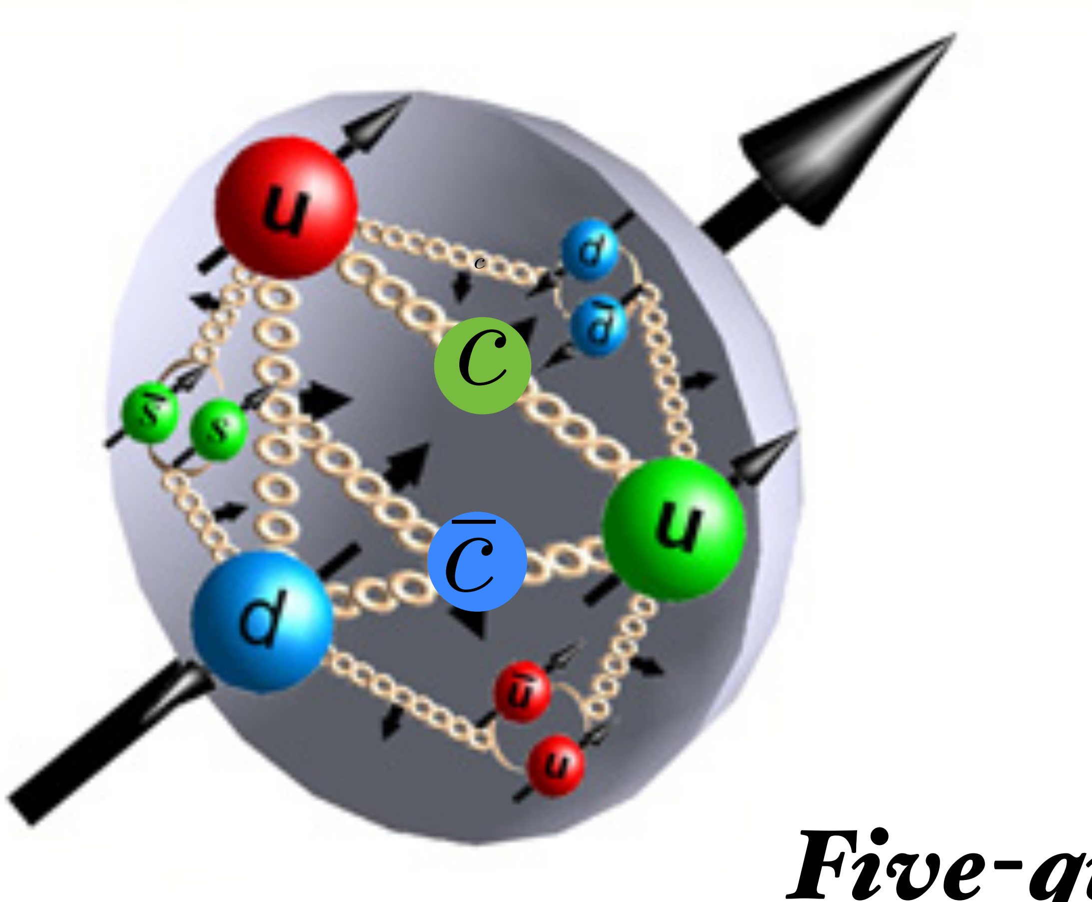
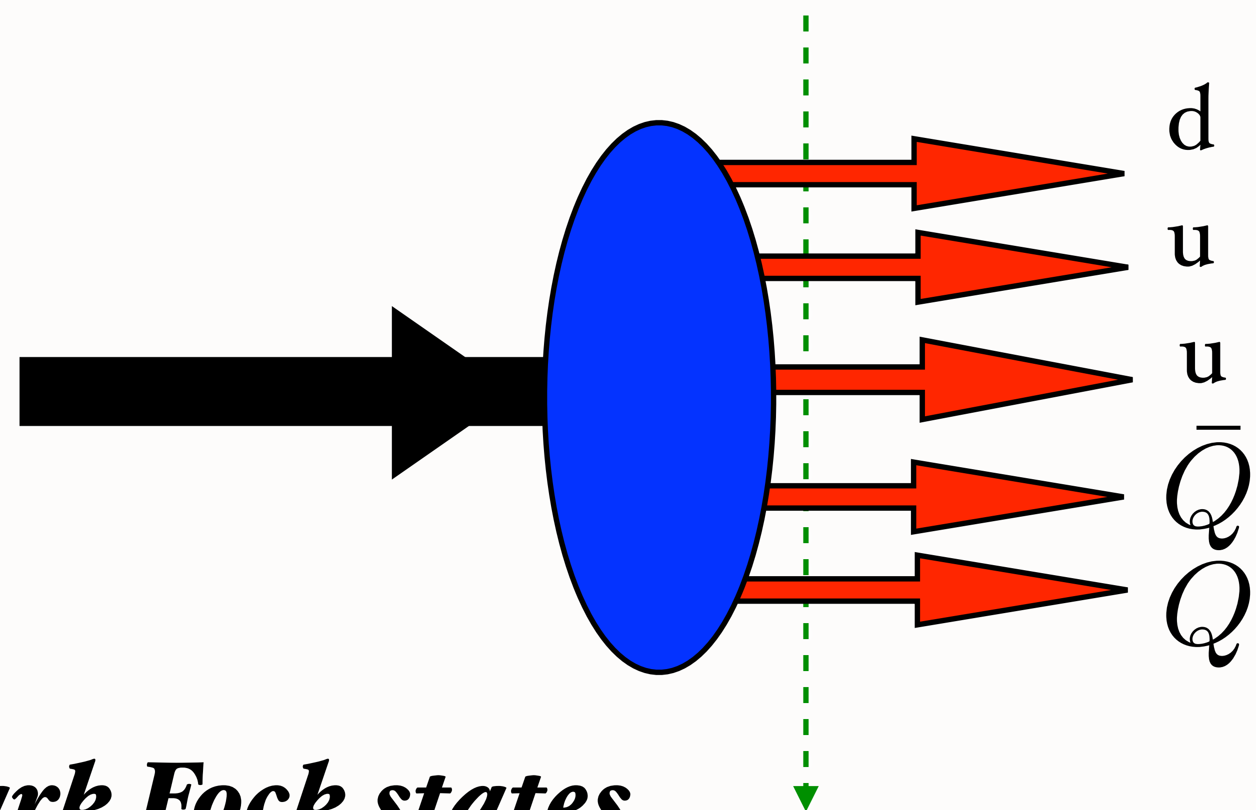
Novel Heavy-Quark Phenomena at Threshold



Fixed $\tau = t + z/c$



Five-quark Fock states

Exploring Hadron Structure with Tagged Structure Functions

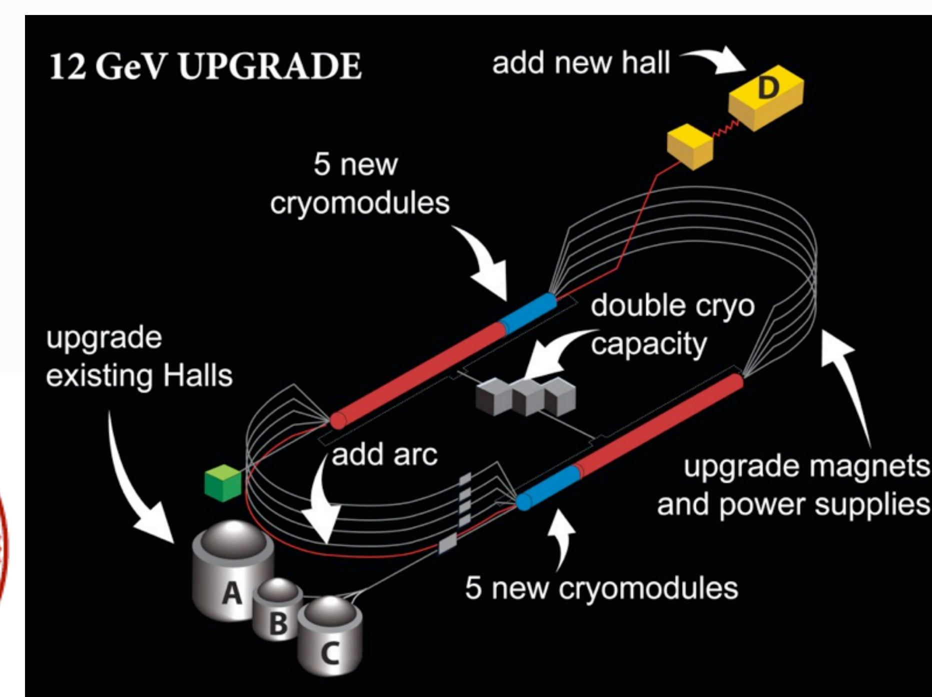
Jefferson Lab

January 16-18, 2014

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

LELAND STANFORD JUNIOR UNIVERSITY

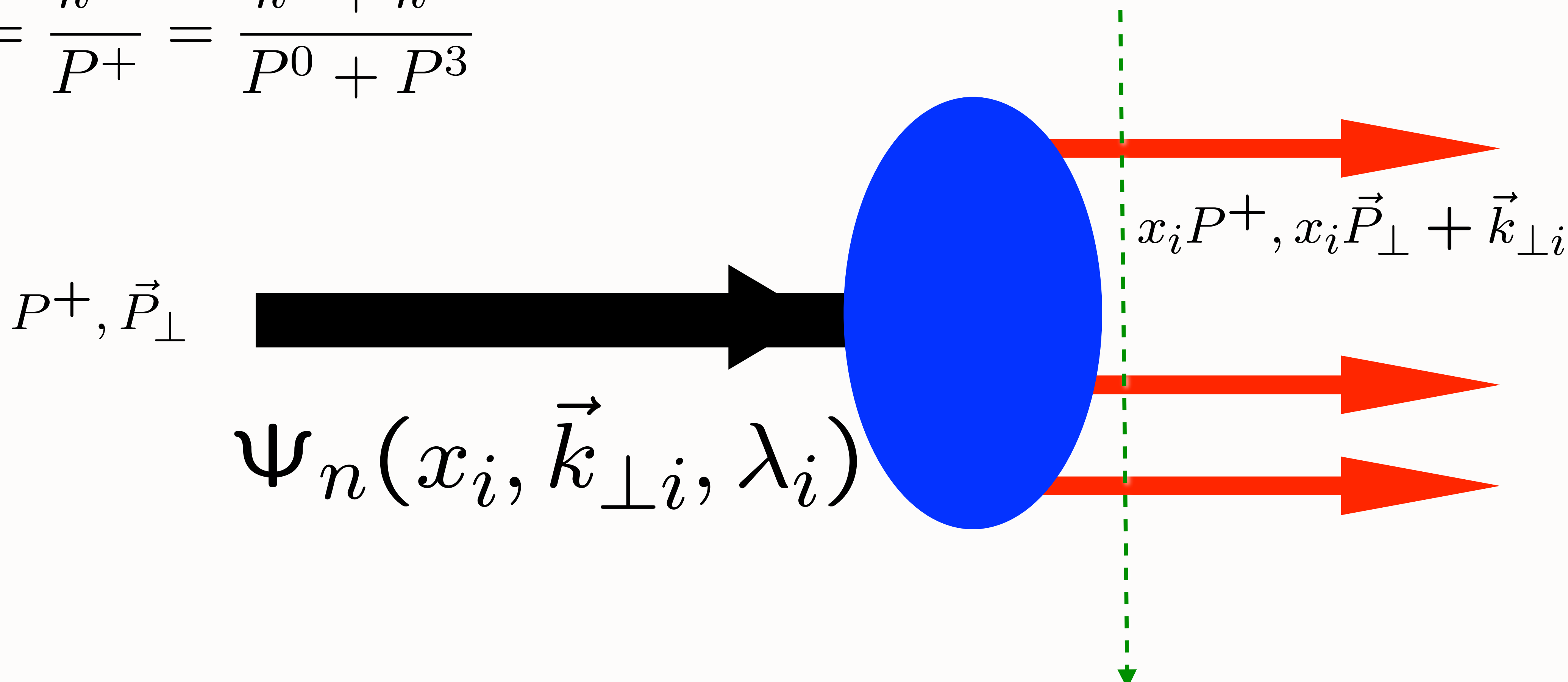


Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

Eigenstate of Light Front Hamiltonian

Fixed $\tau = t + z/c$

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



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

$\sum_i^n x_i = 1$

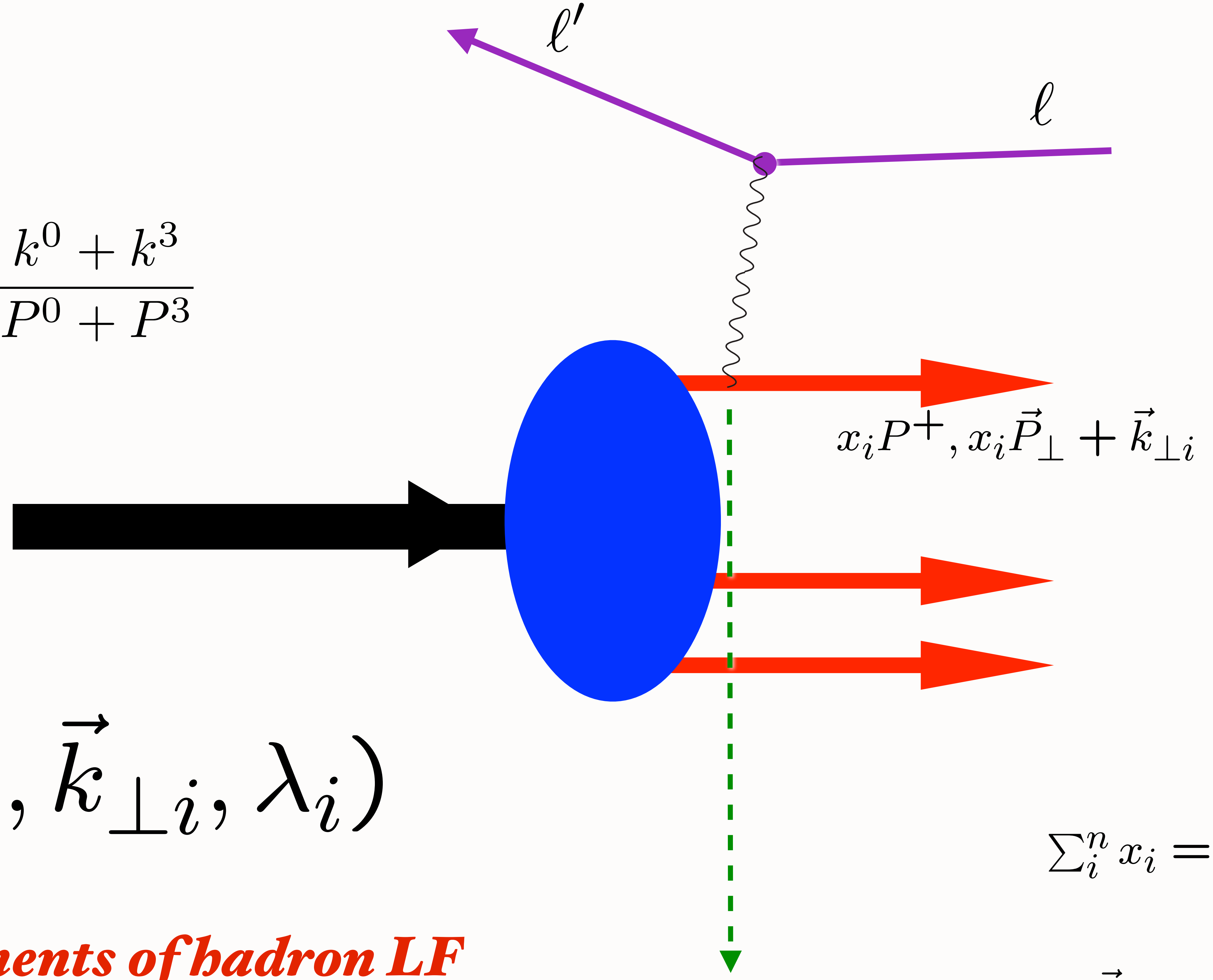
$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

Invariant under boosts! Independent of P^μ

Causal, Frame-independent. Creation Operators on Simple Vacuum, Current Matrix Elements are Overlaps of LFWFS

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

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



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

$\sum_i^n x_i = 1$

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

Measurements of hadron LF wavefunction are at fixed LF time

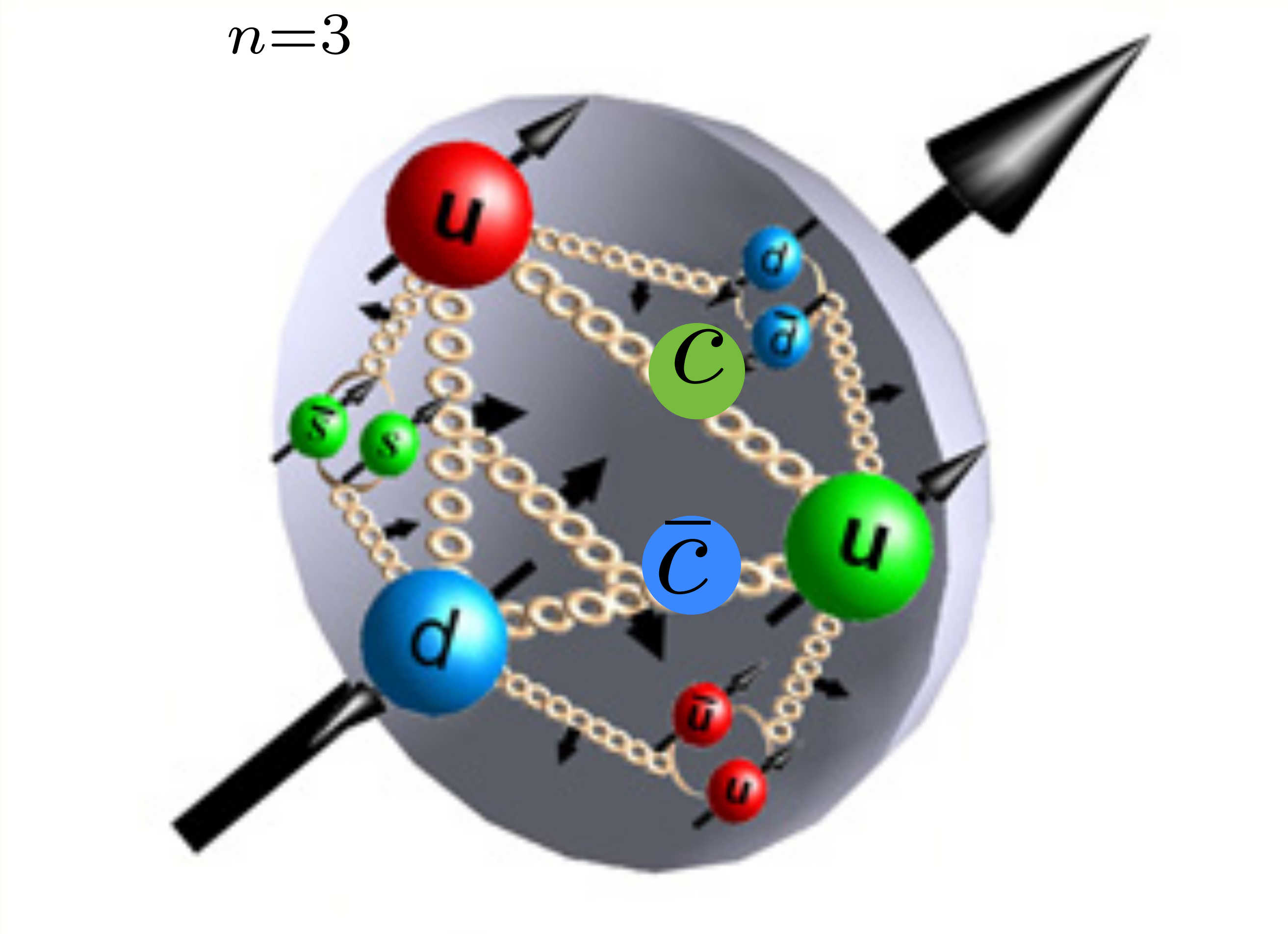
Fixed $\tau = t + z/c$

Like a flash photograph

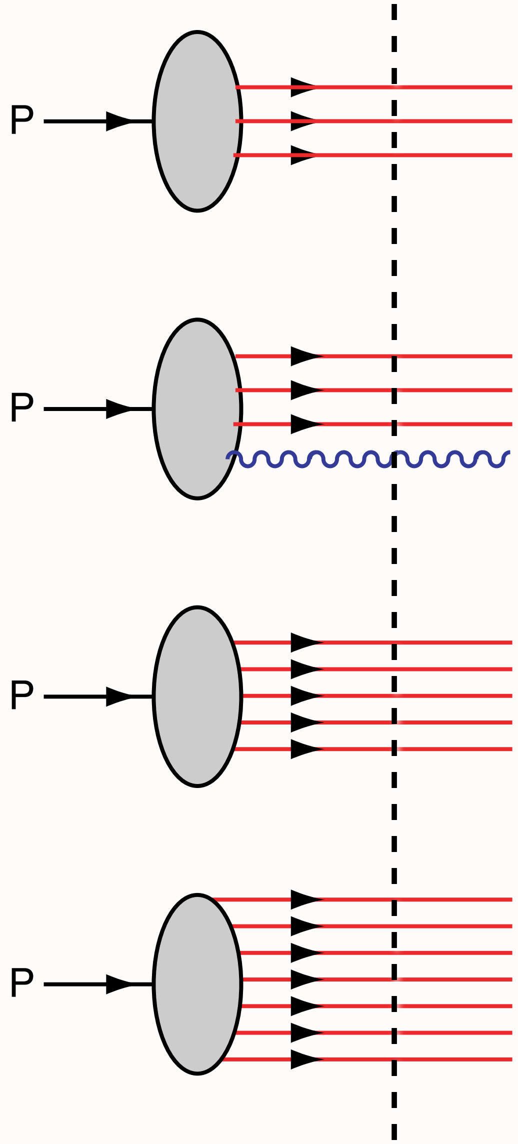
Wavefunction at fixed LF time: Arbitrarily Off-Shell in Invariant Mass

Eigenstate of LF Hamiltonian : all Fock states contribute

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



Higher Fock States of the Proton



Fixed LF time τ

Light-Front QCD

Physical gauge: $A^+ = 0$

Exact frame-independent formulation of nonperturbative QCD!

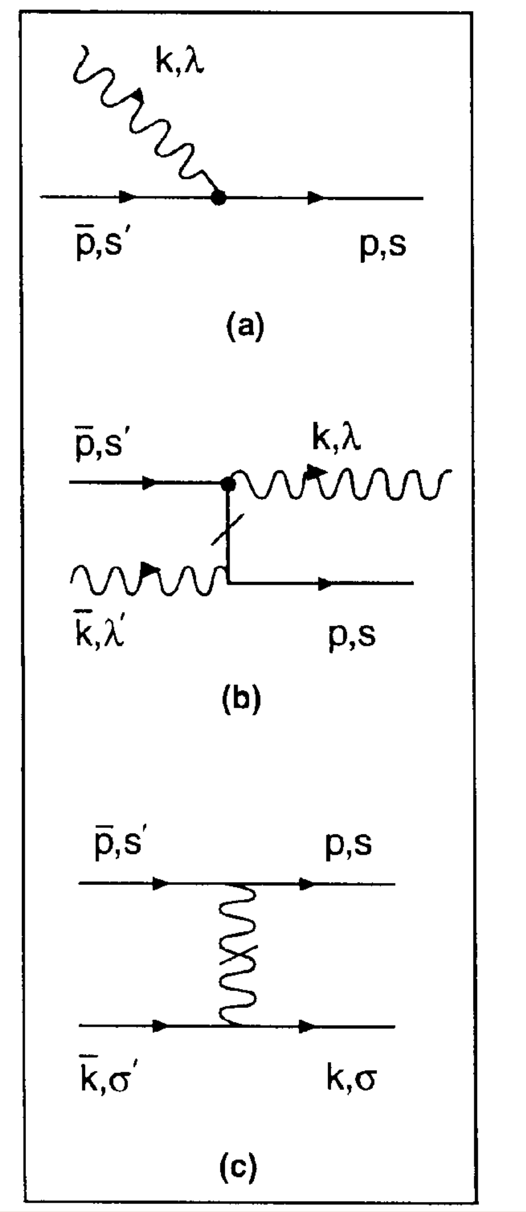
$$L^{QCD} \rightarrow H^{QCD}_{LF}$$

$$H^{QCD}_{LF} = \sum_i [\frac{m^2 + k^2_\perp}{x}]_i + H^{int}_{LF}$$

H^{int}_{LF}: Matrix in Fock Space

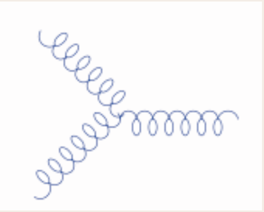
$$H^{QCD}_{LF}|\Psi_h> = \mathcal{M}^2_h|\Psi_h>$$

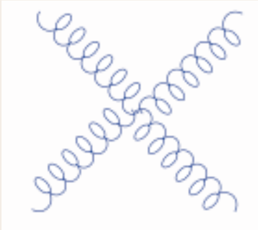
$$|p, J_z> = \sum_{n=3} \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)|n; x_i, \vec{k}_{\perp i}, \lambda_i>$$



Eigenvalues and Eigensolutions give Hadronic Spectrum and Light-Front wavefunctions

LFWFs: Arbitrarily Off-shell in P- and invariant mass





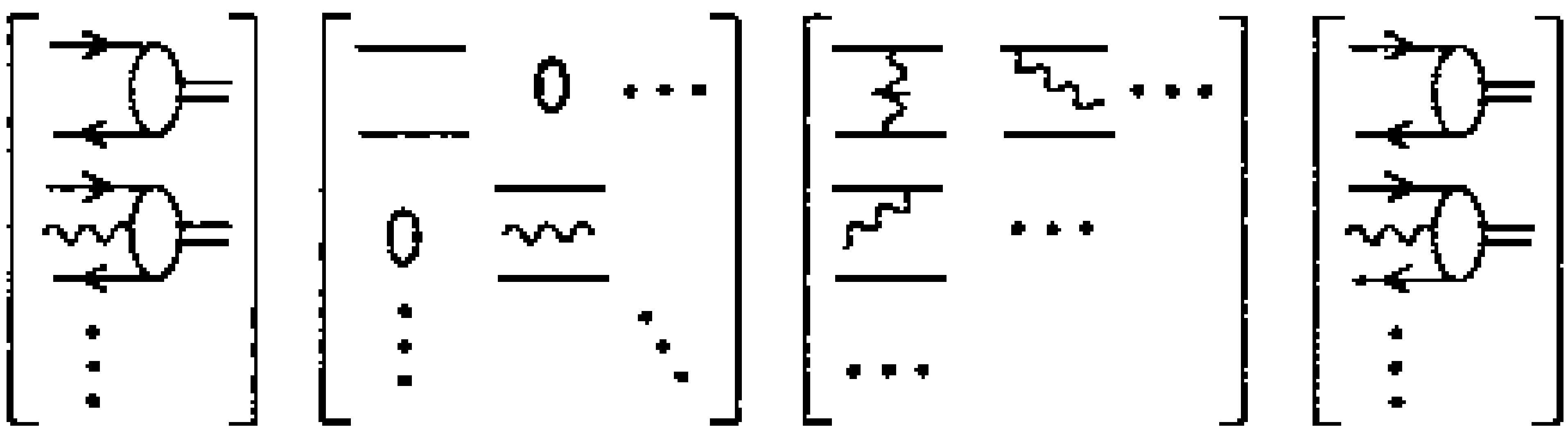
H^{int}_{LF}

LIGHT-FRONT MATRIX EQUATION

Rigorous Method for Solving Non-Perturbative QCD!

$$\left(M_\pi^2 - \sum_i \frac{\vec{k}_{\perp i}^2 + m_i^2}{x_i}\right) \begin{bmatrix} \psi_{q\bar{q}/\pi} \\ \psi_{q\bar{q}g/\pi} \\ \vdots \end{bmatrix} = \begin{bmatrix} \langle q\bar{q}|\, V\, |q\bar{q}\rangle & \langle q\bar{q}|\, V\, |q\bar{q}g\rangle & \cdots \\ \langle q\bar{q}g|\, V\, |q\bar{q}\rangle & \langle q\bar{q}g|\, V\, |q\bar{q}g\rangle & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix} \begin{bmatrix} \psi_{q\bar{q}/\pi} \\ \psi_{q\bar{q}g/\pi} \\ \vdots \end{bmatrix}$$

$A^+ = 0$



Minkowski space; frame-independent; no fermion doubling; no ghosts

- Light-Front Vacuum = vacuum of free Hamiltonian!

New approach: BLFQ

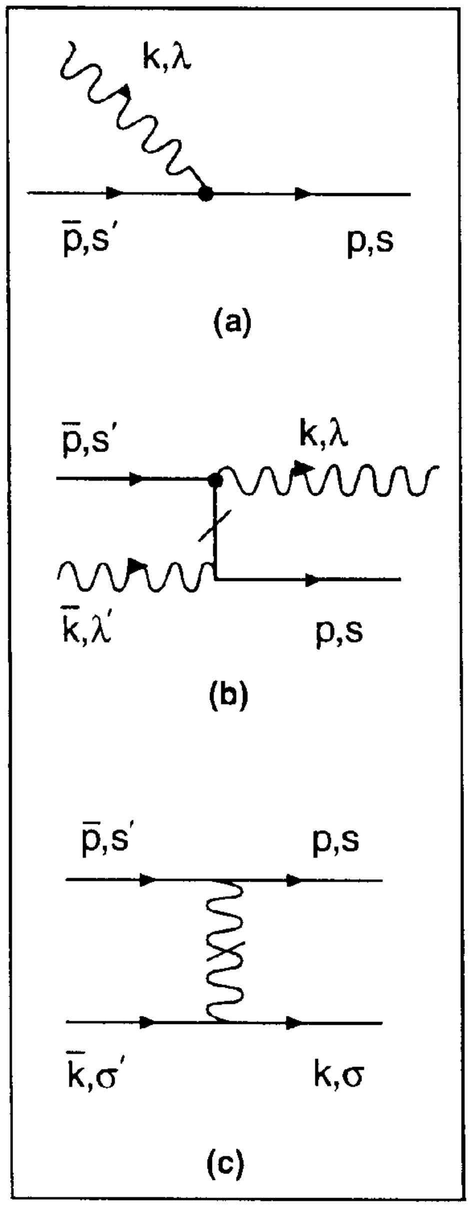
Light-Front QCD

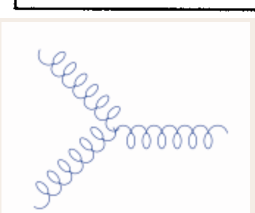
Heisenberg Equation

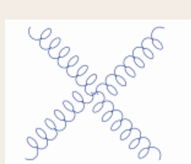
$$\boxed{H_{LC}^{QCD}|\Psi_h\rangle = \mathcal{M}_h^2\,|\Psi_h\rangle}$$

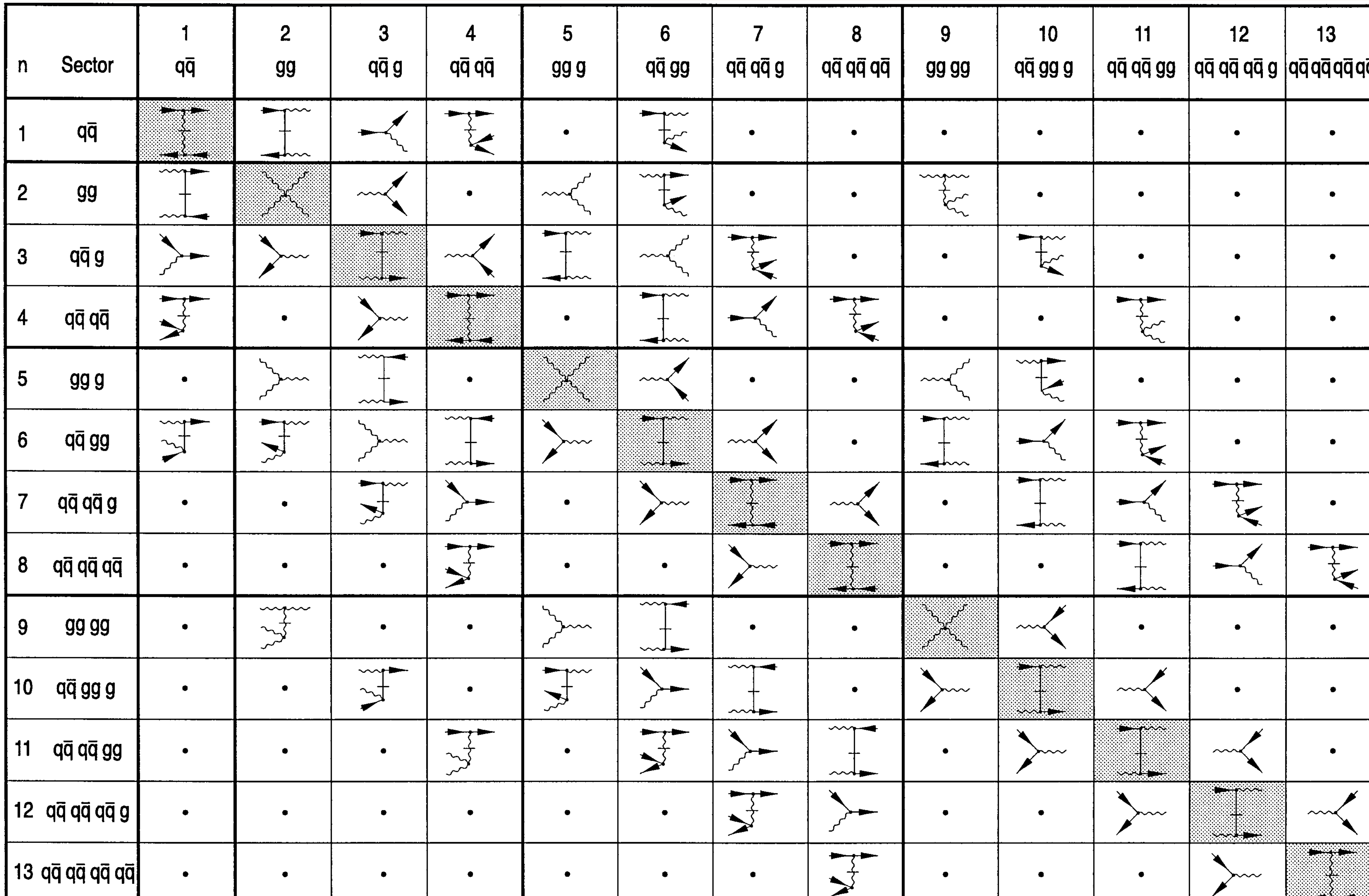
DLCQ: Solve QCD(1+1) for any quark mass and flavors

Hornbostel, Pauli, sjb



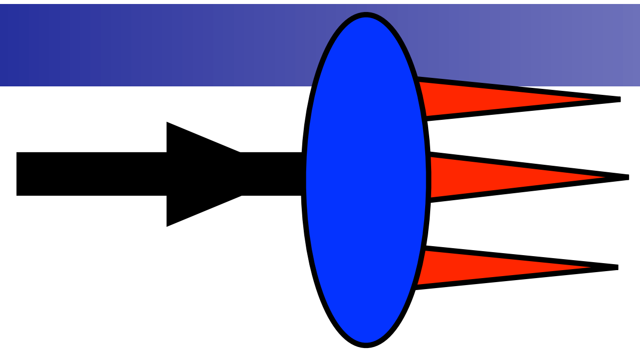






Minkowski space; frame-independent; no fermion doubling; no ghosts

New approach: BLFQ: Diagonalize using AdS/QCD LFWFS



- *Light Front Wavefunctions:*

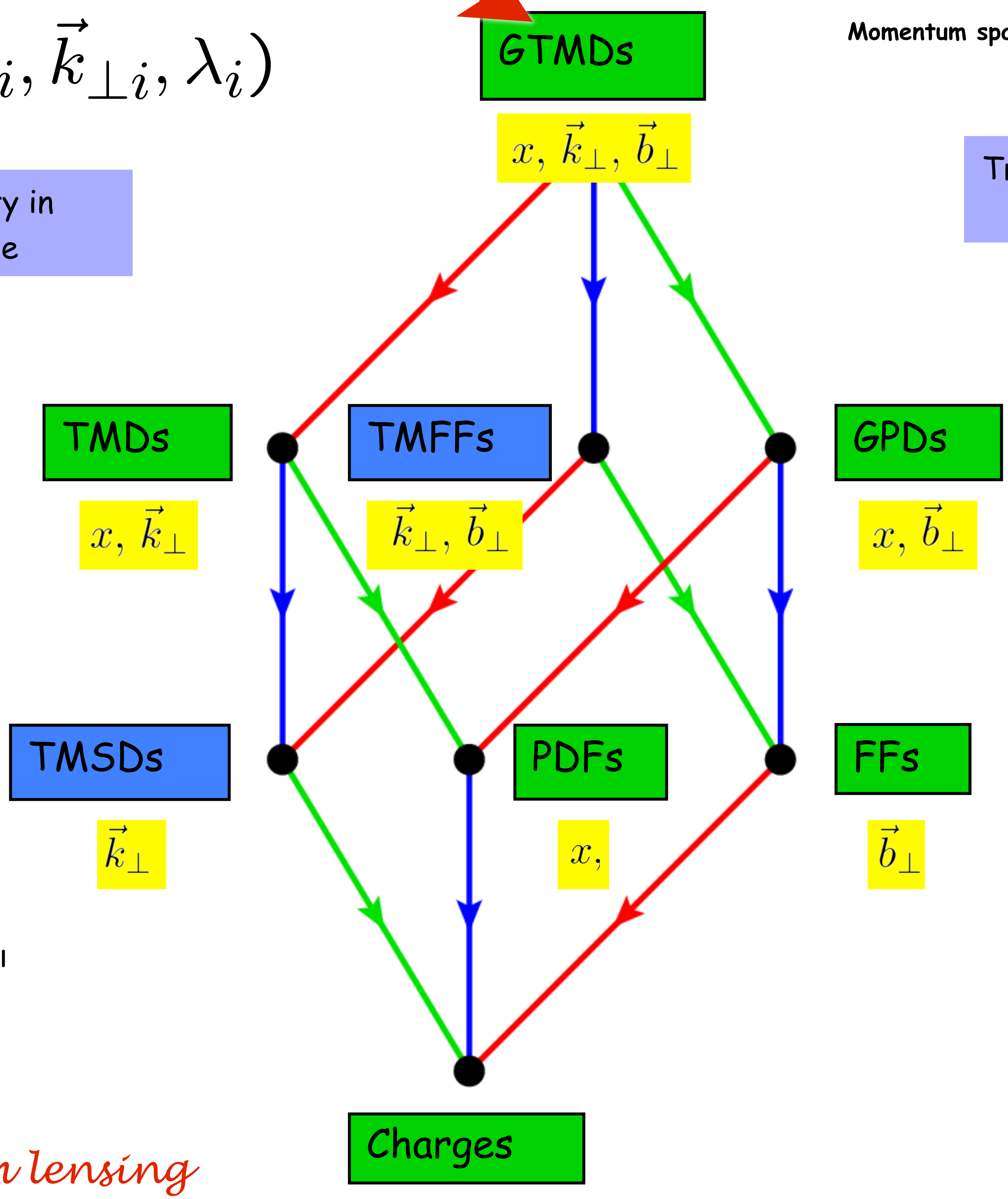
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

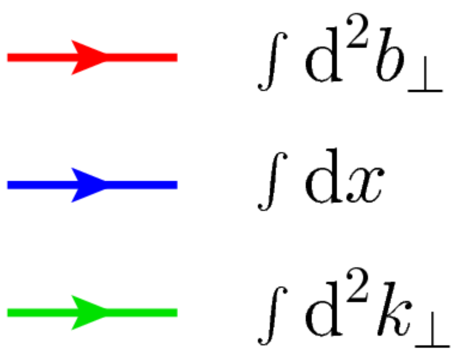
Transverse density in momentum space

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

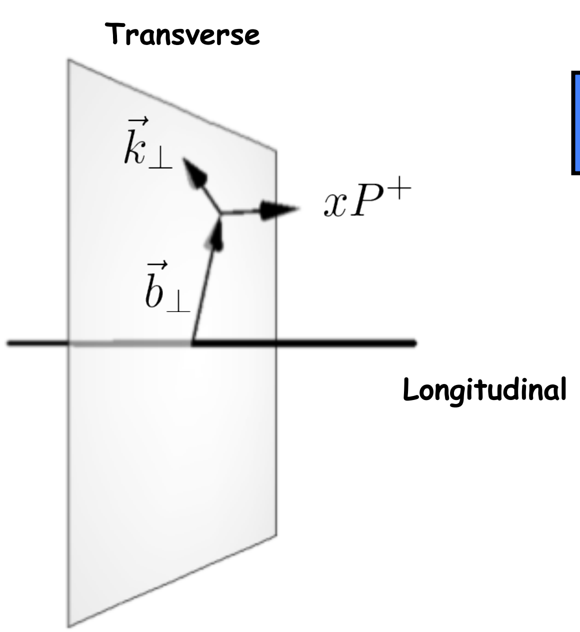
$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$

Transverse density in position space





Lorce, Pasquini



Sivers, T-odd from lensing

Angular Momentum on the Light-Front

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

Conserved
LF Fock-State by Fock-State
Every Vertex

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

n-1 orbital angular momenta

Parke-Taylor Amplitudes **Stasto**

Nonzero Anomalous Moment <--> Nonzero orbital angular momentum

Drell, sjb

Exact LF Formula for Pauli Form Factor

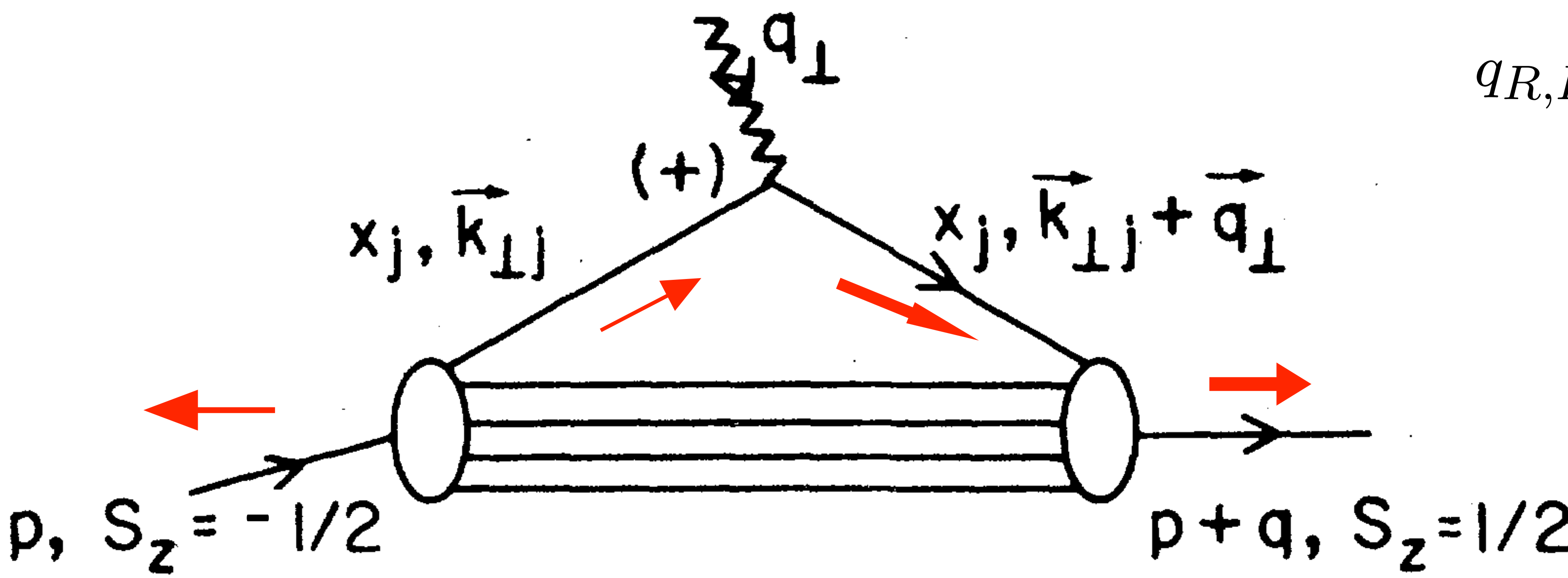
Drell, sjb

$$\frac{F_2(q^2)}{2M} = \sum_a \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp] \sum_j e_j \, \frac{1}{2} \; \times$$

$$\left[-\frac{1}{q^L}\psi_a^{\uparrow *}(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\, \psi_a^{\downarrow}(x_i, \mathbf{k}_{\perp i}, \lambda_i) + \frac{1}{q^R}\psi_a^{\downarrow *}(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\, \psi_a^{\uparrow}(x_i, \mathbf{k}_{\perp i}, \lambda_i) \right]$$

$$\mathbf{k}'_{\perp i} = \mathbf{k}_{\perp i} - x_i \mathbf{q}_\perp \qquad\qquad \mathbf{k}'_{\perp j} = \mathbf{k}_{\perp j} + (1 - x_j)\mathbf{q}_\perp$$

$$q_{R,L} = q^x \pm i q^y$$



$$\boxed{\text{Must have } \Delta\ell_z = \pm 1 \text{ to have nonzero } F_2(q^2)}$$

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

Advantages of the Dirac's Front Form for Hadron Physics

- Measurements are made at fixed τ
- LFWFs: Eigensolutions of QCD H_{LF}
- Structure Functions are squares of LFWFs
- Form Factors are overlap of LFWFs
- LFWFs are frame-independent -- no boosts
- No dependence on observer's frame
- Dual to AdS/QCD
- LF Vacuum trivial -- no condensates
- Implications for Cosmological Constant

Other Features of Light-Front Wavefunctions

- **Cluster Decomposition Theorem**
- **Zero Anomalous Gravitomagnetic Moment**
- **Angular Momentum J^z**
- **J^z Momentum Sum Rule**
- **Bethe-Salpeter WF integrated over k^-**
- **Electron WFs reproduce pQED results**
- **Parke-Taylor (Stasto)**
- **Gauge Dependent WF but observables are GI**
- **Stable hadron: Real LFWF**
- **Causality: Measurement of quantum state at fixed τ**

Single-spin asymmetries

Leading Twist Sivers Effect

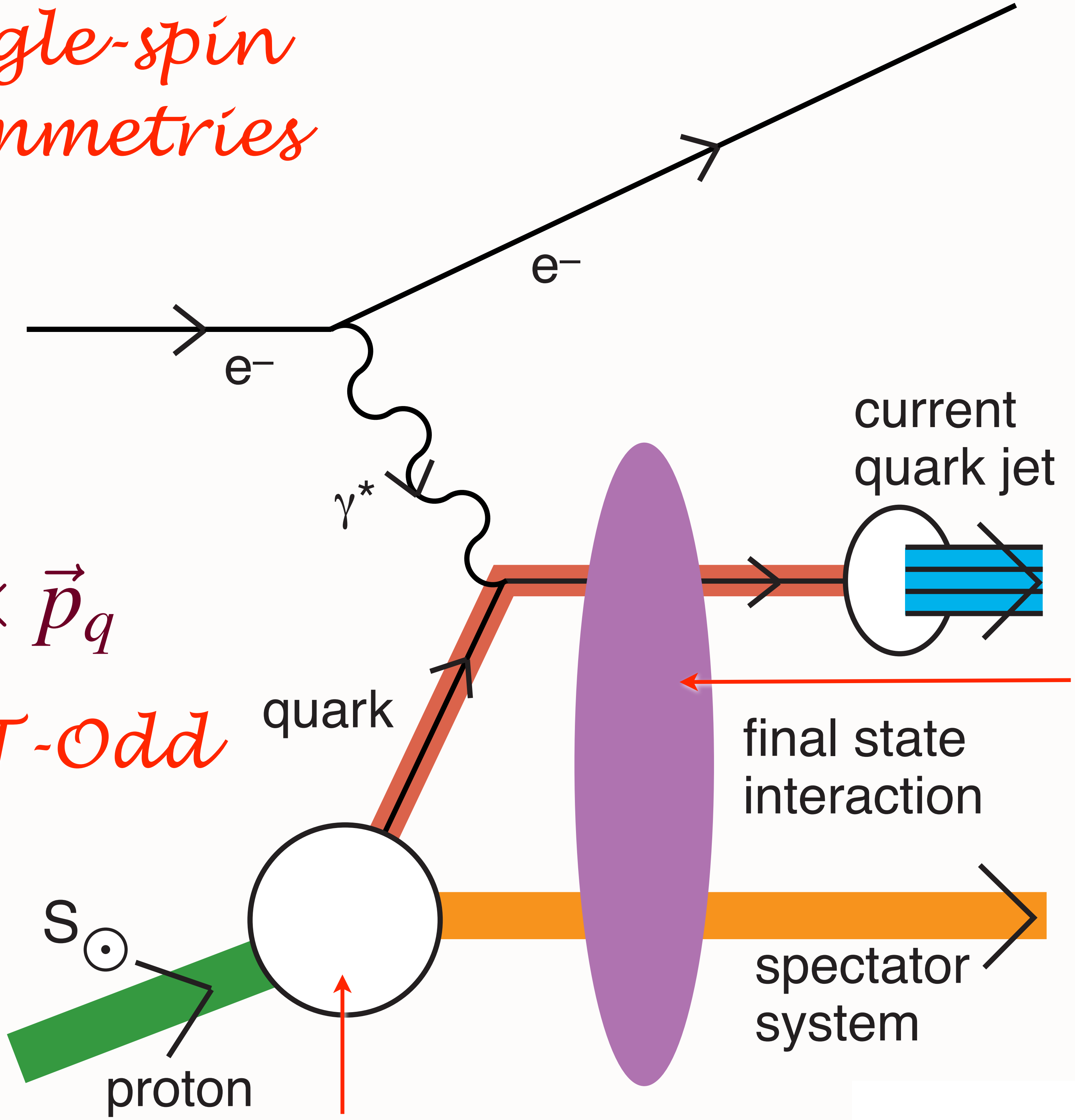
Hwang, Schmidt, sjb

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

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

Pseudo- T-Odd

QED: Lensing involves soft scales



Light-Front Wavefunction
S and P- Waves!

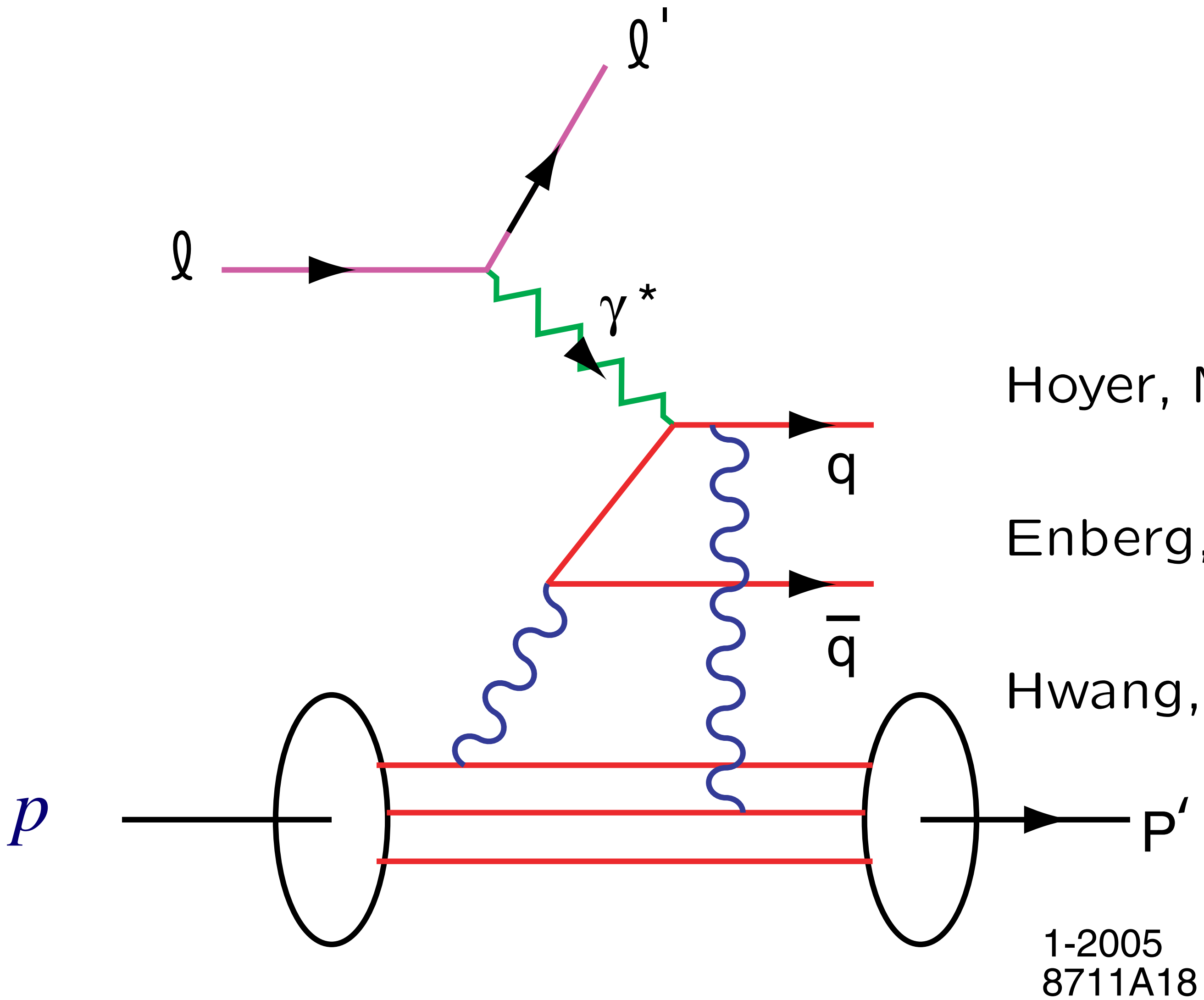
QCD S- and P-
Coulomb Phases
--Wilson Line

"Lensing Effect"

Leading-Twist Rescattering Violates pQCD Factorization!

Relation to confining interaction?

Final-State Interaction Produces Diffractive DIS



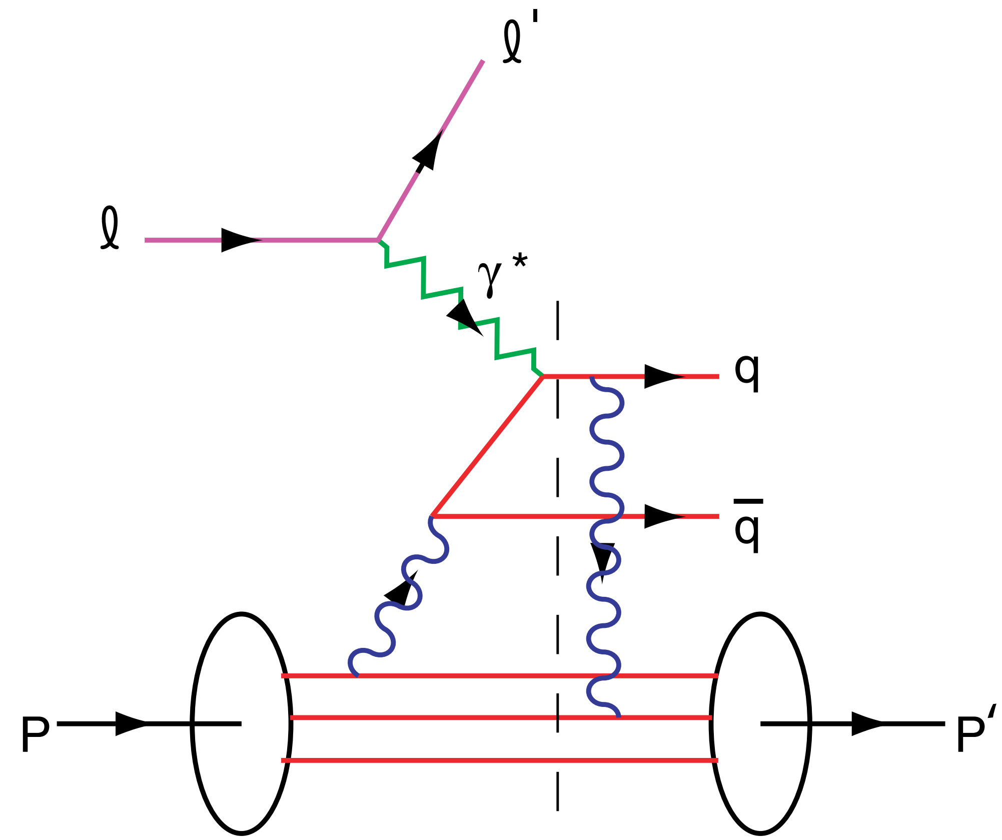
Quark Rescattering

Hoyer, Marchal, Peigne, Sannino, SJB (BHMPS)

Enberg, Hoyer, Ingelman, SJB

Hwang, Schmidt, SJB

Low-Nussinov model of Pomeron



Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate Pomeron and DDIS

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

Physics of FSI not in Wavefunction of Target!

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

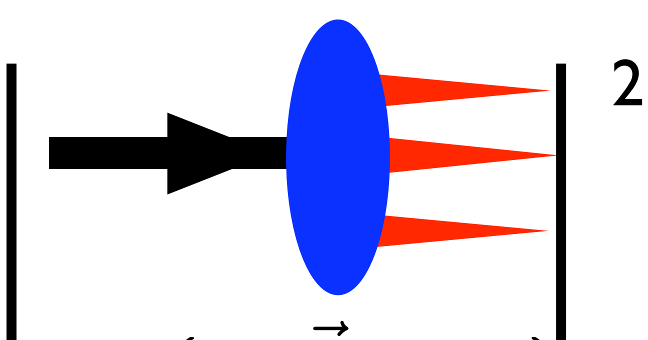
Hwang, Schmidt, sjb,

Mulders, Boer

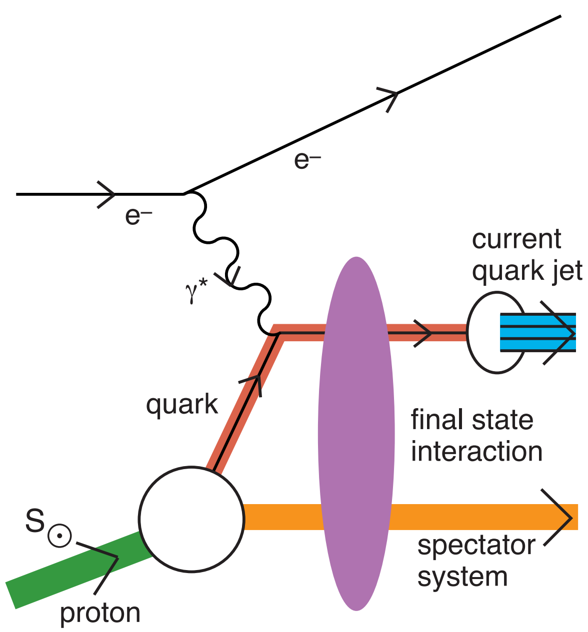
Qiu, Sterman

Collins, Qiu

Pasquini, Xiao, Yuan, sjb



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



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

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

The Light Front Fock State Wavefunctions

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

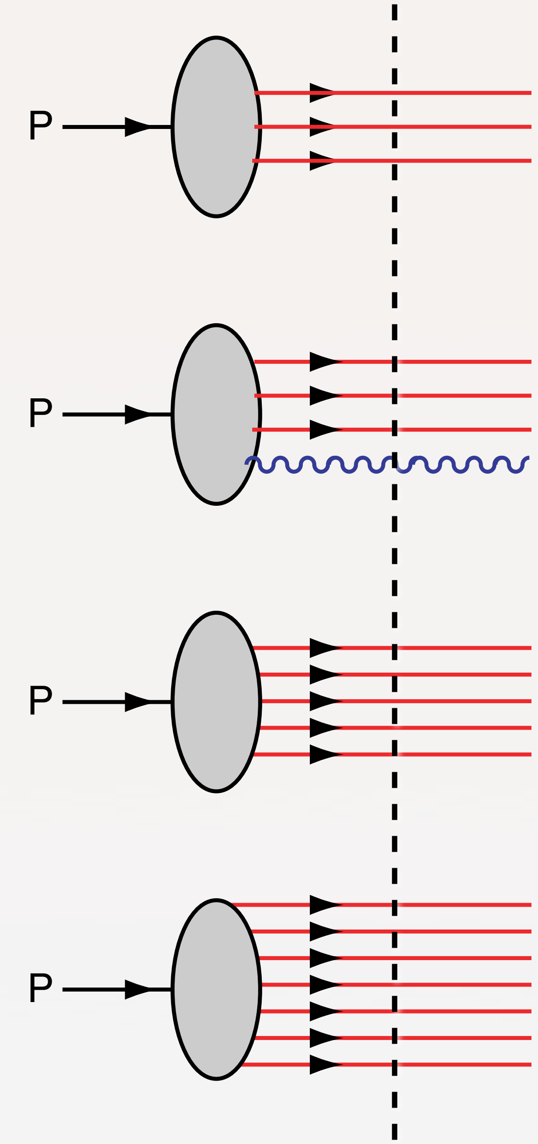
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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 Pomeron

Hidden Color

E866/NuSea (Drell-Yan)

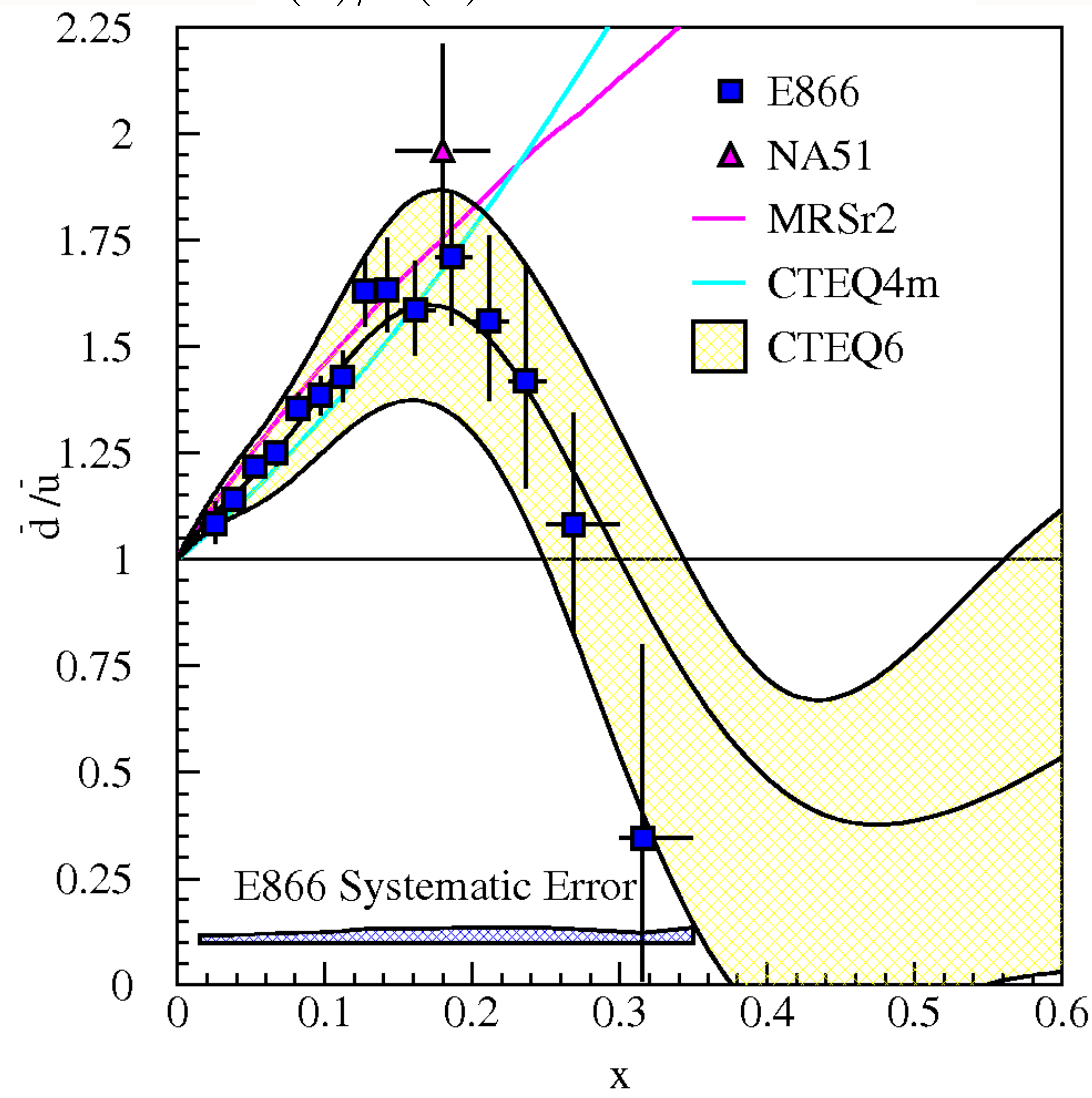
$$\bar{d}(x) \neq \bar{u}(x)$$

Expect:

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

Intrinsic glue, sea, heavy quarks

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



JLab Tagged Structure Functions

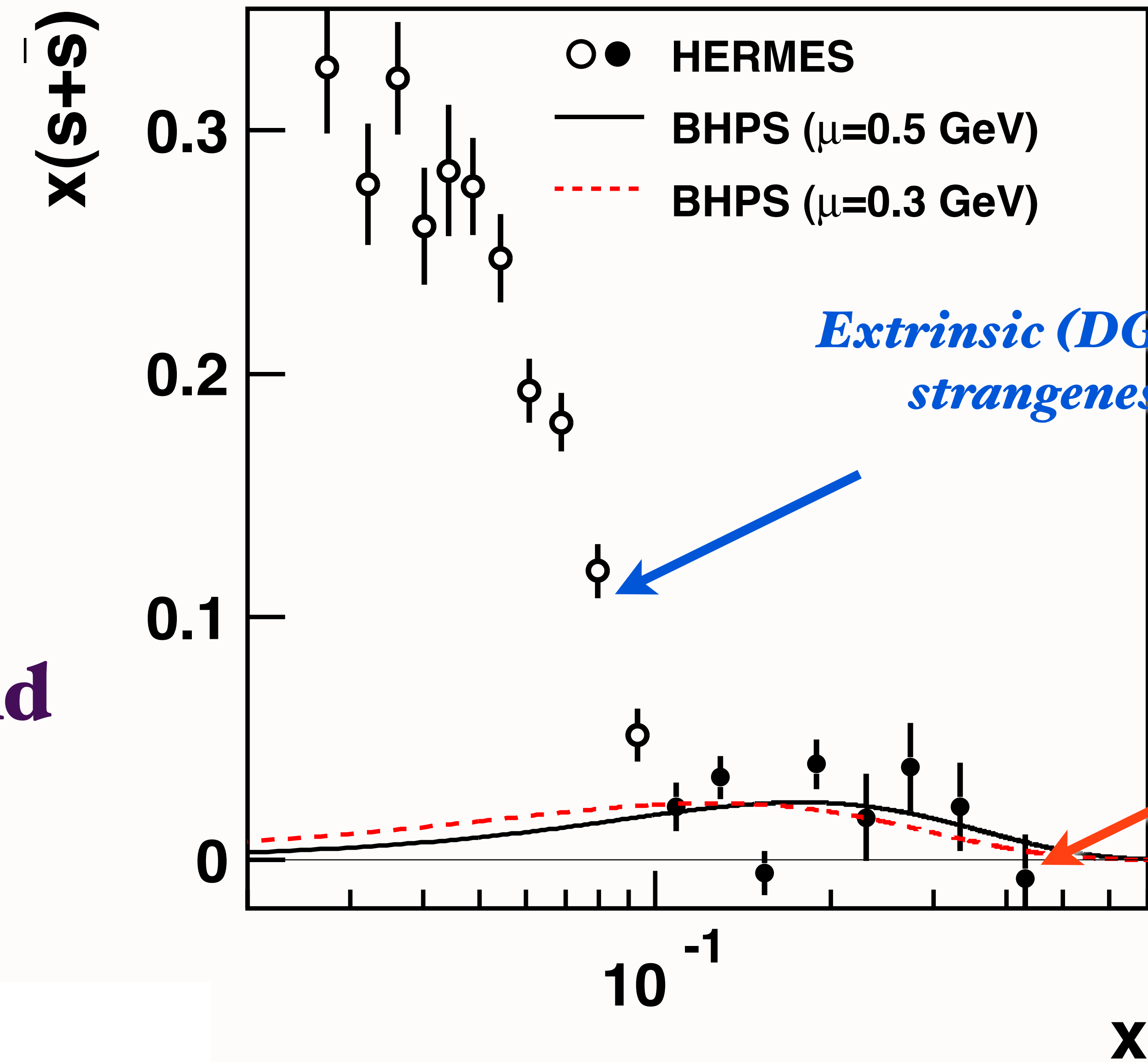
Novel Heavy Quark Phenomena in QCD

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

HERMES: Two components to s(x,Q²)!

BHPS: Hoyer, Sakai, Peterson, sjb



Extrinsic (DGLAP) strangeness!

Intrinsic strangeness!

Consistent with intrinsic charm data

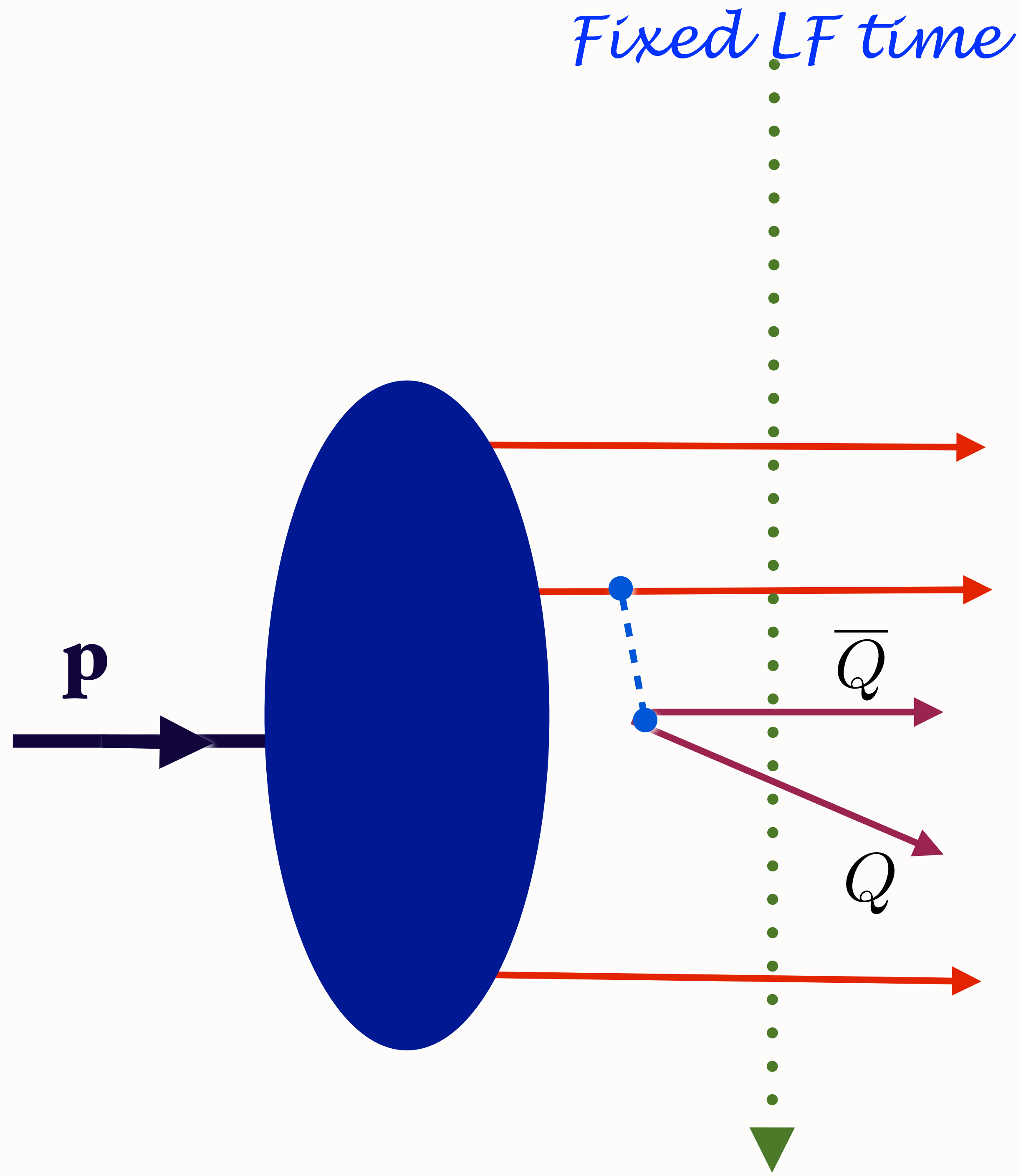
W. C. Chang and J.-C. Peng

arXiv:1105.2381

QCD: $\frac{1}{M_Q^2}$ scaling

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.

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



Proton's 5-quark Fock State from gluon splitting

"Extrinsic" Heavy Quarks

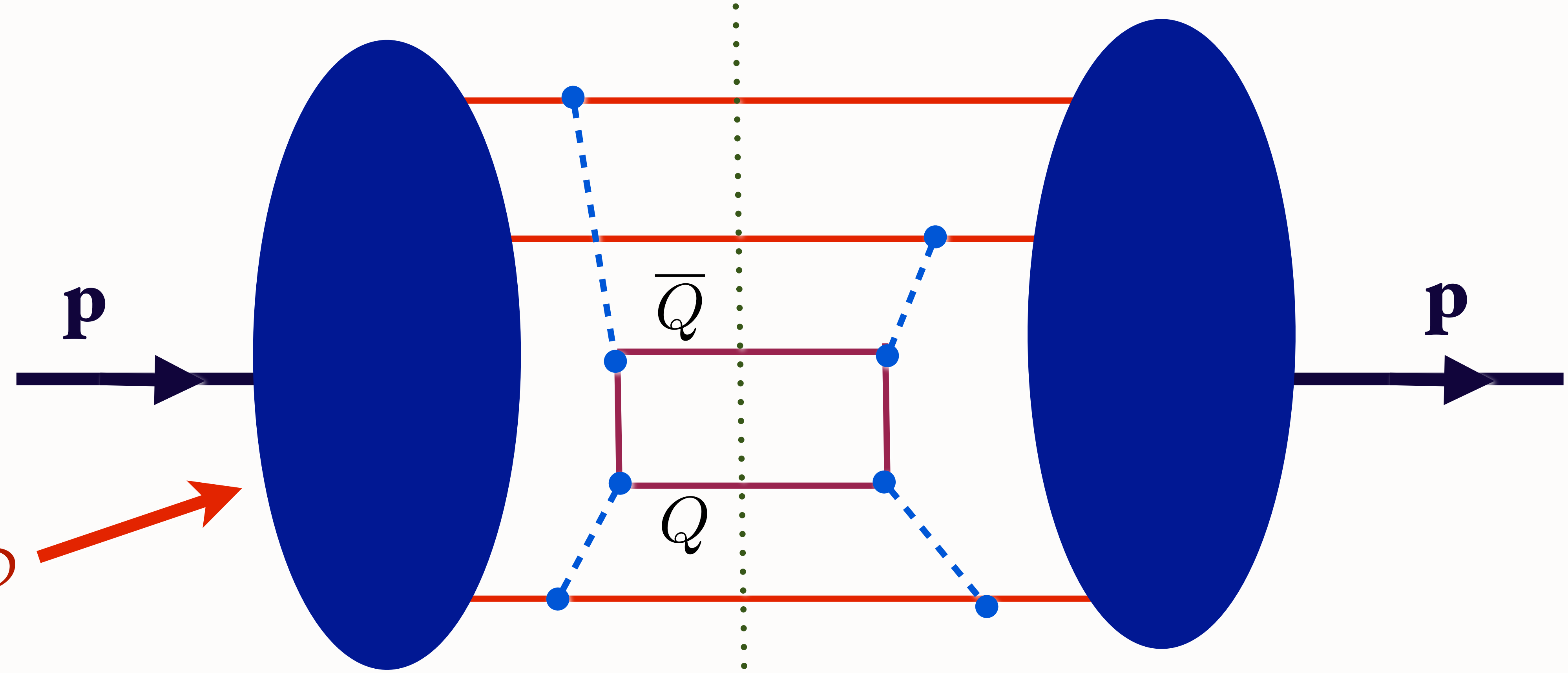
$$s(x,Q^2)_{\text{extrinsic}} \sim (1-x)g(x,Q^2) \sim (1-x)^5$$

Simplest model:

Fixed LF time

Proton Self Energy
Intrinsic Heavy Quarks

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



Use AdS/QCD
LFWF

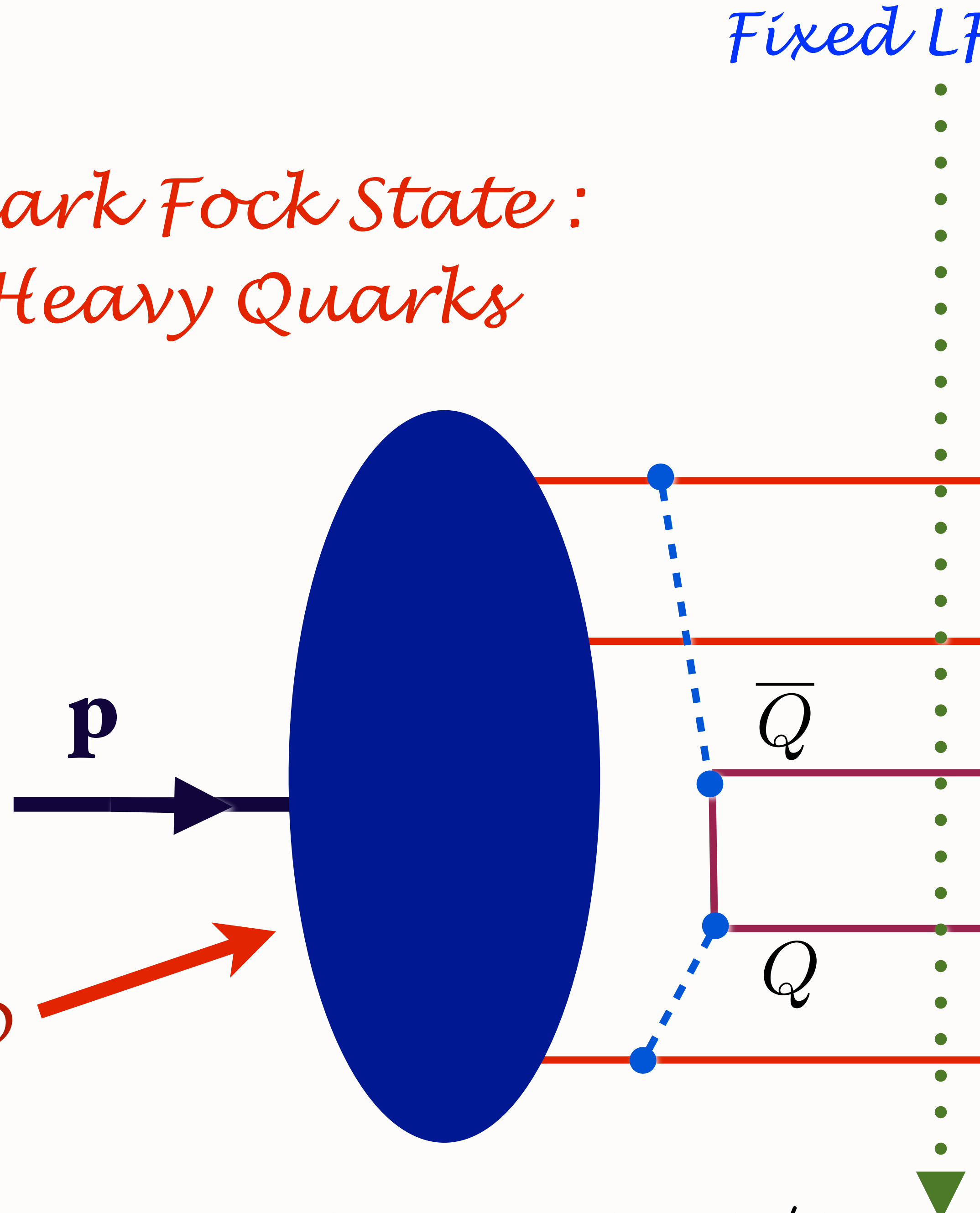
$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4}$$

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

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

Hoyer, Peterson, Sakai, sjb

Proton 5-quark Fock State :
Intrinsic Heavy Quarks



Use AdS/QCD LFWF

QCD predicts Intrinsic Heavy Quarks at high x!

Minimal off-shellness

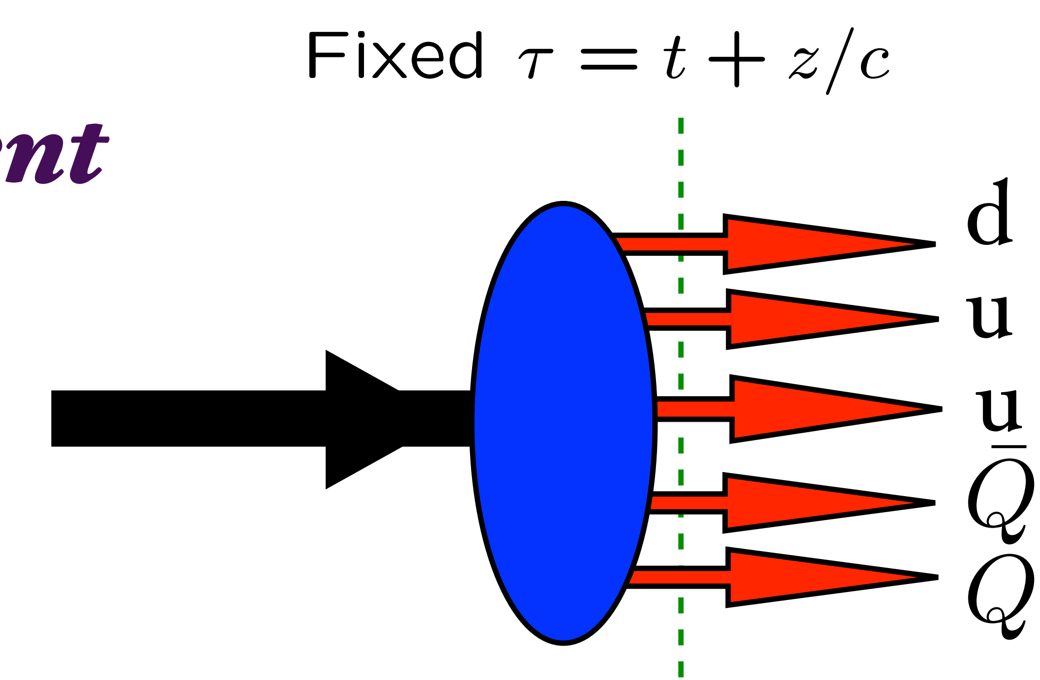
$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$

Probability (QED) $\propto \frac{1}{M_\ell^4}$ Probability (QCD) $\propto \frac{1}{M_Q^2}$

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

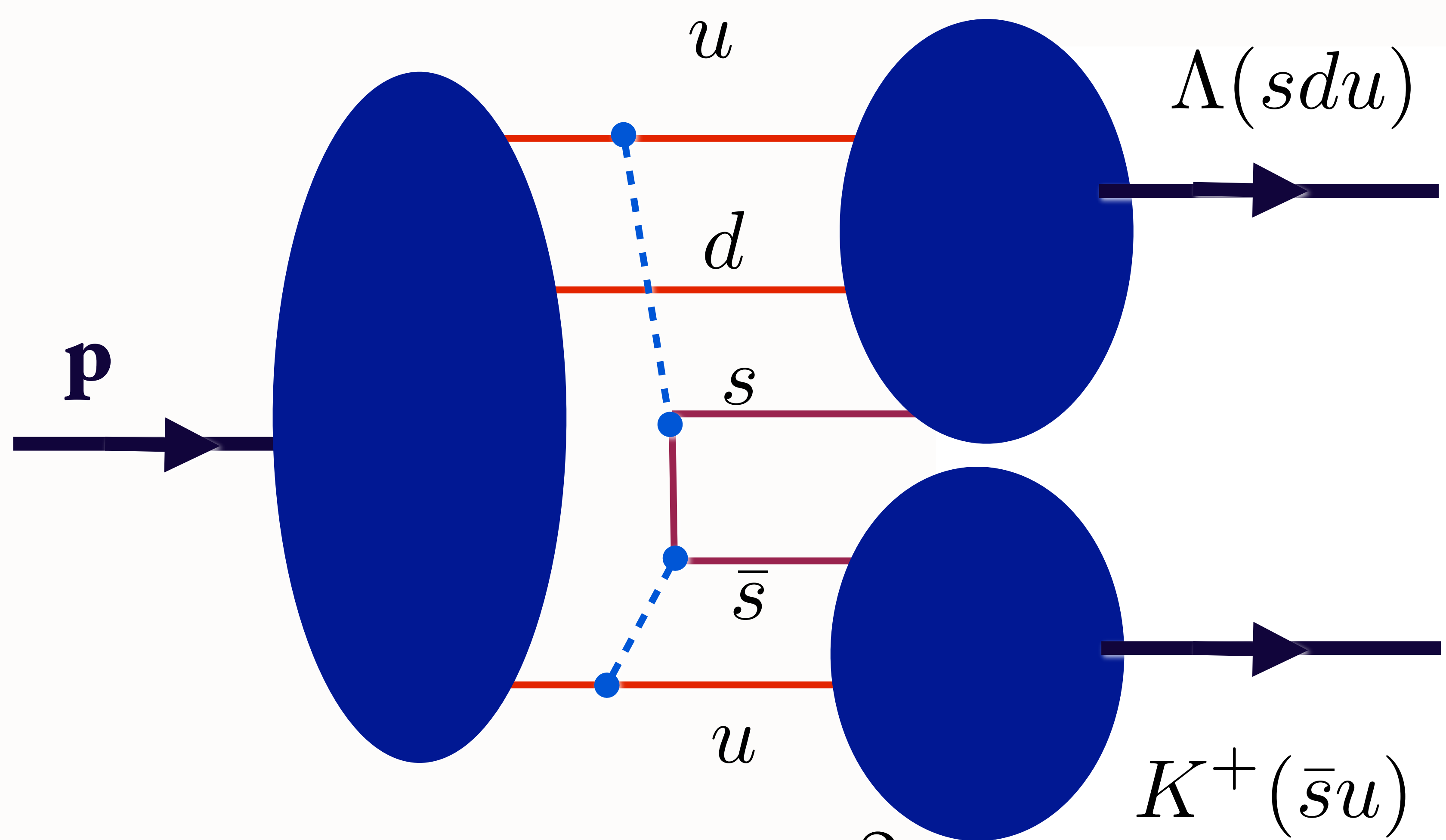
Properties of Non-Perturbative Five-Quark Fock-State

- *Dominant configuration: same rapidity*
- *Heavy quarks have most momentum*
- *Correlated with proton quantum numbers*
- *Duality with meson-baryon channels*
- *strangeness asymmetry at $x > 0.1$*
- *Maximally energy efficient*



Proton 5-quark Fock State : Intrinsic Heavy Quarks Duality to meson baryon channels

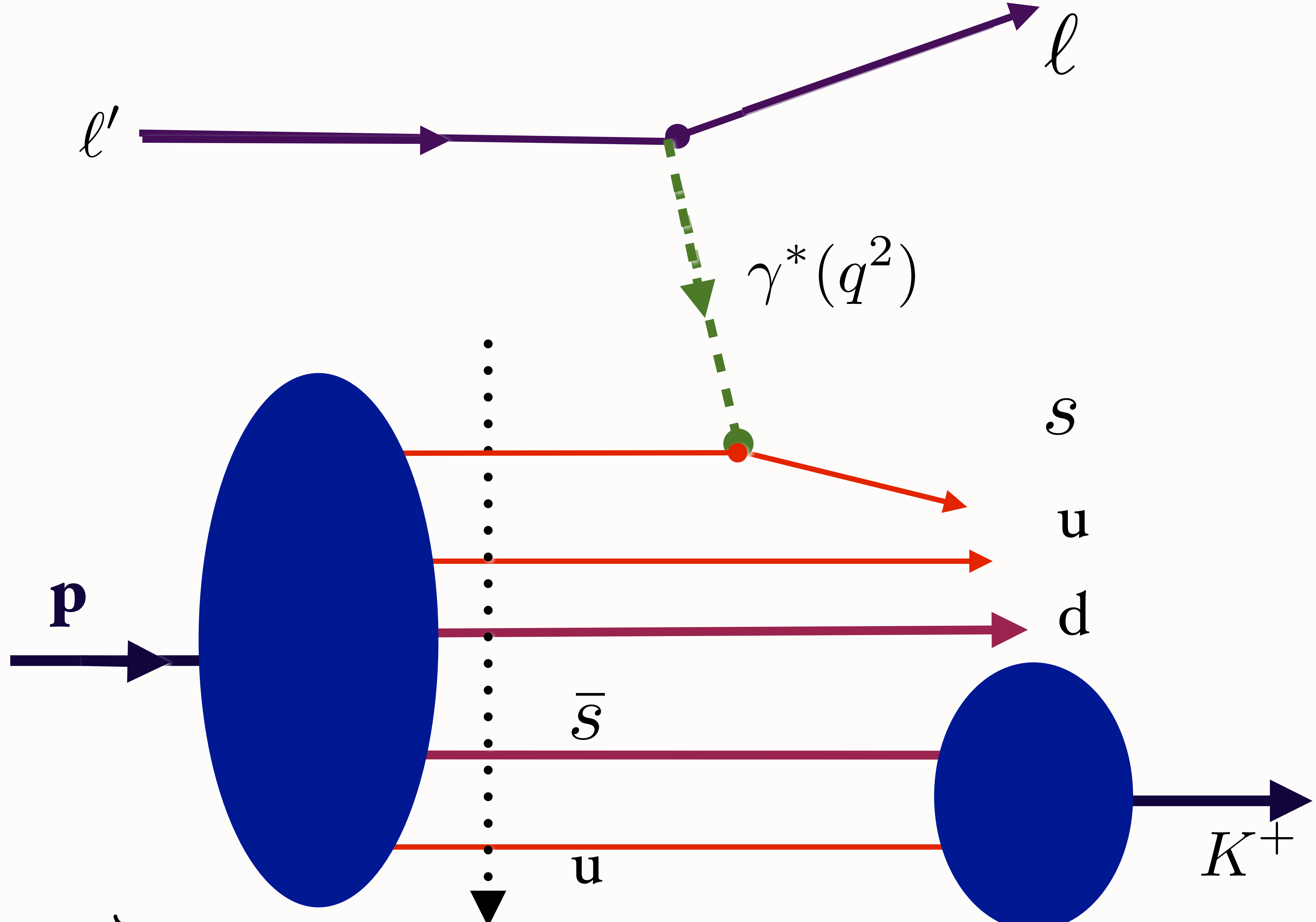
Burkardt and Warr
Ma & Sjb
Londergan
Pumplin



Minimal off-shellness: $x_Q \propto (m_Q^2$

Maximal re-interactions at small relative rapidity Δy

s vs. $\bar{s}$ Spin and Momentum Asymmetries: NuTeV anomaly



$$\psi_5(x_i, \vec{k}_{\perp i}, \lambda_i)$$

Fixed $\tau = x^+$

Proton 5-quark Fock State :

Intrinsic Heavy Quarks

"Tagged" or "Fracture" Function

$$\ell p \to \ell' K^+ X$$

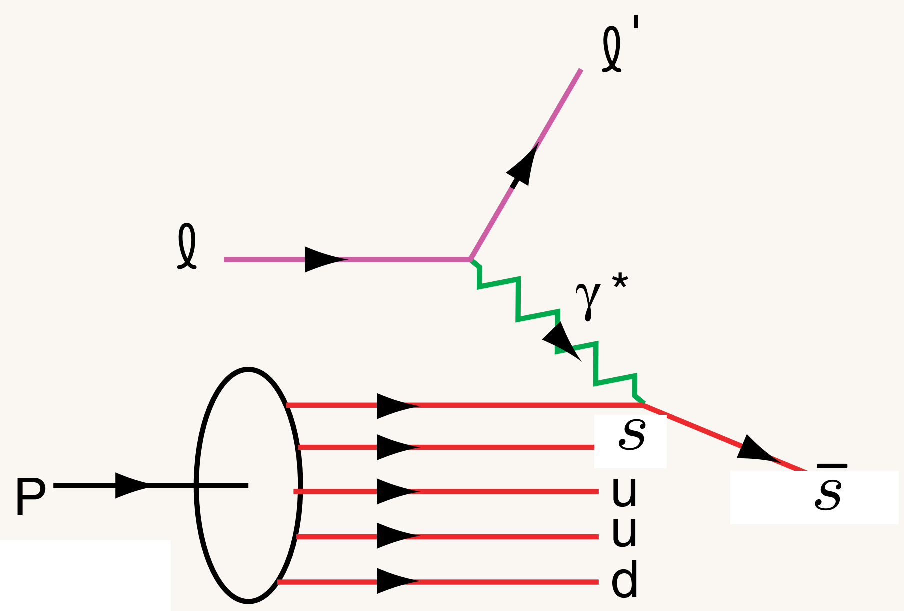
Effective Λ(uds) target

Generalized Sullivan Process

Measure strangeness distribution in Semi-Inclusive DIS at JLab

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

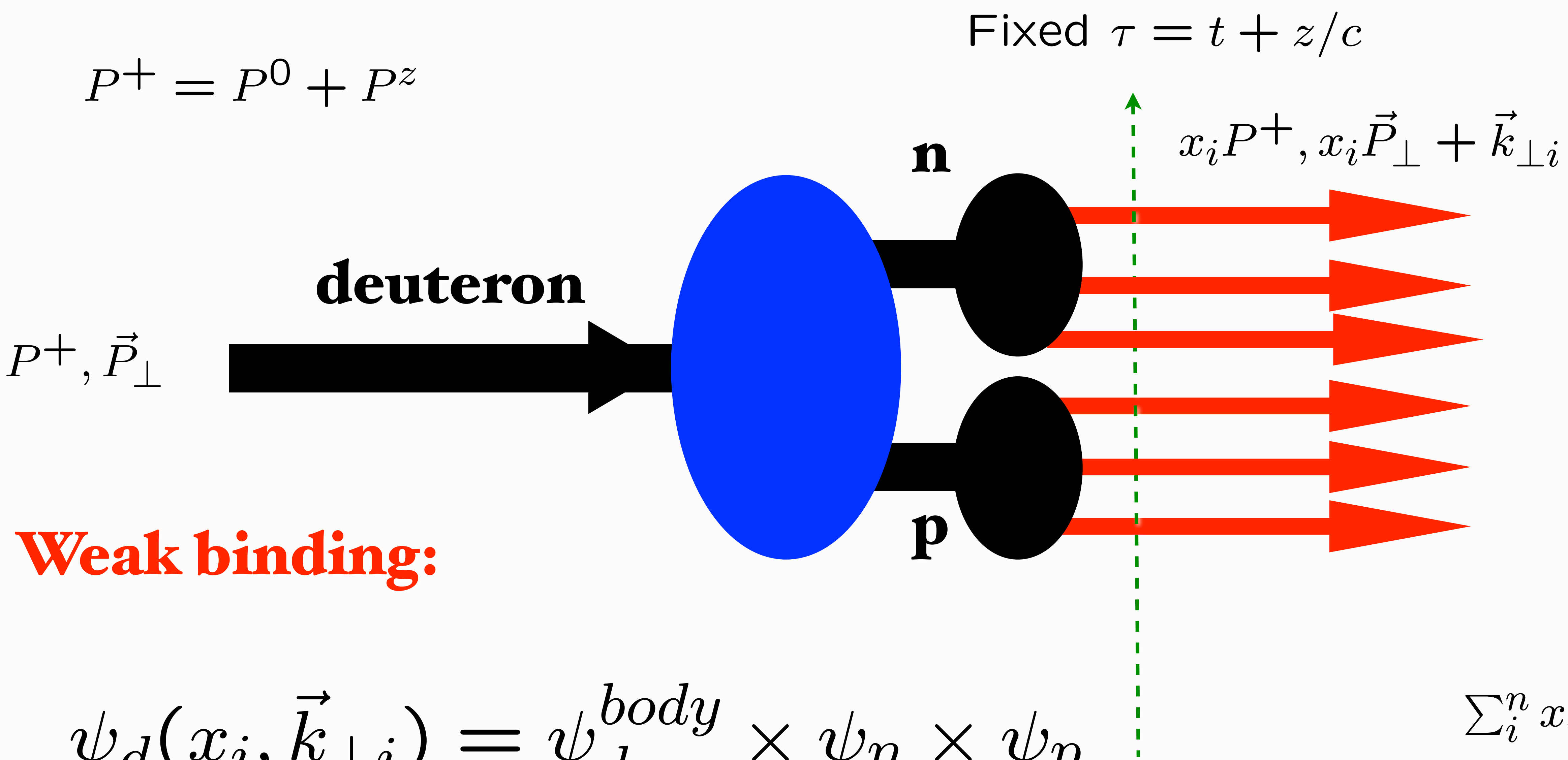
- **Non-symmetric strange and antistrange sea?**
- **Non-perturbative physics; e.g** $|uuds\bar{s}> \simeq |\Lambda(uds)K^{+}(\bar{s}u)>$
- **Crucial for interpreting NuTeV anomaly**



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

Deuteron Light-Front Wavefunction

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



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

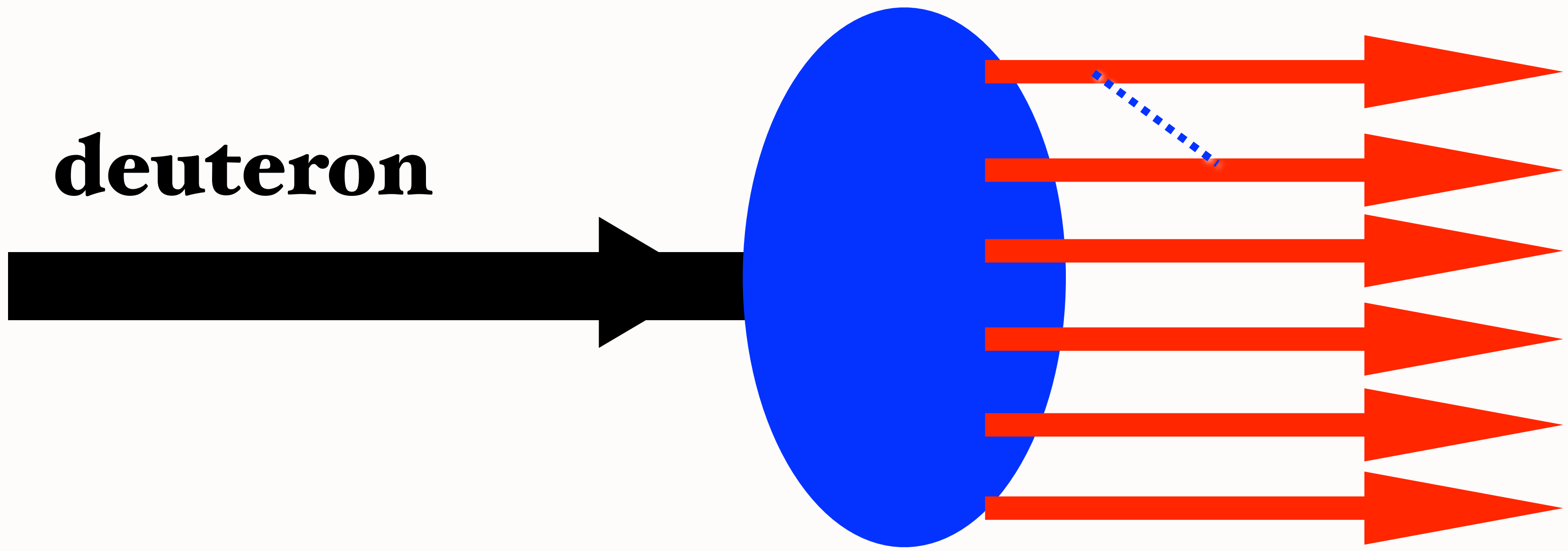
Cluster Decomposition Theorem

Ji, sjb

Ji, Lepage, sjb

Evolution of 5 color-singlet Fock states

$$\psi^d_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



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

$\sum_i^n x_i = 1$

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

5 X 5 Matrix Evolution Equation for deuteron distribution amplitude

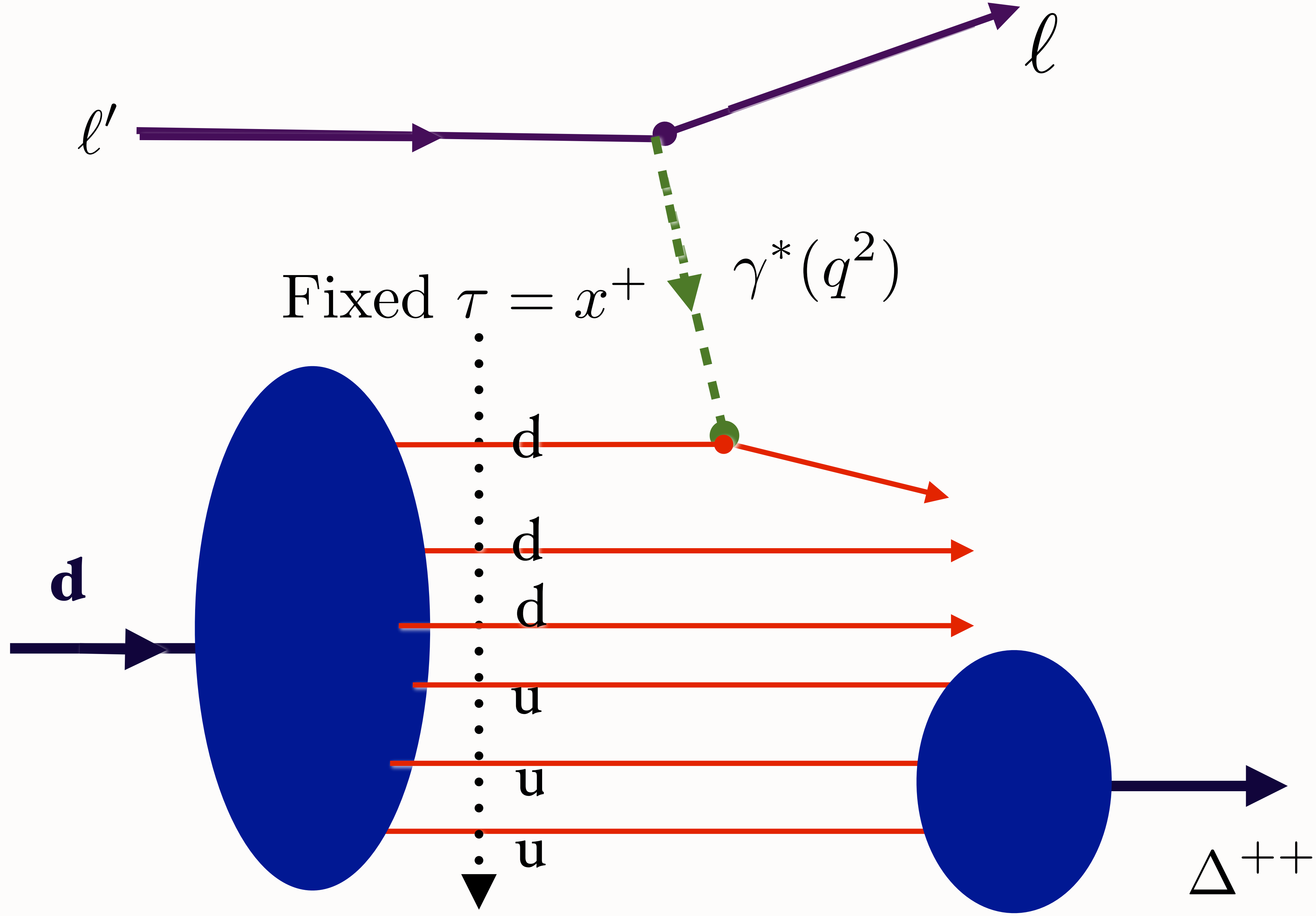
Hidden Color of Deuteron

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



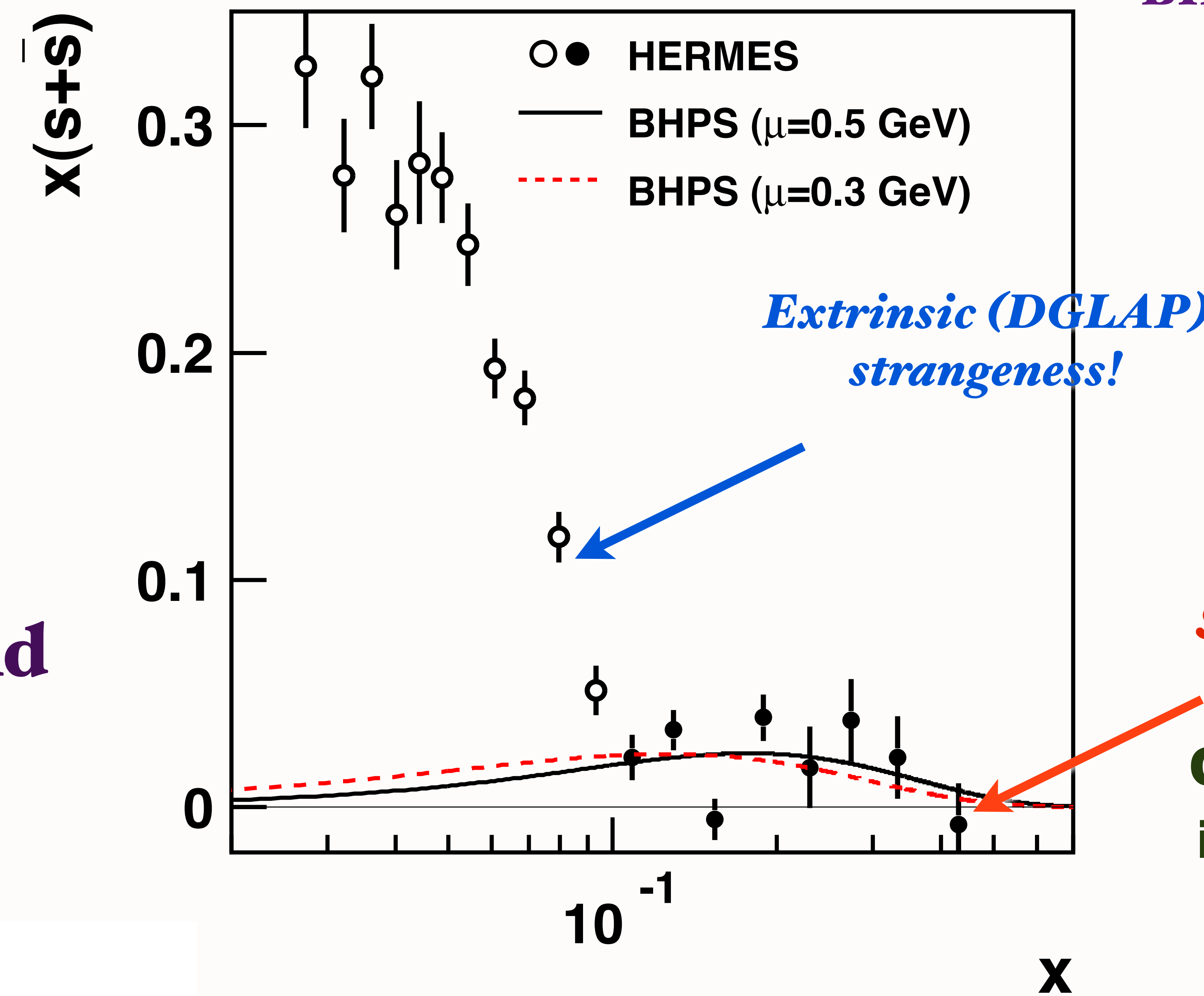
"Tagged" or "Fracture" Function

Deuteron 6-quark Fock State :
Hidden Color

$$\gamma^* d \to \Delta^{++} X$$

HERMES: Two components to s(x,Q²)!

BHPS: Hoyer, Sakai, Peterson, sjb



Intrinsic strangeness!

Consistent with intrinsic charm data

QCD: $\frac{1}{M_Q^2}$ scaling

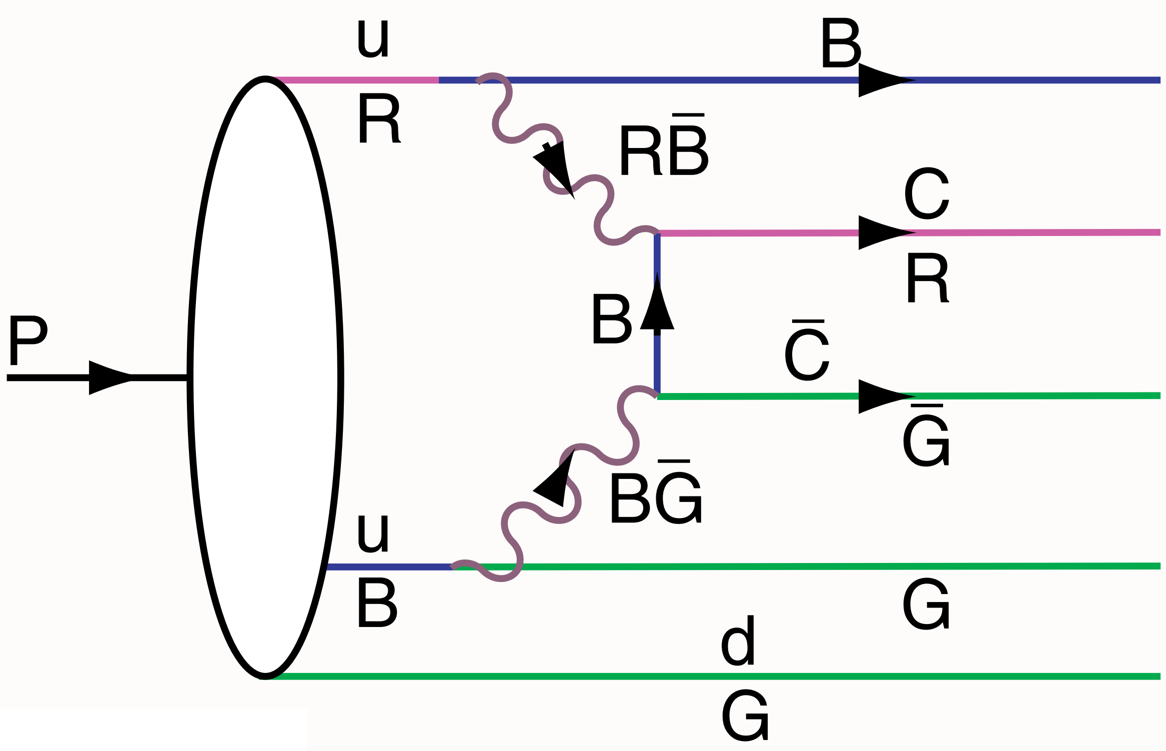
W. C. Chang and J.-C. Peng

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.

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

Hoyer, Peterson, Sakai, sjb



$|uudc\bar{c}>$ Fluctuation in Proton

QCD: Probability $\frac{\sim\Lambda^2_{QCD}}{M^2_Q}$

$|e^+e^-\ell^+\ell^->$ Fluctuation in Positronium

QED: Probability $\frac{\sim(m_e\alpha)^4}{M^4_\ell}$

OPE derivation - M.Polyakov et al.

$< p|\frac{G^3_{\mu\nu}}{m^2_Q}|p >$ vs. $< p|\frac{F^4_{\mu\nu}}{m^4_\ell}|p >$

$c\bar{c}$ in Color Octet

Distribution peaks at equal rapidity (velocity) Therefore heavy particles carry the largest momentum fractions

$$\hat{x}_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

High x charm!

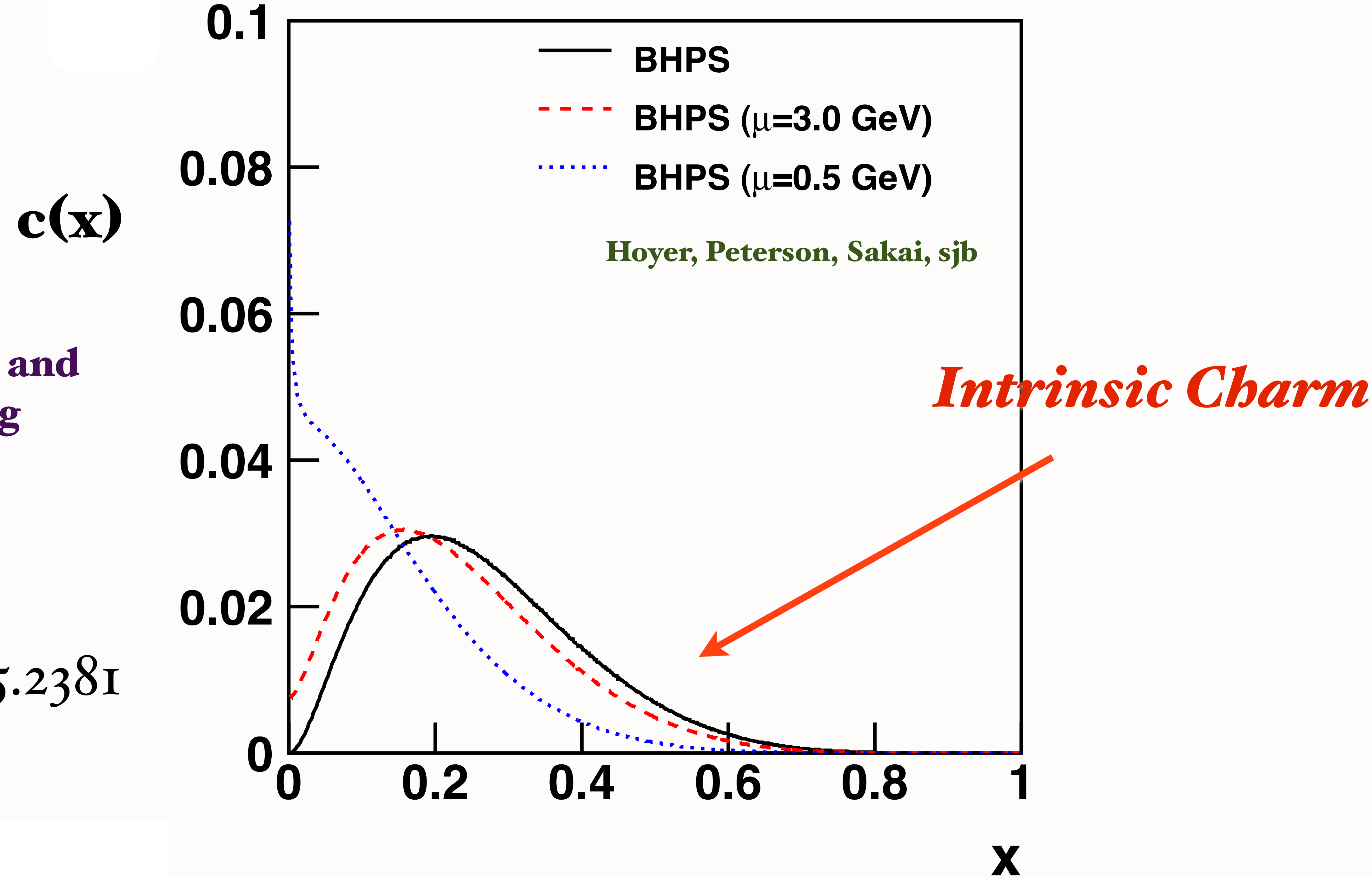
Charm at Threshold

Action Principle: Minimum KE, maximal potential

QCD ($1/m_Q^2$) scaling: predict IC !

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

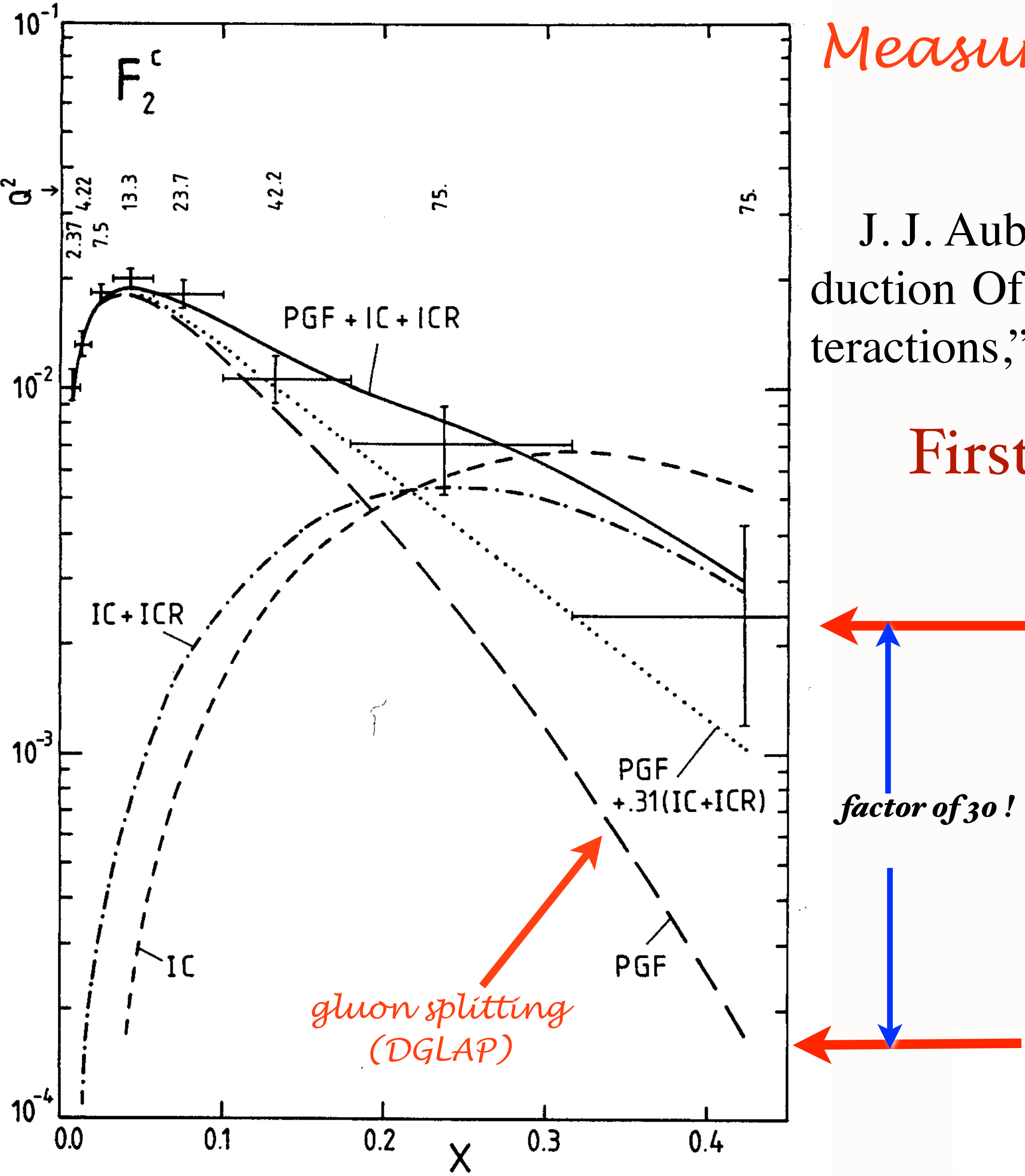
arXiv:1105.2381



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 $\mathcal{P}_5^{c\bar{c}} = 0.01$.

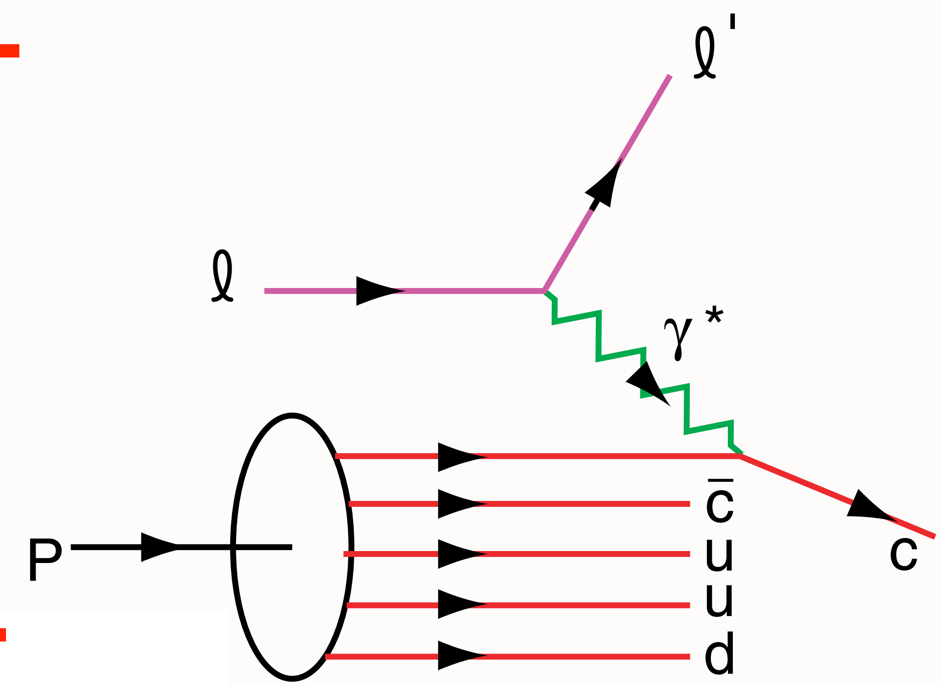
Consistent with EMC

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



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

Two Components (separate evolution):

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

Do heavy quarks exist in the proton at high x?

Conventional wisdom: impossible!

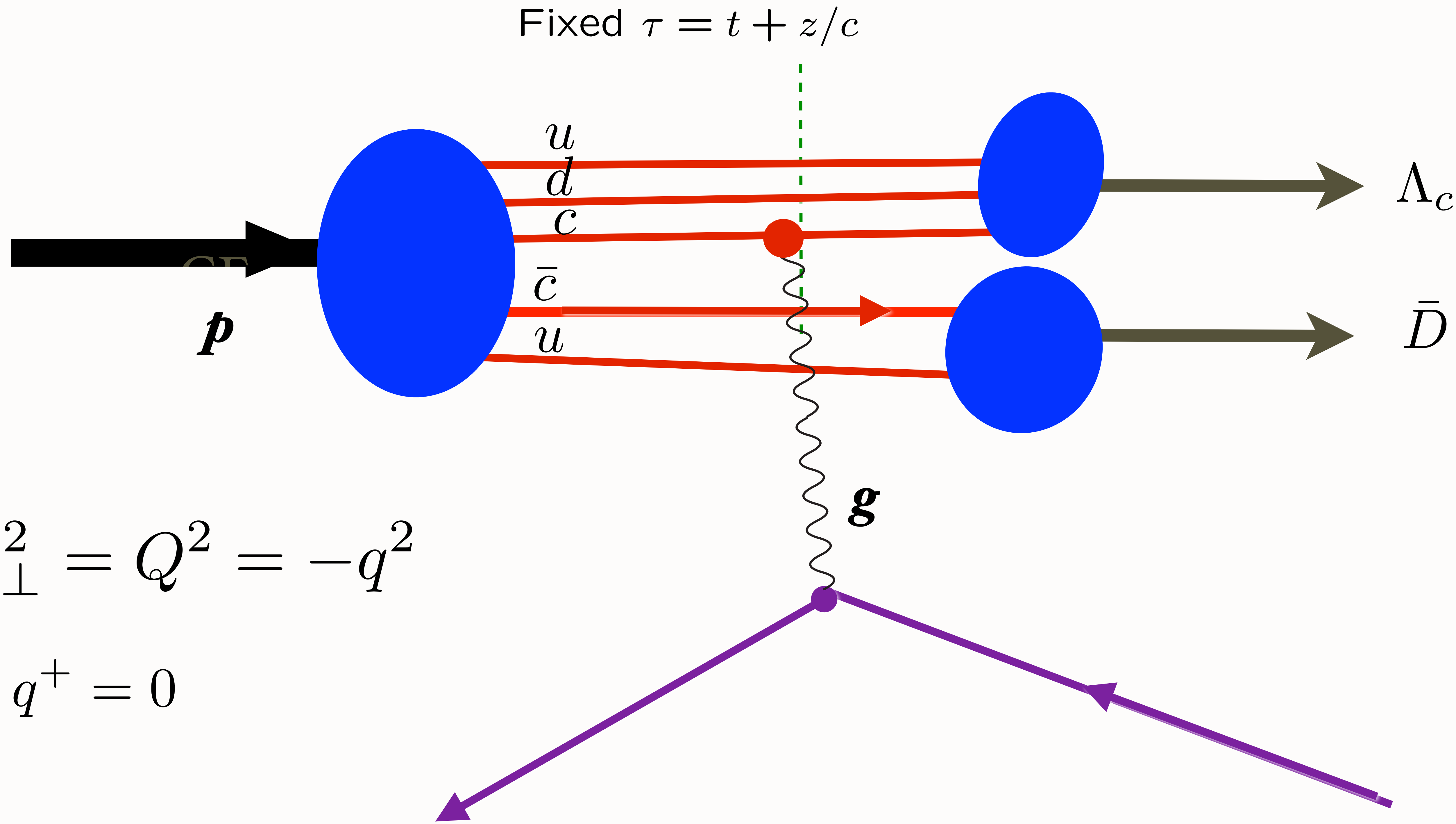
Heavy quarks generated only at low x
via DGLAP evolution
from gluon splitting

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

$$\text{at starting scale } Q_0^2 = \mu_F^2$$

Conventional wisdom is wrong even in QED!

Light-Front Wavefunctions and Heavy Quark Hadroproduction

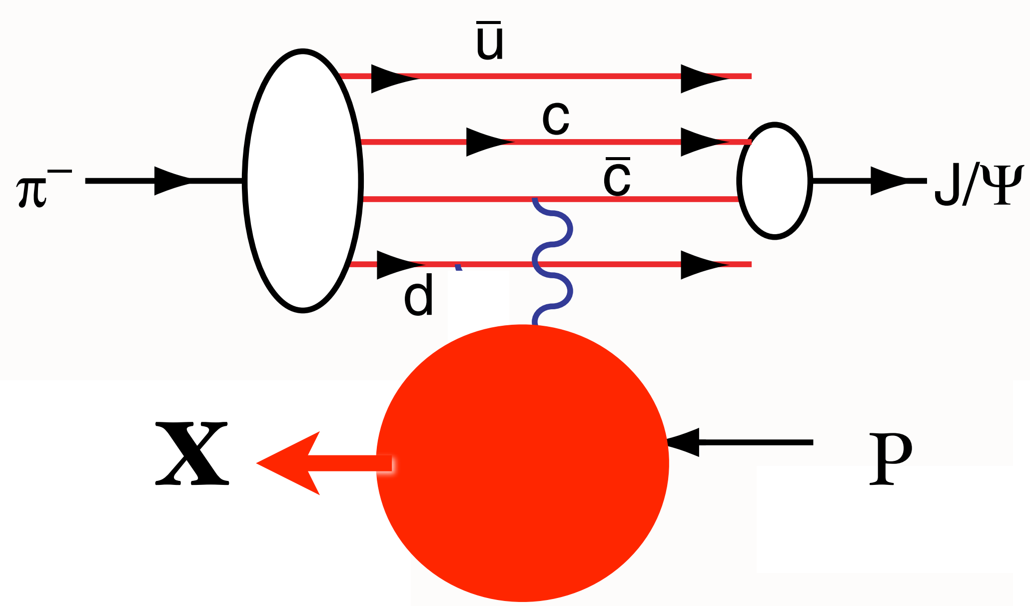


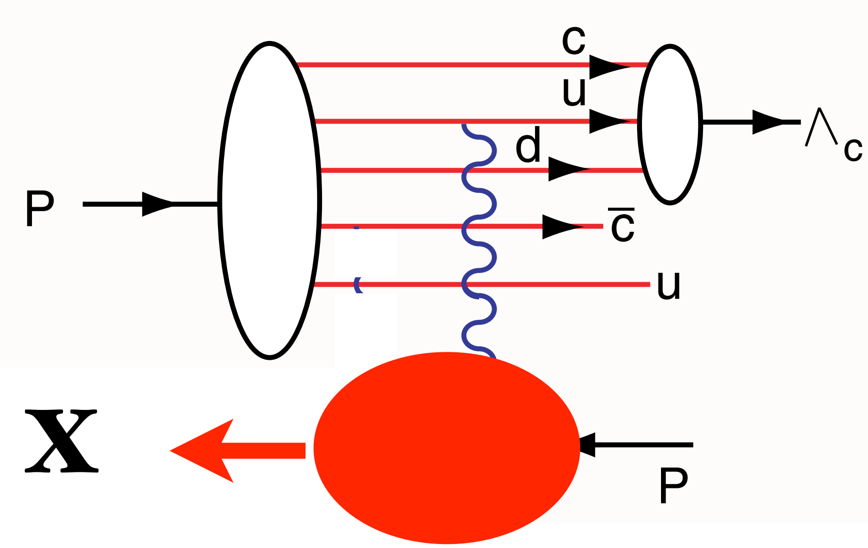
$$q_\perp^2 = Q^2 = -q^2$$

$$q^+ = 0$$

Coalescence of comovers produces $|F >= |\Lambda_c \bar{D} >$ Final State

Leading Hadron Production from Intrinsic Charm



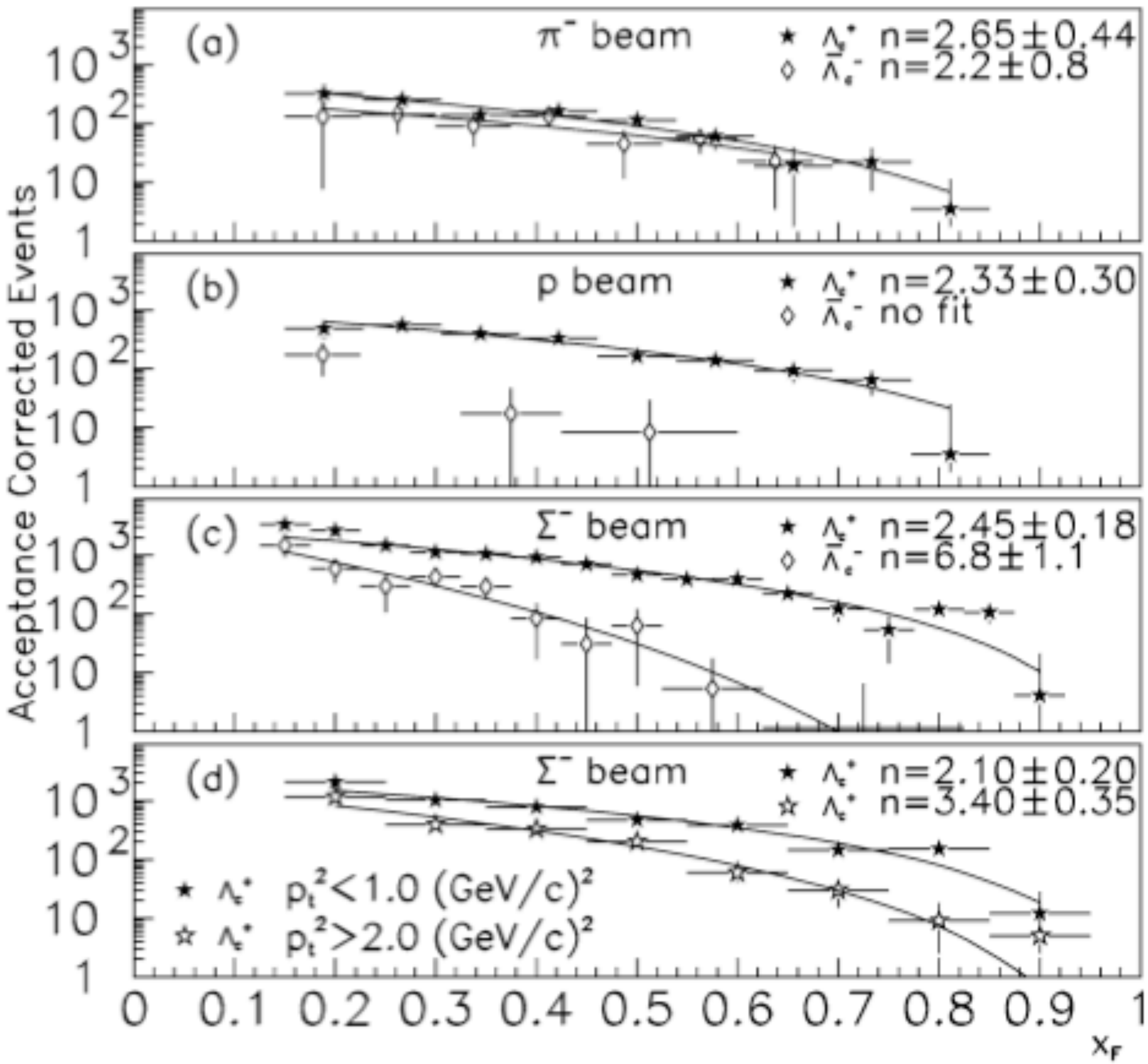


Spectator counting rules

$$\frac{dN}{dx_F} \propto (1 - x_F)^{2n_{spect}-1}$$

Coalescence of Comoving Charm and Valence Quarks Produce J/ψ, Λ_c and other Charm Hadrons at High x_F

SELEX Collaboration / Physics Letters B 528 (2002) 49–57



$$\frac{d\sigma}{dx_F}(pA \to \Lambda_c X) \sim (1 - x_F)^p$$

Large x_F production close to the maximum allowed by phase space!

Spectator counting rules

leaves 2 spectator quarks

$\Lambda_c(cud)$

- 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 $pp \to \Lambda_b X$

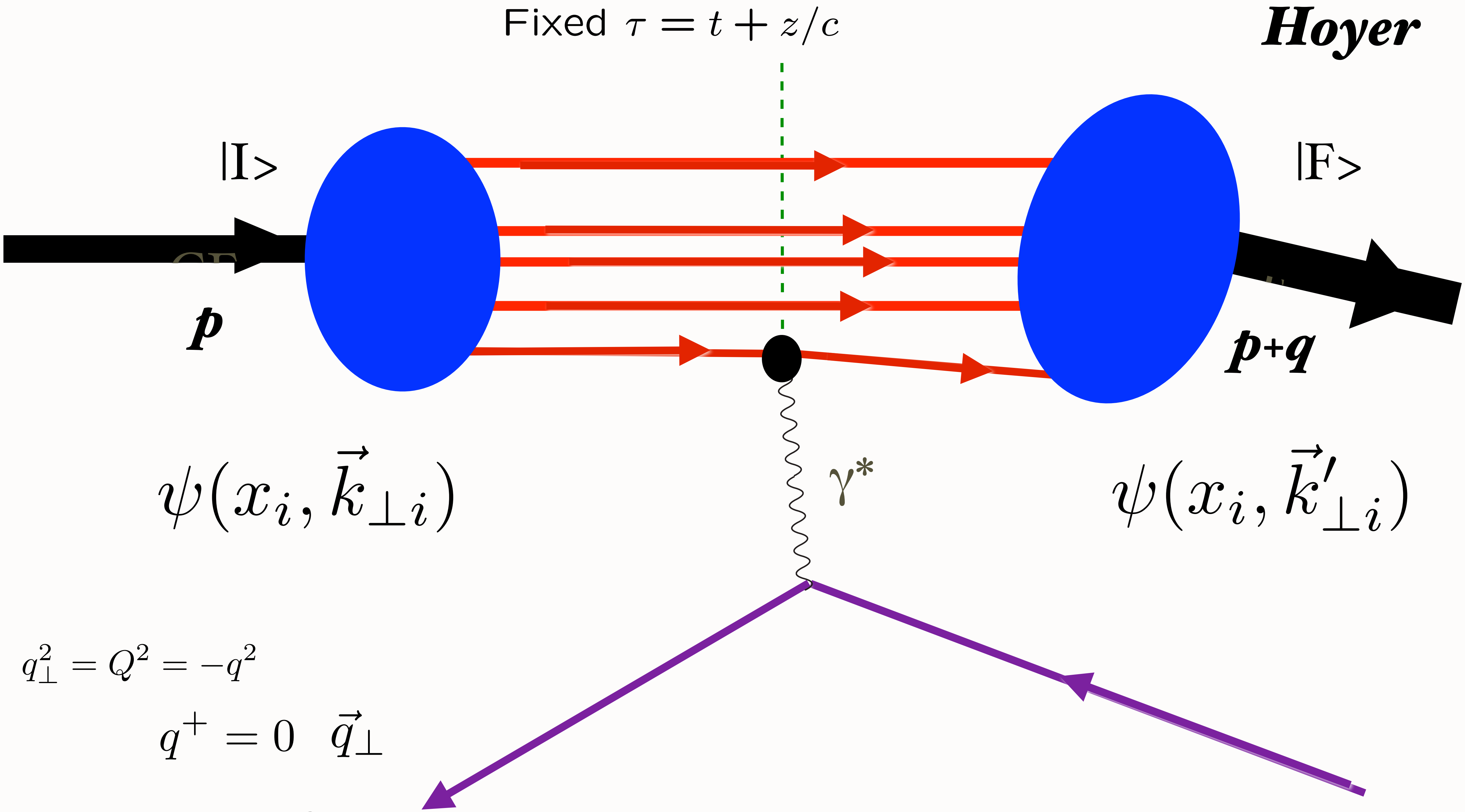
- High x_F $pp \to \Xi(ccd)X$ (SELEX)

Interesting spin, charge asymmetry, threshold, spectator effects

Important corrections to B decays; Quarkonium decays

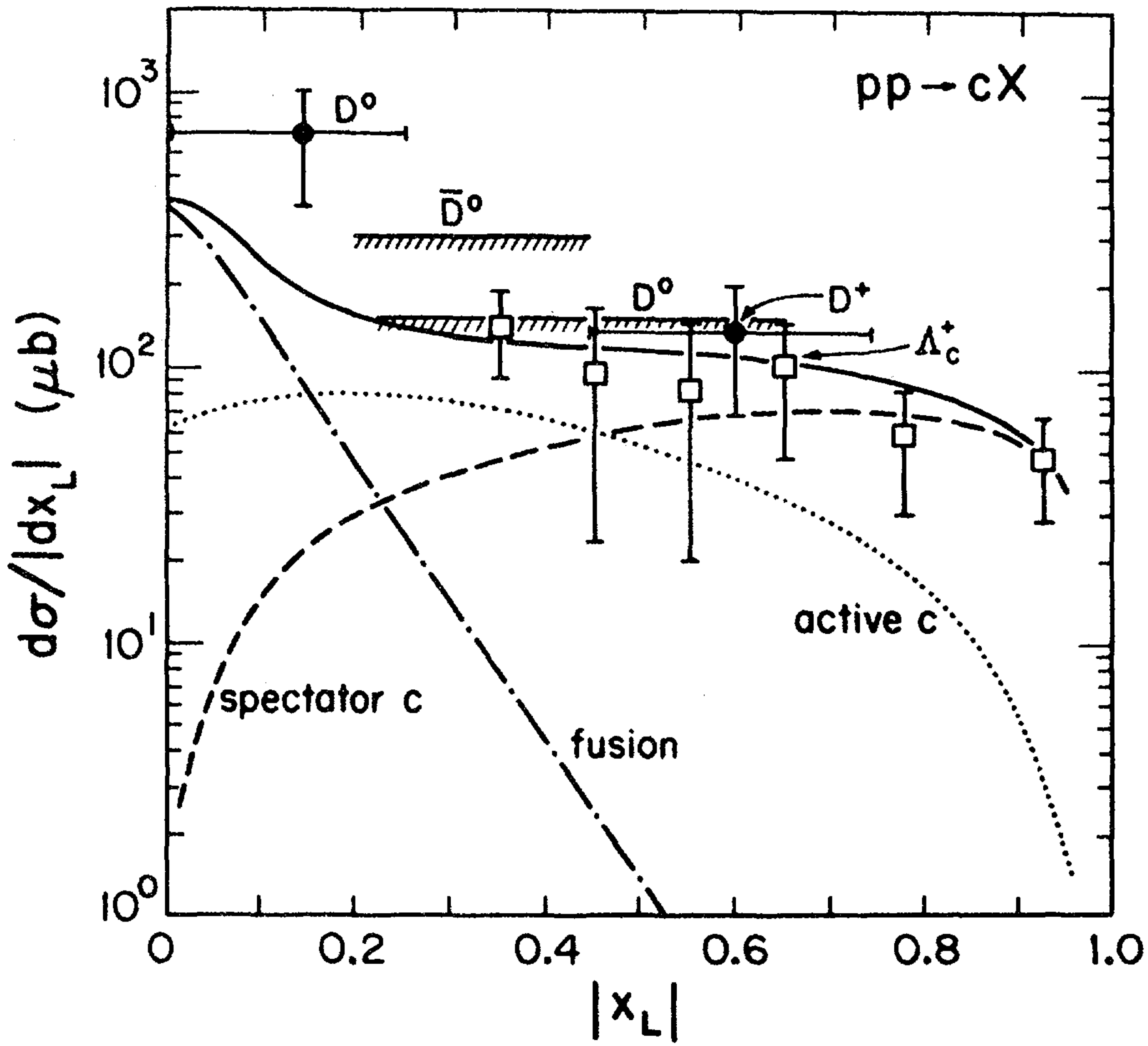
Gardner, Karliner, sjb

Light-Front Wavefunctions and Electron-Proton Collisions



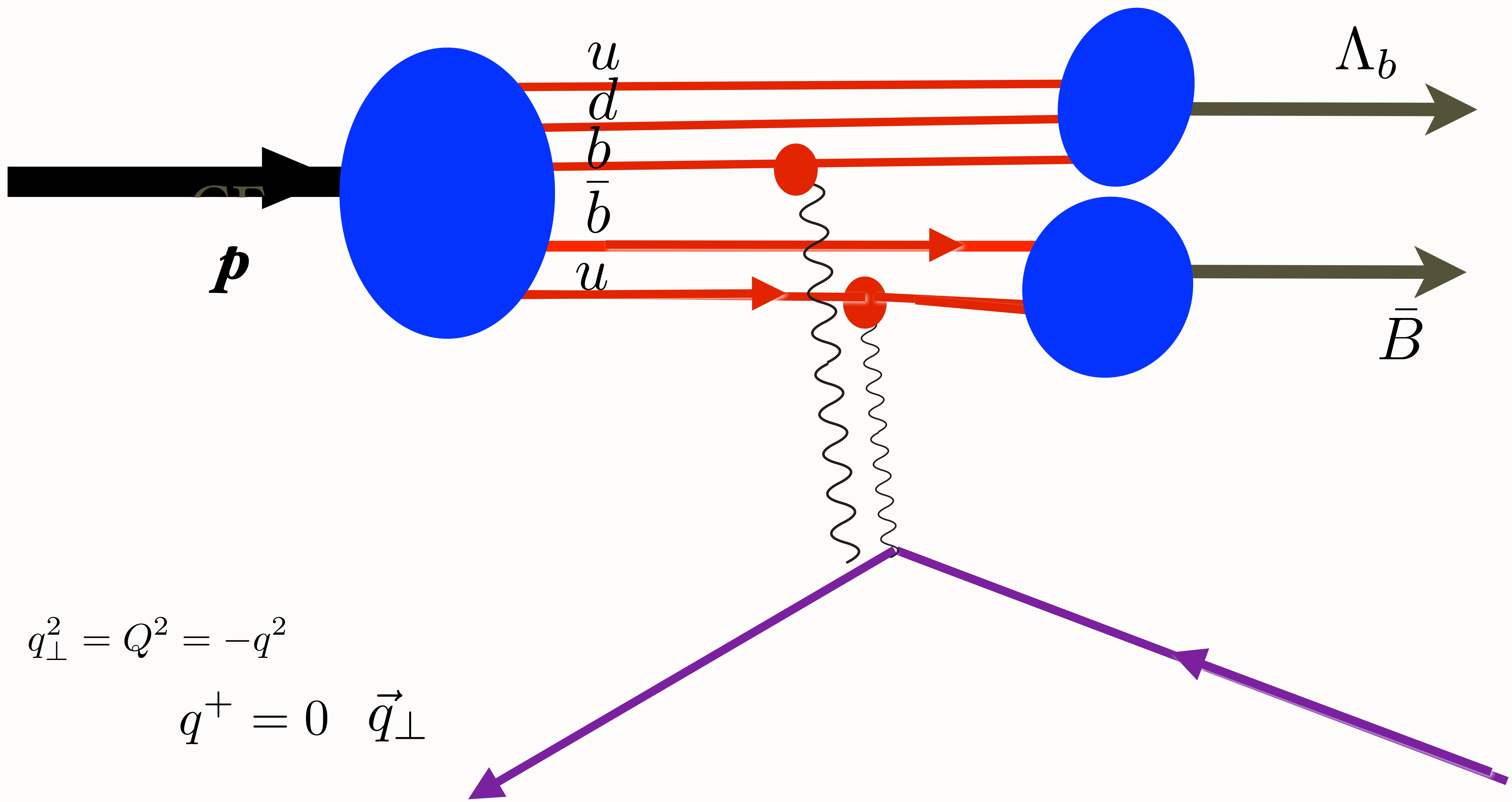
All final states |F> in electroproduction produced
Diagonal n to n overlap of LFWFs

|F> = resonances, multiparticle states.
Confinement: Only Color Singlets!



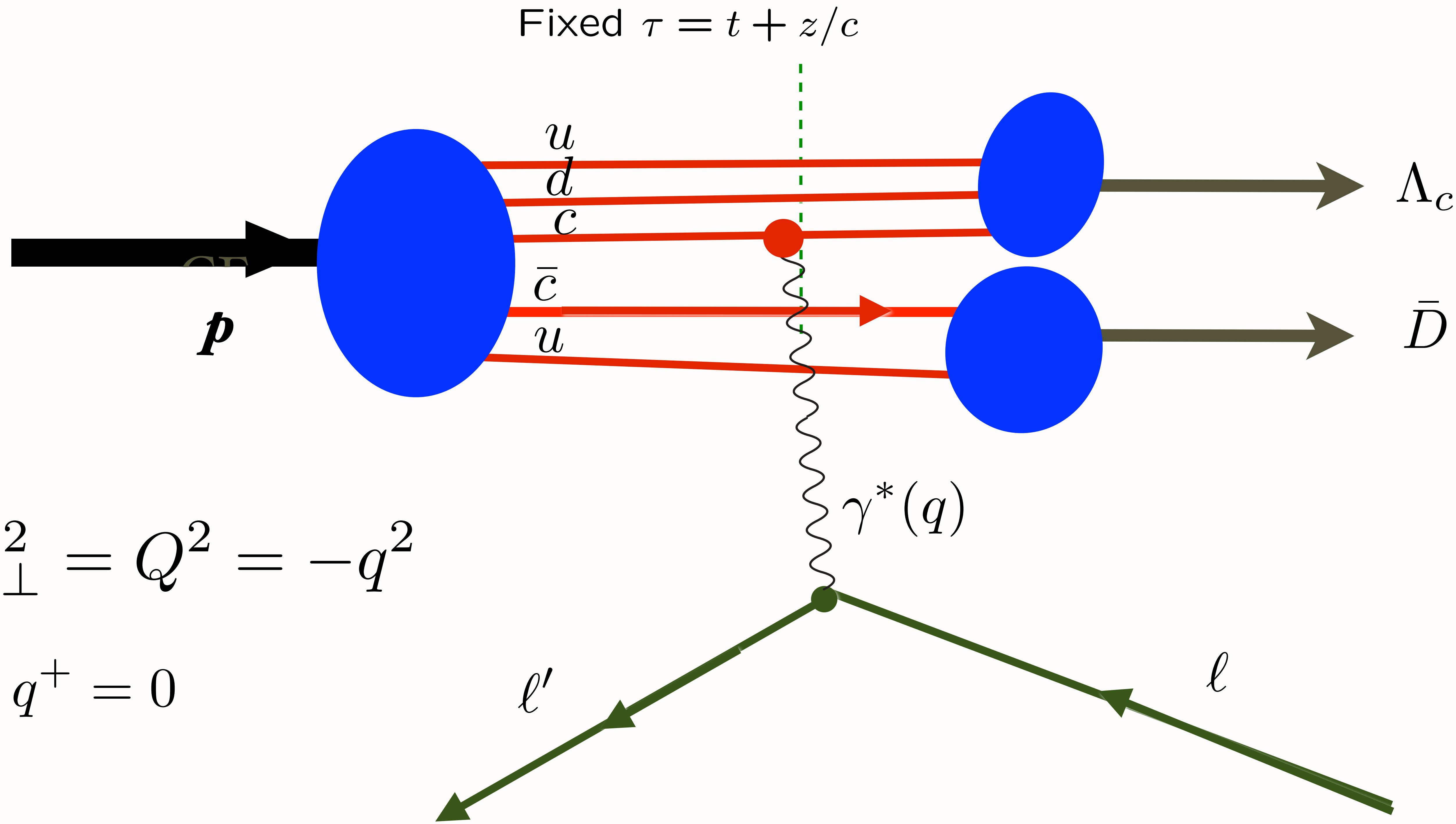
Barger, Halzen, Keung

Light-Front Wavefunctions and Heavy Quark Hadroproduction



Coalescence of comovers produces $|F >= |\Lambda_b \bar{B} >$ Final State

Light-Front Wavefunctions and Heavy-Quark Electroproduction



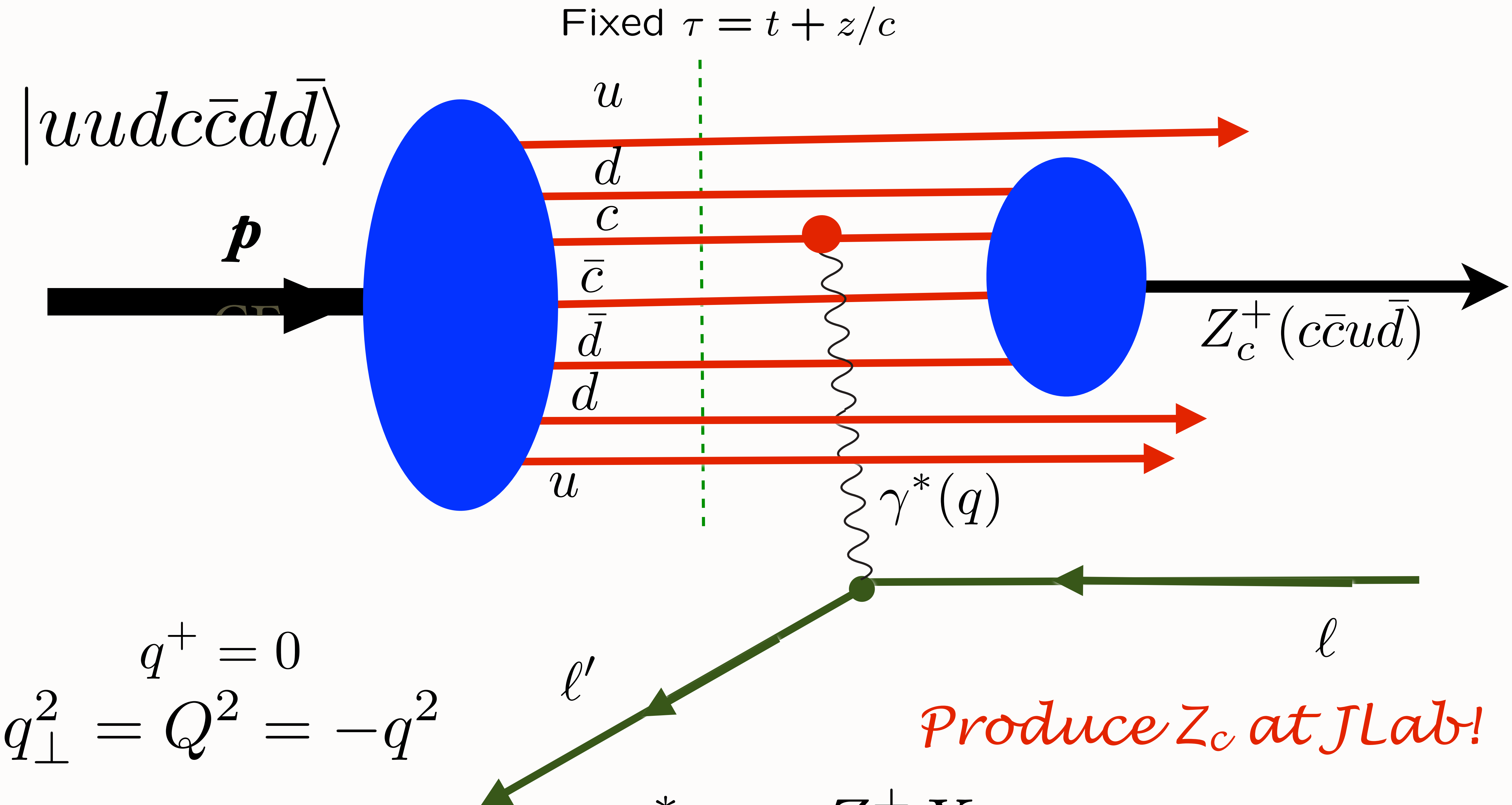
$$q_\perp^2 = Q^2 = -q^2$$

$$q^+ = 0$$

Coalescence of comovers produces $|F> = |\Lambda_c \bar{D}>$ Final State

Threshold Production at JLab!

Light-Front Wavefunctions and Heavy-Quark Electroproduction



$$\gamma^* p \to Z_c^+ X$$

Coalescence of comovers at threshold produces Z_c^+ tetraquark resonance

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 ($90°_{cm}$):

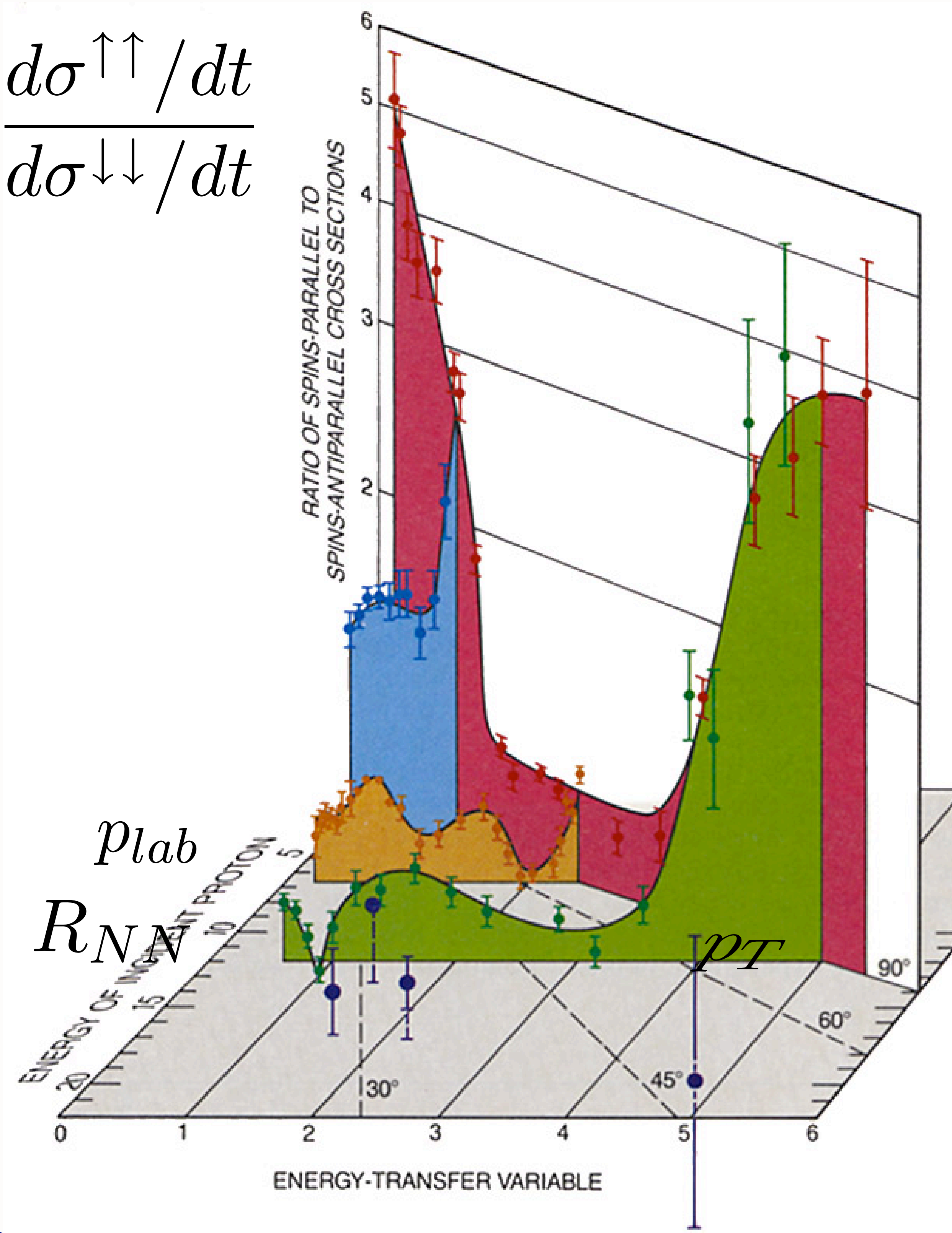
Hard scattering takes place only with spins ↑↑

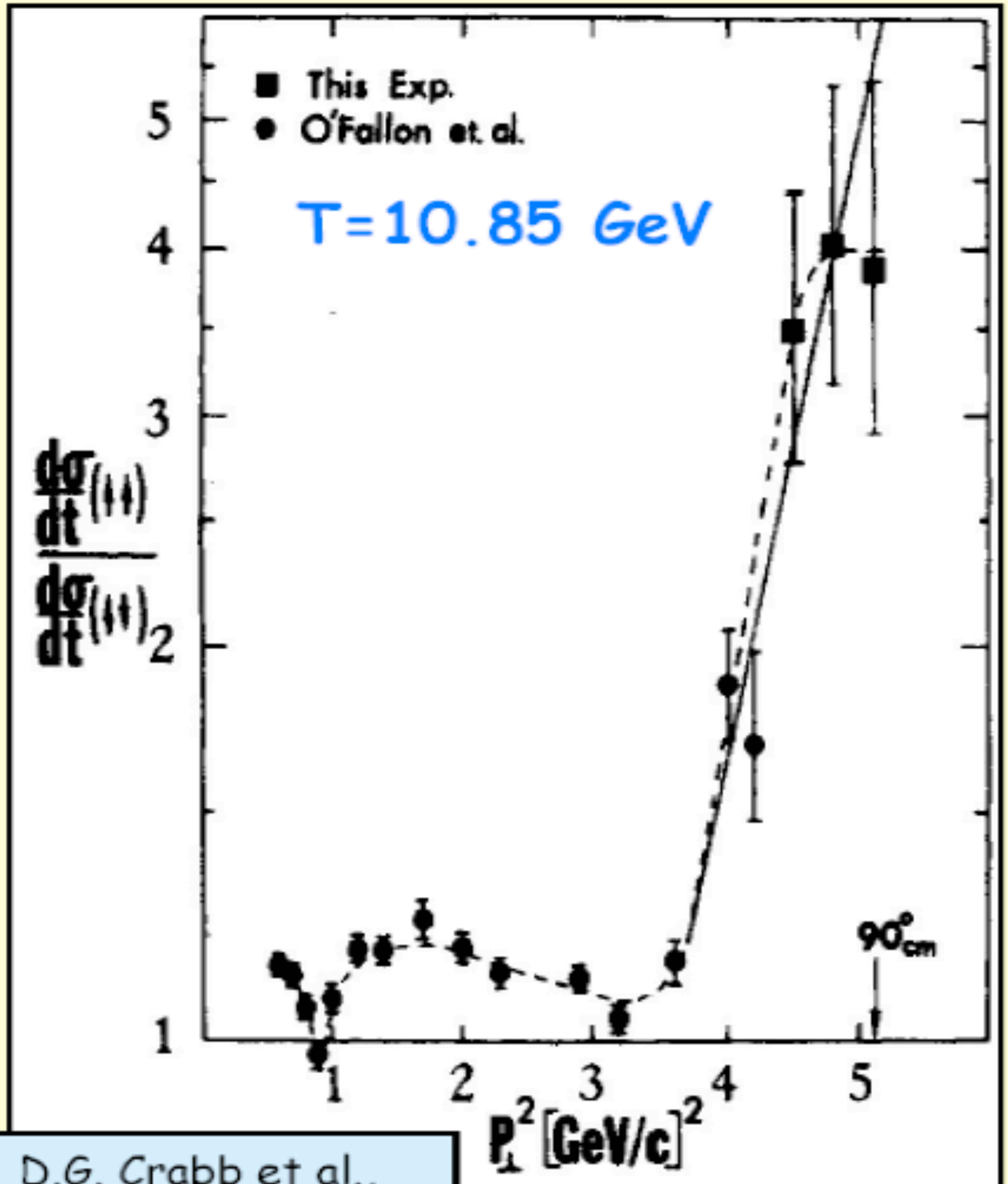
Charm and Strangeness Thresholds

Heppelmann et al: Quenching of Color Transparency

B=2 Octoquark Resonances?

$$\frac{d\sigma^{\uparrow\uparrow}/dt}{d\sigma^{\downarrow\downarrow}/dt}$$





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

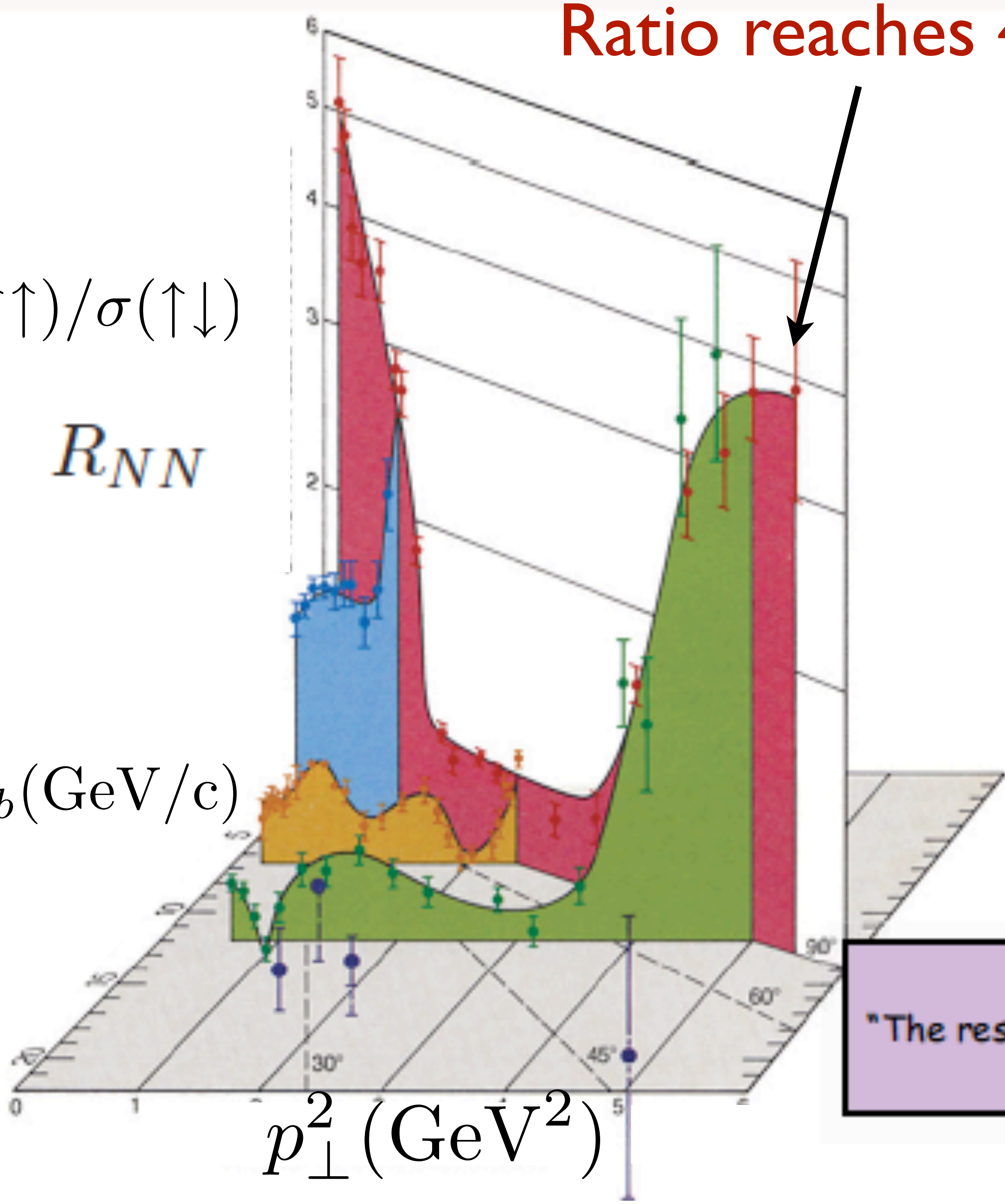
Spin Correlations in Elastic $p-p$ Scattering

Ratio reaches 4:1

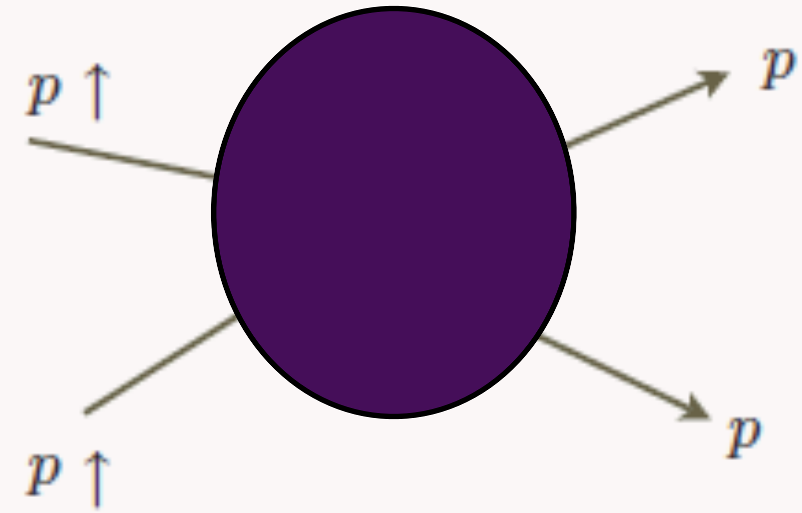
$\sigma(\uparrow\uparrow)/\sigma(\uparrow\downarrow)$

R_{NN}

$p_{lab}(\mathrm{GeV/c})$



$p_\perp^2\,(\mathrm{GeV}^2)$



polarization normal to scattering plane

$|uud\ uud\ c\bar{c}\rangle$

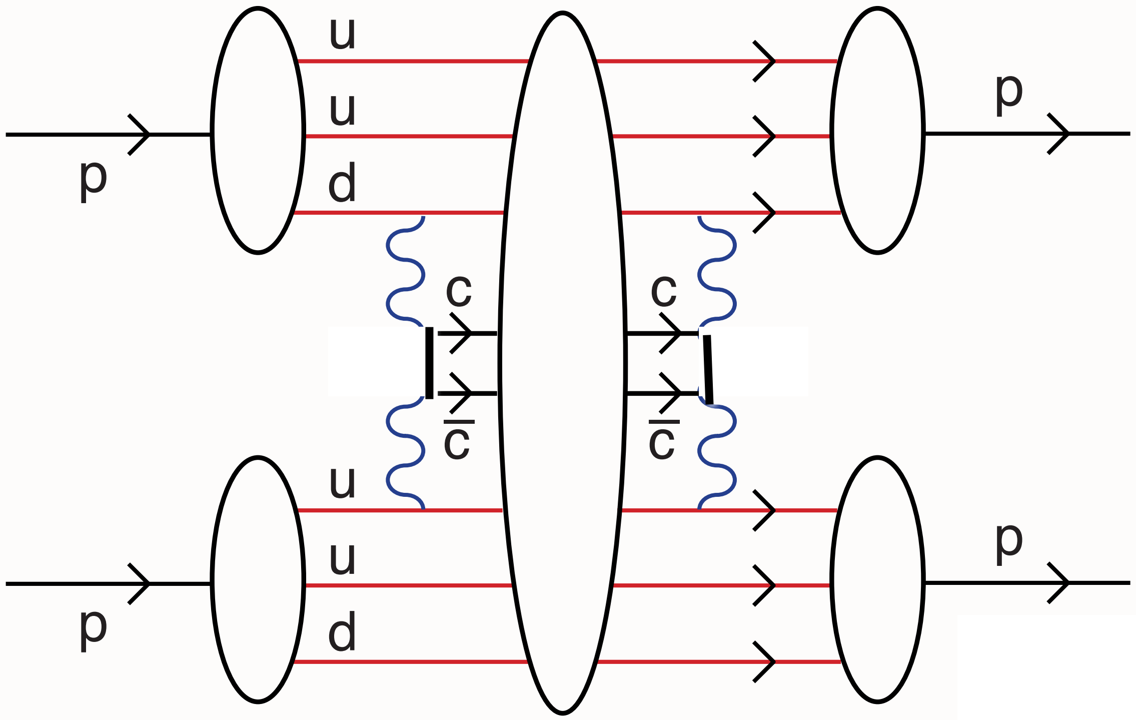
Dibaryon resonance?

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

Large R_{NN} in $pp \to pp$ explained by
$B=2, J=L=1\ |uuduudc\bar{c}>$ resonance
at $\sqrt{s} \sim 5$ GeV

de Teramond and sjb

$$A_{nn} = 1!$$



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).

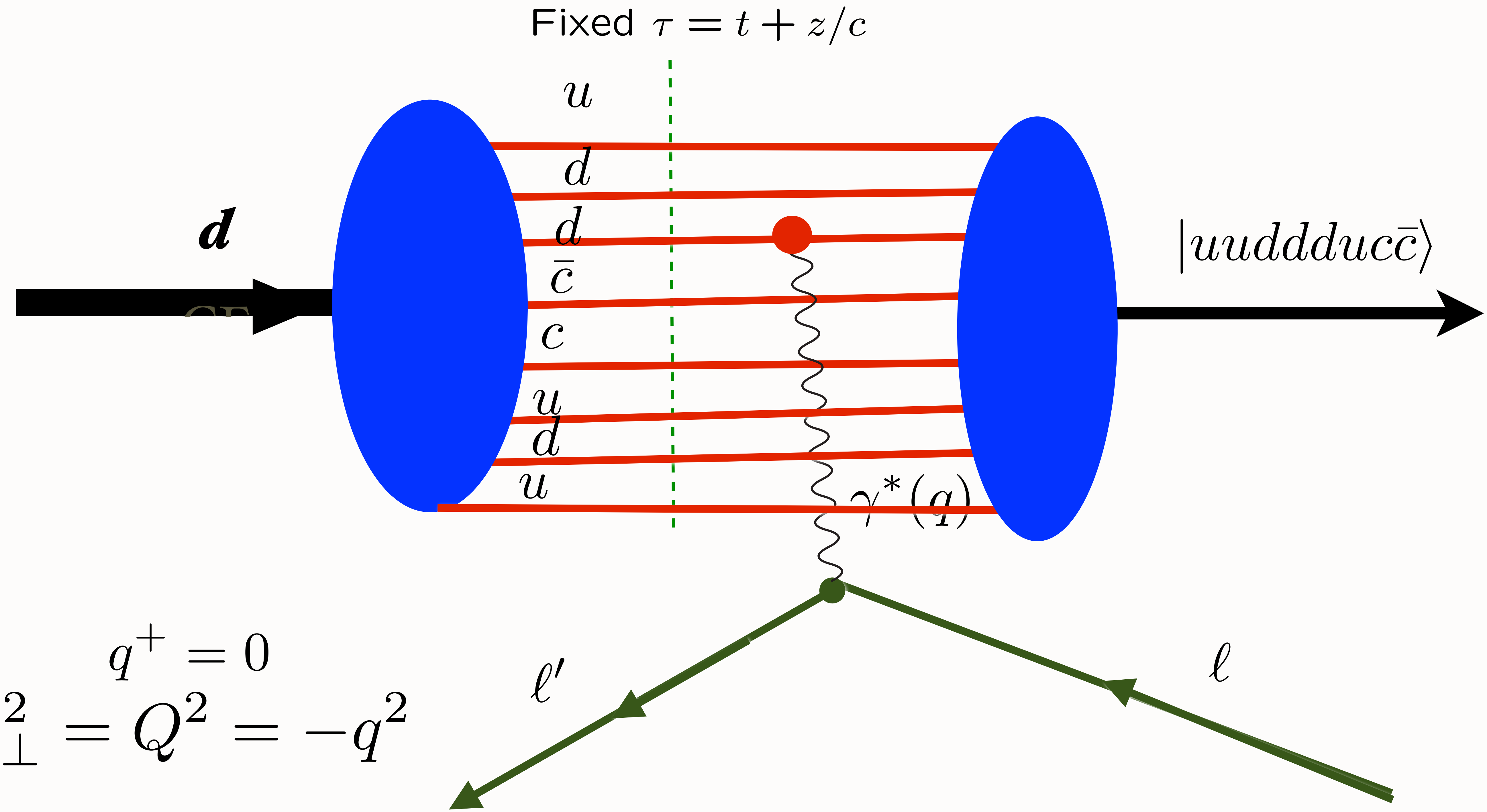
Production of
$uud\,\bar{c}c\,uud$
octoquark resonance

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 $\qquad \sigma(\gamma p \to c\bar{c}X) \simeq 1\ nb$ at threshold

Light-Front Wavefunctions and Heavy-Quark Electroproduction

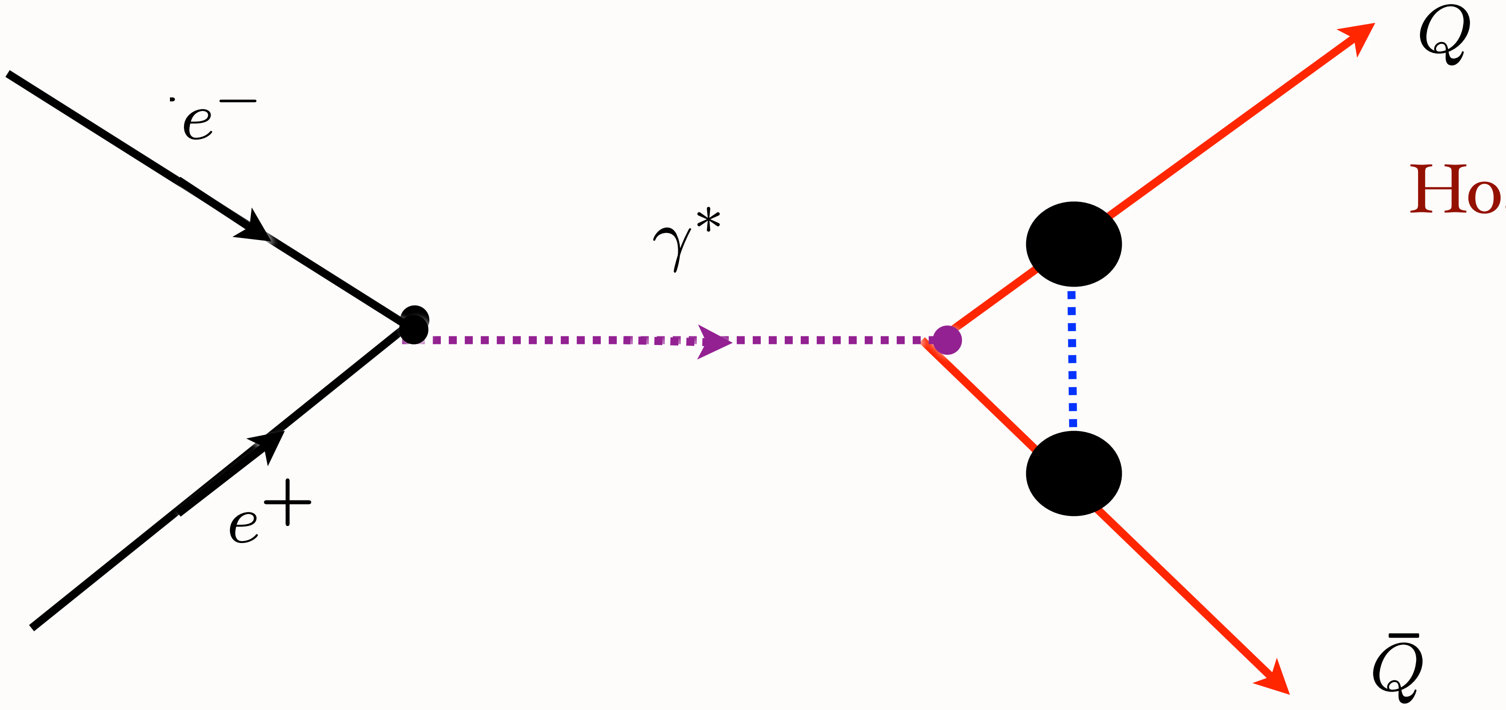


$$q^+ = 0$$

$$q_\perp^2 = Q^2 = -q^2$$

Coalescence of comovers can produce the $B = +2$ $Q = +1$ isospin partner of the $B = +2$ $Q = +2$ resonance $|uduudc\bar{c}\rangle$ which produces the large R_{NN} in p p elastic scattering

Threshold Production at JLab!



Hoang, Kuhn, Teubner, sjb

$$F_1 + F_2 = \left[1 - 2\frac{\alpha_s(se^{3/4}/4)}{\pi}\right] \times \left[1 + \frac{\pi\alpha_s(sv^2)}{4v}\right]$$

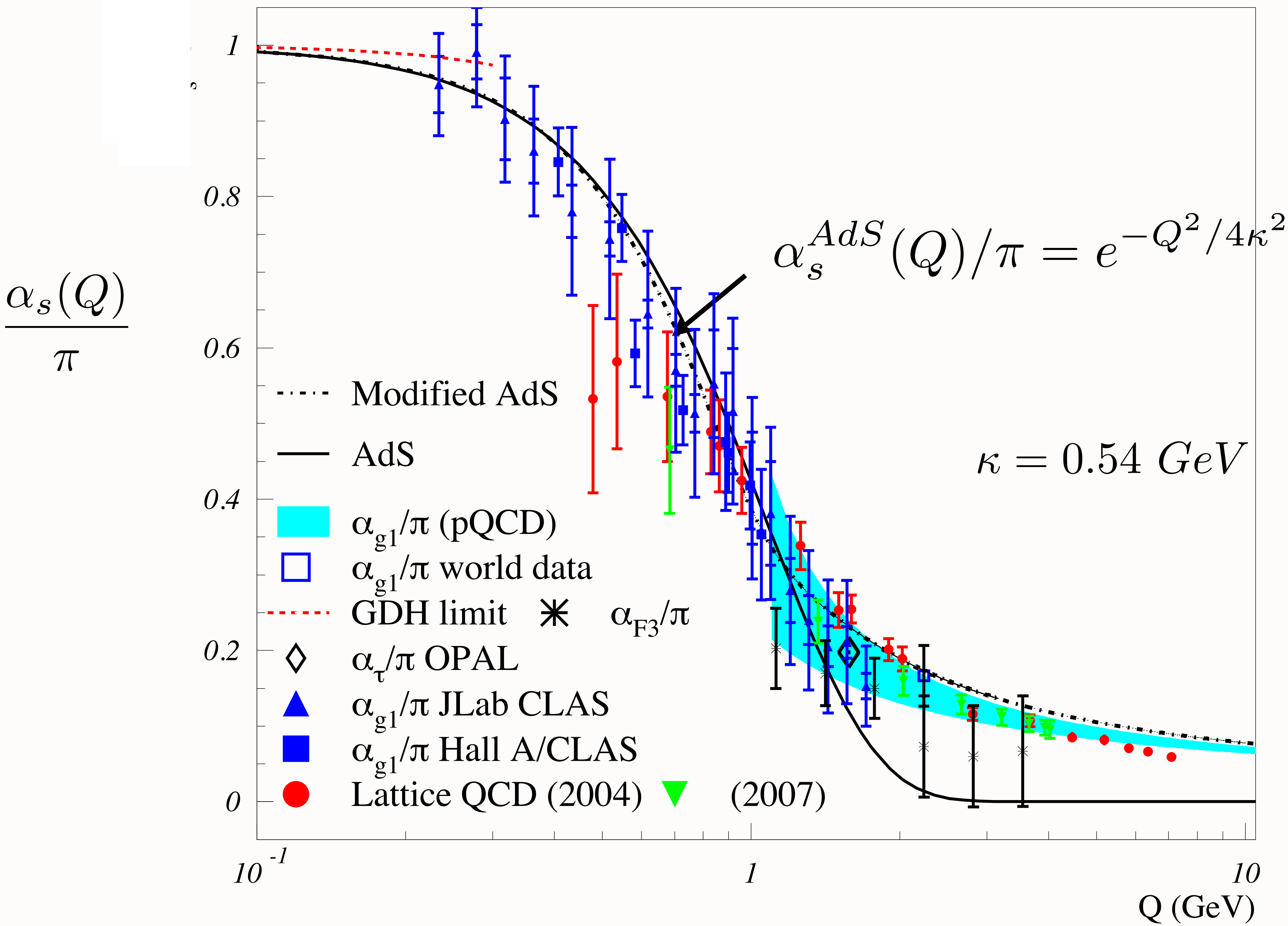
Angular distributions of massive quarks close to threshold.

Example of Multiple BLM/PMC Scales

QCD coupling at small scales at low relative velocity v

Running Coupling from Light-Front Holography and AdS/QCD

Analytic, defined at all scales, IR Fixed Point



AdS/QCD dilaton captures the higher twist corrections to effective charges for Q < 1 GeV

$$e^{\varphi} = e^{+\kappa^2 z^2}$$

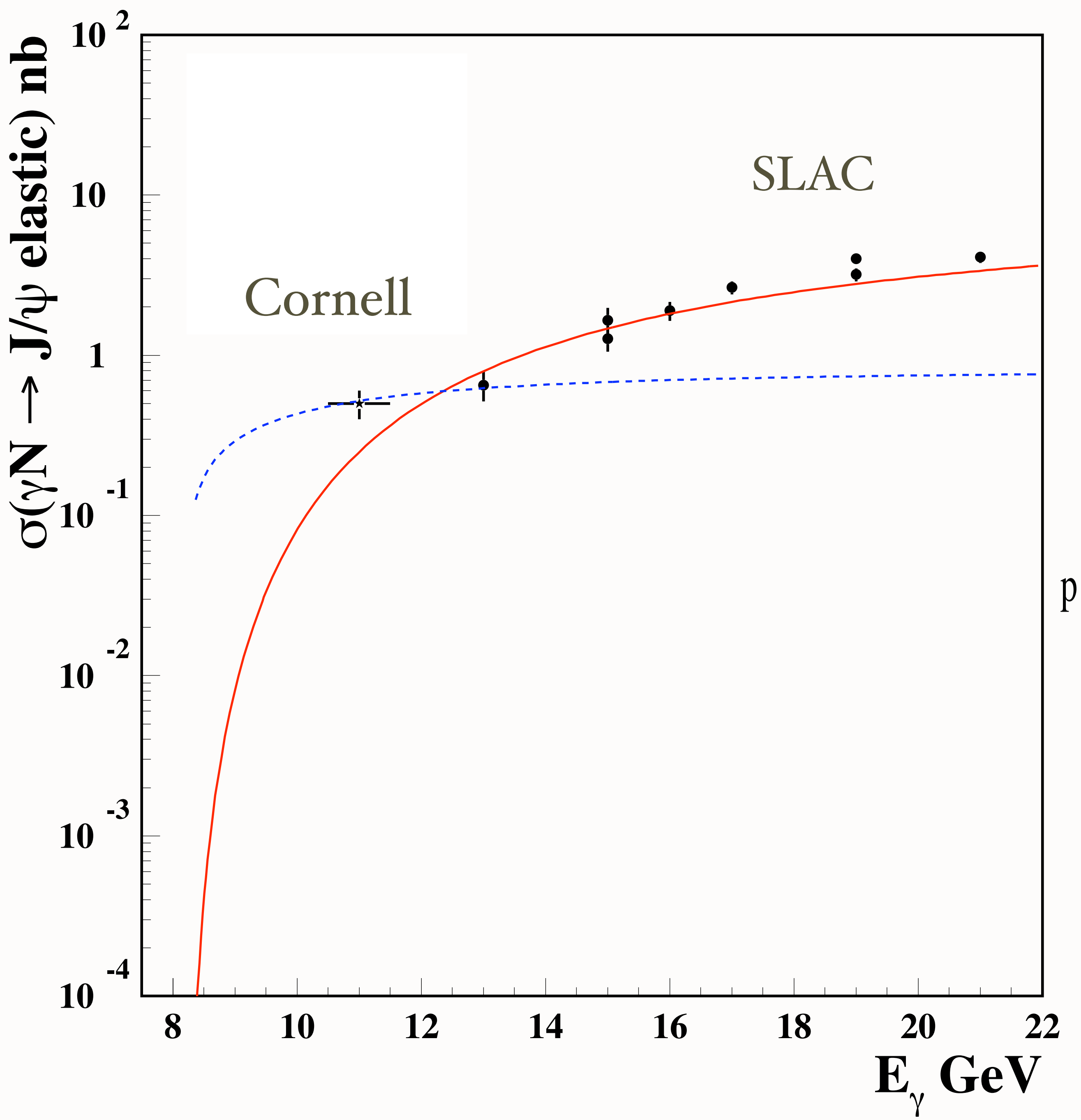
Deur, de Teramond, sjb

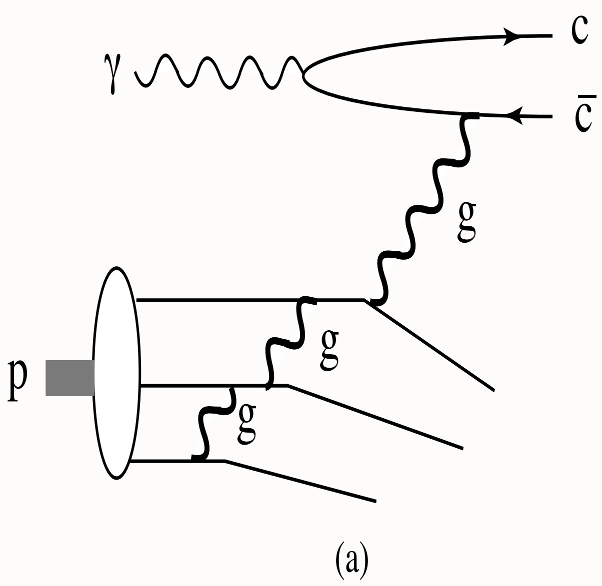
Charm at Threshold

- ***Intrinsic charm Fock state puts 80% of the proton momentum into the electroproduction process***
- ***1/velocity enhancement from FSI***
- ***CLEO data for quarkonium production at threshold***
- ***Krisch effect shows B=2 resonance***
- ***all particles produced at small relative rapidity-- resonance production***
- ***Many exotic hidden and open charm resonances will be produced at JLab (12 GeV)***

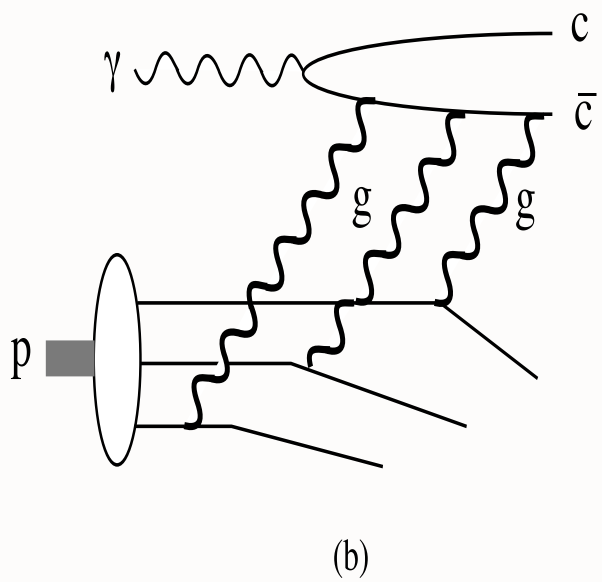
$$\gamma p \rightarrow J/\psi p$$

Chudakov, Hoyer, Laget, sjb



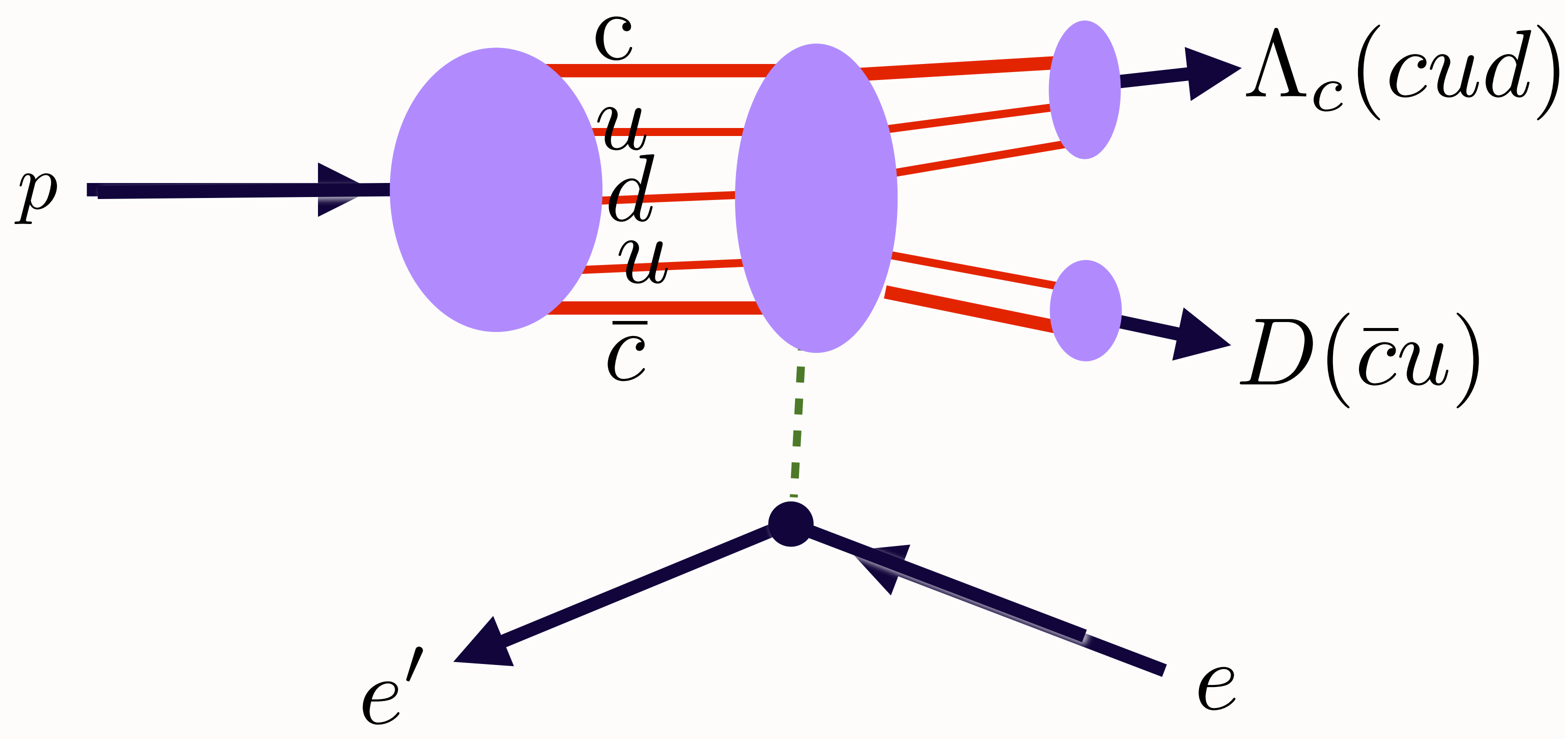


Leading twist contribution



Dominant near threshold

Test Threshold Production at JLab!



Dissociate proton to high x_F heavy-quark pair

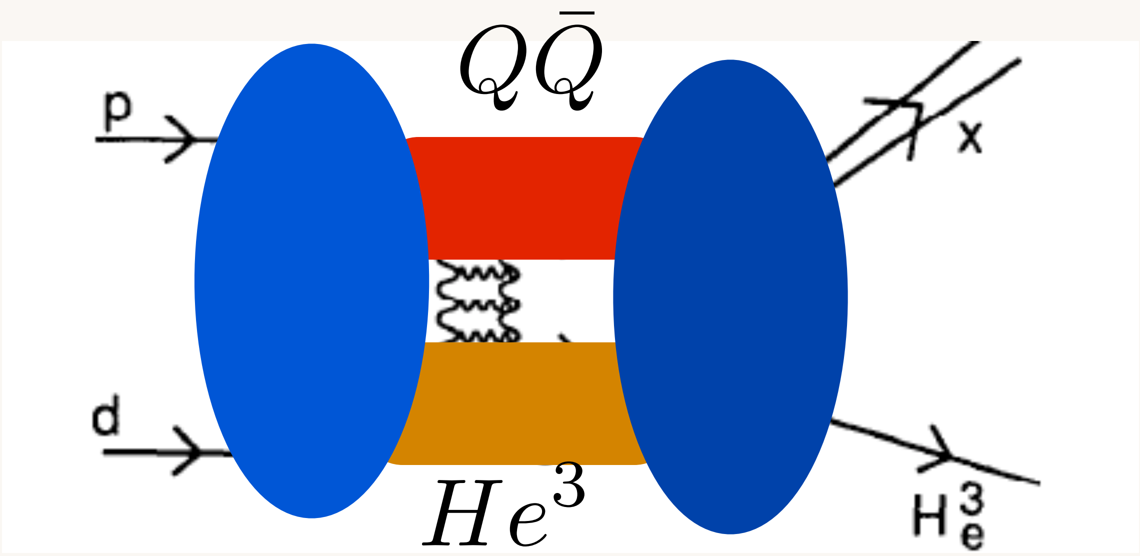
$$\gamma^* p \to \Lambda_c(cdd) + D(\bar{c}u), \gamma^* p \to \Lambda_b(bud)B^+(\bar{b}u)$$

Produce Charm near Threshold at JLab!

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**

Nuclear-Bound Quarkonium $[(Q\bar{Q})A]$



- Binding via QCD Van der Waals
- No valence quarks in common
- Guaranteed J/ψ-A binding for high A

Schmidt, de Teramond, sjb

Manohar

JLab 12 GeV: An Exotic Charm Factory!

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

$$\text{Produce } [J/\psi + p] \text{ bound state}$$
$$|uudc\bar{c}>$$

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

$$\text{Produce } [J/\psi + d] \text{ nuclear-bound quarkonium state}$$
$$|uudduc\bar{c}>$$

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

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

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

Binding at threshold: covalent bond via u-quark interchange

Produce Charge Q=4,I=3,B=2 Hidden-Color Dibaryon State at JLab

- **First suggested by F. Dyson and N-H Xuong (1964)**

"Hexaquark"

$$[B = 2, Q = +4] \leftrightarrow |u^{\uparrow}_{R} u^{\uparrow}_{B} u^{\uparrow}_{Y} u^{\downarrow}_{R} u^{\downarrow}_{B} u^{\downarrow}_{Y} >$$

- **Hidden-Color Six-Quark Configuration**
- **Decays to $\Delta^{++}\Delta^{++}$**

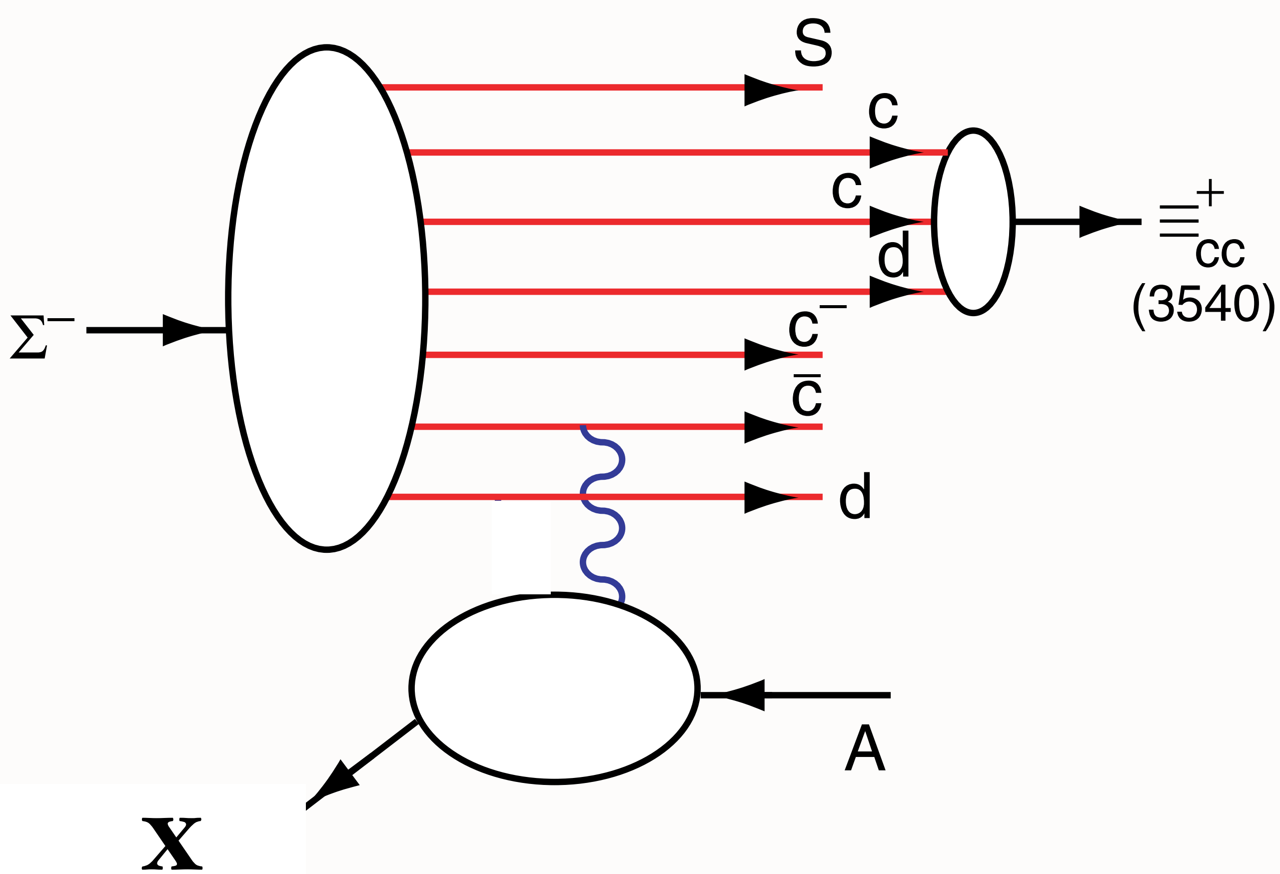
$$\gamma^* d \to [B = 2, Q = 4]\pi^- \pi^- \pi^-$$

Discover at JLab!

Bashkanov, Clement, sjb

Double heavy baryon production

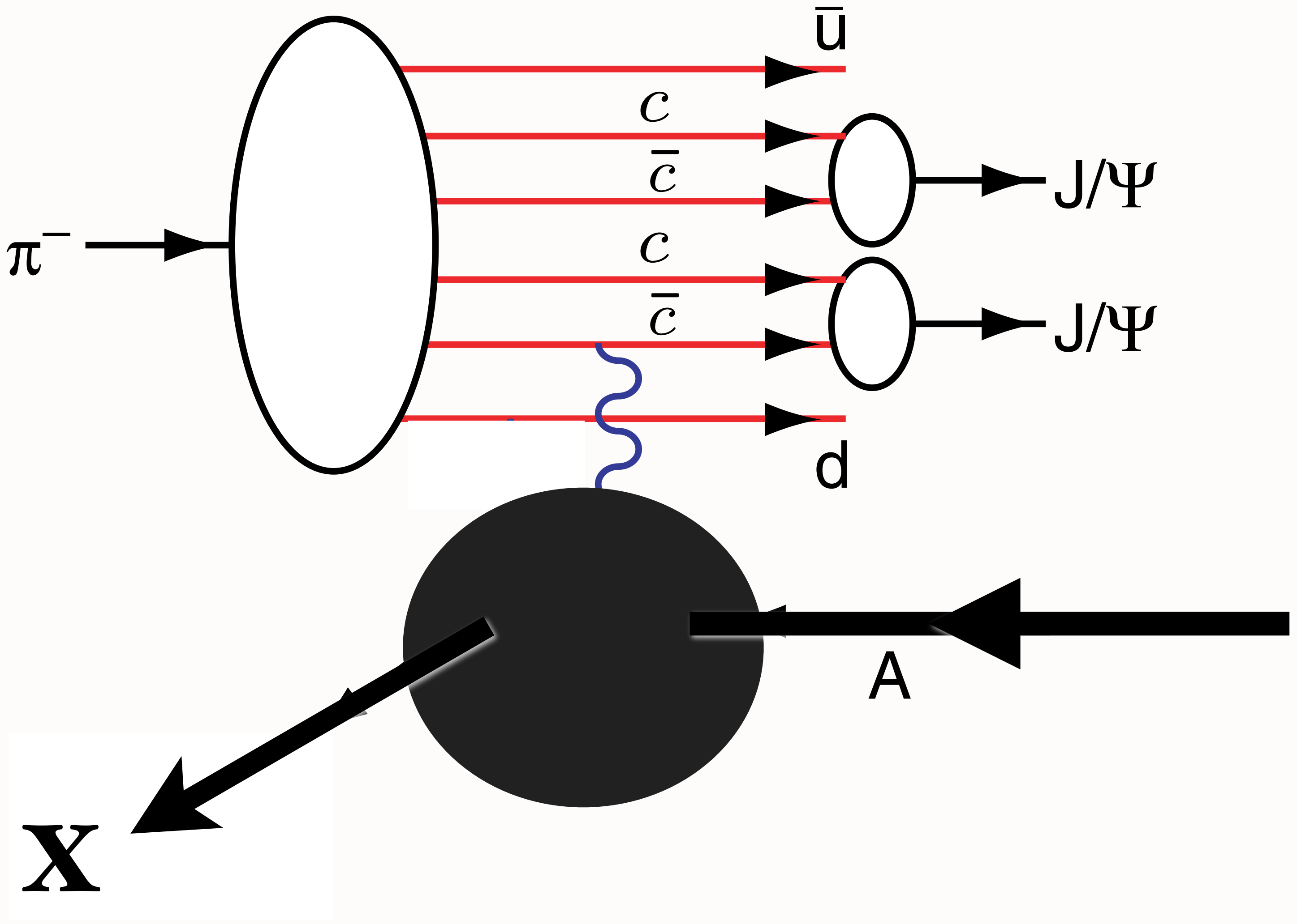
SELEX Mystery: Large isospin separation



Production of a Double-Charm Baryon

SELEX high x_F $< x_F >= 0.33$

Production of Two Charmonia at High x_F



NA3: All events at high $x_F = x_\psi + x_\psi$!

Excludes PYTHIA 'color drag' model!

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

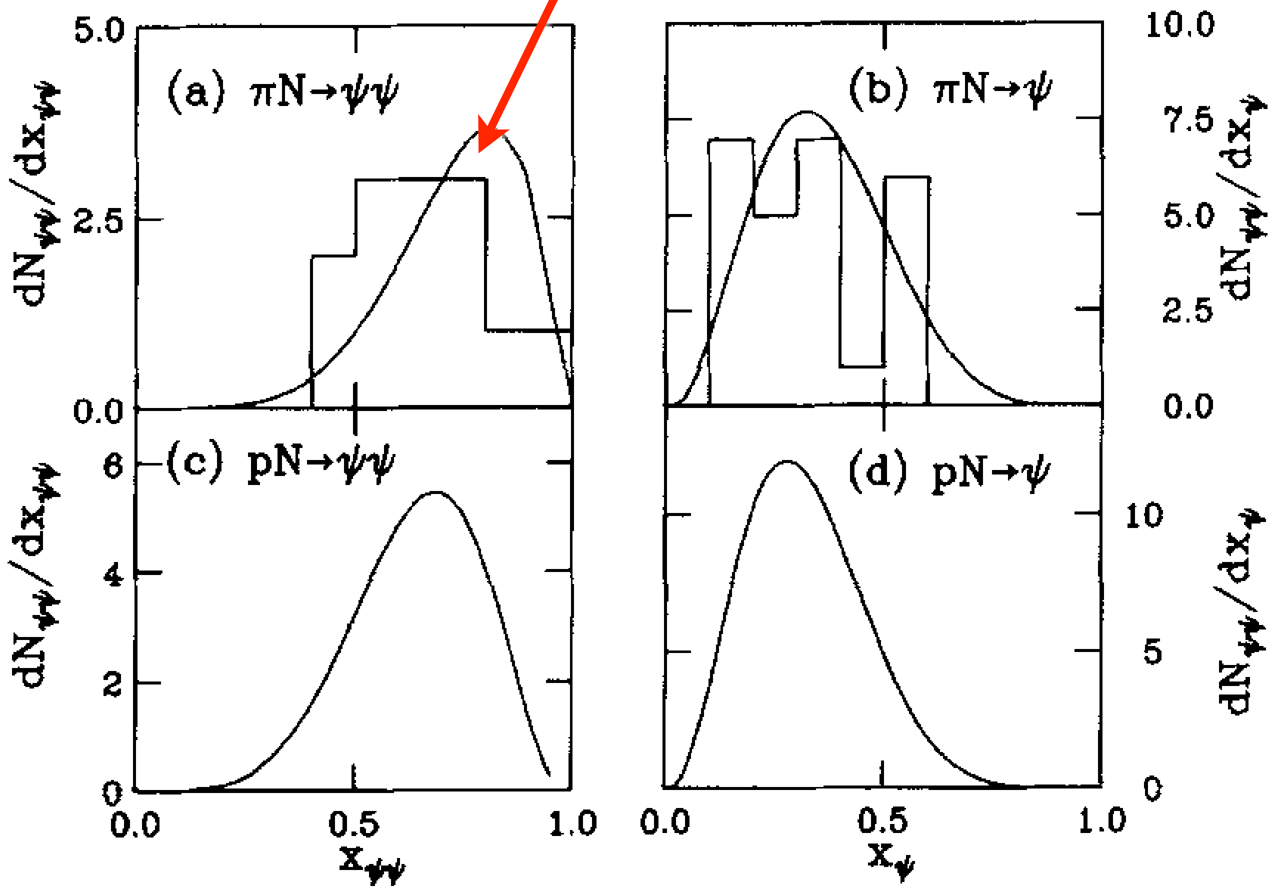


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized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

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

R. Vogt, sjb

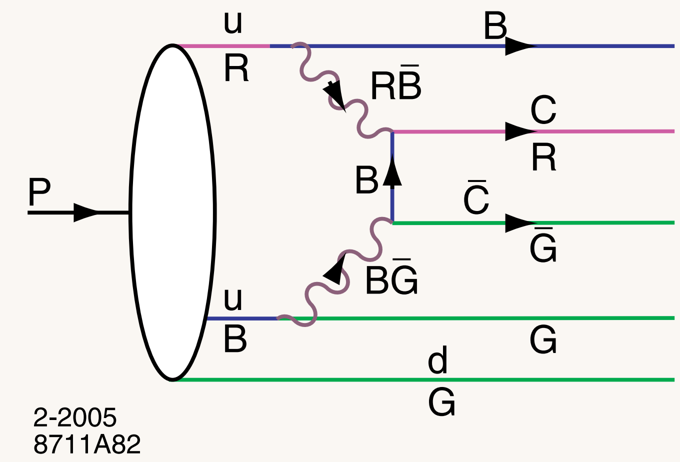
The probability distribution for a general n-particle intrinsic $c\bar{c}$ Fock state as a function of x and $\boldsymbol{k}_T$ is written as

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

NA3 Data

NA3: All double-charmonium events at high $x_F = x_\psi + x_\psi$!

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

- 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

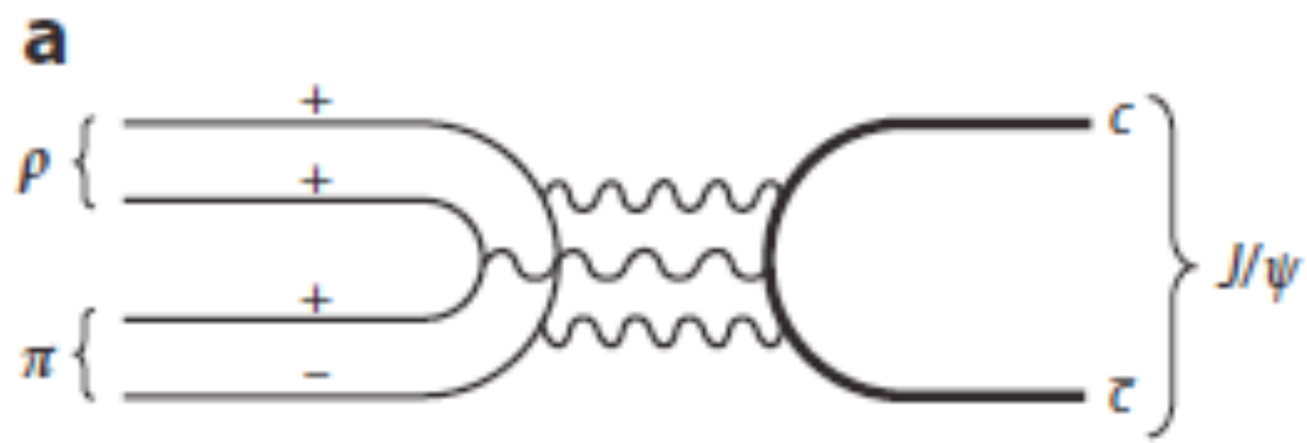
- IC Explains $J/\psi \to \rho\pi$ puzzle (Karliner, SJB)

Node # Conservation

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

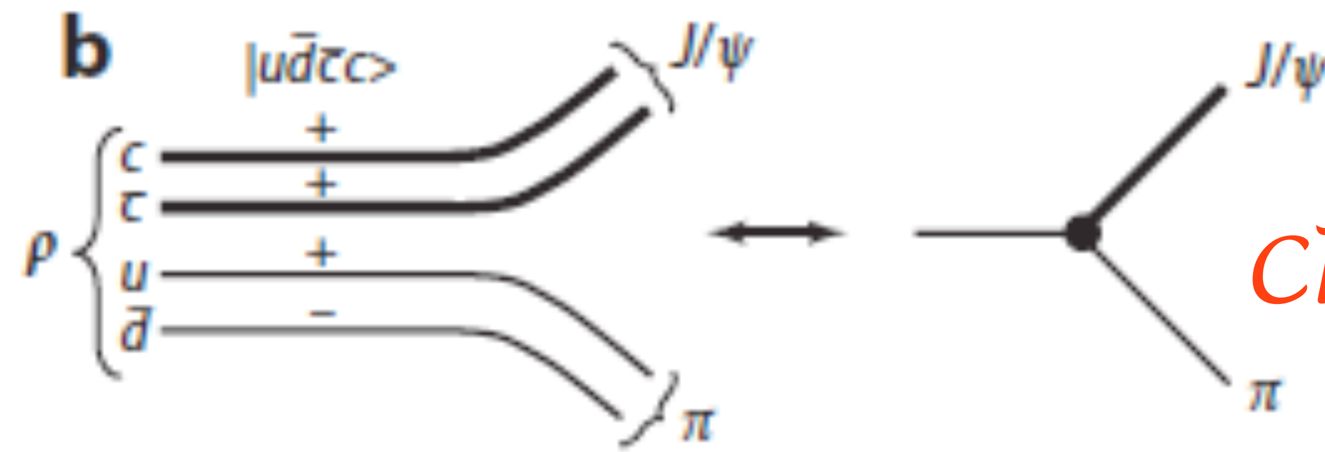
Higgs production at x_F = 0.8

de Teramond, Karliner, sjb



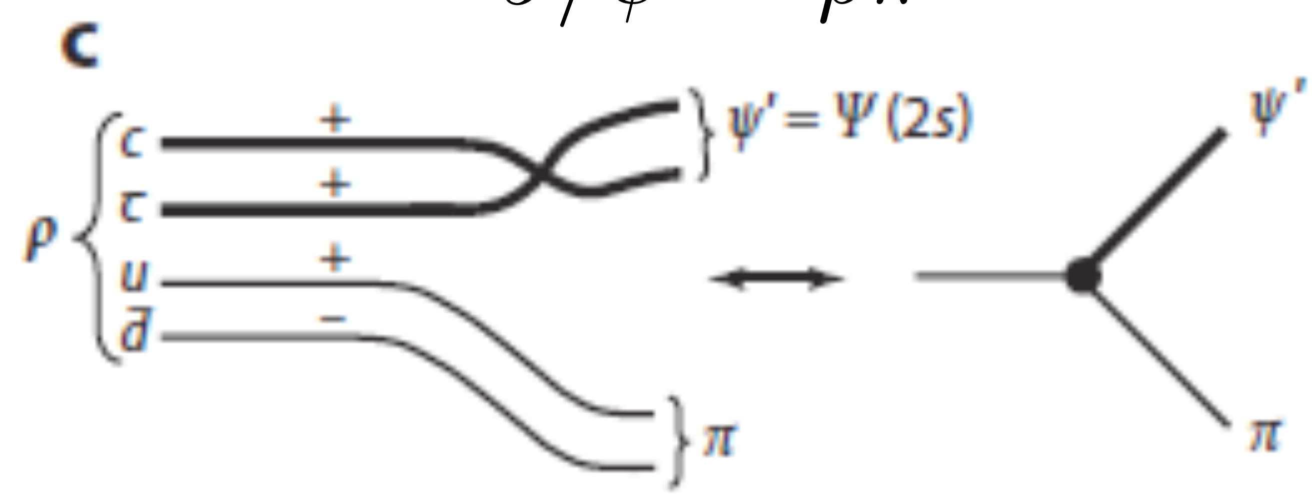
$$J/\psi \to \rho\pi$$

OZI: Zweig Rule



$$J/\psi \to \rho\pi$$

Intrinsic Charm of the ρ



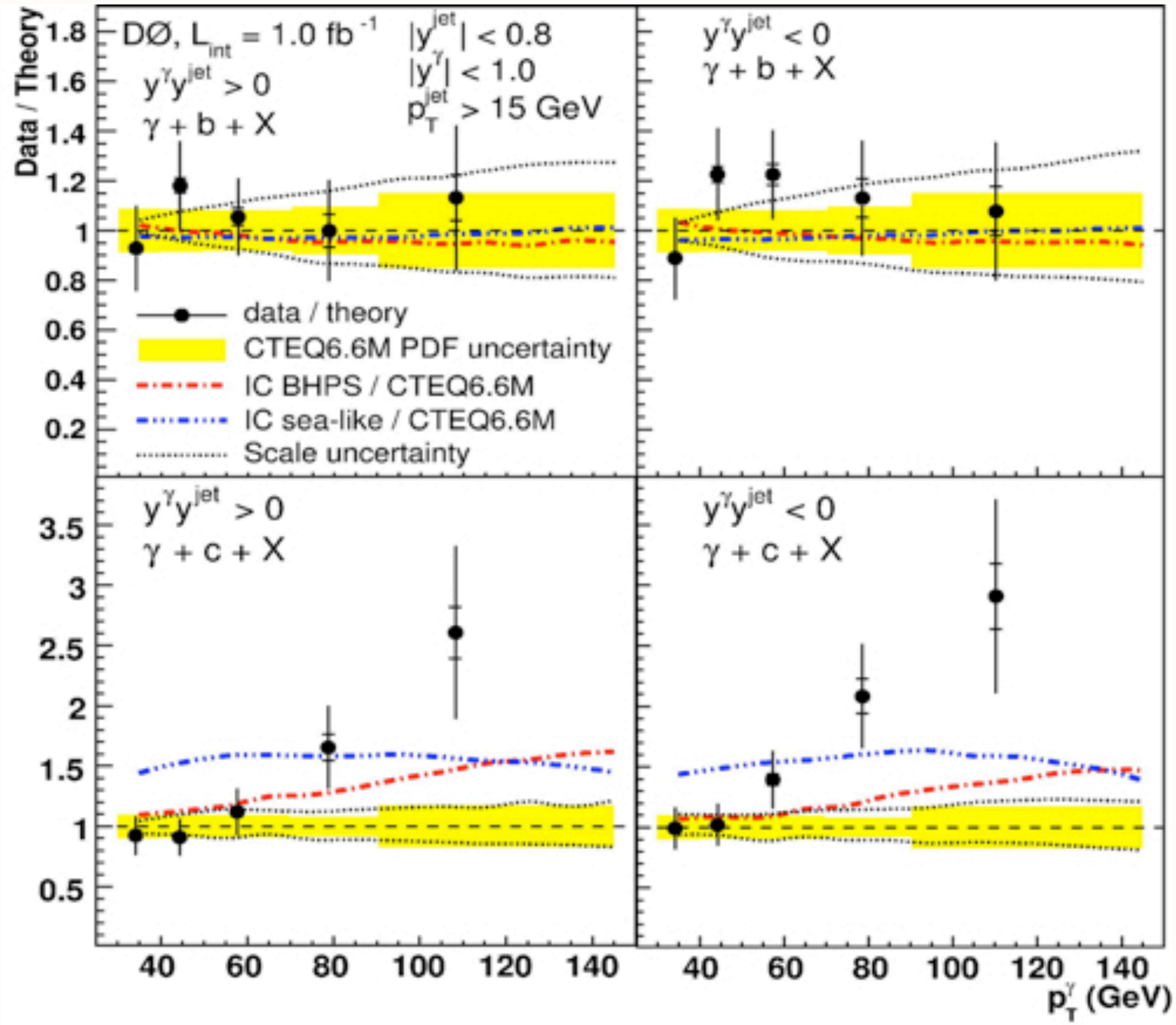
$$\psi' \to \rho\pi$$

Intrinsic Charm

Suppressed by Node # Conservation

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

$$p\bar{p} \to \gamma + Q + X$$



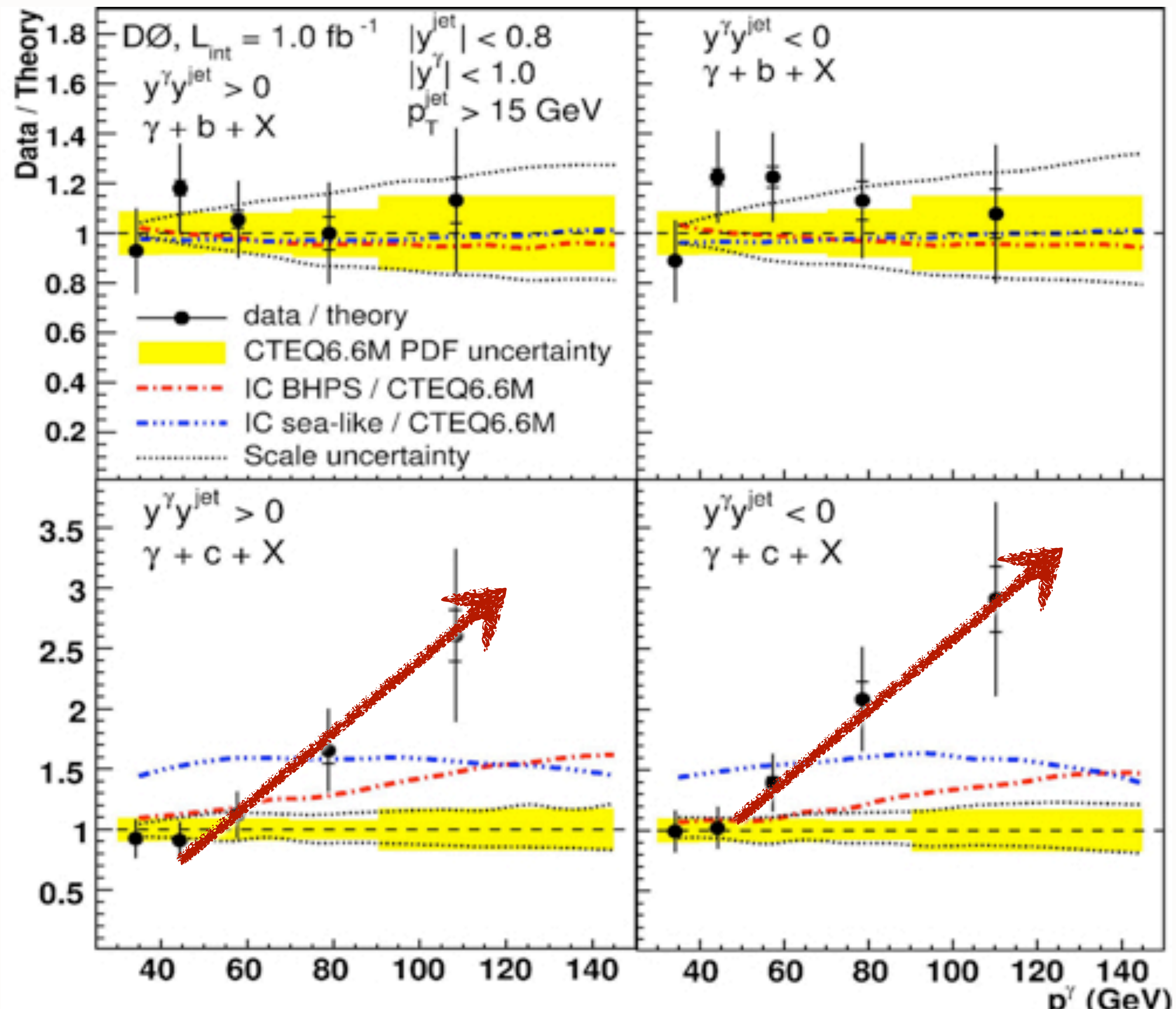
$$\frac{\Delta\sigma(\bar{p}p \to \gamma c X)}{\Delta\sigma(\bar{p}p \to \gamma b X)}$$

Ratio is insensitive to gluon PDF, scales

DØ

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

$$p\bar{p} \to \gamma + Q + X$$



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

Ratio is insensitive to gluon PDF, scales

$$gc \to \gamma c$$

Signal for significant intrinsic charm at x > 0.1 ?

Two Components (separate evolution):

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

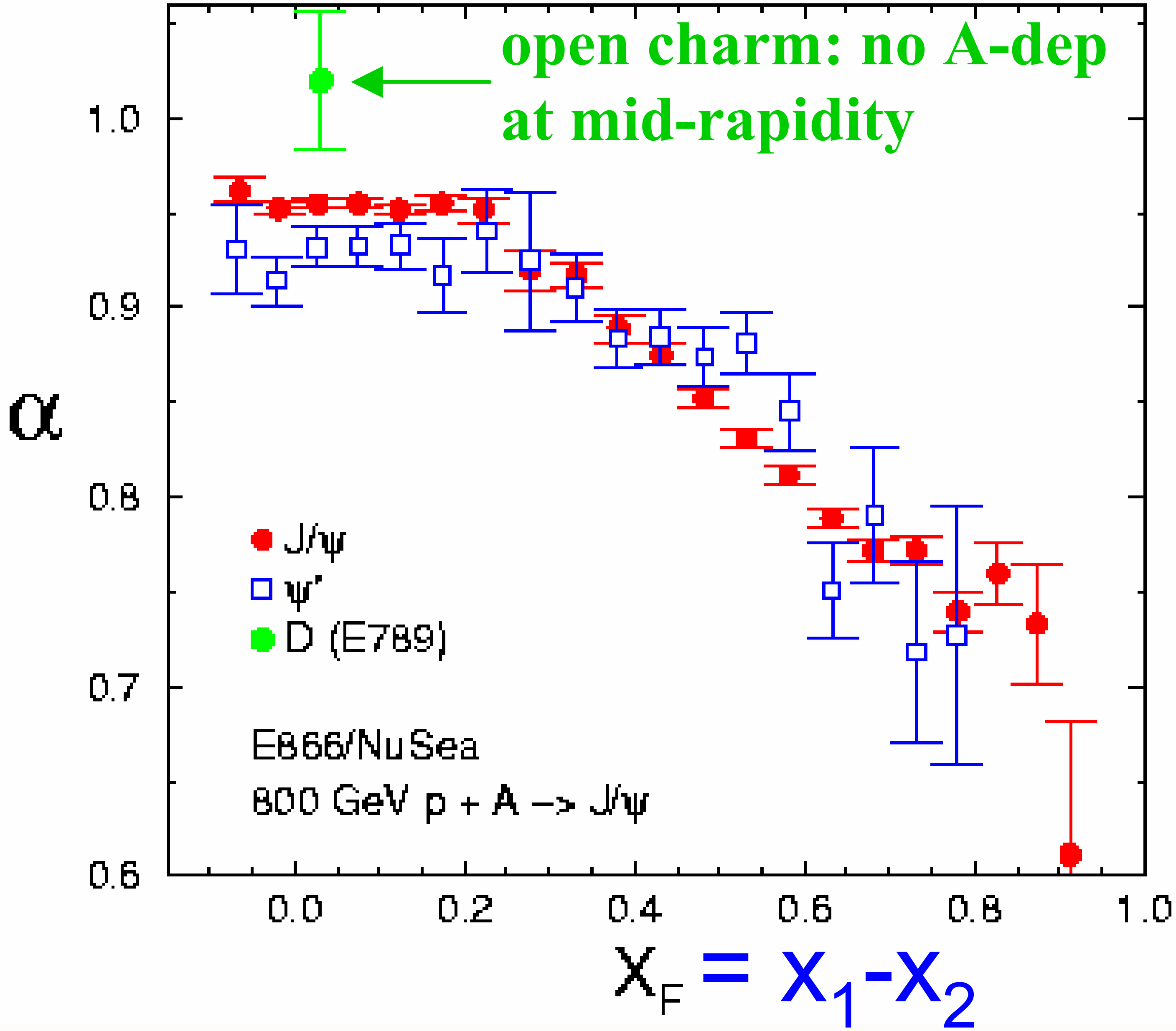
Similar anomaly

$$p\bar{p} \to Z + Q + X$$

M. Leitch

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

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



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

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

Stan Brodsky

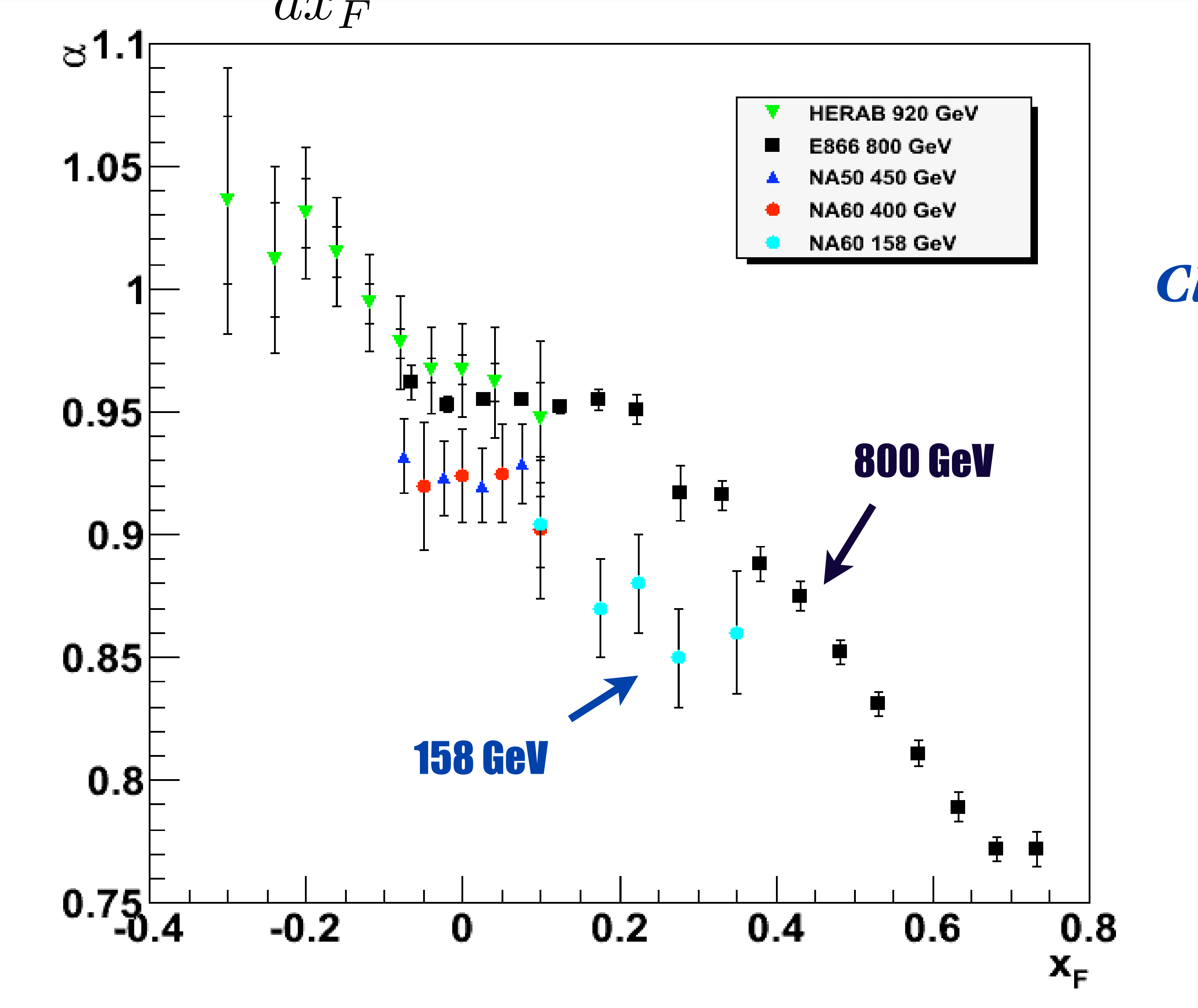
SLAC
NATIONAL ACCELERATOR LABORATORY

JLab Tagged Structure Functions

Novel Heavy Quark Phenomena in QCD

NA60 pA data @ 158GeV

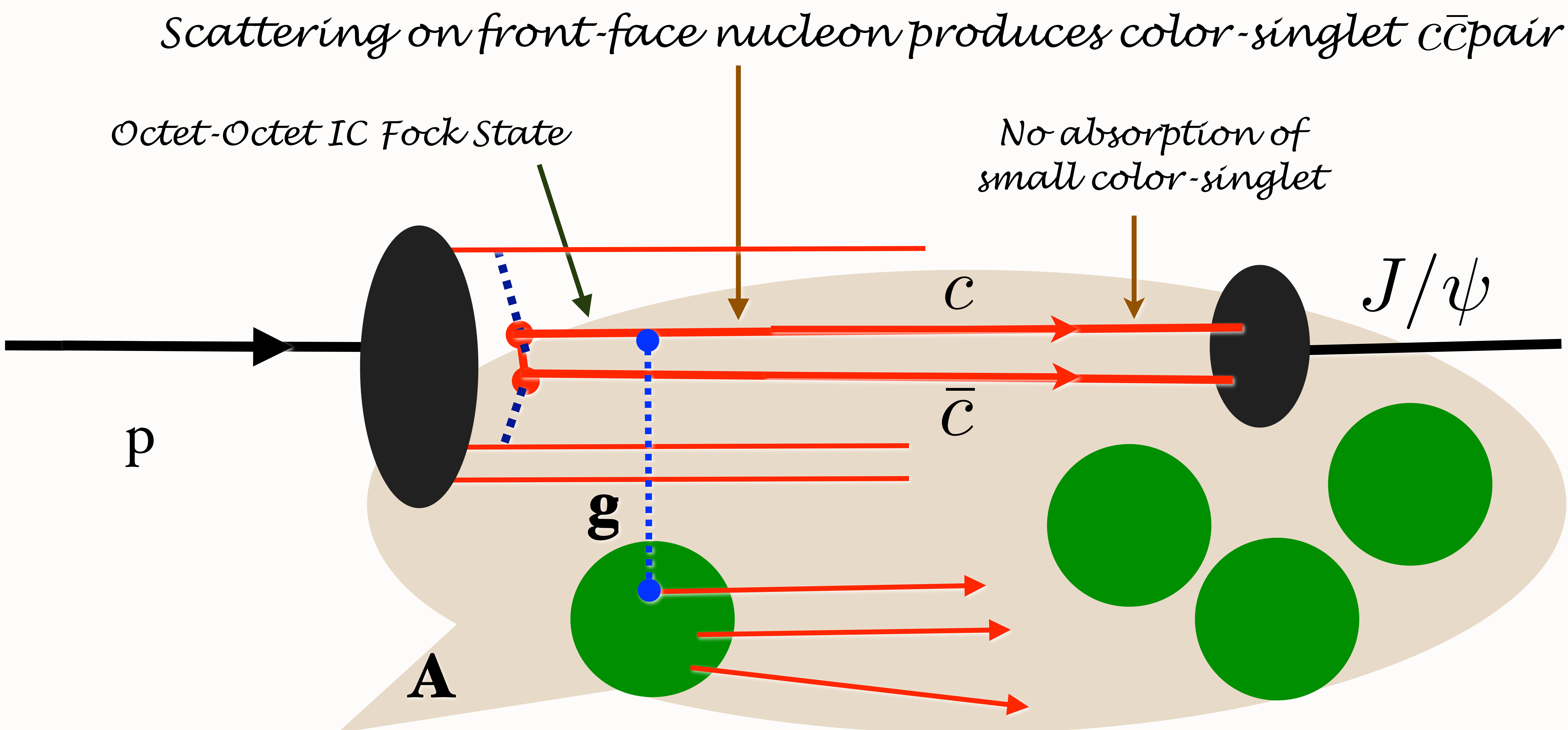
$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) \propto A^{\alpha}$$



Clear dependence on x_F and beam energy

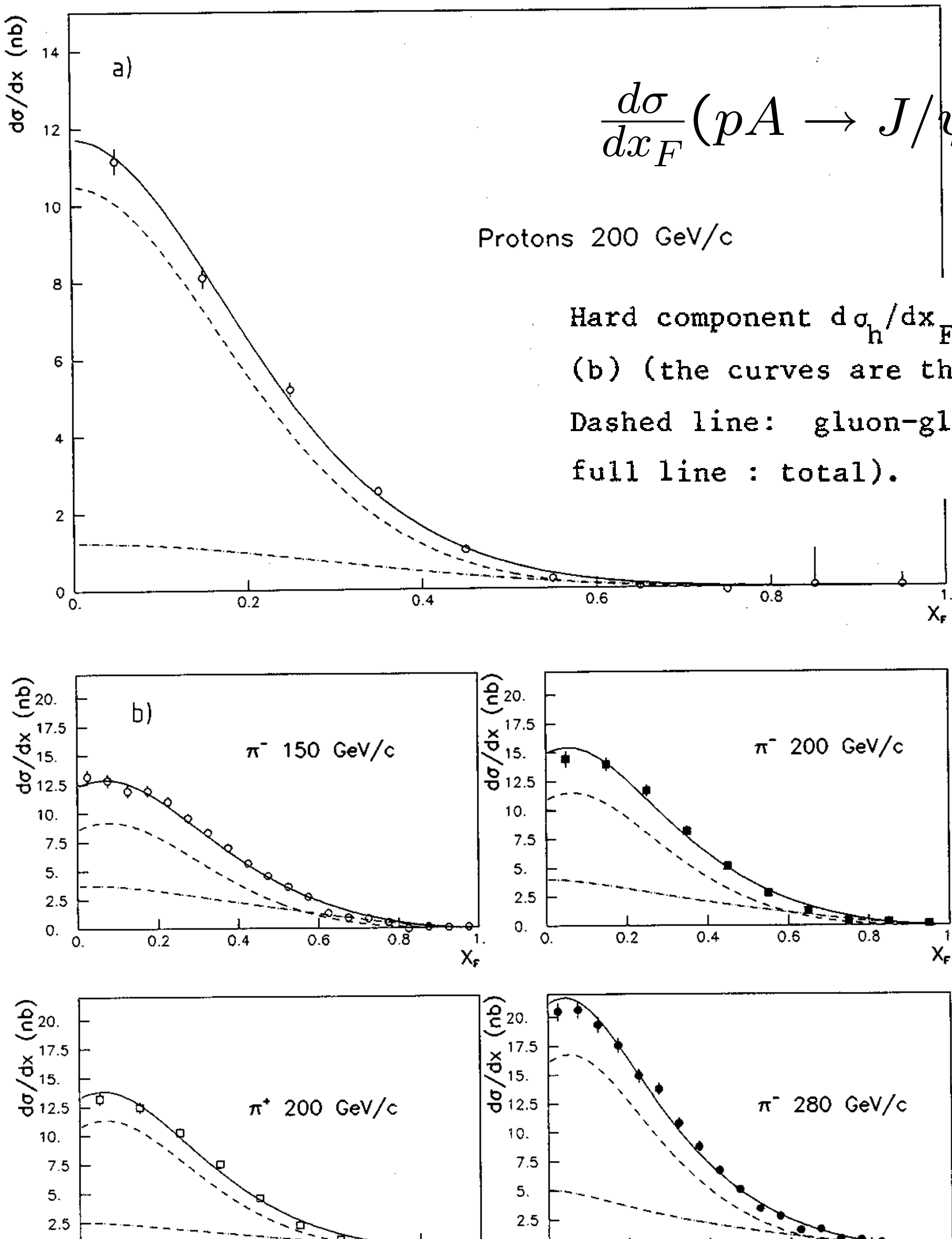
Color-Opaque IC Fock state interacts on nuclear front surface

Kopeliovich, Schmidt, Soffer, sjb



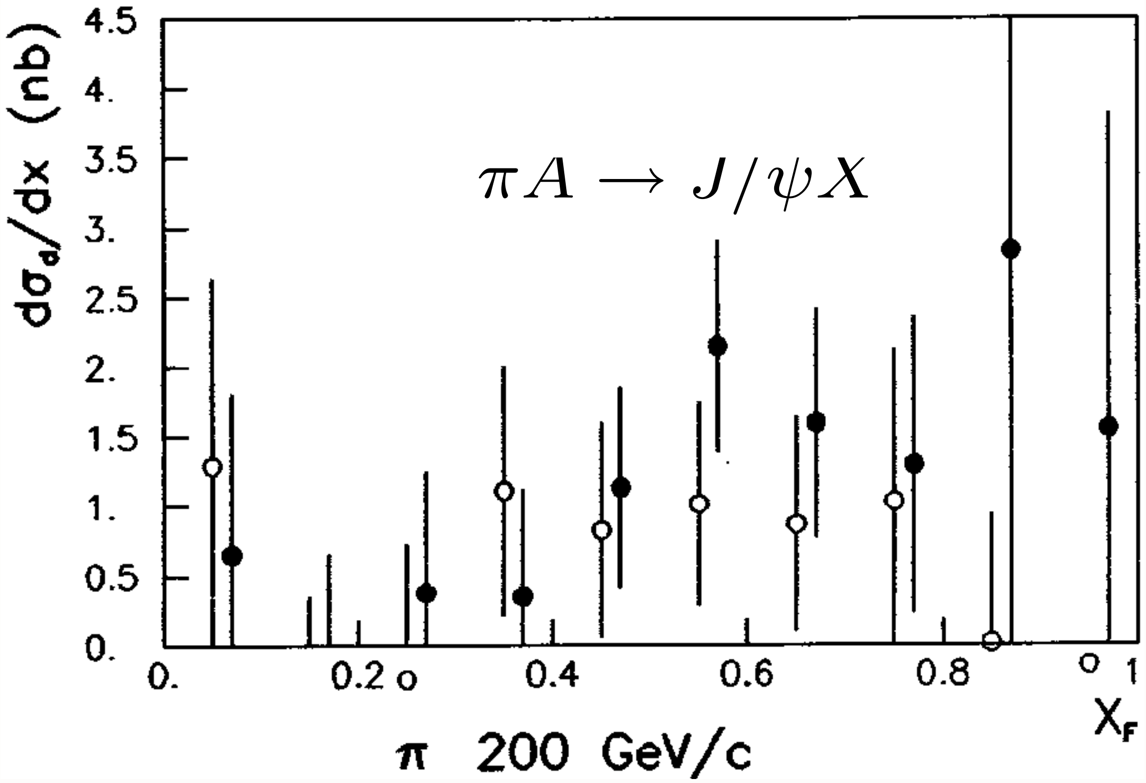
$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$

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



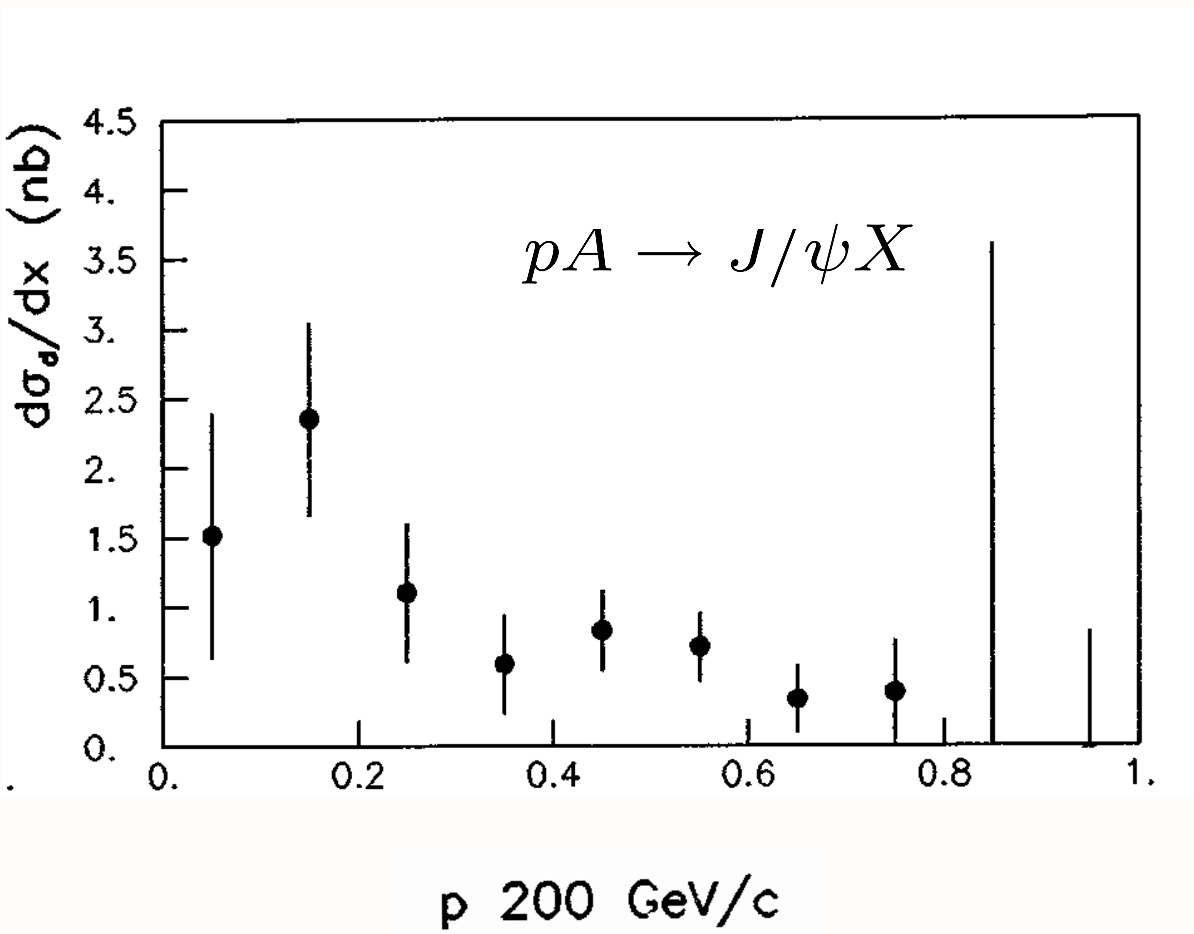
Hard component $d\sigma_h/dx_F$ for incident protons (a) and pions (b) (the curves are the result of the fit described in the text. Dashed line: gluon-gluon fusion; dash-dotted line : $q\bar{q}$ fusion; full line : total).

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



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

$A^{2/3}$ component

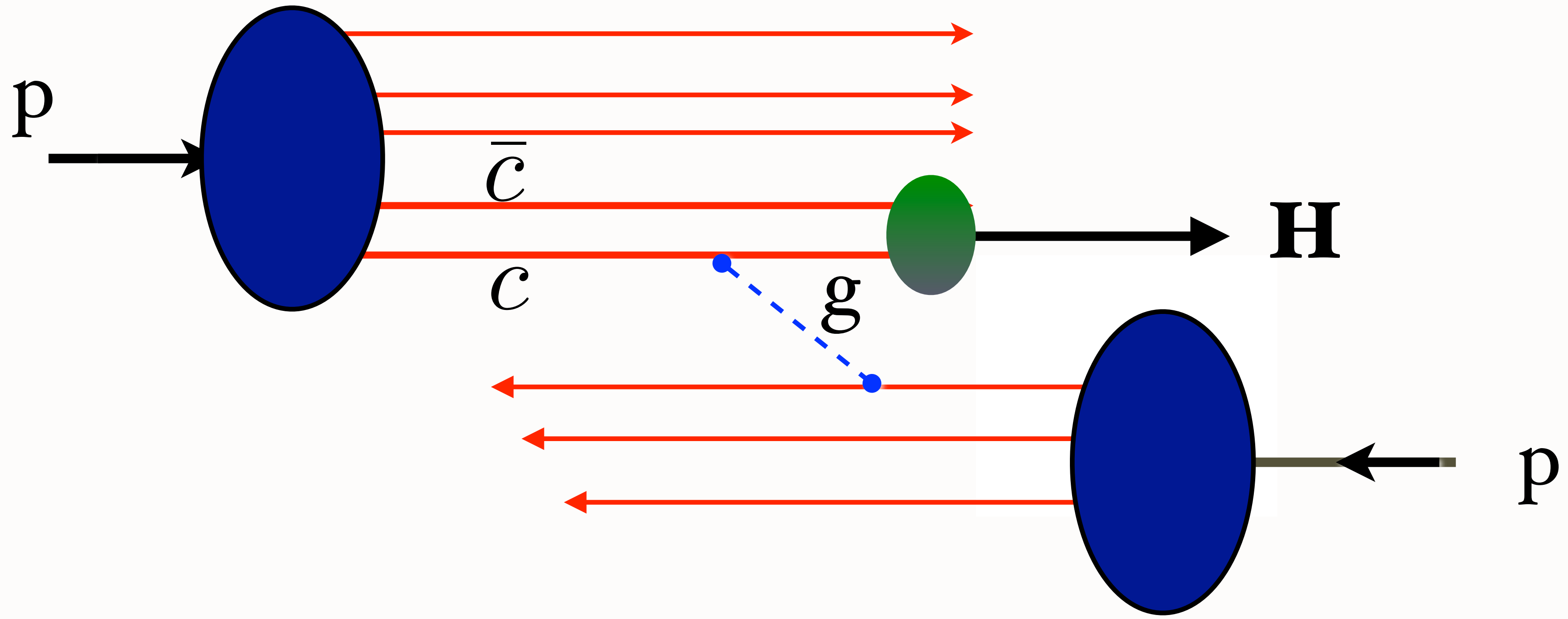


J. Badier et al, NA3

Excess beyond conventional PQCD subprocesses

Goldhaber, Kopeliovich, Schmidt, Soffer sjb

Intrinsic Charm Mechanism for Inclusive High-X_F Higgs Production



$$pp \rightarrow H X$$

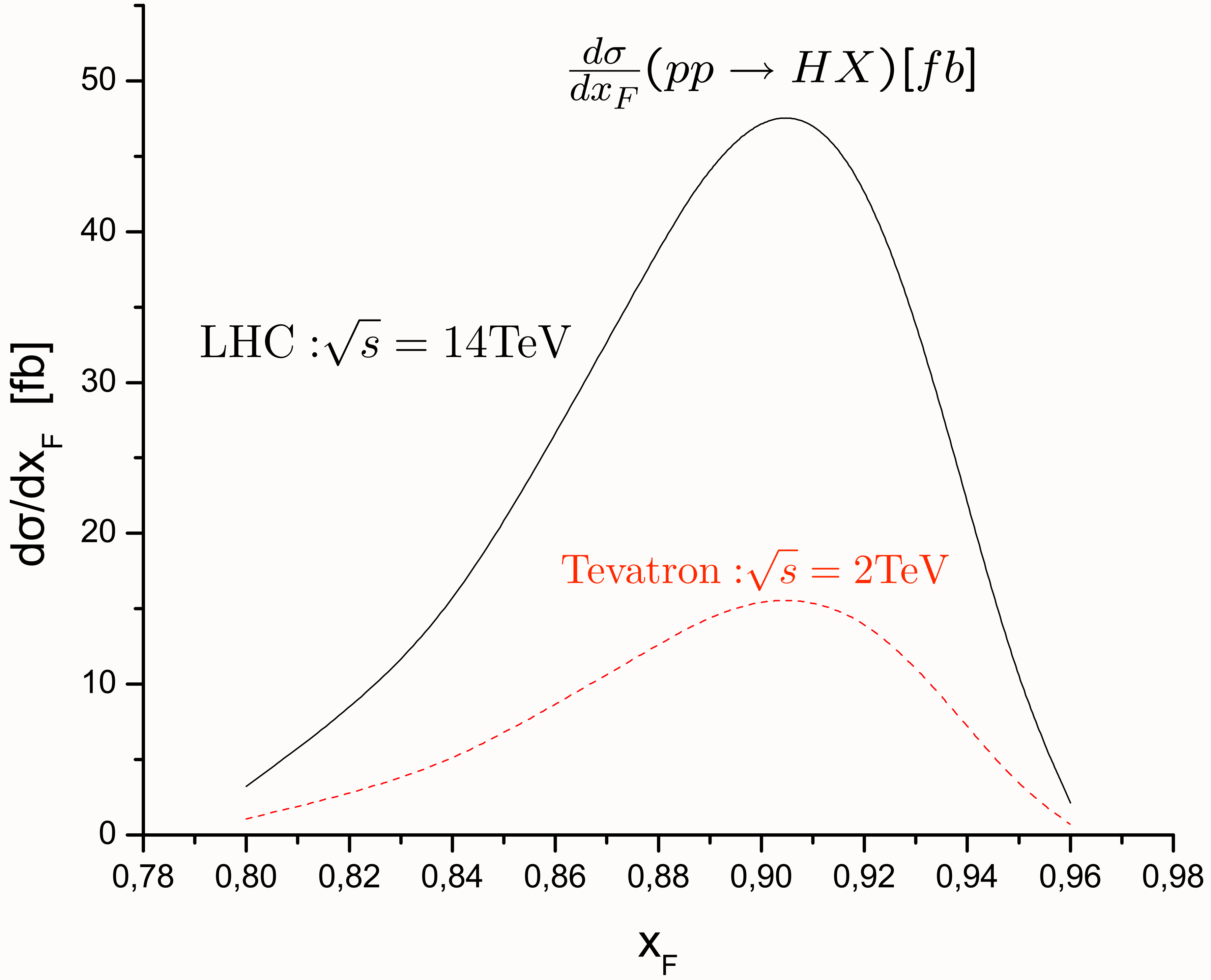
Also: intrinsic strangeness, bottom, top

Higgs can have > 80% of Proton Momentum!

New production mechanism for Higgs

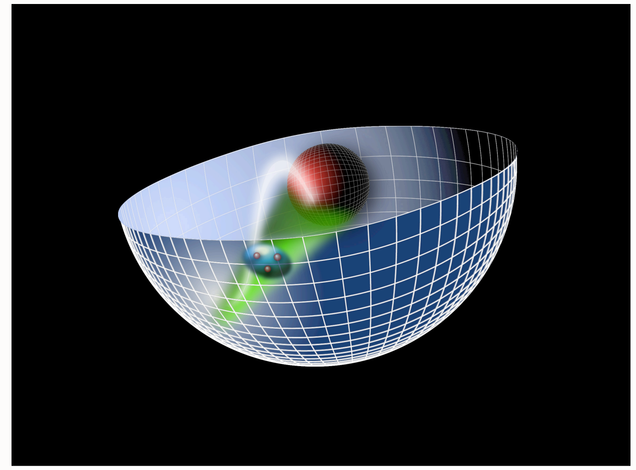
AFTER: Higgs production at threshold!

Intrinsic Heavy Quark Contribution to Inclusive Higgs Production



Goldhaber, Kopeliovich, Schmidt, sjb

de Teramond, Dosch, sjb



AdS/QCD
Soft-Wall Model

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

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

Light-Front Holography

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

Light-Front Schrödinger Equation

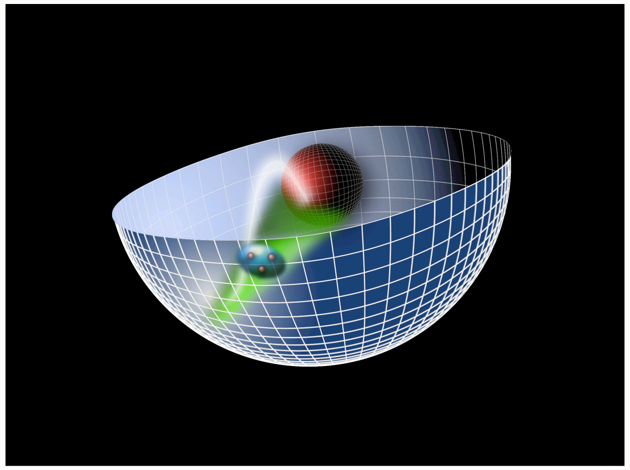
$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L+S-1)$$

Unique Confinement Potential!

Conformal Symmetry
of the action

Confinement mass scale: $\kappa \simeq 0.6\ GeV$

de Teramond, Dosch, sjb



AdS/QCD Soft-Wall Model

Light-Front Holography

Semi-Classical Approximation to QCD

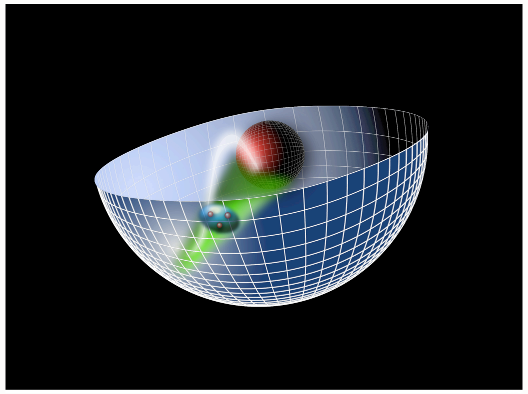
Relativistic, frame-independent
Unique color-confining potential
Zero mass pion for massless quarks
Regge trajectories with equal slopes in n and L
Light-Front Wavefunctions

Conformal Symmetry

Light-Front Schrödinger Equation

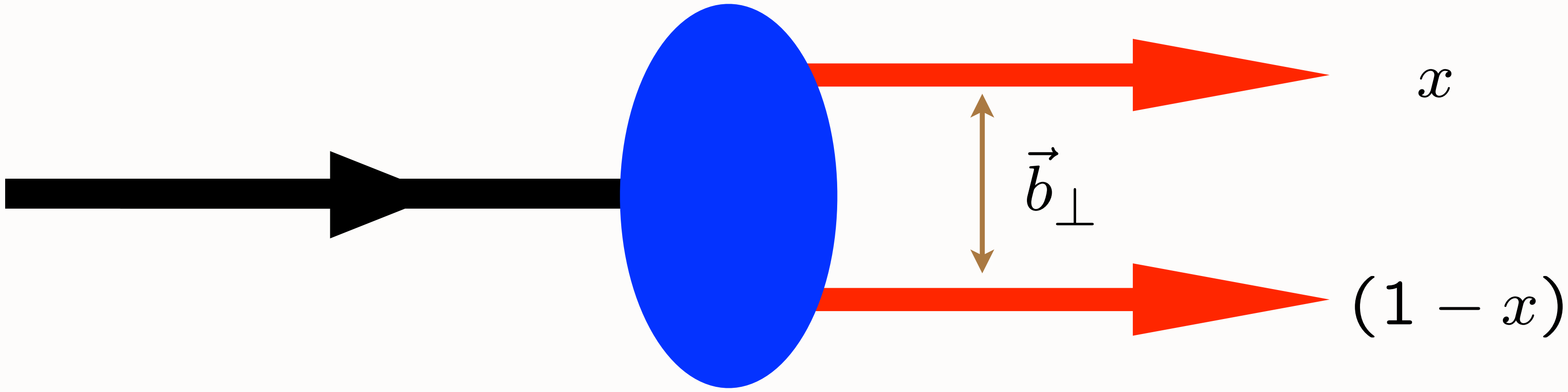
$LF(3+1) \longleftrightarrow AdS_5$

de Teramond, sjb



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

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



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

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

PRL **109,** 081601 (2012) PHYSICAL REVIEW LETTERS week ending 24 AUGUST 2012

AdS/QCD Holographic Wave Function for the ρ Meson and Diffractive ρ Meson Electroproduction

J. R. Forshaw*

Consortium for Fundamental Physics, School of Physics and Astronomy, University of Manchester, Oxford Road, Manchester M13 9PL, United Kingdom

R. Sandapen†

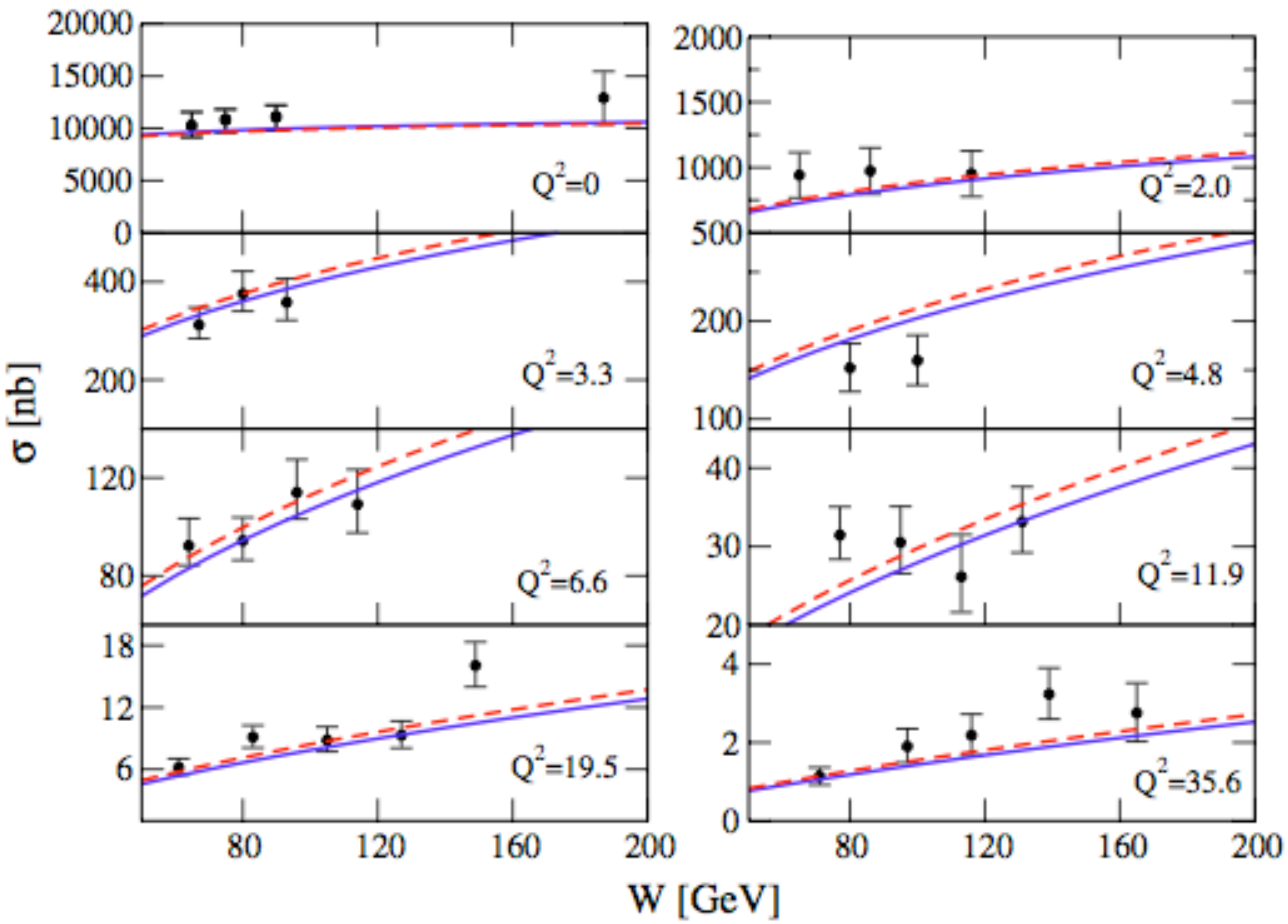
Département de Physique et d'Astronomie, Université de Moncton, Moncton, New Brunswick E1A3E9, Canada

(Received 5 April 2012; published 20 August 2012)

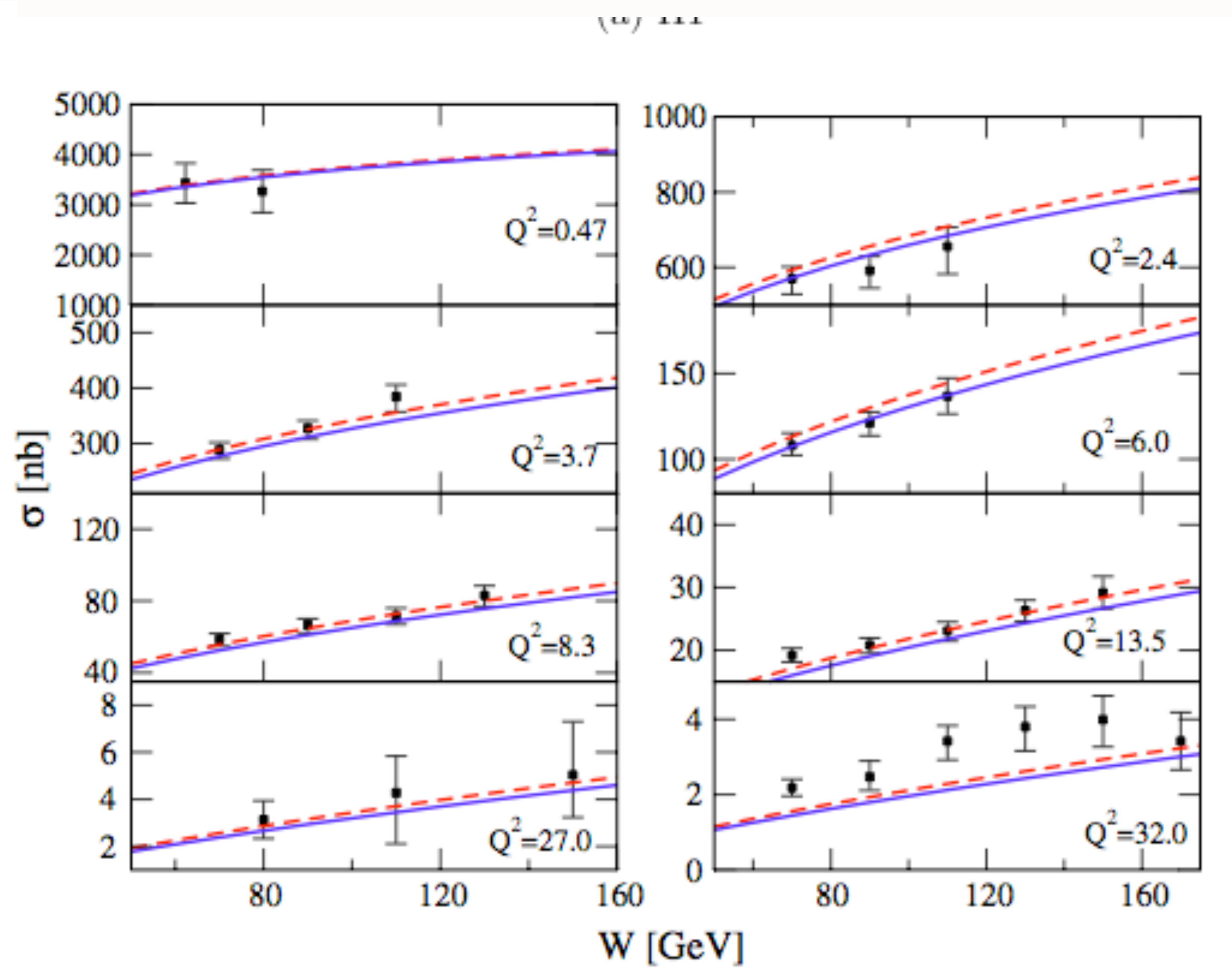
We show that anti–de Sitter/quantum chromodynamics generates predictions for the rate of diffractive ρ-meson electroproduction that are in agreement with data collected at the Hadron Electron Ring Accelerator electron–proton collider.

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

AdS/QCD Holographic Wave Function for the ρ Meson and Diffractive ρ Meson Electroproduction



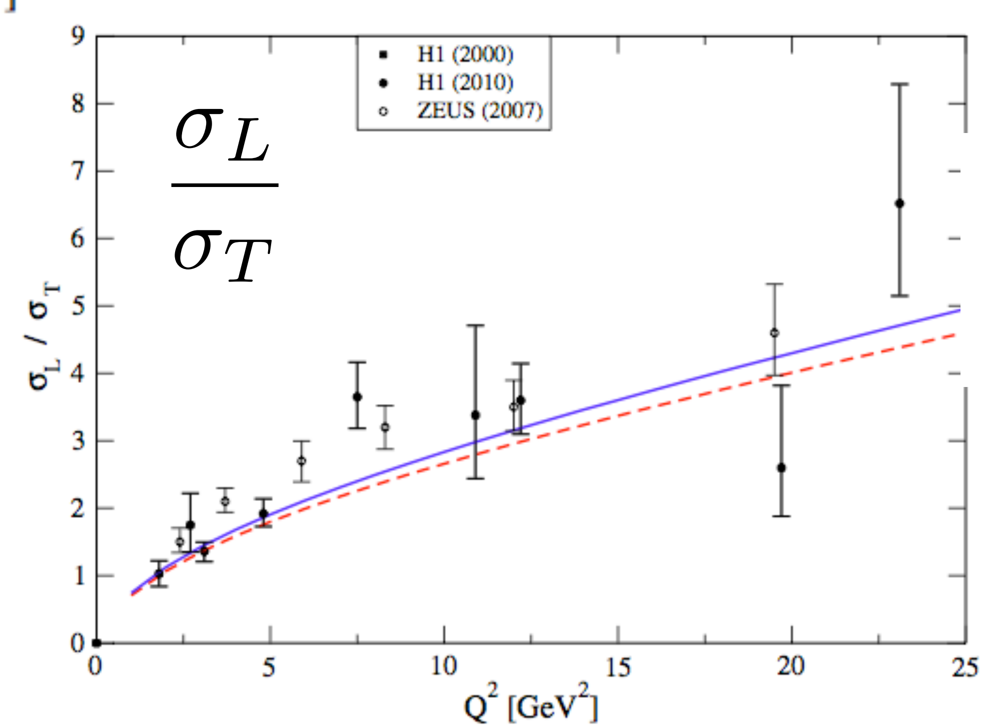
(a) H



(b) ZEUS

J. R. Forshaw,
R. Sandapen

$$\gamma^* p \to \rho^0 p'$$



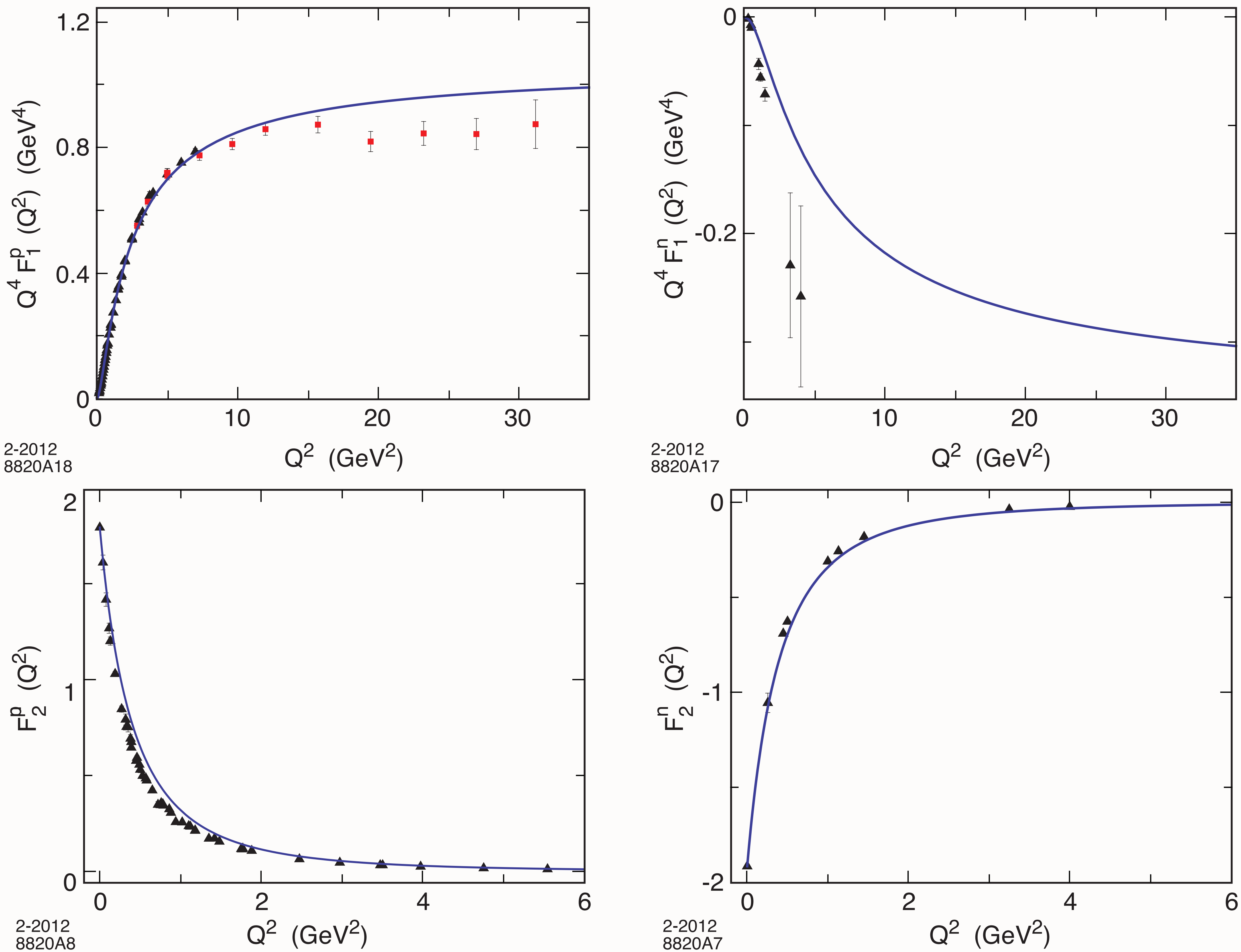
$$\tilde{\phi}(x, k) \propto \frac{1}{\sqrt{x(1-x)}} \exp\left(-\frac{M_{q\bar{q}}^2}{2\kappa^2}\right),$$

Remarkable Features of Light-Front Schrödinger Equation

- ***Relativistic, frame-independent***
- ***QCD scale appears - unique LF potential***
- ***Reproduces spectroscopy and dynamics of light-quark hadrons with one parameter***
- ***Zero-mass pion for zero mass quarks!***
- ***Regge slope same for n and L -- not usual HO***
- ***Splitting in L persists to high mass -- contradicts conventional wisdom based on breakdown of chiral symmetry***
- ***Phenomenology: LFWFs, Form factors, electroproduction***
- ***Extension to heavy quarks***

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

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



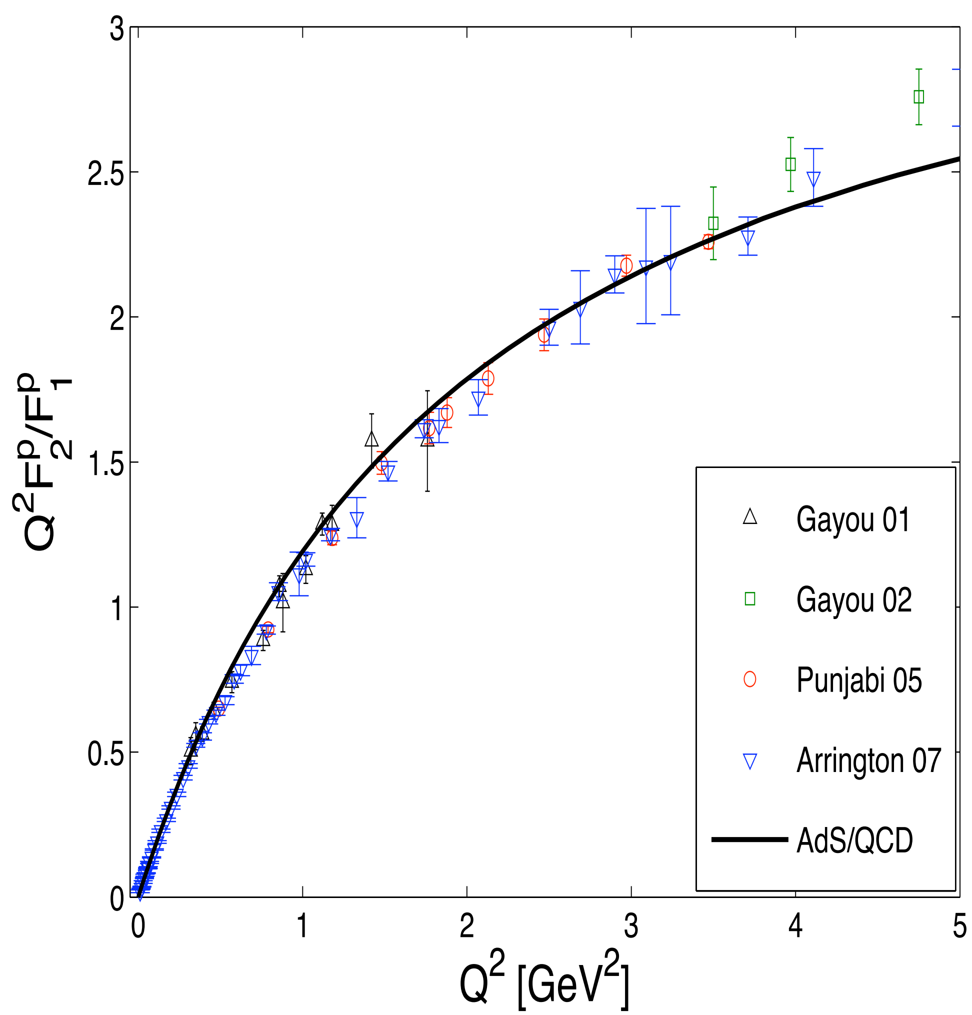
JLab Tagged Structure Functions

Novel Heavy Quark Phenomena in QCD

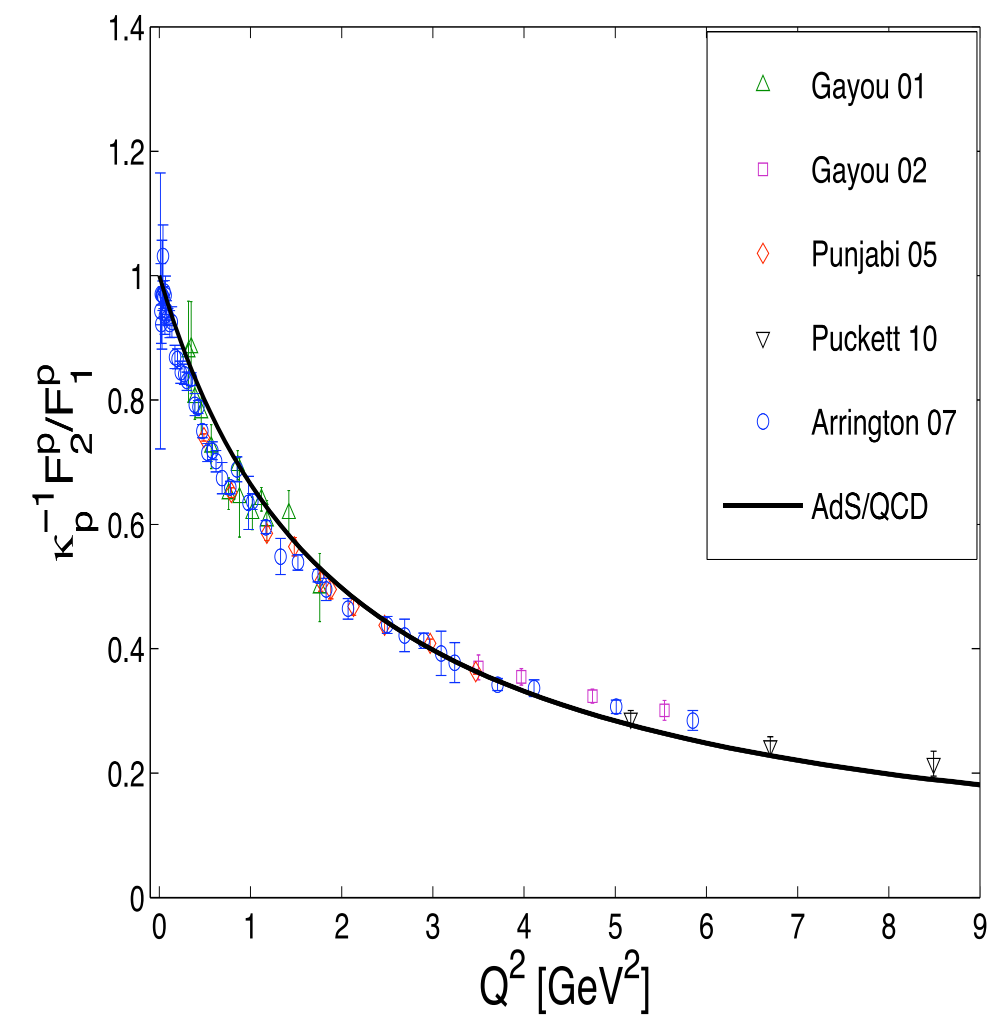
Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

(a)



(b)



The ratio of Pauli and Dirac form factors for the proton

Dipankar Chakrabarti and Chandan Mondal

Nucleon Transition Form Factors

- Compute spin non-flip EM transition $N(940) \to N^*(1440)$: $\Psi_+^{n=0,L=0} \to \Psi_+^{n=1,L=0}$
- Transition form factor

$$F_{1\,N\to N^*}^{p}(Q^2) = R^4 \int \frac{dz}{z^4} \Psi_+^{n=1,L=0}(z) V(Q,z) \Psi_+^{n=0,L=0}(z)$$

- Orthonormality of Laguerre functions $\left(F_{1\,N\to N^*}^{p}(0) = 0, \quad V(Q=0,z) = 1\right)$

$$R^4 \int \frac{dz}{z^4} \Psi_+^{n',L}(z) \Psi_+^{n,L}(z) = \delta_{n,n'}$$

- Find

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

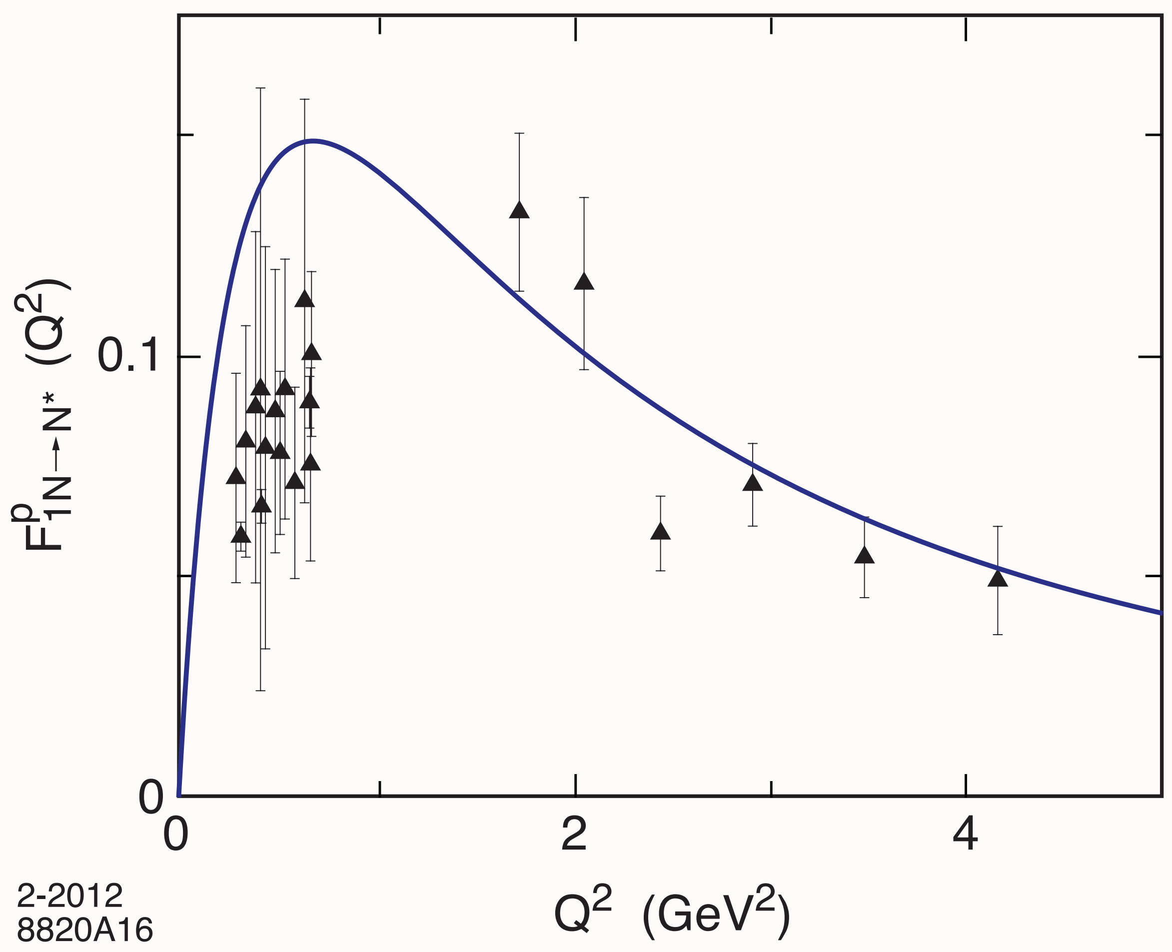
with $\mathcal{M}_{\rho_n}^{\,2} \to 4\kappa^2(n+1/2)$

de Teramond, sjb

Consistent with counting rule, twist 3

Nucleon Transition Form Factors

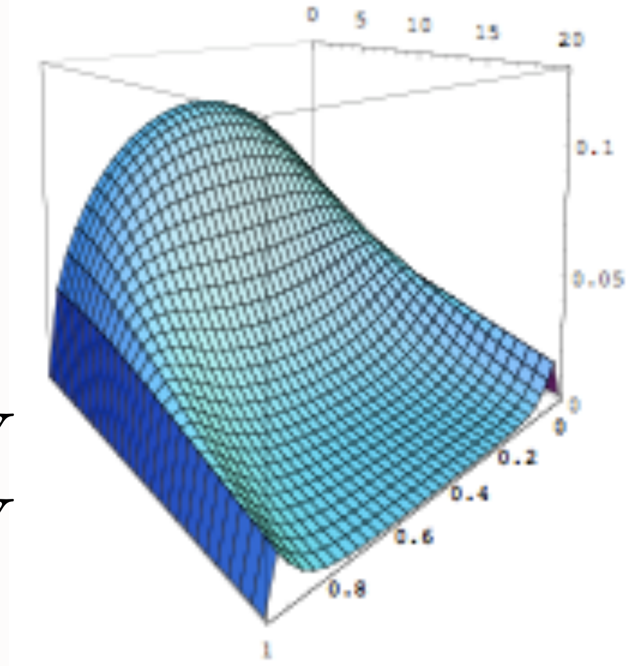
$$F^p_{1\,N\to N^*}(Q^2) = \frac{\sqrt{2}}{3}\frac{\frac{Q^2}{\mathcal{M}^2_\rho}}{\left(1+\frac{Q^2}{\mathcal{M}^2_\rho}\right)\left(1+\frac{Q^2}{\mathcal{M}^2_{\rho'}}\right)\left(1+\frac{Q^2}{\mathcal{M}^2_{\rho''}}\right)}.$$

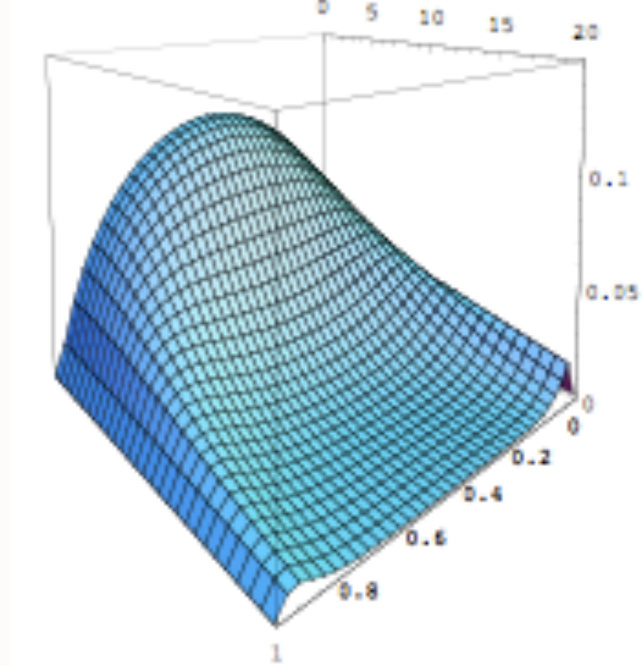


Proton transition form factor to the first radial excited state. Data from JLab

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

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



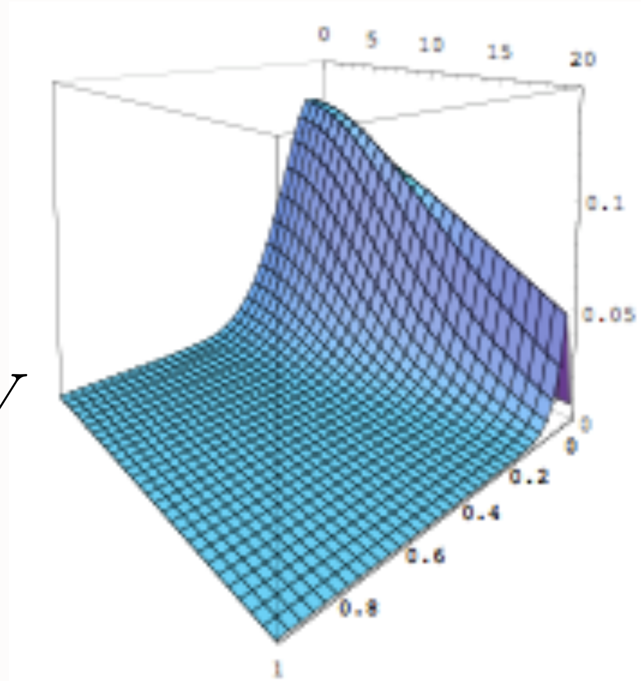


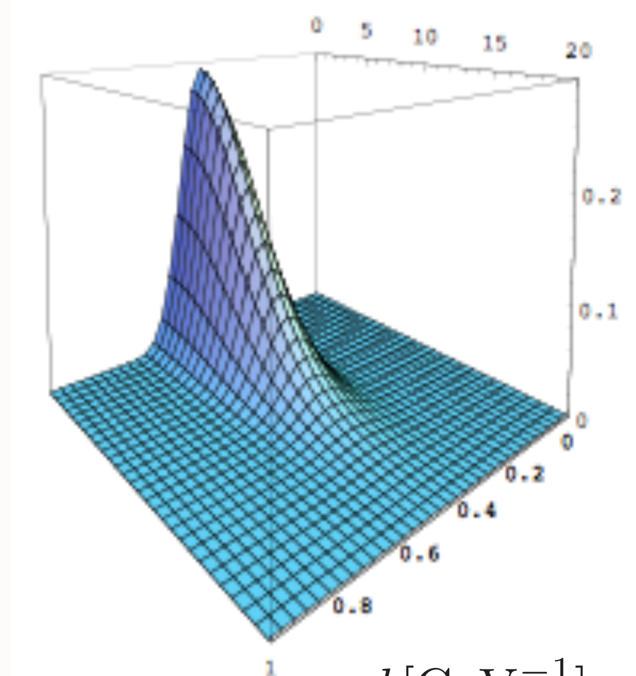
$$|K^+ >= |u\bar{s} >$$

$$m_s = 95\ MeV$$

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

$$m_c = 1.25\ GeV$$

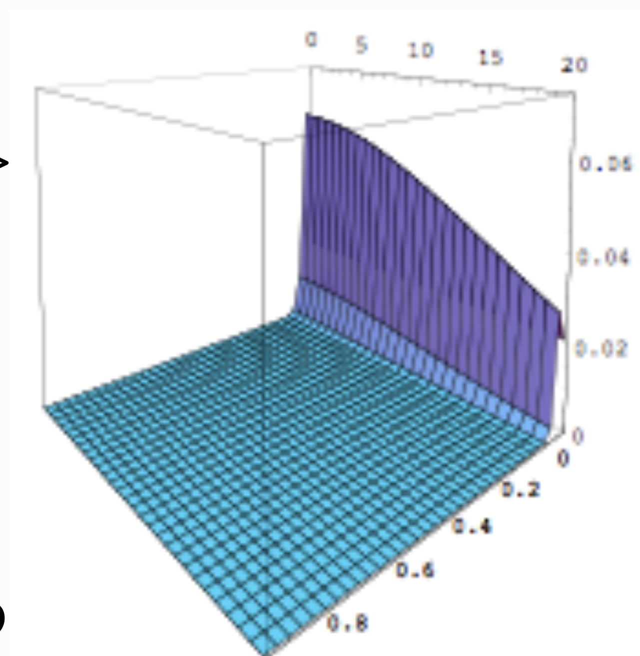


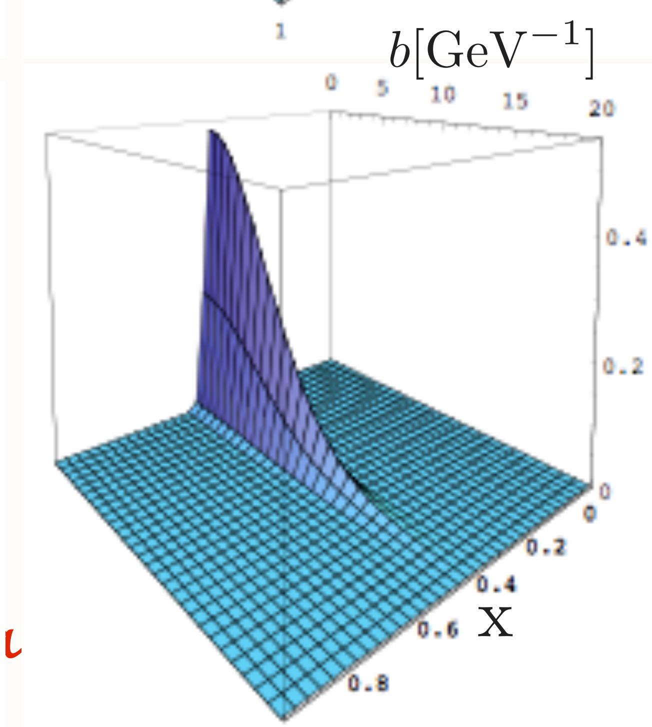


$$|\eta_c >= |c\bar{c} >$$

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

$$m_b = 4.2\ GeV$$





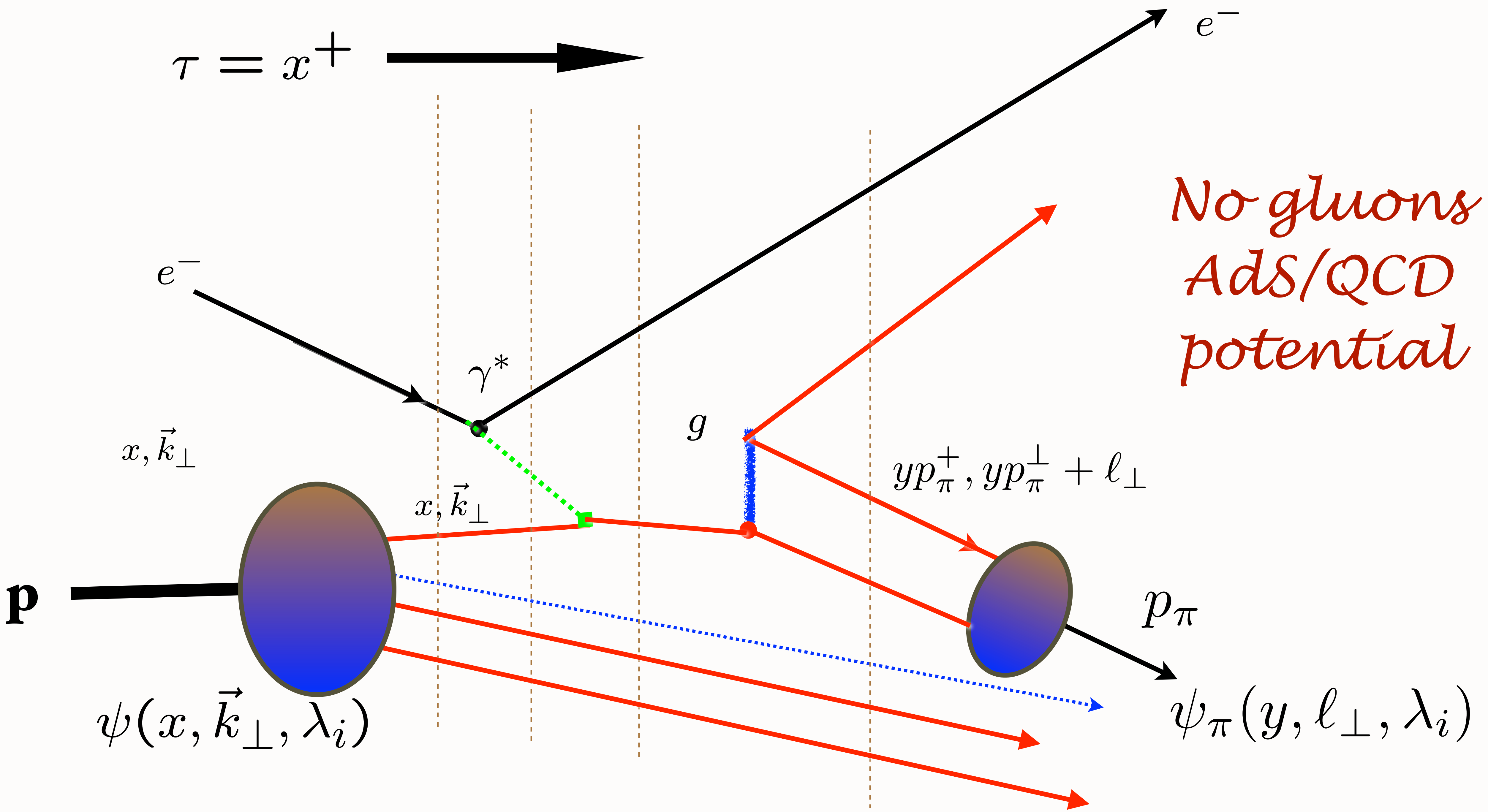
$$|\eta_b >= |b\bar{b} >$$

JLab Tagged Structure Functio

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

Hadronization at the Amplitude Level



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

Only Hadrons can Appear!

JLab 12 GeV: An Exotic Charm Factory!

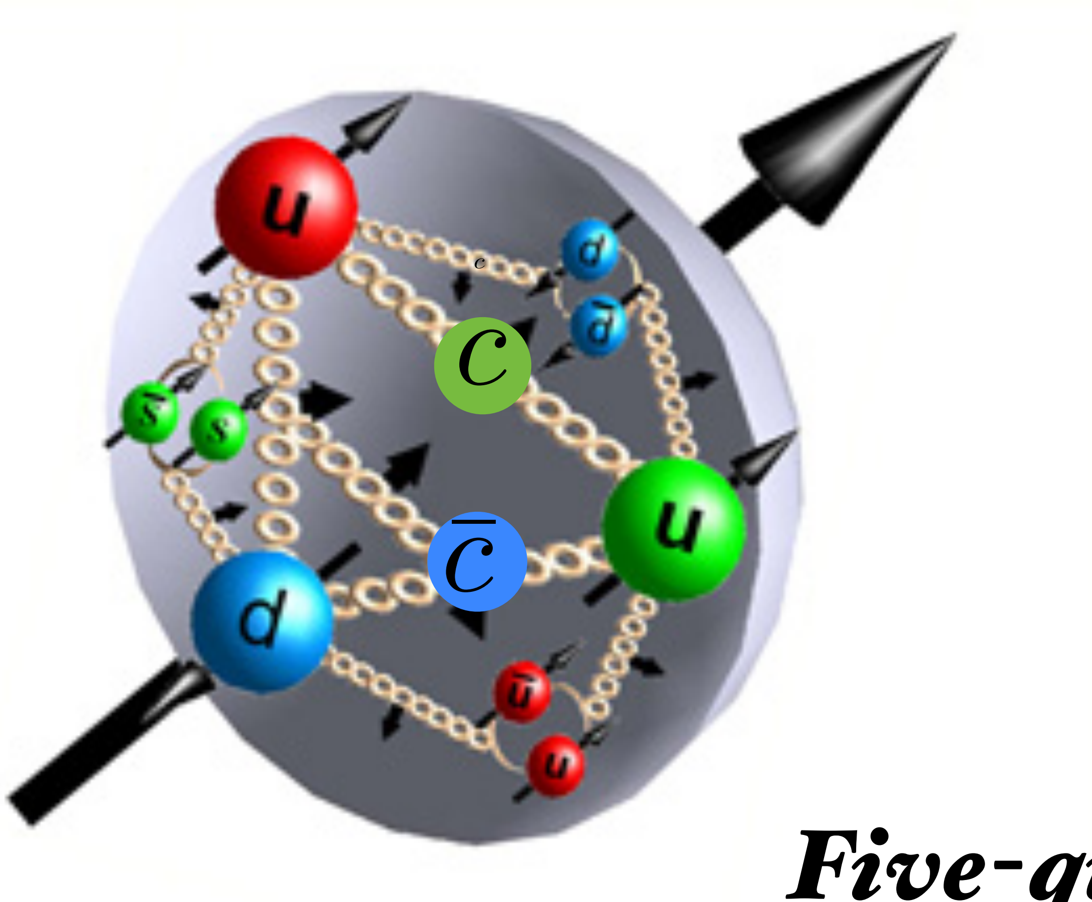
- Charm quarks at high x -- allows charm states to be produced with minimal energy
- Charm produced at low velocities in the target -- the target rapidity domain
- Charm at threshold -- maximal domain for producing exotic states containing charm quarks
- Attractive QCD Van der Waals interaction -- "nuclear-bound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

Novel QCD at JLab 12 GeV

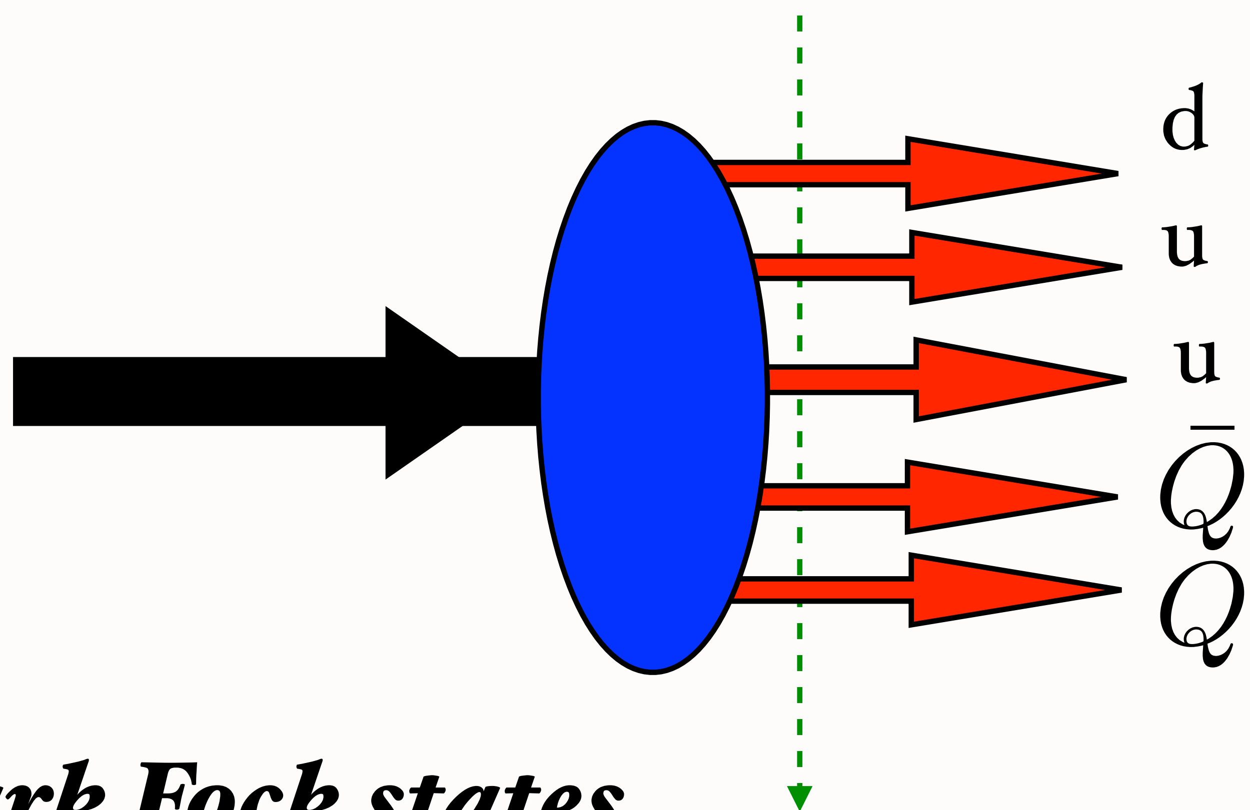
- *Intrinsic Heavy Quarks*
- *Charm at Threshold: exotic states, nuclear-bound quarkonium, anomalous polarization effects*
- *Exclusive and Inclusive Sivers Effect: Breakdown of pQCD Leading-Twist Factorization*
- *Non-universal antishadowing*
- *Hidden Color*
- *J=0 fixed pole*

Illuminate New QCD Physics

Novel Heavy-Quark Phenomena at Threshold



Fixed $\tau = t + z/c$



Five-quark Fock states

Exploring Hadron Structure with Tagged Structure Functions

Stan Brodsky

Jefferson Lab

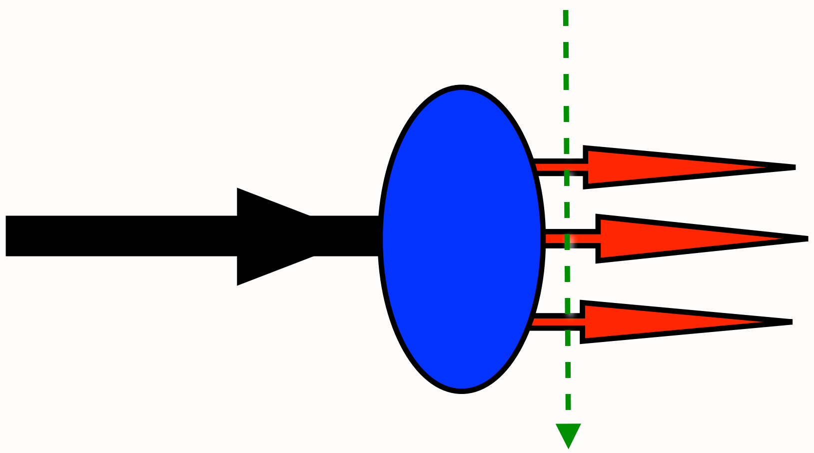
January 16-18, 2014

SLAC NATIONAL ACCELERATOR LABORATORY

Leland Stanford Junior University

Light-Front Wavefunctions

Dirac's Front Form: Fixed $\tau = t + z/c$



$$\psi(x_i, \vec{k}_{\perp i}, \lambda_i) \qquad x_i = \frac{k_i^+}{P^+}$$

Invariant under boosts. Independent of P^μ

$$\mathrm{H}_{LF}^{QCD}|\psi> = M^2|\psi>$$

Can we make a direct connection to QCD Lagrangian?

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

$$H_{QED}$$

QED atoms: positronium and muonium

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

Coupled Fock states

Eliminate higher Fock states (retarded interactions)

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

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

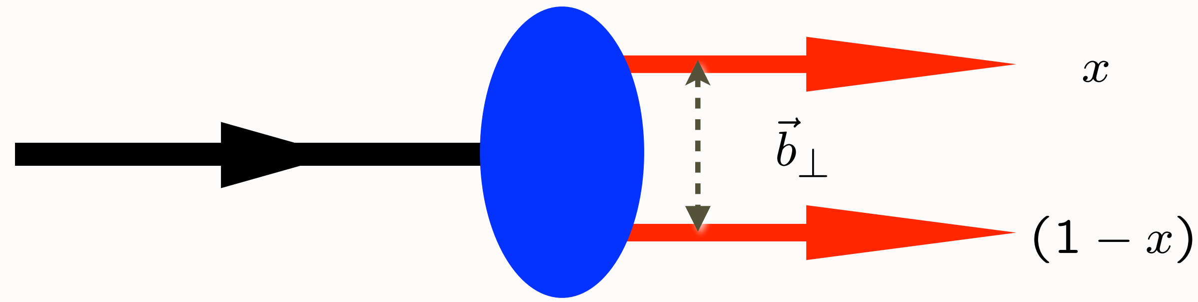
$$V_{eff} \to V_C(r) = -\frac{\alpha}{r}$$

Coulomb potential

Semiclassical first approximation to QED --> **Bohr Spectrum**

Light-Front QCD

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



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

Coupled Fock states

Eliminate higher Fock states (includes retarded interactions)

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

Effective two-particle equation

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

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

AdS/QCD:

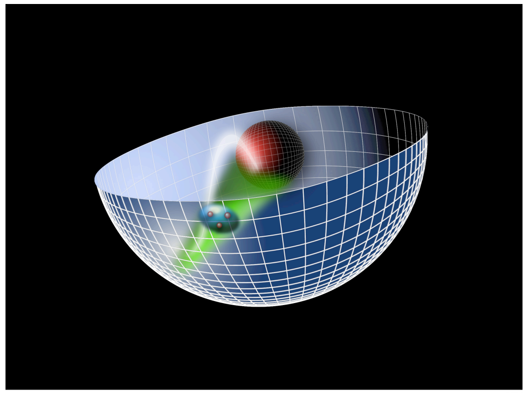
Azimuthal Basis ζ, ϕ

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

Confining AdS/QCD potential!
Mass Gap, Scale κ

Semiclassical first approximation to QCD

Dilaton-Modified AdS/QCD



$$ds^2 = e^{\varphi(z)} \frac{R^2}{z^2}(\eta_{\mu\nu} x^\mu x^\nu - dz^2)$$

- Soft-wall dilaton profile breaks conformal invariance $\quad e^{\varphi(z)} = e^{+\kappa^2 z^2}$
- Color Confinement
- Introduces confinement scale κ
- Uses AdS_5 as template for conformal theory

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

Light-Front Schrödinger Equation

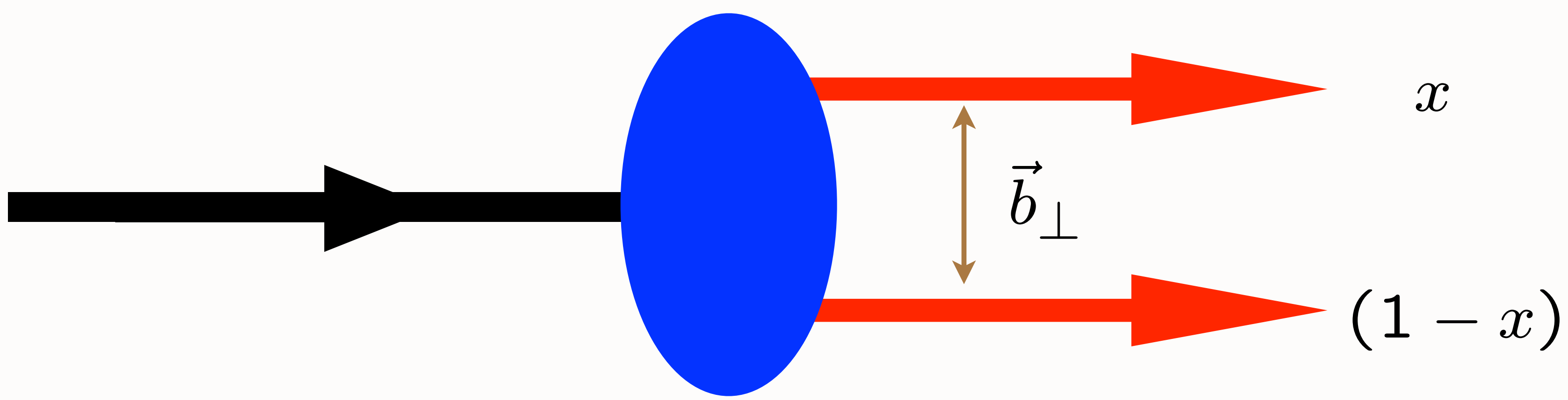
de Teramond, Dosch, sjb

Relativistic LF single-variable radial equation for QCD & QED

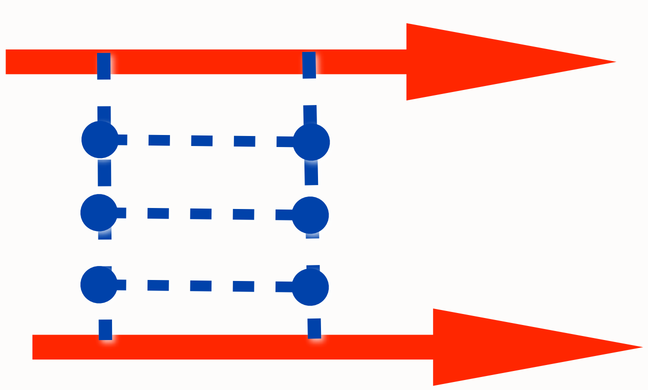
Frame Independent!

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

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



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



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

QCD Lagrangian

Fundamental Theory of Hadron and Nuclear Physics

gluon dynamics

quark kinetic energy + quark-gluon dynamics

quark mass term

$$\mathcal{L}_{QCD} = -\frac{1}{4}Tr(G^{\mu\nu}G_{\mu\nu}) + \sum_{f=1}^{n_f} i\bar{\Psi}_f D_\mu \gamma^\mu \Psi_f + \sum_{f=1}^{n_f} m_f \bar{\Psi}_f \Psi_f$$

$$iD^\mu = i\partial^\mu - gA^\mu \quad G^{\mu\nu} = \partial^\mu A^\mu - \partial^\nu A^\mu - g[A^\mu, A^\nu]$$

Classical Theory Conformal if m_q=0

Yang Mills Gauge Principle: Color Rotation and Phase Invariance at Every Point of Space and Time

Scale-Invariant Coupling
Renormalizable
Asymptotic Freedom
Color Confinement

QCD Mass Scale from Confinement not Explicit!

What determines the QCD mass scale?

- **de Alfaro, Fubini, Furlan 1976**

$$G|\psi(\tau)>= i\frac{\partial}{\partial\tau}|\psi(\tau)>$$

$$G = uH + vD + wK$$

New term

$$G = H_\tau = \frac{1}{2}\left(-\frac{d^2}{dx^2} + \frac{g}{x^2} + \frac{4uw - v^2}{4}x^2\right)$$

Retains conformal invariance of action despite mass scale!

$$4uw - v^2 = \kappa^4 = [M]^4$$

Identical to LF Hamiltonian with unique potential and dilaton!

- **Dosch, de Teramond, sjb**

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

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

What determines the QCD mass scale Λ_{QCD}?

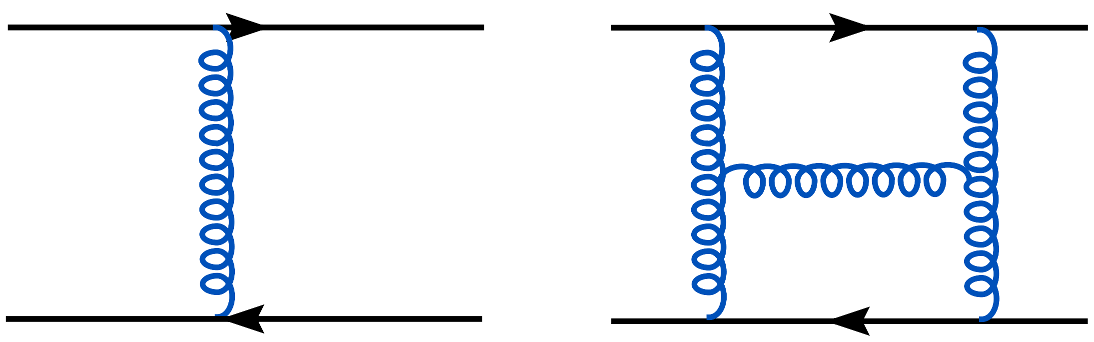
- Dosch, de Teramond, sjb
- de Alfaro, Fubini, Furlan

- Mass scale does not appear in the QCD Lagrangian (massless quarks)
- Dimensional Transmutation? Requires external constraint such as $\alpha_s(M_Z)$
- dAFF: Confinement Scale κ appears spontaneously via the Hamiltonian: $G = uH + vD + wK$ $\quad 4uw - v^2 = \kappa^4 = [M]^4$
- The confinement scale regulates infrared divergences, connects Λ_{QCD} to the confinement scale κ
- Only dimensionless mass ratios (and M times R) predicted
- Mass and time units [GeV] and [sec] from physics external to QCD
- New feature: bounded frame-independent relative time between constituents

Heavy Quark Potential is IR Divergent in QCD

$$V(Q^2) = -\frac{(4\pi)^2 C_F}{Q^2} a(Q^2)\Big[1 + (c_{2,0} + c_{2,1}N_f)a(Q^2) + (c_{3,0} + c_{3,1}N_f + c_{3,2}N_f^2)a(Q^2)^2$$
$$+ (c_{4,0} + c_{4,1}N_f + c_{4,2}N_f^2 + c_{4,3}N_f^3)a(Q^2)^3 + \boxed{8\pi^2 C_A^3 \ln\frac{\mu_{IR}^2}{Q^2} a(Q^2)^3}\Big]$$

Smirnov, Smirnov, Steinhauser, 2010



$$\log \kappa^2 \zeta^2$$

Summation of H graphs could yield confining potential

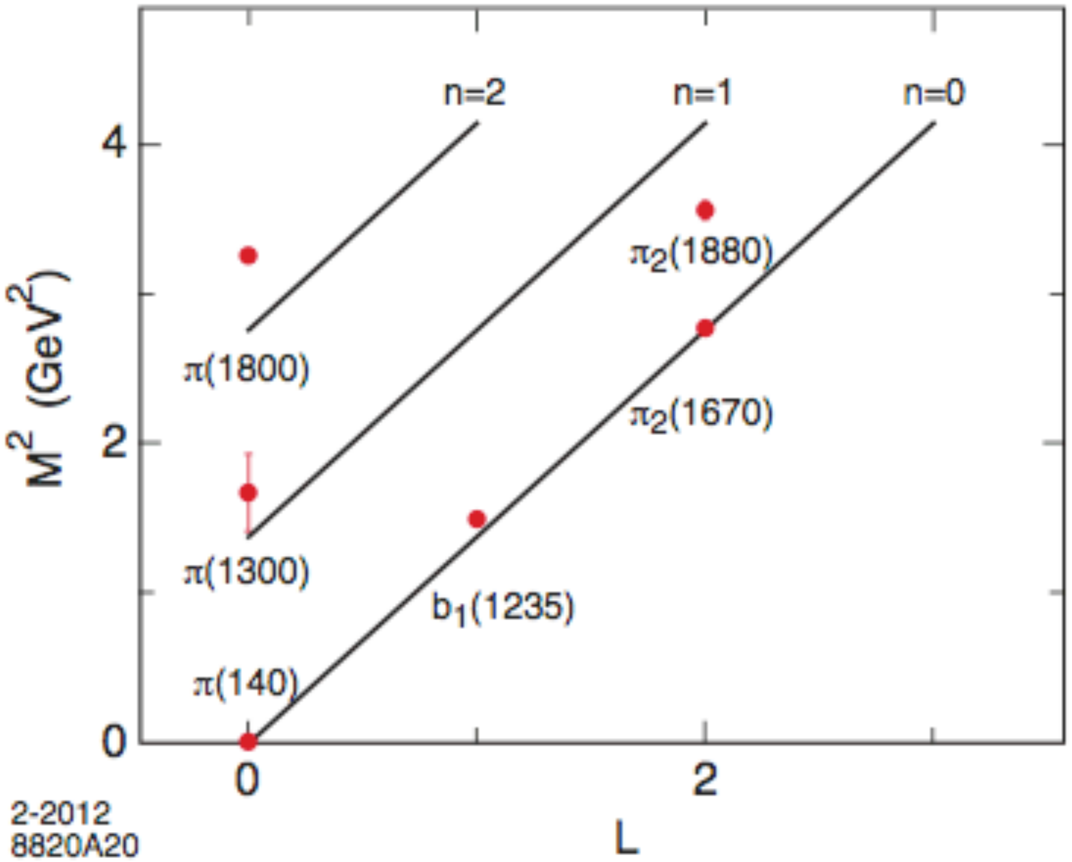
Same graphs could give Isgur-Paton Flux Tube

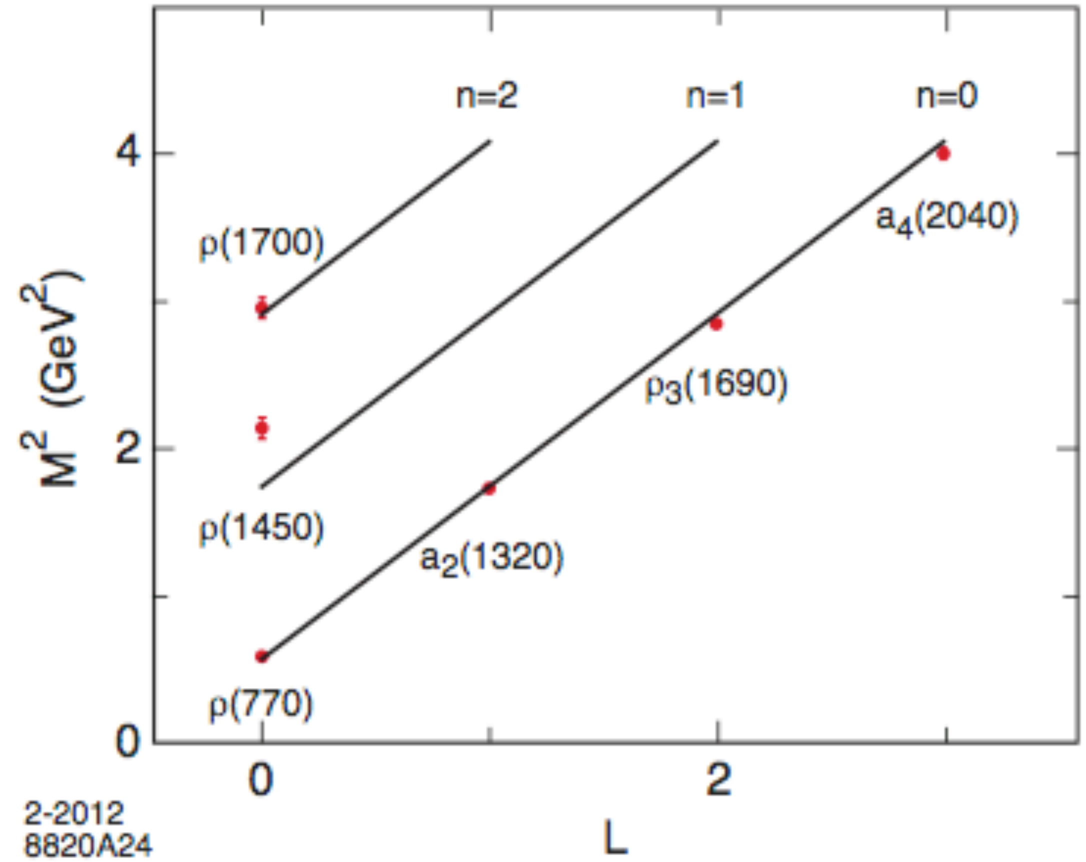
- $J = L + S, I = 1$ meson families $\boxed{\mathcal{M}^2_{n,L,S} = 4\kappa^2\,(n + L + S/2)}$

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

$\boxed{m_q = 0}$

Massless pion in Chiral Limit! ***Same slope in n and L!***



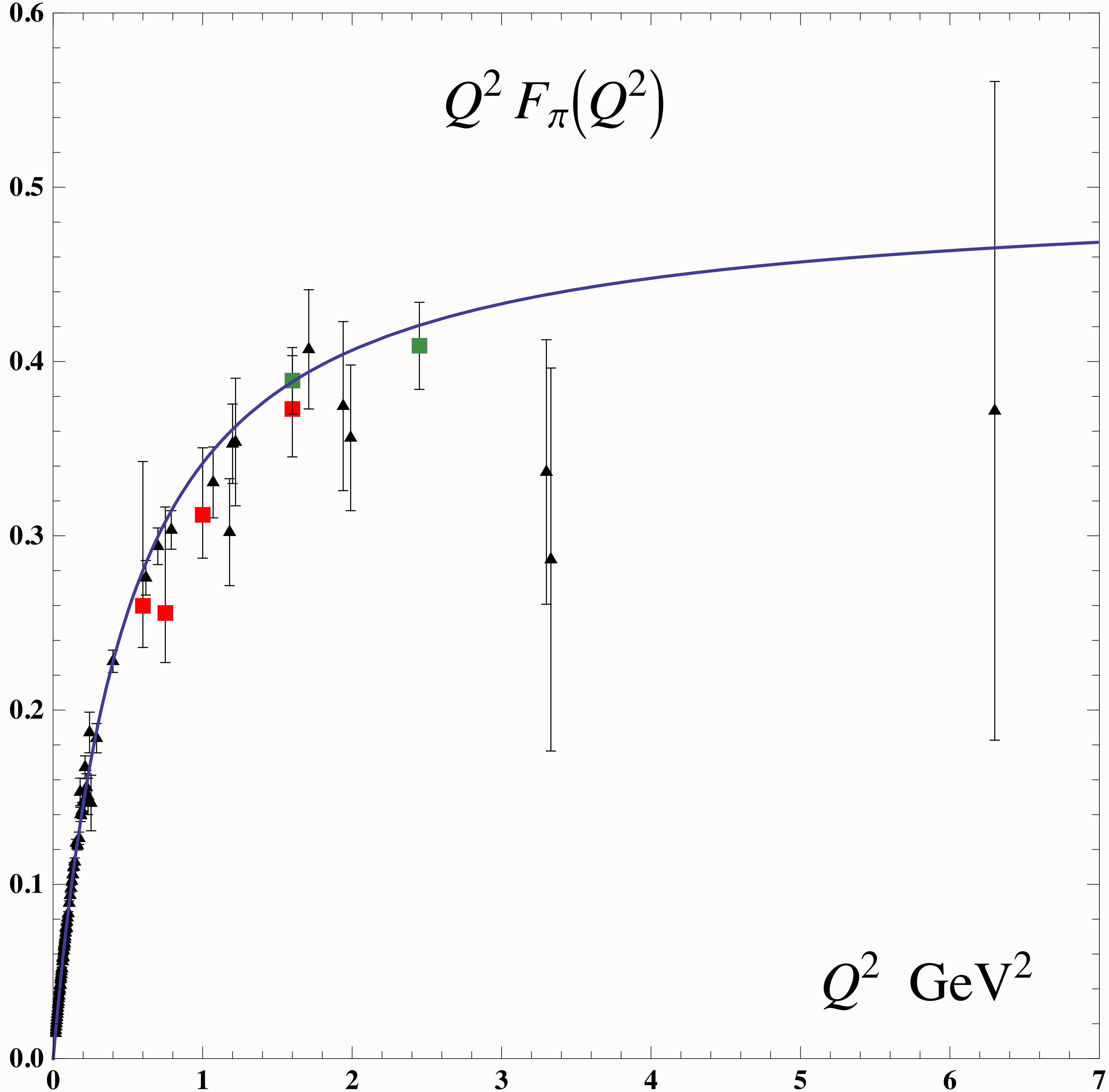


I=1 orbital and radial excitations for the π ($\kappa = 0.59$ GeV) and the ρ-meson families ($\kappa = 0.54$ GeV)

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

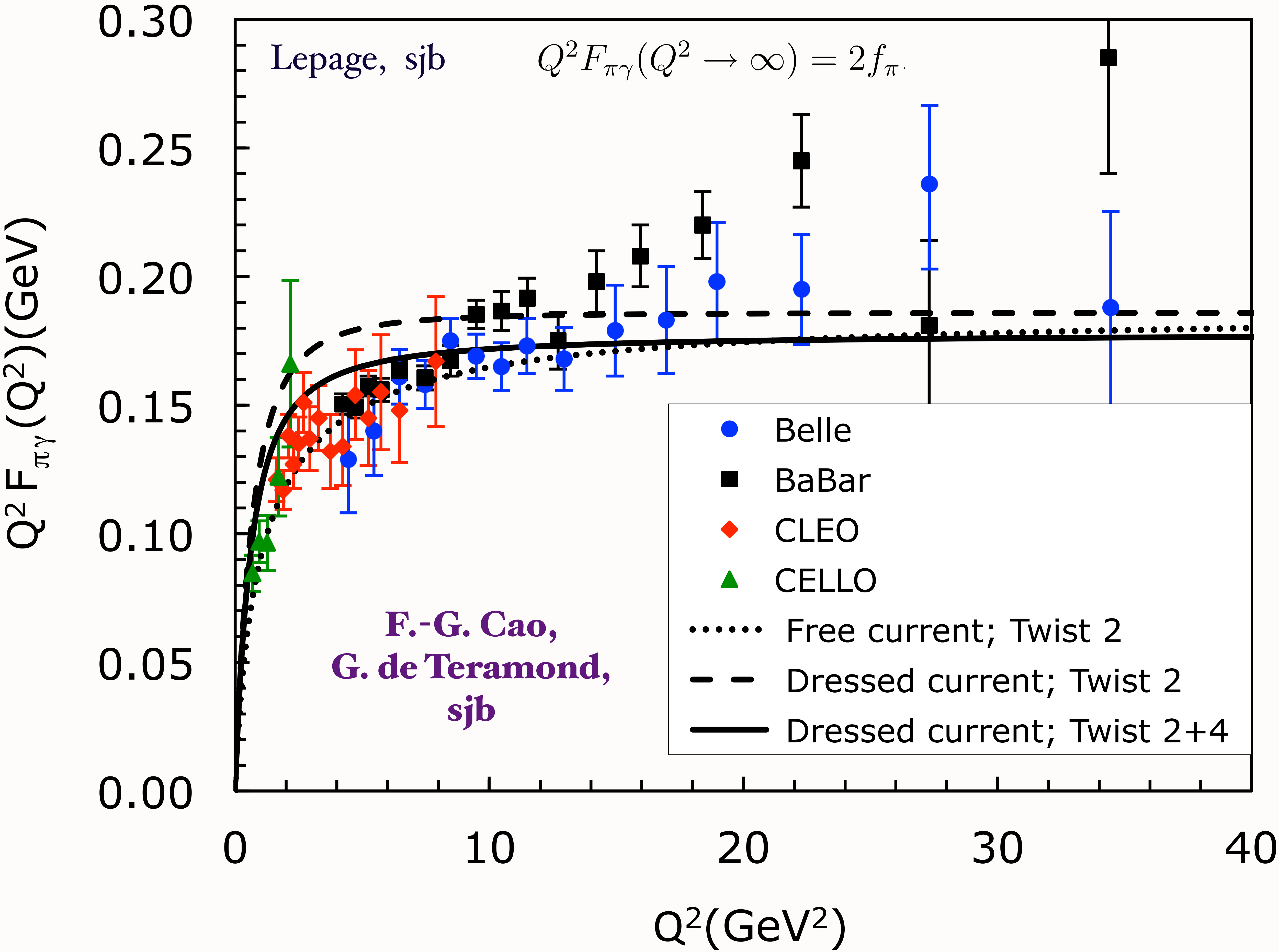
$$\mathcal{M}_{a_2(1320)} > \mathcal{M}_{a_1(1260)} > \mathcal{M}_{a_0(980)}$$

Mass ratio of the ρ and the a_1 mesons: coincides with Weinberg sum rules



$Q^2 F_\pi(Q^2)$
Q^2 GeV^2
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
1
2
3
4
5
6
7

Photon-to-pion transition form factor



- We write the Dirac equation

$$(\alpha\Pi(\zeta) - \mathcal{M})\,\psi(\zeta) = 0,$$

in terms of the matrix-valued operator Π

$$\Pi_\nu(\zeta) = -i\left(\frac{d}{d\zeta} - \frac{\nu+\frac{1}{2}}{\zeta}\gamma_5 - \kappa^2\zeta\gamma_5\right),$$

and its adjoint $\Pi^\dagger$, with commutation relations

$$\left[\Pi_\nu(\zeta), \Pi_\nu^\dagger(\zeta)\right] = \left(\frac{2\nu+1}{\zeta^2} - 2\kappa^2\right)\gamma_5.$$

- Solutions to the Dirac equation

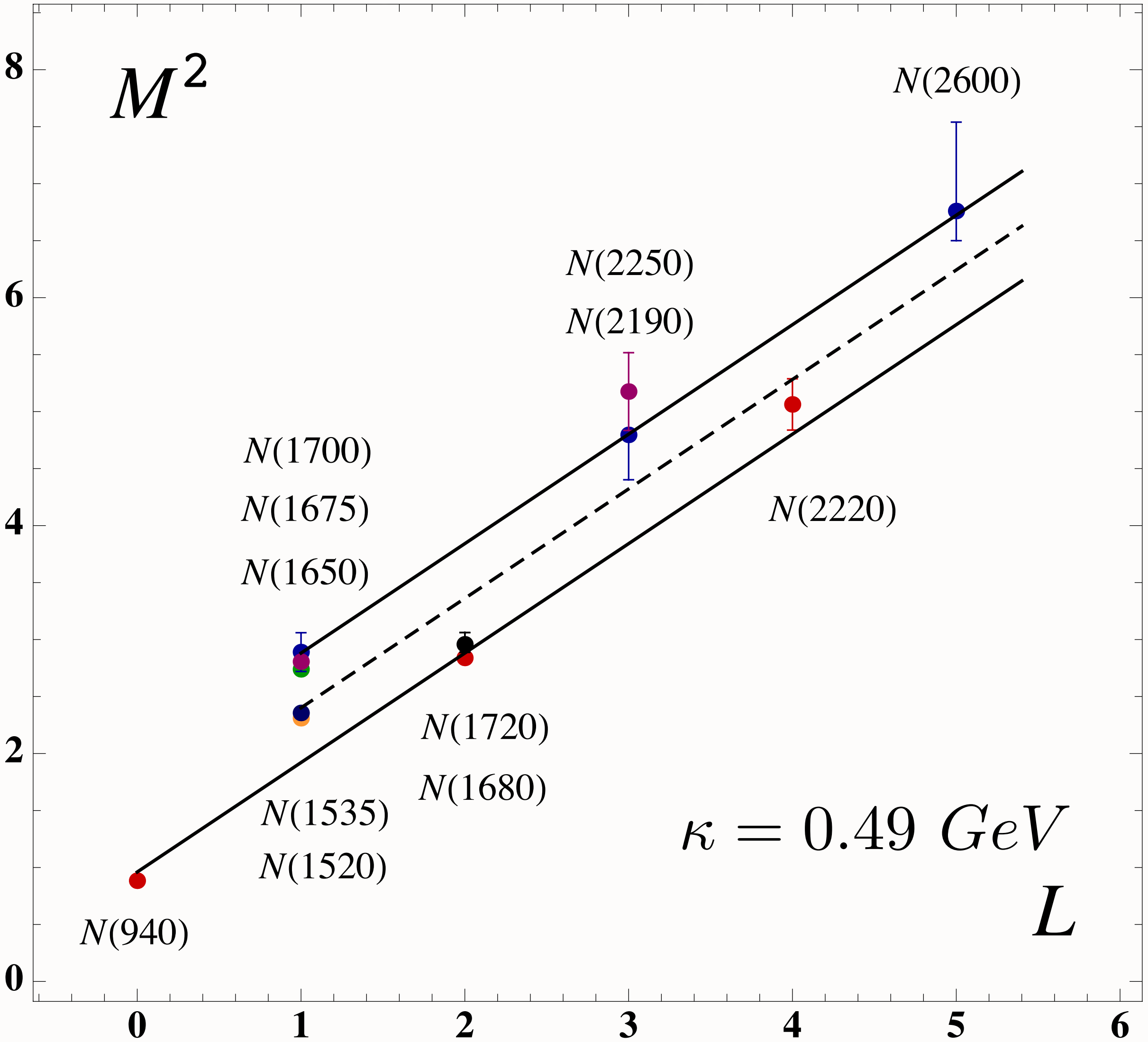
$$\begin{aligned}\psi_+(\zeta) &\sim z^{\frac{1}{2}+\nu}e^{-\kappa^2\zeta^2/2}L_n^\nu(\kappa^2\zeta^2),\\ \psi_-(\zeta) &\sim z^{\frac{3}{2}+\nu}e^{-\kappa^2\zeta^2/2}L_n^{\nu+1}(\kappa^2\zeta^2).\end{aligned}$$

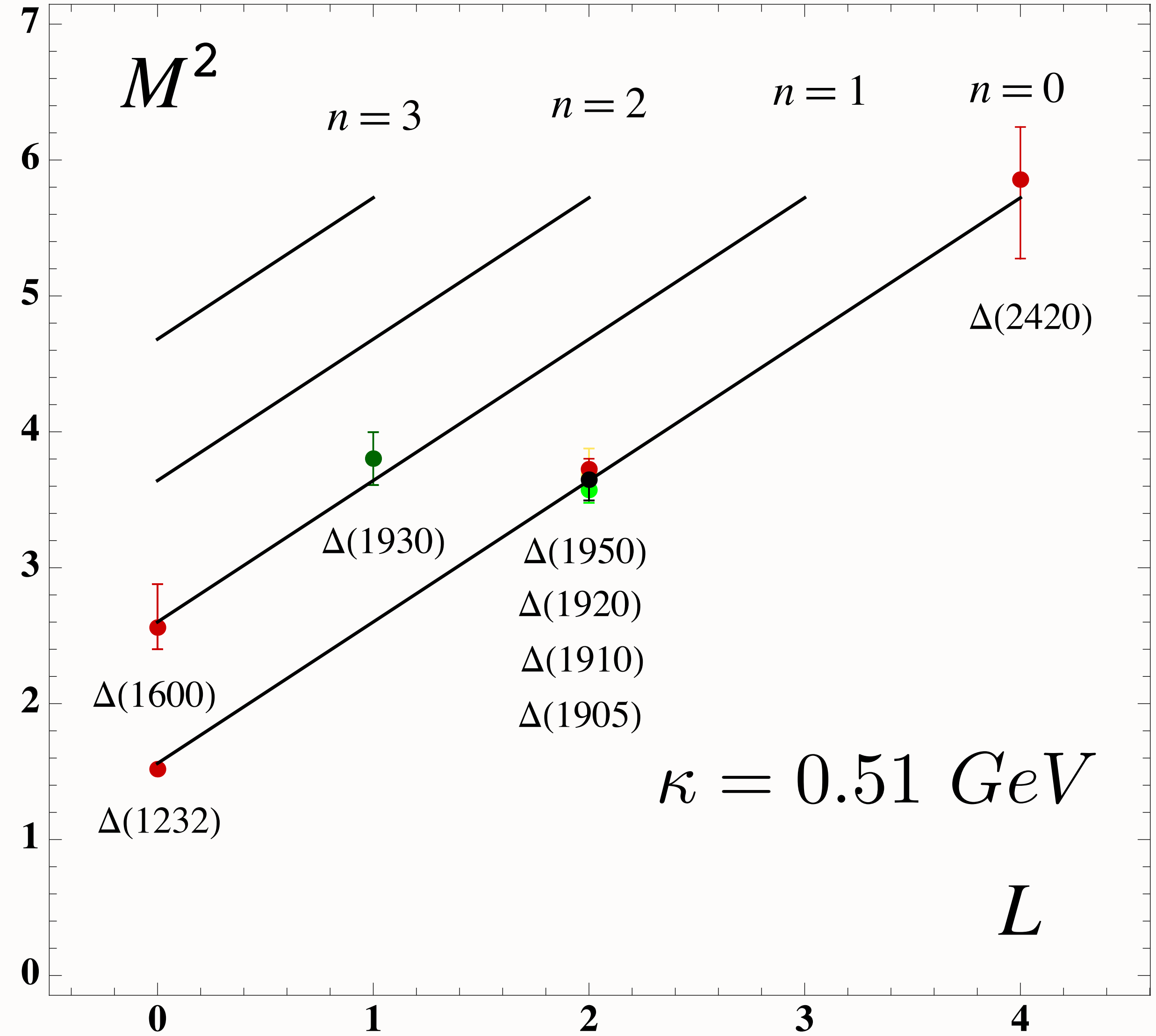
$$\nu = L + 1$$

- Eigenvalues

$$\mathcal{M}^2 = 4\kappa^2(n+\nu+1).$$

Baryon Spectroscopy from AdS/QCD and Light-Front Holography





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**

All confirmed resonances from PDG 2012

See also Forkel, Beyer, Federico, Klempt

Chiral Features of Soft-Wall AdS/QCD Model

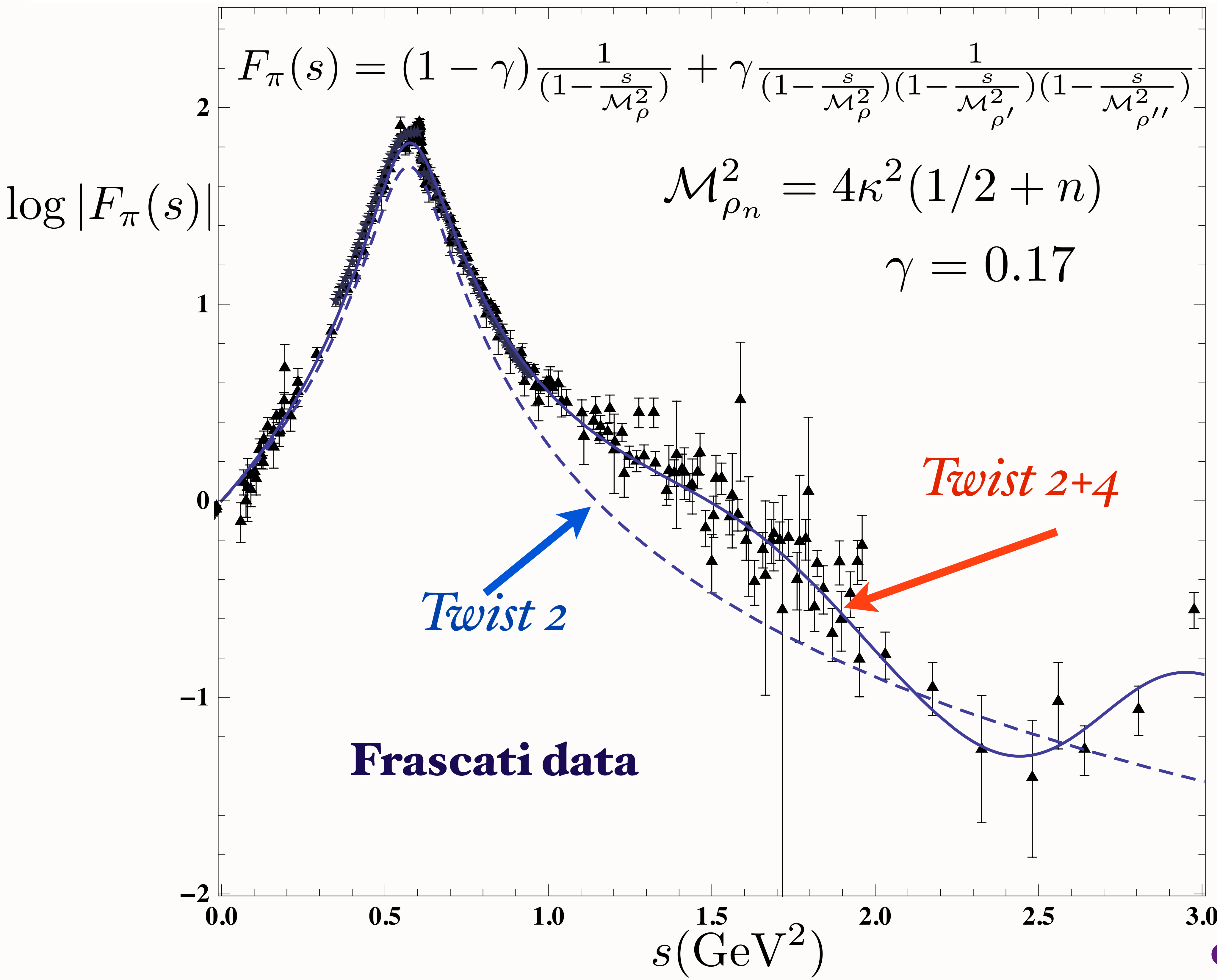
- **Boost Invariant**
- **Trivial LF vacuum! No condensate, but consistent with GMOR**
- **Massless Pion**
- **Hadron Eigenstates have LF Fock components of different L^z**
- **Proton: equal probability** $S^z = +1/2, L^z = 0; S^z = -1/2, L^z = +1$

$$\boxed{J^z = +1/2 :< L^z >= 1/2, < S^z_q = 0 >}$$

Same as Chiral soliton model Ellis, Karliner, sjb

- **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.**

Timelike Pion Form Factor from AdS/QCD and Light-Front Holography



Prescription for Timelike poles :

$$\frac{1}{s - M^2 + i\sqrt{s}\Gamma}$$

14% four-quark probability

G. de Teramond & sjb

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

Revised Gell-Mann Oakes Renner Formula in QCD

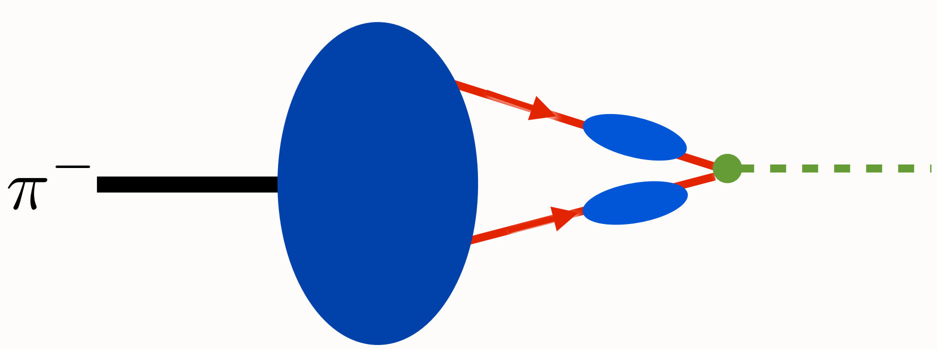
$$m_\pi^2 = -\frac{(m_u + m_d)}{f_\pi^2} < 0|\bar{q}q|0 >$$

current algebra: effective pion field

$$m_\pi^2 = -\frac{(m_u + m_d)}{f_\pi} < 0|i\bar{q}\gamma_5 q|\pi >$$

QCD: composite pion Bethe-Salpeter Eq.

vacuum condensate actually is an "in-hadron condensate"



$$< 0|\bar{q}\gamma_5 q|\pi >$$

Maris, Roberts, Tandy

Two Definitions of Vacuum State

Instant Form: Lowest-Energy Eigenstate of Instant-Form Hamiltonian

$$H|\psi_0>=E_0|\psi_0>, E_0=min\{E_i\}$$

Eigenstate defined at one time t over all space; Acausal! Frame-Dependent

Front Form: Lowest Invariant-Mass Eigenstate of Light-Front Hamiltonian

$$H_{LF}|\psi_0>_{LF}=M_0^2|\psi_0>_{LF}, M_0^2=0.$$

Frame-independent eigenstate at fixed LF time $\tau = t+z/c$ within causal horizon

Front Form Vacuum Describes the Empty, Causal Universe

“One of the gravest puzzles of theoretical physics”

DARK ENERGY AND
THE COSMOLOGICAL CONSTANT PARADOX

A. ZEE
Department of Physics, University of California, Santa Barbara, CA 93106, USA
Kavil Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA
zee@kitp.ucsb.edu

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

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

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

Extraordinary conflict between the conventional definition of the vacuum in quantum field theory and cosmology

Elements of the solution:
(A) Light-Front Quantization: causal frame-independent vacuum
(B) New understanding of QCD “Condensates”
(C) Higgs Light-Front Zero Mode

“One of the gravest puzzles of theoretical physics”

DARK ENERGY AND THE COSMOLOGICAL CONSTANT PARADOX

A. ZEE

Department of Physics, University of California, Santa Barbara, CA 93106, USA
Kavil Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA
zee@kitp.ucsb.edu

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

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

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

$$(\Omega_\Lambda)_{QCD} \propto < 0|q\bar{q}|0 >^4$$

QCD Problem Solved if quark and gluon condensates reside within hadrons, not vacuum!

R. Shrock, sjb Proc.Nat.Acad.Sci. 108 (2011) 45-50 “Condensates in Quantum Chromodynamics and the Cosmological Constant”

C. Roberts, R. Shrock, P. Tandy, sjb Phys.Rev. C82 (2010) 022201 “New Perspectives on the Quark Condensate”

An analytic first approximation to QCD

AdS/QCD + Light-Front Holography

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

Basis Light-Front Quantization Approach to Quantum Field Theory

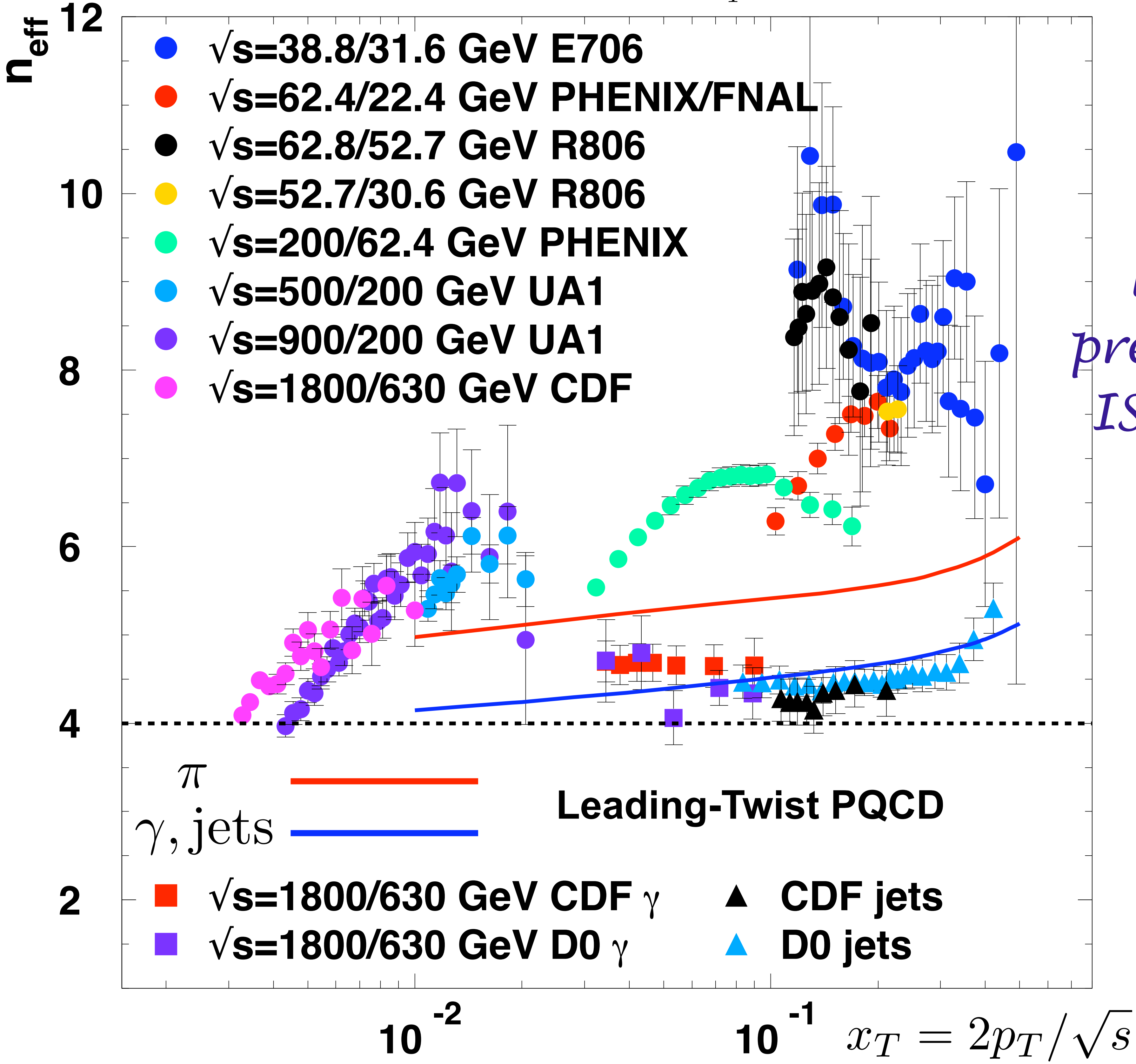
BLFQ

Use AdS/QCD basis functions!

Xingbo Zhao
With Anton Ilderton,
Heli Honkanen, Pieter Maris,
James Vary, Stan Brodsky

Department of Physics and Astronomy
Iowa State University
Ames, USA

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



Leading-twist prediction fails at ISR, FNAL, RHIC, CDF!

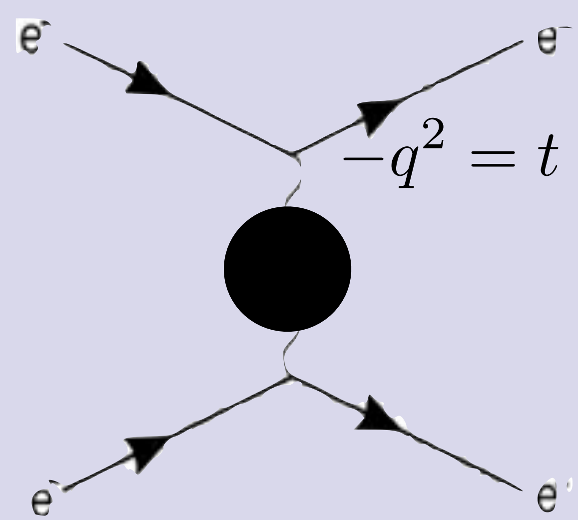
Arleo, Hwang, Sickles, sjb

Lessons from QED

In the (physical) Gell Mann-Low scheme, the momentum scale of the running coupling is the virtuality of the exchanged photon; independent of initial scale.

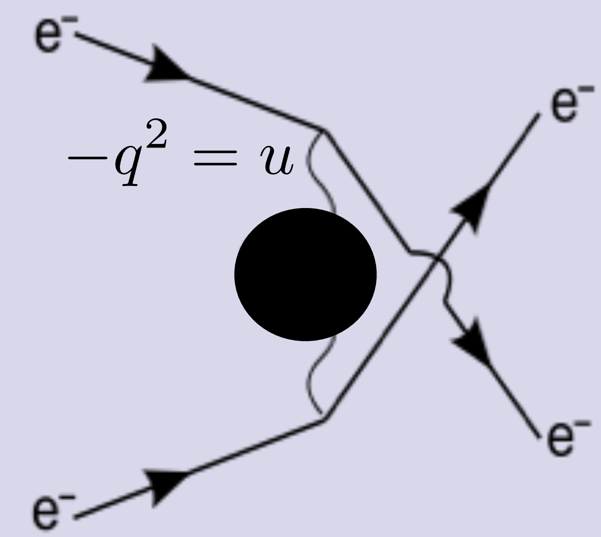
$$\alpha(t) = \frac{\alpha(t_0)}{1 - \Pi(t, t_0)} \qquad \Pi(t, t_0) = \frac{\Pi(t) - \Pi(t_0)}{1 - \Pi(t_0)}$$

Example: ee-scattering



$$\mathcal{M}_{ee\to ee} = \frac{8\pi s}{t}\alpha(t) + \frac{8\pi s}{u}\alpha(u)$$

Two separate scales;
one for each skeleton graph.



For any other scale choice an infinite set of diagrams must be taken into account to obtain the correct result!

In any other scheme, the correct scale displacement must be used

$$\log \frac{\mu^2_{\overline{MS}}}{m_\ell^2} = 6\int_0^1 dx\, x(1-x) \log \frac{m_\ell^2 + Q^2 x(1-x)}{m_\ell^2}, \quad \xrightarrow{Q^2 \gg m_\ell^2} \quad \log \frac{Q^2}{m_\ell^2} - \frac{5}{3}$$

$$\boxed{\alpha_{\overline{MS}}(e^{-5/3}q^2) = \alpha_{GM-L}(q^2).}$$

Principle of Maximum Conformality (PMC)

QCD Observables

$$\mathcal{O} = C(\alpha_s(\mu_0^2)) + B(\beta \log \frac{Q^2}{\mu_0^2}) + D(\frac{m_q^2}{Q^2}) + E(\frac{\Lambda^2_{QCD}}{Q^2}) + F(\frac{\Lambda^2_{QCD}}{m_Q^2}) + G(\frac{m_q^2}{m_Q^2})$$

Scale-Free Conformal Series

Running Coupling Effects

Higher Twist from Hadron Dynamics

Intrinsic Heavy Quarks

Light by Light Loops

BLM/PMC: Absorb β-terms into running coupling

$$\mathcal{O} = C(\alpha_s(Q^{*2})) + D(\frac{m_q^2}{Q^2}) + E(\frac{\Lambda^2_{QCD}}{Q^2}) + F(\frac{\Lambda^2_{QCD}}{m_Q^2}) + G(\frac{m_q^2}{m_Q^2})$$

Set multiple renormalization scales -- Lensing, DGLAP, ERBL Evolution ...

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

↓

$Choose\ \mu_R^{init};\ arbitrary\ initial\ renormalization\ scale$

↓

$Identify\ \{\beta_i^R\} - terms\ using\ n_f - terms$

$through\ the\ PMC - BLM\ correspondence\ principle$

↓

$Shift\ scale\ of\ \alpha_s\ to\ \mu_R^{\rm PMC}\ to\ eliminate\ \{\beta_i^R\} - terms$

↓

$Conformal\ Series$

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

Principle of Maximum Conformality

PMC/BLM

No renormalization scale ambiguity!

Result is independent of Renormalization scheme and initial scale!

QED Scale Setting at N_C=0

Eliminates unnecessary systematic uncertainty

δ -Scheme automatically identifies β -terms!

Xing-Gang Wu, Matin Mojaza Leonardo di Giustino, SJB

Systematic All-Orders Method to Eliminate Renormalization-Scale and Scheme Ambiguities in Perturbative QCD

Matin Mojaza[*]

CP3-Origins, Danish Institute for Advanced Studies, University of Southern Denmark, DK-5230 Odense, Denmark and SLAC National Accelerator Laboratory, Stanford University, Stanford, California 94039, USA

Stanley J. Brodsky[†]

SLAC National Accelerator Laboratory, Stanford University, Stanford, California 94039, USA

Xing-Gang Wu[‡]

Department of Physics, Chongqing University, Chongqing 401331, People's Republic of China

(Received 13 January 2013; published 10 May 2013)

We introduce a generalization of the conventional renormalization schemes used in dimensional regularization, which illuminates the renormalization scheme and scale ambiguities of perturbative QCD predictions, exposes the general pattern of nonconformal $\{\beta_i\}$ terms, and reveals a special degeneracy of the terms in the perturbative coefficients. It allows us to systematically determine the argument of the running coupling order by order in perturbative QCD in a form which can be readily automatized. The new method satisfies all of the principles of the renormalization group and eliminates an unnecessary source of systematic error.

In dim. reg. $1/\epsilon$ poles come in powers of [Bollini & Gambiagi, 't Hooft & Veltman, '72]

$$\ln\frac{\mu^2}{\Lambda^2}+\frac{1}{\epsilon}+c$$

In the modified minimal subtraction scheme (MS-bar) one subtracts together with the pole a constant [Bardeen, Buras, Duke, Muta (1978) on DIS results]:

$$\ln(4\pi)-\gamma_E$$

This corresponds to a shift in the scale:

$$\mu^2_{\overline{\mathrm{MS}}}=\mu^2\exp(\ln 4\pi-\gamma_E)$$

A finite subtraction from infinity is arbitrary. *Let's make use of this!*

Subtract an arbitrary constant and keep it in your calculation: $\mathcal{R}_\delta$-scheme

$$\boxed{\ln(4\pi)-\gamma_E-\delta,}$$

$$\mu_\delta^2=\mu^2_{\overline{\mathrm{MS}}}\exp(-\delta)=\mu^2\exp(\ln 4\pi-\gamma_E-\delta)$$

Xing-Gang Wu, Matin Mojaza, SJB

Exposing the Renormalization Scheme Dependence

Observable in the $\mathcal{R}_\delta$ -scheme:

$$\rho_\delta(Q^2) = r_0 + r_1 a(\mu) + [r_2 + \beta_0 r_1 \delta] a(\mu)^2 + [r_3 + \beta_1 r_1 \delta + 2\beta_0 r_2 \delta + \beta_0^2 r_1 \delta^2] a(\mu)^3 + \cdots$$

$$\mathcal{R}_0 = \overline{\mathrm{MS}}\ , \quad \mathcal{R}_{\ln 4\pi - \gamma_E} = \mathrm{MS} \qquad \mu^2 = \mu^2_{\overline{\mathrm{MS}}} \exp(\ln 4\pi - \gamma_E)\ , \quad \mu^2_{\delta_2} = \mu^2_{\delta_1} \exp(\delta_2 - \delta_1)$$

Note the divergent 'renormalon series' $n!\beta^n \alpha_s^n$

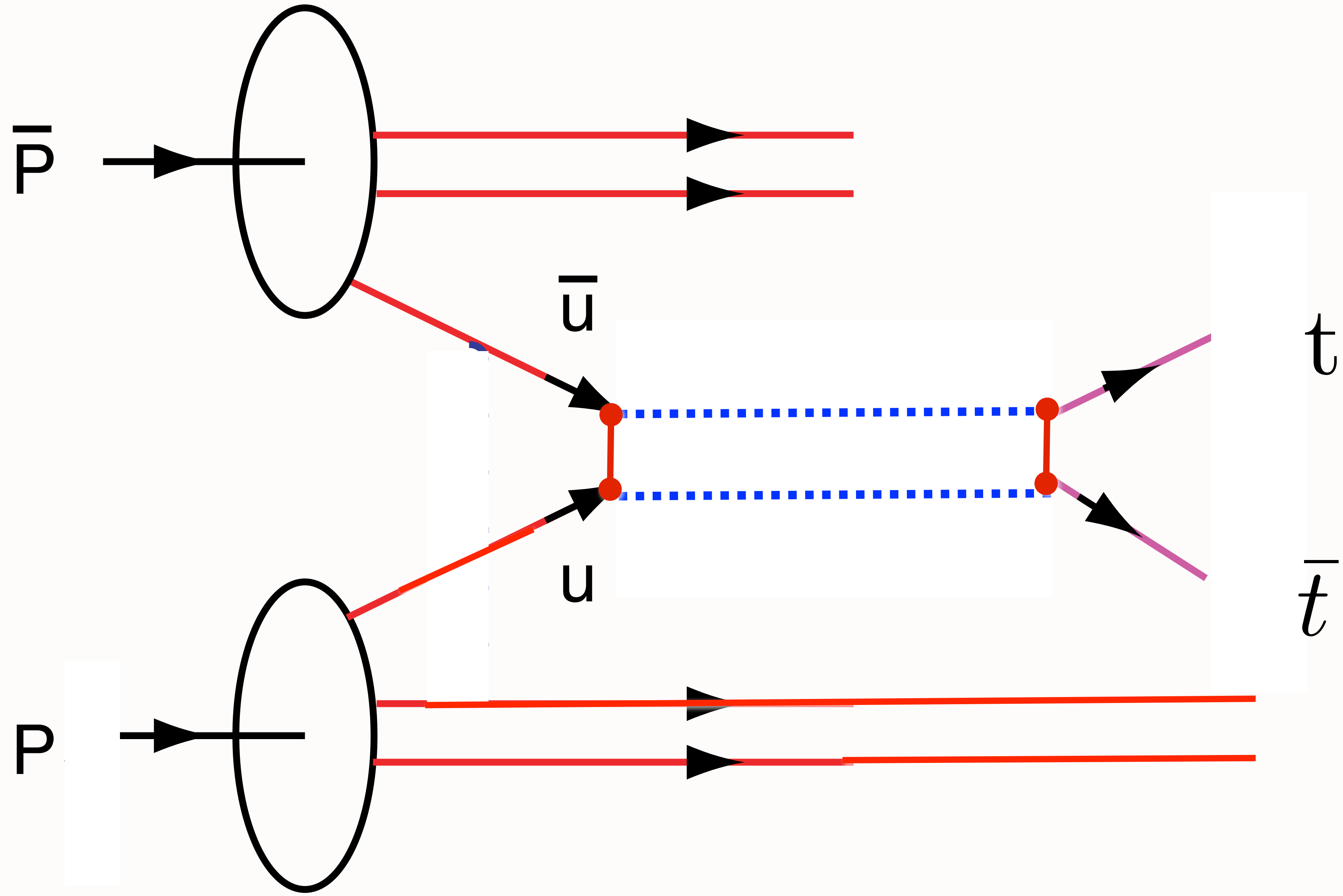
Renormalization Scheme Equation

$$\frac{d\rho}{d\delta} = -\beta(a)\frac{d\rho}{da} \stackrel{!}{=} 0 \quad \longrightarrow \mathrm{PMC}$$

$$\rho_\delta(Q^2) = r_0 + r_1 a_1(\mu_1) + (r_2 + \beta_0 r_1 \delta_1) a_2(\mu_2)^2 + [r_3 + \beta_1 r_1 \delta_1 + 2\beta_0 r_2 \delta_2 + \beta_0^2 r_1 \delta_1^2] a_3(\mu_3)^3$$

The $\delta_k^p a^n$-term indicates the term associated to a diagram with $1/\epsilon^{n-k}$ divergence for any p. Grouping the different δ_k-terms, one recovers in the $N_c \to 0$ Abelian limit the dressed skeleton expansion.

Contributes to the $\bar{p}p \to \bar{t}tX$ asymmetry at the Tevatron



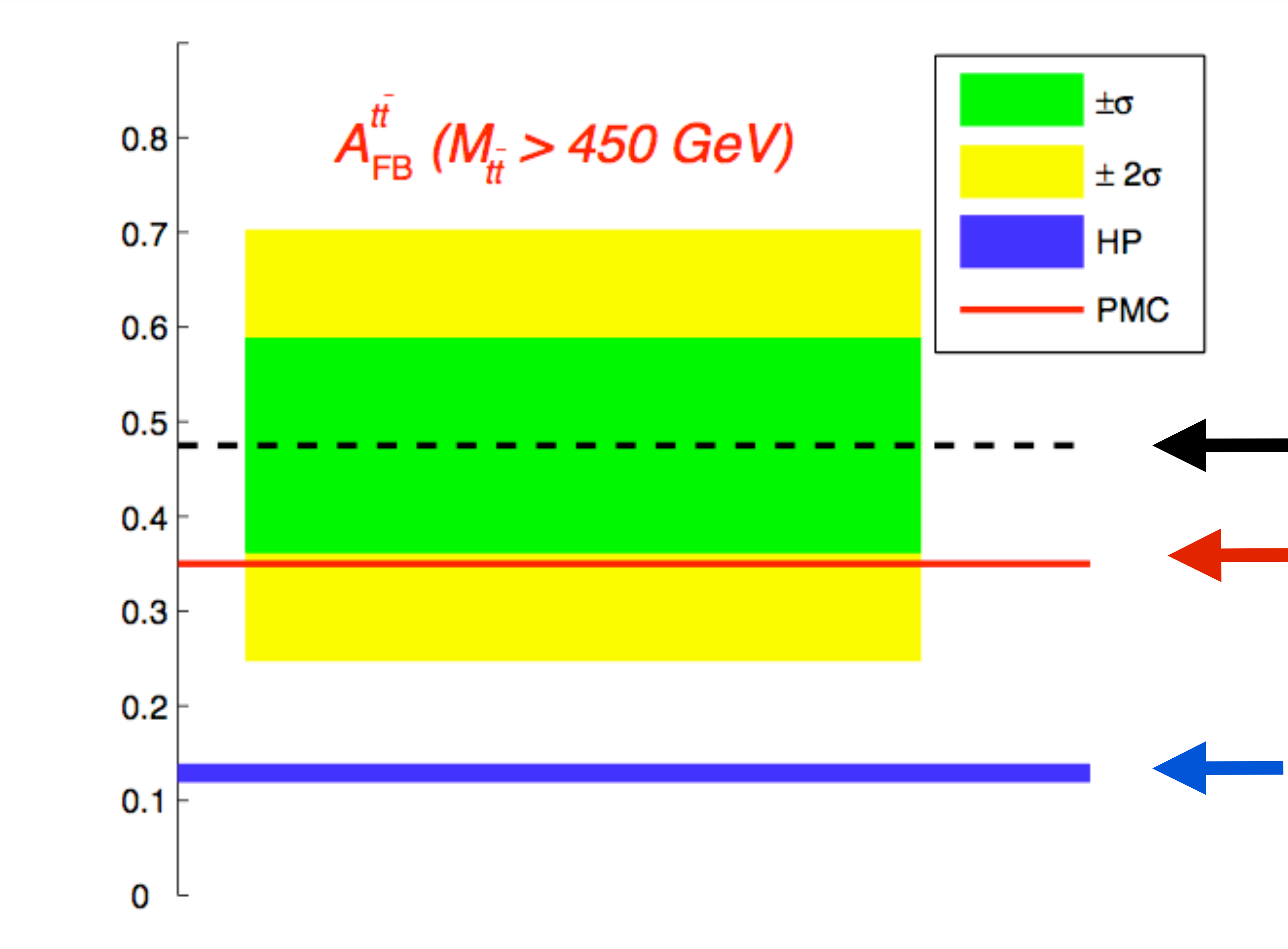
Interferes with Born term.

Small value of renormalization scale increases asymmetry

Xing-Gang Wu, sjb

The Renormalization Scale Ambiguity for Top-Pair Production Eliminated Using the 'Principle of Maximum Conformality' (PMC)

Xing-Gang Wu
SJB

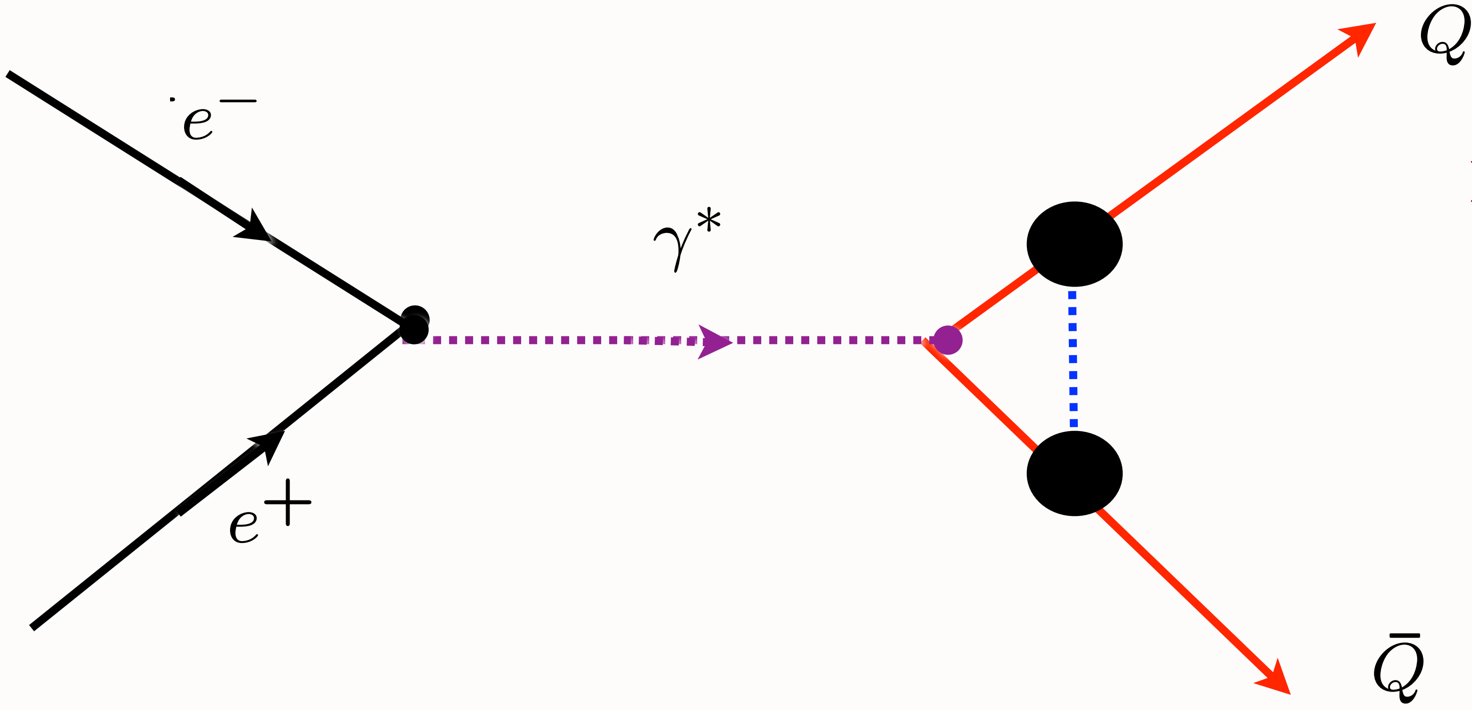


Experimental asymmetry

PMC Prediction

Conventional guess for renormalization scale and range

Top quark forward-backward asymmetry predicted by pQCD NNLO within 1 σ of CDF/D0 measurements using PMC/BLM scale setting



Hoang, Kuhn, Teubner, sjb

$$F_1 + F_2 = [1 - 2\frac{\alpha_s(se^{3/4}/4)}{\pi}] \times [1 + \frac{\pi\alpha_s(sv^2)}{4v}]$$

Angular distributions of massive quarks close to threshold.

Example of Multiple BLM Scales

Need QCD coupling at small scales at low relative velocity v

Novel QCD Phenomena and Perspectives

- **Hadroproduction at large transverse momentum does not derive exclusively from 2 to 2 scattering subprocesses: Baryon Anomaly at RHIC** Sickles, sjb
- **Color Transparency** Mueller, sjb; **Diffractive Di-Jets and Tri-jets** Strikman et al
- **Heavy quark distributions do not derive exclusively from DGLAP or gluon splitting -- component intrinsic to hadron wavefunction.** Hoyer, et al
- **Higgs production at large x_F from intrinsic heavy quarks** Kopeliovitch, Goldhaber, Schmidt, Soffer, sjb
- **Initial and final-state interactions are not always power suppressed in a hard QCD reaction: Sivers Effect, Diffractive DIS, Breakdown of Lam Tung PQCD Relation** Schmidt, Hwang, Hoyer, Boer, sjb; Collins
- **LFWFS are universal, but measured nuclear parton distributions are not universal -- antishadowing is flavor dependent** Schmidt, Yang, sjb
- **Renormalization scale is not arbitrary; multiple scales, unambiguous at given order.** Disentangle running coupling and conformal effects, Skeleton expansion: Gardi, Grunberg, Rathsman, sjb
- **Quark and Gluon condensates reside within hadrons:** Shrock, sjb

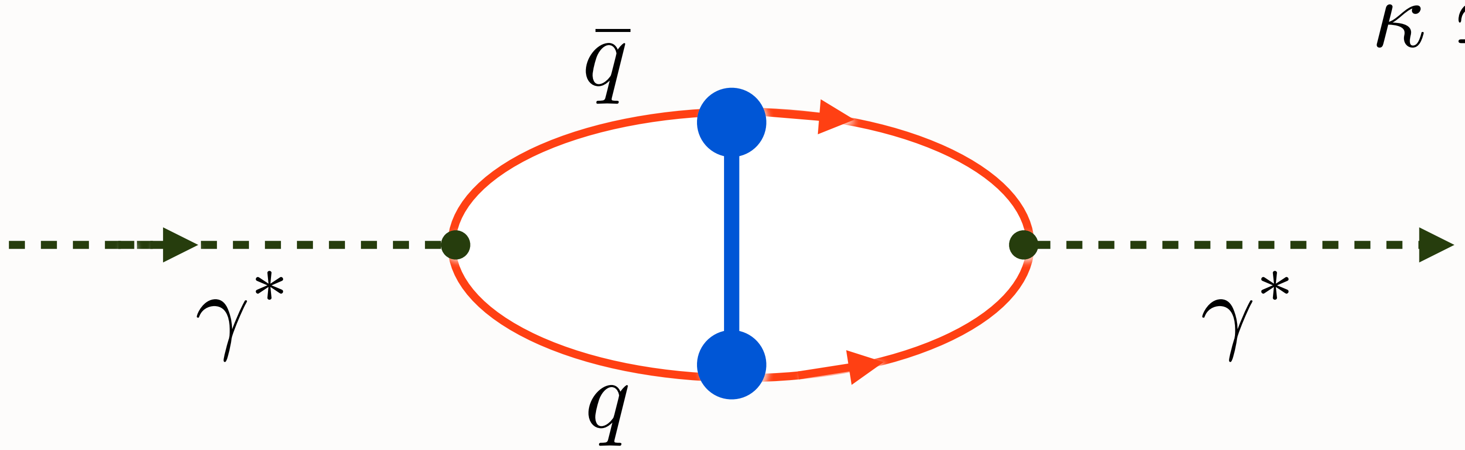
New Directions

- **Hadronization at the Amplitude Level**
- **Direct Processes: Hadron production in subprocess**
- **Compute QCD Corrections at Soft-Scales -e.g. Sivers, Boer-Mulders, DDIS**
- **Double-Parton Processes**
- **Eliminate Factorization Scale: Fracture function determines off-shellness**
- **Sublimated Gluons: Gluons appear only at high virtuality**
- **Heavy Quark Fock States from Confinement Potential**
- **Hidden Color of Nuclear Wavefunctions**
- **Duality: Confinement effects absent at small x^2**

Effective Confinement potential from soft-wall AdS/QCD gives Regge Spectroscopy plus higher-twist correction to current propagator

$$M^2 = 4\kappa^2(n + L + S/2)$$ light-quark meson spectra

$\kappa \simeq 0.5$ GeV



$$R_{e^+e^-}(s) = N_c \sum_q e_q^2 (1 + \mathcal{O}\frac{\kappa^4}{s^2} + \cdots)$$

mimics dimension-4 gluon condensate $< 0|\frac{\alpha_s}{\pi}G^{\mu\nu}(0)G_{\mu\nu}(0)|0 >$ *in*

$e^+e^- \to X$, τ decay, $Q\bar{Q}$ phenomenology

Quark and Gluon condensates reside within hadrons, not vacuum

Casher and Susskind **Maris, Roberts, Tandy** **Shrock and sjb**

- **Light-Front Quantization**
- **Bound-State Dyson Schwinger Equations**
- **AdS/QCD**
- **Implications for cosmological constant -- Eliminates 45 orders of magnitude conflict**

LF Quantization

Bjorken, Kogut, Soper, Susskind

LFWFs and Exclusive QCD

Lepage and SJB, Efremov, Radyushkin

RG and LF Hamiltonians

Glazek & Wilson

DLCQ

Hornbostel, Pauli, & SJB
Pinsky, Hiller

Renormalization of LF

Hiller, Chabysheva, Pauli, Pinsky, McCartor, Suaya, sjb

Rotation Invariance, Regularization

Karmanov, Mathiot

Zero Modes, [illegible]

Srivastava, sjb

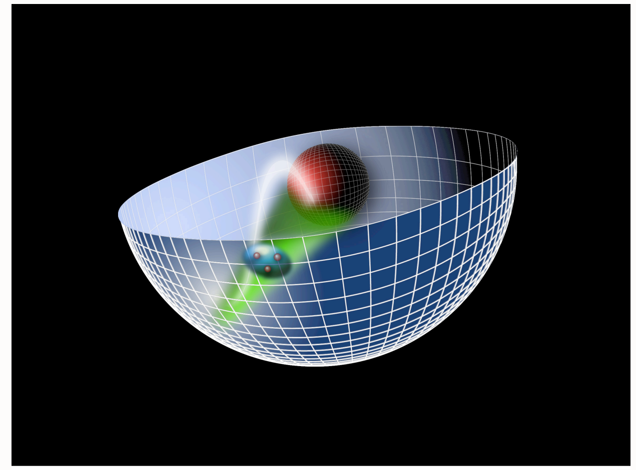
Possible multiparticle ridge-like correlations in very high multiplicity proton-proton collisions

Bjorken, Goldhaber, sjb

We suggest that this "ridge"-like correlation may be a reflection of the rare events generated by the collision of aligned flux tubes connecting the valence quarks in the wave functions of the colliding protons.

The "spray" of particles resulting from the approximate line source produced in such inelastic collisions then gives rise to events with a strong correlation between particles produced over a large range of both positive and negative rapidity.

de Teramond, Dosch, sjb



AdS/QCD
Soft-Wall Model

Light-Front Holography

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

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

Light-Front Schrödinger Equation

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

Unique Confinement Potential!

Conformal Symmetry of the action

Complementary argument: Ehrenfest identity
Glazek &Trawinski

An analytic first approximation to QCD

AdS/QCD + Light-Front Holography

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