Color Transparency

(The study of High – PT , Small Configurations and Filtering)

Steve Heppelmann
Penn State University

The Physics of p+A Collisions at RHIC

7-9 January 2013 *BNL Physics Building*
US/Eastern timezone

New STAR FMS Result: A_N for Forward π^0 's rises with P_T to P_T of 10 GeV/c

The observed increase in A_N with P_T may be associated more with **"isolated" π^0's rather than "jet-like" π^0 fragments**.

(see talk by Len Eun)

How we scatter at High P_T.
Theory of scattering from a target (i.e. proton), has theoretical roots in Optics.

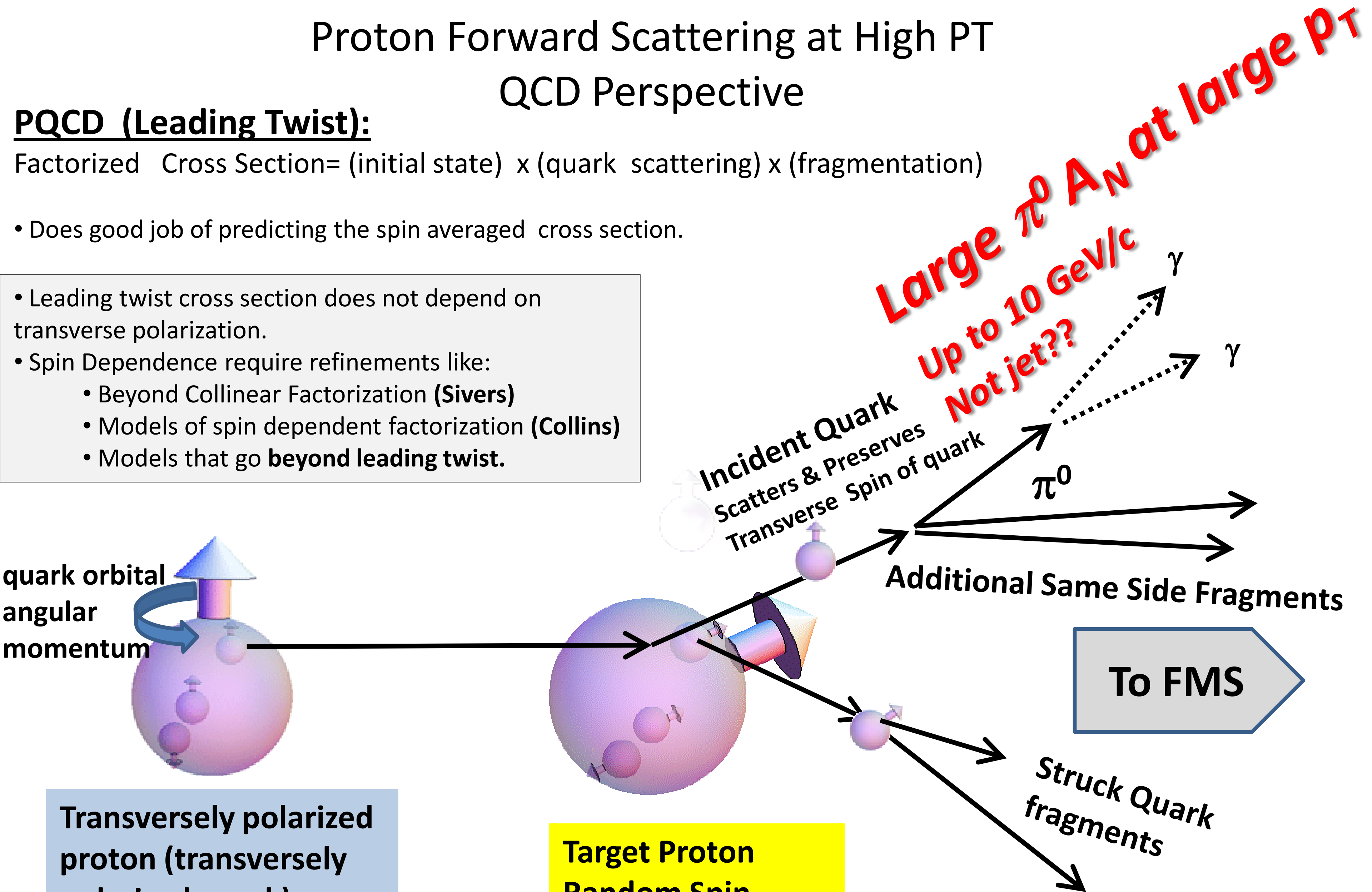
Proton Forward Scattering at High PT
QCD Perspective

PQCD (Leading Twist):

Factorized Cross Section= (initial state) x (quark scattering) x (fragmentation)

- Does good job of predicting the spin averaged cross section.

- Leading twist cross section does not depend on transverse polarization.
- Spin Dependence require refinements like:
    - Beyond Collinear Factorization **(Sivers)**
    - Models of spin dependent factorization **(Collins)**
    - Models that go **beyond leading twist.**



Transversely polarized proton (transversely polarized quark)
RHIC Blue Beam

Target Proton
Random Spin
RHIC Yellow Beam

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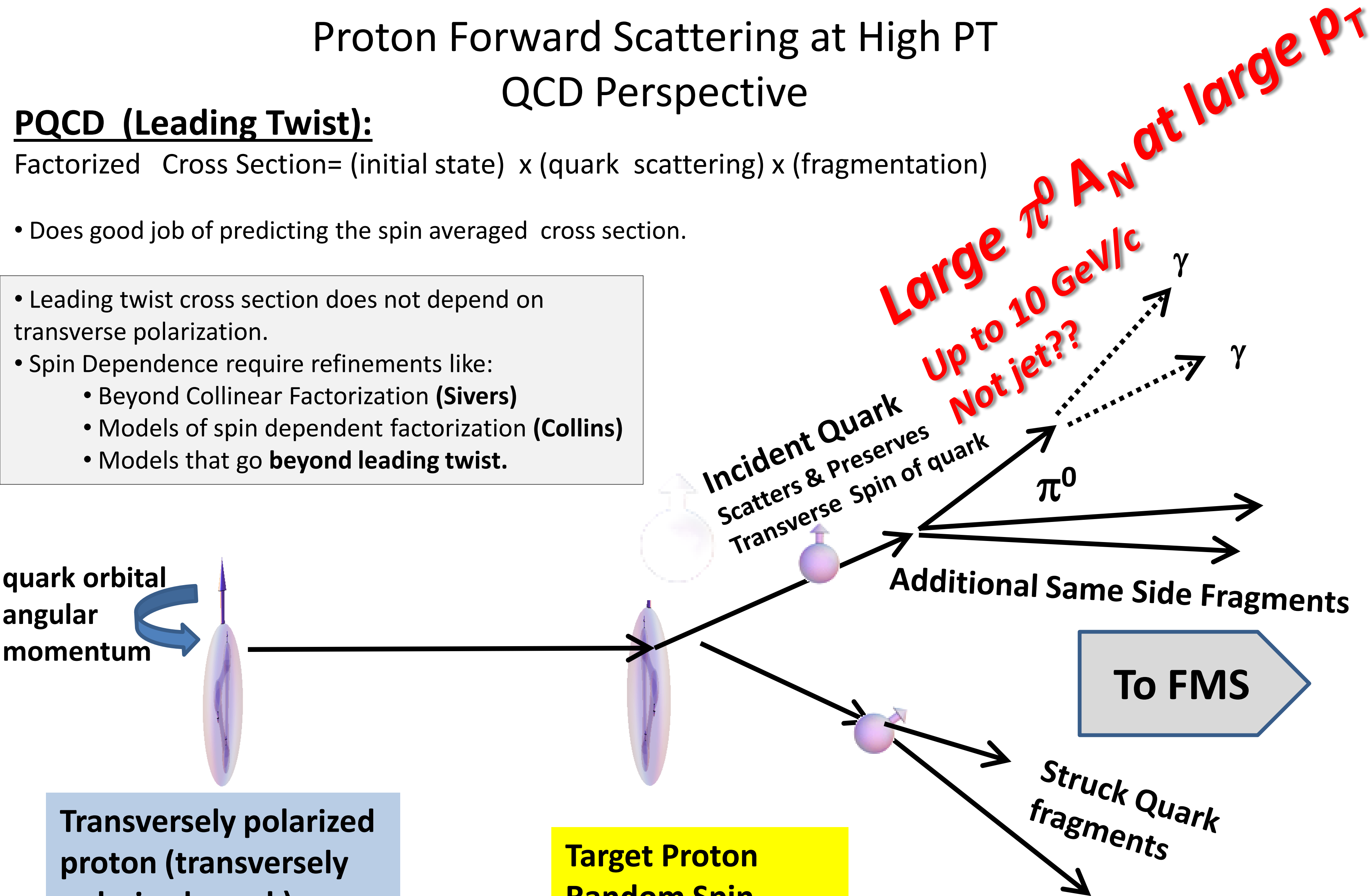

Transversely polarized proton (transversely polarized quark)
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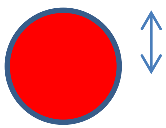
From Optics (Fraunhoffer Diffraction Limit)
If we scatter waves from a 2D object
And the source of the outgoing
wave (pions)
Is the sum of Huygens waves
From all points on the 2D surface.

High p_T means production a very localized point on this surface

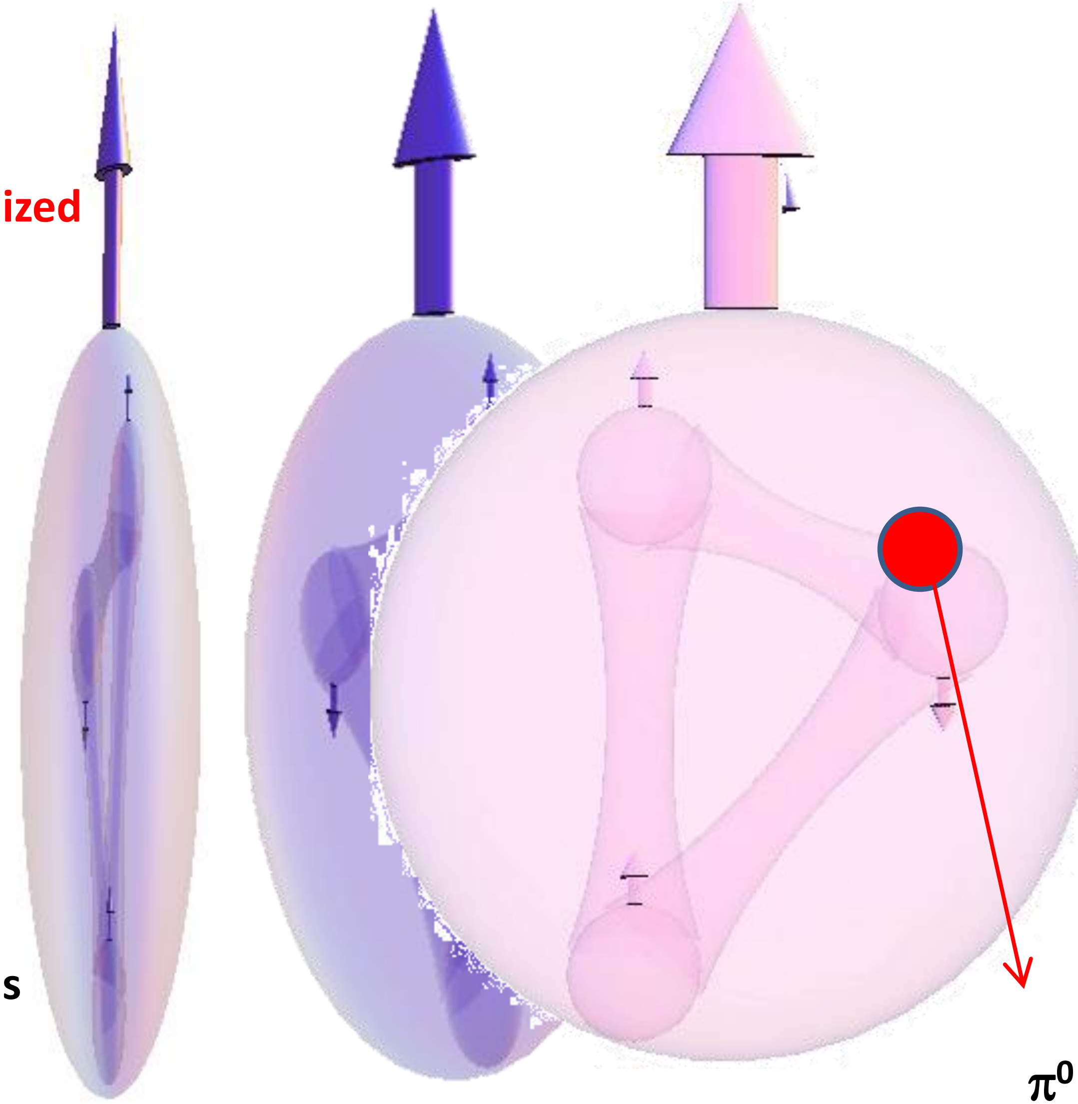


$\Delta R \rightarrow 1/\Delta pT$

If the source size is the full proton
"Diffraction"

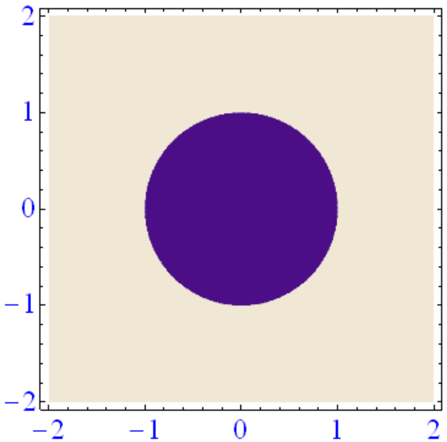
The only small scale structures we know about in protons about are the partons.

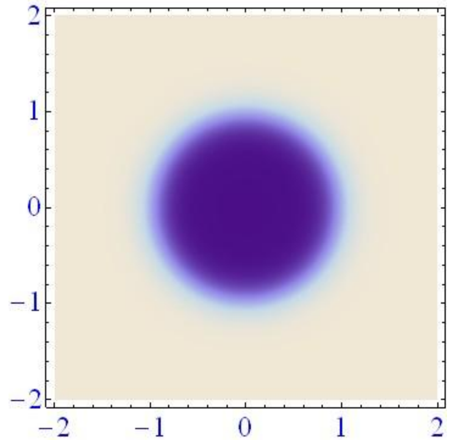
For those small source contributions we use PQCD.



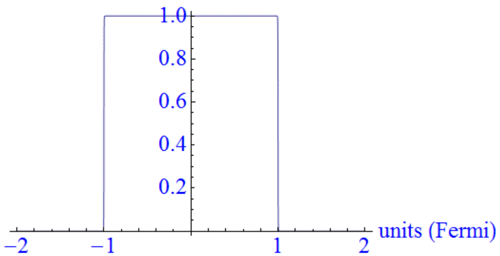
Diffraction Review : (Fraunhoffer Diffraction → Amplitude = Fourier Transform)
Fourier transform of a **circular uniform disk has high p_T components,**

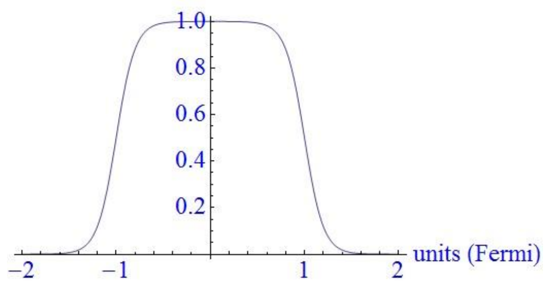
but for a **1 F disk with a smeared edge (ΔR=0.1 F)** , high p_T components are suppressed.

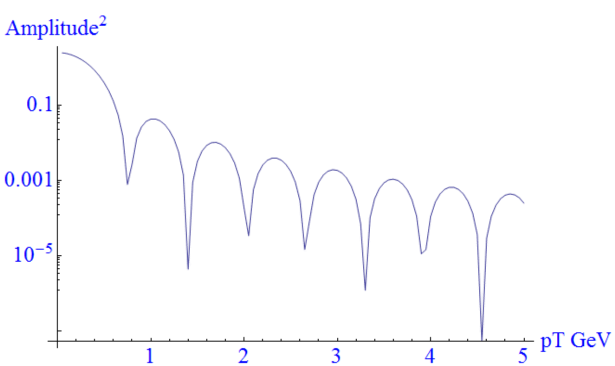


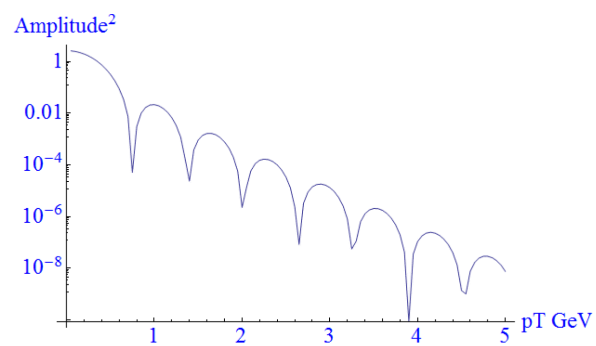


Large p_T cross section is Dominated by Scattering from Small Targets Features!!!









.... **Large p_T does require Scattering from short distance scale features.**
(like a sharp edge)
If not PQCD then what???

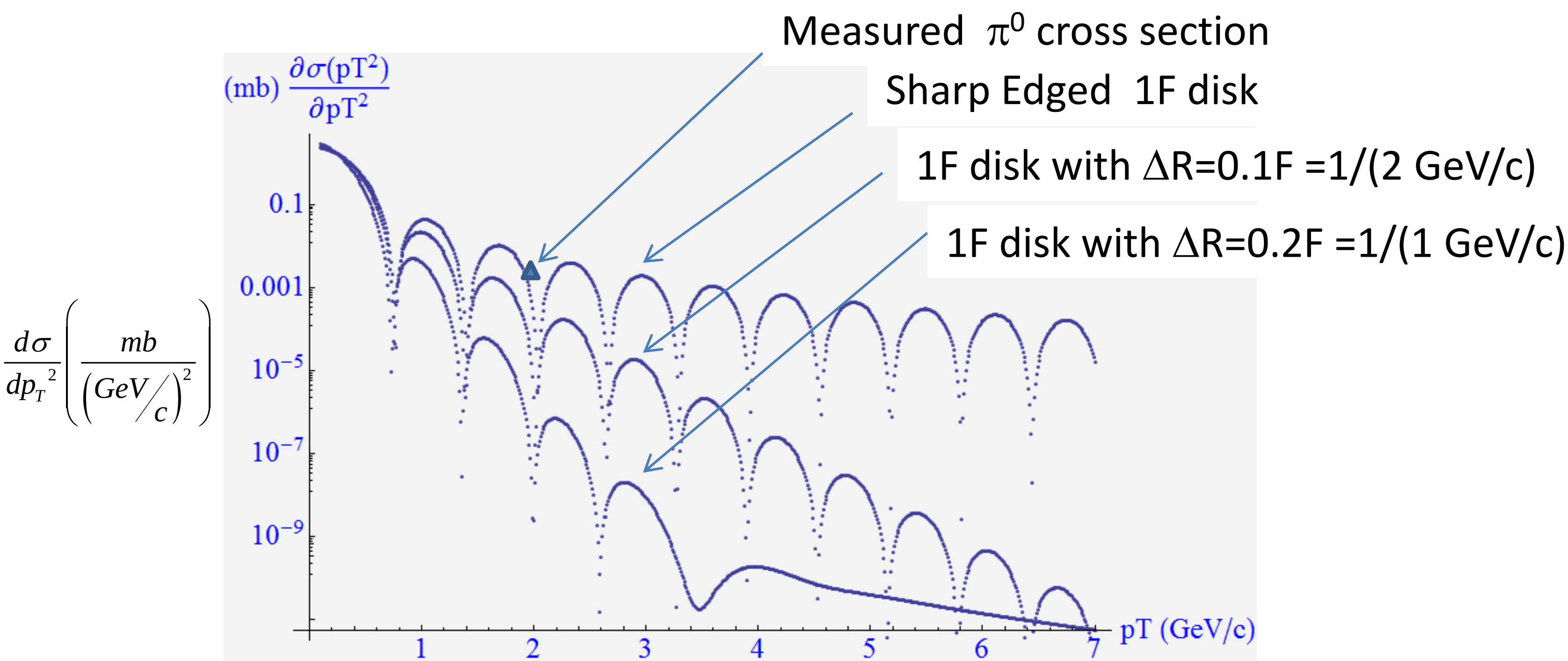
Compare to possible diffraction to pi0.
Consider Pi0 : (0.25<xF<.35, pT ~ 2 GeV/c)
Measured cross section:

$$\left.\frac{d\sigma}{dp_T^{\,2}}\right|_{p_T=2GeV/c} \sim 1\frac{\mu b}{GeV^2}$$

Phys.Rev.D86:051101,2012.
For details see Len Eun's Thesis
Or his talk today.

Suppose the total diffractive cross section for π^0 ($0.25<x_F<0.35$) is 10 mb.

Then diffraction gives p_T dependent cross section for different disk edge sharpness.



1. **Like Fraunhoffer scattering of light from a 2D optical object**

   Amplitude $A(P_T)$ is Fourier Transform of transparency/opacity (with phase) of 2D object.

   a) point-like components: $A(P_T)$ is **transverse Fourier Transform of Hard PQCD Amplitude**

   b) Dist-like object (radius R): $A(P_T) = J_1(r\,P_T)/P_T \propto P_T^{-(3/2)}$ and cuts off at $P_{T\max} = \frac{1}{\Delta R_{edge}}$
   with ΔR_{edge} the width of the disk perimeter.

   c) In general, observation of amplitude at large P_T requires a feature in the scattering profile of size ΔR.

   $$\boxed{P_T = \frac{1}{\Delta R}}$$

2. **Exceptions or enhancements to this can come from:**

   a) Long Range Order (like diffraction grating adding amplitudes) .

   b) Decay of high mass objects

   c) Classical multiple scattering. (adding cross sections not amplitudes)

   d) ???

c. In general, observation of amplitude at large P_T requires a feature (i.e. absorption or transparency)" in the scattering profile of small size

$$\Delta R \sim 1/P_T.$$

For **large A_N** at **large P_T**, there must be a localized absorption or transparency that depend on transverse spin. This at the level of the appropriate size $\Delta R \sim 1/P_T$.

At high energy, π production in **leading twist PQCD**

- does not depend on transverse proton spin.
  - Amplitude is real (no absorption)
  - No helicity flip

Higher twist terms can both flip helicity and introduce a phase in amplitude, required for non-vanishing A_N. But higher twist terms fall with additional powers of P_T.

A_N growing with P_T out to P_T~ 10 GeV is a mystery.

Studying A_N in nuclei can give hints as to the possible role of small color neutral configurations in this observation.

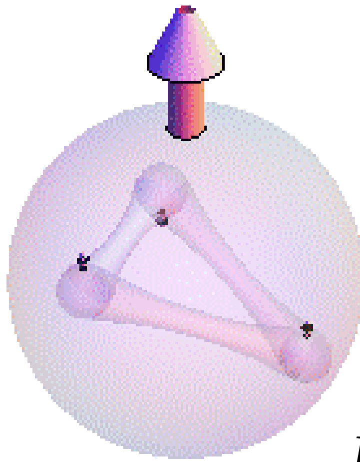
Color Transparency
Polarized Proton Collisions
AGS to RHIC

Steve Heppelmann
Penn State University

- **The Proton is:**
  - A color neutral collection of 3 colored valence quarks
  - Valence quarks are connected with gluon (sea quark) fields.
  - Fields mostly confined to average radius ~ 1 Fermi.
  - Average area Average Cross Section

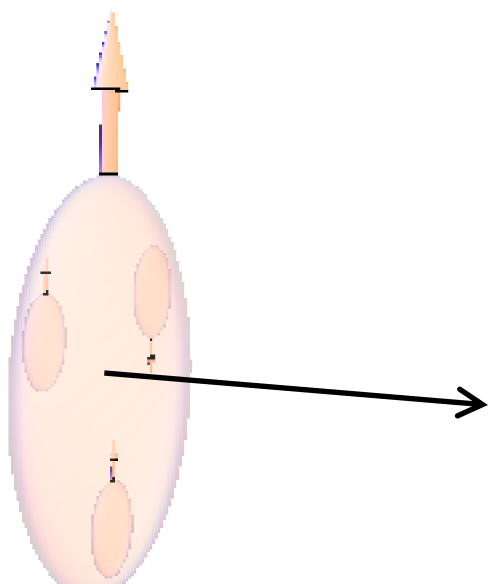
$$\sigma \approx \pi r^2 = \pi\left(10^{-15}\right)^2 m^2$$

  - Radius fluctuates with time! *
  - Proton Absorption Cross Section fluctuates with time.

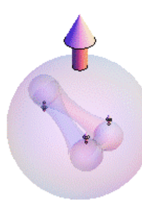


Large proton

$$R_T \approx \frac{1}{p_T}$$

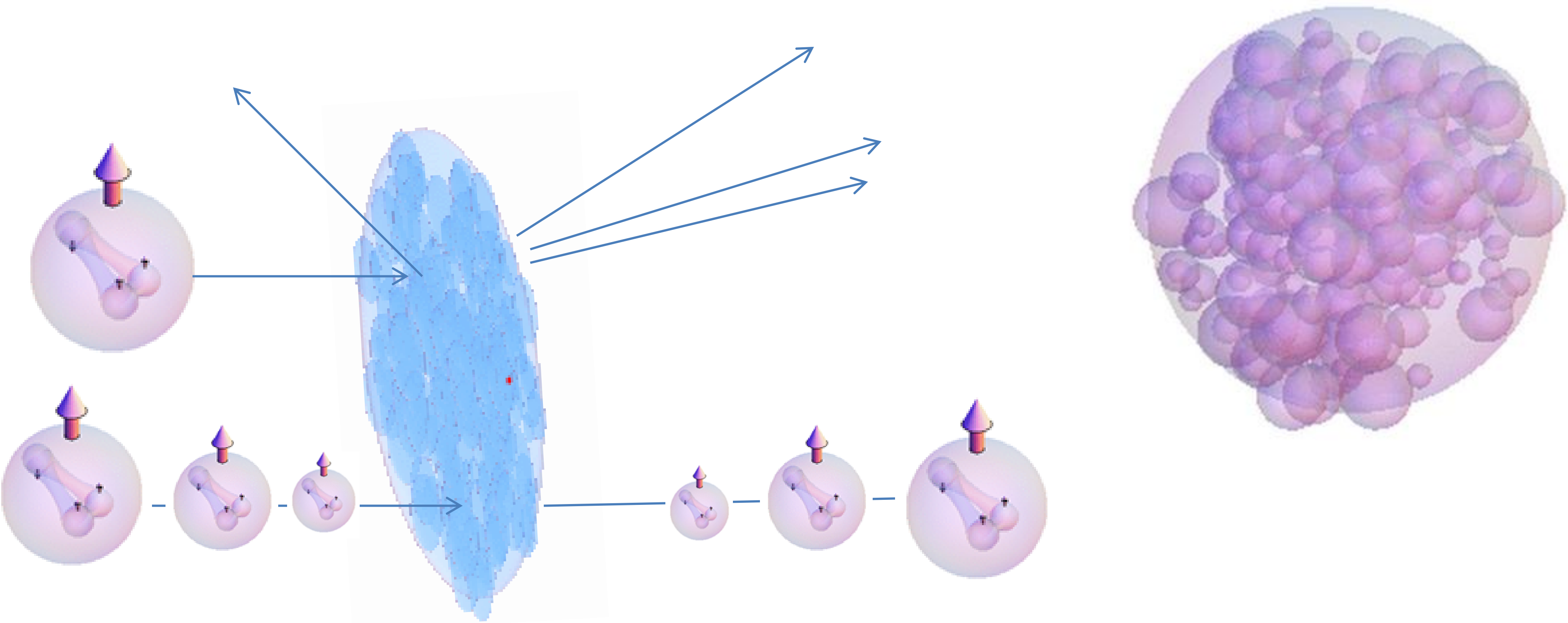


Relativistic proton



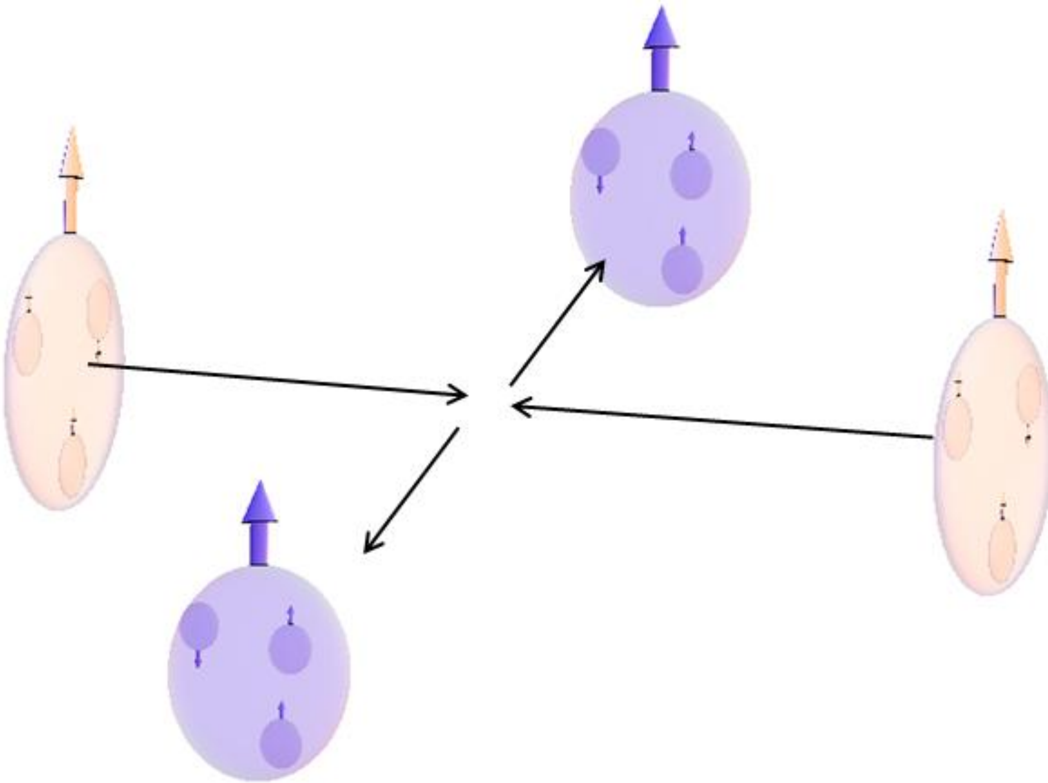
Small proton

At a given instant……
every nucleon in a Gold Nucleus is a different size
……and fluctuating * in time. (relativisticly flattented) *



The nucleus absorbs normal protons much more than small protons.
…. **Nucleus more transparent if proton is a small proton**
….. Likely to pass if proton **hits nuclear edge** or a region of the nucleus near **small nuclear proton or neutron configurations**.

The amplitude for pp elastic scattering involves the probability that quarks come together within a distance given by the p_T scale, and depends on the number of quarks. (Dimensional Scaling).



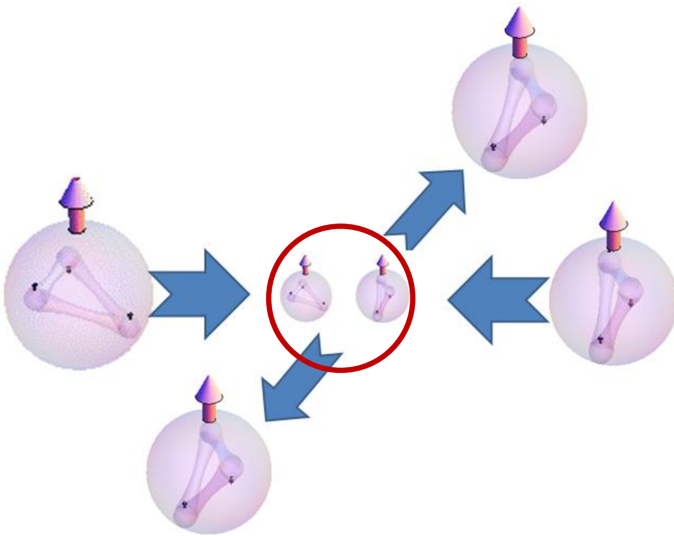
$$p_T \sim \frac{\sqrt{s}}{2}$$

$$a + b \rightarrow c + d$$

$$n_a = n_b = n_c = n_d = 3\,quarks$$

$$\frac{d\sigma}{dp_T{}^2} \propto s^{-(n_a+n_b+n_c+n_d-2)} = s^{-10}$$

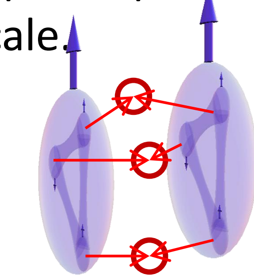
The probability to scattering exclusively is observed to be consistent with the probability (phase space) **<u>for all the quarks</u>** wandering together, to a distance scale ~ $1/p_{T}$.



$$\left(\frac{d\sigma}{dp_T}\right)_{all\,small} \propto s^{-10}$$

Dimensional Scaling

This is much less than the probability that each of 3 quarks of one proton pairs up with one of 3 quarks from the other proton , interacting at the $1/p_T$ distance scale.



(A condition to **turn** the 3 valence quarks
but not gluons and virtual quarks)

? Landshoff Scaling +Sudakov Suppression
=> Dimensional Scaling

$$\left(\frac{d\sigma}{dp_T}\right)_{3\,pairs} \propto s^{-8}$$

Landshoff Scaling

PP Cross Section (90° CM)

$$\frac{d\sigma_{pp\to pp}}{dt} \propto \frac{1}{s^{3+3+3+3-2}} = \frac{1}{s^{10}}$$

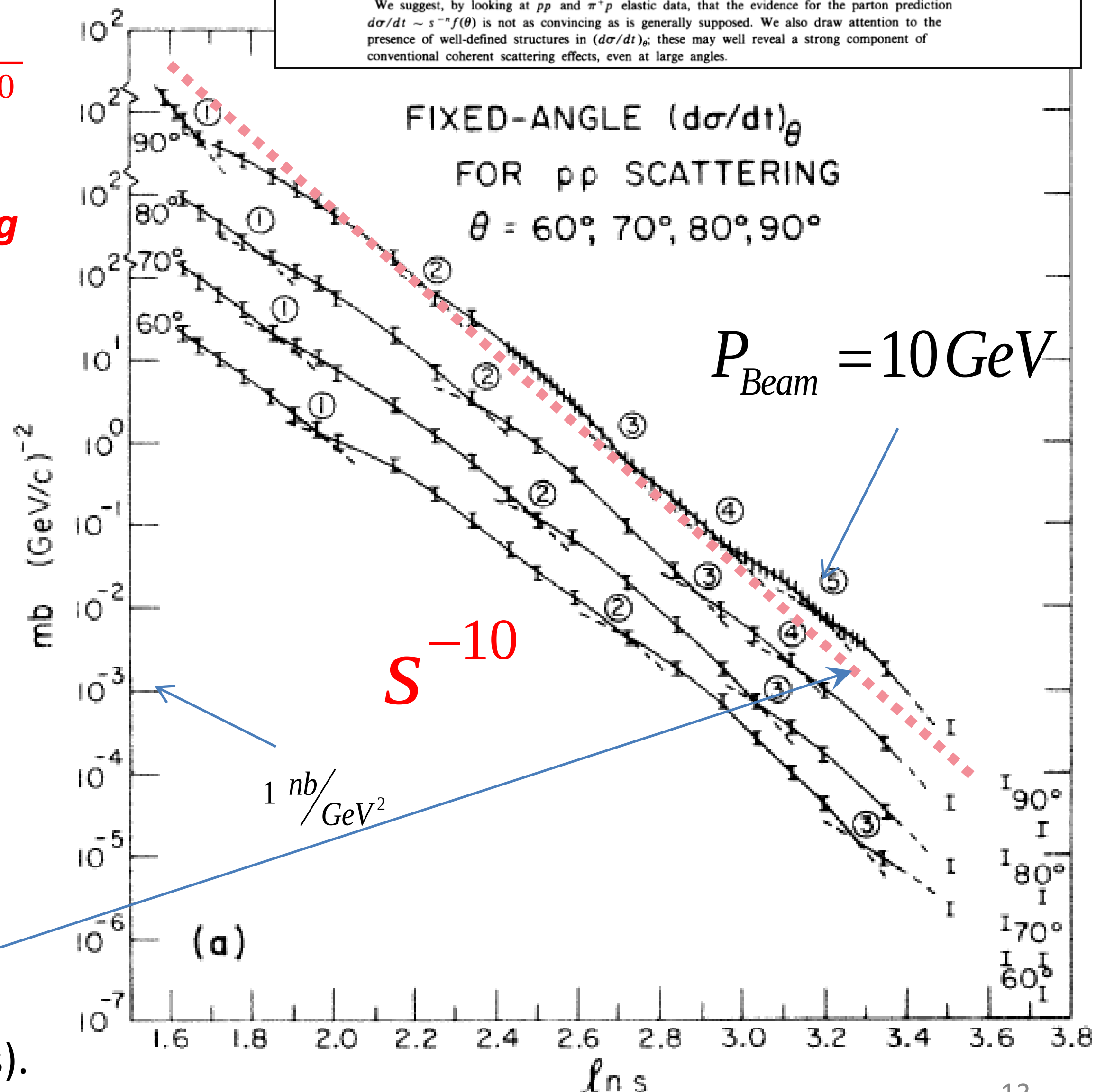
Evidence for Dimensional Scaling In pp Elastic Scattering.

PHYSICAL REVIEW D VOLUME 10, NUMBER 7 1 OCTOBER 1974

Evidence for coherent effects in large-angle hadron-hadron scattering*

Archibald W. Hendry
Physics Department, Indiana University, Bloomington, Indiana 47401
(Received 8 April 1974)

We suggest, by looking at pp and π^+p elastic data, that the evidence for the parton prediction $d\sigma/dt \sim s^{-n}f(\theta)$ is not as convincing as is generally supposed. We also draw attention to the presence of well-defined structures in $(d\sigma/dt)_\theta$; these may well reveal a strong component of conventional coherent scattering effects, even at large angles.

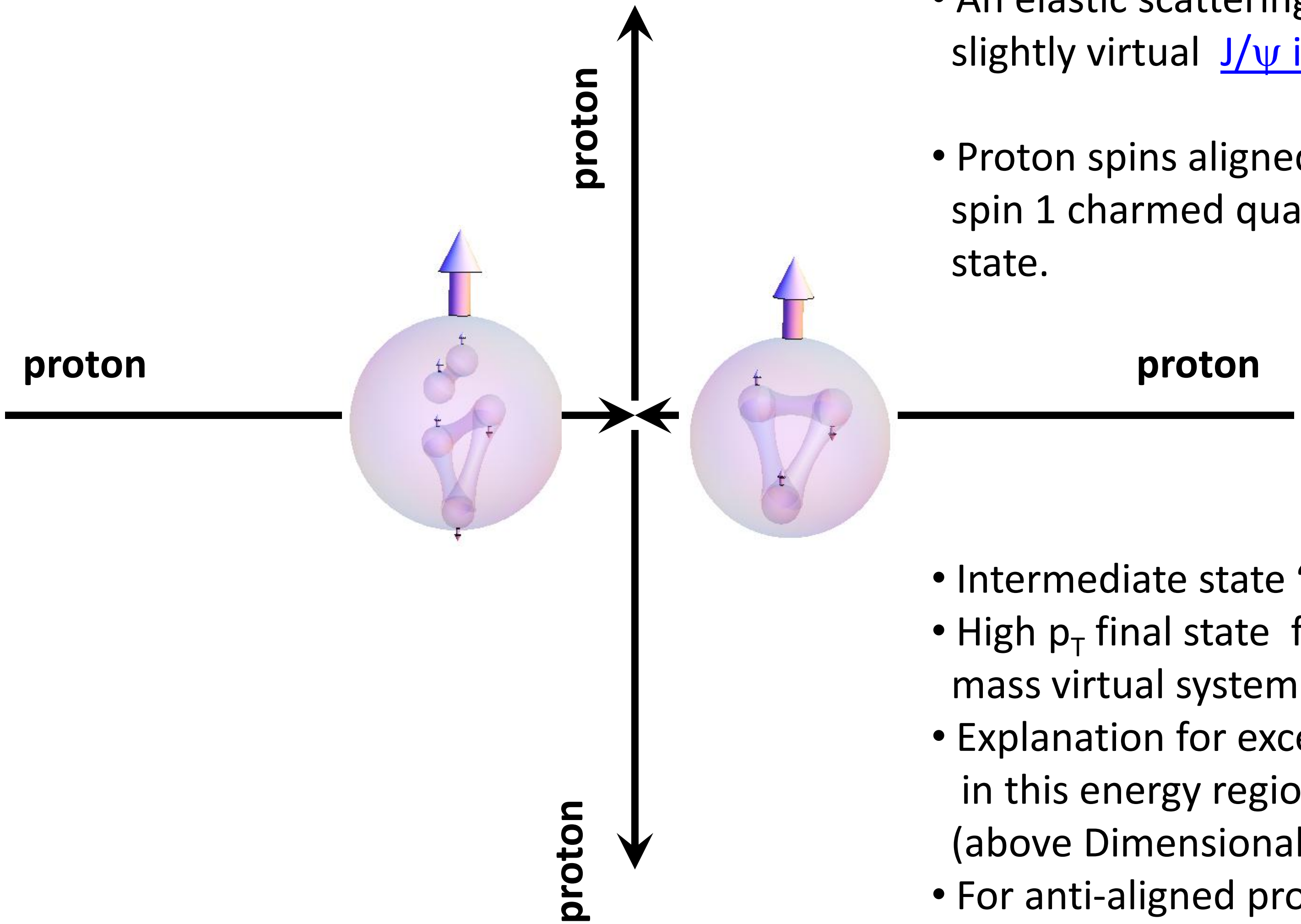


BUT

1. Hendry 1976
   a) Factor of 2 deviations from scaling. (1<R<2)
   b) ?Remnant of diffraction.
2. Ralston –Pire
   a) ?Energy dependent oscillations of Landshoff suppression.
3. Brodsky-DeTeramond 1991
   a) Extra cross section near threshold (in s channel) for **charm** (and strangeness).

Brodsky – deTerramond: Idea about thresholds for quark anti-quark pair *mass scales.

(**charm threshold**) $\sqrt{s} \rightarrow 2m_p + M_{J/\psi} \sim 5\,GeV$



- An elastic scattering channel with slightly virtual J/ψ in "s" channel* .

- Proton spins aligned to favor creation of spin 1 charmed quark pair intermediate state.

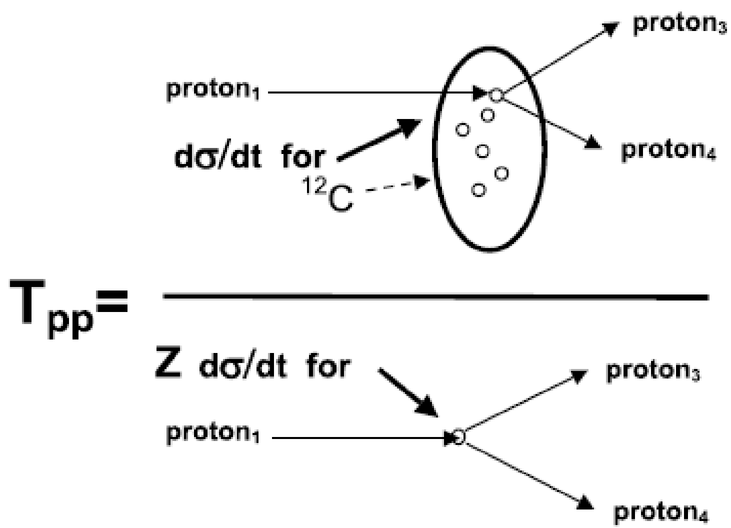
- Intermediate state **"not" small size.**
- High p_T final state from decay of high mass virtual system into two protons.
- Explanation for excess cross section in this energy region . (above Dimensional Scaling)
- For anti-aligned protons, this process should be strongly suppressed.

The **Color Transparency** Variable

T is the fraction of nuclear protons that contribute to pp quasi-elastic scattering.

The ratio of:

- the observed hard scattering cross section in nuclei
- to the same hard scattering cross section with free protons.



90 Degree CM pp Elastic Cross Section at High Energy
Not possible for high energy

AGS :

$$\sqrt{s} = 5\,GeV^2 \qquad \frac{d\sigma}{dt} = 1\frac{nb}{GeV^2}$$

RHIC :

$$\sqrt{s} = 250\,GeV^2 \qquad \frac{d\sigma}{dt} = 10^{-17}\frac{nb}{GeV^2}$$

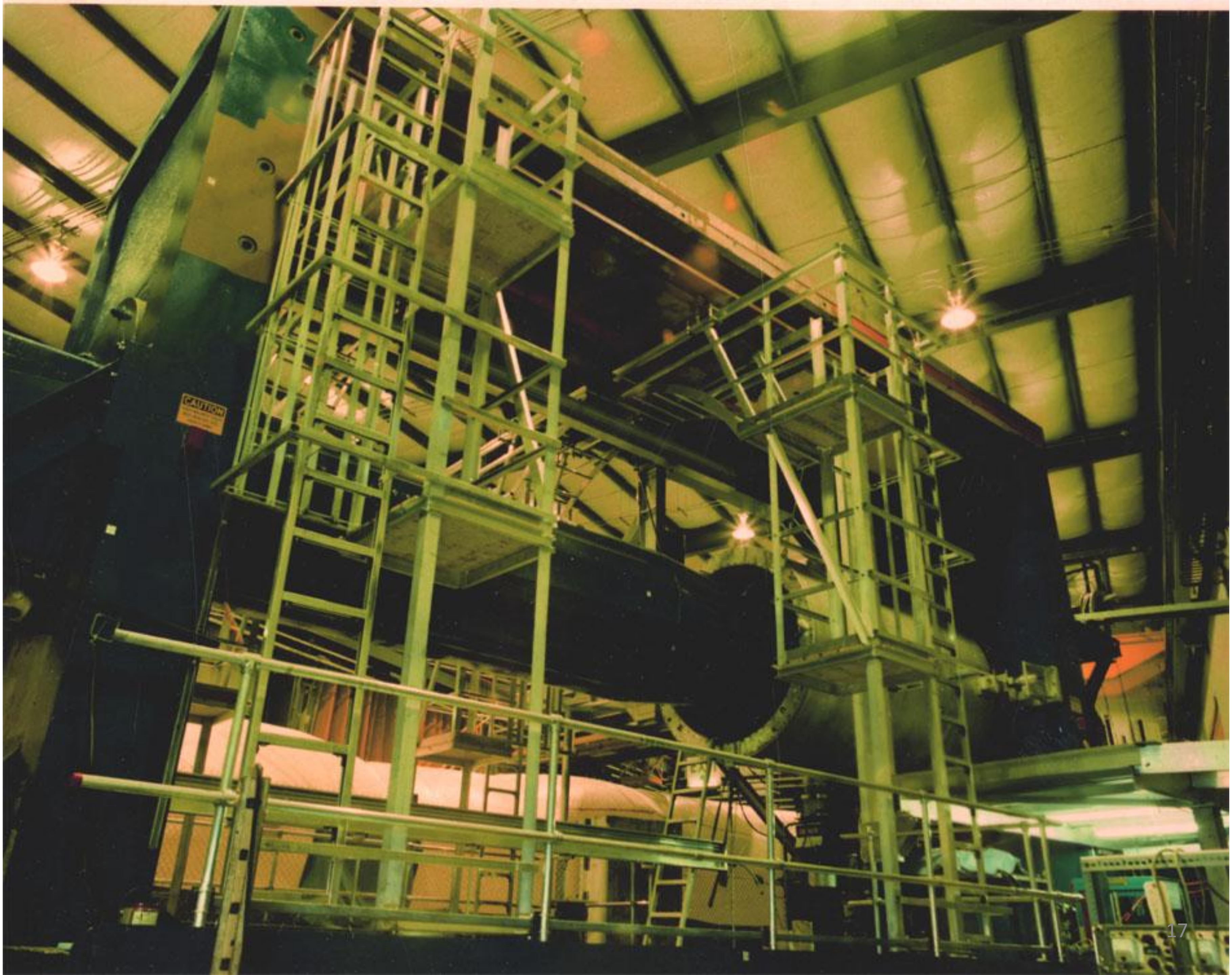
RHIC A_N
Measurement (1%):

$$\frac{d\sigma}{dt} \approx 0.1\frac{nb}{GeV^2}$$

Small cross sections
Rare events

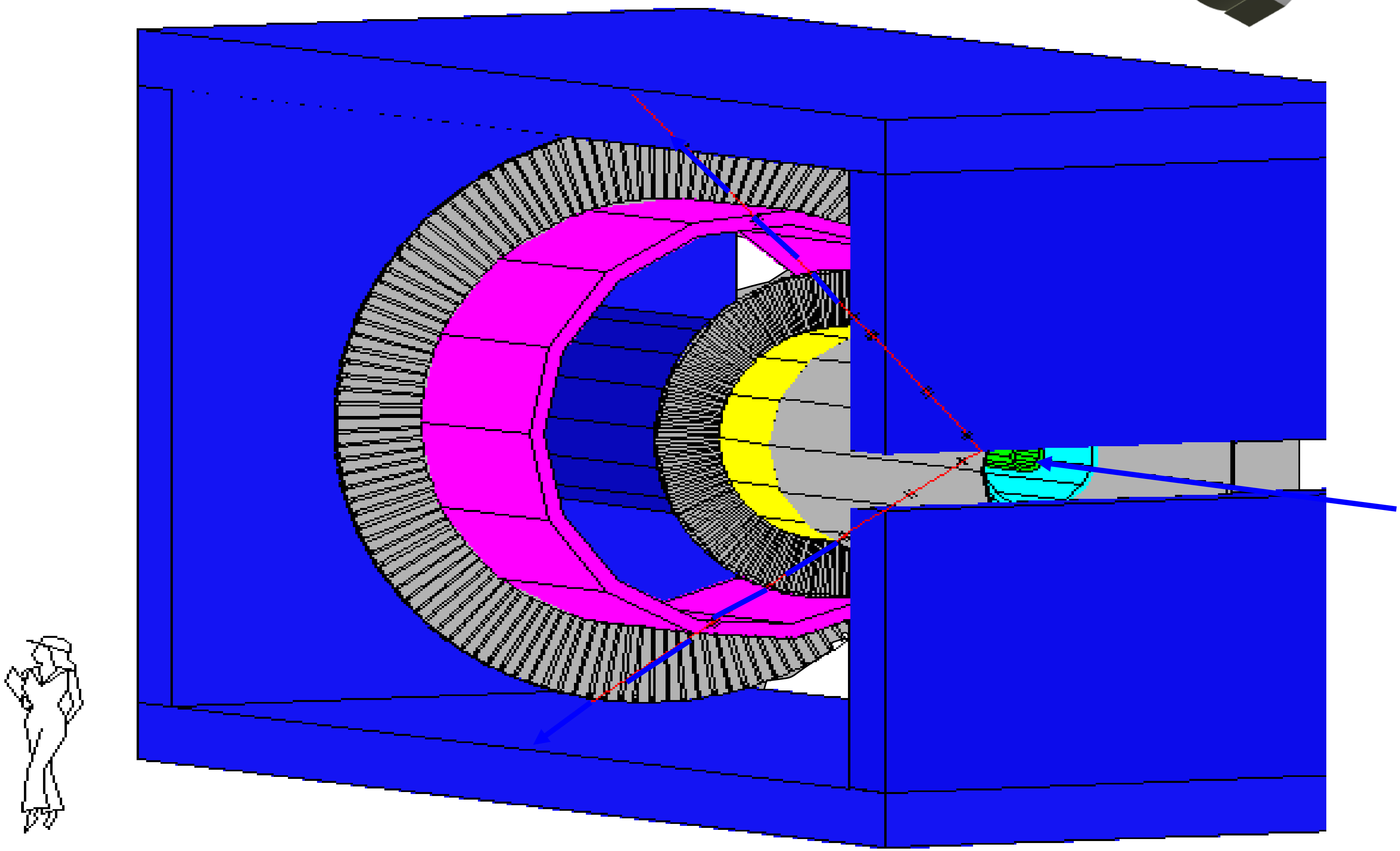
⟷

Small protons


CAUTION

The EVA Apparatus AGS Experiment E850 BNL

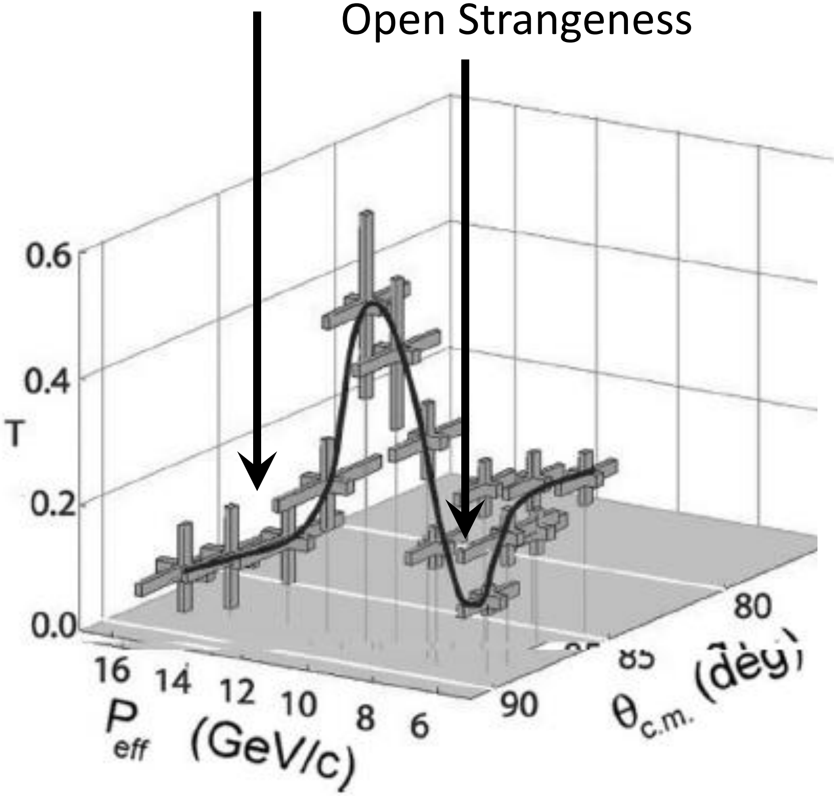
E850 Eva

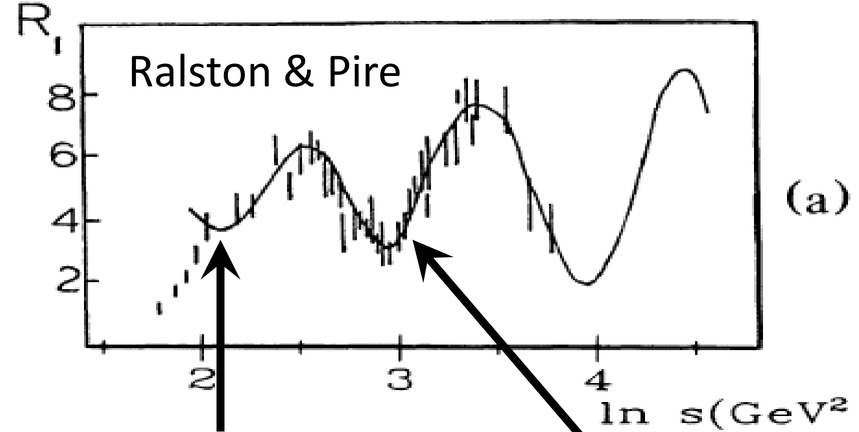


AGS Exp 850
Nuclear Transparency in 90 degree c.m.
Quasielastic A(p,2p) Reactions.
Phys. Rev. C (70) 015208 (2004)

Open Charm

Open Strangeness

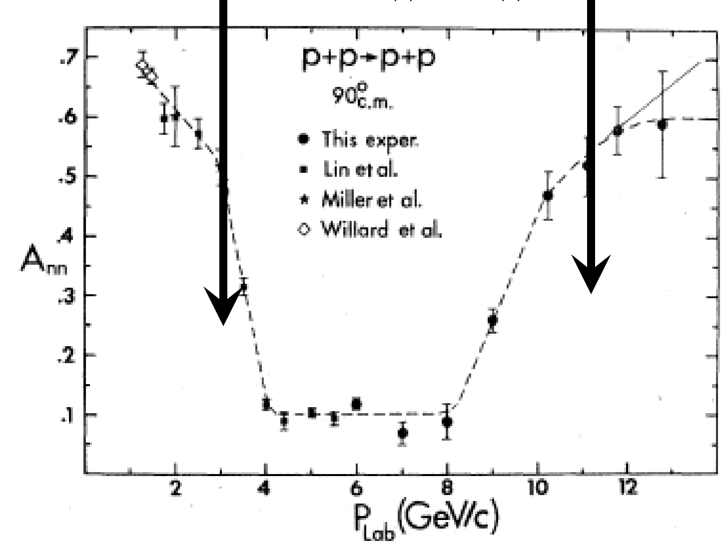




Open Strangeness

Open Charm

$$A = \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}}$$



PHYSICAL REVIEW D VOLUME 23, NUMBER 3 1 FEBRUARY 1981

Energy dependence of spin-spin effects in *p*-*p* elastic scattering at 90°$_{c.m.}$

Crosbie, E.A. and Ratner, L.G. and Schultz, P.F. and O'Fallon, J.R. and Crabb, D.G. et. all.

Transparency for PP and πP quasi-elastic scattering as a function of Atomic Mass.

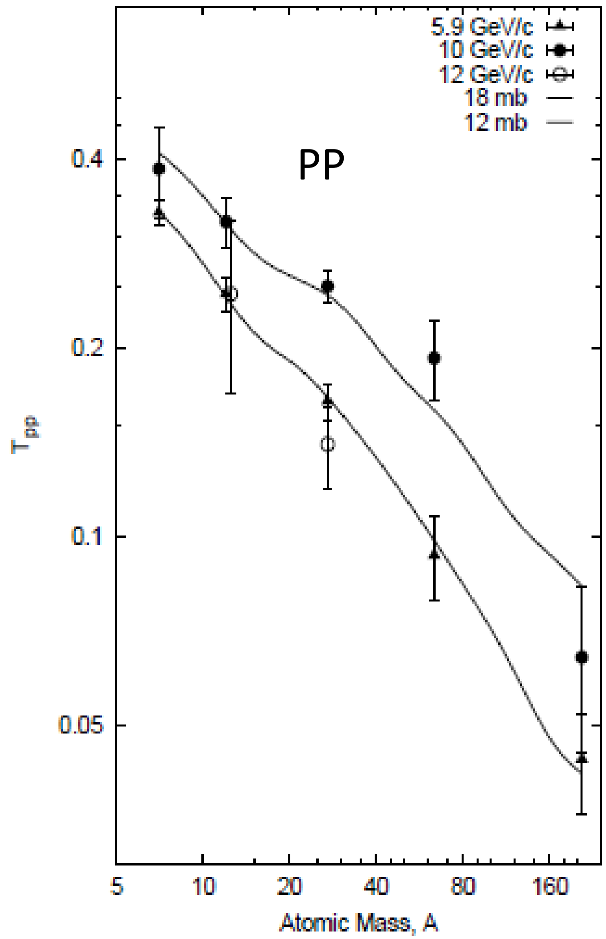


FIG. 20: Nuclear transparency vs Atomic Mass A for the A(p,2p) measurements from E834 for incident momenta of 5.9, 10 and 12 GeV/c as indicated on the figure. The error bars reflect the statistical uncertainties and a 10% target-to-target systematic error. The solid curves represent the fits with constant effective cross sections to the five nuclei at 5.9 and 10 GeV/c as described in the text.

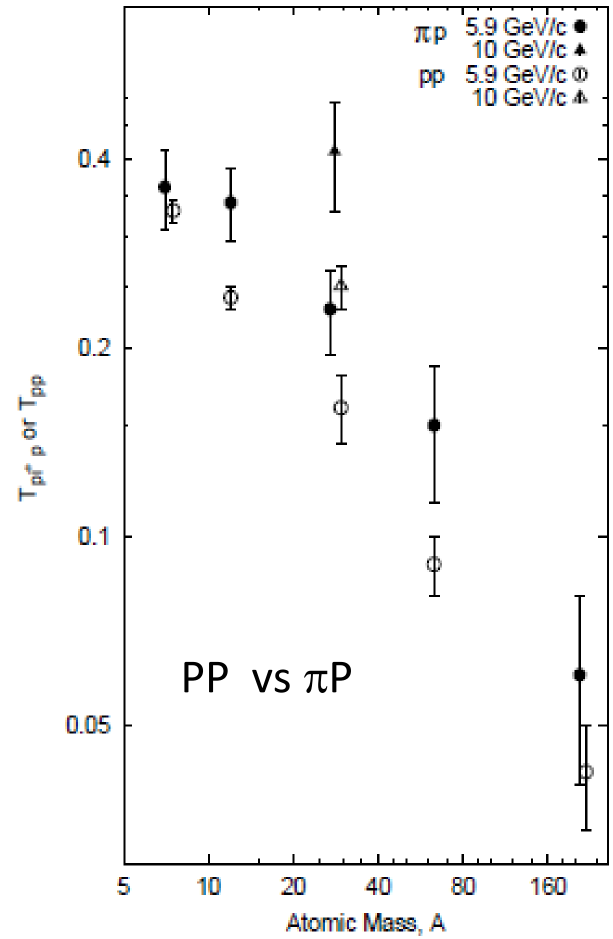


FIG. 21: $T_{\pi+p}$ and T_{pp} transparencies for Li, C, Al, Cu and Pb at 5.9 GeV/c, and Al for 10 GeV/c. The $T_{\pi+p}$ values (solid symbols) are consistently larger than those of T_{pp} (open symbols).

Summary Question

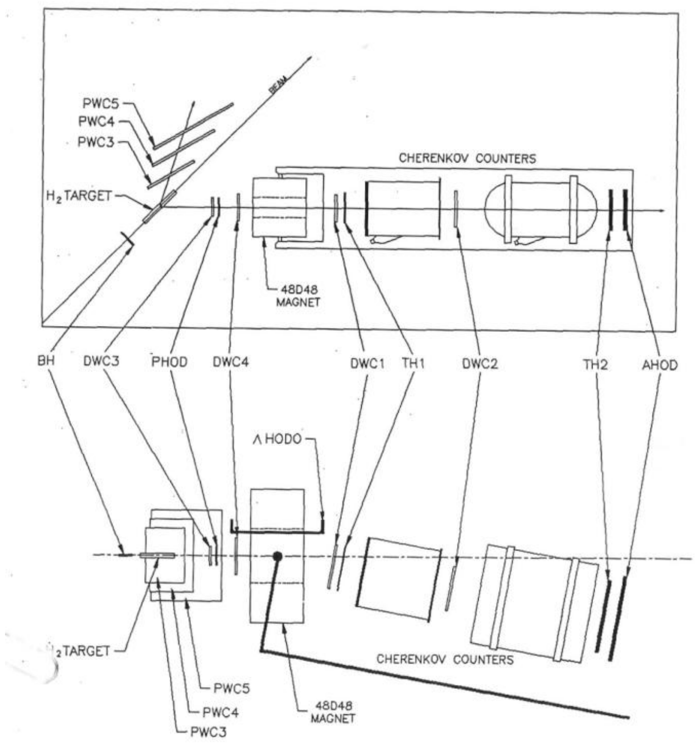
How will π^0 A_N change when filtered through a nucleus?

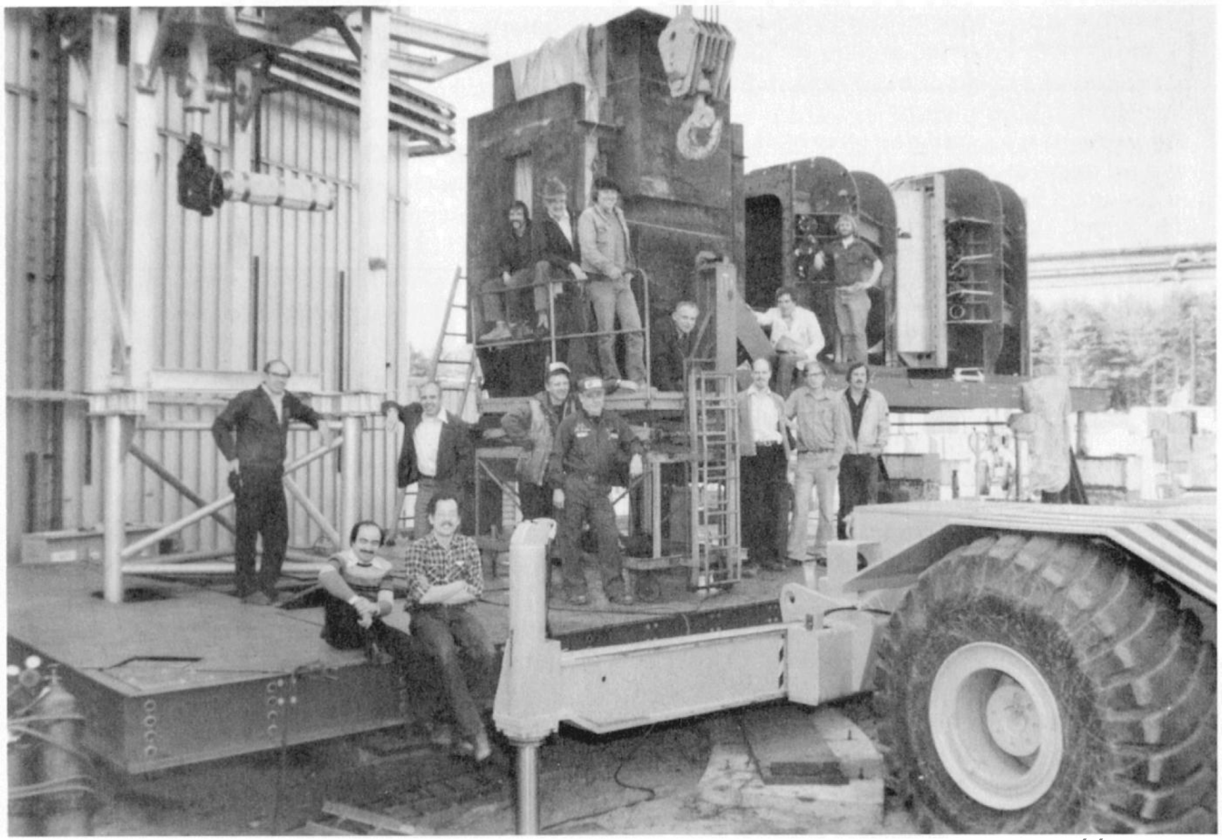
- **Comparison between pp and pA scattering can help identify small color singlet contributions to scattering processes.**
- **Large p_T pp elastic scattering (AGS energies) has transparency which correlate with very large transverse spin asymmetries and with variations of the cross section above dimensional scaling. Interpretations involve competing mechanisms of pp scattering.**
    - For example, this could be an indication of competition between hard scattering amplitudes (small protons) and a "nearly real q qbar pair" of charmed quarks in the s channel for pp scattering.
    - Or it could involve a competition between (small proton) hard dimensional scattering and (large proton) unsuppressed Landshoff scattering processes.
- **RHIC Transverse A_N in forward π^0 production at largest p_T may not come from quark fragmentation events (jets). What then?? Will filtering remove or enhance the "jet-like" vs "non-jet-like" contributions to A_N? Study vs. event multiplicity.**
- **Comparison of transverse A_N for π^0' s in pp and pA may help to establish (or not) contributions from of small color singlets, or large complex proton states, leading to large p_T π^0's.**

BNL-E-0755 Experiment

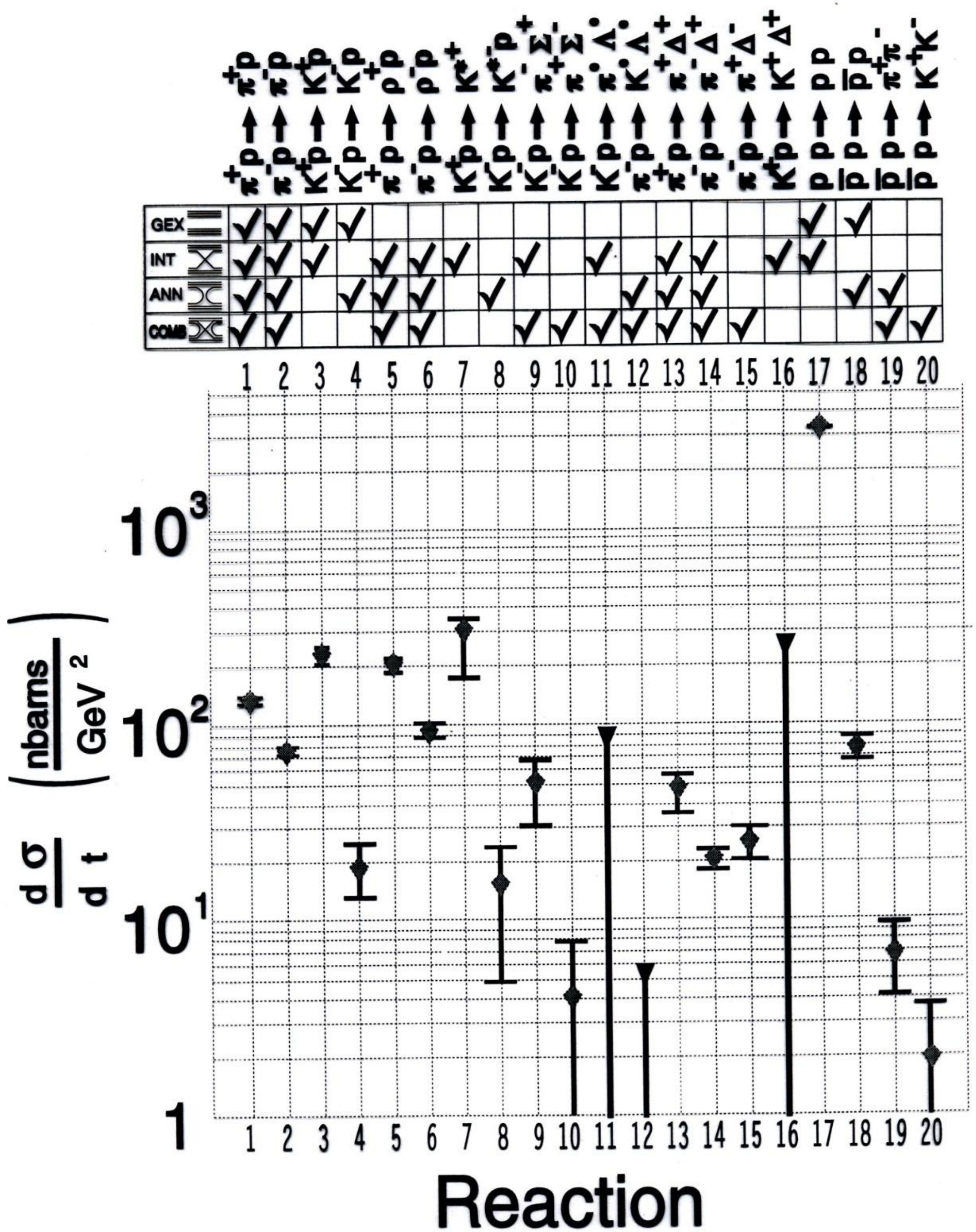
<u>PI- P TWO-BODY EXCLUSIVE REACTIONS AT 90 DEG FROM 8 GEV/C TO 18 GEV/C.</u>

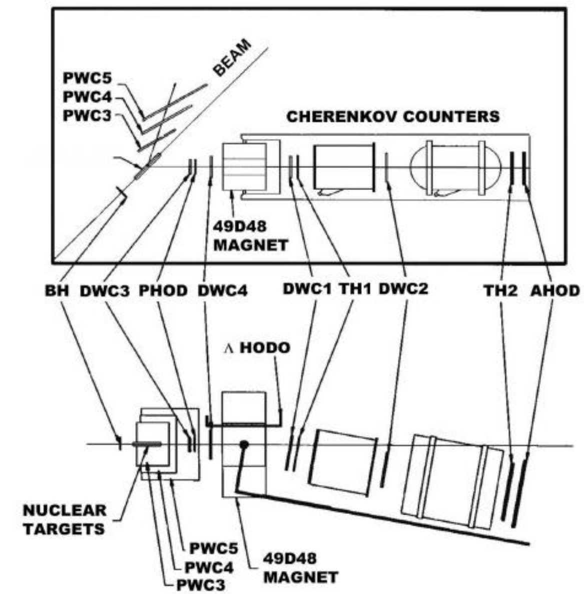
(Proposed: Jan. 1980, Approved: Oct. 1983,
Began: Feb. 1983, Completed: April 1984)





Brookhaven AGS Exp. E755
P beam = 5.9 GeV/c



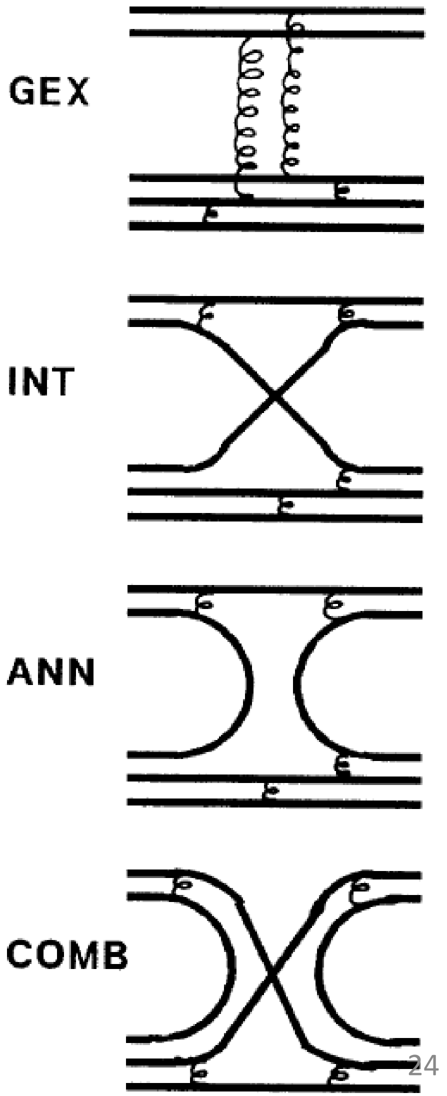


Cerenkov Id of secondary beam
+/- proton/ anti-proton
pi+ / pi-
k+ / k-

1) Final state particle magneticly analyzed with Cerenkov ID.
2) Recoil non-magnetic tracking.

Quark Exchange is the dominant mechanism for large angle scattering.

Those processes for which “INT” graph is possible, where a quark can move from one proton to the other, have the dominant cross sections.



Proton – Anti-proton scattering is nearly 2 orders of magnitude smaller that Proton-Proton cross sections at 90^o and beam momentum of 5.9 GeV/c.

Unknown:
Does Proton – Anti-proton scattering cross section scale with dimensional scaling.

Is transparency for Proton – Anti-proton different from Proton-Proton.?