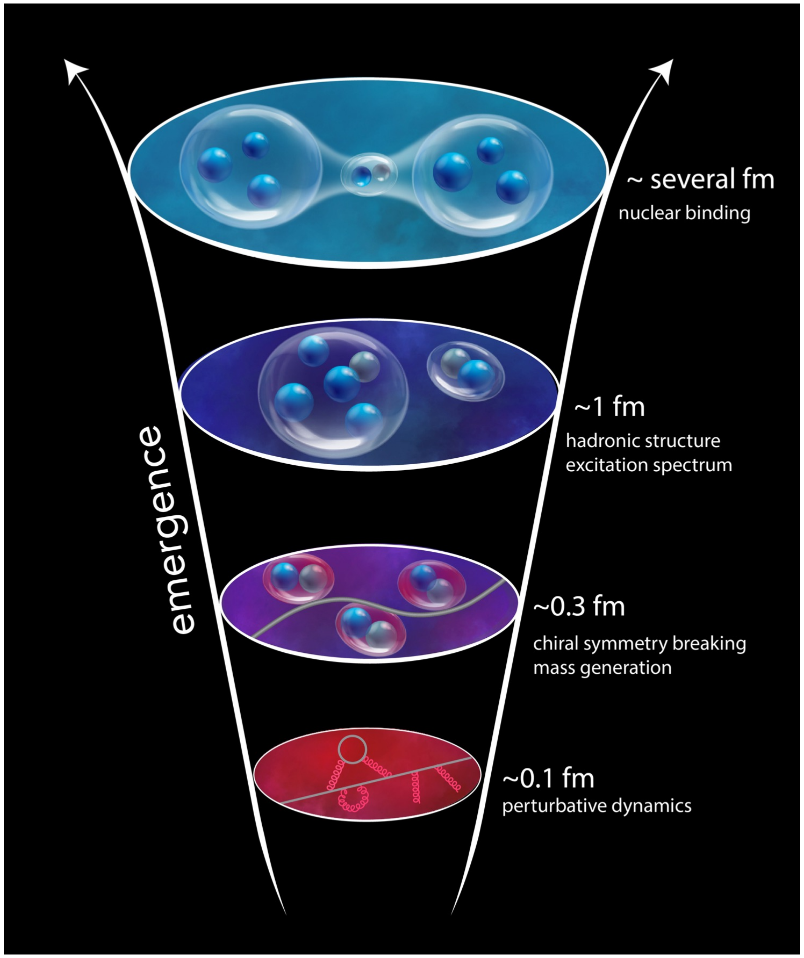
Physics Perspectives for an energy upgrade at Jefferson Lab

Patrizia Rossi

CLAS Collaboration Meeting

Paris, March 21-25, 2023

Why CEBAF @ 22 GeV?



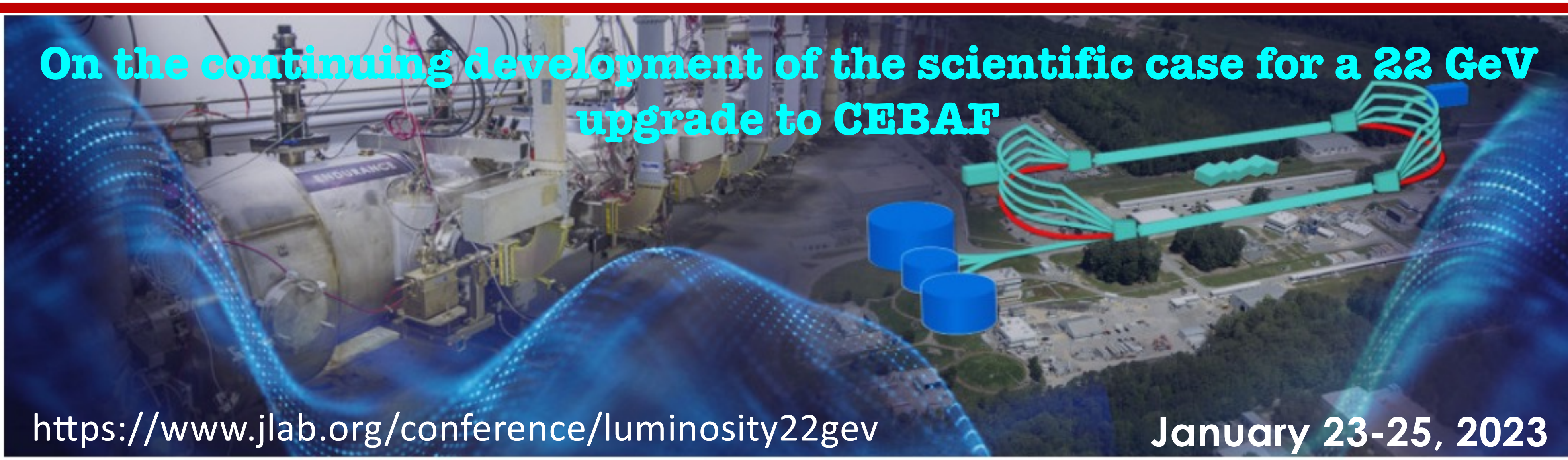
- **How do hadrons/nuclei emerge from fundamental QCD principles?**
  → *understanding the strong interaction dynamics*
- **Complex non-pQCD problem which demands different approaches and measurements to access multiple observables**

<u>What a 22 GeV upgrade will bring:</u>

- **some important thresholds would be crossed → charm, nuclear distances, in fundamental symmetries, etc..**
- **An energy window which sits between JLab @ 11 GeV and EIC**
  → test and validation of our theory from lower to higher energy

- **A rich physics program is under development, leveraging on existing or already-planned infrastructure and on the uniqueness of CEBAF HIGH LUMINOSITY**

Science at the Luminosity Frontier: Jefferson Lab at 22 GeV



1 Introductory Session (D. Dean, A. Bogacz, J. Qiu , R. Ent) + 6 Sessions/WGs

- Spectra and structure of heavy and light hadrons as probes of QCD
  - Ralf Gothe (rwgothe@gmail.com)
  - Matt Shepherd (shepherd@jlab.org)
- Sea and valence partonic structure and spin
  - Jian-Ping Chen (jpchen@jlab.org)
  - Ioana Niculescu (ioana@jlab.org)
  - Nobuo Sato (nsato@jlab.org)
- Form Factors, Generalized Parton Distributions and Energy-Momentum Tensor
  - Latifa Elouadrhiri (latifa@jlab.org)
  - Garth Huber (Garth.Huber@uregina.ca)
  - Christian Weiss (weiss@jlab.org)
- Fragmentation, Transverse Momentum and Parton correlations
  - Harut Avagyan (avakian@jlab.org)
  - Dave Gaskell (gaskelld@jlab.org)
  - Nobuo Sato (nsato@jlab.org)
- Hadron-quark transition and nuclear dynamics at extreme conditions
  - Lamiaa El Fassi (elfassi@jlab.org)
  - Misak Sargisian (sargsian@fiu.edu)
- Low-energy tests of the Standard Model and Fundamental Symmetries
  - Liping Gan (ganl@uncw.edu)
  - Kent Paschke (paschke@jlab.org)

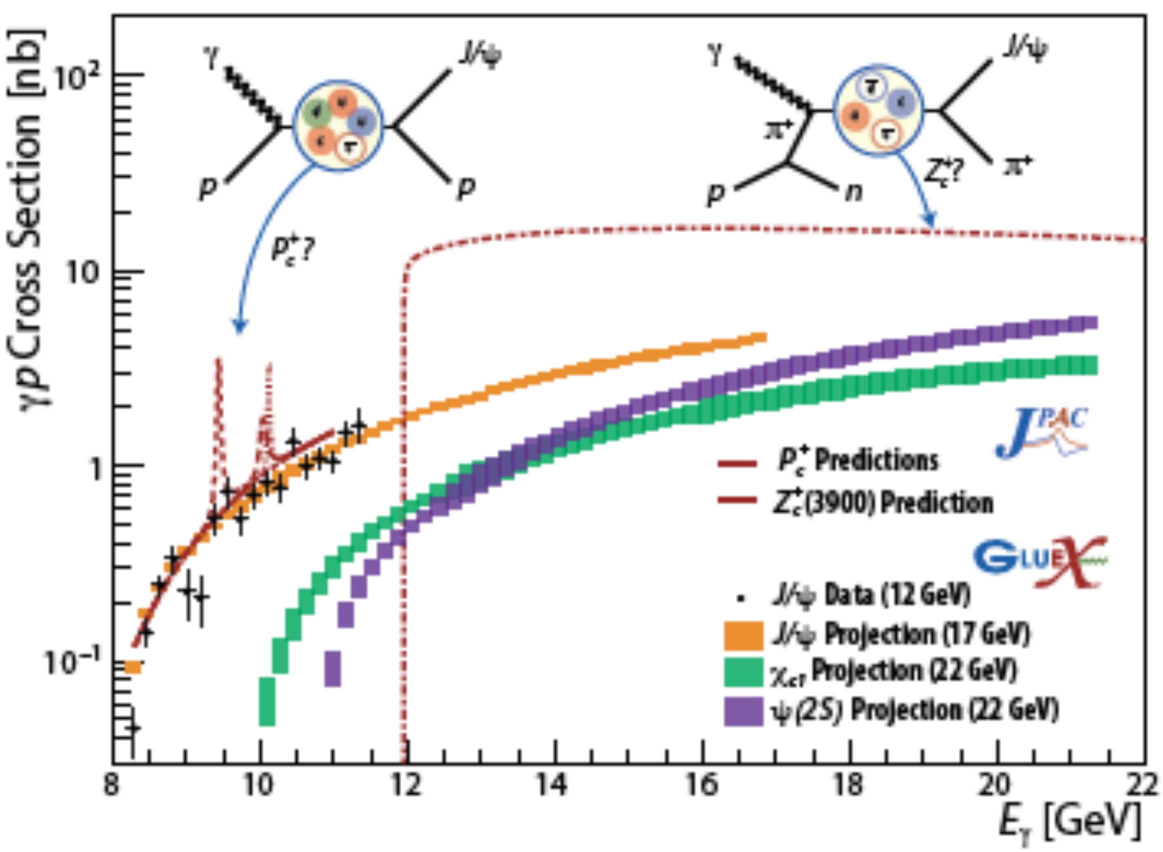
1-page high level message from each WG

Spectroscopy of Exotic States with c-cbar

Photoproduction of hadrons with charm quarks: **<u>new tool for discovery in QCD</u>**

→ potentially decisive information about the **nature of some 5-quark and 4-quark** candidates

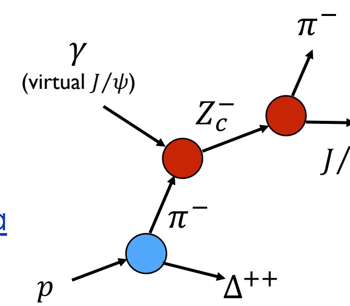
→ a unique method to probe the **structure of the proton**

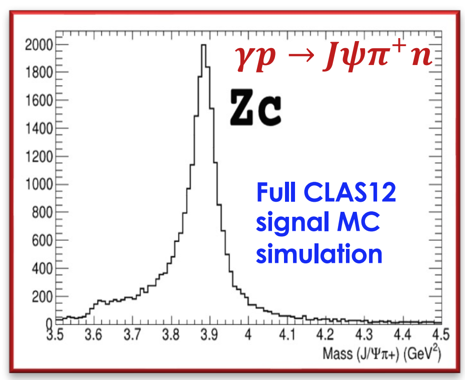


- Tetraquark candidates, **XYZ states**, observed in B decays, e^+e^- colliders but their internal structure not yet understood

- **Never direcly produced** using γ/lepton beams → **Photoproduction alternative mechanisms to study such states**

Direct (photon) probe of the $Z_c \to J/\psi\pi$ coupling without rescattering effects provides <u>unique complementary data</u> to constrain interpretation of e^+e^- data.





Initial simulations from GlueX and CLAS12 demonstrate the **capabilities of the existing detectors to measure these reactions**

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Spectroscopy of Exotic States with c-cbar

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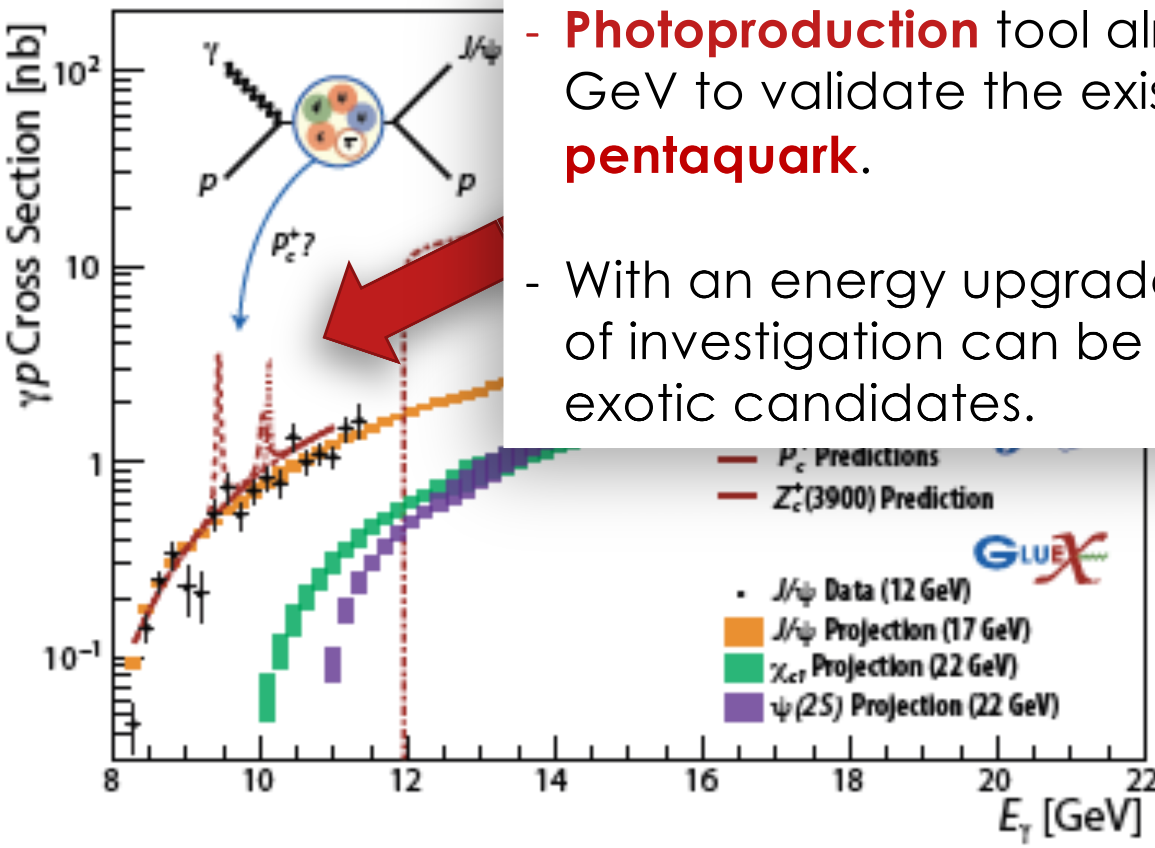

- **Photoproduction** tool already used at 12 GeV to validate the existence of **charmed pentaquark**.

- With an energy upgraded CEBAF, this line of investigation can be extended to other exotic candidates.

YZ states, observed

but their internal

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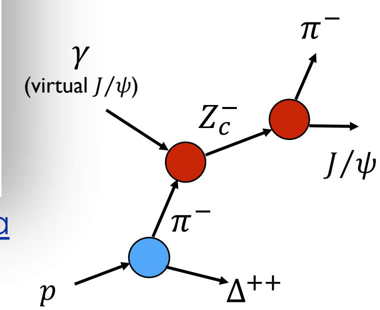
sing γ/lepton beams

ative mechanisms to



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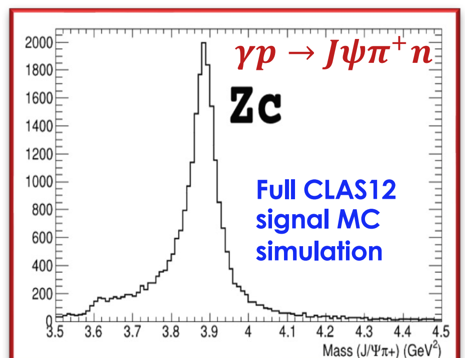

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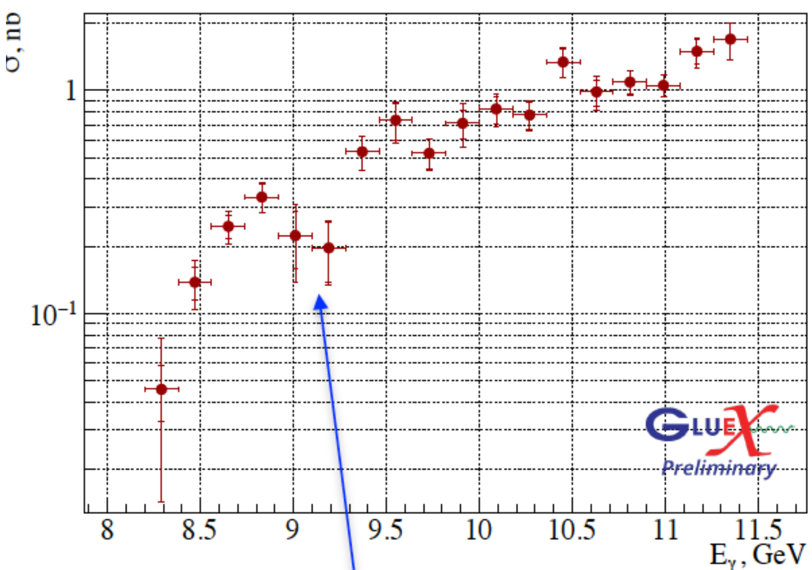
J/ψ photoproduction near threshold

Used to study important aspects of the gluon structure of the proton

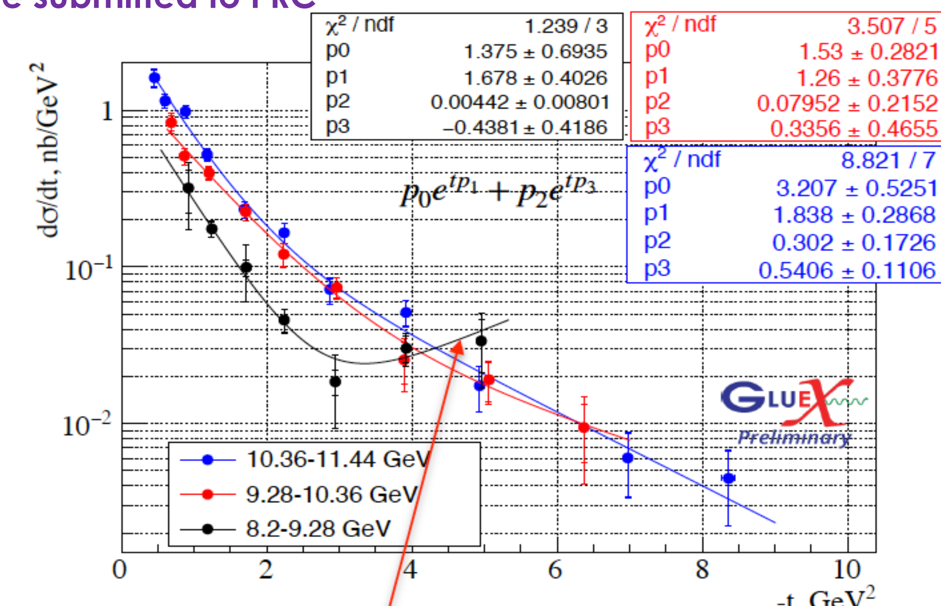
- **gluon GPD**
- **mass radius of the proton,**
- **anomalous contribution to the proton mass.**

..based on some assumptions (mainly 2-g exchange)

GlueX final results to be submitted to PRC

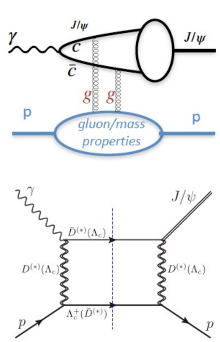


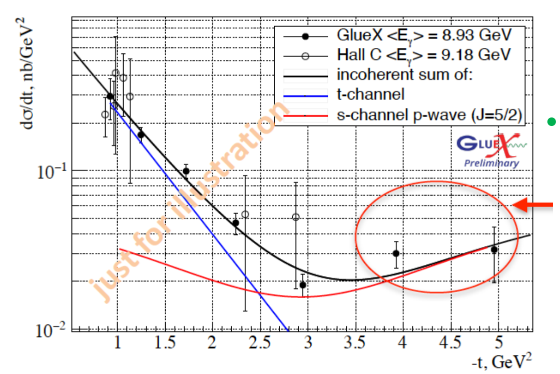
Possible structure at $\Lambda_c \overline{D}^{(*)}$ threshold σ(8.6-9.6) GeV



Enhancement of dσ/dt at high t for the lowest energy slice

- **CANNOT be explained by t-channel (GLUON EXCHANGE) alone**
- Can have contribution from open-charm exchange to both σ and $d\sigma/dt$ at high t





- Can we interpret this as a possible evidence for a s-channel resonance (?) *Pc*

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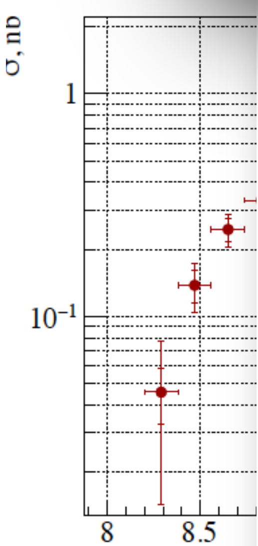
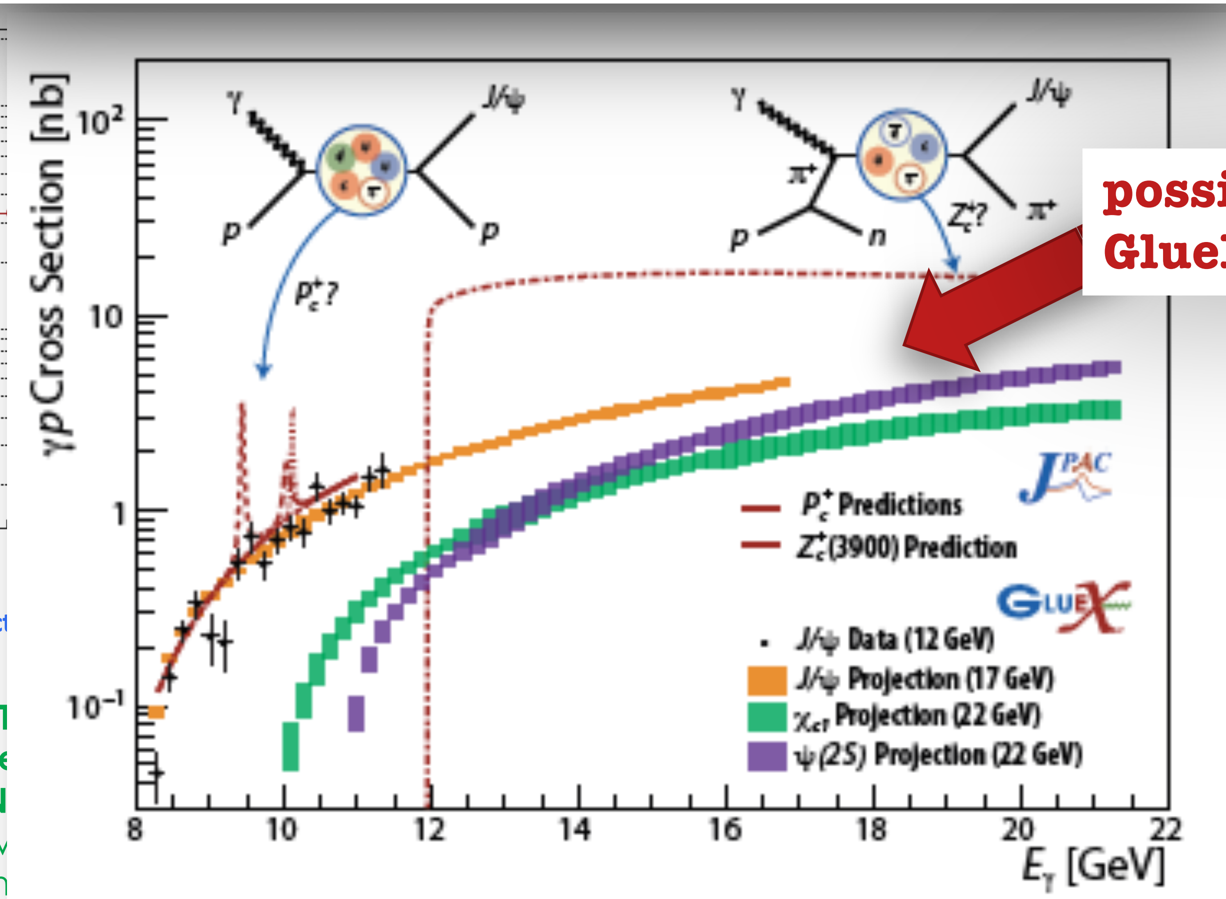
J/ψ photoproduction near threshold

Used to study important aspects of the gluon structure of the proton

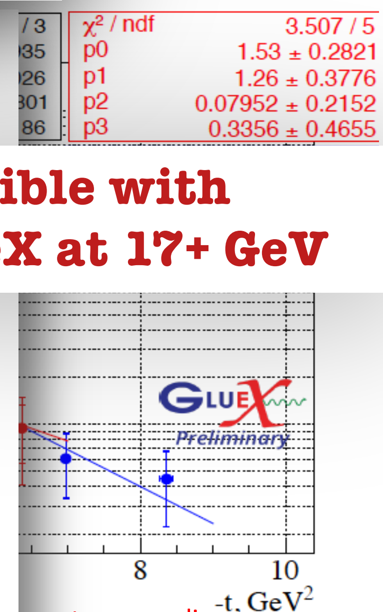
- gluo
- mas ...me assumptions ...xchange)
- anor

Need precise measurements (high statistics) to develop accurate theoretical models to understand the mechanism





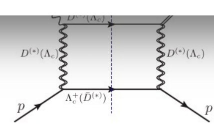
possible with GlueX at 17+ GeV

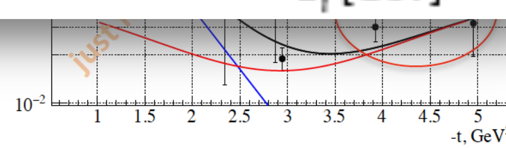


Possible struct

...west energy slice

- CANNO t-channe EXCHAN
- Can hav open-ch both σ and $d\sigma/dt$ at high t

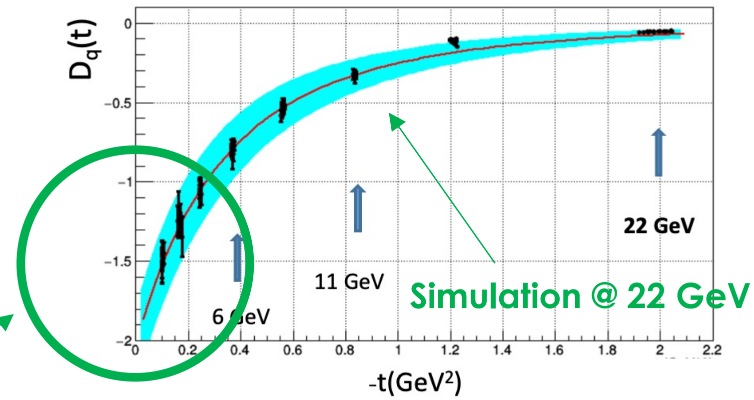




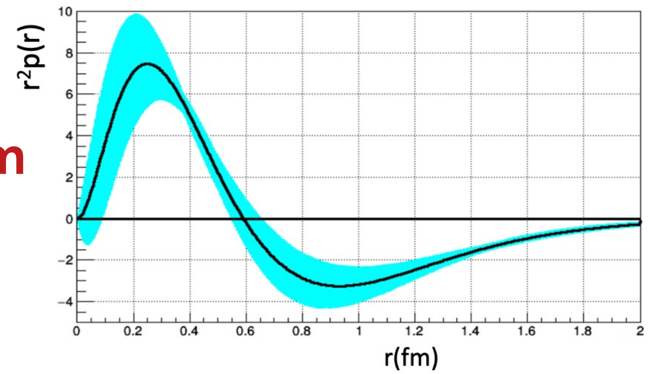
- **Can we interpret this as a possible evidence for a s-channel resonance (?) *Pc***

Spacial q/g Structure & Mechanical Properties of the Proton

- FFs: source of information on the hadron structure
- GFFs : encode the matrix elements of the EMT of QCD and describe how energy, spin, and various mechanical properties of hadrons are carried by q/g constituents.
- GFF D(t): describes the pressure distribution in the nucleon. It is accessible through measurements of the CFFs of DVCS



- **A large -t range is required to perform the Fourier transform with controlled uncertainties → high luminosity**



→ **The 22 GeV beam energy is crucial to this program**

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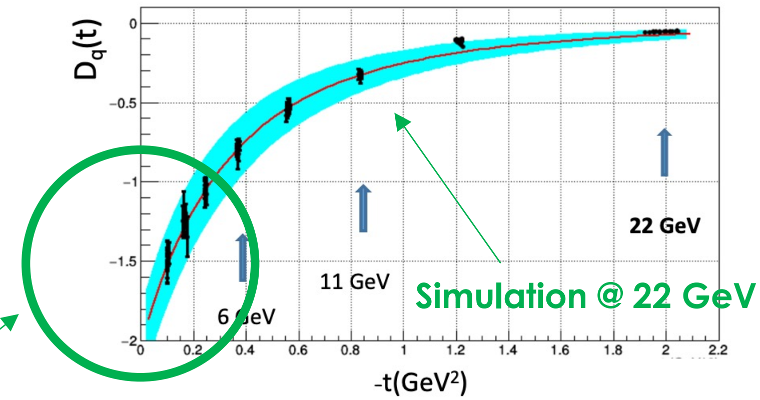
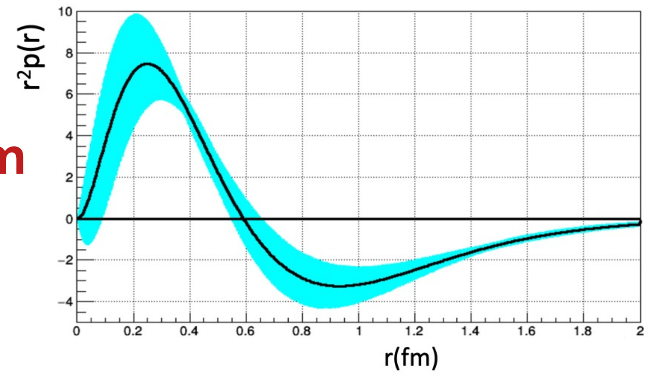


data @ 6 GeV

- **A large -t range is required to perform the Fourier transform with controlled uncertainties ➜ high luminosity**



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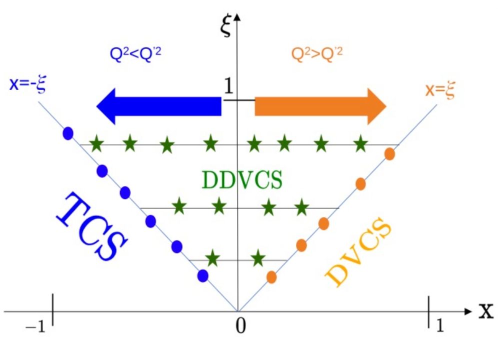
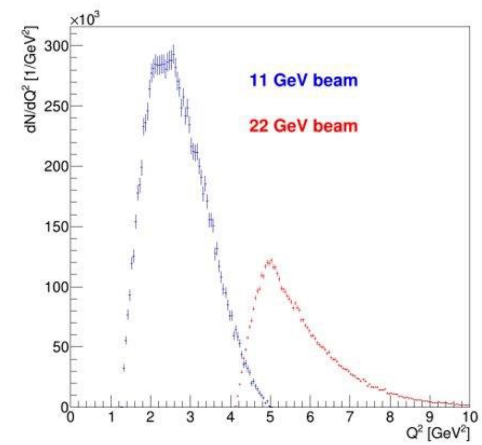
Double DVCS (DDVCS)

- **Direct probe of GPDs away from the x=±ξ line**



- **NEVER been measured (very small cross section).➜ JLAB with high luminosity will be the only place to measure this reaction.**
- **22 GeV upgrade allows to reach higher Q^2**
  - *** Test evolution and scaling of GPDs**
  - *** Study higher twist effects**



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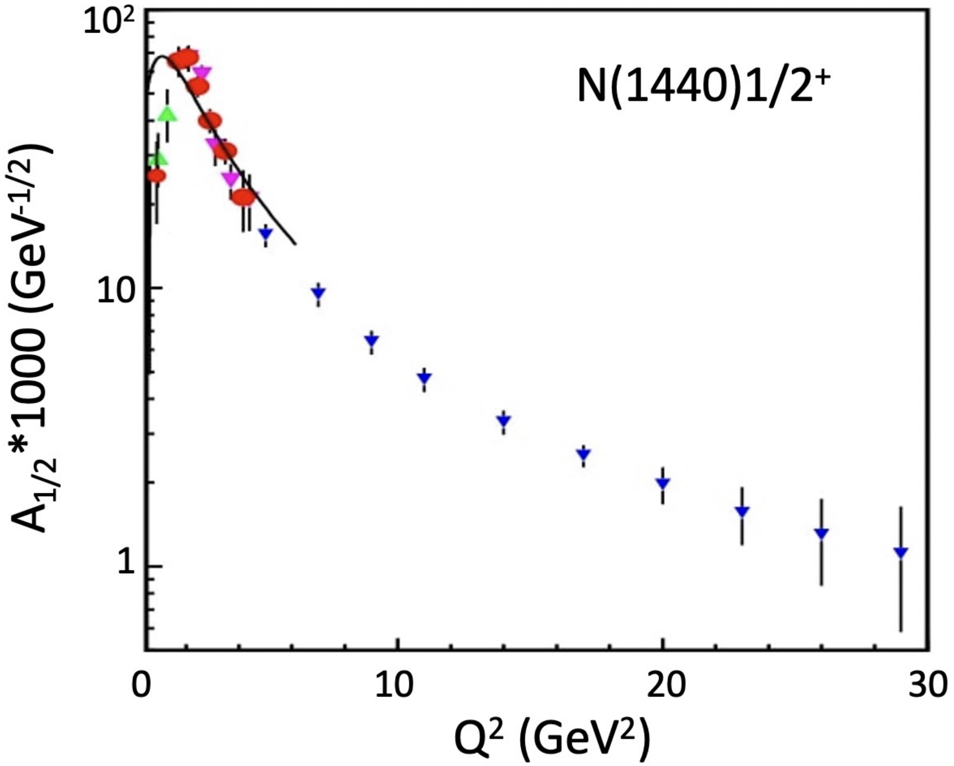
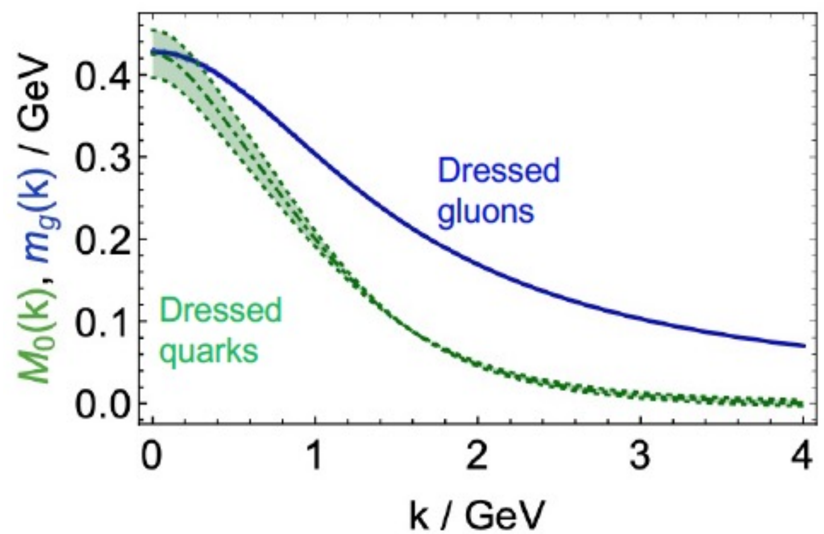
Bound 3 Quark Structure of N*s and Emergence of Mass



Continuum Schwinger Method

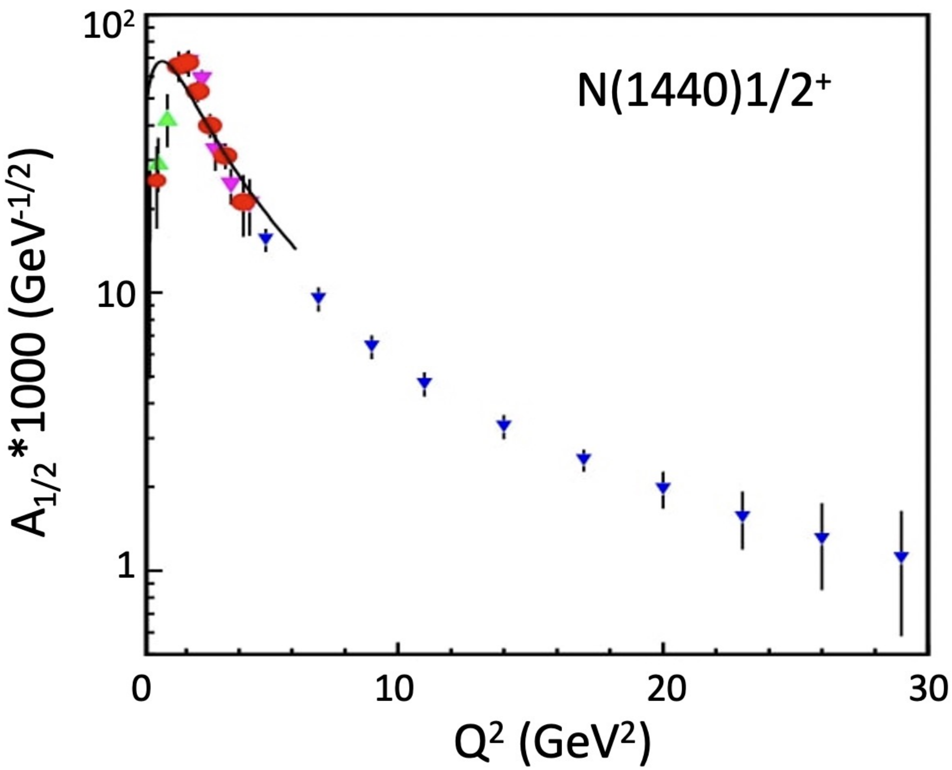
- the solution of the QCD equations of motion for q/g fields reveals existence of dressed q/g with momentum-dependent masses.



- Q^2 evolution of the $\gamma_v p N^*$ electrocouplings could offer an insight into hadron mass generation and the emergence of the N* structure from QCD

- **Simulations indicate JLab22 is the only foreseeable facility to extend these measurements up to 30 GeV^2**

Bound 3 Quark Structure of N*s and Emergence of Mass



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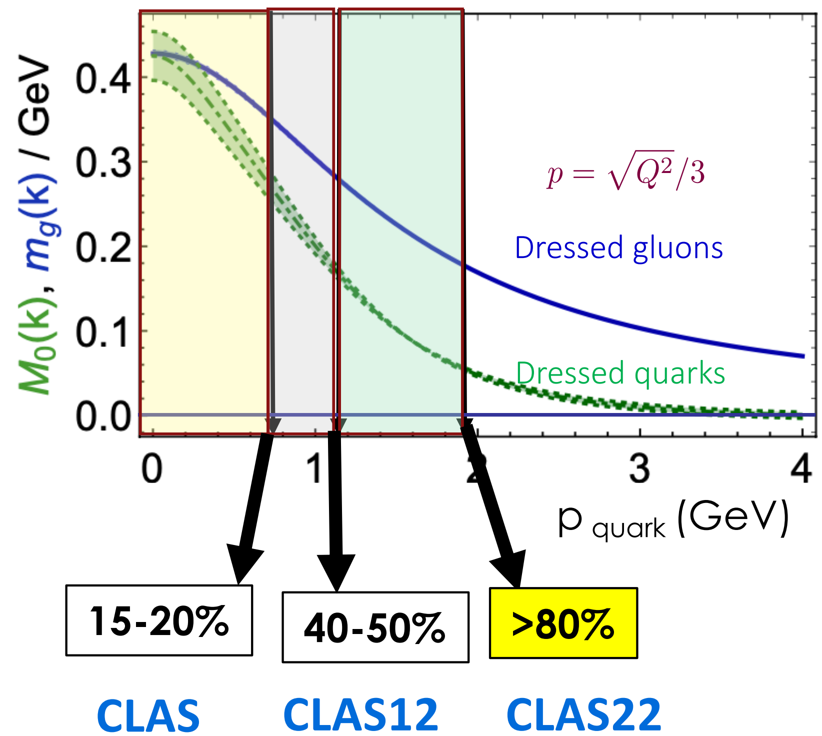


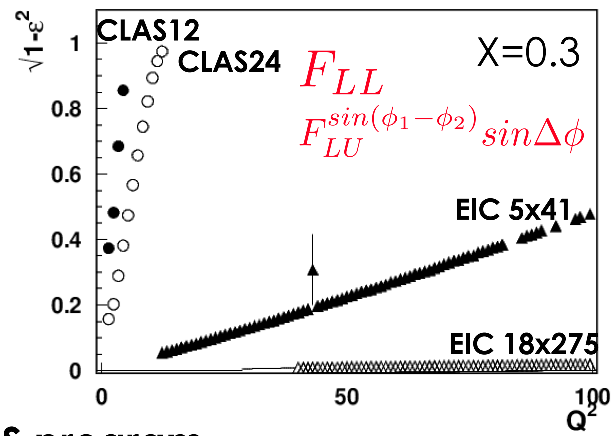
- **Q^2 range(<35 GeV^2) where the dominant portion of hadron mass is expected to be generated**

Fragmentation, Transverse Momentum & Parton Correlations

SIDIS cross section

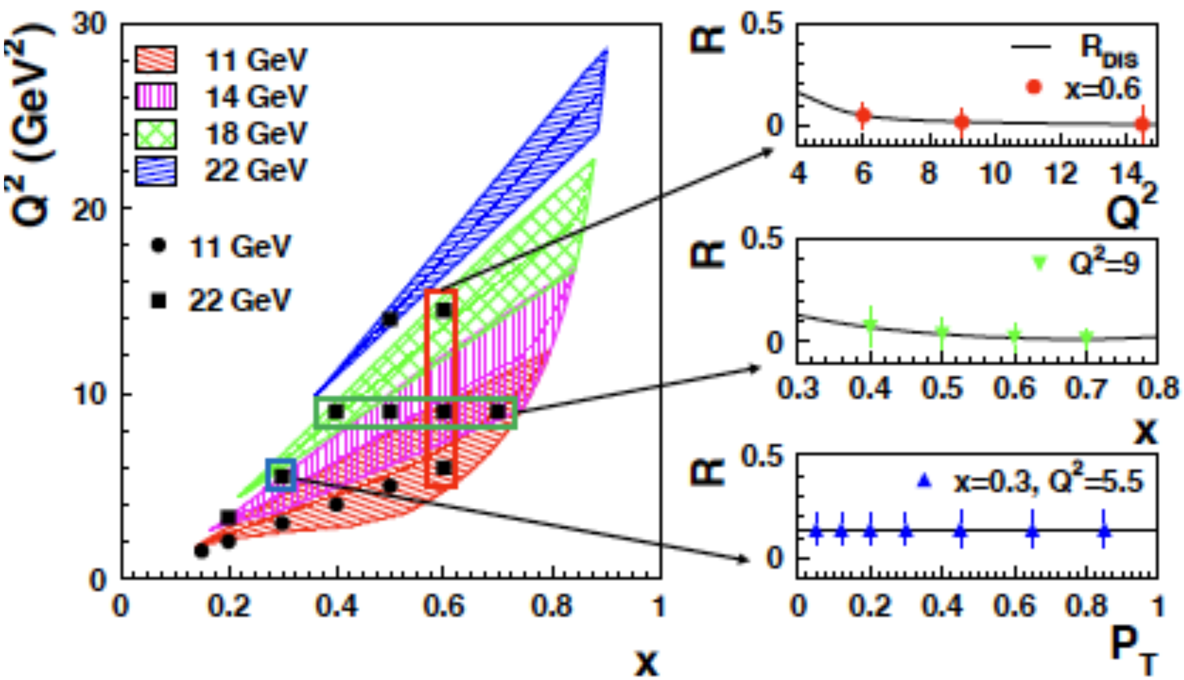
$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} \\
&= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Big\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} \\
&\quad + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big] \\
&\quad + S_L\,\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big] \\
&\quad + S_T\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} \\
&\qquad + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
&\qquad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] + S_T\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \\
&\qquad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}
\end{aligned}
$$

- Separation of SFs highly non-trivial !
- At large x and high energies $\epsilon \to 1$ ➜ certain SFs are suppressed (i.e.helicity dep.)



A combined 11 and 22 GeV SIDIS program

- **will increase our ability to measure a variety of SIDIS SFs across an enhanced multidimensional phase space allowing test and validation of our understanding and interpretation of SIDIS reactions.**



A combined 11 and 22 GeV SIDIS program

- **will provide a unique determination of the ratio of longitudinal to transverse photon SIDIS cross sections essential to properly understand SIDIS multiplicities, Sivers and Collins effects,…**

- **R is assumed to be similar to that of DIS but *never been thoroughly checked***

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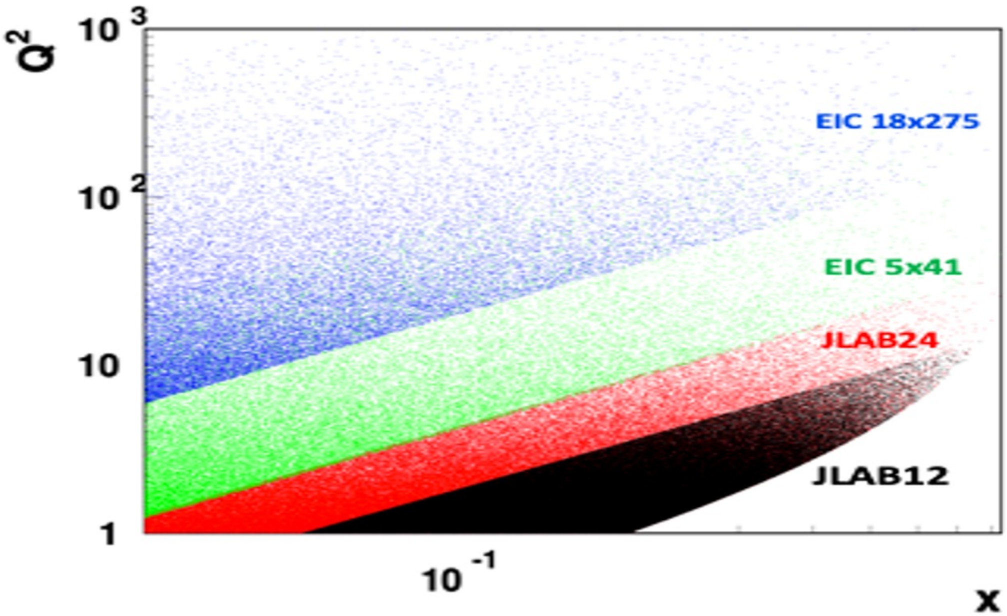
Interpretation of SIDIS data in terms of TMD??



- The connection of SIDIS data with TMDs is only within one of the mechanisms known as *TMD current region.*
- Multiple physical mechanisms contribute to the production of hadrons in the final state depending on the involved energy

➡ **Large acceptance, high precision measurements in multi-dimensional phase space** will allow to evaluate different contributions and evaluate the systematics

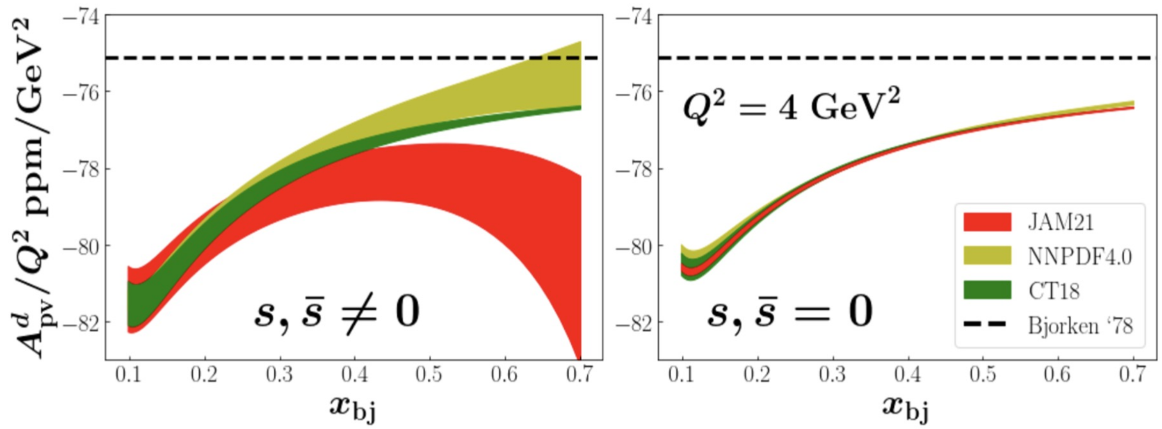
➡ With an extended Q^2 coverage, the 22 GeV upgrade offers a new complementary window that sits in-between the 12 GeV program and the EIC and allow us to **validate the measurements of leading contributions and explore sub-leading contributions**

Partonic Structure and Spin

Nucleon Strangeness

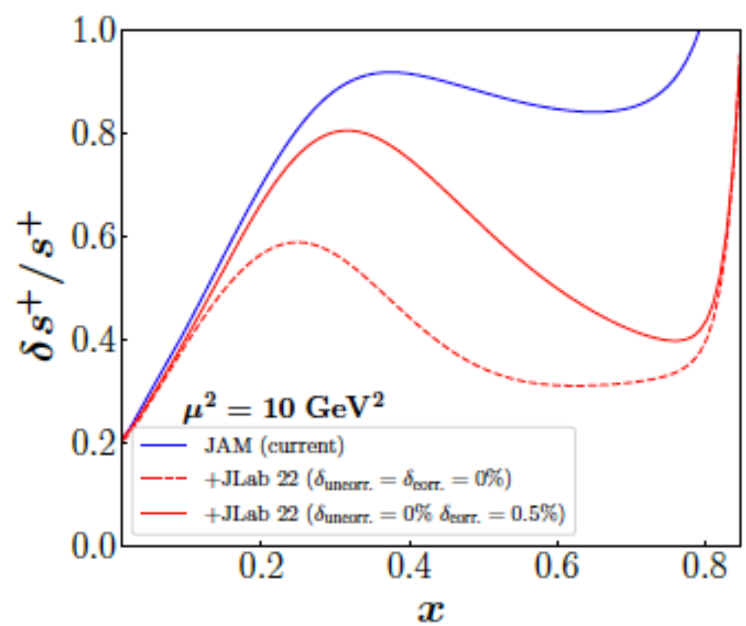
- The nucleon strange sector is largely unexplored with an up to 80% uncertainty in the $s^+ = s + s$ PDF.

- **Precision extraction of $\sin^2\theta_W$**



PVDIS @ 22 GeV with the SoLID

Substantial improvement with a reduction in the s+ uncertainty that can reach more than a factor two at large-x



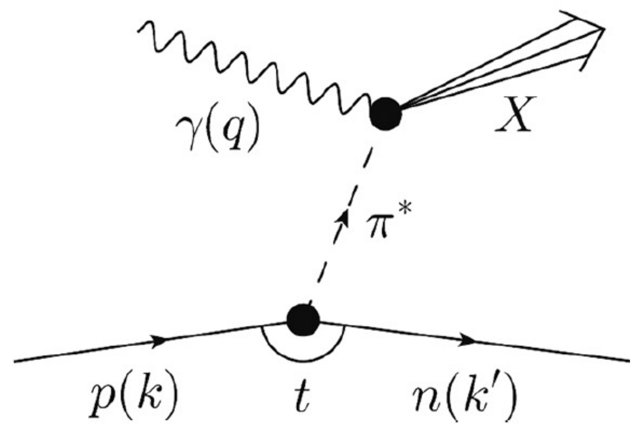
~100 days, 40 μA beam split between 40 cm D and H targets

Partonic Structure and Spin

Meson structure

- Tagged deep inelastic scattering (TDIS) provides a mechanism to access the meson structure via the Sullivan process .

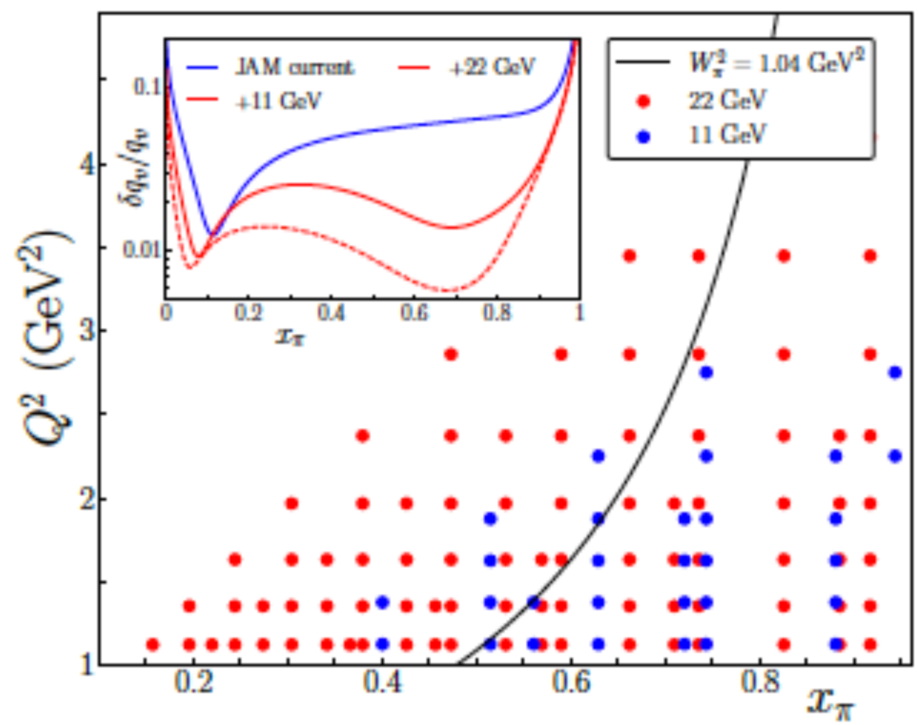
- A cut of $W^2{}_\pi > 1.04$ GeV^2 (to avoid contributions from resonances in a pion analysis,) eliminates most of the data at 11 GeV.



<u>At 22 GeV:</u>

- **Available phase space significantly increased**
  ➔ large improvement in the determination of the valence structure of the pion
  ➔ kin. coverage to smaller x_π region to probe the sea content of mesons

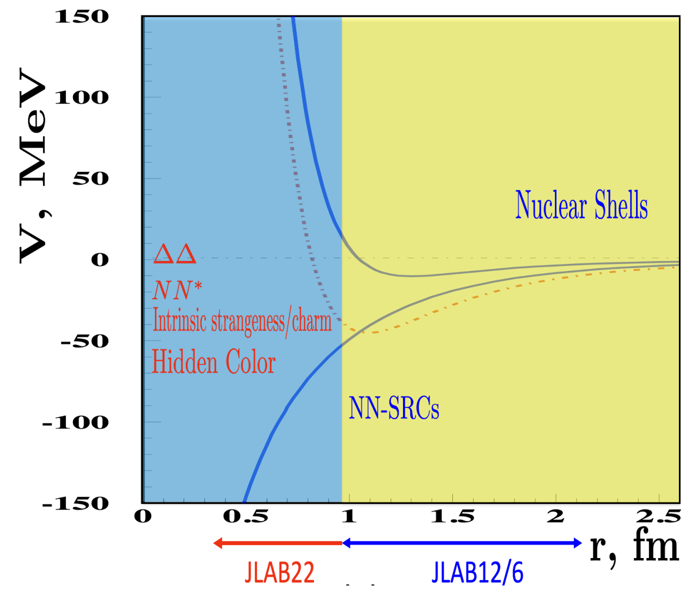
- **Overlap the existing π induced DY data**
  ➔ test the universality of PDFs in the mid to large x_π region

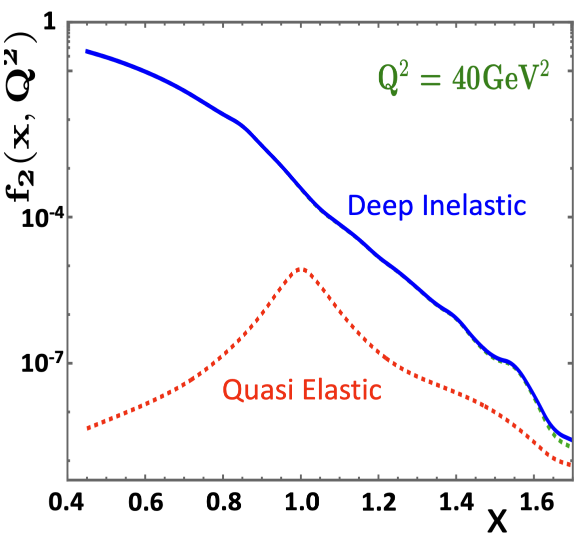


Nuclear Dynamics at Extreme Conditions

The dynamics of the nuclear repulsive core is still poorly understood

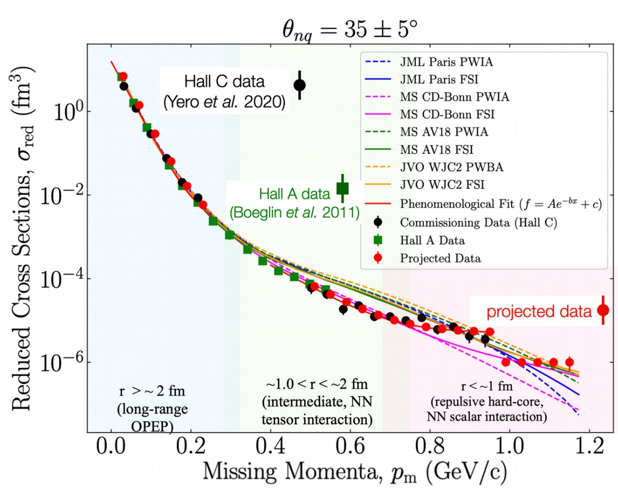
A 22 GeV upgrade will provide reach to the nuclear forces dominated by nuclear repulsion





- **Superfast Quarks**

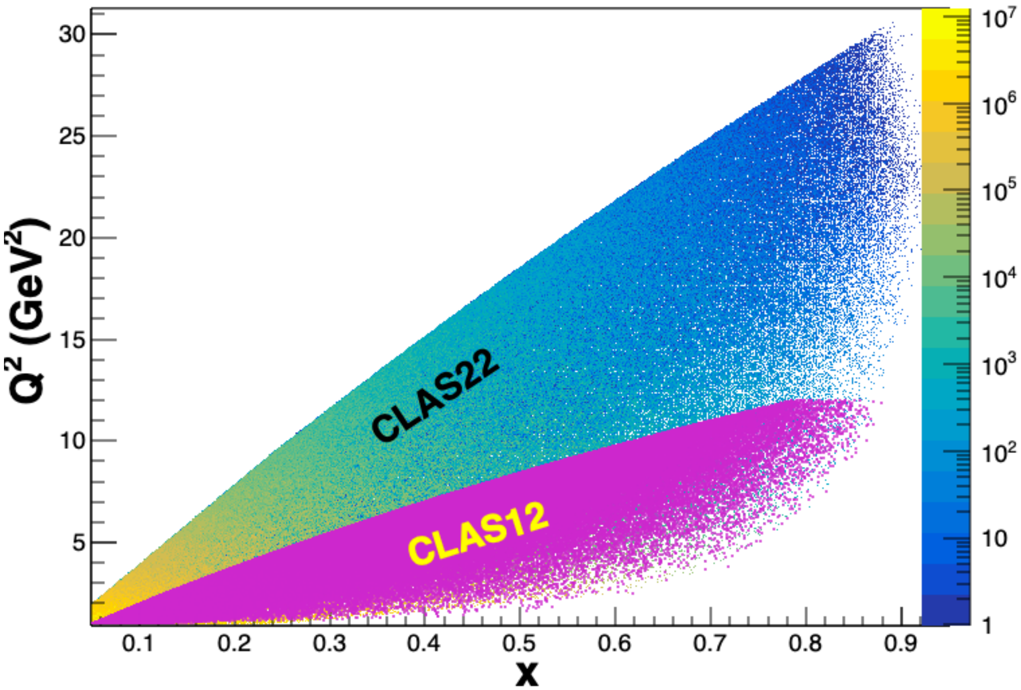
  The high Q^2 reach will allow
  - the suppression of quasi-elastic contributions,
  - the first-ever study of nuclear DIS structure function at Bjorken x > 1.2 (r~ 0.5 fm,)



- **Exploring Deuteron at Very Large Internal Momenta**

  (> 800 MeV/c – non-nucleonic & hidden color components)
  - non-relativistic theory reproduce data up to pm ~ 0.7 GeV/c
  - no model reproduces data (non-nucleonic degrees of freedom?, quarks?) pm > 0.7 GeV/c

Hadron–Quark Transition in Nuclear Medium



Investigation of nuclear-medium effects

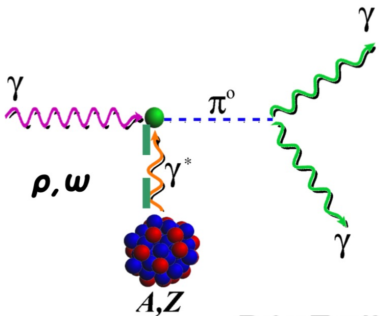
With a 22 GeV e- beam we can access the anti-shadowing region (x~0.1-0.3)

- Region extremely interesting, near-equally dominated by valence quarks, sea-quarks, and gluons → many many models!!
- Anti-Shadowing is the least studied nuclear structure function effect exp.
  - flavor and spin dependence essentially uncharted
  - no tagged measurements
- The transition between shadowing and the EMC regimes → a testing ground for different descriptions

Hadronization and Color Transparency (CT)

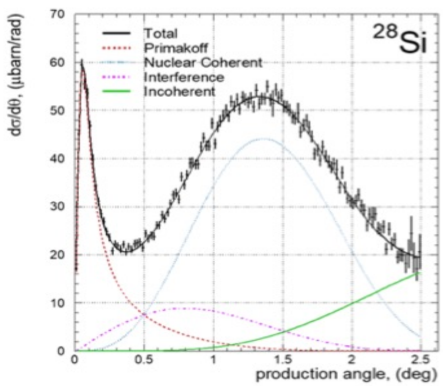
- SIDIS production off nuclei with the unique luminosity of CEBAF will allow a multi-dimentional studies of the hadronization mechanisms in a energy region complementary to EIC
- Extending the Q^2 range in CT studies will allow a deeper understanding of whether the 3-quark system exhibits reduced interaction as observed in $q\bar{q}$ systems

QCD Confinement and Fundamental Symmetries

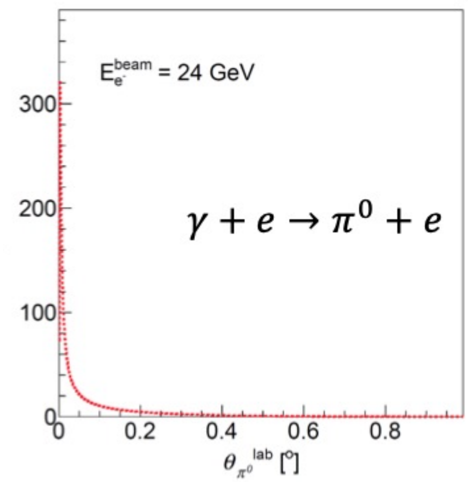


- **π^0 Primakoff production off an electron target**

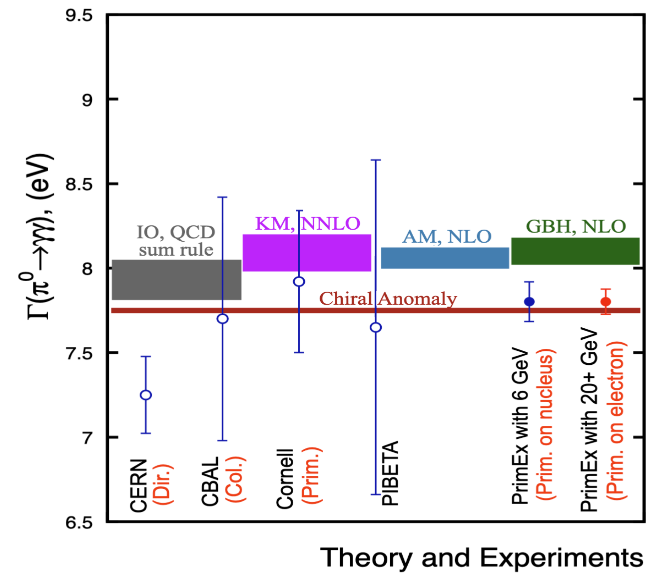
PrimEx-II: $\gamma + {}^{28}Si \rightarrow \pi^0 + {}^{28}Si$



Science 368, 506-509 (2020)



Γ(π⁰ → γγ) can be predicted at ≈ 1% precision



- **Primakoff Productions off Nuclear Target**

A 22 GeV upgrade will greatly enhance the Primakoff experiments for more massive mesons off nuclear target

➡ **first Primakoff measurement of Γ(η′ → γγ)** with ~3.5% precision to study the U(1)A anomaly coupling to the gluon field,

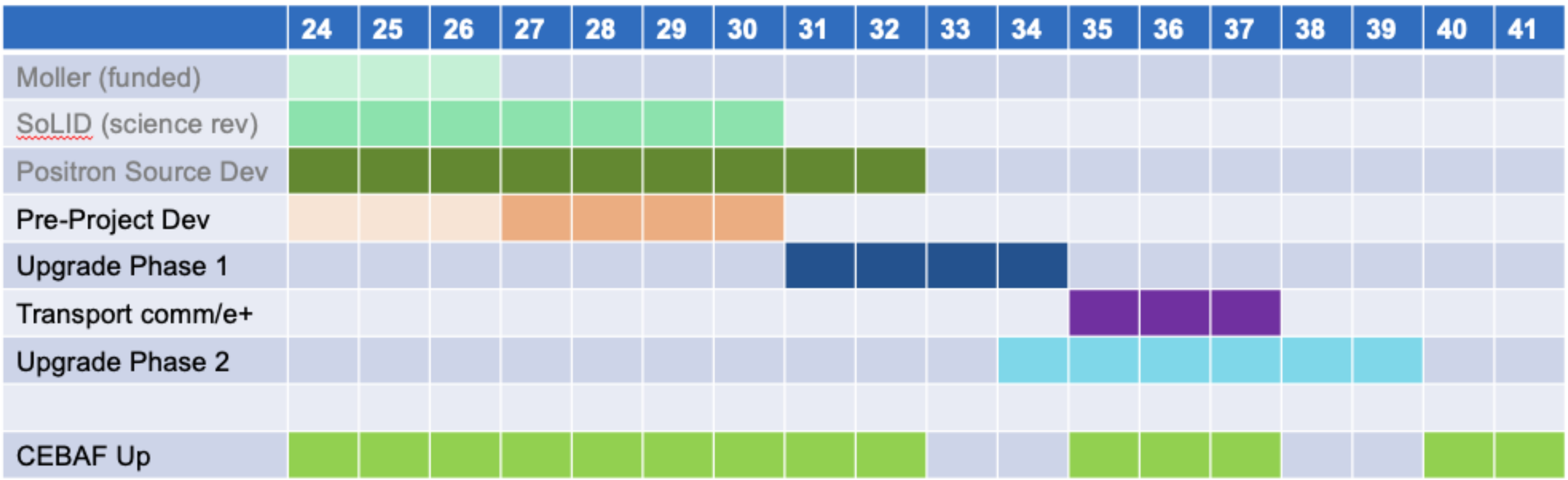
➡ **improve the measurement of Γ(η → γγ)** to a 2% accuracy to determine the light-quark mass ratio

Our Plan

- Short document submitted to the LRP writing Committee last week
- Longer document is under development with a deadline of mid-April
- It will be circulated within the community, ask for feedback and authorship
- We will review community feedback and revise one more time, run this new revision by the workshop organizers (summer, winter, user) for final feedback
- Goal is to post it on (ArXiv) by the end of May and publish it on a refereed journal later on

Notional CEBAF & upgrade schedule (FY24 – FY42)

- Accelerator team has worked up an early schedule and cost estimate
  - Schedule assumptions based on a notional timing of when funds might be available (near EIC ramp down based on EIC V3 profile)
  - For completeness, Moller and SoLID (part of 12 GeV program) are shown; positron source dev shown



- FY23 $$
- Phase 1: tie LERF to CEBAF & injector for e+ — $101M ($78M – $152M)
- Phase 2: High Energy Upgrade (includes FFAs) — $244M ($188M – $366M)
- Total cost (Class 4 estimate) — $345M ($265M – $517M)

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Conclusions and Outlook

- Understanding the strong interaction dynamics of non-pQCD and ``how'' hadrons/nuclei emerge from fundamental QCD principles, is a complex problem

- This complexity requires to observe the chromodynamic fields ``at work'' through multiple observables using different approaches and measurements

- With CEBAF at higher energy some important thresholds would be crossed and an energy window which sits between JLab @ 11 GeV and EIC would be available. This, together with CEBAF uniqueness to run electron scattering experiment at the luminosity frontier can provide a unique insight into the non-pQCD dynamics.

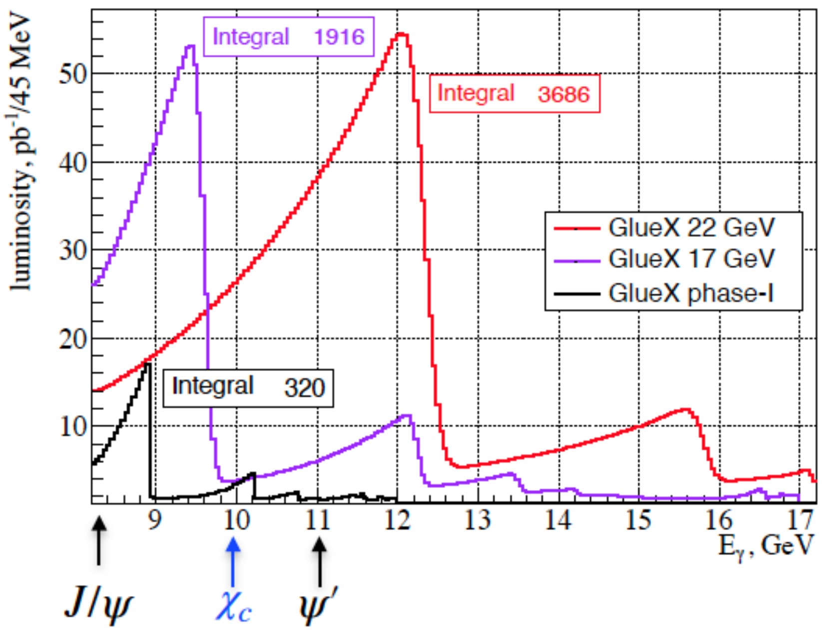
- A very strong science case for such an upgrade is emerging and it will be presented at the next LRP

- Support for an energy upgrade development
  - Users
  - Lab support, including LDRD investment
  - DOE encouragement to develop the science reach and technical aspects of an upgrade

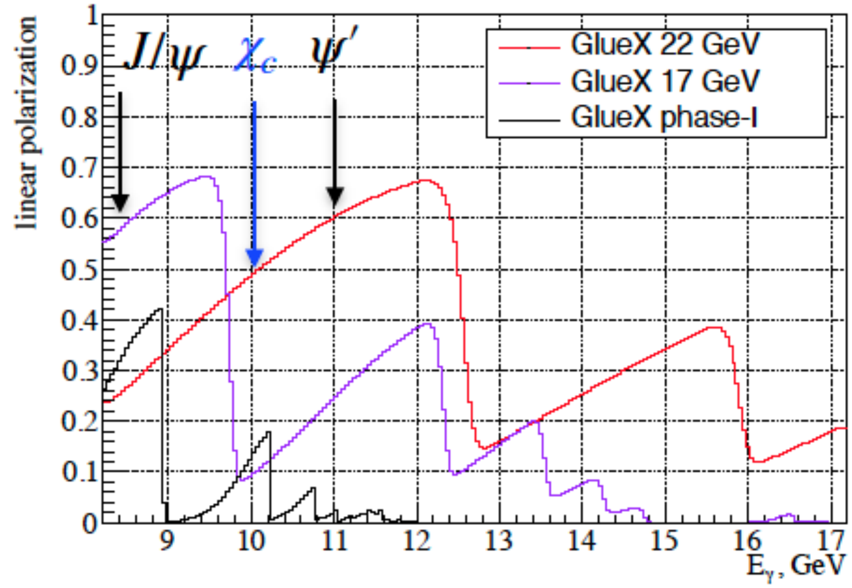
Backup

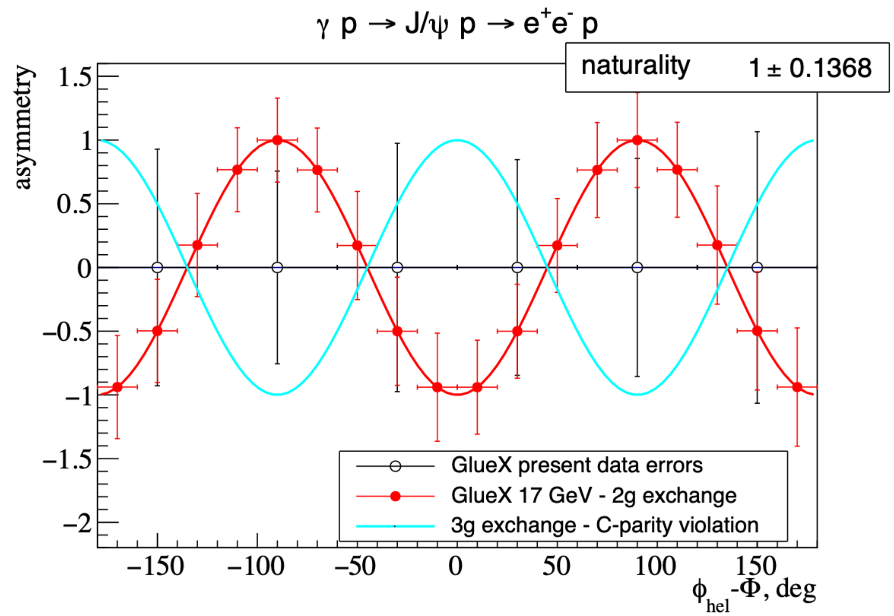
J/ψ photo-production and other charmonium states in Hall D

hiaher fluxes



Increased γ linear polarization





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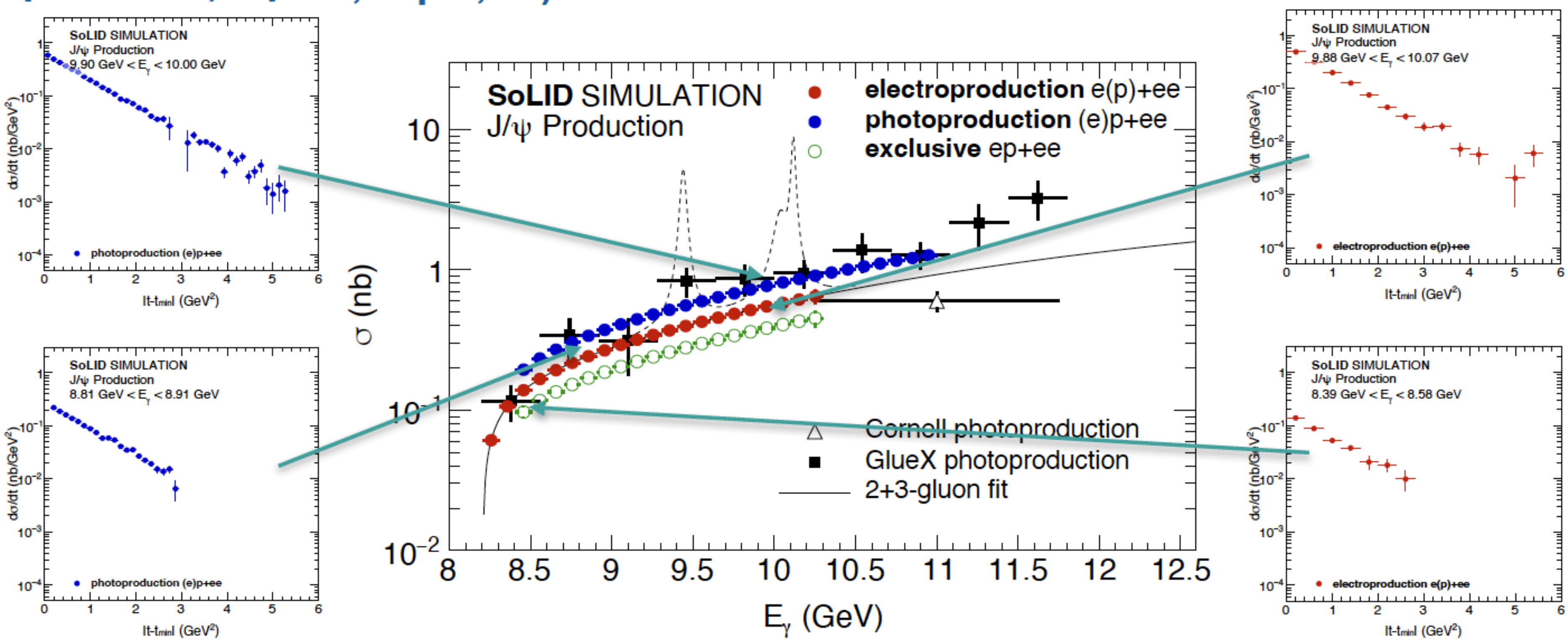
J/Ψ SOLID

SOLID-J/Ψ PROJECTIONS

Precision at high t crucial for extrapolations to the forward limit (exponential, dipole, triple, …)



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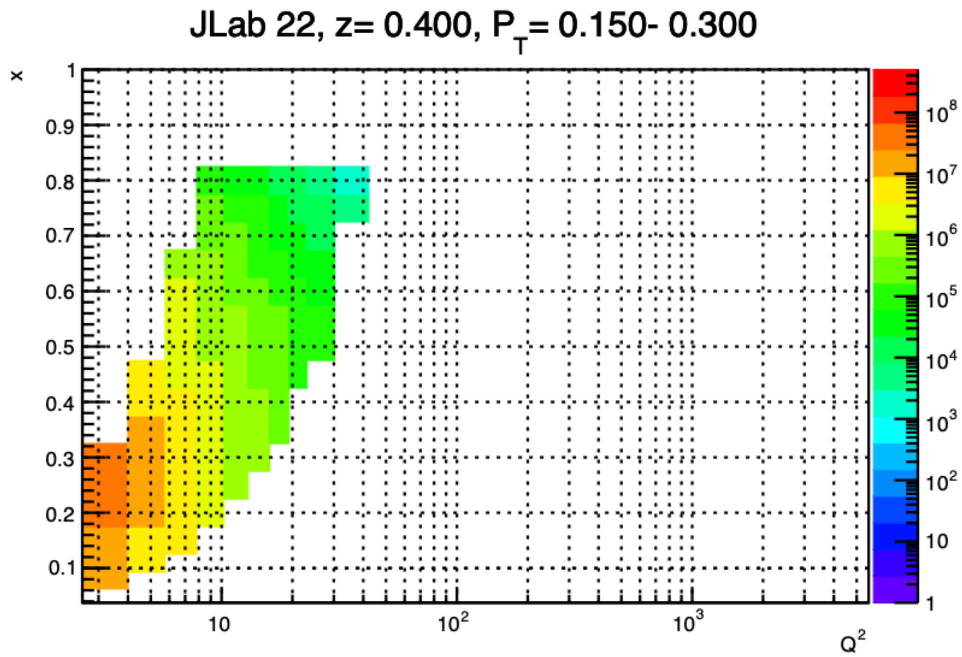
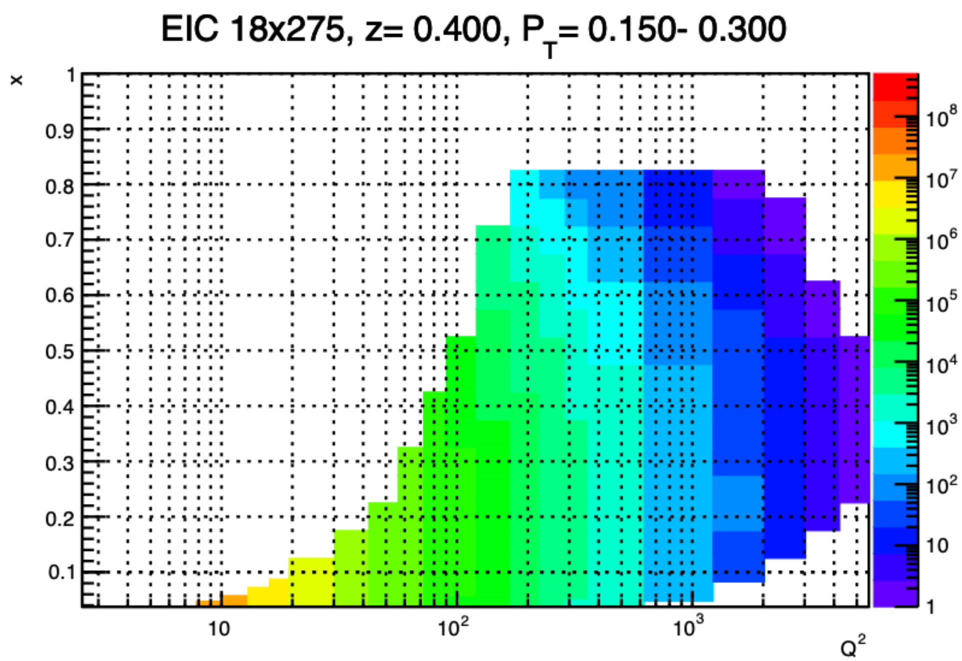
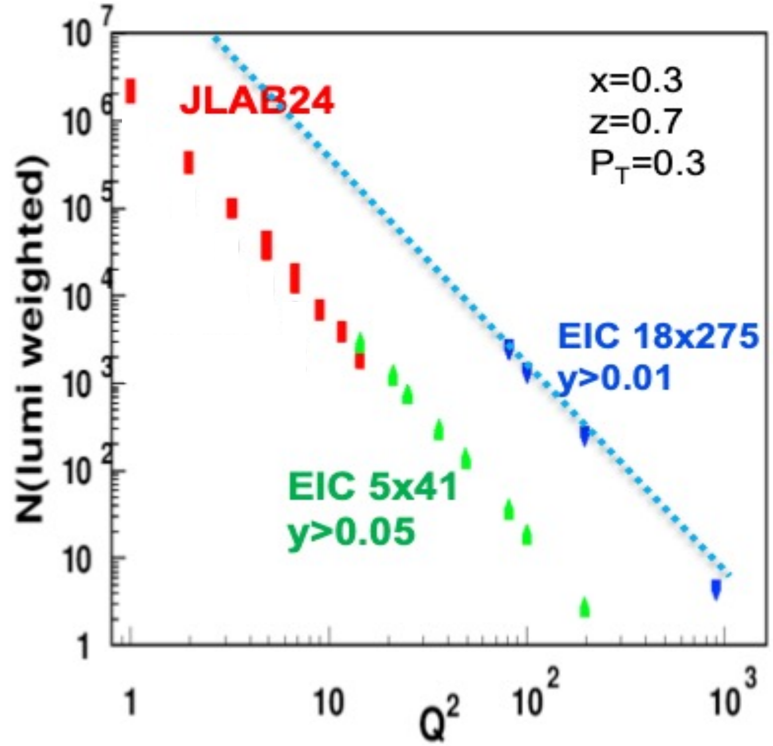
SIDIS at Large x : JLab domain







x-section from Bacchetta et al, 1703.10157

Counts / year

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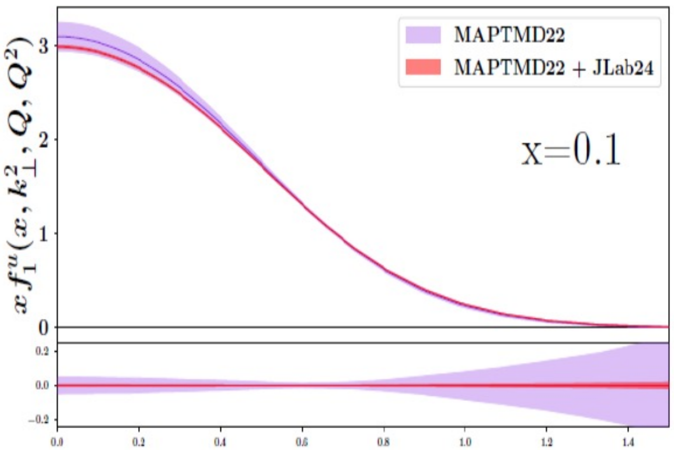
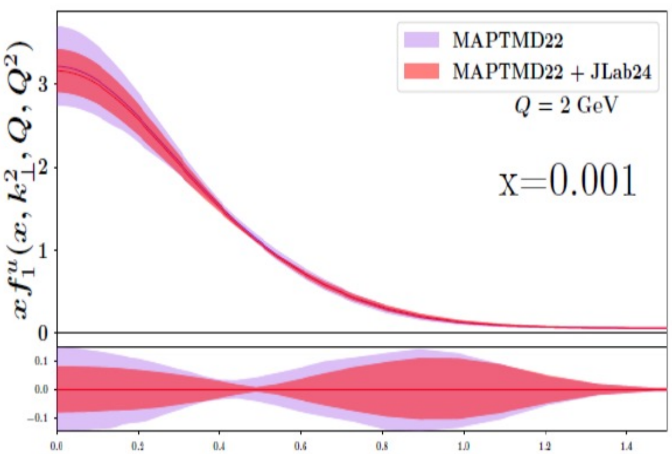
JLAB 20 IMPACT

A. Bacchetta " Beauty and the Beast"

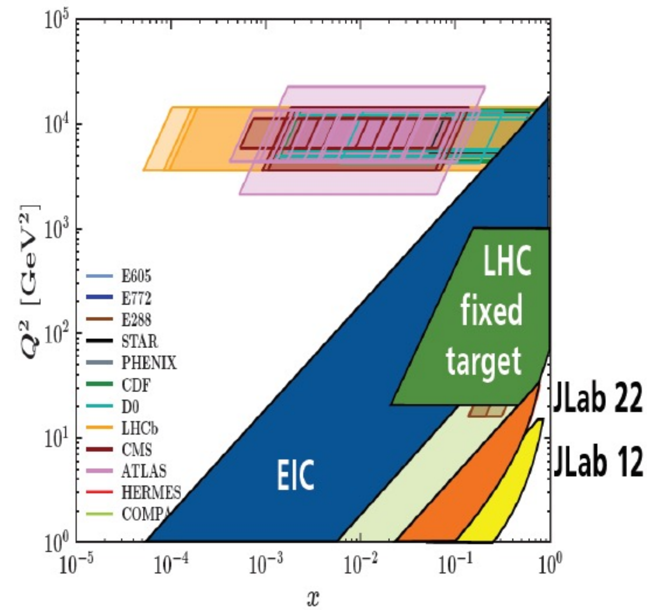
see talk on Wednesday



TMD at large x



TMD at low x



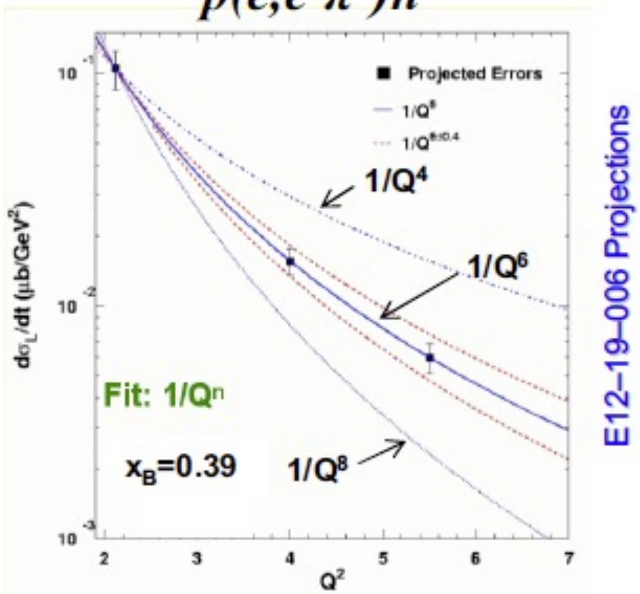
May have more complementarity with LHC than with EIC !

- JLab being efficient at low x, may be as credible as EIC being efficient at large x
- Overlap in kinematics is crucial for tests

Enhancement of the Q^2 range - DVMP

Hall C – HMS-SHMS

$p(e,e'\pi^+)n$

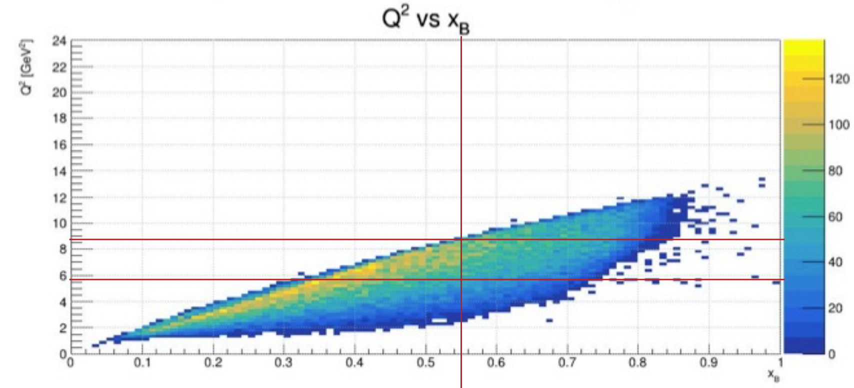


x	Q^2 (GeV^2)	W (GeV)	$-t_{min}$ (GeV^2)
0.31	1.45–3.65	2.02–3.07	0.12
	1.45–6.5	2.02–3.89	
0.39	2.12–6.0	2.05–3.19	0.21
	2.12–8.2	2.05–3.67	
0.55	3.85–8.5	2.02–2.79	0.55
	3.85–11.5	2.02–3.23	

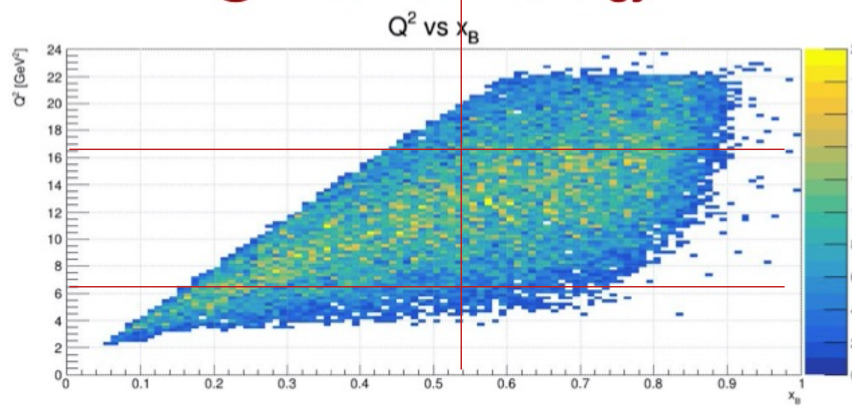
Needed to test GPD formalism applicability

Hall B – CLAS12

@ 10.6 GeV beam energy



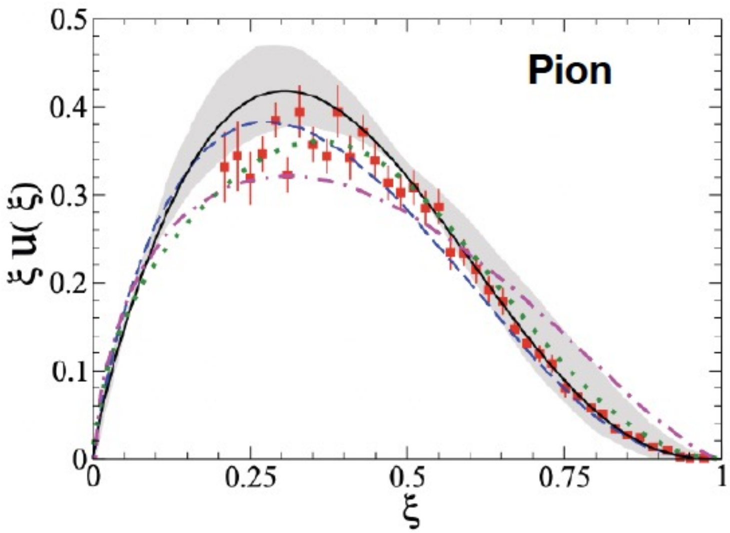
@ 22 GeV beam energy



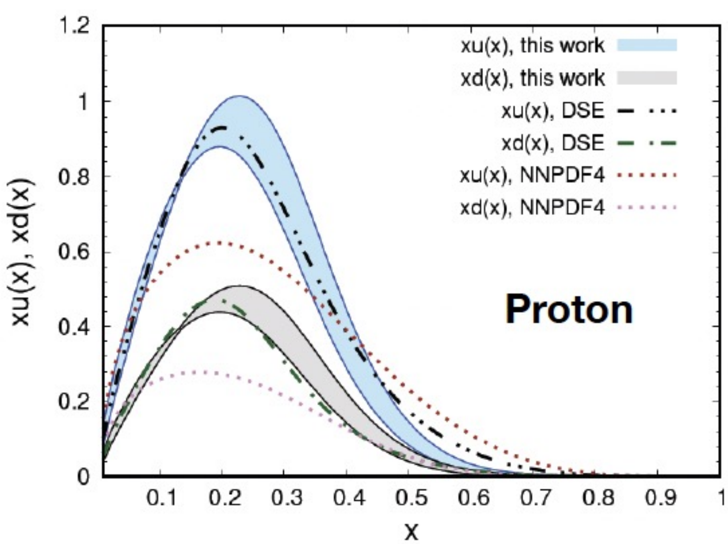
The <u>relevant</u> Q^2 range for the Q^n scaling test significantly increase with 18/22 GeV beam

Pion and Proton Unpolarized PDFs

W. De Paula, E. Ydrefors, J.H. Nogueira Alvarenga, T. Frederico, G. Salmè, PRD 105 (2022) L071505, and in preparation



E. Ydrefors, T. Frederico, PRD 104 (2021) 114012, and arXiv: 2211.10959 [hep-ph]



- From:
- T. Frederico (Instituto Tecnologico de Aeronautica)
- E. Ydrefors (Chinese Academy of Sciences)

- Minkowski space Bethe-Salepeter equation (pion)
- Light-front model (proton)
- See backup for details

- Broader pion PDF compared to proton

- Expect interesting differences between meson and nucleon PDFs

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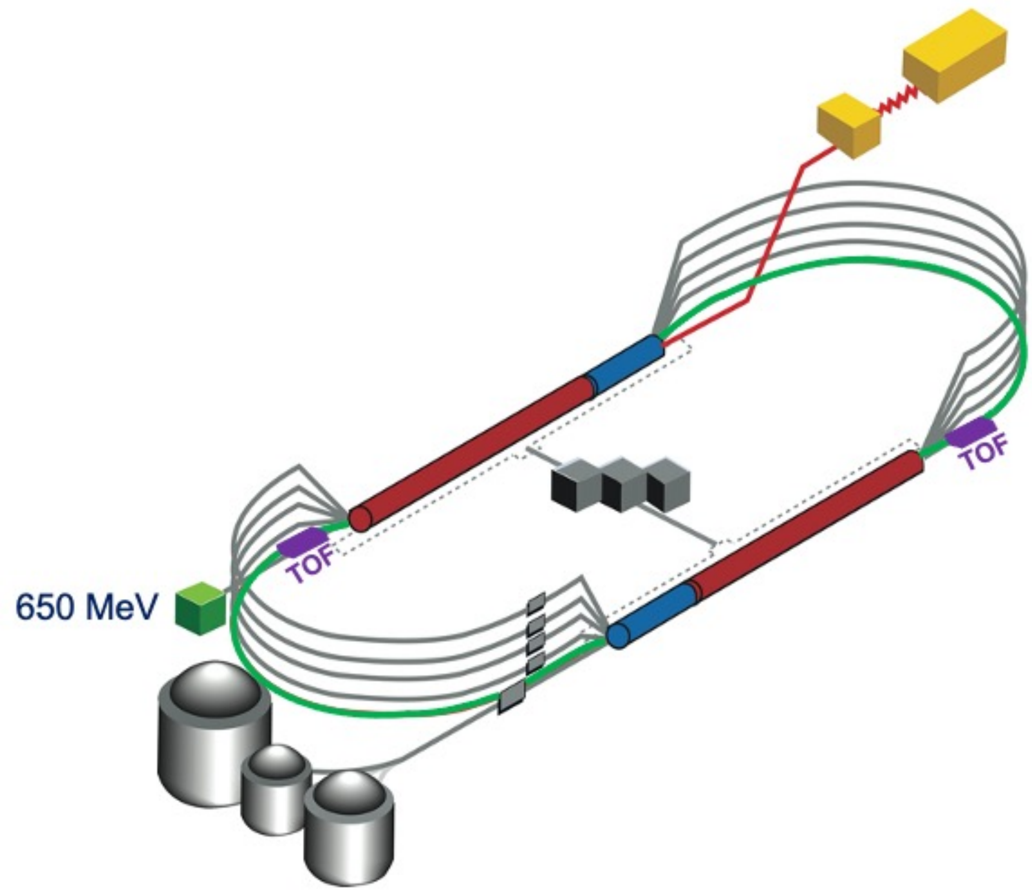
CEBAF FFA Upgrade – Baseline under Study

- Starting with 12 GeV CEBAF
- NO new SRF (1.1 GeV per linac)
- New 650 MeV recirculating injector
- Remove the highest recirculation pass (Arc 9 & A) and replace them with two FFA arcs including time-of-flight chicanes
- Recirculate 4.5 + **6** times to get to **22 GeV**



Pass Arithmetic: **5.5** -1 + **6** = **10.5**

Overview of the CEBAF Accelerator Upgrade 4

A. Bogacz