Overview of Photoproduction Physics at Jefferson Lab

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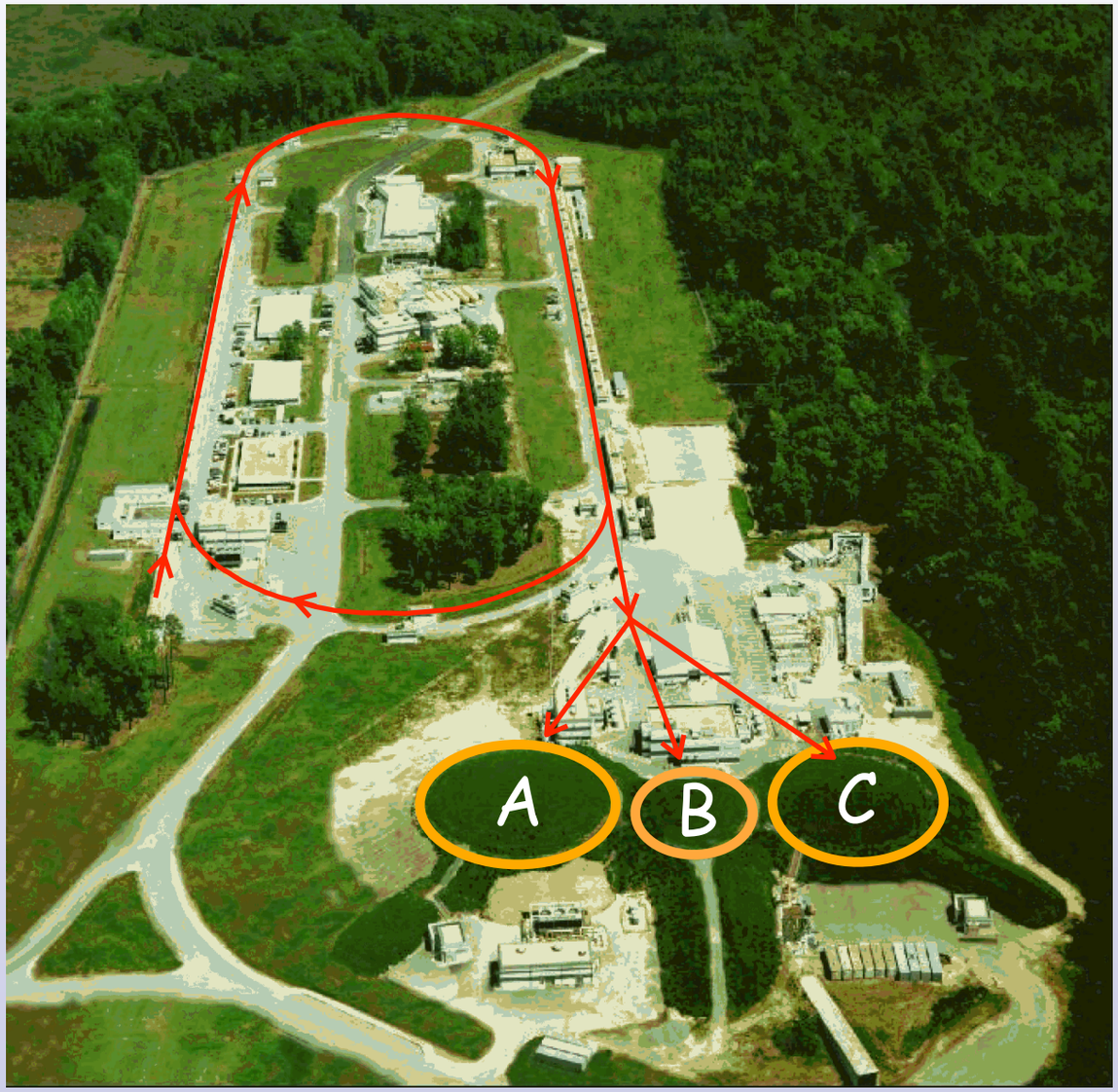
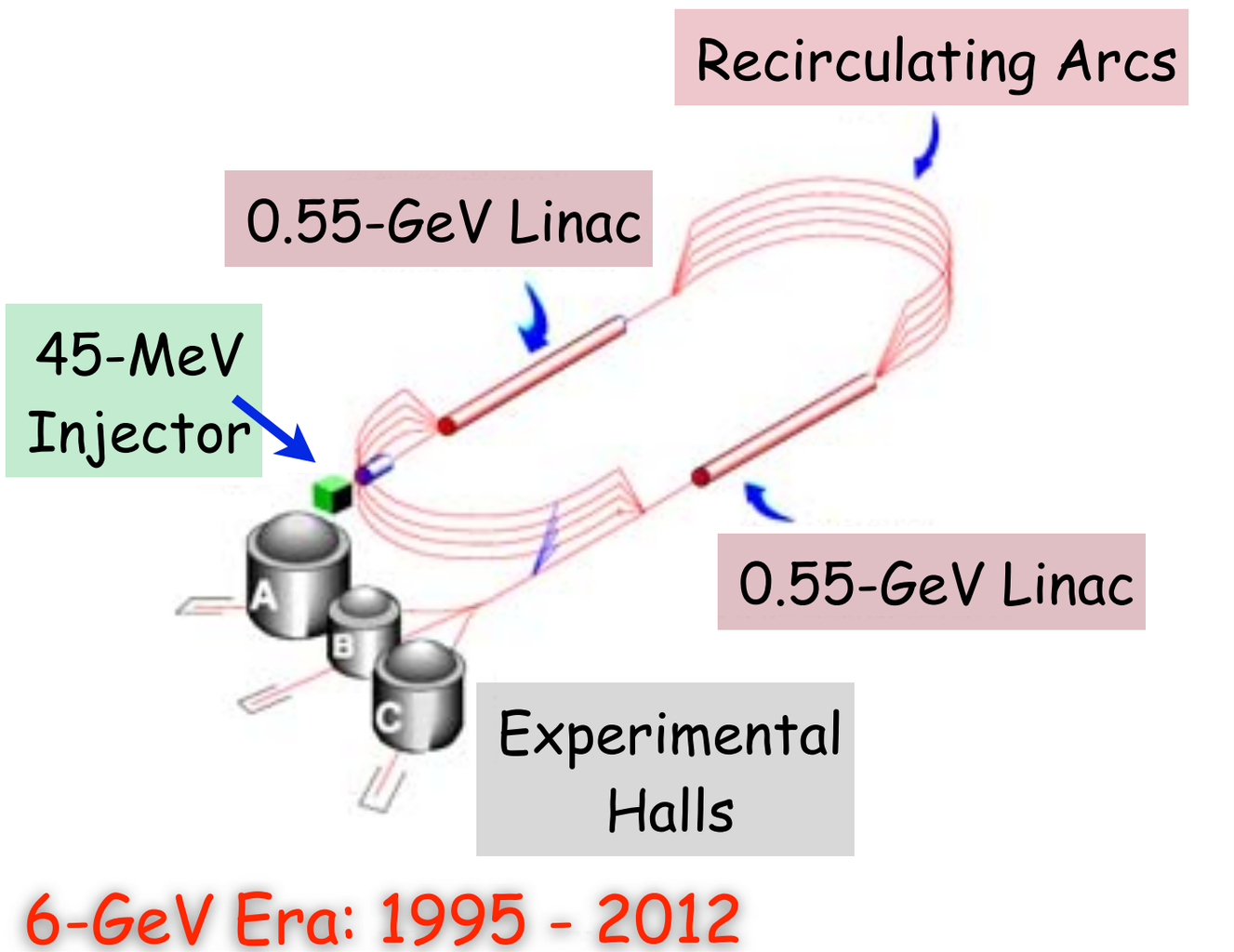
Thomas Jefferson National Accelerator Facility

QCD Machine: Electromagnetic Probes of Hadron Structure



JLab in Newport News, VA

- Superconducting RF electron linacs with up to 5 times recirculation
- Up to 1.1 GeV energy gain per pass



6-GeV Era: 1995 - 2012

- C.W. electron beam: 2-ns wide bunch period, 0.2-ps bunch length
- Polarized Source: $P_e \sim 86\%$
- Beam energies up to $E_0 = 6$ GeV
- Beam Current up to 200 μA

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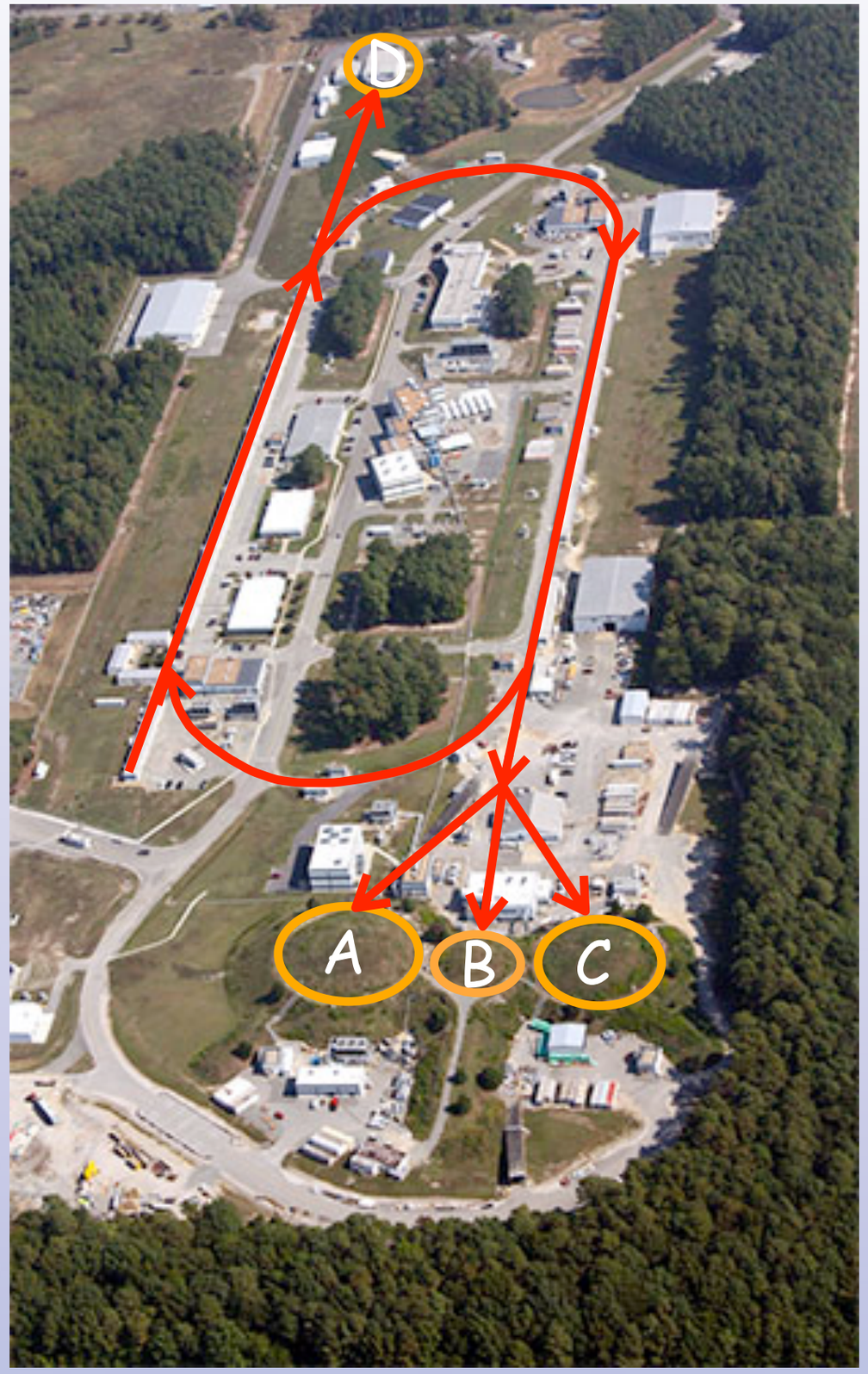
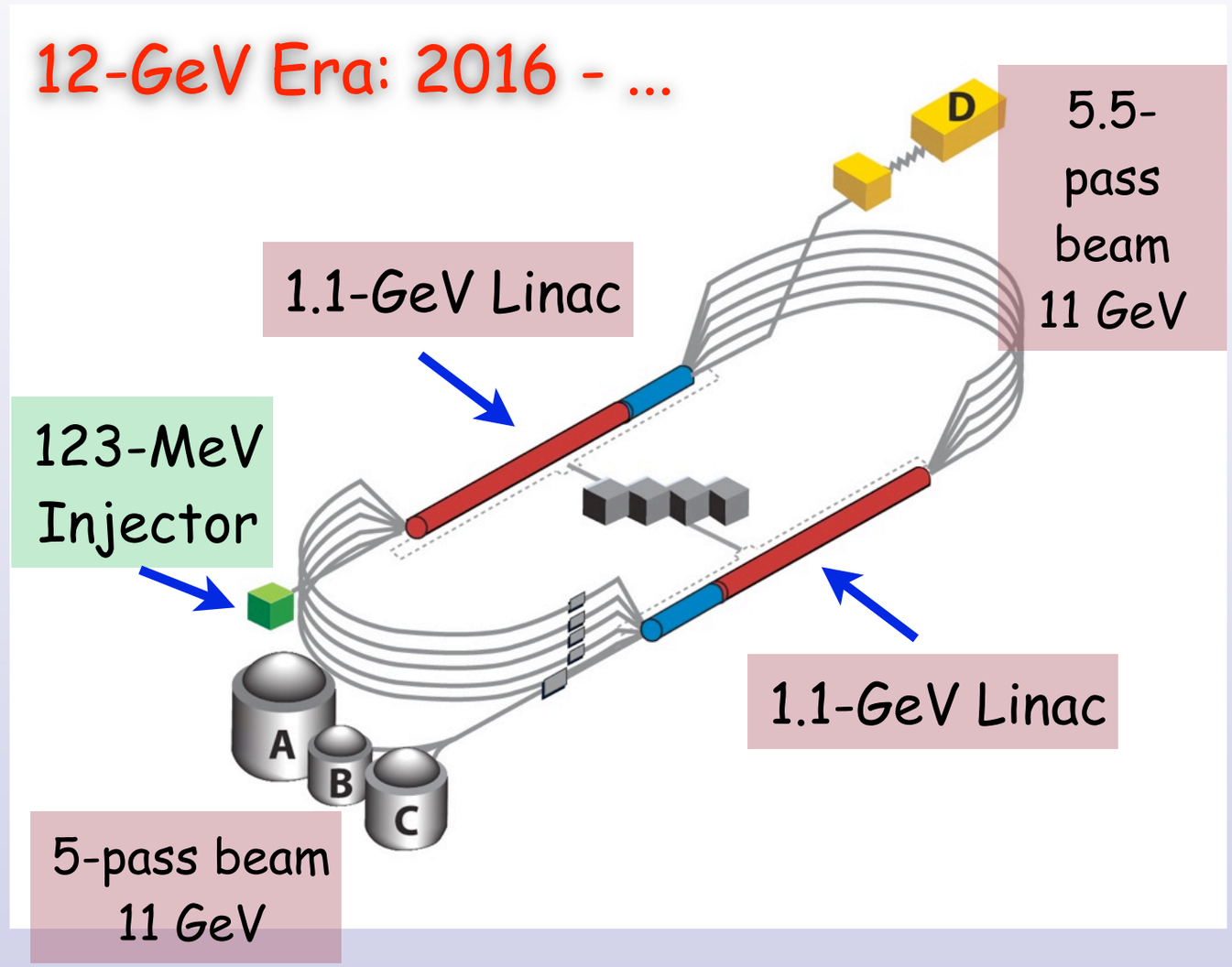
QCD Machine: Electromagnetic Probes of Hadron Structure





- C.W. electron beam: 2-ns wide bunch period, 0.2-ps bunch length
- Polarized Source: $P_e \sim 85\%$
- Beam energies up to E_0 = 11 (12) GeV
- Beam Current up to 85 μA

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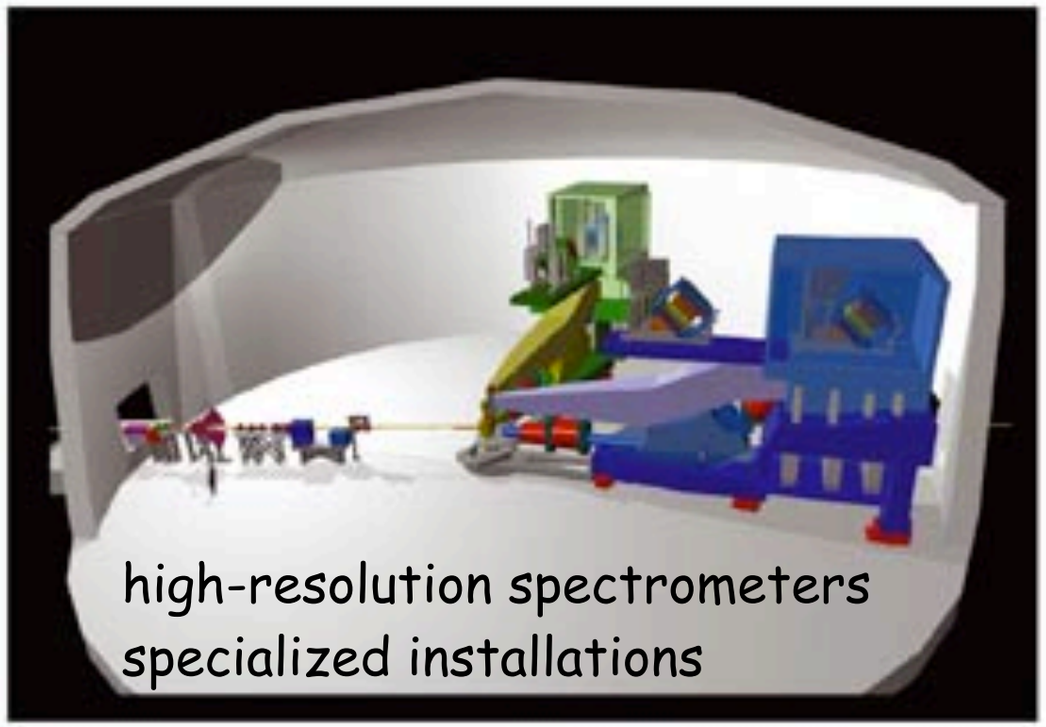
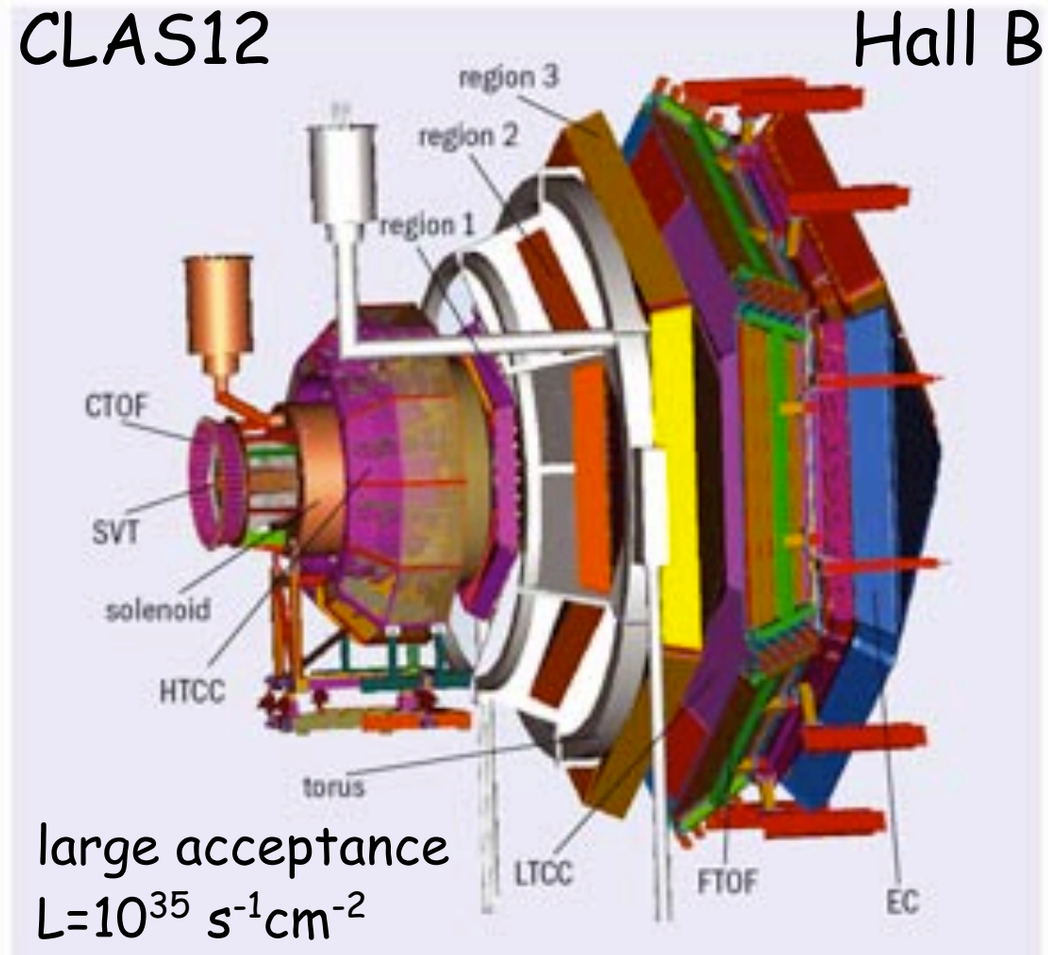
Detector Systems

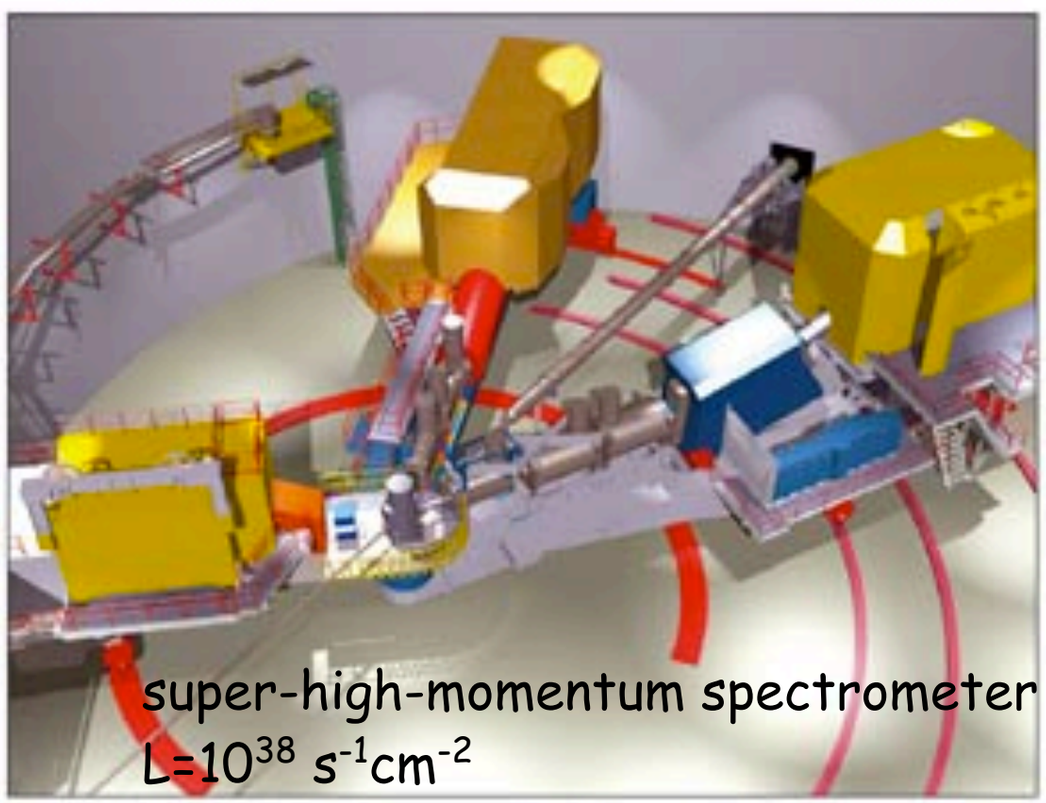
Hall A



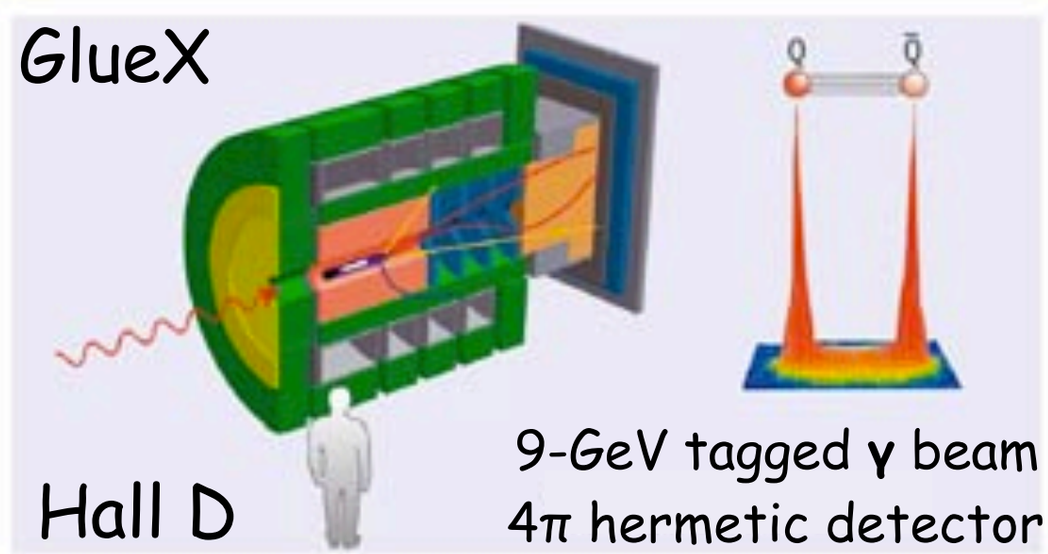
CLAS12 Hall B



Hall C



GlueX



JLab Photoproduction Scientific Program

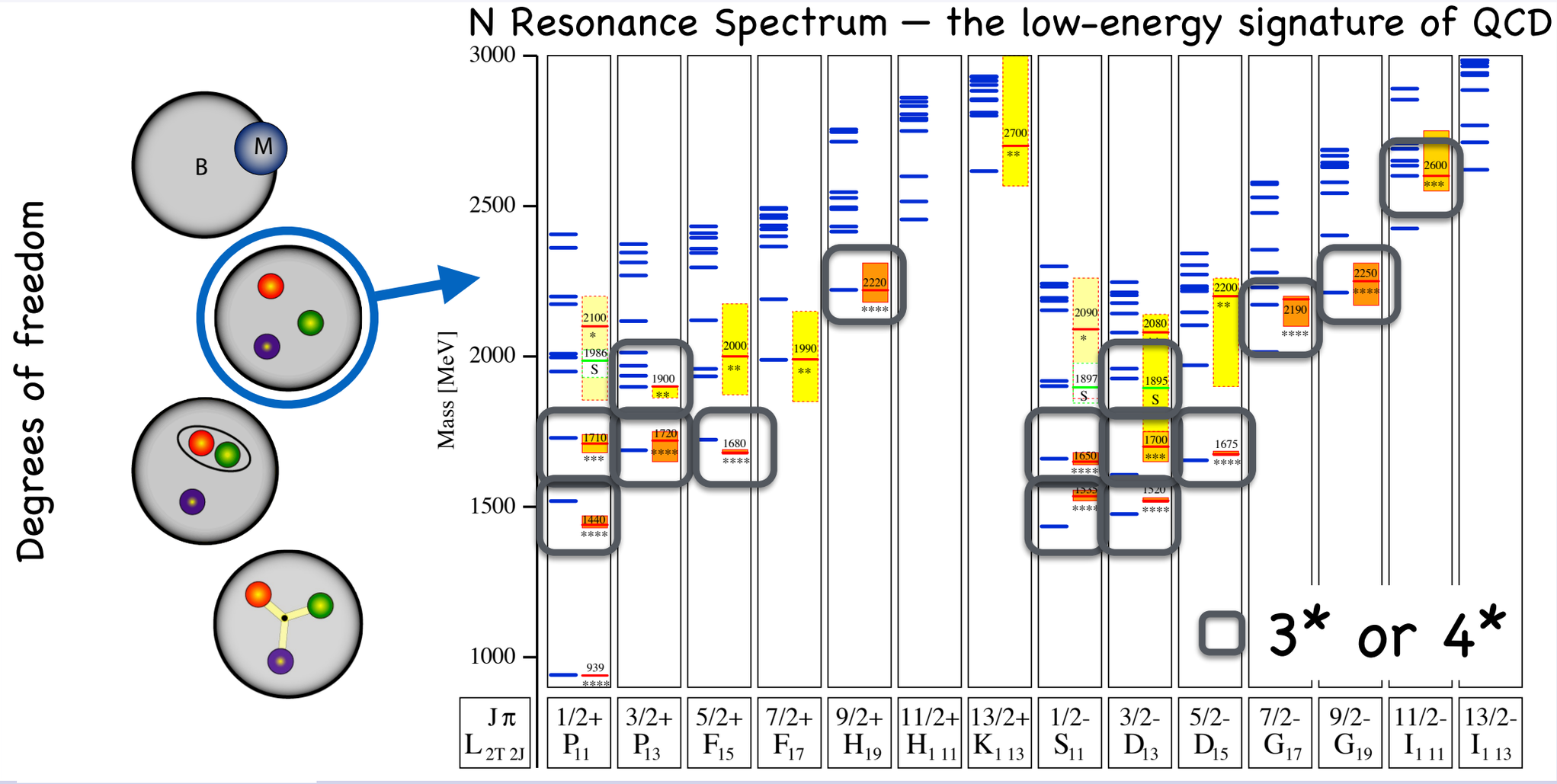
Probing Hadron Structure and Strong Interaction with Real and Virtual Photons

- The Hadron Spectra as Probes of QCD (Halls B, D)
  - Baryon and Meson Spectroscopy
- The Transverse Structure of Hadrons (Halls A, B, C, D)
  - Elastic Form Factors
  - Transition Form Factors
- The Longitudinal Structure of Hadrons (Halls A, B, C)
  - Unpolarized and Polarized Parton Distribution Functions
- The 3D Structure of Hadrons (Halls A, B, C)
  - Generalized Parton Distributions (GPDs)
  - Transverse Momentum Distributions (TMDs)
- Hadrons and Cold Nuclear Matter (Halls A, B, C)
  - Nucleon Medium Modifications; Quark Hadronization
  - NN Correlations; Hypernuclear Spectroscopy; Few-Body Experiments
  - Near Threshold J/ψ Photoproduction
- Heavy Photon Search

Hadron Spectroscopy

Baryon Spectroscopy

Relevant Degrees of Freedom and Missing Resonance Problem



Quark Models

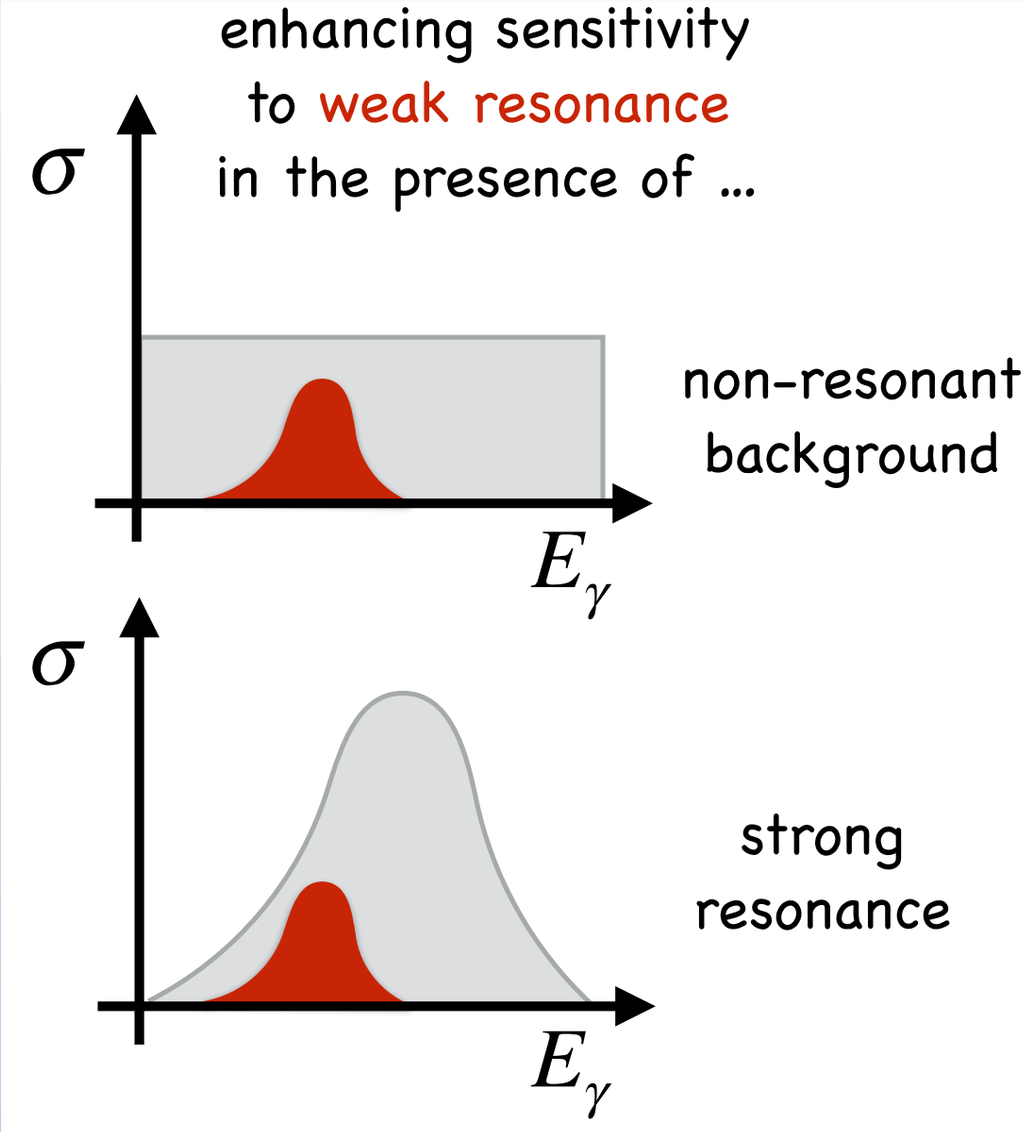
- Constituent Quark Models predict many more of excited states than have been observed; some of the states may only couple weakly to πN.
- Quark-Diquark Models with a tightly bound diquark predict fewer states.
- Quark and Flux-Tube Models predict increased number of states.

CQM: U. Löring, B.C. Metsch, and H.R. Petry, Eur. Phys. J. A10 395 (2001)

Baryon Spectroscopy

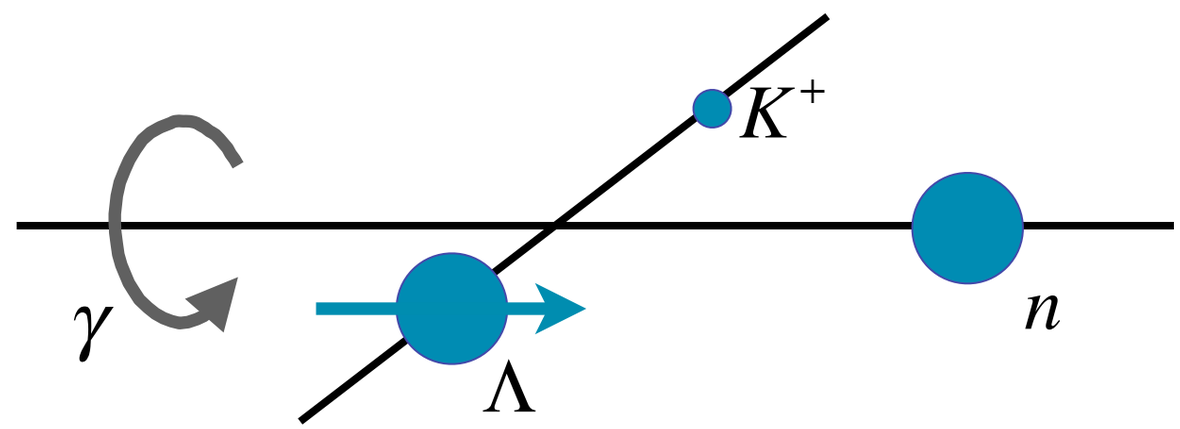
Experimental Observables

Polarization observables give access to reaction amplitudes



$\vec{\gamma} n \rightarrow K^0 \vec{\Lambda}$: Four complex amplitudes describe the reaction

$$\frac{d\sigma}{d\Omega} \sim |N|^2 + |S_1|^2 + |S_2|^2 + |D|^2$$



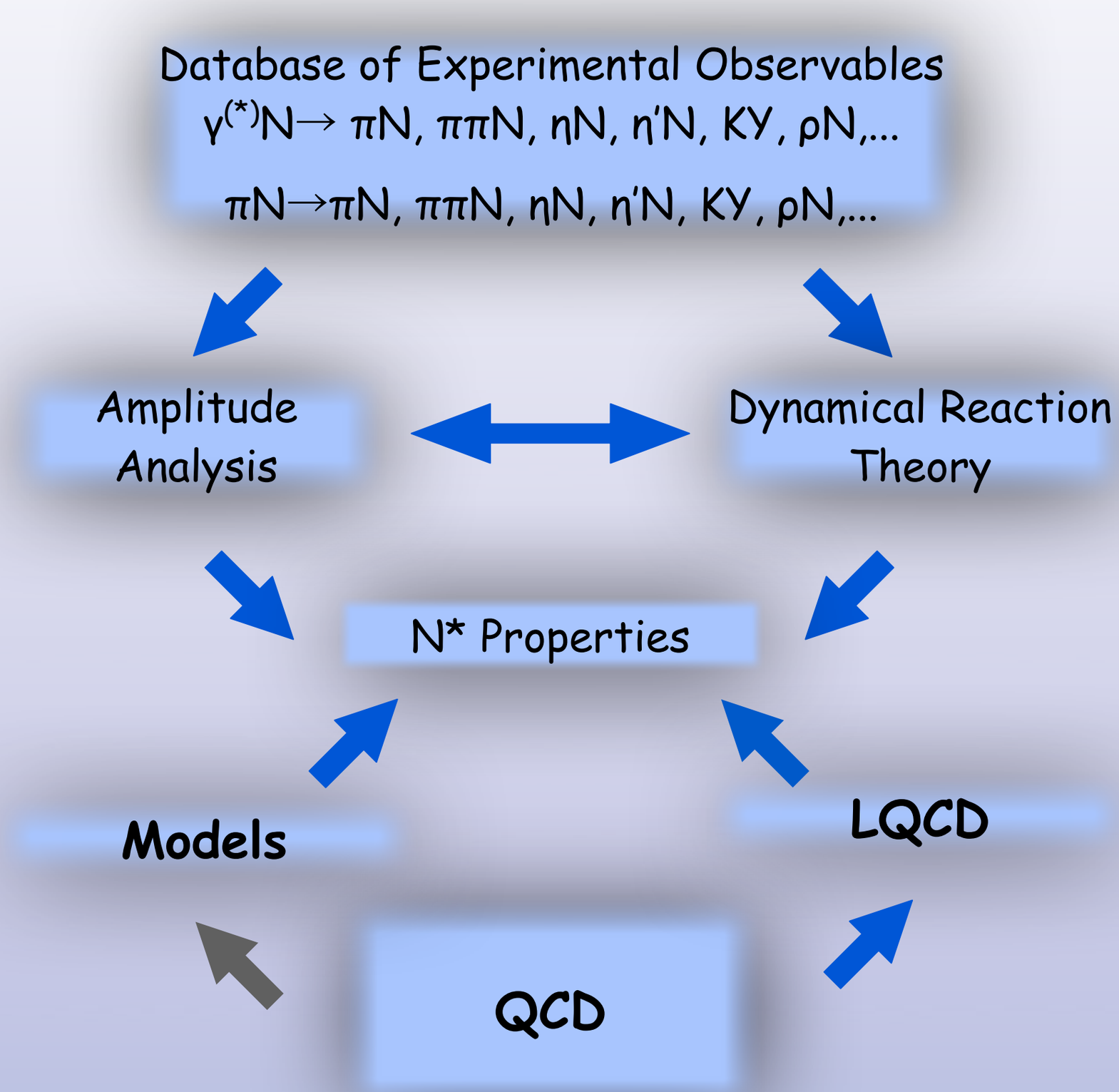
$$C_z \frac{d\sigma}{d\Omega} \sim |S_2|^2 - |S_1|^2 - |N|^2 + |D|^2$$

$$P \frac{d\sigma}{d\Omega} \sim 2\,\mathrm{Im}(S_2 N^* - S_1 D^*)$$

I.S. Barker, A. Donnachie, J.K. Storrow, Nucl. Phys. B 79, 431 (1974).

Baryon Spectroscopy

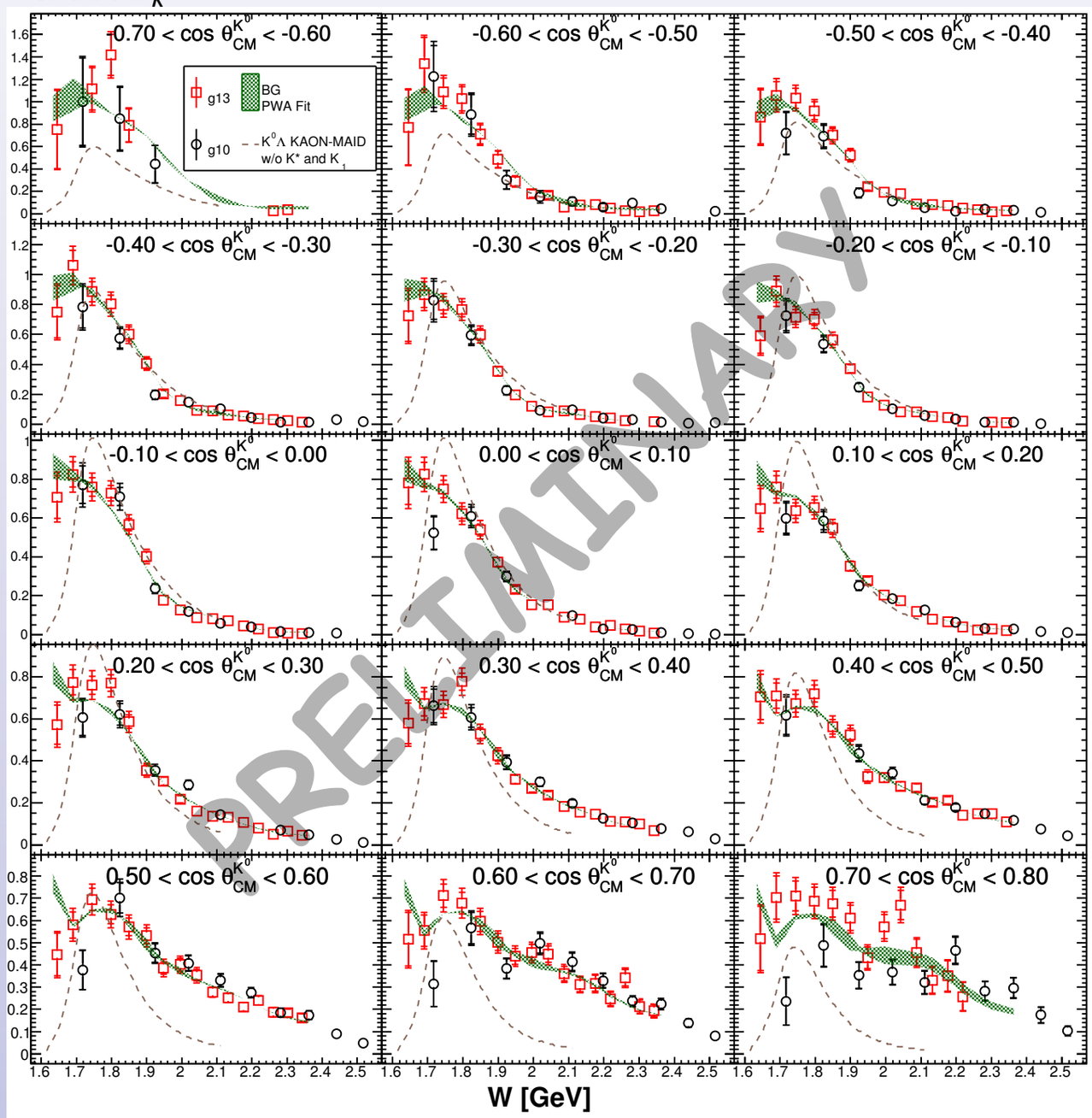
Extracting Nucleon-Resonance Information from Experimental Data



Baryon Spectroscopy

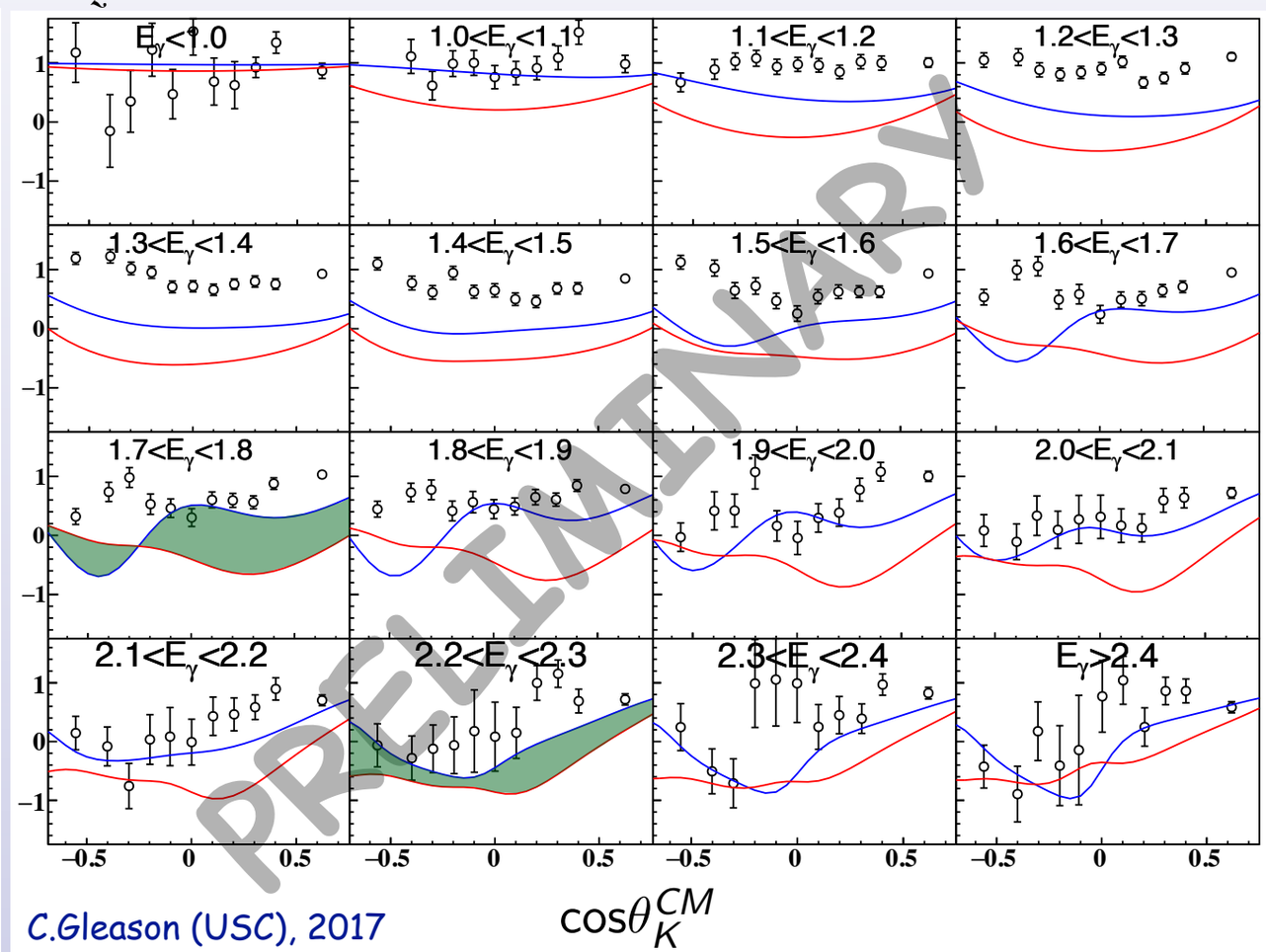
Examples of New Data (CLAS) $\vec{\gamma}(n) \rightarrow K^0 \vec{\Lambda}$

$$\frac{d\sigma}{d\cos\theta_K^{CM}}[\mu b]$$



N.Compton et al. (CLAS Collaboration), submitted to PRC,2017

C_z



C.Gleason (USC), 2017

C_z data not fit yet

Baryon Spectroscopy

Highlights of the Impact of CLAS Data (light-quark states)

Precision data on exclusive photoproduction of light-quark pseudo-scalar and vector mesons (

- Evidence for N(1900)$3/2^+$ (upgraded to *** in PDG).
- N(1710)$1/2^+$ is upgraded to **** in PDG.
- Evidence for Δ(2200)$7/2^-$ with mass 2180 (parity partner of Δ(1950)$7/2^-$).
- Evidence for the "missing" N(2000)$5/2^+$
- Other states: N(1880)$1/2^+$, N(1860)$5/2^+$, N(1895)$1/2^-$, N(1875)$3/2^-$, N(2060)$5/2^-$, N(2150)$3/2^-$, Δ(1940)$3/2^-$.
- Spin-parity measurement of Λ(1405)

Resonance ratings in PDG: * (evidence of existence is poor), ** (Evidence of existence is only fair), *** (Existence is very likely, but further confirmation of decay modes is required), **** (Existence is certain and properties are at least fairly well explored).

Baryon Spectroscopy

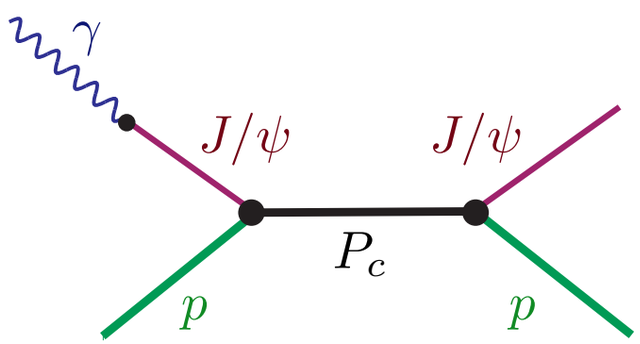
12-GeV Program

- Study of hybrid excitations in the light-quark baryon spectrum: $|qqqg\rangle$.

  E12-16-010.

- Study of S=−2, −3 baryons: spin-parity measurements, search for excited Ω^- states, new and missing Ξ states, ...

- Study of charm pentaquark states $P_c(4450)$, $P_c(4380)$ via $P_c \rightarrow J/\psi + p$ decay



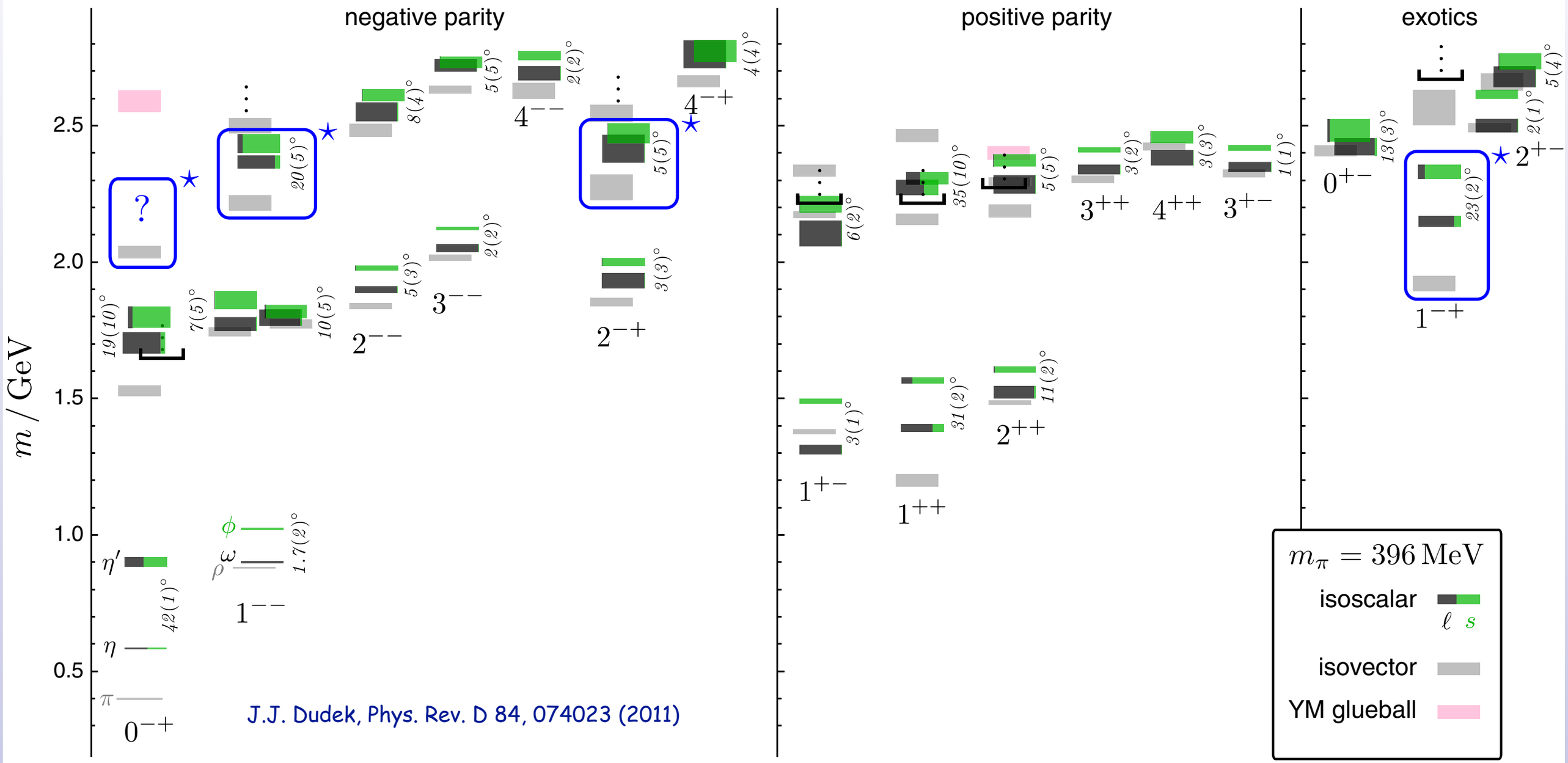
Nature of P_c?
charmonium-nucleon bound state?
hadronic molecule?
kinematic singularity?

- Hall B: tagged and untagged quasi-real photoproduction techniques (expected ~98 $P_c(4450)$ events/day). Extension of E12-12-001.

- Hall A: untagged real photoproduction (expected ~70 $P_c(4450)$ events/day). E12-16-007.

Meson Spectroscopy

Establish the Excited Meson Spectrum and Search for Exotic Mesons



J.J. Dudek, Phys. Rev. D 84, 074023 (2011)

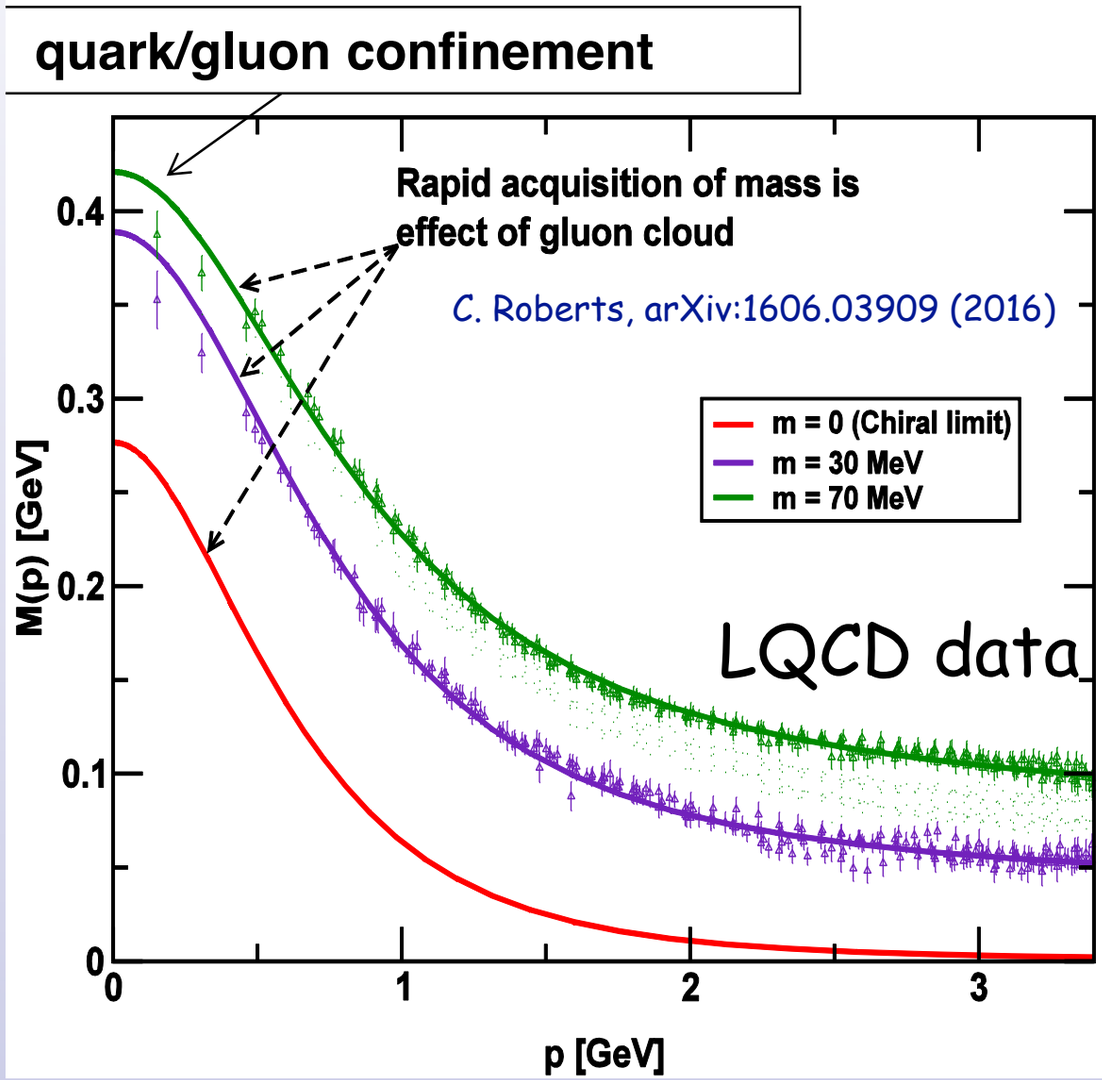
LQCD prediction of the light-quark meson spectrum: $q\bar{q}$, $q\bar{q}g$, glueball

CLAS12 (Hall B) and **GlueX** (Hall D) will probe the mass range 2.0 - 2.5 GeV for such states via exclusive meson photoproduction and multi-particle final states, followed by Partial-Wave Analysis..

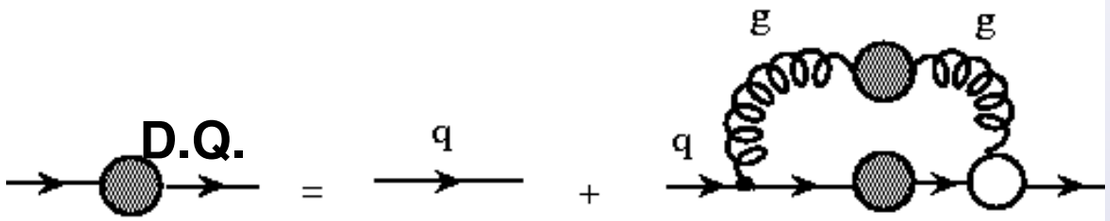
Transition Form Factors

Transition Form Factors N→N*

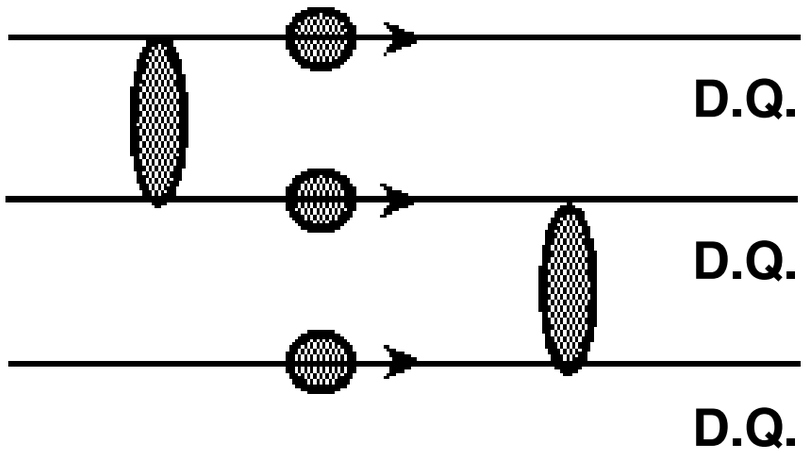
Dynamical constituents of the nucleon and its excited states at varying distance scales



Emergence of dressed dynamical quarks:



N/N* states as the bound systems of dressed dynamical quarks:

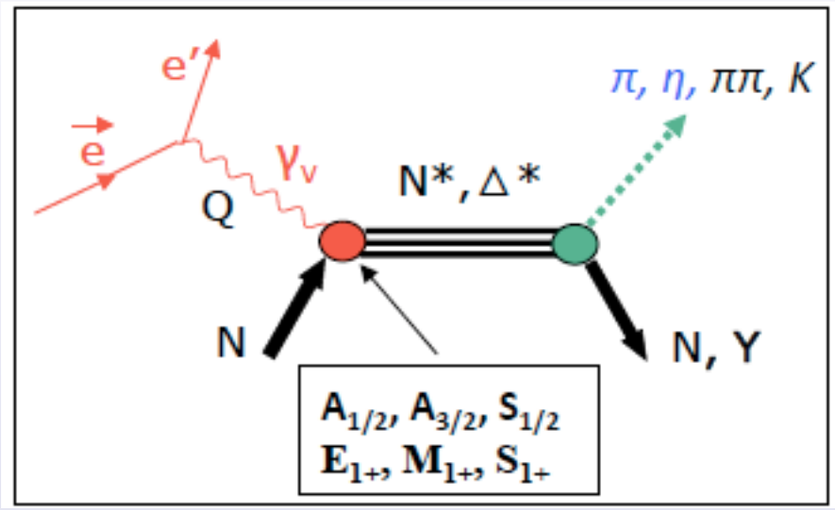


More than 98% of the constituent-quark (N/N*) mass is generated non-perturbatively through its coupling to a low-momentum pion cloud. The Higgs mechanism accounts for less than 2% of the N (N*) mass.

Momentum dependence of the constituent-quark mass reflects the transition from confinement to asymptotic freedom.

Transition Form Factors with CLAS

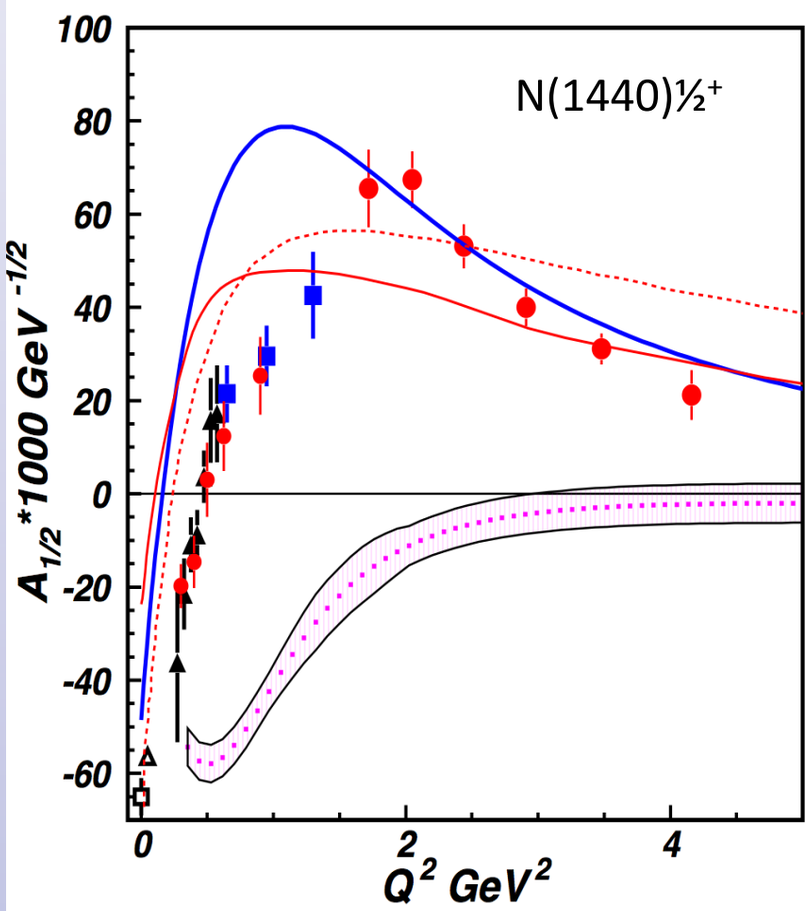
Q^2 Evolution of $\gamma^*NN^*(Q2)$ electro-couplings



Measured: differential, total cross sections, polarizations

Decomposition: σ_L, σ_T, σ_{TT}, σ_{LT}, $\sigma_{LT'}$

Reaction models used: obtain $\gamma^*NN^*(Q^2)$ electro-couplings



Nπ loops to model MB cloud: running quark mass in Light-Front (LF) Relativistic QM. I. G. Aznauryan, V.D. Burkert PR C 85 (2012) 055202.

Nσ loops to model MB cloud: frozen constituent-quark mass in LF RQM. I. T. Obukhovsky et al. PRD 89, (2014) 0140032.

Quark-core contributions from DSE/QCD
J. Segovia et al. PRL 115 (2015) 171801.

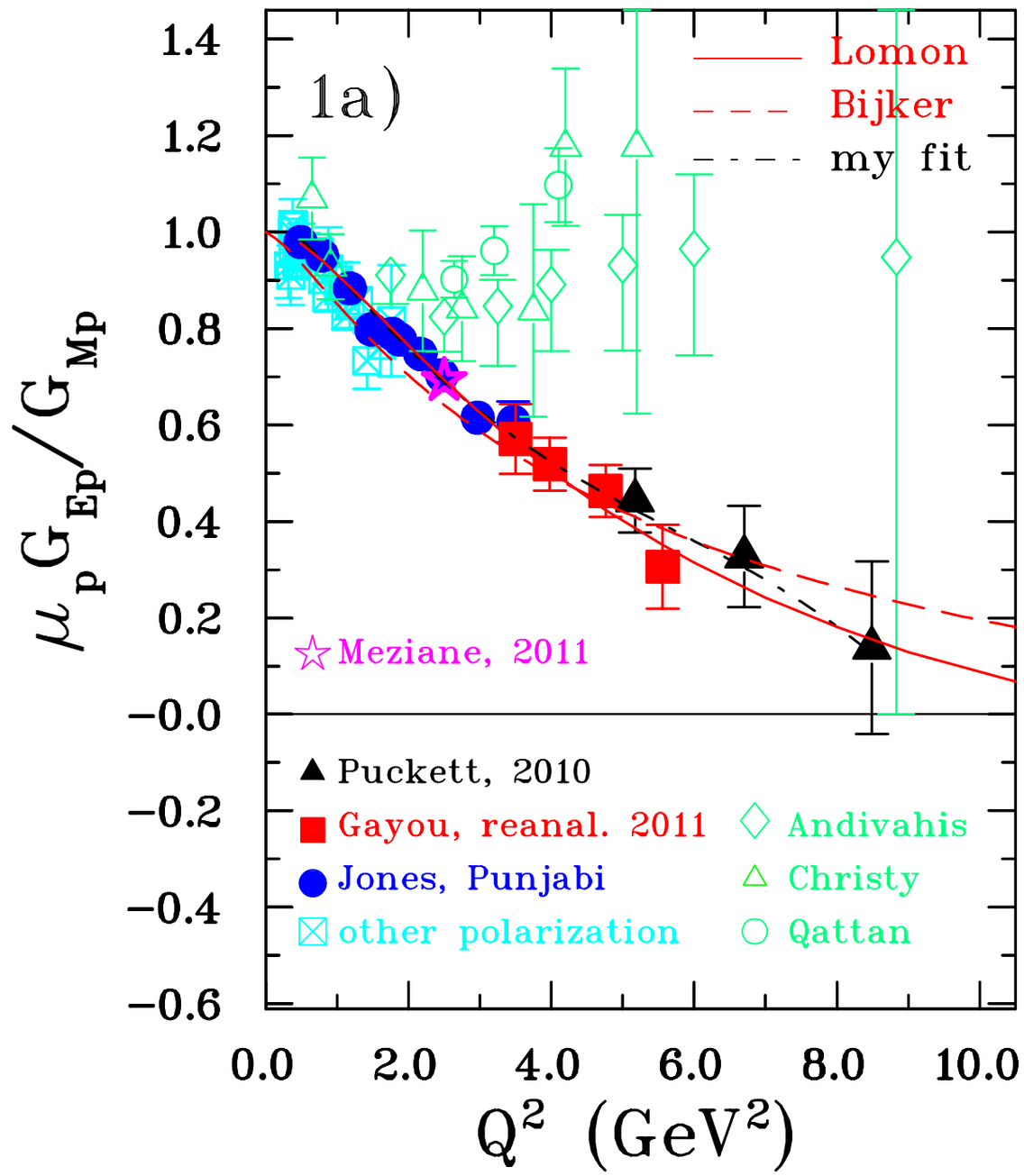
Meson Baryon cloud inferred from CLAS data as the difference between data and the quark-core evaluation in DSE/QCD.
V. Mokeev et al., PR C 93 (2016) 025206.

CLAS12 Program: E12-09-003, E12-06-108A, E12-16-010, E12-16-010A

Elastic Form Factors

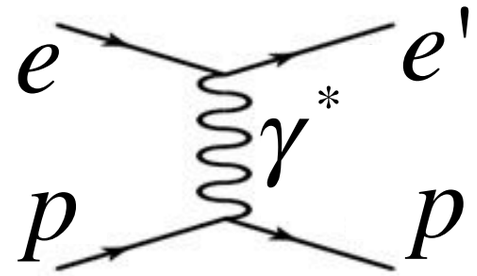
Nucleon Elastic Form Factors

Proton electric-charge distribution is different from its magnetization distribution



Rosenbluth Separation

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_{Mott}}\left(\frac{G_E^2(Q^2)+\tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2}\right)$$



$$\tau = \frac{Q^2}{4m_p^2}$$

Recoil Polarization Ratio

$$\vec{e}p \rightarrow e'\vec{p}$$

$$\frac{G_E}{G_M} = -\sqrt{\frac{\tau(1+\epsilon)}{2\epsilon}}\frac{P_t}{P_l}$$

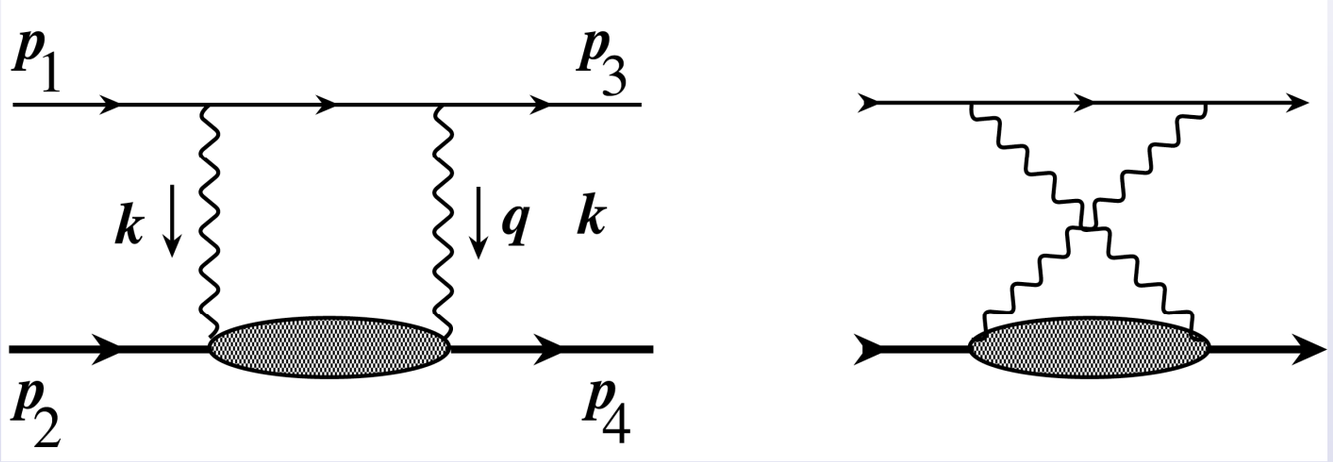
$$\epsilon = (1+2(1+\tau)\tan^2(\theta/2))^{-1}$$

P_l, P_t: recoil-proton polarizations longitudinal and transverse to proton momentum in the scattering plane

Ch. Perdrisat, AIP Conference Proceedings 1441, 153 (2012)

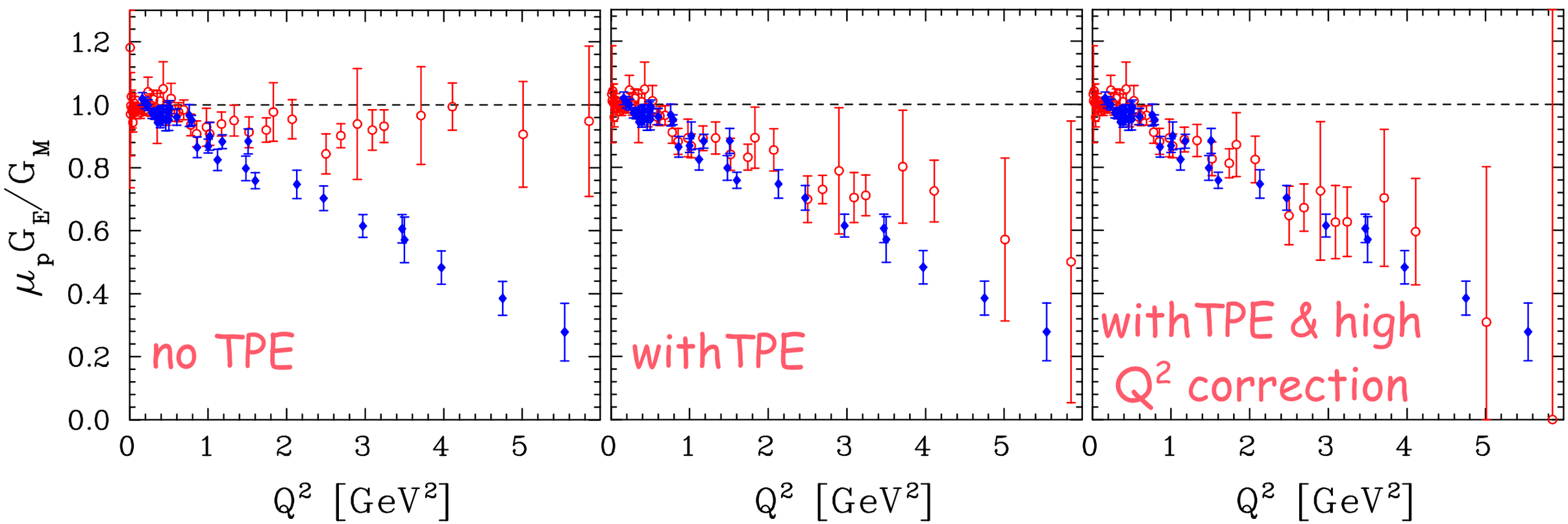
Two-Photon-Exchange Mechanism

Proposed to explain the difference between proton FF ratio from cross-section and from polarization data



TPE Corrections

- sizeable for the cross-section data (Rosenbluth separation)
- very small (≲3% at 5.5 GeV^2) for the polarization-ratio data



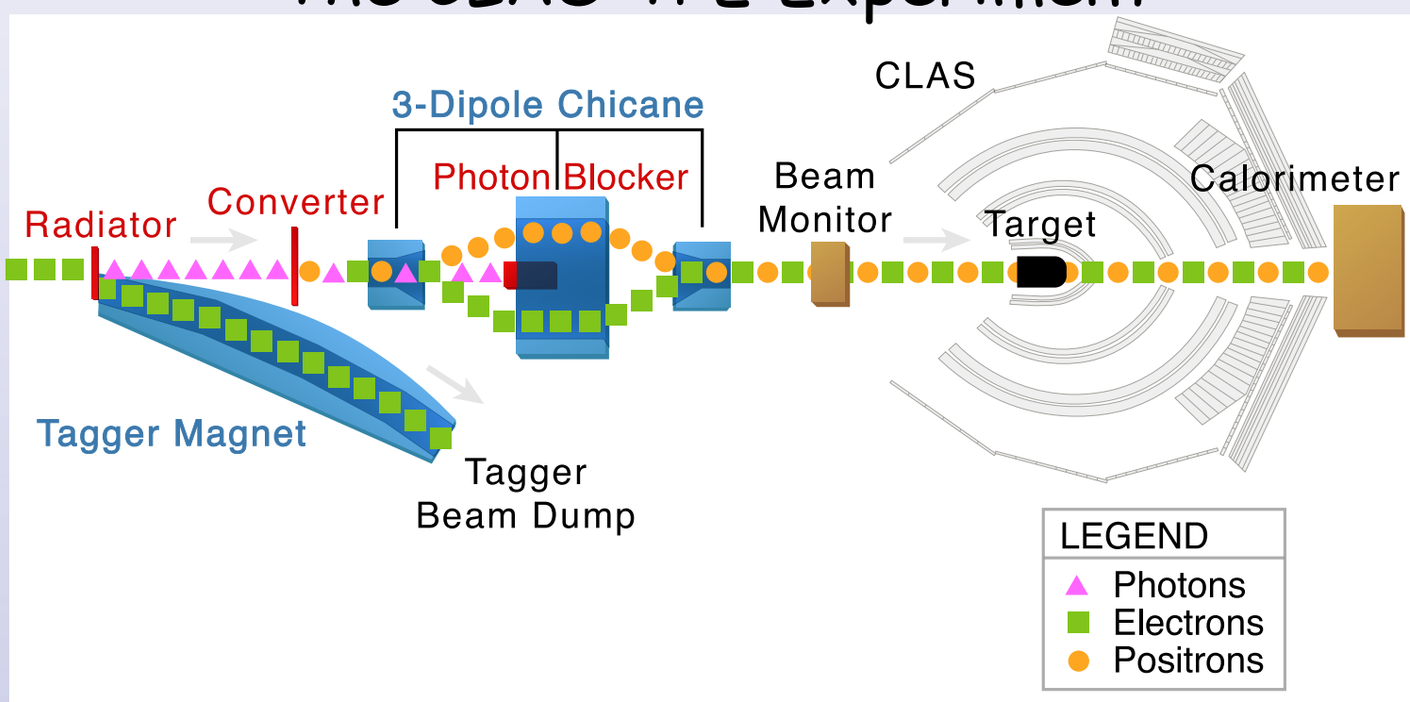
J. Arrington, P.G. Blunden, W. Melnitchouk, Prog. Part. Nucl. Phys. 66, 782 (2011)

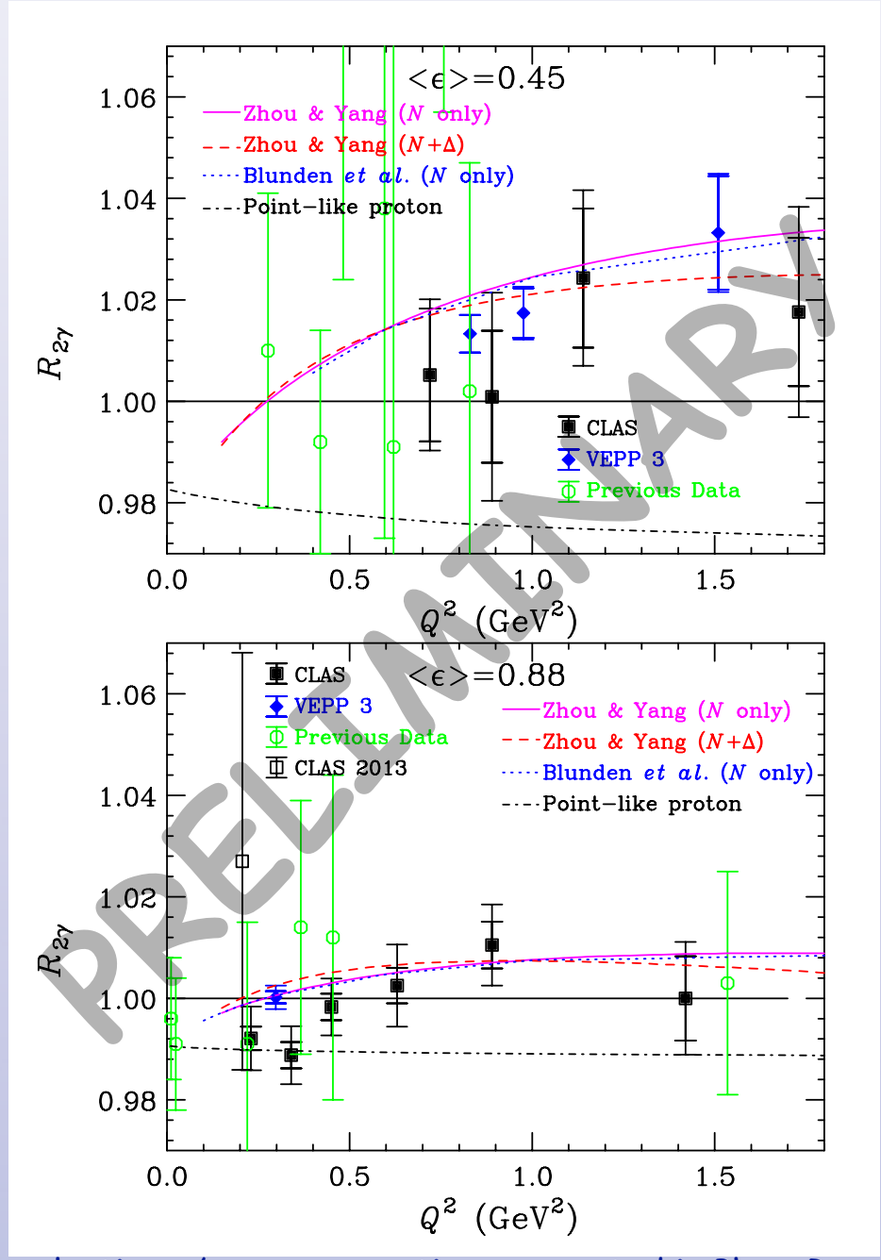
Two-Photon-Exchange Correction

Directly Accessed Experimentally in e^+p vs e^-p Elastic Scattering

$$R = \frac{\sigma^{e^+p}}{\sigma^{e^-p}} \approx \frac{1+\delta_{even}-\delta_{2\gamma}-\delta_{e.p.brems}}{1+\delta_{even}+\delta_{2\gamma}+\delta_{e.p.brems}} \approx \frac{1-2(\delta_{2\gamma}+\delta_{e.p.brems})}{1+\delta_{even}}, \quad R_{2\gamma} \approx 1-2\delta_{2\gamma}$$

The CLAS TPE Experiment





Extracted correction applied to e^-p cross section (Q^2=1.75 GeV^2) , followed by Rosenbluth separation

- $\mu_p G_E/G_M$= 0.910±0.060, uncorrected
- $\mu_p G_E/G_M$= 0.837±0.066, TPE corrected; consistent with polarization-ratio value of 0.789±0.042

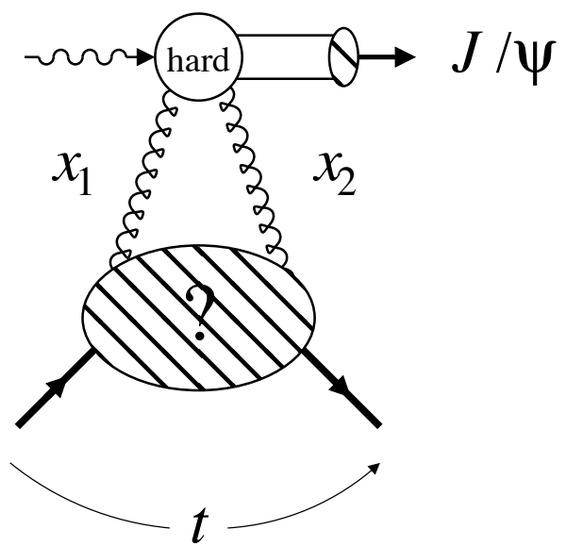
D. Rimal et al. (CLAS Collaboration), Measurement of two-photon exchange effect by comparing elastic e+/- p cross sections, accepted in Phys. Rev. C (2017).

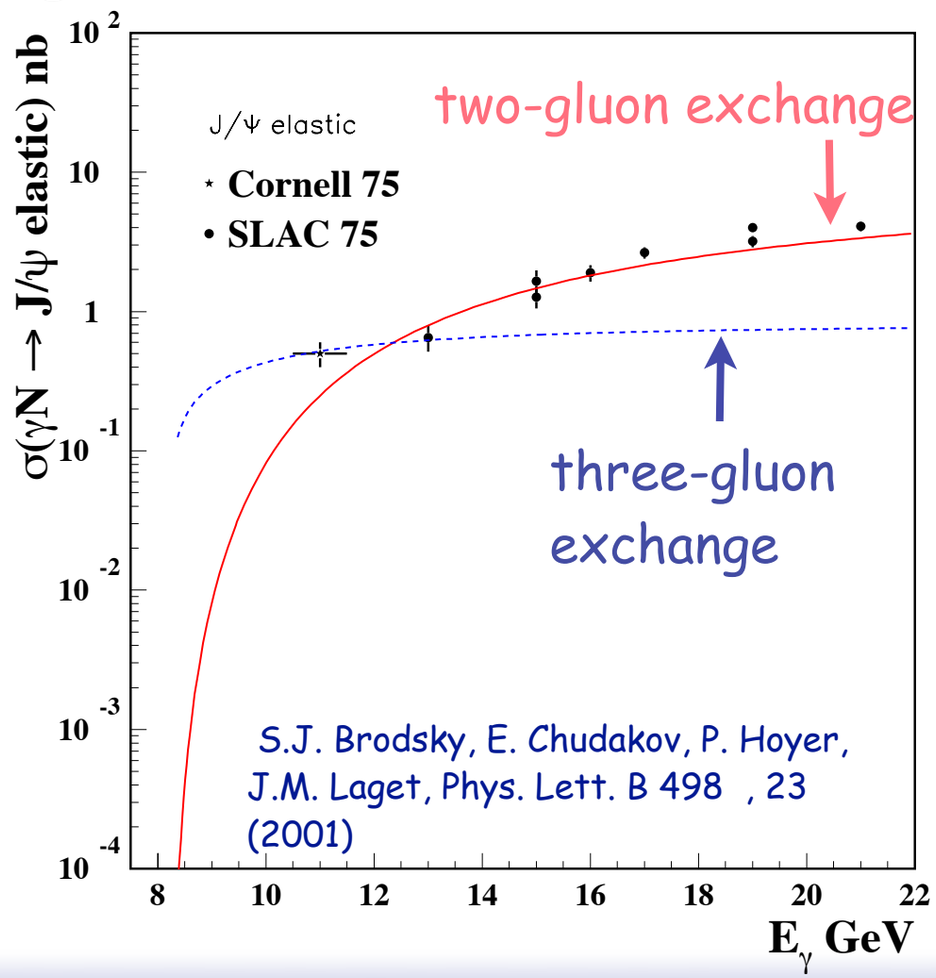
Near-Threshold J/ψ Photoproduction

Near-Threshold J/ψ Photoproduction at 12 GeV

Probing Non-Perturbative Gluon Fields in the Proton

- $E_{\gamma,thr}$=8.20 GeV, $|t_{min}|$=1.7 GeV^2: small transverse-size probe ($r_\perp \sim 1/m_c$=0.13 fm), small impact parameter ($b \sim 1/|t|^{1/2} \sim$0.2 fm).
- Reaction cross section sensitive to short-distance dynamics in the proton and multi-gluon exchange mechanisms; J/ψ-N cross section



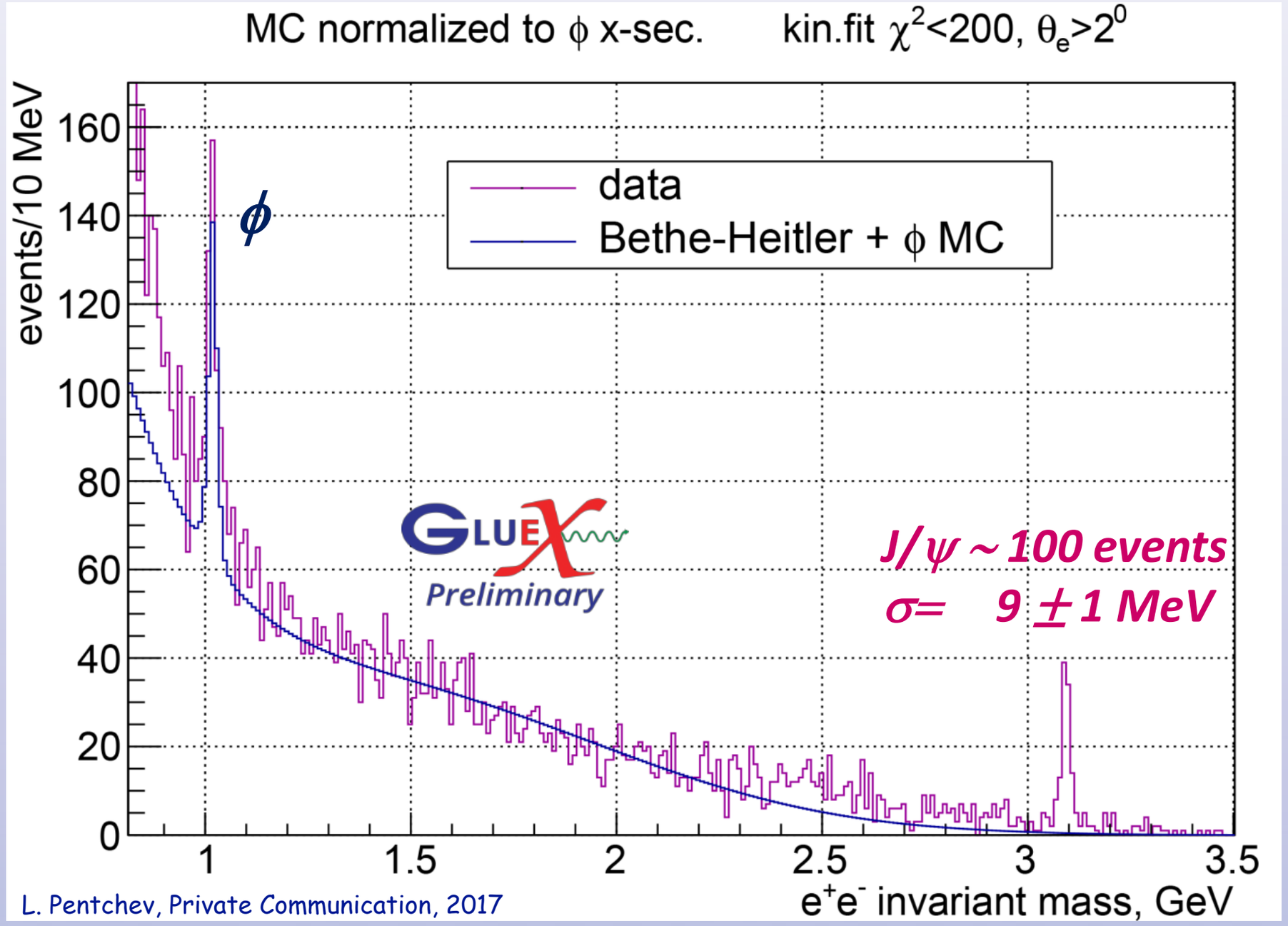


Vigurous Program:
Proton Target:
CLAS12: E12-12-001
Hall A: PR12-12-006
Hall C: E12-16-007
Nuclear Targets:
Hall C: PR12-07106
Planned d target:
CLAS12: LOI2017

Near-Threshold J/ψ Photoproduction at 12

The very first J/ψ Detected at JLab with GlueX

- Exclusive measurement of $\gamma p \rightarrow J/\psi + p$, $J/\psi \rightarrow e^+e^-$ (all final-state particles detected)
- Kinematic fit using tagged-photon energy; e+ e- PID using calorimeters
- Data from first (engineering) run in 2016

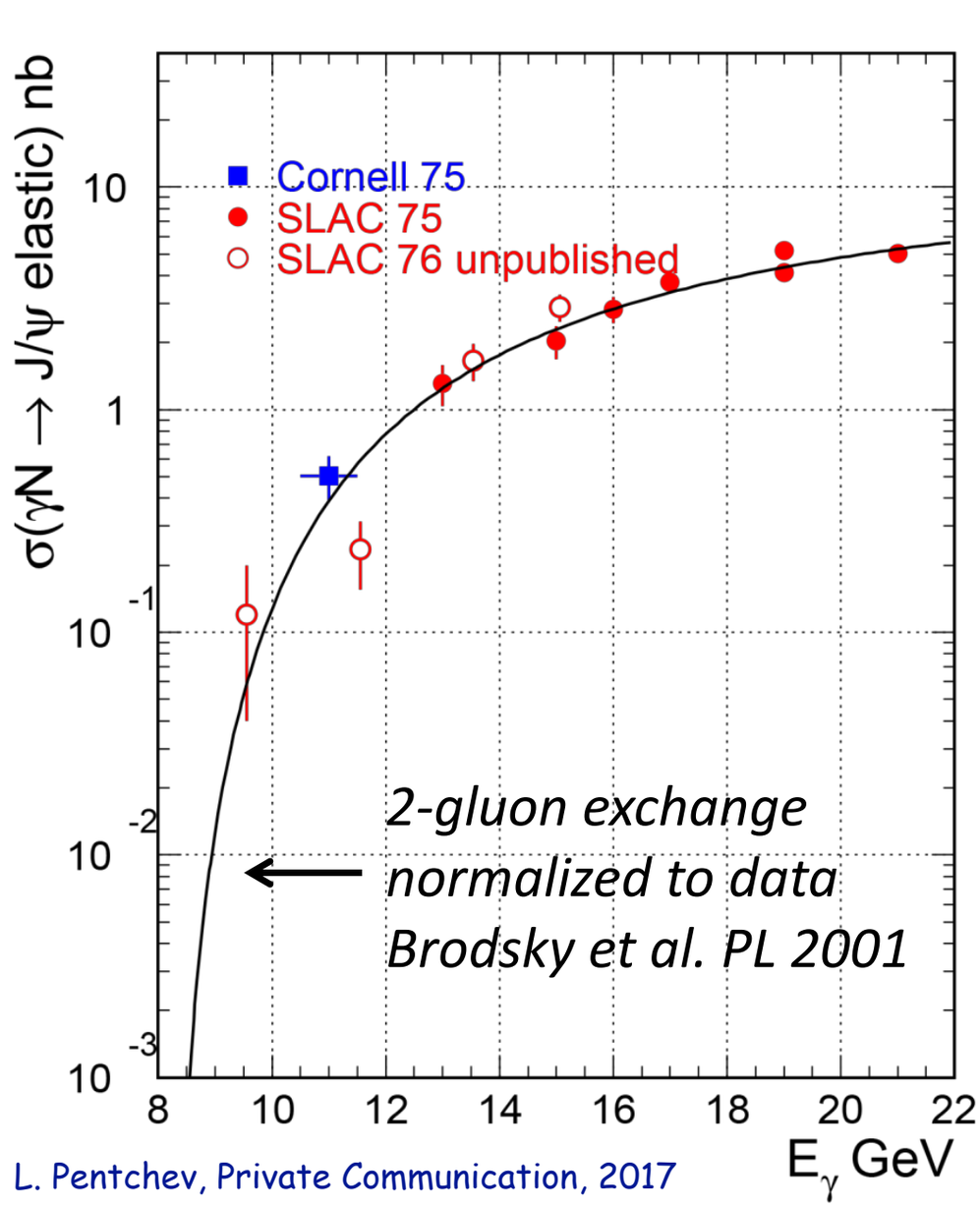


L. Pentchev, Private Communication, 2017

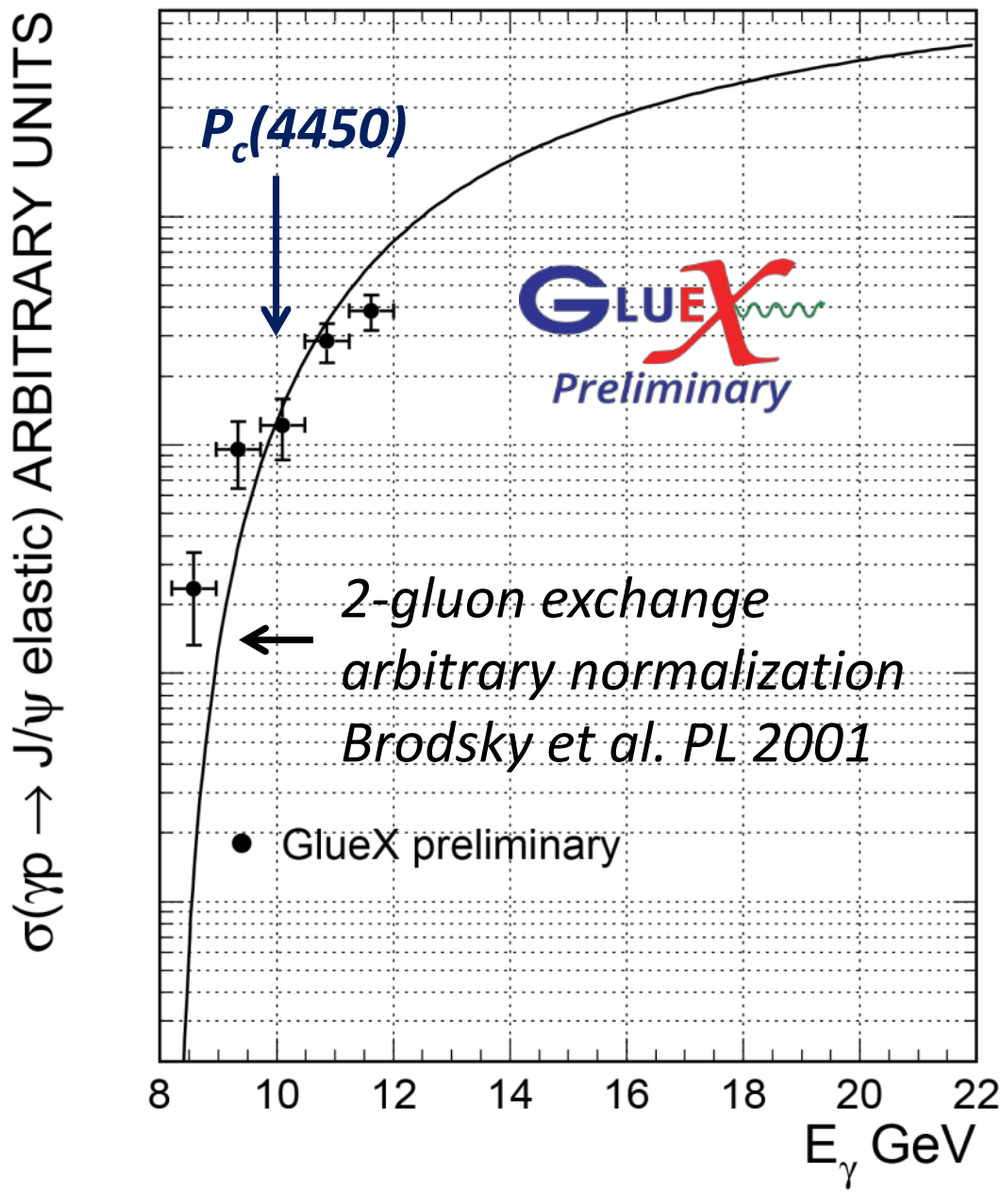
Near-Threshold J/ψ Photoproduction at 12

The very first J/ψ Detected at JLab with GlueX

- First time cross-section measurements down to the threshold, sensitive to gluons at high x
- Can set limits on pentaquark Pc(4450) yield (6 MeV mass resolution)



L. Pentchev, Private Communication, 2017



Summary

JLab Photoproduction Scientific Program

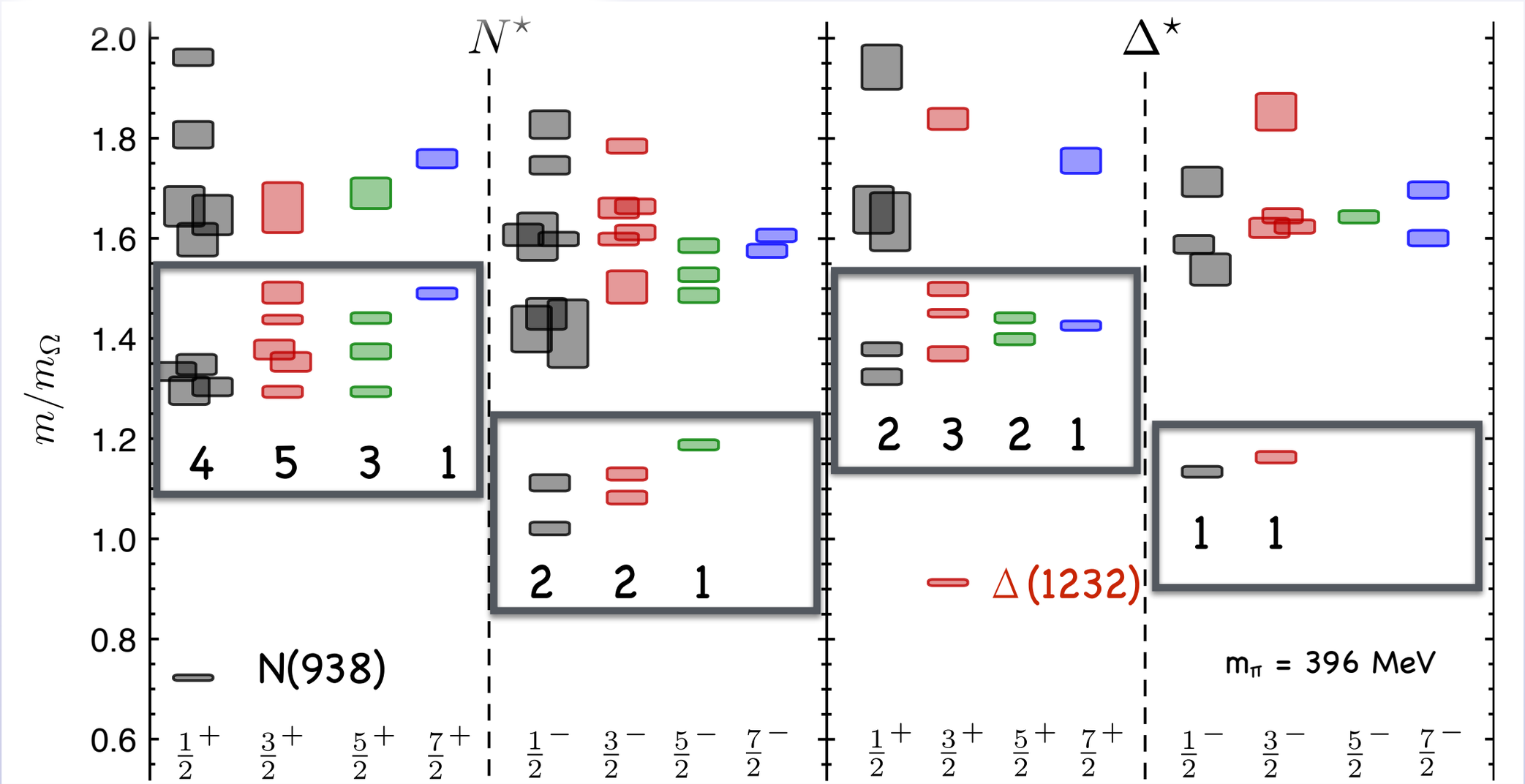
- Baryon Resonances
  - CLAS has been providing precision observables on exclusive meson photoproduction off the nucleon leading to the discovery of several new states and the confirmation of poorly known states.
  - Exclusive electro-production data have provided new insight into the scale dependence of effective degrees of freedom of resonances.
  - Extensive program for studies of hybrid, S=-2, -3 resonances at 12 GeV
- Meson Spectroscopy
  - Studies of hybrid and exotic mesons with GlueX and CLAS12
- Elastic Proton Form Factors
  - Are a highlight of the 6-GeV program; Show importance of 2-photon exchange mechanisms; Extended studies at 12 GeV.
- Near Threshold J/ψ Photoproduction off proton, deuteron, and heavier targets: non-perturbative gluon dynamics, J/ψ-N cross section, charm pentaquarks.

Backup Slides

Baryon Spectroscopy

Resonance Spectrum in Lattice QCD

Hadron-spectrum collaboration



LQCD predicts states with the same quantum numbers as CQMs with underlying SU(6) x O(3) symmetry; more states than have been identified experimentally.

R.G. Edwards, J.J. Dudek, D.G. Richards, and S.J. Wallace, Phys. Rev. D 84, 074508 (2011)

Near-Threshold J/ψ Production at JLab 12

Approved Experiments

Experiment	Beam	Target	Detector	Detect	Days
PR12-12-001	γ (QR)	p	CLAS12	e^+, e^-, p	120
PR12-12-006	e-	p	SoLID	e^+, e^-, p, e' e^+, e^-, e'	60
PR12-16-007	γ (R)	p	Hall C	e^+, e^-	11
PR12-07-106	γ (QR)	p, d, Be, Ca, Al, Cu, Ag, Au	Hall C	e^+, e^-, μ^+,μ^-	CA

CLAS12 Detector Overview

- General
  - 11 GeV polarized electron beam
  - Luminosity: 10^{35} $cm^{-2}s^{-2}$
- Forward Detector (toroidal spectrometer)

Charged Tracks	Neutral Tracks
Ang. Acceptance: 5° - 35°	Ang. Acceptance: 5° - 40° (neutron)
0.5% - 1% for 5 GeV track	Energy resolution: $< 0.1/\sqrt{E}$
1 mrad for the electron track	< 4 mrad

- Central Detector (solenoid magnet): momentum range: 0.3 - 1.3 GeV/c

Charged Tracks	Neutral Tracks
Ang. Acceptance: 35° - 125°	40° - 125° (neutron)
5% for 1 GeV track	Energy resolution: < 5%
5 - 10 mrad	< 10 mrad