Hadron Propagation and Color Transparency at 12 GeV

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Hall C Users Meeting
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Outline

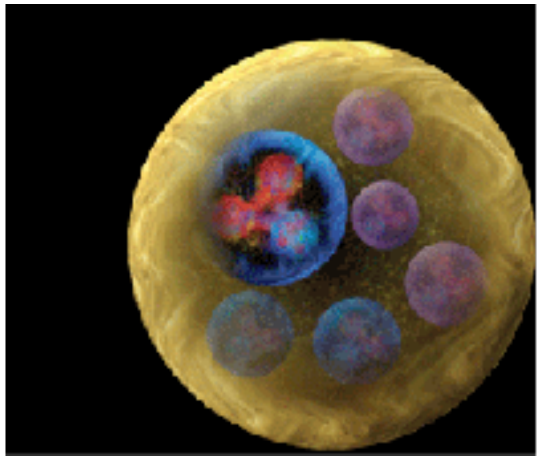
- Nuclear Transparency and Hadron Propagation
- Color Transparency & Small size configurations
- (e,e’p) experiment as a commissioning experiment
- Summary

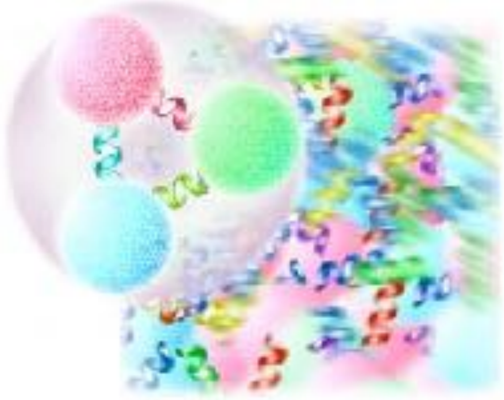
Hadron Propagation through nuclear matter is a key element of the nuclear many body problem.

Needed for interpretation of experiments involving hadrons in the nuclear matter and searches for QCD in nuclei.

An active area of interest.

N. C. R. Makins et al. PRL 72, 1986 (1994) (cited 153 times);
K. Garrow et al. PRC 66, 044613 (2002) (cited 92 times);
B. Clasie et al. PRL (2007) (cited 59 times)
L. El-Fassi et al. PLB 712, 326 (2014) (cited 15 times)





At high energies it is dominated by **reduction of flux**, which is quantified by **Nuclear Transparency**.

Nuclear Transparency is the ratio of cross-sections for exclusive processes from nuclei to nucleons.

$$T = \frac{\sigma_N}{A\sigma_0}$$

σ_0 = free (nucleon) cross-section

σ_N **parameterized as** = $\sigma_0 A^{\alpha}$

Fit to $\sigma(A) = \sigma_0 A^{\alpha}$

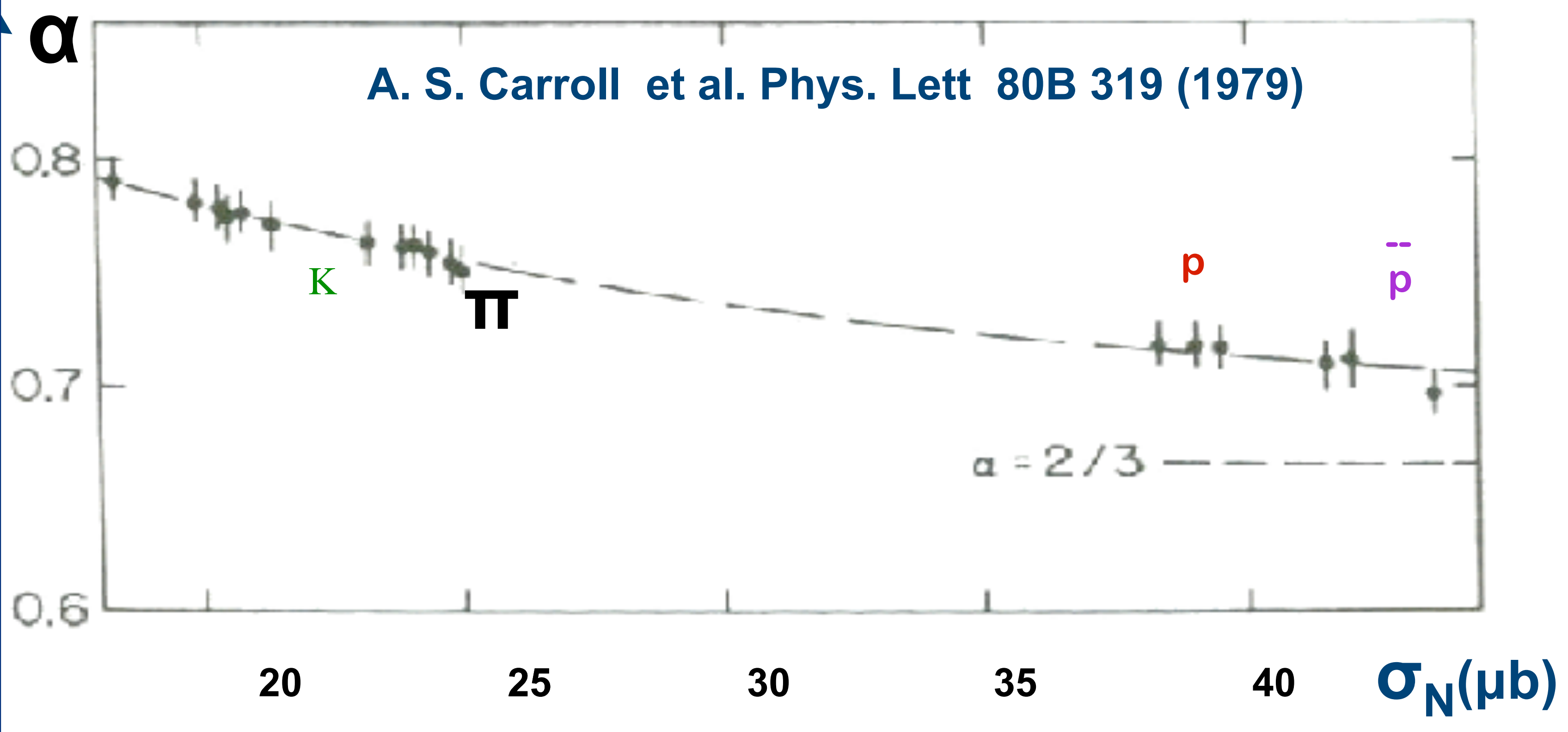
α = 0.72 - 0.78,

for π, K, p

Hadron momentum
60, 200, 250 GeV/c

$$\boxed{T = A^{\alpha-1}}$$

σ_N **Hadron– Nucleus total cross-section**

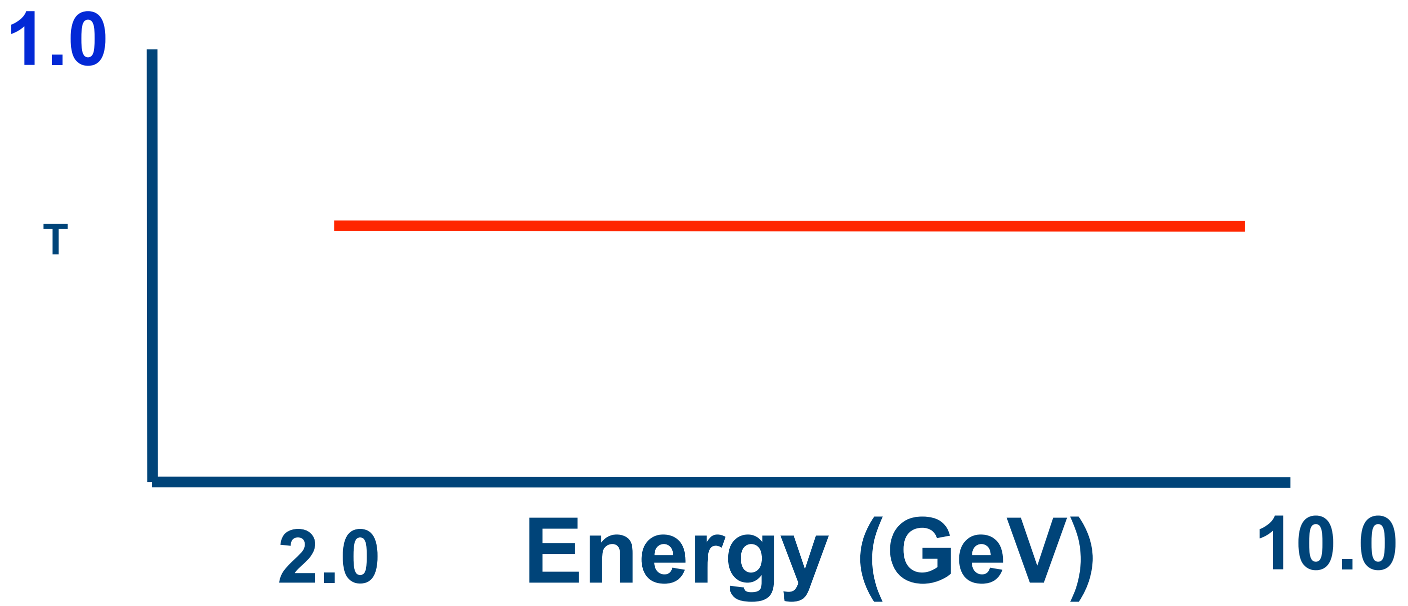


A. S. Carroll et al. Phys. Lett 80B 319 (1979)

α < 1 interpreted as due to the strong interaction nature of the probe

Nuclear Transparency is expected to be energy independent.

Traditional NP calculations



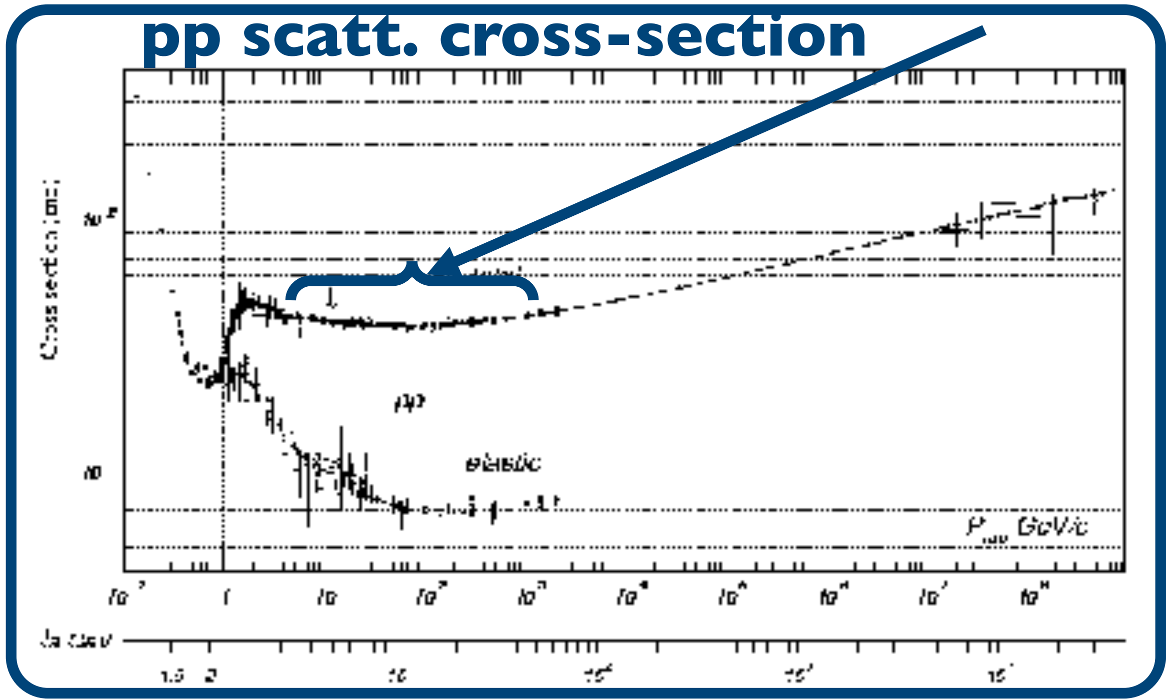
Ingredients

- σ_{hN} h-N cross-section
- Glauber multiple scattering approximation
- Correlations & FSI effects.

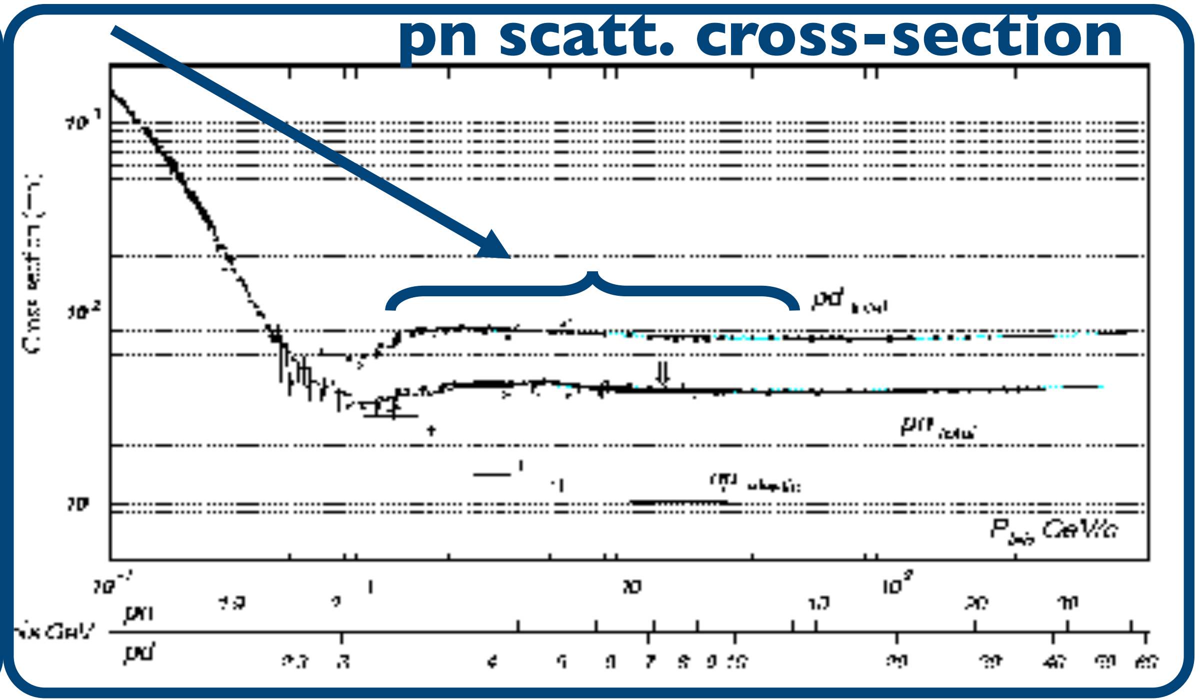
For light nuclei very precise calculations of are possible.

N-N cross-section is energy independent

pp scatt. cross-section

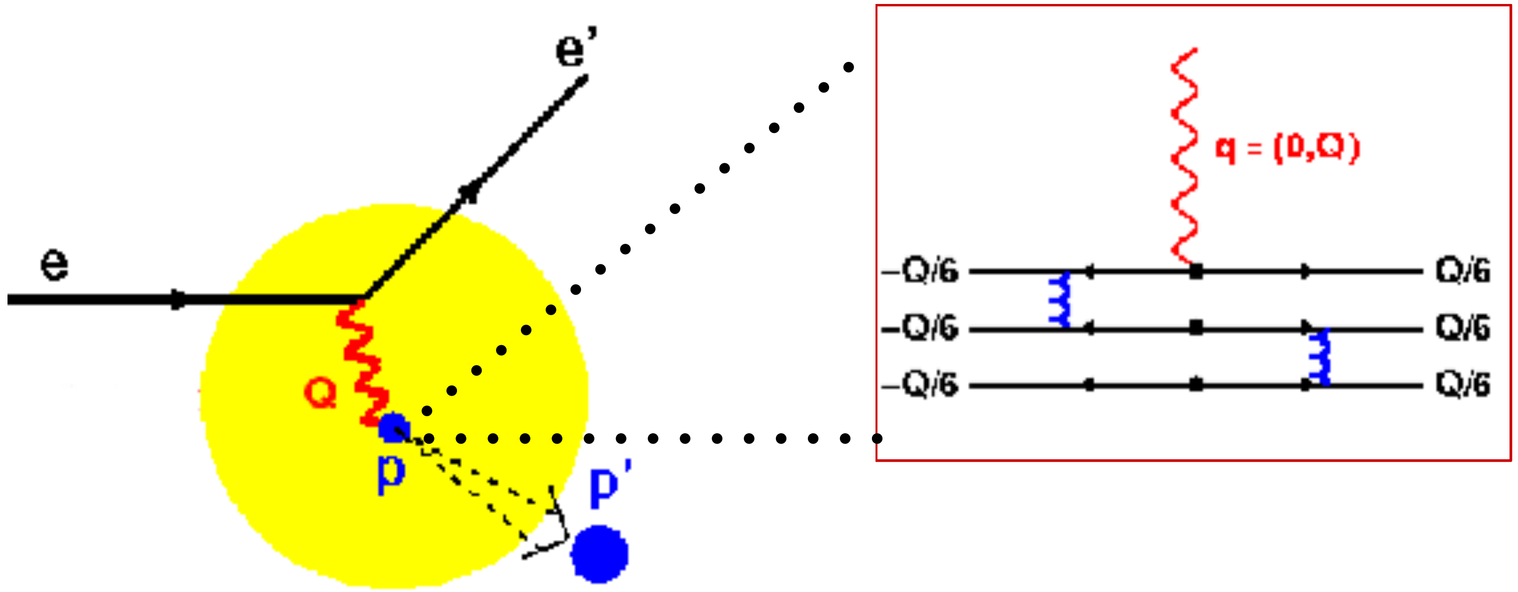


pn scatt. cross-section



All other reaction mechanisms are energy independent!

Color Transparency is the result of “squeezing and freezing”.



At high momentum transfers, scattering takes place via selection of amplitudes characterized by small transverse size (PLC) - “squeezing”

The compact size is maintained while traversing the nuclear medium - “freezing”.

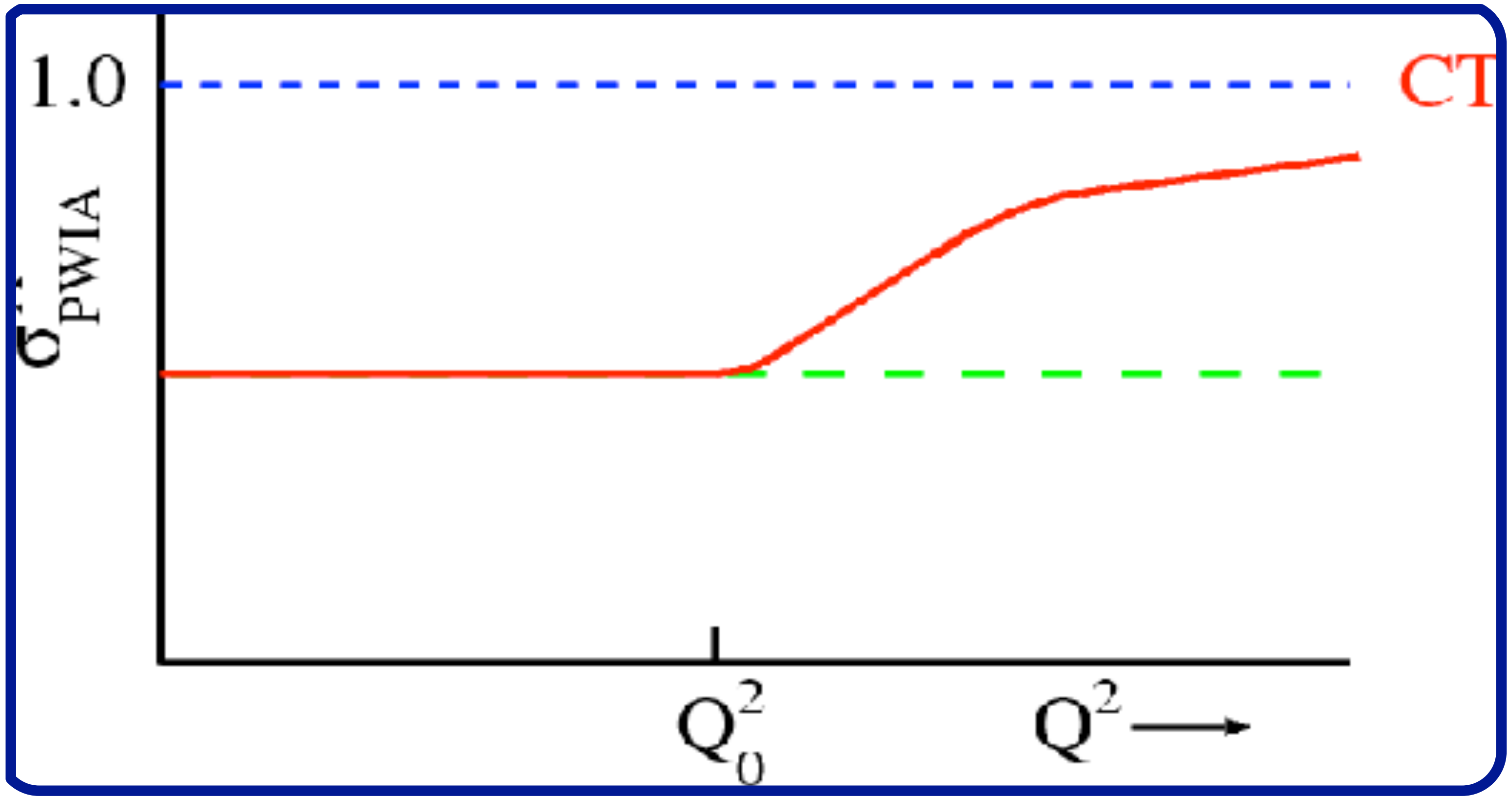
The PLC is ‘color screened’ - it passes undisturbed through the nuclear medium.

$$\sigma_{PLC} \approx \sigma_{hN} \frac{b^2}{R_h^2}$$

Color Transparency is a color coherence property of QCD.

CT leads to vanishing of the hadron-nucleon interaction for hadrons produced at high momentum transfers

CT is unexpected in a strongly interacting hadronic picture. But it is natural in a quark-gluon framework.

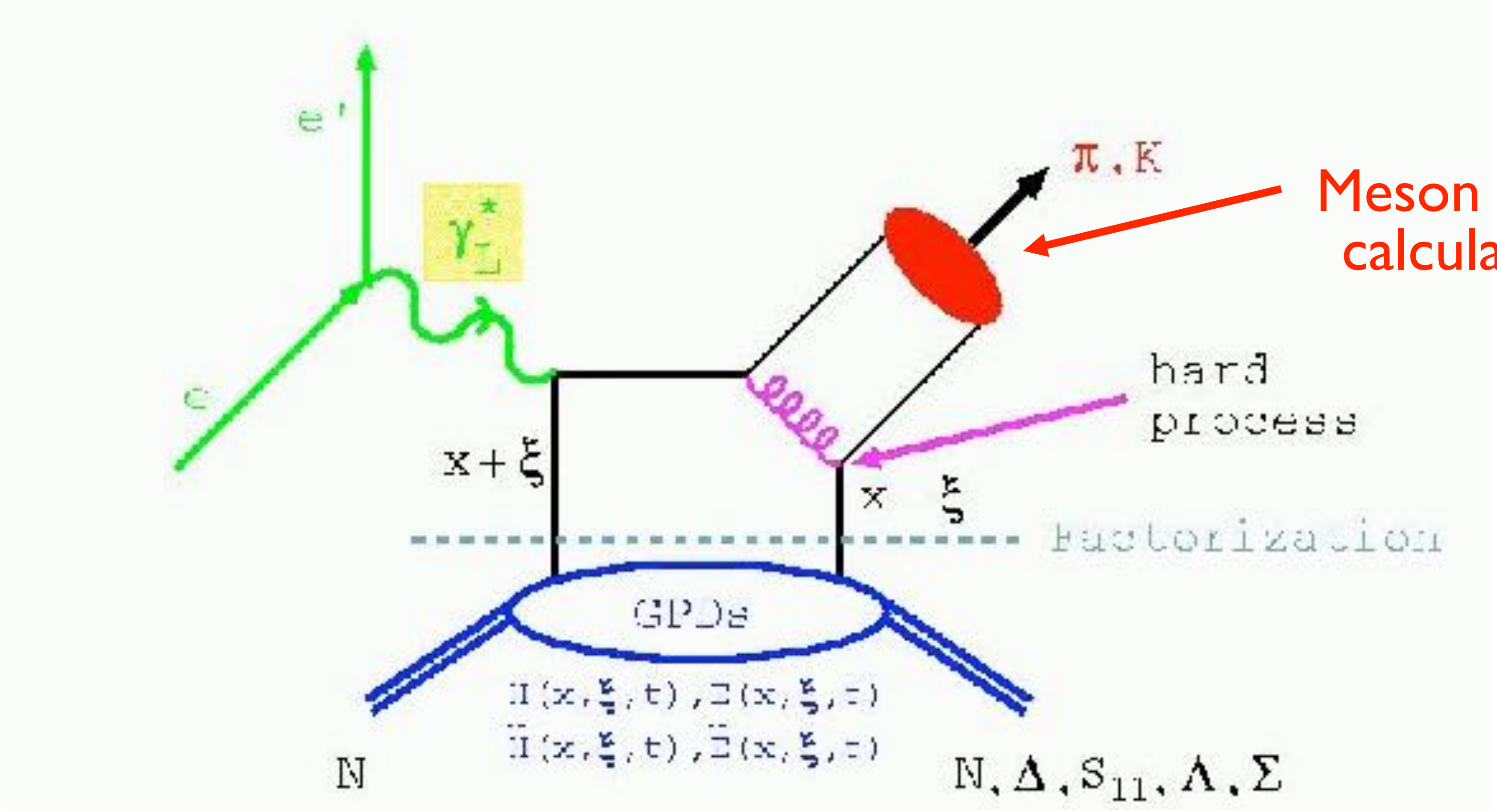


CT is well established at high energies (DIS data cannot be described without assuming CT).

The onset of CT is of primary interest.

Onset of CT would be a signature of the onset of QCD degrees of freedom in nuclei

Factorization is not rigorously possible without the onset of CT



Meson distribution amplitude calculable in pQCD

small size configurations (SSC/PLC) needed for factorization:

It is still uncertain at what Q^2 value reaches the factorization regime

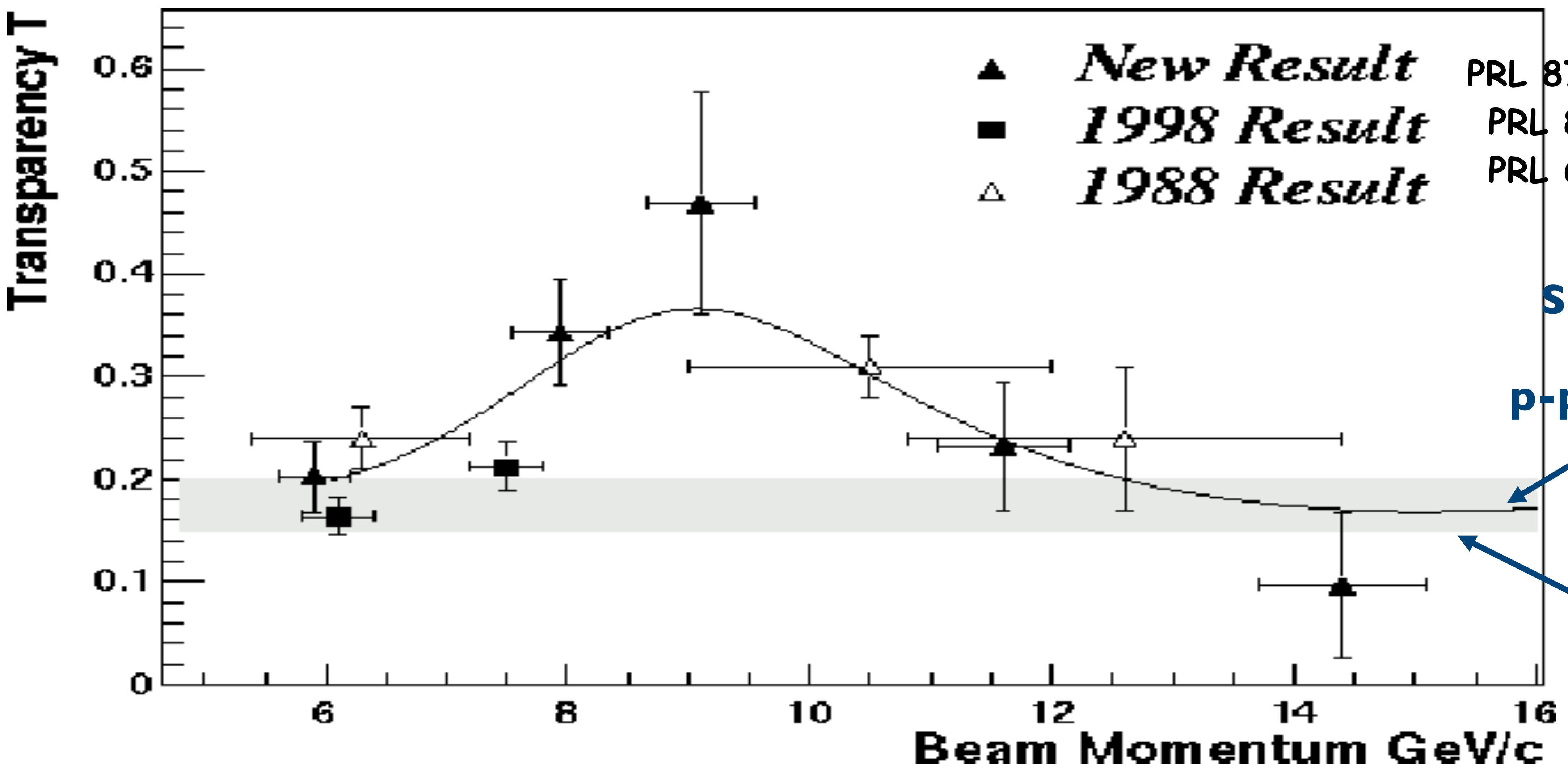
The onset of CT is a necessary (but not sufficient) conditions for factorization. -Strikman, Frankfurt, Miller and Sargsian

CT is well established at high energies.

Evidence for CT at intermediate energies is a mixed bag

First direct search for the onset of CT

Transparency in A(p,2p) Reaction at BNL



PRL 87, 212301 (2001)
PRL 81, 5085 (1998)
PRL 61, 1698 (1988)

Solid line is fit to 1/oscillation in p-p scattering data

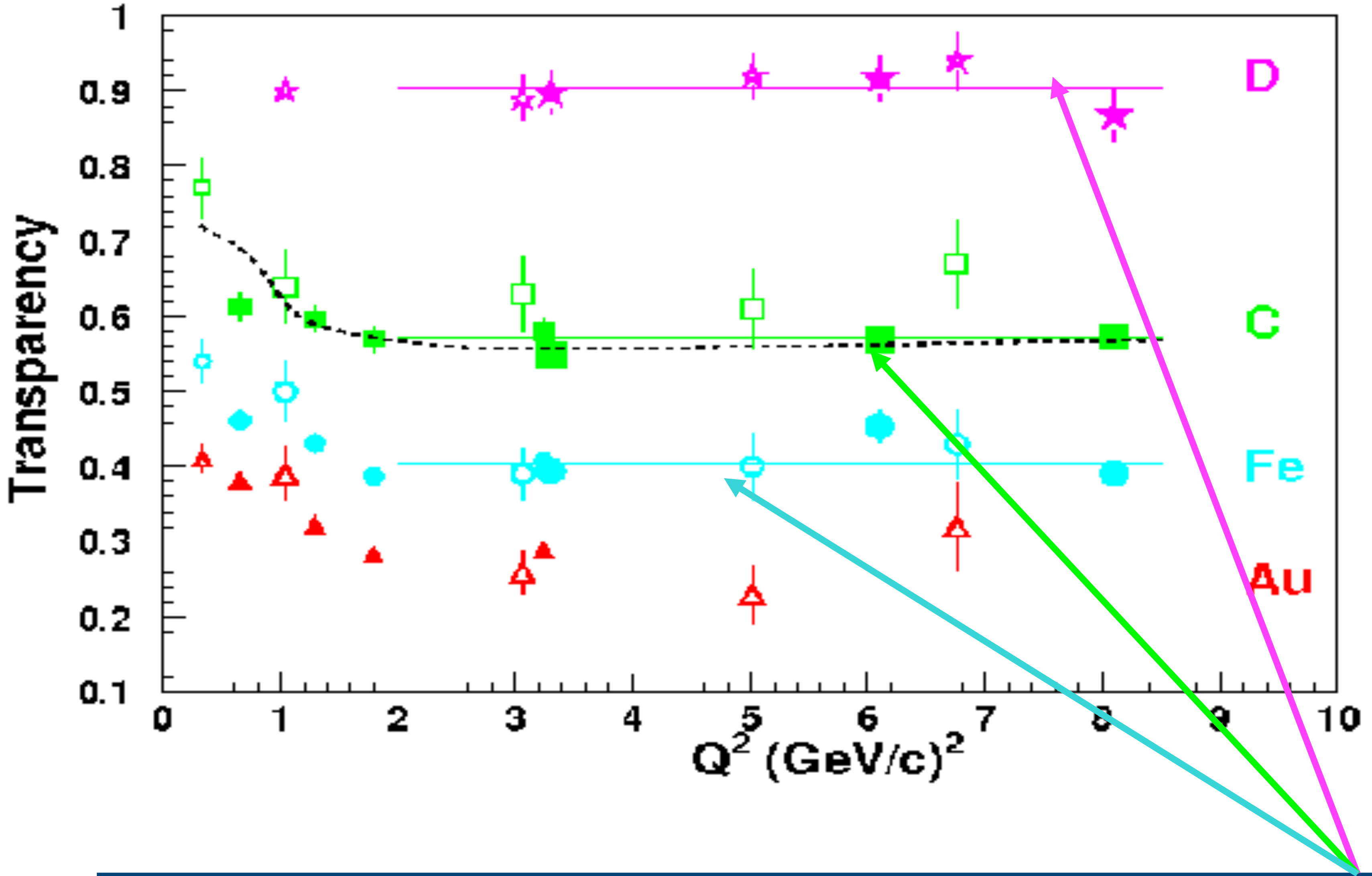
Shaded band Glauber calculation

Results inconsistent with CT only. But can be explained by including additional mechanisms such as nuclear filtering or charm resonance states.

No clear evidence for CT at intermediate energies for protons

A(e,e'p) results

Q^2 dependence consistent with standard nuclear physics calculations



Solid Pts – JLab

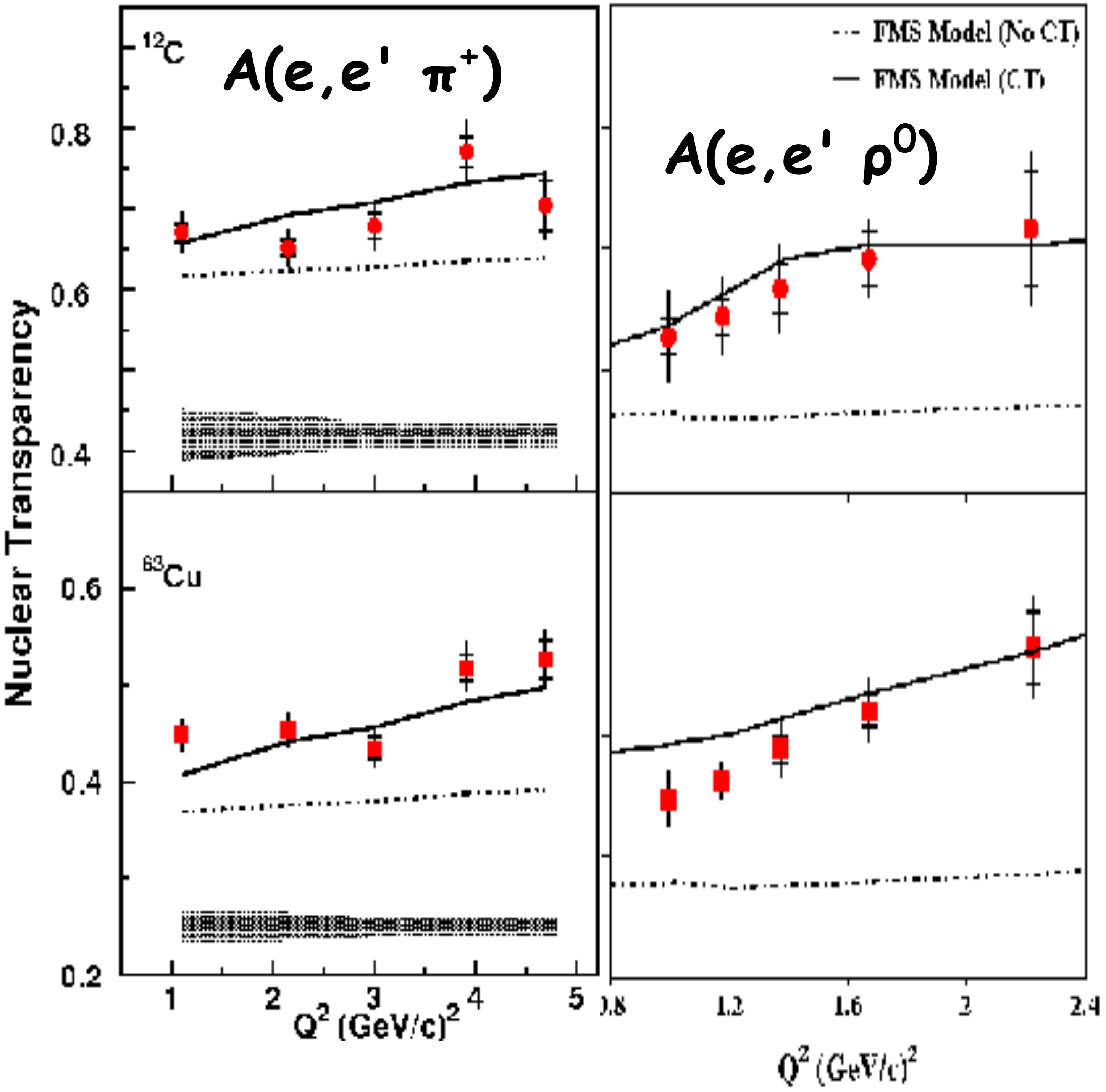
Open Pts -- other

Constant value fit for Q^2 > 2 (GeV/c)^2 has $\chi^2 / \mathrm{df} \sim 1$

N. C. R. Makins et al. PRL 72, 1986 (1994)
G. Garino et al. PRC 45, 780 (1992)

D. Abbott et al. PRL 80, 5072 (1998)
K. Garrow et al. PRC 66, 044613 (2002)

JLab experiments conclusively show the onset of CT in mesons



- **Hall-C Experiment E01-107** pion electroproduction from nuclei found an enhancement in transparency with increasing Q^2 & A, consistent with the prediction of CT.

  (X. Qian et al., PRC81:055209 (2010), B. Clasie et al, PRL99:242502 (2007))

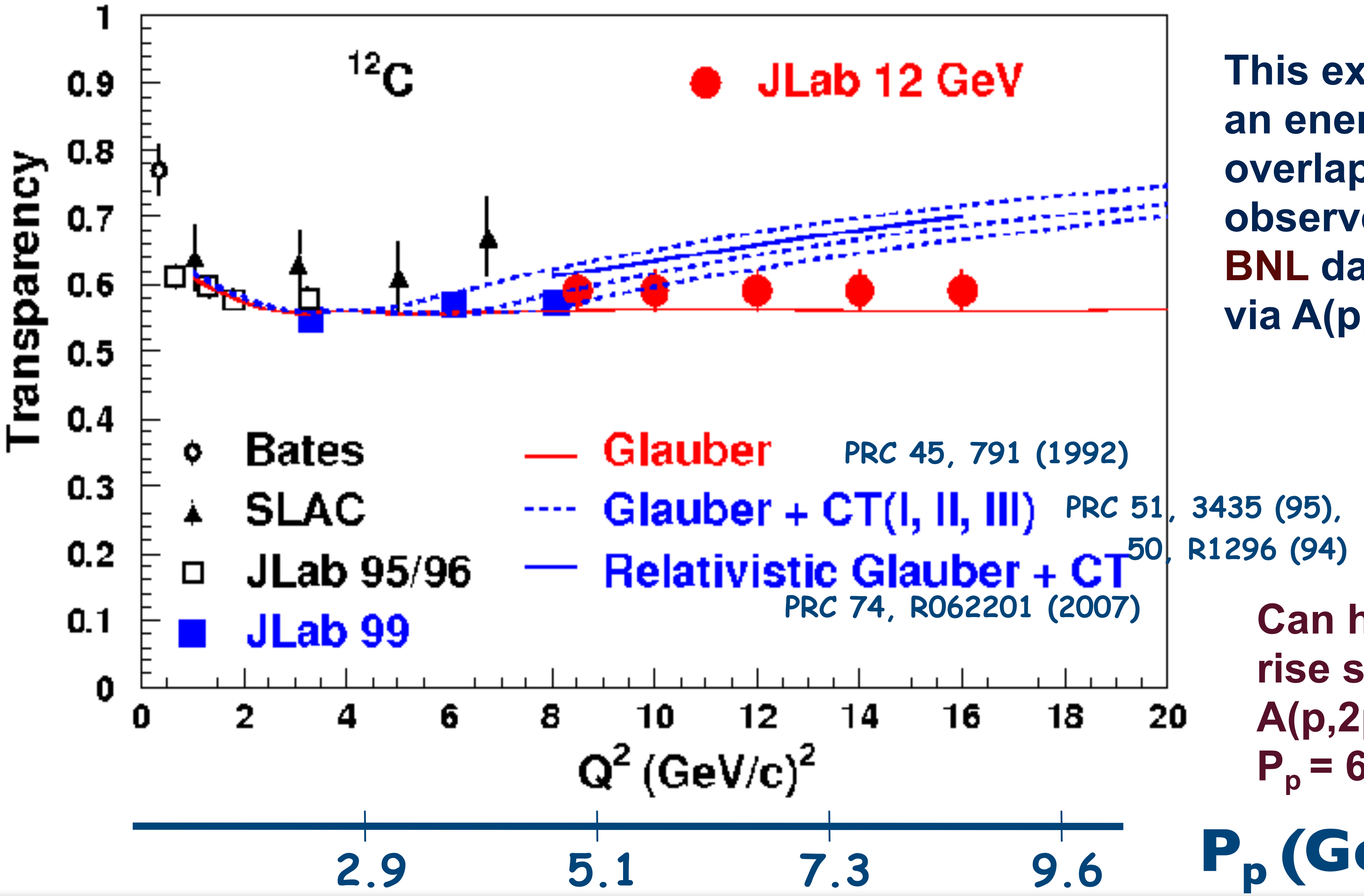
- **CLAS Experiment E02-110** rho electroproduction from nuclei found a similar enhancement, consistent with
- the same predictions

  (L. El-Fassi, et al., PLB 712, 326 (2012))

FMS: Frankfurt, Miller and Strikman, Phys. Rev., C78: 015208, 2008

Experiment E12-06-107: CT @ 11 GeV, will provide answers.

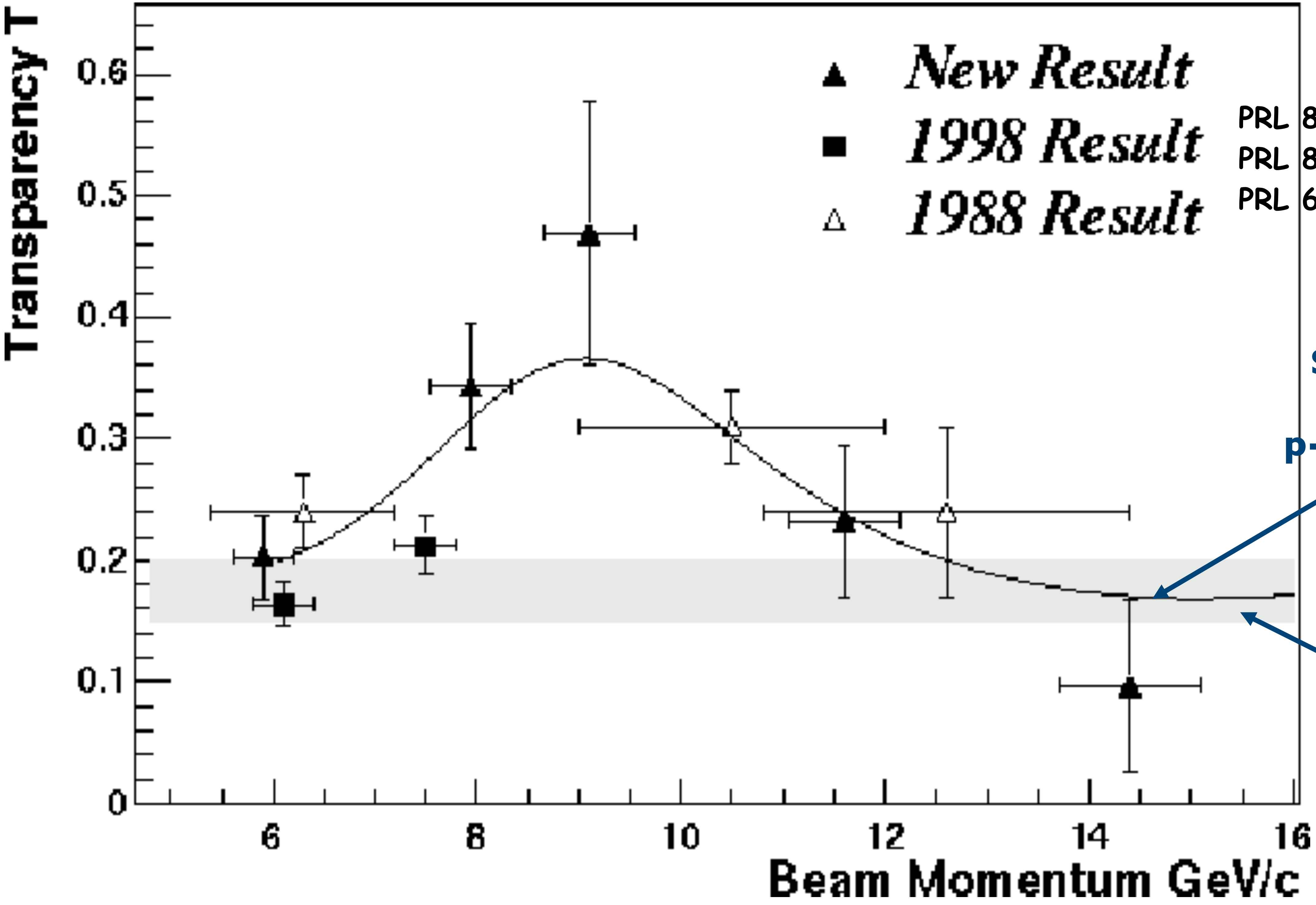
Goal: measure the A(e,e'p) proton knockout cross sections to extract the proton nuclear transparency up to the highest Q^2 at the 12-GeV JLab



This experiment covers an energy range which overlaps with the bump observed in the BNL data (transparency via A(p,2p).

Can help interpret the rise seen in the BNL A(p,2p) data at P_p = 6 - 9 GeV/c

(p,2p) results are related to oscillations in p-p cross sections.



PRL 87, 212301 (2001)
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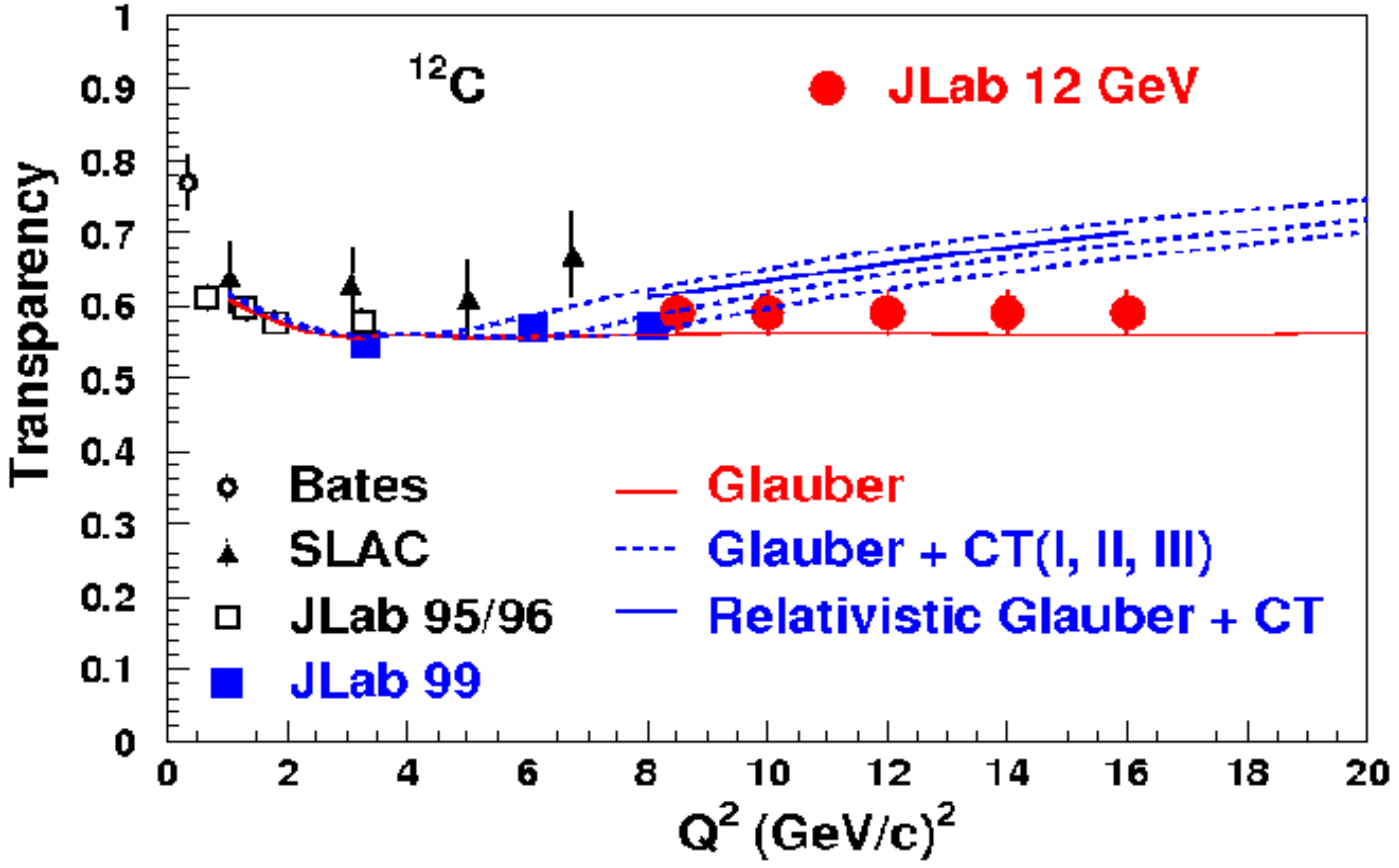
Solid line is fit to 1/oscillation in p-p scattering data

Shaded band Glauber calculation

Experiment E12-06-107 is one of the commissioning experiments.

Experiment E12-06-107:Spokespersons - D. Dutta & R. Ent

Running only A(e,e’p) portion of experiment — 3.5 days @ 8.8 GeV &
6.5 days @ 11 GeV (total 10 days)



A(e,e’p) cross-section on ^{1}H and ^{12}C with 80uA of 8.8 & 11.0 GeV beam.

5 different Q^2 points (8,10, 12, 14 & 16.4 GeV^2)

HMS: electron arm
SHMS: hadron arm

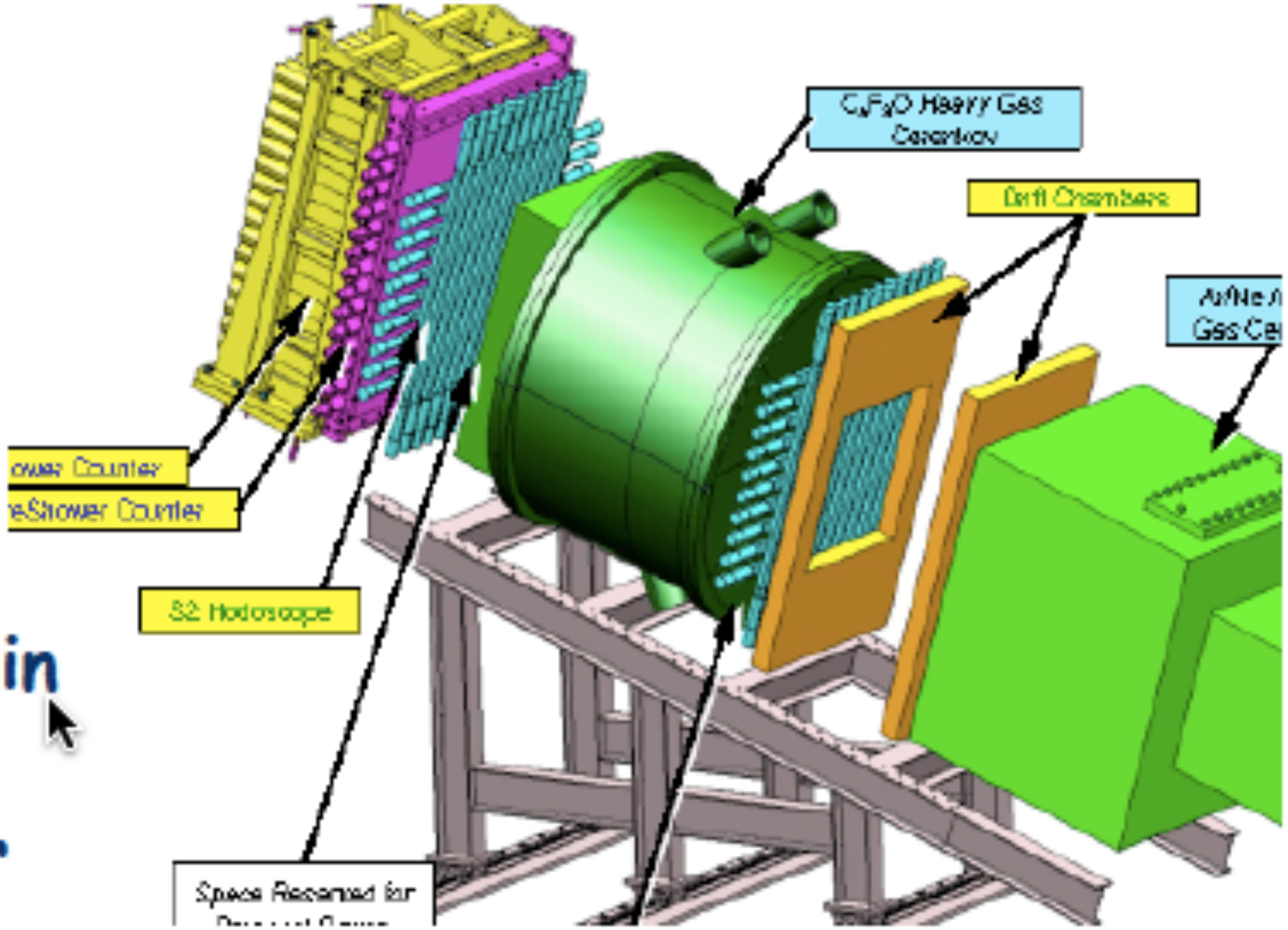
PID: Base detector package + Aerogel in SHMS (for commissioning only)

Total beam time requested for A(e,e'p) = 235 hrs ~ 10 days (for 10 cm LH2)

Requirements for the spectrometers and target are middle of the road.

SHMS used as hadron arm

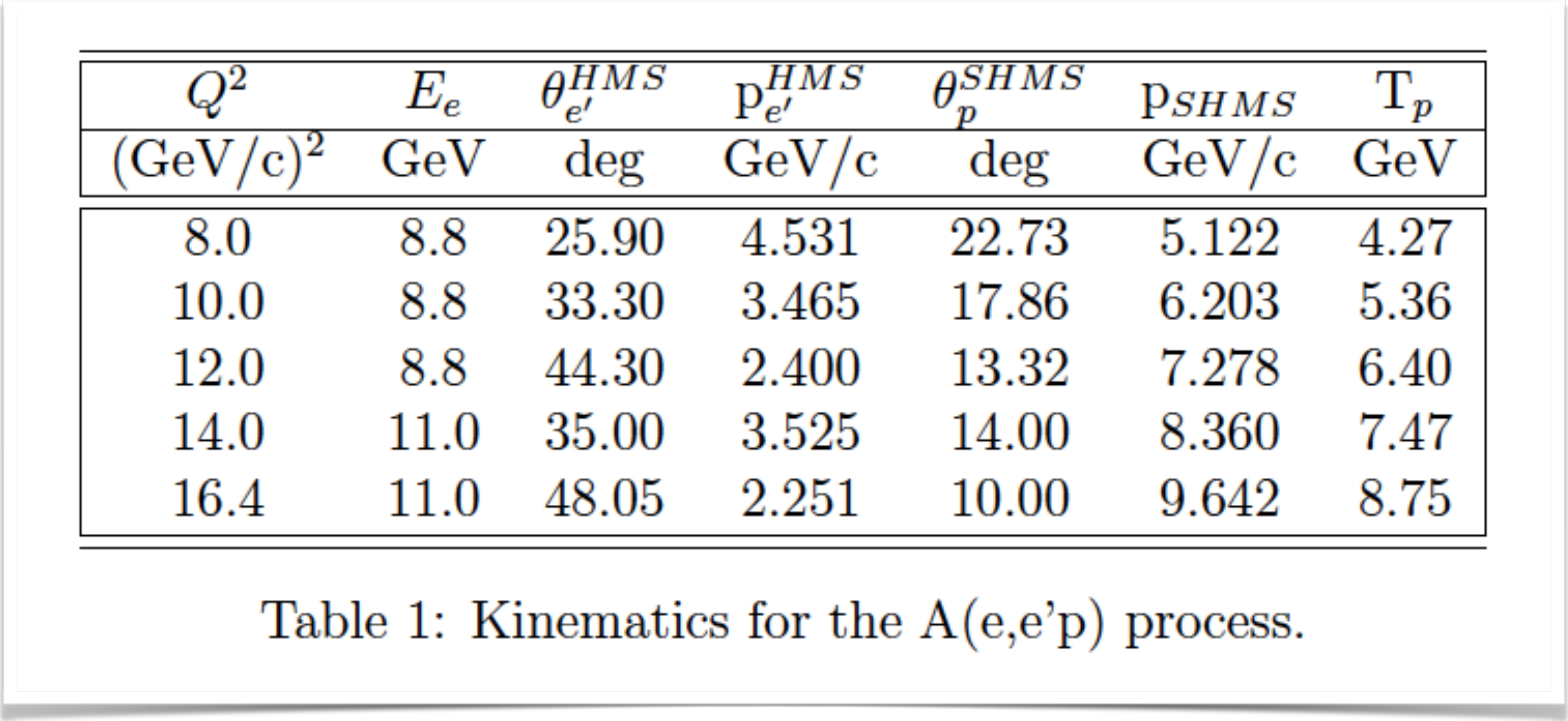
A(e,e'p) needs
p/π separation
Singles rates < 10kHz
p/π ratio 1:1 - 1:2



Targets needed:
10 cm LH_2 , thick and thin
Carbon.
4 cm LH_2 & multi-foil for
commissioning spectrometer

All detectors, associated docs and DAQs are ready:
(see talks by D. Biswas, S. Malace, A. Mkrtchyan, K. Adhikari, E. Pooser, B. Pandey, B. Sawatzky)

Requirements for the spectrometers and target are middle of the road.



Q^2	E_e	$\theta_{e'}^{HMS}$	$p_{e'}^{HMS}$	θ_p^{SHMS}	p_{SHMS}	T_p
$(GeV/c)^2$	GeV	deg	GeV/c	deg	GeV/c	GeV
8.0	8.8	25.90	4.531	22.73	5.122	4.27
10.0	8.8	33.30	3.465	17.86	6.203	5.36
12.0	8.8	44.30	2.400	13.32	7.278	6.40
14.0	11.0	35.00	3.525	14.00	8.360	7.47
16.4	11.0	48.05	2.251	10.00	9.642	8.75

Table 1: Kinematics for the A(e,e'p) process.

HMS: p = 2.25 - 4.53 GeV/c
θ = 25.9 - 48.1 deg

SHMS: p = 5.12 - 9.64 GeV/c
θ = 10 - 22.7 deg

Detector commissioning plan has been developed

https://hallcweb.jlab.org/wiki/index.php/Commissioning_Plan_2017#Detailed_Detector_Checkout

Detailed Detector Checkout

Note: still need to do editing in this detailed detector checkout section but the first-order fixes were made.

```
target : central carbon

HMS angle : 15°
HMS momentum : -3 GeV/c
HMS collimator : large

SHMS angle : 15°
SHMS momentum : -3 GeV/c
SHMS collimator : large
```

Wire Chamber High-Voltage Plateaus

If not already there, rotate the spectrometers to 15° and set the spectrometer momenta at 3.0 GeV/c (negative polarity, assuming >6 GeV beam energy) to increase the count rates. Plot the counts per wire chamber plane vs. the high voltage, determine the wire chamber high-voltage plateaus for electrons for both SHMS and HMS (as there are new wire chambers there – note that these do not require the checkout versus threshold of the previous HMS wire chambers). Choose correct operating voltages for detecting electrons.

Shower Counter Calibration Run

By the time this starts all changes in the electronics and trigger have been made and the ADC gates for the calorimeter signals have been adjusted. With HMS and SHMS still at angles of 15° and momenta of -3.0 GeV/c, take a run with >100K statistics each. Adjust the delay time for the ADC gates with +/-20 ns and measure again. If the gate timing is optimal, the ``maximum' ADC values should change less than 5%. Adjust the gate timing if not optimal and repeat. If the gate timing is optimal, start gain matching by adjusting the HV's. For optimal HV settings the ADC peaks must be in the range between 80 and 100. Adjust the HV of those PMT's which are out of this range (a ±50 V change results in a change of ~15-20% in amplitude). After this procedure NEVER change the HV settings for the calorimeter PMT's anymore. Now take large statistics runs (>250K each). If time permits, one can consider reversing the polarities of both spectrometers and take again large statistics runs (>250K each). Do not use the Particle Id. trigger in any of these runs!

Calibration Spectra: Carbon

Take a large run (250K) for both HMS and SHMS to check wire chamber time-to-distance maps, align the wire chamber positions in software and enable linked stub fitting, check the detector positions, check the timing and calibration constants (shower counter gains, pedestals, timing offsets, pulse height corrections, attenuation lengths, efficiencies, position dependencies). Optimize tracking properties. Make sure that Θ and Φ spectra are wide as expected. Construct x, y, Θ and Φ spectra at the nominal focal plane. Does everything look reasonable? Check tracking with one wire chamber against tracking with two wire chamber sets. Reconstruct target quantities. This run can be used for the initial timing/calorimeter/cherenkov calibrations.

(see talks by B. Sawatzky & J. Bericic)

A(e,e’p) is an ideal commissioning experiment.

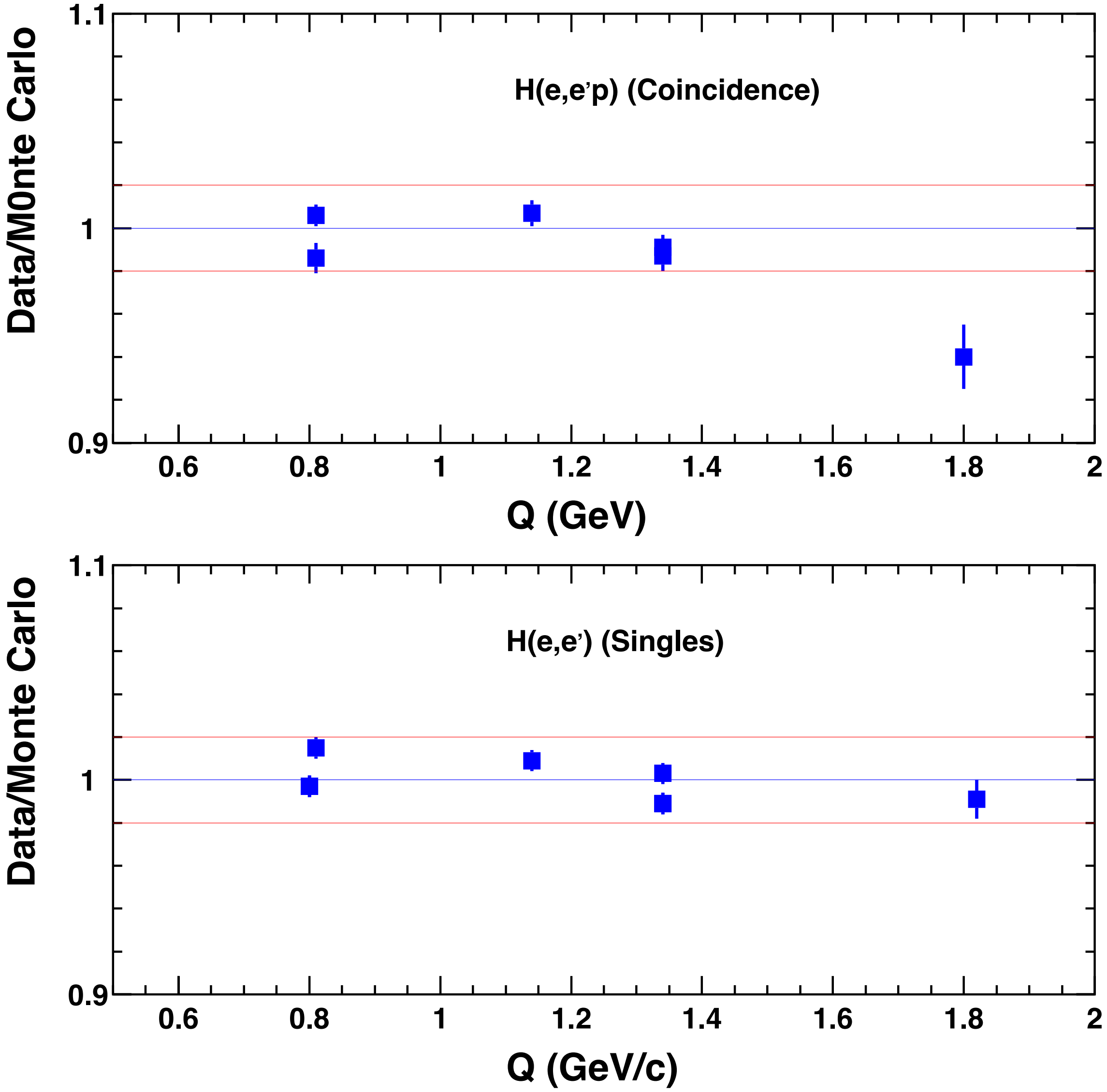
- **H(e,e’p) process critical for SHMS commissioning is part of the experiment.**

- **Smooth well known cross section will aid in quick diagnostic of Spectrometers.**

- **The Hall C Monte Carlo simulation SIMC was built for the A(e,e’p) process.**

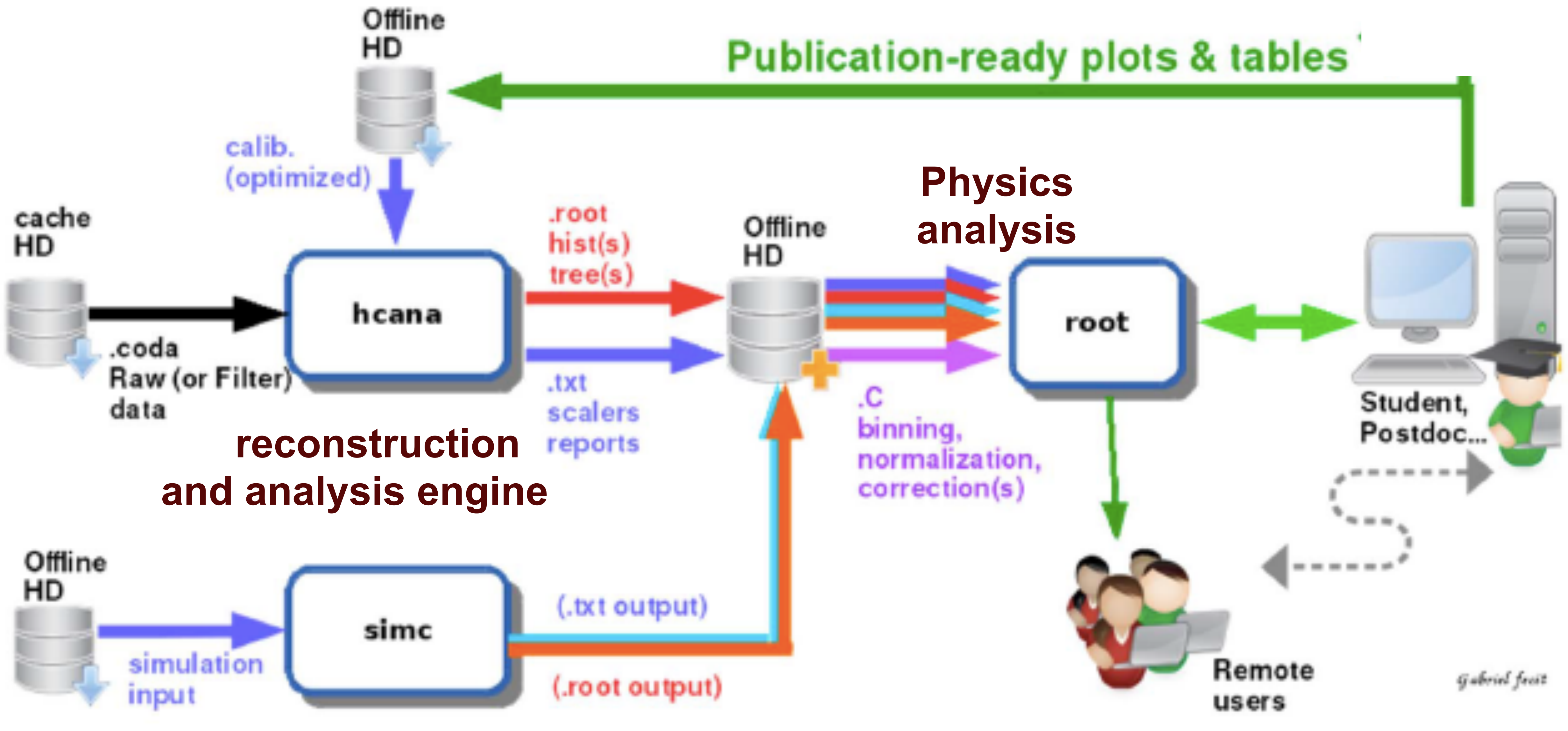
- **Analysis framework and simulation are tested and ready, online results can be used for diagnostics.**

H(e,e’p) results from Hall-C commissioning experiment E91-013



The 1994-95 version of simulations and analysis package was able to monitor rates online at the 10% level. We should be able to do much better now and provide a great diagnostic tool for commissioning.

Hall C analysis components are ready for commissioning



Physics analysis

reconstruction and analysis engine

Monte Carlo simulation

Image from G. Niculescu

HCANA is ready for commissioning and online monitoring

hcana: **Hall C C^{++}/Root based analysis engine**

built on top of the Hall A - C^{++} analyzer - PODD
but retained (and documented) all algorithms
from Hall C Fortran engine

(see Eric Pooser's talks)

- ✓ **decode & reconstruct single arm (HMS/SOS/SHMS) & coincidence (HMS-SOS/HMS-SHMS) events**
- ✓ **read, process & report all scalers (HMS, SOS, SHMS, coinc.)**
- **produce target reconstructed variables (x_{tar}, y_{tar}, x'_{tar}, y'_{tar}, δ) and physics variables (Q^2, W, ν, q, …) for single arm and (Em, Pm, Pm_{par}, Pm_{perp}, Pm_{oop}, …) for coincidence events.**

SIMC was born ready…..

SIMC:

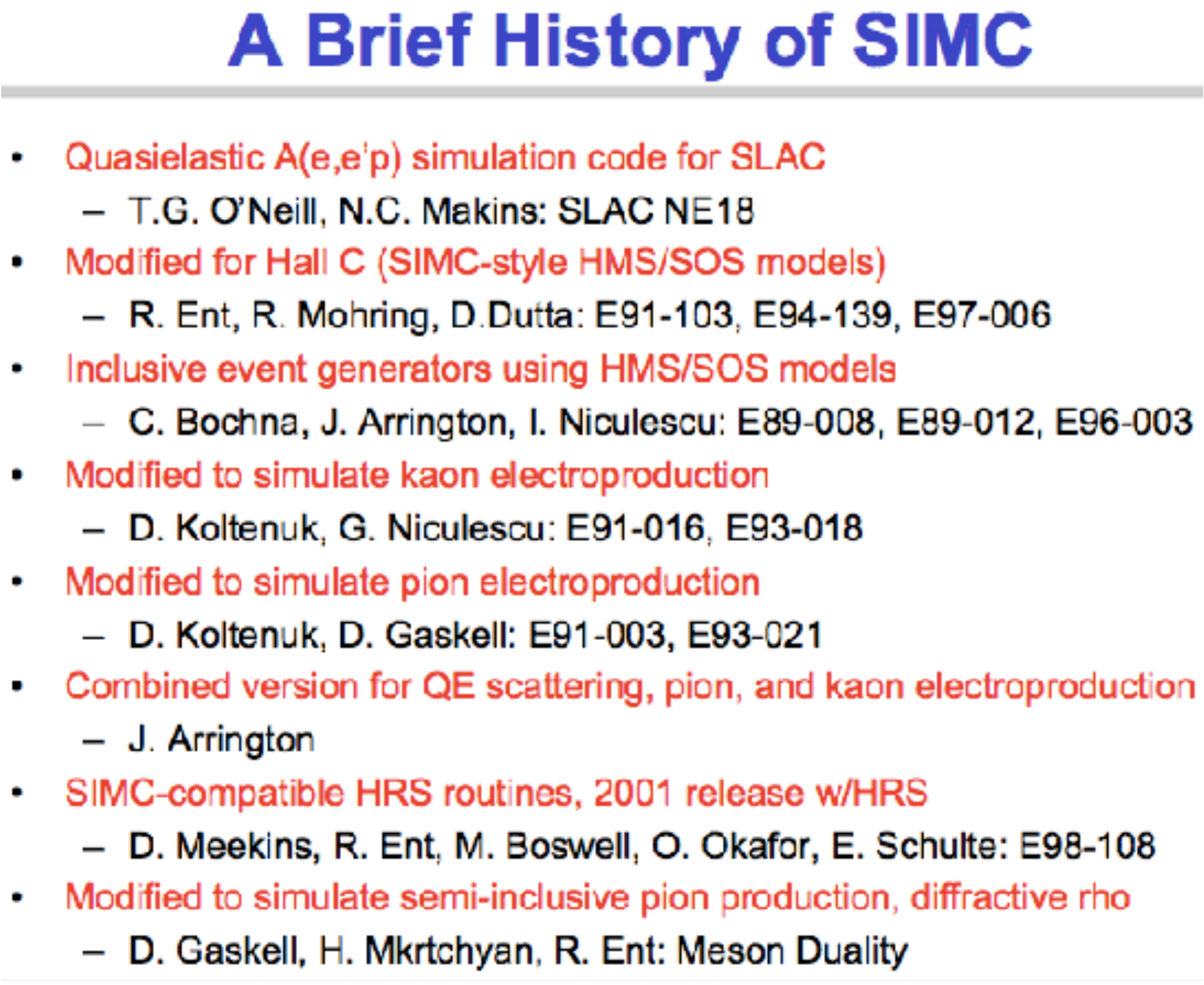
The standard Hall C Monte Carlo

Features:

- ✓ Optics (COSY) and spectrometer apertures
- ✓ Radiative corrections, multiple scattering, ionization energy loss, particle decay
- ✓ prescriptions for FSI, coulomb corrections, off-shell corrections

Reactions:

- ✓ H(e,e’p), A(e,e’p)
- ✓ H(e,e’ $\pi^\pm$)n, A(e,e’ $\pi^\pm$)
- ✓ H(e,e’ $\pi^\pm$)X, D(e,e’ $\pi^\pm$)X
- ✓ H(e,e’ $K^\pm$)$\Lambda\Sigma$, A(e,e’ $K^\pm$)
- ✓ H(e,e’ ρ), D(e,e’ ρ)



A Brief History of SIMC

- Quasielastic A(e,e'p) simulation code for SLAC
  - T.G. O'Neill, N.C. Makins: SLAC NE18
- Modified for Hall C (SIMC-style HMS/SOS models)
  - R. Ent, R. Mohring, D.Dutta: E91-103, E94-139, E97-006
- Inclusive event generators using HMS/SOS models
  - C. Bochna, J. Arrington, I. Niculescu: E89-008, E89-012, E96-003
- Modified to simulate kaon electroproduction
  - D. Koltenuk, G. Niculescu: E91-016, E93-018
- Modified to simulate pion electroproduction
  - D. Koltenuk, D. Gaskell: E91-003, E93-021
- Combined version for QE scattering, pion, and kaon electroproduction
  - J. Arrington
- SIMC-compatible HRS routines, 2001 release w/HRS
  - D. Meekins, R. Ent, M. Boswell, O. Okafor, E. Schulte: E98-108
- Modified to simulate semi-inclusive pion production, diffractive rho
  - D. Gaskell, H. Mkrtchyan, R. Ent: Meson Duality

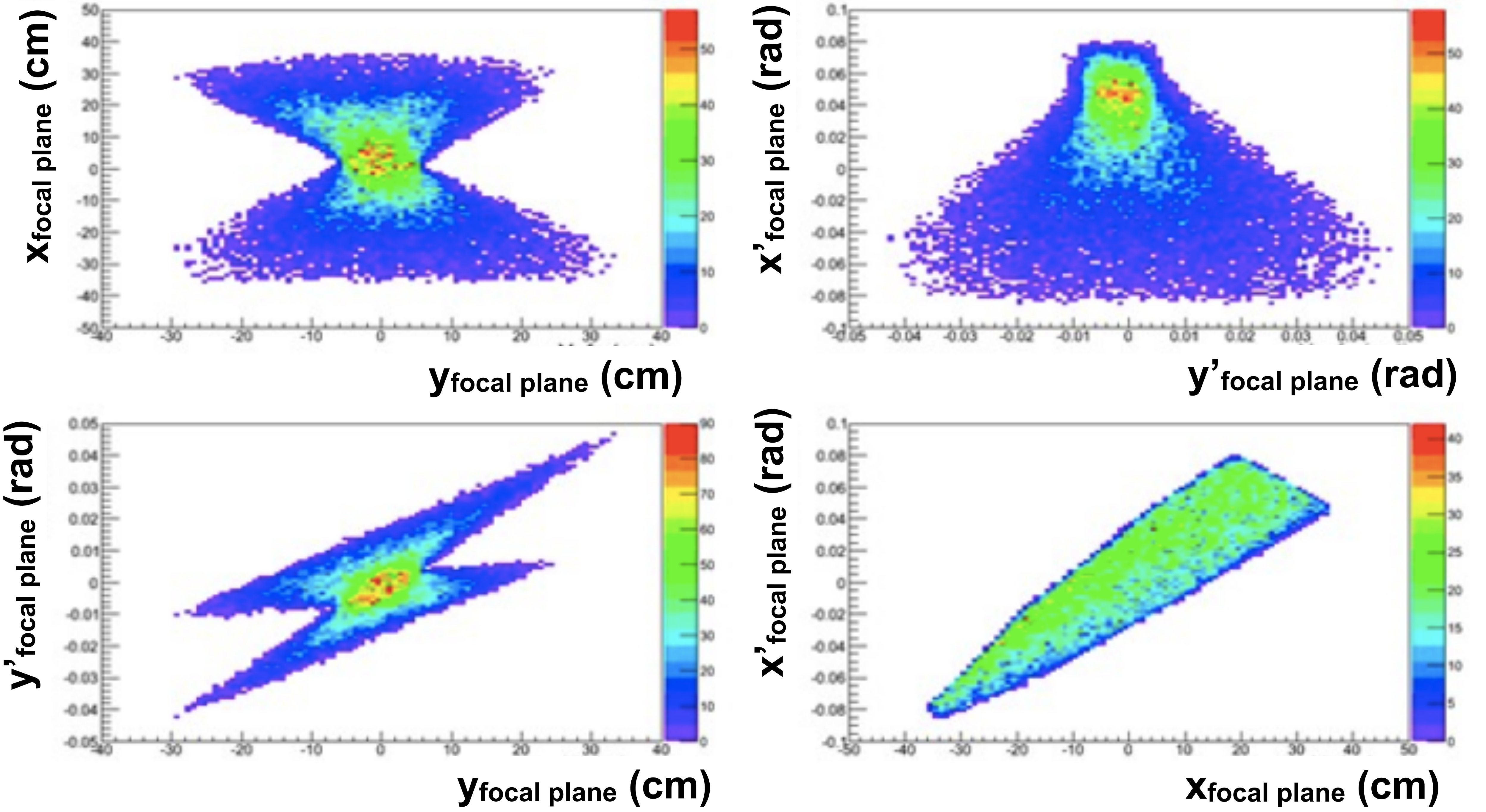
from D. Gaskell

available on git-hub: https://github.com/JeffersonLab/simc_gfortran

SIMC with SHMS has been available for a while now

SHMS Focal plane distributions using SIMC

2 GeV electrons on LH_2 target at 20 deg; point-to-point tune (allows reproducibility)

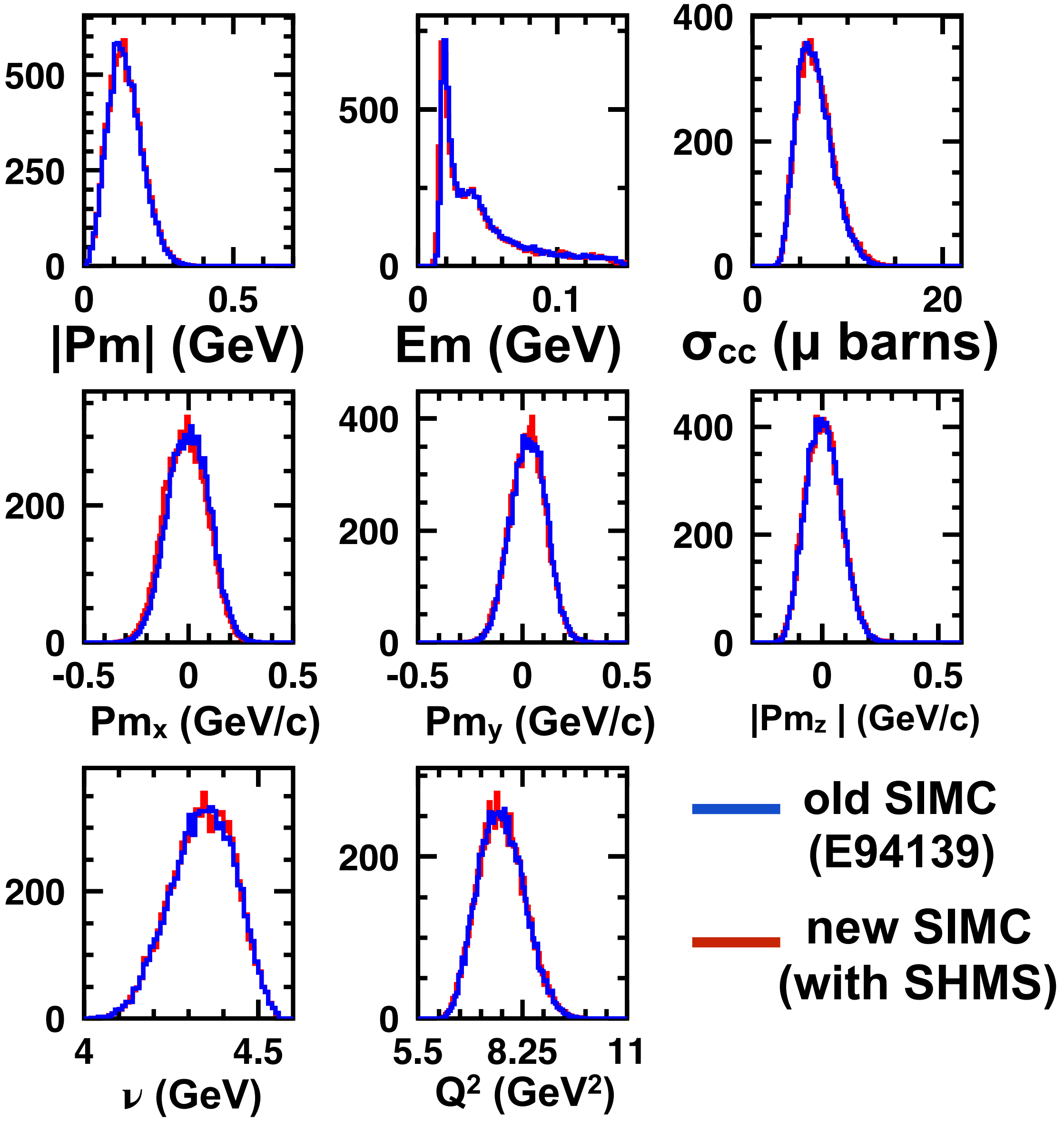


from M. Jones

HCANA and SIMC have been checked for A(e,e'p)

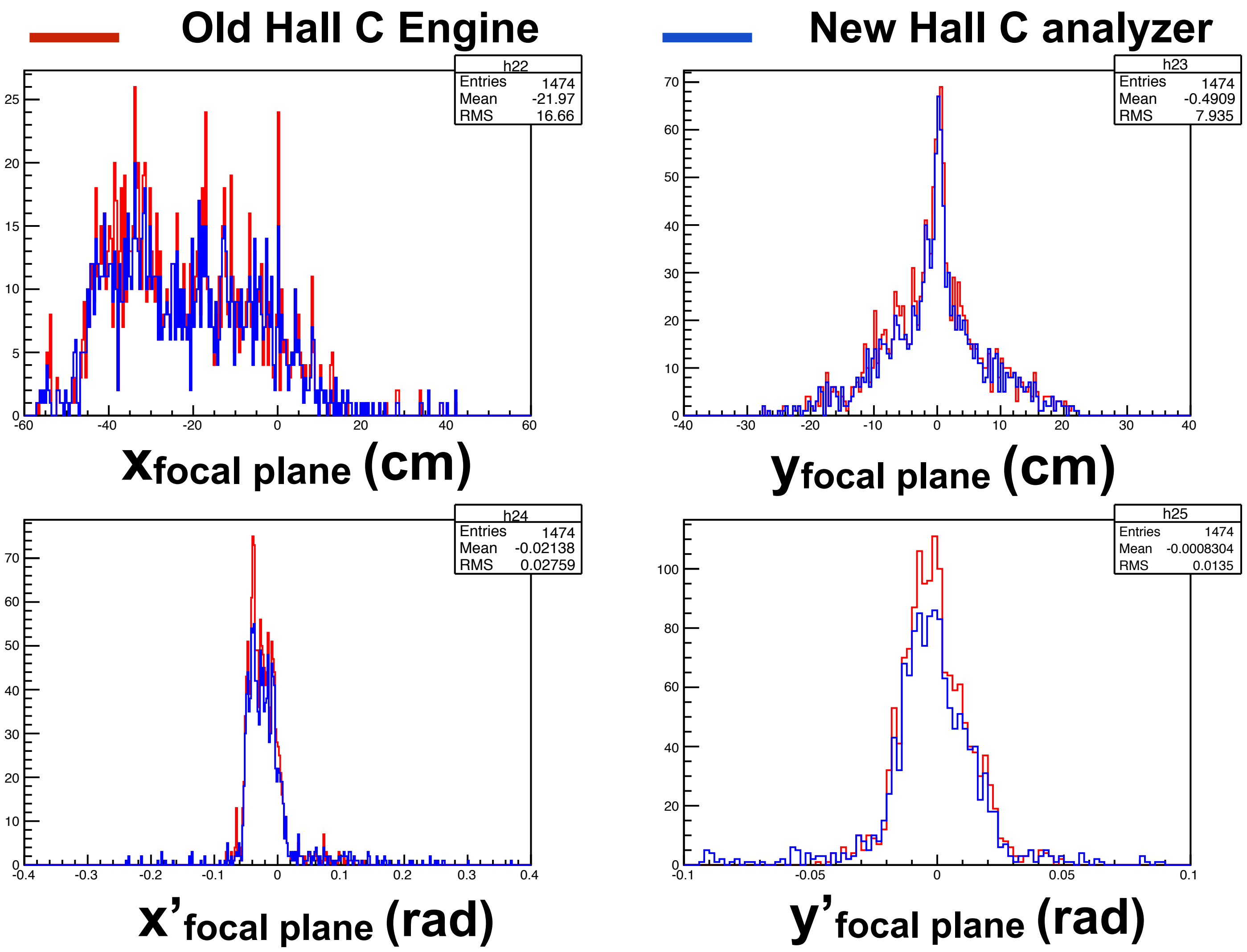
E94-139 measured C(e,e'p) at $Q^2 = 8.1$ GeV^2
this is same as the lowest Q^2 point for E12-06-107

We have used the data and simulation (SIMC) ntuples from E94-139 to test the new Hall-C analyzer and the new SIMC.



SIMC is ready

HMS DC focal plane variables



Analyzer is ready

Hall C software is in good hands

- **Software Manager : Mark Jones, Hall C staff.**
- **Detectors, parameter database, code integration: Steve Wood, Hall C staff.**
- **DAQ, detectors : Brad Sawatzky, Hall C staff.**
- **DAQ, detectors : Eric Pooser, Hall C postdoc.**
- **Optics, Magnet commissioning : Jure Bericic, Hall C postdoc. (commissioning plan by optics working group)**
- **Individual detectors developed by users:**

  Regina (Garth, Ahmed), Yerevan (Simon, Vardan), CUA (Arthur)
  CNU (Ed), FIU (Pete), Miss. State (DD), JMU (Gabriel)

E12-06-107 Collaboration

Hadron Propagation and Color Transparency at 12 GeV

ANSL/Yerevan, Argonne, Catholic, Duke, Hampton, JLab, Mississippi State, Regina

subset of this collaboration commissioned Hall-C in 1994

Collaboration also carried out several nuclear transparency experiments E91-013 (1994-1995), E94-139 (1999) and E01-107 (2004) with strong publications record from these experiments (2 PRLs, 6 PRCs (1 as rapid comm))

373 citations, 5 articles with over 50 citations each

1 thesis student - Deepak Bhetuwal (MSU)
(+5 other students on the other comm. experiments)
1/2 post-doc (MSU) dedicated to this experiment
extensive support from JLab staff and post-docs for building/validating Software and online as well as offline data analysis.

Summary

- Experiment E12-06-107 the commissioning experiment will measure the A(e,e'p) reaction on ^{1}H and ^{12}C targets, and is ideal for commissioning the new spectrometer.

- The Hall C Analysis framework (hcana) and Monte Carlo simulation (SIMC) are ready and have been tested with old ^{12}C(e,e'p) data.

- Given the long history of A(e,e'p) measurements in Hall C the online results can be used for diagnostics.

- Based on the previous experience it should be possible to produce a physics publication within 12-18 months after the experiment.