New Insights for QCD from AdS/CFT and Novel Tests of QCD at GSI

Stan Brodsky, SLAC

Trento GSI-FAIR Workshop

Quantum Chromodynamics (QCD)

- Quantum Chromodynamics is the fundamental theory of hadron and nuclear physics, as fundamental as Quantum Electrodynamics is to atomic physics and chemistry!

- In fact: limit QCD(N_C --> **0**) = Quantum Electrodynamics (QED)

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

- Novel QCD Phenomena: "hidden color", "color transparency", "quark-gluon plasma", "intrinsic charm" anomalous heavy quark phenomena, diffraction, spin effects

- Remarkable new insights from AdS/CFT, the duality between conformal field theory and Anti-de Sitter Space

Hadron Dynamics at the Amplitude Level

- DIS studies have primarily focussed on probability distributions: integrated and unintegrated.
- Test QCD at the amplitude level: Phases, multi-parton correlations, spin, angular momentum, exclusive amplitudes
- Impact of ISI and FSI: Single Spin Asymmetries, Diffractive Deep Inelastic Scattering, Shadowing, Antishadowing
- Hadron wavefunctions: Fundamental QCD Dynamics
- Remarkable new insights from AdS/CFT, the duality between conformal field theory and Anti-de Sitter Space

Novel Tests of QCD at GSI

Polarized 15 GeV stored anti-proton beam

- Characteristic momentum scale of QCD: 300 MeV
- Many Tests of AdS/CFT predictions possible
- Exclusive channels: Conformal scaling laws, quark-interchange
- proton-antiproton scattering: test 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}

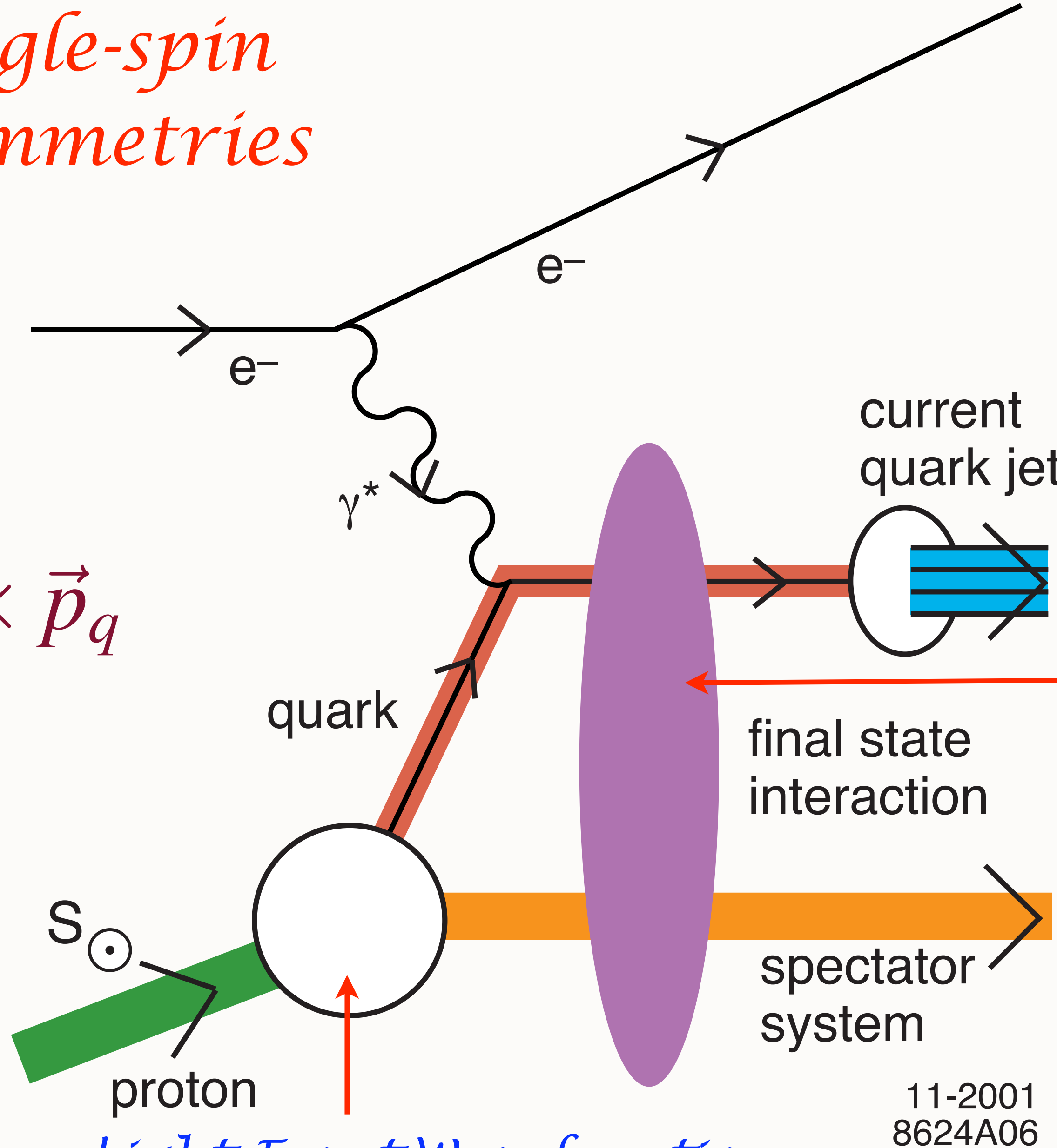
Testing quantum chromodynamics with antiprotons.
Stanley J. Brodsky (SLAC) . SLAC-PUB-10811, Oct 2004. 92pp.
Published in *Varenna 2004, Hadron physics* 345-422
e-Print Archive: **hep-ph/0411046**

Novel QCD Phenomenology, Part 1, Part 2, Part 3, Part 4, Part 5, Part 6, Part 7, Part 8,
International School of Physics Enrico Fermi, Varenna, Italy, 6/2004

Single-spin asymmetries

Sivers Effect

$$\vec{S}_p \cdot \vec{q} \times \vec{p}_q$$



QCD S- and P-
Coulomb Phases

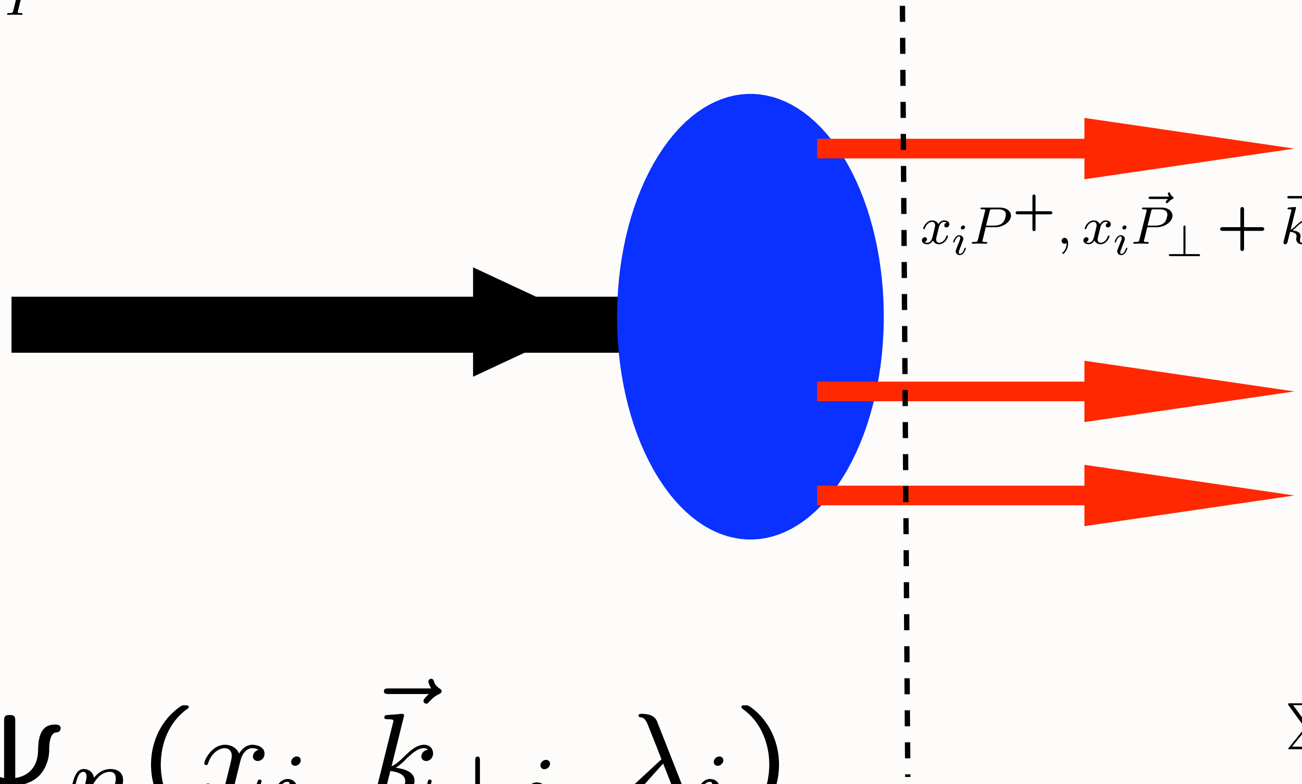
Light-Front Wavefunction
S and P- Waves

Hwang, Schmidt.
sjb

Light-Front Wavefunctions

Fixed $\tau = t + z/c$

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



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

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

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

$\sum_i^n x_i = 1$

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

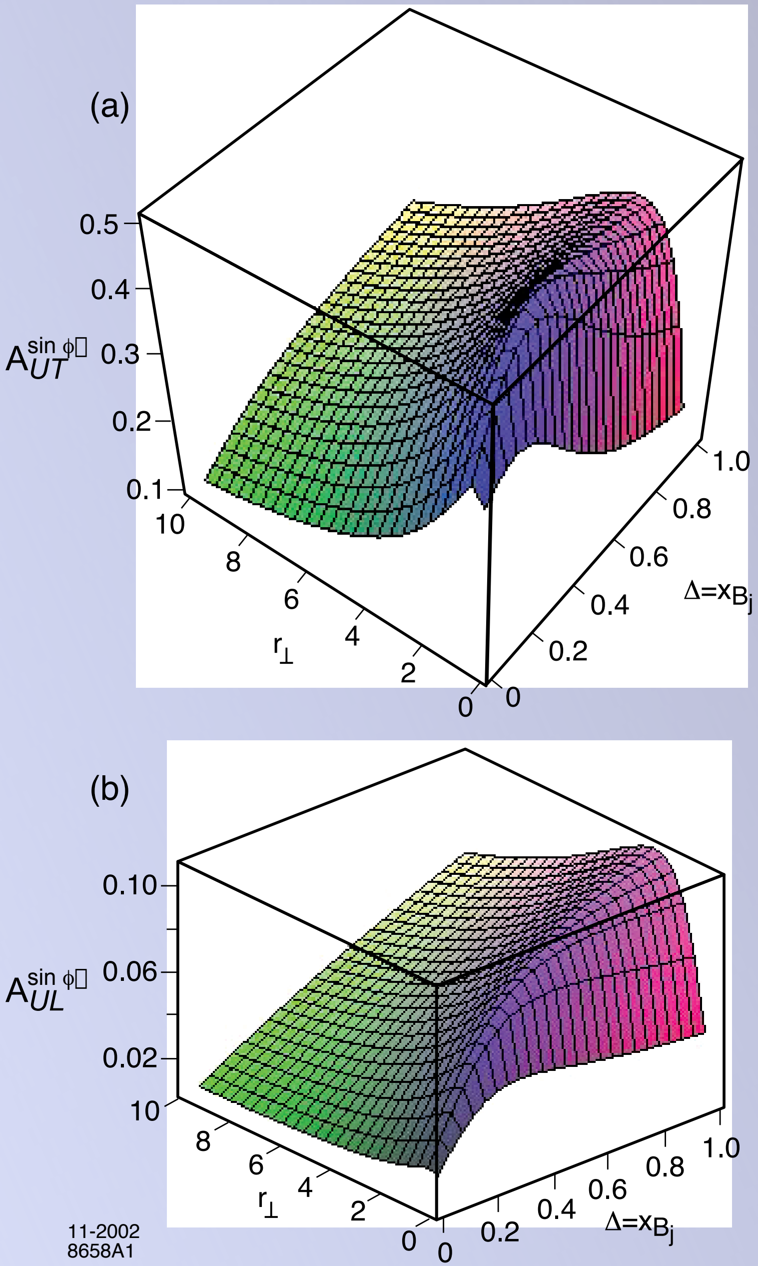
Invariant under boosts! Independent of P^μ

Final-State Interactions Produce T-Odd (Sivers Effect) $\mathbf{i}\ \vec{S} \cdot \vec{p}_{jet} \times \vec{q}$

- Bjorken Scaling!
- Arises from Interference of Final-State Coulomb Phases in S and P waves
- Relate to the quark contribution to the target proton anomalous magnetic moment
- Sum of Sivers Functions for all quarks and gluons vanishes. (Zero gravito-anomalous magnetic moment: B(0)= 0)

Hwang, Schmidt. sjb; Burkardt

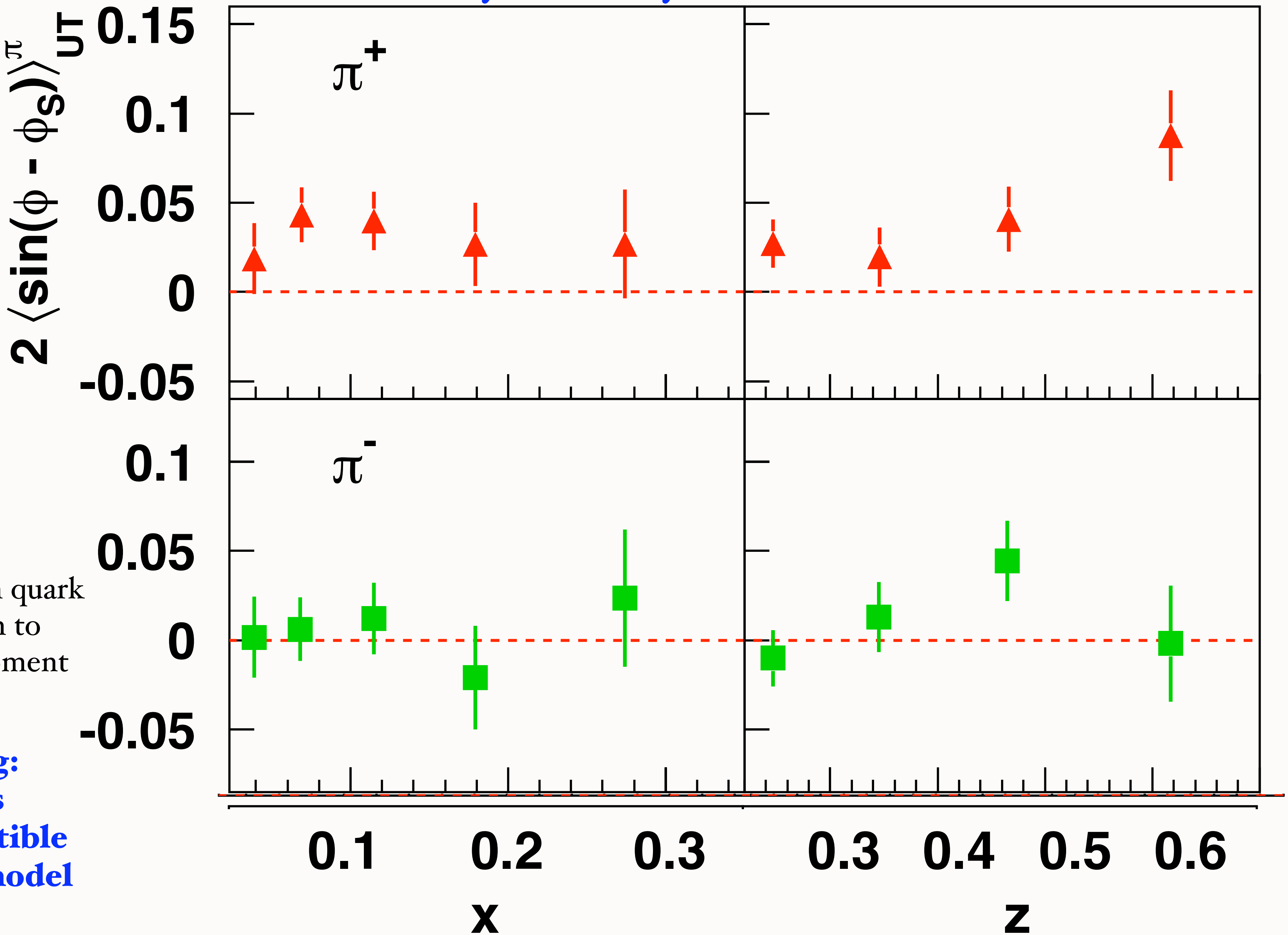
Prediction for Single-Spin Asymmetry



Hwang, Schmidt.
sjb

HERMES coll., A. Airapetian et al., Phys. Rev. Lett. 94 (2005) 012002.

Sivers asymmetry from HERMES

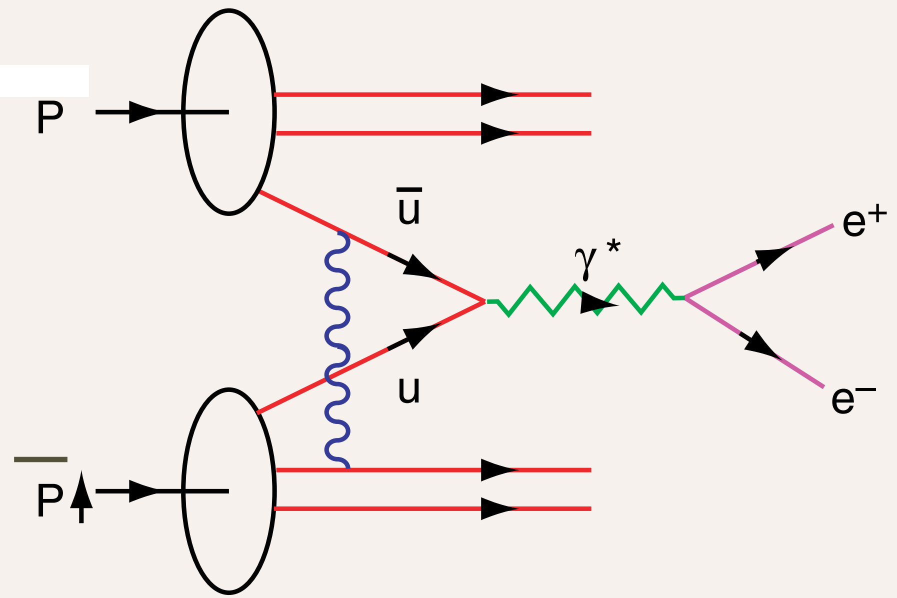


SSA tracks with quark contribution to anomalous moment

Gamberg: Hermes data compatible with BHS model

Key QCD Experiment at GSI

Measure single-spin asymmetry A_N
in Drell-Yan reactions



Leading-twist Bjorken-scaling A_N
from S, P-wave
initial-state gluonic interactions

Predict: $A_N(DY) = -A_N(DIS)$
Opposite in sign!

$$\bar{p} p_\uparrow \to \ell^+ \ell^- X$$

$$Q^2 = x_1 x_2 s$$

$$Q^2 = 4 \text{ GeV}^2, s = 80 \text{ GeV}^2$$

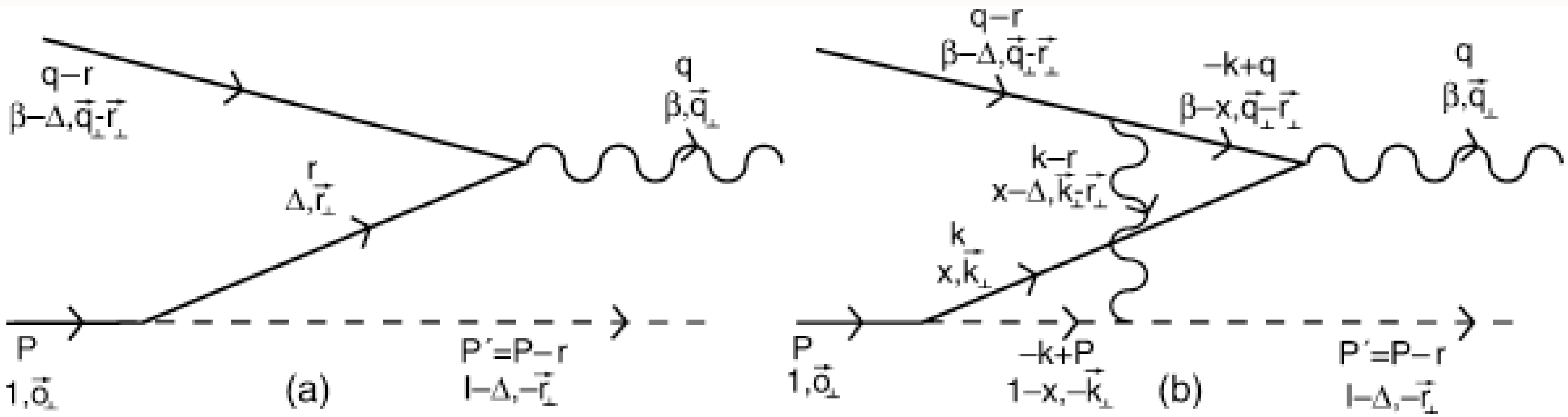
$\vec{S} \cdot \vec{q} \times \vec{p}$ correlation

$$x_1 x_2 = .05, x_F = x_1 - x_2$$

Initial-state interactions and single-spin asymmetries in Drell–Yan processes ☆

Stanley J. Brodsky[a], Dae Sung Hwang[a,b], Ivan Schmidt[c]

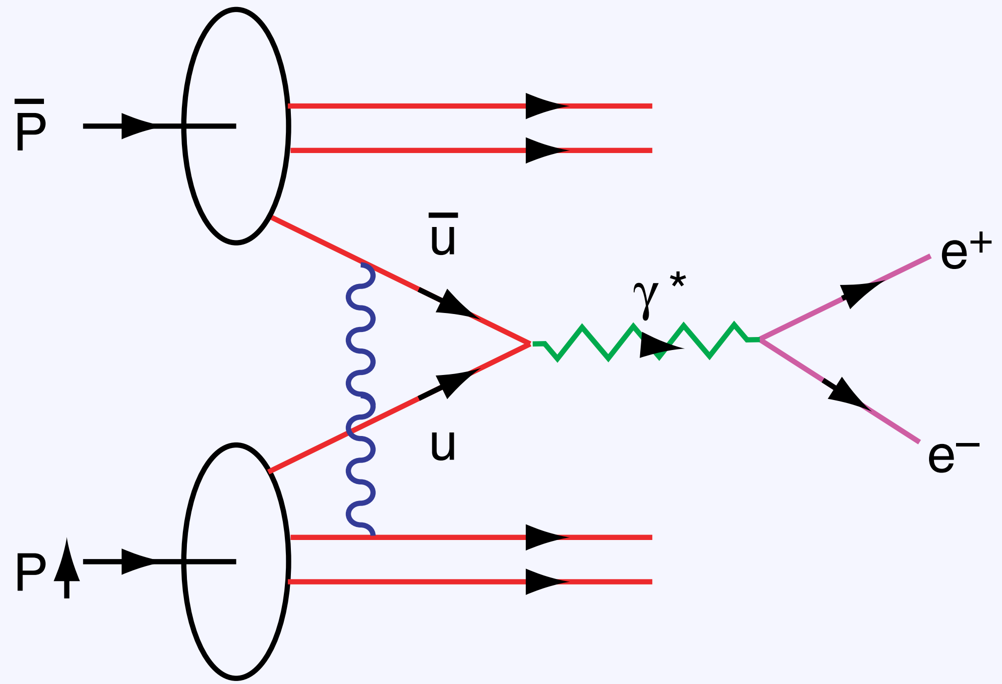
Nuclear Physics B 642 (2002) 344–356



$$\mathcal{P}_y = -\frac{e_1 e_2}{8\pi}\frac{2(\Delta M + m)r^1}{[(\Delta M + m)^2 + \vec{r}_\perp^{\,2}]}\left[\vec{r}_\perp^{\,2} + \Delta(1-\Delta)\left(-M^2 + \frac{m^2}{\Delta} + \frac{\lambda^2}{1-\Delta}\right)\right] \times \frac{1}{\vec{r}_\perp^{\,2}}\ln\frac{\vec{r}_\perp^{\,2} + \Delta(1-\Delta)(-M^2 + \frac{m^2}{\Delta} + \frac{\lambda^2}{1-\Delta})}{\Delta(1-\Delta)(-M^2 + \frac{m^2}{\Delta} + \frac{\lambda^2}{1-\Delta})}.$$

Here $\Delta = \frac{q^2}{2P\cdot q} = \frac{q^2}{2M\nu}$ where ν is the energy of the lepton pair in the target rest frame.

Key QCD Experiment at GSI



Single Spin Asymmetry In the Drell Yan Process

$\vec{S}_p \cdot \vec{\vec{p}} \times \vec{q}_{\gamma^*}$

Quarks Interact in the Initial State

Interference of Coulomb Phases for *S* and *P* states

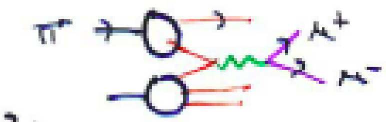
Produce Single Spin Asymmetry [Siver's Effect]Proportional to the Proton Anomalous Moment and α_s.

Opposite Sign to DIS! No Factorization

Collins;
Hwang, Schmidt.
sjb

Drell-Yan Process and Higher Twist

$$\pi^- N \Rightarrow \gamma^* X \Rightarrow \mu^+\mu^- X$$



$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+} = 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi$$

$$\lambda, \mu, \nu = f(x_L, Q^2, Q_\perp^2, s)$$

Leading twist PQCD predicts

$$\lambda \cong 1 \qquad + O(\alpha_s)$$
$$\mu, \nu \cong 0 \qquad + O(\alpha_s)$$

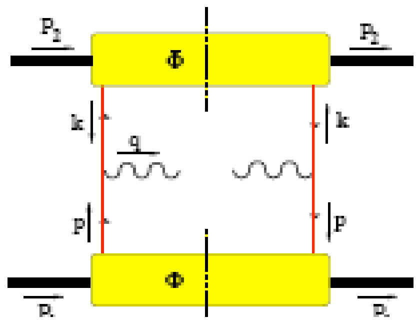
Data: $\lambda \rightarrow$ negative at $x_L \rightarrow 1$?

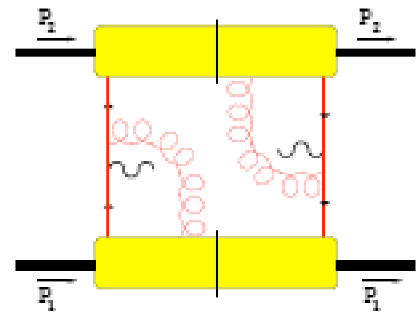
Large μ, ν contributions !

(NA3, CP)

Key QCD Experiment at GSI

$\cos 2\phi$ correlation in DY from double ISI



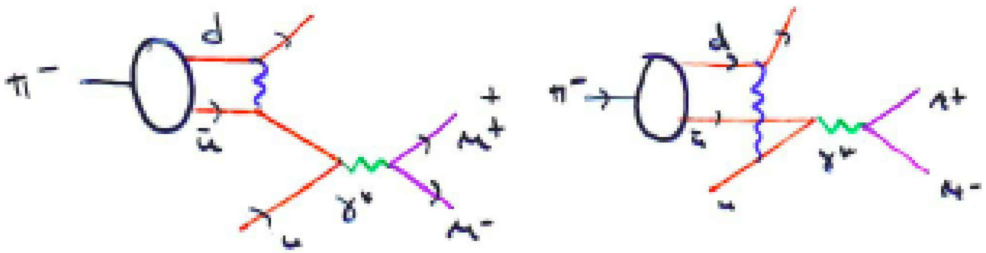


Boer, Hwang, sjb

Abstract

We show that initial-state interactions contribute to the $\cos 2\phi$ distribution in unpolarized Drell-Yan lepton pair production pp and $p\overline{p} \to \ell^+\ell^- X$, without suppression. The asymmetry is expressed as a product of chiral-odd distributions $h_1^\perp(x_1, \boldsymbol{p}_\perp^2) \times \overline{h}_1^\perp(x_2, \boldsymbol{k}_\perp^2)$, where the quark-transversity function $h_1^\perp(x, \boldsymbol{p}_\perp^2)$ is the transverse momentum dependent, light-cone momentum distribution of transversely polarized quarks in an *unpolarized* proton. We compute this (naive) T-odd and chiral-odd distribution function and the resulting $\cos 2\phi$ asymmetry explicitly in a quark-scalar diquark model for the proton with initial-state gluon interaction. In this model the function $h_1^\perp(x, \boldsymbol{p}_\perp^2)$ equals the T-odd (chiral-even) Sivers effect function $f_{1T}^\perp(x, \boldsymbol{p}_\perp^2)$. This suggests that the single-spin asymmetries in the SIDIS and the Drell-Yan process are closely related to the $\cos 2\phi$ asymmetry of the unpolarized Drell-Yan process, since all can arise from the same underlying mechanism. This provides new insight regarding the role of quark and gluon orbital angular momentum as well as that of initial- and final-state gluon exchange interactions in hard QCD processes.

Higher Twist seen in Data NA10, CP



$\pi^- u \to d\, \gamma^*$ subprocess

Depends on pion distribution amplitude

$\phi_\pi(x, Q)$

Calculations by

Berger, SJB, Lepage $\lambda(x_F)$

Brandenburg, Khoze, Müller, SJB

Data consistent with $\phi_{CZ}(x, Q)$

rather than $\phi_{asymptotic}$

Drell-Yan $\pi N \to \ell^+ \ell^- X$

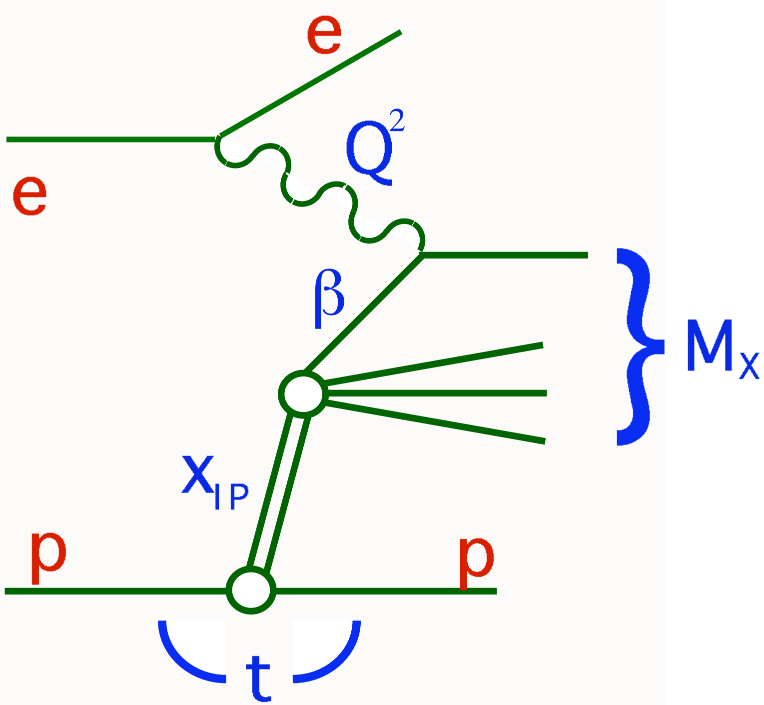
$$\frac{d\sigma}{dx\, d\cos\theta} = A(1-x)^2(1+\cos^2\theta) + B\frac{\sin^2\theta}{Q^2}$$

Higher Twist and Leading Twist comparable at

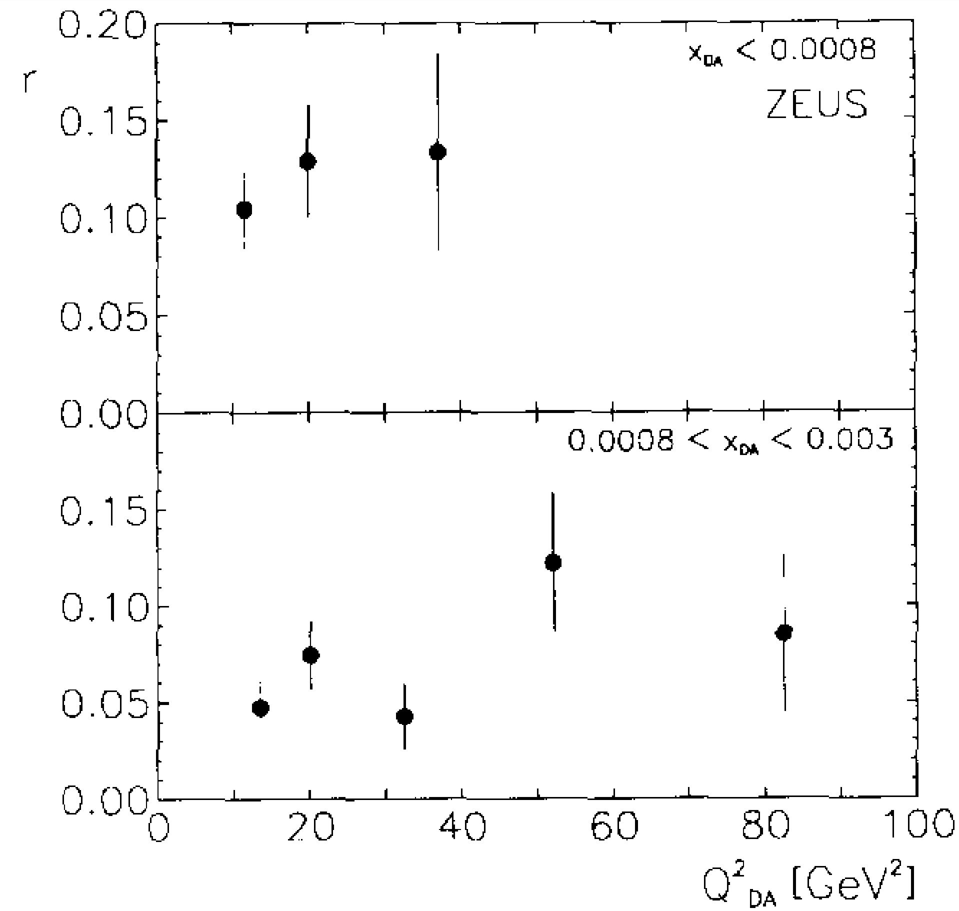
$\mu^2 = (1-x)\,Q^2$

fixed

Remarkable observation at HERA



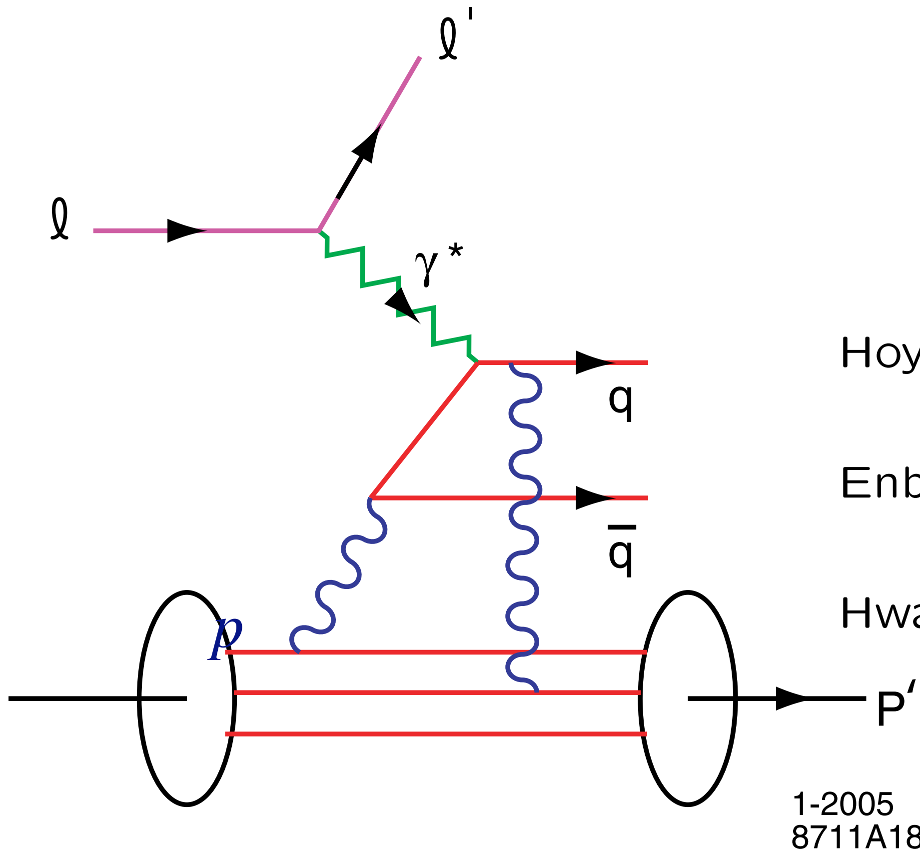
10% of DIS events are diffractive !



Fraction r of events with a large rapidity gap, $\eta_{\max} < 1.5$, as a function of Q^2_{DA} for two ranges of x_{DA}. No acceptance corrections have been applied.

M. Derrick et al. [ZEUS Collaboration], Phys. Lett. B 315, 481 (1993).

Final State Interaction Produces Diffractive DIS



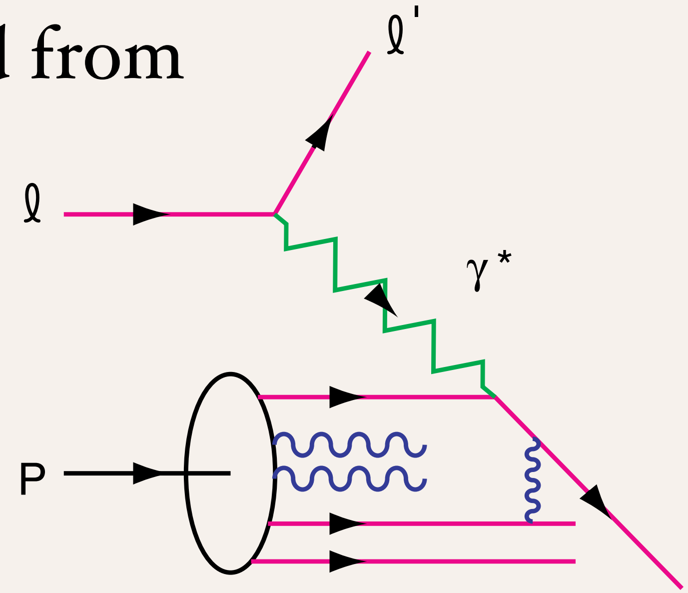
Quark Rescattering

Hoyer, Marchal, Peigne, Sannino, SJB (BHM

Enberg, Hoyer, Ingelman, SJB

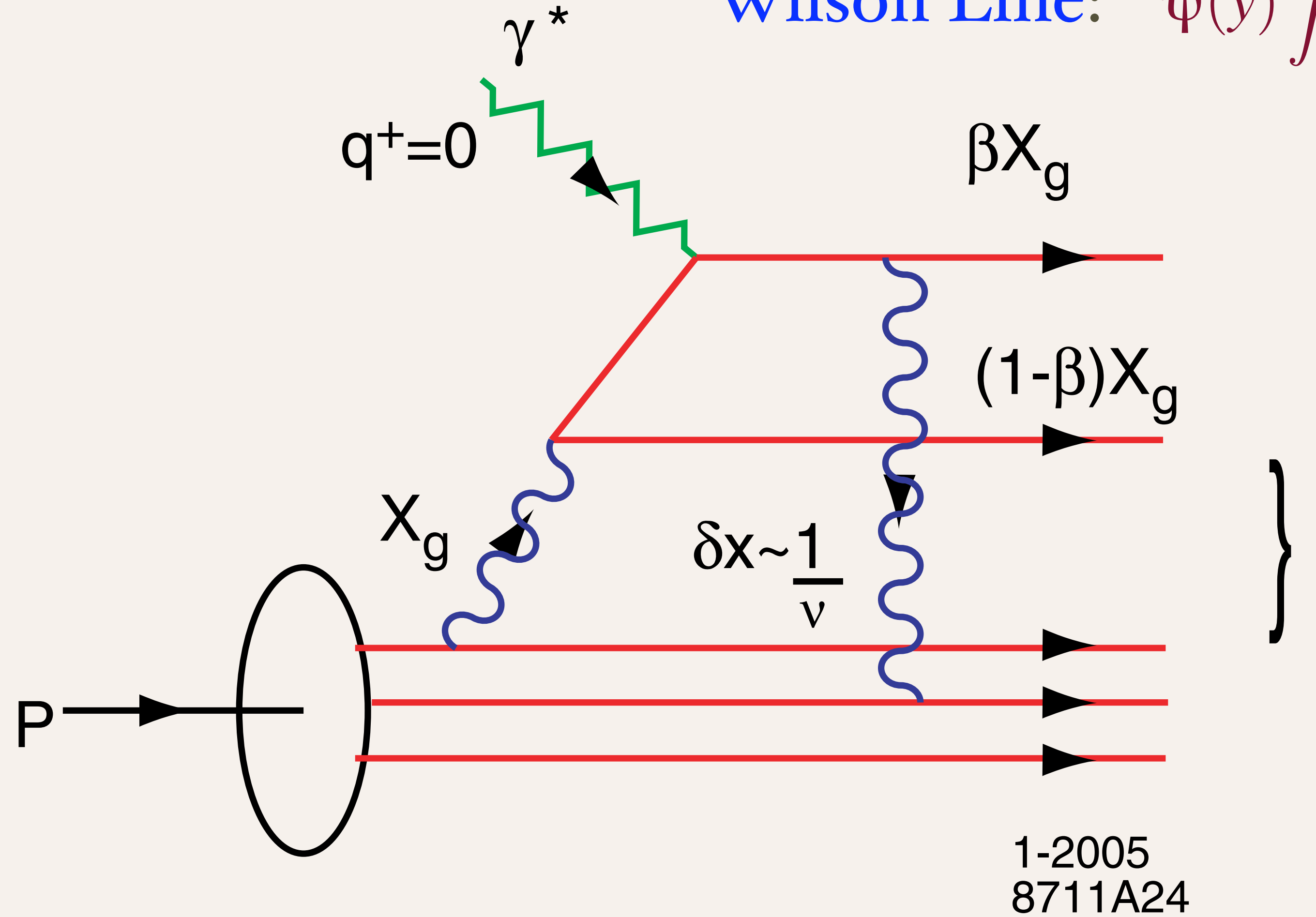
Hwang, Schmidt, SJB

- Quarks Reinteract in Final State
- Analogous to Coulomb phases, but not unitary
- Observable effects: DDIS, SSI, shadowing, antishadowing
- Structure functions cannot be computed from LFWFs computed in isolation
- Wilson line not 1 even in lcg



QCD Mechanism for Rapidity Gaps

Wilson Line: $\overline{\psi}(y) \int_0^y dx\, e^{iA(x)\cdot dx}\, \psi(0)$



Key QCD Experiment at GSI

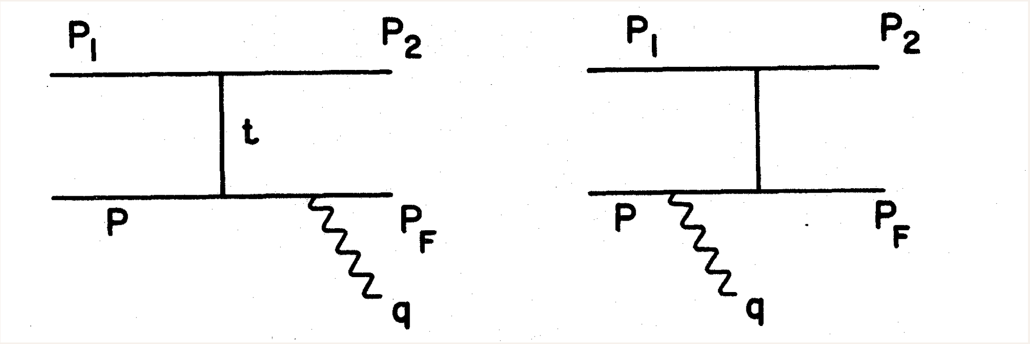
Double-Diffractive Drell-Yan

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

Large-Mass Timelike Muon Pairs in Hadronic Interactions

S. M. Berman*, D. J. Levy, and T. L. Neff§

Phys. Rev. Lett. 23, 1363–1365 (1969)



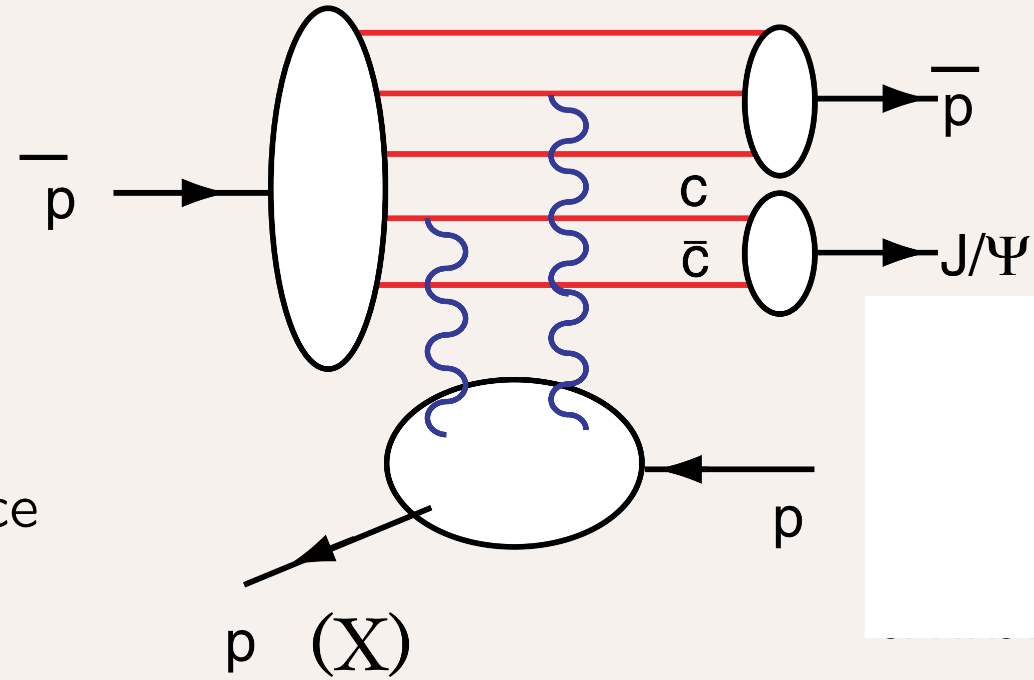
Prototype for exclusive Higgs production

Key QCD Experiment at GSI

Measure diffractive hidden charm production at forward x_F

Even close to threshold

$$\frac{d\sigma}{dt_1 dt_2 dx_F}(\overline{p}p \to \overline{p} + J/\psi + p)$$



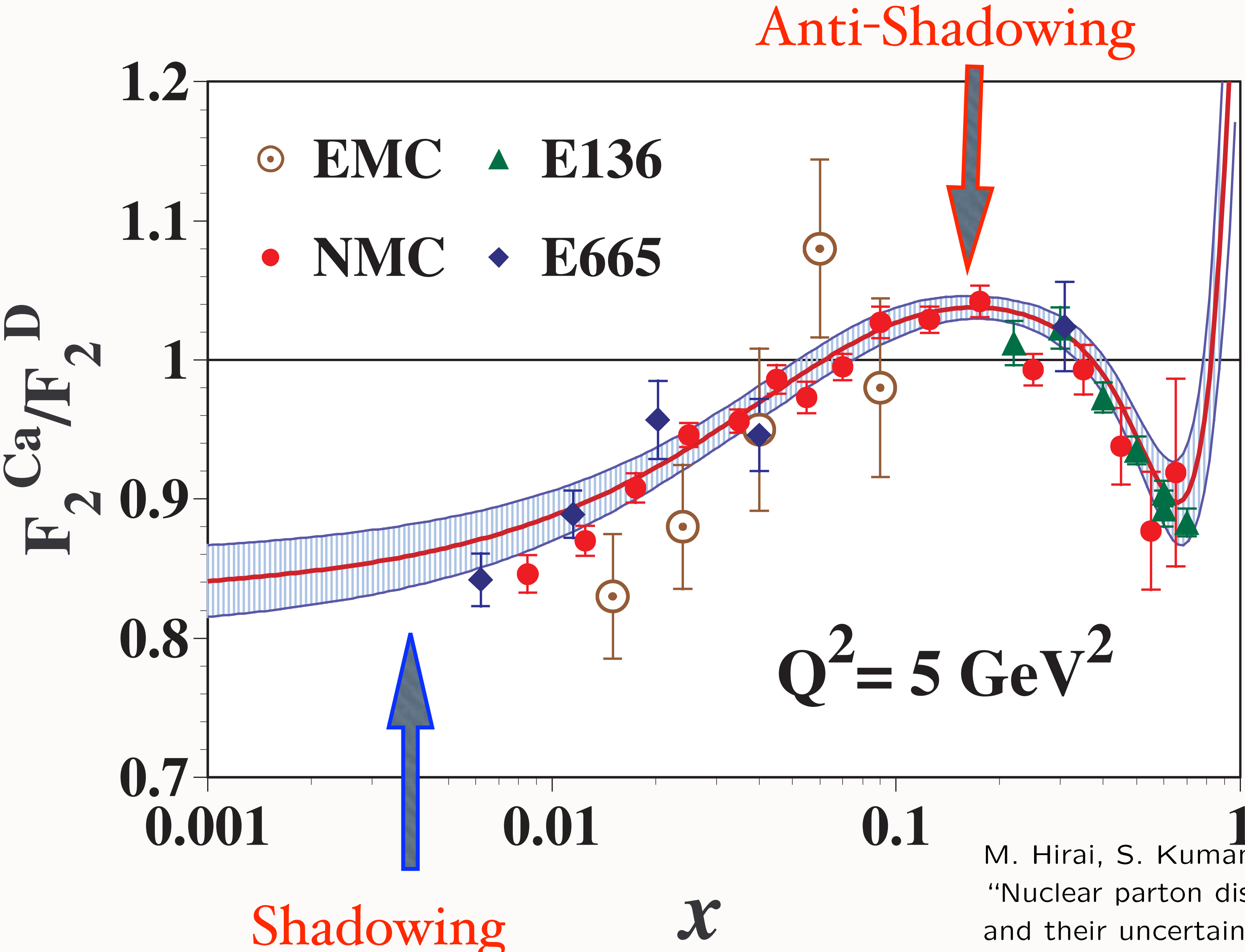
$$\frac{d\sigma}{dt dx_F}(\overline{p}p \to \overline{p} + J/\psi + X)$$

Anomalous nuclear dependence

$$\frac{d\sigma}{dx_F}(\overline{p}A \to J/\psi + X)$$

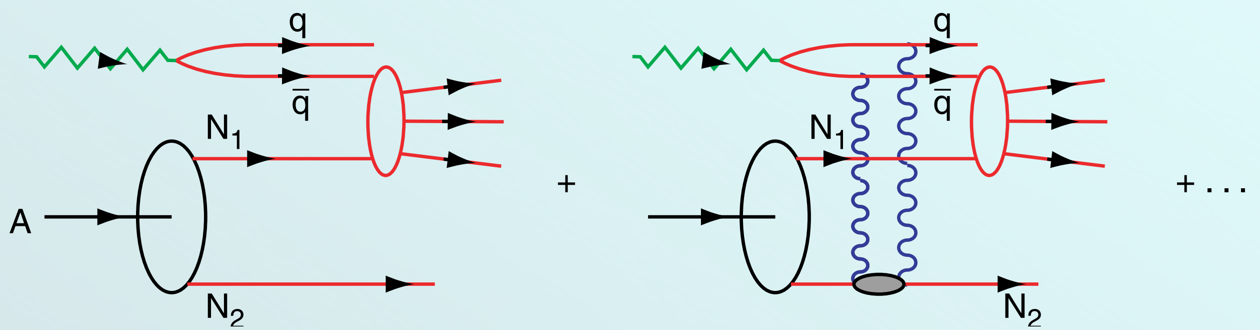
$A^{\alpha(x_2)}$ versus $A^{\alpha(x_F)}$

Important Tests of Intrinsic Charm



M. Hirai, S. Kumano and T. H. Nagai, "Nuclear parton distribution functions and their uncertainties," Phys. Rev. C **70**, 044905 (2004) [arXiv:hep-ph/0404093].

Origin of Nuclear Shadowing in Glauber - Gribov Theory



Interference of one-step and two-step processes

Interaction on upstream leading-twist nucleon diffractive

Phase i X i = - 1 produces destructive interference

No Flux reaches down stream nucleon

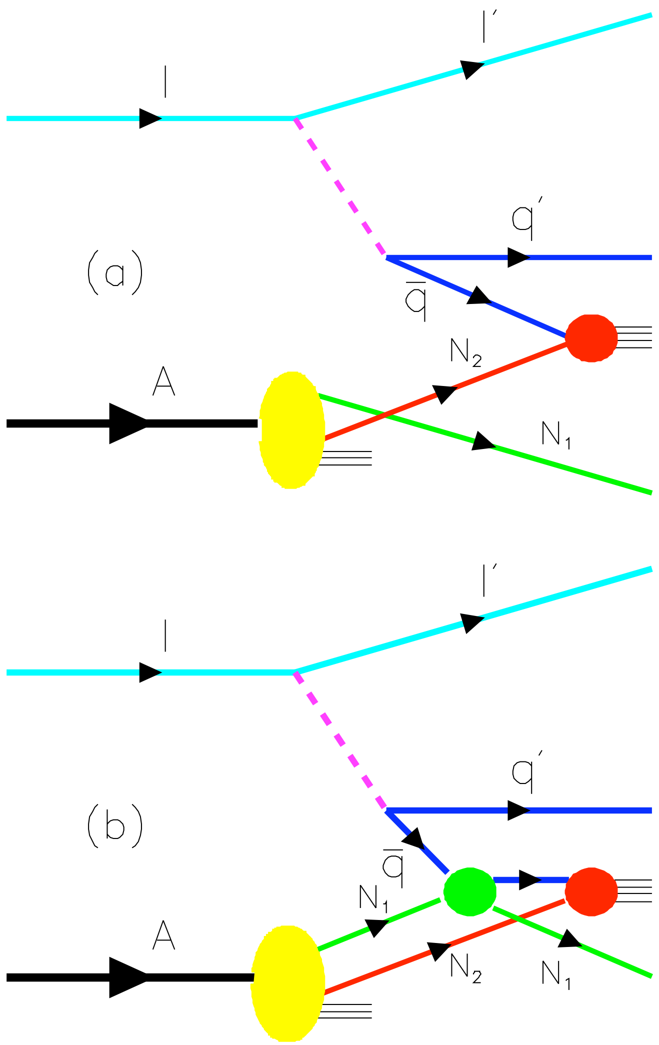
Shadowing and Antishadowing in Lepton-Nucleus Scattering

- Shadowing: Destructive Interference
of Two-Step and One-Step Processes
Pomeron Exchange

- Antishadowing: Constructive Interference
of Two-Step and One-Step Processes!
Reggeon and Odderon Exchange

- Antishadowing is Not Universal!
Electromagnetic and weak currents:
different nuclear effects !
Potentially significant for NuTeV Anomaly}

Schmidt, Yang, Lu, sjb



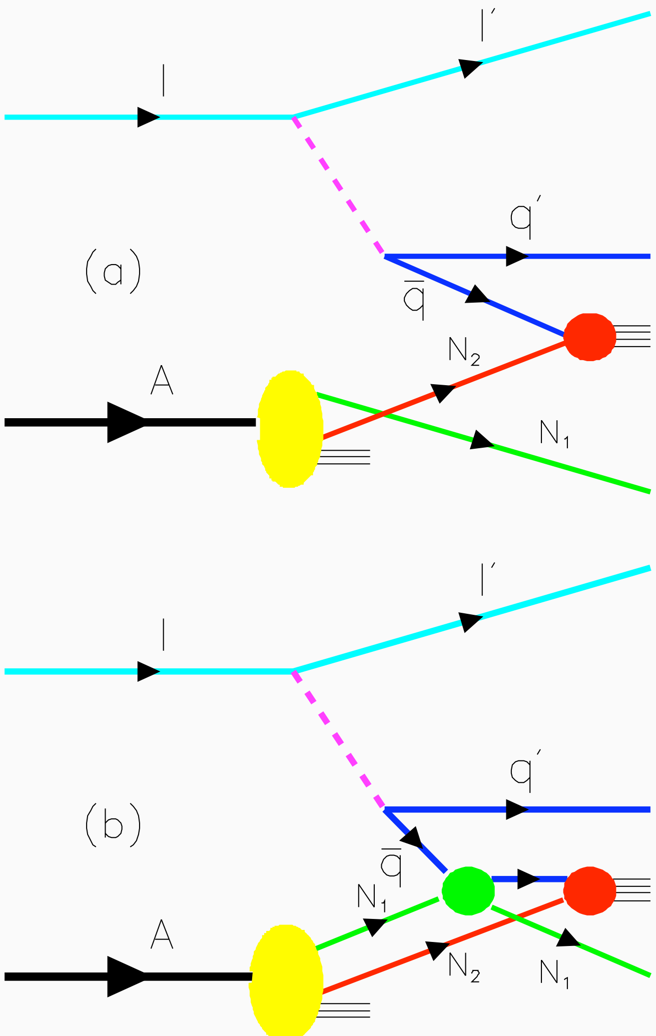
The one-step and two-step processes in DIS on a nucleus.

Coherence at small Bjorken x_B :
$1/Mx_B = 2\nu/Q^2 \geq L_A$.

If the scattering on nucleon N_1 is via pomeron exchange, the one-step and two-step amplitudes are opposite in phase, thus diminishing the $\overline{q}$ flux reaching N_2.

→ Shadowing of the DIS nuclear structure functions.

Kowalski: HERA DDIS produces observed nuclear shadowing



The one-step and two-step processes in DIS on a nucleus.

If the scattering on nucleon N_1 is via $C = -$ Reggeon or Odderon exchange, the one-step and two-step amplitudes are constructive in phase, enhancing the $\bar{q}$ flux reaching N_2

→ Antishadowing of the DIS nuclear structure functions

Reggeon Exchange

Phase of two-step amplitude relative to one step:

$$\frac{1}{\sqrt{2}}(1-i) \times i = \frac{1}{\sqrt{2}}(i+1)$$

Constructive Interference

Depends on quark flavor!

Thus antishadowing is not universal

Different for couplings of $\gamma^*, Z^0, W^\pm$

Crtical test: Tagged Drell-Yan

Shadowing and Antishadowing in Lepton-Nucleus Scattering

- Shadowing and Antishadowing in DIS arise from interference of multi-nucleon processes in nucleus

Phases!

- Not due to nuclear wavefunction

Wavefunction of stable nucleus is real.
Effect of multi-scattering of $q\overline{q}$ in nucleus.

- Bjorken Scaling :

Interference requires leading-twist diffractive DIS processes

Schmidt, Yang, sjb

Key QCD Experiment at GSI

Measure Non-Universal Anti-Shadowing in Drell-Yan

$$\bar{p}A \to \ell^+\ell^- X$$

$Q^2 = x_1 x_2 s$ $\qquad$ $x_1 x_2 = .05, x_F = x_1 - x_2$

$$A^{\alpha}(x_1) = \frac{2\frac{d\sigma}{dQ^2 dx_F}(\bar{p}A \to \ell^+\ell^- X)}{A\frac{d\sigma}{dQ^2 dx_F}(\bar{p}d \to \ell^+\ell^- X)}$$

Flavor
u, d tag

Higher twist effects at high x_F:

Deviations from $(1 + \cos^2\theta)$

$\cos 2\phi$ correlation.

PQCD and Exclusive Processes

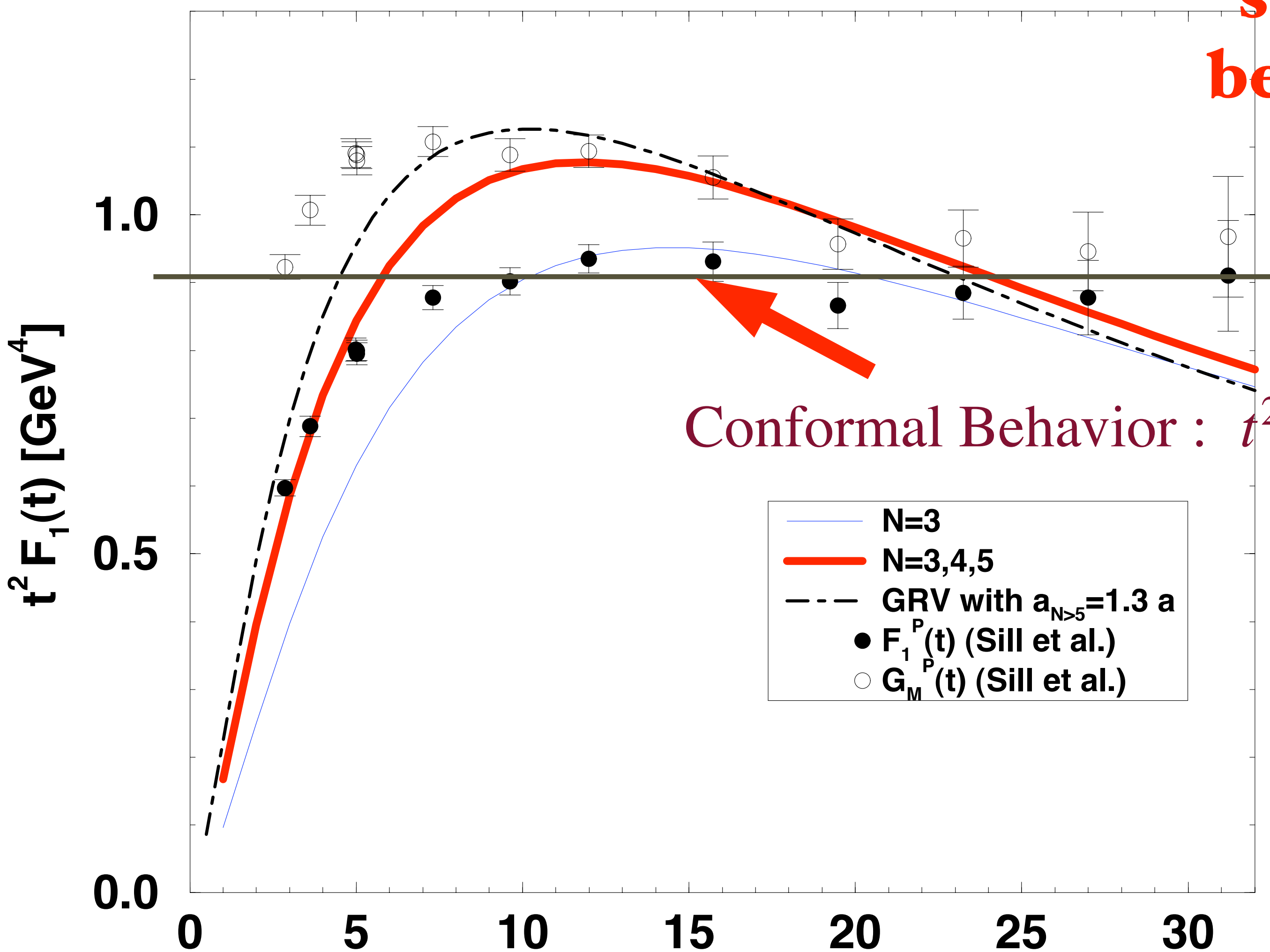
Lepage; SJB
Efremov, Radyuskin

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

- 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

Proton Form Factor

Remarkable scaling behavior



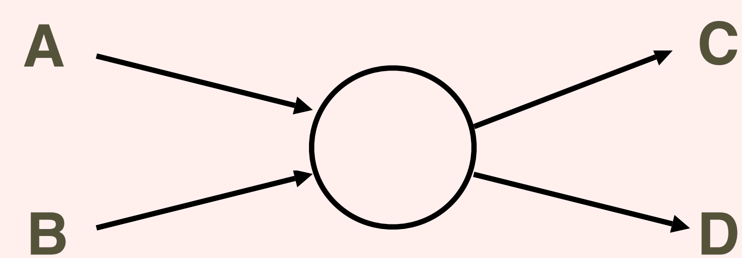
Conformal Behavior : $t^2 F_1(t) = \text{const}$

-t (GeV^2)

Non-perturbative model: Diehl, Kroll

Scaling is a manifestation of asymptotically free hadron interactions and AdS/CFT

From dimensional arguments at high energies in binary reactions:



CONSTITUENT COUNTING RULE

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

Counting Rules:

$$q(x) \sim (1-x)^{2n_{spect}-1} \text{ for } x \to 1$$

$$F(Q^2) \sim \left(\frac{1}{Q^2}\right)^{(n-1)}$$

$$\frac{d\sigma}{dt}(AB \to CD) \sim \frac{F(t/s)}{s^{(n_{participants}-2)}}$$

$$n_{participants} = n_A + n_B + n_C + n_D$$

$$\frac{d\sigma}{d^3p/E}(AB \to CX) \sim F(\hat{t}/\hat{s}) \times \frac{(1-x_R)^{(2n_{spectators}-1)}}{(p_T^2)^{(n_{participants}-2)}}$$

Predictions from conformal symmetry

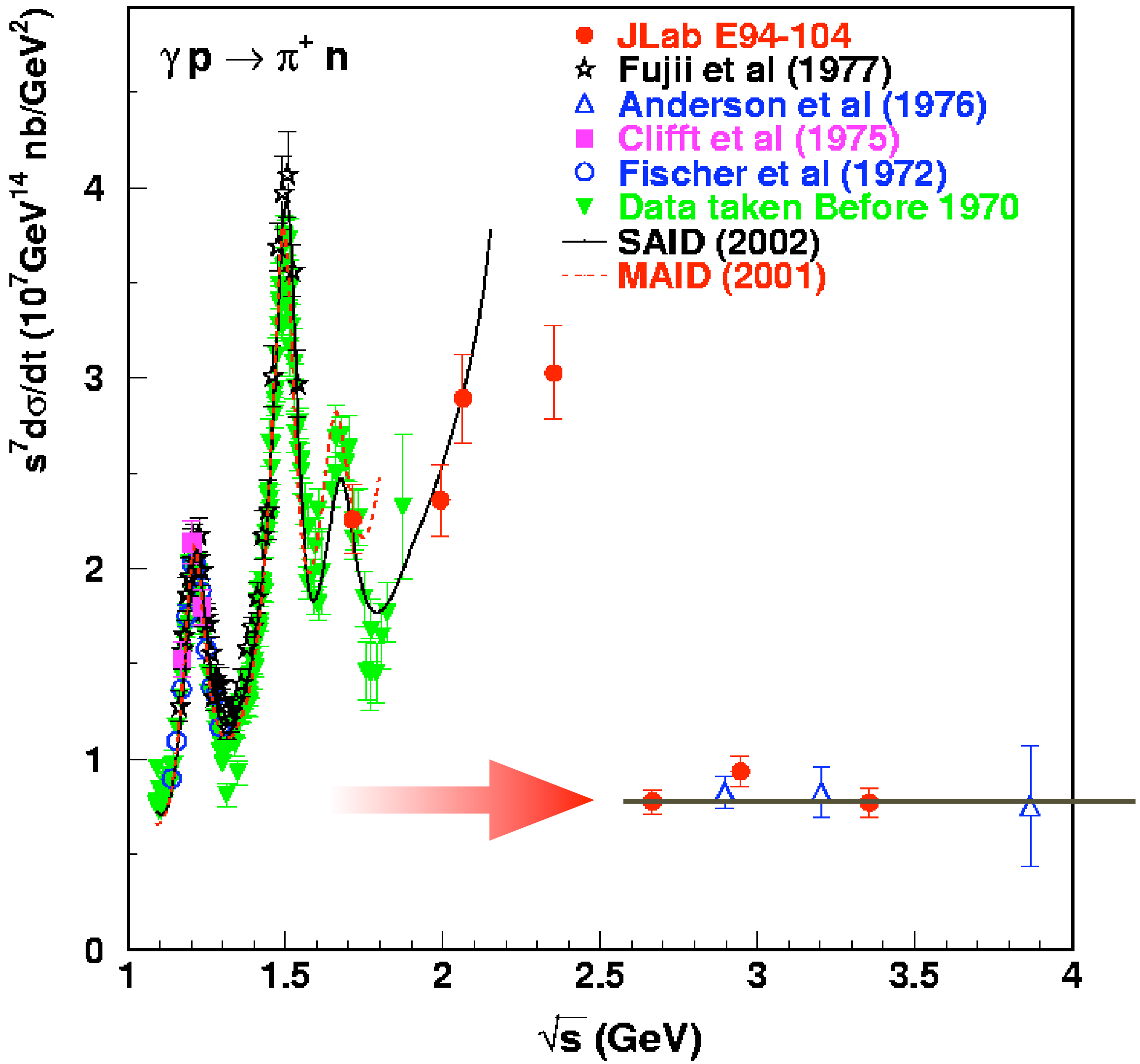
hadron helicity conservation

Farrar, Jackson;
Lepage, sjb;
Burkardt, Schmidt, Sjb

Test of PQCD Scaling

Constituent counting rules

Farrar, sjb; Muradyan, Matveev, Taveklidze



$s^7 d\sigma/dt(\gamma p \to \pi^+ n) \sim const$

fixed θ_{CM} scaling

PQCD and AdS/CFT:

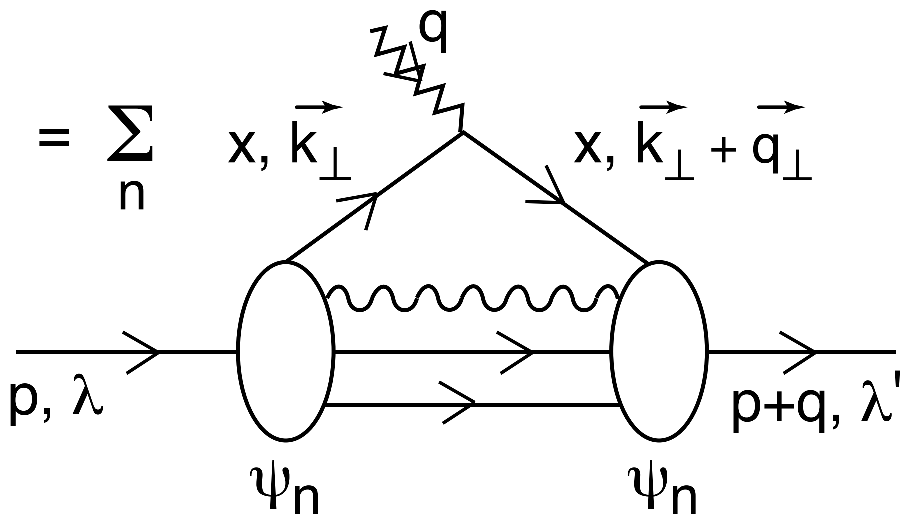
$s^{n_{tot}-2}\frac{d\sigma}{dt}(A+B \to C+D) =$
$F_{A+B\to C+D}(\theta_{CM})$

$s^7\frac{d\sigma}{dt}(\gamma p \to \pi^+ n) = F(\theta_{CM})$
$n_{tot} = 1+3+2+3 = 9$

Conformal invariance at high momentum transfer

Form Factors $\ell p \to \ell' p'$ $\langle p' \lambda' | J^+(0) | p \lambda \rangle$

$$F_{\lambda\lambda'}(Q^2) = \sum_n$$

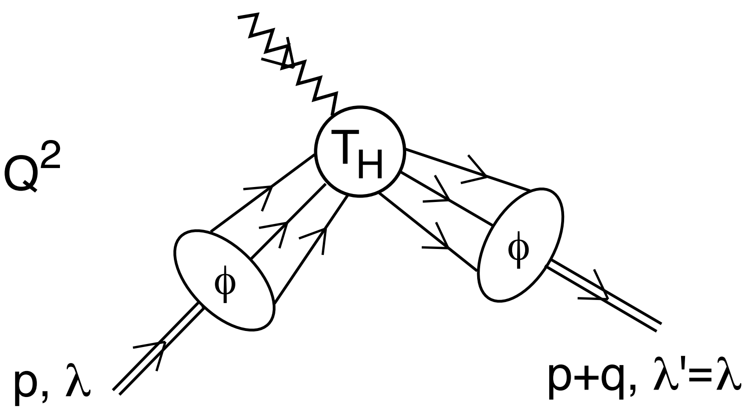


Lepage, Sjb
Efremov
Radyushkin

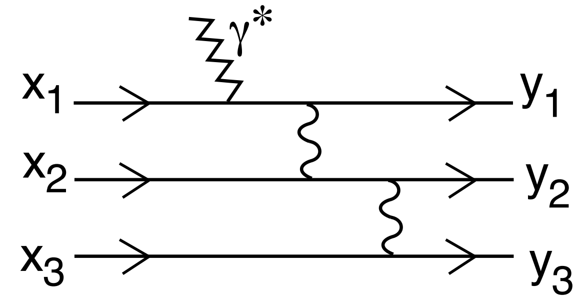
QCD Factorization

Normalization, scale-setting, higher order issues

⇨ Large Q^2



$T_H = \sum$



$+ \ \ldots$

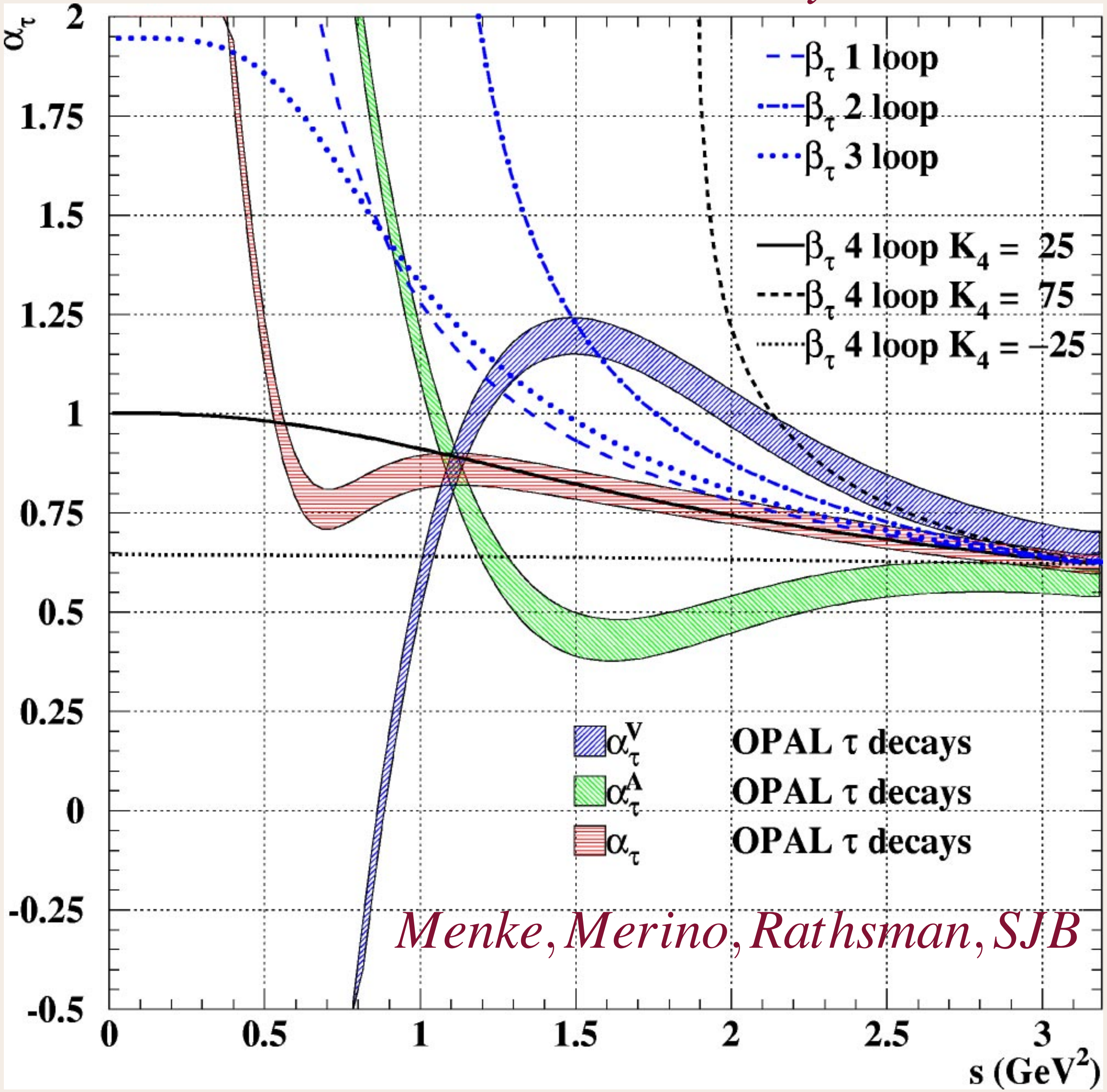
$$= \frac{\alpha_s^2}{Q^4} f(x_i, y_i,)$$

Scaling Laws from PQCD or AdS/CFT

Why do dimensional counting rules work so well?

- PQCD predicts log corrections from powers of α_s, logs, pinch contributions
- QCD coupling evaluated in IR regime.
- IR Fixed point! DSE: Alkofer, von Smekal et al.
- QED, EW -- define coupling from observable, predict other observable
- Underlying Conformal Symmetry of Semi-Classical QCD Lagrangian -- Apply AdS/CFT

QCD Effective Coupling from *hadronic τ decay*

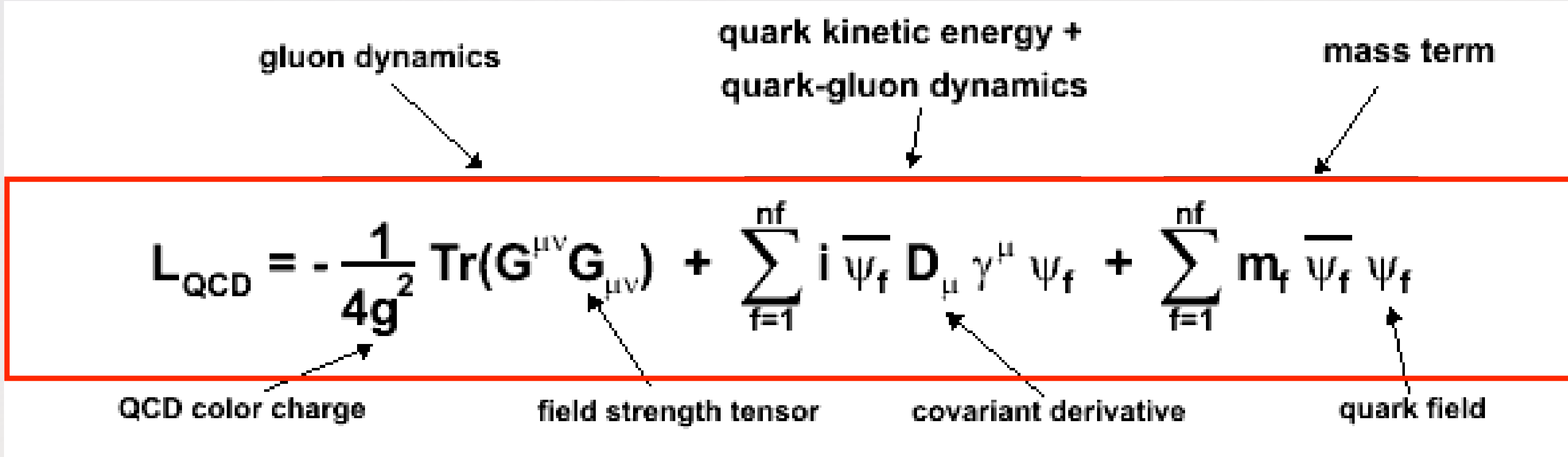


Menke, Merino, Rathsman, SJB

AdS/CFT and QCD

- Non-Perturbative Derivation of Dimensional Counting Rules (Strassler and Polchinski)
- Light-Front Wavefunctions: Confinement at Long Distances and Conformal Behavior at short distances (de Teramond and Sjb)
- Power-law fall-off at large transverse momentum, $x \to 1$
- Hadron Spectra, Regge Trajectories

QCD Lagrangian and Conformal Symmetry



$$L_{QCD} = -\frac{1}{4g^2}\,\mathrm{Tr}(G^{\mu\nu}G_{\mu\nu}) + \sum_{f=1}^{nf} i\,\overline{\psi_f}\,D_\mu \gamma^\mu \psi_f + \sum_{f=1}^{nf} m_f\,\overline{\psi_f}\,\psi_f$$

Conformal Symmetry – Property of classical renormalizable Lagrangian

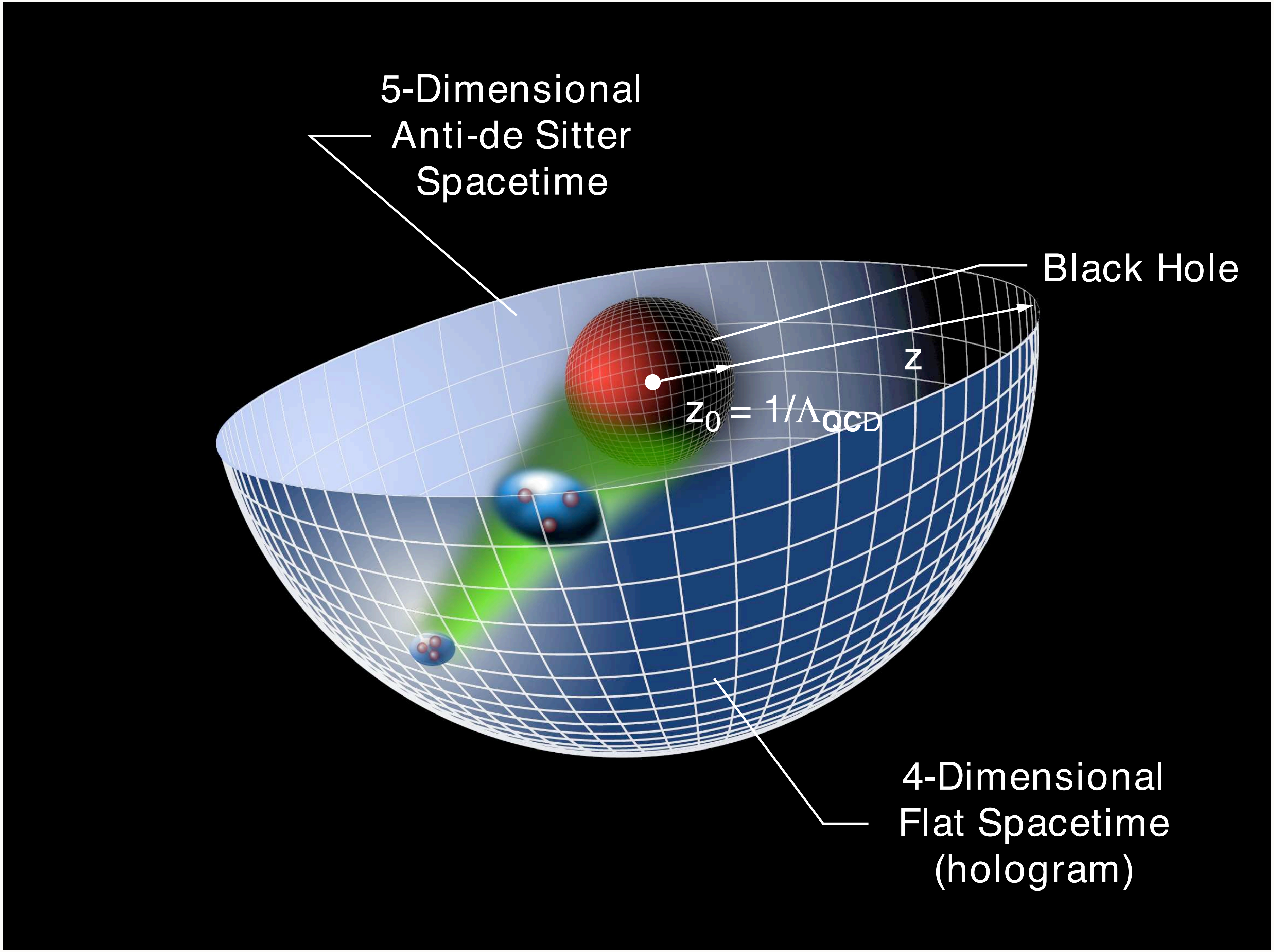
Massless quarks $\quad \beta = \frac{d\alpha_s(Q^2)}{d\log Q^2} = 0$ Parisi

Poincare transformations plus

$$\text{dilatation}: x^\mu \to \lambda x^\mu$$

plus

$$\text{conformal transformations : inversion}[x^\mu \to -\frac{x^\mu}{x^2}] \times \text{translation} \times \text{inversion}$$


5-Dimensional
Anti-de Sitter
Spacetime
Black Hole
z
$z_0 = 1/\Lambda_{QCD}$
4-Dimensional
Flat Spacetime
(hologram)

Features of AdS/QCD

- Semi-Classical Approximation to massless QCD
- Coupling is constant, zero beta function
- Conformal symmetry broken by confinement
- No particle creation, absorption
- Spectrum of Mesons, Baryons, Glueballs
- Light-Front Wavefunctions
- Quark Counting Rules

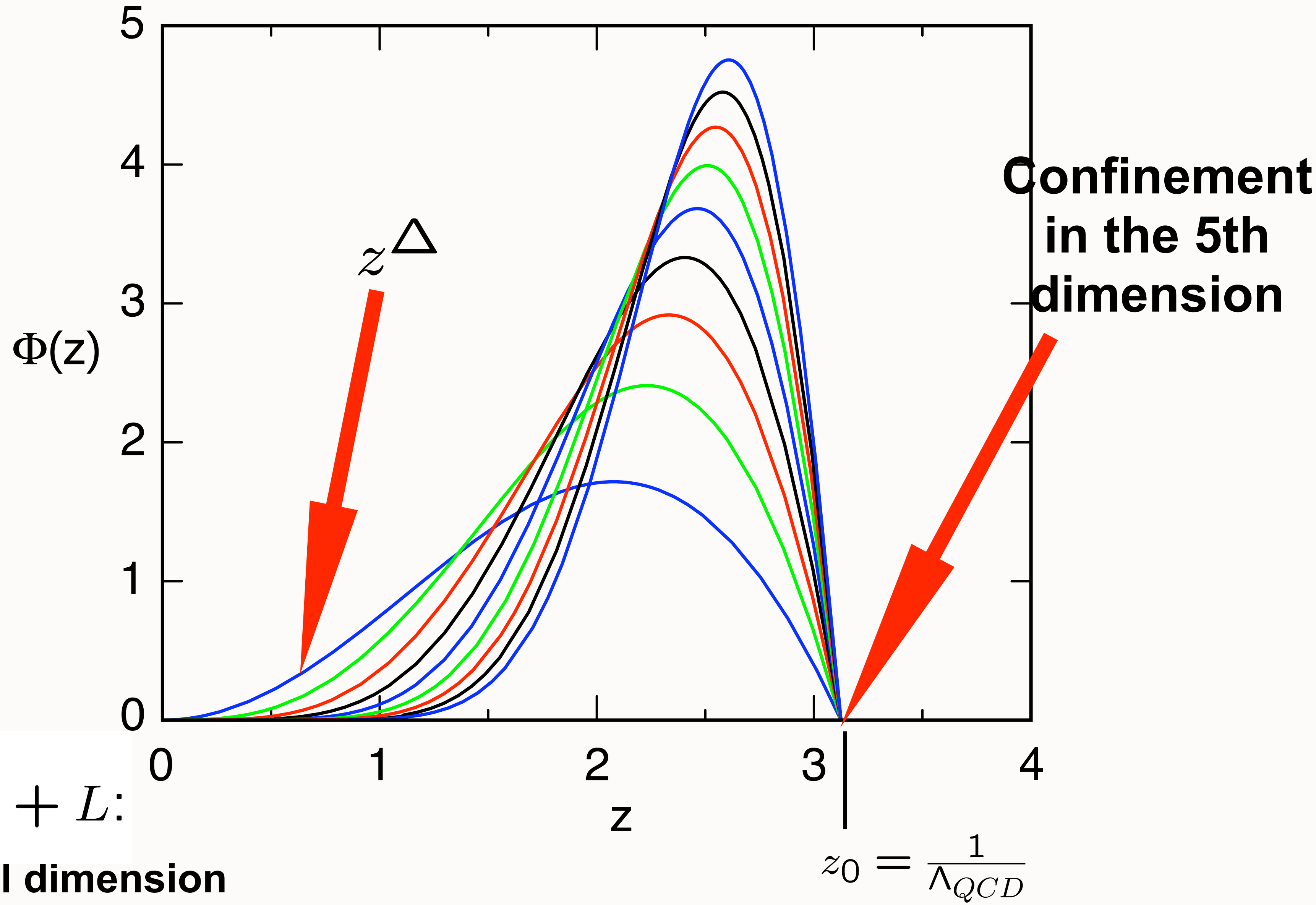
Strongly Coupled Conformal QCD and Holography

- Conformal Theories are invariant under the Poincaré and conformal transformations with $M^{\mu\nu}$, P^μ, D, K^μ, the generators of $SO(4,2)$.

- QCD appears as a nearly-conformal theory in the energy regimes accessible to experiment. Invariance of conformal QCD is broken by quark masses and quantum loops (running coupling). For $\beta = d\alpha_s(Q^2)/dlnQ^2 = 0$ (fixed point theory), PQCD is a conformal theory: Parisi, Phys. Lett. B **39**, 643 (1972).

- Phenomenological success of dimensional scaling laws for exclusive processes $d\sigma/dt \sim 1/s^{n-2}$ (n total number of constituents), implies QCD is a strongly coupled conformal theory at moderate but not asymptotic energies (PQCD predicts powers of α_s and logs).

- Theoretical and empirical evidence that $\alpha_s(Q^2)$ has an IR fixed point (constant in the IR): Alkofer, Fischer and Llanes-Estrada, hep-th/0412330; Brodsky, Menke, Merino and Rathsman, hep-ph/0212078; .



$\Delta = 3 + L$:

Conformal dimension of hadron

Match fall-off at small z to Conformal Dimension of State at short distances

- Pseudoscalar mesons: $\mathcal{O}_{3+L} = \overline{\psi}\gamma_5 D_{\{\ell_1} \dots D_{\ell_m\}}\psi$ ($\Phi_\mu = 0$ gauge).

- 4-d mass spectrum from boundary conditions on the normalizable string modes at $z = z_0$, $\Phi(x, z_o) = 0$, given by the zeros of Bessel functions $\beta_{\alpha,k}$: $\mathcal{M}_{\alpha,k} = \beta_{\alpha,k}\Lambda_{QCD}$

- Normalizable AdS modes $\Phi(z)$

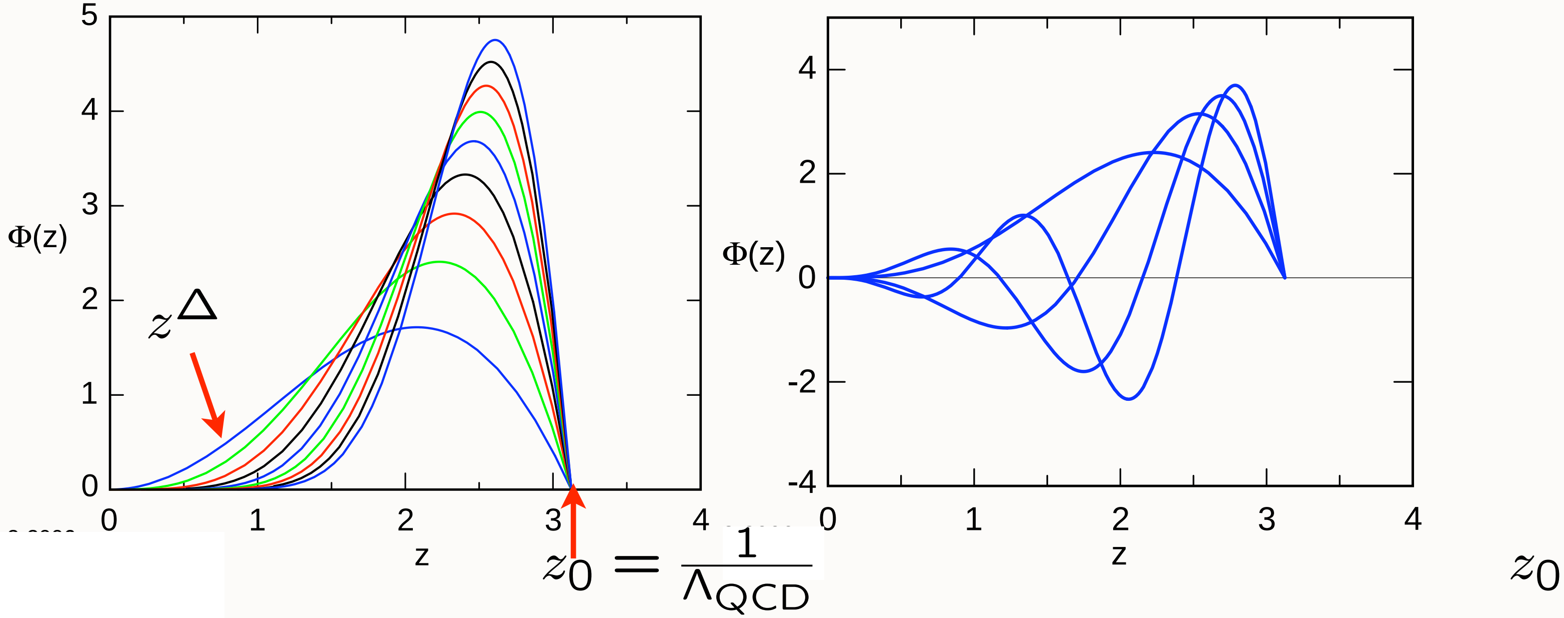


Fig: Meson orbital and radial AdS modes for $\Lambda_{QCD} = 0.32$ GeV.

Predictions of AdS/CFT

Only one parameter!

Entire light quark baryon spectrum

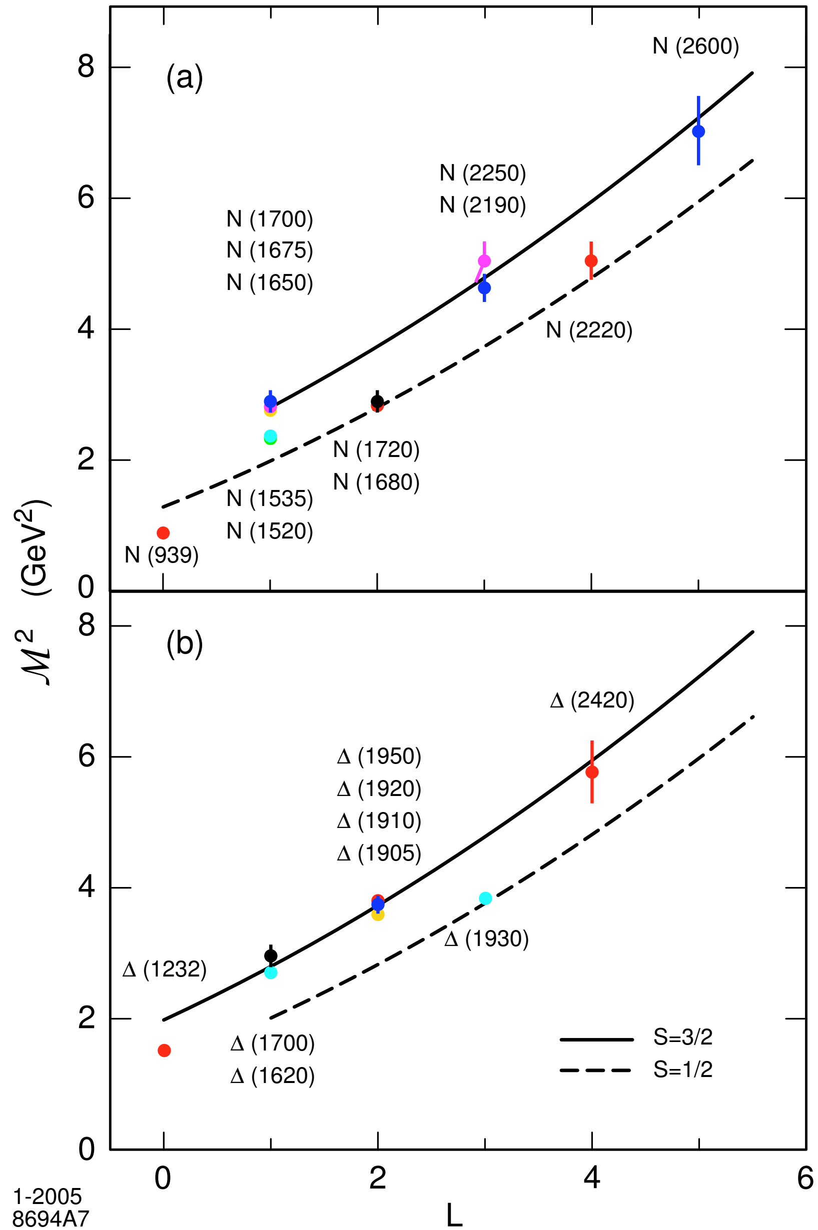


Fig: Predictions for the light baryon orbital spectrum for Λ_{QCD} = 0.22 GeV

Guy de Teramond
SJB

Phys.Rev.Lett.94: 201601,2005

hep-th/0501022

- $SU(6)$ multiplet structure for N and Δ orbital states, including internal spin S and L.

$SU(6)$	S	L	Baryon State
56	$\frac{1}{2}$	0	$N\frac{1}{2}^+(939)$
	$\frac{3}{2}$	0	$\Delta\frac{3}{2}^+(1232)$
70	$\frac{1}{2}$	1	$N\frac{1}{2}^-(1535)$ $N\frac{3}{2}^-(1520)$
	$\frac{3}{2}$	1	$N\frac{1}{2}^-(1650)$ $N\frac{3}{2}^-(1700)$ $N\frac{5}{2}^-(1675)$
	$\frac{1}{2}$	1	$\Delta\frac{1}{2}^-(1620)$ $\Delta\frac{3}{2}^-(1700)$
56	$\frac{1}{2}$	2	$N\frac{3}{2}^+(1720)$ $N\frac{5}{2}^+(1680)$
	$\frac{3}{2}$	2	$\Delta\frac{1}{2}^+(1910)$ $\Delta\frac{3}{2}^+(1920)$ $\Delta\frac{5}{2}^+(1905)$ $\Delta\frac{7}{2}^+(1950)$
70	$\frac{1}{2}$	3	$N\frac{5}{2}^-$ $N\frac{7}{2}^-$
	$\frac{3}{2}$	3	$N\frac{3}{2}^-$ $N\frac{5}{2}^-$ $N\frac{7}{2}^-(2190)$ $N\frac{9}{2}^-(2250)$
	$\frac{1}{2}$	3	$\Delta\frac{5}{2}^-(1930)$ $\Delta\frac{7}{2}^-$
56	$\frac{1}{2}$	4	$N\frac{7}{2}^+$ $N\frac{9}{2}^+(2220)$
	$\frac{3}{2}$	4	$\Delta\frac{5}{2}^+$ $\Delta\frac{7}{2}^+$ $\Delta\frac{9}{2}^+$ $\Delta\frac{11}{2}^+(2420)$
70	$\frac{1}{2}$	5	$N\frac{9}{2}^-$ $N\frac{11}{2}^-$
	$\frac{3}{2}$	5	$N\frac{7}{2}^-$ $N\frac{9}{2}^-$ $N\frac{11}{2}^-(2600)$ $N\frac{13}{2}^-$

Features of HolographicModel

de Teramond sjb

- Ratio of proton to Delta trajectories= ratio of zeroes of Bessel functions.
- One scale Λ_{QCD} determines hadron spectrum (slightly different for mesons and baryons)
- Only quark-antiquark, qqq, and g g hadrons appear at classical level
- Covariant version of bag model: confinement+conformal symmetry

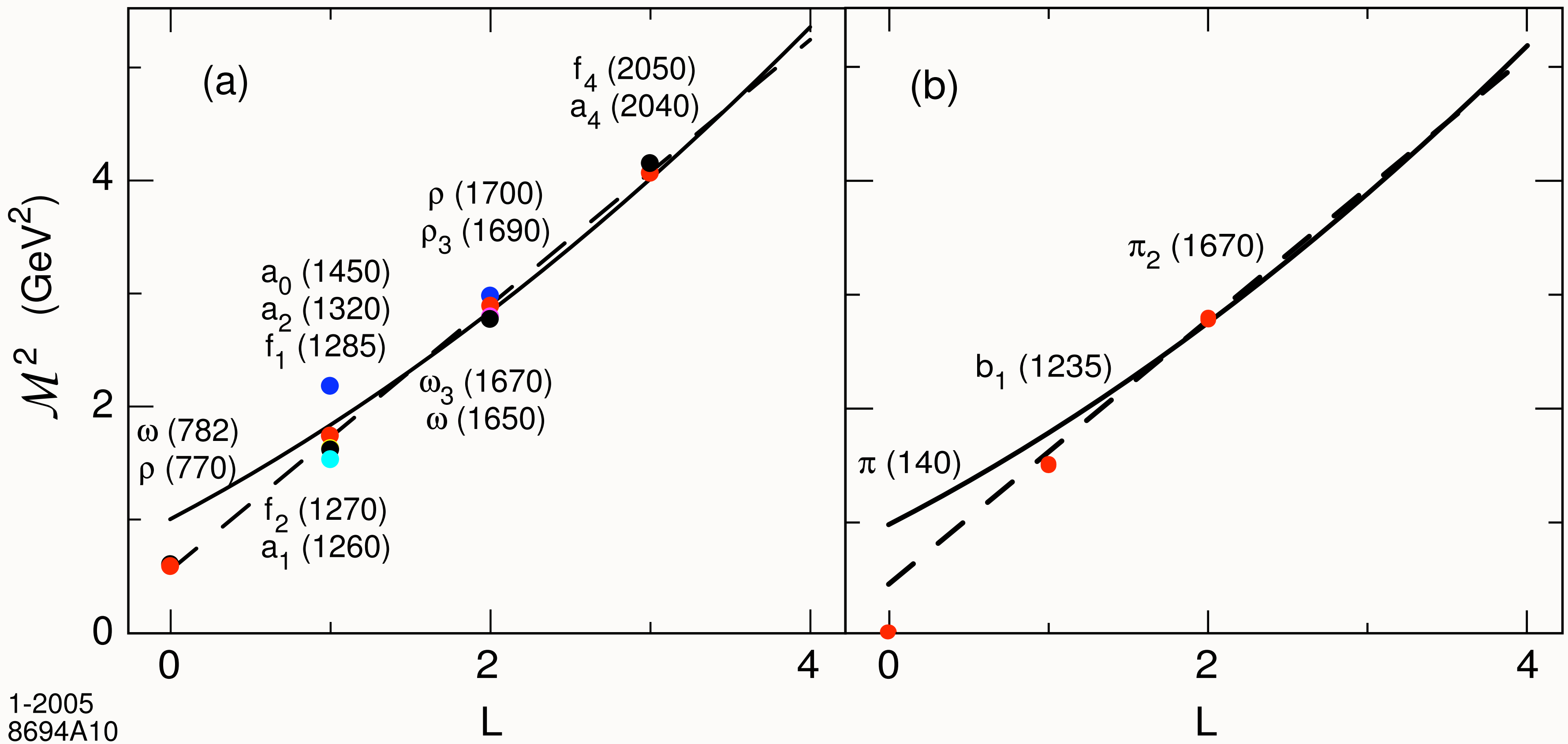


Fig: Light meson orbital spectrum: 4-dim states dual to vector fields in the bulk, $\Lambda_{QCD} = 0.26$ GeV

Guy de Teramond
SJB

Glueball Spectrum

- AdS wave function with effective mass μ:

$$\left[z^2\,\partial_z^2 - (d-1)z\,\partial_z + z^2\,\mathcal{M}^2 - (\mu R)^2\right] f(z) = 0,$$

where $\Phi(x,z) = e^{-iP\cdot x}\, f(z)$ and $P_\mu P^\mu = \mathcal{M}^2$.

- Glueball interpolating operator with twist -dimension minus spin- two, and conformal dimension $\Delta = 4 + L$

$$\mathcal{O}_{4+L} = F D_{\{\ell_1} \dots D_{\ell_m\}} F,$$

where $L = \sum_{i=1}^{m} \ell_i$ is the total internal space-time orbital momentum.

- Normalizable scalar AdS mode (d = 4):

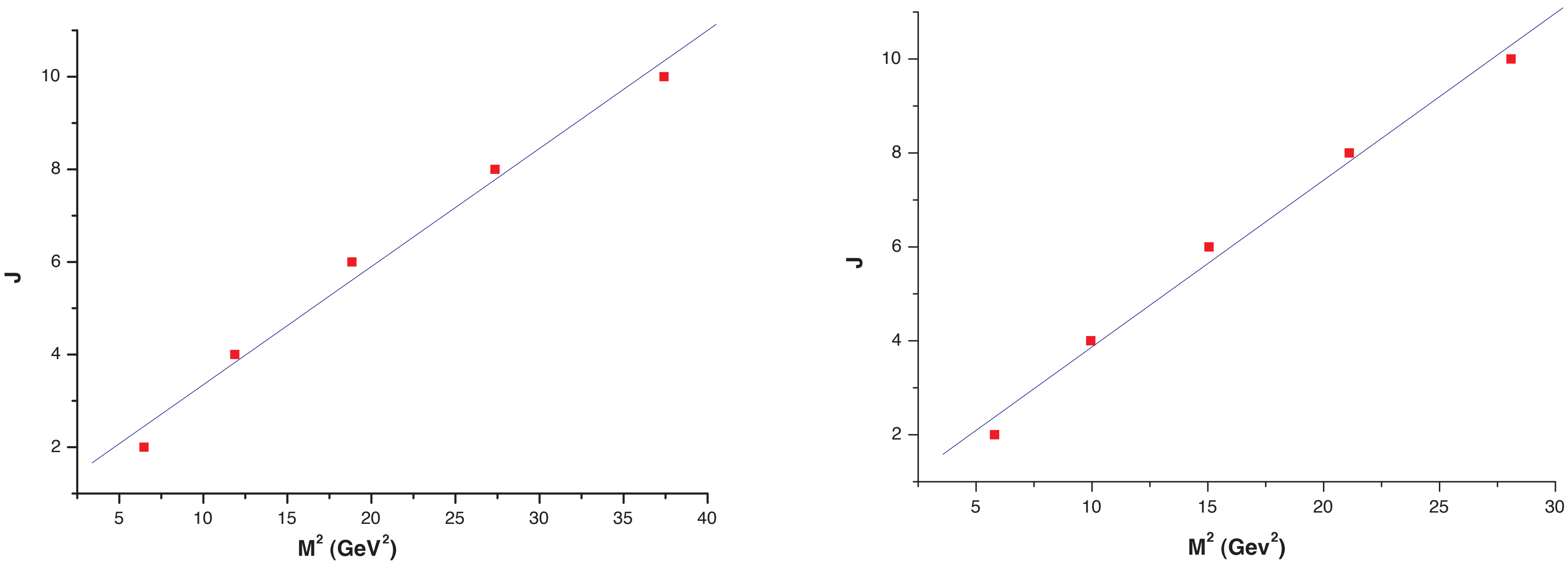
$$\Phi_{\alpha,k}(x,z) = C_{\alpha,k} e^{-iP\cdot x} z^2 J_\alpha\left(z\,\beta_{\alpha,a}\Lambda_{QCD}\right)$$

with $\alpha = 2 + L$ and scaling dimension $\Delta = 4 + L$.

Glueball Regge trajectories from gauge/string duality and the Pomeron

Henrique Boschi-Filho,* Nelson R. F. Braga,† and Hector L. Carrion‡

Instituto de Física, Universidade Federal do Rio de Janeiro,

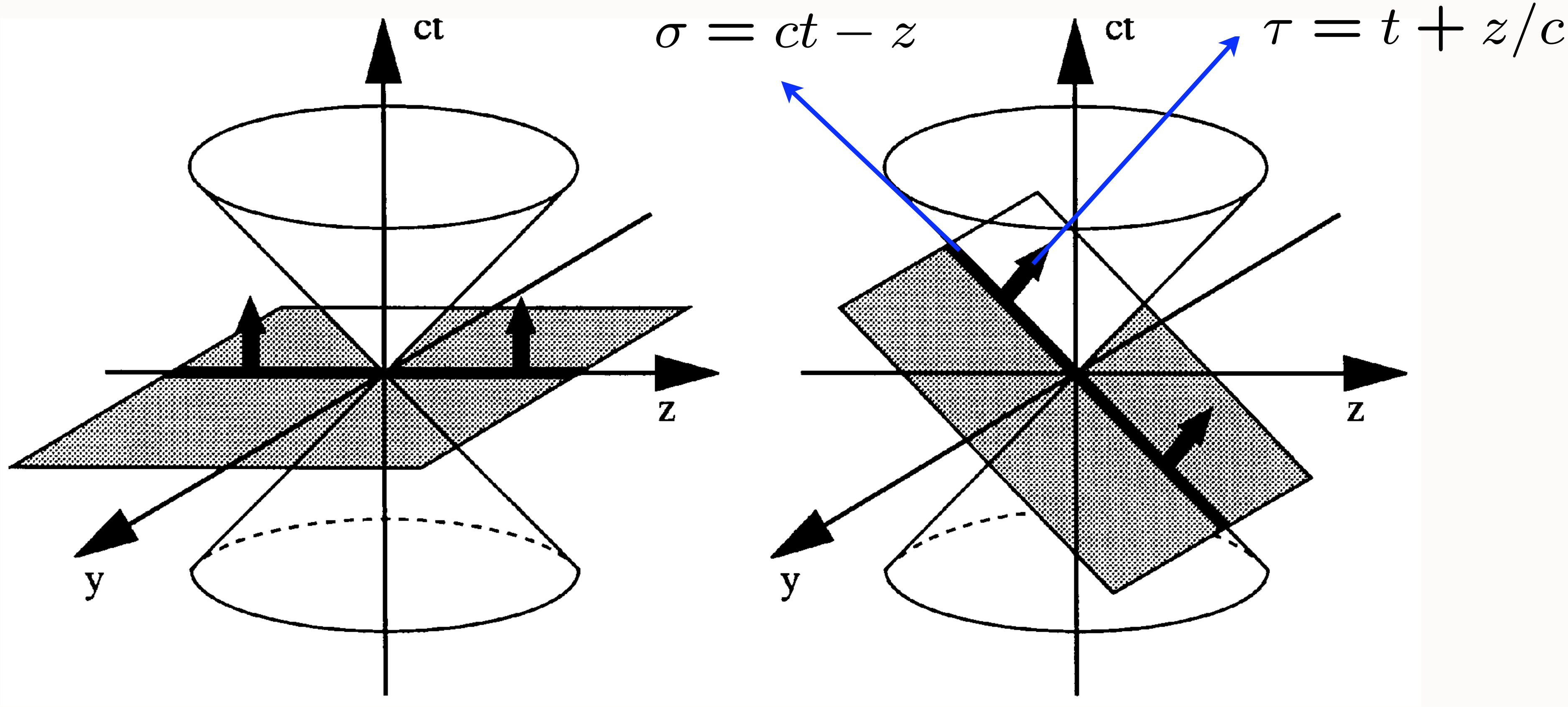


Neumann Boundary Conditions

Dirichlet Boundary Conditions

Dirac's Amazing Idea: The "Front Form"

Evolve in light-front time!



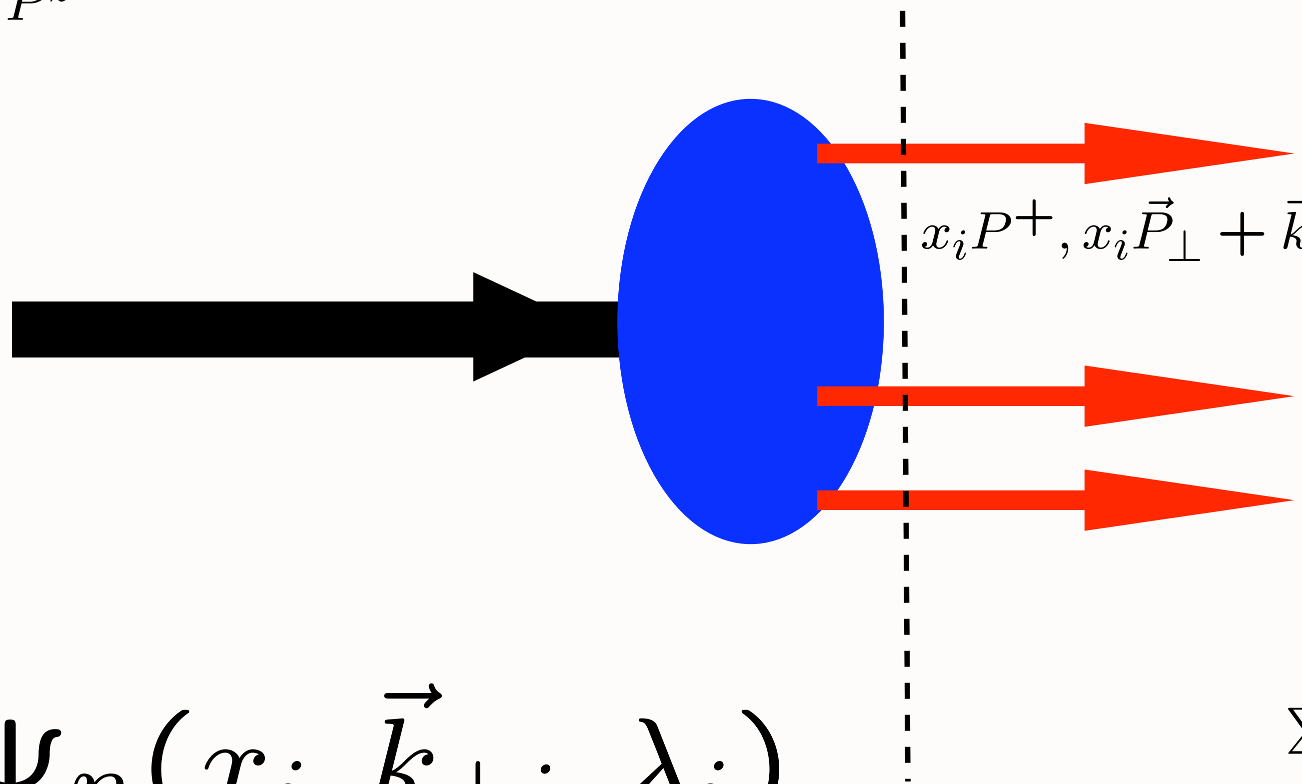
Instant Form

Front Form

Light-Front Wavefunctions

Fixed $\tau = t + z/c$

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



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

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

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

$\sum_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

Angular Momentum on the Light-Front

$$J^z = \sum_{i=1}^{n} s_i^z + \sum_{j=1}^{n-1} l_j^z.$$

Conserved
LF Fock state by Fock State

$$l_j^z = -\mathrm{i}\left(k_j^1 \frac{\partial}{\partial k_j^2} - k_j^2 \frac{\partial}{\partial k_j^1}\right)$$

n-1 orbital angular momenta

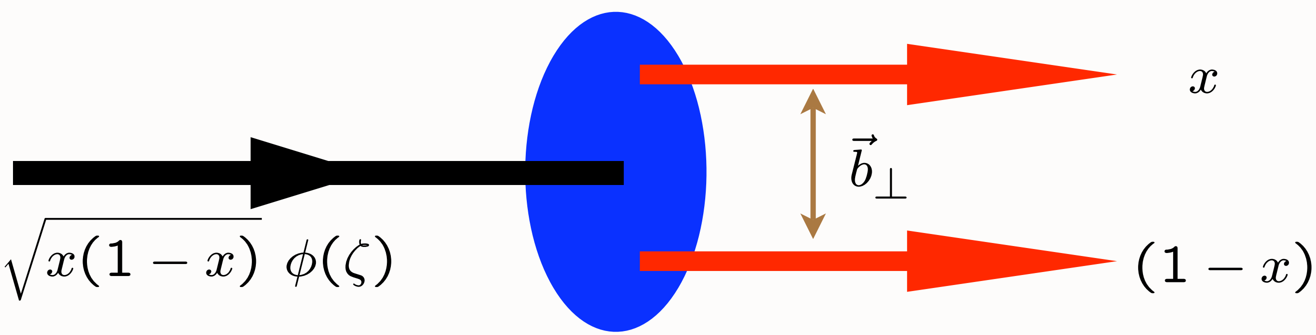
Nonzero Anomalous Moment -->Nonzero orbital angular momentum

Mapping between LF(3+1) and AdS5

LF(3+1) AdS5

$$\psi(x, \vec{b}_\perp) \longleftrightarrow \phi(z)$$

$$\zeta = \sqrt{x(1-x)\vec{b}_\perp^2} \longleftrightarrow z$$



$$\psi(x, \vec{b}_\perp) = \sqrt{x(1-x)}\ \phi(\zeta)$$

G. de Teramond and sjb

Map AdS/CFT to 3+1 LF Theory

Effective radial equation:

$$\left[-\frac{d^2}{d\zeta^2} + V(\zeta)\right]\phi(\zeta) = \mathcal{M}^2\phi(\zeta)$$

$$\zeta^2 = x(1-x)\mathbf{b}_\perp^2.$$

Effective conformal potential:

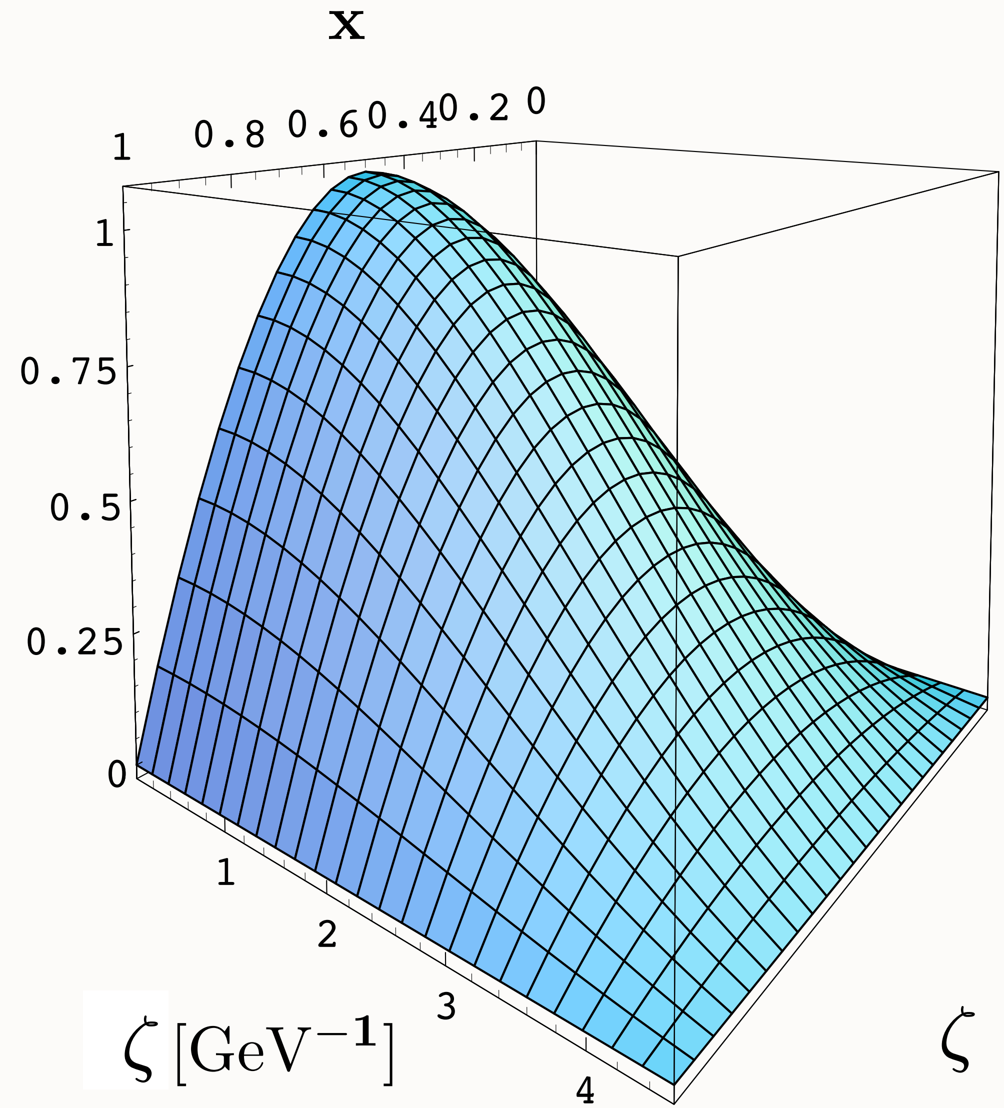
$$V(\zeta) = -\frac{1-4L^2}{4\zeta^2}.$$

General solution:

$$\widetilde{\psi}_{L,k}(x,\vec{b}_\perp) = B_{L,k}\sqrt{x(1-x)}$$

$$J_L\left(\sqrt{x(1-x)}|\vec{b}_\perp|\beta_{L,k}\Lambda_{\rm QCD}\right)\theta\left(\vec{b}_\perp^{\,2} \le \frac{\Lambda_{\rm QCD}^{-2}}{x(1-x)}\right),$$

$\psi(\mathbf{x}, \mathbf{b})$



AdS/CFT prediction for meson LFWF

Holographic Model

Guy de Teramond
SJB

$$\zeta = b\sqrt{x(1-x)}$$

Two-parton ground state LFWF in impact space $\psi(x, b)$ for a for $n = 2, \ell = 0, k = 1$.

Hadron Distribution Amplitudes

Lepage; SJB
Efremov, Radyuskin

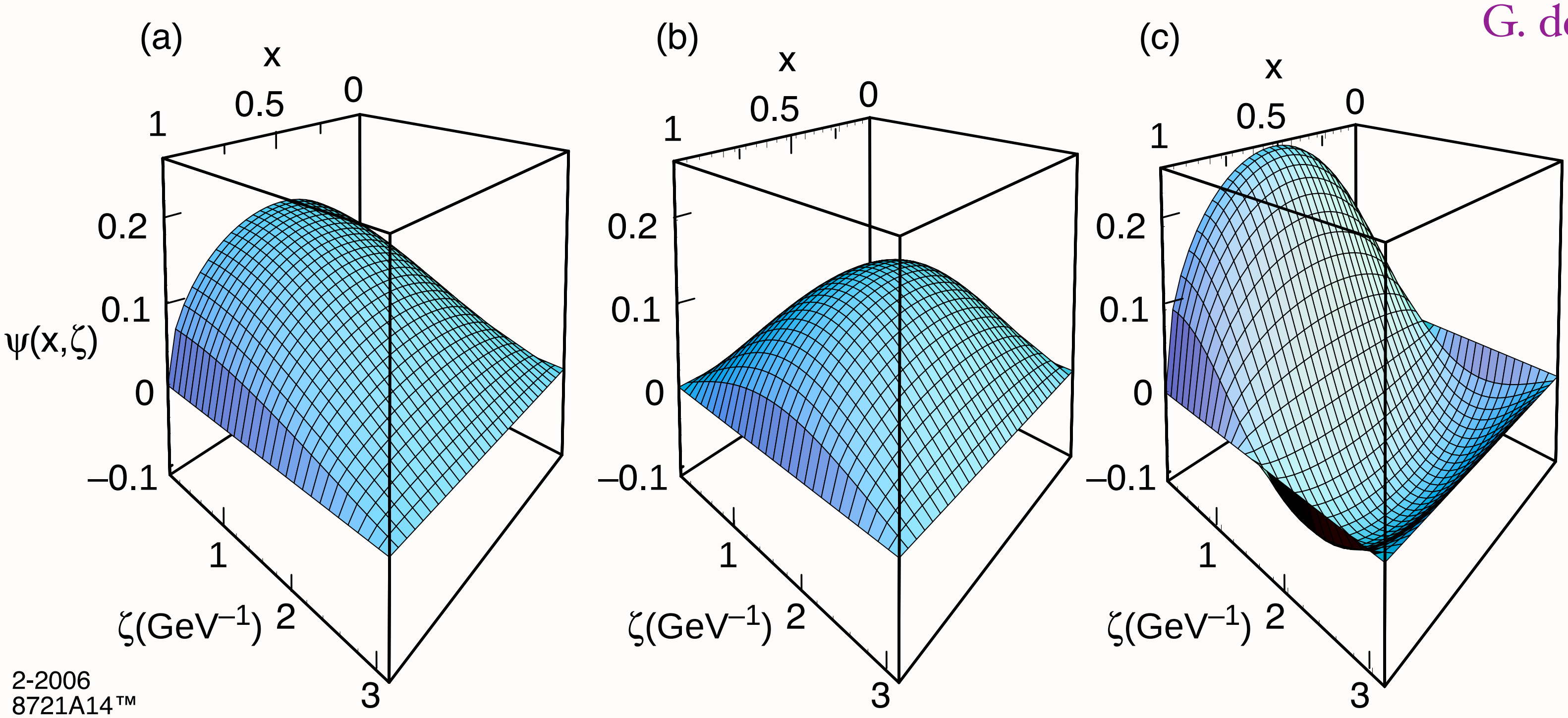
$$\phi(x_i, Q) \equiv \Pi_{i=1}^{n-1} \int^Q d^2\vec{k}_\perp \ \psi_n(x_i, \vec{k}_{\perp i})$$

- Fundamental measure of valence wavefunction
- Gauge Invariant (includes Wilson line)
- Evolution Equations, OPE
- Conformal Expansion
- Hadronic Input in Factorization Theorems

AdS/CFT: $\phi(x, Q_0) \propto \sqrt{x(1-x)}$

AdS/CFT Prediction for Meson LFWF

G. de Teramond
SJB



Two-parton holographic LFWF in impact space $\widetilde{\psi}(x,\zeta)$ for $\Lambda_{QCD} = 0.32$ GeV: (a) ground state $L = 0,\ k = 1$; (b) first orbital exited state $L = 1,\ k = 1$; (c) first radial exited state $L = 0,\ k = 2$. The variable ζ is the holographic variable $z = \zeta = |b_\perp|\sqrt{x(1-x)}$.

$$\widetilde{\psi}(x,\zeta) = \frac{\Lambda_{\rm QCD}}{\sqrt{\pi}J_1(\beta_{0,1})}\sqrt{x(1-x)}J_0\left(\zeta\beta_{0,1}\Lambda_{QCD}\right)\theta\left(z \le \Lambda^{-1}_{\rm QCD}\right)$$

Hadronic Form Factor in Space and Time-Like Regions

SJB and GdT in preparation

- The form factor in AdS/QCD is the overlap of the normalizable modes dual to the incoming and outgoing hadron Φ_I and Φ_F and the non-normalizable mode J, dual to the external source (hadron spin σ):

$$F(Q^2)_{I\to F} = R^{3+2\sigma}\int_0^\infty \frac{dz}{z^{3+2\sigma}}\, e^{(3+2\sigma)A(z)}\Phi_F(z)\, J(Q,z)\, \Phi_I(z)$$
$$\simeq R^{3+2\sigma}\int_0^{z_o} \frac{dz}{z^{3+2\sigma}}\, \Phi_F(z)\, J(Q,z)\, \Phi_I(z),$$

- $J(Q,z)$ has the limiting value 1 at zero momentum transfer, $F(0)=1$, and has as boundary limit the external current, $A^\mu = \epsilon^\mu e^{iQ\cdot x} J(Q,z)$. Thus:

$$\lim_{Q\to 0} J(Q,z) = \lim_{z\to 0} J(Q,z) = 1.$$

- Solution to the AdS Wave equation with boundary conditions at $Q=0$ and $z\to 0$:

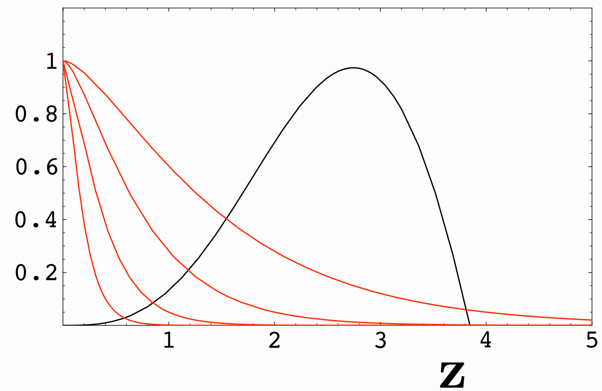
$$J(Q,z) = zQK_1(zQ).$$

Polchinski and Strassler, hep-th/0209211; Hong, Yong and Strassler, hep-th/0409118.

- Propagation of external perturbation suppressed inside AdS.

- At large enough $Q \sim r/R^2$, the interaction occurs in the large-r conformal region. Important contribution to the FF integral from the boundary near $z \sim 1/Q$.

$\mathbf{J}(\mathbf{Q}, \mathbf{z}), \quad \mathbf{\Phi}(\mathbf{z})$

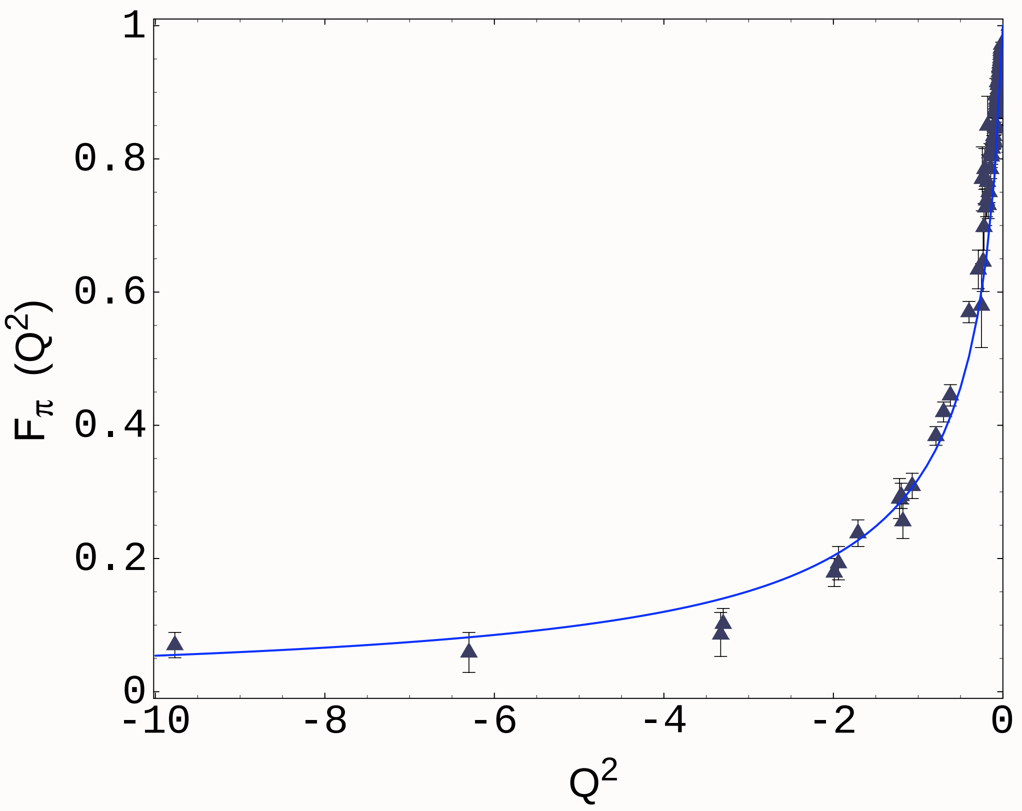


- Consider a specific AdS mode $\Phi^{(n)}$ dual to an n partonic Fock state $|n\rangle$. At small z, $\Phi^{(n)}$ scales as $\Phi^{(n)} \sim z^{\Delta_n}$. Thus:

$$F(Q^2) \to \left[\frac{1}{Q^2}\right]^{\tau - 1},$$

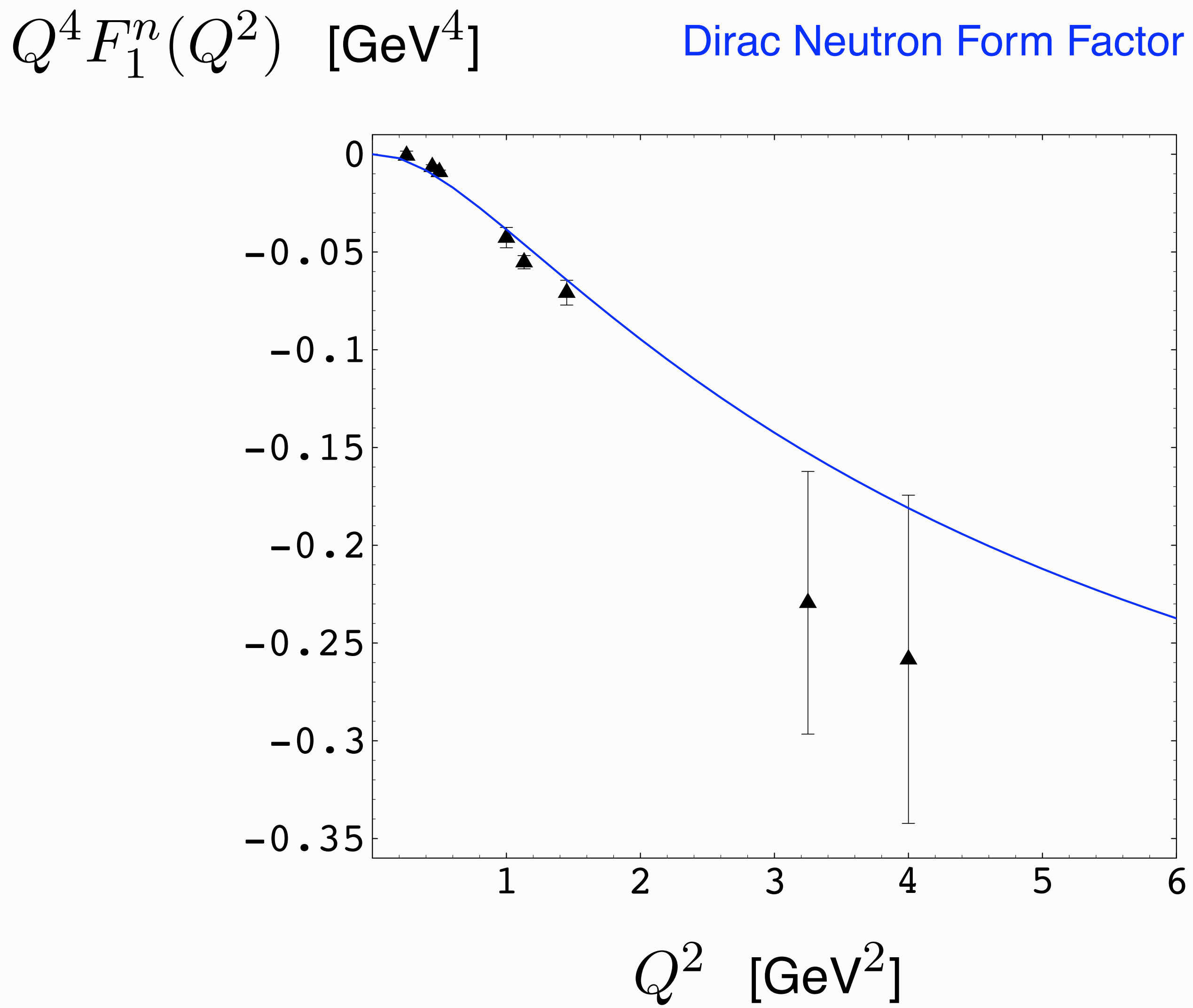
General result from AdS/CFT

where $\tau = \Delta_n - \sigma_n$, $\sigma_n = \sum_{i=1}^{n} \sigma_i$. The twist is equal to the number of partons, $\tau = n$.



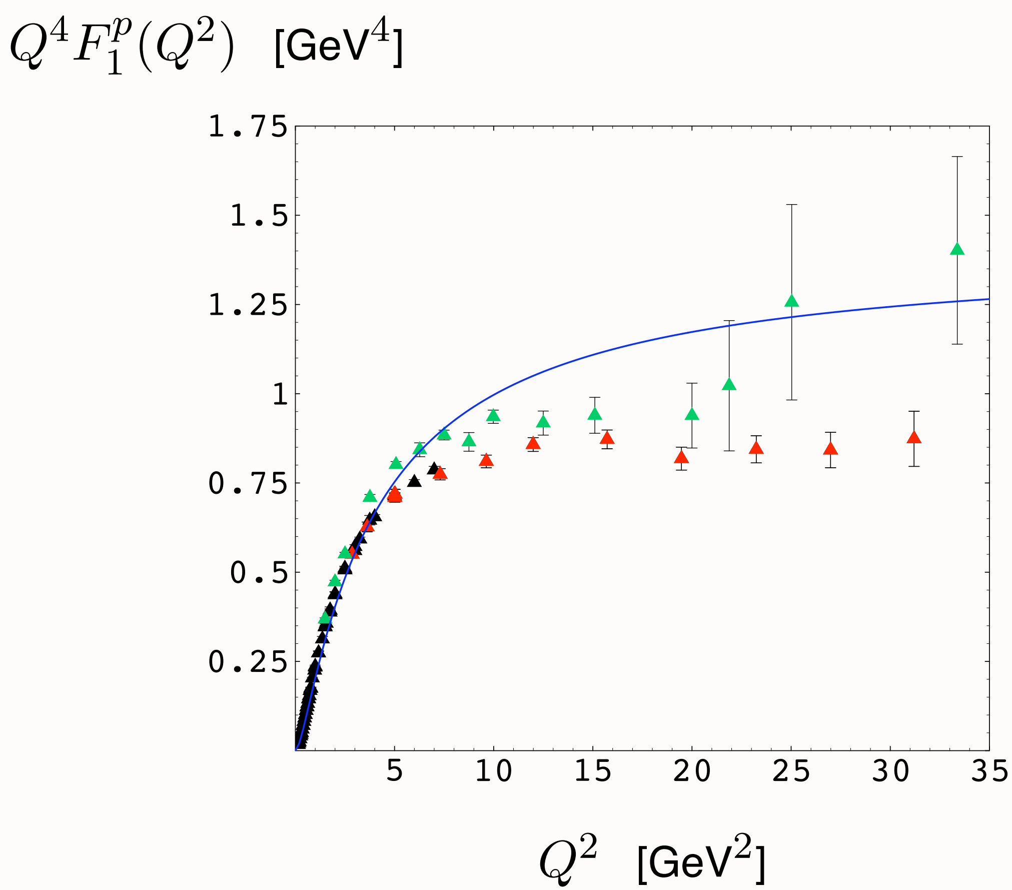
Space-like pion form factor in holographic model for $\Lambda_{QCD} = 0.2$ GeV.

Dirac Neutron Form Factor F_1^n



Prediction for $Q^4 F_1^n(Q^2)$ for $\Lambda_{\rm QCD} = 0.21$ GeV in the infinite wall approximation.

Dirac Proton Form Factor F_1^p



Prediction for $Q^4 F_1^p(Q^2)$ for $\Lambda_{\mathrm{QCD}} = 0.21$ GeV in the infinite wall approximation from Kirk (superimposed green points assuming $G_E^p = G_M^p$): P. N. Kirk *et al.*, Phys. Rev. D **8** (1973) 63.

New Perspectives on QCD from AdS/CFT

- Holographic Model from AdS/CFT : Confinement at large distances and conformal behavior at short distances

- AdS/CFT predicts Light-front wavefunctions: Fundamental description of hadrons at amplitude level

- AdS/CFT: gluonium (gg) , meson ($q\bar{q}$), and baryon (qqq) spectra

- No ggg bound states -- No Odderon!

- Quark-interchange dominates scattering amplitudes !!

- Polchinski & Strassler: AdS/CFT builds in conformal symmetry at short distances, counting, rules for form factors and hard exclusive processes; non-perturbative derivation

- Goal: Use AdS/CFT to provide models of hadron structure: confinement at large distances, near conformal behavior at short distances

- Holographic Model: Initial "classical" approximation to QCD: Remarkable agreement with light hadron spectroscopy

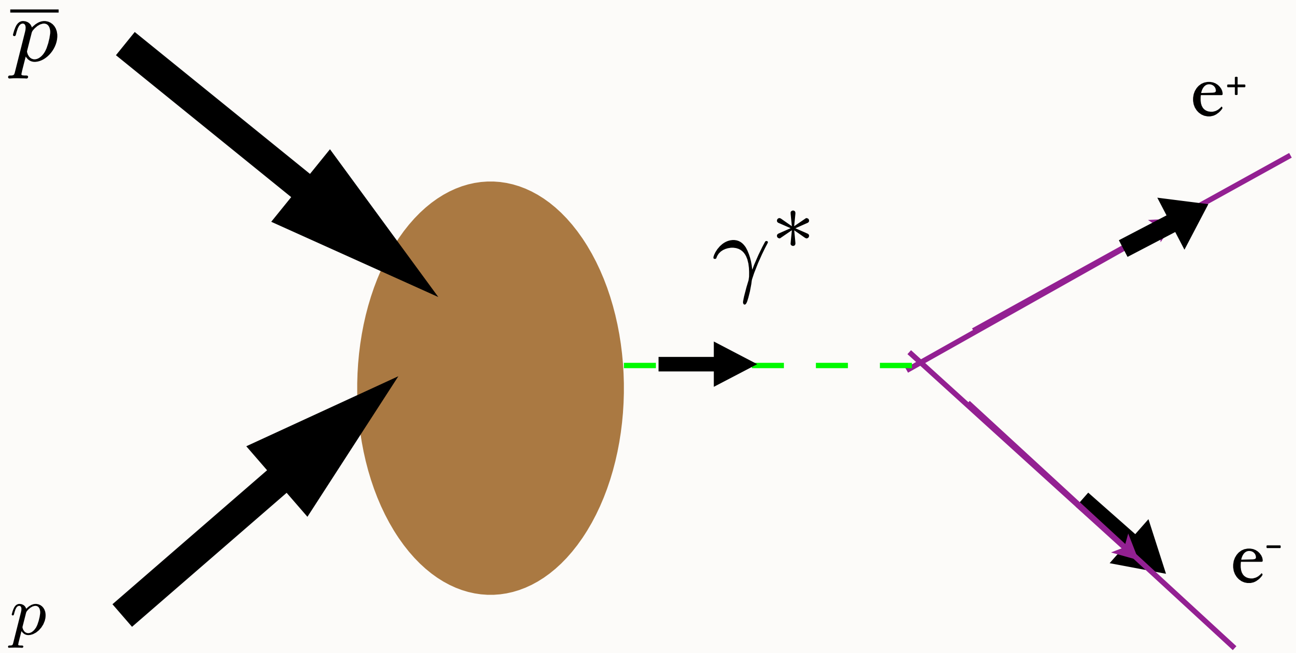
- Use AdS/CFT wavefunctions as expansion basis for diagonalizing H^{LF}_{QCD} ; variational methods

Consequences of AdS/CFT for Antiproton physics

- Analytic form for form factors, distribution amplitude
- Matrix elements and LFWFs for baryon scattering amplitudes: Quark Counting Rules!
- Orbital angular momentum in baryon wavefunction for Pauli form factor, SSAs
- Dominance of quark interchange at short distances
- Effective Regge trajectories

Measurement of hadron time-like form factors angular distributions

Separate F1, F2

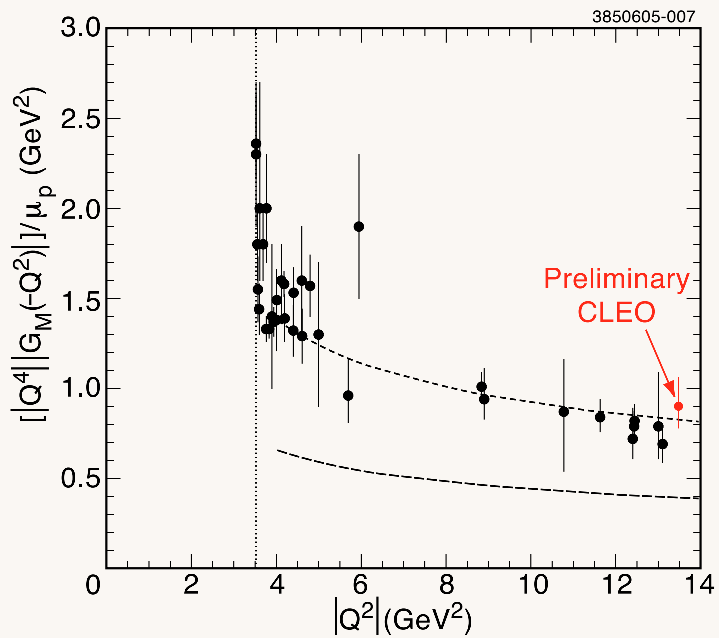


Leading power in QCD

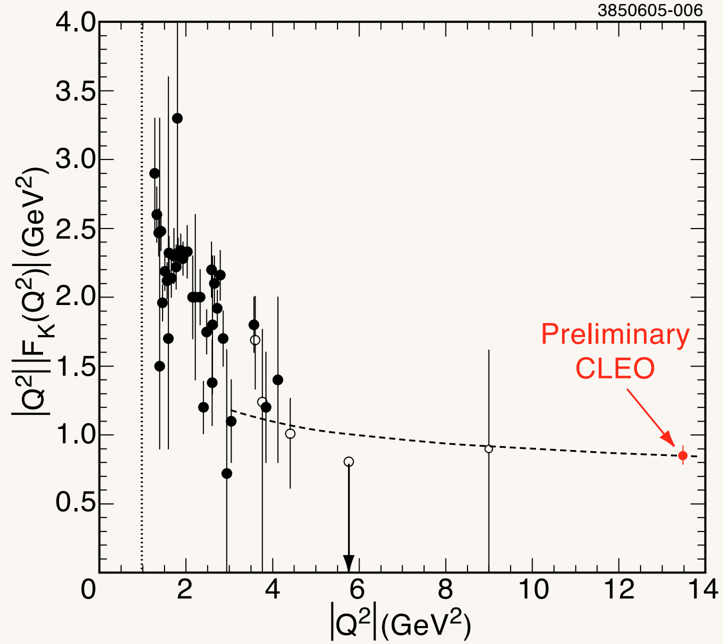
$$F_H(s) \propto [\frac{1}{s}]^{n_H - 1}$$

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

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

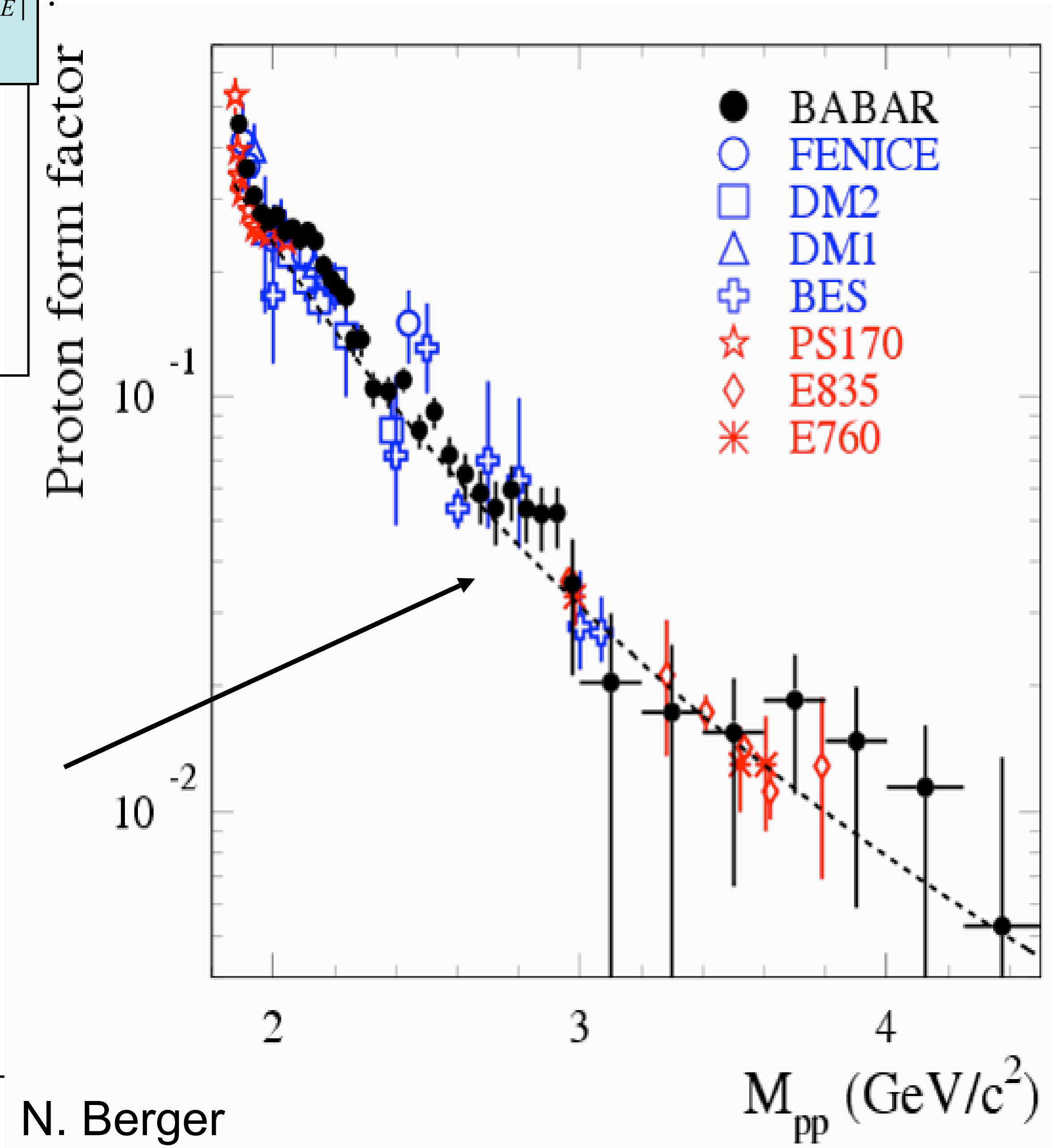
The proton magnetic form factor result agrees with that measured in the reverse reaction $p\bar{p} \to e^+e^-$ at Fermilab. **The kaon form factor measurement is the first ever direct measurement at $|Q^2| > 4$ GeV^2.**

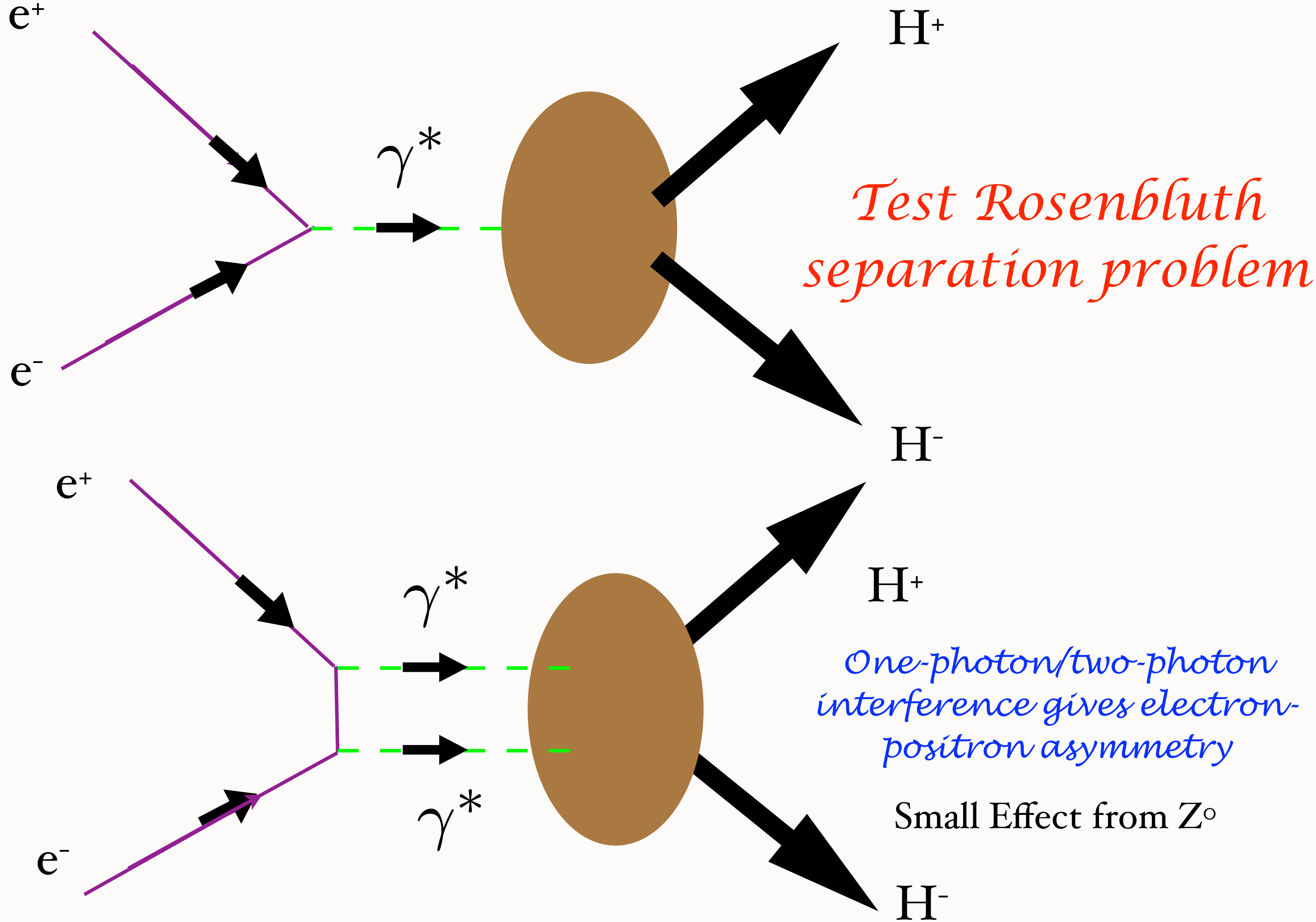
- Define "Effective" form factor by

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

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

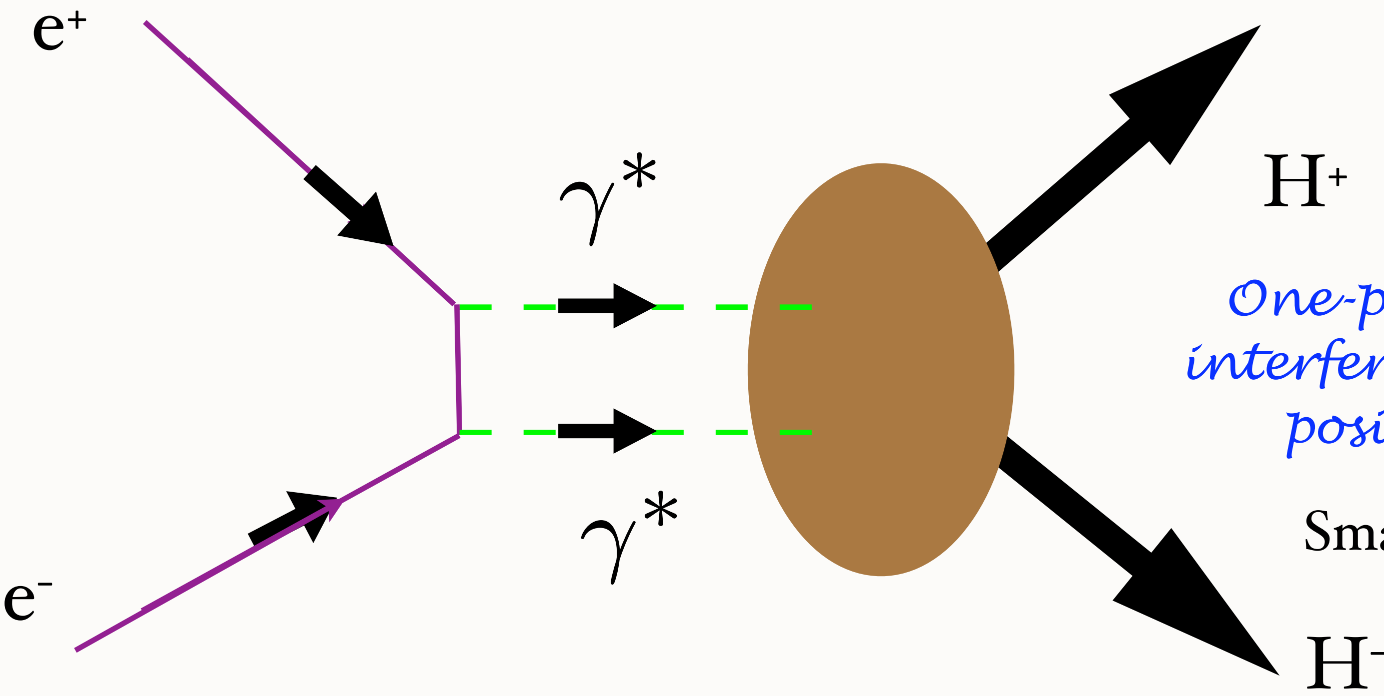
$$F(s) \propto \frac{\log^{-2}\frac{s}{\Lambda^2}}{s^2}$$




e+
e-
γ*
H+
H-
Test Rosenbluth separation problem
e+
e-
γ*
γ*
H+
H-
One-photon/two-photon interference gives electron-positron asymmetry
Small Effect from Z0

- 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



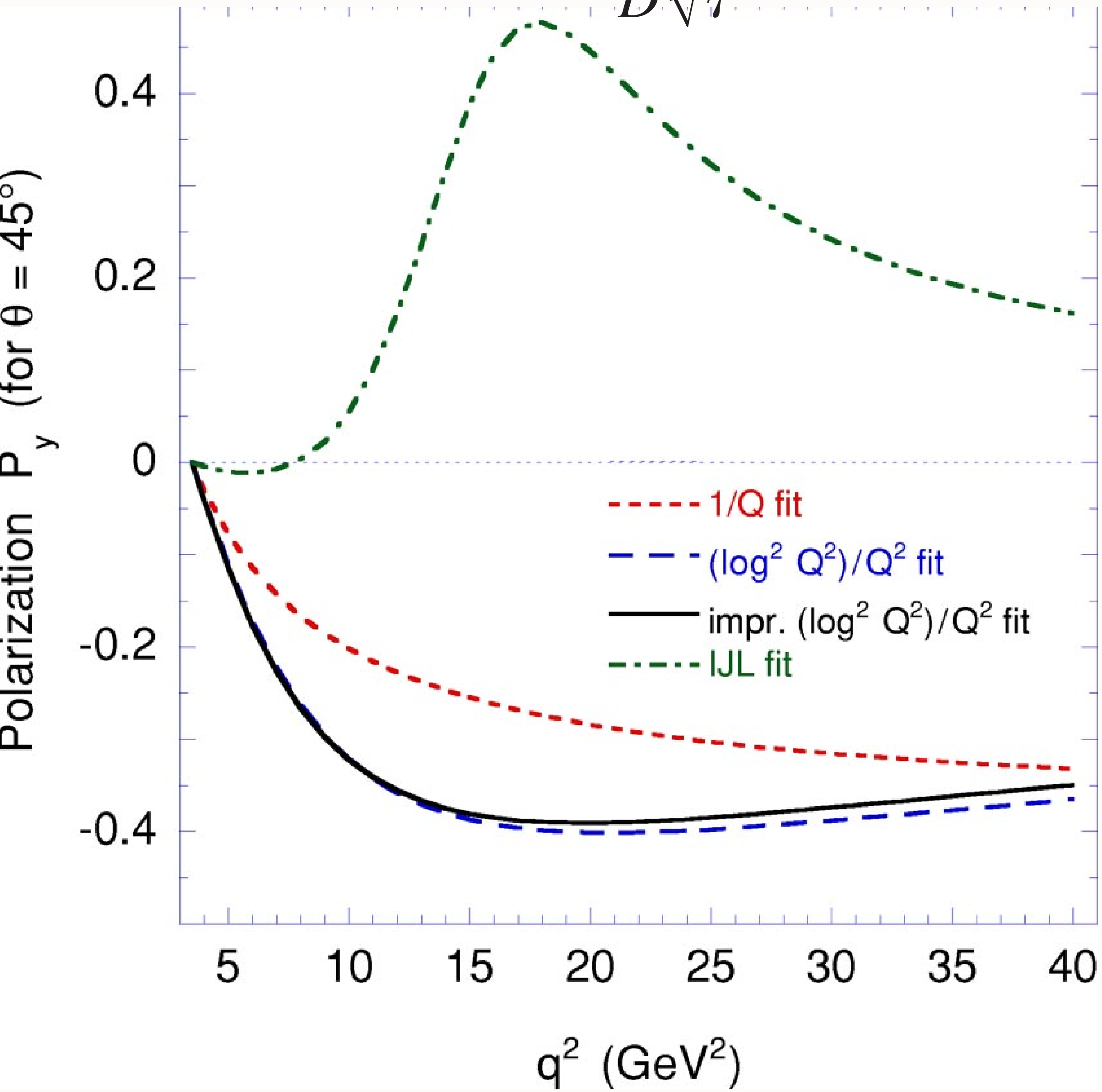
One-photon/two-photon interference gives electron-positron asymmetry

Small Effect from Z^{o}

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



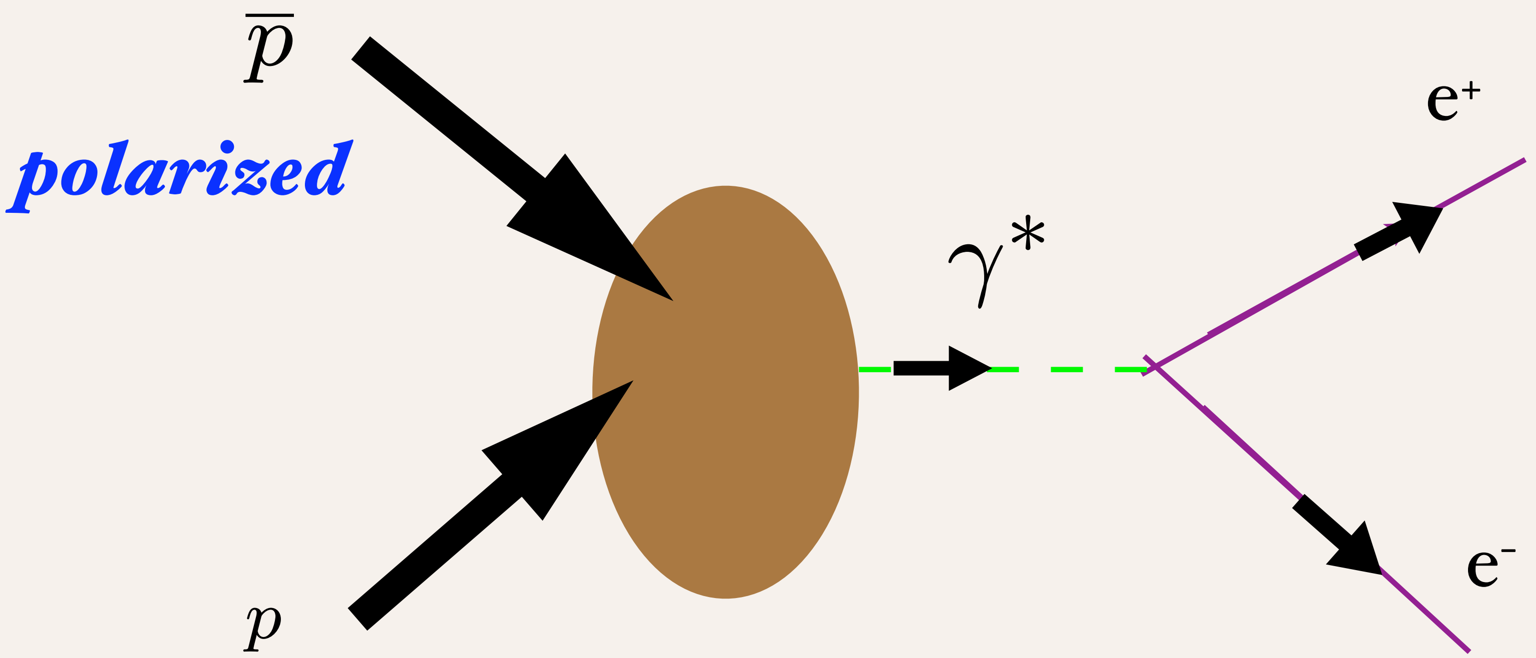
$$D = |G_M|^2(1+\cos^2\theta) + \frac{1}{\tau}|G_E|^2 \sin^2\theta;$$

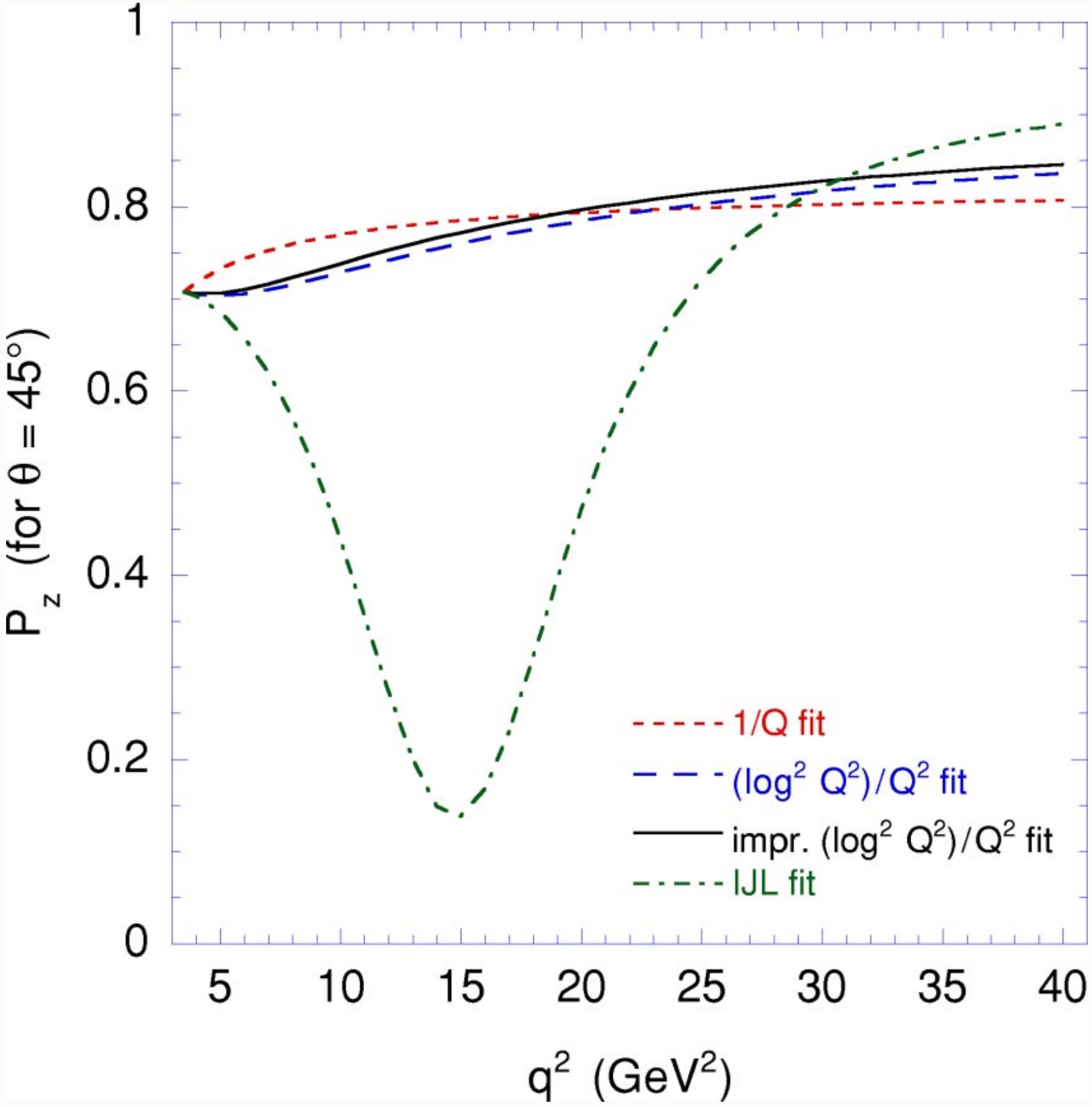
$$\tau \equiv q^2/4m_B^2$$

Measure interference of form factors

Key QCD Experiment at GSI

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



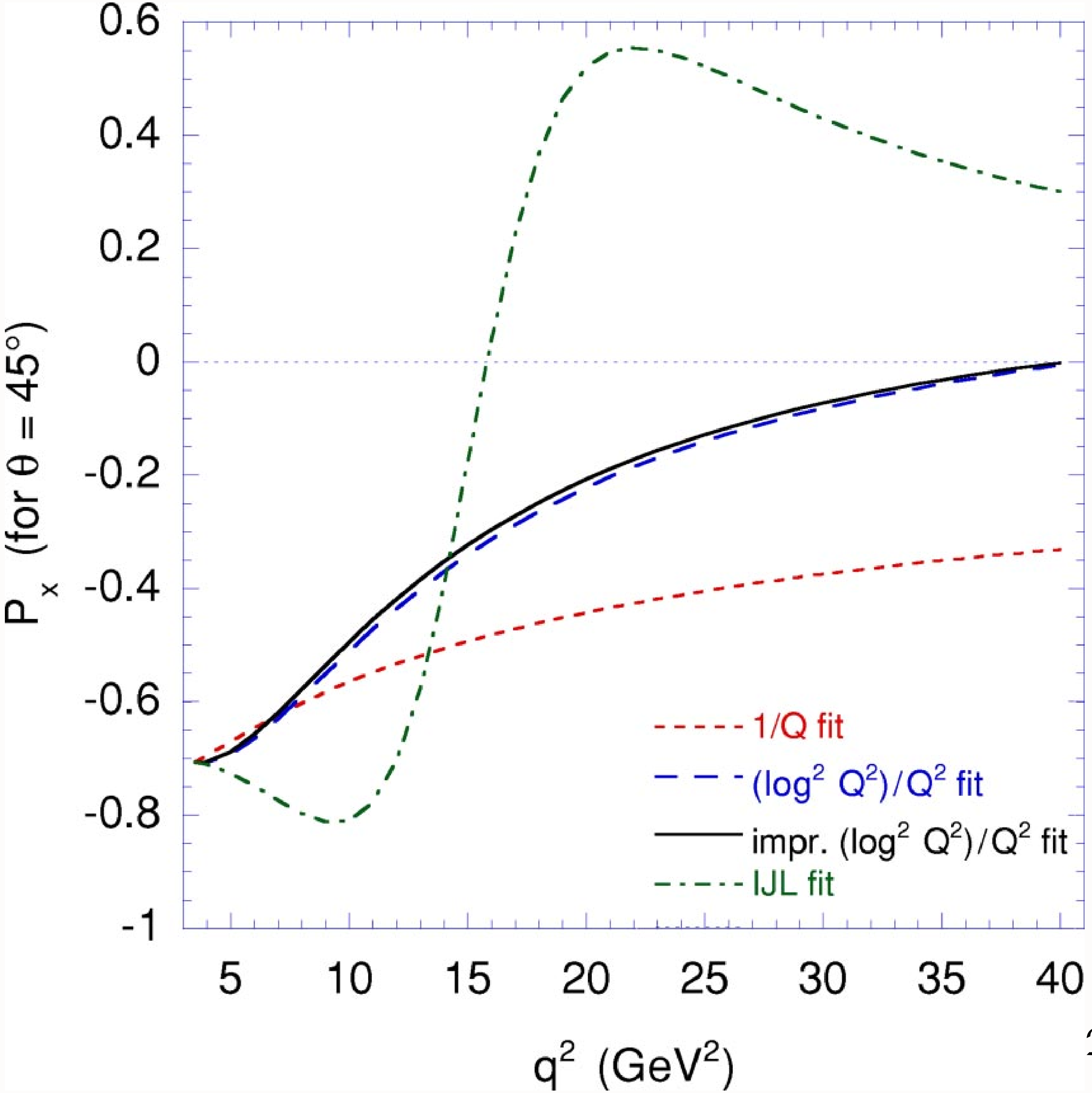


Carlson, Hiller, Hwang, sjb

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

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

Requires beam and lepton polarization



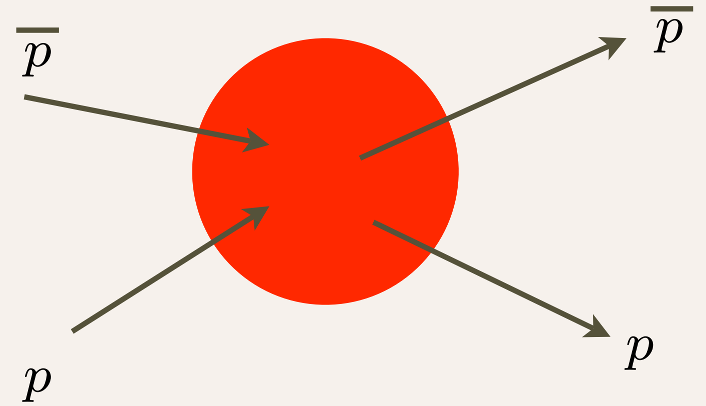
Carlson, Hiller, Hwang, sjb

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

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

Requires beam and lepton polarization

Key QCD Experiment at GSI



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

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

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

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

Test Quark Interchange Mechanism

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

Single-spin asymmetry A_N

Exclusive Transversity A_{NN}

Study Fundamental Aspects of Nuclear Force

Test color transparency

$$\frac{d\sigma}{dt}(pp \to pp) = \frac{F(t/s)}{s^{9.7 \pm 0.5}}$$

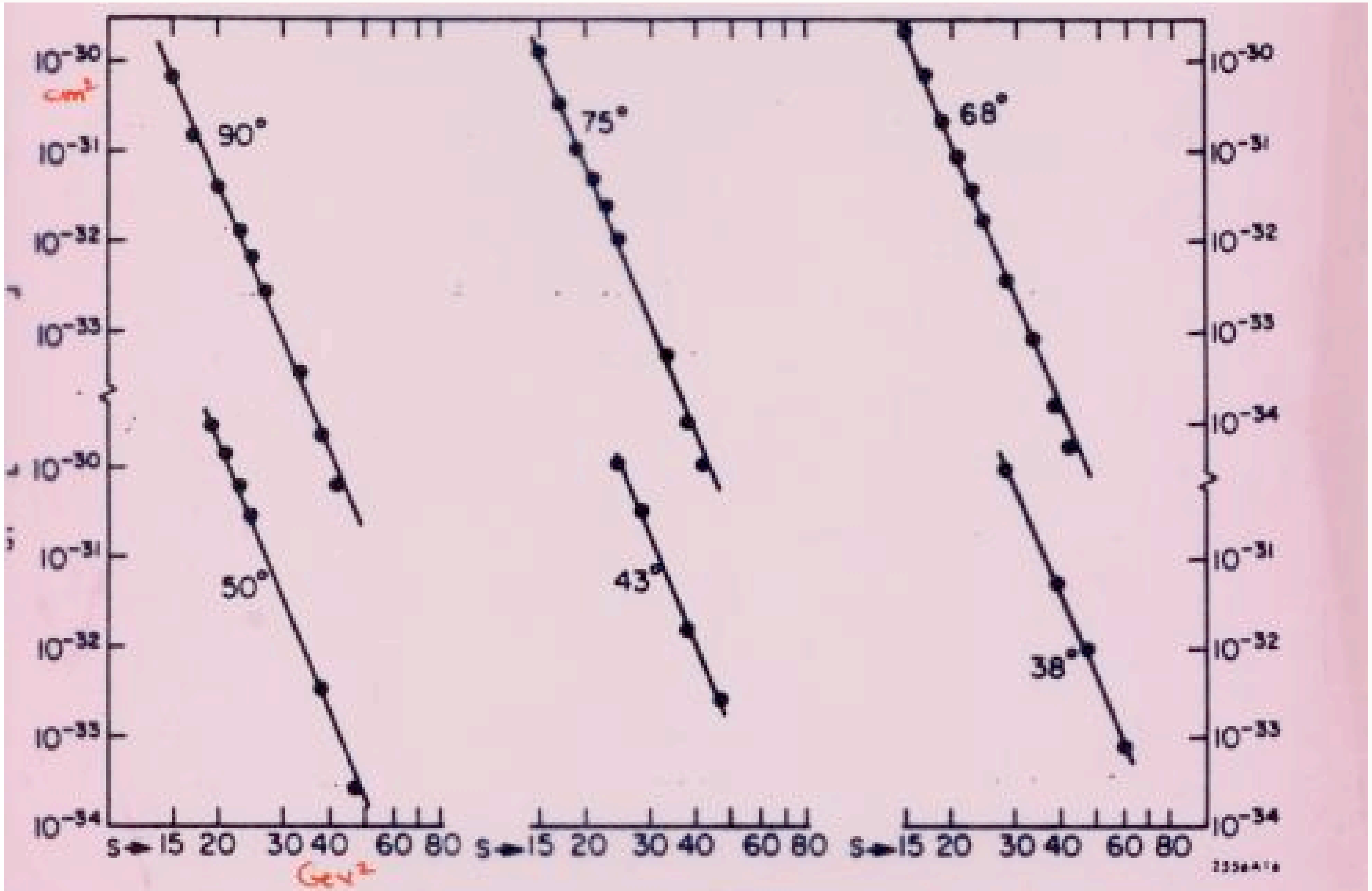
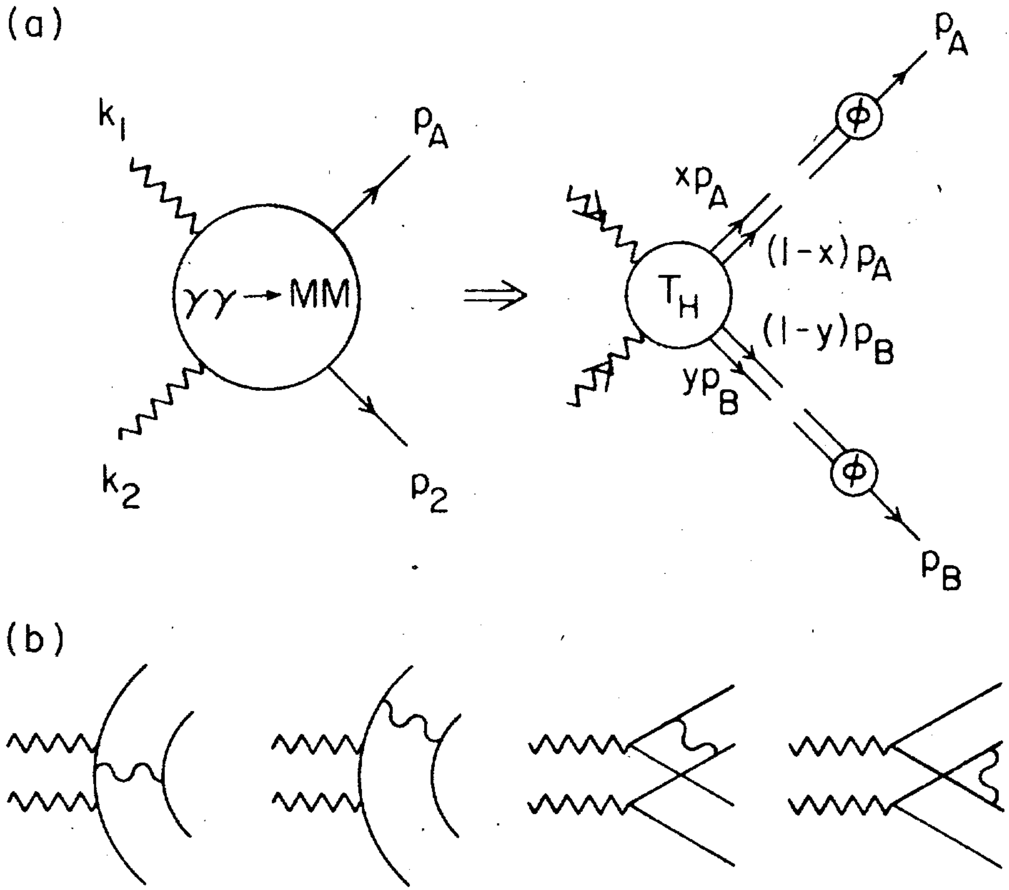
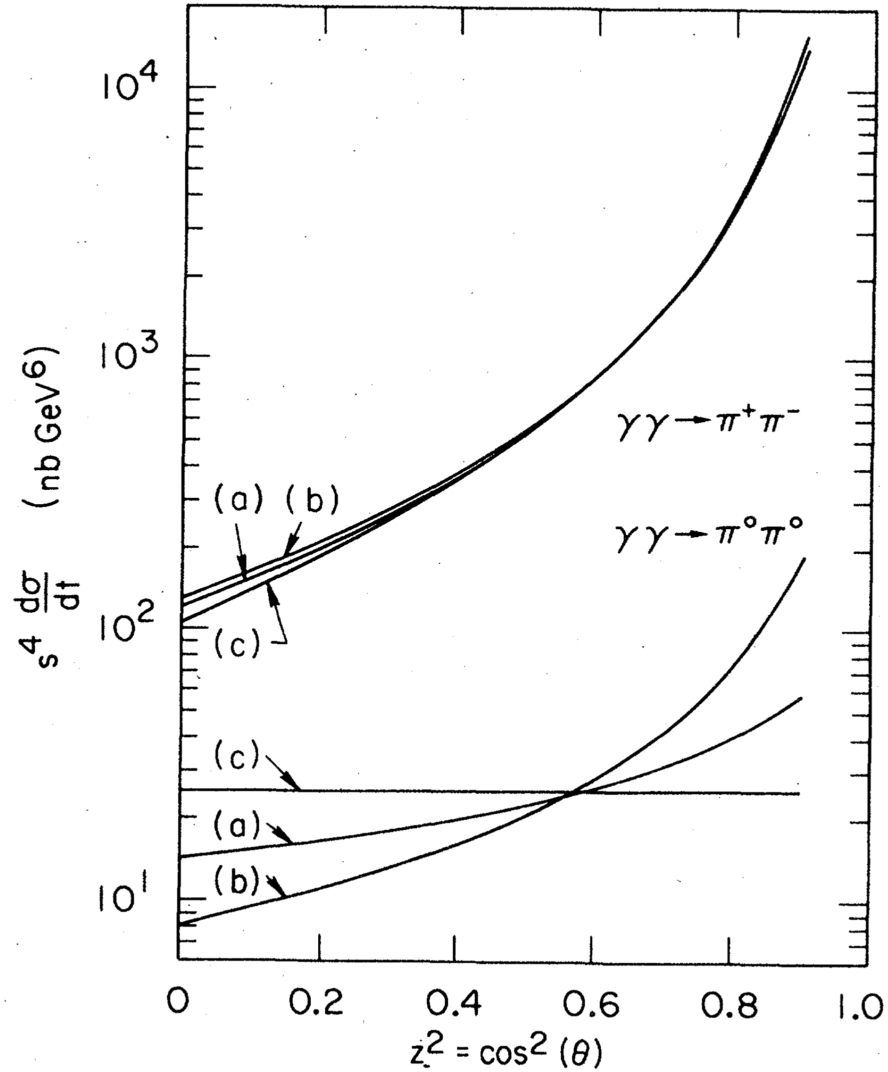


Figure 22. Test of fixed θ_{CM} scaling for elastic pp scattering. The data compilation is Landshoff and Polkinghorne.

But: Oscillations, Anomalous A_N, A_{NN}

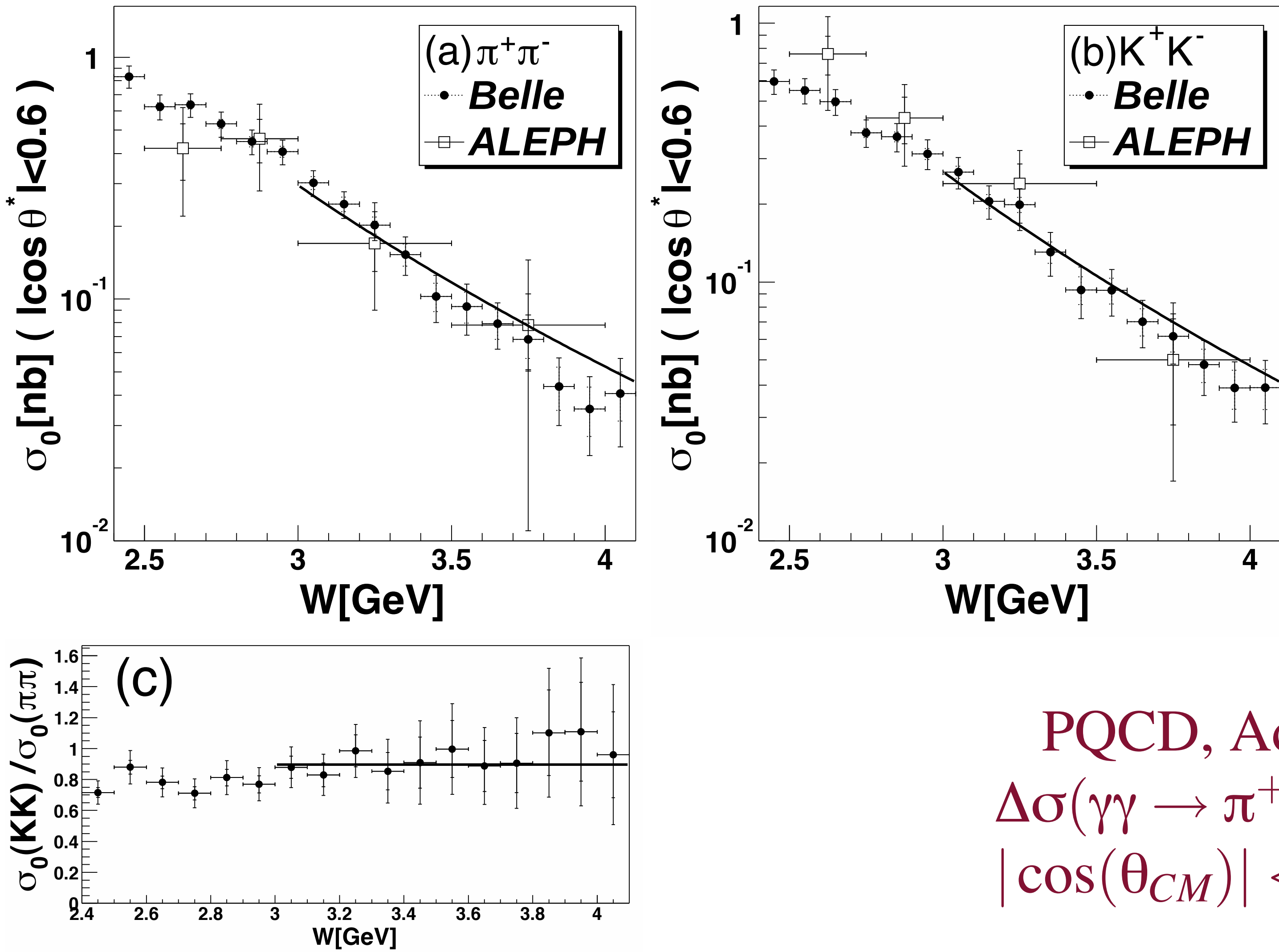




$$\frac{\dfrac{d\sigma}{dt}(\gamma\gamma\to\pi^+\pi^-)}{\dfrac{d\sigma}{dt}(\gamma\gamma\to\mu^+\mu^-)} \sim \frac{4\,|F_\pi(s)\,|^2}{1-\cos^4\theta_{c.m.}}$$

Lepage & sjb

Ratio: Crucial test of Kroll's handbag model



Two Photon Reactions

Hard Exclusive Processes: Fixed angle

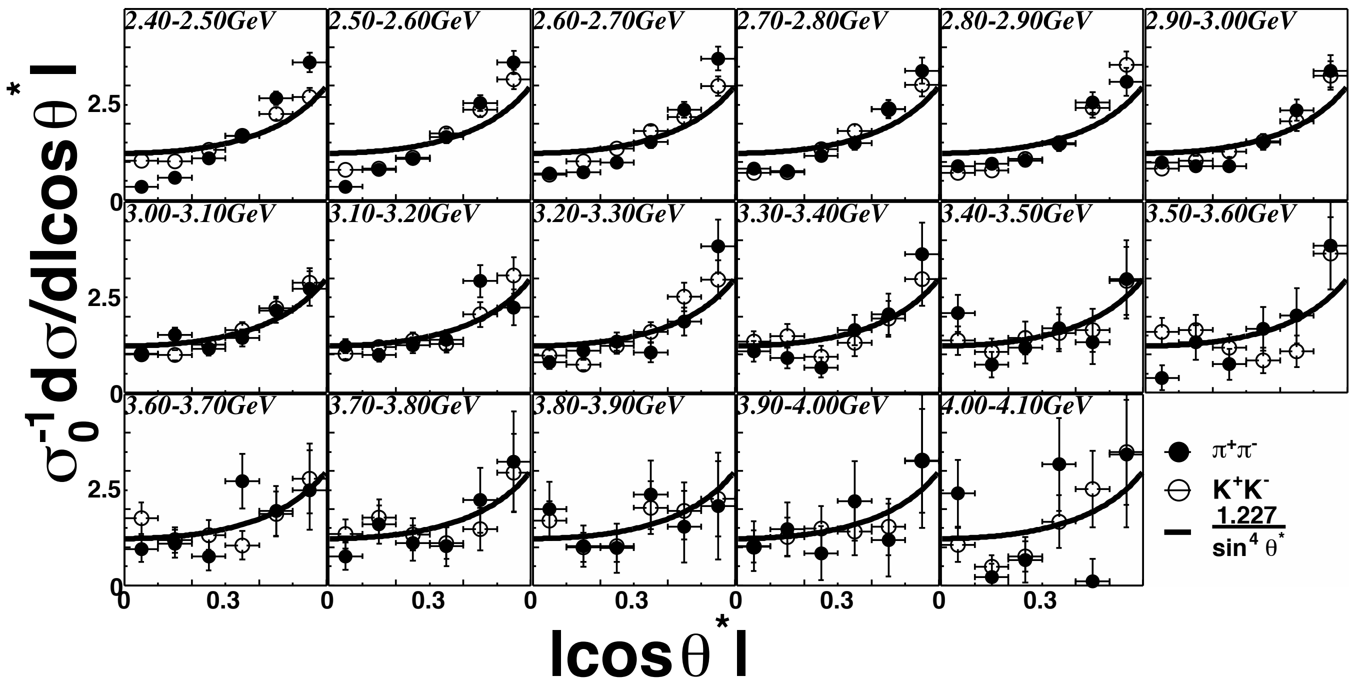
PQCD, AdS/CFT:

$$\Delta\sigma(\gamma\gamma \to \pi^+\pi^-, K^+, K^-) \sim 1/W^6$$

$$|\cos(\theta_{CM})| < 0.6$$

Fig. 5. Cross section for (a) $\gamma\gamma \to \pi^+\pi^-$, (b) $\gamma\gamma \to K^+K^-$ in the c.m. angular region $|\cos\theta^*| < 0.6$ together with a W^{-6} dependence line derived from the fit of $s|R_M|$. (c) shows the cross section ratio. The solid line is the result of the fit for the data above 3 GeV. The errors indicated by short ticks are statistical only.

PQCD: $$\frac{d\sigma}{d|\cos\theta^*|}(\gamma\gamma \to M^+M^-) \approx \frac{16\pi\alpha^2}{s}\frac{|F_M(s)|^2}{\sin^4\theta^*},$$



4. Angular dependence of the cross section, $\sigma_0^{-1}d\sigma/d|\cos\theta^*|$, for the $\pi^+\pi^-$(closed circles) and K^+K^-(open circles) processes. The curves are $1.227 \times \sin^{-4}\theta^*$. The errors are statistical only.

Measurement of the $\gamma\gamma \to \pi^+\pi^-$ and $\gamma\gamma \to K^+K^-$ processes at energies of 2.4–4.1 GeV

Belle Collaboration

Key QCD Experiment at GSI

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

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

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

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

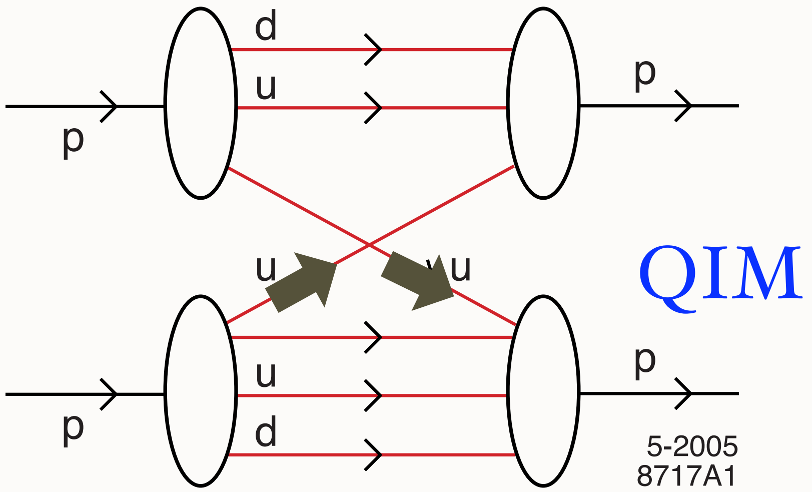
$M_{QIM} = \int d^2k_\perp dx \; \psi^\dagger_C \psi^\dagger_D \Delta \psi_A \psi_B$

Holographic model (Classical level):

Hadrons enter 5th dimension of AdS_5

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

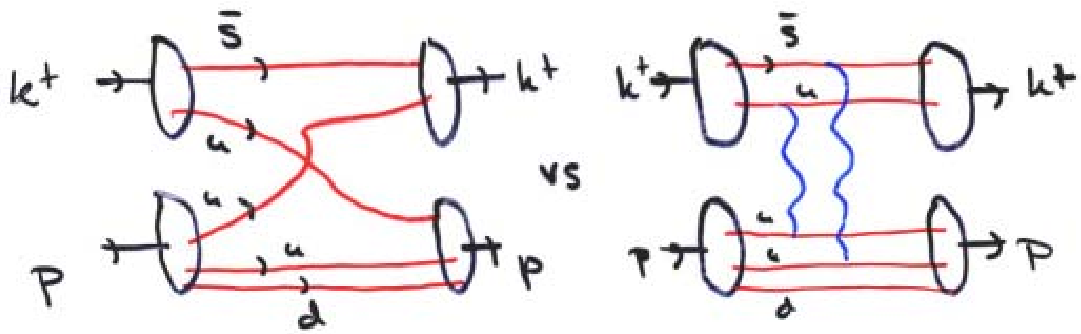
LFWFs obey conformal symmetry producing quark counting rules.



Angular Distribution $-t/s = \frac{1}{2}(1-\cos\theta_{cm})$

$$\frac{d\sigma}{dt} = \frac{1}{s^{n_{TOT}-2}} F(t/s)$$

determined by scattering mechanism



Quark Interchange vs gluon exchange

analogous to spin exchange in atom-atom scattering

Van der Waals

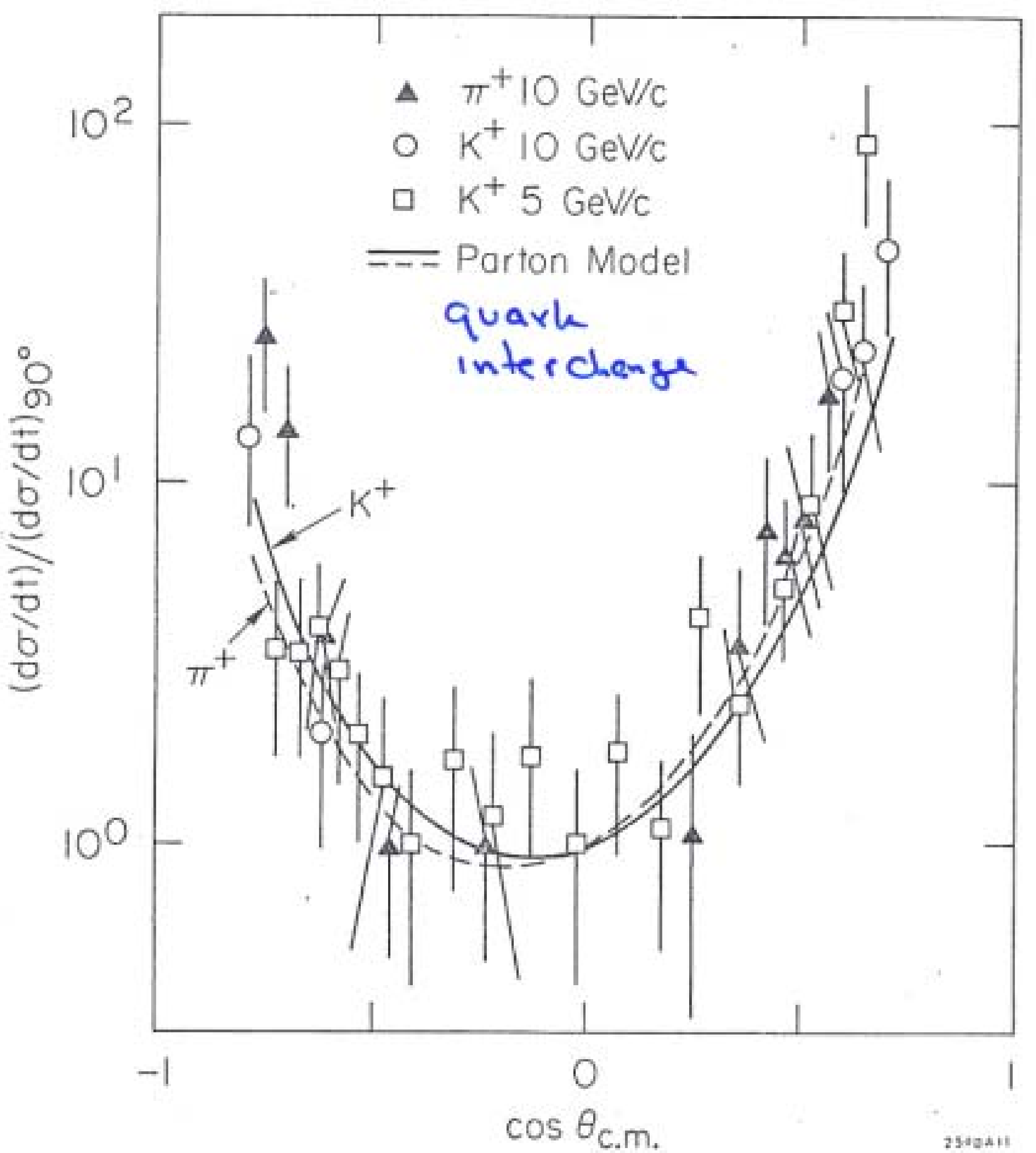
Large N_c: Quark Interchange Dominant

$$\mathcal{M} \sim \frac{1}{u}\frac{1}{t^2}$$

't Hooft Limit, AdS/CFT

Blankenbecler, Gunion, sjb

MIT Bag Model predicts dominance of quark interchange: deTar



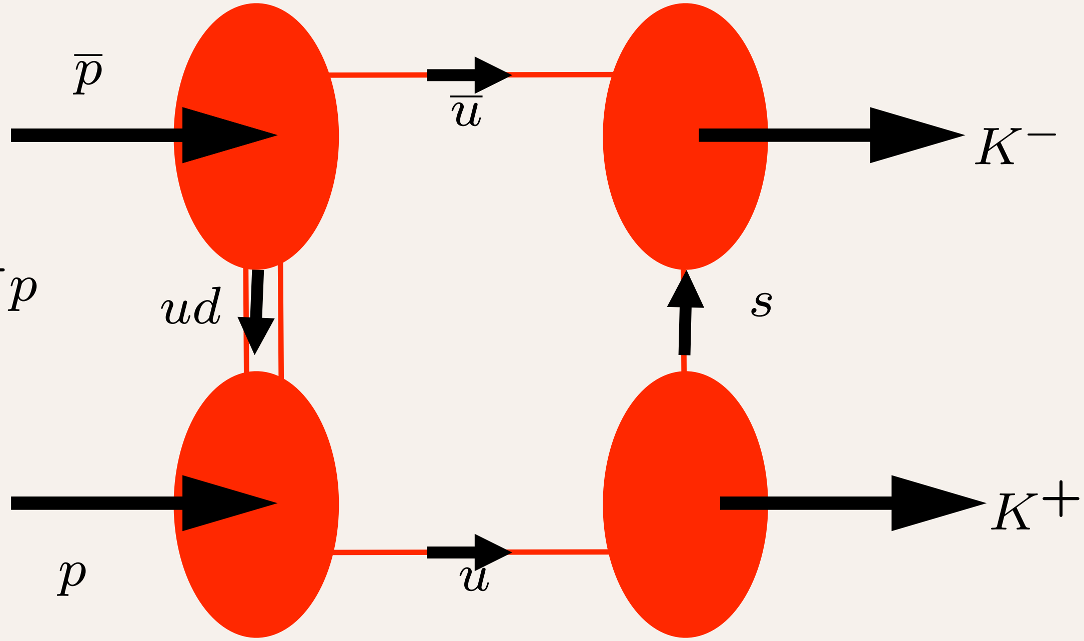
π⁺ 10 GeV/c
K⁺ 10 GeV/c
K⁺ 5 GeV/c
Parton Model
quark interchange
K⁺
π⁺
10²
10¹
10⁰
(dσ/dt)/(dσ/dt)90°
-1
0
1
cos θc.m.

Key QCD Experiment at GSI

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

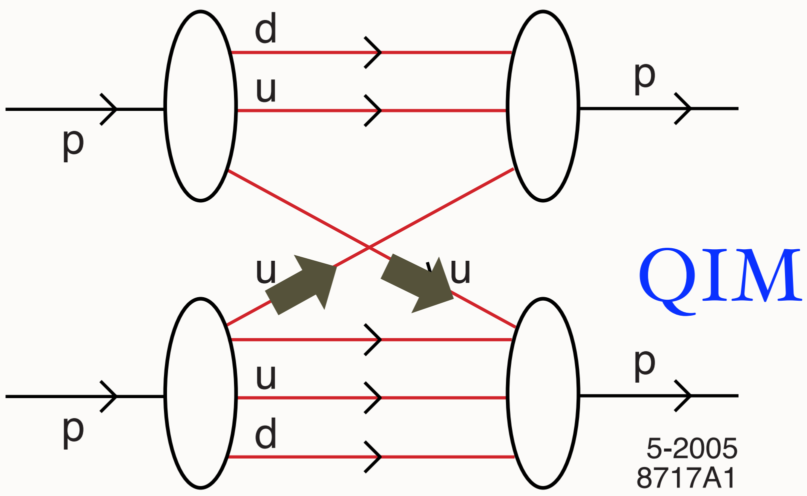
$s \leftrightarrow t$ $t \leftrightarrow u$ crossing of $K^+p \to K^+p$

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



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

at large t, u



$$\frac{d\sigma}{dt}(pp \to pp) = C\,\frac{F_p^{\,2}(t)F_p^{\,2}(u)}{s^2}$$

$$\frac{d\sigma}{dt} = \frac{1}{s^{10}} f(\theta_{c.m.})\,, \quad f(\theta_{c.m.}) \sim \left(\frac{1}{1-\cos^2\theta}\right)^4 .$$

The biggest failure of the interchange mechanism is in the spin correlation. For all angles we predict from Table I

$$A_{nn} = \frac{1}{3}\,\frac{1-(\frac{3}{31})^2\chi^2}{1+\frac{1}{3}(\frac{3}{31})^2\chi^2}\,, \qquad (3.11)$$

where

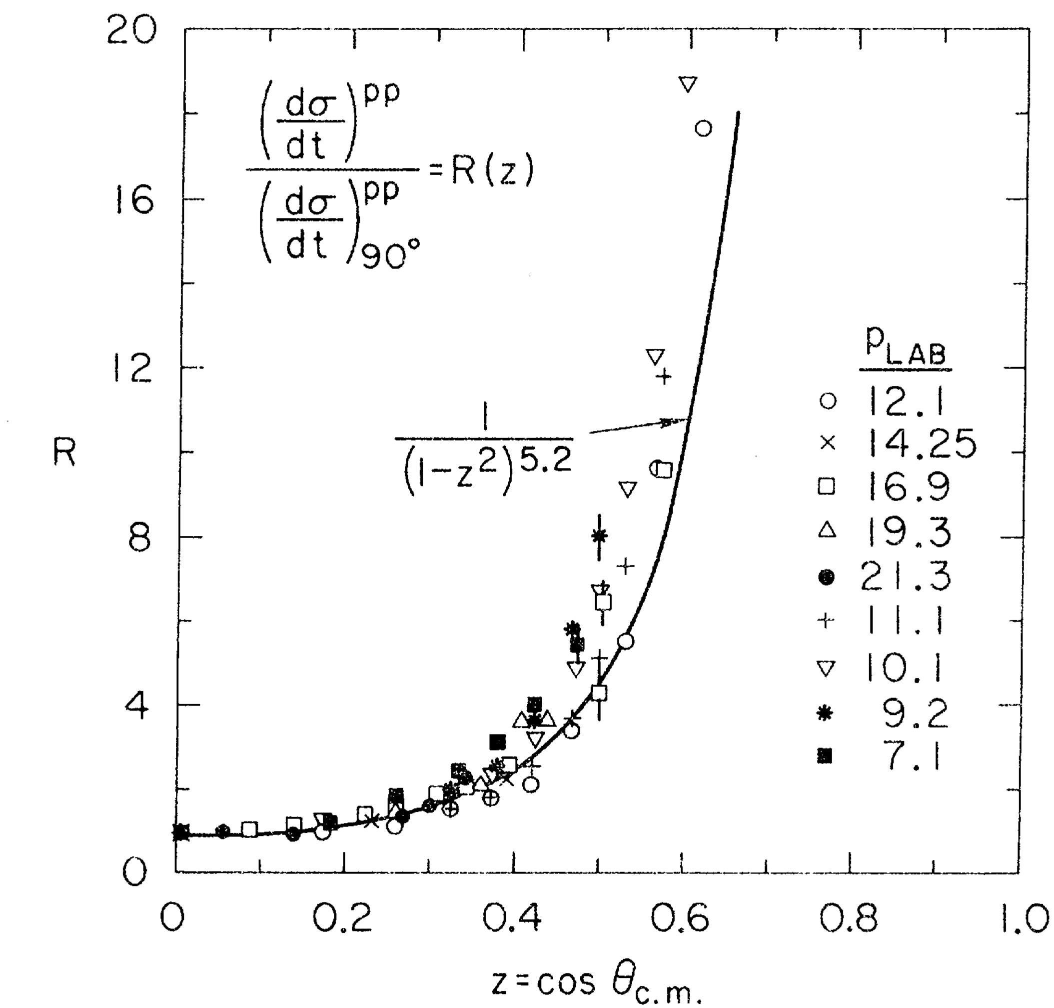
$$\chi = \frac{f(\theta)-f(\pi-\theta)}{f(\theta)+f(\pi-\theta)}\,.$$

Thus A_{nn} is predicted to be within 2% of $\frac{1}{3}$ even when $\chi = 1$ [$\chi = 0$ for the form in Eq. (3.6)]. The data clearly indicate that A_{nn} is not a constant near $\frac{1}{3}$.

Our expectation, then, is that there is an additional amplitude which strongly interferes with the quark-interchange contributions at Argonne energies; most plausibly, the quark-interchange contribution is dominant at asymptotic t and u, and the interfering amplitude is most important at low t and u. As we shall discuss below, the behavior of A_{ll} and A_{ss} in the interference region can play an important role in sorting out the possible subasymptotic contributions.

These results for the quark-interchange model have also been obtained by Farrar, Gottlieb, Sivers, and Thomas,[12] who also consider the possibility that nonperturbative effects (quark-quark scattering via instantons) can explain the data.

Test of Quark Interchange Mechanism in QCD



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

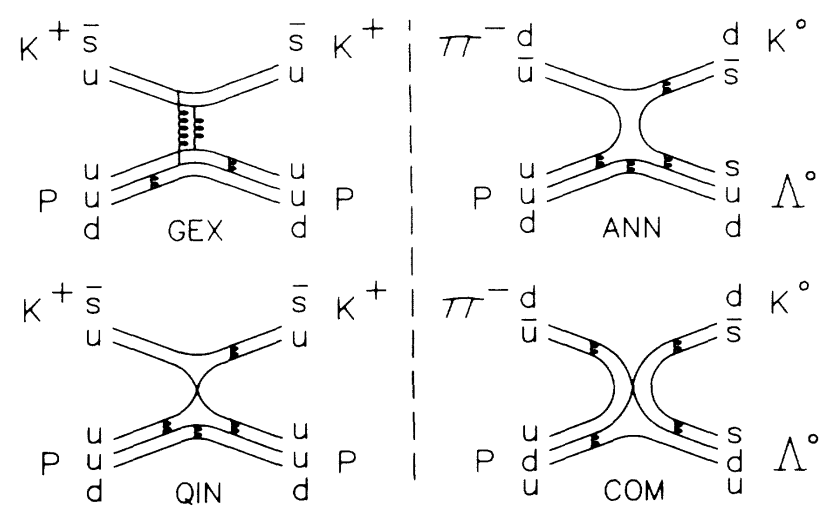
D. S. Barton, G. Bunce, A. S. Carroll, and Y. I. Makdisi
Brookhaven National Laboratory, Upton, New York 11973

and

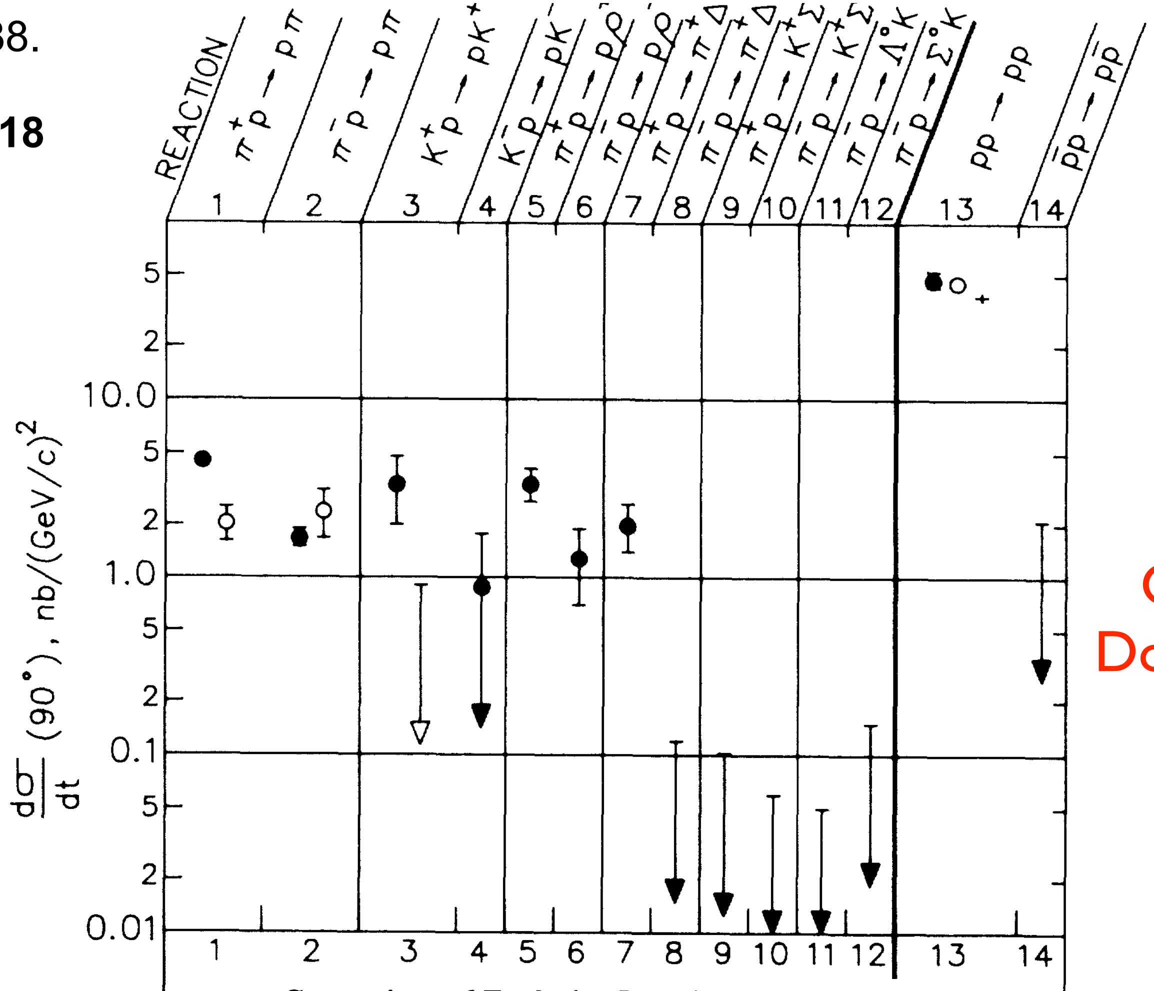
S. Gushue[e] and J. J. Russell
Southeastern Massachusetts University, North Dartmouth, Massachusetts 02747
(Received 28 October 1987; revised manuscript received 3 February 1988)

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.

$$\pi^{\pm}p \to p\pi^{\pm},$$
$$K^{\pm}p \to pK^{\pm},$$
$$\pi^{\pm}p \to p\rho^{\pm},$$
$$\pi^{\pm}p \to \pi^{+}\Delta^{\pm},$$
$$\pi^{\pm}p \to K^{+}\Sigma^{\pm},$$
$$\pi^{-}p \to \Lambda^0K^0, \Sigma^0K^0,$$
$$p^{\pm}p \to pp^{\pm}.$$



B.R. Baller *et al.*. 1988.
Published in
Phys.Rev.Lett.60:1118 -1121,1988



Comparison of Exclusive Reactions at Large *t*

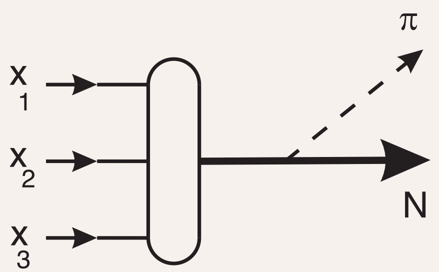
Quark Interchange: Dominant Dynamics at large t, u

Relative Rates Correct

The cross section and upper limits (90% confidence level) measured by this experiment are indicated by the filled circles and arrowheads. Values from this experiment and from previous measurements represent an average over the angular region of $-0.05 < \cos\theta_{\rm c.m.} < 0.10$. The other measurements were obtained from the following references: π^+p and K^+p elastic, Ref. 5; $\pi^-p \to p\pi^-$, Ref. 6; $pp \to pp$, Ref. 7: Allaby, open circle; Akerlof, cross. Values for the cross sections [(Reaction), cross section in nb/(GeV/c)^2] are as follows: (1), 4.6 ± 0.3; (2), 1.7 ± 0.2; (3), 3.4 ± 1.4; (4), $0.9^{+0.7}_{-0.9}$; (5), 3.4 ± 0.7; (6), 1.3 ± 0.6; (7), 2.0 ± 0.6; (8), < 0.12; (9), < 0.1; (10), < 0.06; (11), < 0.05; (12), < 0.15; (13), 48 ± 5; (14), < 2.1.

Key QCD Experiment at GSI

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

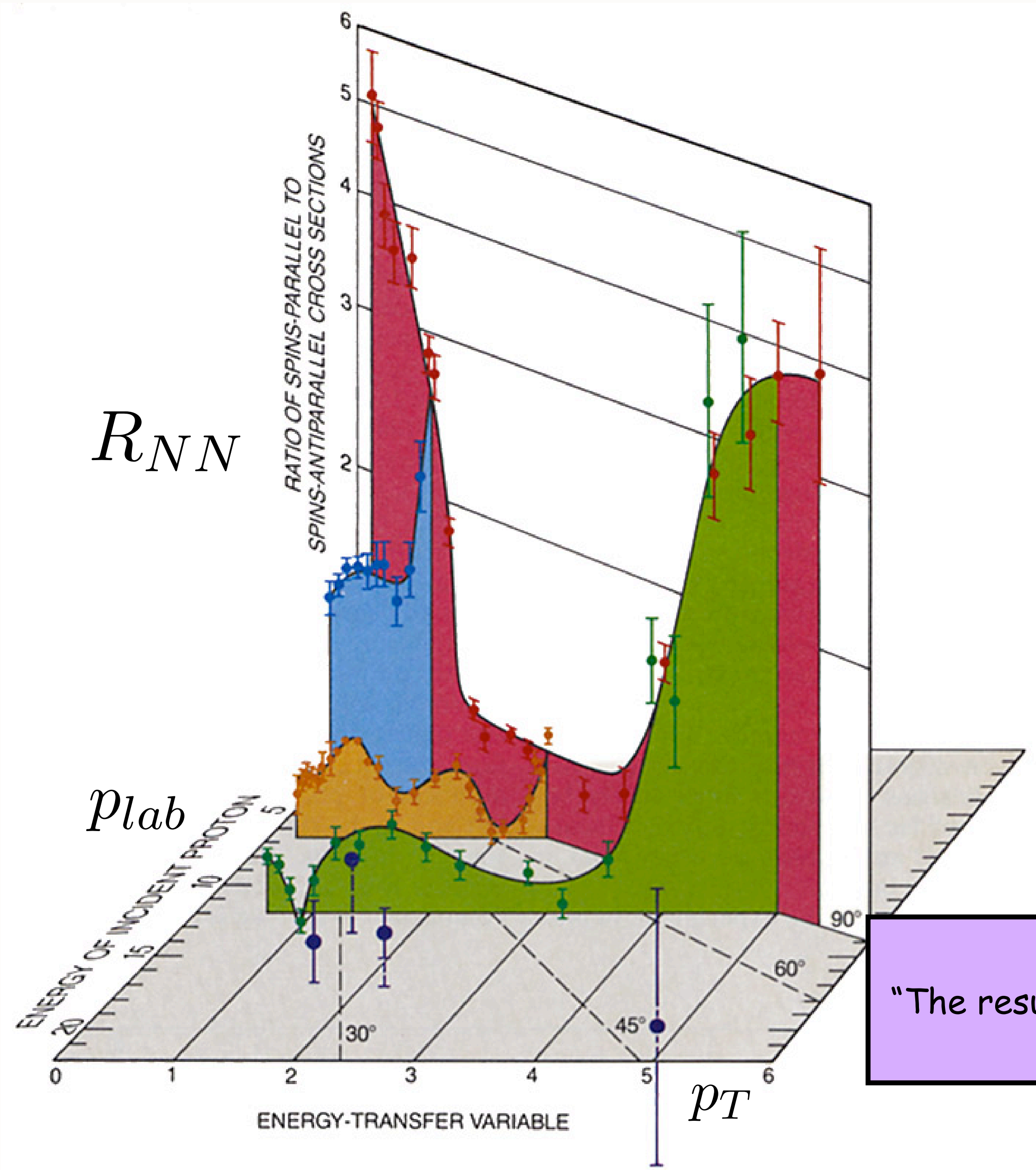
$$\frac{d\sigma}{dt}(\overline{p}p \to \overline{p}p) = \frac{F(\theta_{cm})}{s^{10}}$$

The remarkable anomalies of proton-proton scattering

- Double spin correlations
- Single spin correlations
- Color transparency

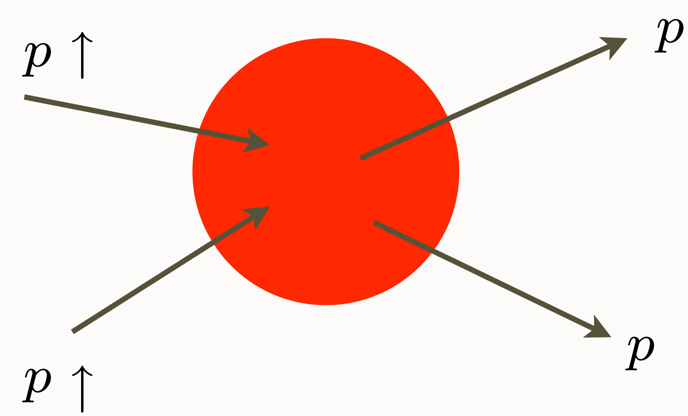
Spin Correlations in Elastic $p - p$ Scattering

R_{NN}



p_{lab}

p_T

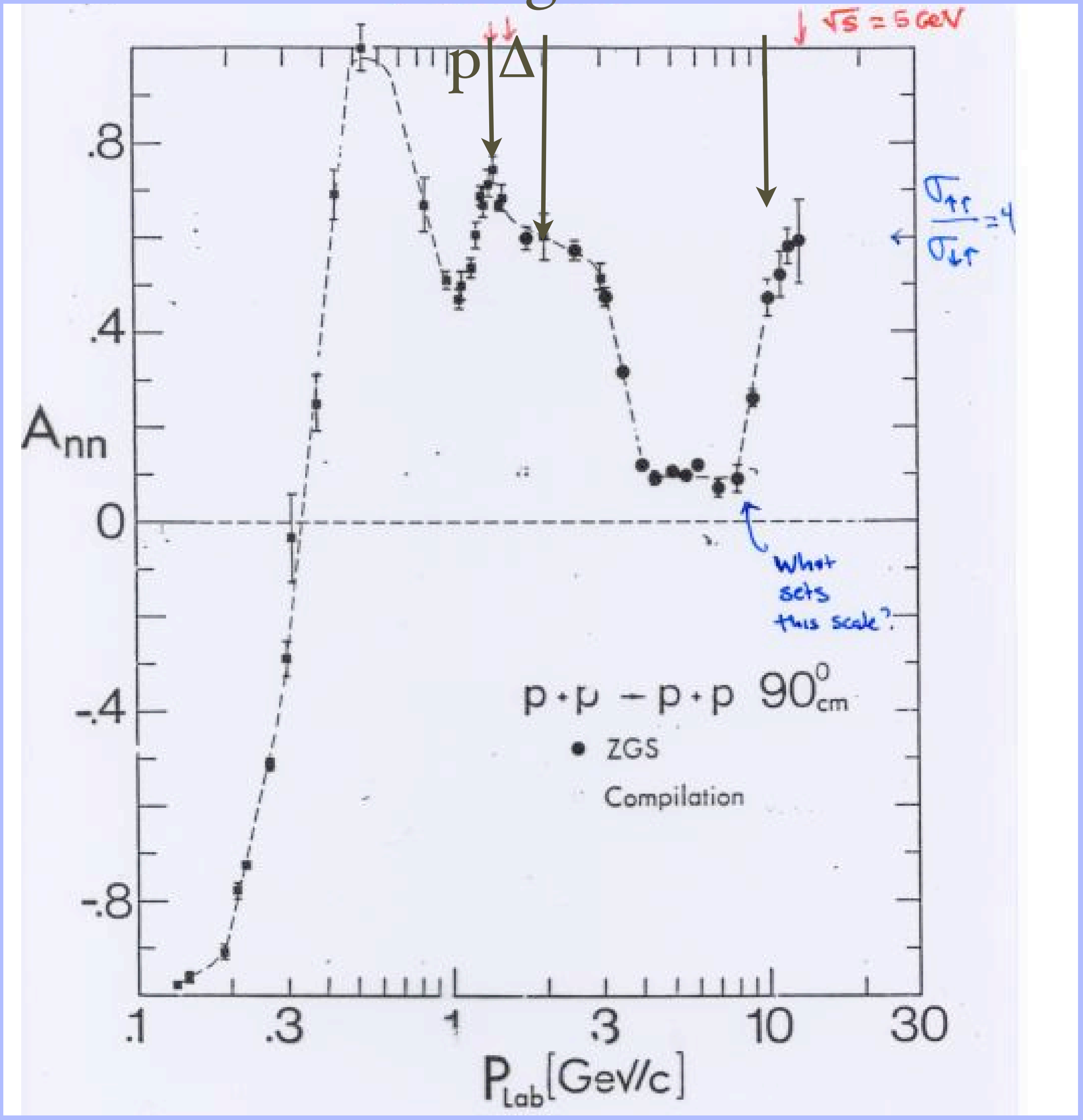


polarization normal to scattering plane

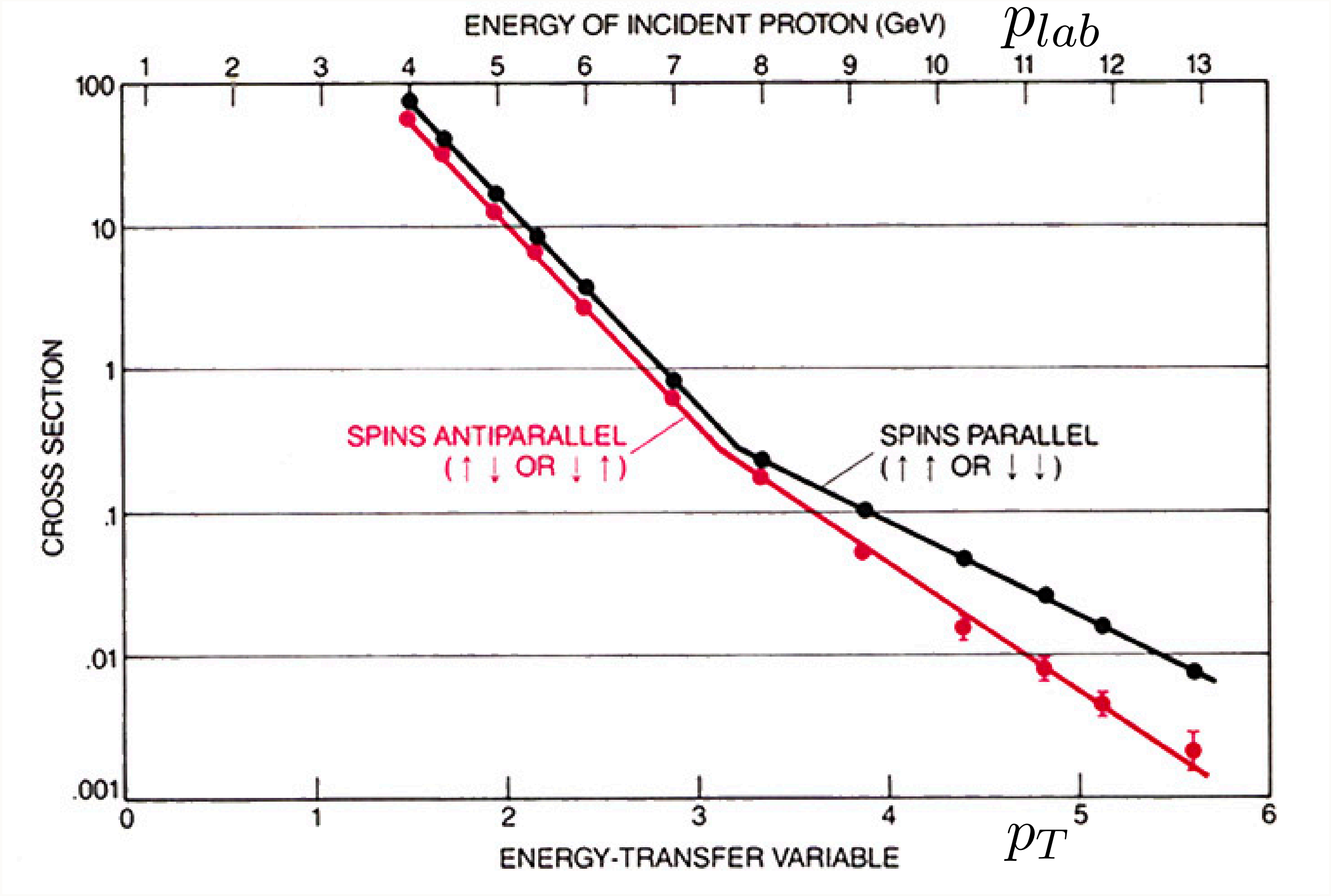
Ratio reaches 4:1 !

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

Strangeness Charm



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



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

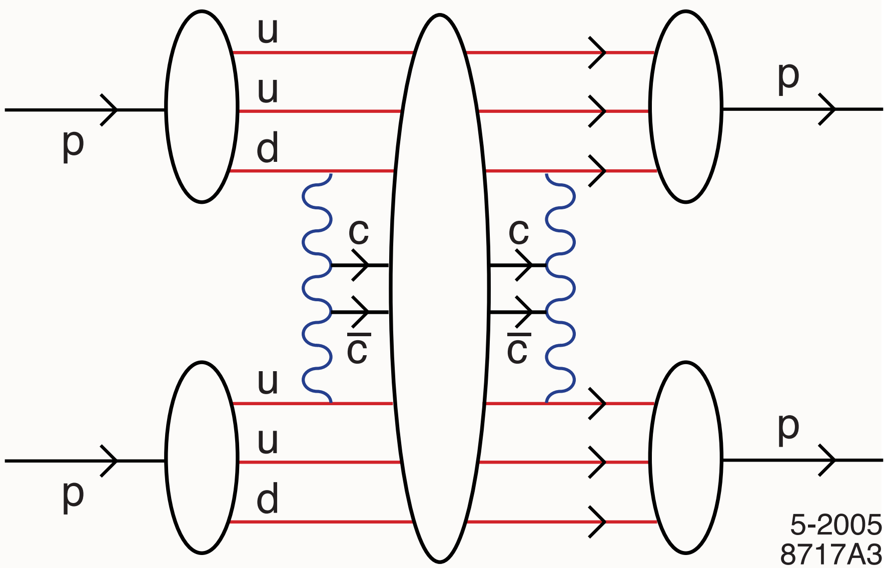
Interference of QIM and Landshoff "Pinch" (triple scattering) contributions

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

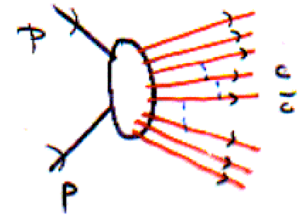


QCD
Schwinger - Sommerfeld
Enhancement

Hebecker, Kuhn, sjb

Spin, Coherence at heavy quark thresholds

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



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!

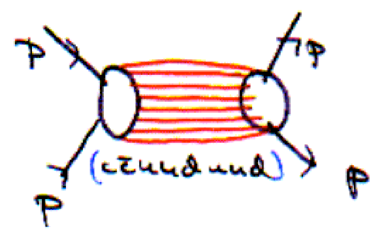
$\therefore\ J = L = S = 1$ for pp

$B = 2$ resonance near threshold?

sjb + deTeramond

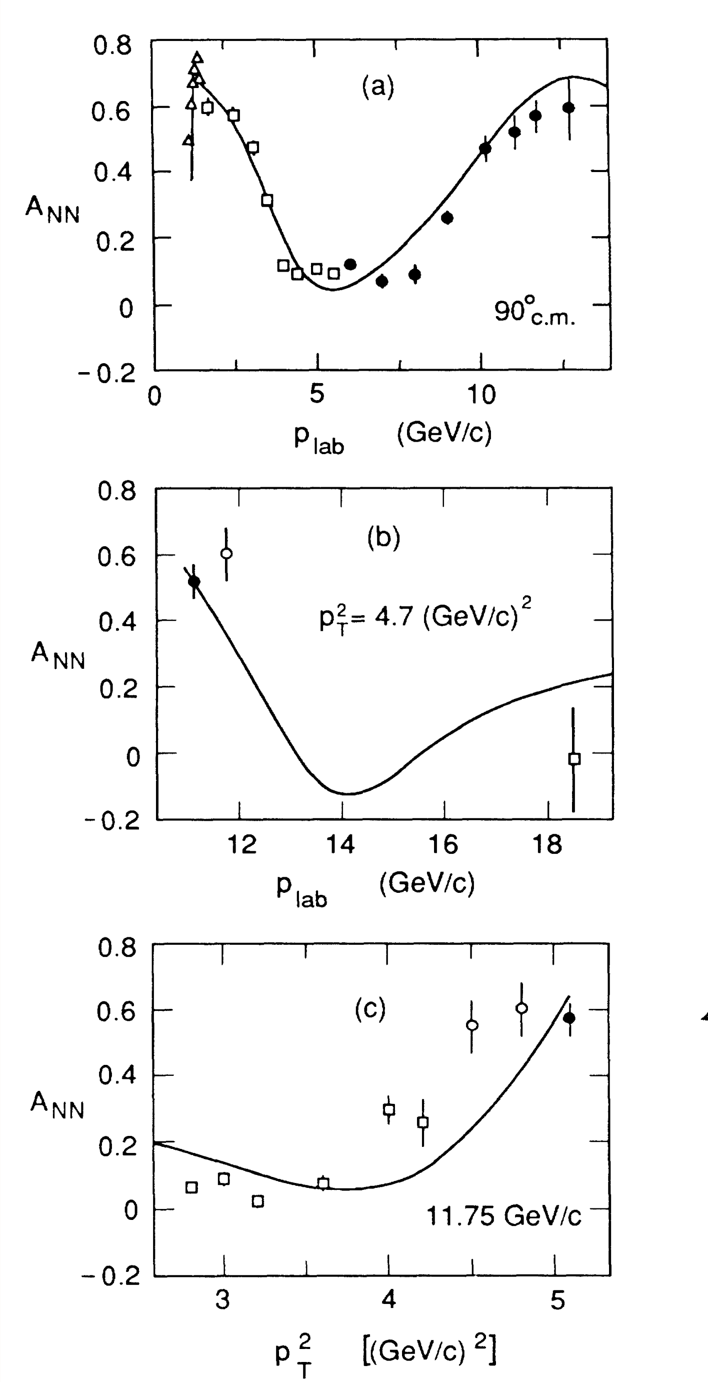
$\frac{d\sigma}{dt}(pp \to pp)$

$\sqrt{s} \sim 5$ 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).

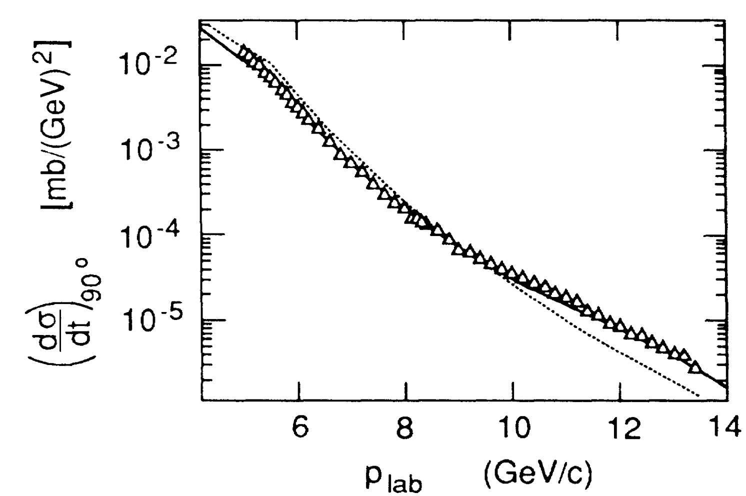
Quark Interchange + 8-Quark Resonance

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

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

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

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



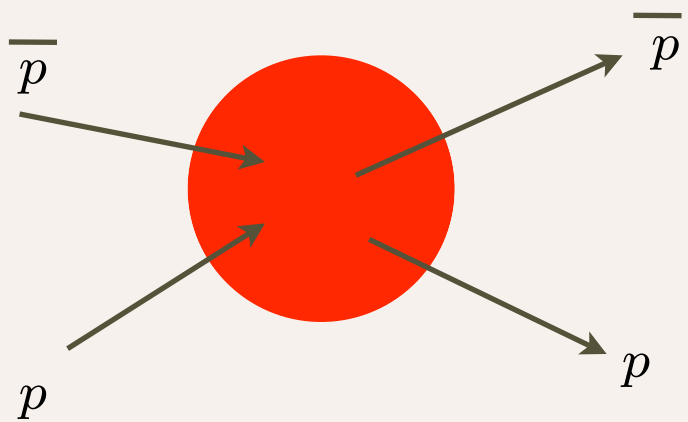
- New QCD physics in proton-proton elastic scattering at the charm threshold
- Anomalously large charm production at threshold!!?
- Octoquark resonances?
- Color Transparency disappears at charm threshold
- Key physics at GSI: second charm threshold

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

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

Key QCD Experiment at GSI

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



Key QCD Experiment at GSI

Total open charm cross section at threshold

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

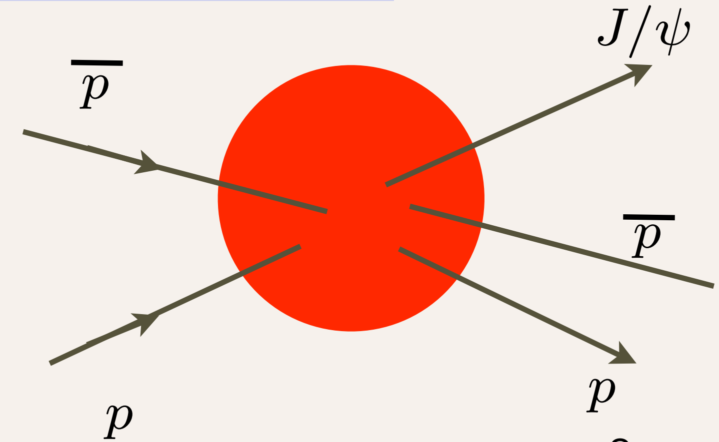
needed to explain Krisch A_{NN}

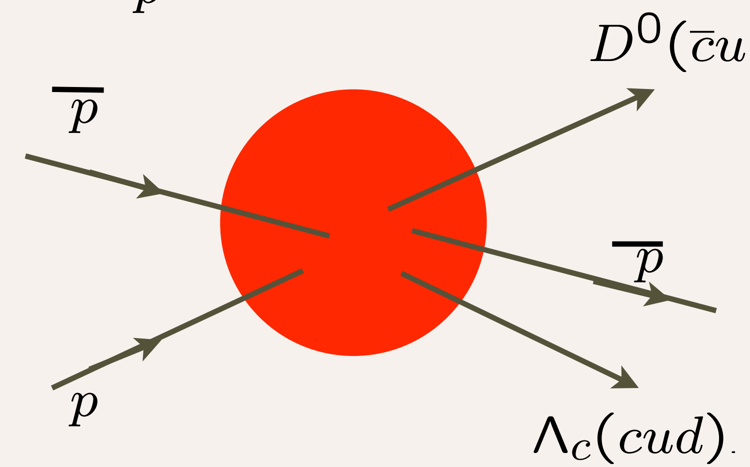
$$\overline{p}p \to \overline{p} + J/\psi + p$$

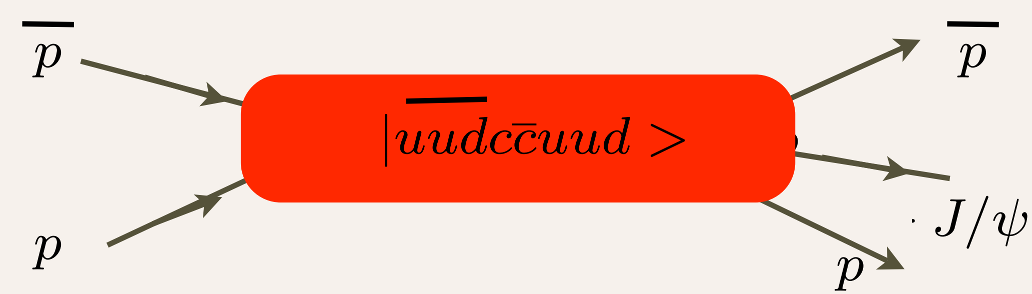
$$\overline{p}p \to \overline{p} + \eta_c + p$$

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

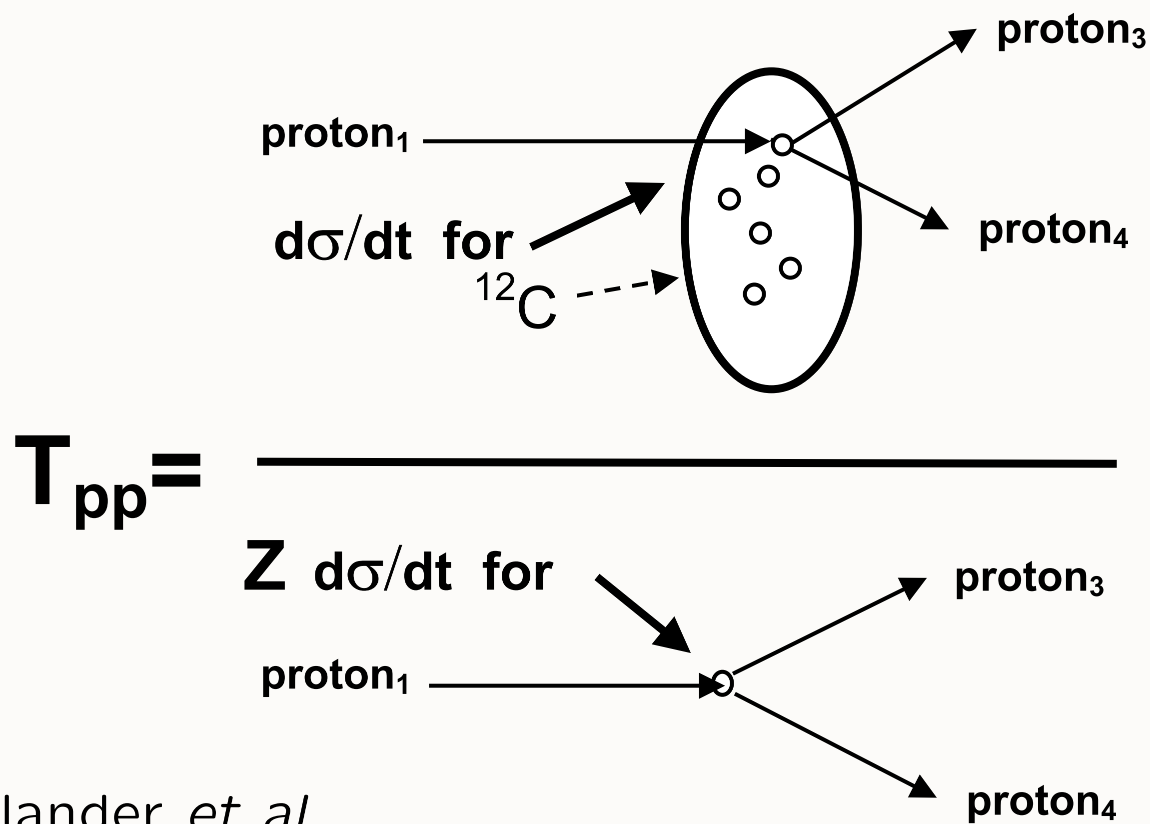
Octoquark: $|\overline{uud}c\bar{c}uud>$





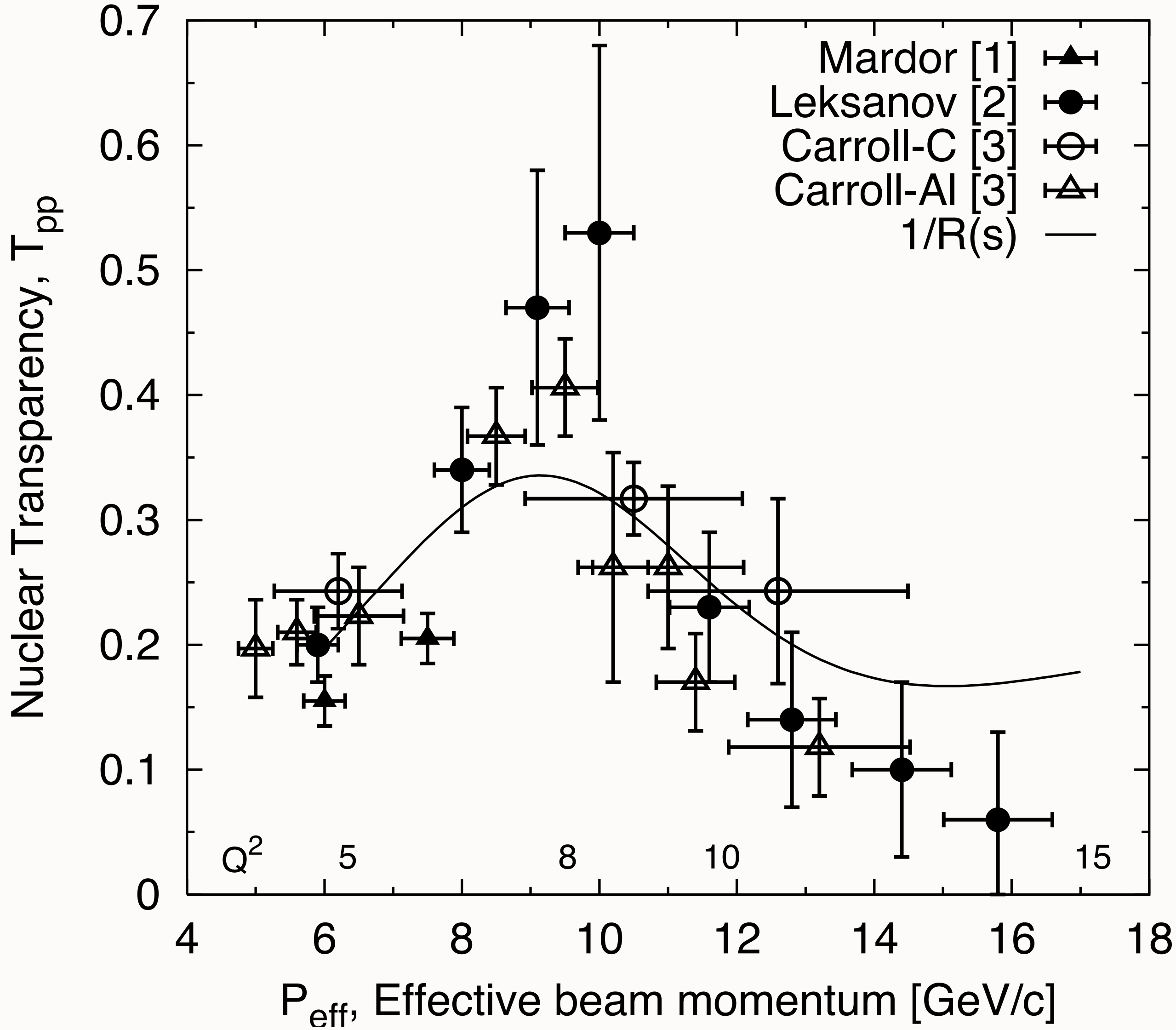


Color Transparency Ratio



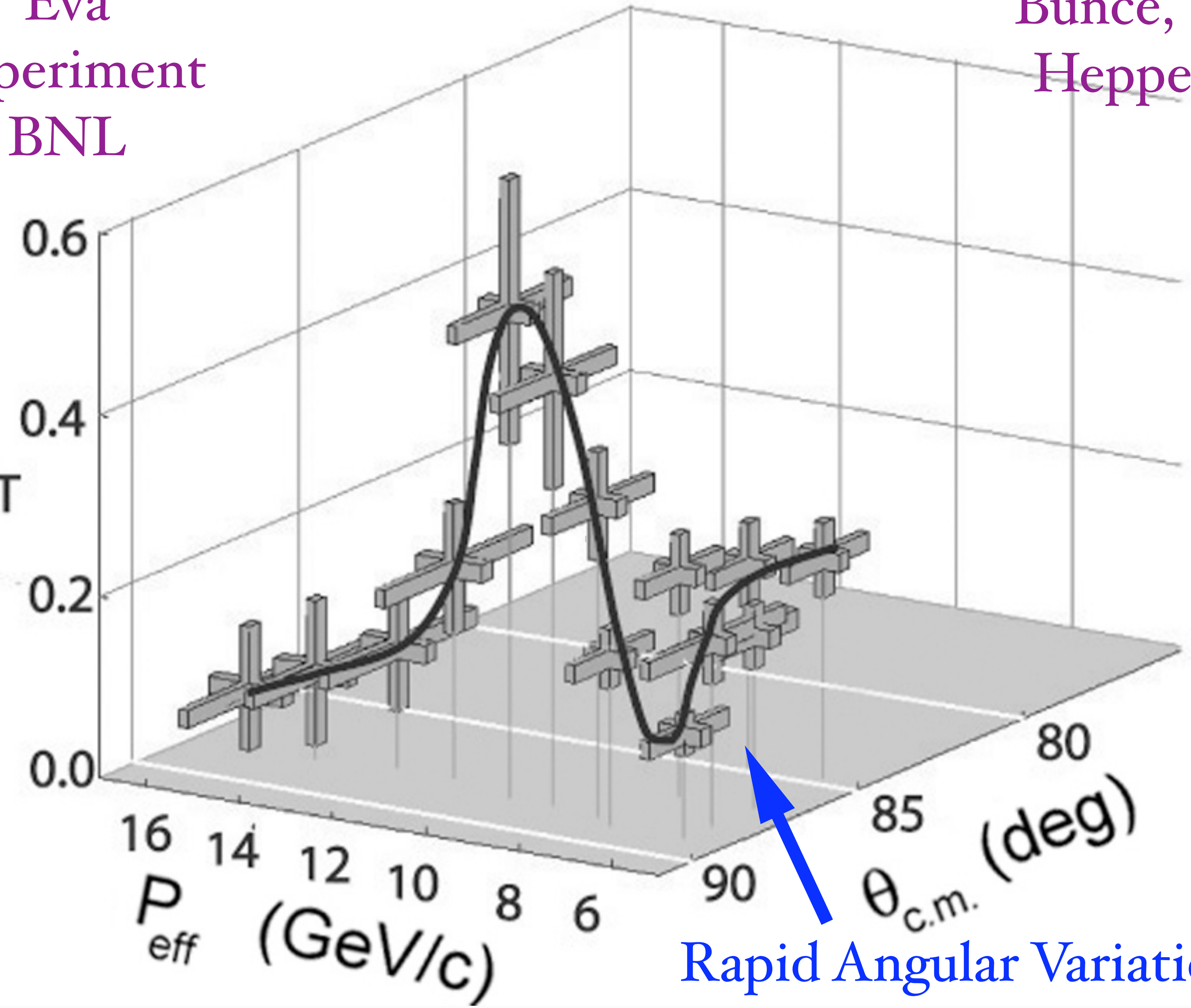
J. L. S. Aclander *et al.*,
"Nuclear transparency in $\theta_{CM} = 90^0$ quasielastic $A(p, 2p)$ reactions,"
Phys. Rev. C **70**, 015208 (2004), [arXiv:nucl-ex/0405025].

Color Transparency fails when A_{nn} is large



Eva
Experiment
BNL

Bunce, Carroll,
Heppelman...



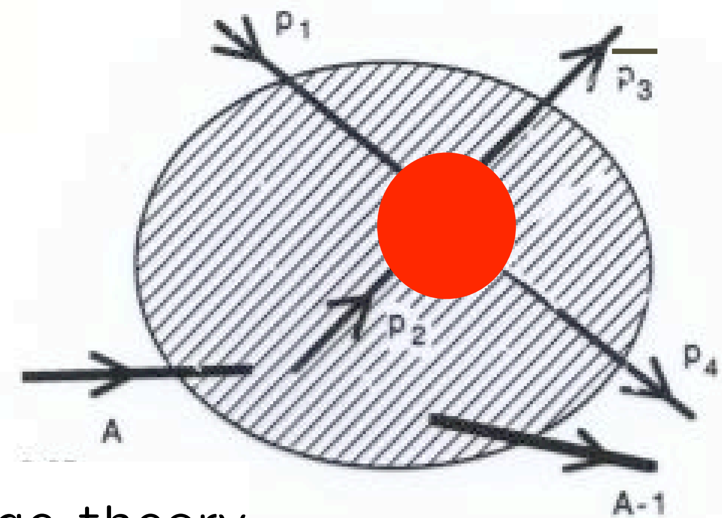
Rapid Angular Variation!

Key QCD Experiment at GSI

Test Color Transparency

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

No absorption of small color dipole
at high p_T

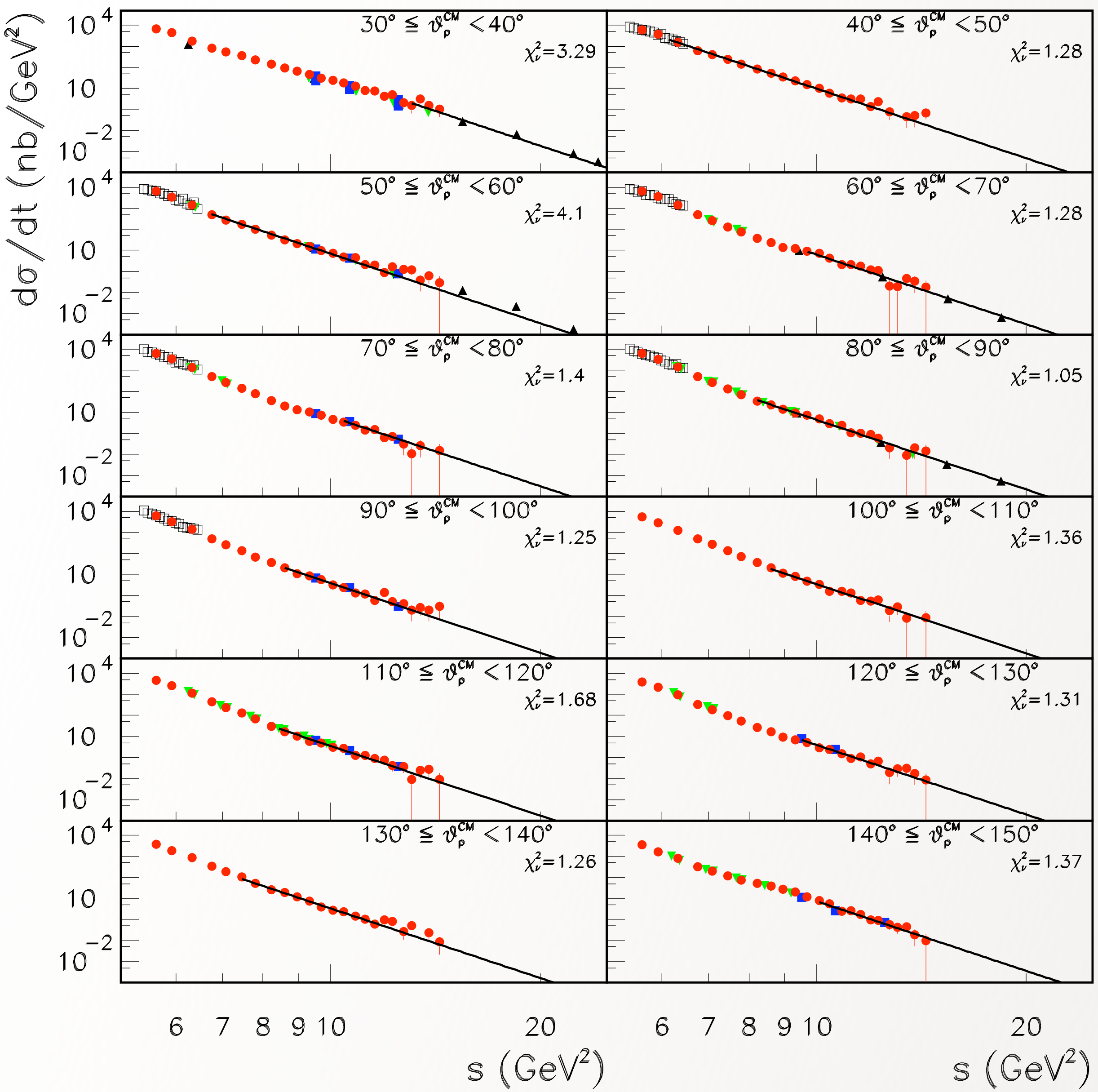


Key test of local gauge theory

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

A.H. Mueller, SJB

Deuteron Photodisintegration & 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

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

Same large momentum transfer behavior as pion form factor

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

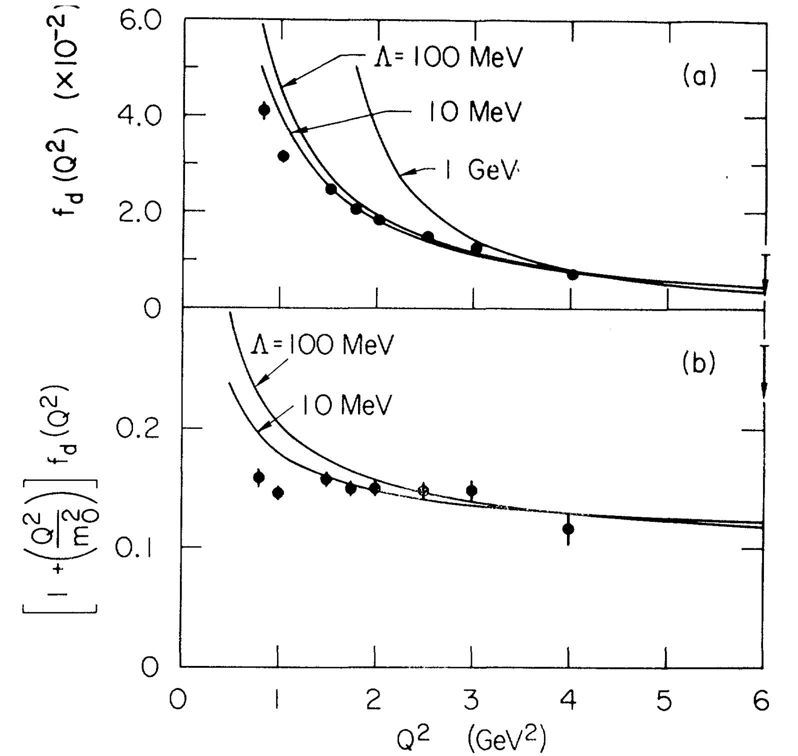
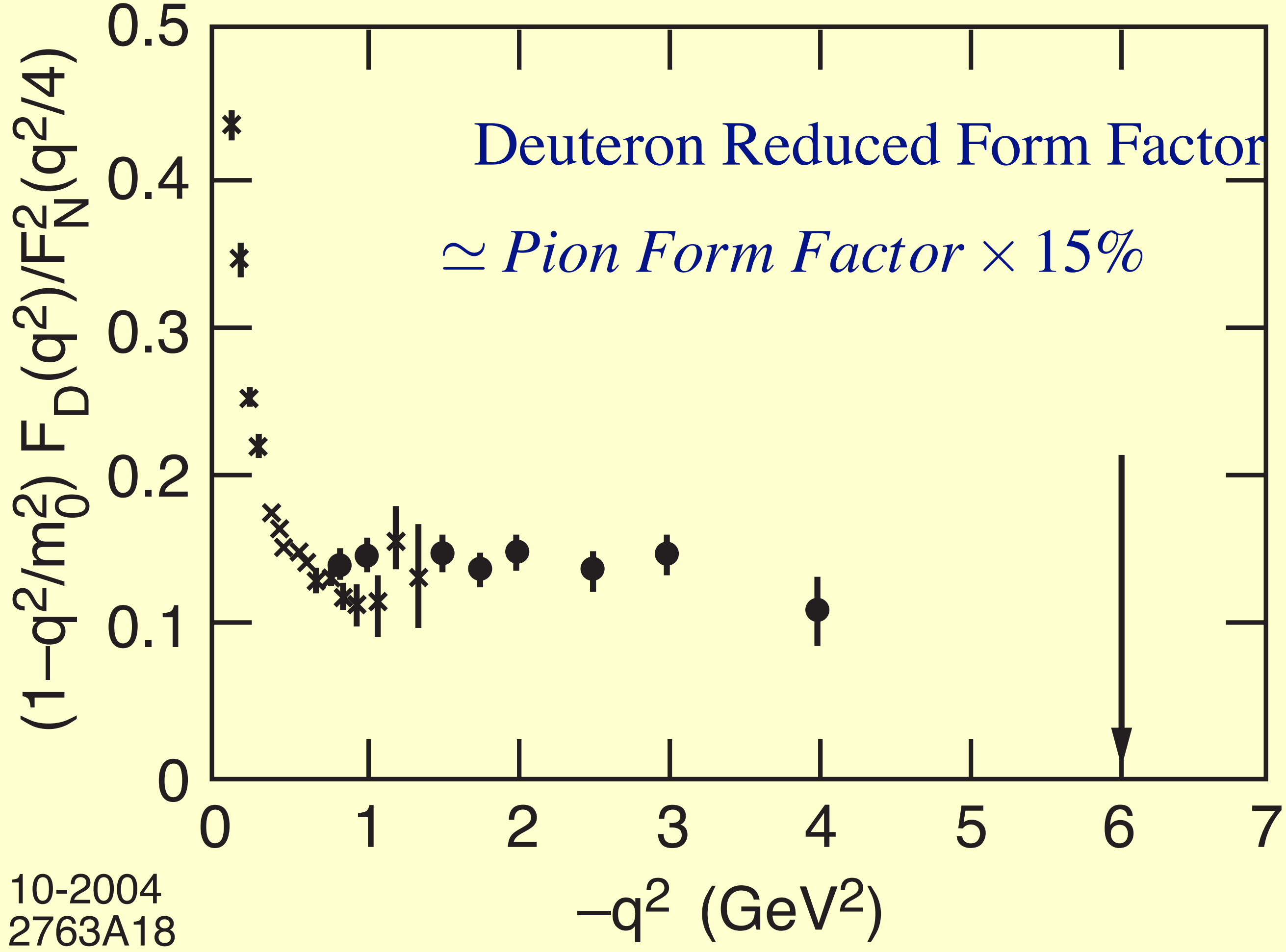


FIG. 2. (a) Comparison of the asymptotic QCD pre diction $f_d(Q^2) \propto (1/Q^2)[\ln(Q^2/\Lambda^2)]^{-1-(2/5)C_F/\beta}$ with fin data of Ref. 10 for the reduced deuteron form factor where $F_N(Q^2) = [1 + Q^2/(0.71\ \text{GeV}^2)]^{-2}$. The normaliz tion is fixed at the $Q^2 = 4$ GeV^2 data point. (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 $m_0{}^2 = 0.28$ GeV^2 is used (Ref. 8).



- 15% Hidden Color in the Deuteron

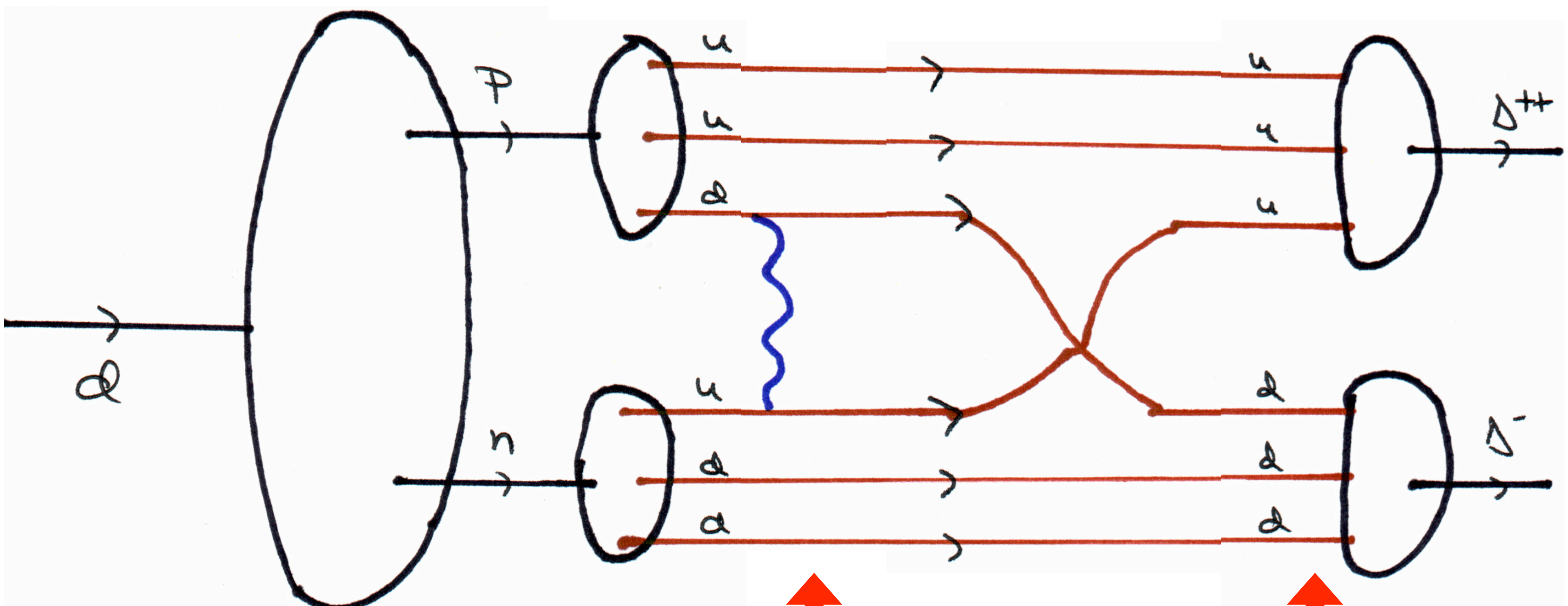
Hidden Color in QCD

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

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

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

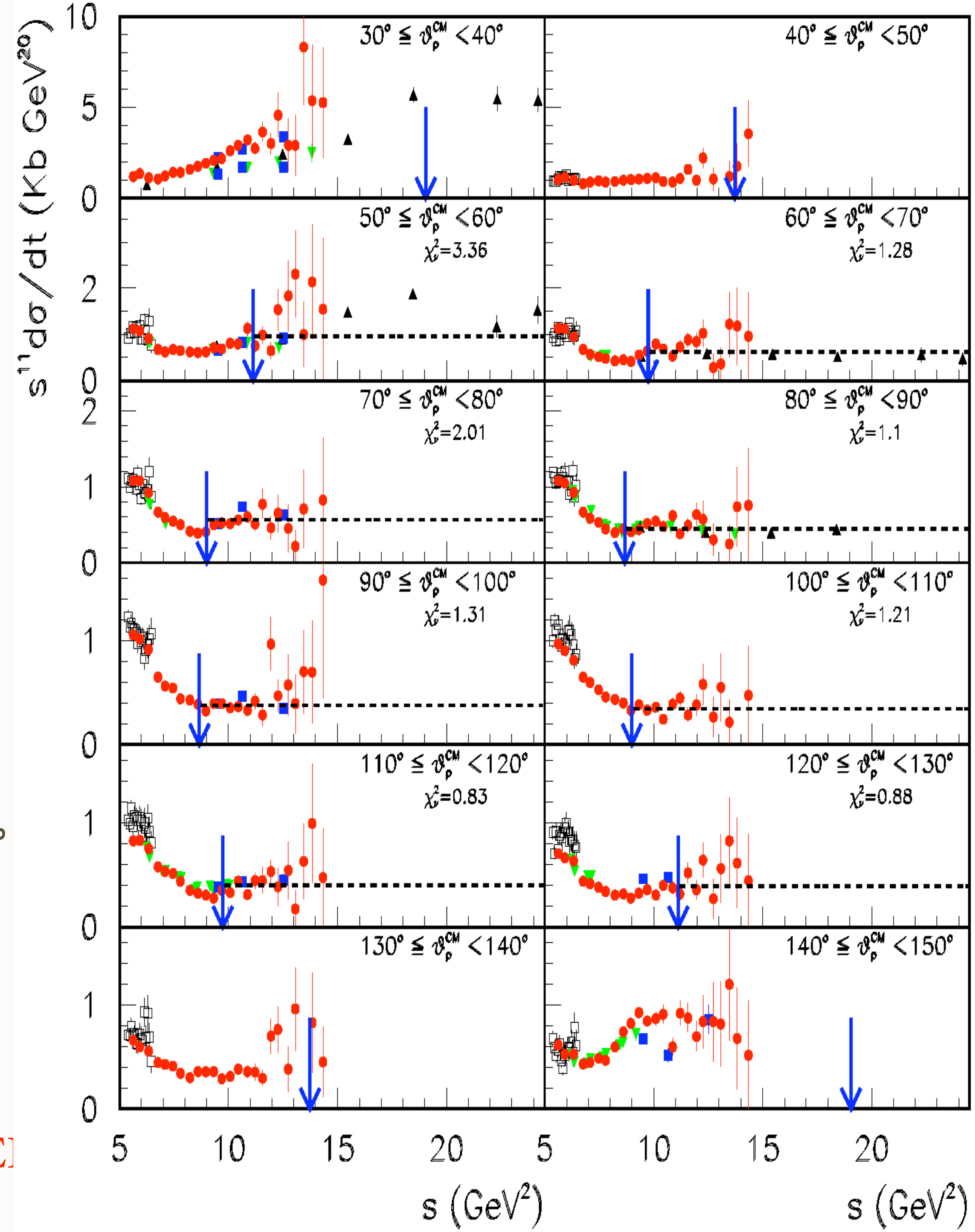
$A\ s^{-11}$

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



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

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

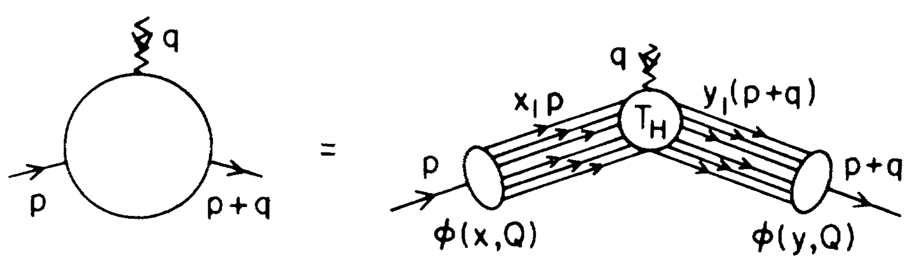


FIG. 1. The general structure of the deuteron form factor at large Q^2.

Ji, Lepage, sjb

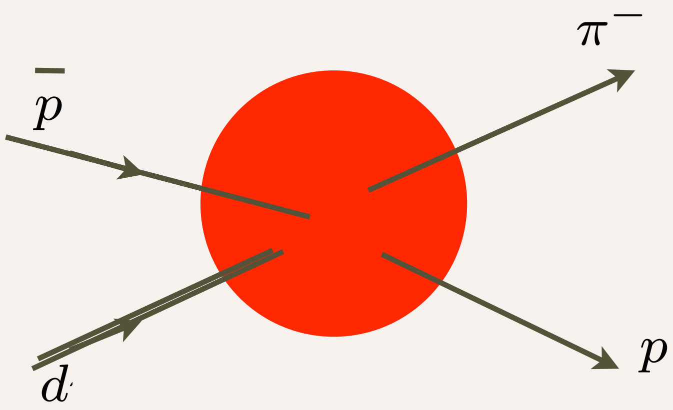
Key QCD Experiment at GSI

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

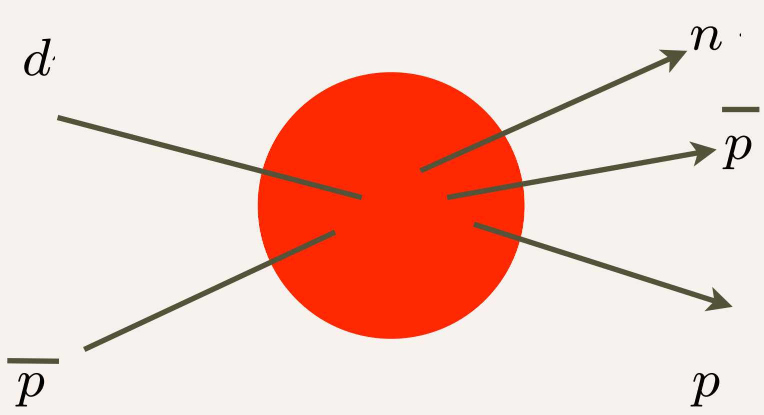
Manifestations of Hidden Color in Deuteron Wavefunction

Compare at high t.

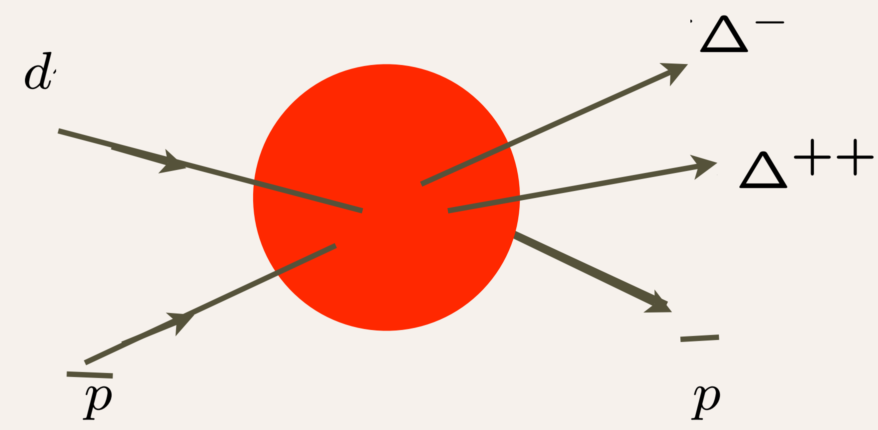
$$d\bar{p} \to \Delta^{++}\Delta^{-} + \bar{p}$$

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

Ratio predicted to approach 2:5



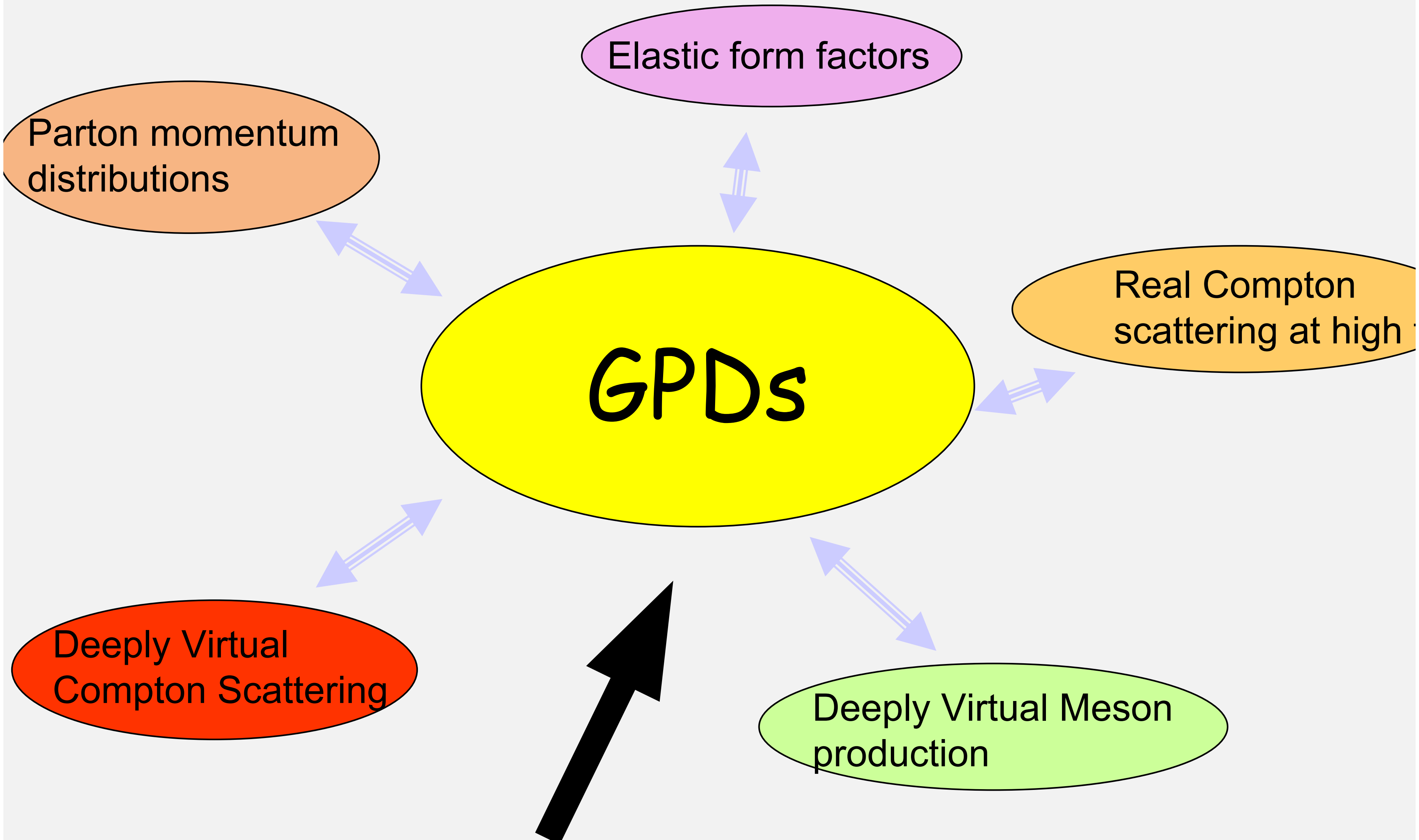
vs.



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

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

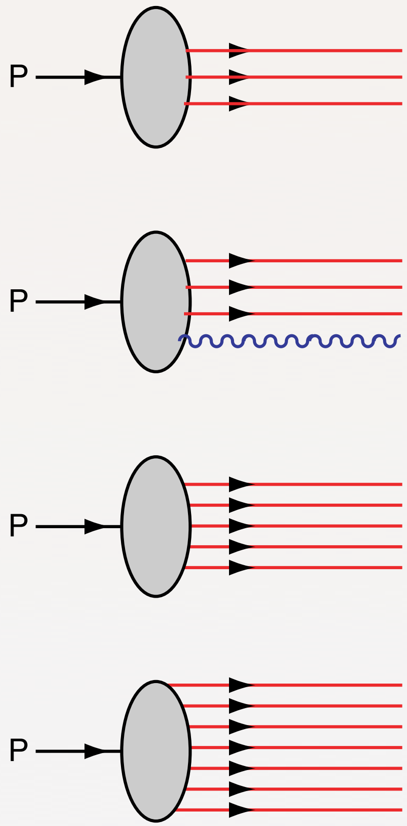
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

The light-cone momentum fraction

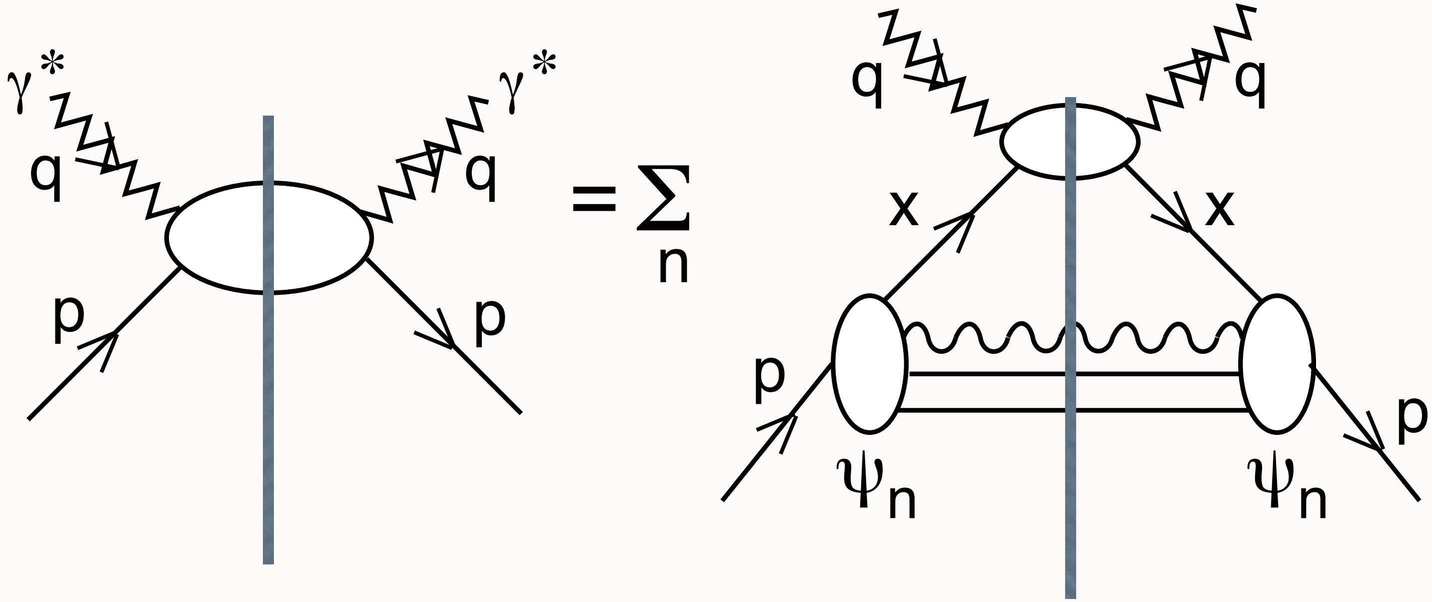
$$x_i = \frac{k_i^+}{p^+} = \frac{k_i^0 + k_i^z}{P^0 + P^z}$$

are boost invariant.

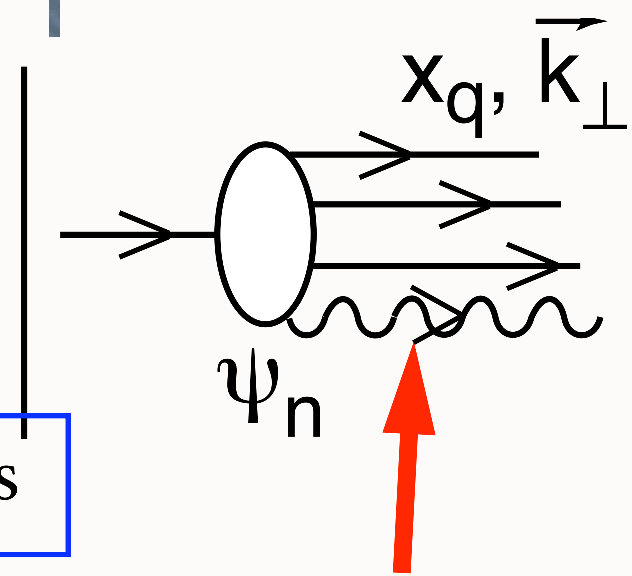
$$\sum_i^n k_i^+ = P^+, \ \sum_i^n x_i = 1, \ \sum_i^n \vec{k}_i^\perp = \vec{0}^\perp.$$



Deep Inelastic Lepton Proton Scattering



Imaginary Part of
Forward Virtual Compton Amplitude



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

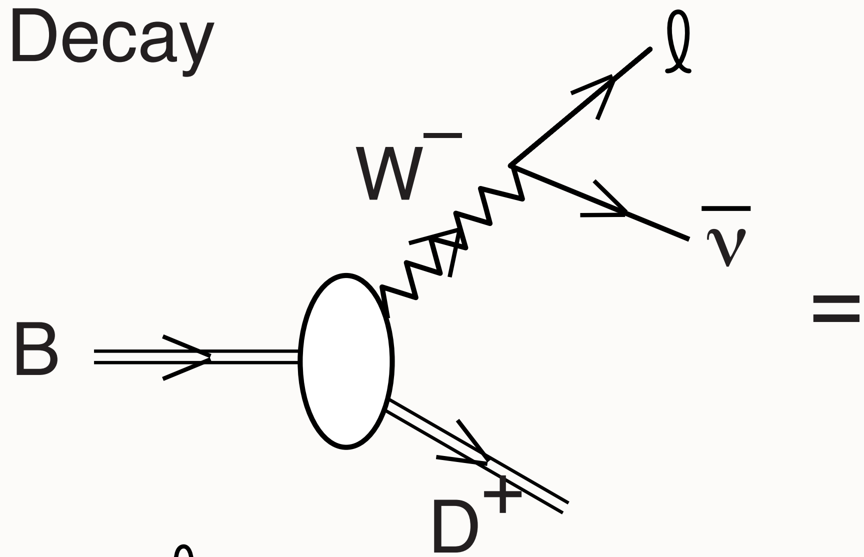
$x = x_q$

All spin, flavor distributions

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

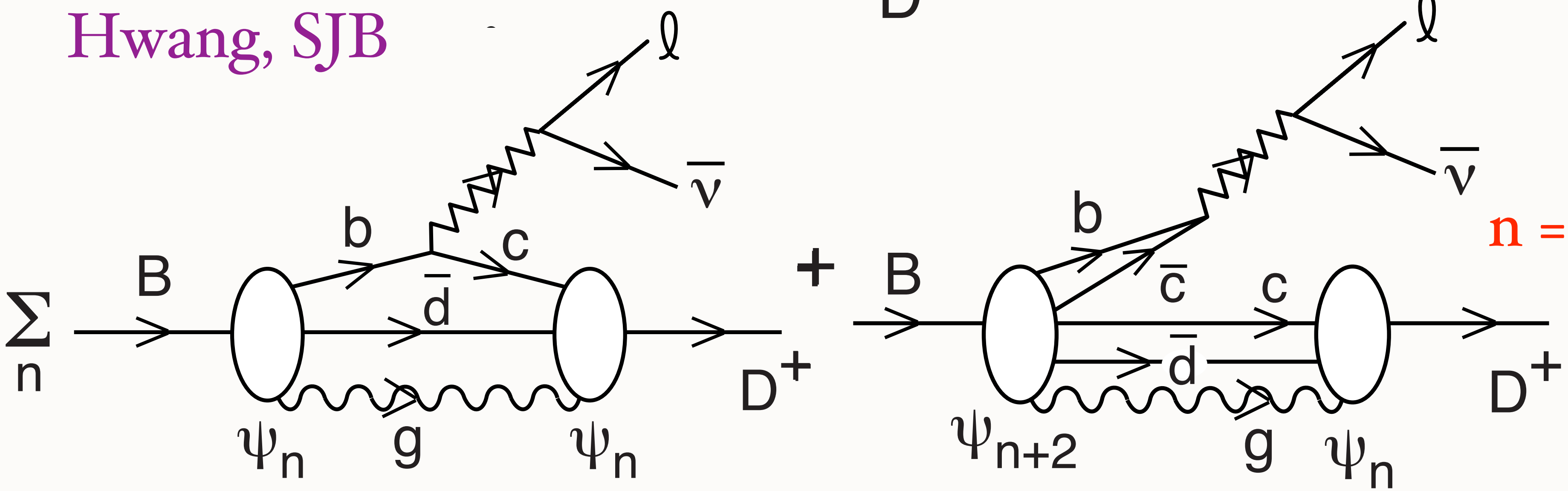
Weak Exclusive Decay

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



Exact Formula

Hwang, SJB



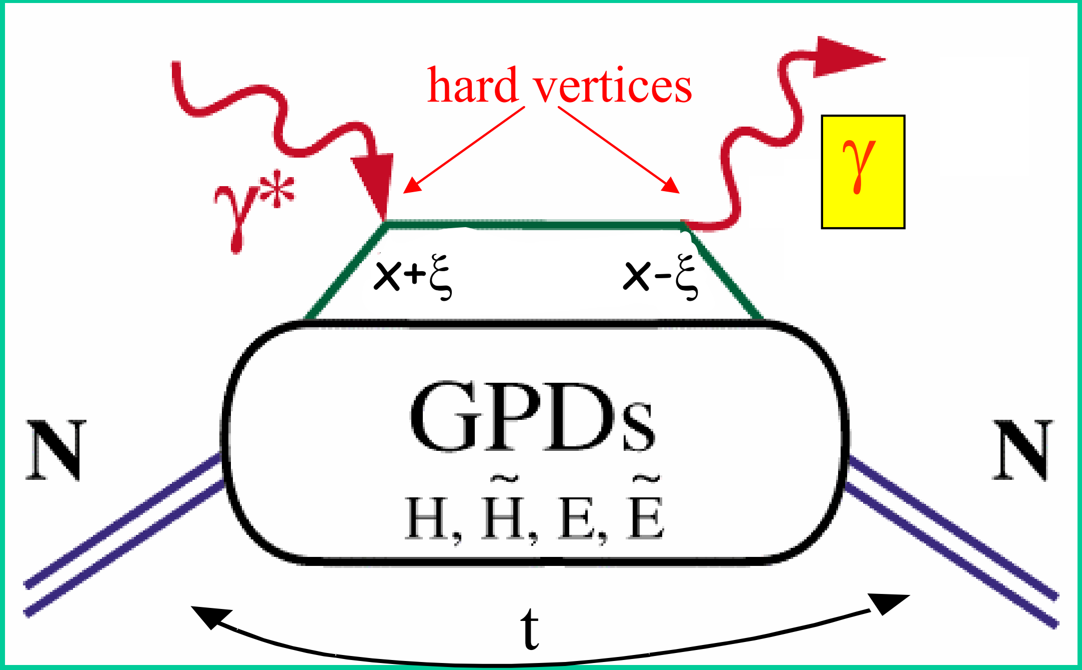
$n = n' + 2$

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,ξ,t), E(x,ξ,t), . .

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

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)

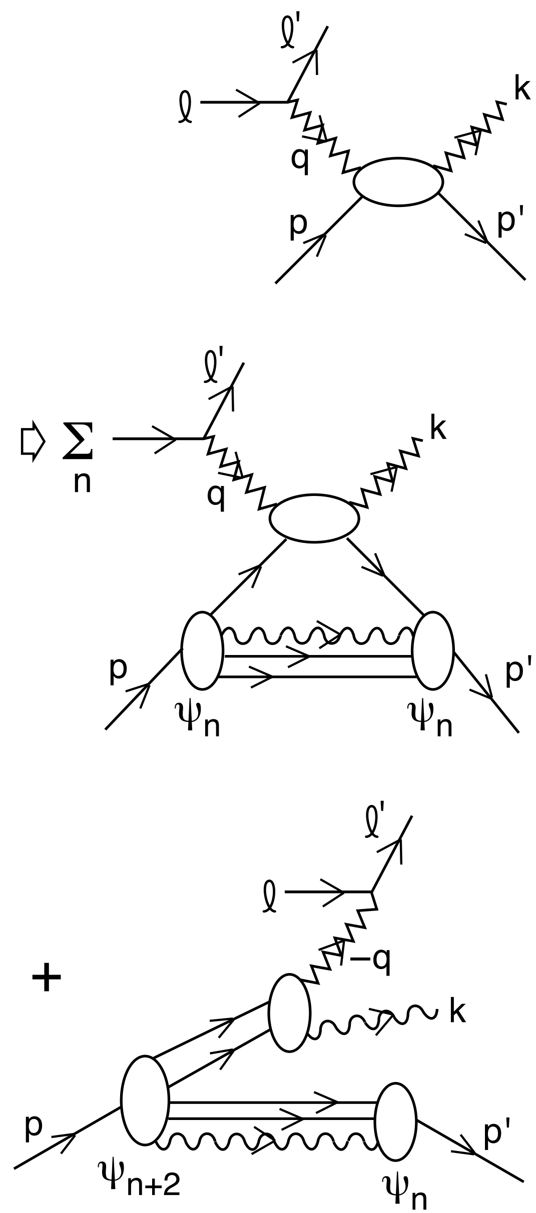
Close, Gunion, sjb

- 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

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

Large $-q^2 = Q^2$

$\gamma^* p \rightarrow \gamma p'$



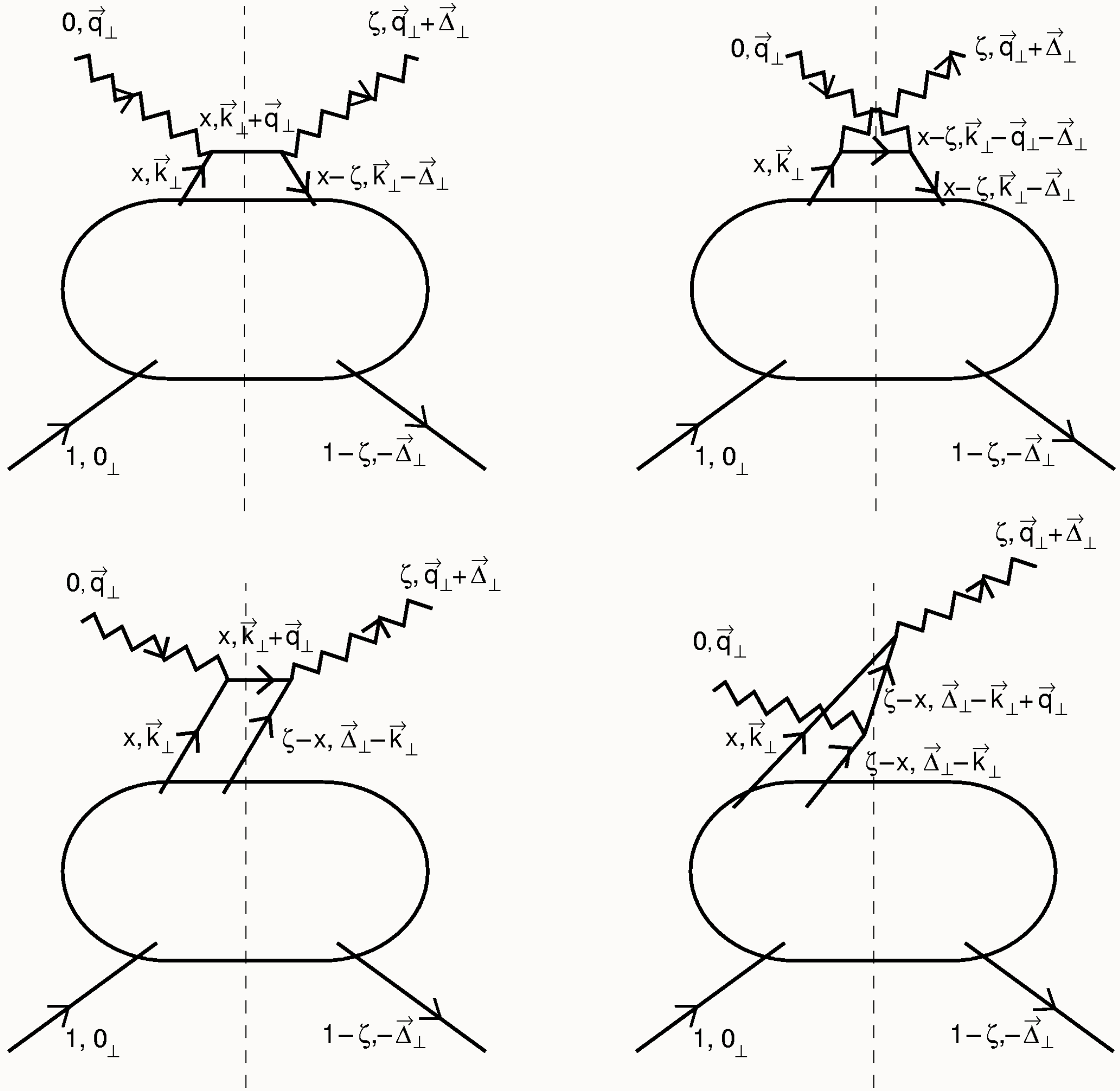
Given LFWFs, compute all GPDs !

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 $\xi = t = 0$

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

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

Form factors (sum rules)

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

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

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

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

Verified using LFWFs

Diehl, Hwang, sjb

Quark angular momentum (Ji's sum rule)

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

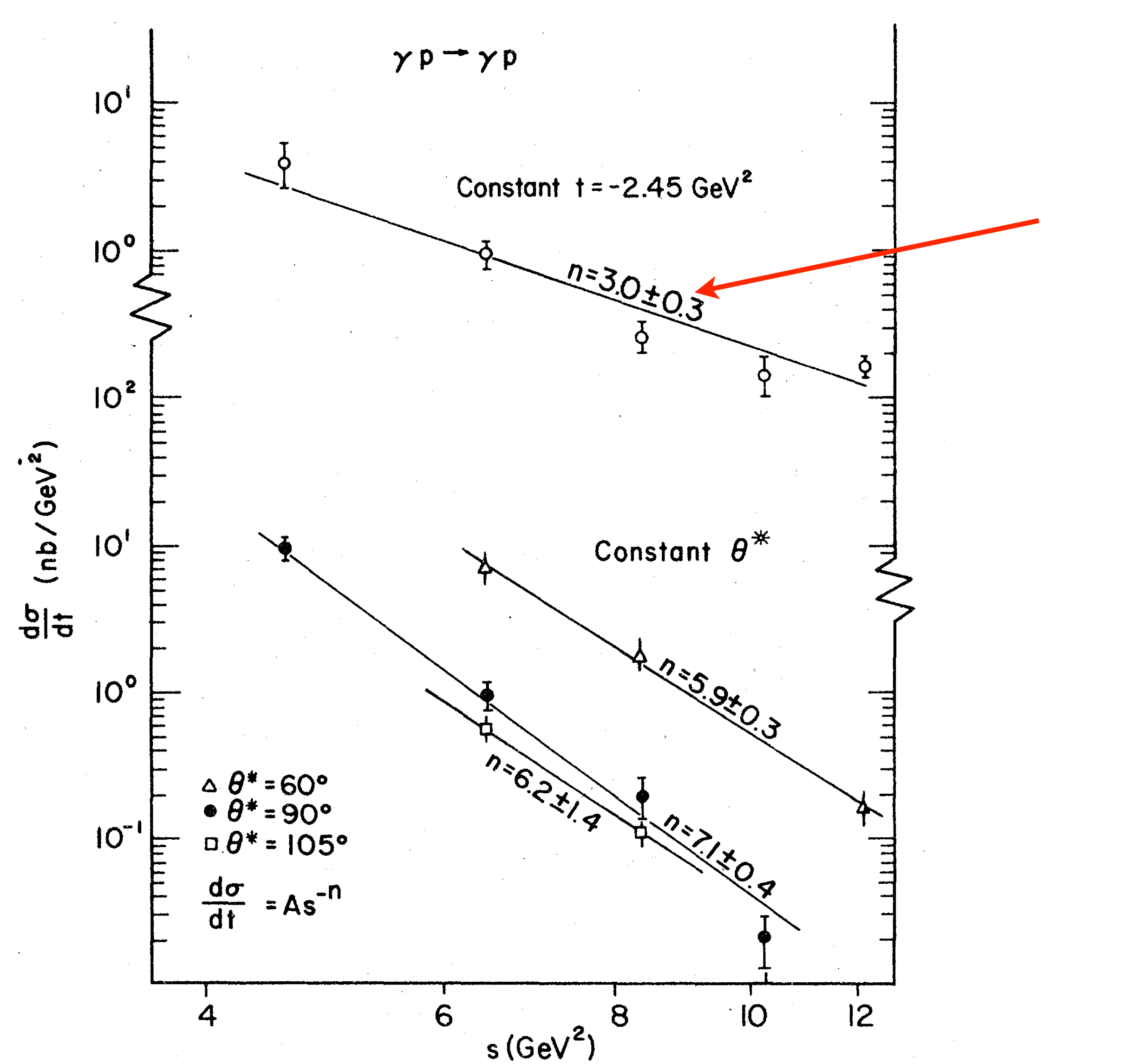
X. Ji, Phy.Rev.Lett.78,610(1997)

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 q^2 independent
- Analytic Continuation of GPDs
- Light-Front Wavefunctions
- charge asymmetry from interference

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

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}