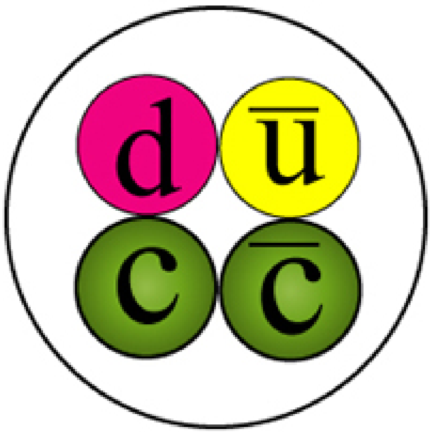
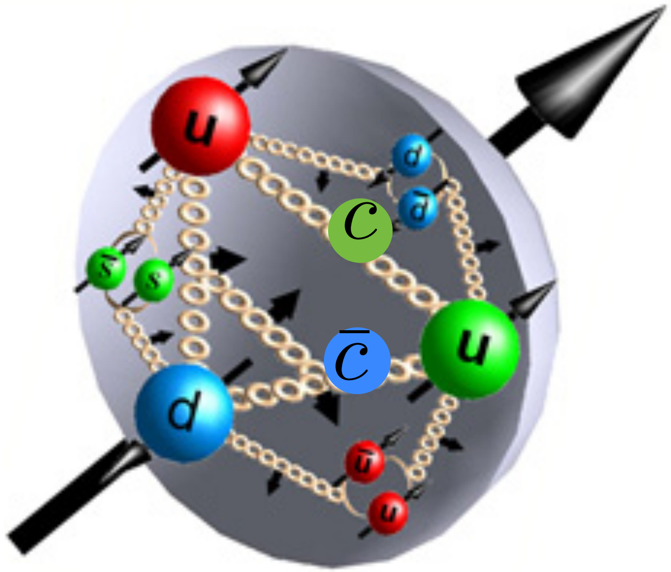
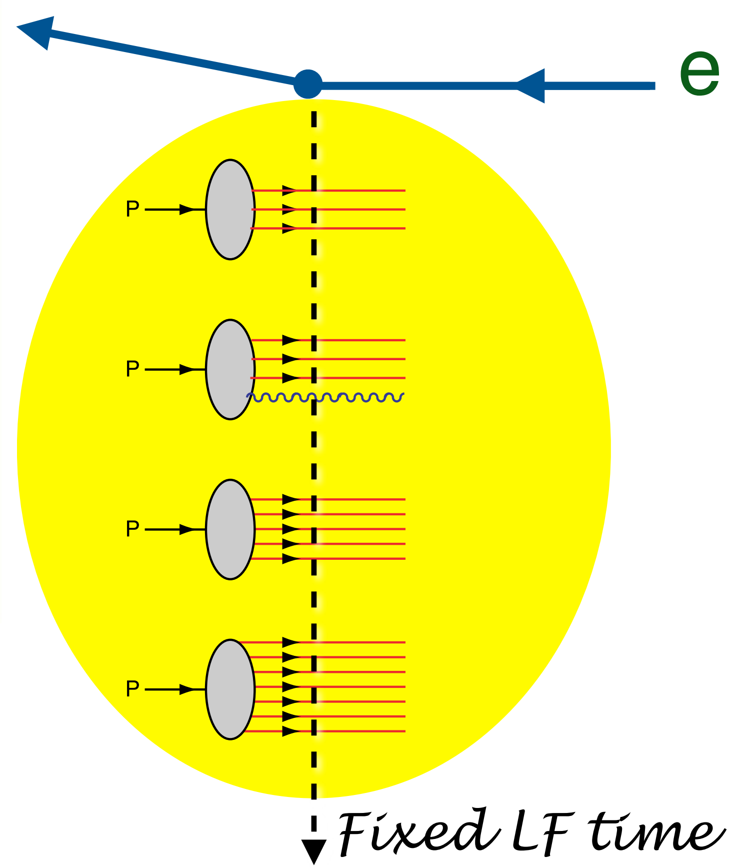
Novel QCD Phenomena in Nuclear Photo - and Electroproduction

Exotic Hadrons

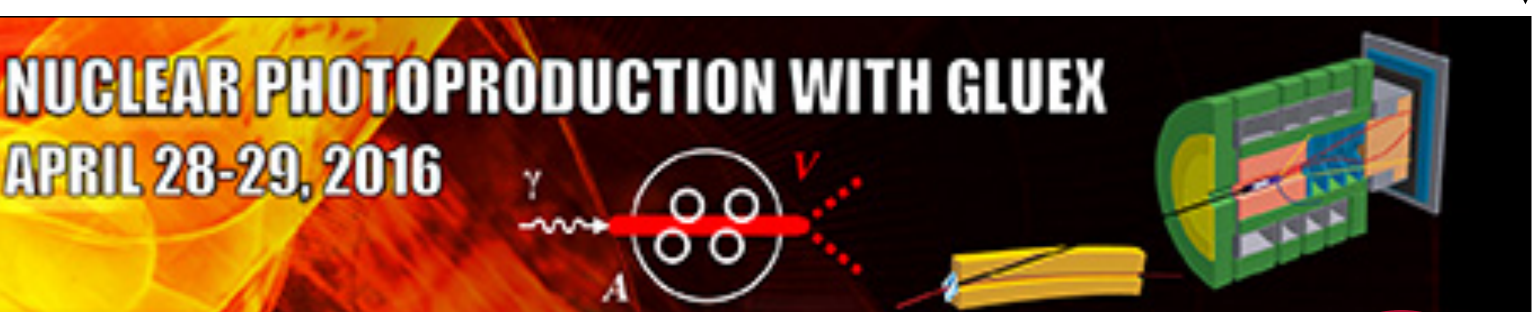






Fixed LF time

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



Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

LELAND STANFORD JUNIOR UNIVERSITY

Jefferson Lab

April 29, 2016

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

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

The Light Front Fock State Wavefunctions

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

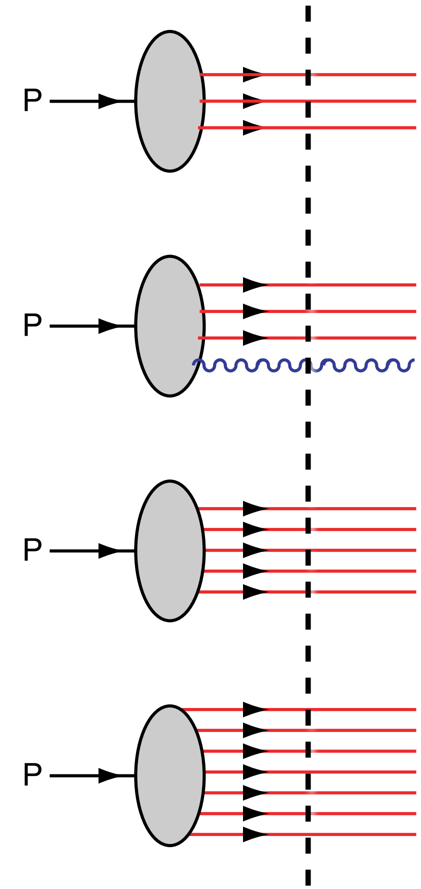
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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

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

Intrinsic heavy quarks

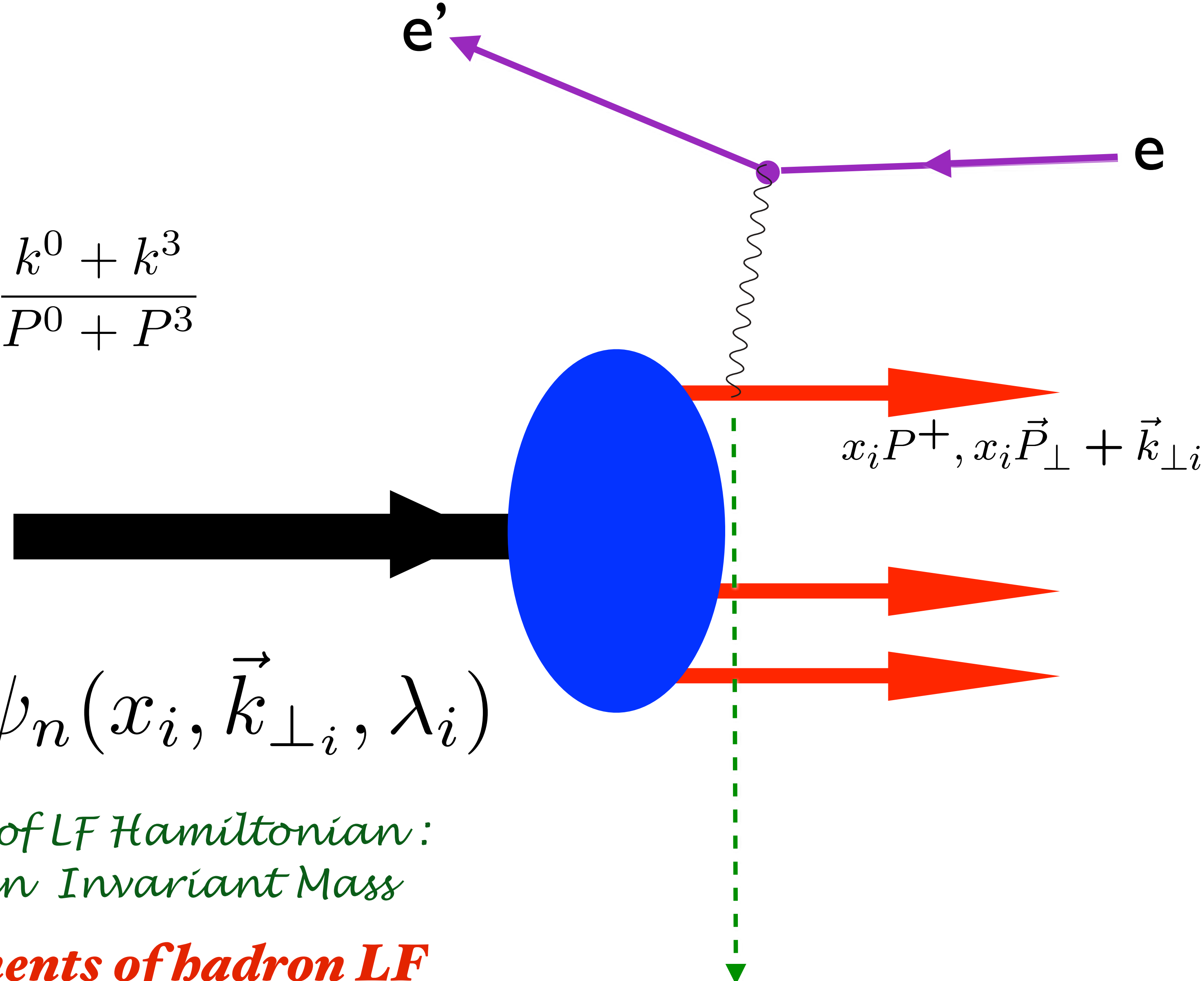
s(x), c(x), b(x) at high x !

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

Deuteron: Hidden Color

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

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



$$\psi_n(x_i, \vec{k}_{\perp_i}, \lambda_i)$$

Fixed $\tau = t + z/c$

Eigenstate of LF Hamiltonian :
Off-shell in Invariant Mass

Measurements of hadron LF wavefunction are at fixed LF time

Like a flash photograph

$$x_{bj} = x = \frac{k^+}{P^+}$$

Each element of flash photograph illuminated along the light front **at a fixed**

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

Evolve in LF time

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

Eigenvalue

$$P^- = \frac{\mathcal{M}^2 + \vec{P}_\perp^2}{P^+}$$

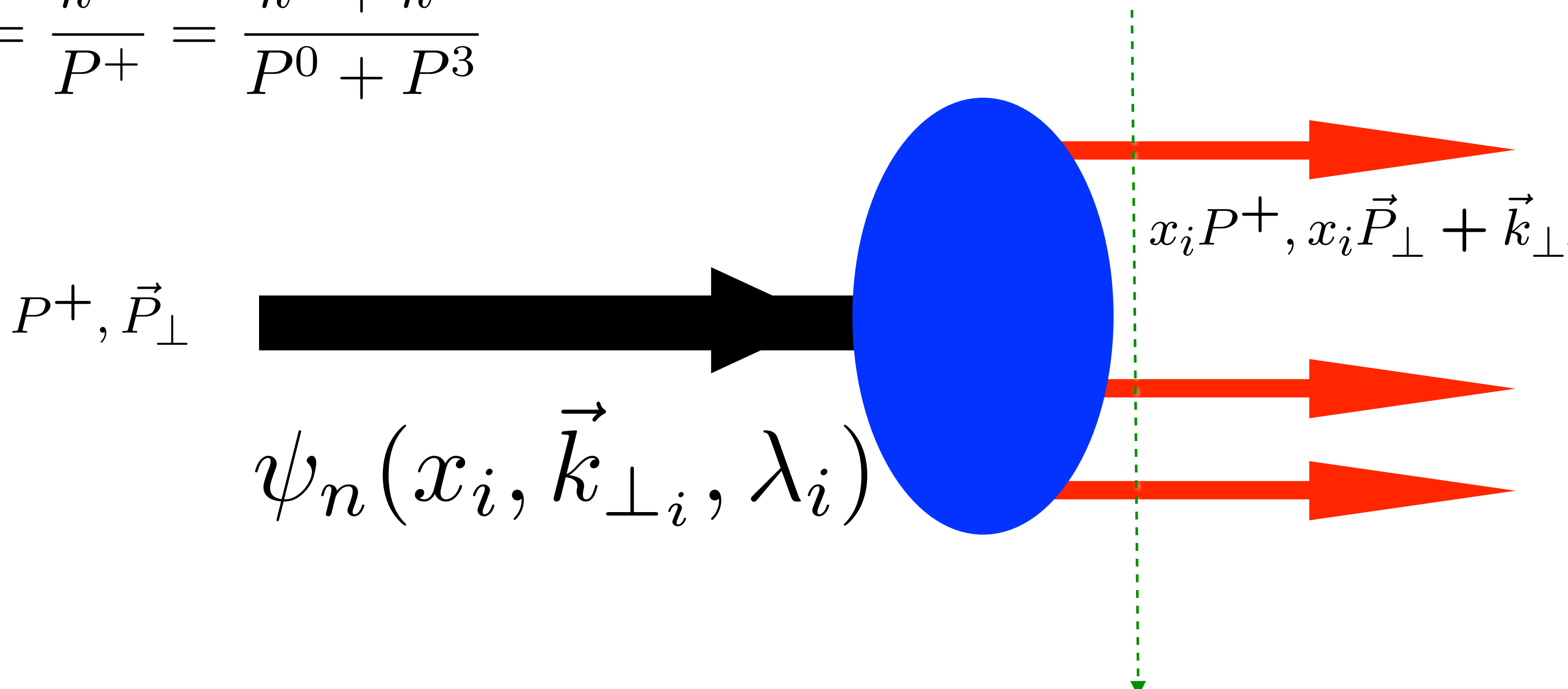
$$H^{QCD}_{LF}|\Psi_h> = \mathcal{M}^2_h|\Psi_h>$$

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

Eigenstate of LF Hamiltonian : Off-shell in Invariant Mass

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

Fixed $\tau = t + z/c$ *Fixed LF time*



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

$\sum_i^n x_i = 1$

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

Sum Rules

Invariant under boosts! Independent of P^μ

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

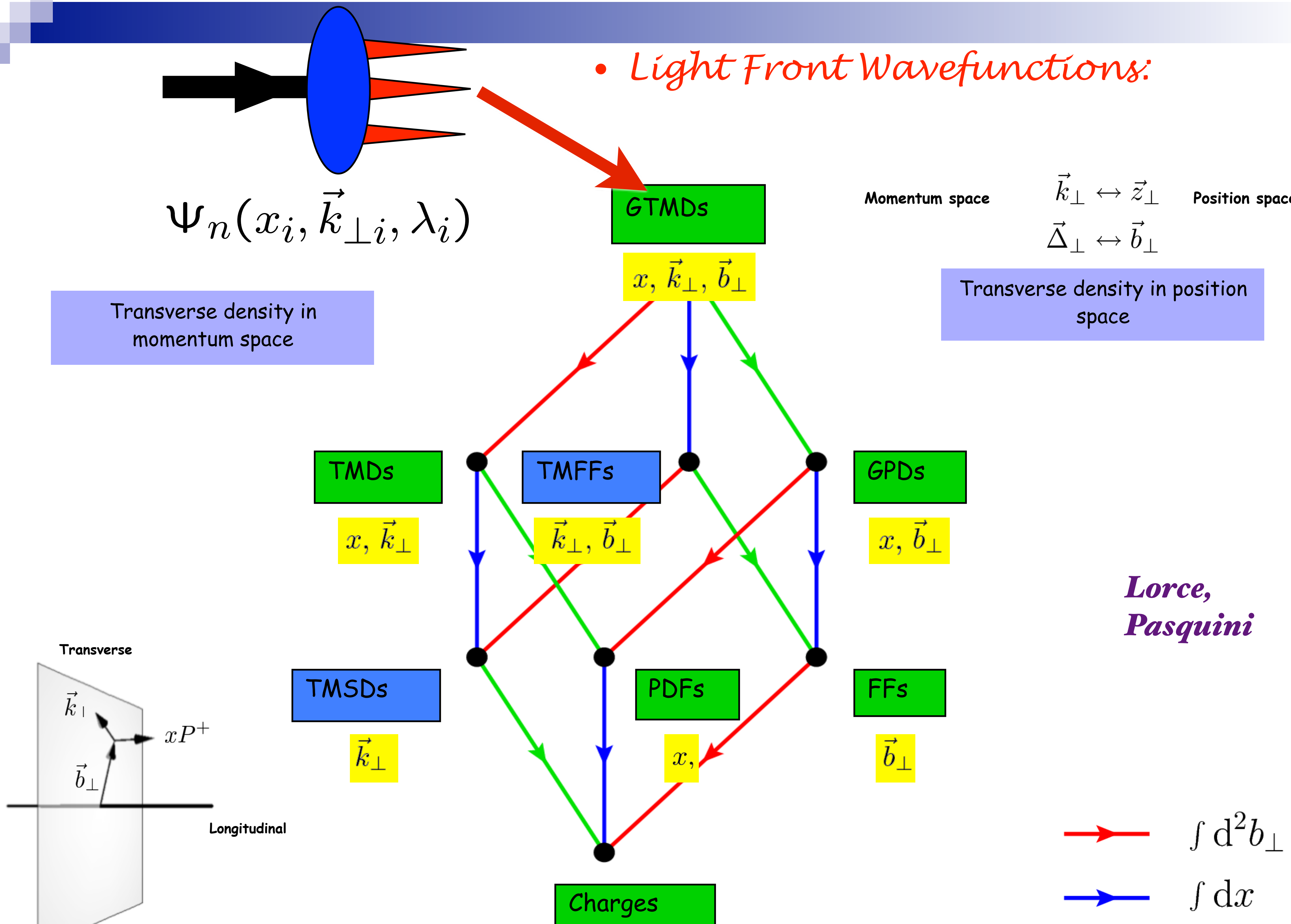
Advantages of the Dirac's Front Form for Hadron Physics

Independent of Observer's Motion

- Measurements are made at fixed τ
- Causality is automatic
- Structure Functions are squares of LFWFs
- Form Factors are overlap of LFWFs
- LFWFs are frame-independent: no boosts, no pancakes!
- Same structure function measured at an e p collider and the proton rest frame
- No dependence on observer's frame
- LF Holography: Dual to AdS space
- LF Vacuum trivial -- no vacuum condensates!
- Profound implications for Cosmological Constant

Roberts, Shrock, Tandy, sjb

- *Light Front Wavefunctions:*



+ Factorization-Breaking Lensing Corrections: Sivers, T-odd

Some Key QCD Issues in Electroproduction

- **Intrinsic Heavy Quarks at high x;** $s(x) \neq \bar{s}(x)$
- **Role of Color Confinement in DIS**
- **Hadronization at the Amplitude Level**
- **Leading-Twist Lensing: Sivers Effect**
- **Diffractive DIS**
- **Static versus Dynamic Structure Functions**
- **Origin of Shadowing and Anti-Shadowing**
- **Is Anti-Shadowing Non-Universal: Flavor Specific?**
- **Nuclear Correlations and Effects**

Color Transparency

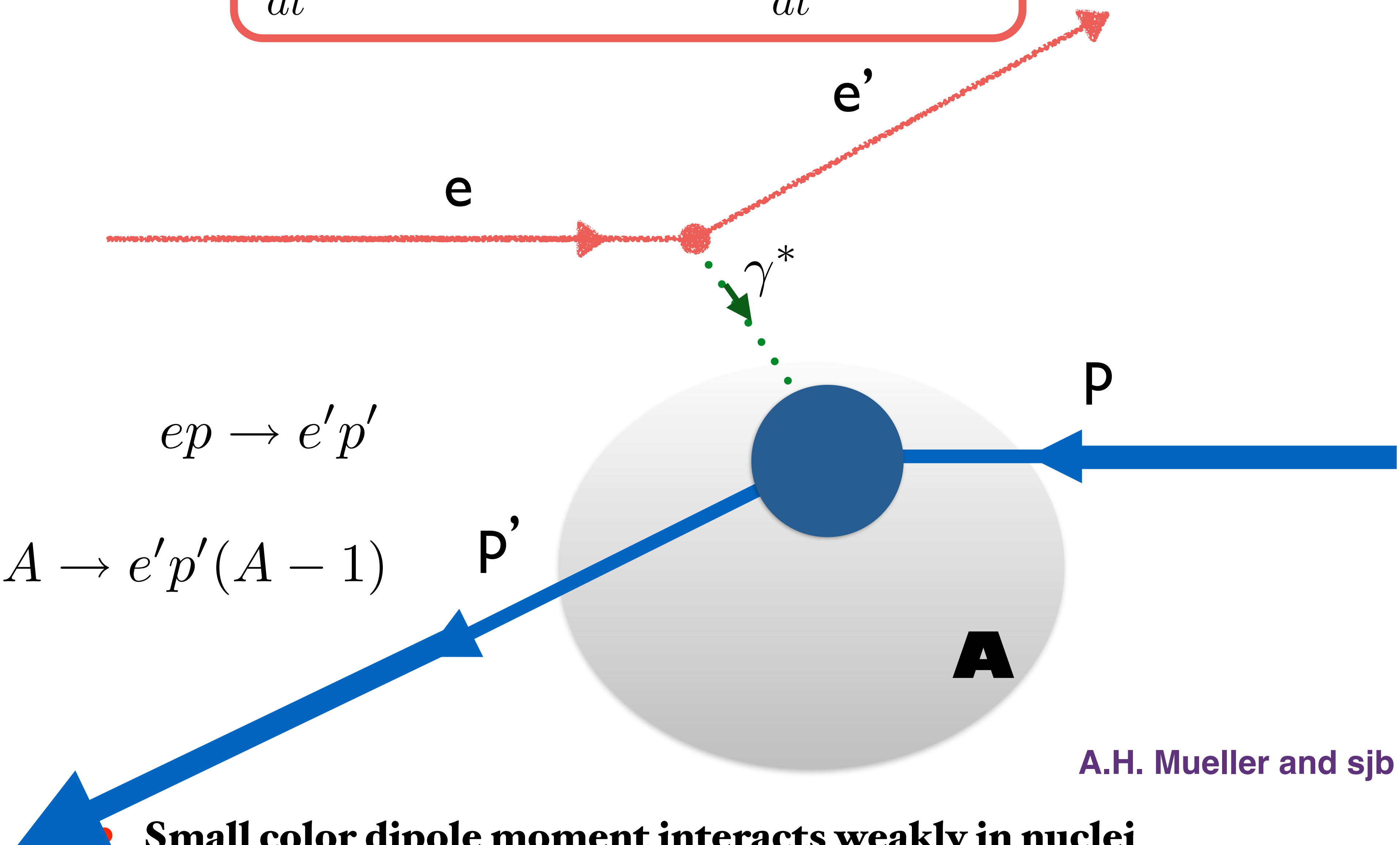
Bertsch, Gunion, Goldhaber, sjb
Mueller, sjb
Frankfurt, Strikman, Miller

$$\frac{d\sigma}{dt}(eA \to ep(A-1)) = Z\frac{d\sigma}{dt}(ep \to ep)$$ at high momentum transfer

- **Fundamental test of gauge theory in hadron physics**
- **Small color dipole moment interacts weakly in nuclei**
- **Complete coherence at high energies** *See Strikman Talk*
- **Many tests in hard exclusive processes**
- **Clear Demonstration of CT from Diffractive Di-Jets**
- **Explains Baryon Anomaly at RHIC**

Color Transparency

$$\frac{d\sigma}{dt}(eA \to ep(A-1)) = Z\frac{d\sigma}{dt}(ep \to ep)$$



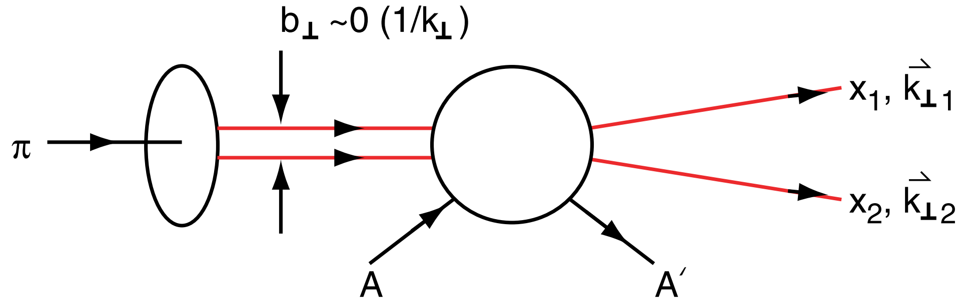
$$ep \to e'p'$$

$$eA \to e'p'(A-1)$$

A.H. Mueller and sjb

- **Small color dipole moment interacts weakly in nuclei**

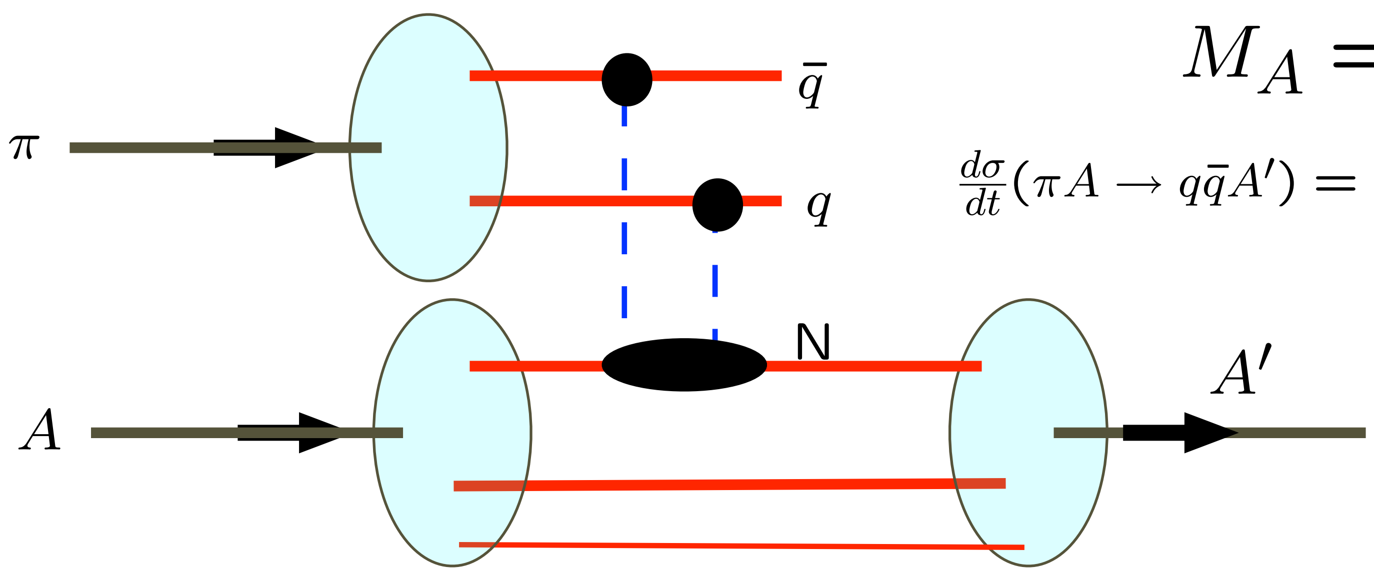
Fermilab E791 Experiment, Ashery et al.



large $k_\perp$, small $b_\perp$

Small color-dipole moment pion not absorbed; interacts with each nucleon coherently

QCD COLOR Transparency



$$M_A = A\ M_N$$

$$\frac{d\sigma}{dt}(\pi A \to q\bar{q}A') = A^2\ \frac{d\sigma}{dt}(\pi N \to q\bar{q}N')\ F^2_A(t)$$

Target left intact

Diffraction, Rapidity gap

Frankfurt Miller Strikman

Mueller, sjb; Bertsch et al;
Frankfurt, Miller, Strikman

Measure pion LFWF in diffractive dijet production
Confirmation of color transparency

A-Dependence results: $\sigma \propto A^{\alpha}$

k_t range (GeV/c)	α	α (CT)
$1.25 < k_t < 1.5$	$1.64\ +0.06\ -0.12$	1.25
$1.5 < k_t < 2.0$	1.52 ± 0.12	1.45
$2.0 < k_t < 2.5$	1.55 ± 0.16	1.60

Ashery E791

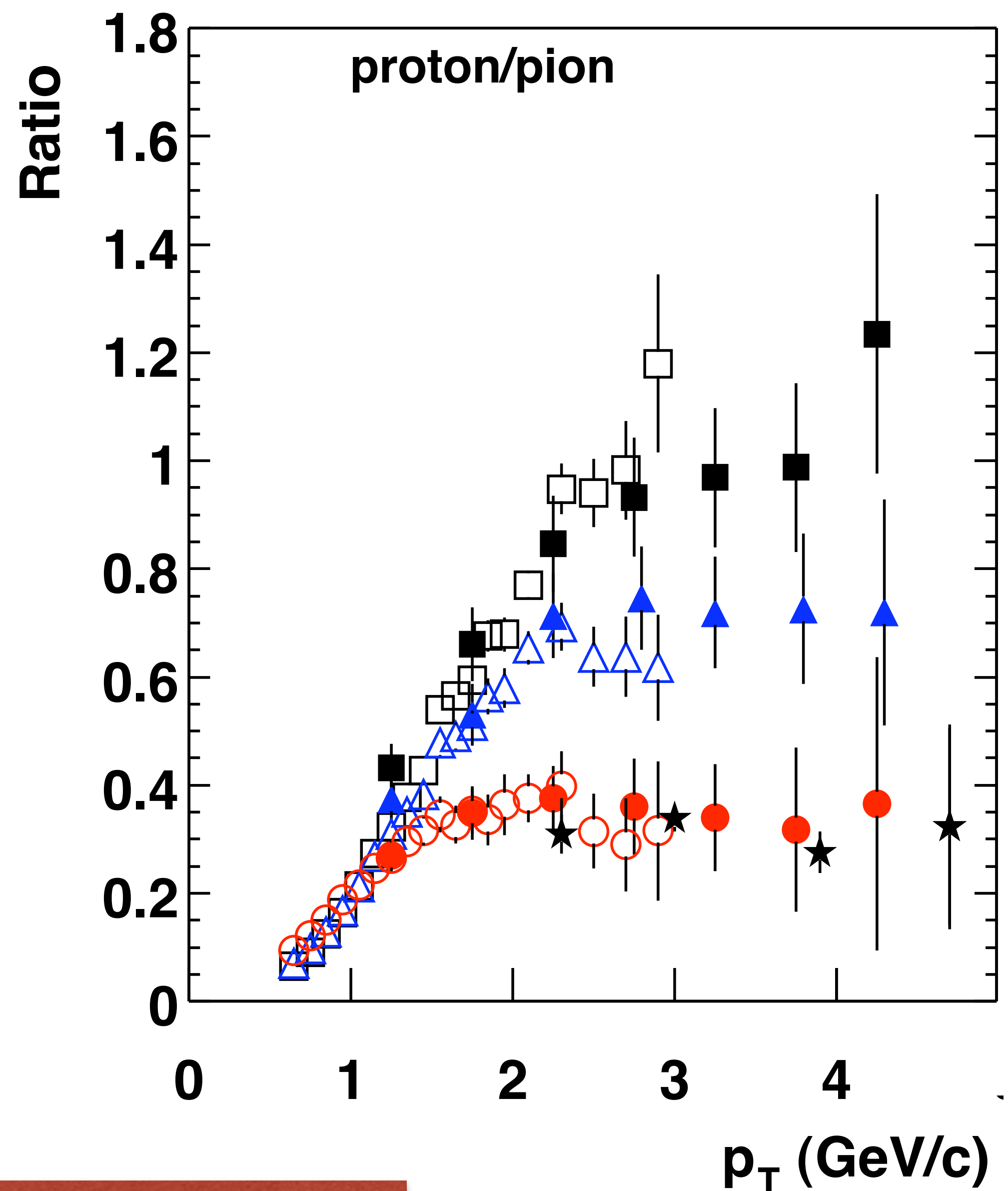
α (Incoh.) $= 0.70 \pm 0.1$

Conventional Glauber Theory Ruled Out !

Factor of 7

S. S. Adler *et al*. PHENIX Collaboration *Phys. Rev. Lett*. **91**, 172301 (2003).

Particle ratio changes with centrality!



← **Central**

← **Peripheral**

Protons less absorbed in nuclear collisions than pions because of dominant color-transparent higher twist process

Arleo, Hwang, Sickles, sjb

Tannenbaum: Baryon Anomaly

Evidence for Direct, Higher-Twist, Color Transparent Subprocesses at RHIC

- *Anomalous power behavior at fixed x_T*
- *Protons more likely to come from direct subprocess than pions*
- *Protons less absorbed than pions in "central" nuclear collisions because of color transparency*
- *Predicts increasing proton to pion ratio in "central" collisions*
- *Exclusive-inclusive connection at $x_T = 1$*

EIC: Resolves complex physics signals at hadron and ion colliders

Hidden Color in QCD

Gluon or Quark Exchange within nucleus

Lepage, Ji, sjb

- Deuteron six-quark wavefunction:

- 5 color-singlet combinations of six color-triplets --

- Only one of the five states is |n p>

- Components evolve towards equality at short distances

- Hidden color states dominate deuteron form factor and photodisintegration at high momentum transfer

- Dominates x > 1 domain of deep inelastic scattering on nuclei: quark carries momentum of more than one nucleus!

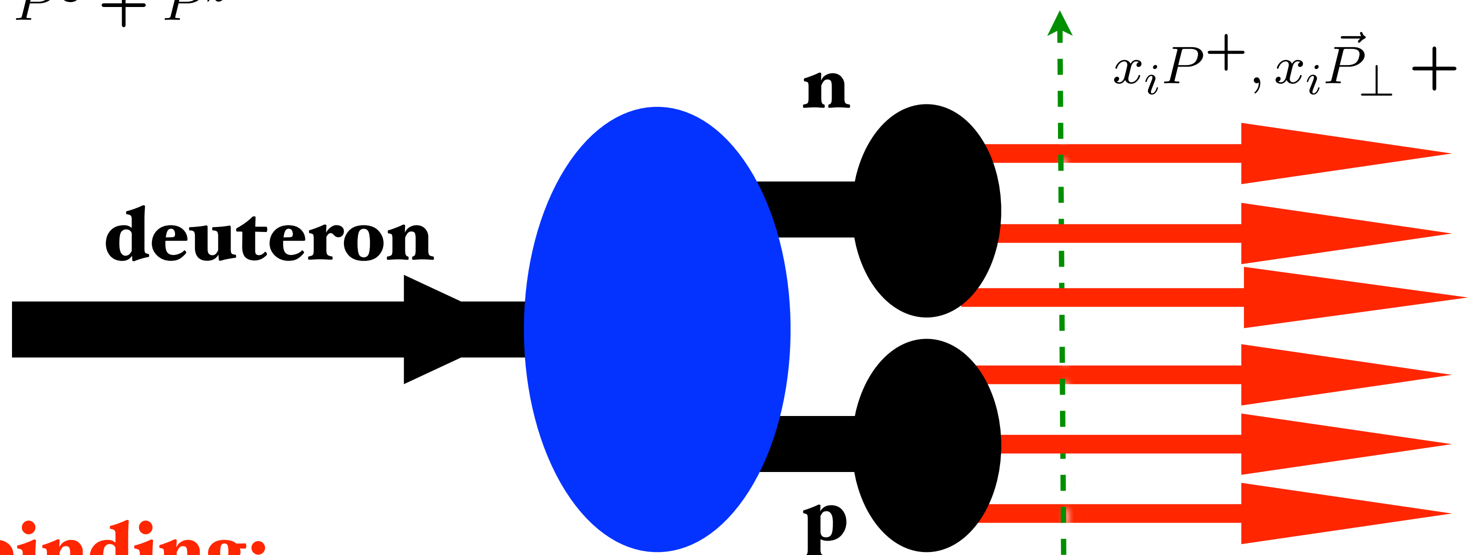
$$\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-}) \simeq \frac{d\sigma}{dt}(\gamma d \to pn) \text{ at high } Q^2$$

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

Fixed $\tau = t + z/c$

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

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



Weak binding:

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

$\Sigma_i^n x_i = 1$

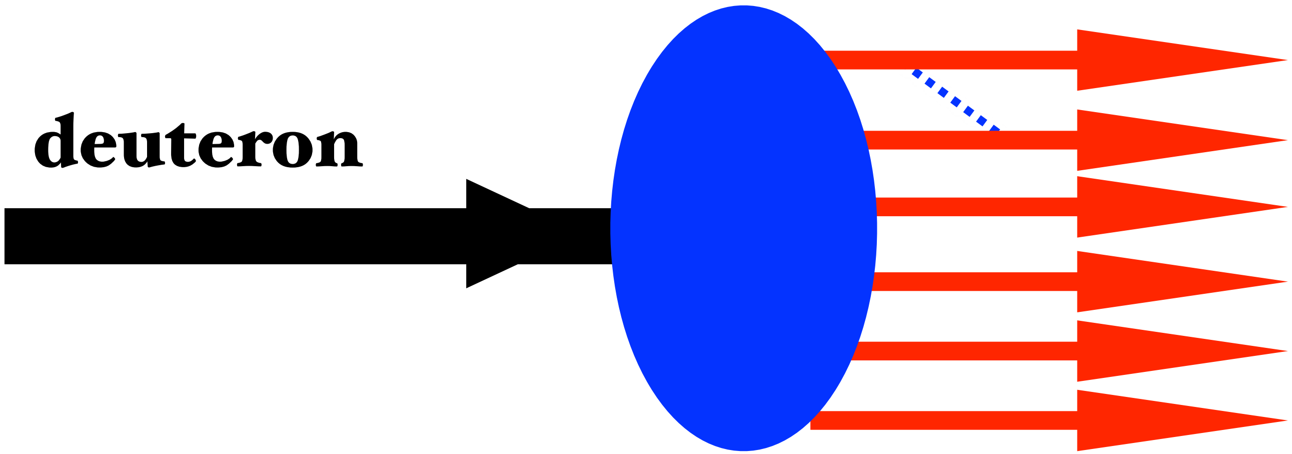
$\Sigma_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

Nuclear Physics:
Two color-singlet combinations of three 3_C

pQCD Evolution of 5 color-singlet Fock states

Lepage, Ji, sjb

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



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

$\sum_i^n x_i = 1$

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

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

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

ERBL Evolution: Transition to Delta-Delta

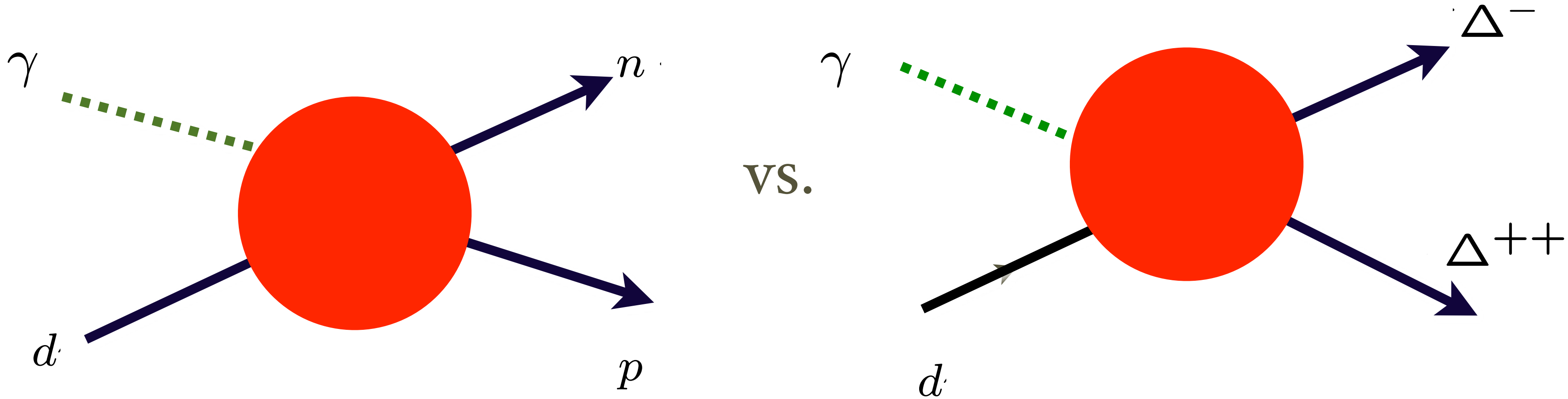
Lepage, Ji, sjb

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.

Lepage, Ji, sjb

Hidden Color in QCD

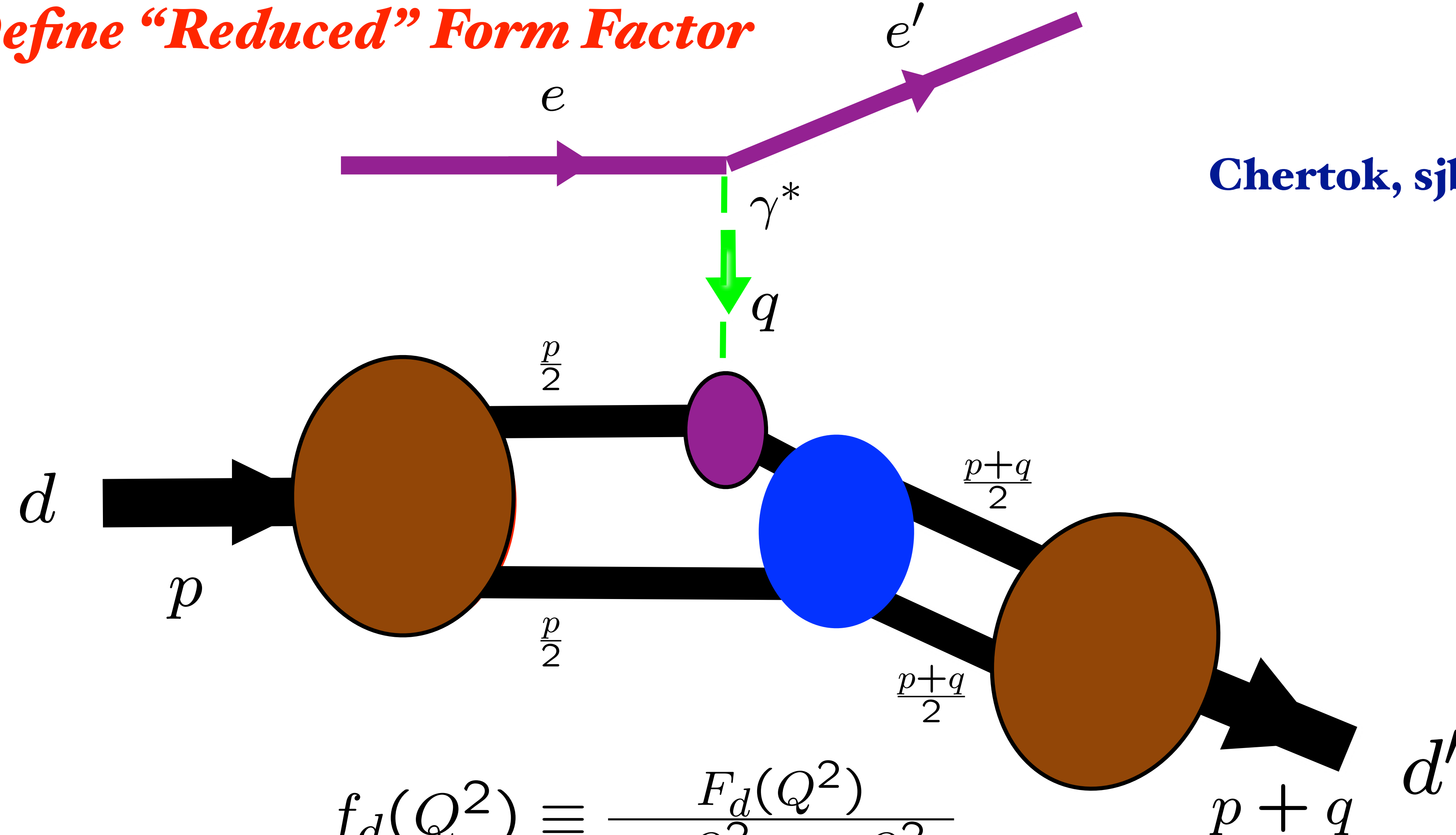
Study the Deuteron as a QCD Object

- **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**

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

Define "Reduced" Form Factor

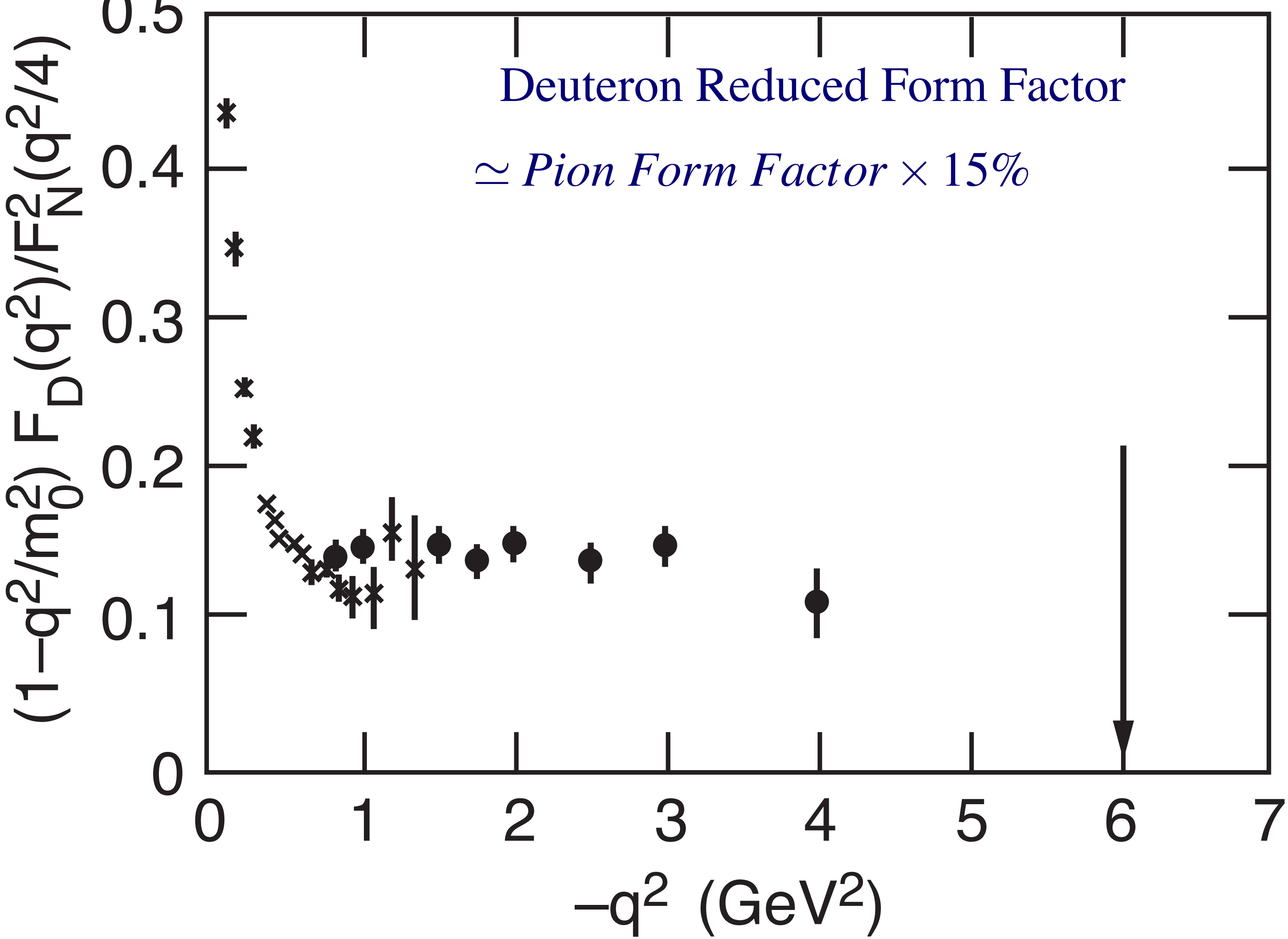
Chertok, sjb



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

Elastic electron-deuteron scattering

Chertok, sjb



Deuteron Reduced Form Factor
≃ Pion Form Factor × 15%
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
6
7
(1−q²/m₀²) F_D(q²)/F_N²(q²/4)
−q² (GeV²)

QCD Prediction for Deuteron Form Factor

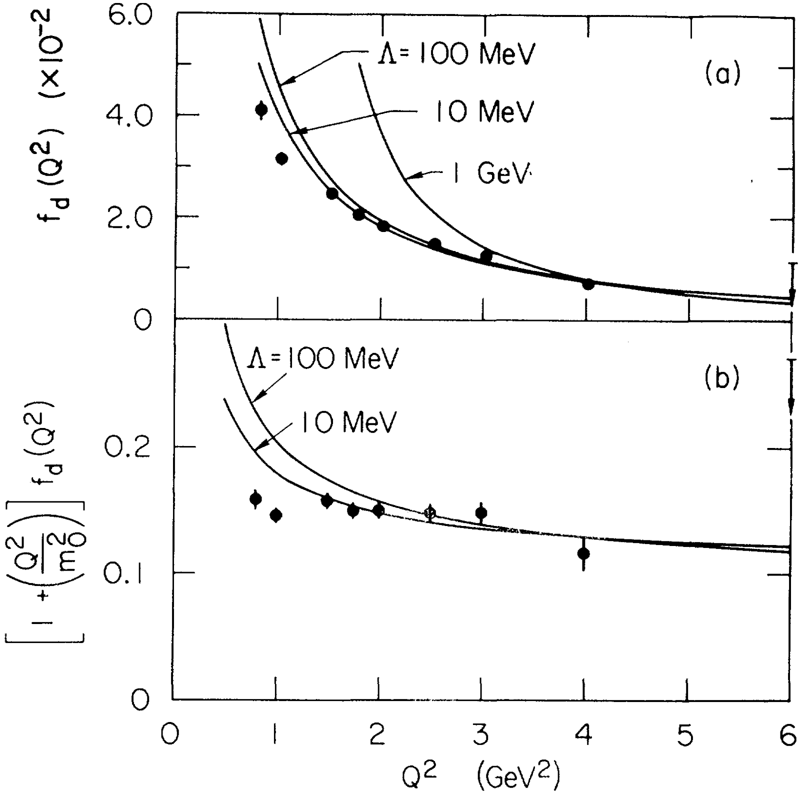
Lepage, Ji, sjb

$$F_d(Q^2) = \left[\frac{\alpha_s(Q^2)}{Q^2}\right]^5 \sum_{m,n} d_{mn} \left(\ln \frac{Q^2}{\Lambda^2}\right)^{-\gamma_n^d - \gamma_m^d} \left[1 + O\left(\alpha_s(Q^2), \frac{m}{Q}\right)\right]$$

Define "Reduced" Form Factor

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

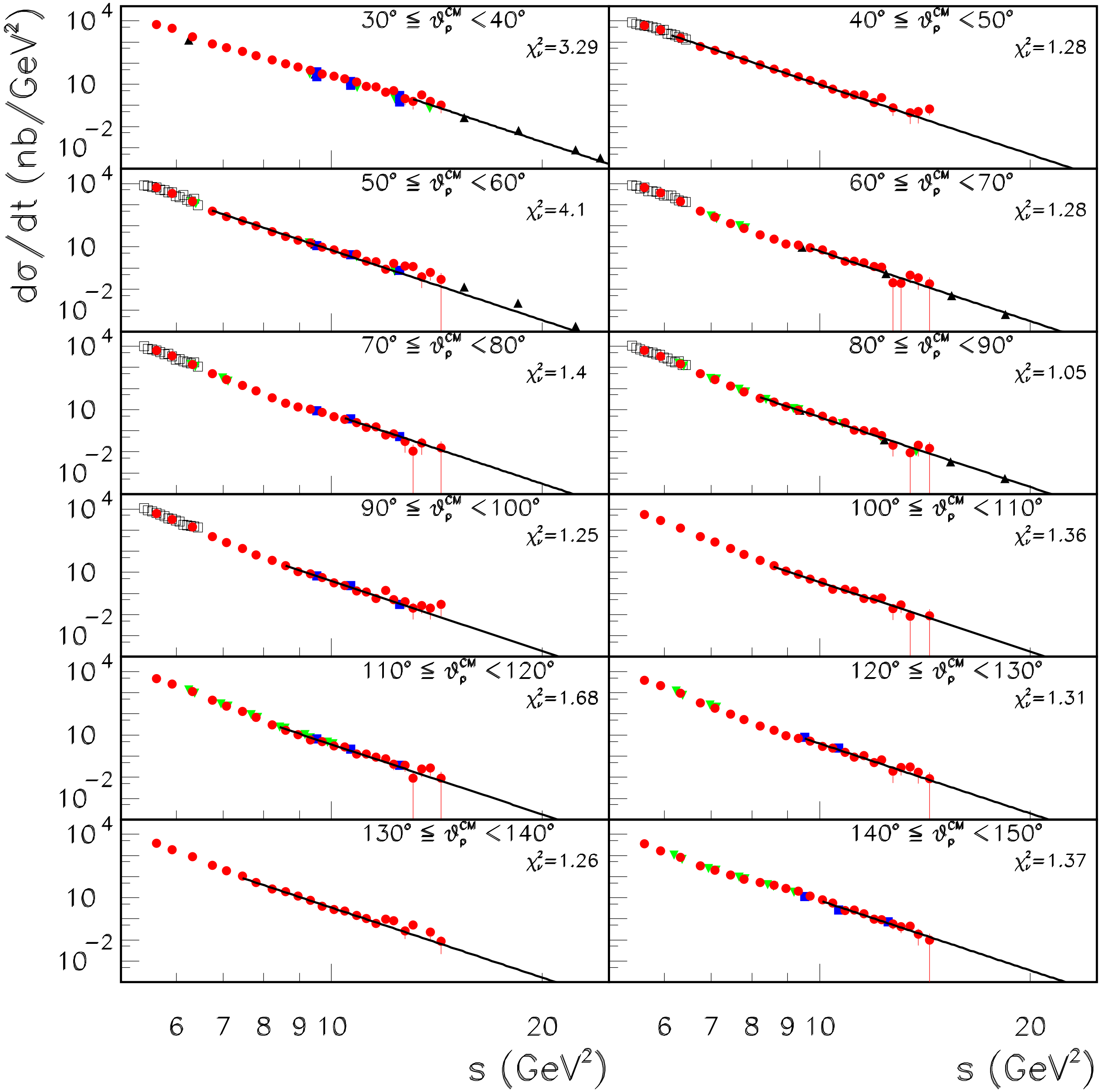
$$f_d(Q^2) \sim \frac{\alpha_s(Q^2)}{Q^2} \left(\ln \frac{Q^2}{\Lambda^2}\right)^{-(2/5)\,C_F/\beta}$$



(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

Same large momentum transfer behavior as pion form factor

Deuteron Photodisintegration



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

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 — no gluon exchange evident**
- **Renormalization group invariance**
- **No renormalization scale ambiguity**
- **Exclusive inclusive connection with spectator counting rules**
- **Diffractive reactions from pomeron, Reggeon, odderon**

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

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

The Light Front Fock State Wavefunctions

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

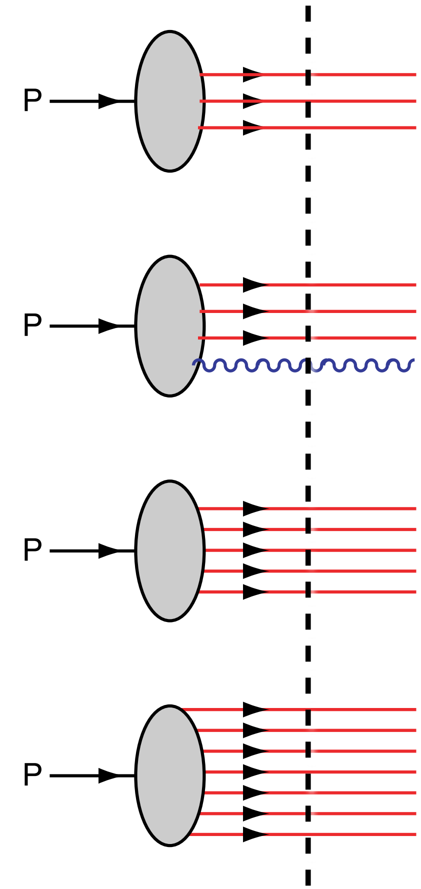
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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 !

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

Hidden Color

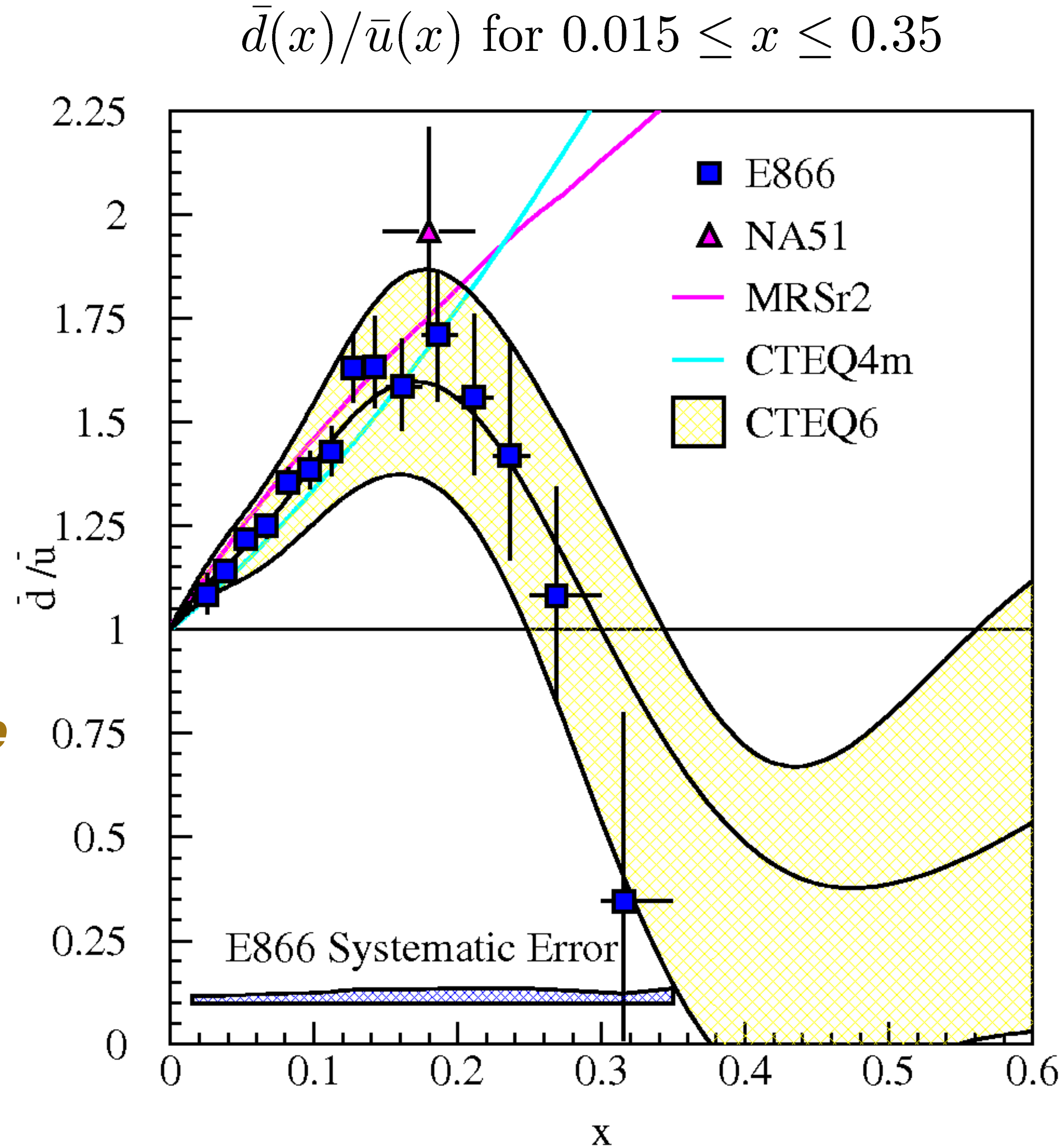
Mueller: gluon Fock states BFKL

■ E866/NuSea (Drell-Yan)

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

Interactions of quarks at same rapidity in 5-quark Fock state

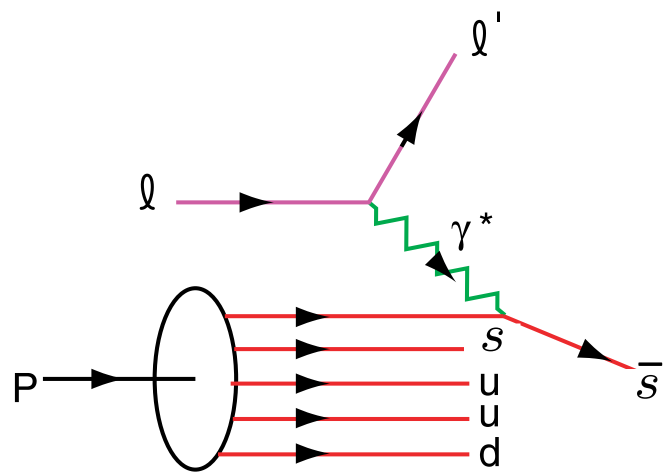
Intrinsic sea quarks



Measure strangeness distribution in Semi-Inclusive DIS at JLab

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

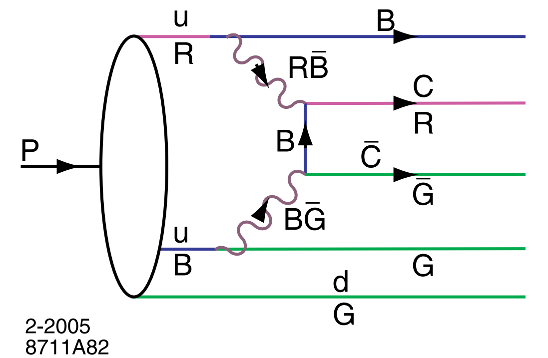
- **Non-symmetric strange and antistrange sea?**
- **Non-perturbative physics; e.g** $|uuds\bar{s}> \simeq |\Lambda(uds)K^+(\bar{s}u)>$
- **Important for interpreting NuTeV anomaly** **B. Q. Ma, sjb**



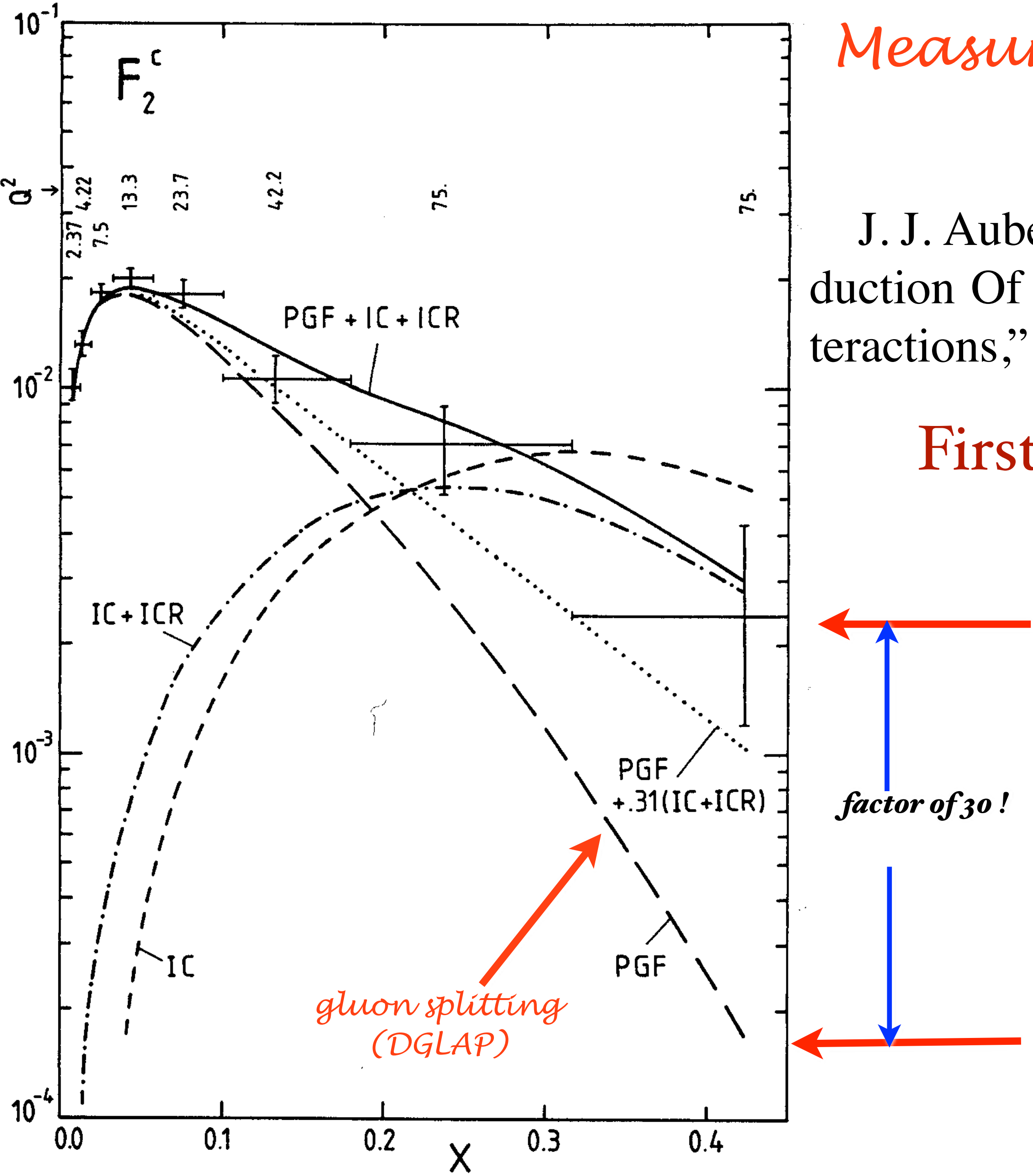
Tag struck quark flavor in semi-inclusive DIS $ep \to e' K^+ X$

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, ..)

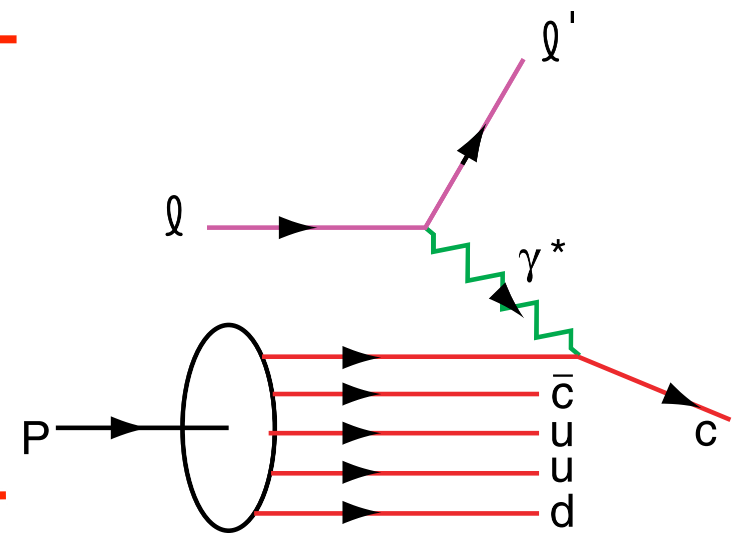


Measurement of Charm Structure Function!

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

Hoyer, Peterson, Sakai, sjb

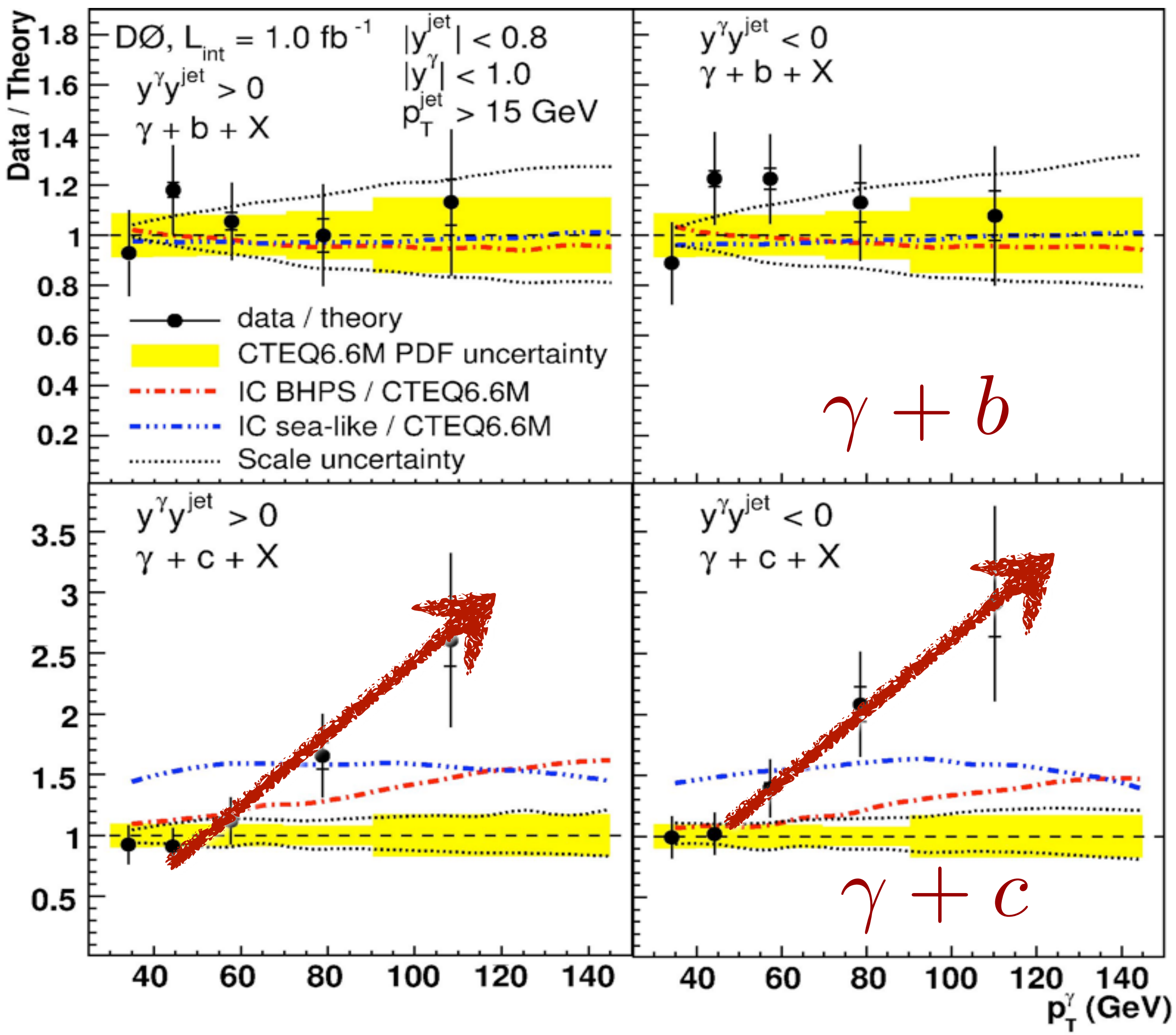


DGLAP / Photon-Gluon Fusion: factor of 30 too small

Two Components (separate evolution):

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

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



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

Ratio insensitive to gluon PDF, scales

Signal for significant IC at x > 0.1

Need COMPASS Measurement of $c(x,Q^2)$!

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

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

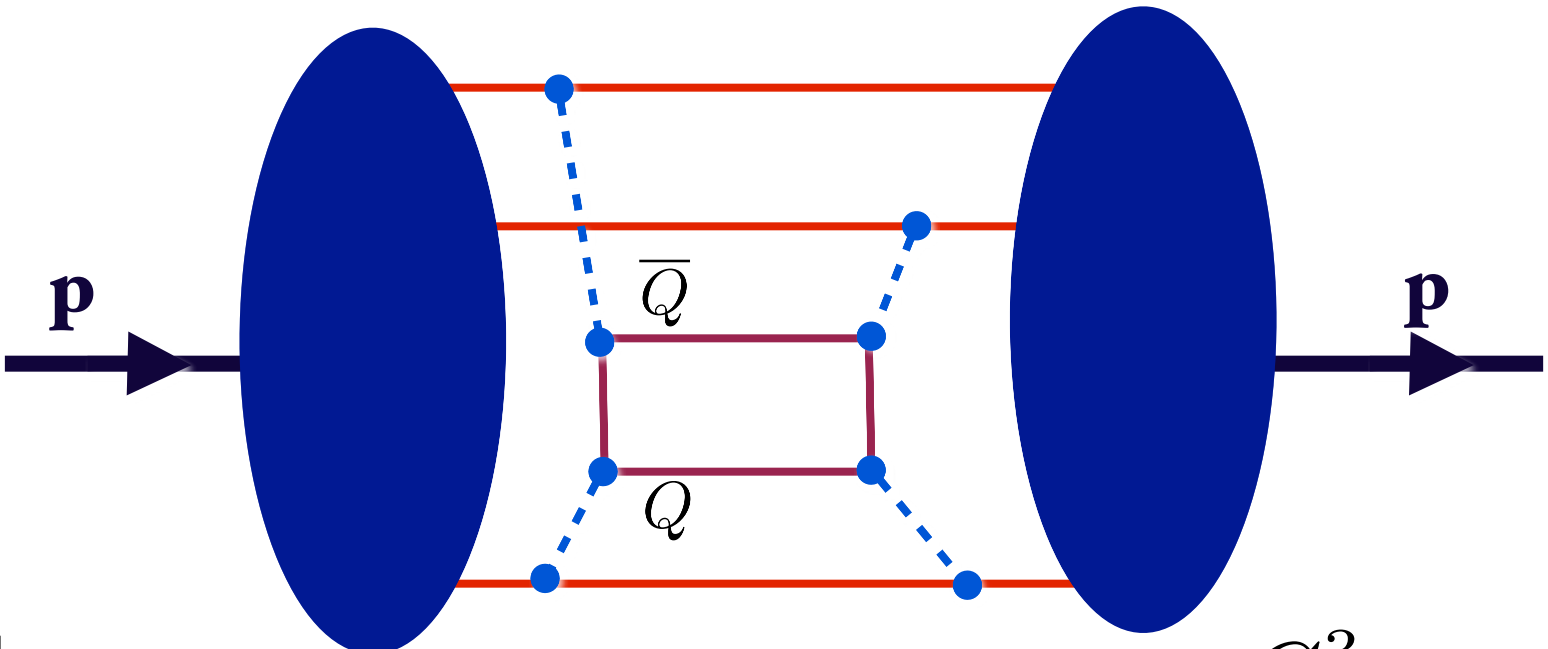
at starting scale μ_F^2

Conventional wisdom is wrong even in QED!

Proton Self Energy from g g to gg scattering

QCD predicts Intrinsic Heavy Quarks!

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



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

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

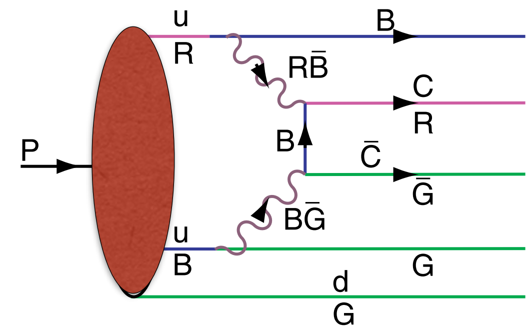
Probability (QED) $\propto \frac{1}{M_\ell^4}$

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

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

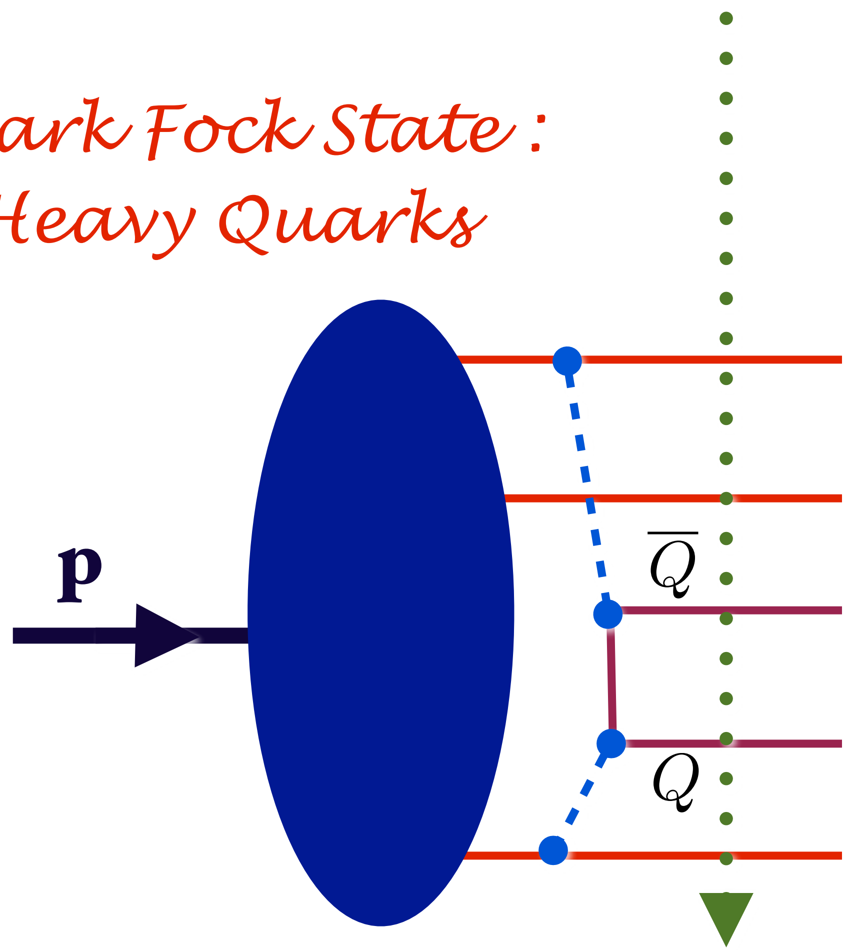
Hoyer, Peterson, Sakai, sjb

Intrinsic Heavy-Quark Fock



- **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)**
- **Underestimated in conventional parameterizations of heavy quark distributions (Pumplin, Tung)**

Proton 5-quark Fock State : Intrinsic Heavy Quarks



QCD predicts Intrinsic Heavy Quarks at high x

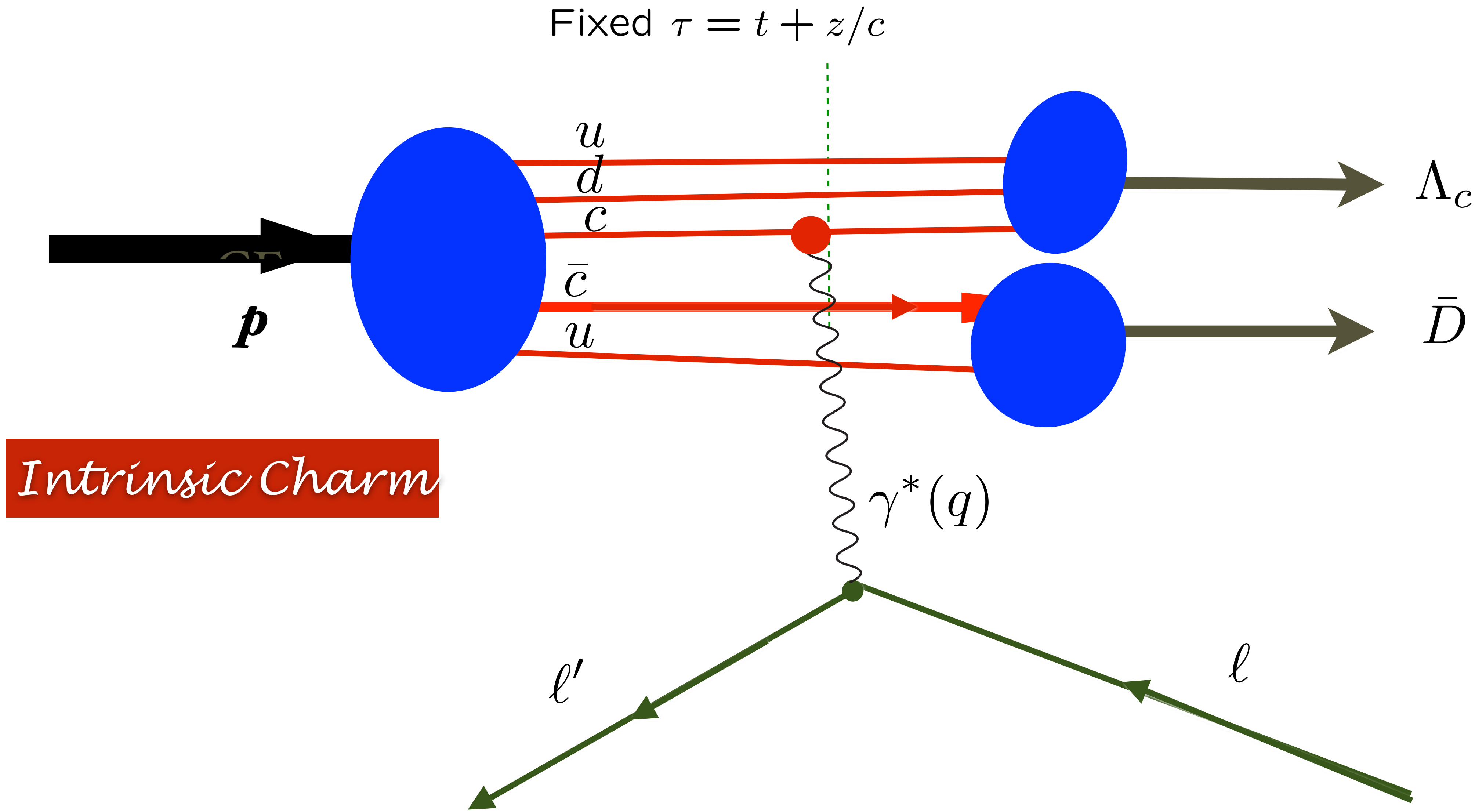
Minimal off-shellness

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

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

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

Light-Front Wavefunctions and Heavy-Quark Electroproduction



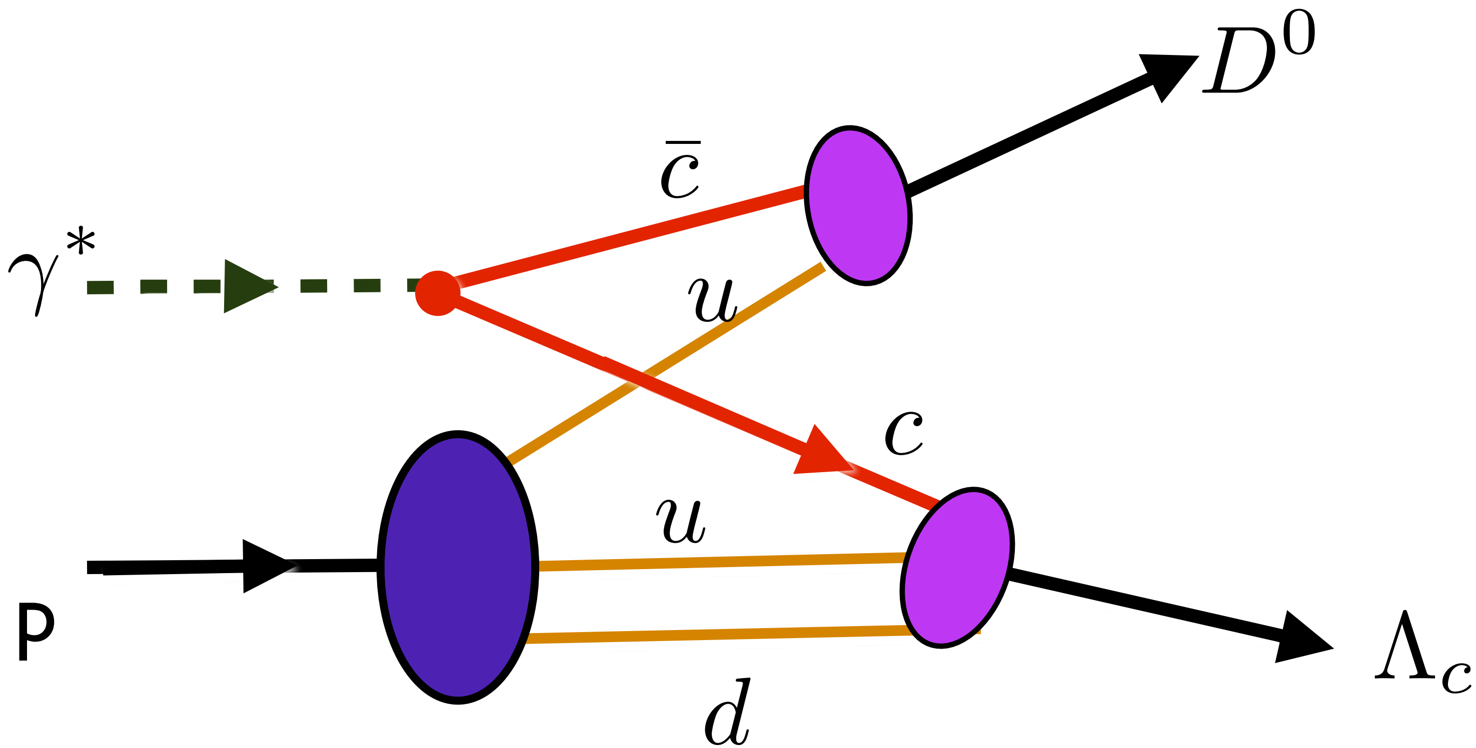
Threshold Production at JLab!

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

Charm Produced in Target-Rapidity Domain

Open Charm Production at Threshold!

JLab 12 GeV: A Charm Factory!

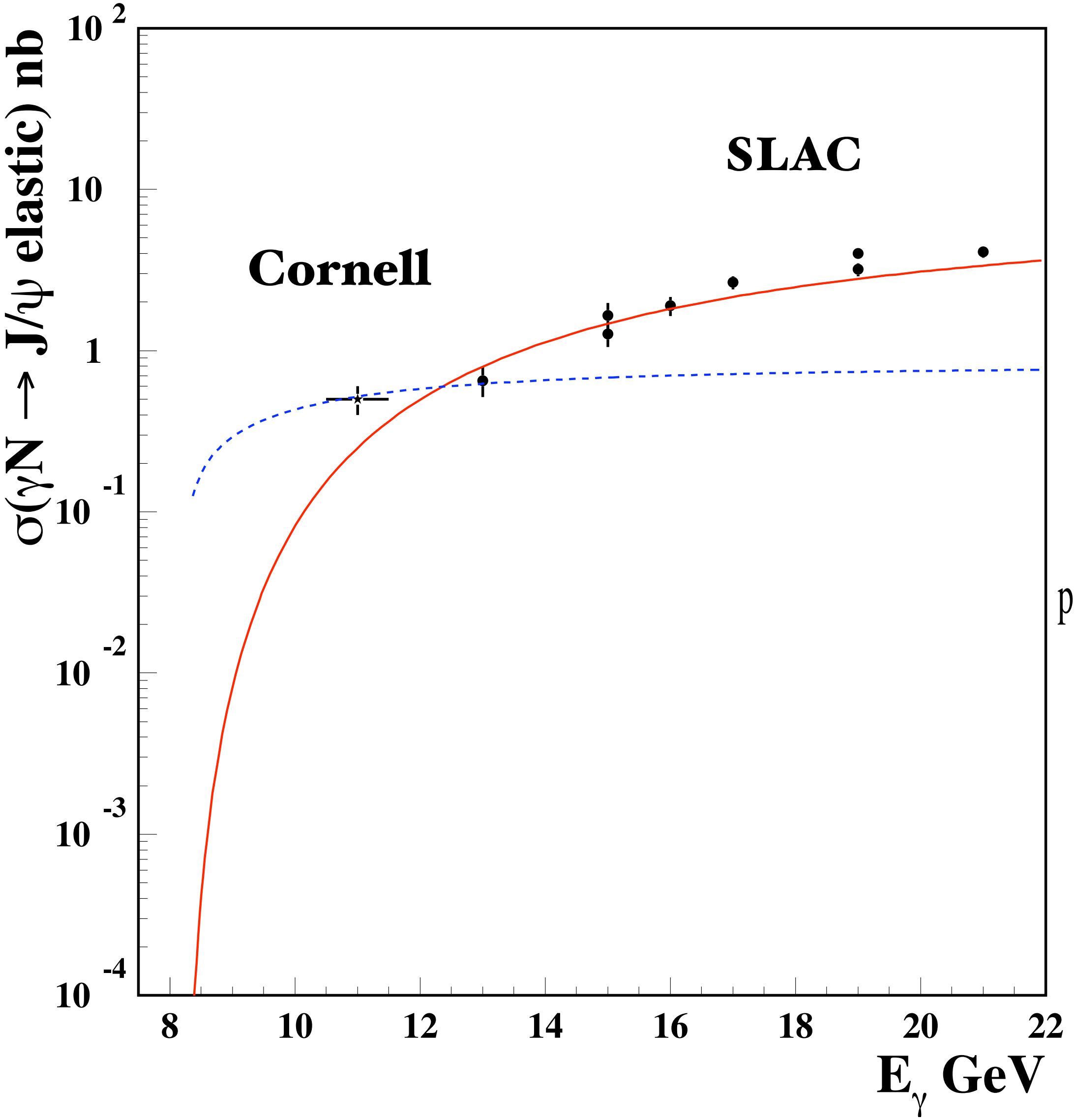


$$\gamma^* p \to \overline{D}^0(\bar{c}u)\Lambda_c(cud)$$

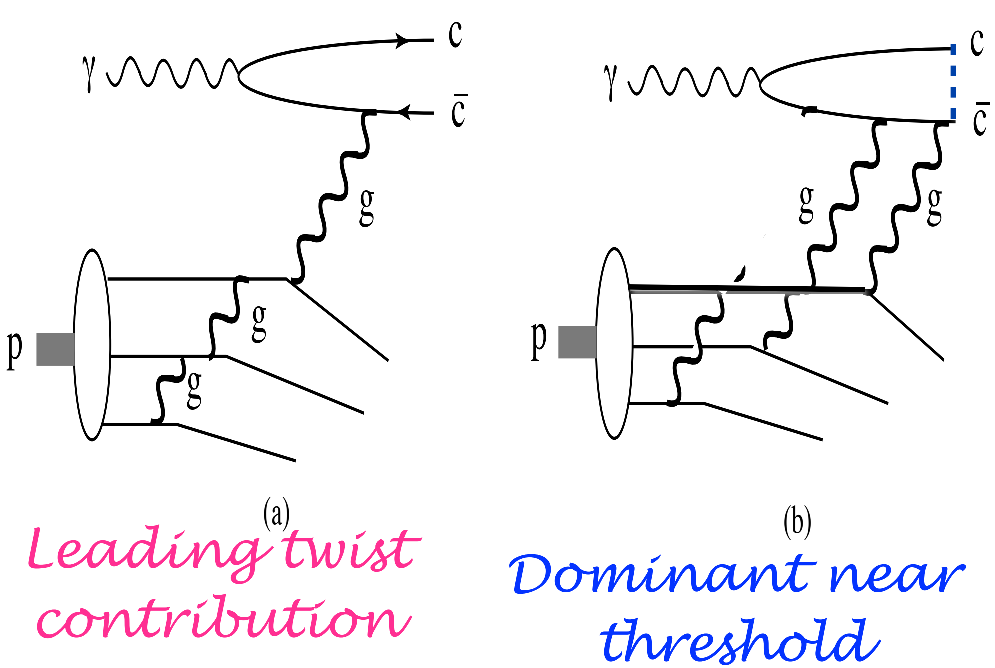
c and u quark interchange

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

Chudakov, Hoyer, Laget, sjb



cross section: 1 nb

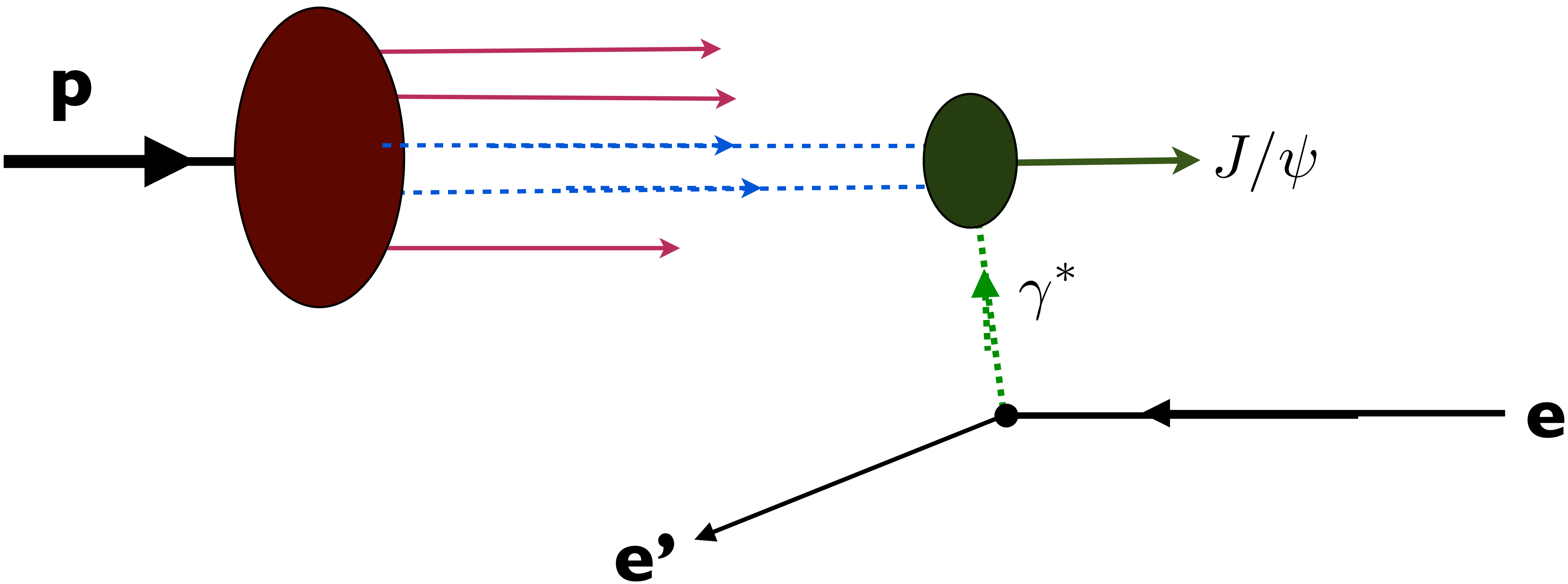


Phase space factor β cancelled by gluonic final-state interactions

Sommerfeld-Schwinger-Sakharov Effect

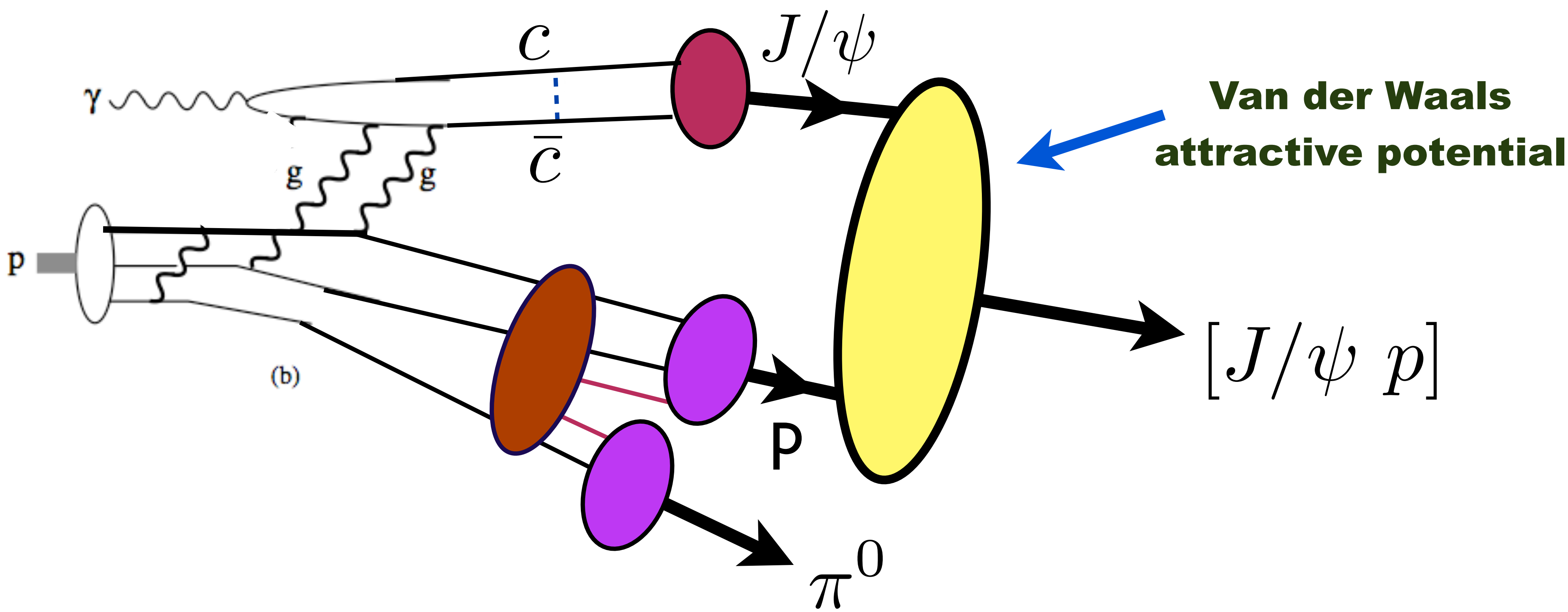
$$\gamma^* p \to J/\psi X$$

$$(gg)_{1C} + \gamma^* \to J/\psi$$



Digluon-initiated subprocess in ep and γp collisions

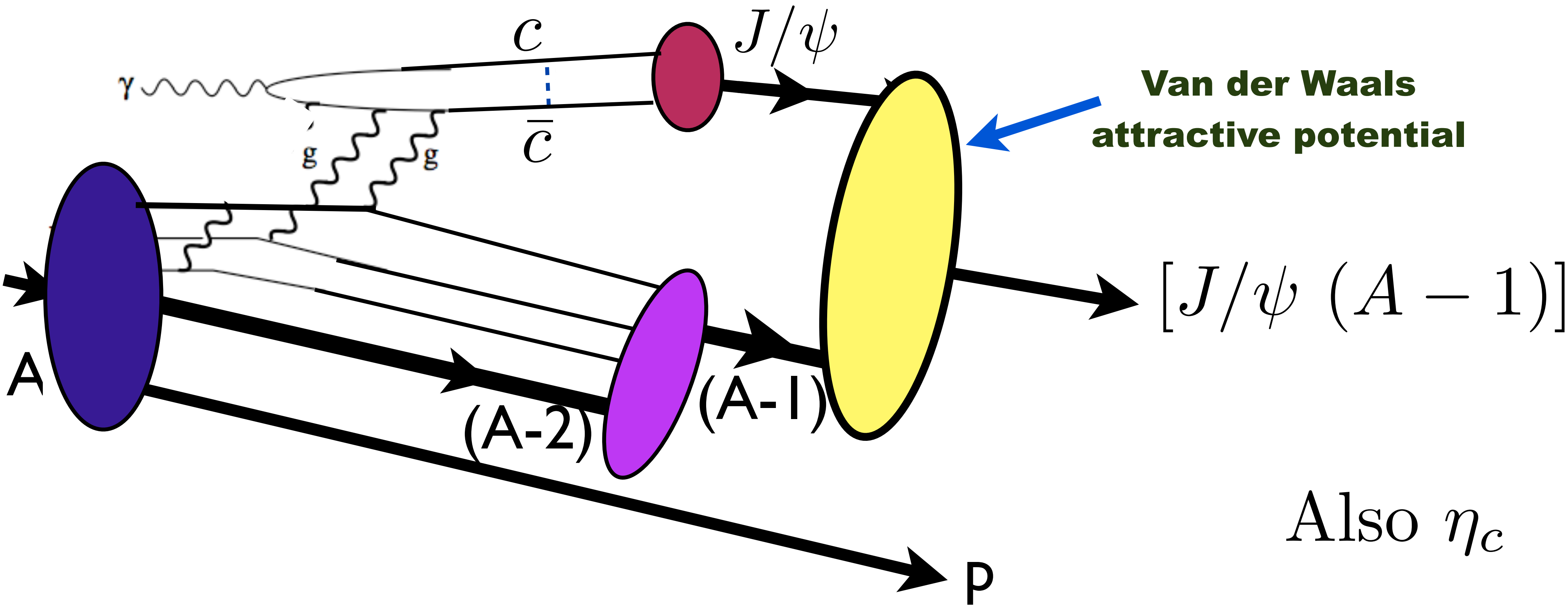
Charmonium Production at Threshold



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

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

Charmonium Production on Nuclei at Threshold



Also η_c

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

Form "nuclear-bound" charmonium bound-states!

JLab 12 GeV: An Exotic Charm Factory!

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

$$\gamma^* p \to X(3872) + p'$$
$$|c\bar{c}q\bar{q}>$$ *tetraquark*

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

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

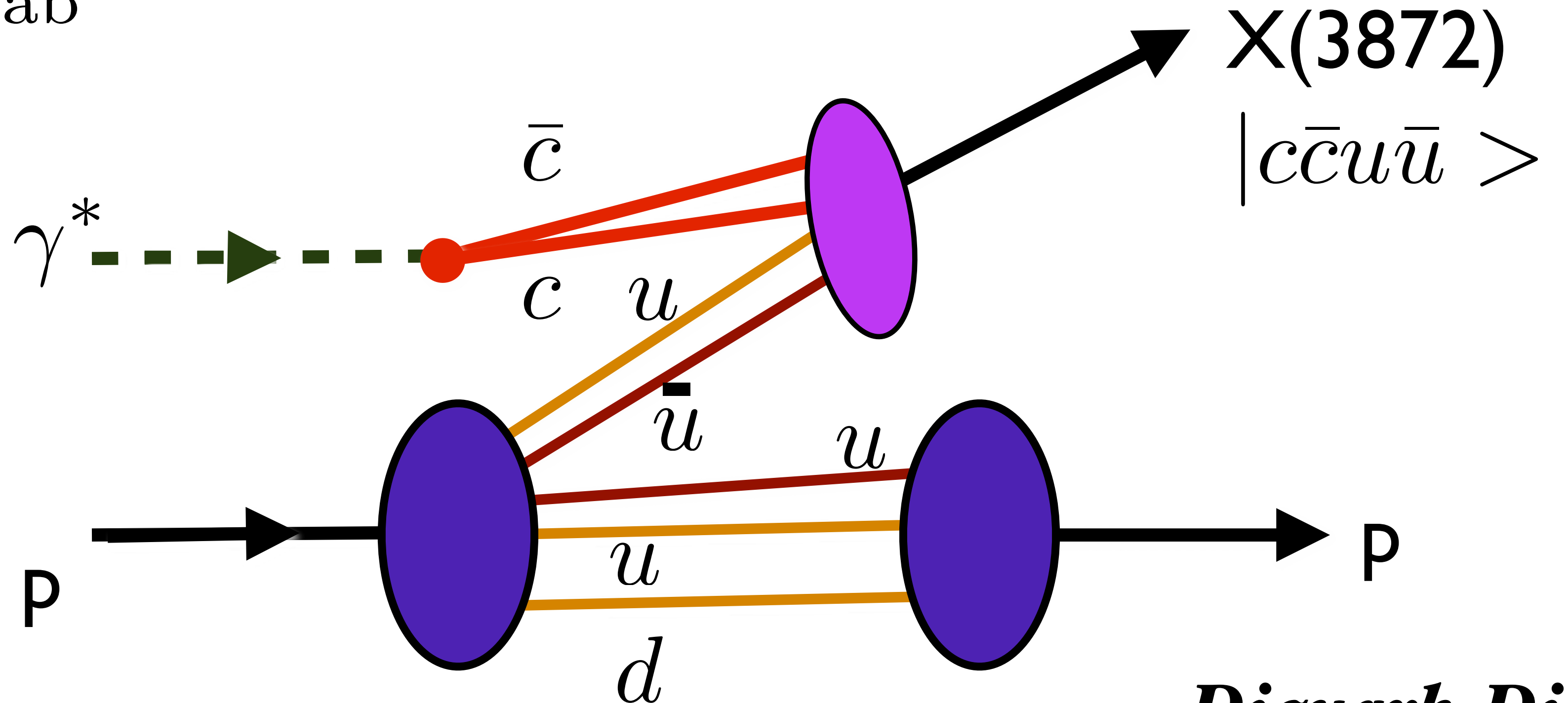
$$\gamma^* d \to J/\psi + d \text{ threshold}$$
$$\text{at } \sqrt{s} \simeq 5 \text{ GeV}, \; E_{\text{lab}}^{\gamma^*} \simeq 6 \text{ GeV}.$$

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

$$|uuddduc\bar{c}>$$ *octoquark!*

Tetraquark Production at Threshold

$E^{\gamma}_{\rm lab} > 11.9 \text{ GeV}$



Diquark-Diquark vs Molecular State?

$$\gamma^* p \to X(3872) + p'$$

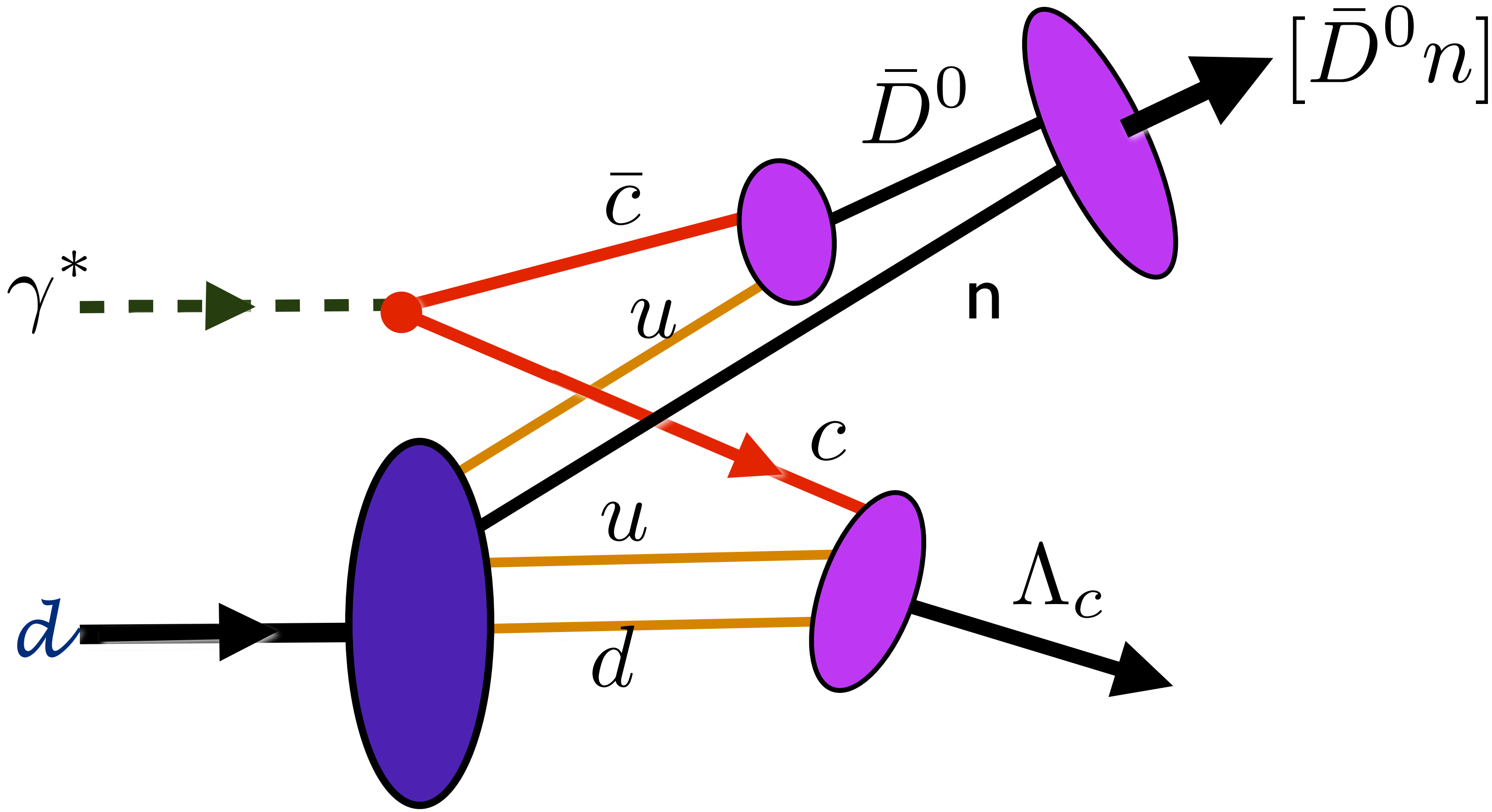
$$|c\bar{c}q\bar{q} >$$

New approach to hadronic decays

Dominance of Ψ' vs J/Ψ decays

Lebed, Hwang, sjb

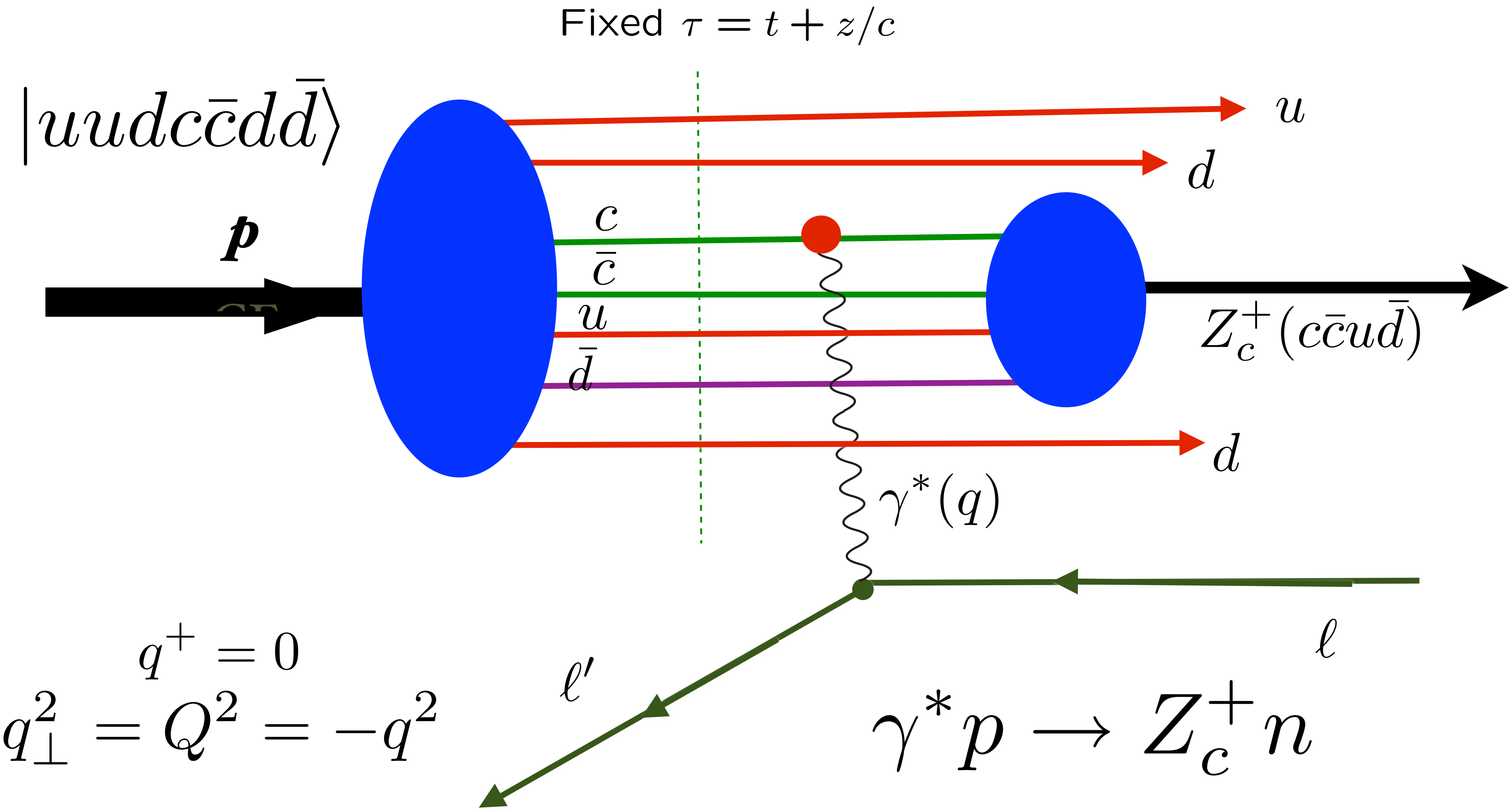
Open Charm Production at Threshold



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

Create pentaquark on deuteron at low relative velocity

Light-Front Wavefunctions and Heavy-Quark Electroproduction

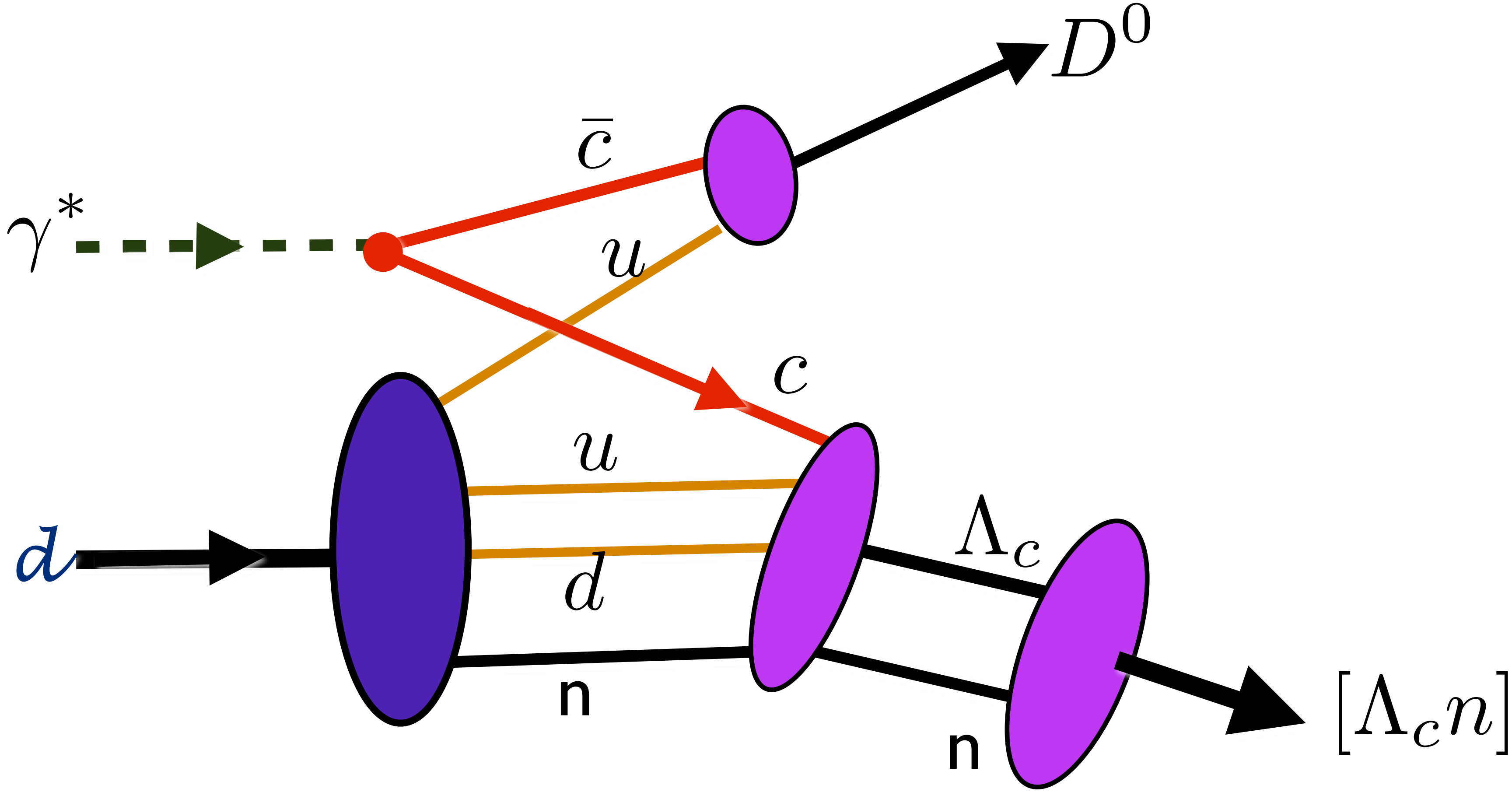


Produce Charged Tetraquarks at JLab!

Coalescence of comovers at threshold produces
Z_c^+ tetraquark resonance

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

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 $\Delta^{++}\Delta^{++}$**

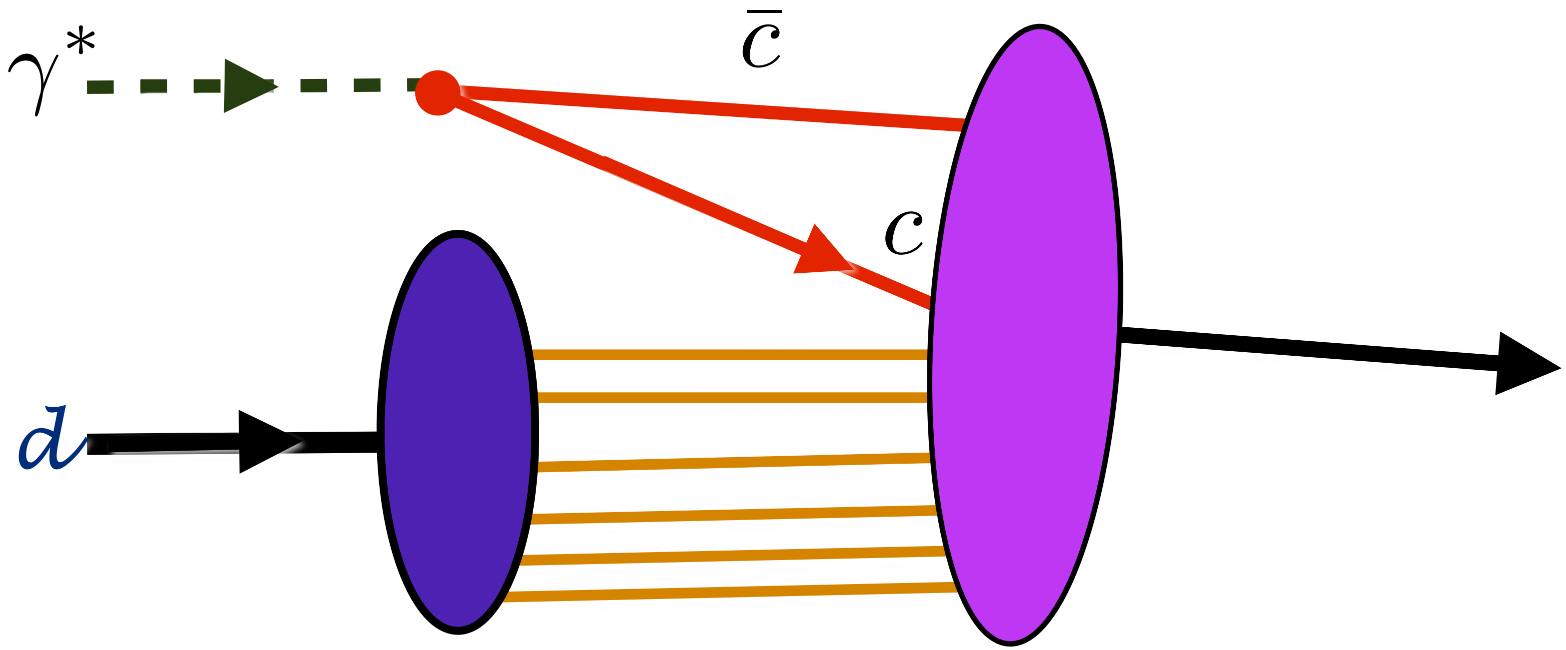
$$\gamma d \rightarrow [B = +2, Q = +4]\pi^- \pi^- \pi^-$$

Discover at JLab!

Bashkanov, Clement, sjb

Octoquark Production at Threshold

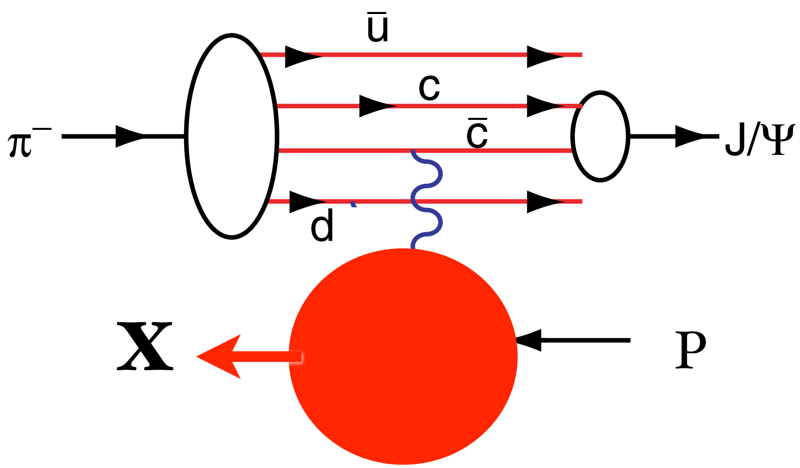
$$M_{\rm octoquark} \sim 5 \text{ GeV}$$

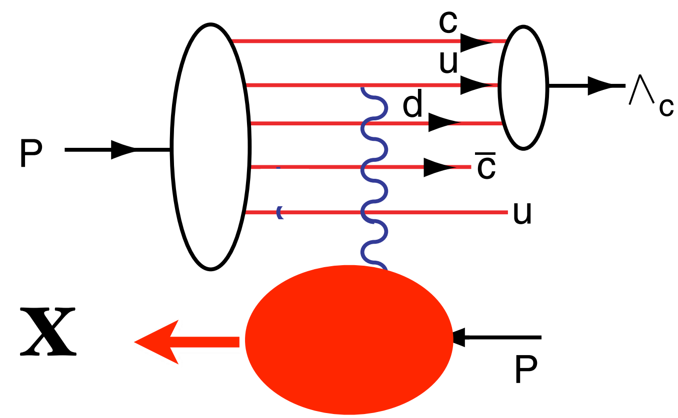


$$\gamma^* D \to |uuduudc\bar{c}>$$

Explains Krisch Effect!

Leading Hadron Production from Intrinsic Charm

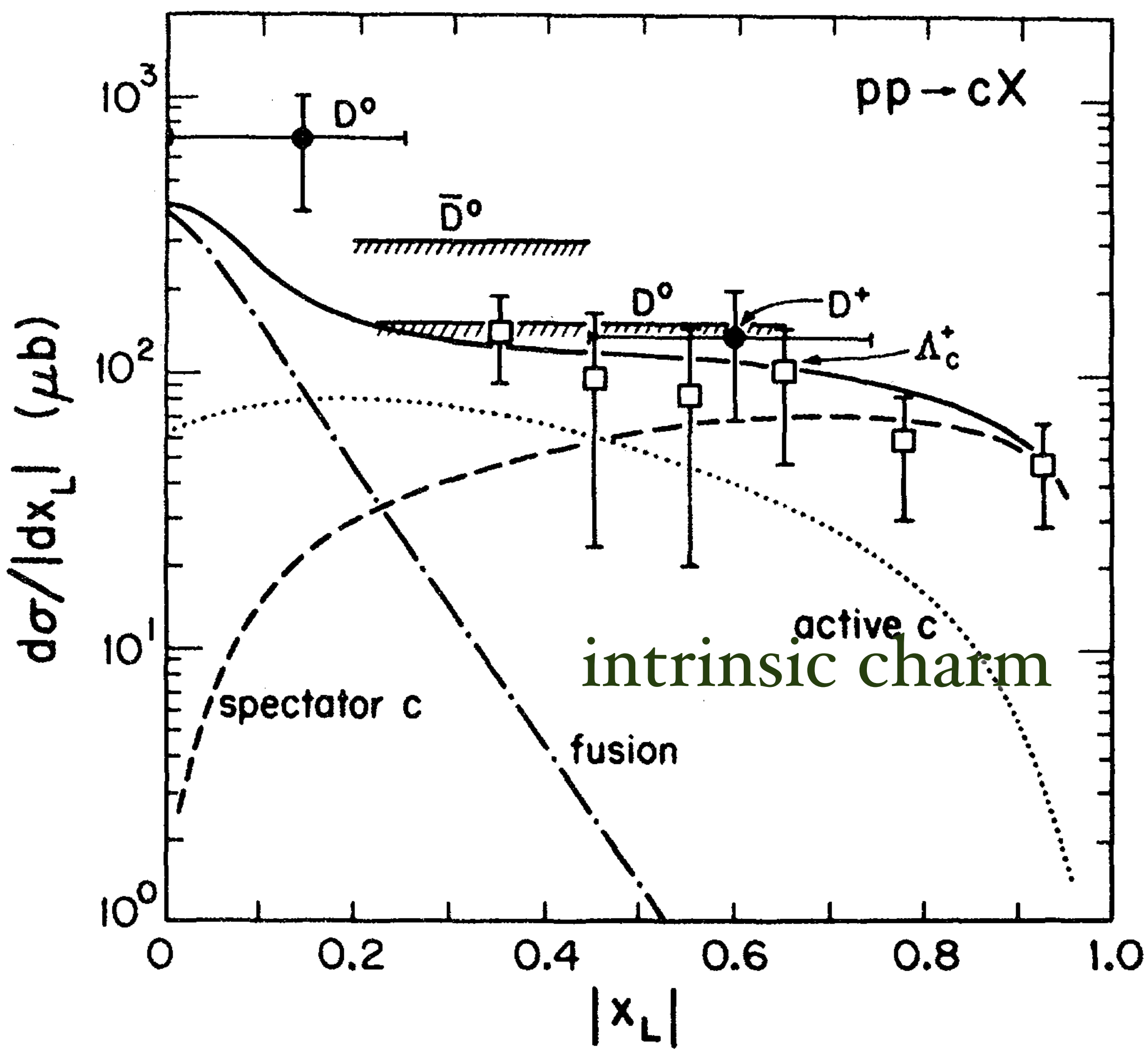




Spectator counting rules

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

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



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 $pp \to \Lambda_b X$

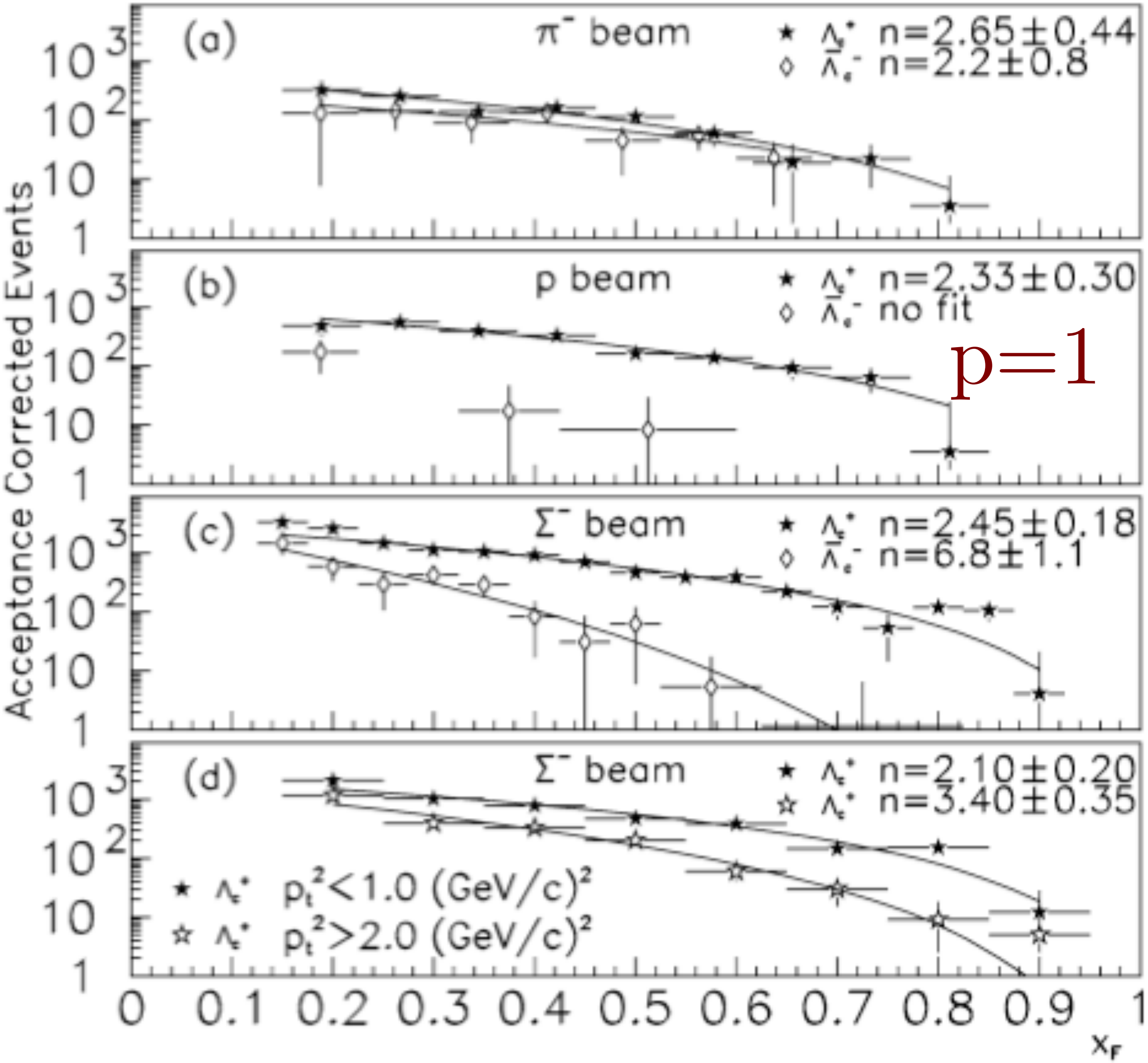
- High x_F $pp \to \Xi(ccd) X$ (SELEX)

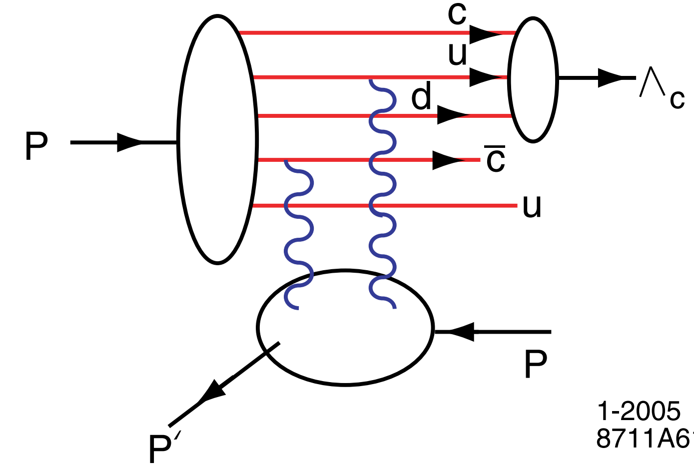
Critical Measurements at threshold for JLab, PANDA

Interesting spin, charge asymmetry, threshold, spectator effects

Important corrections to B decays; Quarkonium decays

Gardner, Karliner, sjb





$$p(uudc\bar{c}) \rightarrow \Lambda_c(cud)$$

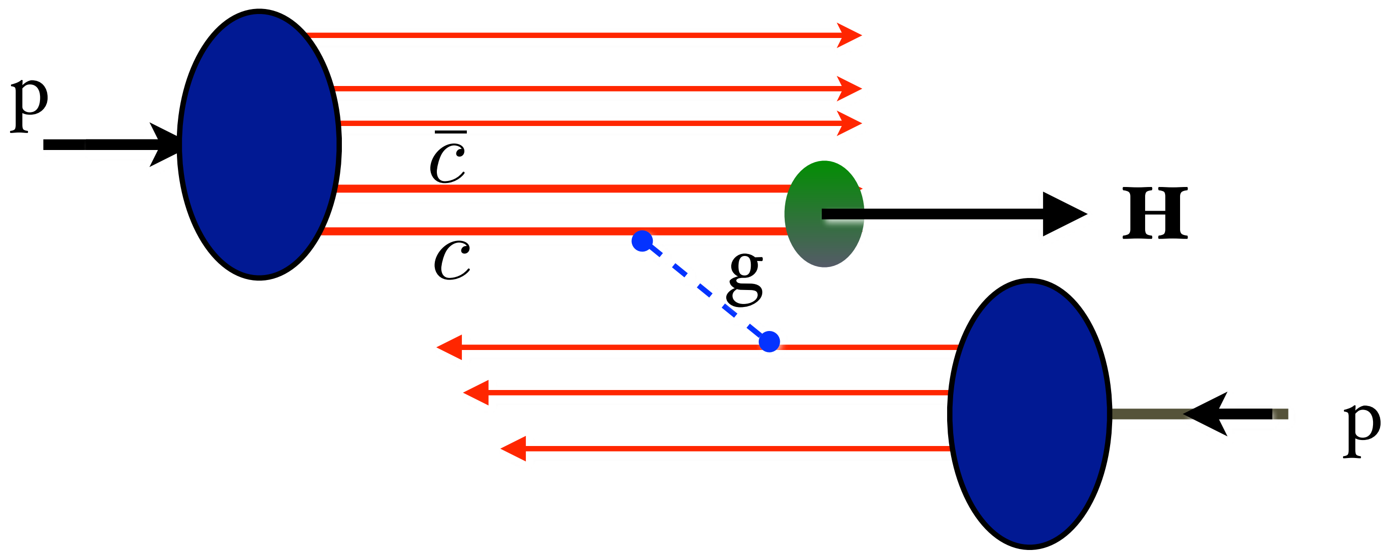
$$n_s = 2$$

Phase space alone gives minimum power

$$(1 - x_F)^p, p = n_s - 1$$

Maximum fraction of projectile momentum carried by charm quarks!

Intrinsic Charm Mechanism for Inclusive High-X_F Higgs Production



$$pp \to HX$$

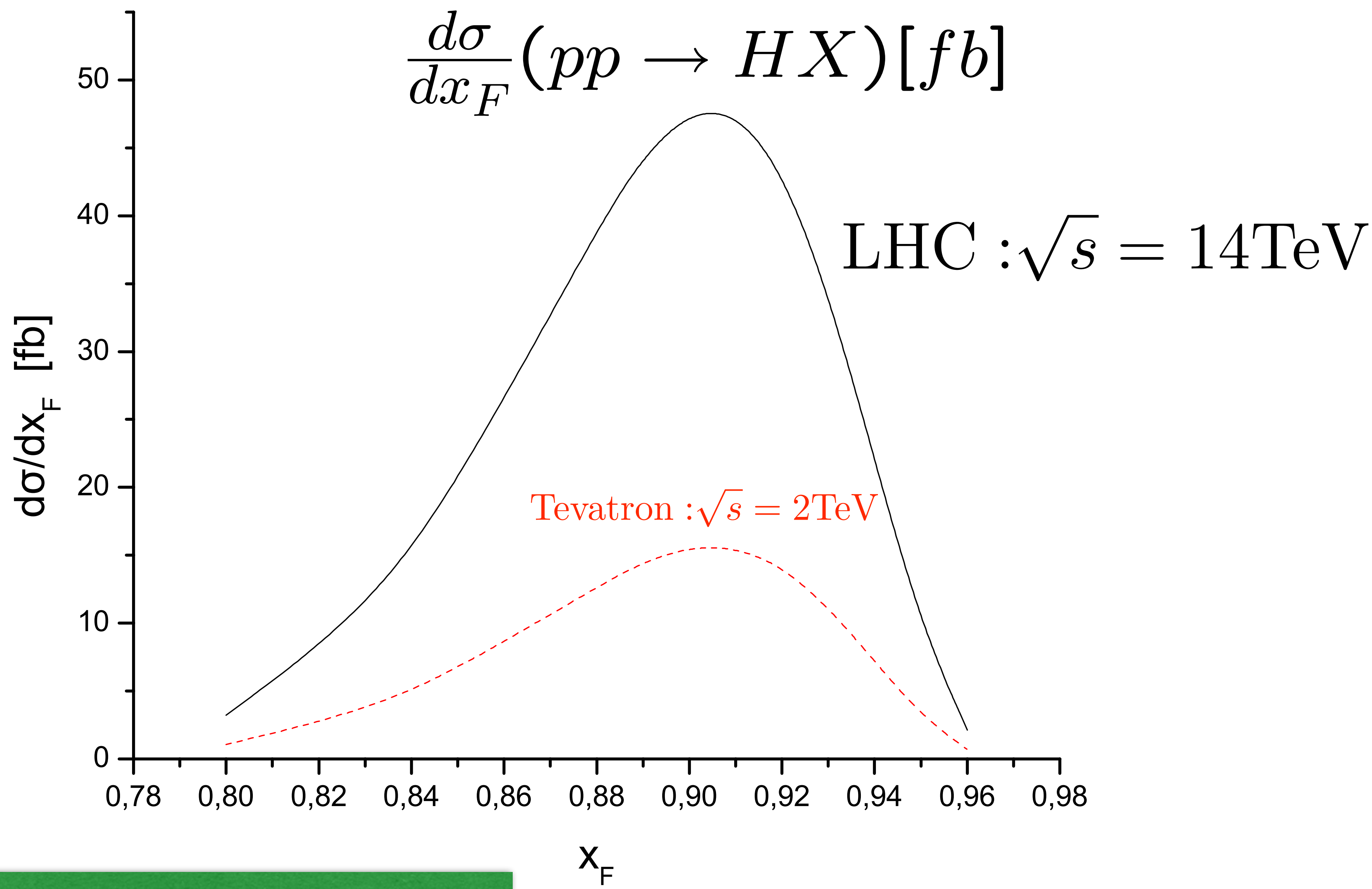
Goldhaber, Soffer, Kopeliovich, Schmidt, sjb

Also: intrinsic bottom, top

Higgs can have 80% of Proton Momentum!

New search strategy for Higgs

AFTER: Higgs production at threshold!



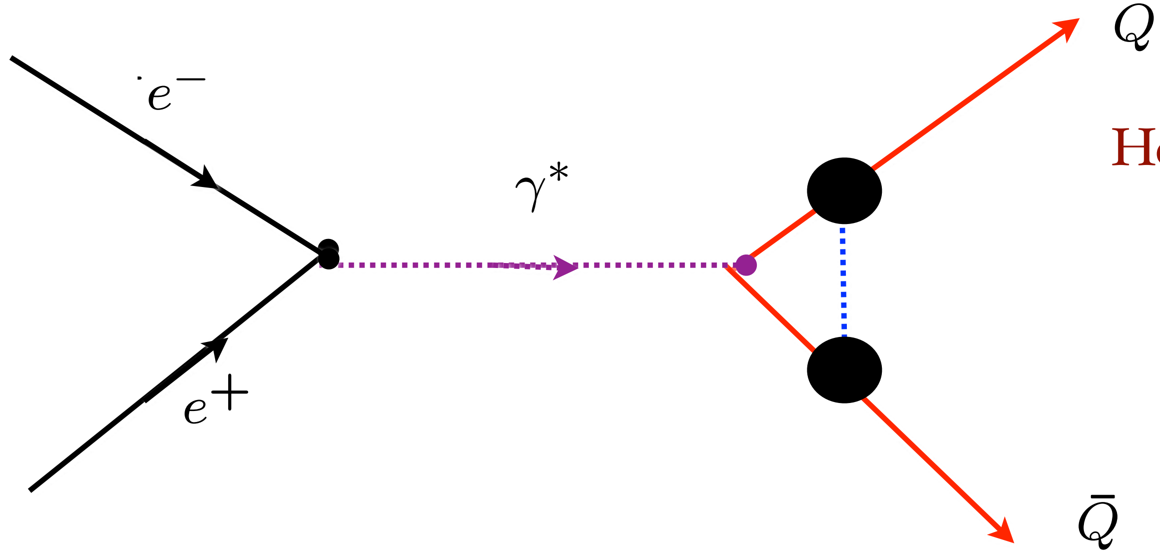
Need High x_F Acceptance

Most practical: Higgs to 2 or 4 muons

Goldhaber, Kopeliovich, Schmidt, Soffer, 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)



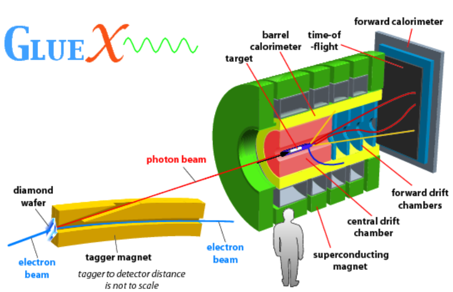
Hoang, Kuhn, Teubner, sjb

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

Angular distributions of massive quarks close to threshold.

Example of Multiple BLM/PMC Scales

QCD coupling at small scales at low relative velocity v



Novel Nuclear Photo-and Electroproduction Physics

JLab, April 29, 2016

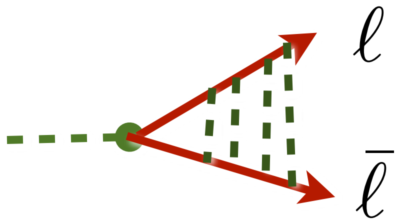
Stan Brodsky

SLAC
NATIONAL ACCELERATOR LABORATORY

Coulomb Enhancement of Pair Production at Threshold

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

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



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

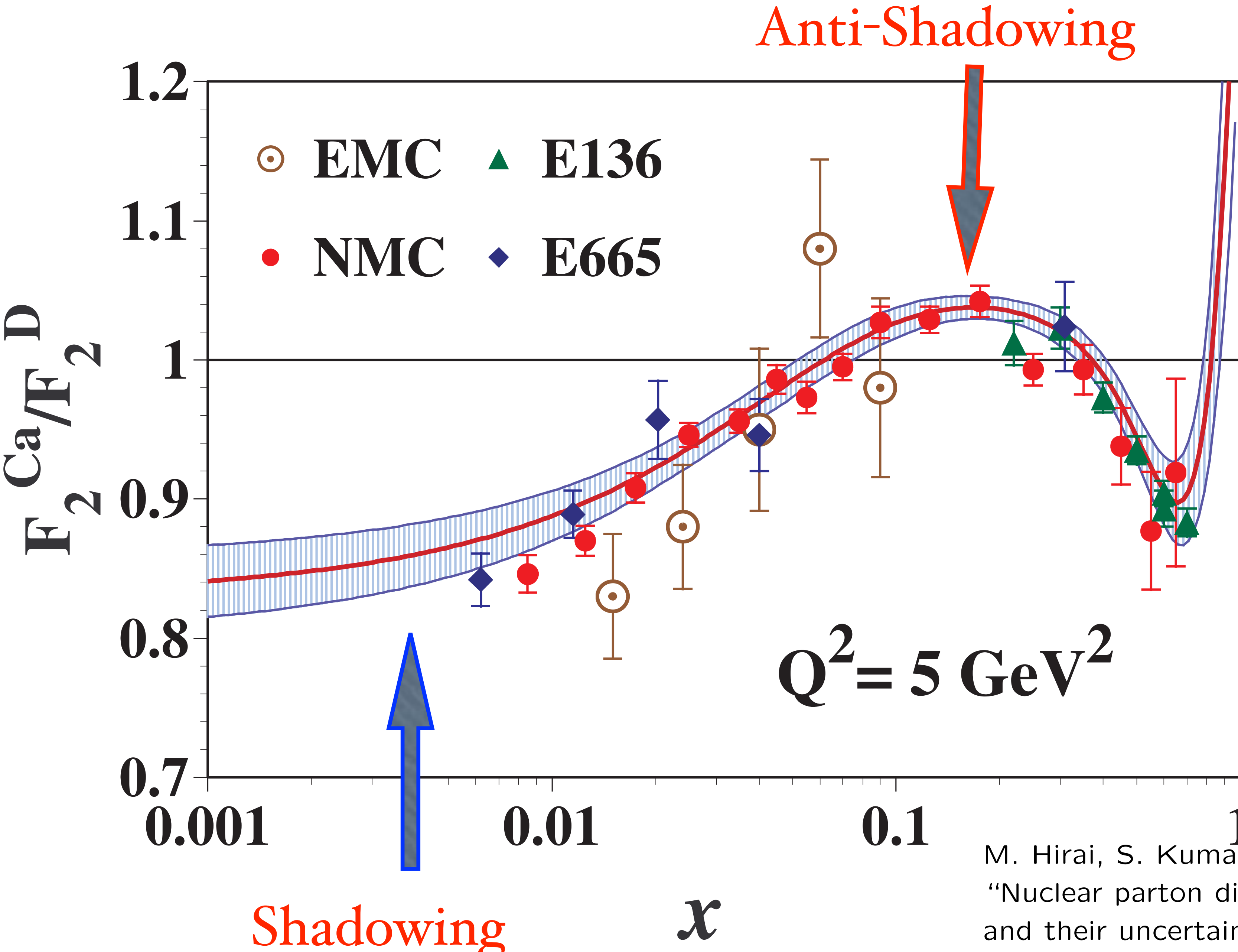
$$S(\beta) = \frac{X(\beta)}{1 - e^{-X(\beta)}}$$

Sommerfeld-Schwinger-Sakharov Effect

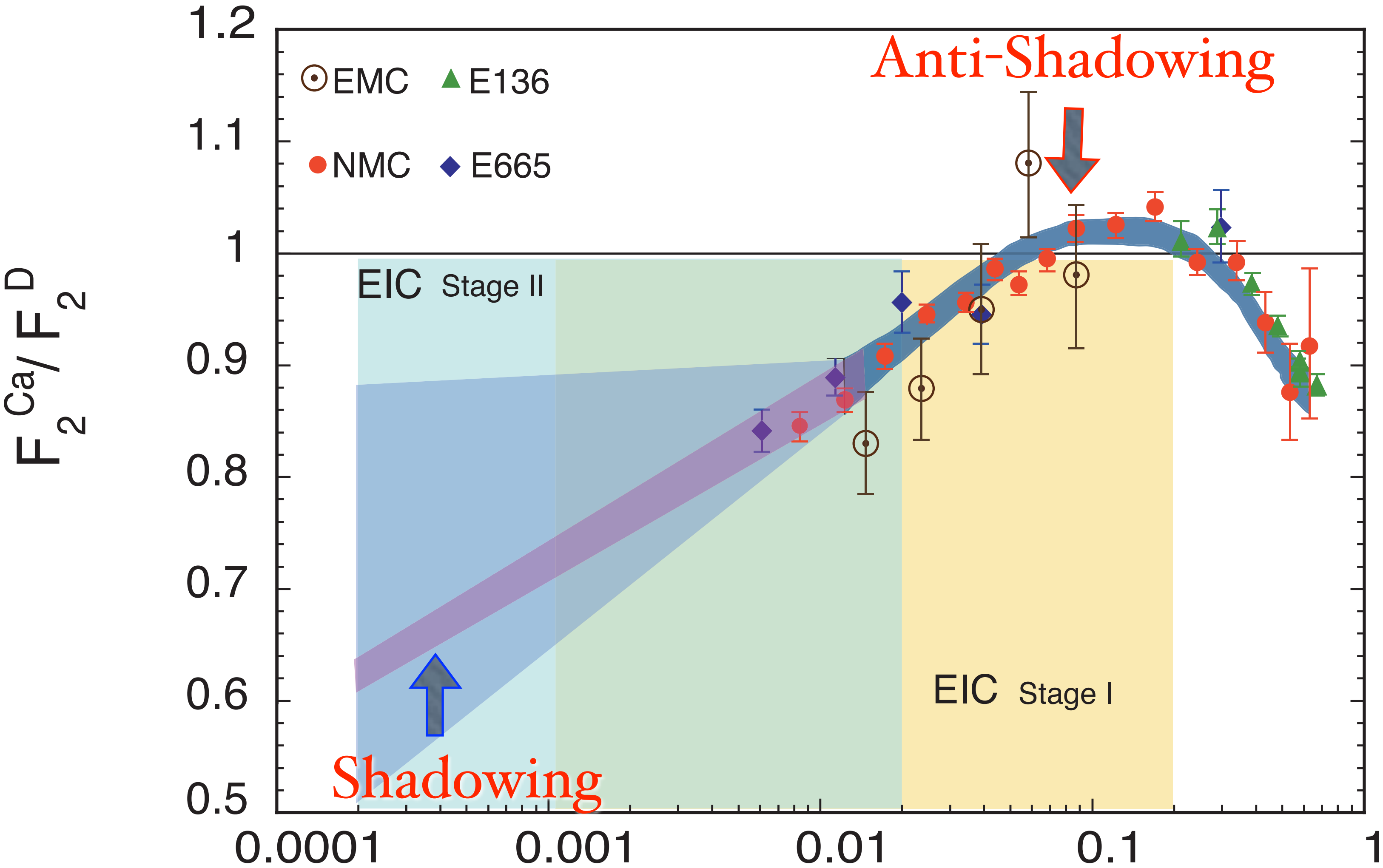
Bjorken: Analytical Connection to Rydberg Levels below Threshold

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

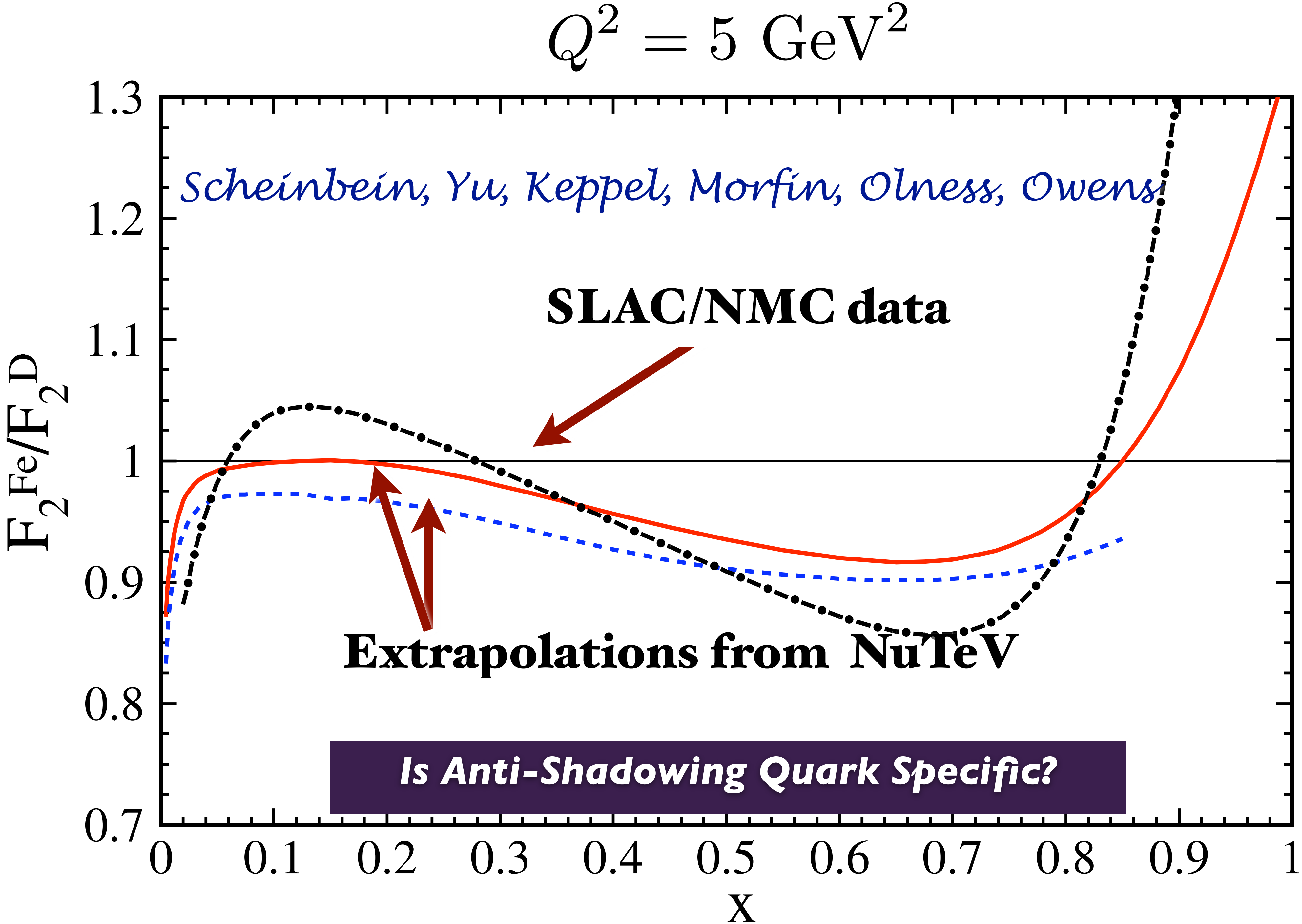
Kühn, Hoang, sjb



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].

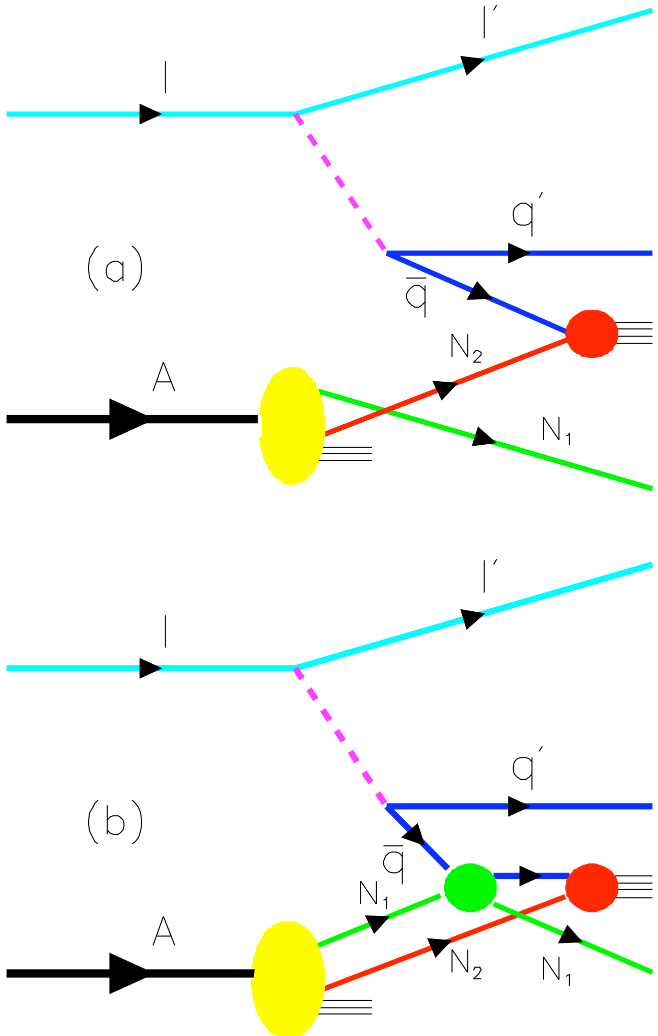


The ratio of nuclear over nucleon F_2 structure function, R_2, as a function of Bjorken x, with data from existing fixed target DIS experiments at $Q^2 > 1$ GeV^2, along with the QCD global fit from EPS09 [153]. Also shown are the respective coverage and resolution of the same measurements at the EIC at Stage-I and Stage-II. The purple error band is the expected systematic uncertainty at the EIC assuming a $\pm 2\%$ (a total of 4%) systematic error, while the statistical uncertainty is expected to be much smaller.



No anti-shadowing in deep inelastic neutrino scattering !

Is Antishadowing in DIS Non-Universal, Flavor-Dependent?



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.

Interior nucleons shadowed

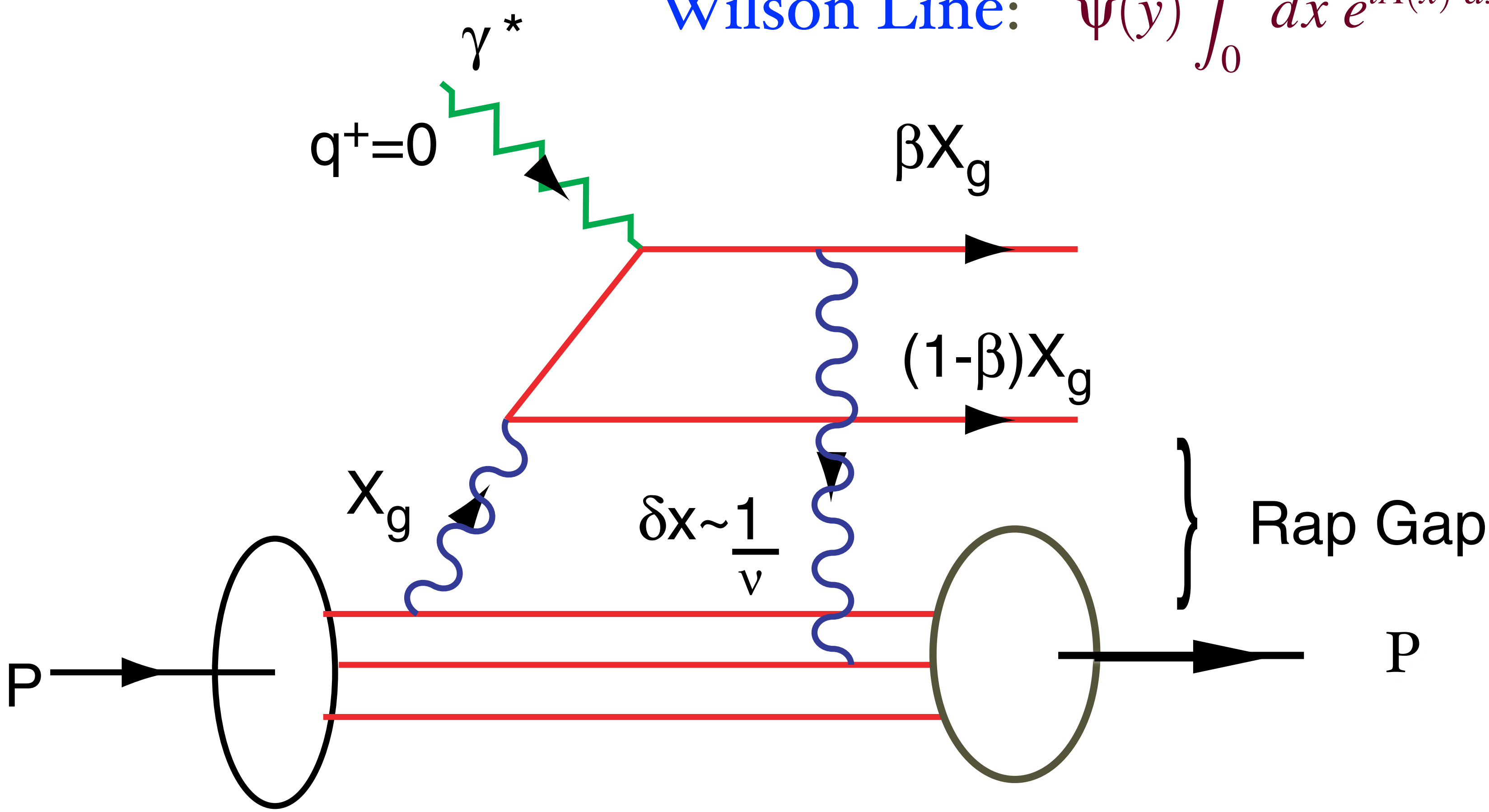
$\rightarrow$ Shadowing of the DIS nuclear structure functions.

Observed HERA DDIS produces nuclear shadowing

Hoyer, Marchal, Peigne, Sannino, sjb

QCD Mechanism for Rapidity Gaps

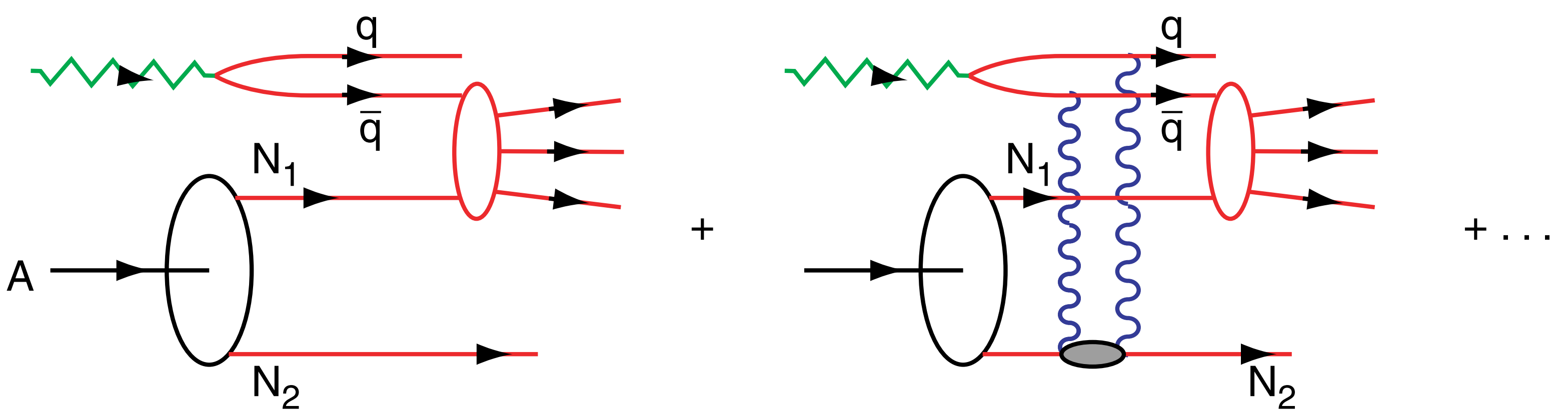
Wilson Line: $\overline{\psi}(y) \int_0^y dx\, e^{iA(x)\cdot dx}\, \psi(0)$



Reproduces lab-frame color dipole approach

Stodolsky
Pumplin, sjb
Gribov

Nuclear Shadowing in QCD



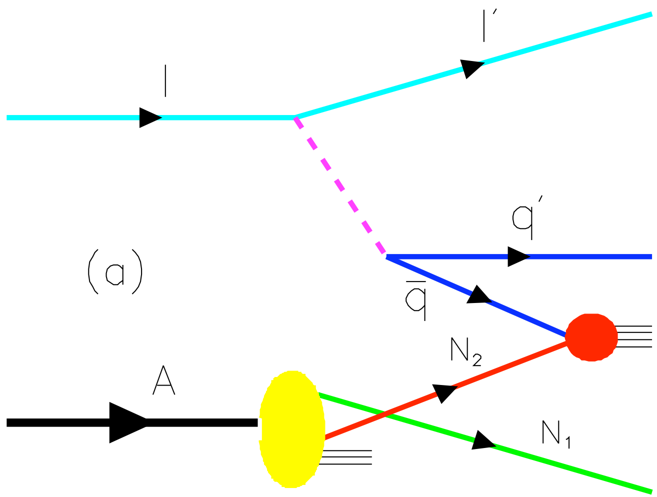
Shadowing depends on understanding leading twist-diffraction in DIS

Nuclear Shadowing not included in nuclear LFWF !

Dynamical effect due to virtual photon interacting in nucleus

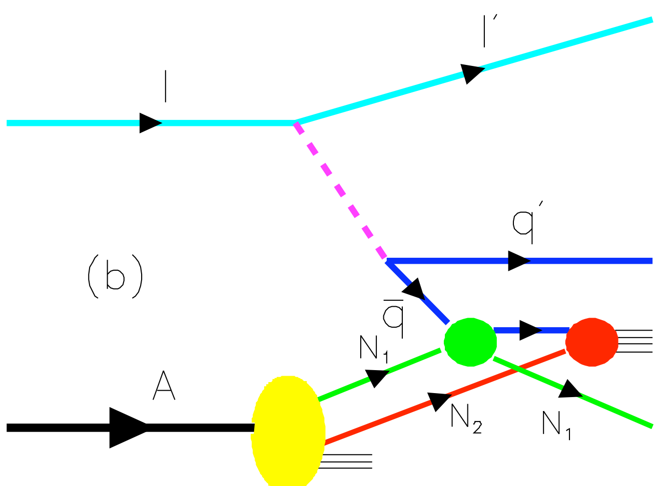
Diffraction via Reggeon gives constructive interference!

Anti-shadowing not universal



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.

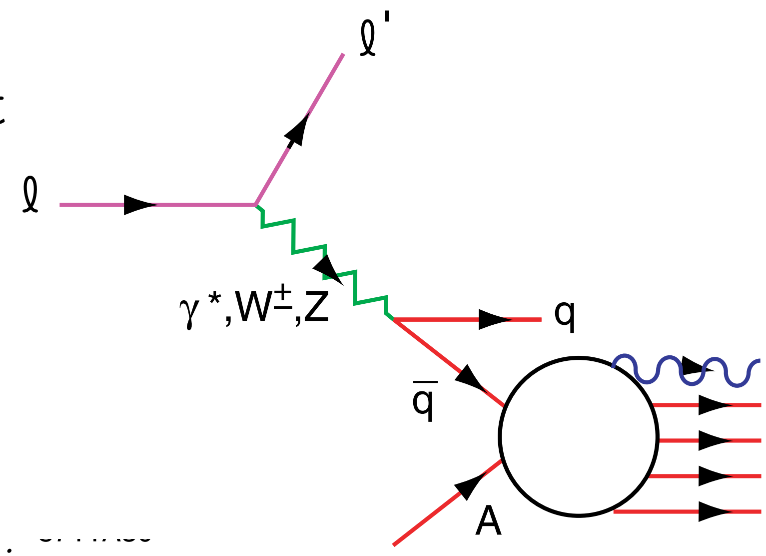
Diffraction via Pomeron gives destructive interference!

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}.

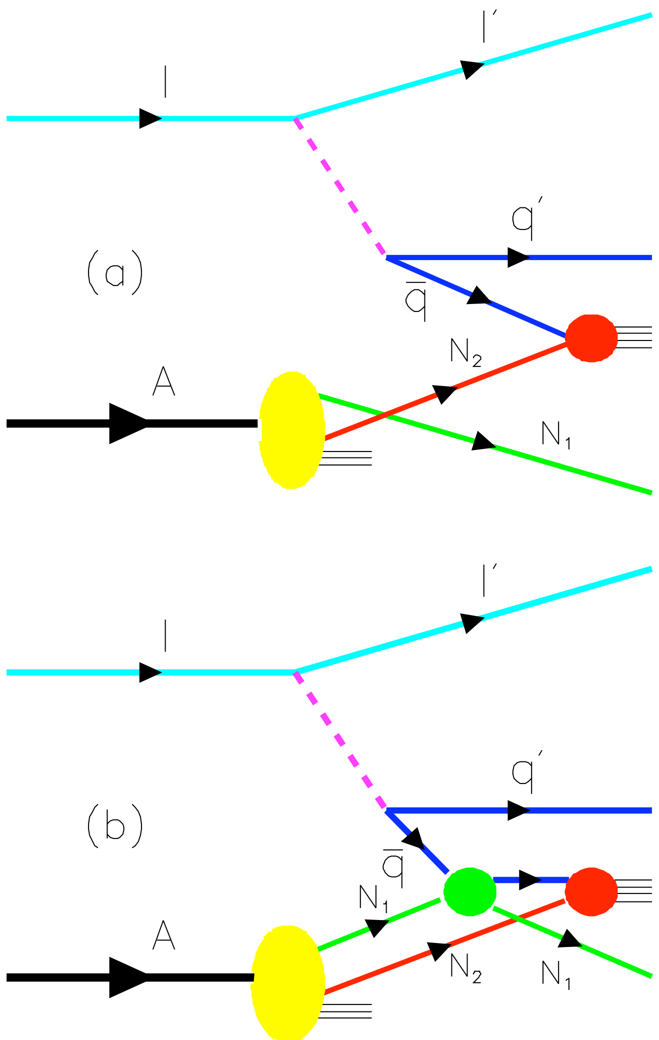
Shadowing of $\sigma_{\bar{q}M}$ produces shadowing of nuclear structure function.

Landshoff, Polkinghorne, Short

Close, Gunion, sjb

Schmidt, Yang, Lu, sjb

Schmidt, Lu, Yang, sjb



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

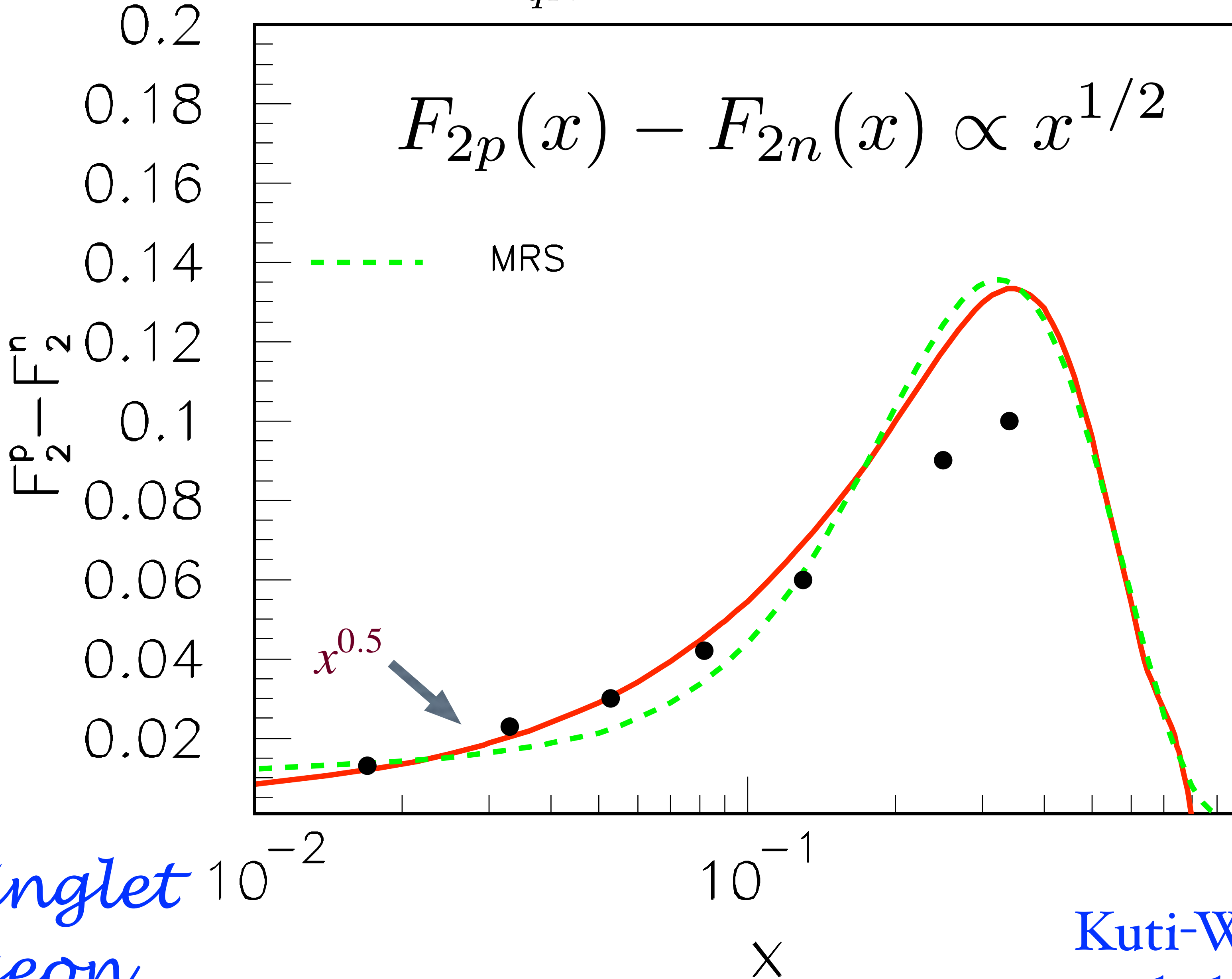
Coherence at small Bjorken x_B :
$1/Mx_B = 2\nu/Q^2 \geq L_A.$

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

Interior nucleons anti-shadowed

Regge Exchange in DDIS produces nuclear anti-shadowing

Regge contribution: $\sigma_{\bar{q}N} \sim \hat{s}^{\alpha_R - 1}$ $\alpha_R \simeq 1/2$



Non-singlet Reggeon Exchange

Kuti-Weisskopf behavior

Reggeon Exchange

Phase of two-step amplitude relative to one step:

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

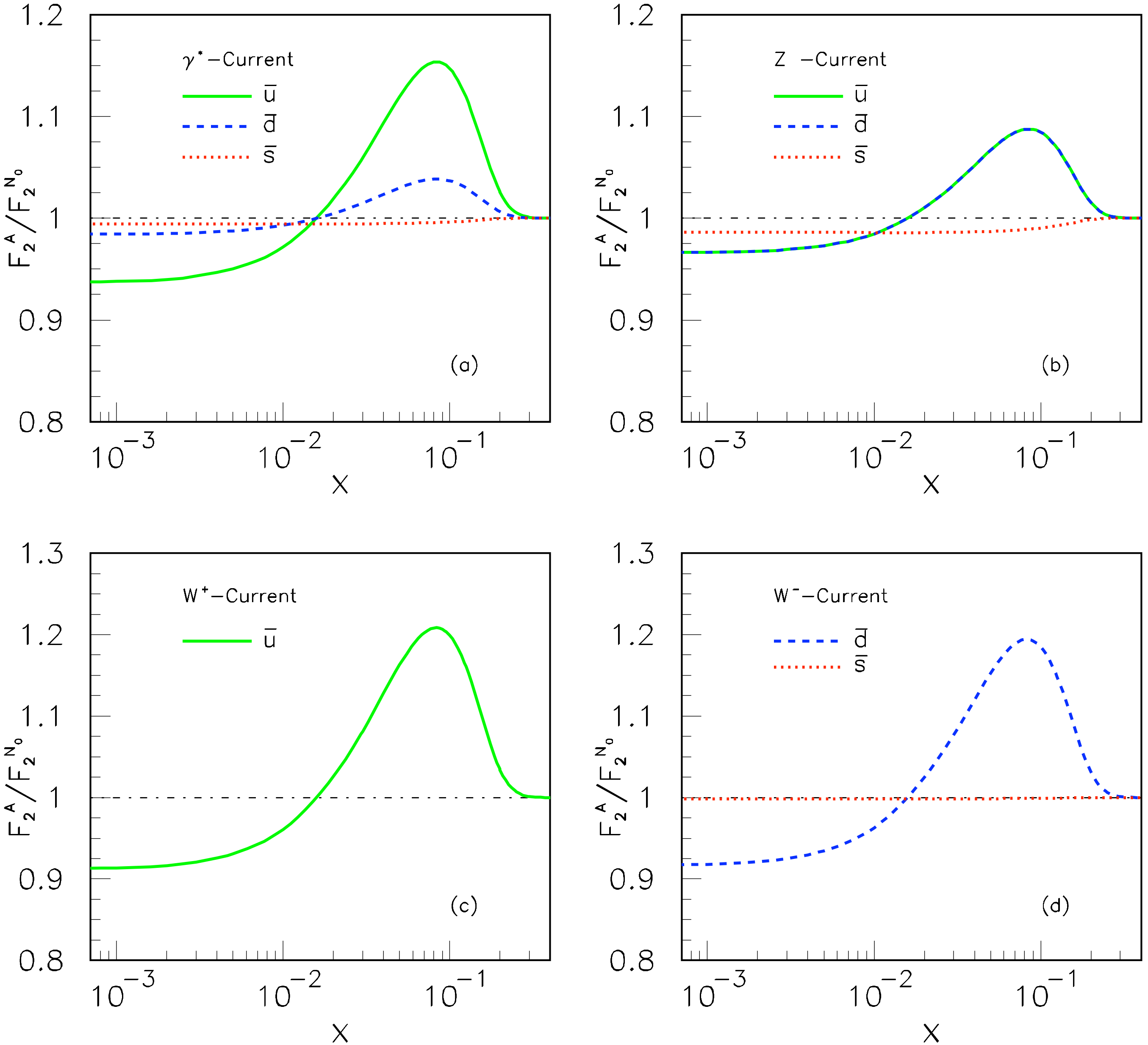
Constructive Interference

Depends on quark flavor!

Thus antishadowing is not universal

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

Critical test: Tagged Drell-Yan



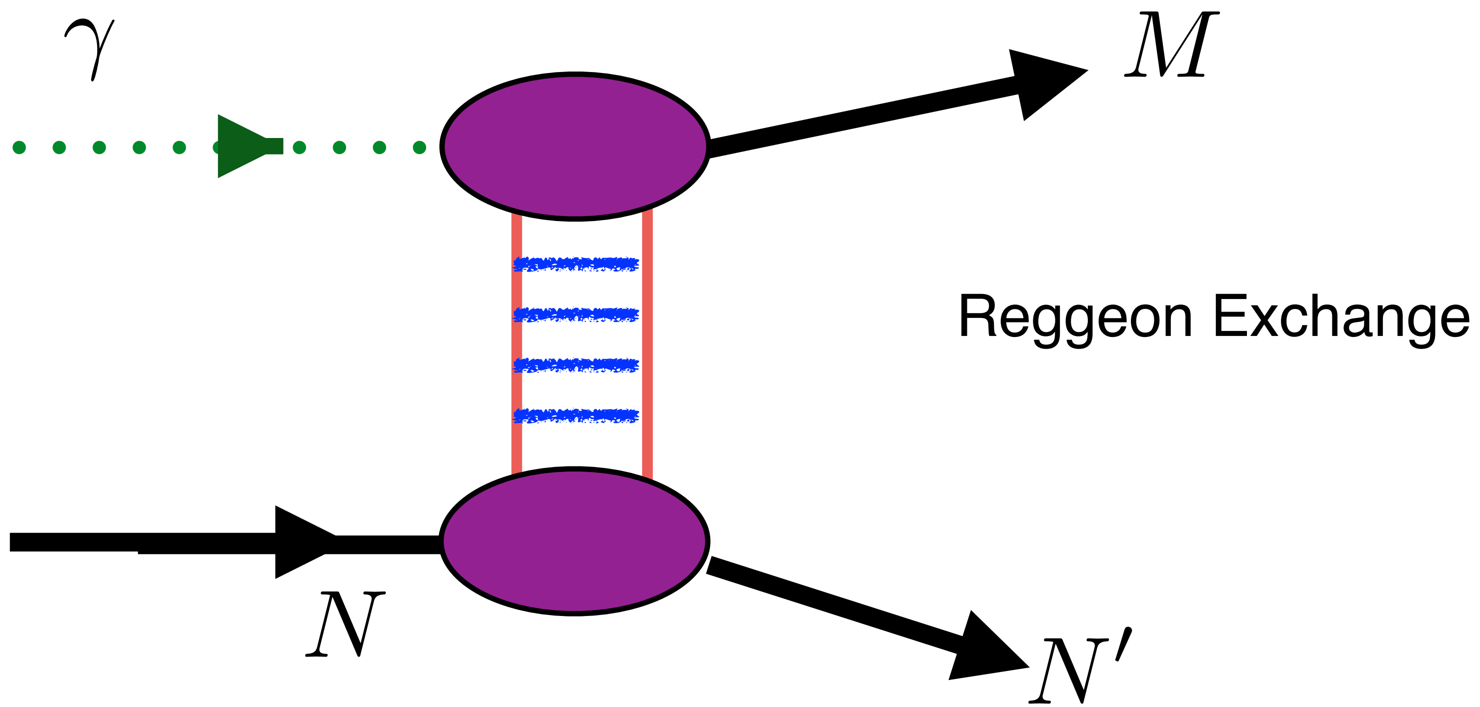
Schmidt, Yang; sjb

Modifies NuTeV extraction of

$\sin^2 \theta_W$

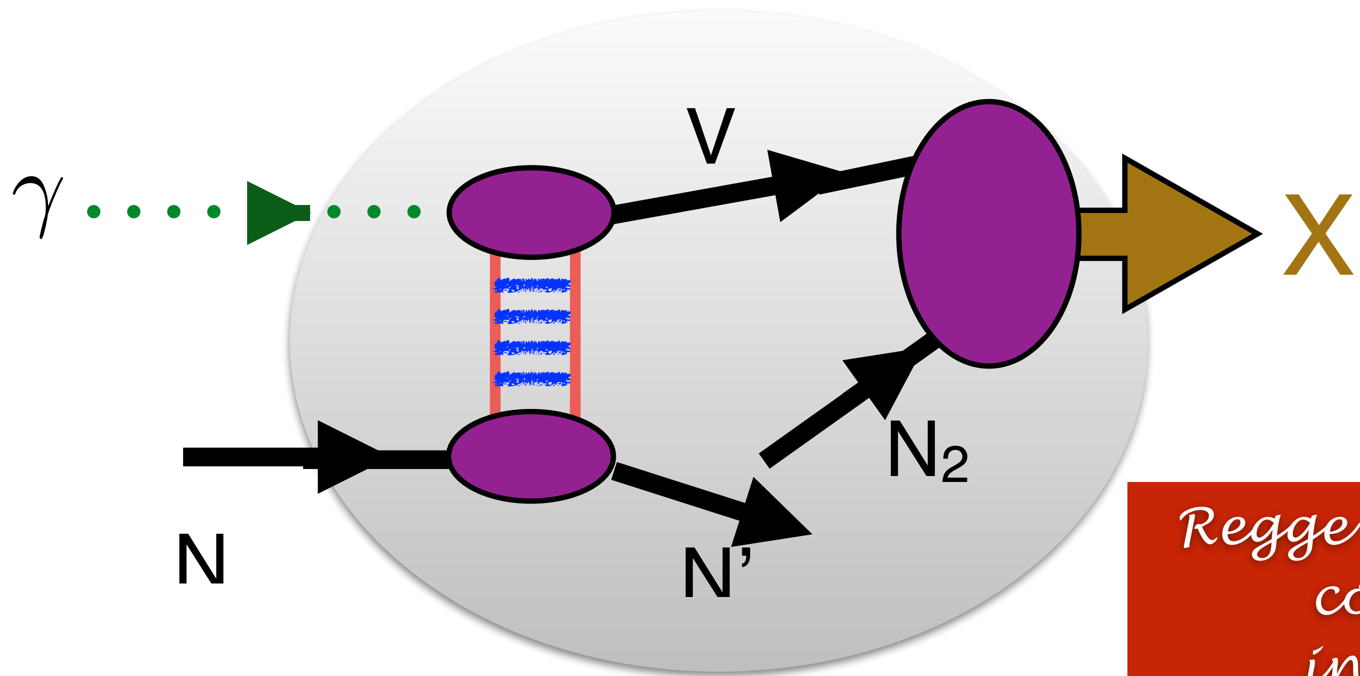
Test in flavor-tagged DIS at the EIC

Nuclear Antishadowing not universal !

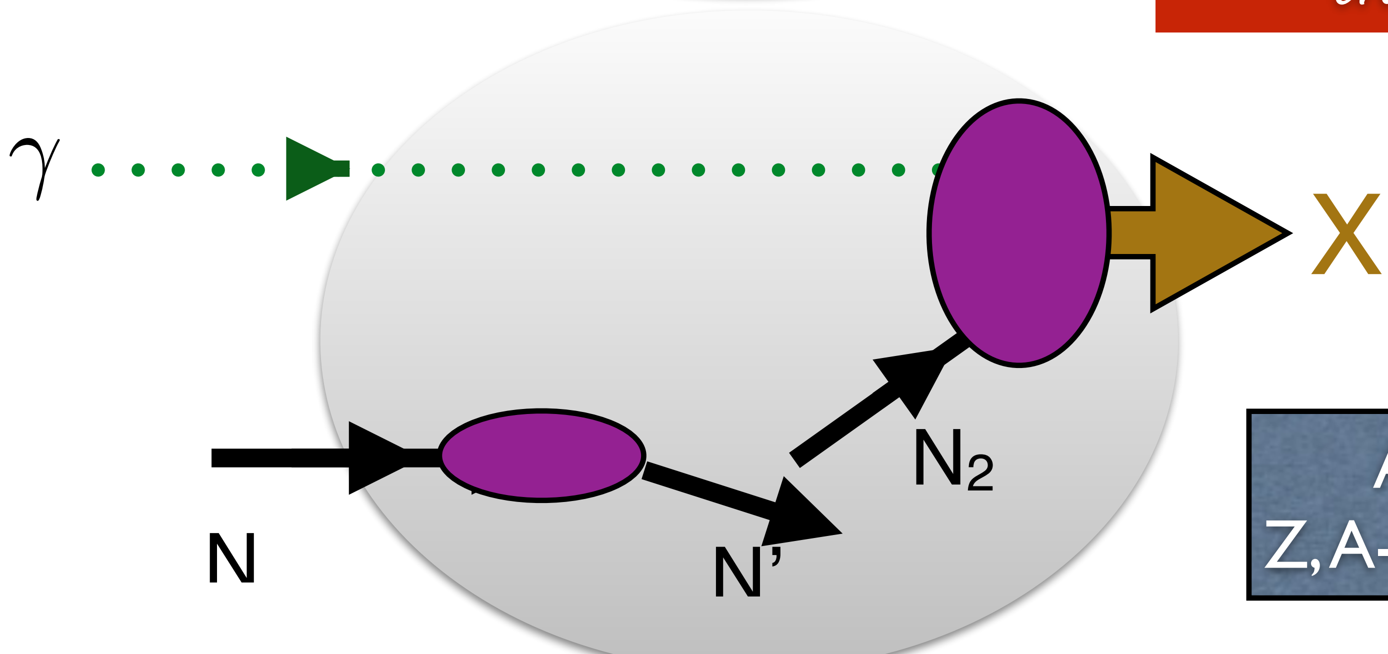

γ
M
Reggeon Exchange
N
N'

Two-step and One-Step Glauber processes

I=1 Reggeon Exchange on N_1



Regge Phase can give constructive interference!



Anomalous
Z, A-Z dependence

Novel QCD Physics at the EIC

- Control Collisions of Flux Tubes and Ridge Phenomena
- Study Flavor-Dependence of Anti-Shadowing
- Heavy Quarks at Large x; Exotic States
- Direct, color-transparent hard subprocesses and the baryon anomaly
- Tri-Jet Production and the proton's LFWF
- Odderon-Pomeron Interference
- Digluon-initiated subprocesses and anomalous nuclear dependence of quarkonium production
- Factorization-Breaking Lensing Corrections

Regge Behavior of Scattering Amplitudes

$$M = \sum_R s^{\alpha_R(t)} F_R(t) e^{i\phi_R} \qquad \frac{d\sigma}{dt} \propto \frac{|M|^2}{s^2}$$

$$F_2(x) \sim x^{1-\alpha_R}$$

$$R = Pomeron(\alpha_{\mathcal{P}} \simeq 1 + \epsilon), C = +, phase = Imaginary$$

$$Odderon(\alpha_{\mathcal{O}} \simeq 1), C = -, phase = Real$$

$$Reggeon(\alpha_{\mathcal{R}} \simeq 1/2), C = \pm, phase = Real + Imaginary$$

$$\mathcal{FP}(\alpha_{\mathcal{FP}} \simeq 0), C = +, phase = Real$$

Reggeon Exchange

Regge contribution: $\sigma_{\bar{q}N} \sim \hat{s}^{\alpha_R - 1}$ $\alpha_R \simeq 1/2$

Phase of two-step amplitude relative to one step:

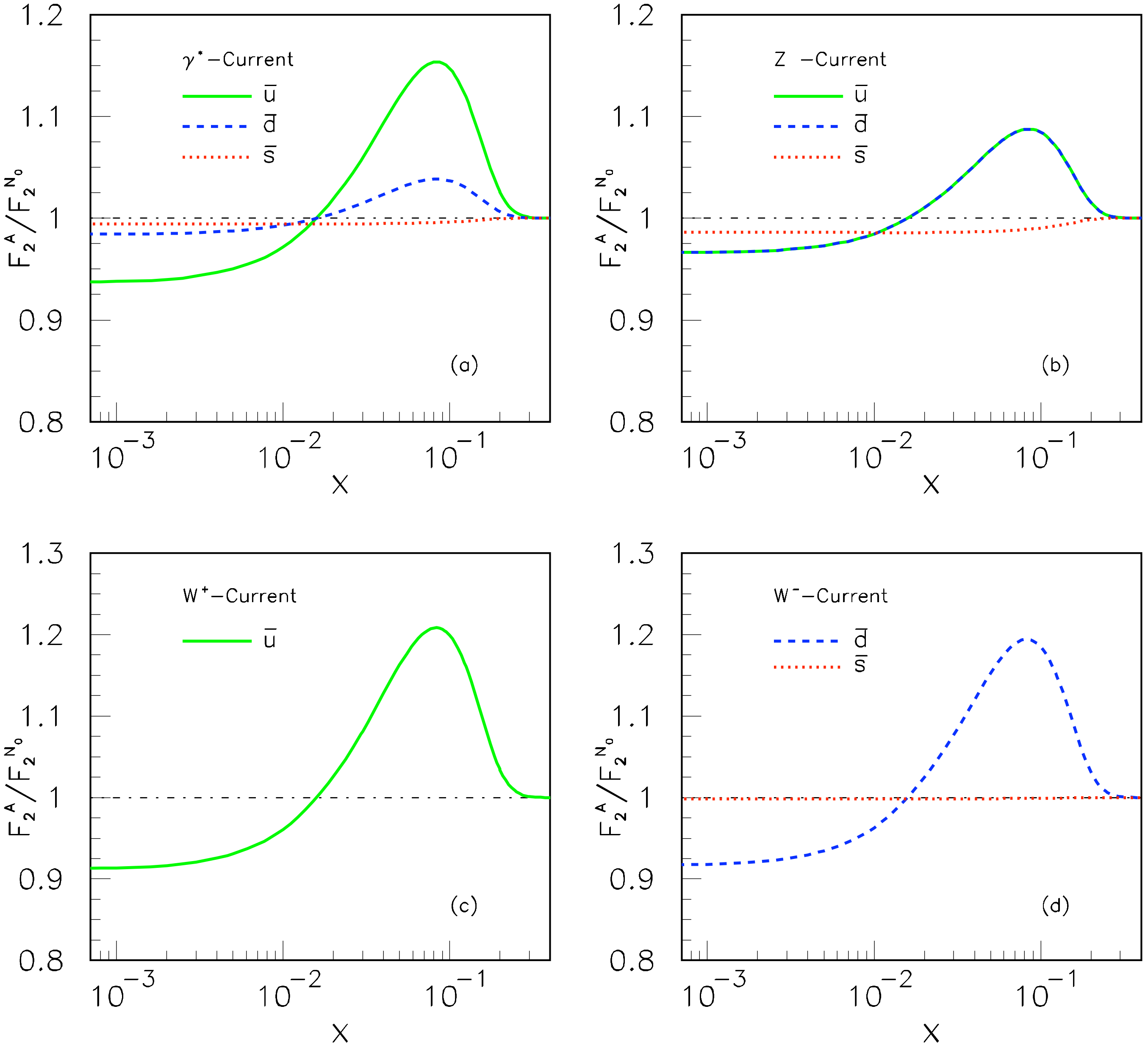
$$\frac{1}{\sqrt{2}}(1 - i) \times i = \frac{1}{\sqrt{2}}(i + 1)$$

Constructive Interference

Depends on quark flavor!

Thus antishadowing is not universal

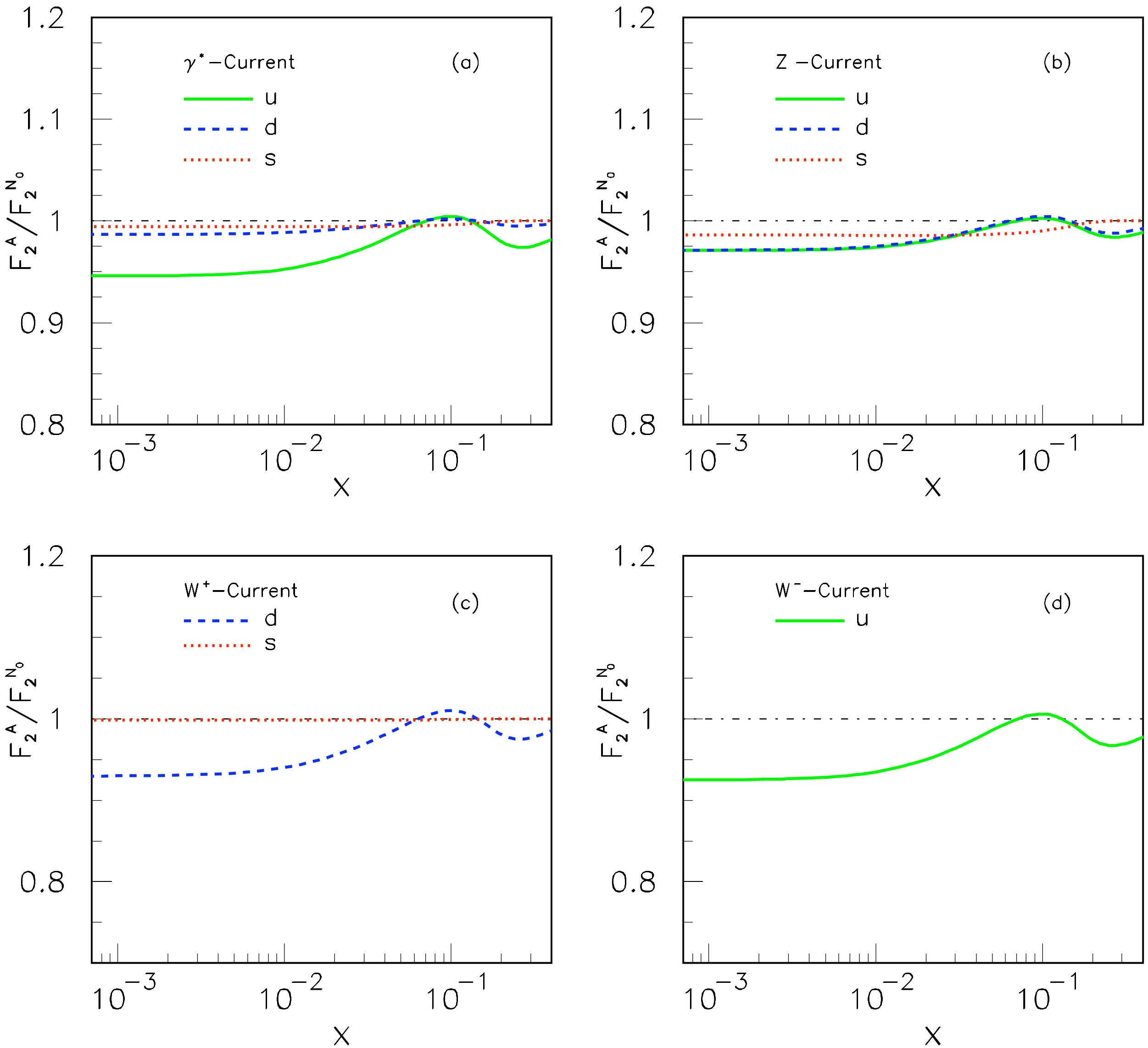
Different for couplings of $\gamma^*, Z^0, W^\pm$



Schmidt, Lu, Yang, sjb

Nuclear Antishadowing not universal !

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

$$\sin^2\theta_W$$

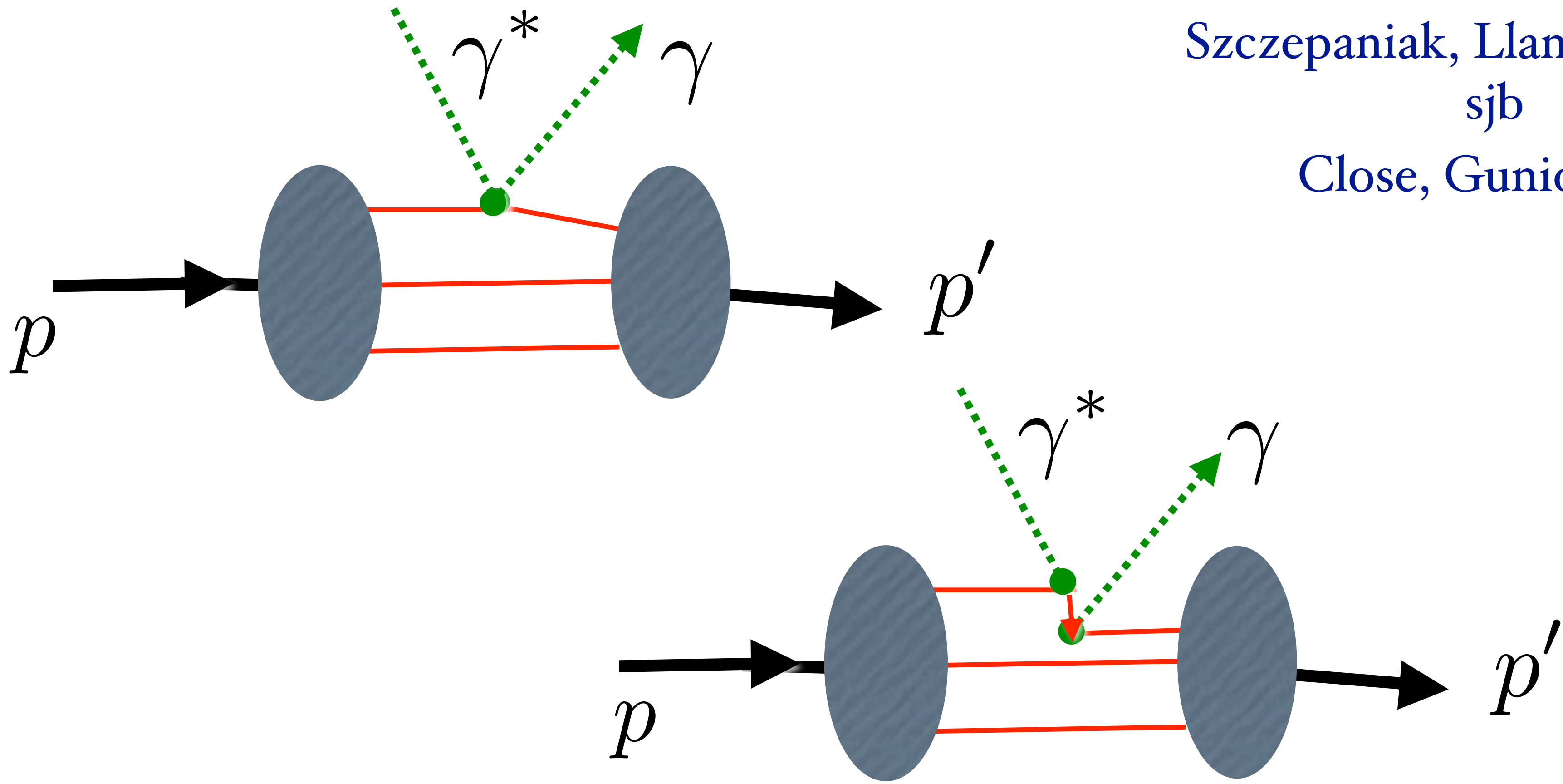
Test in flavor-tagged lepton-nucleus collisions

Crucial JLab Experiments

- *Measure Diffractive DIS: Agree with Shadowing of Nuclear Structure Functions?*
- *Isospin Dependence of Diffractive DIS — Reggeon Exchange*
- *Flavor Dependence of Antishadowing: Tagged Quark Distributions?*
- *Test for Odderon Exchange in DDIS*

J=0 Fixed Pole Contribution to DVCS

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



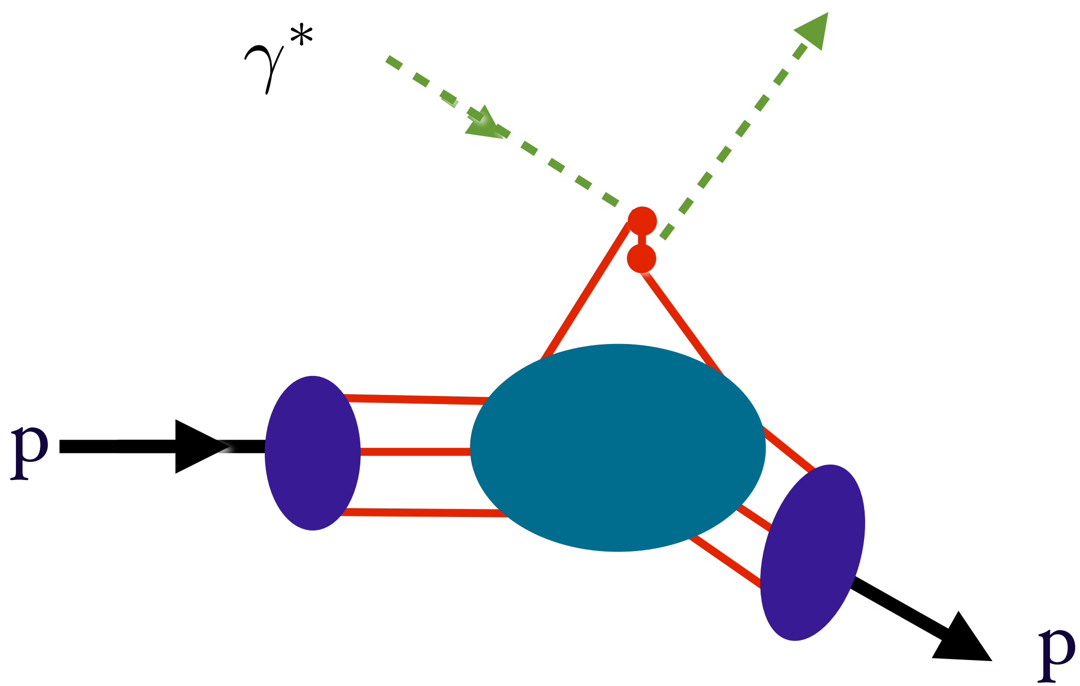
Szczepaniak, Llanes-Estrada, sjb

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

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

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

J=0 Fixed pole in real and virtual Compton scattering

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

Effective two-photon contact term

Seagull for scalar quarks

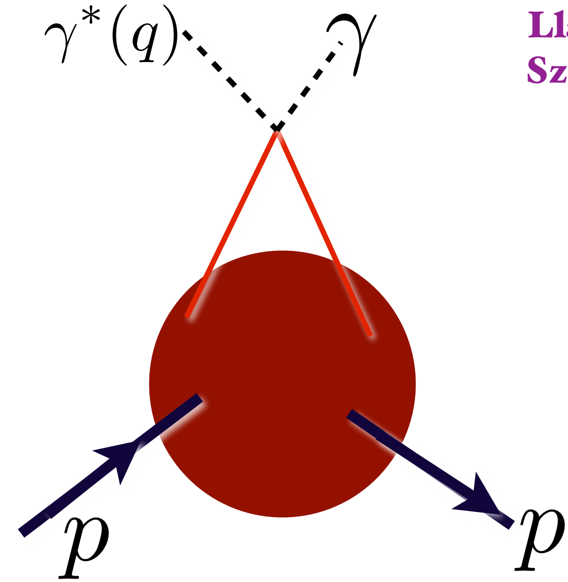
Real phase

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

Independent of Q^2 at fixed t

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

Fundamental test of local gauge theory



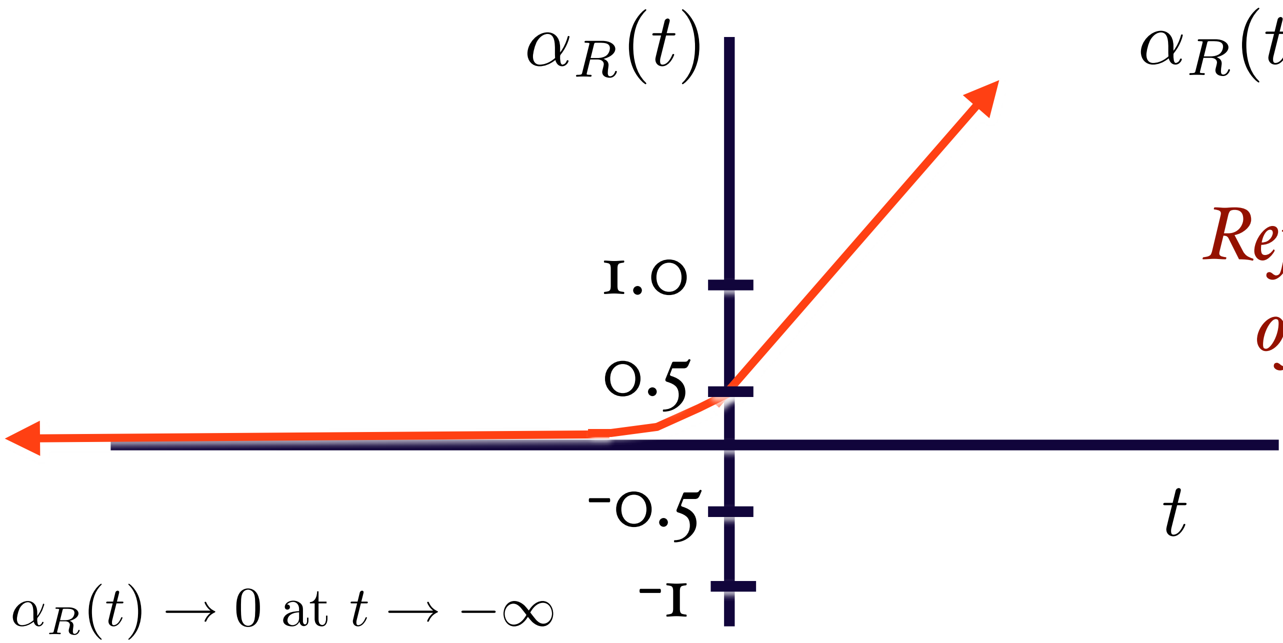
Q^2-independent contribution to Real DVCS amplitude

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

independent of 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 $t \to -\infty$

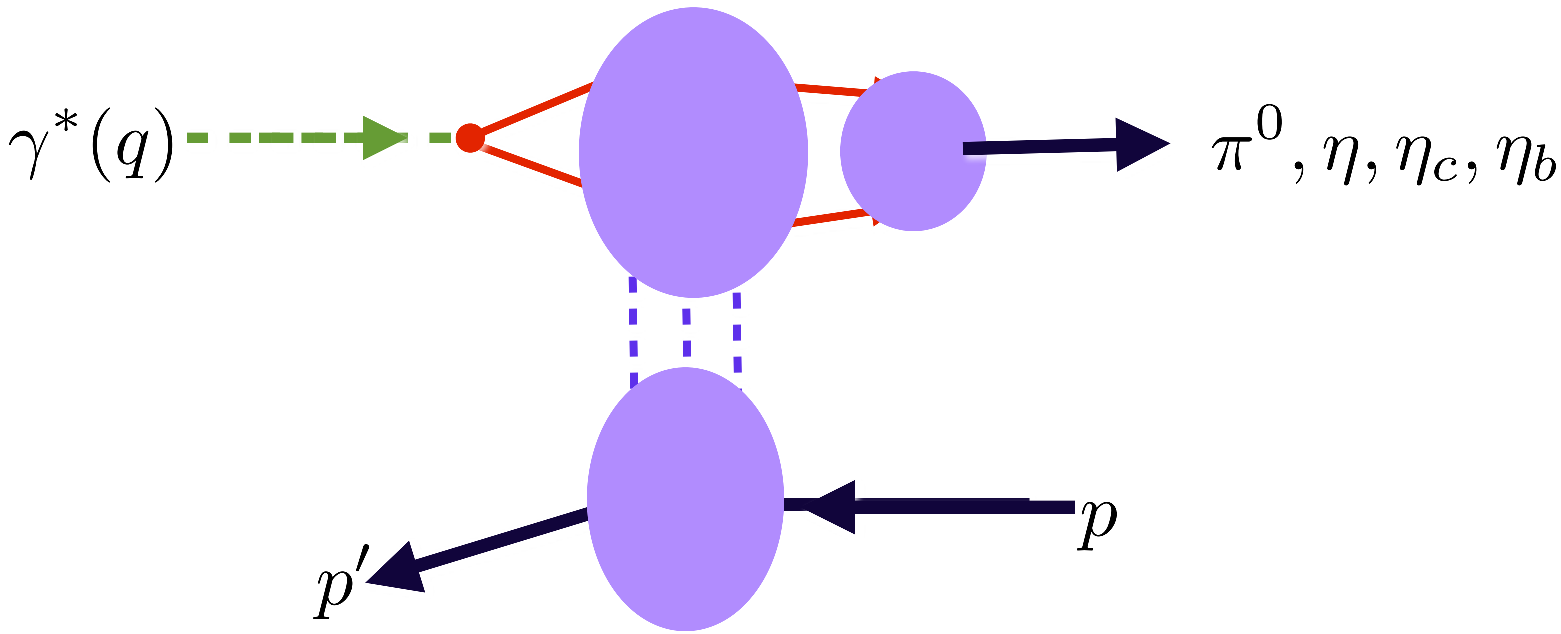
J=0 fixed pole

Reflects elementary coupling of two photons to quarks

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

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

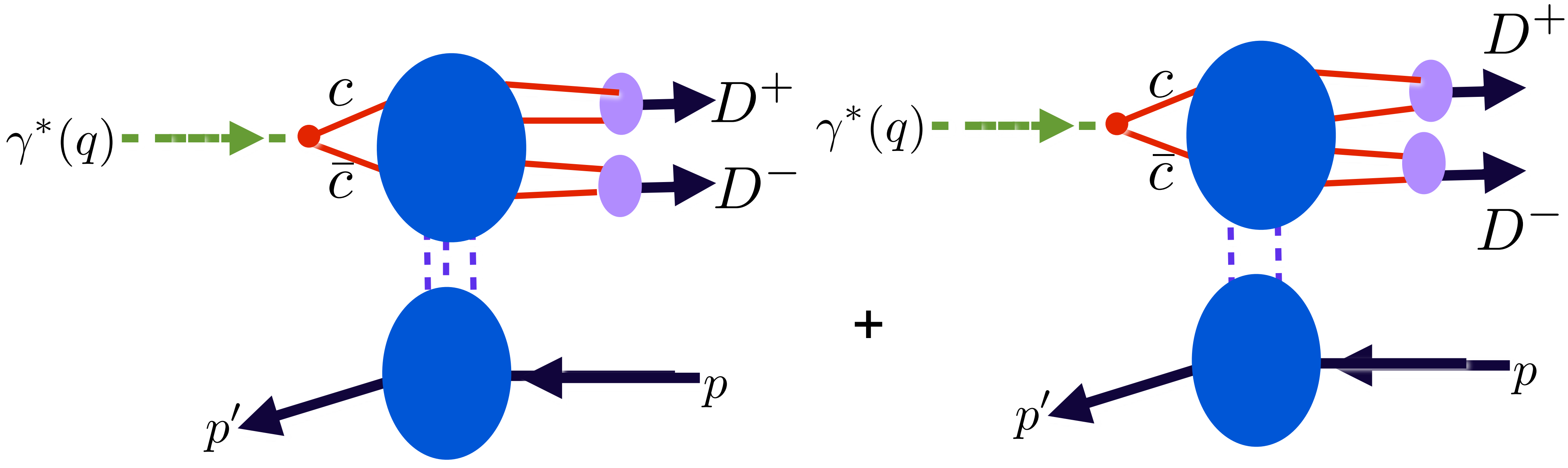
Fundamental test of QCD



Odderon has never been observed!

Look for Charge Asymmetries from Odderon-Pomeron Interference

Merino, Rathsman, sjb



Odderon-Pomeron Interference leads to $K^+ K^-$, $D^+ D^-$ and $B^+ B^-$ charge and angular asymmetries

Odderon at amplitude level

Merino, Rathsman, sjb

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

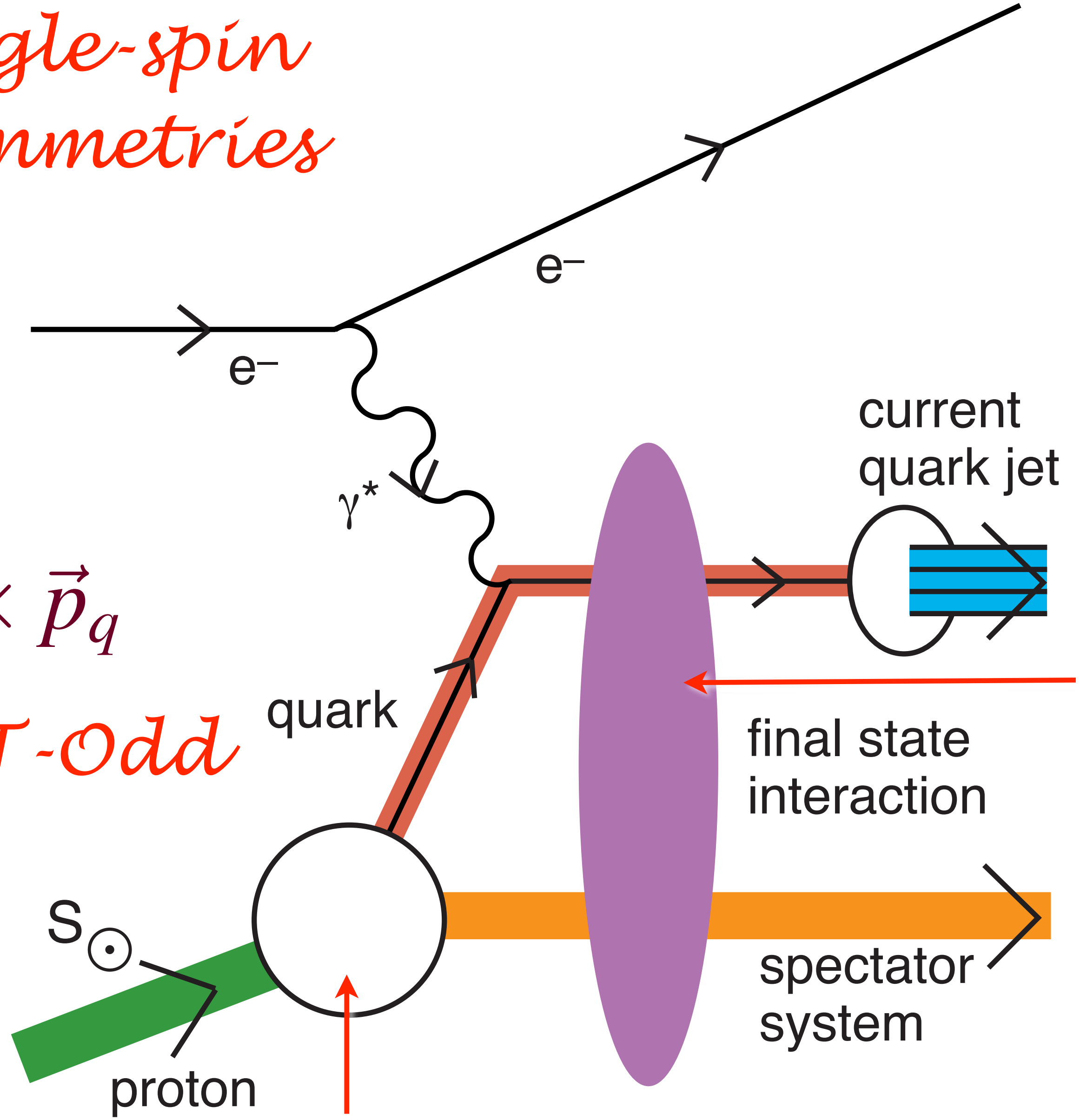
$$\frac{\pi \alpha_s(\beta^2 s)}{\beta}$$

Hoang, Kuhn, sjb

Leading Twist Sivers Effect

Single-spin asymmetries

Hwang, Schmidt, sjb



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

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

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

"Lensing Effect"

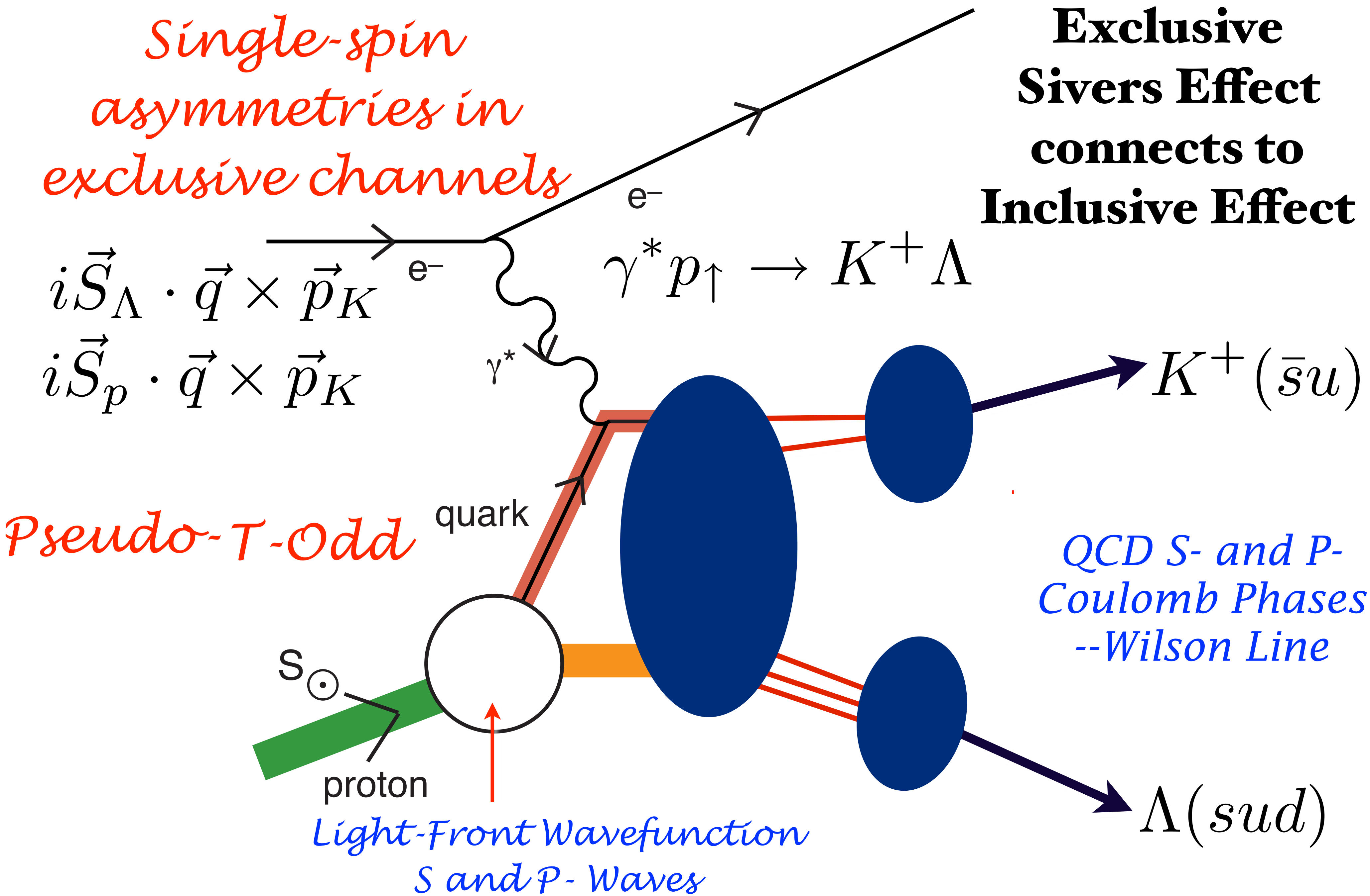
Pseudo-T-Odd

QED: Lensing involves soft scales

Light-Front Wavefunction S and P- Waves!

Leading-Twist Rescattering Violates pQCD Factorization!

Sign reversal in DY!


Single-spin asymmetries in exclusive channels
Exclusive Sivers Effect connects to Inclusive Effect
e⁻
e⁻
$i\vec{S}_\Lambda \cdot \vec{q} \times \vec{p}_K$
$i\vec{S}_p \cdot \vec{q} \times \vec{p}_K$
$\gamma^* p_\uparrow \to K^+ \Lambda$
γ^*
$K^+(\bar{s}u)$
quark
Pseudo-T-Odd
QCD S- and P- Coulomb Phases --Wilson Line
$S_\odot$
proton
$\Lambda(sud)$
Light-Front Wavefunction S and P- Waves

What is measured!

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,

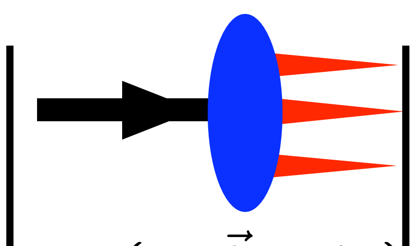
Mulders, Boer

Qiu, Sterman

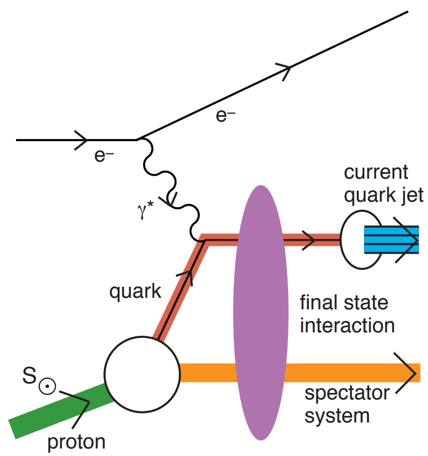
Collins, Qiu

Pasquini, Xiao, Yuan, sjb

Liuti, sjb

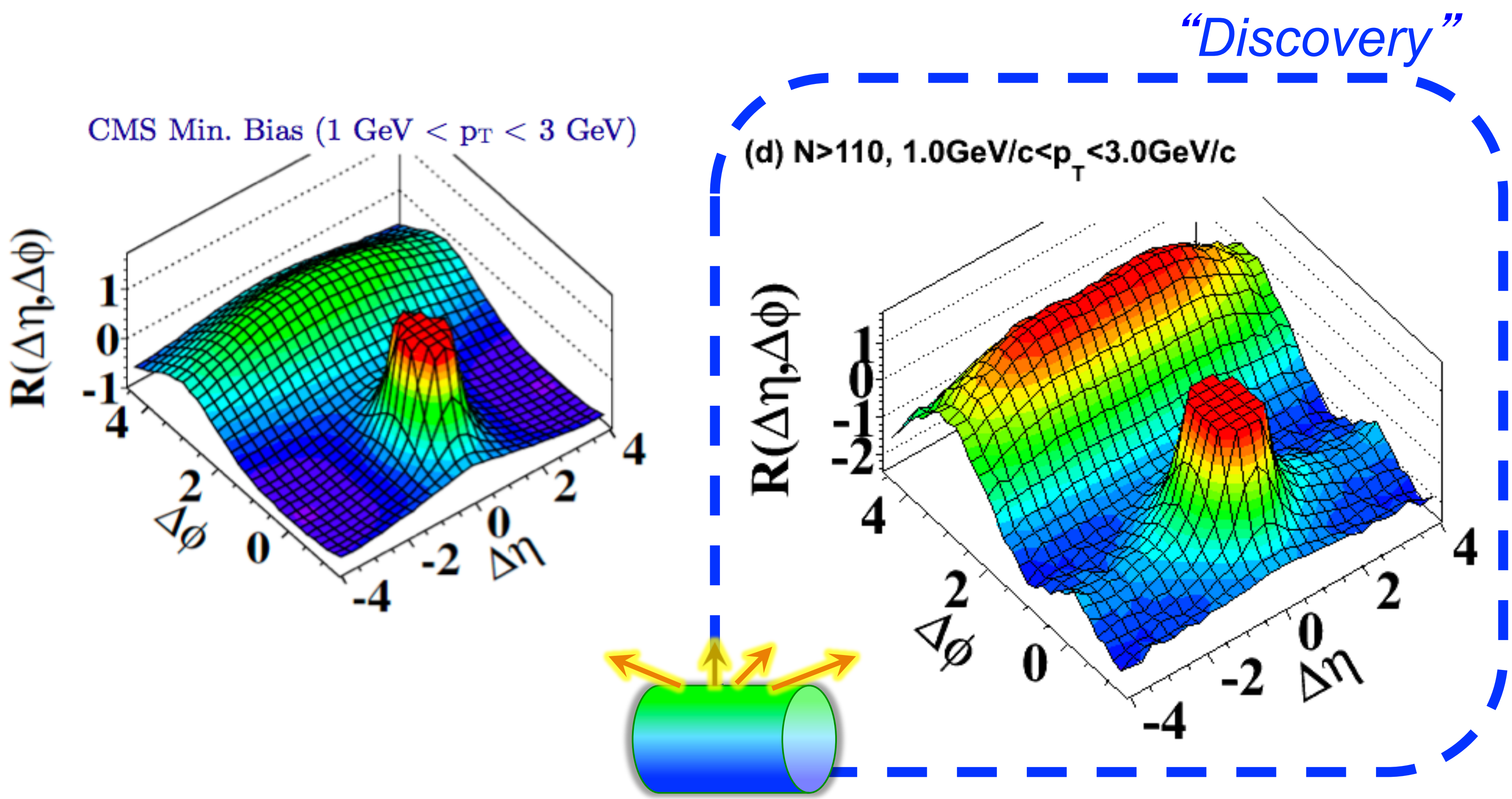


$$\left|\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)\right|^2$$



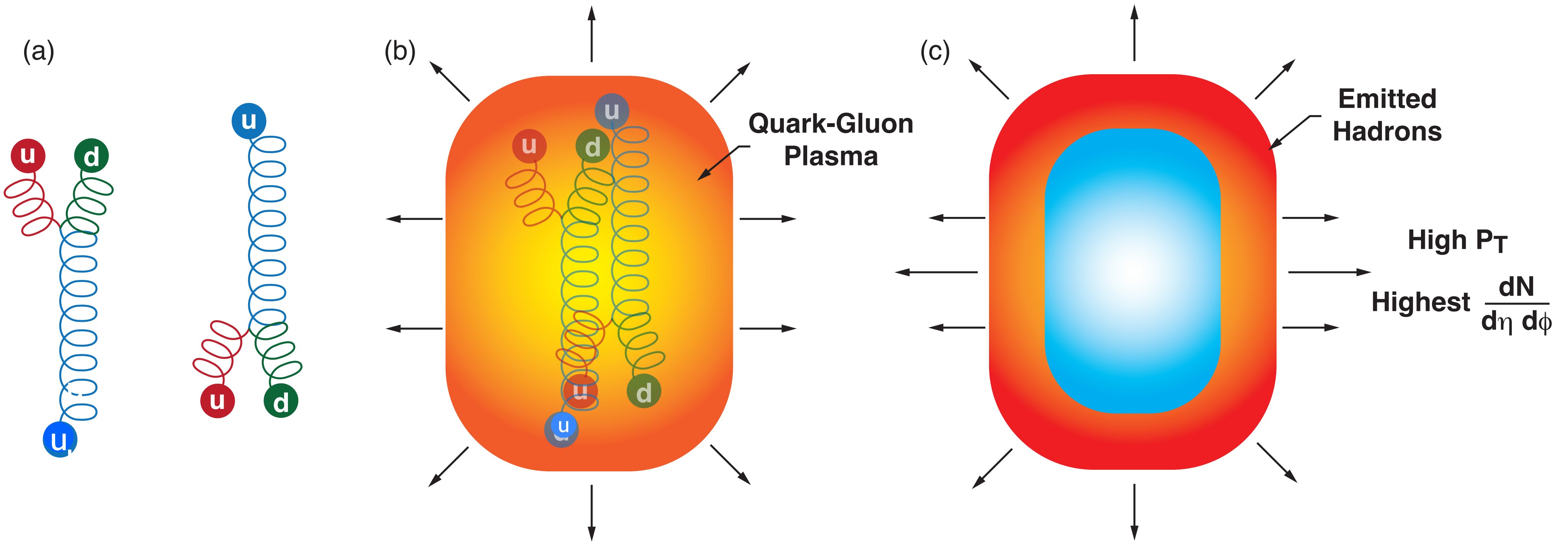
Ridge in high-multiplicity p p collisions

Two-particle correlations: CMS results



◆ **Ridge: Distinct long range correlation in η collimated around ΔΦ≈ 0 for two hadrons in the intermediate 1 < p_T, q_T < 3 GeV**

Ridge may reflect collision of aligned flux tubes



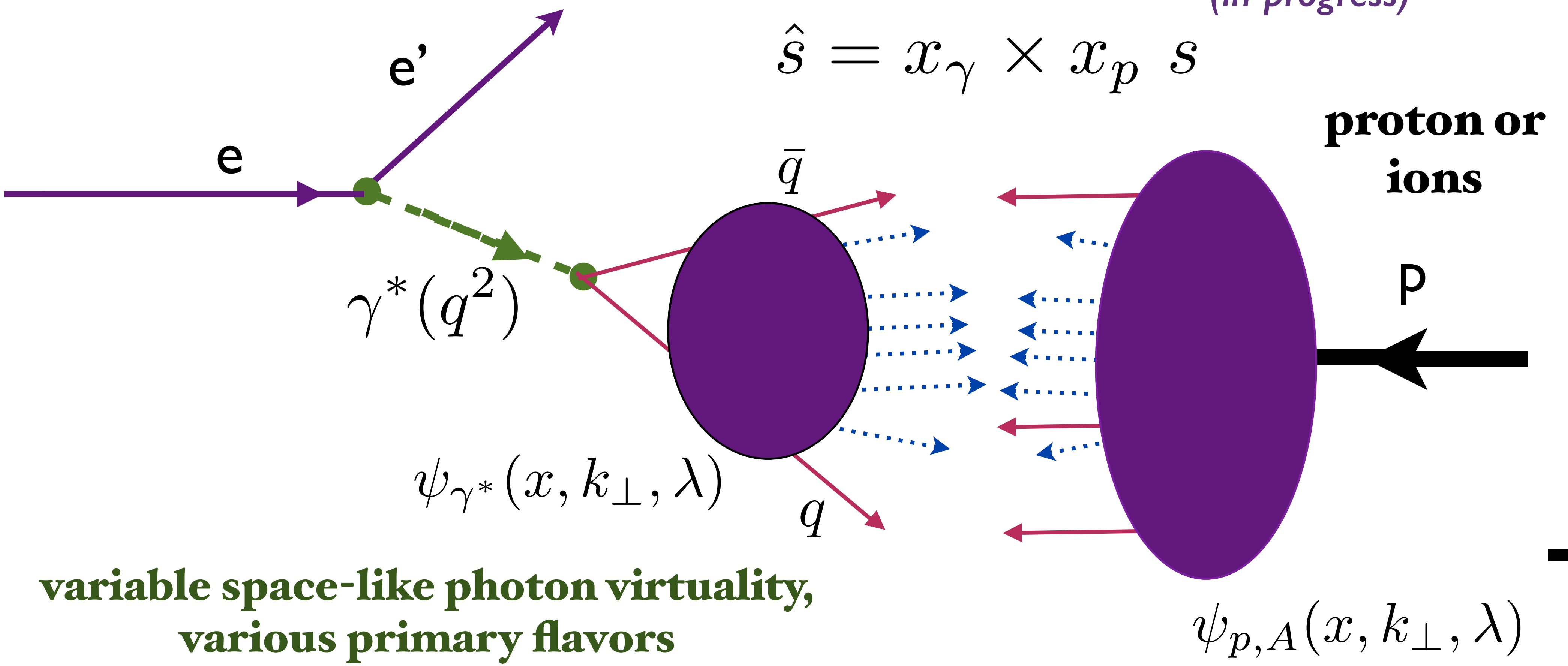
Bjorken, Goldhaber, sjb

Electron-Ion Collider:
Virtual Photon-Ion Collider

Perspective from the e-p collider frame

S. Glazek, P. Kubiczek, sjb
(in progress)

$\hat{s} = x_\gamma \times x_p \; s$



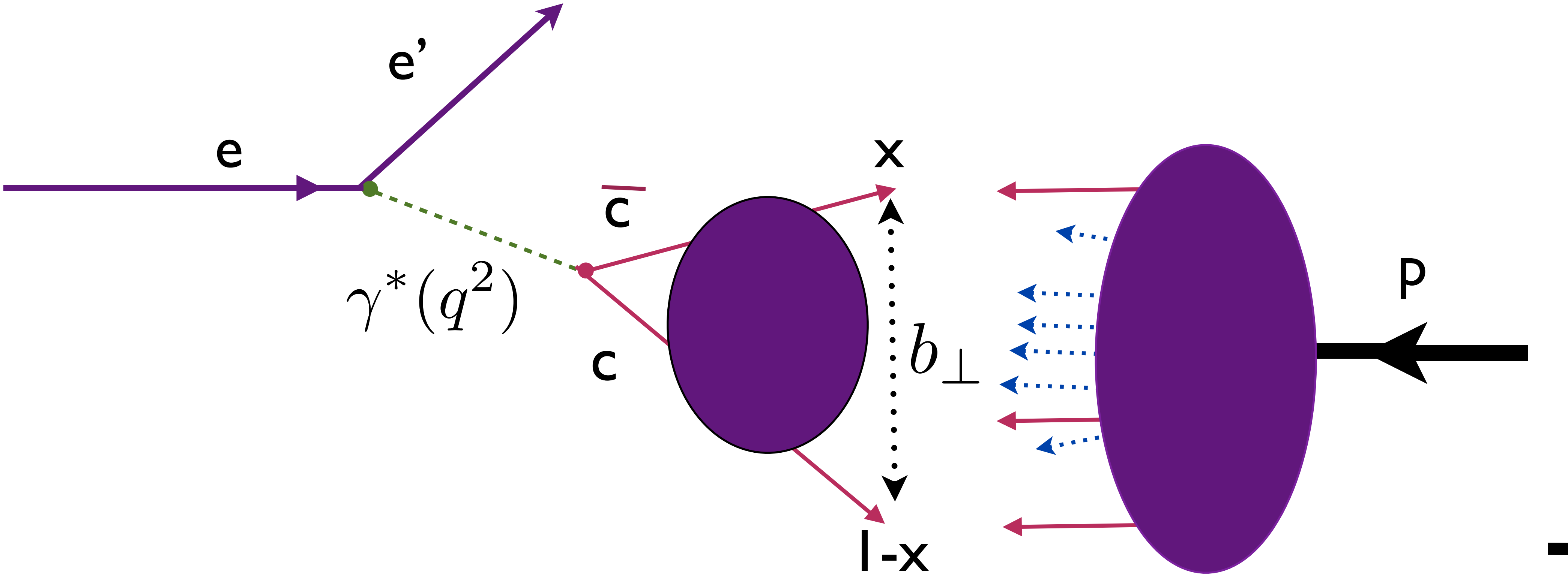
**variable space-like photon virtuality,
various primary flavors**

$\bar{q}$ q plane aligned with lepton scattering plane ~ cos²φ

Front-surface dynamics: shadowing/antishadowing

$\bar{c}$ c acts as a 'drill'

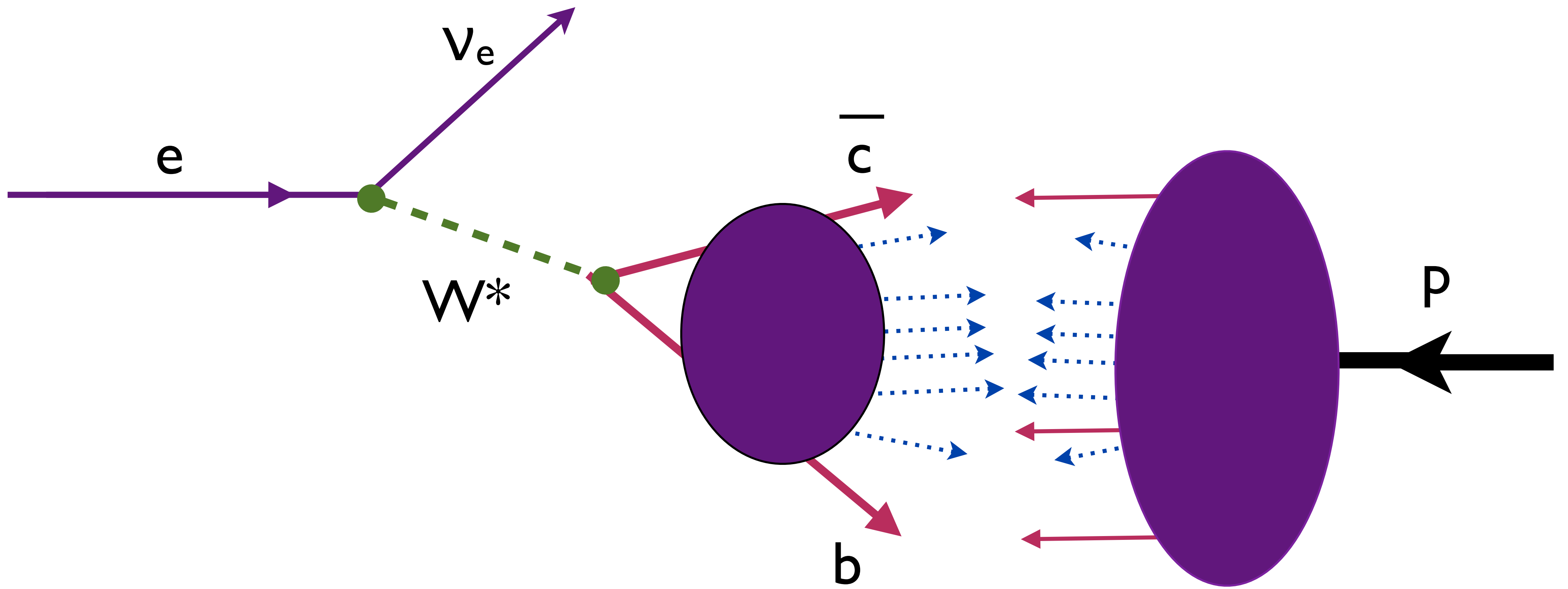
$$< b_\perp^2 > \sim \frac{1}{Q^2 x(1-x) + m_c^2}$$



High Q² virtual photon at an EIC acts as a precision, small bore, linearly oriented, flavor-dependent probe acting on a proton or nuclear target.

Study final-state hadron multiplicity distributions, ridges, nuclear dependence, etc.

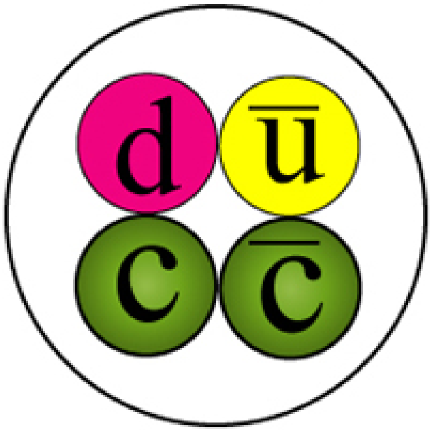
EIC: Virtual Weak Boson-Proton Collider



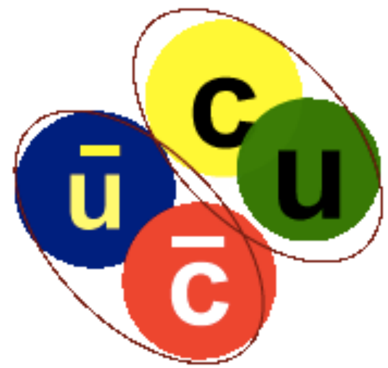
variable W* virtuality,
variable flavors

proton or ions

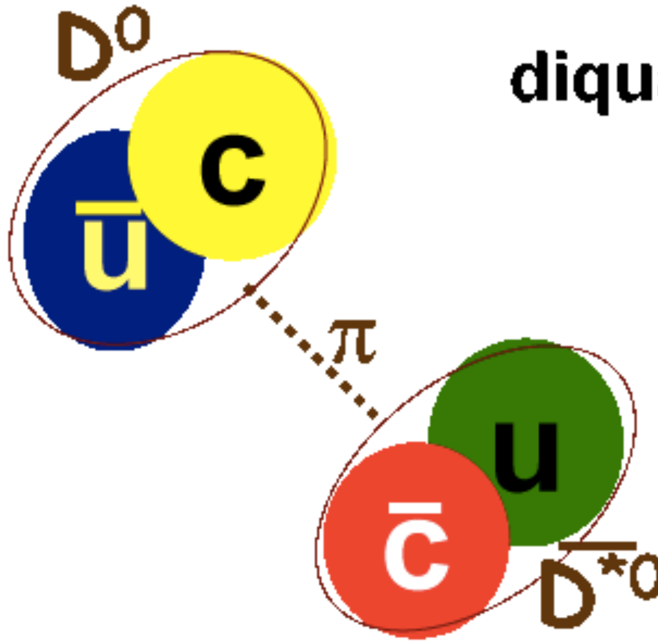
Z(4430)



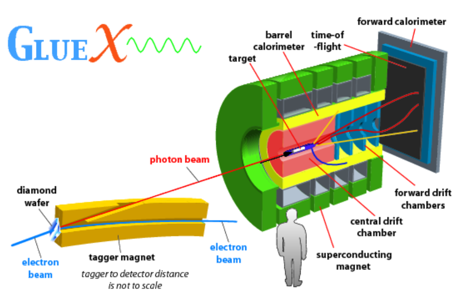
$[\bar{u}\bar{c}]_{3C}[uc]_{\bar{3}C}$ diquarks



diquark-diantiquark



$D^0 - \overline{D^{*0}}$ "molecule"



Novel Nuclear Photo-and Electroproduction Physics

JLab, April 29, 2016

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

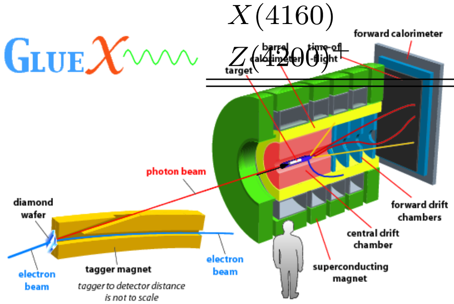
Four-Quark Hadrons: an Updated Review

arXiv:1411.5997v2

A. ESPOSITOA, L. GUERRIERI, F. PICCININI, A. PILLONI and A. POLOSA

State	M (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)
$X(3823)$	3823.1 ± 1.9	< 24	$?^{?-}$	$B \to K(\chi_{c1}\gamma)$	Belle[23] (4.0)
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle[24,25] (>10), *BABAR*[26] (8.6)
				$p\bar{p} \to (\pi^+\pi^- J/\psi)\ldots$	CDF[27,28] (11.6), D0[29] (5.2)
				$pp \to (\pi^+\pi^- J/\psi)\ldots$	LHCb[30,31] (np)
				$B \to K(\pi^+\pi^-\pi^0 J/\psi)$	Belle[32] (4.3), *BABAR*[33] (4.0)
				$B \to K(\gamma\, J/\psi)$	Belle[34] (5.5), *BABAR*[35] (3.5)
					LHCb[36] (> 10)
				$B \to K(\gamma\, \psi(2S))$	*BABAR*[35] (3.6), Belle[34] (0.2)
					LHCb[36] (4.4)
				$B \to K(D\bar{D}^*)$	Belle[37] (6.4), *BABAR*[38] (4.9)
$Z_c(3900)^+$	3888.7 ± 3.4	35 ± 7	1^{+-}	$Y(4260) \to \pi^-(D\bar{D}^*)^+$	BES III[39] (np)
				$Y(4260) \to \pi^-(\pi^+ J/\psi)$	BES III[40] (8), Belle[41] (5.2)
					CLEO data[42] (>5)
$Z_c(4020)^+$	4023.9 ± 2.4	10 ± 6	1^{+-}	$Y(4260) \to \pi^-(\pi^+ h_c)$	BES III[43] (8.9)
				$Y(4260) \to \pi^-(D^*\bar{D}^*)^+$	BES III[44] (10)
$Y(3915)$	3918.4 ± 1.9	20 ± 5	0^{++}	$B \to K(\omega J/\psi)$	Belle[45] (8), *BABAR*[33,46] (19)
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle[47] (7.7), *BABAR*[48] (7.6)
$Z(3930)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$	Belle[49] (5.3), *BABAR*[50] (5.8)
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\bar{D}^*)$	Belle[51,52] (6)
$Y(4008)$	3891 ± 42	255 ± 42	1^{--}	$e^+e^- \to (\pi^+\pi^- J/\psi)$	Belle[41,53] (7.4)
$Z(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle[54] (5.0), *BABAR*[55] (1.1)
$Y(4140)$	4145.6 ± 3.6	14.3 ± 5.9	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF[56,57] (5.0), Belle[58] (1.9),
					LHCb[59] (1.4), CMS[60] (>5)
					D∅[61] (3.1)
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi\,(D^*\bar{D}^*)$	Belle[52] (5.5)
$Z(4200)^+$	4196^{+35}_{-30}	370^{+99}_{-110}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle[62] (7.2)

GLUEX



Novel Nuclear Photo-and Electroproduction Physics

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

JLab, April 29, 2016

de Tèramond, Dosch, Lorce, sjb

New World of Tetraquarks

$$3_C \times 3_C = \bar{3}_C + 6_C$$

Bound!

- Diquark Color-Confined Constituents: Color $\bar{3}_C$
- Diquark-Antidiquark bound states

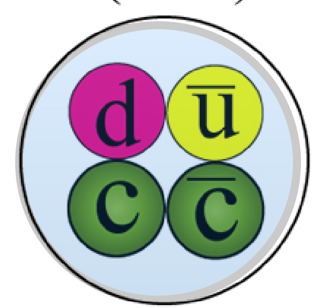
Complete Regge spectrum in n, L

- Confinement Force Similar to quark-antiquark $\bar{3}_C \times 3_C = 1_C$ mesons
- Isospin $I = 0, \pm 1, \pm 2$ Charge $Q = 0, \pm 1, \pm 2$

$uu\bar{d}\bar{d}$ $uu\bar{s}\bar{d}$ $uu\bar{s}\bar{s}$

Q= +2

Z(4430)



Q= - 1

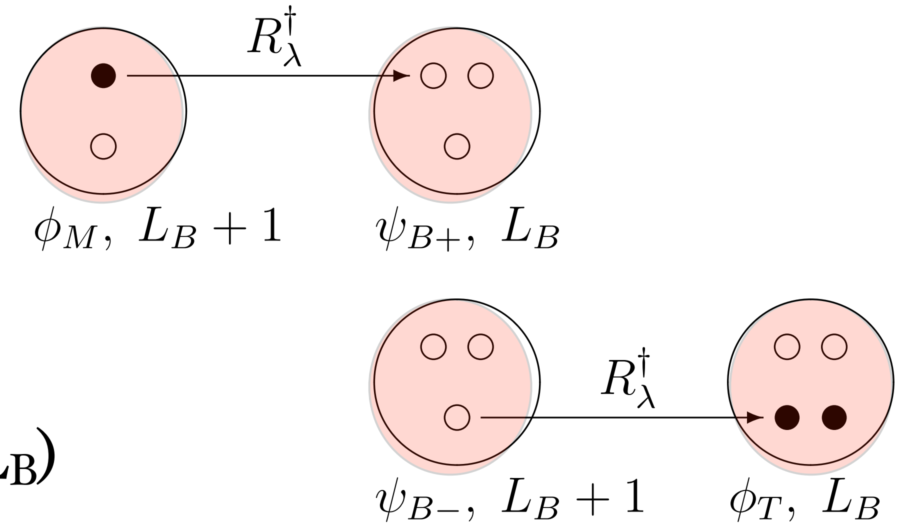
de Tèramond, Dosch, Lorce, sjb

Superconformal Algebra

2X2 Hadronic Multiplets

$$\begin{pmatrix} \phi_M(L_M = L_B + 1) & \psi_{B-}(L_B + 1) \\ \psi_{B+}(L_B) & \phi_T(L_T = L_B) \end{pmatrix}$$

- quark-antiquark meson ($L_M = L_B+1$)
- quark-diquark baryon (L_B)
- quark-diquark baryon (L_B+1)
- diquark-antidiquark tetraquark ($L_T = L_B$)
- Universal Regge slopes $\lambda = \kappa^2$



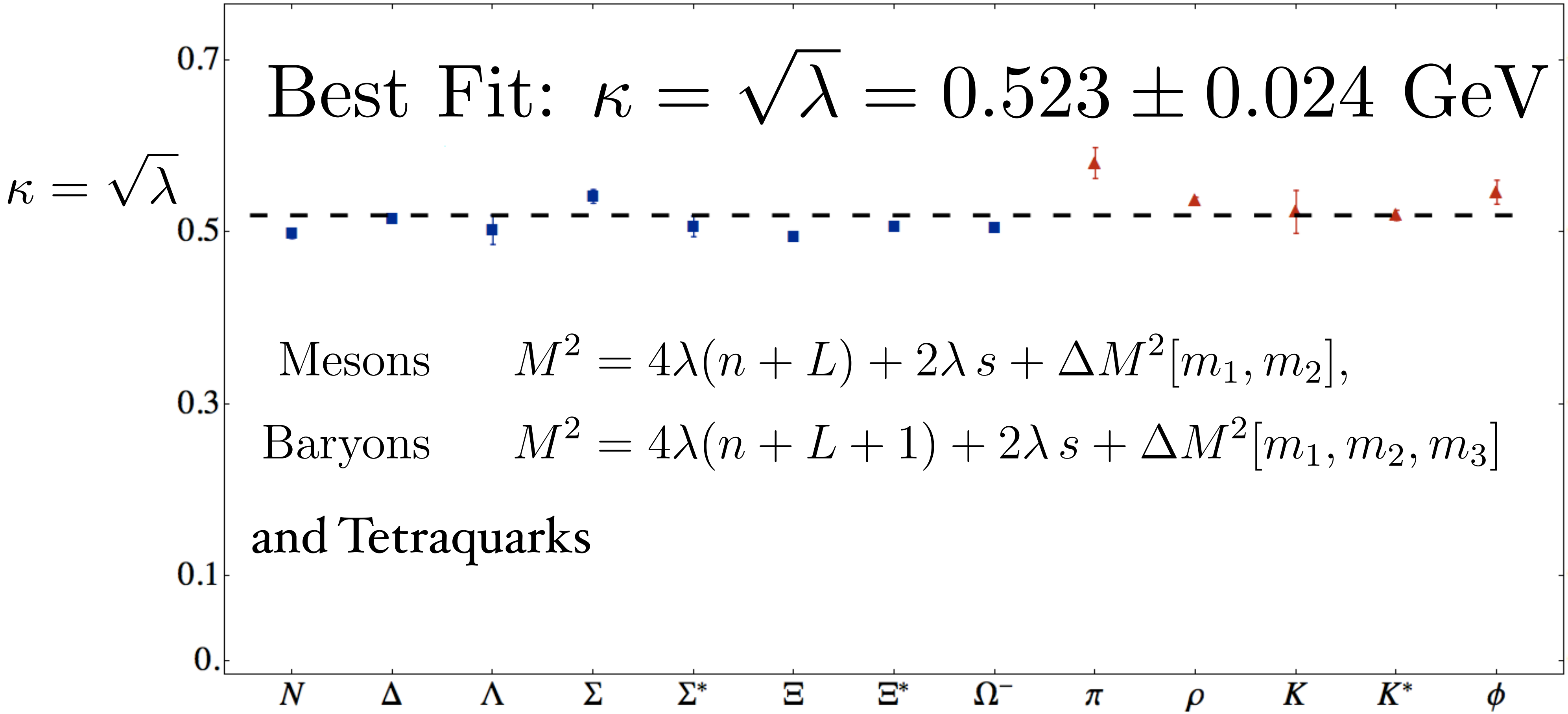
$$M^2_H/\lambda = \overbrace{\underbrace{(2n + L_H + 1)}_{kinetic} + \underbrace{(2n + L_H + 1)}_{potential}}^{contribution\ from\ 2\text{-}dim\ light\text{-}front\ harmonic\ oscillator} + \overbrace{2(L_H + s) + 2\chi}^{contribution\ from\ AdS\ and\ superconformal\ algebra} + < \sum_i \frac{m_i^2}{x_i} >$$

$\chi(mesons) = -1$ $\chi(baryons, tetraquarks) = +1$

- Universal Regge slopes

Dosch, de Teramond, Lorce, sjb

$$M_H^2 = 4\lambda(n+L) + \cdots$$



Best fit for the value of the hadronic scale $\sqrt{\lambda}$ for the different Regge trajectories for baryons and mesons including all radial and orbital excitations using Eqs. (23) and (24). The dotted line is the average value $\sqrt{\lambda} = 0.523$ GeV; it has the standard deviation $\sigma = 0.024$ GeV. For the baryon sample alone the values are 0.509 ± 0.015 GeV and for the mesons 0.524 ± 0.023 GeV.

de Tèramond, Dosch, Lorce, sjb

New World of Tetraquarks

$$3_C \times 3_C = \bar{3}_C + 6_C$$

Bound!

- Diquark: Color-Confined Constituents: Color $\bar{3}_C$
- Diquark-Antidiquark bound states $\bar{3}_C \times 3_C = 1_C$

$$\sigma(TN) \simeq 2\sigma(pN) - \sigma(\pi N)$$

$$2\left[\sigma([\{qq\}N) + \sigma(qN)\right] - [\sigma(qN) + \sigma(\bar{q}N)] = [\sigma(\{qq\}N) + \sigma(\{qq\}N)]$$

Candidates $f_0(980) I = 0, J^P = 0^+$, partner of proton

$a_1(1260) I = 0, J^P = 1^+$, partner of $\Delta(1233)$

Belle, BaBar:

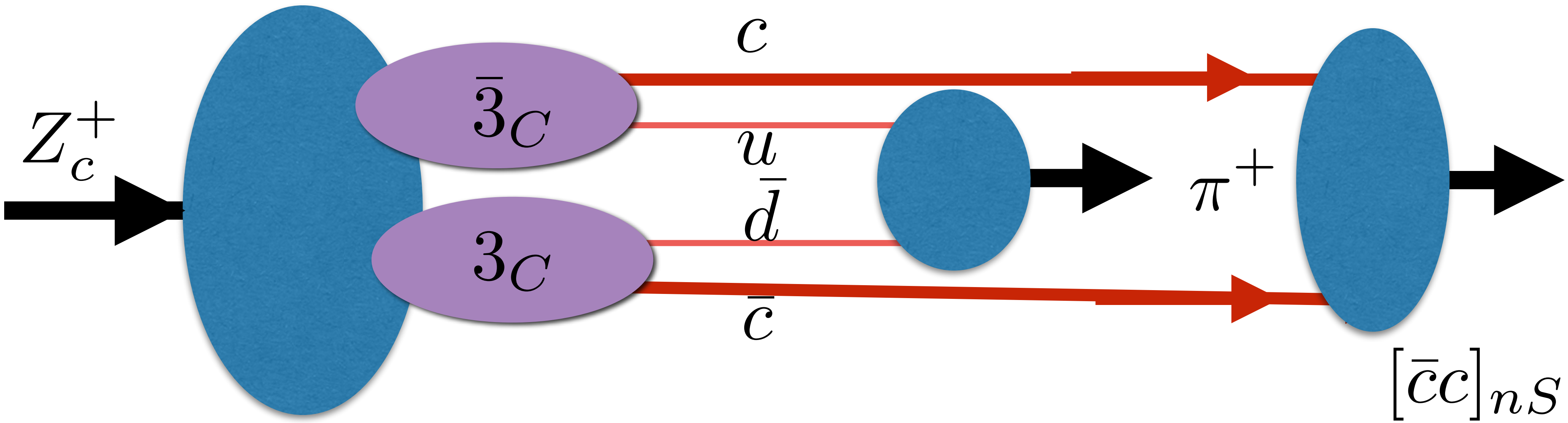
$$\mathcal{B}\left(B^0 \to K^+ Z(4430)^-\right) \times \mathcal{B}\left(Z(4430)^- \to \psi(2S)\pi^-\right) = \left(6.0^{+1.7+2.5}_{-2.0-1.4}\right) \times 10^{-5}.$$

$$\mathcal{B}\left(B^0 \to K^+ Z(4430)^-\right) \times \mathcal{B}\left(Z(4430)^- \to J/\psi\,\pi^-\right) = \left(5.4^{+4.0+1.1}_{-1.0-0.6}\right) \times 10^{-6}.$$

Surprising Result:

Dominance of large size $\psi'(2S)$ vs. J/ψ decays

Diquark Anti-diquark Model



$$Z_c^+([cu]_{\bar{3}C}[\bar{c}\bar{d}]_{3C}) \to \pi^+\psi'$$

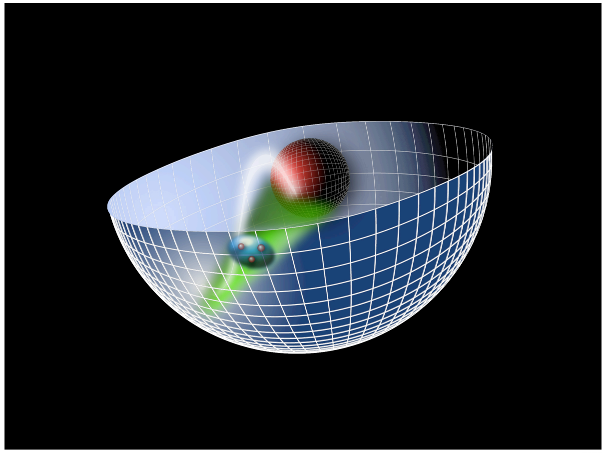
Formation of charmonium at large separation:

Dominance of overlap with large-size Ψ' vs J/Ψ decays

Lebed, Hwang, sjb

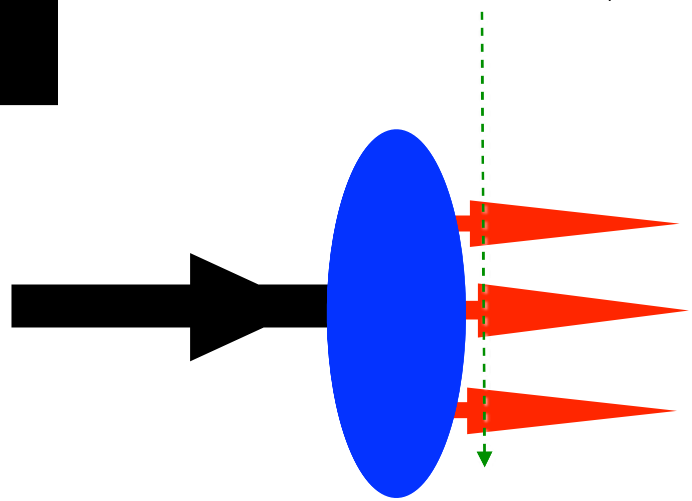
$\phi(z)$

AdS5: Conformal Template for QCD

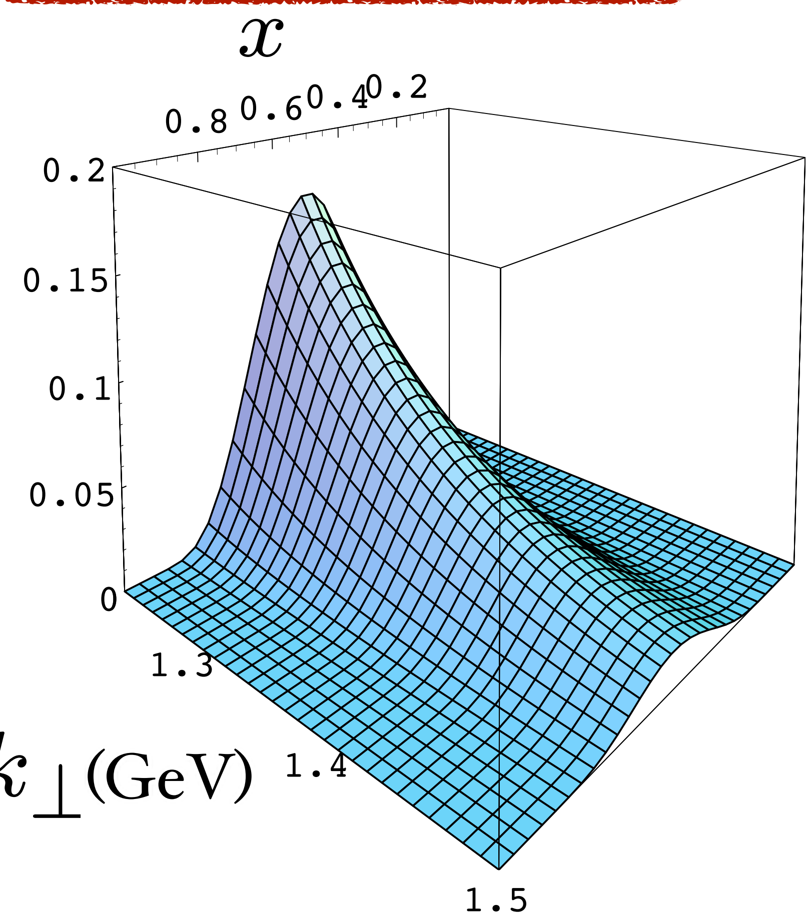


- *Light-Front Holography*

Duality of AdS₅ with LF Hamiltonian Theory



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



- *Light Front Wavefunctions:*

Light-Front Schrödinger Equation
Spectroscopy and Dynamics

with Guy de Teramond, Alexandre Deur, Cedric Lorce, Hans Guenter Dosch

QCD Lagrangian

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

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

Classical Chiral Lagrangian is Conformally Invariant

Where does the QCD Mass Scale Λ_{QCD} come from?

How does color confinement arise?

- **de Alfaro, Fubini, Furlan:**

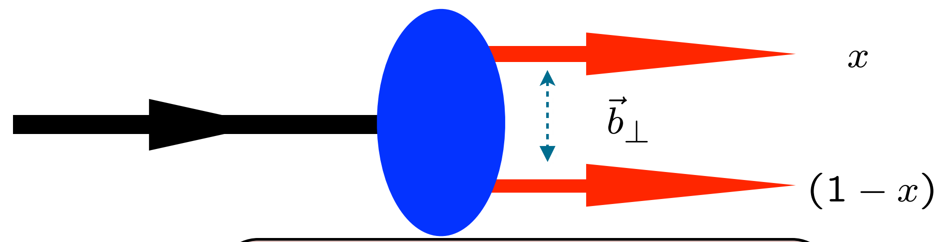
Scale can appear in Hamiltonian and EQM without affecting conformal invariance of action!

Unique confinement potential!

Light-Front QCD

Fixed $\tau = t + z/c$

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



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

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

Coupled Fock states

Eliminate higher Fock states and retarded interactions

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

Effective two-particle equation

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

Azimuthal Basis

ζ, ϕ

$m_q = 0$

AdS/QCD:

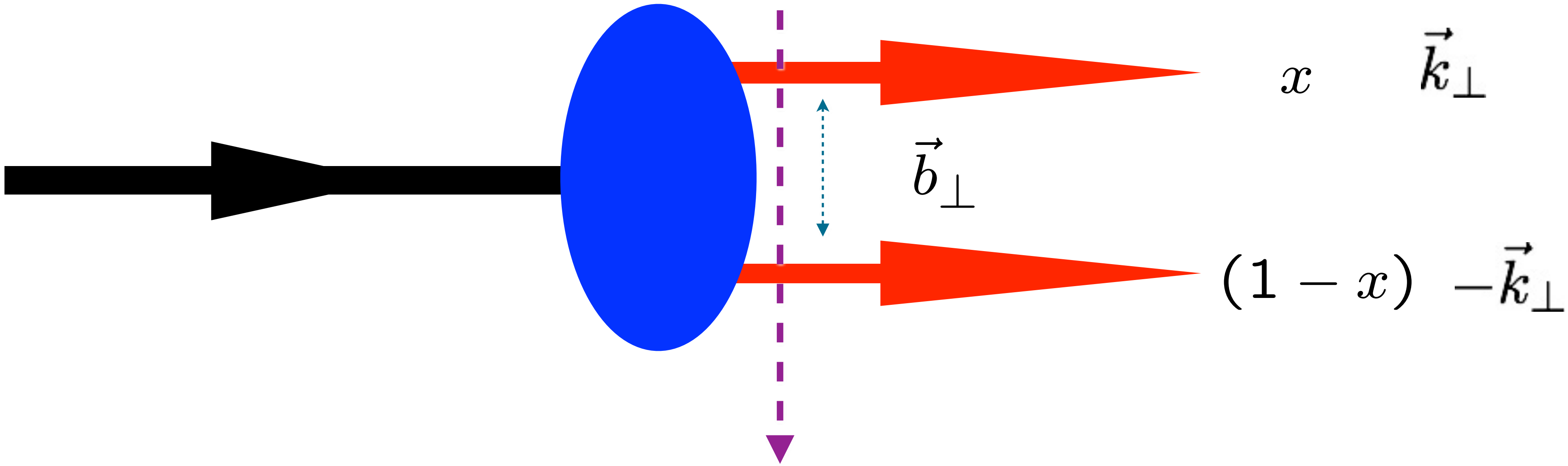
$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L+S-1)$$

Confining AdS/QCD potential!

Sums an infinite # diagrams

Semiclassical first approximation to QCD

Fixed $\tau = t + z/c$



$$\zeta^2 \equiv b_\perp^2 x(1-x)$$

Invariant transverse separation

$$\zeta^2 \text{ conjugate to } \frac{k_\perp^2}{x(1-x)} = (p_q + p_{\bar{q}})^2 = \mathcal{M}^2_{q+\bar{q}}$$

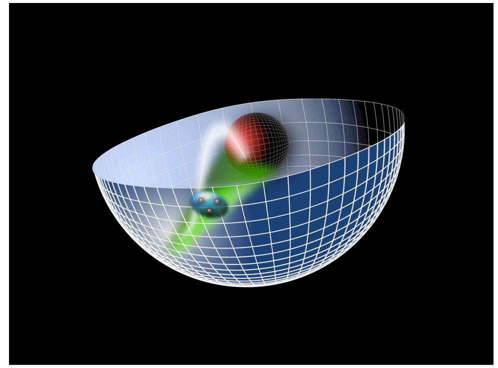
$$\int dk^- \Psi_{BS}(P,k) \to \psi_{LF}(x, \vec{k}_\perp)$$

de Tèramond, Dosch, sjb

AdS/QCD
Soft-Wall Model

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

Single scheme-independent fundamental mass scale



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!

Preserves Conformal Symmetry of the action

Confinement scale:

$$\kappa \simeq 0.6\ GeV$$

$$1/\kappa \simeq 1/3\ fm$$

$$m_q = 0$$

- **de Alfaro, Fubini, Furlan:**
- **Fubini, Rabinovici:**

Scale can appear in Hamiltonian and EQM without affecting conformal invariance of action!

Light-Front Schrödinger Equation

G. de Teramond, sjb

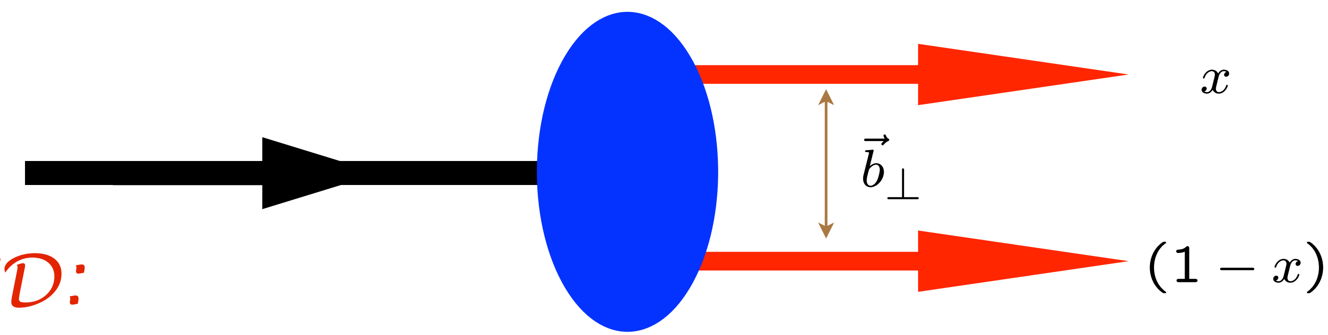
Relativistic LF single-variable radial equation for QCD & QED

Frame Independent!

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

$$m_q \sim 0$$

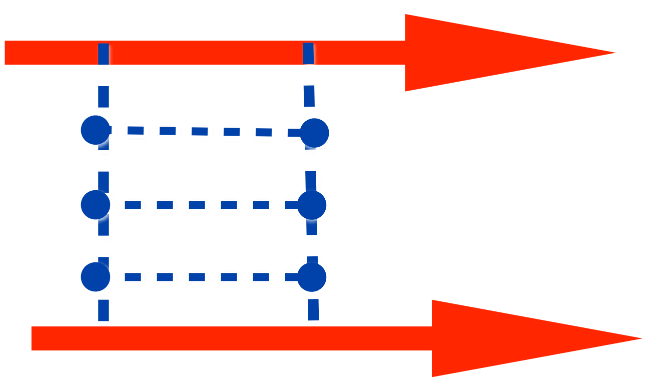
$$\zeta^2 = x(1-x)\mathbf{b}_\perp^2 .$$



AdS/QCD:

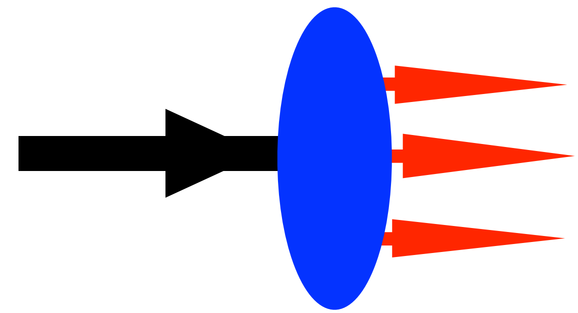
$$U(\zeta, S, L) = \kappa^2 \zeta^2 + \kappa^2 (L + S - 1/2)$$

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



AdS/QCD and Light-Front Holography

- A first, semi-classical approximation to nonpertubative QCD
- Hadron Spectroscopy and LF Dynamics
- Color Confinement Potential
- Running QCD Coupling α(Q²) at All Scales Q²
- What sets the QCD Mass Scale?
- Connection of Hadron Masses to $\Lambda_{\overline{MS}}$

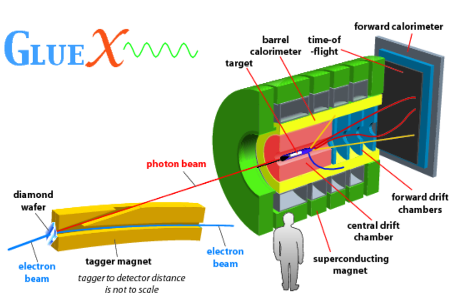


$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

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

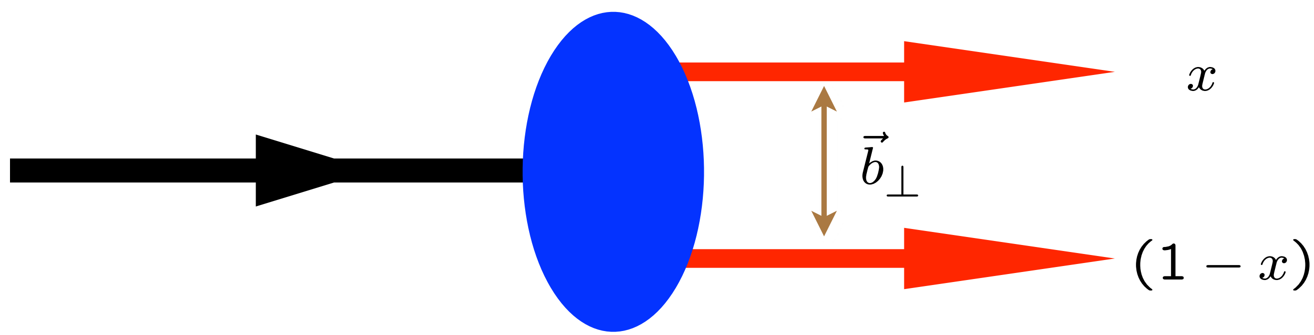


de Teramond, sjb

$LF(3+1) \longleftrightarrow AdS_5$

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

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



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

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

Meson Spectrum in Soft Wall Model

Pion: Negative term for J=0 cancels positive terms from LFKE and potential

- Effective potential: $U(\zeta^2) = \kappa^4\zeta^2 + 2\kappa^2(J-1)$
- LF WE

$$\left(-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + \kappa^4\zeta^2 + 2\kappa^2(J-1)\right)\phi_J(\zeta) = M^2\phi_J(\zeta)$$

- Normalized eigenfunctions $\langle\phi|\phi\rangle = \int d\zeta\, \phi^2(z)^2 = 1$

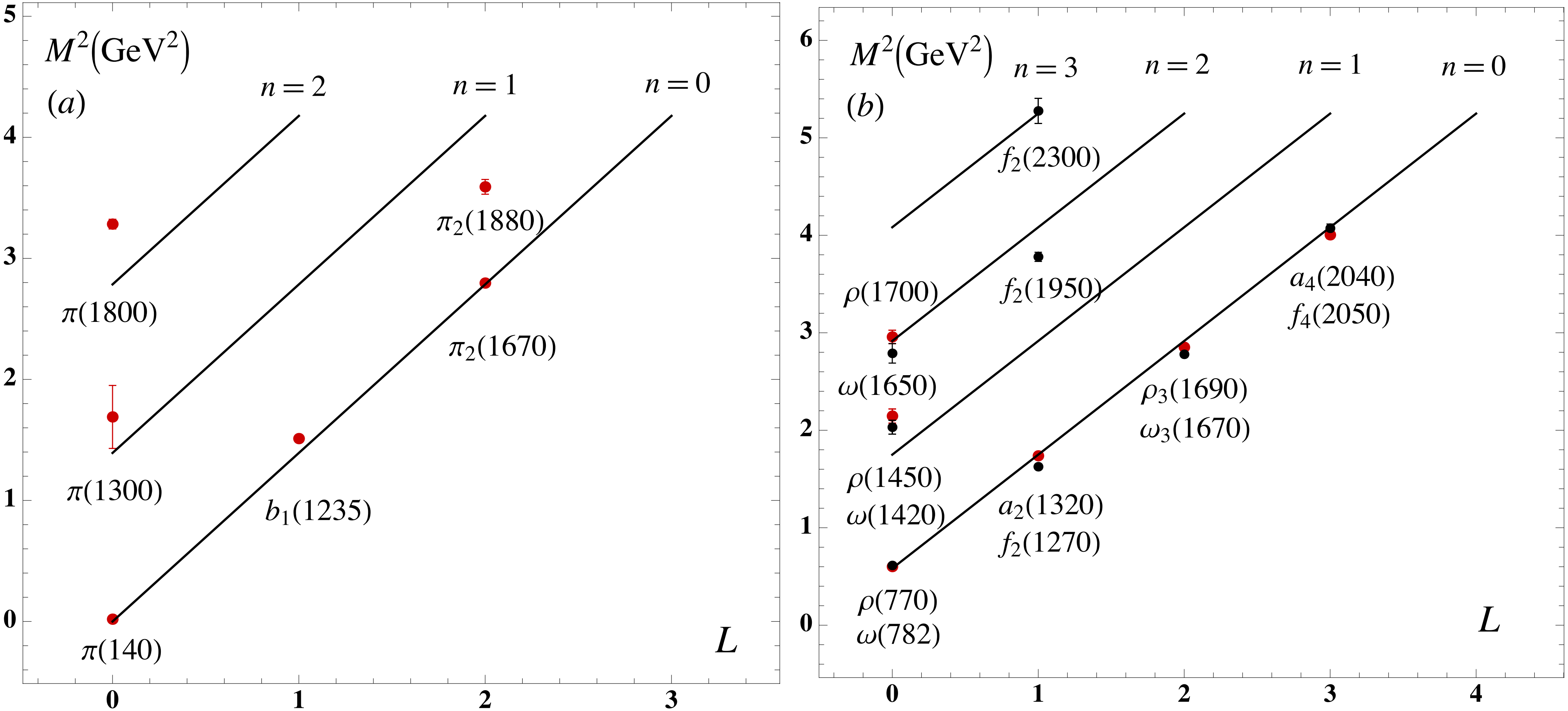
$$\phi_{n,L}(\zeta) = \kappa^{1+L}\sqrt{\frac{2n!}{(n+L)!}}\,\zeta^{1/2+L}e^{-\kappa^2\zeta^2/2}L_n^L(\kappa^2\zeta^2)$$

- Eigenvalues

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

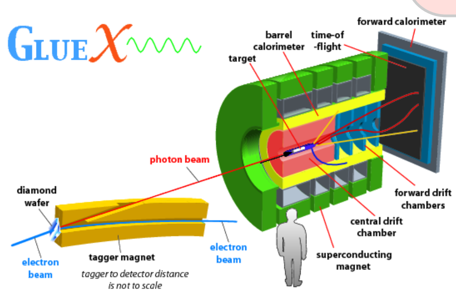
G. de Teramond, H. G. Dosch, sjb

Prediction from AdS/QCD



$$m_u = m_d = 0$$

$$M^2(n, L, S) = 4\kappa^2(n + L + S/2)$$



Novel Nuclear Photo-and Electroproduction Physics

JLab, April 29, 2016

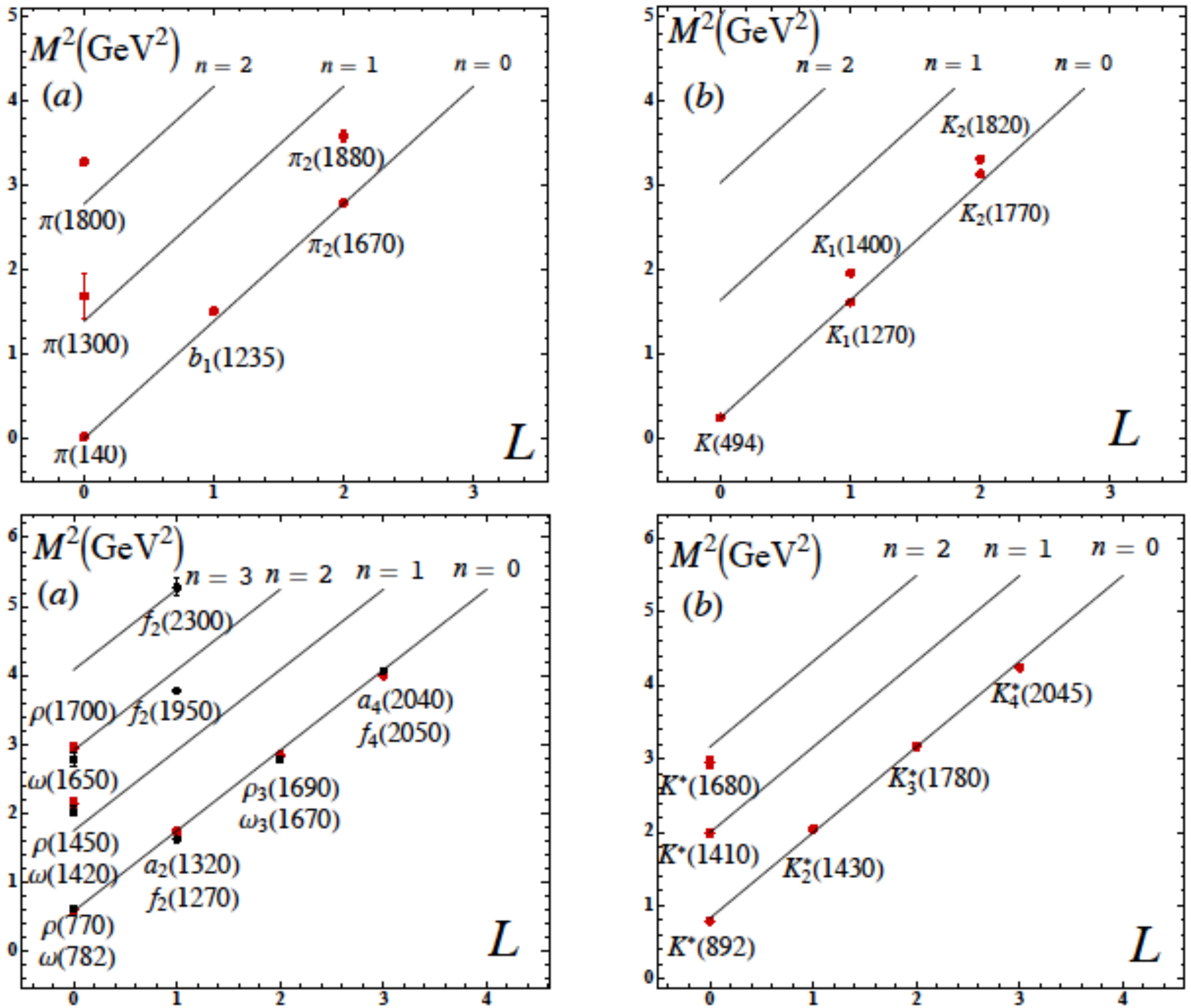
Stan Brodsky

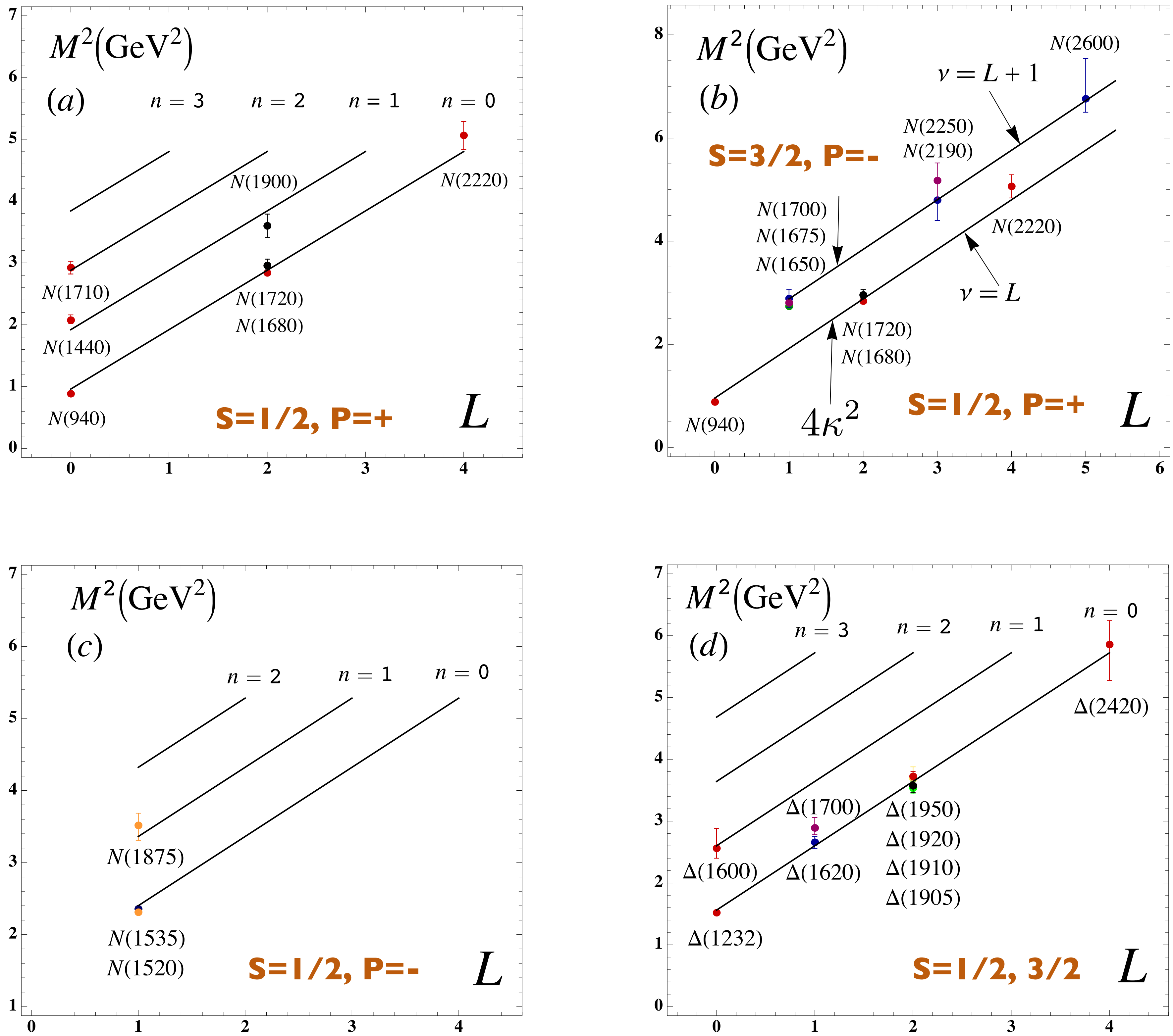
SLAC
NATIONAL ACCELERATOR LABORATORY

De Tèramond, Dosch, sjb

$$m_u = m_d = 46 \text{ MeV}, \quad m_s = 357 \text{ MeV}$$

$$M^2 = M_0^2 + \left\langle X \left| \frac{m_q^2}{x} \right| X \right\rangle + \left\langle X \left| \frac{m_{\bar{q}}^2}{1-x} \right| X \right\rangle$$





$M^2(\mathrm{GeV}^2)$
(a)
n = 3
n = 2
n = 1
n = 0
N(1900)
N(2220)
N(1710)
N(1440)
N(1720)
N(1680)
N(940)
S=1/2, P=+
L
$M^2(\mathrm{GeV}^2)$
(b)
N(2600)
$\nu = L + 1$
N(2250)
N(2190)
S=3/2, P=-
N(1700)
N(1675)
N(1650)
N(2220)
$\nu = L$
N(1720)
N(1680)
N(940)
$4\kappa^2$
S=1/2, P=+
L
$M^2(\mathrm{GeV}^2)$
(c)
n = 2
n = 1
n = 0
N(1875)
N(1535)
N(1520)
S=1/2, P=-
L
$M^2(\mathrm{GeV}^2)$
(d)
n = 3
n = 2
n = 1
n = 0
Δ(2420)
Δ(1700)
Δ(1950)
Δ(1920)
Δ(1910)
Δ(1905)
Δ(1600)
Δ(1620)
Δ(1232)
S=1/2, 3/2
L

LF Holography

Baryon Equation

$$\left(-\partial_\zeta^2 + \kappa^4\zeta^2 + 2\kappa^2(L_B+1) + \frac{4L_B^2-1}{4\zeta^2}\right)\psi_J^+ = M^2\psi_J^+$$ G_{22}

$$\left(-\partial_\zeta^2 + \kappa^4\zeta^2 + 2\kappa^2 L_B + \frac{4(L_B+1)^2-1}{4\zeta^2}\right)\psi_J^- = M^2\psi_J^-$$ G_{11}

$$M^2(n, L_B) = 4\kappa^2(n + L_B + 1)$$

S=1/2, P=+

both chiralities

Meson Equation

$$\left(-\partial_\zeta^2 + \kappa^4\zeta^2 + 2\kappa^2(J-1) + \frac{4L_M^2-1}{4\zeta^2}\right)\phi_J = M^2\phi_J$$ G_{11}

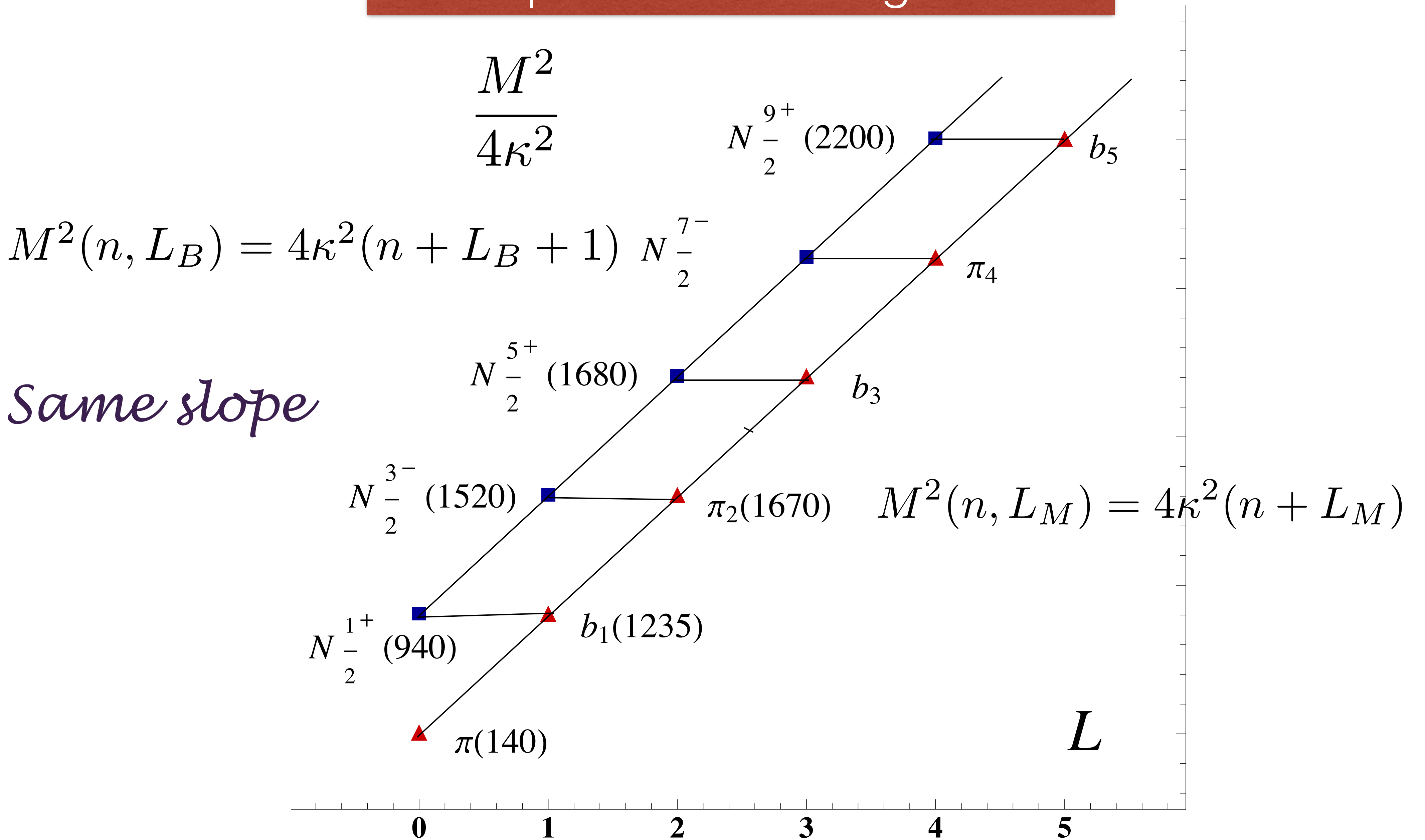
$$M^2(n, L_M) = 4\kappa^2(n + L_M)$$

Same κ!

S=0, I=1 Meson is superpartner of S=1/2, I=1 Baryon

Meson-Baryon Degeneracy for $L_M=L_B+1$

Superconformal Algebra

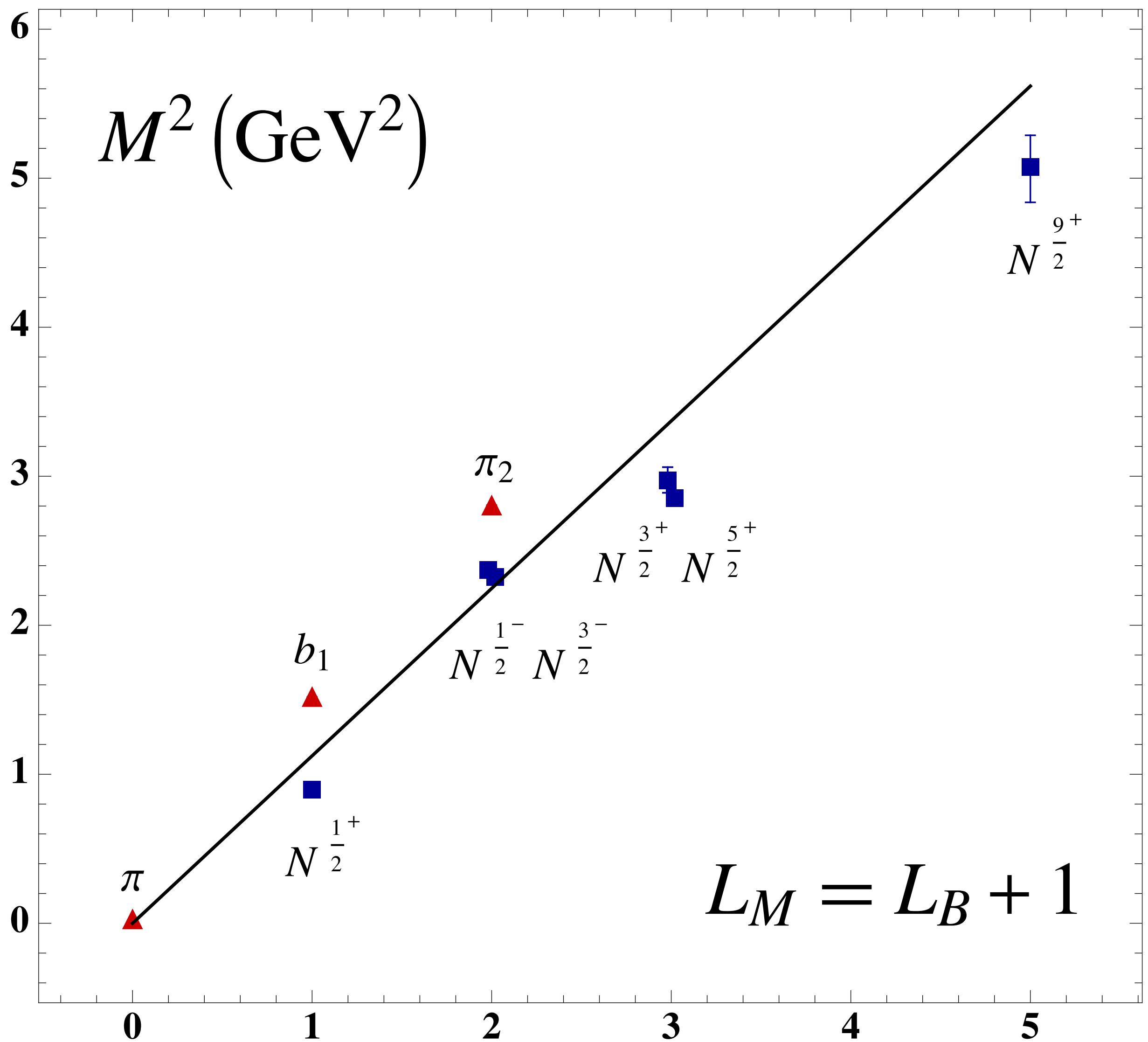


Same slope

Meson-Baryon Mass Degeneracy for $L_M = L_B + 1$

Dosch, de Teramond, sjb

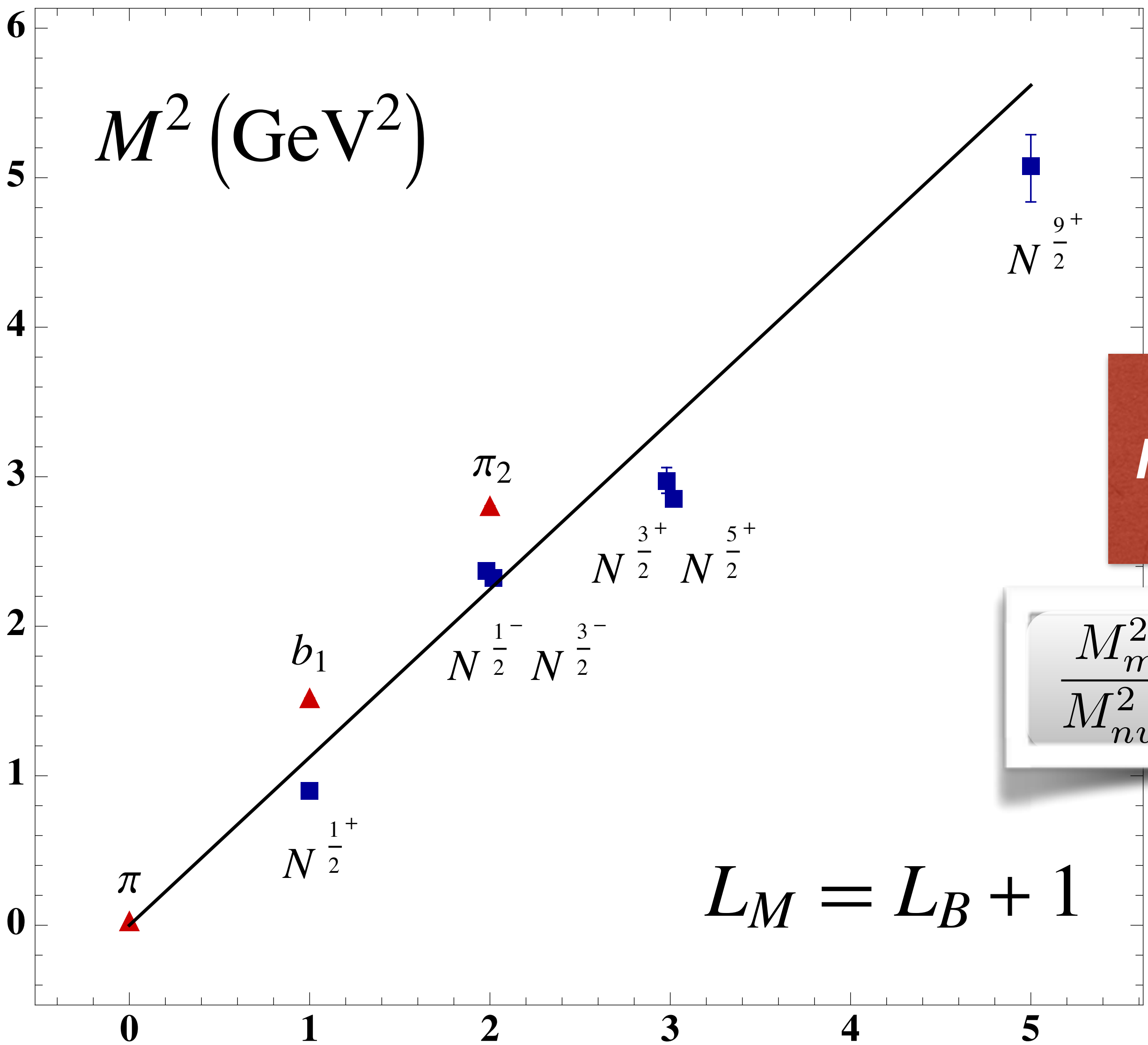
Superconformal AdS Light-Front Holographic QCD (LFHQCD): Identical meson and baryon spectra!



Meson-Baryon Mass Degeneracy for $L_M=L_B+1$

S=0, I=1 Meson is superpartner of S=1/2, I=1 Baryon

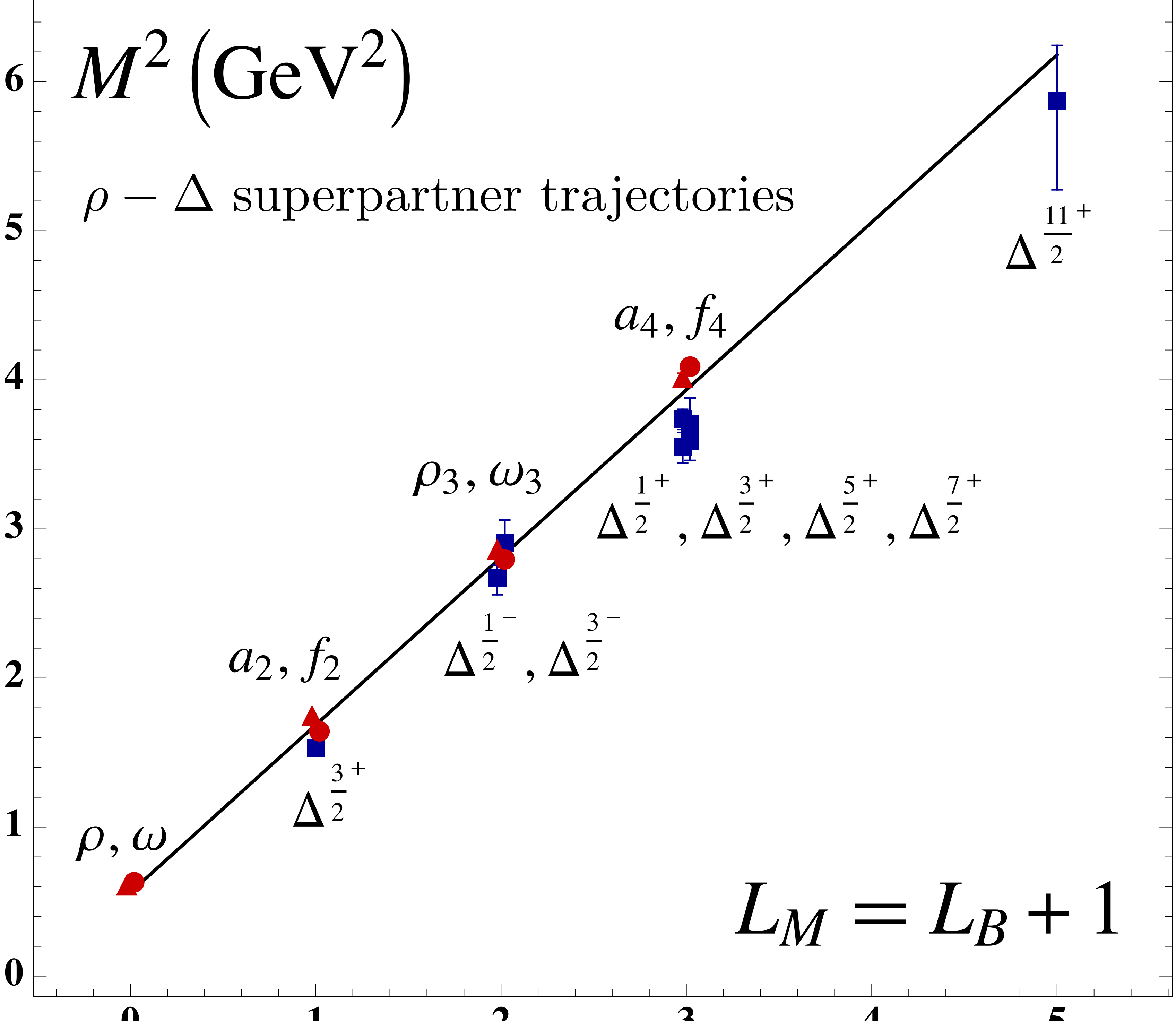
Superconformal AdS Light-Front Holographic QCD (LFHQCD): Identical meson and baryon spectra!



Meson-Baryon Mass Degeneracy for L_M=L_B+1

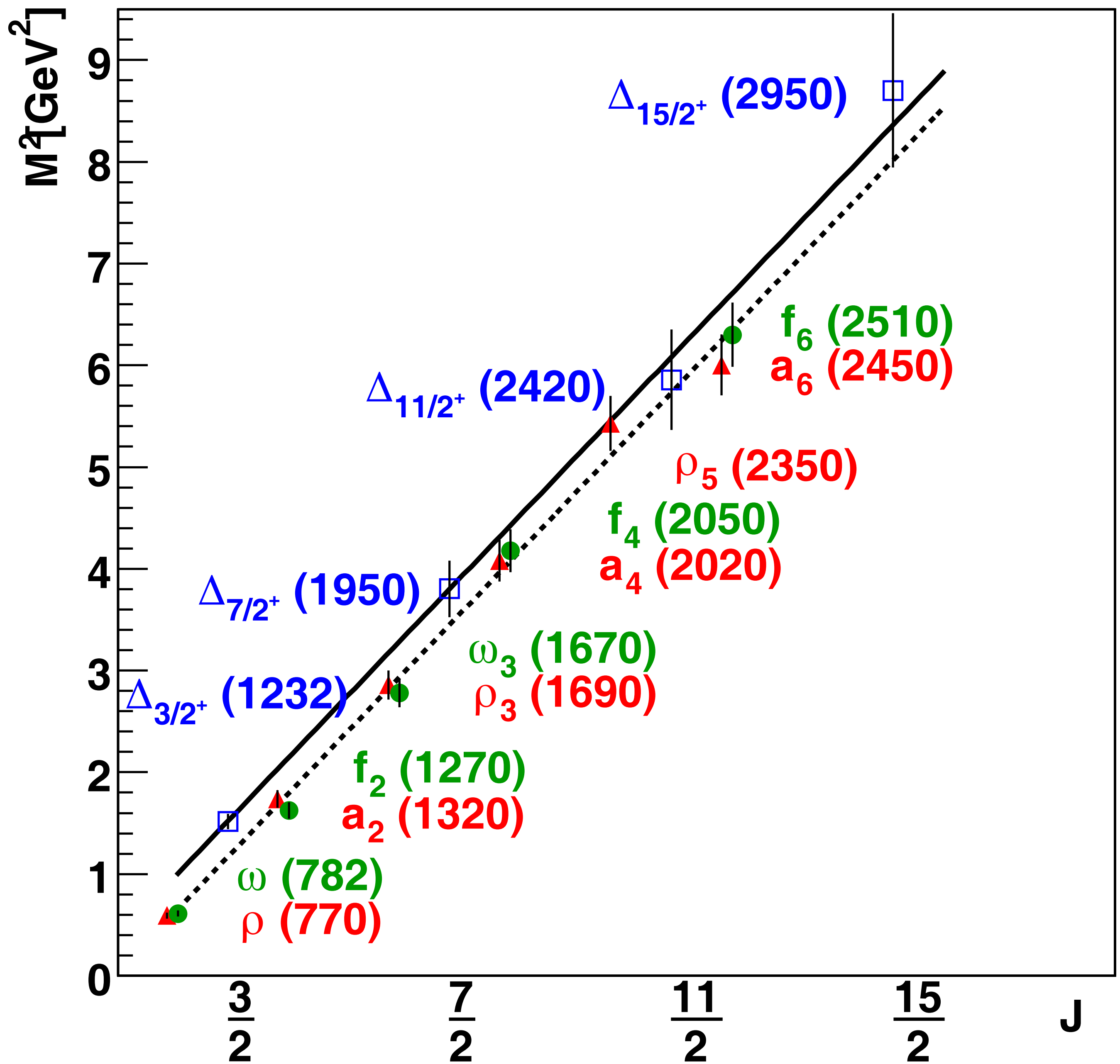
$$\frac{M^2_{meson}}{M^2_{nucleon}} = \frac{n + L_M}{n + L_B + 1}$$

S=0, I=1 Meson is superpartner of S=1/2, I=1 Baryon



Dosch, de Teramond, sjb

E. Klempt and B. Ch. Metsch



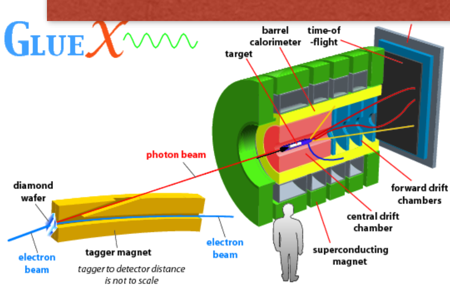
The leading Regge trajectory: Δ resonances with maximal J in a given mass range.
Also shown is the Regge trajectory for mesons with J = L+S.

Some Features of AdS/QCD

- ***Regge spectroscopy—same slope in n,L for mesons,***
- ***Chiral features for m_q=0: m_π =0, chiral-invariant proton***
- ***Hadronic LFWFs : Single dynamical LF radial variable*** ζ
- ***Counting Rules***
- ***Connection between hadron masses and*** $\Lambda_{\overline{MS}}$

Superconformal AdS Light-Front Holographic QCD (LFHQCD)

Meson-Baryon Mass Degeneracy for $L_M=L_B+1$



Novel Nuclear Photo-and Electroproduction Physics

Grunberg

Deur, de Teramond, sjb

Bjorken sum rule defines effective charge

$\alpha_{g1}(Q^2)$

$$\int_0^1 dx[g_1^{ep}(x,Q^2) - g_1^{en}(x,Q^2)] \equiv \frac{g_a}{6}[1 - \frac{\alpha_{g1}(Q^2)}{\pi}]$$

- ***Can be used as standard QCD coupling***
- ***Well measured***
- ***Asymptotic freedom at large Q^2***
- ***Computable at large Q^2 in any pQCD scheme***
- ***Universal β_0, β_1***

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

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

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

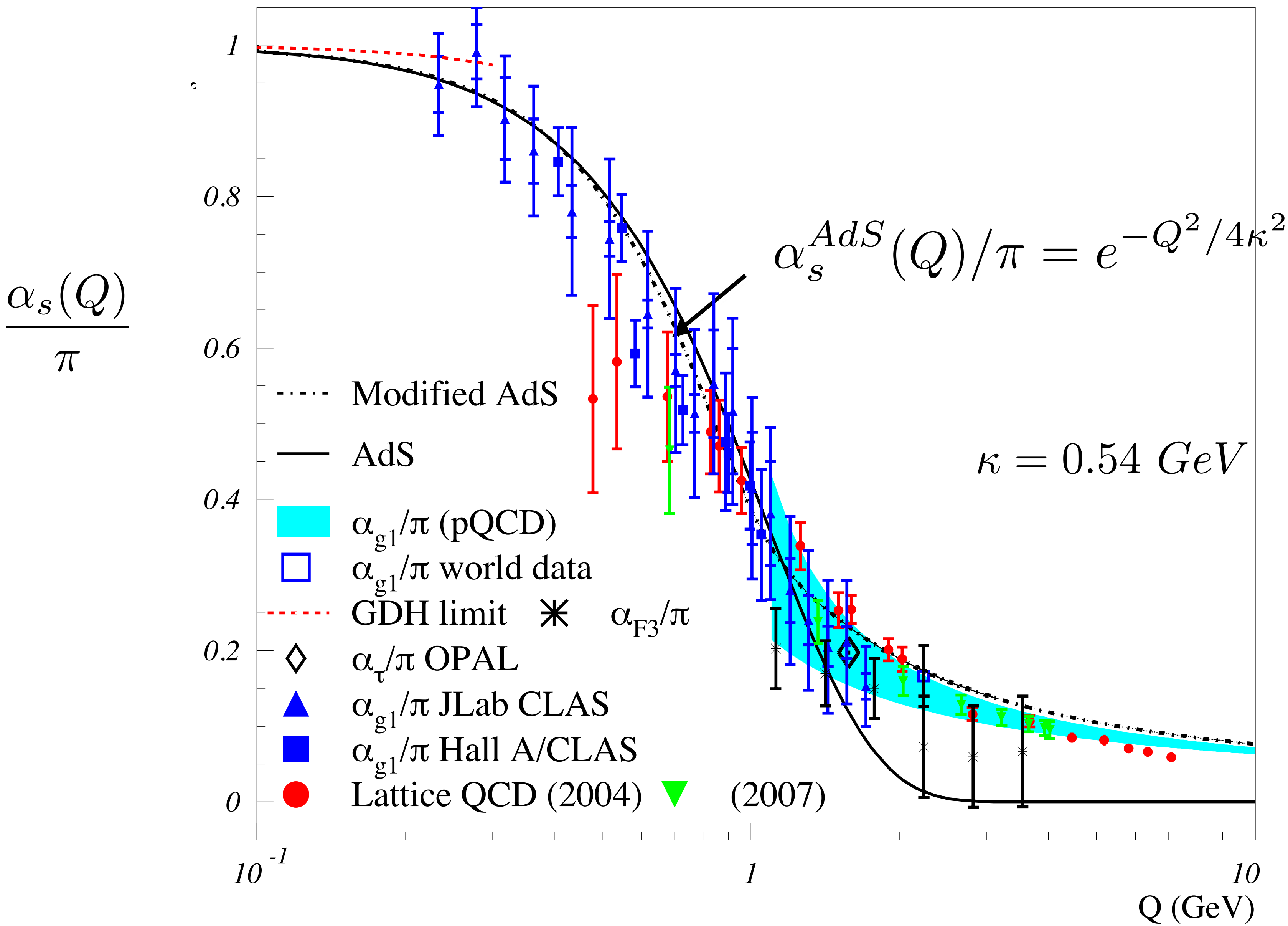
- Solution

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

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



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

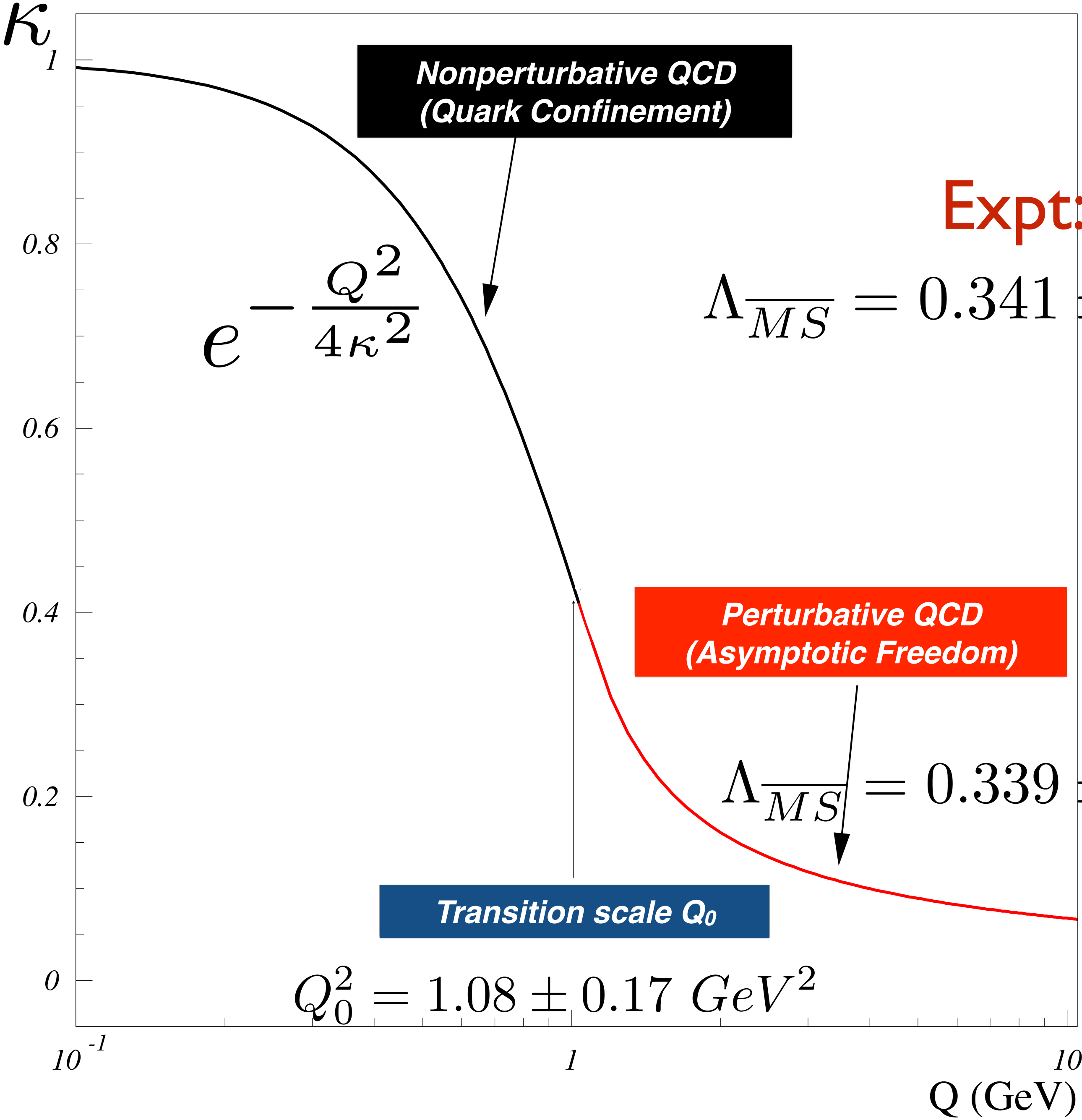
Deur, de Tèramond, sjb

All-Scale QCD Coupling

$$m_\rho = \sqrt{2}\kappa$$

$$m_p = 2\kappa$$

$$\frac{\alpha^s_{g_1}(Q^2)}{\pi}$$



$$e^{-\frac{Q^2}{4\kappa^2}}$$

Expt:

$$\Lambda_{\overline{MS}} = 0.341 \pm 0.024\ GeV$$

$$\Lambda_{\overline{MS}} = 0.339 \pm 0.016\ GeV$$

$$Q_0^2 = 1.08 \pm 0.17\ GeV^2$$

$$\lambda \equiv \kappa^2$$

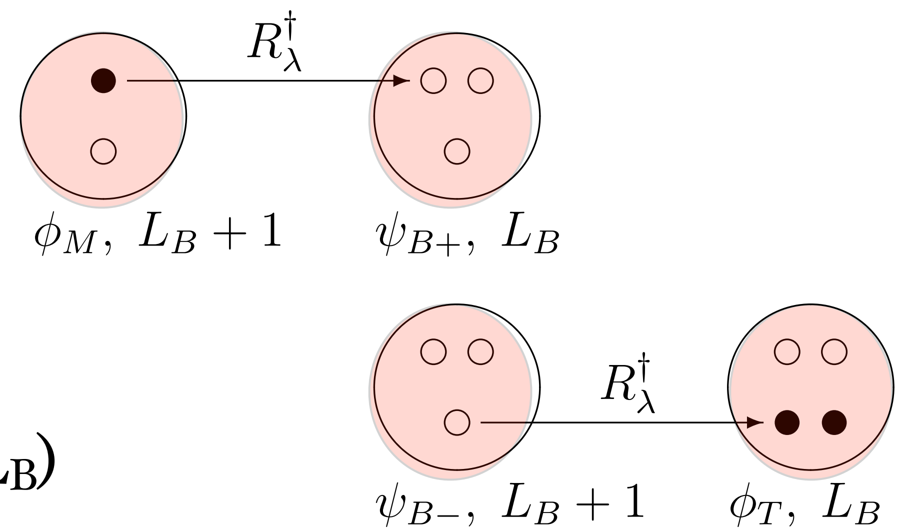
de Tèramond, Dosch, Lorce, sjb

Superconformal Algebra

2X2 Hadronic Multiplets

$$\begin{pmatrix} \phi_M(L_M = L_B + 1) & \psi_{B-}(L_B + 1) \\ \psi_{B+}(L_B) & \phi_T(L_T = L_B) \end{pmatrix}$$

- quark-antiquark meson ($L_M = L_B+1$))
- quark-diquark baryon (L_B)
- quark-diquark baryon (L_B+1)
- diquark-antidiquark tetraquark ($L_T = L_B$)
- Universal Regge slopes $\lambda = \kappa^2$



$$M_H^2/\lambda = \overbrace{\underbrace{(2n + L_H + 1)}_{kinetic} + \underbrace{(2n + L_H + 1)}_{potential}}^{\text{contribution from 2-dim light-front harmonic oscillator}} + \overbrace{2(L_H + s) + 2\chi}^{\text{contribution from AdS and superconformal algebra}} + < \sum_i \frac{m_i^2}{x_i} >$$

$\chi(mesons) = -1$ $\chi(baryons, tetraquarks) = +1$

Universal Hadronic Decomposition

$$\frac{\mathcal{M}_H^2}{\lambda} = (1 + 2n + L) + (1 + 2n + L) + (2L + 2S + 4|B| - 2)$$

$$\lambda = \kappa^2$$

- ***Universal quark light-front kinetic energy***

$$\Delta \mathcal{M}^2_{LFKE} = \lambda(1 + 2n + L)$$

- ***Universal quark light-front potential energy***

$$\Delta \mathcal{M}^2_{LFPE} = \lambda(1 + 2n + L)$$

Equal: Virial Theorem

- ***Universal Constant Contribution from AdS and Superconformal Quantum Mechanics***

$$\Delta \mathcal{M}^2_{spin} = \lambda(2L + 2S + 4|B| - 2)$$

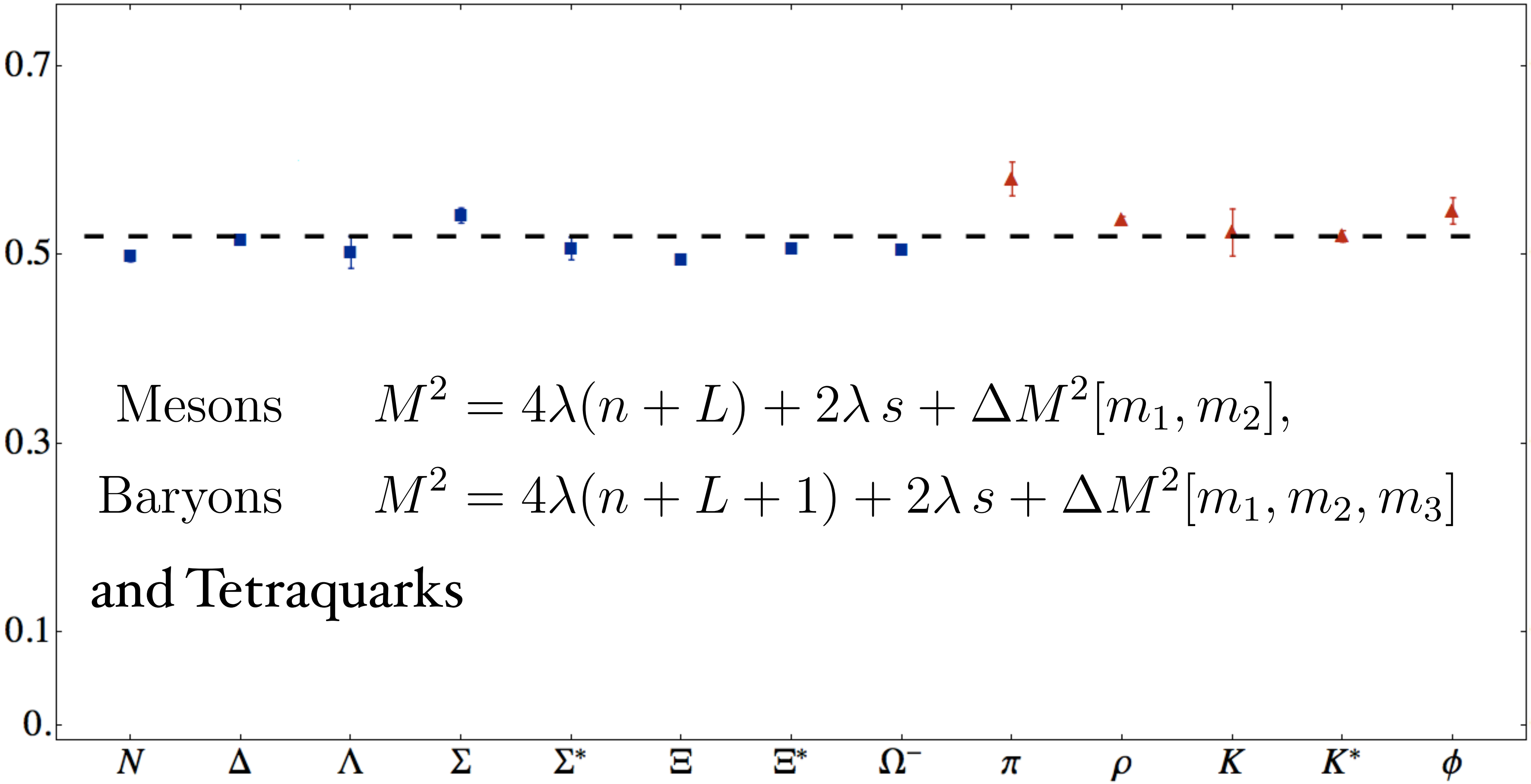
hyperfine spin-spin

- plus $\Delta \mathcal{M}^2_{quark\ mass} = \sum_q \frac{m_q^2}{x_q}$

$$\kappa = \sqrt{\lambda}$$

- Universal Regge slopes

$$M_H^2 = 4\lambda(n + L) + \cdots$$



Mesons $\quad M^2 = 4\lambda(n + L) + 2\lambda\, s + \Delta M^2[m_1, m_2],$

Baryons $\quad M^2 = 4\lambda(n + L + 1) + 2\lambda\, s + \Delta M^2[m_1, m_2, m_3]$

and Tetraquarks

Interpretation of Mass Scale κ

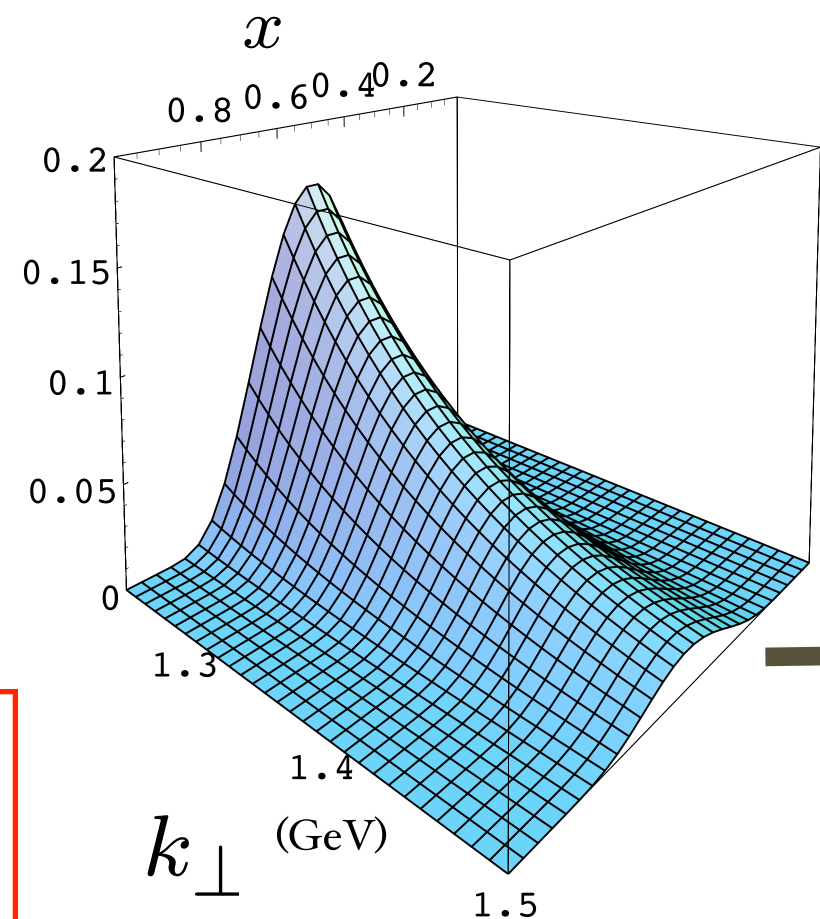
- Does not affect conformal symmetry of QCD action
- Self-consistent regularization of IR divergences
- Determines all mass and length scales for zero quark mass
- Compute scheme-dependent $\Lambda_{\overline{MS}}$ determined in terms of κ
- Value of κ itself not determined -- place holder
- Need external constraint such as f_π

$$\kappa = \sqrt{\lambda}$$

Prediction from AdS/QCD: Meson LFWF

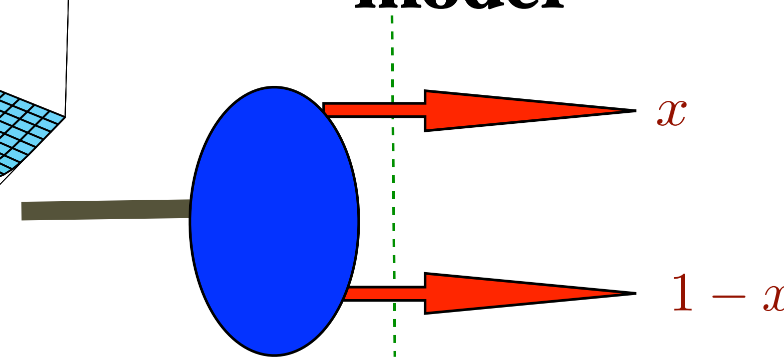
$$e^{\varphi(z)} = e^{+\kappa^2 z}$$

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



de Teramond, Cao, sjb

"Soft Wall" model



massless quarks

Note coupling

$$k_\perp^2, x$$

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

$$\phi_\pi(x) = \frac{4}{\sqrt{3}\pi} f_\pi \sqrt{x(1-x)}$$

$$f_\pi = \sqrt{P_{q\bar{q}}} \frac{\sqrt{3}}{8} \kappa = 92.4 \text{ MeV}$$

Same as DSE!

Provides Connection of Confinement to Hadron Structure

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

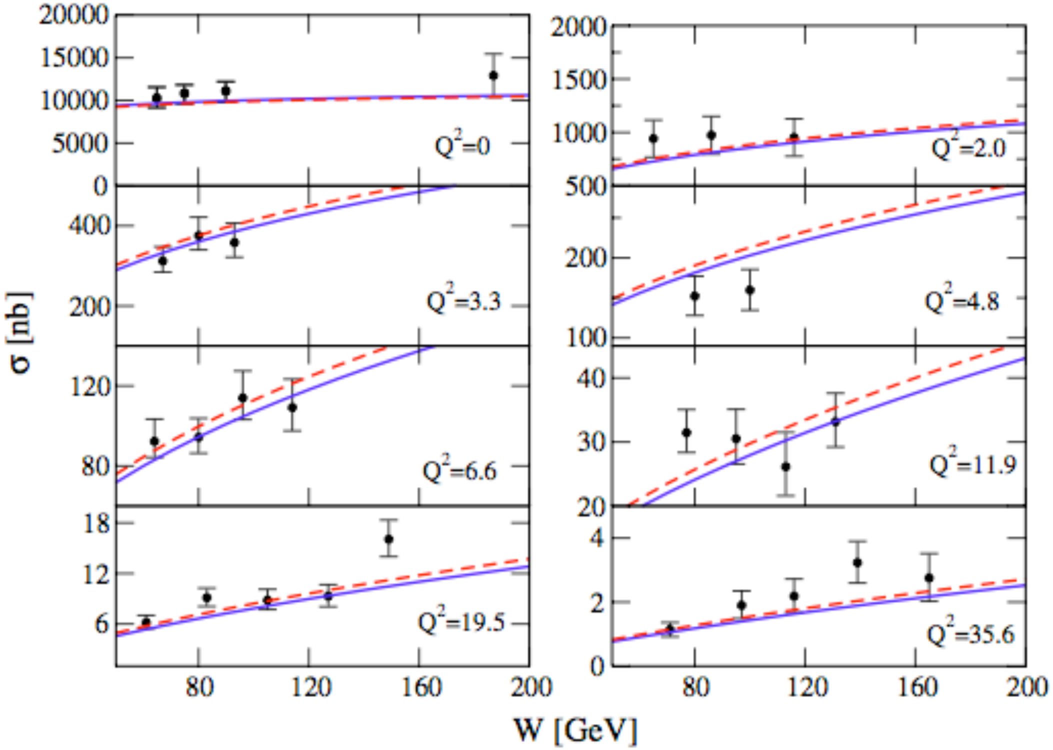
R. Sandapen†
Département de Physique et d'Astronomie, Université de Moncton, Moncton, New Brunswick E1A3E9, Canada
(Received 5 April 2012; published 20 August 2012)

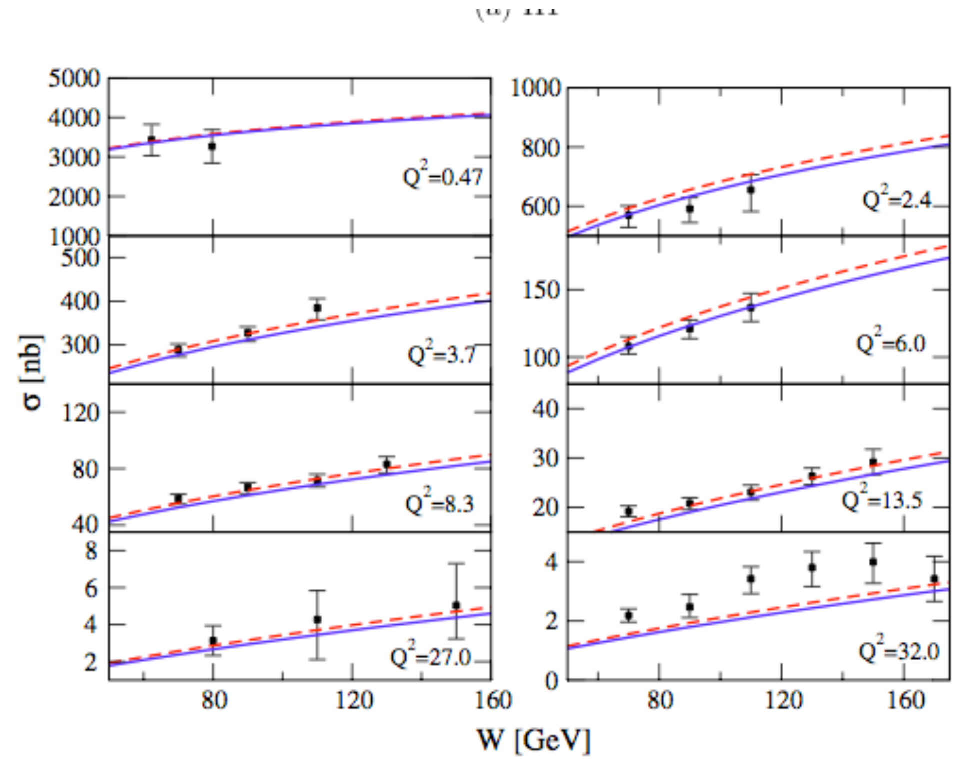
We show that anti–de Sitter/quantum chromodynamics generates predictions for the rate of diffractive ρ-meson electroproduction that are in agreement with data collected at the Hadron Electron Ring Accelerator electron–proton collider.

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

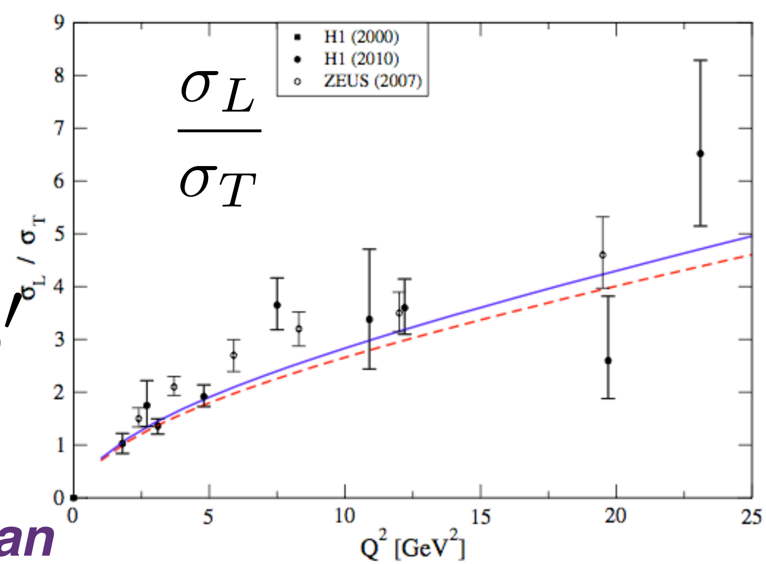
PRL 109, 081601 (2012) PHYSICAL REVIEW LETTERS week ending 24 AUGUST 2012

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





(b) ZEUS



$$\frac{\sigma_L}{\sigma_T}$$

J. R. Forshaw, R. Sandapen

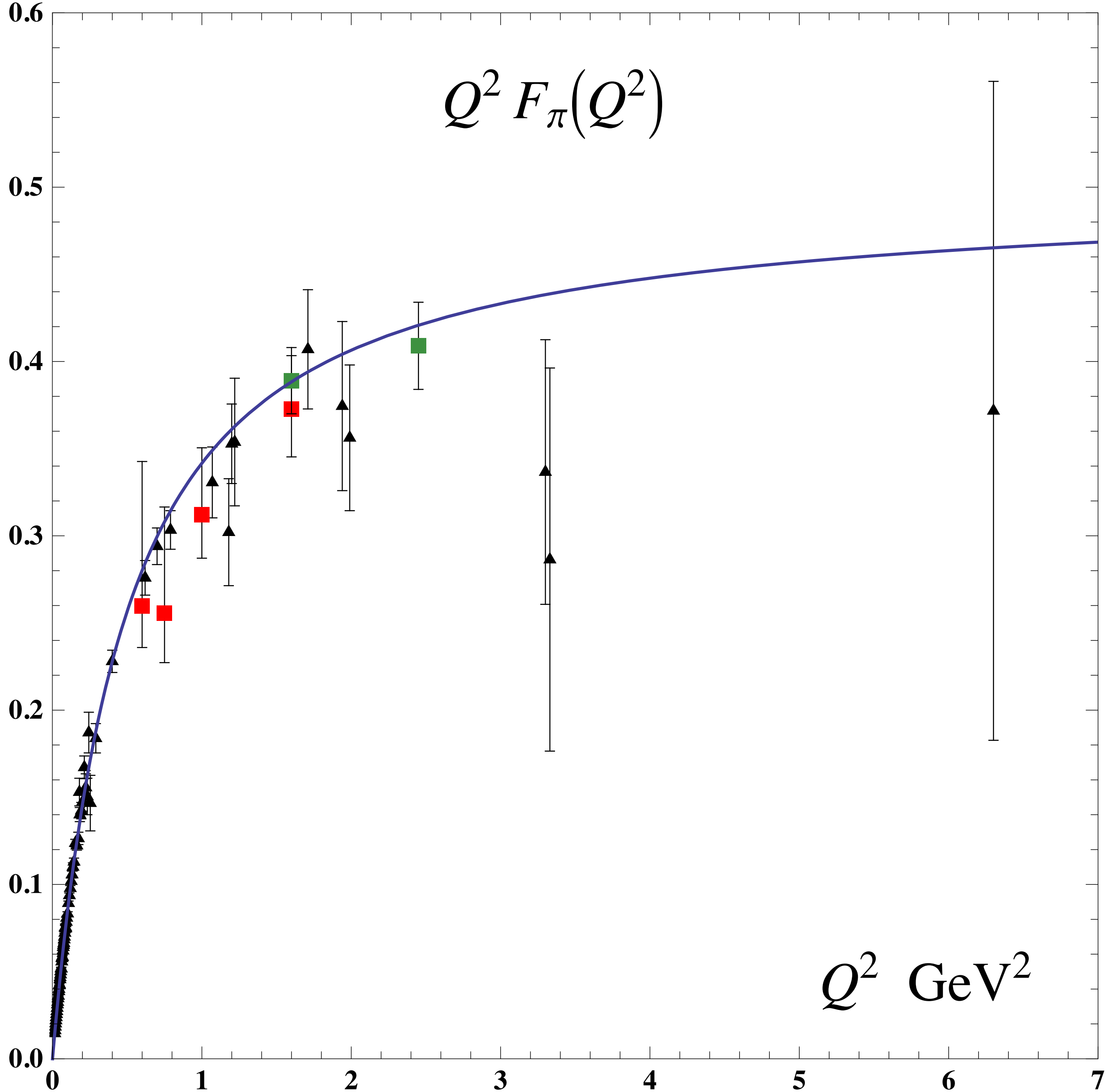
$$\gamma^* p \to \rho^0 p'$$

Nuclear effects: Sergey Gevorkyan

Prediction from Light-Front Holography

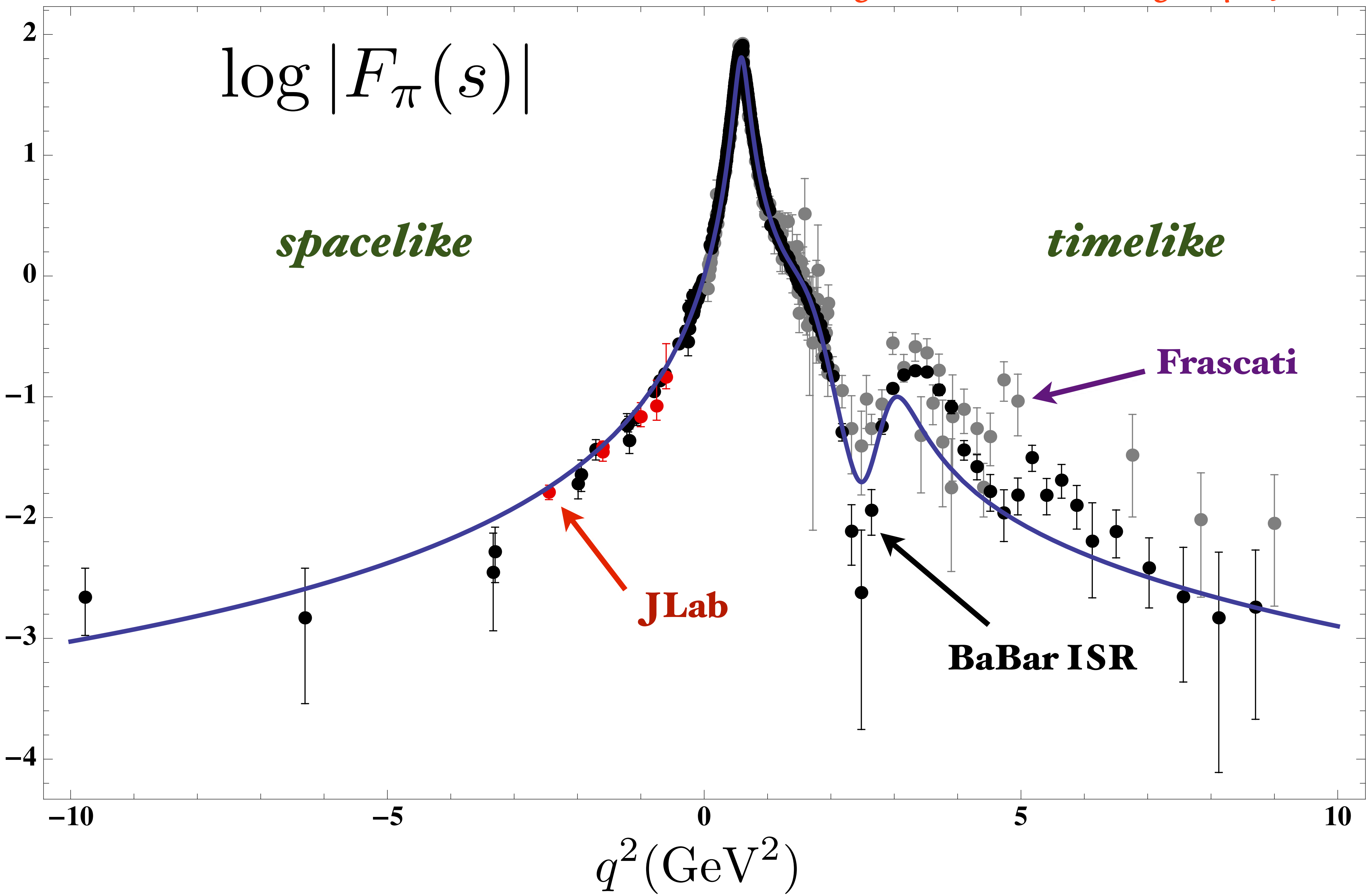
$$\psi_M(x, k_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x)}} e^{-\frac{k_\perp^2}{2\kappa^2 x(1-x)}}$$

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

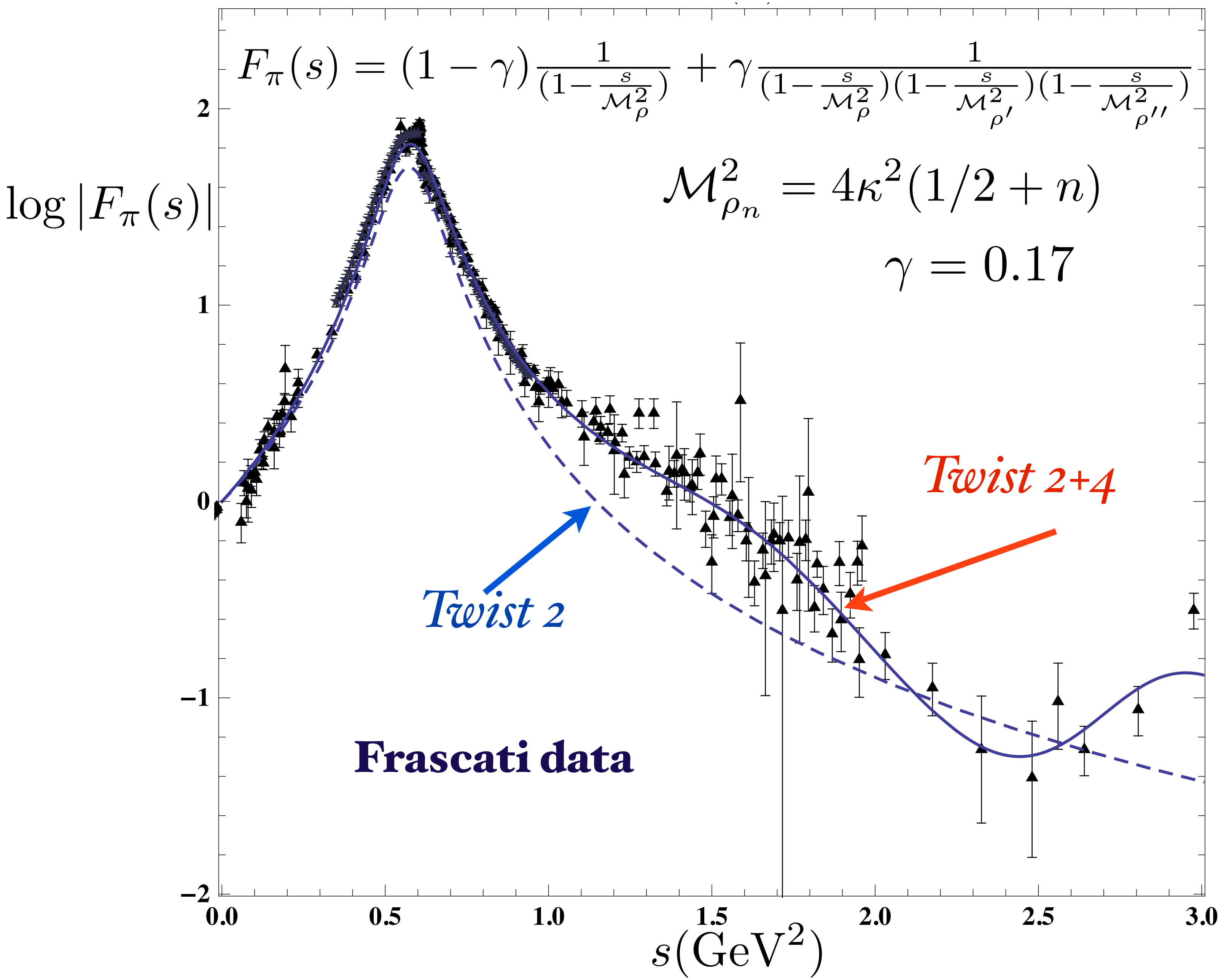


Counting Rules from Leading Twist Obeyed

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



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

- Compute Dirac proton form factor using SU(6) flavor symmetry

$$F_1^p(Q^2) = R^4 \int \frac{dz}{z^4} \, V(Q,z) \Psi_+^2(z)$$

- Nucleon AdS wave function

$$\Psi_+(z) = \frac{\kappa^{2+L}}{R^2} \sqrt{\frac{2n!}{(n+L)!}} z^{7/2+L} L_n^{L+1}\left(\kappa^2 z^2\right) e^{-\kappa^2 z^2/2}$$

- Normalization $\quad (F_1{}^p(0) = 1, \quad V(Q=0,z) = 1)$

$$R^4 \int \frac{dz}{z^4} \, \Psi_+^2(z) = 1$$

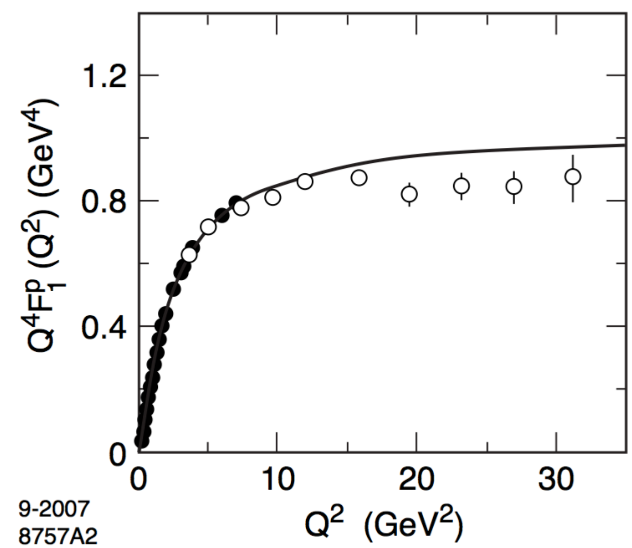
- Bulk-to-boundary propagator [Grigoryan and Radyushkin (2007)]

$$V(Q,z) = \kappa^2 z^2 \int_0^1 \frac{dx}{(1-x)^2} \, x^{\frac{Q^2}{4\kappa^2}} \, e^{-\kappa^2 z^2 x/(1-x)}$$

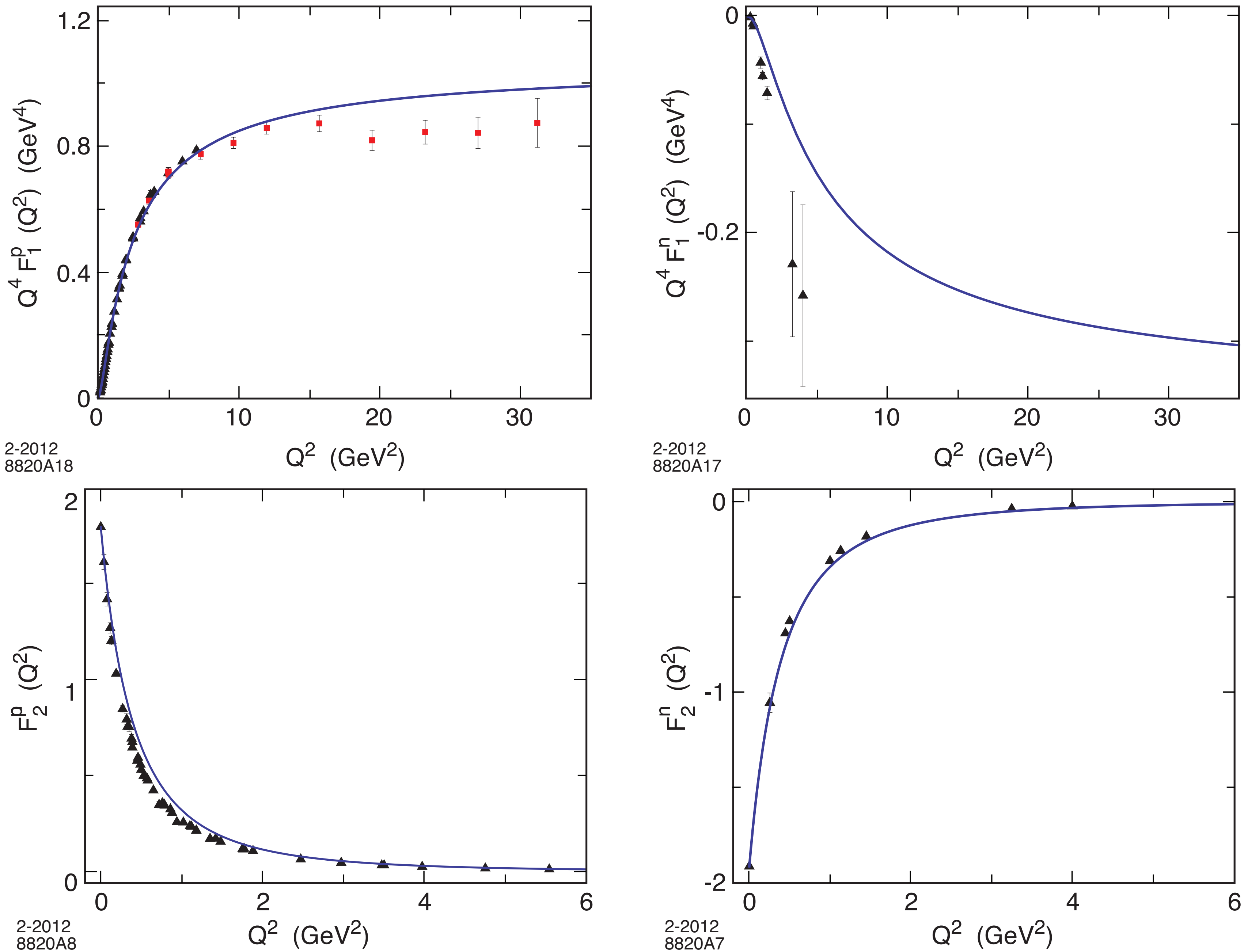
- Find

$$F_1^p(Q^2) = \frac{1}{\left(1 + \frac{Q^2}{\mathcal{M}_\rho^2}\right)\left(1 + \frac{Q^2}{\mathcal{M}_{\rho'}^2}\right)}$$

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

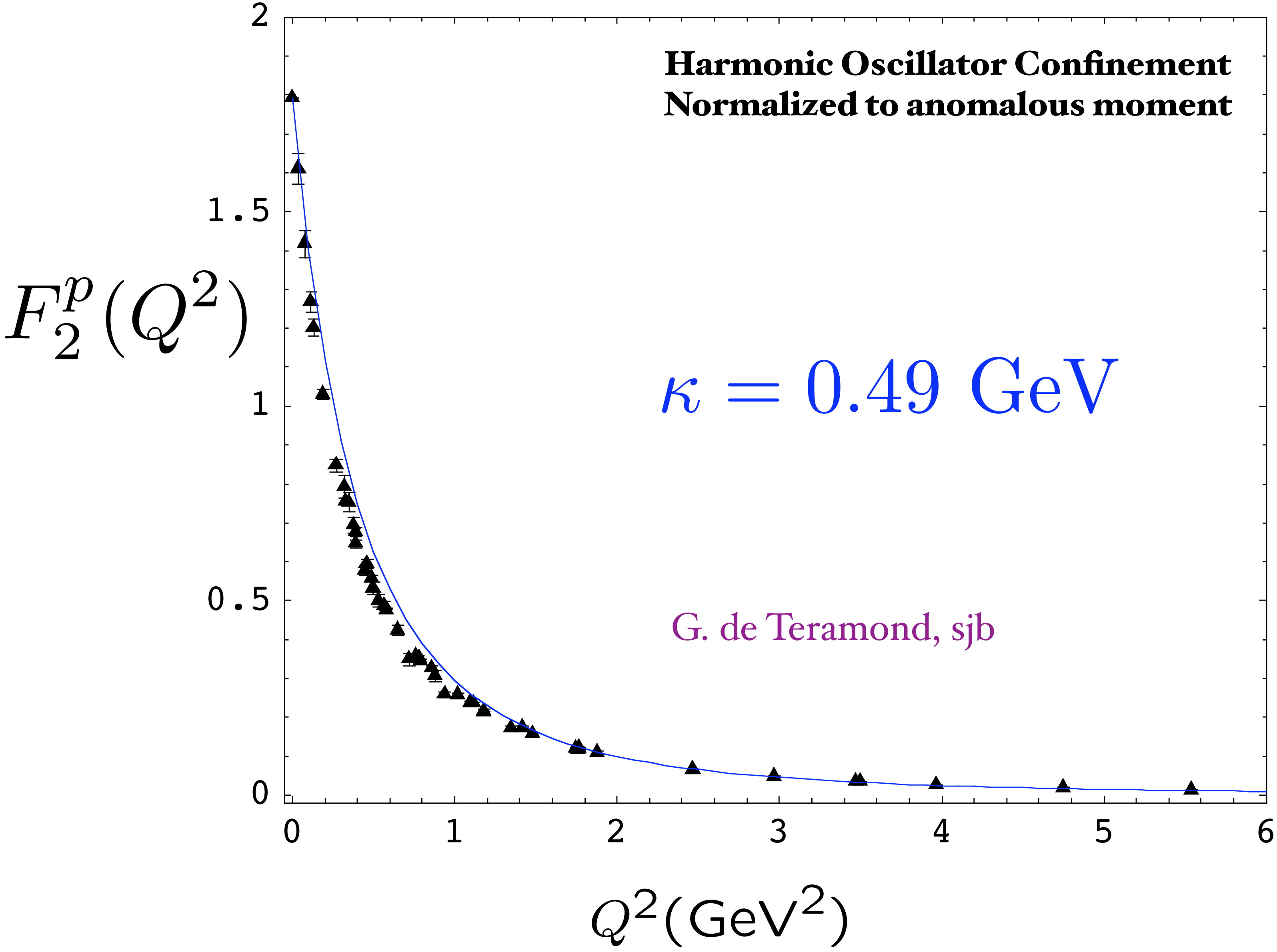


Using $SU(6)$ flavor symmetry and normalization to static quantities

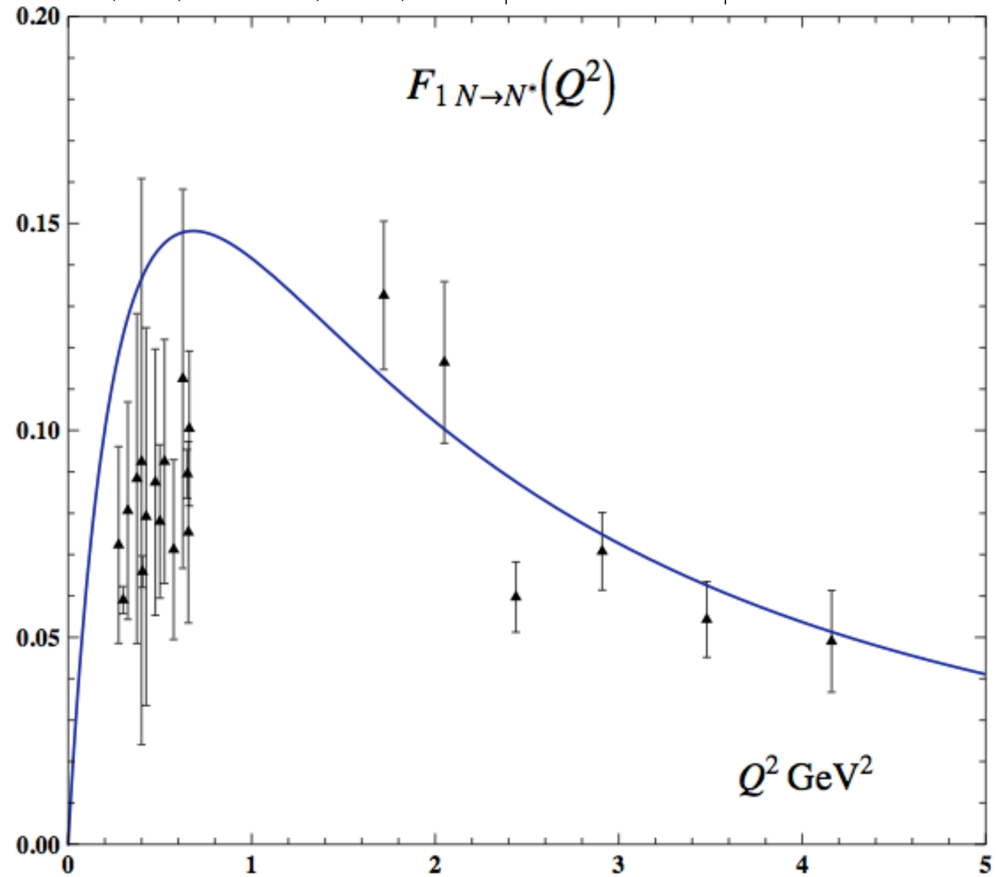


Spacelike Pauli Form Factor

From overlap of $L = 1$ and $L = 0$ LFWFs



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



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

Predictions from AdS Holographic QCD

Dosch, Deur, de Teramond, sjb

- Zero-Mass pion for zero quark mass
- Regge Spectroscopy
- Same slope in n, L
- LFWFs, Distribution Amplitudes
- Form Factors, Structure Functions, GPDs
- Non-perturbative running coupling
- Meson-Baryon Supersymmetry for $L_M = L_B + 1$

$$M_\pi^2(n, L) = 4\kappa^2(n + L)$$

$$\phi_\pi(x) \propto f_\pi \sqrt{x(1-x)}$$

$$\alpha_s(Q^2) \propto e^{-\frac{Q^2}{4\kappa^2}}$$

$$\lambda = \kappa^2$$

Interpretation of Mass Scale κ

- Does not affect conformal symmetry of QCD action
- Self-consistent regularization of IR divergences
- Determines all mass and length scales for zero quark mass
- Compute scheme-dependent $\Lambda_{\overline{MS}}$ determined in terms of κ
- Value of κ itself not determined -- place holder
- Need external constraint such as f_π

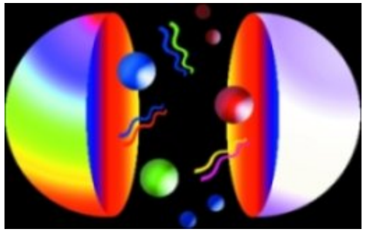
Tests of AdS/QCD and LF Holography JLab 12 GeV

- Spacelike-Transition Form Factors $F_{\pi \to b_1}(Q^2)$ $F_{p \to N^*}(Q^2)$
- Supersymmetric QCD Relations: Spectra, Dynamics
- Baryons: q + diquark $[q]_{3C}[qq]_{\bar{3}C}$
- Pentaquarks: diquark-antidiquark $[qq]_{\bar{3}C}[\bar{q}\bar{q}]_{3C}$

Fermionic Modes and Baryon Spectrum

[Hard wall model: GdT and S. J. Brodsky, PRL **94**, 201601 (2005)]

[Soft wall model: GdT and S. J. Brodsky, (2005), arXiv:1001.5193]



From Nick Evans

- Nucleon LF modes

$$\psi_+(\zeta)_{n,L} = \kappa^{2+L}\sqrt{\frac{2n!}{(n+L)!}}\zeta^{3/2+L}e^{-\kappa^2\zeta^2/2}L_n^{L+1}\left(\kappa^2\zeta^2\right)$$

$$\psi_-(\zeta)_{n,L} = \kappa^{3+L}\frac{1}{\sqrt{n+L+2}}\sqrt{\frac{2n!}{(n+L)!}}\zeta^{5/2+L}e^{-\kappa^2\zeta^2/2}L_n^{L+2}\left(\kappa^2\zeta^2\right)$$

- Normalization

$$\int d\zeta\,\psi_+^2(\zeta) = \int d\zeta\,\psi_-^2(\zeta) = 1$$

Chiral Symmetry of Eigenstate!

- Eigenvalues

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

- "Chiral partners"

$$\frac{\mathcal{M}_{N(1535)}}{\mathcal{M}_{N(940)}} = \sqrt{2}$$

Features of Supersymmetric Equations

- J =L+S baryon simultaneously satisfies both equations of G with L , L+1 for same mass eigenvalue

- $J^z = L^z + 1/2 = (L^z + 1) - 1/2$ $S^z = \pm 1/2$

- Baryon spin carried by quark orbital angular momentum: $\langle J^z \rangle = L^z + 1/2$

- Mass-degenerate meson "superpartner" with $L_M = L_B + 1$. *"Shifted meson-baryon Duality"*

Meson and baryon have same κ !

Counting Rules Obeyed

AdS/QCD and Light-Front Holography

$$\mathcal{M}^2_{n,J,L} = 4\kappa^2\big(n + \frac{J+L}{2}\big)$$

- **Zero mass pion for m_q =0 (n=J=L=0)**
- **Regge trajectories: equal slope in n and L**
- **Form Factors at high Q^2: Dimensional counting** $[Q^2]^{n-1} F(Q^2) \to \text{const}$
- **Space-like and Time-like Meson and Baryon Form Factors**
- **Running Coupling for NPQCD** $\alpha_s(Q^2) \propto e^{-\frac{Q^2}{4\kappa^2}}$
- **Meson Distribution Amplitude** $\phi_\pi(x) \propto f_\pi \sqrt{x(1-x)}$

Features of AdS/QCD

de Tèramond, Dosch, Deur, sjb

- **Color confining potential $\kappa^4\zeta^2$ and universal mass scale from dilaton**

$$e^{\phi(z)} = e^{\kappa^2 z^2} \qquad \alpha_s(Q^2) \propto \exp -Q^2/4\kappa^2$$

- **Dimensional transmutation** $\Lambda_{\overline{MS}} \leftrightarrow \kappa \leftrightarrow m_H$

- **Chiral Action remains conformally invariant despite mass scale** *DAFF*

- **Light-Front Holography: Duality of AdS and frame-independent LF QCD**

- **Reproduces observed Regge spectroscopy — same slope in n, L, and J for mesons and baryons**

- **Massless pion for massless quark**

- **Supersymmetric meson-baryon dynamics and spectroscopy: $L_M=L_B+1$**

Superconformal Quantum Mechanics
Fubini and Rabinovici

Tests of AdS/QCD and LF Holography at JLab 12 GeV

- **Compare Spacelike-Transition Form Factors, Counting Rules**

$$F_{\pi \to b_1}(Q^2) \quad \textbf{vs.} \quad F_{p \to N^*}(Q^2)$$

- **Supersymmetric QCD Relations: Spectra, Dynamics**

- **Baryons: q + diquark:** $[q]_{3C}[qq]_{\bar{3}C}$

- **Tetraquarks: diquark-antidiquark?:** $[qq]_{\bar{3}C}[\bar{q}\bar{q}]_{3C}$

$$M_H^2/\lambda = \overbrace{\underbrace{(2n + L_H + 1)}_{kinetic} + \underbrace{(2n + L_H + 1)}_{potential}}^{\text{contribution from 2-dim light-front harmonic oscillator}} + \overbrace{2(L_H + s) + 2\chi}^{\text{contribution from AdS and superconformal algebra}}$$

de Tèramond, Dosch, sjb

Tony Zee

"Quantum Field Theory in a Nutshell"

Dreams of Exact Solvability

"In other words, if you manage to calculate m_P it better come out proportional to Λ_{QCD} since Λ_{QCD} is the only quantity with dimension of mass around.

Light-Front Holography:

Similarly for m_ρ.

$$m_p \simeq 3.21\ \Lambda_{\overline{MS}}$$

$$m_\rho \simeq 2.2\ \Lambda_{\overline{MS}}$$

Put in precise terms, if you publish a paper with a formula giving m_ρ/m_P in terms of pure numbers such as 2 and π, the field theory community will hail you as a conquering hero who has solved QCD exactly."

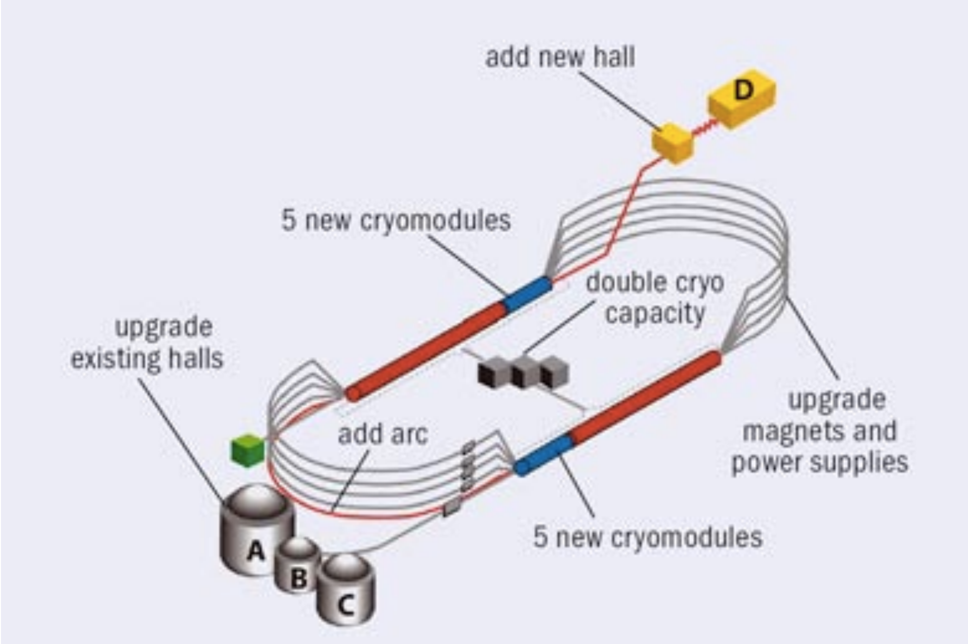
$$(m_q = 0)$$

$$m_\pi = 0$$

$$\frac{m_\rho}{m_P} = \frac{1}{\sqrt{2}}$$

$$\frac{\Lambda_{\overline{MS}}}{m_\rho} = 0.455 \pm 0.031$$

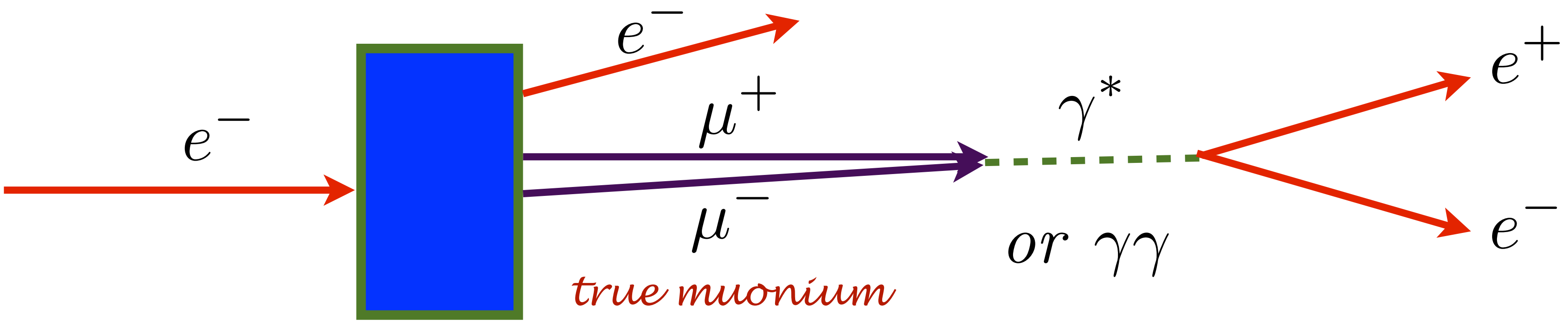
- *Test Meson-Baryon Supersymmetry*
- *Intrinsic Heavy Quarks*
- *Charm at Threshold*
- *Novel Heavy-Quark Resonances at Threshold*
- *Tetraquarks and Nuclear-Bound Quarkonium*
- *Exclusive and Inclusive Sivers Effect.*
- *Breakdown of pQCD Leading-Twist Factorization*
- *Non-Universal antishadowing*
- *Color Transparency*
- *Hidden Color*
- *J=0 Fixed Pole in DVCS*
- *Diffractive DIS*



QED:
Measure Lamb Shift of
"True Muonium" $[\mu^+\mu^-]$

• Production of True Muonium [μ⁺μ⁻]

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



- 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 [μ⁺μ⁻]

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

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

Stanley J. Brodsky*
SLAC National Accelerator Laboratory, Stanford University, Stanford, California 94309, USA

Richard F. Lebed†
Department of Physics, Arizona State University, Tempe, Arizona 85287-1504, USA
(Received 22 April 2009; published 26 May 2009)

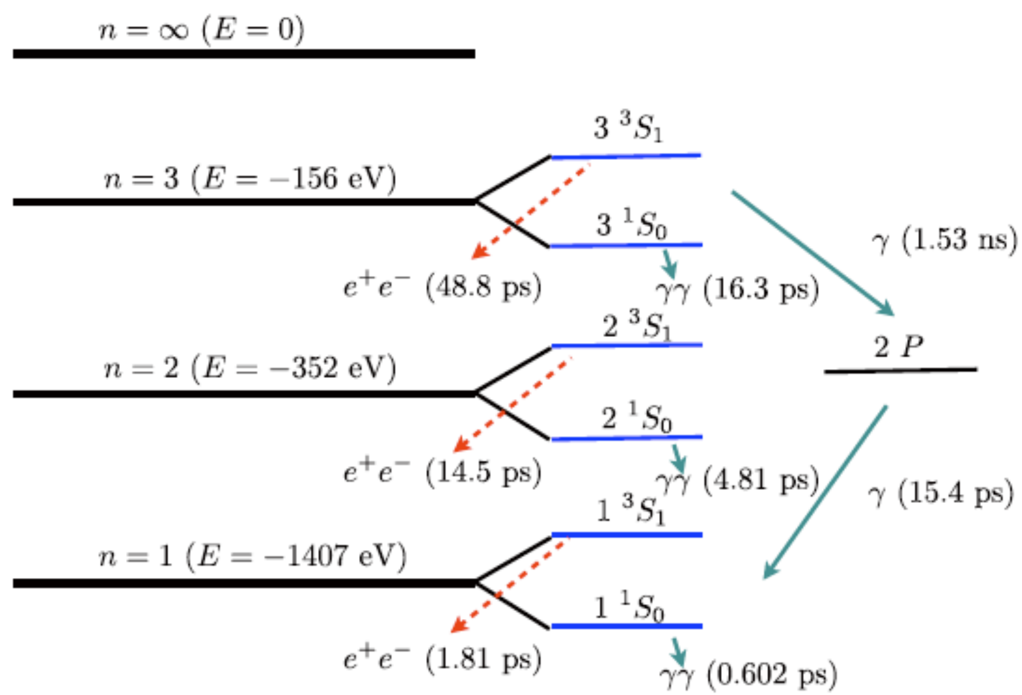
Rydberg Levels and Decays

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

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

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

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



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**

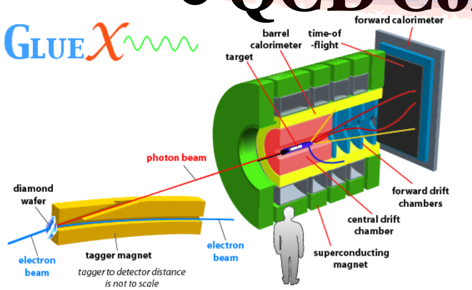
Light-Front vacuum can simulate empty universe

Shrock, Tandy, Roberts, sjb

- Independent of observer frame
- Causal
- Lowest invariant mass state M= 0.
- Trivial up to $k^+=0$ zero modes-- already normal-ordering
- Higgs theory consistent with trivial LF vacuum (Srivastava, sjb)
- QCD and AdS/QCD: "In-hadron"condensates (Maris, Tandy Roberts) -- GMOR satisfied.
- QED vacuum; no loops
- Zero cosmological constant from QED, QCD, EW

QCD Myths

- Anti-Shadowing is Universal
- ISI and FSI are higher twist effects and universal
- High transverse momentum hadrons arise only from jet fragmentation -- baryon anomaly!
- Heavy quarks only from gluon splitting
- Renormalization scale cannot be fixed
- QCD condensates are vacuum effects
- QCD gives 10^{42} to the cosmological constant
- QCD Confinement and Mass Scale from $\Lambda_{\overline{MS}}$



Novel Nuclear Photo-and Electroproduction Physics

JLab, April 29, 2016

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

Hot Topics in QCD

- *Intrinsic Heavy Quarks*
- *Breakdown of pQCD Leading-Twist Factorization*
- *Top/anti-Top asymmetry*
- *Non-universal antishadowing*
- *Demise of QCD Vacuum Condensates*
- *Elimination of the QCD Renormalization Scale Ambiguity*
- *AdS/QCD and Light-Front Holography*

Crucial to Understand QCD to High Precision to Illuminate New Physics

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*

Principle of Maximum Conformality

PMC/BLM

No renormalization scale ambiguity!

Result is independent of Renormalization scheme and initial scale!

QED Scale Setting at $N_C=0$

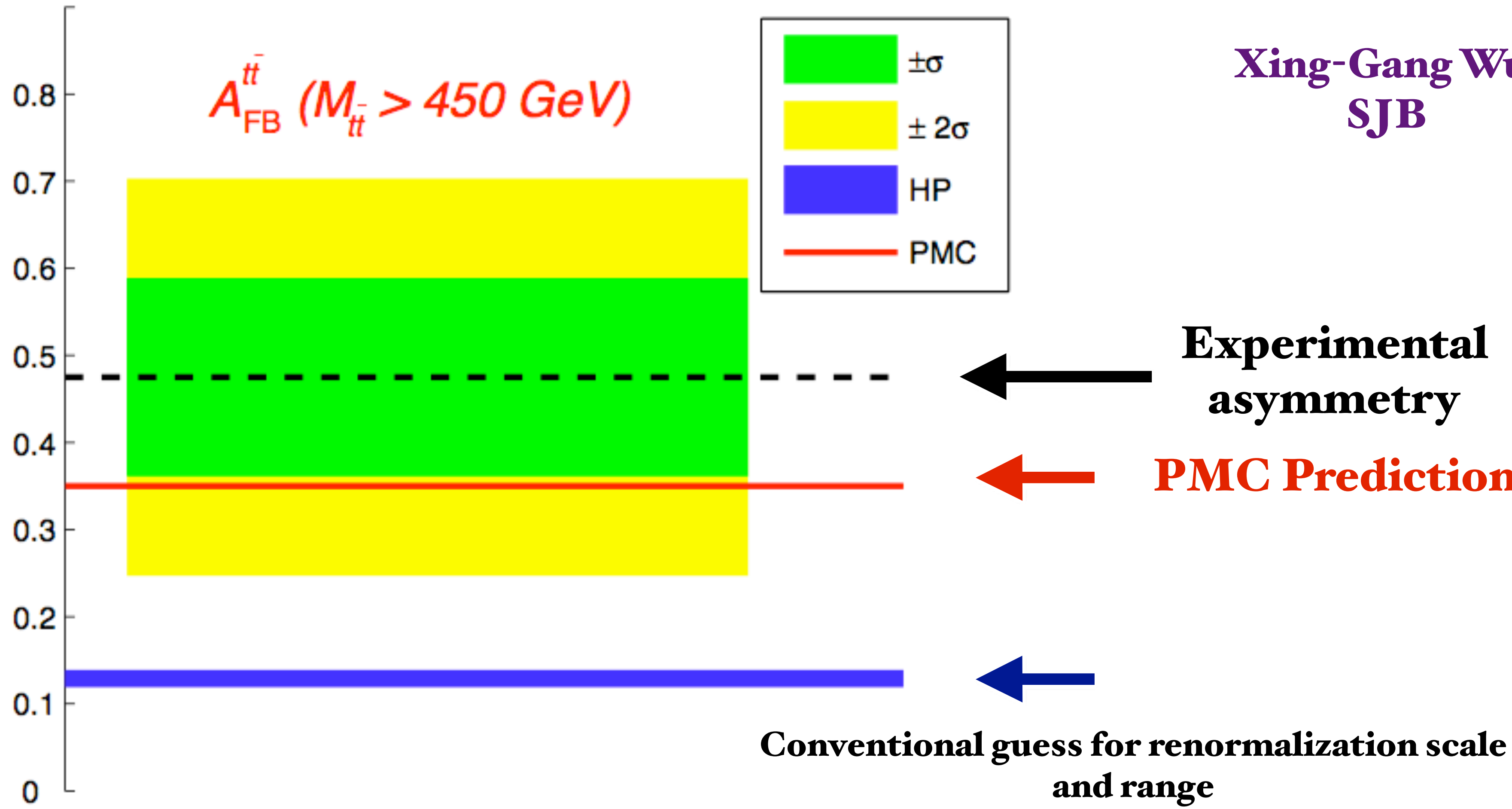
Eliminates unnecessary systematic uncertainty

Scale fixed at each order

δ-Scheme automatically identifies β-terms!

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

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



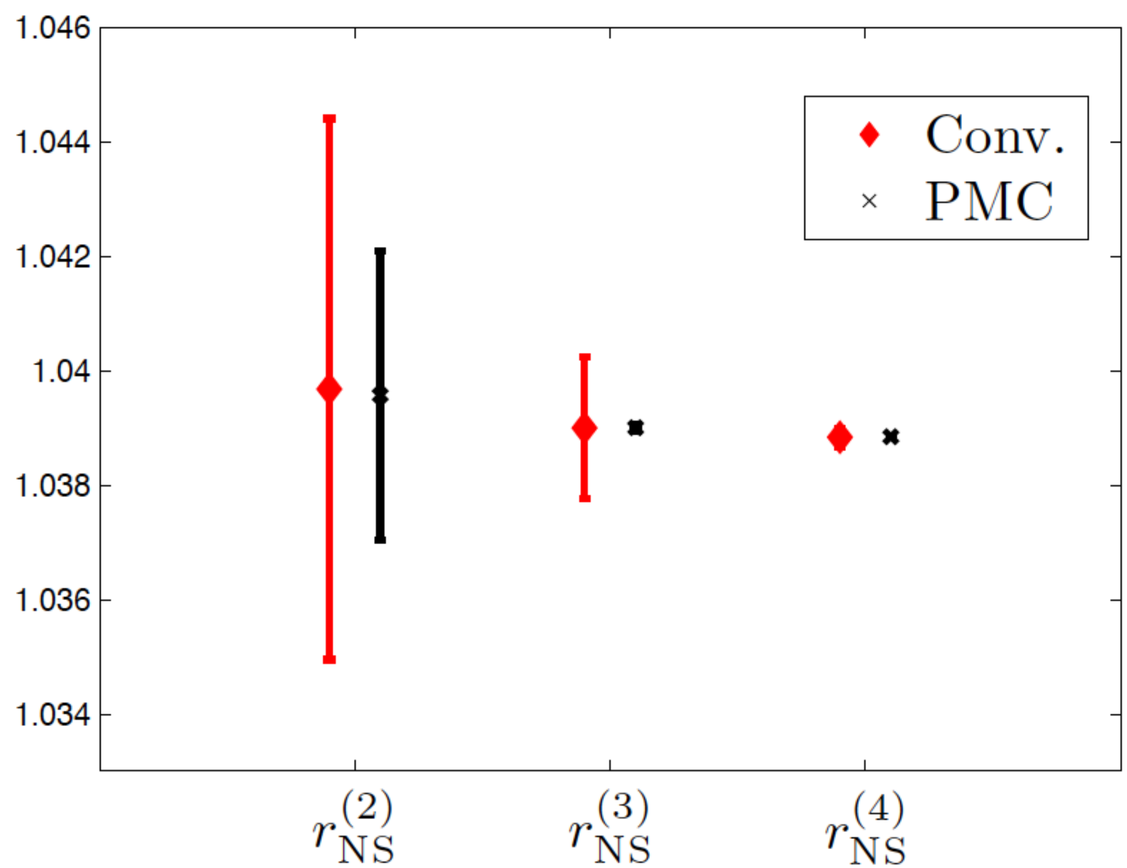
Xing-Gang Wu
SJB

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

Reanalysis of the Higher Order Perturbative QCD corrections to Hadronic Z Decays using the Principle of Maximum Conformality

S-Q Wang, X-G Wu, sjb

P.A. Baikov, K.G. Chetyrkin, J.H. Kuhn, and J. Rittinger, Phys. Rev. Lett. 108, 222003 (2012).



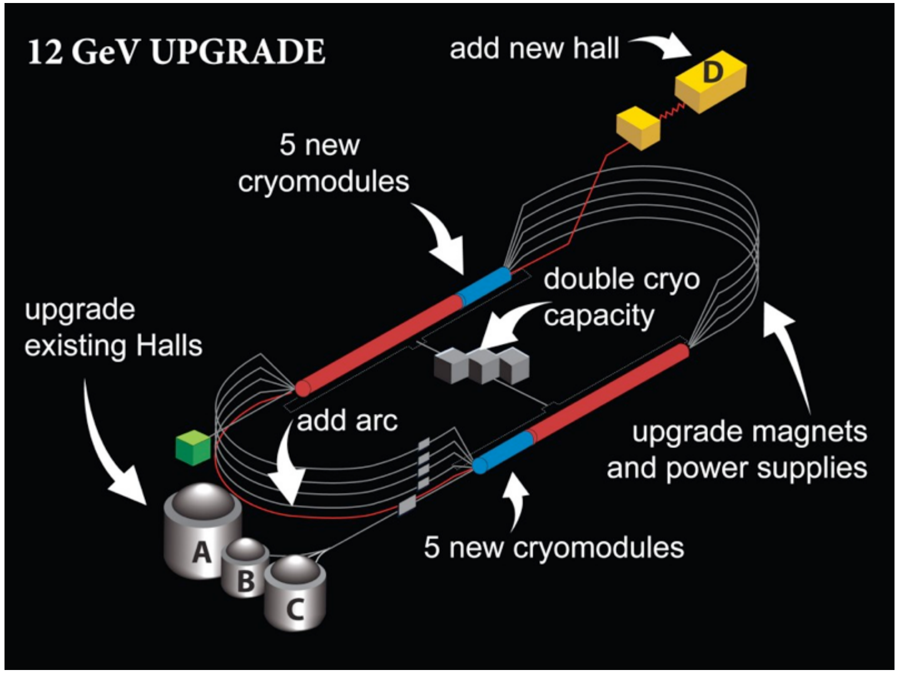
The values of $r_{\mathrm{NS}}^{(n)} = 1 + \sum_{i=1}^{n} C_i^{\mathrm{NS}} a_s^i$ and their errors $\pm|C_n^{\mathrm{NS}} a_s^n|_{\mathrm{MAX}}$. The diamonds and the crosses are for conventional (Conv.) and PMC scale settings, respectively. The central values assume the initial scale choice $\mu_r^{\mathrm{init}} = M_Z$.

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**

Novel QCD Phenomena at JLab 12 GeV and the EIC

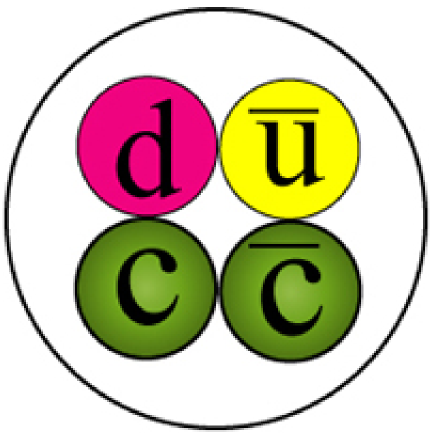
- *Intrinsic Heavy Quarks*
- *Charm at Threshold*
- *Novel Heavy Quark Resonances at Threshold*
- *Nuclear-Bound Quarkonium*
- *Exclusive and Inclusive Sivers Effect.*
- *Breakdown of pQCD Leading-Twist Factorization*
- *Non-universal antishadowing*
- *Hidden Color*
- *J=0 Fixed pole in DVCS*

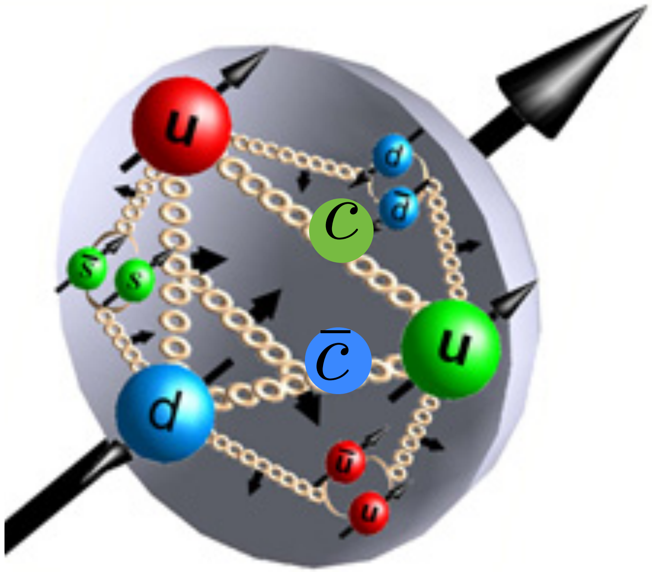


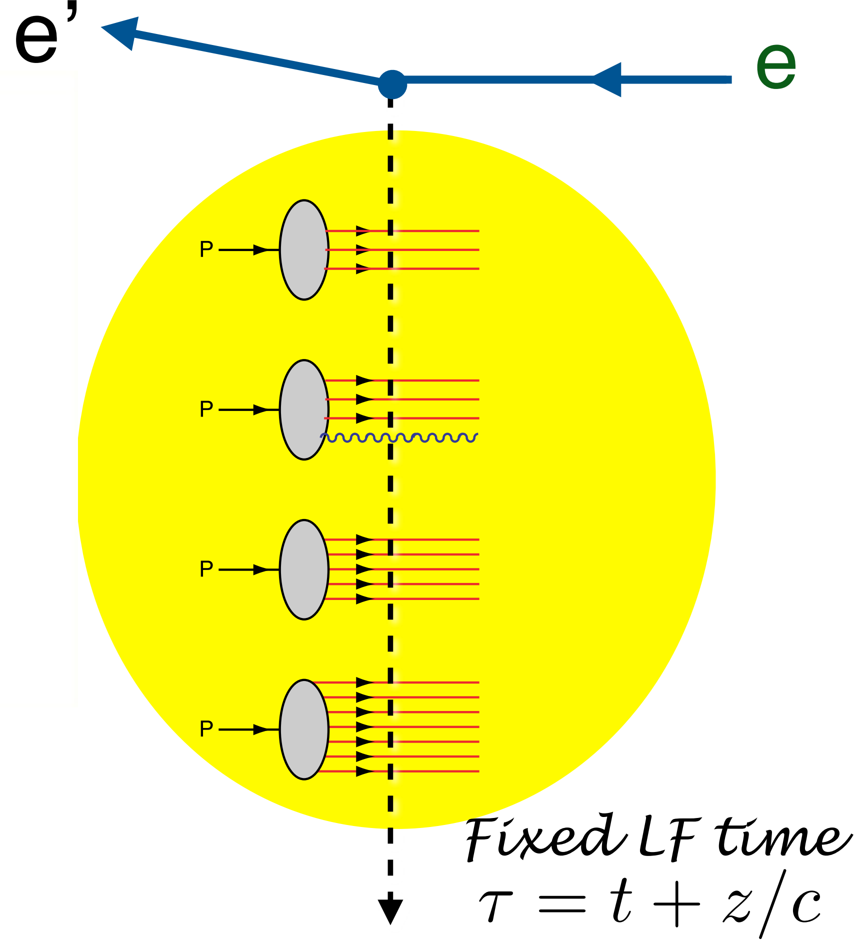
Illuminate New Hadronic Physics

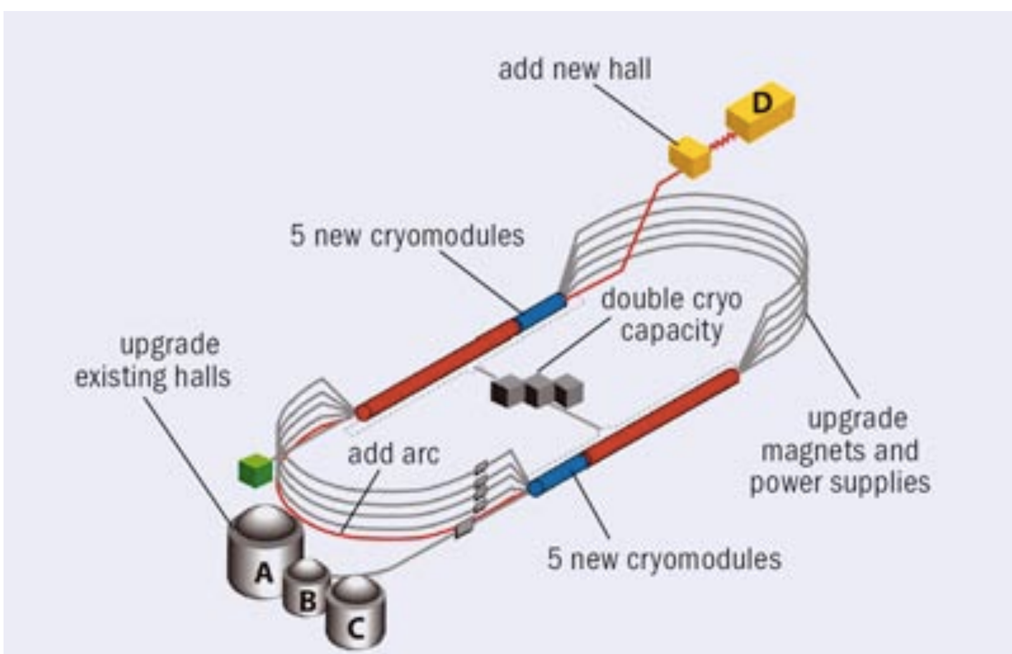
Tests of Novel QCD Phenomena at JLab

Exotic Hadrons









Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

Jefferson Lab

May 26, 2015