Studies of Baryon Structure and Baryon Interactions at Thomas Jefferson National Accelerator Facility

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for the CLAS Collaboration

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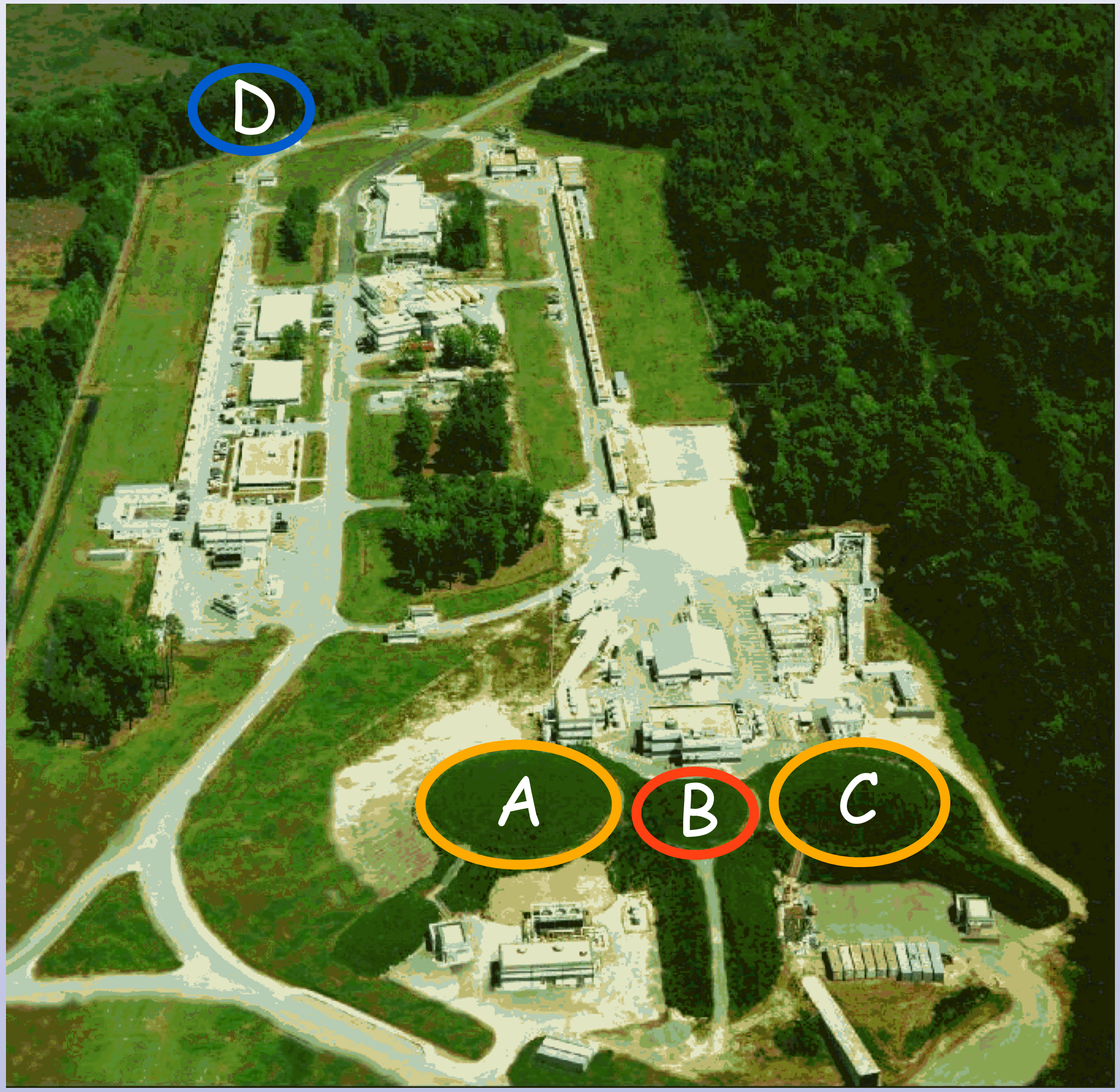
61st DAE-BRNS Symposium on Nuclear Physics, Dec 2 – 9, 2016, SINP

Research supported in part by the U.S. National Science Foundation

Thomas Jefferson National Accelerator Facility

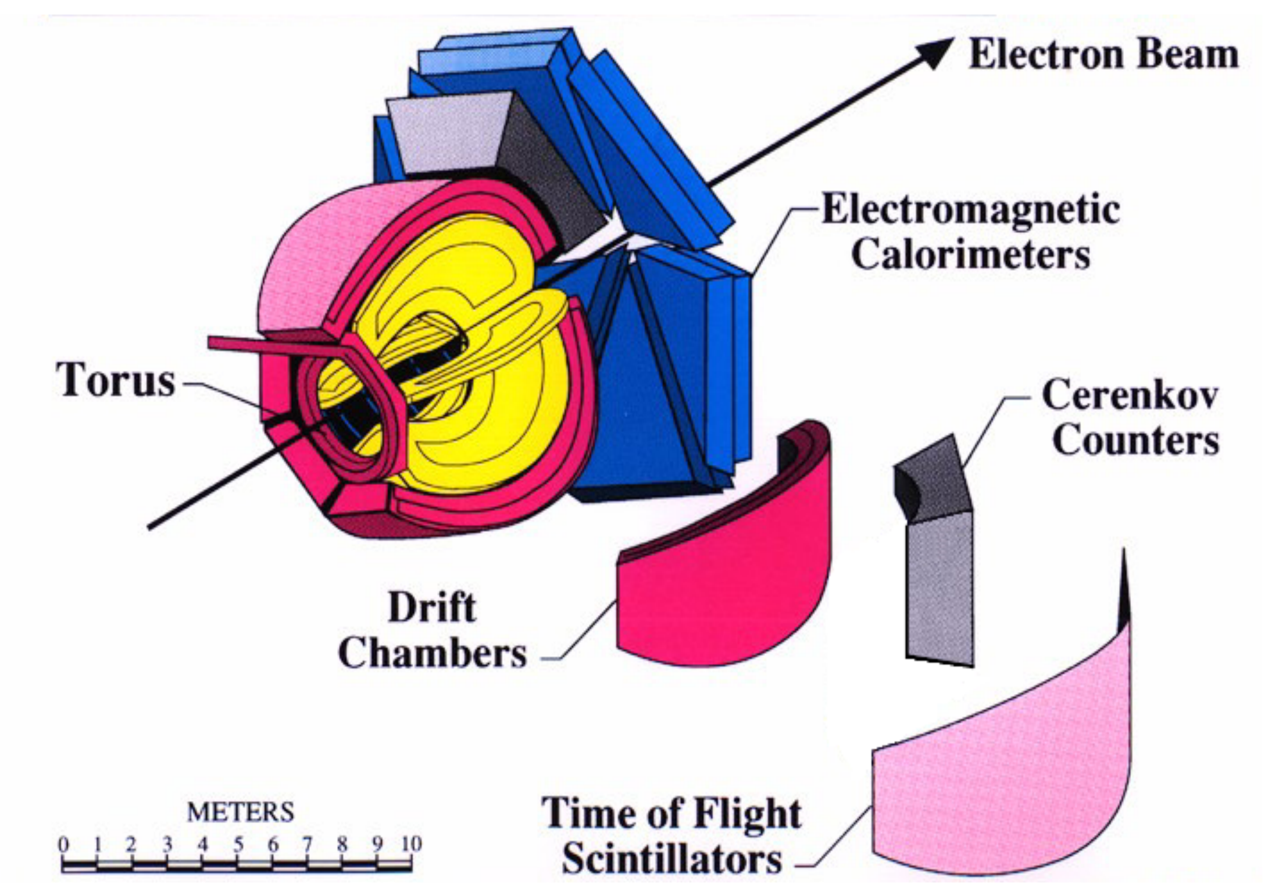
Premier U.S. Facility to study Quantum Chromodynamics: quantitative understanding of the internal structure of nucleons and nuclei

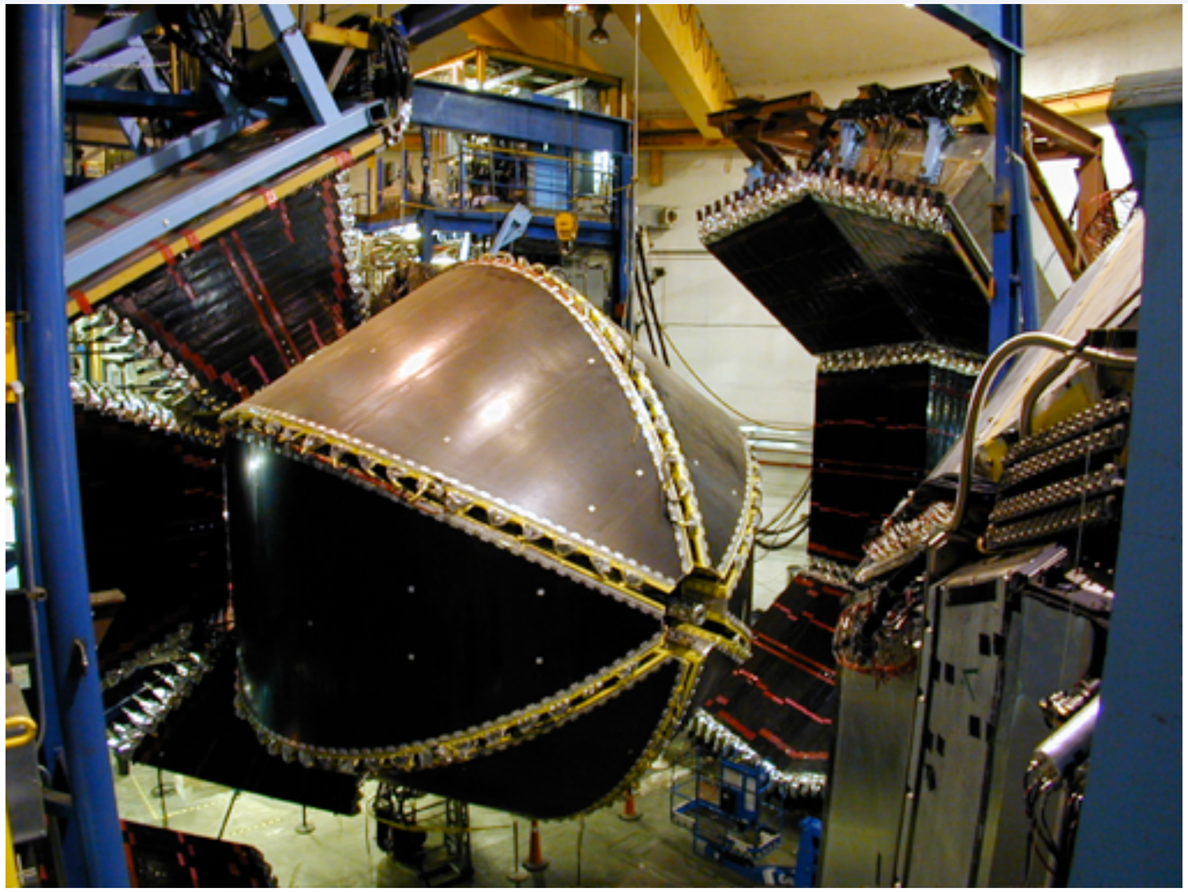


JLab in Newport News, VA

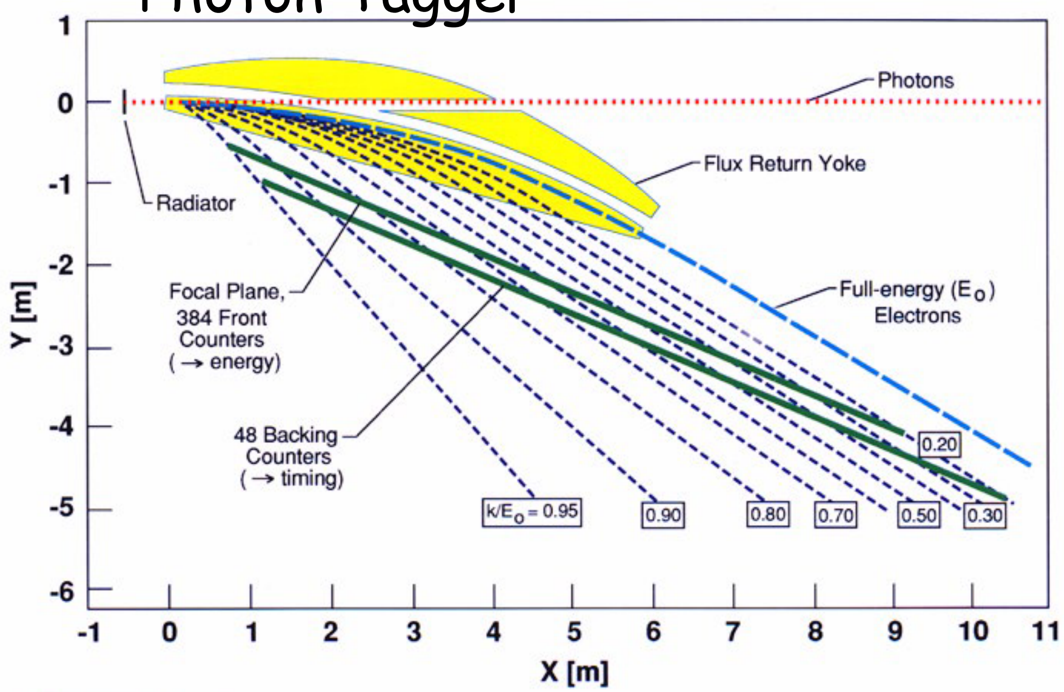
- Polarized c.w. electron beam: $P_e \sim 86\%$
- Beam energies up to E_0 = 6 GeV (recently upgraded to 12 GeV)
- Four experimental Halls A, B, C, and D

The CEBAF Large Acceptance Spectrometer CLAS





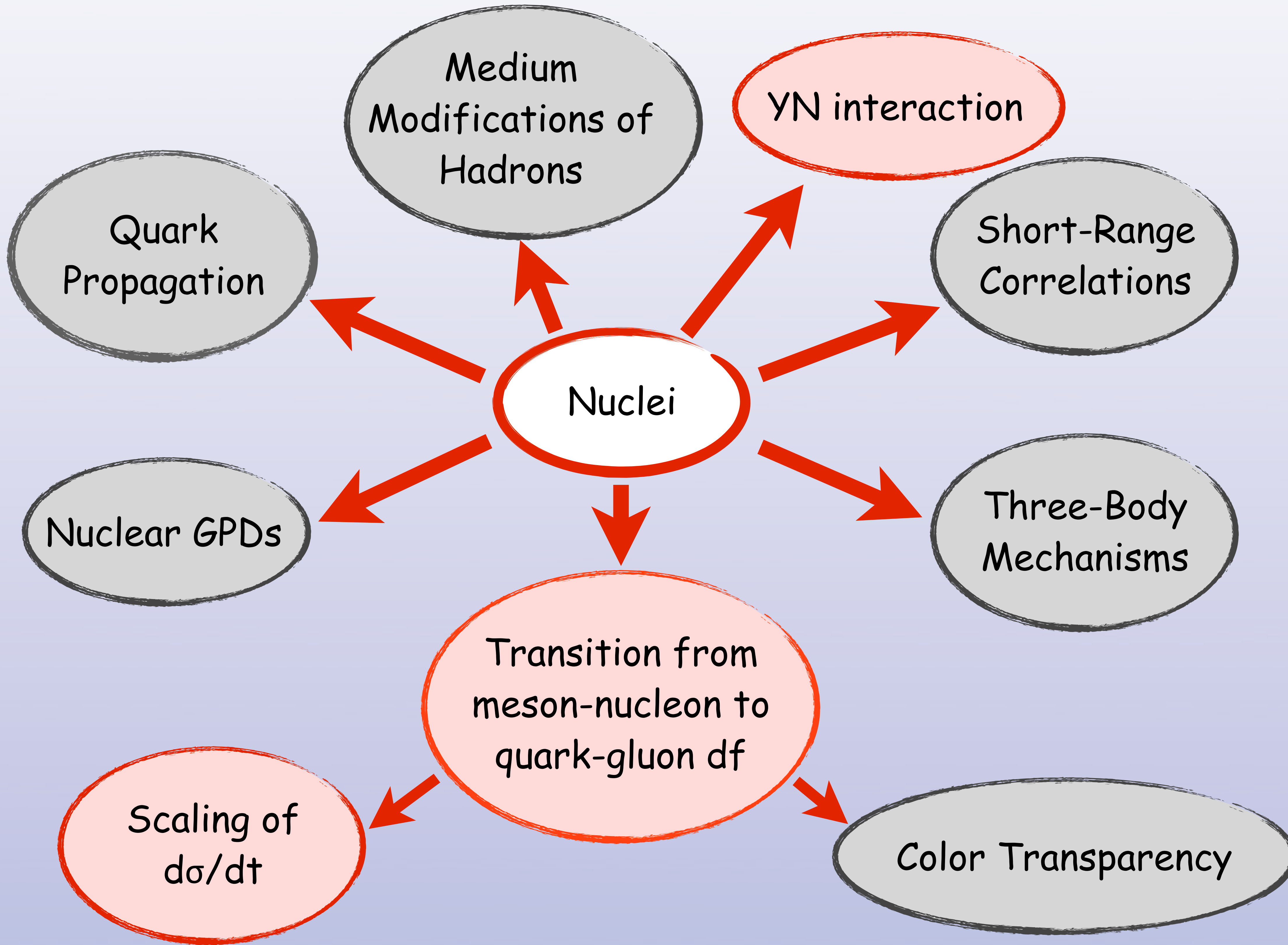
Photon Tagger



Performance

- $L = 10^{34}\ cm^{-2}\ s^{-1}$
- $\int B\, dl = 2.5$ T m
- $\Delta p/p \sim 0.5 - 1$ %
- $\sim 4\pi$ acceptance
- Best suited for charged multiparticle final states
- Bremsstrahlung Photon Tagger ($\Delta E_\gamma / E_\gamma \sim 10^{-3}$)

Physics of Nuclei with the CLAS



Outline

Transition from Hadronic to Partonic Degrees of Freedom

Photodisintegration of Few-Nucleon Systems

Hyperon-Nucleon Interaction

Final-State Interactions in Strangeness Photoproduction

Future Perspectives: Studies at 12 GeV

Near-Threshold J/ψ Photoproduction off Deuteron

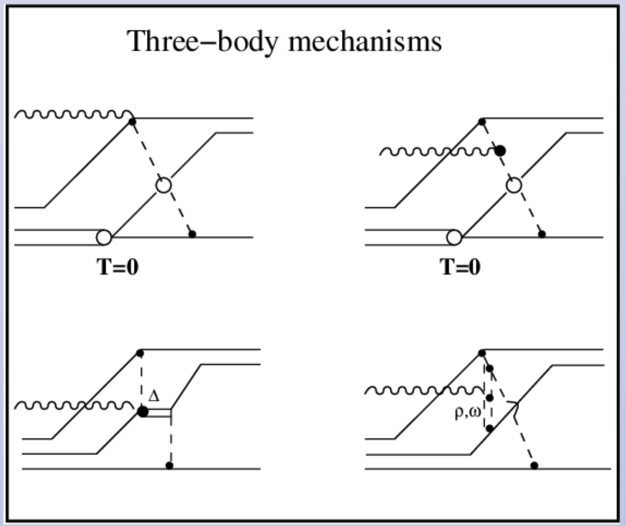
Transition from Hadronic to Partonic Degrees of Freedom

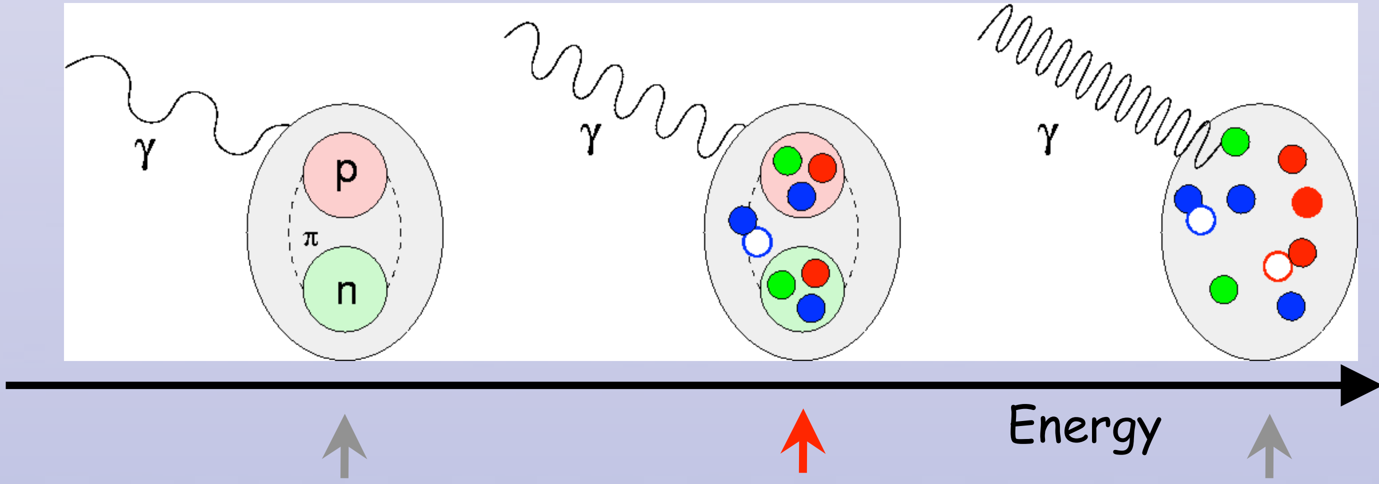
Photodisintegration of Few-Nucleon Systems at Medium Energies

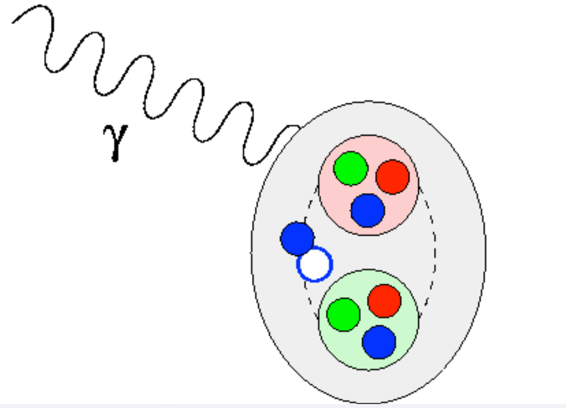
Large Momentum Transfer Exclusive Processes (Hard Scattering)

Short-range dynamics (quark content of nuclei)

Transition from hadronic to partonic degrees of freedom







Studying the Strong Interaction through Hard Scattering

- Identify large-momentum-transfer (hard) subprocess
- Apply factorization (separation of scales):
  - Apply pQCD to hard subprocess
  - Non-perturbative contributions expressed through measurable/calculable quantities

Why Hard Photodisintegration?

- Real photon: $Q^2=0$. Factorization not proved.

- Hard scale is given by the overall momentum transfer in the reaction (size of interaction volume): search for onset of partonic dynamics in nuclei

  - experimental tool: dimensional scaling of invariant cross sections

Dimensional Scaling Laws in Nuclear Physics

Brodsky, Farrar (1973): from dimensional analysis and perturbative QCD

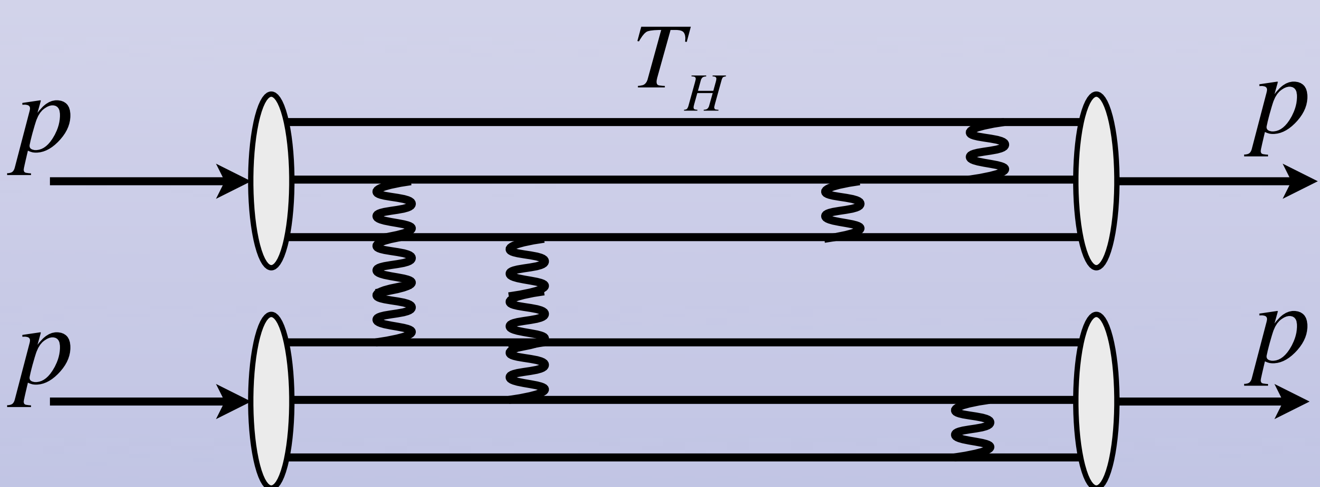
- At high t and high s, power-law behavior of the invariant cross section of an exclusive process A + B $\rightarrow$ C + D at fixed CM angle:

$$\frac{d\sigma}{dt} = \frac{1}{s^{n-2}} f(t/s)$$

where n is the total number of the initial and final elementary fields.

- The energy dependence of the scattering amplitude given by the 'hard-scattering amplitude' T_H for scattering collinear constituents from the initial to the final state

$$pp \rightarrow pp \equiv 3q3q \rightarrow 3q3q$$



$$\frac{d\sigma}{dt} \sim \frac{|M|^2}{s^2},$$

$$\text{where } [M] = [T_H] = \left(\sqrt{s}\right)^{4-n}$$

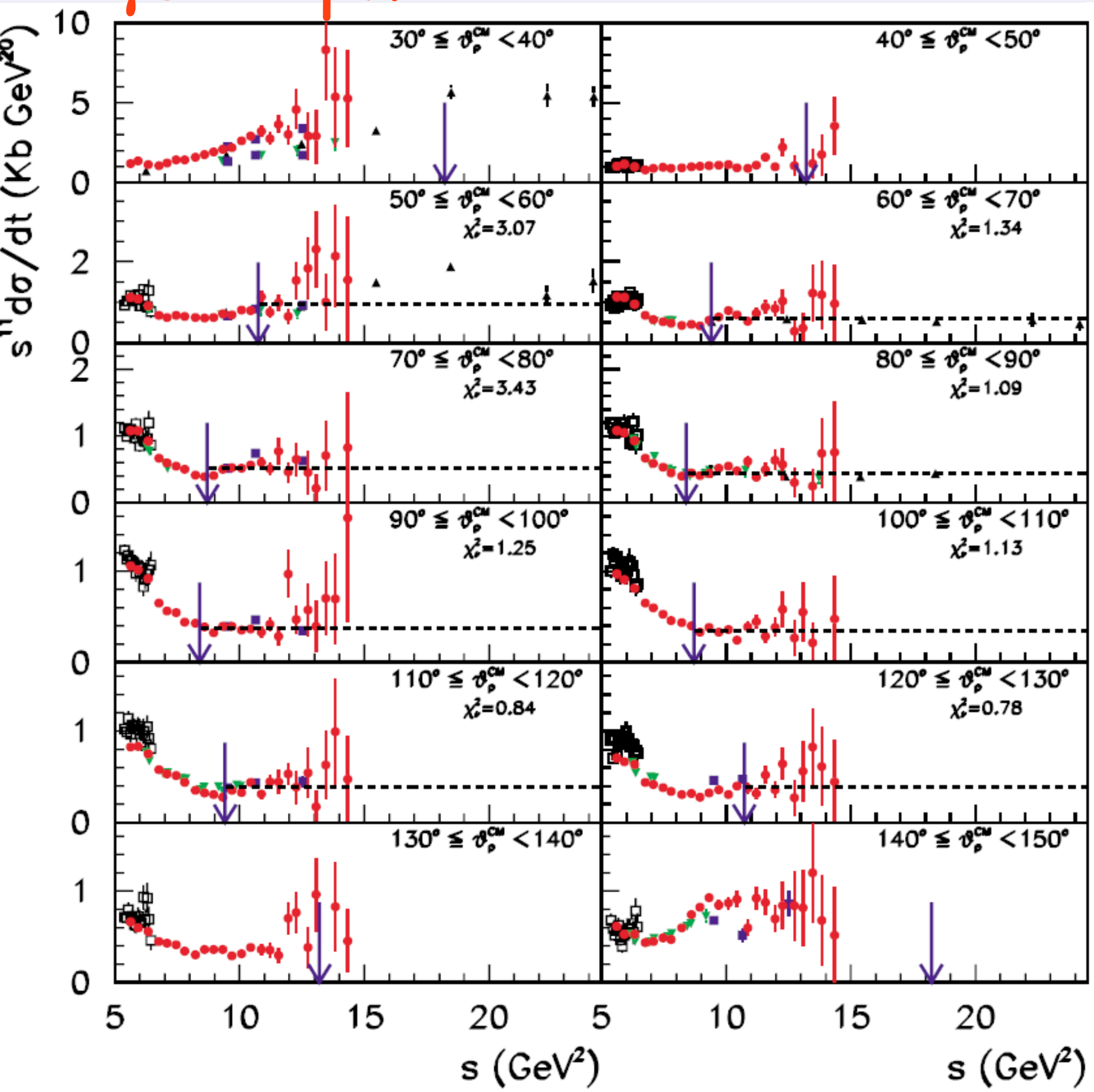
$$\frac{d\sigma}{dt} \sim \frac{1}{s^{n-2}}$$

S.J. Brodsky and G.R. Farrar, Phys. Rev. Lett **31**, 1153 (1973); S.J. Brodsky and J.R. Miller, Phys. Rev. C **28**, 475 (1983)

Previous Experimental Findings in Two-Nucleon Systems

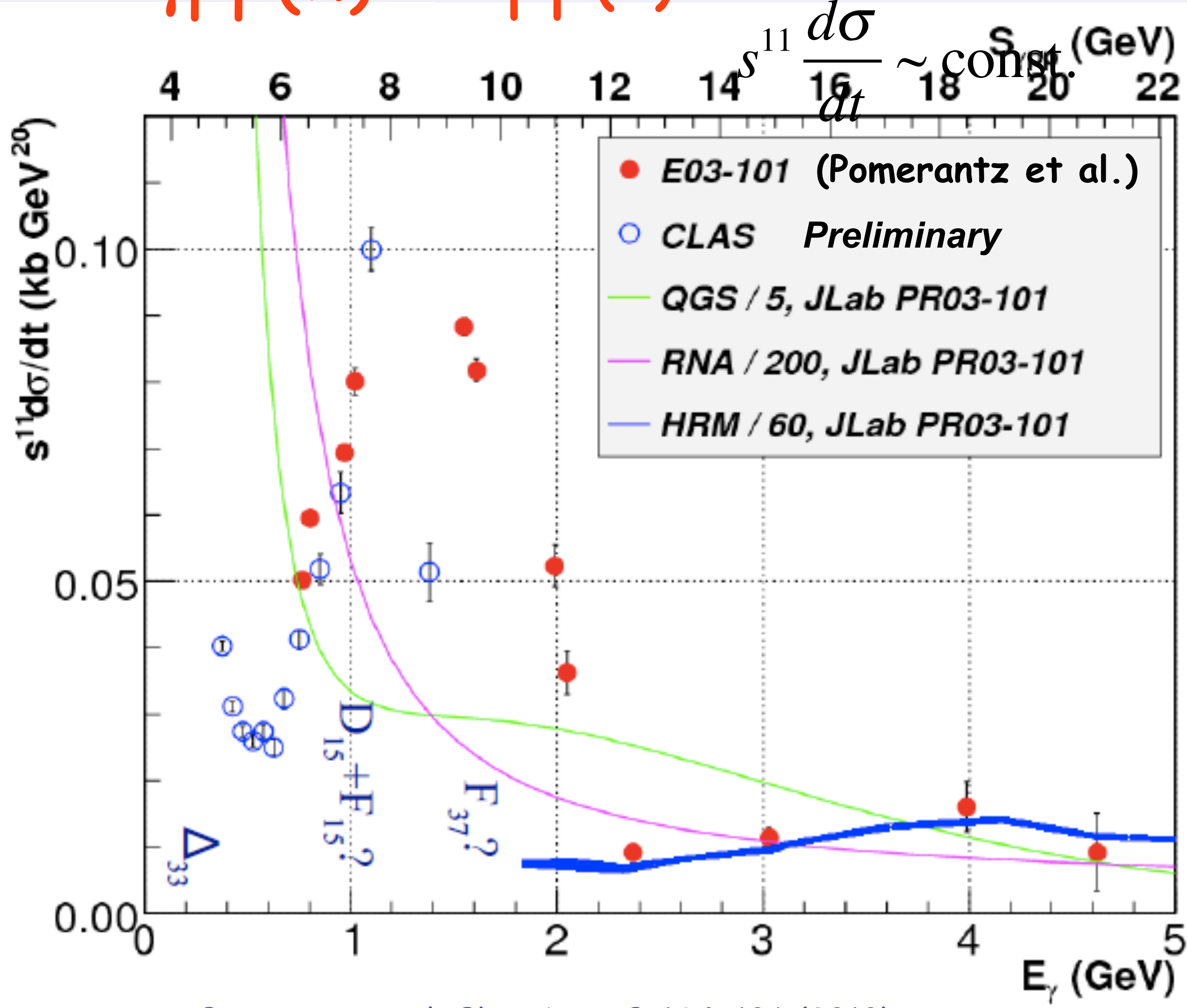
$$s^{11}\frac{d\sigma}{dt} \sim \text{const.}$$

$\gamma d \rightarrow pn$



P. Rossi et al., Phys. Rev. Lett. **94**, 012301 (2005)

$\gamma pp(n) \rightarrow pp(n)$



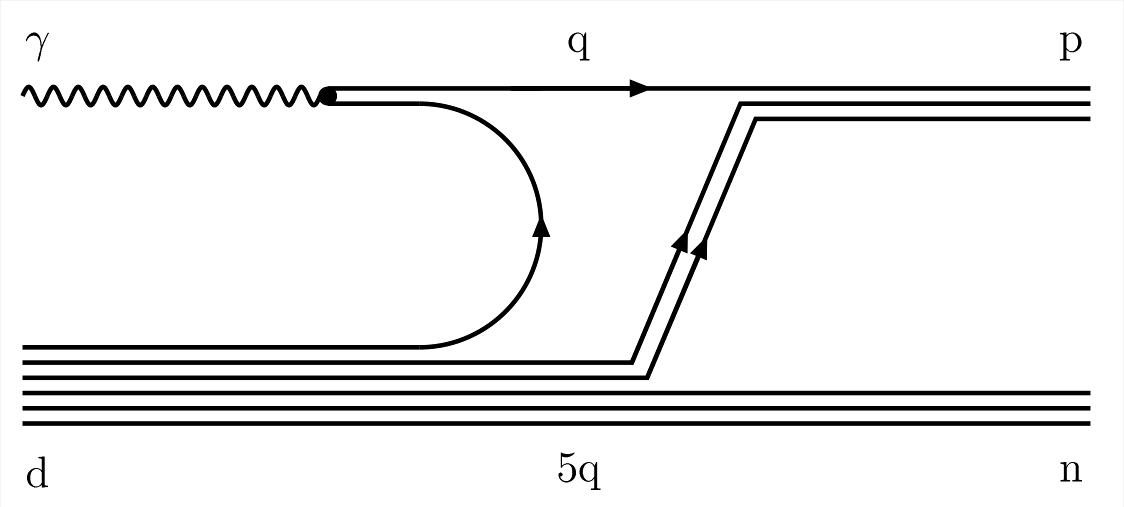
I. Pomerantz et al., Phys. Lett. B **684**, 106 (2010)
Figure from R. Gilman

- Scaling at $p_T > 1.1$ GeV/c
- Scaling at $p_T > 1.4$ GeV/c

Dynamics of Hard Deuteron Photodisintegration in the Scaling Regime

Quark Gluon String Model (QGSM)

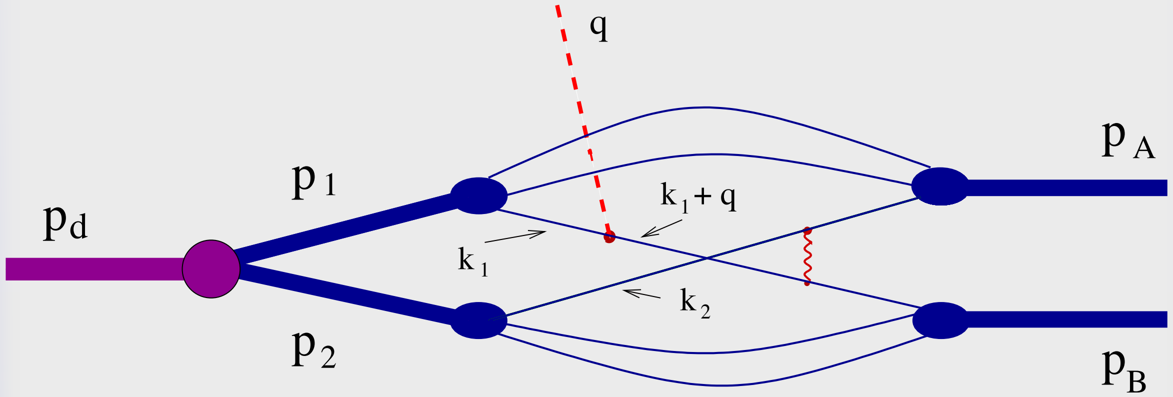
- Three quark exchange with arbitrary number of gluon exchanges
- Nonlinear Regge trajectories



V. Y. Grishina, L. Kondratyuk, W. Cassing, E. De Sanctis, M. Mirazita, F. Ronchetti, and P. Rossi, Eur. Phys. J. A 19, 117 (2004).

Hard Rescattering Model (HRM)

- Photon absorbed by a quark in one nucleon, followed by a hard scattering off a quark in the second nucleon
- Requires phenomenological input on pn elastic scattering



L.L. Frankfurt, G.A. Miller, M.M. Sargsian, and M.I. Strikman, Phys. Rev. Lett. 84, 3045 (2000)

Previous Cross-Section and Polarization-Transfer cannot select between the models → **New Spin Observable is expected to make an impact.**

Dynamics of Hard Deuteron Photodisintegration in the Scaling Regime

New Spin Observable: Beam Spin Asymmetry

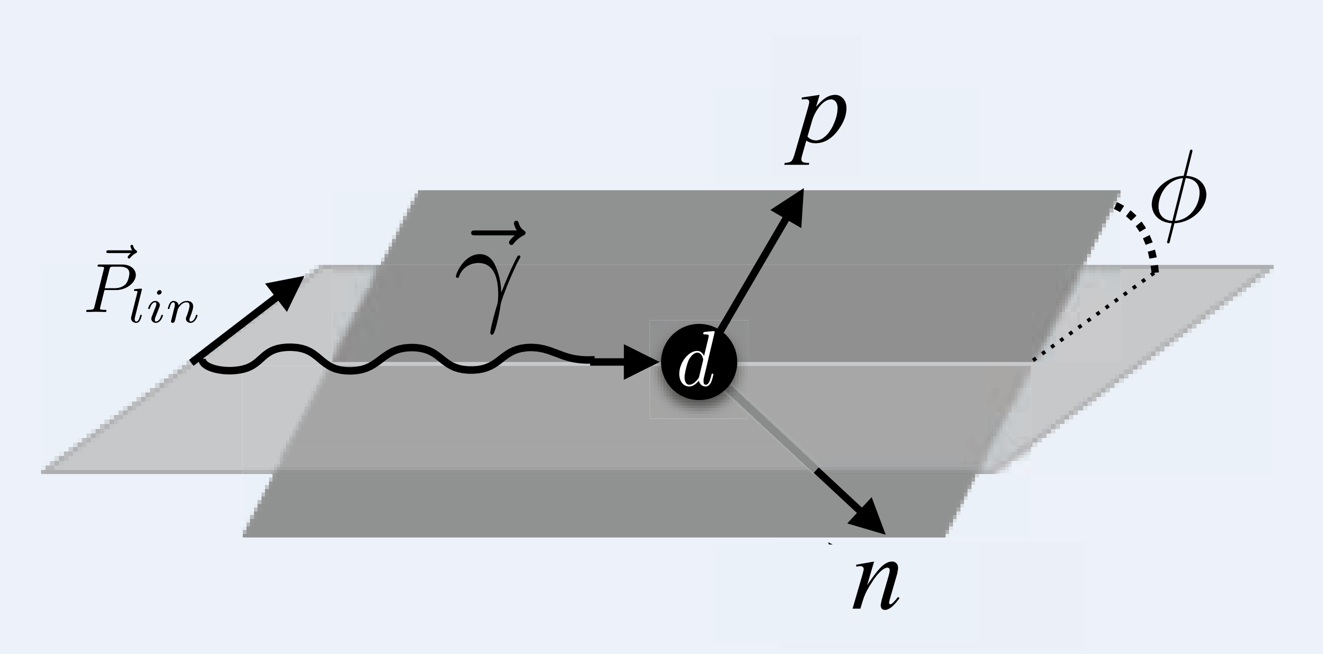


Figure from Nick Zachariou

Linearly Polarized Photons (E06-103)

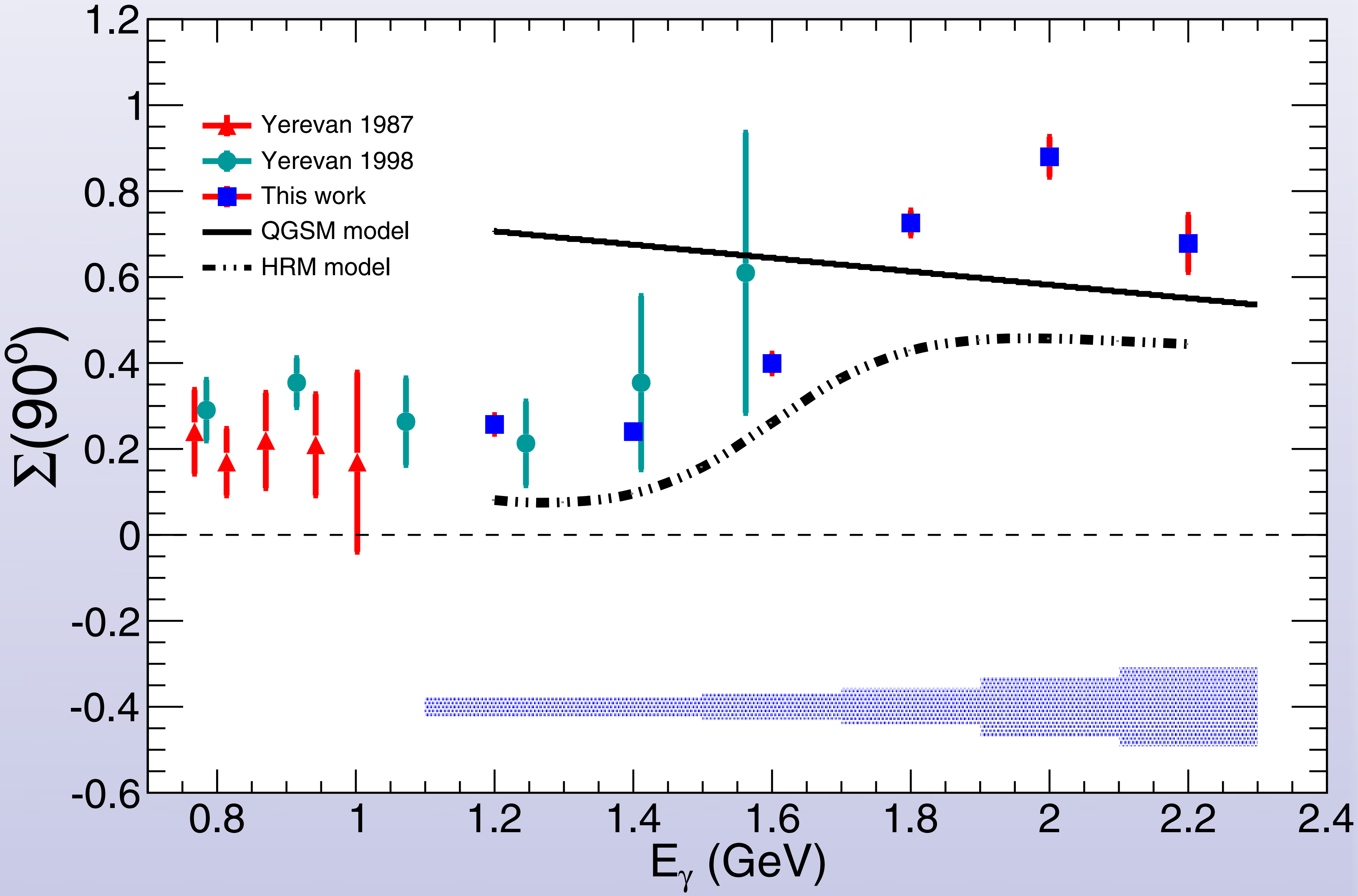
- CLAS Detector
- E_e = 3.3 - 5.2 GeV
- coherent edge at: 1.3, 1.5, 1.7, 1.9, 2.1, 2.3 GeV
- $P\gamma$ = 70% - 90%
- ~30×10^9 triggers

Linearly Polarized Photons:

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_0}\left[1 - P_{lin}\Sigma\cos 2\varphi\right]$$

Dynamics of Hard Deuteron Photodisintegration in the Scaling Regime

Beam Spin Asymmetry: New Results

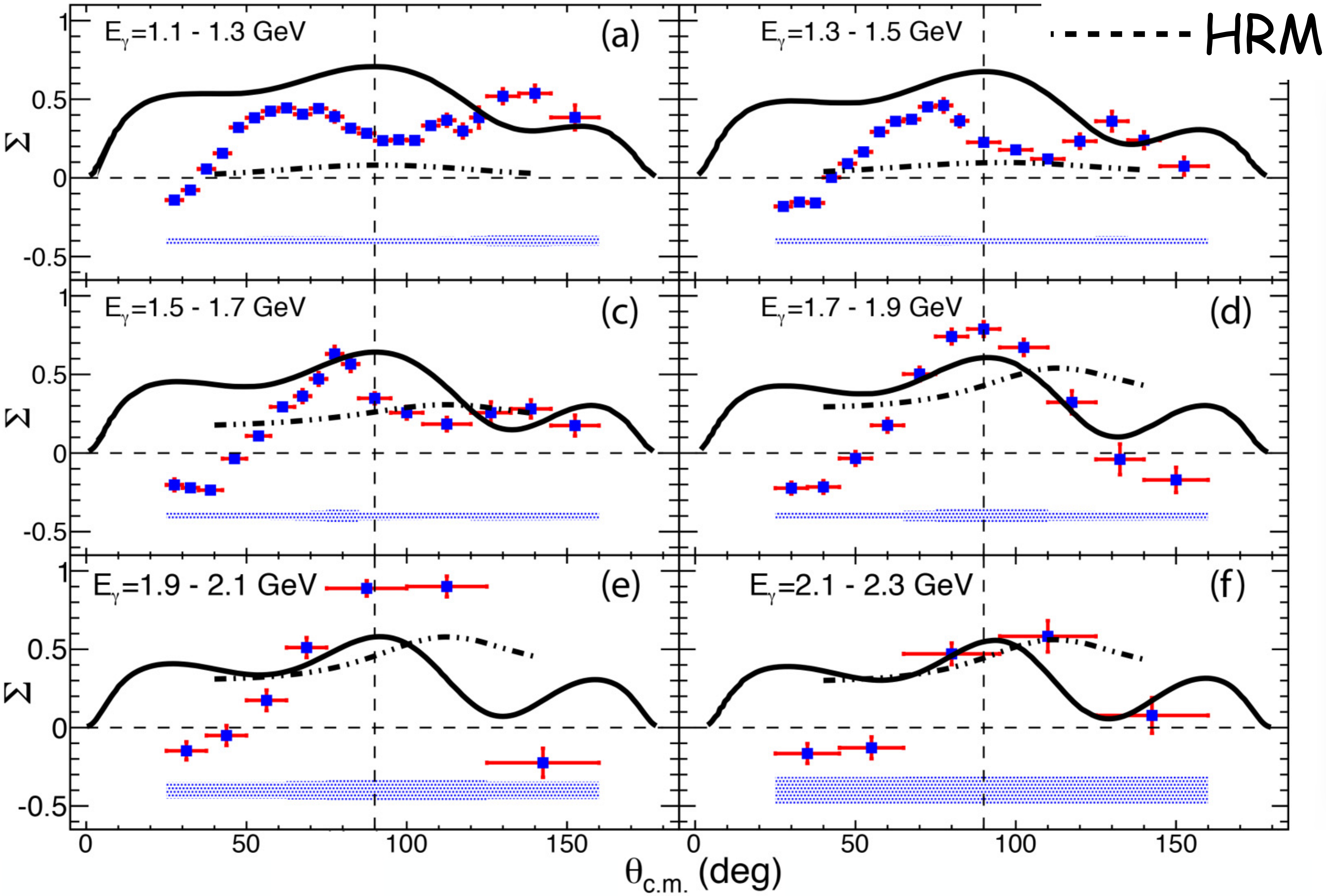


N. Zachariou, Y. Ilieva, B.L. Berman, N.Ya. Ivanov, M.M. Sargsian, R. Avakian, G. Feldman, P. Nadel-Turonski et al., Phys. Rev. C **91**, 055202 (2015)

- Σ at θ_{cm}= 90°
  - σ_{stat} = 6% — 15%
  - σ_{syst} < 6%
- The beam spin asymmetry is positive at E_γ = 0.75 - 2.3 GeV.
- Data suggest a continuous increase up to E_γ of 2 GeV.
- Current QGSM calculations do not reproduce the shape of the energy distribution.
- HRM reproduces the shape, underestimates the magnitude.

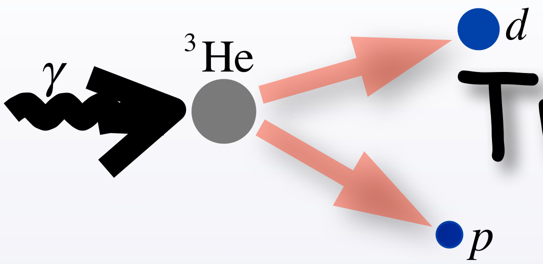
Dynamics of Deuteron Hard Photodisintegration in the Scaling Regime

Beam Spin Asymmetry: New Results



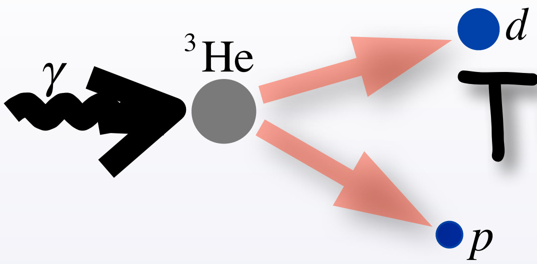
- Rich structures at low energies evolving to a single peak at 90° at higher E_γ.
- Kinematics at the limit of applicability of HRM.
- Complex dynamics - QGSM needs more work.

N. Zachariou, Y. Ilieva, B.L. Berman, N.Ya. Ivanov, M.M. Sargsian, R. Avakian, G. Feldman, P. Nadel-Turonski et al., Phys. Rev. C **91**, 055202 (2015)



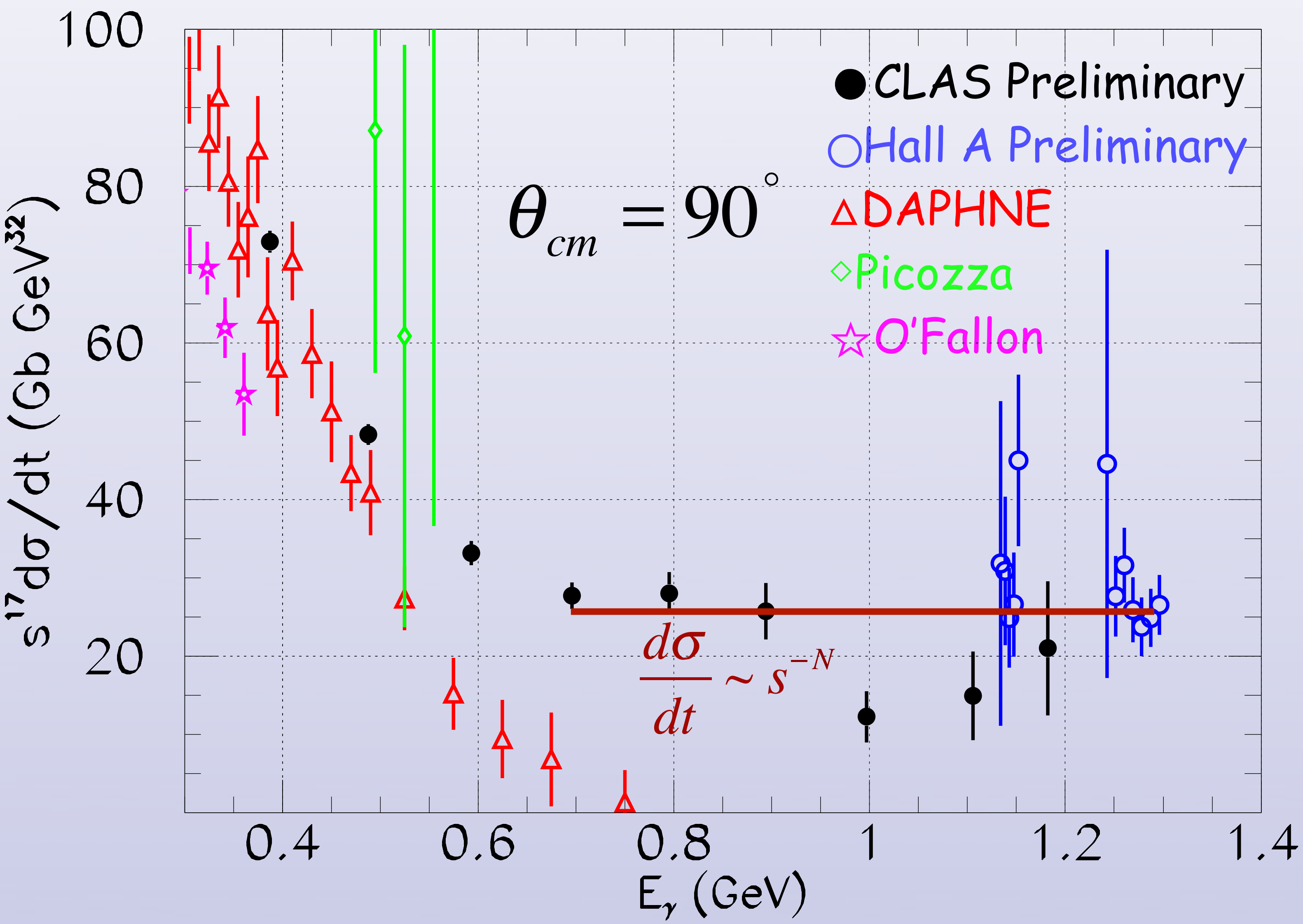
Two-Body Photodisintegration of ^{3}He

Scaling in A > 2 expected at energies much higher than 1 GeV, however...



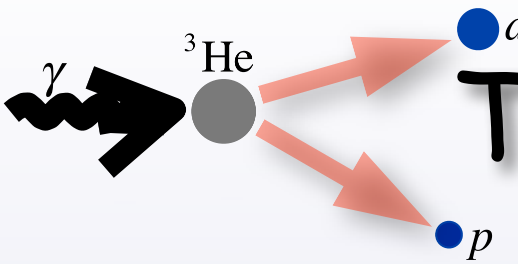
Two-Body Photodisintegration of ^{3}He

Scaling in A > 2 expected at energies much higher than 1 GeV, however...



Data fitted by: $\dfrac{d\sigma}{dt} = As^{-N}$

I. Pomerantz, Y. Ilieva, R. Gilman, D. Higginbotom, E. Piazetski, S.Strauch et al., Phys. Rev. Lett. 110, 242301 (2013).



Two-Body Photodisintegration of ^{3}He

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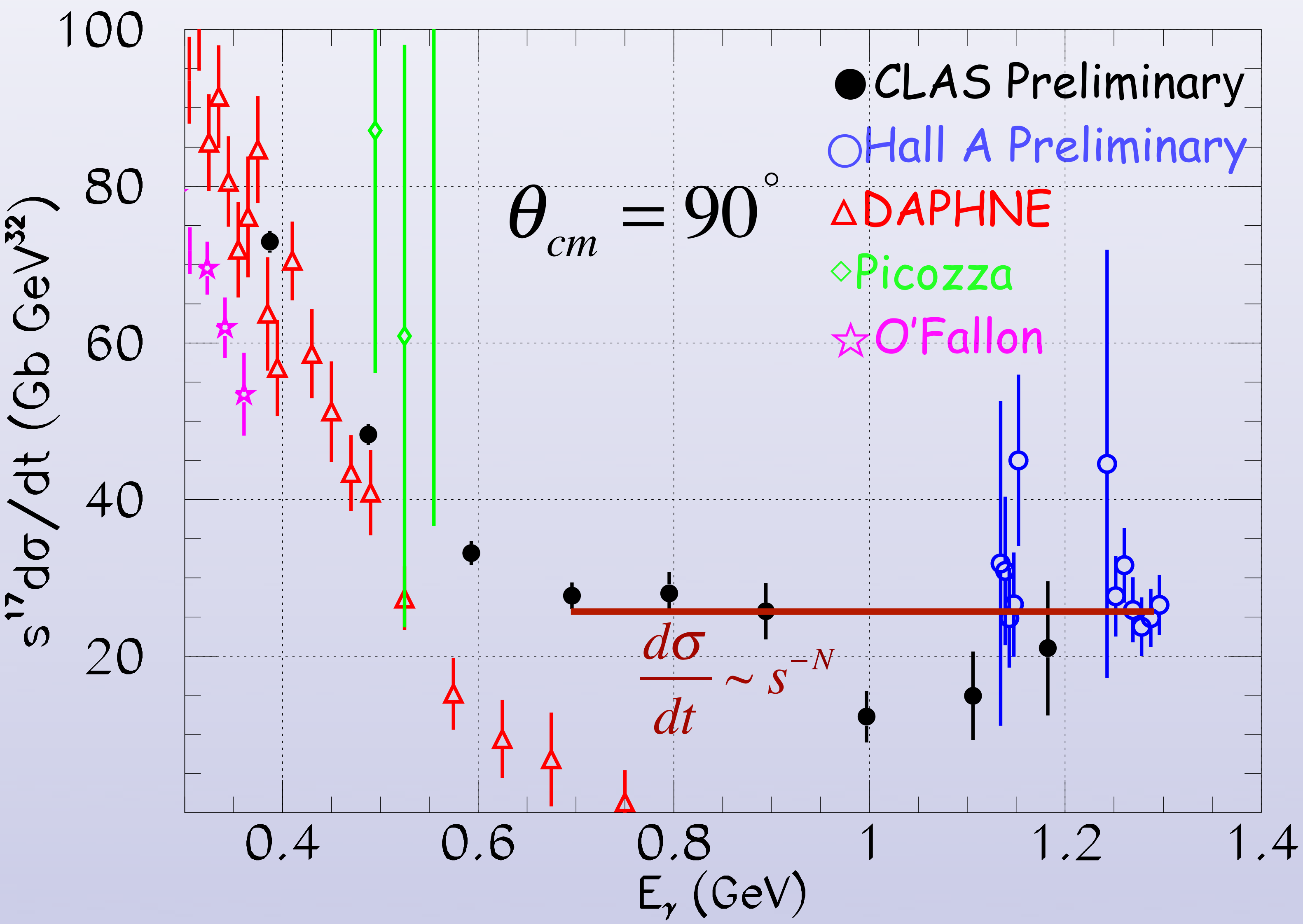


Data fitted by: $$\frac{d\sigma}{dt} = As^{-N}$$

- Extracted value from fits to JLab data:

  N = 17 $\pm$ 1

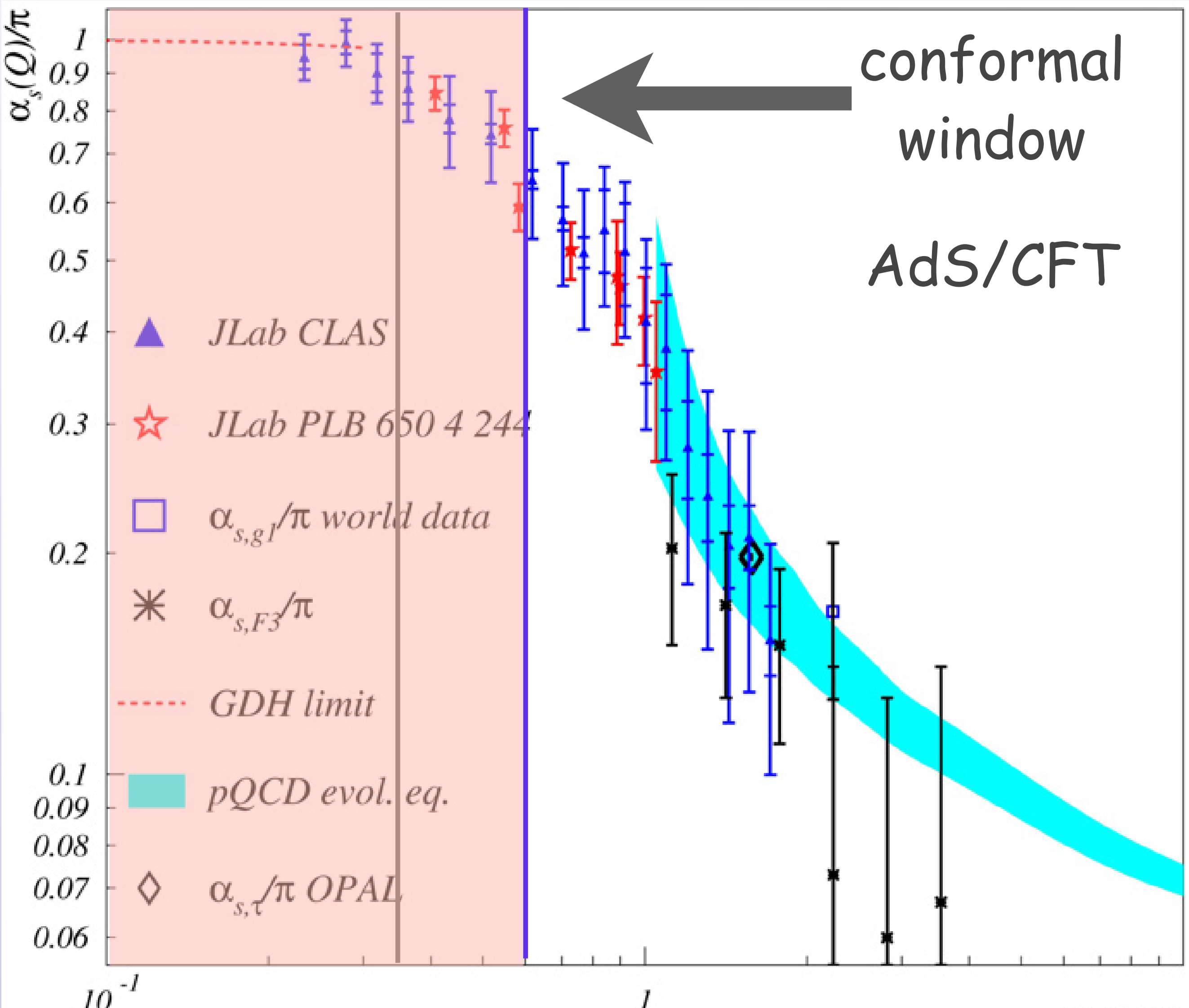
- $|t|_{thr}$ and $p_{\perp thr}$ are too low to support hard scattering hypothesis:
  $|t|_{thr}$ = 0.64 (GeV/c)^2
  $p_{\perp thr}$ = 0.95 GeV/c

- **What is the phenomenology of the observed scaling?**

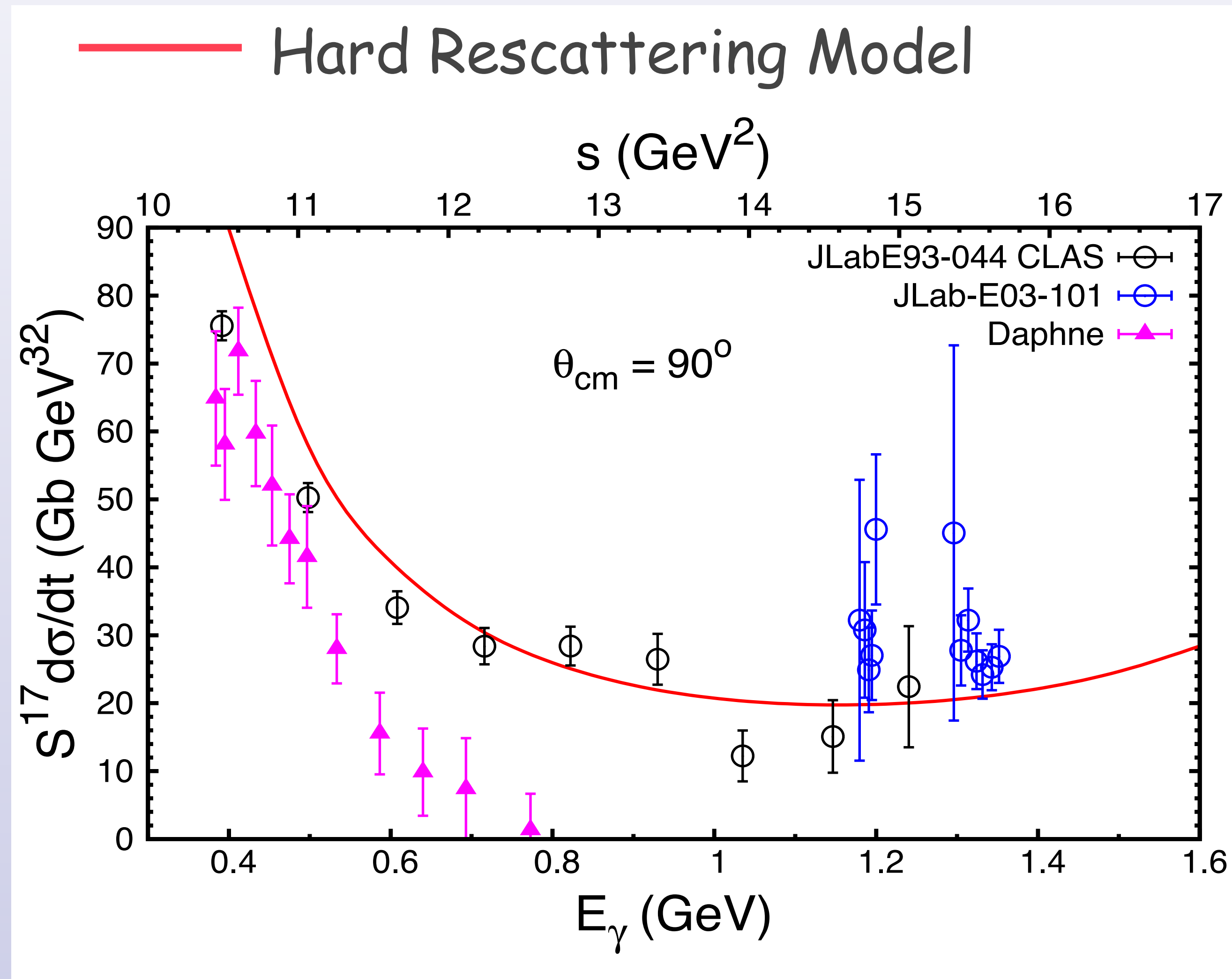
I. Pomerantz, Y. Ilieva, R. Gilman, D. Higginbotom, E. Piazetski, S.Strauch et al., Phys. Rev. Lett. 110, 242301 (2013).

Dynamics of ^{3}He Hard Photodisintegration in the Scaling Regime

Why does it scale at such low energies?



A. Deur et al, Phys. Lett B **665**, 349 (2008)



H. Maheswari, M. Sargsian, arXiv:1606.09617 (2016)

$$\frac{\sqrt{u}}{constituent} = 0.06 - 0.6 \text{ GeV/c}$$

$$\frac{\sqrt{t}}{constituent} = 0.035 - 0.35 \text{ GeV/c}$$

$$u = 0.01 - 3.2 \text{ (GeV/c)}^2$$

$$t = 0.04 - 4.4 \text{ (GeV/c)}^2$$

Photodisintegration of Few-Nucleon Systems: Summary

Hard Deuteron Photodisintegration

- New data on the beam-spin asymmetry is in general consistent with the hard-rescattering mechanism.
- Data can be used to constrain the helicity amplitudes of the underlying pn elastic scattering (at kinematics where no data exist).

Hard ^{3}He Photodisintegration

- Unexpected dimensional scaling observed at $E_\gamma > 0.7$ GeV.
- The origin of dimensional scaling is a puzzle (regime of conformal window or hard rescattering?).

The phenomenology of QCD transition between scales will be further explored at 12 GeV.

Studies of Hyperon-Nucleon Interaction

Why Study?

YN interaction not well known

- not all free parameters of the YN potential can be obtained from the NN potential via flavor SU(3) symmetry
- example: large uncertainties of YN scattering lengths:

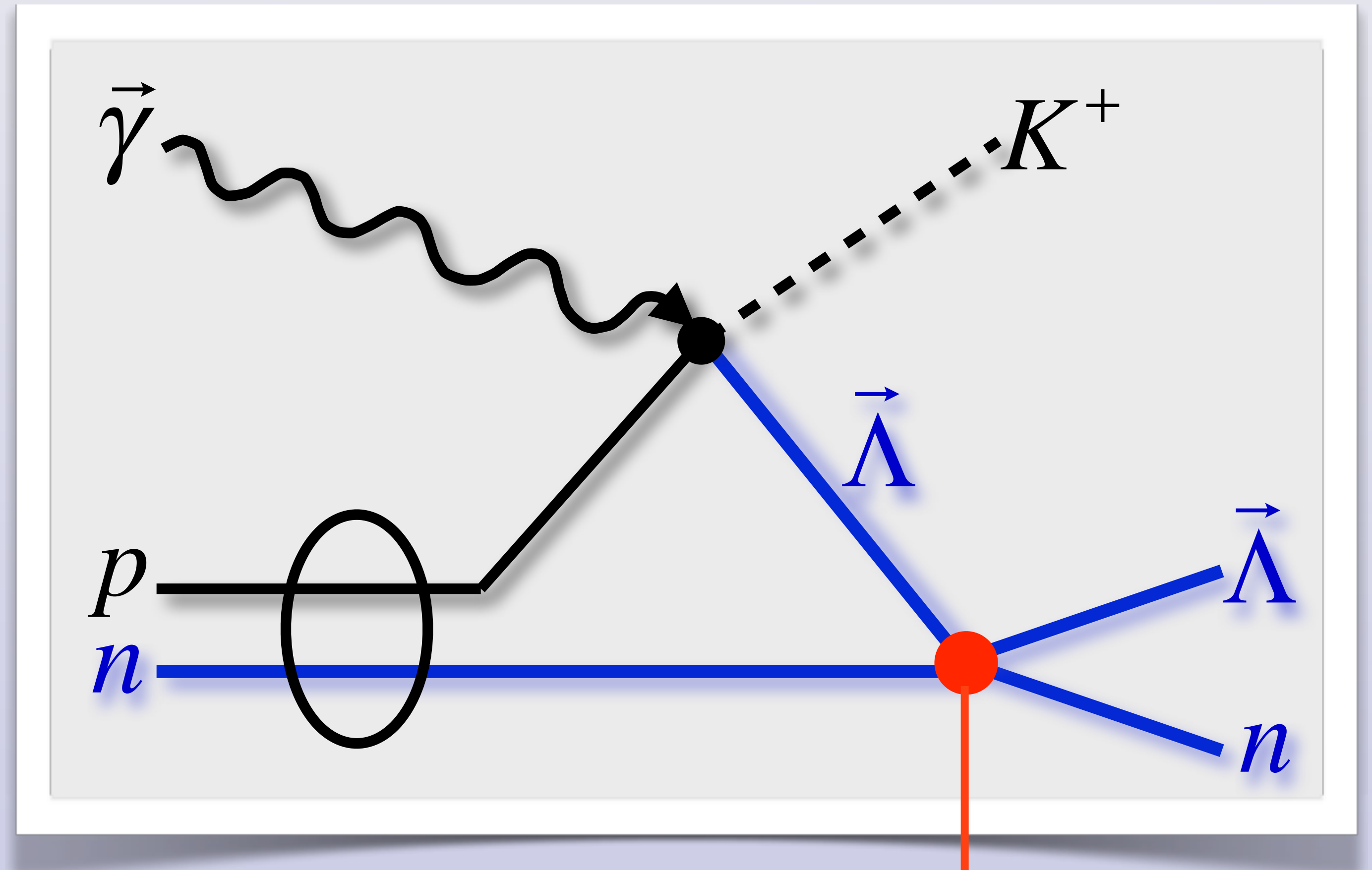
  $a(^1S_0) = -0.7 - -2.6$ fm,

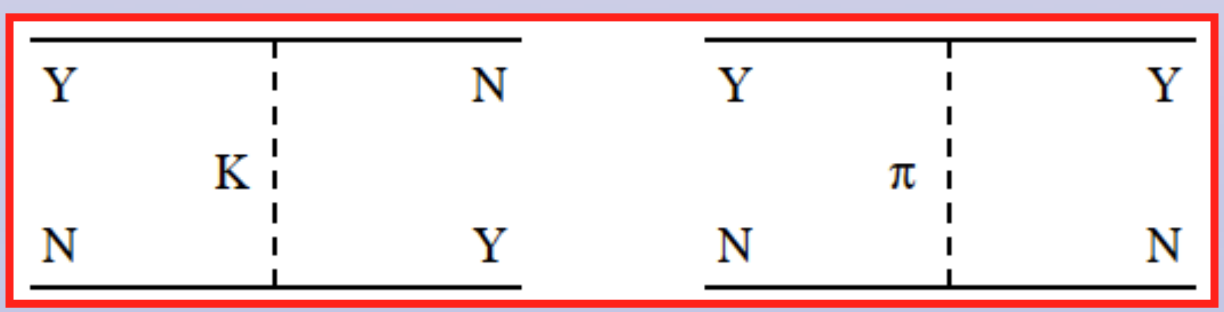
  $a(^3S_1) = -1.7 - 2.15$ fm
- YN elastic scattering database poor
- alternative approaches:
  - hypernuclear spectroscopy
  - studies of FSI in production reactions:

$$\gamma d \rightarrow K^+ \Lambda n \qquad pp \rightarrow K^+ \Lambda p$$

$$\gamma d \rightarrow K^0 \Lambda p$$

YN Interaction and Exclusive Hyperon Photoproduction off Deuteron





New approach

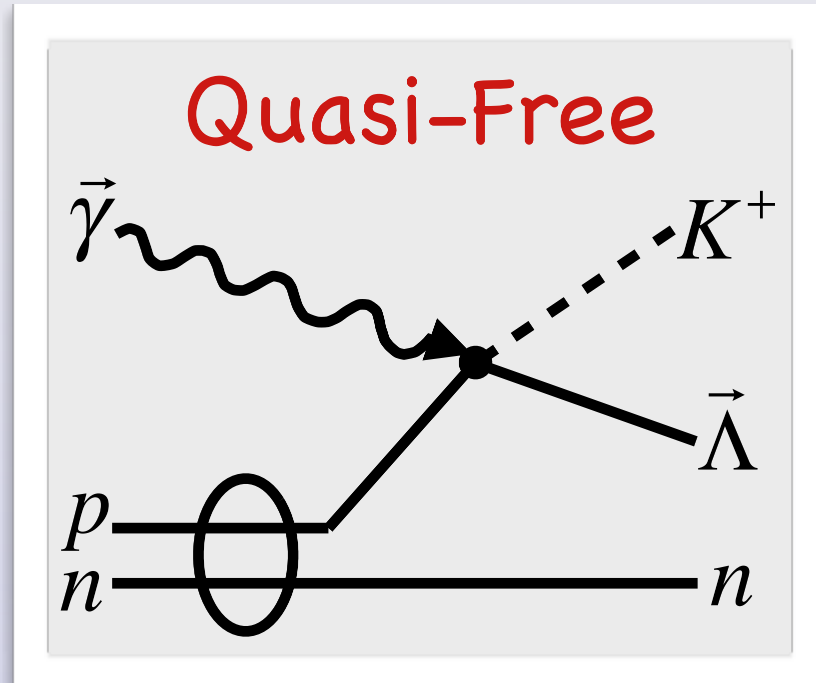
- Hyperon Beam produced in first step
- Hyperons scatter off neutrons in a second step

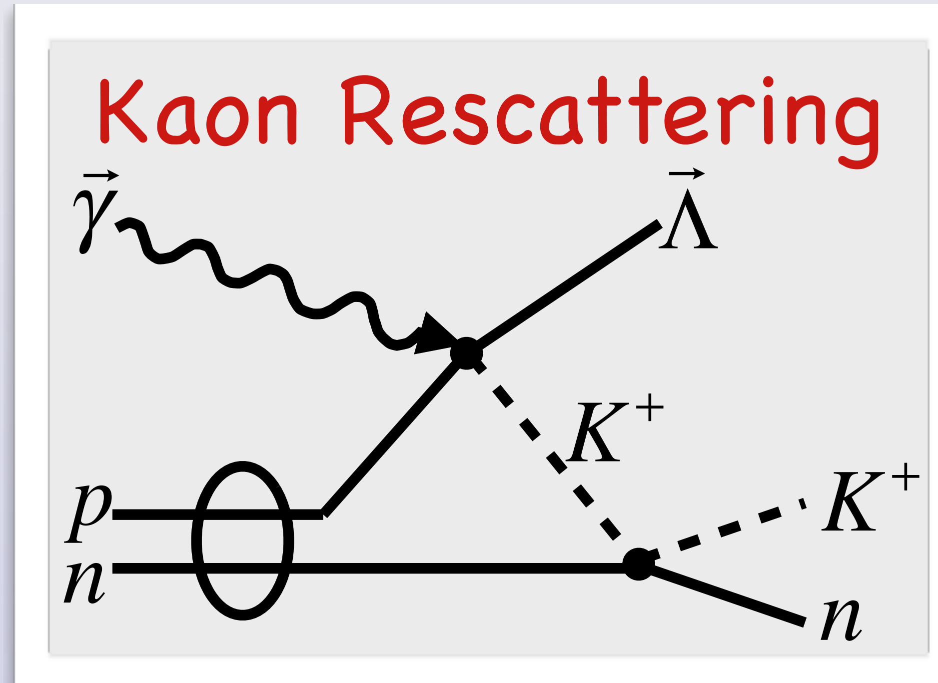
Theoretical Studies

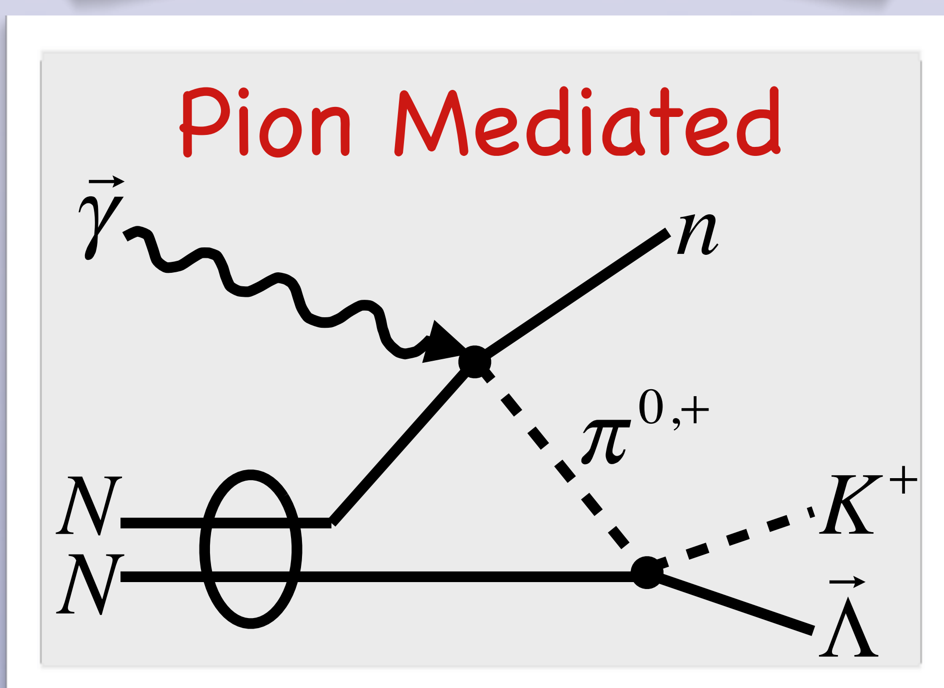
- Observables sensitive to YN potentials at certain kinematics at a level of ~10% (K. Miyagawa et al., Phys. Rev. C **74**, 034002 (2006); A. Salam et al., Phys. Rev. C **74**, 044004 (2006); H. Yamamura et al., Phys. Rev. C **61**, 014001 (1999))
- Spin-averaged scattering length can be extracted from data close to threshold (A. Gasparian et al., Phys. Rev. C 69, 034006 (2004))

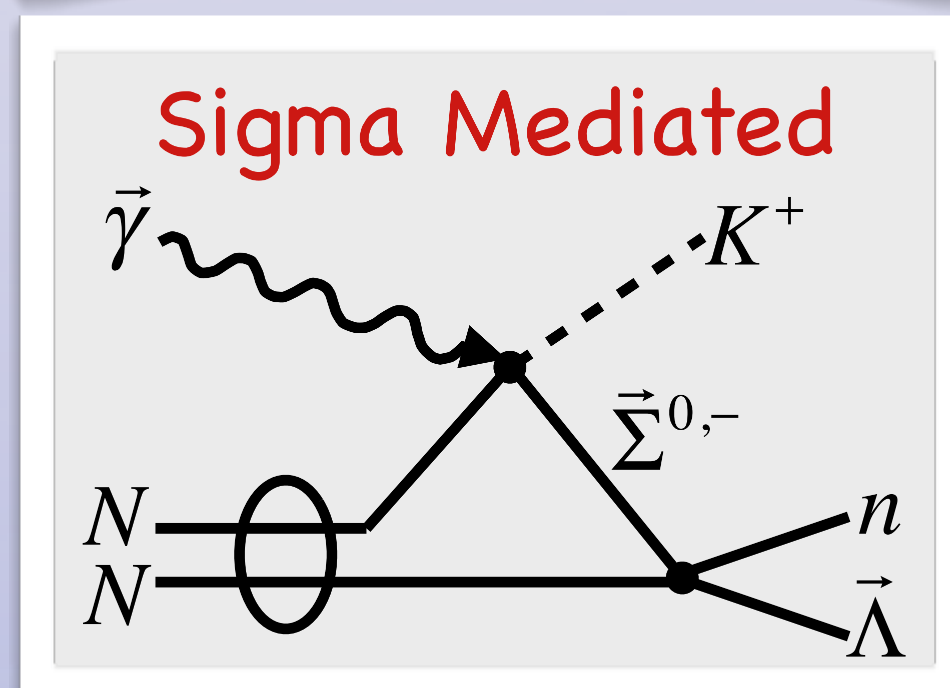
Exclusive Hyperon Photoproduction off Deuteron

Background Mechanisms









Exclusive Hyperon Photoproduction off Deuteron

Polarization Observables

$$\frac{d\sigma}{d\Omega}=\frac{d\sigma}{d\Omega_0}\left[1-P_{lin}\Sigma\cos 2\varphi-\alpha\cos\theta_x(P_{lin}O_x\sin 2\phi+P_{circ}C_x)-\alpha\cos\theta_z(P_{lin}O_z\sin 2\phi+P_{circ}C_z)+\ldots\right]$$

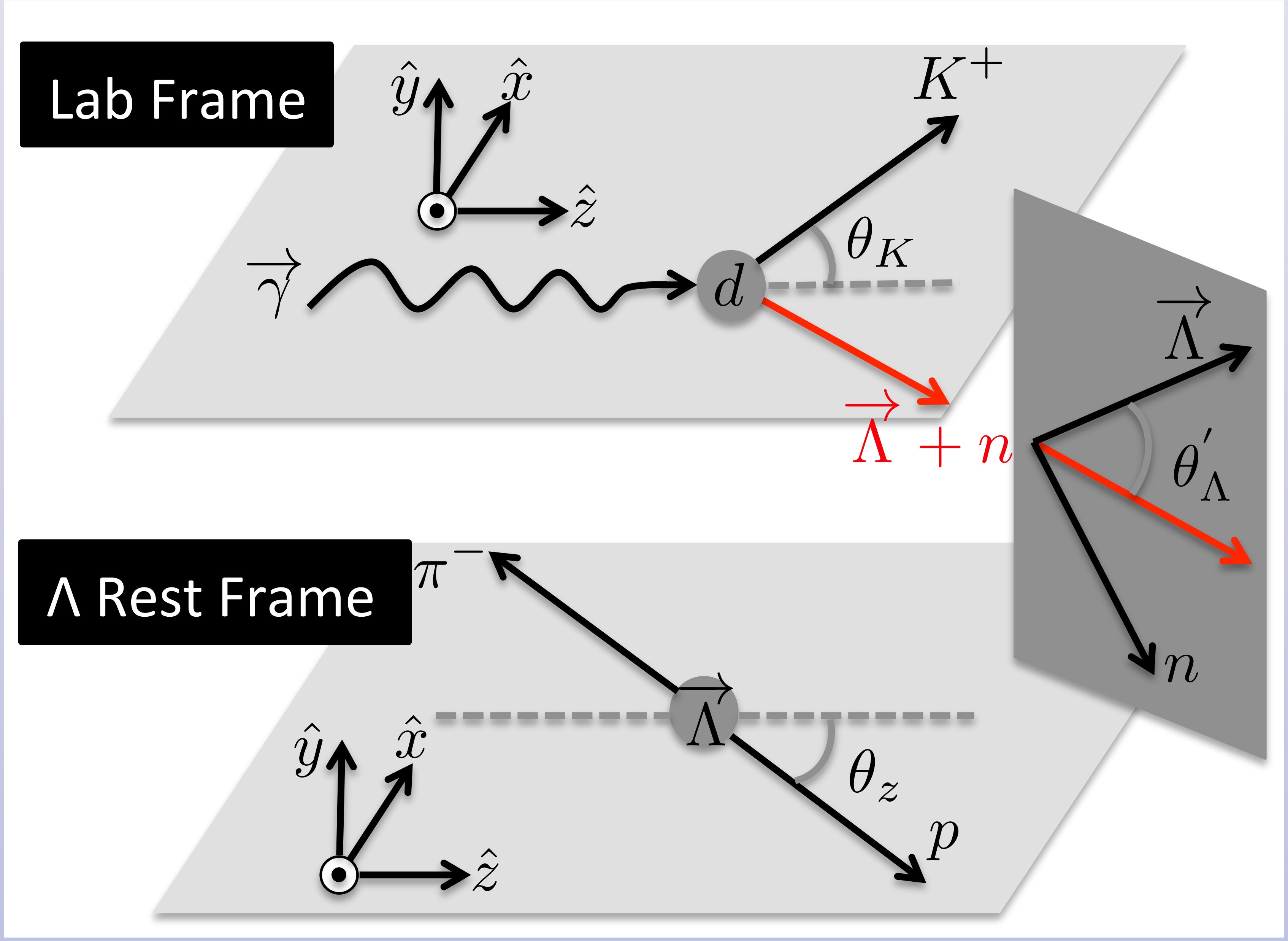


Figure from Tongtong Cao

Λ self-analysing power:

$\alpha=0.642\pm0.013$

Relevant Kinematic Variables:

- From $\Lambda n\to\Lambda n$: θ'_Λ, $W_{\Lambda n}\equiv IM_{\Lambda n}$
- From $\gamma p\to K^+\Lambda$: E_γ, p_K, θ_K

$\Sigma(E_\gamma, p_K, \theta_K, \theta'_\Lambda, W_{\Lambda n})$

$C_x(E_\gamma, p_K, \theta_K, \theta'_\Lambda, W_{\Lambda n})$

$C_z(E_\gamma, p_K, \theta_K, \theta'_\Lambda, W_{\Lambda n})$

…

Experimental Facility: CLAS at Jefferson Lab

Experiment E06-103 (g13)

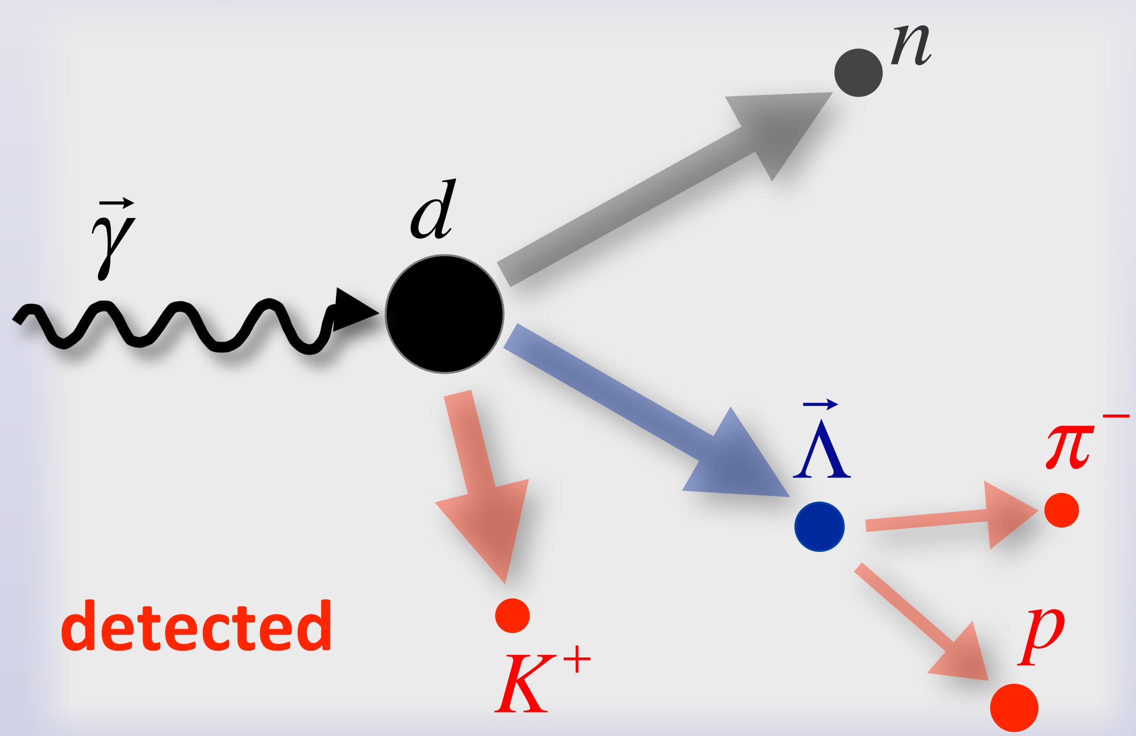
Circularly Polarized Photons (g13a)

- E_e = 2 GeV; 2.65 GeV
- electron polarization: ~ 80%
- triggers: ~20×10^9 triggers

Linearly Polarized Photons (g13b)

- E_e = 3.3 - 5.2 GeV
- coherent edge at: 1.3, 1.5, 1.7, 1.9, 2.1, 2.3 GeV
- $P\gamma$ = 70% - 90%
- ~30×10^9 triggers

Fully Exclusive Measurement



K^+ and Λ: measured

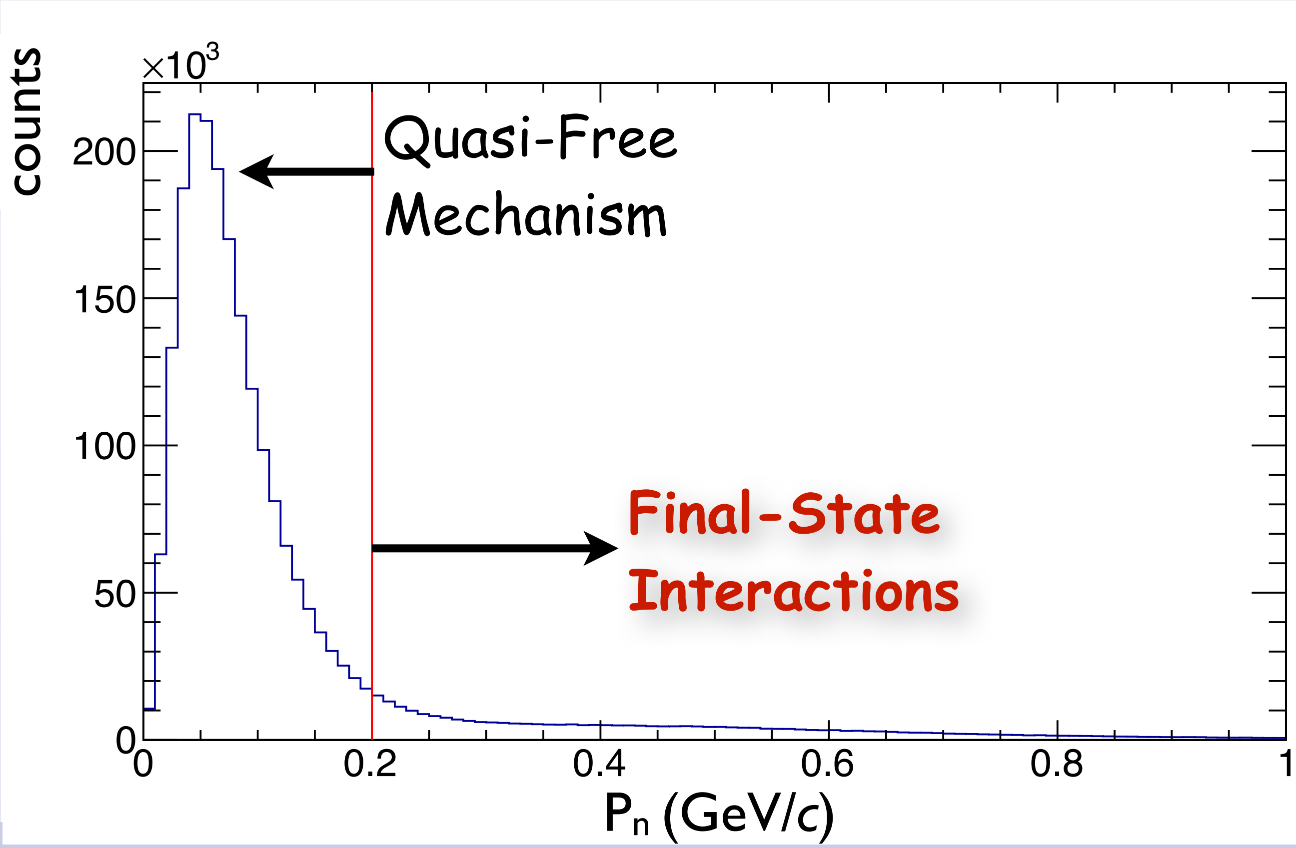
n: reconstructed from 4-momentum vector conservation

P. Nadel-Turonski, B. Berman, Y. Ilieva, D. Ireland, A. Tkabladze et al., E06-103: “Kaon Production on the Deuteron Using Polarized Photons”

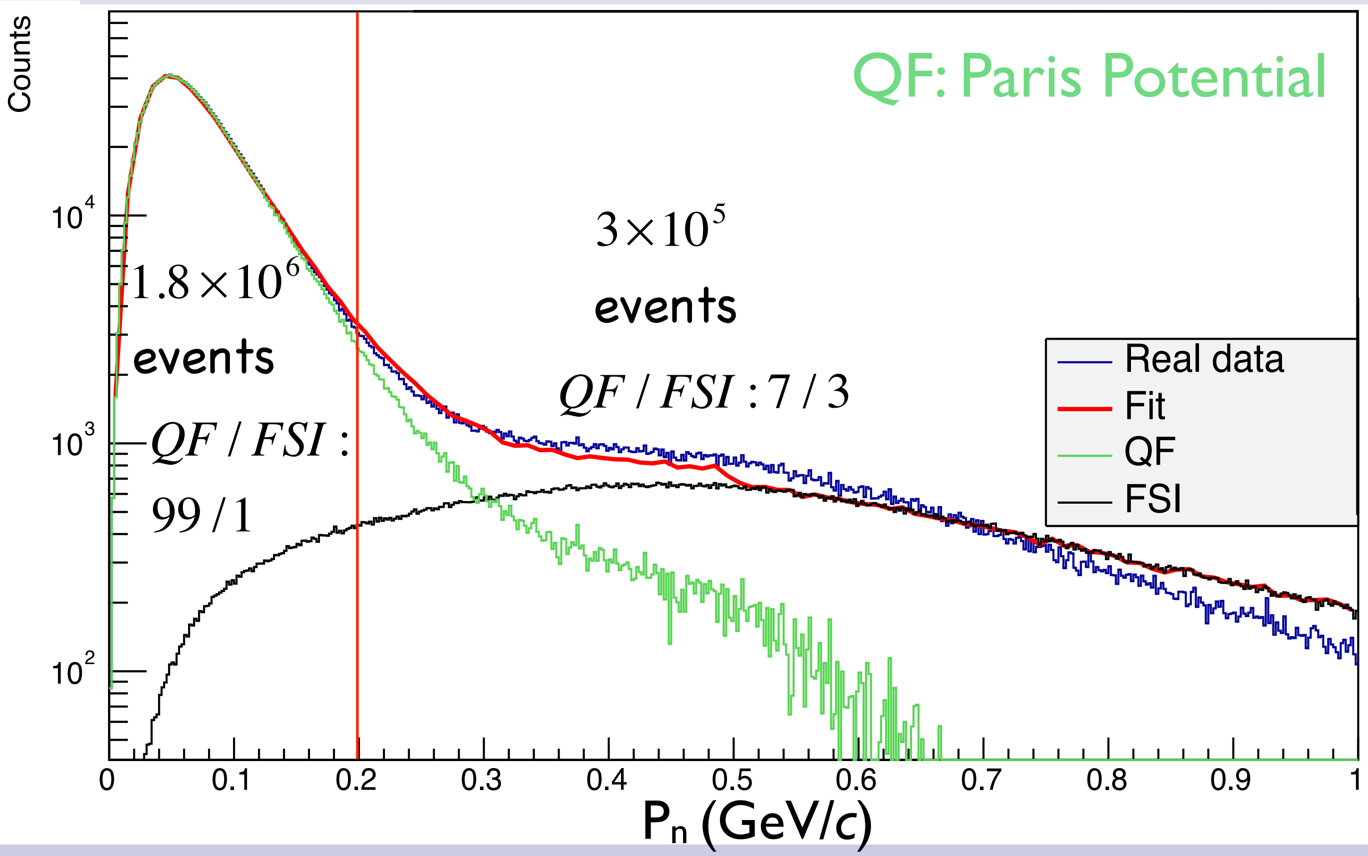
Selection of Quasi-Free and FSI Mechanisms

Event Distribution over Spectator Momentum

$P_n \ (\gamma d \rightarrow K^+ \Lambda n)$



Comparison with Model Distribution



The removal of events with P_n < 0.2 GeV/c provides a sample that is by far dominated by FSI events. Standard analysis procedure.

Paris Potential describes well low P_n data. High-momentum tail drops off at ~0.6 GeV/c: effect on data interpretation.

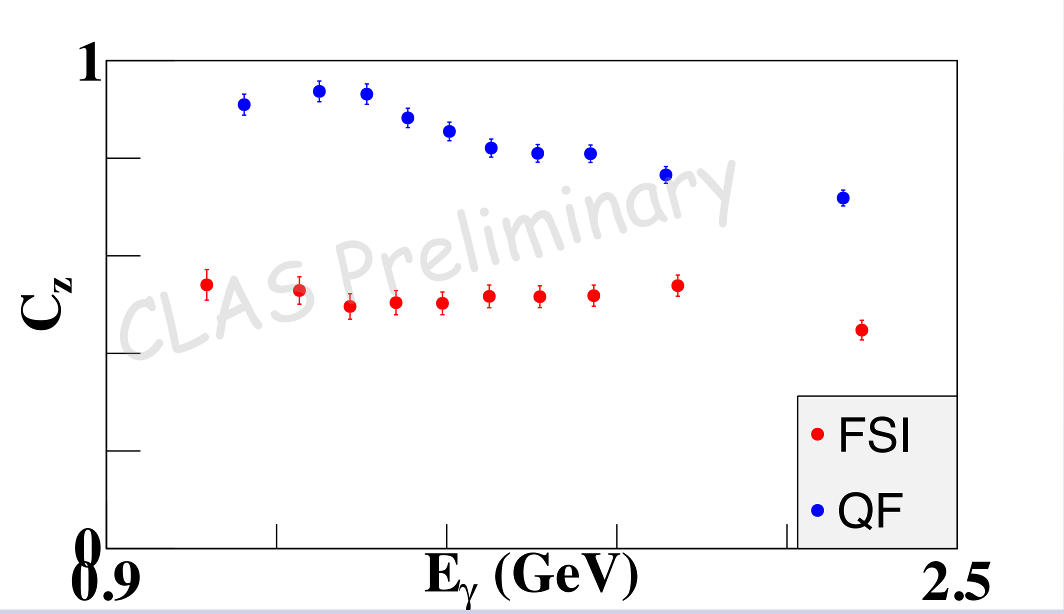
Work of Tongtong Cao

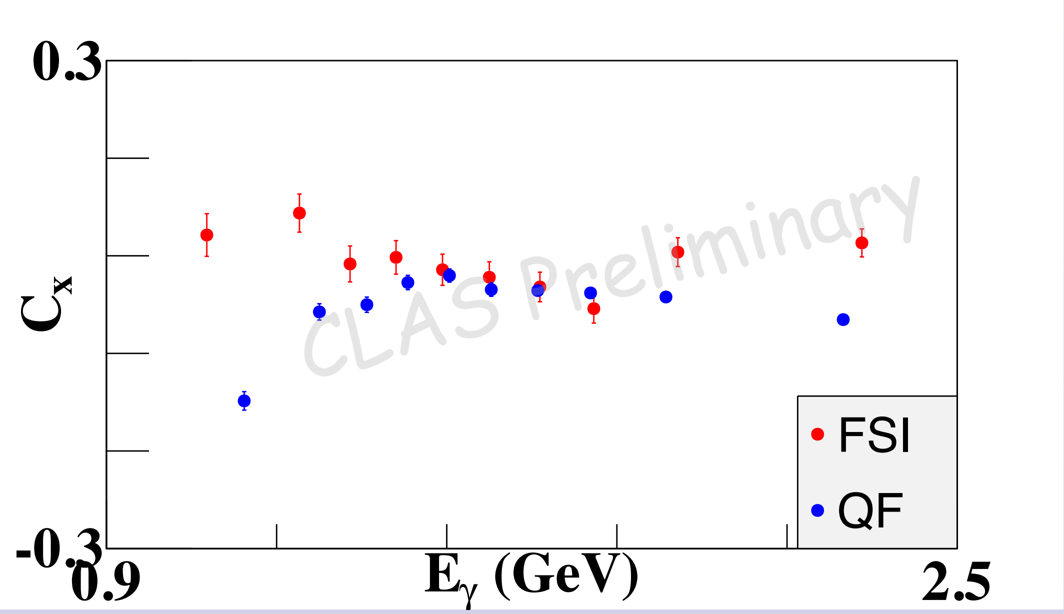
Preliminary Results

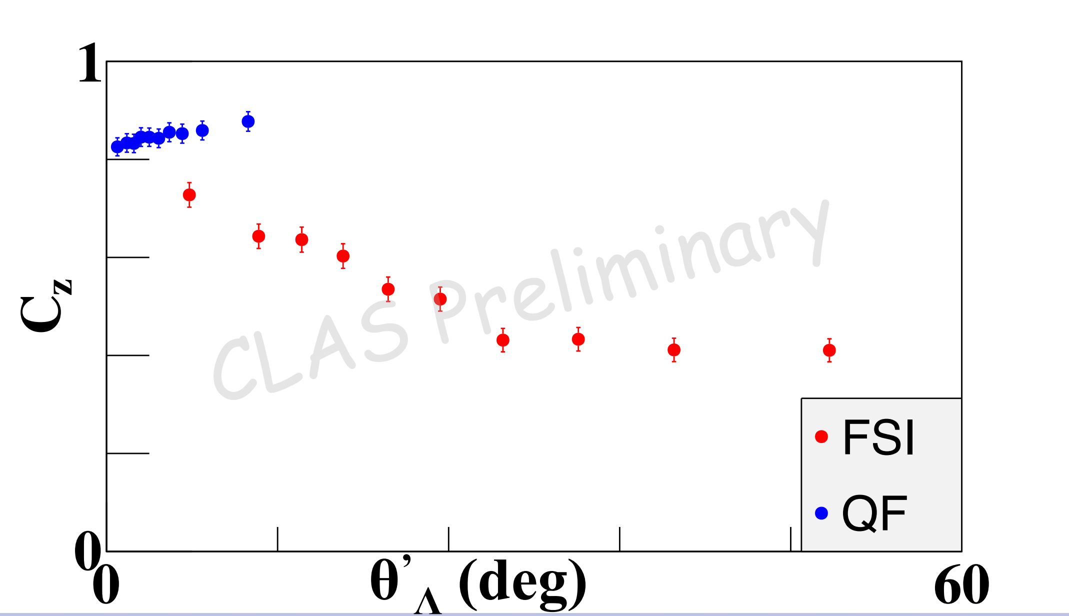
Observables for Circularly-Polarized Photons

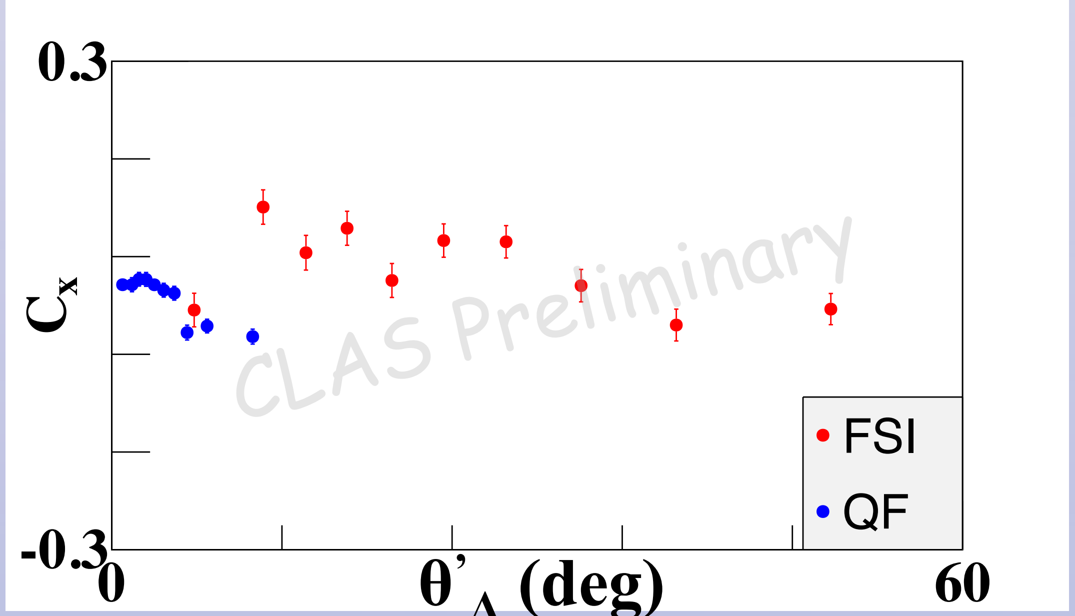
$$\frac{d\sigma^{\pm}}{d\Omega} = \frac{d\sigma}{d\Omega_{unp}}\left[1 \pm P_{circ} C_x \alpha \cos\theta_x \pm P_{circ} C_z \alpha \cos\theta_z + \alpha P_y \cos\theta_y \ldots\right]$$

Work by Tongtong Cao

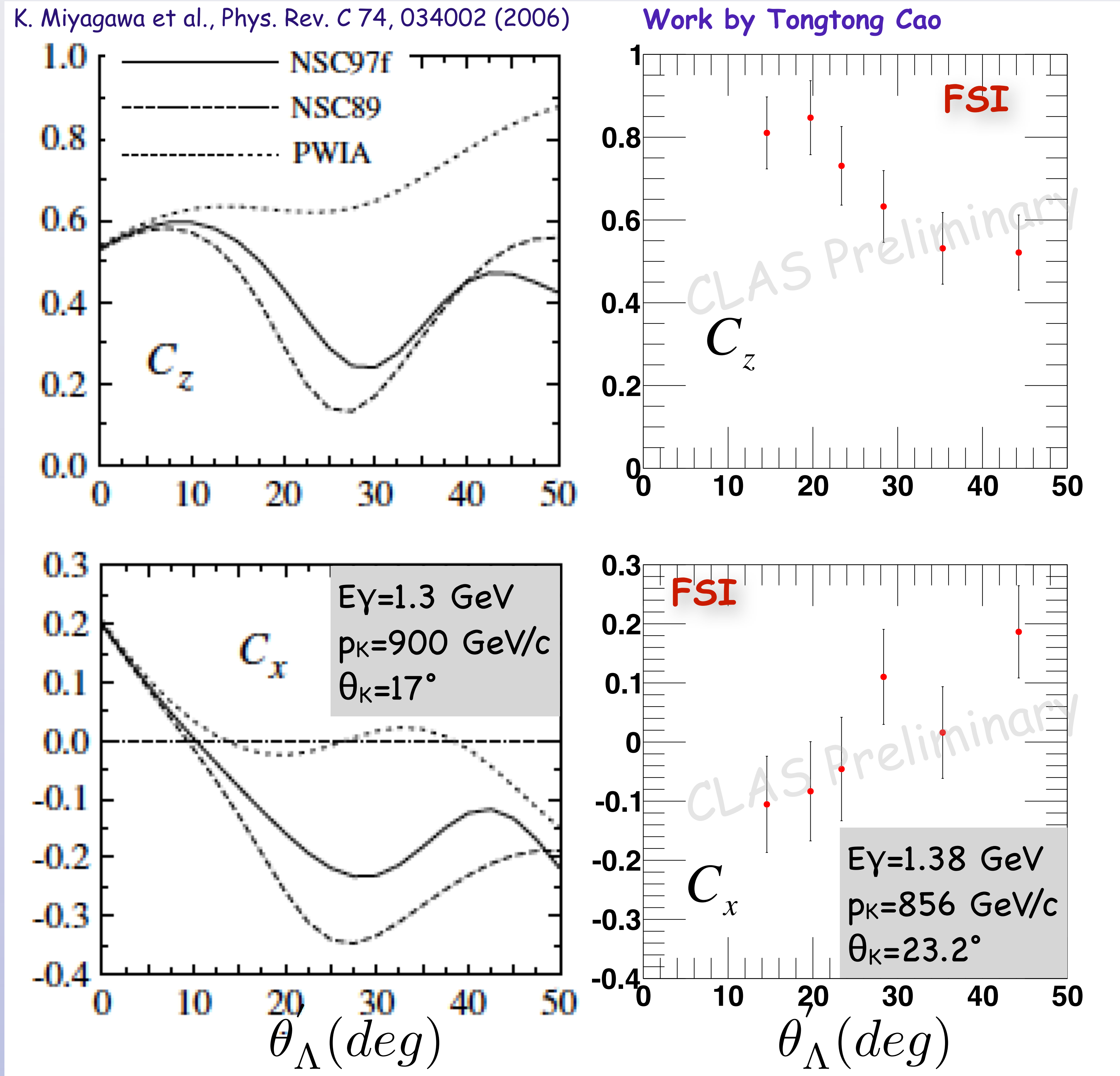








Model Comparison: Perspectives



- one-, ..., four-fold differential observables will be extracted
- experimental observables are integrated over the CLAS acceptance
- direct comparison with models is not trivial
  - collaboration with theorists
  - use the model as event generator and process through CLAS simulation
  - provide a sample of FSI events that can be binned in any way

Exclusive Hyperon Photoproduction off Deuteron

Polarization Observables: Beam-Spin Asymmetry

Linearly Polarized Photons: $\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_0}\left[1 - P_{lin}\Sigma\cos 2\varphi + \ldots\right]$

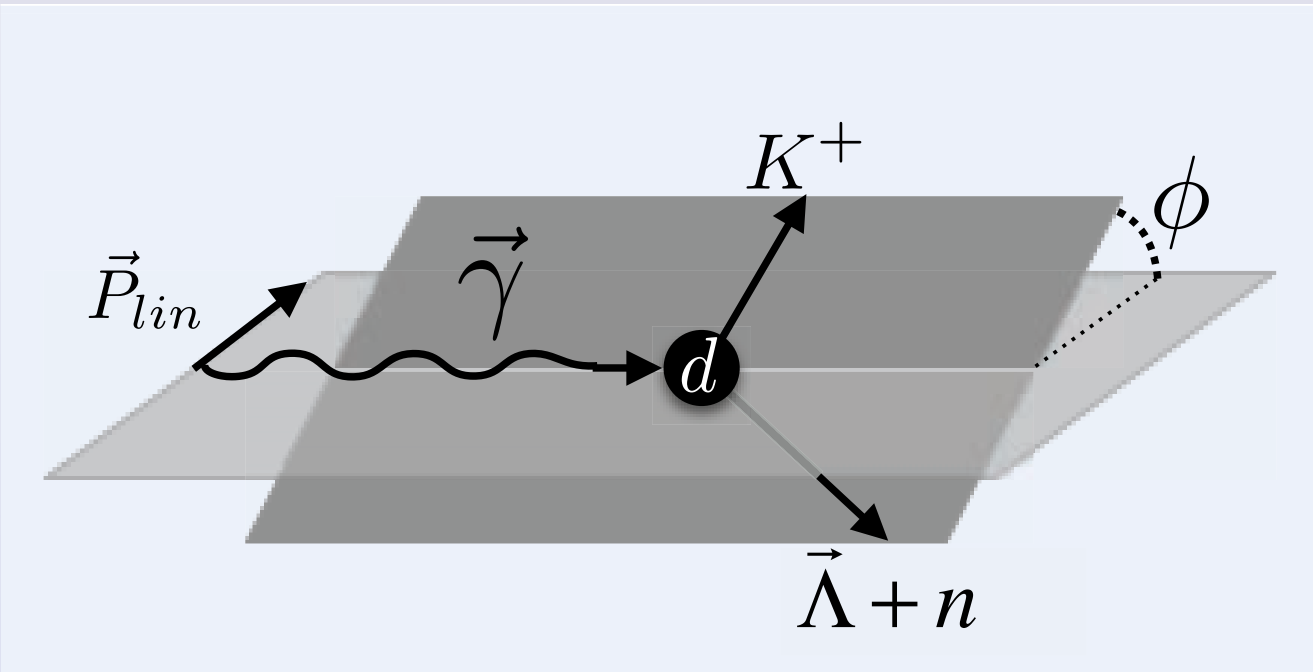
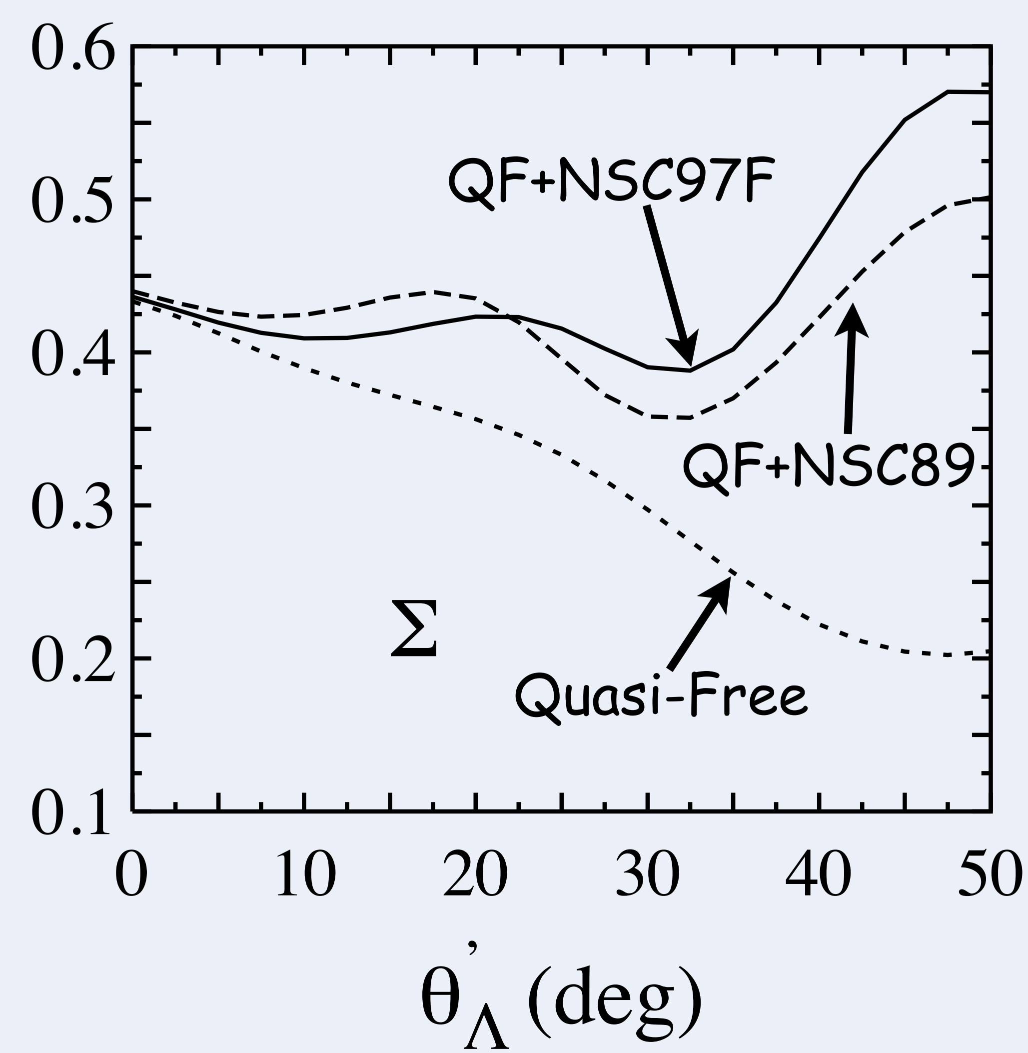


Figure from Nick Zachariou

- Single-polarization observable, i.e. smallest statistical uncertainties
- For the $K^+\Lambda n$ final state, ϕ is not uniquely defined: ϕ_K, ϕ_Λ, ϕ_n, $\phi_{K\Lambda}$, $\phi_{\Lambda n}$, ϕ_{Kn}
- Observable can be used as a probe for dominance of various FSI mechanisms

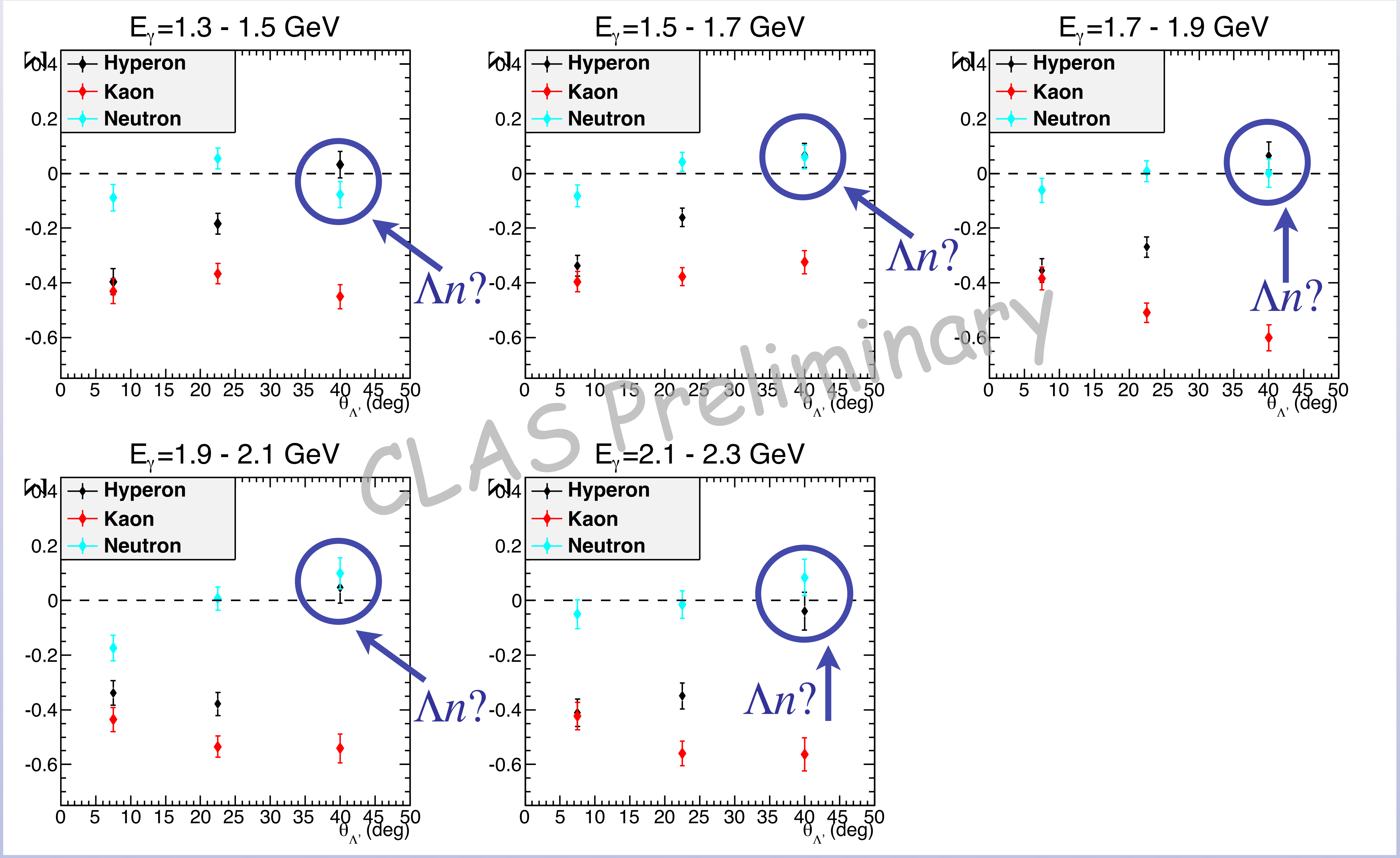
Theoretical Prediction



K. Miyagawa et al., Phys. Rev. C 74, 034002 (2006);

Preliminary Results: Beam Spin Asymmetry

Work by Nick Zachariou



Preliminary Results

Observables for Linearly-Polarized Photons

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_{unp}}\left[1 - P_{lin}\Sigma\cos 2\varphi - P_{lin}O_x\alpha\cos\theta_x - P_{lin}O_z\alpha\cos\theta_z + \ldots\right]$$

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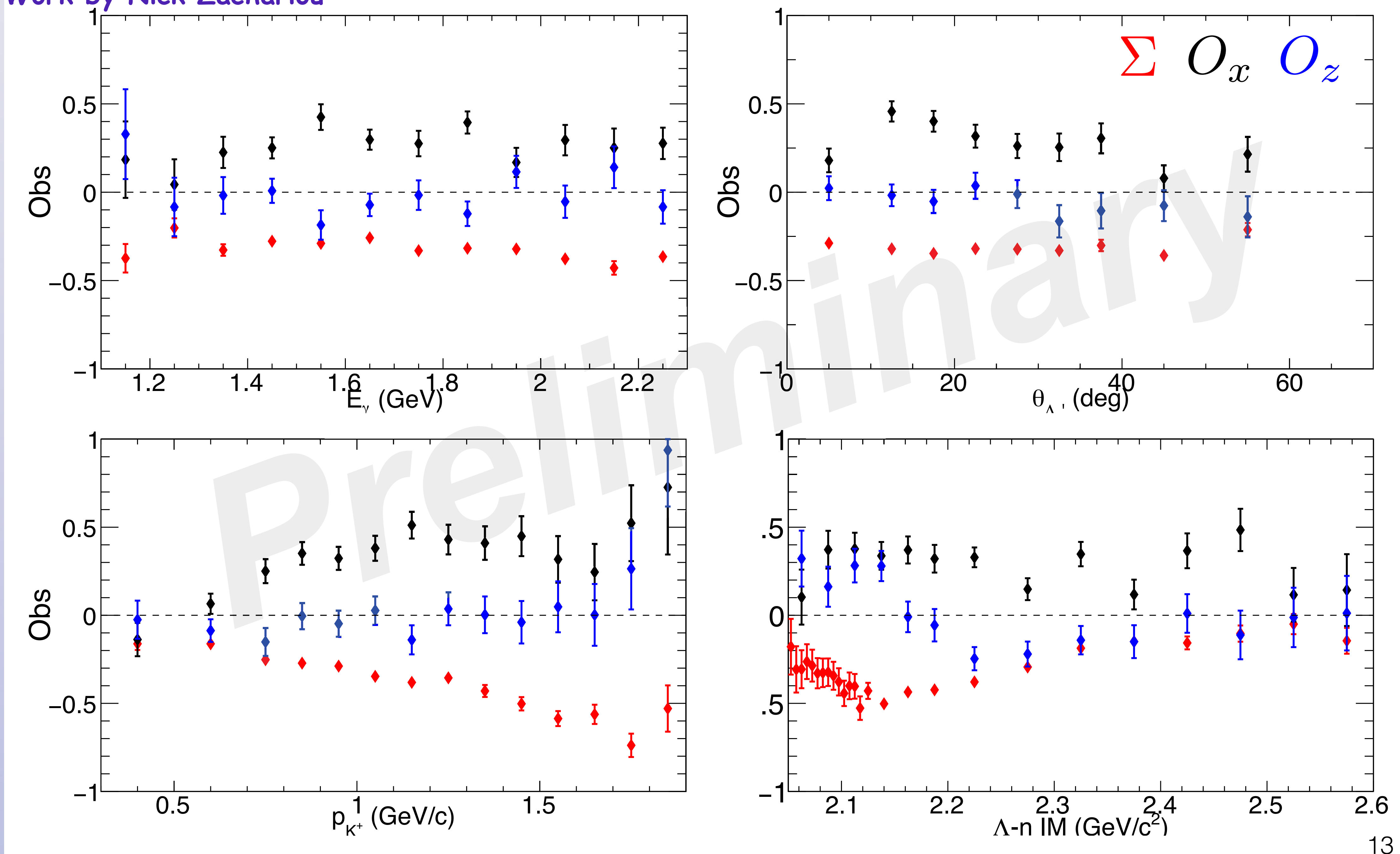


Hyperon-Nucleon Interaction: Summary

First ever estimates of a large set of polarization observables for FSI in the reaction $\gamma d \to K^+ \Lambda n$ have been obtained from JLab g13 experiment.

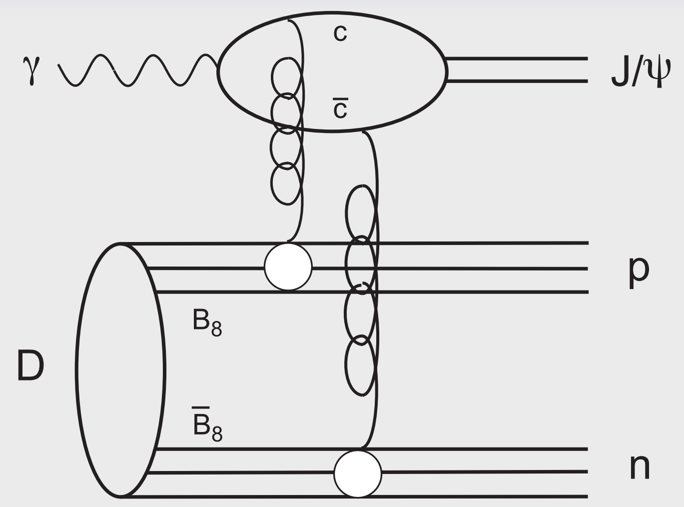
- One-, two-, three-, and four-fold differential estimates are obtained with adequate statistical uncertainty.
- Beam-spin asymmetry provides indication that $\Lambda n \to \Lambda n$ mechanism may be dominant at large θ_Λ'.
- Beam-spin asymmetry can be binned sufficiently fine at low $W_{\Lambda n}$ to be suitable for extraction of the Λn scattering length.
- Data have sufficient coverage and statistical significance to impact YN.

Future Perspectives: Studies at 12 GeV

Near-Threshold J/ψ Production off Deuteron

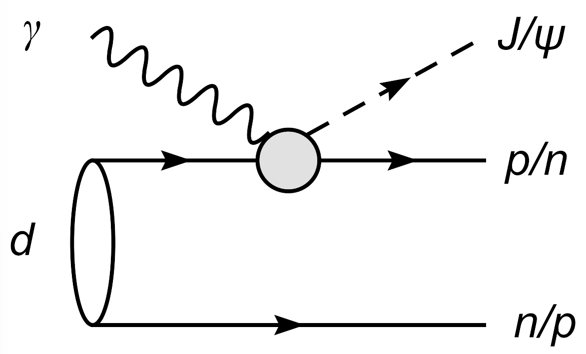
Why Study?

- Determination of the elementary J/ψN total cross section (l_F~1fm).
- Studies of the gluonic structure of deuteron
  - gluonic structure of short-range correlations
  - deuteron gluonic form factor
- Studies of the hidden color component of deuteron?

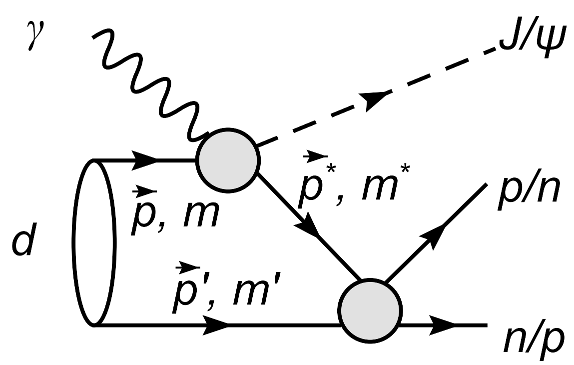


J.-M. Laget, Nucl. Phys. A **581**, 397 (1995)
M. Sargsian, private communication

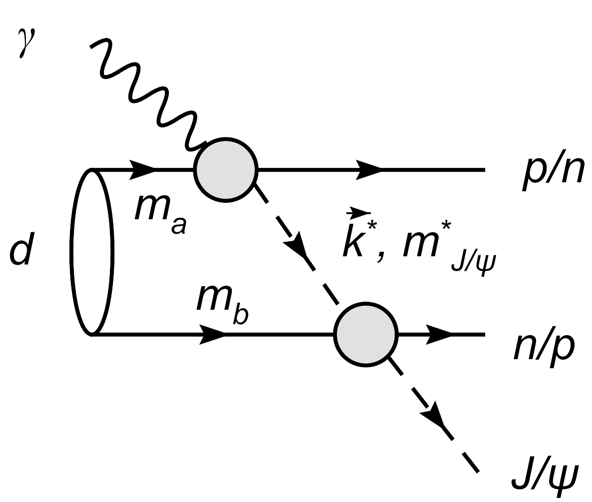
Near-Threshold Exclusive Incoherent Photoproduction: Theoretical Studies



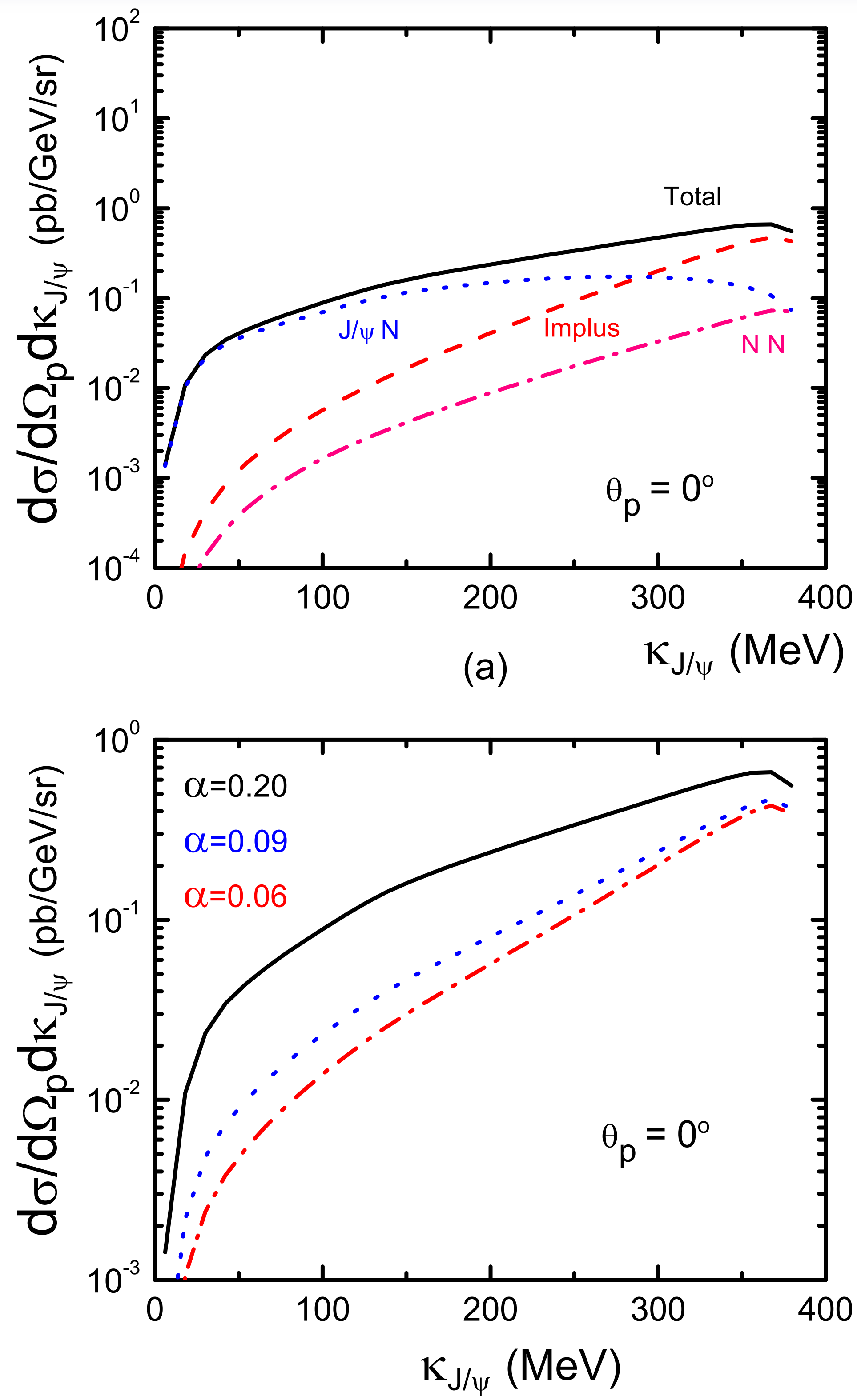
(a) Impulse



(b) NN Re-scattering



(c) J/ψ N Re-scattering



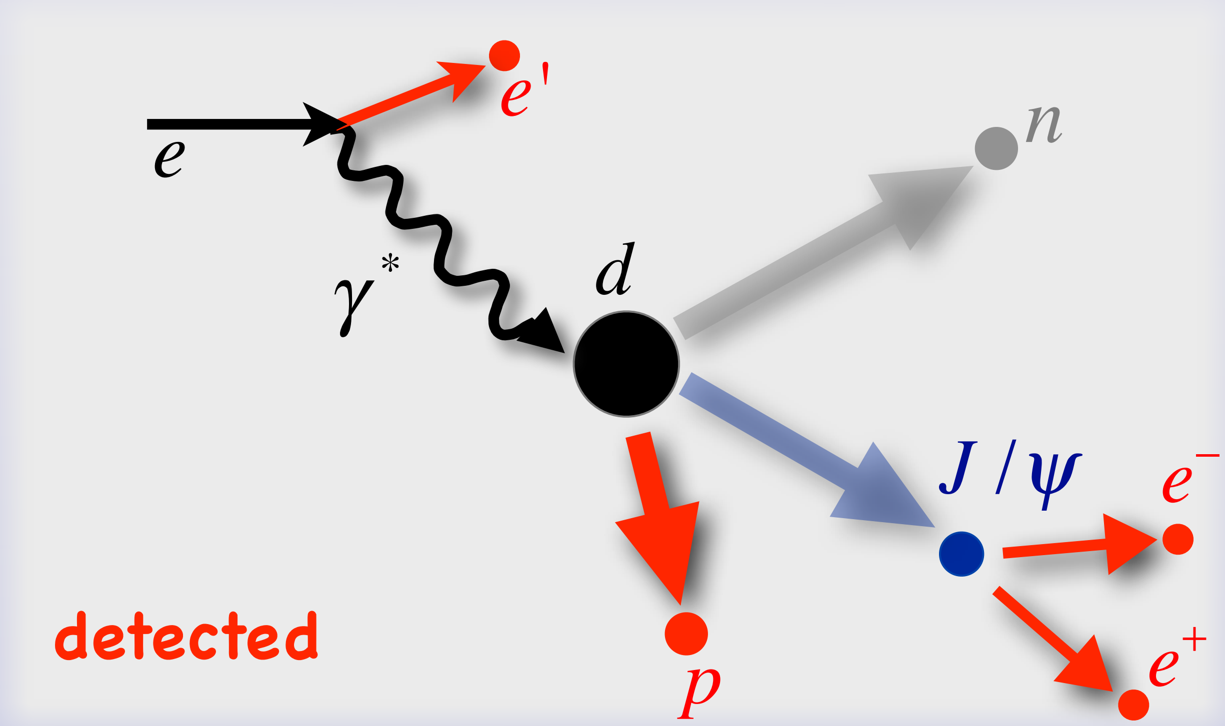
J.-J. Wu, T.-S. H. Lee, Phys. Rev. C **88,** 015205 (2013)

J/ψ Photoproduction off Deuteron with CLAS 12

Fully Exclusive Measurement of Incoherent Photoproduction of J/ψ

Types of data samples:

- Quasi-real Photoproduction:
  - e′, p, J/ψ - measured
  - n - reconstructed
  - $Q^2 \geqq 0.05\ (GeV/c)^2$
- Untagged real photoproduction
  - n, p, J/ψ - measured
  - γ - reconstructed



Summary

The CLAS detector at 6 GeV produced a wealth of **unpolarized and polarized data** that have been critical for the quantitative description of baryon structure and baryon dynamics

- Phenomenology of the transition from long to short scales in few-nucleon systems
- Final-State Interactions: key to access YN properties

The 12 GeV upgrade will allow to study **charm baryons near threshold**

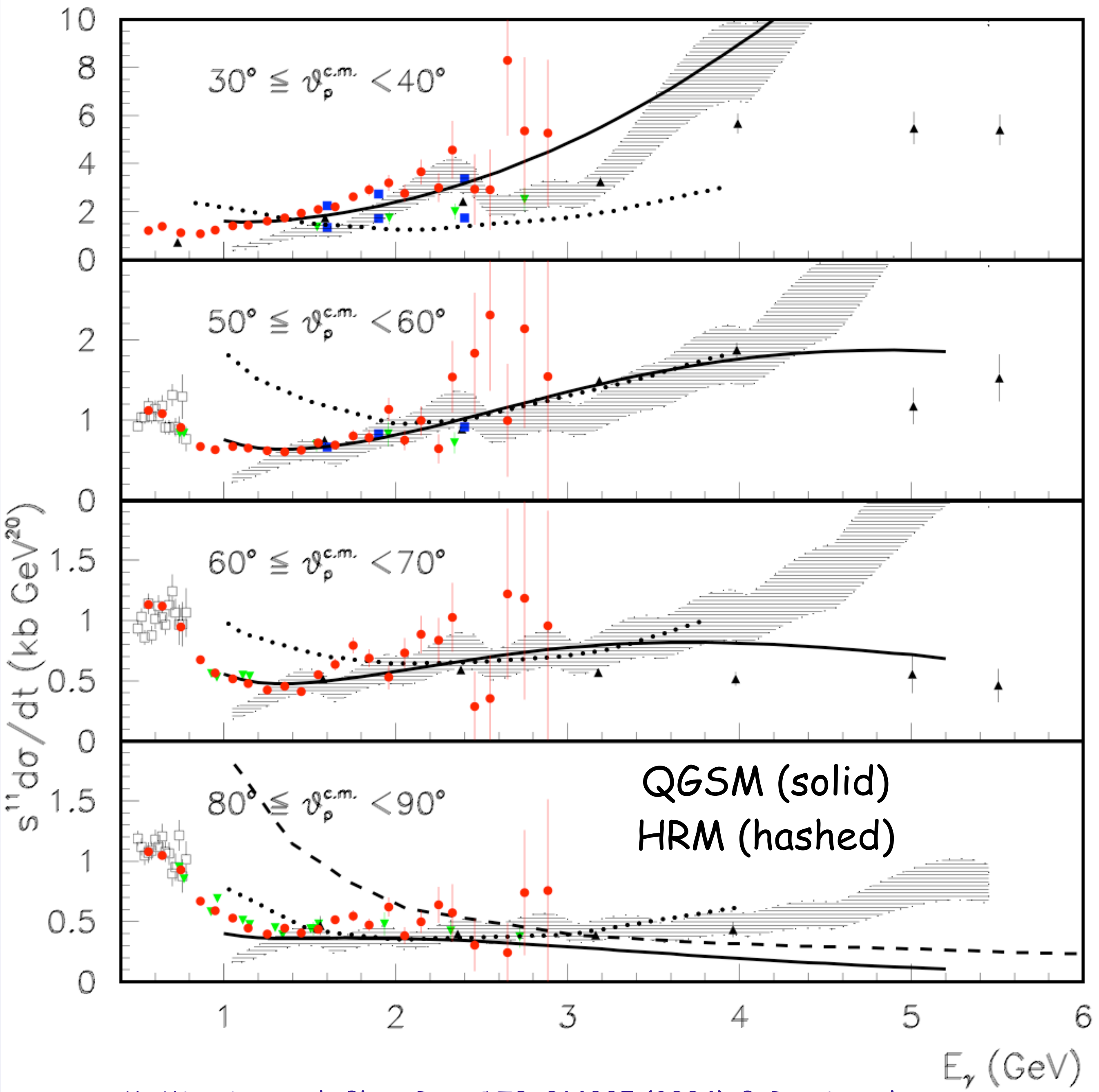
- Gluonic structure of deuteron
- Elementary $J/\psi N$ elastic cross section

The End

Dynamics of Hard Photodisintegration in the Scaling Regime

Both, QGSM and HRM, models for $\gamma d \rightarrow pn$ describe well measured experimental observables.

E_γ=2.0 GeV



M. Mirazita et al., Phys. Rev. C **70**, 014005 (2004); P. Rossi et al., Phys. Rev. Lett. **94**, 012301 (2005)

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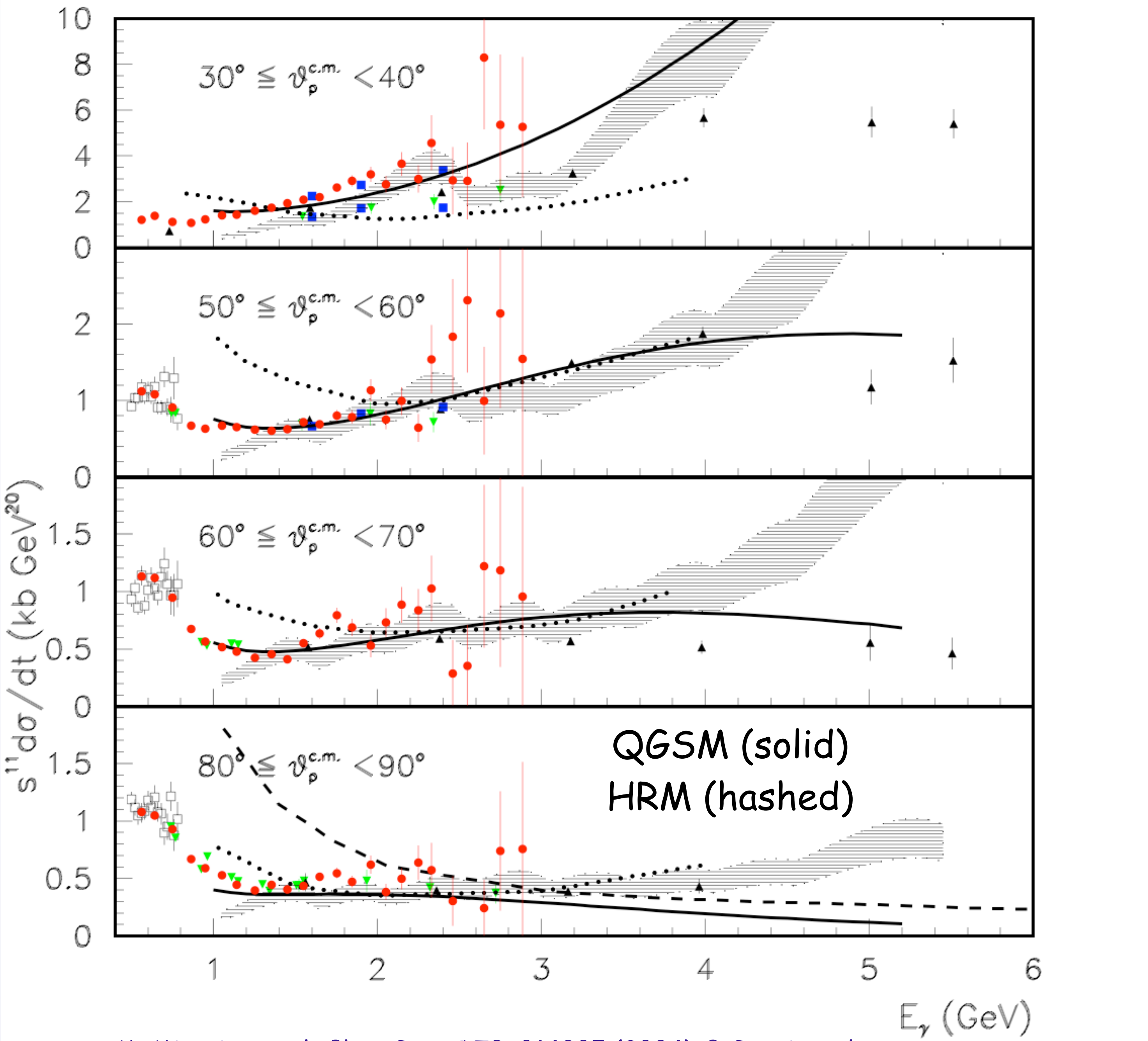
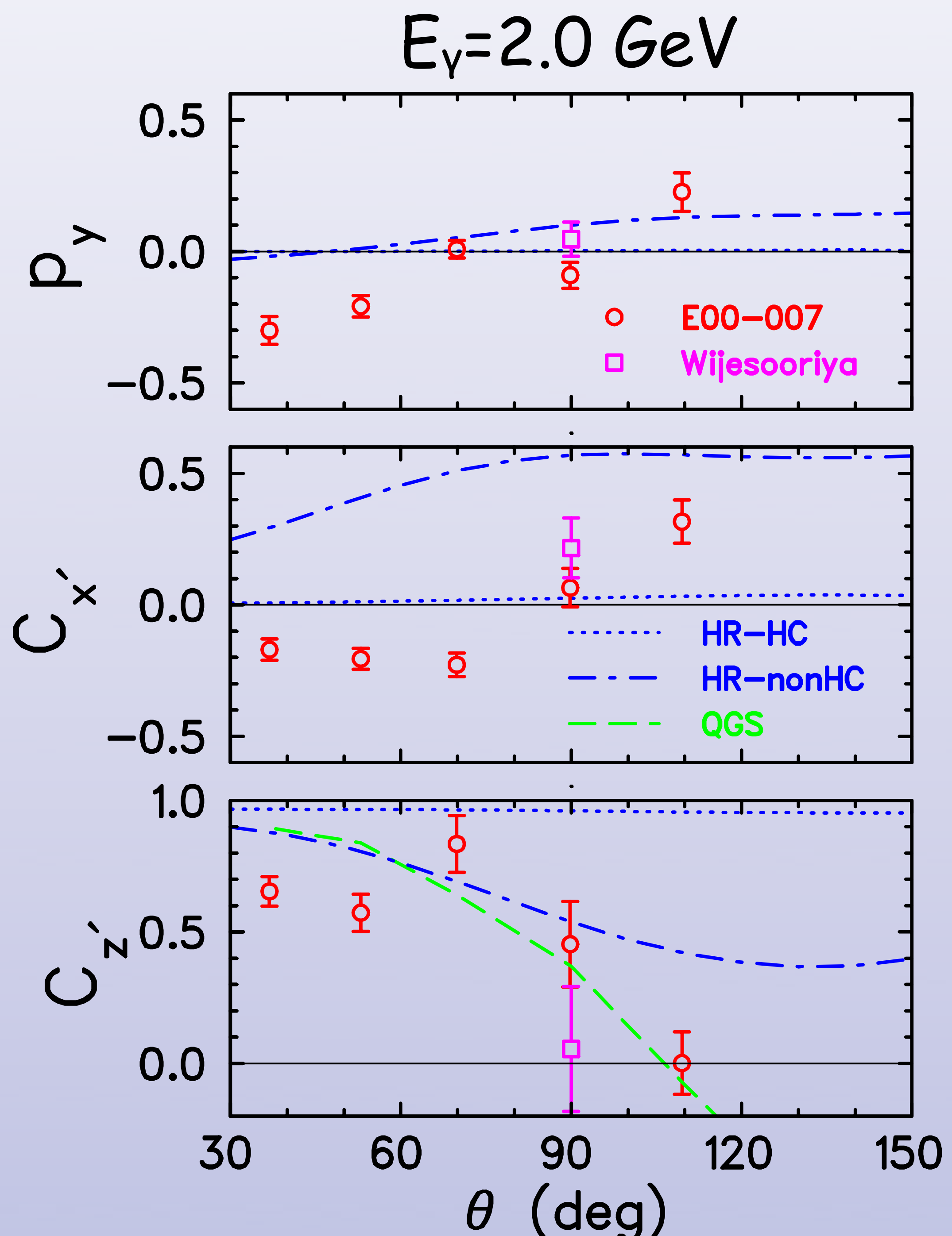


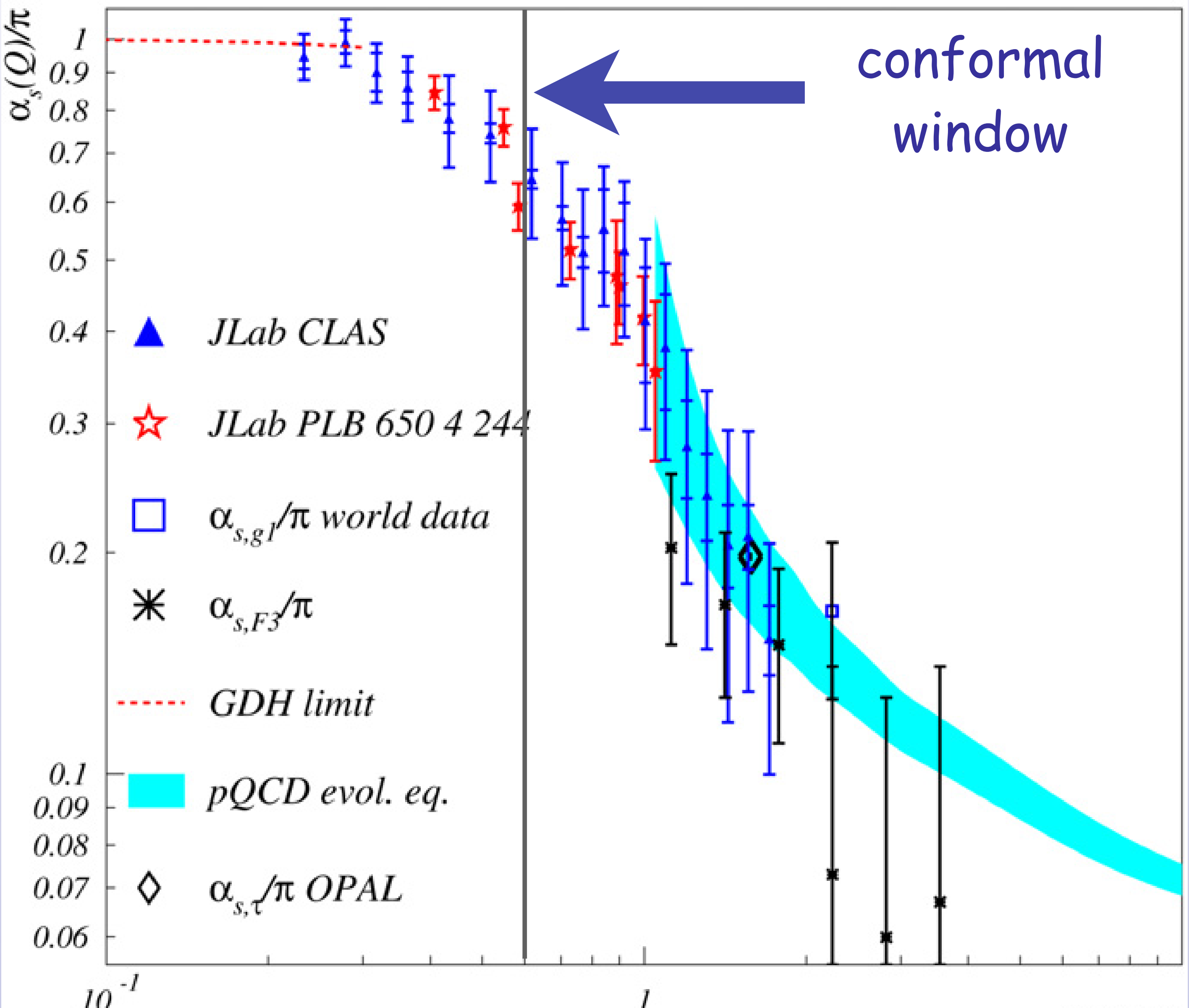
M. Mirazita et al., Phys. Rev. C **70**, 014005 (2004); P. Rossi et al., Phys. Rev. Lett. **94**, 012301 (2005)



X. Jiang et al., Phys. Rev. Lett. **98**, 182302 (2007)

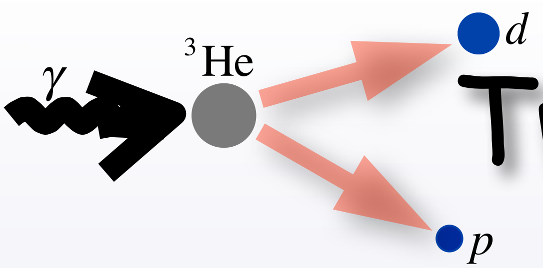
AdS/CFT: Conformal Window

- At short distances, dimensional scaling laws reflect the scale independence of α_s (asymptotic freedom)
- At large distances, dimensional scaling laws reflect the existence of infrared fixed point of QCD: α_s is large but scale-independent
- Scale-invariance is broken in the transition between these two dynamical regimes



A. Deur et al, Phys. Lett B **665**, 349 (2008)

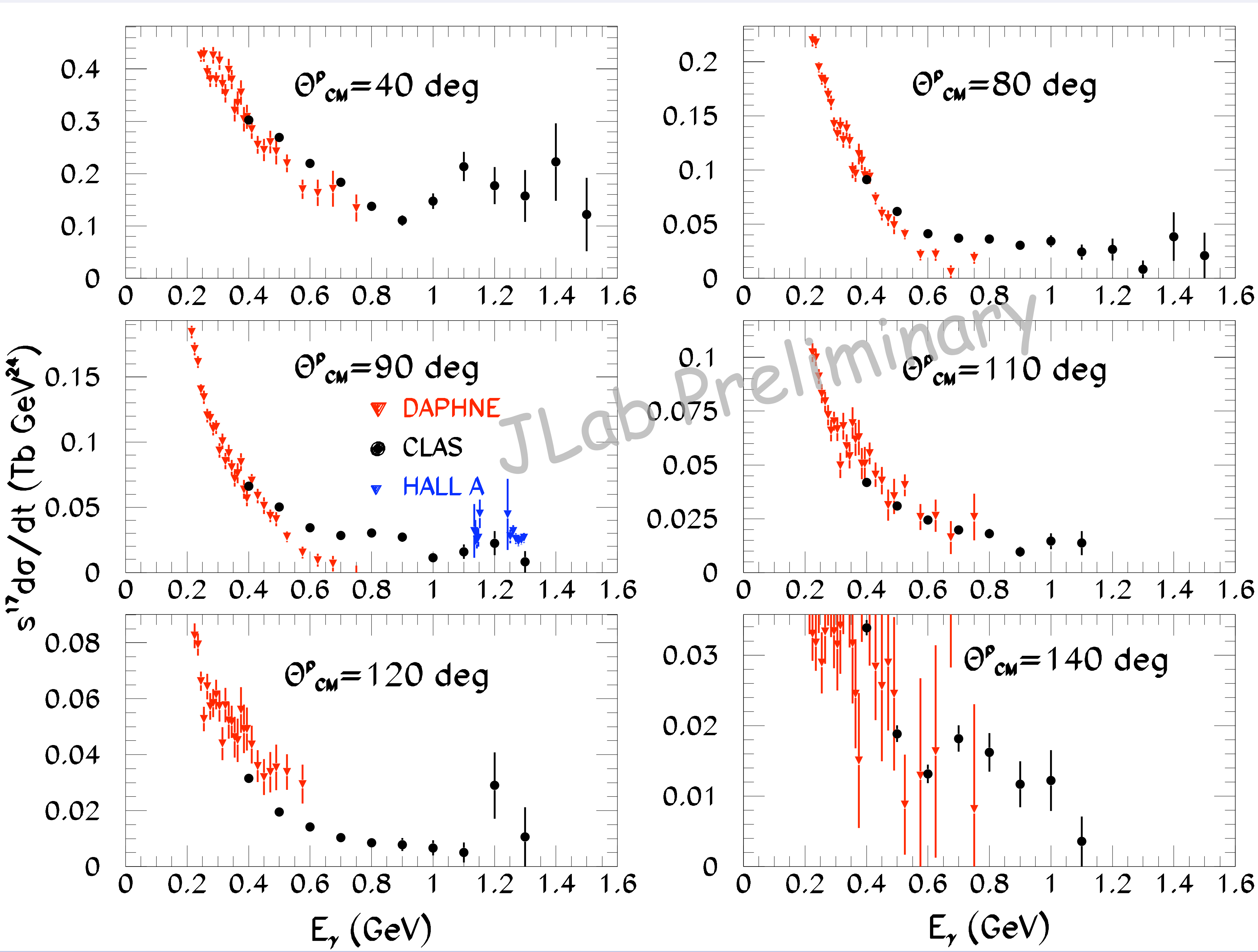
S.J. Brodsky and G.F. de Teramond, Phys. Rev. D **77**, 056007 (2008);
J. Polchinski and G.R. Strassler, Phys. Rev. Lett. **88**, 031601 (2002).



Two-Body Photodisintegration of ^{3}He

Scaling of invariant cross sections

$$s^{17}\frac{d\sigma}{dt} \sim \text{const.}$$



- Indication that above ~0.7 GeV data consistent with scale invariance for all CM angles
- Onset of dimensional scaling depends on the momentum transfer to individual constituents: supports AdS/CFT hypothesis

V. Isbert et al., Nucl. Phys. A **578**, 525 (1994)   I. Pomerantz et al., private communication

Suppression of Quasi-Free Mechanism

Event Distribution over Missing Momentum

$$P_x \ (\gamma d \rightarrow K^+ \Lambda X)$$

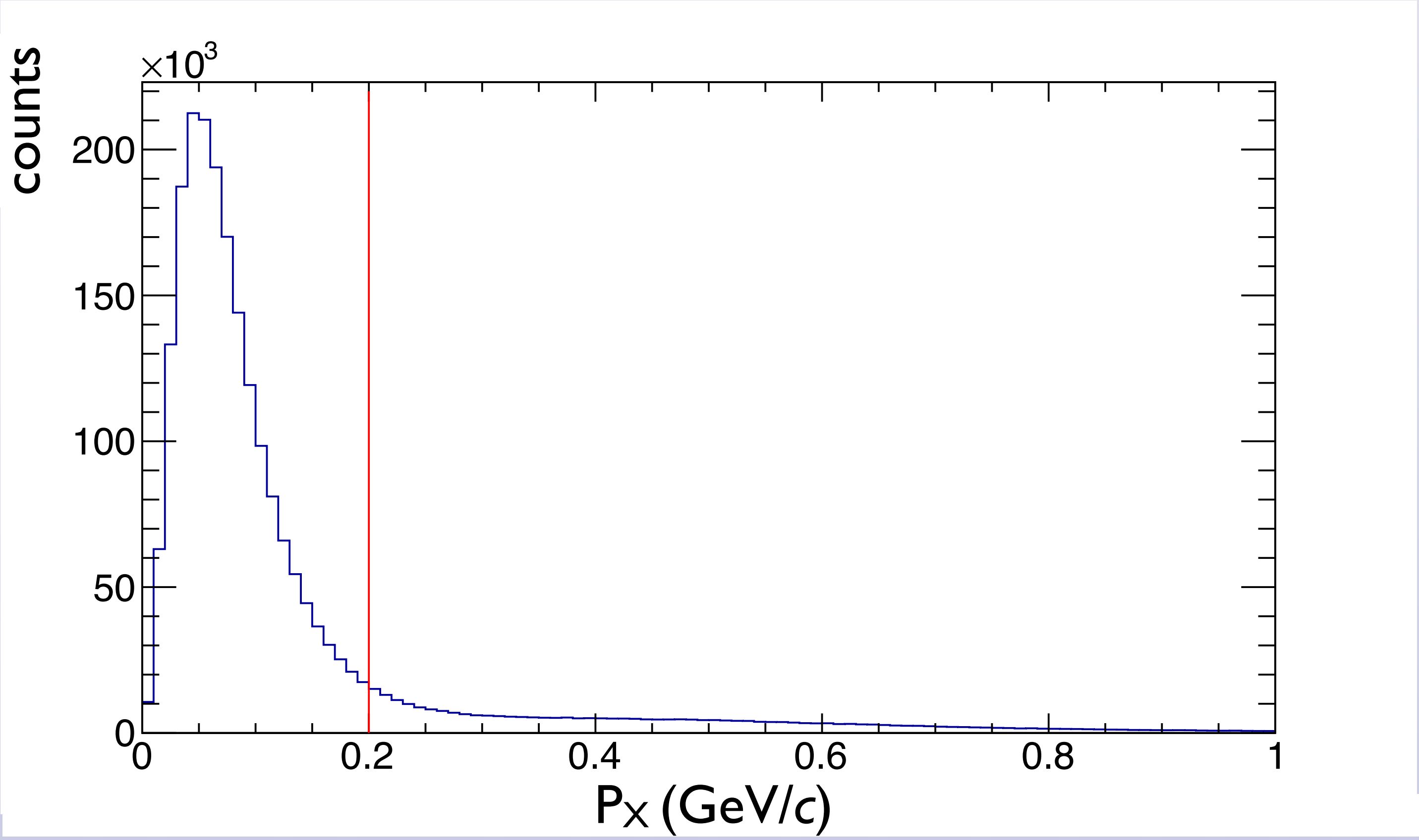


Figure from Tongtong Cao

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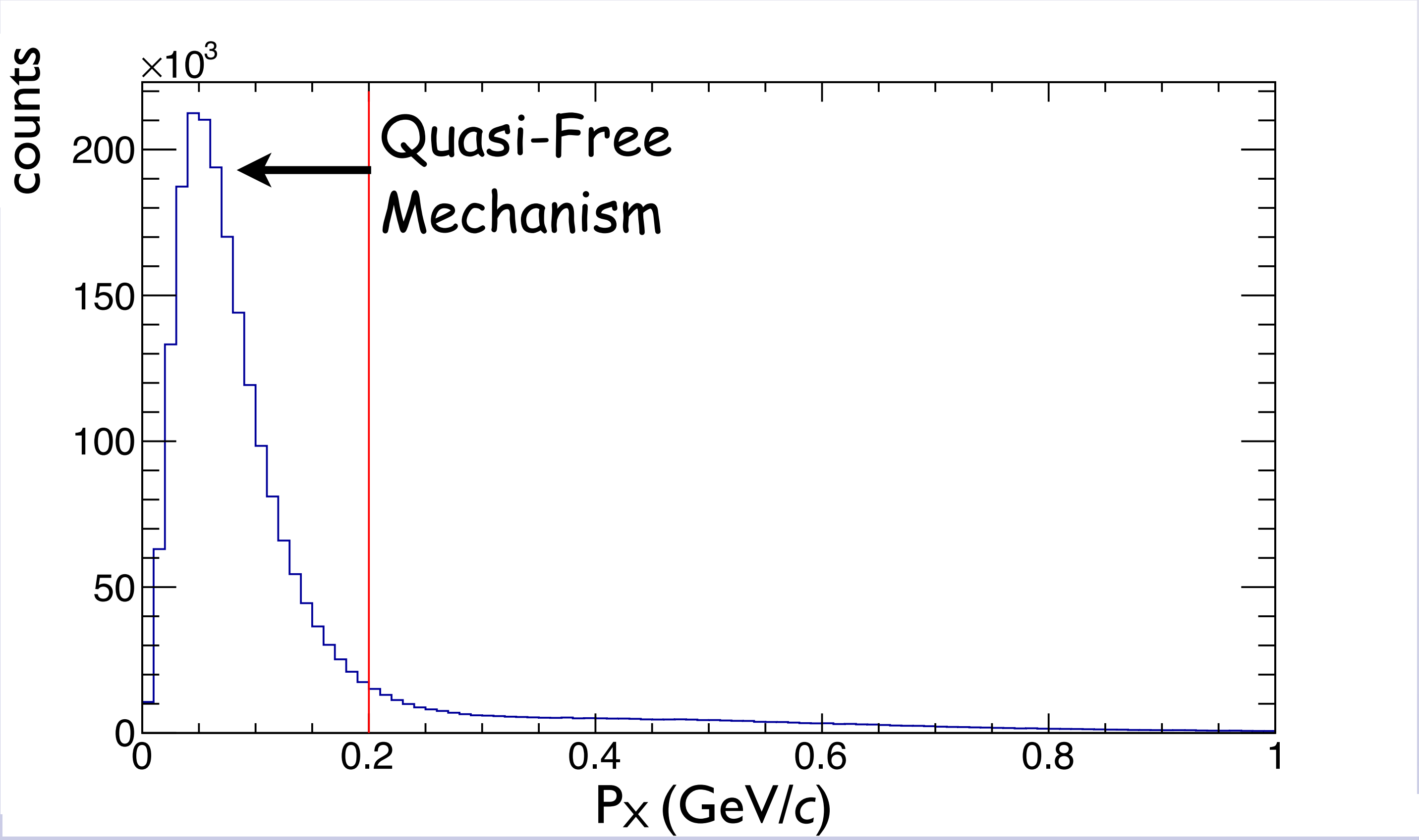

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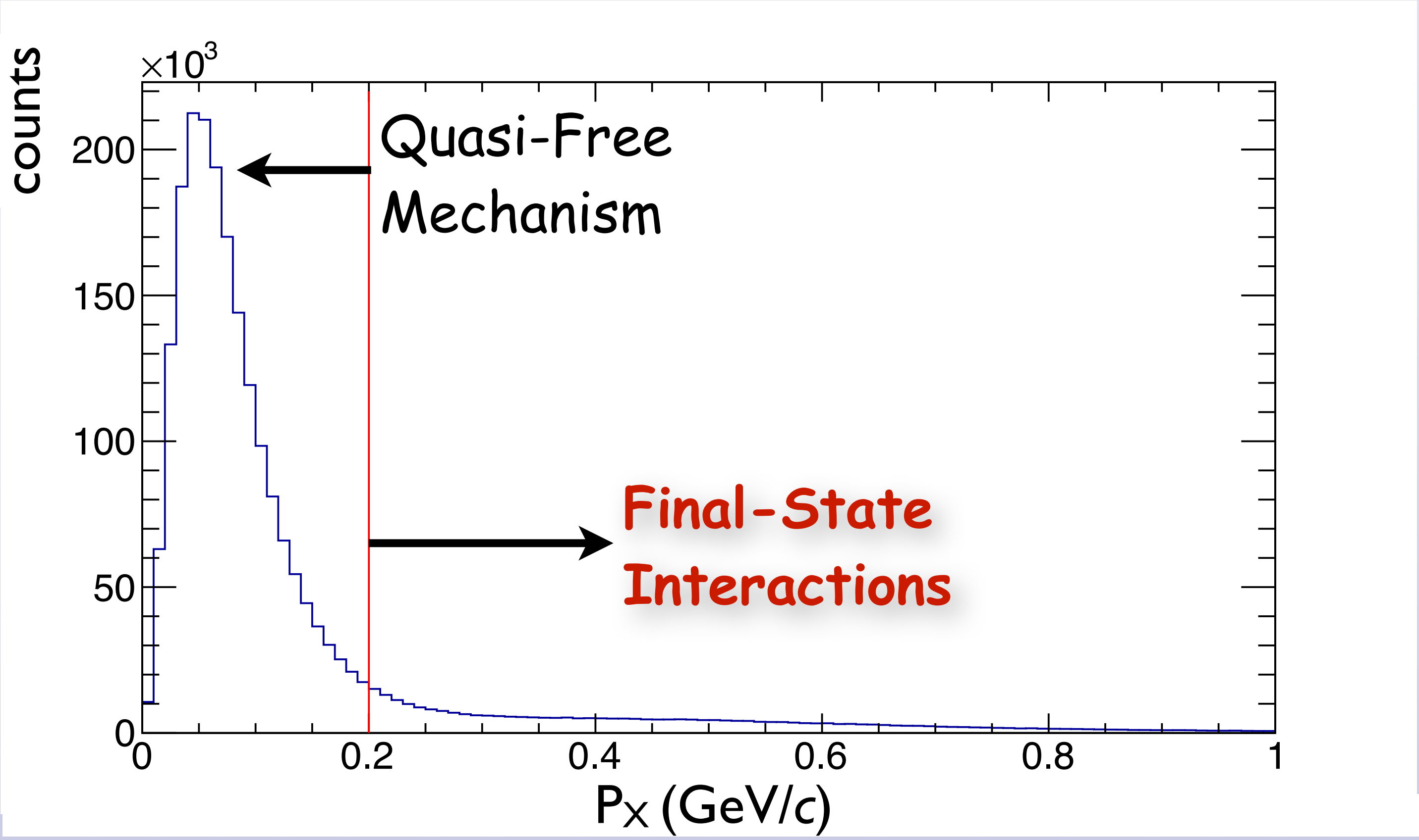

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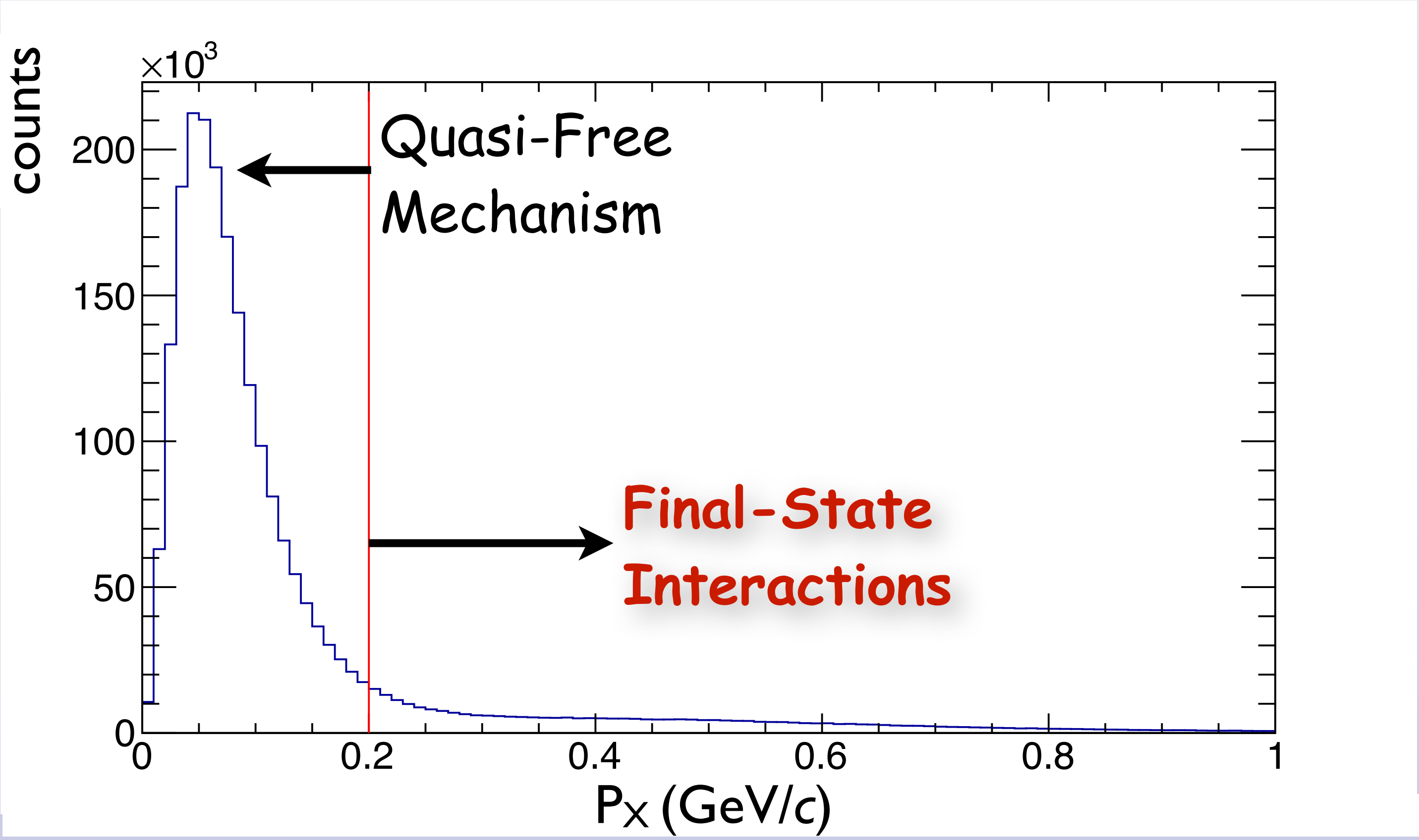

The removal of events with Px < 0.2 GeV/c provides a sample that is by far dominated by FSI events. Standard analysis procedure.

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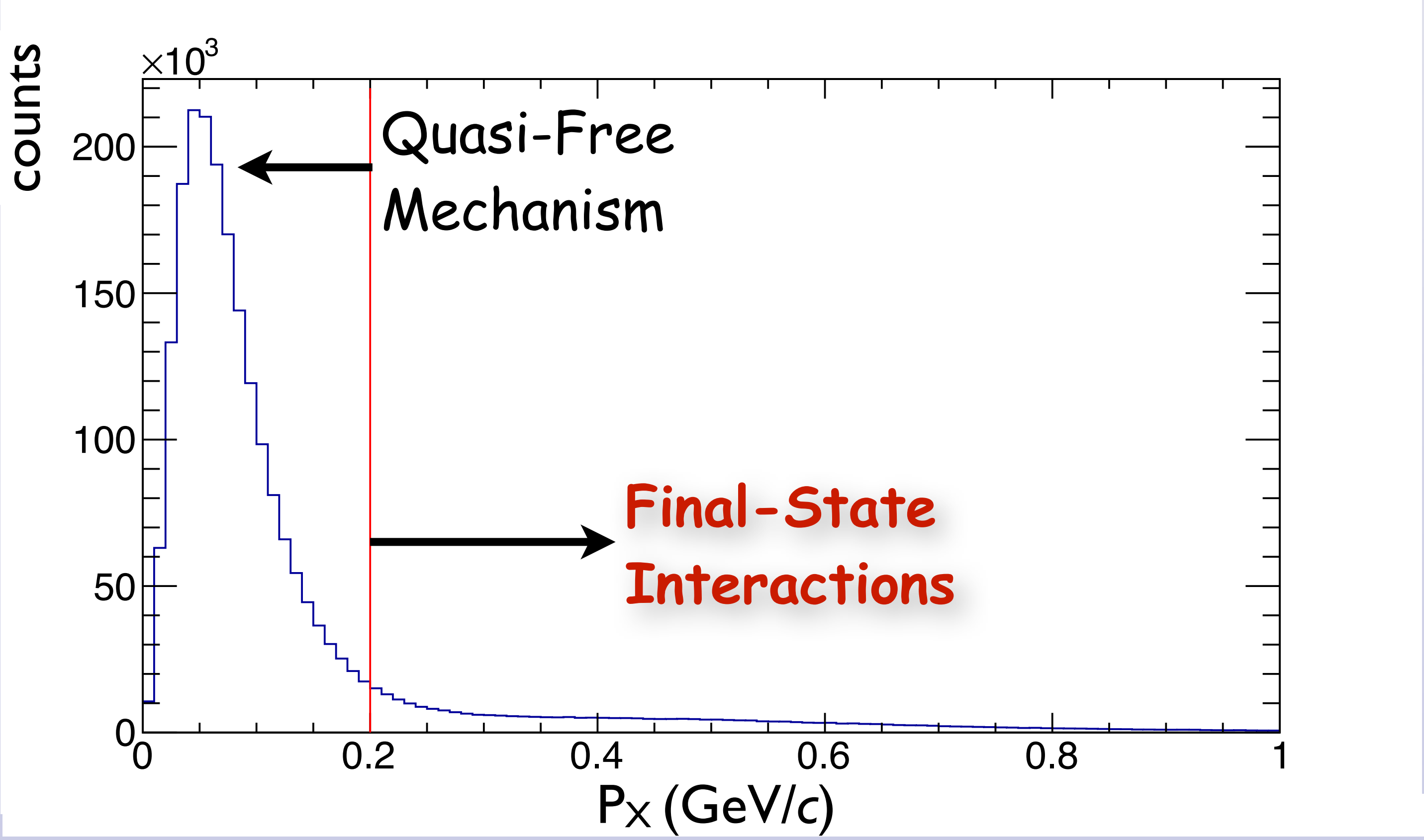

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Selection of Exclusive Events

Event Distribution over Missing Mass

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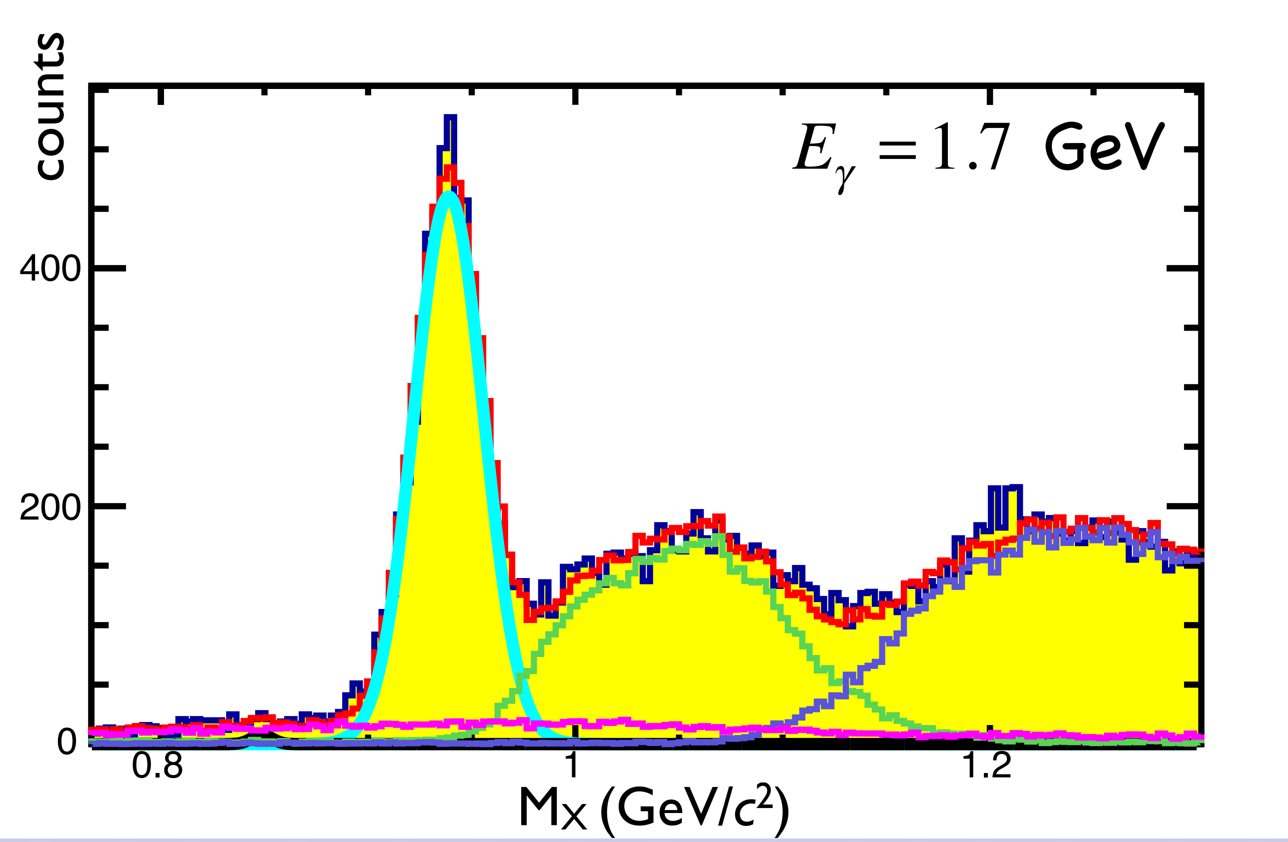

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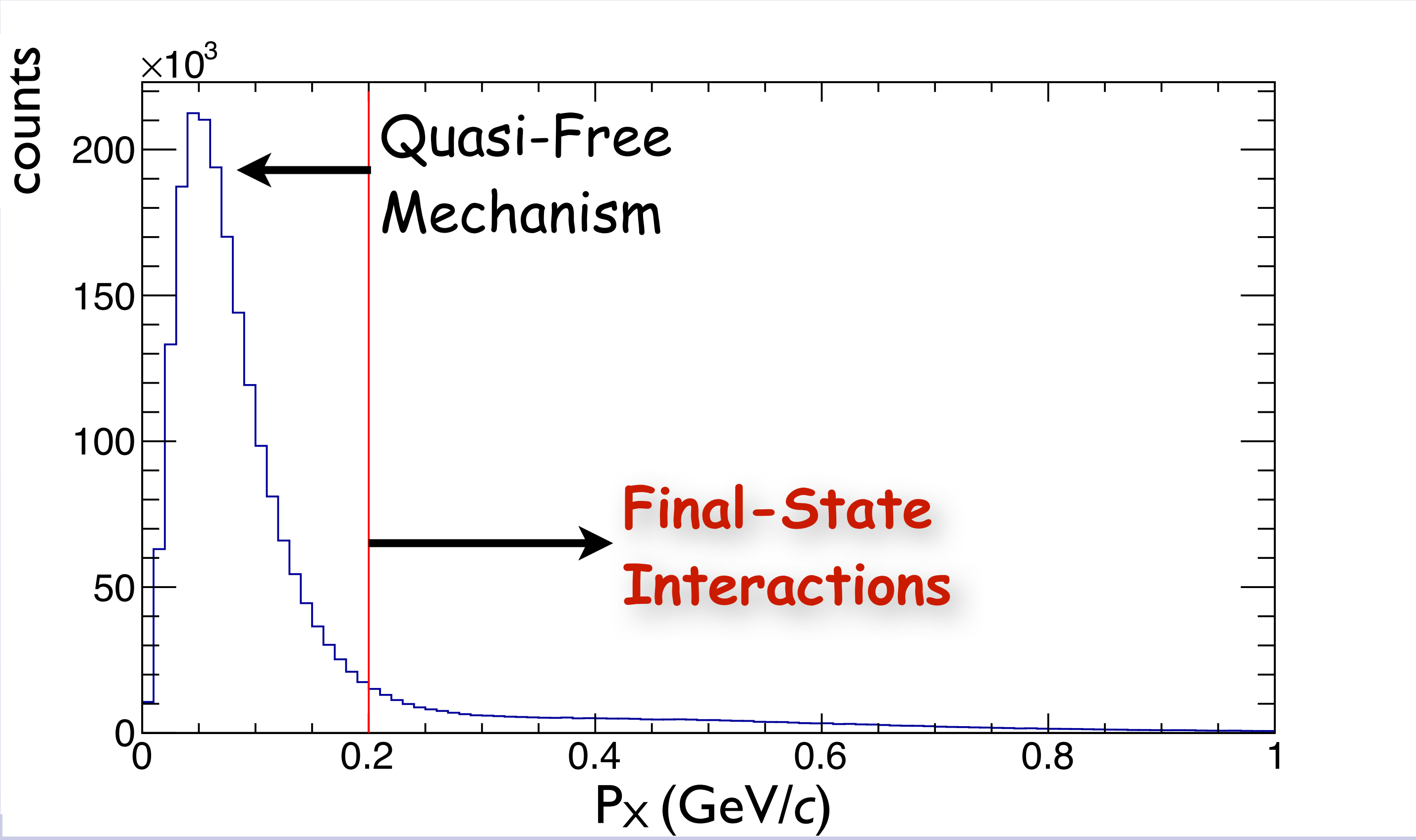

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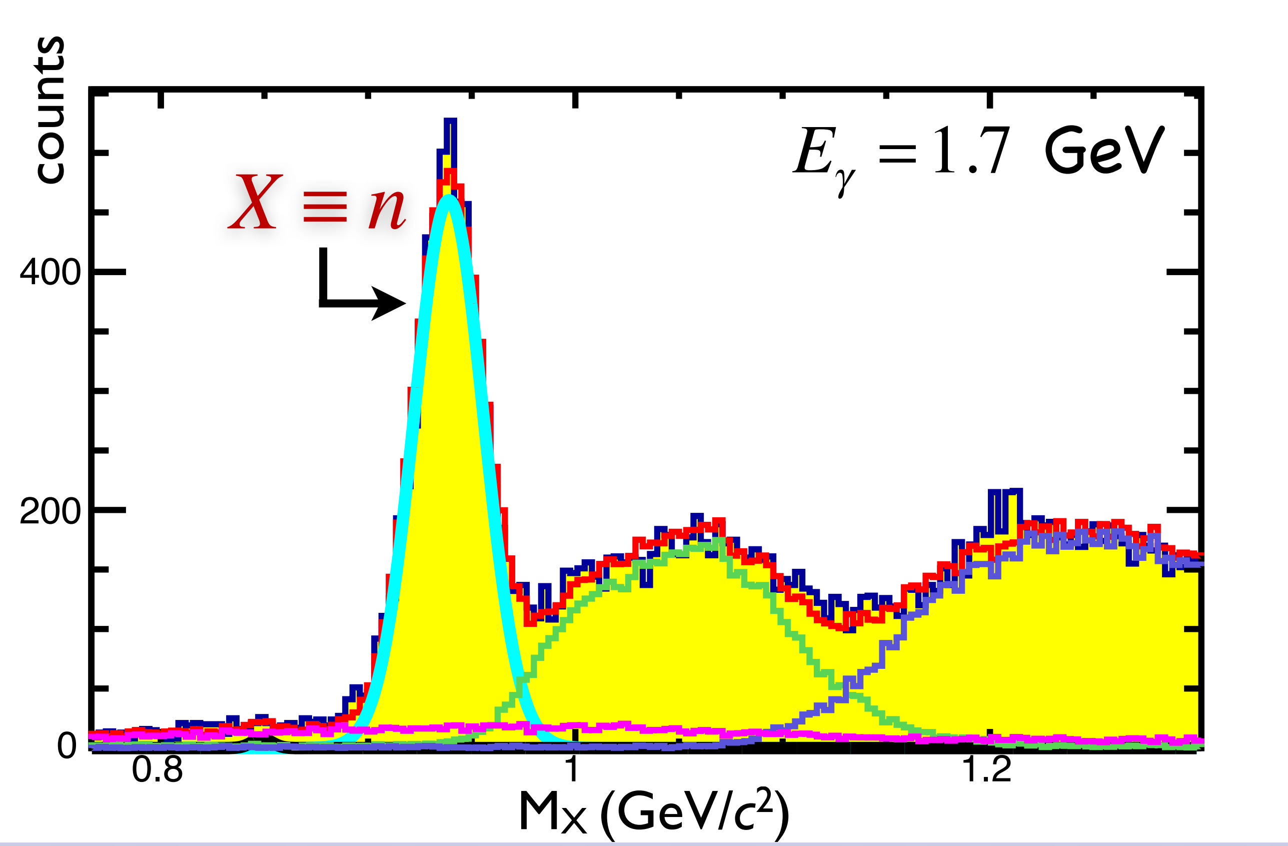

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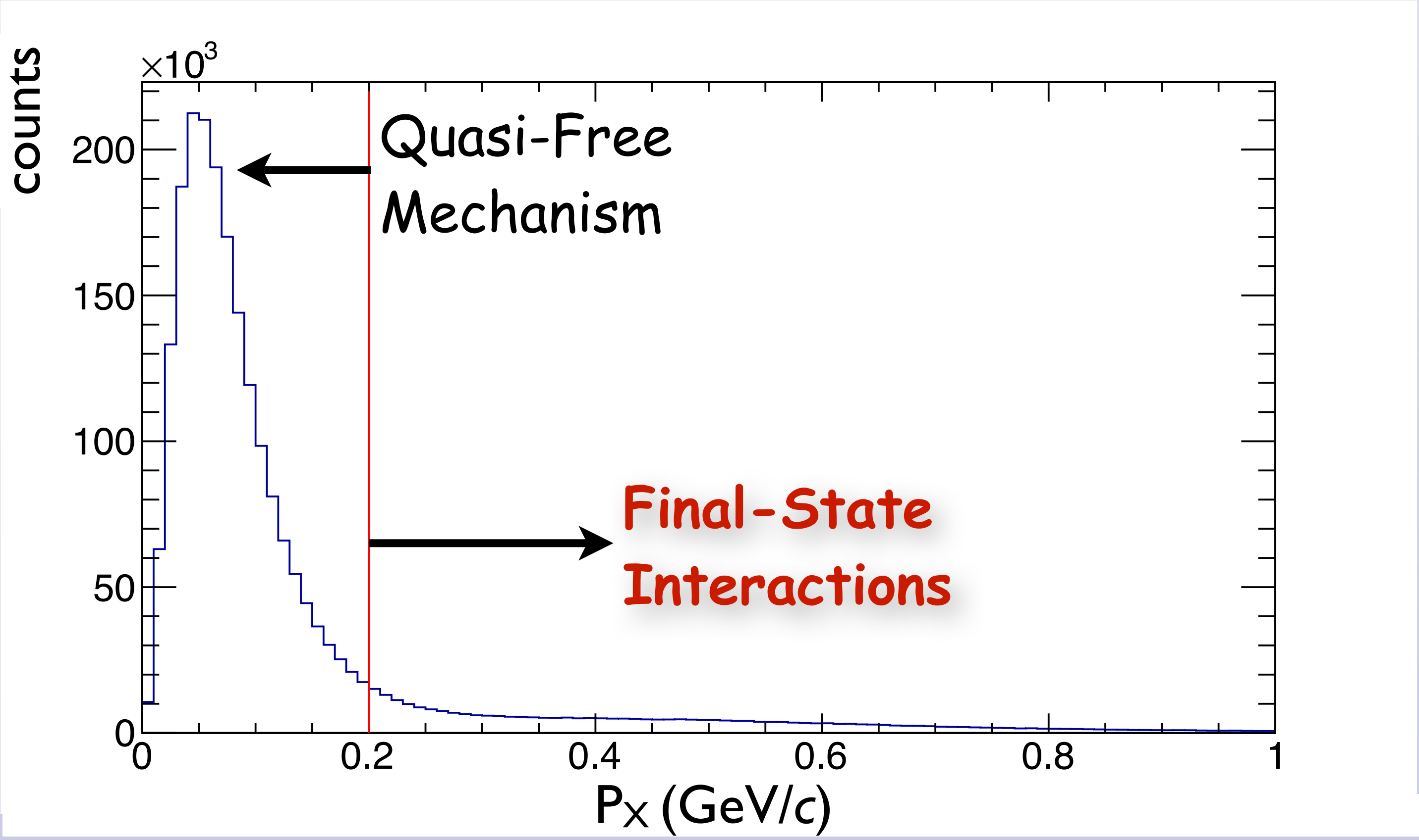

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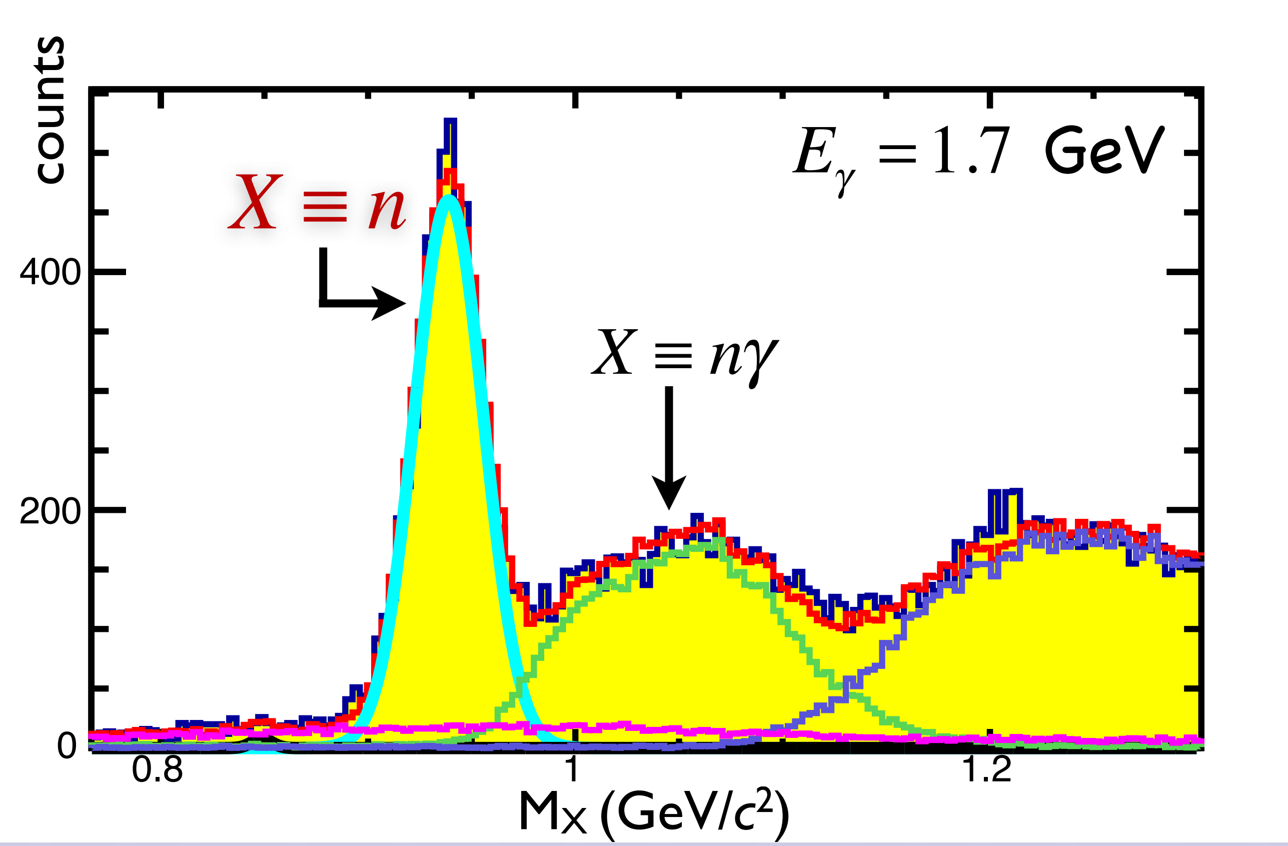

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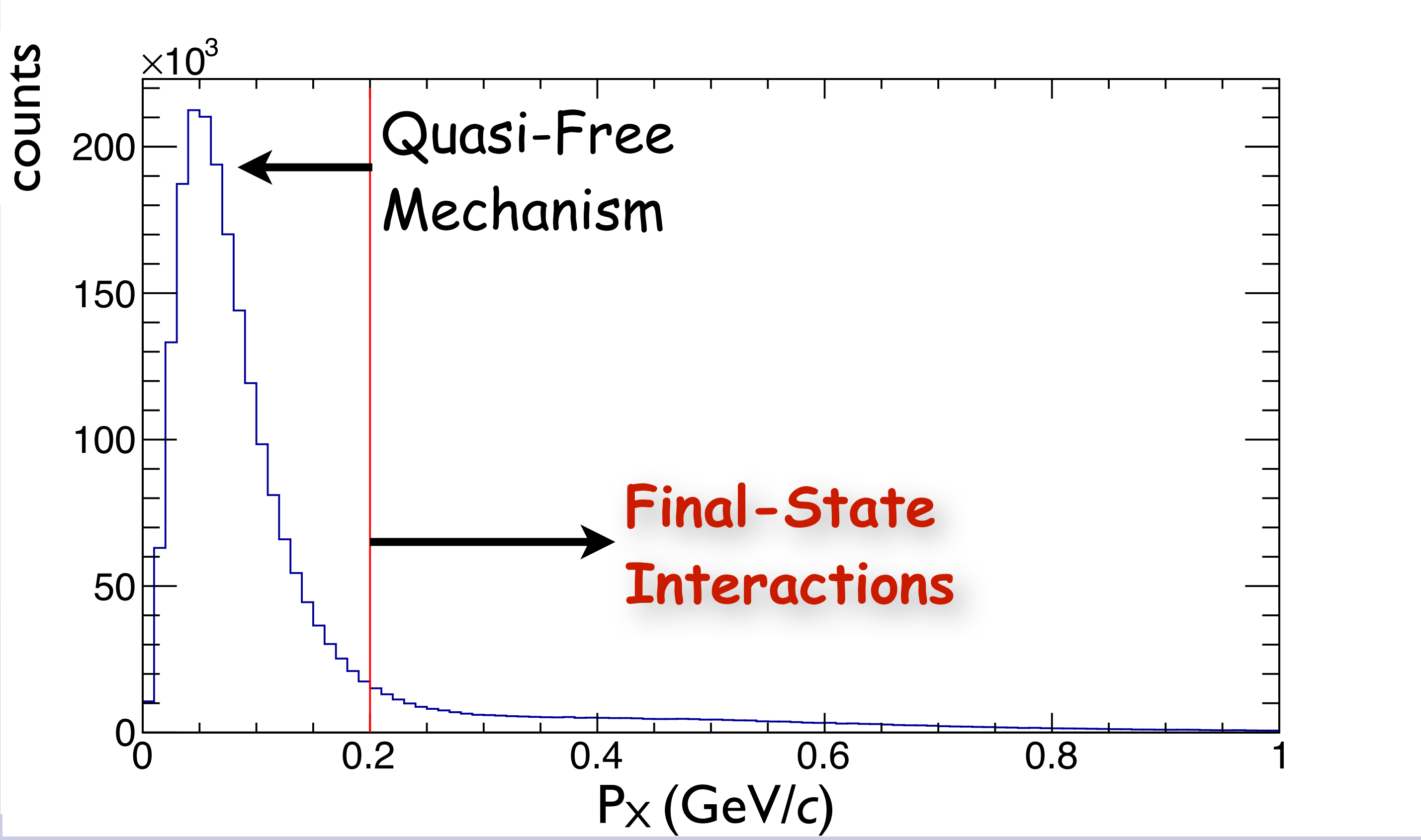

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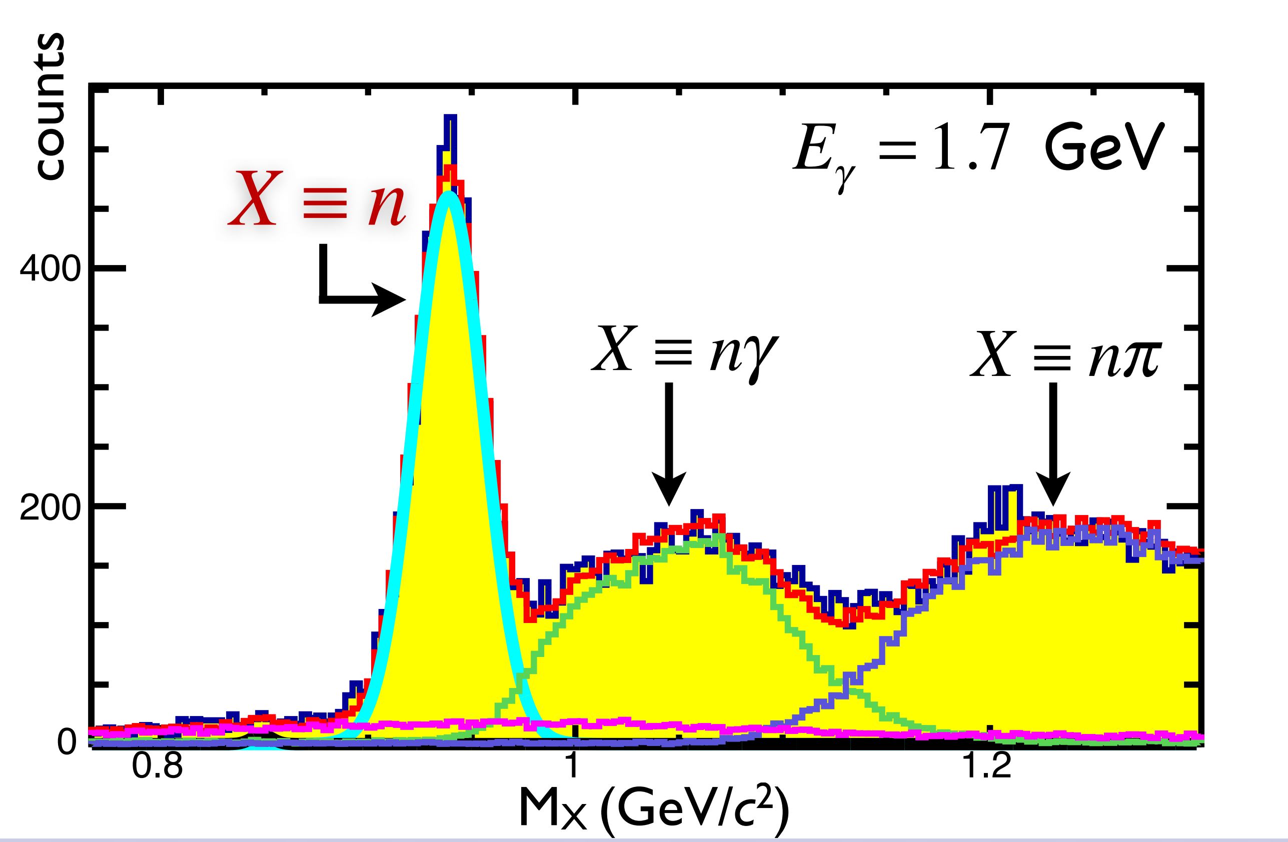

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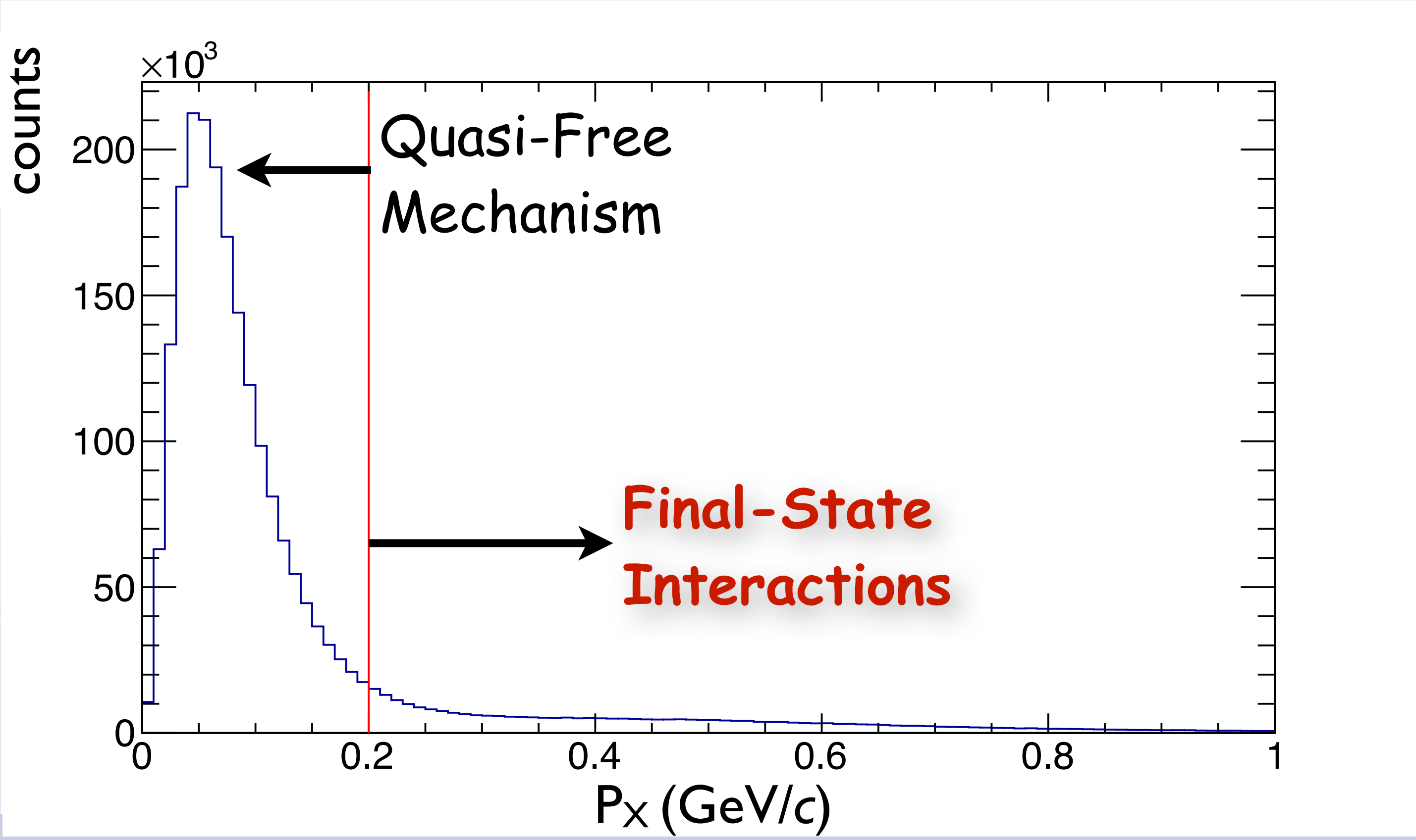

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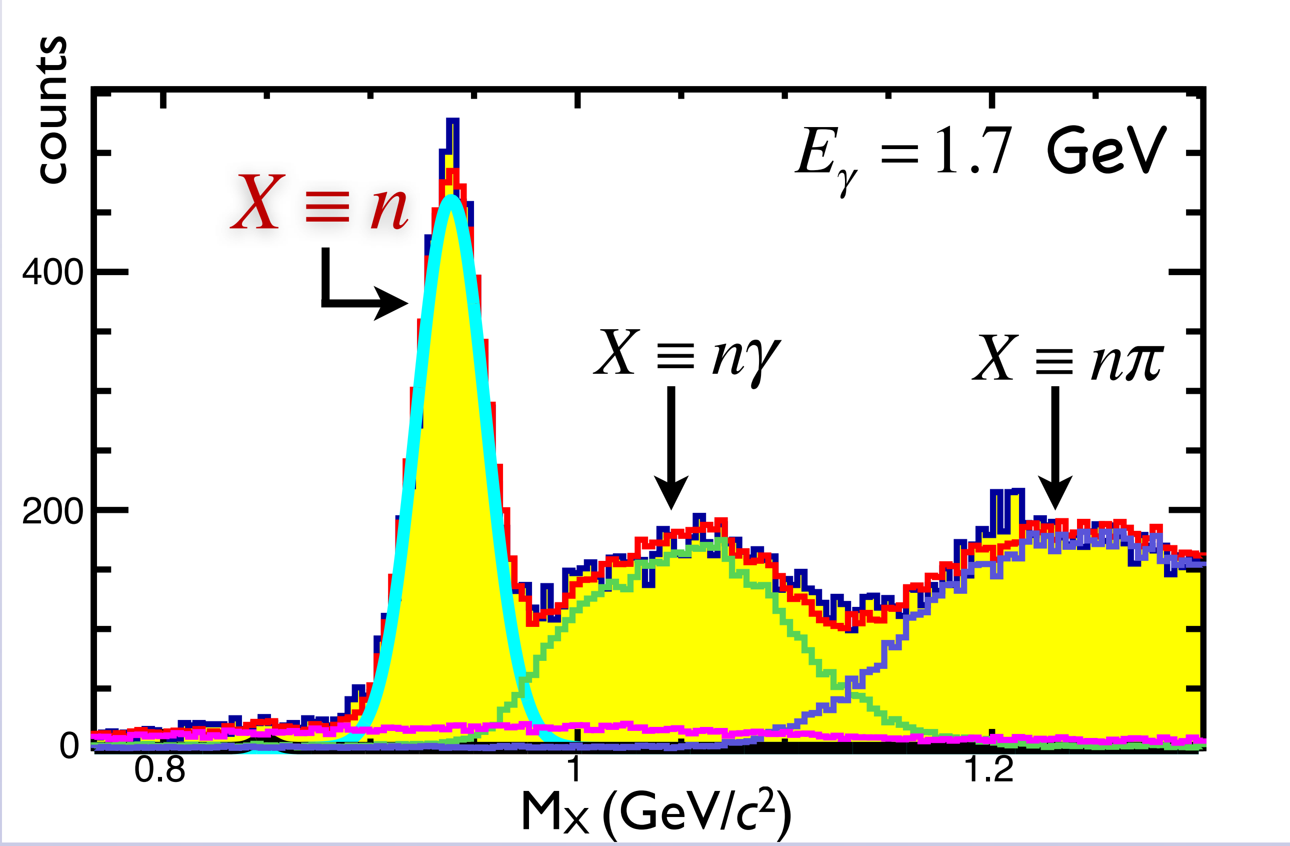

Removal of physics background based on realistic simulation of reactions, detector, and accidentals, followed by histogram or event-by-event fits for each kinematic bin.

Figure from Nick Zachariou