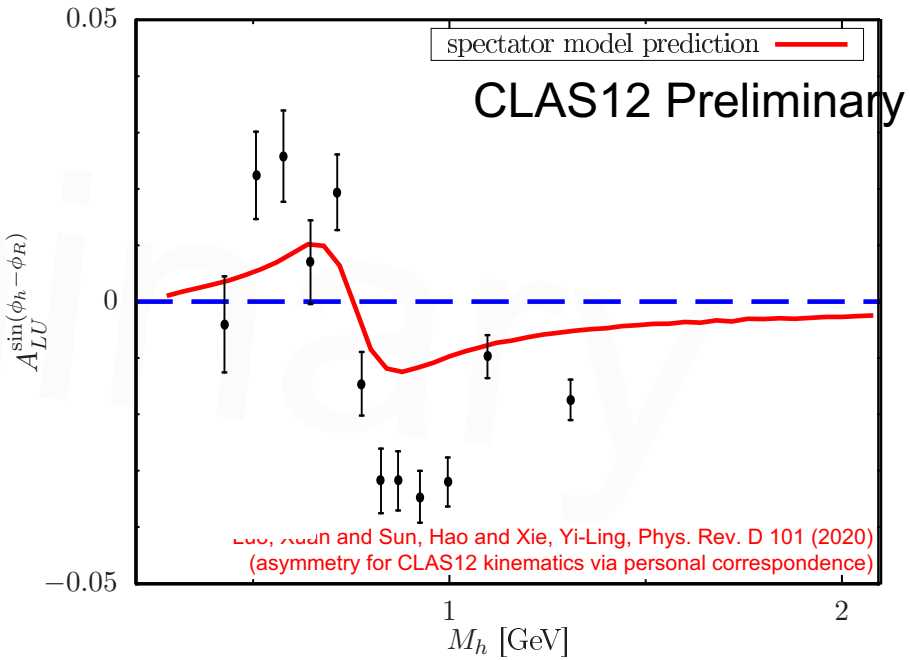
CLAS12 First Publication in Preparation

Measurements of Dihadron Beam-spin Asymmetries

- Intent to publish a PRL paper with RGA dipion beam spin asymmetries.
- Physics quantities of interest:
  - A_{LU} **$\sin(\phi_R)$** modulation: allowing the **first significant access in a collinear framework** to the twist-3 PDF **e(x),** which gives insight into largely unexplored quark-gluon correlations.
  - A_{LU} **$\sin(\phi_H-\phi_R)$** modulation: **first measurement** sensitive to the DiFF $G_1^{\perp}$, which describes the helicity dependent fragmentation of a dihadron pair.



The PDF **e(x)** can be extracted point by point from this asymmetry

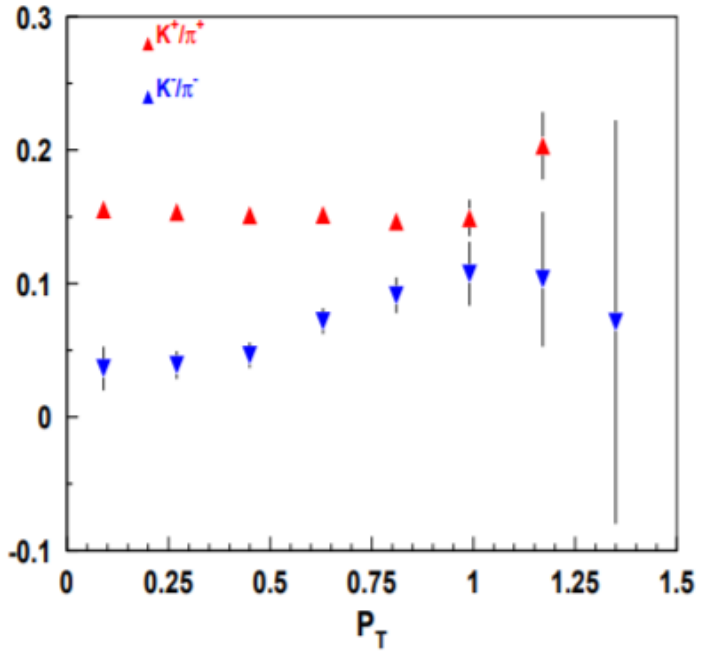


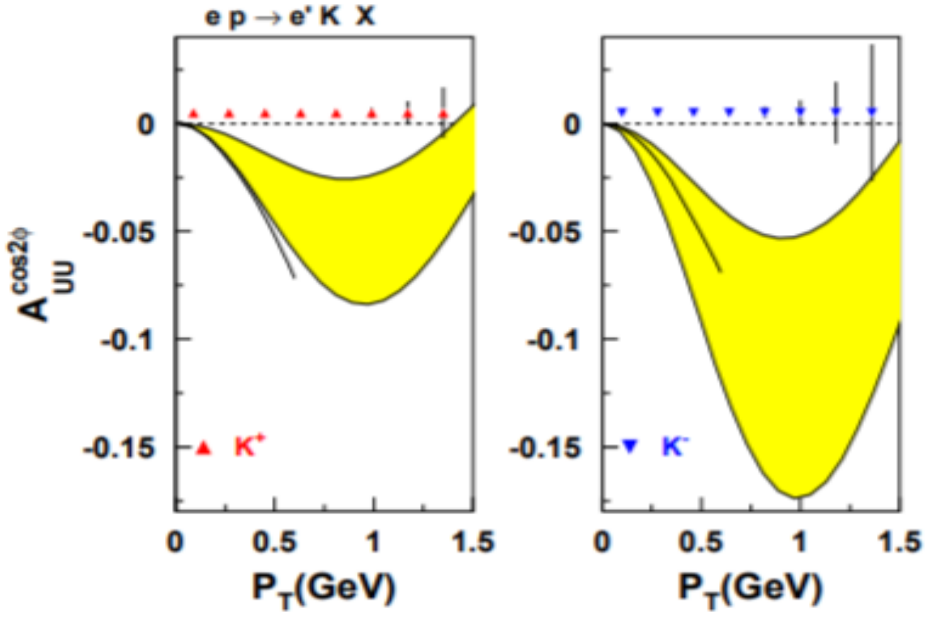
A sign change is observed around the ρ mass

Measurements of Boer-Mulders effect for Kaons

Boer-Mulders structure function, $F_{UU}^{\cos\phi}$, provides access to Boer-Mulders distribution and Collins fragmentation function, which are under intensive studies worldwide, including SIDIS and DY experiments

$$F_{UU} \propto h_1^{\perp} H_1^{\perp}$$





Significantly smaller fraction of kaons, K^- in particular, require more statistics for studies of Boer-Mulders effects on proton for kaons

Hadron Structure Experiments (E12-09-003, E12-06-108A)

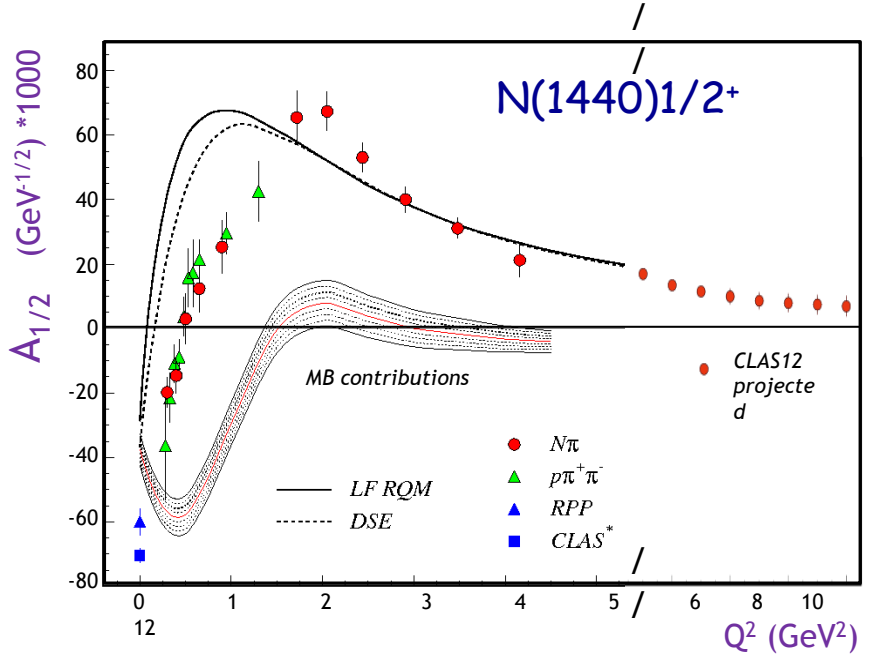
N* electroexcitation studies with CLAS12 will address the critical open questions:

How is >98% of hadron mass generated and how is it related to Dynamical Chiral Symmetry Breaking?

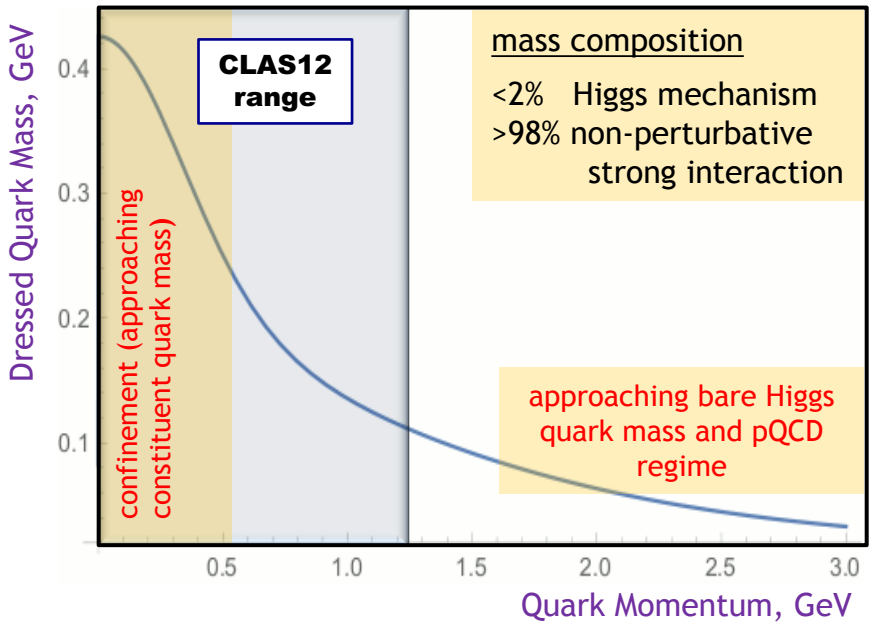
What is the behavior of QCD's running coupling at infrared momenta?

Mapping out the quark mass function from CLAS12 data on the $\gamma_v pN^*$ electrocouplings of spin-isospin flip, radial, and orbital excited nucleon resonances for Q^2:[5:12] GeV^2 will allow us to explore how the dominant part of hadron mass is generated in the transition from the strong QCD to pQCD regimes

Chart the QCD running coupling from the results on the electrocouplings of orbital excited resonances



CLAS results vs. theory expectations with running quark mass

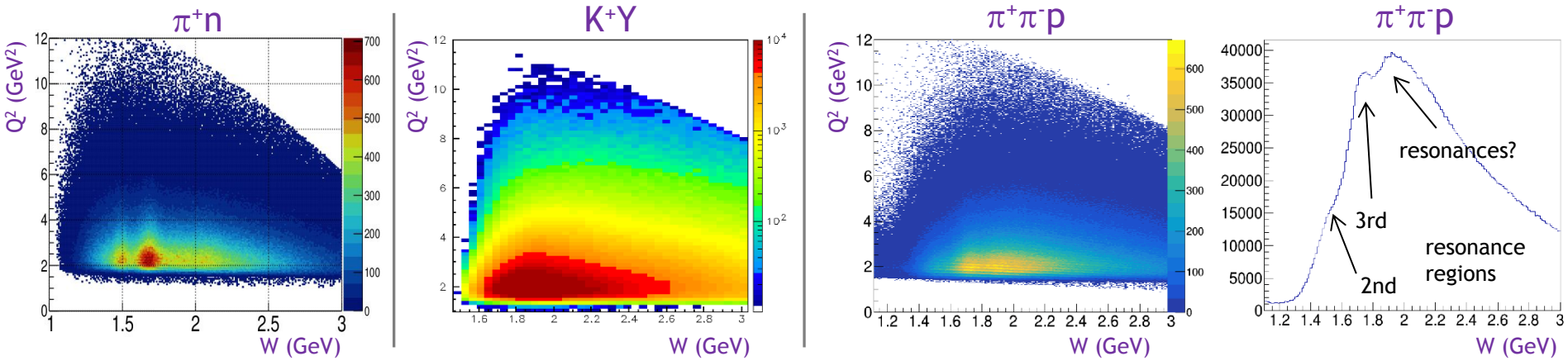


V.D. Burkert, C.D. Roberts, Rev. Mod. Phys. 91, 011003 (2019)
D.S. Carman, K. Joo, V.I. Mokeev, FBS 61, 29 (2020)

N* Electroexcitation to high Q^2 with CLAS12

Expected outcome: The first results on the $\gamma_v pN^*$ electrocouplings of most N* states from data in the range $W < 3.0$ GeV and $Q^2 > 5.0$ GeV^2 for exclusive reaction channels: πN, $\pi\pi N$, KY, K^*Y, KY^*

kinematic coverage for RG-A data @ 10.6 GeV



Expected events per Q^2/W bin for full RG-A dataset

π^+n			$K^+\Lambda$ & $K^+\Sigma^0$					$\pi^+\pi^-p$		
Q^2 [GeV^2]	W [GeV] 1.5-1.55	W [GeV] 1.7-1.75	Q^2 [GeV^2]	W_Λ [GeV] 1.7-1.75	W_Σ [GeV] 1.7-1.75	W_Λ [GeV] 1.9-1.95	W_Σ [GeV] 1.9-1.95	Q^2 [GeV^2]	W [GeV] 1.7-1.75	W [GeV] 1.9-1.95
			1.4-2.2	63417	6012	66564	33170			
			2.2-3.0	72144	5364	77443	28720			
5.2-5.8	15272	4175	3.0-4.0	52358	3945	51991	18936	5.2-5.8	2813	2808
5.8-6.5	10737	2637	4.0-5.0	24833	3103	26690	5925	5.8-6.5	1822	1969
6.5-7.2	7367	1684	5.0-6.0	11203	1598	11160	2642	6.5-7.2	1159	1294
7.2-8.1	4567	1290	6.0-7.0	5566	648	6300	943	7.2-8.1	661	924
8.1-9.1	2742	540	7.0-8.0	2606	338	3276	633	8.1-9.1	364	414
9.1-10.5	1453	194	8.0-9.0	1440	244	936	86	9.1-10.5	118	179

Collecting the remainder of the approved RG-A beam time will give a factor of two more statistics

This will extend the Q^2 range of the $\gamma_v pN^*$ electrocouplings to 8-10 GeV^2 for each of these channels – *the data collected so far will limit us to 6-8 GeV^2*

E12-12-001 – Time-like Compton Scattering and J/ψ photoproduction

Lepton pair photoproduction using untagged electron scattering with exclusive final state (*kinematics of the missing e' constrained to $Q^2 \sim 0$*)

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

The analysis framework is ready, validated using the 60% of the available data to analyze

Since the approval of the original proposal:

- new additions to the Hall-B program, RG proposals for J/ψ production on deuterium and hydrogen, search for LHCb pentaquarks
- proposals in Hall-C to search for LHCb pentaquarks and Time-like Compton scattering (TCS) with the transversely polarized target (C2)

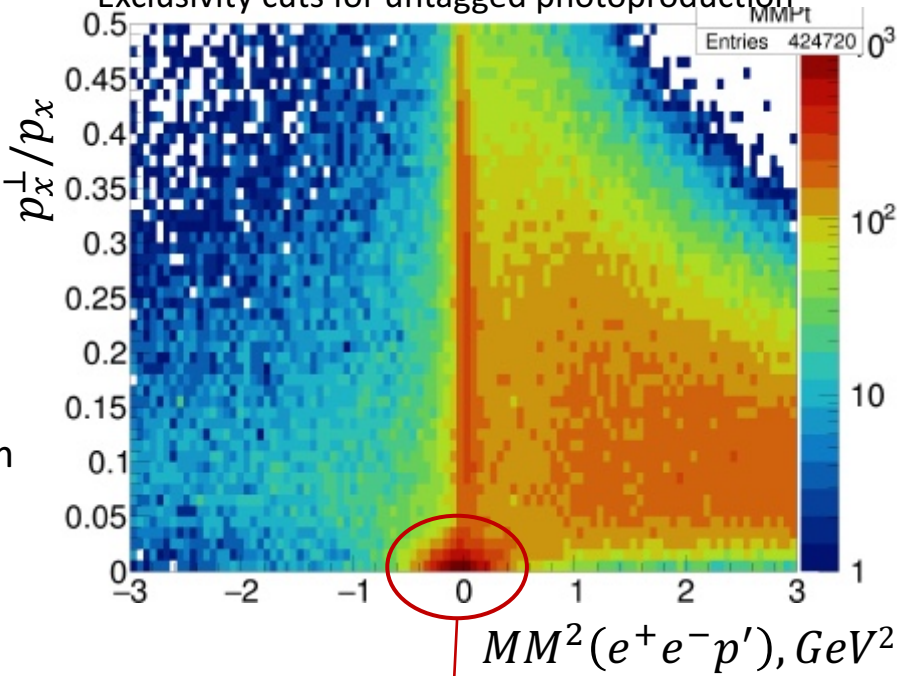
The first results from GlueX on J/ψ photoproduction, 461 events. No evidence for LHCb pentaquarks, upper limits on branching ratios have been evaluated. The Hall-C experiment is expected to release their results soon.

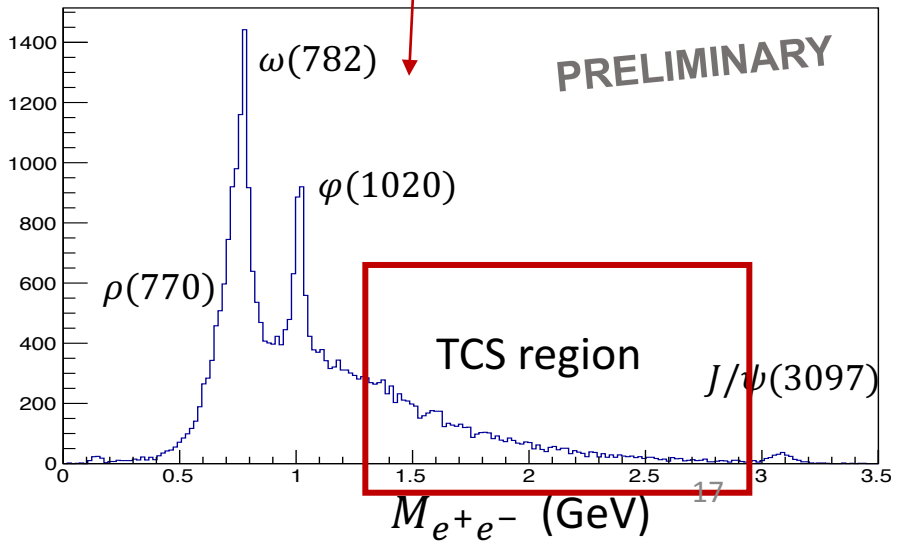
There have been several publications on the phenomenology of TCS, next-to-leading order corrections, new observables.

A renewed interest in near-threshold J/ψ production - J/ψ-N scattering length, QCD trace anomaly in proton mass decomposition.

E12-12-001(A) will complement GlueX and Hall-C experiments in J/ψ production and will be the first to publish experimental results on TCS.

Exclusivity cuts for untagged photoproduction





Time-like Compton Scattering

A key reaction for studying the Generalized Parton Distributions:

- *access to the real part of CFFs, $\widetilde{M}^{--}$, **sensitive to the D-term** in GPD parametrization. Observables **R** ratio and forward backward asymmetry, **A_{FB}***
- *study universality of GPDs, accessing imaginary part of CFF in **BSA** (similar to DVCS)*

Promising results with the analyzed data set, good agreement with model predictions and previous analysis results.

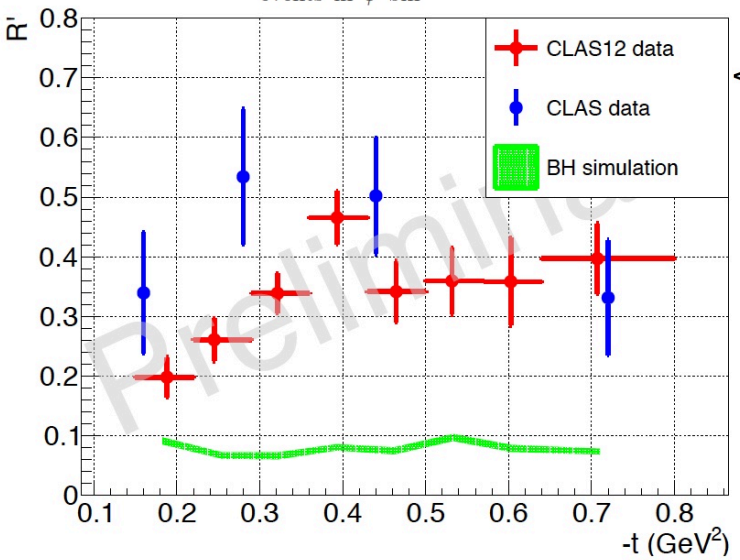
CLAS12 can deliver all three observables for the unpolarized target, in multidimensional parameter space (E_γ, t, Q'^2). **A full statistics of the approved beam time will be needed to reach the experiment goals.**

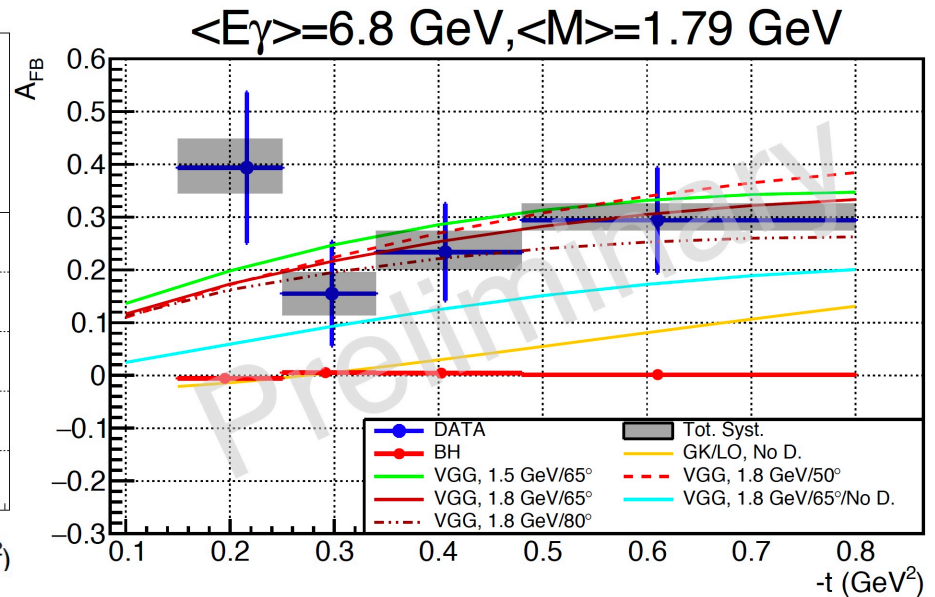
$$R' = \frac{\sum_\phi Y_\phi \cos(\phi)}{\sum_\phi Y_\phi}$$

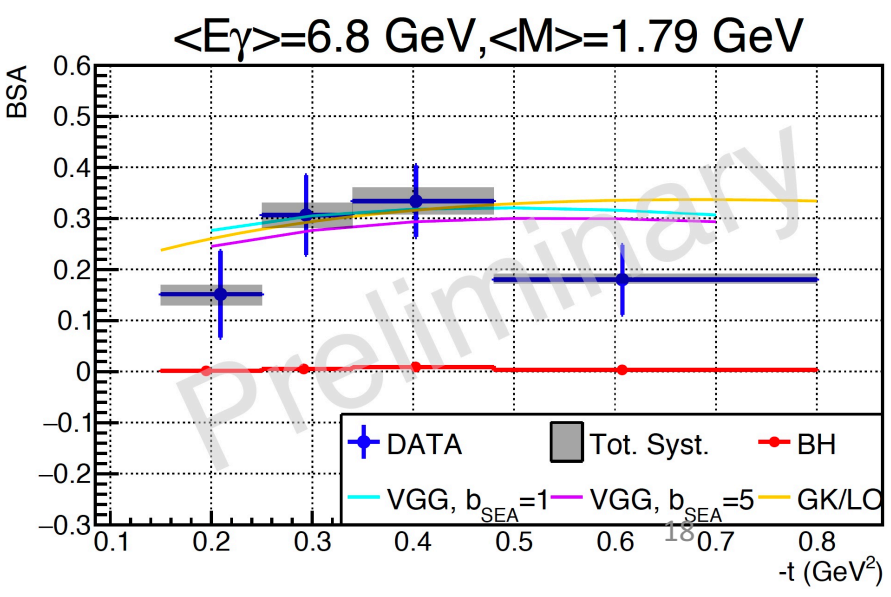
$$Y_\phi = \sum_{\text{events in } \phi \text{ bin}} \left(\frac{L}{L_0}\right)\left(\frac{1}{Acc}\right)$$

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

$$BSA(-t,|E\gamma,M;\phi) = \frac{1}{Pol_{eff}}\frac{N^+ - N^-}{N^+ + N^-},$$







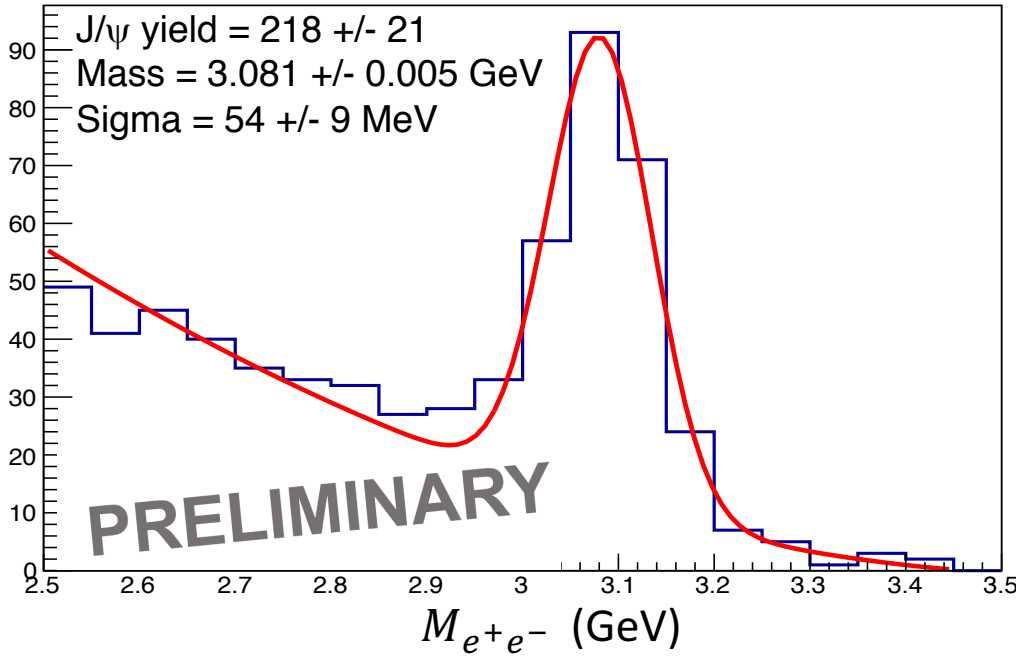
J/ψ photoproduction

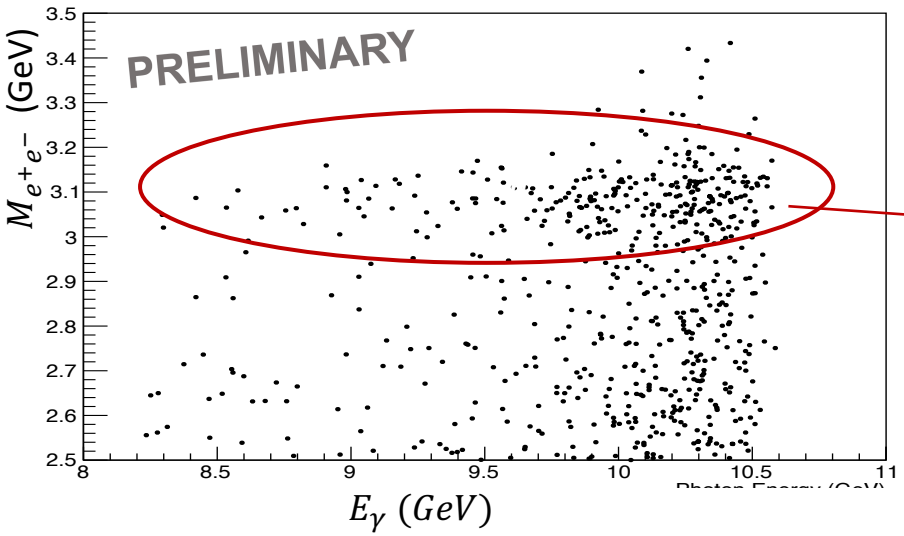
Experiment goals:

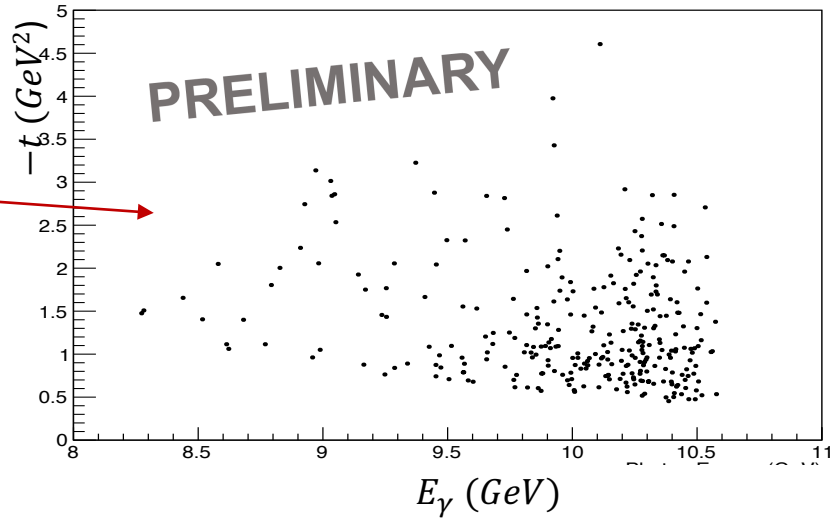
- Measure $\sigma(E_\gamma)$ near threshold – production mechanism
- Probe the distribution of color charge in the nucleon by measure the t-dependence of the differential cross section
- Study the forward-backward asymmetry to access the real part of the forward J/ψ–p scattering amplitude
- Search for LHCb pentaquarks

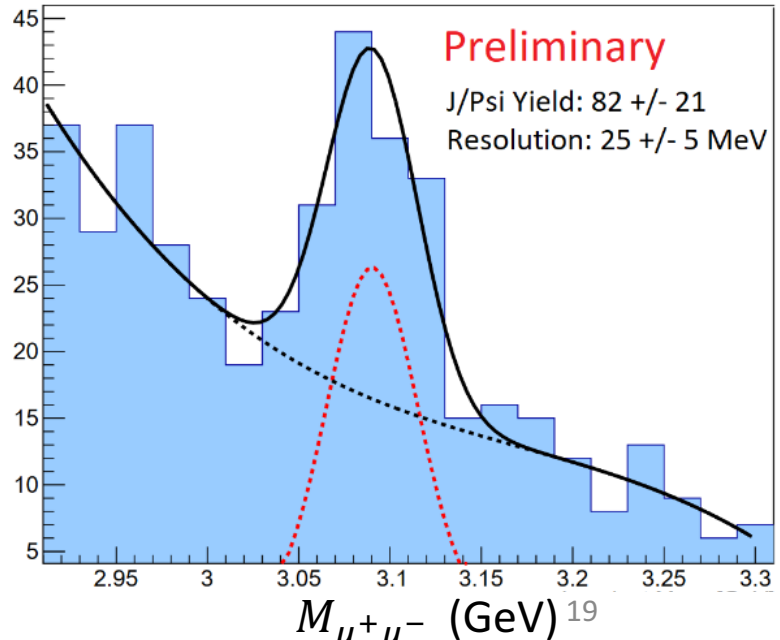
A clean signal for J/ψ in both lepton decay modes. Complementary to other studies at JLAB.

Need full statistics of approved beam time to reach the experiment goals.









MesonEx and Very Strange

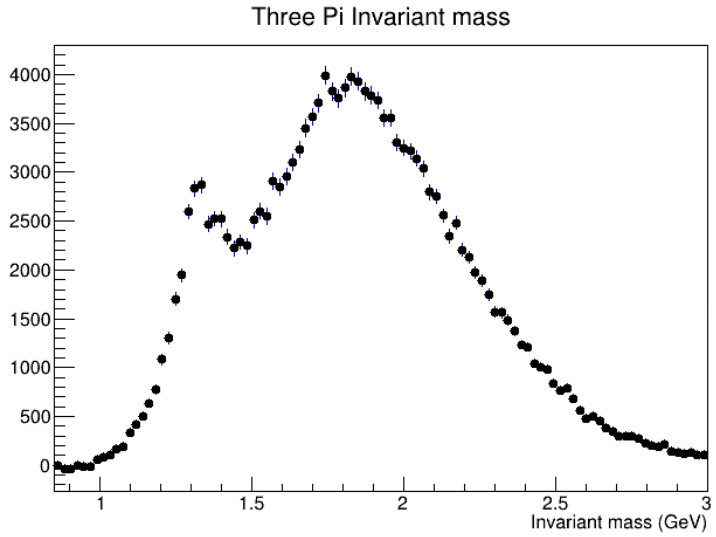
Motivations

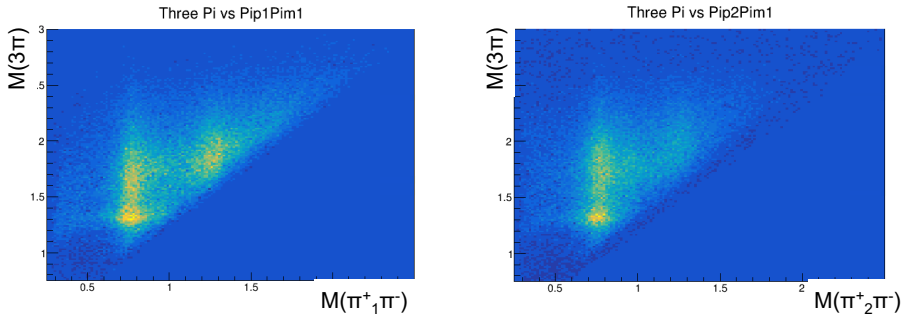
- World-wide effort to understand the meson spectrum (COMPASS, LHCb, BES-III, BELLE, …)
- Extensive scientific program at JLab to understand the role of gluonic excitations in the spectroscopy of light mesons
- Hall-B is using of a combination of low-Q2 electron scattering (equivalent to an high intensity photon beam) and the CLAS12 detector (4π acceptance, excellent Pid, high resolution) to measure exclusive final states and perform a full Partial Wave Analysis on mesonic and baryonic systems
  - MesonEx (E-12-11-005): Study of meson spectrum in the 1-3 GeV mass range to identify gluons excitation of mesons (hybrids) and other quark configurations beyond the CQM
  - Very Strange (E-11-12-008): Serach for mission excited hyperon states
- Unique opportunity to extend baryon photo production to the complementary electroproduction with the same data set

Assessment

I) MesonEx example: Search for exotic $\pi_1(1600)$ in e p → e' n π+ π+ π-

Results for inbending fall 2018 e- data
- CLAS12 acceptance low for $2\pi^-$
- Extra data required for $a_2(1230)$ region





- Low cross sections in interesting mass region 1.5-2.5 GeV/c^2, containing several interesting resonances including π_1
- Other final states with kaons have lower cross section but still accessible with CLAS12

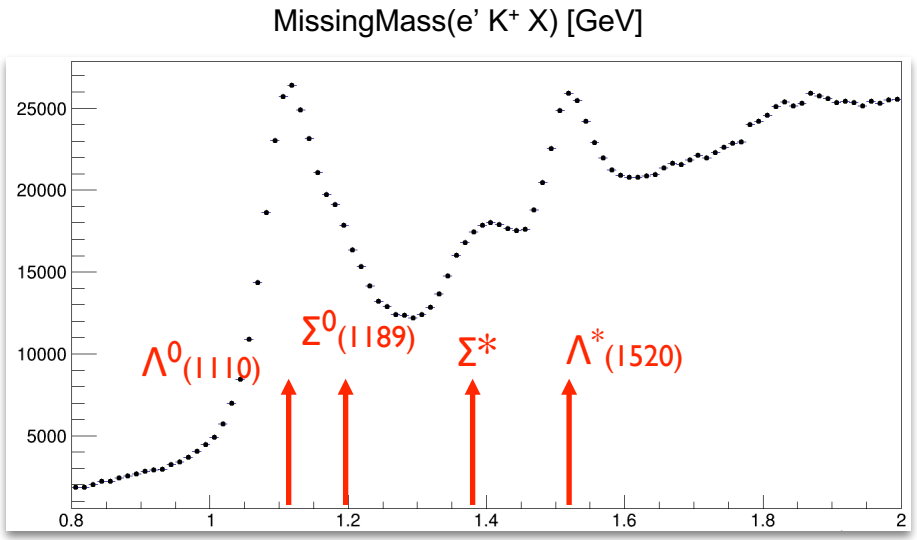
MesonEx and Very Strange

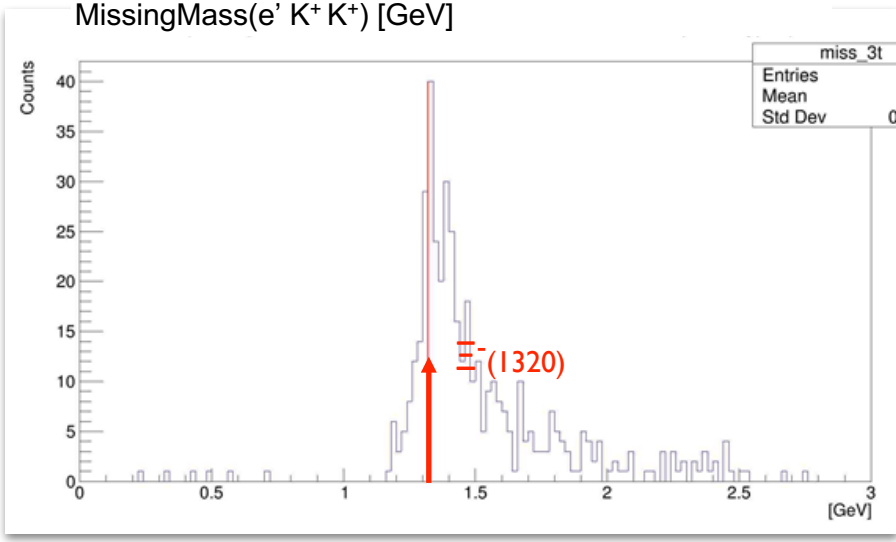
Assessment

II) Very Strange example: Strange and very strange hyperons

Results for inbending fall 2018 e- data

- Clearly see hyperon resonances
- Cascade electroproduction easily accessible and any results are new
- Electroproduction (Q^2 dependence) provides with new and complementary information on these states





Future plans

- Good performance of the CLAS12-FT to provide low Q2 electroproduction data
- Clear benefit by collecting the remaining 50% of approved statistics
- **MesonEx: PWA requires high statistics to pin down the tiny signal (~1%) of exotic mesons**
- Very Strange: high statistics is needed to study excited cascades and Ω^- that require detection of final states with many particles(kaons)

SUMMARY

- **The RG-A science program is broad and rich and addresses several of the most fundamental questions in hadronic physics.**

- **We have also designed and optimized a smart trigger to run successfully all 13 experiments simultaneously! The data processing and analysis of the 50% of RG-A data that is already on tape is in an advanced stage and preparation of the first publications is underway.**

- **We request the approval of the 70 remaining days to fully realize the goals of the RG-A science program, the full statistics is required to allow:**
  - significant extension in Q^2 promised by the CLAS12 &12-GeV upgrade to chart the transition from strong to perturbative QCD.
  - multi-dimensional analysis for the 3D imaging program & hadron structure
  - advance amplitude analyses for hadron spectroscopy and structure
  - measurement of rare processes
  - **potential for science discovery!**