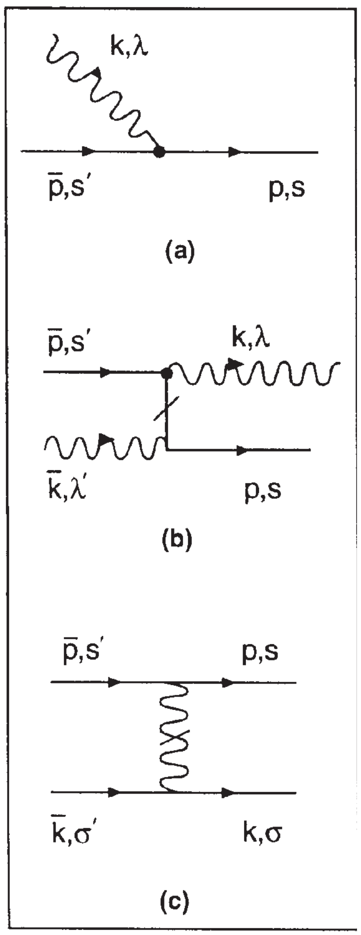
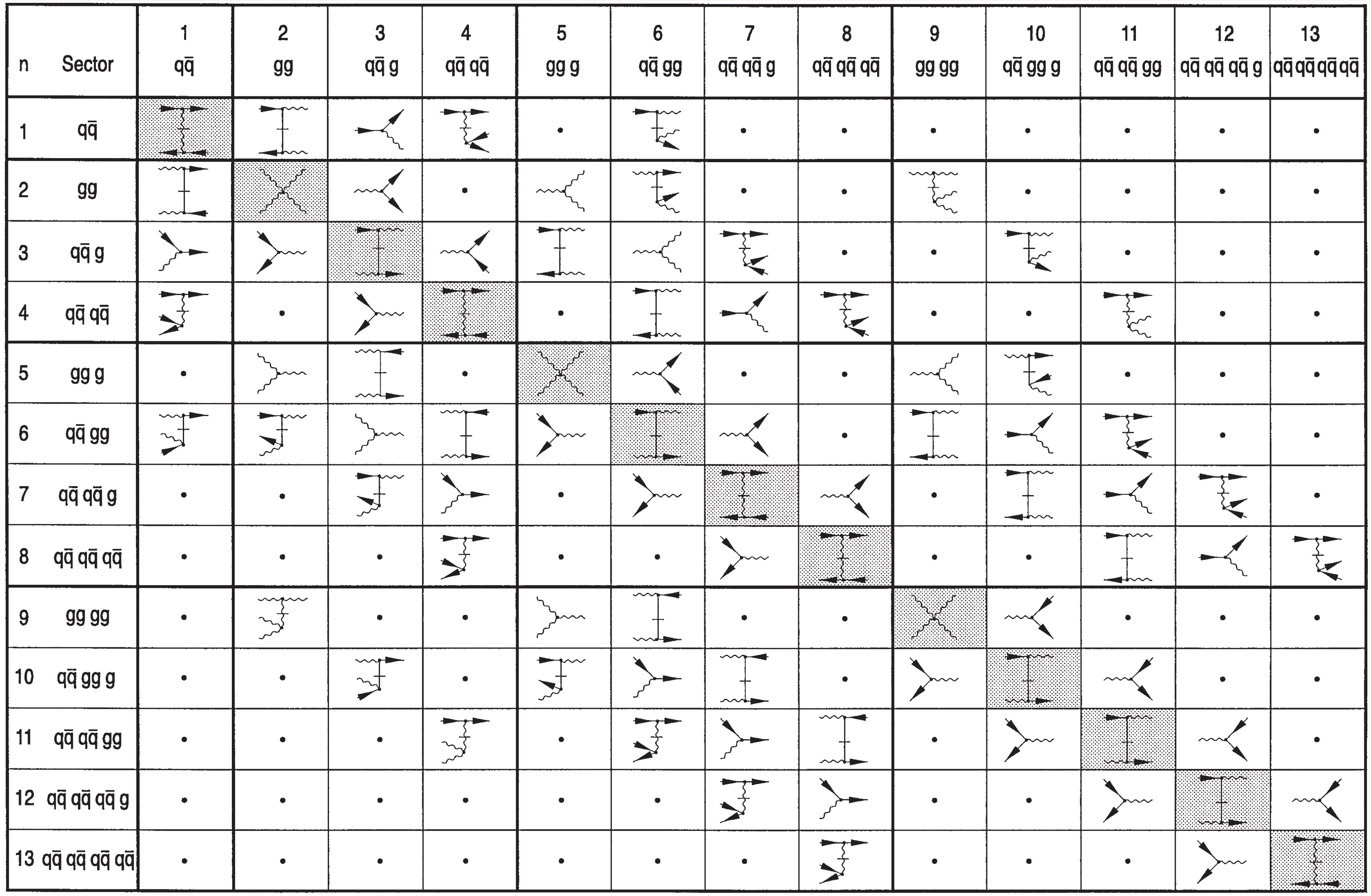
## Light-Front QCD Heisenberg Equation

$$H_{LC}^{QCD}|\Psi_h\rangle = \mathcal{M}_h^2\,|\Psi_h\rangle$$




## Use AdS/QCD basis functions

# Use AdS/CFT orthonormal Light Front Wavefunctions as a basis for diagonalizing the QCD LF Hamiltonian

- Good initial approximation
- Better than plane wave basis

Pauli, Hornbostel, Hiller, McCartor, sjb

- DLCQ discretization -- highly successful 1+1
- Use independent HO LFWFs, remove CM motion
- Similar to Shell Model calculations

- **Hamiltonian light-front field theory within an AdS/QCD basis.**
  J.P. Vary, H. Honkanen, Jun Li, P. Maris, A. Harindranath,
  G.F. de Teramond, P. Sternberg, E.G. Ng, C. Yang, sjb

# AdS/QCD and Light-Front Holography

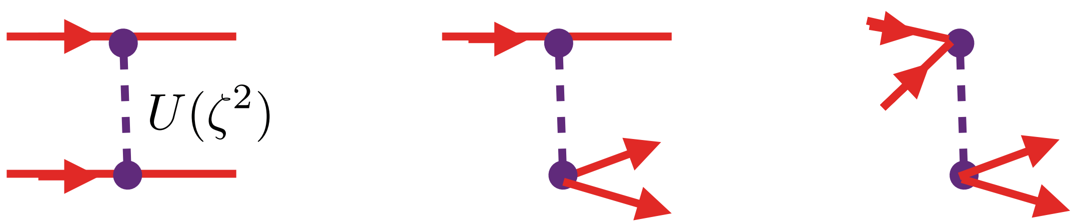
- Hadrons are composites of quark and anti-quark constituents
- Explicit gluons absent!
- Higher Fock states with extra quark/anti-quark pairs created by confining potential
- Dominance of Quark Interchange in Hard Exclusive Reactions
- Short-distance behavior matches twist of interpolating operator at short distance -- guarantees dimensional counting rules --

# Higher Fock States

- Exposed by timelike form factor through dressed current.
- Created by confining interaction

$$H_I = \bar{\psi}\psi U(\zeta^2)\bar{\psi}\psi$$

- Similar to QCD(1+1) in lcg



PHYSICAL REVIEW D VOLUME 49, NUMBER 1 1 JANUARY 1994

# Comparison of 20 exclusive reactions at large $t$

C. White,[4,*] R. Appel,[1,5,†] D. S. Barton,[1] G. Bunce,[1] A. S. Carroll,[1]
H. Courant,[4] G. Fang,[4,‡] S. Gushue,[1] K. J. Heller,[4] S. Heppelmann,[2]
K. Johns,[4,§] M. Kmit,[1,||] D. I. Lowenstein,[1] X. Ma,[3] Y. I. Makdisi,[1]
M. L. Marshak,[4] J. J. Russell,[3]
and M. Shupe[4,§]

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(Received 28 May 1993)

We report a study of 20 exclusive reactions measured at the AGS at 5.9 GeV/$c$ incident momentum, 90° center of mass. This experiment confirms the strong quark flow dependence of two-body hadron-hadron scattering at large angle. At 9.9 GeV/$c$ an upper limit had been set for the ratio of cross sections for $(\bar{p}p \to \bar{p}p)/(pp \to pp)$ at 90° c.m., with the ratio less than 4%. The present experiment was performed at lower energy to gain sensitivity, but was still within the fixed angle scaling region. A ratio $R(\bar{p}p/pp) \approx 1/40$ was measured at 5.9 GeV/$c$, 90° c.m. in comparison to a ratio near 1.7 for small angle scattering. In addition, many other reactions were measured, often for the first time at 90° c.m. in the scaling region, using beams of $\pi^\pm$, $K^\pm$, $p$, and $\bar{p}$ on a hydrogen target. There are similar large differences in cross sections for other reactions: $R(K^-p \to \pi^+\Sigma^-/K^-p \to \pi^-\Sigma^+)$ $\approx 1/12$, for example. The relative magnitudes of the different cross sections are consistent with the dominance of quark interchange in these 90° reactions, and indicate that pure gluon exchange and quark-antiquark annihilation diagrams are much less important. The angular dependence of several elastic cross sections and the energy dependence at a fixed angle of many of the reactions are also presented.

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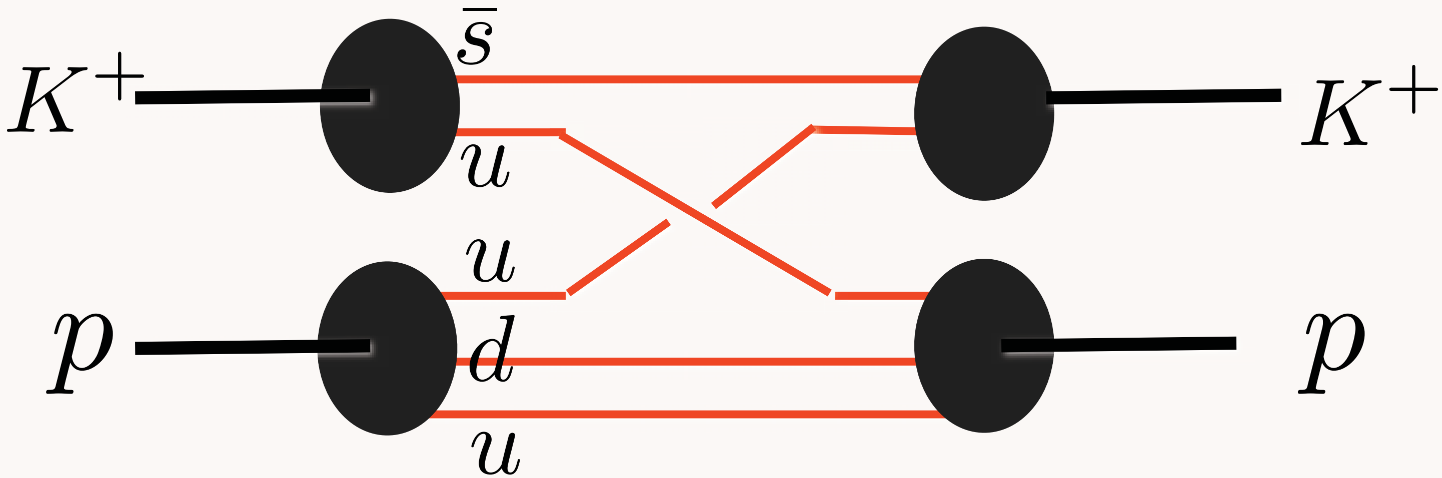
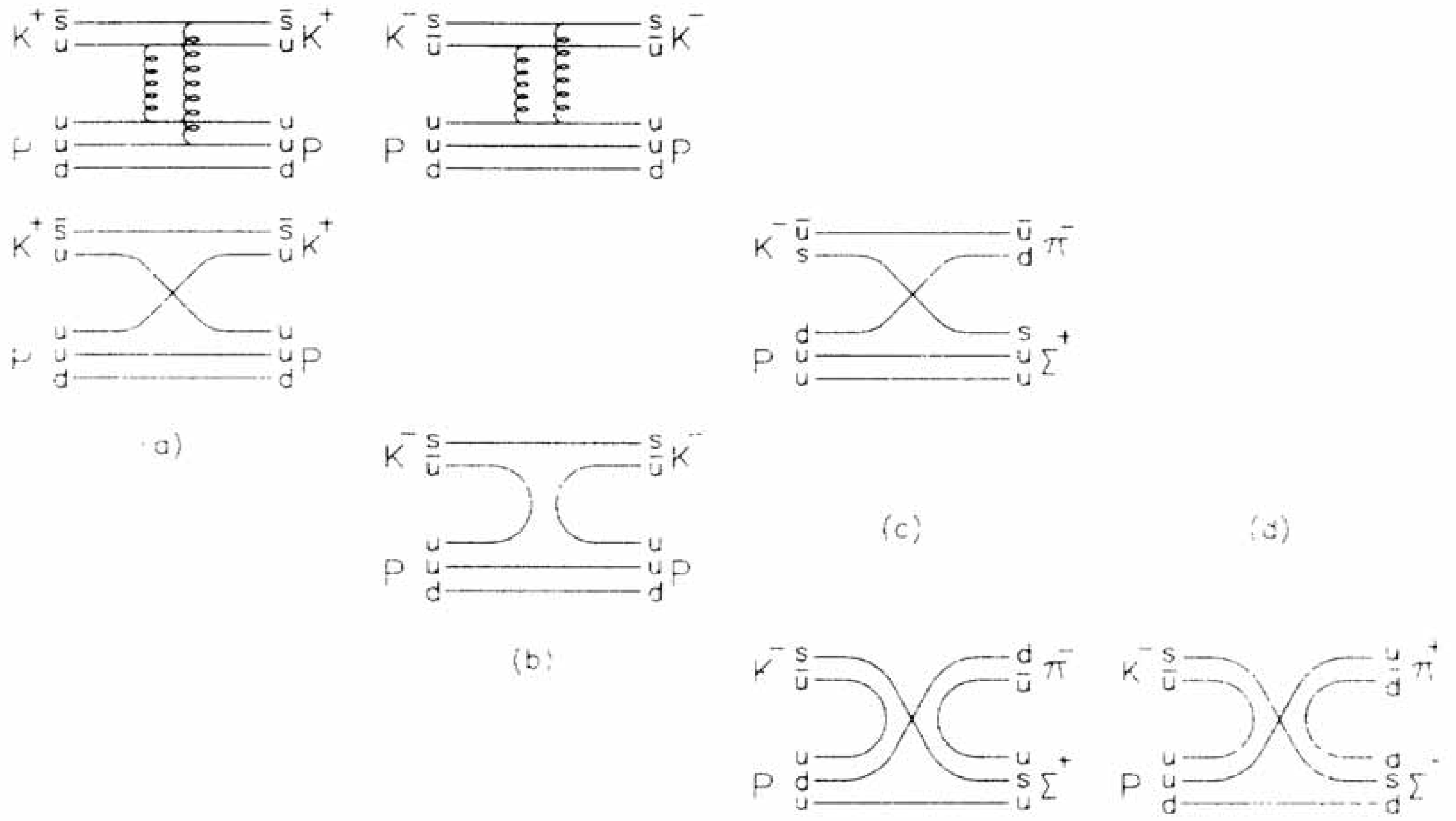
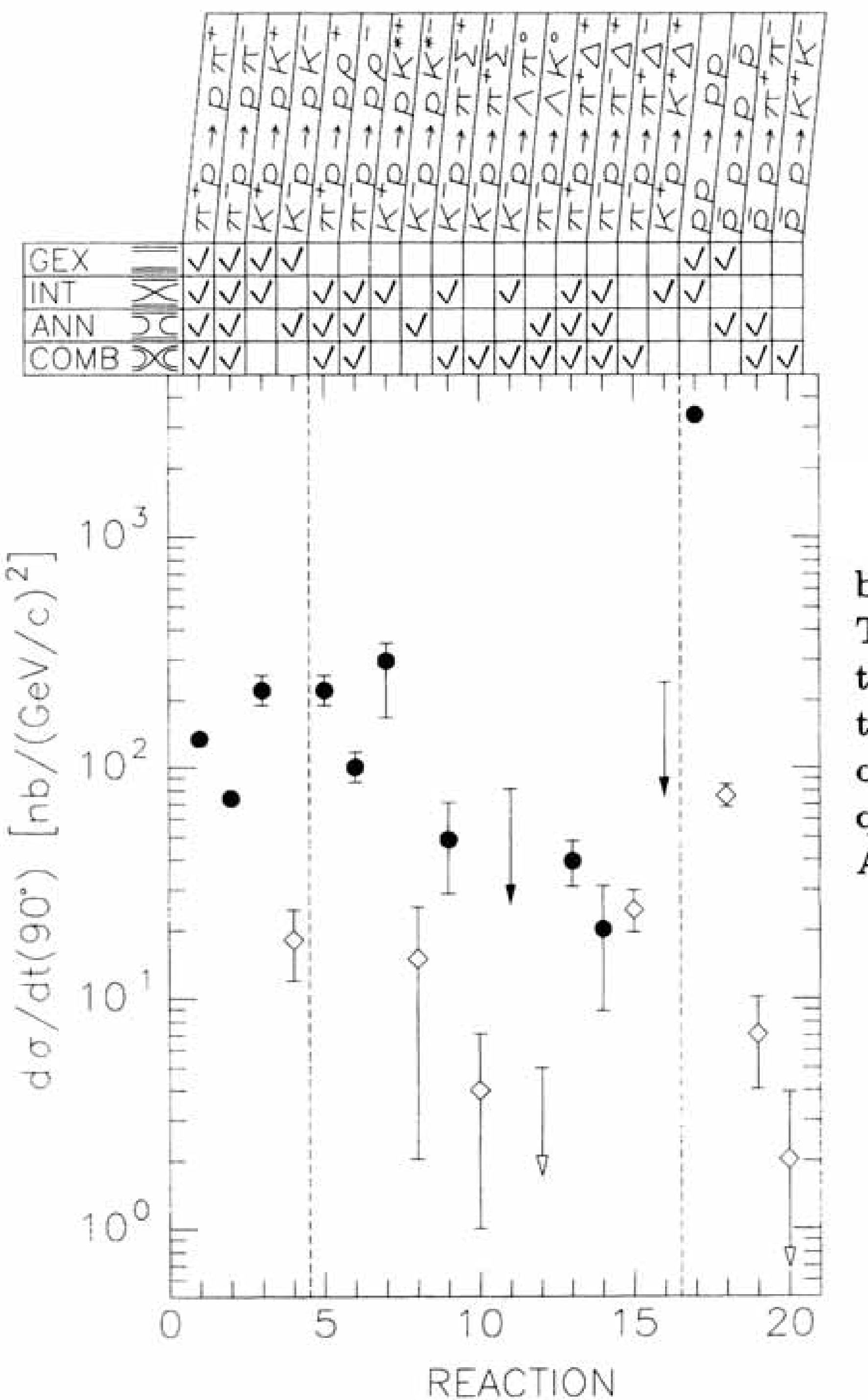





Quark flow diagrams which contribute to (a) $K^+p$ and (b) $K^-p$ elastic scattering, (c) the reaction $K^-p \to \pi^-\Sigma^+$, and (d) the reaction $K^-p \to \pi^+\Sigma^-$.

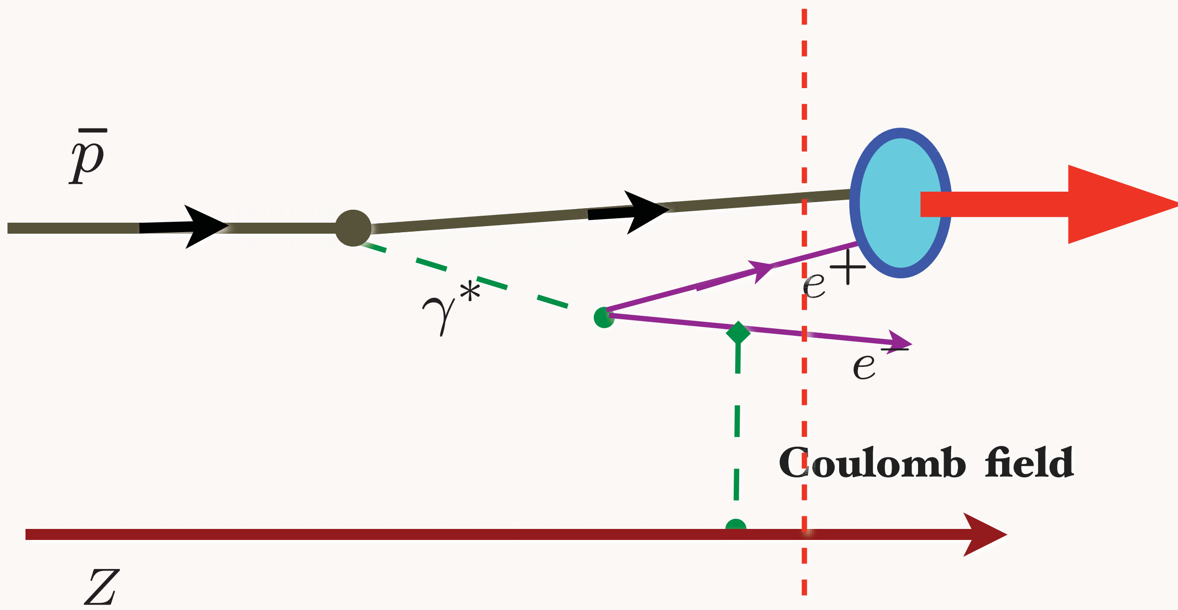



Differential cross sections for the 16 meson-baryon and 4 baryon-baryon measured in this experiment. The cross sections are at, or extrapolated from, near 90° center of mass. The four quark flow diagrams which contribute to each of the 20 reactions are given in the chart at the top of the figure. Those reactions which have a contribution from quark interchange(INT) are given by the solid black points. As can be seen, these are the largest cross sections.

# Formation of Relativistic Anti-Hydrogen

***Measured at CERN-LEAR and FermiLab***

Munger, Schmidt, sjb




$$b_\perp \leq \frac{1}{m_{red}\alpha}$$

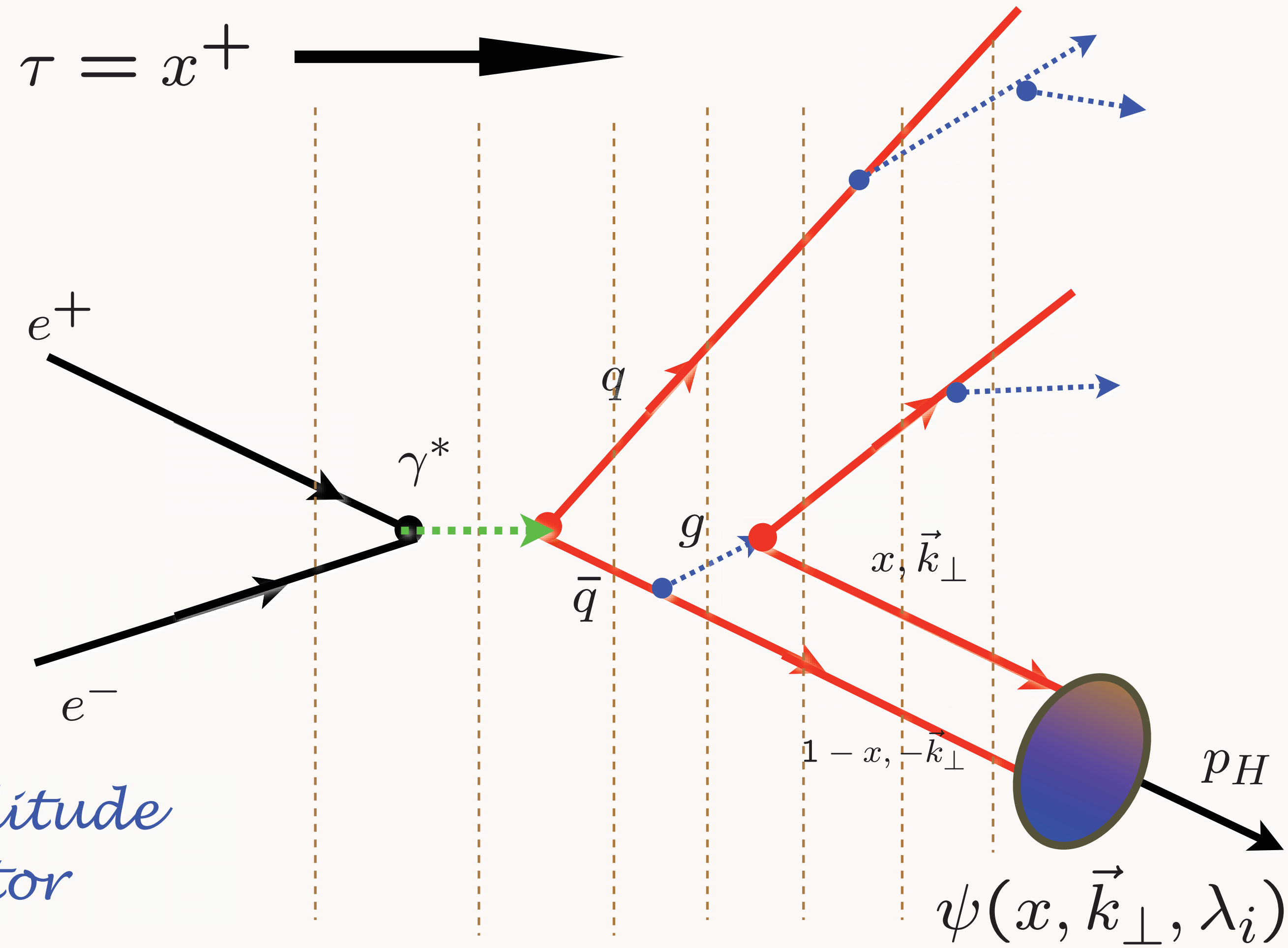
$$y_{\bar{p}} \simeq y_{e^+}$$

*Coalescence of off-shell co-moving positron and antiproton*

*Wavefunction maximal at small impact separation and equal rapidity*

"Hadronization" at the Amplitude Level

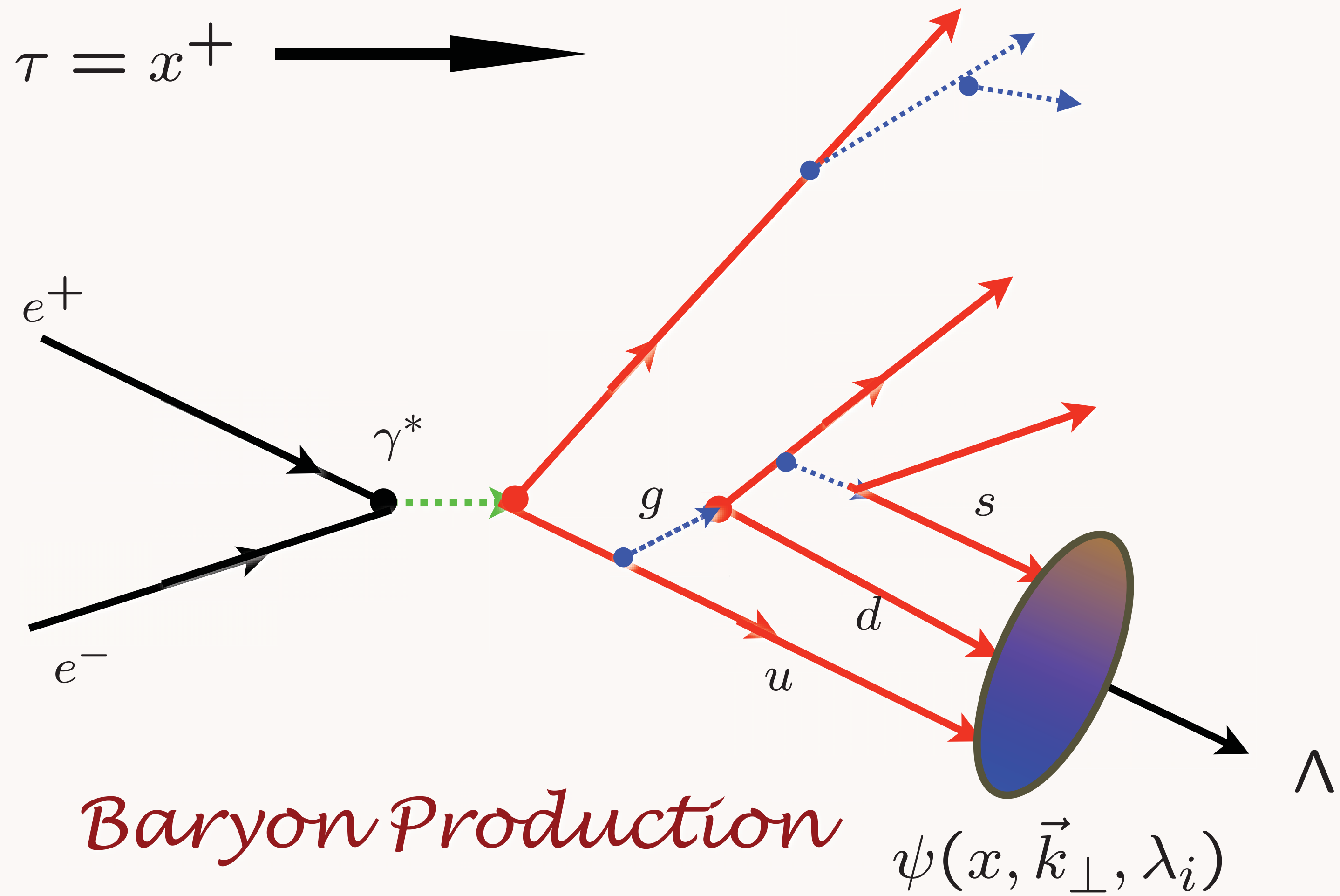
# Hadronization at the Amplitude Level




Event amplitude generator

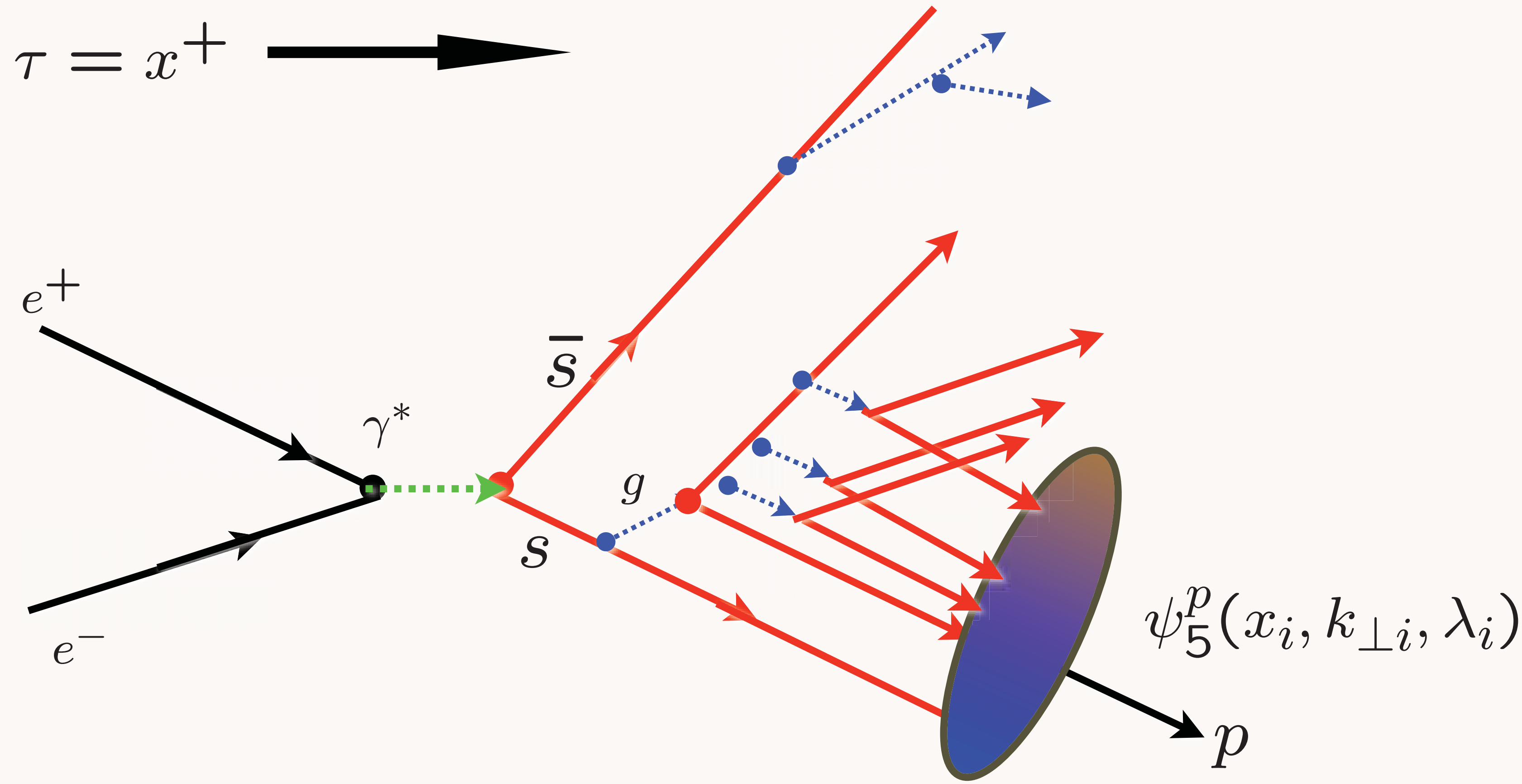
**Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via LFWFs**

# Hadronization at the Amplitude Level




Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via LFWFs

# Hadronization at the Amplitude Level




**Higher Fock State Coalescence** $|uuds\bar{s}>$

**Asymmetric Hadronization !** $D_{s \to p}(z) \neq D_{s \to \bar{p}}(z)$

B-Q Ma, sjb

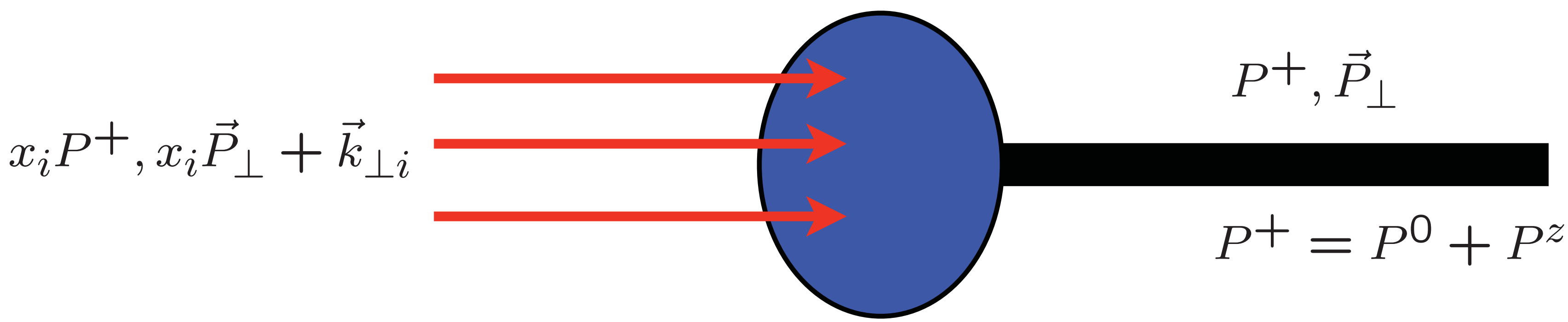
# Features of LF T-Matrix Formalism
# "Event Amplitude Generator"

- Coalesce color-singlet cluster to hadronic state if

$$\mathcal{M}_n^2 = \sum_{i=1}^{n} \frac{k_{\perp i}^2 + m_i^2}{x_i} < \Lambda_{QCD}^2$$

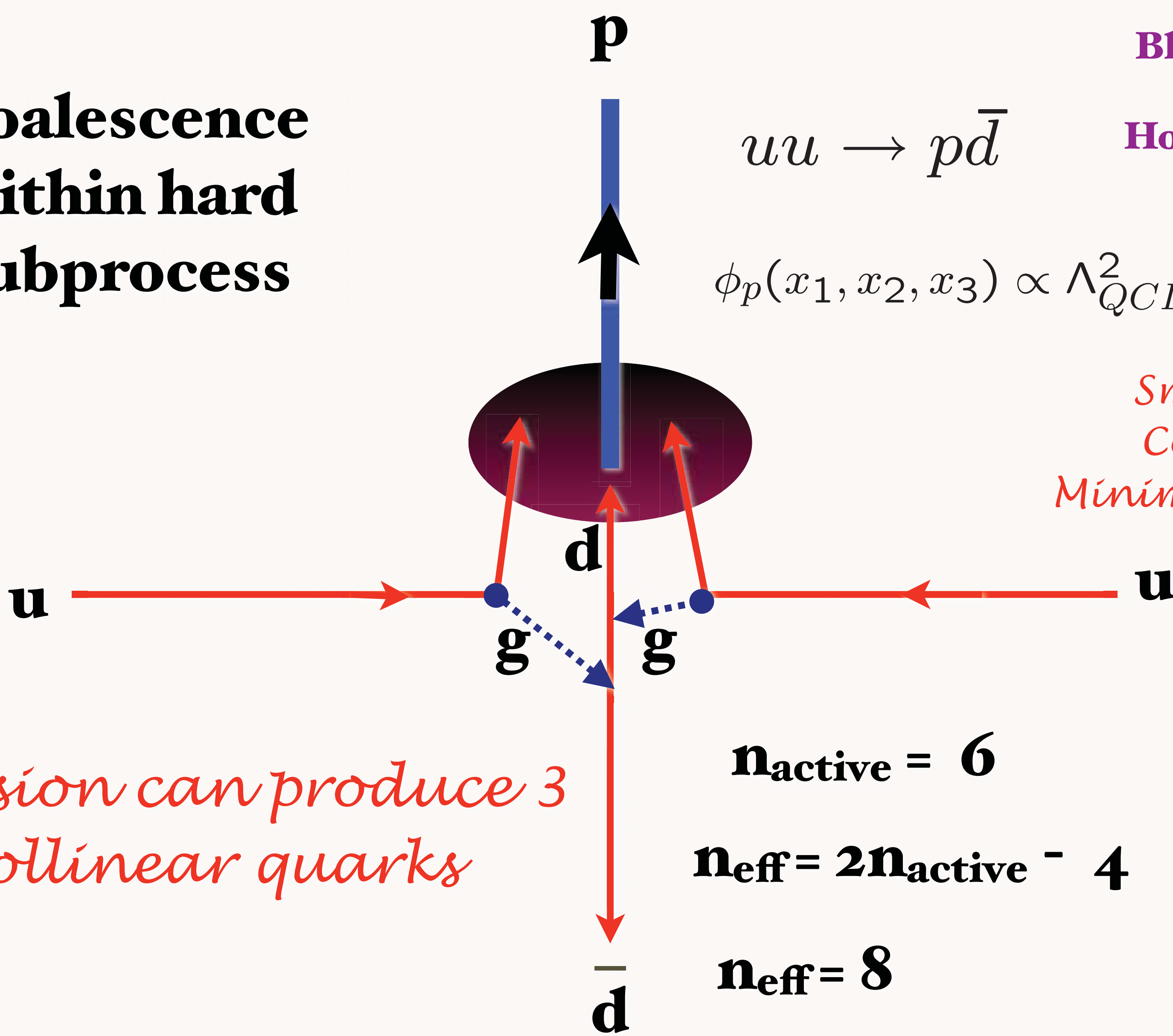
- The coalescence probability amplitude is the LF wavefunction $\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$

- No IR divergences: Maximal gluon and quark wavelength from confinement



# Baryon can be made directly within hard subprocess

**Coalescence within hard subprocess**




$$uu \rightarrow p\bar{d}$$

$$\phi_p(x_1, x_2, x_3) \propto \Lambda^2_{QCD}$$

Bjorken
Blankenbecler, Gunion, sjb
Berger, sjb
Hoyer, et al: Semi-Exclusive

**Sickles; sjb**

*Small color-singlet*
*Color Transparent*
*Minimal same-side energy*

*Collision can produce 3 collinear quarks*

$n_{active} = 6$

$n_{eff} = 2n_{active} - 4$

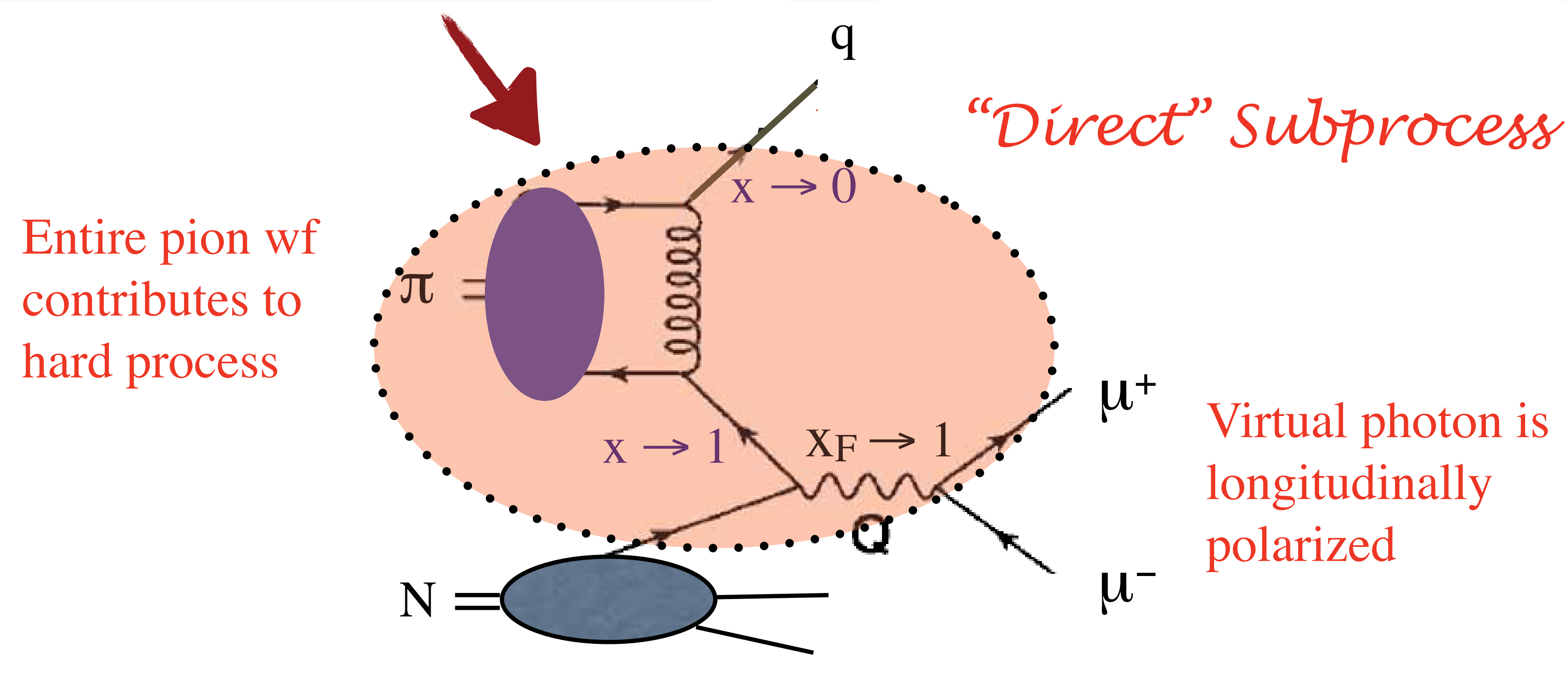
$n_{eff} = 8$

$$qq \rightarrow B\bar{q}$$

# $\pi N \to \mu^+ \mu^- X$ at high $x_F$

In the limit where $(1-x_F)Q^2$ is fixed as $Q^2 \to \infty$

*Light-Front Wavefunctions from AdS/CFT*




Berger, sjb
Khoze, Brandenburg, Muller, sjb

Hoyer Vanttinen

$\pi^- N \to \mu^+ \mu^- X$ at 80 GeV/c

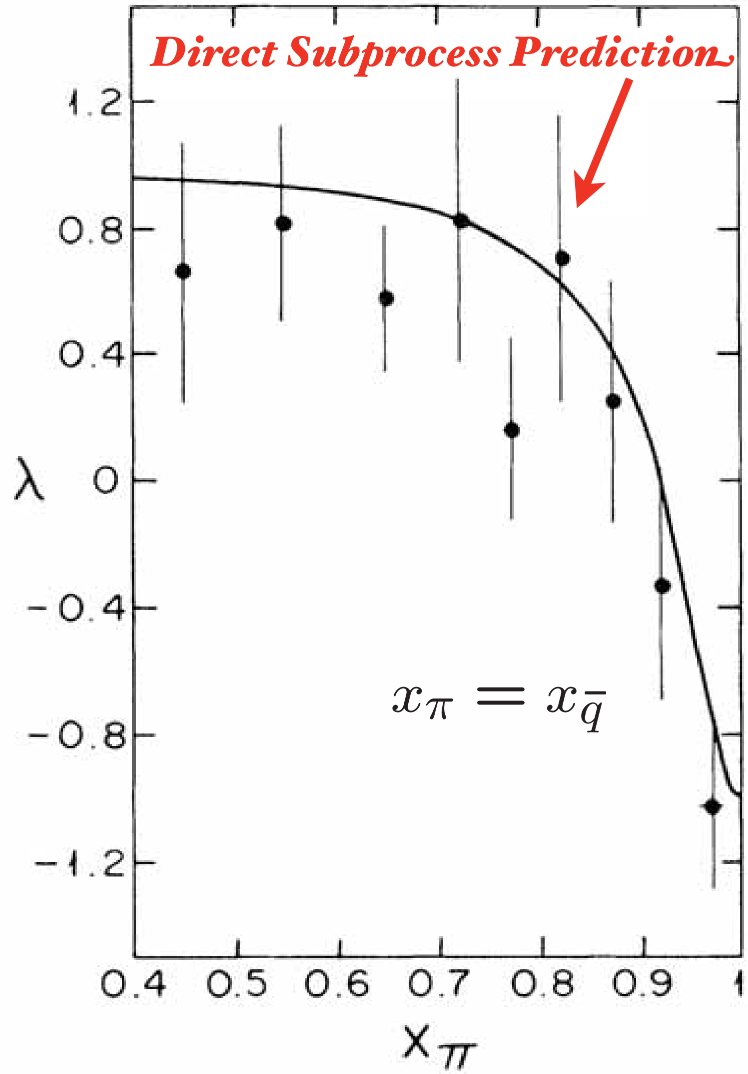
$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \rho \sin 2\theta \cos\phi + \omega \sin^2\theta \cos 2\phi .$$

$$\frac{d^2\sigma}{dx_\pi d\cos\theta} \propto x_\pi \left[ (1-x_\pi)^2 (1+\cos^2\theta) + \frac{4}{9} \frac{\langle k_T^2 \rangle}{M^2} \sin^2\theta \right]$$

$$\langle k_T^2 \rangle = 0.62 \pm 0.16 \ \mathrm{GeV}^2/c^2$$

$$Q^2 = M^2$$

Dramatic change in angular distribution at large $x_F$




**Example of a higher-twist direct subprocess**

Chicago-Princeton Collaboration

Phys.Rev.Lett.55:2649,1985

# Crucial Test of Leading -Twist QCD: Scaling at fixed $x_T$

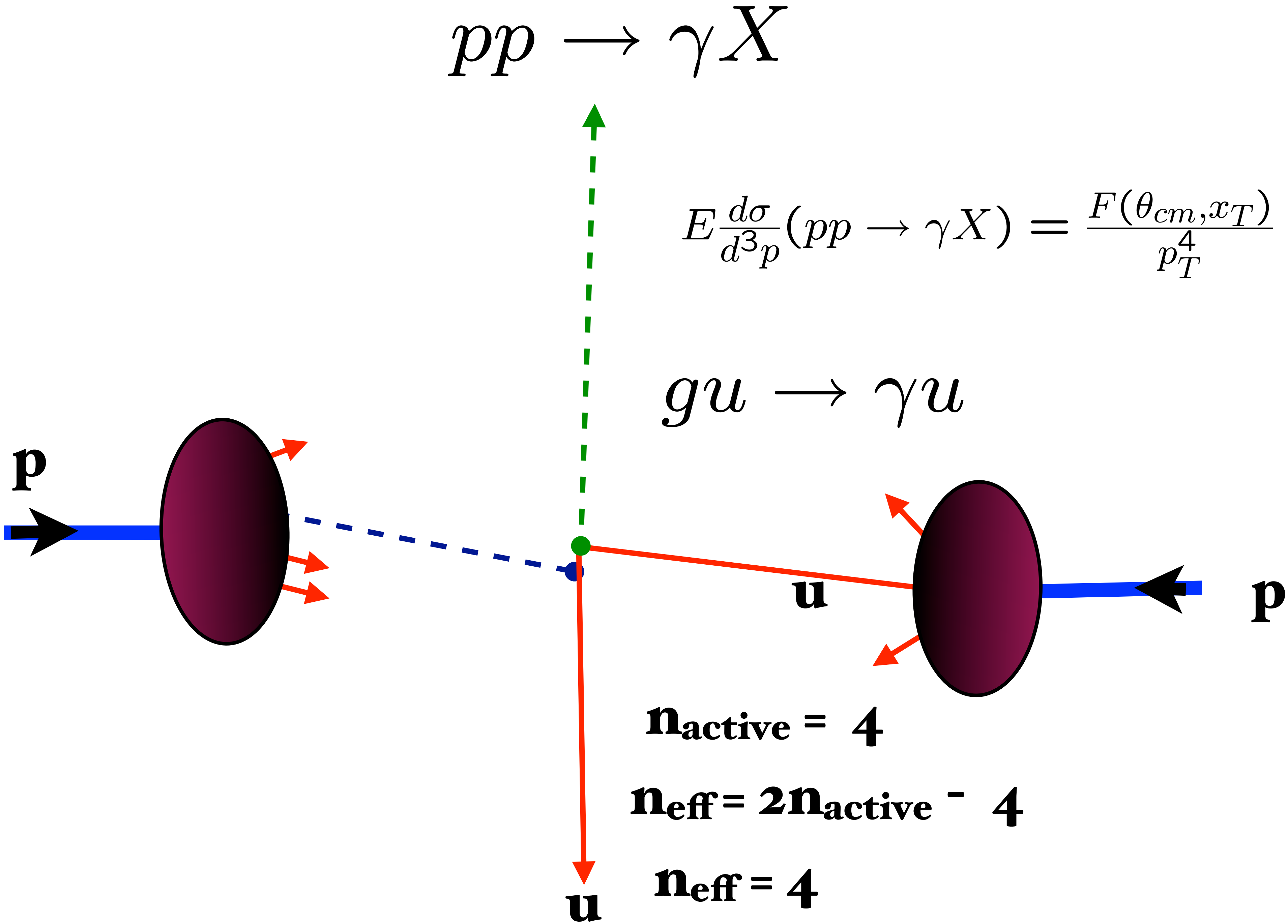
$$x_T = \frac{2p_T}{\sqrt{s}}$$

$$E\frac{d\sigma}{d^3p}(pN \to \pi X) = \frac{F(x_T,\theta_{CM})}{p_T^{neff}}$$

***Parton model: $n_{eff} = 4$***

***As fundamental as Bjorken scaling in DIS***

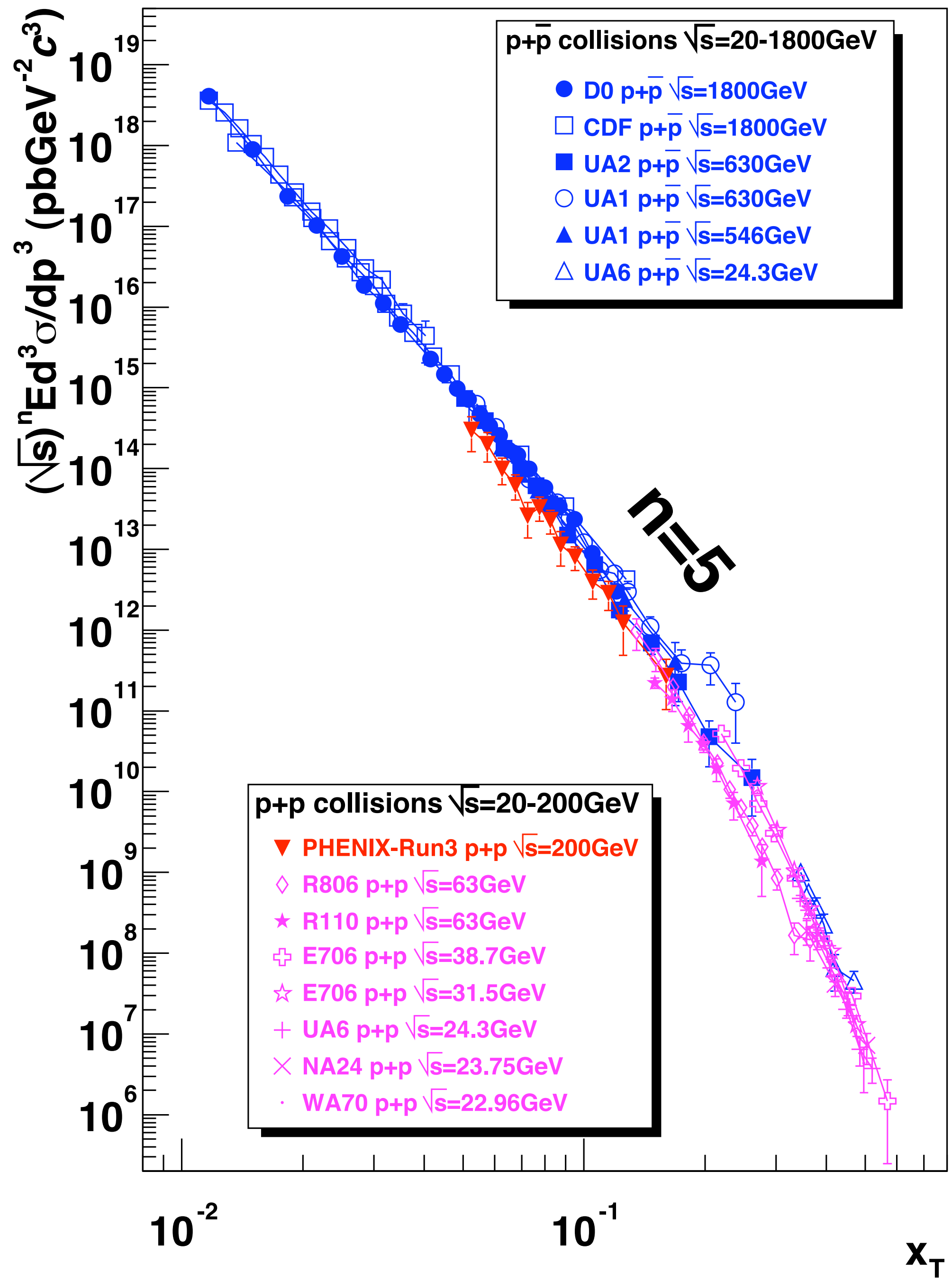
**Conformal scaling: $n_{eff} = 2\, n_{active} - 4$**



$pp \longrightarrow \gamma X$
$E\frac{d\sigma}{d^3p}(pp \rightarrow \gamma X) = \frac{F(\theta_{cm}, x_T)}{p_T^4}$
$gu \longrightarrow \gamma u$
p
u
p
u
$n_{active} = 4$
$n_{eff} = 2n_{active} - 4$
$n_{eff} = 4$

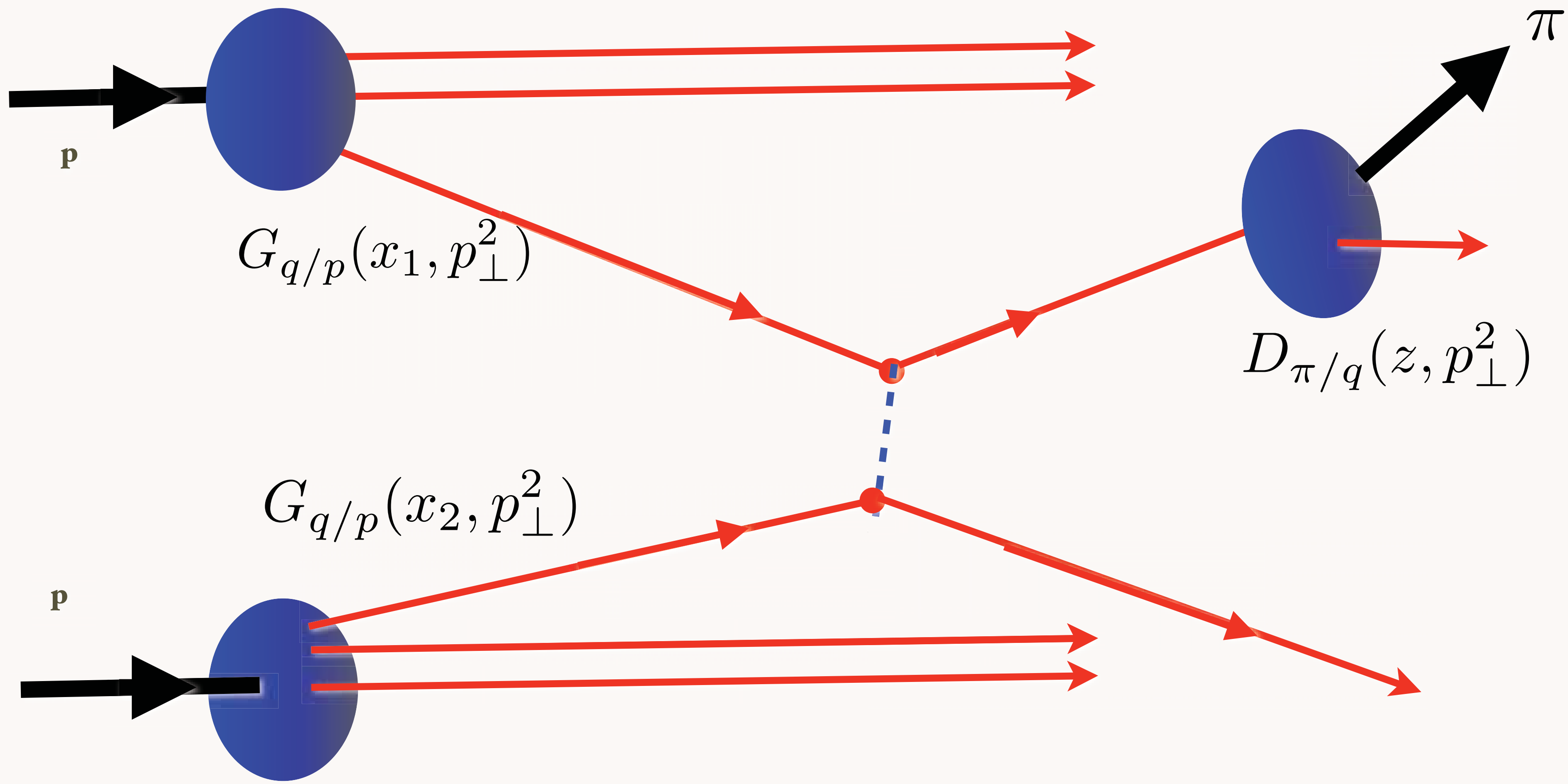
$\sqrt{s}^n E \frac{d\sigma}{d^3p}(pp \rightarrow \gamma X)$ at fixed $x_T$

Tannenbaum




**$x_T$-scaling of direct photon production is consistent with PQCD**

# Leading-Twist Contribution to Hadron Production



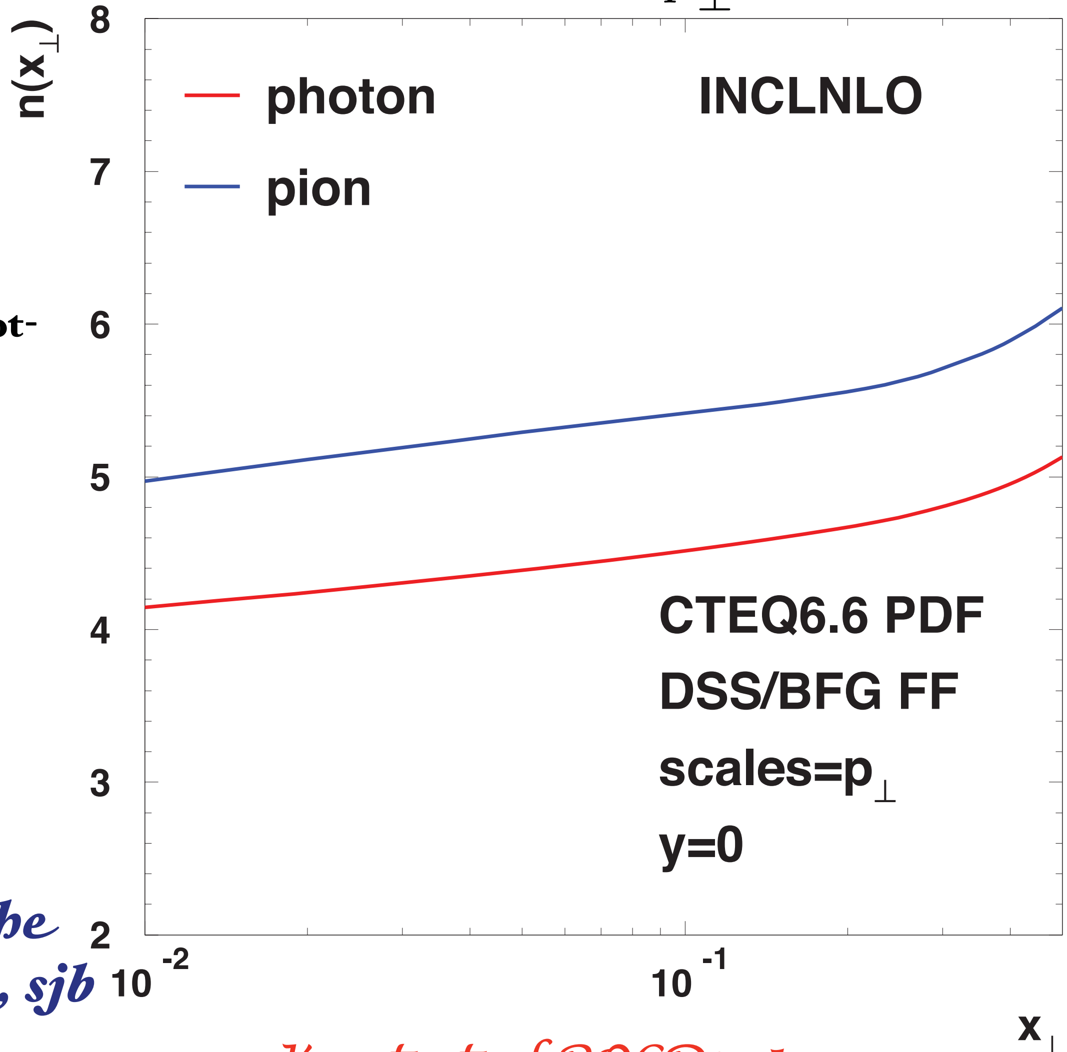

Parton model and Conformal Scaling:

$$\frac{d\sigma}{d^3p/E} = \alpha_s^2 \frac{F(x_\perp, y)}{p_\perp^4}$$

# QCD prediction: Modification of power fall-off due to DGLAP evolution and the Running Coupling

$$\frac{d\sigma}{d^3p/E} = \frac{F(x_\perp, y)}{p_\perp^{n(x_\perp)}}$$

**DSS**
**(De Florian-Sassot-Stratmann)**




$$pp \to \pi X$$

$$pp \to \gamma X$$

$$5 < p_\perp < 20\ GeV$$

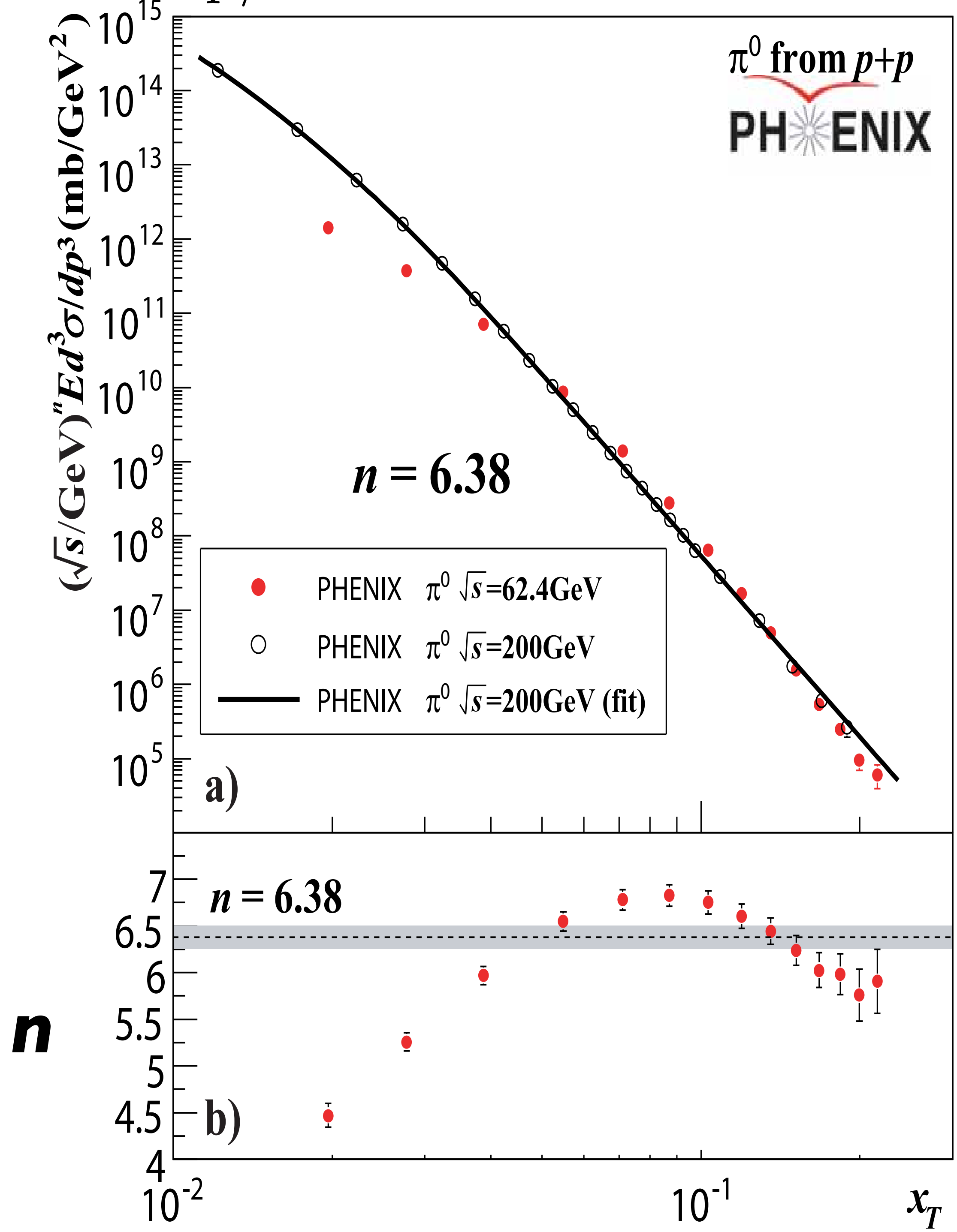
$$70\ GeV < \sqrt{s} < 4\ TeV$$

***Arleo, Aurenche***
***Hwang, Sickles, sjb***

***Pirner, Raufeisen, sjb***

Key test of PQCD: power-law fall-off at fixed $x_T$

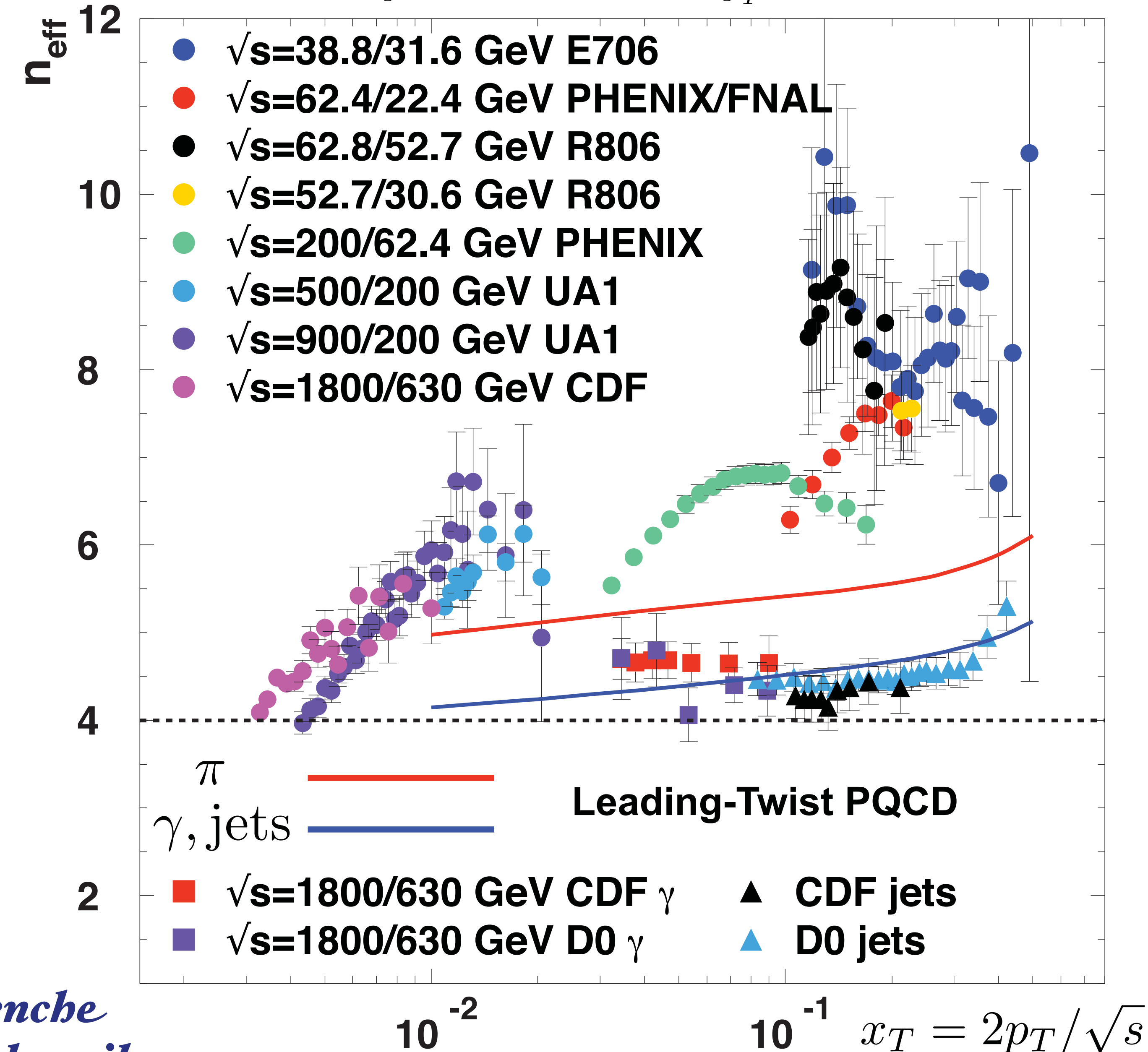
$$[\sqrt{s}]^n \frac{d\sigma}{d^3p/E}(pp \to \pi^0 X) \text{ at fixed } x_T = \frac{2p_T}{\sqrt{s}}$$



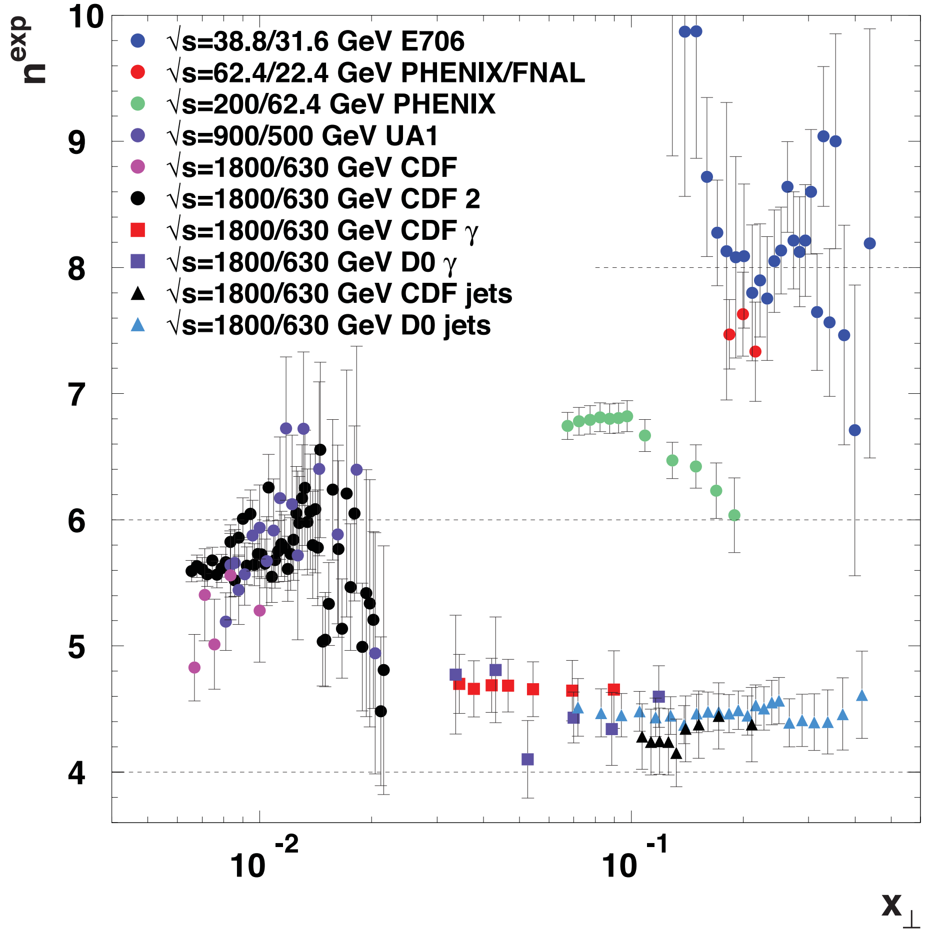

M. J. Tannenbaum

PHENIX 62.4 and 200 GeV data

$$E\frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T, \theta_{CM} = \pi/2)}{p_T^{n_{\rm eff}}}$$

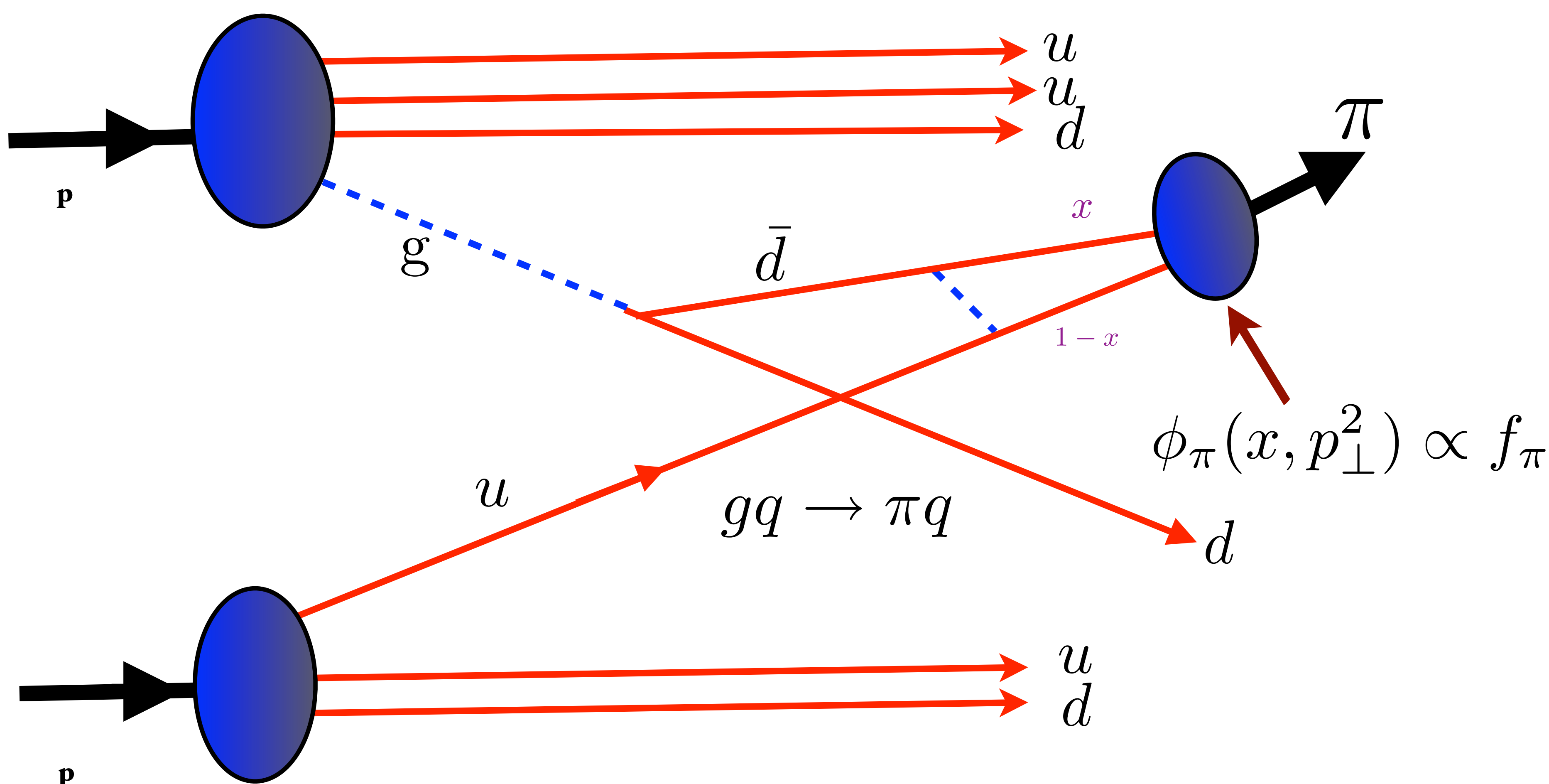



*Arleo, Aurenche*
*Hwang, Sickles, sjb*




- Significant increase of the hadron $n^{\rm exp}$ with $x_\perp$
  - $n^{\rm exp} \simeq 8$ at large $x_\perp$
- Huge contrast with photons and jets !
  - $n^{\rm exp}$ constant and slight above 4 at all $x_\perp$

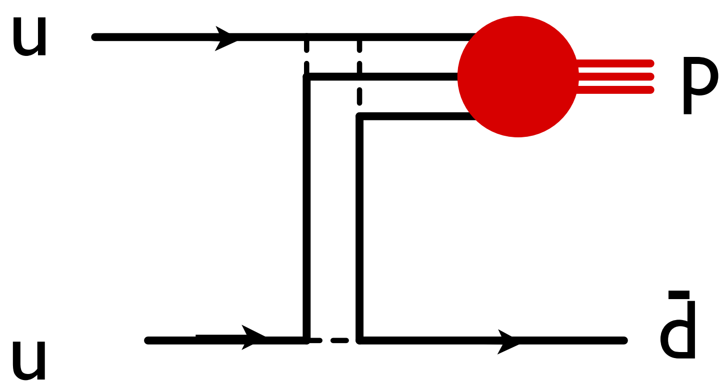
# Direct Contribution to Hadron Production




$$\frac{d\sigma}{d^3p/E} = \alpha_s^3 f_\pi^2 \frac{F(x_\perp, y)}{p_\perp^6}$$

No Fragmentation Function

# Direct Proton Production




$$n_{\rm active} = 6$$

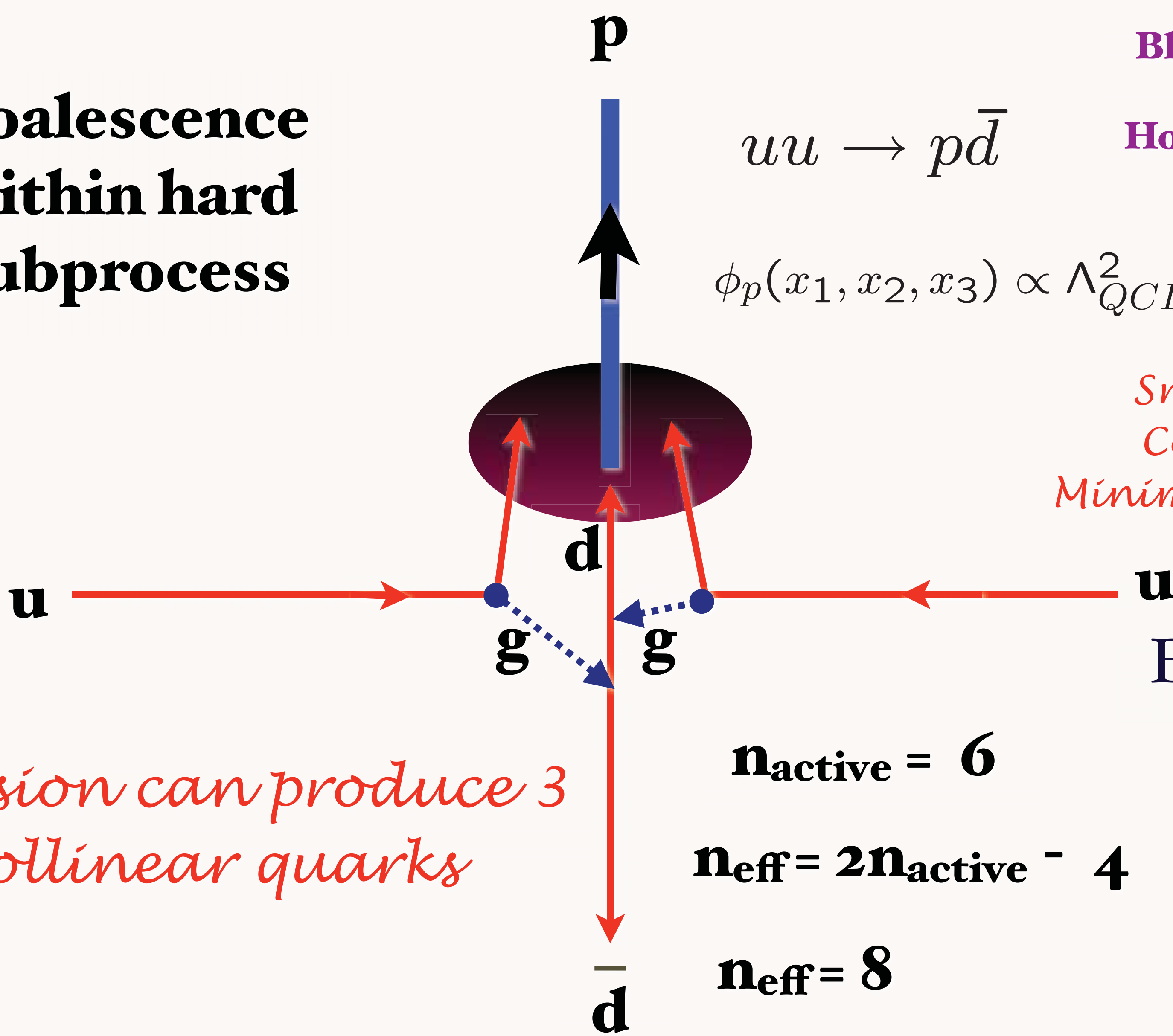
$$E \frac{d\sigma}{d^3p}(p\ p \to p\ X) \sim \frac{F(x_\perp, \vartheta^{\rm cm})}{p_\perp^8}$$

**Explains "Baryon anomaly" at RHIC**

Sickles, sjb

# *Baryon can be made directly within hard subprocess*

**Coalescence within hard subprocess**




$$uu \rightarrow p\bar{d}$$

$$\phi_p(x_1, x_2, x_3) \propto \Lambda^2_{QCD}$$

**Bjorken**
**Blankenbecler, Gunion, sjb**
**Berger, sjb**
**Hoyer, et al: Semi-Exclusive**

**Sickles; sjb**

*Small color-singlet*
*Color Transparent*
*Minimal same-side energy*

Baryon anomaly

$$qq \rightarrow B\bar{q}$$

*Collision can produce 3 collinear quarks*

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$n_{eff} = 8$

# *Chiral Symmetry Breaking in AdS/QCD*

Erlich et al.

- **Chiral symmetry breaking effect in AdS/QCD depends on weighted $z^2$ distribution, not constant condensate**

$$\delta M^2 = -2m_q < \bar{\psi}\psi > \times \int dz \ \phi^2(z) z^2$$

- **$z^2$ weighting consistent with higher Fock states at periphery of hadron wavefunction**
- **AdS/QCD: confined condensate**
- **Suggests "In-Hadron" Condensates**

**de Teramond, Shrock, sjb**

In presence of quark masses the Holographic LF wave equation is ($\zeta = z$)

$$\left[-\frac{d^2}{d\zeta^2} + V(\zeta) + \frac{X^2(\zeta)}{\zeta^2}\right]\phi(\zeta) = \mathcal{M}^2\phi(\zeta), \tag{1}$$

and thus

$$\boxed{\delta M^2 = \left\langle \frac{X^2}{\zeta^2} \right\rangle.} \tag{2}$$

The parameter $a$ is determined by the Weisberger term

$$a = \frac{2}{\sqrt{x}}.$$

Thus

$$\boxed{X(z) = \frac{m}{\sqrt{x}} z - \sqrt{x}\langle\bar{\psi}\psi\rangle z^3,} \tag{3}$$

and

$$\delta M^2 = \sum_i \left\langle \frac{m_i^2}{x_i} \right\rangle - 2\sum_i m_i \langle\bar{\psi}\psi\rangle\langle z^2\rangle + \langle\bar{\psi}\psi\rangle^2\langle z^4\rangle, \tag{4}$$

where we have used the sum over fractional longitudinal momentum $\sum_i x_i = 1$.

*Mass shift from dynamics inside hadronic boundary*

PHYSICAL REVIEW D VOLUME 9, NUMBER 2 15 JANUARY 1974

# Chiral magnetism (or magnetohadrochironics)

Aharon Casher and Leonard Susskind
*Tel Aviv University Ramat Aviv, Tel-Aviv, Israel*
(Received 20 March 1973)

## I. INTRODUCTION

The spontaneous breakdown of chiral symmetry in hadron dynamics is generally studied as a vacuum phenomenon.[1] Because of an instability of the chirally invariant vacuum, the real vacuum is "aligned" into a chirally asymmetric configuration.

On the other hand an approach to quantum field theory exists in which the properties of the vacuum state are not relevant. This is the parton or constituent approach formulated in the infinite-momentum frame.[2] A number of investigations have indicated that in this frame the vacuum may be regarded as the structureless Fock-space vacuum. Hadrons may be described as nonrelativistic collections of constituents (partons). In this framework the spontaneous symmetry breakdown must be attributed to the properties of the hadron's wave function and not to the vacuum.[3]

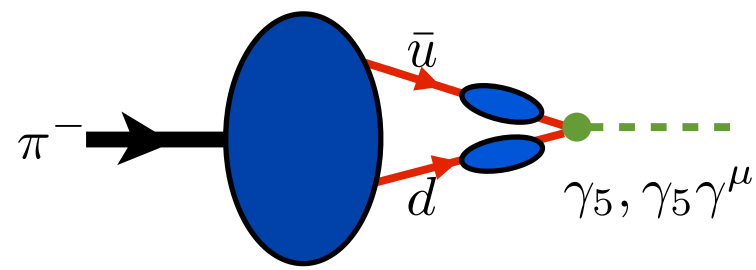
*Light-Front Formalism*

# Bethe-Salpeter Analysis

$$f_H P^\mu = Z_2 \int^\Lambda \frac{d^4q}{(2\pi)^4} \; \frac{1}{2} \big[T_H \gamma_5 \gamma^\mu \mathcal{S}(\frac{1}{2}P + q)) \Gamma_H(q;P) \mathcal{S}(\frac{1}{2}P - q))\big]$$

**Maris, Roberts, Tandy**

$f_H$ Meson Decay Constant
$T_H$ flavor projection operator,
$Z_2(\Lambda)$, $Z_4(\Lambda)$ renormalization constants
$S(p)$ dressed quark propagator
$\Gamma_H(q;P) = F.T.\langle H|\psi(x_a)\bar{\psi}(x_b)|0\rangle$
Bethe-Salpeter bound-state vertex amplitude.




$$i\rho_\zeta^H \equiv \frac{-\langle q\bar{q}\rangle_\zeta^H}{f_H} = Z_4 \int^\Lambda \frac{d^4q}{(2\pi)^4} \; \frac{1}{2} \big[T_H \gamma_5 \mathcal{S}(\frac{1}{2}P + q)) \Gamma_H(q;P) \mathcal{S}(\frac{1}{2}P - q))\big]$$

*In-Hadron Condensate!*

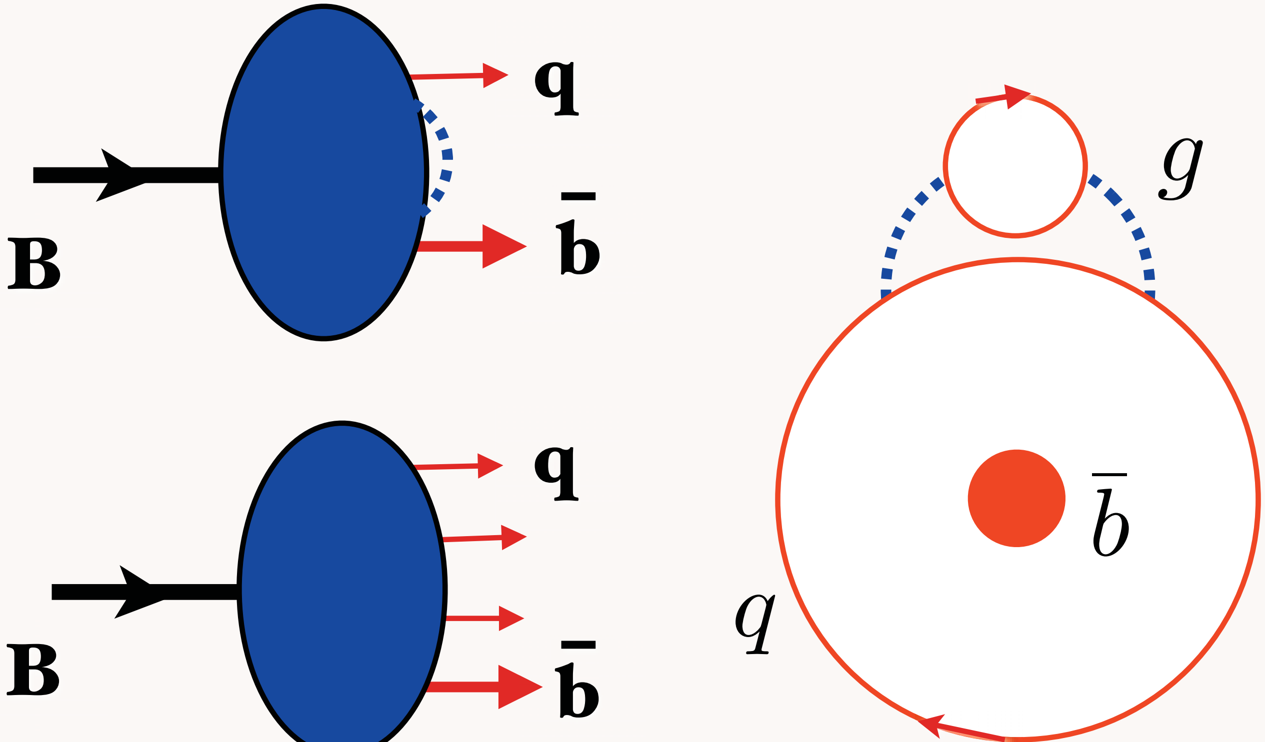
$$f_H m_H^2 = -\rho_\zeta^H \mathcal{M}_H \qquad \mathcal{M}_H = \sum_{q\in H} m_q$$

$$m_\pi^2 \propto (m_q + m_{\bar{q}})/f_\pi \qquad \textit{GMOR}$$

# Simple physical argument for "in-hadron" condensate

Roberts, Shrock, Tandy, sjb

**Gribov pairs**

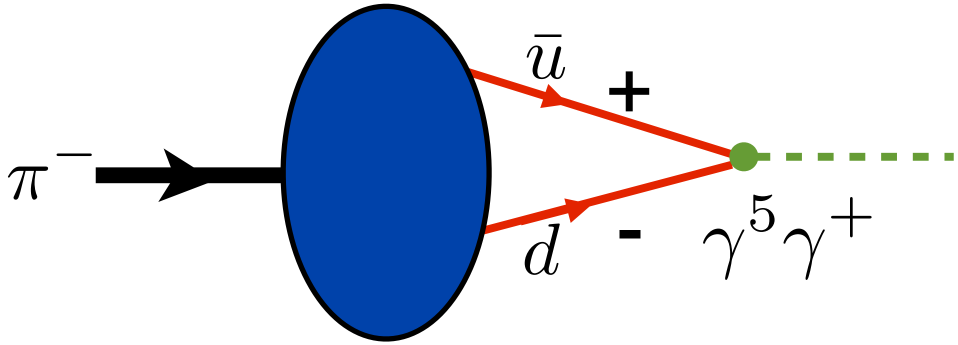



B-Meson

*Use Dyson-Schwinger Equation for bound-state quark propagator: find confined condensate*

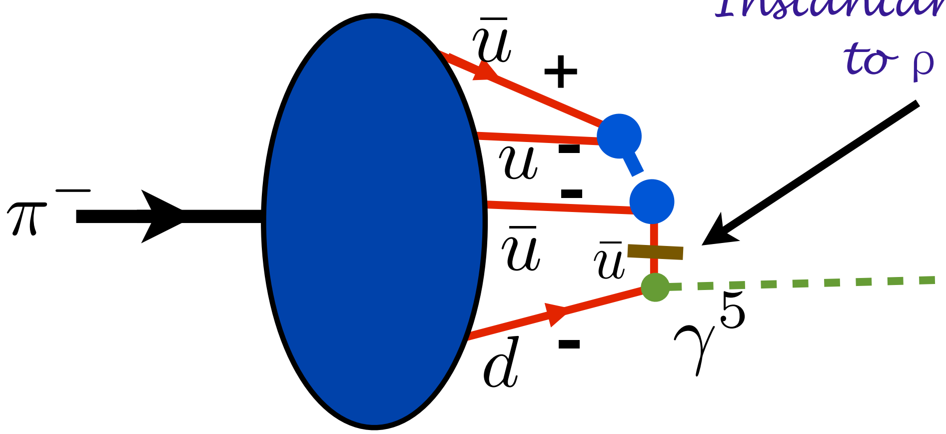
$$< B|\bar{q}q|B > \text{ not } < 0|\bar{q}q|0 >$$

# Higher Light-Front Fock State of Pion Simulates DCSB

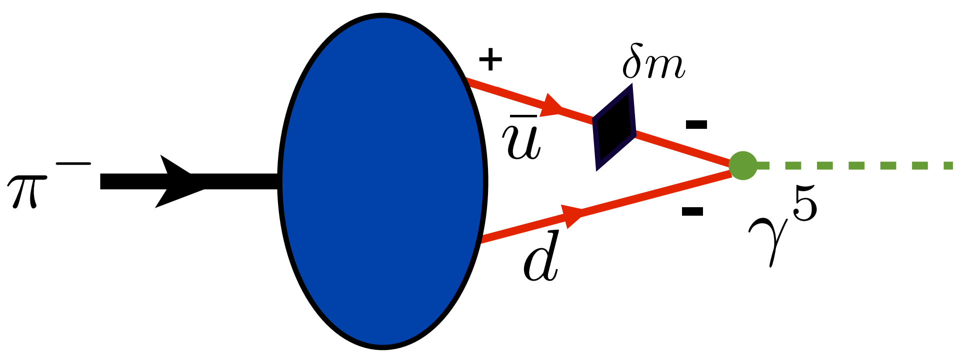



$$f_\pi P^+ =< 0|\bar{q}\gamma^5\gamma^+ q|\pi >$$

Instantaneous quark propagator contribution to ρ π derived from higher Fock state




$$i\rho_\pi =< 0|\bar{q}\gamma^5 q|\pi >$$




Higher Fock state acts like mass insertion

**Roberts, Tandy, Shrock, sjb**

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **82**, 022201(R) (2010)

# New perspectives on the quark condensate

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[3] *Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[4] *Department of Physics, Peking University, Beijing 100871, China*
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(Received 25 May 2010; published 18 August 2010)

We show that the chiral-limit vacuum quark condensate is qualitatively equivalent to the pseudoscalar meson leptonic decay constant in the sense that they are both obtained as the chiral-limit value of well-defined gauge-invariant hadron-to-vacuum transition amplitudes that possess a spectral representation in terms of the current-quark mass. Thus, whereas it might sometimes be convenient to imagine otherwise, neither is essentially a constant mass-scale that fills all spacetime. This means, in particular, that the quark condensate can be understood as a property of hadrons themselves, which is expressed, for example, in their Bethe-Salpeter or light-front wave functions.

# Quark and Gluon condensates reside within hadrons, not vacuum

Casher and Susskind     Maris, Roberts, Tandy     Shrock and sjb

- **Bound-State Dyson Schwinger Equations**
- **AdS/QCD**
- **Analogous to finite size superconductor**
- **Implications for cosmological constant -- Eliminates 45 orders of magnitude conflict**

R. Shrock, sjb
PNAS
ArXiv:0905.1151

# "One of the gravest puzzles of theoretical physics"

**DARK ENERGY AND THE COSMOLOGICAL CONSTANT PARADOX**

A. ZEE

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$$(\Omega_\Lambda)_{QCD} \sim 10^{45}$$

$$\Omega_\Lambda = 0.76(expt)$$

$$(\Omega_\Lambda)_{EW} \sim 10^{56}$$

*QCD Problem Solved if Quark and Gluon condensates reside within hadrons, not vacuum!*

**R. Shrock, sjb**

**arXiv:0905.1151 [hep- th], Proc. Nat'l. Acad. Sci., (in press);**
**``Condensates in Quantum Chromodynamics and the Cosmological Constant."**

# Quark and Gluon condensates reside within hadrons, not LF vacuum

Maris, Roberts, Tandy

Casher Susskind

- Bound-State Dyson-Schwinger Equations
- Spontaneous Chiral Symmetry Breaking within infinite-component LFWFs
- Finite size phase transition - infinite # Fock constituents
- AdS/QCD Description -- CSB is in-hadron Effect
- Analogous to finite-size superconductor!
- Phase change observed at RHIC within a single-nucleus-nucleus collisions-- quark gluon plasma!
- Implications for cosmological constant

Shrock, sjb

"Confined QCD Condensates"

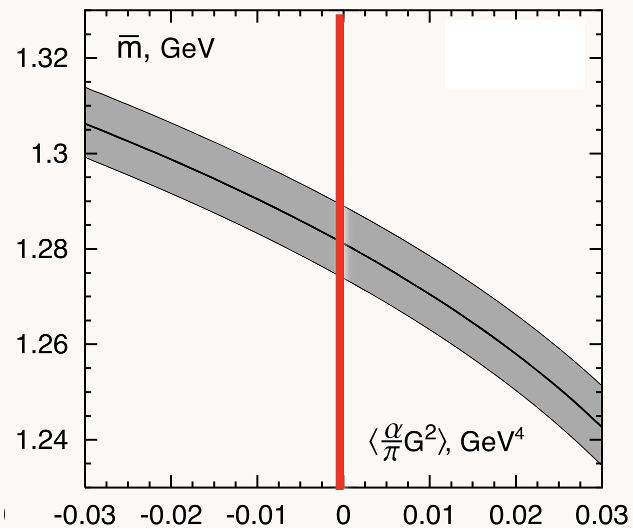
# Determinations of the vacuum Gluon Condensate

$$< 0|\frac{\alpha_s}{\pi}G^2|0 > [\mathrm{GeV}^4]$$

$$-0.005 \pm 0.003 \text{ from } \tau \text{ decay.}$$ Davier et al.

$$+0.006 \pm 0.012 \text{ from } \tau \text{ decay.}$$ Geshkenbein, Ioffe, Zyablyuk

$$+0.009 \pm 0.007 \text{ from charmonium sum rules}$$ Ioffe, Zyablyuk




Consistent with zero vacuum condensate

# Features of AdS/QCD LF Holography

- Based on Conformal Scaling of Infrared QCD Fixed Point
- Conformal template: Use isometries of $AdS_5$
- Interpolating operator of hadrons based on twist, superfield dimensions
- Finite Nc = 3: Baryons built on 3 quarks -- Large Nc limit not required
- Break Conformal symmetry with dilaton
- Dilaton introduces confinement -- positive exponent
- Origin of Linear and HO potentials: Stochastic arguments (Glazek); General 'classical' potential for Dirac Equation (Hoyer)
- Effective Charge from AdS/QCD at all scales
- Conformal Dimensional Counting Rules for Hard Exclusive Processes

$$H^{LF}_{QCD}$$

QCD Meson Spectrum

$$(H^0_{LF} + H^I_{LF})|\Psi >= M^2|\Psi >$$

Coupled Fock states

$$[\frac{\vec{k}^2_\perp + m^2}{x(1-x)} + V^{LF}_{\rm eff}]\ \psi_{LF}(x,\vec{k}_\perp) = M^2\ \psi_{LF}(x,\vec{k}_\perp)$$

Effective two-particle equation

$$\zeta^2 = x(1-x)b^2_\perp$$

$$[-\frac{d^2}{d\zeta^2} + \frac{-1+4L^2}{\zeta^2} + U(\zeta,S,L)]\ \psi_{LF}(\zeta) = M^2\ \psi_{LF}(\zeta)$$

Azimuthal Basis $\zeta, \phi$

$$U(\zeta,S,L) = \kappa^2\zeta^2 + \kappa^2(L+S-1/2)$$

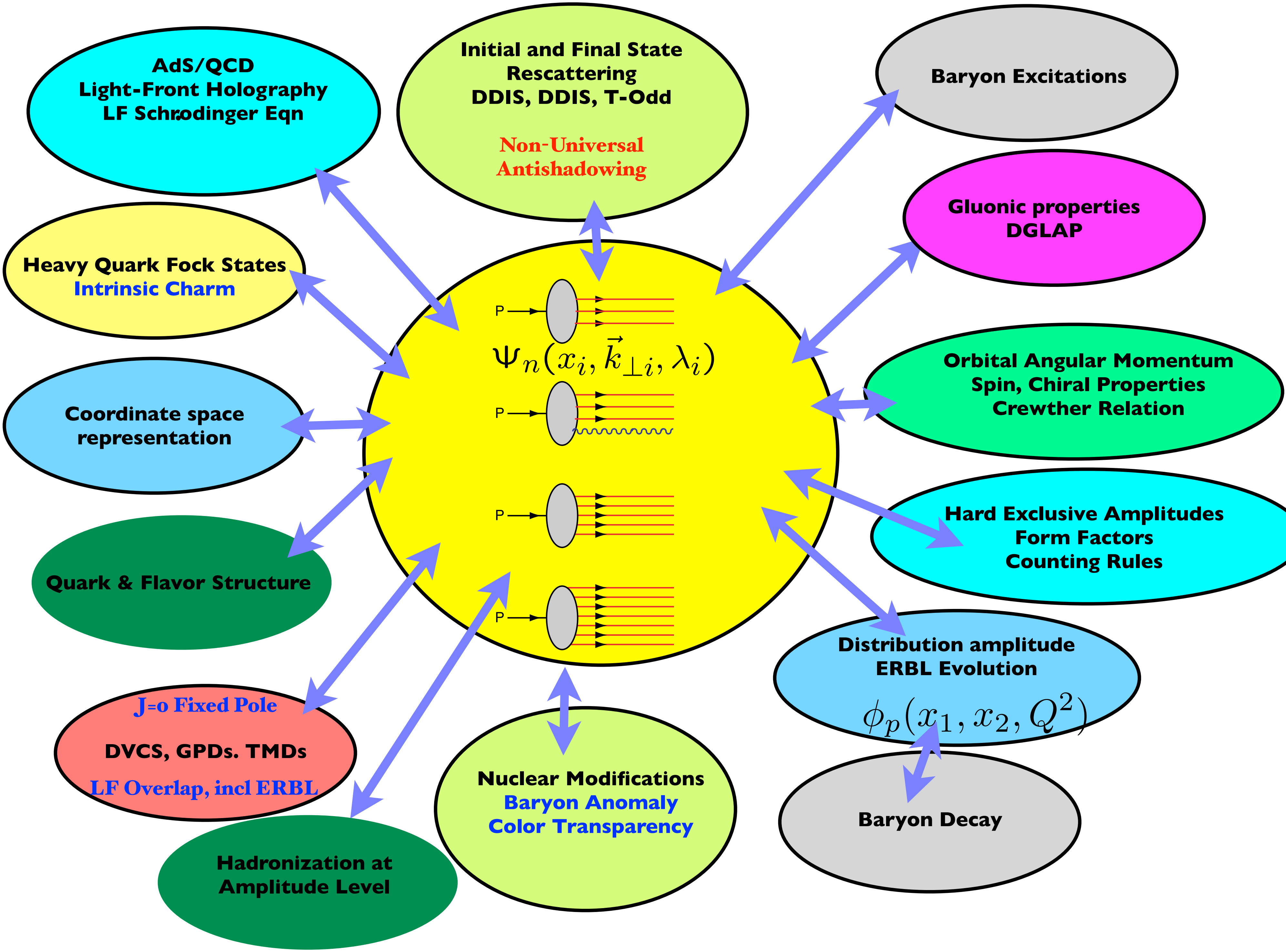
Confining AdS/QCD potential

Semiclassical first approximation to QCD

# An analytic first approximation to QCD
## AdS/QCD + Light-Front Holography

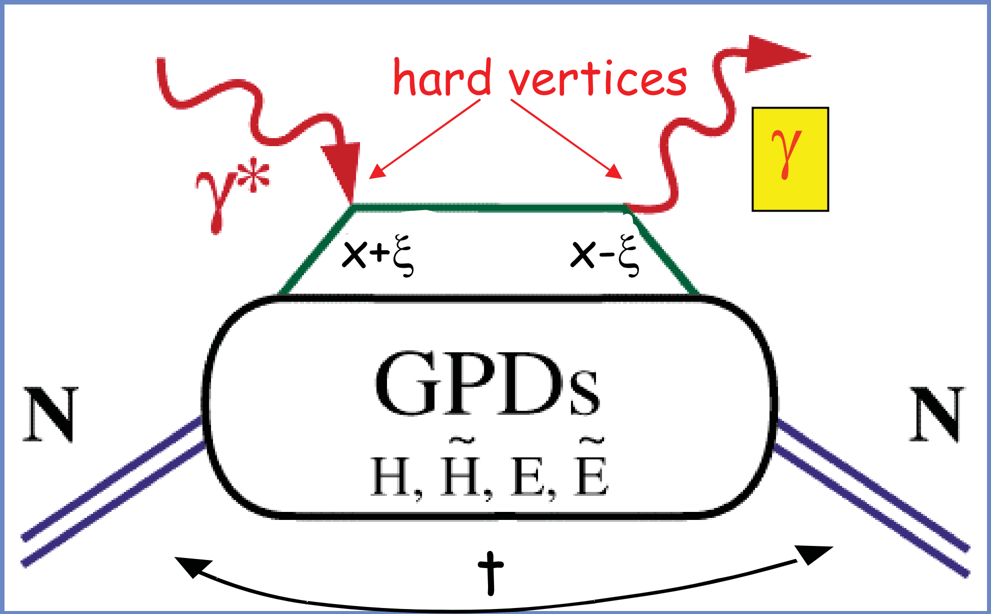
- **As Simple as Schrödinger Theory in Atomic Physics**
- **LF radial variable $\zeta$ conjugate to invariant mass squared**
- **Relativistic, Frame-Independent, Color-Confining**
- **QCD Coupling at all scales: Essential for Gauge Link phenomena**
- **Hadron Spectroscopy and Dynamics from one parameter $\kappa$**
- **Wave Functions, Form Factors, Hadronic Observables, Constituent Counting Rules**
- **Insight into QCD Condensates: Zero cosmological constant!**
- **Systematically improvable with DLCQ Methods**

# QCD and the LF Hadron Wavefunctions



# GPDs & Deeply Virtual Exclusive Processes
## - New Insight into Nucleon Structure

Deeply Virtual Compton Scattering (DVCS)




x – quark momentum fraction

ξ– longitudinal momentum transfer

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

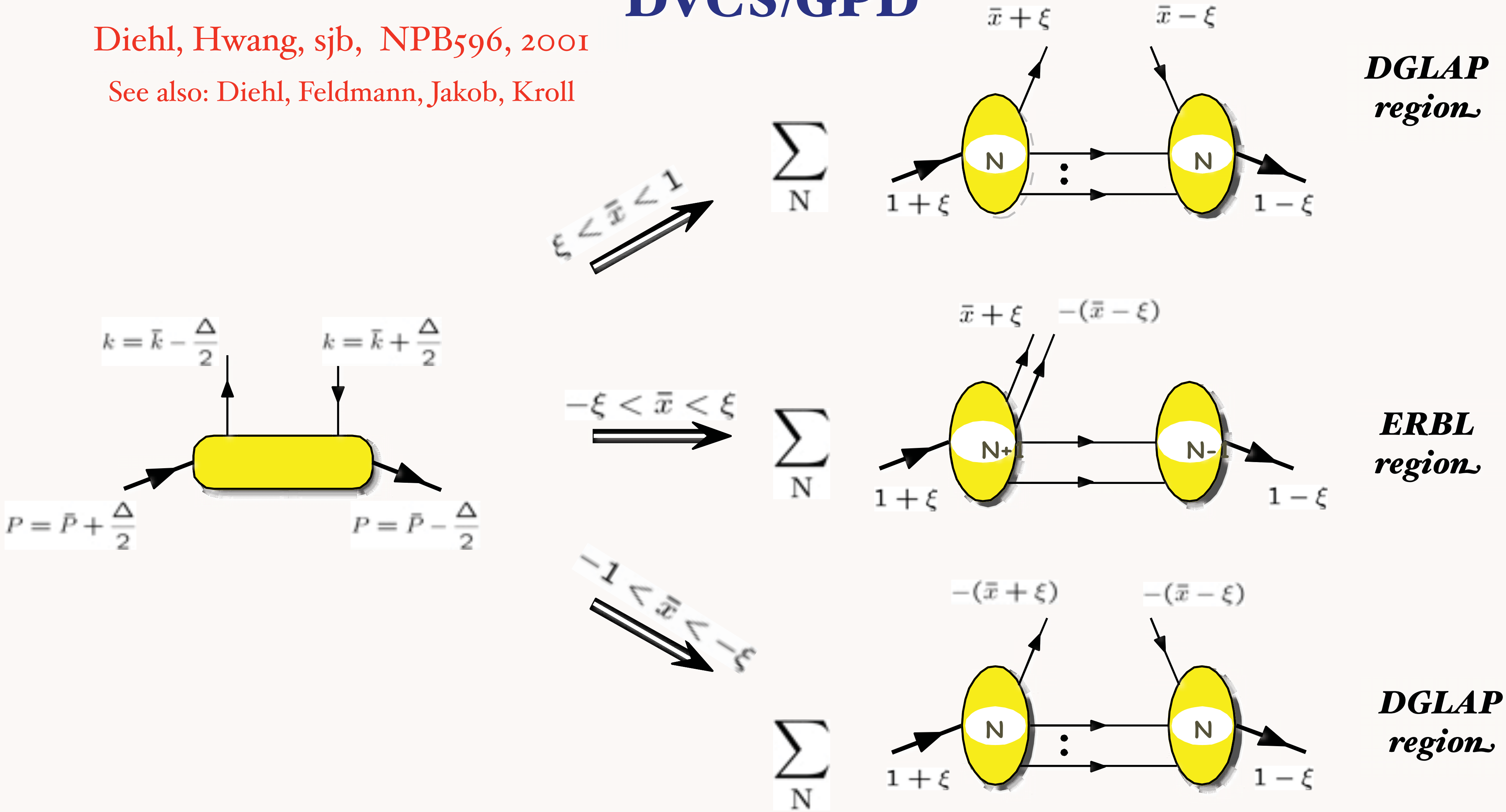
$H(x,\xi,t), E(x,\xi,t), \ldots$ "Generalized Parton Distributions"

# Light-Front Wave Function Overlap Representation

## DVCS/GPD

Diehl, Hwang, sjb, NPB596, 2001

See also: Diehl, Feldmann, Jakob, Kroll



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

Diehl, Hwang, sjb

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

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

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

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

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

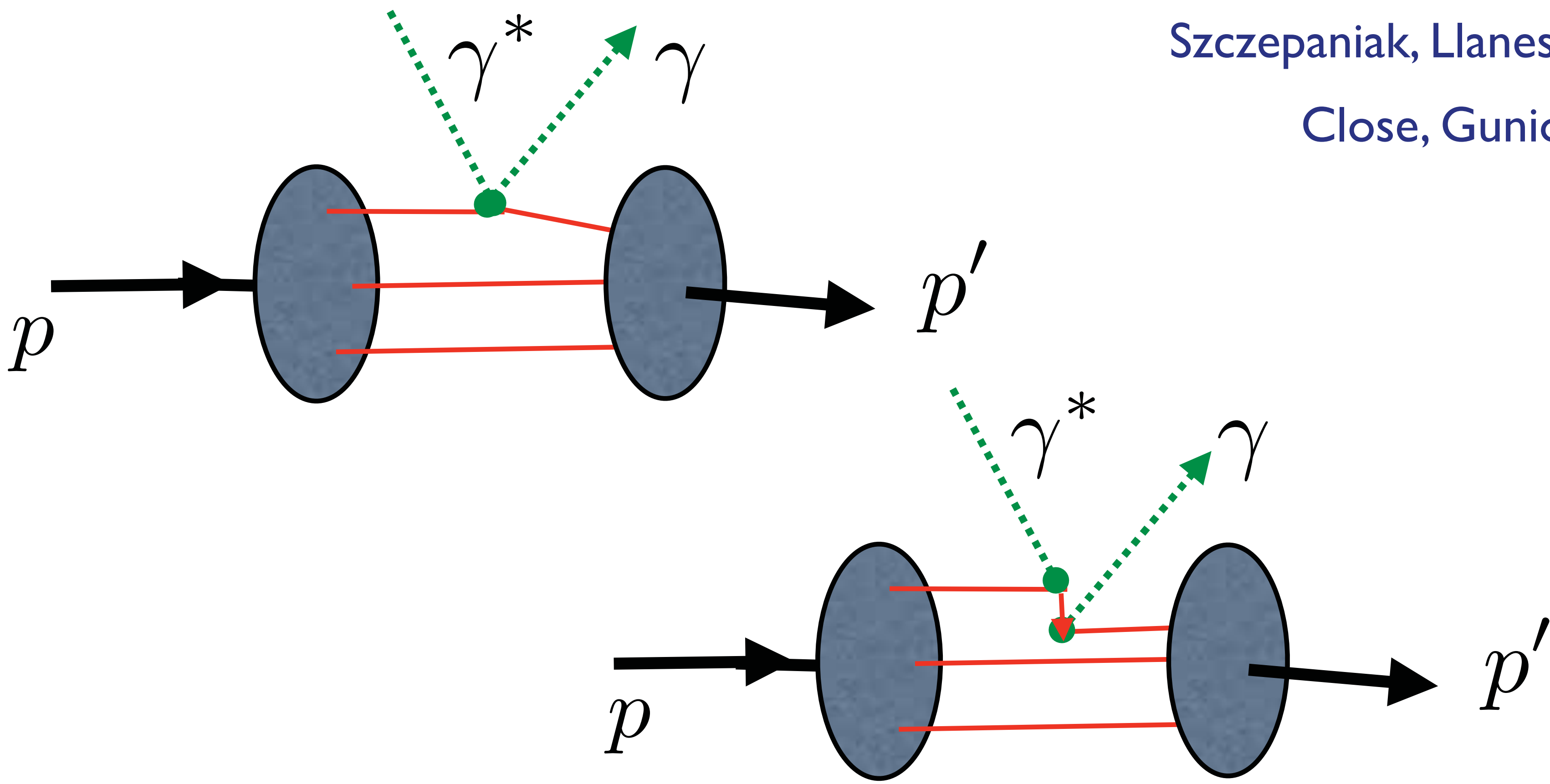
$$x'_i = \frac{x_i}{1-\zeta}, \qquad \vec{k}'_{\perp i} = \vec{k}_{\perp i} + \frac{x_i}{1-\zeta}\vec{\Delta}_\perp .$$

# J=0 Fixed Pole Contribution to DVCS

- J=0 fixed pole -- direct test of QCD locality -- from seagull or instantaneous contribution to Feynman propagator

Szczepaniak, Llanes-Estrada, sjb

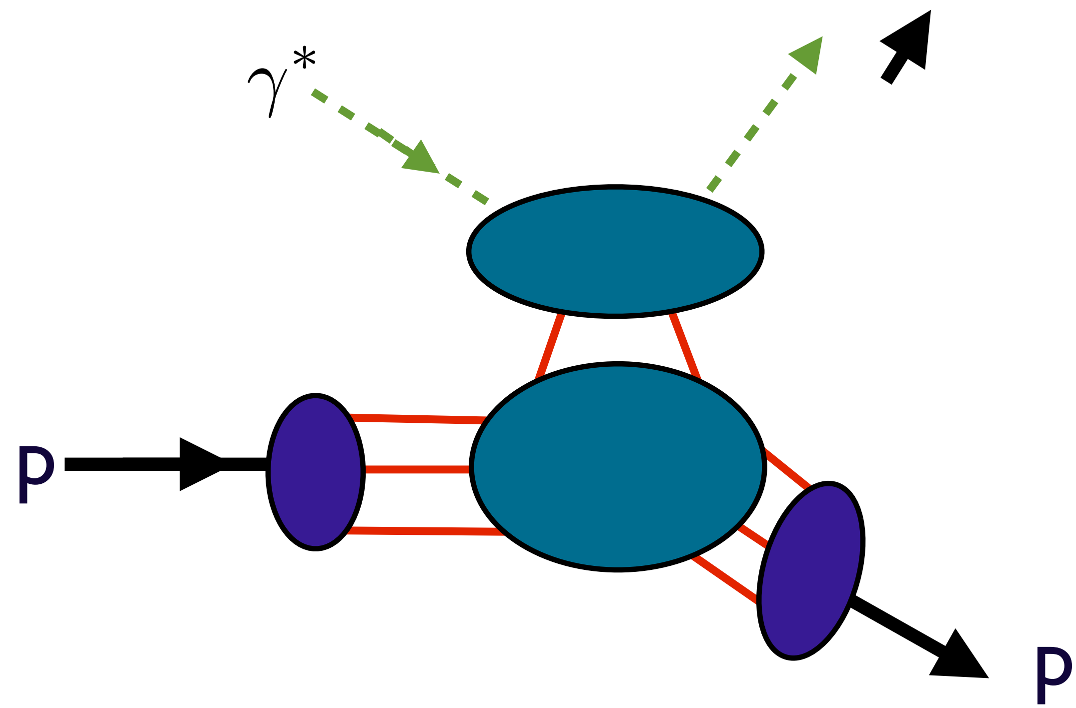
Close, Gunion, sjb




Real amplitude, independent of $Q^2$ at fixed $t$

# Deeply Virtual Compton Scattering

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




## Hard Reggeon Domain

$$s >> -t, Q^2 >> \Lambda^2_{QCD}$$

$$T(\gamma^*(q)p \to \gamma(k) + p) \sim \epsilon \cdot \epsilon' \sum_R s_R^{\alpha}(t) \beta_R(t)$$

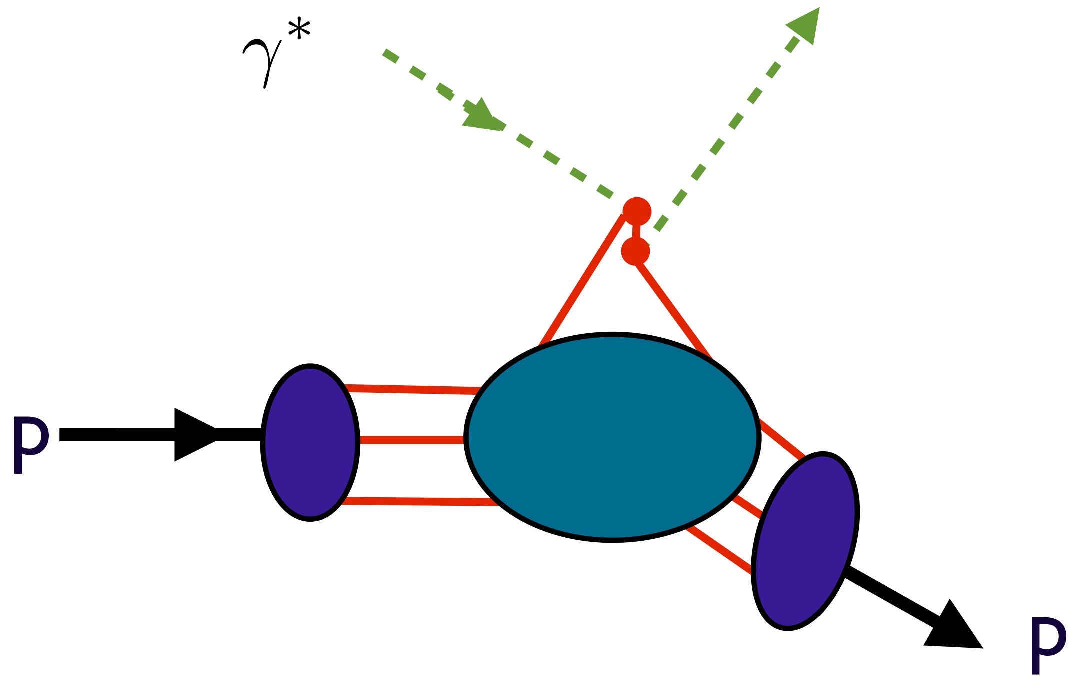
$$\alpha_R(t) \to 0$$

*Reflects elementary coupling of two photons to quarks*

$$\beta_R(t) \sim \frac{1}{t^2} \qquad \frac{d\sigma}{dt} \sim \frac{1}{s^2}\frac{1}{t^4} \sim \frac{1}{s^6} \text{ at fixed } \frac{Q^2}{s}, \frac{t}{s}$$

# Deeply Virtual Compton Scattering

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




*Seagull interaction (instantaneous quark exchange or Z-graph)*

$$s >> -t, Q^2 >> \Lambda^2_{QCD}$$

Hard Reggeon Domain

$$T(\gamma^*(q)p \to \gamma(k) + p) \sim \epsilon \cdot \epsilon' \sum_R s_R^{\alpha}(t)\beta_R(t)$$

$$\alpha_R(t) \to 0$$

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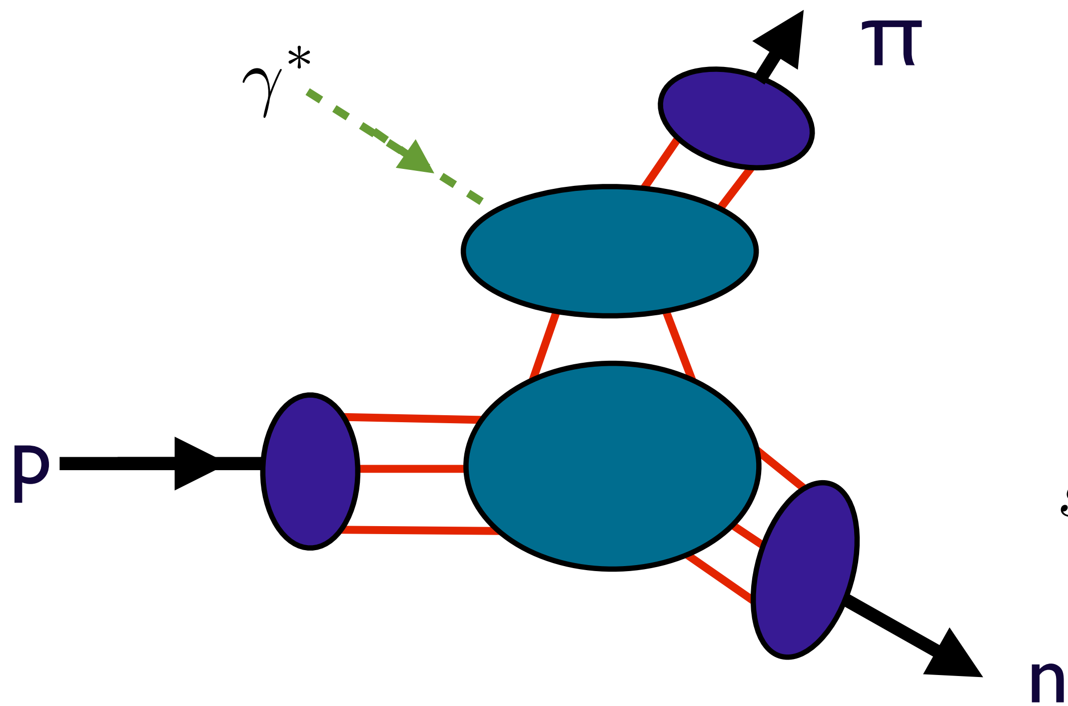
# Exclusive Electroproduction

$$ep \to e'\pi^+ n$$




## Hard Reggeon Domain

$$s >> -t, Q^2 >> \Lambda^2_{QCD}$$

$$T(\gamma^* p \to \pi^+ n) \sim \epsilon \cdot p_i \sum_R s_R^{\alpha}(t)\beta_R(t)$$

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

*Reflects elementary exchange of quarks in t-channel*

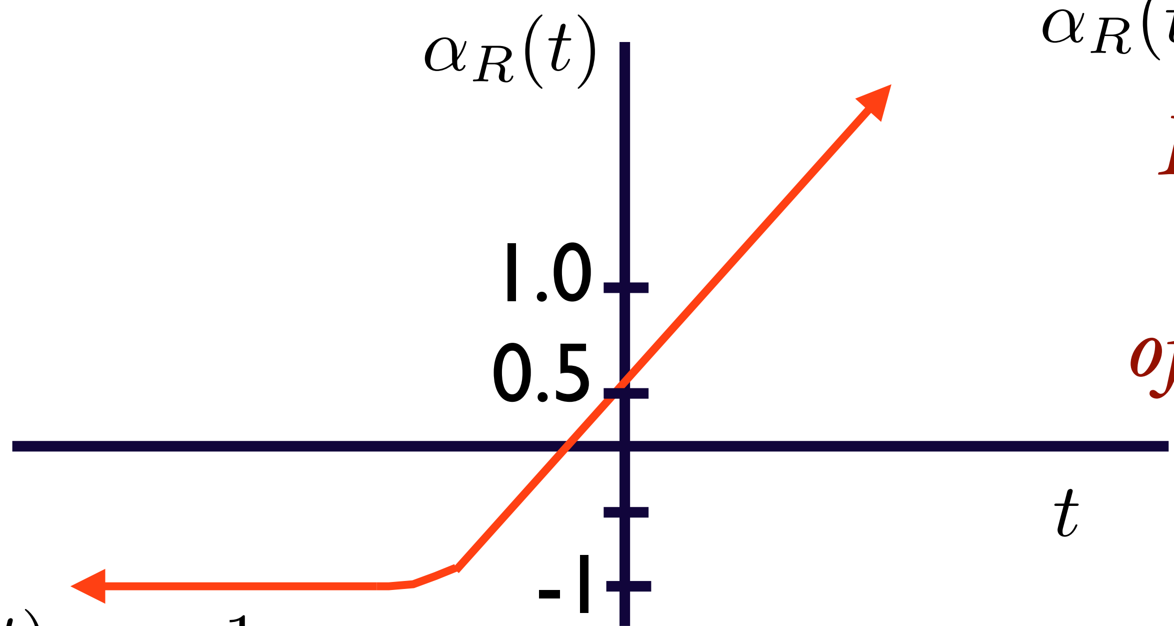
$$\beta_R(t) \sim \frac{1}{t^2}$$

$$\frac{d\sigma}{dt} \sim \frac{1}{s^7} \text{ at fixed } \frac{Q^2}{s}, \frac{t}{s}$$

Gunion, Blankenbecler, Savit, sjb

# *Regge domain*

$$T(\gamma^* p \to \pi^+ n) \sim \epsilon \cdot p_i \sum_R s_R^{\alpha}(t)\beta_R(t) \qquad s >> -t, Q^2$$




$\alpha_R(t) \to -1$

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

*Reflects elementary exchange of quarks in t-channel*

$$\beta_R(t) \sim \frac{1}{t^2}$$

$$\frac{d\sigma}{dt}(\gamma^* p \to \pi^+ n) \to \frac{1}{s^3}\beta_R^2(t)$$

$$\frac{d\sigma}{dt} \sim \frac{1}{s^3}\frac{1}{t^4} \sim \frac{1}{s^7} \text{ at fixed } \frac{Q^2}{s}, \frac{t}{s}$$

*Fundamental test of QCD*

# J=0 Fixed pole in real and virtual Compton scattering

Damashek, Gilman
Close, Gunion, sjb
Llanes-Estrada,
Szczepaniak, sjb

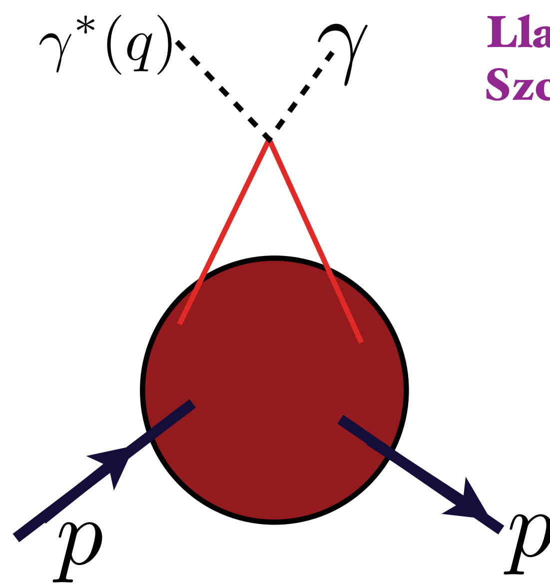
Effective two-photon contact term

Seagull for scalar quarks

Real phase

$$M = s^0 \sum e_q^2 F_q(t)$$

Independent of $Q^2$ at fixed t




<1/x> Moment: Related to Feynman-Hellman Theorem

Fundamental test of local gauge theory

No ambiguity in D-term

$Q^2$-independent contribution to Real DVCS amplitude

$$s^2 \frac{d\sigma}{dt}(\gamma^* p \to \gamma p) = F^2(t)$$

*Single-spin asymmetries*

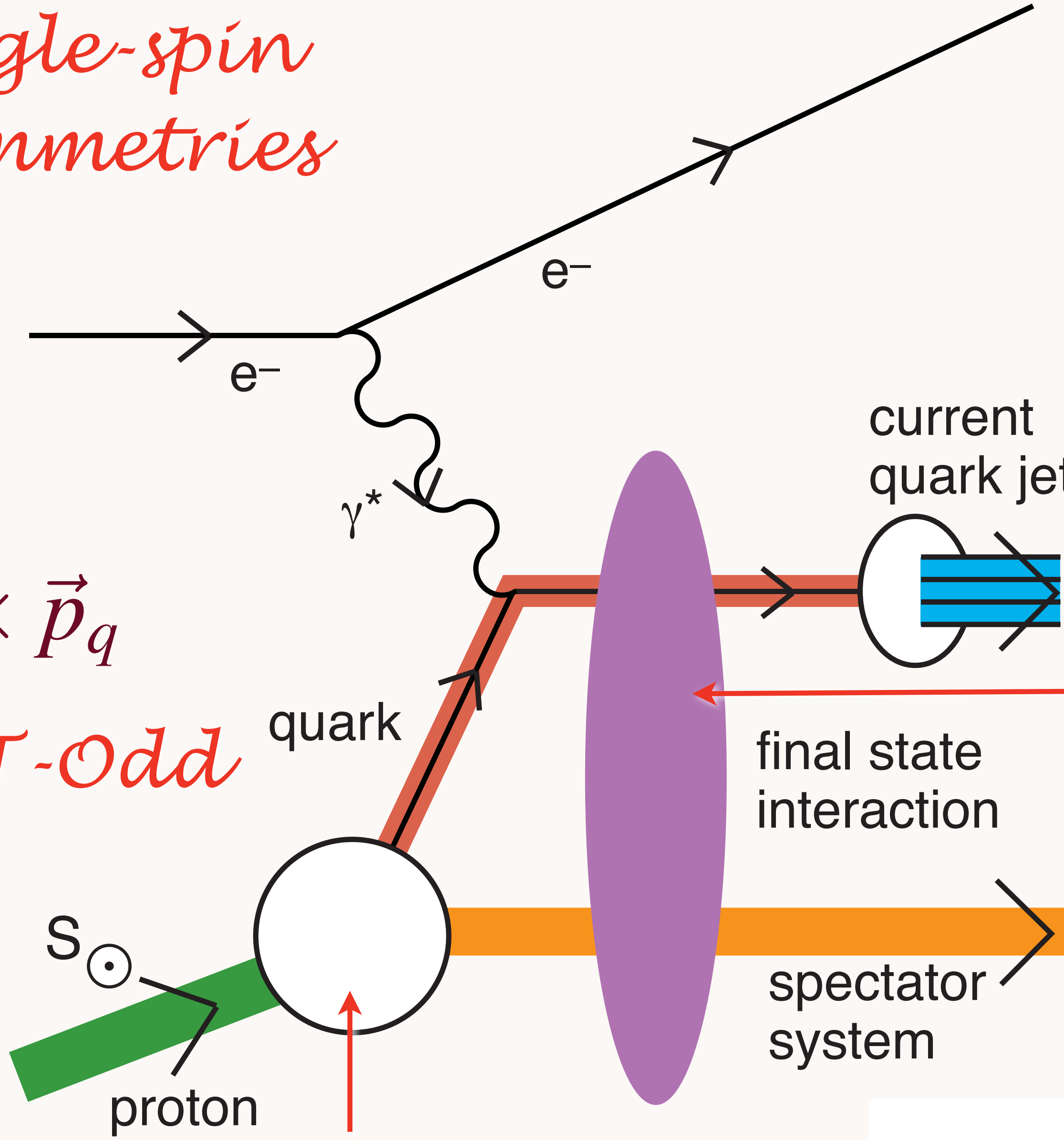
**Leading Twist Sivers Effect**

Hwang, Schmidt, sjb

Collins, Burkardt Ji, Yuan

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

*Pseudo-T-Odd*




*QCD S- and P-Coulomb Phases --Wilson Line*

*Leading-Twist Rescattering Violates pQCD Factorization!*

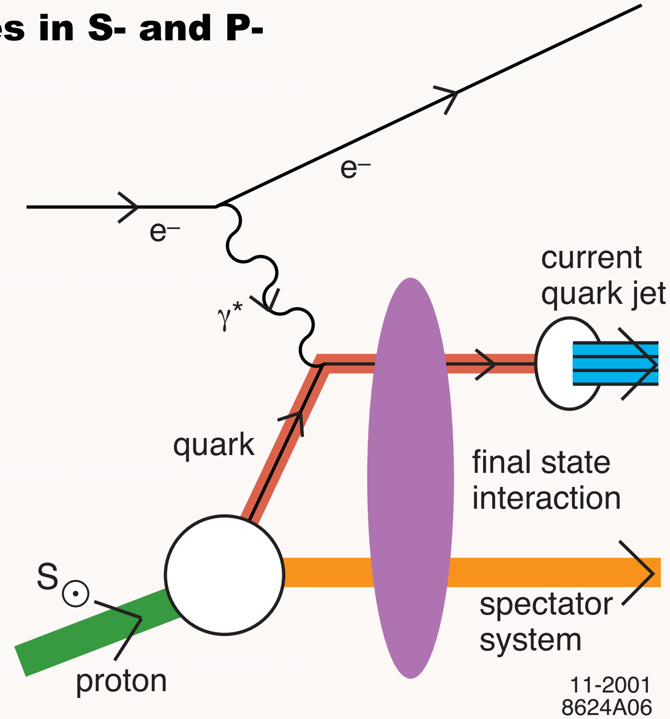
*Light-Front Wavefunction S and P- Waves*

# Final-State Interactions Produce Pseudo T-Odd (Sivers Effect)

Hwang, Schmidt, sjb
Collins

$$i \; \vec{S} \cdot \vec{p}_{jet} \times \vec{q}$$

- **Leading-Twist Bjorken Scaling!**
- **Requires nonzero orbital angular momentum of quark**
- **Arises from the interference of Final-State QCD Coulomb phases in S- and P-waves;**
- **Wilson line effect -- gauge independent**
- **Relate to the quark contribution to the target proton anomalous magnetic moment and final-state QCD phases**
- **QCD phase at soft scale!**
- **New window to QCD coupling and running gluon mass in the IR**
- **QED S and P Coulomb phases infinite -- difference of phases finite!**
- **Alternate: Retarded and Advanced Gauge: Augmented LFWFs**




Pasquini, Xiao, Yuan, sjb
Mulders, Boer Qiu, Sterman

# Final State Interactions Produce T-Odd (Sivers Effect)

- 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 anomalous gavitomagnetic moment)

$$\vec{S} \cdot \vec{p}_{jet} \times \vec{q}$$

Hwang, Schmidt. sjb; Burkardt

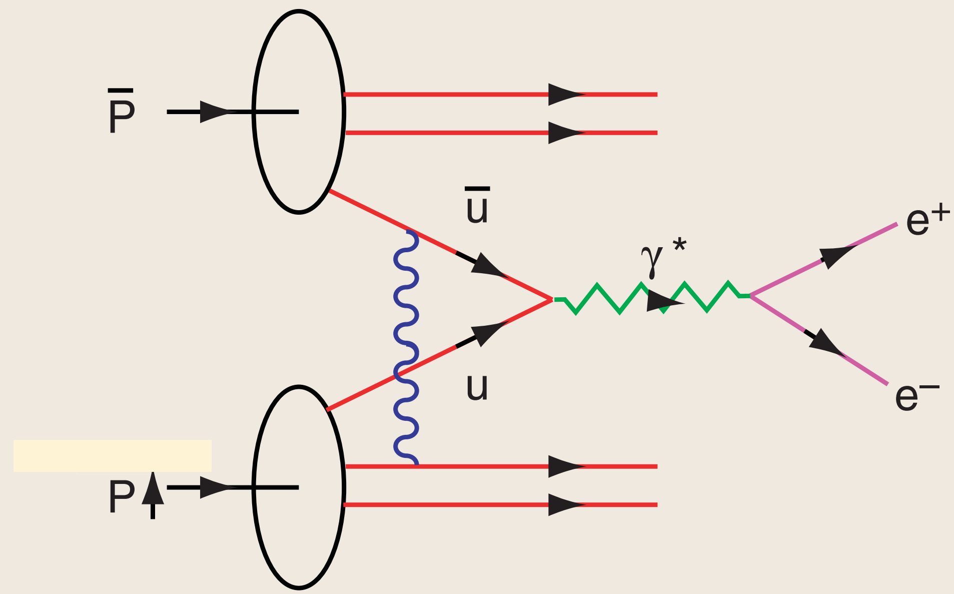
# Key QCD Experiment

Collins; Hwang, Schmidt. sjb

Measure single-spin asymmetry $A_N$ in Drell-Yan reactions

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

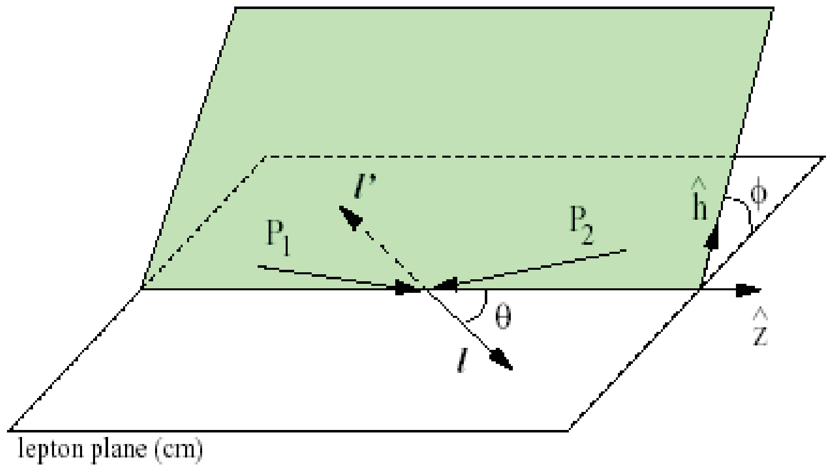
Predict: $A_N(DY) = -A_N(DIS)$
Opposite in sign!




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

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

# Drell-Yan angular distribution




*Unpolarized DY*

- Experimentally, a violation of the Lam-Tung sum rule is observed by sizeable cos2Φ moments
- Several model explanations
  - higher twist
  - spin correlation due to non-triva QCD vacuum
  - Non-zero Boer Mulders function

$\text{Lam} - \text{Tung SR}: \; 1 - \lambda = 2\nu$

$\text{NLO pQCD}: \lambda \approx 1 \; \mu \approx 0 \; \nu \approx 0$

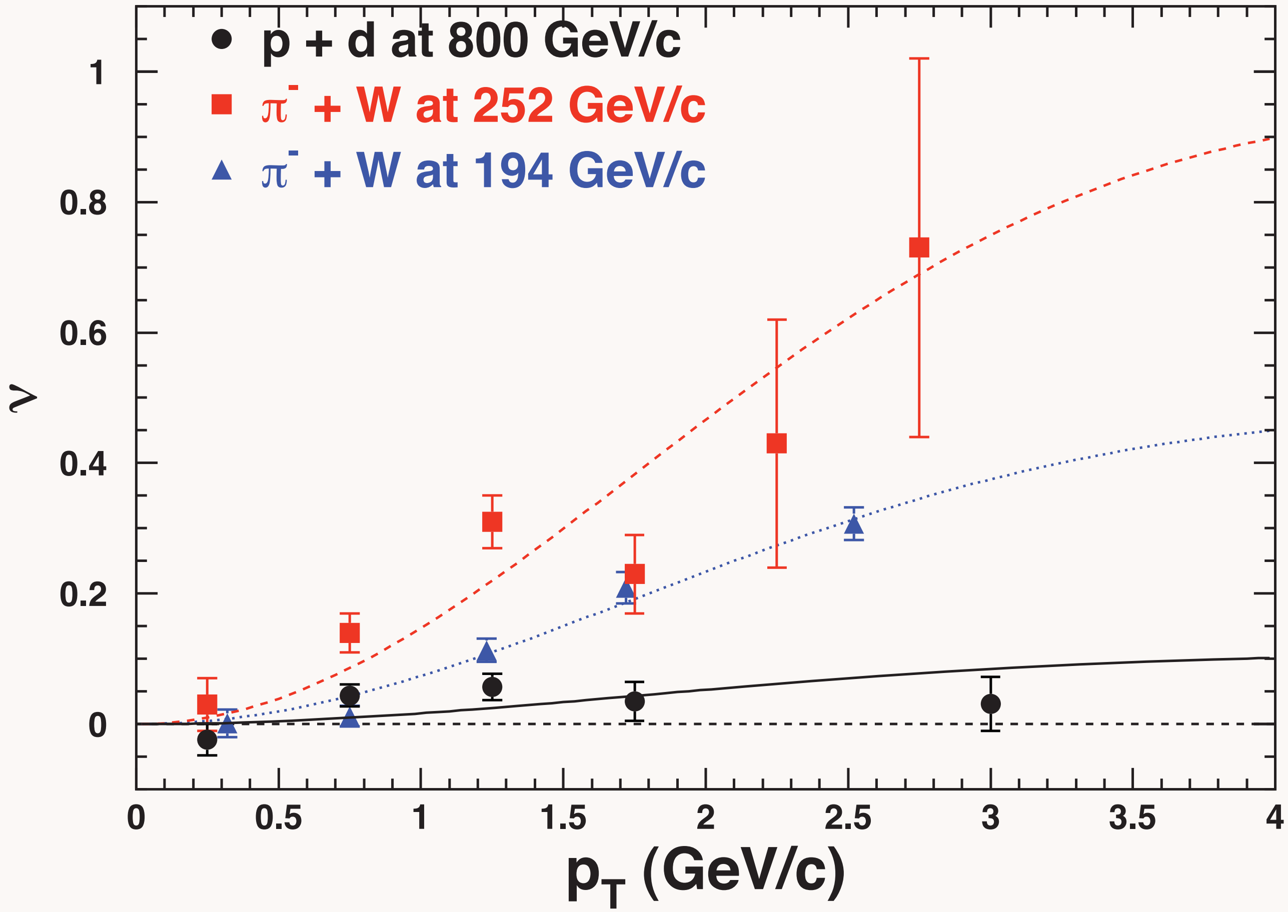
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right)$$

$$\text{Experiment: } \nu \simeq 0.6$$

**B. Seitz**

Measurement of Angular Distributions of Drell-Yan Dimuons in $p+d$ Interaction at 800 GeV/c

(FNAL E866/NuSea Collaboration)

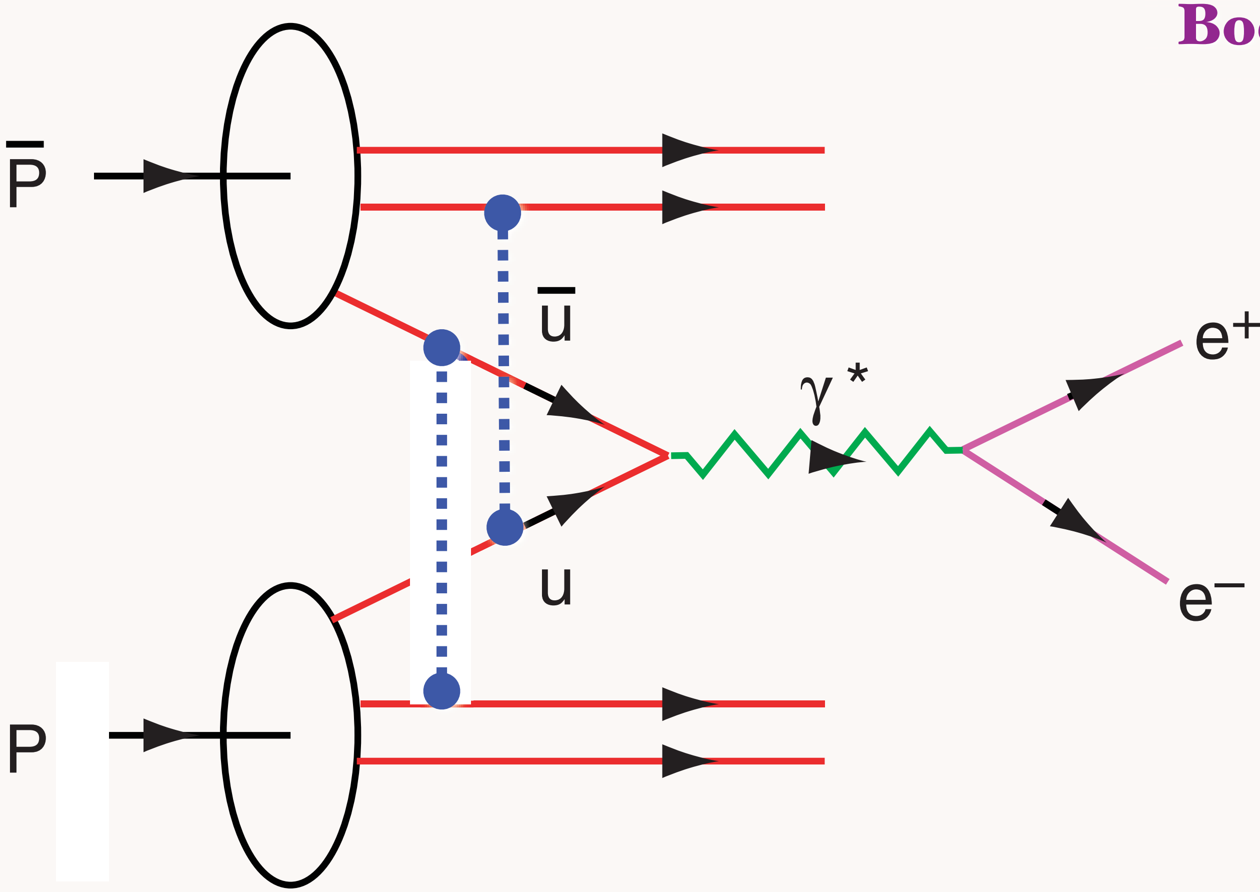



Huge Effect in $\pi W \to \mu^+ \mu^- X$

Negligible Effect $pd \to \mu^+ \mu^- X$

Parameter $\nu$ vs. $p_T$ in the Collins-Soper frame for three Drell-Yan measurements. Fits to the data using Eq. 3 and $M_C = 2.4$ GeV/c$^2$ are also shown.

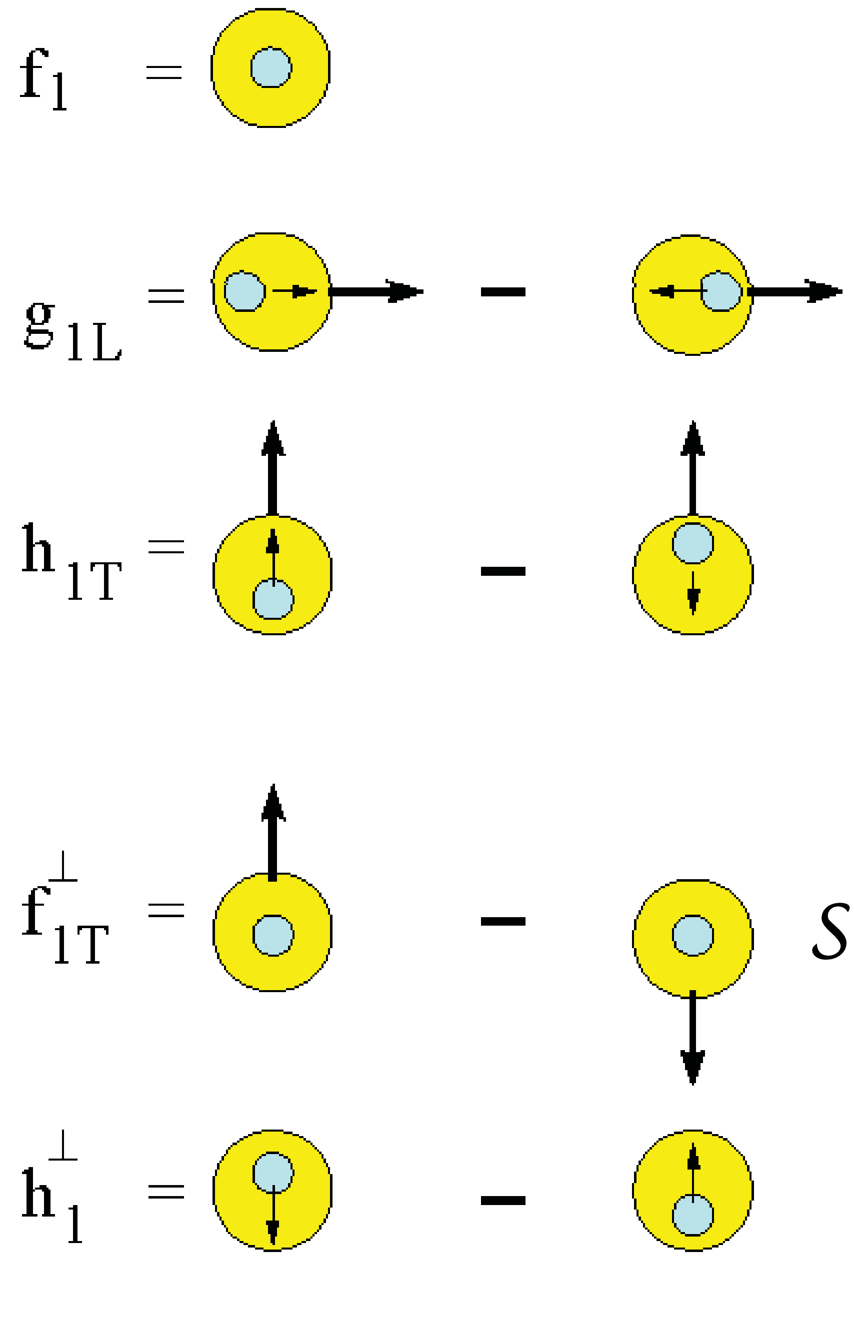
Boer, Hwang, sjb




**DY $\cos 2\phi$ correlation at leading twist from double ISI**

*Product of Boer - Mulders Functions*

$$h_1^{\perp}(x_1, \boldsymbol{p}_\perp^2) \times \bar{h}_1^{\perp}(x_2, \boldsymbol{k}_\perp^2)$$




Unpolarized Distribution

Bj Sum Rule

Transversity

Sivers Function

Boer-Mulders Function

T-Odd:
Require ISI or FSI

*Double Initial-State Interactions generate anomalous* $\cos 2\phi$

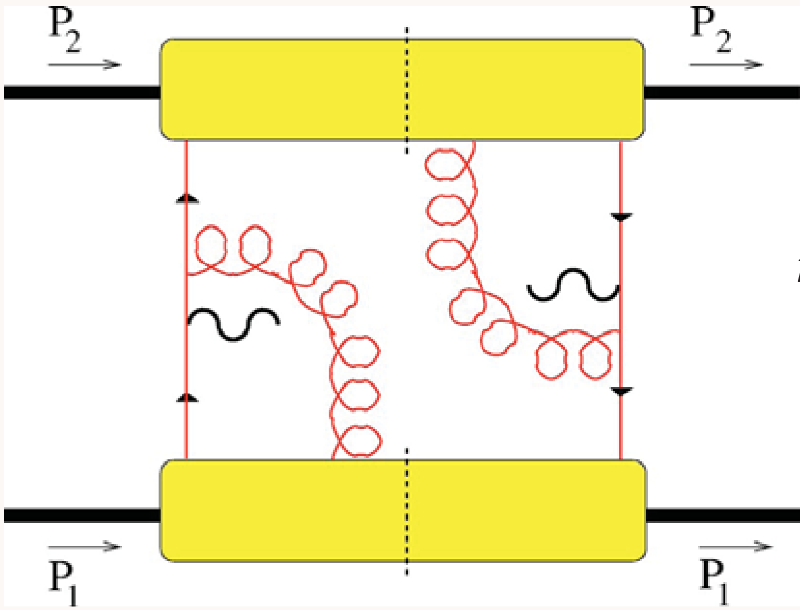
Boer, Hwang, sjb

## Drell-Yan planar correlations

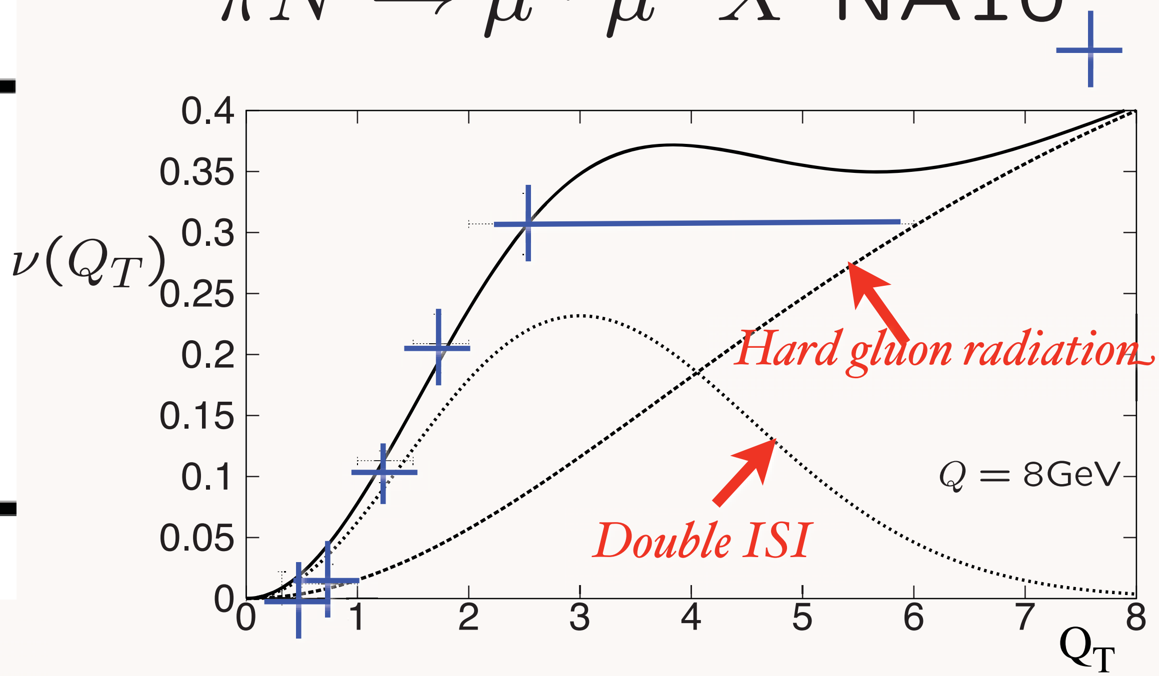
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \left(1 + \lambda \cos^2\theta + \mu \sin 2\theta \, \cos\phi + \frac{\nu}{2}\sin^2\theta \cos 2\phi\right)$$

PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

$$\frac{\nu}{2} \propto h_1^{\perp}(\pi)\, h_1^{\perp}(N)$$



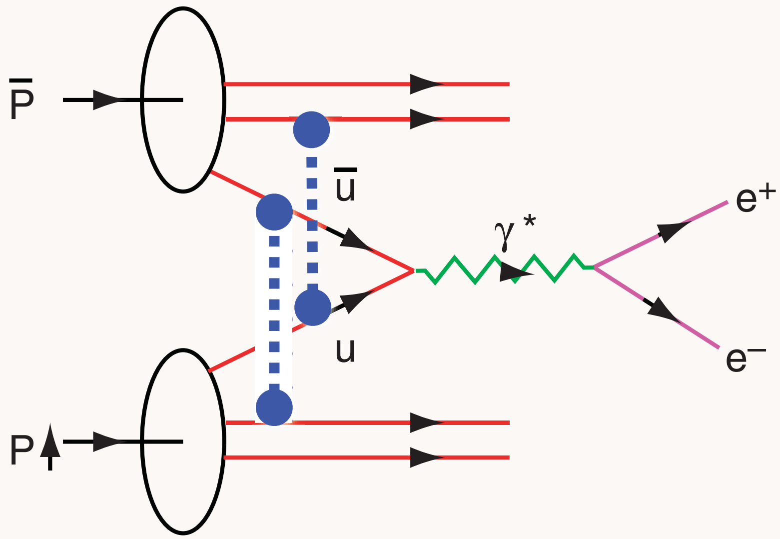

$\pi N \to \mu^+\mu^- X$ NA10




**Violates Lam-Tung relation!**

Model: Boer,

# DY $\cos 2\phi$ correlation at leading twist from double ISI




Product of Boer - Mulders Functions

$$h_1^{\perp}(x_1,\boldsymbol{p}_{\perp}^2)\times\bar{h}_1^{\perp}(x_2,\boldsymbol{k}_{\perp}^2)$$

$$F\equiv\mathcal{F}[(2\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_{\perp}\ \hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{\perp}-\boldsymbol{p}_{\perp}\cdot\boldsymbol{k}_{\perp})h_1^{\perp}\bar{h}_1^{\perp}]$$

$$=\int d^2\boldsymbol{p}_{\perp}d^2\boldsymbol{k}_{\perp}\,\delta^2(\boldsymbol{p}_{\perp}+\boldsymbol{k}_{\perp}-\boldsymbol{q}_{\perp})(2\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_{\perp}\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{\perp}-\boldsymbol{p}_{\perp}\cdot\boldsymbol{k}_{\perp})$$

$$\times h_1^{\perp}(\Delta,\boldsymbol{p}_{\perp}^2)\bar{h}_1^{\perp}(\bar{\Delta},\boldsymbol{k}_{\perp}^2),$$

$$\nu=\frac{2}{M_1M_2}\frac{\sum_{a,\bar{a}}e_a^2F_a}{\sum_{a,\bar{a}}e_a^2G_a}. \qquad (40$$

$$G\equiv\mathcal{F}[f_1\bar{f}_1]$$

$$=\int d^2\boldsymbol{p}_{\perp}\ d^2\boldsymbol{k}_{\perp}\,\delta^2(\boldsymbol{p}_{\perp}+\boldsymbol{k}_{\perp}-\boldsymbol{q}_{\perp})f_1(\Delta,\boldsymbol{p}_{\perp}^2)\bar{f}_1(\bar{\Delta},\boldsymbol{k}_{\perp}^2),$$

**Boer, Hwang, sjb**

| Static | Dynamic |
|---|---|
| Square of Target LFWFs | Modified by Rescattering: ISI & FSI |
| No Wilson Line | Contains Wilson Line, Phases |
| Probability Distributions | No Probabilistic Interpretation |
| Process-Independent | Process-Dependent - From Collision |
| T-even Observables | T-Odd (Sivers, Boer-Mulders, etc.) |
| No Shadowing, Anti-Shadowing | Shadowing, Anti-Shadowing, Saturation |
| Sum Rules: Momentum and $J^z$ | Sum Rules Not Proven |
| DGLAP Evolution; mod. at large x | DGLAP Evolution |
| No Diffractive DIS | Hard Pomeron and Odderon Diffractive DIS |

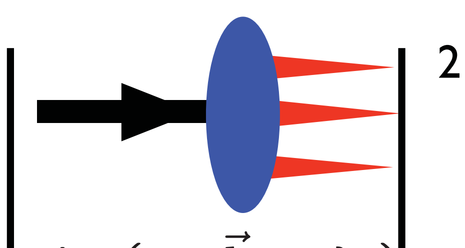
**Hwang, Schmidt, sjb,**

**Mulders, Boer**

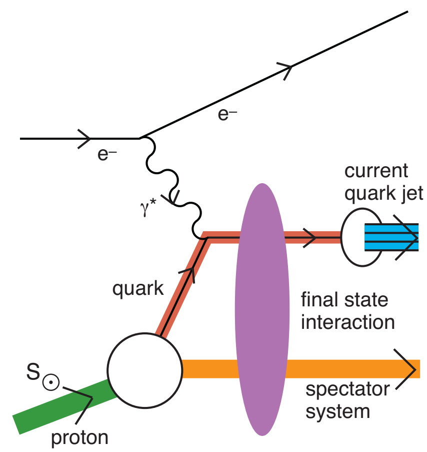
**Qiu, Sterman**

**Collins, Qiu**

**Pasquini, Xiao, Yuan, sjb**




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



# Applications of Nonperturbative Running Coupling from AdS/QCD

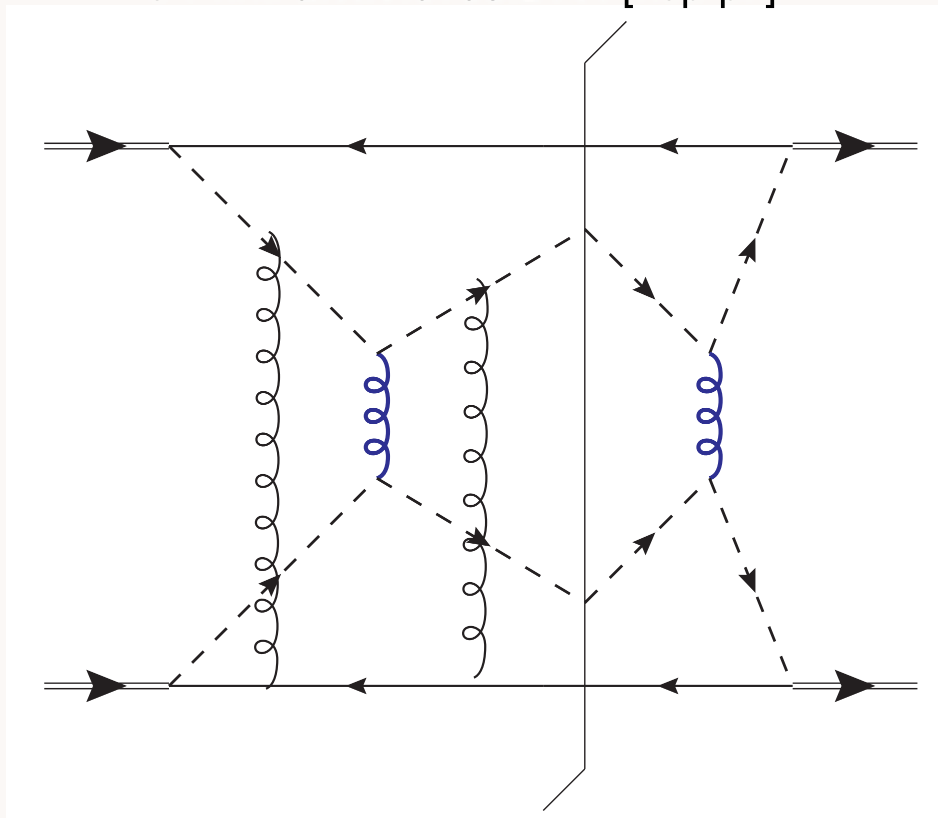
- Sivers Effect in SIDIS, Drell-Yan
- Double Boer-Mulders Effect in DY
- Diffractive DIS
- Heavy Quark Production at Threshold

*All involve gluon exchange at small momentum transfer*

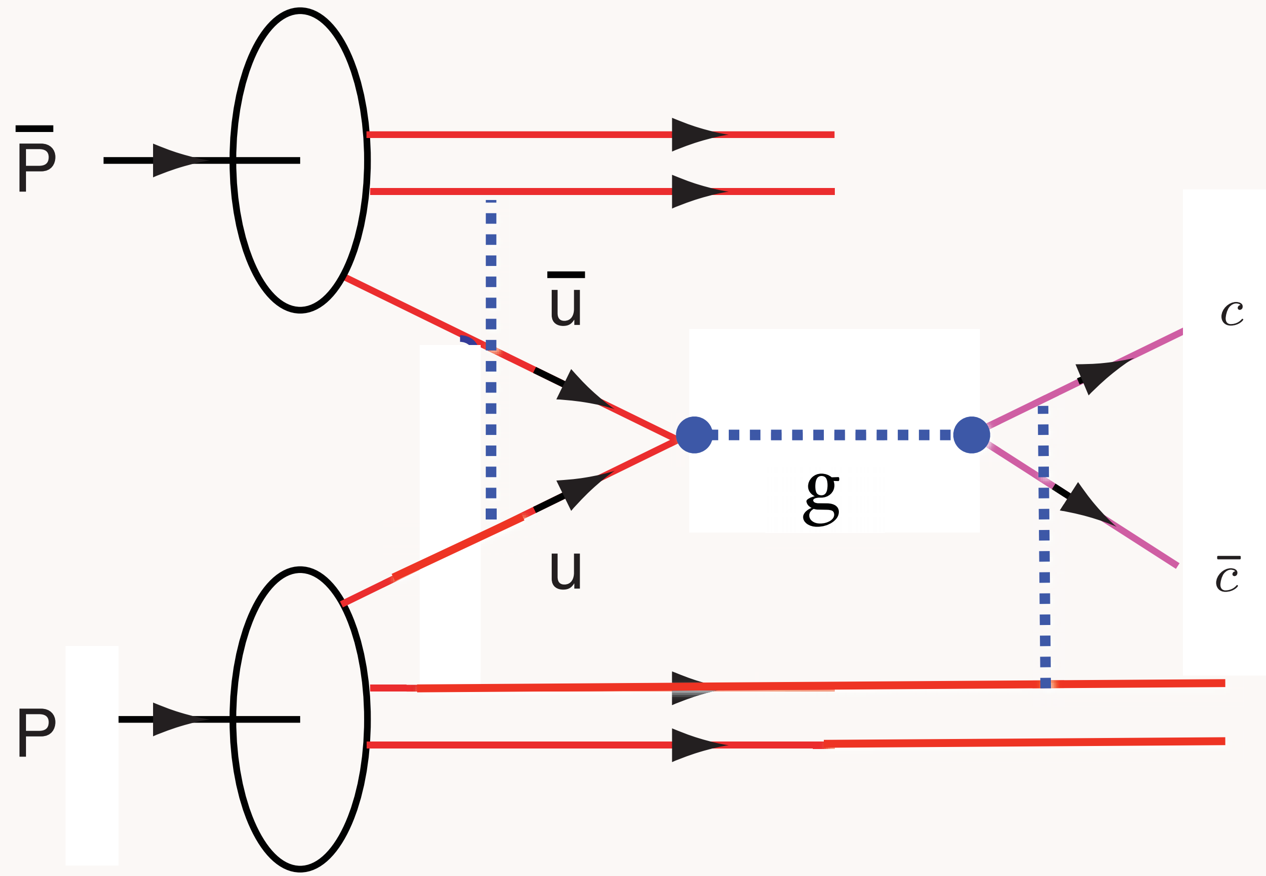
# Factorization is violated in production of high-transverse-momentum particles in hadron-hadron collisions

John Collins, Jian-Wei Qiu . ANL-HEP-PR-07-25, May 2007.

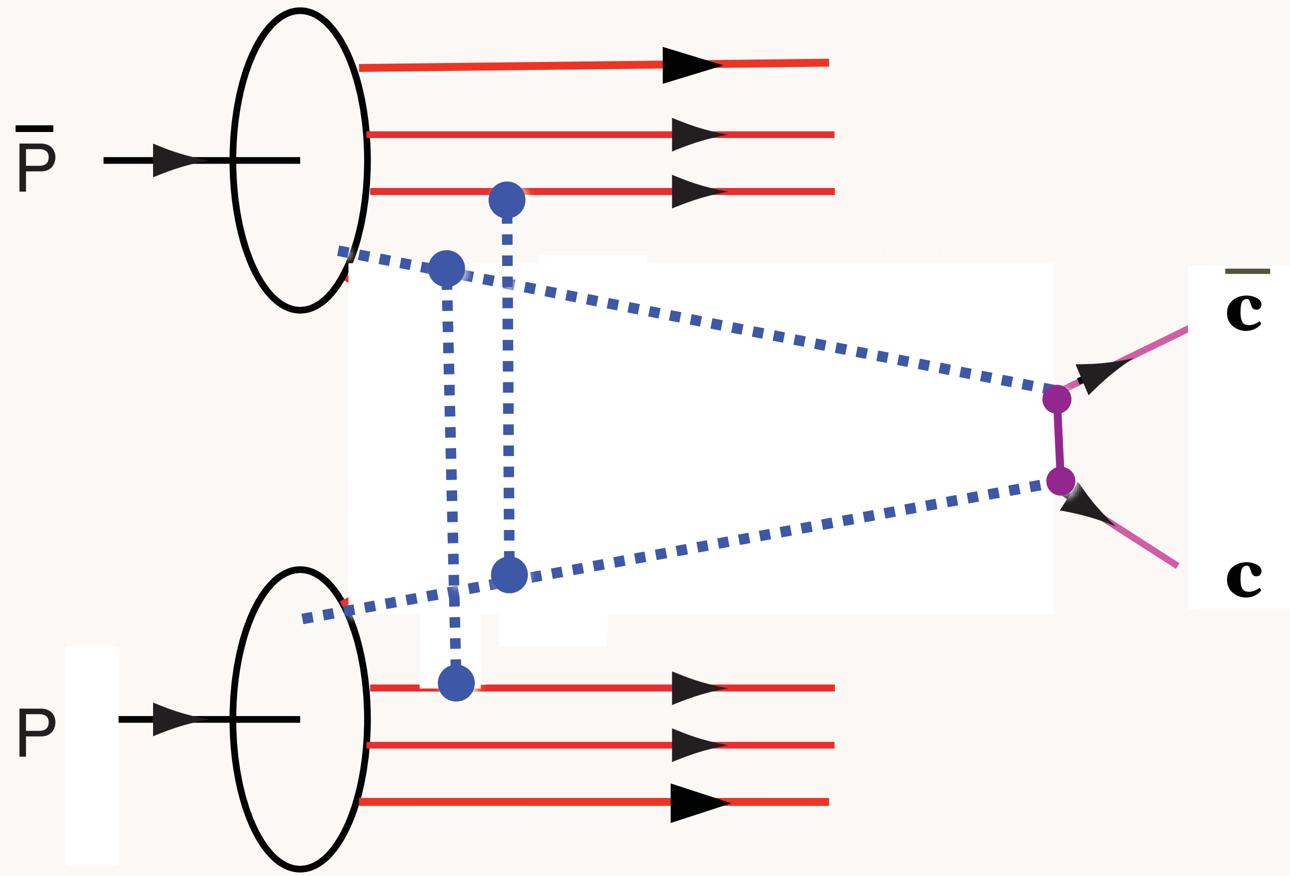
e-Print: **arXiv:0705.2141** [hep-ph]



The exchange of two extra gluons, as in this graph, will tend to give non-factorization in unpolarized cross sections.

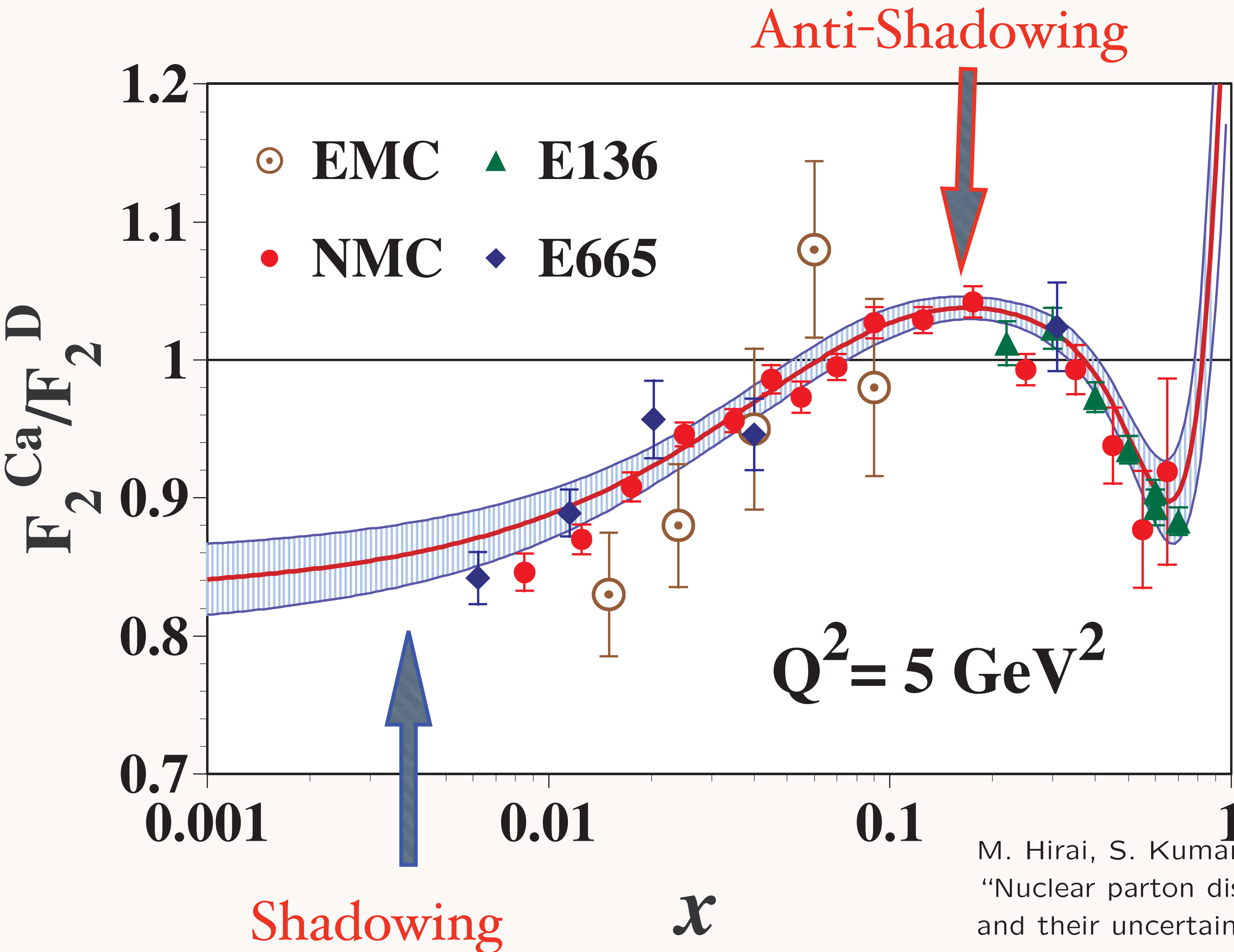



*Problem for factorization when both ISI and FSI occur*




$\cos 2\phi$ **correlation for quarkonium production at leading twist from double ISI**

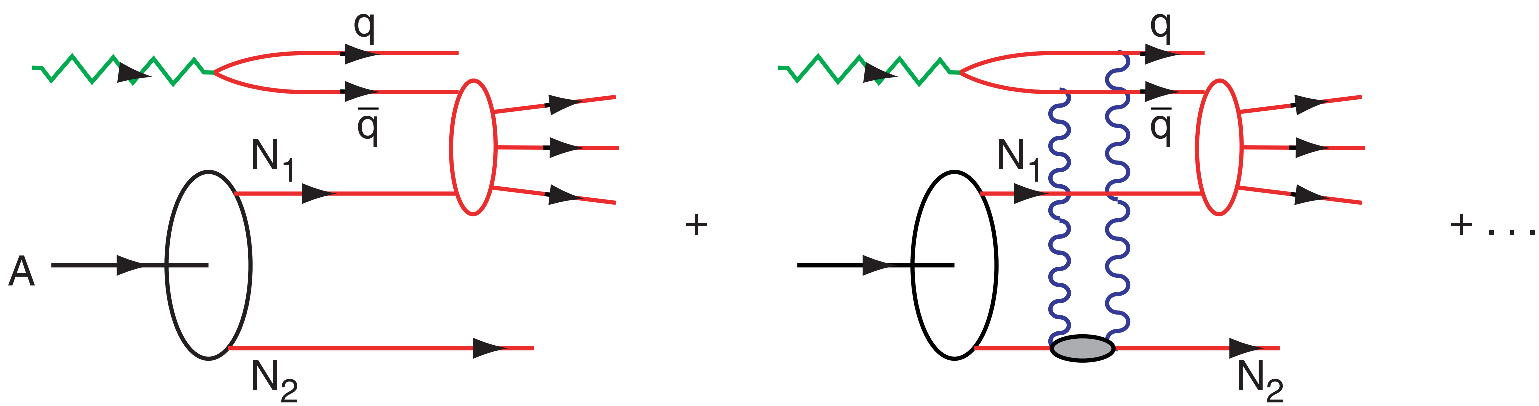
**Enhanced by gluon color charge**




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].

Stodolsky
Pumplin, sjb
Gribov

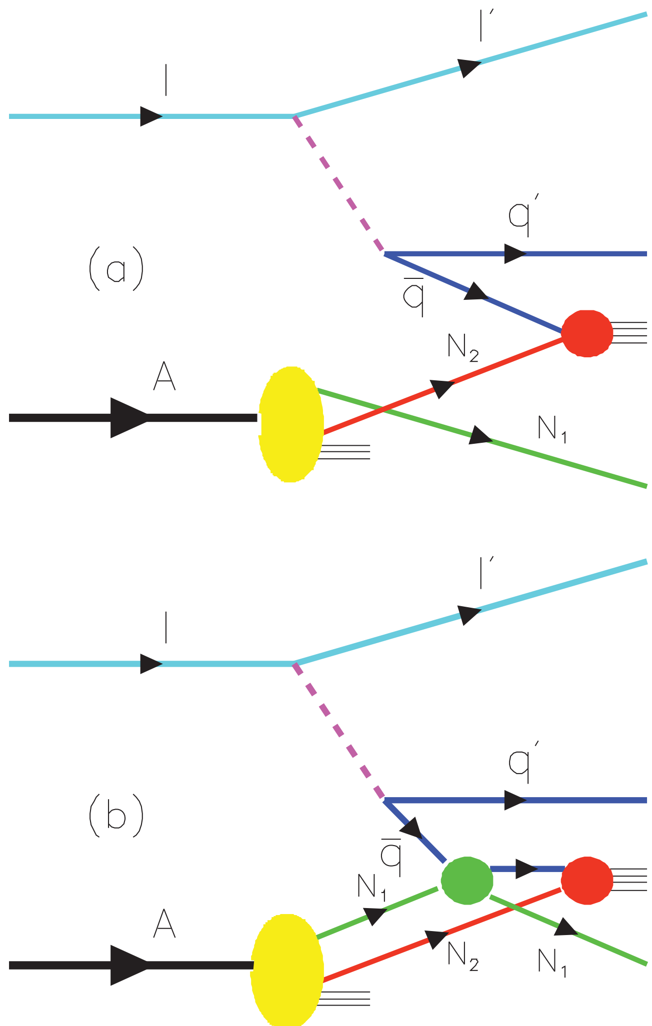
# Nuclear Shadowing in QCD




*Shadowing depends on understanding leading twist-diffraction in DIS*

**Nuclear Shadowing not included in nuclear LFWF !**

**Dynamical effect due to virtual photon interacting in nucleus**



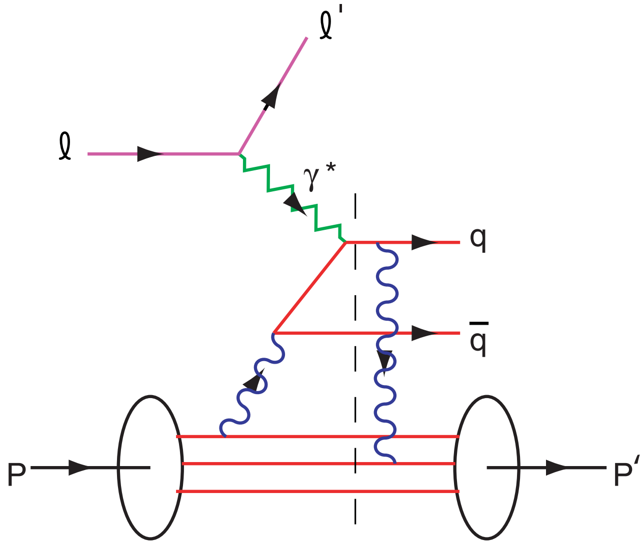

The one-step and two-step processes in DIS on a nucleus.

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 $\bar{q}$ flux reaching $N_2$.

$\rightarrow$ Shadowing of the DIS nuclear structure functions.

# Observed HERA DDIS produces nuclear shadowing




# Shadowing depends on leading-twist DDIS

***Integration over on-shell domain produces phase i***

***Need Imaginary Phase to Generate Pomeron***

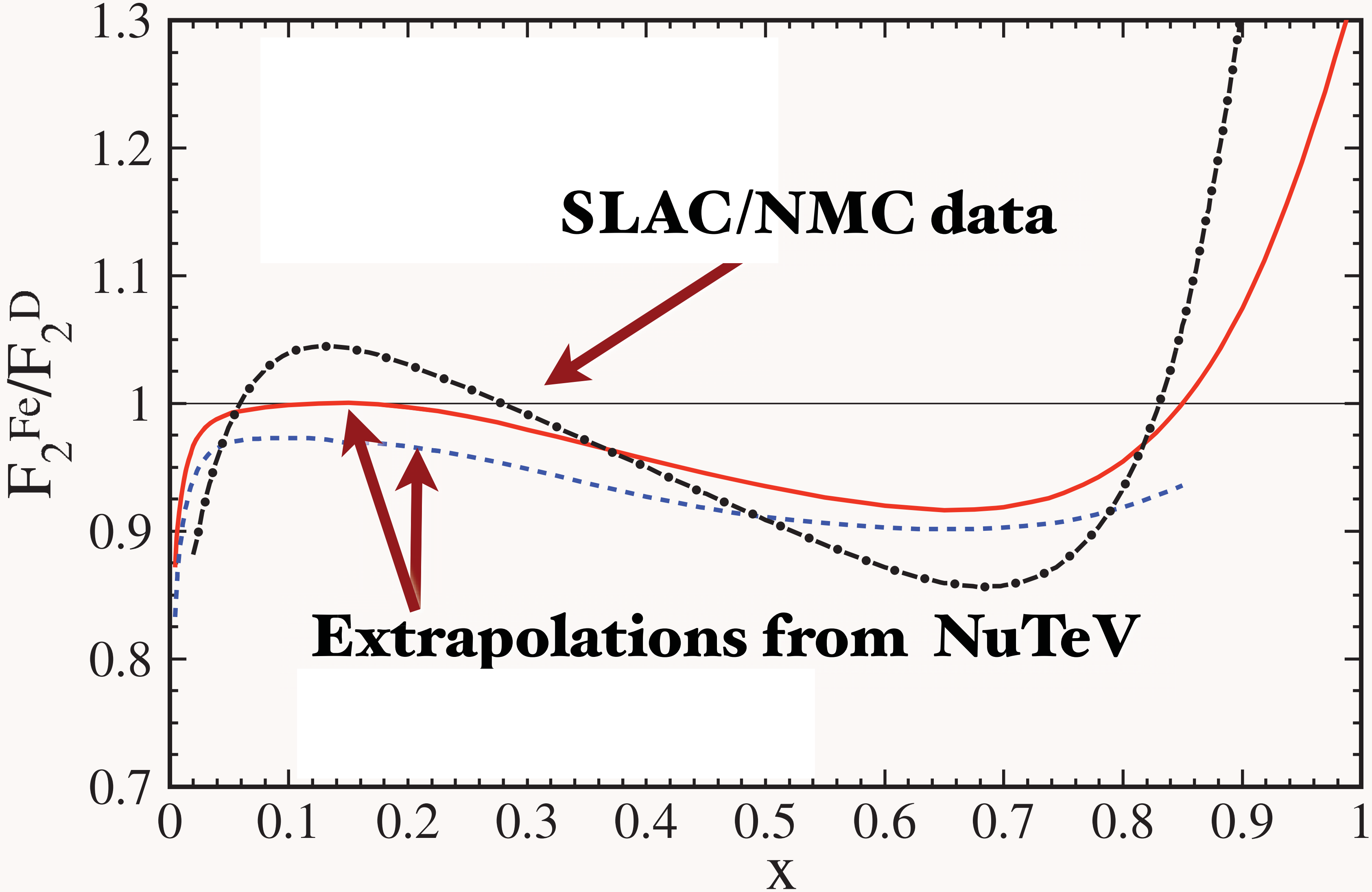
***Need Imaginary Phase to Generate T-Odd Single-Spin Asymmetry***

*Physics of FSI not in Wavefunction of Target*

*Antishadowing (Reggeon exchange) is not universal!*

**Schmidt, Yang, sjb**

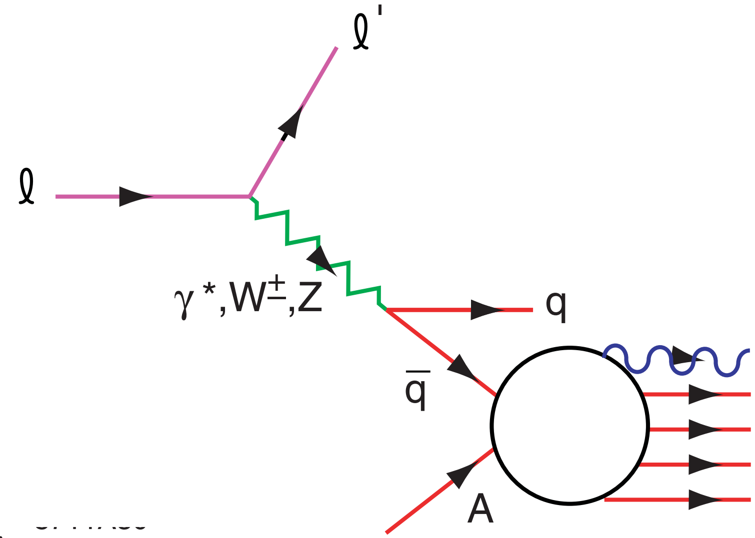
$Q^2 = 5\ \mathrm{GeV}^2$




*Scheinbein, Yu, Keppel, Morfin, Olness, Owens*

# Origin of Regge Behavior of Deep Inelastic Structure Functions

Antiquark interacts with target nucleus at energy $\widehat{s} \propto \frac{1}{x_{bj}}$




Regge contribution: $\sigma_{\bar{q}N} \sim \widehat{s}^{\alpha_R - 1}$

Nonsinglet Kuti-Weisskoff $F_{2p} - F_{2n} \propto \sqrt{x_{bj}}$ at small $x_{bj}$.

Shadowing of $\sigma_{\bar{q}M}$ produces shadowing of nuclear structure function.

Landshoff, Polkinghorne, Short

Close, Gunion, sjb

Schmidt, Yang, Lu, sjb

# Reggeon Exchange

Phase of two-step amplitude relative to one step:

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

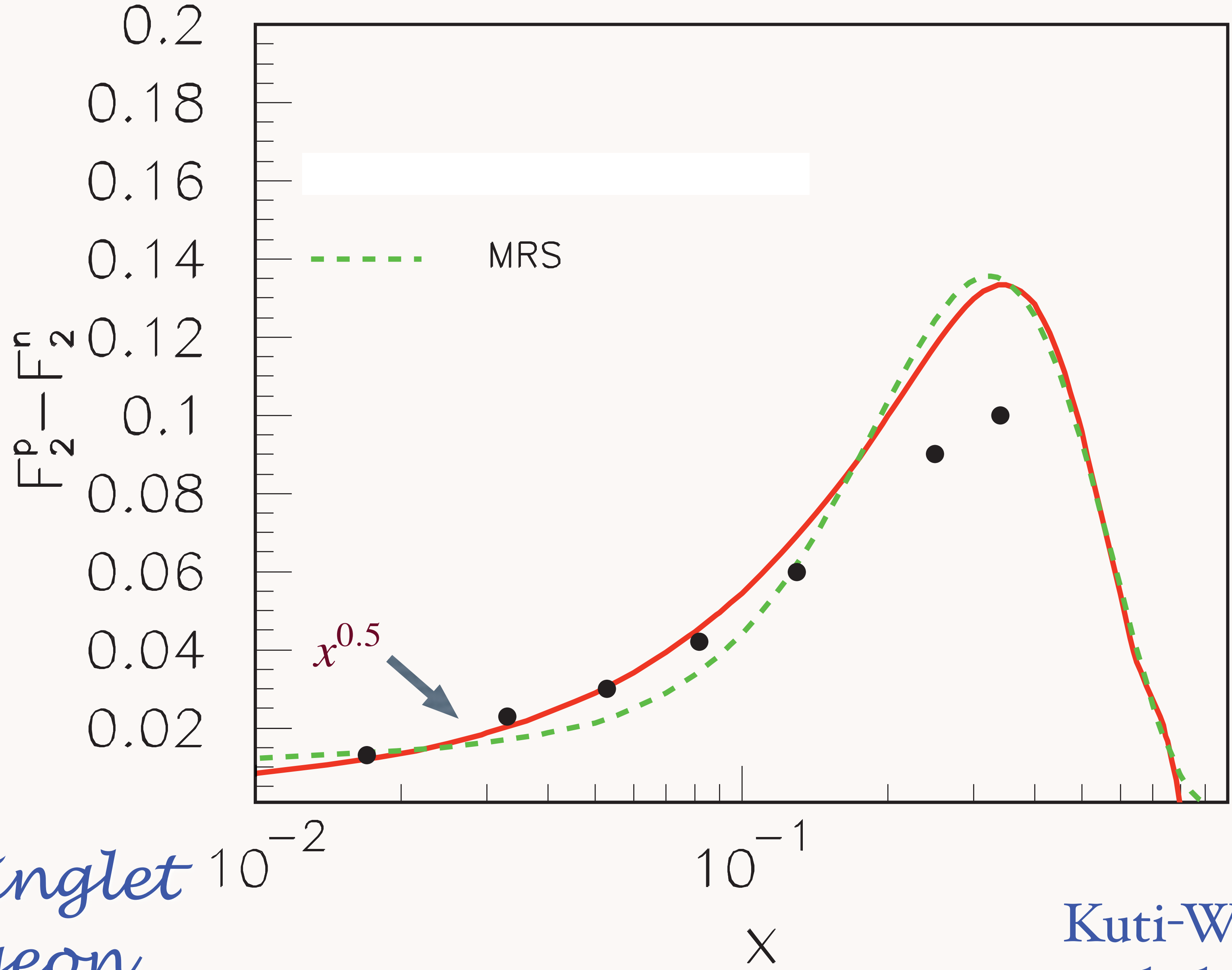
Constructive Interference

Depends on quark flavor!

Thus antishadowing is not universal

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

*Critical test: Tagged Drell-Yan*




Non-singlet Reggeon Exchange

Kuti-Weisskopf behavior

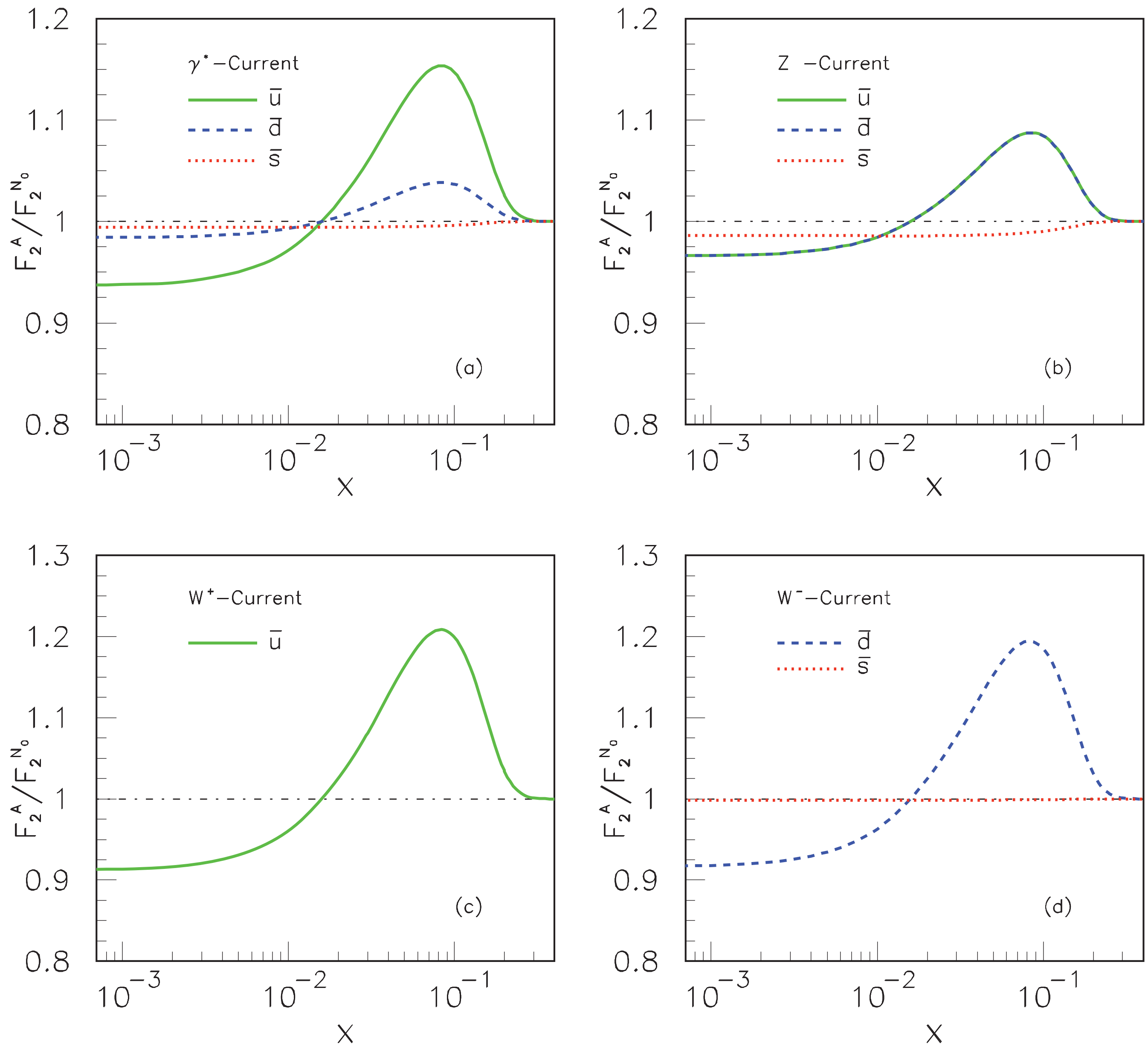
# Shadowing and Antishadowing in Lepton-Nucleus Scattering

- 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}

Jian-Jun Yang
Ivan Schmidt
Hung Jung Lu
sjb

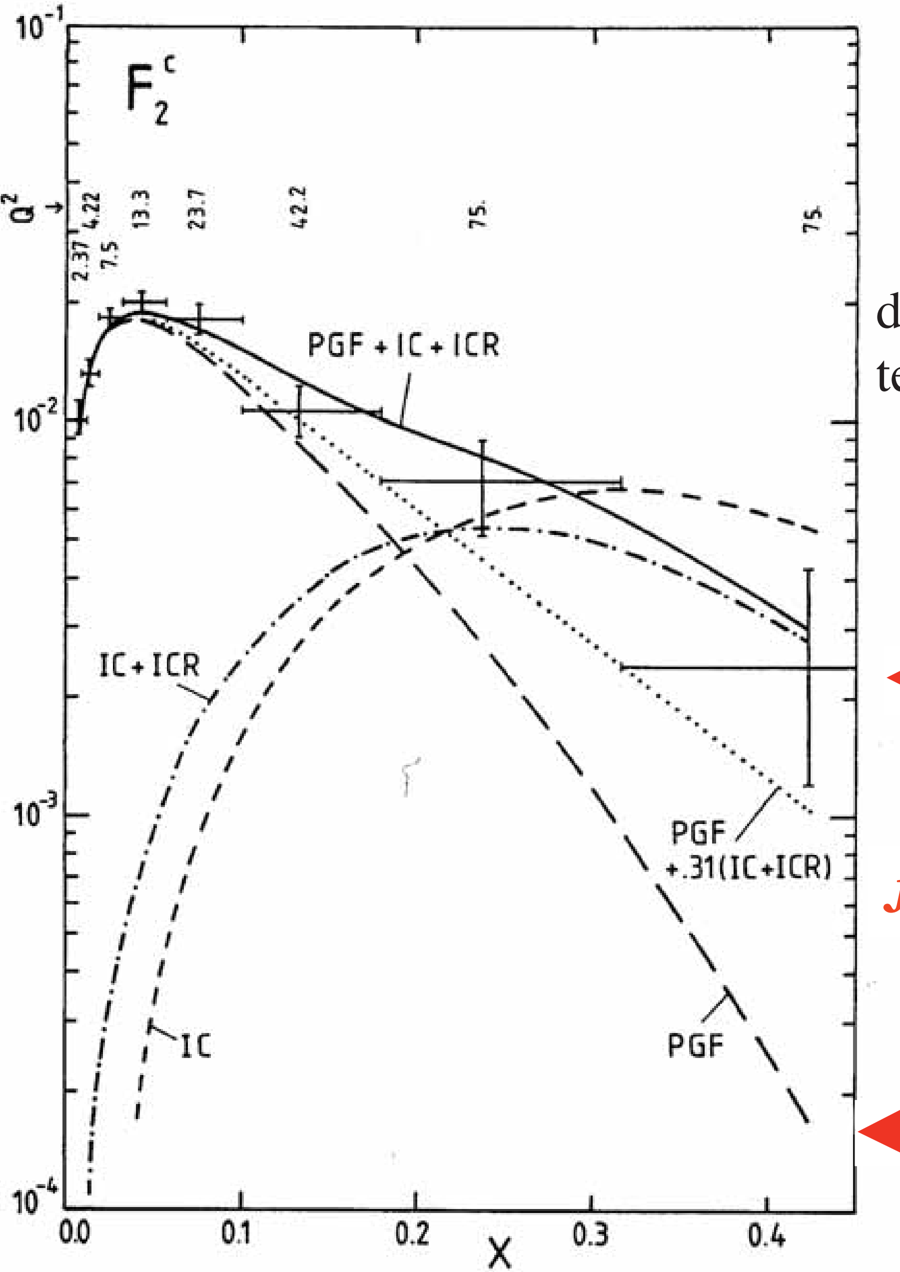



Schmidt, Yang; sjb

**Modifies NuTeV extraction of**

$$\sin^2\theta_W$$

*Nuclear Antishadowing not universal !*

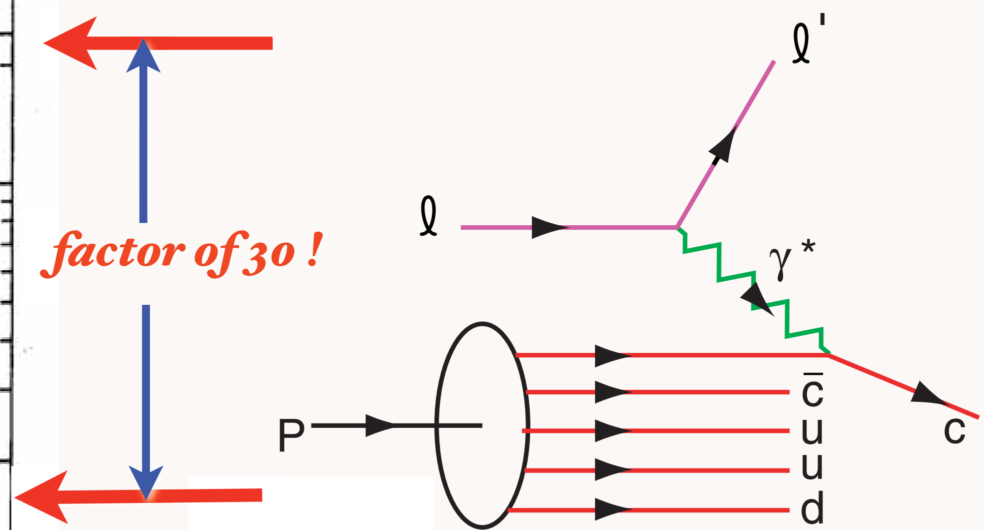



# Measurement of Charm Structure Function

J. J. Aubert et al. [European Muon Collaboration], "Production Of Charmed Particles In 250-Gev Mu+ - Iron Interactions," Nucl. Phys. B 213, 31 (1983).

## First Evidence for Intrinsic Charm

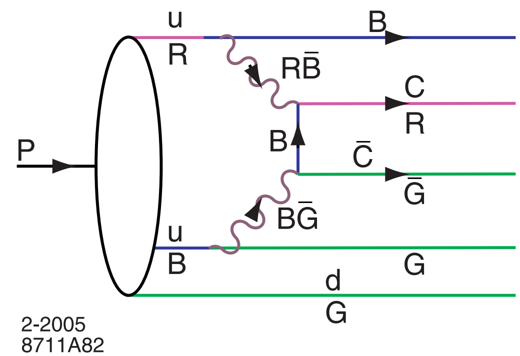
## ***Never been checked!***




***DGLAP / Photon-Gluon Fusion: factor of 30 too small***

Hoyer, Peterson, Sakai, sjb M. Polyakov et al.

# Intrinsic Heavy-Quark Fock States




- Rigorous prediction of QCD, OPE
- Color-Octet Color-Octet Fock State!
- Probability $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- Large Effect at high x
- Greatly increases kinematics of colliders such as Higgs production (Kopeliovich, Schmidt, Soffer, sjb)
- Severely underestimated in conventional parameterizations of heavy quark distributions (Pumplin, Tung)
- Many empirical tests

- EMC data: $c(x, Q^2) > 30 \times$ DGLAP
  $Q^2 = 75$ GeV$^2$, $x = 0.42$

- High $x_F$ $pp \to J/\psi X$

- High $x_F$ $pp \to J/\psi J/\psi X$

- High $x_F$ $pp \to \Lambda_c X$ ISR

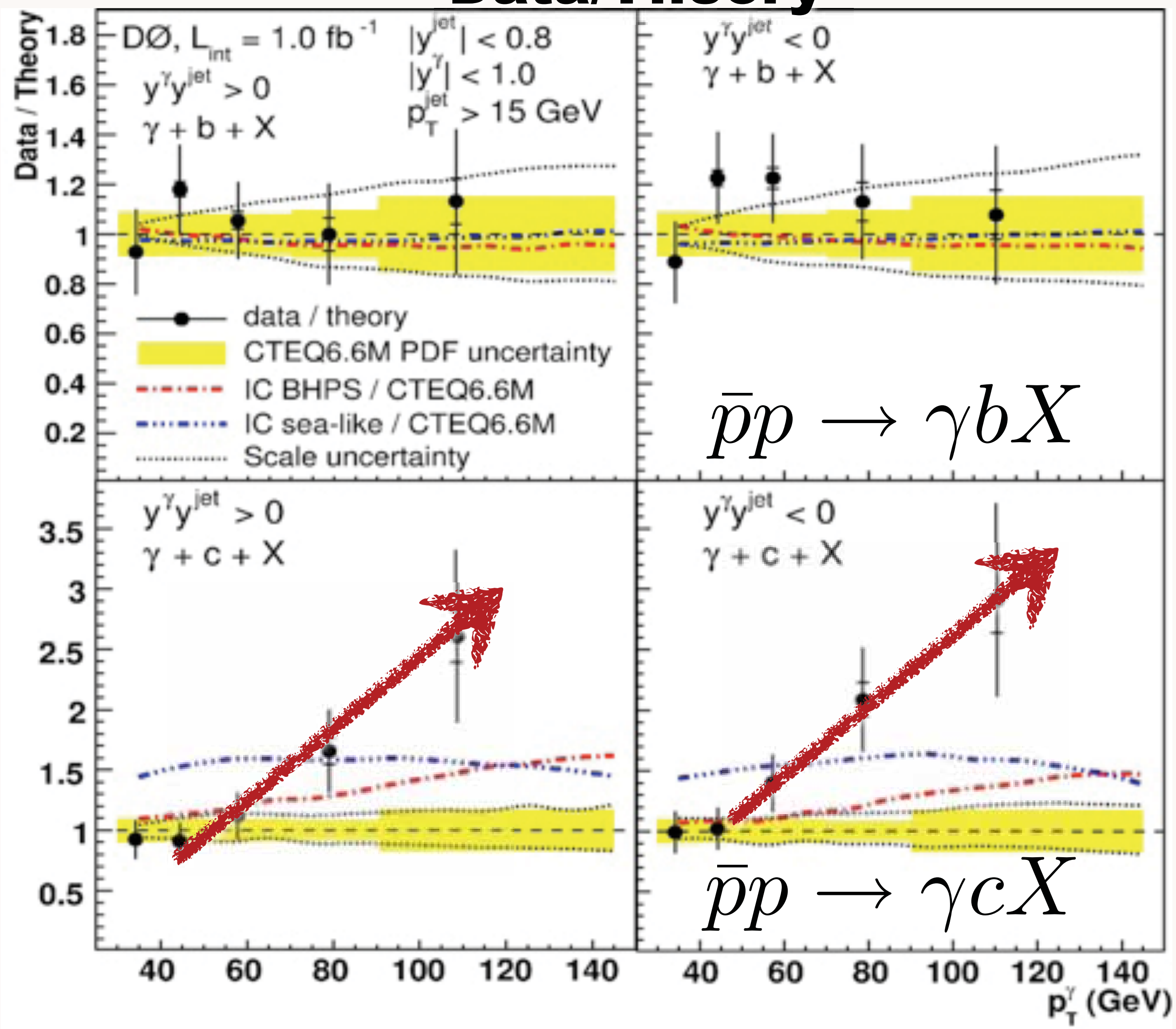
- High $x_F$ $pp \to \Lambda_b X$ ISR

- High $x_F$ $pp \to \Xi(ccd) X$ (SELEX)

PRL **102**, 192002 (2009) PHYSICAL REVIEW LETTERS week ending 15 MAY 2009

**Measurement of $\gamma + b + X$ and $\gamma + c + X$ Production Cross Sections in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV**

# Data/Theory

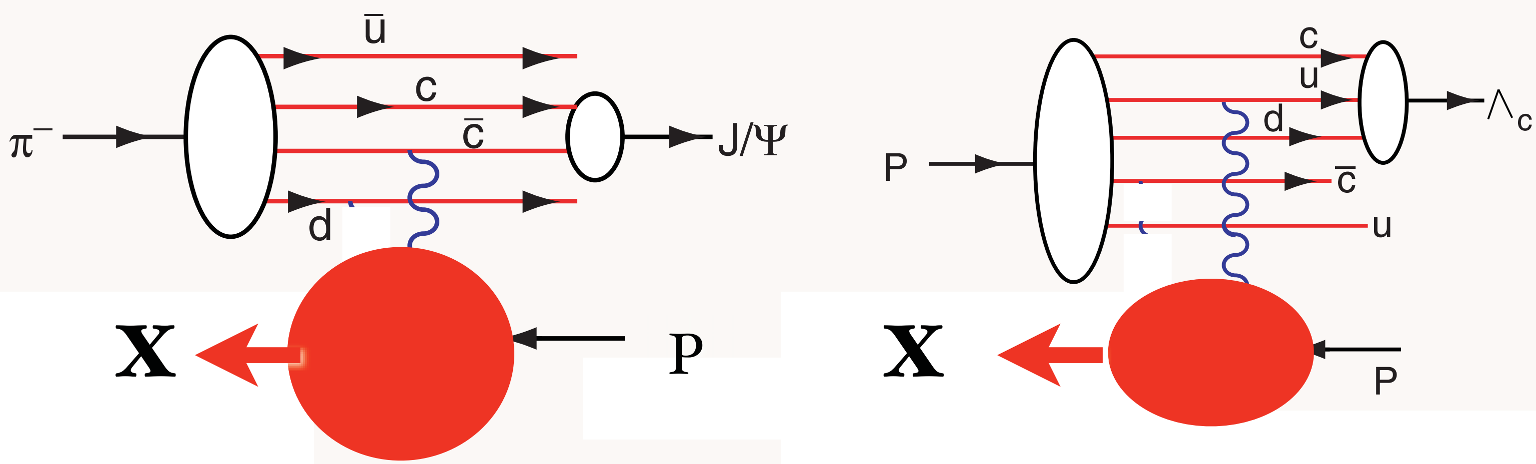



$$\frac{\Delta\sigma(\bar{p}p \to \gamma c X)}{\Delta\sigma(\bar{p}p \to \gamma b X)}$$

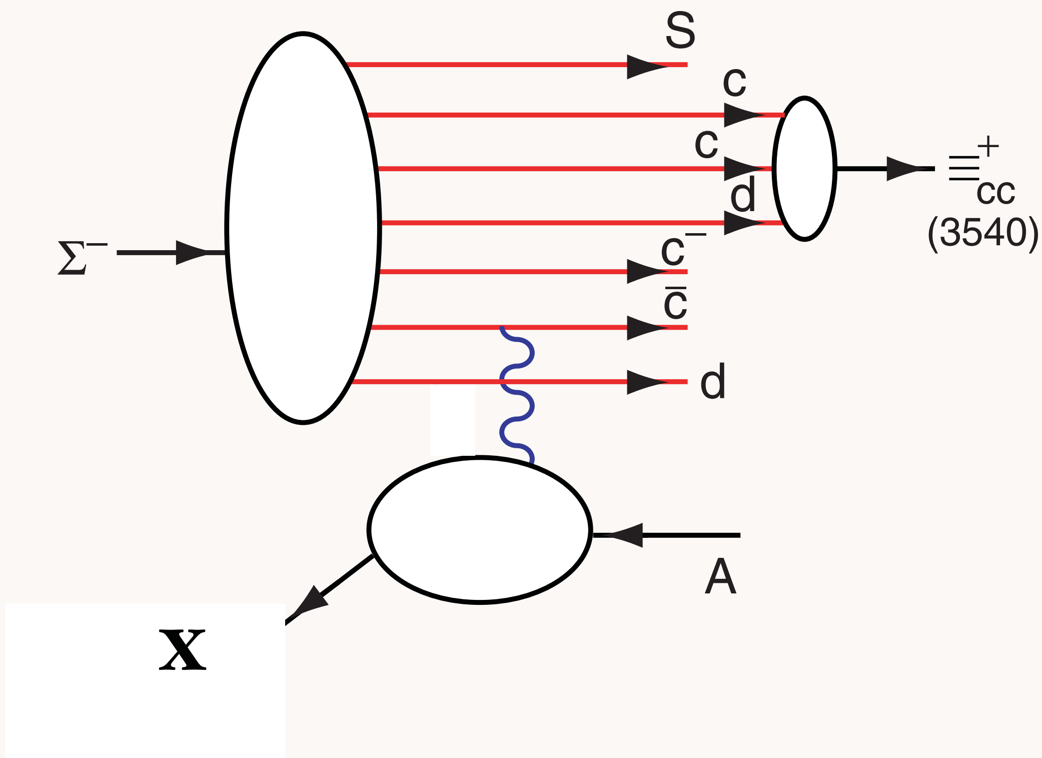
**Ratio insensitive to gluon PDF, scales**

**Signal for significant IC at x > 0.1**

# Leading Hadron Production from Intrinsic Charm




Coalescence of Comoving Charm and Valence Quarks Produce $J/\psi$, $\Lambda_c$ and other Charm Hadrons at High $x_F$




# *Production of a Double-Charm Baryon*

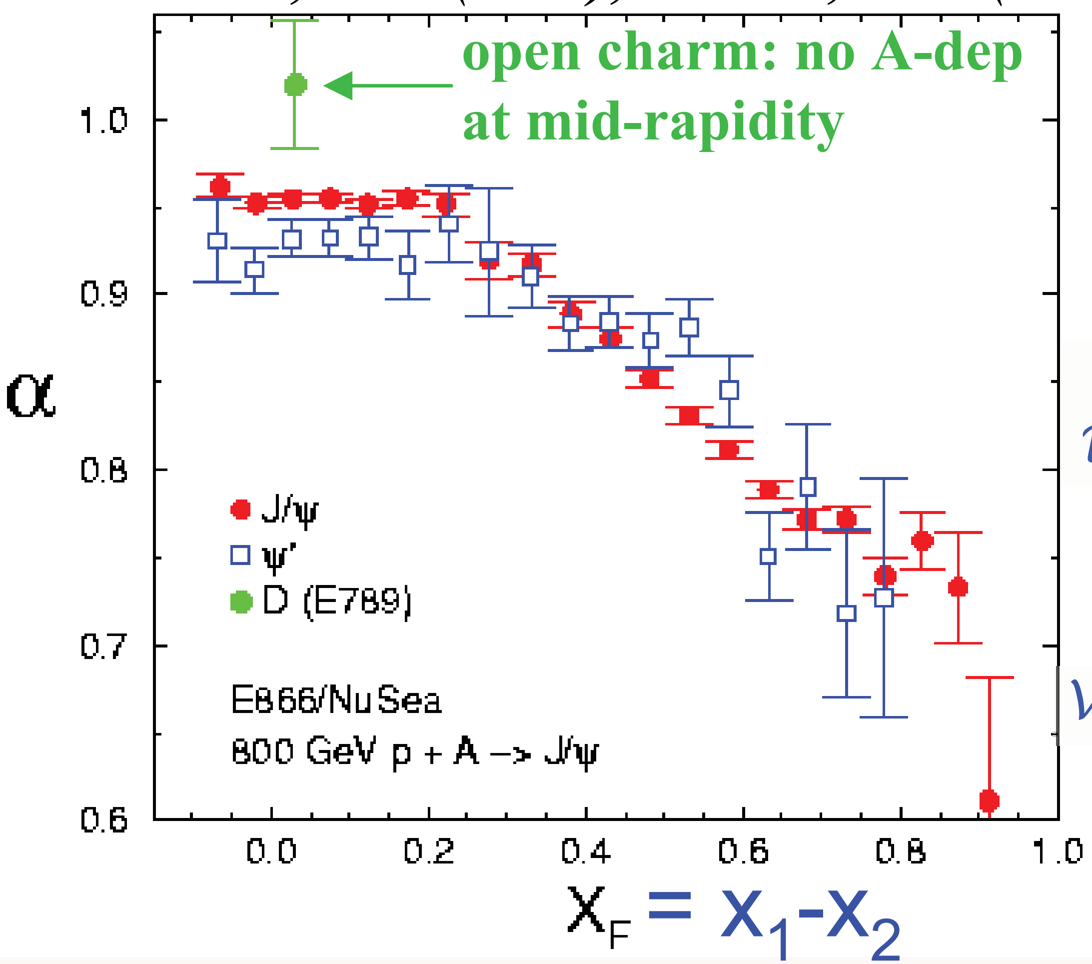
**SELEX high $x_F$** $< x_F >= 0.33$

**800 GeV p-A (FNAL)** $\sigma_A = \sigma_p * A^{\alpha}$

***PRL 84, 3256 (2000); PRL 72, 2542 (1994)***

M. Leitch

$$\frac{d\sigma}{dx_F}(pA \rightarrow J/\psi X)$$




*Remarkably Strong Nuclear Dependence for Fast Charmonium*

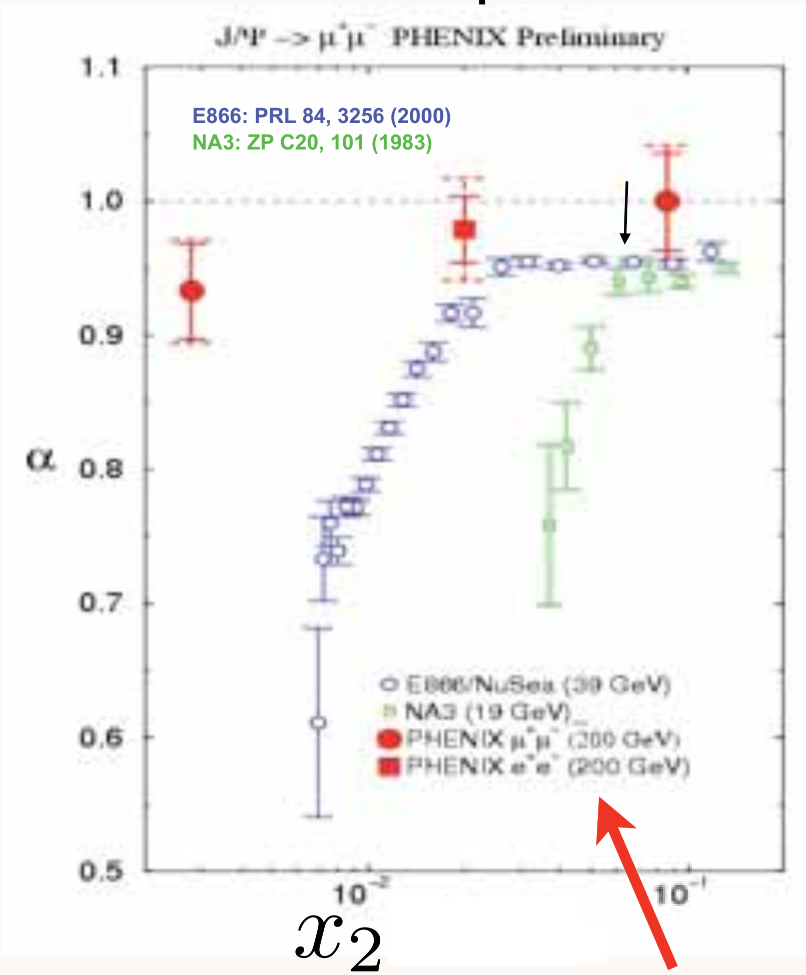
*Violation of PQCD Factorization!*

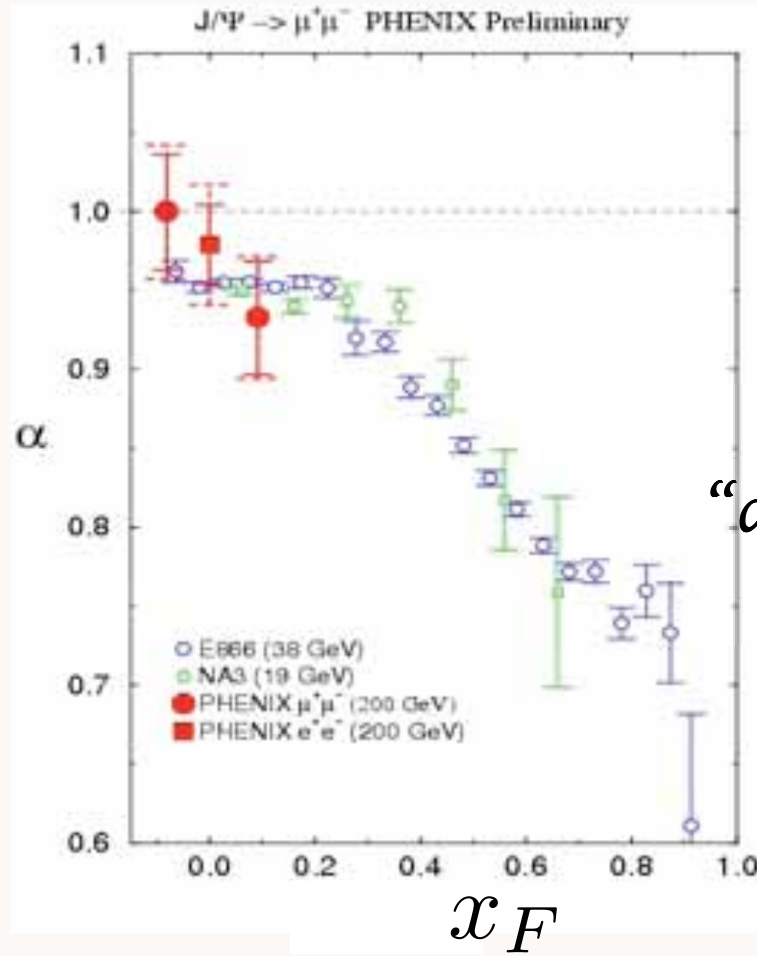
**Violation of factorization in charm hadroproduction.**
P. Hoyer, M. Vanttinen (Helsinki U.) , U. Sukhatme (Illinois U., Chicago) . HU-TFT-90-14, May 1990. 7pp.
Published in Phys.Lett.B246:217-220,1990

# J/ψ nuclear dependence vrs rapidity, $x_{Au}$, $x_F$

M.Leitch

PHENIX compared to lower energy measurements




*Huge "absorption" effect*

Klein,Vogt, PRL 91:142301,2003
Kopeliovich, NP A696:669,2001

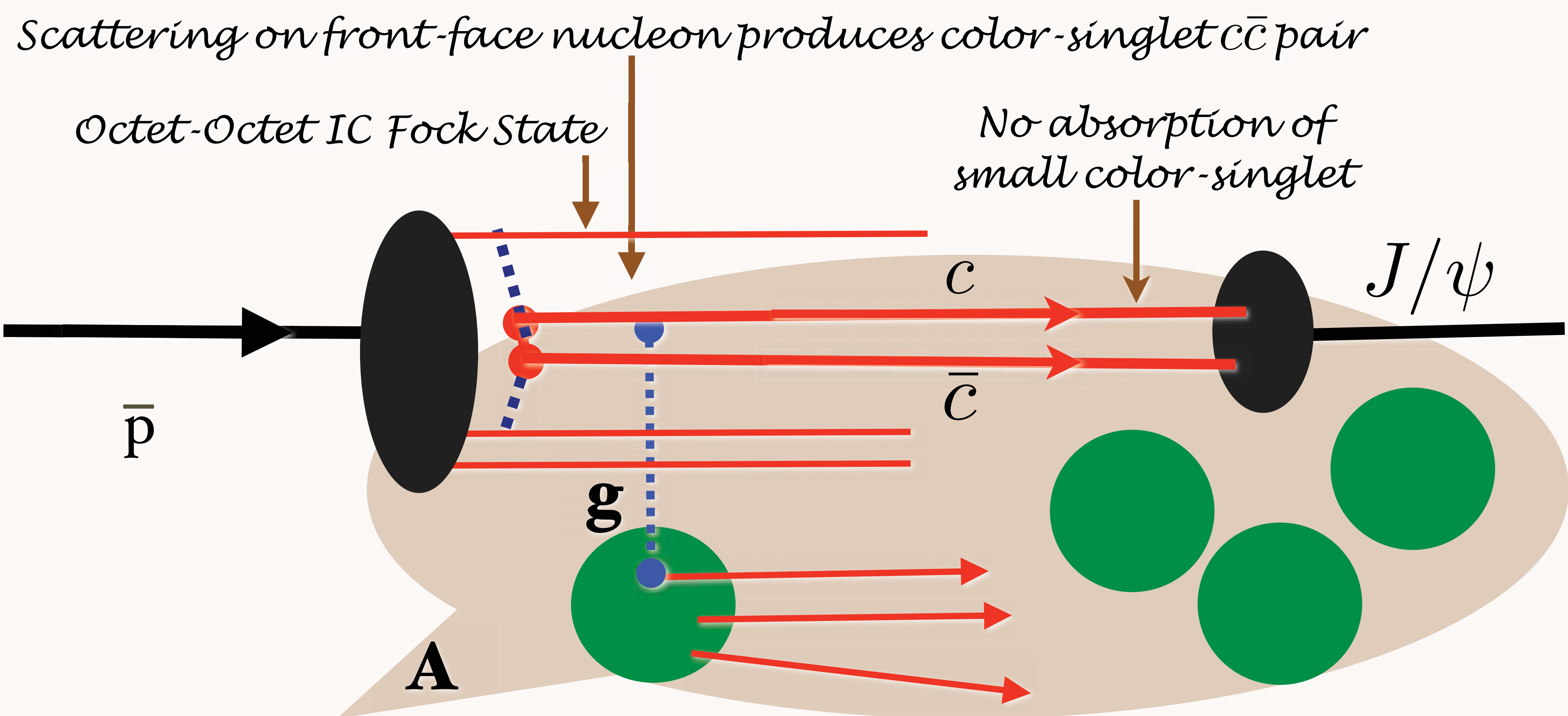
*Violates PQCD factorization!*

$$\frac{d\sigma}{dx_F}(pA \to J/\psi X)$$

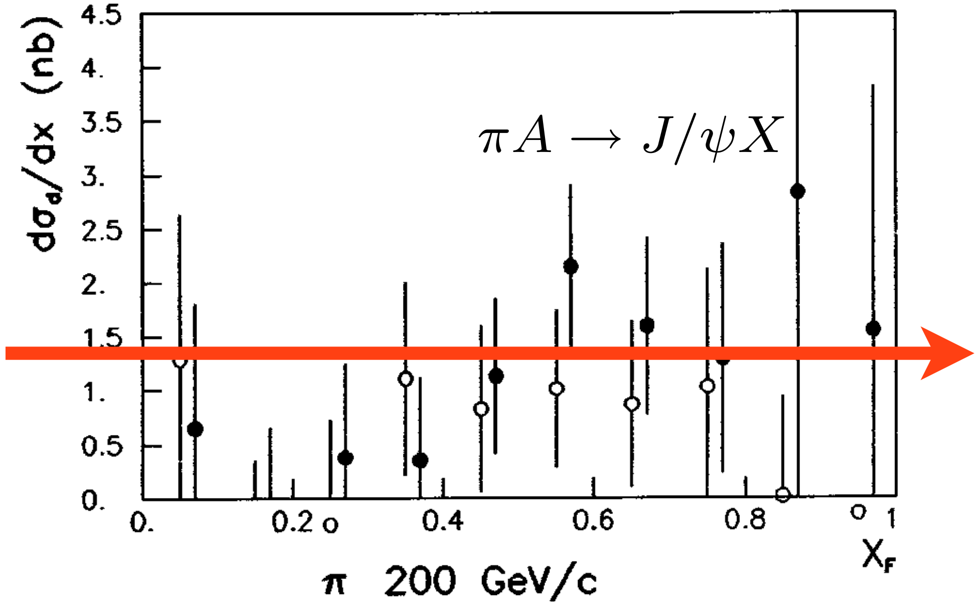
Hoyer, Sukhatme, Vanttinen

Kopeliovich, Schmidt, Soffer, sjb

# Color-Opaque IC Fock state interacts on nuclear front surface

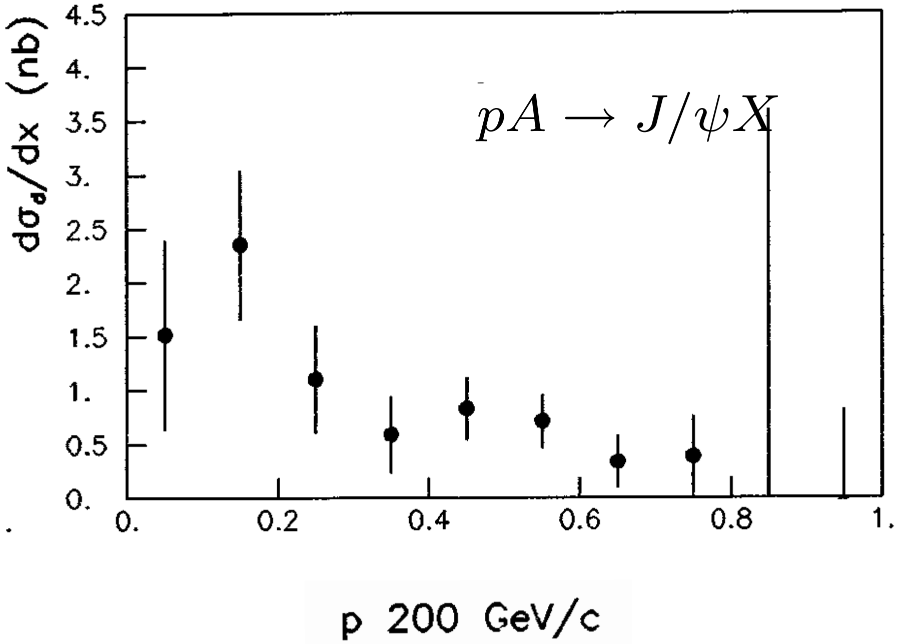



$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$




$A^{2/3}$ component

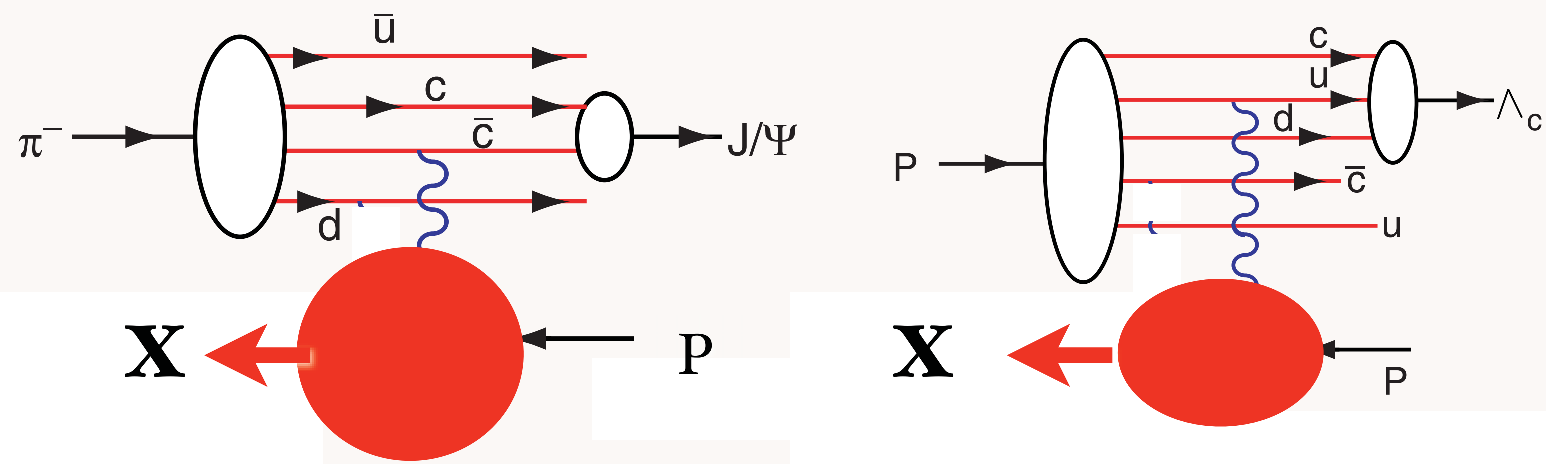
J. Badier et al, NA3




$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^1 \frac{d\sigma_1}{dx_F} + A^{2/3}\frac{d\sigma_{2/3}}{dx_F}$$

**Excess beyond conventional PQCD subprocesses**

# Leading Hadron Production from Intrinsic Charm




Coalescence of Comoving Charm and Valence Quarks Produce $J/\psi$, $\Lambda_c$ and other Charm Hadrons at High $x_F$

- IC Explains Anomalous $\alpha(x_F)$ not $\alpha(x_2)$ dependence of $pA \to J/\psi X$ (Mueller, Gunion, Tang, SJB)

- Color Octet IC Explains $A^{2/3}$ behavior at high $x_F$ (NA3, Fermilab) (Kopeliovitch, Schmidt, Soffer, SJB)

*Color Opaqueness*

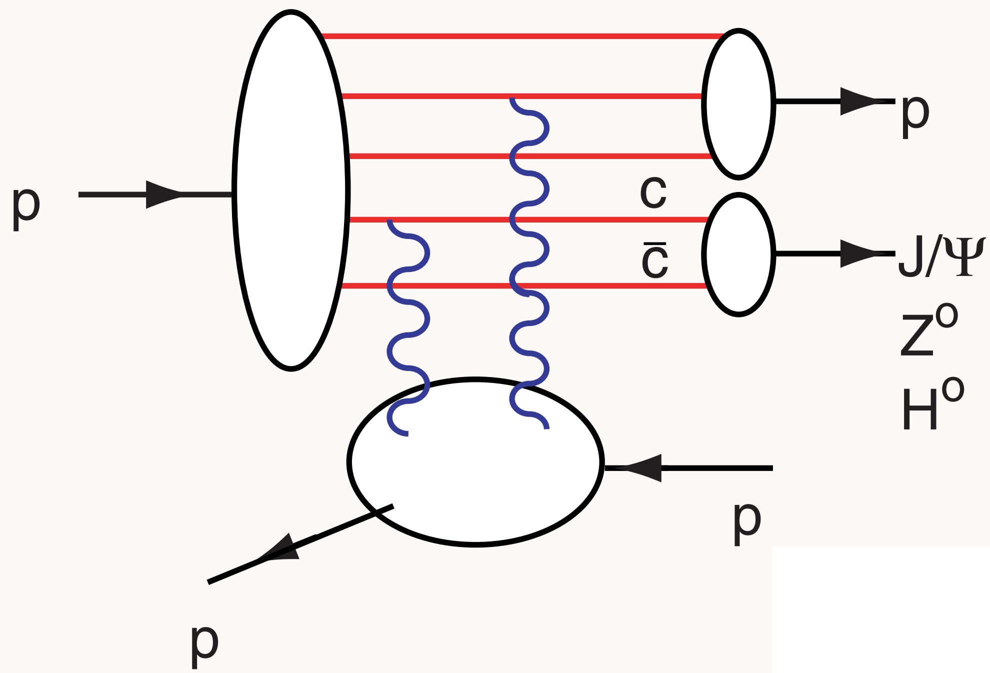
- IC Explains $J/\psi \to \rho\pi$ puzzle (Karliner, SJB)

- IC leads to new effects in $B$ decay (Gardner, SJB)

**Higgs production at $x_F$ = 0.8 !**

Goldhaber, Kopeliovich, Schmidt, Soffer, sjb

# Intrinsic Charm Mechanism for Exclusive Diffraction Production




$$\mathrm{p\,p} \to J/\psi\; p\; p$$

$$x_{J/\psi} = x_c + x_{\bar{c}}$$

Exclusive Diffractive
High-$X_F$ Higgs Production!

Kopeliovich, Schmidt, Soffer, sjb

Intrinsic $c\bar{c}$ pair formed in color octet $8_C$ in proton wavefunction Large Color Dipole

Collision produces color-singlet $J/\psi$ through color exchange

RHIC Experiment

$$H^{LF}_{QCD}$$

QCD Meson Spectrum

$$(H^0_{LF} + H^I_{LF})|\Psi>= M^2|\Psi>$$

Coupled Fock states

$$\left[\frac{\vec{k}^2_\perp + m^2}{x(1-x)} + V^{LF}_{\rm eff}\right] \psi_{LF}(x, \vec{k}_\perp) = M^2 \; \psi_{LF}(x, \vec{k}_\perp)$$

Effective two-particle equation

$$\zeta^2 = x(1-x) b^2_\perp$$

$$\left[-\frac{d^2}{d\zeta^2} + \frac{-1+4L^2}{\zeta^2} + U(\zeta, S, L)\right] \psi_{LF}(\zeta) = M^2 \; \psi_{LF}(\zeta)$$

Azimuthal Basis $\zeta, \phi$

$$U(\zeta, S, L) = \kappa^2\zeta^2 + \kappa^2(L + S - 1/2)$$

Confining AdS/QCD potential

Semiclassical first approximation to QCD

## *Use AdS/CFT orthonormal Light Front Wavefunctions as a basis for diagonalizing the QCD LF Hamiltonian*

- Good initial approximation
- Better than plane wave basis
- DLCQ discretization -- highly successful 1+1
- Use independent HO LFWFs, remove CM motion
- Similar to Shell Model calculation
- Hamiltonian LF Methods -- e.g. Use Lippmann-Schwinger Perturbation Theory to build Higher Fock States.

**Pauli, Hornbostel, Hiller, McCartor, sjb**

**J.P. Vary, H. Honkanen, Jun Li, P. Maris, A. Harindranath, G.F. de Teramond, P. Sternberg, E.G. Ng, C. Yang, J. Hiller, sjb**

# An analytic first approximation to QCD
## AdS/QCD + Light-Front Holography

- **As Simple as Schrödinger Theory in Atomic Physics**
- **LF radial variable $\zeta$ conjugate to invariant mass squared**
- **Relativistic, Frame-Independent, Color-Confining**
- **QCD Coupling at all scales: Essential for Gauge Link phenomena**
- **Hadron Spectroscopy and Dynamics from one parameter $\kappa$**
- **Wave Functions, Form Factors, Hadronic Observables, Constituent Counting Rules**
- **Insight into QCD Condensates: Zero cosmological constant!**
- **Systematically improvable with DLCQ Methods**

- **Color Confinement: Maximum Wavelength of Quark and Gluons**
- **Conformal symmetry of QCD coupling in IR**
- **Conformal Template (BLM, CSR, BFKL scale)**
- **Motivation for AdS/QCD**
- **QCD Condensates inside of hadronic LFWFs**
- **Technicolor: confined condensates inside of technihadrons -- alternative to Higgs**
- **Simple physical solution to cosmological constant conflict with Standard Model**

**Roberts, Shrock, Tandy, and sjb**