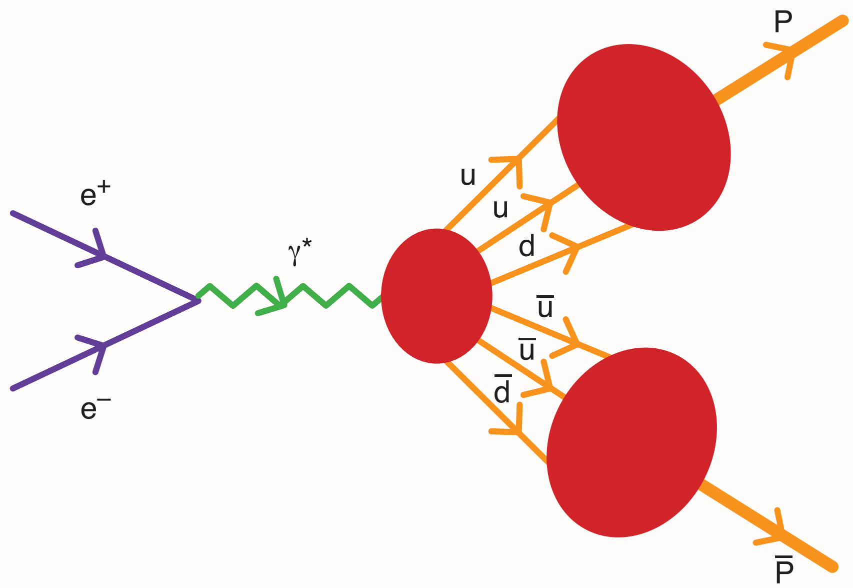
Timelike proton form factor in PQCD



$$G_M(Q^2) \rightarrow \frac{\alpha_s^2(Q^2)}{Q^4} \sum_{n,m} b_{nm} \left(\log \frac{Q^2}{\Lambda^2}\right)^{\gamma_n^B + \gamma_n^B}$$

$$\times \left[1 + \mathcal{O}\left(\alpha_s(Q^2), \frac{m^2}{Q^2}\right)\right]$$

Lepage and Sjb

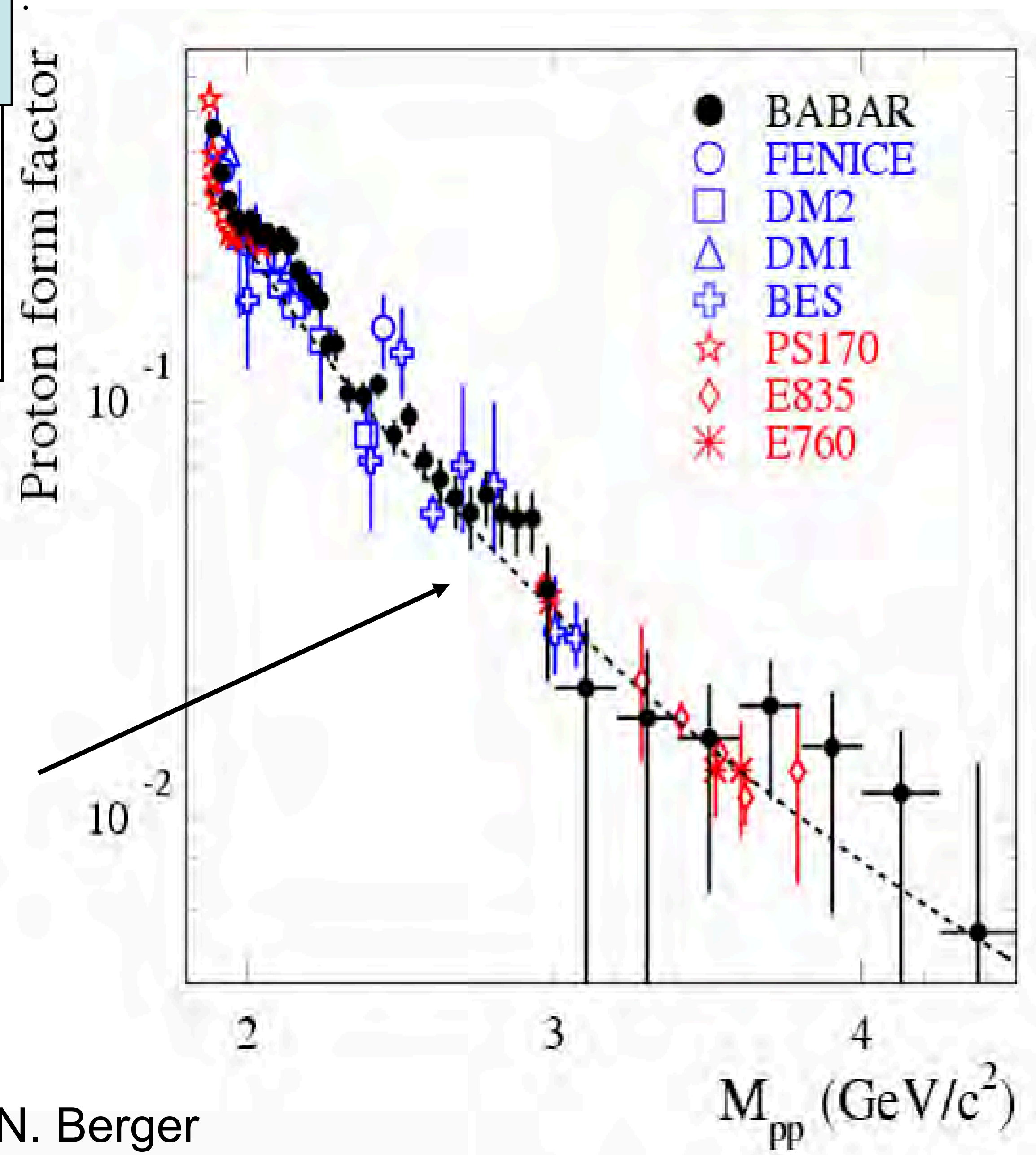
Timelike Proton Form Factor

- Define "Effective" form factor by

$$\sigma = \frac{4\pi\alpha^2\beta C}{3m_{p\bar{p}}^2}|F|^2, \quad |F| = \sqrt{|G_M|^2 + \frac{2m_p^2}{m_{p\bar{p}}^2}|G_E|^2}.$$

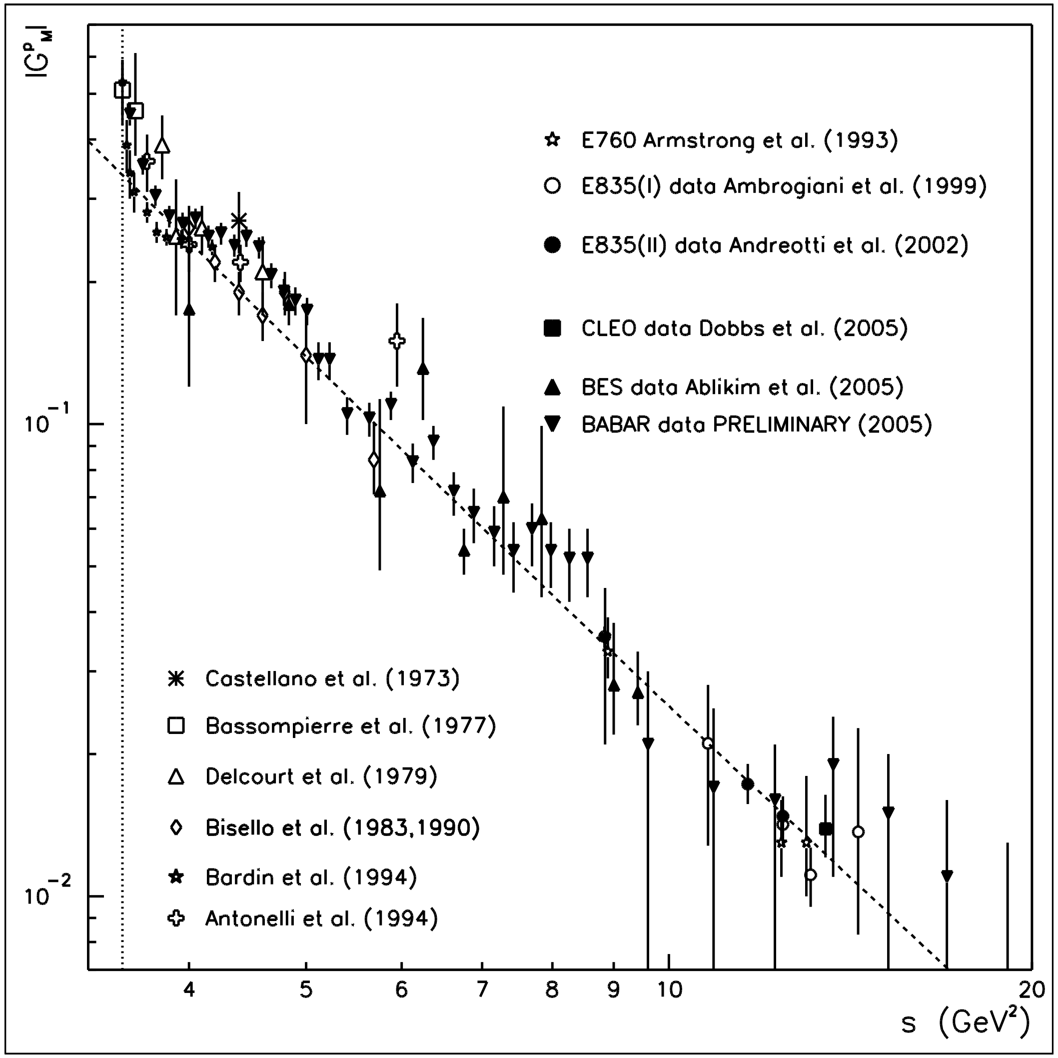
- Peak at threshold, sharp dips at 2.25 GeV, 3.0 GeV.
- Good fit to pQCD prediction for high m_{pp}.

$$F(s) \propto \frac{\log^{-2}\frac{s}{\Lambda^2}}{s^2}$$



Time-like Form Factors

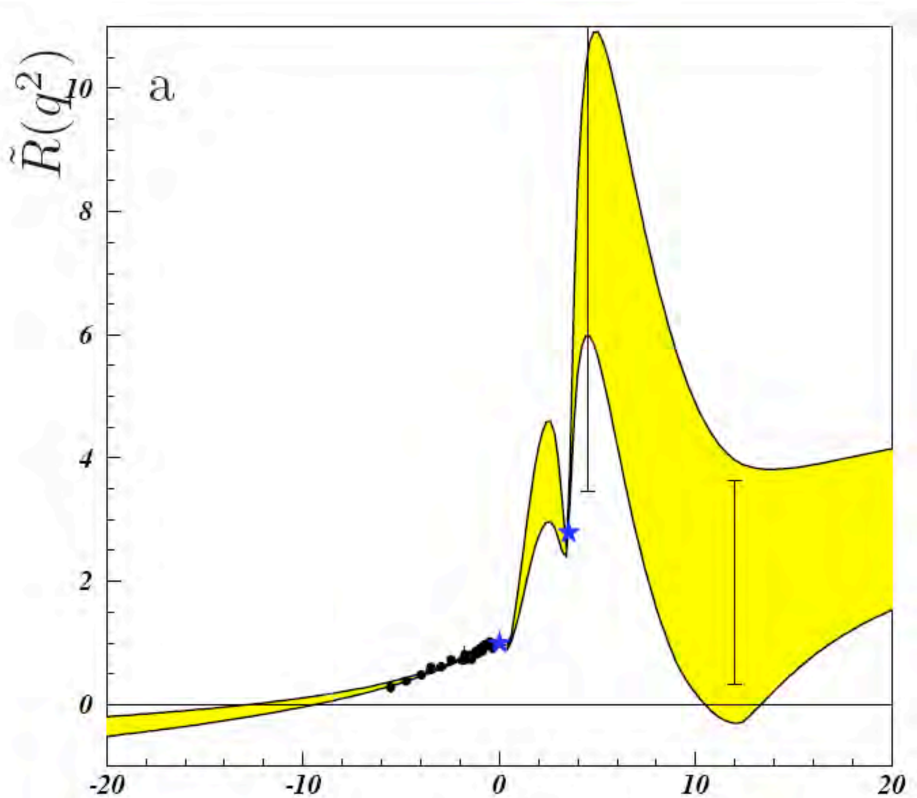
- All data measure absolute cross section $G_E = G_M$
- PANDA will provide independent measurement of G_E and G_M
- widest kinematic range in a single experiment
- Time-like form factors are complex
- precision experiments will reveal these structures

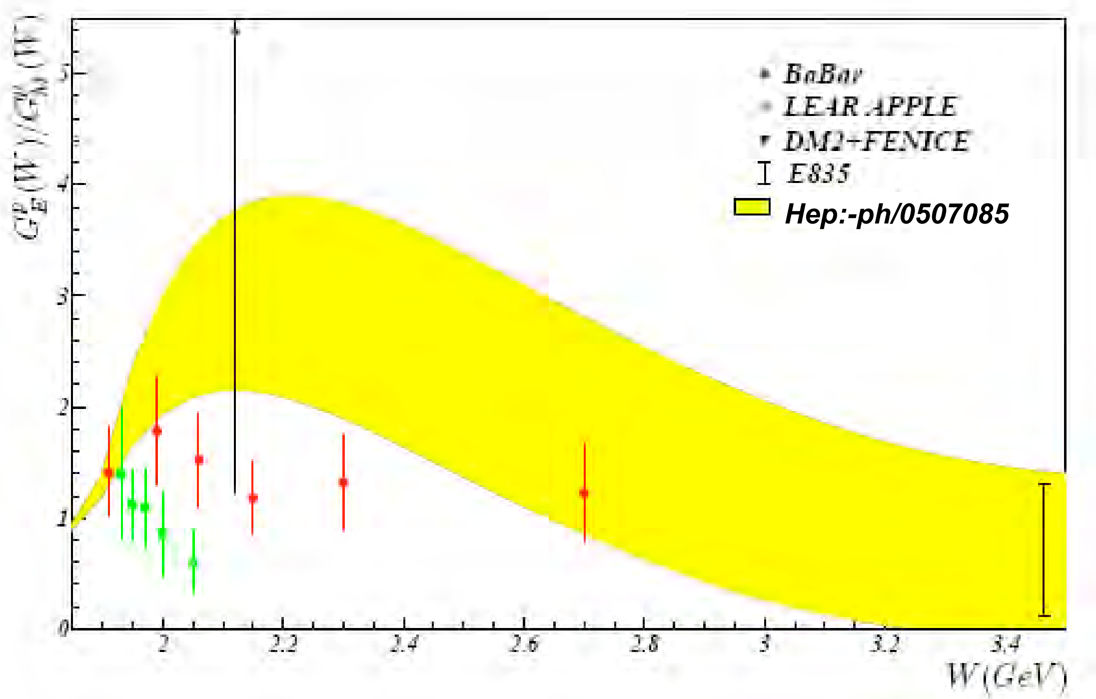


PANDA range

B. Seitz

More to explore





R. Baldini et al. EPJ C 46(2006) 412

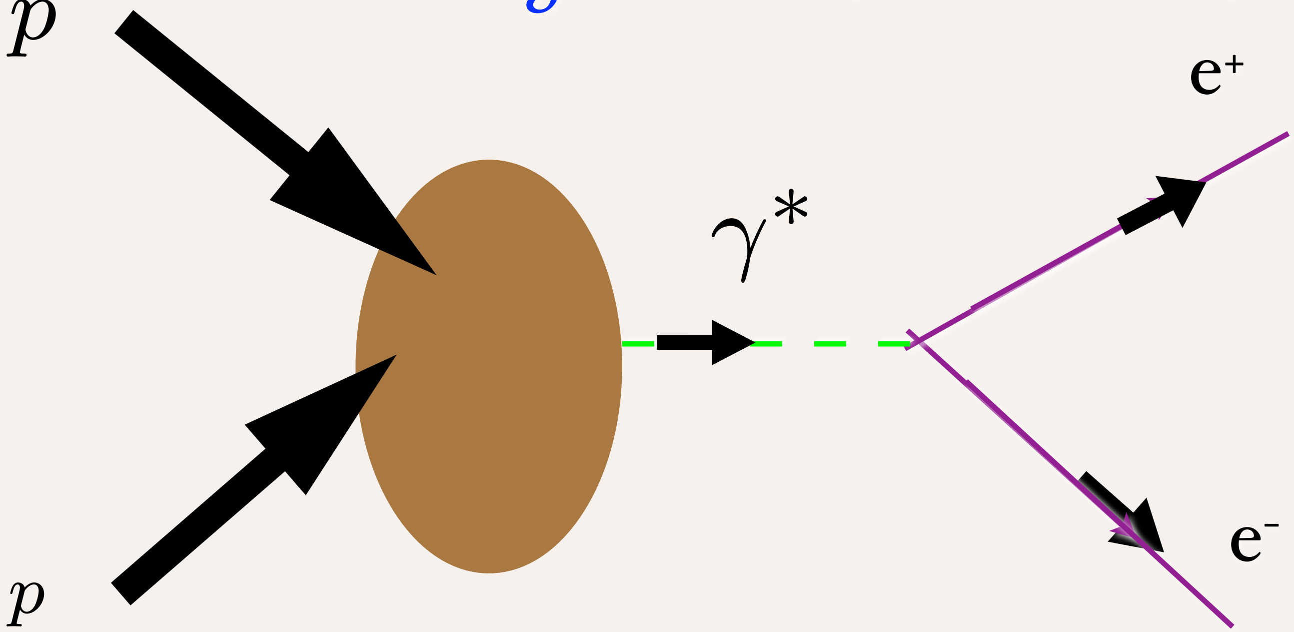
- Time-like form factors are analytically connected to space-like form factors
- Time-like form factors are complex, get phase in addition
- expect a rich structure in time-like region from dispersion relation model
- even more to learn from single spin asymmetries

B. Seitz

Key QCD Experiment at FAIR

Measurement of hadron time-like form factors

angular distributions ***Separate F1, F2***



Leading power in QCD

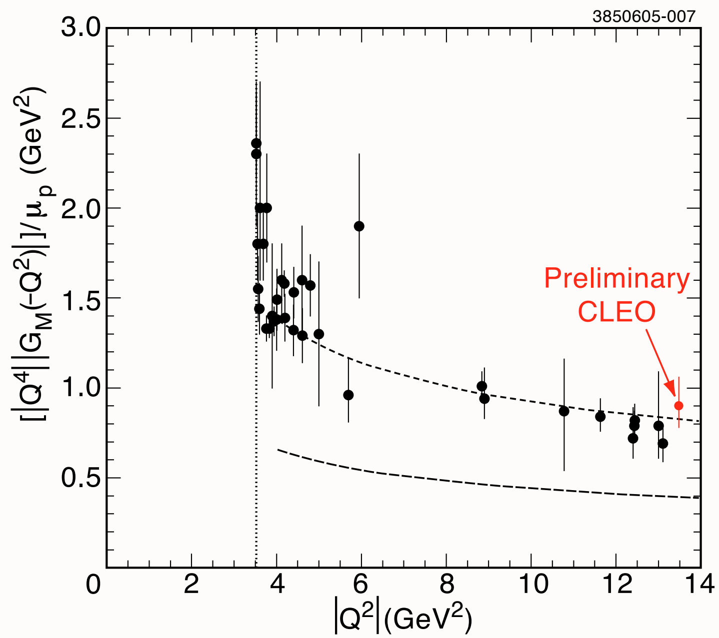
$$F_H(s) \propto [\frac{1}{s}]^{n_H - 1}$$

Test QCD Counting Rules

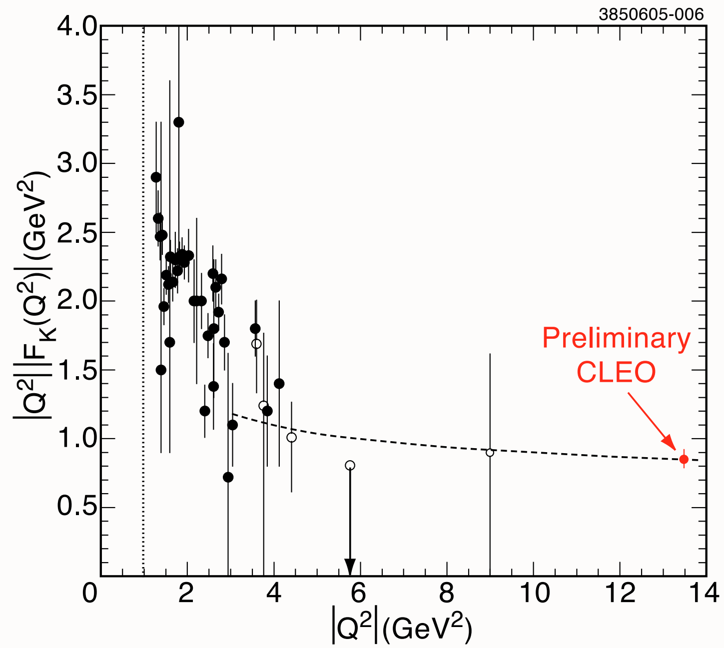
Conformal Symmetry: AdS/CFT

Hadron Helicity Conservation

$$\sum_{\text{initial}} \lambda_H - \sum_{\text{total}} \lambda_H = 0 ,$$



Proton timelike form factor.



Kaon timelike form factor.

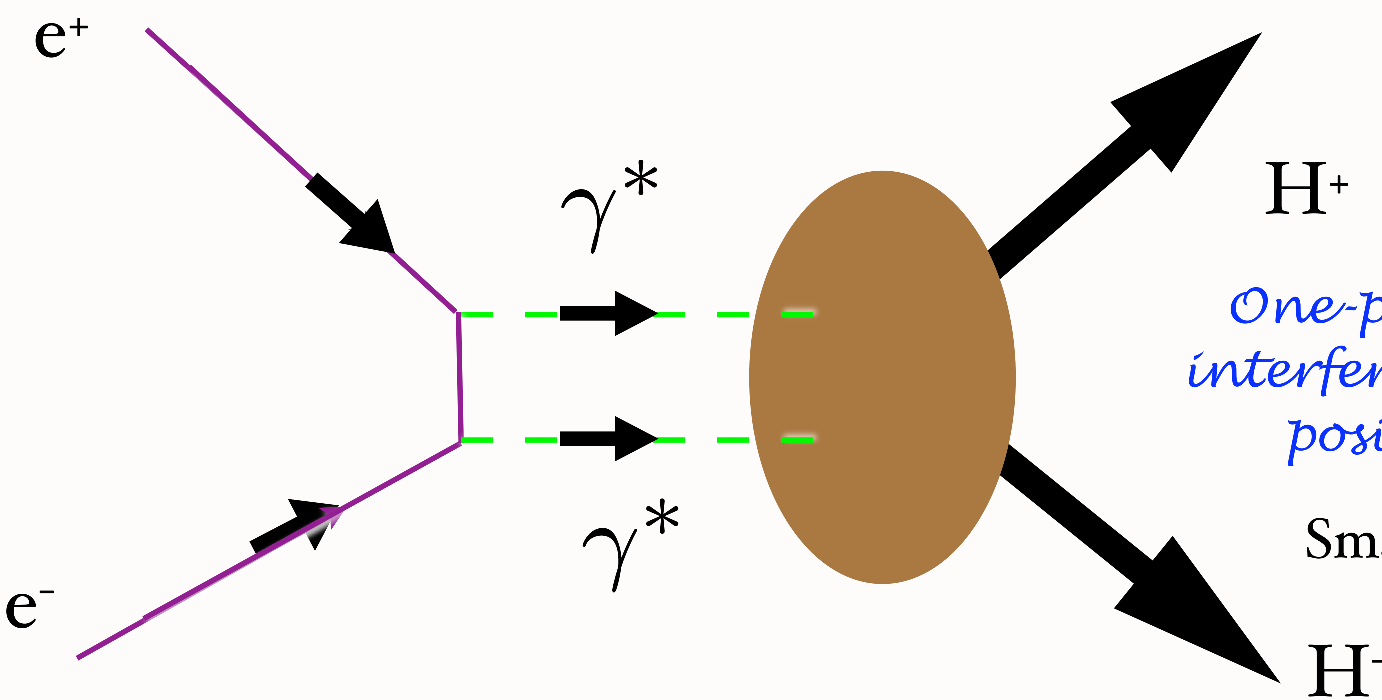
New results from CLEO

$$Q^2|F_K(13.48\ \mathrm{GeV}^2)| = 0.85 \pm 0.05(\mathrm{stat}) \pm 0.02(\mathrm{syst})\ \mathrm{GeV}^2$$
$$Q^4|G_M^p(13.48\ \mathrm{GeV}^2)| = 2.54 \pm 0.36(\mathrm{stat}) \pm 0.16(\mathrm{syst})\ \mathrm{GeV}^4$$

The proton magnetic form factor result agrees with that measured in the reverse reaction $p\bar{p} \to e^+e^-$ at Fermilab. **The kaon form factor measurement is the first ever direct measurement at $|Q^2| > 4$ GeV^2.**

- Two-photon exchange correction, elastic and inelastic nucleon channels, give significant; interference with one-photon exchange, destroys Rosenbluth method

Blunden, Melnitchouk; Afanasev, Chen,Carlson, Vanderhaegen, sjb



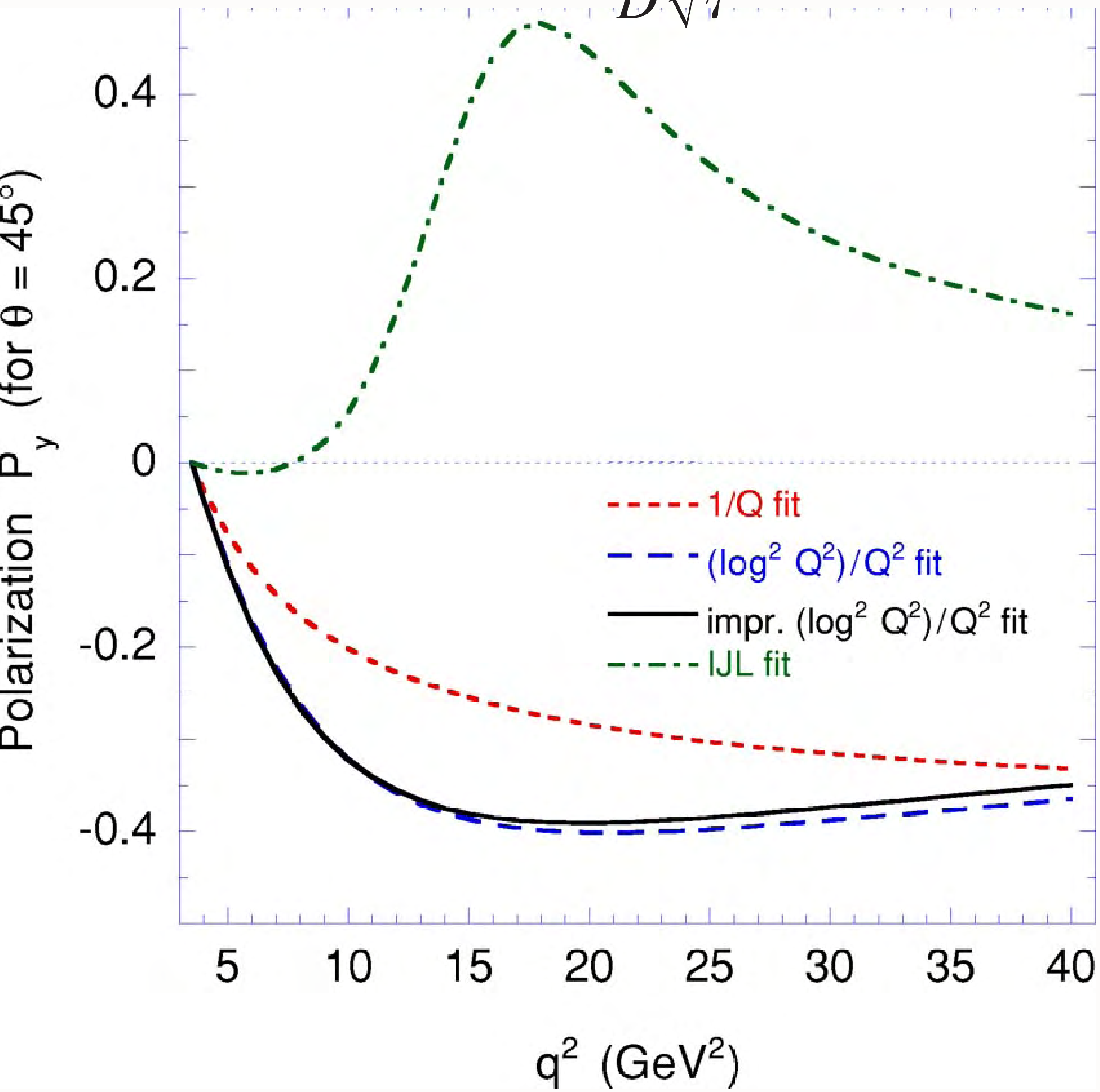
One-photon/two-photon interference gives electron-positron asymmetry

Small Effect from Z°

Single-spin polarization effects and the determination of timelike proton form factors

$$\mathcal{P}_y = \frac{\sin 2\theta \, \mathrm{Im}\, G_E^* G_M}{D\sqrt{\tau}} = \frac{(\tau - 1)\sin 2\theta \, \mathrm{Im}\, F_2^* F_1}{D\sqrt{\tau}}$$

Carlson, Hiller, Hwang, sjb



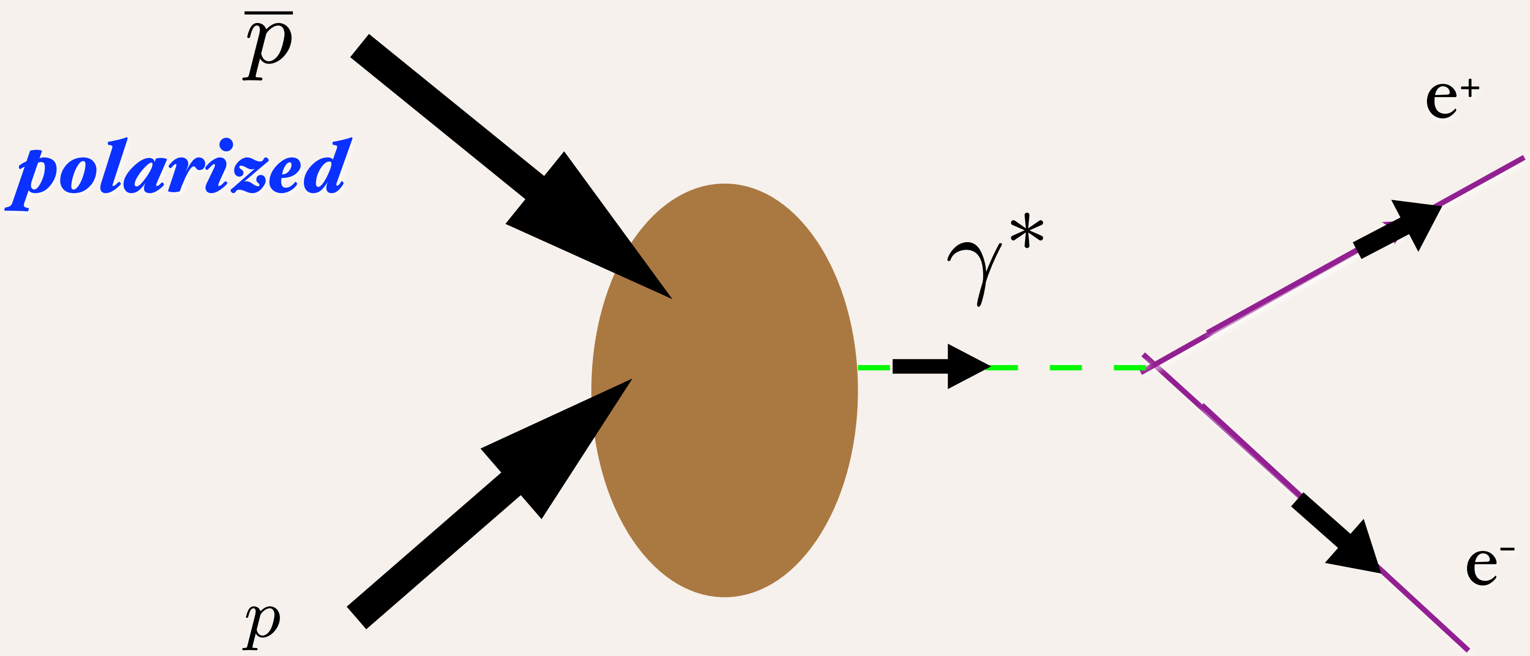
$$D = |G_M|^2(1+\cos^2\theta) + \frac{1}{\tau}|G_E|^2 \sin^2\theta;$$

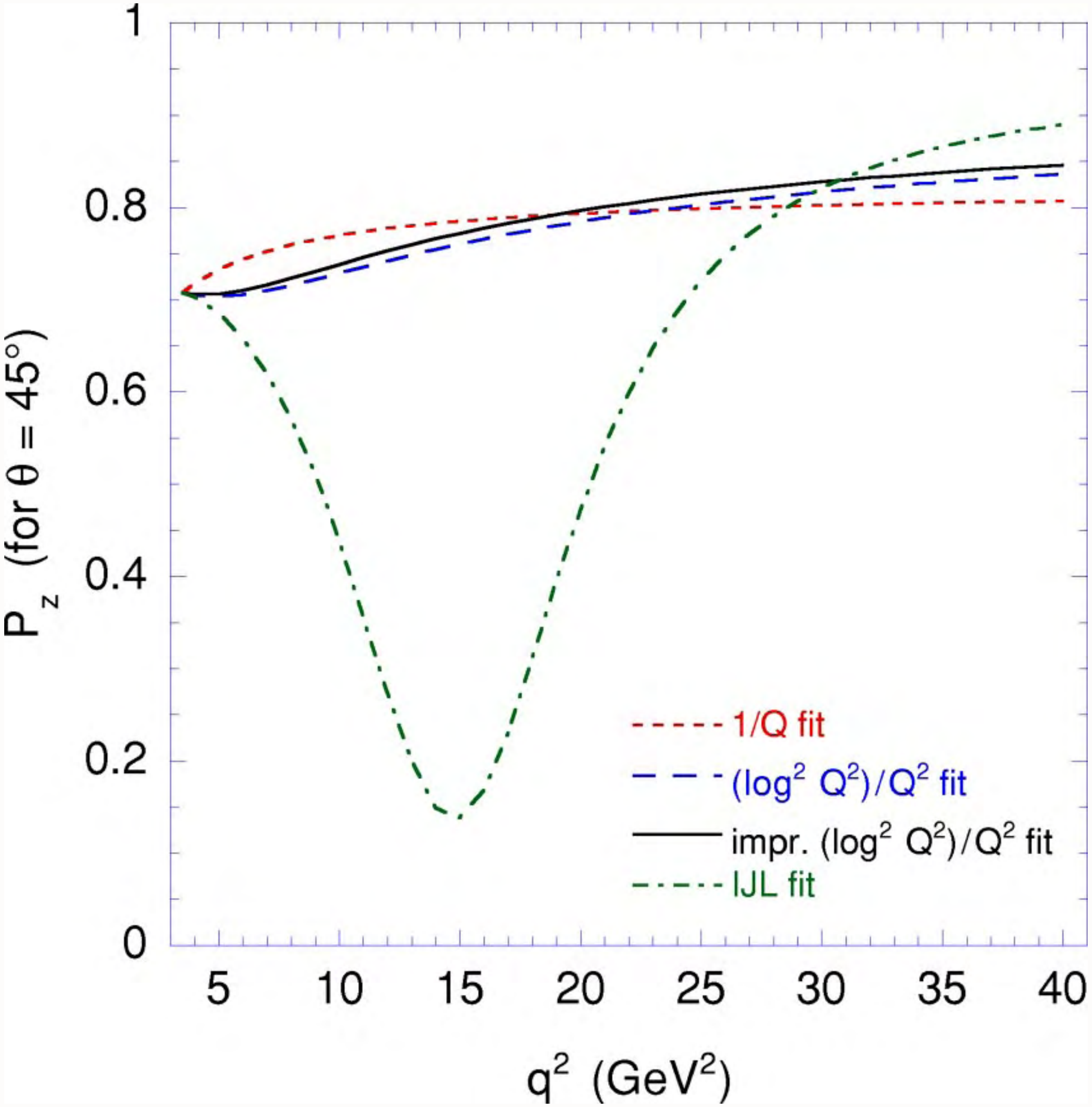
$$\tau \equiv q^2/4m_B^2$$

Measure relative phase of form factors

Key QCD Experiment at FAIR

$$\mathcal{P}_y = \frac{\sin 2\theta \, \mathrm{Im}\, G_E^* G_M}{D\sqrt{\tau}} = \frac{(\tau - 1)\sin 2\theta \, \mathrm{Im}\, F_2^* F_1}{D\sqrt{\tau}}$$



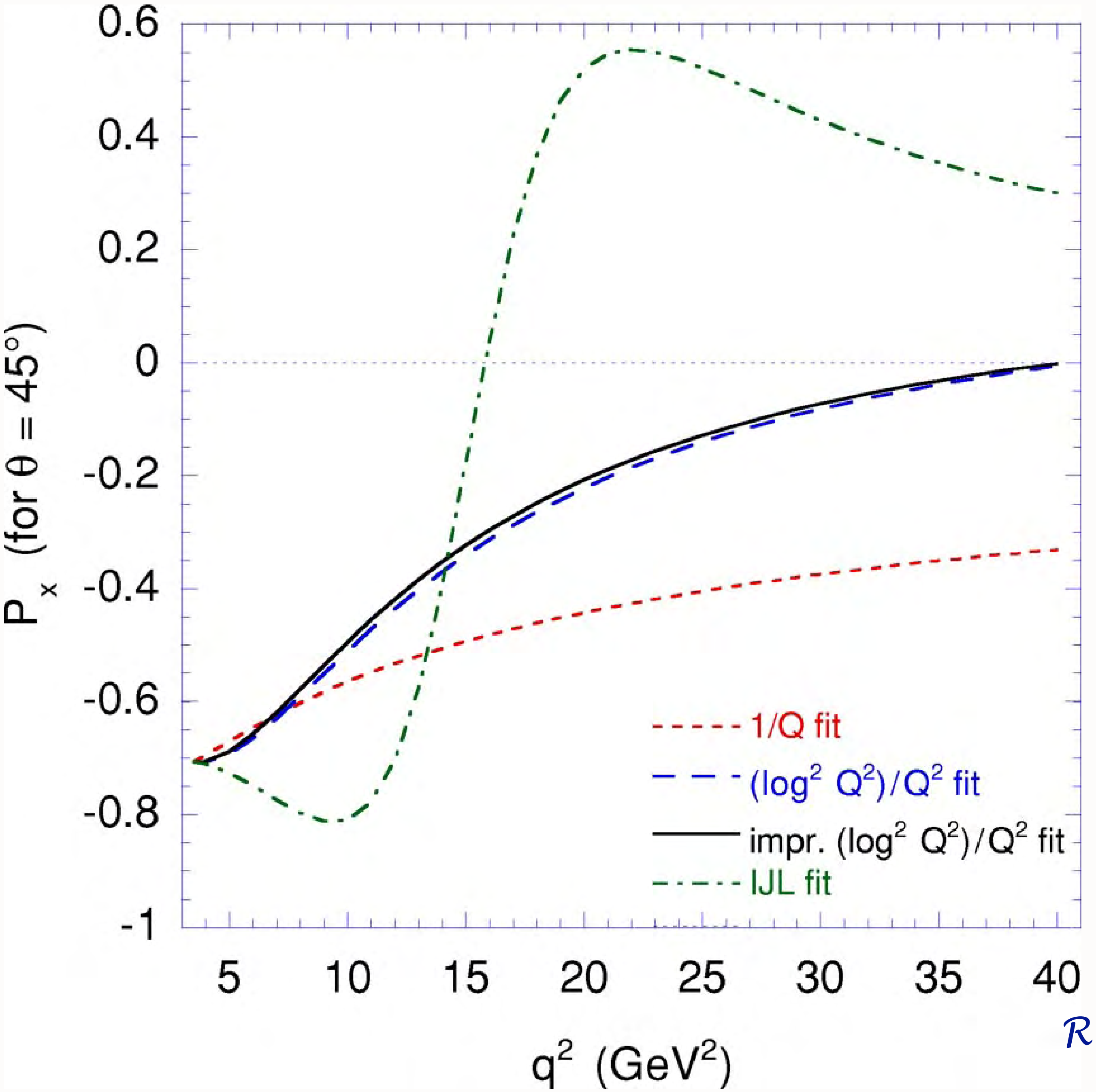


Carlson, Hiller, Hwang, sjb

$$\mathcal{P}_z = P_e \frac{2\cos\theta |G_M|^2}{D}$$

$$D = |G_M|^2(1+\cos^2\theta) + \frac{1}{\tau}|G_E|^2 \sin^2\theta;$$

Requires beam and lepton polarization



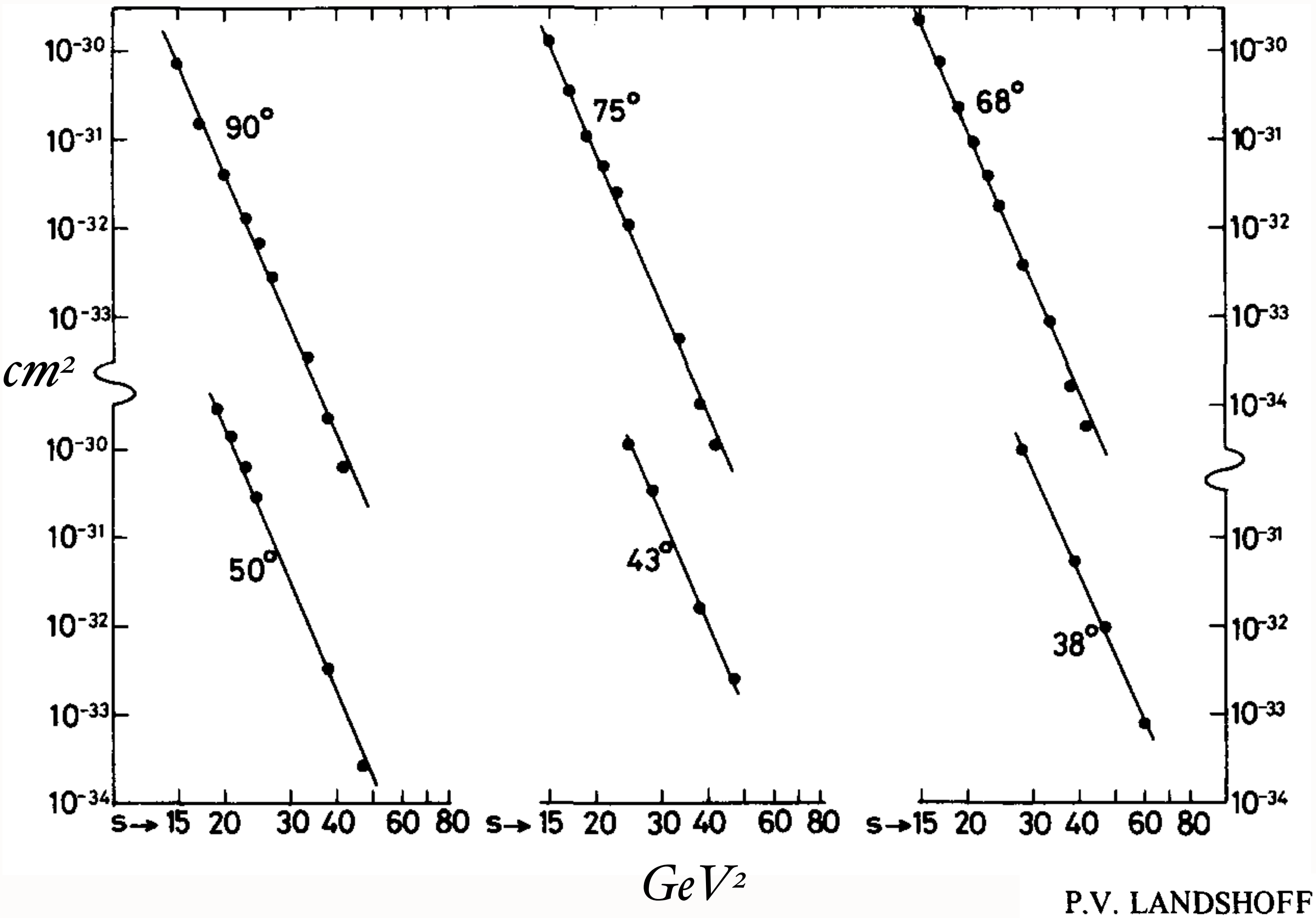
Carlson, Hiller, Hwang, sjb

$$\mathcal{P}_x = -P_e \frac{2 \sin\theta \,\mathrm{Re}\, G_E^* G_M}{D\sqrt{\tau}}$$

$$D = |G_M|^2(1+\cos^2\theta) + \frac{1}{\tau}|G_E|^2 \sin^2\theta;$$

Requires beam and lepton polarization

Quark-Counting : $\frac{d\sigma}{dt}(pp \to pp) = \frac{F(\theta_{CM})}{s^{10}}$ $n = 4 \times 3 - 2 = 10$



P.V. LANDSHOFF and J.C. POLKINGHORNE

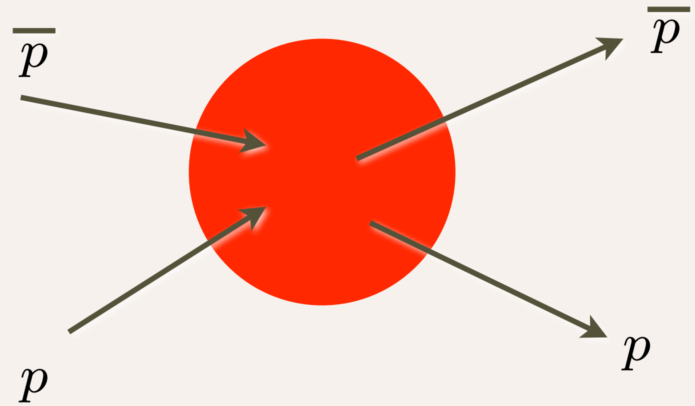
Best Fit

$n = 9.7 \pm 0.5$

Reflects underlying conformal scale-free interactions

Key QCD Experiment at FAIR

$\frac{d\sigma}{dt}(\bar{p}p \to \bar{p}p)$ at large p_T



Test PQCD AdS/CFT conformal scaling:
twist = dimension - spin = 12

$$\frac{d\sigma}{dt}(\bar{p}p \to \bar{p}p) \sim \frac{|F(t/s)|^2}{s^{10}}$$

$$M(s,t) \sim \frac{F(t/s)}{s^4}$$

Test Quark Interchange Mechanism

$$M \propto \frac{1}{s^2 u^2}$$

Single-spin asymmetry A_N

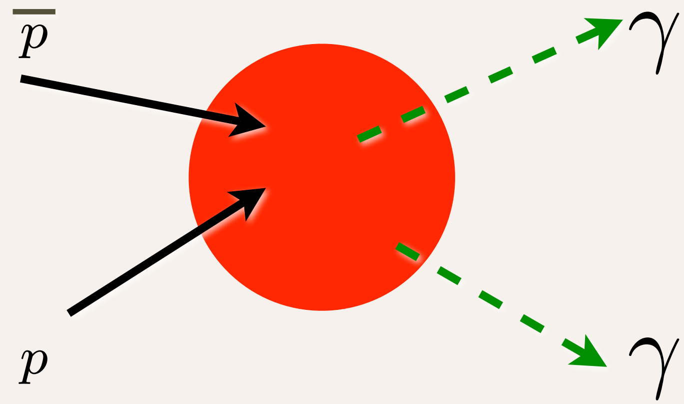
Exclusive Transversity A_{NN}

Test color transparency

Study Fundamental Aspects of Nuclear Force

Key QCD Experiment at FAIR

$\frac{d\sigma}{dt}(\bar{p}p \to \gamma\gamma)$ at fixed angle, large p_T



$$\frac{d\sigma}{dt}(\bar{p}p \to \gamma\gamma) = \frac{F(t/s)}{s^6}$$

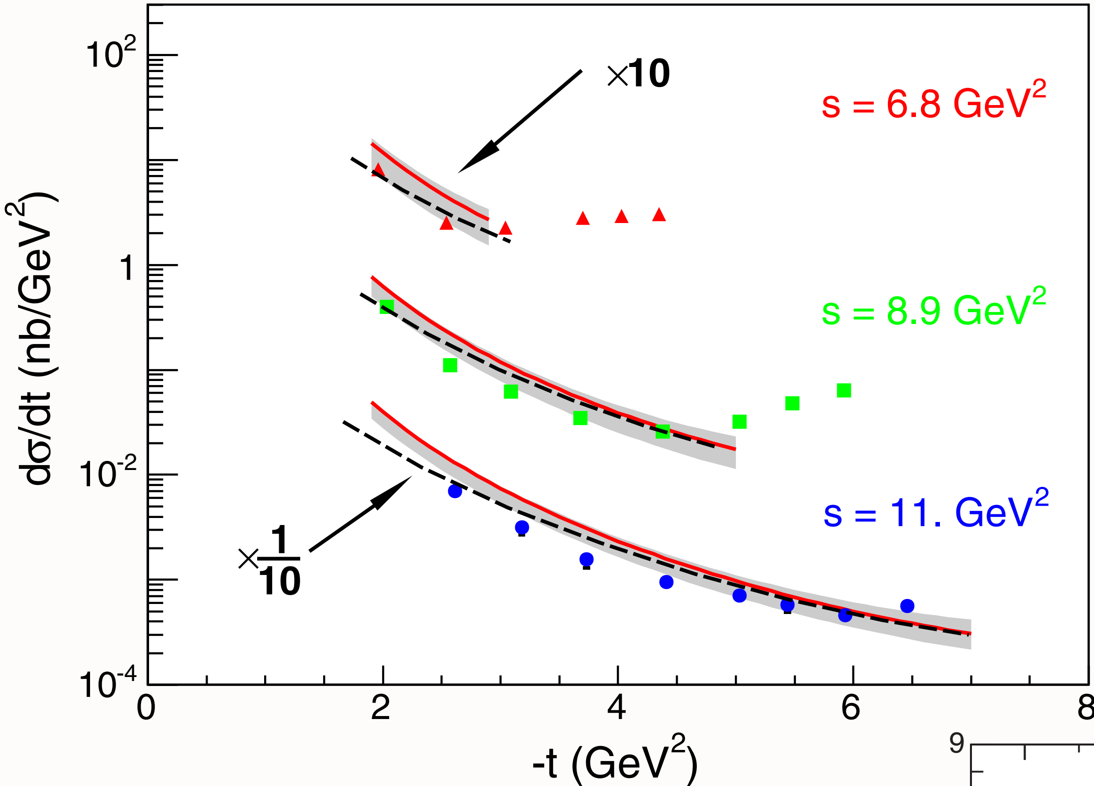
Tests PQCD and AdS/CFT Conformal Scaling

Handbag Approximation Invalid in PQCD

Single-spin asymmetry A_N

Exclusive Transversity A_{NN}

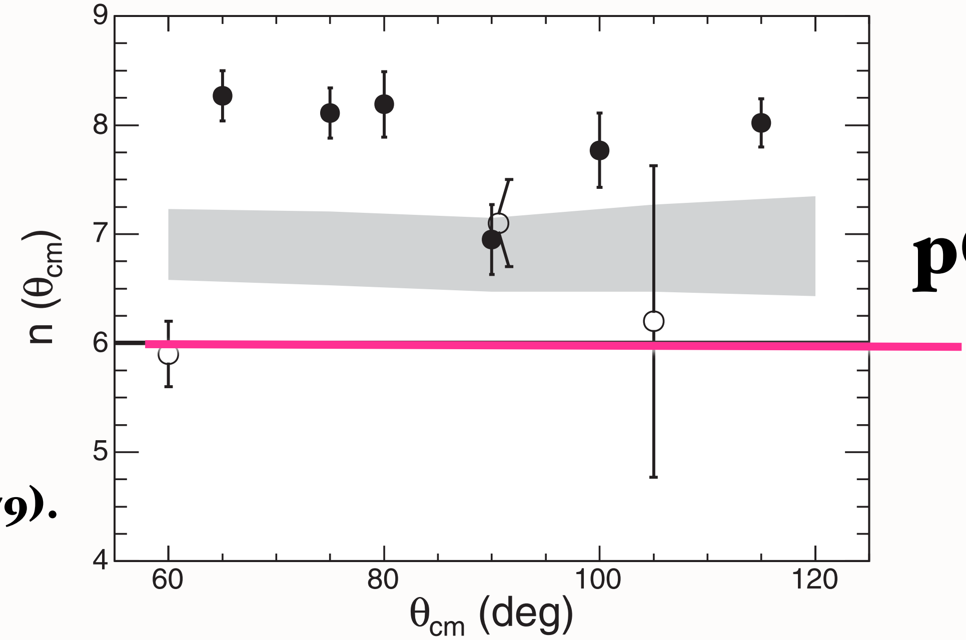
Test color transparency



Jefferson Lab
Hall A
Collaboration

Alan Nathan, et al

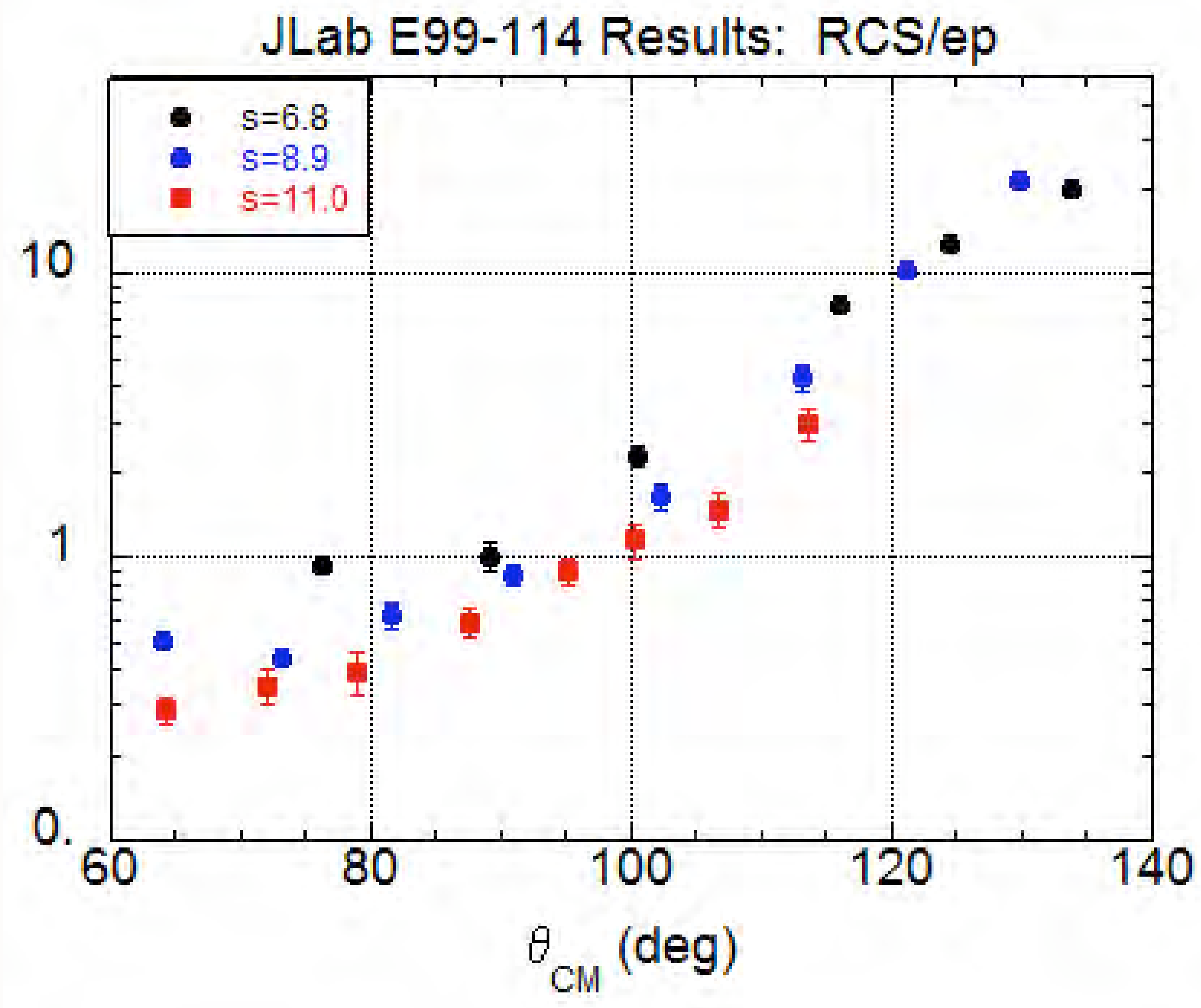
Compton at fixed angles falls faster than photoproduction!



pQCD
n=6

Open points: Cornell measurement
M. A. Shupe et al., Phys. Rev. D 19, 1921 (1979).

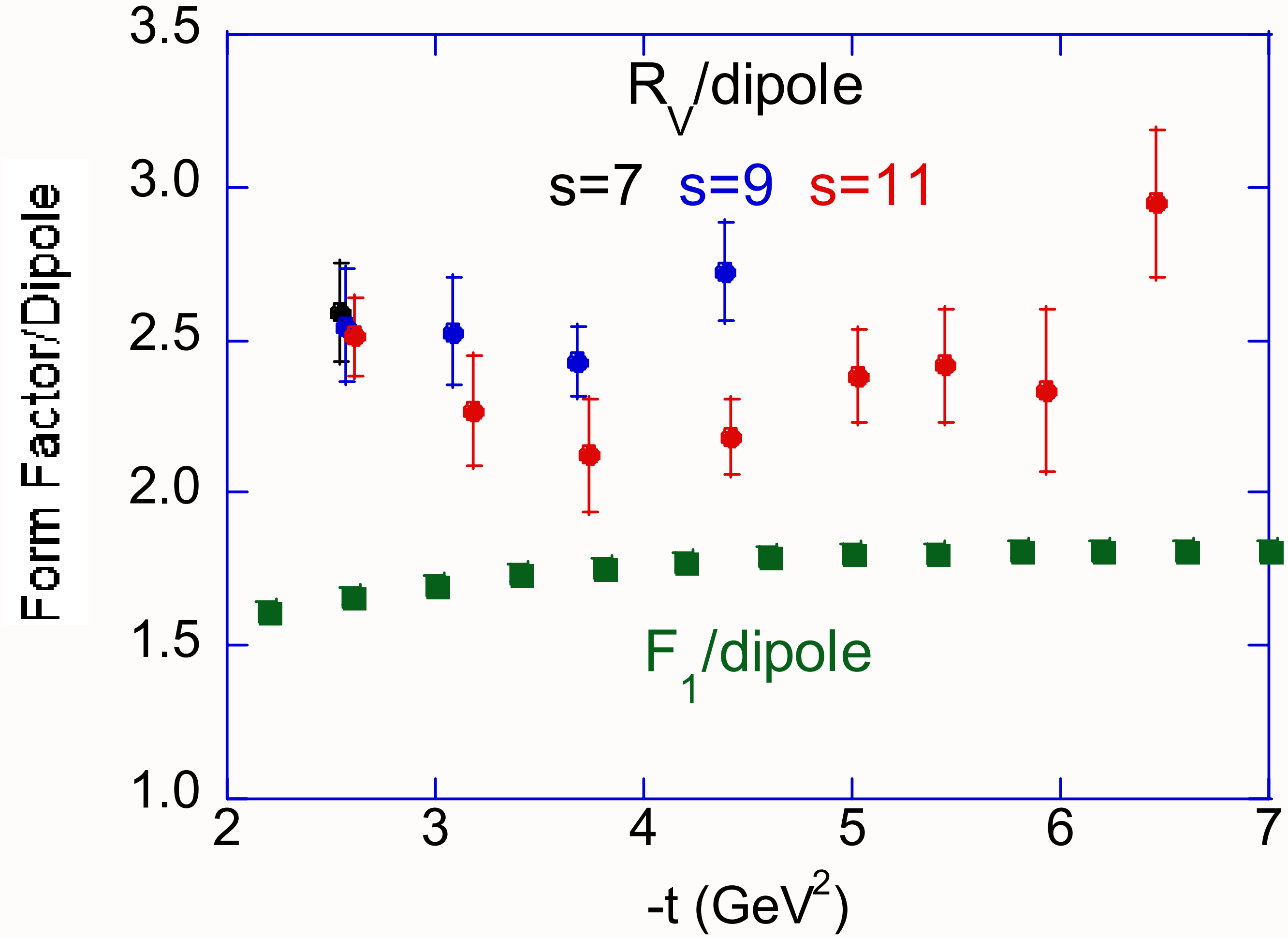
Ratio of Real Compton-Scattering Cross Section to Electron -Proton Scattering at Fixed CM Angle



Ratio becomes energy-independent at large s ?

A. Nathan

$$\frac{d\sigma}{dt} = \left(\frac{d\sigma}{dt}\right)_{KN} \left[f_V R_V^2(t) + f_A R_A^2(t) \right]$$



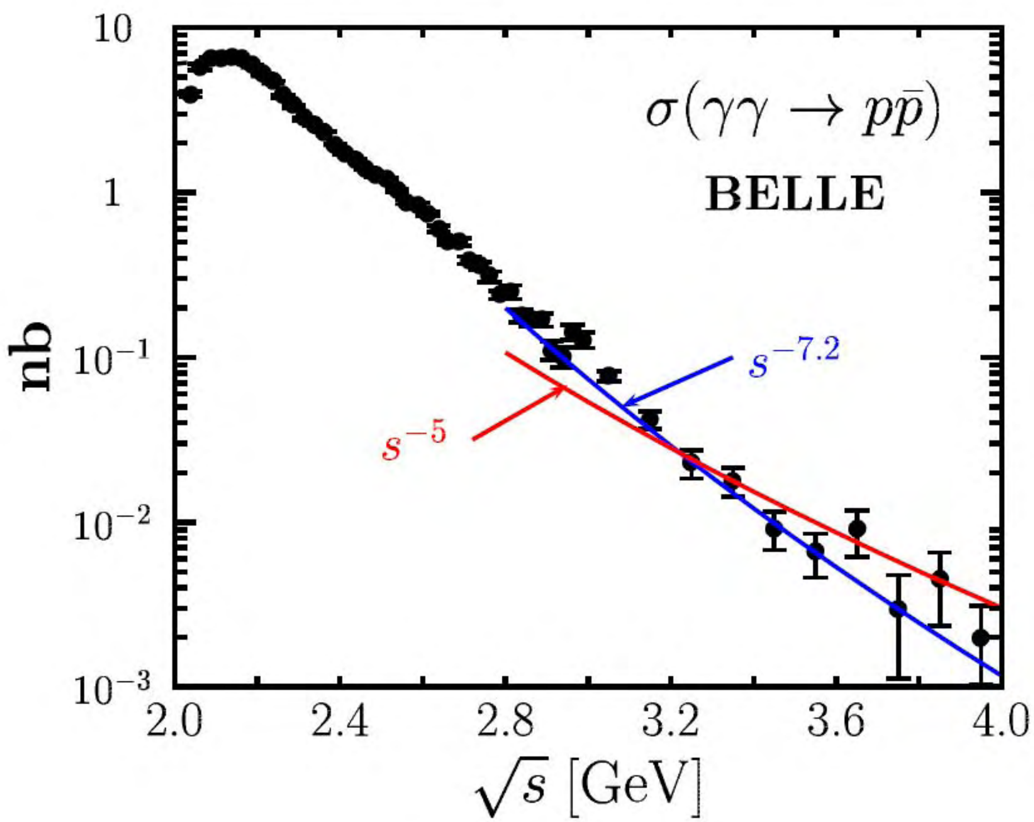
Agrees with PQCD

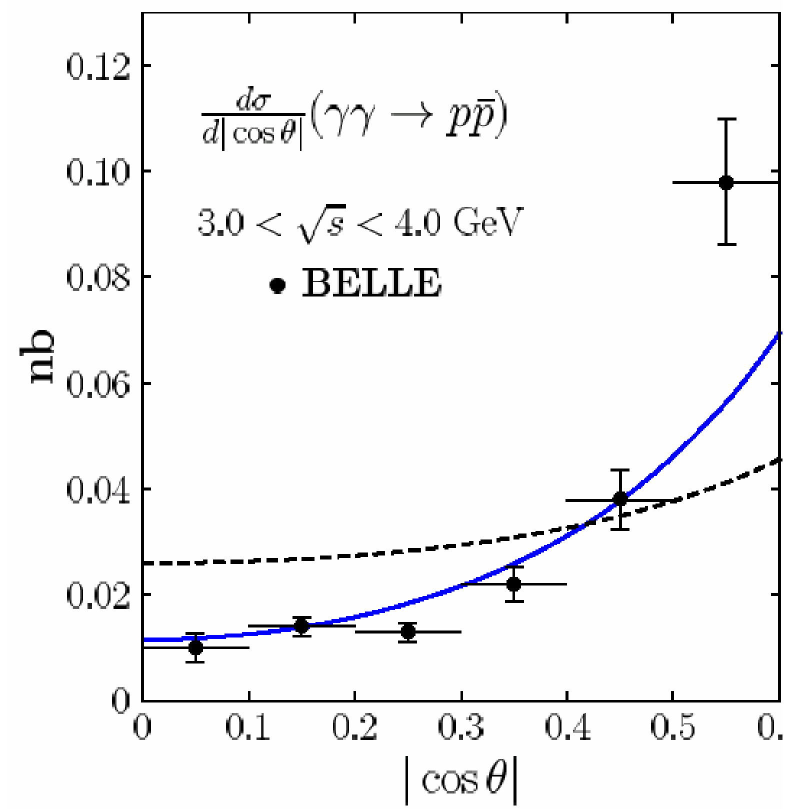
Recent results from Belle

$\gamma\gamma \to p\bar{p}$

PQCD Conformal Scaling for range of θ_{CM}

$s^5 \Delta\sigma(\gamma\gamma \to \bar{p}p) \simeq \text{const}$





Energy dependence

Angular dependence
(GPD curve from Kroll/Schäfer)

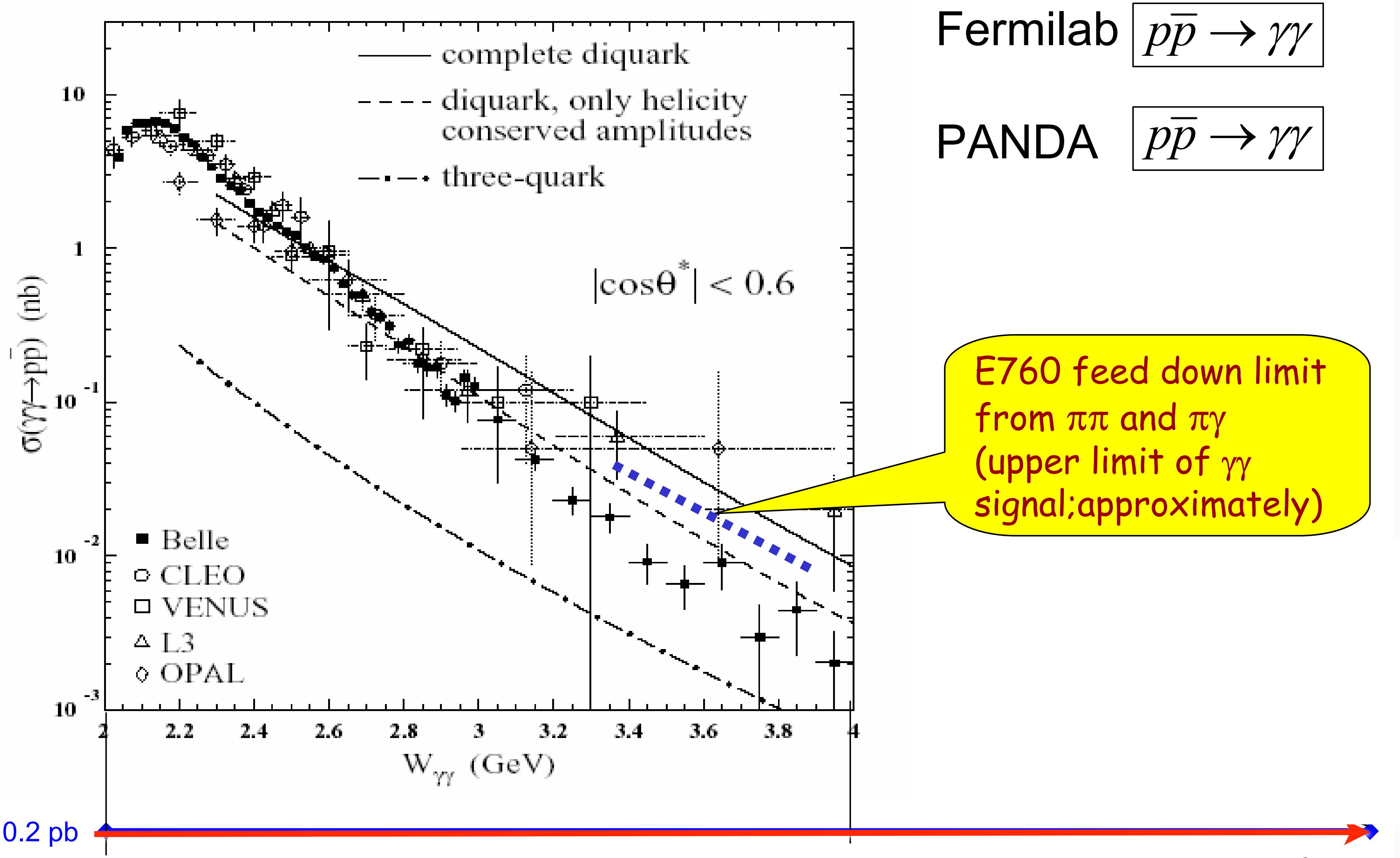
Michael Düren

Cross section comparison

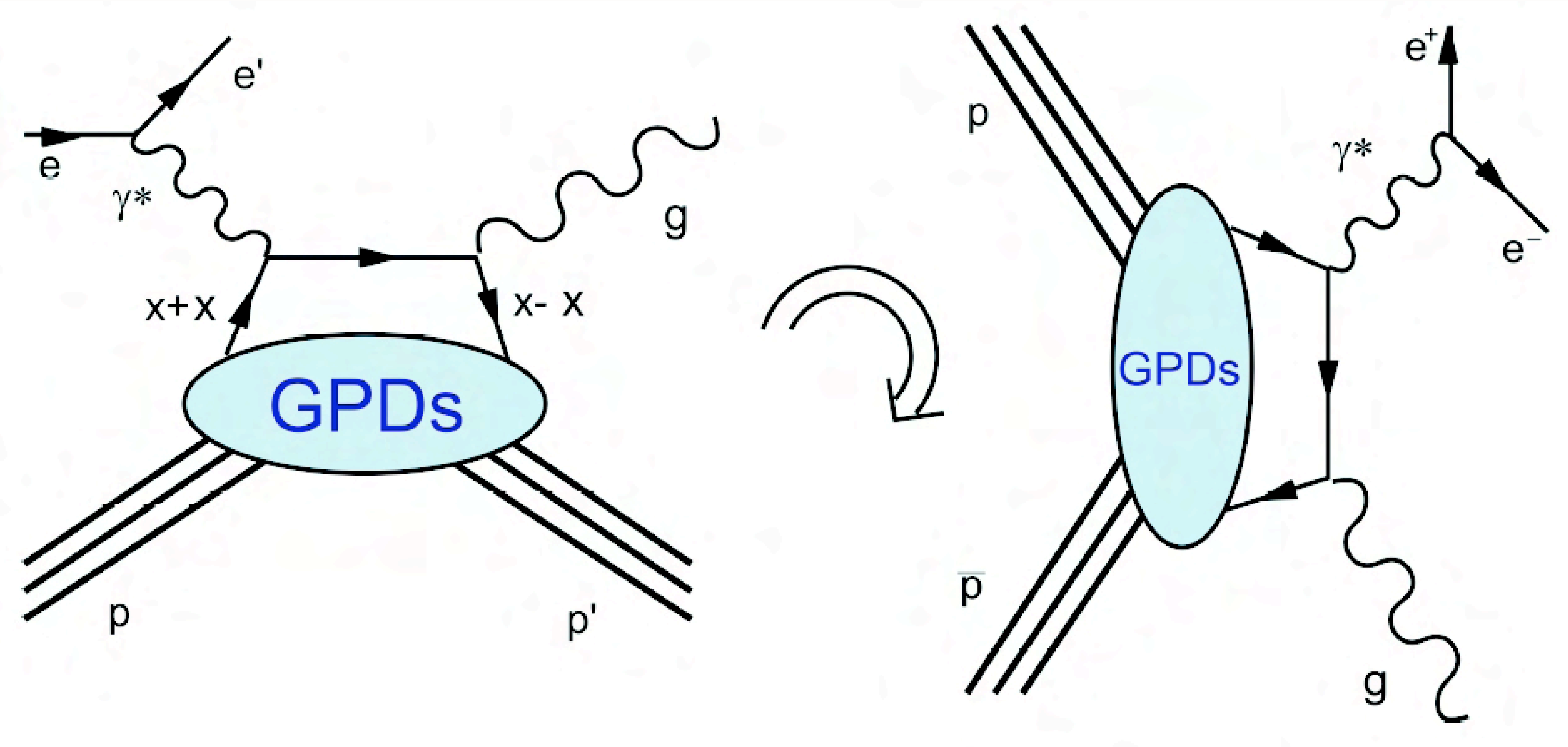
Belle $\gamma\gamma \to p\bar{p}$

Fermilab $p\bar{p} \to \gamma\gamma$

PANDA $p\bar{p} \to \gamma\gamma$



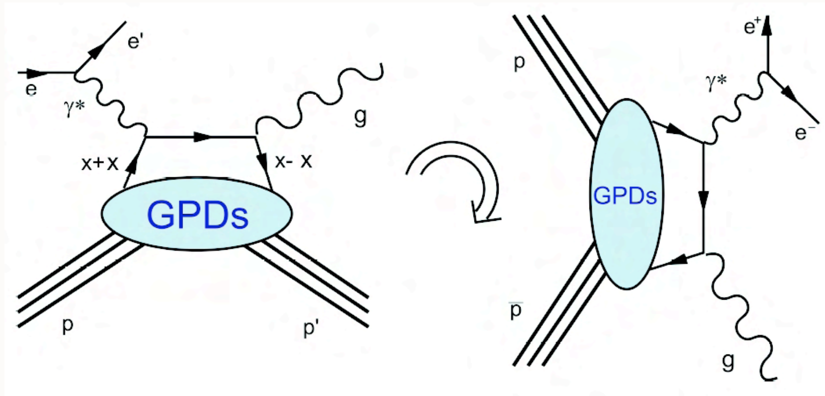
Michael Düren


e
e'
γ*
g
x+x
x- x
GPDs
p
p'
p
e+
γ*
e−
GPDs
p
g

Key QCD Experiment at FAIR

$$\bar{p}p \longrightarrow \gamma^* \gamma$$

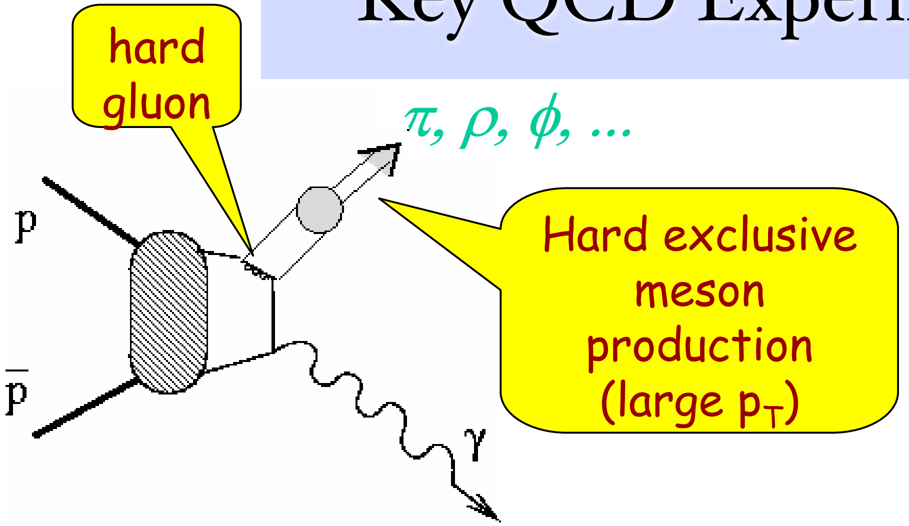
- Test DVCS in Timelike Regime
- J=0 Fixed pole: q^2 independent
- Analytic Continuation of GPDs
- Light-Front Wavefunctions
- charge asymmetry from interference



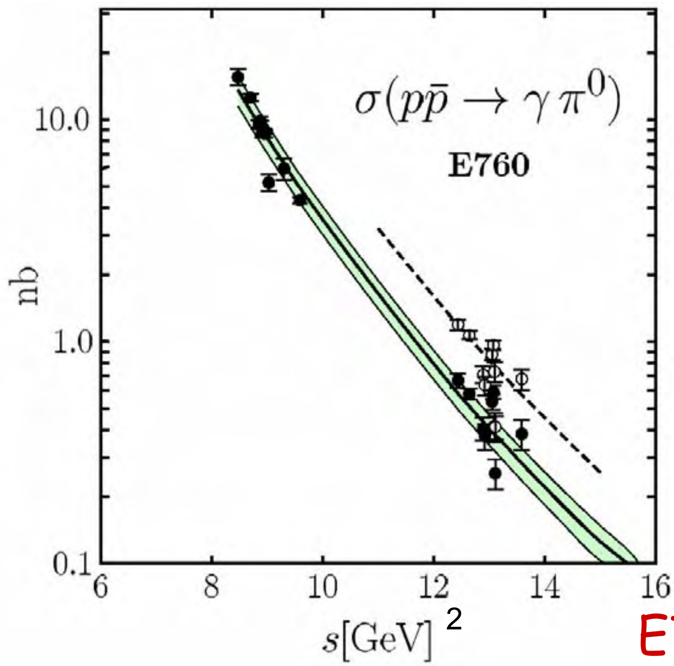
$$\bar{p}p \to \gamma^* \to \ell^+\ell^- \to \ell^+\ell^-\gamma$$

$$\bar{p}p \to \bar{p}p\gamma \to \gamma^*\gamma \to \ell^+\ell^-\gamma$$

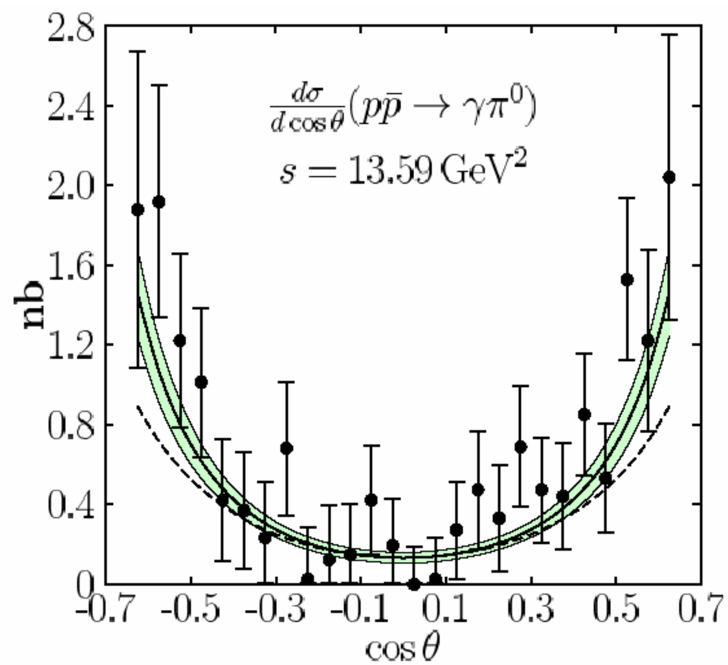
Key QCD Experiment at FAIR



- Much larger cross section (compared to $\gamma\gamma$) makes it easier to access!
- 3-γ final state



E760 results

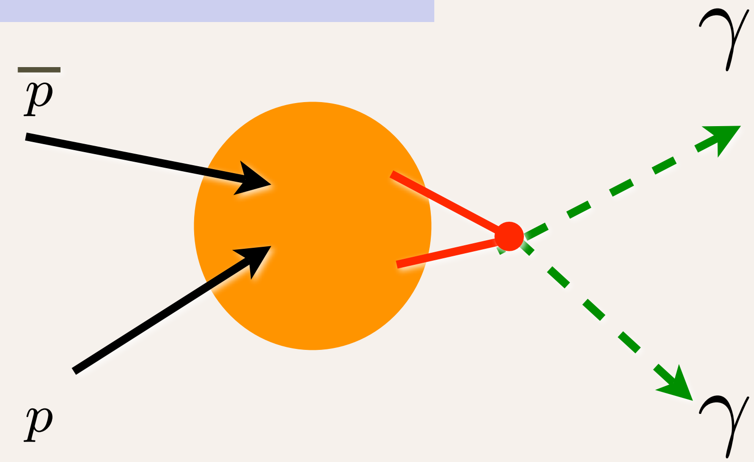


(curve from Kroll/Schäfer)

Michael Düren

Key QCD Experiment at FAIR

$\frac{d\sigma}{dt}(\bar{p}p \to \gamma\gamma)$ at fixed angle, large p_T



$$\frac{d\sigma}{dt}(\bar{p}p \to \gamma\gamma) = \frac{F(t/s)}{s^6}$$

Local Two-Photon (Seagull) Interaction

Close, Gunion, sjb

Tests PQCD and AdS/CFT Conformal Scaling

Angle-Independent J=0 Fixed Pole Contribution:

$$M(\bar{p}p \to \gamma\gamma) = F(s) \propto \frac{1}{s^2} \qquad \frac{d\sigma}{dt}(\bar{p}p \to \gamma\gamma) \propto \frac{1}{s^6}$$

Key QCD Experiment at FAIR

Measure all antiproton + proton exclusive channels

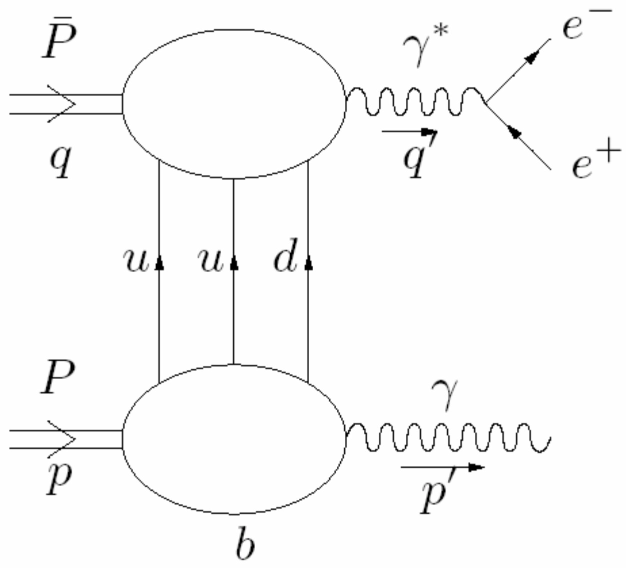
$\overline{p}p \to \gamma\gamma$

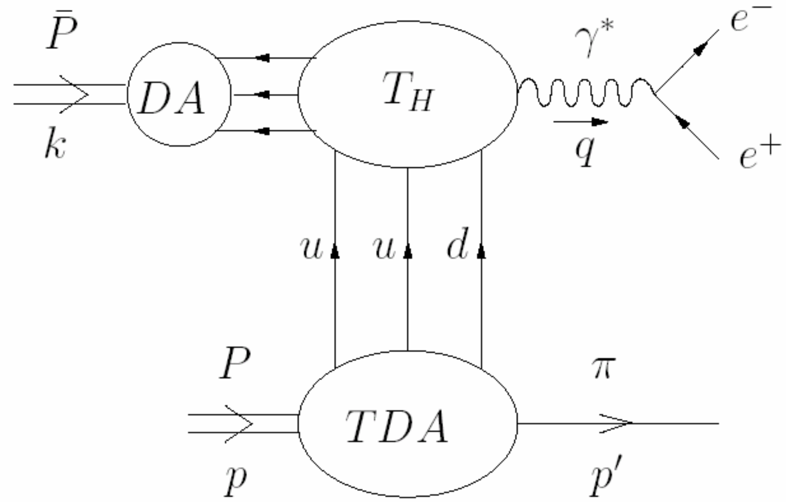
PQCD: No handbag dominance for real photons

$J = 0$ fixed pole from local $q\overline{q} \to \gamma\gamma$ interactions

$\overline{p}p \to \gamma\pi^0$

$\overline{p}p \to K^+K^-$





- No handbag diagram
- Here the photons and the pion are produced in forward direction!
- Measure „Transition distribution amplitudes"

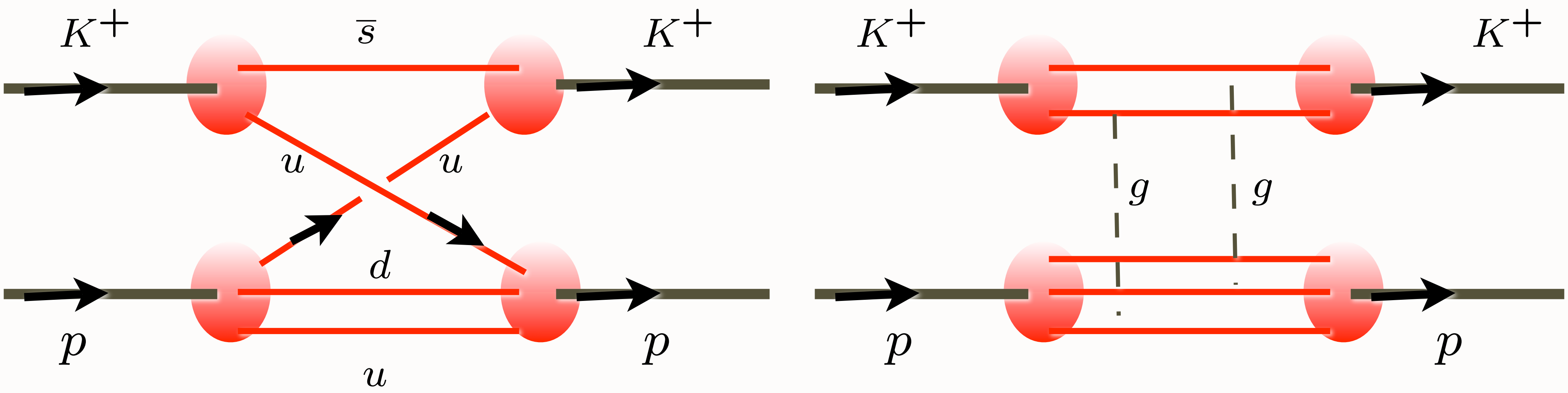
$p\bar{p} \to \gamma^* \pi$	explores the pion cloud
$p\bar{p} \to \gamma^* \rho$	explores the ρ cloud
$p\bar{p} \to \gamma^* \gamma$	explores the photon cloud

(Study next to lowest Fock state of the proton)

Michael Düren

B. Pire and L. Szymanowski

CIM: Blankenbecler, Gunion, sjb



Quark Interchange
(Spin exchange in atom-atom scattering)

Gluon Exchange
(Van der Waal -- Landshoff)

$$\frac{d\sigma}{dt} = \frac{|M(s,t)|^2}{s^2}$$

$M(t,u)_{\text{interchange}} \propto \frac{1}{ut^2}$

$M(s,t)_{\text{gluonexchange}} \propto sF(t)$

MIT Bag Model (de Tar), large N_C, ('t Hooft), AdS/CFT all predict dominance of quark interchange:

Remarkable prediction of AdS/CFT: Dominance of quark interchange

Example: $M(K^+ p \to K^+ p) \propto \frac{1}{ut^2}$

Exchange of common u quark

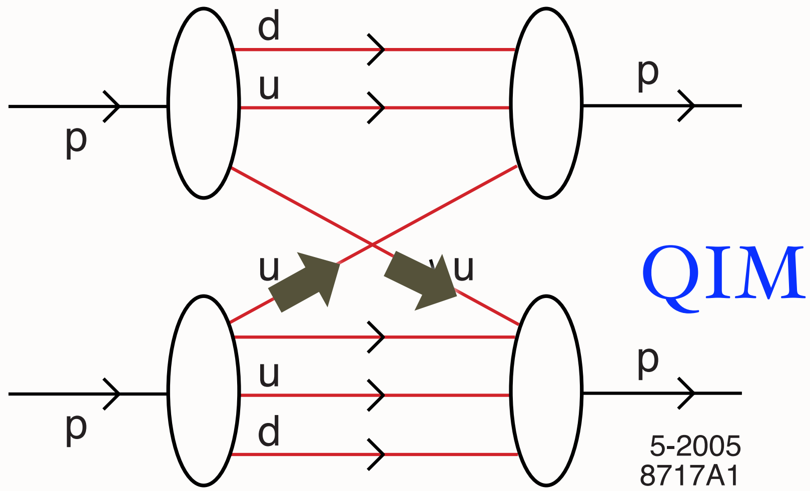
$M_{QIM} = \int d^2k_\perp dx\ \psi^\dagger_C \psi^\dagger_D \Delta \psi_A \psi_B$

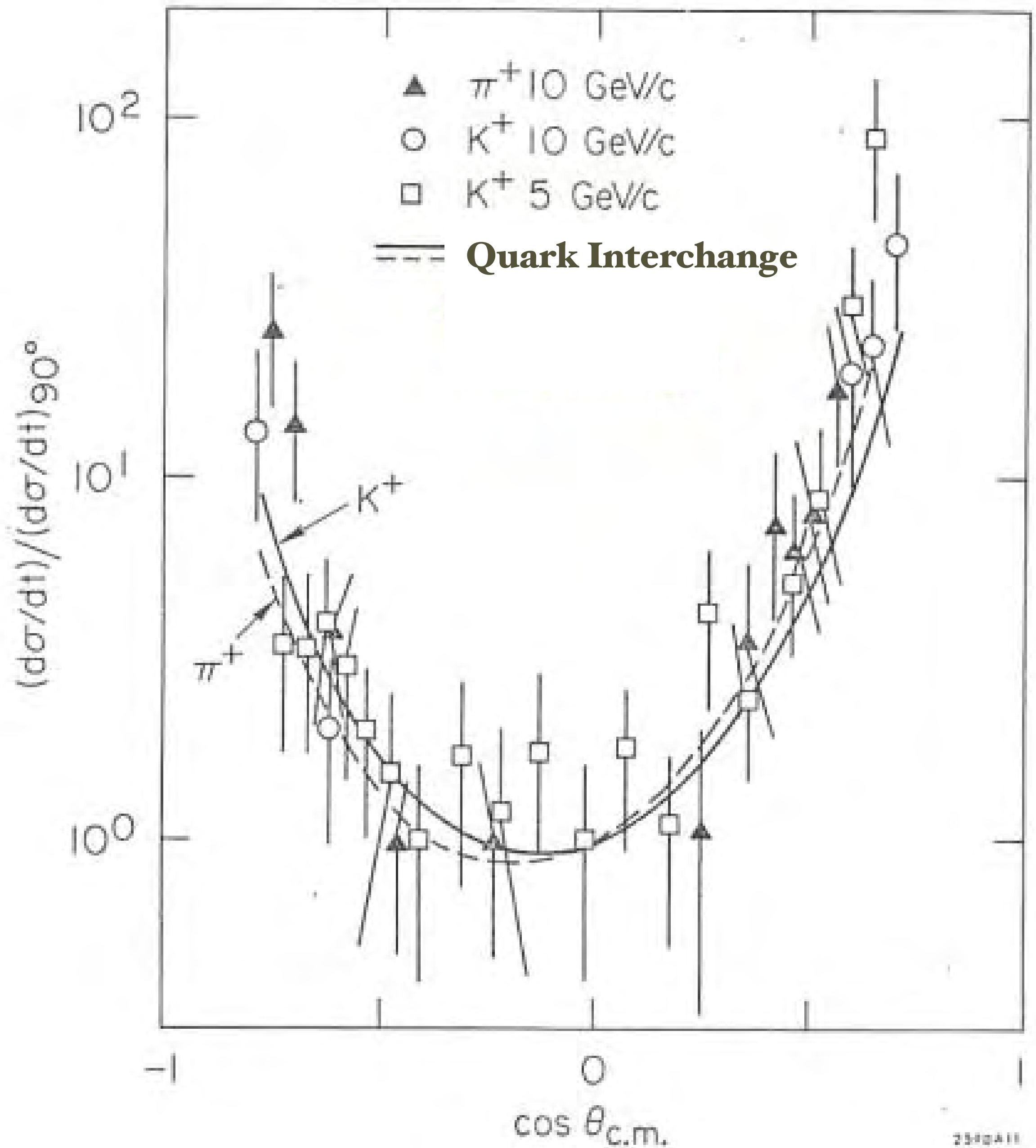
Holographic model (Classical level):

Hadrons enter 5th dimension of AdS_5

Quarks travel freely within cavity as long as separation $z < z_0 = \frac{1}{\Lambda_{QCD}}$

LFWFs obey conformal symmetry producing quark counting rules.





AdS/CFT explains why quark interchange is dominant interaction at high momentum transfer in exclusive reactions

$$M(t,u)_{\text{interchange}} \propto \frac{1}{ut^2}$$

Non-linear Regge behavior:

$$\alpha_R(t) \to -1$$

Comparison of Exclusive Reactions at Large t

B. R. Baller,[a] G. C. Blazey,[b] H. Courant, K. J. Heller, S. Heppelmann,[c] M. L. Marshak, E. A. Peterson, M. A. Shupe, and D. S. Wahl[d]
University of Minnesota, Minneapolis, Minnesota 55455

D. S. Barton, G. Bunce, A. S. Carroll, and Y. I. Makdisi
Brookhaven National Laboratory, Upton, New York 11973

and

S. Gushue[e] and J. J. Russell
Southeastern Massachusetts University, North Dartmouth, Massachusetts 02747
(Received 28 October 1987; revised manuscript received 3 February 1988)

Cross sections or upper limits are reported for twelve meson-baryon and two baryon-baryon reactions for an incident momentum of 9.9 GeV/c, near 90° c.m.: $\pi^{\pm}p \rightarrow p\pi^{\pm}, p\rho^{\pm}, \pi^{+}\Delta^{\pm}, K^{+}\Sigma^{\pm}, (\Lambda^{0}/\Sigma^{0})K^{0}$; $K^{\pm}p \rightarrow pK^{\pm}$; $p^{\pm}p \rightarrow pp^{\pm}$. By studying the flavor dependence of the different reactions, we have been able to isolate the quark-interchange mechanism as dominant over gluon exchange and quark-antiquark annihilation.

$\pi^{\pm}p \rightarrow p\pi^{\pm}$,

$K^{\pm}p \rightarrow pK^{\pm}$,

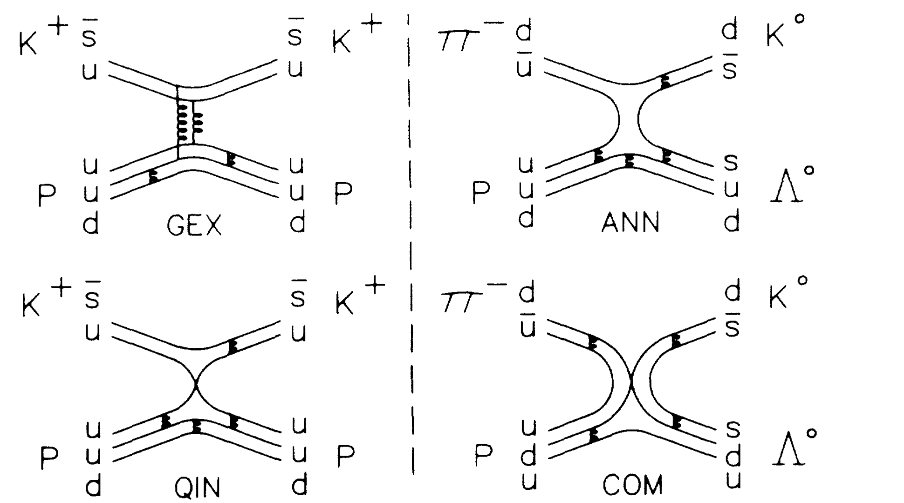
$\pi^{\pm}p \rightarrow p\rho^{\pm}$,

$\pi^{\pm}p \rightarrow \pi^{+}\Delta^{\pm}$,

$\pi^{\pm}p \rightarrow K^{+}\Sigma^{\pm}$,

$\pi^{-}p \rightarrow \Lambda^{0}K^{0}, \Sigma^{0}K^{0}$,

$p^{\pm}p \rightarrow pp^{\pm}$.

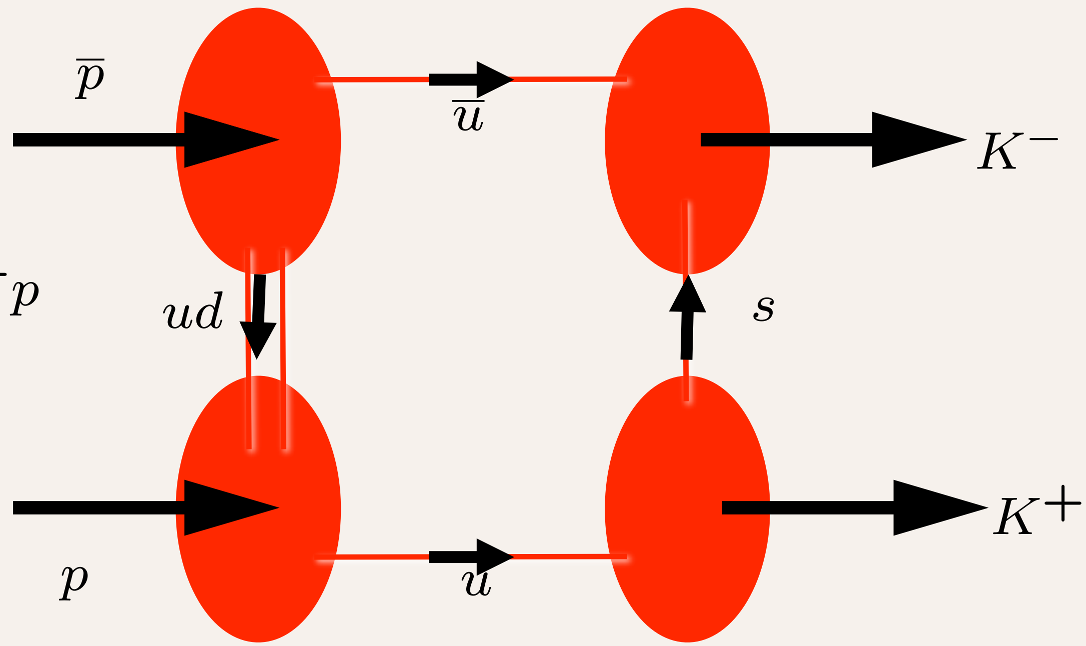


Key QCD Experiment at FAIR

$$\bar{p}p \to K^+K^-$$

$s \leftrightarrow t$ $t \leftrightarrow u$ crossing of $K^+p \to K^+p$

$$M(\bar{p}p \to K^+K^-) \propto \frac{1}{ts^2}$$

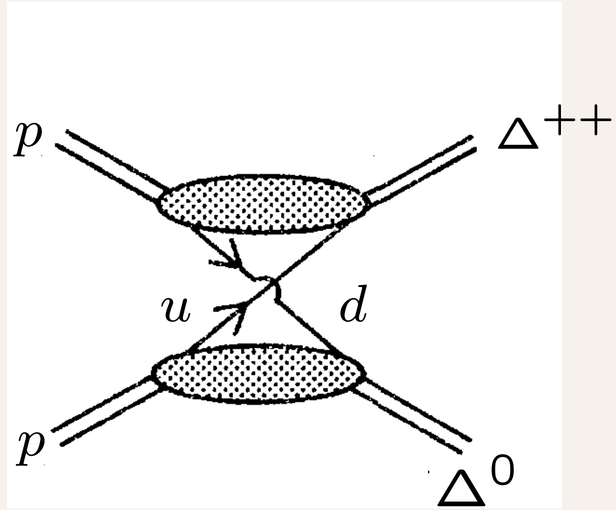


$$\frac{d\sigma}{dt} \propto \frac{1}{s^6 t^2}$$

at large t, u

Key QCD Experiment at FAIR

$pp \to \Delta^{++}\Delta^{0} \to (p\pi^{+}) + (p\pi^{-})$



$M \propto \frac{1}{u^2 t^2}$

Test quark interchange mechanism

Measure Ratio

$\frac{d\sigma}{dt}(pp \to \Delta^{++}\Delta^{0}) : \frac{d\sigma}{dt}(pp \to pp)$

Test $\frac{d\sigma}{dt} = \frac{F(\theta_{cm})}{s^{10}}$ AdS/CFT conformal scaling

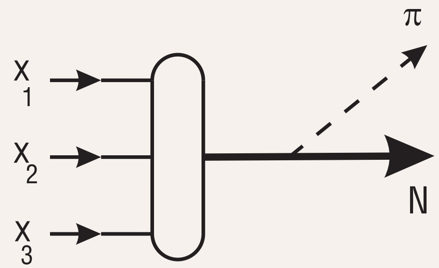
Single-Spin Asymmetry A_N of Δ

Test Hadron Helicity Conservation:

$\lambda_{\Delta^{++}} + \lambda_{\Delta^{-}} = \lambda_p + \lambda_p = -1, 0, +1.$

Key QCD Experiment at FAIR

P. V. Pobylitsa, V. Polyakov
and M. Strikman,
"Soft pion theorems for hard near-threshold
pion production,"
Phys. Rev. Lett. **87**, 022001 (2001)



Small $p\pi$ invariant mass; low relative velocity

Soft-pion theorem relates
near-threshold pion production
to the nucleon distribution amplitude.

$$\frac{d\sigma}{dt}(\overline{p}p \to (\pi\overline{p})p) = \frac{F(\theta_{cm})}{s^{10}}$$

No extra fall-off

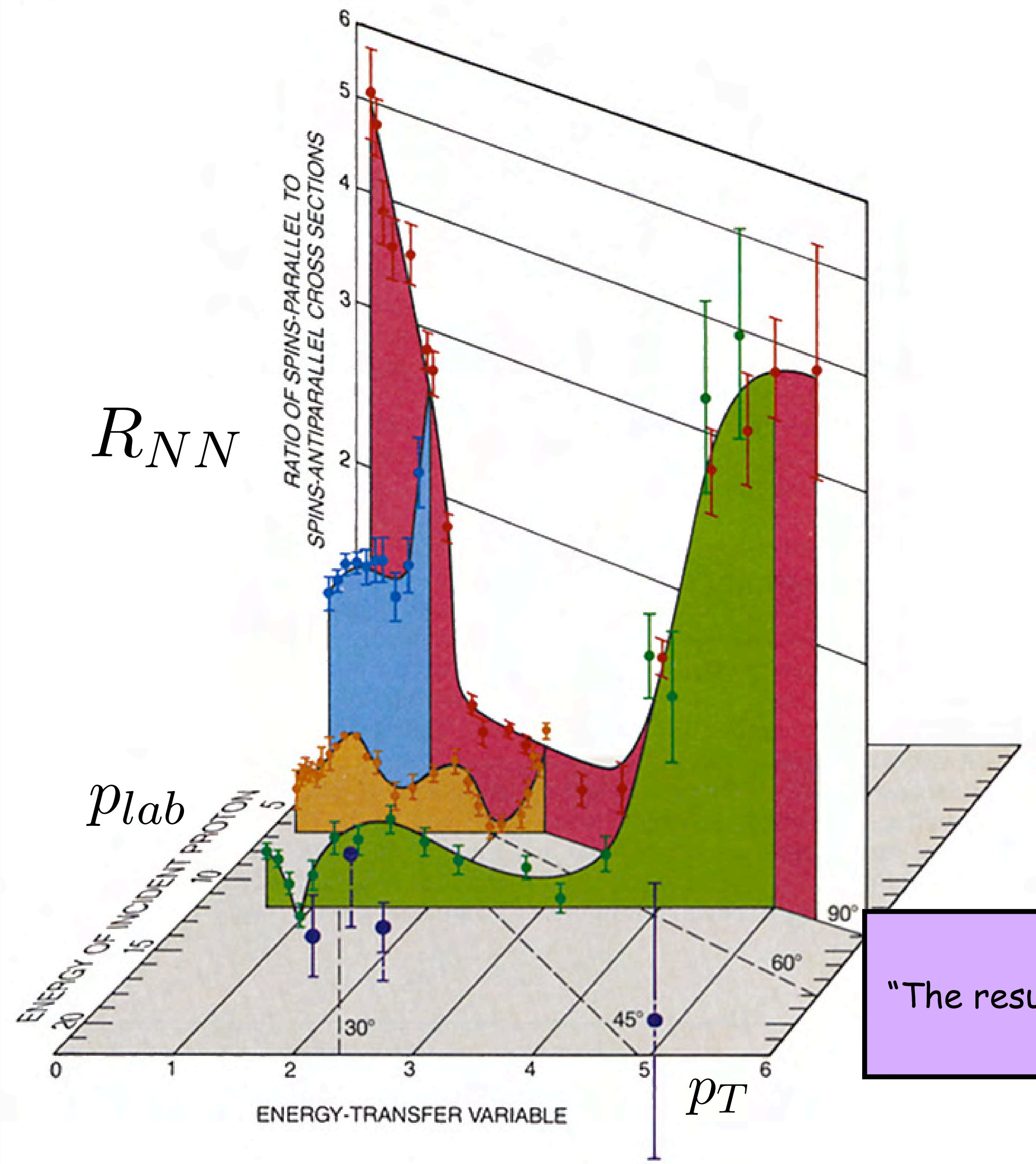
Same scaling as

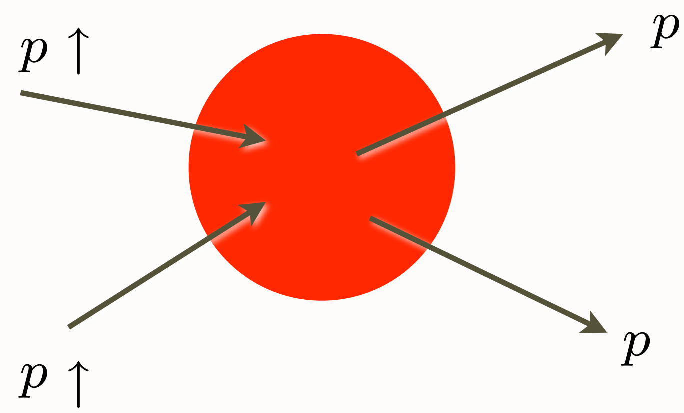
$$\frac{d\sigma}{dt}(\overline{p}p \to \overline{p}p) = \frac{F(\theta_{cm})}{s^{10}}$$

The remarkable anomalies of proton-proton scattering

- Double spin correlations
- Single spin correlations
- Color transparency

Spin Correlations in Elastic $p - p$ Scattering





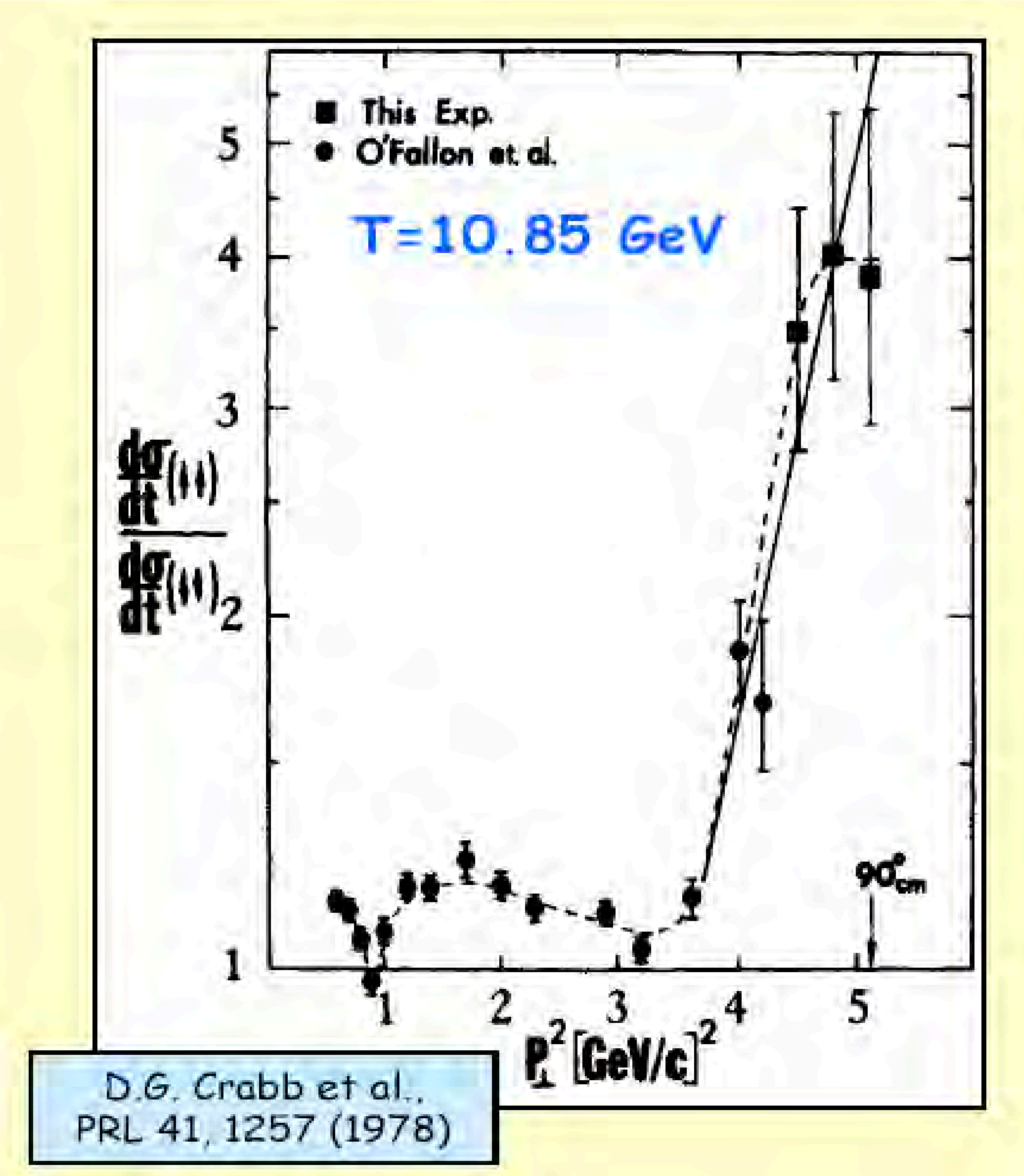
polarization normal to scattering plane

Ratio reaches 4:1 !

A. Krisch, Sci. Am. 257 (1987)
"The results challenge the prevailing theory that describes the proton's structure and forces"

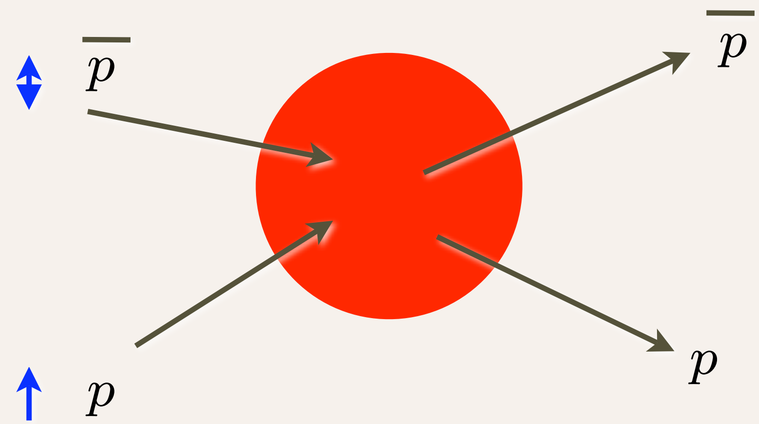
Unexpected spin effects in pp elastic scattering

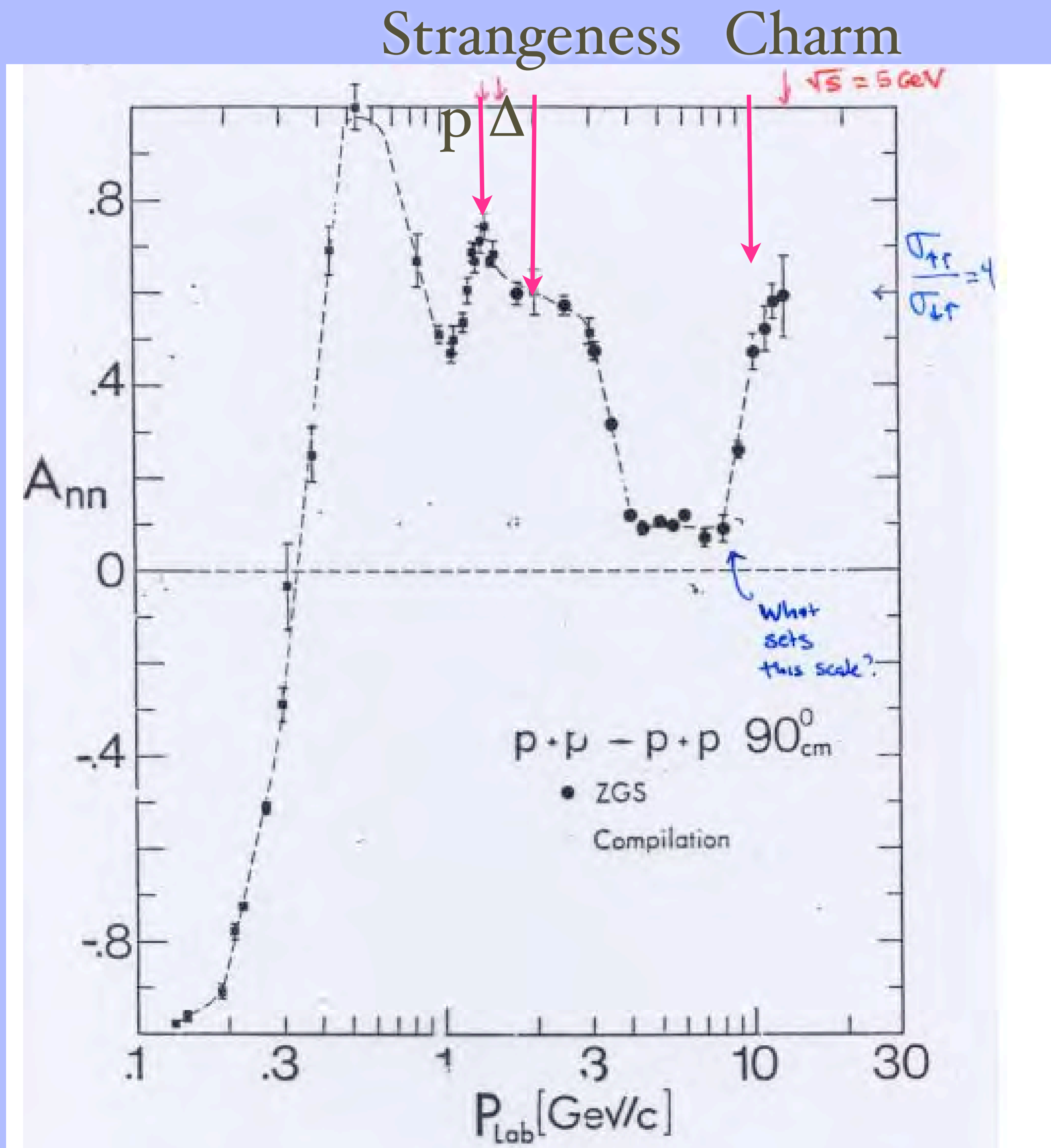
larger t region can be explored in $p\bar{p}$



Key QCD Experiment at FAIR

$$A_{NN} \text{ for } \overline{p}p \to \overline{p}p$$





Strangeness
Charm
p
Δ
√s = 5 GeV
.8
.4
0
-.4
-.8
A_{nn}
What sets this scale?
p + p → p + p 90°cm
ZGS
Compilation
.1
.3
1
3
10
30
P_{Lab} [GeV/c]

A. Krisch, Sci. Am. 257 (1987)
"The results challenge the prevailing theory that describes the proton's structure and forces"

"Exclusive Transversity"

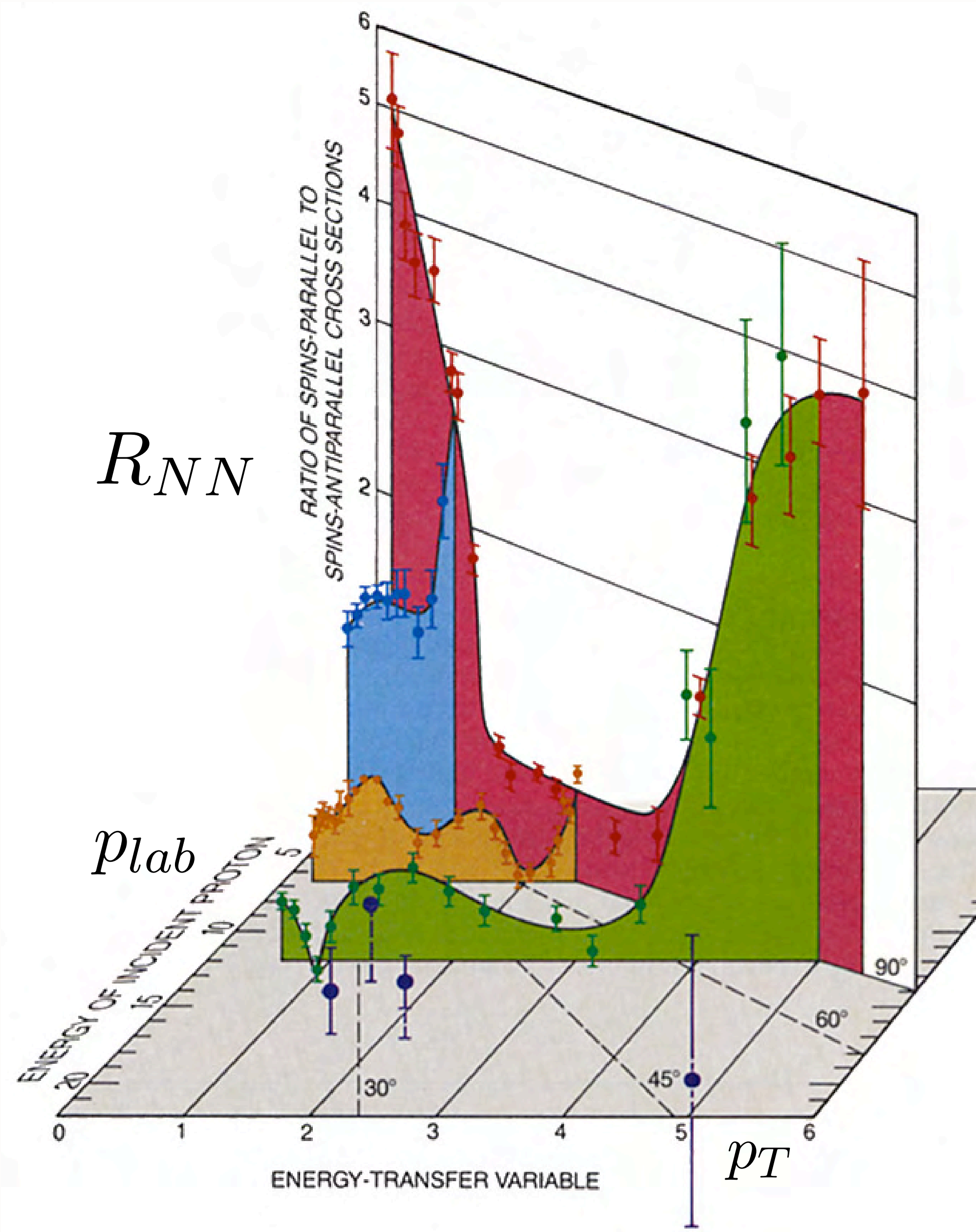
Spin-dependence at large-P_T ($90°_{cm}$):

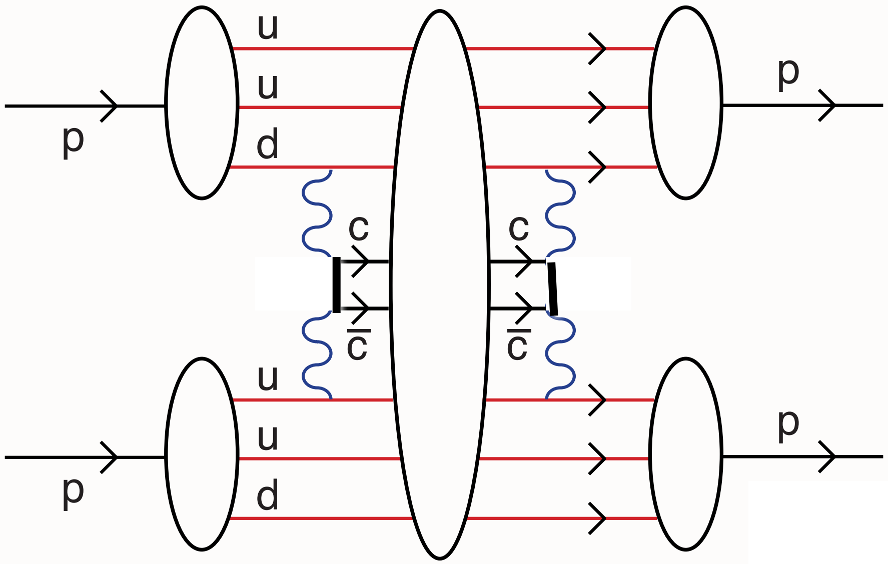
Hard scattering takes place only with spins ↑↑

Coincidence?: Quenching of Color Transparency

Coincidence?: Charm and Strangeness Thresholds

Alternative: Six-Quark Hidden-Color Resonances





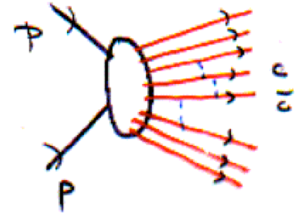
QCD Schwinger-Sommerfeld Enhancement at Heavy Quark Threshold

Hebecker, Kuhn, sjb

S. J. Brodsky and G. F. de Teramond, "Spin Correlations, QCD Color Transparency And Heavy Quark Thresholds In Proton Proton Scattering," Phys. Rev. Lett. **60**, 1924 (1988).

Spin, Coherence at heavy quark thresholds

$p\bar p \to Q\bar Q X$



Strong distortion at threshold $\vec p_{rel} \sim 0$

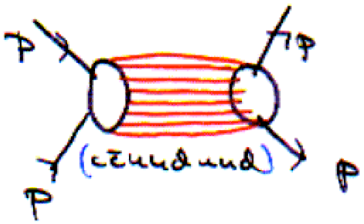
$\sqrt{s}_{Th} = 3+2 \simeq 5$ GeV $\quad pp \to c\bar c X$

8 quarks in S-wave odd parity!

$\therefore$ $J = L = S = 1$ for pp

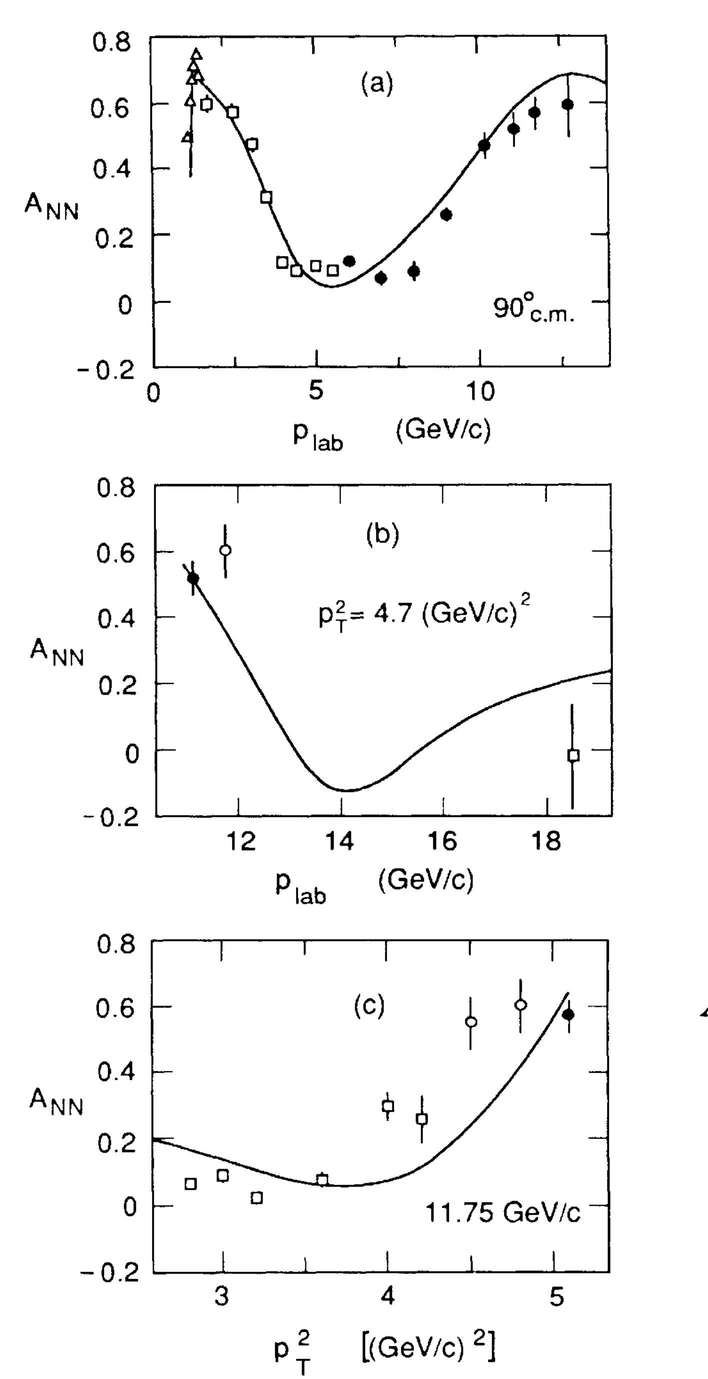
$B = 2$ resonance near threshold?

$\frac{d\sigma}{dt}(pp \to pp)$ $\sqrt{s} \sim 5$ GeV



$A_{NN} = 1$ for $J=L=S=1$ $\quad p\uparrow p\uparrow$ only

expect increase of A_{NN} at $\sqrt{s} = 3, 5, 12$ GeV, $\theta_{cm} = 90°$



S. J. Brodsky and G. F. de Teramond, "Spin Correlations, QCD Color Transparency And Heavy Quark Thresholds In Proton Proton Scattering," Phys. Rev. Lett. **60**, 1924 (1988).

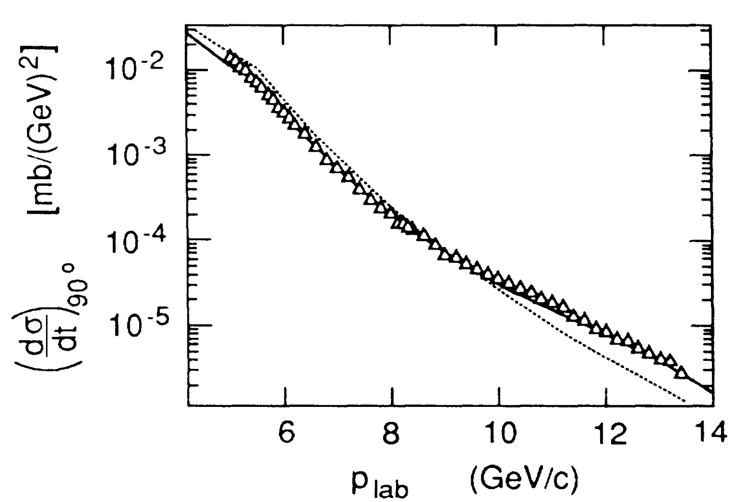
Quark Interchange + 8-Quark Resonance

$|uuduudc\bar{c}>$ Strange and Charm Octoquark!

$M = 3$ GeV, $M = 5$ GeV.

$J = L = S = 1, \; B = 2$

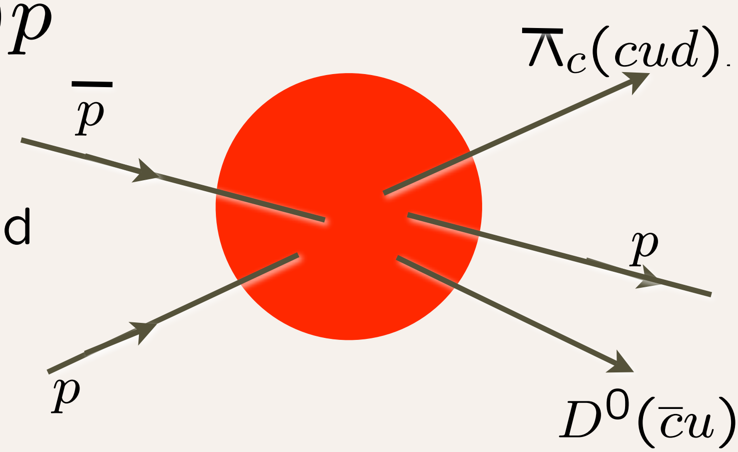
$$A_{NN} = \frac{d\sigma(\uparrow\uparrow) - d\sigma(\uparrow\downarrow)}{d\sigma(\uparrow\uparrow) + d\sigma(\uparrow\downarrow)}$$



Key QCD Experiment at FAIR

Open Charm

$$\bar{p}p \to \bar{\Lambda}_c(\overline{cud}) D^0(\bar{c}u)p$$



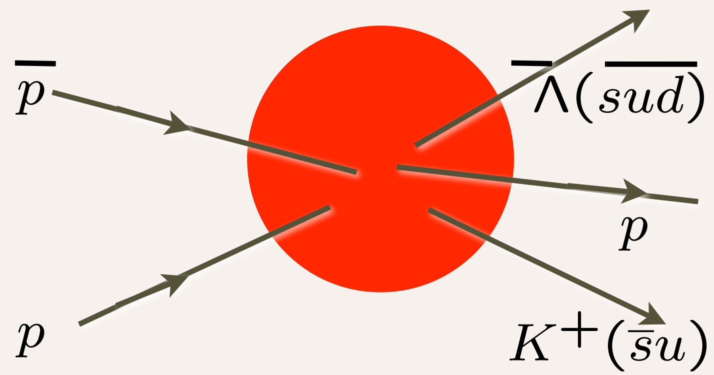
Total open charm cross section at threshold

$$\sigma(pp \to cX) \simeq 1\mu b$$

needed to explain Krisch A_{NN}

Compare with strangeness channels

$$pp \to \Lambda(sud)K^+(\bar{s}u)p$$



Key QCD Experiment at FAIR

- New QCD physics in proton-proton elastic scattering at the charm threshold

- Anomalously large charm production at threshold!!?

- Octoquark resonances?

- Color Transparency disappears at charm threshold

- Key physics at GSI: second charm threshold

$$\bar{p}p \to \bar{p}pJ/\psi$$

$$\bar{p}p \to \bar{p}\Lambda_c D$$

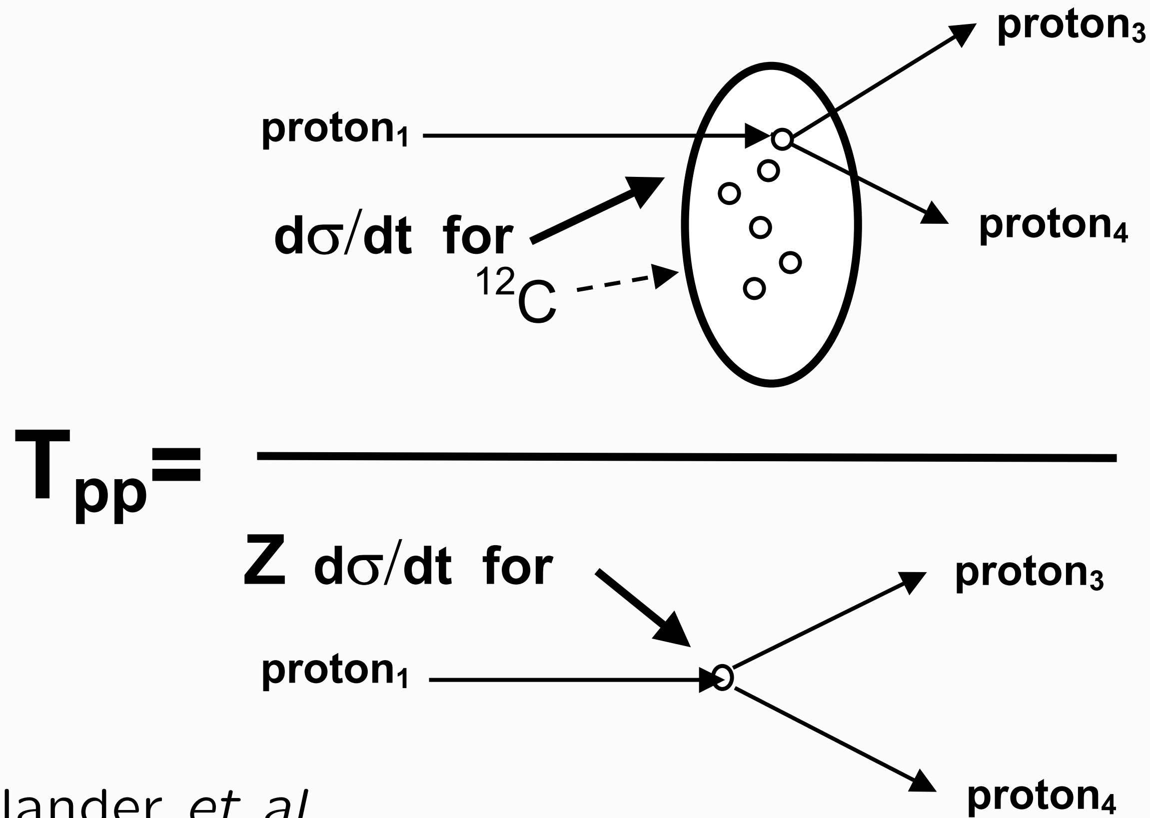
Color Transparency

Bertsch, Gunion, Goldhaber, sjb

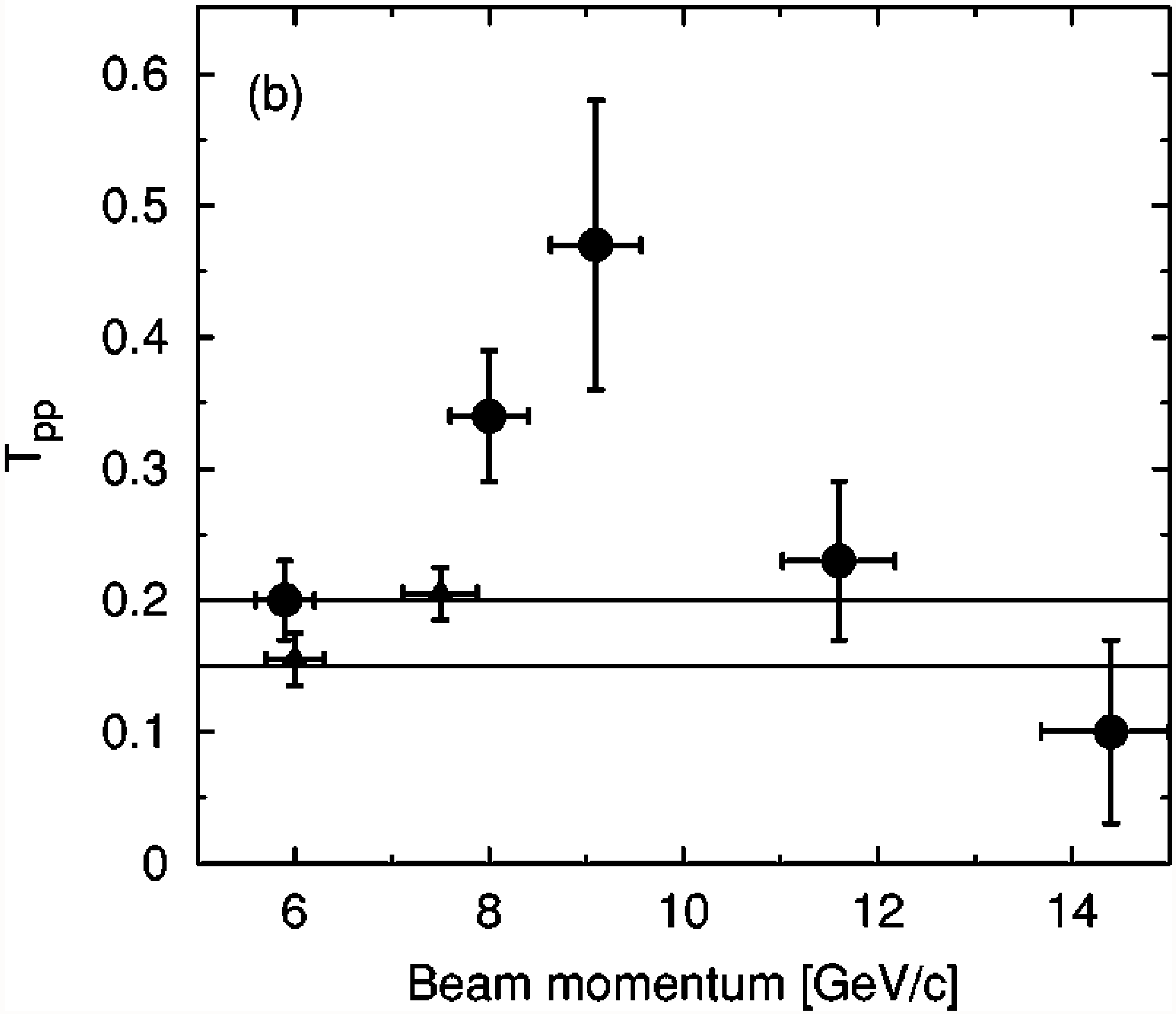
A. H. Mueller, sjb

- Fundamental test of gauge theory in hadron physics
- Small color dipole moments interact weakly in nuclei
- Complete coherence at high energies
- Clear Demonstration of CT from Diffractive Di-Jets

Color Transparency Ratio



J. L. S. Aclander *et al.*,
"Nuclear transparency in $\theta_{CM} = 90^0$ quasielastic $A(p, 2p)$ reactions,"
Phys. Rev. C **70**, 015208 (2004), [arXiv:nucl-ex/0405025].

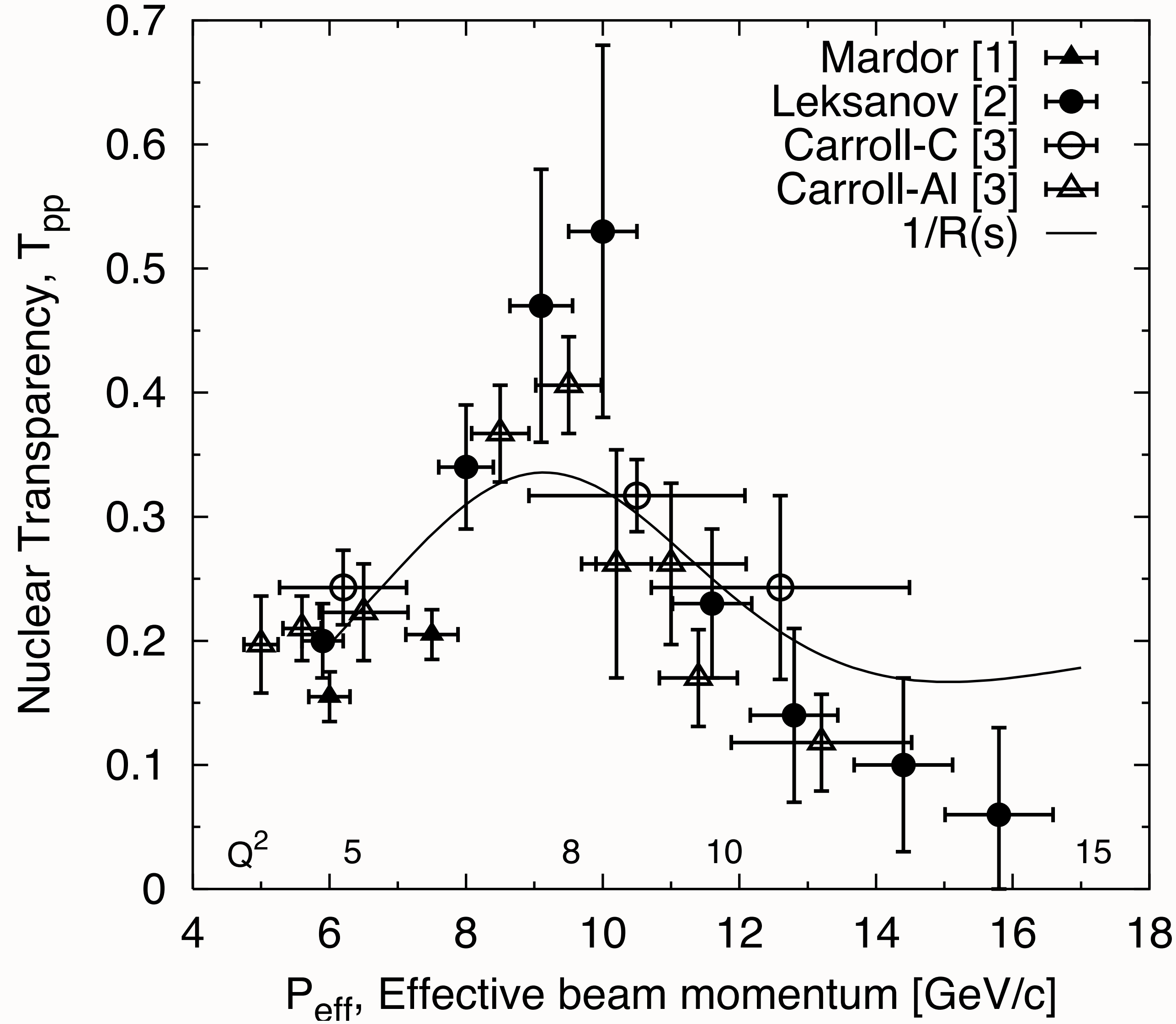


PHYSICAL REVIEW C **70**, 015208 (2004)

Nuclear transparency in $90^{\circ}_{c.m.}$ quasielastic $A(p,2p)$ reactions

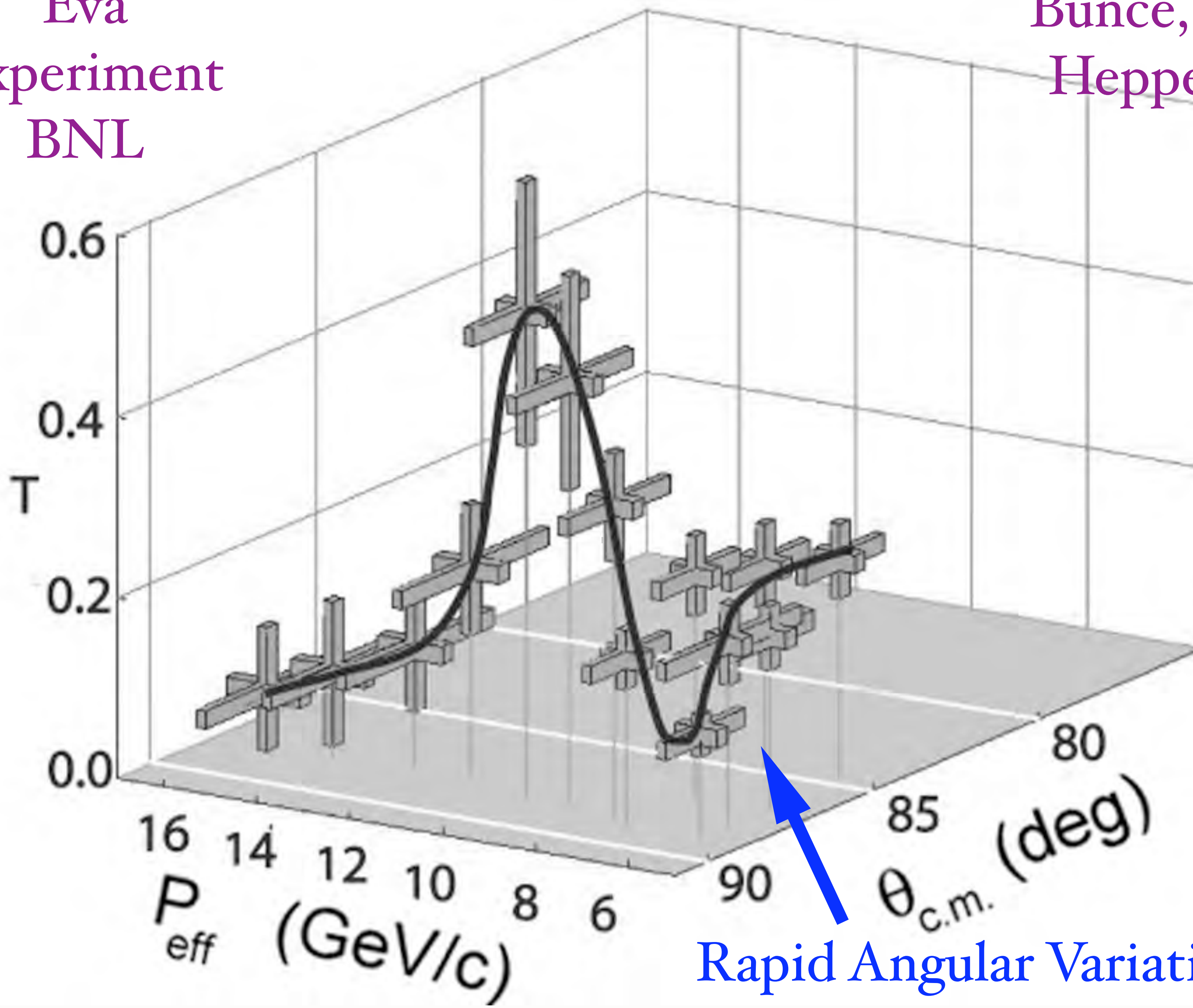
J. Aclander,[7] J. Alster,[7] G. Asryan,[1,*] Y. Averiche,[5] D. S. Barton,[1] V. Baturin,[2,†] N. Buktoyarova,[1,†] G. Bunce,[1] A. S. Carroll,[1,‡] N. Christensen,[3,§] H. Courant,[3] S. Durrant,[2] G. Fang,[3] K. Gabriel,[2] S. Gushue,[1] K. J. Heller,[3] S. Heppelmann,[2] I. Kosonovsky,[7] A. Leksanov,[2] Y. I. Makdisi,[1] A. Malki,[7] I. Mardor,[7] Y. Mardor,[7] M. L. Marshak,[3] D. Martel,[4] E. Minina,[2] E. Minor,[2] I. Navon,[7] H. Nicholson,[8] A. Ogawa,[2] Y. Panebratsev,[5] E. Piasetzky,[7] T. Roser,[1] J. J. Russell,[4] A. Schetkovsky,[2,†] S. Shimanskiy,[5] M. A. Shupe,[3,∥] S. Sutton,[8] M. Tanaka,[1,¶] A. Tang,[6] I. Tsetkov,[5] J. Watson,[6] C. White,[3] J-Y. Wu,[2] and D. Zhalov[2]

Color Transparency fails when A_{nn} is large



Eva Experiment BNL

Bunce, Carroll, Heppelman...



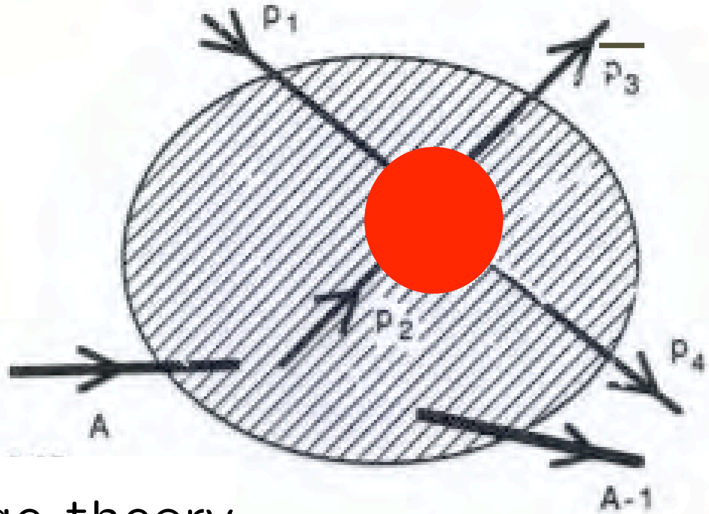
Rapid Angular Variation!

Key QCD Experiment at FAIR

Test Color Transparency

$$\frac{d\sigma}{dt}(\overline{p}A \to \overline{p}p(A-1)) \to Z \times \frac{d\sigma}{dt}(\overline{p}p \to \overline{p}p)$$

No absorption of small color dipole at high p_T

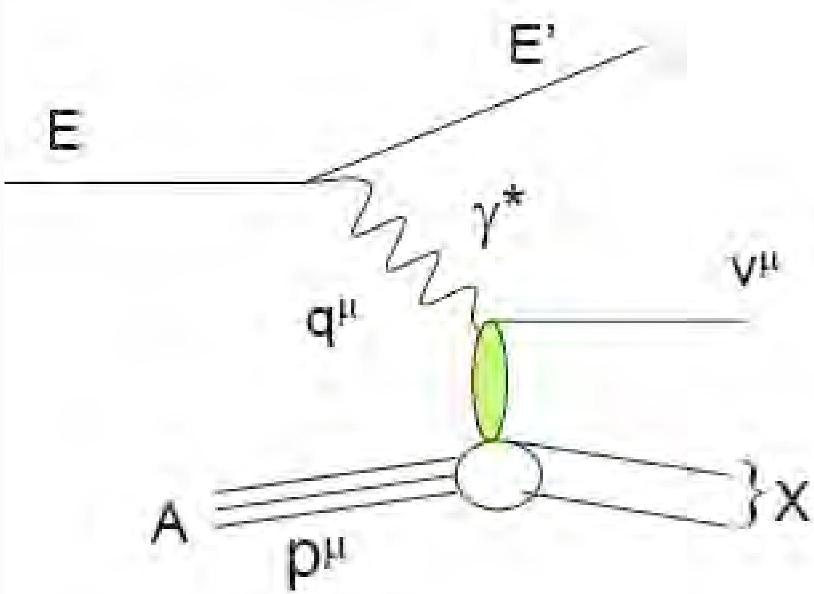


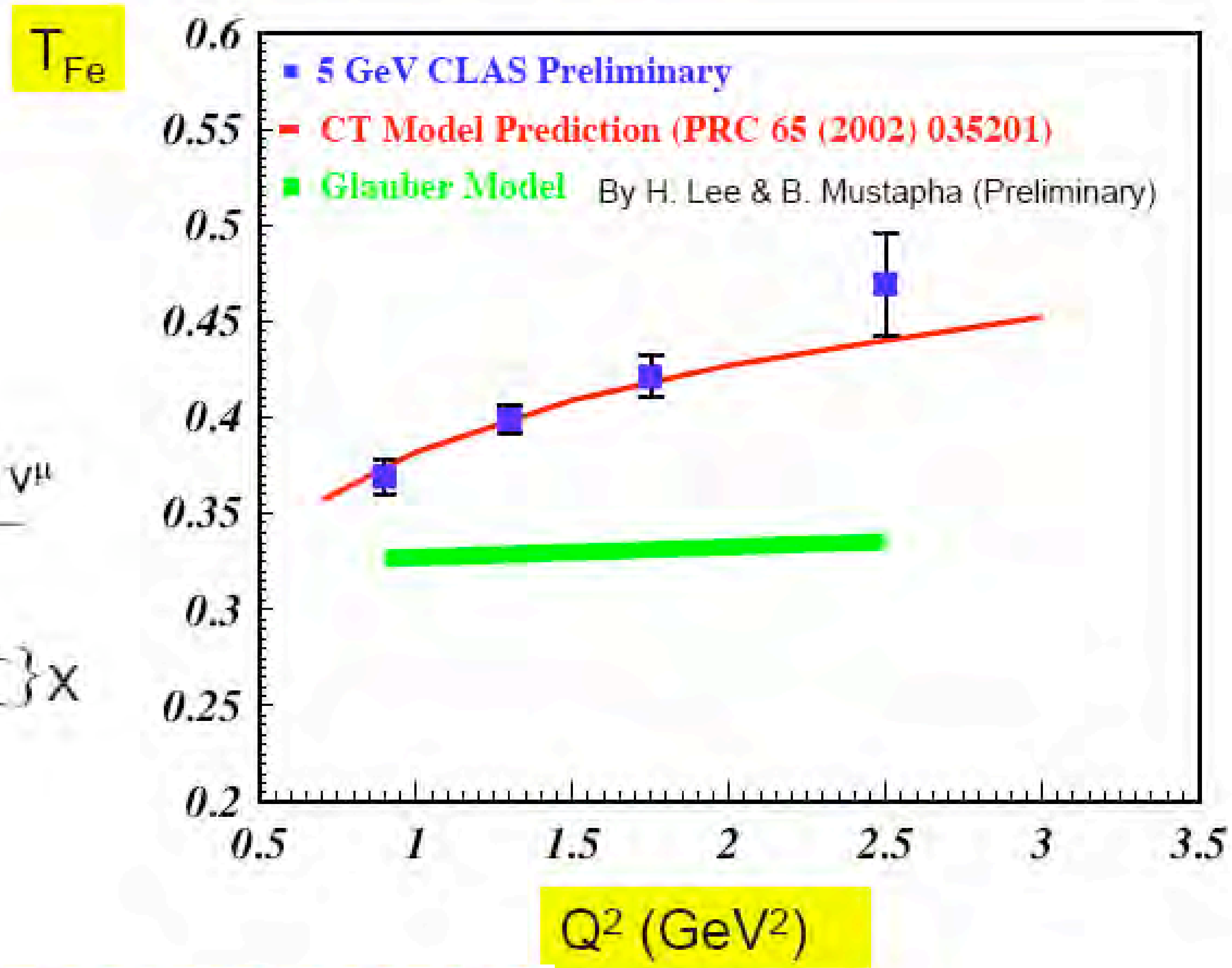
Key test of local gauge theory

Traditional Glauber Theory: $\sigma_A \sim Z^{1/3}\sigma_p$

A.H. Mueller, SJB

Kawtar Hafidi



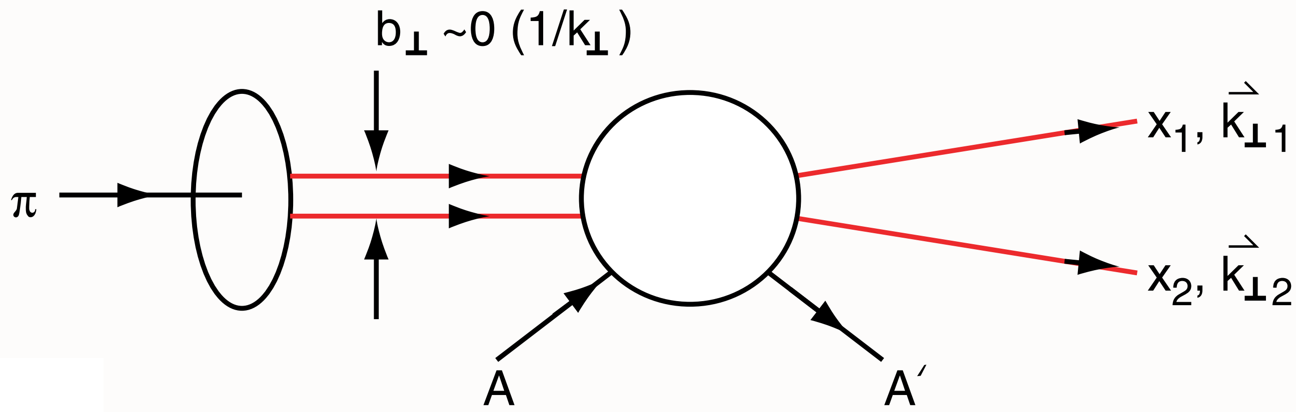


Theory:

Kopeliovich et al., PRC 65 (2002) 035201

Diffractive Dissociation of Pion into Quark Jets

E791 Ashery et al.



$$M \propto \frac{\partial^2}{\partial^2 k_\perp} \psi_\pi(x, k_\perp)$$

Measure Light-Front Wavefunction of Pion

Minimal momentum transfer to nucleus
Nucleus left Intact!

Mueller, sjb; Bertsch et al;
Frankfurt, Miller, Strikman

Measure pion LFWF in diffractive dijet production
Confirmation of color transparency

A-Dependence results: $\sigma \propto A^{\alpha}$

k_t range (GeV/c)	α	α (CT)
$1.25 < k_t < 1.5$	1.64 +0.06 -0.12	1.25
$1.5 < k_t < 2.0$	1.52 ± 0.12	1.45
$2.0 < k_t < 2.5$	1.55 ± 0.16	1.60

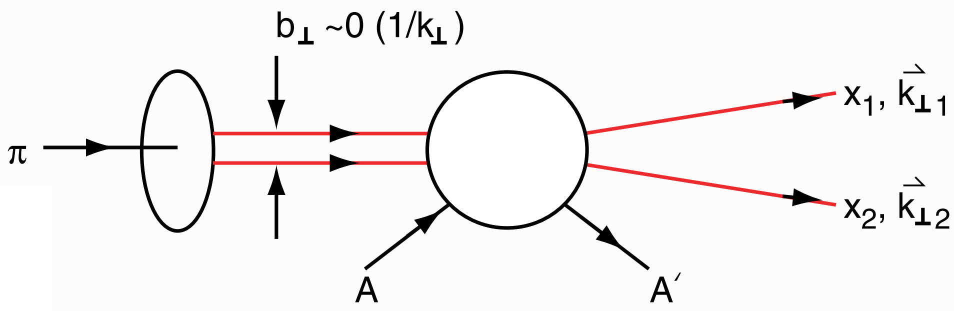
Ashery E791

α (Incoh.) $= 0.70 \pm 0.1$

Conventional Glauber Theory Ruled Out !

Factor of 7

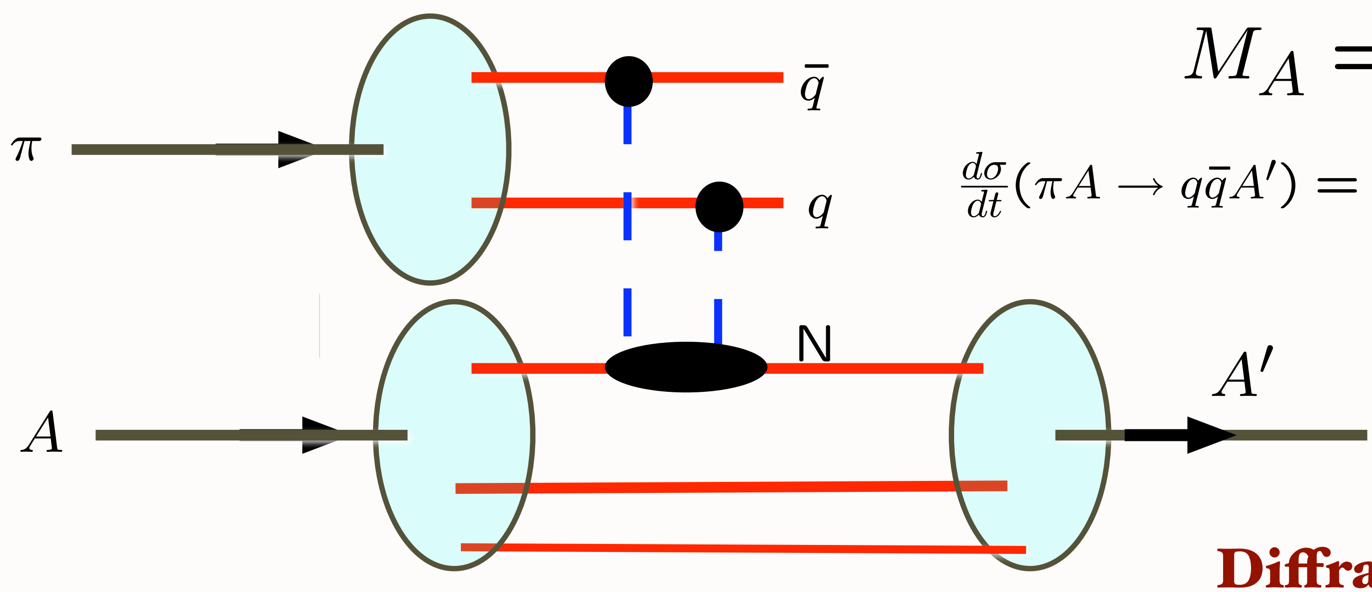
Key Ingredients in E791 Experiment



Brodsky Mueller
Frankfurt Miller Strikman

Small color-dipole moment pion not absorbed;
interacts with each nucleon coherently

QCD COLOR Transparency



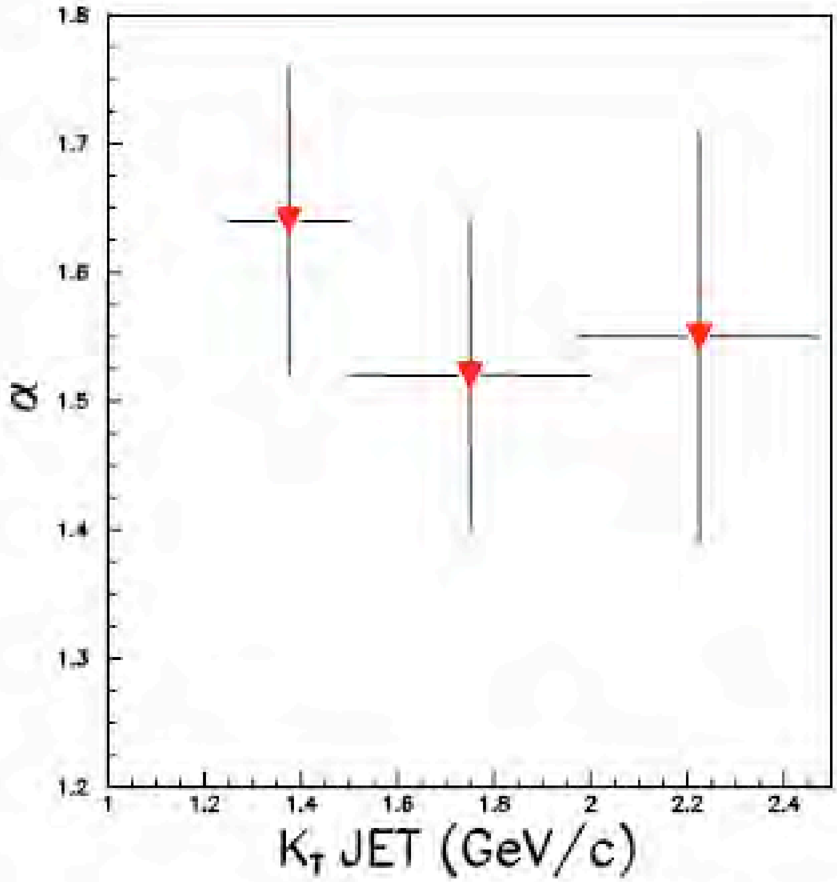
$$M_A = A\ M_N$$

$$\frac{d\sigma}{dt}(\pi A \to q\bar{q}A') = A^2\ \frac{d\sigma}{dt}(\pi N \to q\bar{q}N')\ F^2_A(t)$$

Target left intact

Diffraction, Rapidity gap

$A(\pi,\text{dijet})$ data from FNAL



Coherent π^+ diffractive dissociation with 500 GeV/c pions on Pt and C.

Fit to $\sigma = \sigma_0 A^\alpha$

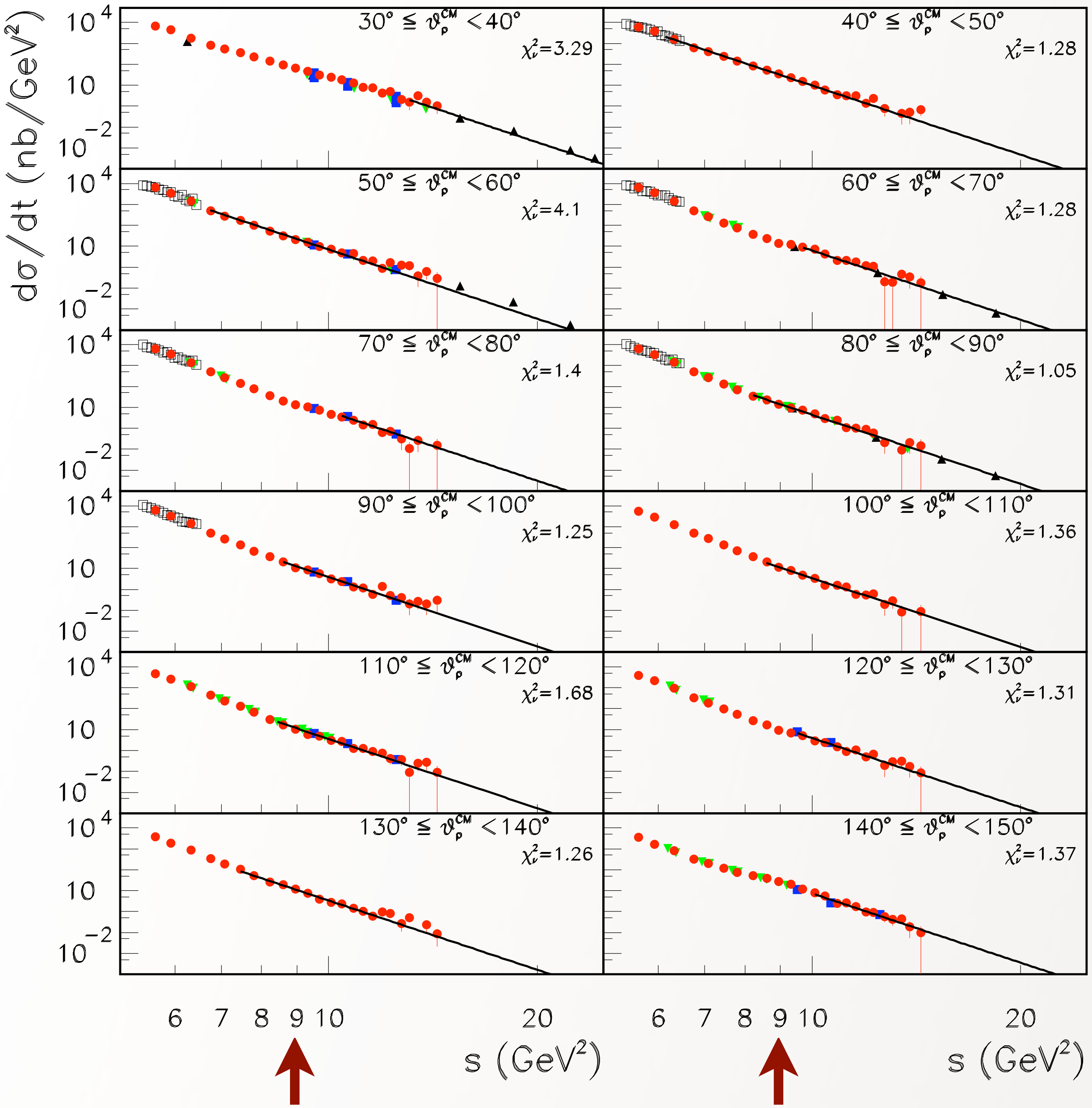
α = 0.76 from pion-nucleus total cross-section.

Aitala et al., PRL 86 4773 (2001)

L. L. Frankfurt, G. A. Miller, and M. Strikman, Found. Of Phys. 30 (2000) 533

Deuteron Photodisintegration and Dimensional Counting

P.Rossi et al, P.R.L. 94, 012301 (2005)



PQCD and AdS/CFT:

$$s^{n_{tot}-2}\frac{d\sigma}{dt}(A+B \to C+D) = F_{A+B\to C+D}(\theta_{CM})$$

$$s^{11}\frac{d\sigma}{dt}(\gamma d \to np) = F(\theta_{CM})$$

$$n_{tot} - 2 =$$
$$(1 + 6 + 3 + 3) - 2 = 11$$

$$\gamma d \to (uuddd u s \bar{s}) \to np$$

at $s \simeq 9$ GeV^2

$$\gamma d \to (uuddd u c \bar{c}) \to np$$

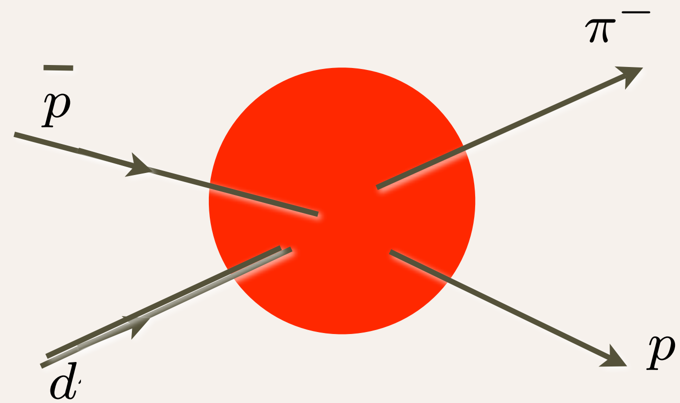
at $s \simeq 25$ GeV^2

Key QCD Experiment at FAIR

Test QCD scaling in hard exclusive nuclear amplitudes

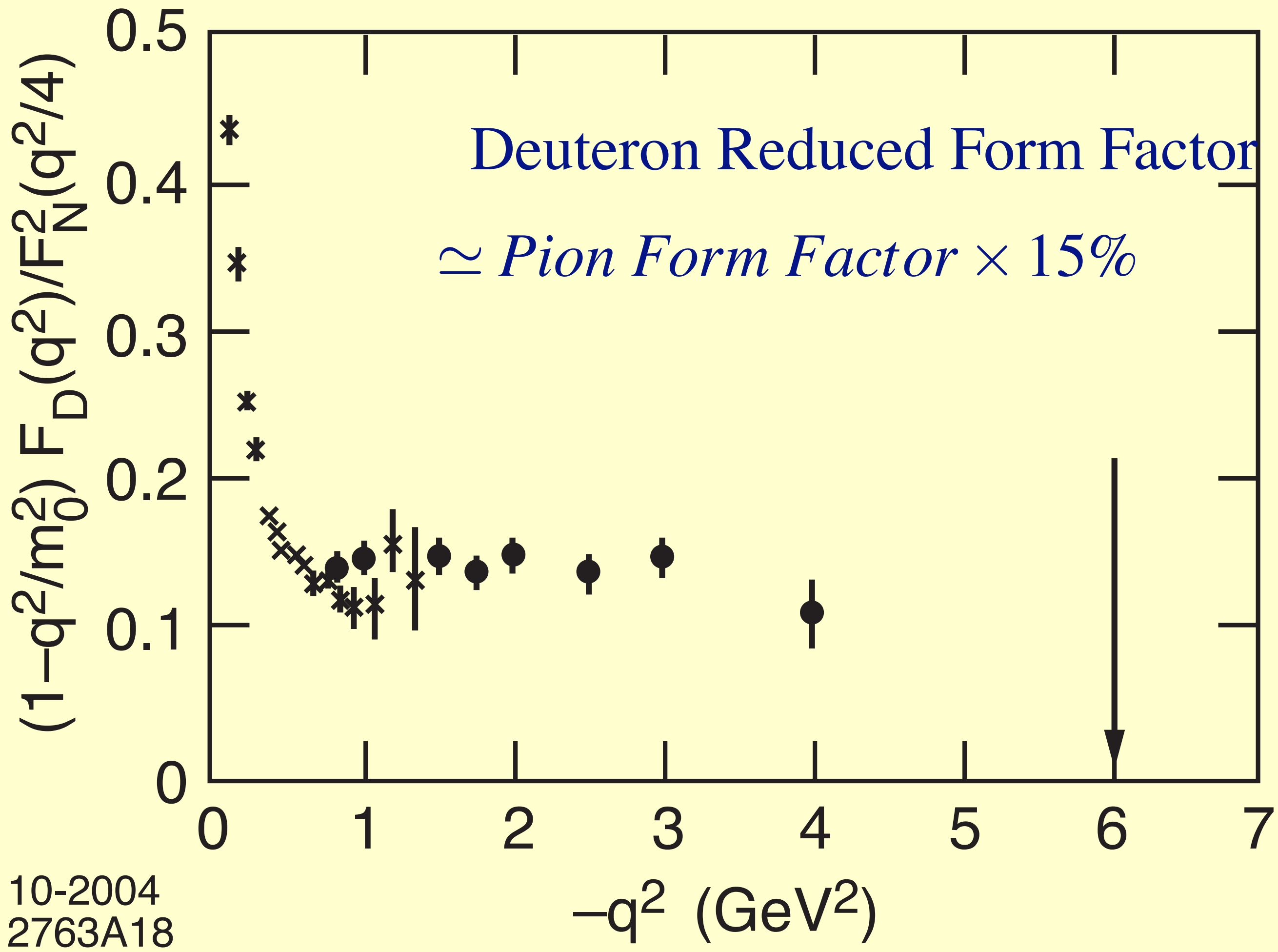
Manifestations of Hidden Color in Deuteron Wavefunction

$$\bar{p}d \to \pi^- p$$
$$\bar{p}d \to n\gamma$$
$$\bar{p}d \to \bar{p}d$$



Conformal Scaling, AdS/CFT

$$\frac{d\sigma}{dt}(\bar{p}d \to \pi^- p) = \frac{F(\theta_{cm})}{s^{12}}$$



- 15% Hidden Color in the Deuteron

- Remarkable Test of Quark Counting Rules
- Deuteron Photo-Disintegration $\gamma d \to np$

$$\frac{d\sigma}{dt} = \frac{F(t/s)}{s^{n_{tot}-2}}$$

- $$n_{tot} = 1 + 6 + 3 + 3 = 13$$

Scaling characteristic of
scale-invariant theory at short distances

Conformal symmetry

Hidden color: $\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-}) \simeq \frac{d\sigma}{dt}(\gamma d \to pn)$

at high p_T

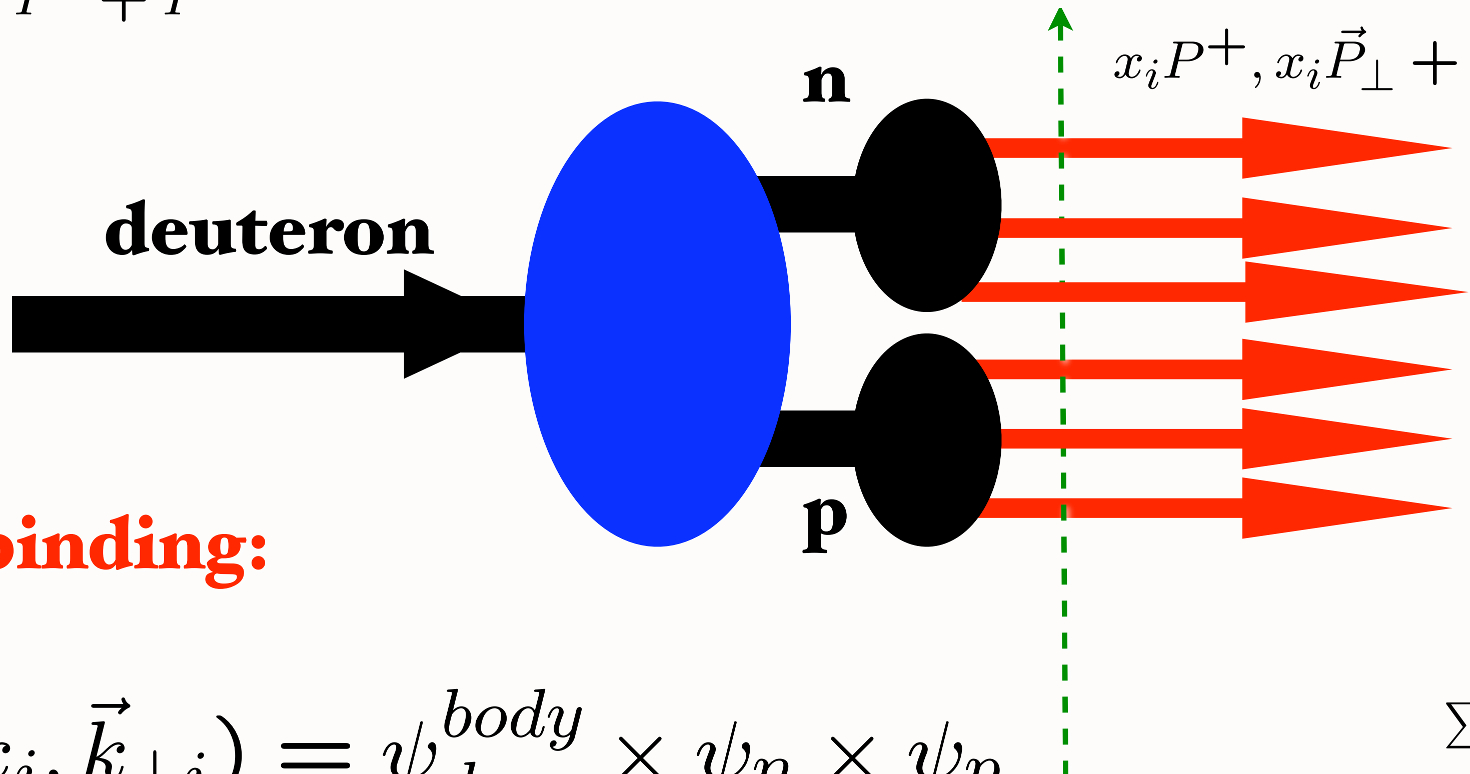
Ratio predicted to approach 2:5

Deuteron Light-Front Wavefunction

Fixed $\tau = t + z/c$

$P^+ = P^0 + P^z$

$P^+, \vec{P}_\perp$



Weak binding:

$$\psi_d(x_i, \vec{k}_{\perp i}) = \psi_d^{body} \times \psi_n \times \psi_p$$

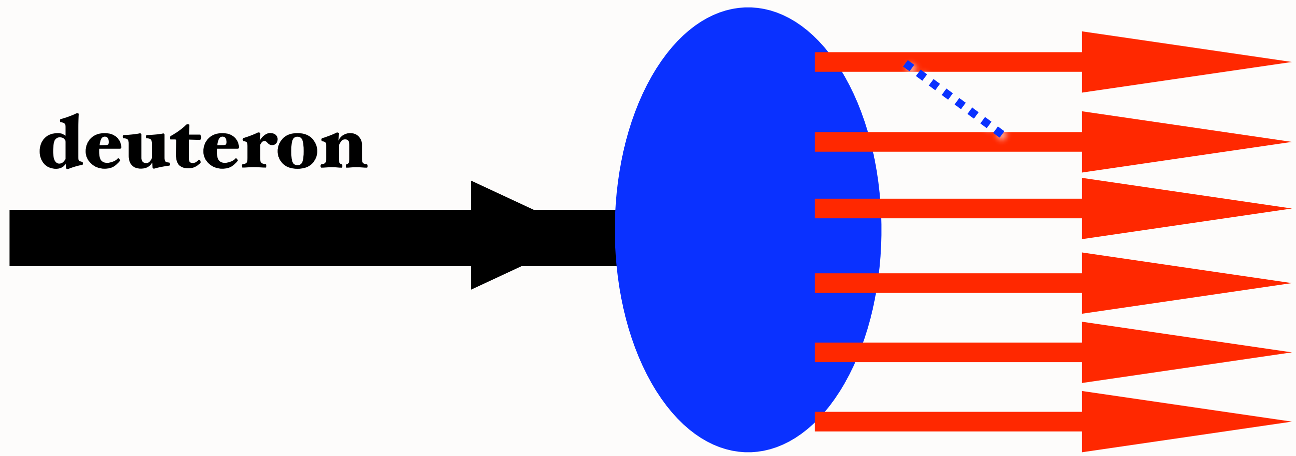
$\Sigma_i^n x_i = 1$

$\Sigma_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

Two color-singlet combinations of three 3_C

Evolution of 5 color-singlet Fock states

$$\Psi^{\mathbf{d}}_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

$\sum_i^n x_i = 1$

$$\Phi_n(x_i, Q) = \int^{k^2_{\perp i} < Q^2} \Pi' d^2 k_{\perp j} \psi_n(x_i, \vec{k}_{\perp j})$$

5 X 5 Matrix Evolution Equation for deuteron distribution amplitude

Hidden Color in QCD

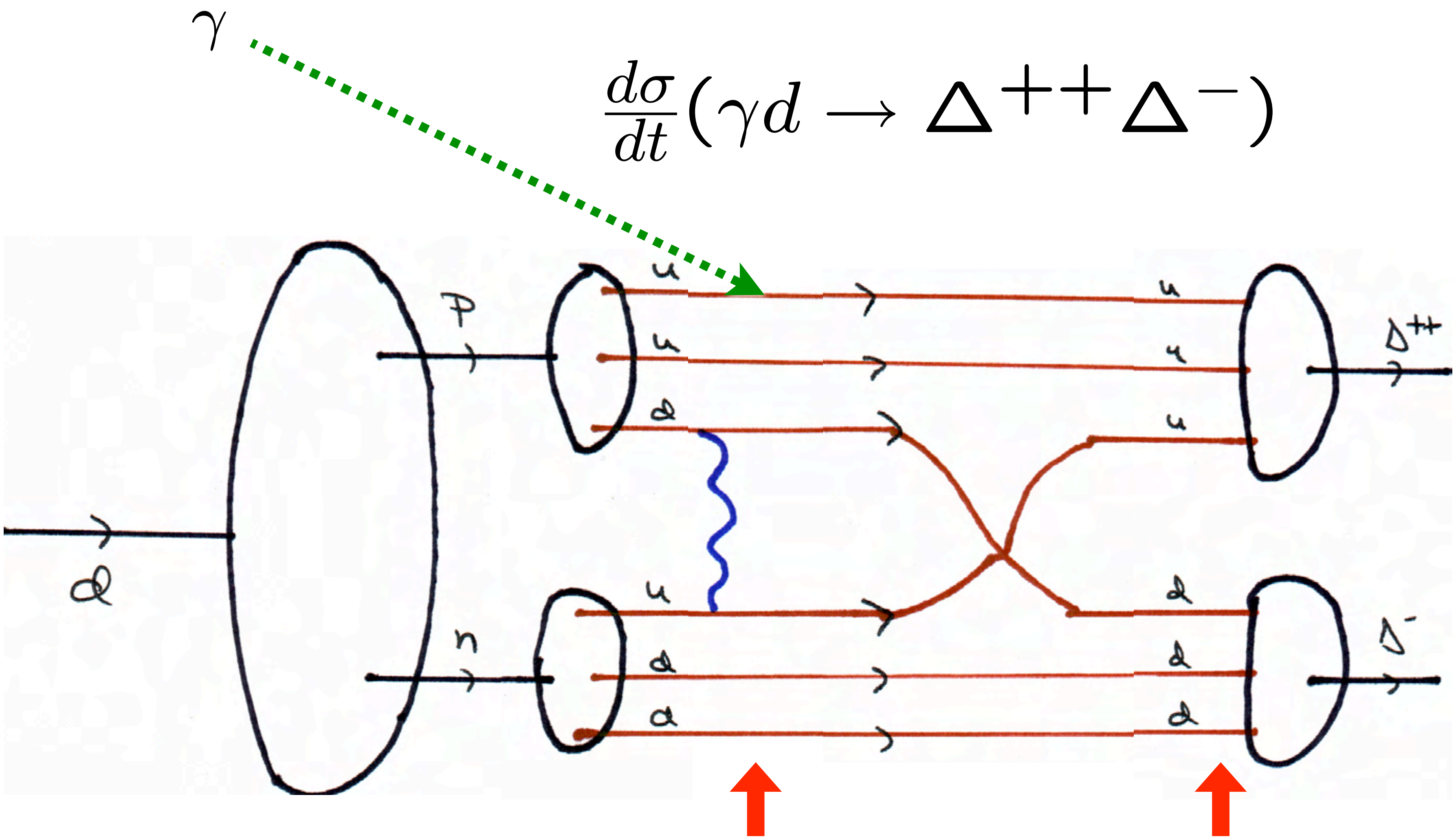
Lepage, Ji, sjb

- Deuteron six quark wavefunction:
- 5 color-singlet combinations of 6 color-triplets -- one state is |n p>
- Components evolve towards equality at short distances
- Hidden color states dominate deuteron form factor and photodisintegration at high momentum transfer
- Predict $\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-}) \simeq \frac{d\sigma}{dt}(\gamma d \to pn)$ at high Q^2

Ratio = 2/5 for asymptotic wf

Test of Hidden Color in Deuteron Photodisintegration

$$\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-})$$



Hidden Color Fock State

Delta-Delta Fock State

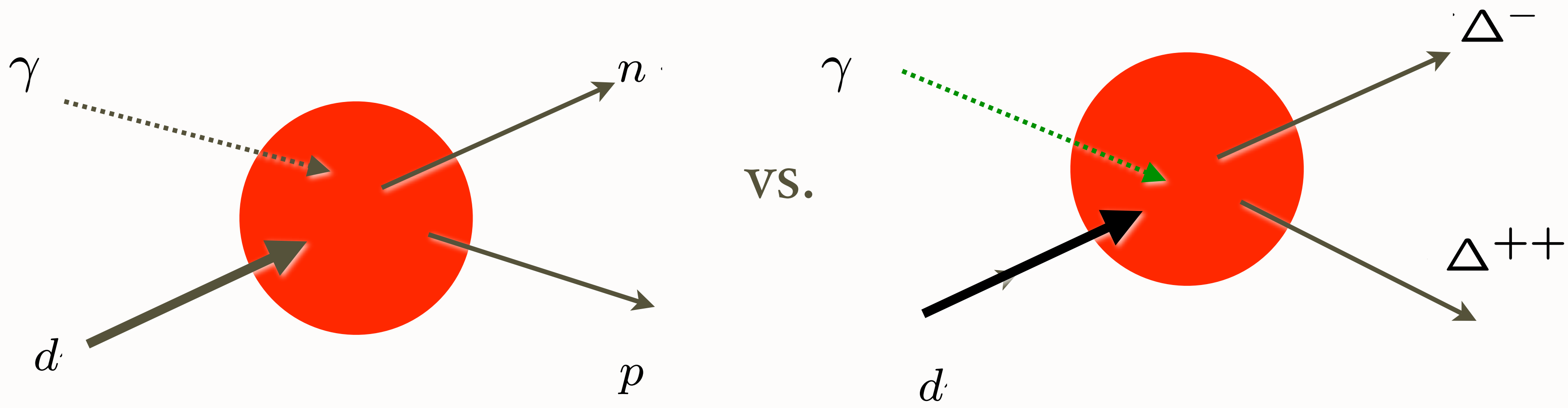
Test of Hidden Color in Deuteron Photodisintegration

$$R = \frac{\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{--})}{\frac{d\sigma}{dt}(\gamma d \to pn)}$$

Ratio predicted to approach 2:5

Possible contribution from pion charge exchange at small t.

Ratio should grow with transverse momentum as the hidden color component of the deuteron grows in strength.

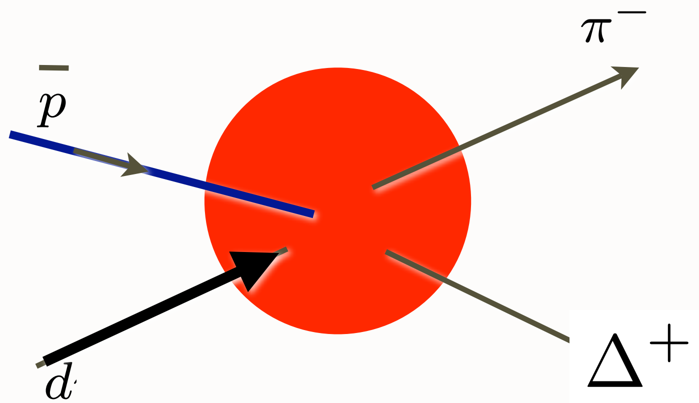


Key Experiment at GSI FAIR

Test QCD scaling in hard exclusive nuclear amplitudes

Manifestations of Hidden Color in Deuteron Wavefunction

$$\bar{p}d \to \pi^- p$$



Ratio predicted to approach 2:5

$$\bar{p}d \to \pi^- \Delta^+$$

Conformal Scaling, AdS/CFT

$$\frac{d\sigma}{dt}(\bar{p}d \to \pi^- p) = \frac{F(\theta_{cm})}{s^{12}}$$

Topics for FAIR in Exclusive Processes

QCD at the Amplitude Level

- Measures of LFWFs, distribution amplitudes, transition distribution amplitudes
- Scaling of Fixed-Angle Amplitudes tests conformal window of QCD
- Quark-Interchange Dominance at large p_T
- Crossing and Analyticity $\bar{p}p \to \gamma\pi$ vs. $\gamma p \to \pi p$
- Timelike GPDs from DVCS $\bar{p}p \to \gamma * \gamma$, charge and spin asymmetry, $J = 0$

Local seagull-like Interactions

- Transition to Regge theory at forward and backward angles
- Regge poles $\alpha_R(t) \to -1, -2$ at large $-t$.
- Charm and Charmonium at Threshold
- Odderon Tests
- Second Charm Threshold $\bar{p}p \to \bar{p}pJ/\psi$
- Diffractive Drell-Yan $\bar{p}p \to \bar{\ell}\ell J/\psi$
- Exclusive A_N, A_{NN}, especially at strange and charm thresholds
- Color Transparency
- Hidden Color of Nuclear Wavefunctions in $\bar{p}d$ reactions
- Exotic $\bar{q}\bar{q}qq$ and gluonium Spectra in $p\bar{p} \to \gamma M_X$

Topics for FAIR in Di-Muon Production

- Direct Higher Twist Processes
- Single-Spin Asymmetry
- Double Spin Correlation: Transversity
- Lam-Tung Violation in Continuum and J/Psi Production: Double ISI
- Role of quark-quark scattering plus bremsstrahlung: color dipole approach
- Double Drell-Yan: Glauber vs Handbag
- Associated System - Tetraquark and Gluonium States

Heavy Quark Topics for FAIR

- Mechanisms for Heavy Hadron and Quarkonium Production Near Threshold
- Tests of Intrinsic Charm
- Quarkonium Attenuation at High x_F
- Non-Universal Anti-Shadowing

- Although we know the QCD Lagrangian, we have only begun to understand its remarkable properties and features.

- Novel QCD Phenomena: hidden color, color transparency, strangeness asymmetry, intrinsic charm, anomalous heavy quark phenomena, anomalous spin effects, single-spin asymmetries, odderon, diffractive deep inelastic scattering, dangling gluons, shadowing, antishadowing ...

Truth is stranger than fiction, but it is because Fiction is obliged to stick to possibilities.

—Mark Twain

Thanks to Diego Bettoni

Some references

Testing quantum chromodynamics with anti**protons.**
Stanley J. Brodsky (SLAC) . SLAC-PUB-10811, Oct 2004. 92pp.
Published in *Varenna 2004, Hadron physics* 345-422
e-Print Archive: **hep-ph/0411046**

Light-front QCD.
Stanley J. Brodsky (**SLAC**) **. SLAC-PUB-10871, Nov 2004. 66pp.**
Invited lectures and talk presented at the 58th Scottish University Summer School in Physics: A NATO Advanced Study Institute and EU Hadronic Physics 13 Summer Institute (SUSSP58), St. Andrews, Scotland, 30 Aug - 1 Sep 2004.
e-Print Archive: hep-ph/0412101