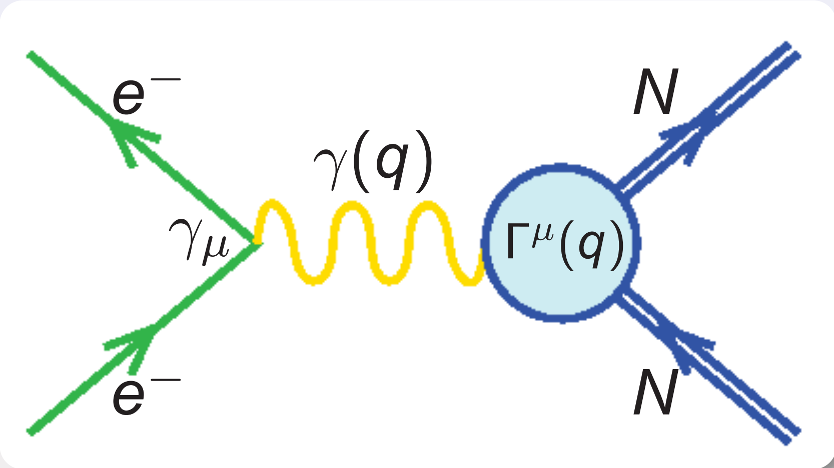
Novel Dynamical Tests of QCD at PANDA

- Characteristic momentum scale of QCD: 300 MeV
- Many Tests of AdS/CFT predictions possible
- Exclusive channels: Conformal scaling laws, quark-interchange
- $\bar{p}p$ scattering: fundamental aspects of nuclear force
- Color transparency: Coherent color effects
- Nuclear Effects, Hidden Color, Anti-Shadowing
- Anomalous heavy quark phenomena
- Spin Effects: A_N, A_{NN}

Nucleon Form Factors



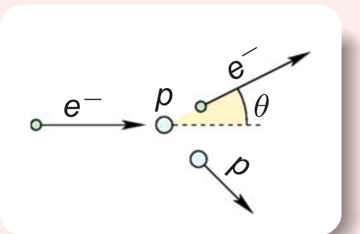
Nucleon current operator (Dirac & Pauli)

$$\Gamma^\mu(q) = \gamma^\mu F_1(q^2) + \frac{i}{2M_N}\sigma^{\mu\nu} q_\nu F_2(q^2)$$

Electric and Magnetic Form Factors

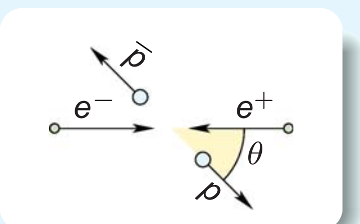
$$G_E(q^2) = F_1(q^2) + \tau F_2(q^2)$$

$$G_M(q^2) = F_1(q^2) + F_2(q^2) \qquad \tau = \frac{q^2}{4M_N^2}$$



Elastic scattering $\quad ep \longrightarrow ep$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 E_e' \cos^2\frac{\theta}{2}}{4E_e^3 \sin^4\frac{\theta}{2}} \left[G_E^2 + \tau\left(1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right) G_M^2 \right] \frac{1}{1+\tau}$$

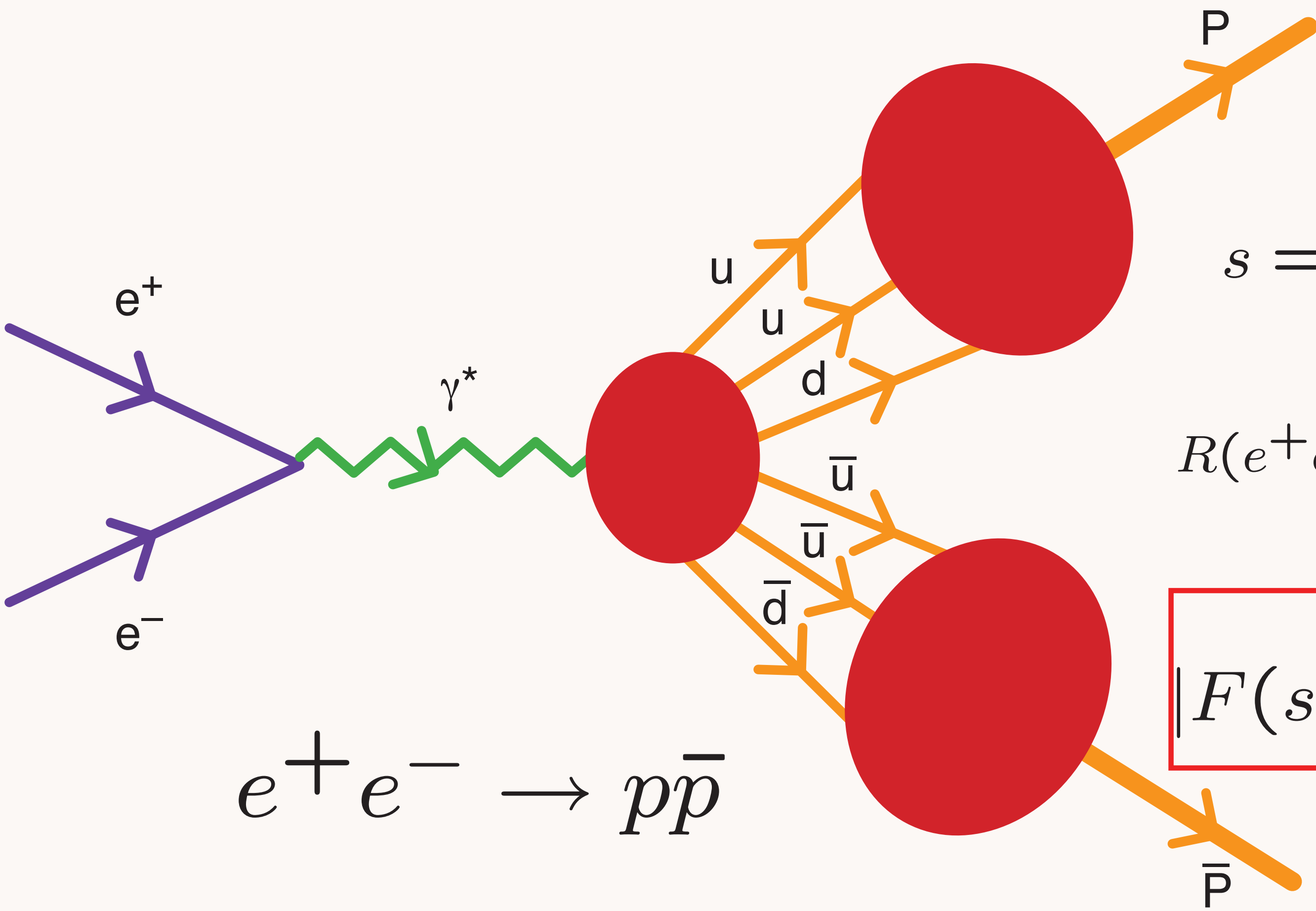


Annihilation $\quad e^+e^- \longrightarrow p\bar{p}$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2\sqrt{1 - 1/\tau}}{4q^2}\left[(1+\cos^2\theta)|G_M|^2 + \frac{1}{\tau}\sin^2\theta |G_E|^2\right]$$

Simone Pacetti | Ratio $|G_E^p(q^2)/G_M^p(q^2)|$ and dispersion relations

Exclusive Processes



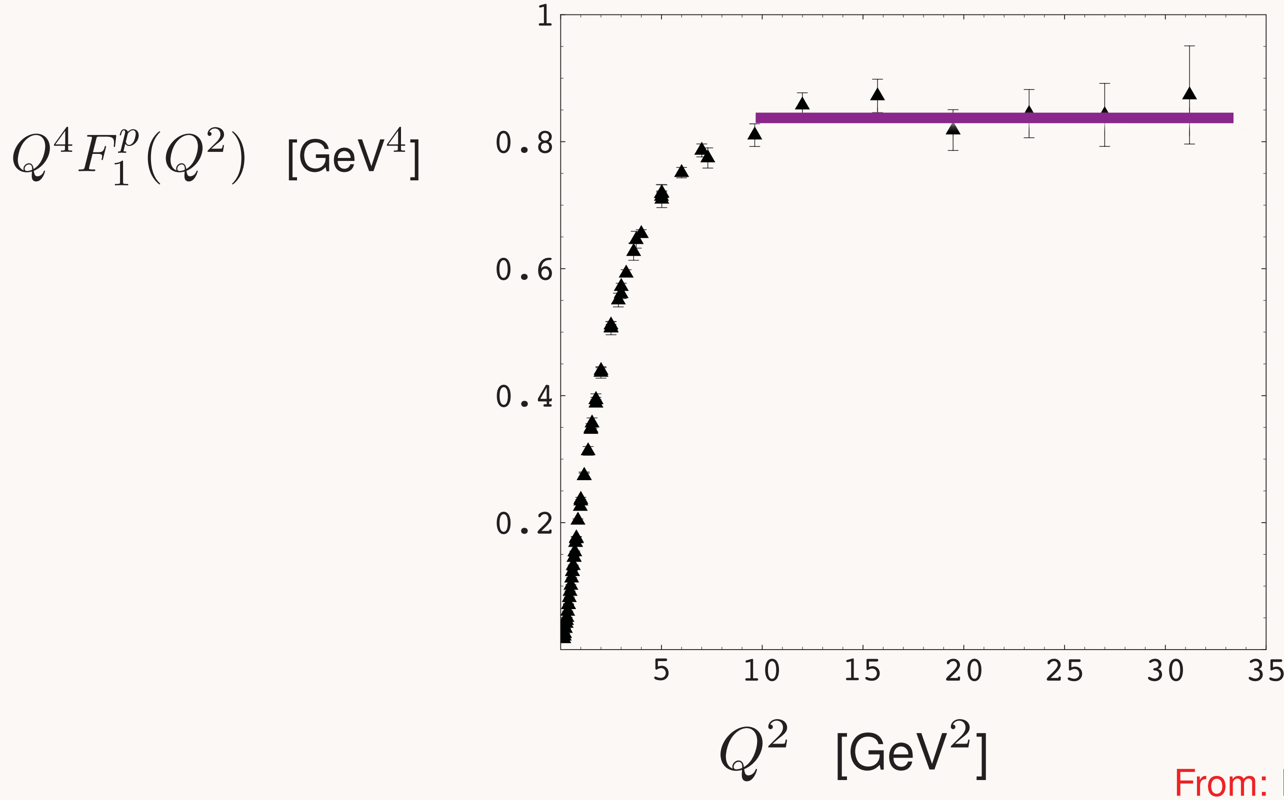
$$e^+e^- \rightarrow p\bar{p}$$

$$s = (E_{e^+} + E_{e^-})^2$$

$$R(e^+e^- \rightarrow H\bar{H}) \propto |F(s)|^2$$

$$|F(s)| \propto [\frac{1}{s}]^{n_q - 1}$$

Probability decreases with number of constituents!



$$F_1(Q^2) \sim \left[1/Q^2\right]^{n-1}, \;\; n = 3$$

measured in electron-proton elastic scattering

From: M. Diehl *et al.* Eur. Phys. J. C **39**, 1 (2005).

- Phenomenological success of dimensional scaling laws for exclusive processes

$$d\sigma/dt \sim 1/s^{n-2}, \quad n = n_A + n_B + n_C + n_D,$$

implies QCD is a strongly coupled conformal theory at moderate but not asymptotic energies
Farrar and sjb (1973); Matveev *et al.* (1973).

- Derivation of counting rules for gauge theories with mass gap dual to string theories in warped space (hard behavior instead of soft behavior characteristic of strings) Polchinski and Strassler (2001).

Brodsky and Farrar, Phys. Rev. Lett. 31 (1973) 1153
Matveev et al., Lett. Nuovo Cimento, 7 (1973) 719

Quark Counting Rules for Exclusive Processes

- Power-law fall-off of the scattering rate reflects degree of compositeness
- The more composite -- the faster the fall-off
- Power-law counts the number of quarks and gluon constituents
- Form factors: probability amplitude to stay intact
- $F_H(Q) \propto \frac{1}{(Q^2)^{n-1}}$ n = # elementary constituents

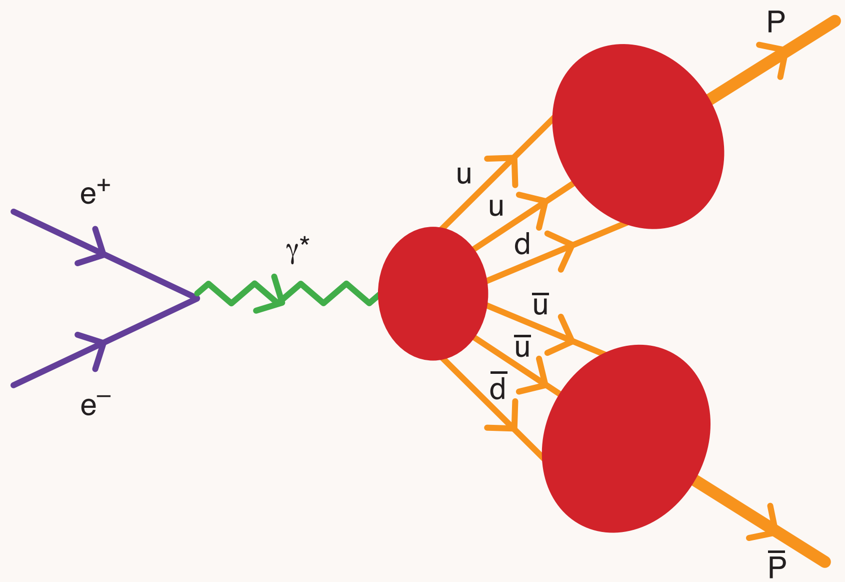
PQCD and Exclusive Processes

Lepage; SJB
Efremov, Radyuskin

$$M = \int \prod dx_i dy_i \phi_F(x, \tilde{Q}) \times T_H(x_i, y_i, \tilde{Q}) \phi_I(y_i, Q)$$

- Iterate kernel of LFWFs when at high virtuality; distribution amplitude contains all physics below factorization scale
- Rigorous Factorization Formulae: Leading twist
- Underly Exclusive B-decay analyses
- Distribution amplitude: gauge invariant, OPE, evolution equations, conformal expansions
- BLM scale setting: sum nonconformal contributions in scale of running coupling
- Derive Dimensional Counting Rules/ Conformal Scaling

Timelike proton form factor in PQCD



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

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

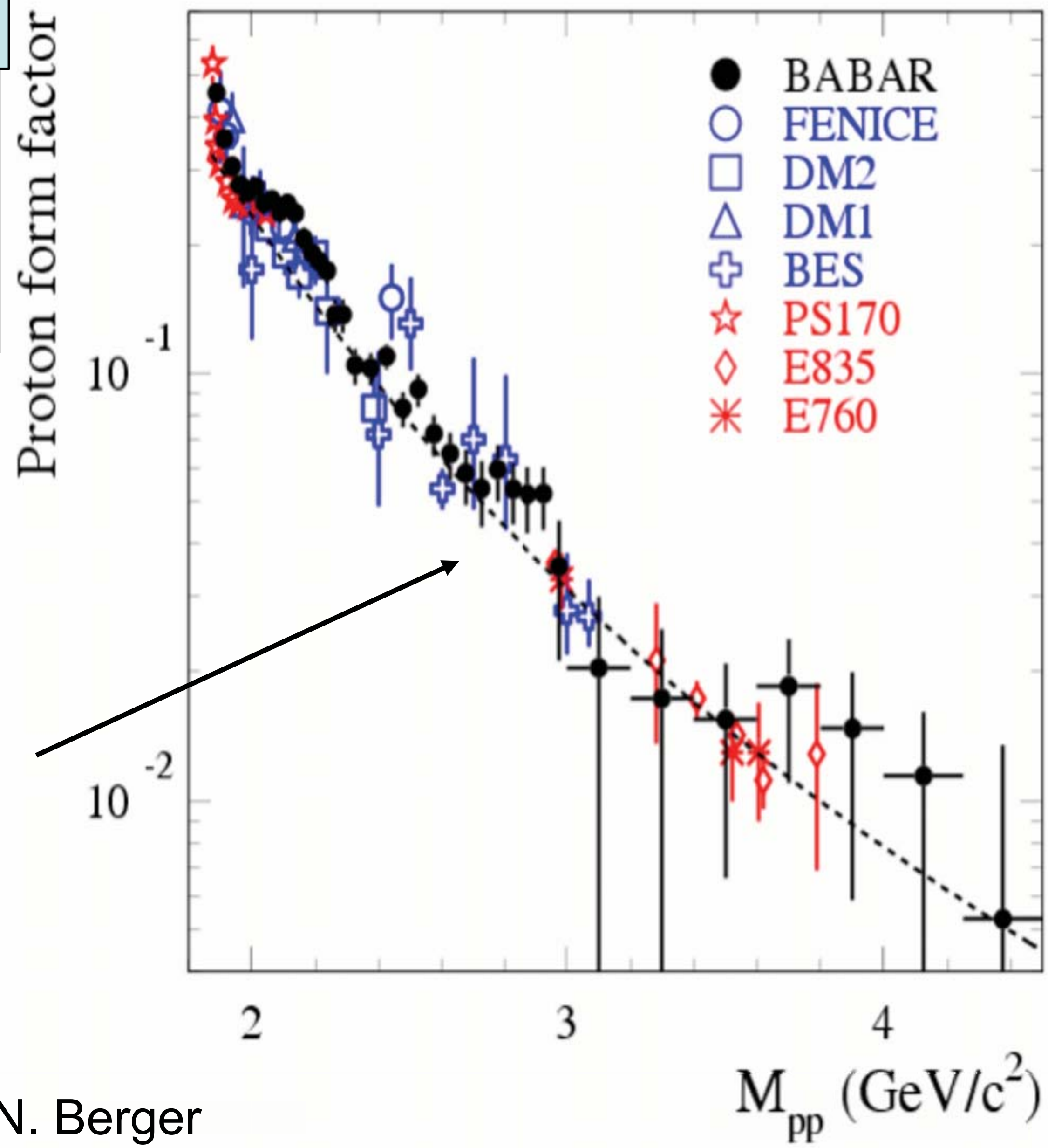
Lepage and Sjb

- Define "Effective" form factor by

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

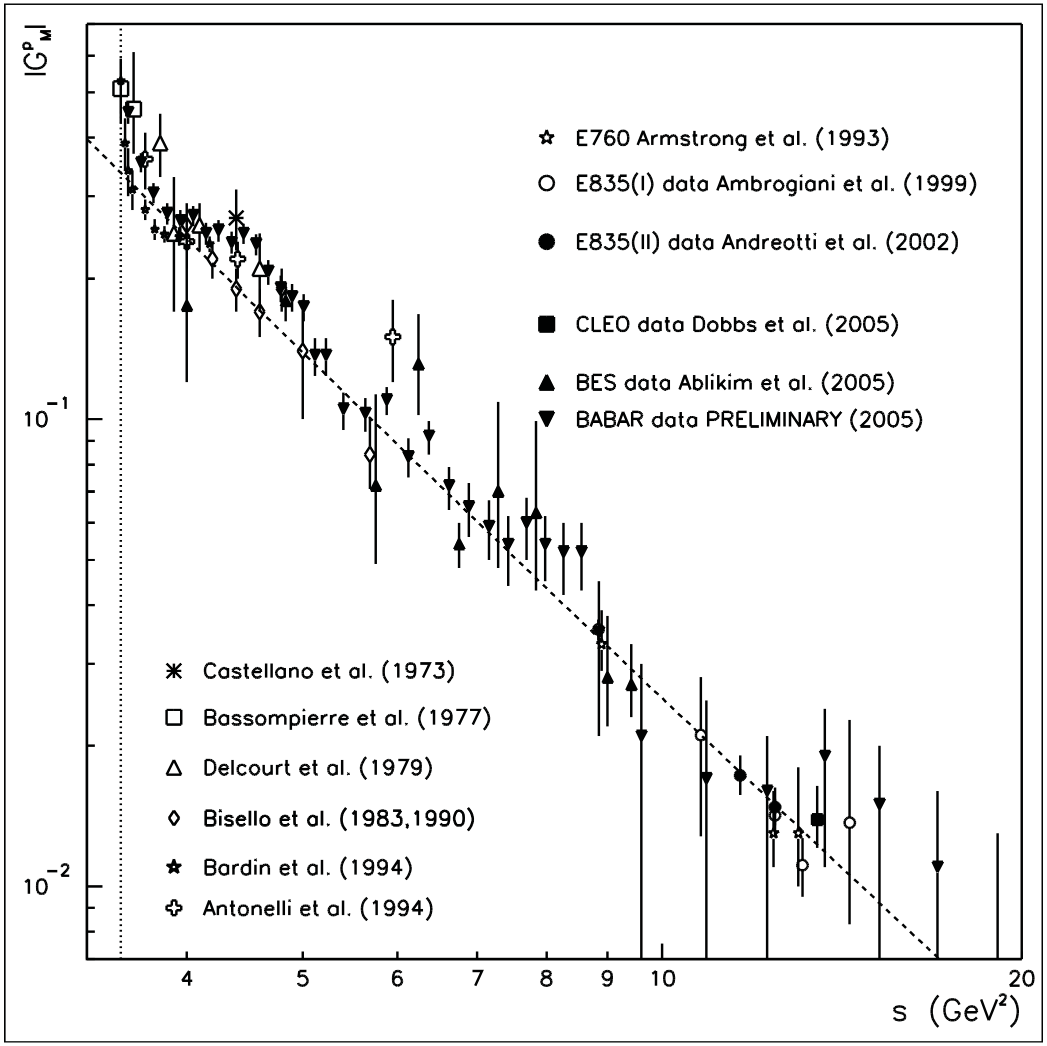
- Peak at threshold, sharp dips at 2.25 GeV, 3.0 GeV.
- Good fit to pQCD prediction for high m_{pp}.

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



Time-like Form Factors

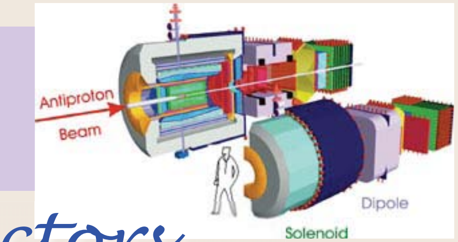
- All data measure absolute cross section $G_E = G_M$
- PANDA will provide independent measurement of G_E and G_M
- widest kinematic range in a single experiment
- Time-like form factors are complex
- precision experiments will reveal these structures



B. Seitz

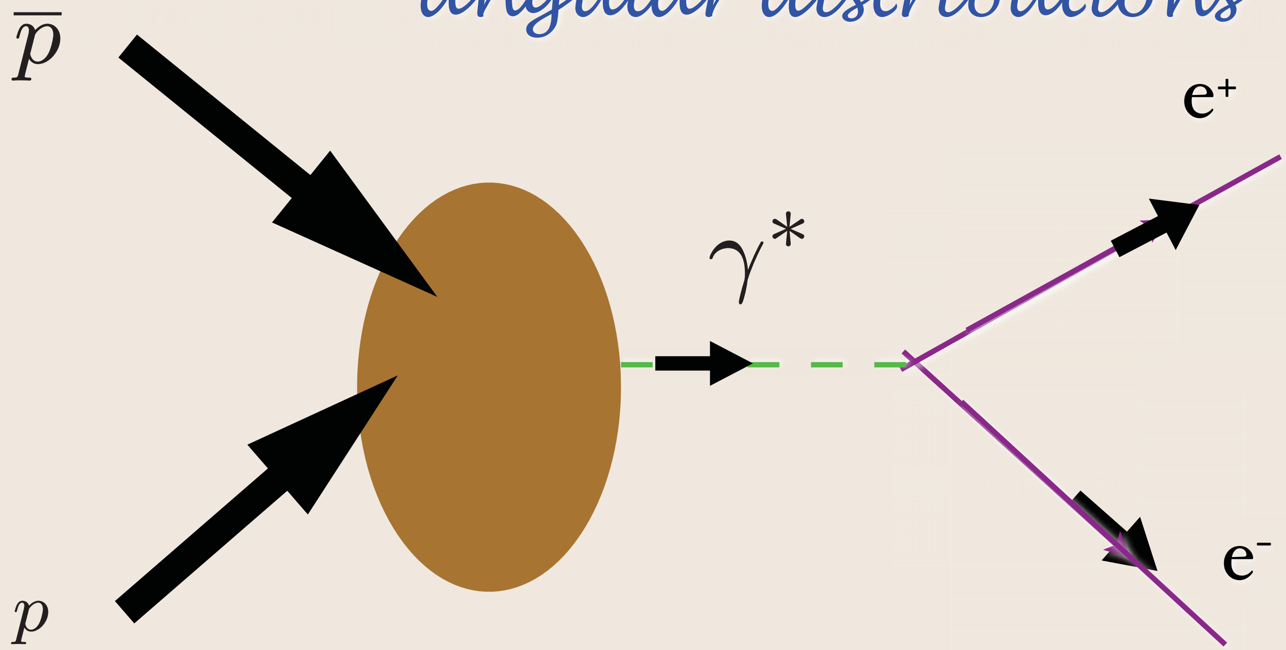
PANDA range

Key QCD Panda Experiment



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

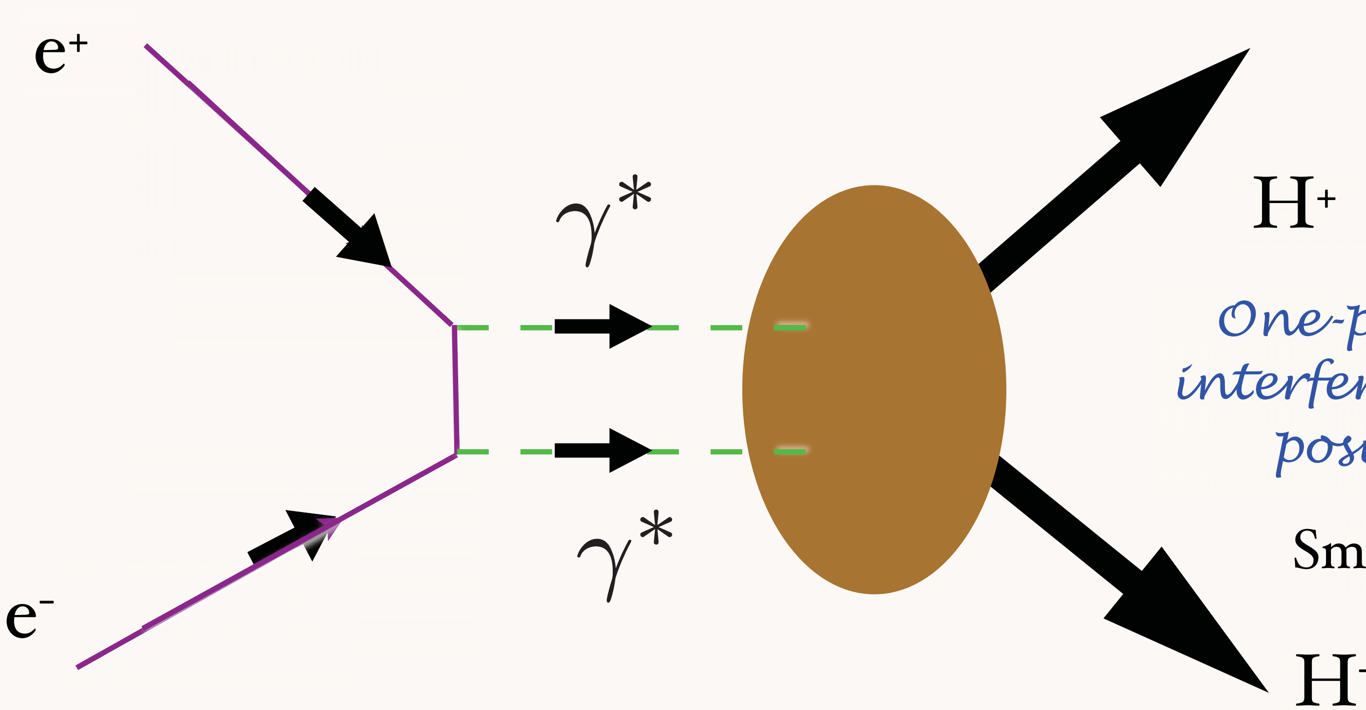
Conformal Symmetry: AdS/CFT

Hadron Helicity Conservation

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

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

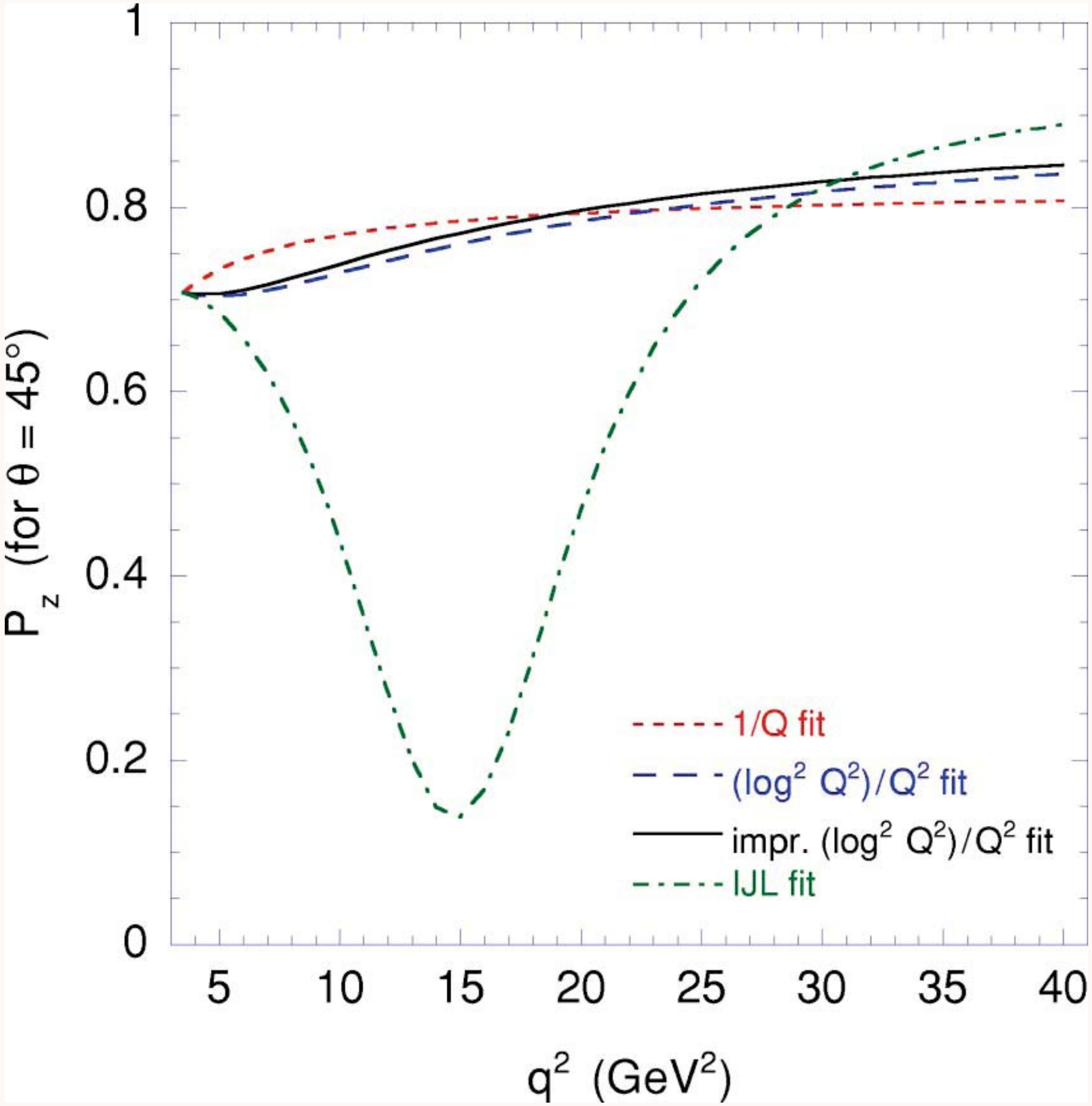
Blunden, Melnitchouk; Afanasev, Chen,Carlson, Vanderhaegen, sjb



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



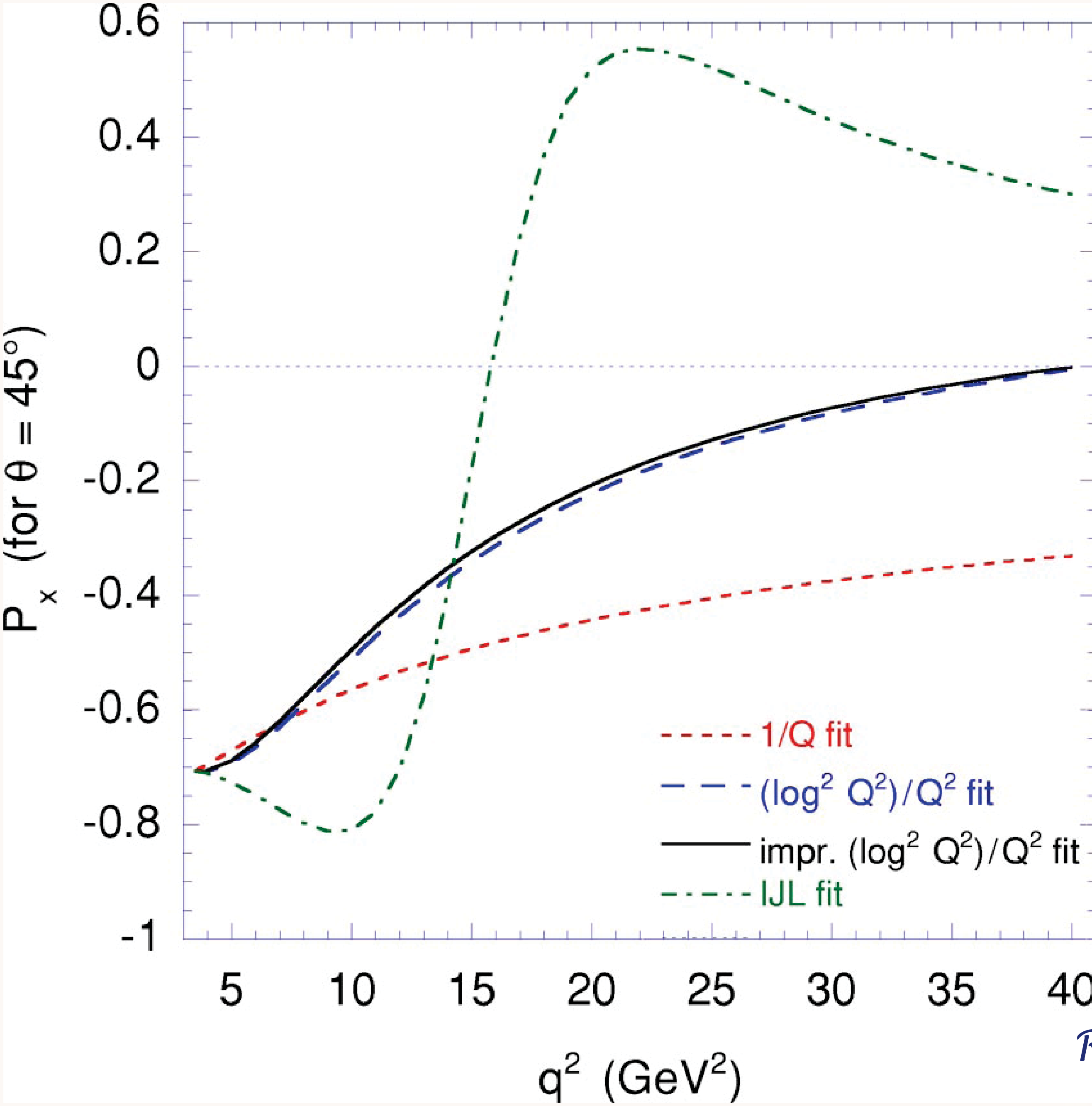
Carlson, Hiller, Hwang, sjb

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

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

Requires beam and lepton polarization

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



Carlson, Hiller, Hwang, sjb

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

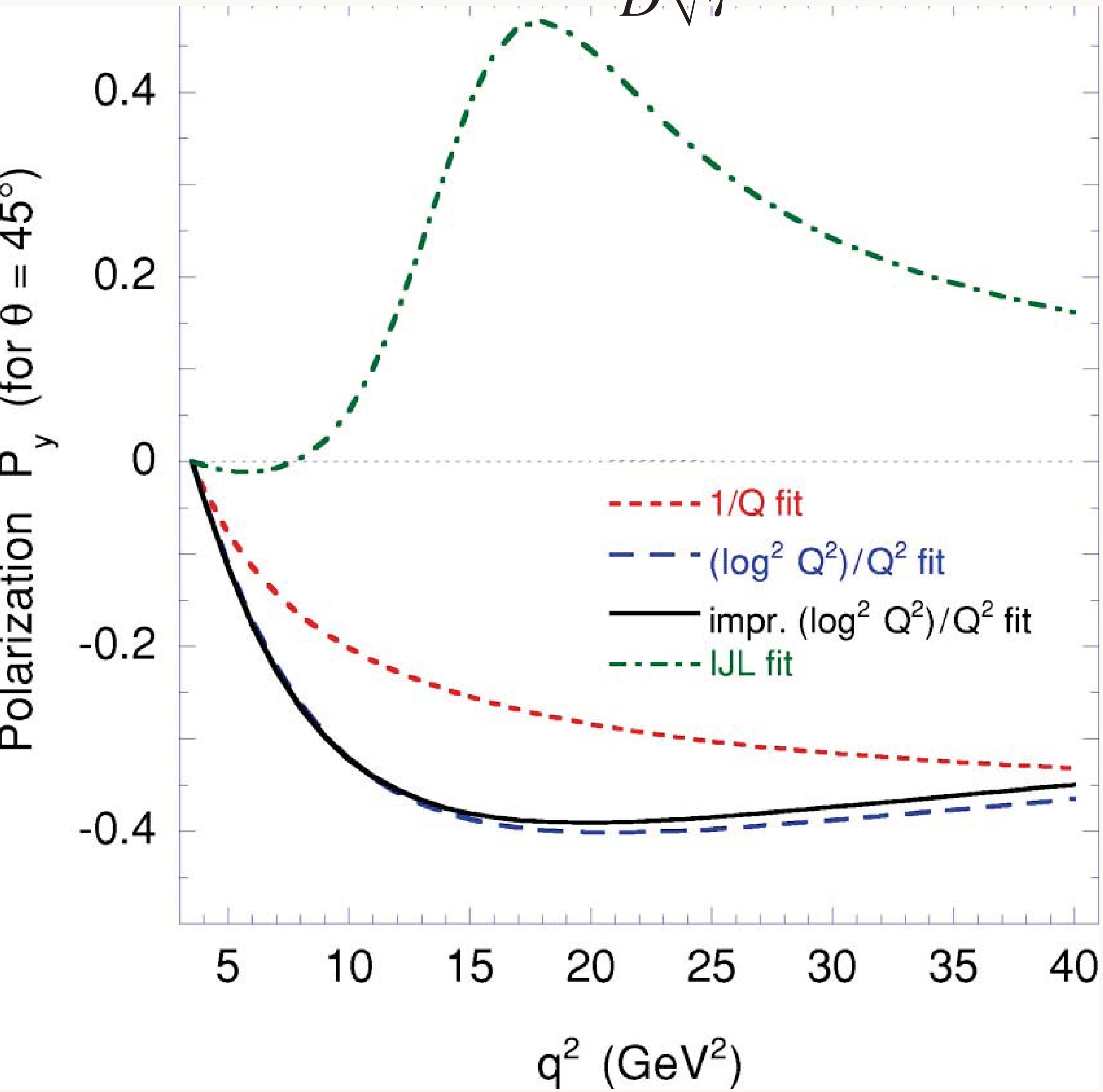
$$D = |G_M|^2(1+\cos^2\theta) + \frac{1}{\tau}|G_E|^2 \sin^2\theta;$$

Requires beam and lepton polarization

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

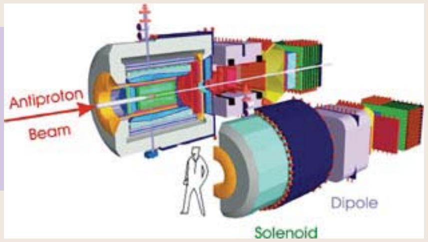


$$D = |G_M|^2(1+\cos^2\theta) + \frac{1}{\tau}|G_E|^2 \sin^2\theta;$$

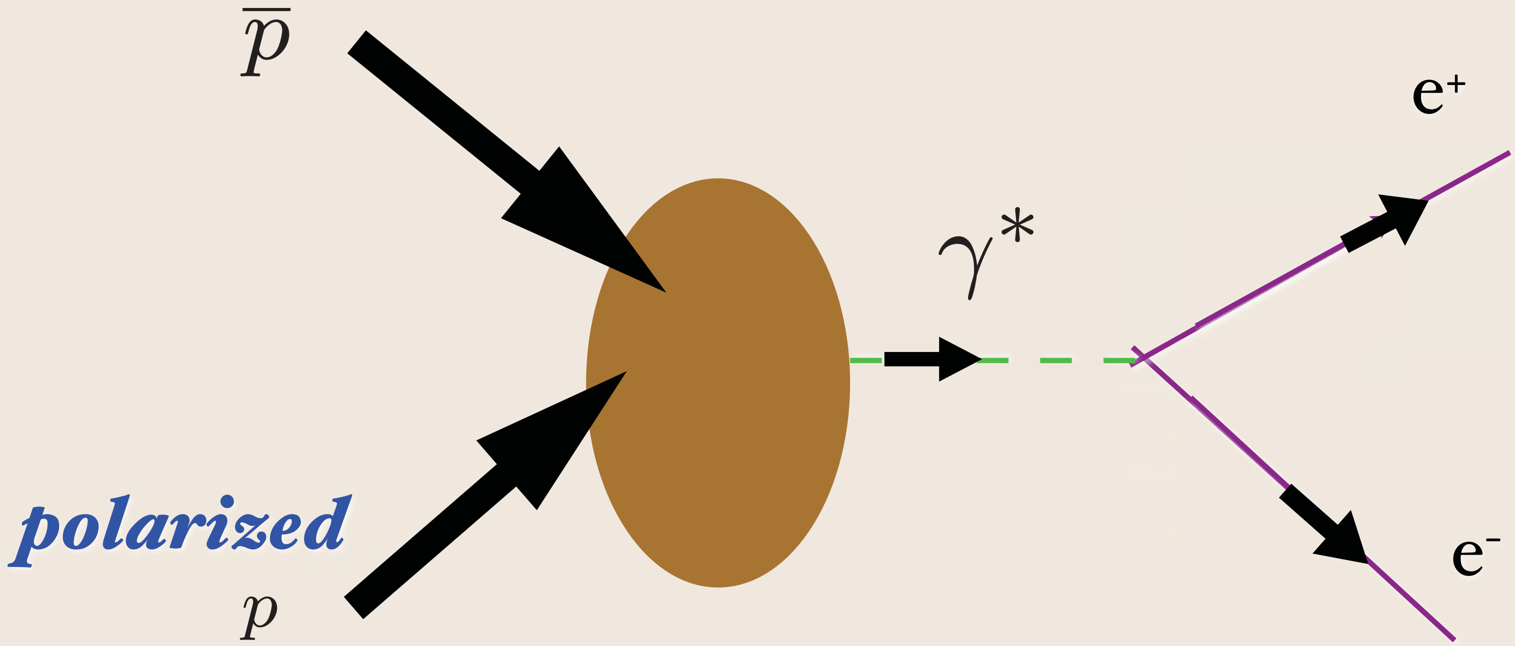
$$\tau \equiv q^2/4m_B^2$$

Measure relative phase of form factors

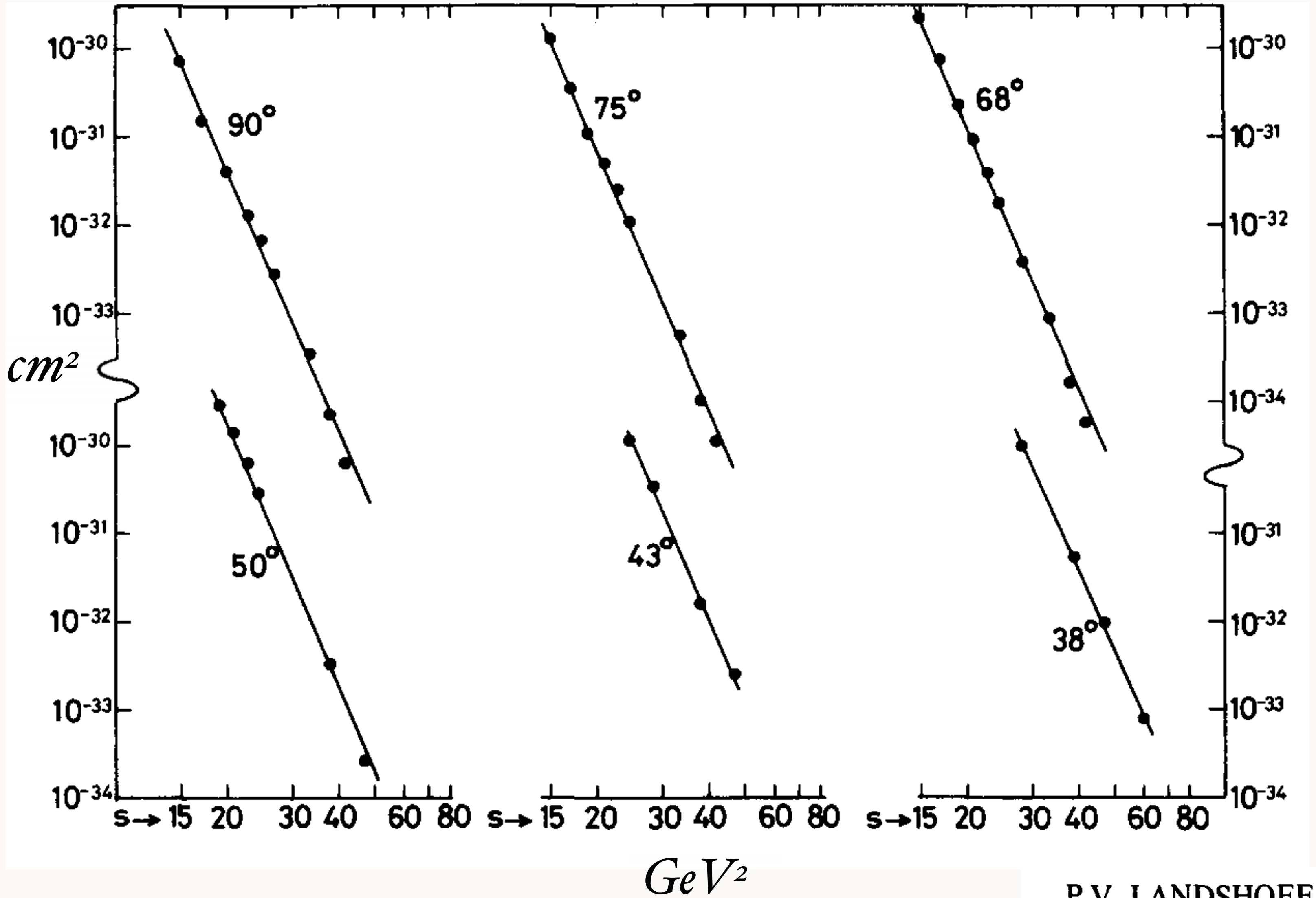
Key QCD Panda Experiment



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



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



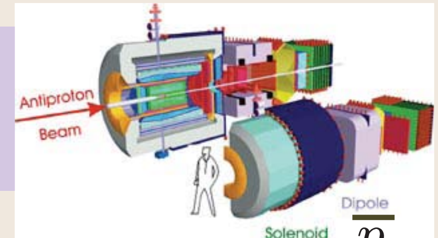
P.V. LANDSHOFF and J.C. POLKINGHORNE

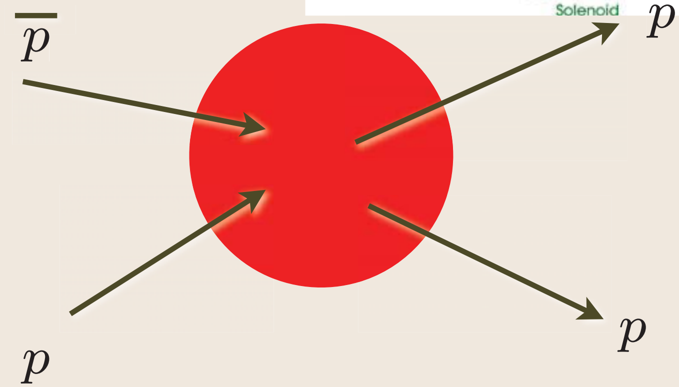
Best Fit

$n = 9.7 \pm 0.5$

Reflects underlying conformal scale-free interactions

Key QCD Panda Experiment





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

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

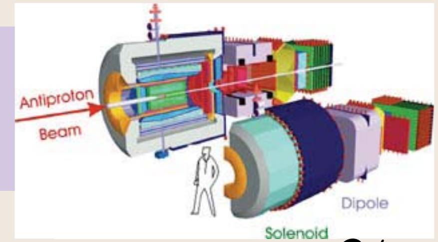
Single-spin asymmetry A_N

Exclusive Transversity A_{NN}

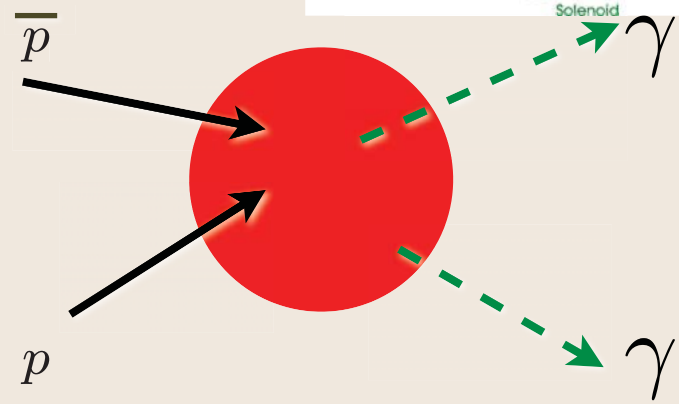
Test color transparency

Study Fundamental Aspects of Nuclear Force

Key QCD Panda Experiment



$\frac{d\sigma}{dt}(\bar{p}p \to \gamma\gamma)$ 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

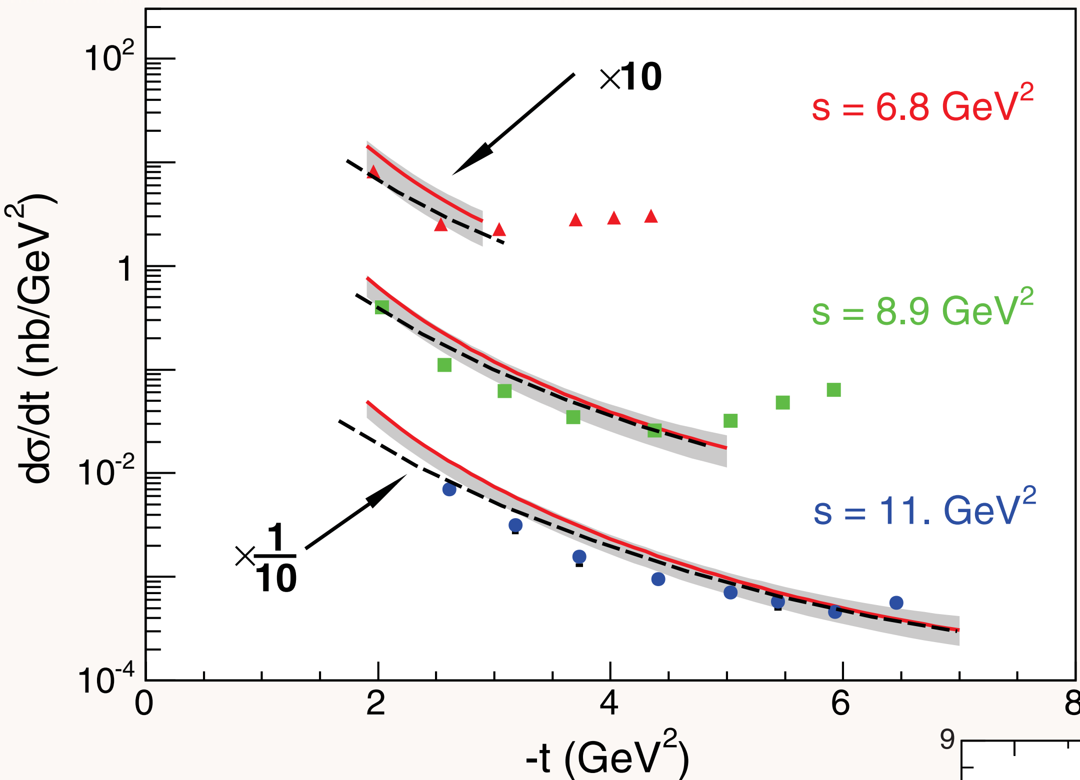
Handbag Approximation Invalid in PQCD

Single-spin asymmetry A_N

Exclusive Transversity A_{NN}

Test color transparency

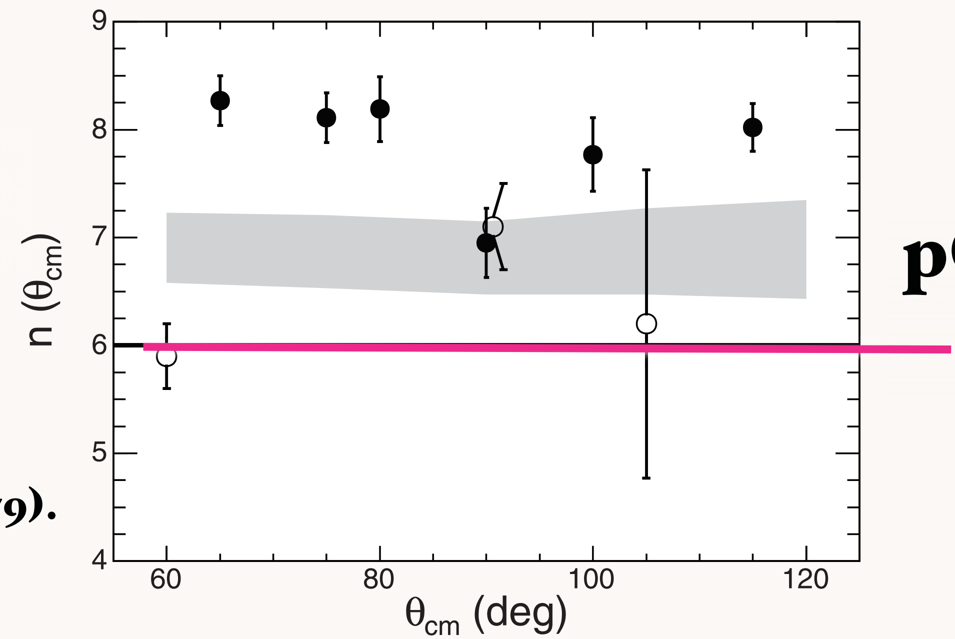
Compton-Scattering Cross Section on the Proton at High Momentum Transfer



Jefferson Lab
Hall A
Collaboration

Alan Nathan, et al

Compton at fixed angles falls faster than photoproduction!



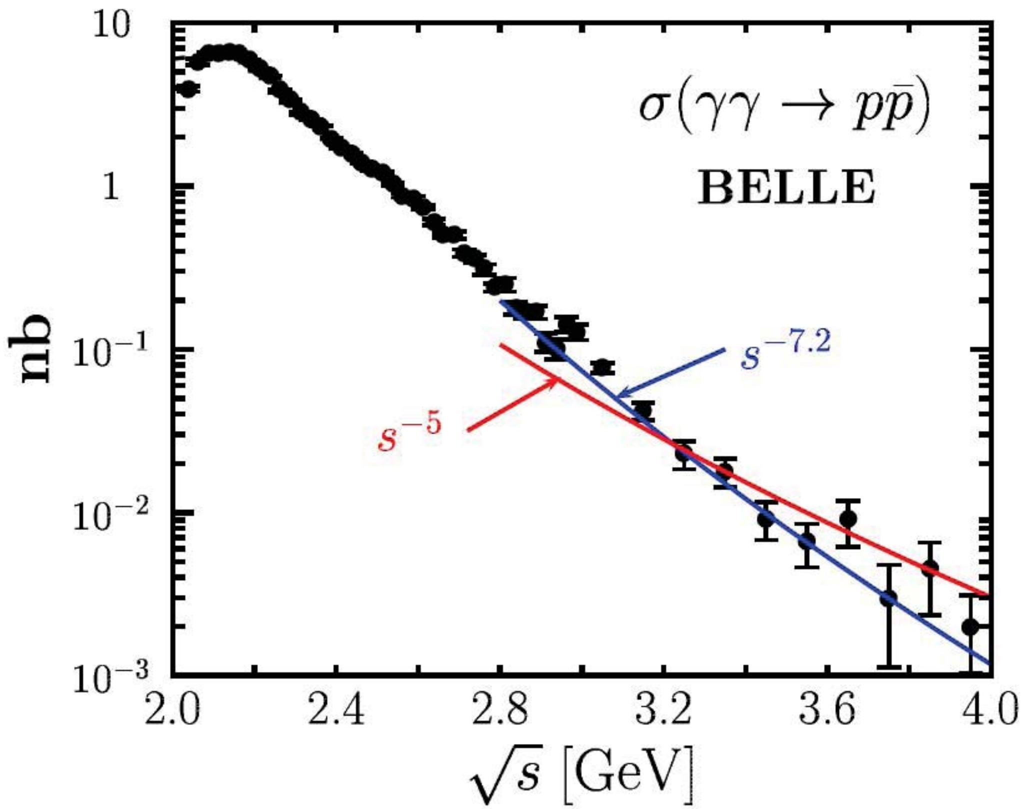
pQCD
n=6

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

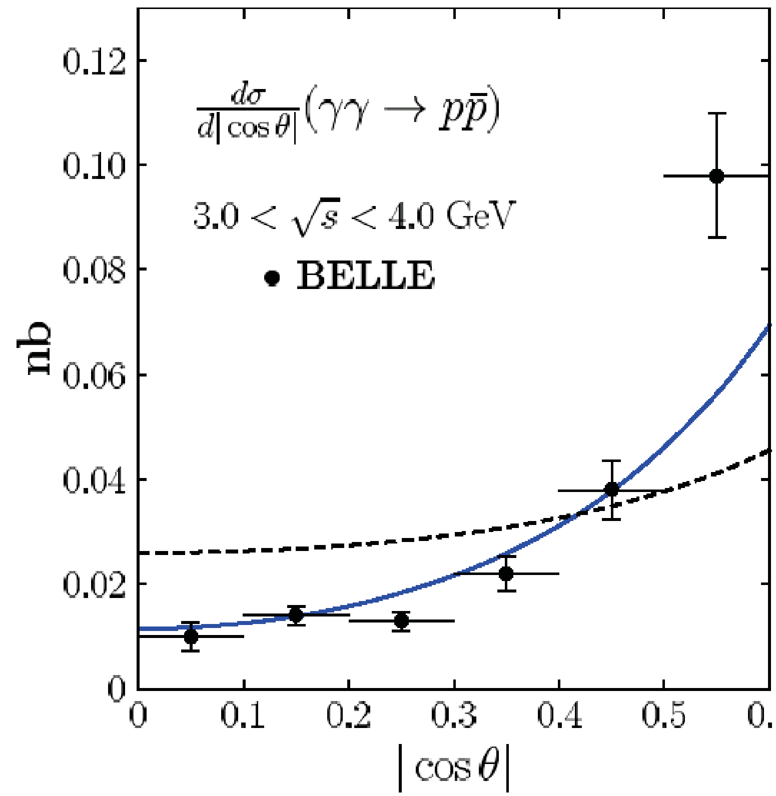
Recent results from Belle

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

PQCD Conformal Scaling for range of θ_{CM}
$s^5 \Delta\sigma(\gamma\gamma \to \bar{p}p) \simeq \text{const}$

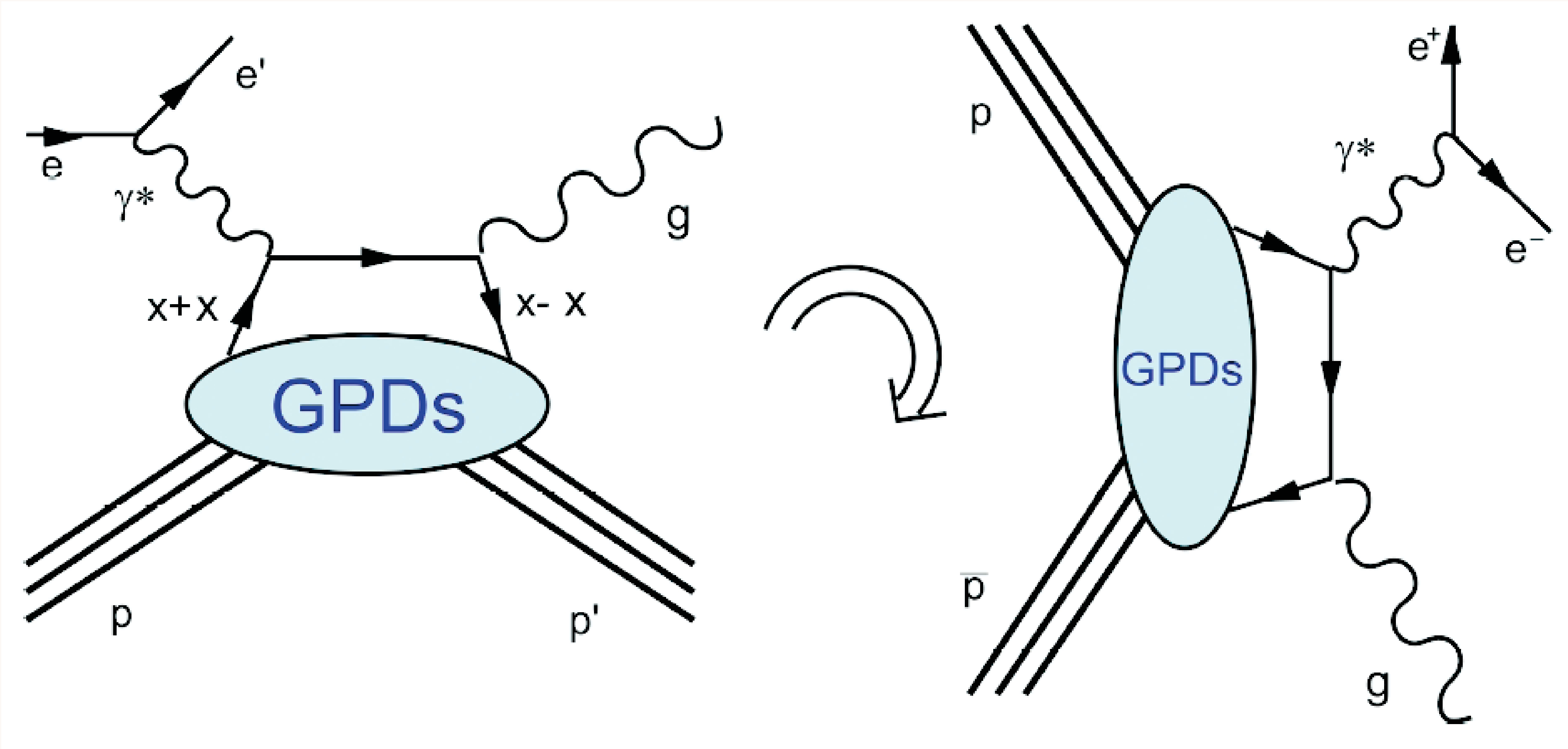


Energy dependence



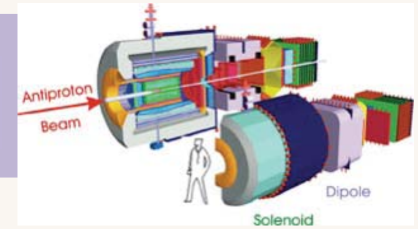
Angular dependence
(GPD curve from Kroll/Schäfer)

Michael Düren



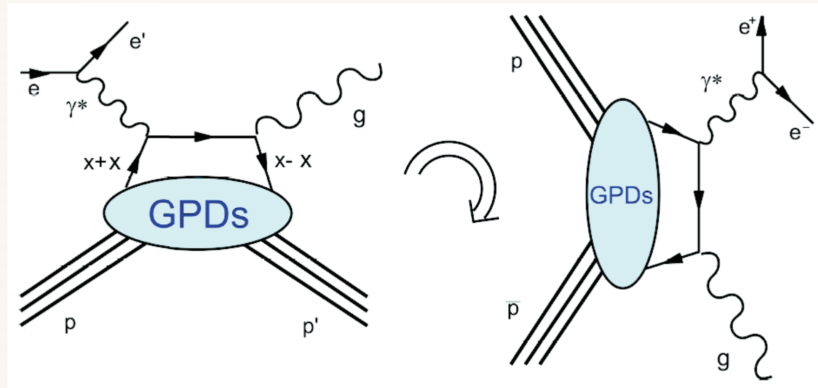
e'
e
γ*
g
x+x
x- x
GPDs
p
p'
p
e+
γ*
e−
GPDs
p̄
g

Key QCD Panda Experiment



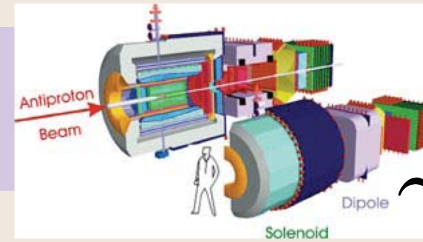
$$\bar{p}p \to \gamma^* \gamma$$

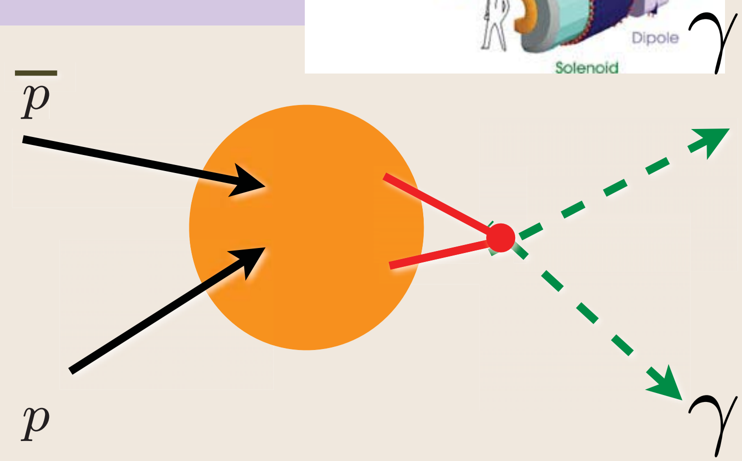
- Test DVCS in Timelike Regime
- J=0 Fixed pole: q^2 independent
- Analytic Continuation of GPDs
- Light-Front Wavefunctions
- charge asymmetry from interference



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

Key QCD Panda Experiment





$\frac{d\sigma}{dt}(\bar{p}p \to \gamma\gamma)$ 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

Tests PQCD and AdS/CFT Conformal Scaling

Close, Gunion, sjb
Szczepaniak, Llanes Estrada, sjb

Angle-Independent J=0 Fixed Pole Contribution:

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

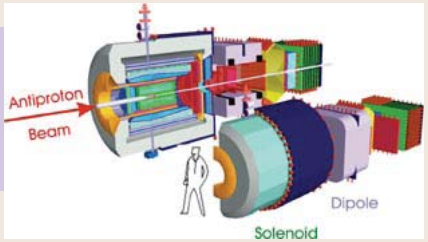
J=0 Fixed pole in real and virtual Compton scattering

Damashek, Gilman; Close, Gunion, sjb

- Effective two-photon contact term
- Seagull for scalar quarks
- Real phase
- $M = s^0 F(t)$
- Independent of Q^2 at fixed t
- <1/x> Moment: Related to Feynman-Hellman Theorem
- Fundamental test of local gauge theory

Test J=0 Fixed Pole: $s^2\, d\sigma/dt(\gamma\, p \to \gamma\, p) \simeq F^2_0(t)$

Key QCD Panda Experiment



Measure all antiproton + proton exclusive channels

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

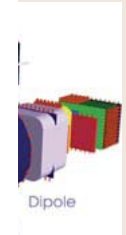
PQCD: No handbag dominance
for real photons

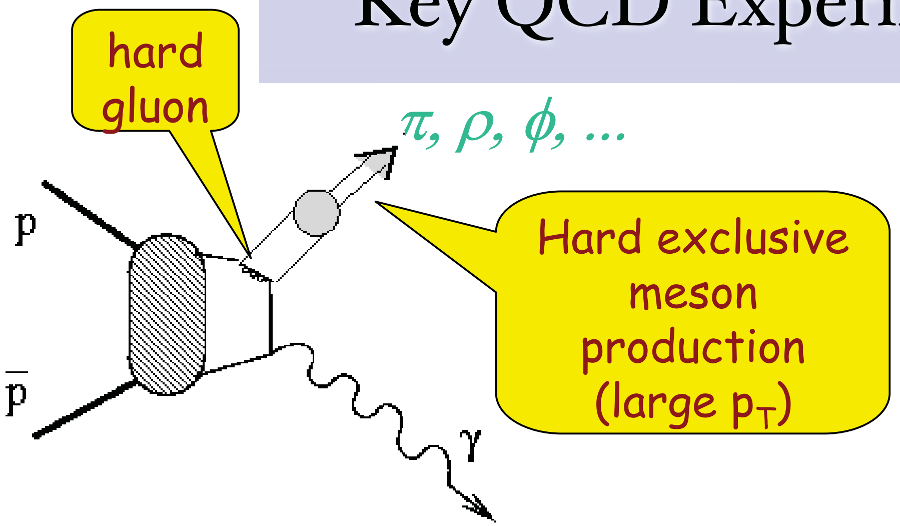
$J = 0$ fixed pole from
local $q\bar{q} \to \gamma\gamma$ interactions

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

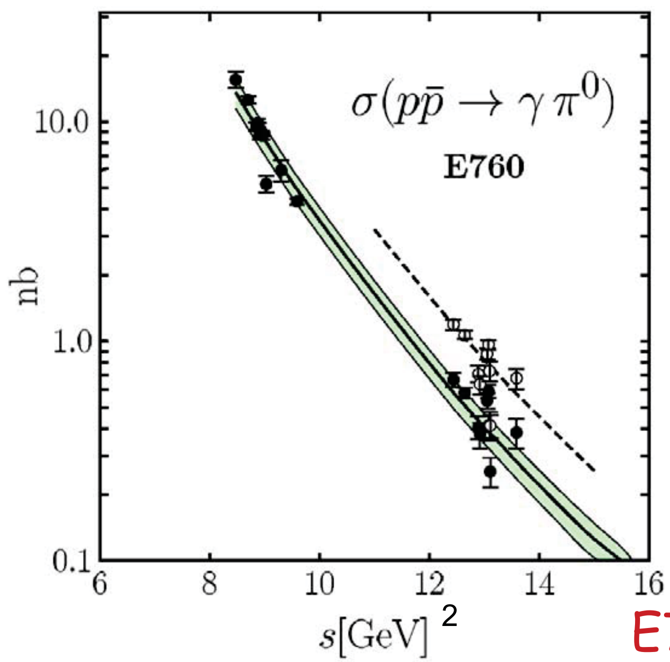
$\bar{p}p \to K^+K^-$

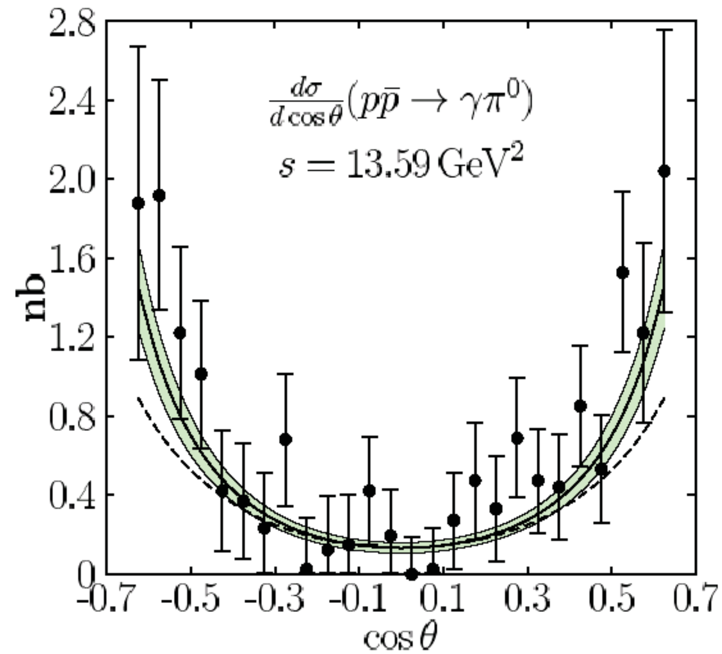
Key QCD Experiment at FAIR





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

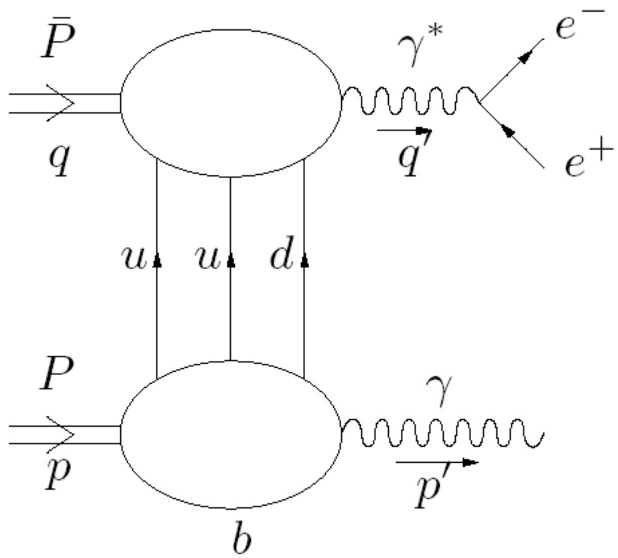


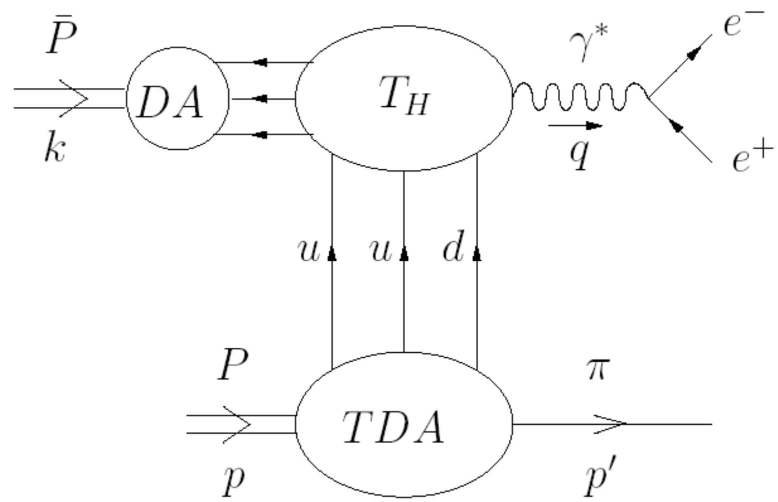


E760 results

(curve from Kroll/Schäfer)

Michael Düren





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

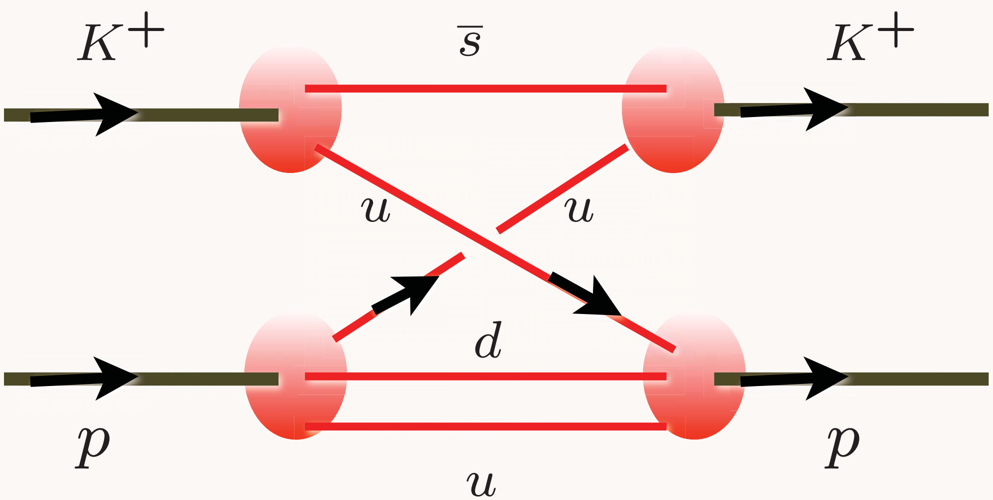
$p\bar{p} \to \gamma^* \pi$	explores the pion cloud
$p\bar{p} \to \gamma^* \rho$	explores the ρ cloud
$p\bar{p} \to \gamma^* \gamma$	explores the photon cloud

(Study next to lowest Fock state of the proton)

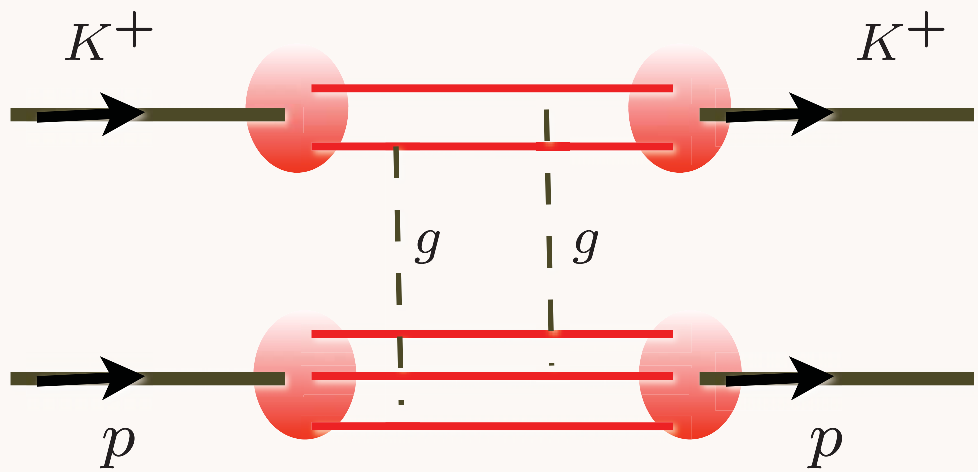
Michael Düren

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

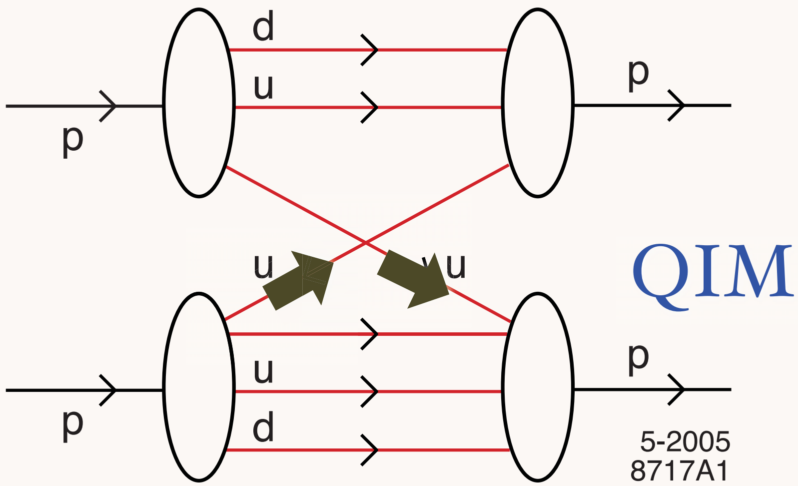
$M_{QIM} = \int d^2k_\perp dx\ \psi^\dagger_C \psi^\dagger_D \Delta \psi_A \psi_B$

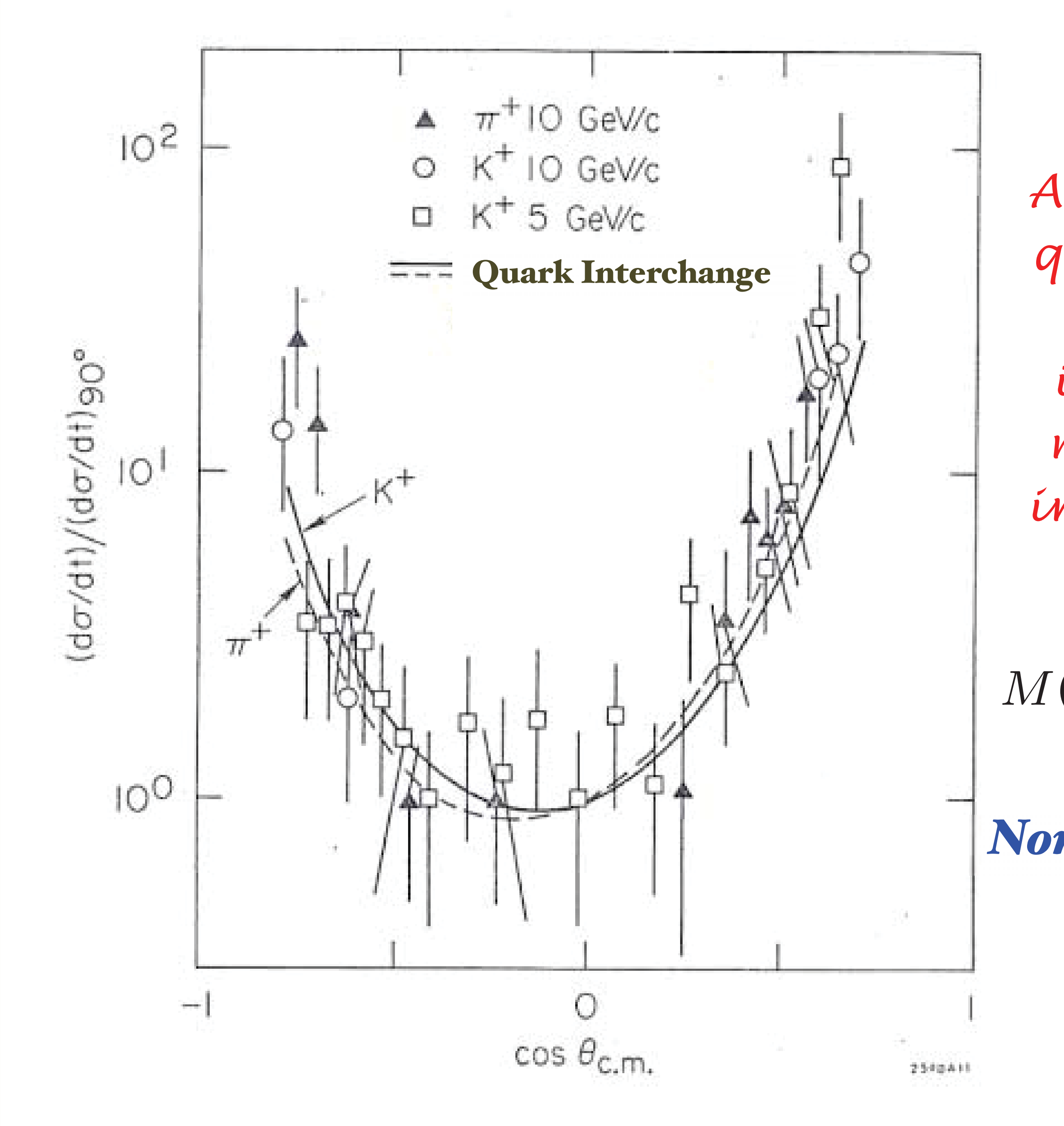
Holographic model (Classical level):

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.: $\pi^{\pm}p \to p\pi^{\pm}, p\rho^{\pm}, \pi^{+}\Delta^{\pm}, K^{+}\Sigma^{\pm}, (\Lambda^0/\Sigma^0)K^0$; $K^{\pm}p \to pK^{\pm}$; $p^{\pm}p \to pp^{\pm}$. 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.

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

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

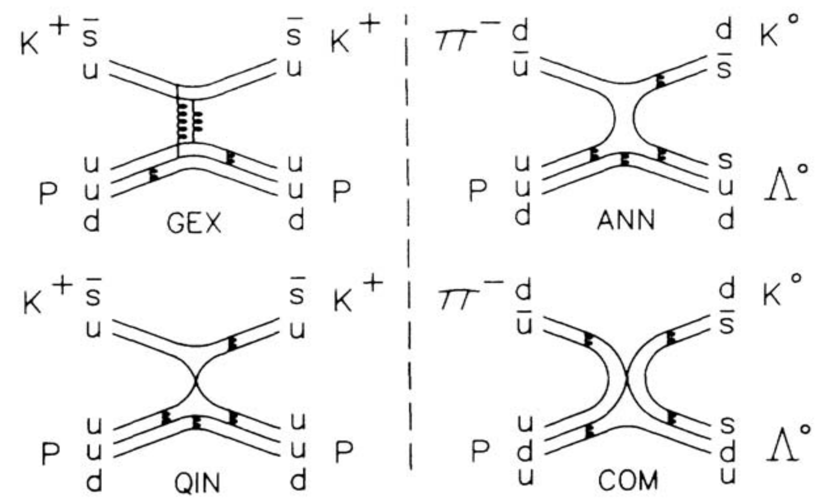
$\pi^{\pm}p \to p\rho^{\pm}$,

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

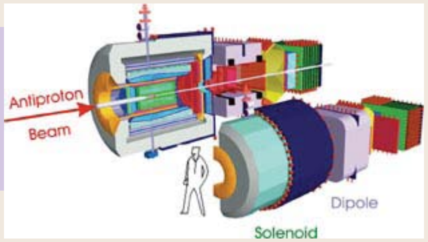
$\pi^{\pm}p \to K^{+}\Sigma^{\pm}$,

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

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



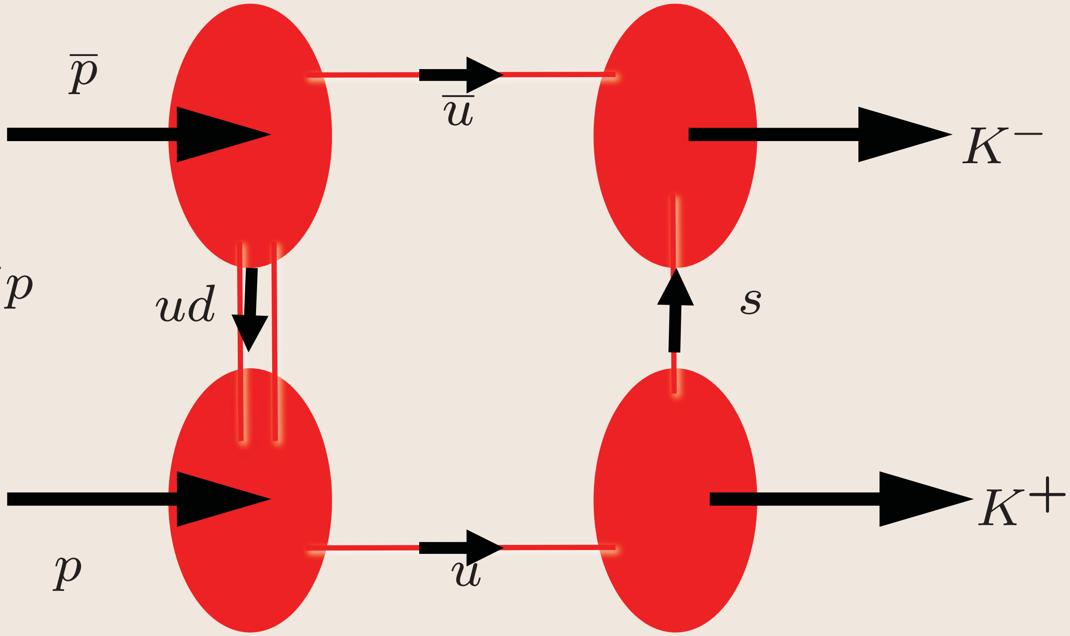
Key QCD Panda Experiment



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

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

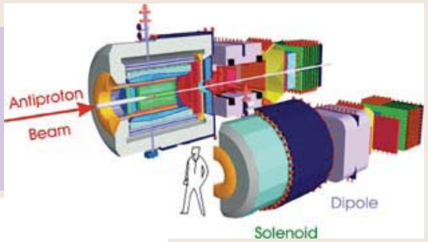
$M(\overline{p}p \rightarrow K^+K^-) \propto \frac{1}{ts^2}$



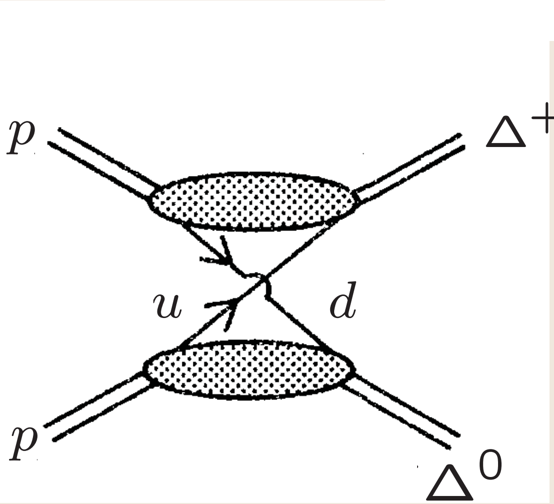
$$\frac{d\sigma}{dt} \propto \frac{1}{s^6t^2}$$

at large t, u

Key QCD Panda Experiment



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



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

Test quark interchange mechanism

Measure Ratio

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

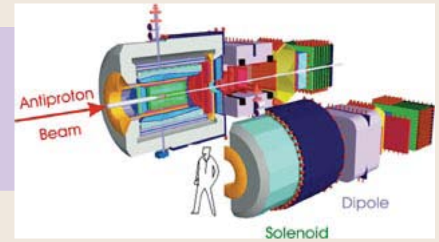
Test $\frac{d\sigma}{dt} = \frac{F(\theta_{cm})}{s^{10}}$ AdS/CFT conformal scaling

Single-Spin Asymmetry A_N of Δ

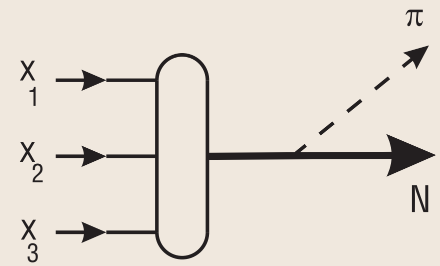
Test Hadron Helicity Conservation:

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

Key QCD Panda Experiment



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

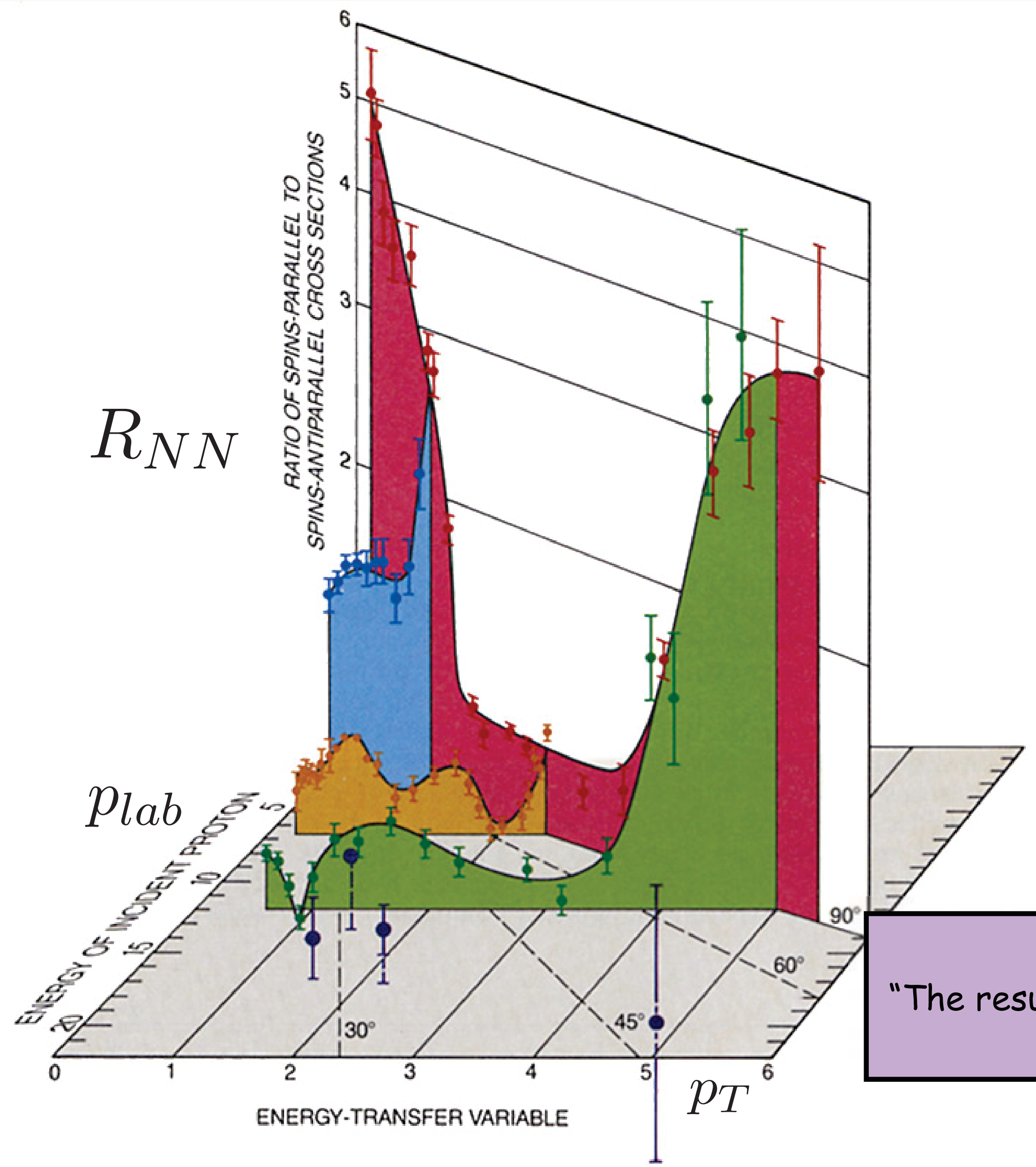
Same scaling as

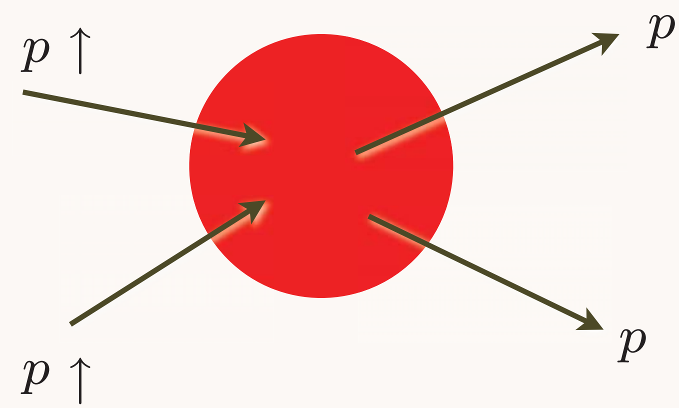
$$\frac{d\sigma}{dt}(\overline{p}p \to \overline{p}p) = \frac{F(\theta_{cm})}{s^{10}}$$

The remarkable anomalies of proton-proton scattering

- Double spin correlations
- Single spin correlations
- Color transparency

Spin Correlations in Elastic $p-p$ Scattering





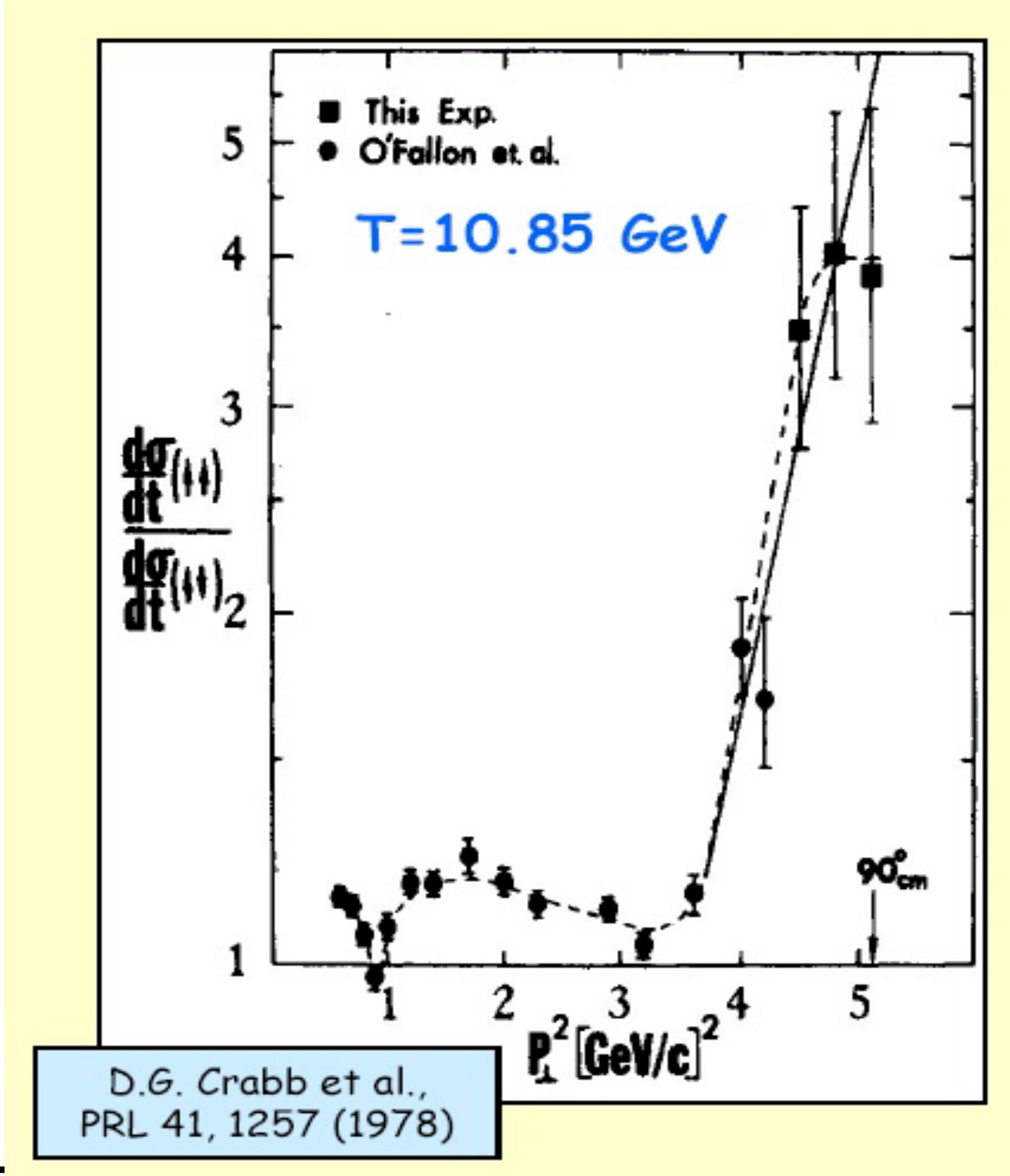
polarization normal to scattering plane

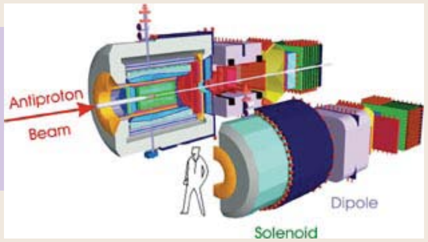
Ratio reaches 4:1 !

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

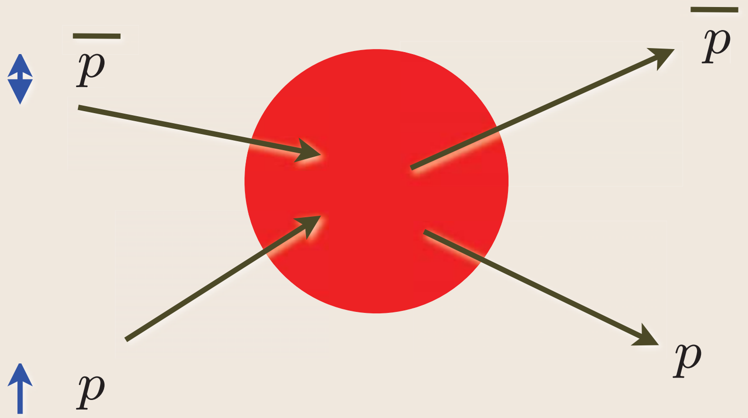
Unexpected spin effects in pp elastic scattering

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

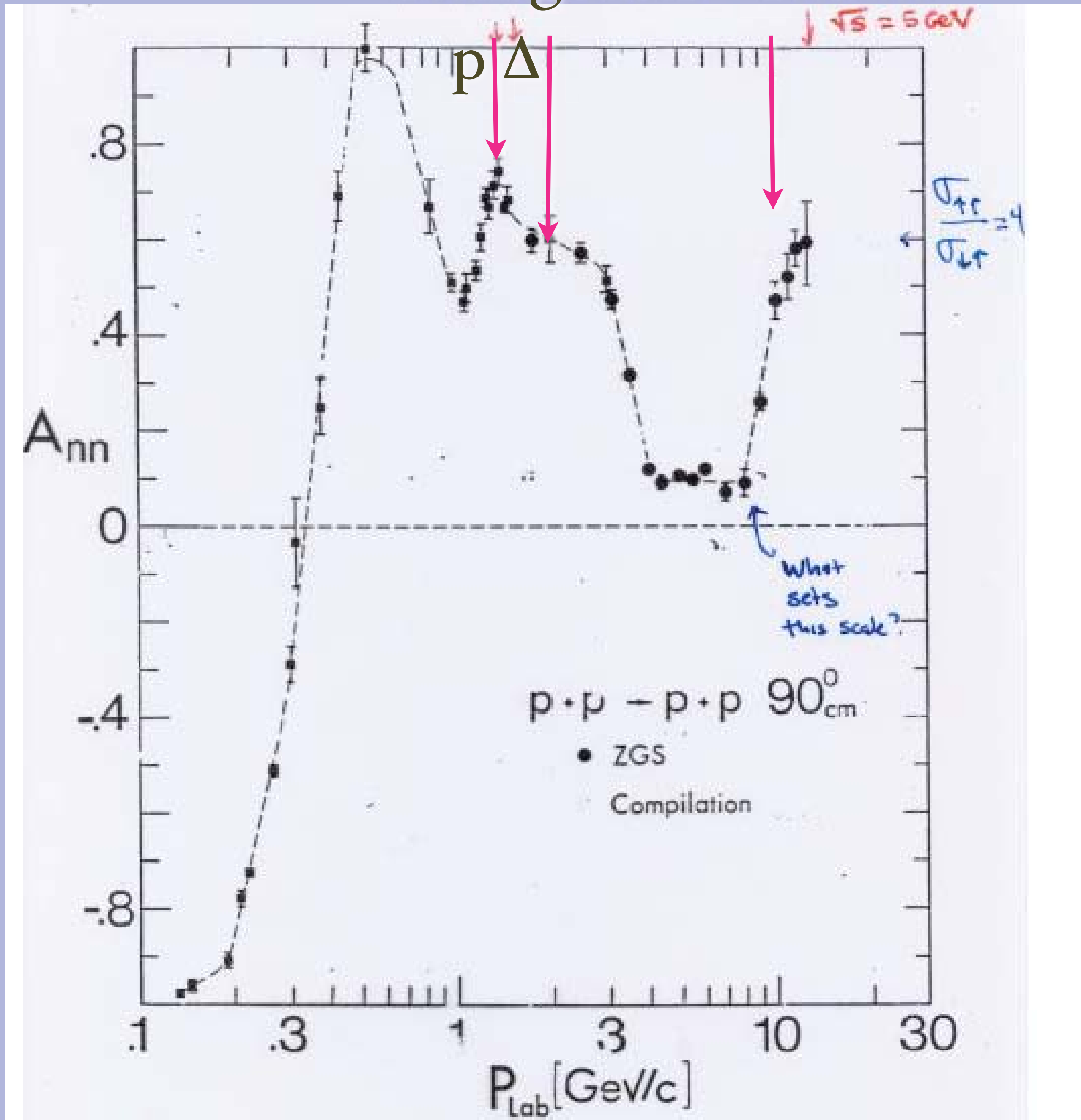




A_{NN} for $\bar{p}p \to \bar{p}p$



Strangeness Charm



“Exclusive Transversity”

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

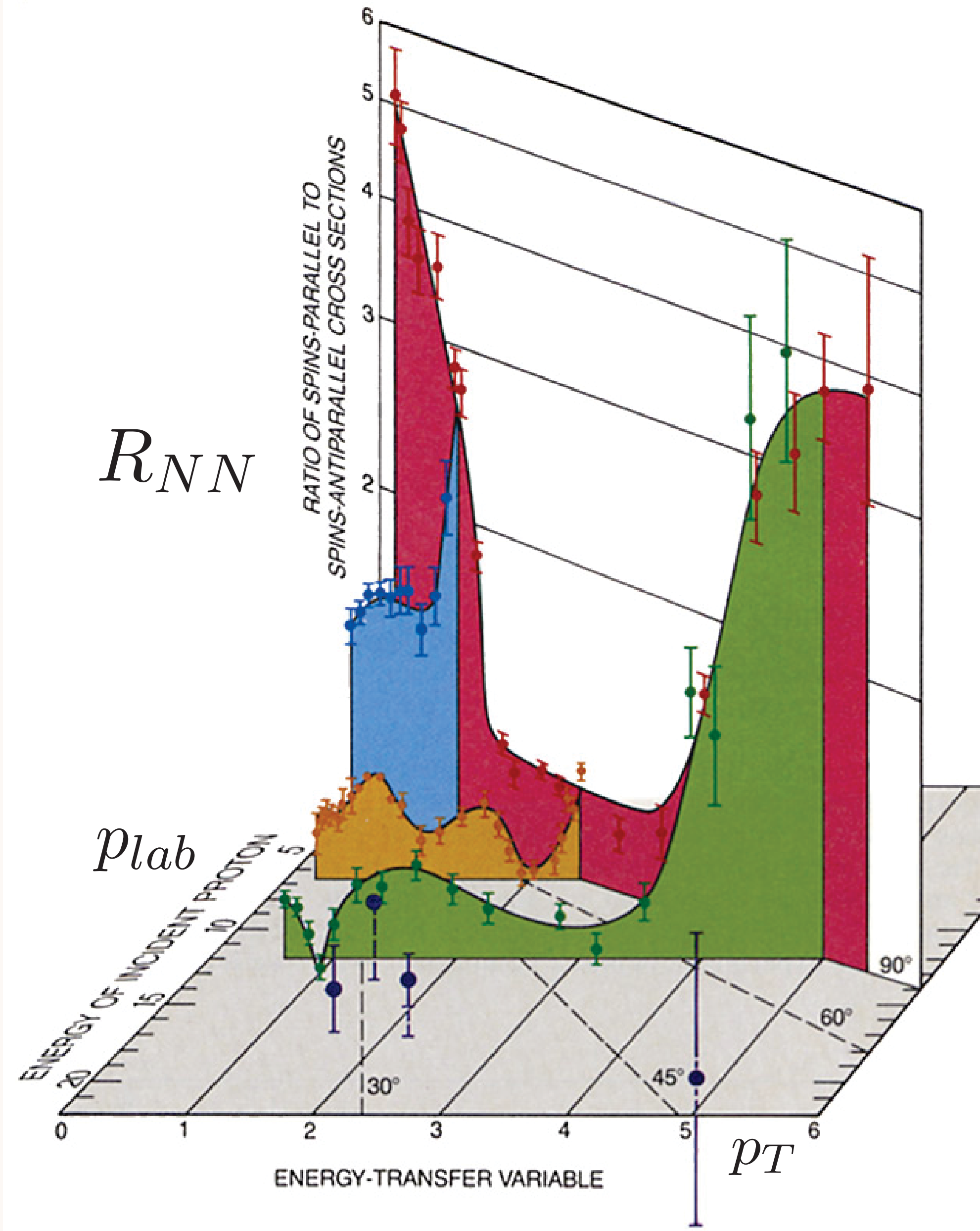
Spin-dependence at large-P_T ($90°_{cm}$):

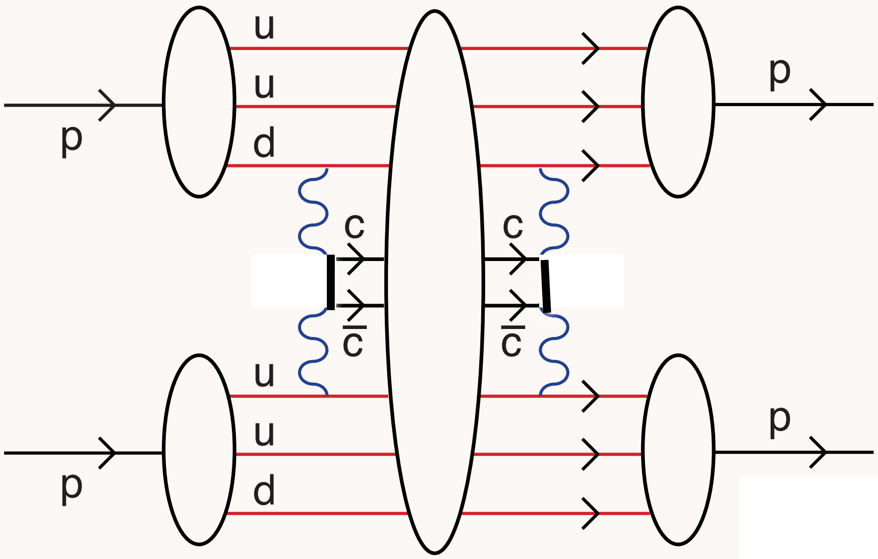
Hard scattering takes place only with spins ↑↑

Coincidence?: Quenching of Color Transparency

Coincidence?: Charm and Strangeness Thresholds

Alternative: Six-Quark Hidden-Color Resonances

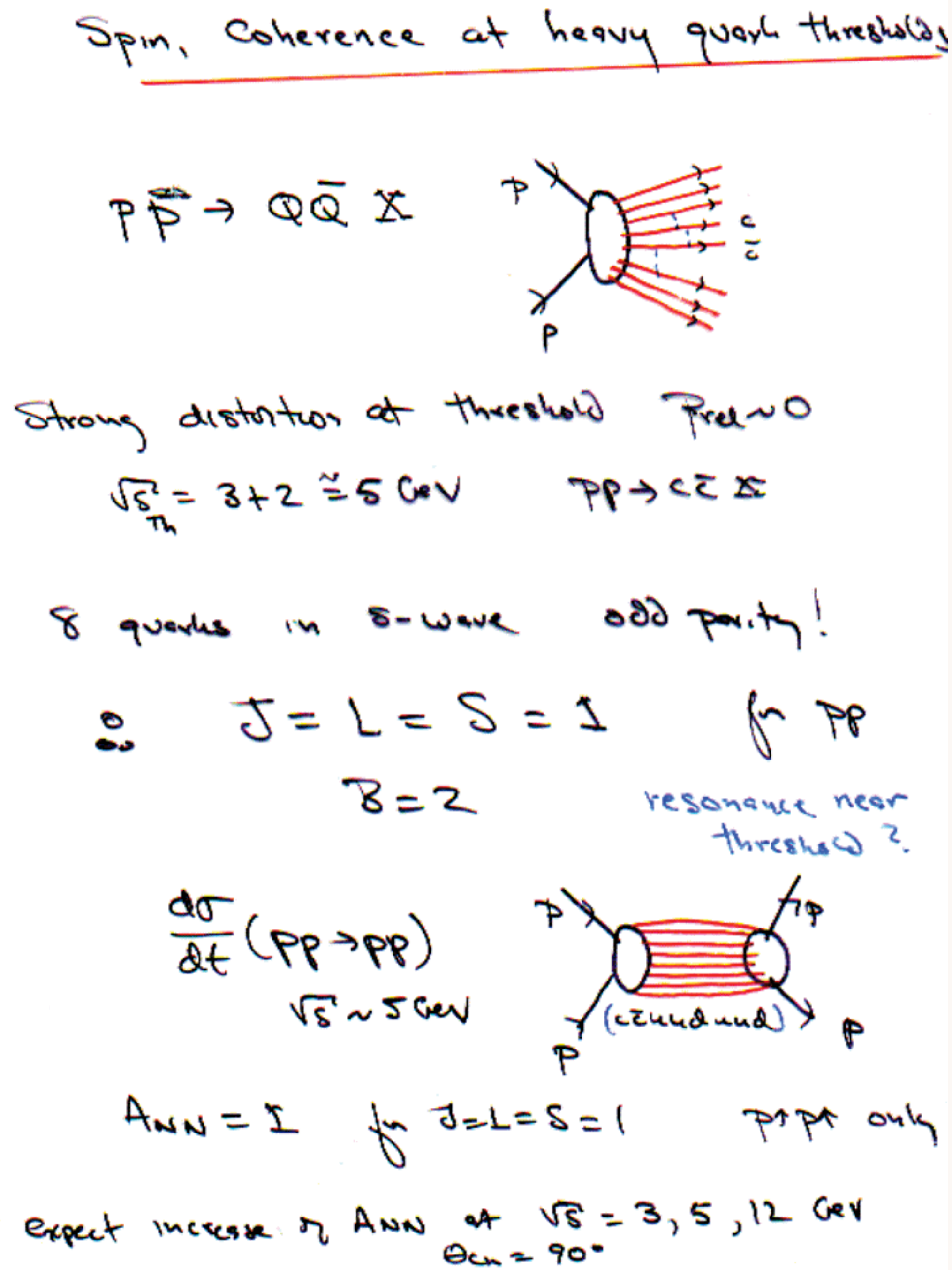


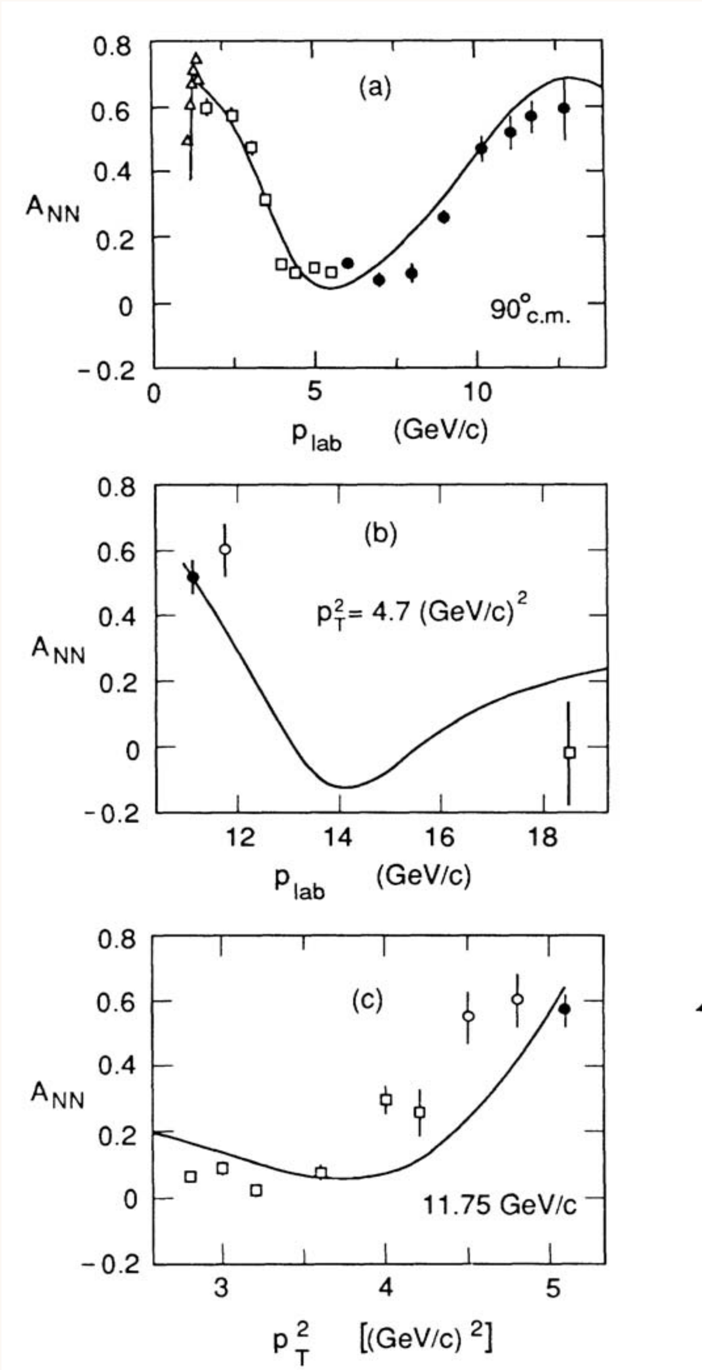


QCD Schwinger-Sommerfeld Enhancement at Heavy Quark Threshold

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).





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).

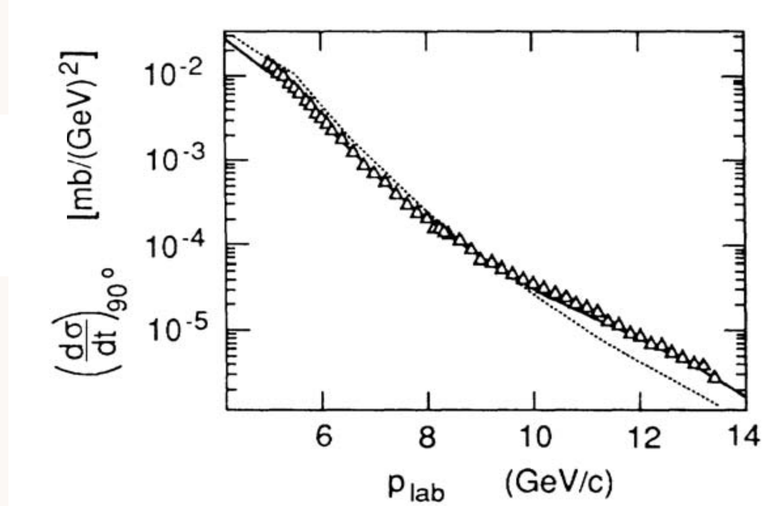
Quark Interchange + 8-Quark Resonance

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

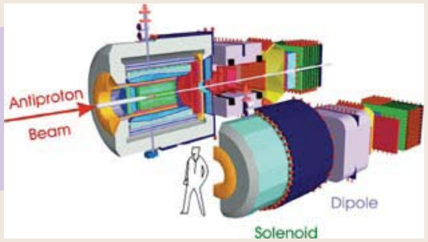
$M = 3$ GeV, $M = 5$ GeV.

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

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

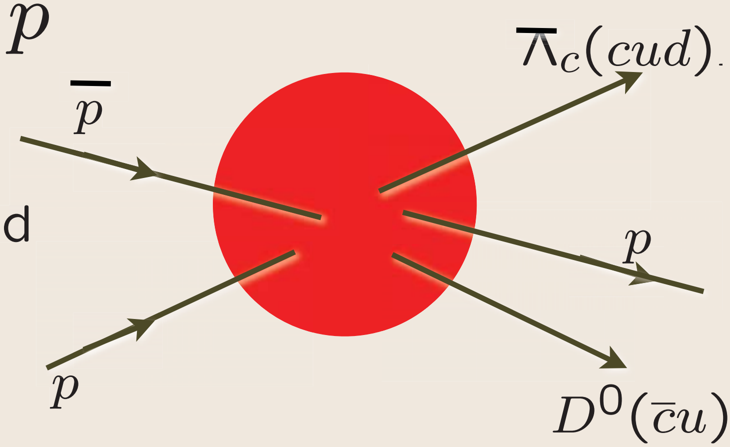


Key QCD Panda Experiment



Open Charm

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



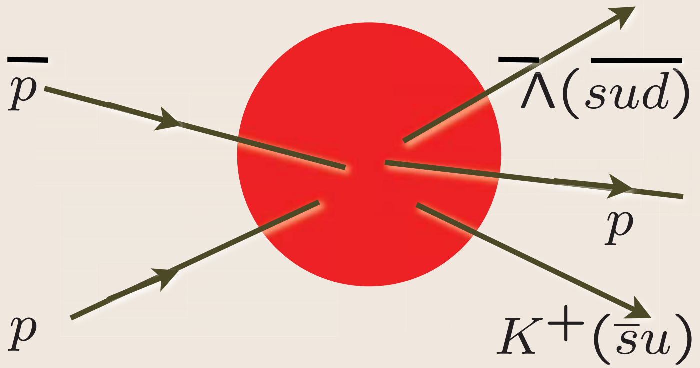
Total open charm cross section at threshold

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

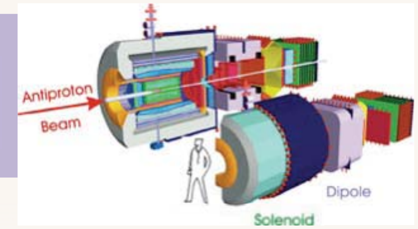
needed to explain Krisch A_{NN}

Compare with strangeness channels

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



Key QCD Panda Experiment



- 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

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

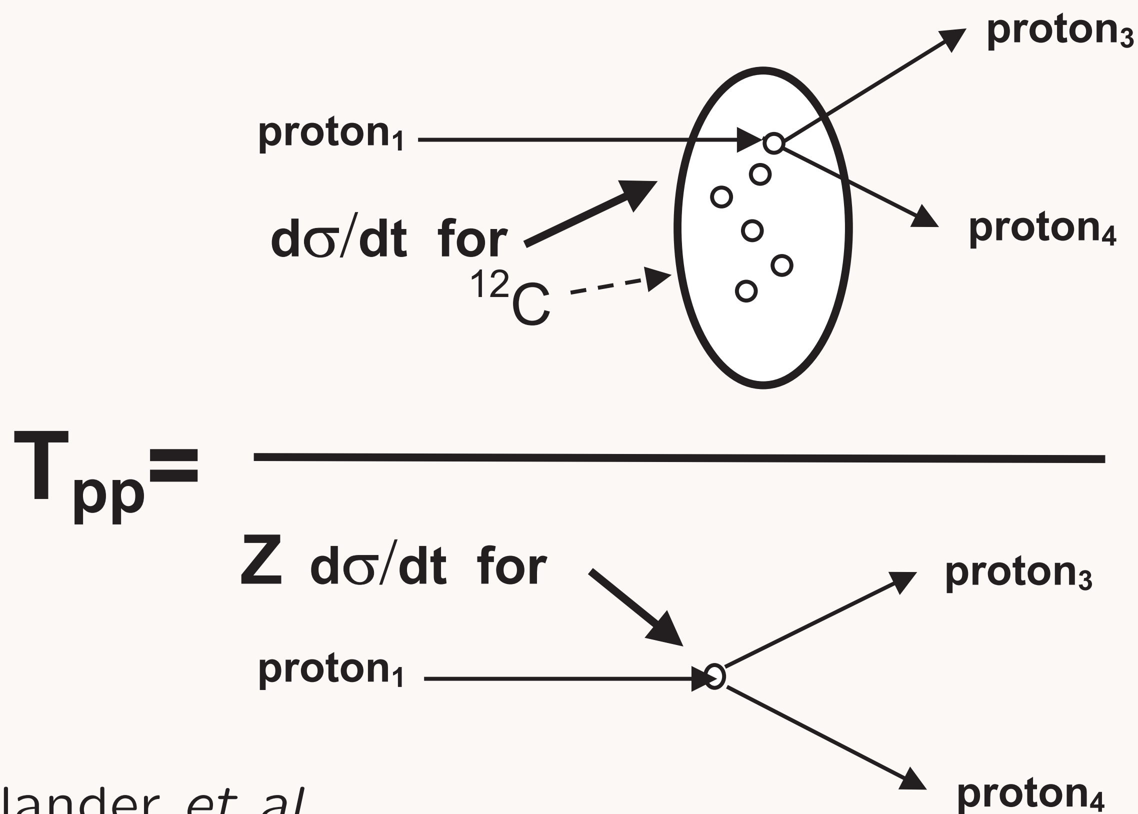
$$\bar{p}p \to \bar{p}\Lambda_c D$$

Color Transparency

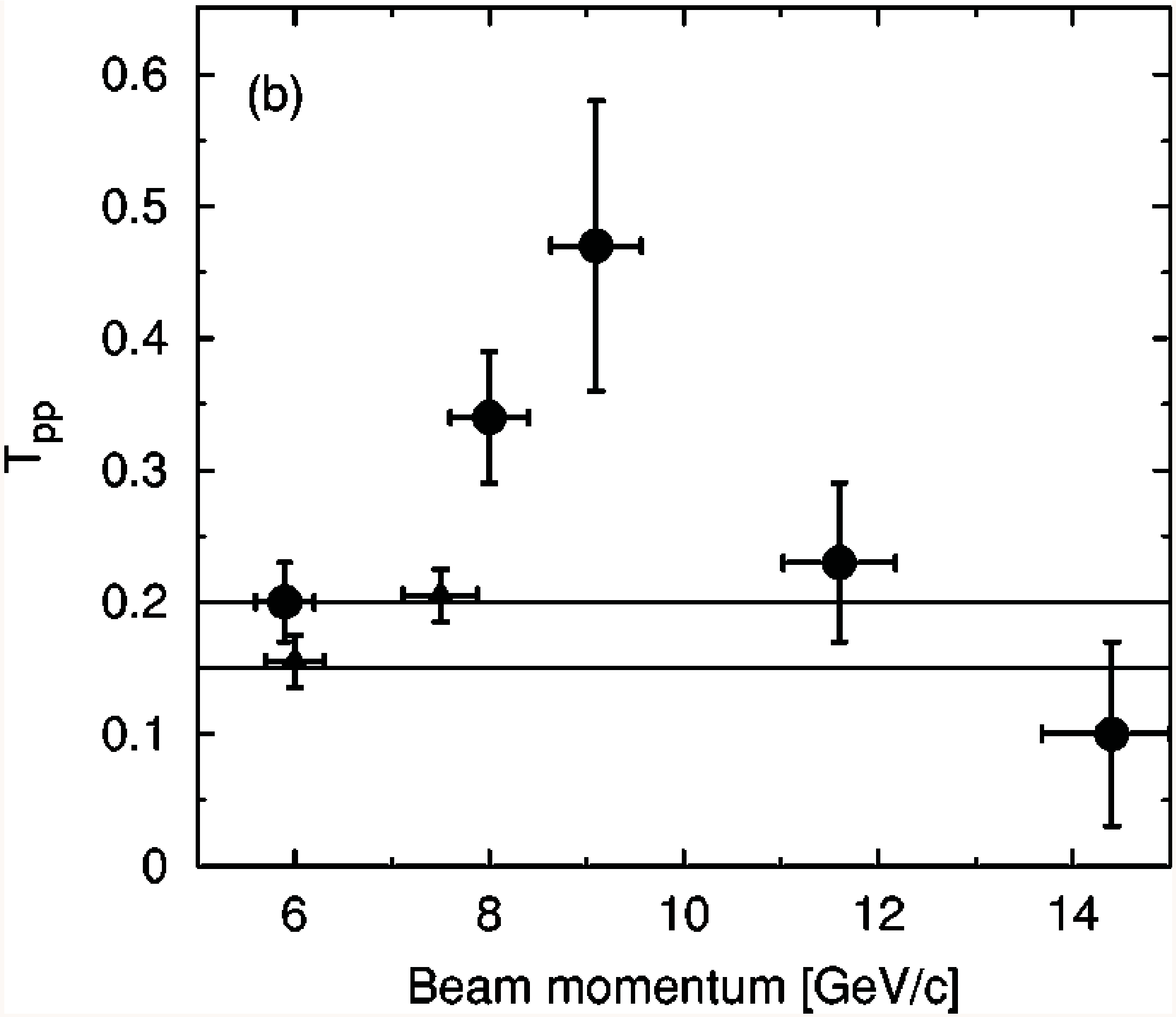
Bertsch, Gunion, Goldhaber, sjb
A. H. Mueller, sjb

- 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].

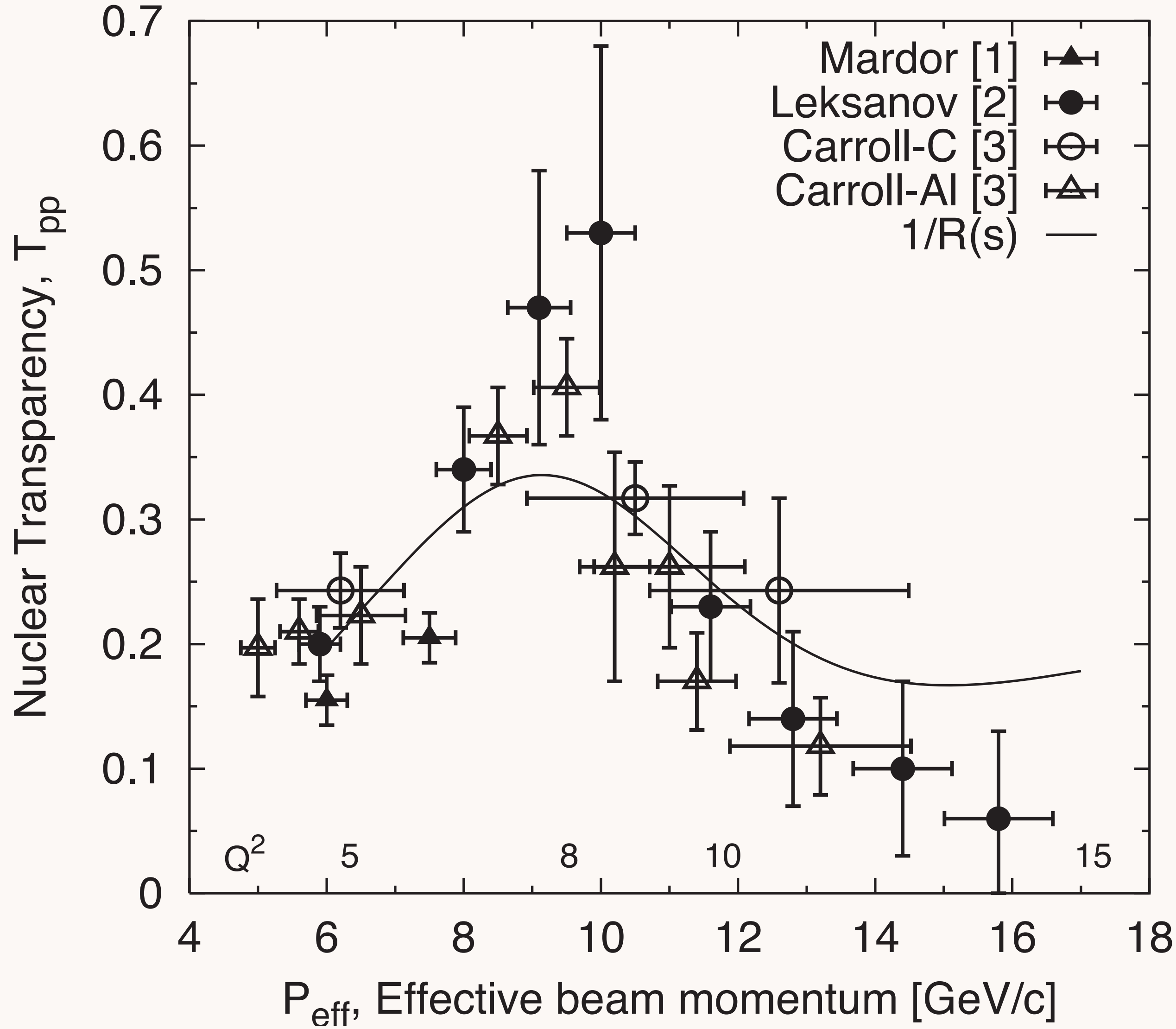


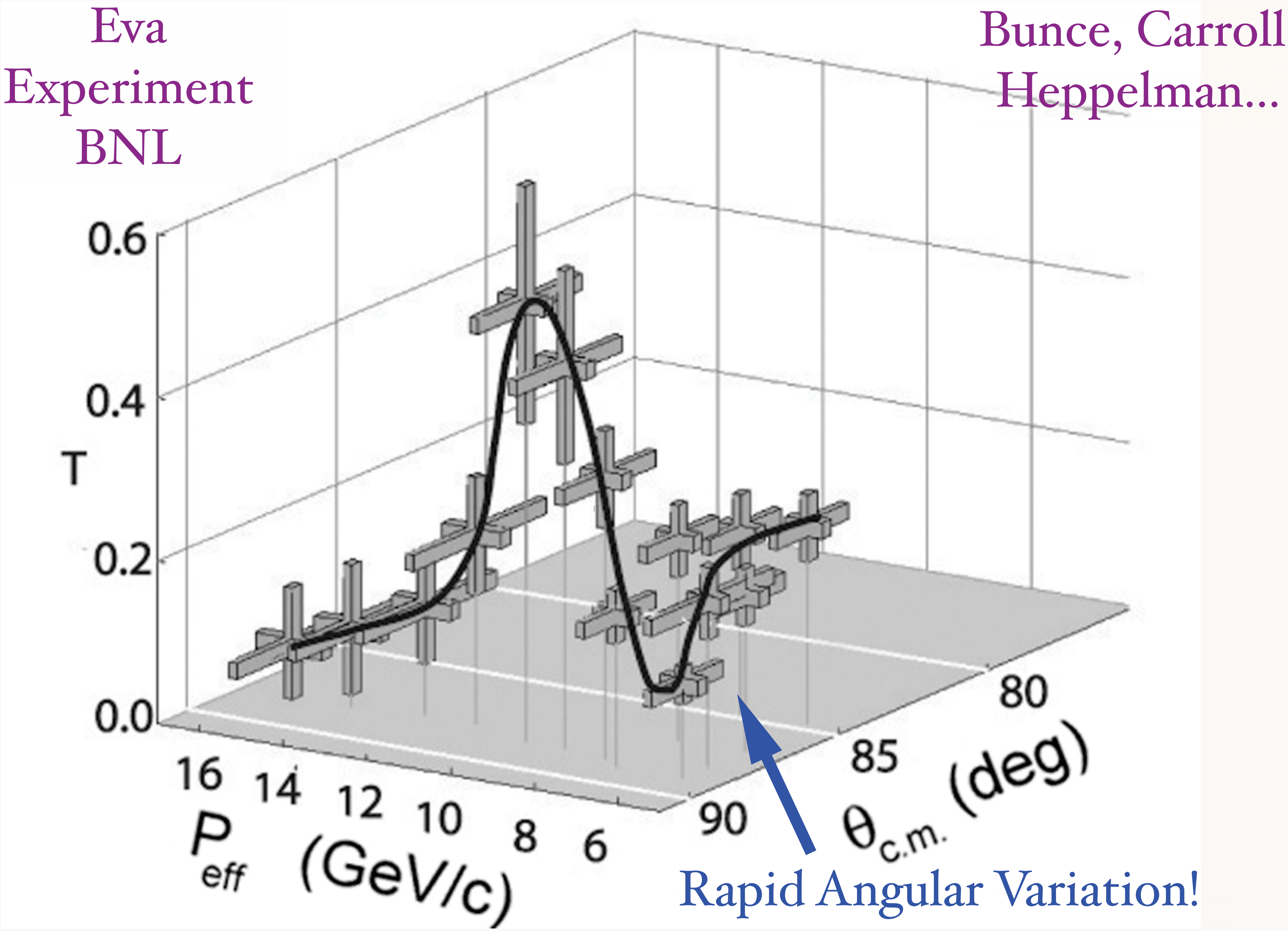
PHYSICAL REVIEW C **70**, 015208 (2004)

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

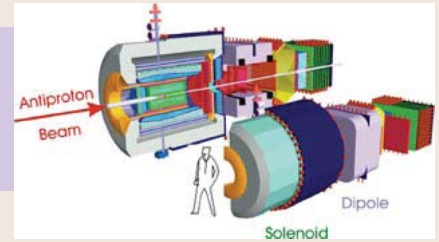
J. Aclander,[7] J. Alster,[7] G. Asryan,[1,*] Y. Averiche,[5] D. S. Barton,[1] V. Baturin,[2,†] N. Buktoyarova,[1,†] G. Bunce,[1] A. S. Carroll,[1,‡] N. Christensen,[3,§] H. Courant,[3] S. Durrant,[2] G. Fang,[3] K. Gabriel,[2] S. Gushue,[1] K. J. Heller,[3] S. Heppelmann,[2] I. Kosonovsky,[7] A. Leksanov,[2] 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...
0.6
0.4
T
0.2
0.0
16
14
12
10
8
6
P eff (GeV/c)
80
85
90
θ c.m. (deg)
Rapid Angular Variation!

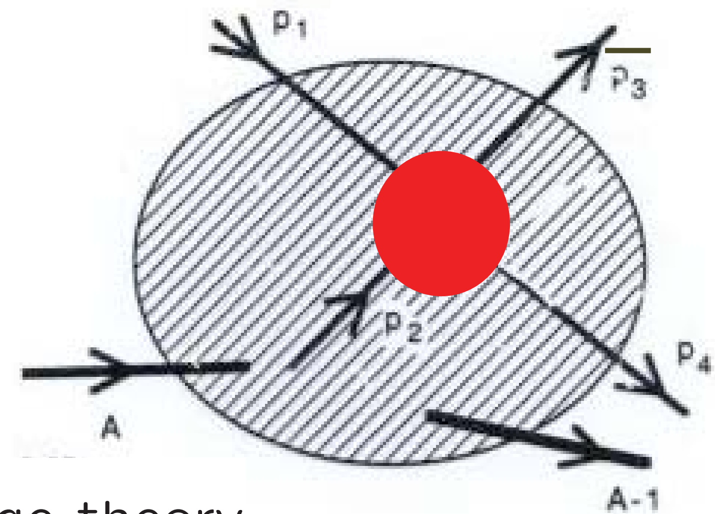
Key QCD Panda Experiment



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



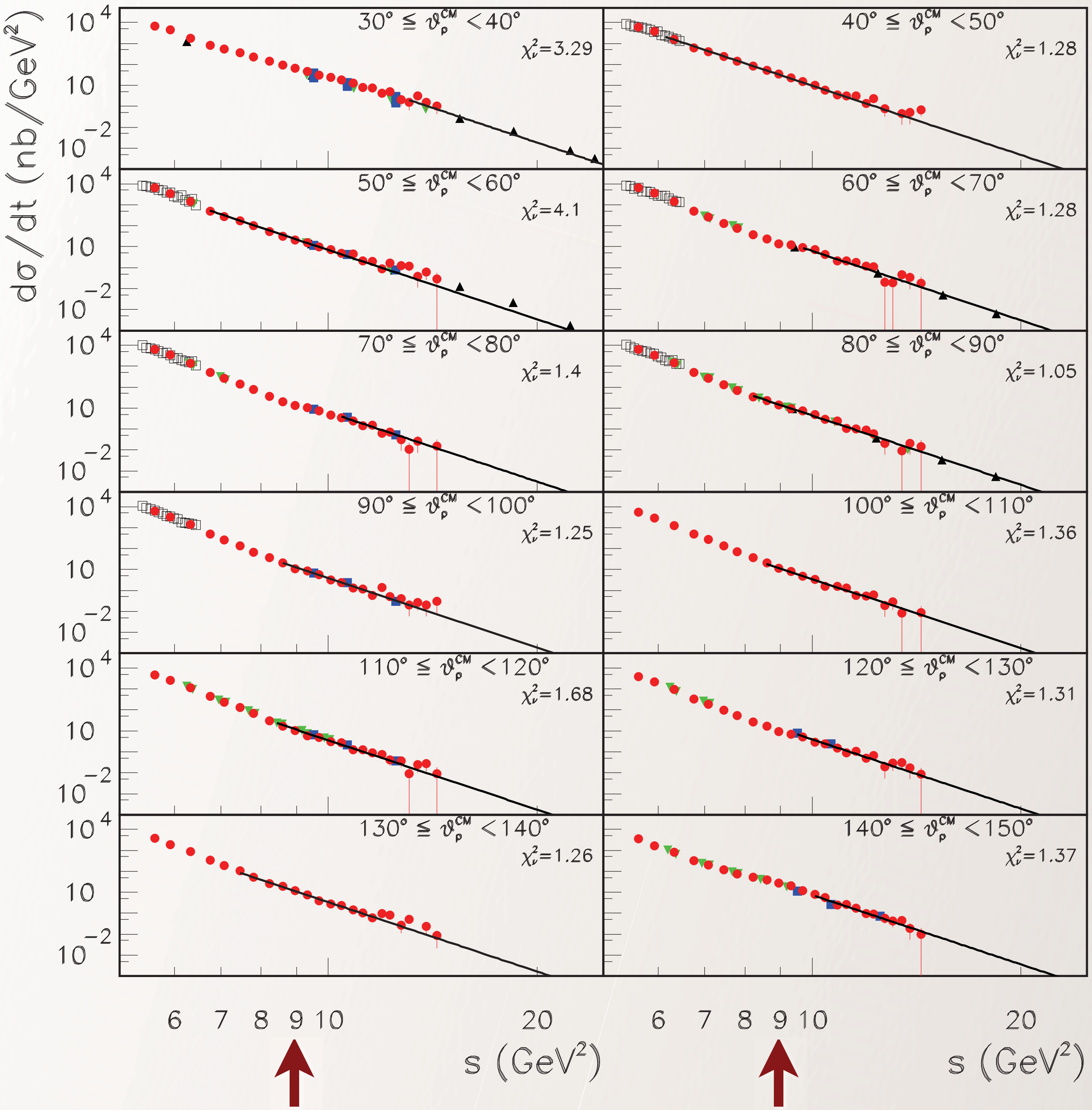
Key test of local gauge theory

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

A.H. Mueller, SJB

Deuteron Photodisintegration and Dimensional Counting

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



PQCD and AdS/CFT:

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

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

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

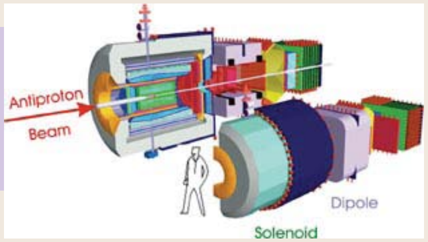
$$\gamma d\to(uuddd us\bar{s})\to np$$

at $s\simeq 9$ GeV^2

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

at $s\simeq 25$ GeV^2

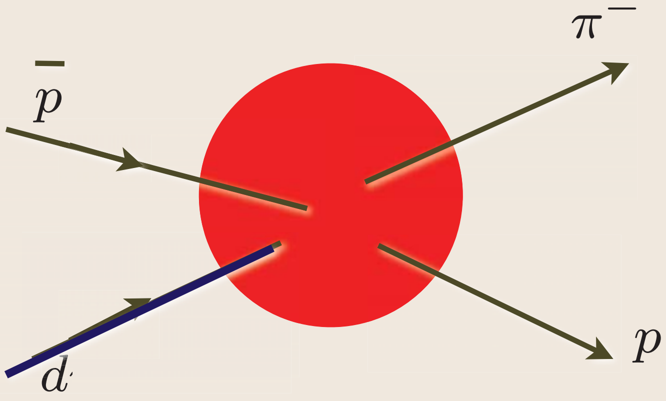
Key QCD Panda Experiment



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

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

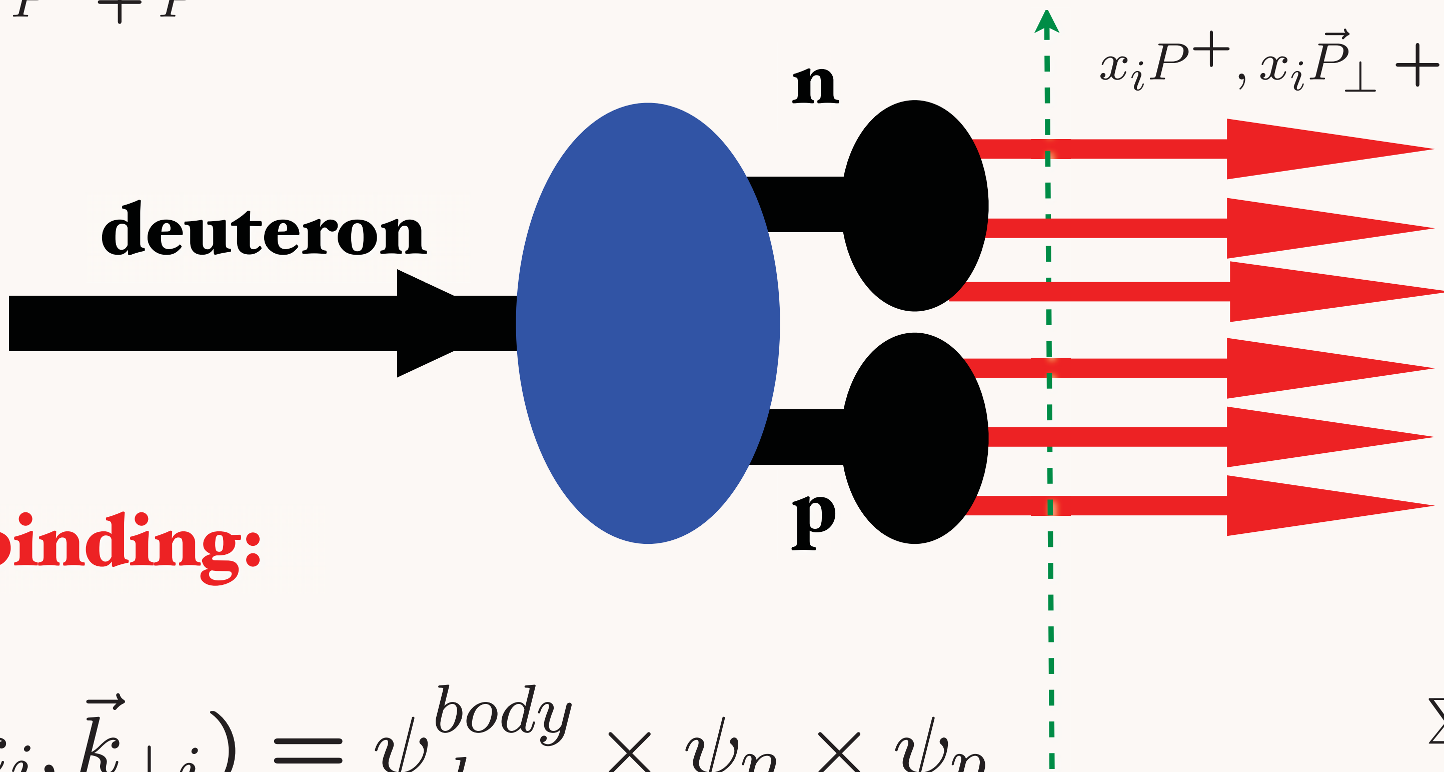
Deuteron Light-Front Wavefunction

Fixed $\tau = t + z/c$

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

$x_i P^+, x_i \vec{P}_\perp + \vec{k}_{\perp i}$

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



Weak binding:

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

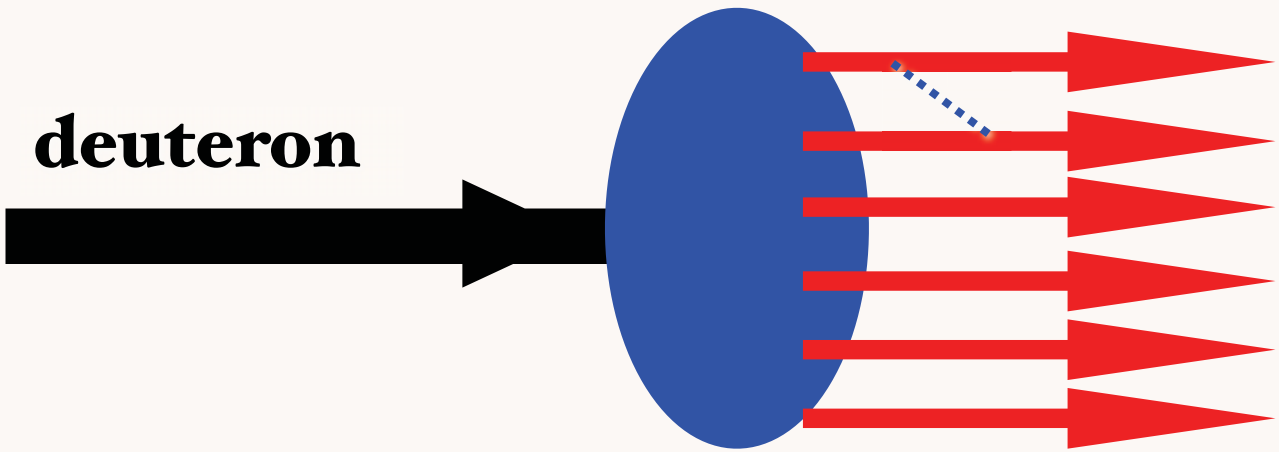
$\Sigma_i^n x_i = 1$

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

Two color-singlet combinations of three 3_C

Evolution of 5 color-singlet Fock states

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



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

$\sum_i^n x_i = 1$

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

5 X 5 Matrix Evolution Equation for deuteron distribution amplitude

QCD Prediction for Deuteron Form Factor

$$F_d(Q^2) = \left[\frac{\alpha_s(Q^2)}{Q^2}\right]^5 \sum_{m,n} d_{mn}\left(\ln\frac{Q^2}{\Lambda^2}\right)^{-\gamma_n^d-\gamma_m^d}\left[1+O\left(\alpha_s(Q^2),\frac{m}{Q}\right)\right]$$

Define "Reduced" Form Factor

$$f_d(Q^2) \equiv \frac{F_d(Q^2)}{F_N^{\,2}(Q^2/4)}\,.$$

Same large momentum transfer behavior as pion form factor

$$f_d(Q^2) \sim \frac{\alpha_s(Q^2)}{Q^2}\left(\ln\frac{Q^2}{\Lambda^2}\right)^{-(2/5)\,C_F/\beta}$$

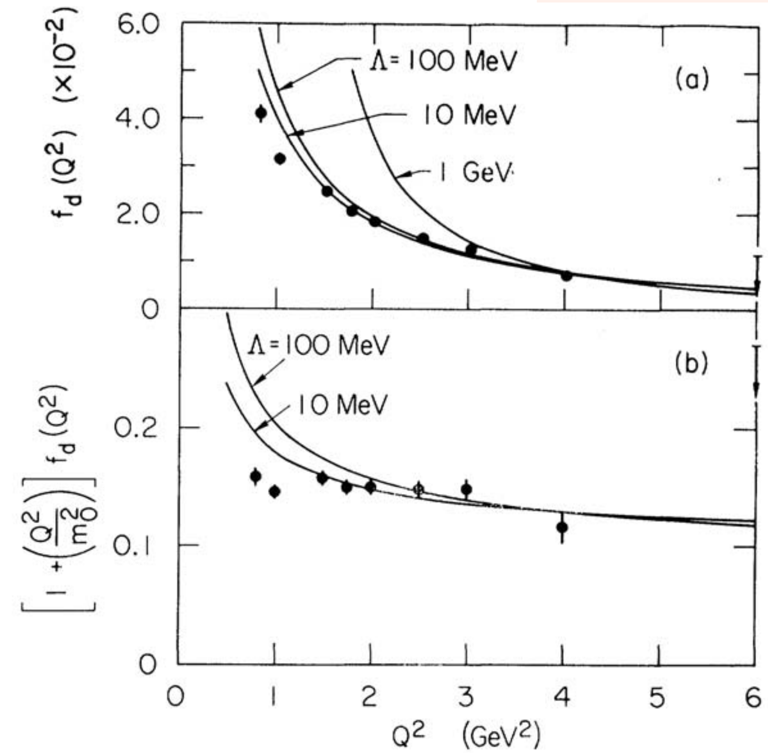
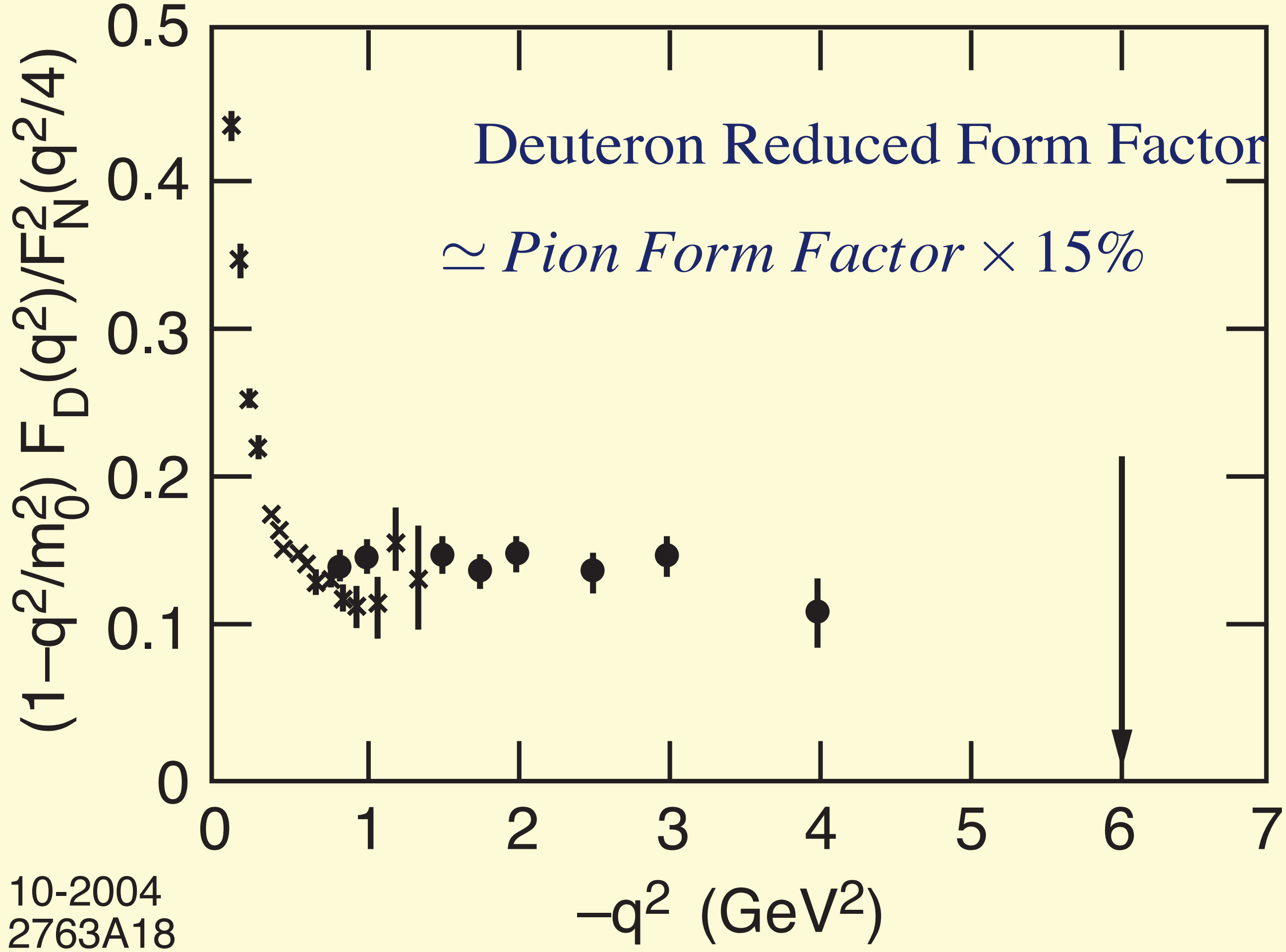


FIG. 2. (a) Comparison of the asymptotic QCD prediction $f_d(Q^2) \propto (1/Q^2)[\ln(Q^2/\Lambda^2)]^{-1-(2/5)C_F/\beta}$ with final data of Ref. 10 for the reduced deuteron form factor, where $F_N(Q^2) = [1+Q^2/(0.71\ \mathrm{GeV}^2)]^{-2}$. The normalization is fixed at the $Q^2 = 4\ \mathrm{GeV}^2$ data point. (b) Comparison of the prediction $[1+(Q^2/m_0^2)]f_d(Q^2) \propto [\ln(Q^2/\Lambda^2)]^{-1-(2/5)C_F/\beta}$ with the above data. The value $m_0^2 = 0.28\ \mathrm{GeV}^2$ is used (Ref. 8).



- 15% Hidden Color in the Deuteron

- Remarkable Test of Quark Counting Rules
- Deuteron Photo-Disintegration γd → 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

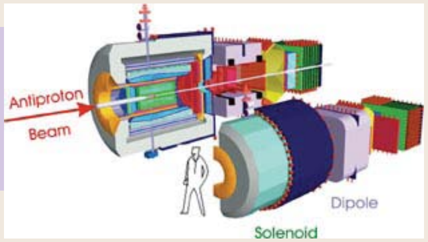
Hidden Color in QCD

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

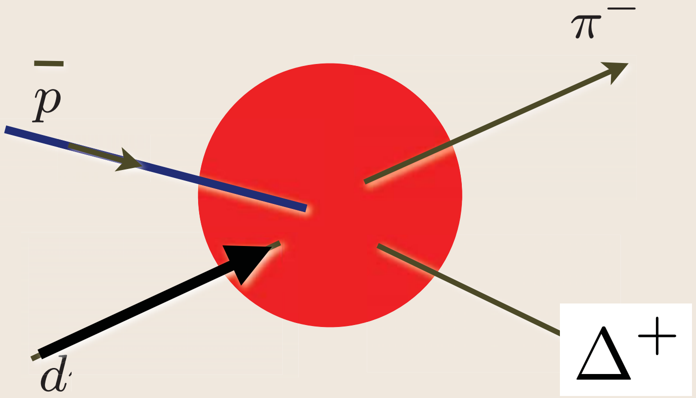
Key QCD Panda Experiment



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 BaBar in Exclusive Processes

- Diffractive Processes
- Odderon from pbar p and p p difference
- Timelike DVCS
- DVCS: Charge Asymmetry, J=0
- Double lepton pairs
- DVCS: Constraints on GPDs

Topics for PANDA 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 $p\bar{p} \to \gamma M_X$

Heavy Quark Topics for Panda

- 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, rescattering, shadowing, non-universal antishadowing ...

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

—Mark Twain

Looking forward to great physics from PANDA!