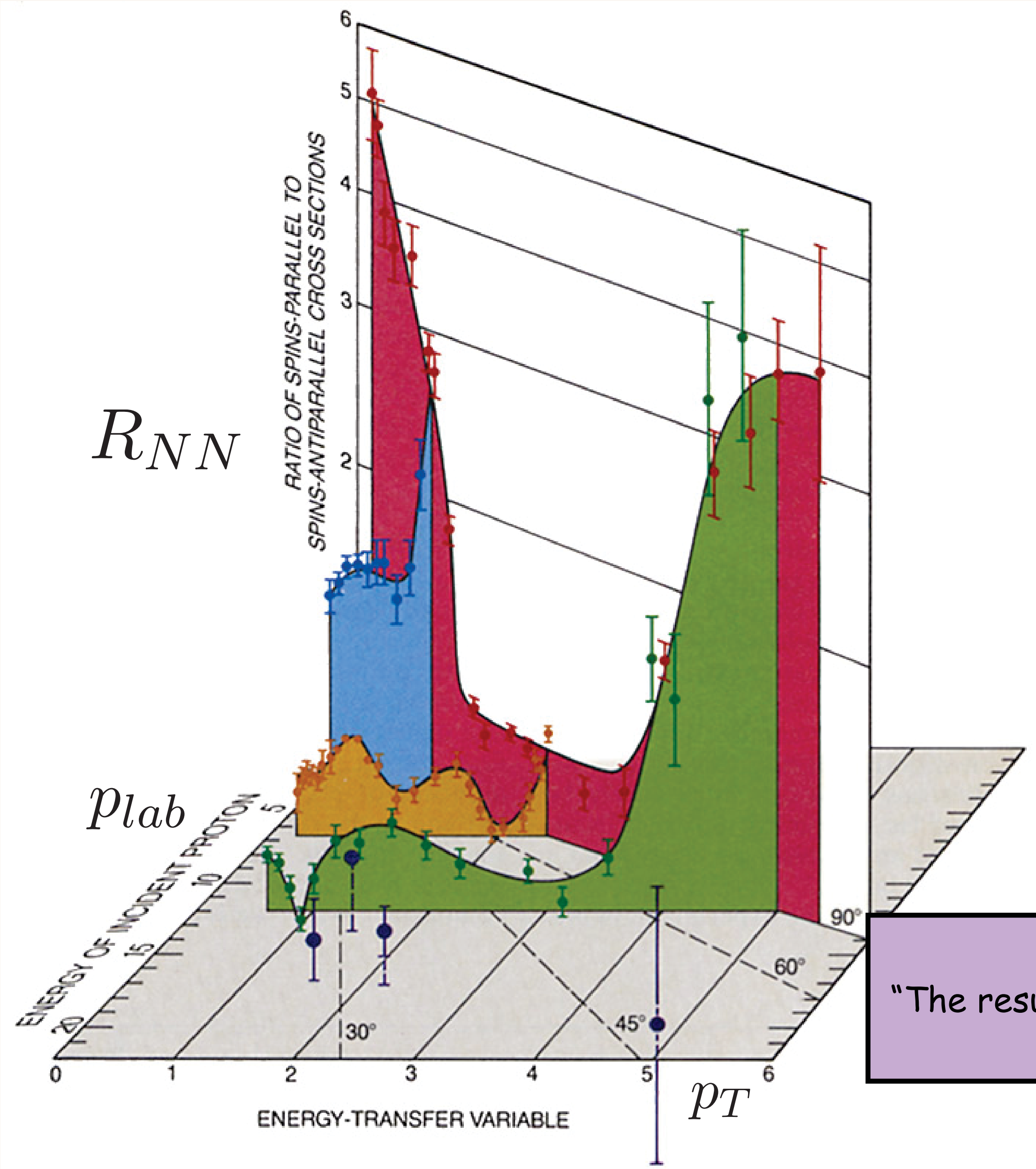
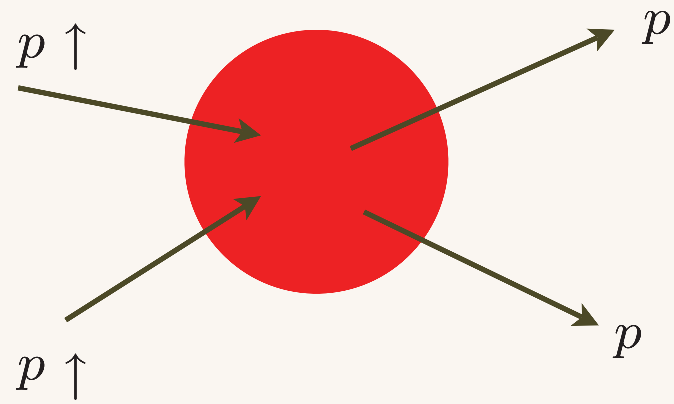
The remarkable anomalies of proton-proton scattering

- Double spin correlations
- Single spin correlations
- Color transparency

Spin Correlations in Elastic $p-p$ Scattering

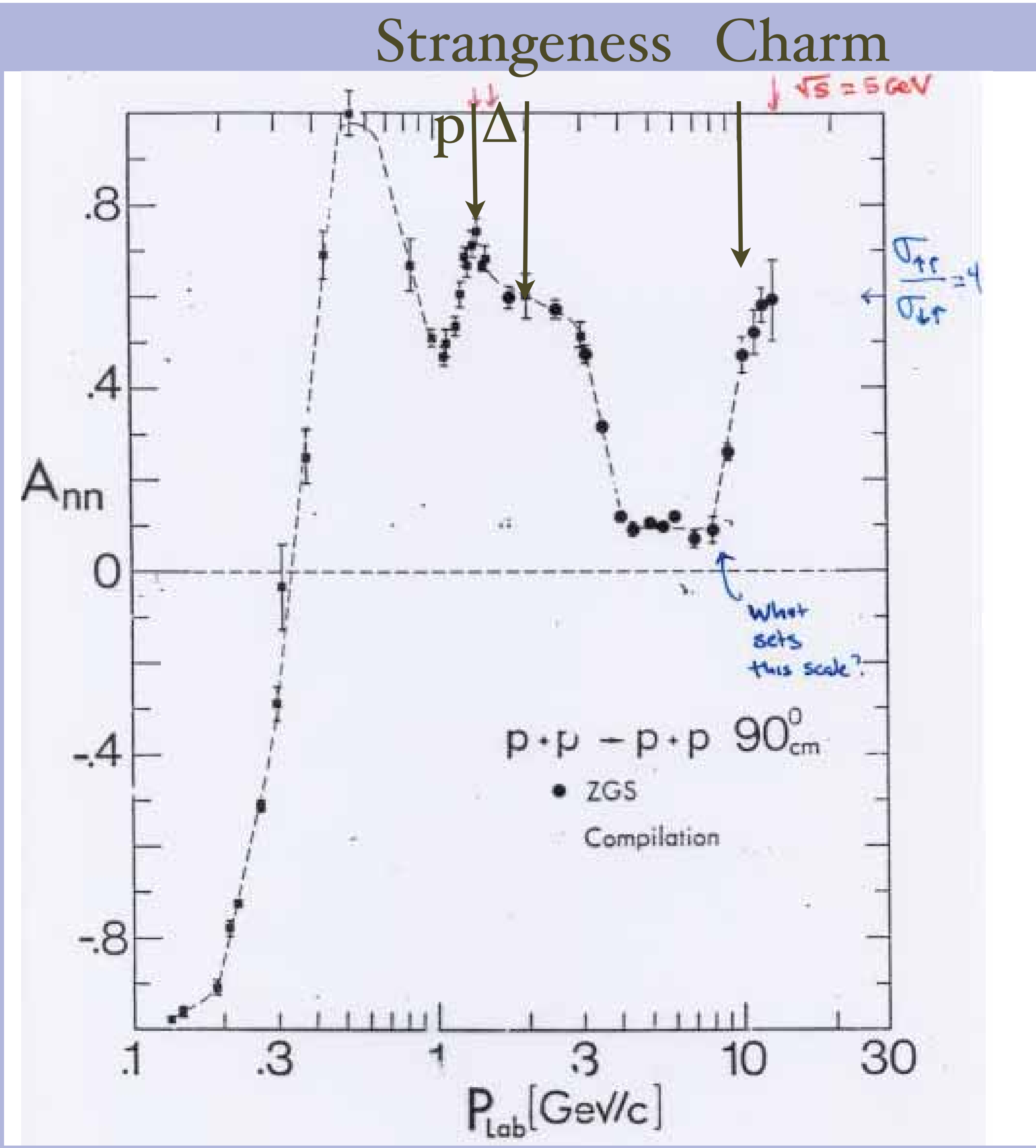




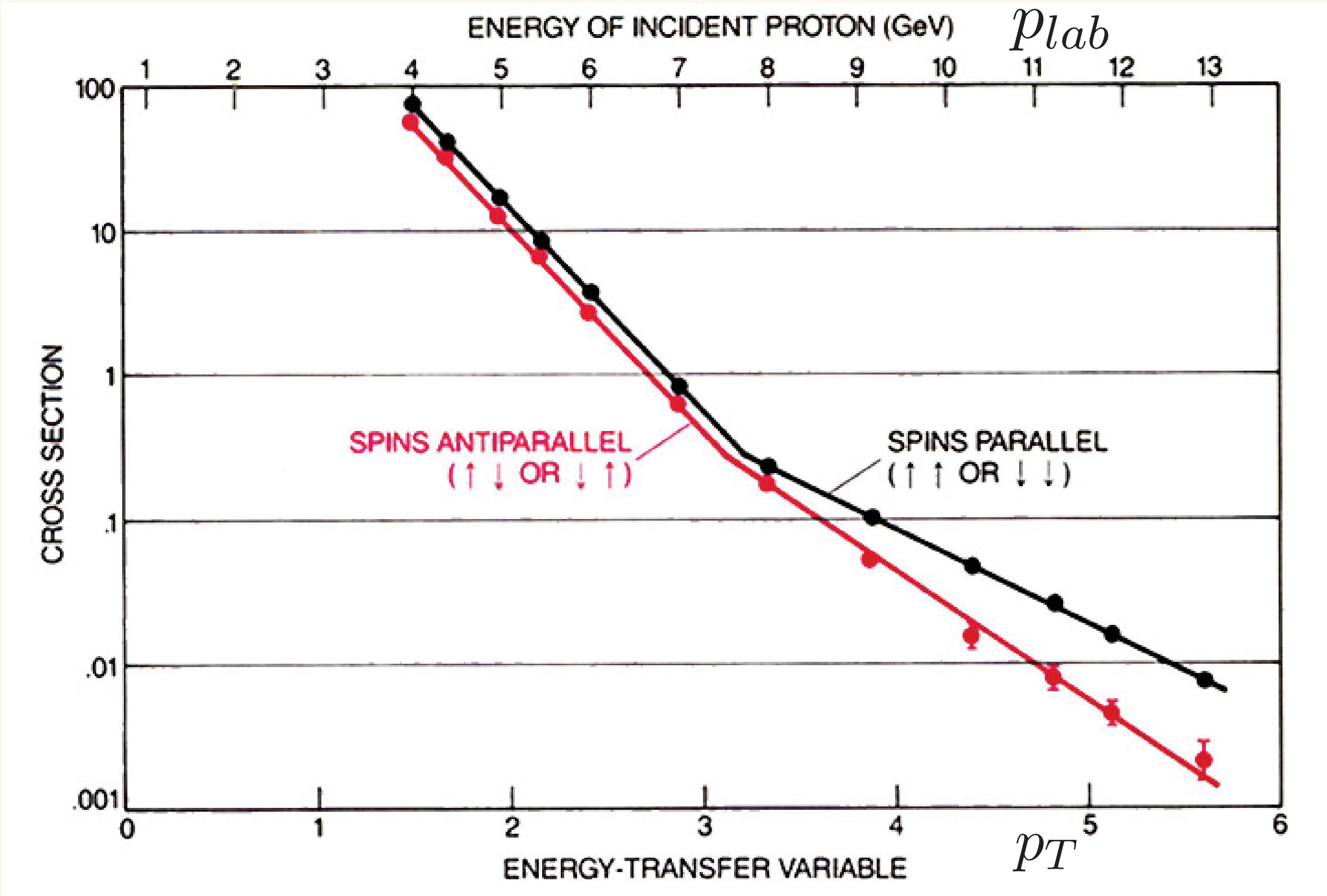
polarization normal to scattering plane

Ratio reaches 4:1 !

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


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

$$\frac{d\sigma_{\uparrow\downarrow\uparrow\uparrow}}{dt}(pp \to pp) \text{ at } \theta_{CM} = \pi/2$$



Collisions Between Spinning Protons (A. D. Krisch)
Scientific American, 255, 42-50 (August, 1987).

What causes the Krisch Effect?

Largest spin-spin correlation in hadron physics!

An outstanding problem confronting QCD

Carlson, Lipkin, SJB:

Complete analysis of spin correlations

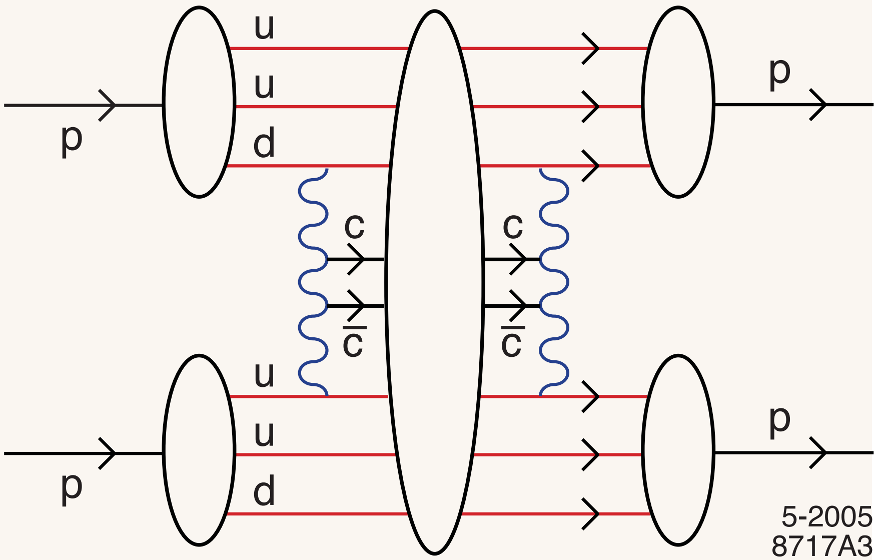
Interference of QIM and Landshoff "Pinch" (triple scattering) contributions

de Teramond, SJB:

Peaks in R_{NN} associated with $p\Delta$, strangeness, charm thresholds

Predict significant strangeness production $\sigma(pp \to sX) \sim 1\ mb$ just above threshold

Predict significant charm production $\sigma(pp \to cX) \sim 1\ \mu b$ just above threshold

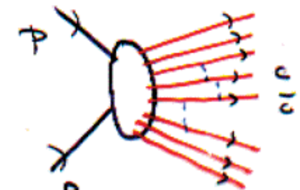


QCD
Schwinger - Sommerfeld
Enhancement

Hebecker, Kuhn, sjb

Spin, Coherence at heavy quark thresholds

$p\vec{\bar{p}} \to Q\bar{Q}X$



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

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

8 quarks in S-wave odd parity!

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

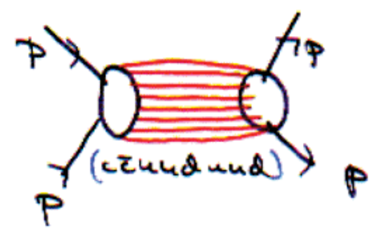
$B = 2$

resonance near threshold?

SJB + deTeramond

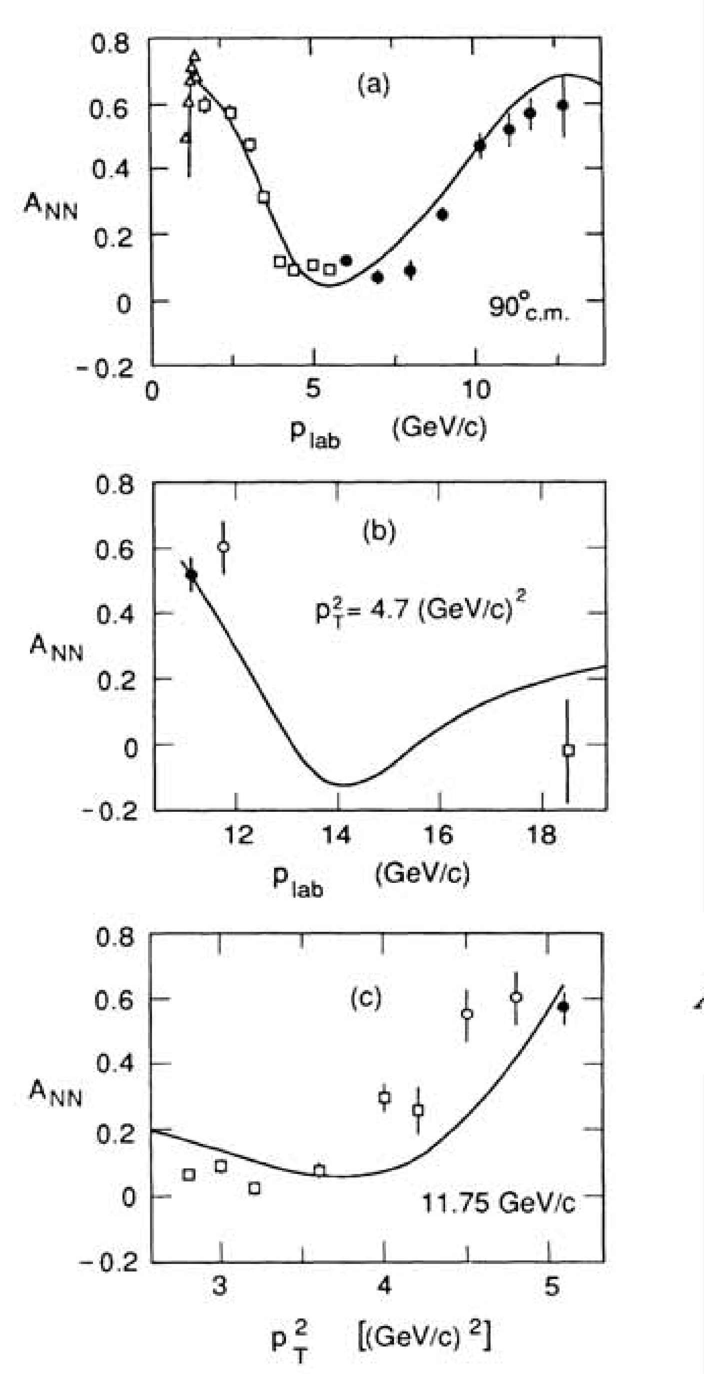
$\frac{d\sigma}{dt}(pp \to pp)$

$\sqrt{s} \sim 5$ GeV



$A_{NN} = 1$ for $J=L=S=1$ $p\uparrow p\uparrow$ 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).

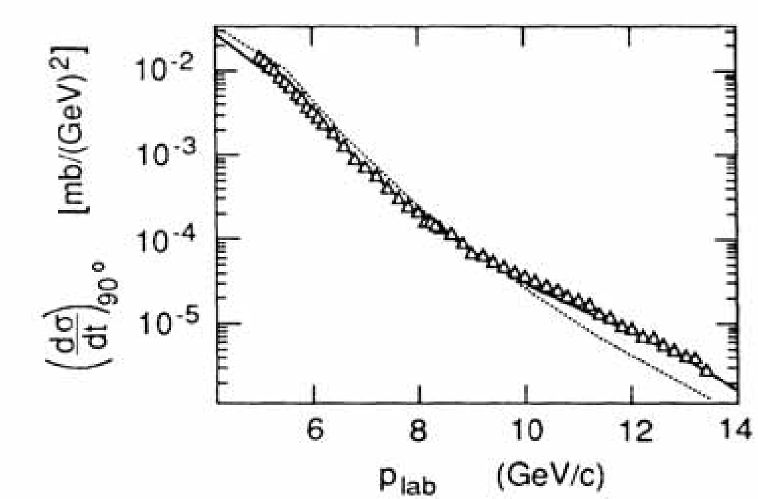
Quark Interchange + 8-Quark Resonance

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

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

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

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



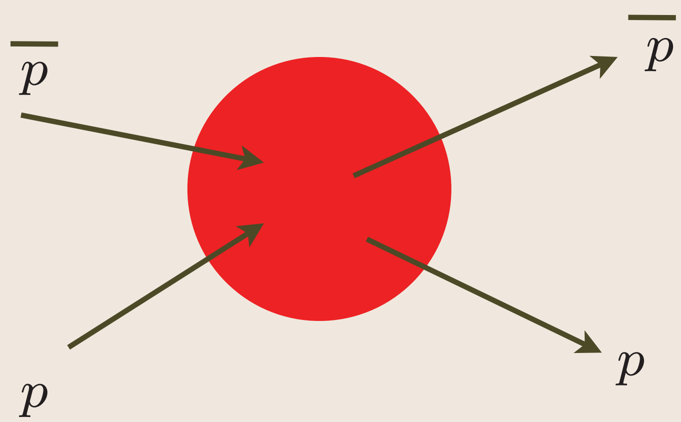
- New QCD physics in proton-proton elastic scattering at the charm threshold
- Anomalously large charm production at threshold!!?
- Octoquark resonances?
- Color Transparency disappears at charm threshold
- Key physics at GSI: second charm threshold

$$\overline{p}p \rightarrow \overline{p}pJ/\psi$$

$$\overline{p}p \rightarrow \overline{p}\Lambda_c D$$

Key QCD Experiment at GSI

A_{NN} for $\overline{p}p \rightarrow \overline{p}p$



Key QCD Experiment at GSI

Total open charm cross section at threshold

$$\sigma(\overline{p}p \to cX) \simeq 1 \mu b$$

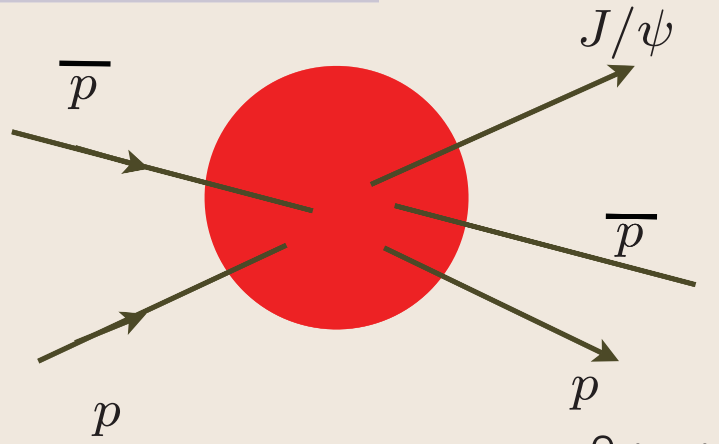
needed to explain Krisch A_{NN}

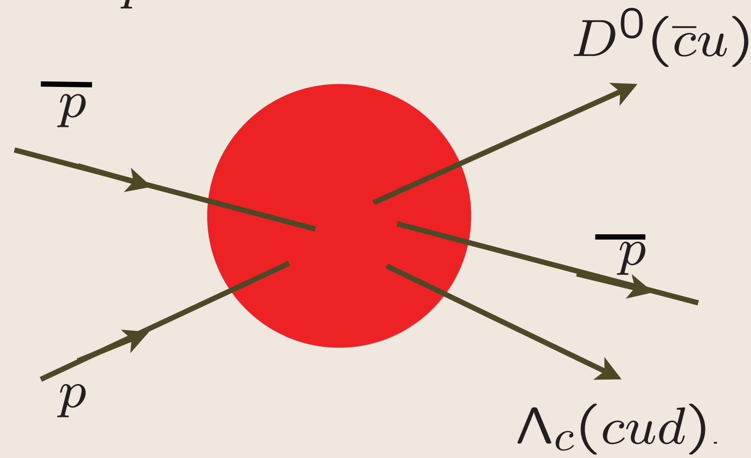
$$\overline{p}p \to \overline{p} + J/\psi + p$$

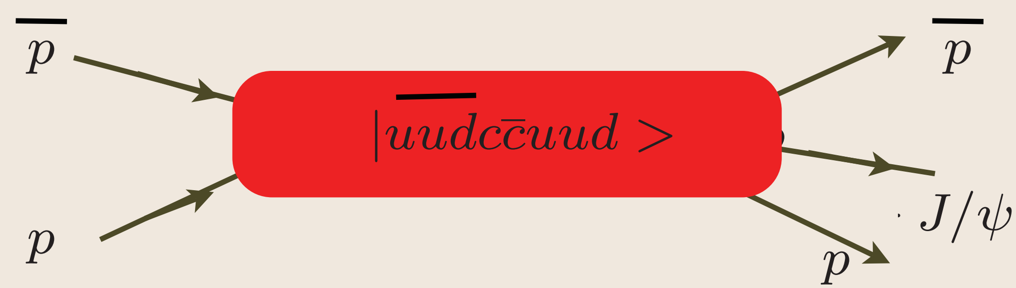
$$\overline{p}p \to \overline{p} + \eta_c + p$$

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

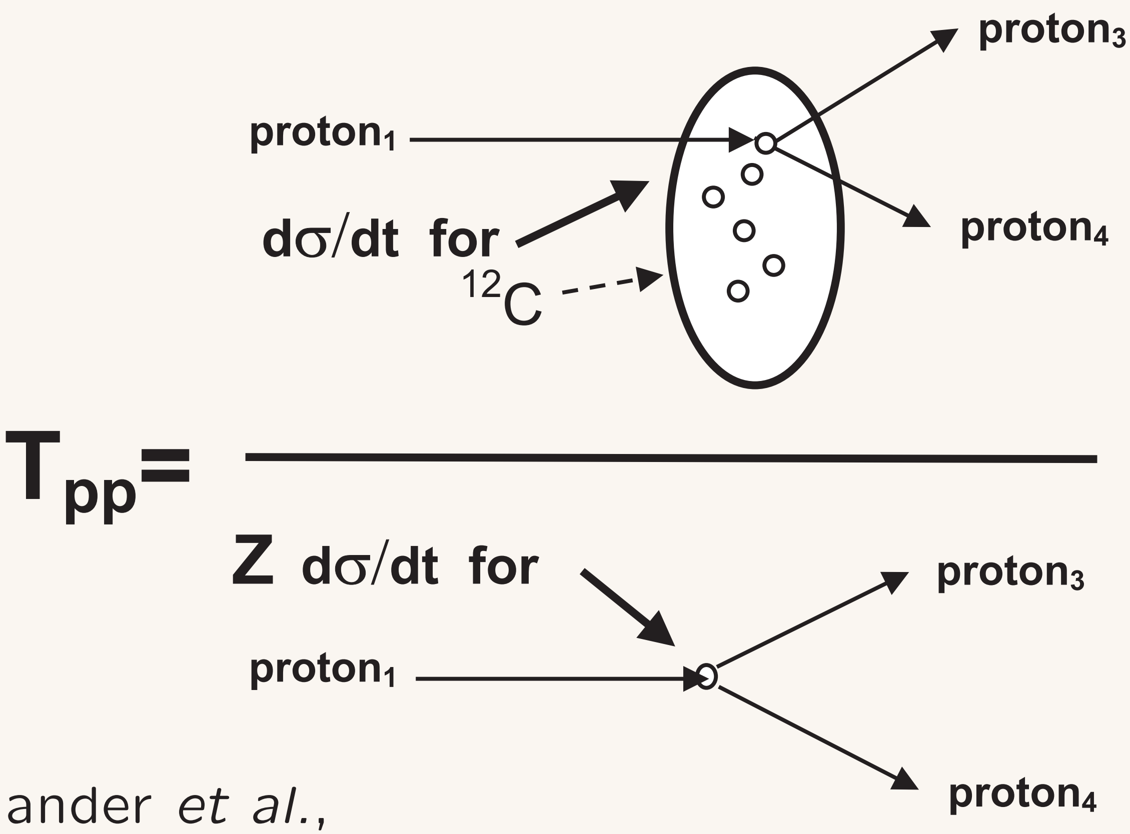
Octoquark: $|\overline{uud}c\bar{c}uud >$





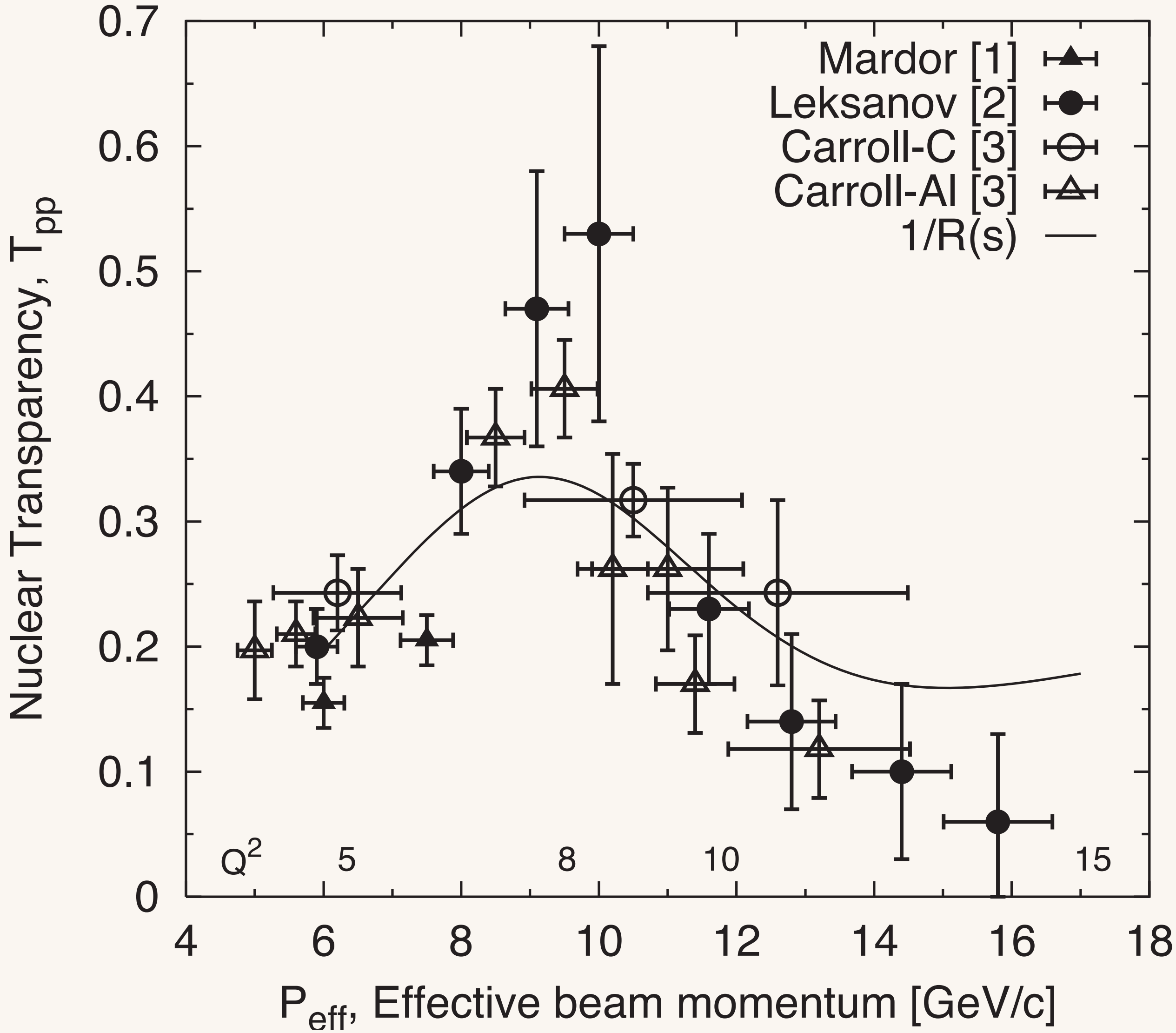


Color Transparency Ratio



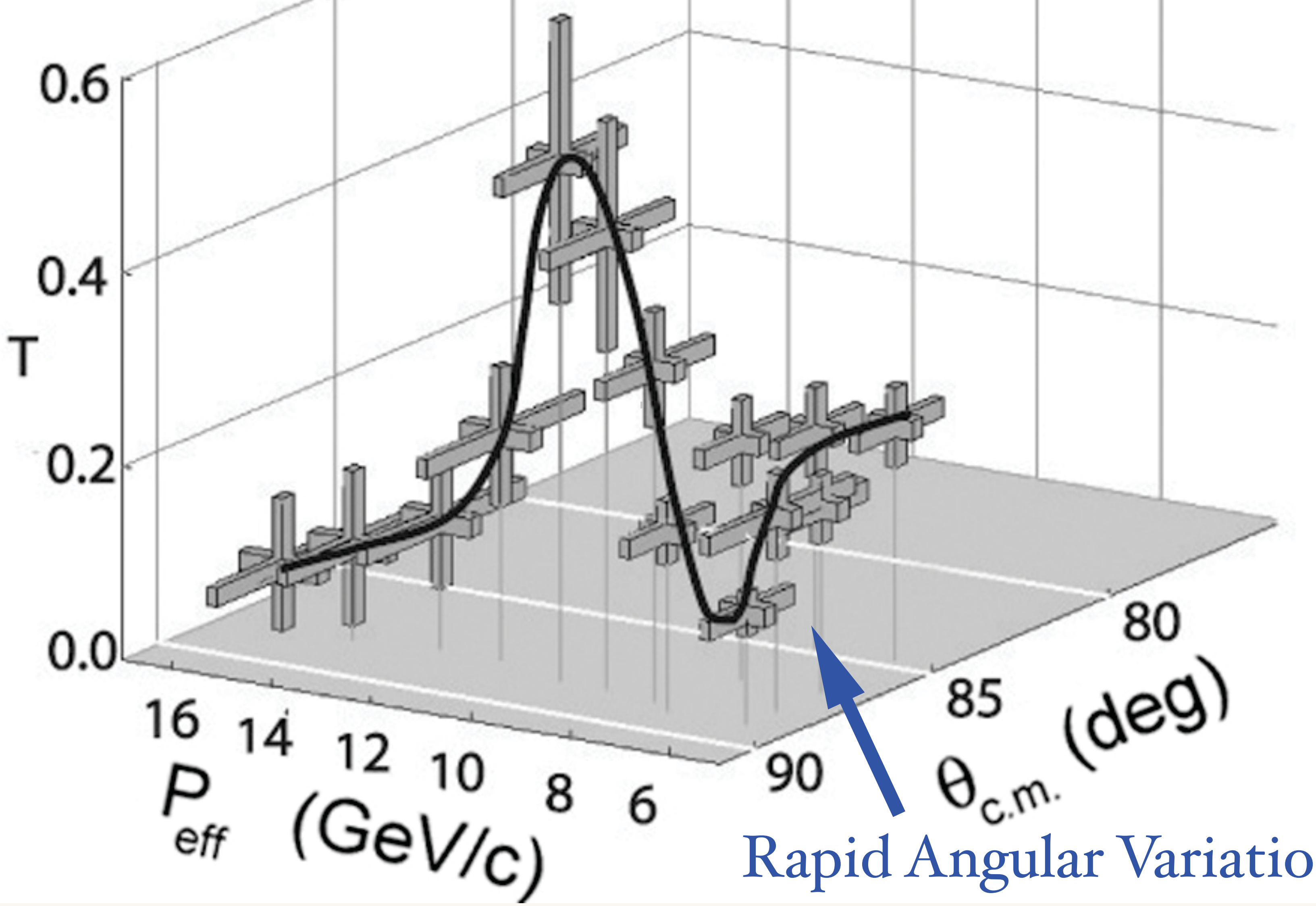
J. L. S. Aclander *et al.*,
"Nuclear transparency in $\theta_{CM} = 90^0$ quasielastic $A(p,2p)$ reactions,"
Phys. Rev. C **70**, 015208 (2004), [arXiv:nucl-ex/0405025].

Color Transparency fails when A_{nn} is large



Eva Experiment BNL

Bunce, Carroll, Heppelman...



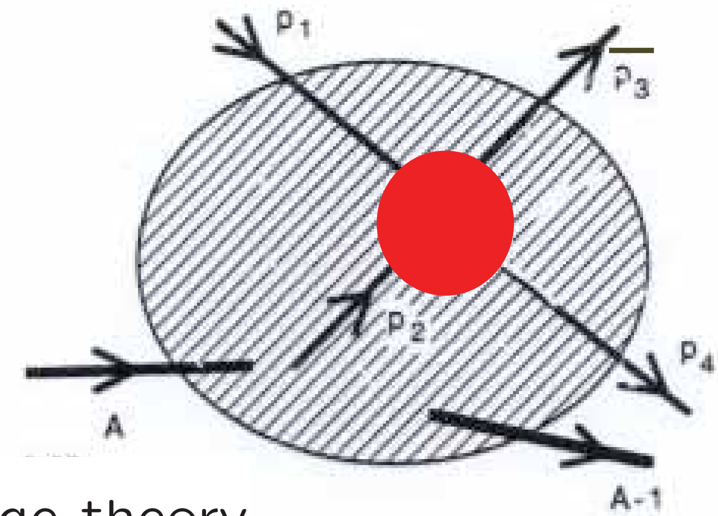
Rapid Angular Variation!

Key QCD Experiment at GSI

Test Color Transparency

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

No absorption of small color dipole at high p_T

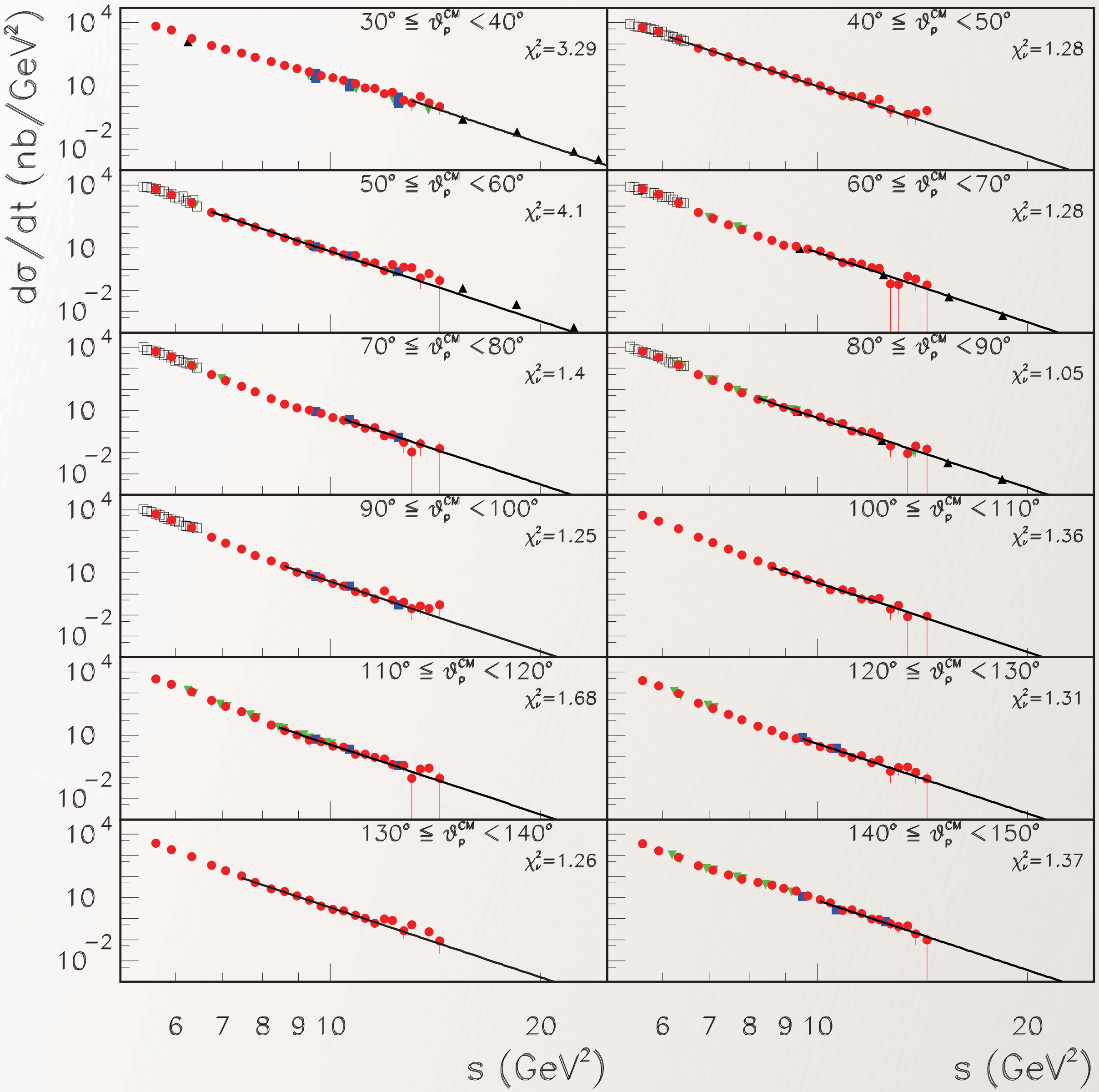


Key test of local gauge theory

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

A.H. Mueller, SJB

Deuteron Photodisintegration & Dimensional Counting Rules



PQCD and AdS/CFT:

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

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

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

- 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

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

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

Same large momentum transfer behavior as pion form factor

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

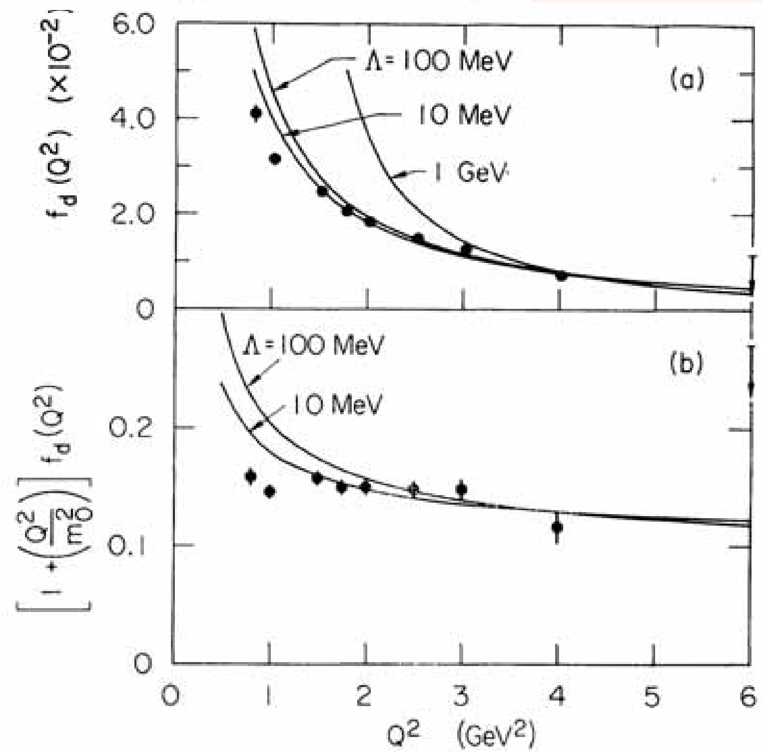
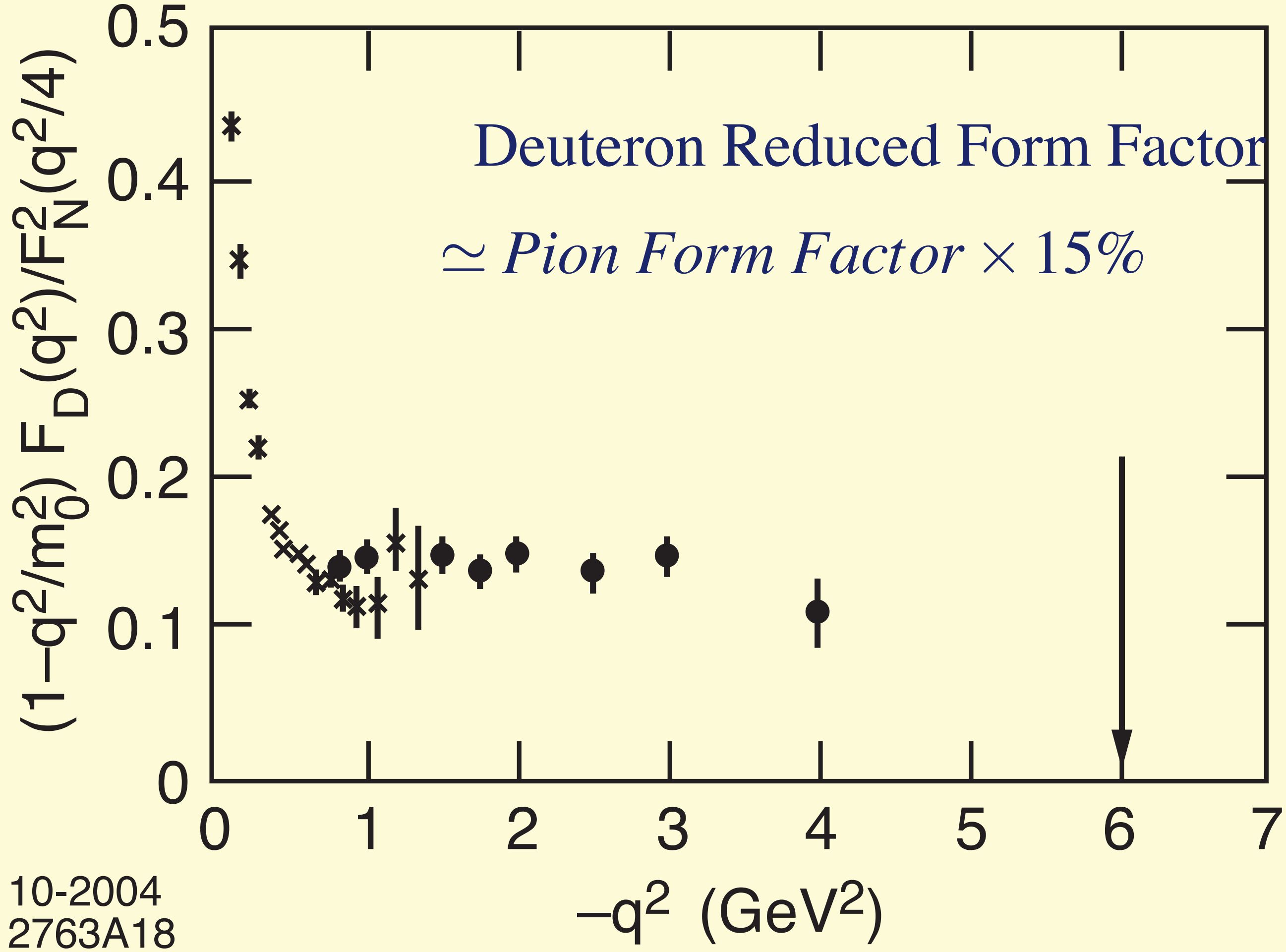


FIG. 2. (a) Comparison of the asymptotic QCD pre diction $f_d(Q^2) \propto (1/Q^2)[\ln(Q^2/\Lambda^2)]^{-1-(2/5)C_F/\beta}$ with fin data of Ref. 10 for the reduced deuteron form factor where $F_N(Q^2) = [1 + Q^2/(0.71\ \mathrm{GeV}^2)]^{-2}$. The normaliz tion is fixed at the $Q^2 = 4\ \mathrm{GeV}^2$ data point. (b) Compa son 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

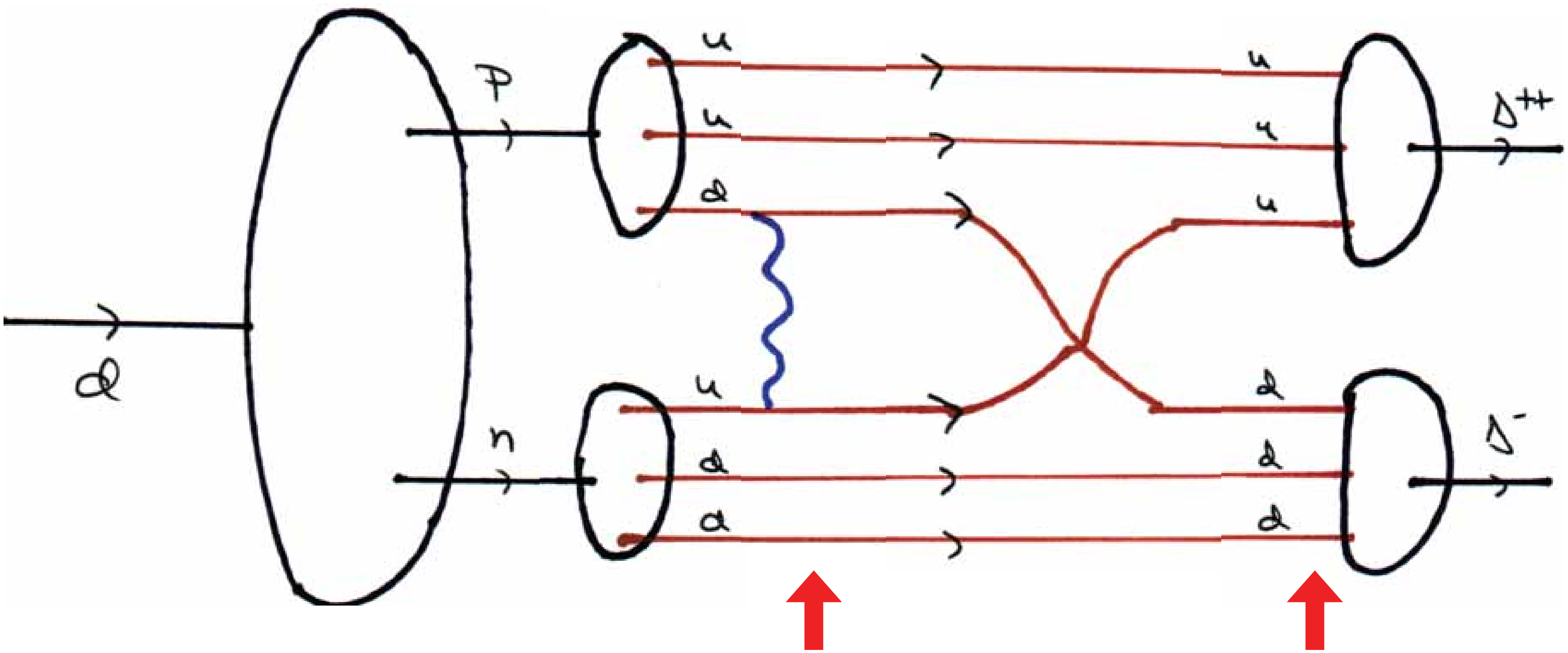
Hidden Color in QCD

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

Structure of Deuteron in QCD



Hidden Color Fock State

Delta-Delta Fock State

The evolution equation for six-quark systems in which the constituents have the light-cone longitudinal momentum fractions x_i $(i=1,2,\ldots,6)$ can be obtained from a generalization of the proton (three-quark) case.[2] A nontrivial extension is the calculation of the color factor, C_d, of six-quark systems[5] (see below). Since in leading order only pairwise interactions, with transverse momentum Q, occur between quarks, the evolution equation for the six-quark system becomes $\{[dy]=\delta(1-\sum_{i=1}^{6}y_i)\prod_{i=1}^{6}dy_i$, $C_F=(n_c^2-1)/2n_c=\frac{4}{3}$, $\beta=11-\frac{2}{3}n_f$, and n_f is the effective number of flavors$\}$

$$\prod_{k=1}^{6} x_k\left[\frac{\partial}{\partial\xi}+\frac{3C_F}{\beta}\right]\tilde{\Phi}(x_i,Q)=-\frac{C_d}{\beta}\int_0^1[dy]V(x_i,y_i)\,\tilde{\Phi}(y_i,Q),$$

$$\xi(Q^2)=\frac{\beta}{4\pi}\int_{Q_0^2}^{Q^2}\frac{dk^2}{k^2}\alpha_s(k^2)\sim\ln\left(\frac{\ln(Q^2/\Lambda^2)}{\ln(Q_0^2/\Lambda^2)}\right).$$

$$V(x_i,y_i)=2\prod_{k=1}^{6}x_k\sum_{i\neq j}^{6}\theta(y_i-x_i)\prod_{l\neq i,j}^{6}\delta(x_l-y_l)\frac{y_j}{x_j}\left(\frac{\delta_{h_i\bar{h}_j}}{x_i+x_j}+\frac{\Delta}{y_i-x_i}\right)$$

where $\delta_{h_i\bar{h}_j}=1$ (0) when the helicities of the constituents $\{i,j\}$ are antiparallel (parallel). The infrared singularity at $x_i=y_i$ is cancelled by the factor $\Delta\tilde{\Phi}(y_i,Q)=\tilde{\Phi}(y_i,Q)-\tilde{\Phi}(x_i,Q)$ since the deuteron is a color singlet.

Hidden Color of Deuteron

Deuteron six-quark state has five color - singlet configurations, only one of which is n-p.

Asymptotic Solution has Expansion

$$\psi_{[6]\{33\}} = \left(\frac{1}{9}\right)^{1/2} \psi_{NN} + \left(\frac{4}{45}\right)^{1/2} \psi_{\Delta\Delta} + \left(\frac{4}{5}\right)^{1/2} \psi_{CC}$$

Look for strong transition to Delta-Delta

Fit of dσ/dt data for the central angles and $P_T \geq 1.1$ GeV/c with

$A\ s^{-11}$

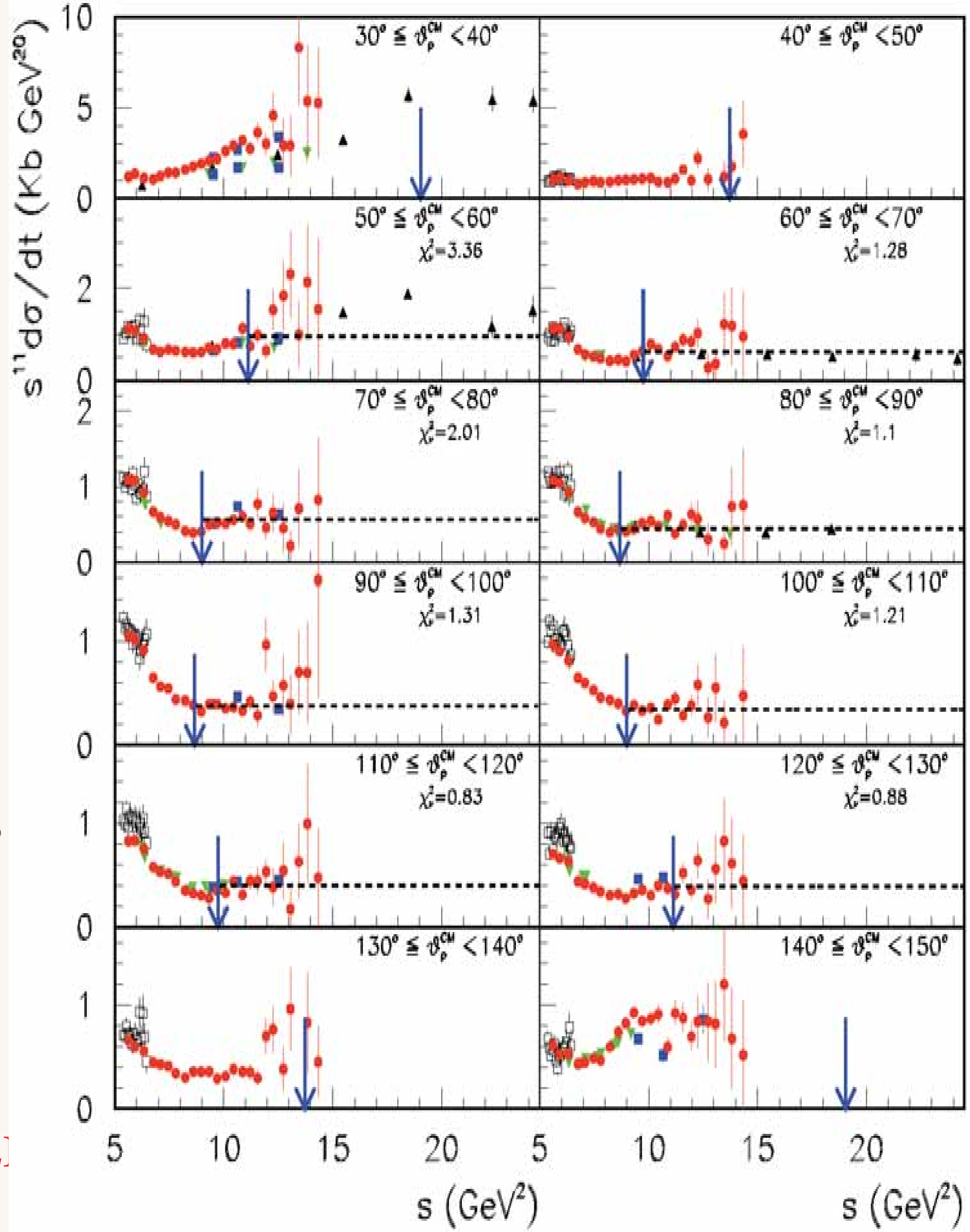
For all but two of the fits

$\chi^2 \leq 1.34$

- Better χ^2 at 55° and 75° if different data sets are renormalized to each other
- No data at $P_T \geq 1.1$ GeV/c at forward and backward angles
- Clear s^{-11} behaviour for last 3 points at 35°

Data consistent with CCR

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



Quantum Chromodynamic Predictions for the Deuteron Form Factor

$$F_d(Q^2) = \int_0^1 [dx][dy]\varphi_d^\dagger(y,Q) \times T_H^{6q+\gamma^*\to 6q}(x,y,Q)\varphi_d(x,Q), \quad (1)$$

where the hard-scattering amplitude

$$T_H^{6q+\gamma^*\to 6q} = [\alpha_s(Q^2)/Q^2]^5 t(x,y) \times [1+O(\alpha_s(Q^2))] \quad (2)$$

gives the probability amplitude for scattering six quarks collinear with the initial to the final deuteron momentum and

$$\varphi_d(x_i,Q) \propto \int^{k_{\perp i}<Q}[d^2k_\perp]\psi_{qqq\,qqq}(x_i,\vec{k}_{\perp i}) \quad (3)$$

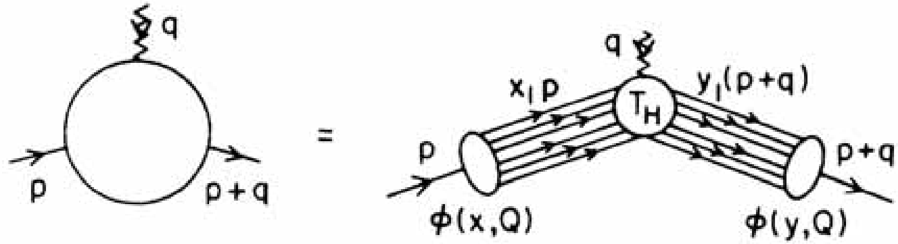


FIG. 1. The general structure of the deuteron form factor at large Q^2.

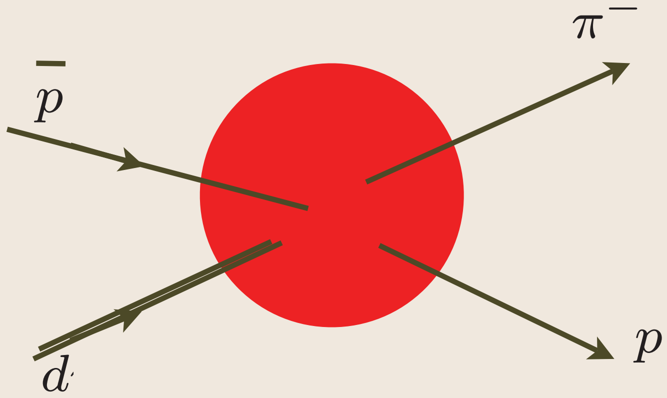
Ji, Lepage, sjb

Key QCD Experiment at GSI

Test QCD scaling in hard exclusive nuclear amplitudes

Manifestations of Hidden Color in Deuteron Wavefunction

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



$$\bar{p}d \to \bar{p}d$$

Conformal Scaling, AdS/CFT

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

Key QCD Experiment at GSI

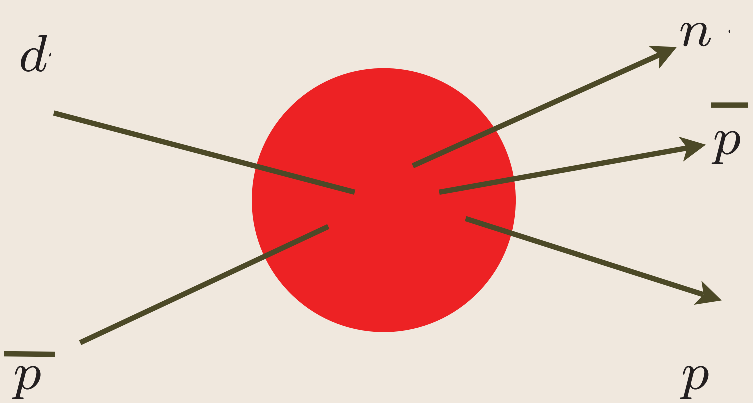
Manifestations of Hidden Color in Deuteron Wavefunction

Compare at high t.

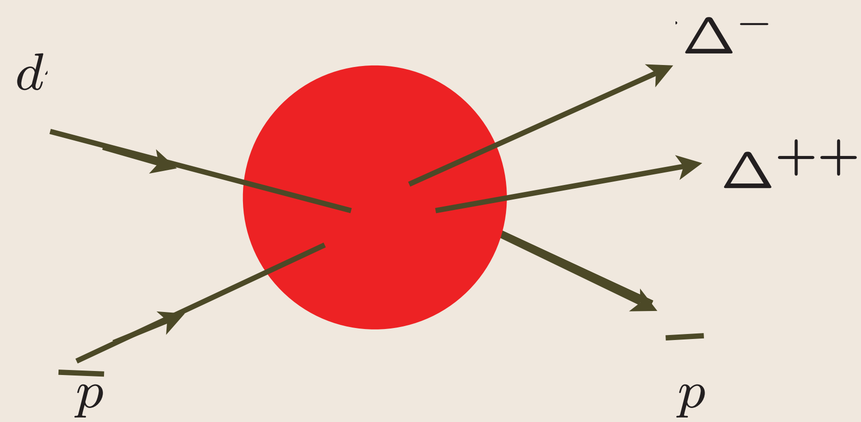
$$d\bar{p} \to \Delta^{++}\Delta^{-} + \bar{p}$$

$$d\bar{p} \to p\ n + \bar{p}$$

Ratio predicted to approach 2:5



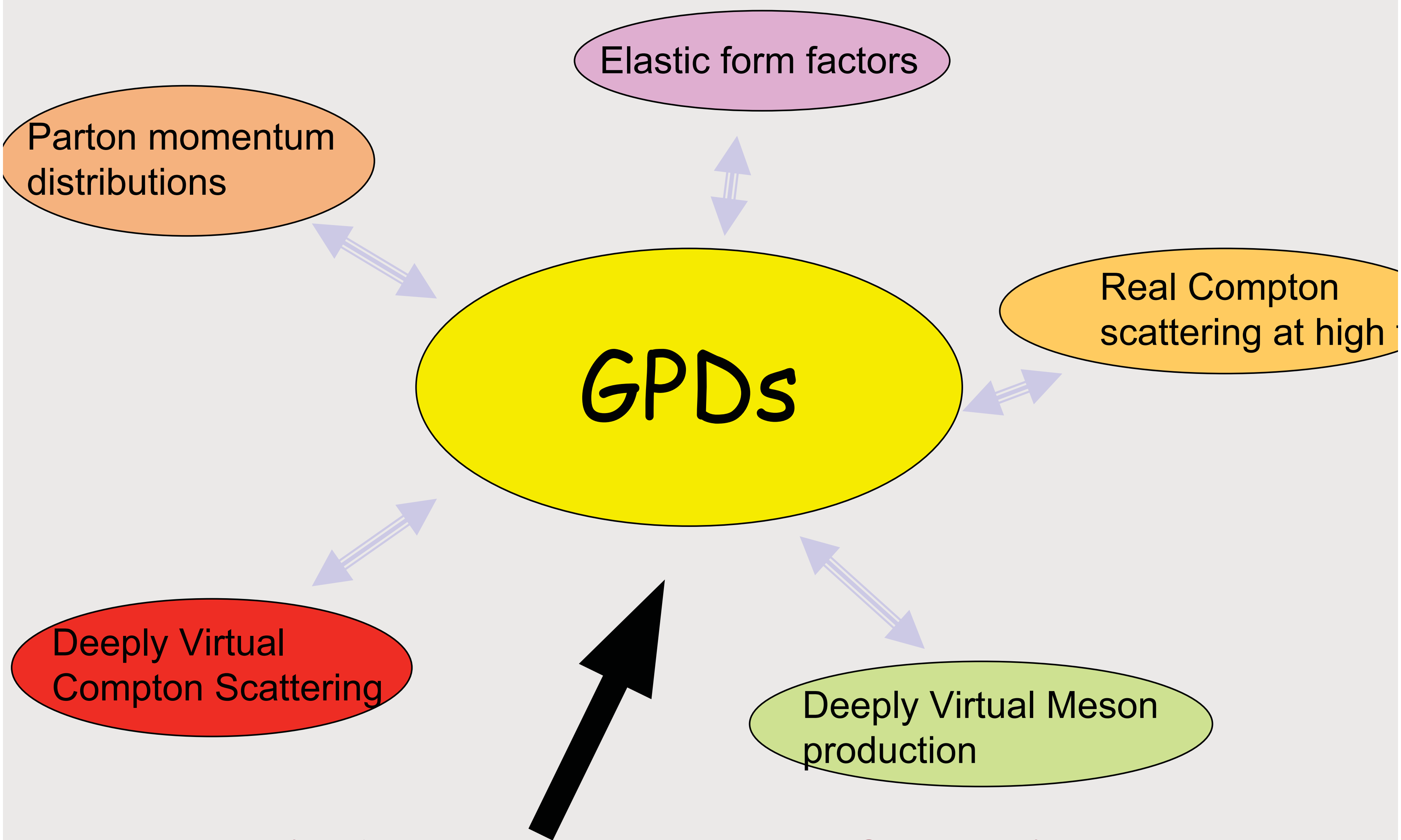
vs.



QCD at The Amplitude Level

- Light-Front Fock Expansions
- LFWFs boost invariant
- Direct connection to form factors, structure functions, distribution amplitudes, GPDs
- Higher Twist Correlations
- Orbital Angular Momentum
- Validated in QED, Bethe-Salpeter
- AdS/CFT Holographic Model

A Unified Description of Hadron Structure



Light Front Wavefunctions

LFWFS give a fundamental description of hadron observables

- LFWFS underly form factors, structure functions generalized parton distributions, scattering amplitudes
- Parton number not conserved: n=n’ & n=n’+2 at nonzero skewness
- GPDs are not densities or probability distributions
- Nonperturbative QCD: Lattice, DLCQ, Bethe-Salpeter, AdS/CFT

$$|p, S_z> = \sum_{n=3} \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) | n; \vec{k}_{\perp_i}, \lambda_i >$$

The Light Front Fock State Wavefunctions

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

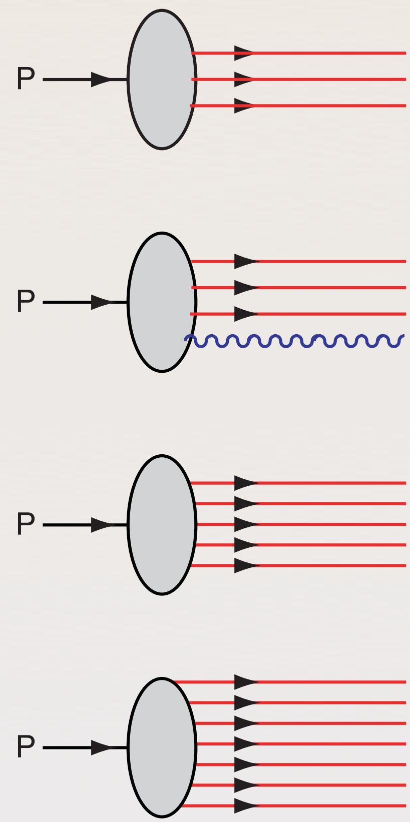
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

The light-cone momentum fraction

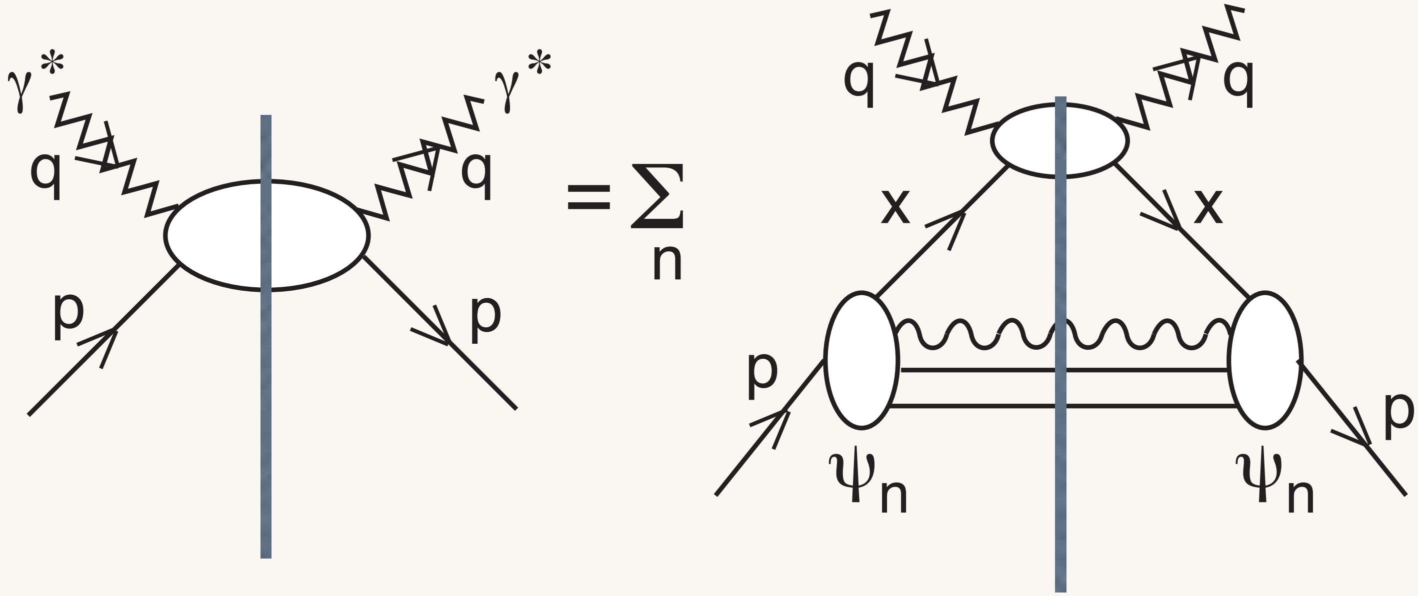
$$x_i = \frac{k_i^+}{p^+} = \frac{k_i^0 + k_i^z}{P^0 + P^z}$$

are boost invariant.

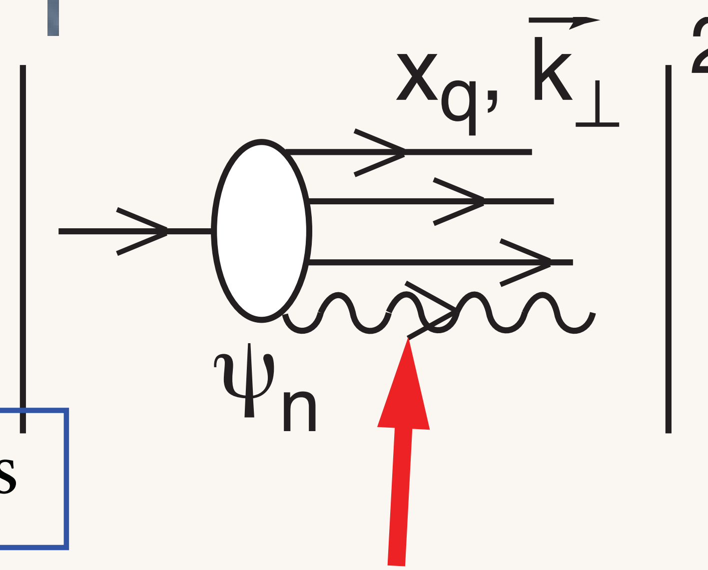
$$\sum_i^n k_i^+ = P^+, \ \sum_i^n x_i = 1, \ \sum_i^n \vec{k}_i^\perp = \vec{0}^\perp.$$



Deep Inelastic Lepton Proton Scattering



Imaginary Part of
Forward Virtual Compton Amplitude



$q(x,Q^2) = \sum_n \int^{k_\perp^2 \le Q^2 \perp} d^2k_\perp \, |\Psi_n(x,k_\perp)|^2$

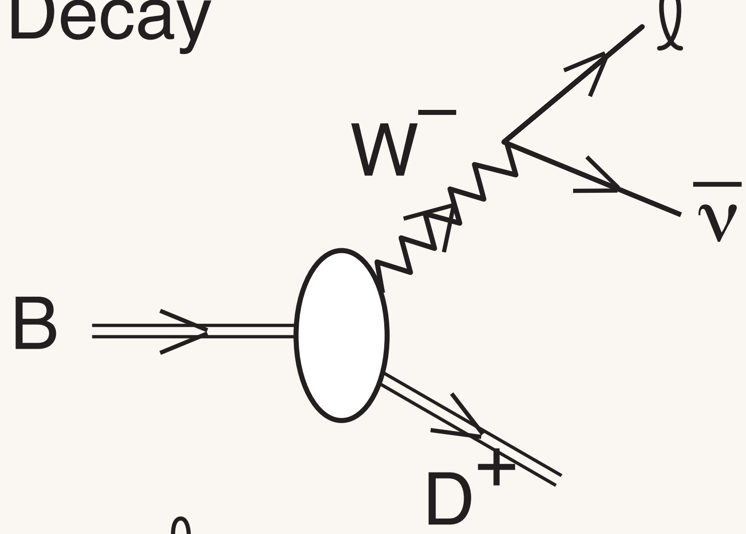
$x = x_q$

All spin, flavor distributions

Light-Front Wave Functions $\psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$

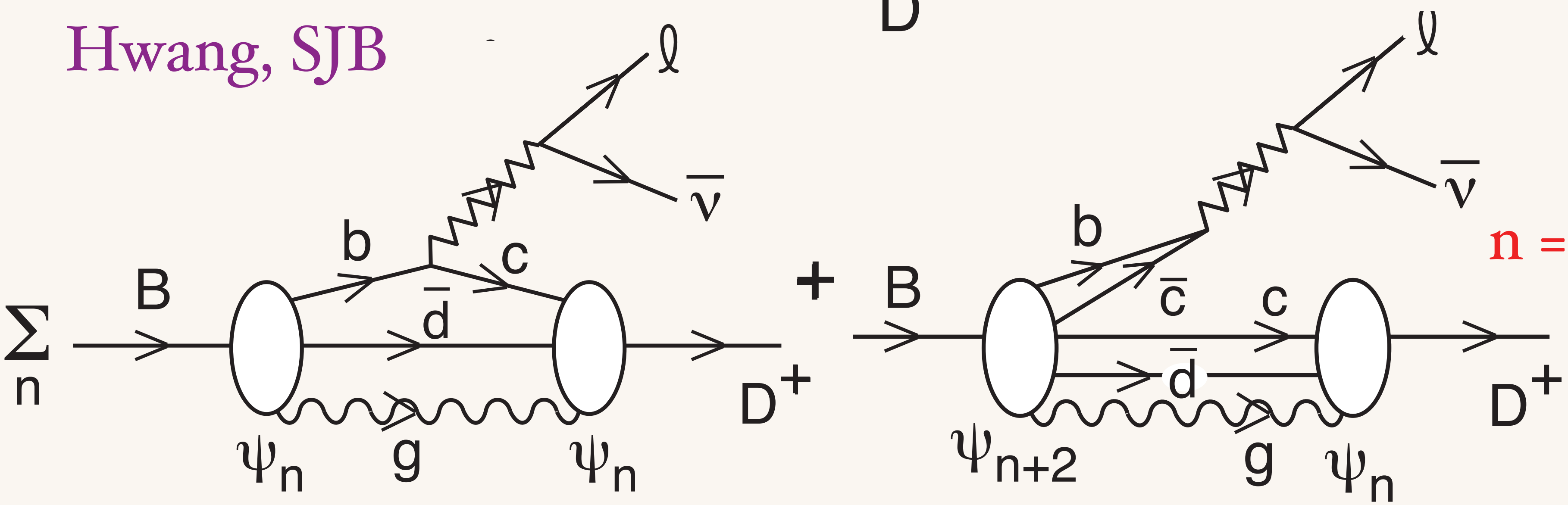
Weak Exclusive Decay

$\langle D | J^+(0) | B \rangle$



Exact Formula

Hwang, SJB



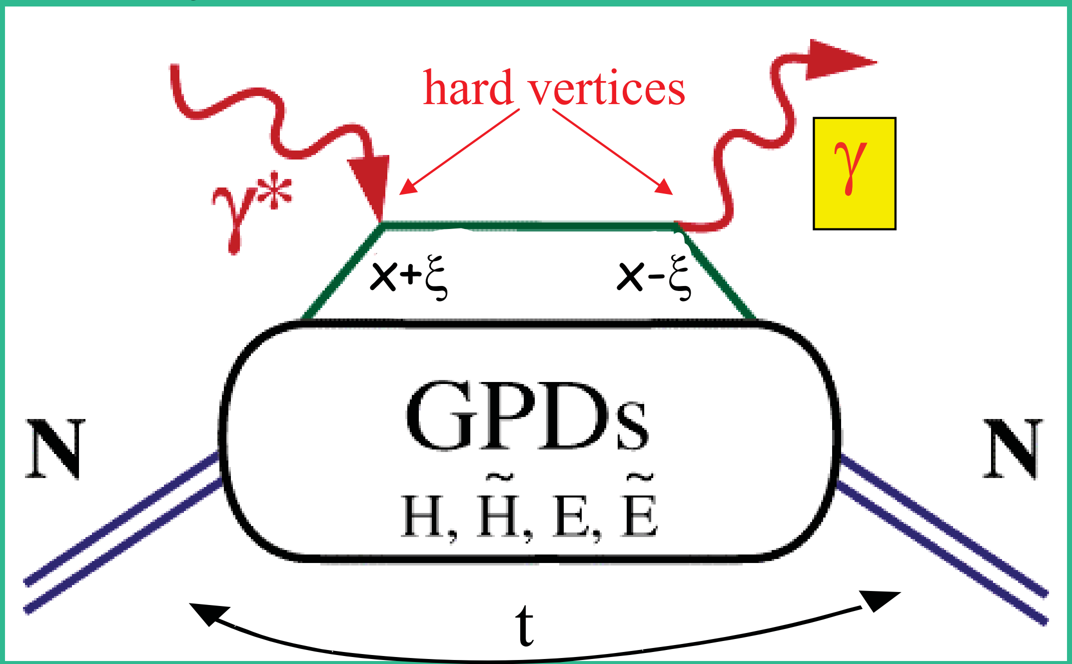
n = n' + 2

Annihilation amplitude needed for Lorentz Invariance

GPDs & Deeply Virtual Exclusive Processes

"handbag" mechanism

Deeply Virtual Compton Scattering (DVCS)



x – longitudinal quark momentum fraction

2ξ – longitudinal momentum transfer

$\sqrt{-t}$ – Fourier conjugate to transverse impact parameter

$H(x,\xi,t), E(x,\xi,t), \ldots$

$$\xi = \frac{x_B}{2 - x_B}$$

Deeply Virtual Compton Scattering

$$\gamma^* p \to \gamma p', \gamma^* p \to \pi^+ n',$$

- Remarkable sensitivity to spin, flavor, dynamics
- Measure Real and Imaginary parts from Bethe-Heitler interference; phase determined by Regge theory (Kuti-Weiskopf)

Close, Gunion, sjb

- J=0 fixed pole: test QCD contact interaction!
- Sum Rules connecting to form factors, Lz
- Evolution Equations (ERBL), PQCD constraints
- Convolutions of Light-front wavefunctions

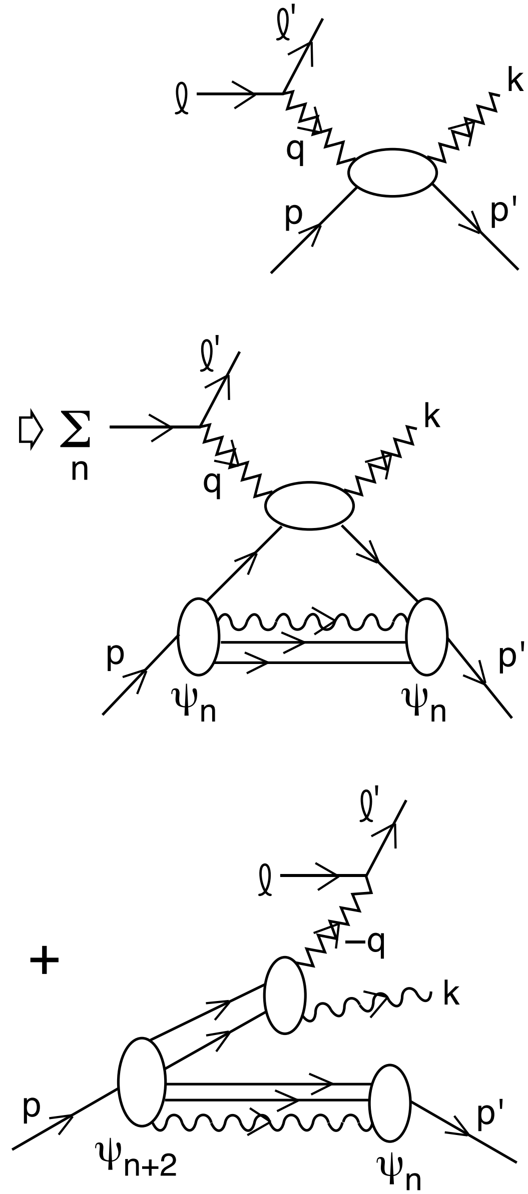
$$\langle p' \lambda' | J^{\mu}(z) J^{\nu}(0) | p \lambda \rangle$$

$$\text{Large} - q^2 = Q^2$$

$$\gamma^* p \to \gamma p'$$

Given LFWFs, compute all GPDs !

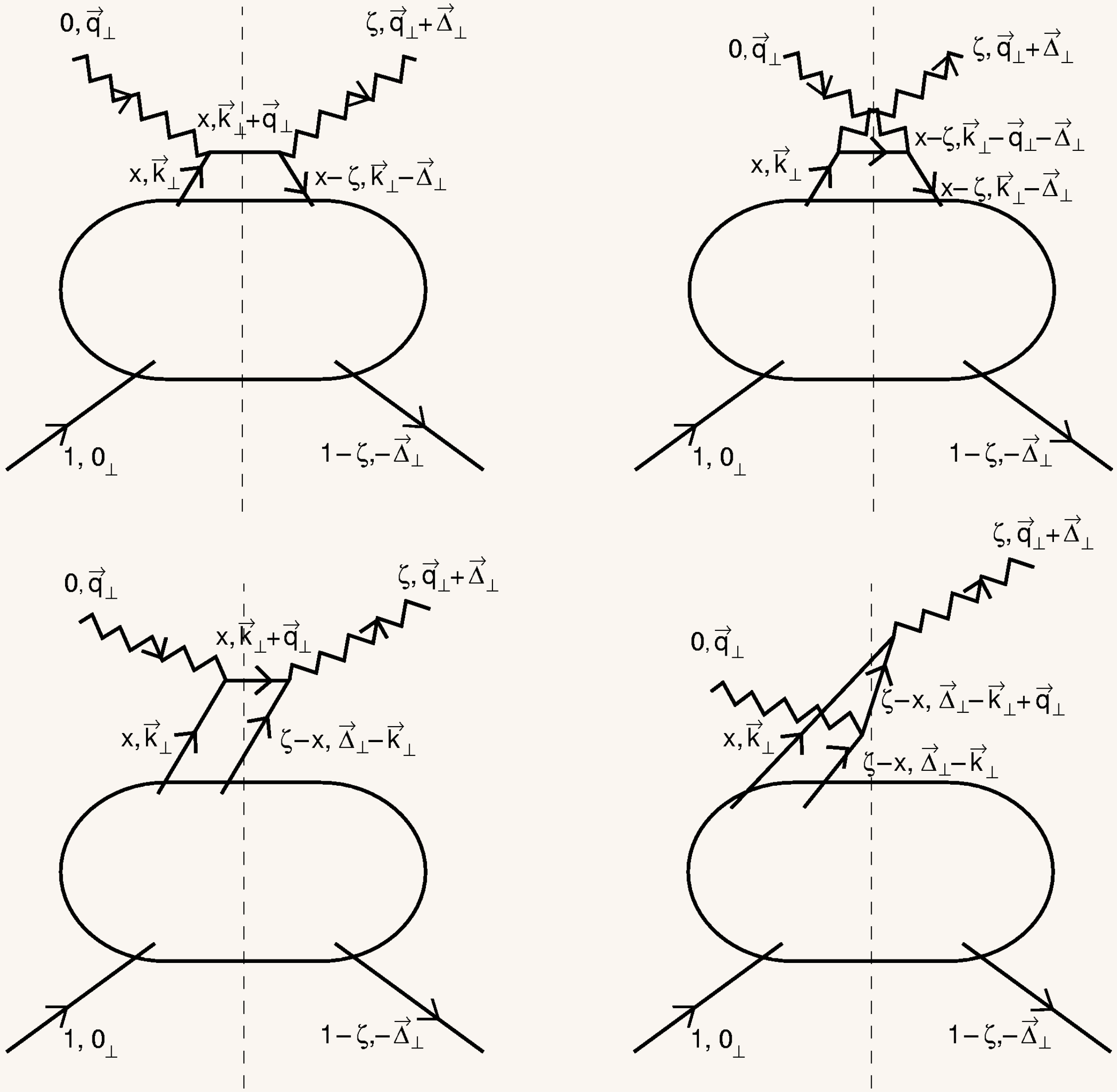
ERBL Evolution



Deeply Virtual Compton Scattering

n = n' + 2

Required for Lorentz Invariance



Light-cone wavefunction representation of deeply virtual Compton scattering ☆

Stanley J. Brodsky [a], Markus Diehl [a,1], Dae Sung Hwang [b]

Example of LFWF representation of GPDs (n => n)

Diehl,Hwang, sjb

$$\frac{1}{\sqrt{1-\zeta}}\frac{\Delta^1 - i\Delta^2}{2M} E_{(n\to n)}(x,\zeta,t)$$

$$= \left(\sqrt{1-\zeta}\right)^{2-n} \sum_{n,\lambda_i} \int \prod_{i=1}^{n} \frac{\mathrm{d}x_i\, \mathrm{d}^2\vec{k}_{\perp i}}{16\pi^3}\, 16\pi^3 \delta\left(1 - \sum_{j=1}^{n} x_j\right) \delta^{(2)}\left(\sum_{j=1}^{n} \vec{k}_{\perp j}\right)$$

$$\times\, \delta(x - x_1)\, \psi^{\uparrow *}_{(n)}(x'_i, \vec{k}'_{\perp i}, \lambda_i)\, \psi^{\downarrow}_{(n)}(x_i, \vec{k}_{\perp i}, \lambda_i),$$

where the arguments of the final-state wavefunction are given by

$$x'_1 = \frac{x_1 - \zeta}{1-\zeta}, \qquad \vec{k}'_{\perp 1} = \vec{k}_{\perp 1} - \frac{1-x_1}{1-\zeta}\vec{\Delta}_\perp \quad \text{for the struck quark,}$$

$$x'_i = \frac{x_i}{1-\zeta}, \qquad \vec{k}'_{\perp i} = \vec{k}_{\perp i} + \frac{x_i}{1-\zeta}\vec{\Delta}_\perp \quad \text{for the spectators } i = 2, \ldots, n.$$

Example of LFWF representation of GPDs (n+1 => n-1)

Diehl,Hwang, sjb

Diehl, Kroll

$$\frac{1}{\sqrt{1-\zeta}}\frac{\Delta^1 - i\Delta^2}{2M} E_{(n+1\to n-1)}(x,\zeta,t)$$

$$= \left(\sqrt{1-\zeta}\right)^{3-n} \sum_{n,\lambda_i} \int \prod_{i=1}^{n+1} \frac{\mathrm{d}x_i\, \mathrm{d}^2\vec{k}_{\perp i}}{16\pi^3}\, 16\pi^3 \delta\left(1-\sum_{j=1}^{n+1} x_j\right) \delta^{(2)}\left(\sum_{j=1}^{n+1} \vec{k}_{\perp j}\right)$$

$$\times\, 16\pi^3 \delta(x_{n+1}+x_1-\zeta)\delta^{(2)}(\vec{k}_{\perp n+1}+\vec{k}_{\perp 1}-\vec{\Delta}_\perp)$$

$$\times\, \delta(x-x_1)\psi^{\uparrow *}_{(n-1)}(x'_i,\vec{k}'_{\perp i},\lambda_i)\,\psi^{\downarrow}_{(n+1)}(x_i,\vec{k}_{\perp i},\lambda_i)\,\delta_{\lambda_1 -\lambda_{n+1}},$$

where $i = 2, \ldots, n$ label the $n-1$ spectator partons which appear in the final-state hadron wavefunction with

$$x'_i = \frac{x_i}{1-\zeta}, \qquad \vec{k}'_{\perp i} = \vec{k}_{\perp i} + \frac{x_i}{1-\zeta}\vec{\Delta}_\perp .$$

Link to DIS and Elastic Form Factors

DIS at $\xi = t = 0$

$$H^q(x,0,0) = q(x), \quad -\bar{q}(-x)$$

$$\widetilde{H}^q(x,0,0) = \Delta q(x), \quad \Delta\bar{q}(-x)$$

Form factors (sum rules)

$$\int_{-1}^{1} dx \sum_q \left[H^q(x,\xi,t)\right] = F_1(t) \quad \text{Dirac f.f.}$$

$$\int_{-1}^{1} dx \sum_q \left[E^q(x,\xi,t)\right] = F_2(t) \quad \text{Pauli f.f.}$$

$$\int_{-1}^{1} dx\, \widetilde{H}^q(x,\xi,t) = G_{A,q}(t), \quad \int_{-1}^{1} dx\, \widetilde{E}^q(x,\xi,t) = G_{P,q}(t)$$

$$H^q, E^q, \widetilde{H}^q, \widetilde{E}^q(x,\xi,t)$$

Verified using LFWFs

Diehl, Hwang, sjb

Quark angular momentum (Ji's sum rule)

$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^{1} x\,dx \left[H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$

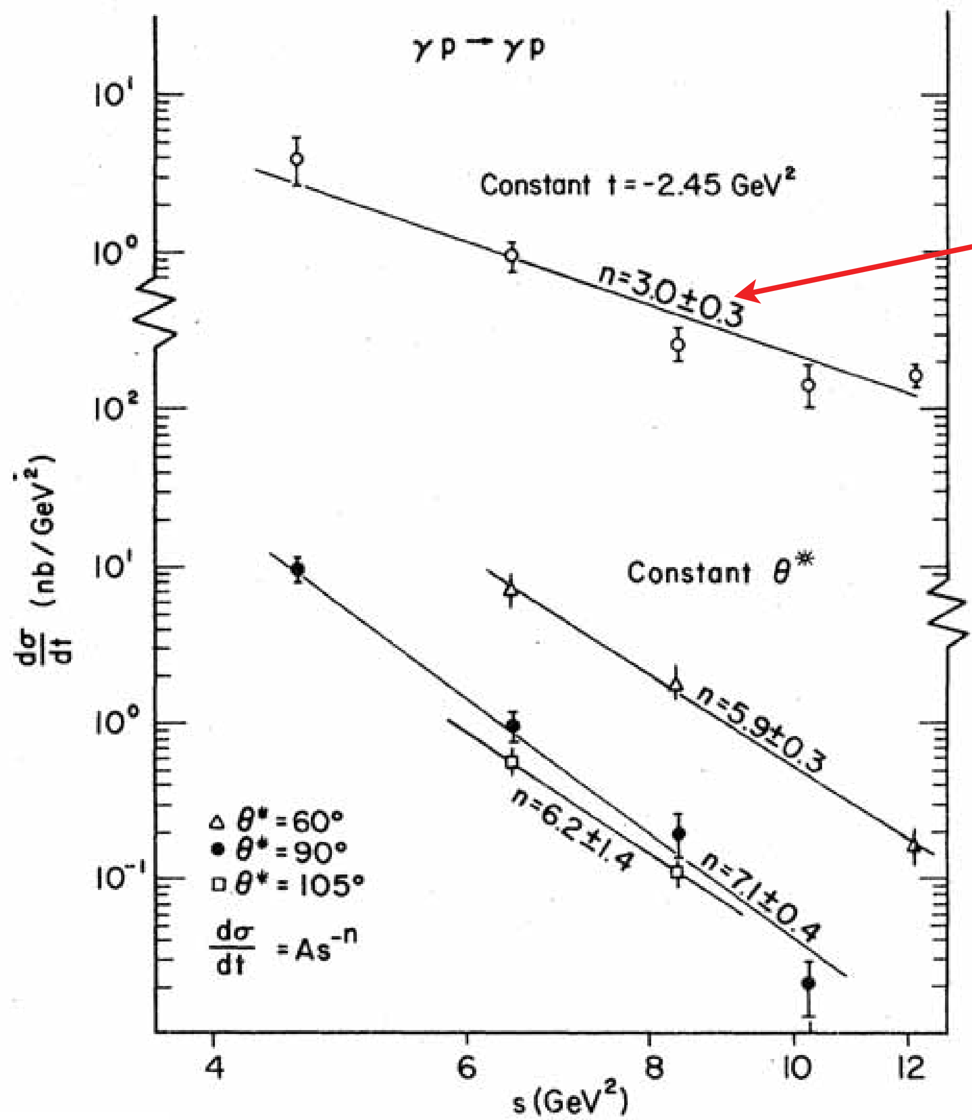
X. Ji, Phy.Rev.Lett.78,610(1997)

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: $s^2 \, d\sigma/dt(\gamma p \to \gamma p) \simeq F^2_0(t)$



Compton-scattering cross sections at constant t and at constant θ^*. The straight lines are fits to the data. The fits shown here have no energy cuts.

J=0 fixed pole:
Predict n=2

Cornell

Key QCD Experiment at GSI

- Test DVCS in Timelike Regime $\bar{p}p \longrightarrow \gamma^*\gamma$
- J=0 Fixed pole q² independent
- Analytic Continuation of GPDs
- Light-Front Wavefunctions
- charge asymmetry from interference

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

AdS/QCD

- Only one scale Λ_{QCD} determines hadronic spectrum (slightly different for mesons and baryons).
- Ratio of Nucleon to Delta trajectories determined by zeroes of Bessel functions.
- String modes dual to baryons extrapolate to three fermion fields at zero separation in the AdS boundary.
- Only dimension $3, \frac{9}{2}$ and 4 states $\overline{q}q$, qqq, and gg appear in the duality at the classical level!
- Non-zero orbital angular momentum and higher Fock-states require introduction of quantum fluctuations.
- Simple description of space and time-like structure of hadronic form factors.
- Dominance of quark-interchange in hard exclusive processes emerges naturally from the classical duality of the holographic model. Modified by gluonic quantum fluctuations.
- Covariant version of the bag model with confinement and conformal symmetry.

Essential to test QCD

- J-PARC
- GSI antiprotons
- 12 GeV Jlab
- BaBar/Belle: ISR, two-gamma, timelike DVCS
- RHIC/LHC Nuclear Collisions; LHCb
- electron-proton, electron-nucleus collisions

Novel Tests of QCD at GSI

Polarized antiproton Beam   Secondary Beams

- 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}