Opportunities with the JLab 22 GeV upgrade and the role of Hall C

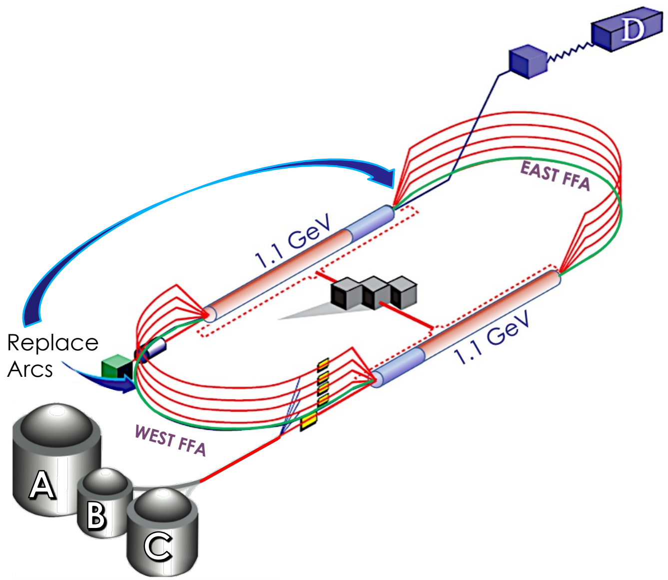
Patrizia Rossi

Hall C Collaboration Meeting

Jefferson Lab, January 13, 2023

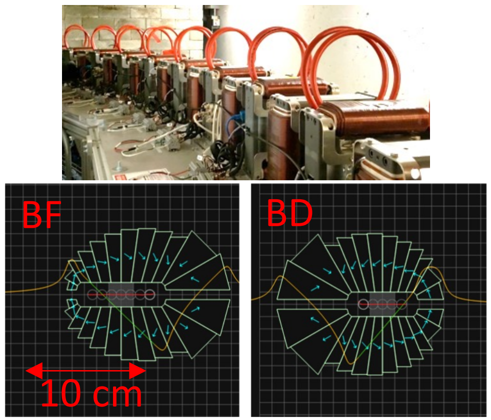
What is FFA@CEBAF?

- Replace highest energy arcs with Fixed-Field Alternating Gradient (FFA) arcs
  - Permanent, multi-function magnets
  - **Current design assumes 6 passes through single pair of FFA arcs**
- Upgraded injector will be 650 MeV
- Nominal linac energy 1100 MeV/pass
- **10 total passes in machine ⇒ higher final energy ⇒ 20-24 GeV**



Permanent FFA Magnets

- Small transverse size, slightly longer than 1 m each
- Demonstrated at CBETA (Cornell)
- Electromagnetic correctors



Magnets by Stephen Brooks, BNL

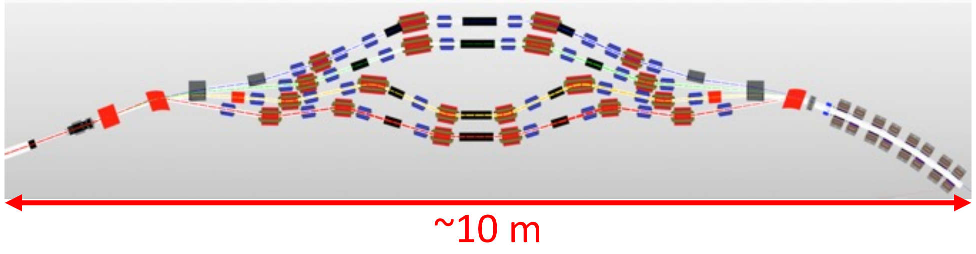
Courtesy of R. Bodenstein

Design Work

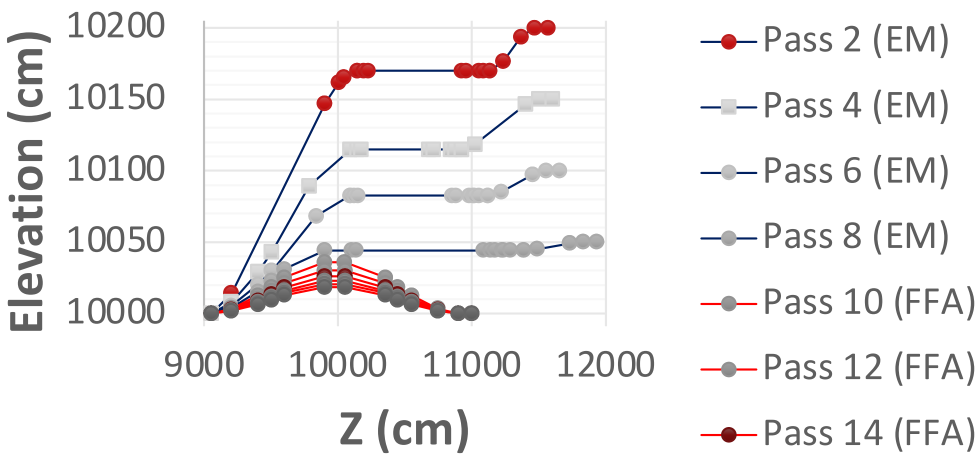
- New injector and long transfer line to NL from LERF
- Upgraded vertical spreaders/recombiners for increased energy
- Horizontal splitters to be designed for 6 FFA passes
- New linac optics
- Investigate upgrades to BSY and hall lines

- **Start-to-End beam dynamics simulations (LDRD)**
  - Error studies, diagnostics, correction schemes

CBETA 4-Pass Horizontal Splitter

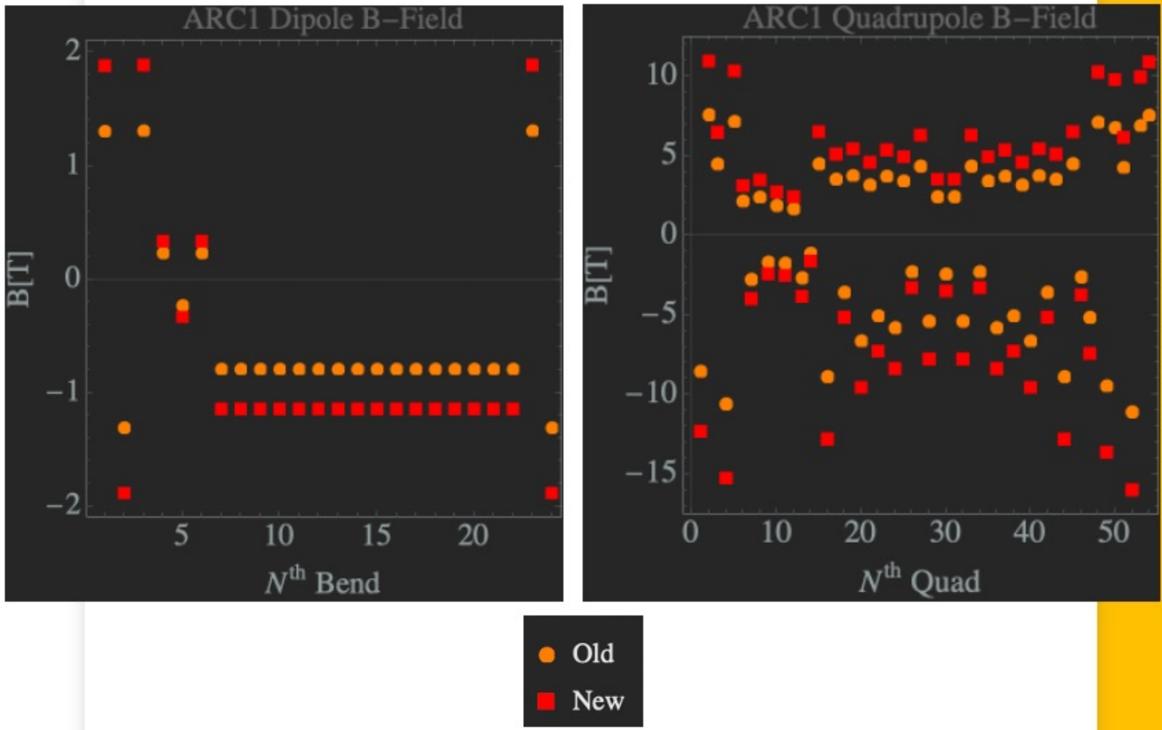


SW Spreader Elevations vs. Z



Increase Injection Energy Into Machine By 650 MeV

- Requires rescaling of magnets to preserve nominal optics ($\vec{\beta}, \vec{\alpha}$)
- Will require stronger fields to accommodate the larger beam rigidity ($^{|\vec{p}|}/_{e}$)



Slides provided by Donish Khan

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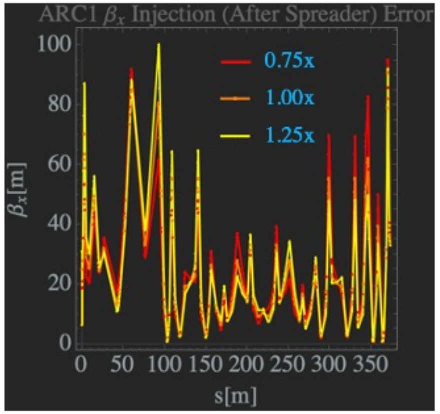
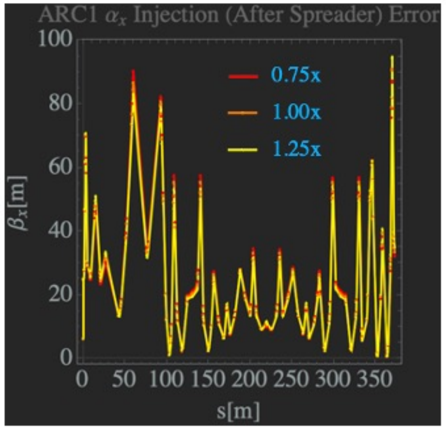
Twiss Mismatch At ARC Proper Entrance

Achromatic condition makes the ARC stable in the **x-plane**

$\delta\beta_x$

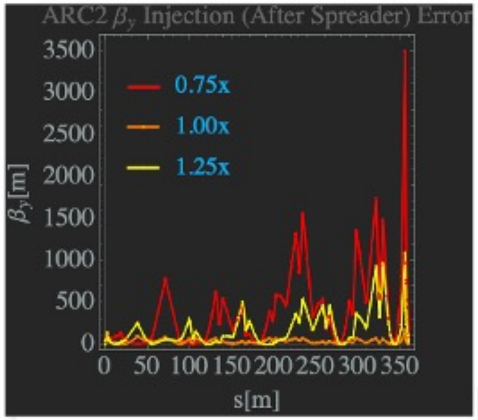


$\delta\alpha_x$

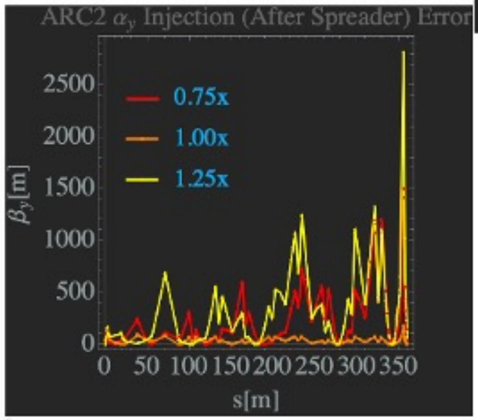


Injection Error

$\delta\beta_y$



$\delta\alpha_y$



Slides provided by Donish Khan

- Spreaders can heavily impact the **y-plane** optics
- Need care when matching into ARC proper or can blow up

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Workshops to support Future Opportunities

Internationally

- **J-FUTURE**
  Messina (Italy) March 28-30, 2022
- **Hadron Physics Opportunities with JLab Energy and Luminosity Upgrade**
  Pohang (Korea) July 18-21, 2022
- **Opportunities with Jlab Energy and Luminosity Upgrade**
  ECT* Trento (Italy) September 26-30, 2022

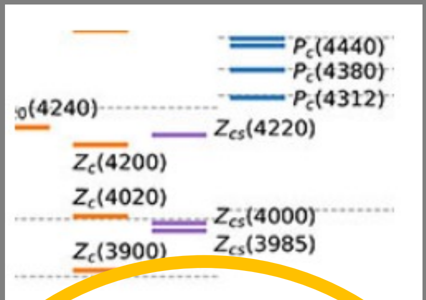
- **Gather theorists and experimentalists to discuss the physics opportunities and technical options for each of the possible upgrade scenarios: energy, positron, luminosity**

@ JLab Worshop Summer Series

- **Probe the science that would be opened up by a E_e 20+ GeV Initially utilizing largely existing or already-planned Hall equipment**

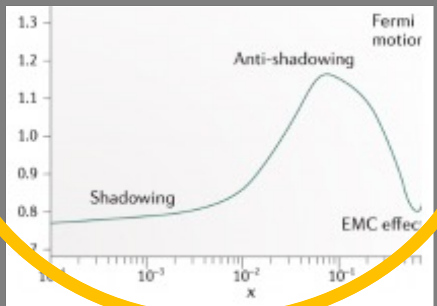
U = Uniqueness
E = Enrichment
C = Complementarity (EIC)

Hadron Spectroscopy with a CEBAF Energy Upgrade

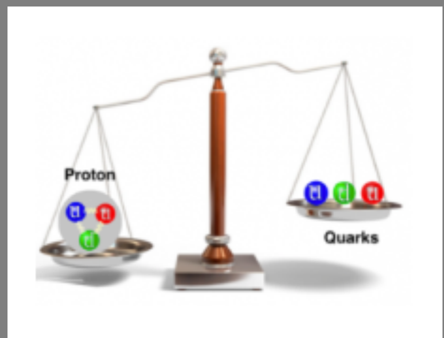


The Next Generation of 3D Imaging

Science at Mid x: Anti-shadowing and the Role of the Sea



Physics Beyond the Standard Model



J/Psi and Beyond

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Next workshop

SCIENCE AT THE LUMINOSITY FRONTIER: JEFFERSON LAB AT 22 GEV

Conference Date
January 23, 2023 to January 25, 2023

Mark your calendar!!

Conference Location
CEBAF Center Auditorium. In-person attendance is strongly encouraged, but a Zoom link will be provided.

This workshop will focus on the continuing development of the scientific case for a 22 GeV upgrade to CEBAF made possible by recent novel advances in accelerator technology. CEBAF's envisioned capabilities, at the highest luminosities, will enable exciting opportunities that give scientists the full suite of tools necessary to comprehensively understand how QCD builds hadronic matter in the valence region. Through this workshop, JLab and its user community will continue to build the science case with descriptions and concrete projections for experiments that would become possible with an upgrade. We encourage our users and others interested to submit talks and ideas to the relevant topical organizers listed below.

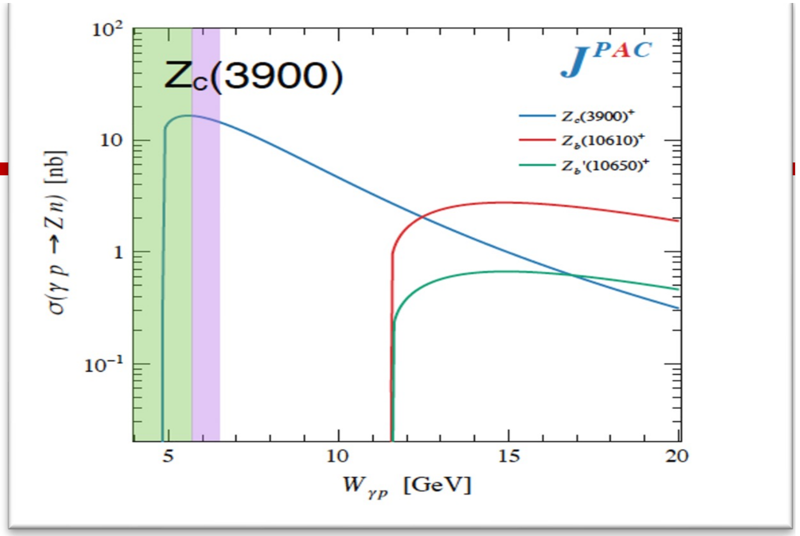
Hadron Spectroscopy

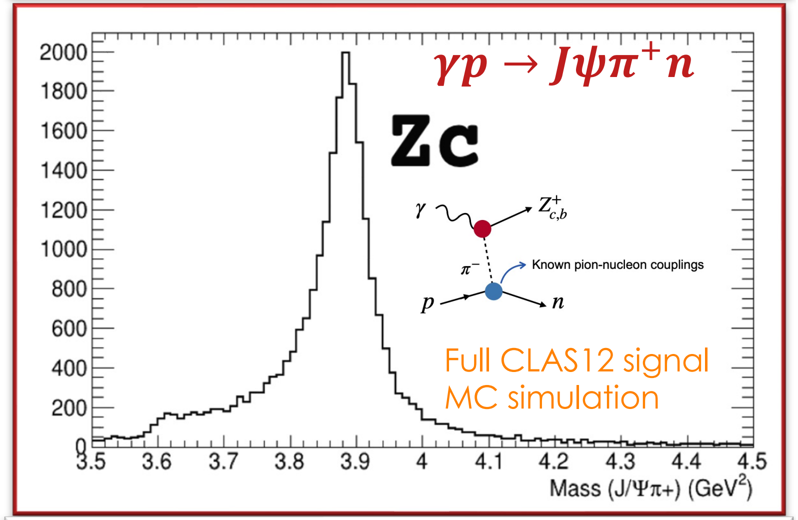
CEBAF @ 20+ GeV : XYZ states
& other charmonia

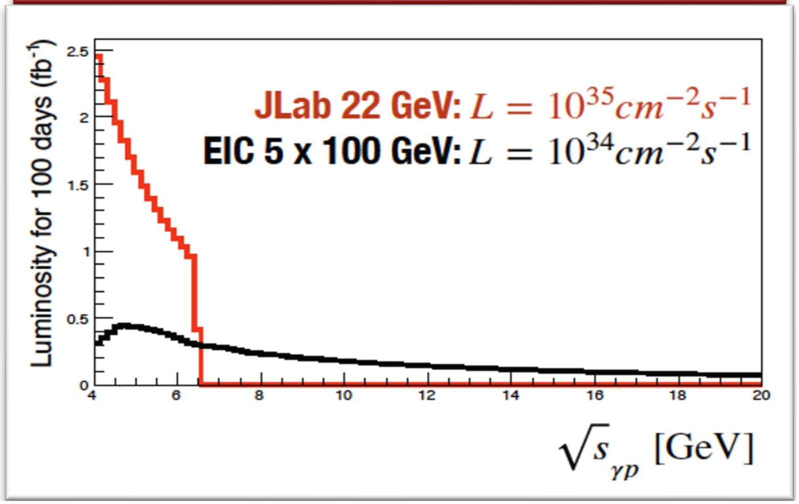
- Tetraquark candidates observed in B decays, e^+e^- colliders
- Significant theoretical interest and progress, but internal structure not yet understood
- **Never direcly produced** using γ/lepton beams

D. Glazier
S. Dobbs

- **Photoproduction provides an alternative mechanisms to study such states**
- Initial simulations from GlueX and CLAS12 demonstrate the **capabilities of the existing detectors to measure these reactions**





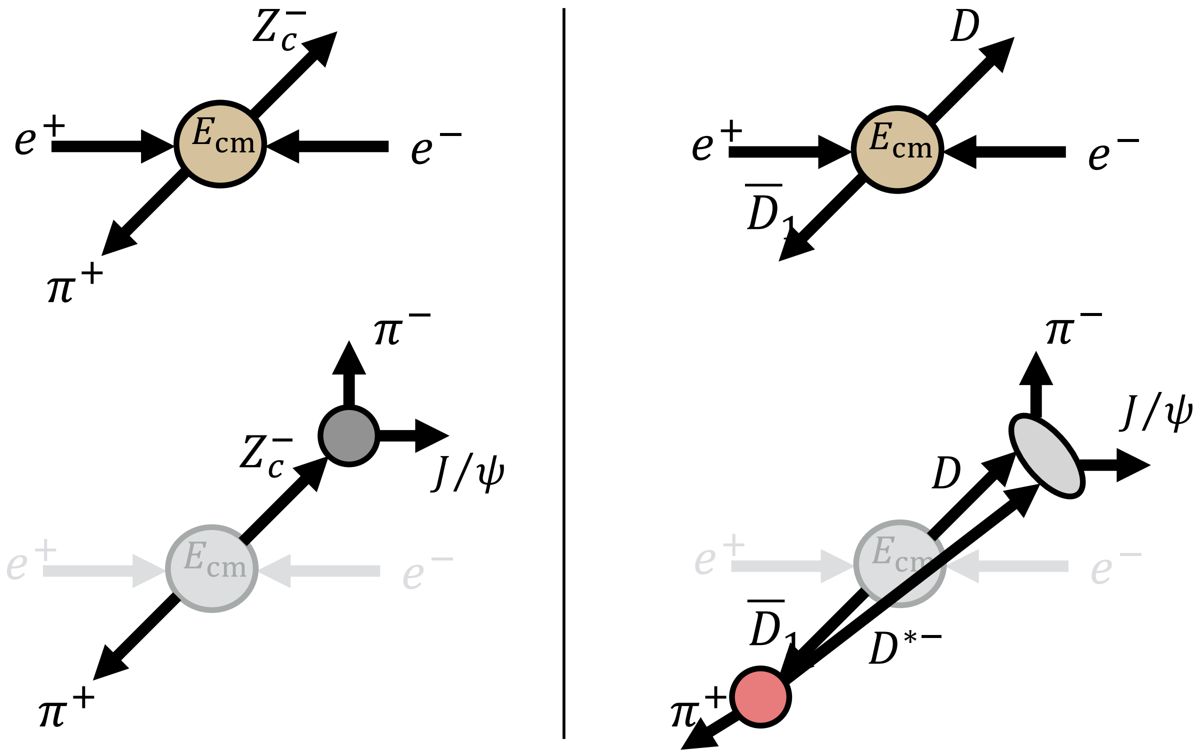


J. Stevens

XYZ States: Production Mechanism

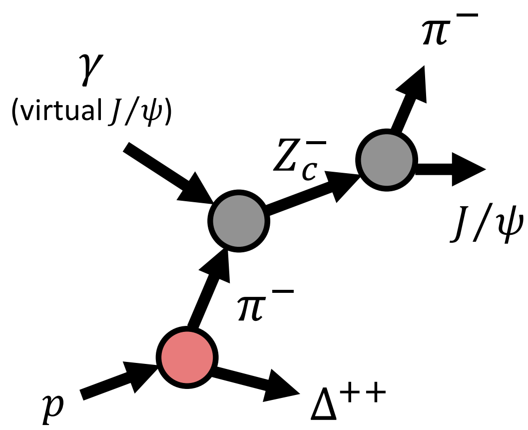
$e^+e^- \to \pi^+\pi^- J/\psi$

via a tetraquark Z_c^-?



Interpretation of data is complicated by nonresonant $D^{*-}D \to J/\psi\pi^-$ scattering that can produce peaks in invariant mass spectra for certain choices of E_{cm} and π^+ momentum that result in a $D^{*-}D$ interaction. These peaks are effects of initial state kinematics and do not require a resonance in $\boldsymbol{\pi^- J/\psi}$.

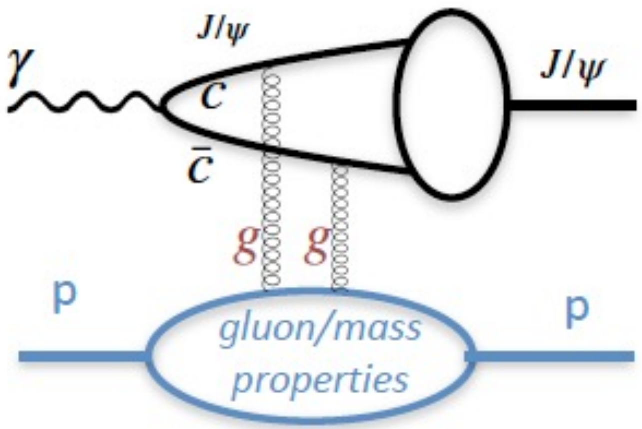
$\gamma p \to \pi^+ J/\psi \Delta^{++}$



Direct probe of the $\boldsymbol{Z_c \to J/\psi\pi}$ coupling without rescattering effects provides unique complementary data to constrain interpretation of $\boldsymbol{e^+e^-}$ data.

Courtesy M. Shepherd

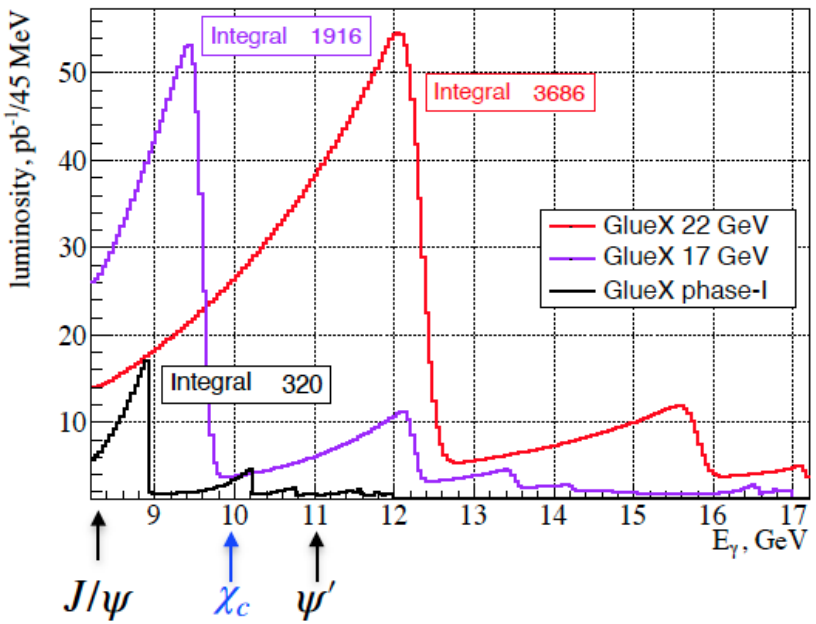
Charmonium threshold photo-production

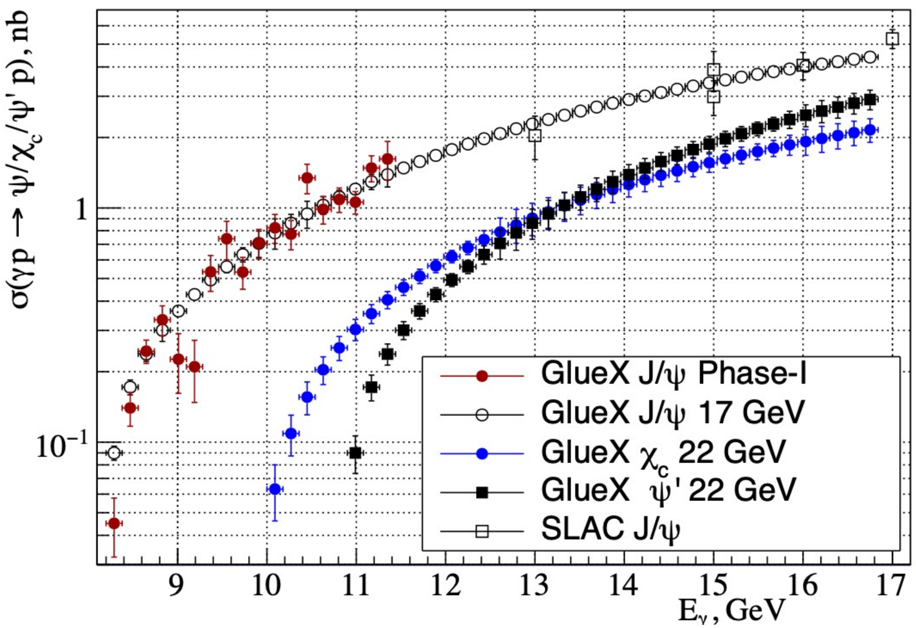


- Exclusive charmonium production near threshold probes gluon/mass properties of proton (mass radius, gravitational form factors, D-term, anomalous contribution to proton mass), however
  … assuming factorization
  … assuming two-gluon exchange

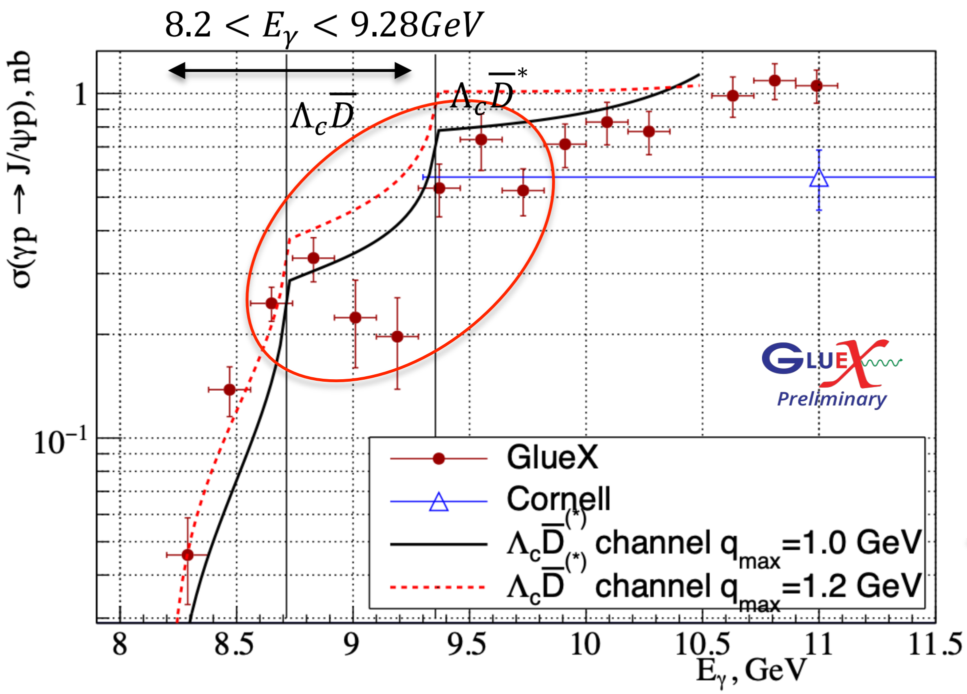
Energy increase gives higher fluxes and allows <u>detailed studies</u> of reaction mechanism using *J/ψ* and higher charmonium states

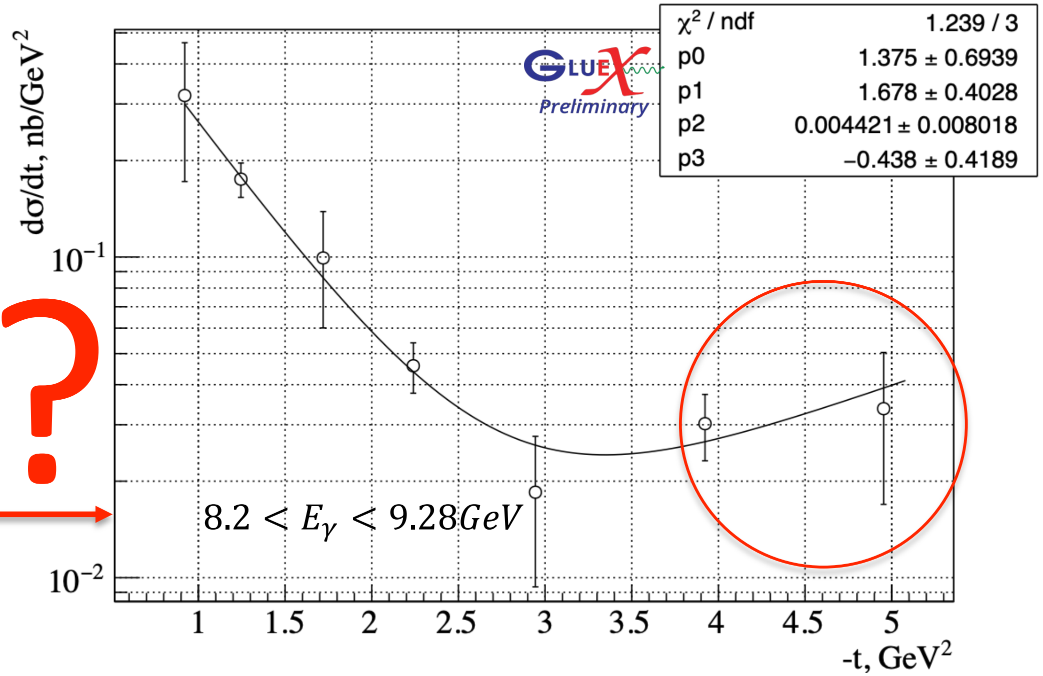
L. Pentchev



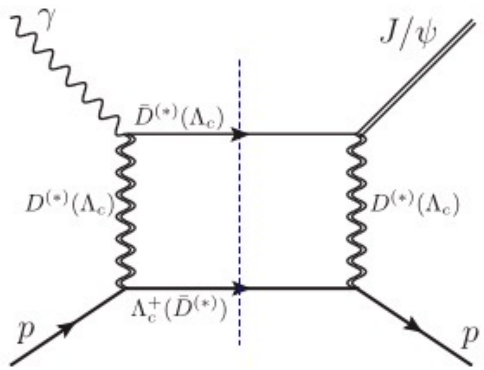


Is the t-channel (gluon exchange) dominating?





- **Possible structures in σ at $\Lambda_c\overline{D}^{(*)}$ thresh.**
- **dσ/dt enhancement at high t**



Feynman diagramfor the proposed CC mechanism.
Dashed line: open-charm intermediate state

Du, Baru, Guo, Hanhart, Meissner, Nefediev, Strakovsky EPJ C80 (2020)

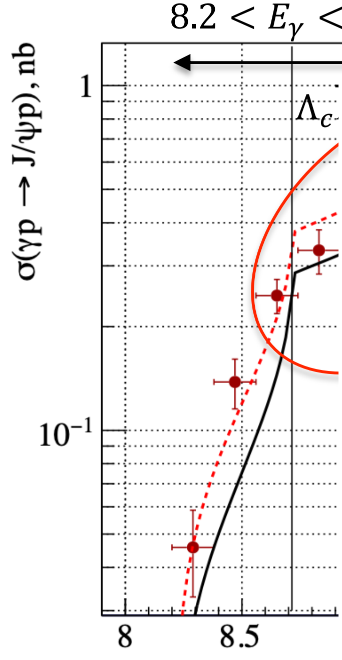
- **CANNOT be explained by t-channel (GLUON EXCHANGE) alone**
- Can have contribution from open-charm exchange to both σ and $d\sigma/dt$ at high t

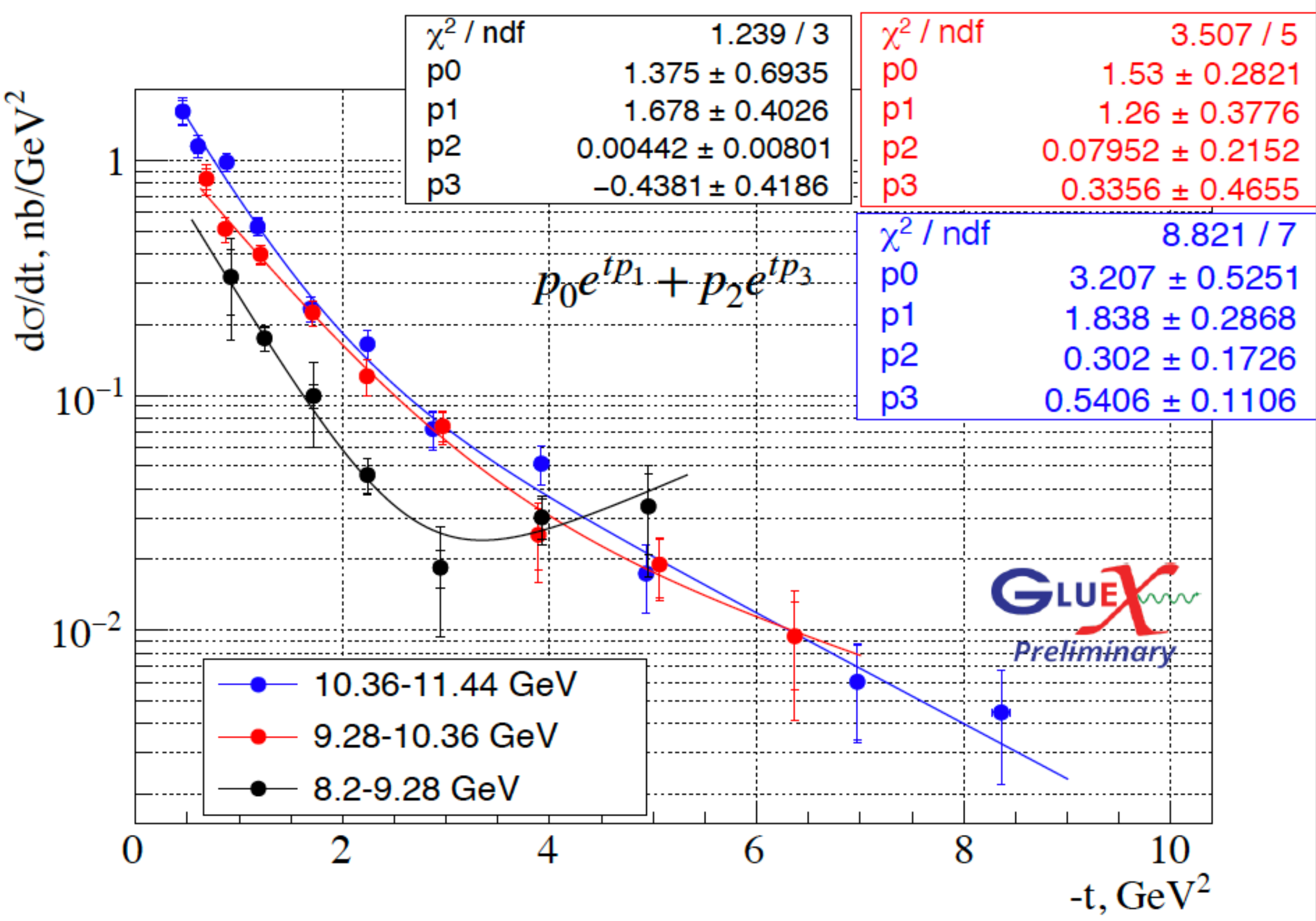
L. Pentchev

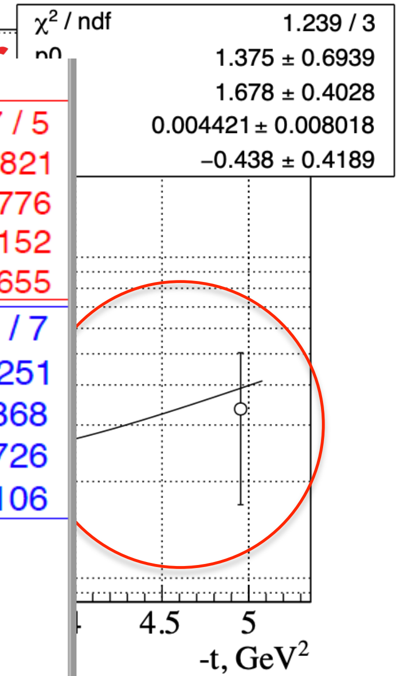
Jefferson Lab

Is the t-channel (gluon exchange) dominating?

L. Pentchev



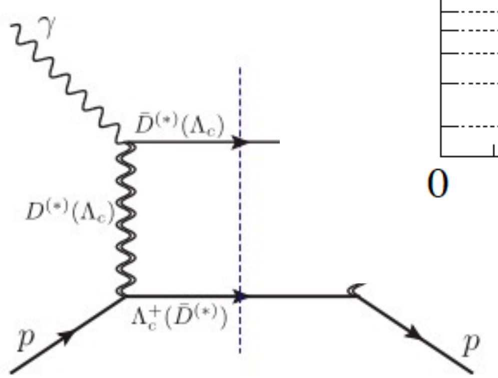




- **Possible st[…] high t**

[…]CHANGE) alone

[…]ge to both σ



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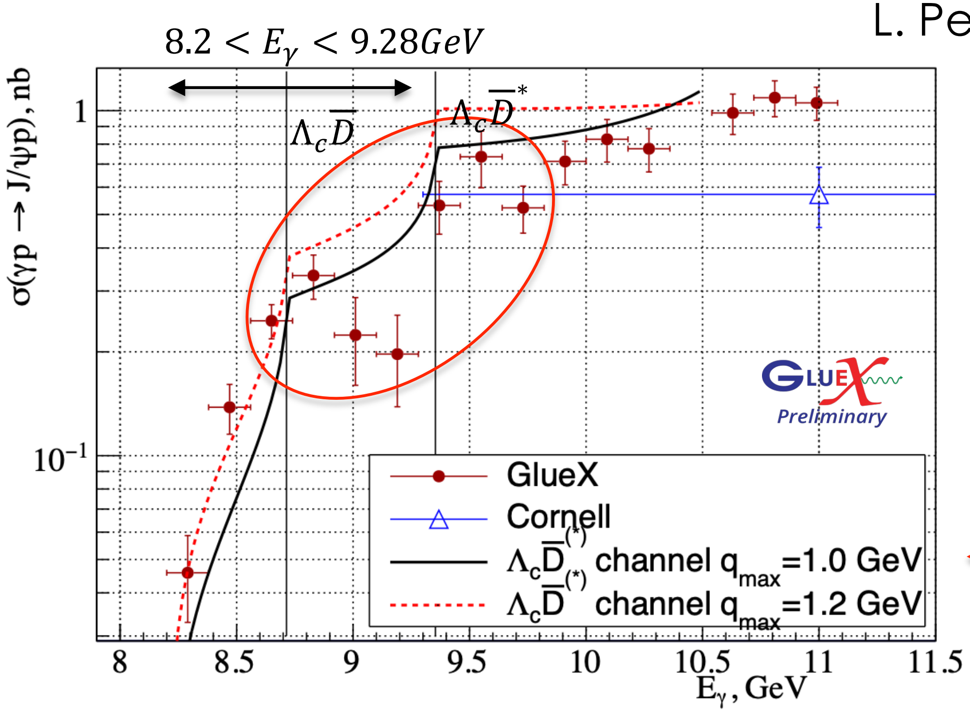

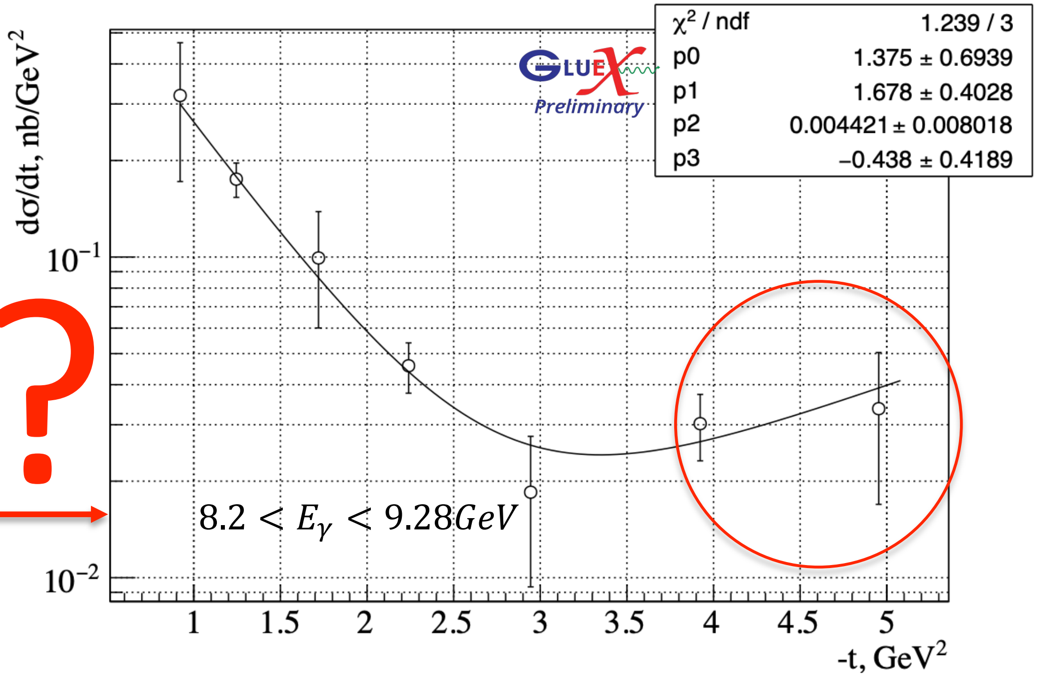

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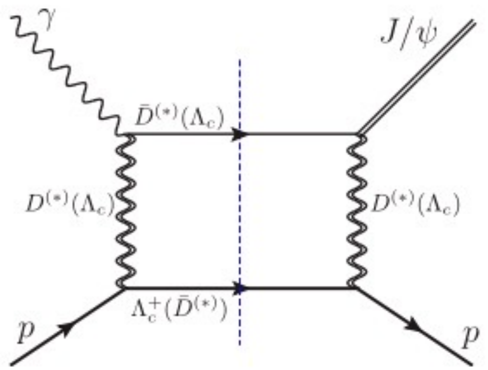

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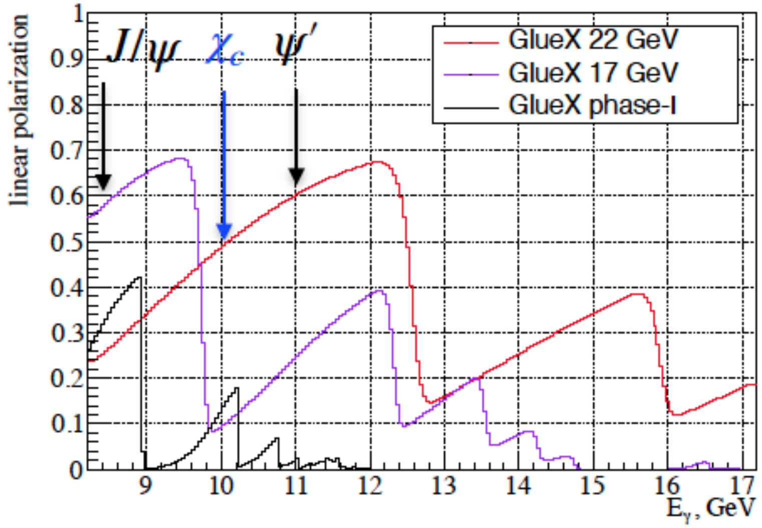
- **CANNOT be explained by t-channel (GLUON EXCHANGE) alone**
- Can have contribution from open-charm exchange to both σ and $d\sigma/dt$ at high t

Need higher statistics near threshold to understand the mechanism

➡ **possible with GlueX at 17+ GeV**

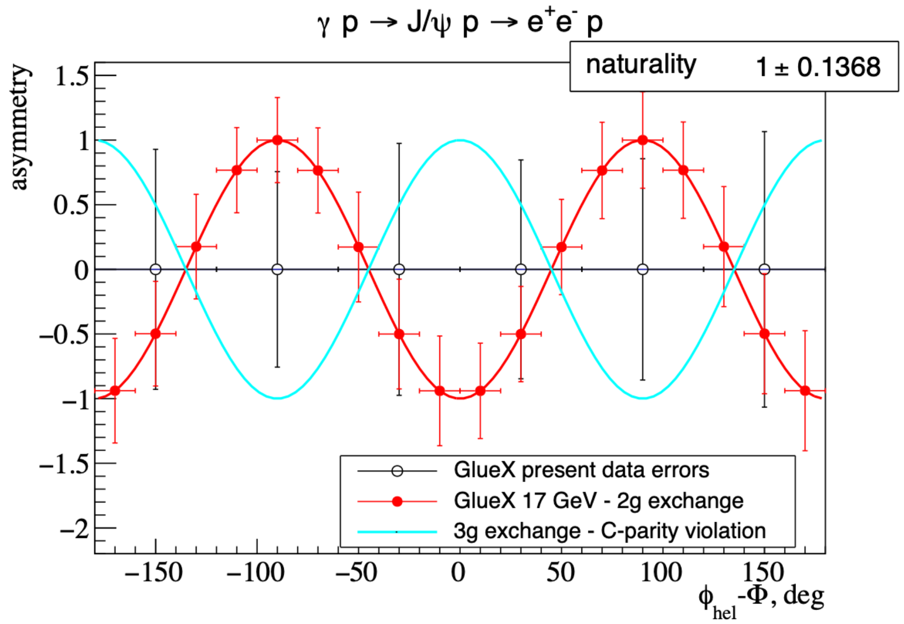
J/ψ photo-production in Hall D - polarization

Energy upgrade gives significant **increase** of **photon linear polarization**

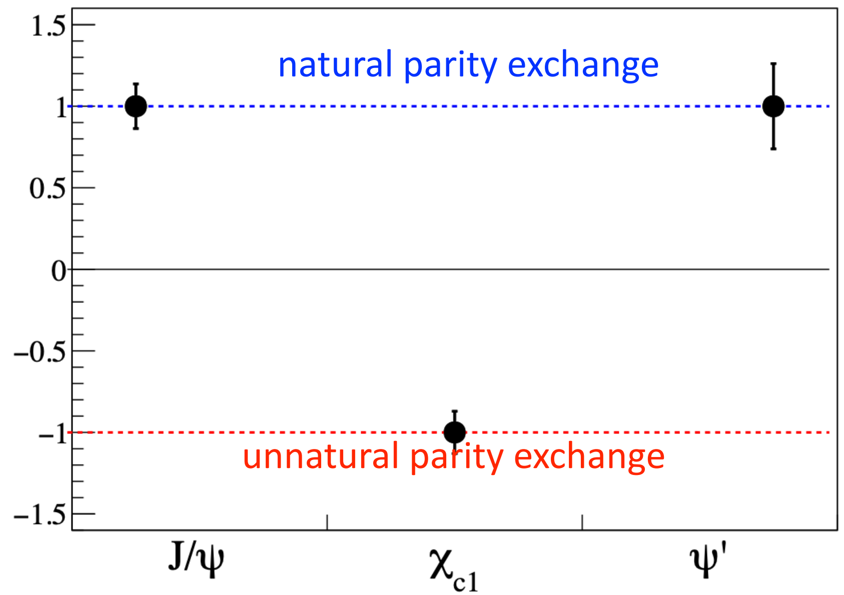


… ..allowing unique studies of the gluon exchange for J/ψ and higher charmonium states

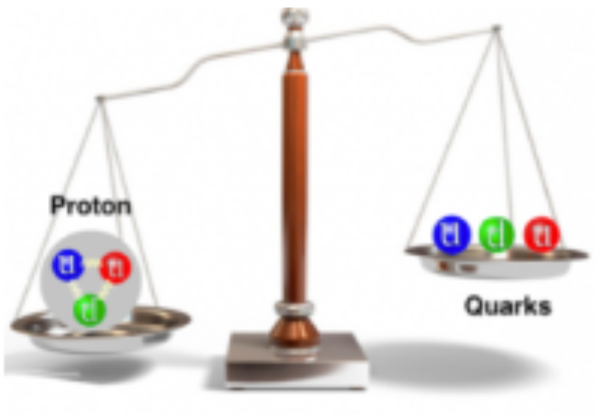
L. Pentchev



naturality = $P(-1)^J$



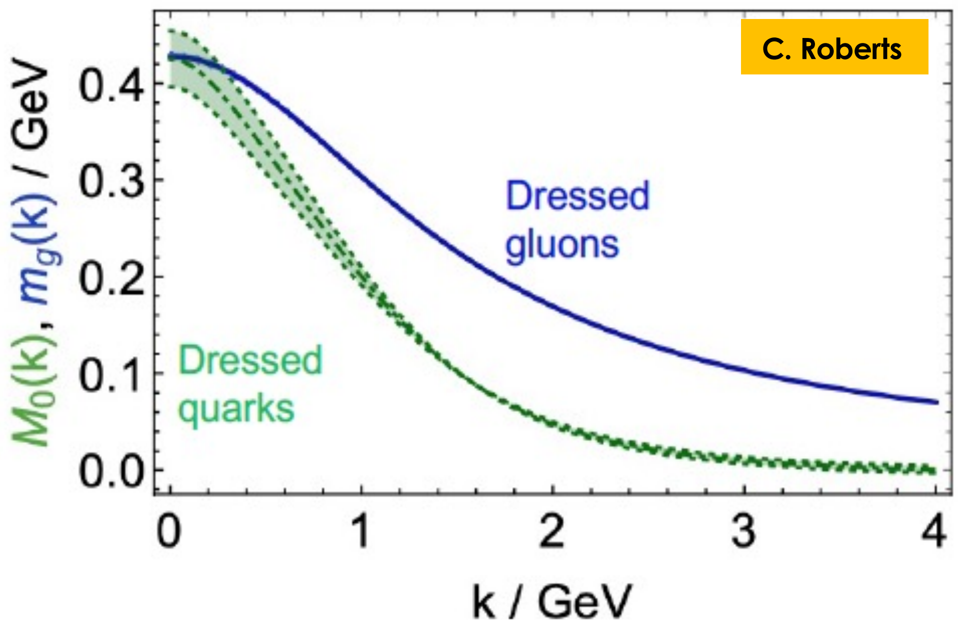
Shedding Light on the Emergence of Hadron Mass



- Topic of high interest in QCD: express the nucleon mass in terms of contributions from quarks & gluons energies

- **Lattice**
- **Trace anomaly of the QCD EMT**
  - Different opinions → different mass decompositions proposed
- **Functional QCD approach- Continuum Schwinger Method (CSM)**
  - In strong QCD regime, the solution of the QCD equations of motion for quark/gluon fields reveals existence of dressed q/g with momentum-dependent masses.

C.D. Roberts, Symmetry 12, 1468 (2020), AAPS Bull 31, 6 (2021)



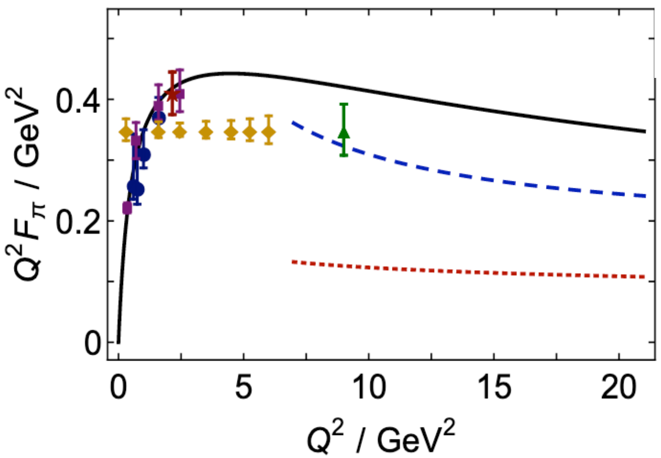
- Results supported by LQCD

O. Olivera et al., PRD 99, 094506 (2019)

CSM Experimental Expectations

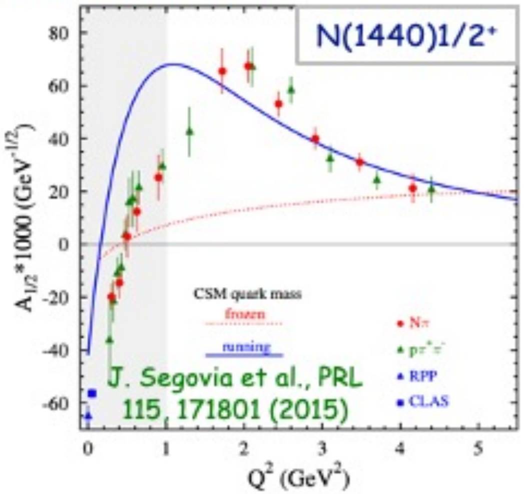
- **CSM employing the same dressed quark mass function** capable to describe
  - N* electrocoupling for nucleon resonances of ≠ structure,
  - π and N FFs

Pion Elastic FF



Program unique to JLab Hall C:
- started at 6 GeV
- continued at 12 GeV
- Proposed at EIC
- **JLab @ 22 GeV:**

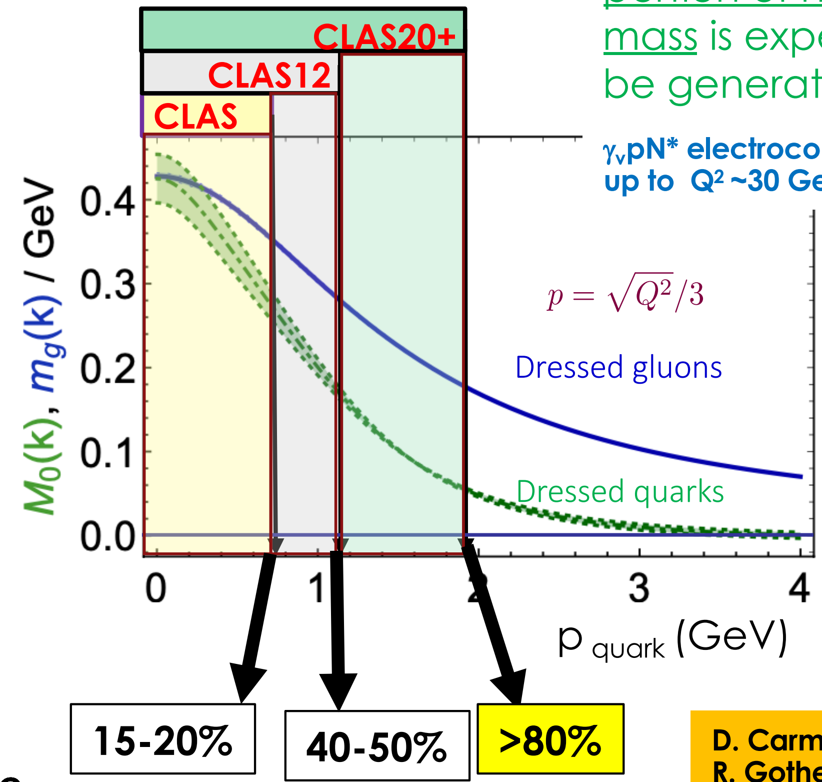
increases *Fπ* data set overlap between JLab and EIC (quality L/T-separations impossible @ EIC - can't access ε<0.95)



CLAS results vs. CSM expectations

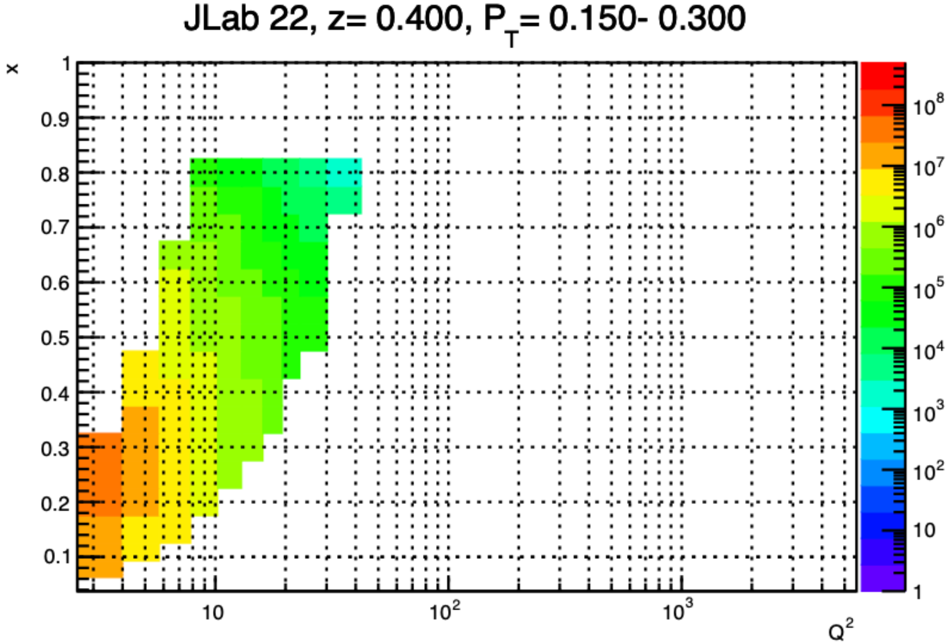
CEBAF @ 22 GeV:
only foreseeable opportunity to explore N* electroexcitation within the Q^2 range where the dominant portion of hadron mass is expected to be generated

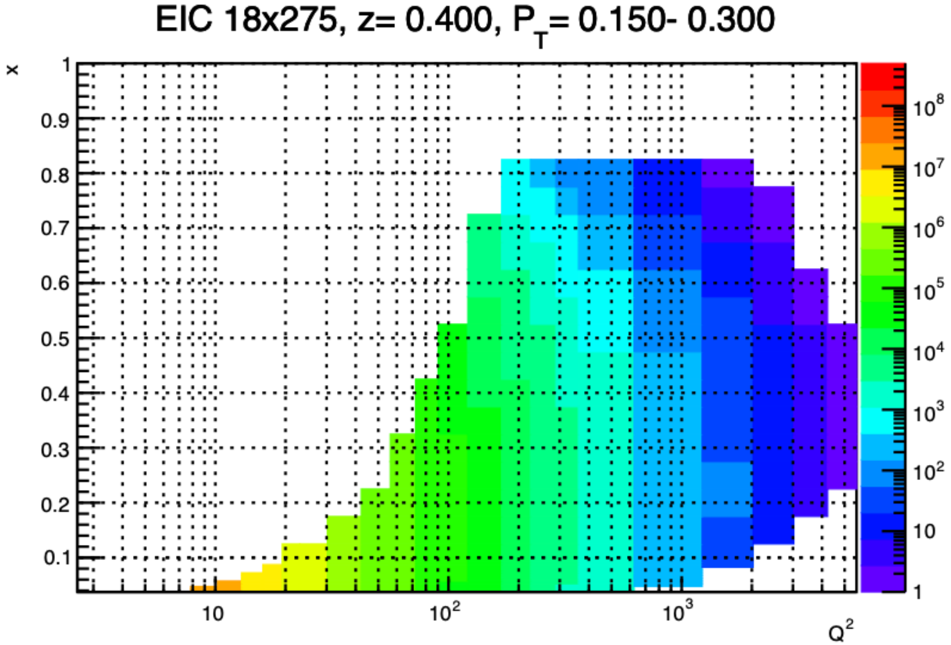
$\gamma_v pN^*$ electrocouplings up to Q^2 ~30 GeV^2

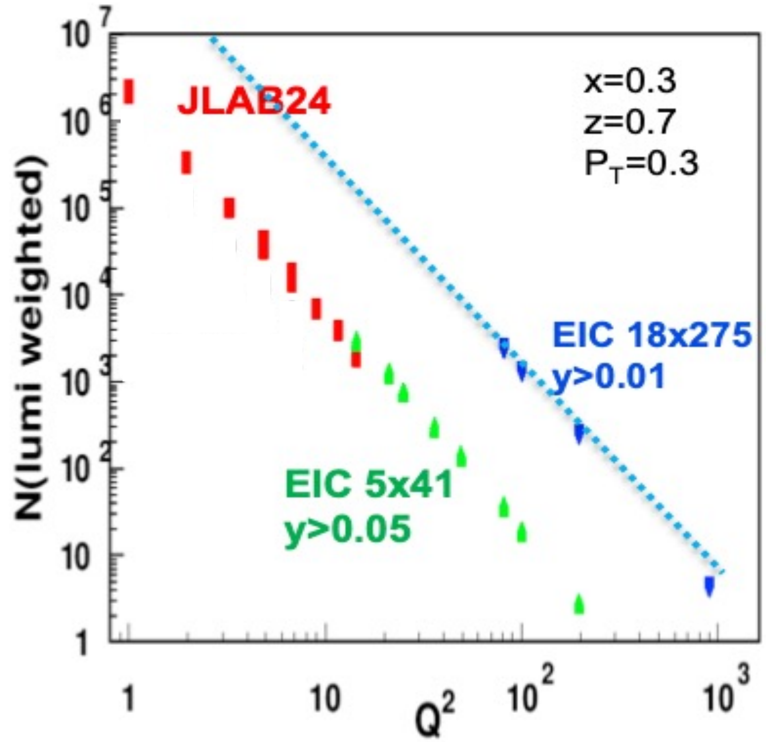


D. Carman
R. Gothe
V. Mokeev

SIDIS at Large x : JLab domain







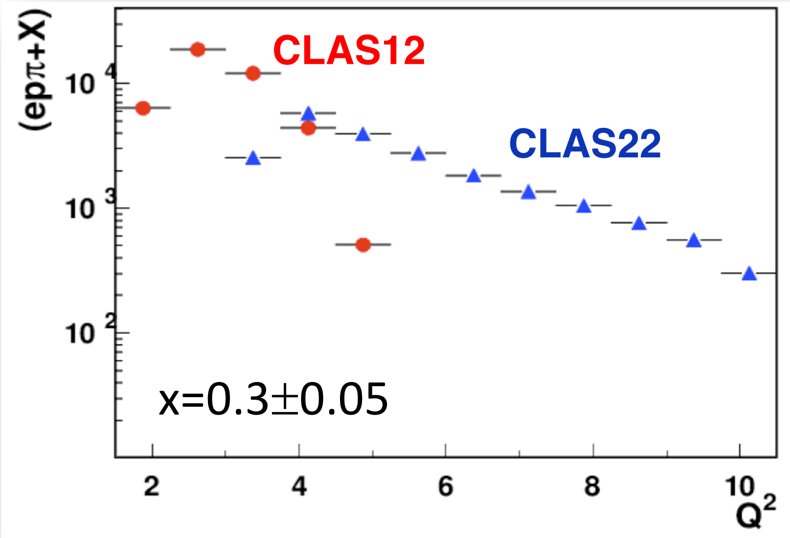
x-section from Bacchetta et al, 1703.10157

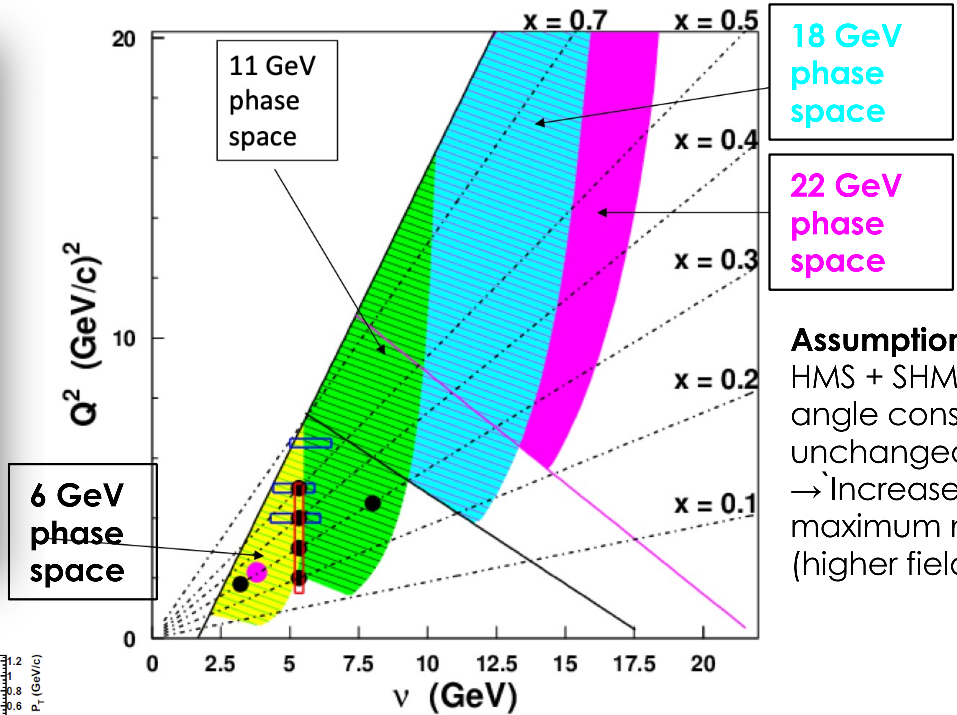
H. Avakian
M. Mirazita

Counts / year

Enhancement of the Q^2 range

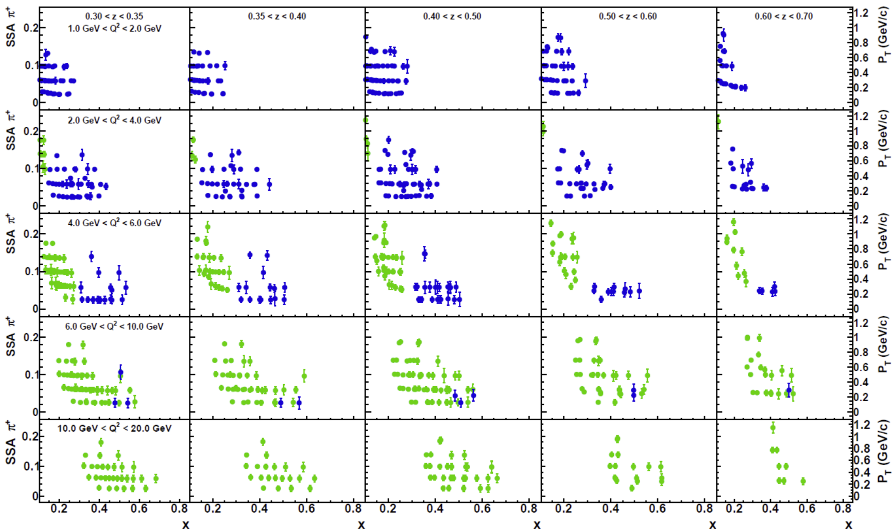
- **Jlab @ 22 GeV will expand P_T and Q^2 range)**





Assumptions:
HMS + SHMS minimum angle constraints unchanged
→ Increase in HMS maximum momentum (higher field magnets)

SoLID @ 11 GeV **SoLID @ 22 GeV**

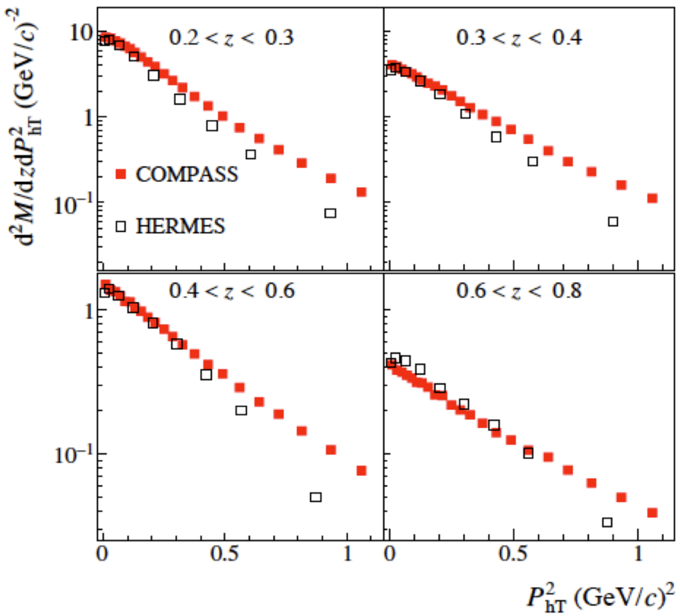


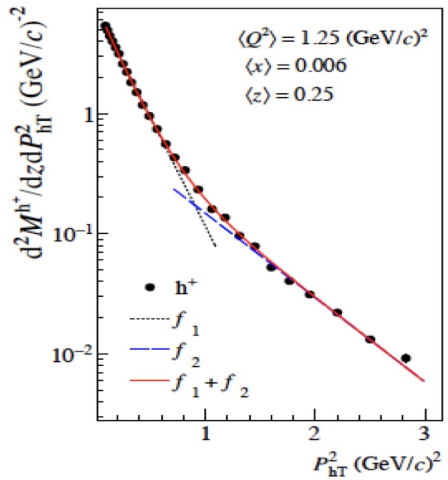
- **Q^2 evolution studies possible**

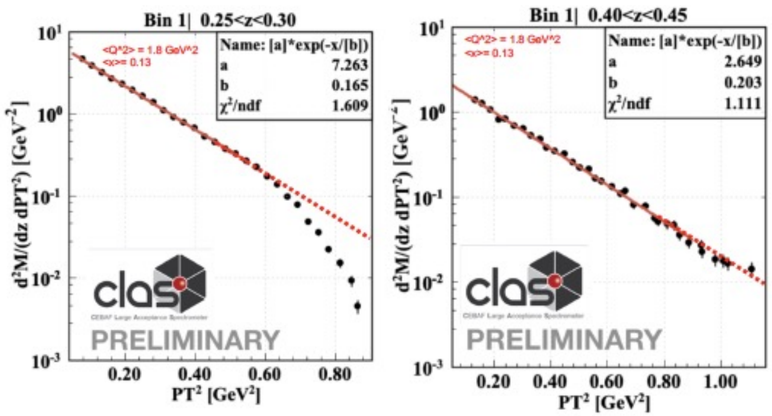
QCD predicts <u>only</u> the Q^2 dep. of PDFs

V. Khachatryan
H. Avakian
D. Gaskell

Enhancement of the P_T range



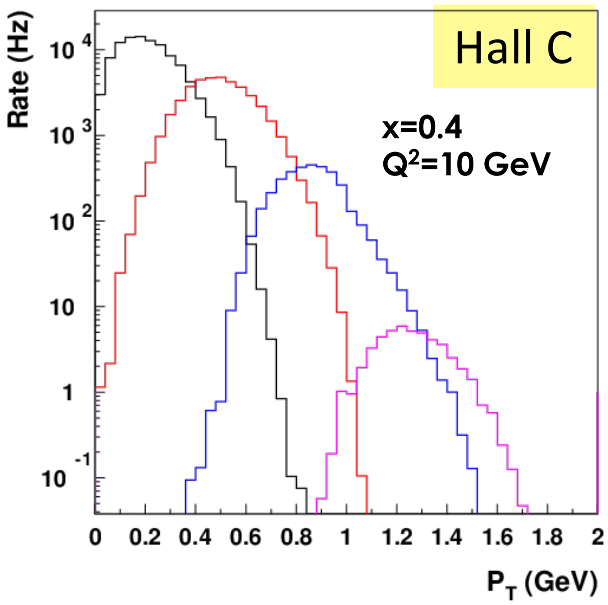




H. Avakian

- **TMDs universal, so what is the origin of the differences observed ?**
- **What is the origin of the "high" P_T (0.8-1.8) tail?** perturbative/non pert contributions?
- **For some kinematic regions, at low z, the high P_T distribution appear suppressed: there is no enough energy in the system to produce hadron with high P_T (phase space effect).**
- **JLab: not enough energy to produce large P_T; HERMES: not enough luminosity to access large P_T**

Projected rates:
10 cm LH2
80 μA
40 MeV bins in PT



D. Gaskell

Larger P_T range and high luminosity is the key for a better insight into the problem

D. Gaskell

Jefferson Lab

Hall C Role

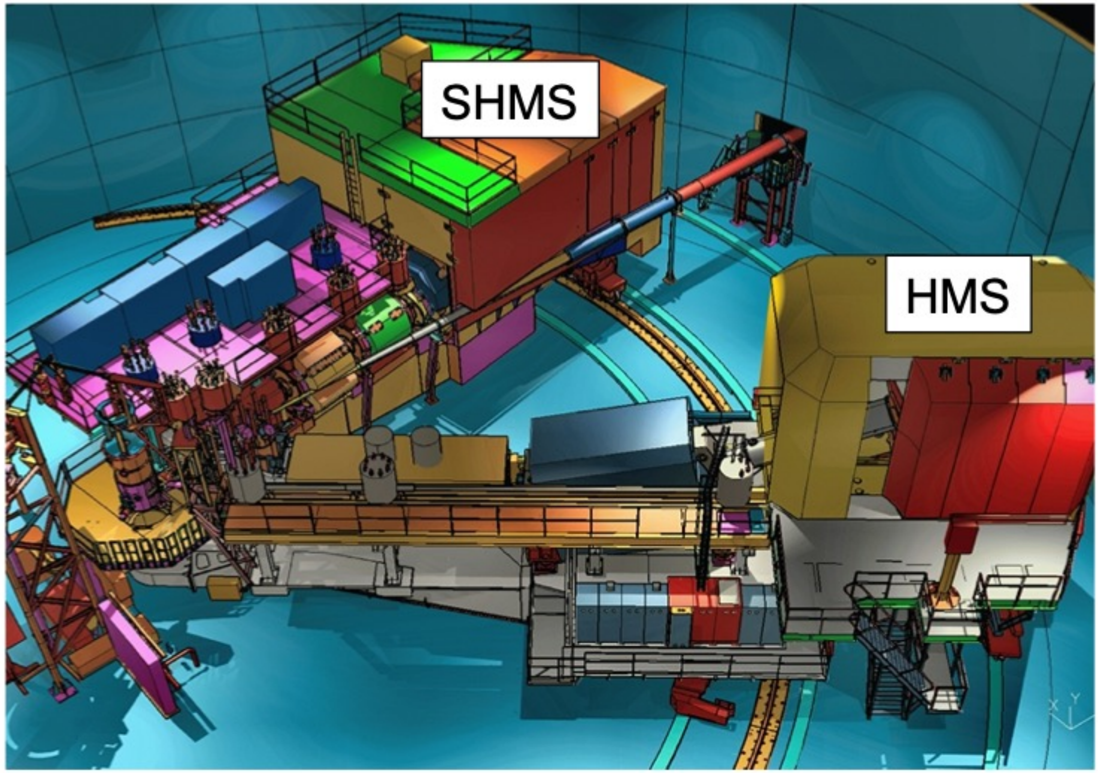
SHMS: hadron arm
P_0=1 – 11GeV/c
π/k/ p separation with Cerevkov detector

HMS: electron arm
P_0=0.5 – 7GeV/c

- Identical acceptance for positive and negative polarity ➤ precision measurement of charged meson ratios
- Excellent control of point-to-point systematic uncertainties required for **precise L-T separation**

▼

Crucial measurement as it yields the **fundamental quantity of R** which relates the cross sections (experimental observables) to the structure functions (objects of theoretical models)



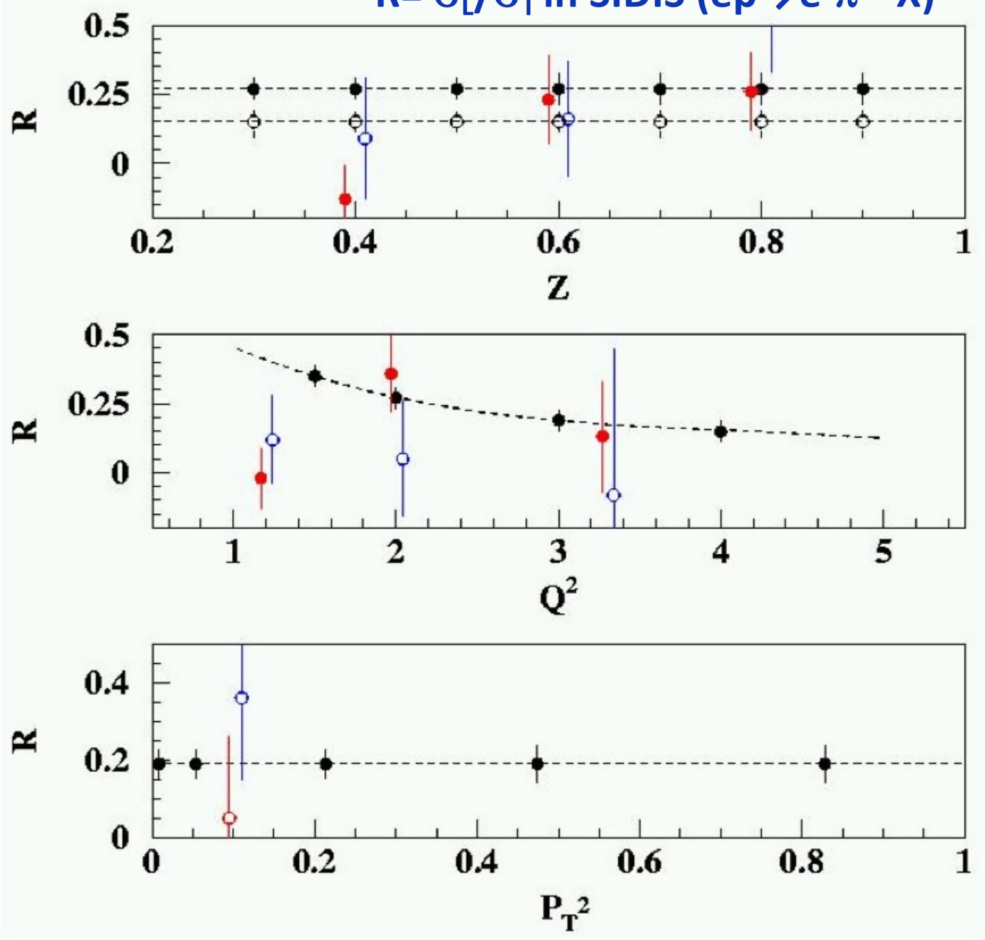
↪ needed in SIDIS, DEMP, DIS measurements on nucleon and nuclei

SIDIS L/T Separation

$R=\sigma_L/\sigma_T$

- DIS: R asymptotically scales like Q^2, at fixed x_B
- SIDIS: R is assumed to be similar to that of DIS but ***never been thoroughly checked***

$R=\sigma_L/\sigma_T$ in SIDIS ($ep\rightarrow e'\pi^{+/-}X$)



- SHMS/HMS will allow precise L-T separations

- E12-06-104: Measurement of the Ratio R=sL/sT in Semi-Inclusive Deep-Inelastic Scattering
  Spokespersons: R. Ent, P. Bosted, E. Kinney, H. Mkrtchyan

- Is R in SIDIS same as DIS?
- Has R the same behavior at mid and large x?
- What is the R dependence on P_T?

Jefferson Lab

L-T separation in SIDIS

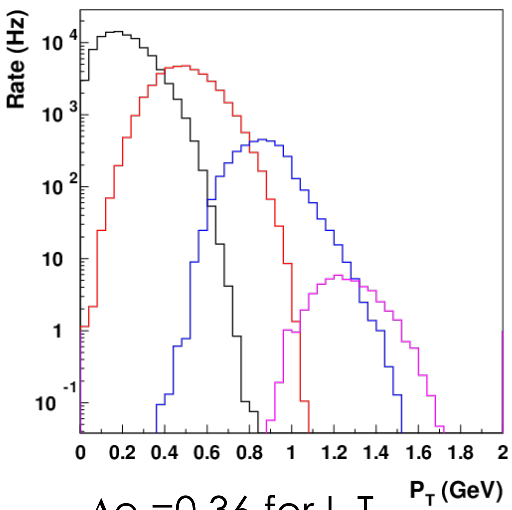
Target pol.

Beam pol. Virtual photon pol.

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \mathcal{K}(x,y)/Q^4 \Big\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

H.T

$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + \ldots.$$



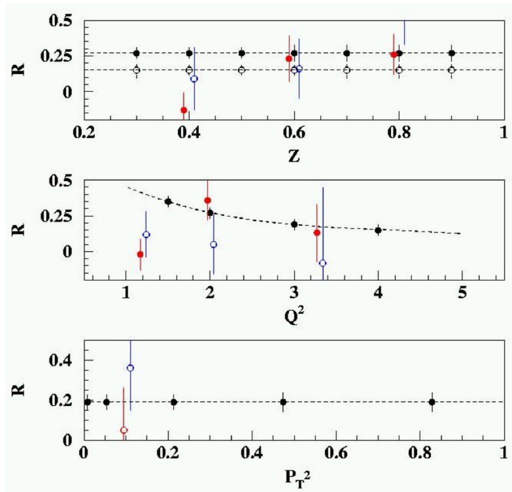
Δe =0.36 for L-T separation

L/T separation to extract $F_{UU,T}$, $F_{UU,L}$

- Typically done with Rosenbluth technique
- At least measurements for two ε values (but preferably more) at fixed x and Q^2
- Perform a linear fit to the reduced cross section to extract σ_T and σ_L

Fit results sensitive to:

a) point-to-point uncertainty of the reduced x-section,
b) number of ε points
c) overall ε range used for fitting.



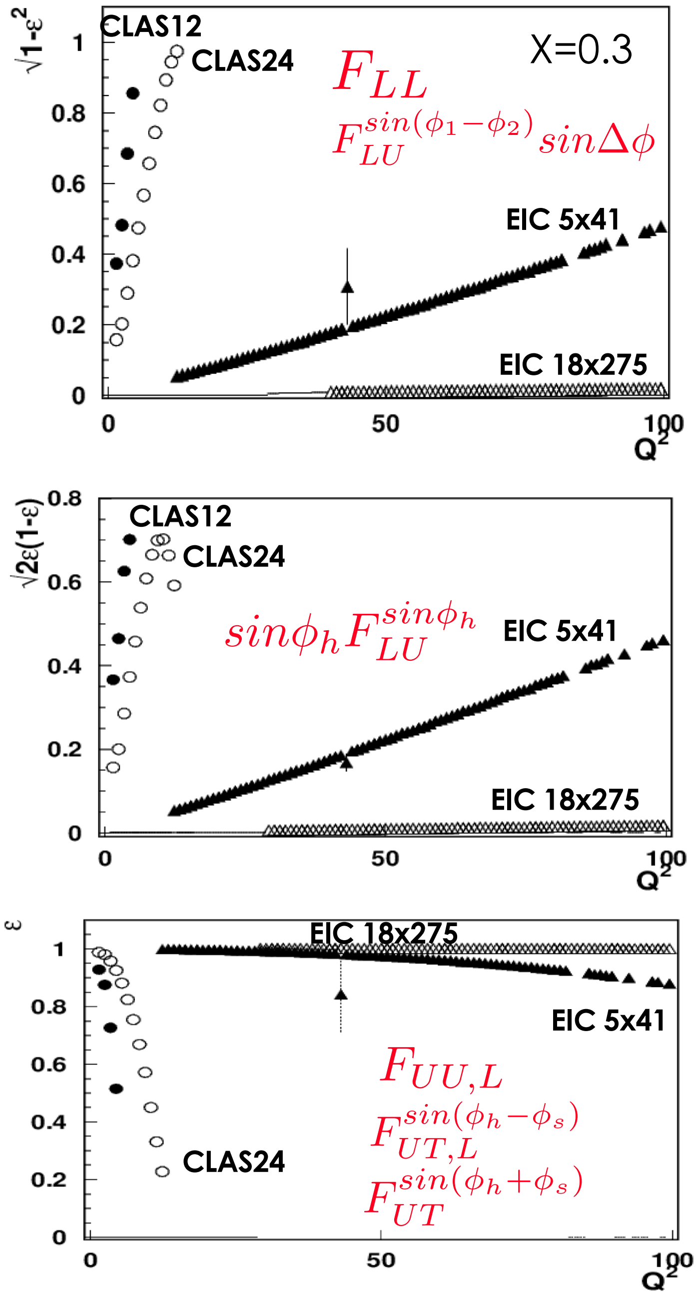
- Evaluation of the $F_{UU,L}$ contribution is very important at large P_T

Simple estimate
R~0.2 @ <P_T> ~0.4 GeV→ P_T~1 GeV R>1 ??

- Can be evaluated only with fixed target experiments

Kinematic Suppression at Large x

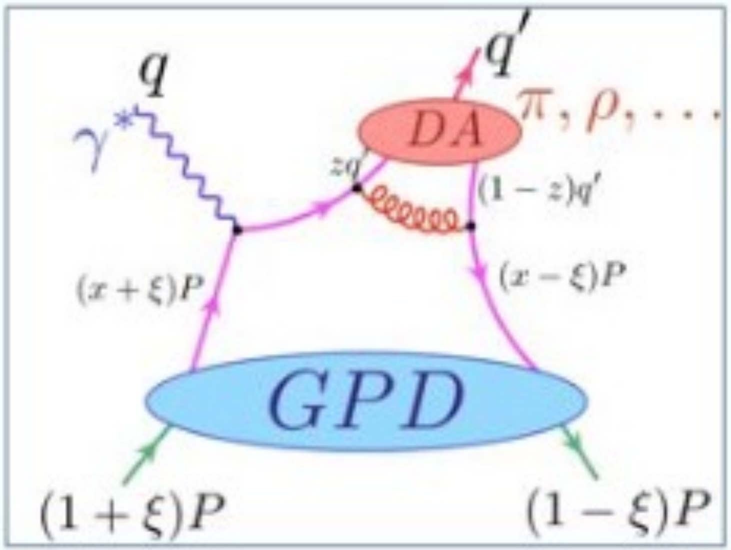
$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x\,y\,Q^2}\frac{y^2}{2\,(1-\varepsilon)}\Bigg\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}$$
$$+ \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\ph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



- **At large x fixed target experiments are sensitive to all Structure Functions**
- **For EIC, observables surviving the $\varepsilon\to1$ limit (F_{UU}, F_{UL}, Transversely pol. F_{UT})**

H.Avakian/A. Bacchetta

DVMP: L/T Separated π Cross Sections



- Validate the understanding of the hard-exclusive reaction towards 3D imaging. **The key to this validation is precision longitudinal-transverse (L/T) separated data.**
- **The handbag factorization, tells us that for asymptotically large Q^2 longitudinally polarized photons dominate**
- According to the handbag approach, the amplitudes for transverse photons are suppressed
  - σ_L scales to leading order as Q^{-6}
  - σ_T does not, expectation of Q^{-8}
  - As Q^2 becomes large: $\sigma_L >> \sigma_T$

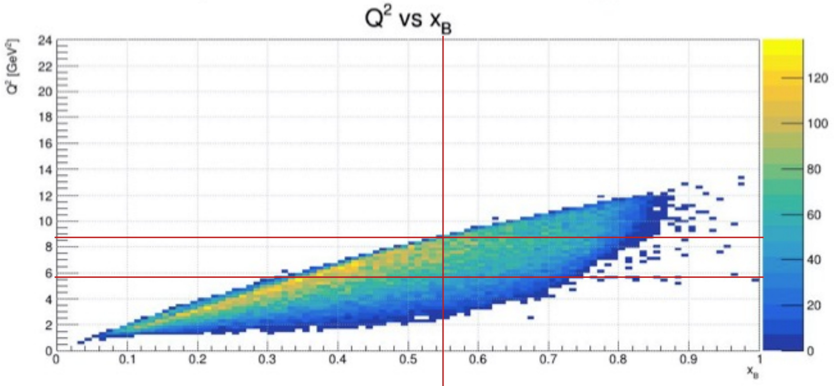
- High precision L/T separated data were taken at 6 GeV in Hall C provided clear evidence for strong contributions from transversely polarized virtual photons.

Experimental validation of onset of hard scattering regime is essential for reliable interpretation of JLab GPD program results

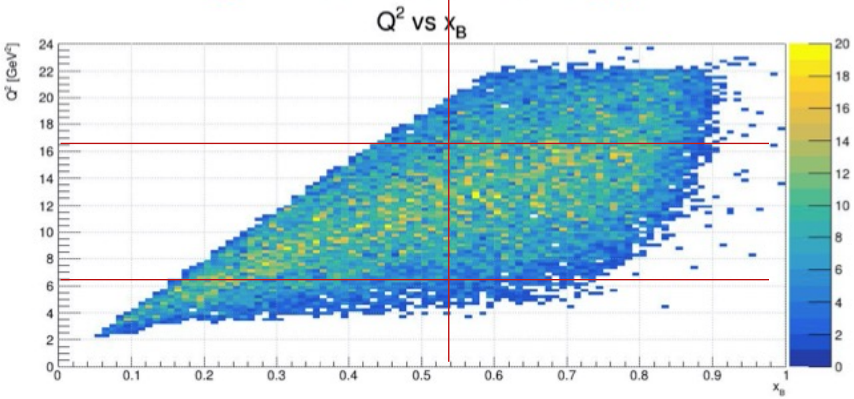
DEMP

Hall B – CLAS12

@ 10.6 GeV beam energy

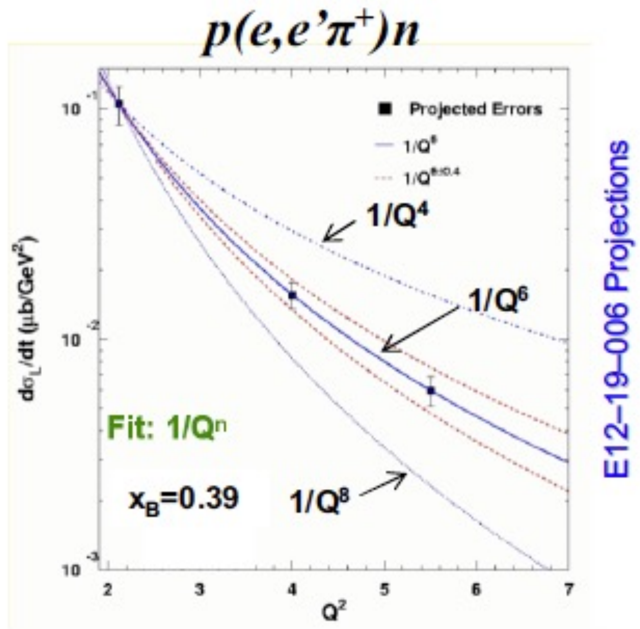


@ 22 GeV beam energy



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

Hall C – HMS-SHMS

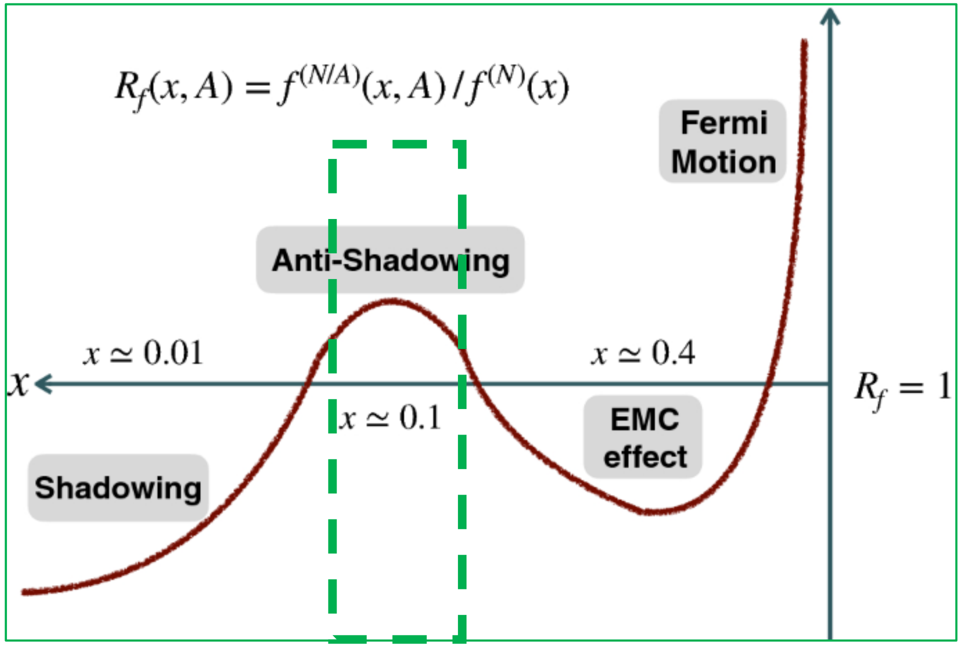


x	Q^2 (GeV²)	W (GeV)	$-t_{min}$ (GeV²)
0.31	1.45–3.65	2.02–3.07	0.12
	1.45–6.5	2.02–3.89	
0.39	2.12–6.0	2.05–3.19	0.21
	2.12–8.2	2.05–3.67	
0.55	3.85–8.5	2.02–2.79	0.55
	3.85–11.5	2.02–3.23	

G. Huber
A. Kim

Anti-Shadowing

JLab at ~22 GeV is an anti-shadowing regime machine !



~22 GeV

- 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

What is needed

- High precision → high luminosity
- e-A (x, Q^2) range accessible
- Ability to change targets quickly,…
- Pol./unpol. mapping across A, N, Z,
- Nuclear tagging → links between nuclear dynamic & quark structure

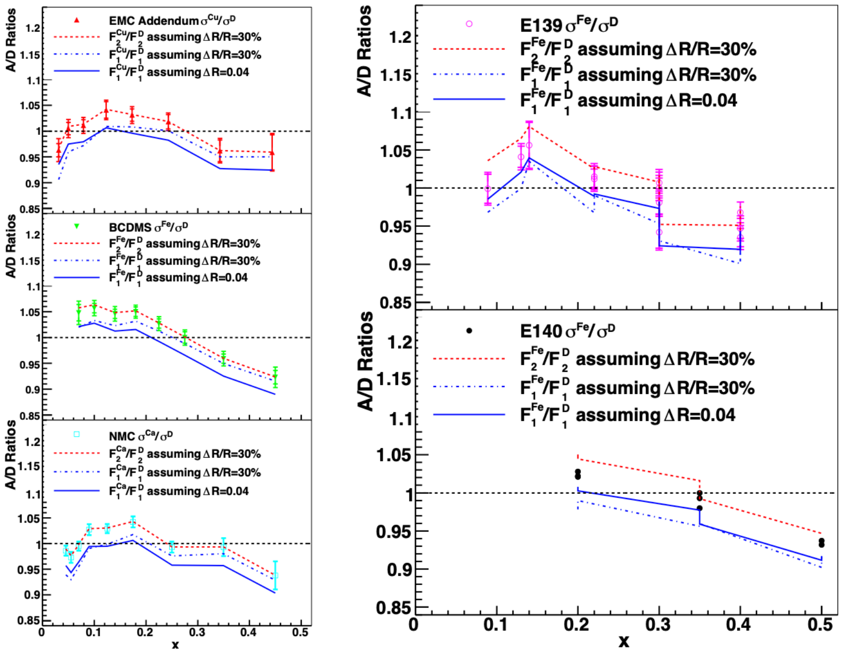
ALL Possible @ Jlab 22 GeV

Nuclear Dependence of R

- Anti-shadowing small effect (~few %) →`normalization uncertainties crucial
- Anti-shadowing data/measurements from unseparated cross sections

↳
  - **Lack of true Rosenbluth precision measurements of $R_A - R_D$**
  - **Determination of the nuclear dependence of the individual structure functions is necessary for a complete understanding of the enhancement in the anti-shadowing region of the cross-section ratio**

Hall C !



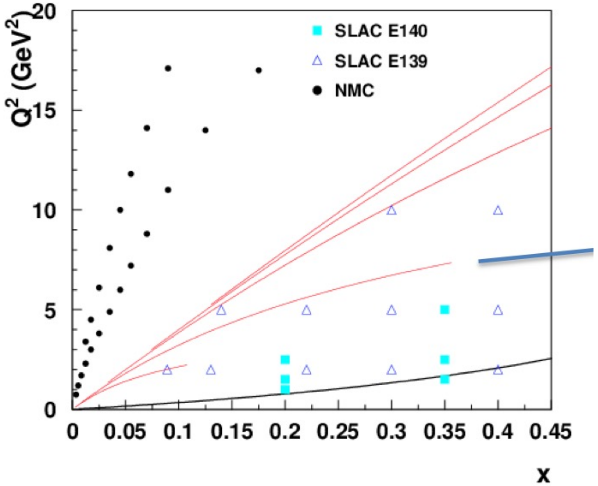
Impact of the nontrivial nuclear dependence of R on the structure function ratios around the anti-shadowing region

E12-14-002 (JLab @11 GeV)

- high-precision Rosenbluth separations to extract the ratio $R = \sigma_L / \sigma_T$, $R_d - R_p$, $R_A - R_D$, and F_1, F_L, F_2 structure functions in a model-independent fashion.
- Limitations:
  - Modest Q^2 range at low x
  - Few targets (C, Cu, Au)

R_A-R_D @ JLab24

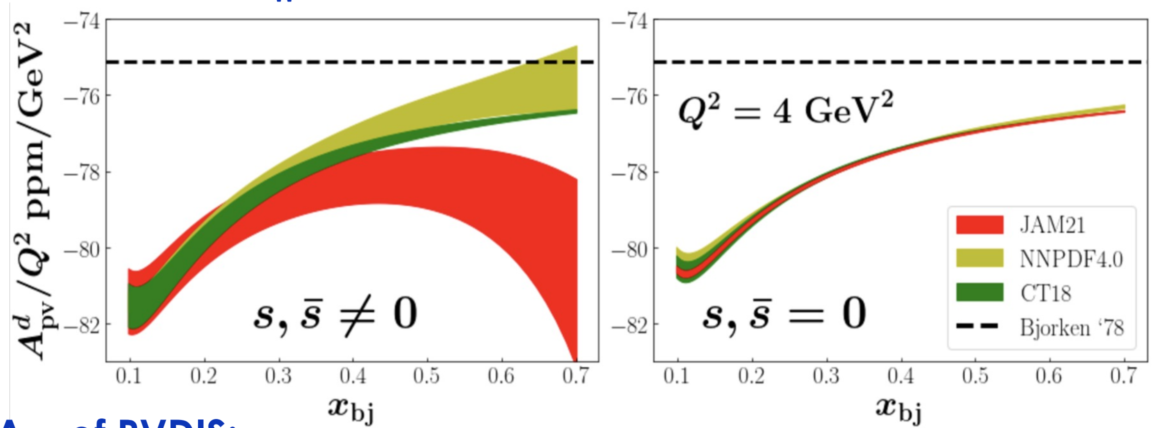
- Feasibility studies on-going



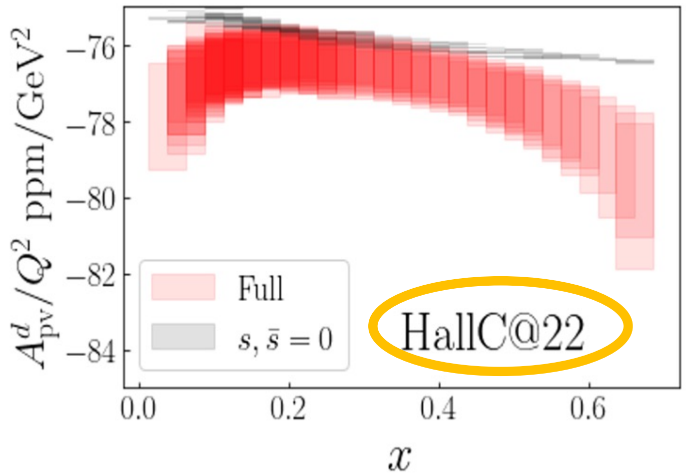
Impact on Strange Quark Puzzle

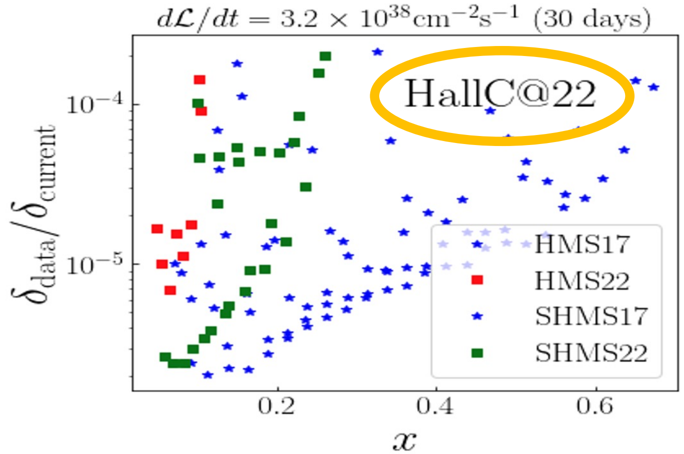
- Parity-violating DIS allows for a large contribution of the strange. $F_2^{\gamma Z,p}$ is 5 times more sensitive to the strange

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



- Impact on A_{PV} of PVDIS:



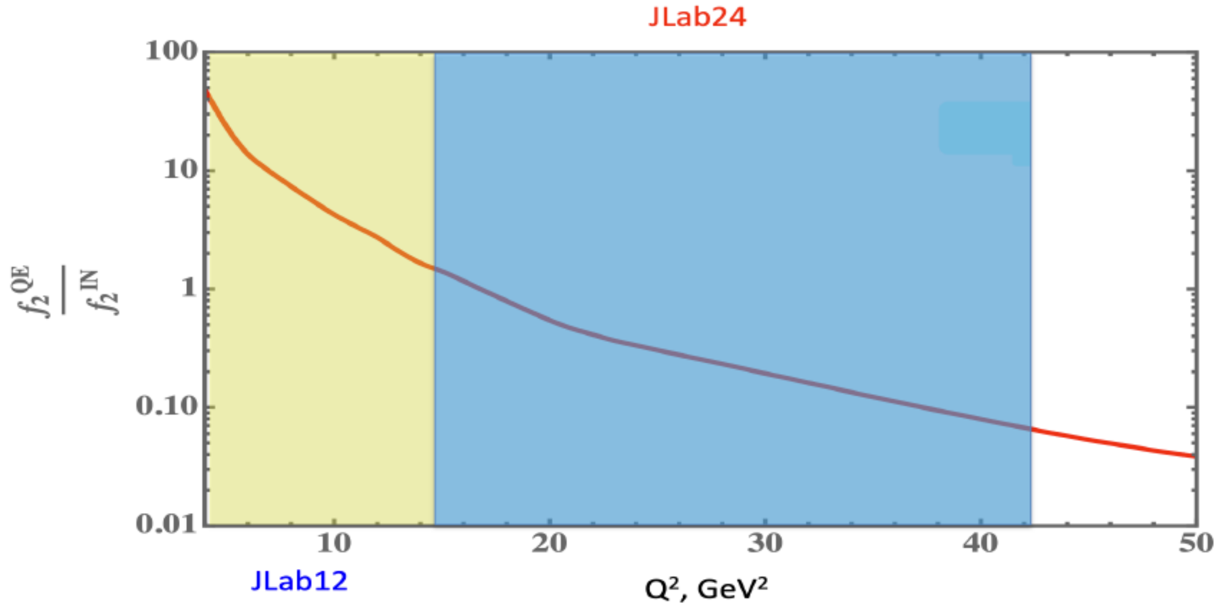


- Projections with SoLID@22 GeV have significant impact as well

Jefferson Lab

Nuclear Forces at Extreme Dynamics

- **Investigation of Nuclear Repulsive Core (< 0.5 fm)**
  - Crucial for understanding the dynamics of transition between hadronic to quark-gluon phases of matter
    - at high temperatures relevant to the evolution of the universe
    - at low (near zero) temperatures and high densities relevant to the dynamics of superdense matter at the cores of neutron stars



- **Probing super-fast quarks in nuclei**
  - ❖ **DIS from nuclear targets at x > 1**
  - ❖ **Q^2 above 30 GeV^2**

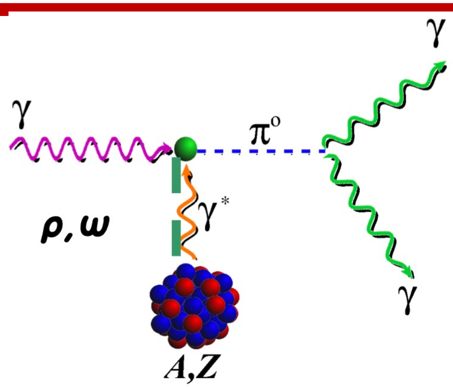
The energy upgrade will allow to measure for the first time the super-fast quark distribution in the deuteron

M. Sargisian

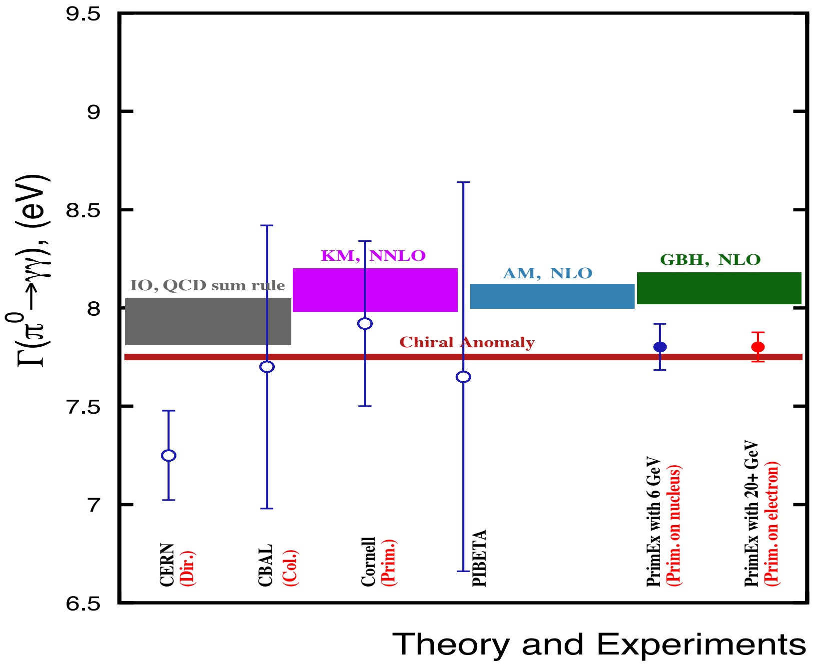
Jefferson Lab

π^0 Primakoff production off an electron target

- **process of high-energy photo- or electro-production of mesons in the Coulomb field of a target**



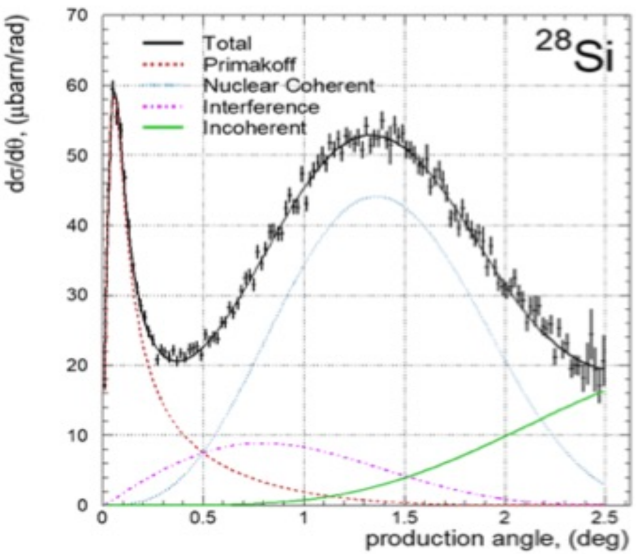
- **π^0 radiative decay width**: can be predicted at ≈ 1% precision in the low energy QCD



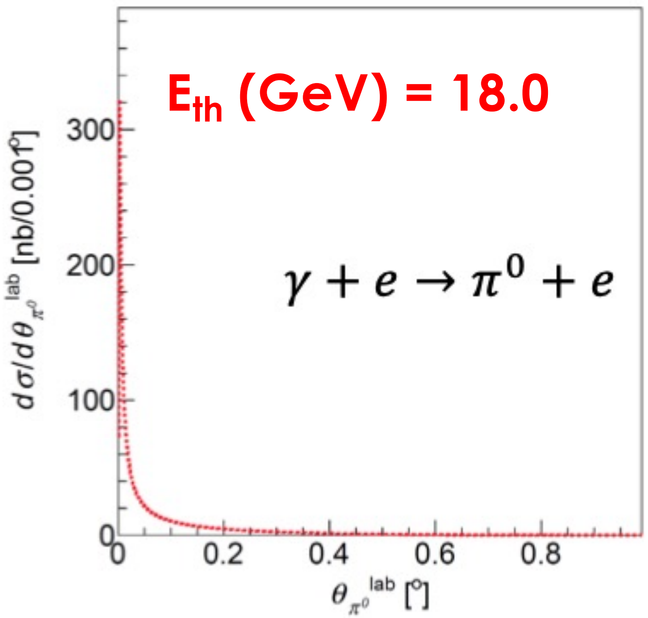
L. Gan

π^0 Primakoff off an e- target: eliminate nuclear bkg

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



Science 368, 506-509 (2020)



b

Conclusions

- **CEBAF 22 GeV upgrade capitalizes on existing investments**
  - Scientific program with existing Hall equipment
  - *Leverage new FFA accelerator technology with resistive magnets*
- **Strong science case for JLab energy upgrade <u>in</u> <u>development</u>**
  - Unique measurements at the luminosity frontier
  - Complementary to EIC
  - Leverages precision capabilities of Jefferson Lab
- **Hall C program at Higher Energy**

  Precision cross sections !!
  - L/T separations → key measurements in SIDIS, DIS, DEMP
  - Precision ratios (π^+/π^-, and more)
  - Excellent π/K/p separation
  - Neutral particle capabilities w/calorimeter (NPS)