Photodisintegration of Light Nuclei

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Outline

- Experimentally Accessible Phenomena: Dimensional scaling
- Study of dimensional scaling in the two-body photodisintegration of ^{3}He

$$\gamma\,^3He \rightarrow pd$$

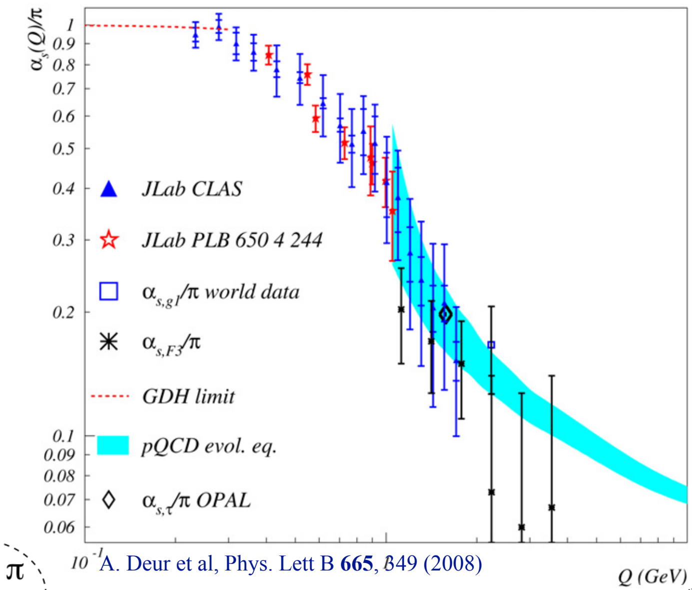
- Study of the beam-spin asymmetry of two-body photodisintegration of deuteron

$$\gamma d \rightarrow pn$$

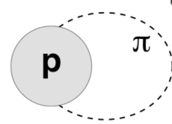
Motivation

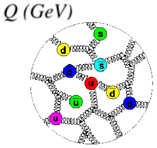
- One of the long standing challenges in nuclear physics has been to understand hadron interactions and nuclear structure

- High-energy regime
  pQCD (asymptotic freedom)
- Low-energy regime
  Hadronic degrees of freedom (confinement)
- Intermediate energies
  Hadronic ⟷ pQCD
  transition region



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



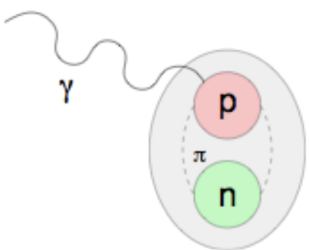


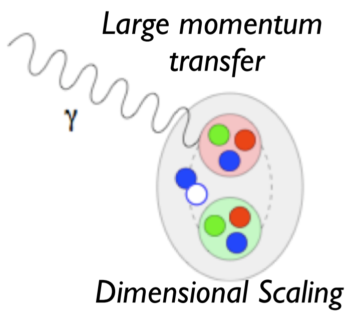
- Standing questions:
  - What are the relevant degrees of freedom?
  - Is there a clear transition?
  - Can we understand nuclei in terms of quarks and gluons?

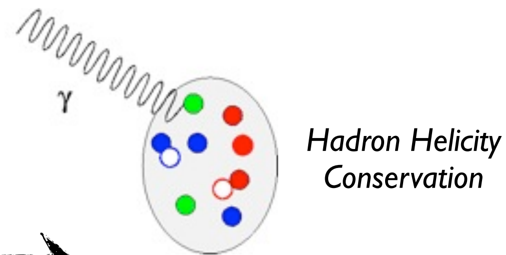
Photodisintegration of Few-Nucleon Systems at Medium Energies

Large momentum transfer

Exclusive processes







transition

Access to quark-gluon dynamics

Dimensional scaling: Evidence for onset of quark-gluon dynamics in nuclear processes

Experimentally accessible phenomena predicted by QCD

Dimensional Scaling Laws

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 → C + D at fixed CM angle:

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

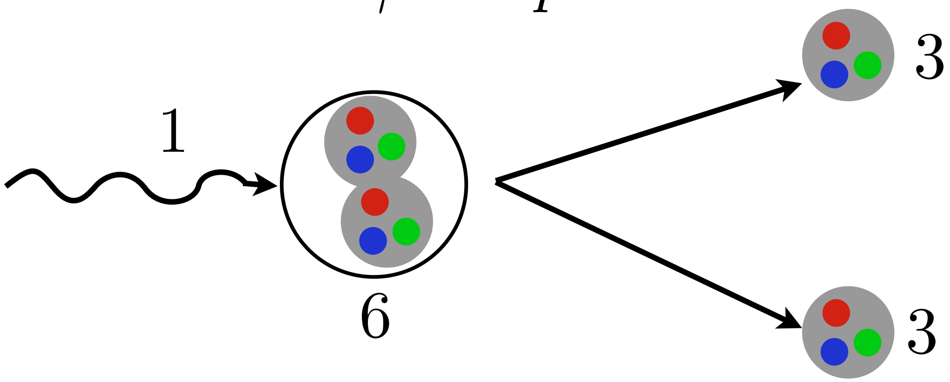
where n is the total number of the initial and final elementary fields.

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

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

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

$$\gamma d \to pn$$



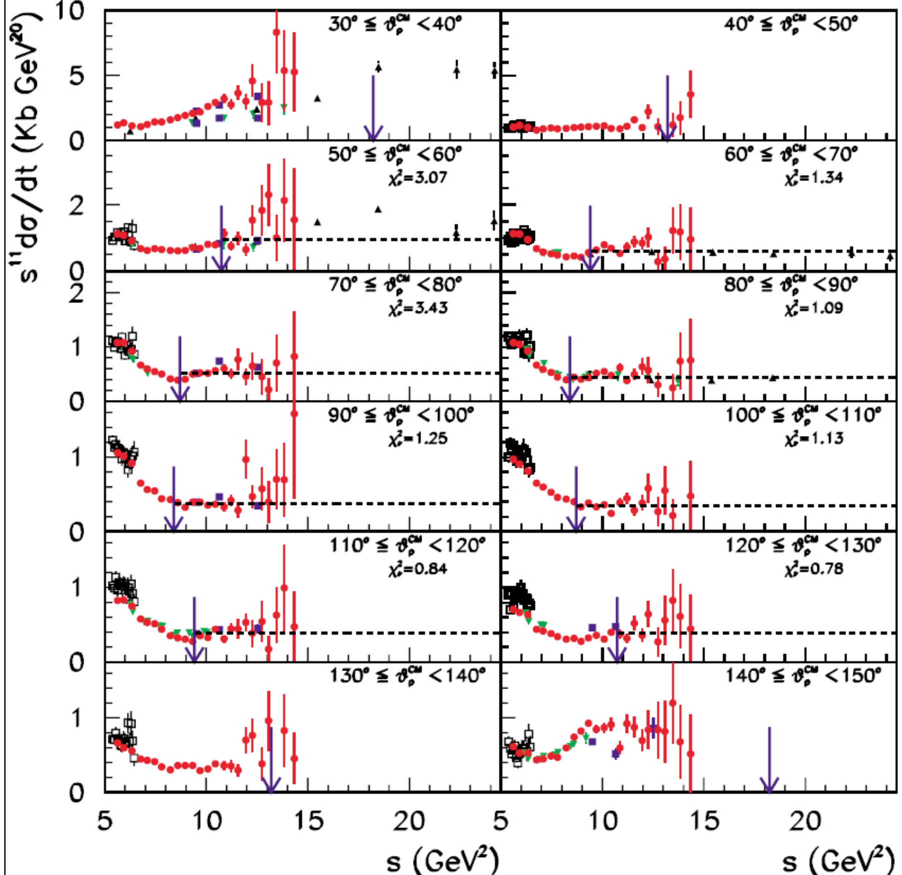
$$n = 1 + 6 + 3 + 3 = 13$$

V. A. Matveev, R. M. Muradian, and A. N. Tavkhelidze, Nuovo Cimento Lett. 7, 719 (1973).

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)

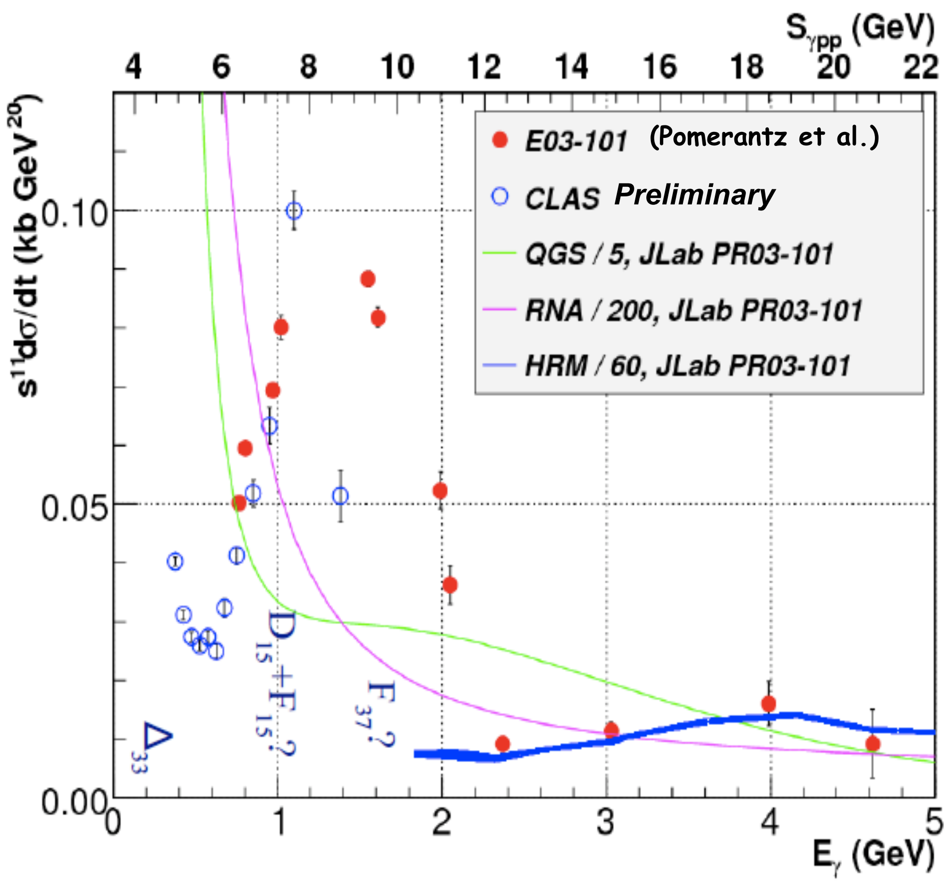
Previous Studies of Two-Nucleon Systems

$\gamma d \to pn$ $\quad s^{11}\frac{d\sigma}{dt} \sim \text{const.}$



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

$\gamma pp(n) \to pp(n)$ $\quad s^{11}\frac{d\sigma}{dt} \sim \text{const.}$



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

Dimensional Scaling Laws

Extensively studied in hadronic and nuclear reactions

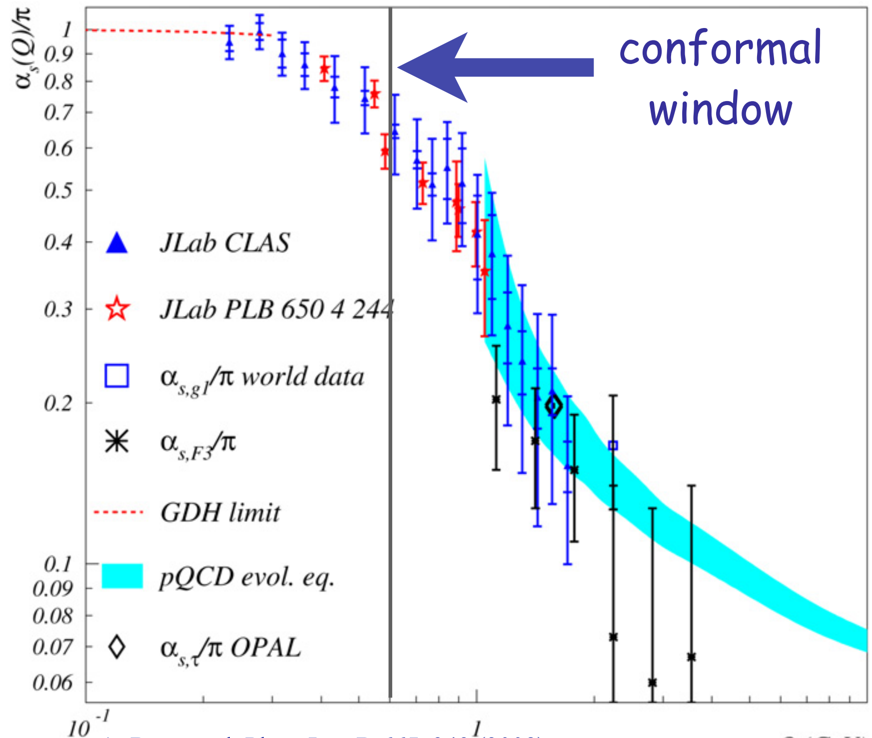
Reaction	s (GeV^2)	$\theta_{c.m.}$ (deg)	n Predicted	n Measured
$pp \to pp$	15–60	38–90	10	9.7 ± 0.5
$p\pi^- \to p\pi^-$	14–19	90	8	8.3 ± 0.3
$\gamma p \to \gamma p$	7–12	70–120	6	8.2 ± 0.5
$\gamma p \to \rho^0 p$	6–10	80–120	7	7.9 ± 0.3
$\gamma p \to p\pi^0$	8–10	90	7	7.6 ± 0.7
$\gamma p \to n\pi^+$	1–16	90	7	7.3 ± 0.4
$\gamma p \to K^+\Lambda$	5–8	84–120	7	7.1 ± 0.1
$\gamma d \to pn$	1–4	50–90	11	11.1 ± 0.3
$\gamma pp \to pp$	2–5	90	11	11.1 ± 0.1
$\gamma ^3\text{He} \to pd$	11–15.5	90	17	17.0 ± 0.6

I. Pomerantz, et al. Phys. Rev. Lett. **110**, 242301 (2013)

To date there is no common model or theory that can describe all the available data in a consistent manner.

Dimensional Scaling

- Non-perturbative derivation of Dimensional Scaling Laws
- At short distances, dimensional scaling laws reflect the scale independence of a_s
- At large distances, interactions amongst hadron constituents are also scale invariant (conformal window)



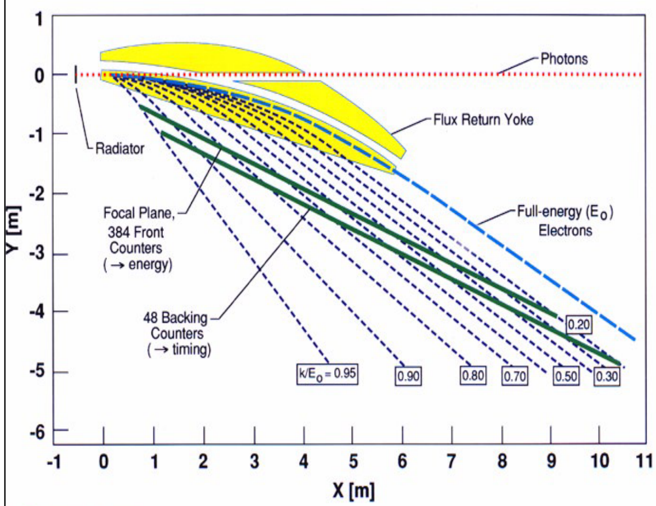
A. Deur et al, Phys. Lett B **665**, 349 (2008)

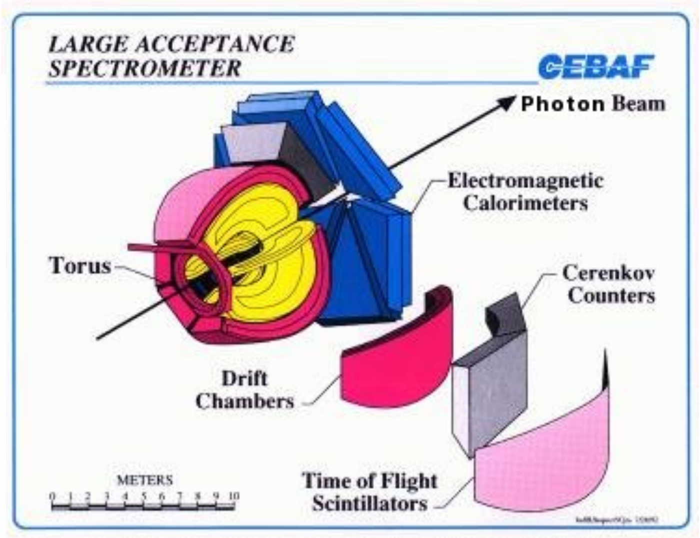
- Dimensional Scaling Laws probe two very different dynamical regimes
- Nuclear photodisintegration provides an excellent tool to study these two regimes

Photodisintegration of Light Nuclei with the CEBAF Large Acceptance Spectrometer (CLAS)

Efficient detection of charged particles over a large fraction of the full solid angle.

Photon Tagger





Angular Coverage

$8^\circ < \theta < 140^\circ$

$\phi \sim 1.7\pi$

Angular Resolution

$\sigma_\theta \sim 1$ mrad

$\sigma_\phi \sim 4$ mrad

Momentum Resolution

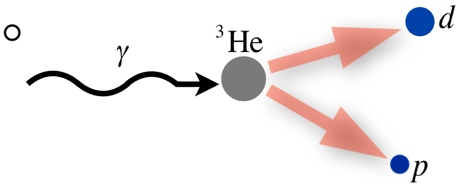
$\sigma_p/p \sim 1\%$

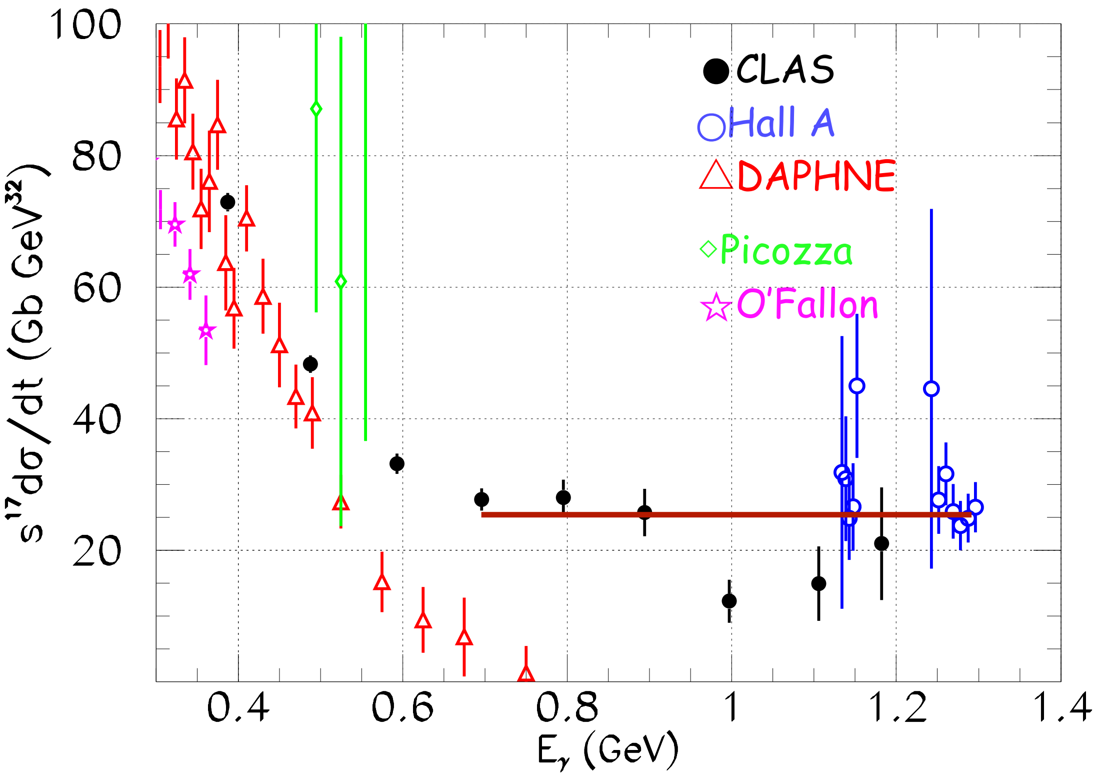
- Measured differential cross sections of two-body photodisintegration of ^{3}He at E_γ=0.4 - 1.4 GeV, $\theta_{p,c.m.}$=30° - 140° (JLab E93-044)

- Measured beam-spin asymmetry of two-body photodisintegration of d at E_γ=1.1 - 2.3 GeV, $\theta_{p,c.m.}$=35° - 145° with linearly polarized photon beam (JLab E06-103)

Two-body Photodisintegration of ^{3}He

Scaling of invariant cross sections at 90°





- Extracted value from fits to JLab data:

  N = 17 ± 1

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

- Our data are qualitatively consistent with the hypothesis of conformal window from AdS/CFT

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

I. Pomerantz, et al., Phys. Rev. Lett. 110, 242301 (2013)

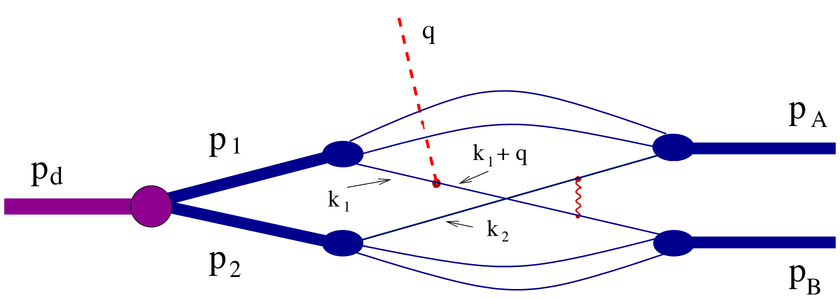
Where do we Stand?

- Supports qualitatively the non-perturbative interpretation of scaling.
- Indicates the quark-gluon picture maybe relevant for nuclei even at energies below 1 GeV.
- Deuteron photodisintegration can be used to better understand the origin of dimensional scaling and the role of quark and gluons in nuclear reactions in the GeV energy region.

Deuteron Photodisintegration

Hard Rescattering Mechanism (HRM)

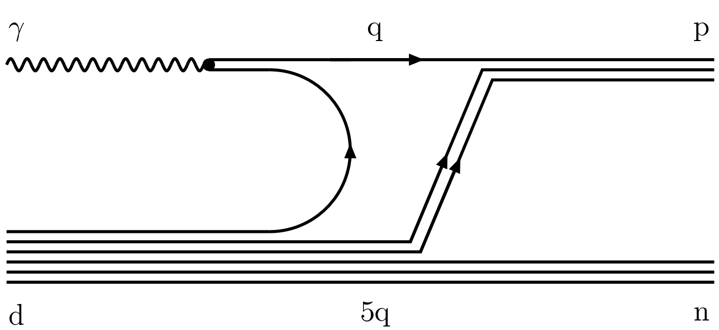
Photon is absorbed by a quark of one nucleon, followed by a high-momentum (hard) rescattering with a quark from the second nucleon



L. Frankfurt *et al.,* Phys. Rev. Lett. 84 3045 (2000)

Quark-Gluon String Model (QGSM)

The amplitude is calculated by the exchange of three valence quarks with any number of gluon exchanges between them



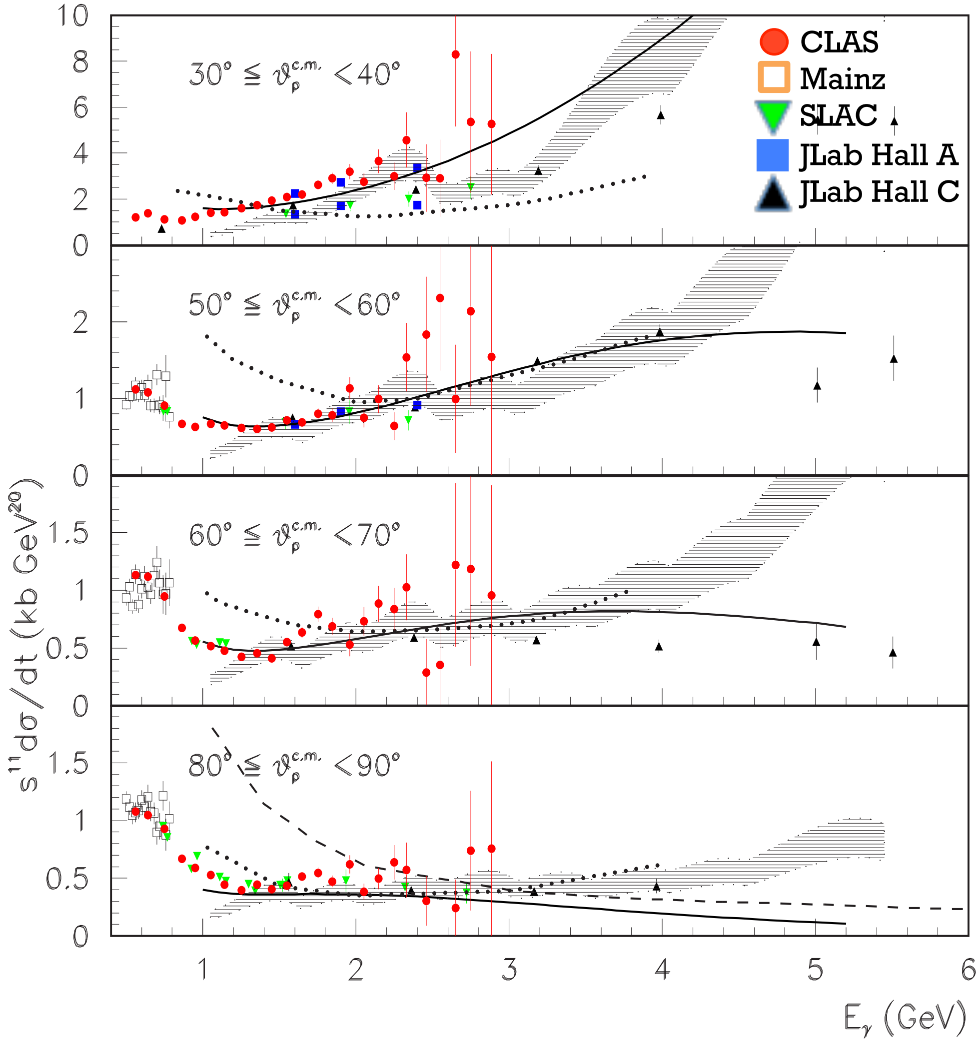
A.B. Kaidalov, Z. Phys C 12, 63 (2001)

Deuteron Photodisintegration

Theoretical Predictions
QGSM (solid line)
HRM (hatched area)

Both, QGSM and HRM describe the differential cross section with the same degree of success

Cross section alone does not provide enough information to understand the underlying dynamics



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

Deuteron Photodisintegration

Polarization observables

Only two sets of data for the recoil proton polarization obtained at JLab Hall A

K. Wijesooriya *et. al.*, Phys Rev Lett 86, 2975 (2001)

pQCD Limits (HHC)

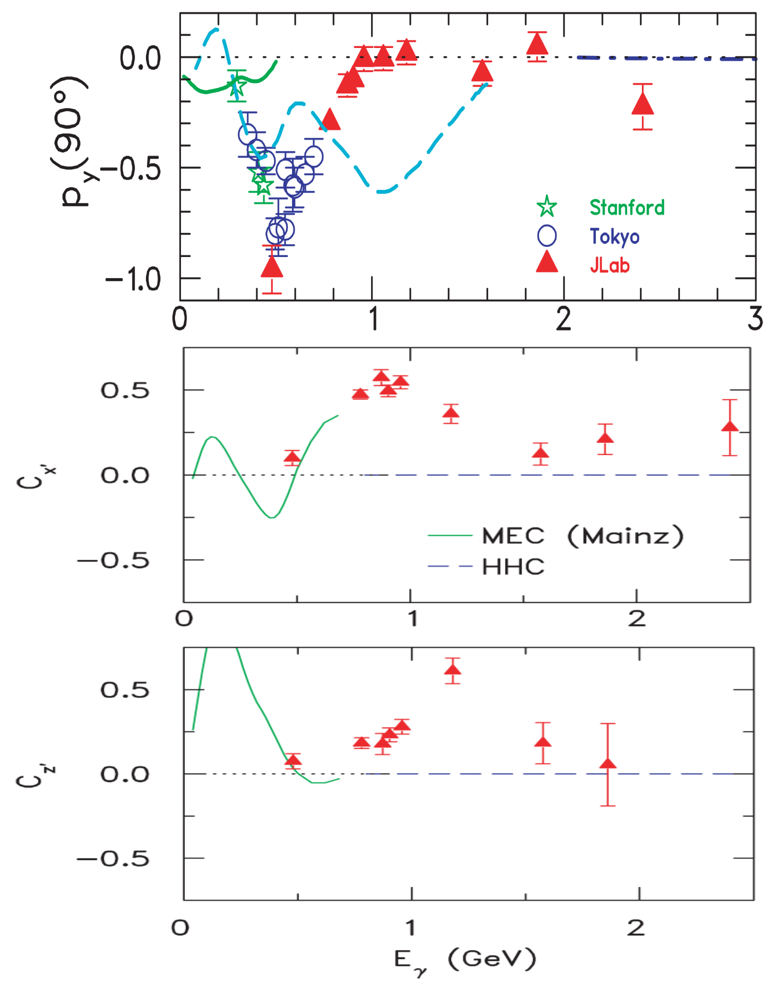
$$P_y \rightarrow 0$$
$$C_{x'} \rightarrow 0$$
$$C_{z'} \rightarrow 0$$

P_y consistent with 0 for $E_\gamma > 1$ GeV

$C_{x'}$ and $C_{z'}$ do not vanish above 1 GeV, inconsistent with HHC

Comparison between theoretical predictions and available data is inconclusive

$\theta_{c.m.} = 90^\circ$



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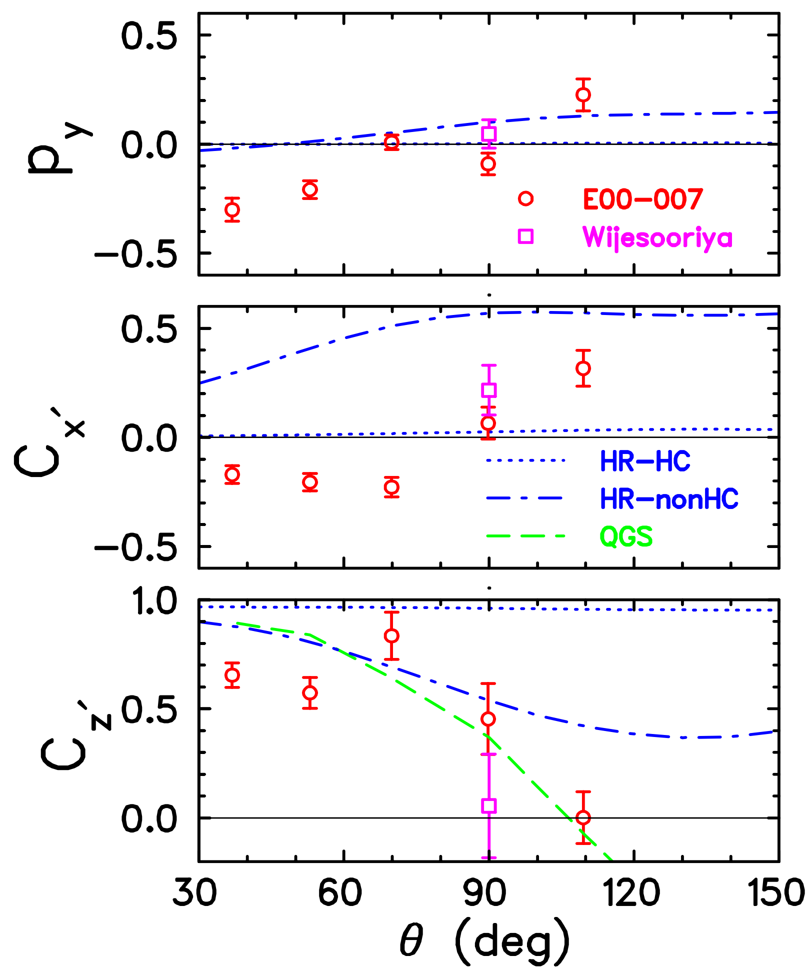
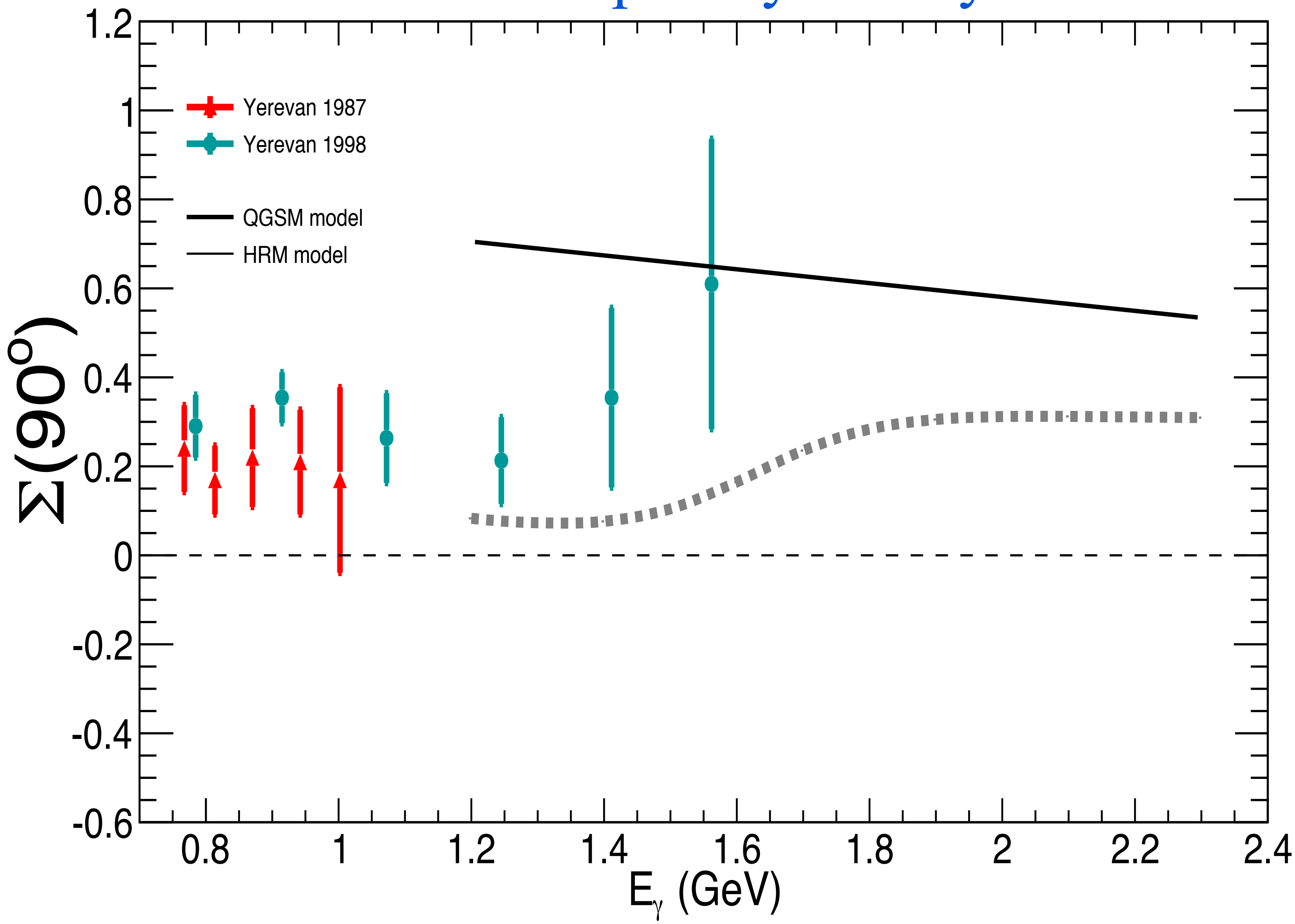
$E_\gamma = 1.86$ GeV



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

Deuteron Photodisintegration

Beam-spin asymmetry



Deuteron Photodisintegration

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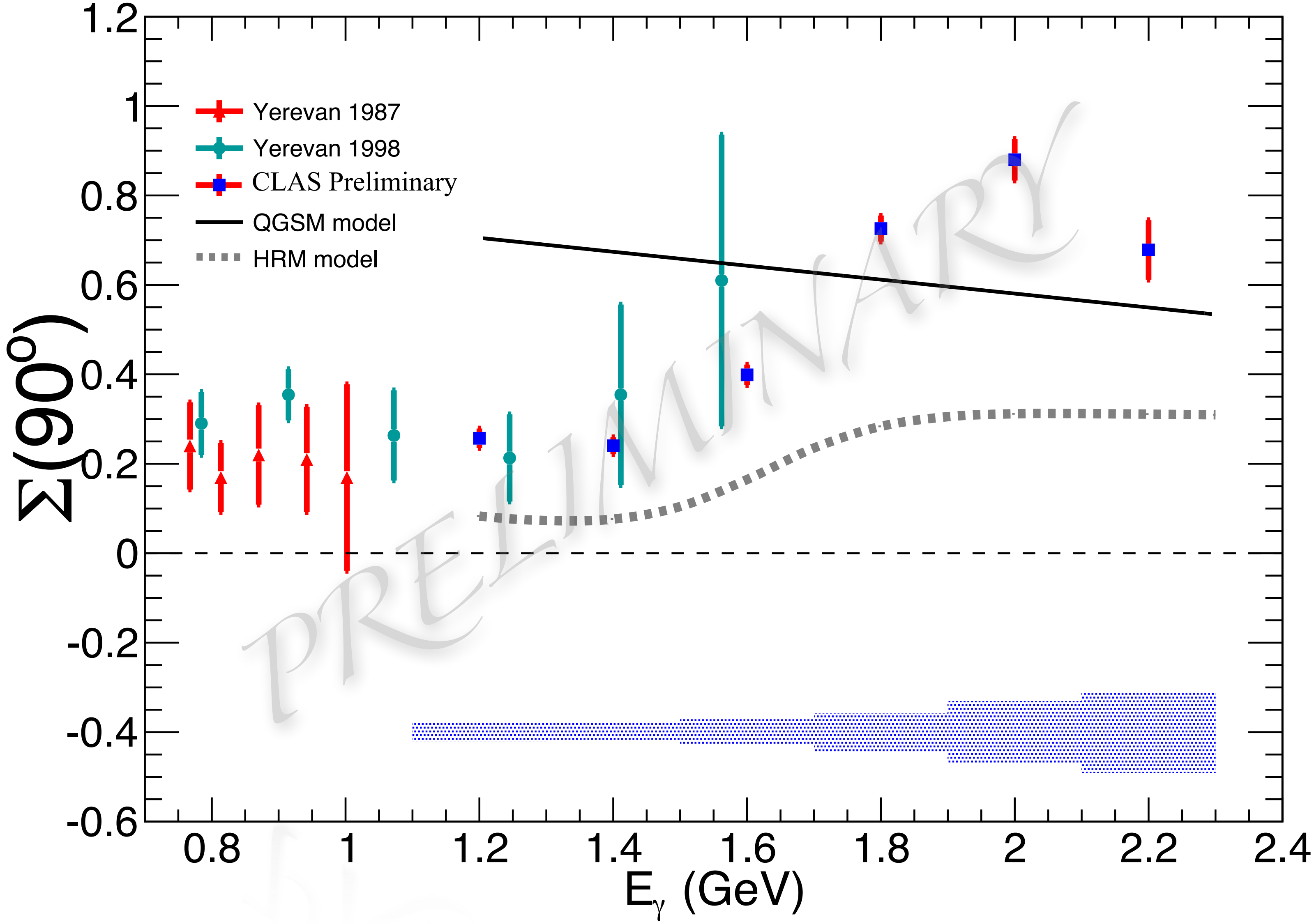

Deuteron Photodisintegration

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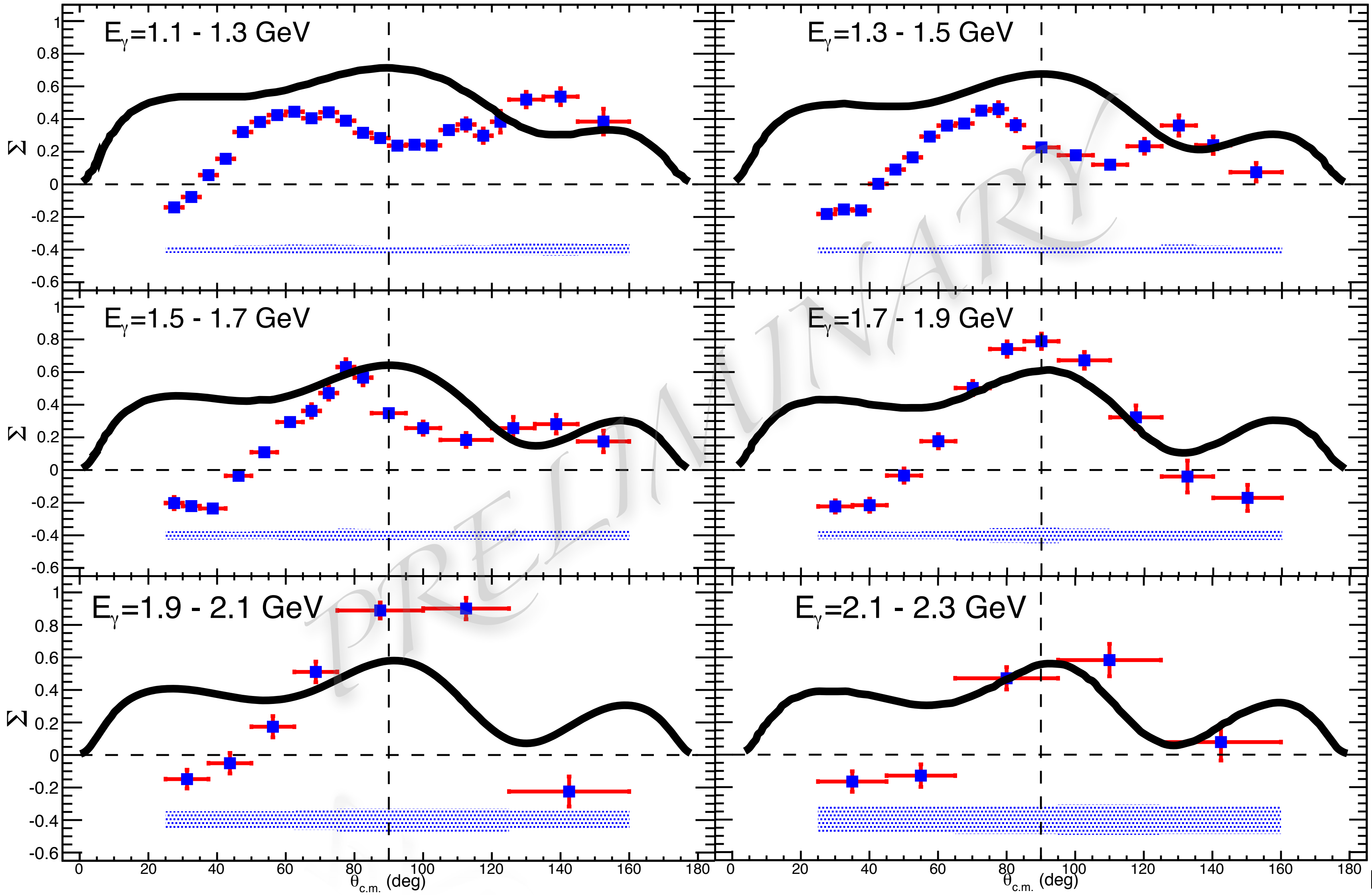


Summary and Outlook

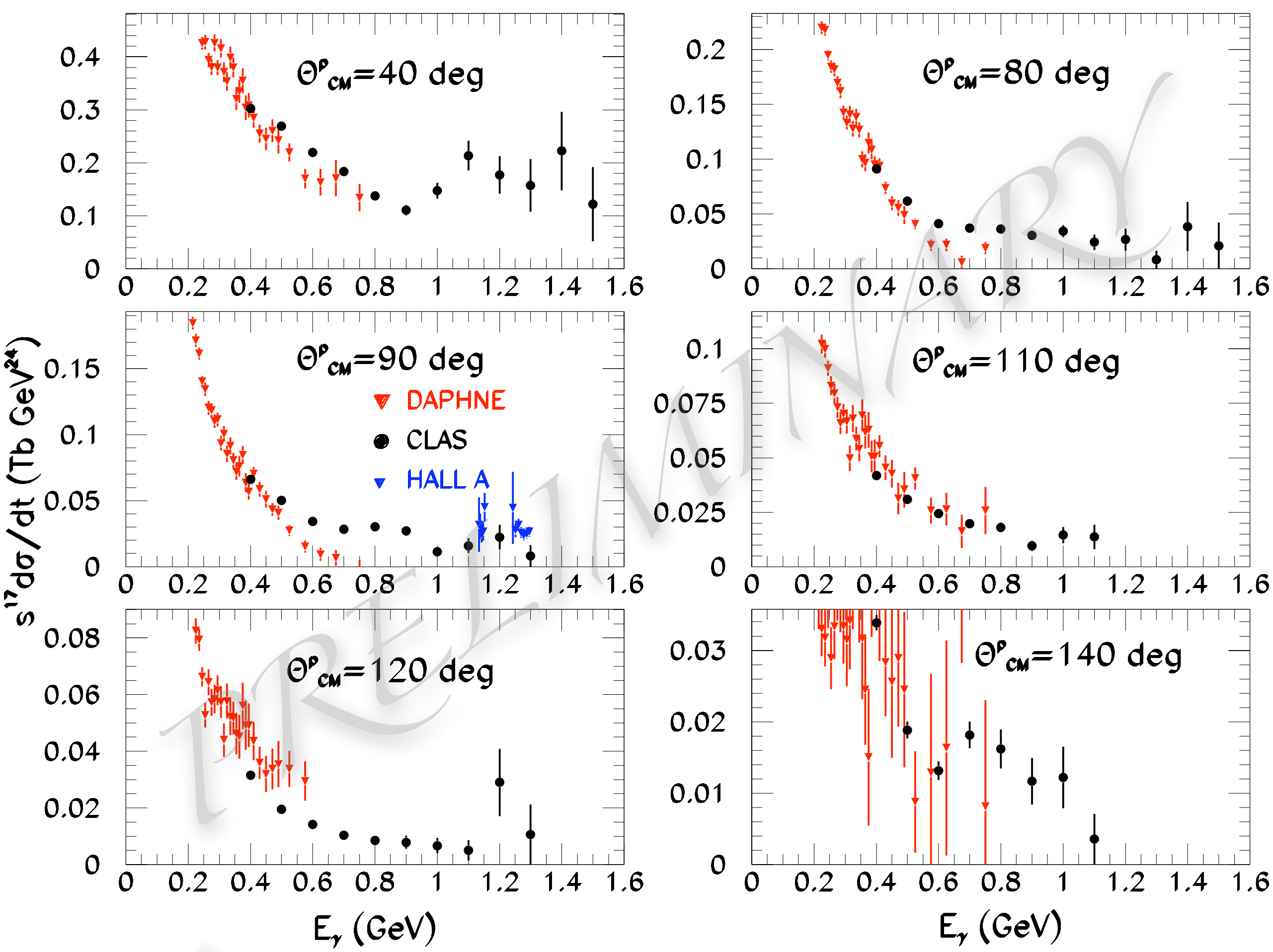
- Dimensional scaling probes two different dynamical regimes.
- Studies of ^{3}He breakup at low energies qualitatively support the conformal window interpretation of the scaling. This may be validated through the study of ^{3}He breakup at higher energies.
- Beam-spin asymmetry of deuteron photodisintegration is very sensitive to the underlying reaction mechanism.
- The available theoretical predictions, at their current state fail to adequately predict the energy and angular dependence of the beam-spin asymmetry.
- Ongoing collaboration with theorists to better describe and understand the underlying dynamics.

Extra

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)

Dimensional Scaling

- Overwhelming experimental evidence for success at momentum transfer as low as 1 GeV. Kinematics depends on the exclusive process.
- pQCD interpretation ruled out.
- A comprehensive theoretical description of exclusive processes in the non-perturbative regime has proved difficult.
- Overwhelming evidence for dimensional scaling. However, there is no general framework for interpretation across all processes.

Analysis

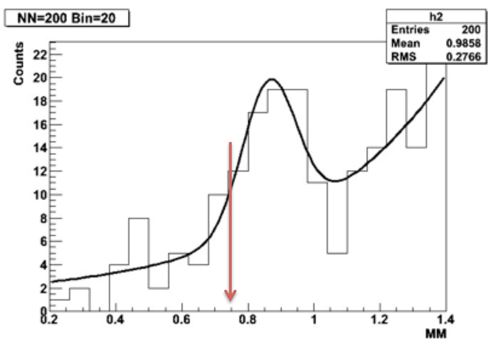
Event selection

Background subtraction

Probabilistic event weighting: Calculate probability of a given event being a signal event by fitting the missing-mass distribution of the events closest neighbors (in θ and φ) with a predetermined function

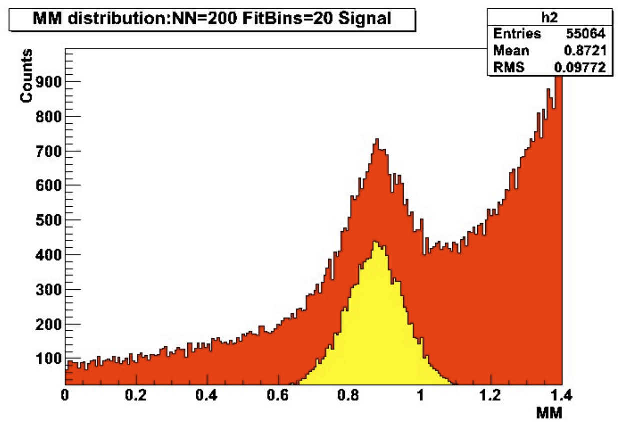
Signal: $g(m_X^2) = Ae^{-\frac{1}{2}\left(\frac{m_X^2-\mu}{\sigma}\right)^2}$

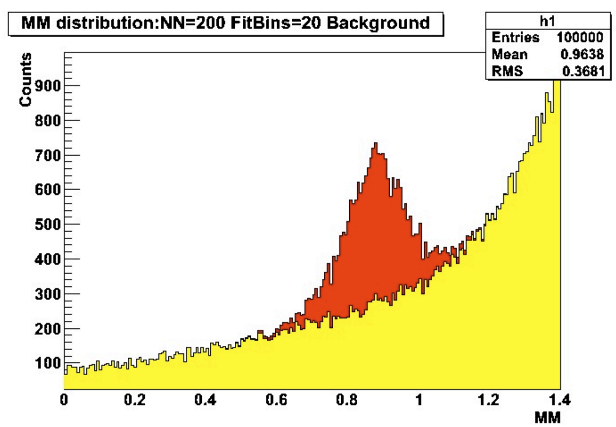
Background: $b(m_X^2) = A_1 e^{A_2 m_X^2} + B_1 e^{B_2 m_X^2}$



Probability: $P(s) = \frac{g(m_{Xi}^2)}{g(m_{Xi}^2) + b(m_{Xi}^2)}$

Dynamic bin width: number of closest neighbors determine the size of the bin





Analysis

Photon polarization

Degree of photon polarization was determined by fitting enhancement distributions with the Analytic Bremsstrahlung Calculation (ANB)

Degree of polarization depends on:

- Orientation of the crystal radiator
- Beam collimation
- Beam energy and divergence

5 fit parameters

θ Angle: Beam/crystal plane

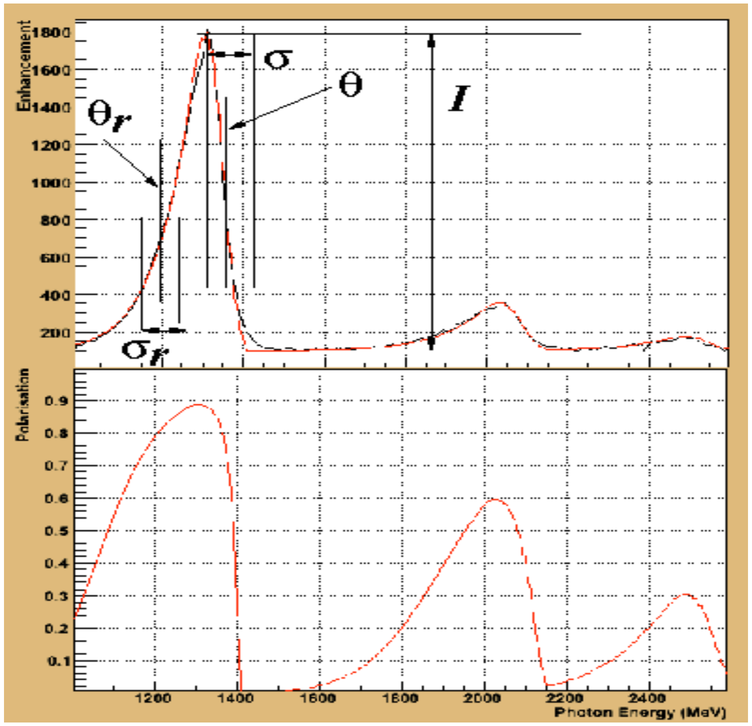
σ Gaussian smearing of θ to account for *beam divergence* and *multiple scattering*

θ_r Angle of collimation

σ_r Smearing factor

Amplitudes of peaks

$I_2^0, I_4^0, \ldots, I_6^0$

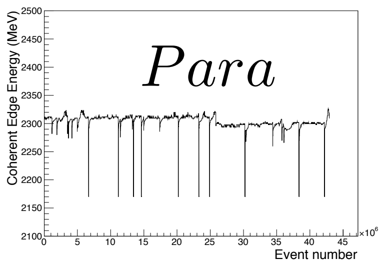


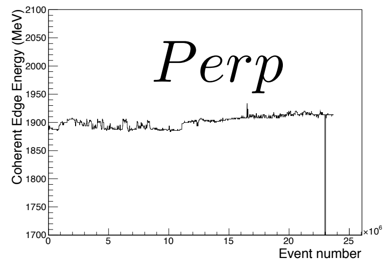
Tight photon beam collimation used during the experiment resulted in a good separation between primary and secondary coherent peaks

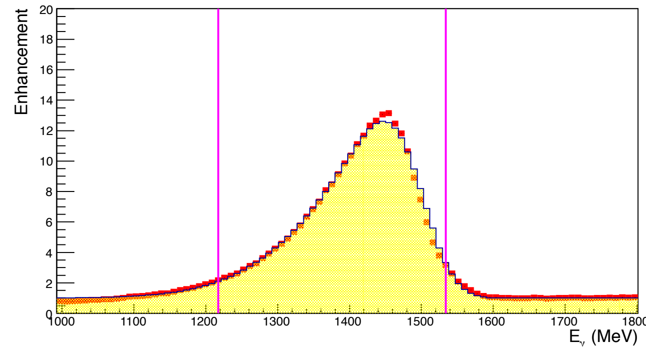
Analysis

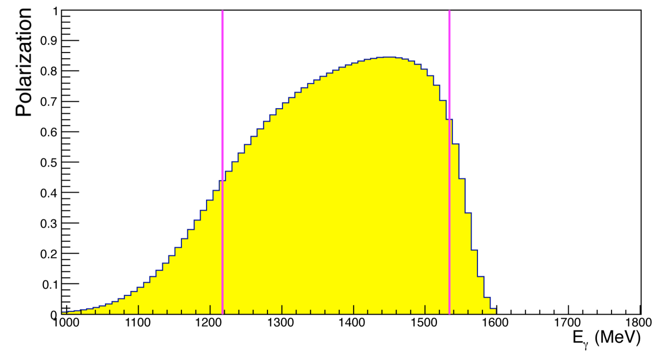
Photon polarization

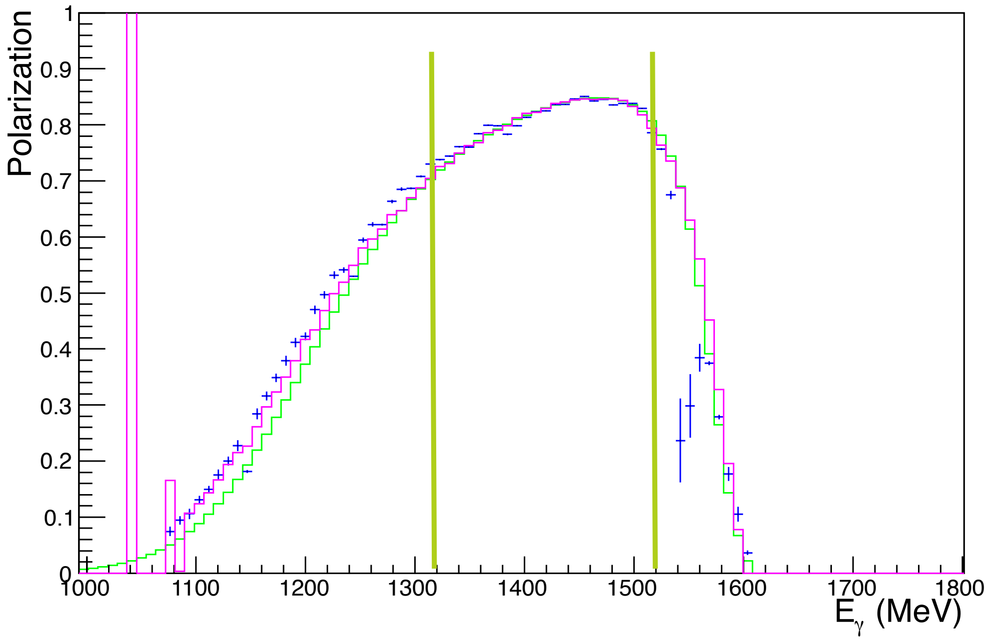
Key features











Fit

Corrected for diff

Reduce effect due to stat. fluc.

200 MeV cut to reduce systematic uncertainties

Analysis

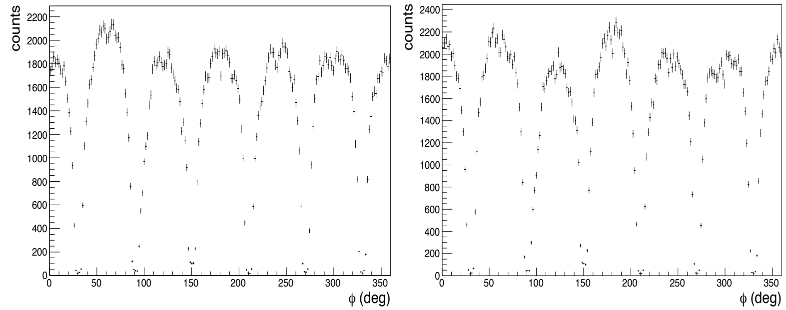
Determination of Σ

φ-bin method

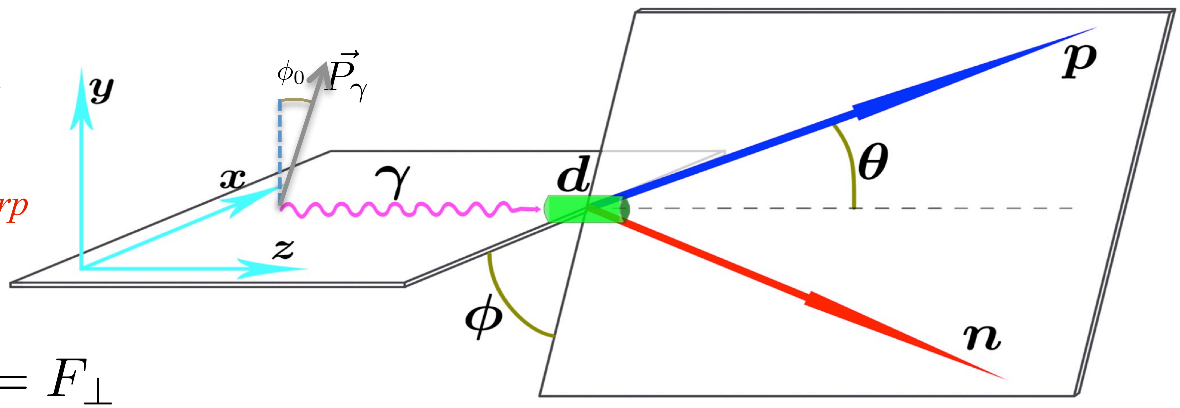
For linearly polarized photons

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 (1 + P_\gamma \Sigma \cos[2\phi])$$

$$N(\phi)_{||,\perp} \propto F_{||,\perp}(1 \pm P_{||,\perp}\Sigma\cos(2[\phi + \phi_0]))A(\phi)$$



- ϕ angle between lab *x*-axis and reaction plane
- ϕ_0 offset of photon polarization from *Perp* and *Para* orientation
- θ proton polar angle



$$\text{if } F_{||} = F_\perp$$

$$\text{and } P_{||} = P_\perp = P$$

$$\text{then } \frac{N(\phi)_{||} - N(\phi)_\perp}{N(\phi)_{||} + N(\phi)_\perp} = P\Sigma\cos 2(\phi - \phi_0)$$

Analysis

Determination of Σ

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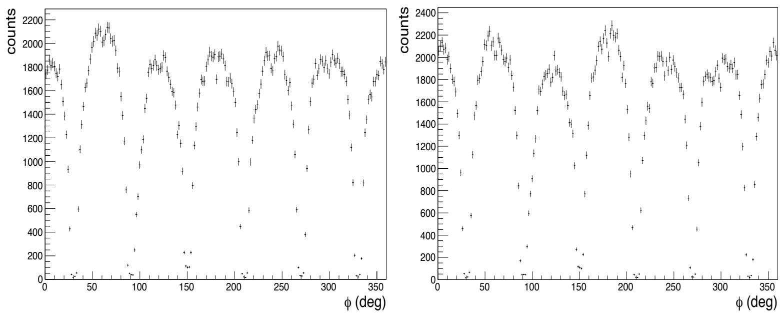

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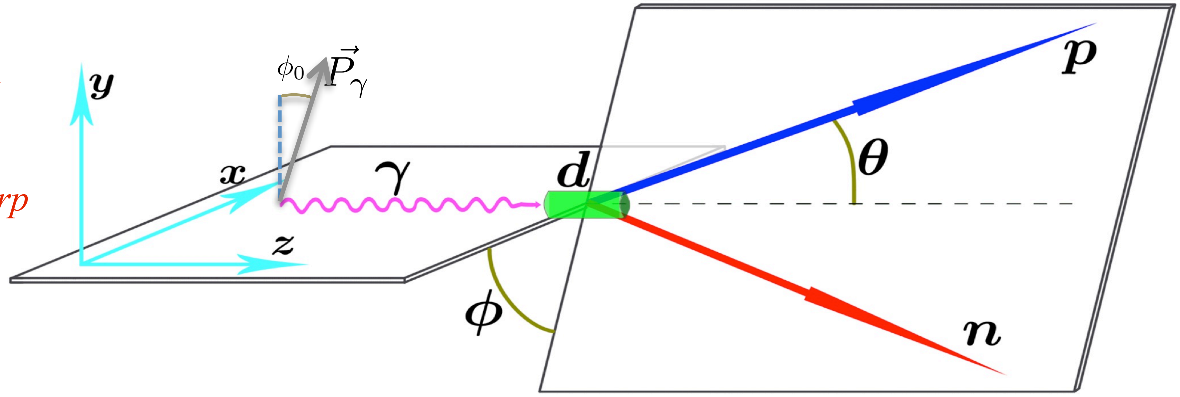


$$\frac{N(\phi)_{||} - N(\phi)_\perp}{N(\phi)_{||} + N(\phi)_\perp} = \frac{F_R - 1 + \frac{F_R P_R + 1}{P_R + 1} 2\bar{P}\Sigma\cos 2(\phi - \phi_0)}{F_R + 1 + \frac{F_R P_R - 1}{P_R + 1} 2\bar{P}\Sigma\cos 2(\phi - \phi_0)}$$

with: $F_R = \frac{F_{||}}{F_\perp}$, $P_R = \frac{P_{||}}{P_\perp}$

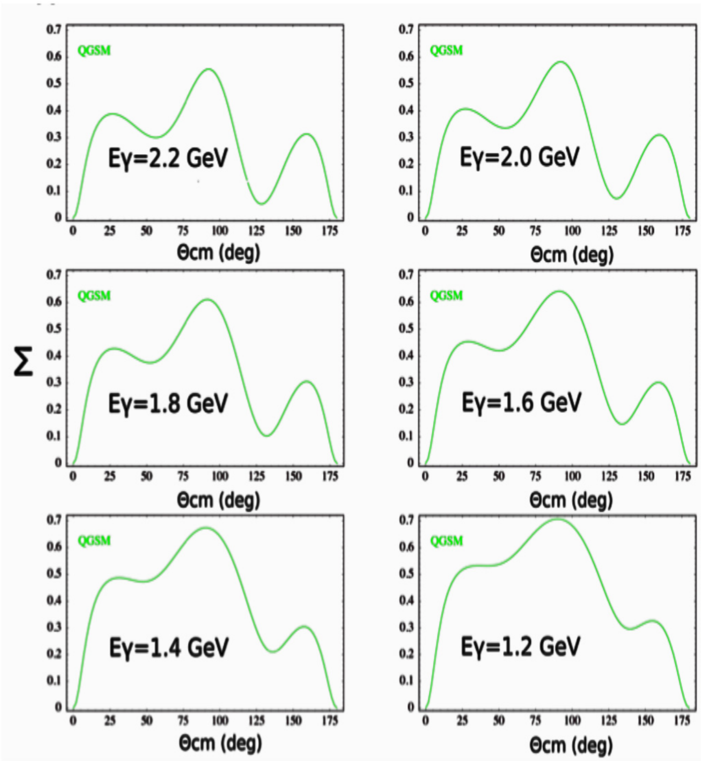
$\bar{P} = \frac{P_{||} + P_\perp}{2}$,

Systematic studies

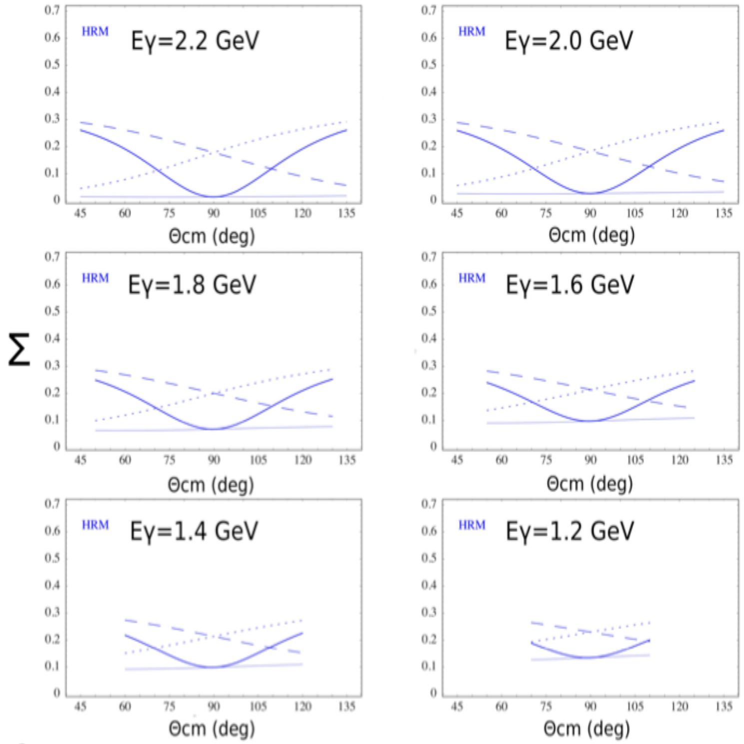
Photon polarization	Comparing asymmetries determined using overlapping coherent peaks	5%
φ_0 offset	Simulated data by sampling φ_0 from a Gaussian distribution	<0.01%
Photon flux ratio	Simulated data by sampling F_R from a Gaussian distribution	<0.1%
φ-bin width	Systematic error well understood and under control. Can be accounted for. Uncertainty is a result of a variable bin width	<0.001%
Particle ID cuts	3σ vs 2σ PID cut	0.1%
Fiducial cuts	Nominal vs 3^o tighter cuts	0.05%
Missing-mass cut	3σ vs 2σ MM cut	0.1%
Detector acceptance	Simulated data by using three functional form of acceptance	<1%
Background subtraction	Probabilistic event weighting vs bin scaling	0.5%

What are the underlying dynamics in the transition regime?

QGSM



HRM



$$\frac{d^2\sigma}{dtd\phi}(s,t,\phi) = \frac{1}{2\pi}\frac{d\sigma_{unp}}{dt}(s,t)[1 + \mathcal{P}_\gamma \Sigma(s,t)\cos 2\phi]$$

Thomas Jefferson Laboratory

Hall B

CLAS

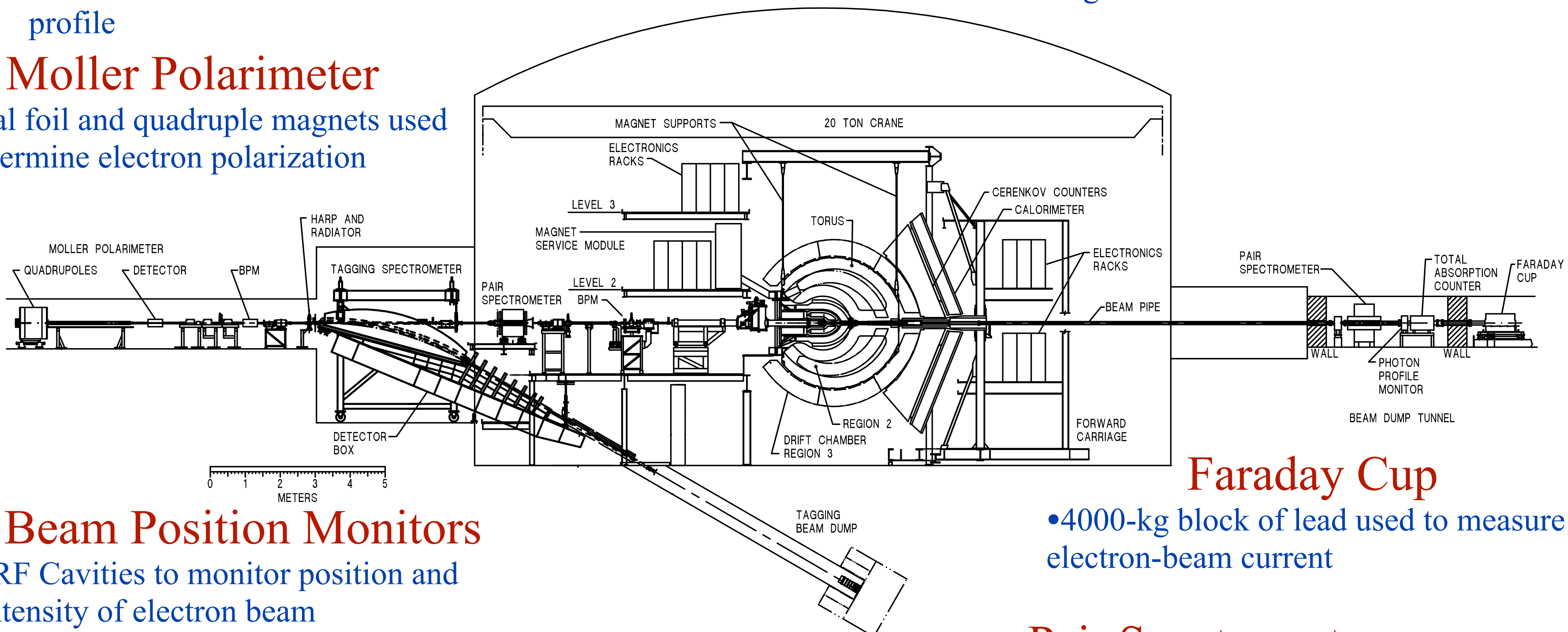
•Used to detect charged and neutral particles over a large fraction of the full solid angle

Harps

•Set of wires oriented perpendicular to the beam used to determine the beam profile

Moller Polarimeter

•Metal foil and quadruple magnets used to determine electron polarization



Faraday Cup

•4000-kg block of lead used to measure electron-beam current

Beam Position Monitors

•RF Cavities to monitor position and intensity of electron beam

Pair Spectrometer

•Used to identify the incident photon flux by detecting electron-positron pairs

Tagger Spectrometer

•Used to produce and tag photon beam