Coherence, Hadron Formation and Color Transparency

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Introduction

- Almost everyone believes that Quantum Chromodynamics (QCD) is the theory of the strong interaction.
- Great successes have been seen for large-momentum-transfer reactions, where perturbation theory is applicable.
- Effective field theories such as chiral perturbation theory provide a rigorous calculational approach at very low momentum transfers.
- We know little about the terrain in between.
- Lattice QCD is still in its infancy.
- Therefore, the rich phenomena of QCD, from proton structure to pentaquarks, remain largely undiscovered.

Expansions

- Suppose I want to calculate $e^{0.17}$.
- Let's expand in a Taylor series: $e^{0.17} = 1 + 0.17/1! + (0.17)^2/2! + ... = 1.18445$, which is not far from 1.185304851. (QED *quod erat demonstrandum*).
- Now suppose I want to calculate $e^{17.17}$.
- $1 + 17.17/1! + (17.17)^2/2! = 165.57445$ which isn't even close to 28630982.68! (QCD)
- We could decide that $e^{17.17}$ isn't interesting ... or
- We could invent renormalization: $e^{17.17} = eeeeeeeeeeeeeeeee(1 + 0.17/1! + (0.17)^2/2!) = 28610333.79$.
- But what about sin(17.17)? (Ask afterwards if you're curious)

Kinematics

- 4-vectors:

lepton: k and k'
nucleon: p and p'
virtual photon: $q = k - k'$

- nucleon mass: M
- Lorentz invariants:

$\nu = p \cdot q / M = (E - E')_{\rm lab}$

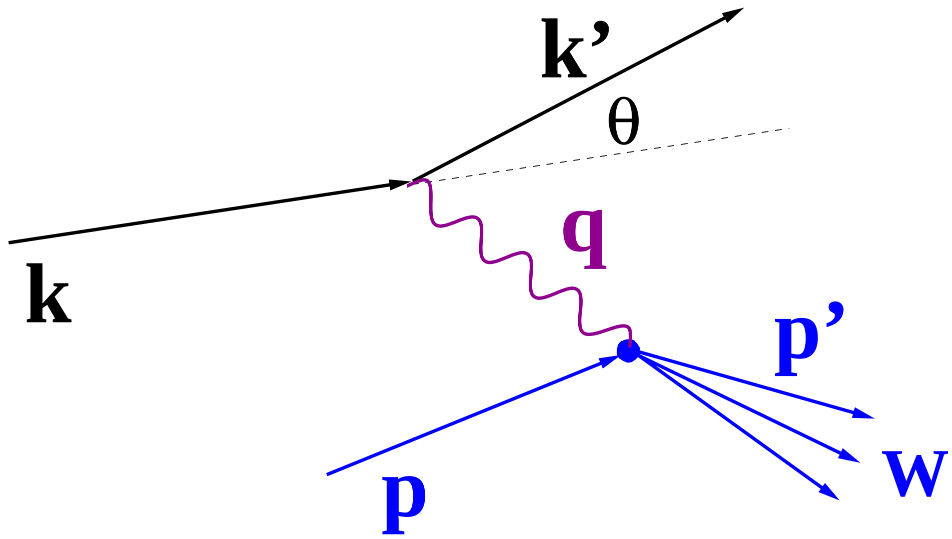
$Q^2 = -q \cdot q = (4EE' \sin^2 \frac{\theta}{2})_{\rm lab}$

$x = -q \cdot q / 2p \cdot q = (Q^2/2M\nu)_{\rm lab}$

$y = p \cdot q / p \cdot k = (\nu / E)_{\rm lab}$

$W^2 = (p+q)^2 = (M^2 + 2M\nu - Q^2)_{\rm lab}$

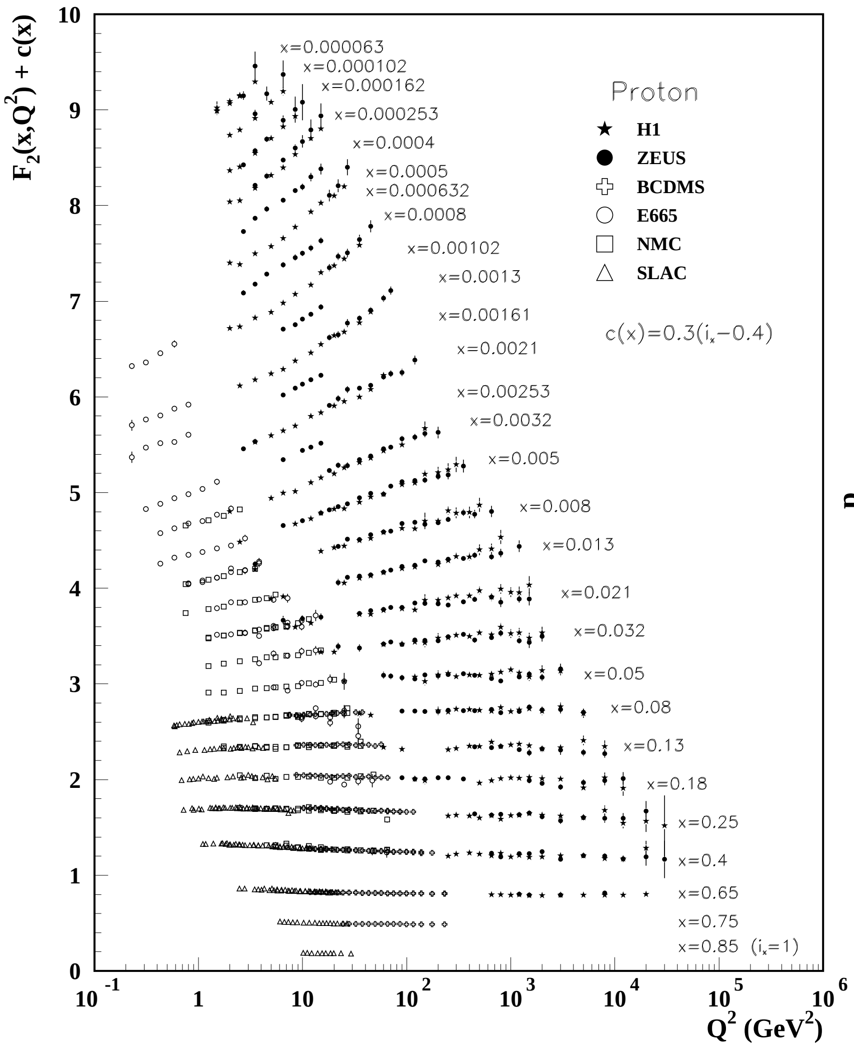
$s = (k+p)^2 = (2EM + M^2)_{\rm lab}$



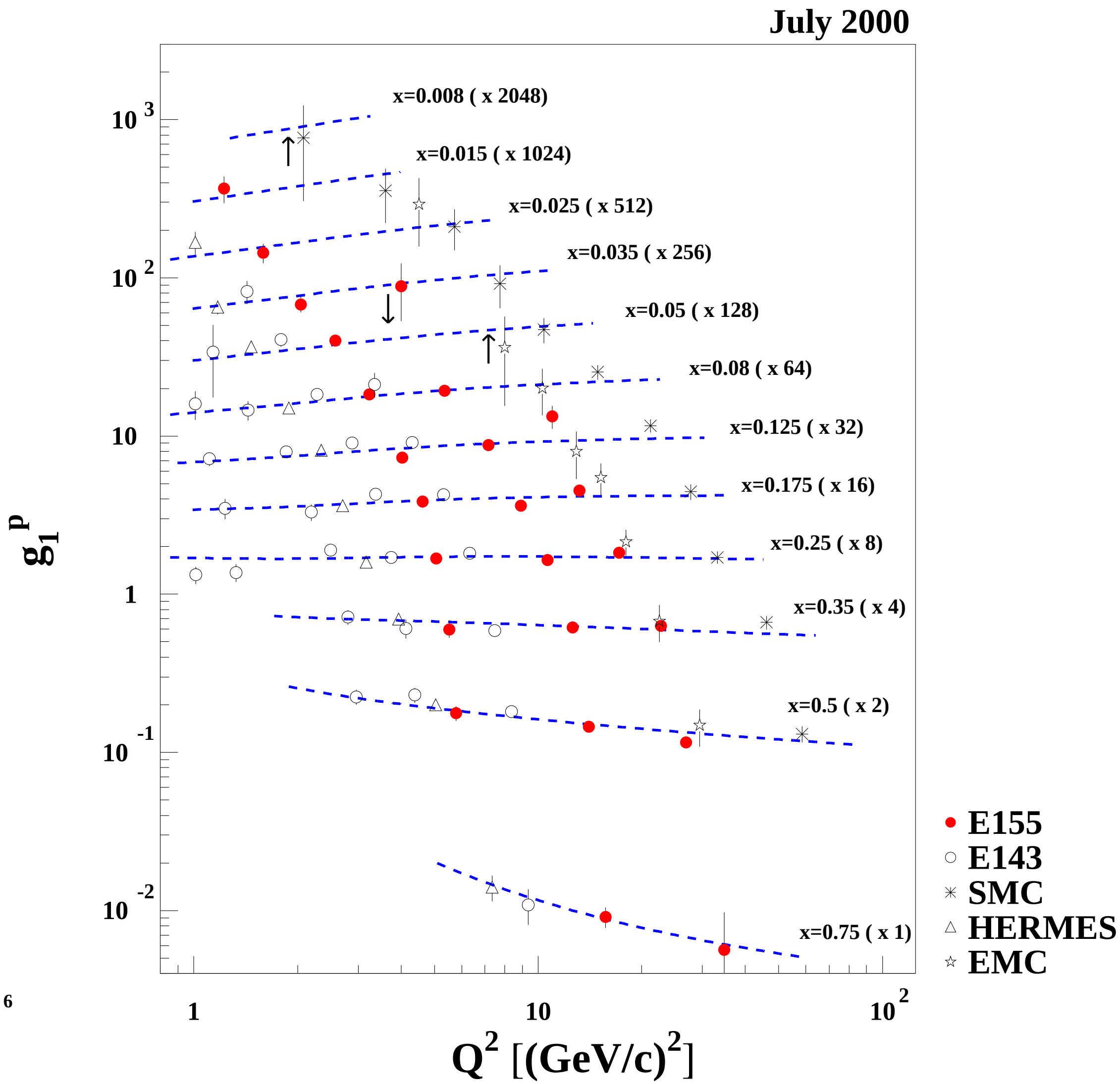
- Need two (*e.g.* x and Q^2) to describe inclusive scattering

Structure Functions

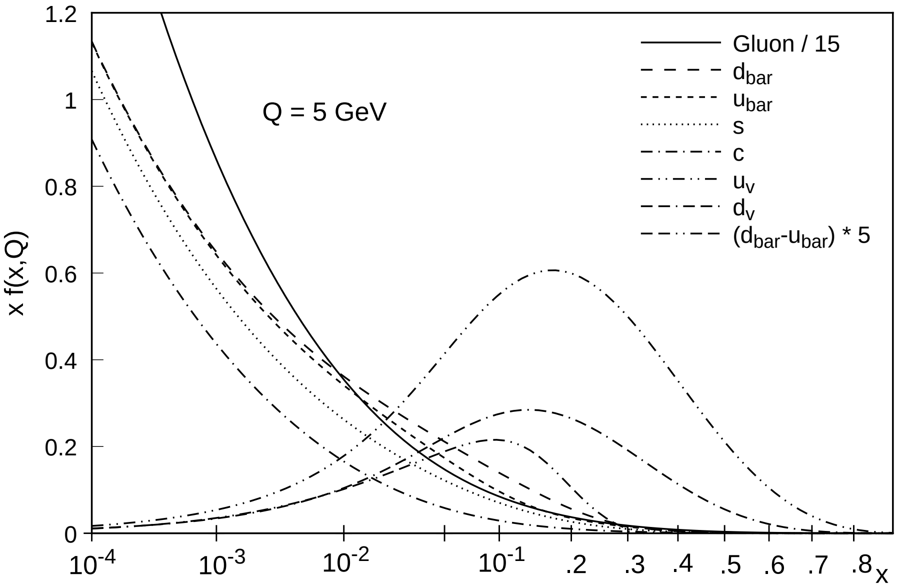
unpolarized: $F_2(x,Q^2)$

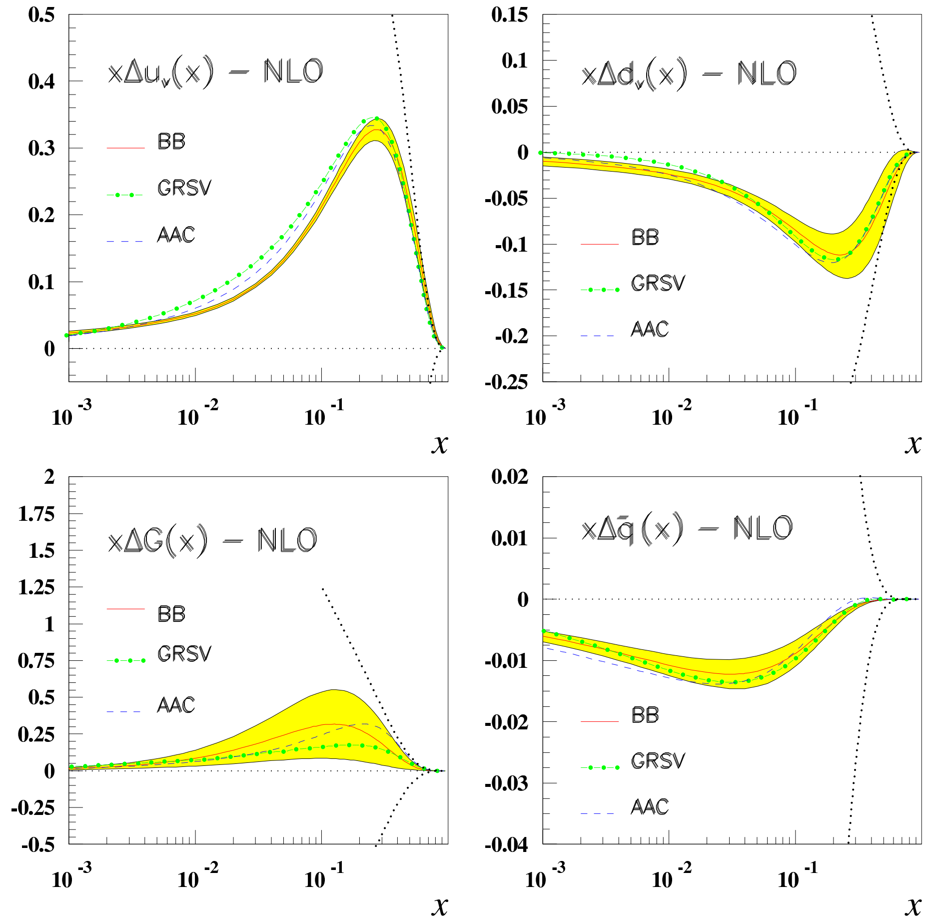


polarized: $g_1(x,Q^2)$



PDFs

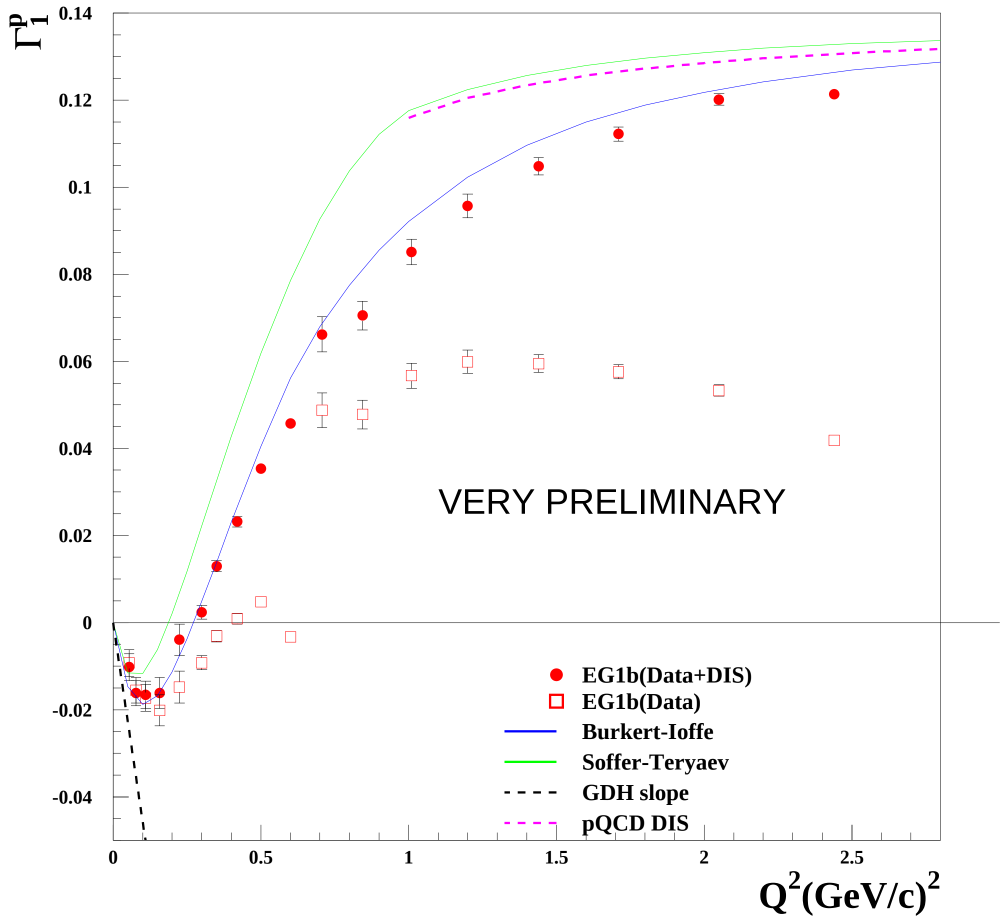




- Above: CTEQ, H.L. Lai *et al.*, Eur. Phys. J. **C12** (00) 375.
- Right: J. Blümlein and H. Böttcher, Nucl. Phys. **B636** (02) 225.

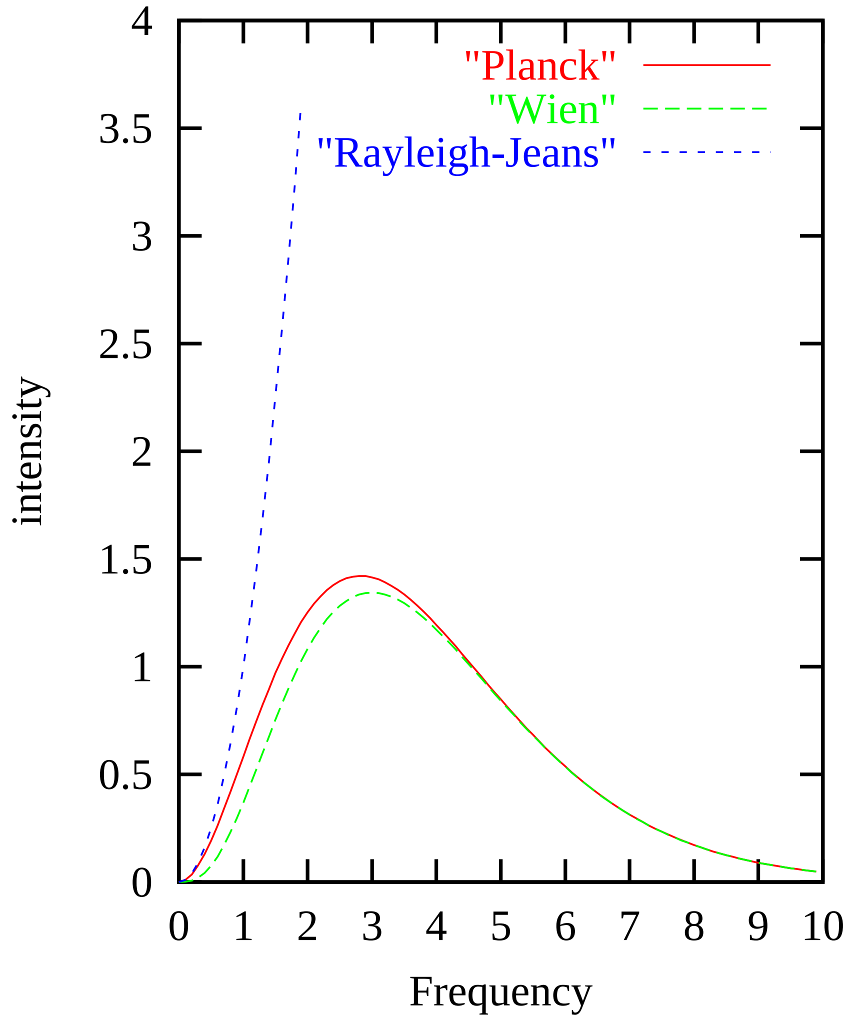
parton distributions are empirical!

- Hall B, JLab
- $\Gamma_1^p(Q^2) = \int_0^1 g_1(x,Q^2)dx$
- $E_e =$ 1–6 GeV
- g_1 measured in resonance region and beyond
- Combined with high-energy data for integrals



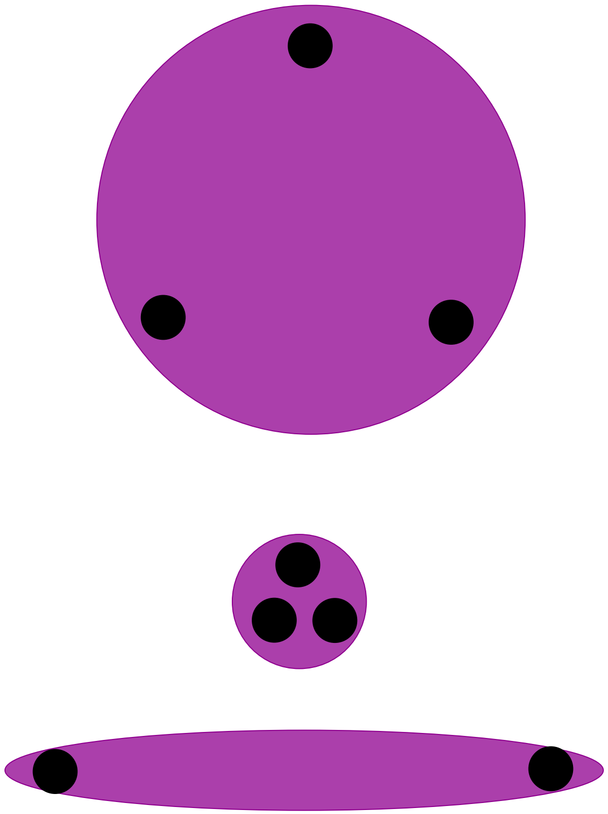
Black Body Radiation

- Wien's Law (empirical; derived from classical thermodynamics)
- Rayleigh-Jean's Law (derived from classical electromagnetism)
- Planck's Law (derived with light quanta)
- Black body radiation is dirty and complicated, but it started two revolutions: quantum physics and the big bang.



Color

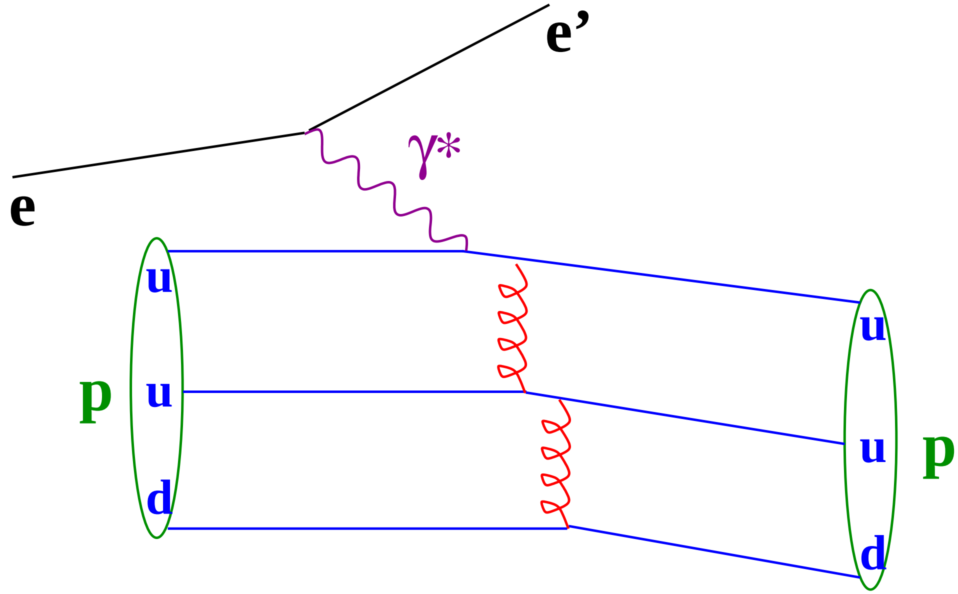
- Where does mass come from? The glue!
- QCD: color field is contained in the vicinity of valence quarks.
- When valence quarks are close together, color field is small; object remains colorless to the outside world.
- When two quarks are pulled apart, the color field forms a flux tube, much like a string connecting the two quarks.



hadronic $\sigma \propto \pi R^2$

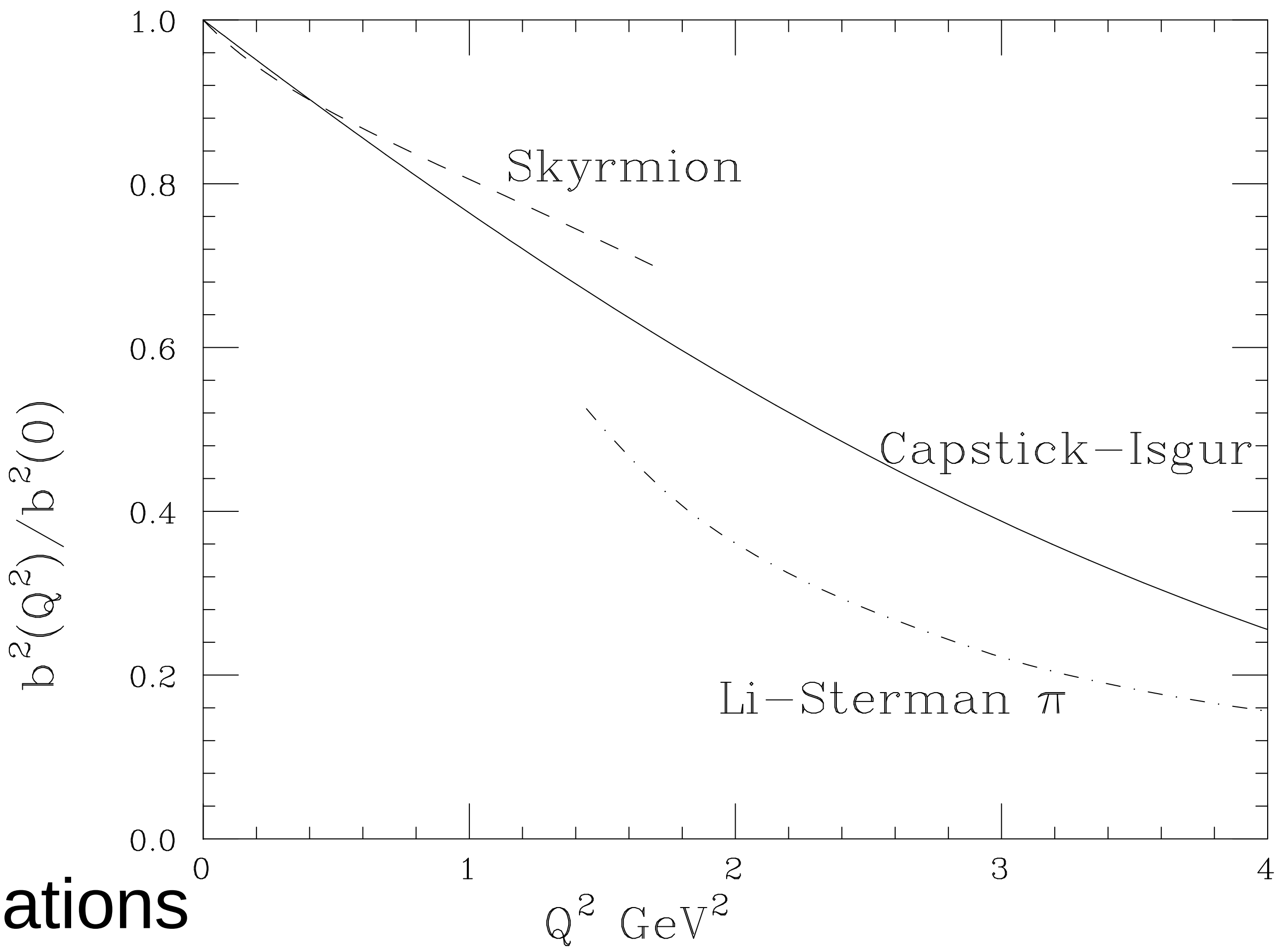
Color Transparency

- Brodsky and Müller, 1981
- Consider elastic ep scattering at high momentum transfer Q^2.

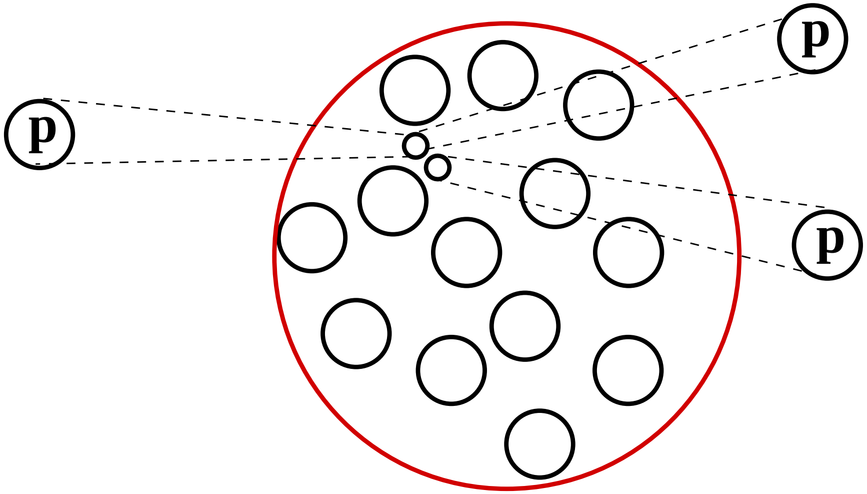


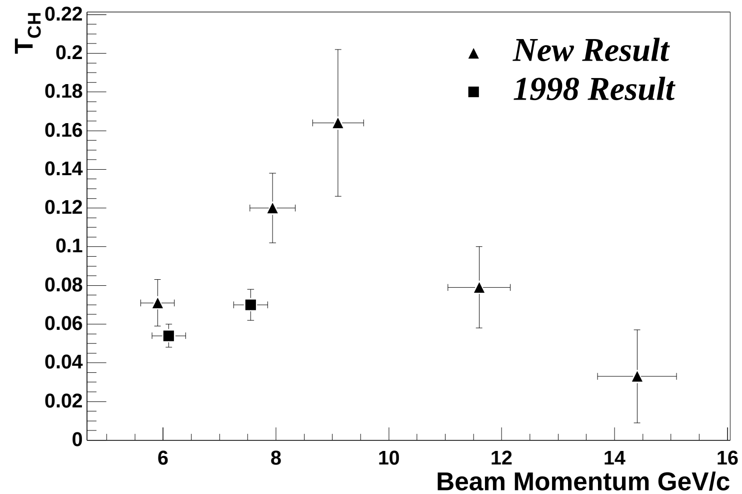
- The only way for the proton to survive the absorption of a photon on one quark, is if two gluon exchanges carry the other quarks along.
- Reaction time decreases with Q^2, implying that the quarks must be close together to react quickly.
- Transverse size $b(Q^2) \sim 2/Q$ from uncertainty principle: $Q\tau \sim 1$.

Pointlike Objects

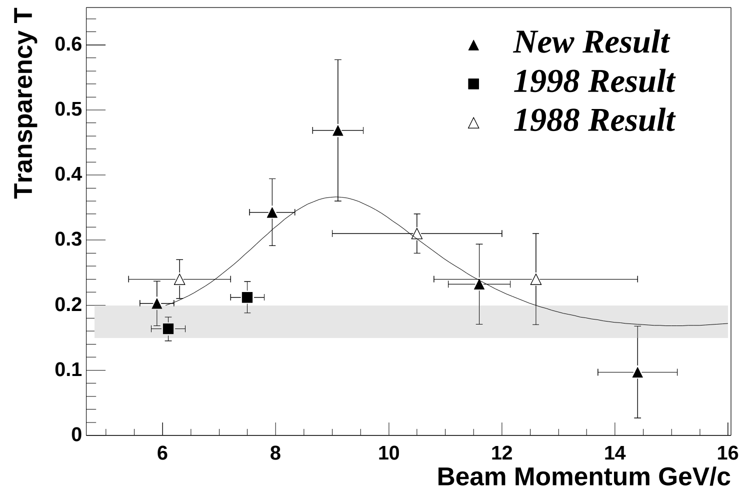


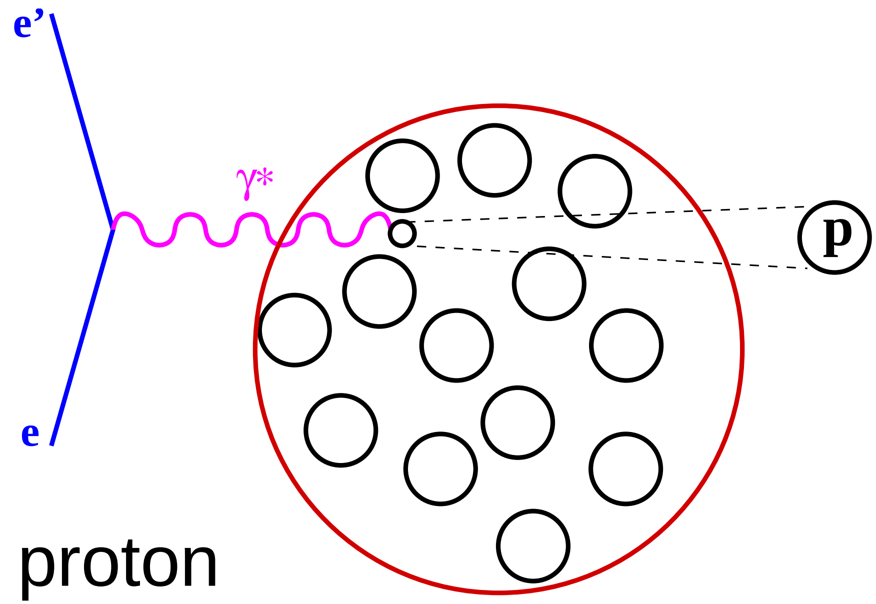
- Various calculations show decreasing transverse size with increasing momentum transfer





- A. Leksanov *et al.*, PRL 87 (01) 212301
- $pA \rightarrow ppX$
- $T = \frac{\sigma_{\text{pp QE}}}{\sigma_{\text{pp elastic off-shell}}}$
- Rise and fall of T: nuclear filtering (nucleus reacts differently to long and short-range scattering terms)? Not CT!

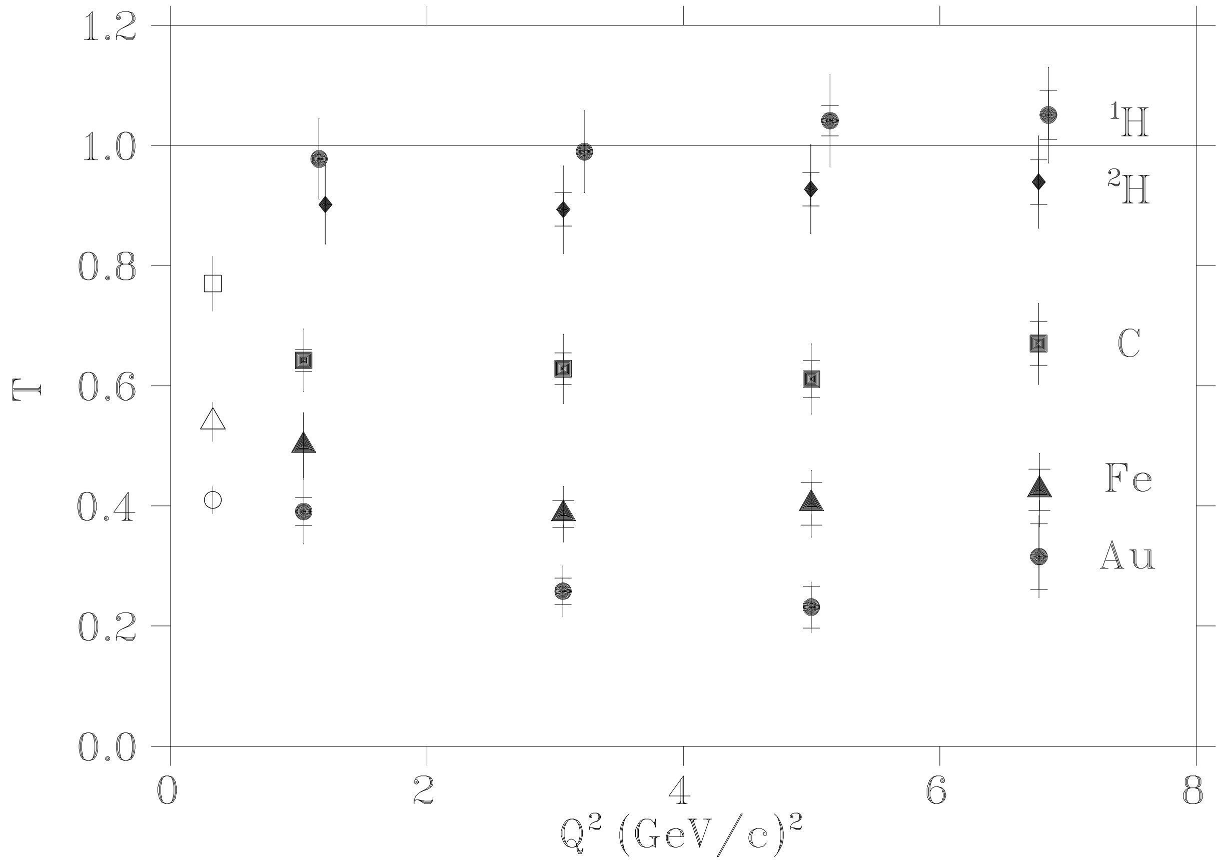




- In PWIA $d^6\sigma/dE'_e d\Omega'_e d^3p' = \sigma_{ep} S(E_m, \vec{p_i})$
- E'_e and Ω'_e are energy and solid angle outgoing electron
- p' is momentum of outgoing proton
- $S(E_m, \vec{p_i})$ is spectral function (probability of finding a proton with initial momentum $\vec{p_i}$ and separation energy E_m)
- σ_{ep} is the off-shell ep elastic cross section
- Transparency $T \equiv \sigma_{\mathrm{measured}}/\sigma_{\mathrm{PWIA}}$

SLAC $A(e, e'p)$

- SLAC ESA
- T.G. O'Neill *et al.*, PLB **351** (95) 87
- No sign of a rise in T with Q^2 as many expected

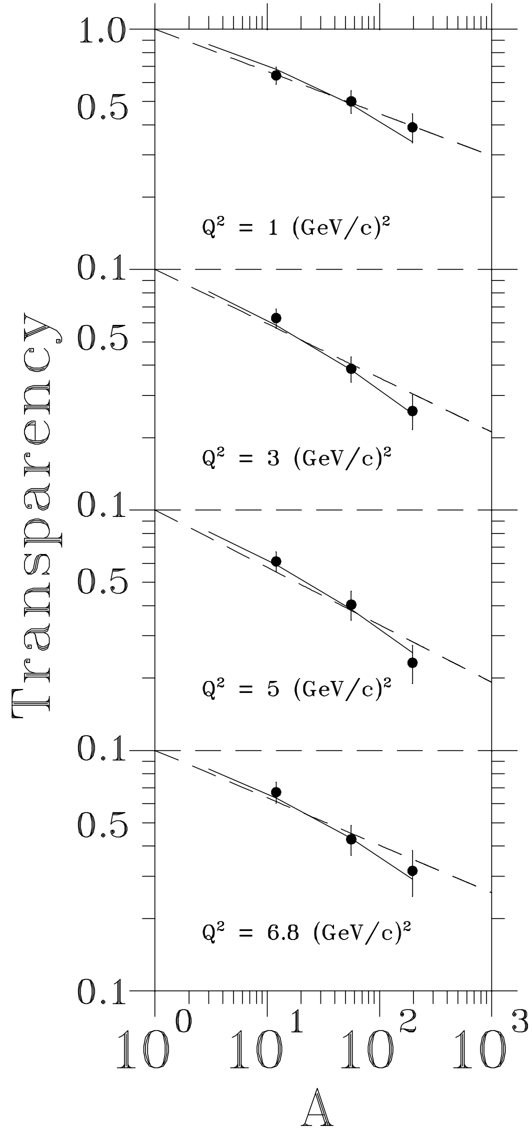


SLAC $A(e,e'p)$

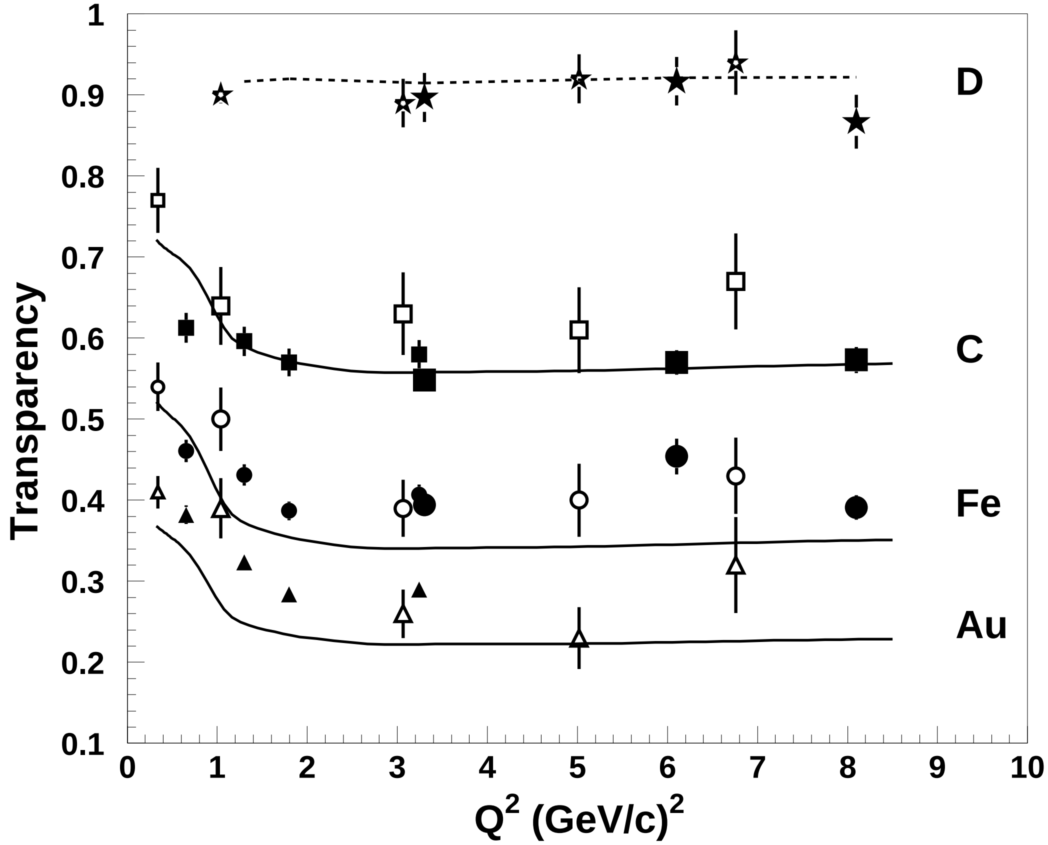
- O'Neill, *ibid.*
- Solid: classical attenuation model (Glauber)
- Dashed: A^α fit

$Q^2 = 1$ GeV^2: $\alpha = -0.18 \pm 0.02$
$Q^2 = 3$ GeV^2: $\alpha = -0.24 \pm 0.02$
$Q^2 = 5$ GeV^2: $\alpha = -0.24 \pm 0.02$
$Q^2 = 6.8$ GeV^2: $\alpha = -0.20 \pm 0.02$

- No increase in α with Q^2 (no CT)



- K. Garrow *et al.* PRC **66** (02) 044613; large solid
- D. Abbott *et al.* PRL **80** (98) 5072; small solid
- O'Neill (SLAC); large open
- G. Garino *et al.* PRC **45** (92) 780 (BATES); small open

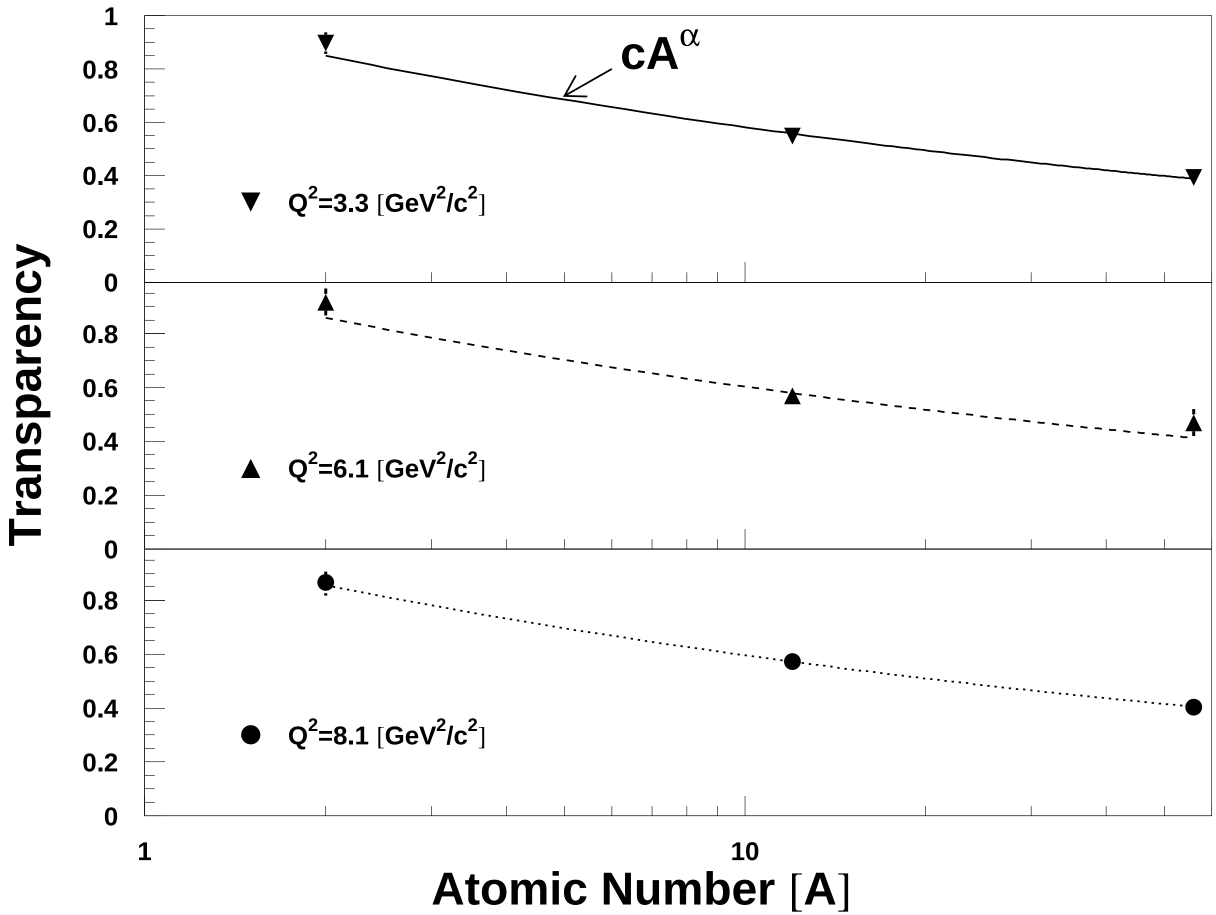


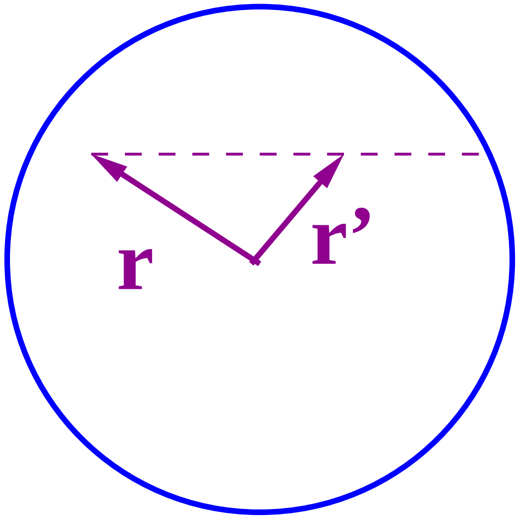
- Garrow, *ibid.*
- Fits to A^α:

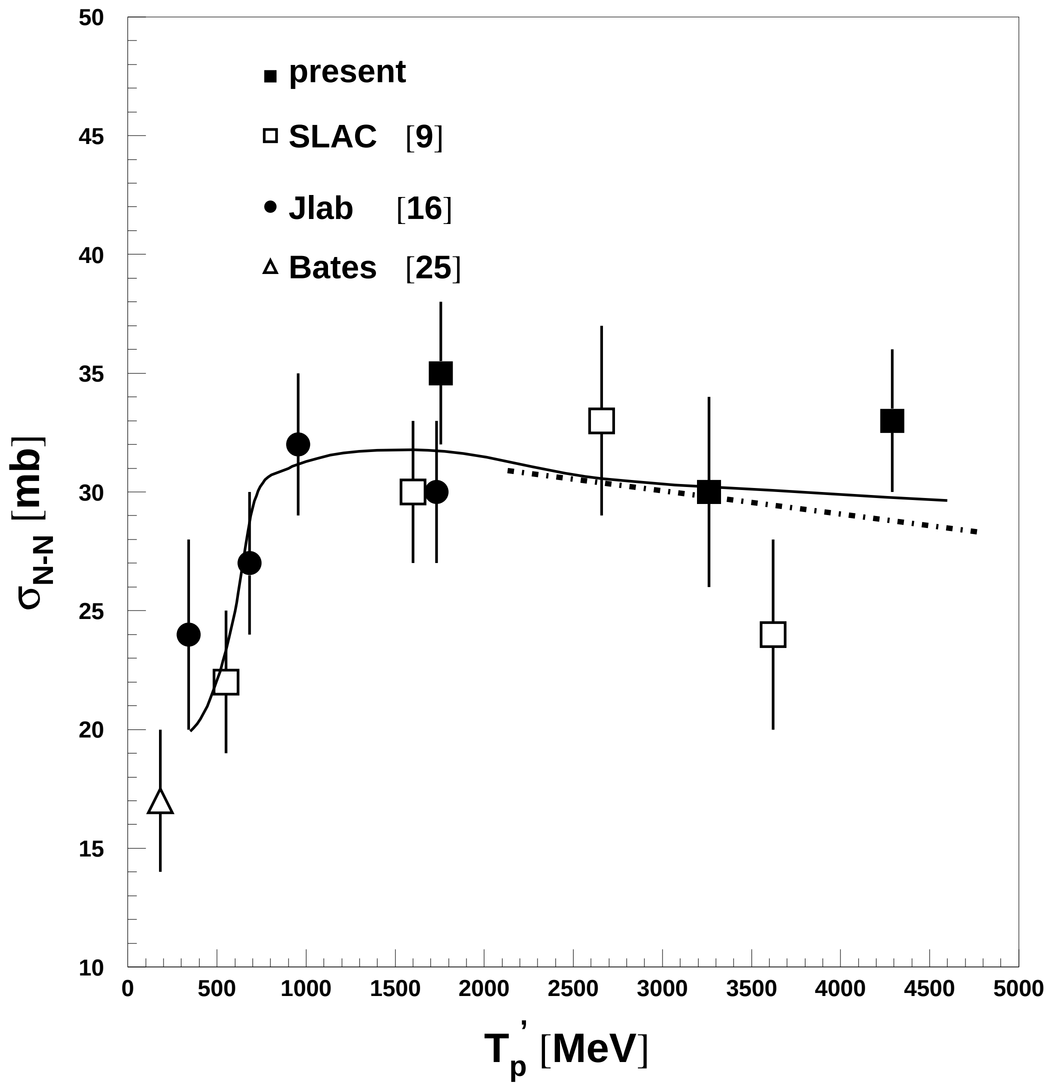
$Q^2 = 3.3$ GeV: $\alpha = -0.24 \pm 0.02$

$Q^2 = 6.1$ GeV: $\alpha = -0.24 \pm 0.03$

$Q^2 = 8.1$ GeV: $\alpha = -0.23 \pm 0.03$







- Garrow, *ibid.*
- $T = \frac{1}{Z} \int d^3 r \rho_Z(\vec{r}) \times$

$\exp\left[- \int dz' \sigma_{\text{eff}} \rho_{A-1}(\vec{r}')\right]$

- Just what you'd expect: 30 mb

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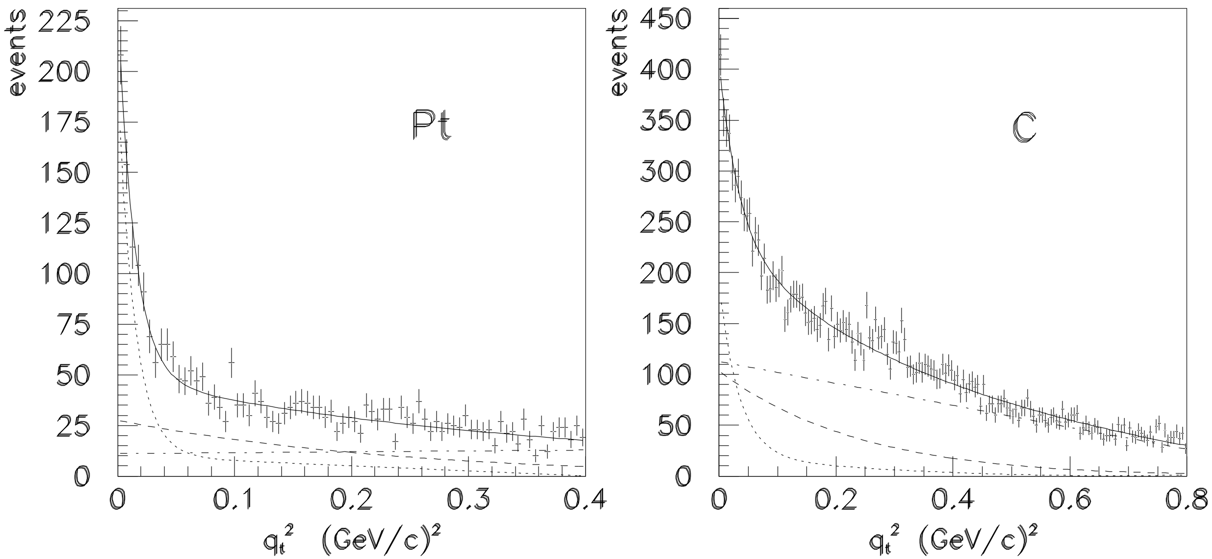
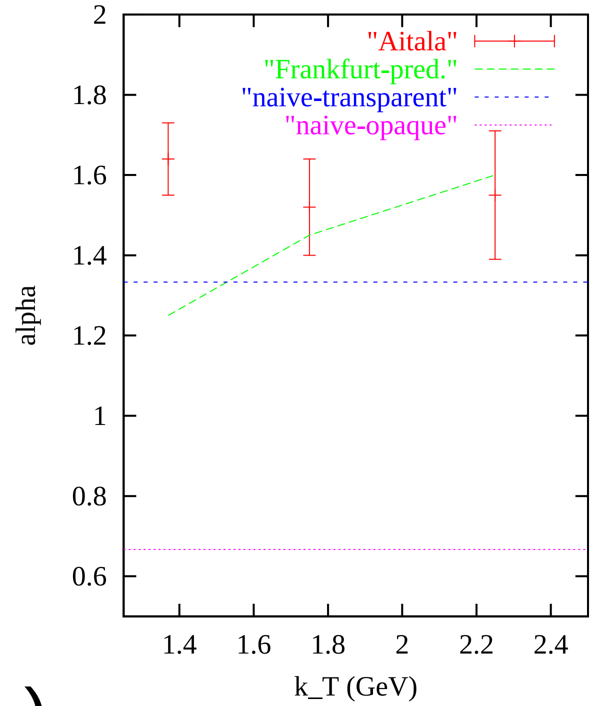
Diffraction



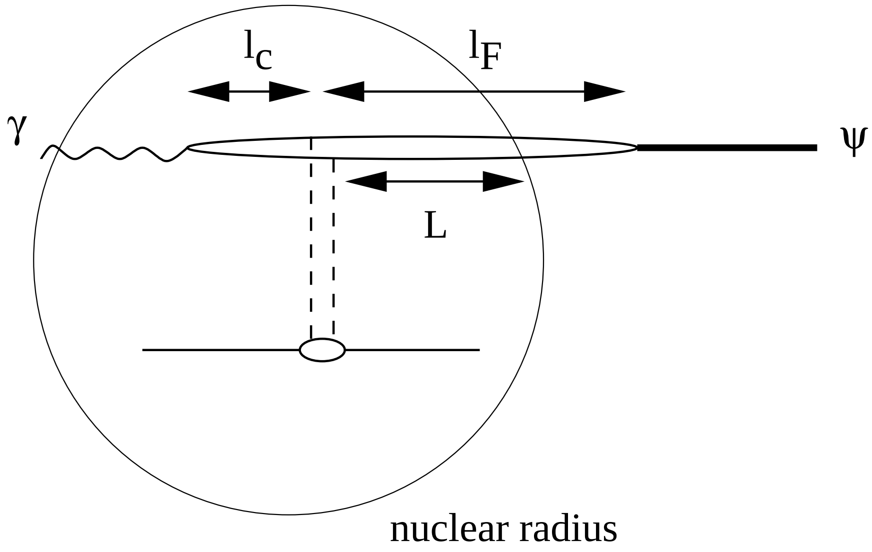


- E.M. Aitala *et al.* PRL 86 (01) 4773.
- $\pi A \to 2$ jets (diffractive dissociation of π)
- $\sigma = \sigma_0 A^{\alpha}$; coherent amplitude $\propto A$
- Integral of elastic scattering form factor

$\int \exp(-\beta R_0^2 t)dt \propto A^{-2/3}$ since $R_0 \propto A^{1/3}$; $\sigma \propto |A|^2 A^{-2/3}$

- Transparency ($A^{4/3}$) is different from normal hadronic interactions that see only the nuclear surface ($A^{2/3}$).

Lengths



$\ell_C = \frac{2\nu}{Q^2+m_{q\bar{q}}^2}$

$\ell_F = \frac{2\nu}{m_{V'}^2-m_V^2}$

L: length of absorption trajectory

$\frac{\sigma_A^V}{A\sigma_N^V} = e^{-L\rho_0\sigma_{\rm tot}^{VN}}$

ρ_0: nuclear density

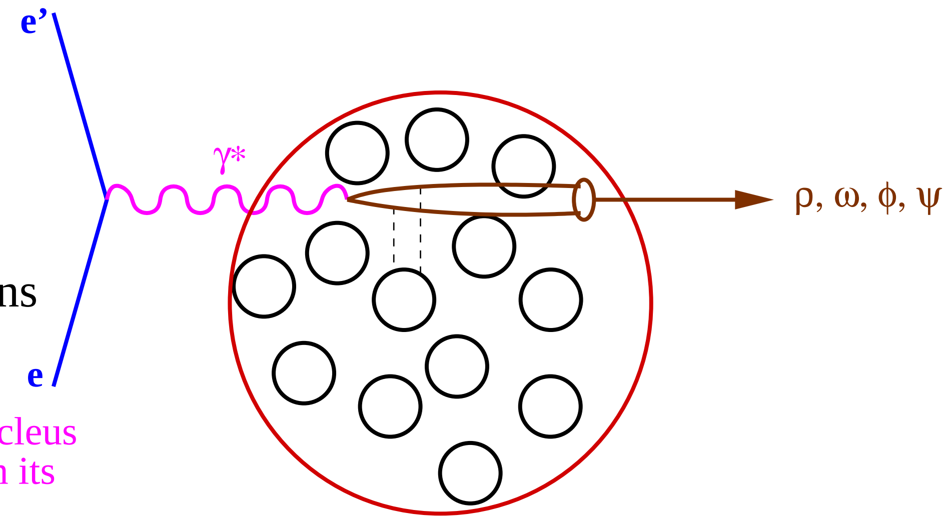
$\sigma_{\rm tot}^{VN}$: V-N cross section

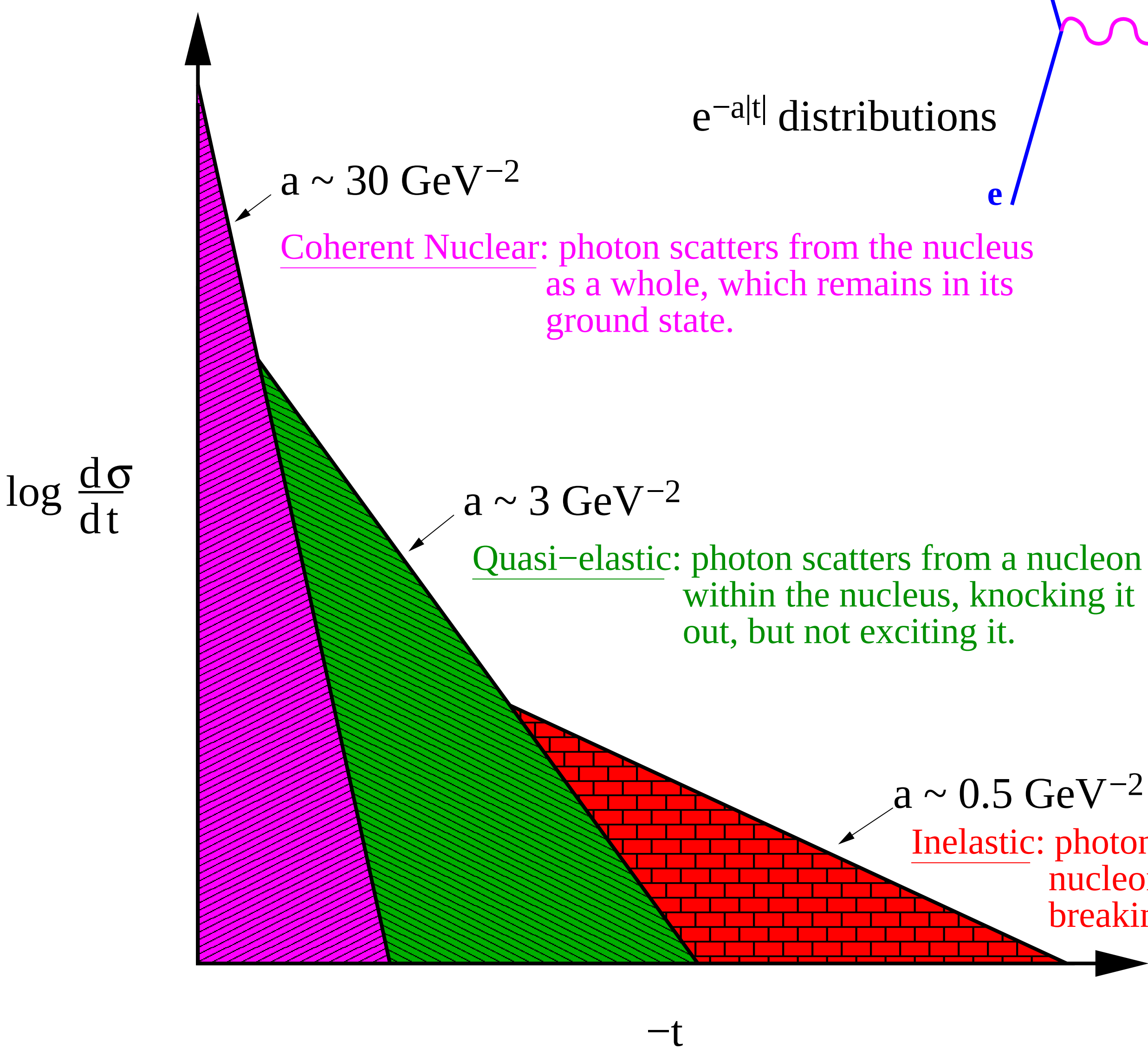
Uncertainty Principle Argument:

$\Delta E = m_{V'} - m_V$; mass = $(m_{V'} + m_V)/2$

$\gamma = \nu/\text{mass}$; $\ell_F = \gamma/\Delta E$

Vector Mesons

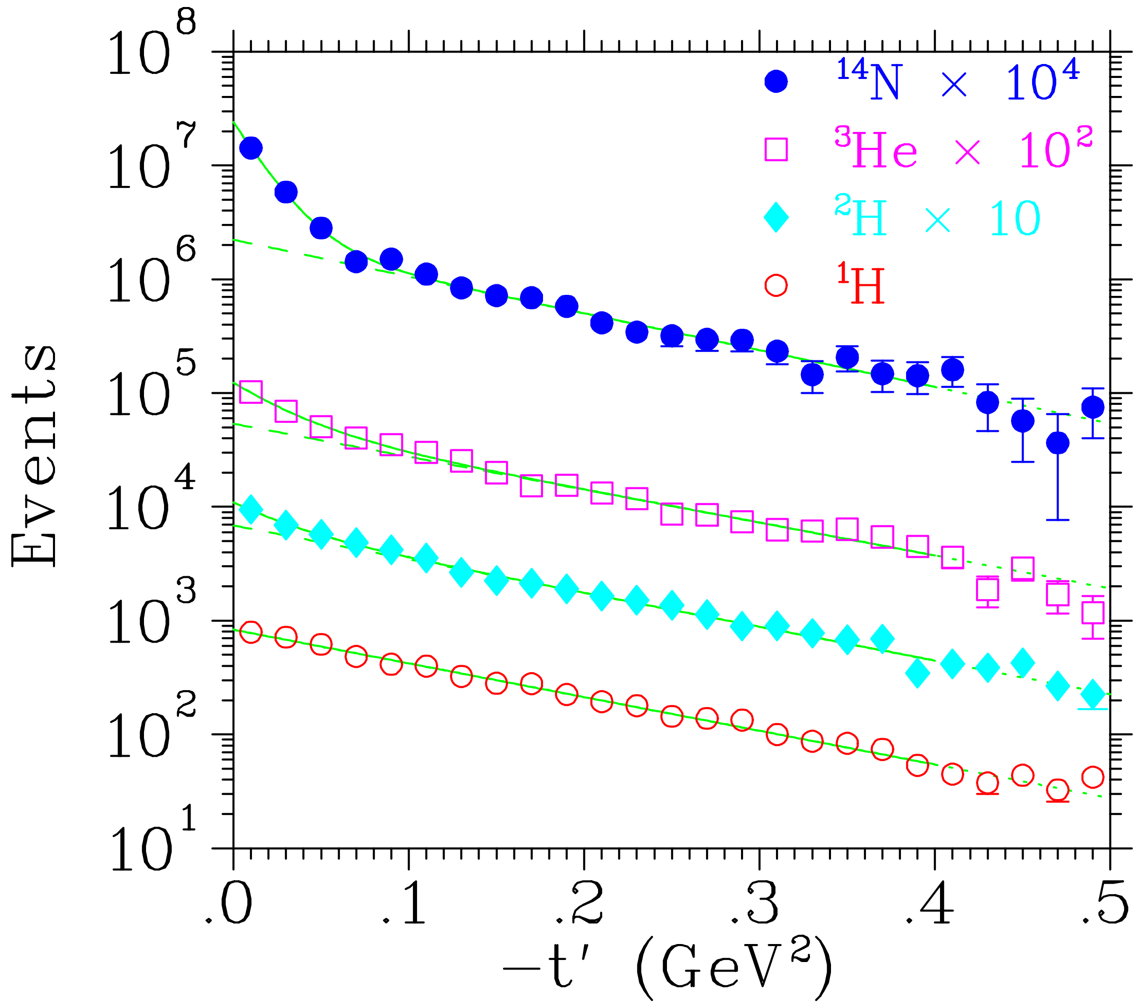




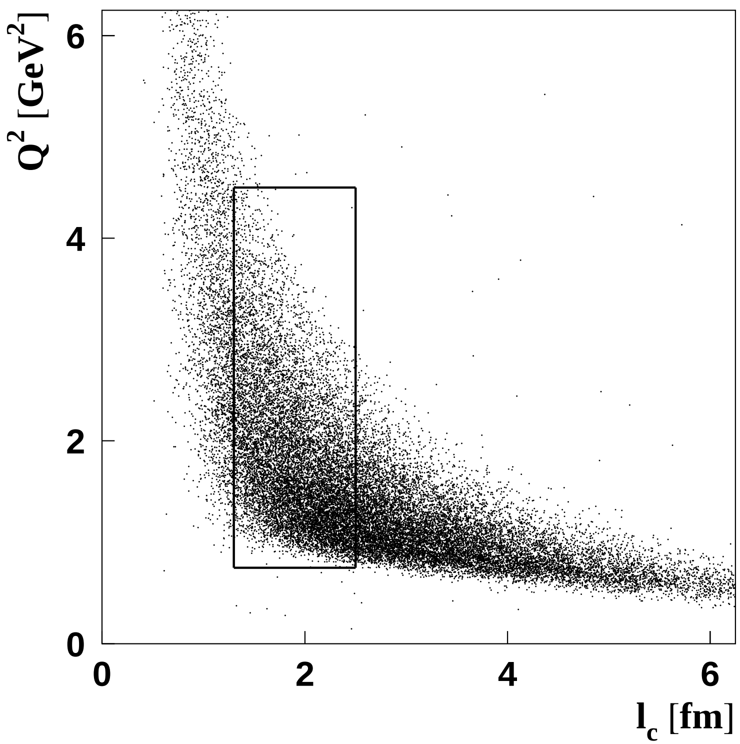
t: squared momentum transfer

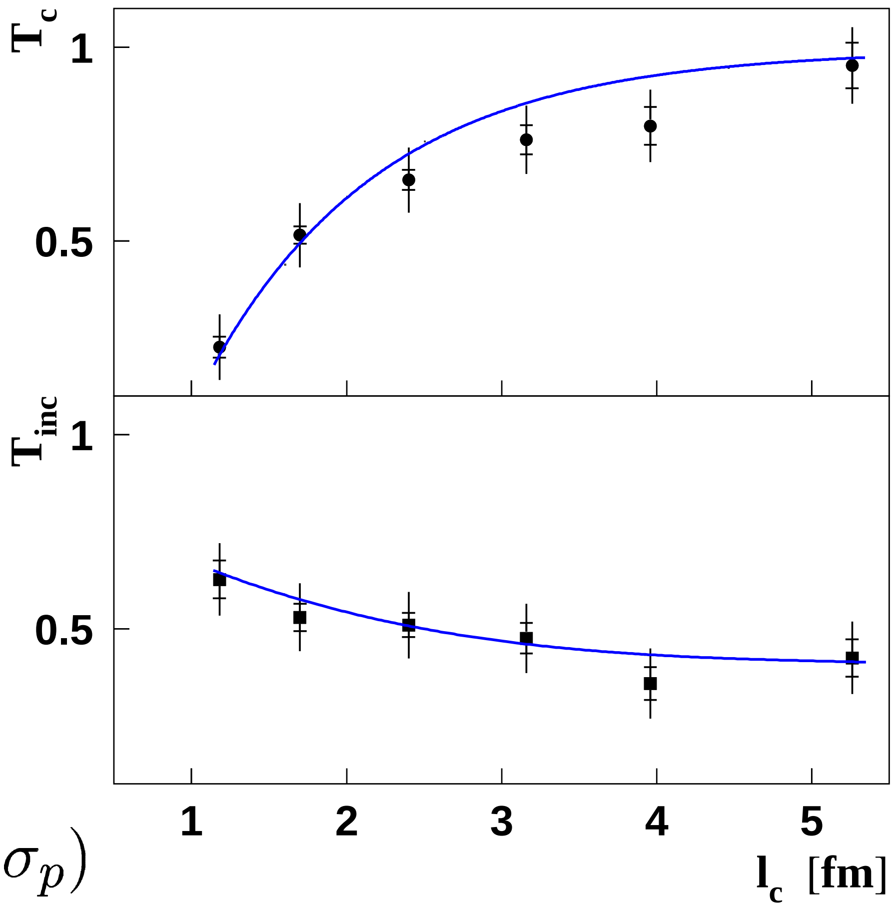
$p_T^2 \approx -t$

- K. Akerstaff *et al.* PRL **82** (99) 3025; A. Airapetian *et al.* PRL **90** (03) 052501
- $eA \rightarrow e'\rho_0 A'$ coherent and incoherent production



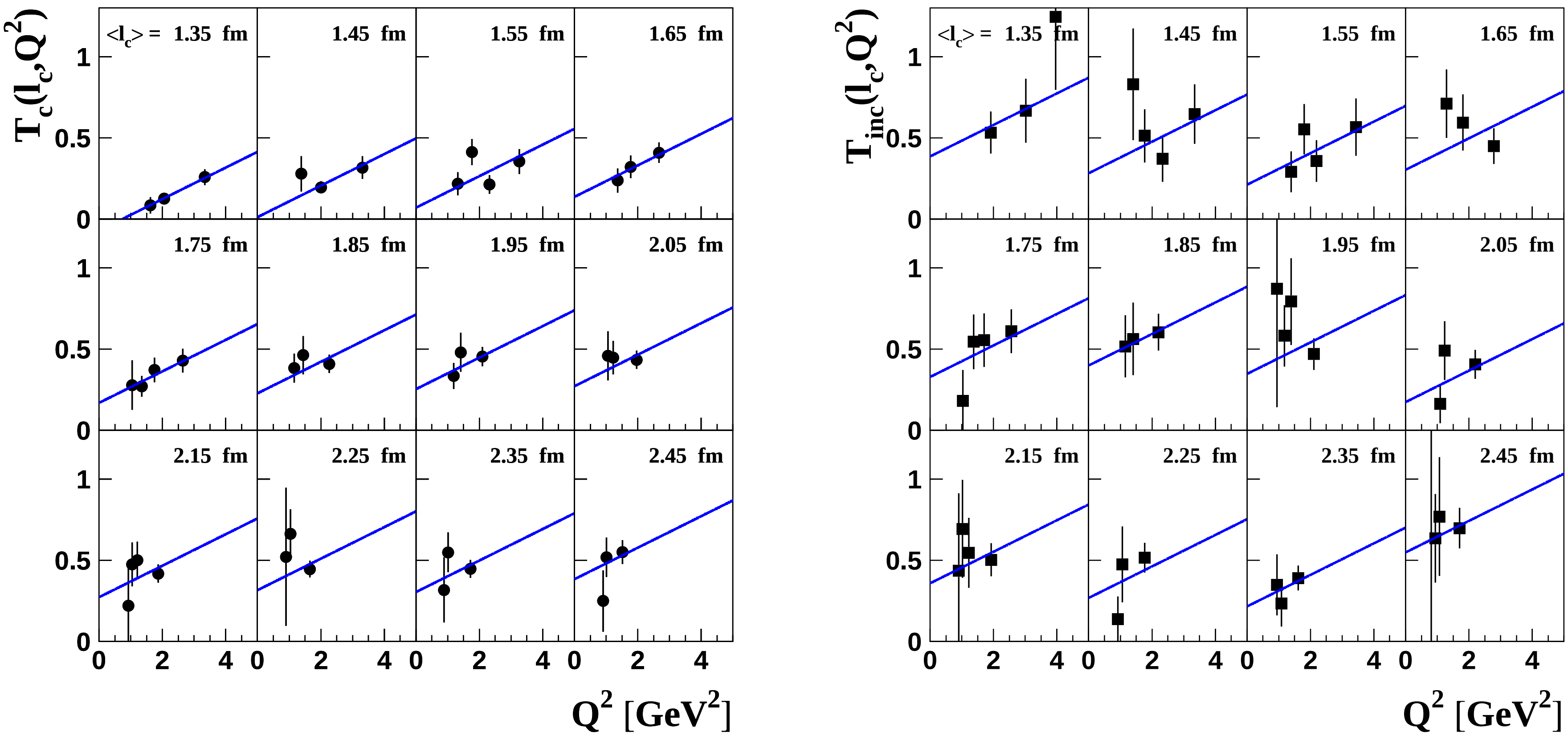
HERMES ρ_0





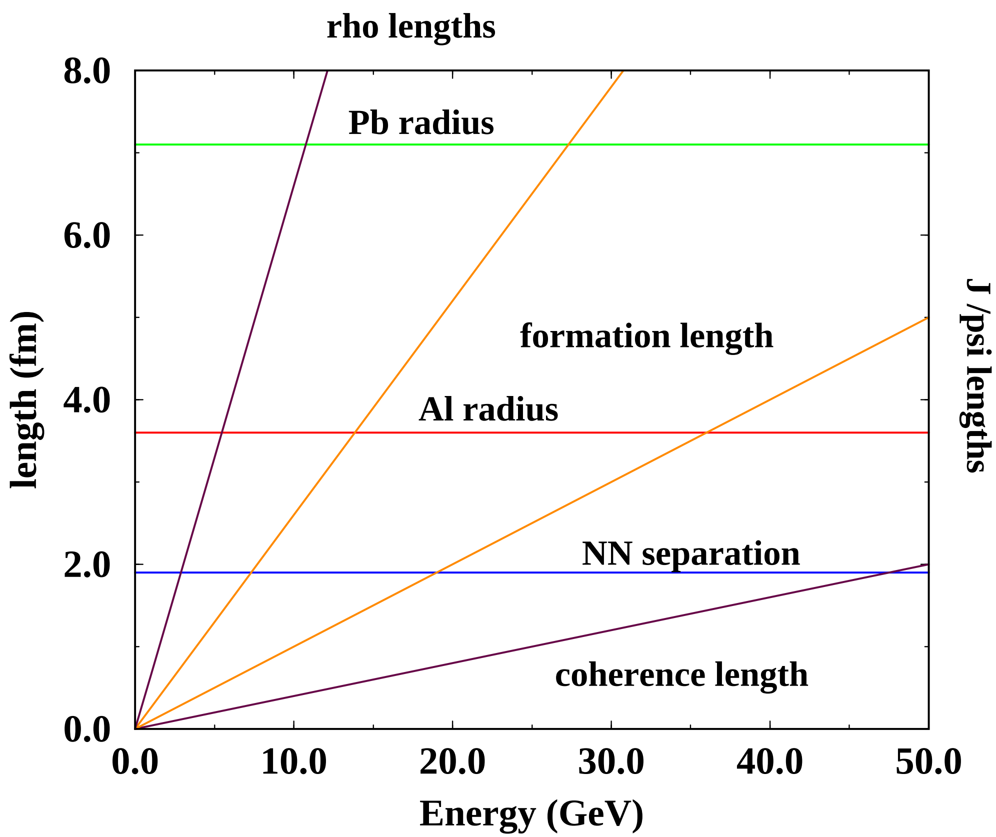
- $T_c = \sigma_c^A/(A\sigma_p)$; $T_{\rm inc} = \sigma_{\rm inc}^A/(A\sigma_p)$
- $\ell_c = 2\nu/(Q^2 + M^2_{\bar{q}q})$; $\ell_F = 2\nu/(M^2_{V'} - M^2_V)$
- Box shows region of ‘constant’ ℓ_c for analysis

HERMES ρ_0

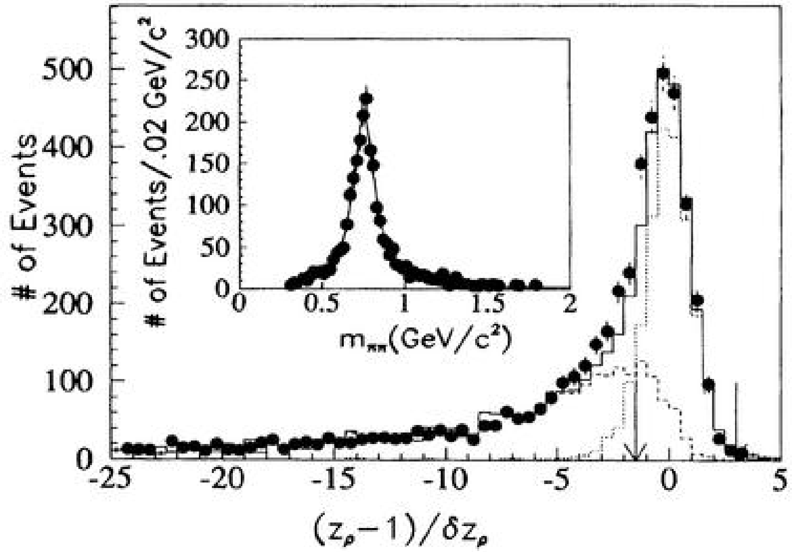


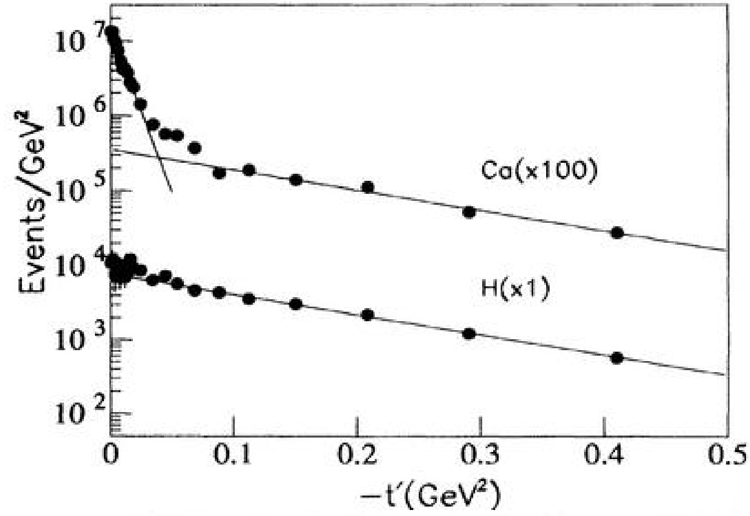
- coherent slope: $0.070 \pm 0.021 \pm 0.017$; CT model: 0.060
- incoherent slope: $0.089 \pm 0.046 \pm 0.020$; CT model: 0.048
- CT model: Kopeliovich *et al.* PRC **65** (02) 035201

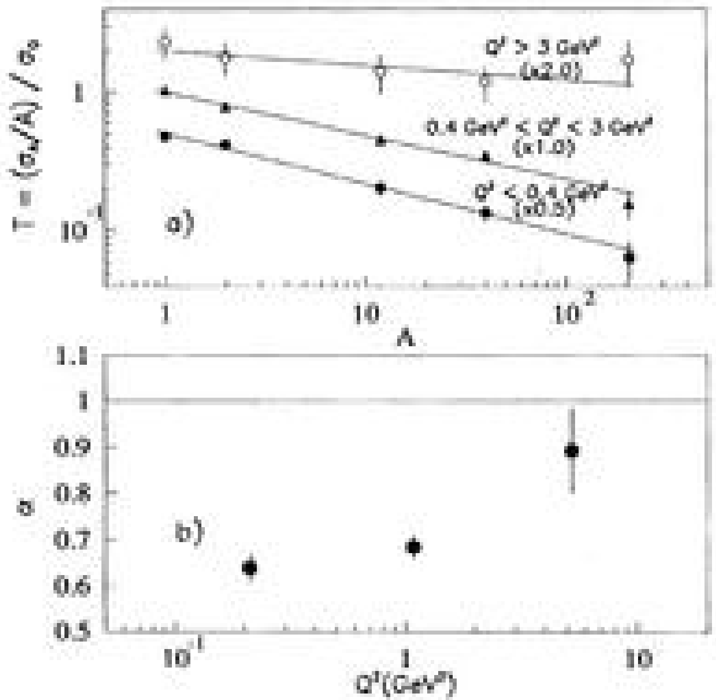
- $\gamma A \to J/\psi A'$ at FNAL at 120 GeV
- Sokoloff *et al.* PRL **57** (86) 3003
- Coherent production depends on A^α with $\alpha = 1.40 \pm 0.06 \pm 0.04$, which is consistent with $\alpha = 4/3$ (CT)
- Photoproduction: ρ_0: $\ell_c = 0.66\nu > \ell_F = 0.26\nu$; J/ψ: $\ell_c = 0.04\nu < \ell_F = 0.10\nu$



FNAL E665 ρ_0

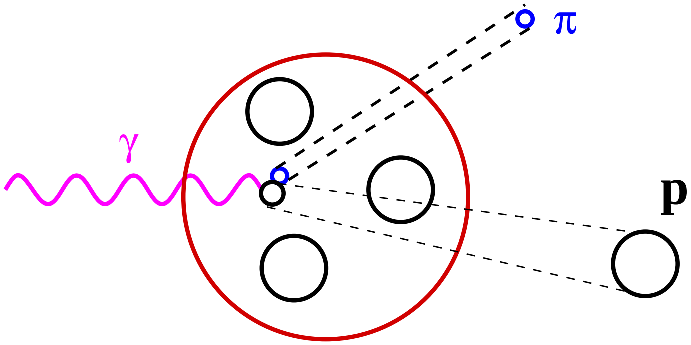






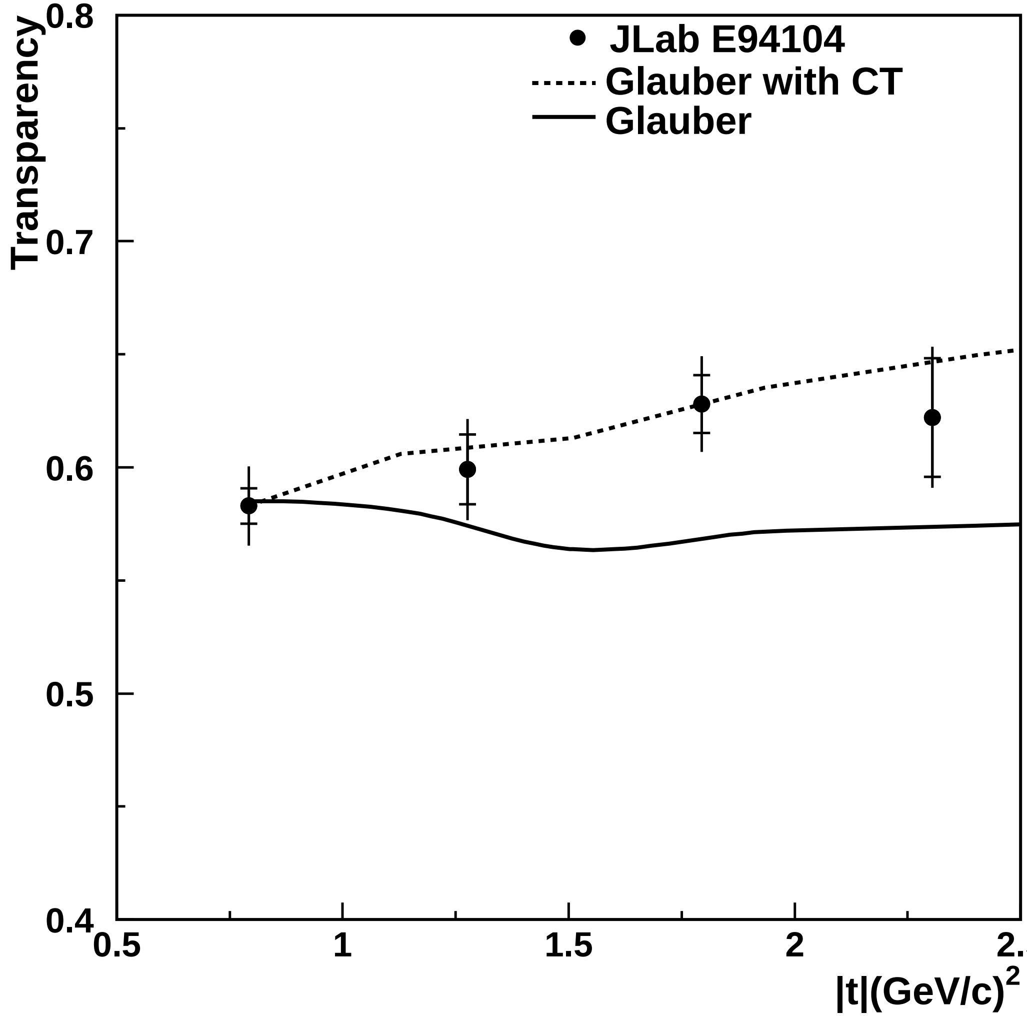
- M.R. Adams *et al.* PRL **74** (95) 1525
- 470 GeV μ exclusive incoherent ρ_0 production
- $\alpha = 2/3$ at low Q^2 (opaque) and rises toward $\alpha = 1$ at $Q^2 = 6$ GeV^2
- Hint of transparency with poor statistics

JLab E94104

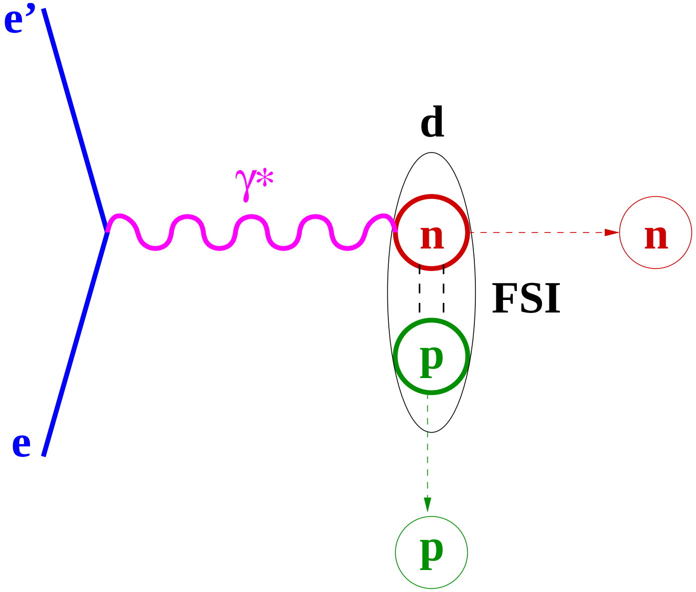


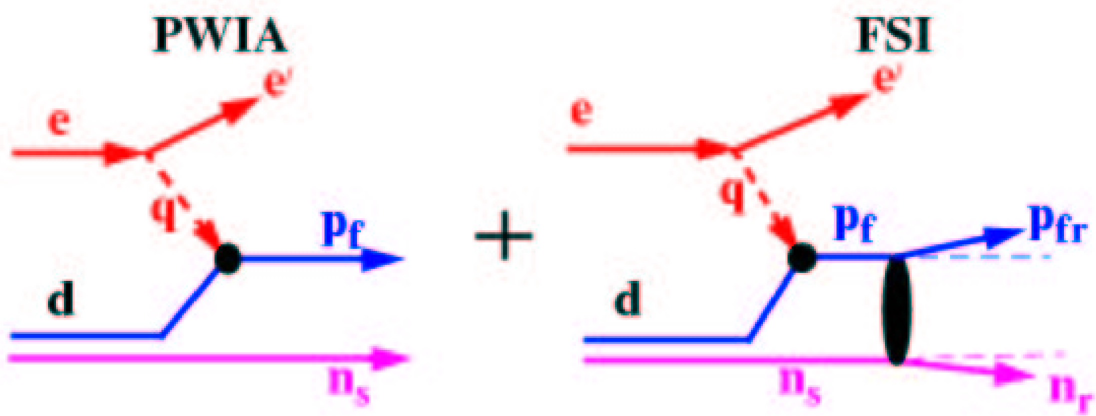
- Hall A, JLab
- PRC **68**(2003)021001
- $\gamma n \to \pi^- p$ in ^{4}He
- E_e = 1.6–4.5 GeV
- 6% Cu radiator
- Measure p and π^-
- CT increases with t

$$T(^4\mathrm{He}) = \frac{\frac{N_{\mathrm{data}}(^4\mathrm{He})}{N_{\mathrm{MC}}(^4\mathrm{He})}}{\frac{N_{\mathrm{data}}(^2\mathrm{H})}{N_{\mathrm{MC}}(^2\mathrm{H})}} T(^2\mathrm{H})$$



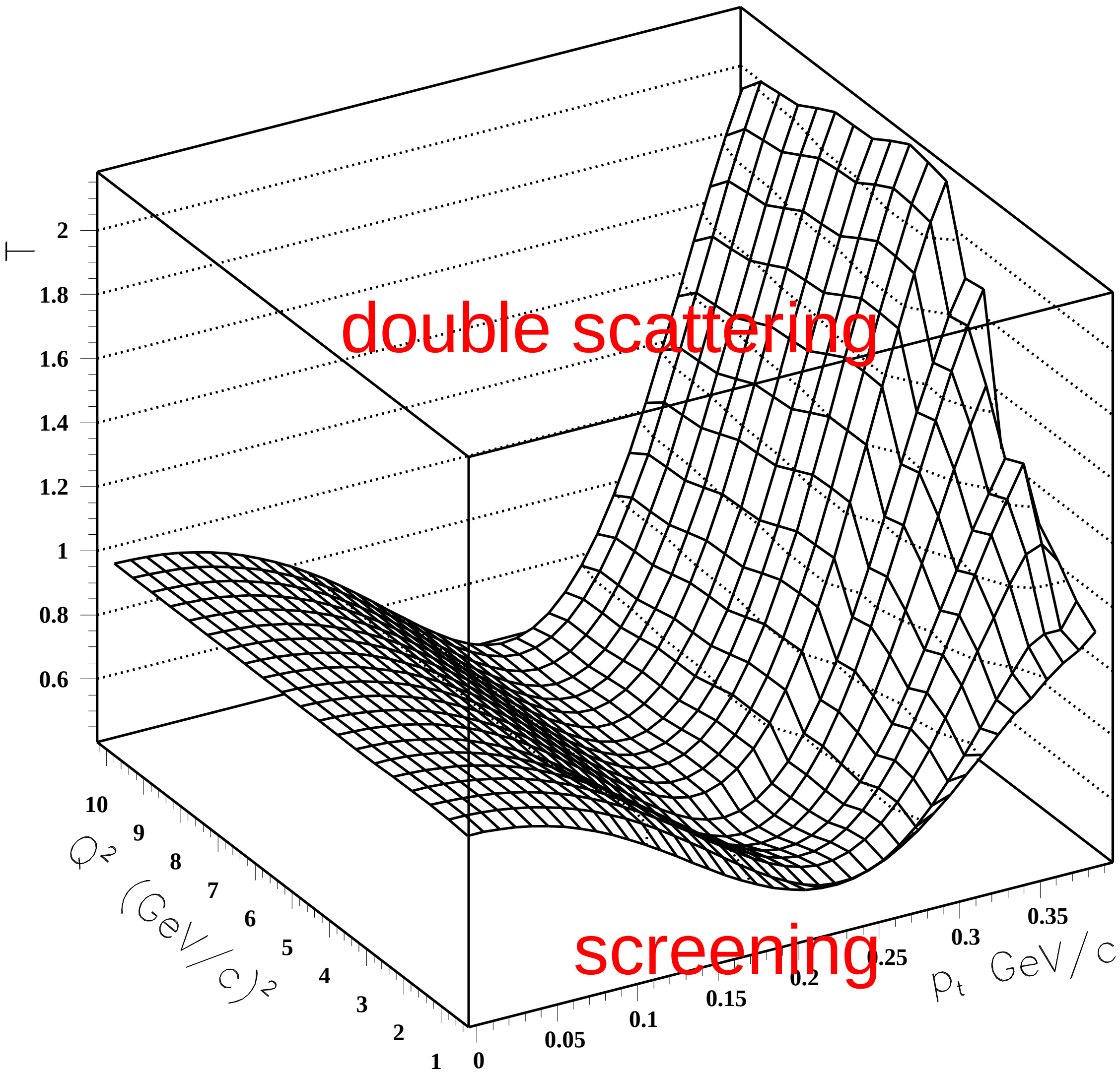
$D(e, e'p_s)$



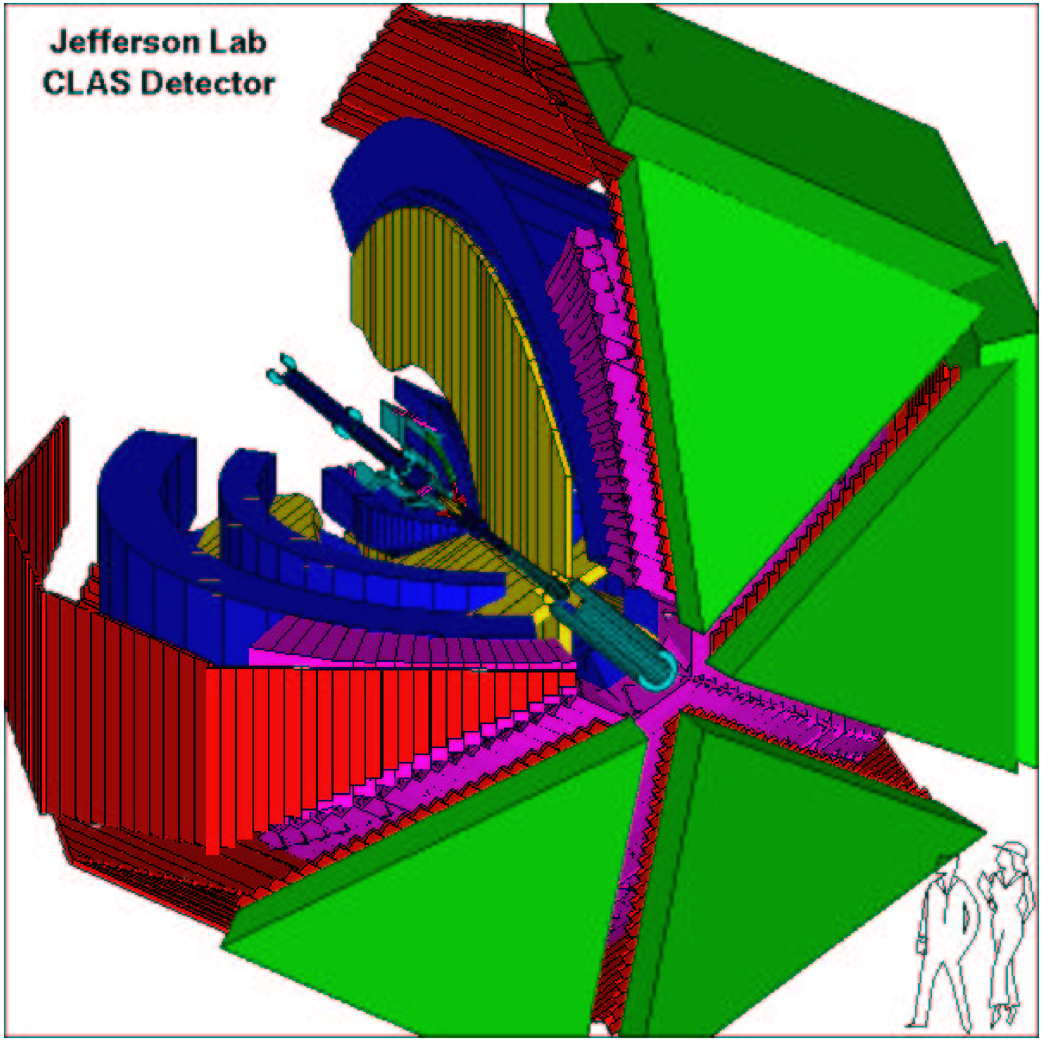


- If PLC expands to normal size within the internucleon spacing, then the *smallest* nucleus is the best
- $\sigma = |PWIA + FSI|^2 = |PWIA|^2 + 2\Re(PWIA^* FSI) + |FSI|^2$
- $|FSI|^2$ is called *double scattering*; $2\Re(PWIA^* FSI)$ is called *screening* because it is negative
- Either deduce recoil neutron momentum from struck proton, or measure recoil proton momentum directly

- Frankfurt, Strikman, Sargsian
- Contours of $T \equiv \frac{|PWIA+FSI|^2}{|PWIA|^2}$
- p_t: transverse recoil momentum of spectator



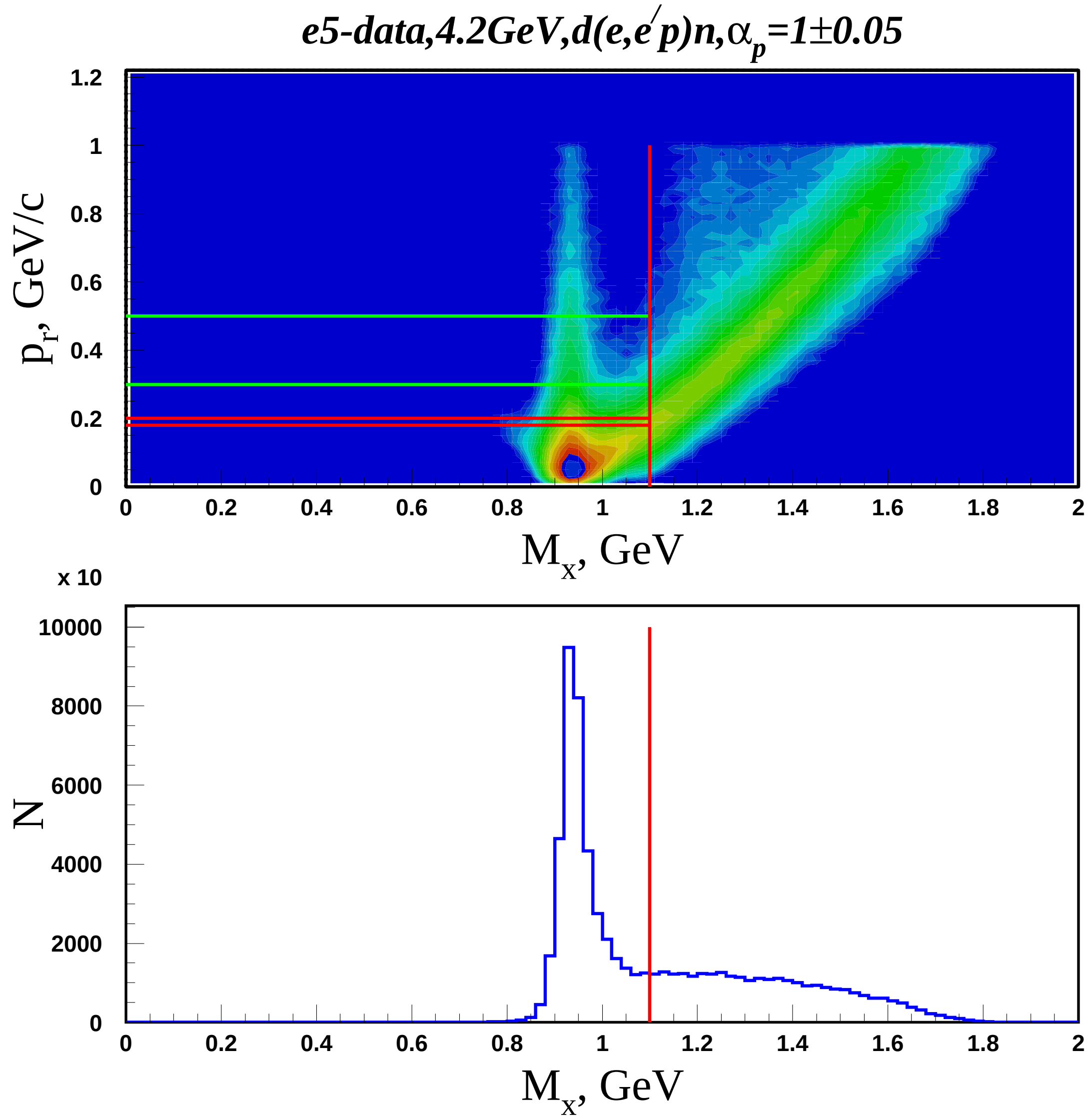
CLAS spectrometer



$E_e =$ 5.8, 4.2, 2.6 GeV
LD target
Luminosity: 10^{34}/cm^{2}s
green: EM calorimeter
magenta: Cherenkov
red: TOF scintillators
blue: drift chambers
yellow: SC magnet

JLab $D(e, e'p_f)n_s$

- Need to select quasi-elastic events
- Cuts on missing mass and two regions of recoil momenta



JLab $D(e, e'p_f)n_s$

- Light-cone fraction of momentum carried by spectator:

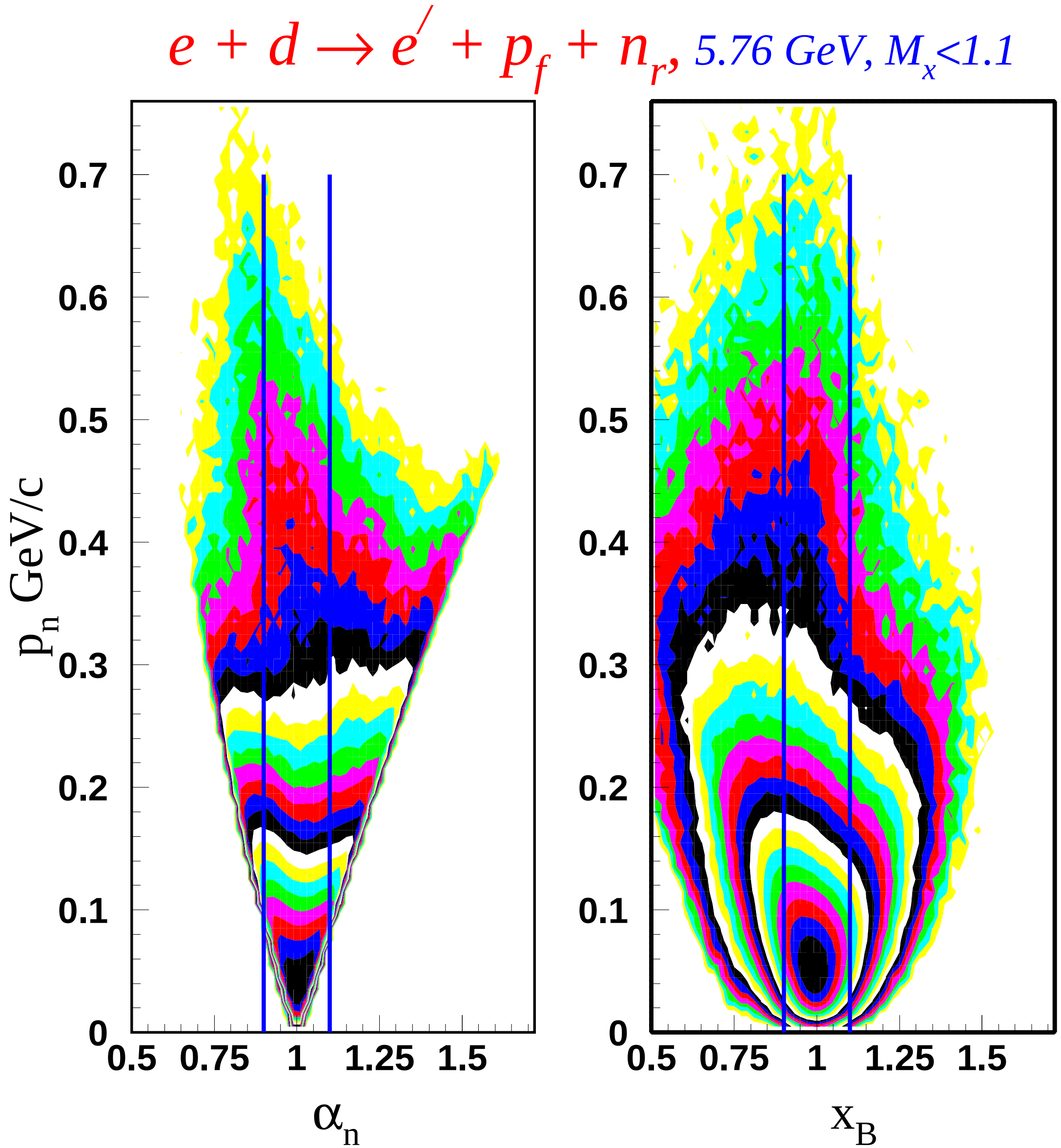
$\alpha = (E_n - p_n \cos\theta_{\gamma n})/M$

- Cut on α and $x_{Bj} = Q^2/2M\nu$ near 1
- Spectator model:

$E_n = \sqrt{M^2 + p_n^2}$

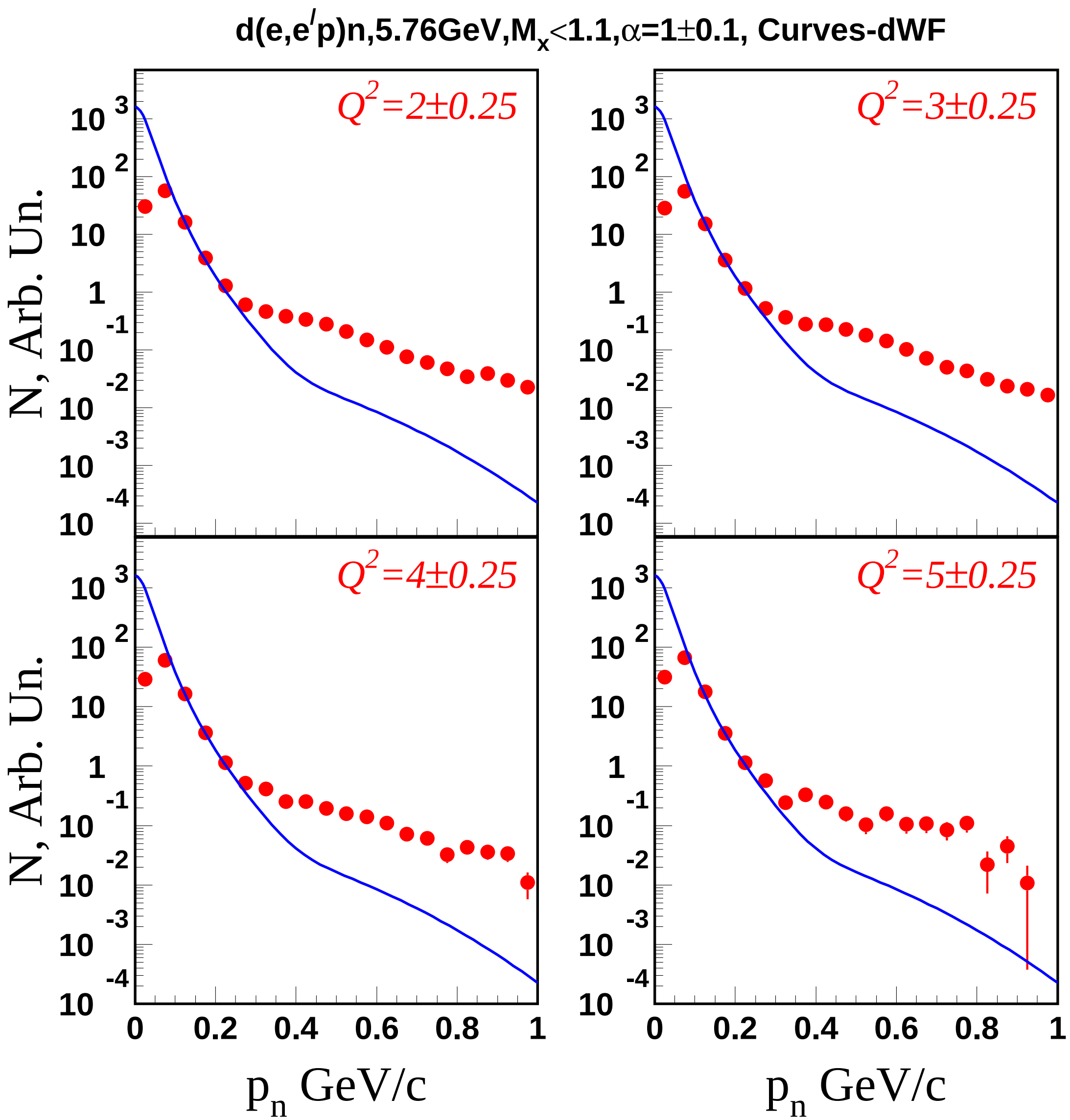
$E_p = \sqrt{M^{*2} + p_n^2}$

$E_n + E_p = 2M$



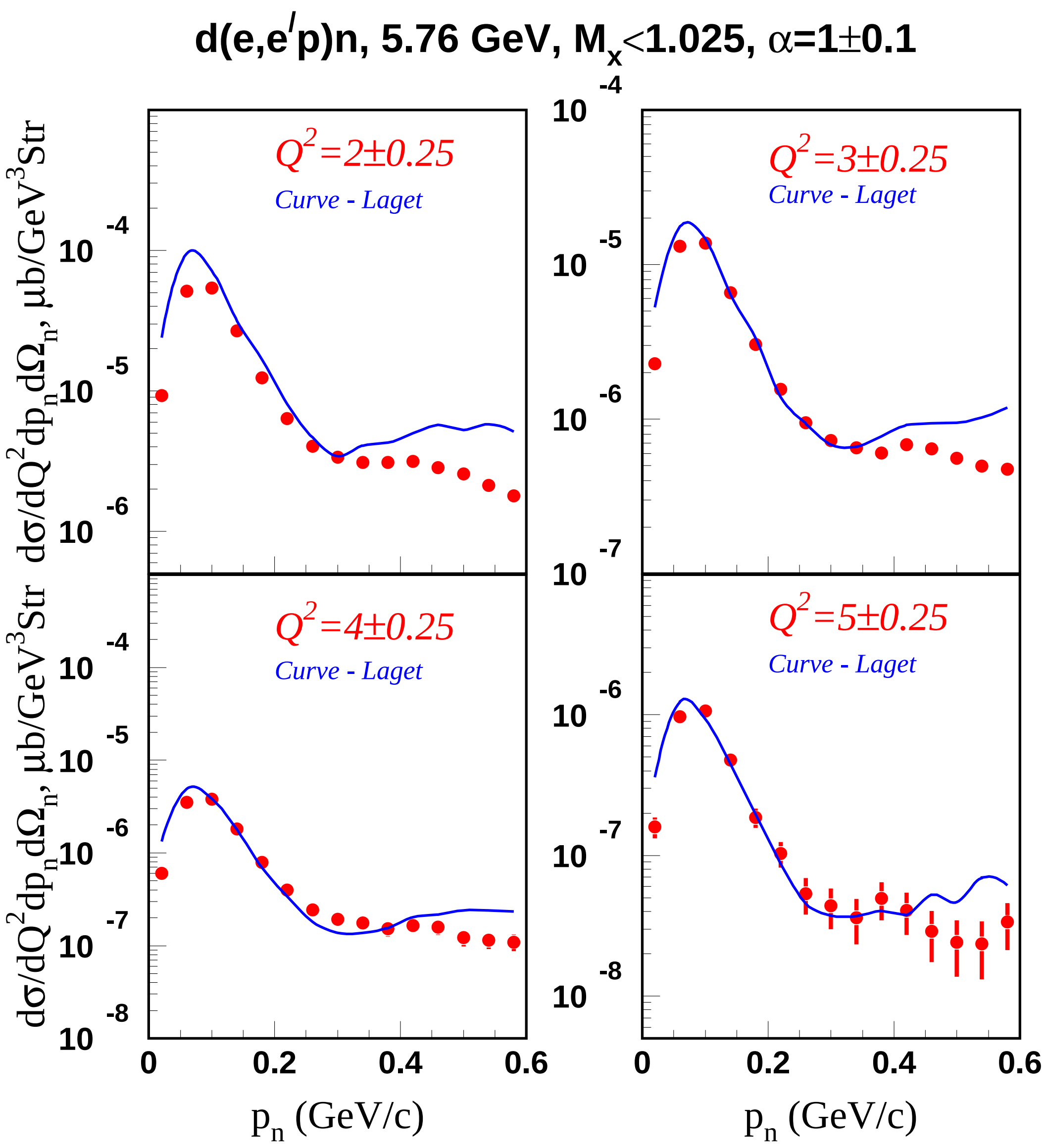
JLab $D(e, e'p_f)n_s$

- In pure spectator model p_n momentum distribution follows deuteron wave function
- In reality, clear deviation above 300 MeV/c



JLab $D(e,e'p_f)n_s$

- Realistic models of p_n momentum distribution include FSIs
- These models overpredict cross sections above 300 MeV/c

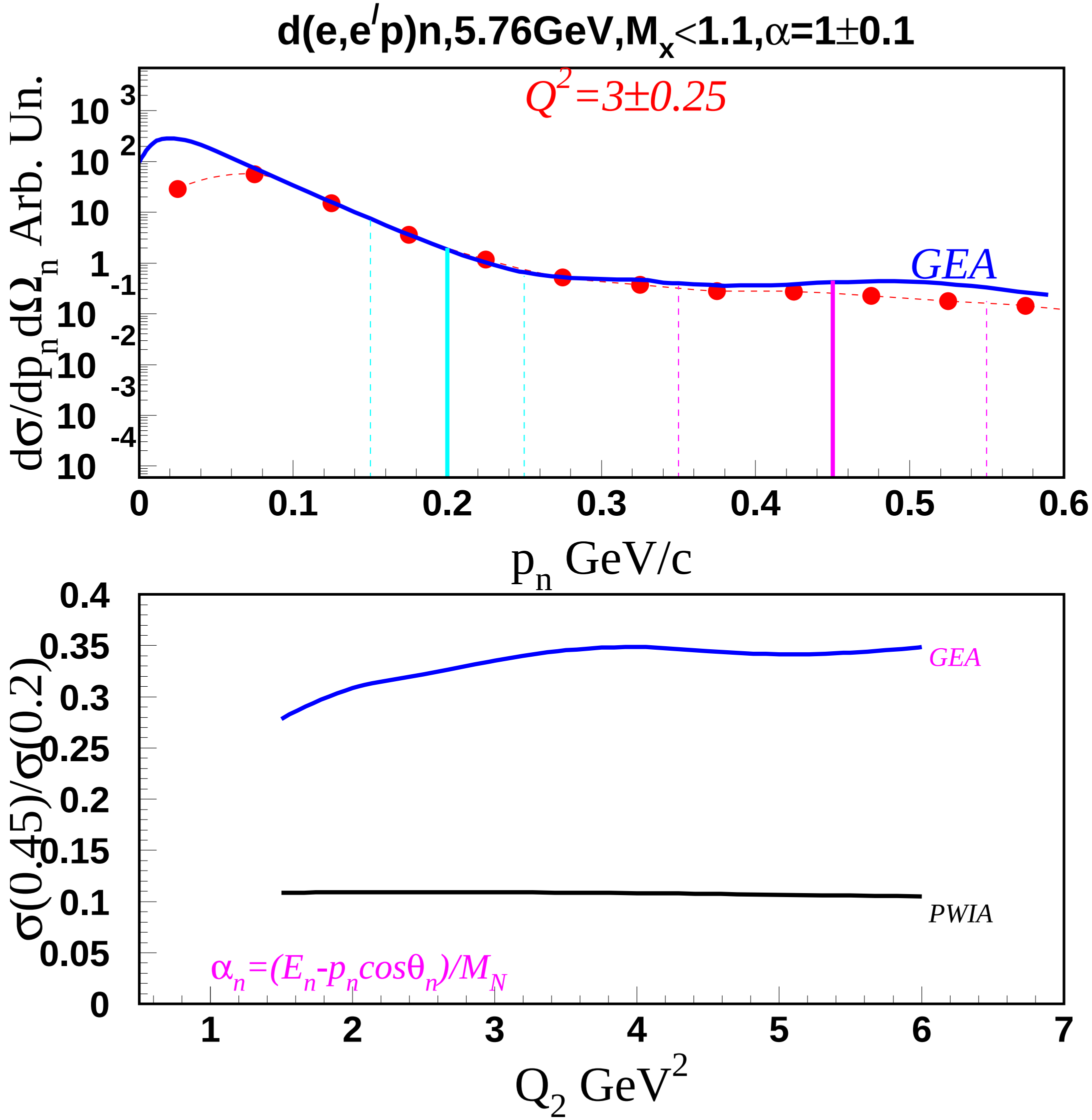


- Upper: p_n distribution with event selection regions

$p_n \sim 0.2$ GeV/c (screening)

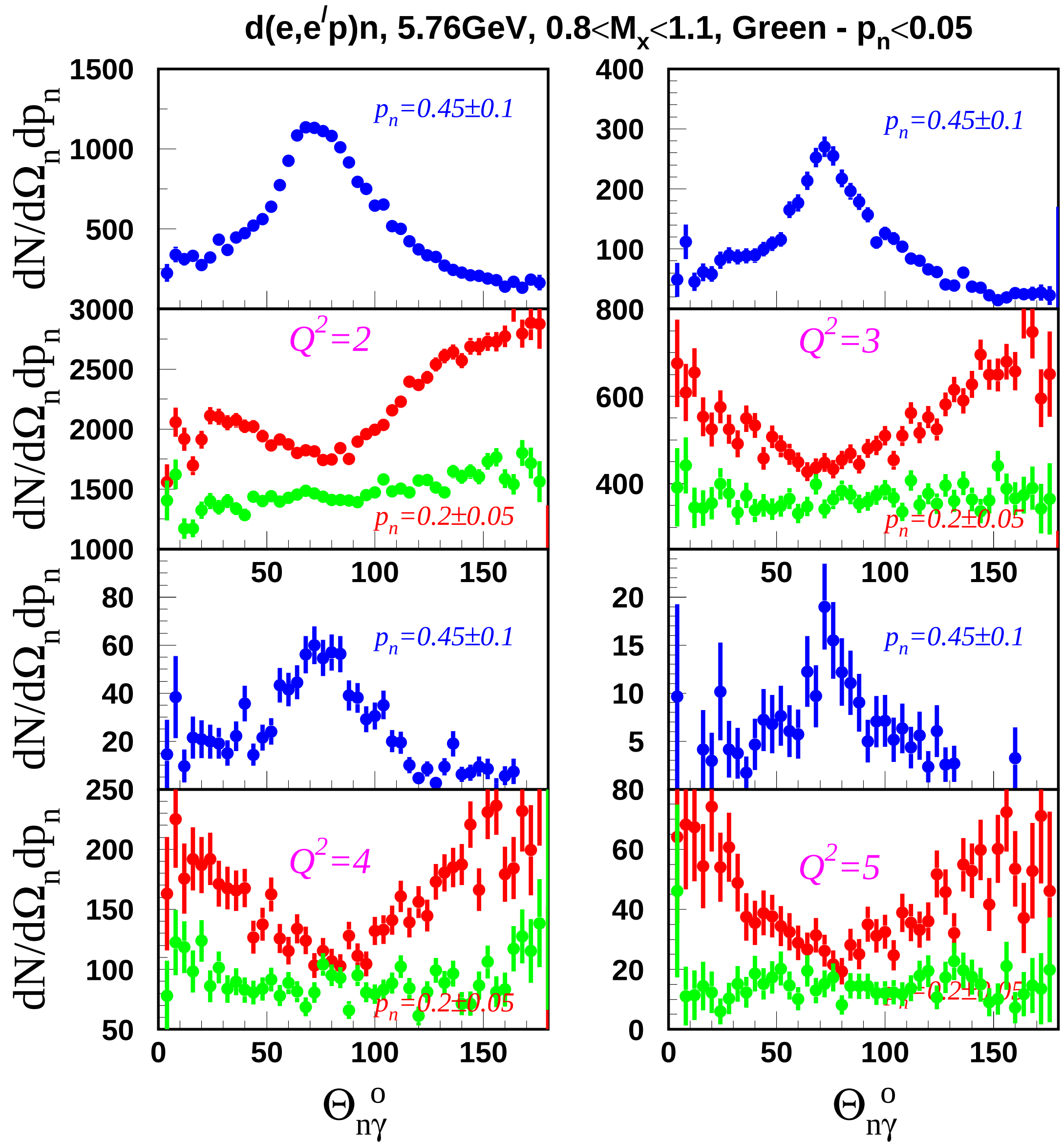
$p_n \sim 0.45$ GeV/c (double scattering)

- Lower: enormous difference in ratio with and w/o FSIs

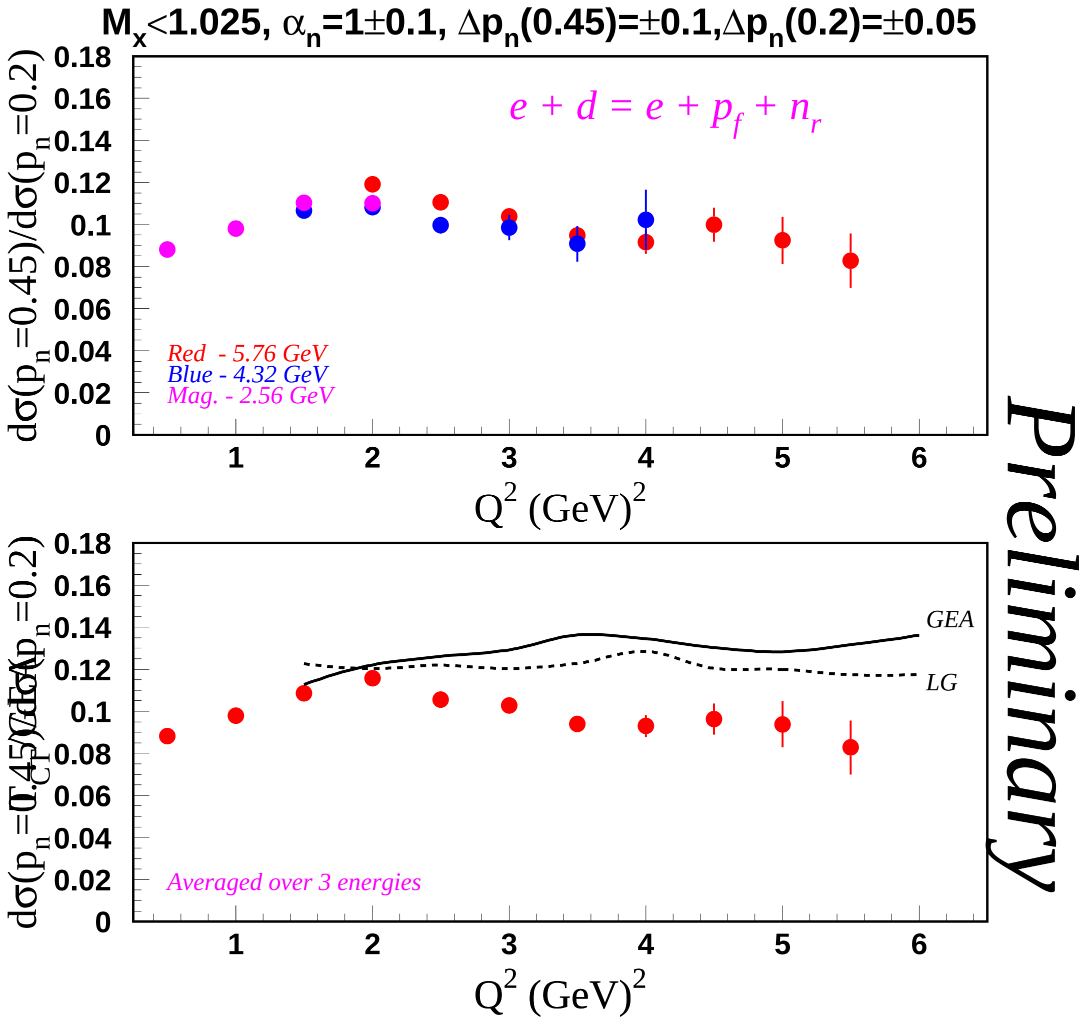


JLab $D(e,e'p_f)n_s$

- blue: 0.45 GeV/c
- red: 0.2 GeV/c
- green: <0.05 GeV/c
- red enhancement due to FSIs
- blue depletion due to FSIs
- green uninfluenced by FSIs



- Top: 3 data sets compared
- Bottom: average ratio $\frac{d\sigma(p_n=0.45)}{d\sigma(p_n=0.2)}$ with calculations of expectations with FSIs
- Depletion in ratio is clear evidence for CT



Conclusions

- QCD is remarkably rich in phenomena.
- A first generation of experiments has established the rough outlines of color transparency (formation length effects) and color coherence (coherence length effects) for both mesons and baryons.
- These experiments provide the first glimpse of the space-time evolution of hadronic wave functions.
- Data and theoretical models agree in broad strokes.
- The next generation of precision measurements and rigorous calculations is yet to come.
- Like for PDFs, many different experiments are required.