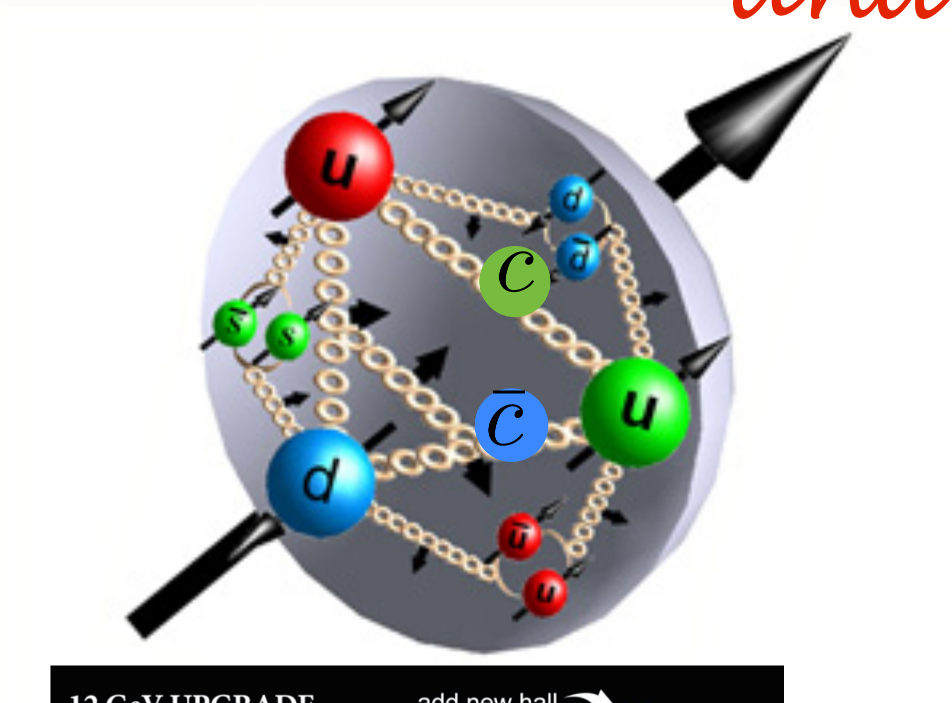
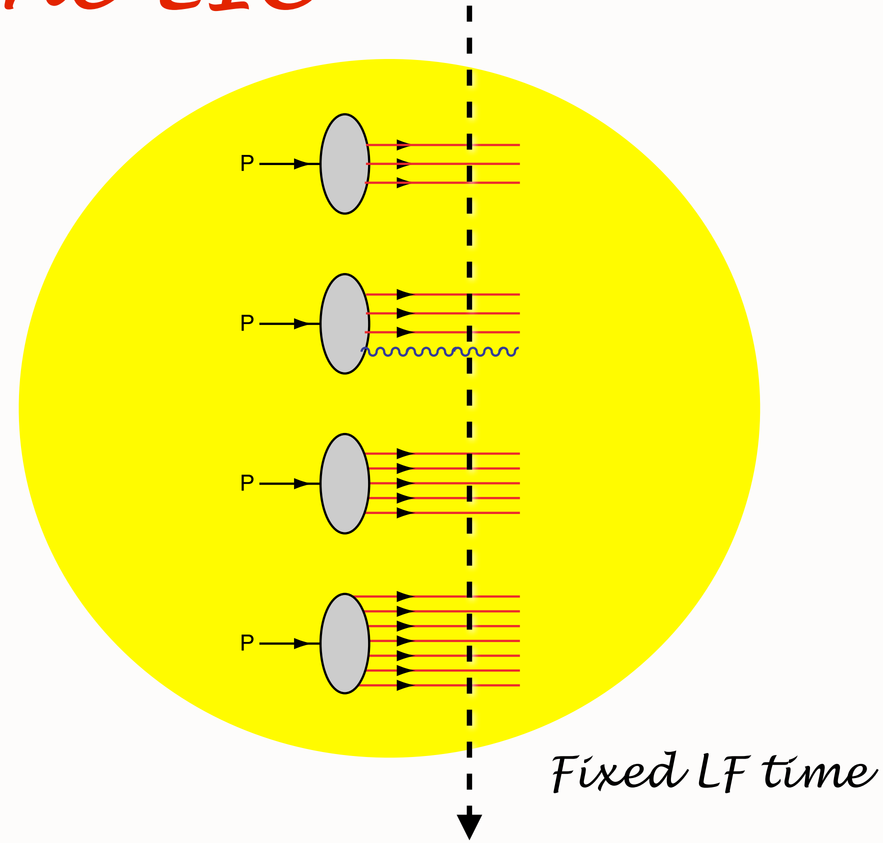
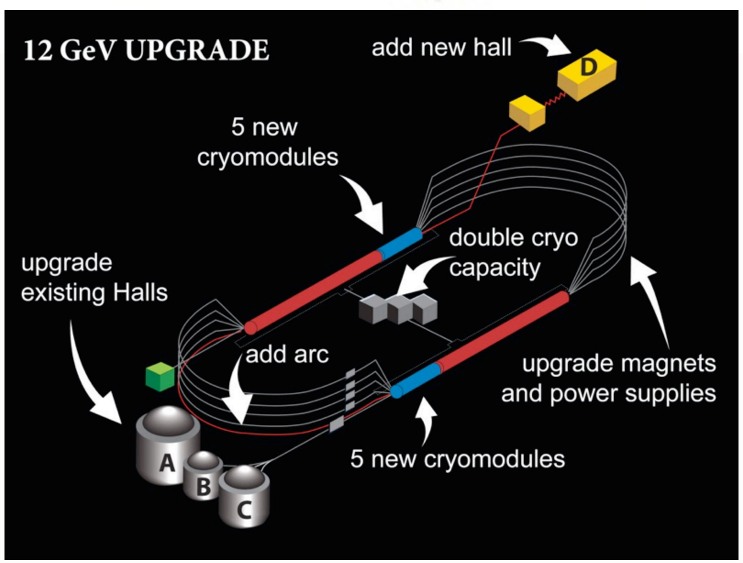
Novel QCD Phenomena at JLab 12 GeV and the EIC







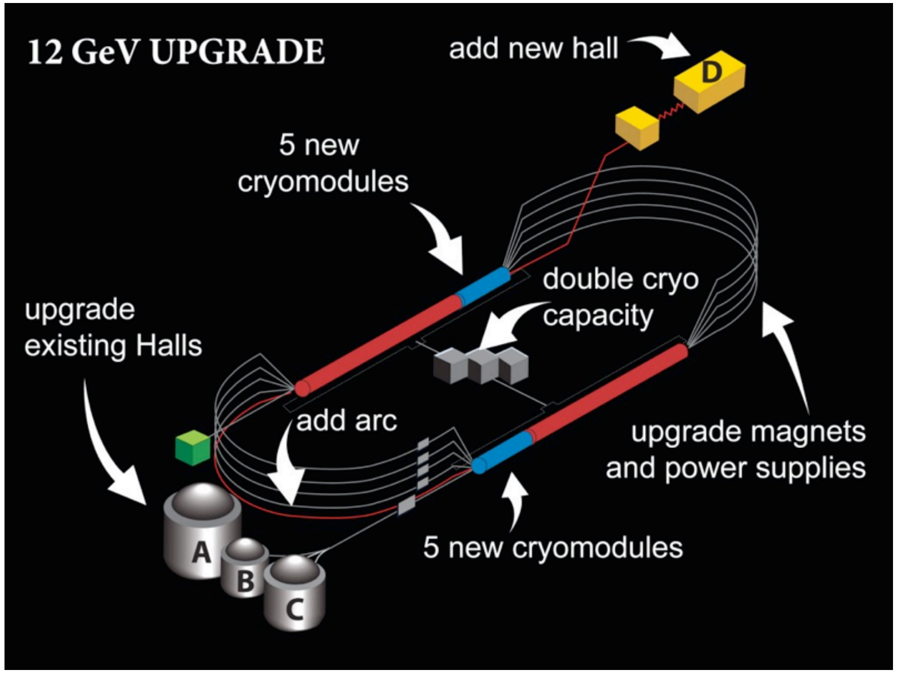
Stan Brodsky

SLAC
NATIONAL ACCELERATOR LABORATORY

Fourth Workshop on Hadron Physics in China and Opportunities in US
Beijing, July 16-20, 2012
Kavli Institute for Theoretical Physics China (KITPC)

Novel QCD Phenomena at JLab 12 GeV and the EIC

- Intrinsic Heavy Quarks
- Charm at Threshold
- Novel Heavy Quark Resonances at Threshold
- Nuclear-Bound Quarkonium
- Exclusive and Inclusive Sivers Effect.
- Breakdown of pQCD Leading-Twist Factorization
- Non-universal antishadowing
- Hidden Color
- J=0 Fixed pole in DVCS



Illuminate New Hadronic Physics

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

sum over states with n=3, 4, ...constituents

The Light Front Fock State Wavefunctions

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

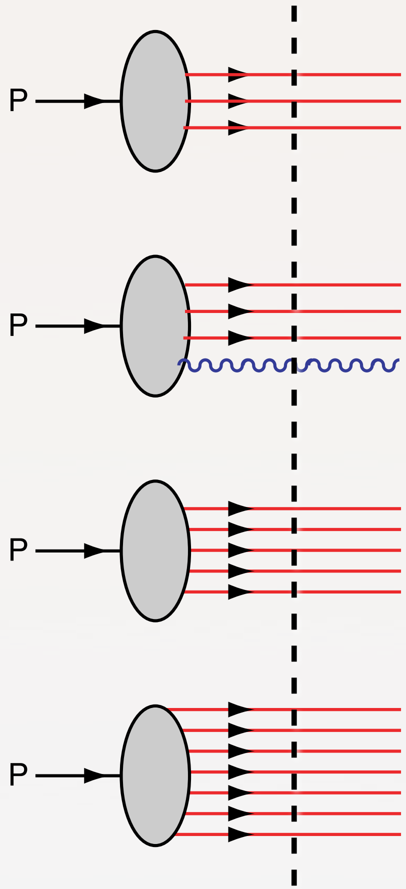
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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.

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



Fixed LF time

Intrinsic heavy quarks

s(x), c(x), b(x) at high x !

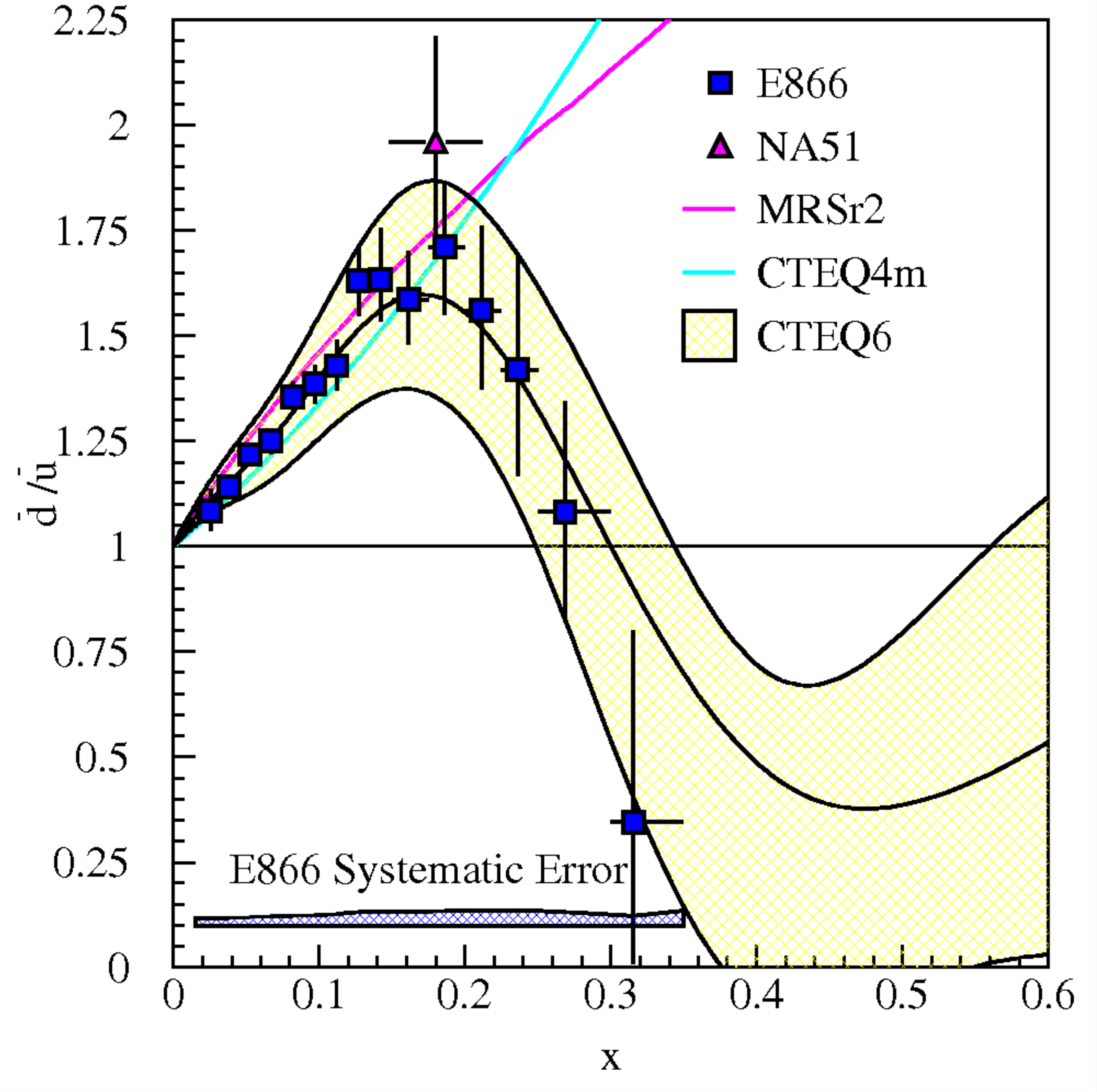
$\bar{s}(x) \neq s(x)$

$\bar{u}(x) \neq \bar{d}(x)$

Mueller: gluon Fock states BFKL

Hidden Color

$\bar{d}(x)/\bar{u}(x)$ for $0.015 \leq x \leq 0.35$



- E866/NuSea (Drell-Yan)

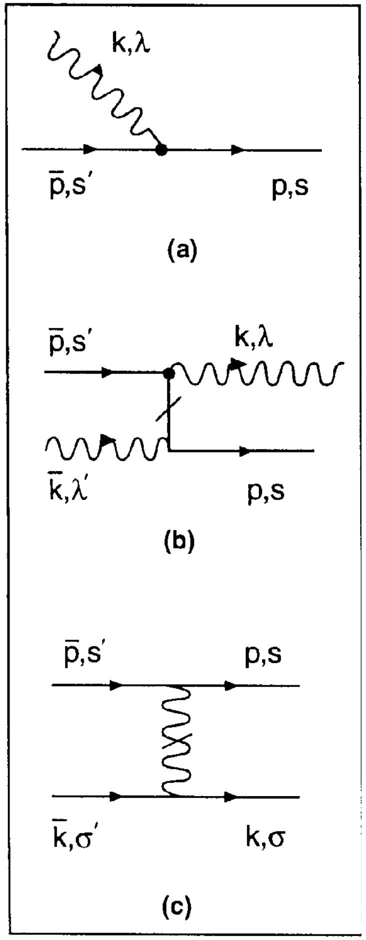
$$\bar{d}(x) \neq \bar{u}(x)$$

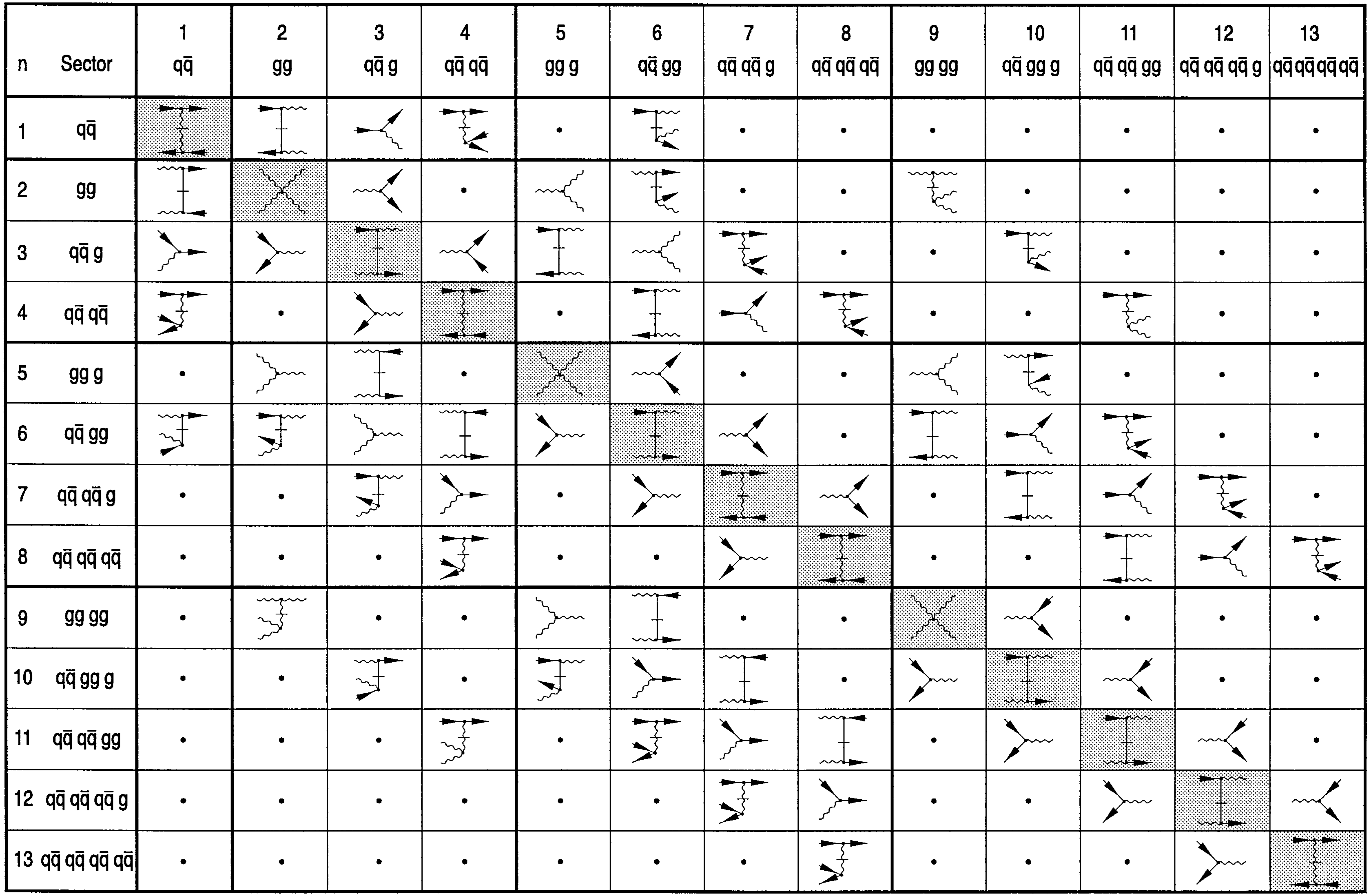
Intrinsic glue, sea, heavy quarks

Light-Front QCD

Heisenberg Equation

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

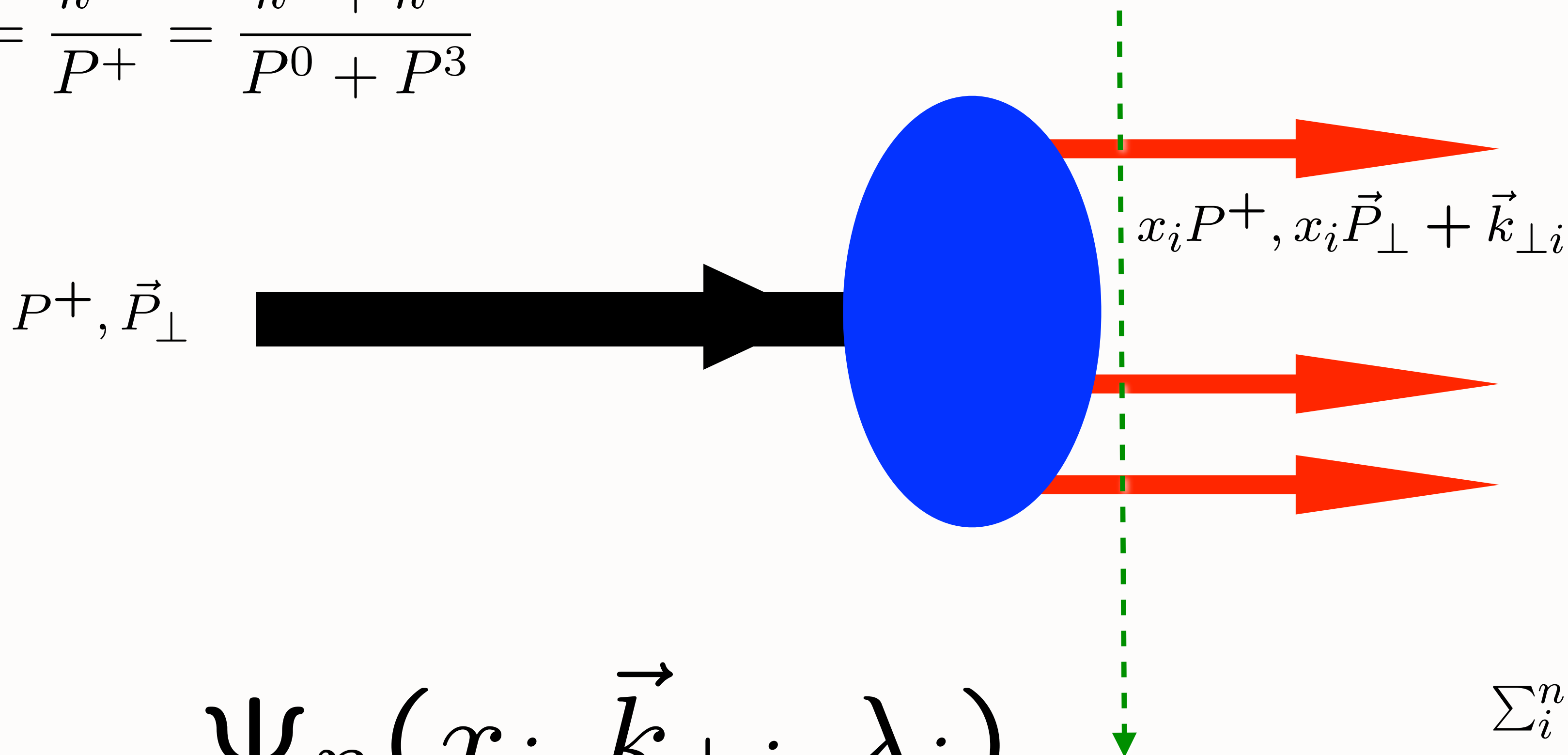




Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$

Fixed $\tau = t + z/c$



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

$\sum_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

Bethe-Salpeter WF integrated over k^-

Each element of flash photograph illuminated at same LF time

$$\tau = t + z/c$$

Evolve in LF time

$$P^- = i\frac{d}{d\tau}$$

Eigenstate -- independent of τ

Causality: Measurements never at fixed time t

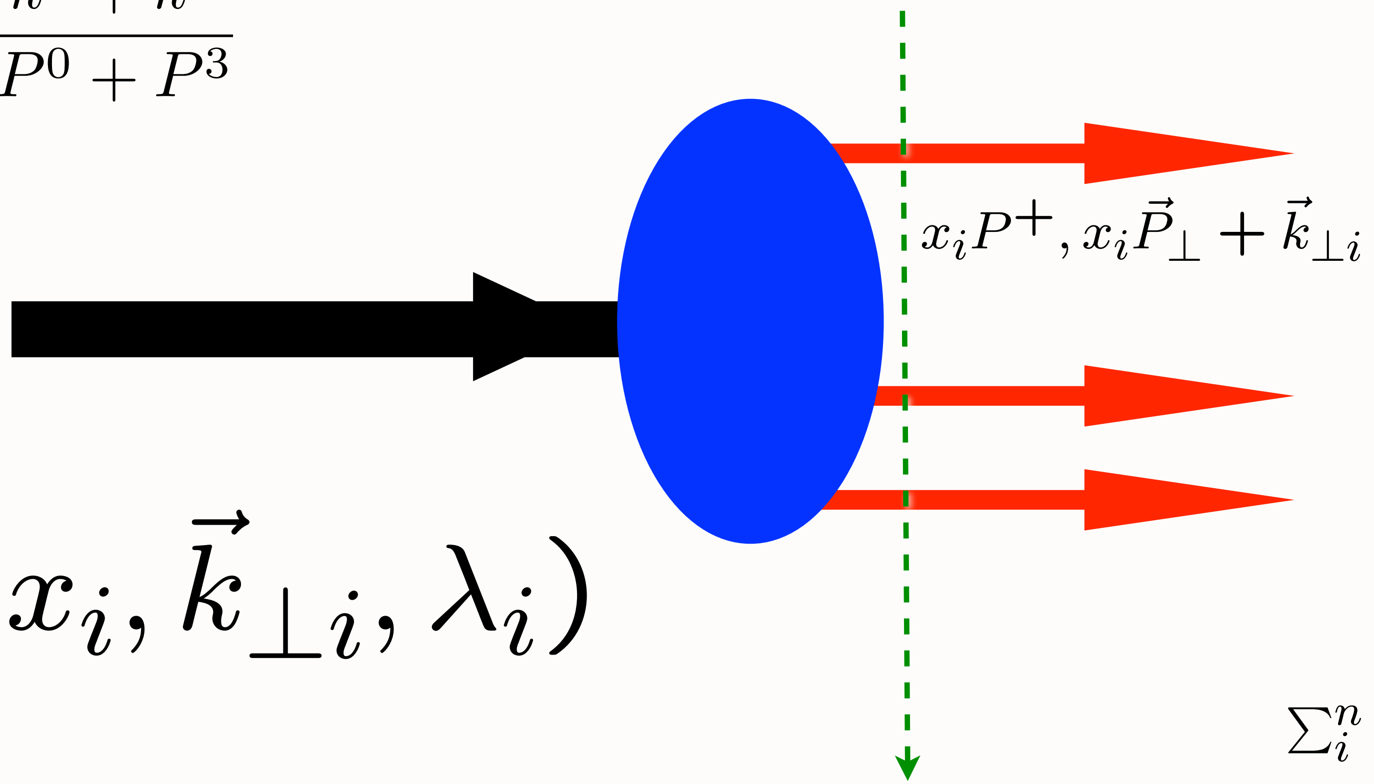
HELEN BRADLEY - PHOTOGRAPHY

Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$

Fixed $\tau = t + z/c$

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



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

$\sum_i^n x_i = 1$

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

Structure functions and other distributions computed from the square of the LFWFs

Goal: Predict all features from first principles in QCD

Angular Momentum on the Light-Front

LC gauge

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

Conserved
LF Fock state by Fock State
All scales

Gluon orbital angular momentum defined in physical lc gauge

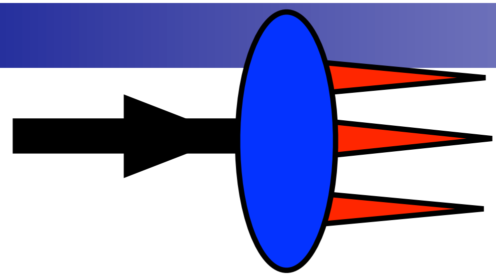
$$l_j^z = -\mathrm{i}\left(k_j^1 \frac{\partial}{\partial k_j^2} - k_j^2 \frac{\partial}{\partial k_j^1}\right)$$

n-1 orbital angular momenta

Orbital Angular Momentum is a property of LFWFS

Nonzero Anomalous Moment -->
Nonzero quark orbital angular momentum!

- *Light Front Wavefunctions:*



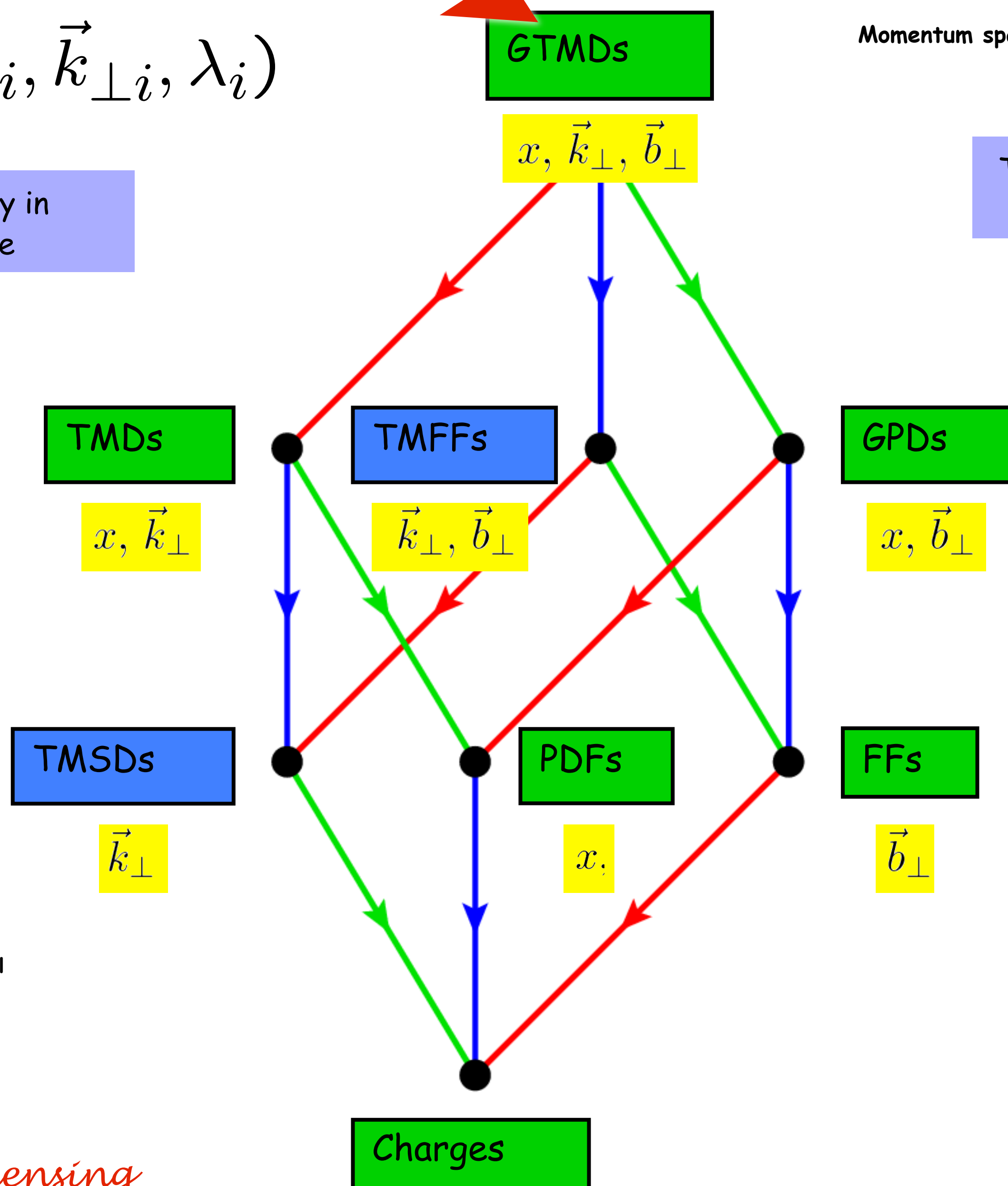
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

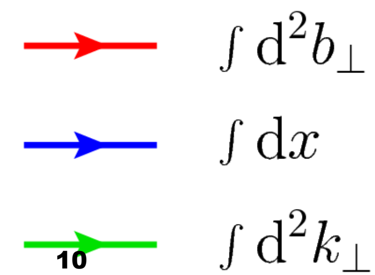
Transverse density in momentum space

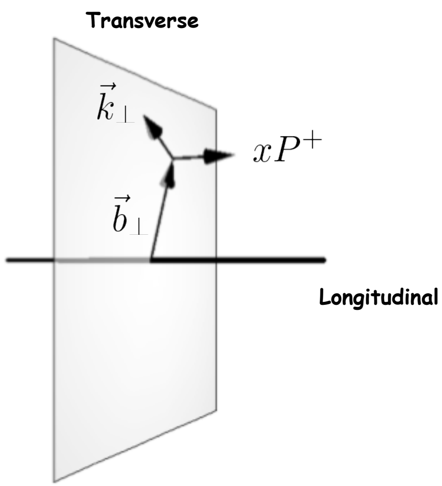
Momentum space $\vec{k}_\perp \leftrightarrow \vec{z}_\perp$ Position space

$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$

Transverse density in position space







Sivers, T-odd from lensing

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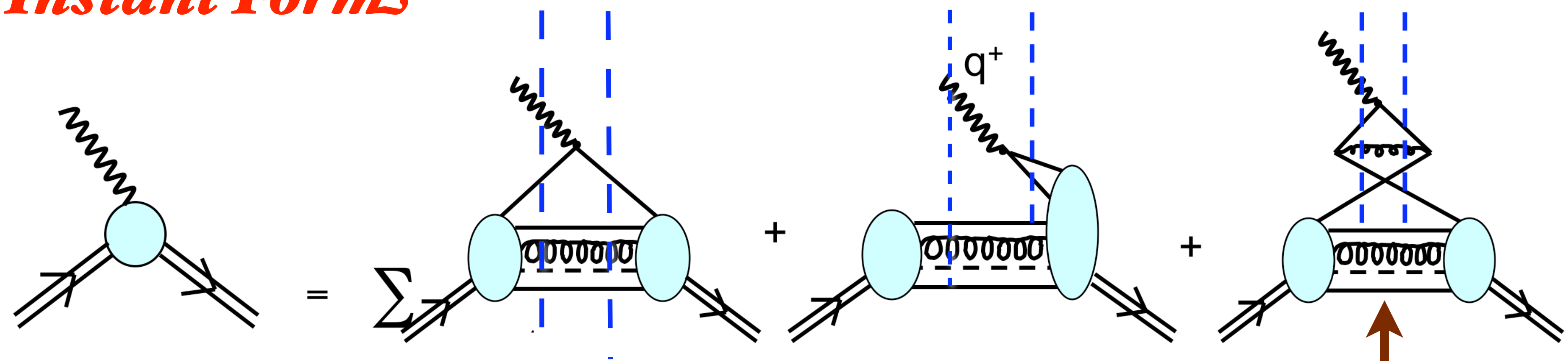
Calculation of Form Factors in Equal-Time Theory

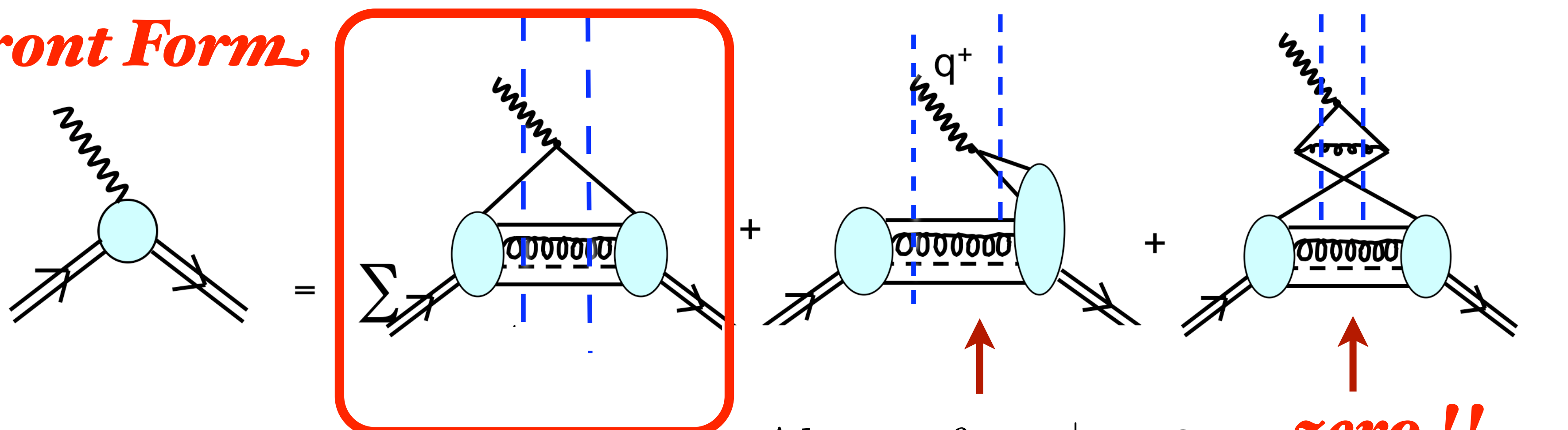
Instant Form



Need vacuum-induced currents

Calculation of Form Factors in Light-Front Theory

Front Form



Complete Answer

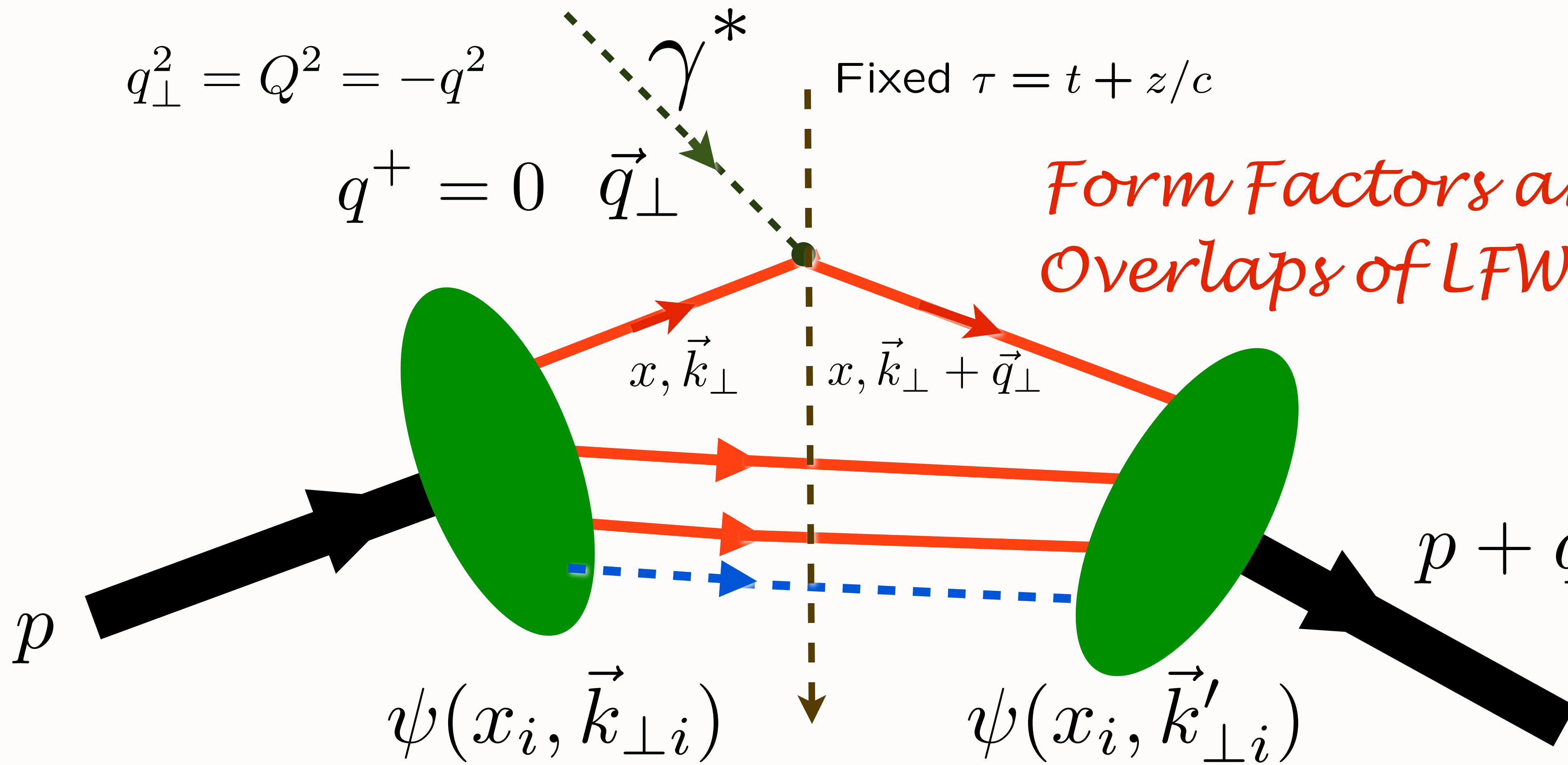
Absent for $q^+ = 0$

zero !!

No vacuum graphs

$$< p+q|j^+(0)|p >= 2p^+F(q^2)$$

Interaction picture



Form Factors are Overlaps of LFWFs

struck $\vec{k}'_{\perp i} = \vec{k}_{\perp i} + (1-x_i)\vec{q}_\perp$

spectators $\vec{k}'_{\perp i} = \vec{k}_{\perp i} - x_i\vec{q}_\perp$

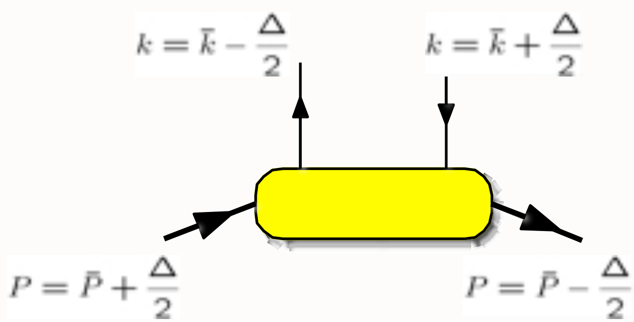
Drell &Yan, West
Exact LF formula

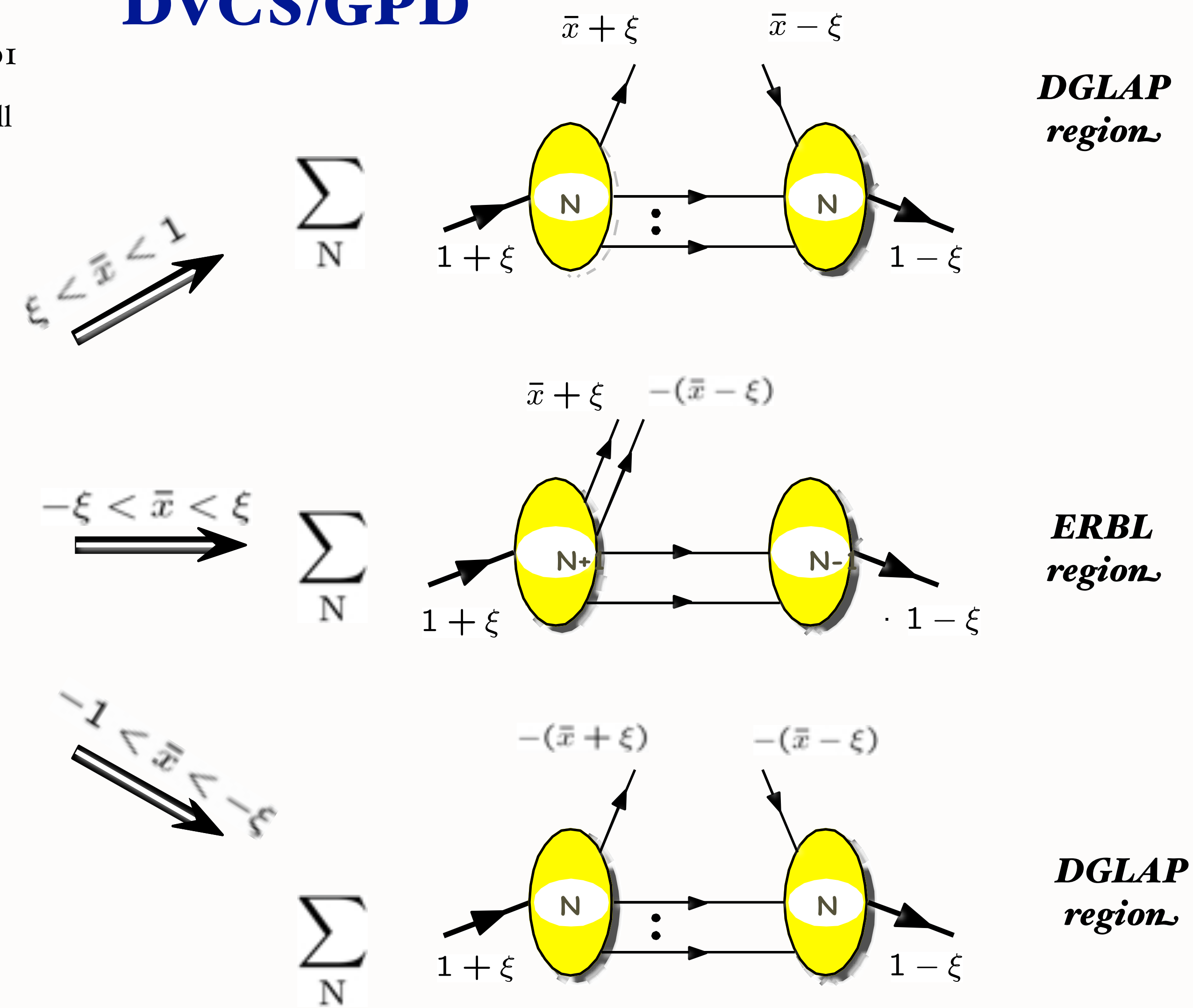
Light-Front Wave Function Overlap Representation

DVCS/GPD

Diehl, Hwang, sjb, NPB596, 2001

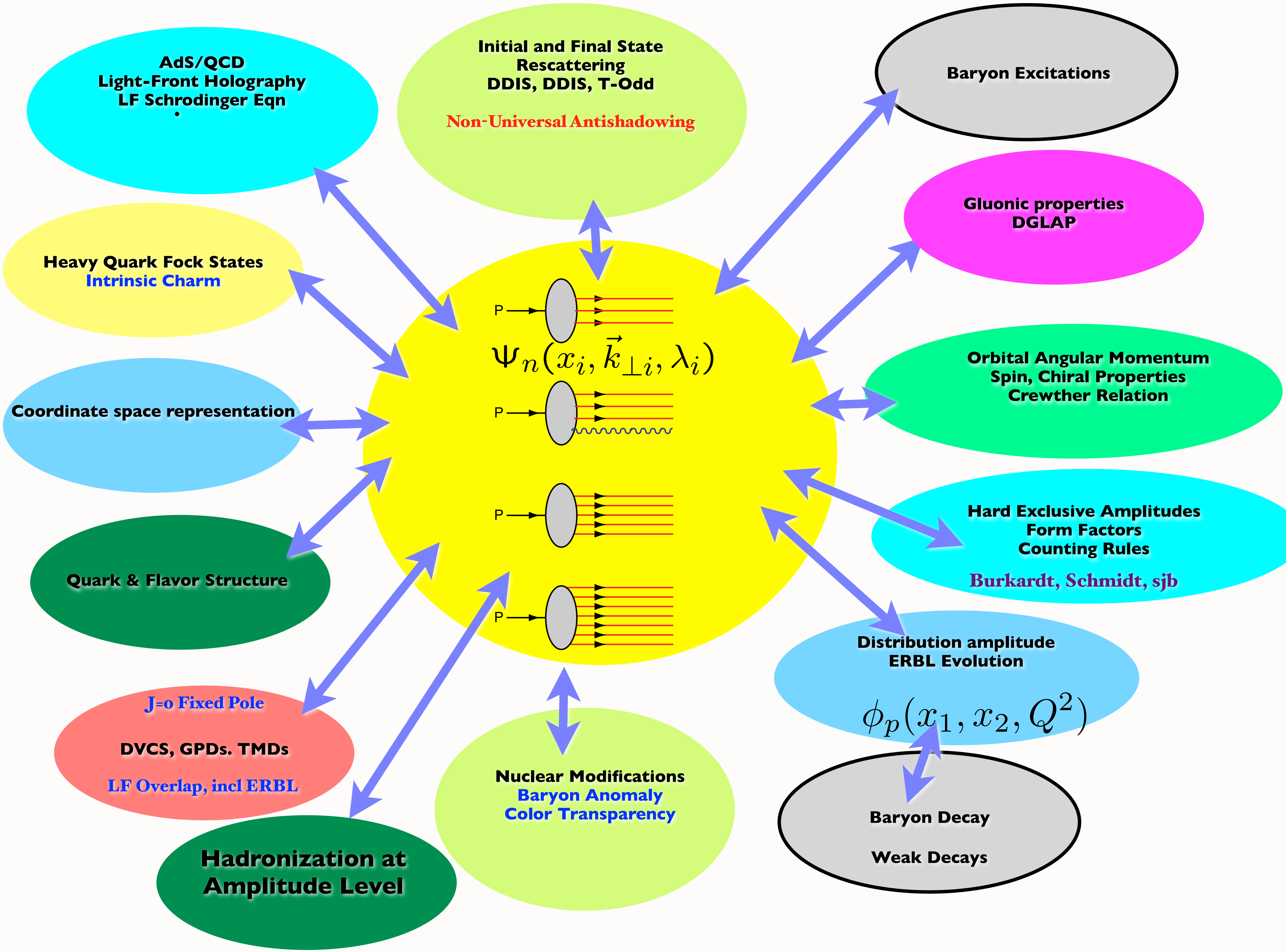
See also: Diehl, Feldmann, Jakob, Kroll



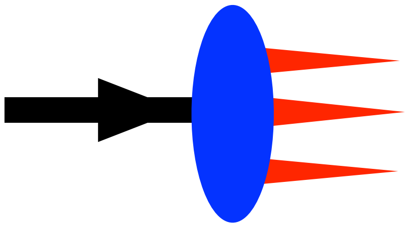


Bakker & Ji
Lorce

QCD and the LF Hadron Wavefunctions



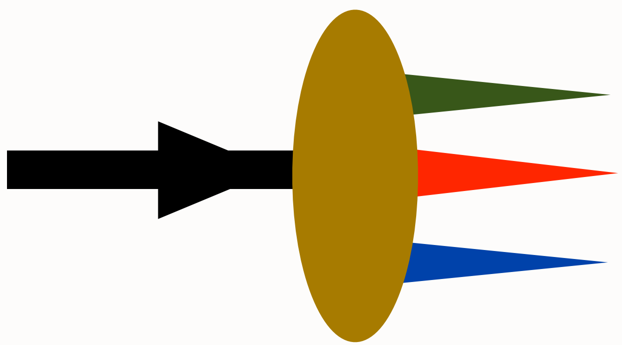
- **LF wavefunctions play the role of Schrödinger wavefunctions in Atomic Physics**



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

- **LFWFs=Hadron Eigensolutions: Direct Connection to QCD Lagrangian**
- **Relativistic, frame-independent: no boosts, no disc contraction, Melosh built into LF spinors**
- **Hadronic observables computed from LFWFs: Form factors, Structure Functions, Distribution Amplitudes, GPDs, TMDs, Weak Decays, ... modulo `lensing' from ISIs, FSIs**
- **Cannot compute current matrix elements using instant or point form from eigensolutions alone -- need to include vacuum currents!**
- **Hadron Physics without LFWFs is like Biology without DNA!**

- *Hadron Physics without LFWFs is like Biology without DNA!*



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

Do heavy quarks exist in the proton at high x?

Conventional wisdom: impossible!

Standard Assumption: Heavy quarks are generated via DGLAP evolution from gluon splitting

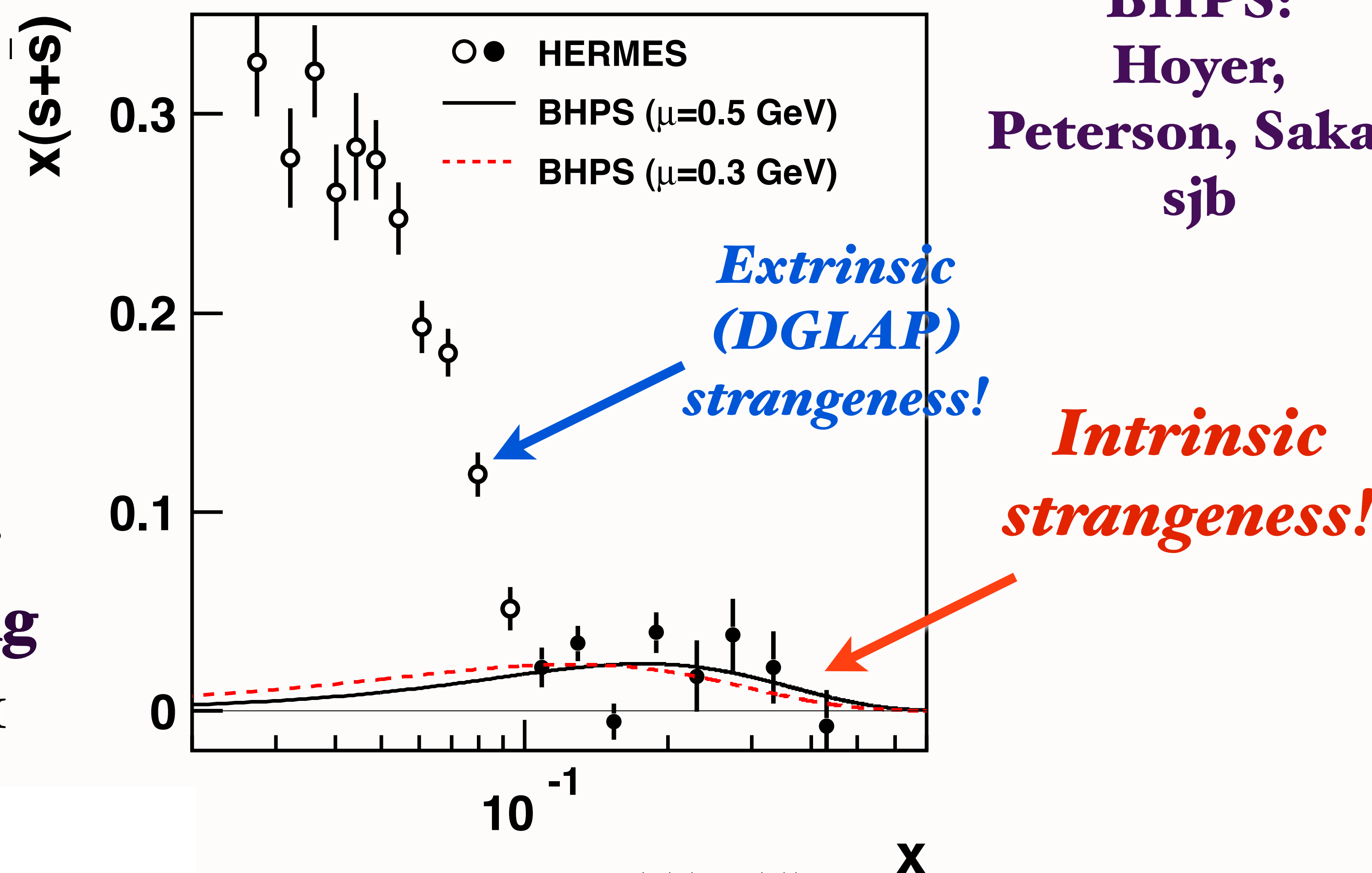
$$s(x, \mu_F^2) = c(x, \mu_F^2) = b(x, \mu_F^2) \equiv 0$$

at starting scale μ_F^2

Conventional wisdom is wrong even in QED!

HERMES: Two components to s(x,Q²)!

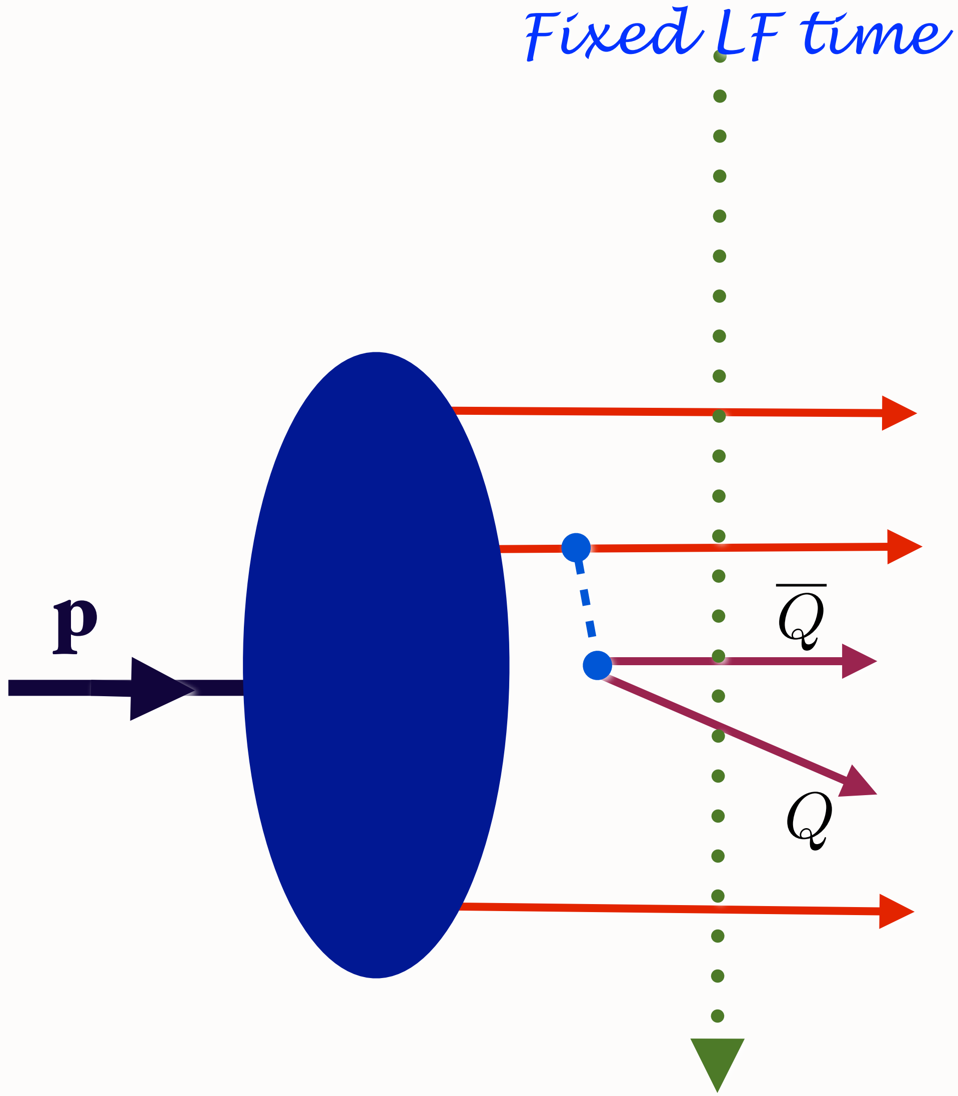
BHPS: Hoyer, Peterson, Sakai, sjb



W. C. Chang and J.-C. Peng
arXiv:1105.2381

Comparison of the HERMES $x(s(x)+\bar{s}(x))$ data with the calculations based on the BHPS model. The solid and dashed curves are obtained by evolving the BHPS result to $Q^2 = 2.5$ GeV^2 using $\mu = 0.5$ GeV and $\mu = 0.3$ GeV, respectively. The normalizations of the calculations are adjusted to fit the data at $x > 0.1$ with statistical errors only, denoted by solid circles.

$$s(x,Q^2) = s(x,Q^2)_{\rm extrinsic} + s(x,Q^2)_{\rm intrinsic}$$



Proton's 5-quark Fock State from gluon splitting

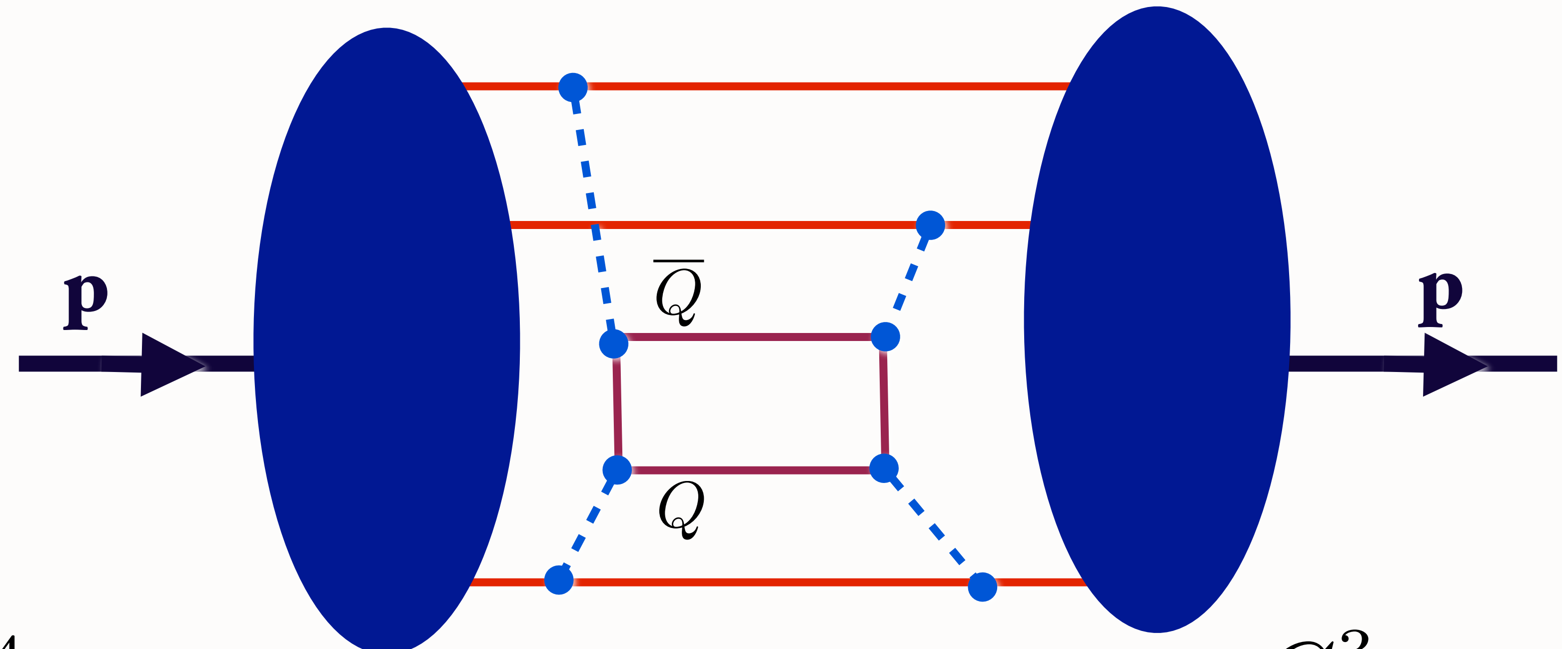
"Extrinsic" Heavy Quarks

$$s(x,Q^2)_{\text{extrinsic}} \sim (1-x)g(x,Q^2) \sim (1-x)^5$$

Proton Self Energy from g g to gg scattering

QCD predicts Intrinsic Heavy Quarks!

$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$



$$\frac{F_{\mu\nu}^4}{M_\ell^2}$$

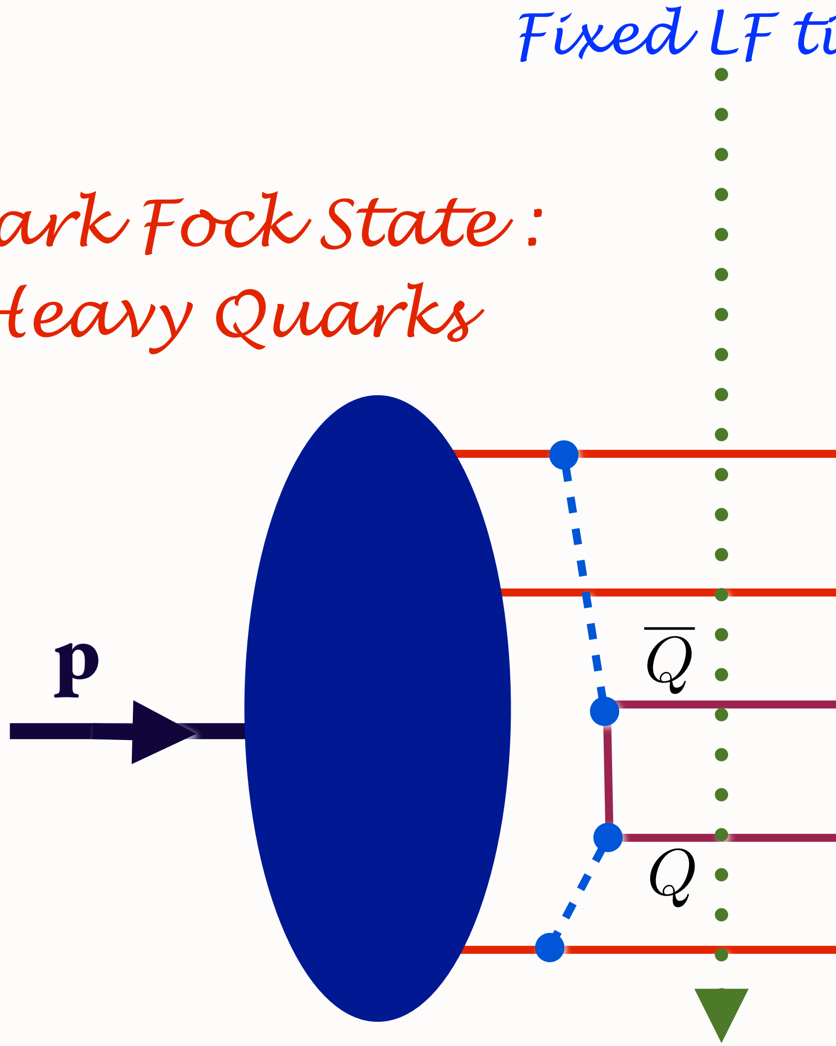
$$\frac{G_{\mu\nu}^3}{M_Q^2}$$

$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4}$$

$$\text{Probability (QCD)} \propto \frac{1}{M_Q^2}$$

Collins, Ellis, Gunion, Mueller, sjb
M. Polyakov, et al.

Proton 5-quark Fock State :
Intrinsic Heavy Quarks



QCD predicts Intrinsic Heavy Quarks at high x

Minimal off-shellness

$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$

Probability (QED) $\propto \frac{1}{M_\ell^4}$

Probability (QCD) $\propto \frac{1}{M_Q^2}$

Collins, Ellis, Gunion, Mueller, sjb
M. Polyakov

INTRINSIC CHEVROLETS AT THE SSC

Stanley J. Brodsky

Stanford Linear Accelerator Center, Stanford University, Stanford CA 94305

John C. Collins

Department of Physics, Illinois Institute of Technology, Chicago IL 60616
and
High Energy Physics Division, Argonne National Laboratory, Argonne IL 60439

Stephen D. Ellis

Department of Physics, FM-15, University of Washington, Seattle WA 98195

John F. Gunion

Department of Physics, University of California, Davis CA 95616

Alfred H. Mueller

Department of Physics, Columbia University, New York NY 10027

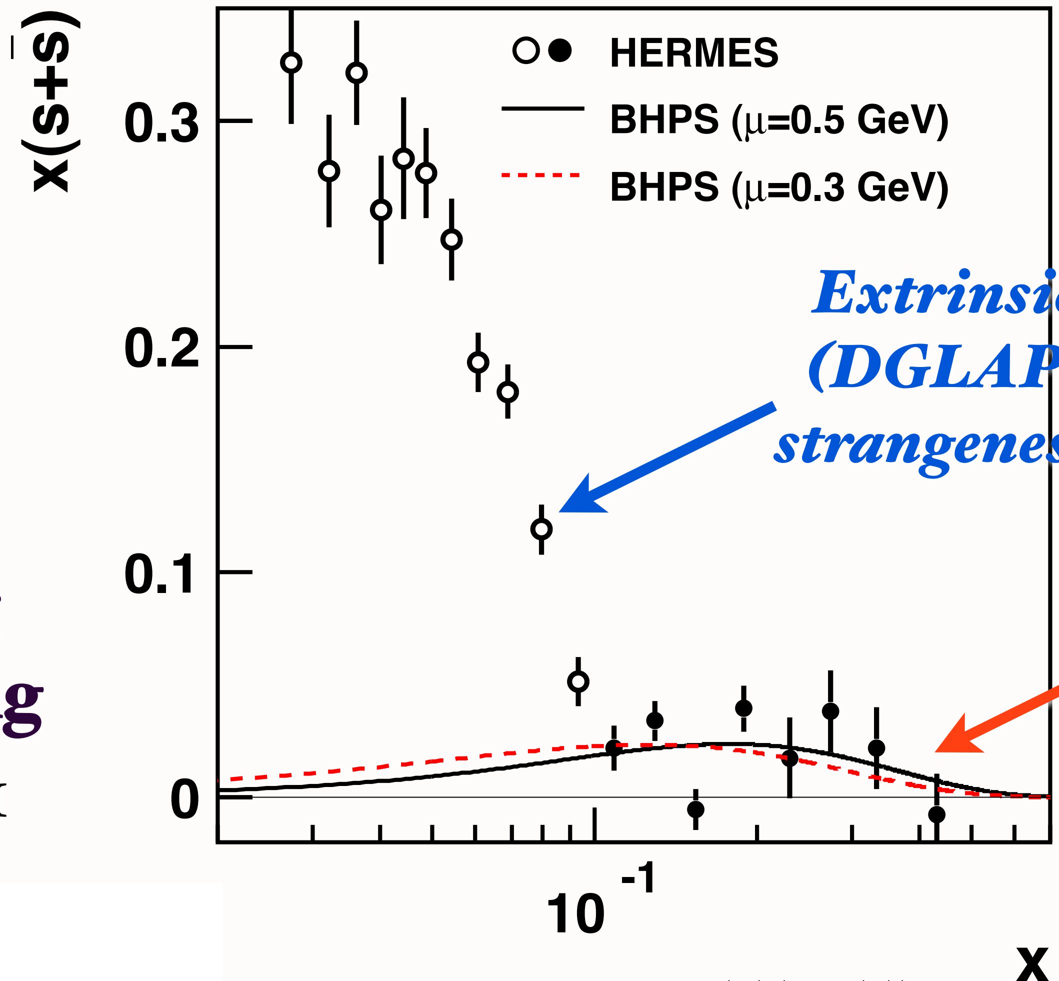
$$\mathcal{L}^{eff}_{QCD} = -\frac{1}{4}F_{\mu\nu a}F^{\mu\nu a} - \frac{g^2 N_C}{120\pi^2 M_Q^2} D_\alpha F_{\mu\nu a} D^\alpha F^{\mu\nu a} + C\frac{g^2 N_C}{120\pi^2 M_Q^2} F_\mu^{a\nu} F_\nu^{b\tau} F_\tau^{c\mu} f_{abc} + \mathcal{O}(\frac{1}{M_Q^4})$$

Probability of Intrinsic Heavy Quarks ~ $1/M^2_Q$

Published in Snowmass Summer Study 1984:0227 (QCD184:S7:1984)

HERMES: Two components to s(x,Q²)!

BHPS: Hoyer, Peterson, Sakai, sjb



Extrinsic (DGLAP) strangeness!

Intrinsic strangeness!

W. C. Chang and J.-C. Peng

arXiv:1105.2381

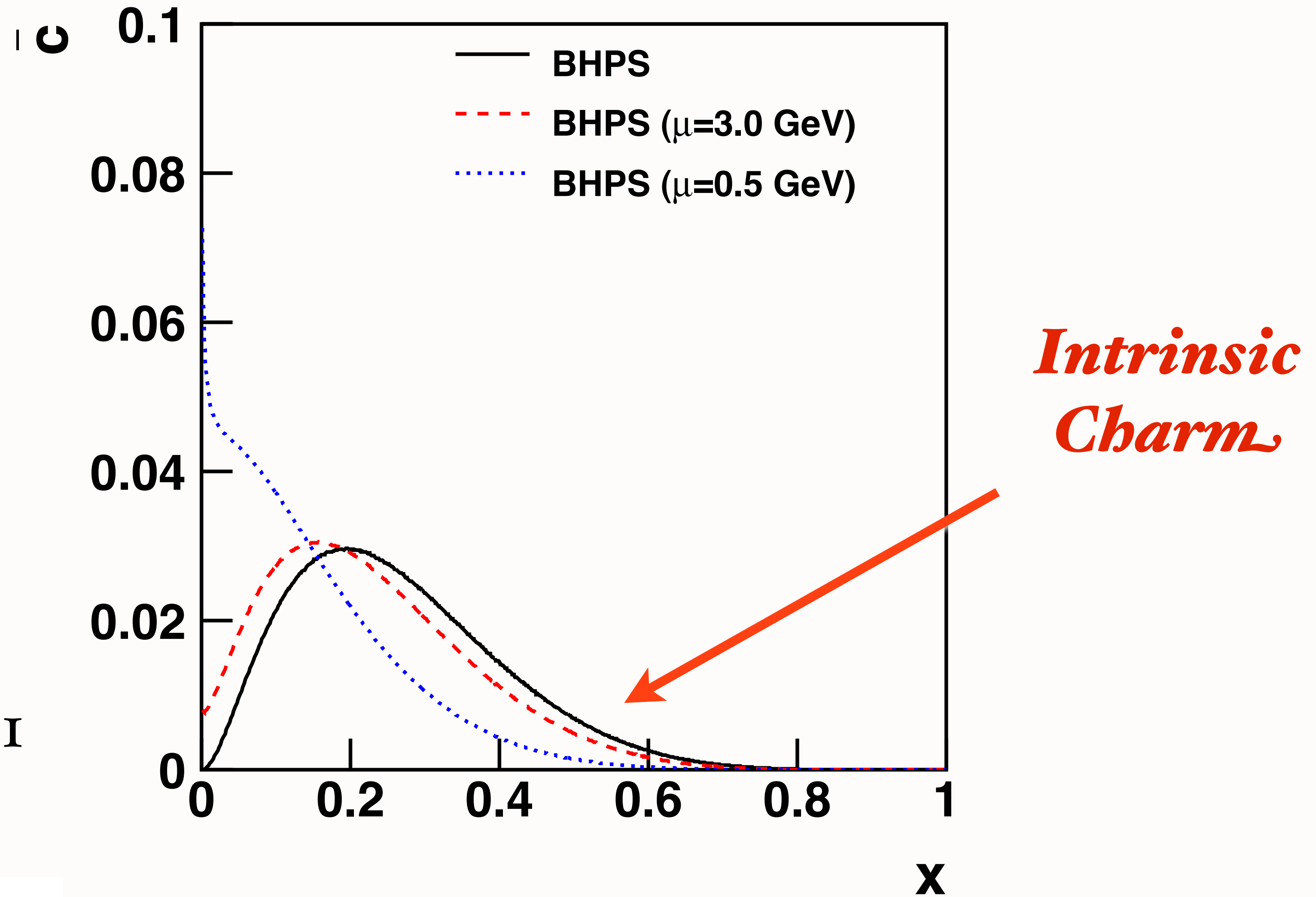
Comparison of the HERMES $x(s(x) + \bar{s}(x))$ data with the calculations based on the BHPS model. The solid and dashed curves are obtained by evolving the BHPS result to $Q^2 = 2.5$ GeV^2 using $\mu = 0.5$ GeV and $\mu = 0.3$ GeV, respectively. The normalizations of the calculations are adjusted to fit the data at $x > 0.1$ with statistical errors only, denoted by solid circles.

$$s(x, Q^2) = s(x, Q^2)_{\text{extrinsic}} + s(x, Q^2)_{\text{intrinsic}}$$

Apply $\frac{1}{m_Q^2}$ scaling, predict intrinsic charm

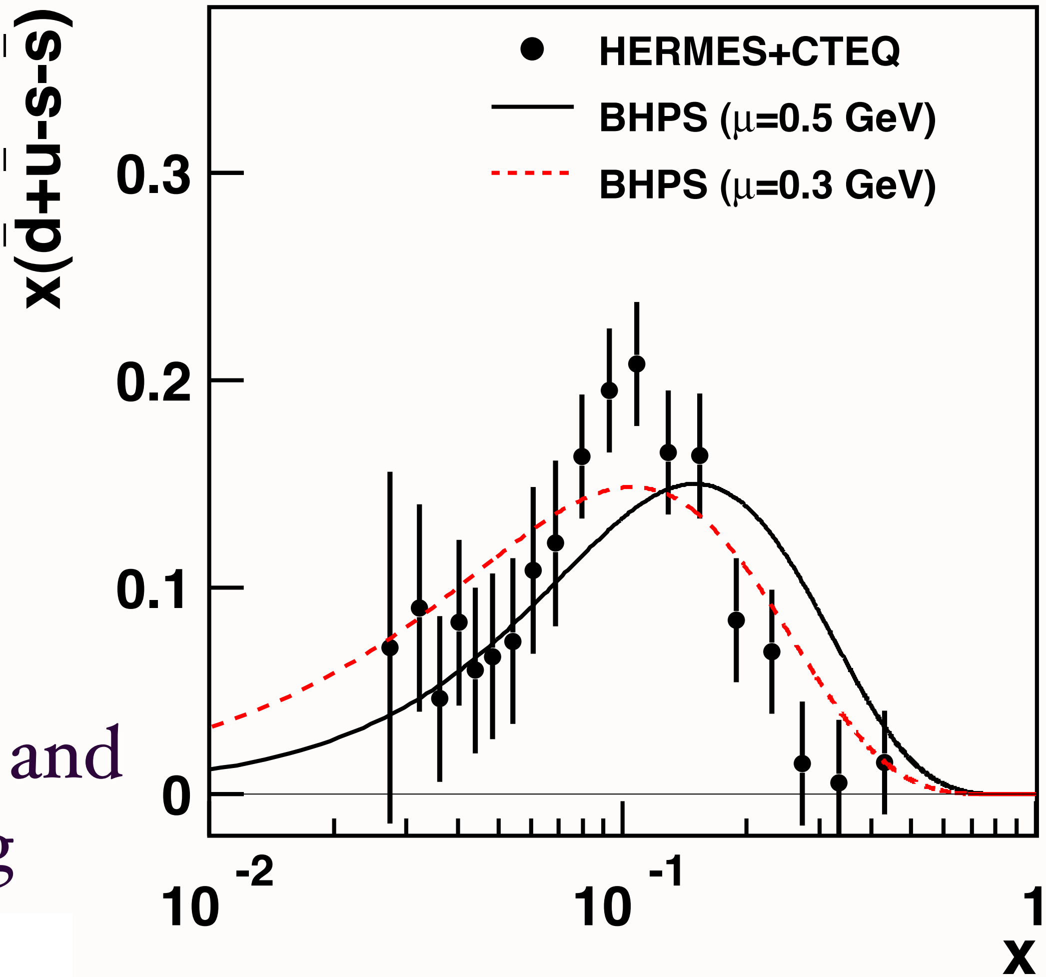
W. C. Chang and J.-C. Peng

arXiv:1105.2381



Calculations of the $\bar{c}(x)$ distributions based on the BHPS model. The solid curve corresponds to the calculation using Eq. 1 and the dashed and dotted curves are obtained by evolving the BHPS result to $Q^2 = 75$ GeV^2 using $\mu = 3.0$ GeV, and $\mu = 0.5$ GeV, respectively. The normalization is set at $\mathcal{P}_5^{c\bar{c}} = 0.01$.

Consistent with EMC



W. C. Chang and J.-C. Peng

Comparison of the $x(\bar{d}(x)+\bar{u}(x)-s(x)-\bar{s}(x))$ data with the calculations based on the BHPS model. The values of $x(s(x)+\bar{s}(x))$ are from the HERMES experiment [6], and those of $x(\bar{d}(x)+\bar{u}(x))$ are obtained from the PDF set CTEQ6.6 [11]. The solid and dashed curves are obtained by evolving the BHPS result to $Q^2 = 2.5$ GeV^2 using $\mu = 0.5$ GeV and $\mu = 0.3$ GeV, respectively. The normalization of the calculations are adjusted to fit the data.

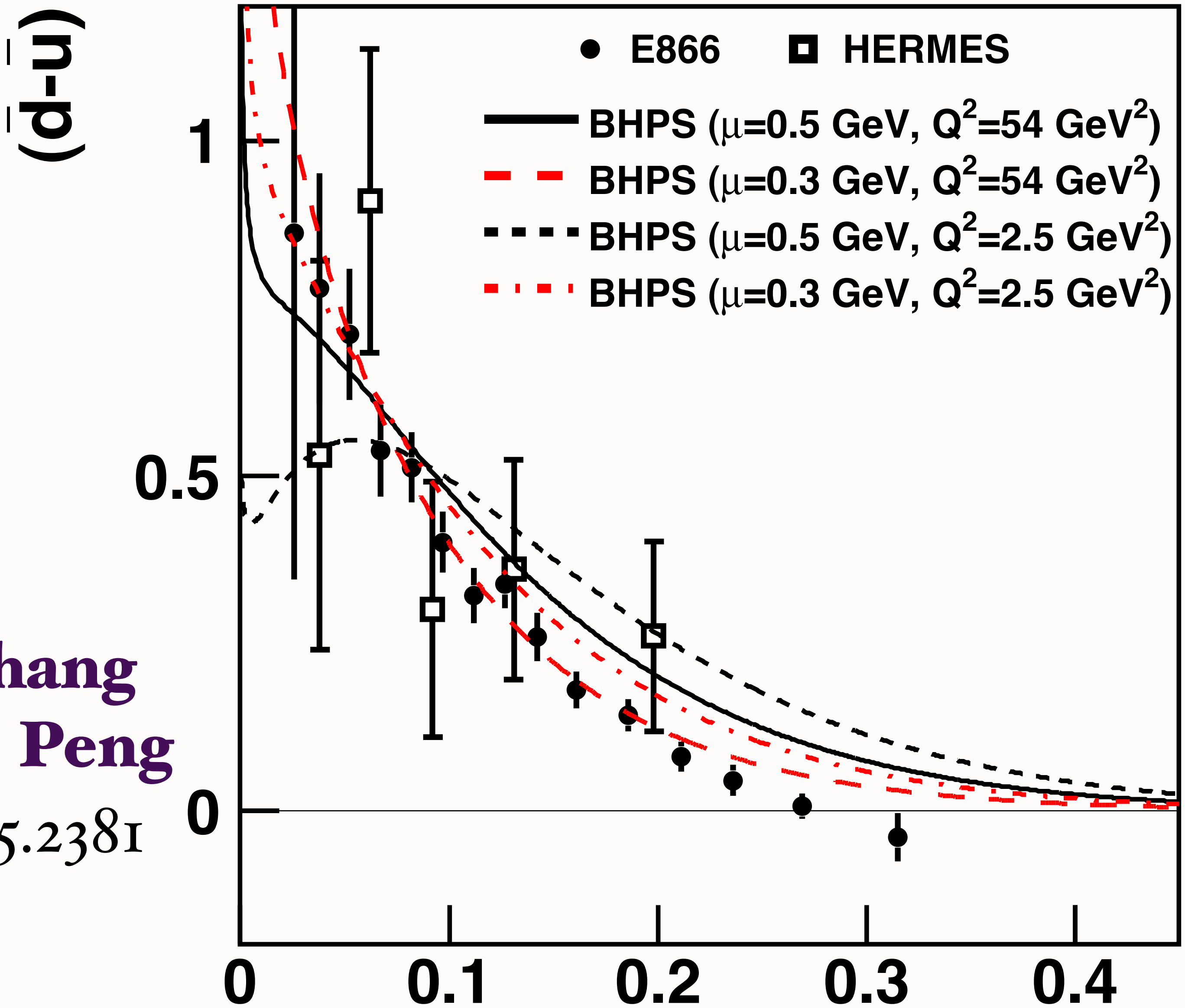


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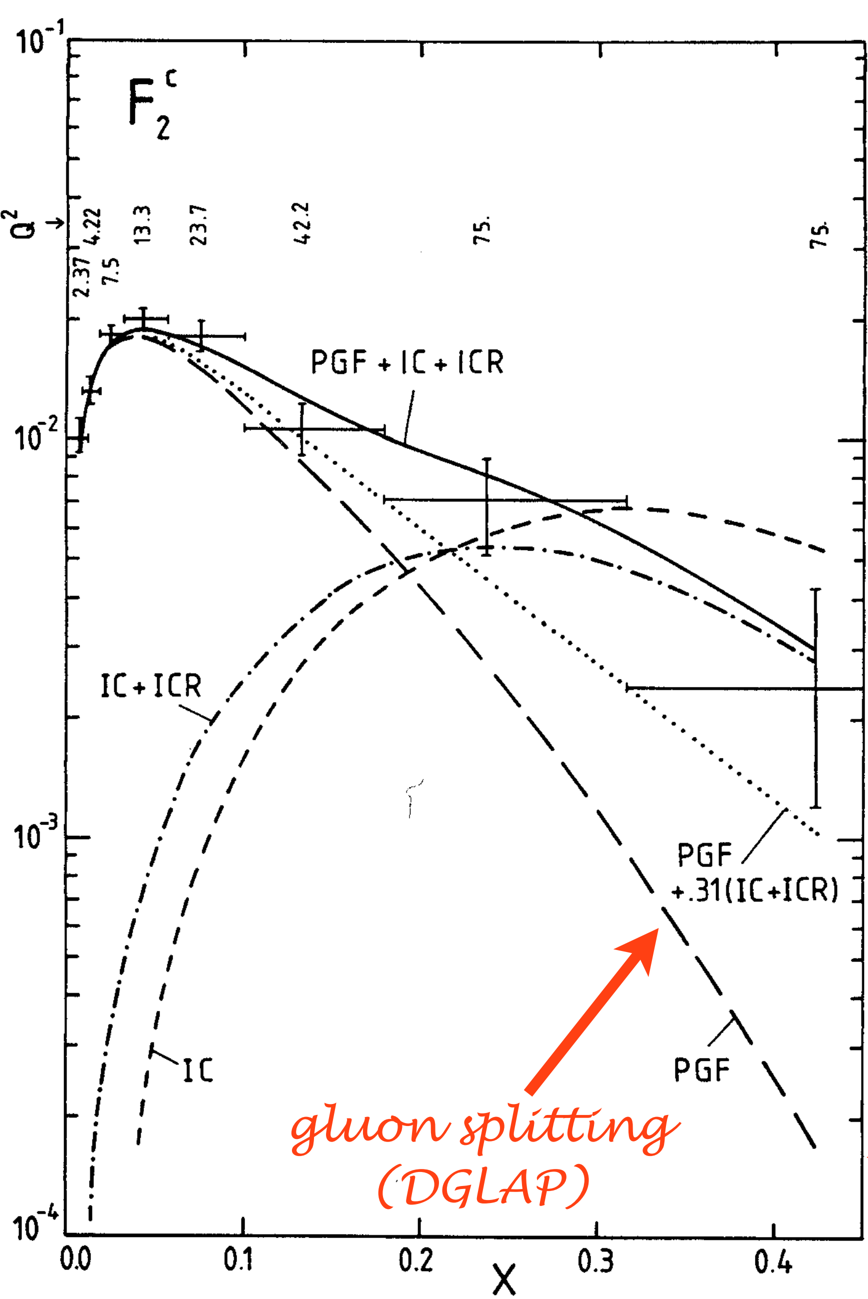
Figure 1: Comparison of the $\bar{d}(x)-\bar{u}(x)$ data from Fermilab E866 and HERMES with the calculations based on the BHPS model. Eq. 1 and Eq. 3 were used to calculate the $\bar{d}(x)-\bar{u}(x)$ distribution at the initial scale. The distribution was then evolved to the Q^2 of the experiments and shown as various curves. Two different initial scales, $\mu = 0.5$ and 0.3 GeV, were used for the E866 calculations in order to illustrate the dependence on the choice of the initial scale.

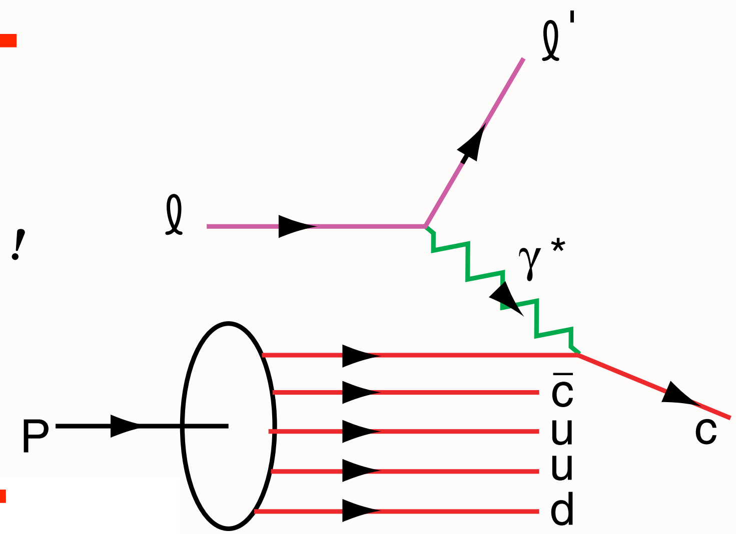
Measurement of Charm Structure Function

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

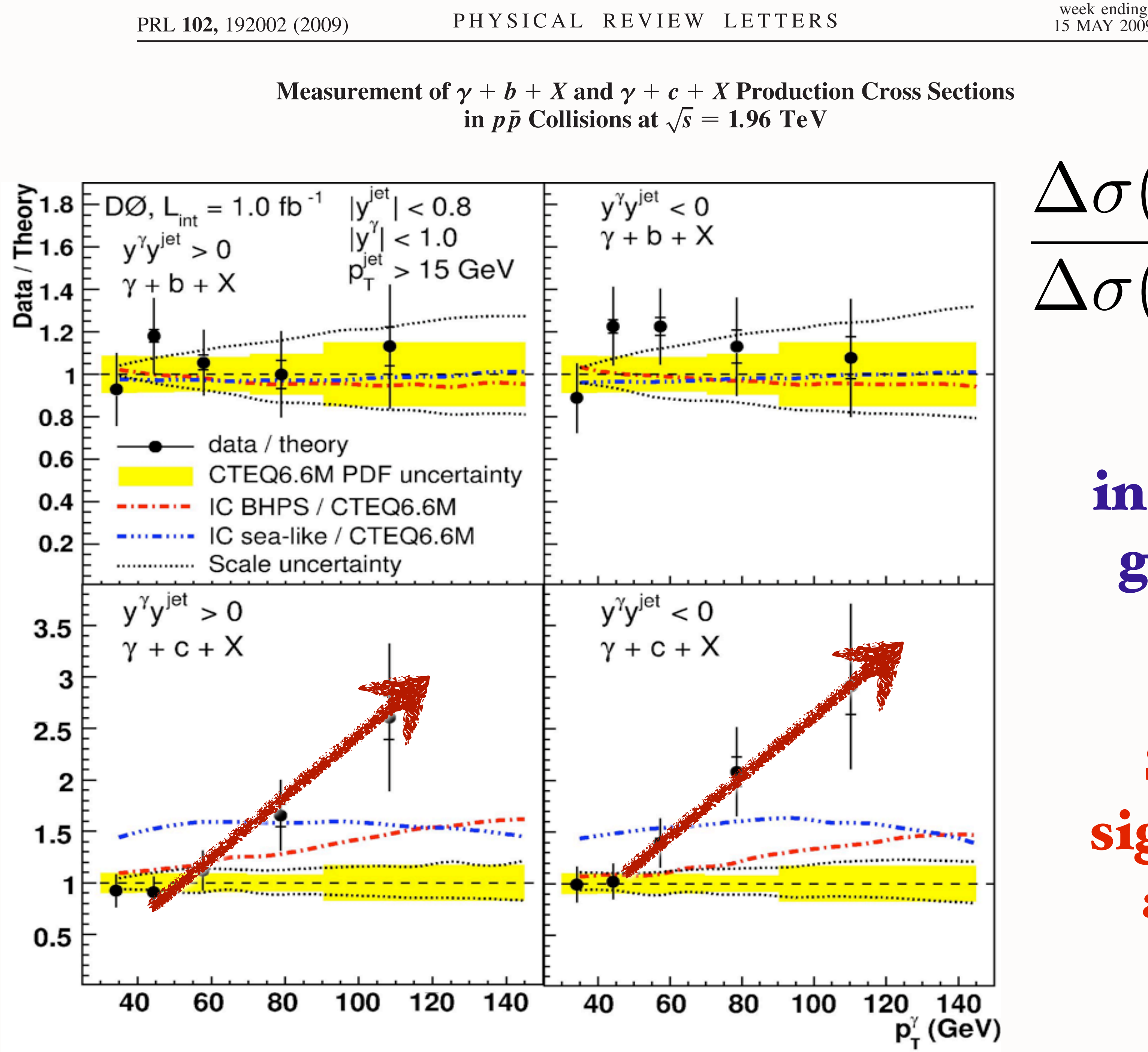
factor of 30 !



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

Two Components (separate evolution):

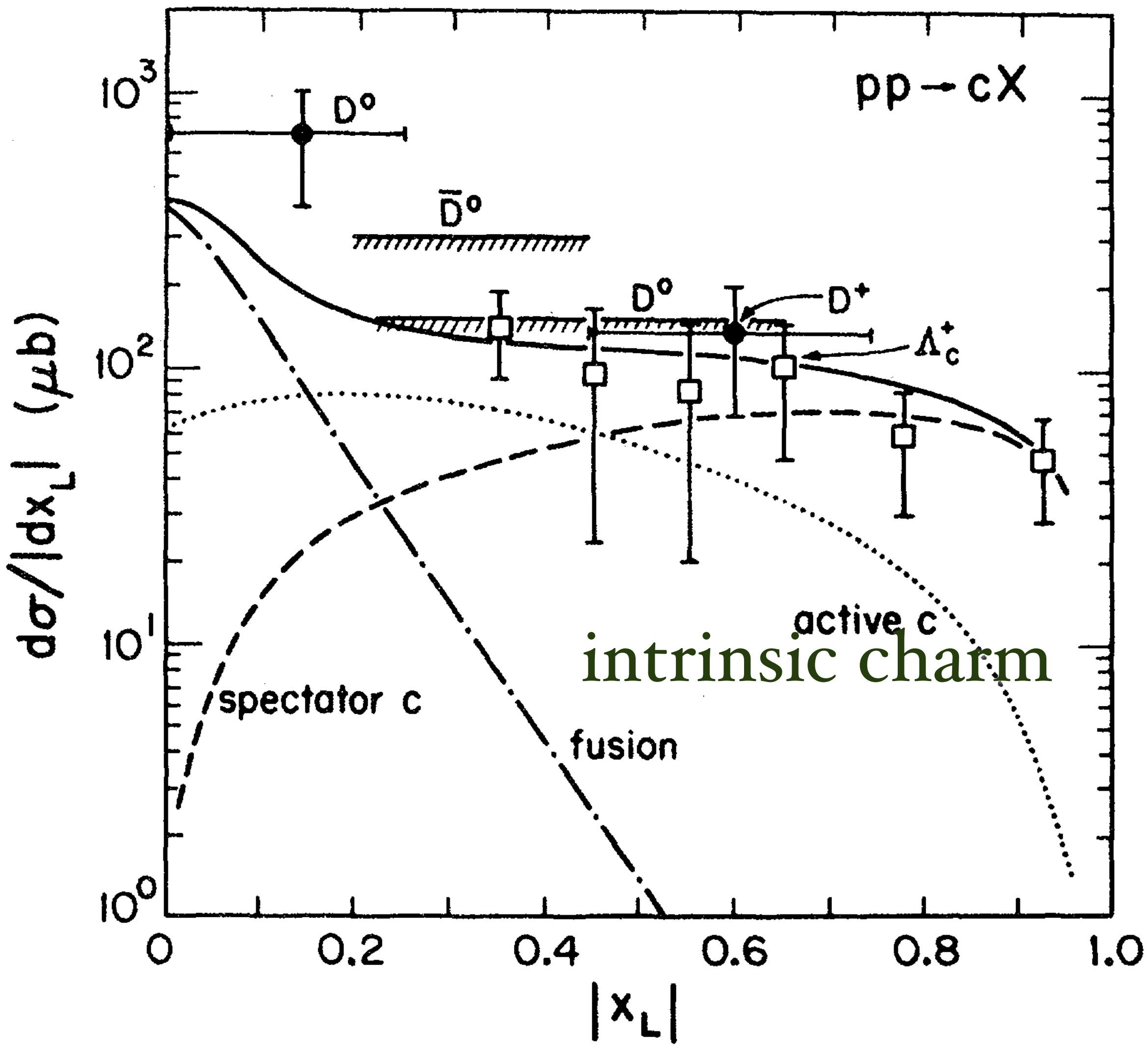
$$c(x, Q^2) = c(x, Q^2)_{\text{extrinsic}} + c(x, Q^2)_{\text{intrinsic}}$$



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

Ratio insensitive to gluon PDF, scales

Signal for significant IC at x > 0.1 ?



Barger, Halzen, Keung

Evidence for charm at large x

- 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 $pp \to \Lambda_c X$

- High x_F $pp \to \Lambda_b X$

C.H. Chang, J.P. Ma, C.F. Qiao and X.G.Wu,

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

Critical Measurements at threshold for JLab, PANDA

Interesting spin, charge asymmetry, threshold, spectator effects

Important corrections to B decays; Quarkonium decays

Gardner, Karliner, sjb

All events have $x^F_{\psi\psi} > 0.4$!

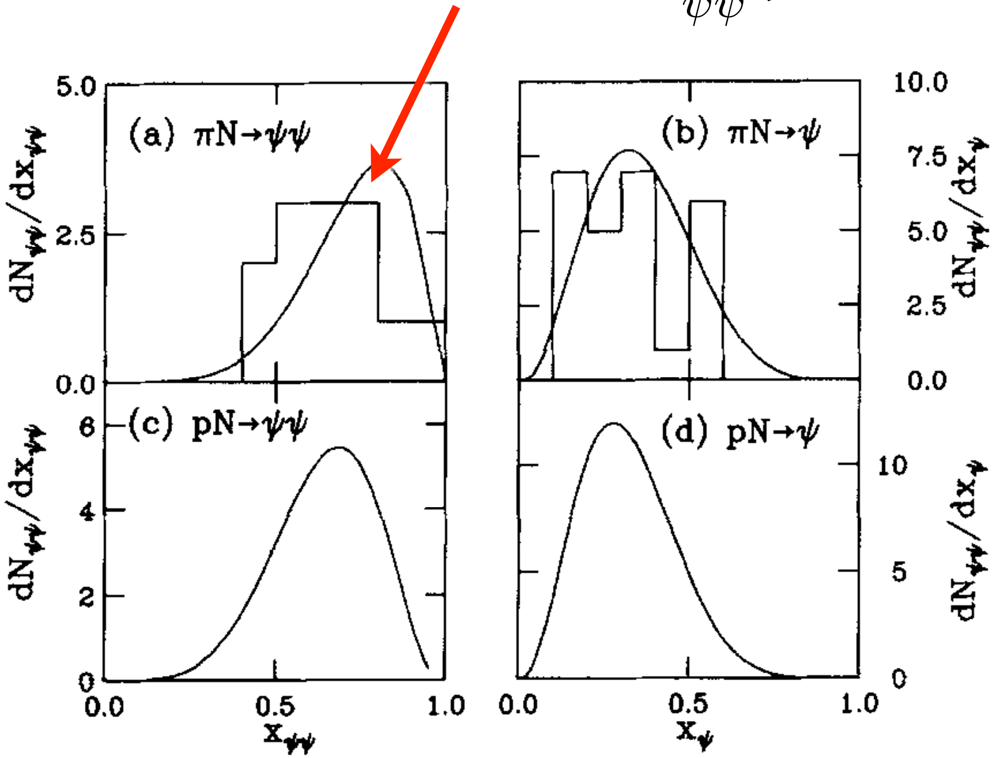


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized to the number of pairs from both pion beams (a) and the number of pairs from the 400 GeV proton measurement (c). The number of single J/ψ's is twice the number of pairs.

NA3 Data

Excludes PYTHIA 'color drag' model

$\pi A \rightarrow J/\psi J/\psi X$

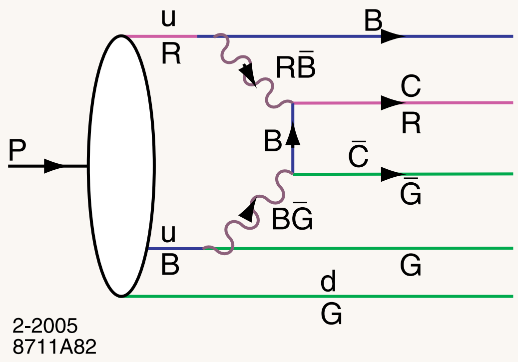
R, Vogt, sjb

The probability distribution for a general n-particle intrinsic $c\bar{c}$ Fock state as a function of x and $\boldsymbol{k}_T$ is written as

$$\frac{dP_{\rm ic}}{\prod_{i=1}^n dx_i d^2k_{T,i}} = N_n \alpha_s^4(M_{c\bar{c}}) \frac{\delta(\sum_{i=1}^n \boldsymbol{k}_{T,i})\delta(1-\sum_{i=1}^n x_i)}{(m_h^2 - \sum_{i=1}^n (m_{T,i}^2/x_i))^2},$$

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

Intrinsic Heavy-Quark Fock States

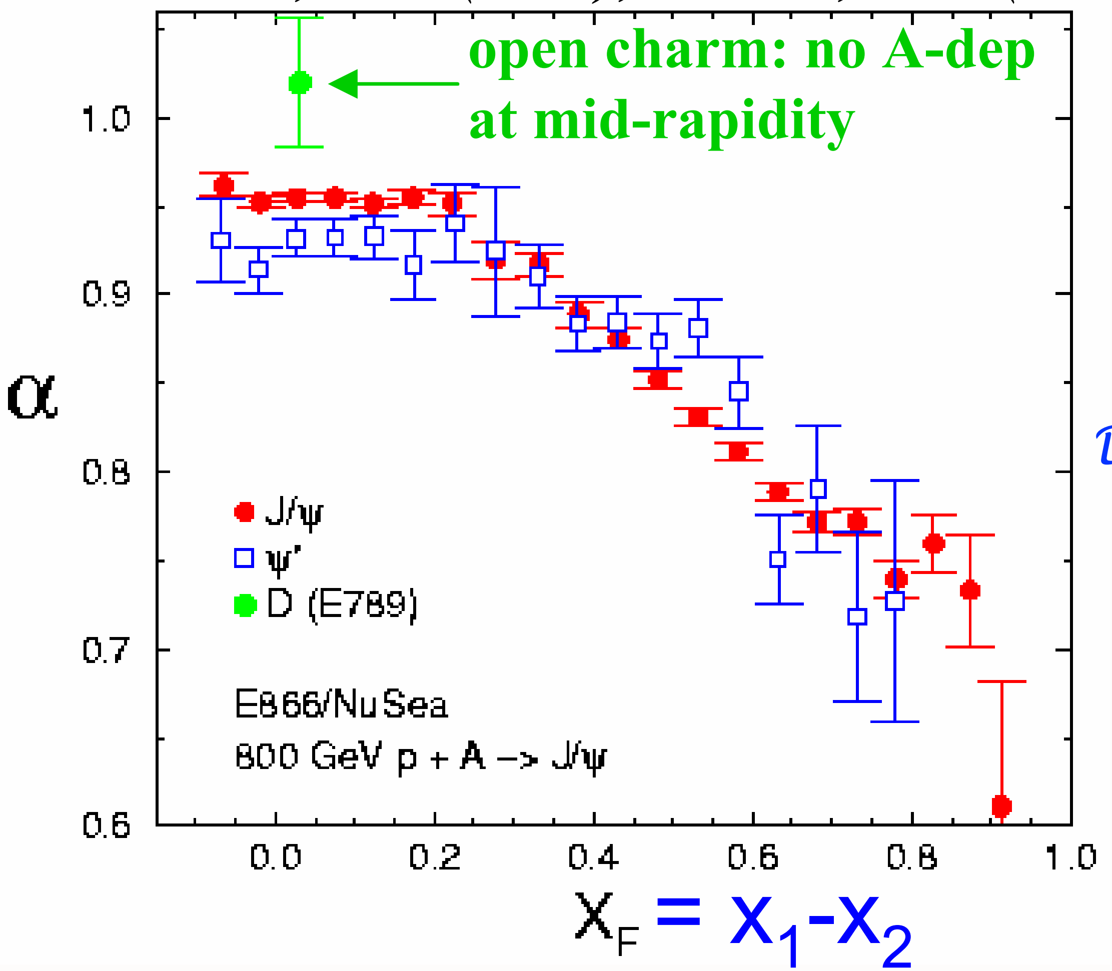


- Rigorous prediction of QCD, OPE
- Color-Octet Color-Octet Fock State!
- Probability $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- Large Effect at high x
- Greatly increases kinematics of colliders such as Higgs production at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

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

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

M. Leitch



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

Remarkably Strong Nuclear Dependence for Fast Charmonium

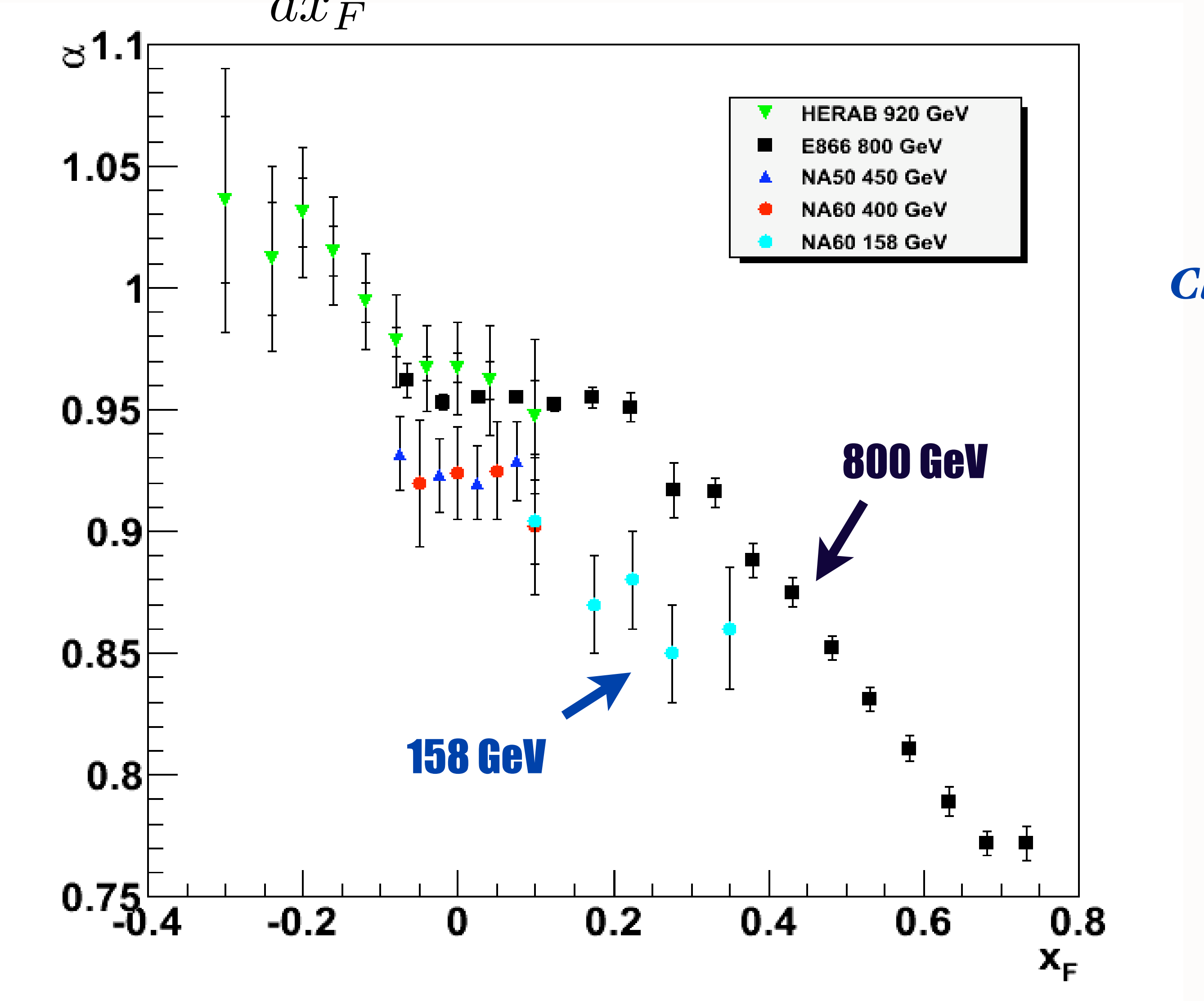
Violation of PQCD Factorization

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

IC Explains large excess of quarkonia at large x_F, A-dependence

NA60 pA data @ 158GeV

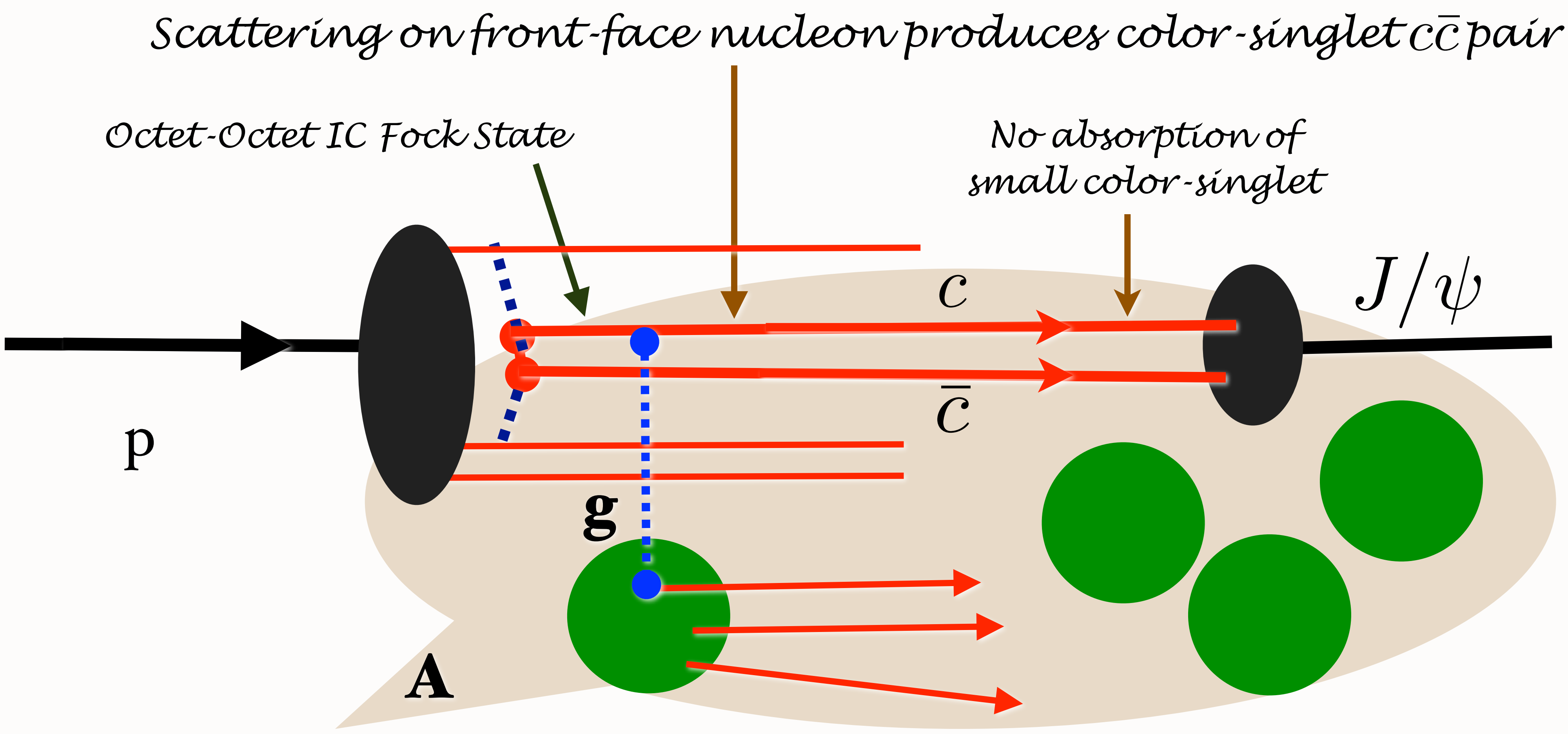
$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) \propto A^{\alpha}$$



Clear dependence on x_F and beam energy

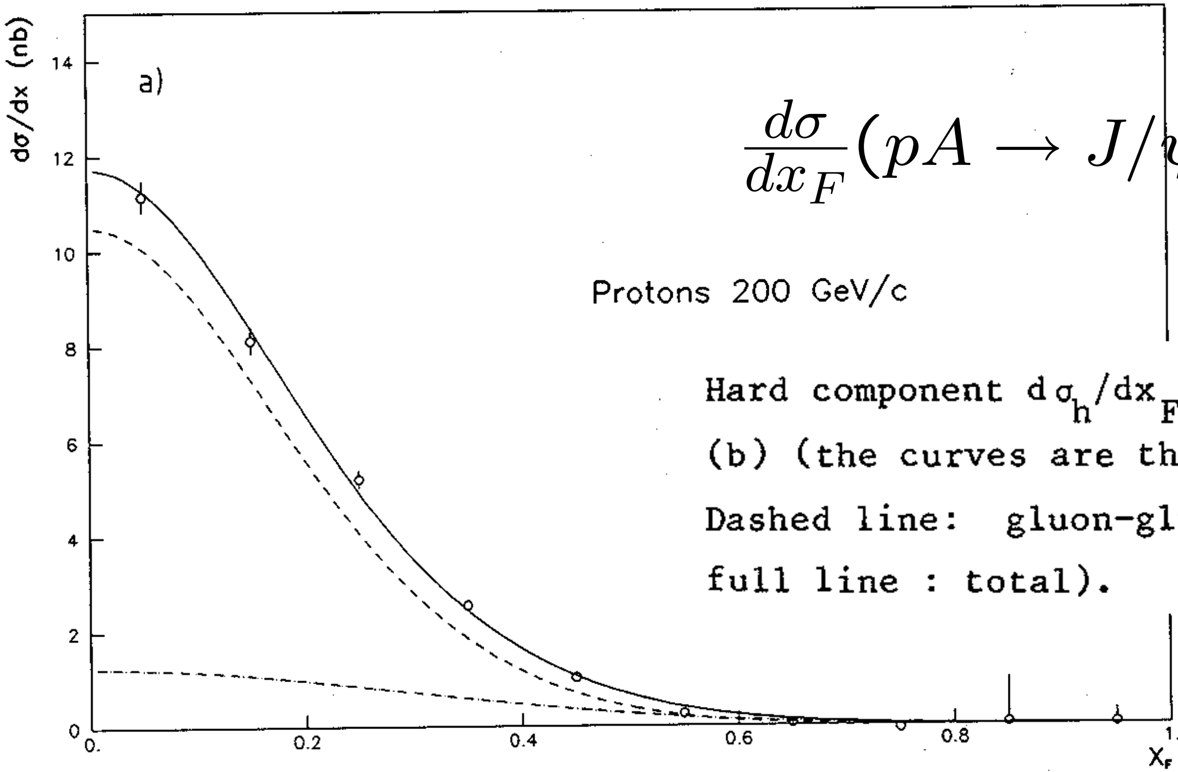
Color-Opaque IC Fock state interacts on nuclear front surface

Kopeliovich, Schmidt, Soffer, sjb

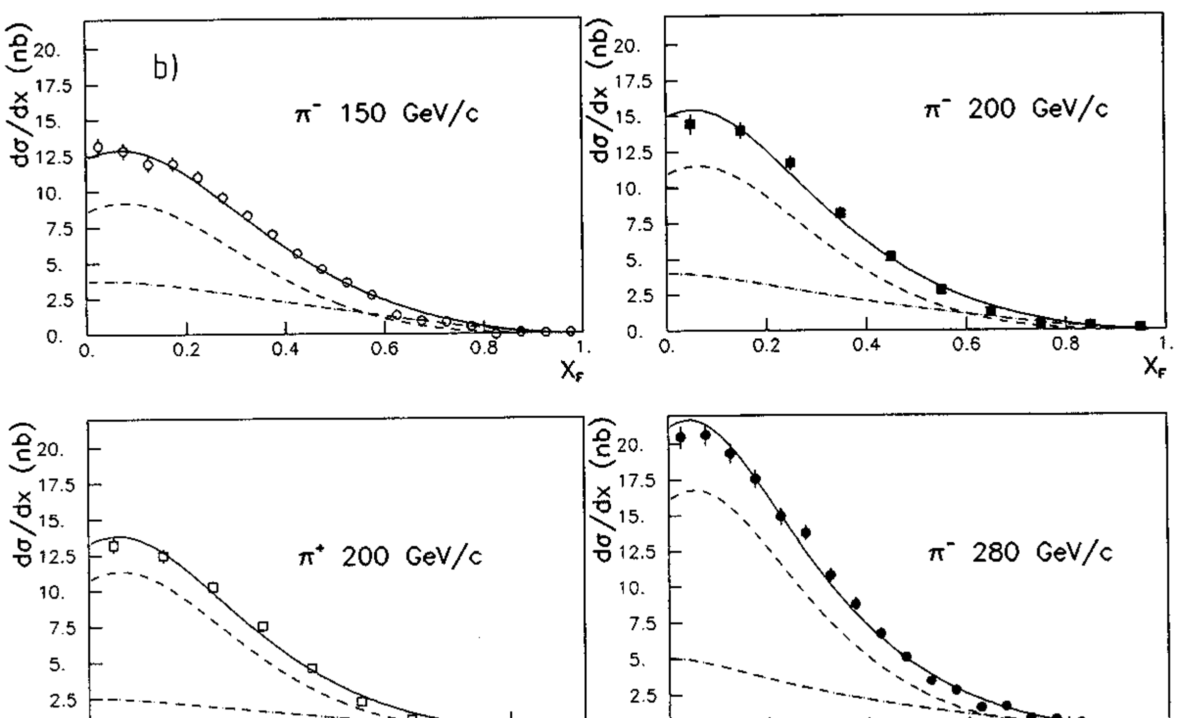


$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$

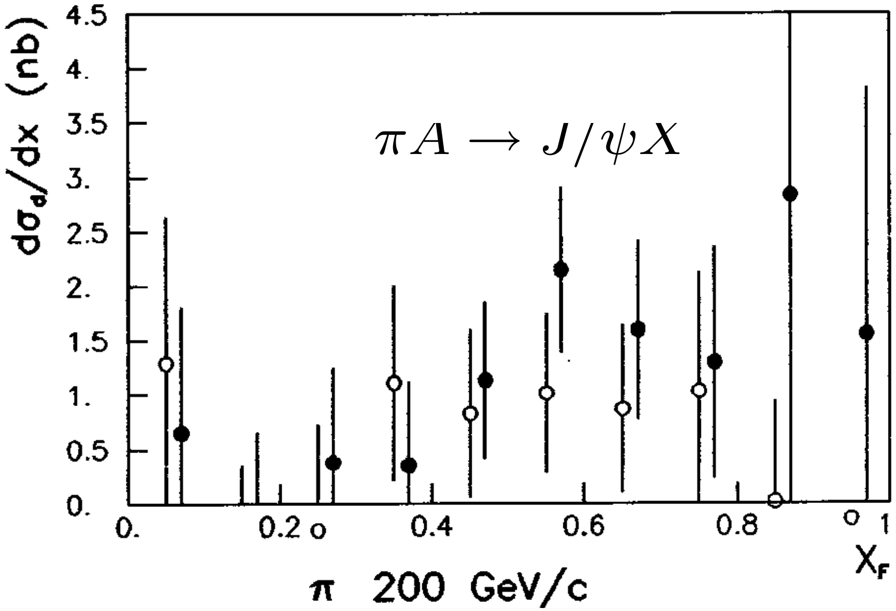
$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^1 \frac{d\sigma_1}{dx_F} + A^{2/3}\frac{d\sigma_{2/3}}{dx_F}$$



Hard component $d\sigma_h/dx_F$ for incident protons (a) and pions (b) (the curves are the result of the fit described in the text. Dashed line: gluon-gluon fusion; dash-dotted line : $q\bar{q}$ fusion; full line : total).

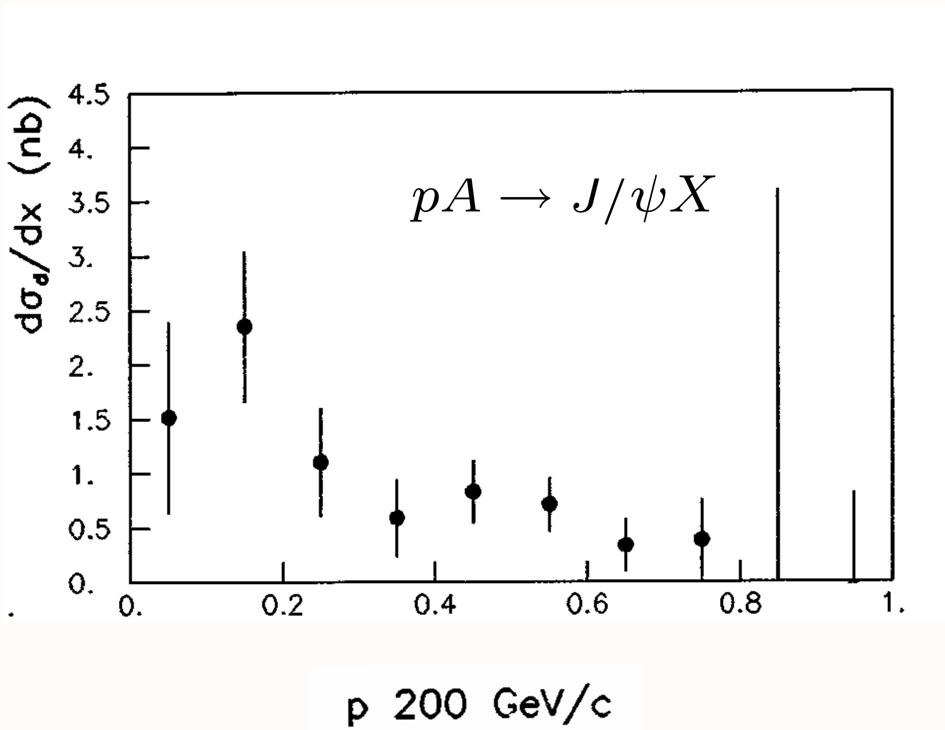


A^1 component consistent with sum of gg and $\bar{q}q$ fusion



J. Badier et al, NA3

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

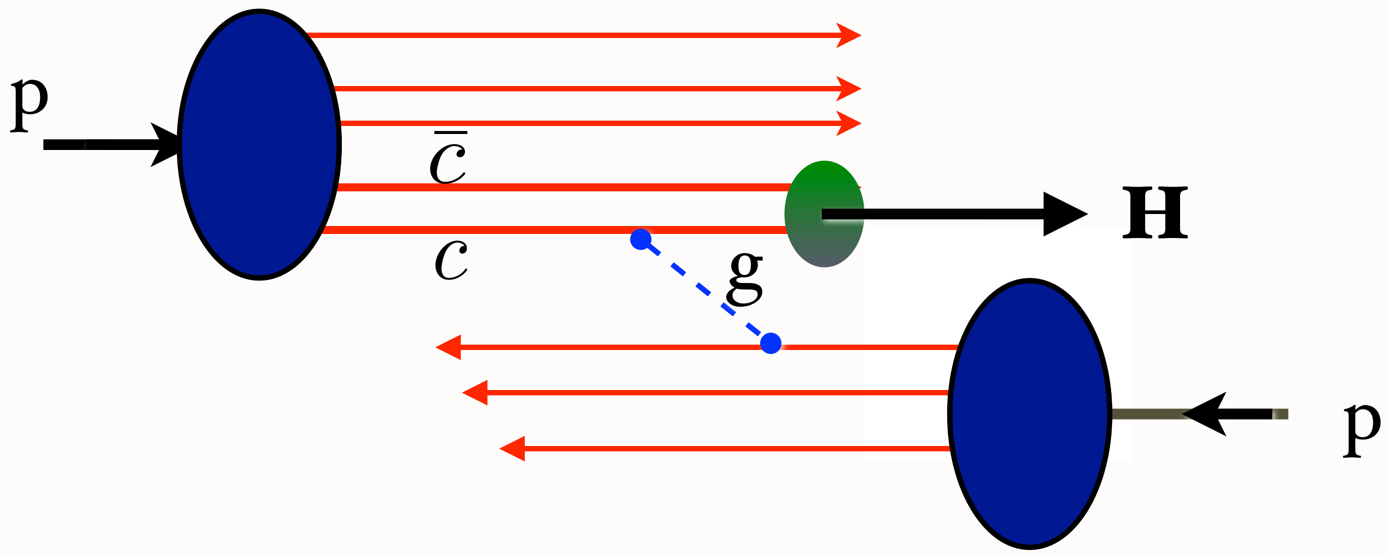


$A^{2/3}$ contribution at high x_F!

Consistent with color -octet intrinsic charm!

Energy loss effects?: Check $\gamma^* A \to J/\psi X$

Intrinsic Charm Mechanism for Inclusive High-X_F Higgs Production



$$pp \to H X$$

Goldhaber, Soffer, Kopeliovich, Schmidt, sjb

Also: intrinsic bottom, top

Higgs can have 80% of Proton Momentum!

New search strategy for Higgs

JLab 12 GeV: An Exotic Charm Factory!

$$\gamma^* p \to J/\psi + p \text{ threshold}$$
$$\text{at } \sqrt{s} \simeq 4 \text{ GeV}, \; E^{\gamma^*}_{\rm lab} \simeq 7.5 \text{ GeV}.$$

Produce $[J/\psi + p]$ bound state

$$|uudc\bar{c} >$$

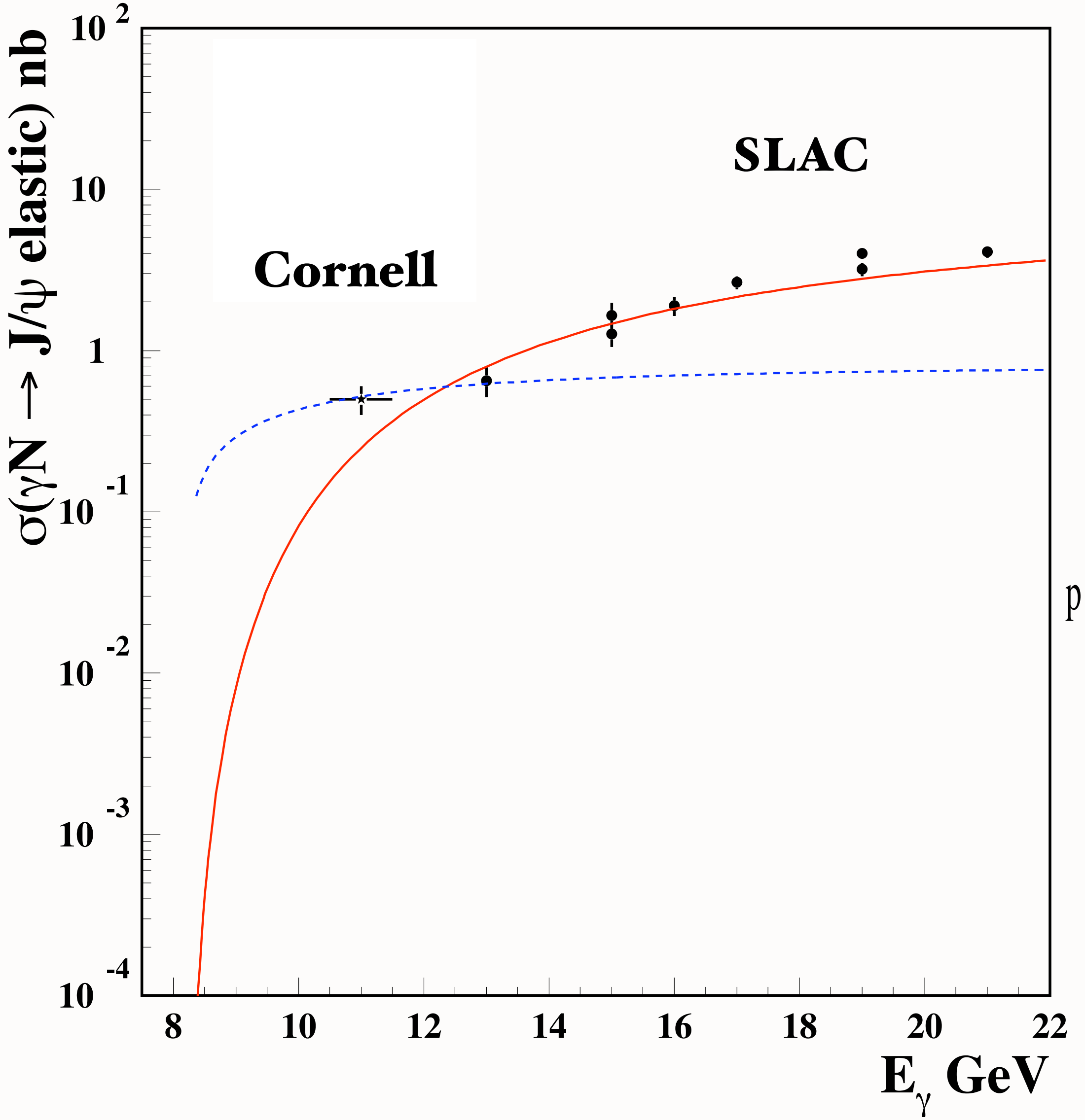
$$\gamma^* d \to J/\psi + d \text{ threshold}$$
$$\text{at } \sqrt{s} \simeq 5 \text{ GeV}, \; E^{\gamma^*}_{\rm lab} \simeq 6 \text{ GeV}.$$

Produce $[J/\psi + d]$ nuclear-bound quarkonium state

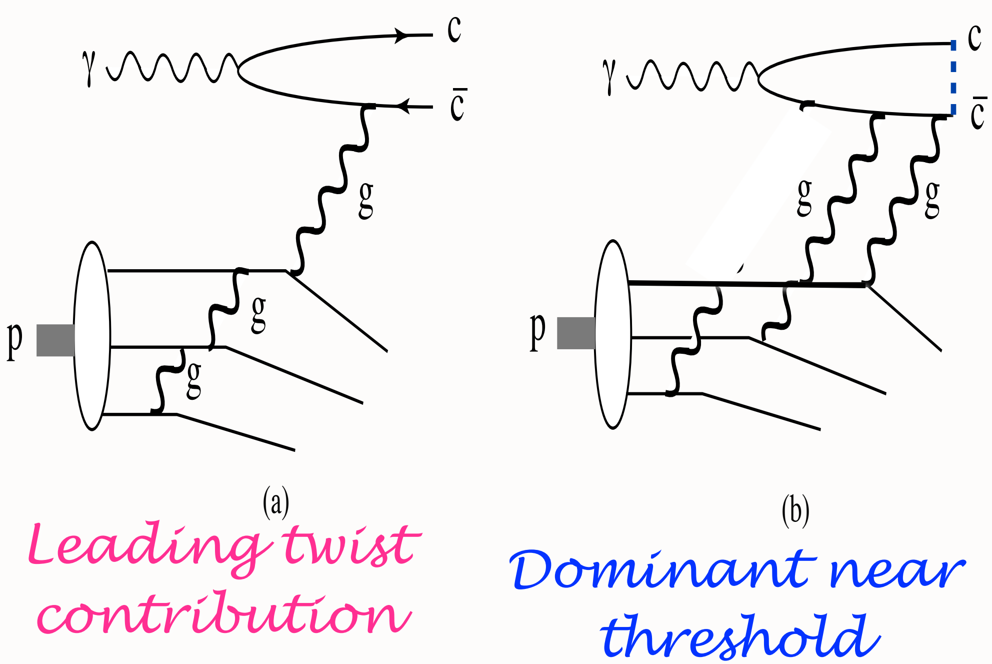
$$|uudduc\bar{c} >$$

$$\gamma p \to J/\psi p$$

Chudakov, Hoyer, Laget, sjb



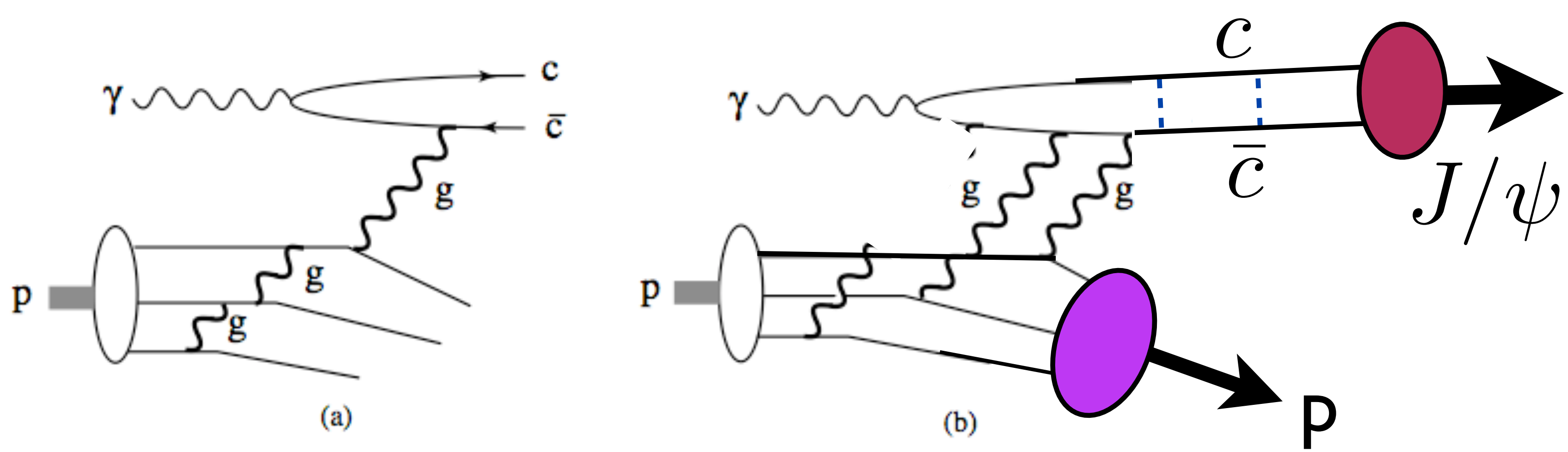
cross section: 1 nb



Phase space factor β cancelled by gluonic final-state interactions

Sommerfeld-Schwinger-Sakharov Effect

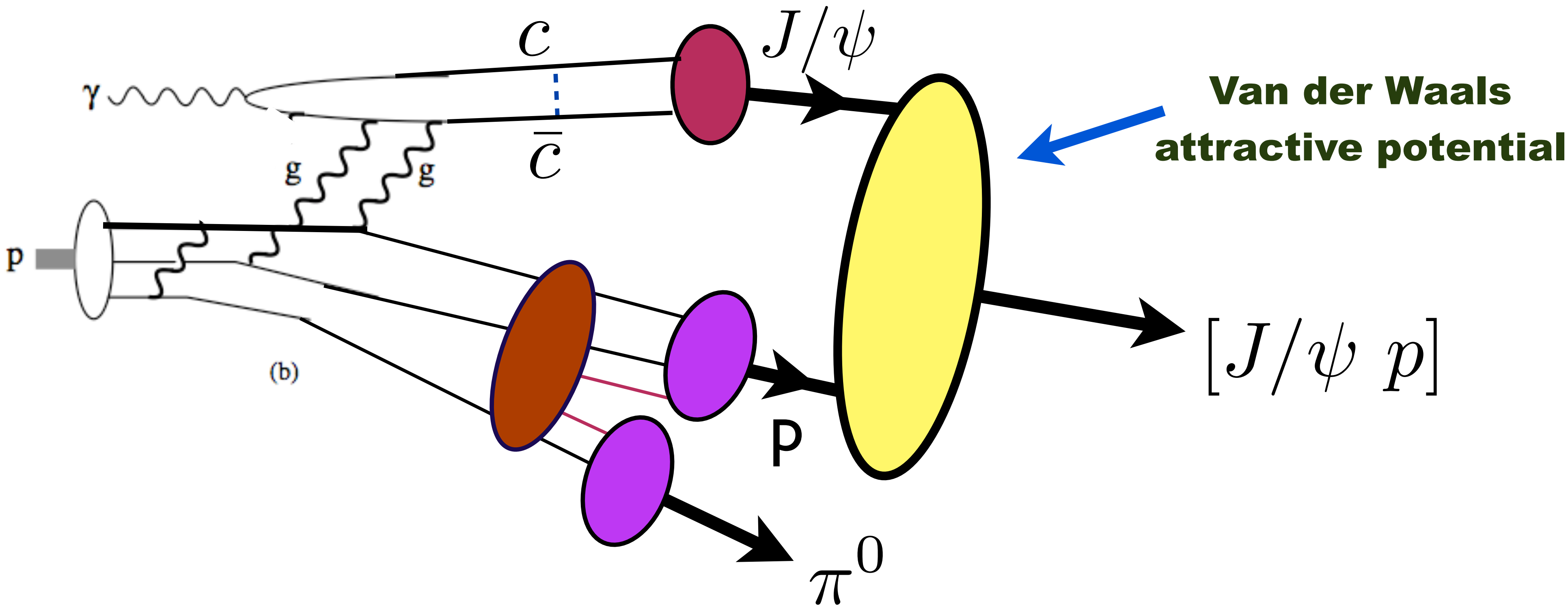
Charmonium Production at Threshold



$$\gamma\ p \rightarrow J/\psi\ p$$

- **Each gluon transfers energy $m_c/3$**
- **Compact proton size $1/m_c$**
- **Equivalent to intrinsic charm**
- **SSS final state corrections enhance rate at small relative velocity**
- **color\`singlet coalescence** $c\bar{c} \rightarrow J/\psi$

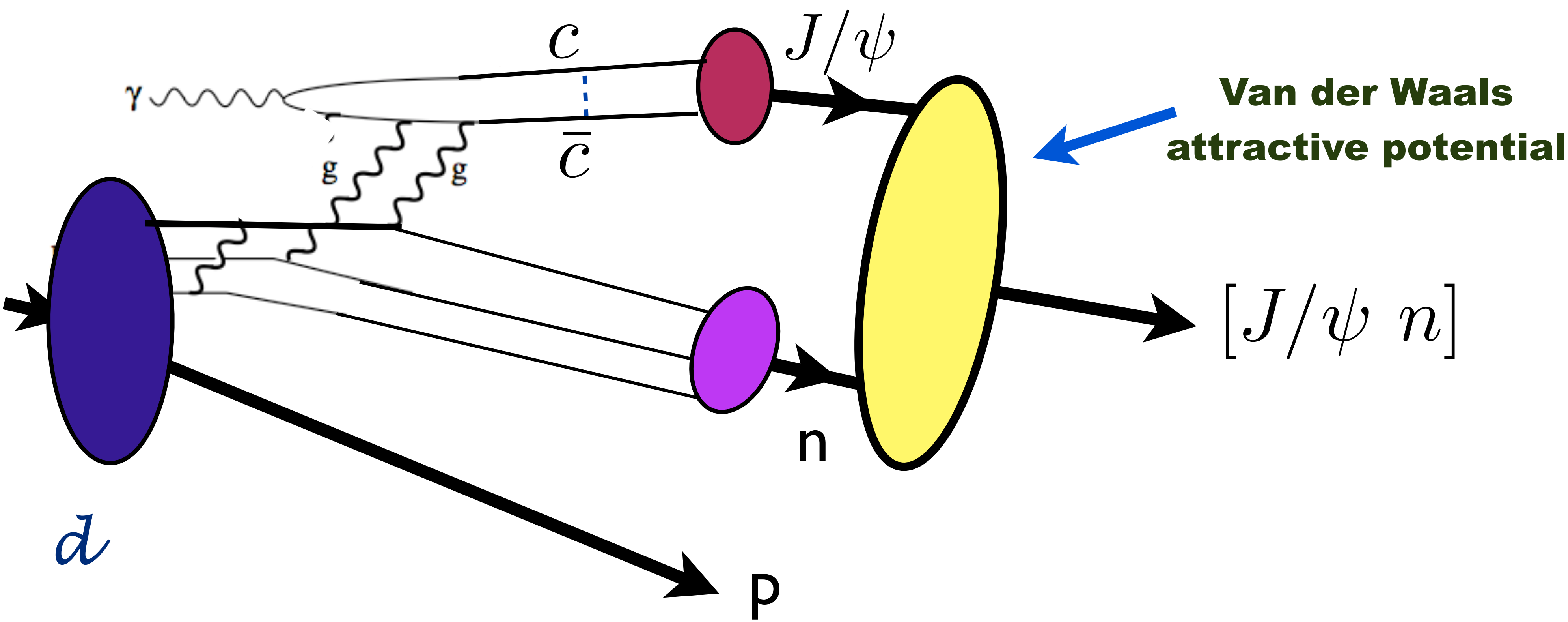
Charmonium Production at Threshold



$$\gamma\ p \rightarrow [J/\psi\ p]\ \pi^0 \qquad \gamma\ p \rightarrow [J/\psi\ n]\ \pi^+$$

Form proton-charmonium bound state! $|uudc\bar{c}>$

Charmonium Production at Threshold

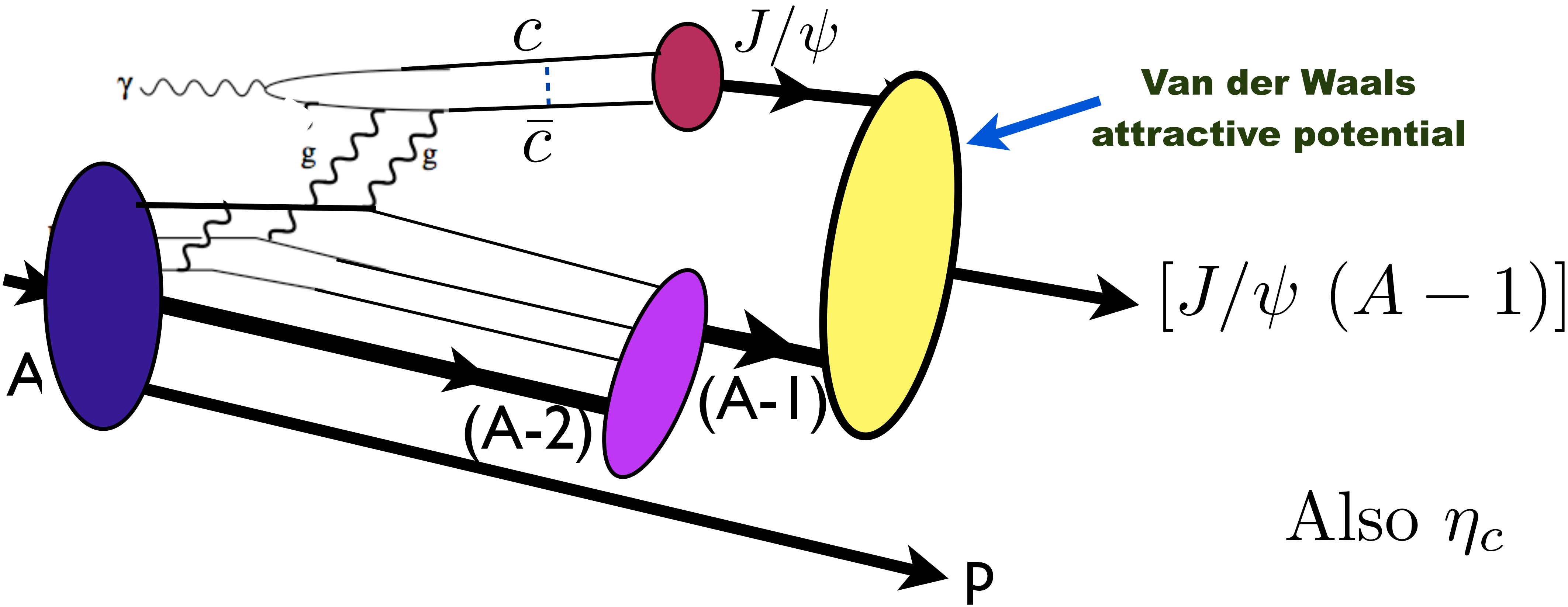


$$\gamma\ d \to [J/\psi\ n]\ p$$

$$\gamma\ d \to [J/\psi\ p]\ n$$

Form nucleon-charmonium bound state! $|uudc\bar{c}>$

Charmonium Production at Threshold



Also η_c

$$\gamma\ A \to [J/\psi\ (A-1)]\ p$$

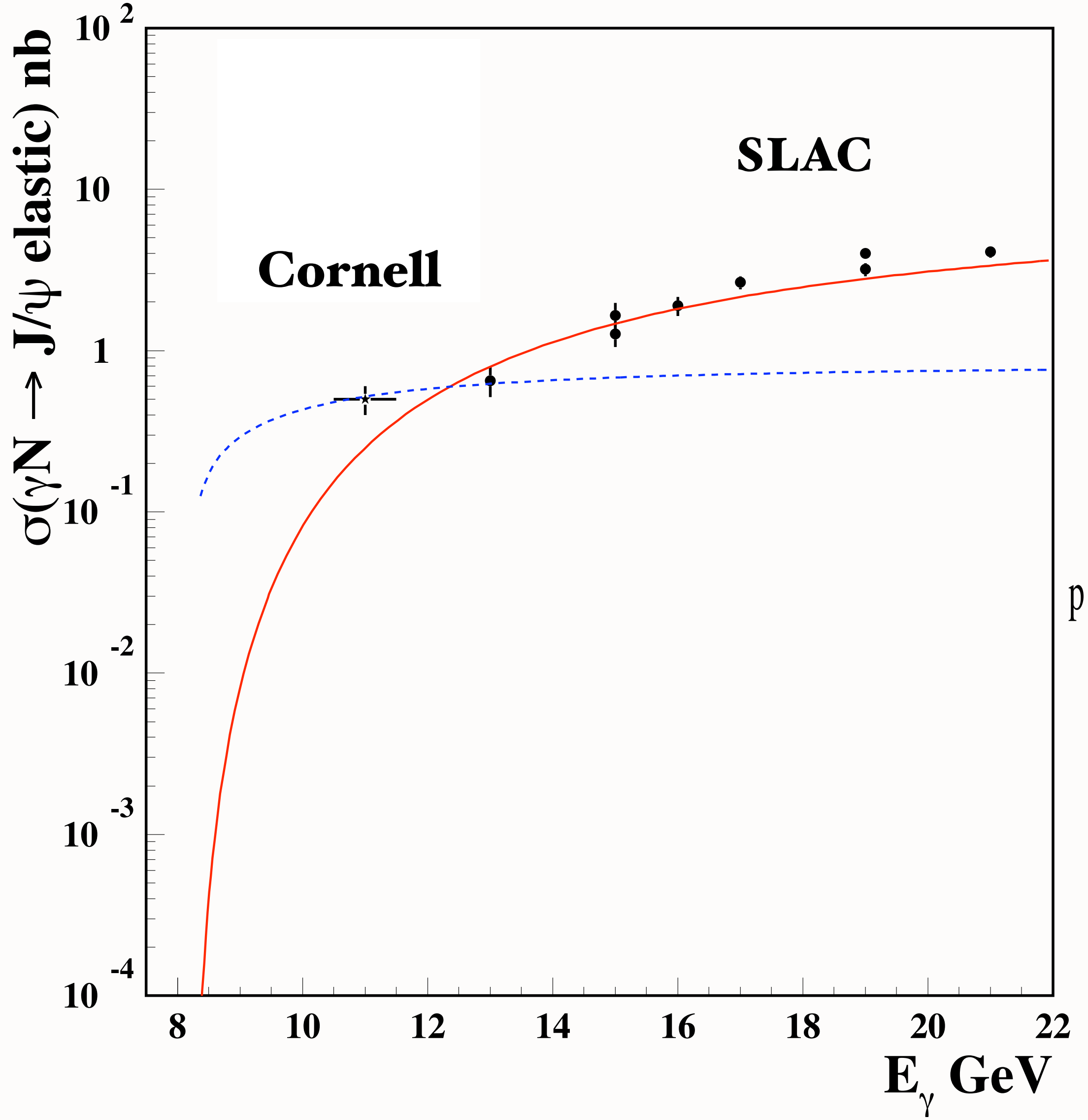
Form nuclear bound-charmonium bound state!

JLab 12 GeV: An Exotic Charm Factory!

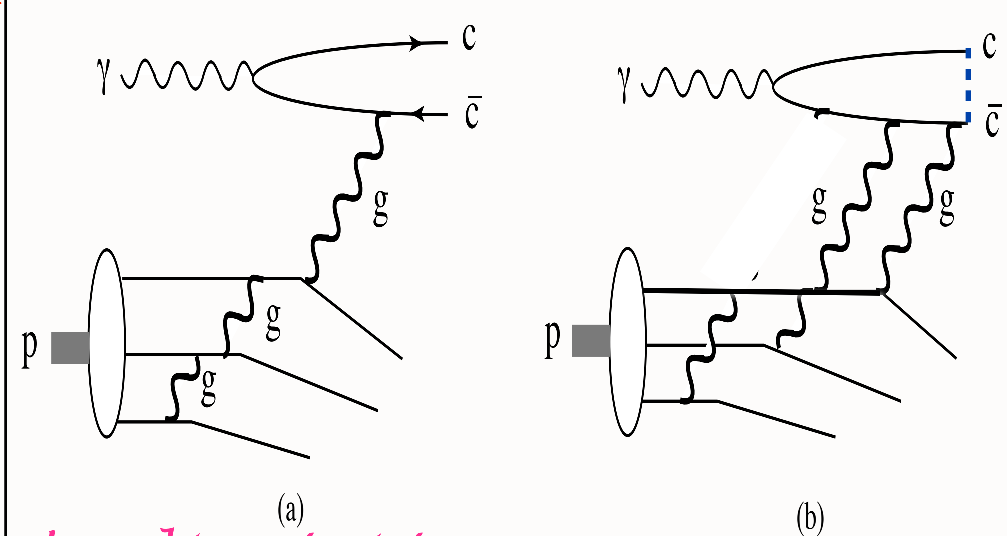
- **Charm quarks at high x -- allows charm states to be produced with minimal energy**
- **Charm produced at low velocities in the target -- the target rapidity domain** $x_F \sim -1$
- **Charm at threshold -- maximal domain for producing exotic states containing charm quarks**
- **Attractive QCD Van der Waals interaction -- "nuclear-bound quarkonium"**
  Miller, sjb; de Teramond,sjb
- **Dramatic Spin Correlations in the threshold Domain** σ_L vs. σ_T, A_{NN}
- **Strong SSS Threshold Enhancement**

$$\gamma p \to J/\psi p$$

Chudakov, Hoyer, Laget, sjb



cross section: 1 nb



Leading twist contribution

Dominant near threshold

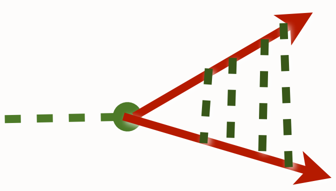
Phase space factor β cancelled by gluonic final-state interactions

Also: Dramatic Spin Effects Possible at Threshold!

Coulomb Enhancement of Pair Production at Threshold

$$\sigma \longrightarrow \sigma S(\beta)$$

$$\beta = \sqrt{1 - \frac{4m_\ell^2}{s}}$$



$$X(\beta) = \frac{\pi\alpha\sqrt{1-\beta^2}}{\beta}$$

$$S(\beta) = \frac{X(\beta)}{1 - e^{-X(\beta)}}$$

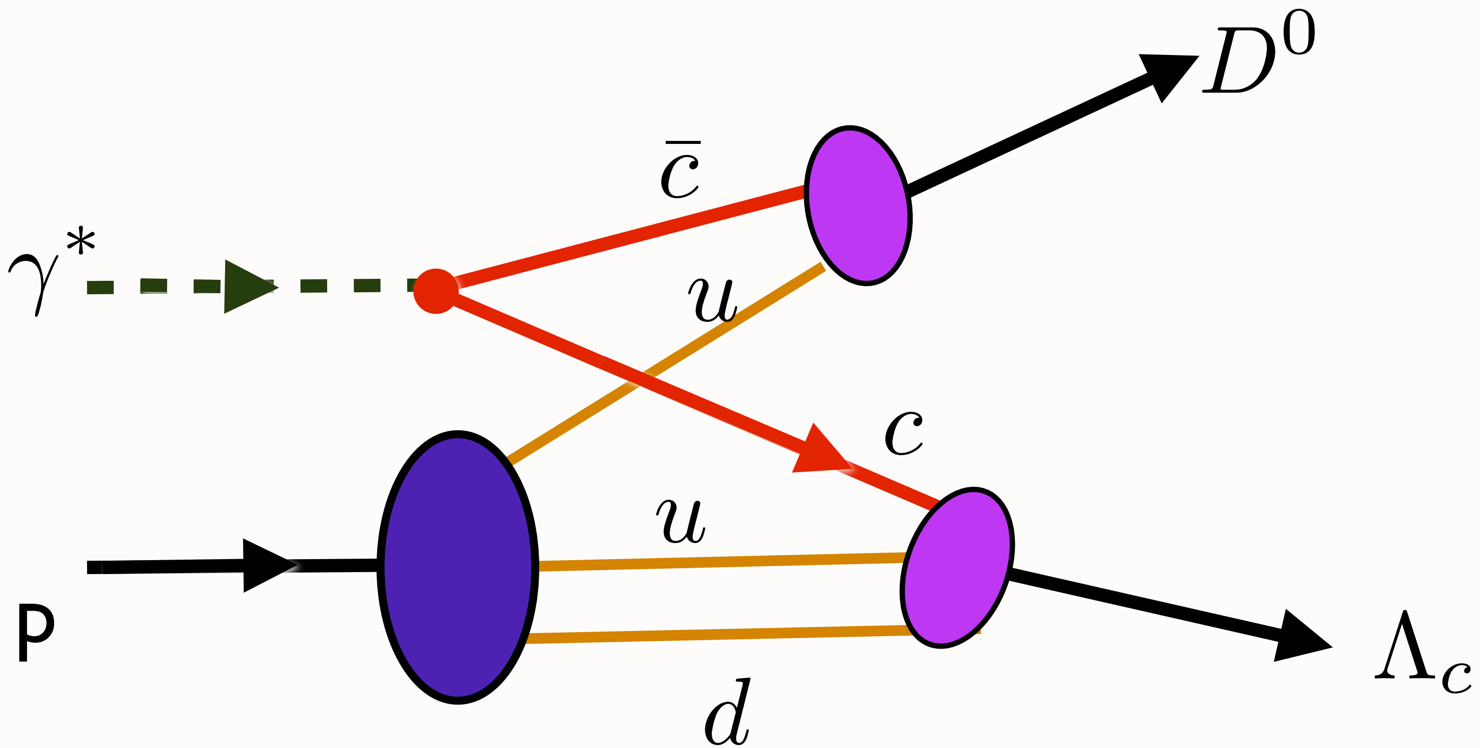
Sommerfeld-Schwinger-Sakharov Effect

Bjorken: Analytical Connection to Rydberg Levels below Threshold

$$QCD : \pi\alpha \rightarrow \frac{4}{3}\alpha_s(\beta^2 s)$$

Kühn, Hoang, sjb

Open Charm Production at Threshold

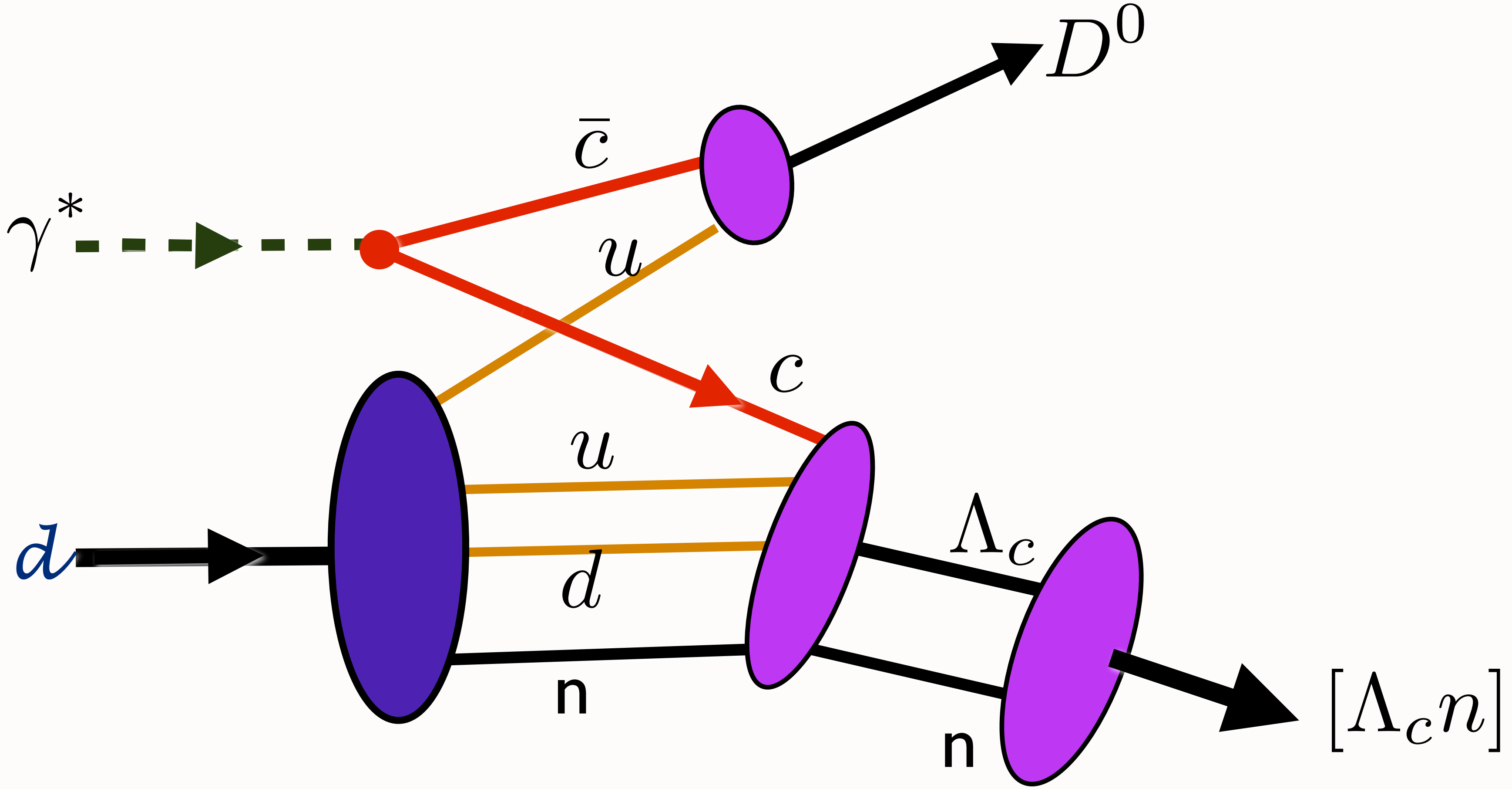


$$\gamma^* p \to \overline{D}^0(\bar{c}u)\Lambda_c(cud)$$

c- and u- quark interchange

Open Charm Production at Threshold

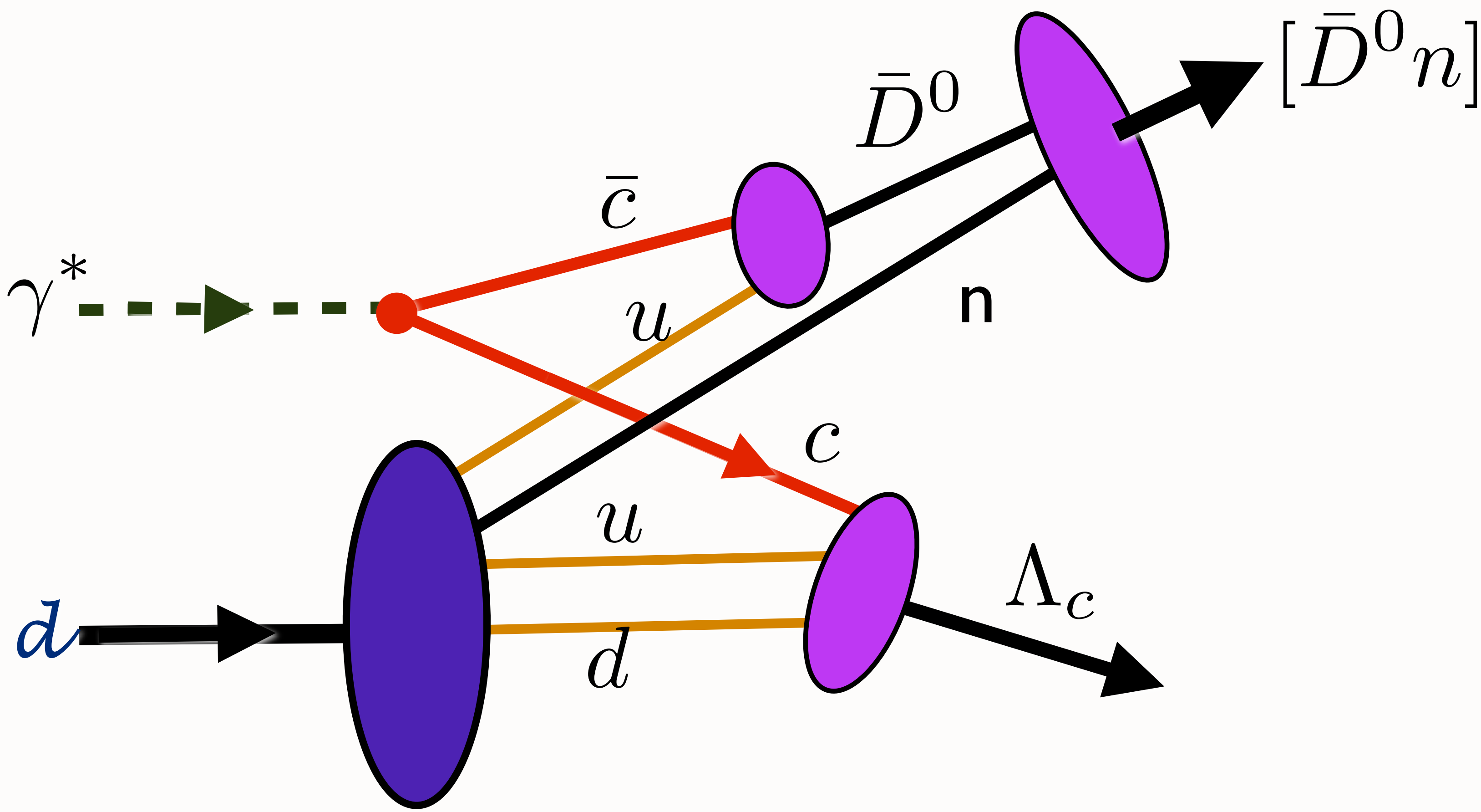
Nuclear binding at low relative velocity



$$\gamma^* d \to \overline{D}^0(\bar{c}u)[\Lambda_c n](cududd)$$

Possible charmed B= 2 nucleus

Open Charm Production at Threshold



$$\gamma^* d \to \Lambda_c + [\overline{D}^0(\bar{c}u)n](\bar{c}uudd)$$

Possible charmed pentaquark formed at low relative velocity

JLab 12 GeV: An Exotic Charm Factory!

Electroproduce open charm at threshold

$$\gamma^* p \to D^0(u\bar{c})\Lambda_c(udc)$$

Use deuteron or light nuclear target

$$\gamma^* d \to D + [\Lambda_c n]$$

New baryonic state

$$\gamma^* d \to \Lambda_c + [D^0 n]$$

Pentaquark

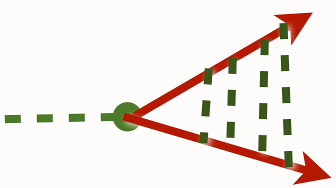
Binding at threshold: covalent bonds from quark interchange

Also: Dramatic Spin Effects Possible at Threshold!

Coulomb Enhancement of Pair Production at Threshold

$$\sigma \longrightarrow \sigma S(\beta)$$

$$\beta = \sqrt{1 - \frac{4m_\ell^2}{s}}$$



$$X(\beta) = \frac{\pi\alpha\sqrt{1-\beta^2}}{\beta}$$

$$S(\beta) = \frac{X(\beta)}{1 - e^{-X(\beta)}}$$

Sommerfeld-Schwinger-Sakharov Effect

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Kühn, Hoang, sjb

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- **Attractive QCD Van der Waals interaction -- "nuclear-bound quarkonium"**
- **Dramatic Spin Correlations in the threshold Domain**
- **Strong SSS Threshold Enhancement**

Why is IQ Important for Flavor Physics?

- **New perspective on fundamental nonperturbative hadron structure**
- **Charm structure function at high x**
- **Dominates high x_F charm and charmonium production**
- **Hadroproduction of new heavy quark states such as ccu, ccd, bcc, bbb, at high x_F**
- **Intrinsic charm -- long distance contribution to penguin mechanisms for weak decay** *Gardner, sjb*
- $J/\psi \rightarrow \rho\pi$ ***BES* puzzle explained** *Karliner , sjb*
- **Novel Nuclear Effects from color structure of IC, Heavy Ion Collisions**
- **New mechanisms for high x_F Higgs hadroproduction**
- **Dynamics of b production: LHCb** *New Multi-lepton Signals*
- **AFTER: Fixed target program at LHC: produce bbb states**

- 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)

BES

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

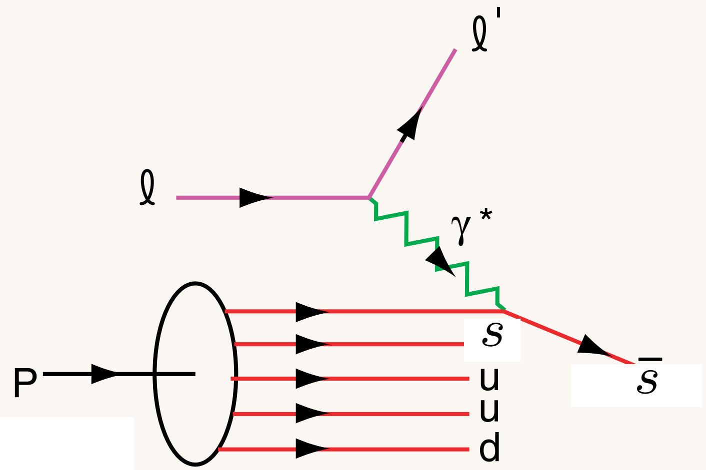
Higgs production at x_F = 0.8

Use extreme caution when using $\gamma g \to c\bar{c}$ or $gg \to \bar{c}c$ to tag gluon dynamics

Measure strangeness distribution in Semi-Inclusive DIS at JLab

$$\text{Is } s(x) = \bar{s}(x)?$$

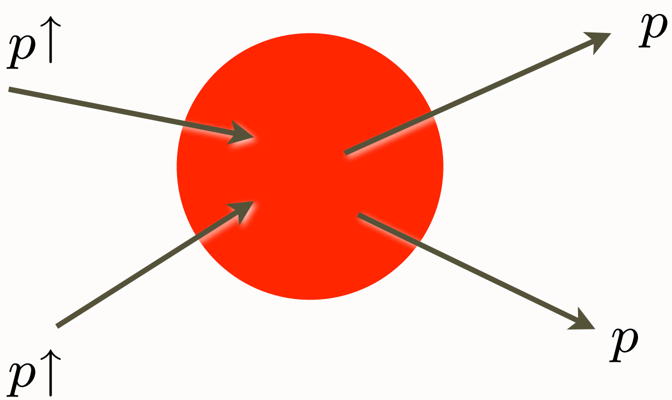
- **Non-symmetric strange and antistrange sea?**
- **Non-perturbative physics; e.g** $|uuds\bar{s}> \simeq |\Lambda(uds)K^+(\bar{s}u)>$
- **Crucial for interpreting NuTeV anomaly** **B. Q. Ma, sjb**



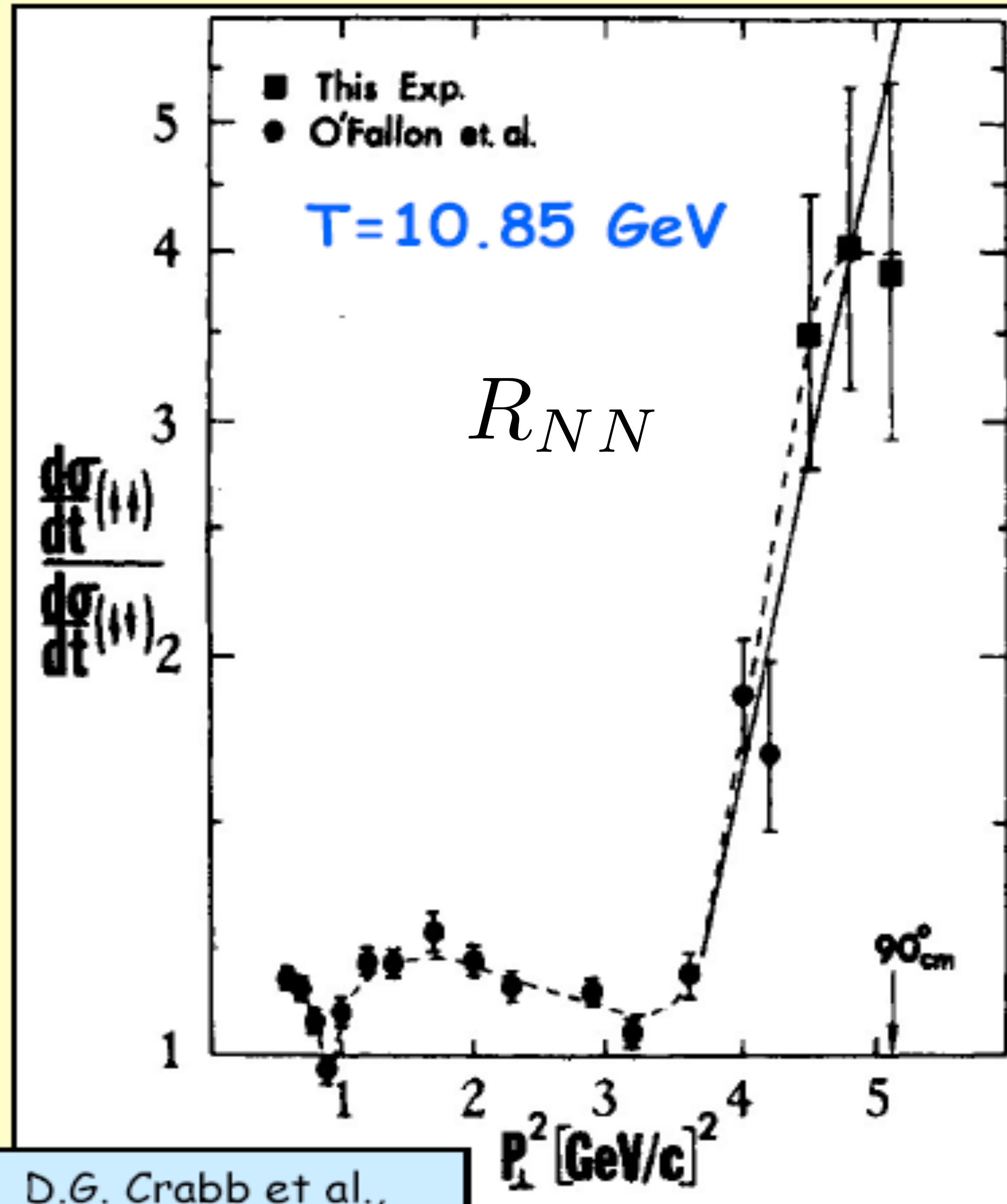
Tag struck quark flavor in semi-inclusive DIS $ep \to e'K^+X$

Krisch, Crabb, et al

Unexpected spin-spin correlation in pp elastic scattering



polarizations normal to scattering plane



D.G. Crabb et al., PRL 41, 1257 (1978)

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

"Exclusive Transversity"

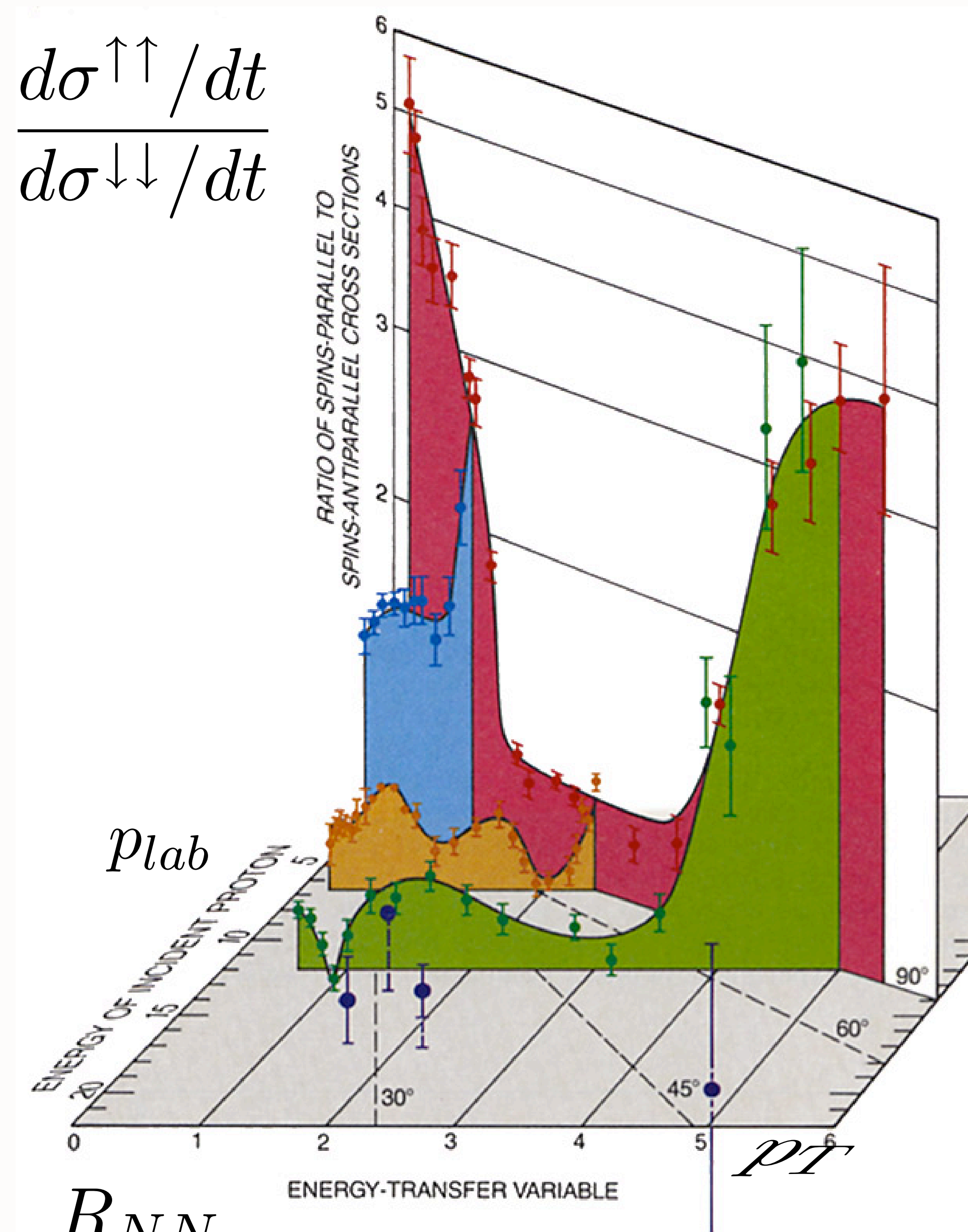
Spin-dependence at large-P_T ($90°_{cm}$):

Hard scattering takes place only with spins ↑↑

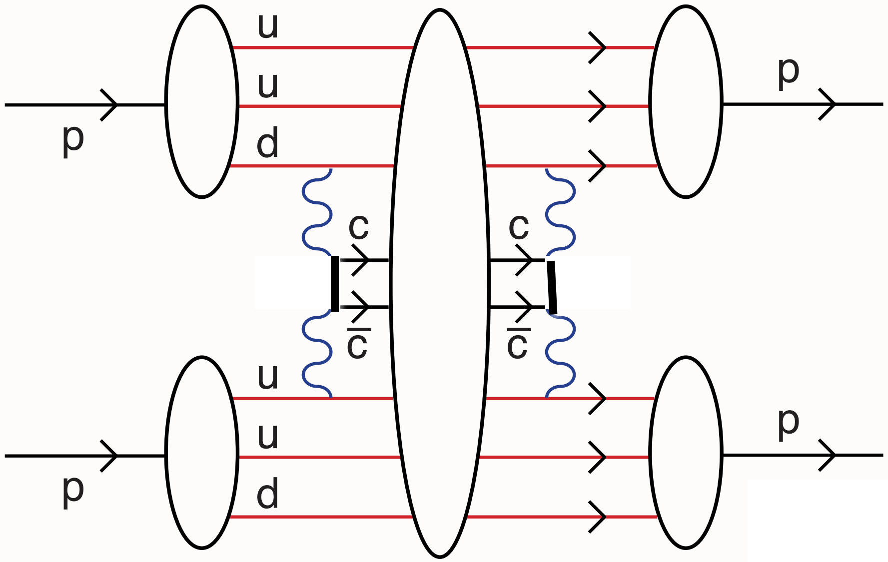
Charm and Strangeness Thresholds

> *Heppelmann et al: Quenching of Color Transparency*

> *B=2 Octoquark Resonances?*



$$A_{nn} = 1!$$



QCD Schwinger-Sommerfeld Enhancement at Heavy Quark Threshold

Hebecker, Kuhn, sjb

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

Production of $uud\,\bar{c}\,c\,uud$ octoquark resonance

J=L=S=1, C=-, P=- state

8 quarks in S-wave: odd parity

$\sigma(pp \to c\bar{c}X) \simeq 1\ \mu b$ at threshold $\quad\quad \sigma(\gamma p \to c\bar{c}X) \simeq 1\ nb$ at threshold

- 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

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

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

Dramatic Spin Effects Possible at Threshold!

$$H_{QED}$$

QED atoms: positronium and muonium

$$(H_0 + H_{int}) \; |\Psi > = E \; |\Psi >$$

Coupled Fock states

$$[-\frac{\Delta^2}{2m_{\rm red}} + V_{\rm eff}(\vec{S}, \vec{r})] \; \psi(\vec{r}) = E \; \psi(\vec{r})$$

Effective two-particle equation

Includes Lamb Shift, quantum corrections

$$[-\frac{1}{2m_{\rm red}}\frac{d^2}{dr^2} + \frac{1}{2m_{\rm red}}\frac{\ell(\ell+1)}{r^2} + V_{\rm eff}(r, S, \ell)] \; \psi(r) = E \; \psi(r)$$

Spherical Basis r, θ, ϕ

$$V_{eff} \to V_C(r) = -\frac{\alpha}{r}$$

Coulomb potential

Bohr Spectrum

Semiclassical first approximation to QED

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

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

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

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

Azimuthal Basis ζ, ϕ

$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L + S - 1)$$

Confining AdS/QCD potential

Semiclassical first approximation to QCD

Light-Front Schrödinger Equation

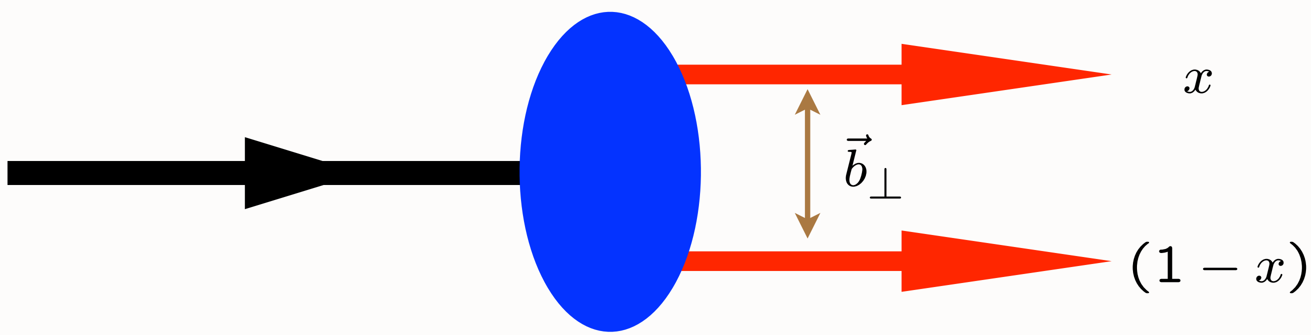
G. de Teramond, sjb

Relativistic LF single-variable radial equation for QCD & QED

Frame Independent!

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

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



where the potential $U(\zeta^2, J, L, M^2)$ represents the contributions from higher Fock states. It is also the kernel for the forward scattering amplitude $q\bar{q} \to q\bar{q}$ at $s = M^2$. It has only "proper" contributions; i.e. it has no $q\bar{q}$ intermediate state. The potential can be constructed systematically using LF time-ordered perturbation theory. Thus the exact QCD theory has the identical form as the AdS theory, but with the quantum field-theoretic corrections due to the higher Fock states giving a general form for the potential. This provides a novel way to solve nonperturbative QCD. **Complex eigenvalues for excited states n>0**

Light-Front Schrödinger Equation

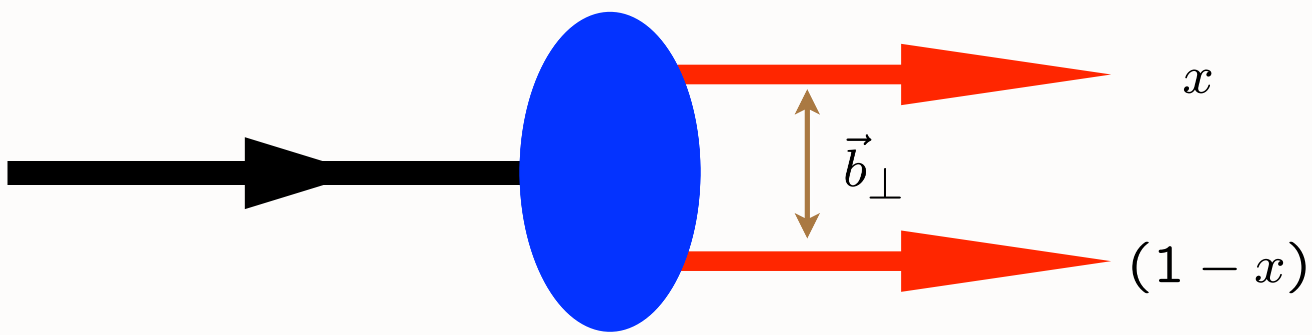
G. de Teramond, sjb

Relativistic LF single-variable radial equation for QCD & QED

Frame Independent!

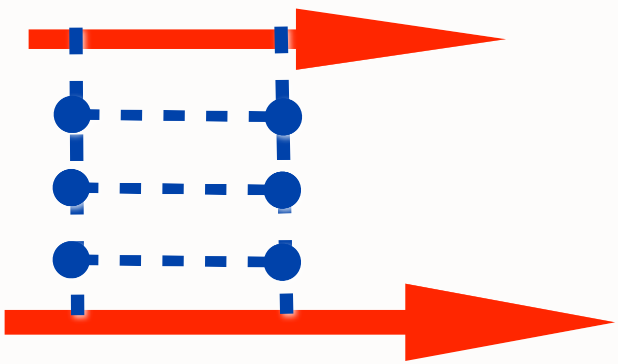
$$\left[-\frac{d^2}{d\zeta^2} + \frac{4L^2-1}{4\zeta^2} + U(\zeta^2, J, L, M^2)\right]\Psi_{J,L}(\zeta^2) = M^2\Psi_{J,L}(\zeta^2)$$

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



U is the exact QCD potential
Conjecture: 'H'-diagrams generate

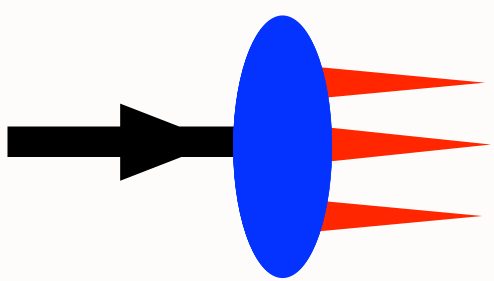
$$U(\zeta, S, L) = \kappa^2\zeta^2 + \kappa^2(L+S-1/2)$$



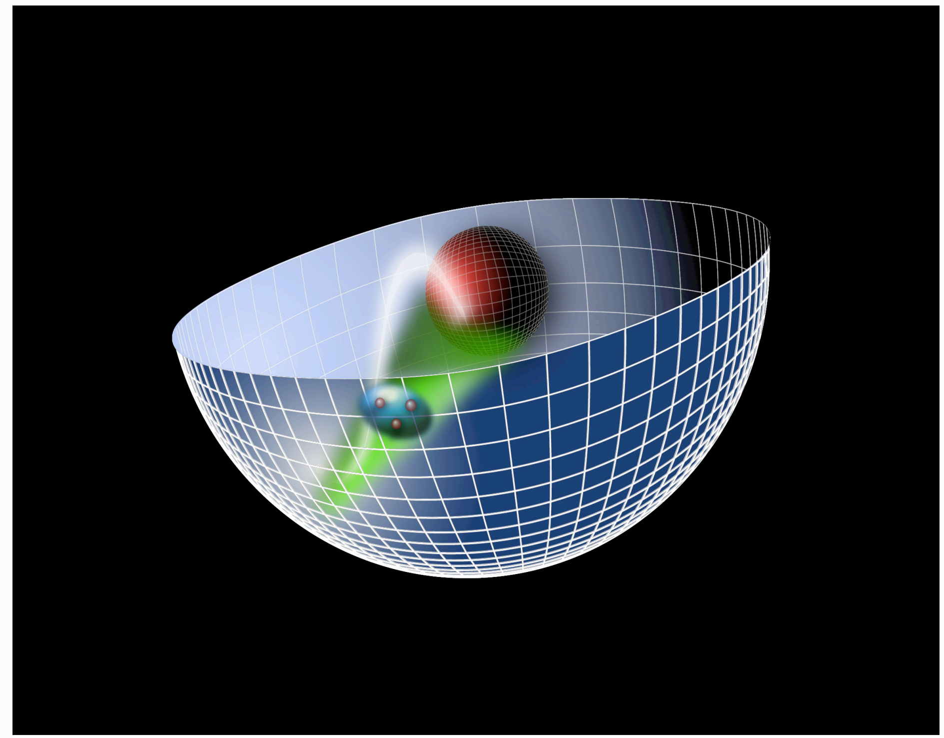
Light-Front Holography and Non-Perturbative QCD

Goal:
Use AdS/QCD duality to construct a first approximation to QCD

Hadron Spectrum
Light-Front Wavefunctions,
Running coupling in IR



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



in collaboration with
Guy de Teramond

Central problem for strongly-coupled gauge theories

4th China-US Workshop
July 16, 2012

Novel QCD Opportunities
at JLab 12 GeV and the EIC

Stan Brodsky, SLAC

$$e^{\phi(z)} = e^{+\kappa^2 z^2}$$

- de Teramond, sjb

Positive-sign dilaton

AdS Soft-Wall Schrodinger Equation for bound state of two scalar constituents:

$$\left[-\frac{d^2}{dz^2} - \frac{1-4L^2}{4z^2} + U(z)\right]\Phi(z) = \mathcal{M}^2\Phi(z)$$

$$U(z) = \kappa^4 z^2 + 2\kappa^2(L+S-1)$$

Derived from variation of Action Dilaton-Modified AdS_5

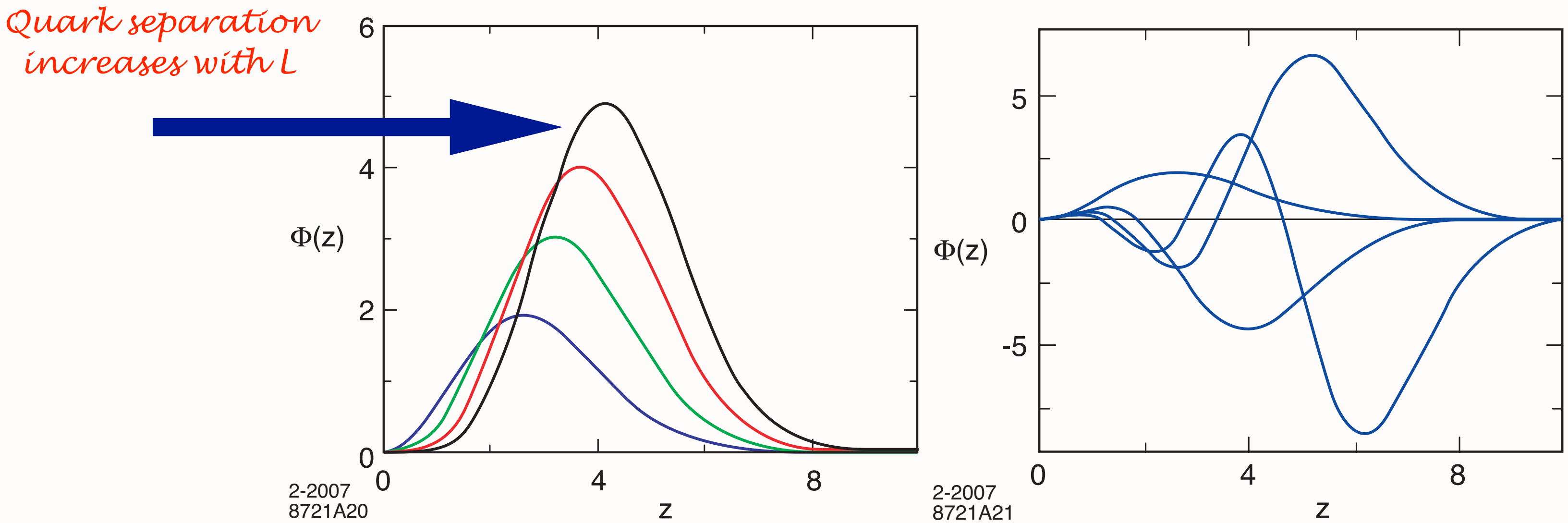
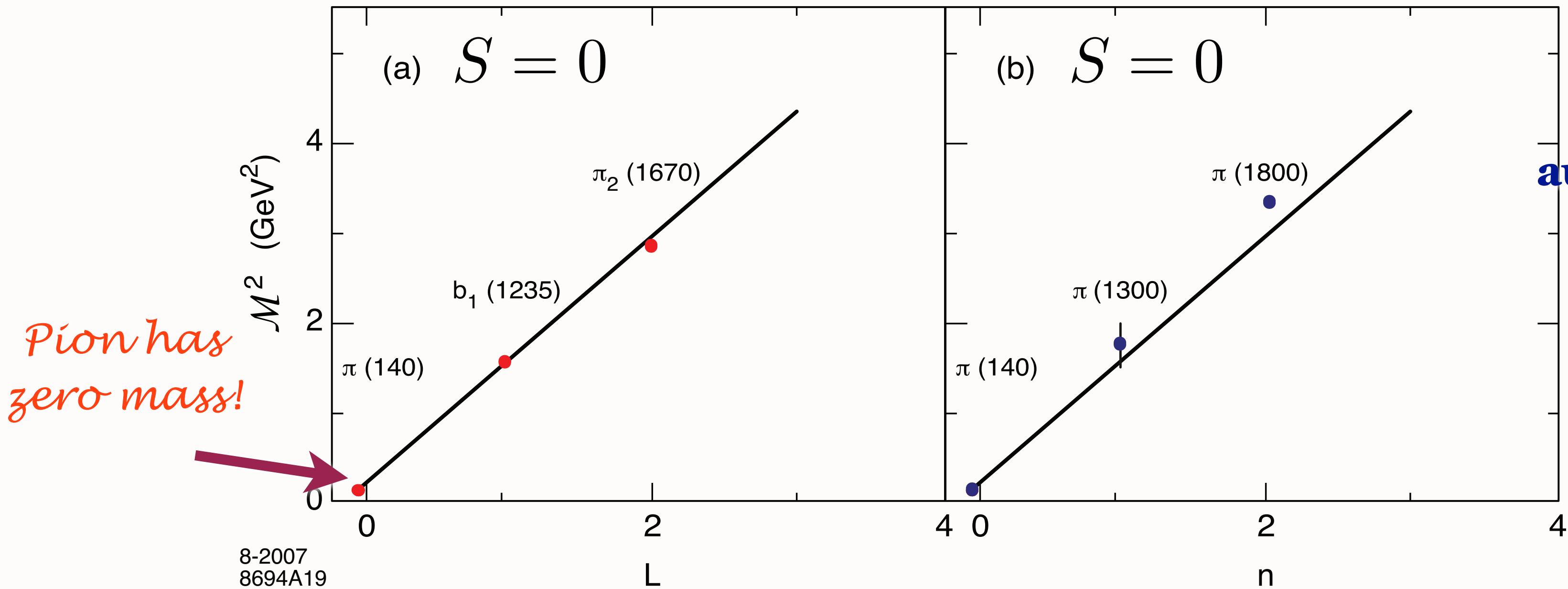


Fig: Orbital and radial AdS modes in the soft wall model for κ = 0.6 GeV .

Soft Wall Model



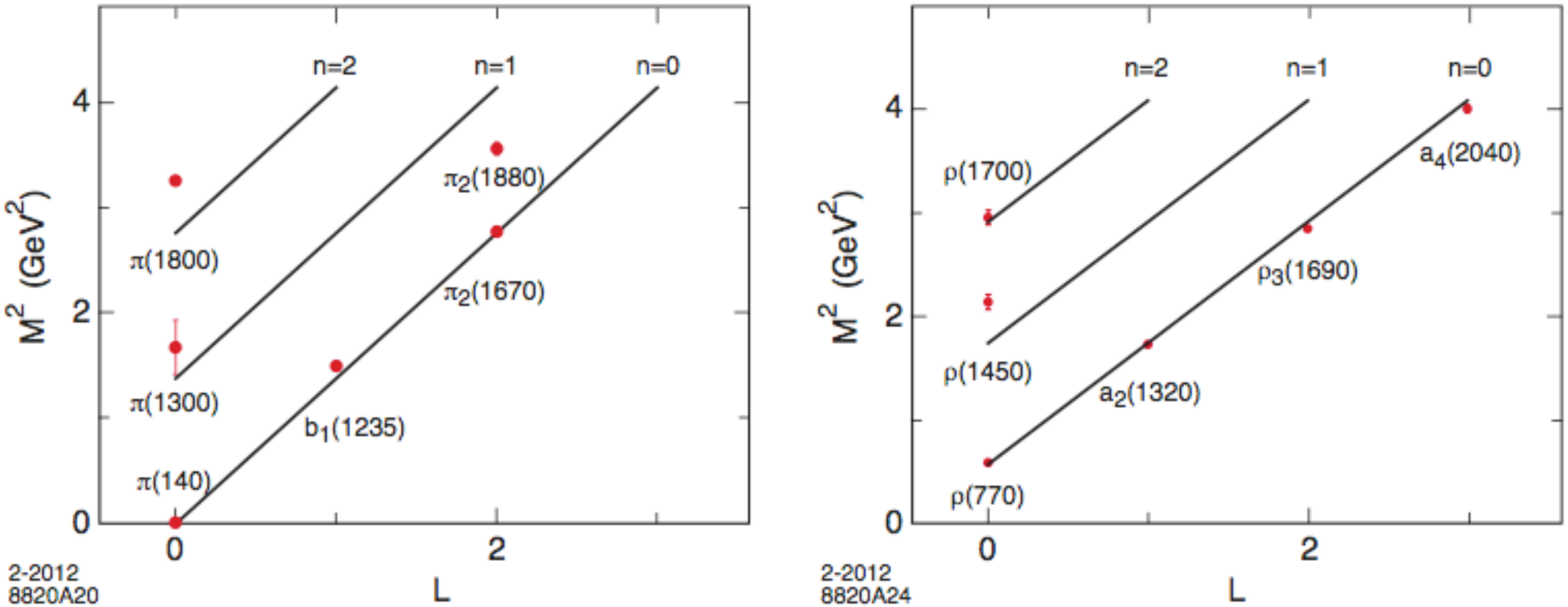
Pion mass automatically zero!

$$m_q = 0$$

Light meson orbital (a) and radial (b) spectrum for $\kappa = 0.6$ GeV.

- $J = L + S, I = 1$ meson families $\mathcal{M}^2_{n,L,S} = 4\kappa^2 \left(n + L + S/2\right)$

$4\kappa^2$ for $\Delta n = 1$
$4\kappa^2$ for $\Delta L = 1$
$2\kappa^2$ for $\Delta S = 1$



I=1 orbital and radial excitations for the π ($\kappa = 0.59$ GeV) and the ρ-meson families ($\kappa = 0.54$ GeV)

- Triplet splitting for the $I = 1, L = 1, J = 0, 1, 2$, vector meson a-states

$$\mathcal{M}_{a_2(1320)} > \mathcal{M}_{a_1(1260)} > \mathcal{M}_{a_0(980)}$$

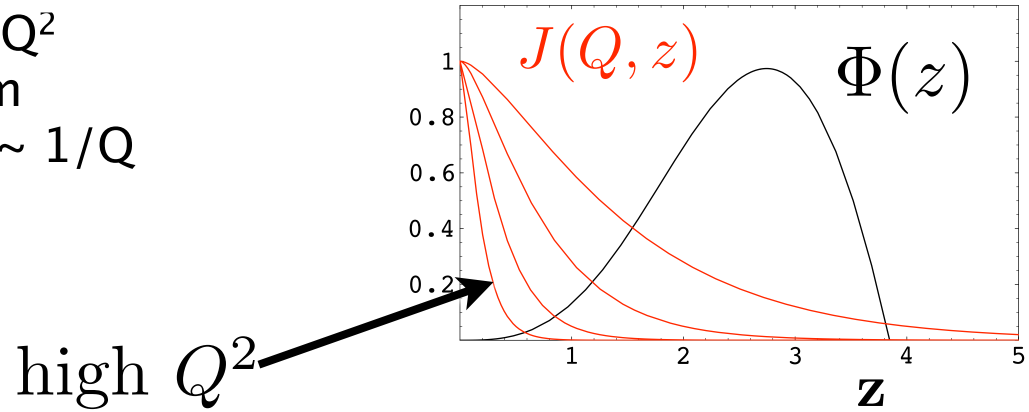
Hadron Form Factors from AdS/CFT

Propagation of external perturbation suppressed inside AdS.

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

$$F(Q^2)_{I\to F} = \int \frac{dz}{z^3}\Phi_F(z)J(Q,z)\Phi_I(z)$$

High Q^2
from
small z ~ 1/Q



Polchinski, Strassler
de Teramond, sjb

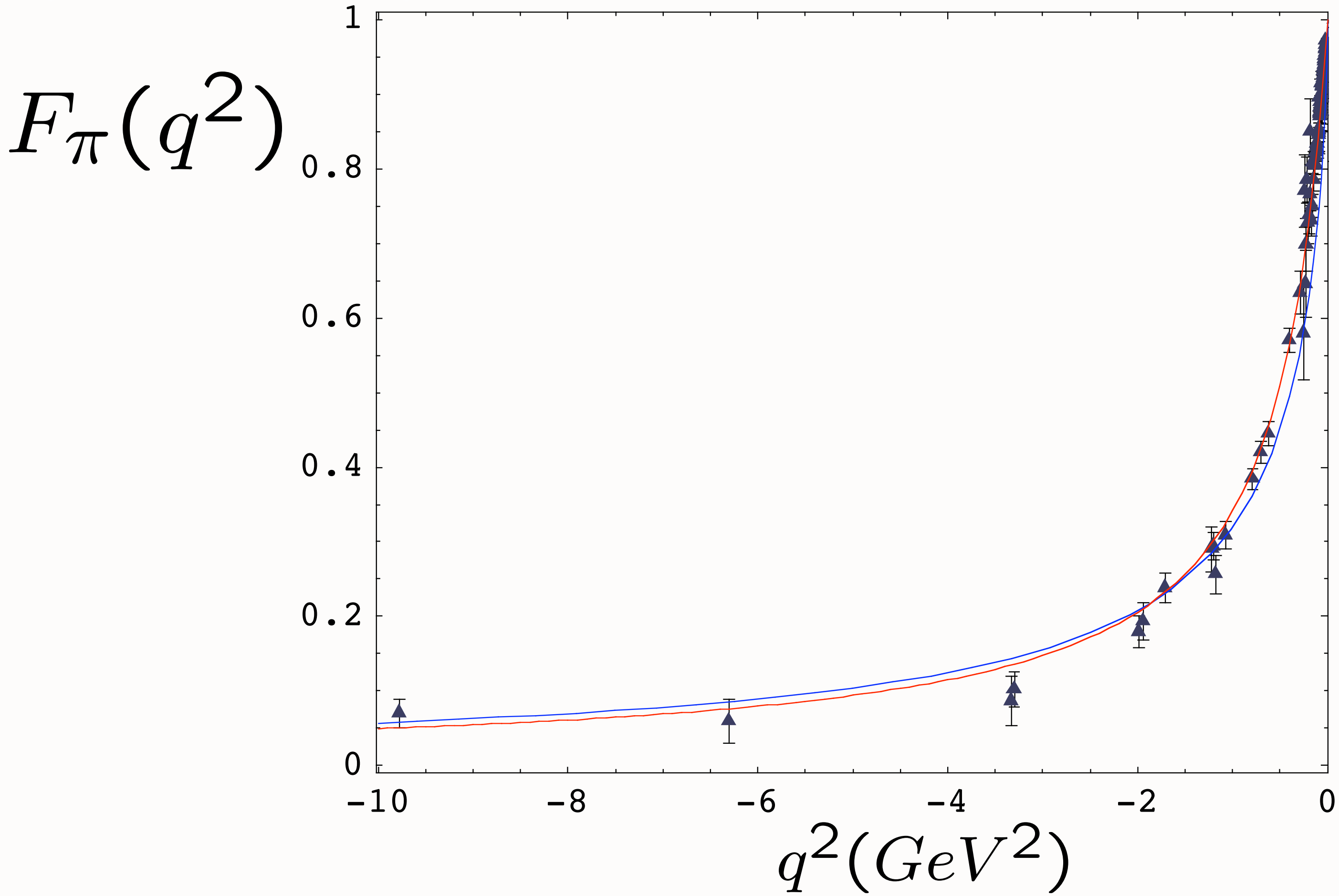
Consider a specific AdS mode $\Phi^{(n)}$ dual to an n partonic Fock state $|n\rangle$. At small z, Φ scales as $\Phi^{(n)} \sim z^{\Delta_n}$. Thus:

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

Dimensional Quark Counting Rules:
General result from
AdS/CFT and Conformal Invariance

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

Spacelike pion form factor from AdS/CFT



Data Compilation
Baldini, Kloe and Volmer

Soft Wall: Harmonic Oscillator Confinement

Hard Wall: Truncated Space Confinement

One parameter - set by pion decay constant

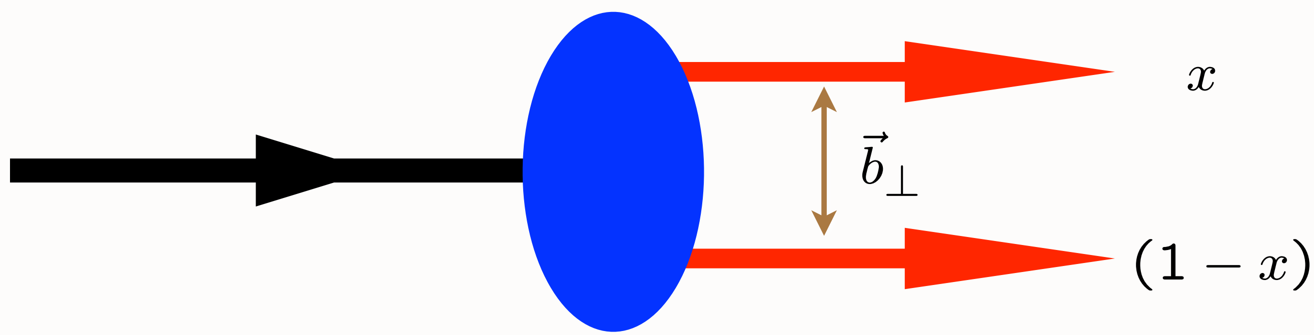
de Teramond, sjb
See also: Radyushkin

de Teramond, sjb

LF(3+1) ⟷ AdS$_5$

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

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



$$\psi(x,\zeta) = \sqrt{x(1-x)}\,\zeta^{-1/2}\phi(\zeta)$$

Light Front Holography: Unique mapping derived from equality of LF and AdS formula for EM and gravitational current matrix elements

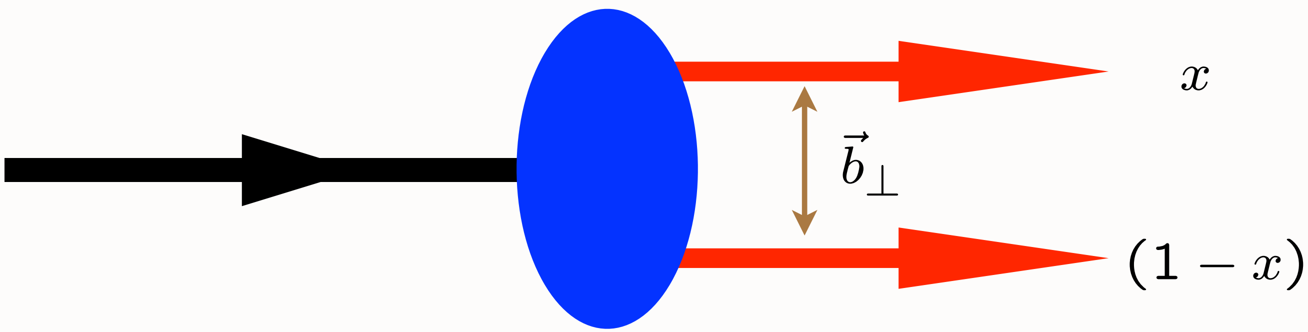
Light-Front Holography:
Map AdS/CFT to 3+1 LF Theory

Relativistic LF radial equation

Frame Independent

$$\left[-\frac{d^2}{d\zeta^2} + \frac{1-4L^2}{4\zeta^2} + U(\zeta)\right]\psi(\zeta) = \mathcal{M}^2\psi(\zeta)$$

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



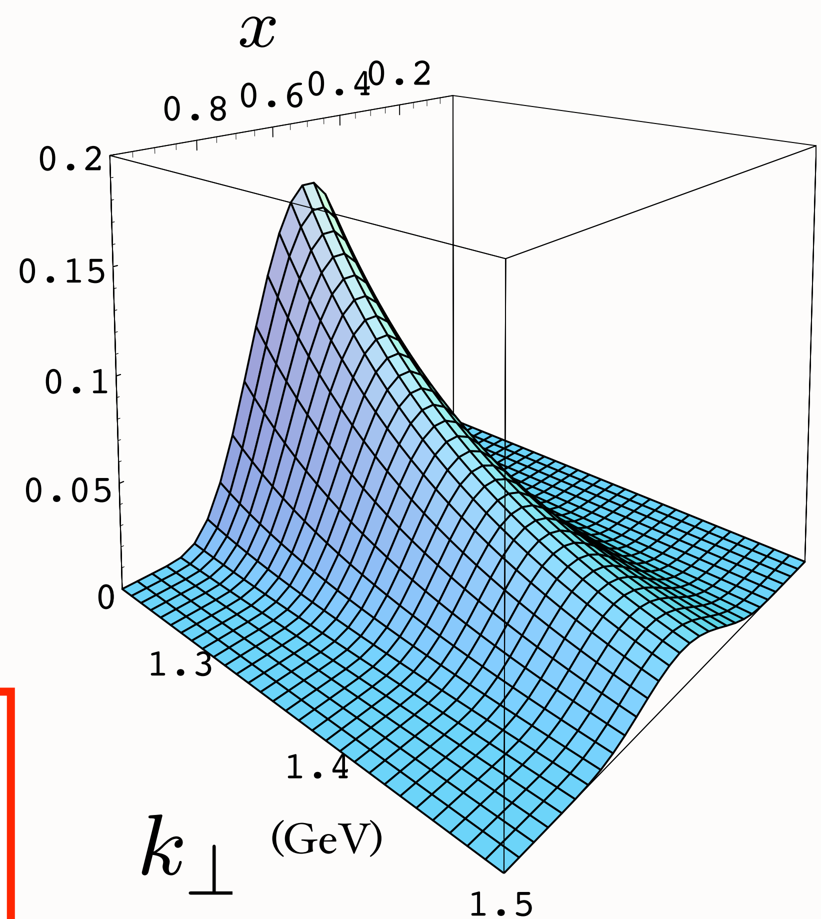
$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L+S-1)$$

soft wall
confining potential:

G. de Teramond, sjb

Prediction from AdS/CFT: Meson LFWF

$$\psi_M(x, k_\perp^2)$$



de Teramond, sjb

"Soft Wall" model

$\kappa = 0.375$ GeV

massless quarks

Note coupling
$k_\perp^2, x$

$$\psi_M(x, k_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x)}} e^{-\frac{k_\perp^2}{2\kappa^2 x(1-x)}}$$

$$\phi_M(x, Q_0) \propto \sqrt{x(1-x)}$$

Connection of Confinement to TMDs

Second Moment of Pion Distribution Amplitude

$$< \xi^2 >= \int_{-1}^{1} d\xi \; \xi^2 \phi(\xi)$$

$$\xi = 1 - 2x$$

$$< \xi^2 >_\pi = 1/5 = 0.20 \qquad \phi_{asympt} \propto x(1-x)$$

$$< \xi^2 >_\pi = 1/4 = 0.25 \qquad \phi_{AdS/QCD} \propto \sqrt{x(1-x)}$$

Lattice (I) $< \xi^2 >_\pi = 0.28 \pm 0.03$ Donnellan et al.

Lattice (II) $< \xi^2 >_\pi = 0.269 \pm 0.039$ Braun et al.

Second Moment of Pion Distribution Amplitude

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Lattice (I) $< \xi^2 >_\pi = 0.28 \pm 0.03$ — Donnellan et al.

Lattice (II) $< \xi^2 >_\pi = 0.269 \pm 0.039$ — Braun et al.

Generalized parton distributions in AdS/QCD

Alfredo Vega[1], Ivan Schmidt[1], Thomas Gutsche[2], Valery E. Lyubovitskij[2*]

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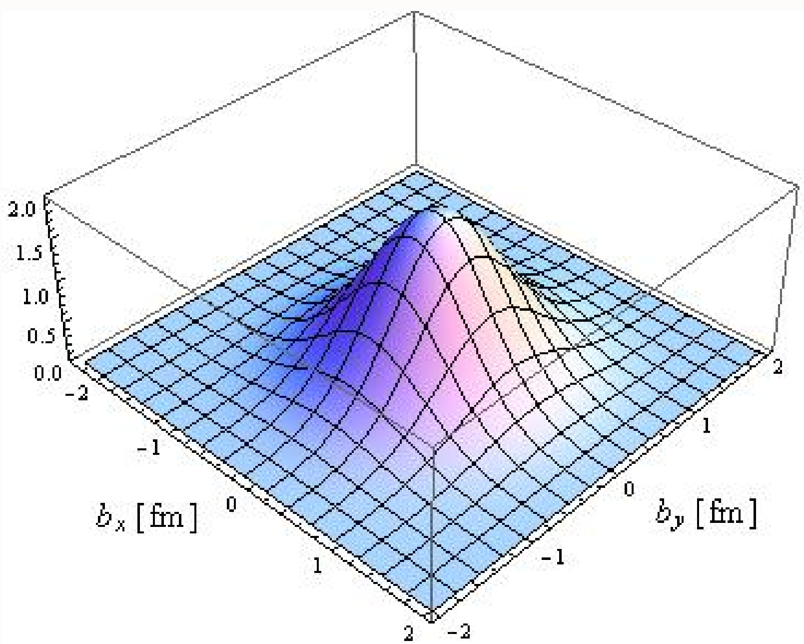
Universidad Técnica Federico Santa María,
Casilla 110-V, Valparaíso, Chile

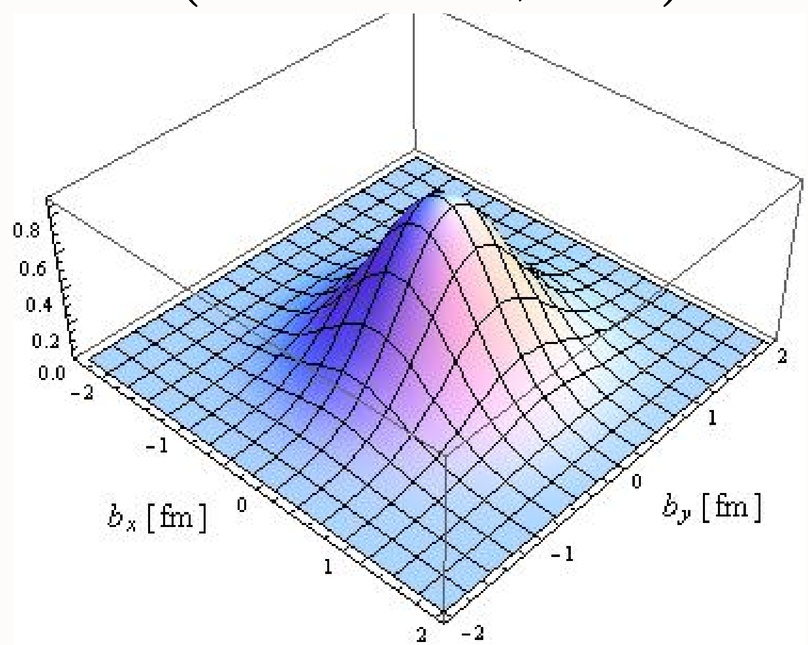
[2] *Institut für Theoretische Physik, Universität Tübingen,*
Kepler Center for Astro and Particle Physics,
Auf der Morgenstelle 14, D–72076 Tübingen, Germany

(Dated: January 19, 2011)

$$u(x = 0.1, \vec{b}_\perp)$$



$$d(x = 0.1, \vec{b}_\perp)$$

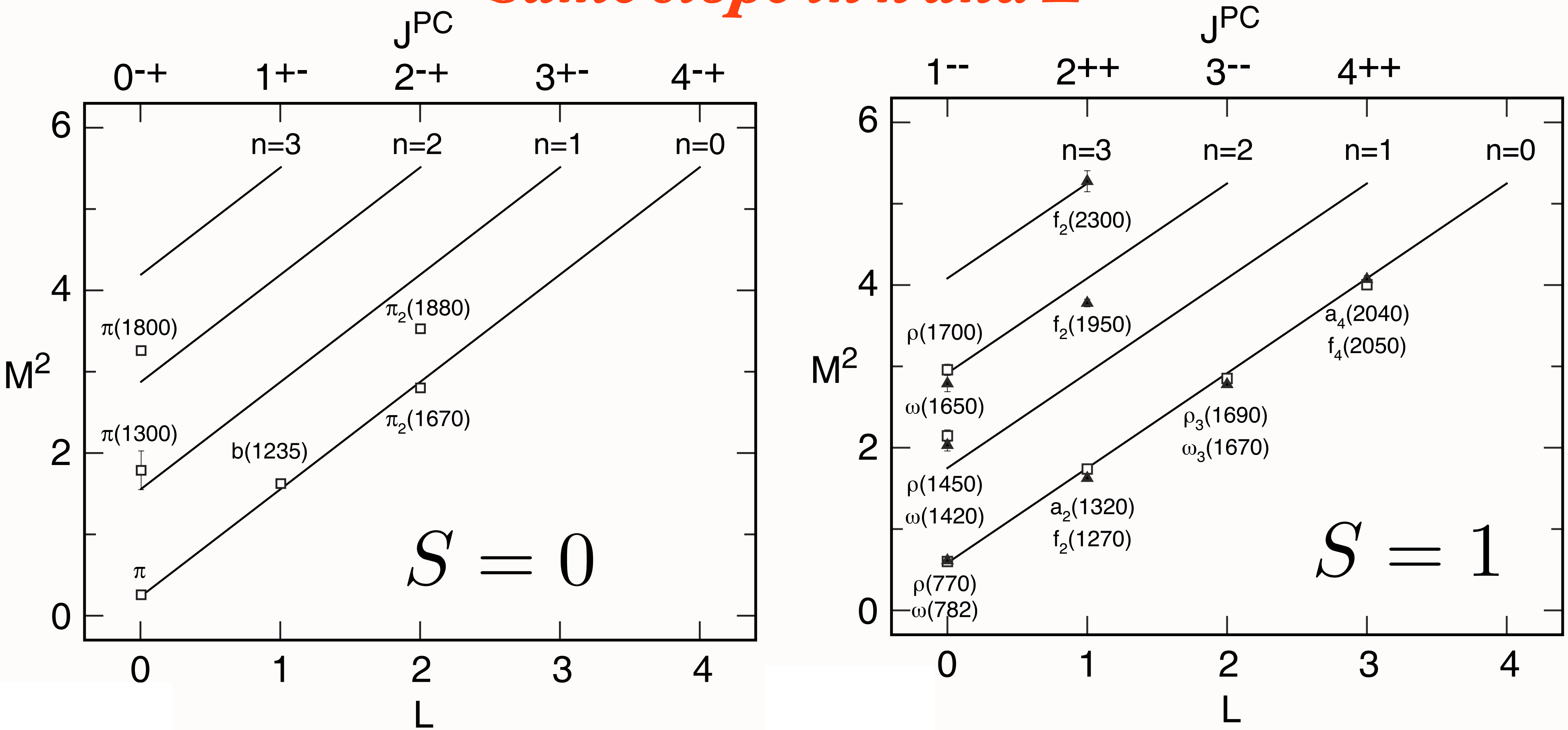


Bosonic Modes and Meson Spectrum

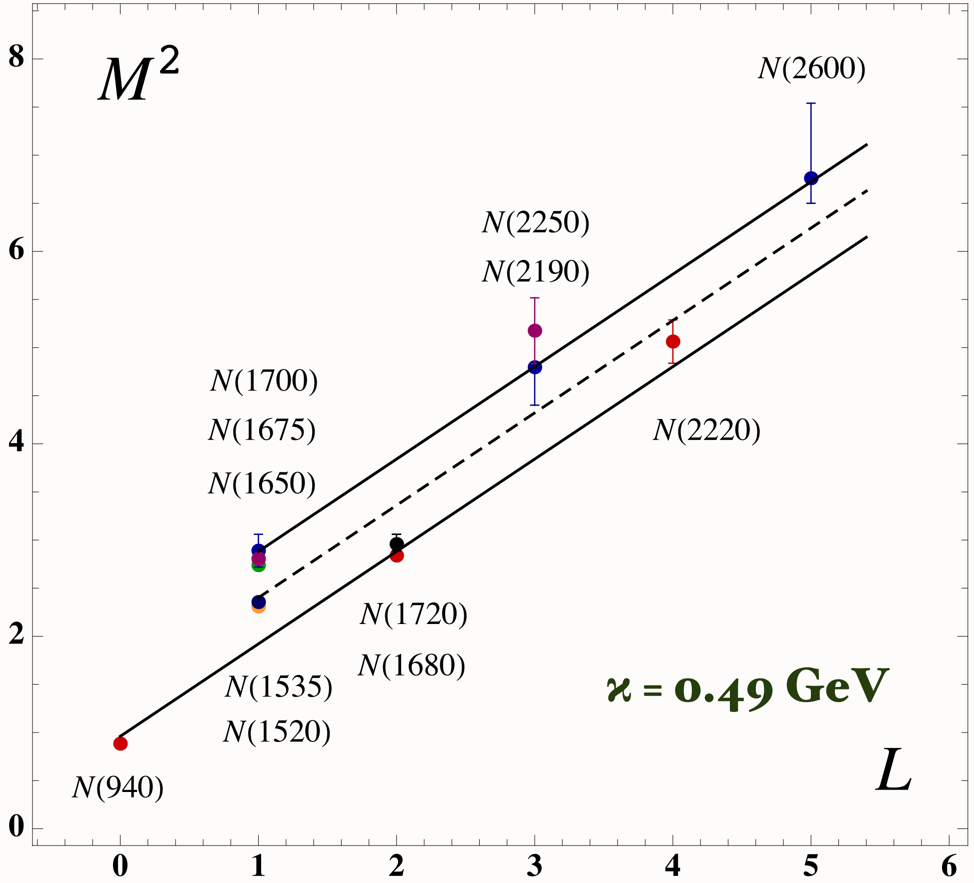
$$\mathcal{M}^2 = 4\kappa^2(n + J/2 + L/2) \to 4\kappa^2(n + L + S/2)$$

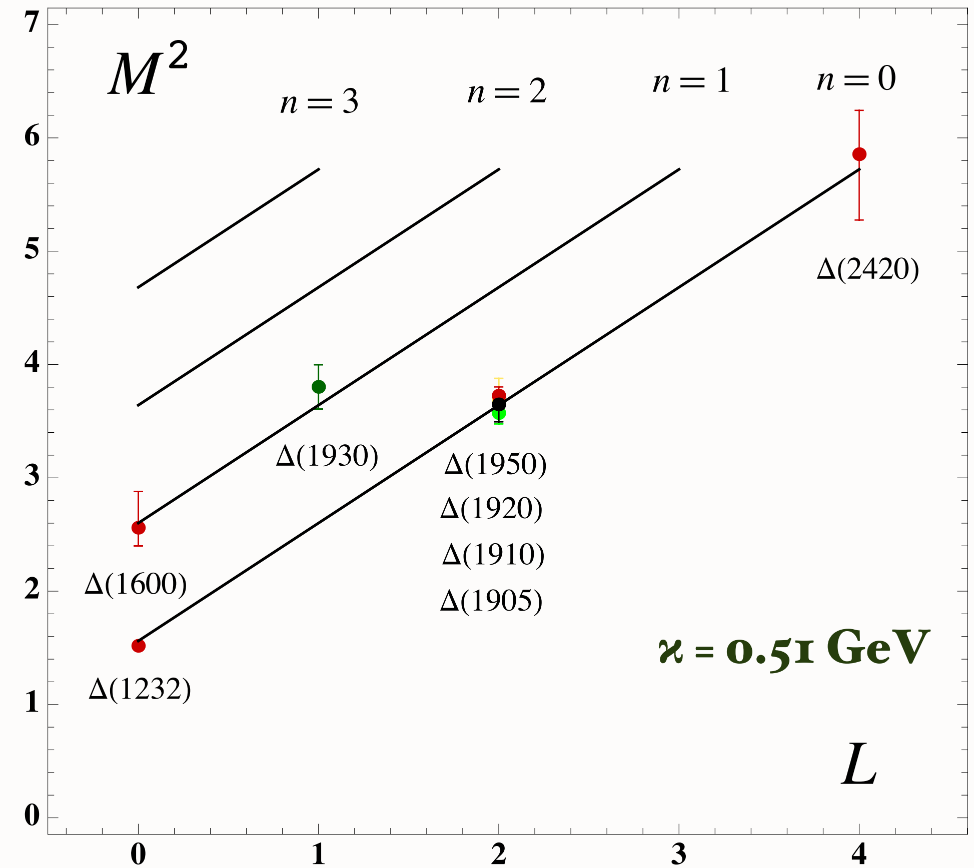
$4\kappa^2$ for $\Delta n = 1$
$4\kappa^2$ for $\Delta L = 1$
$2\kappa^2$ for $\Delta S = 1$

Same slope in n and L



Regge trajectories for the π ($\kappa = 0.6$ GeV) and the $I = 1$ ρ-meson and $I = 0$ ω-meson families ($\kappa = 0.54$ GeV)





de Teramond, sjb

$$\mathcal{M}^{2\,(+)}_{n,L,S} = 4\kappa^2\left(n + L + \frac{S}{2} + \frac{3}{4}\right),$$ positive parity

$$\mathcal{M}^{2\,(-)}_{n,L,S} = 4\kappa^2\left(n + L + \frac{S}{2} + \frac{5}{4}\right),$$ negative parity

Includes all confirmed resonances from PDG 2012

See also Forkel, Beyer, Federico, Klempt

- Fix the energy scale to the proton mass for the lowest state $n = 0, L = 0$
- Subtraction to mass scale may be understood as displacement required to describe nucleons with $N_C = 3$ as composite system with twist $3 + L$ instead of a *quark-squark* bound state with twist $2 + L$
- Phenomenological rules for increase in mass $\mathcal{M}^2$ to construct full baryon spectrum from proton state

  $4\kappa^2$ for $\Delta n = 1$

  $4\kappa^2$ for $\Delta L = 1$

  $2\kappa^2$ for $\Delta S = 1$

  $2\kappa^2$ for $\Delta P = \pm$
- Eigenvalues

$$\mathcal{M}^{2(+)}_{n,L,S} = 4\kappa^2 \left(n + L + S/2 + 3/4\right)$$

$$\mathcal{M}^{2(-)}_{n,L,S} = 4\kappa^2 \left(n + L + S/2 + 5/4\right)$$

Baryon Spectrum in Soft-Wall Model

- Upon substitution $z \to \zeta$ and

$$\Psi_J(x,z) = e^{-iP\cdot x} z^2 \psi^J(z) u(P),$$

find LFWE for $d = 4$

AdS Soft Wall Dirac Equation

$$\begin{aligned} \frac{d}{d\zeta}\psi_+^J + \frac{\nu+\frac{1}{2}}{\zeta}\psi_+^J + U(\zeta)\psi_+^J &= \mathcal{M}\psi_-^J, \\ -\frac{d}{d\zeta}\psi_-^J + \frac{\nu+\frac{1}{2}}{\zeta}\psi_-^J + U(\zeta)\psi_-^J &= \mathcal{M}\psi_+^J, \end{aligned}$$

Linear potential $U(\zeta) = \kappa^2 \zeta$

- Eigenfunctions

$$\psi_+^J(\zeta) \sim \zeta^{\frac{1}{2}+\nu} e^{-\kappa^2\zeta^2/2} L_n^\nu(\kappa^2\zeta^2), \qquad \psi_-^J(\zeta) \sim \zeta^{\frac{3}{2}+\nu} e^{-\kappa^2\zeta^2/2} L_n^{\nu+1}(\kappa^2\zeta^2)$$

- Eigenvalues

$$\mathcal{M}^2 = 4\kappa^2(n+\nu+1), \quad \nu = L+1 \quad (\tau = 3)$$

- Full $J - L$ degeneracy (different J for same L) for baryons along given trajectory !

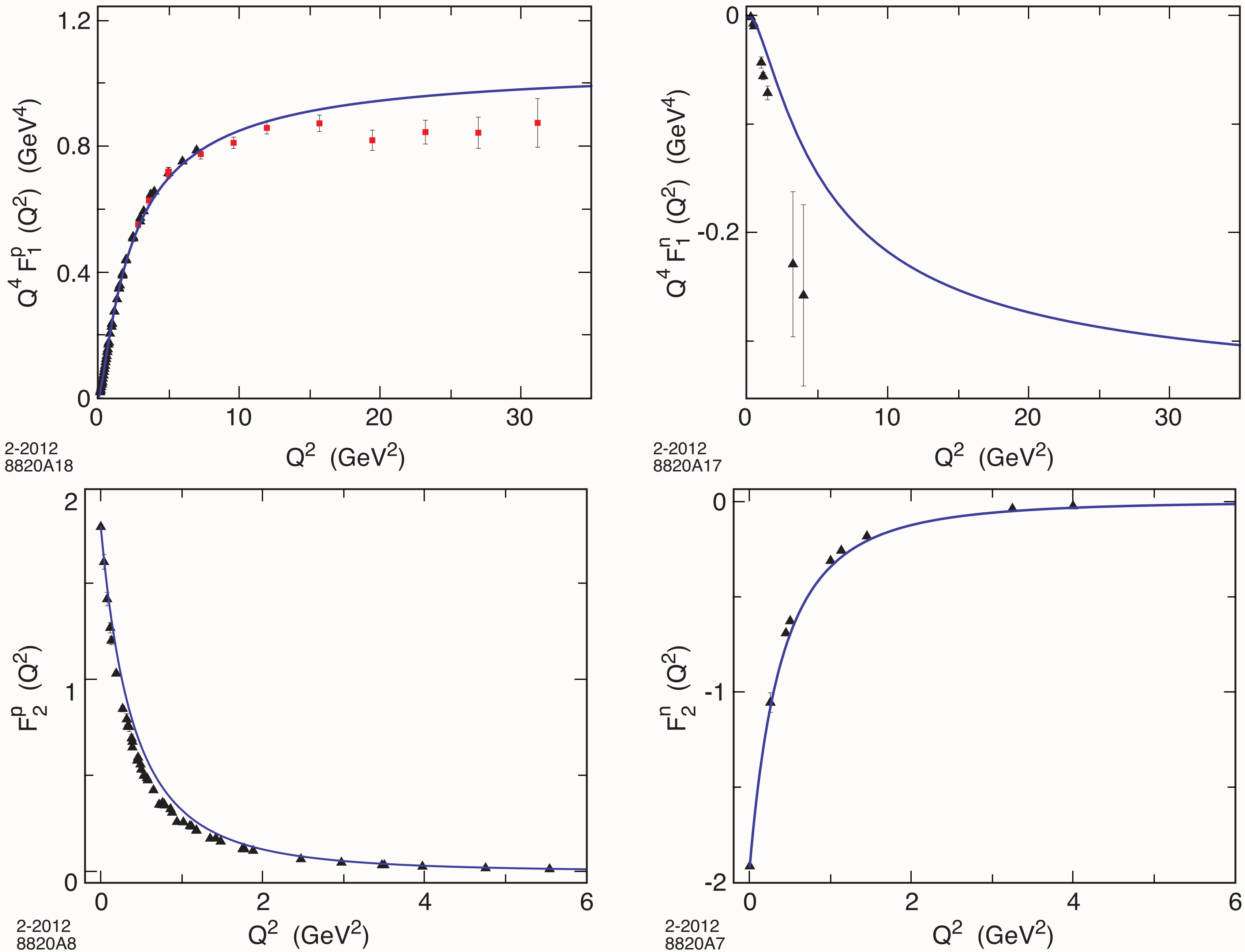
Table 1: $SU(6)$ classification of confirmed baryons listed by the PDG. The labels S, L and n refer to the internal spin, orbital angular momentum and radial quantum number respectively. The $\Delta\frac{5}{2}^-(1930)$ does not fit the $SU(6)$ classification since its mass is too low compared to other members **70**-multiplet for $n=0$, $L=3$.

$SU(6)$	S	L	n	Baryon State
56	$\frac{1}{2}$	0	0	$N\frac{1}{2}^+(940)$
	$\frac{1}{2}$	0	1	$N\frac{1}{2}^+(1440)$
	$\frac{1}{2}$	0	2	$N\frac{1}{2}^+(1710)$
	$\frac{3}{2}$	0	0	$\Delta\frac{3}{2}^+(1232)$
	$\frac{3}{2}$	0	1	$\Delta\frac{3}{2}^+(1600)$
70	$\frac{1}{2}$	1	0	$N\frac{1}{2}^-(1535)$ $N\frac{3}{2}^-(1520)$
	$\frac{3}{2}$	1	0	$N\frac{1}{2}^-(1650)$ $N\frac{3}{2}^-(1700)$ $N\frac{5}{2}^-(1675)$
	$\frac{3}{2}$	1	1	$N\frac{1}{2}^-$ $N\frac{3}{2}^-(1875)$ $N\frac{5}{2}^-$
	$\frac{1}{2}$	1	0	$\Delta\frac{1}{2}^-(1620)$ $\Delta\frac{3}{2}^-(1700)$
56	$\frac{1}{2}$	2	0	$N\frac{3}{2}^+(1720)$ $N\frac{5}{2}^+(1680)$
	$\frac{1}{2}$	2	1	$N\frac{3}{2}^+(1900)$ $N\frac{5}{2}^+$
	$\frac{3}{2}$	2	0	$\Delta\frac{1}{2}^+(1910)$ $\Delta\frac{3}{2}^+(1920)$ $\Delta\frac{5}{2}^+(1905)$ $\Delta\frac{7}{2}^+(1950)$
70	$\frac{1}{2}$	3	0	$N\frac{5}{2}^-$ $N\frac{7}{2}^-$
	$\frac{3}{2}$	3	0	$N\frac{3}{2}^-$ $N\frac{5}{2}^-$ $N\frac{7}{2}^-(2190)$ $N\frac{9}{2}^-(2250)$
	$\frac{1}{2}$	3	0	$\Delta\frac{5}{2}^-$ $\Delta\frac{7}{2}^-$
56	$\frac{1}{2}$	4	0	$N\frac{7}{2}^+$ $N\frac{9}{2}^+(2220)$
	$\frac{3}{2}$	4	0	$\Delta\frac{5}{2}^+$ $\Delta\frac{7}{2}^+$ $\Delta\frac{9}{2}^+$ $\Delta\frac{11}{2}^+(2420)$
70	$\frac{1}{2}$	5	0	$N\frac{9}{2}^-$ $N\frac{11}{2}^-$
	$\frac{3}{2}$	5	0	$N\frac{7}{2}^-$ $N\frac{9}{2}^-$ $N\frac{11}{2}^-(2600)$ $N\frac{13}{2}^-$

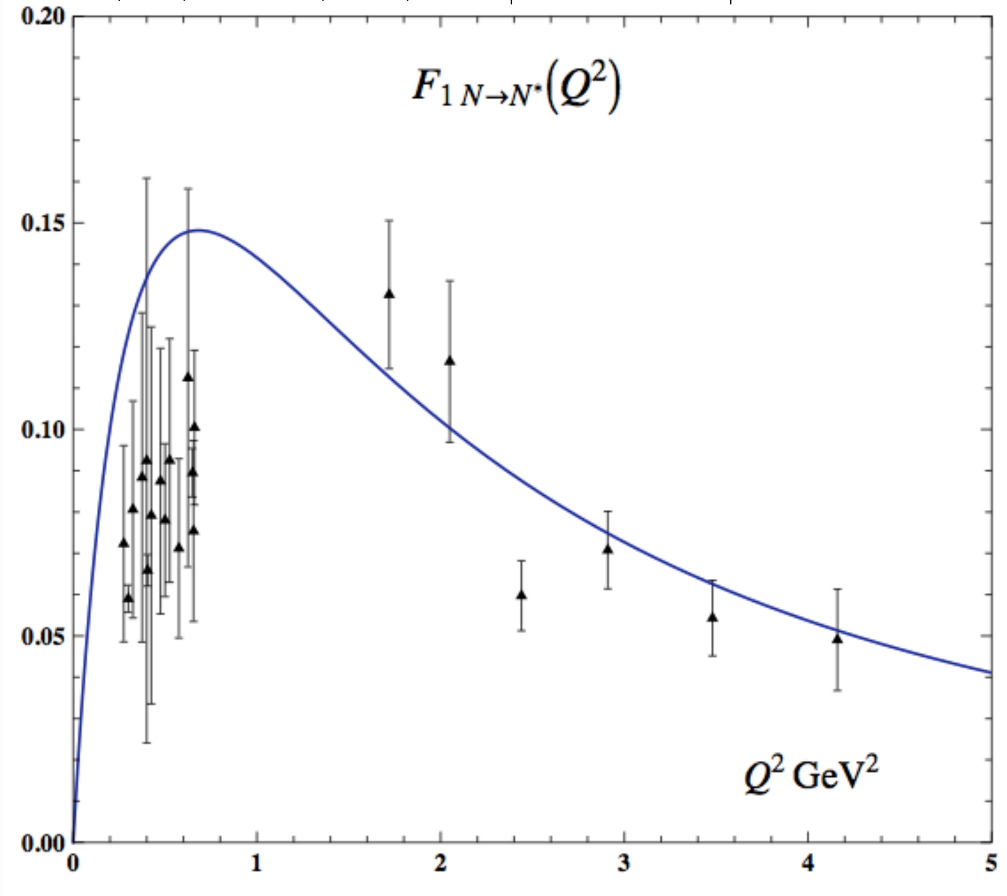
PDG 2012

New PDG 2012 confirmed baryon resonances the N(1875) and the N(1900) are also well described

Using $SU(6)$ flavor symmetry and normalization to static quantities



$N(940) \to N^*(1440)$: $\Psi_+^{n=0,L=0} \to \Psi_+^{n=1,L=0}$



Data from I. Aznauryan, *et al.* CLAS (2009)

$$F_1{}^{p}_{N \to N^*}(Q^2) = \frac{2\sqrt{2}}{3} \frac{\frac{Q^2}{M_P^2}}{\left(1 + \frac{Q^2}{\mathcal{M}_\rho^2}\right)\left(1 + \frac{Q^2}{\mathcal{M}_{\rho'}^2}\right)\left(1 + \frac{Q^2}{\mathcal{M}_{\rho''}^2}\right)}$$

with $\mathcal{M}_{\rho_n}^2 \to 4\kappa^2(n + 1/2)$

Chiral Features of Soft-Wall AdS/QCD Model

- **Boost Invariant**
- **Trivial LF vacuum.**
- **Massless Pion**
- **Hadron Eigenstates have LF Fock components of different L^z**
- **Proton: equal probability** $S^z = +1/2, L^z = 0; S^z = -1/2, L^z = +1$

$$J^z = +1/2 :< L^z >= 1/2, < S_q^z = 0 >$$

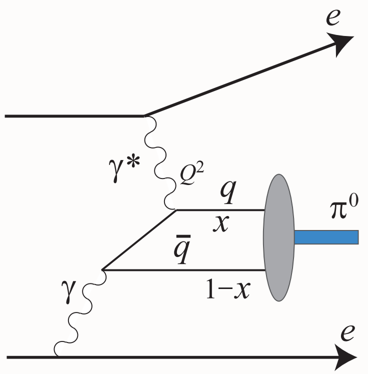
- **Self-Dual Massive Eigenstates: Proton is its own chiral partner.**
- **Label State by minimum L as in Atomic Physics**
- **Minimum L dominates at short distances**
- **AdS/QCD Dictionary: Match to Interpolating Operator Twist at z=0.**

AdS/QCD and Light-Front Holography

- AdS/QCD: Incorporates scale transformations characteristic of QCD with a single scale -- RGE
- Light-Front Holography; unique connection of AdS_5 to Front-Form
- Profound connection between gravity in 5th dimension and physical 3+1 space time at fixed LF time τ
- Gives unique interpretation of z in AdS to physical variable ζ in 3+1 space-time

Pion Transition Form-Factor

Cao, de Teramond, sjb



- Definition of $\pi - \gamma$ TFF from $\gamma^* \pi^0 \to \gamma$ vertex in the amplitude $e\pi \to e\gamma$

$$\Gamma^\mu = -ie^2 F_{\pi\gamma}(q^2)\epsilon_{\mu\nu\rho\sigma}(p_\pi)_\nu \epsilon_\rho(k) q_\sigma, \quad k^2 = 0$$

- Asymptotic value of pion TFF is determined by first principles in QCD: $Q^2 F_{\pi\gamma}(Q^2 \to \infty) = 2 f_\pi$ [Lepage and Brodsky (1980)]

- Pion TFF from 5-dim Chern-Simons structure [Hill and Zachos (2005), Grigoryan and Radyushkin (2008)]

$$\int d^4x \int dz \, \epsilon^{LMNPQ} A_L \partial_M A_N \partial_P A_Q$$

$$\sim (2\pi)^4 \delta^{(4)} \left(p_\pi + q - k\right) F_{\pi\gamma}(q^2) \epsilon^{\mu\nu\rho\sigma} \epsilon_\mu(q)(p_\pi)_\nu \epsilon_\rho(k) q_\sigma$$

- Find for $A_z \propto \Phi_\pi(z)/z$

$$F_{\pi\gamma}(Q^2) = \frac{1}{2\pi} \int_0^\infty \frac{dz}{z} \, \Phi_\pi(z) V\left(Q^2, z\right)$$

with normalization fixed by asymptotic QCD prediction

- $V(Q^2, z)$ bulk-to-boundary propagator of γ^*

Meson Transition Form-Factors

[S. J. Brodsky, Fu-Guang Cao and GdT, arXiv:1005.39XX]

- Pion TFF from 5-dim Chern-Simons structure [Hill and Zachos (2005), Grigoryan and Radyushkin (2008)]

$$\int d^4x \int dz \, \epsilon^{LMNPQ} A_L \partial_M A_N \partial_P A_Q$$

$$\sim (2\pi)^4 \delta^{(4)}\left(p_\pi + q - k\right) F_{\pi\gamma}(q^2) \epsilon^{\mu\nu\rho\sigma} \epsilon_\mu(q)(p_\pi)_\nu \epsilon_\rho(k) q_\sigma$$

- Take $A_z \propto \Phi_\pi(z)/z, \quad \Phi_\pi(z) = \sqrt{2 P_{q\bar{q}}}\, \kappa\, z^2 e^{-\kappa^2 z^2/2}, \quad \langle \Phi_\pi | \Phi_\pi \rangle = P_{q\bar{q}}$
- Find $\quad \left(\phi(x) = \sqrt{3} f_\pi x(1-x), \quad f_\pi = \sqrt{P_{q\bar{q}}}\, \kappa / \sqrt{2}\pi\right)$

$$Q^2 F_{\pi\gamma}(Q^2) = \frac{4}{\sqrt{3}} \int_0^1 dx \frac{\phi(x)}{1-x} \left[1 - e^{-P_{q\bar{q}} Q^2 (1-x)/4\pi^2 f_\pi^2 \, x}\right]$$

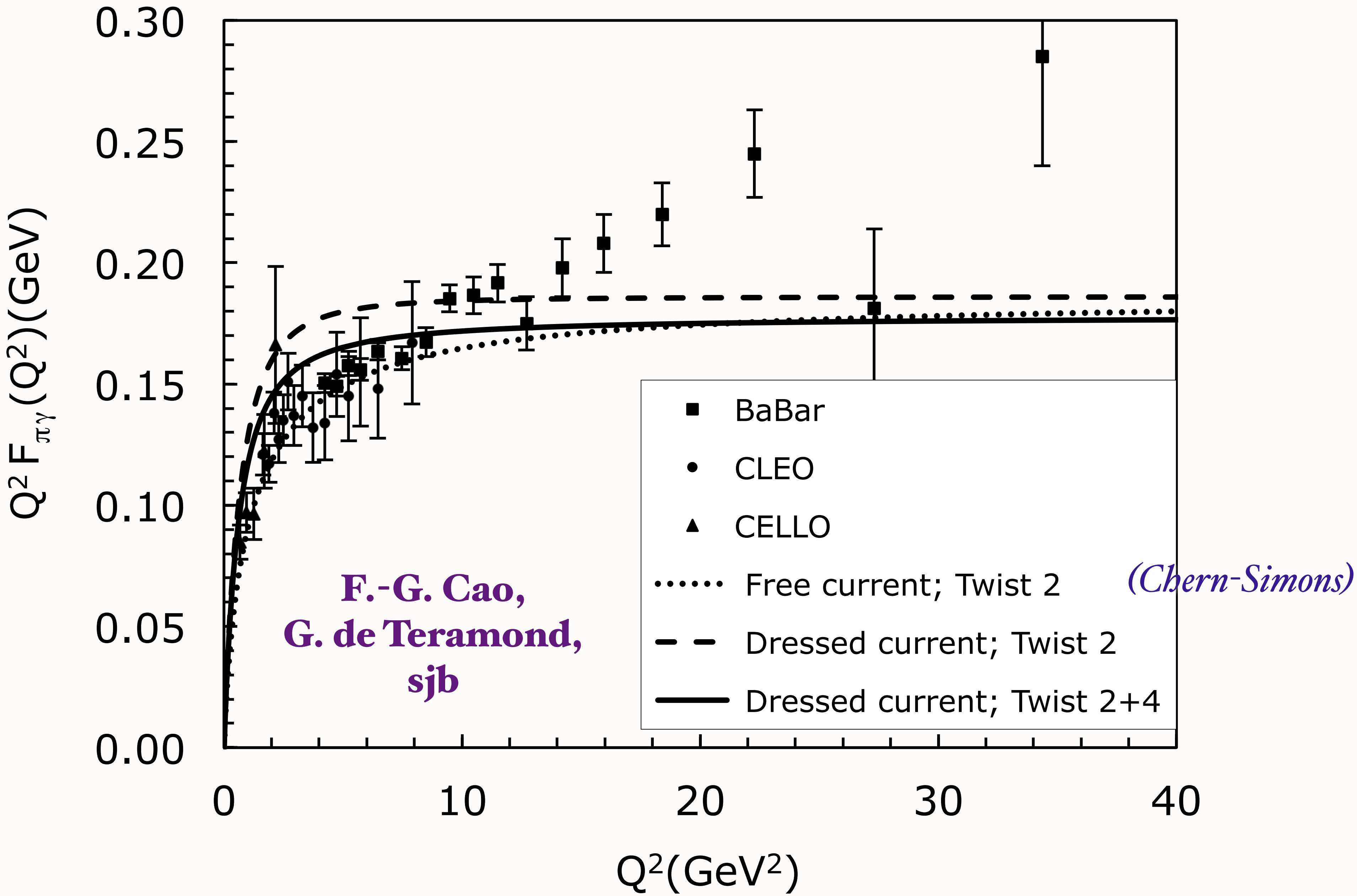
normalized to the asymptotic DA [$P_{q\bar{q}} = 1 \to$ Musatov and Radyushkin (1997)]

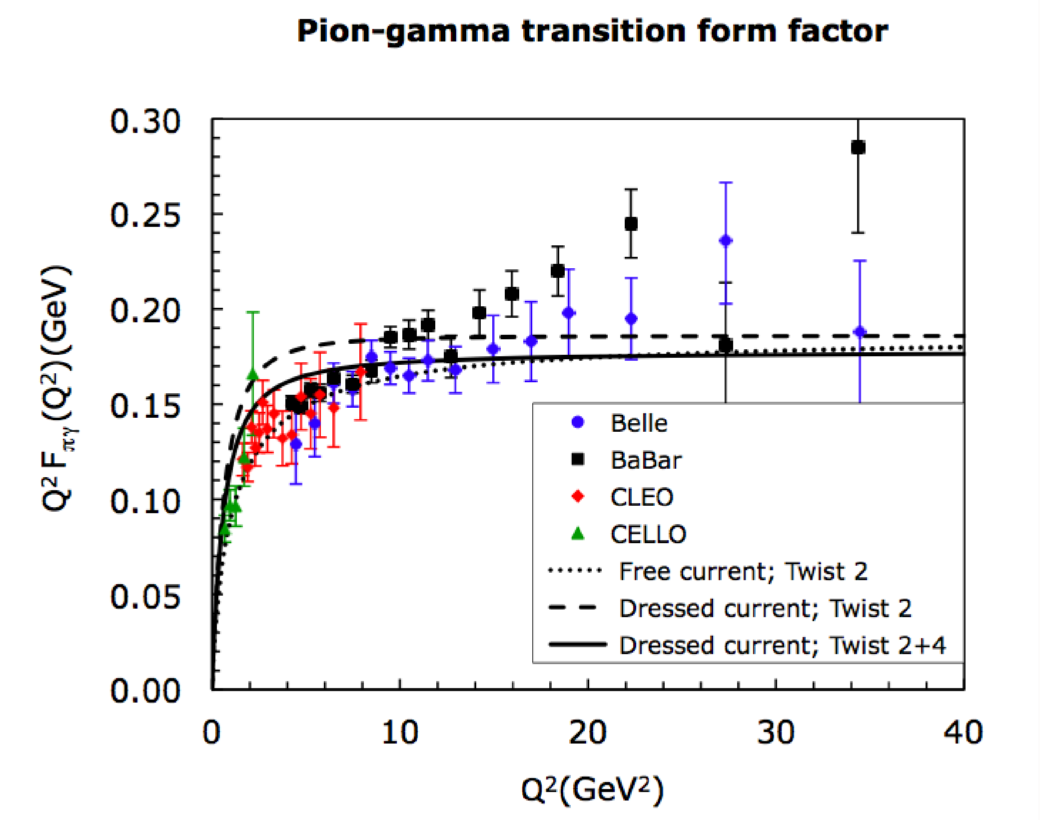
G.P. Lepage, sjb

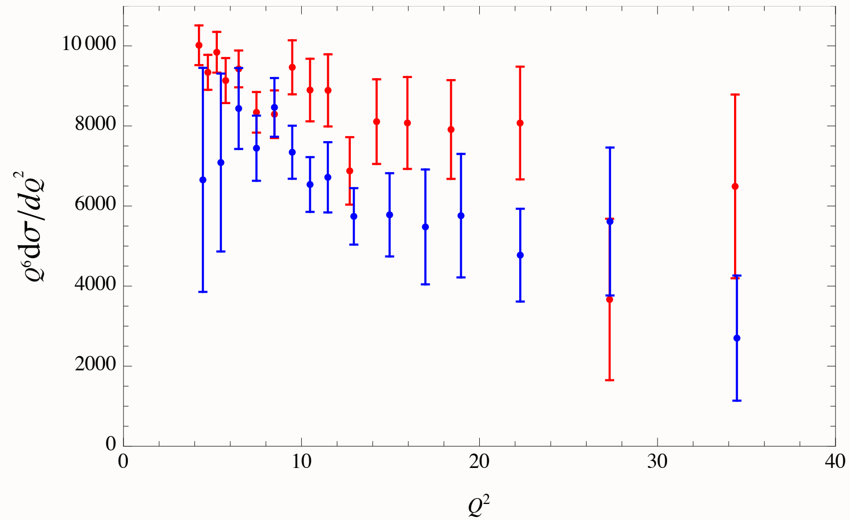
- Large Q^2 TFF is identical to first principles asymptotic QCD result $\quad Q^2 F_{\pi\gamma}(Q^2 \to \infty) = 2 f_\pi$
- The CS form is local in AdS space and projects out only the asymptotic form of the pion DA

Photon-to-pion transition form factor

Lepage, sjb $\qquad Q^2 F_{\pi\gamma}(Q^2 \to \infty) = 2 f_\pi$




Pion-gamma transition form factor
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
Q2(GeV2)
Belle
BaBar
CLEO
CELLO
Free current; Twist 2
Dressed current; Twist 2
Dressed current; Twist 2+4


10 000
8000
6000
4000
2000
0
0
10
20
30
40
Q2

Running Coupling from Modified AdS/QCD

Deur, de Teramond, sjb

- Consider five-dim gauge fields propagating in AdS_5 space in dilaton background $\varphi(z) = \kappa^2 z^2$

$$S = -\frac{1}{4} \int d^4x \, dz \, \sqrt{g} \, e^{\varphi(z)} \, \frac{1}{g_5^2} \, G^2$$

- Flow equation

$$\frac{1}{g_5^2(z)} = e^{\varphi(z)} \frac{1}{g_5^2(0)} \quad \text{or} \quad g_5^2(z) = e^{-\kappa^2 z^2} g_5^2(0)$$

where the coupling $g_5(z)$ incorporates the non-conformal dynamics of confinement

- YM coupling $\alpha_s(\zeta) = g_{YM}^2(\zeta)/4\pi$ is the five dim coupling up to a factor: $g_5(z) \to g_{YM}(\zeta)$

- Coupling measured at momentum scale Q

$$\alpha_s^{AdS}(Q) \sim \int_0^\infty \zeta d\zeta \, J_0(\zeta Q) \, \alpha_s^{AdS}(\zeta)$$

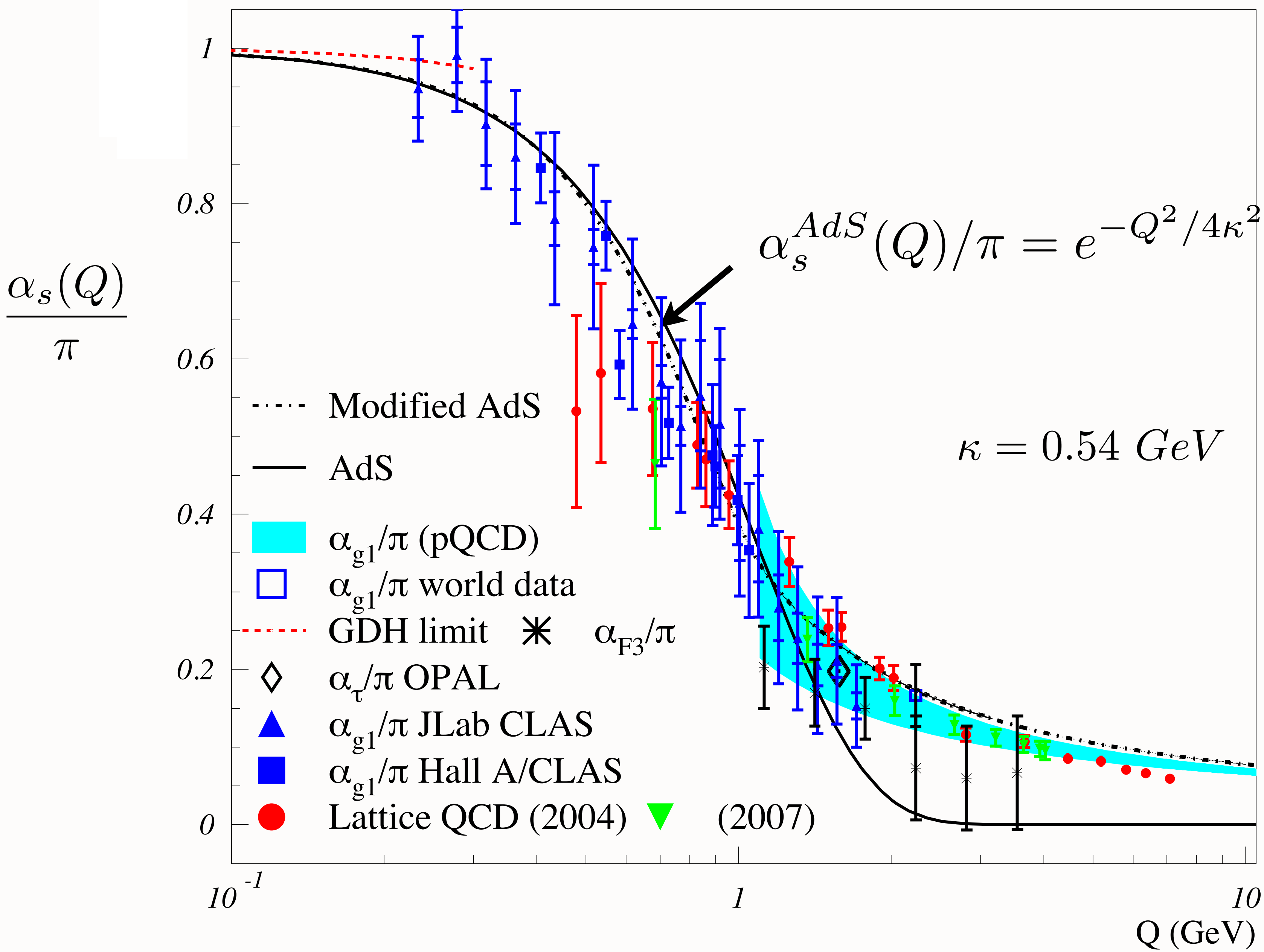
- Solution

$$\alpha_s^{AdS}(Q^2) = \alpha_s^{AdS}(0) \, e^{-Q^2/4\kappa^2}.$$

where the coupling α_s^{AdS} incorporates the non-conformal dynamics of confinement

Running Coupling from Light-Front Holography and AdS/QCD

Analytic, defined at all scales, IR Fixed Point



"Sublimated gluons"

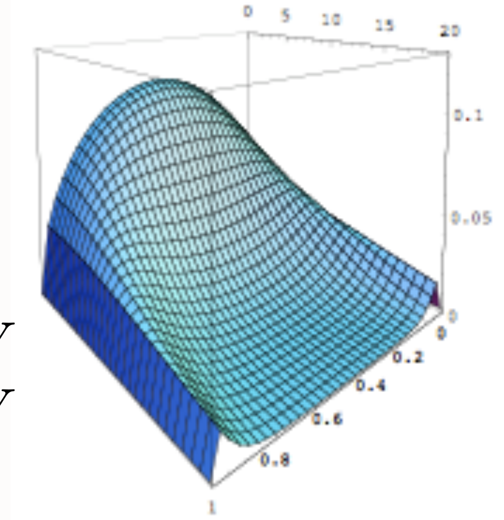
Deur, de Teramond, sjb

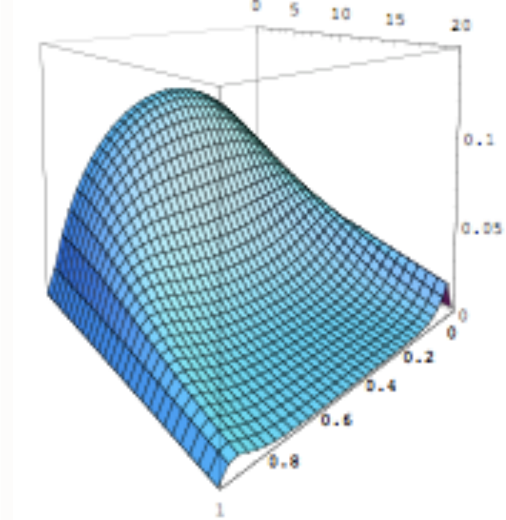
Features of Soft-Wall AdS/QCD

- Single-variable frame-independent radial Schrödinger equation
- Massless pion (m_q =0)
- Regge Trajectories: universal slope in n and L
- Valid for all integer J & S.
- Dimensional Counting Rules for Hard Exclusive Processes
- Phenomenology: Space-like and Time-like Form Factors
- LF Holography: LFWFs; broad distribution amplitude
- No large Nc limit required
- Add quark masses to LF kinetic energy
- Systematically improvable -- diagonalize H_{LF} on AdS basis

$|\pi^+> = |u\bar{d}>$

$m_u = 2\ MeV$
$m_d = 5\ MeV$



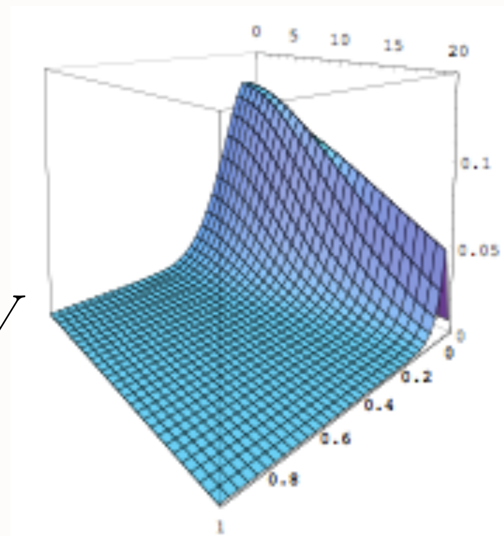


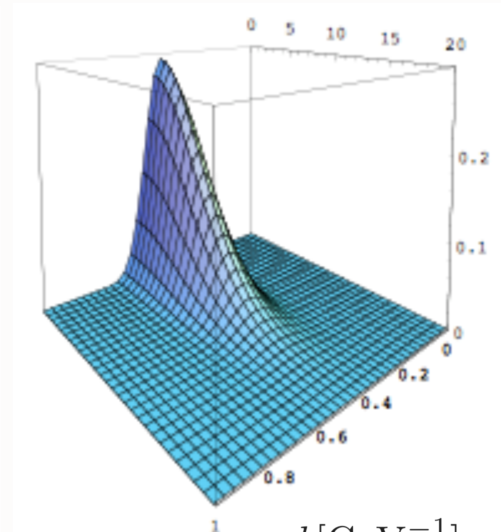
$|K^+> = |u\bar{s}>$

$m_s = 95\ MeV$

$|D^+> = |c\bar{d}>$

$m_c = 1.25\ GeV$

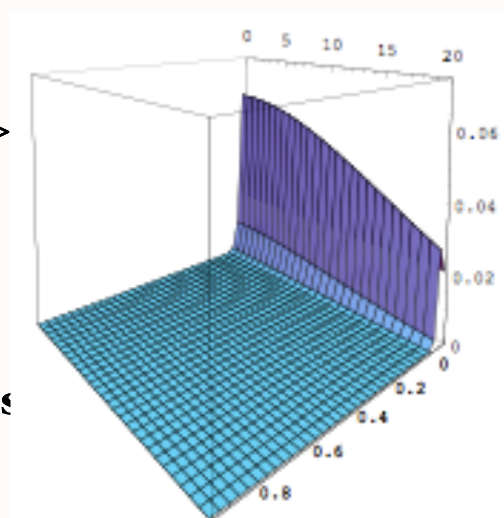


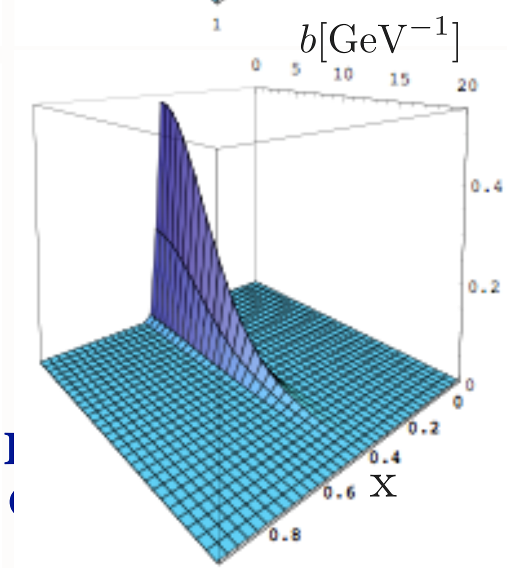


$|\eta_c> = |c\bar{c}>$

$|B^+> = |u\bar{b}>$

$m_b = 4.2\ GeV$

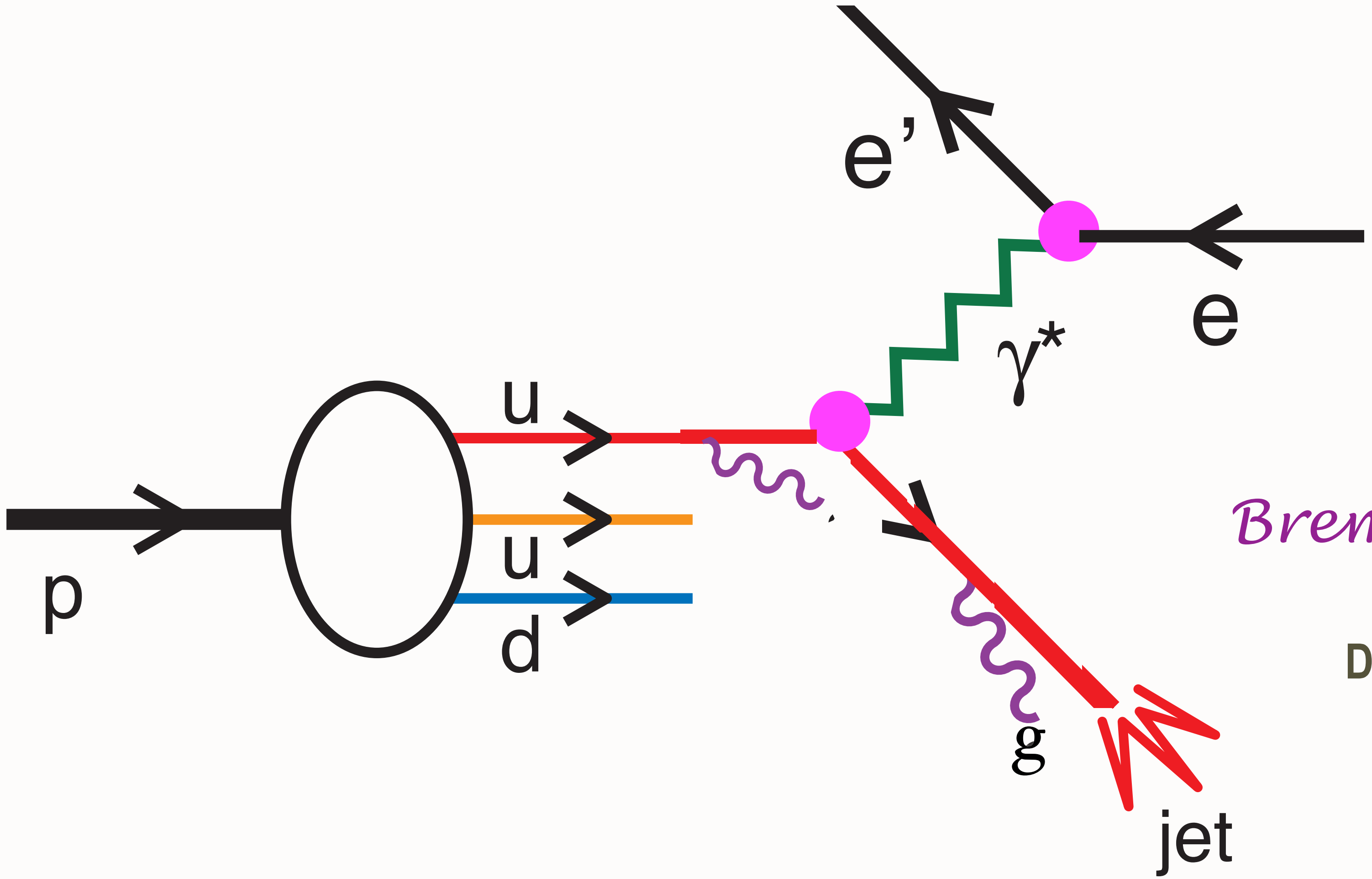




$|\eta_b> = |b\bar{b}>$

$\kappa = 375\ MeV$

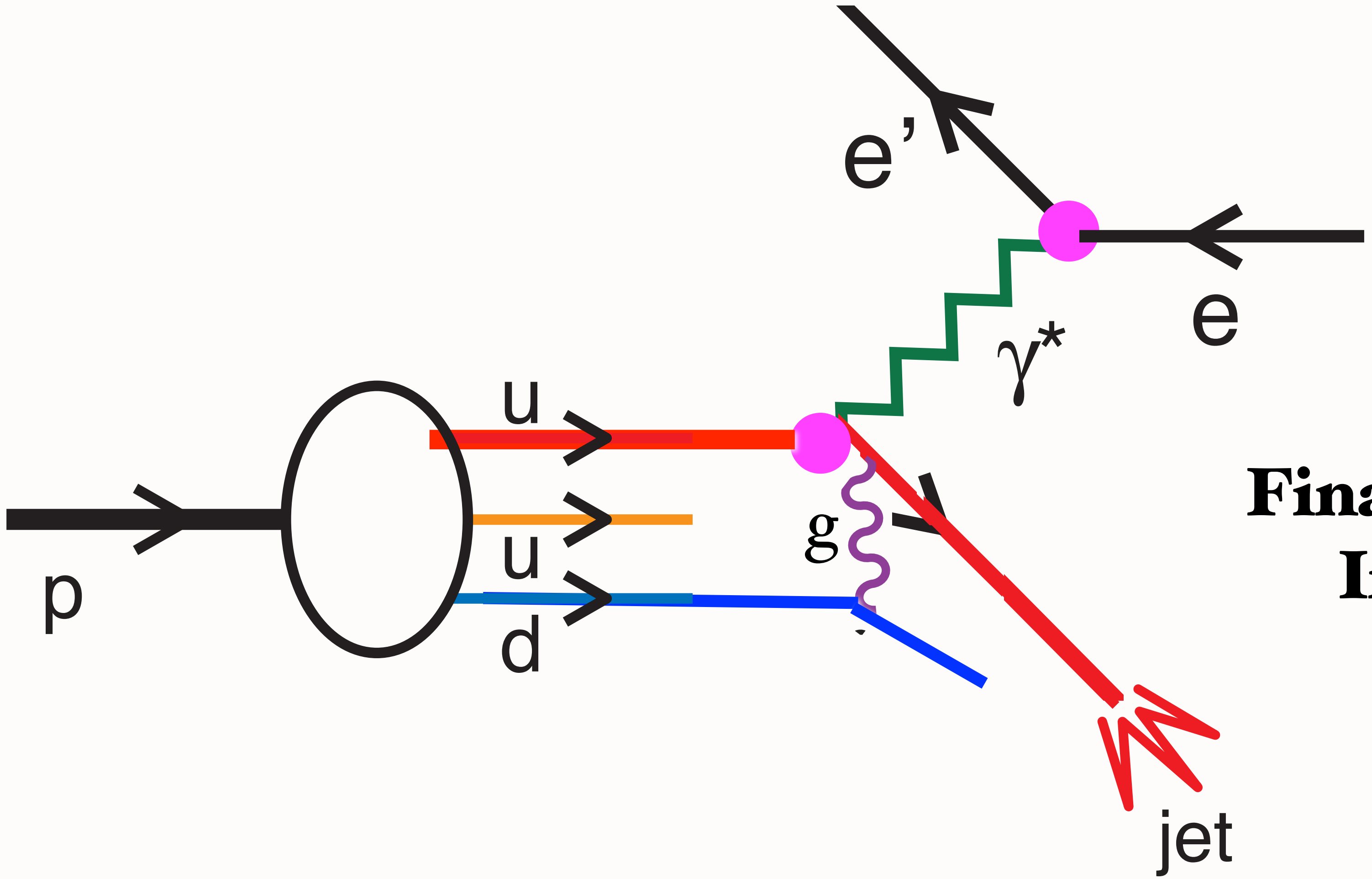
Deep Inelastic Electron-Proton Scattering



Gluonic Bremmstrahlung

DGLAP Evolution

Deep Inelastic Electron-Proton Scattering



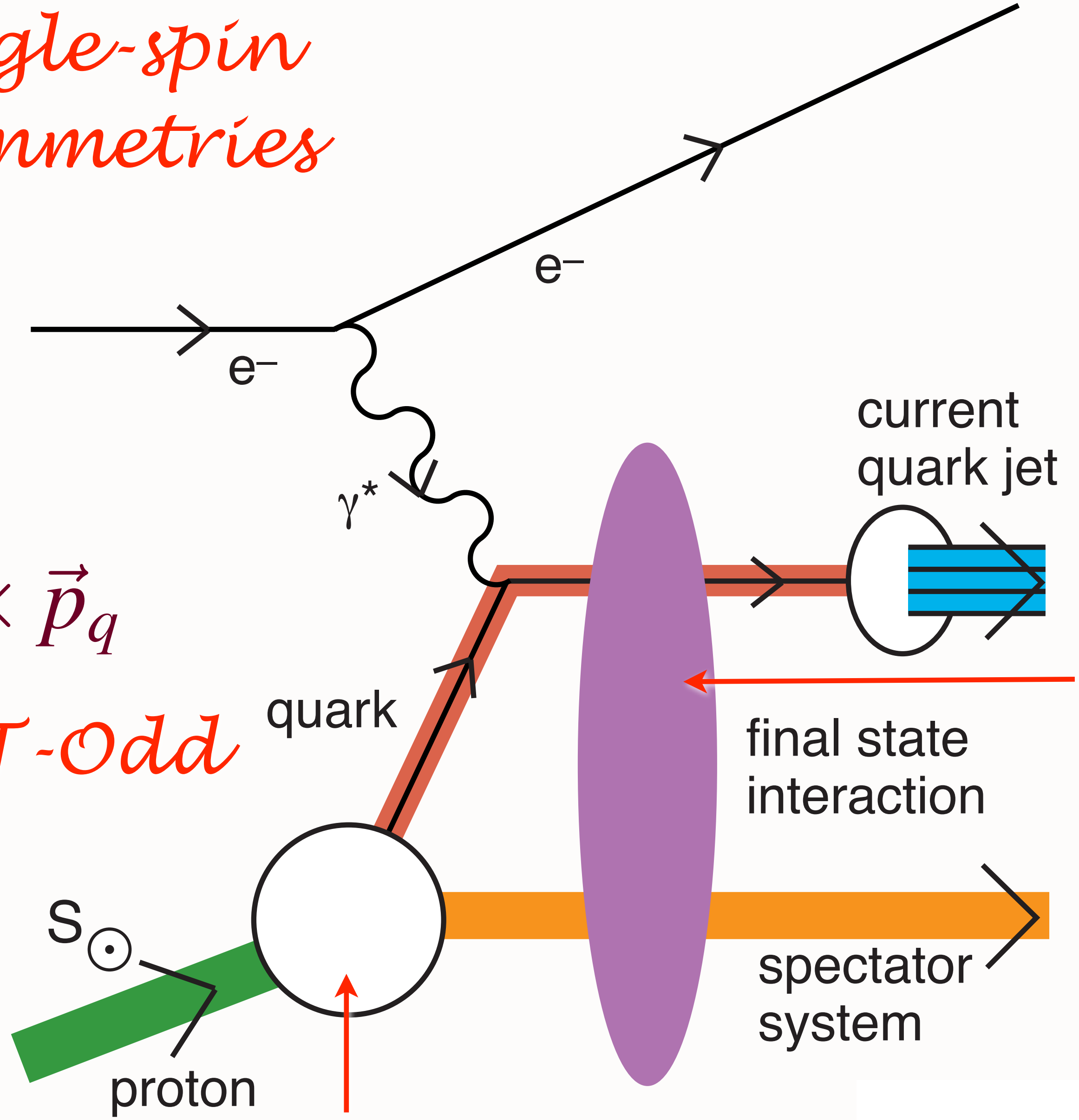
Final-State QCD Interaction

Conventional wisdom:
Final-state interactions of struck quark can be neglected

Single-spin asymmetries

Leading Twist Sivers Effect

Hwang, Schmidt, sjb



Collins, Burkardt, Ji, Yuan. Xiao, Pasquini, ...

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

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

Pseudo-T-Odd

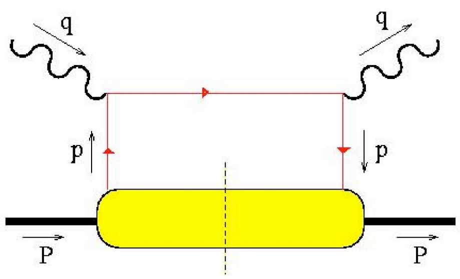
"Lensing Effect"

QED: Lensing involves soft scales

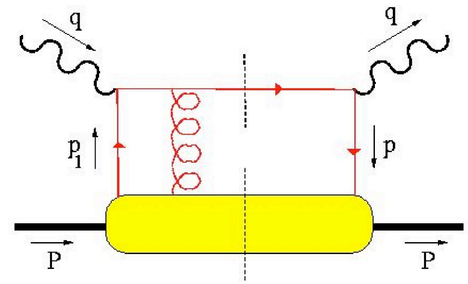
Light-Front Wavefunction S and P- Waves!

Leading-Twist Rescattering Violates pQCD Factorization!

Sign reversal in DY!



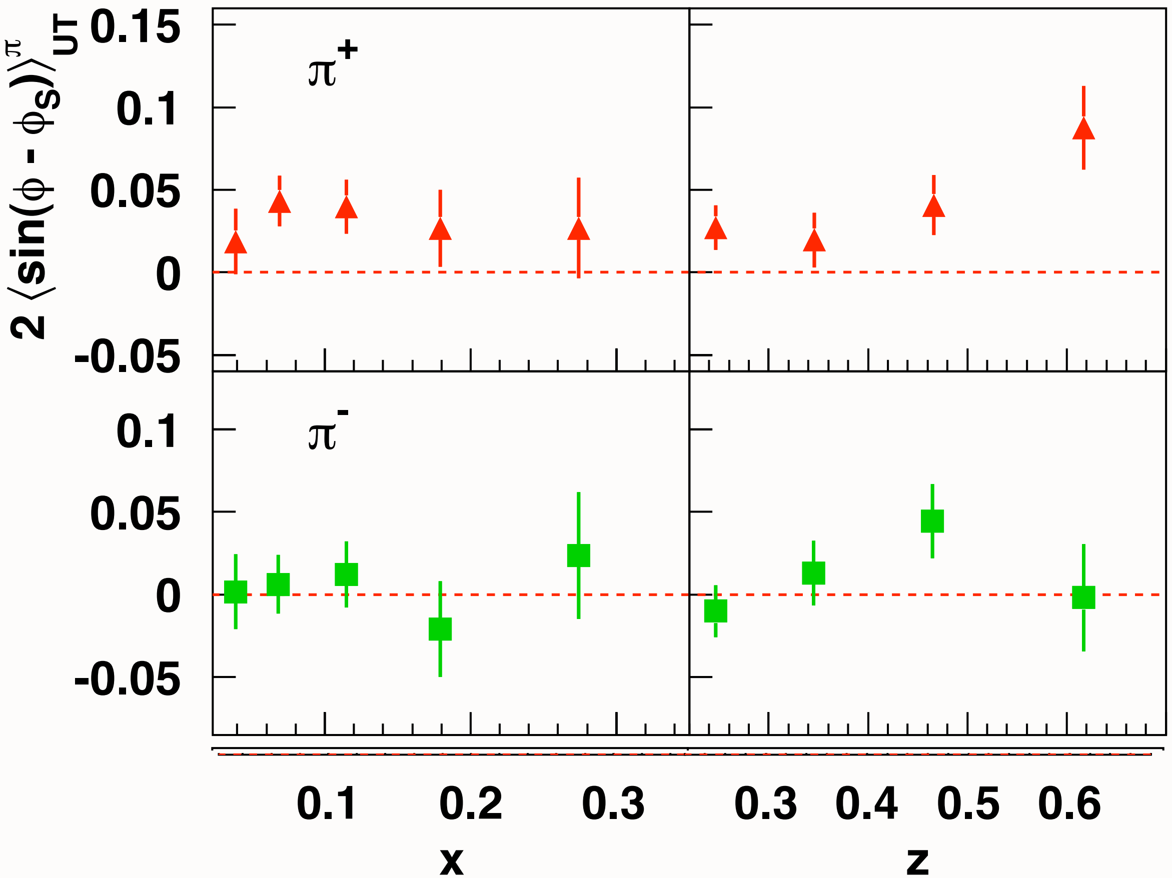
can interfere with



and produce a T-odd effect! (also need $L_z \neq 0$)

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

Sivers asymmetry from HERMES



- First evidence for non-zero Sivers function!
- ⇒ presence of non-zero **quark orbital angular momentum**!
- Positive for **π⁺**... Consistent with zero for **π⁻**...

Gamberg: Hermes data compatible with BHS model

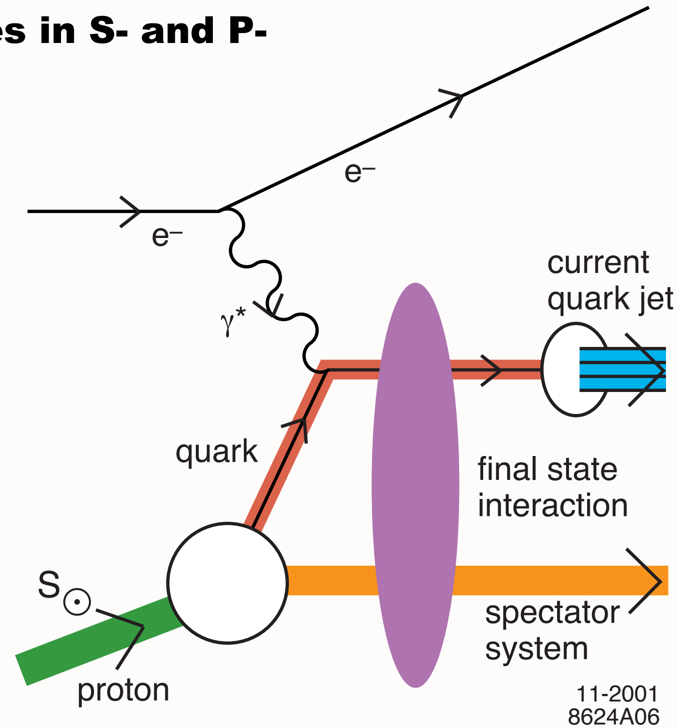
Schmidt, Lu: Hermes charge pattern follow quark contributions to anomalous moment

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

Hwang, Schmidt, sjb
Collins

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

- **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**

Single-spin asymmetries in exclusive channels

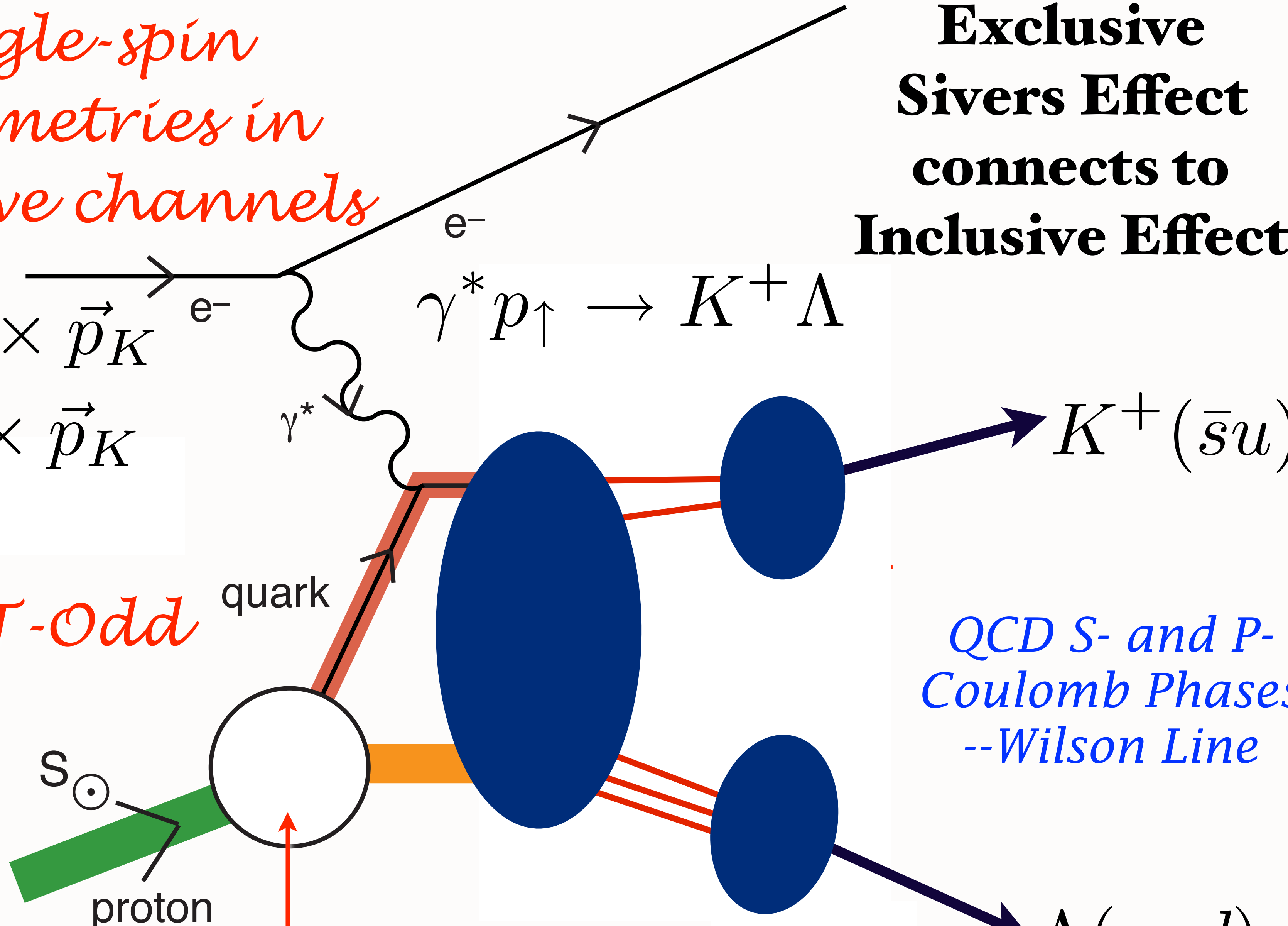
Exclusive Sivers Effect connects to Inclusive Effect

$$i\vec{S}_\Lambda \cdot \vec{q} \times \vec{p}_K$$

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

$$\gamma^* p_\uparrow \to K^+ \Lambda$$

Pseudo-T-Odd



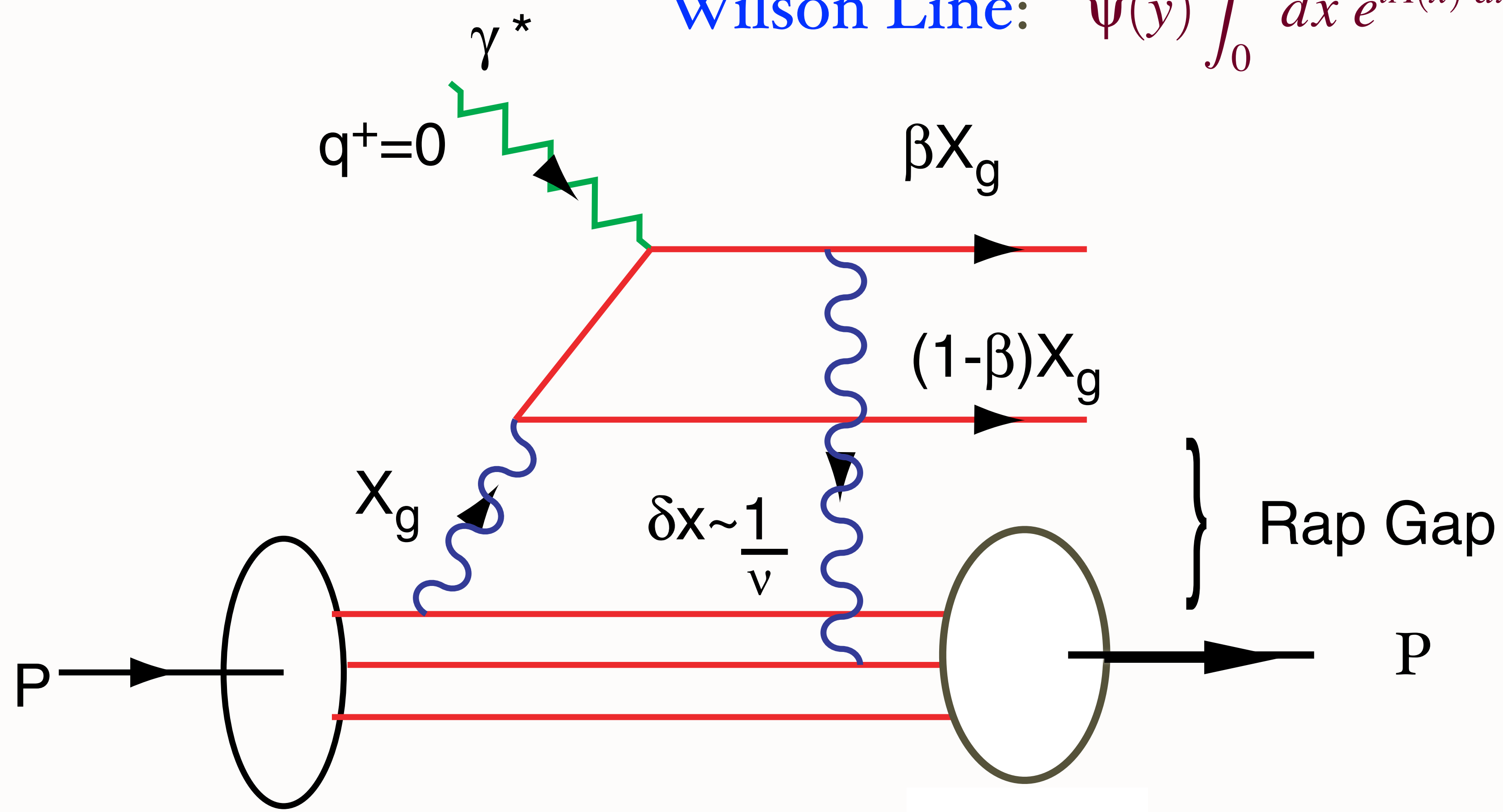
QCD S- and P- Coulomb Phases --Wilson Line

Light-Front Wavefunction S and P- Waves

Hoyer, Marchal, Peigne, Sannino, sjb

QCD Mechanism for Rapidity Gaps

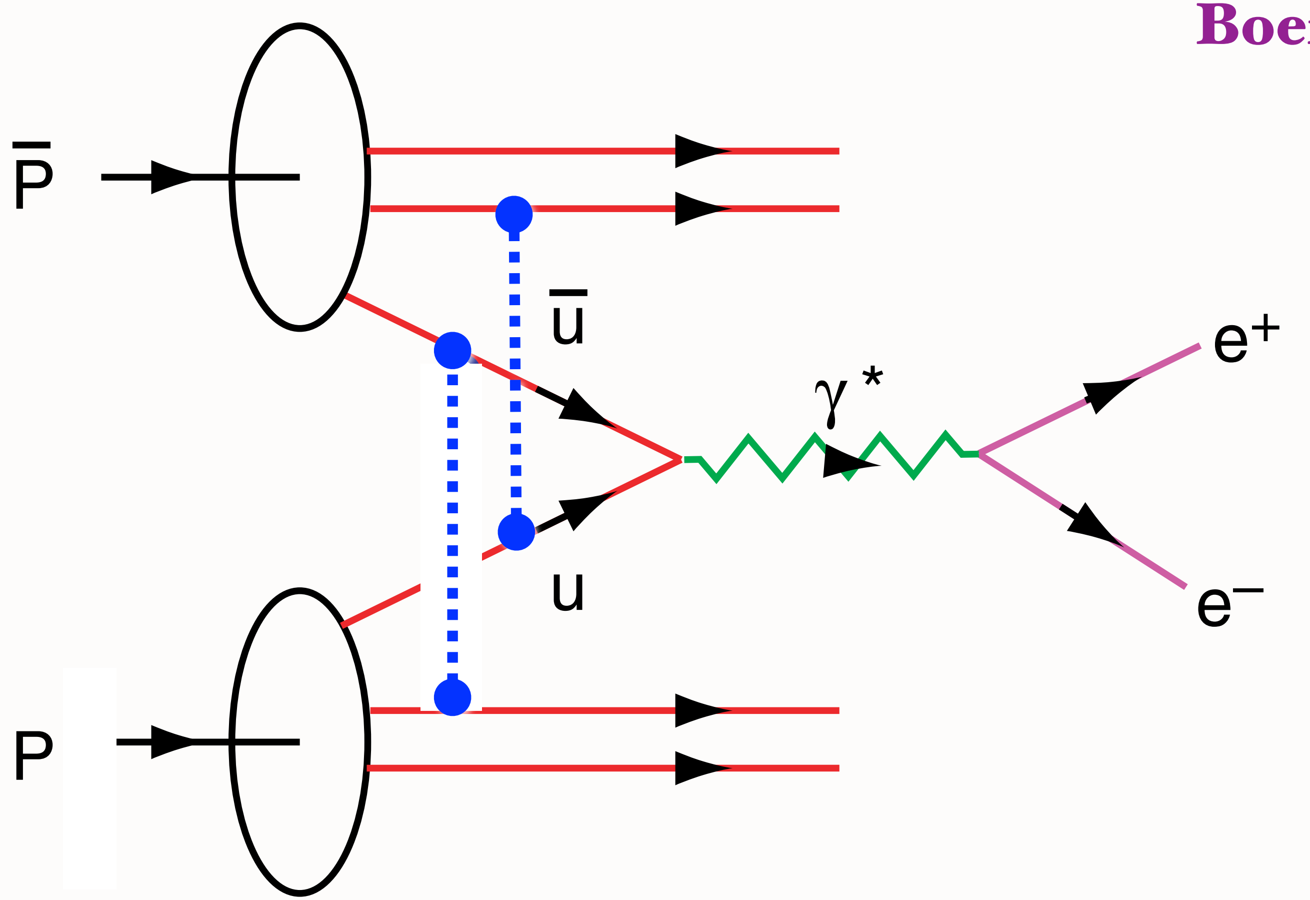
Wilson Line: $\overline{\psi}(y) \int_0^y dx\, e^{iA(x)\cdot dx}\, \psi(0)$



Reproduces lab-frame color dipole approach

DDIS: Input for leading twist nuclear shadowing

Boer, Hwang, sjb



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

Product of Boer - Mulders Functions

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

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

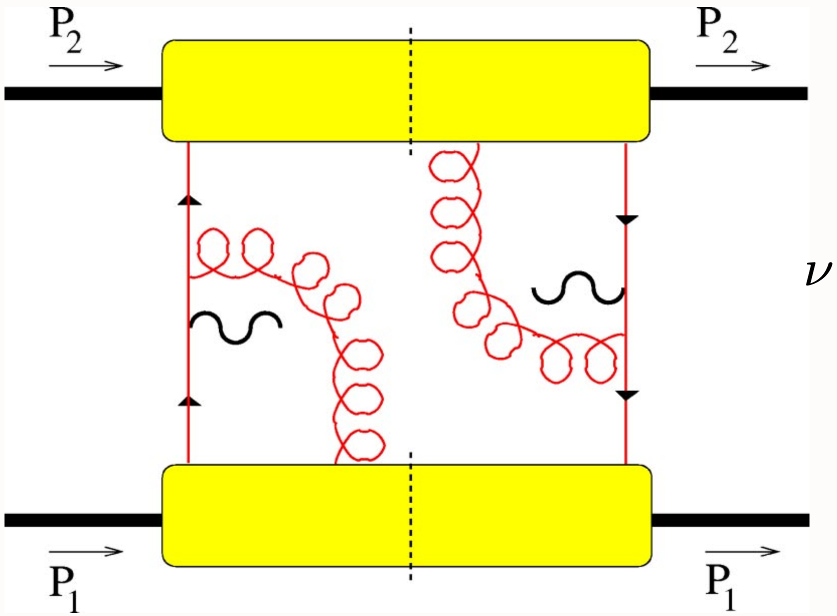
Boer, Hwang, sjb

Drell-Yan planar correlations

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

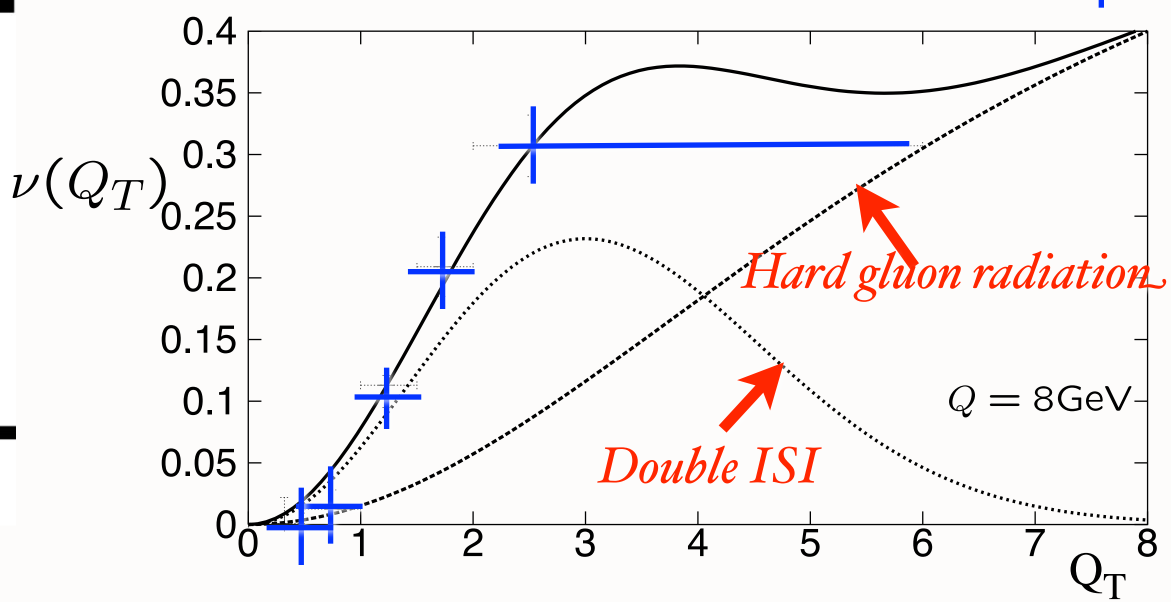
PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

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



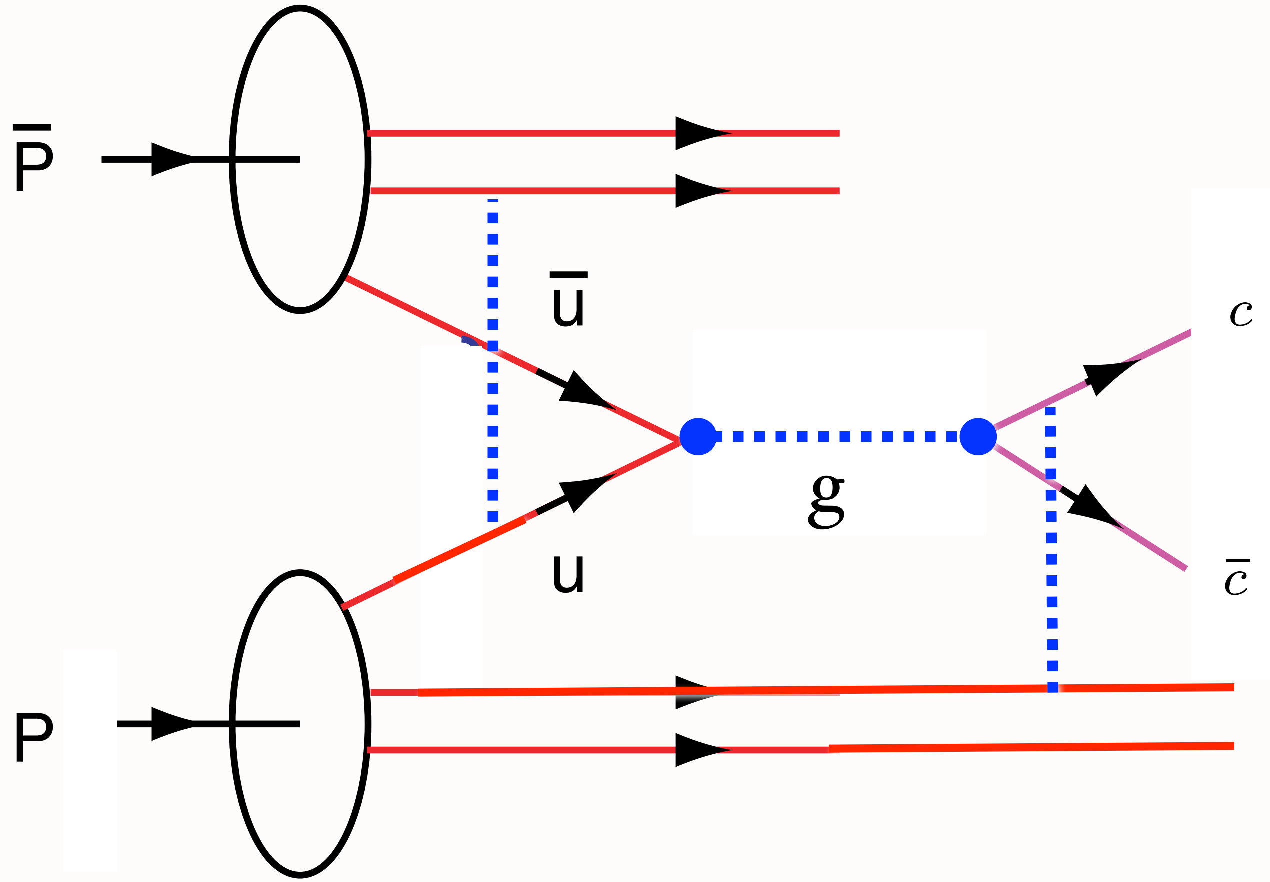
Violates Lam-Tung relation!

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



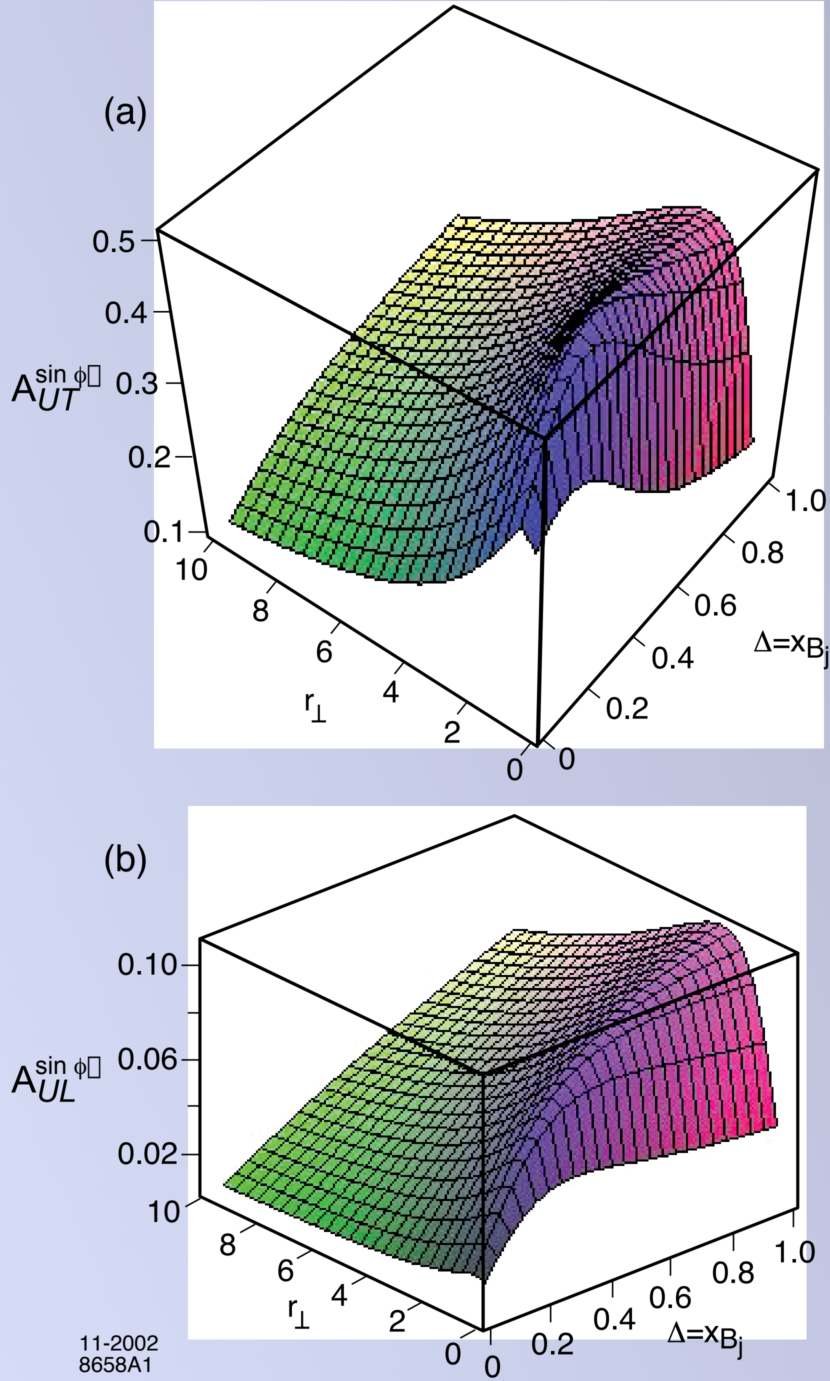
Model: Boer,

See also: Collins and Qiu



Problem for factorization when both ISI and FSI occur

Prediction for Single-Spin Asymmetry



Hwang, Schmidt, 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

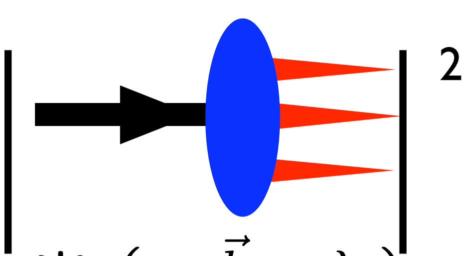
Hwang, Schmidt, sjb,

Mulders, Boer

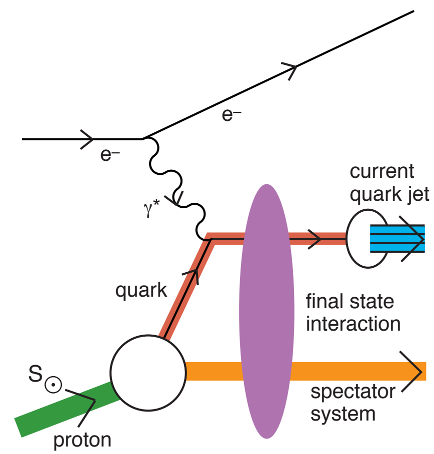
Qiu, Sterman

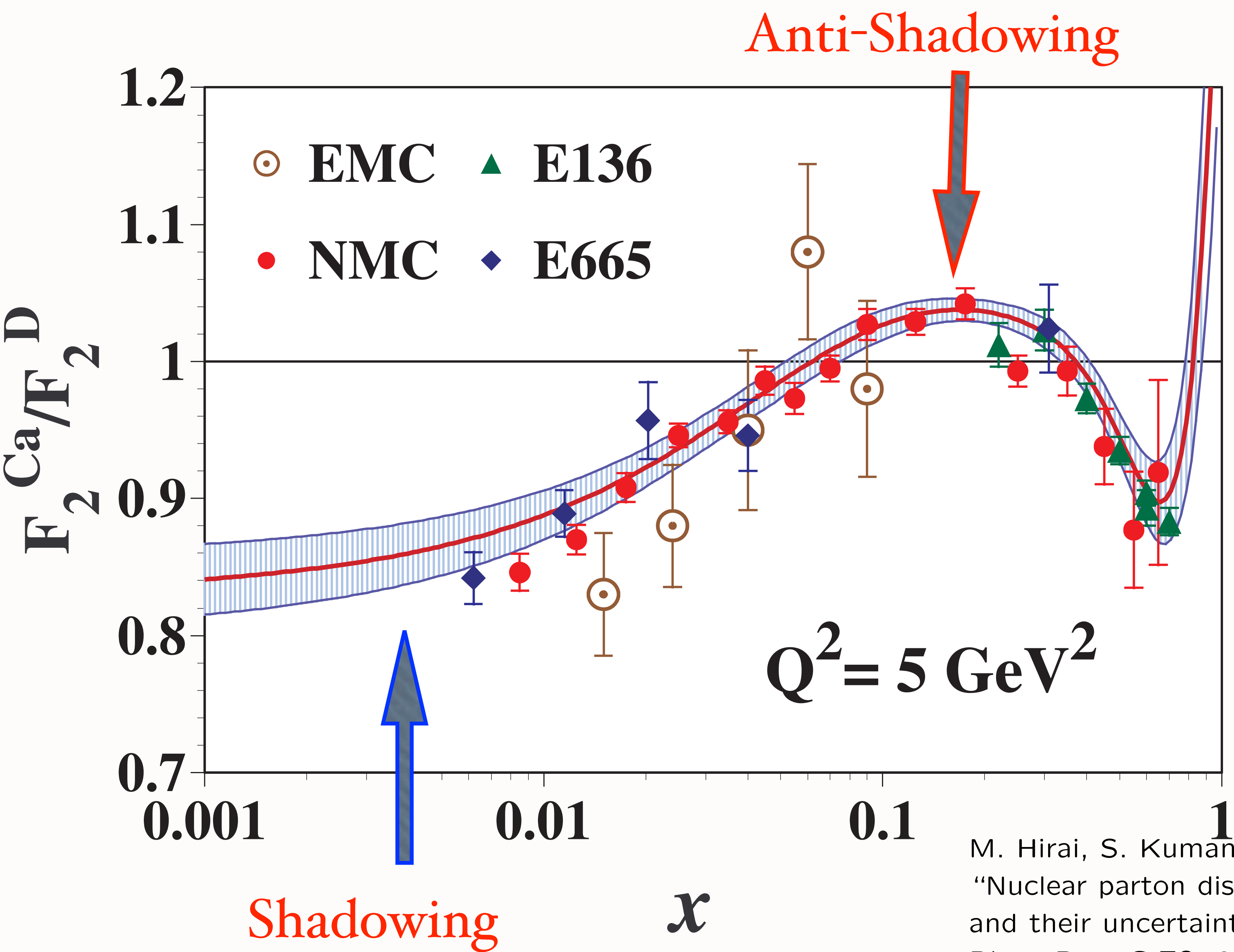
Collins, Qiu

Pasquini, Xiao, Yuan, sjb



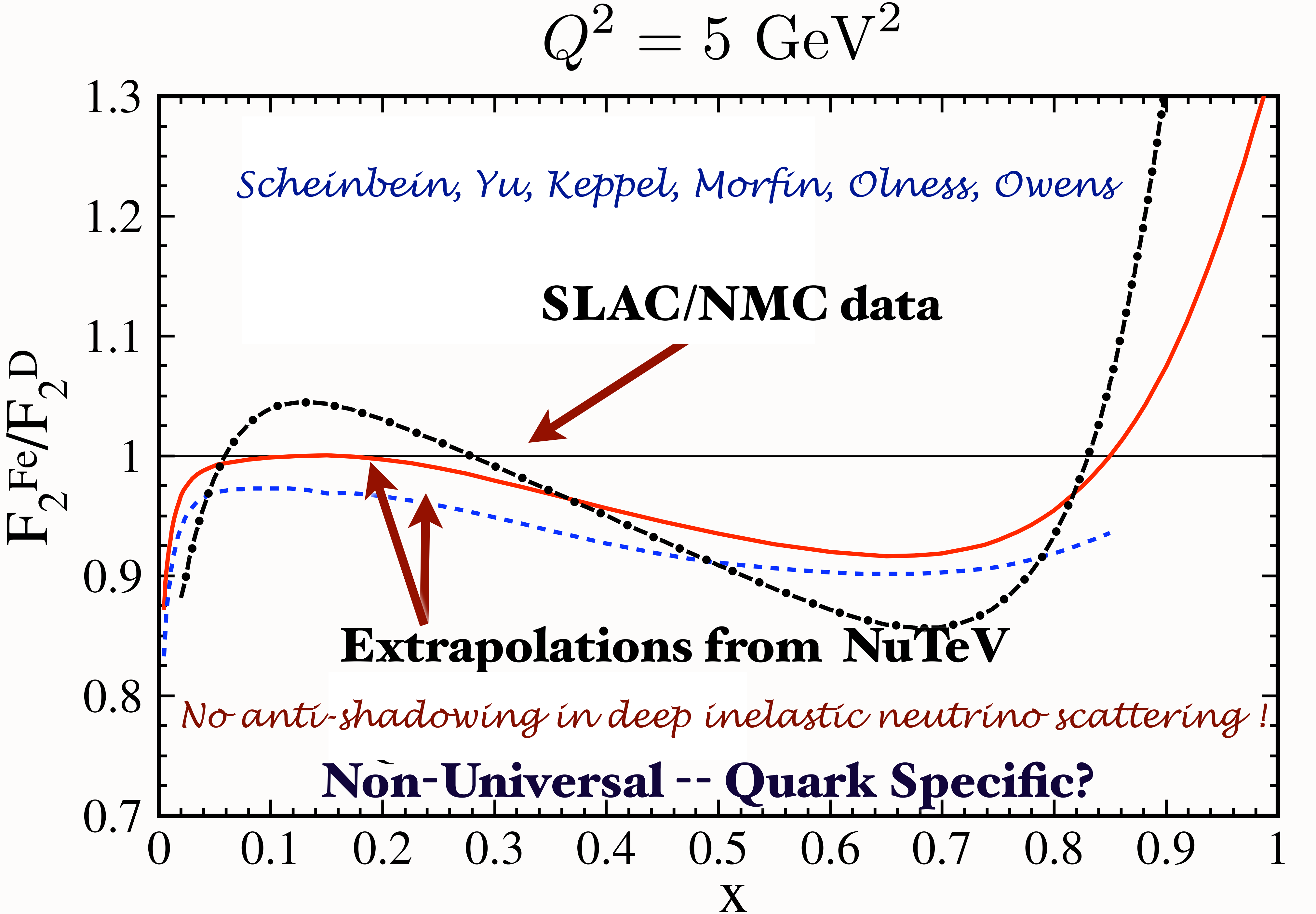
$$\left|\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)\right|^2$$





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].

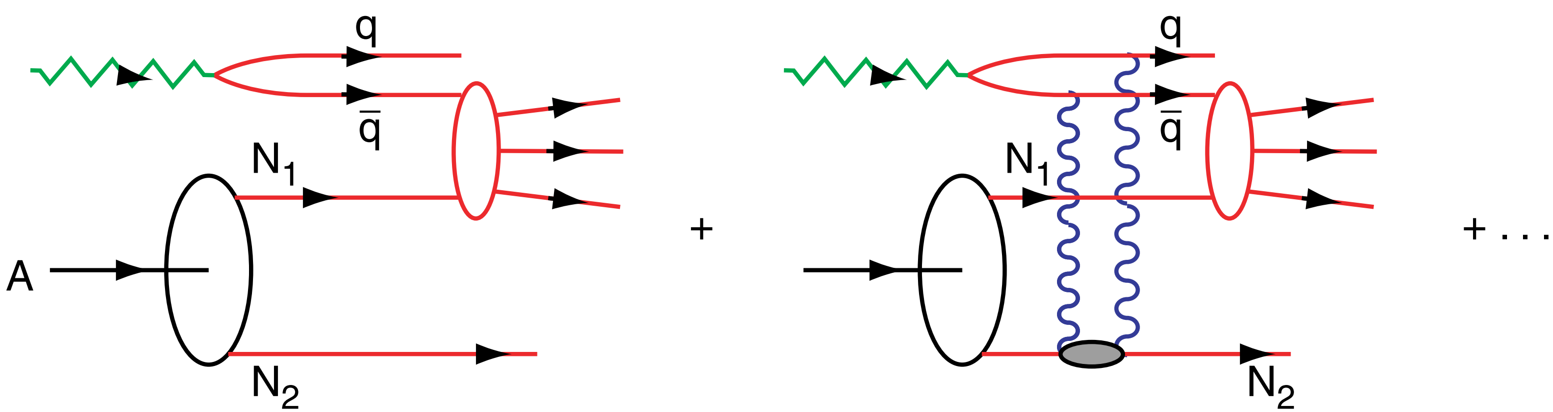
Is Antishadowing Non-Universal, Flavor Dependent?



$Q^2 = 5\ \text{GeV}^2$
1.3
1.2
1.1
1
0.9
0.8
0.7
F_2^{Fe}/F_2^D
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
x
Scheinbein, Yu, Keppel, Morfin, Olness, Owens
SLAC/NMC data
Extrapolations from NuTeV
No anti-shadowing in deep inelastic neutrino scattering !
Non-Universal -- Quark Specific?

Stodolsky
Pumplin, sjb
Gribov

Nuclear Shadowing in QCD



Shadowing depends on understanding leading twist-diffraction in DIS

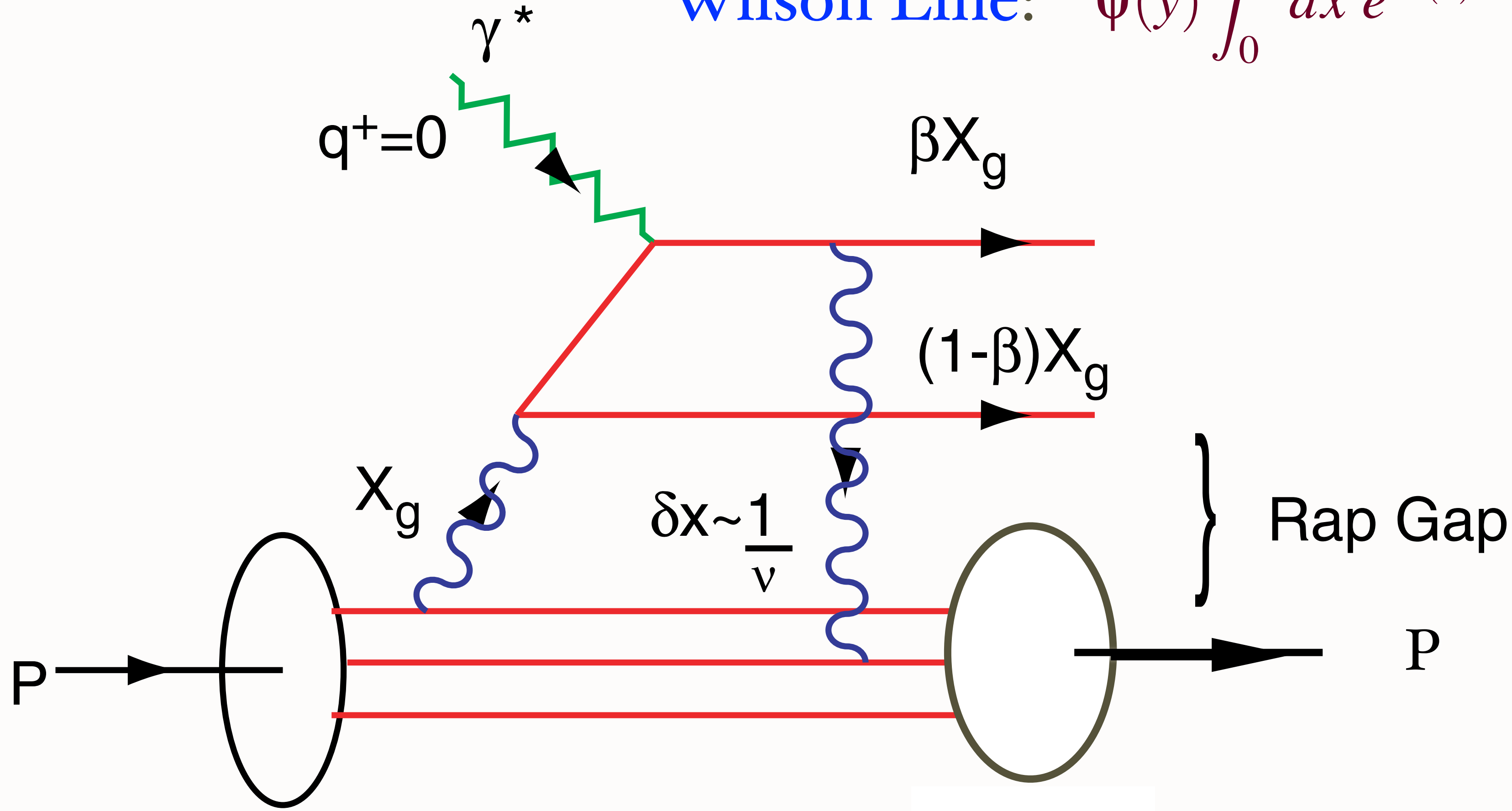
Nuclear Shadowing not included in nuclear LFWF !

Dynamical effect due to virtual photon interacting in nucleus

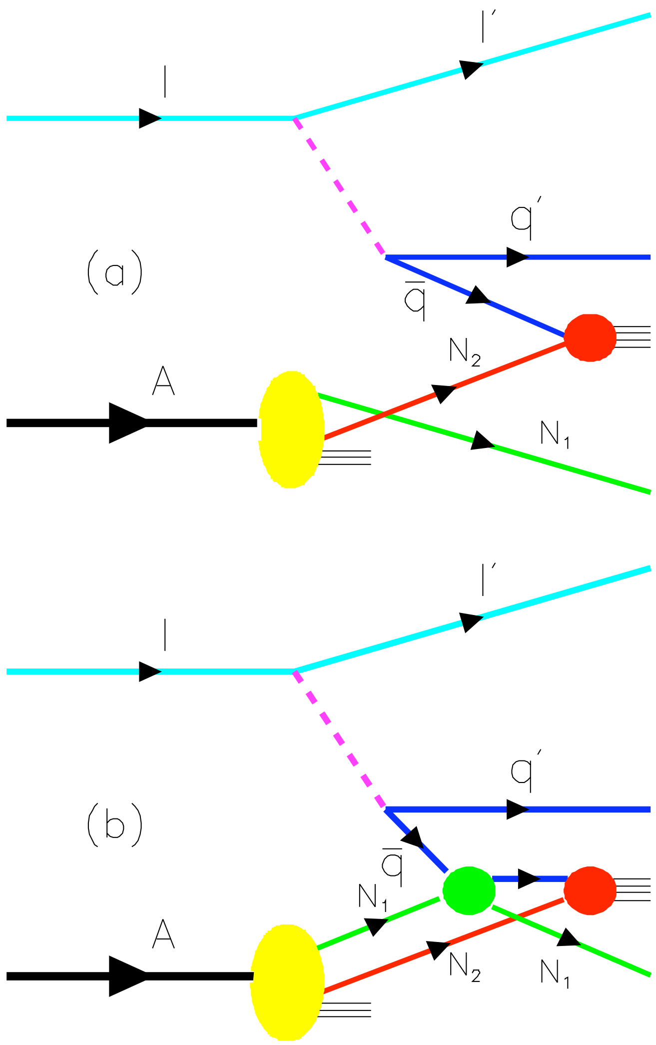
Hoyer, Marchal, Peigne, Sannino, sjb

QCD Mechanism for Rapidity Gaps

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



Reproduces lab-frame color dipole approach



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.

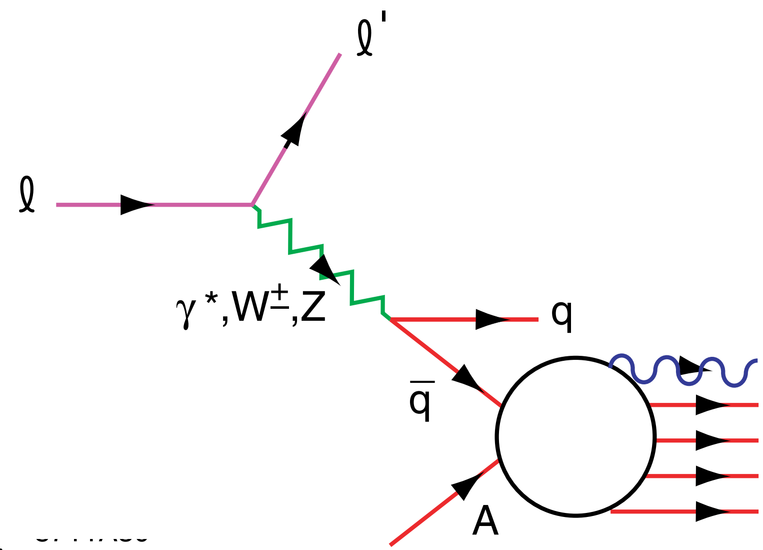
$\rightarrow$ Shadowing of the DIS nuclear structure functions.

Observed HERA DDIS produces nuclear shadowing

Origin of Regge Behavior of Deep Inelastic Structure Functions

$$F_{2p}(x) - F_{2n}(x) \propto x^{1/2}$$

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



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

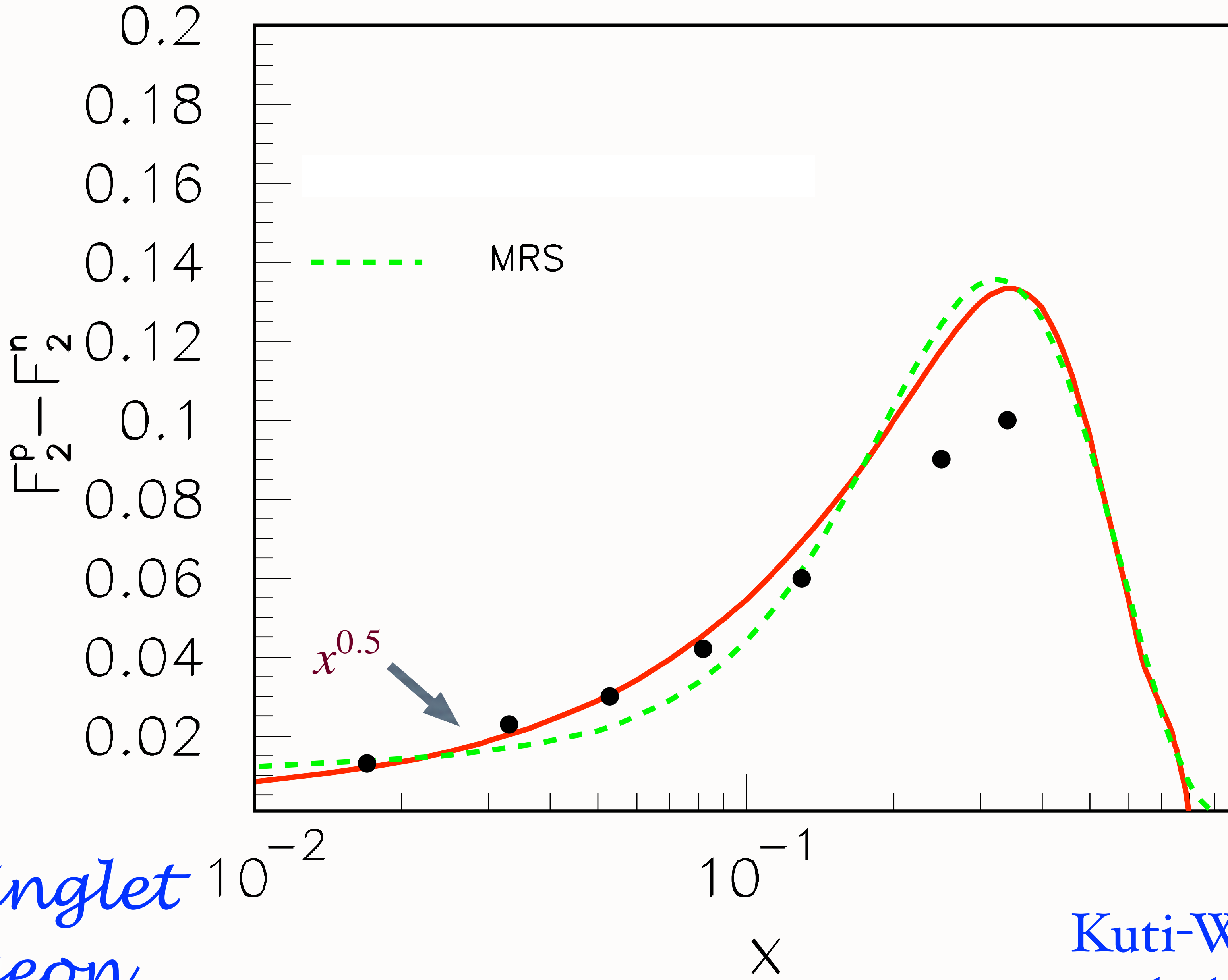
Nonsinglet Kuti-Weisskoff $F_{2p} - F_{2n} \propto \sqrt{x_{bj}}$ at small x_{bj}.

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

Landshoff, Polkinghorne, Short

Close, Gunion, sjb

Schmidt, Yang, Lu, sjb



Non-singlet Reggeon Exchange

Kuti-Weisskopf behavior

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

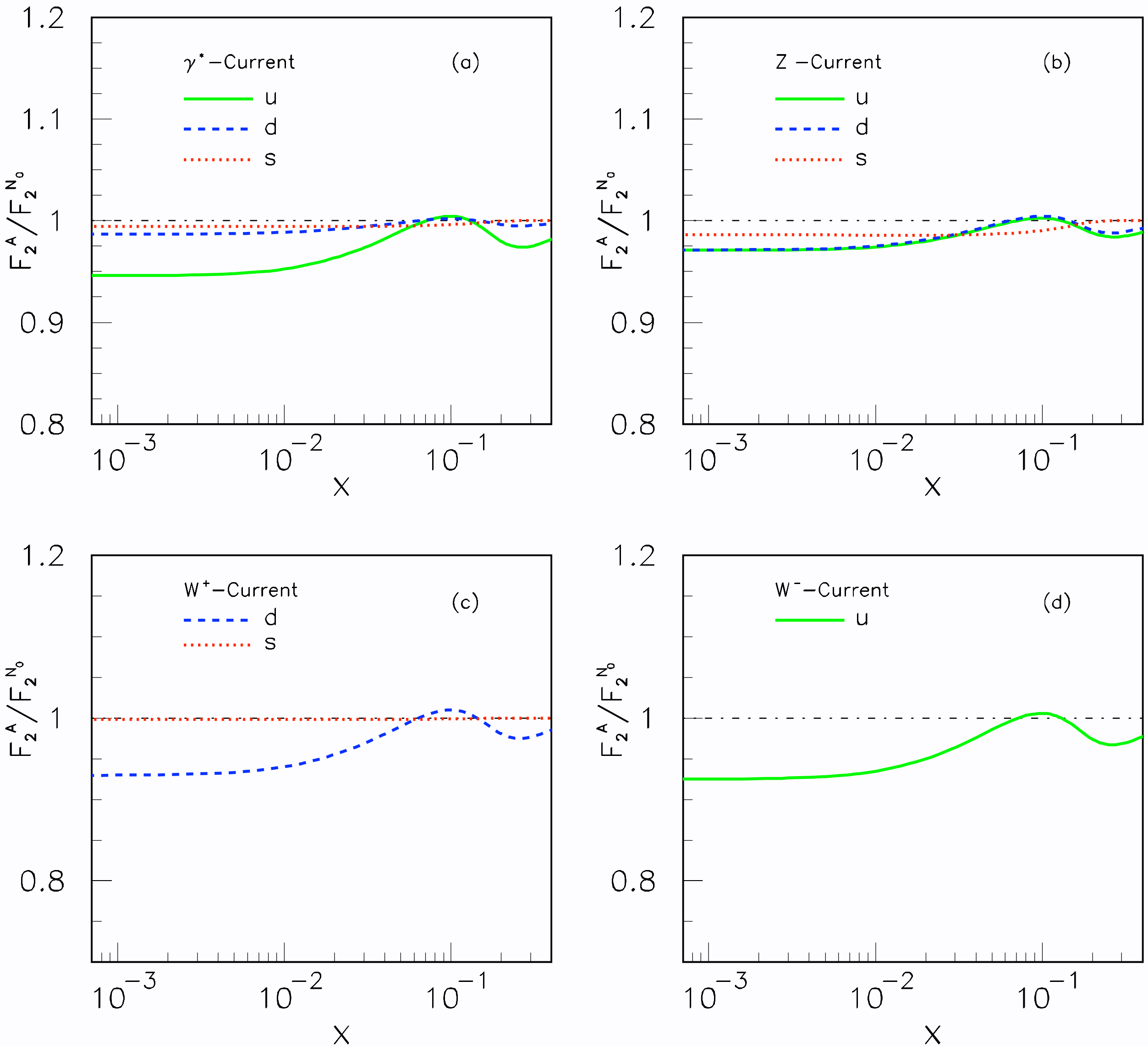
Depends on quark flavor!

Thus antishadowing is not universal

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

Critical test: Tagged Drell-Yan

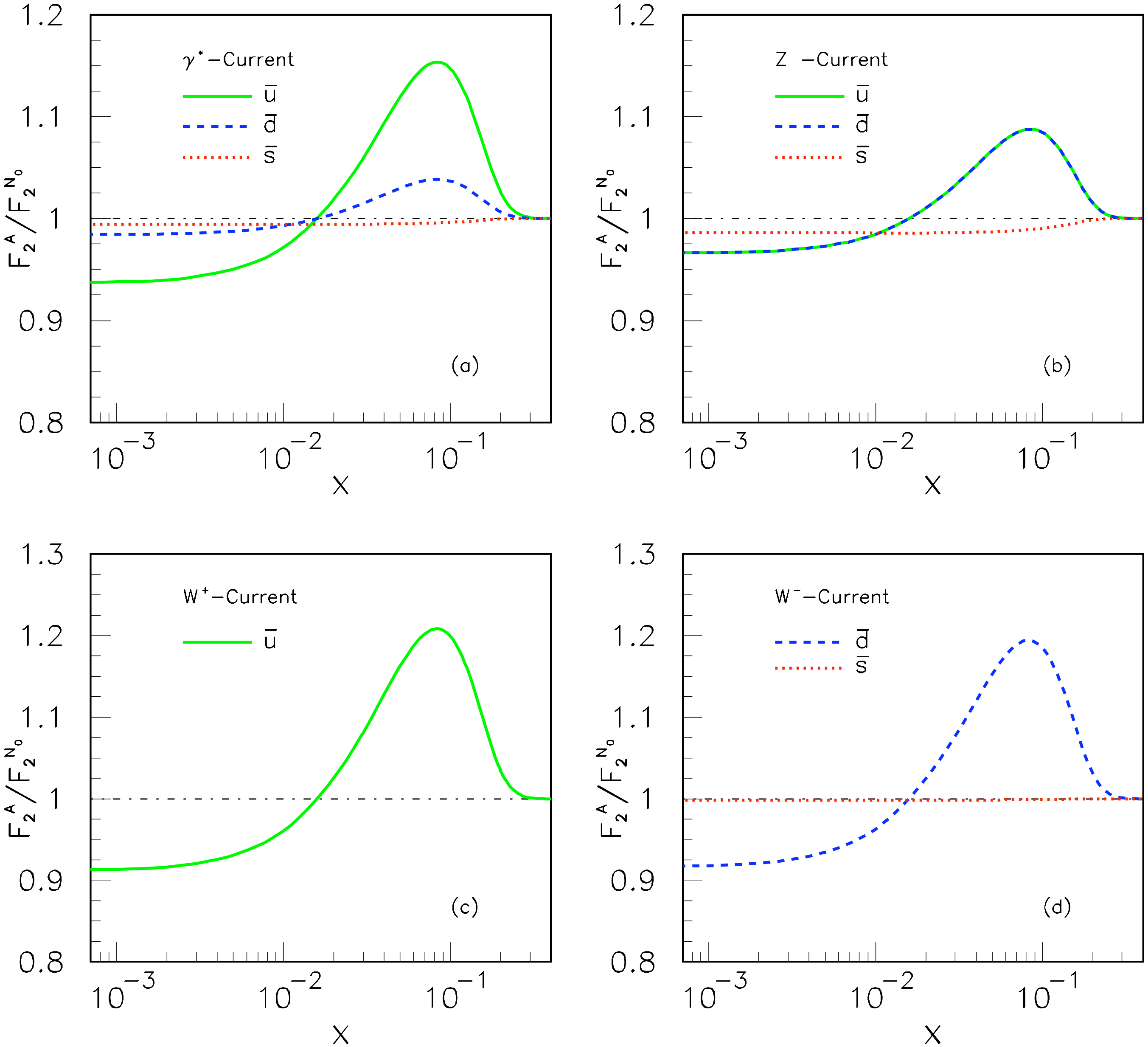
Shadowing and Antishadowing of DIS Structure Functions



S. J. Brodsky, I. Schmidt and J. J. Yang, "Nuclear Antishadowing in Neutrino Deep Inelastic Scattering," Phys. Rev. D 70, 116003 (2004) [arXiv:hep-ph/0409279].

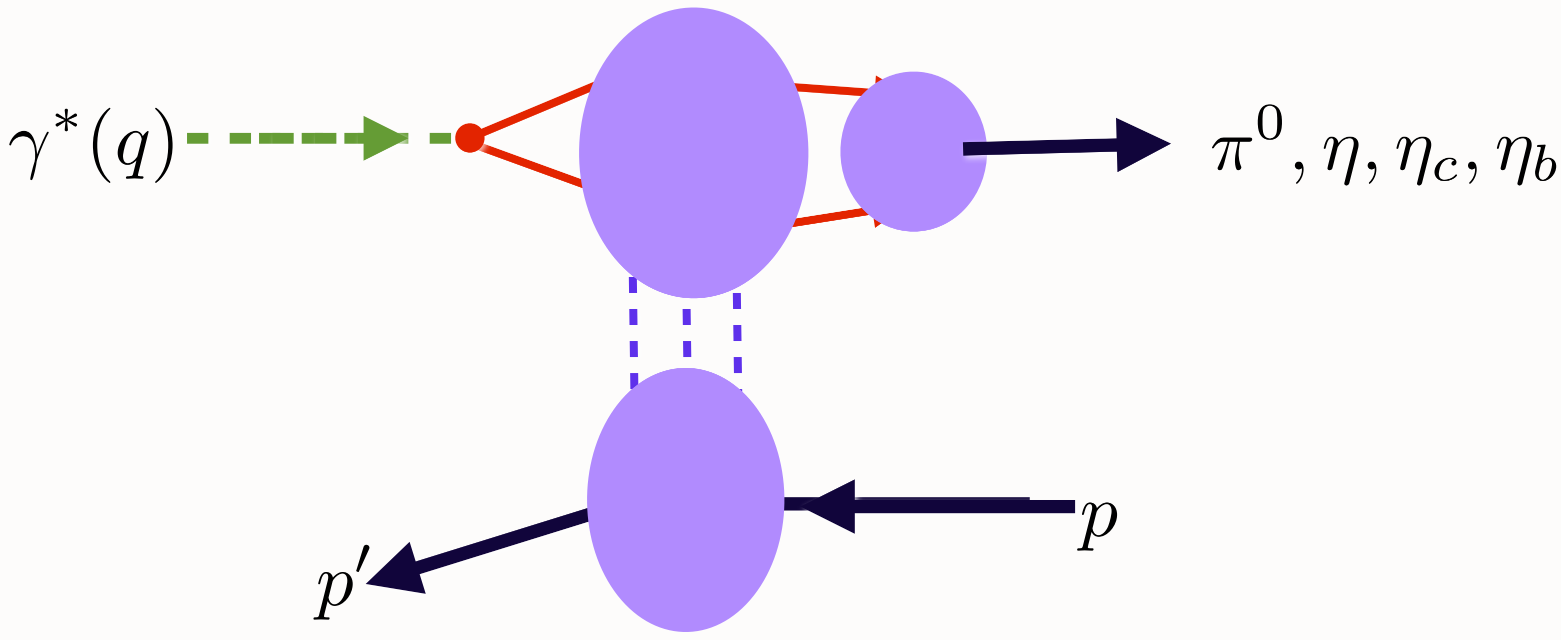
Modifies NuTeV extraction of $\sin^2\theta_W$

Test in flavor-tagged lepton-nucleus collisions

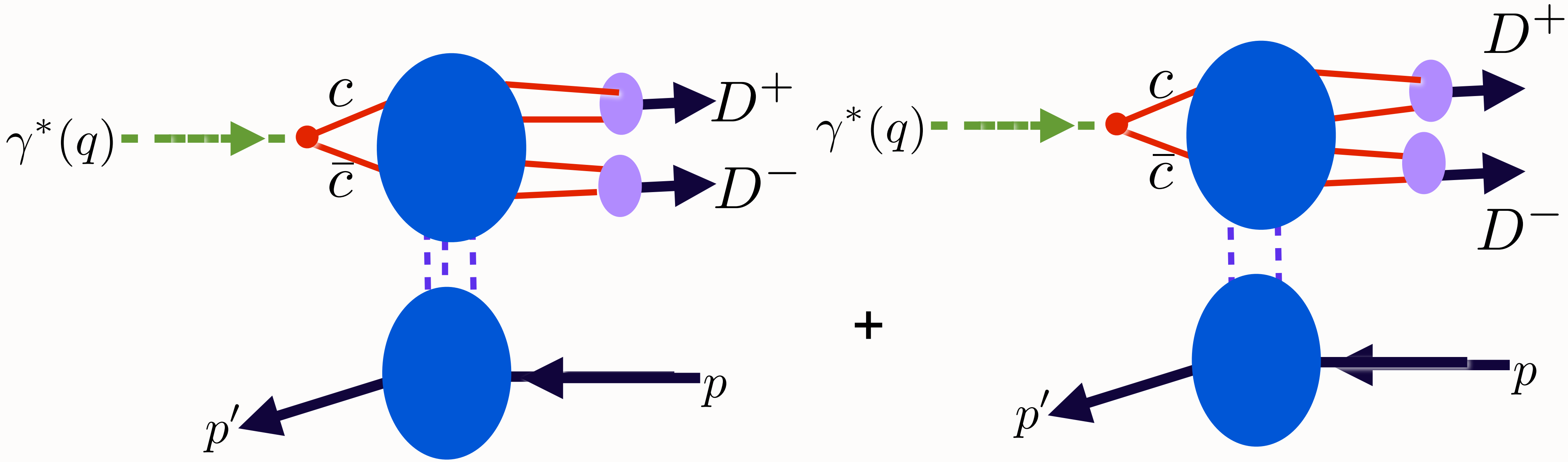


Schmidt, Yang; sjb

Nuclear Antishadowing not universal !



Odderon has never been observed!



Odderon-Pomeron Interference leads to D^+ D^- and B^+ B^- charge and angular asymmetry

Merino, Rathsman, sjb

Odderon at amplitude level

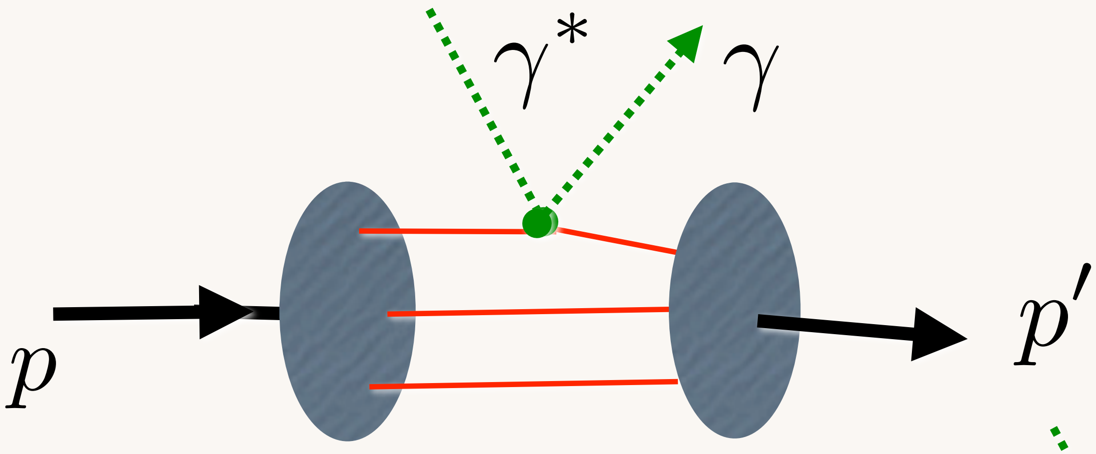
Strong enhancement at heavy-quark pair threshold from QCD Sakharov-Schwinger-Sommerfeld effect

$$\frac{\pi \alpha_s(\beta^2 s)}{\beta}$$

Hoang, Kuhn, sjb

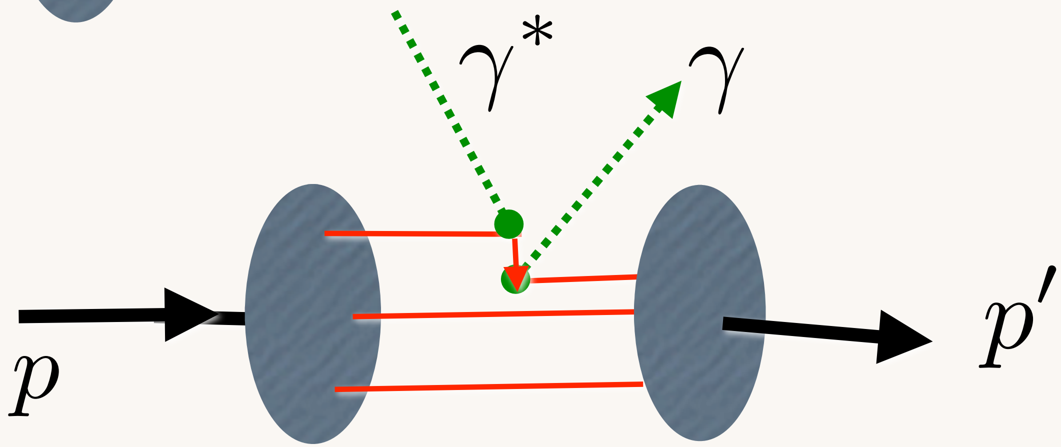
J=0 Fixed Pole Contribution to DVCS

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



Szczepaniak, Llanes-Estrada, sjb

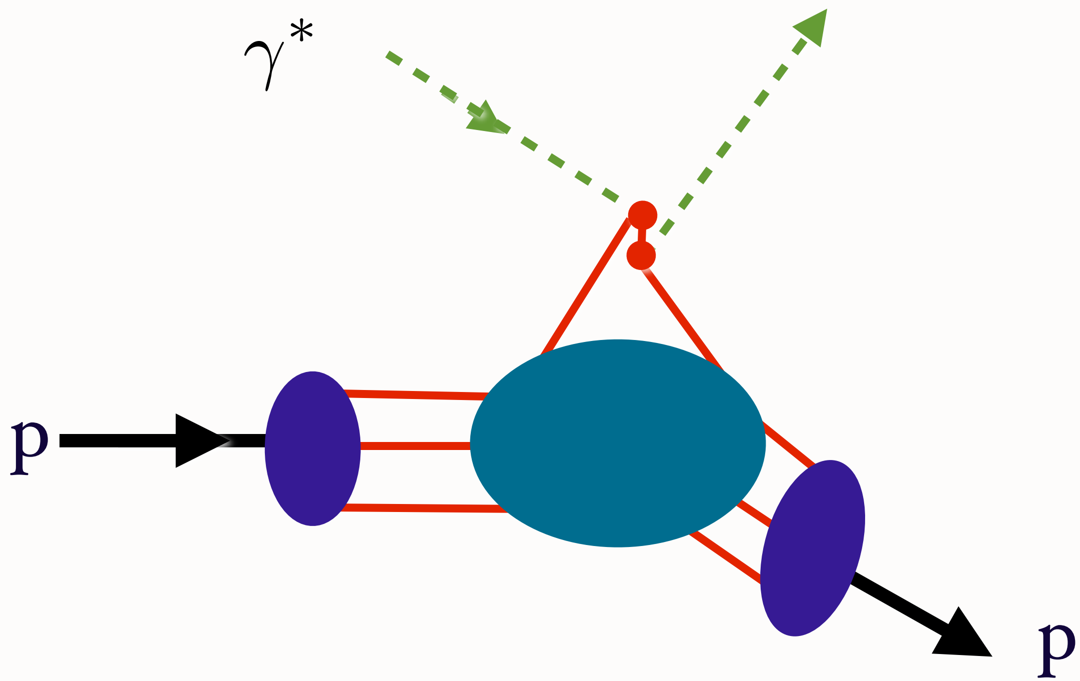
Close, Gunion, sjb



Real amplitude, independent of Q^2 at fixed t

Deeply Virtual Compton Scattering

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



Seagull interaction (instantaneous quark exchange or Z-graph)

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

Hard Reggeon Domain

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

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

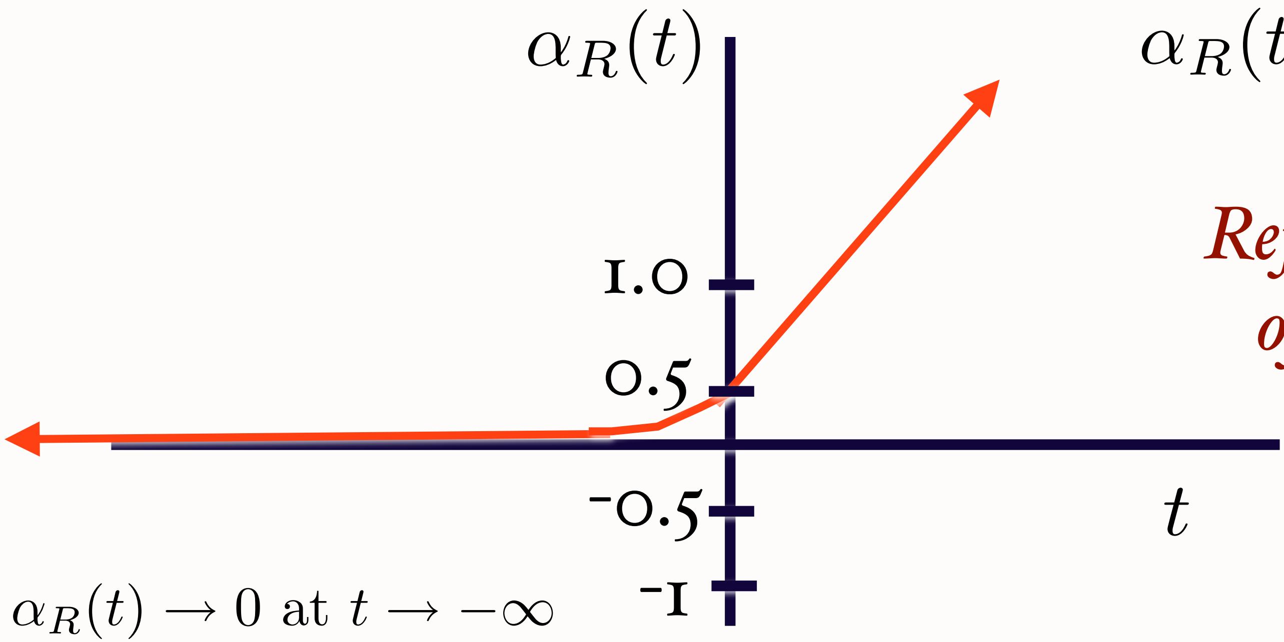
Reflects elementary coupling of two photons to quarks

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

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

Regge domain

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



$\alpha_R(t) \to 0$ at $t \to -\infty$

$\alpha_R(t) \to 0$ at $t \to -\infty$

J=0 fixed pole

Reflects elementary coupling of two photons to quarks

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

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

Fundamental test of QCD

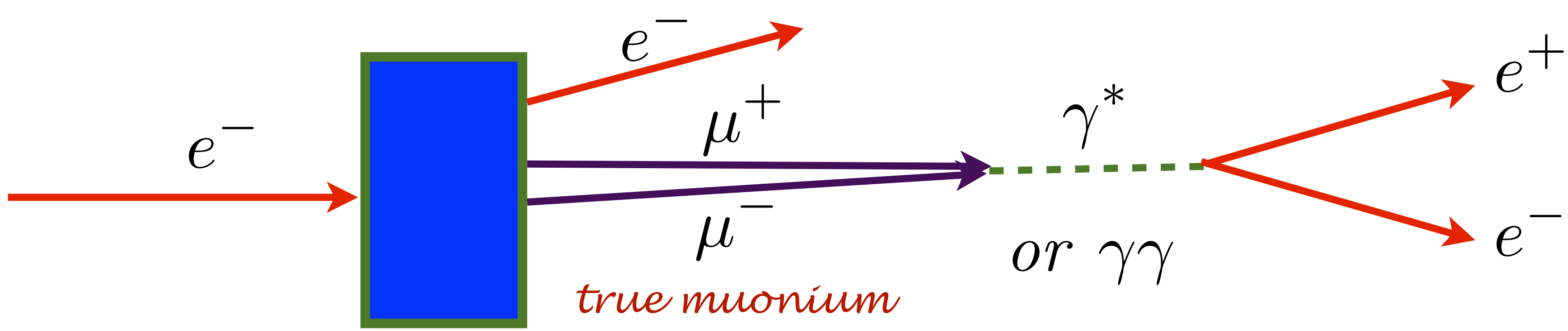
Novel Lepton Physics Studies in electron-nucleus reactions

Use JLab 4 GeV Intense Electron Beam

- **Production, spectroscopy of True Muonium $[\mu^+\mu^-]$**
- **Production of Relativistic Muonium $[\mu^+e^-]$**
- **Test All-Orders Bethe-Maximon Formula for Pair Production**
- **Lepton Charge Asymmetry**
- **Test Landau-Pomeranchuk-Migdal (LPM) Effect**

• Production of True Muonium [μ⁺μ⁻]

$$eZ \rightarrow eZ[\mu^+\mu^-]_{nS} \qquad q_{min} \simeq \frac{M^2_{\mu^+\mu^-}}{\nu} \sim 10 \text{ MeV}$$



- Produces all Rydberg Levels
- Analytic connection to continuum production -- enhanced by SSS at threshold
- Gap extends in cm multiplied by Lorentz boost
- Excite/De-excite levels with external fields, lasers

Production of True Muonium $[\mu^+\mu^-]$

PRL **102,** 213401 (2009) PHYSICAL REVIEW LETTERS week ending 29 MAY 2009

Production of the Smallest QED Atom: True Muonium ($\mu^+\mu^-$)

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(Received 22 April 2009; published 26 May 2009)

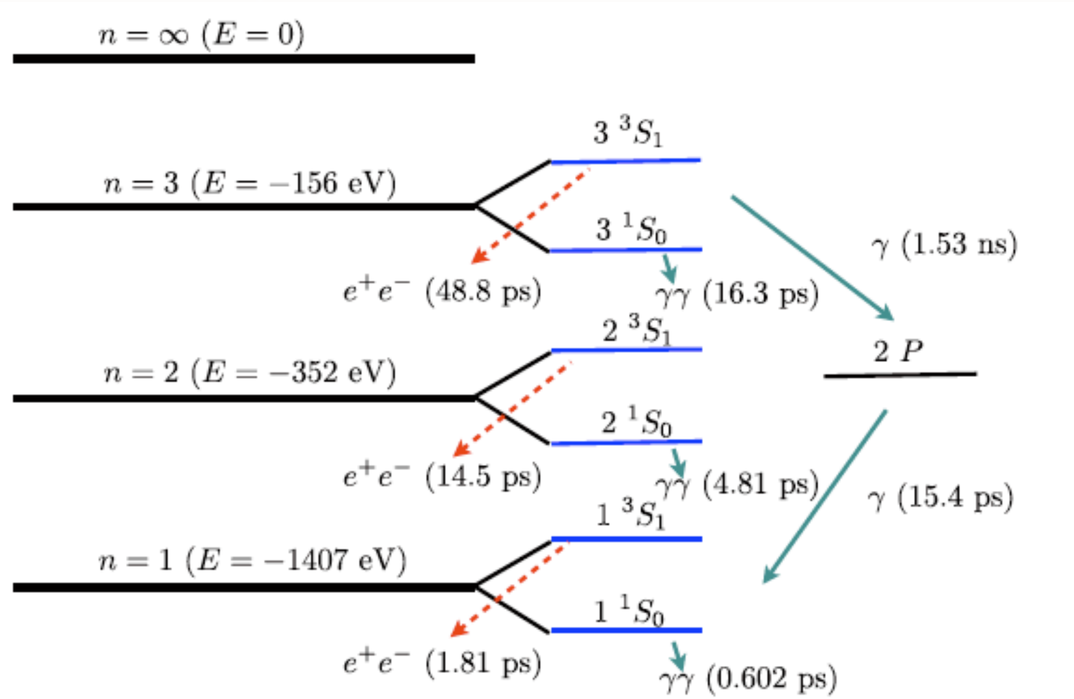
Rydberg Levels and Decays

$$\tau(n^3S_1 \to e^+e^-) = \frac{6\hbar n^3}{\alpha^5 mc^2}, \qquad \tau(n^1S_0 \to \gamma\gamma) = \frac{2\hbar n^3}{\alpha^5 mc^2},$$

$$\tau(2P \to 1S) = \left(\frac{3}{2}\right)^8 \frac{2\hbar}{\alpha^5 mc^2}, \qquad \tau(3S \to 2P) = \left(\frac{5}{2}\right)^9 \frac{4\hbar}{3\alpha^5 mc^2},$$

$$\frac{\tau(n^3S_1 \to e^+e^-)}{\tau(n^1S_0 \to \gamma\gamma)} = 3, \qquad \frac{\tau(2P \to 1S)}{\tau(n^1S_0 \to \gamma\gamma)} = \left(\frac{3}{2}\right)^8 \frac{1}{n^3} = \frac{25.6}{n^3},$$

$$\frac{\tau(3S \to 2P)}{\tau(2P \to 1S)} = \left(\frac{5}{3}\right)^9 = 99.2.$$

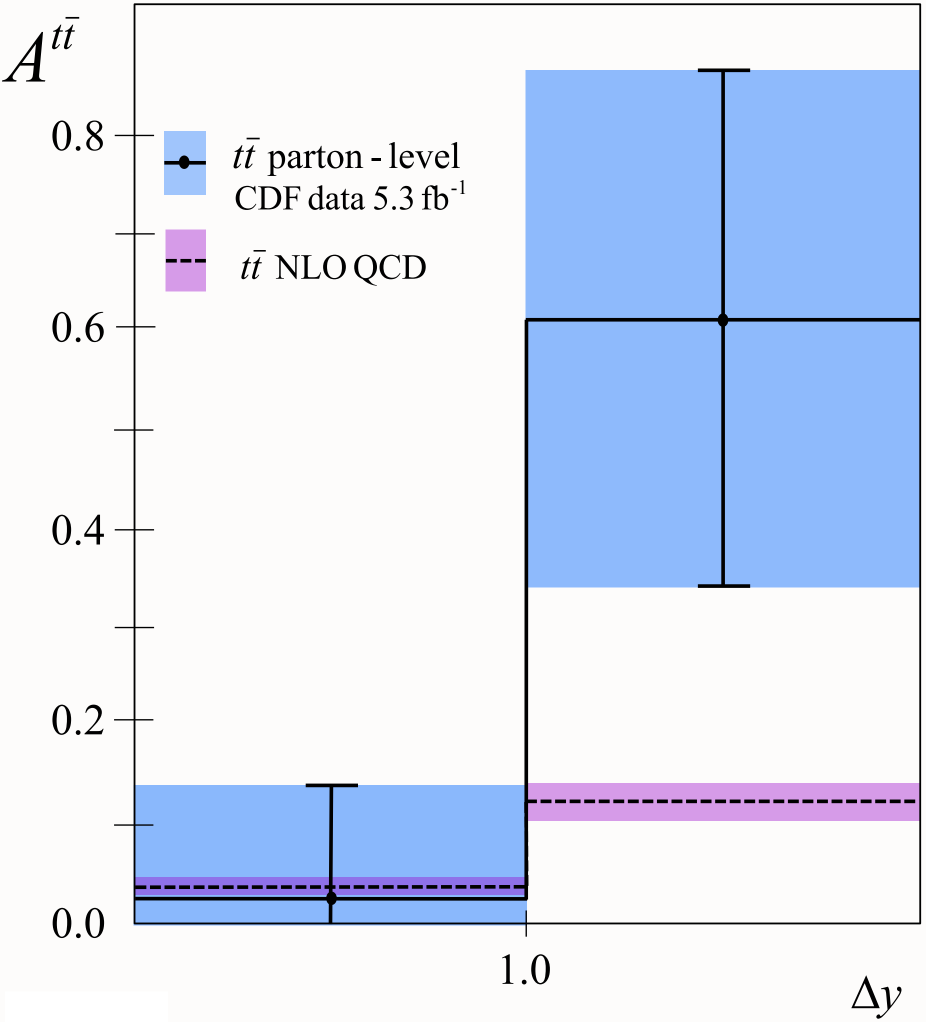


Production of bound triplet mu+ mu- system in collisions of electrons with atoms.
N. Arteaga-Romero, C. Carimalo, (Paris U., VI-VII) , V.G. Serbo, (Paris U., VI-VII & Novosibirsk State U.) . Jan 2000. 10pp.
Published in **Phys.Rev. A62:032501, 2000**.
e-Print: **hep-ph/0001278**

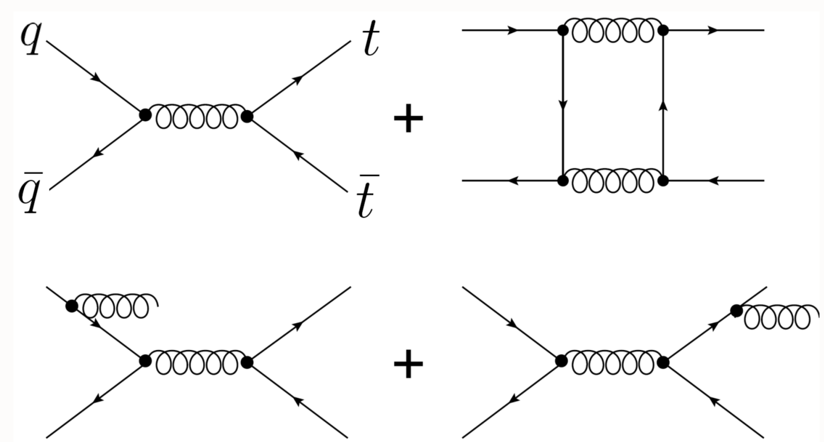
Goals

- Test QCD to maximum precision
- High precision determination of $\alpha_s(Q^2)$ at all scales
- Relate observable to observable --no scheme or scale ambiguity
- Eliminate renormalization scale ambiguity in a scheme-independent manner
- Relate renormalization schemes without ambiguity
- Maximize sensitivity to new physics at the colliders

Large $t\bar{t}$ asymmetries seen at CDF



$$A^{t\bar{t}}(\Delta y_i) = \frac{N(\Delta y_i) - N(-\Delta y_i)}{N(\Delta y_i) + N(-\Delta y_i)}$$



Fermilab-Pub-10-525-E

Evidence for a Mass Dependent Forward-Backward Asymmetry in Top Quark Pair Production

CDF Collaboration

Need to set multiple renormalization scales -- Lensing, DGLAP, ERBL Evolution ...

Choose renormalization scheme; e.g. $\alpha_s^R(\mu_R^{\rm init})$

↓

Choose μ_R^{init}*; arbitrary initial renormalization scale*

↓

Identify $\{\beta_i^R\}$ *− terms using* n_f *− terms*

through the PMC − BLM correspondence principle

↓

Shift scale of α_s *to* $\mu_R^{\rm PMC}$ *to eliminate* $\{\beta_i^R\}$ *− terms*

↓

Conformal Series

Result is independent of $\mu_R^{\rm init}$ *and scheme at fixed order*

PMC/BLM

No renormalization scale ambiguity

Result is independent of Renormalization scheme and initial scale

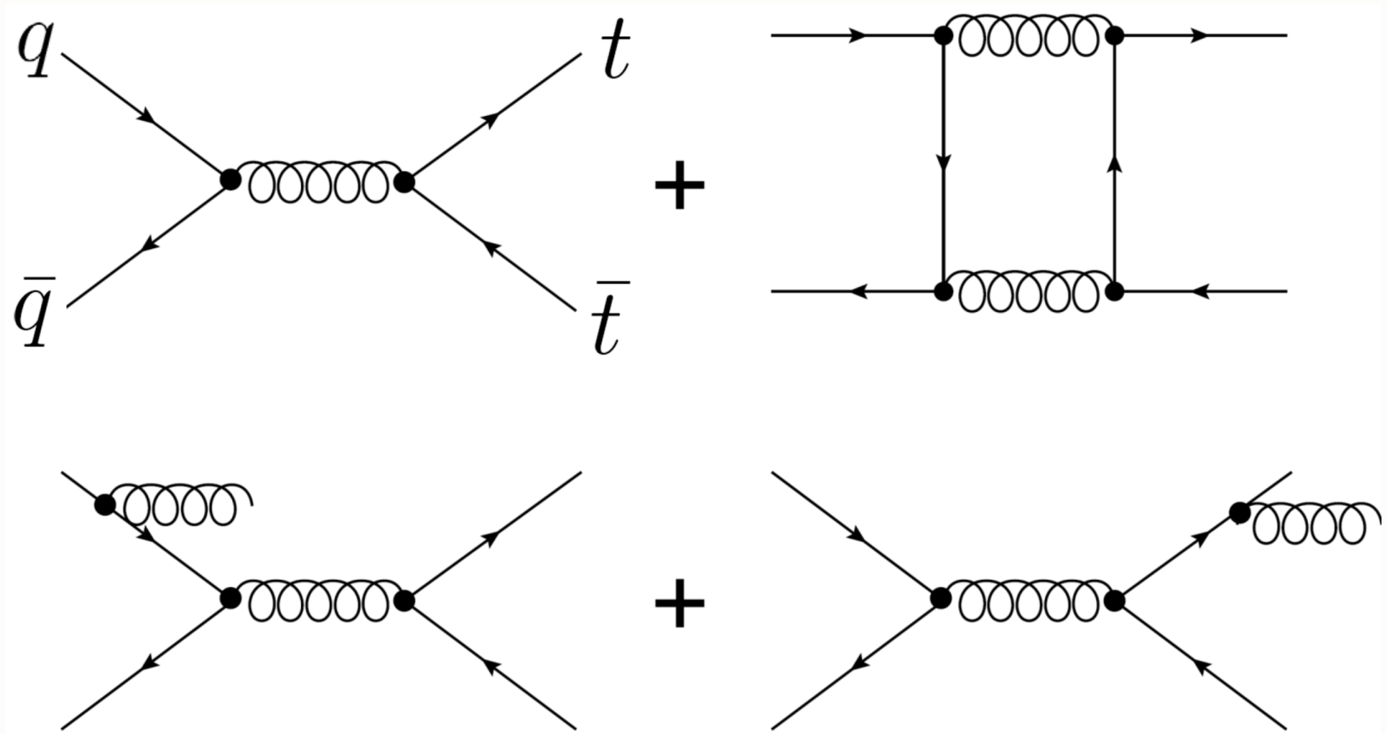
Apply to Evolution kernels, hard subprocesses

Eliminates unnecessary systematic uncertainty

Principle of Maximum Conformality

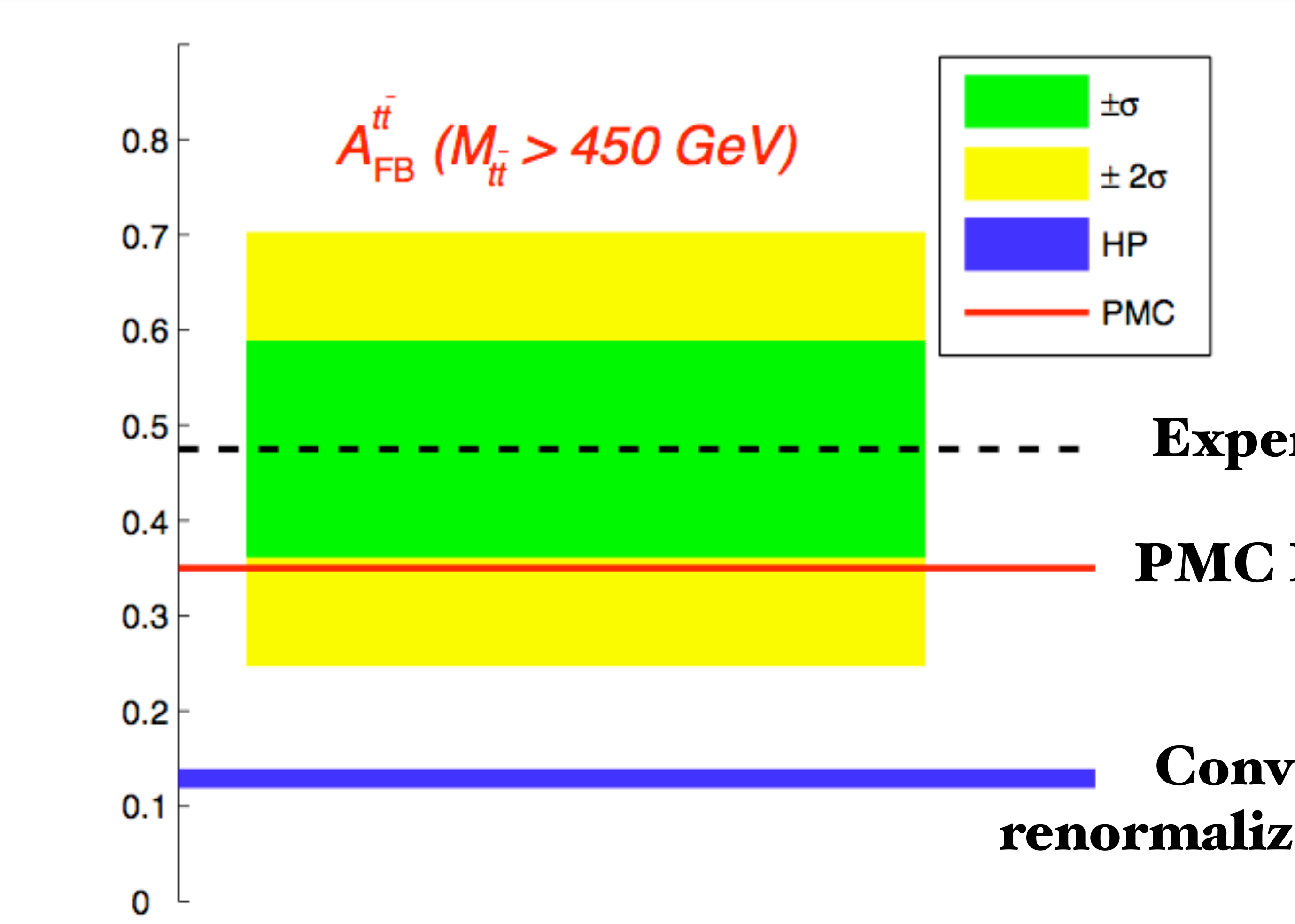
Xing-Gang Wu
Leonardo di Giustino, SJB

Reduced renormalization scale



Conventional pQCD approach

Xing-Gang Wu
Leonardo di Giustino, SJB



Experimental asymmetry

PMC Prediction

Conventional: guess renormalization scale and range

$t\bar{t}$ asymmetry predicted by pQCD NNLO within
1 σ of CDF/D0 measurements using PMC/BLM scale setting

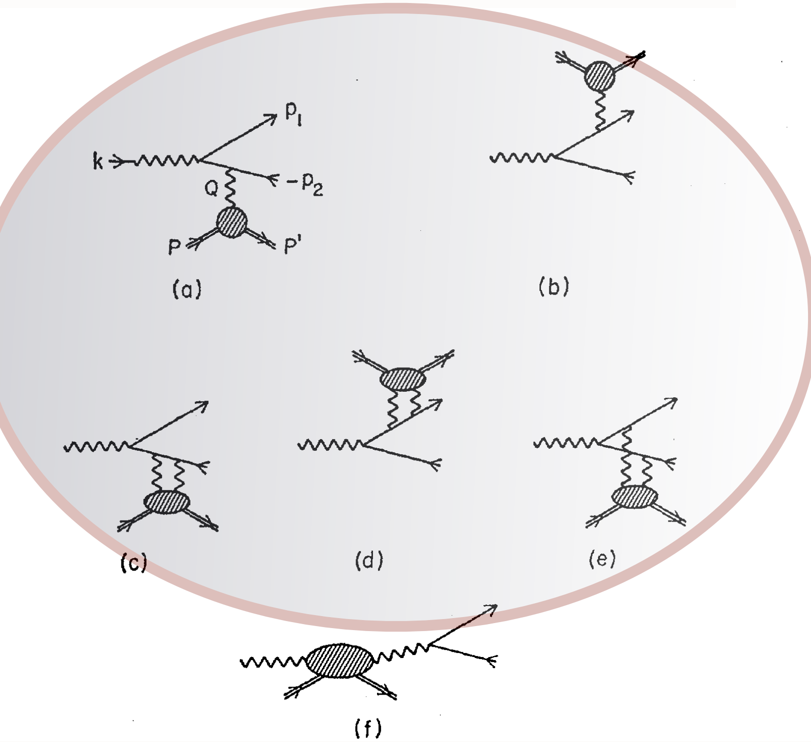
Eliminating the Renormalization Scale Ambiguity for Top-Pair Production Using the Principle of Maximum Conformality

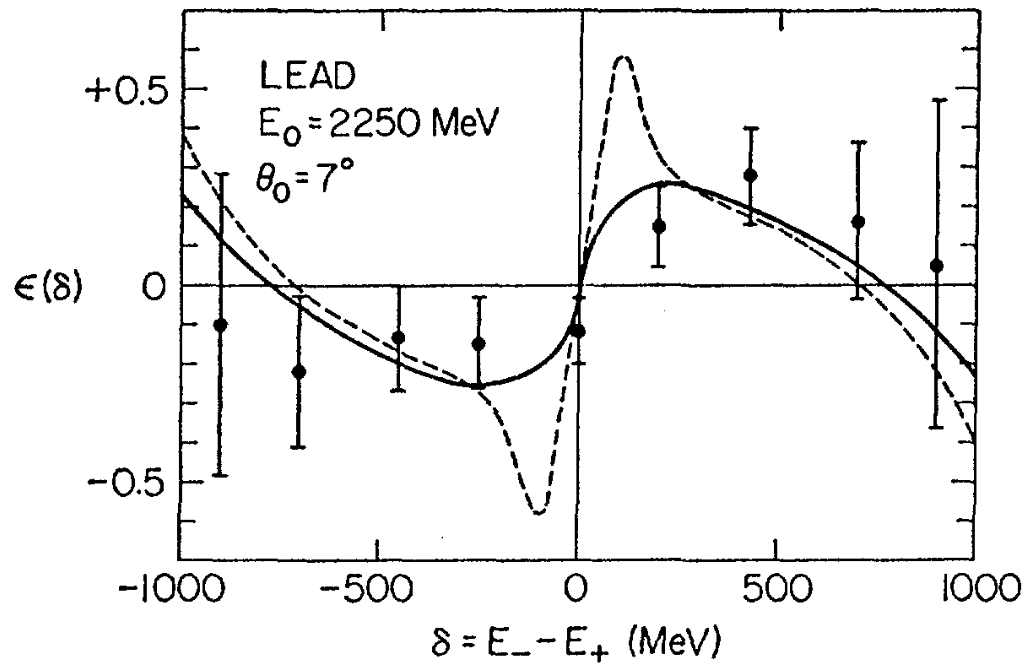
Second Born Corrections to Wide-Angle High-Energy Electron Pair Production and Bremsstrahlung*

J. Gillespie and sjb

PR 173 1011 (1968)

$$\gamma Z \to e^+ e^- Z$$





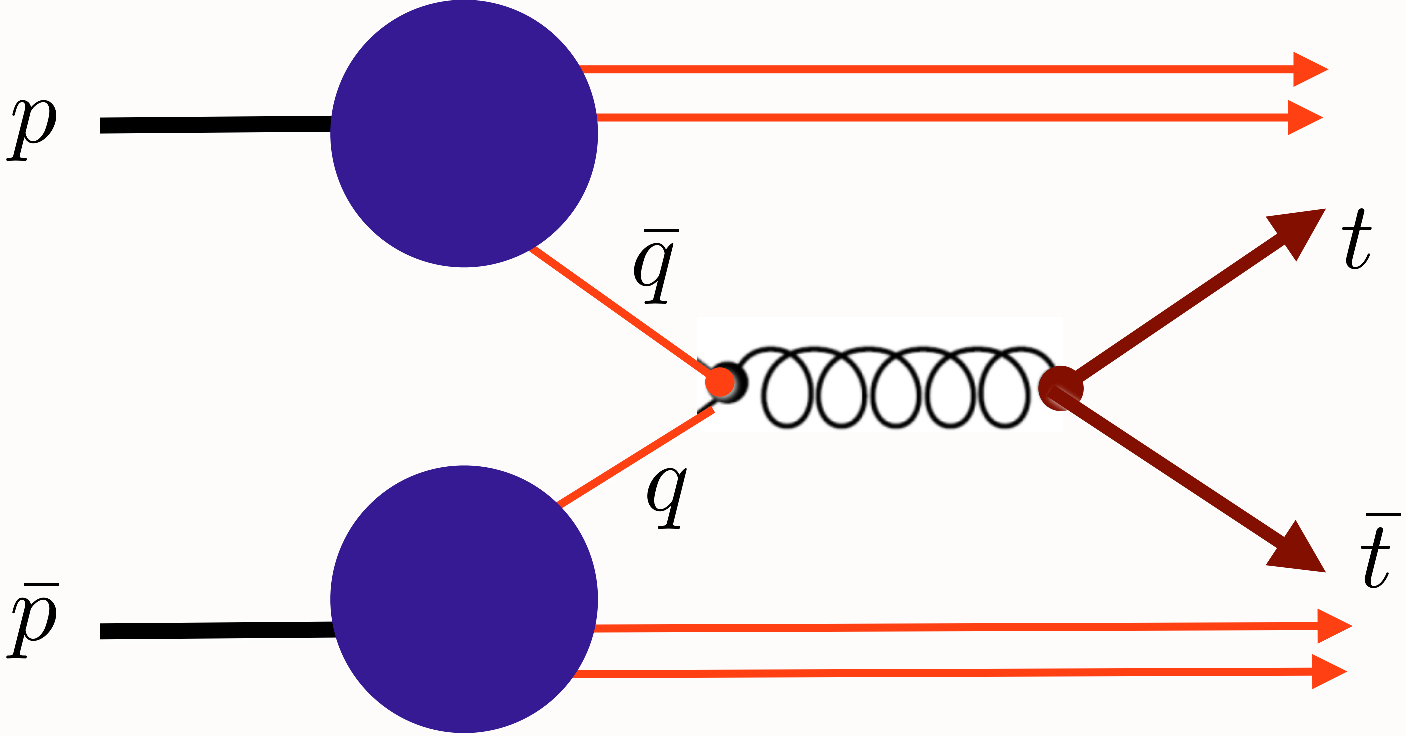
[4] J. G. Asbury, W. K. Bertram, U. Becker, P. Joos, M. Rohde, A. J. S. Smith, S. Friedlander, C. L. Jordan, and S. C. C. Ting, Phys. Rev. **161**, 1344 (1967), and references therein.

Ting: DESY 1967

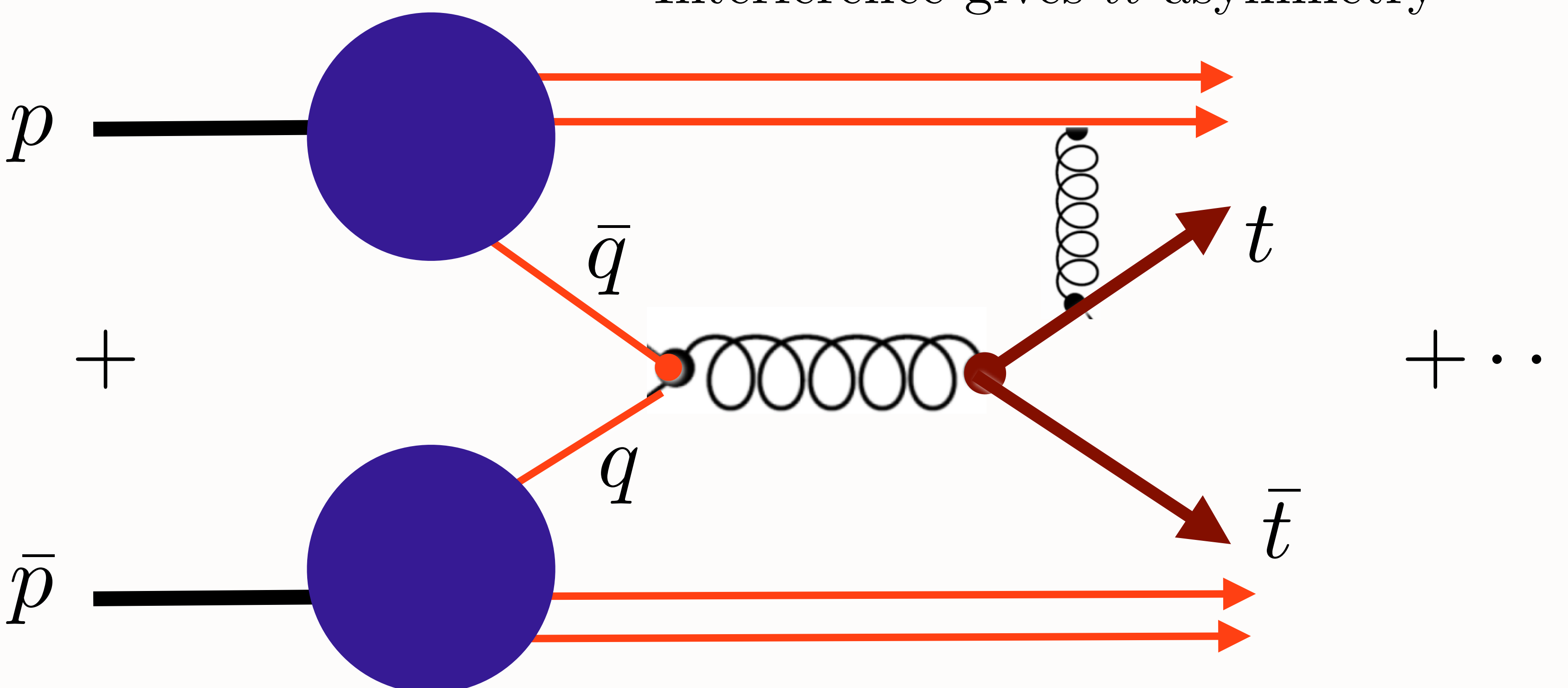
$$\Re \equiv \frac{d\sigma_{\text{int}}}{d\sigma_{\text{Born}}} = \tfrac{1}{4} Z\alpha\pi |\mathbf{Q}|$$

$$\times \left[\frac{(E_2 - E_1)Q^2 + 2E_2 k\cdot p_2 - 2E_1 k\cdot p_1}{E_1E_2Q^2 + (k\cdot p_1)(k\cdot p_2)} \right] + O(Z\alpha)^3$$

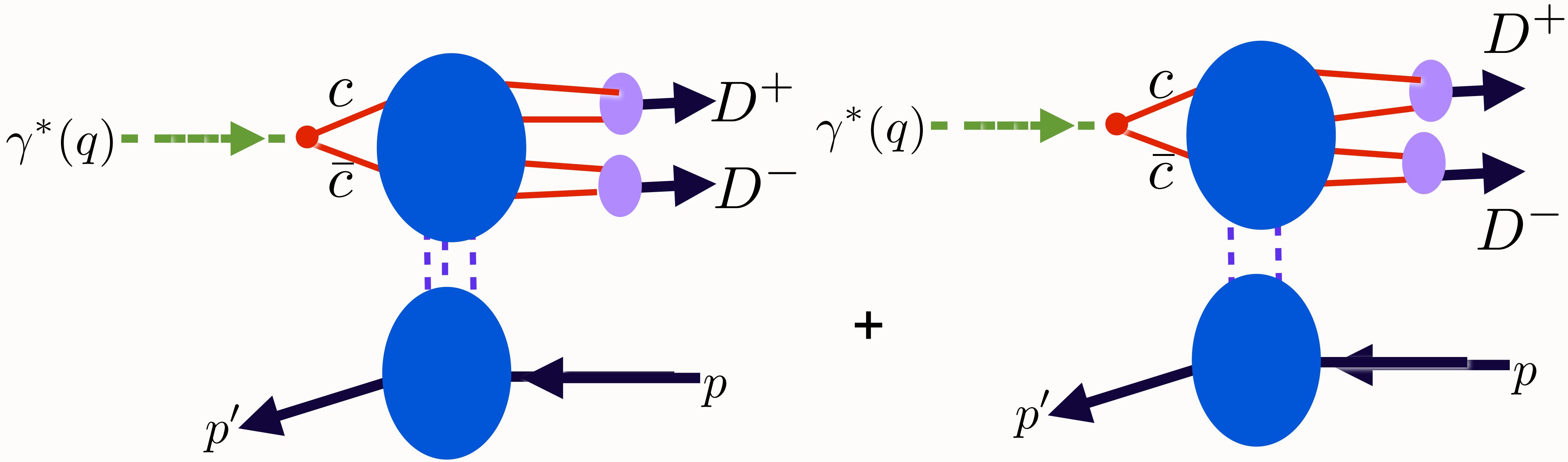
(spin zero, point nucleus).



Interference gives $t\bar{t}$ asymmetry



QCD Analysis: B. von Harling, Y. Zhao, sjb



Odderon-Pomeron Interference leads to D+ D- and B+ B- charge and angular asymmetry

Merino, Rathsman, sjb

Odderon at amplitude level

Strong enhancement at heavy-quark pair threshold from QCD Sakharov-Schwinger-Sommerfeld effect

$$\frac{\pi \alpha_s(\beta^2 s)}{\beta}$$

Hoang, Kuhn, sjb

Strangeness Asymmetry

The strange and anti-strange distributions of the proton need not be $s(x, Q^2) \neq \bar{s}(x, Q^2)$; this asymmetry reflects fundamental nonperturbative aspects of the proton's structure.

Meson-Baryon fluctuations produce asymmetry

Compare $D(s\bar{c})$ and $D(\bar{s}c)$
in proton fragmentation region at the EIC

Relate Observables to Each Other

- Eliminate intermediate scheme
- No scale ambiguity
- Transitive!
- Commensurate Scale Relations
- Conformal Template
- Example: Generalized Crewther Relation

$$R_{e^+e^-}(Q^2) \equiv 3 \sum_{\text{flavors}} e_q^{\,2} \left[1 + \frac{\alpha_R(Q)}{\pi} \right] .$$

$$\int_0^1 dx \left[g_1^{ep}(x,Q^2) - g_1^{en}(x,Q^2) \right] \equiv \frac{1}{3} \left| \frac{g_A}{g_V} \right| \left[1 - \frac{\alpha_{g_1}(Q)}{\pi} \right]$$

$$\frac{\alpha_R(Q)}{\pi} = \frac{\alpha_{\overline{MS}}(Q)}{\pi} + \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^2 \left[\left(\frac{41}{8} - \frac{11}{3}\zeta_3\right) C_A - \frac{1}{8} C_F + \left(-\frac{11}{12} + \frac{2}{3}\zeta_3\right) f\right]$$
$$+ \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^3 \left\{\left(\frac{90445}{2592} - \frac{2737}{108}\zeta_3 - \frac{55}{18}\zeta_5 - \frac{121}{432}\pi^2\right) C_A^2 + \left(-\frac{127}{48} - \frac{143}{12}\zeta_3 + \frac{55}{3}\zeta_5\right) C_A C_F - \frac{23}{32} C_F^2\right.$$
$$+ \left[\left(-\frac{970}{81} + \frac{224}{27}\zeta_3 + \frac{5}{9}\zeta_5 + \frac{11}{108}\pi^2\right) C_A + \left(-\frac{29}{96} + \frac{19}{6}\zeta_3 - \frac{10}{3}\zeta_5\right) C_F\right] f$$
$$\left. + \left(\frac{151}{162} - \frac{19}{27}\zeta_3 - \frac{1}{108}\pi^2\right) f^2 + \left(\frac{11}{144} - \frac{1}{6}\zeta_3\right) \frac{d^{abc}d^{abc}}{C_F d(R)} \frac{\left(\sum_f Q_f\right)^2}{\sum_f Q_f^2}\right\}.$$

$$\frac{\alpha_{g_1}(Q)}{\pi} = \frac{\alpha_{\overline{MS}}(Q)}{\pi} + \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^2 \left[\frac{23}{12} C_A - \frac{7}{8} C_F - \frac{1}{3} f\right]$$
$$+ \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^3 \left\{\left(\frac{5437}{648} - \frac{55}{18}\zeta_5\right) C_A^2 + \left(-\frac{1241}{432} + \frac{11}{9}\zeta_3\right) C_A C_F + \frac{1}{32} C_F^2\right.$$
$$\left. + \left[\left(-\frac{3535}{1296} - \frac{1}{2}\zeta_3 + \frac{5}{9}\zeta_5\right) C_A + \left(\frac{133}{864} + \frac{5}{18}\zeta_3\right) C_F\right] f + \frac{115}{648} f^2\right\}.$$

Eliminate MSbar, Find Amazing Simplification

Lu, Kataev, Gabadadze, Sjb

Generalized Crewther Relation

$$[1 + \frac{\alpha_R(s^*)}{\pi}][1 - \frac{\alpha_{g_1}(q^2)}{\pi}] = 1$$

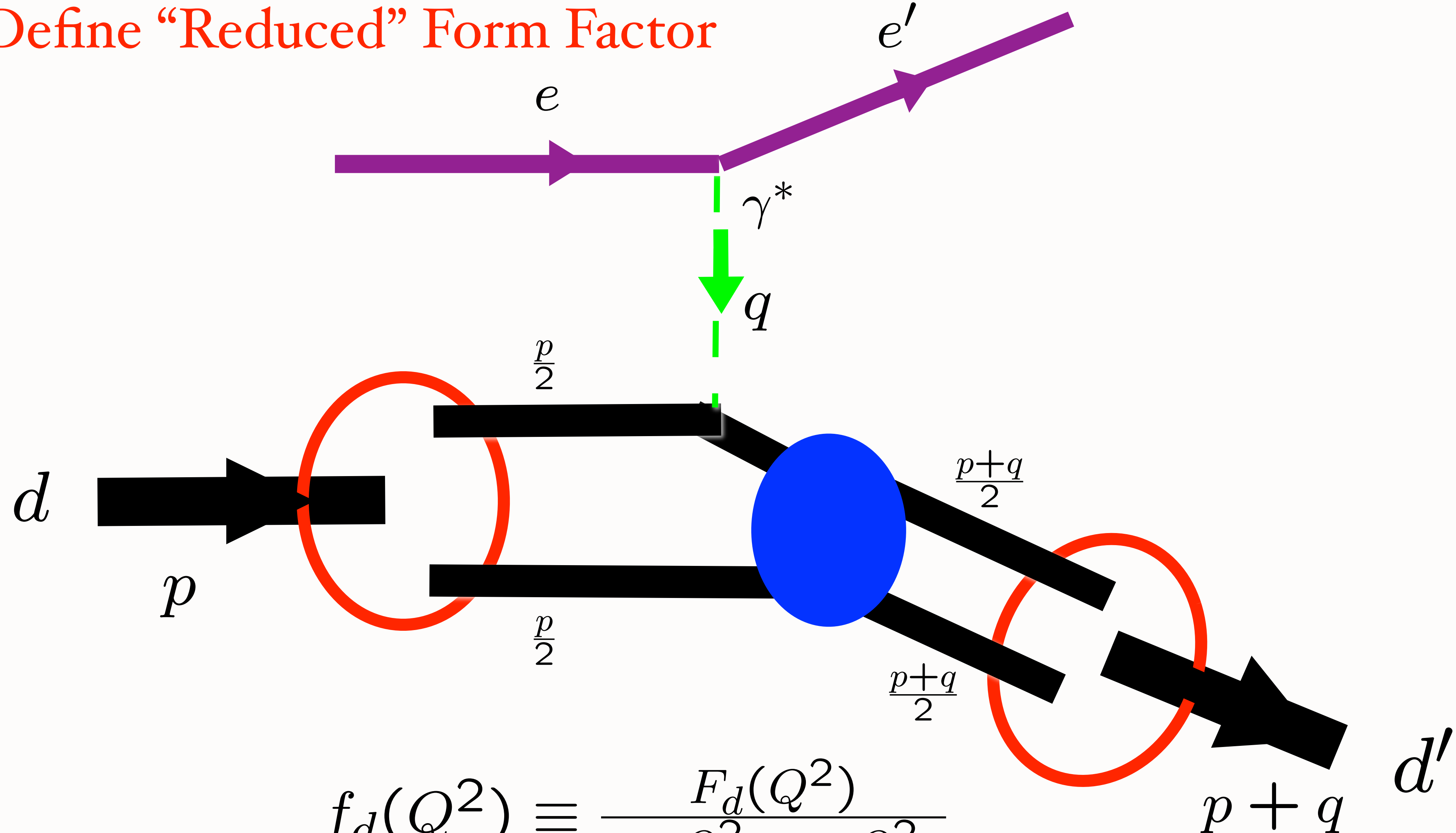
$$\sqrt{s^*} \simeq 0.52Q$$

Conformal relation true to all orders in perturbation theory

No radiative corrections to axial anomaly

Nonconformal terms set relative scales (BLM)
Analytic matching at quark thresholds
No renormalization scale ambiguity!

Define "Reduced" Form Factor



$$f_d(Q^2) \equiv \frac{F_d(Q^2)}{F_p(\frac{Q^2}{4})F_n(\frac{Q^2}{4})}$$

Elastic electron-deuteron scattering

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

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

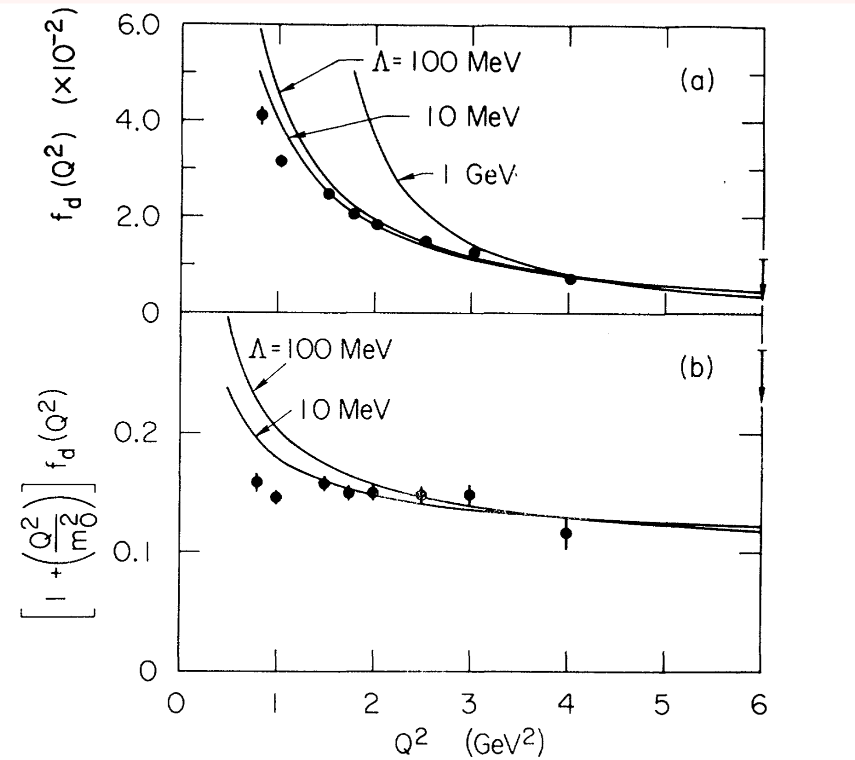
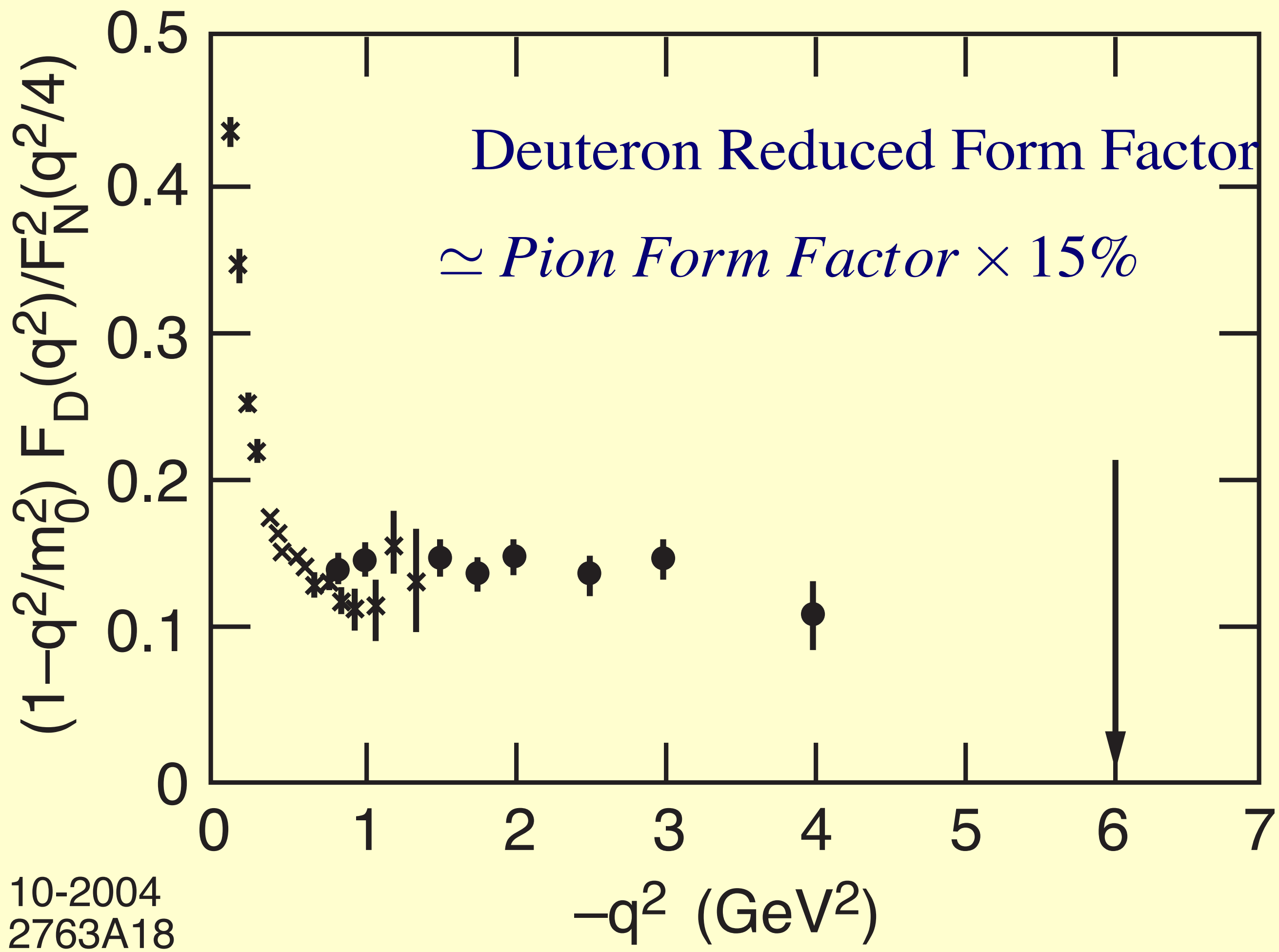


FIG. 2. (a) Comparison of the asymptotic QCD prediction $f_d(Q^2) \propto (1/Q^2)[\ln(Q^2/\Lambda^2)]^{-1-(2/5)C_F/\beta}$ with final data of Ref. 10 for the reduced deuteron form factor, where $F_N(Q^2) = [1+Q^2/(0.71\ \mathrm{GeV}^2)]^{-2}$. The normalization is fixed at the $Q^2 = 4\ \mathrm{GeV}^2$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

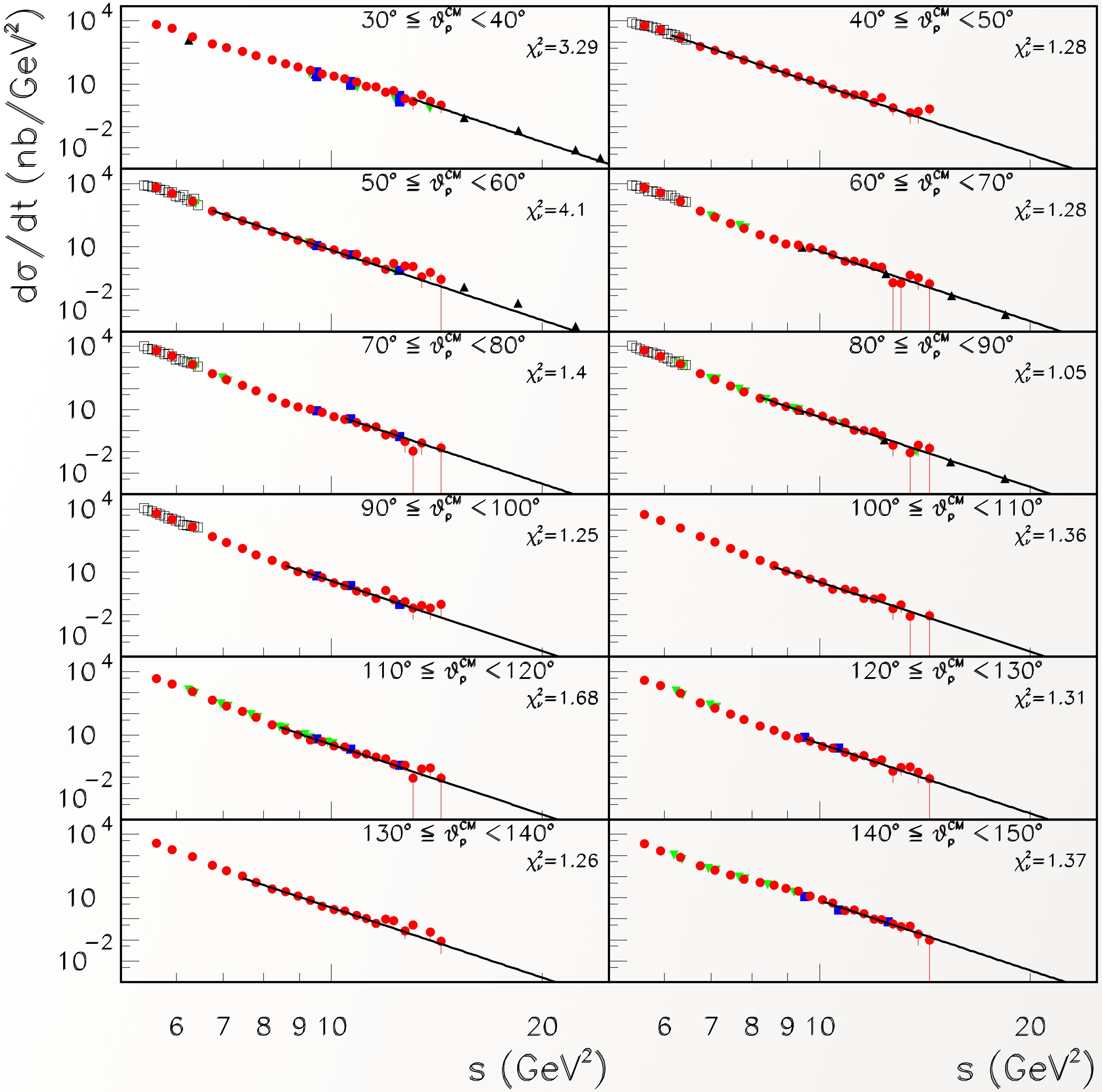
Same large momentum transfer behavior as pion form factor

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



- 15% Hidden Color in the Deuteron

Deuteron Photodisintegration



J-Lab

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

Reflects conformal invariance

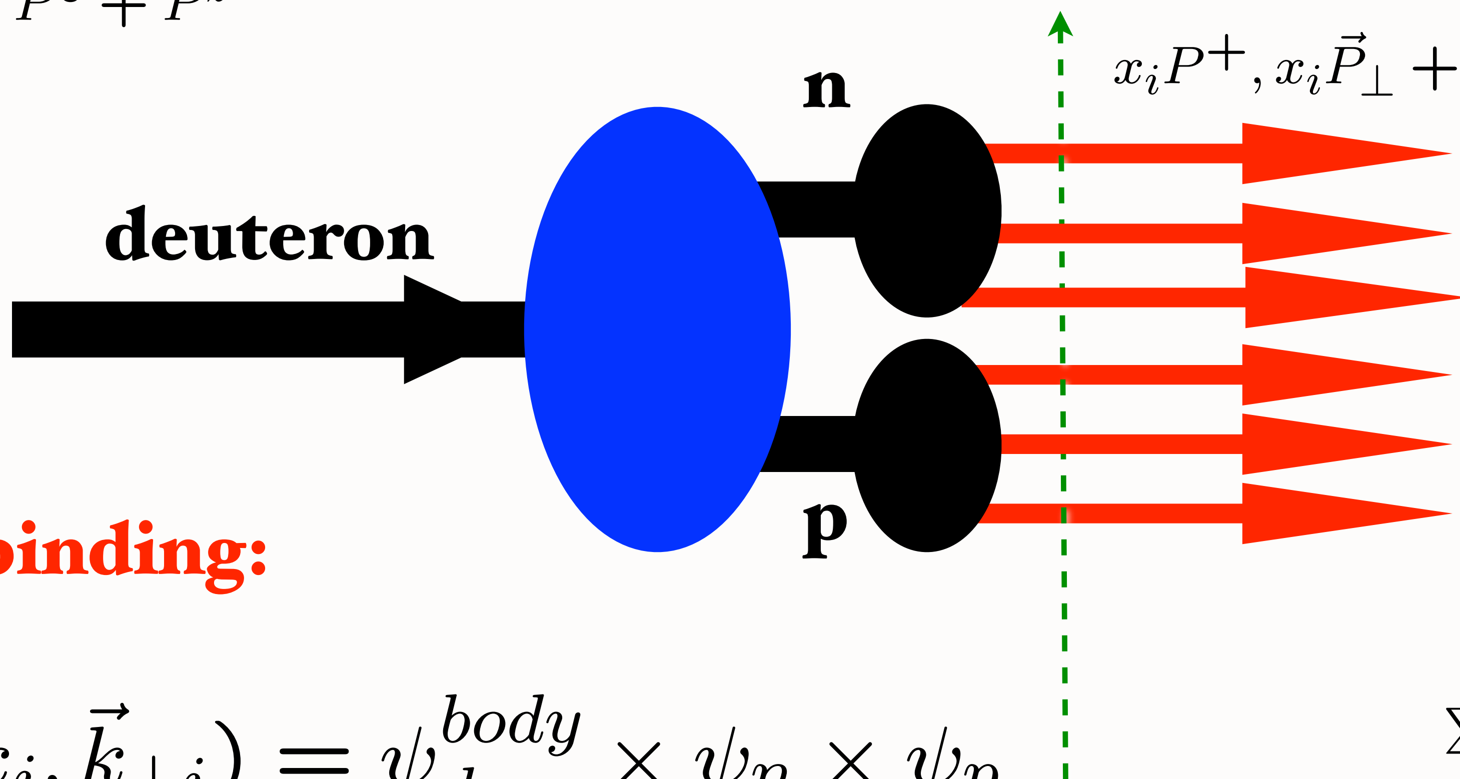
Deuteron Light-Front Wavefunction

Fixed $\tau = t + z/c$

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

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

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



Weak binding:

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

$\sum_i^n x_i = 1$

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

Two color-singlet combinations of three 3_C

Hidden Color in QCD

Lepage, Ji, sjb

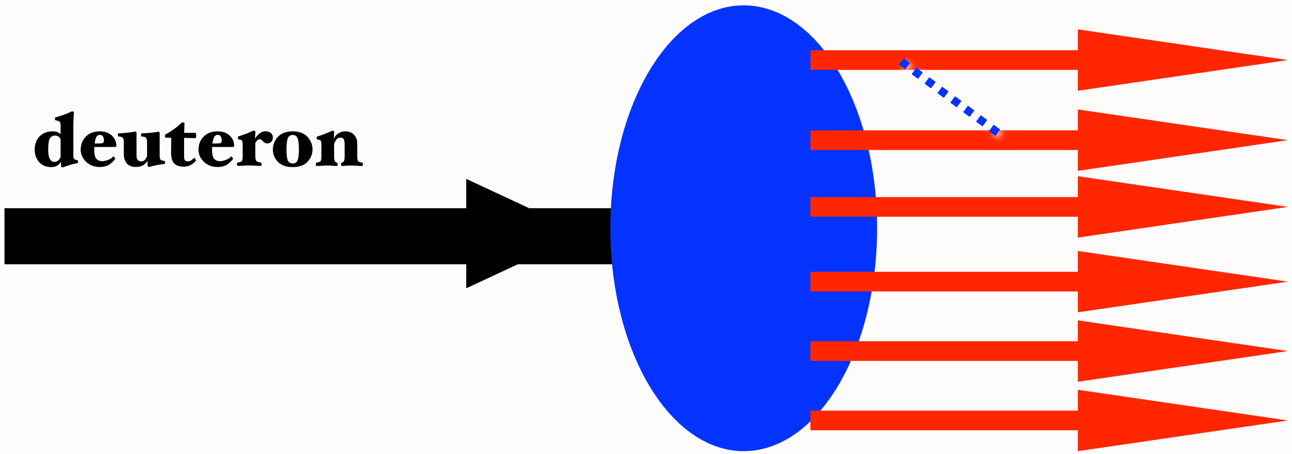
Study the Deuteron as a QCD Object

- **Deuteron six-quark wavefunction**
- **5 color-singlet combinations of 6 color-triplets -- only 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**

$$\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-}) \simeq \frac{d\sigma}{dt}(\gamma d \to pn) \text{ at high } Q^2$$

Evolution of 5 color-singlet Fock states

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



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

$\sum_i^n x_i = 1$

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

5 X 5 Matrix Evolution Equation for deuteron distribution amplitude

Hidden Color of Deuteron

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

Asymptotic Solution has Expansion

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

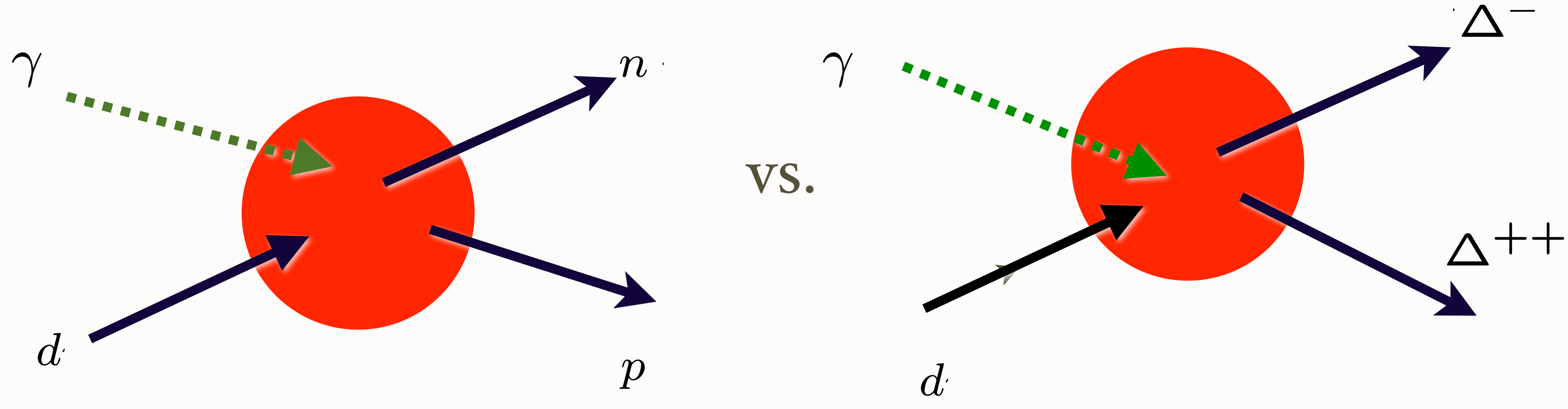
Look for strong transition to Delta-Delta

Test of Hidden Color in Deuteron Photodisintegration

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

Ratio predicted to approach 2:5

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



Possible contribution from pion charge exchange at small t.

Remarkable Features of Hadron Structure

- Valence quark helicity represents less than half of the proton's spin and momentum
- Non-zero quark orbital angular momentum!
- Asymmetric sea: $\bar{u}(x) \neq \bar{d}(x)$ relation to meson cloud
- Non-symmetric strange and antistrange sea $\bar{s}(x) \neq s(x)$

  $\Delta s(x) \neq \Delta \bar{s}(x)$
- Intrinsic charm and bottom at high x
- Hidden-Color Fock states of the Deuteron

Properties of Hard Exclusive Reactions

- **Dimensional Counting Rules at fixed CM angle**
- **Hadron Helicity Conservation**
- **Color Transparency**
- **Hidden color**
- **$s >> -t >> \Lambda_{QCD}$: Reggeons have negative-integer intercepts at large -t**
- **J=0 Fixed pole in DVCS**
- **Quark interchange**
- **Renormalization group invariance**
- **No renormalization scale ambiguity**
- **Exclusive inclusive connection with spectator counting rules**
- **Diffractive reactions from pomeron, Reggeon, odderon**

Novel QCD at JLab 12 GeV and the EIC

- *Intrinsic Heavy Quarks*
- *Charm at Threshold: exotic states, nuclear-bound quarkonium, anomalous polarization effects*
- *Exclusive and Inclusive Sivers Effect: Breakdown of pQCD Leading-Twist Factorization*
- *Non-universal antishadowing*
- *Hidden Color*
- *J=0 fixed pole*

Illuminate New QCD Physics

JLab 12 GeV: An Exotic Charm Factory!

- **Charm quarks at high x -- allows charm states to be produced with minimal energy**
- **Charm produced at low velocities in the target -- the target rapidity domain** $x_F \sim -1$
- **Charm at threshold -- maximal domain for producing exotic states containing charm quarks**
- **Attractive QCD Van der Waals interaction -- "nuclear-bound quarkonium"**
- **Dramatic Spin Correlations in the threshold Domain**
- **Strong SSS Threshold Enhancement**

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

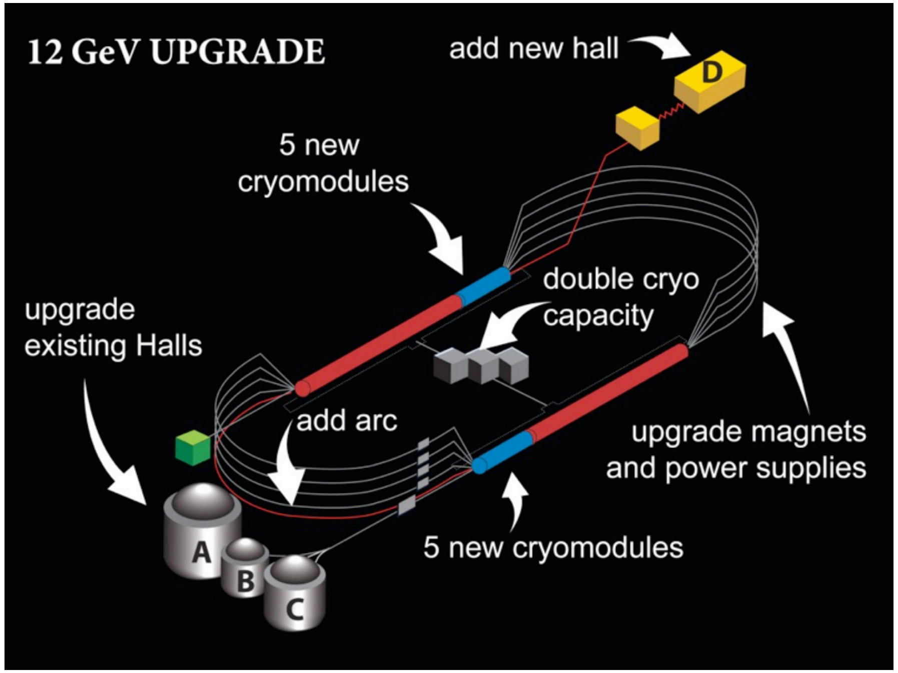
- Novel QCD Phenomena: hidden color, color transparency, strangeness asymmetry, intrinsic charm, anomalous heavy quark phenomena, anomalous spin effects, single-spin asymmetries, odderon, diffractive deep inelastic scattering, rescattering, shadowing, non-universal antishadowing ...

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

—Mark Twain

Novel QCD Phenomena at JLab 12 GeV and the EIC

- *Intrinsic Heavy Quarks*
- *Charm at Threshold*
- *Novel Heavy Quark Resonances at Threshold*
- *Nuclear-Bound Quarkonium*
- *Exclusive and Inclusive Sivers Effect.*
- *Breakdown of pQCD Leading-Twist Factorization*
- *Non-universal antishadowing*
- *Hidden Color*
- *J=0 Fixed pole in DVCS*



Illuminate New Hadronic Physics