# Hadron Propagation and Color Transparency at 12 GeV E12-06-107

**Carlos Ayerbe Gayoso**

On behalf of **Holly Szumila-Vance (FIU)** and
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# Outline

- Color transparency (CT)
- Summary of proton results
- Pion CT at Hall C

# Nuclear transparency

- Nuclear transparency:
  - The ratio of the cross section per nucleon for a process on a bound nucleon in the nucleus to the cross section for the process on a free nucleon

$$T_A = \frac{\sigma_A}{A\,\sigma_N}$$

**$\sigma_A$ Nuclear cross-section**

**$\sigma_N$ Free Nucleon cross-section**

$$\sigma_A = \sigma_N A^{\alpha}$$

A.S. Carroll et al. Phys Lett 80B 319 (1979) and many other papers

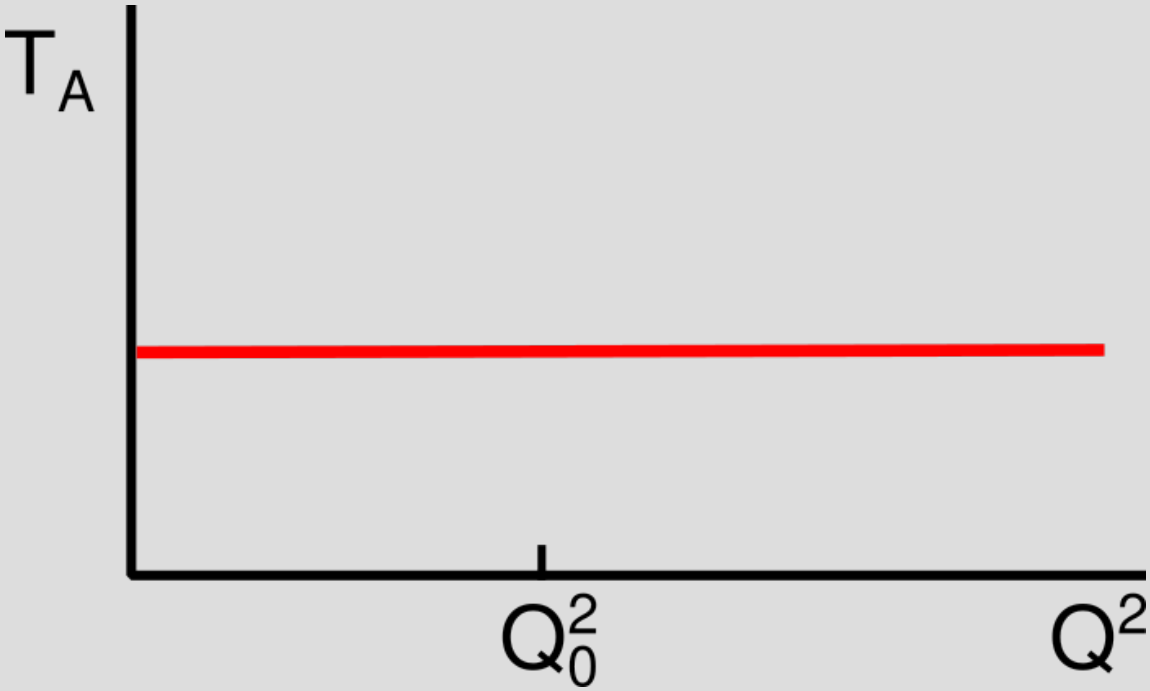
Transparency refers to the probability that a knocked out nucleon is deflected or absorbed (escape probability)

$$T_A = A^{\alpha-1}$$

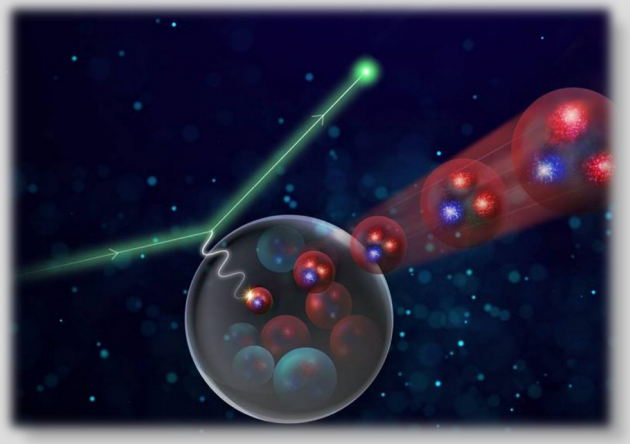
$\alpha < 1$ interpreted as due to the strong interaction nature of the probe

# Nuclear transparency

Traditional nuclear physics calculations (Glauber) predict energy independent transparency



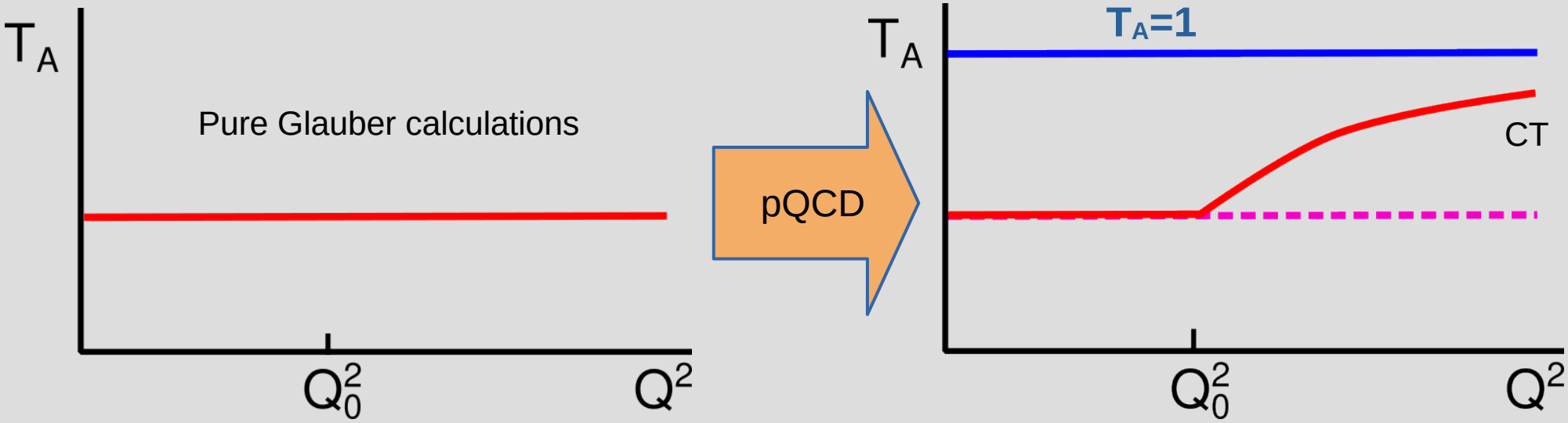

Measuring transparency includes:
- scattering cross section
- Glauber multiple scattering
- Correlations and Final State Interaction (FSI) effects



# Color transparency (CT)

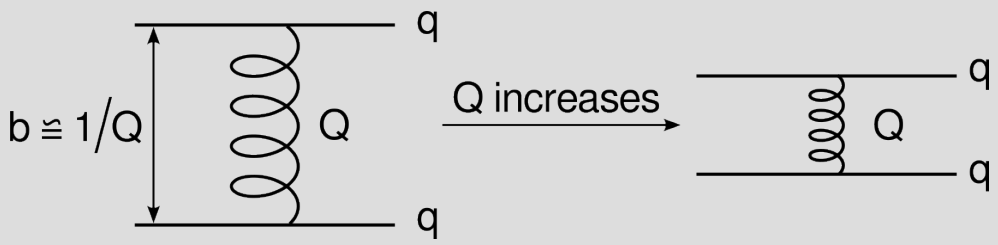
- From fundamental considerations (quantum mechanics, relativity, QCD) it is predicted (Brodsky, Mueller) that fast protons scattered from the nucleus will have decreased final state interactions

A.H. Mueller in Proc. of 17th recontre de Moriond, Morionf, p13 (1982)
S.J. Brodsky in Proc of 13th Intl. Symposium on Multipartcile Dynamics, p963 (1982)



# Color transparency (CT)

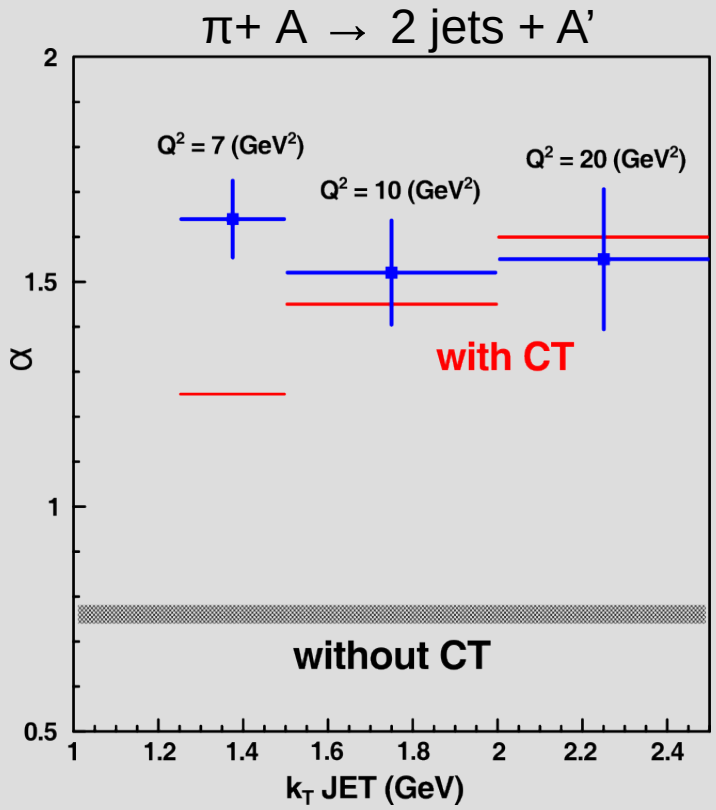
- The **onset** of CT requires the following conditions
  - "squeezing" Hadrons fluctuate to small transverse size, pointlike configuration (PLC) (achievable at high energies) (QM)
  - "freezing" The compact size is maintained while traversing the nuclear medium (Relativity)
  - The PLC is 'color screened' - it passes undisturbed through the nuclear medium (Strong Force)




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

# CT established at high energies

Coherent diffractive dissociation of 500 GeV/c pions on C and Pt



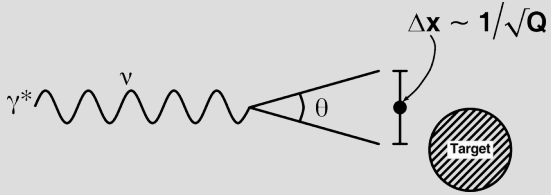

Aitala et al., PRL 86, 4773 (2001)

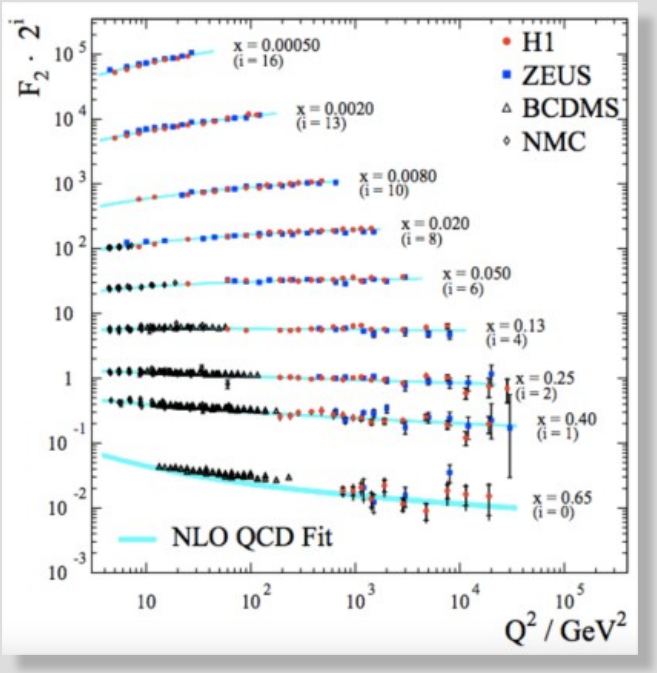
Fit to $\sigma = \sigma_0 A^{\alpha}$
Pion-nucleus total cross section, $\alpha$=1.6

**CT predictions** by L. L. Frankfurt, G. A. Miller, and M.Strikman, Phys. Lett. B304, 1 (1993)

# Onset of CT

- The onset of CT can be taken as a signature of QCD reaching the perturbative domain, i.e. description of nuclei in terms of **quarks and gluons instead baryons and mesons.**
- CT is implied by successful description of DIS.
  - Scaling at low x requires a suppression of interaction.




- Color Transparency is closely linked to the concept of soft-hard factorization in exclusive processes. **Factorization is not rigorously possible without the onset of CT.** [Strikman, Frankfurt, Miller and Sargsian]

The question is:

**At what $Q^2$ does the onset of nuclear color transparency begin?**

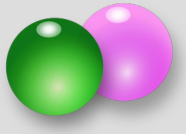
# CT onset experiments

CT onset experiments

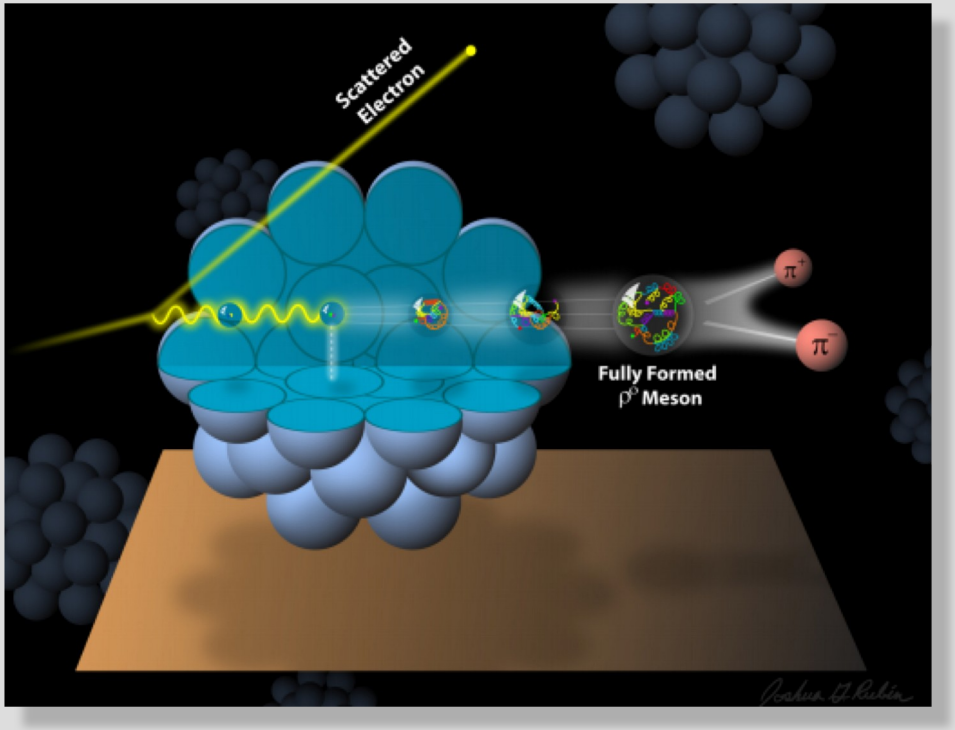
Baryon

A(p,2p) : BNL
A(e,e'p): SLAC, JLab

Meson

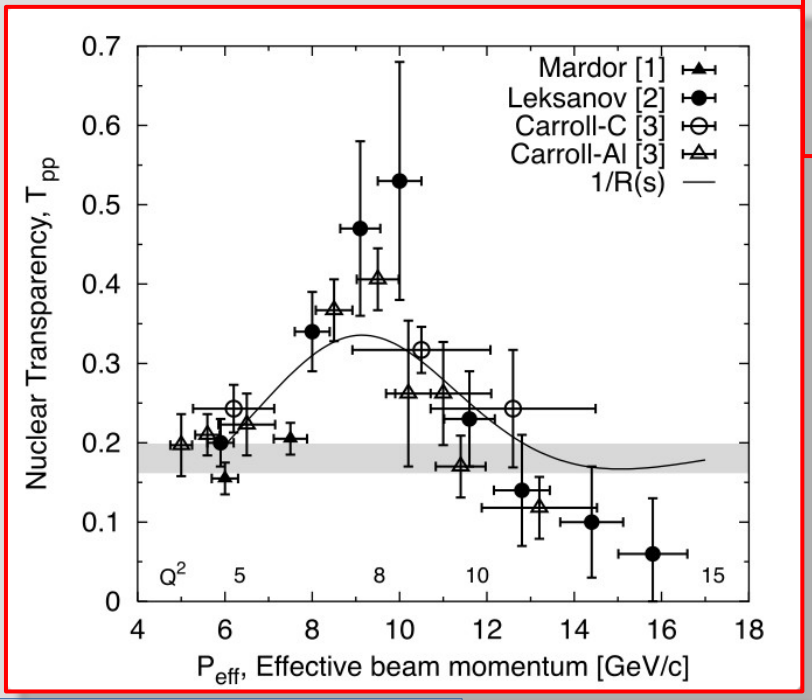


A(**π**,di-jet): FNAL
A($\gamma$, **π**$^-$ p) : JLab
A(e, e'**π**$^+$) : JLab
A(e, e'**ρ**$^0$) : DESY & JLab



# Baryon CT Experiments

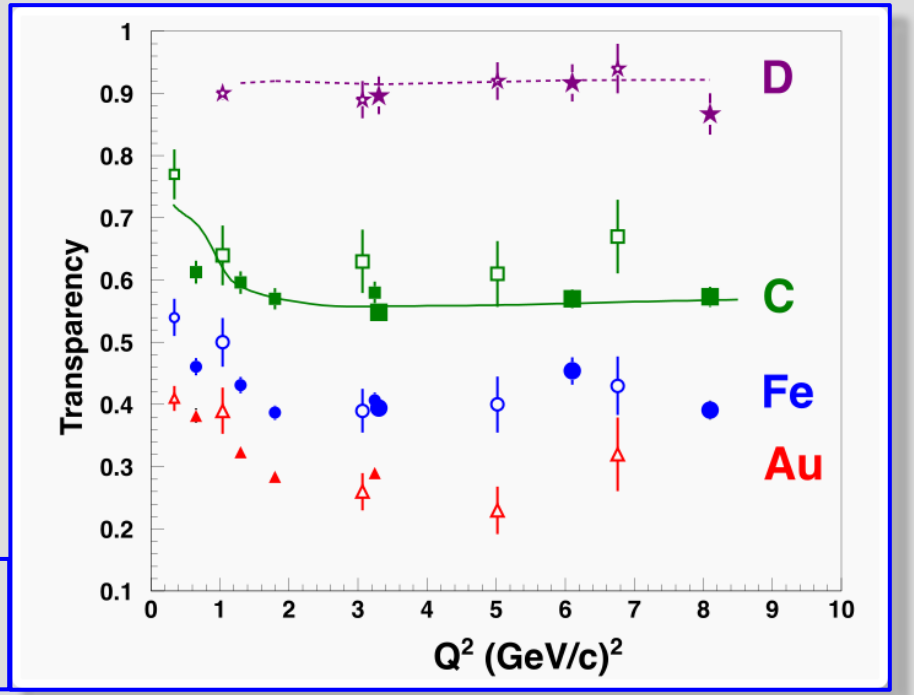
## A(p,pp) (BNL)




A. Leksanov et al. PRL 87 (2001)
J. L. S. Aclander et al., PRC 70 (2004)

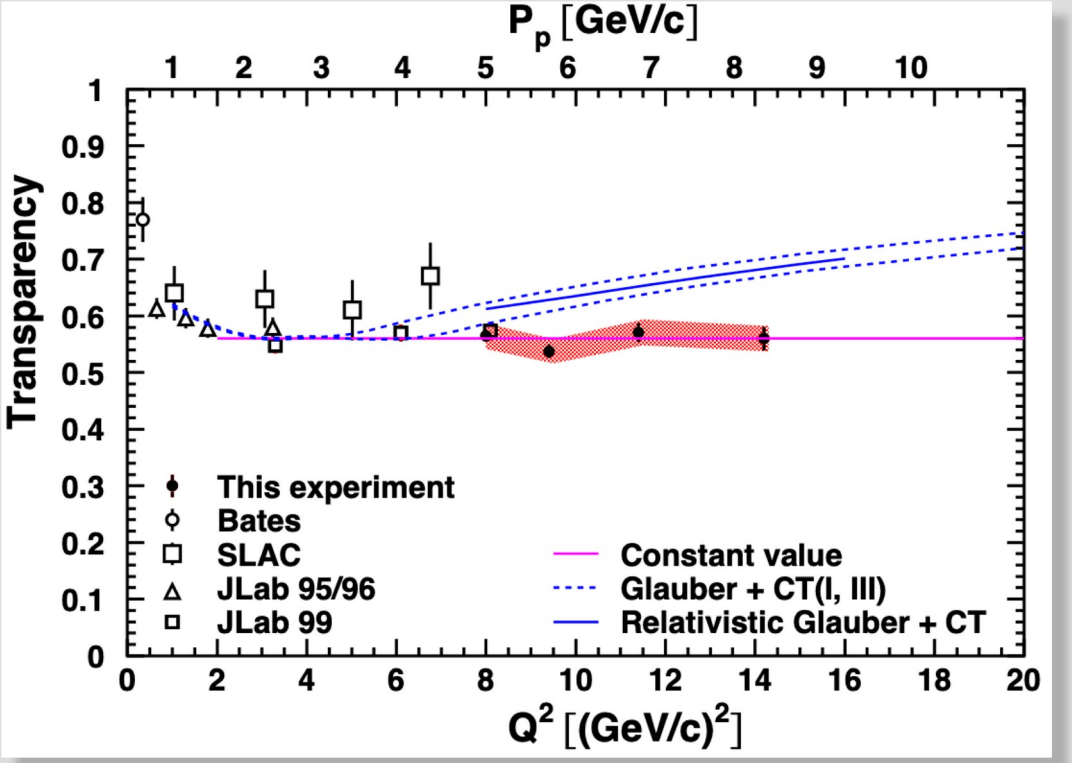
- observed enhancement in transparency
- inconsistent with CT only
- could be explained by including nuclear filtering or charm resonance

## A(e,e'p) (SLAC, BATES & JLab)




$Q^2$ dependence consistent with standard nuclear physics calculations

# Proton E12-06-107 $^{12}$C(e,e'p)




D. Bhetuwal et al, PRL126:082301 (2021)
D. Bhetuwal, et al, Phys. Rev. C 108, 025203 (2023)

Recent proton experiment shows **no onset** up to $Q^2<14$ GeV$^2$

## Possible explanations

- **No PLC** was formed (Feynman Mechanism)

G. Miller, Physics 2022, 4(2), 590-596; https://doi.org/10.3390/physics4020039
O. Caplow-Munro and G. Miller, PRC 104, L012201 (2021)

- **Not high enough in $Q^2$** (Holographic light front QCD predictions)

S. Brodsky and G. de Téramond, Physics 2022, 4(2), 633-646; https://doi.org/10.3390/physics4020042

# No onset?

There is **no evidence** of CT onset in the baryonic sector

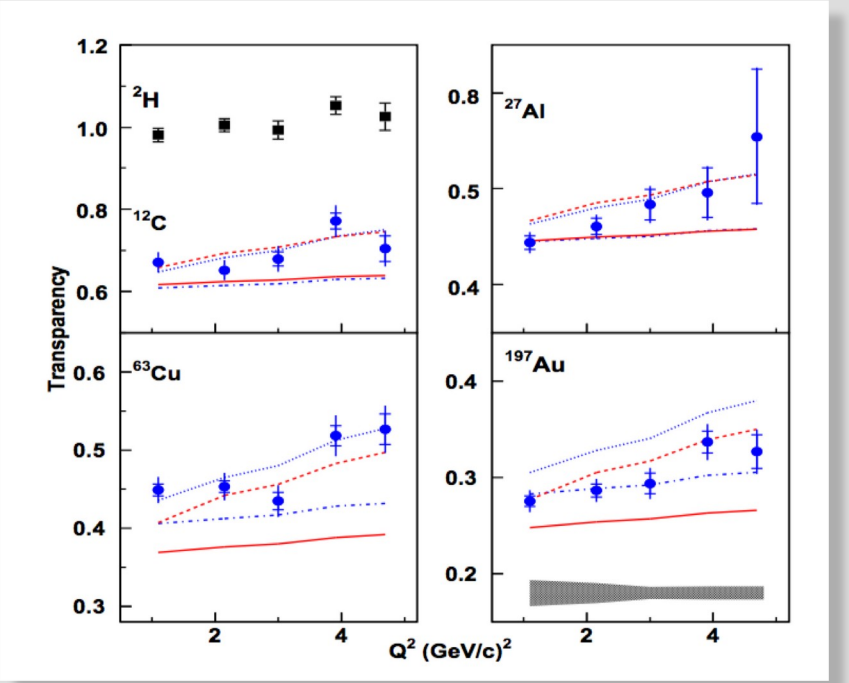
Nature of Strong force, may make harder to achieve the PLC conditions.

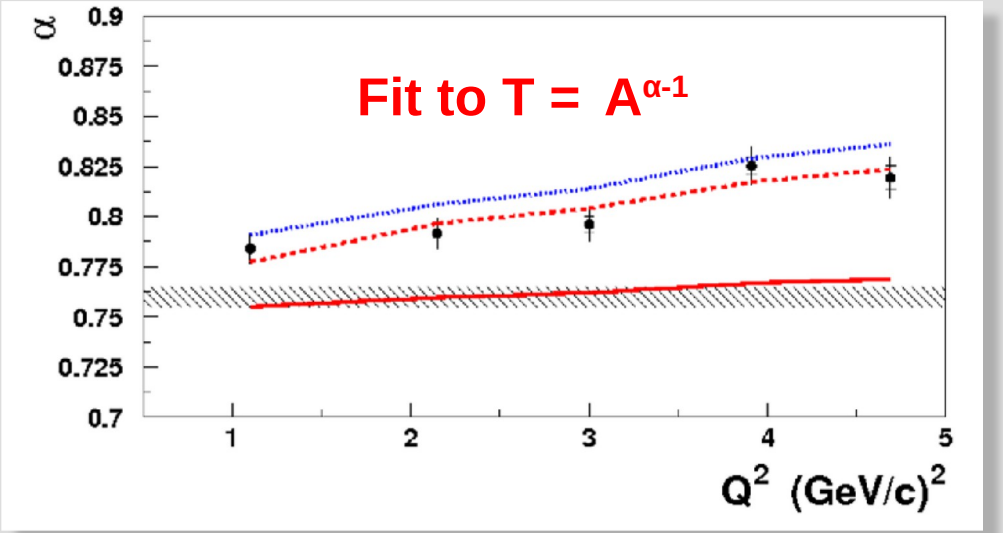

Perhaps **pions or mesons** in general, are more suitable to achieve the PLC

# Meson CT experiments

Hall-C Experiment E01-107

A(e,e' π+)



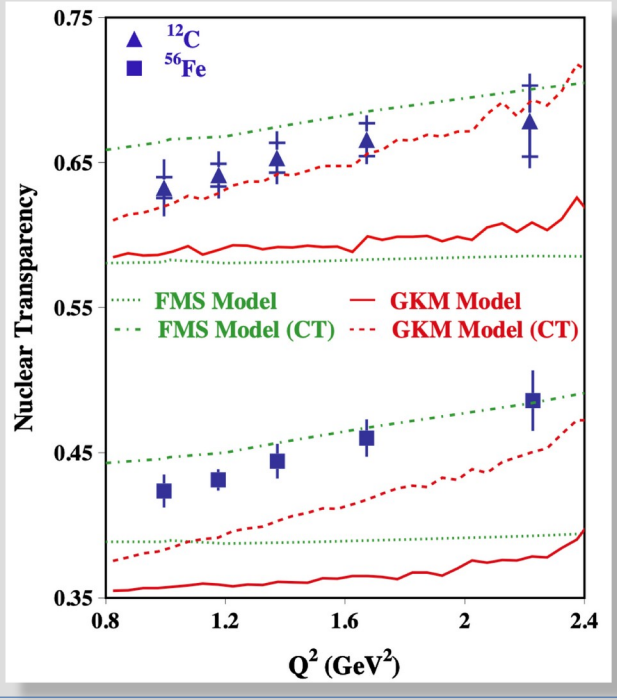

We observe both, a **T and A dependence** of the transparency **as evidence for CT**

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

# Meson CT experiments

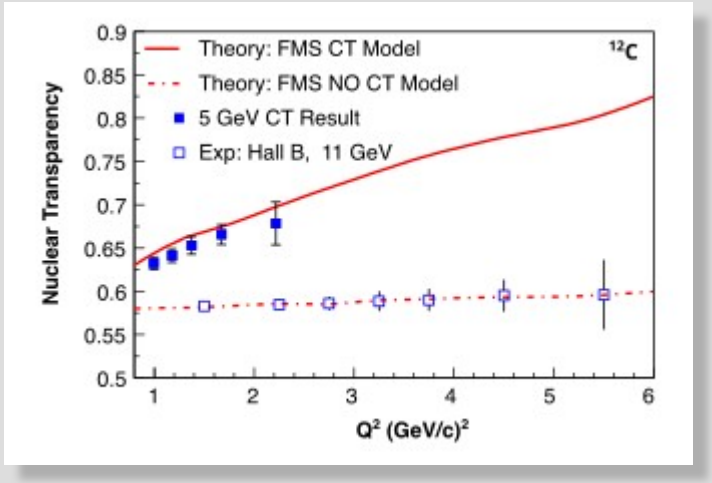
CLAS E02-110 rho electro-production

$A(e,e'\rho^0)$




L. El Fassi et al., Phys. Lett. B 712:326-330 (2012)
https://doi.org/10.1016/j.physletb.2012.05.019

**E12-06-106**: Study of Color Transparency (CT) in Exclusive Vector Meson Electroproduction off Nuclei
*Spokespeople*: W. Armstrong, L. El Fassi,K. Hafidi, M. Holtrop, B. Mustapha




$^{12}$C projections. $^{63}$Cu and $^{118}$Sn targets also used.
Data taken during the **2023/24 beam period**

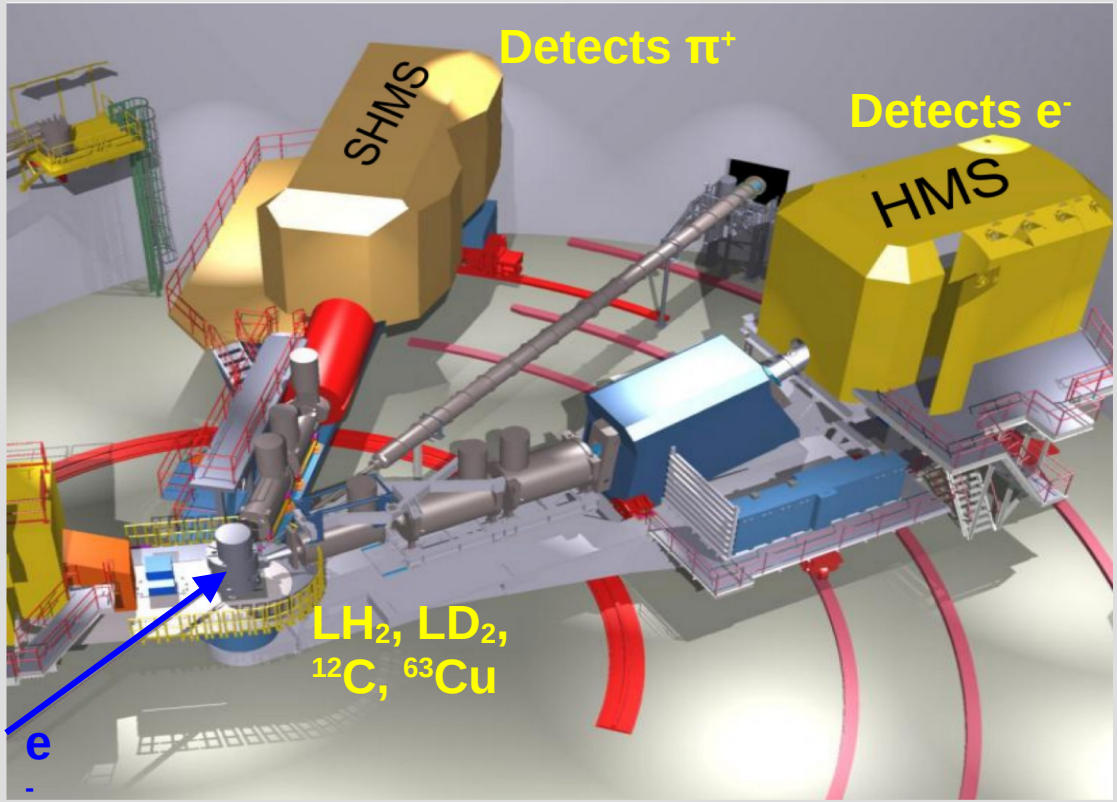
# Pion CT E12-06-107

**Second part** of E12-06-107 (**first** was proton CT)

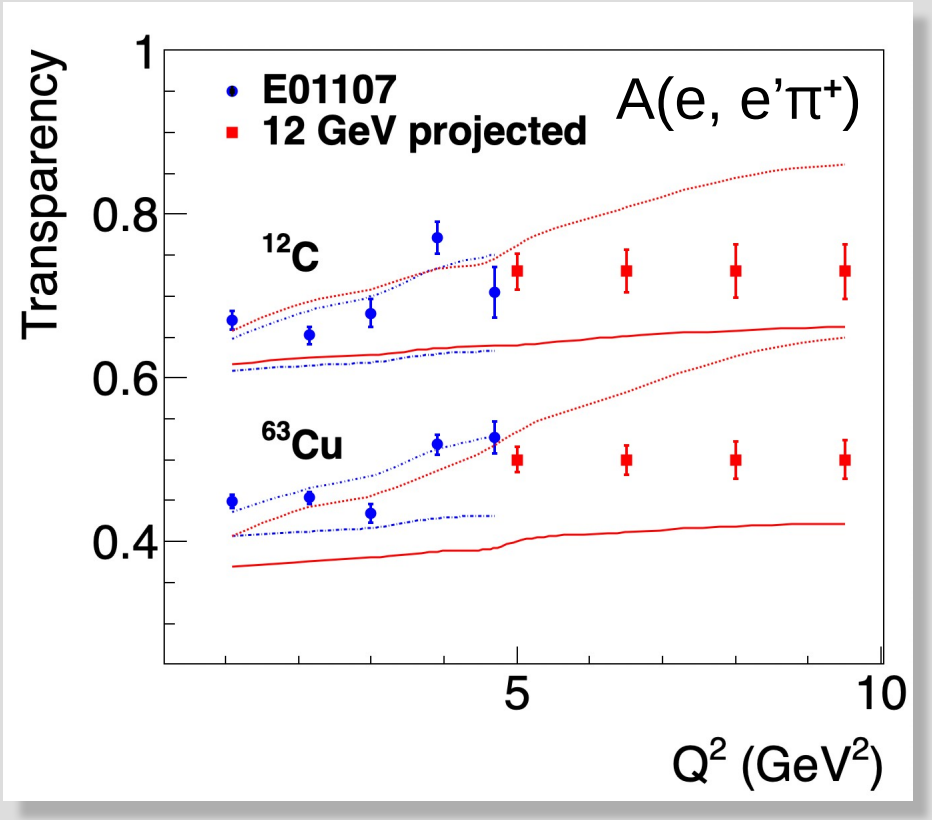
- A(e, e'π⁺)
- 17.5 PAC days of running
- 11 GeV beam
- $^{1}H$, $^{2}H$, $^{12}C$, $^{63}Cu$
- 0.4< -t <0.48 GeV$^2$ minimized contributions from rescattering or multi-nucleon effects

| $Q^2$ | $W$ | $\theta_{e'}^{HMS}$ | $E_{e'}$ | $\theta_{\pi}^{SHMS}$ | $p_{\pi}$ | $k_{\pi}$ |
|---|---|---|---|---|---|---|
| $(GeV/c)^2$ | GeV | deg | GeV | deg | GeV/c | GeV |
| 5.0 | 2.43 | 16.28 | 5.67 | 15.96 | 5.110 | 0.67 |
| 6.5 | 2.74 | 22.13 | 4.010 | 11.72 | 6.771 | 0.67 |
| 8.0 | 3.02 | 32.37 | 2.340 | 7.90 | 8.442 | 0.67 |
| 9.5 | 3.09 | 47.71 | 1.320 | 5.52 | 9.42 | 0.74 |

The final analysis will evaluate the **A and T dependence** driven by the less understood reaction mechanism.



# Measure the onset over a large momentum range




Extending the momentum range will allows to map onset of CT through factorization regime

# Summary

✔ Onset of CT is an exciting opportunity to explore the connection between hadronic and partonic degrees of freedom in nuclei

✗ Not observed in protons in the recent Hall C experiment

➔ Hall C will measure A(e, e'$\pi^+$) in FY2026

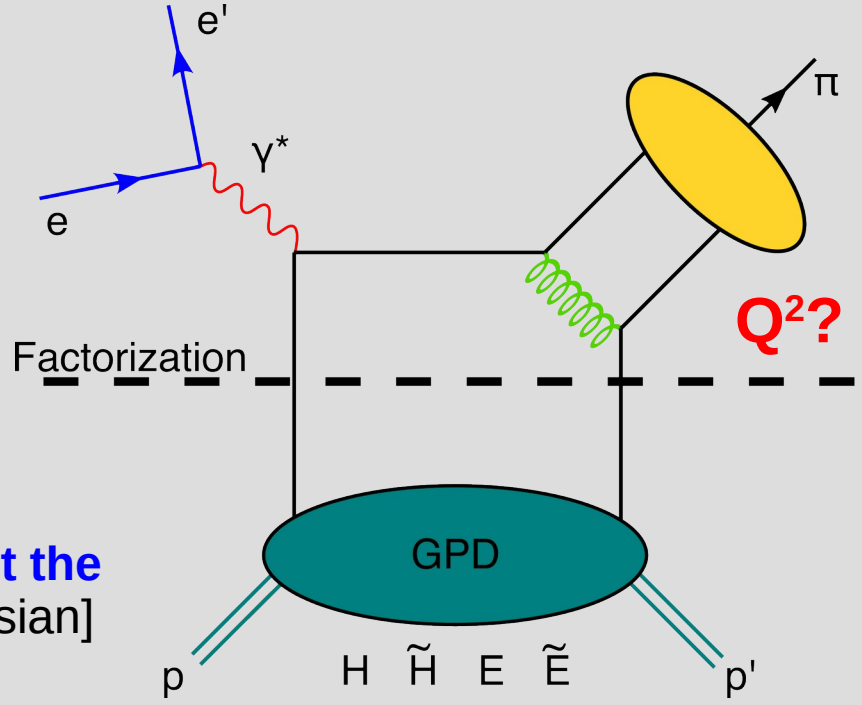
- Pion propagation in nuclear matter
- Map onset of CT through factorization regime

**Looking forward to running next year.**
**Sign up for shifts, and join our team!**

# Onset of CT

Understanding **nucleons and nuclei** in terms of **quarks and gluons** is still one of the important unsolved problem of the Standard Model of nuclear and particle physics.

- The onset of CT can be taken as a signature of QCD reaching the perturbative domain, i.e. description of nuclei in terms of quarks and gluons instead baryons and mesons.
- Color Transparency is closely linked to the concept of soft-hard factorization in exclusive processes.

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