Nuclear Transparency Measurements in large-angle quasi-elastic A(p,2p) scattering at Brookhaven National Lab

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The Future of Color Transparency and Hadronization Studies at Jefferson Lab and Beyond

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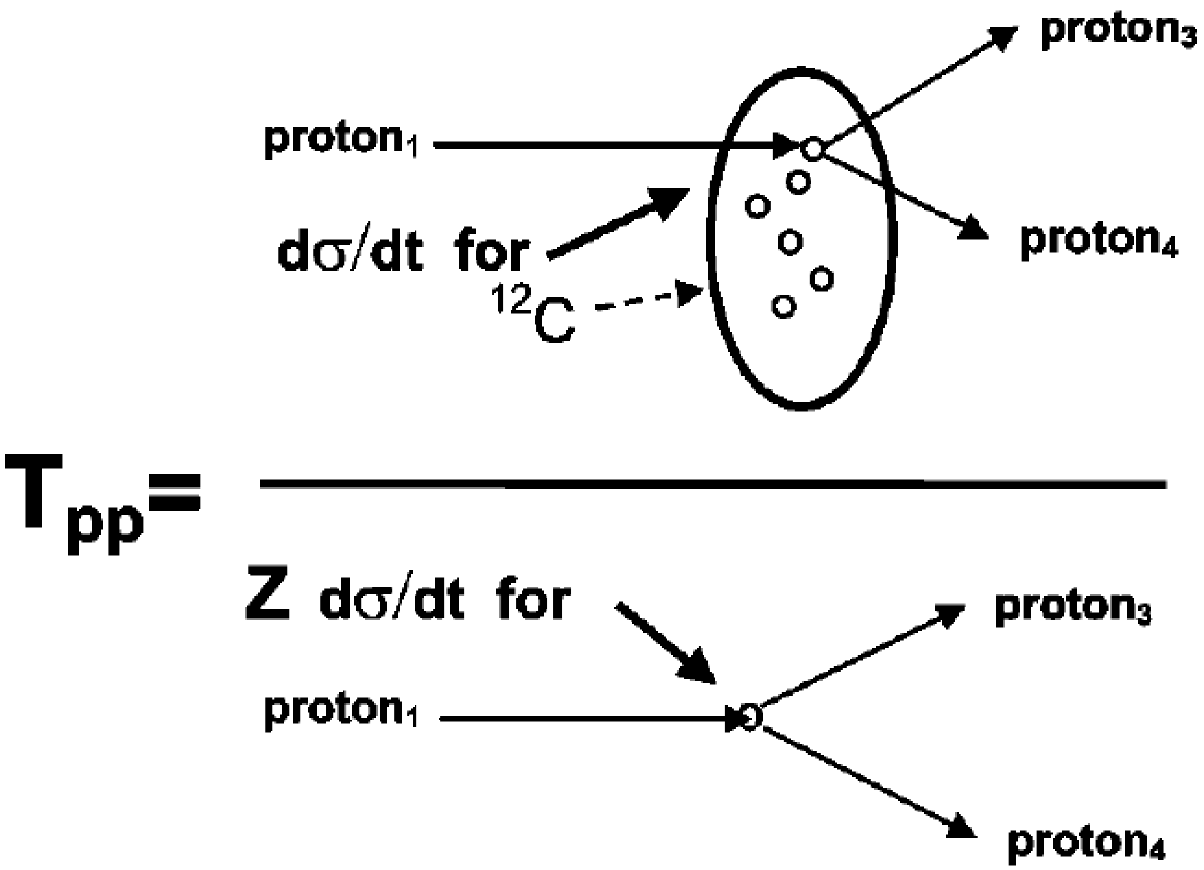
Talk outline

- Nuclear Transparency (NT) via A(p,2p)
- The BNL A(p,2p) experiments
  - E834 (1980's)
    - Incident proton momentum up to 12 GeV/c
    - A = Li, C, Al, Cu, Pb
  - E850 (1990's)
    - Incident proton momentum 5.9 - 14.4 GeV/c
    - A = D, C
- Experimental results
- Possible physics interpretations
- Outlook

Presentation is based mainly on: J. Aclander et al., Phys. Rev. C 70, 015208 (2004)

Nuclear Transparency for A(p,2p) (1/3)

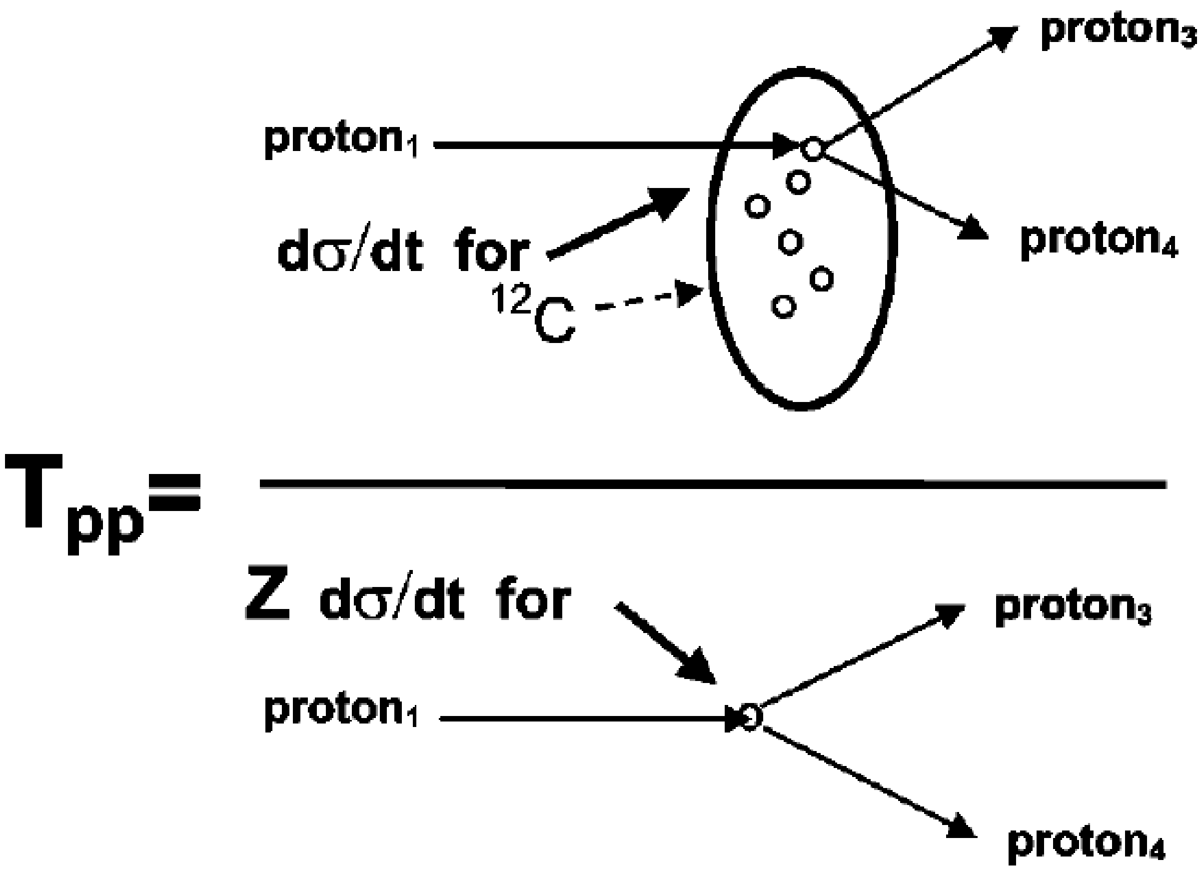
- **NT Definition:** The survival probability for protons to enter and exit a nucleus
- **In standard Glauber models:** NT is independent of p incoming momentum
- Complicated by nucleon momentum and binding energy distributions
- **In practice:** Implicitly integrate over binding energy distributions and consider only nuclear momentum distributions



$$T = \frac{(d\sigma/dt)(p\text{-}p \text{ elastic in nucleus})}{(d\sigma/dt)(p\text{-}p \text{ elastic in hydrogen})}$$

Nuclear Transparency for A(p,2p) (2/3)

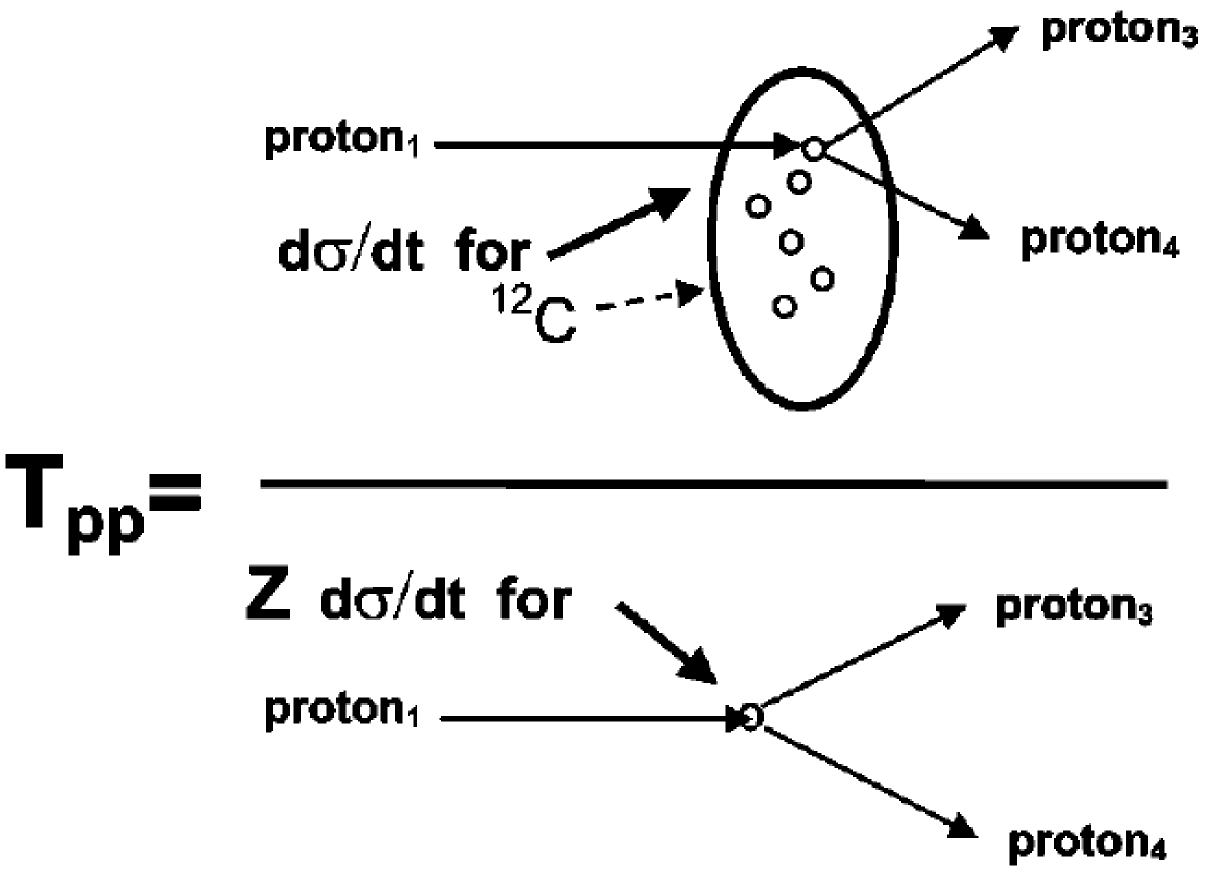
- **Assumption:** pp scattering in nucleus can be factorized from initial and final state interactions (ISI and FSI)
- **Nee to take into account:** Energy-momentum behavior of the elementary pp differential cross section
- **Recall**: pp cross section at large angles depends very strongly on energy
- **Procedure**:
  - Select protons with a narrow range of Fermi longitudinal momentum
  - Correct quasi-elastic distributions with the known differential pp cross section



$$T = \frac{(d\sigma/dt)(p\text{-}p \text{ elastic in nucleus})}{(d\sigma/dt)(p\text{-}p \text{ elastic in hydrogen})}$$

Nuclear Transparency for A(p,2p) (3/3)

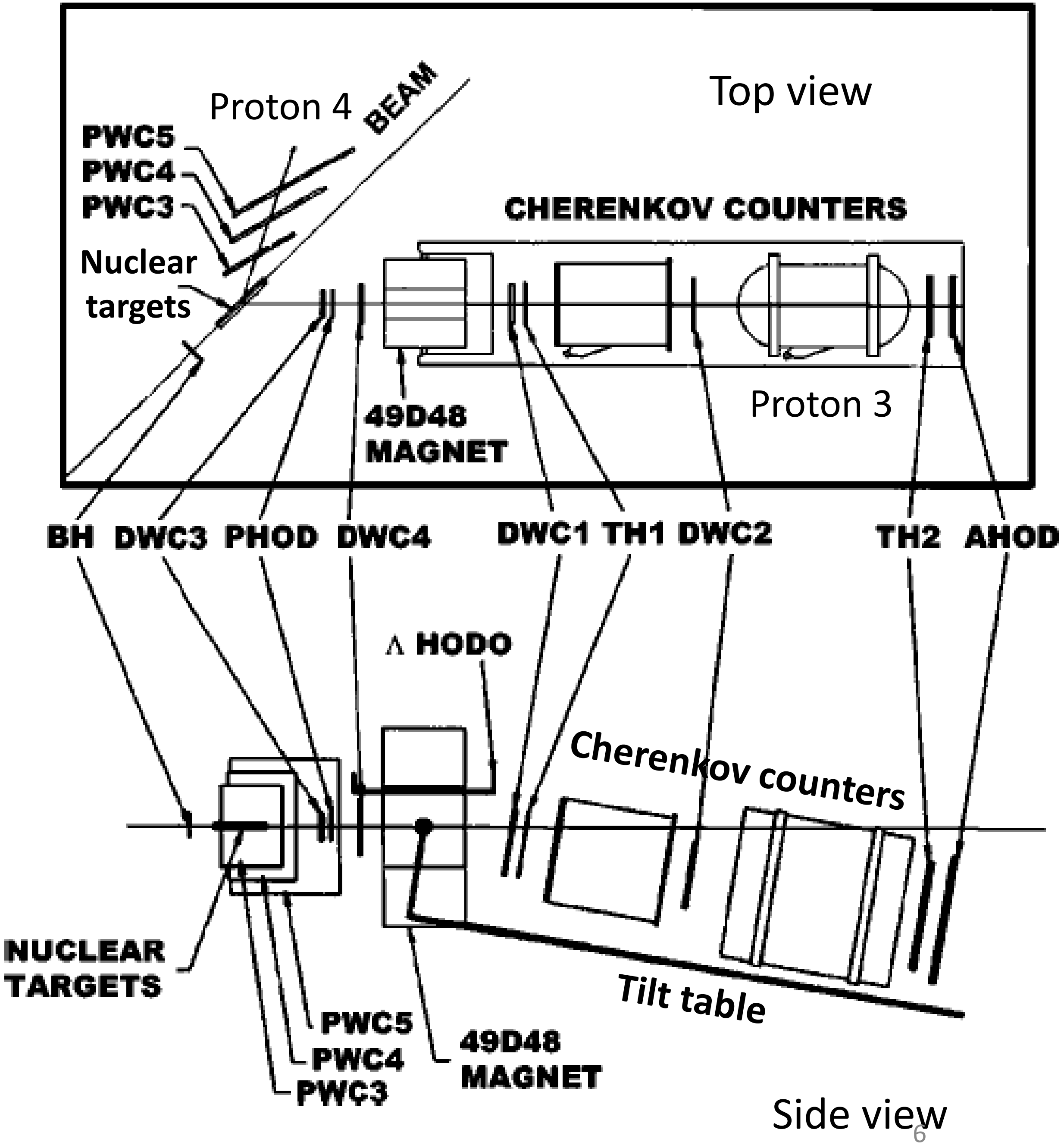
- Measurements were performed near 90° in the pp CM
- Elastic scattering at such large angles is supposed to single out **Point Like Configurations (PLC)** of the protons
- When in PLC, quark colors are assumed to ‘overlap’, rendering the proton **color transparent**, significantly decreasing ISI and FSI
- As incident momentum increases, PLC is assumed to become more dominant
- Thus, an increase of T_{pp} (90° CM) as a function of incident momentum may be **a signature of color transparency**



$$T = \frac{(d\sigma/dt)(p\text{-}p \text{ elastic in nucleus})}{(d\sigma/dt)(p\text{-}p \text{ elastic in hydrogen})}$$

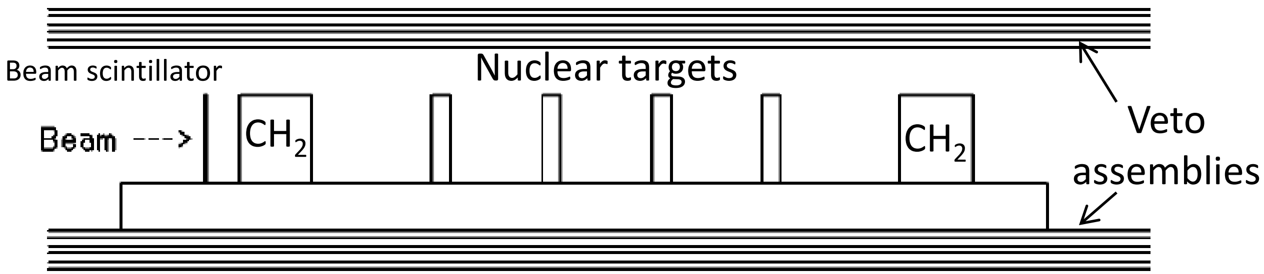
BNL Experiment E834 (1980's)

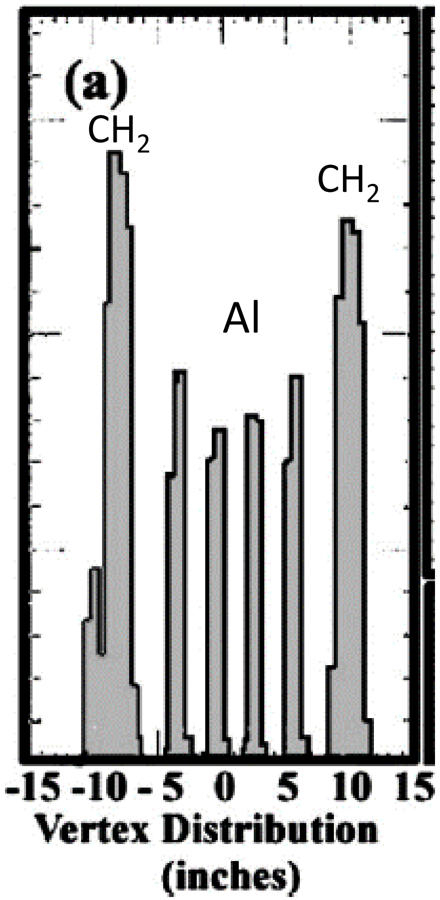
- Measure directions of both final state particles, momentum of only one track
- Set up for 2-body exclusive ~90°$_{c.m.}$ reactions
- Direction and momentum of one particle measured by drift wire chambers before (DWC3,4) and after (DWC1,2) a magnet
- Proportional wire chambers (PWC3-5) measured direction of second particle
- Cernenkov counters identified π and k, so p could be selected
- Level I trigger – TH1,2 scintillation hodoscopes
- Level II trigger – DWC1,2 momentum trigger



BNL Experiment E834 (1980's)

- Veto – reject events with additional charged and π^0 tracks (lead-scintillator sandwiches)
- 4 Identical targets – Li, C, Al, Cu or Pb
- # of bound protons the 4 targets was ~5 times the # of free protons in the 2 CH_2 targets
- 4 targets were interchanged regularly
- Vertex identification of targets via tracking was unambiguous





E834 Kinematics

P_{beam} = 6 GeV/c

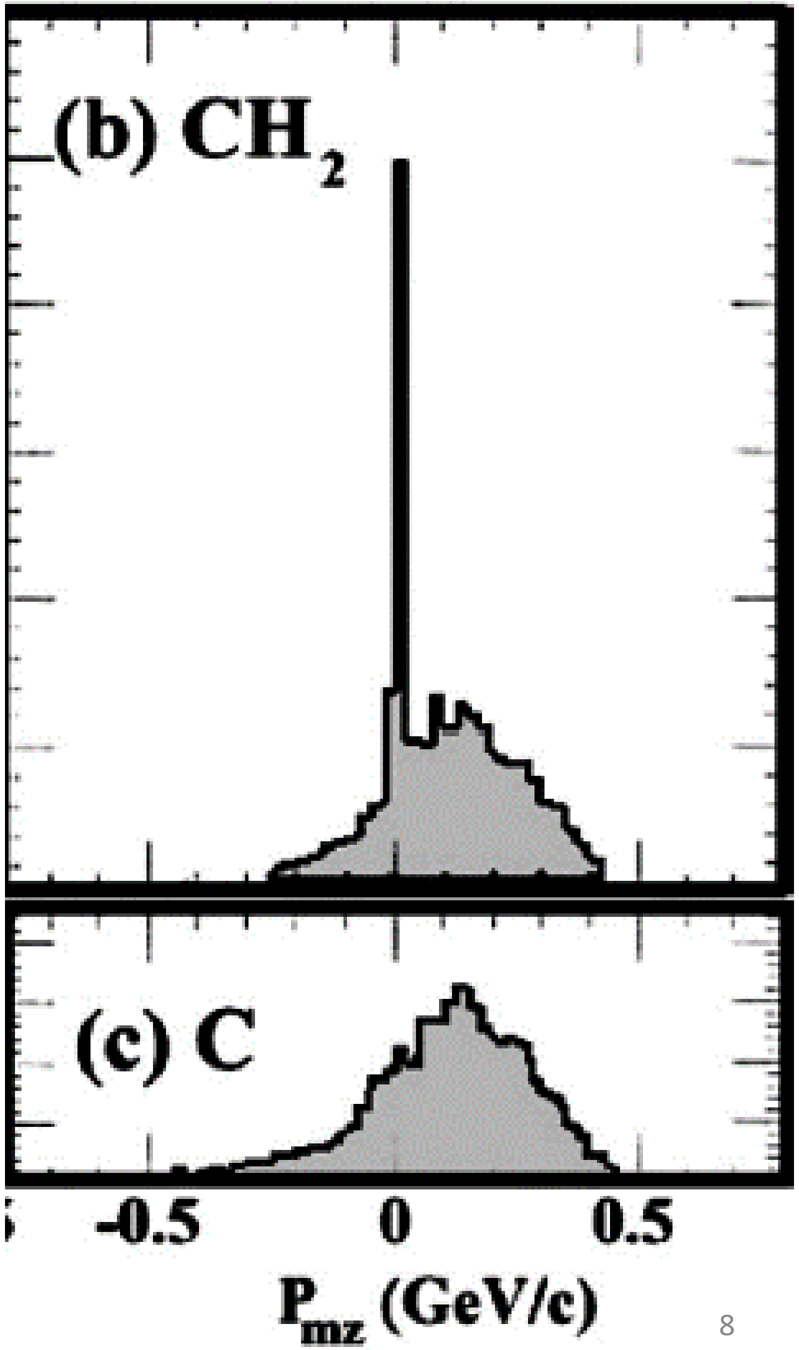
ΔP_{mz} = 10 MeV/c

- Missing energy and momentum

$$\epsilon_m = E_3 + E_4 - E_1 - m_p,$$

$$\vec{P}_m = \vec{P}_3 + \vec{P}_4 - \vec{P}_1.$$

- $\hat{z}$ - incident beam direction
- $\hat{x}$ - in plane containing $\vec{P}_1$ and $\vec{P}_3$
- $\hat{y}$ - perpendicular to $\hat{x}$
- $\vec{P}_4$ was not measured.
  Assumed $\varepsilon_m = 0$ and then extracted E_4 from energy conservation, and from it $\vec{P}_4$ and $\vec{P}_m$
- ~0.5% effect on nuclear momenta
- Clear extraction of hydrogen elastic signal in P_{mz}, determined by the lab polar angles of $\vec{P}_3$ and $\vec{\mathrm{P}}_4$



E834 Kinematics

- P_{my} is mainly determined by the out-of-plane azimuthal angle. Only weakly dependent on magnitudes of P_3 and P_4
  - $\Delta P_{my} = \pm 30\ MeV/c$
- P_{mx} mainly depends on difference of P_3 and P_4 magnitudes
  - $\Delta P_{mx} = \pm 100\ MeV/c$
- QE signal is after background subtraction, and the cuts:

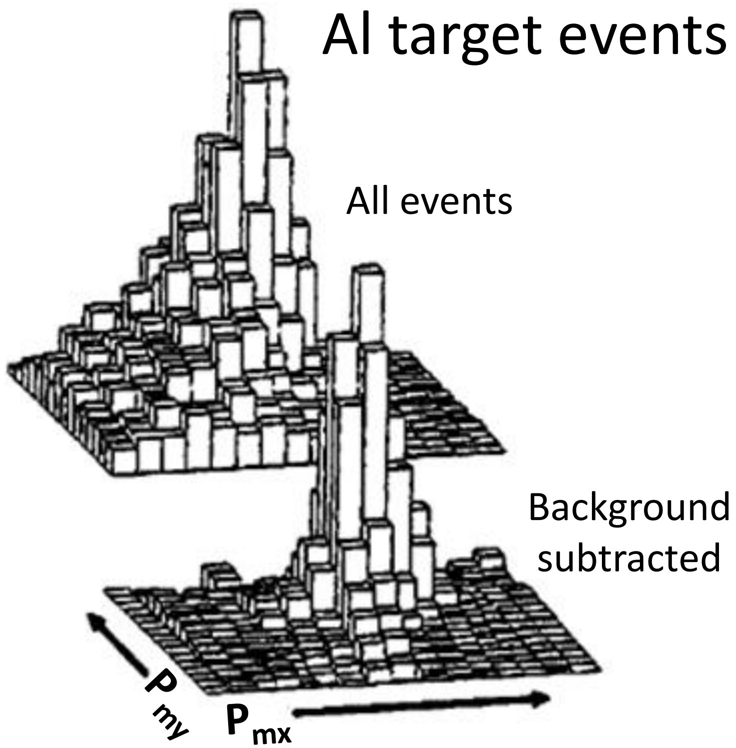
$$|P_{mx}| < 0.25\ \mathrm{GeV}/c,\ \ |P_{my}| < 0.25\ \mathrm{GeV}/c,$$

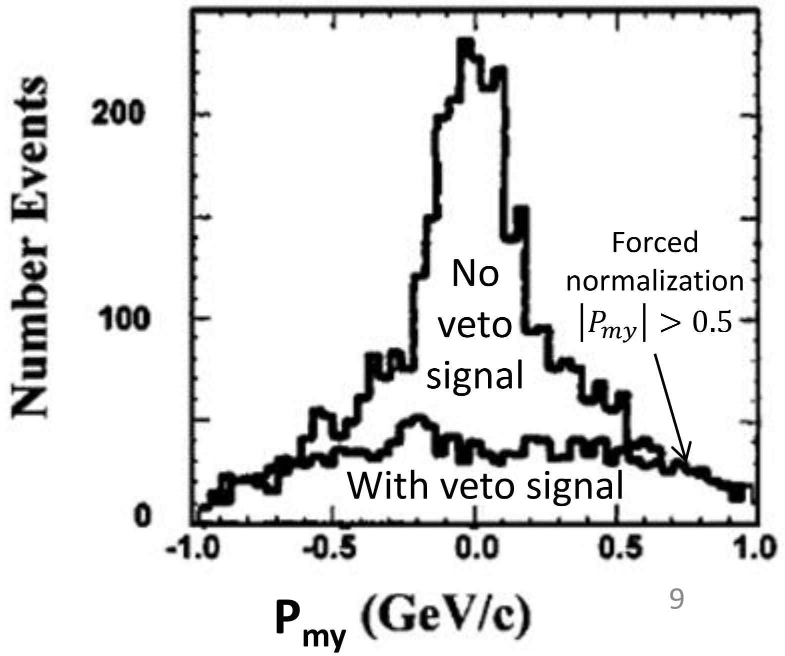
$$0.9 < \alpha_0 < 1.2.$$

- Where:

$$\alpha_0 \equiv 1 - \frac{2\beta\cos[(\theta_3-\theta_4)/2]\cos[(\theta_3+\theta_4)/2] - p_{1z}}{m_p}\ ;\ \ \beta \equiv \sqrt{\left(\frac{E_1+m_p}{2}\right)^2 - m_p^2}$$

- Primary systematic error – 20±5% background subtraction uncertainty





E834 nuclear transparency

$$\frac{N(p_a,p_b)}{N'_{\mathrm{H}}} = T\int_{p_a}^{p_b} dp_z \left[\int\int dp_x\, dp_y\, F(\mathbf{p})A(\mathbf{p})\frac{(d\sigma/dt)(s)}{(d\sigma/dt)(s_0)}\right]$$

- T: nuclear transparency
- $N(p_a,p_b)$: # of QE events with $p_a < p_z < p_b$
- N'_{H} : # of H elastic events, times the ratio of target nuclear protons to hydrogen protons (5.1 for Al)
- $F(\mathbf{p})$: Normalized Fermi momentum distribution
- $A(\mathbf{p})$: Acceptance, normalized to H acceptance
- s_0 : nominal c.m. energy squared for hydrogen
- s : c.m energy squared of the QE event, taking into account the struck proton 4-momentum (m_p, p_x, p_y, p_z)
- s dependence of $d\sigma/dt$ on a proton in the nucleus is assumed to be the same as on a free proton

Al results $P_{\mathrm{eff}} \approx P_0[1-(p_a+p_b)/2m_p]$

P_0	p_a	p_b	P_{eff}	$N(p_a,p_b)$	$\int_{p_a}^{p_b} dp_z\,[\ldots]$	T
6	−0.2	0.0	6.6	322	0.17	0.22 ± 0.04
6	0.0	0.1	5.7	721	0.31	0.25 ± 0.03
6	0.1	0.2	5.0	800	0.52	0.18 ± 0.03
6	0.2	0.3	4.4	400	0.29	0.15 ± 0.03
10	−0.2	0.0	11.0	158	0.22	0.25 ± 0.06
10	0.0	0.1	9.5	384	0.25	0.48 ± 0.05
10	0.1	0.2	8.4	481	0.45	0.32 ± 0.04
10	0.2	0.3	7.3	450	0.49	0.28 ± 0.06
12	−0.2	0.0	13.2	25	0.17	0.12 ± 0.04
12	0.0	0.1	11.4	65	0.29	0.20 ± 0.04
12	0.1	0.2	10.2	100	0.35	0.24 ± 0.08
12	0.2	0.3	8.8	140	0.26	0.46 ± 0.07

A. Carroll et al., Phys. Rev. Lett. 61, 1698 (1988)

E834 nuclear transparency

$$\frac{N(p_a,p_b)}{N'_{\mathrm{H}}} = T\int_{p_a}^{p_b} dp_z \left[\int\int dp_x\, dp_y\, F(\mathbf{p})A(\mathbf{p})\frac{(d\sigma/dt)(s)}{(d\sigma/dt)(s_0)}\right]$$

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- $N(p_a,p_b)$: # of QE events with $p_a < p_z < p_b$
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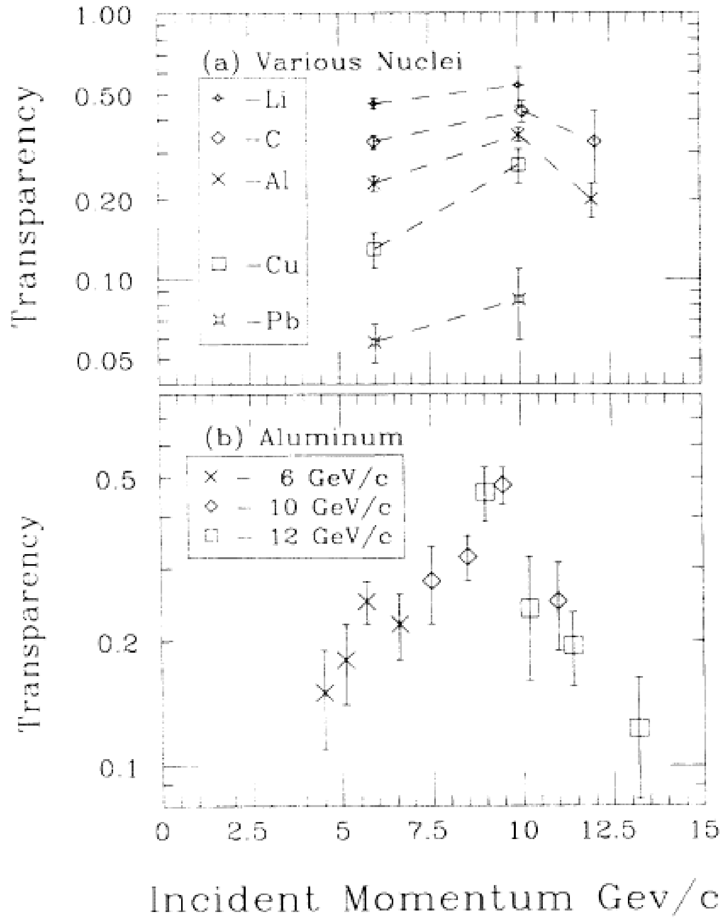
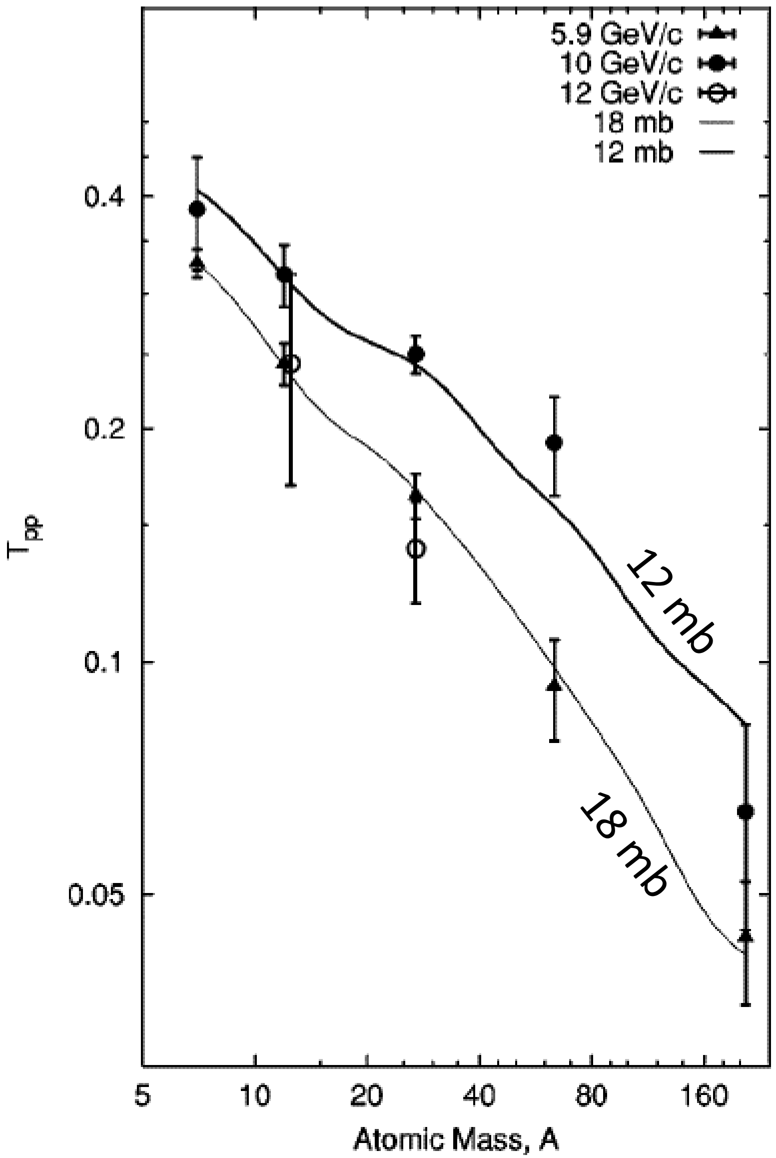
- s dependence of $d\sigma/dt$ on a proton in the nucleus is assumed to be the same as on a free proton

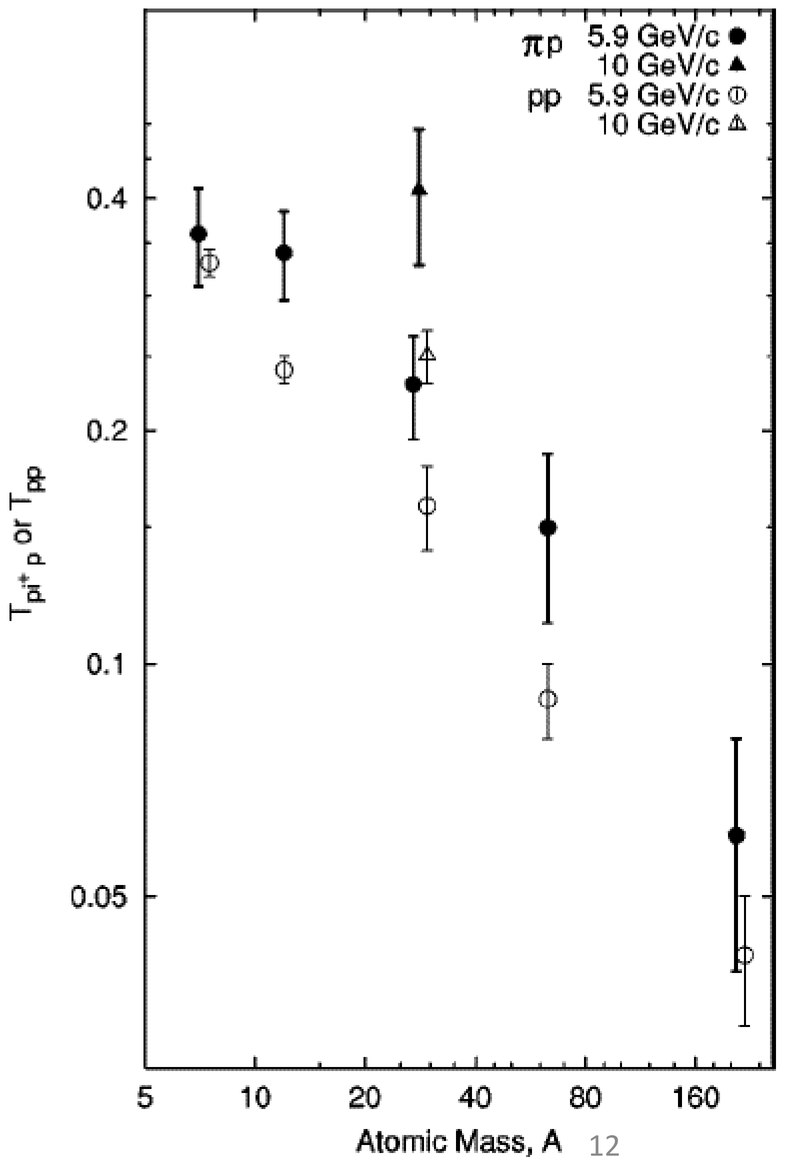


A. Carroll et al., Phys. Rev. Lett. 61, 1698 (1988)

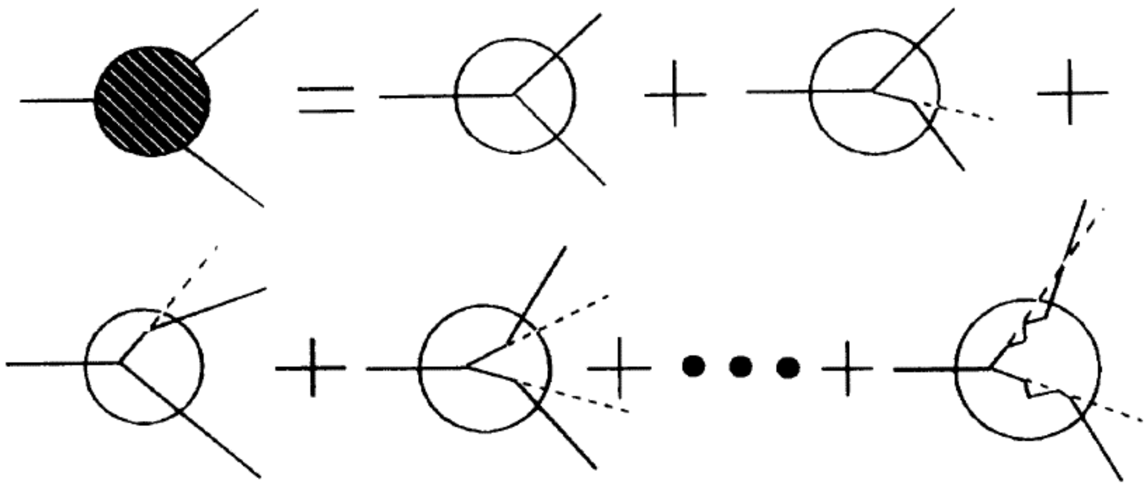
E834 nuclear transparency - A and particle dependence

- A dependence yields effective cross sections of p in nuclei
- ~18 mb at 5.9 and 12 GeV/c, ~12 mb at 10 GeV/c
- The absorption of protons for large Q^2 QE events is less than that predicted by free proton-nucleon scattering
- $T[A(\pi^+,\pi^+p)]$ is ~1.5 times higher than T[A(p,2p)], with large uncertainty and some variation with A

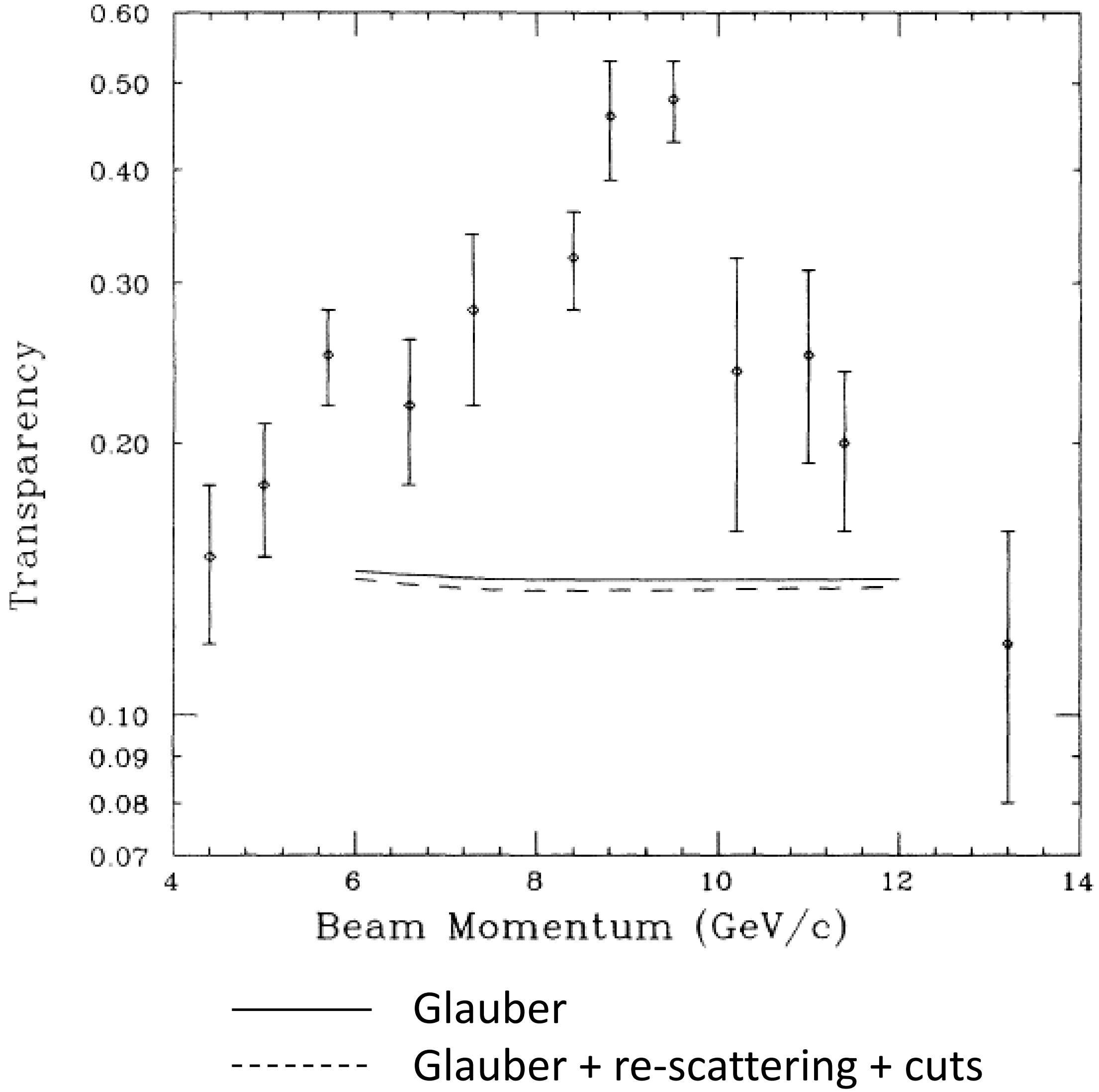




NT energy dependence due to multiple scattering?



- Wrote explicit NT expression taking into account re-scattering of protons in the nucleus, before reaching detectors
- Re-scattering will alter s and t, and might affect NT due to strong s dependence of $d\sigma/dt(pp \rightarrow pp)$
- Performed MC calculation with up to 4 re-scatterings for each proton
- Applied cuts of Carroll et al. and plotted NT as a function of incoming momentum



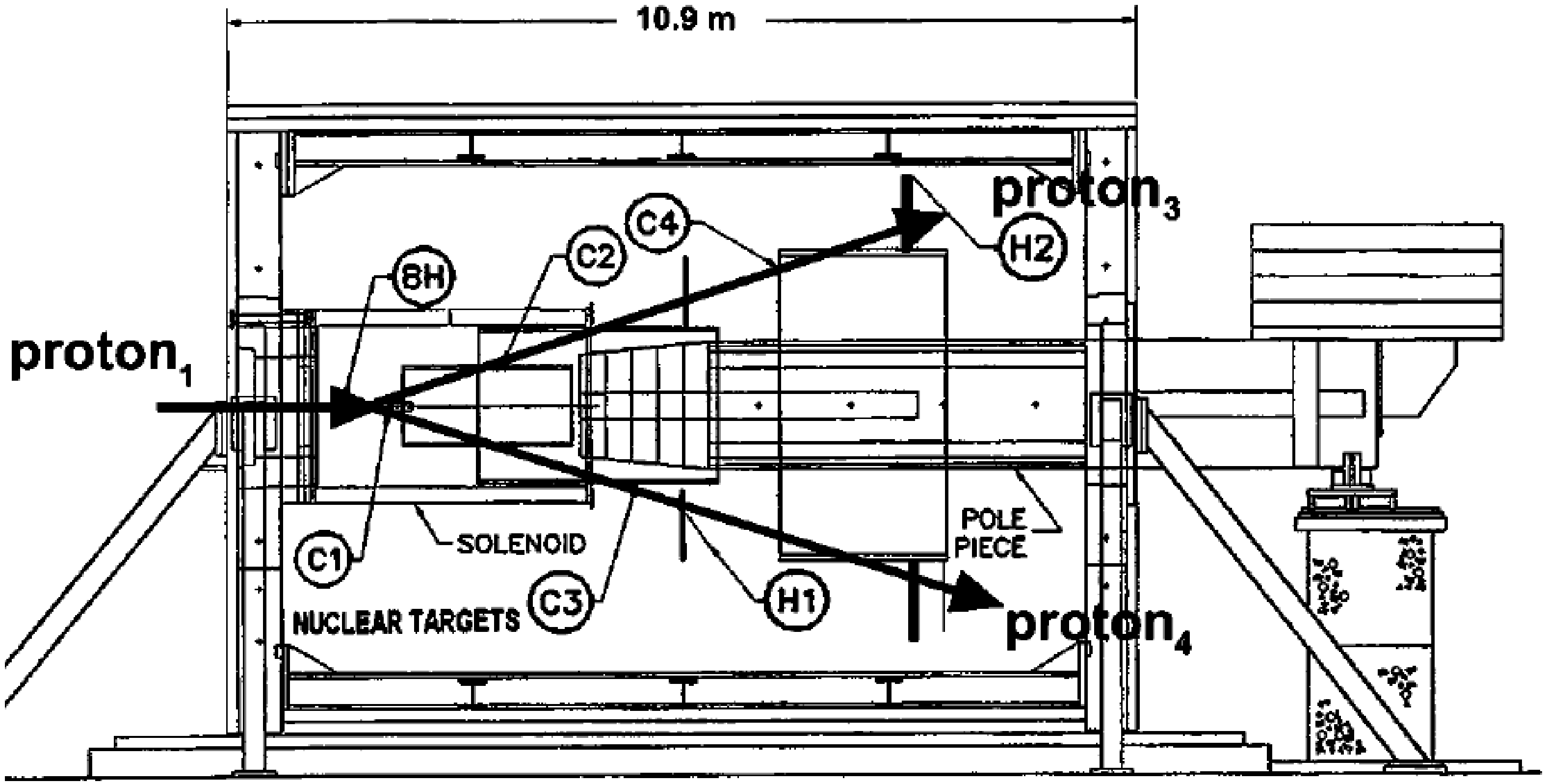
I. Mardor et al., Phys. Rev. C 46, 761 (1992)

BNL Experiment E850 (1990’s)

- The E850 experiment allowed full and symmetrical tracking with momentum reconstruction of **both** final state particles
- The E850 measurement addressed the concerns about the background subtraction in the determination of the quasi-elastic signal in the E834 experiment

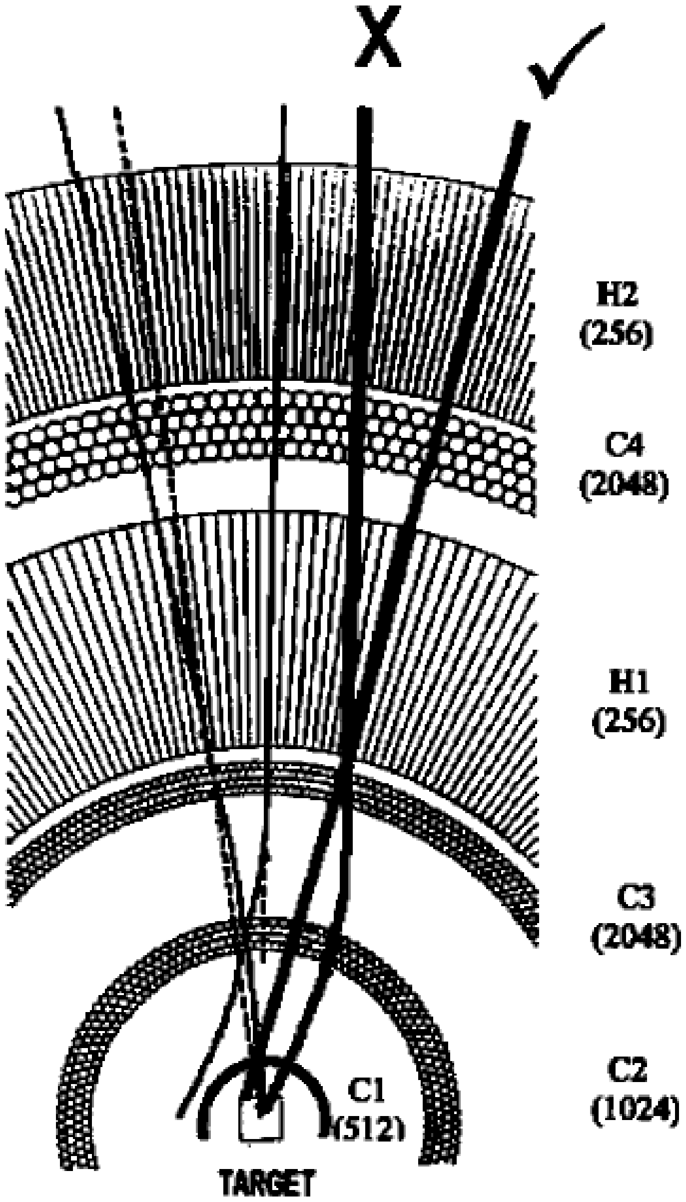
E850: EVA – Exclusive Variable Apparatus (1/2)

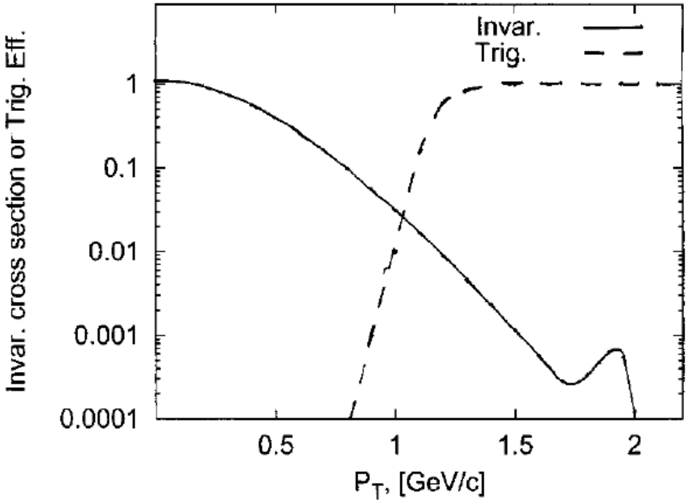
- **BH**: Beam Hodoscope
- **C1-C4**: 4-layer cylindrical straw-tube drift-chamber arrays.
  3D Tracking and transverse momentum measurement
- **H1-H2**: Cylindrical scintillation counter arrays.
  Events triggers
- C, CH_2 and CD_2 targets inside C1
- Solenoid: SC, 0.8 Tesla
- Pole piece: Minimize transverse fringe fields, beam dump
- Protons identified by differential Cerenkov counters



E850: EVA – Exclusive Variable Apparatus (2/2)

- Transverse cut of EVA
- Trigger based on high transverse momentum (V)
- Rejection of low transverse momentum events (X)
- Level I trigger (H1, H2) – 75 nsec
- Level II trigger (C2, C3, C4) – 1 μsec
- Higher level triggers – micro-processor based checks for exactly 2 tracks, roughly co-planar
- Trigger rate < 100 Hz for incident beams of up to 10^8 Hz (10^7 interactions per spill)





EVA Trigger acceptance vs invariant pp CS at 8 GeV/c

E850 Kinematics

- Missing energy, momentum and mass

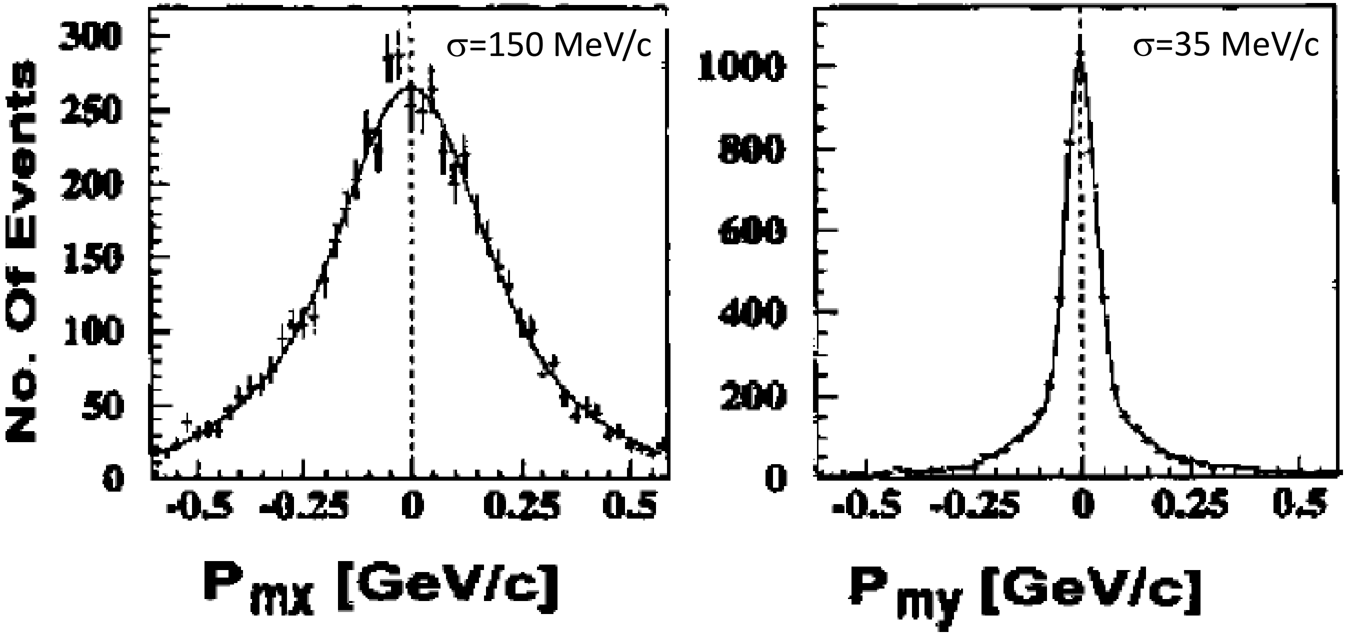
$$\epsilon_m = E_3 + E_4 - E_1 - m_p,$$
$$\vec{P}_m = \vec{P}_3 + \vec{P}_4 - \vec{P}_1,$$
$$m_M^2 = \epsilon_m^2 - \vec{P}_m^2.$$

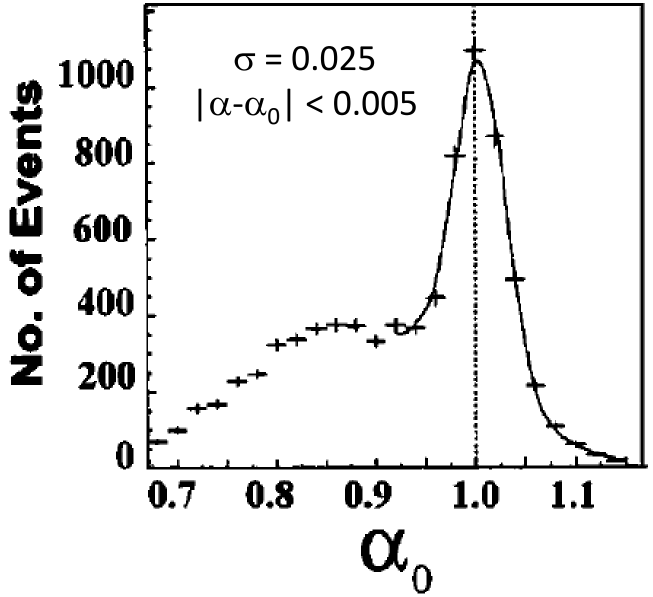
- $\hat{z}$ - incident beam direction
- $\hat{x}$ - in plane containing $\vec{P}_1$ and $\vec{P}_3$
- $\hat{y}$ - perpendicular to $\hat{x}$
- P_{my} : out-of-plane azimuthal angle
- P_{mx} : difference of P_3 and P_4 magnitudes

$$\alpha \equiv A\frac{(E_m - P_{mz})}{M_A} \simeq 1 - \frac{P_{mz} - \epsilon_m}{m_p} \simeq 1 - \frac{P_{mz}}{m_p}$$

$$\alpha_0 \equiv 1 - \frac{2\beta \cos[(\theta_3 - \theta_4)/2]\cos[(\theta_3 + \theta_4)/2] - p_{1z}}{m_p}$$

Selected H events from the CH_2 targets for P_1 = 5.9 GeV/c

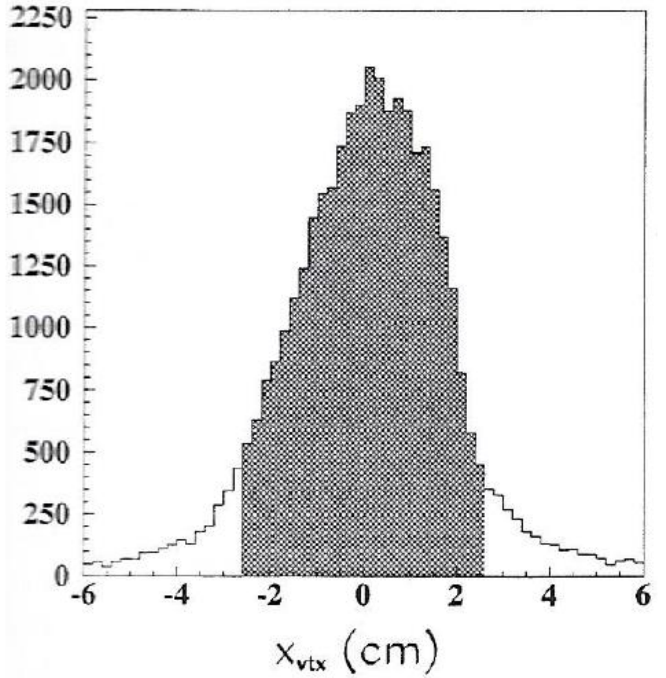


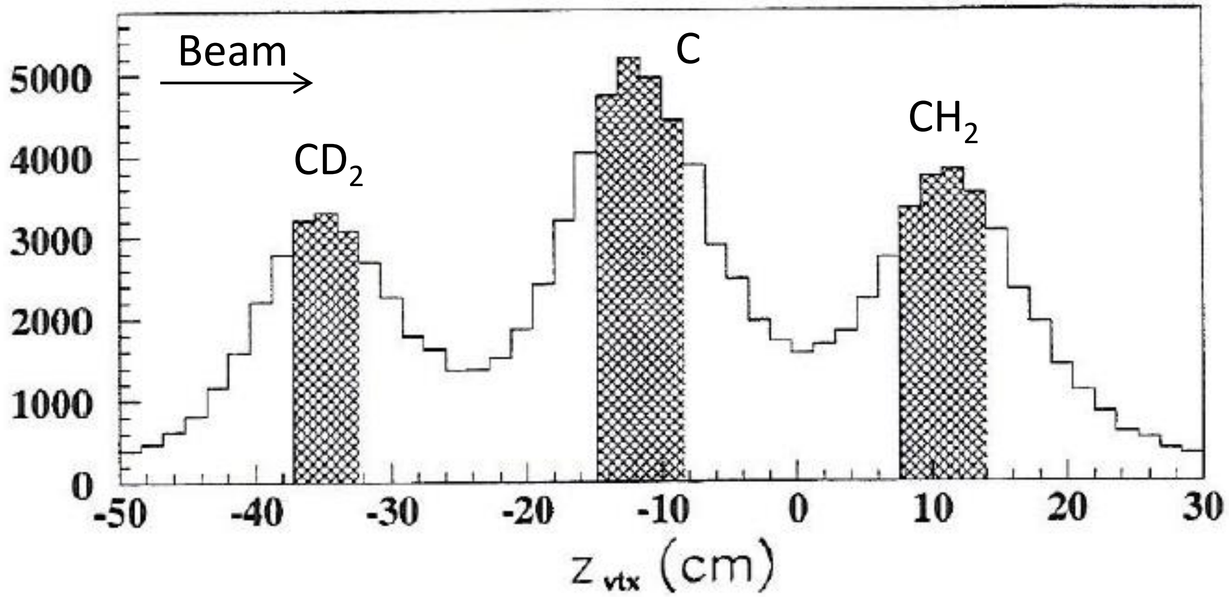


E850 target cuts and identification

- Reconstructed vertices enabled to remove events not originating from targets
- Longitudinal vertex location enables to identify the event target
- Limited longitudinal vertex resolution caused
  - Loss of many ambiguous events
  - Possible mis-identification of event target

Shaded regions are actual targets sizes and locations





I. Mardor, Ph.D. thesis (1998)

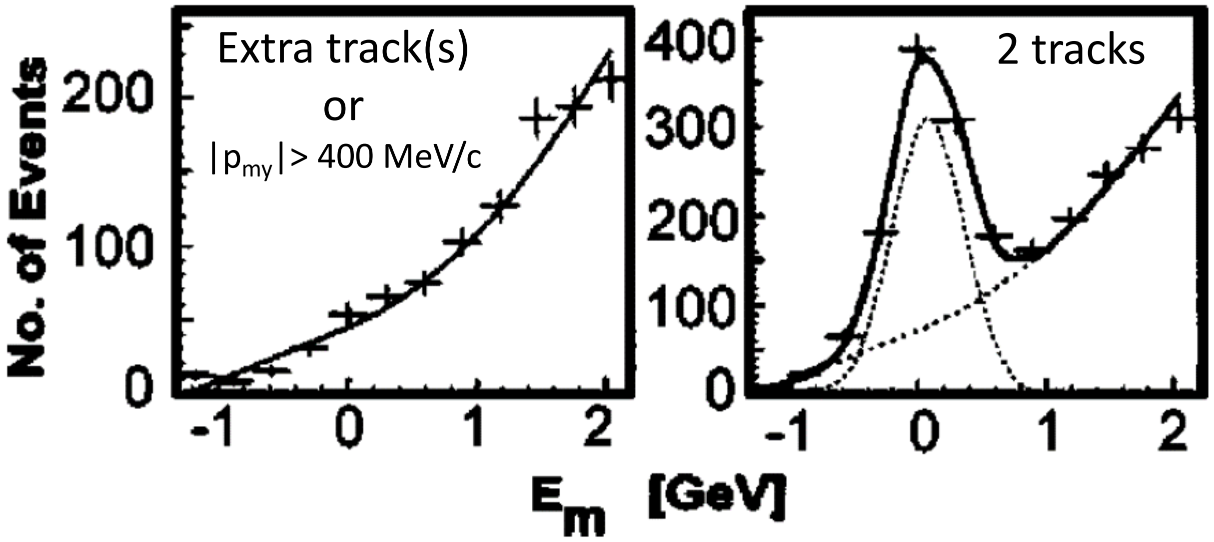
E850 QE signal and background

- Background events have (too) large Fermi momentum and/or extra track(s)
- QE peak in missing energy plot observed only with exactly 2 tracks and reasonable Fermi momentum
- Worked for 5.9 & 7.5 GeV/c. At higher energy E_m resolution was too broad
- A method that worked for all relevant energies – used density of measured events per unit 4D missing-momentum space:

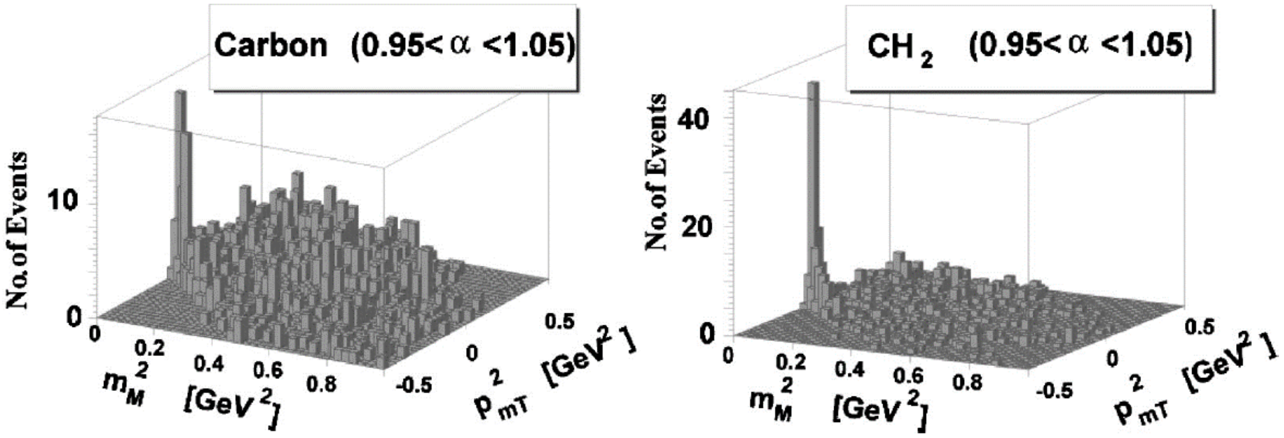
$$d\epsilon_m d^3\vec{P}_m \rightarrow d^2\vec{P}_{mT}\, d\alpha\, d(m_M^2)$$

- Elastic H peak: $m_M^2 = 0,\ P_{mT}^2 = 0,\ \alpha = 1$

Selected (0.95 < α_0 < 1.05) C target events P_1 = 5.9 GeV/c



P_1 = 5.9 GeV/c



E850 QE signal and background

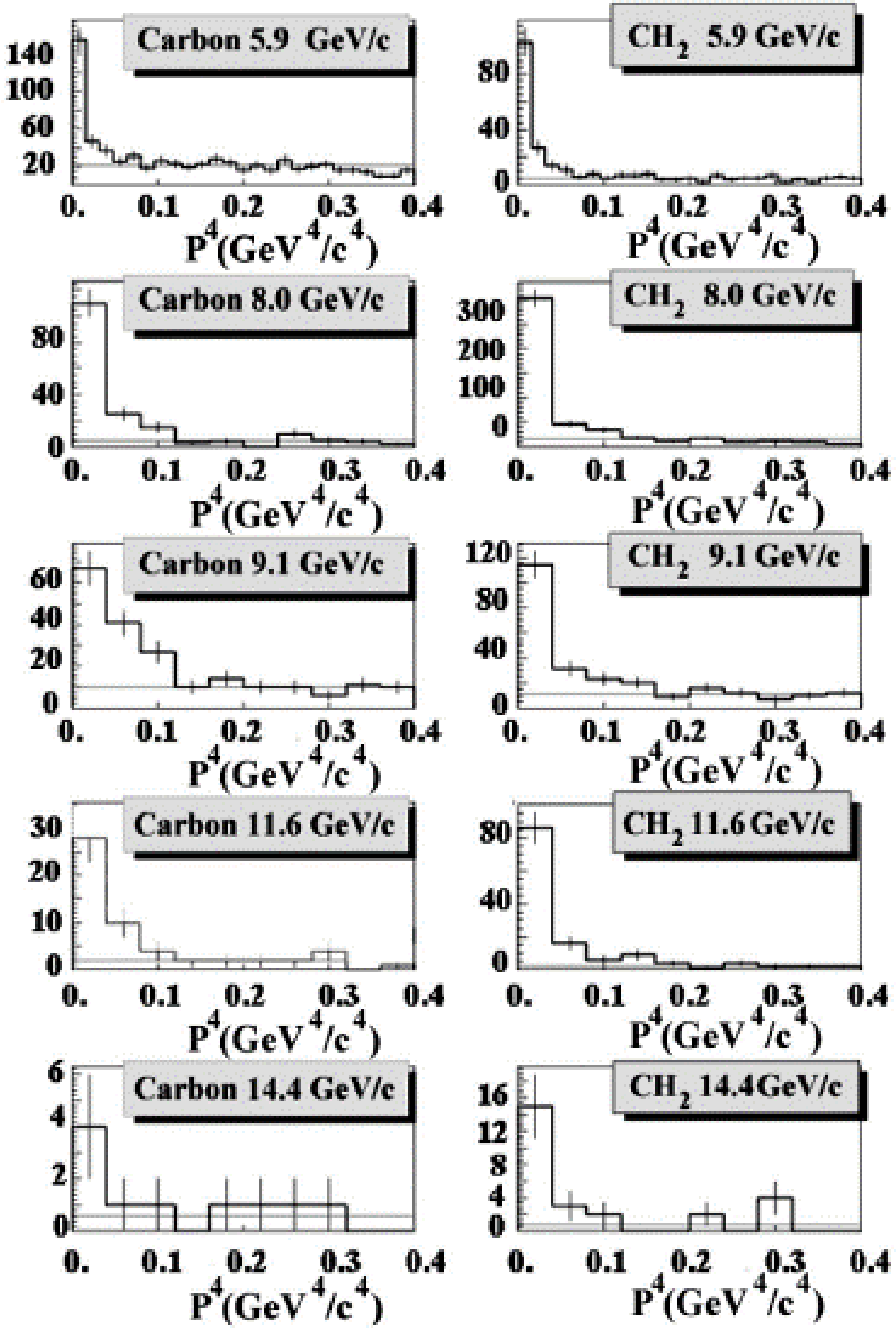
- Used radial projection of the 4D missing-momentum variable to extract signal from background for QE and elastic events:

$$\mathbf{P}^4 \equiv P_{mT}^4 + m_M^4$$

- Obtained clear signals over background for all measured incoming momenta
- Smooth background at $0.15 < \mathbf{P}^4 < 0.35\ (\mathrm{GeV}^4/c^4)$ extended to QE peak at $\mathbf{P}^4 < 0.1\ (\mathrm{GeV}^4/c^4)$
- Cuts - exactly 2 nearly-coplanar tracks, and:

$$|P_{mx}| < 0.5\ \mathrm{GeV}/c,\ \ |P_{my}| < 0.3\ \mathrm{GeV}/c,$$

$$|1 - \alpha_0| < 0.05$$



E850 Nuclear transparency

$$T_{\rm CH} = T_{pp}\int_{\alpha_1}^{\alpha_2} d\alpha \int d^2\vec{P}_{mT} n(\alpha,\vec{P}_{mT}) \frac{\frac{d\sigma}{dt}_{pp}(s(\alpha))}{\frac{d\sigma}{dt}_{pp}(s_0)}$$

$$T_{\rm CH} = \frac{1}{3}\frac{R_{\rm C}}{R_{\rm CH_2} - R_{\rm C}}$$

R_x: event rate in each nucleus

- T_{pp} is extracted from T_{CH} by taking into account the Fermi momentum distribution and the strong longitudinal momentum dependence of $d\sigma/dt(pp)$
- For deuterium: $$T_{\rm DH} = \frac{R_{\rm CD_2} - R_{\rm C}}{R_{\rm CH_2} - R_{\rm C}}$$
- $Tpp(D) \approx T_{DH}$, because the kinematical cuts cover the entire deuteron wave function
- Consistency with 1 provides a consistency check on nuclear transparency normalization

P_1(GeV/c)	$\theta_{\rm c.m.}$(deg)	α_0	P_{eff}(GeV/c)	$T_{\rm CH}$	$\int_{\alpha_1}^{\alpha_2}$	T_{pp}
			E850 carbon data: Leksanov *et al.* (2001) [2]			
5.9	86.2–90	0.95–1.05	5.9	0.071±0.012	0.350	0.20±0.03
8.0	87.0–90	0.95–1.05	8.0	0.120±0.018	0.350	0.34±0.05
9.1	86.8–90	0.95–1.05	9.1	0.164±0.038	0.350	0.47±0.11
11.6	85.8–90	0.95–1.05	11.6	0.079±0.021	0.340	0.23±0.06
14.4	86.3–90	0.95–1.05	14.4	0.033±0.024	0.340	0.10±0.07
			E850 carbon data for $\alpha > 1$ [29]			
9.1	86.8–90	1.05–1.15	10.0	0.059±0.015	0.11	0.53±0.15
11.6	85.8–90	1.05–1.15	12.8	0.016±0.007	0.12	0.14±0.07
14.4	86.3–90	1.05–1.15	15.8	0.007±0.007	0.11	0.06±0.07
			E850 carbon results: Mardor *et al.* (1998) [1]			
5.9	85.8–90	0.95–1.05	5.9	0.054±0.006	0.350	0.16±0.02
7.5	85.8–90	0.95–1.05	7.5	0.072±0.006	0.350	0.20±0.02
			E850 deuterium results: Mardor *et al.* (1988) [1,28]			
5.9	85.5–90	0.85–1.05	5.6	—	~1.0	1.06±0.07
7.5	85.5–90	0.85–1.05	7.1	—	~1.0	1.10±0.10

E850 Nuclear transparency

$$T_{\mathrm{CH}} = T_{pp}\int_{\alpha_1}^{\alpha_2} d\alpha \int d^2\vec{P}_{mT}\, n(\alpha,\vec{P}_{mT}) \frac{\frac{d\sigma}{dt}_{pp}(s(\alpha))}{\frac{d\sigma}{dt}_{pp}(s_0)} \qquad T_{\mathrm{CH}} = \frac{1}{3}\frac{R_{\mathrm{C}}}{R_{\mathrm{CH}_2} - R_{\mathrm{C}}}$$

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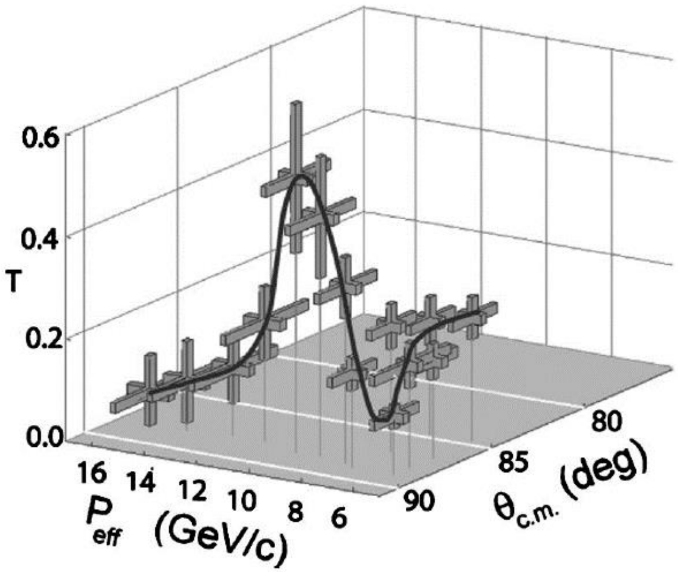
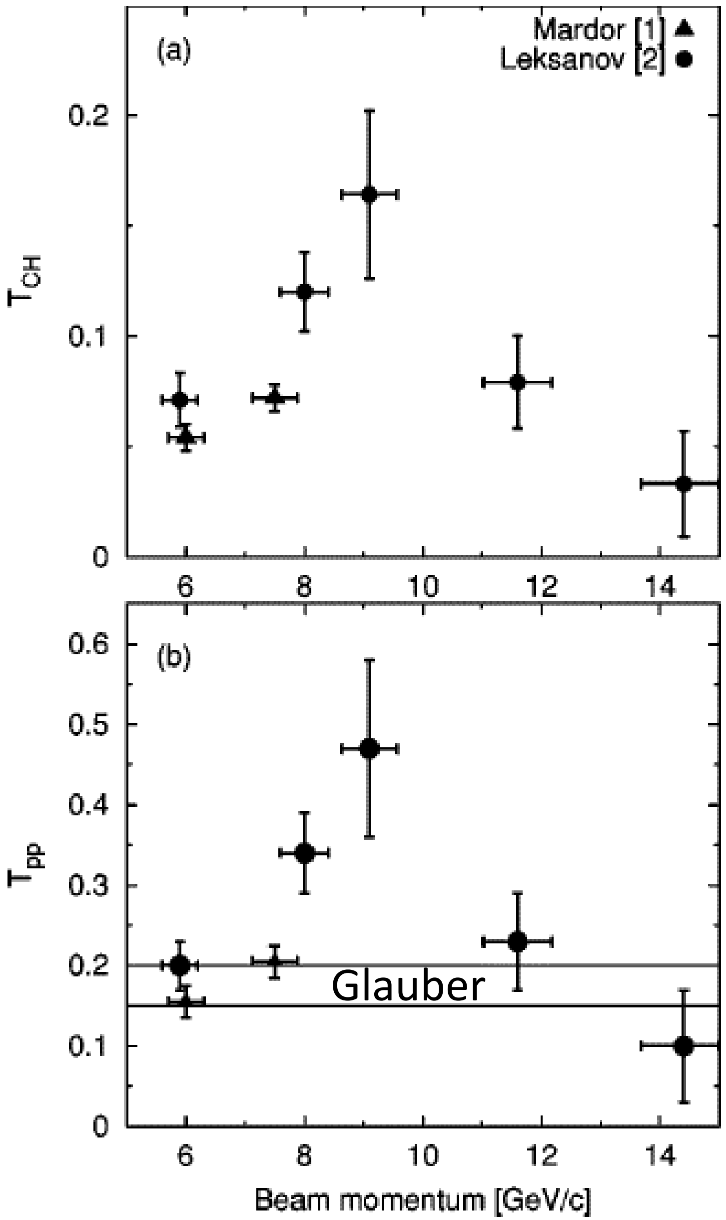
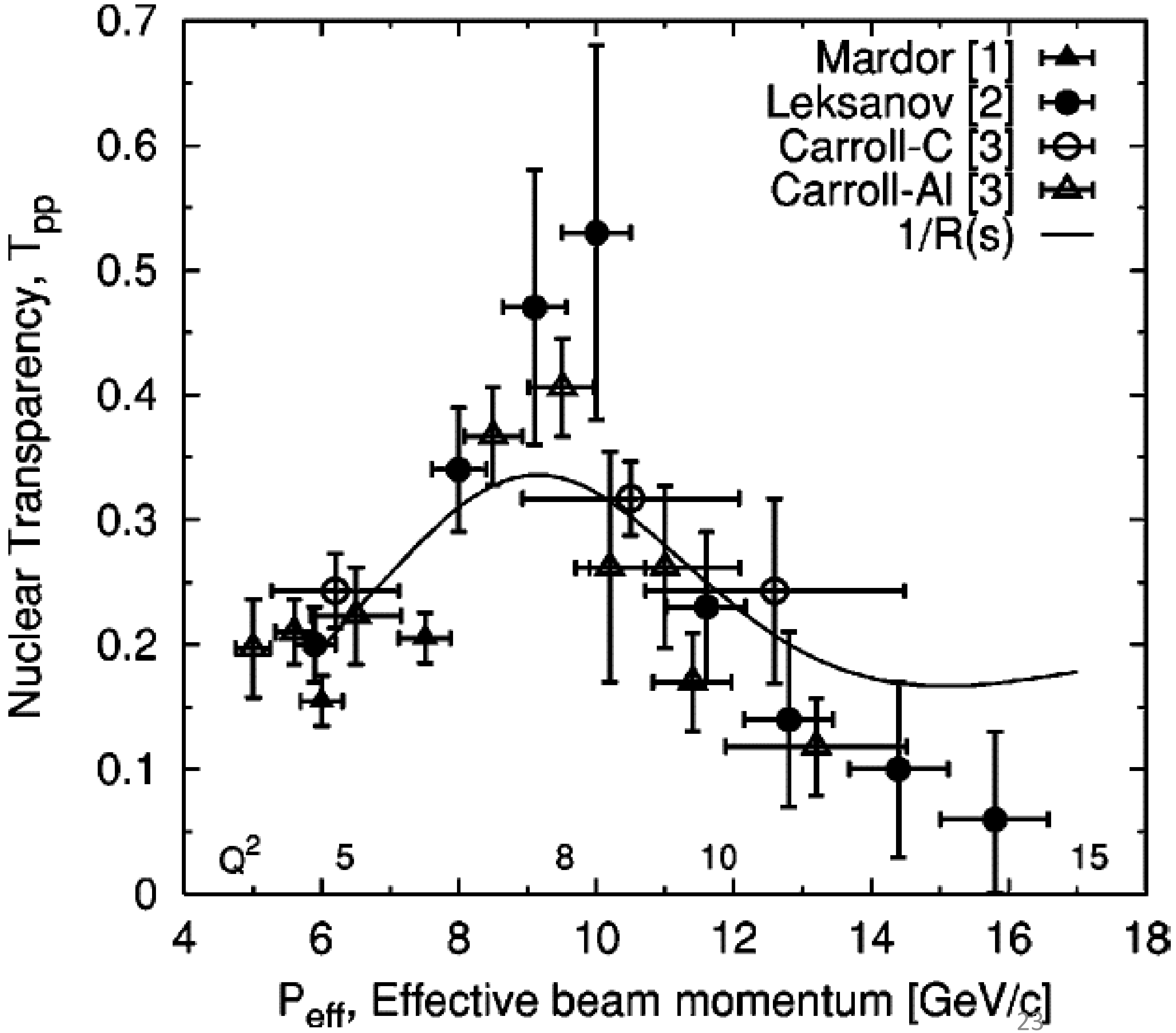




E834 + E850 Nuclear transparency results

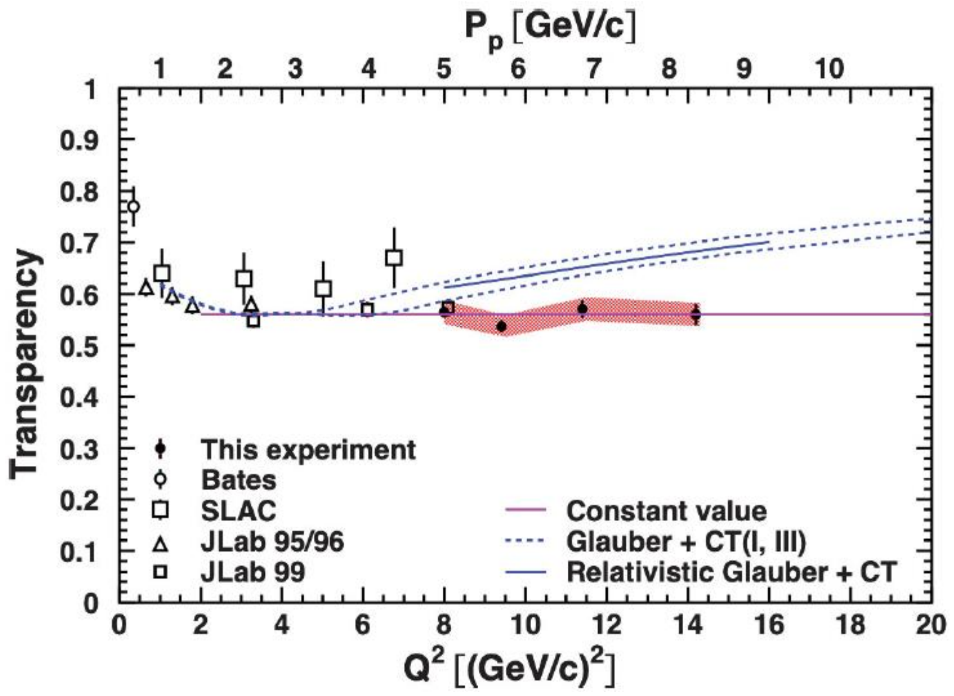
- Used an updated parametrization for the Fermi momentum distributions
- Combine Al and C transparencies by multiplying the Al data by $(27/12)^{1/3}$
- Solid line is the inverse of the ds/dt(pp) dependence around the s-10 trend. Normalization is adjusted to best fit the transparency data

$$\frac{d\sigma}{dt_{pp}}(\theta = 90^{\circ}_{\text{c.m.}}) = R(s)s^{-10}$$

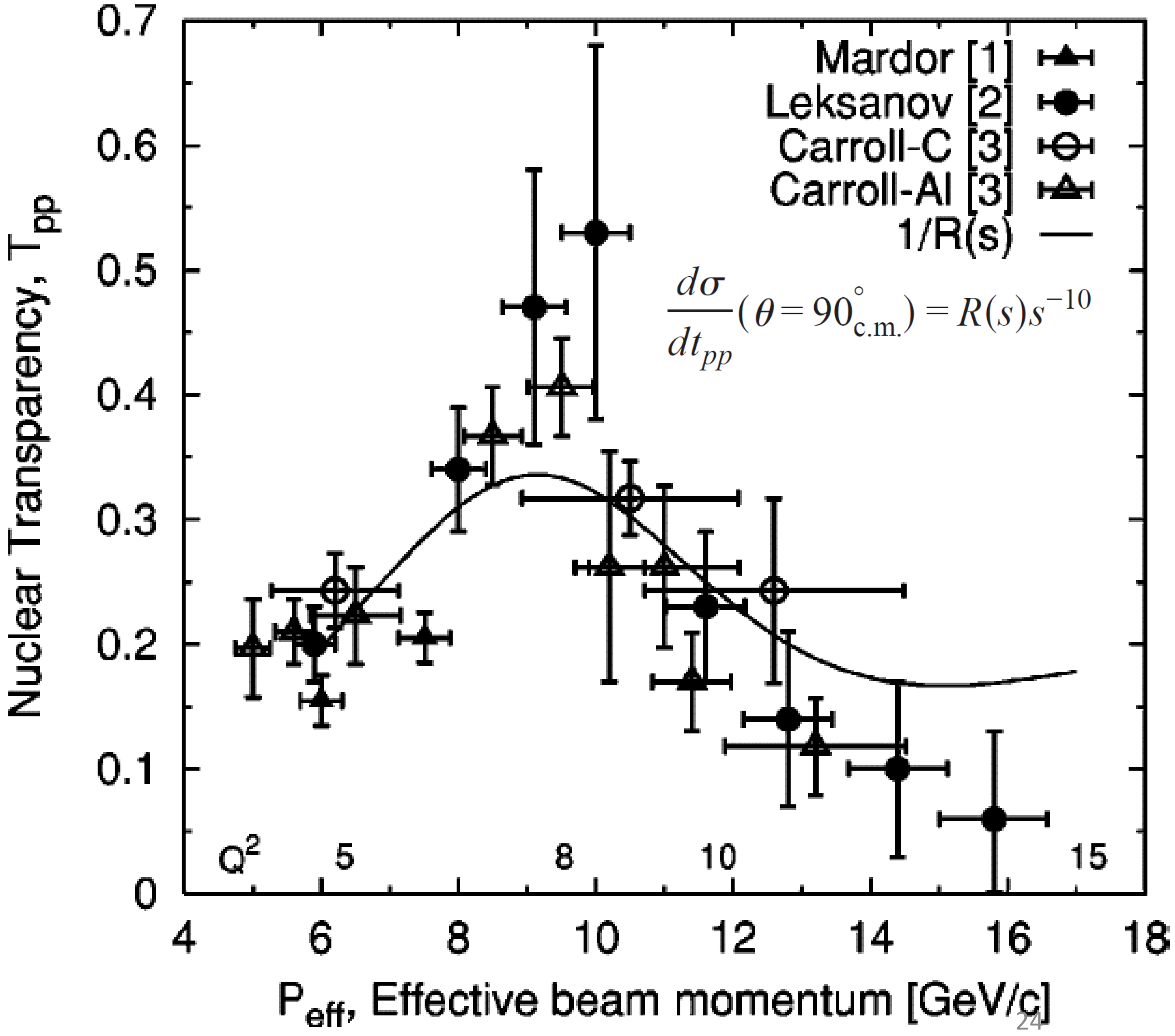


Possible interpretations for the BNL A(p,2p) results

- Probably not Color Transparency, because
  - Decrease in NT above 9.5 GeV/c
  - Recent (e,e'p) data up to Q^2 equivalent to outgoing proton momenta similar to BNL show no Color Transparency

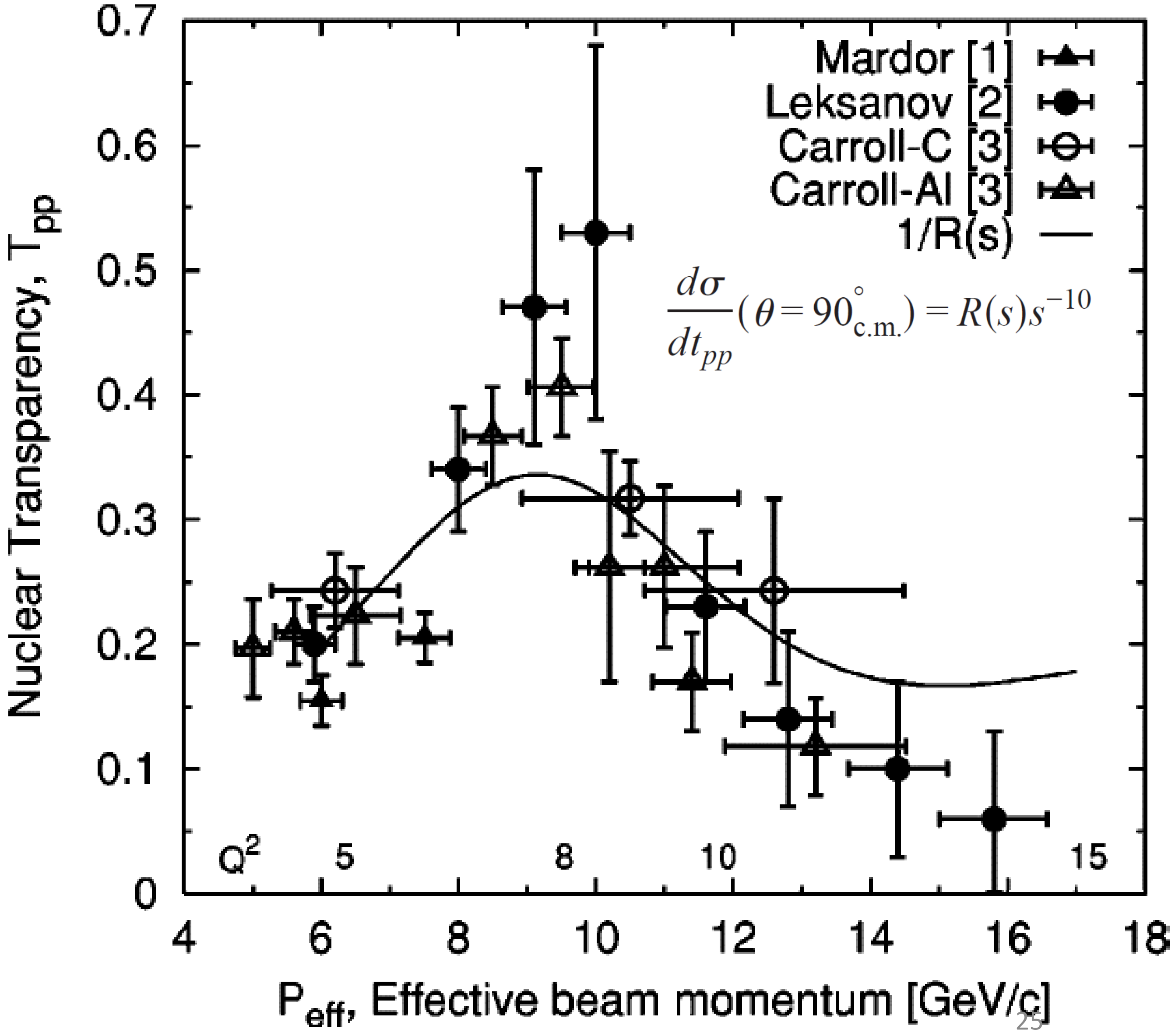


D. Bhetuwal et al., Phys. Rev. Lett. 126, 082301 (2021)



Possible interpretations for the BNL A(p,2p) results

- Perhaps 'nuclear filtering' of certain part(s) of the pp reaction amplitude
- Free pp cross section is a combination of the perturbative QCD "small" component and a "large" component (Ralston & Pire)
- Large component is filtered by the nucleus, so NT behaves like inverse of the pp cross section (s^{-10} cancelled out)
- Large component may be:
  - Independent quark scattering (Landshoff)
  - Open-charm resonance (Brodsky & De Teramond)
  - …



Outlook – possible extensions of NT experiments

- **Increase A(p, 2p) incoming momentum to > 20 GeV/c** - will NT rise again, as anticipated by 1/R(s)?
- **A-dependent studies of A(p,2p) in the 12 to 15 GeV/c range** - will the effective absorption cross section continue to fall after NT stops rising at 9.5 GeV/c?
- **Singly or doubly polarized measurements** – will a relatively pure pQCD state be selected, and are spin dependent effects attenuated?
- **Use of π, k and $\overline{p}$ induced reactions** – how will different mechanisms and cross sections affect NT?
- **Production of resonances, such as ρ or Λ** - Will the interference terms that generate asymmetries disappear for reactions that take place in the nucleus?
- **Investigate FSI of light nuclei at special kinematics** – Will short distance between first and second hard scatter overcome PLC expansion and reveal CT?

Many thanks to all E834 and E850 Collaborators