JLab's Unique Contributions to Strong QCD: Recent Results and Future Goals

Ralf W. Gothe for the CLAS Collaboration

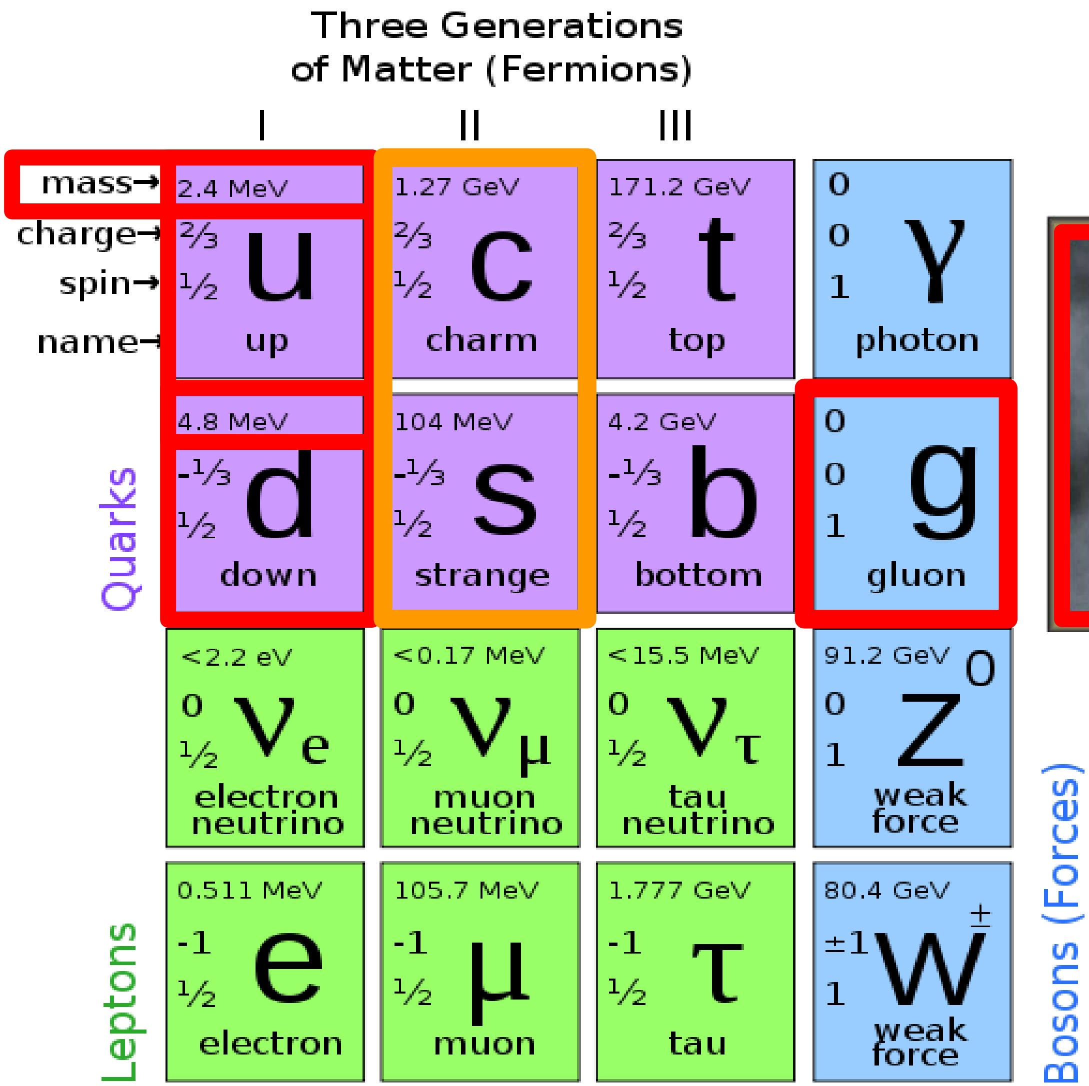
UNIVERSITY OF SOUTH CAROLINA

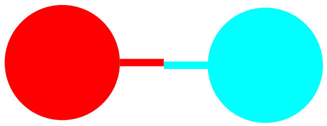
The 2021 School on the Physics of Baryons
October 18-22, 2021, Seville, Spain

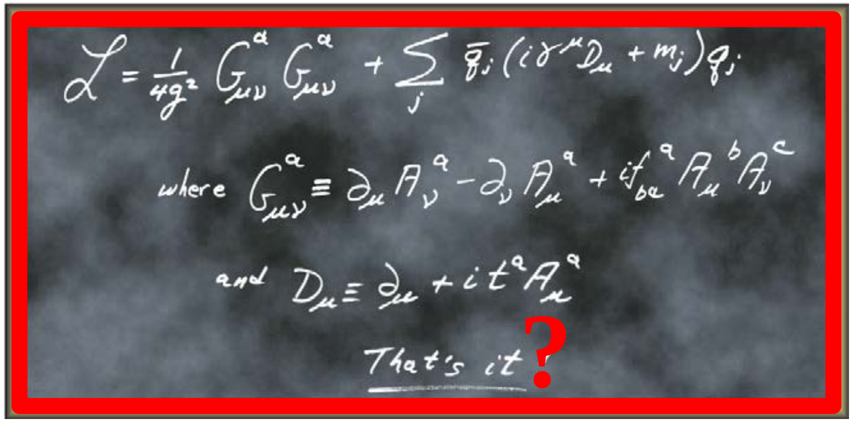
➢ **Are dressed quarks fictious model creatures?** Do we have evidence that they exist?
➢ **Why are quarks in DIS pointlike?** What is the difference between a large-x valence quark and a dressed quark?
➢ **Recent Results and Future Goals** JLab12 … now and then …

This work is supported in parts by the National Science Foundation under Grant PHY 10011349.

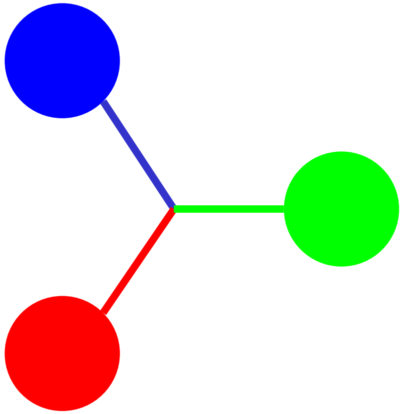
Build your Mesons and Baryons …







Frank Wilczek, Physics Today, August 2000

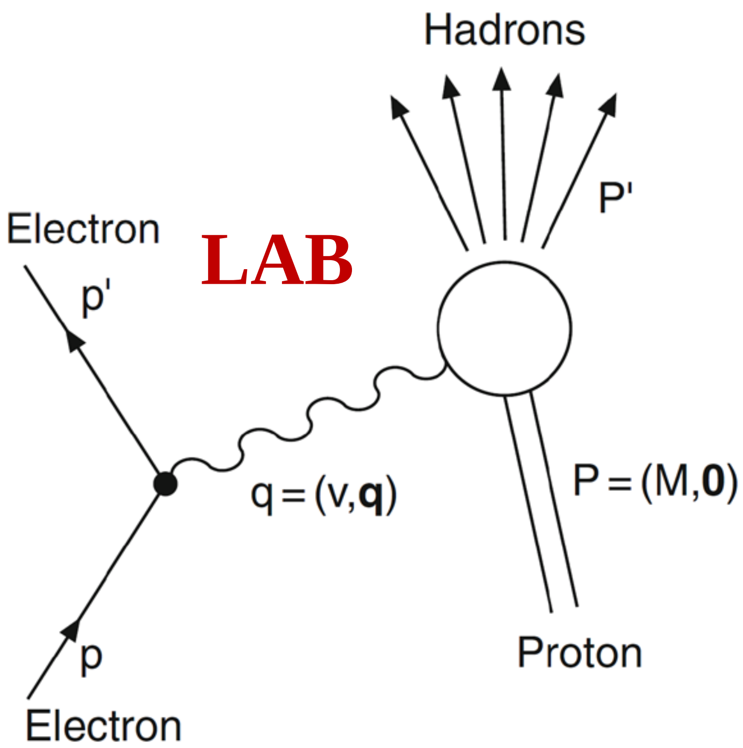


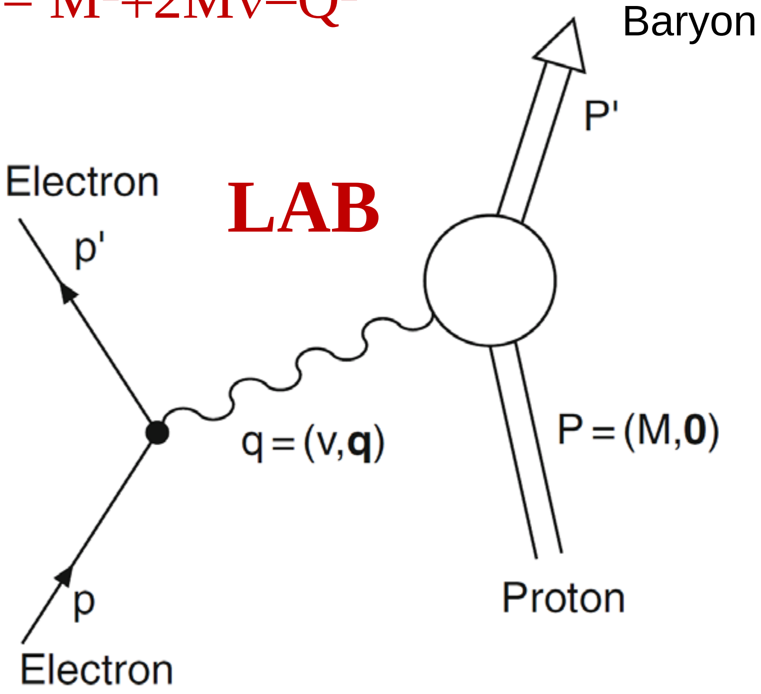
Electron Scattering

Electron Scattering Kinematics

$s = W^2 = P_\mu'^2 = (P_\mu + q_\mu)^2 = P_\mu^2 + 2P_\mu q^\mu + q_\mu^2 = M^2 + 2M\nu - Q^2$

$x \equiv Q^2 / 2P_\mu q^\mu = Q^2 / 2M\nu$





Electron Scattering Kinematics

$s = W^2 = P_\mu'^2 = (P_\mu+q_\mu)^2 = P_\mu^2+2P_\mu q^\mu +q_\mu^2 = M^2+2M\nu-Q^2 = M^2$

$x \equiv Q^2/2P_\mu q^\mu = Q^2/2M\nu$

⇩

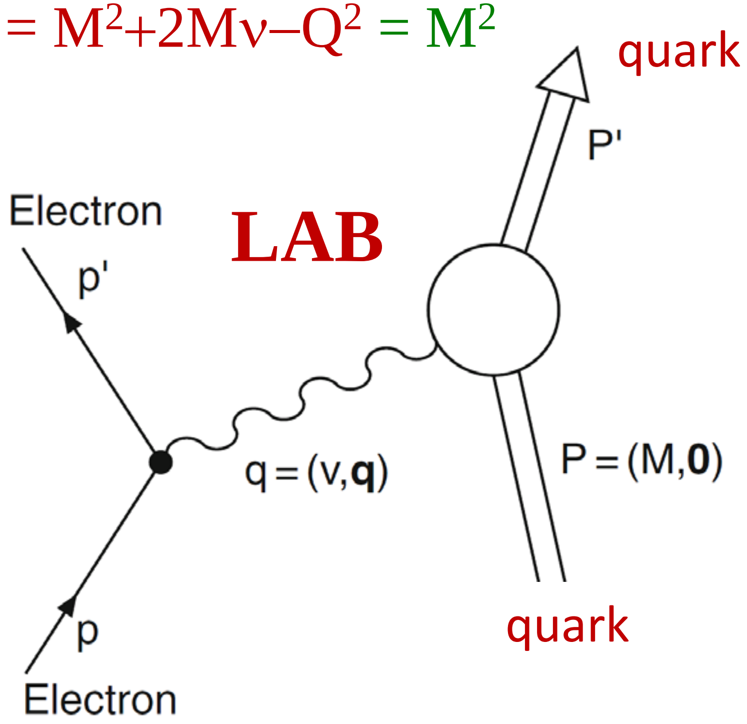
elastic off proton: $x = Q^2/2P_\mu q^\mu = Q^2/2M\nu$ **= 1**

elastic off quark: $x_{qf} = Q^2/2P_\mu q^\mu = Q^2/2m\nu$ **= 1**

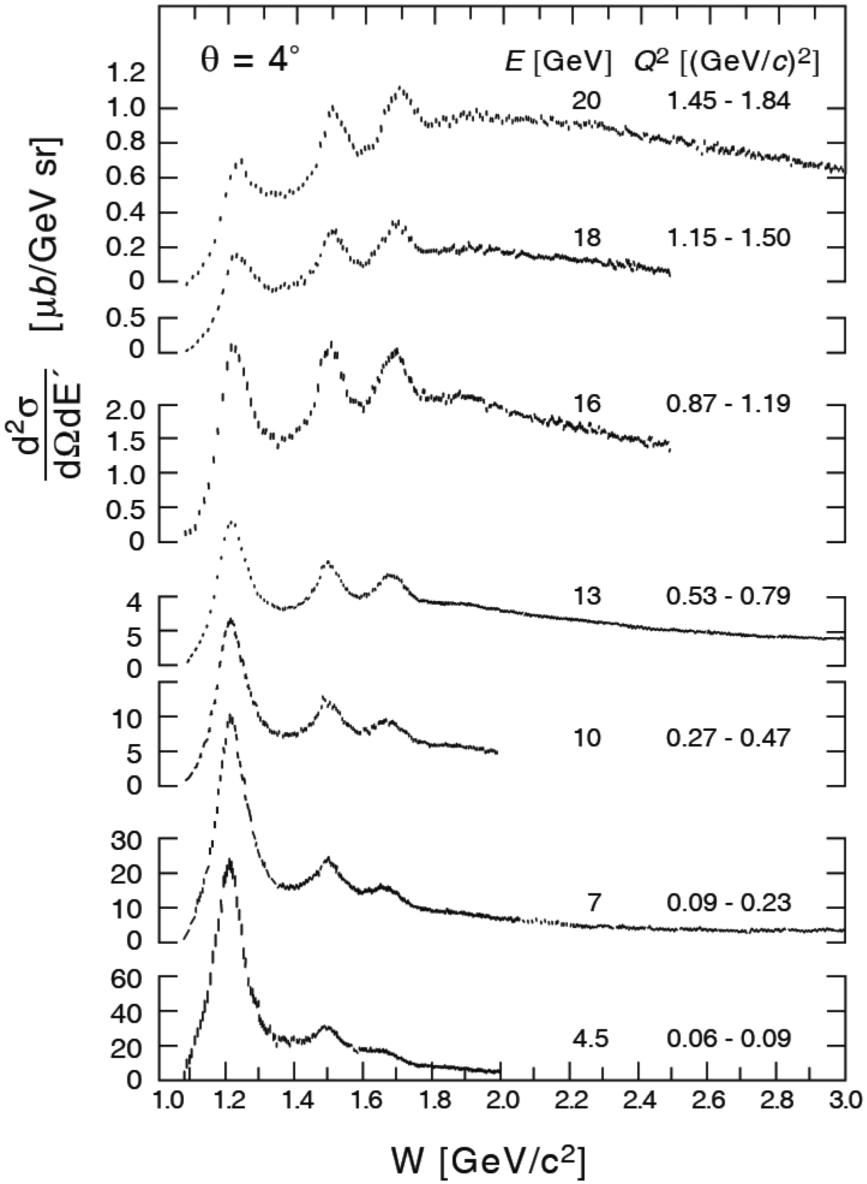
⇩ ⇩

$m = Q^2/2\nu$

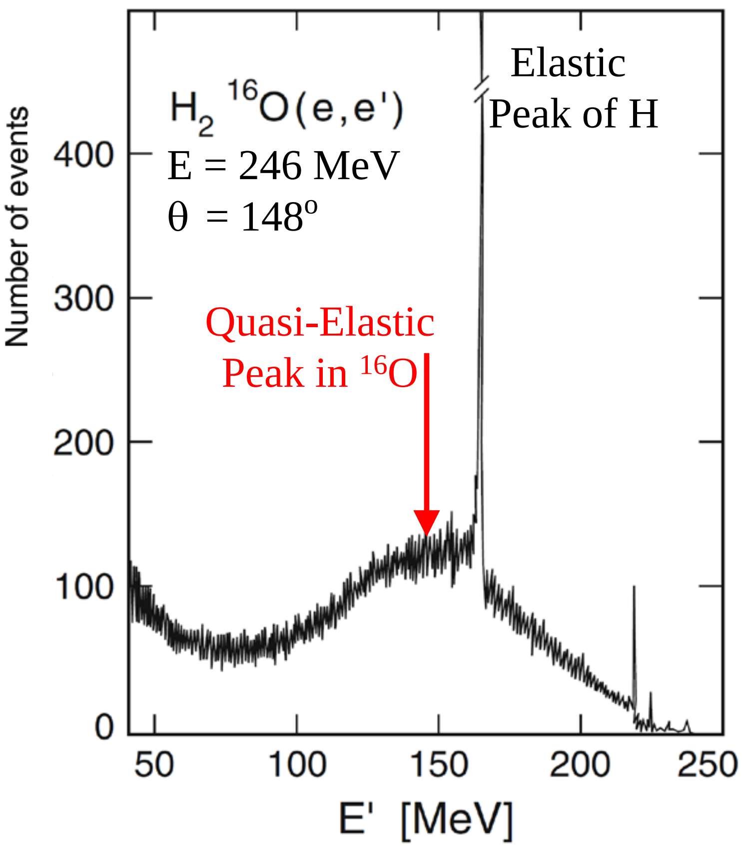
x = m/M



Baryon Excitations and Quasi-Elastic Scattering

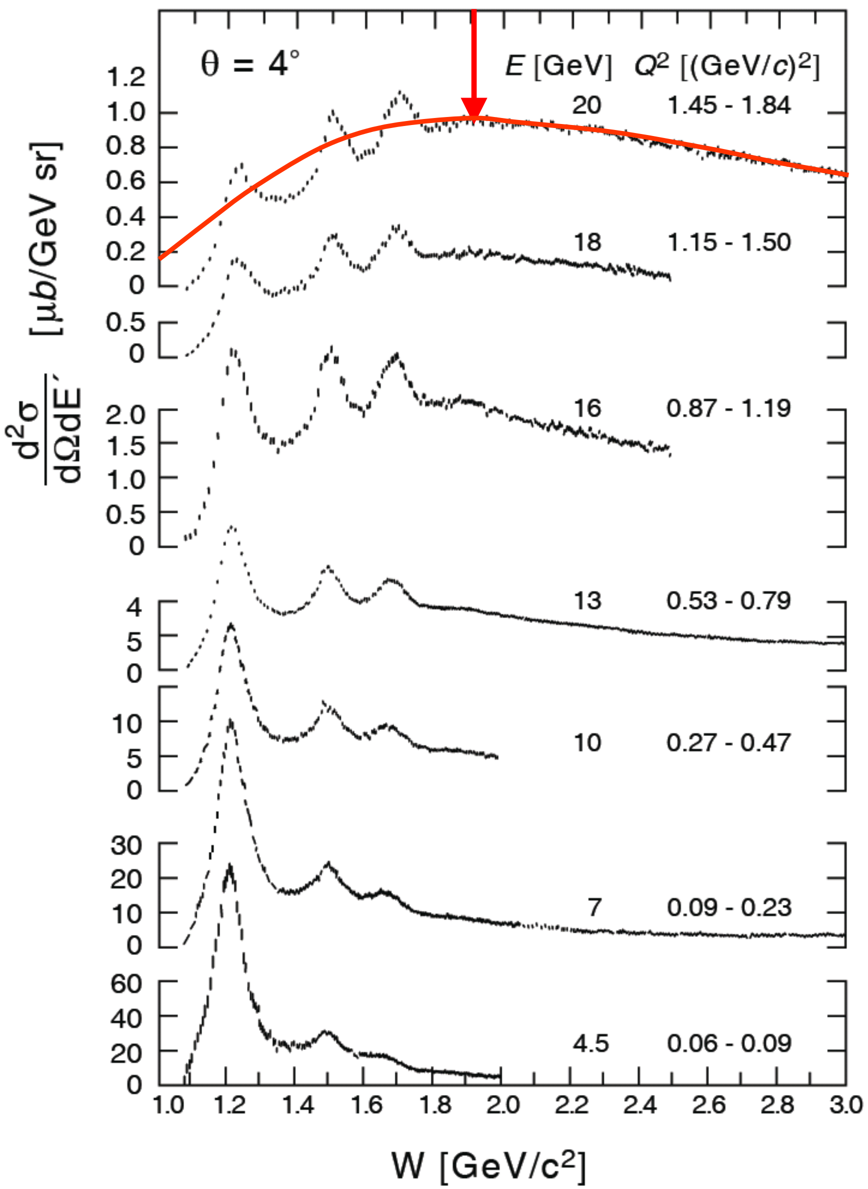


Paticle and Nuclei, Povh et al., MAMI B



Deep Inelastic Scattering
S. Stein et al., PR **D22** (1975) 1884

Baryon Excitations and Quasi-Elastic Scattering



PRL **16** (1970) 1140, PR **D4** (1971) 2901
E.D. Bloom and F.J. Gilman

W = 1.9 GeV

E' = 17.6 GeV

ν = 2.37 GeV

Q^2 = 1.72 GeV

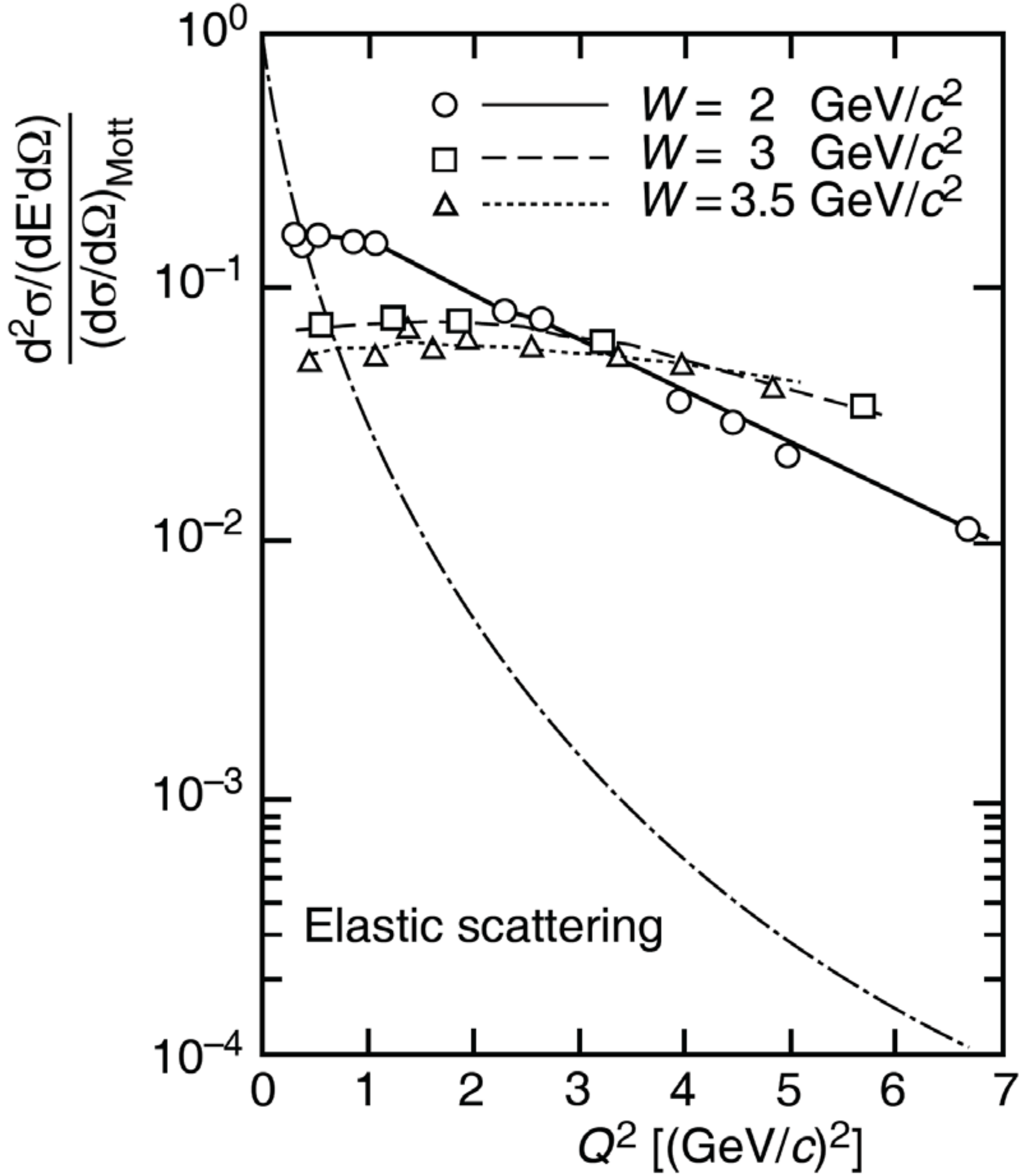
m_q = 0.36 GeV $\qquad m_q = Q^2/2\nu$

p_F = 0.67 GeV

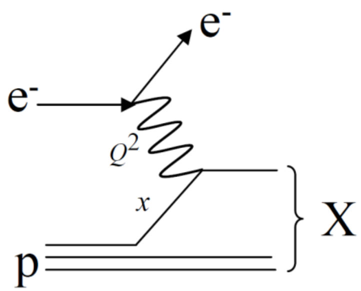
r_F = 0.79 fm $\qquad \Delta r_F = \frac{\hbar c}{\Delta p_F} * \sqrt{9\pi/2}$

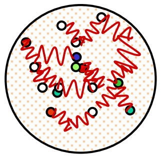
Deep Inelastic Scattering
S. Stein et al., PR **D22** (1975) 1884

Baryon Excitations and Quasi-Elastic Scattering



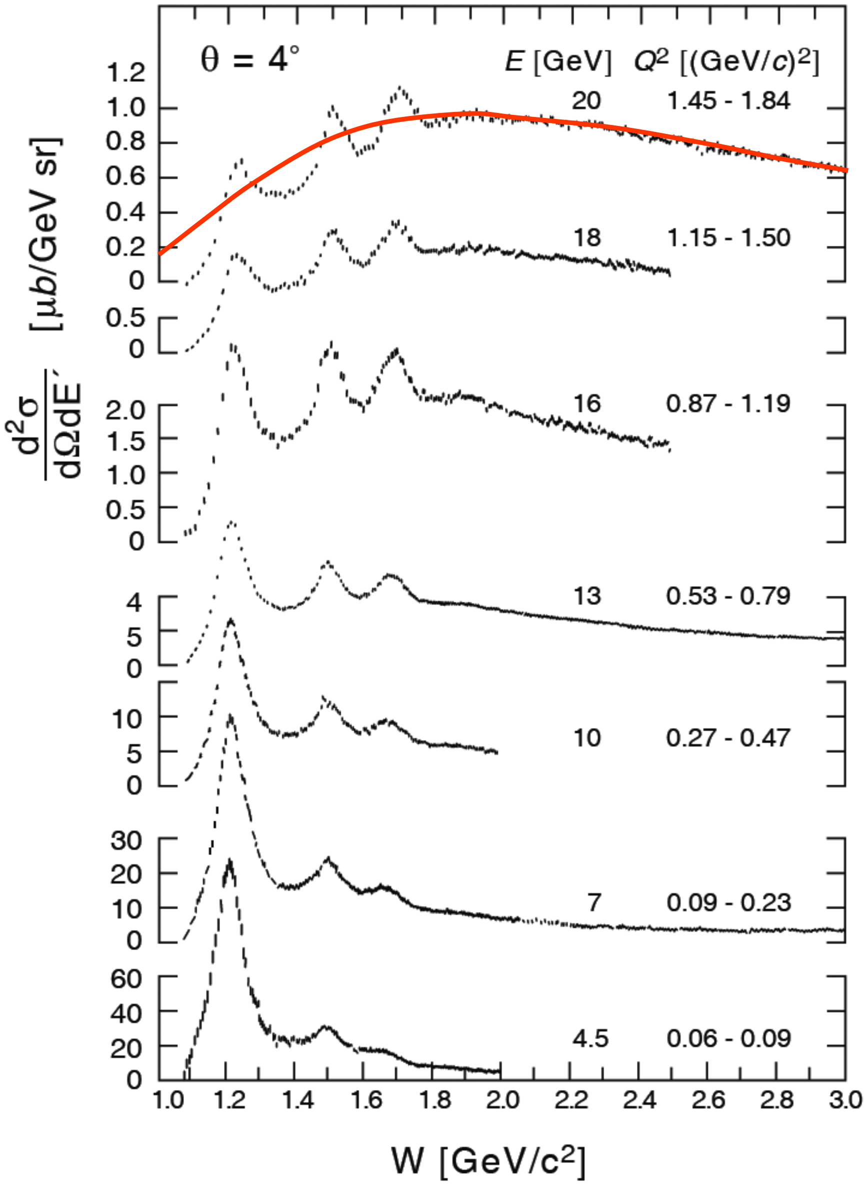
quasi-elastic off
point-like
constituents



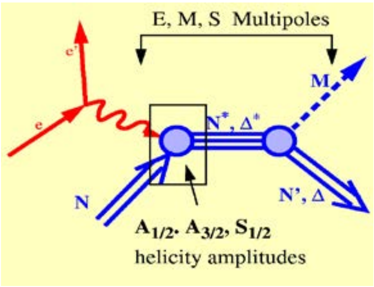


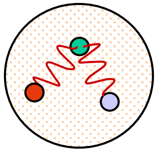
Deep Inelastic Scattering
M. Breidenbach et al.,
Phys. Rev. Lett. **23** (1969) 935

Baryon Excitations and Quasi-Elastic Scattering



hard and confined



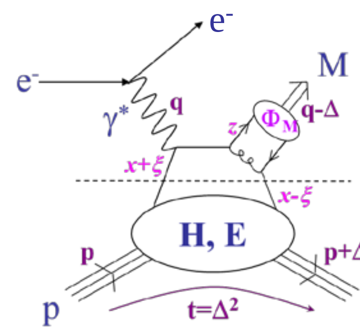


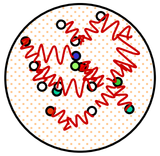
Transition Form Factors

Elastic Form Factors

hard

soft





Deep Inelastic Scattering

S. Stein et al., PR **D22** (1975) 1884

Structure Analysis of the Baryon

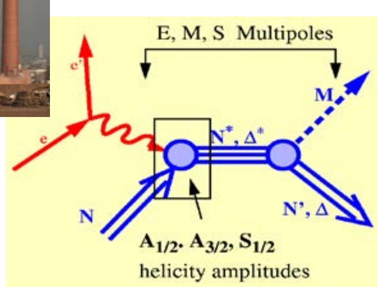
Demolition of a chimney at the "Henninger Brewery" in Frankfurt am Main, Germany, on 2 December 2006

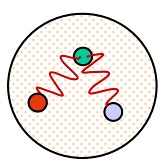
hard and confined

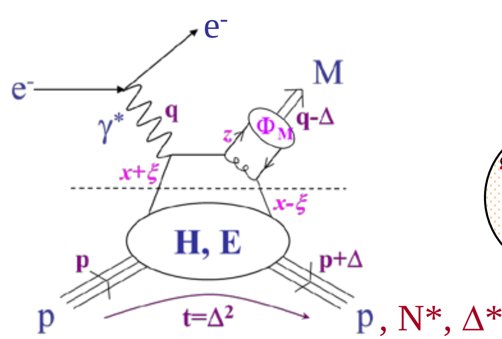
...

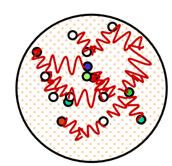
hard and soft

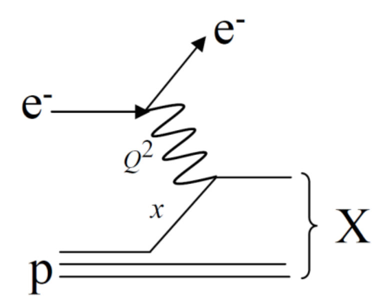
hard and quasi-elastic



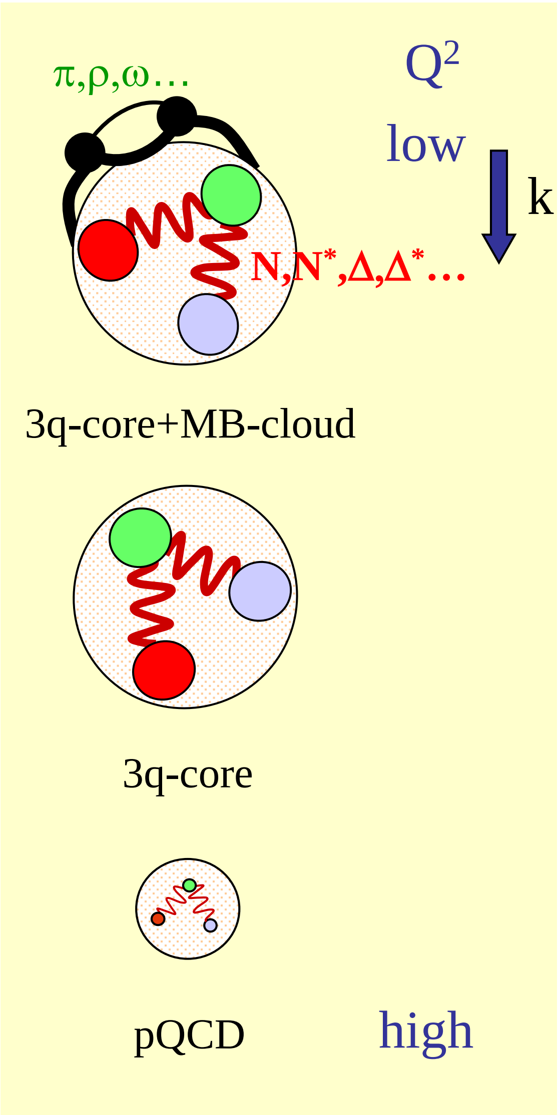






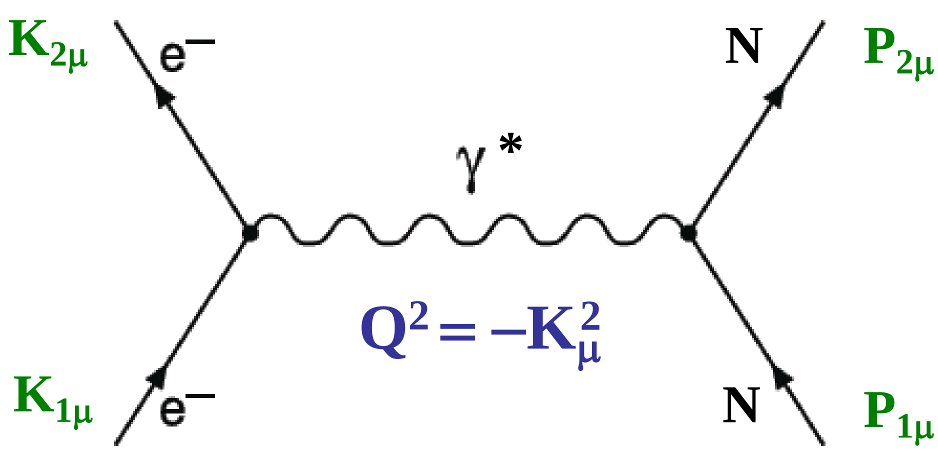


Hadron Structure with Electromagnetic Probes

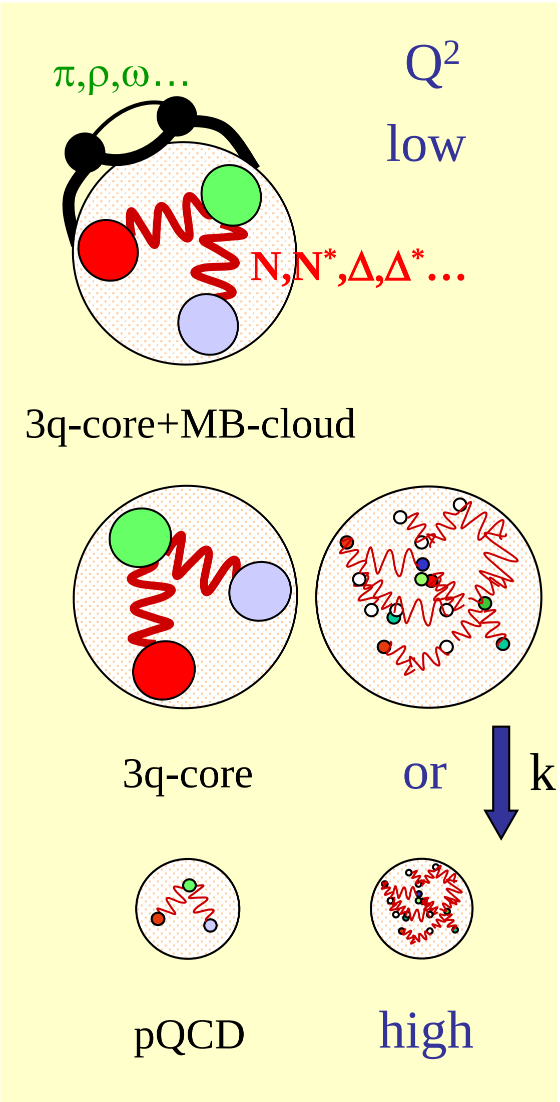


- Study the structure of the nucleon spectrum in the domain where dressed quarks are the major active degree of freedom.
- Explore the formation of excited nucleon states in interactions of dressed quarks and their emergence from QCD.

hard and combined

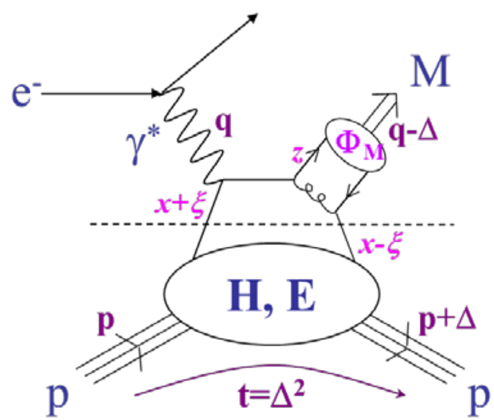


Hadron Structure with Electromagnetic Probes

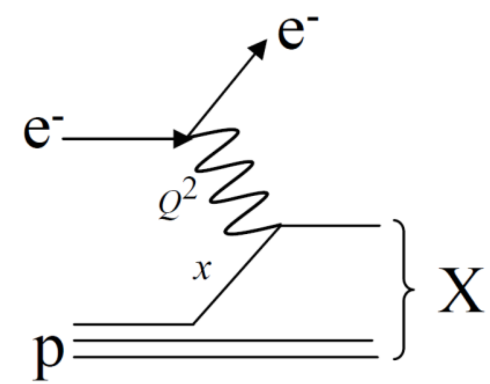


- Study the structure of the nucleon ground states in the domain of strong QCD.
- Explore the formation of the nucleon ground states and their emergence from QCD.

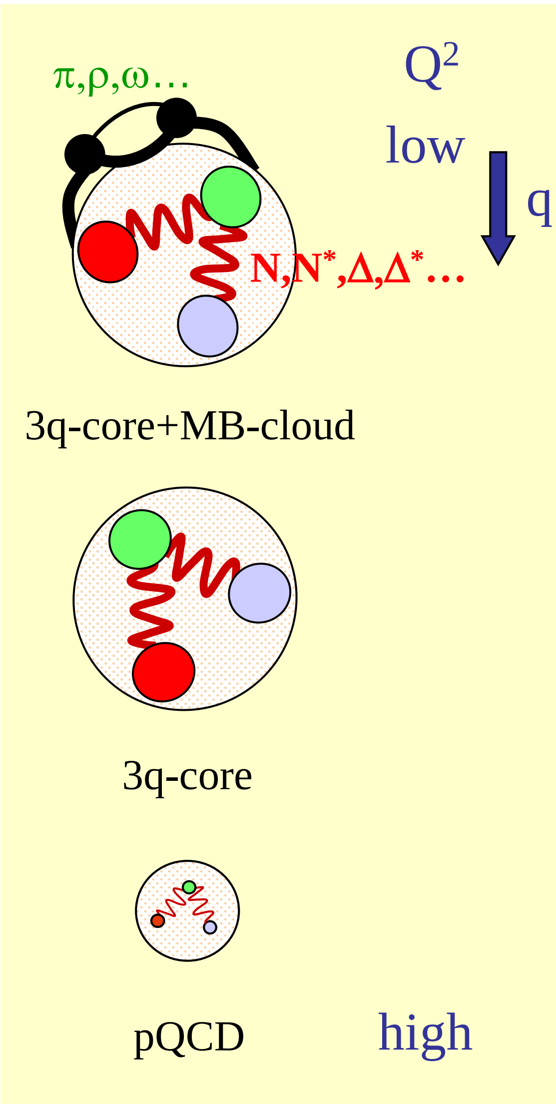
hard and quasi-free



or

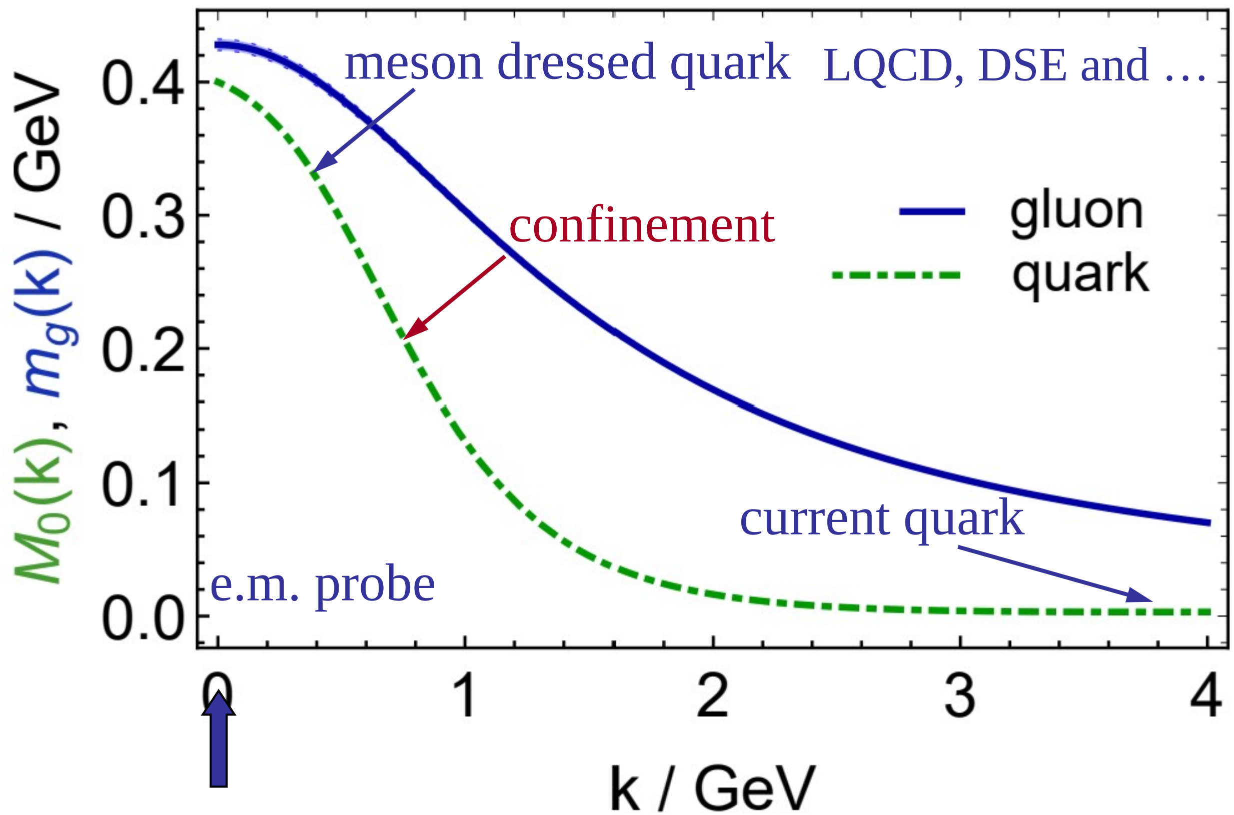


Hadron Structure with Electromagnetic Probes

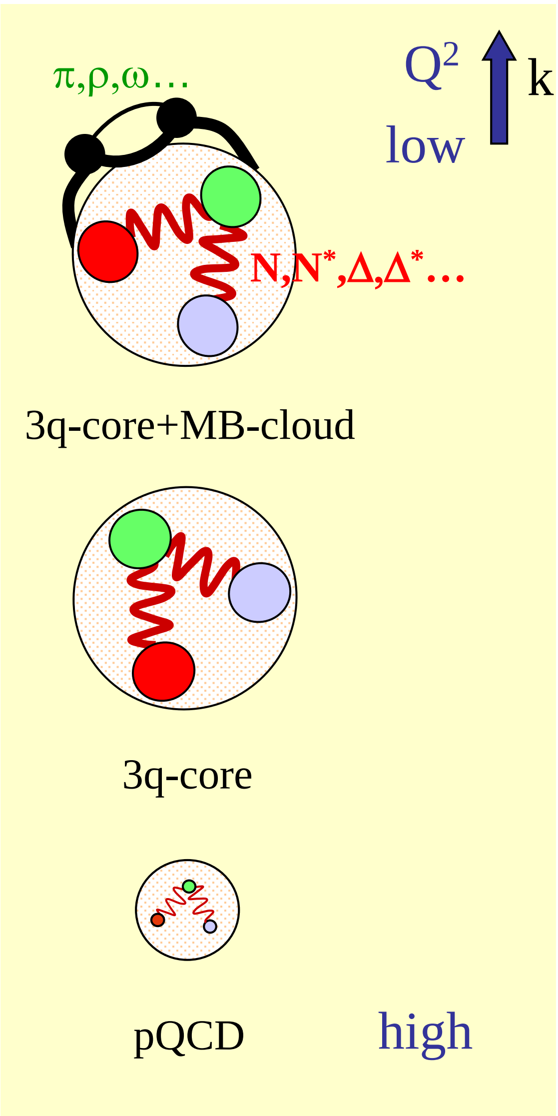


- Study the structure of the nucleon spectrum in the domain where dressed quarks are the major active degree of freedom.

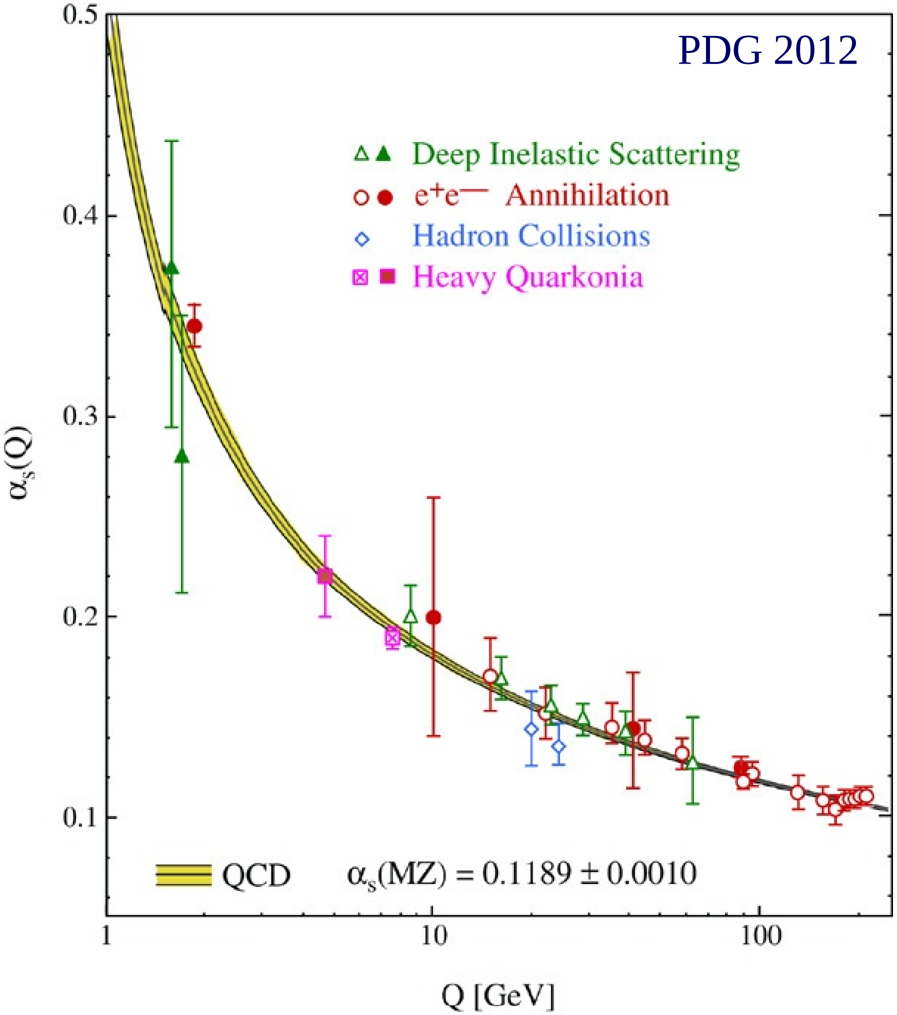
Zhu-Fang Cui et al., Chin. Phys. C **44** (2020) 083102/1-10



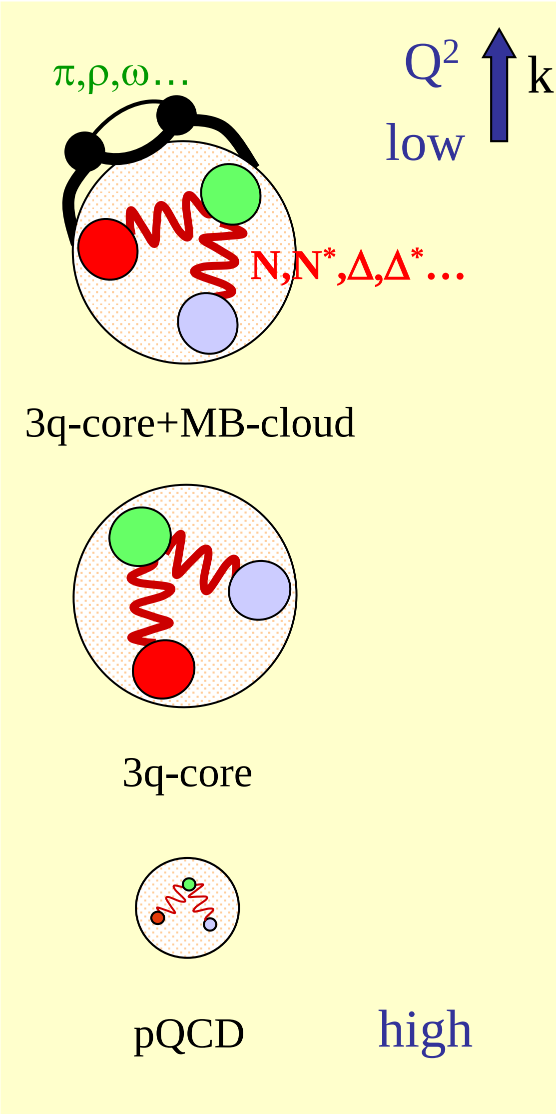
Hadron Structure with Electromagnetic Probes



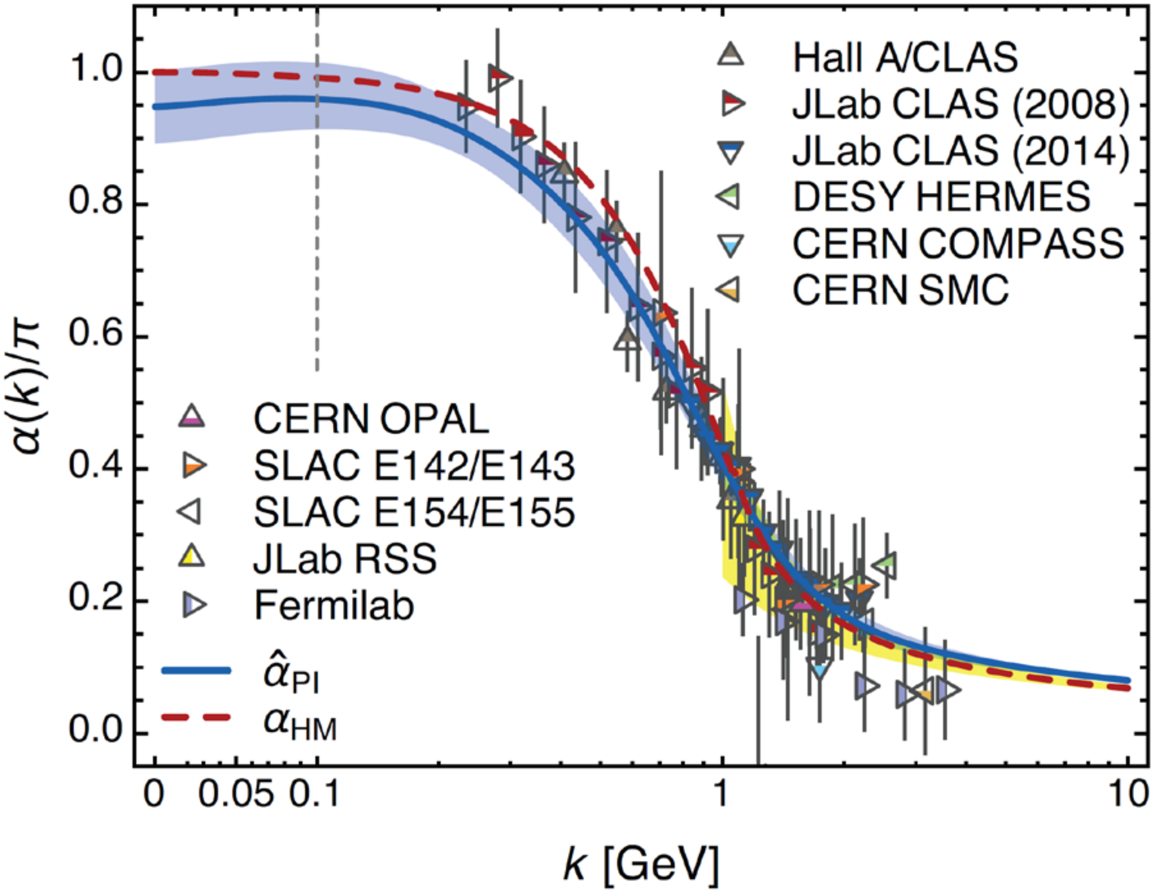
- The SM α_s diverges as Q^2 approaches zero, but confinement and the meson cloud heal this artificial divergence as QCD becomes non-perturbative.



Hadron Structure with Electromagnetic Probes



- Modern continuum QCD & lattice QCD methods enable a process-independent calculation of the running coupling constant.

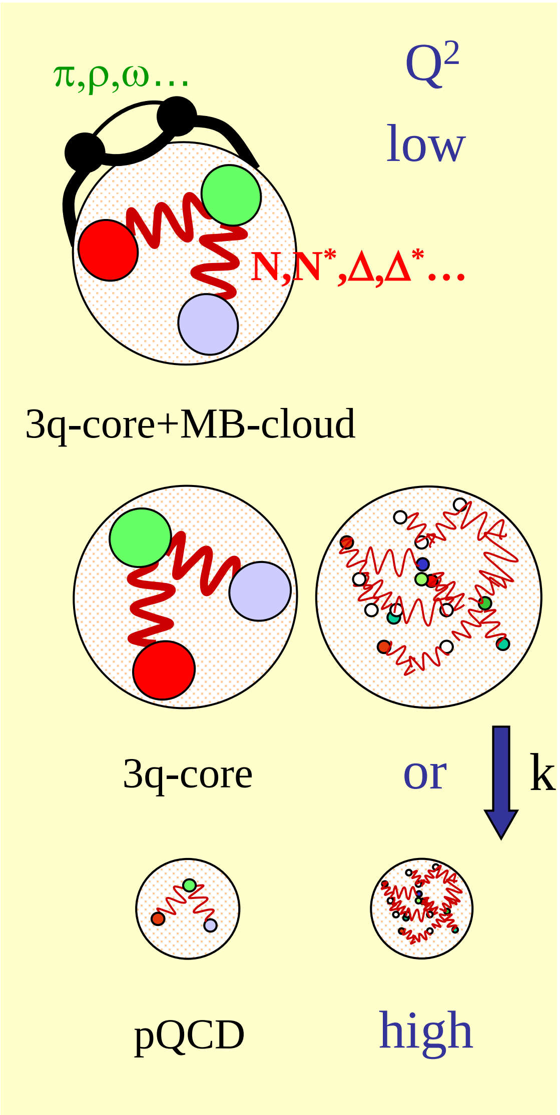


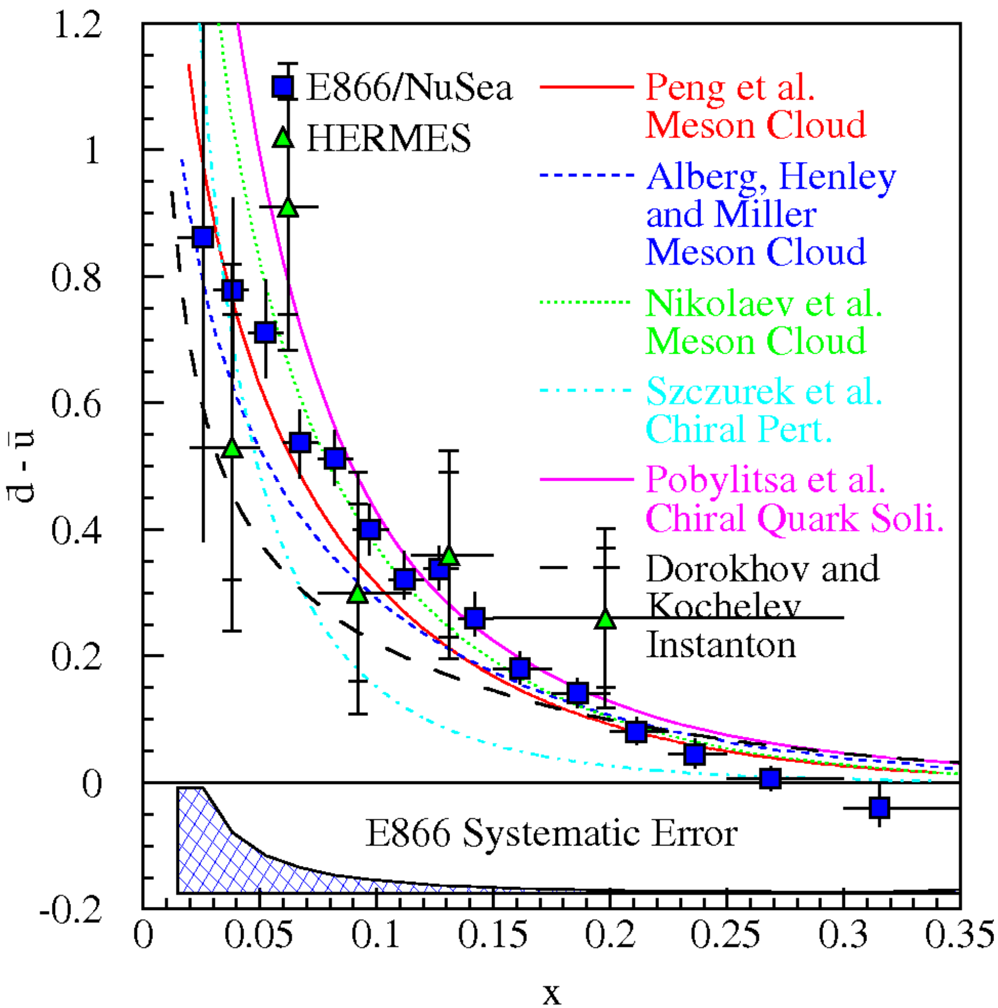
Daniele Binosi et al., Phys. Rev. D 96 (2017) 054026/1-7

Hadron Structure with Electromagnetic Probes

Rolf Ent

- The pion, or a meson cloud, explains light-quark asymmetry of the sea quarks in the nucleon.

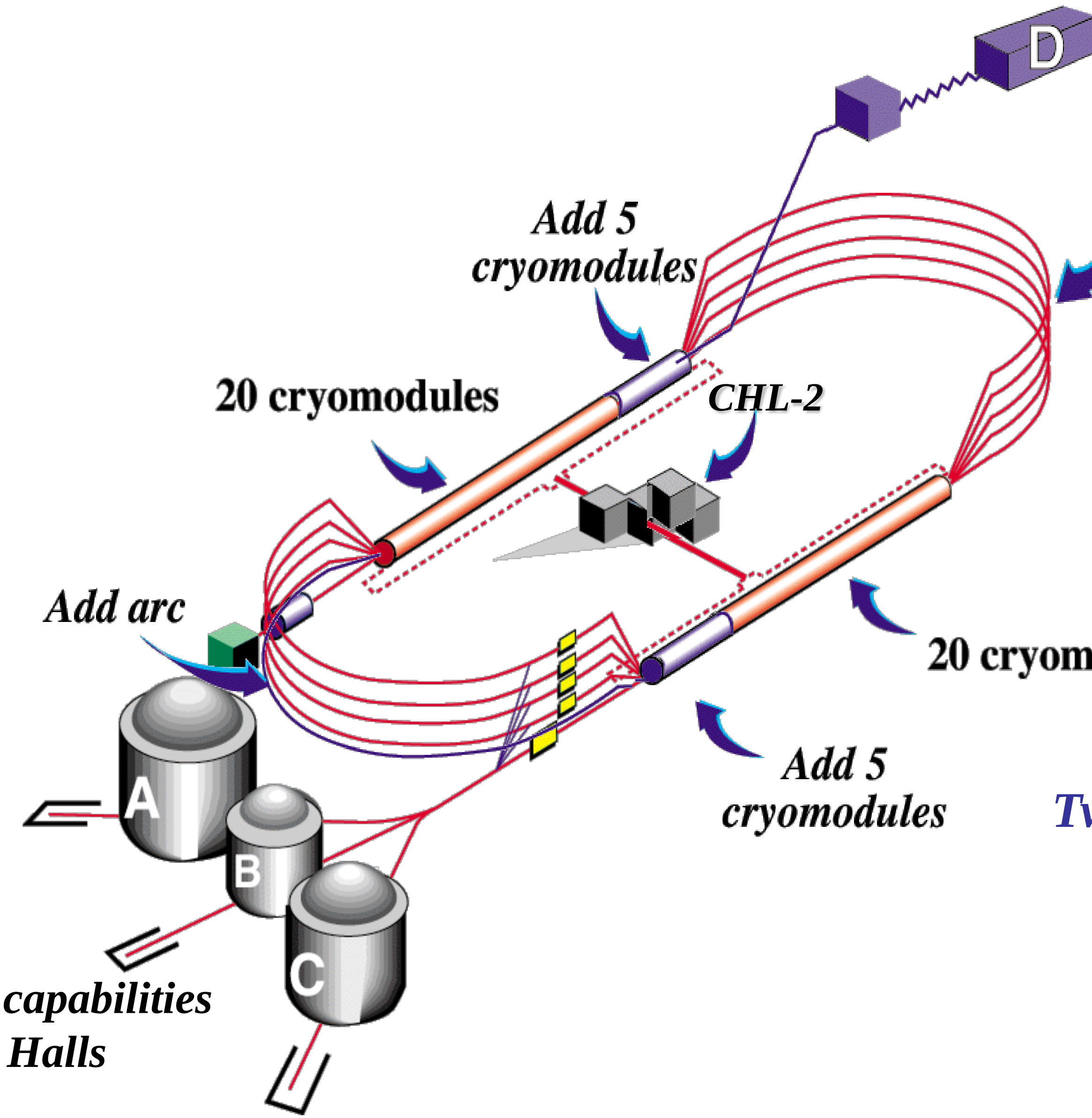




JLab12

… now and then …

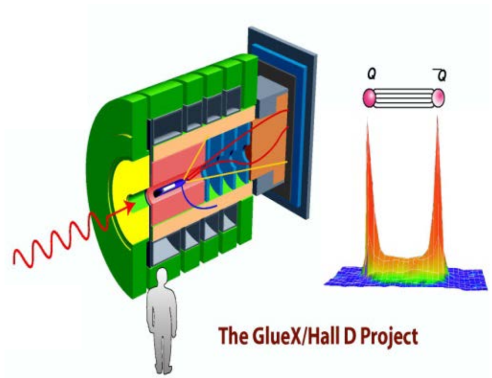
12 GeV CEBAF … now

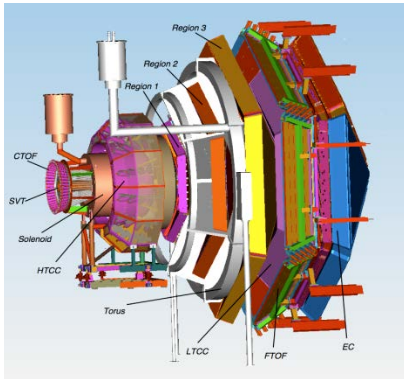


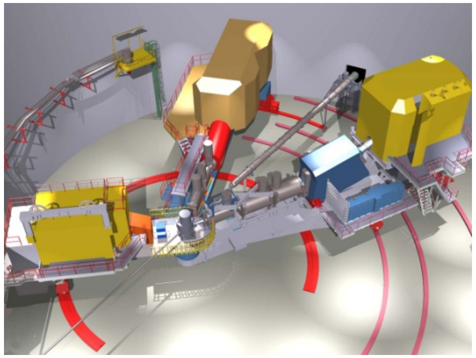
Two 1.1 GeV linacs

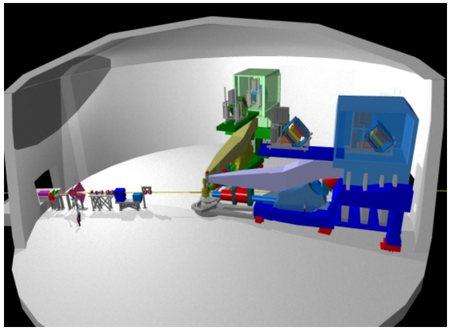
Enhanced capabilities in existing Halls

Overview of Upgraded Technical Hall Performances









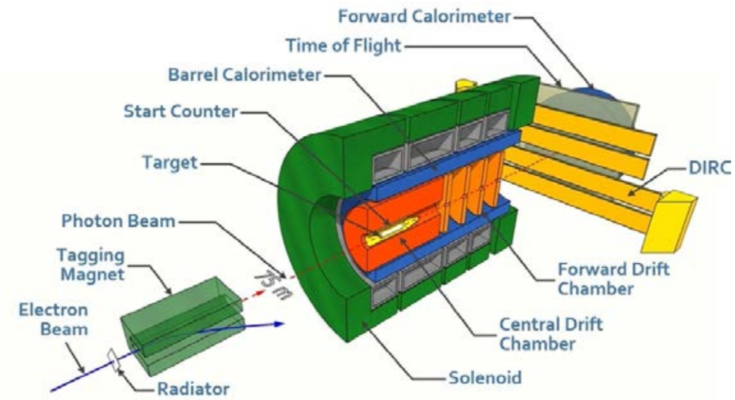
<table>
<tr><th>Hall D</th><th>Hall B</th><th>Hall C</th><th>Hall A</th></tr>
<tr><td>4π hermetic detector GlueEx</td><td>luminosity 10^{35} CLAS12</td><td>High Momentum Spectrometer SHRS</td><td>High Resolution Spectrometer HRS</td></tr>
<tr><td>polarized photons</td><td>hermeticity</td><td>precision</td><td>space</td></tr>
<tr><td>$E_\gamma \sim 8.5$-9.0 GeV</td><td colspan="3">11 GeV beamline</td></tr>
<tr><td>10^8 photons/s</td><td colspan="3">target flexibility</td></tr>
<tr><td colspan="2">good momentum/angle resolution</td><td colspan="2">excellent momentum resolution</td></tr>
<tr><td colspan="2">high multiplicity reconstruction</td><td colspan="2">luminosity up to 10^{38}</td></tr>
</table>

Hall D … now

Eugene Chudakov

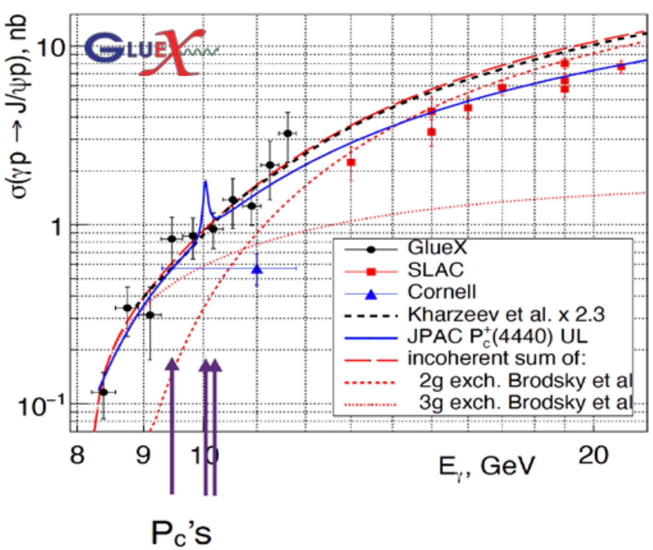
JLAB Hall D

- Tagged photon Bremsstahlung beam, linearly polarized at ≈9 GeV
- A hermetic spectrometer based on a solenoid magnet
- Running: experiment **GlueX** – search for hybrid mesons
  - **GlueX-I** data taking in 2016-2019 complete
  - Inclusive trigger: a very large statistics of photoproduction



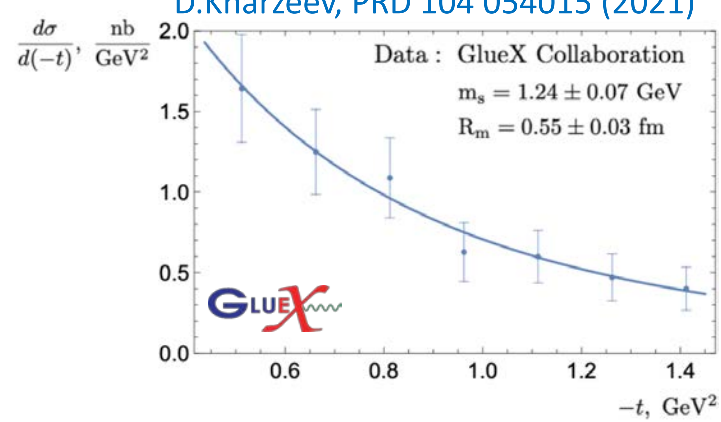
Early results from GlueX

γp → p J/ψ Cross section at threshold: *PRL 123, 072001 (2019)* about 25% of the GlueX-I statistics
100 citations



- No evidence for the LHCB pentaquarks in **γ p → Pc → J/ψ p :** Br(Pc→J/ψp) < few %
- Production mechanism at threshold may probe QCD objects, as the gravitational form factor (*Kharzeev and others*)

D.Kharzeev, PRD 104 054015 (2021)



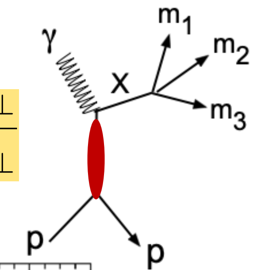
mass radius: R_m = 0.55 +/- 0.03 fm
charge radius: R_c = 0.8409 +/- 0.0004 fm

Hall D … now

Eugene Chudakov

JLAB Hall D   Early results from GlueX (continued)

Meson Production

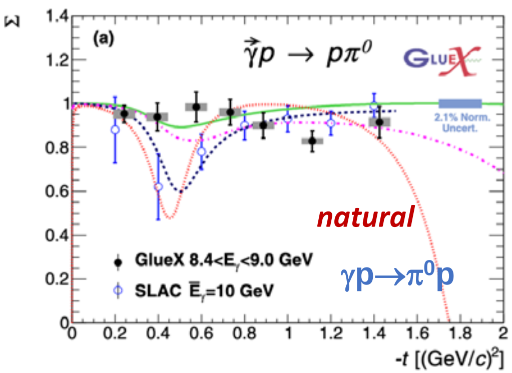


Meson Spectroscopy: Data Analysis Path

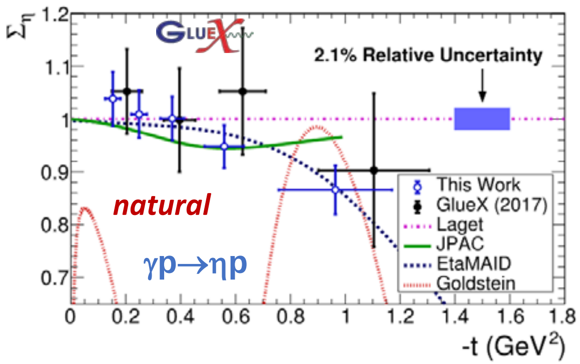
- Understand production mechanisms: Natural $J^P=0^+, 1^-, 2^+$, …and unnatural $J^P=0^-, 1^+, 2^-$ exchanges: measure the beam asymmetry Σ using linearly polarized beam

$$\Sigma = \frac{\sigma_{\parallel} - \sigma_{\perp}}{\sigma_{\parallel} + \sigma_{\perp}}$$

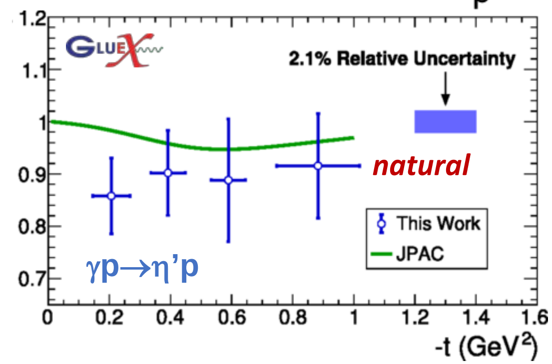
PRC 95, 042201 (2017)



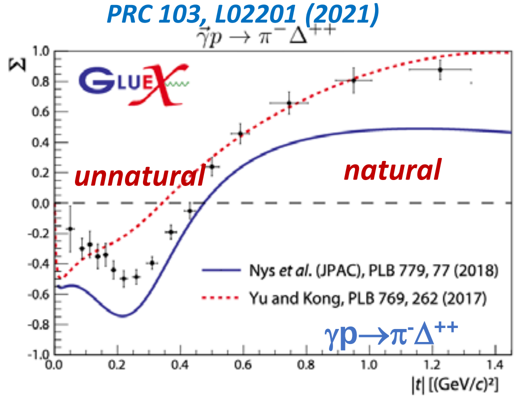
PRC 100, 052201 (2019)



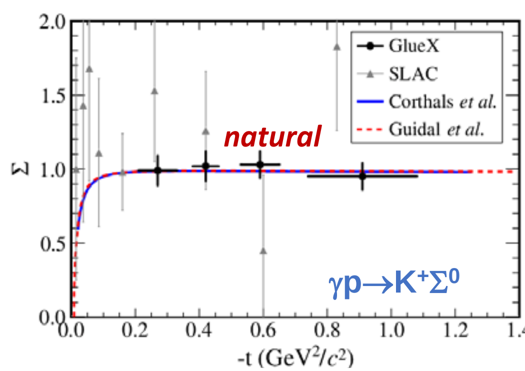
PRC 100, 052201 (2019)



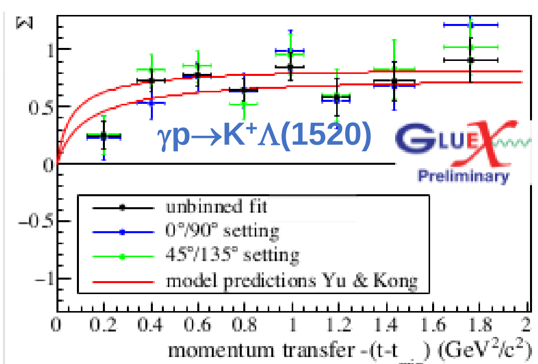
PRC 103, L02201 (2021)



PRC 101, 065206 (2020)



2107.12314 (2021)



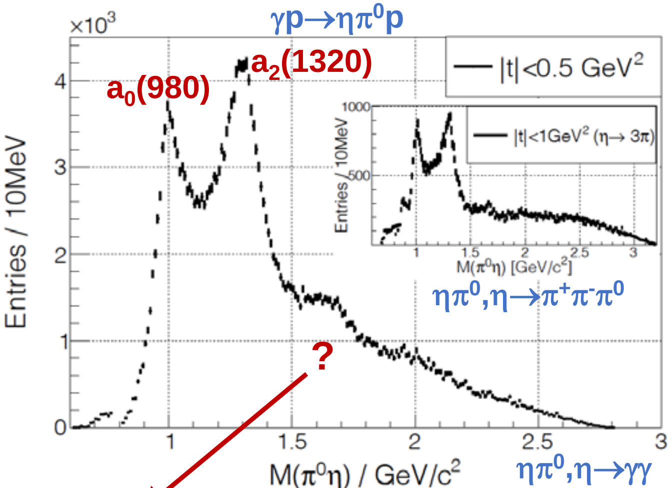
Hall D … then

Eugene Chudakov

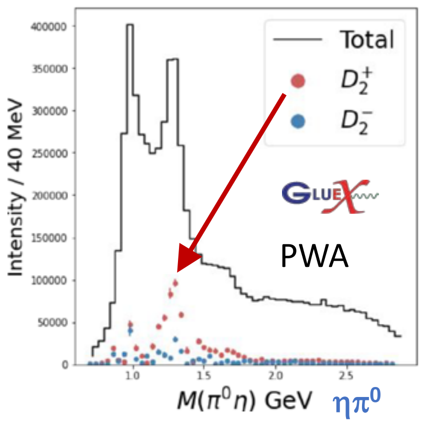
JLAB Hall D

Expected results and future plans

- **GlueX-I** data analysis:
  - **J/ψ :** increase statistics x4; known mesons: measure SDMEs, cross sections
  - **Hybrid search:** Partial Wave Analysis (PWA) in progress

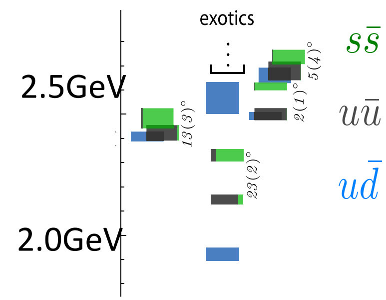


to be resolved using PWA



PWA identifies the well known $a_2(1320)$:
D waves for +/- naturality

Hybrid Mesons Lattice QCD



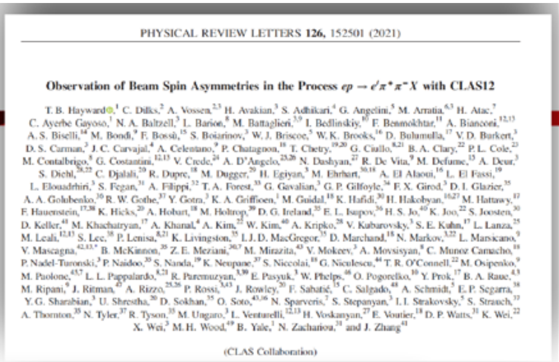
Non quark-antiquark
J^{PC} 0^{+-} 1^{-+} 2^{+-}
Experimental evidence for 1^{-+}

Approved Future Experiments

- Measurement of $\Gamma(\eta\to\gamma\gamma)$ in Primakoff production
- Pion Polarizabilities in Primakoff production
- Short-range Correlations
- GDH sum rule
- Spectroscopy in K_L beam (with a modified beam line)

- **GlueX-II** started data taking (enhanced PID and x5 statistics)

The present: CLAS12 physics program


PHYSICAL REVIEW LETTERS 126, 152501 (2021)

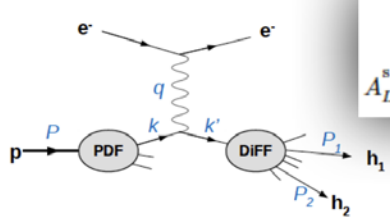
Observation of Beam Spin Asymmetries in the Process $ep \to e'\pi^+\pi^- X$ with CLAS12

(CLAS Collaboration)

PI: T.Hayward

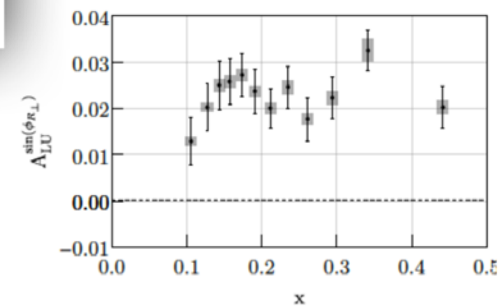
First Observation of Beam Spin Asymmetries in the Process
$e\,p \to e'\,\pi^+\,\pi^-\,X$ with CLAS12

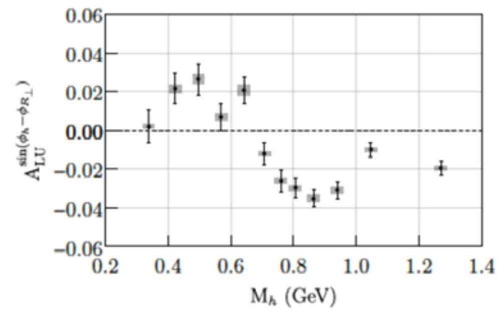
- SIDIS ingredients: q in the nucleon (PDF), hadronization (Fragmentation Functions)
- Fragmentation in 2h is sensitive to *several* TMDs and Dihadron Fragmentation Functions (DiFFs)
- Spin-momentum correlations in hadronization
- Access to PDF e(x) (trans pol. q in a unp nucleon, tw-3) and Dihadron FF G1-perp (helicity of fragmenting q)
- Complement single-hadron SIDIS, with the advantage of another degree of freedom

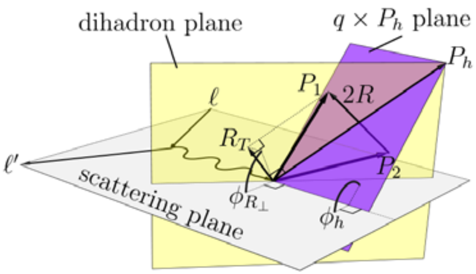


$$A_{LU} = \frac{1}{P_{\text{beam}}} \frac{N^+(\phi_h, \phi_{R\perp}) - N^-(\phi_h, \phi_{R\perp})}{N^+(\phi_h, \phi_{R\perp}) + N^-(\phi_h, \phi_{R\perp})} = A_{LU}^{\sin(\phi_h - \phi_{R\perp})} \sin(\phi_h - \phi_{R\perp}) + A_{LU}^{\sin(\phi_{R\perp})} \sin(\phi_{R\perp}),$$

- e(x)≠ 0 in valence region
- From known H-function, e(x) can be extracted







- Ph = P1 + P2 pions 3-mom
- RT is the component of R perpendicular to Ph
- Φh = azimuthal angle of q × Ph plane
- ΦR⊥ = azimuthal angle of di-hadron plane

★ First measurement of BSA in di-h production
★ Sub-leading PDF e(x) different from 0
★ First helicity-deg FF $G_1^\perp$ observation

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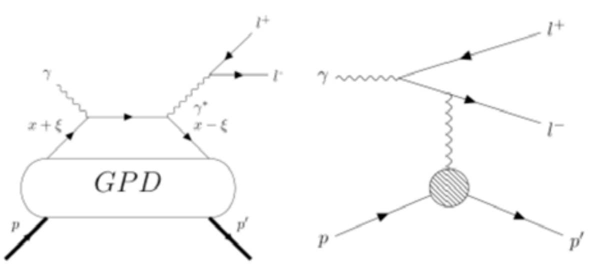
Hall B … now

Marco Battaglieri

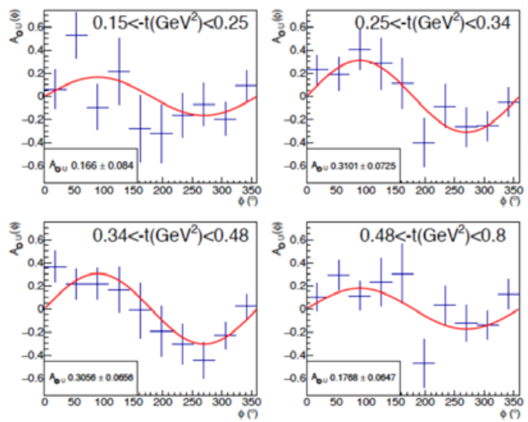
The present: CLAS12 physics program

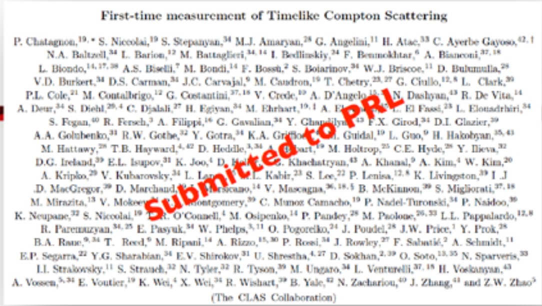
Timelike Compton Scattering

TCS: $\gamma p \rightarrow e^+ e^- p'$



TCS　　　　Bethe-Heitler




First-time measurement of Timelike Compton Scattering

(The CLAS Collaboration)

PI: P.Chatagnon

$$BSA = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{-\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{m_p}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\sin\phi\frac{(1+\cos^2\theta)}{\sin(\theta)}\,\mathrm{Im}\tilde{M}^{--}}{d\sigma_{BH}}$$

Test of universality of GPDs

- TCS is parametrized by GPDs
- **Comparison between DVCS and TCS** results allows to test the universality of GPDs
- TCS does not involve Distribution Amplitudes unlike Deeply Virtual Meson Production → direct comparison between DVCS and TCS

Real part of CFFs and nucleon D-term

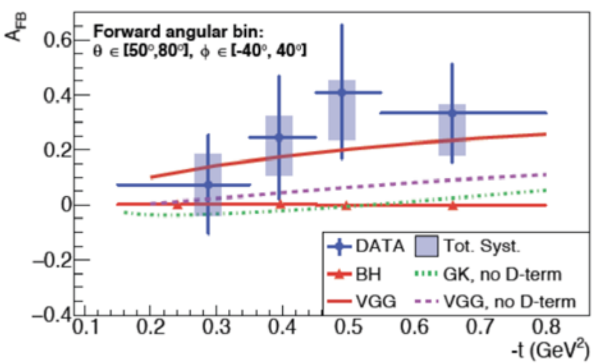
- As for DVCS, TCS unpolarized cross section is sensitive to $\mathrm{Re}\mathcal{H}$, which is still not well constrained by existing data.
- The CFFs dispersion relation at leading order and leading twist :

$$\mathrm{Re}\mathcal{H}(\xi,t) = \mathcal{P}\int_{-1}^{1} dx \left(\frac{1}{\xi - x} - \frac{1}{\xi + x}\right)\mathrm{Im}\mathcal{H}(\xi,t) + D(t)$$

- $D(t)$ can be related to the mechanical properties of the nucleon.

Review in Polyakov, Schweitzer, *International Journal of Modern Physics A*, 2018

- **First measurement ever!**
- **Sizeable Asymmetry**
- **Good agreement with GPD model fit to DVCS**



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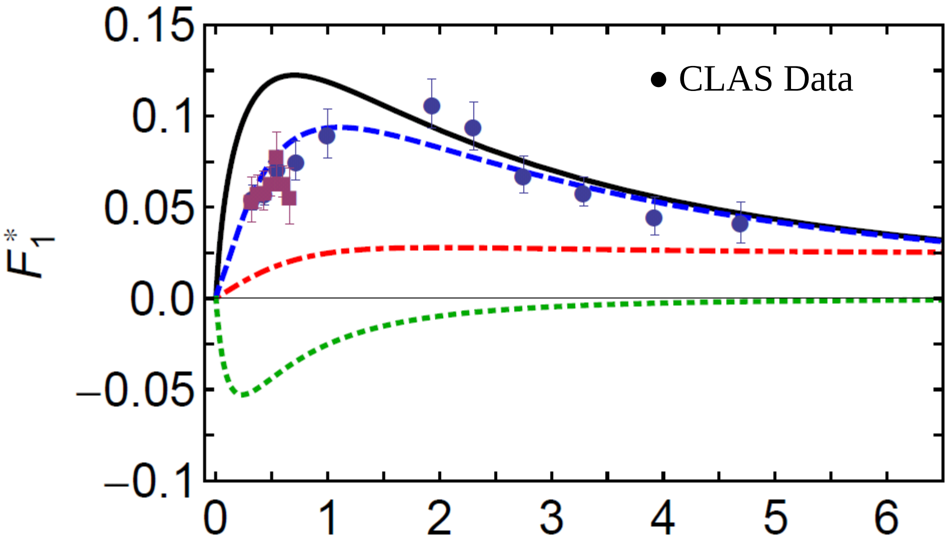
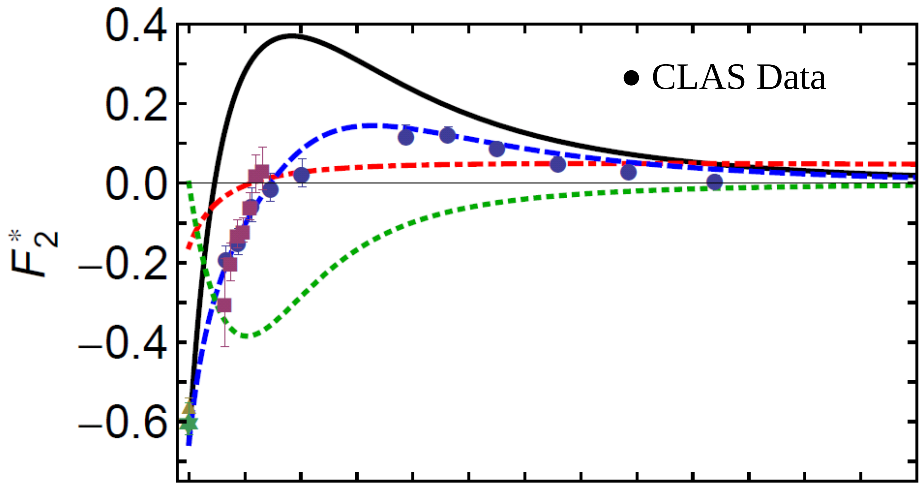
Hall B … now

$N(1440)P_{11}$

J. Segovia *et al.*, Phys. Rev. Lett. **115**, 171801



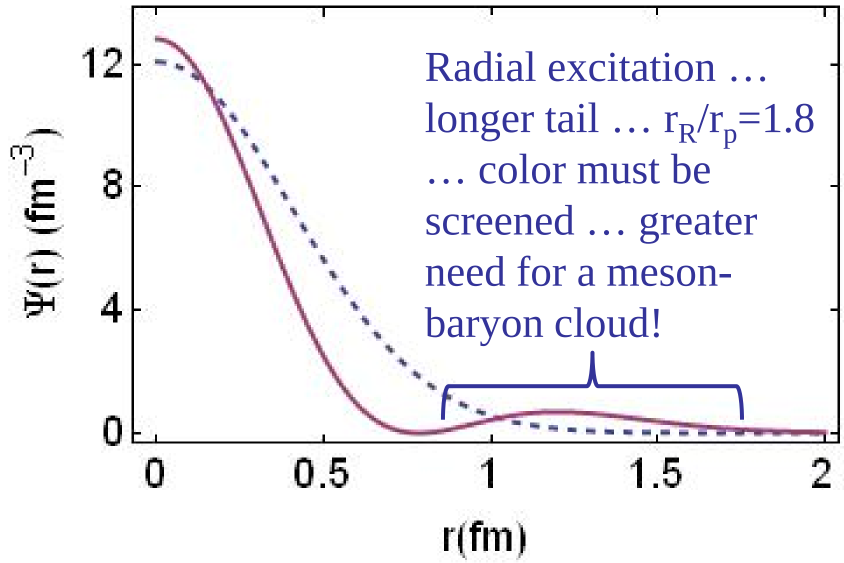


DSE Contact

DSE Realistic

Inferred meson-cloud contribution

Anticipated complete result

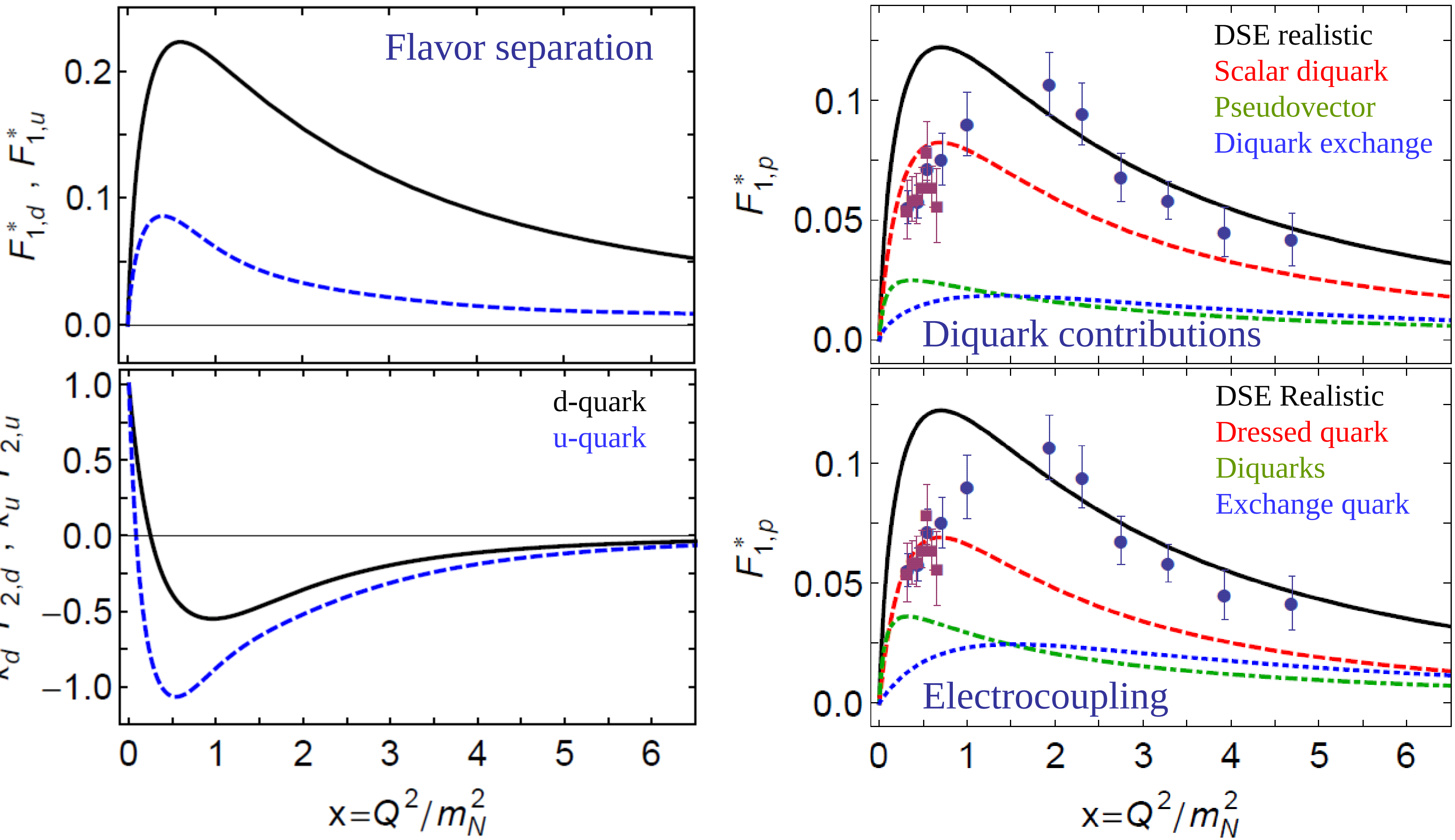


Importantly, the existence of a zero in F_2 is not influenced by meson-cloud effects, although its precise location is.

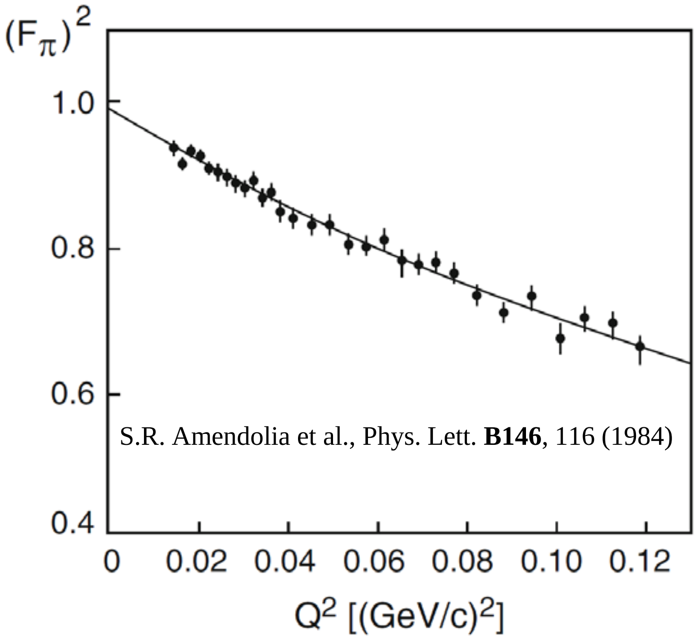
Hall B … now

N(1440)P_{11}

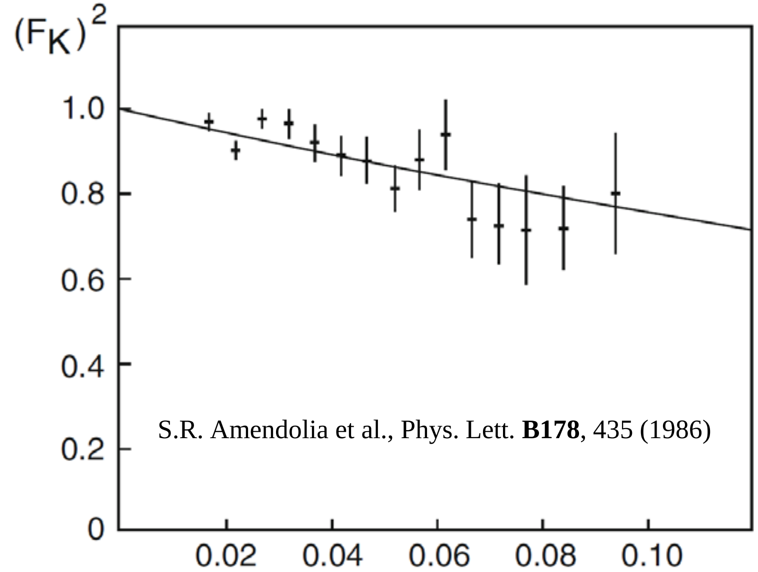
J. Segovia and C.D. Roberts, arXiv:1607.04405



History of Form Factors

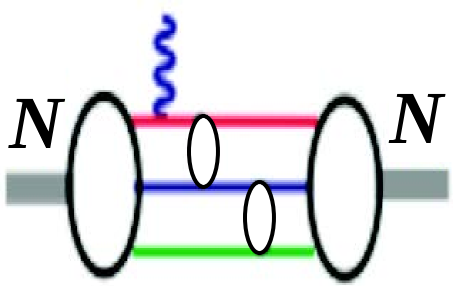


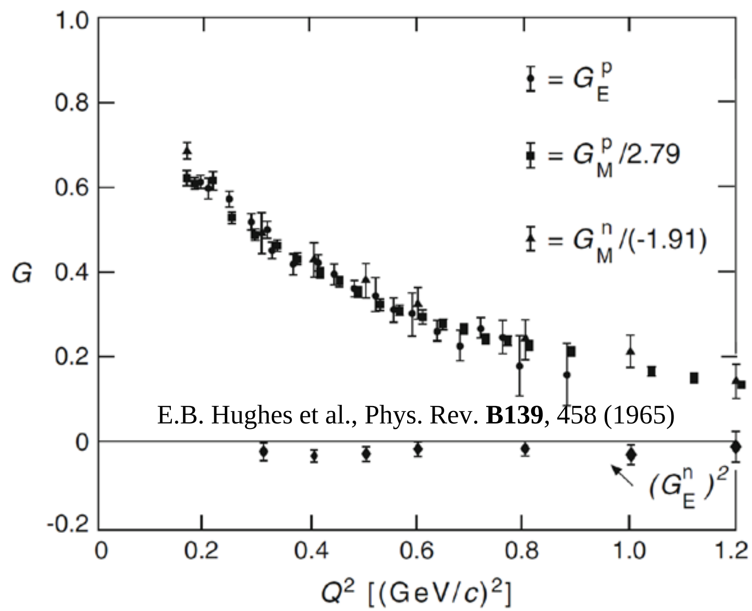
S.R. Amendolia et al., Phys. Lett. **B146**, 116 (1984)



S.R. Amendolia et al., Phys. Lett. **B178**, 435 (1986)

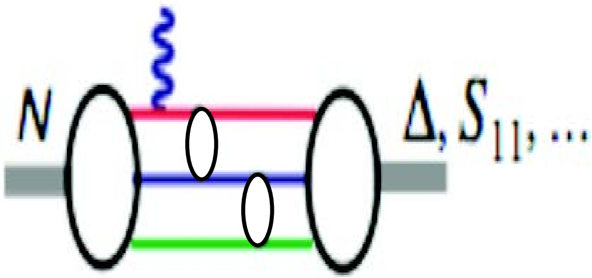
$$F(Q^2) = G_E(Q^2) = \left(1 + Q^2/a^2\hbar^2\right)^{-2}$$





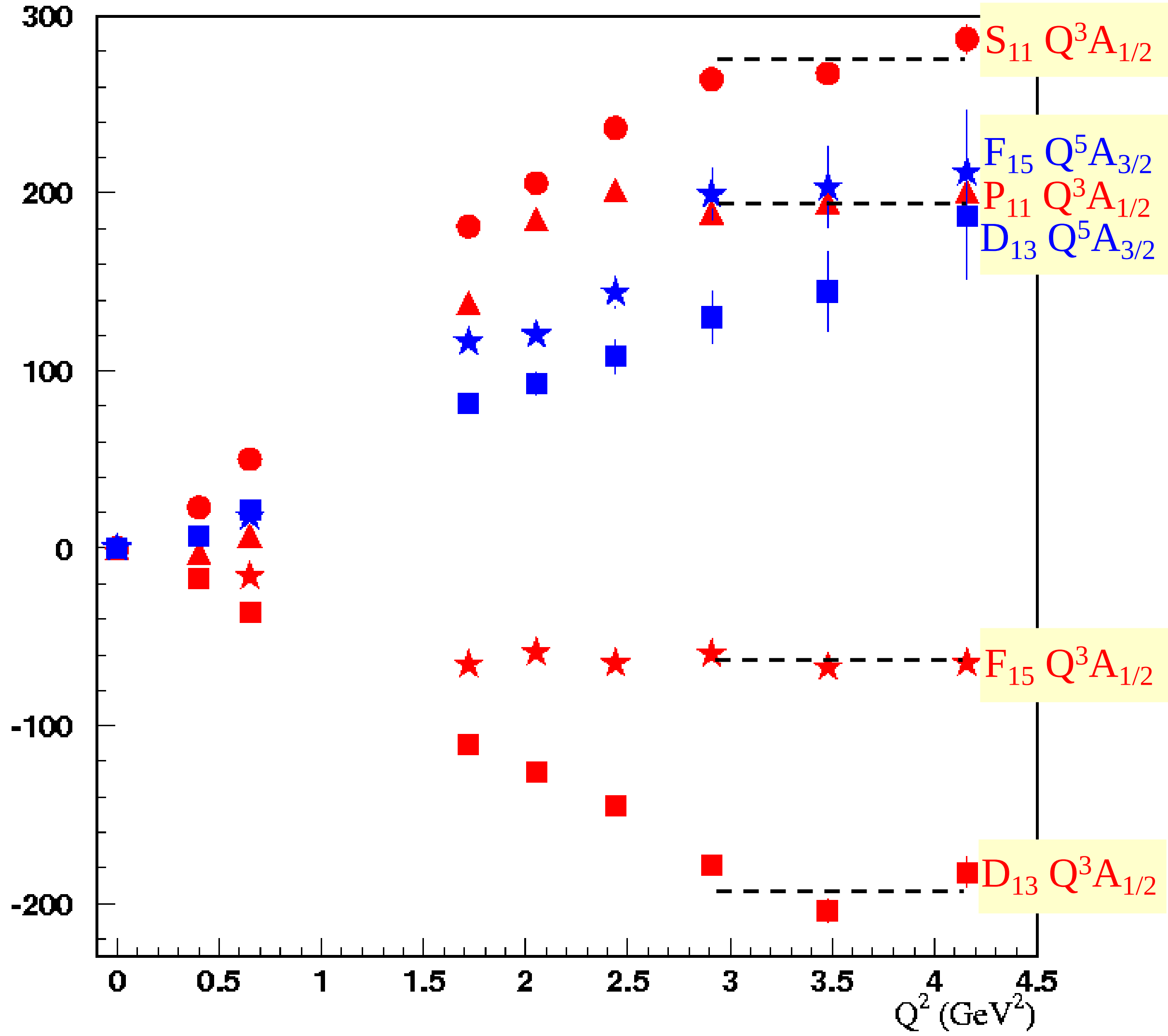
E.B. Hughes et al., Phys. Rev. **B139**, 458 (1965)

Evidence for the Onset of Precocious Scaling?



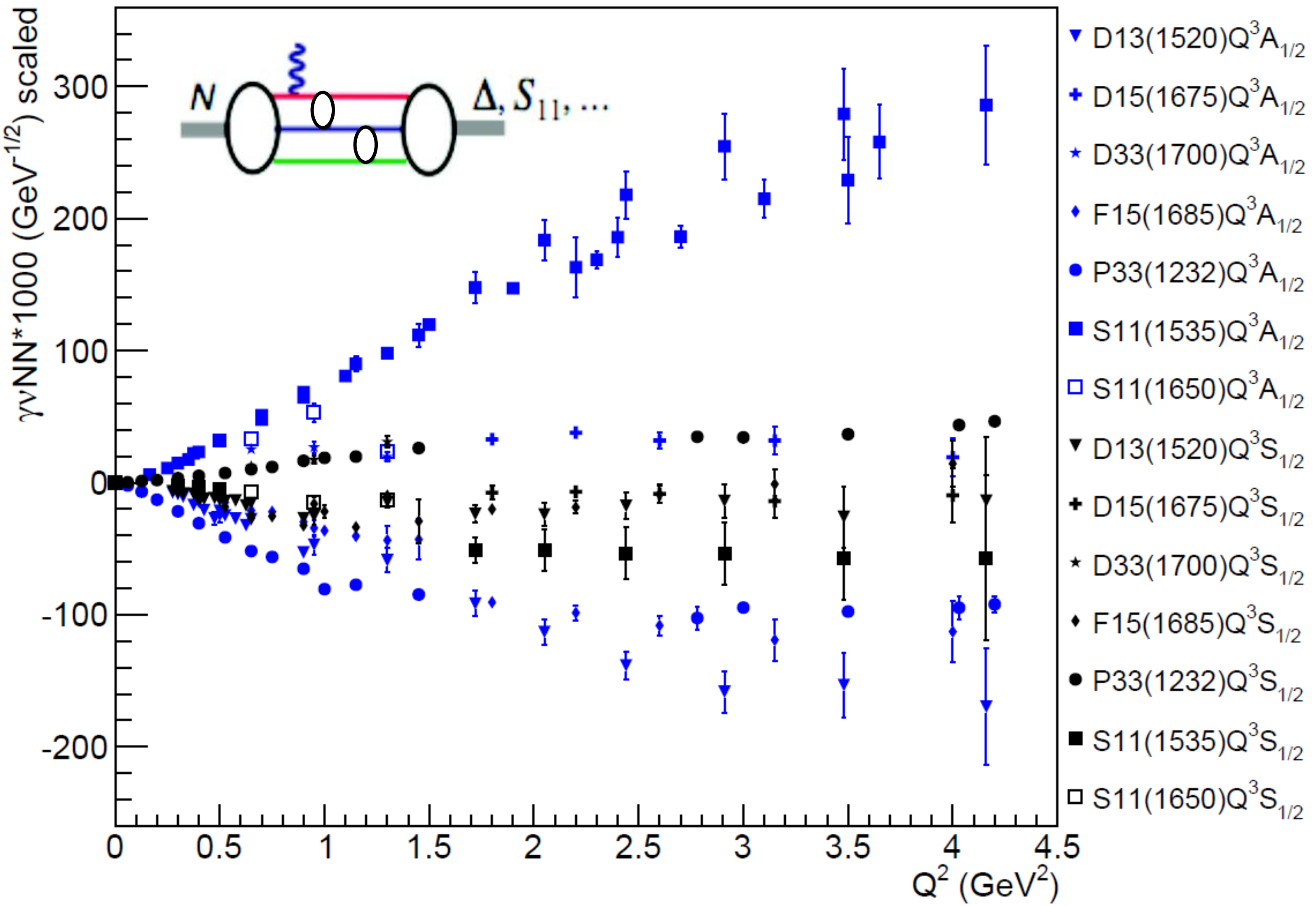
- $A_{1/2} \propto 1/Q^3$
- $A_{3/2} \propto 1/Q^5$

I. G. Aznauryan *et al.*, Phys. Rev. C80, 055203 (2009)



Evidence for the Onset of Precocious Scaling?

Ye Tian



V. Mokeev, userweb.jlab.org/~mokeev/resonance_electrocouplings/ (2016)

Hall B … now

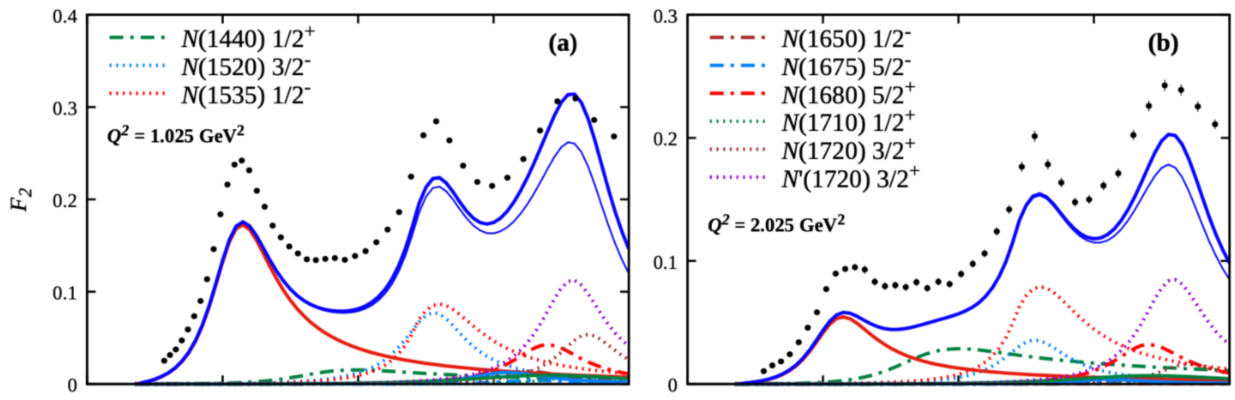
Resonant Contributions into Inclusive $F_2(W,Q^2)$ Structure Functions

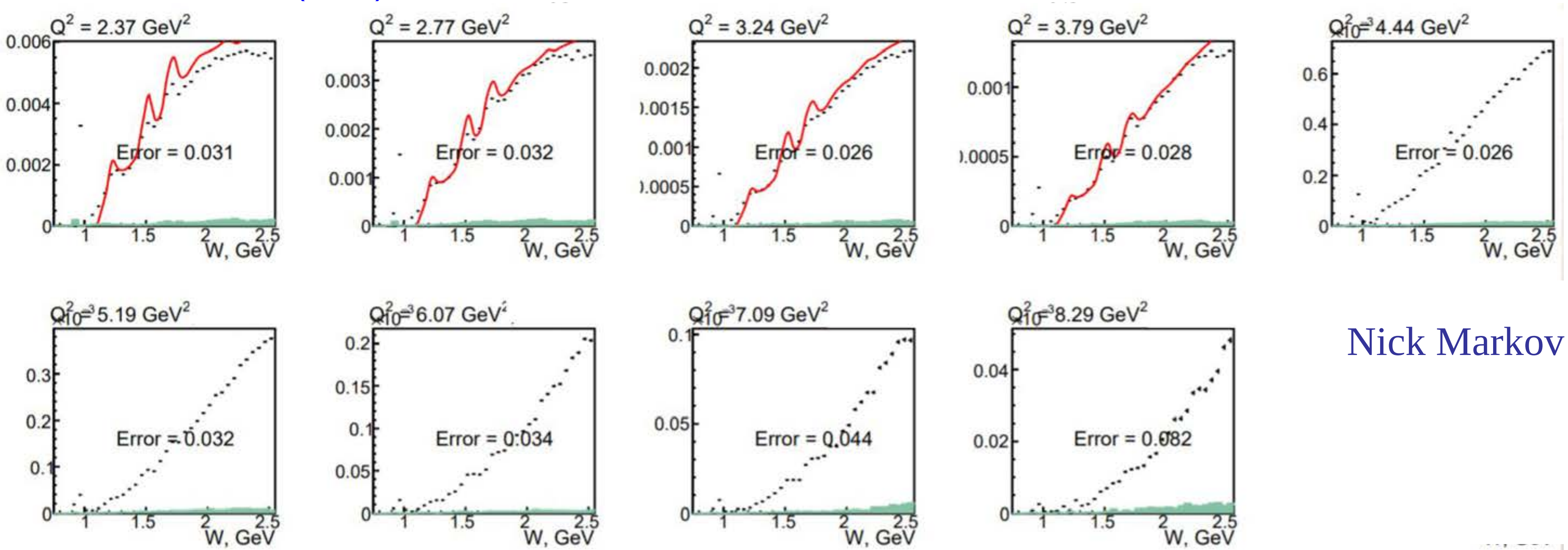
Viktor Mokeev

Data points are from interpolation of the CLAS results re-evaluated with the σ_L/σ_T ratio from Hall C data

CLAS data: M. Osipenko et al., PRD 67, 92001 (2003)
Hall C data: Y. Liang, Ph.D. thesis of American University (2003)

N* contributions :
A.N. Hiller Blin et al., Phys. Rev. C 104, 025201 (2021)





Nick Markov

Hall B … then

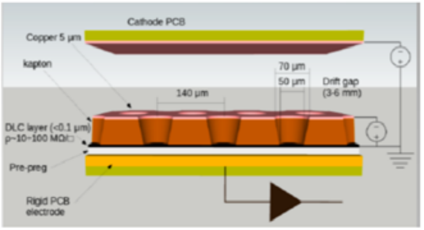
Marco Battaglieri

The future: CLAS12 HI-LUMI upgrade

Goal: double the current luminosity to operate CLAS12 at L~2 x 10^{35} cm^{-2} s^{-1} within the next 2-3 years

- CLAS12 High Luminosity operation has been included in the Lab Agenda
- Hall-B Task Forces (S.Stepanyan and S.Boyarinov)) conclusions: required a 1) new tracking detector & 2) new DAQ

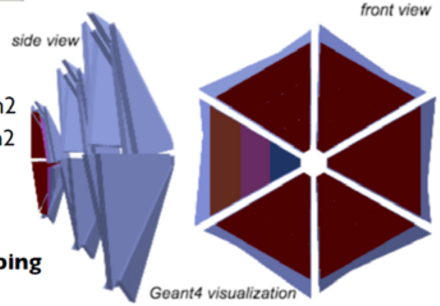
1) New CLAS12 tracking system: μ-Rwell



The μ-RWELL features:
- Compactness
- Easy assembly
- Easy powering
- Intrinsic spark quenching

Same technology proposed for EIC

The performance
- Gas gain: 10^4
- Rate capability HR version: 10 MHz/cm2
- Rate capability LR version: 100 kHz/cm2
- Spatial resolution: down to 60 μm
- Time resolution: 5-6 ns

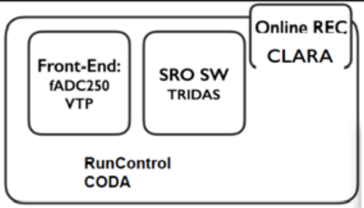


Status: CLAS12 μ-RWELL prototyping
- a prototype is being built by UVa
- full implementation in GEMC/REC software

2) New CLAS12 Streaming Readout (SRO) DAQ

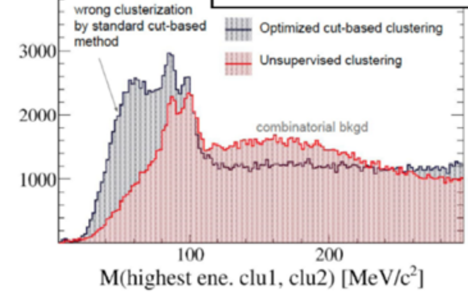
- current 'triggered' CLAS12 DAQ limited to 50 kHz acquisition rate
- working on a full streaming mode with 100kHz bandwidth
- Use of the current FE electronics (fADC250,VTP) and new backend software (TRIDAS)
- On-beam tests with CLAS12- FT are promising

Streaming RO CLAS12 FT tests: triggerless DAQ chain



CLAS12-FT SRO tests

π0 peak identified using a real-time AI-supported clustering



Options for μ-RWELL readout
- under test: SAMPA (ALICE) ,VMM3 (ATLAS) and FATIC2 LHCb)

Hall B … then

Marco Battaglieri

The future: physics opportunity with CLAS12

within 4-5 years

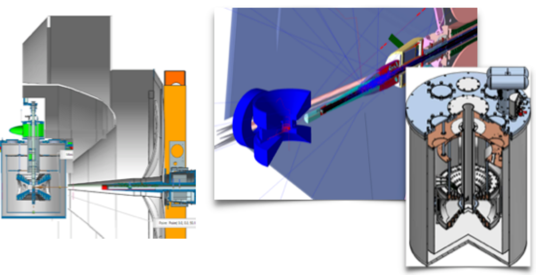
RG-H - Tansverse polarized target

Transverse Polarized target alternatives

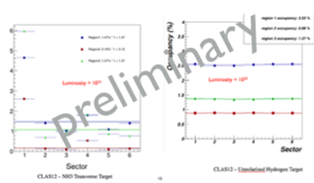
- HDIce does not demonstrate to be able to support RG-H physics program (unfortunately!)
- Identified NH3/ND3 DNP target as an alternative
- currently studying the impact on CLAS12, impact on approved physics program
- MgB2 can mitigate the impact of 5T external field to CLAS12 solenoidal field
- Possible follow up for ^{3}He pol target (neutron)

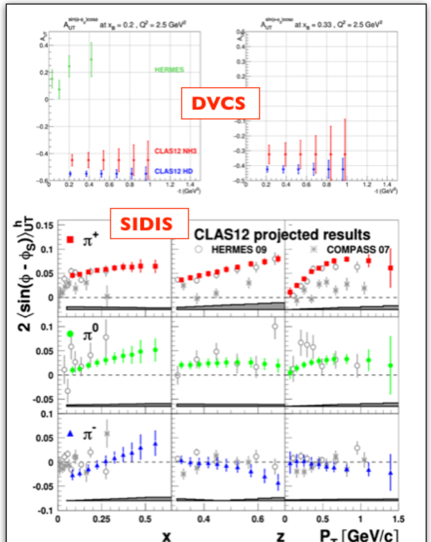
Physics impact

- A Reduction in luminosity from 5×10^{33} cm^{-2}s^{-1} to 1×10^{33} cm^{-2}s^{-1};
- Increase in polarization from 60% to 80%;
- Change in the dilution factor from 1/3 to 3/17;
- Operating 5 sectors (instead of 6) of CLAS12 Forward Detector due to electromagnetic background;
- Removing the Forward Tagger covering small angle photons (this only affects the DVCS program);
- Removing the CLAS12 Central Detector (this only affects the DVCS program).

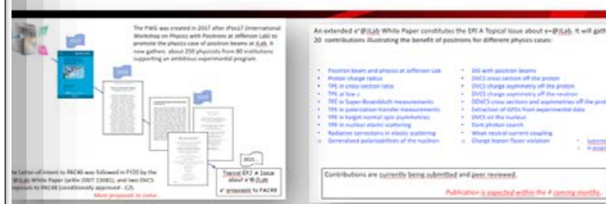


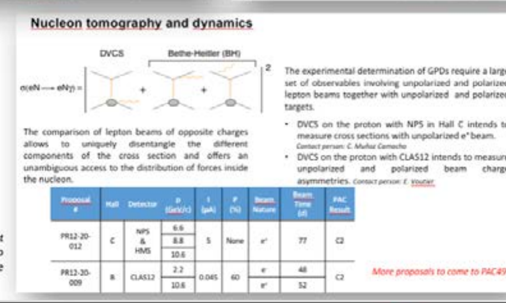
Particle background in CLAS12





based on the studies so far an overall factor 10 less in statistics





within 5-7 years

From JLab PAC48 Report:
"The Committee sees great physics potential in a positron program. We encourage a vigorous effort to explore the technical feasibility of providing positron beams, and we are looking forward to receiving further proposals in this area. Clearly, it is difficult at the present stage to predict the characteristics of positron beams that will be achievable."

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Hall B … then

Marco Battaglieri

The future: physics opportunity with CLAS12

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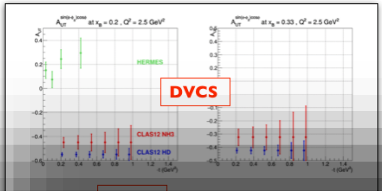
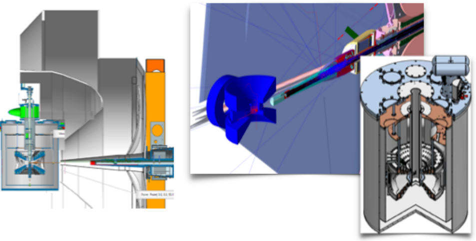
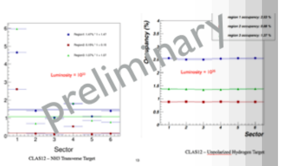




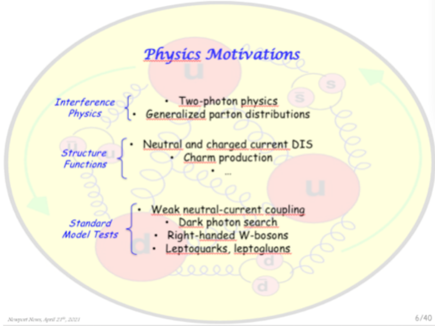
Particle background in CLAS12

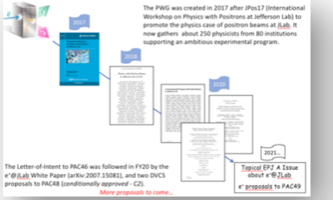


within 4-5 years

JLAB positron beam

- Positron beam of high energy (up to 11 GeV), high current (I_{e^+}~0.5-1uA), high polarisation (P_{e^+}~60%)





An extended e⁺@JLab White Paper constitutes the EPJ A Topical Issue about e+@JLab. It will gather 20 contributions illustrating the benefit of positrons for different physics cases:

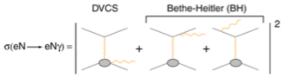
- Positron beam and physics at Jefferson Lab
- Proton charge radius
- TPE in cross-section ratio
- TPE at low ε
- TPE in Super-Rosenbluth measurements
- TPE in polarization transfer measurements
- TPE in target-normal spin asymmetries
- TPE in nuclear elastic scattering
- Radiative corrections in elastic scattering
- ○ Generalized polarizabilities of the nucleon
- DIS with positron beams
- DVCS cross section off the proton
- DVCS charge asymmetry off the proton
- DVCS charge asymmetry off the neutron
- DDVCS cross sections and asymmetries off the proton
- Extraction of GPDs from experimental data
- DVCS on the nucleus
- Dark photon search
- Weak neutral-current coupling
- ○ Charge lepton flavor violation

• Submitted
○ In progress

Contributions are currently being submitted and peer reviewed.

Publication is expected within the 4 coming months..

Nucleon tomography and dynamics



The experimental determination of GPDs require a large set of observables involving unpolarized and polarized lepton beams together with unpolarized and polarized targets.

The comparison of lepton beams of opposite charges allows to uniquely disentangle the different components of the cross section and offers an unambiguous access to the distribution of forces inside the nucleon.

- DVCS on the proton with NPS in Hall C intends to measure cross sections with unpolarized e⁺ beam. *Contact person: C. Muñoz Camacho*
- DVCS on the proton with CLAS12 intends to measure unpolarized and polarized beam charge asymmetries. *Contact person: E. Voutier*

Proposal #	Hall	Detector	p (GeV/c)	I (μA)	P (%)	Beam Nature	Beam Time (d)	PAC Result
PR12-20-012	C	NPS & HMS	6.6	5	None	e⁺	77	C2
			8.8					
			10.6					
PR12-20-009	B	CLAS12	2.2	0.045	60	e⁻	48	C2
			10.6			e⁺	52	

More proposals to come to PAC49.

From JLab PAC48 Report:
"The Committee sees great physics potential in a positron program. We encourage a vigorous effort to explore the technical feasibility of providing positron beams, and we are looking forward to receiving further proposals in this area. Clearly, it is difficult at the present stage to predict the characteristics of positron beams that will be achievable."

within 5-7 years

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Hall C … now

Stephen Wood

Hall C

Nucleon structure:

- Precision measurements of:
  - Unpolarized structure functions
  - Polarized structure functions
  - Semi-inclusive and exclusive
    - meson production
    - (TMD’s, pi/K form factors)
  - Nucleon Form Factors

Two high momentum spectrometers

(11 GeV/c, 6+ GeV/c)

Several msr solid angle

Momentum bite > 15%

Good Particle ID, ΔP/P ≤ 1x10^{-3}

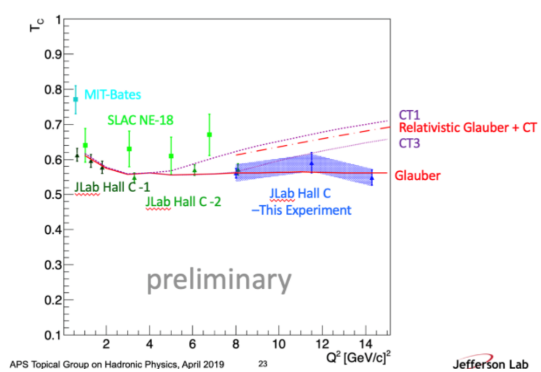
High power cryogenic targets

Polarized Targets (p, d, 3He) and beam

Nuclear:

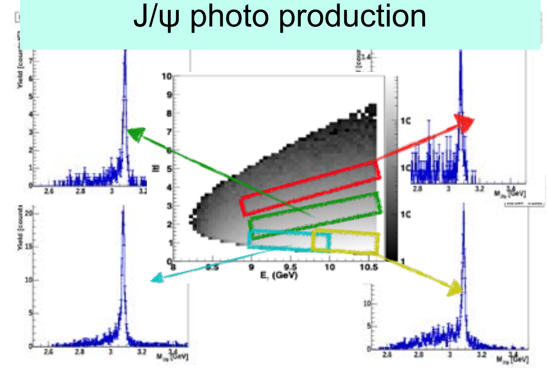
- Color Transparency
- EMC effect
- Short range correlations

Color Transparency



LHCb pentaquark detected in

J/ψ photo production

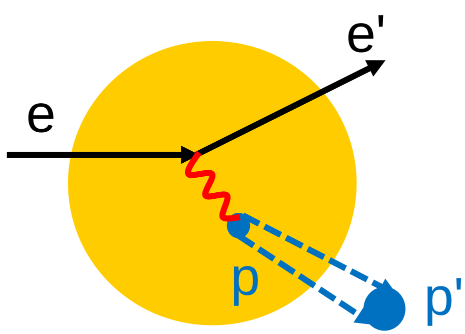


Color Transparency

Stephen Wood

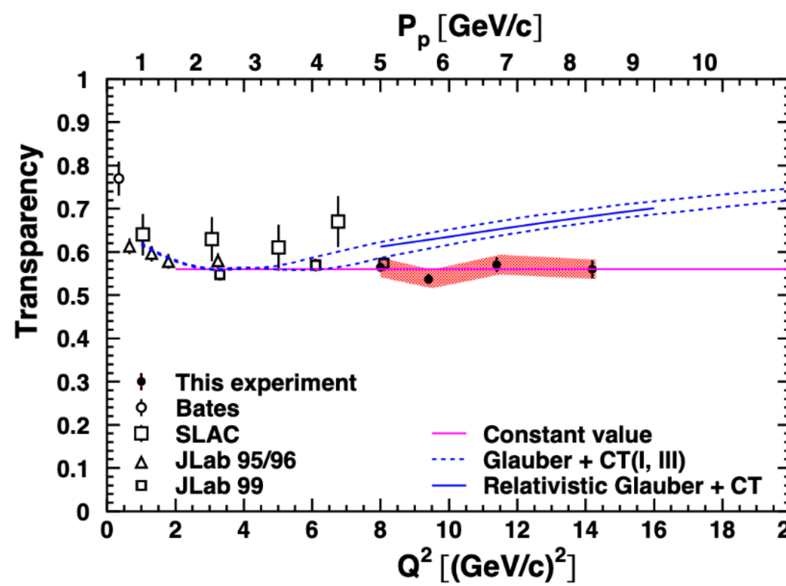
Transparency:
Probability that proton struck in nucleus will emerge without being absorbed or rescattering.

A(e,e′p)



Color Transparency:
QCD predicts that at sufficiently high Q^2, struck proton will be "point-like" and nucleus will be more transparent.

Recent JLab Hall C doubled Q^2 range – saw no onset of Color Transparency in ^{12}C despite hints from other reactions that nucleus should be more transparent.

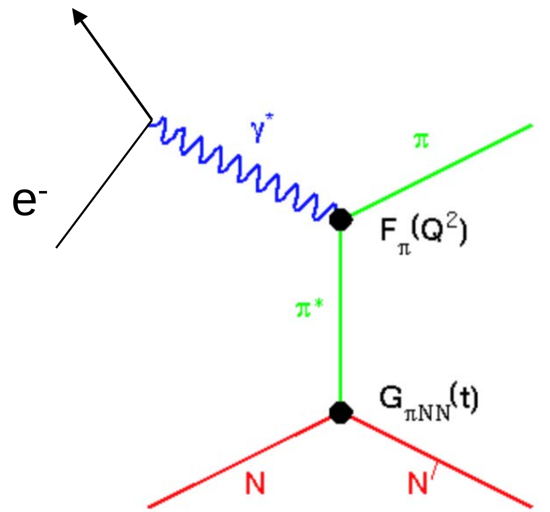


Bhetuwal, et al., Phys. Rev. Lett 126, 082301 (2021)

Hall C … then

Stephen Wood

Pion Form Factor

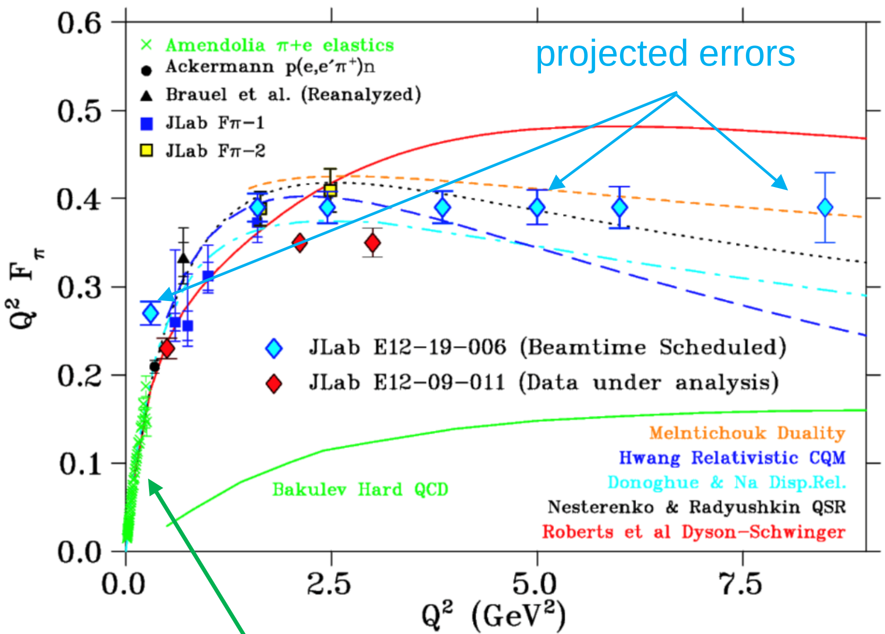


The pion form factor, F_π, is clear test case to study the QCD transition from non perturbative to perturbative regions.

F_π can be accessed by using electrons to knock out pions from the nucleon's virtual pion cloud.

Hall C provides a unique capability to push pion form factor measurements to much higher Q^2.

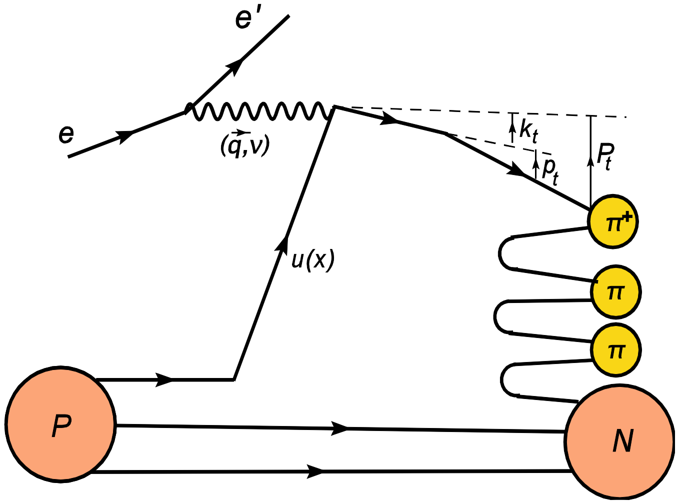
These measurements also extend to low Q2 allowing comparison with previous F_π measurements made with elastic π+e- scattering.



Hall C … then

Stephen Wood

Semi-Inclusive Deep Inelastic Scattering (SIDIS)

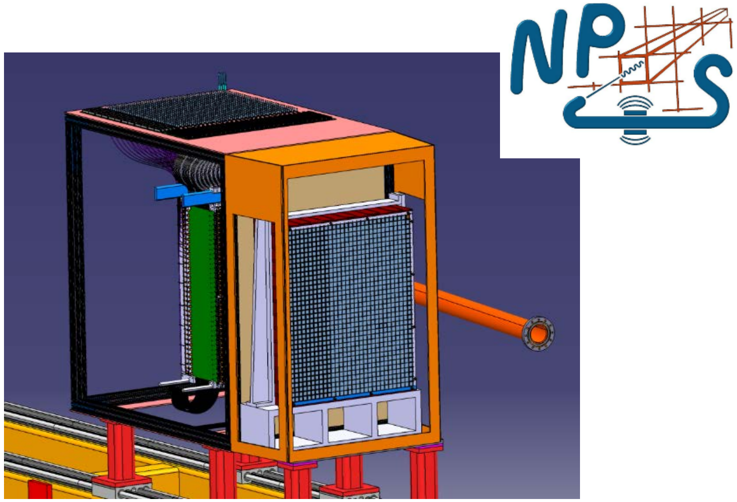


If p(e, e′ π) and d(e, e′ π) reactions can be factorized into the hard process of hitting a quark and the soft process of the struck quark fragmenting into pions, SIDIS can be used to study quark transverse momentum distributions and charge symmetry.

Lower energy energy JLab measurements hint that such factorization holds.

(e, e′ π^+) and (e, e′ π^-) SIDIS measurements are underway in Hall C and a new “Neutral Particle Spectrometer” is being built to measure (e, e′ π^0) to validate factorization.

The NPS will also be used as a photon detector for other reactions such as Deeply Virtual Compton Scattering and Wide Angle Compton Scattering.



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