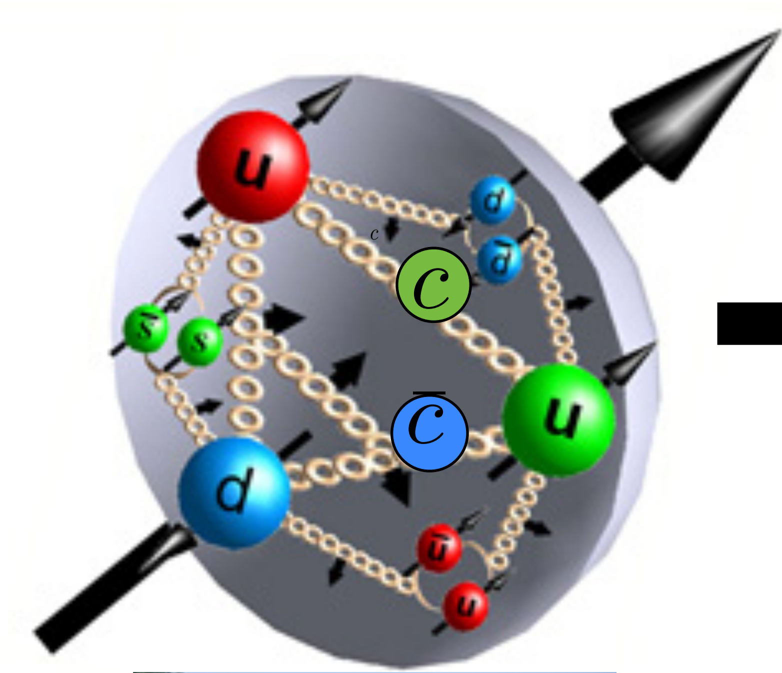
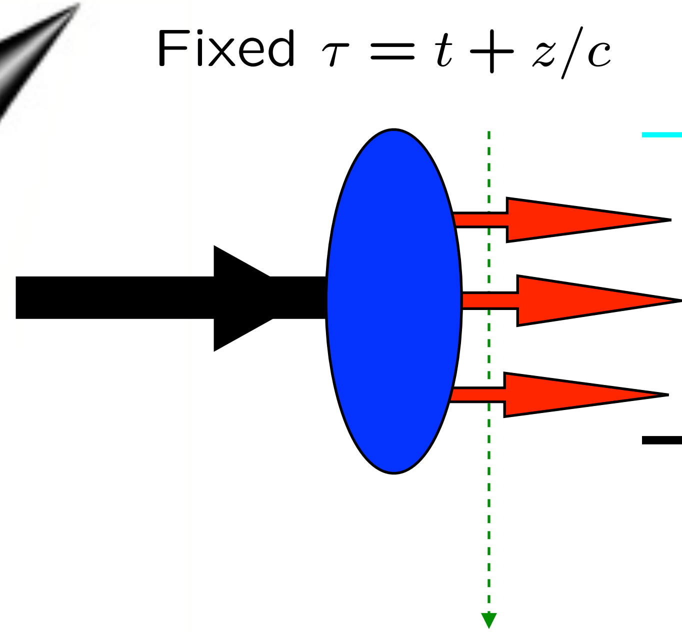
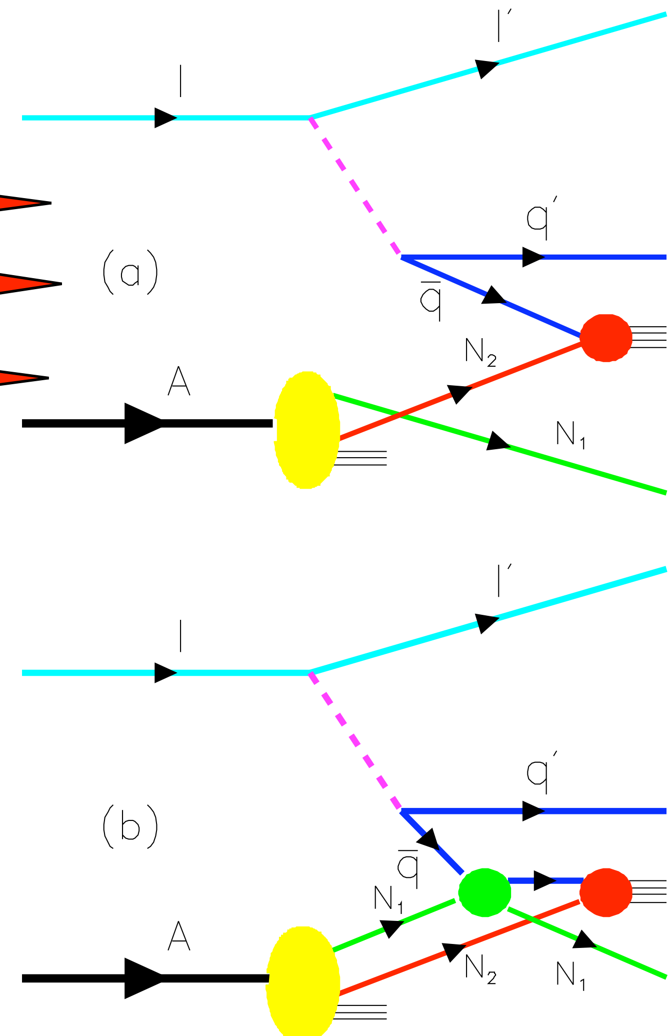
Novel QCD Features of Hadrons and Nuclei







Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

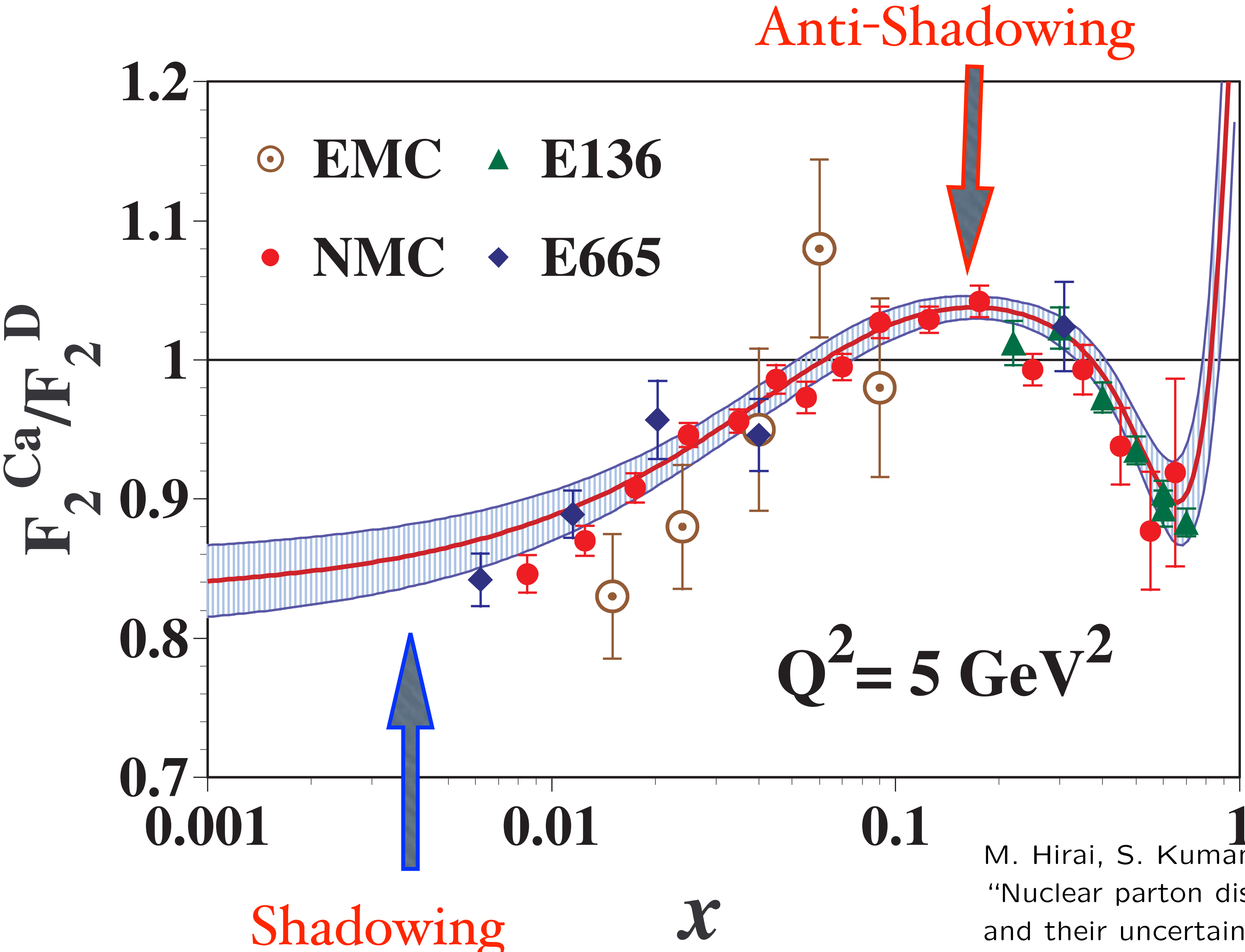
IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

with Guy de Tèramond, Hans Günter Dosch, Cedric Lorce, Kelly Chiu, and Alexandre Deur

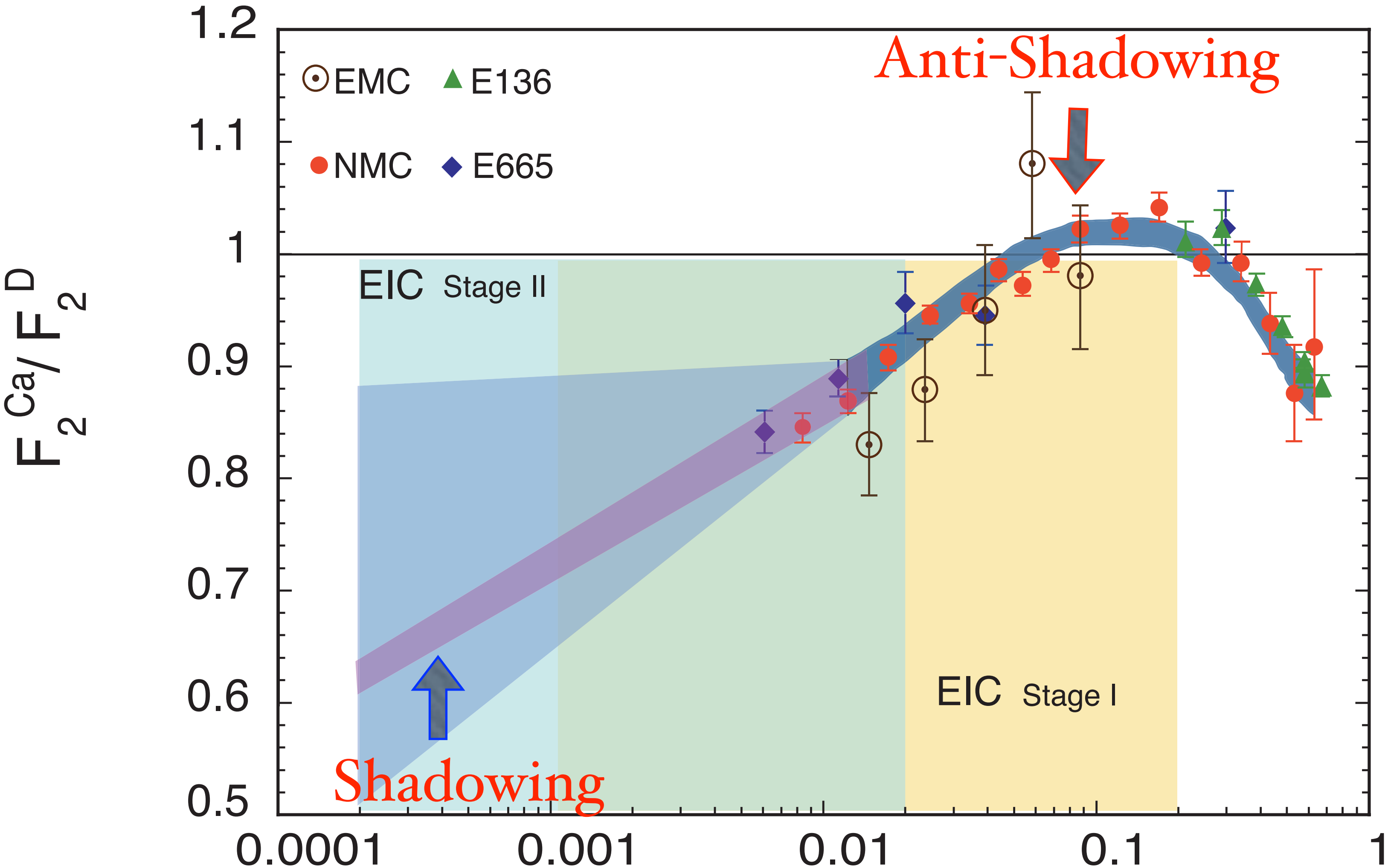
CDR QCD: Partons and Nuclei Orsay June 1, 2017

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

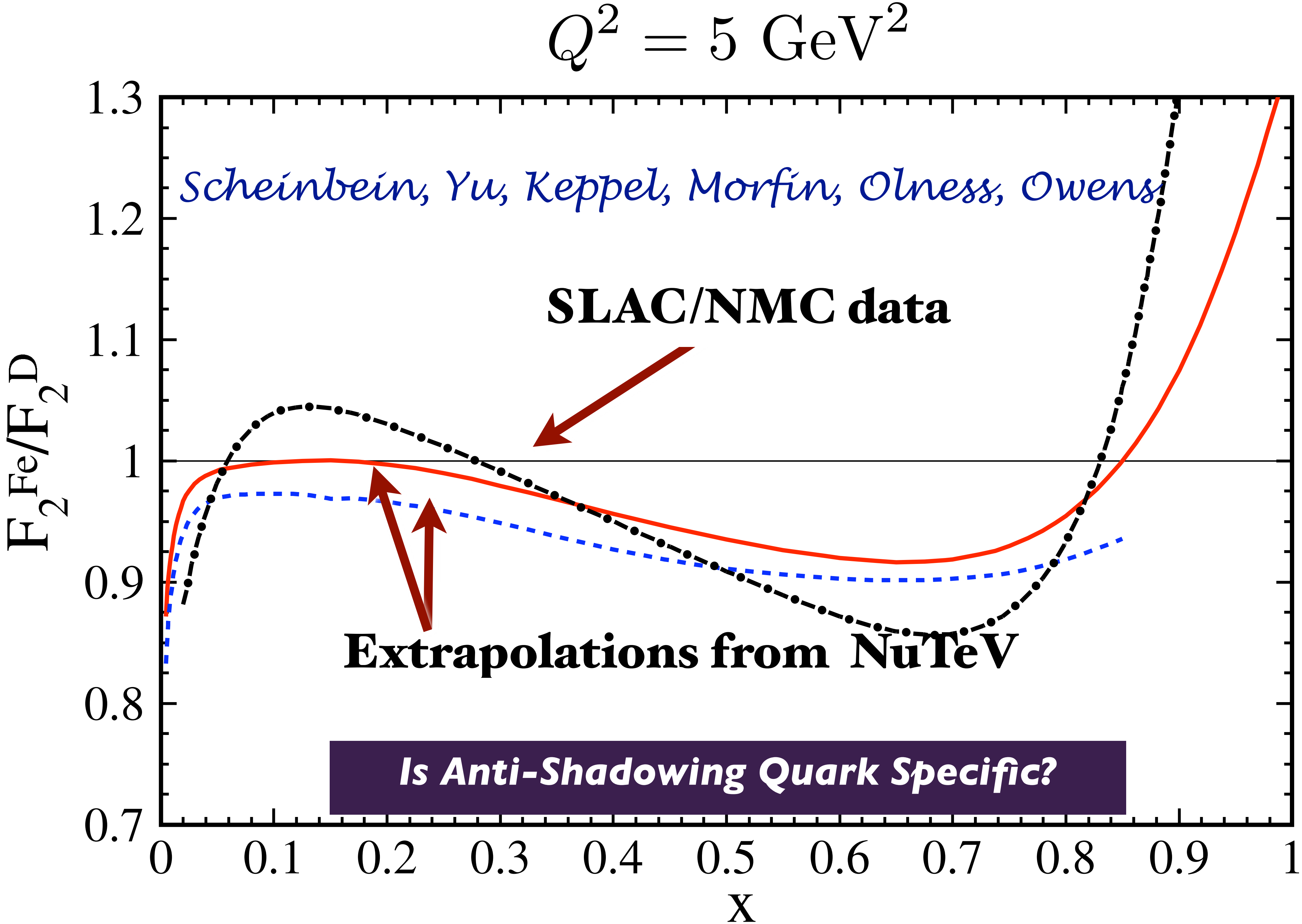
Do Nuclear PDFS
Obey Momentum and other Sum Rules?



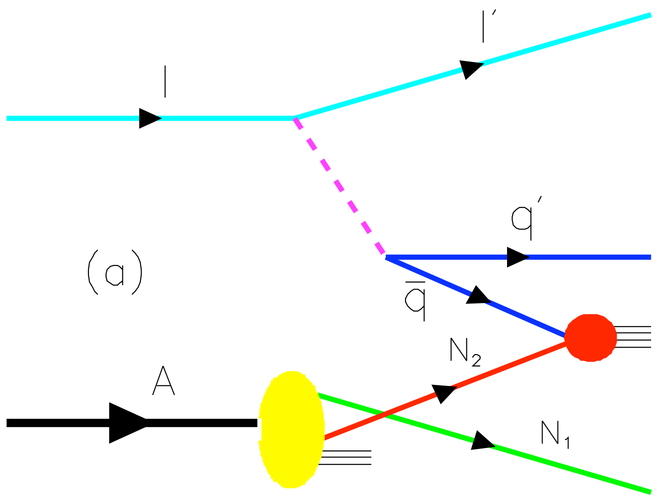
M. Hirai, S. Kumano and T. H. Nagai,
"Nuclear parton distribution functions and their uncertainties,"
Phys. Rev. C **70**, 044905 (2004)
[arXiv:hep-ph/0404093].



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.

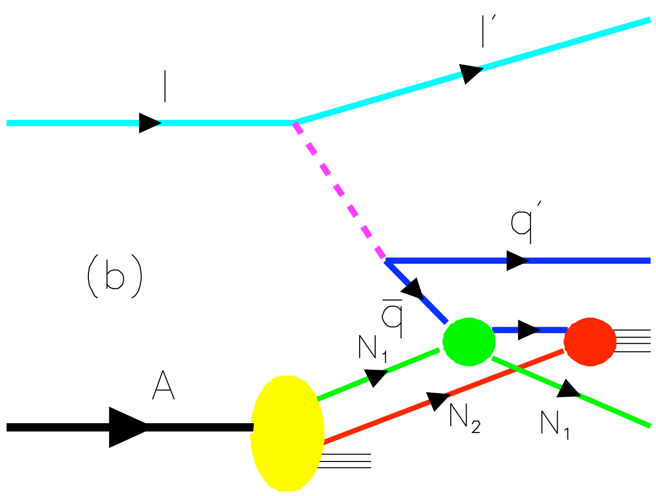


No anti-shadowing in deep inelastic neutrino scattering !



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.

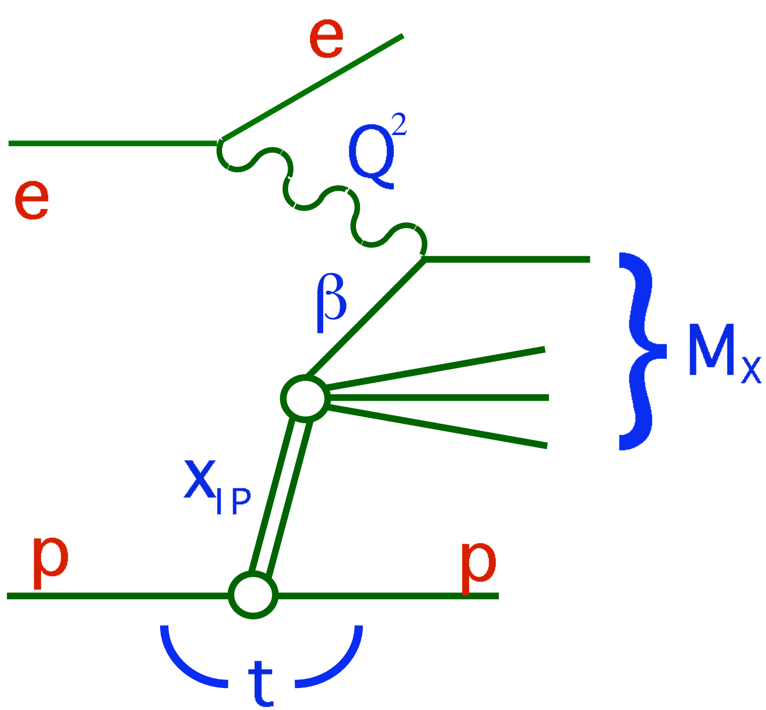
Diffraction via Pomeron gives destructive interference!

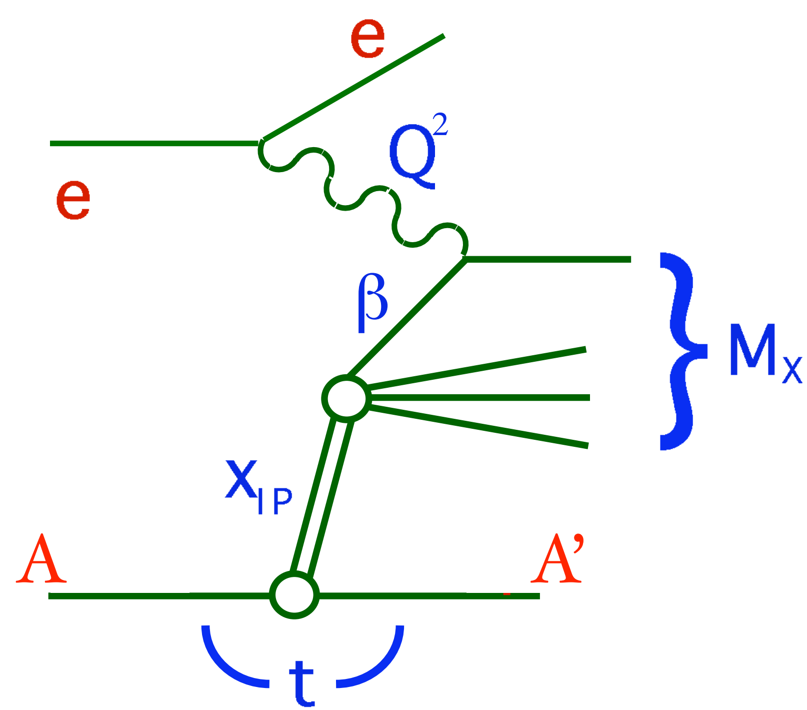
Shadowing

Diffractive Deep Inelastic Scattering

Diffractive DIS $ep \to epX$ where there is a large rapidity gap and the target nucleon remains intact probes the final state interaction of the scattered quark with the spectator system via gluon exchange.

Diffractive DIS on nuclei $eA \to e'AX$ and hard diffractive reactions such as $\gamma^* A \to VA$ can occur coherently leaving the nucleus intact.

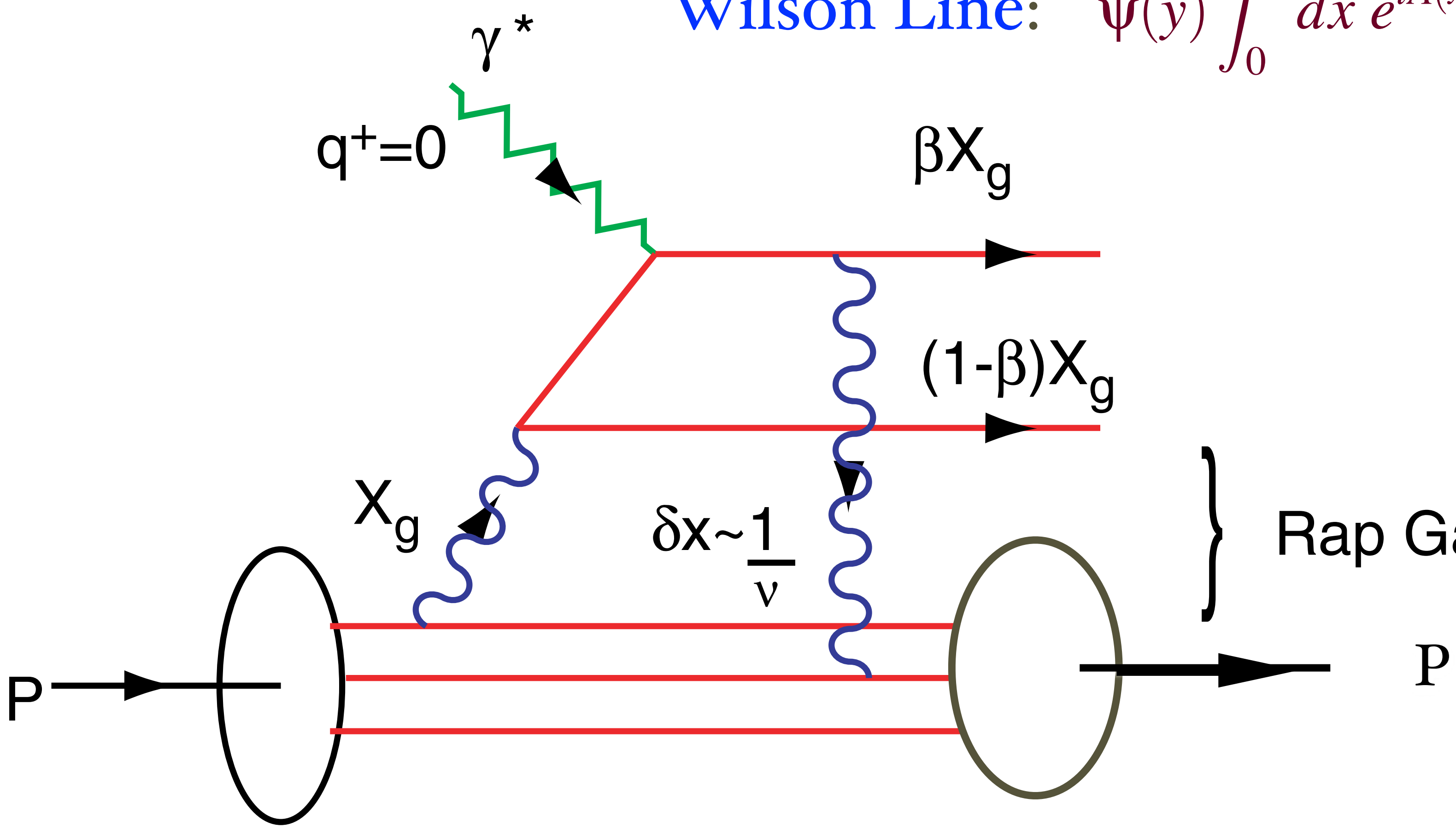




Hoyer, Marchal, Peigne, Sannino, sjb

QCD Mechanism for Rapidity Gaps

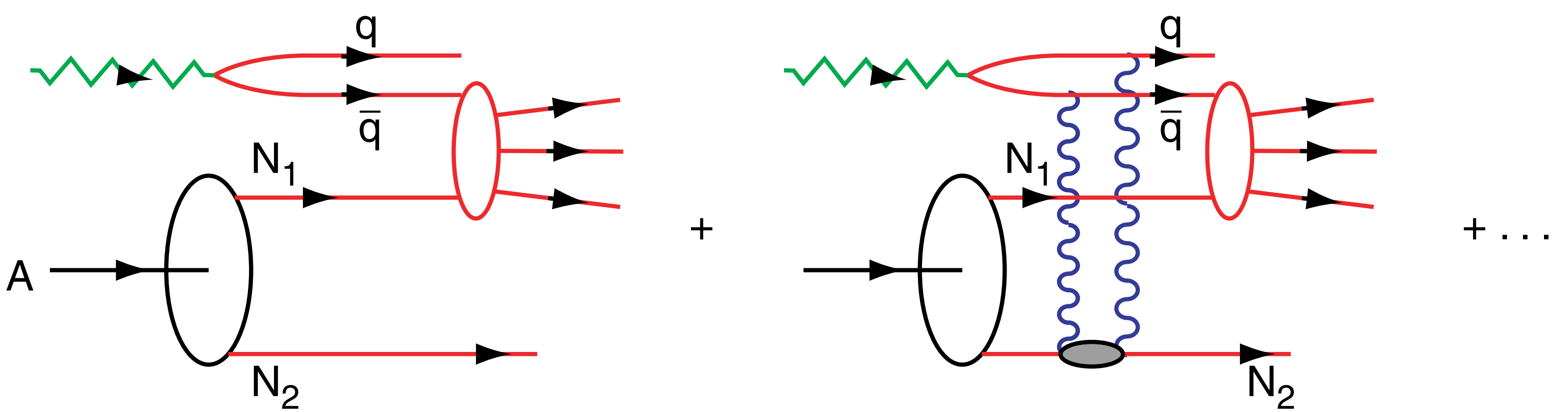
Wilson Line: $\overline{\psi}(y) \int_0^y dx\, e^{iA(x)\cdot dx}\, \psi(0)$



Reproduces lab-frame color dipole approach

Stodolsky
Pumplin, sjb
Gribov

Nuclear Shadowing in QCD



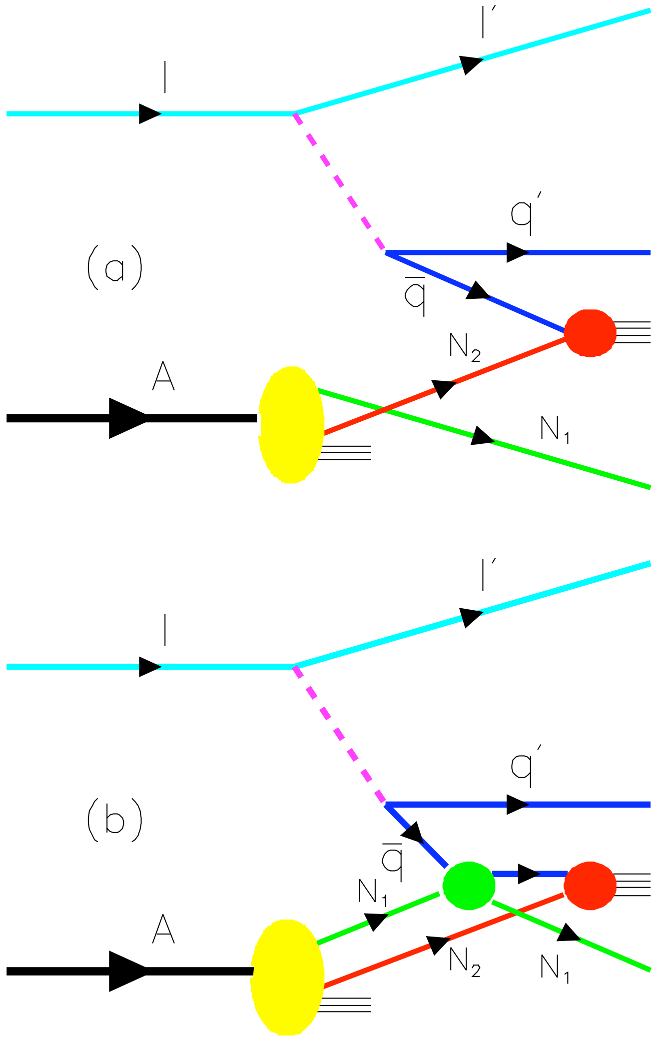
Shadowing depends on understanding leading twist-diffraction in DIS

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



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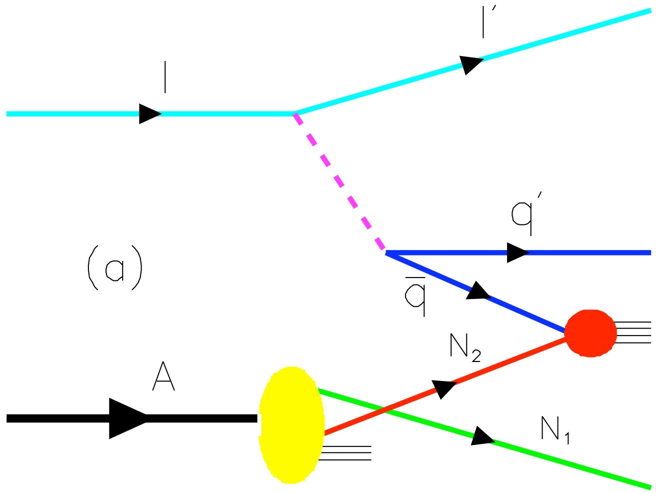
Interior nucleons shadowed

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

Observed HERA DDIS produces nuclear shadowing

Schmidt, Lu, Yang, sjb



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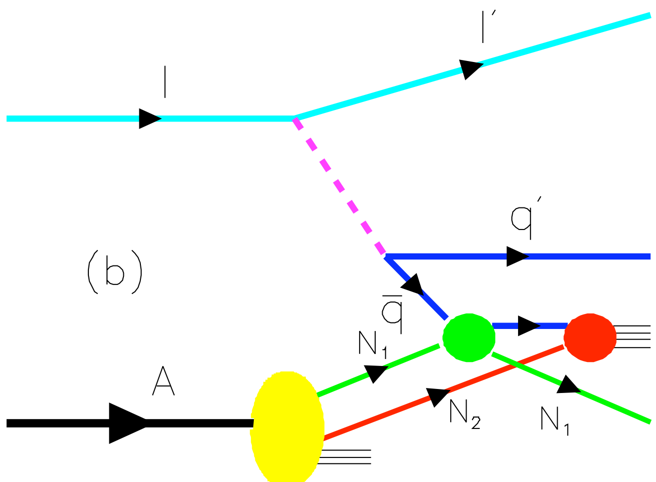


Regge

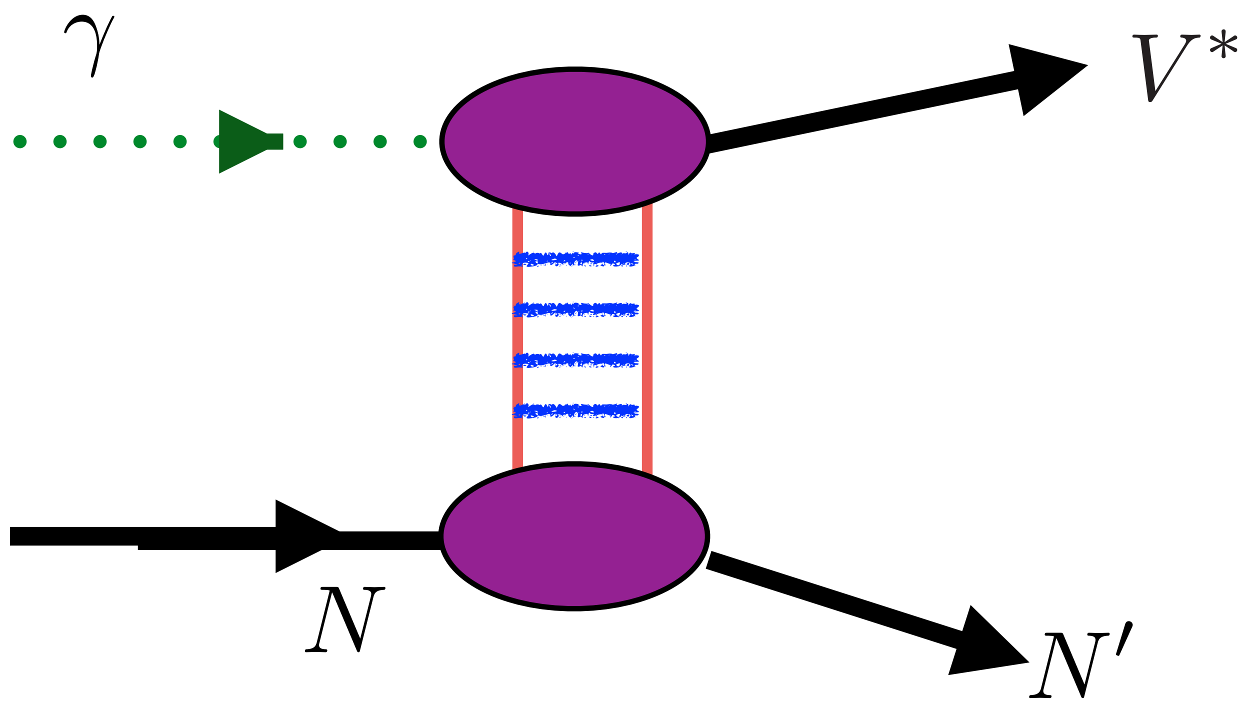
If the scattering on nucleon N_1 is via ~~pomeron~~ exchange, the one-step and two-step amplitudes are ~~opposite in phase, thus diminishing the $\bar{q}$ flux reaching N_2.~~

constructive in phase

thus ***increasing*** the flux reaching N_2

Interior nucleons anti-shadowed

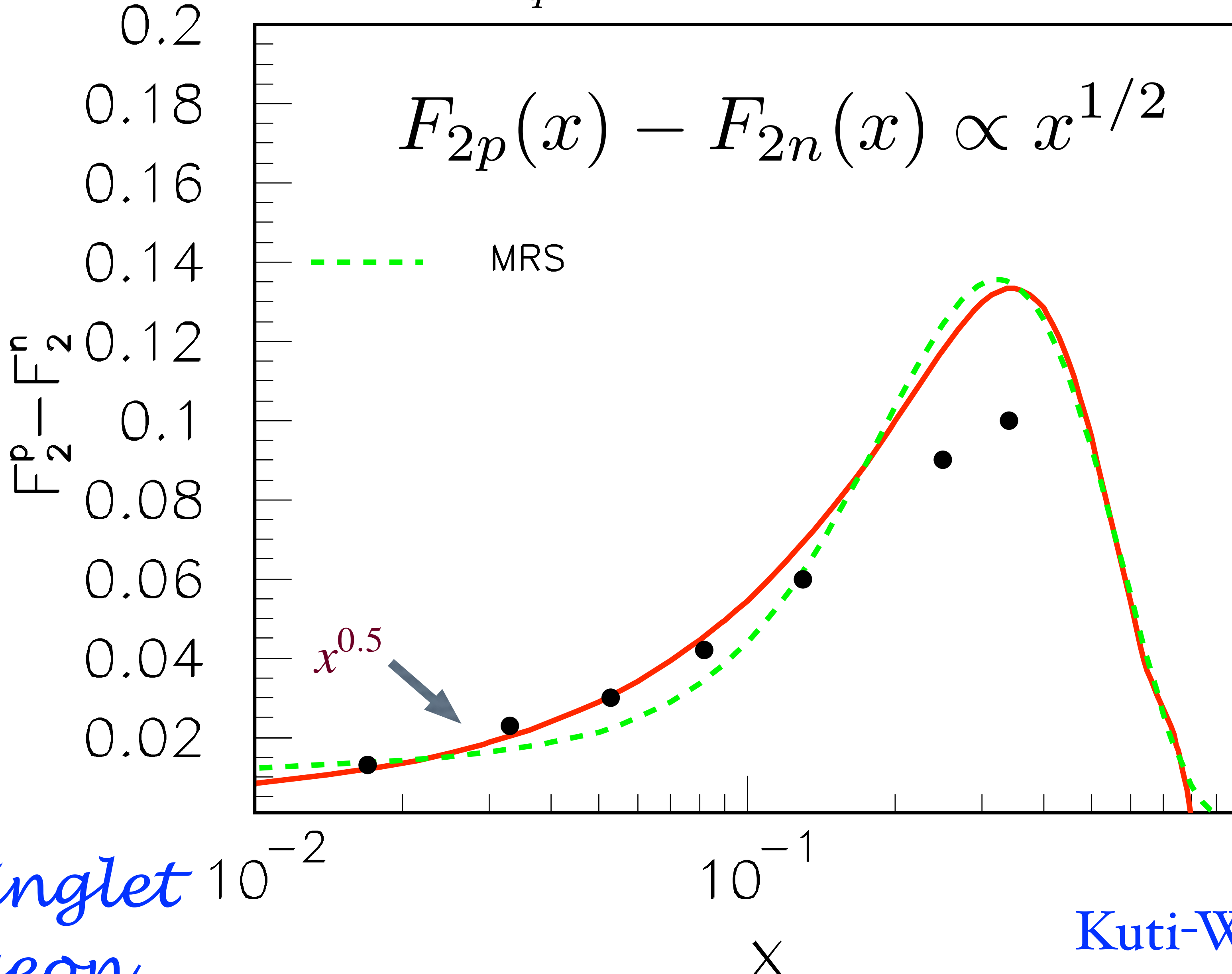
Regge Exchange in DDIS produces nuclear anti-shadowing



Reggeon Exchange Contribution to DDIS

$$\gamma^* n \to p V^{*-}$$

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



Non-singlet Reggeon Exchange

Kuti-Weisskopf behavior

Regge Behavior of Scattering Amplitudes

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

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

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

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

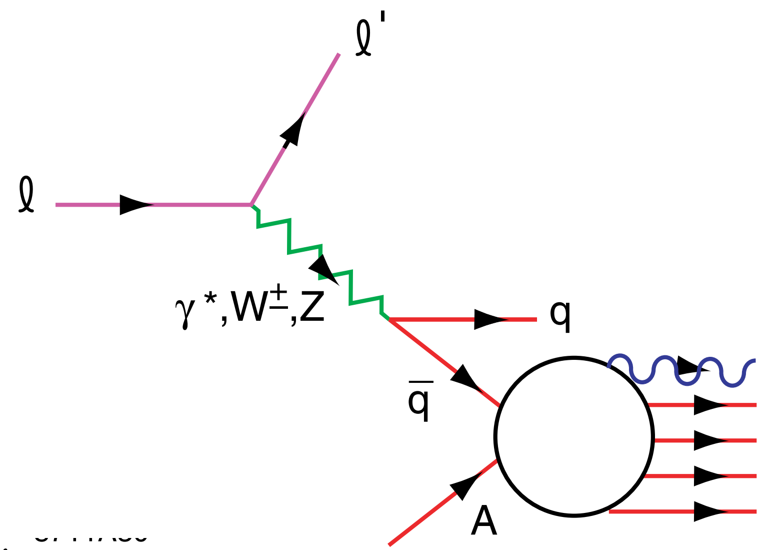
$$Reggeon(\alpha_{\mathcal{R}} \simeq 1/2), C = \pm, phase = Real + Imaginary$$

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

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

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!

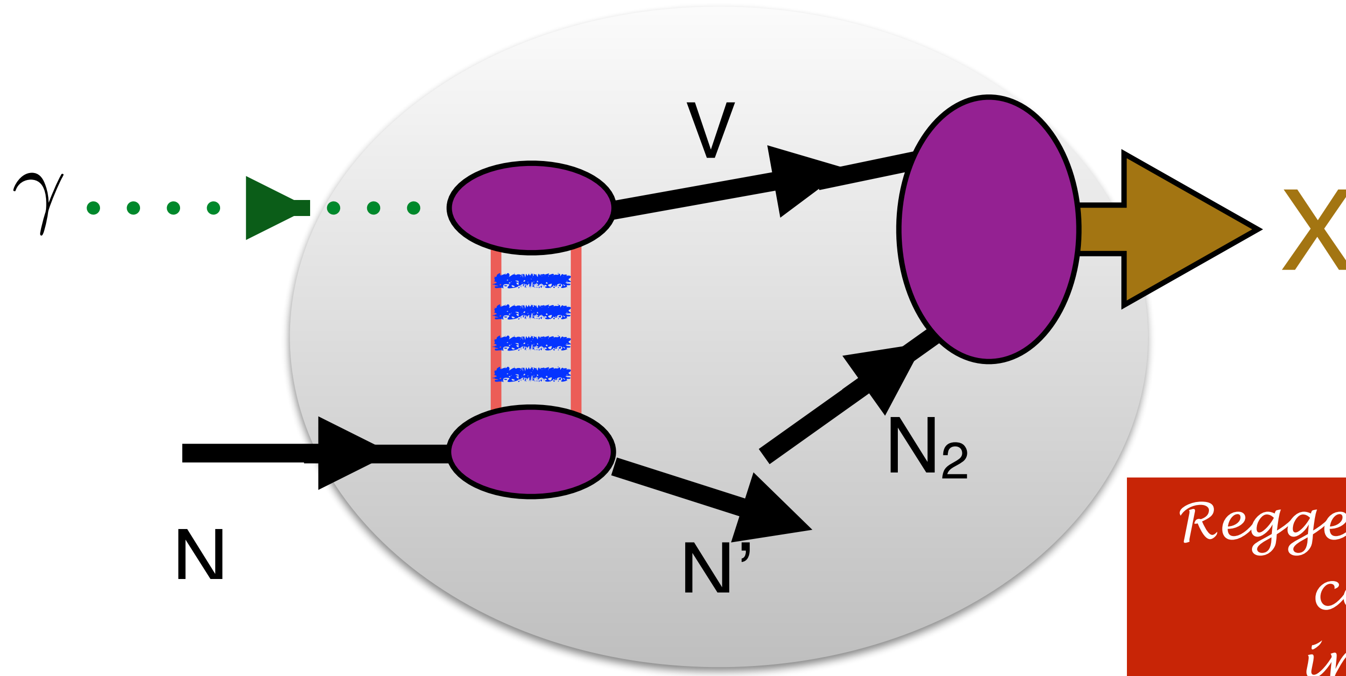
Thus antishadowing is not universal

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

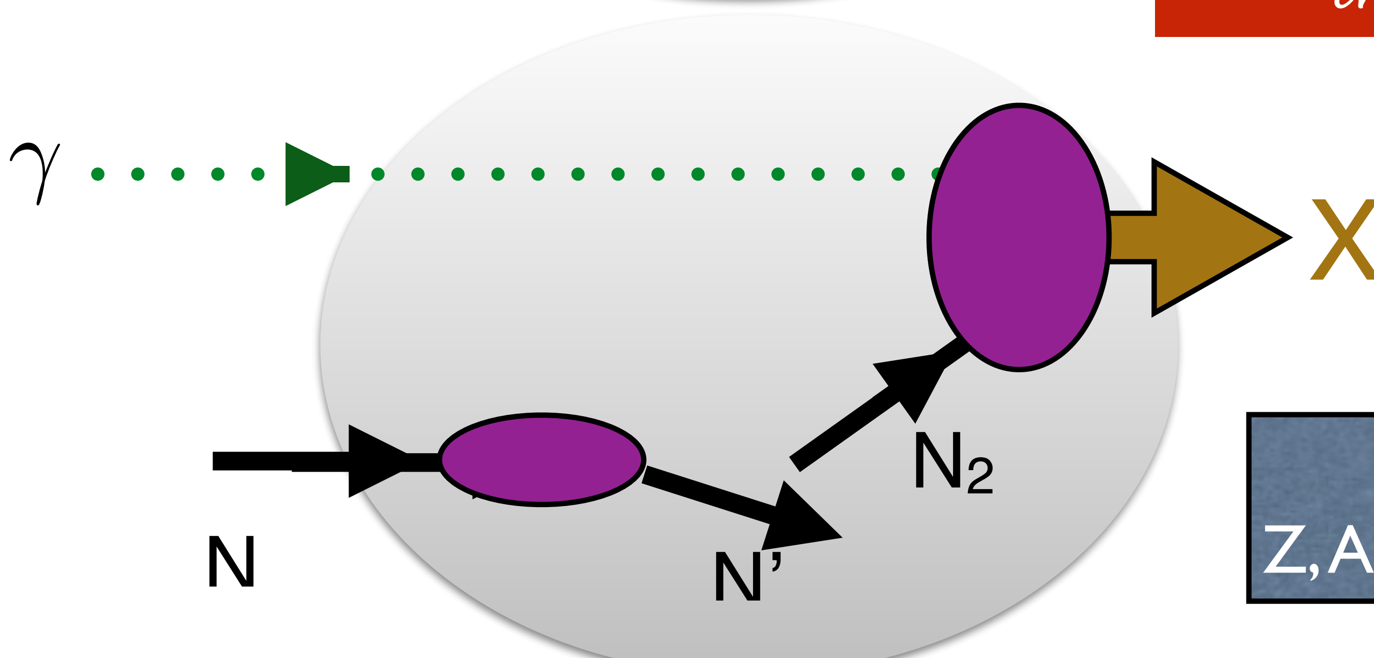
Test: Tagged Drell-Yan

Two-step and One-Step Glauber processes

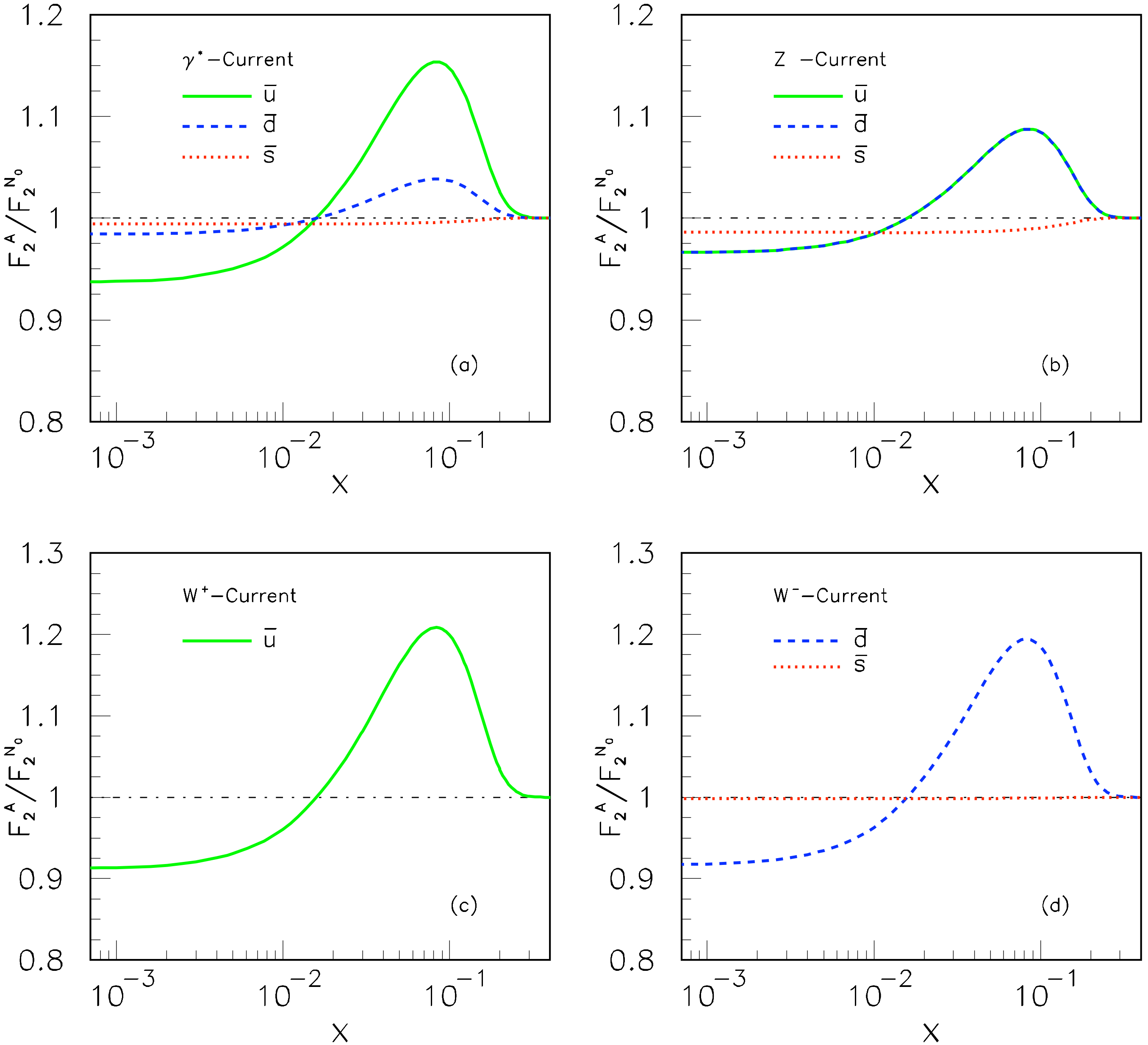
I=1 Reggeon Exchange on N_1



Regge Phase can give constructive interference!



Anomalous Z, A-Z dependence



Lu, Schmidt, Yang; sjb

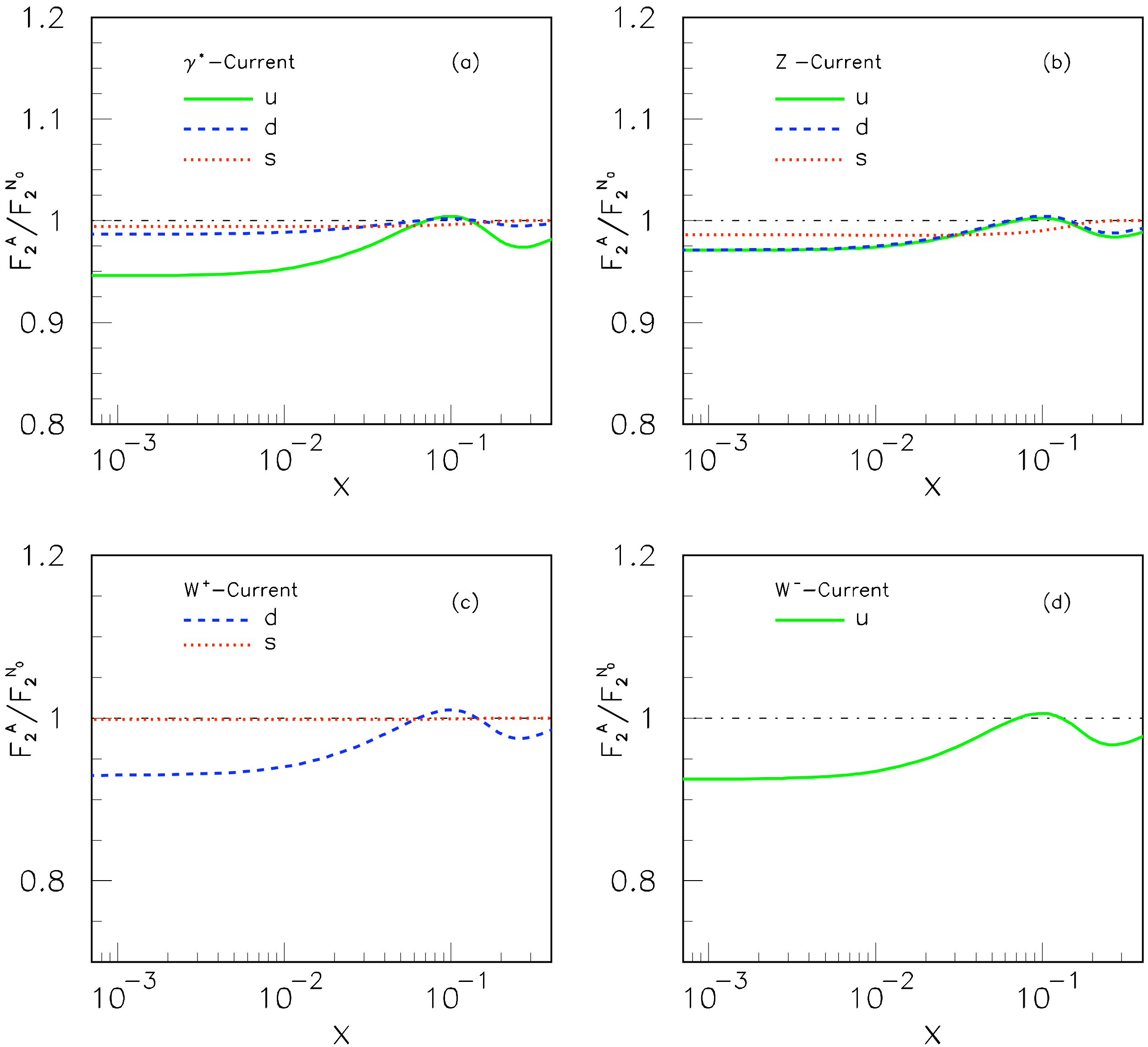
Modifies NuTeV extraction of

$\sin^2\theta_W$

Test in flavor-tagged DIS at the EIC

Nuclear Antishadowing not universal !

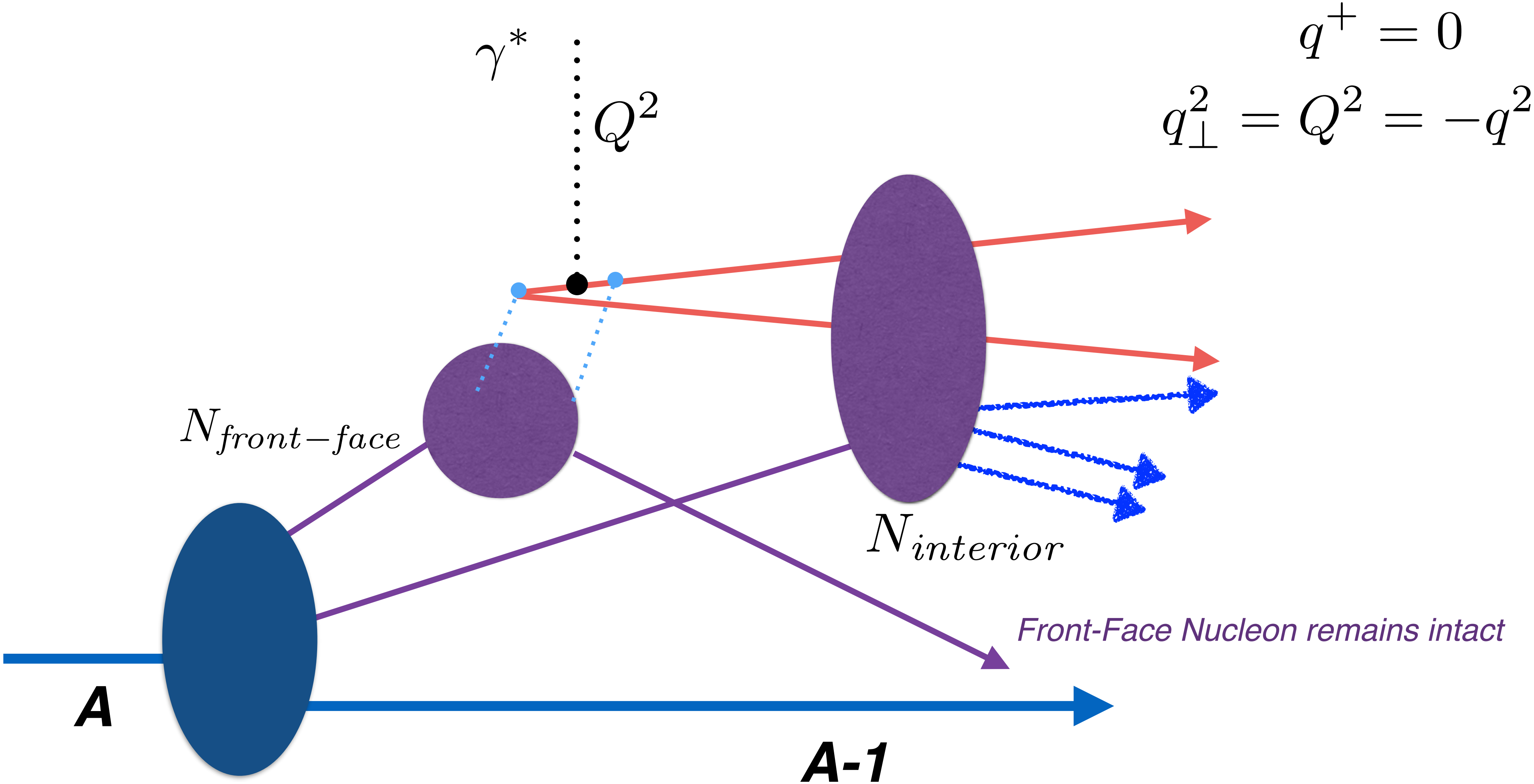
Shadowing and Antishadowing of DIS Structure Functions



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

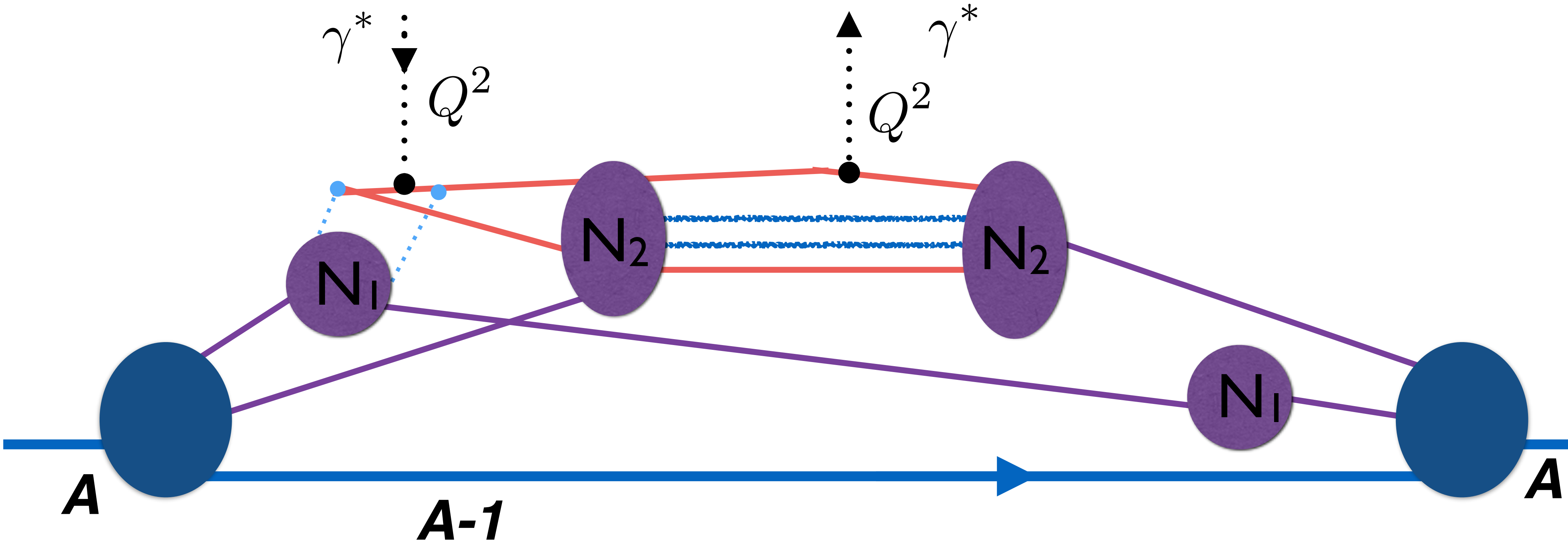


Two-Step Process in the $q^+=0$ Parton Model Frame

Illustrates the LF time sequence

$$q^+ = 0 \quad q_\perp^2 = Q^2 = -q^2$$

Illustrates the LF time sequence



Front-Face Nucleon N_1 struck

Front-Face Nucleon N_1 not struck

One-Step / Two-Step Interference

Study Double Virtual Compton Scattering $\gamma^* A \to \gamma^* A$

Cannot reduce to matrix element of local operator! No Sum Rules!

LFWFs are real for stable hadrons, nuclei

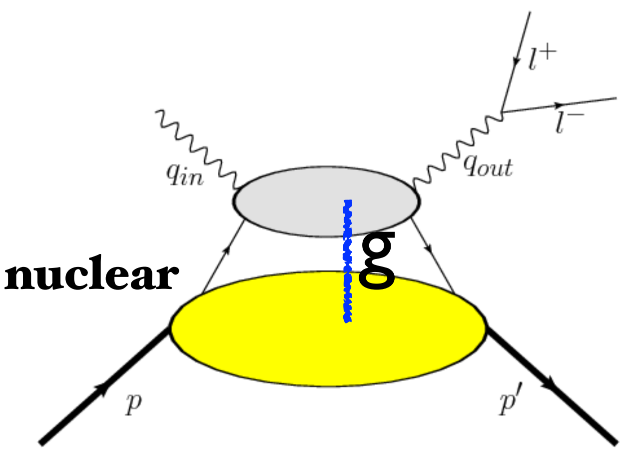
Liuti, sjb

Crucial JLab Experiments

- *Measure Diffractive DIS: Agree with Shadowing of Nuclear Structure Functions?*
- *Isospin Dependence of Diffractive DIS — Reggeon Exchange -*
- *Use deuteron: see n to p*
- *Flavor Dependence of Antishadowing: Tagged Quark Distributions?*

“Handbag” Approximation

- **Parton model: assumes current-current correlator carried by single quark propagator at high photon virtuality**
- **Imaginary Part of Virtual Forward Compton Amplitude gives DIS structure Functions**
- **Leading-Twist Dominance — Motivated by the Operator Product Expansion**
- **Produces Momentum and Baryon Number Sum Rules**
- **Real Part: J=0 Fixed Pole from local two-photon operators**
- **Will show: Handbag Approximation invalid for DVCS on a nuclear target because of shadowing, antishadowing!**
- **Recall: Sivers Effect and Diffractive DIS are leading twist!**



The GPD's are non-forward matrix elements of the PDF operator:

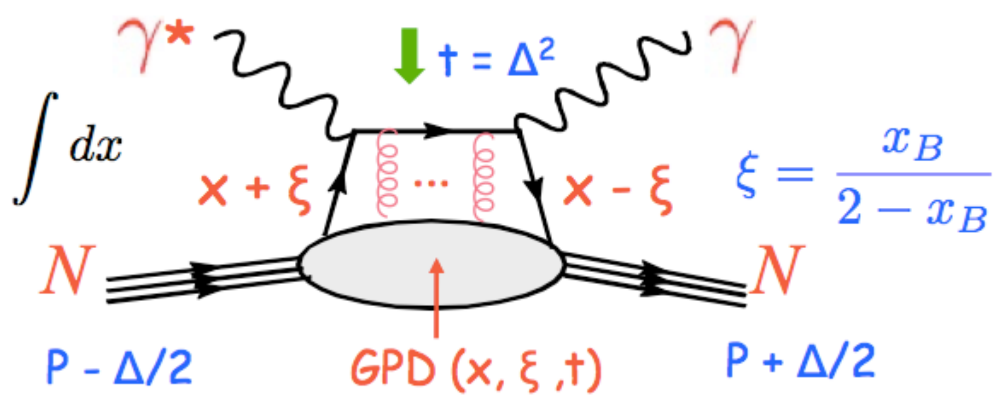
$$\frac{1}{8\pi}\int dr^- e^{imxr^-/2}\langle P+\tfrac{1}{2}\Delta|\bar{q}(-\tfrac{1}{2}r)\gamma^+ W[\tfrac{1}{2}r^-,-\tfrac{1}{2}r^-]q(\tfrac{1}{2}r)|P-\tfrac{1}{2}\Delta\rangle_{r^+=r_\perp=0}$$

$$=\frac{1}{2P^+}\bar{u}(P+\tfrac{1}{2}\Delta)\left[H(x,\xi,t)\gamma^+ + E(x,\xi,t)i\sigma^{+\nu}\frac{\Delta_\nu}{2m}\right]u(P-\tfrac{1}{2}\Delta)$$

The GPD amplitudes can be accessed experimentally through the Deeply Virtual Compton Scattering cross section at leading twist: $Q^2 \to \infty$.

DVCS: $e\,N \to e' + \gamma + N$

Through $\Delta_\perp$, the GPD's contain information about the parton distributions in transverse space.



Handbag modified by leading-twist lensing!

Color Transparency

Bertsch, Gunion, Goldhaber, sjb

Mueller, sjb

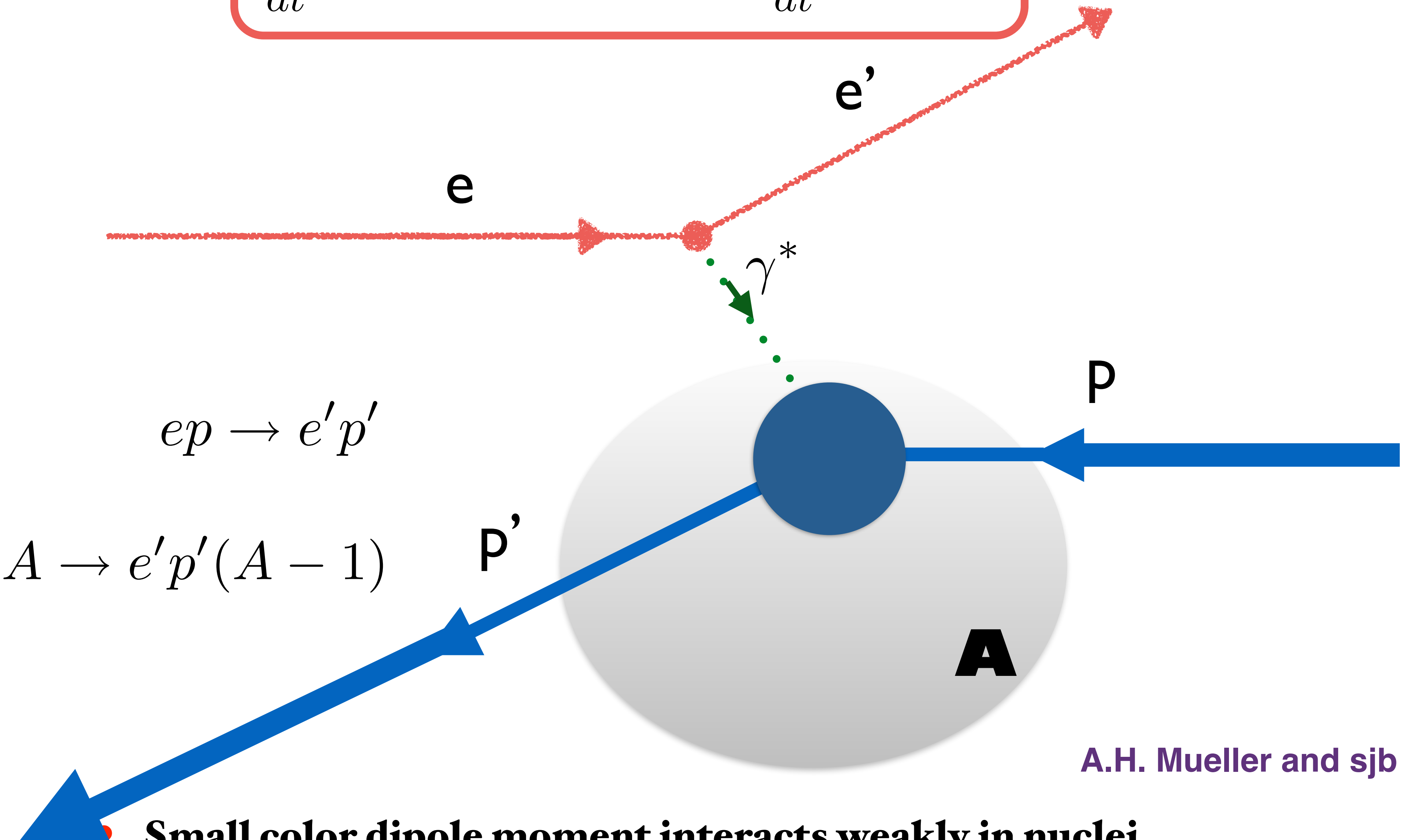
Frankfurt, Strikman, Miller

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

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



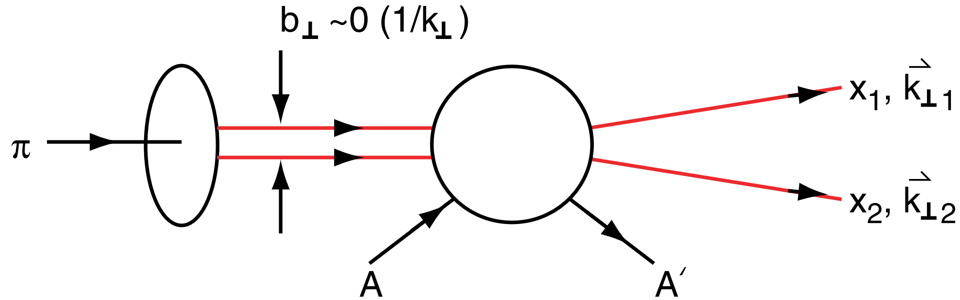
$$ep \to e'p'$$

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

A.H. Mueller and sjb

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

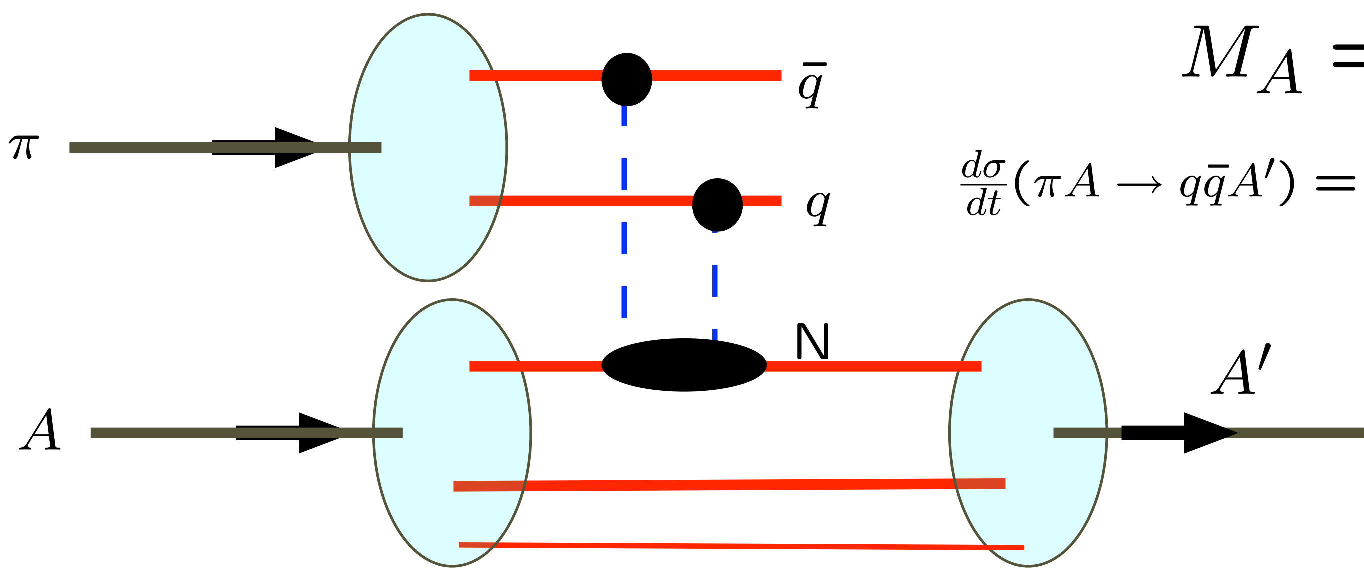
Fermilab E791 Experiment, Ashery et al.



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

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

QCD COLOR Transparency



$$M_A = A\ M_N$$

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

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

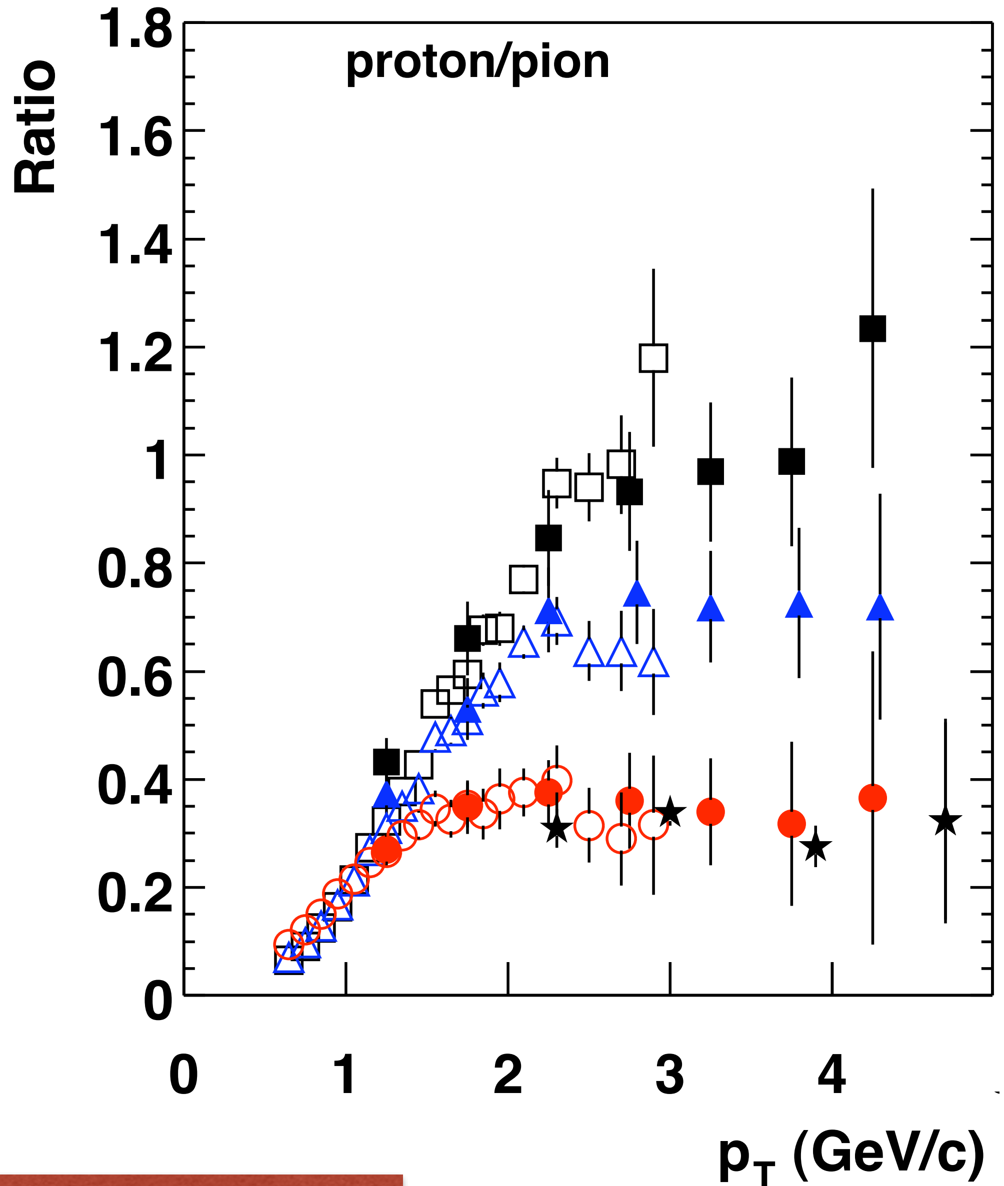
α (Incoh.) $= 0.70 \pm 0.1$

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!



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 not from jets! No same-side hadrons*
- *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 $x_T = 1$*

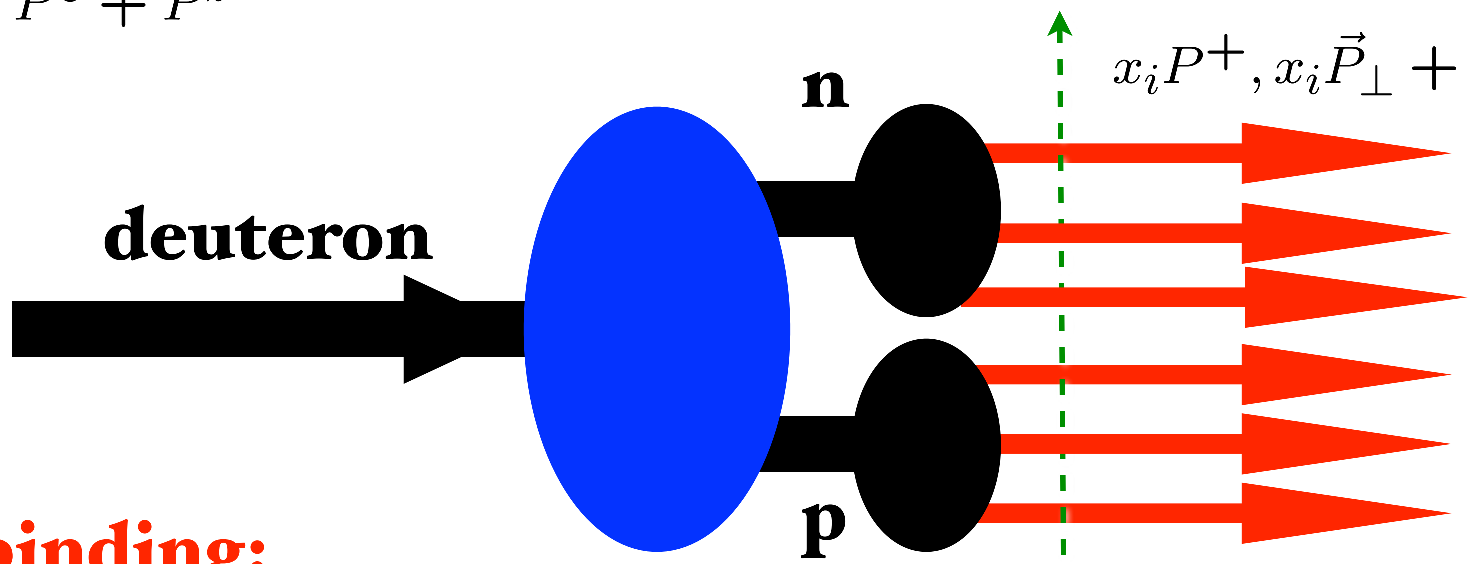
EIC: Resolves complex physics signals at hadron and ion colliders

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

Fixed $\tau = t + z/c$

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

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



Weak binding:

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

$\sum_i^n x_i = 1$

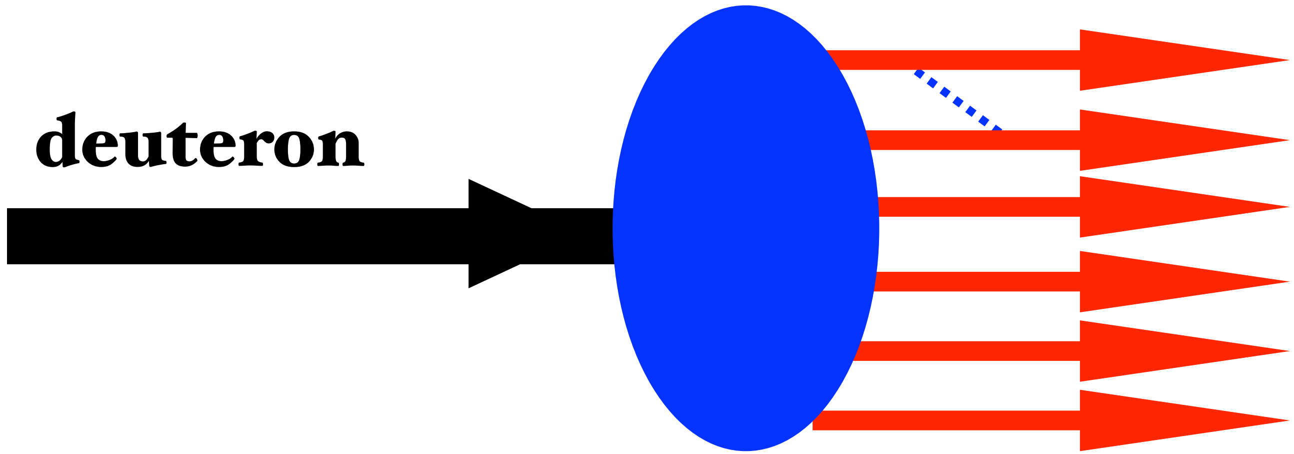
$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

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 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!

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

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
- Expense Dominance at x > 1
- Predict $\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-}) \simeq \frac{d\sigma}{dt}(\gamma d \to pn)$ at high Q^2

Hidden Color of Deuteron

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

Asymptotic Solution has Expansion

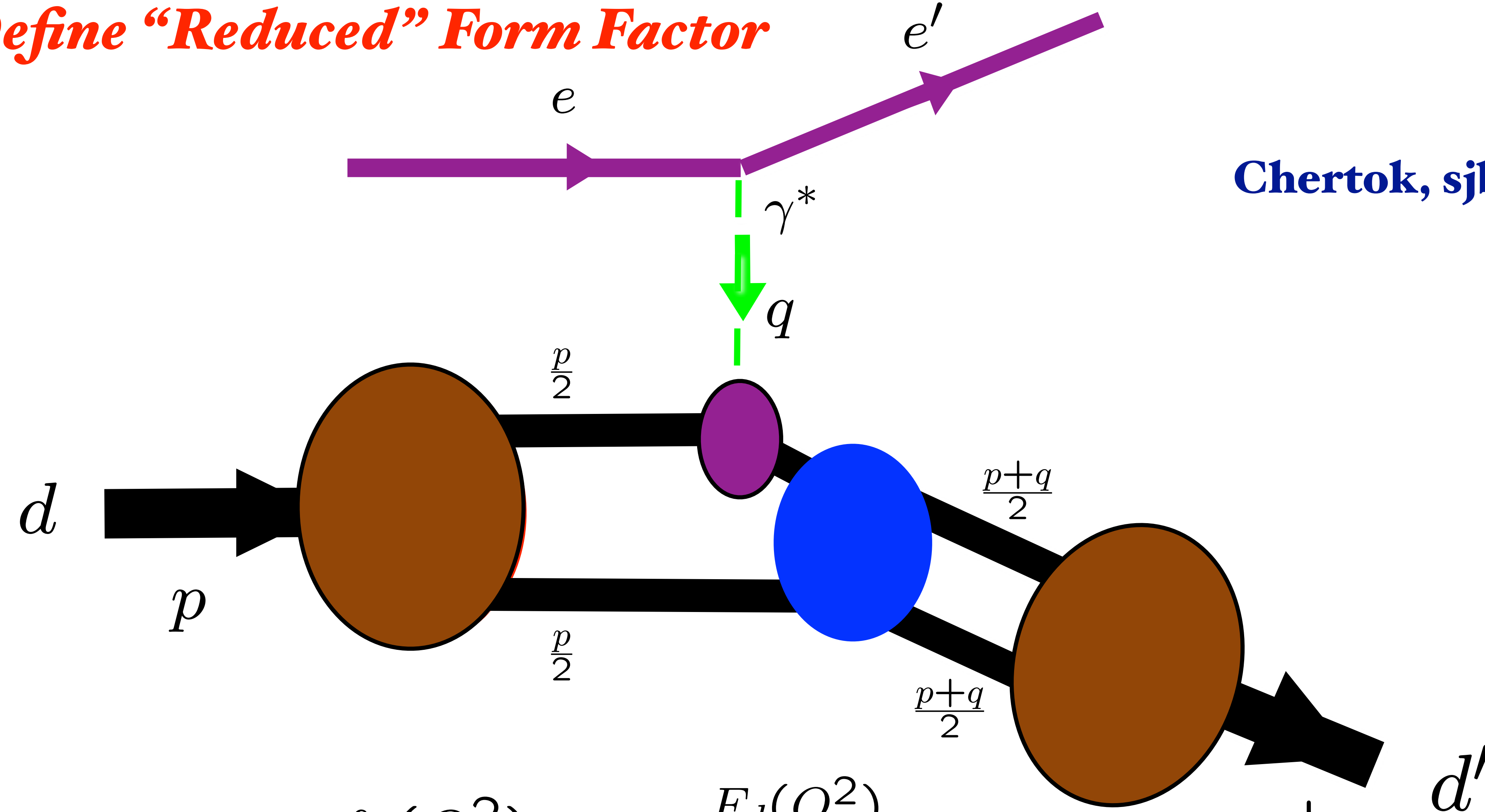
$$\psi_{[6]\{33\}} = \left(\frac{1}{9}\right)^{1/2} \psi_{NN} + \left(\frac{4}{45}\right)^{1/2} \psi_{\Delta\Delta} + \left(\frac{4}{5}\right)^{1/2} \psi_{CC}$$

ERBL Evolution: Transition to Delta-Delta

Lepage, Ji, sjb

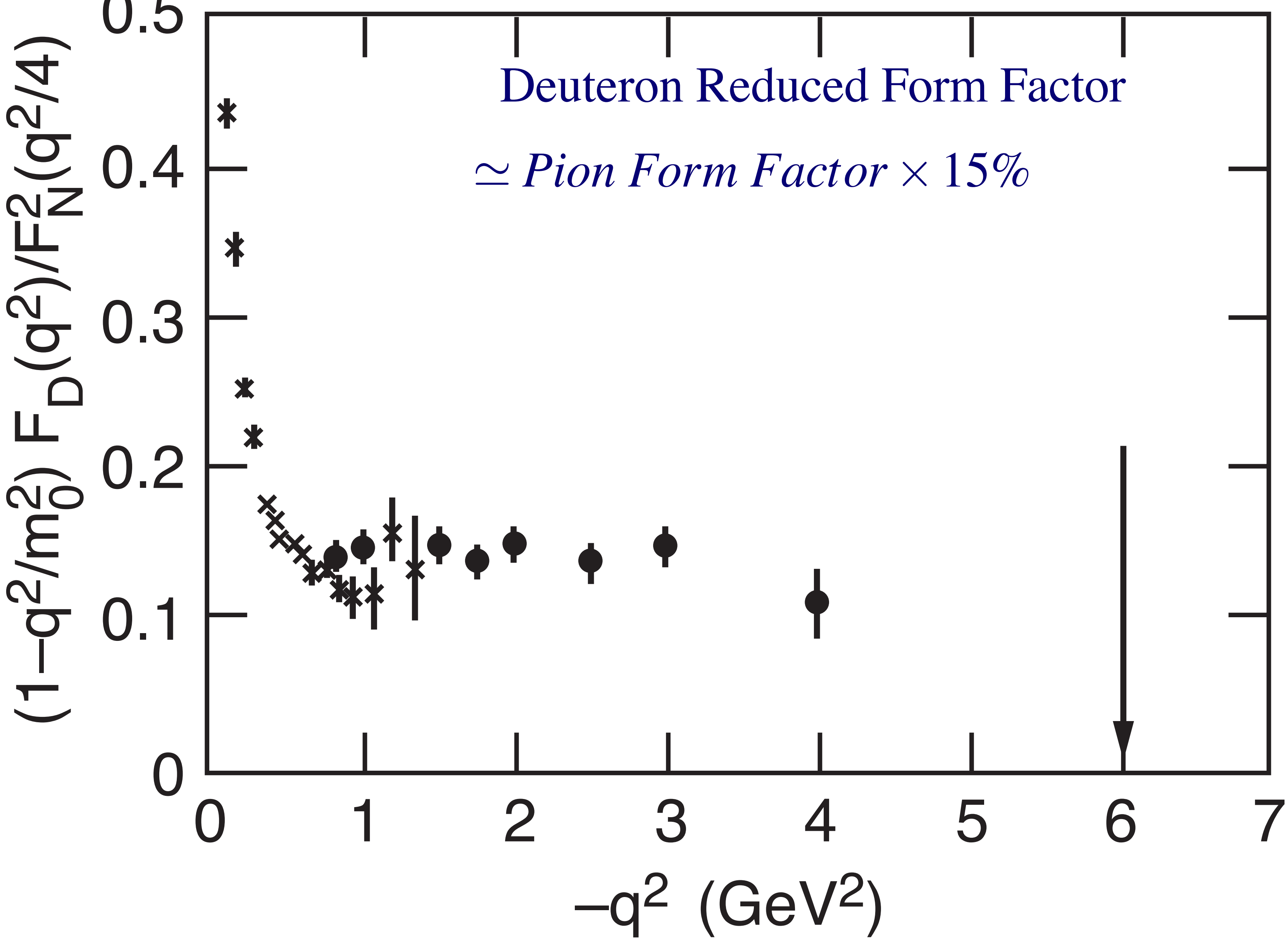
Define "Reduced" Form Factor

Chertok, sjb



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

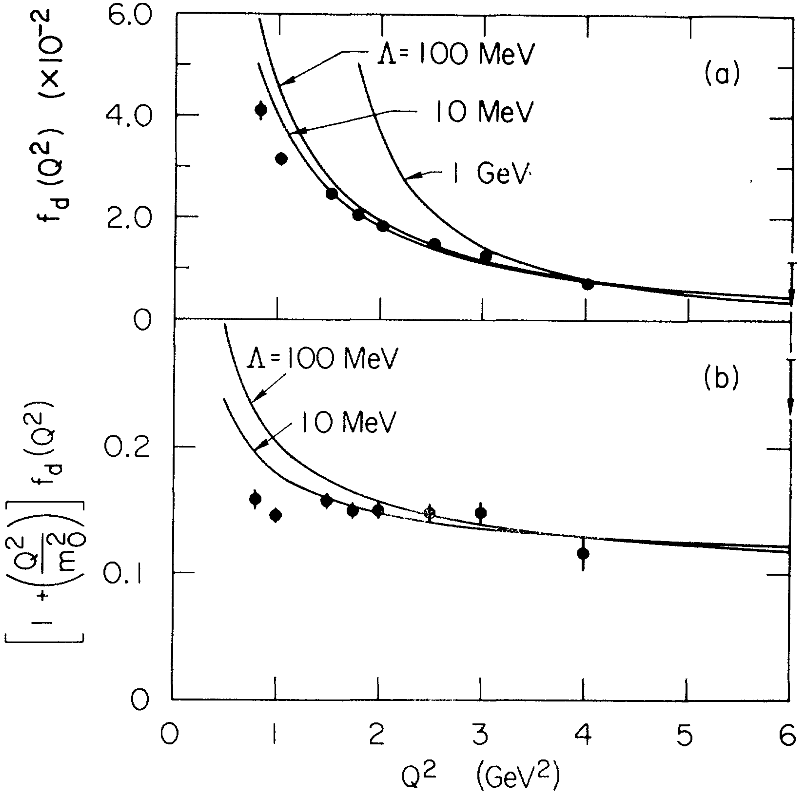
Elastic electron-deuteron scattering


Deuteron Reduced Form Factor
$\simeq$ *Pion Form Factor* $\times$ 15%
$(1-q^2/m_0^2)\ F_D(q^2)/F_N^2(q^2/4)$
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
6
7
$-q^2$ (GeV^2)

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

Nuclear physics in soft-wall AdS/QCD: deuteron electromagnetic form factors

Thomas Gutsche, Valery E. Lyubovitskij, Ivan Schmidt, and Alfredo Vega

$$F_D(Q^2) \equiv f_D(Q^2) F_p(\frac{Q^2}{4}) F_n(\frac{Q^2}{4})$$

Chertok, sjb

Ji, Lepage, sjb

$$\left[-\frac{d^2}{dz^2} + \frac{4(L+4)^2-1}{4z^2} + \kappa^4 z^2 + \kappa^2 U_0\right] \Phi_n(z) = M^2_{d,n} \Phi_n(z)$$

AdS/QCD, LF Holography

Katz, et al

de Tèramond, sjb

$$f_d(Q^2) = \frac{30(a+1)(a+2)}{(a+3)(a+4)(a+5)}, \quad F_N(Q^2/4) = \frac{2}{(a+1)(a+2)}$$

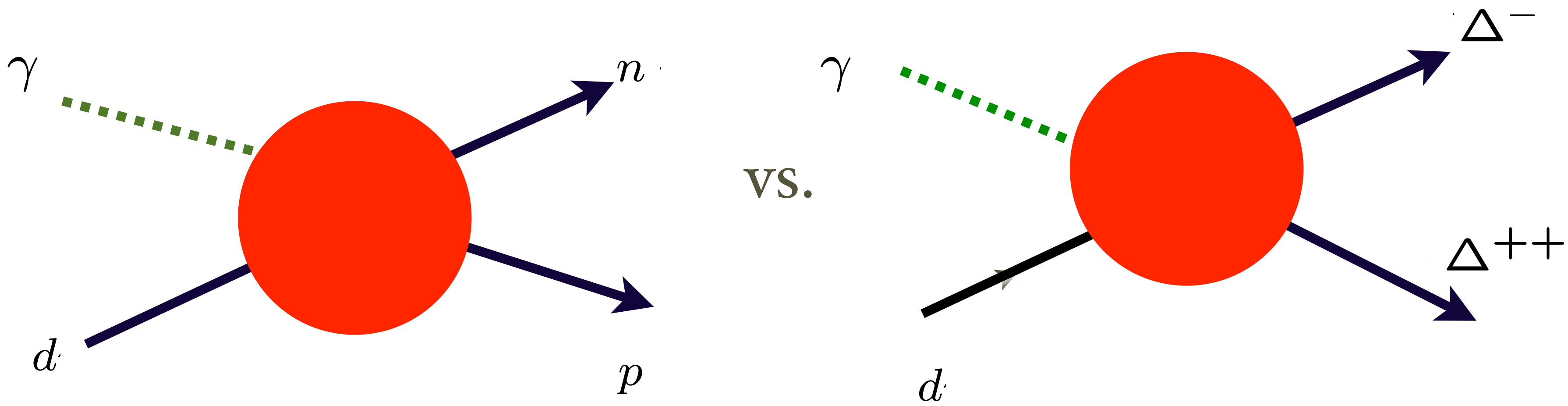
$$a = Q^2/4\kappa^2 = Q^2/m_\rho^2 \qquad Q^2 f_d(Q^2) \to const$$

Test of Hidden Color in Deuteron Photodisintegration

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

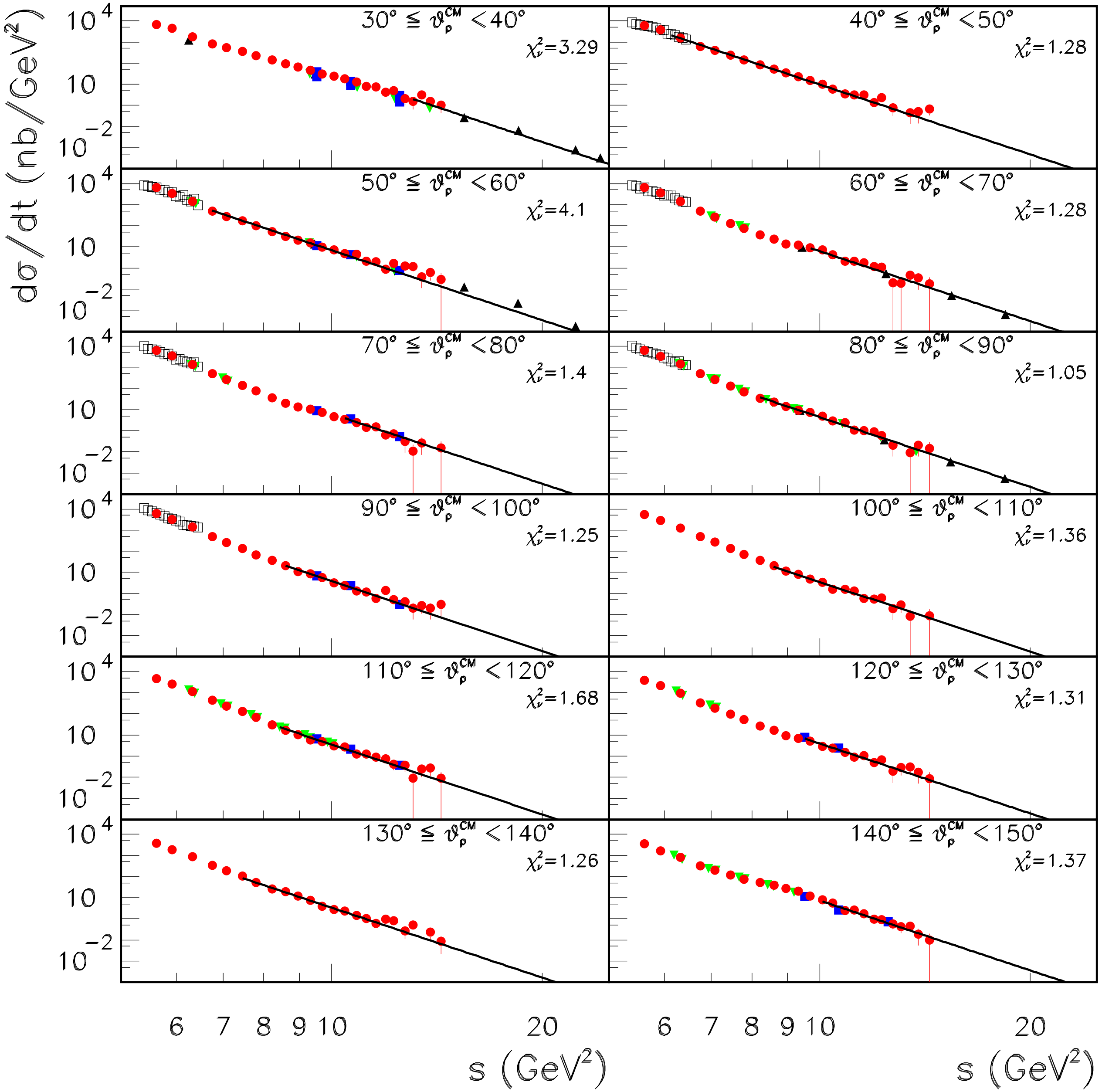
Ratio predicted to approach 2:5

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.

Deuteron Photodisintegration



PQCD and AdS/CFT:

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

$$s^{11}\frac{d\sigma}{dt}(\gamma d \to np) = F(\theta_{CM})$$

$n_{tot} - 2 =$
(1 + 6 + 3+ 3) - 2 = 11

Reflects conformal invariance

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

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

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

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

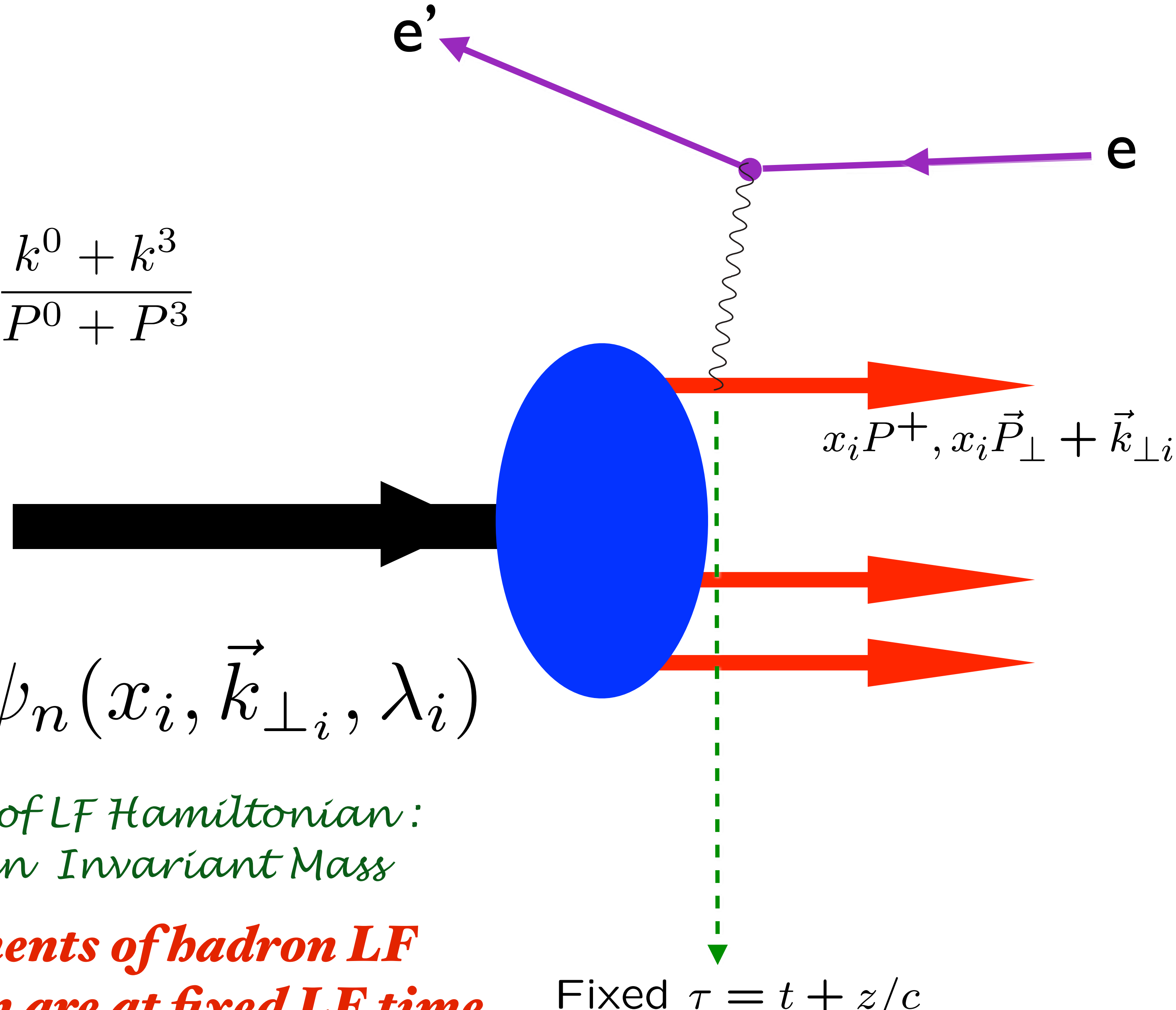
Advantages of the Dirac's Front Form for Hadron Physics

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

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



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

Eigenstate of LF Hamiltonian :
Off-shell in Invariant Mass

Measurements of hadron LF wavefunction are at fixed LF time

Like a flash photograph

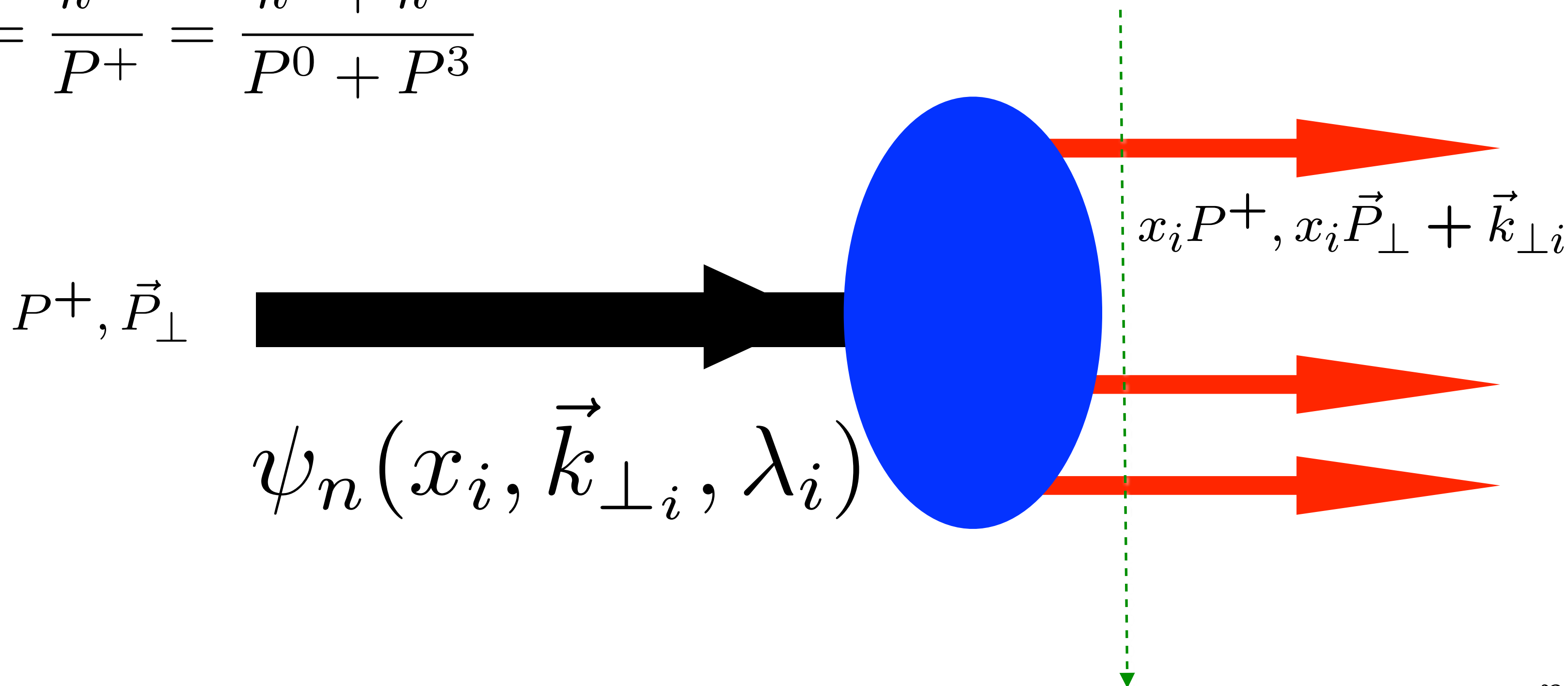
$$x_{bj} = x = \frac{k^+}{P^+}$$

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

Eigenstate of LF Hamiltonian : Off-shell in Invariant Mass

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

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



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

$\sum_i^n x_i = 1$

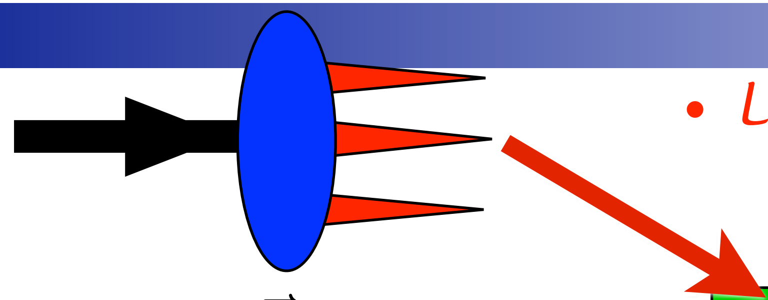
$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

Sum Rules

Invariant under boosts! Independent of P^μ

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

- *Light Front Wavefunctions:*



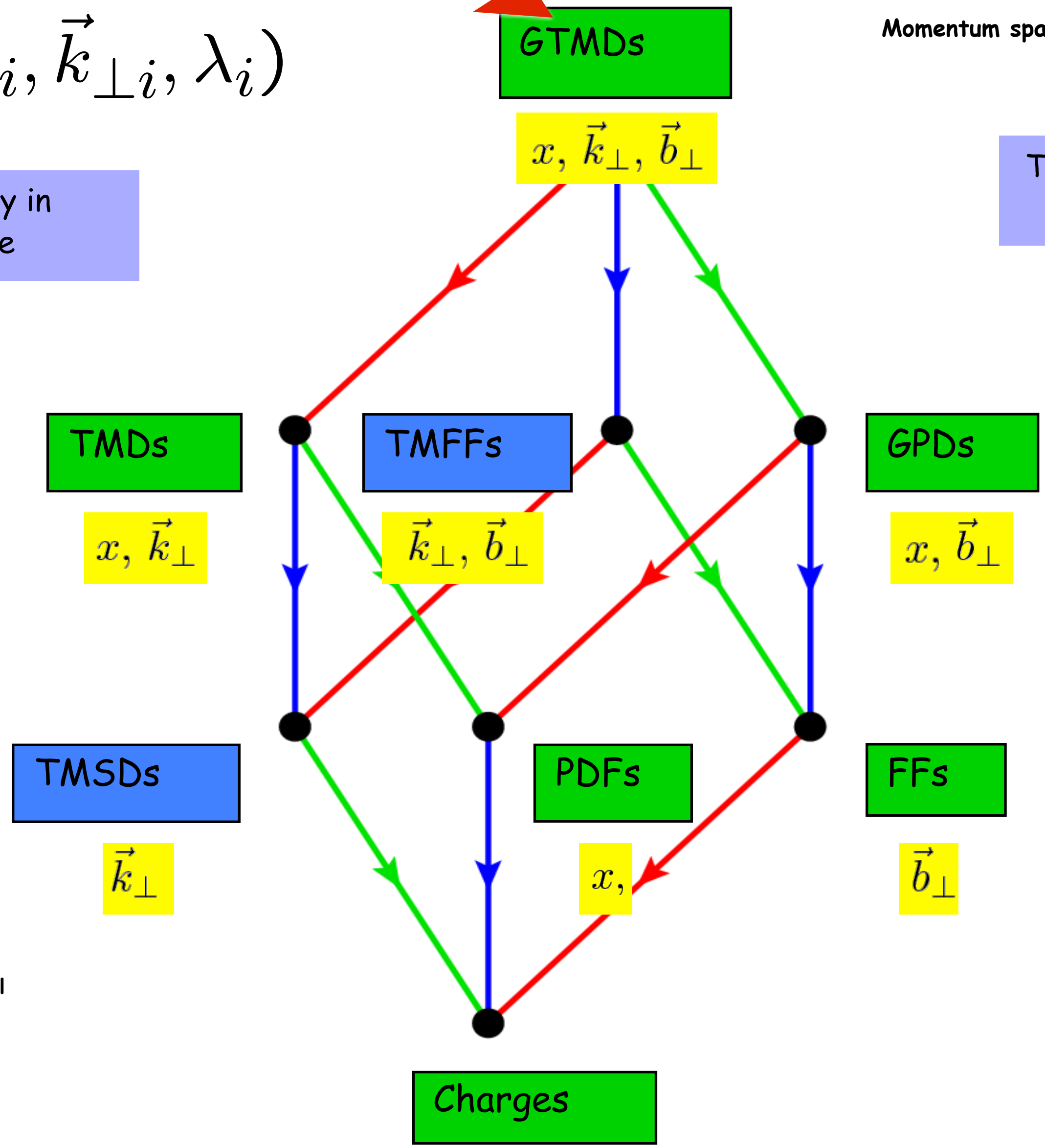
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

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

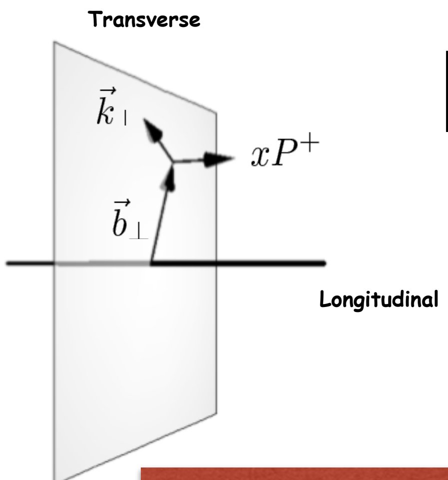
$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$

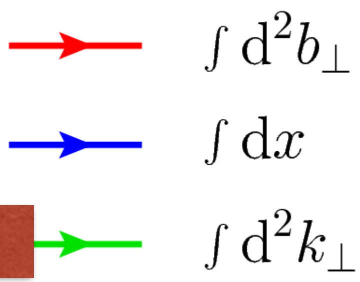
Transverse density in momentum space

Transverse density in position space



Lorce, Pasquini





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

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

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

The Light Front Fock State Wavefunctions

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

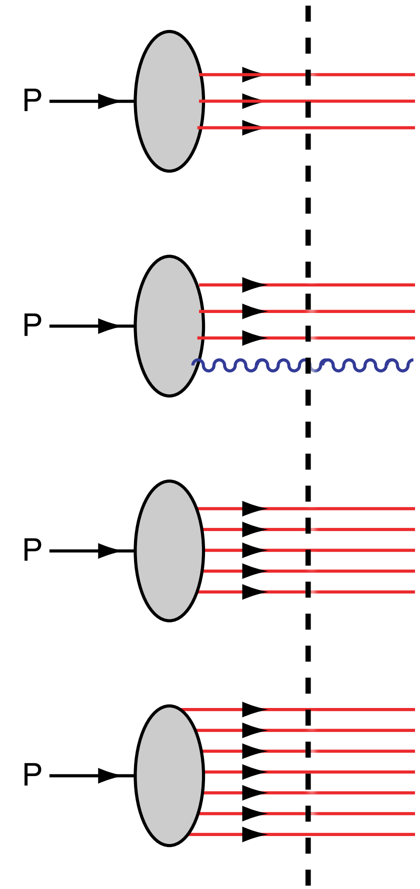
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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 !

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

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

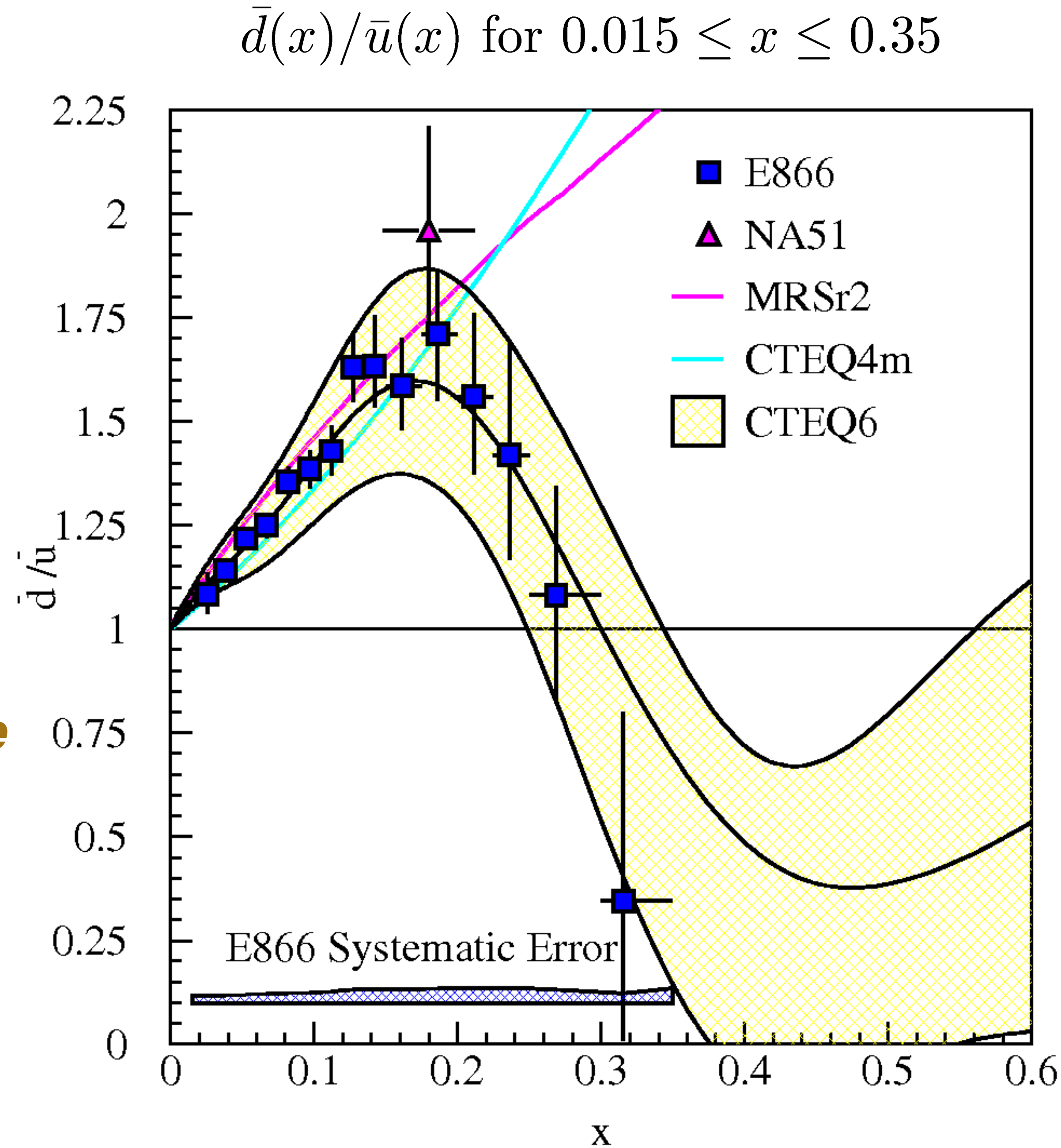
Deuteron: Hidden Color

- E866/NuSea (Drell-Yan)

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

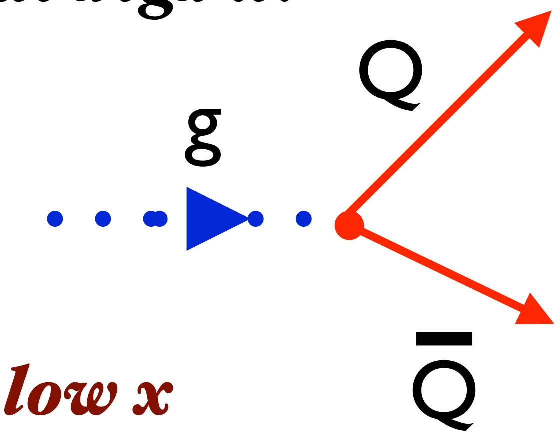
Interactions of quarks at same rapidity in 5-quark Fock state

Intrinsic sea quarks



Do heavy quarks exist in the proton at high x?

Conventional wisdom:
gluon splitting



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

Maximally off-shell - requires low x, high W^2

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

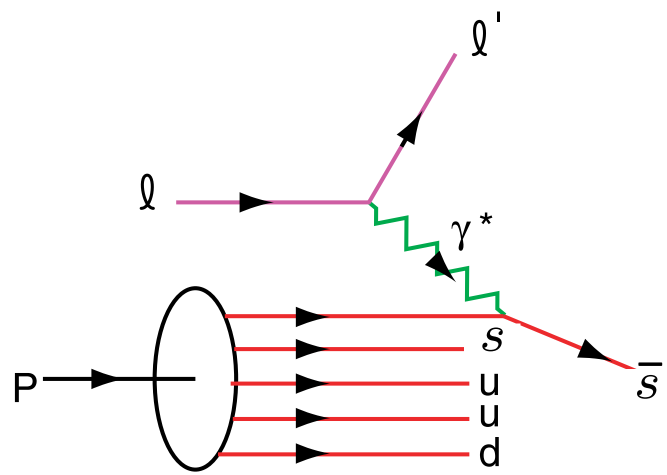
$$\text{at starting scale } Q_0^2 = \mu_F^2$$

Conventional wisdom is wrong even in QED!

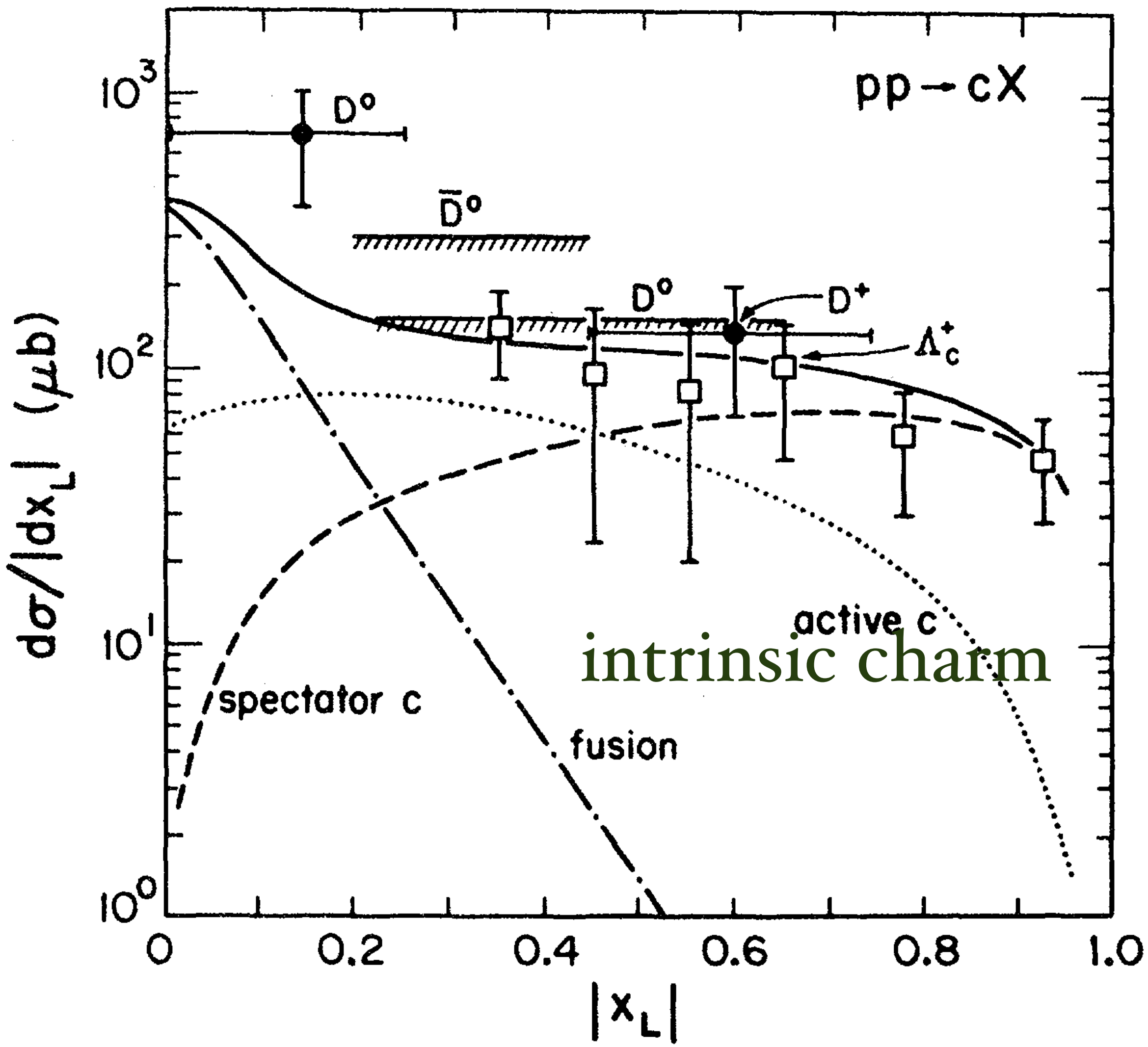
Measure strangeness distribution in Semi-Inclusive DIS at JLab

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

- **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 $ep \to e' K^+ X$



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

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**

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

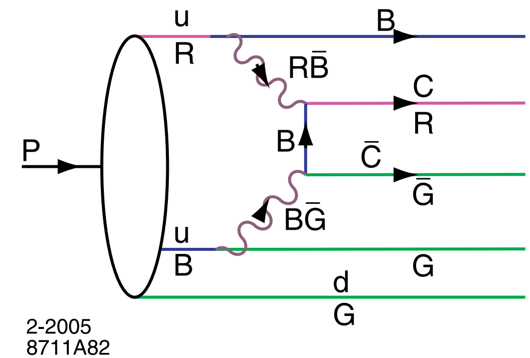
$$s(x, \mu_F^2) = c(x, \mu_F^2) = b(x, \mu_F^2) \equiv 0$$

at starting scale μ_F^2

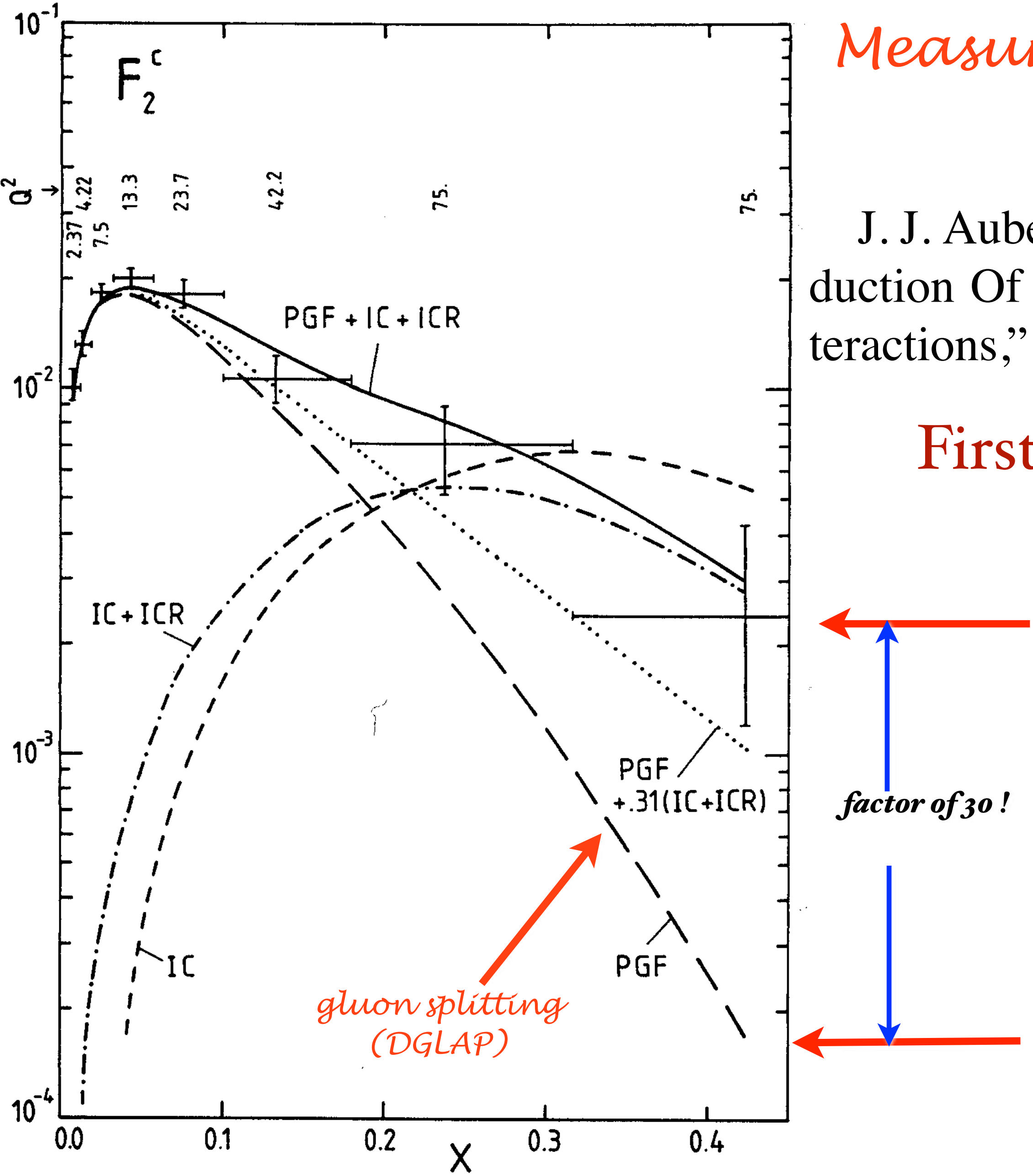
Conventional wisdom is wrong even in QED!

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, ..)

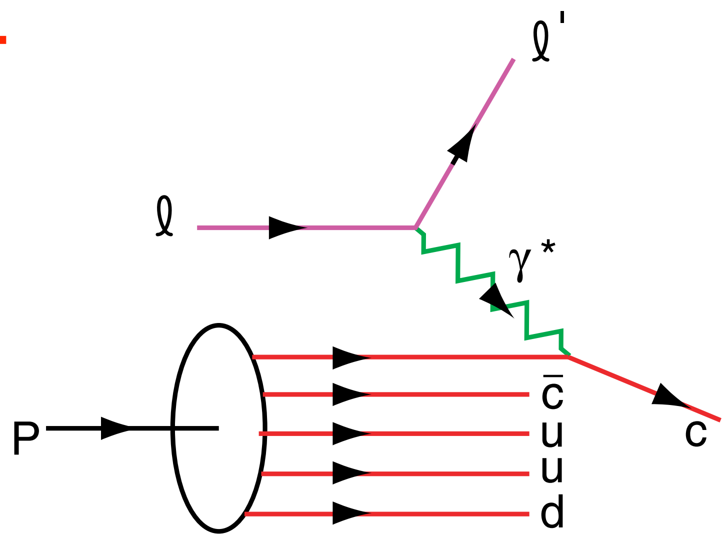


Measurement of Charm Structure Function!

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



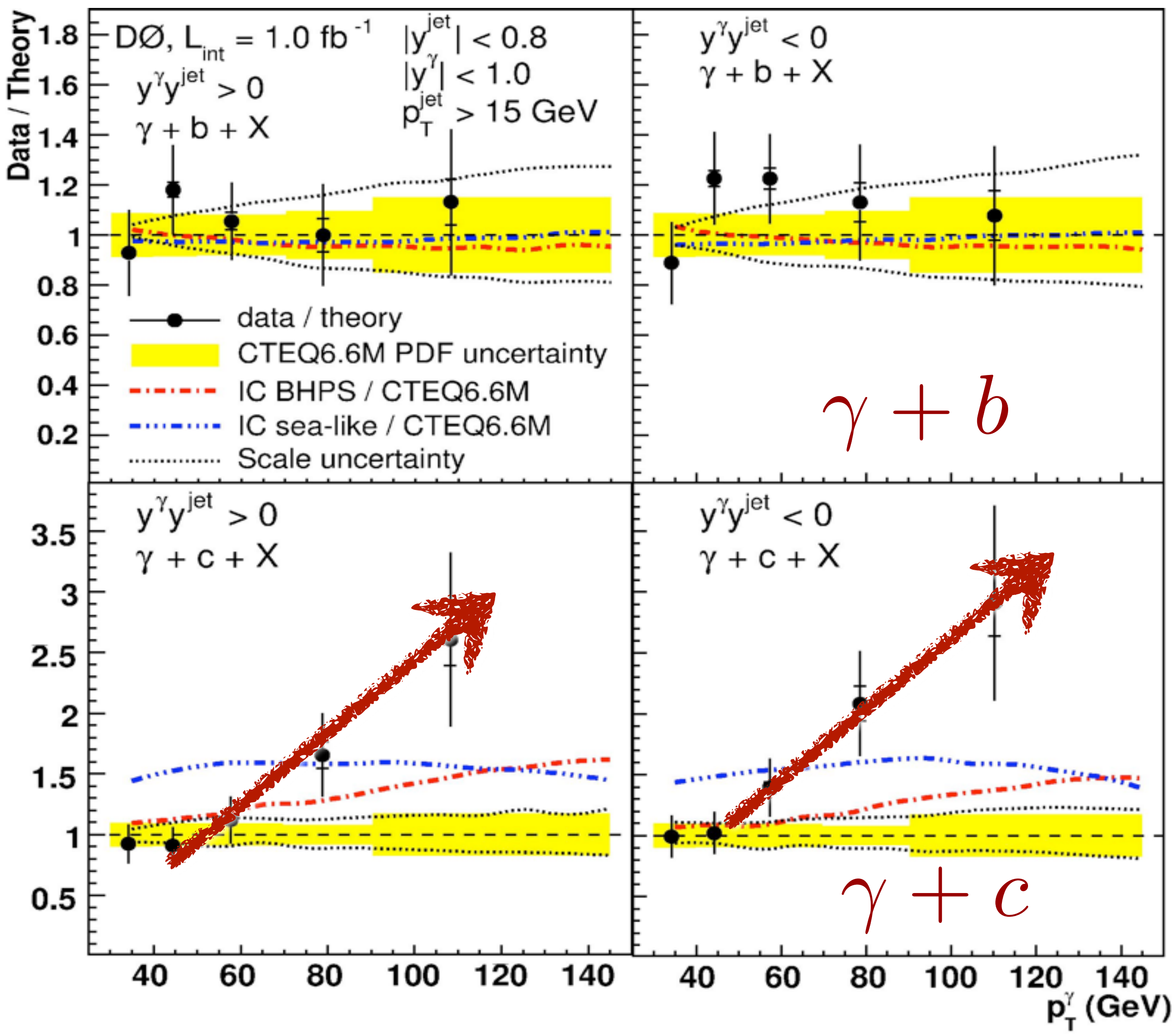
DGLAP / Photon-Gluon Fusion: factor of 30 too small

Two Components (separate evolution):

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

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

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



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

Ratio insensitive to gluon PDF, scales

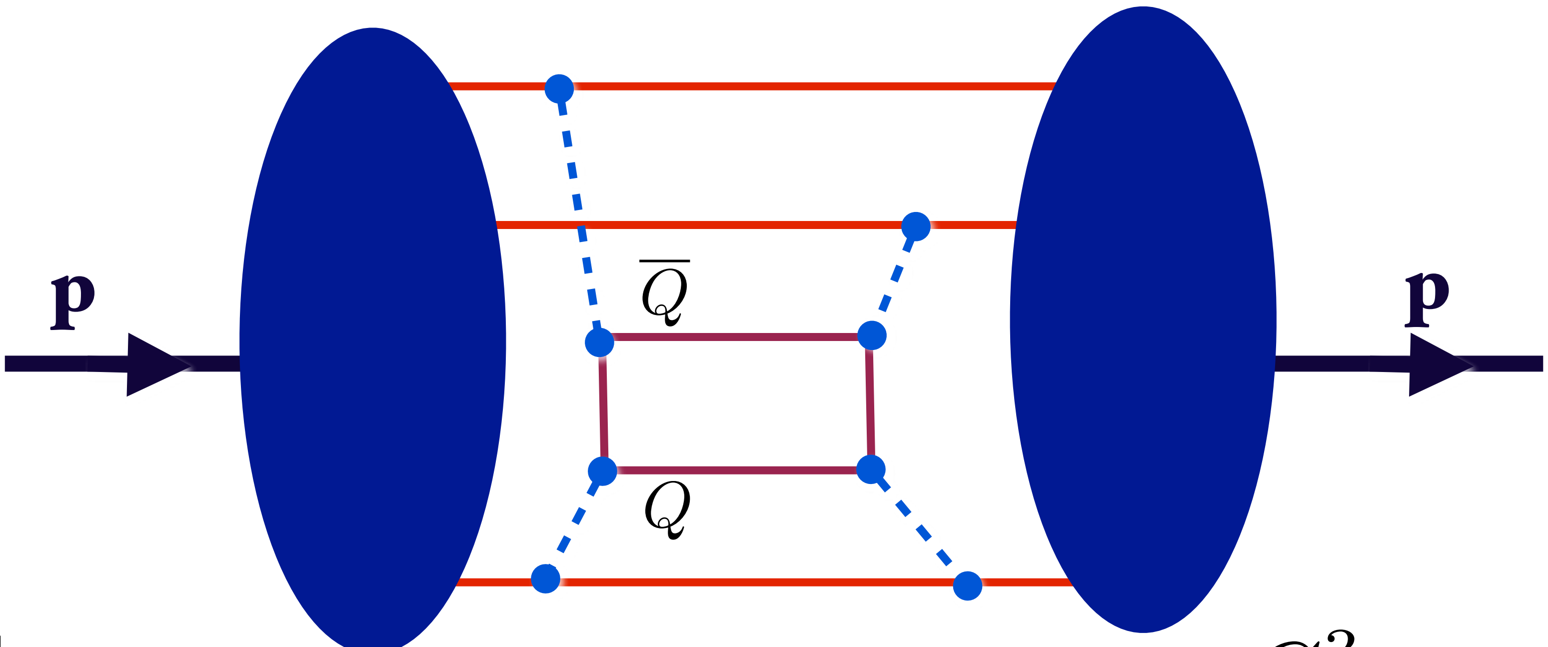
Signal for significant IC at x > 0.1

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

Proton Self Energy from g g to gg scattering

QCD predicts Intrinsic Heavy Quarks!

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



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

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

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

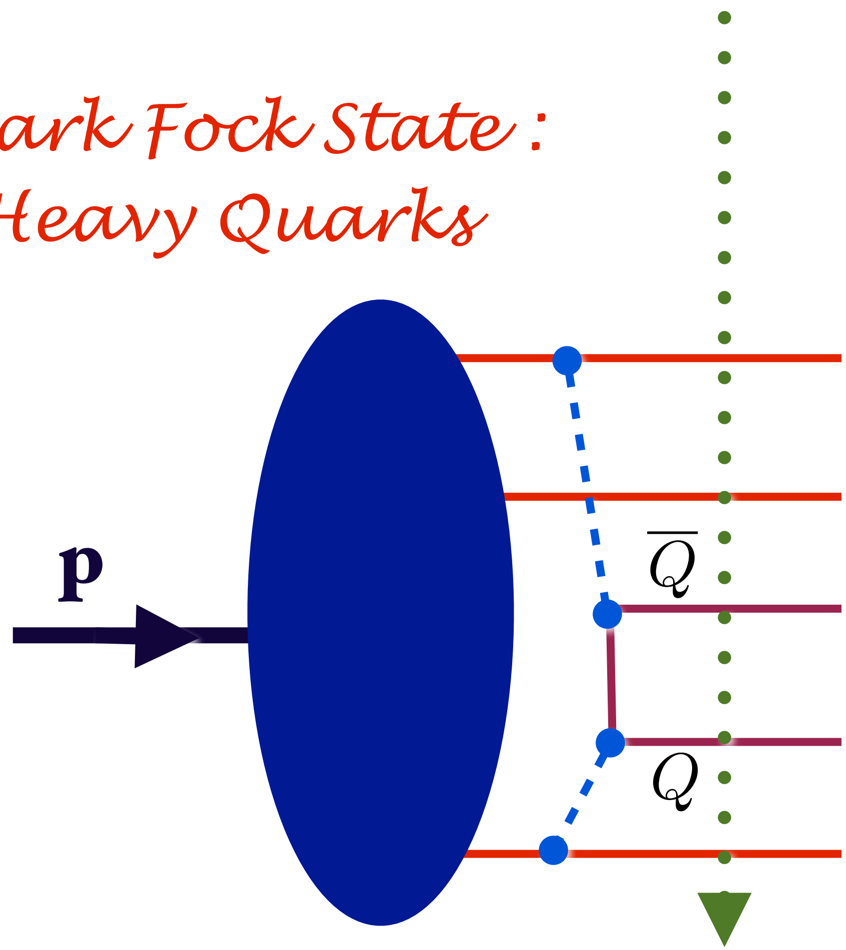
Probability (QCD) $\propto \frac{1}{M_Q^2}$

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

Fixed LF time

Proton 5-quark Fock State :

Intrinsic Heavy Quarks



QCD predicts Intrinsic Heavy Quarks at high x

Minimal off-shellness

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

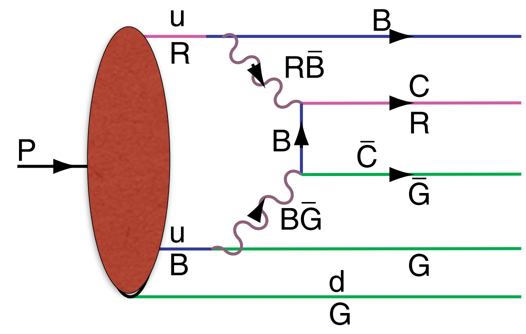
$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4} \qquad \text{Probability (QCD)} \propto \frac{1}{M_Q^2}$$

Collins, Ellis, Gunion, Mueller, sjb

M. Polyakov

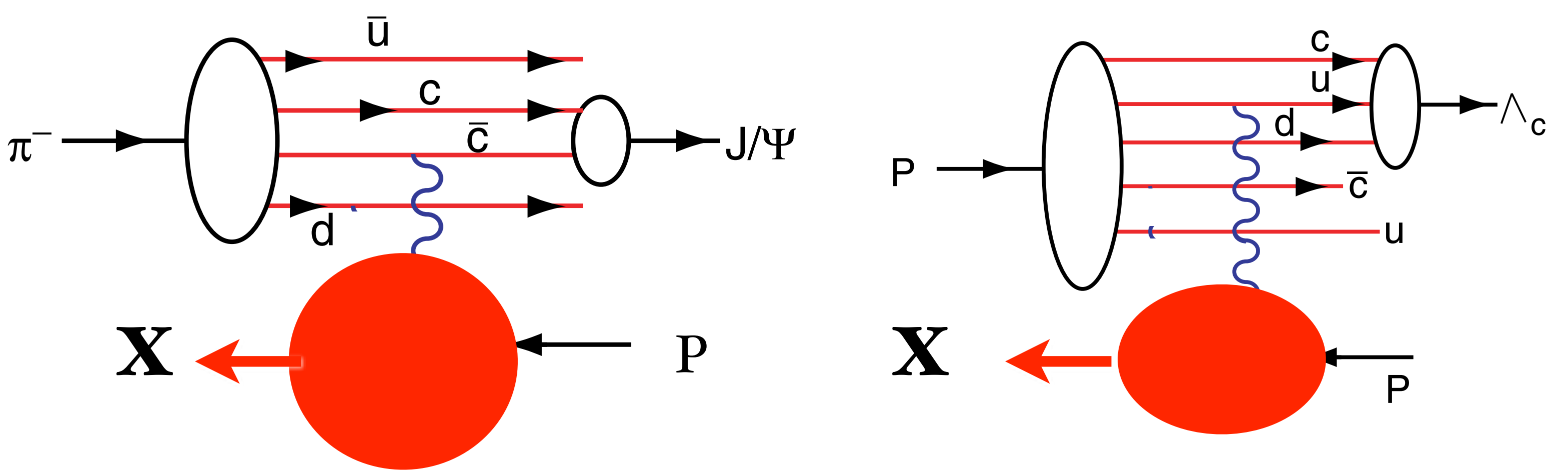
Hoyer, Peterson, Sakai, sjb

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)**

Leading Hadron Production from Intrinsic Charm

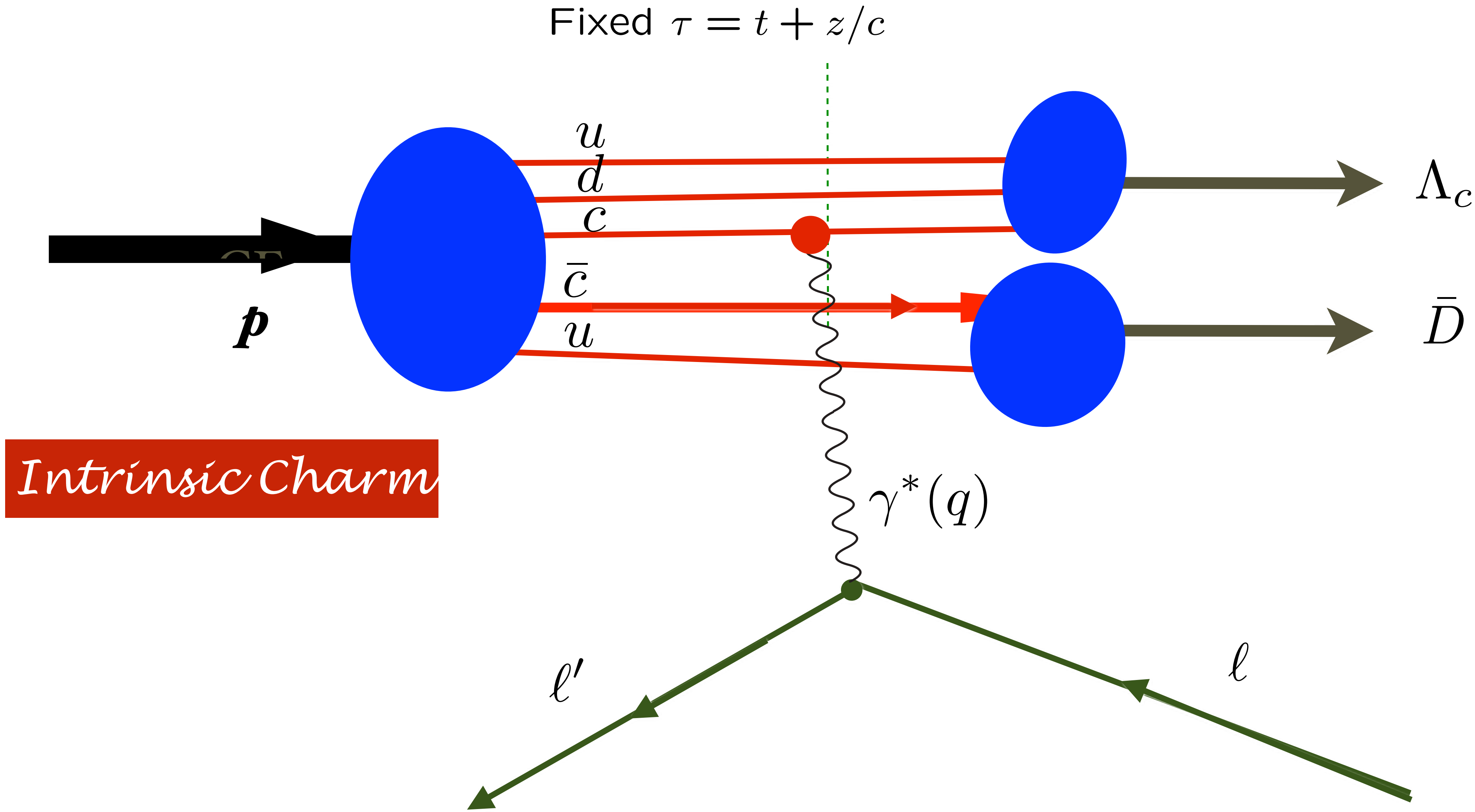


Spectator counting rules

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

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

Light-Front Wavefunctions and Heavy-Quark Electroproduction

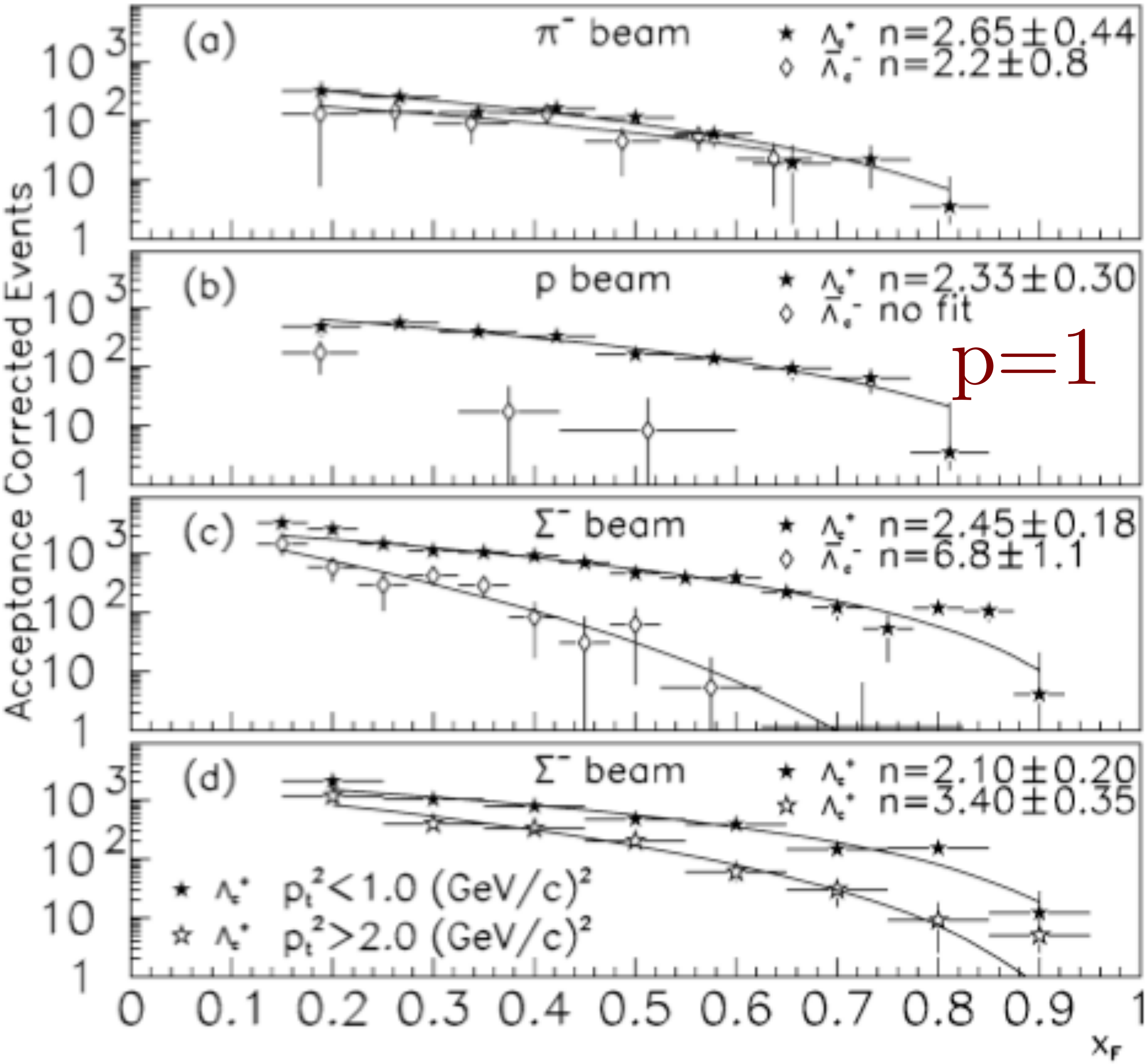


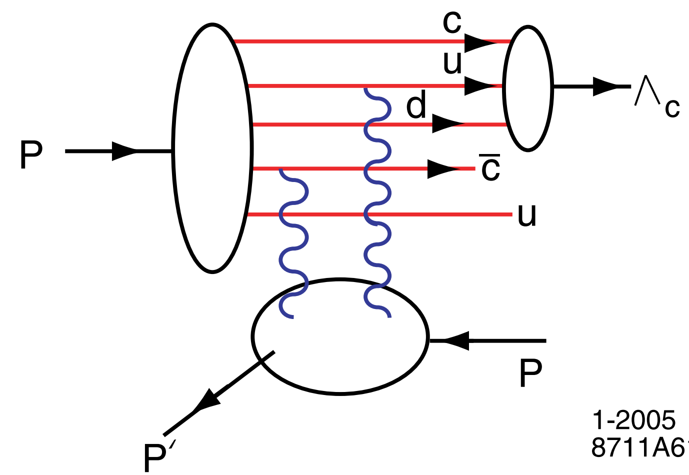
Threshold Production at JLab!

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

Charm Produced in Target-Rapidity Domain

SELEX





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

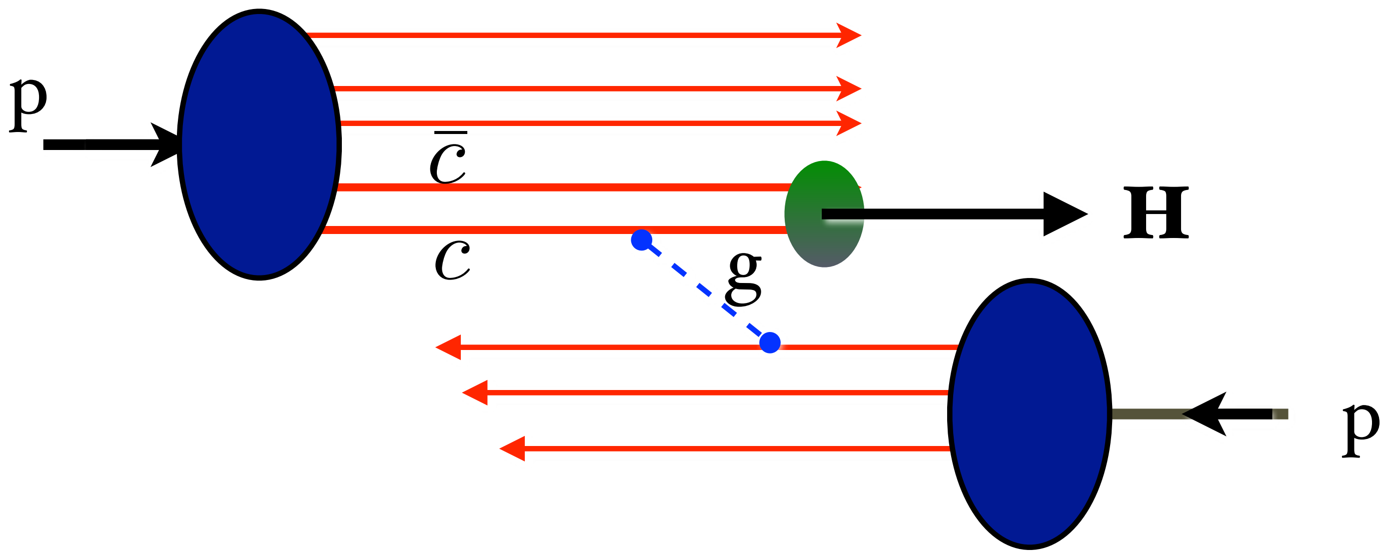
$$n_s = 2$$

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



$$pp \rightarrow H X$$

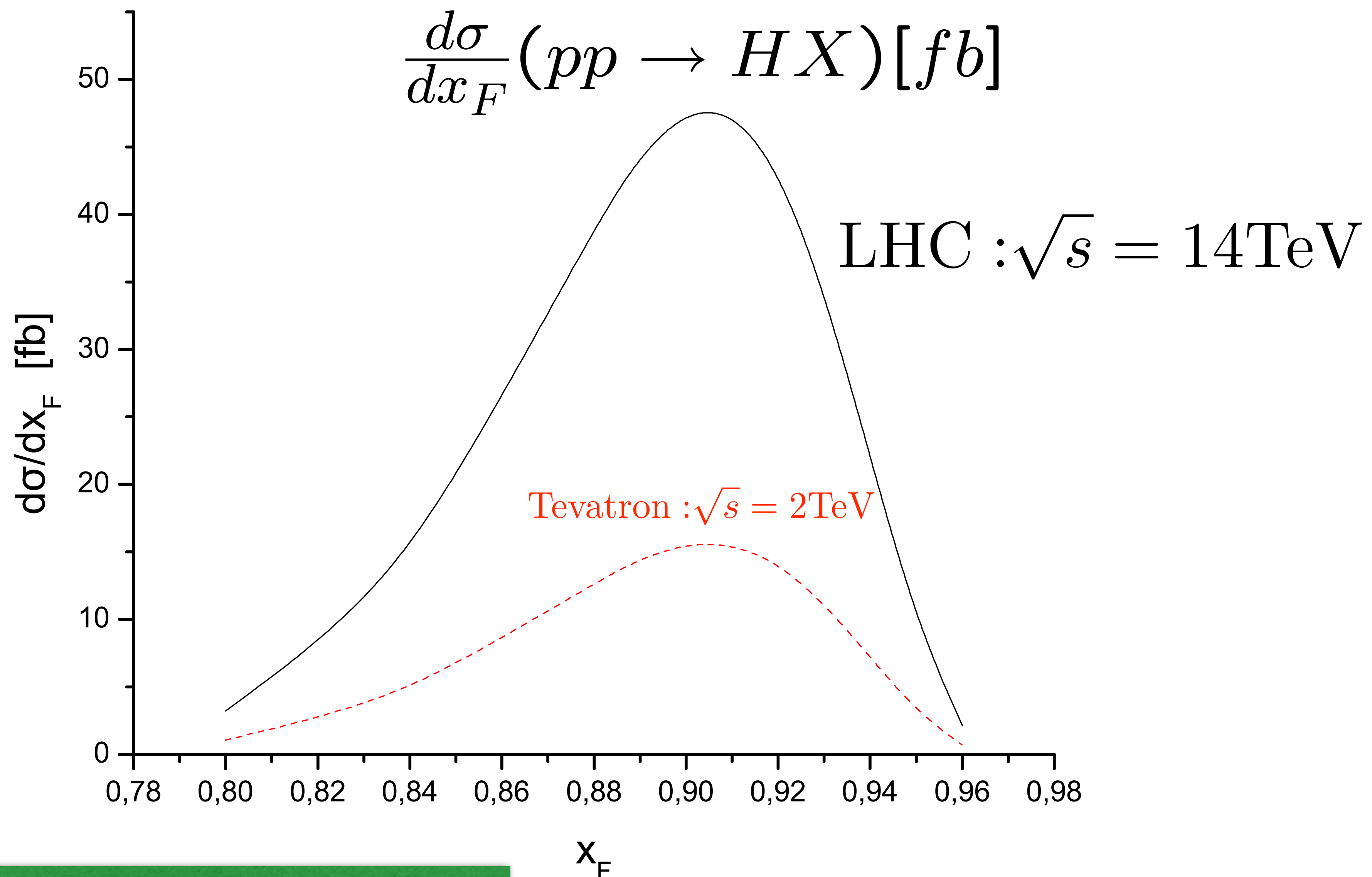
Goldhaber, Soffer, Kopeliovich, Schmidt, sjb

Also: intrinsic bottom, top

Higgs can have 80% of Proton Momentum!

New search strategy for Higgs

AFTER: Higgs production at threshold!



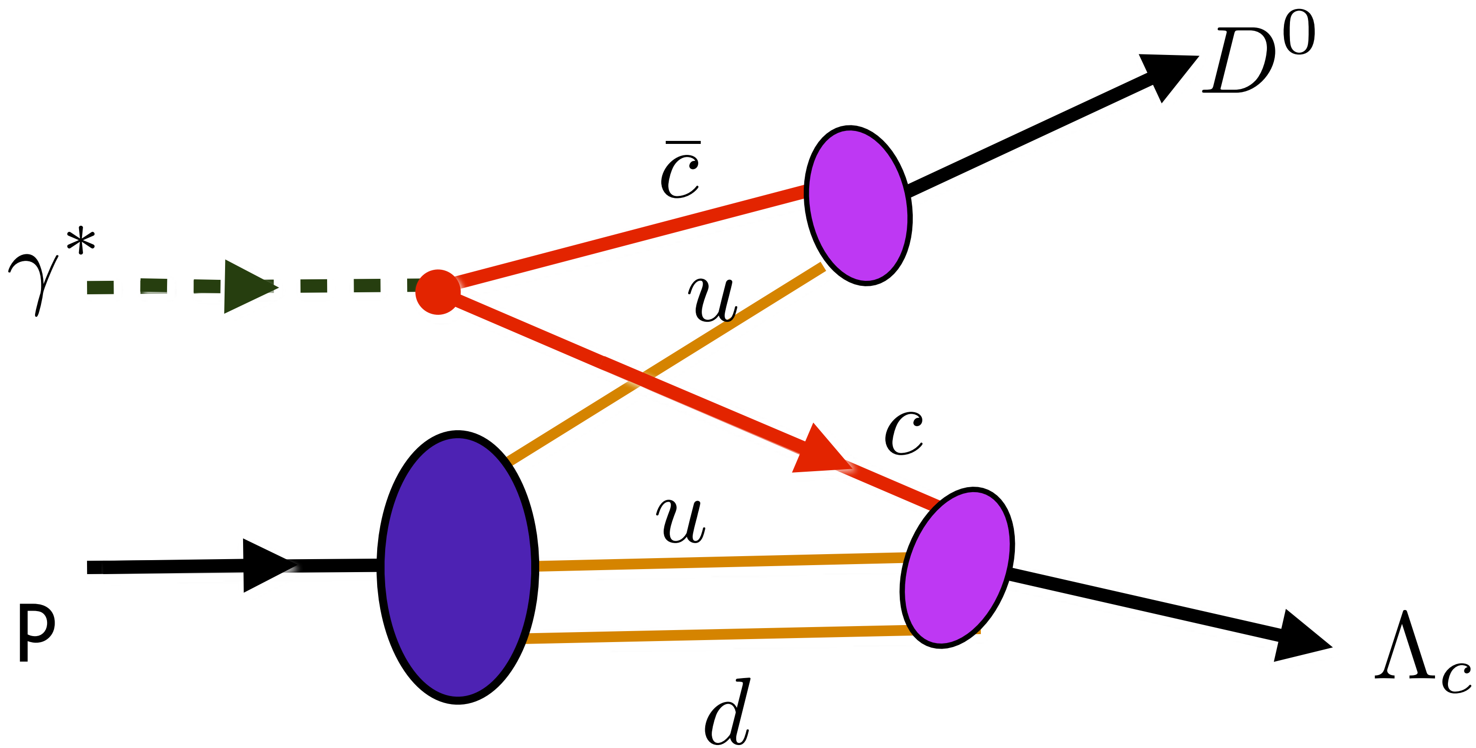
Need High x_F Acceptance

Most practical: Higgs to 2 or 4 muons

Goldhaber, Kopeliovich, Schmidt, Soffer, sjb

Open Charm Production at Threshold!

JLab 12 GeV: A Charm Factory!

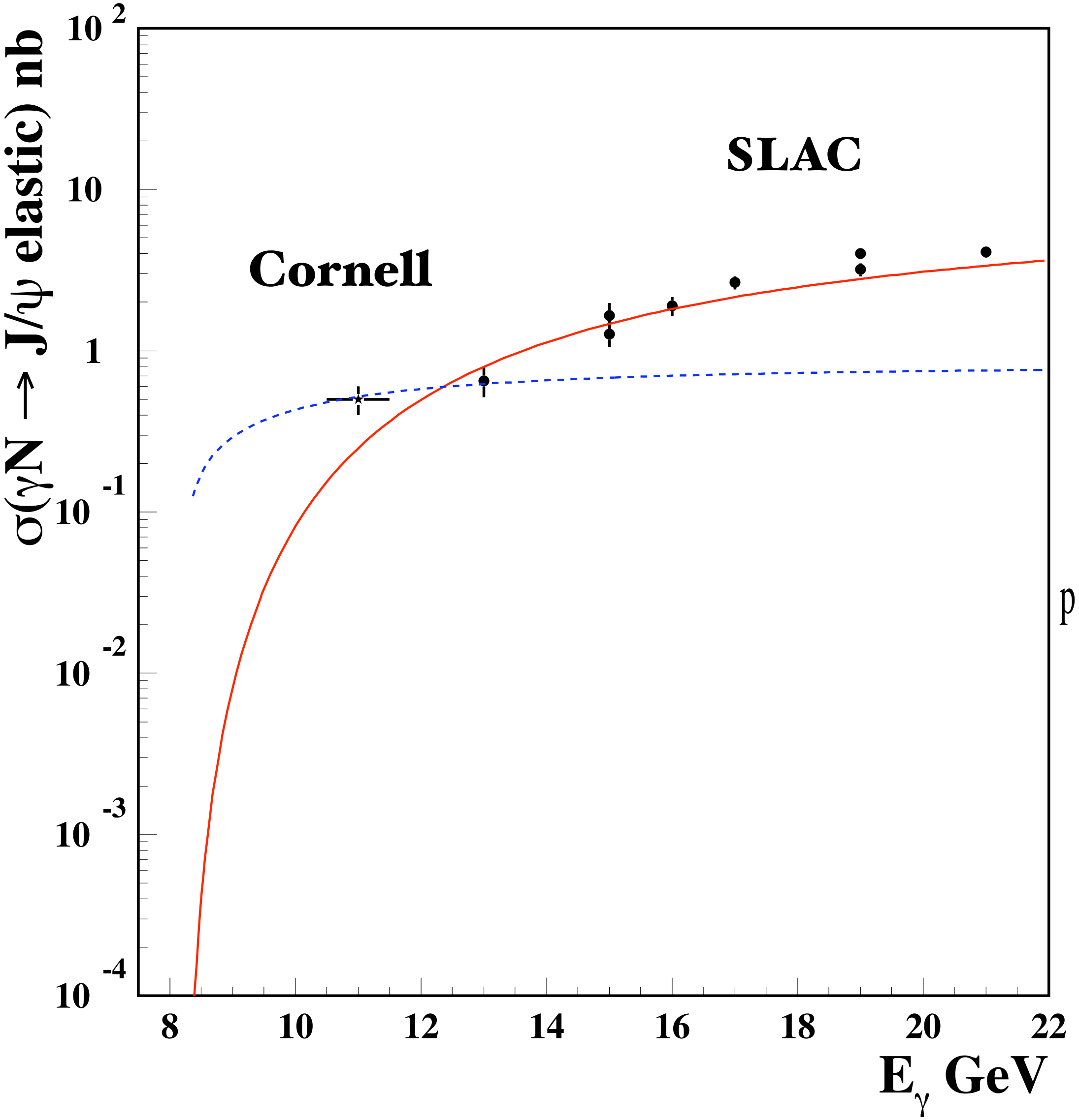


$$\gamma^* p \to \overline{D}^0(\bar{c}u)\Lambda_c(cud)$$

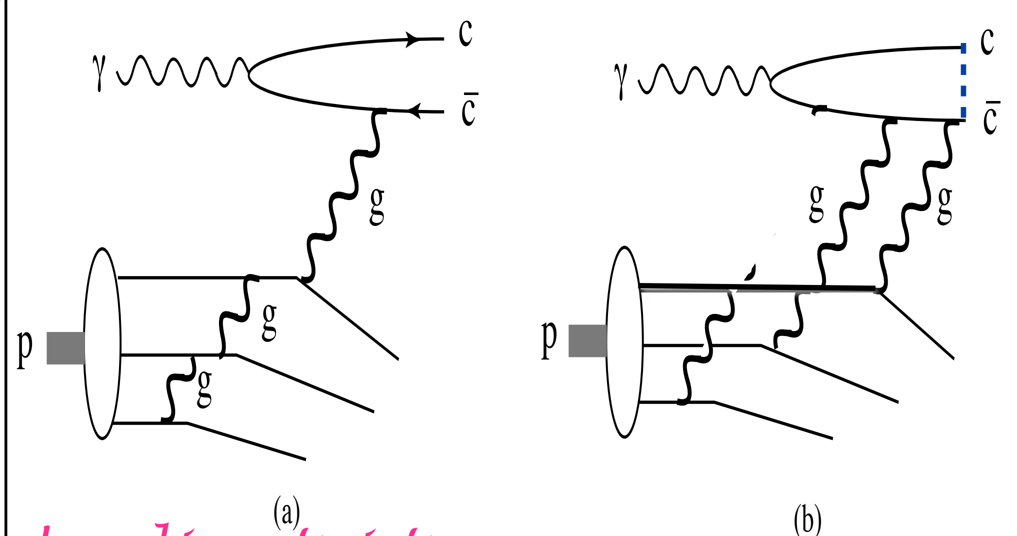
c and u quark interchange

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

Chudakov, Hoyer, Laget, sjb



cross section: 1 nb



Leading twist contribution

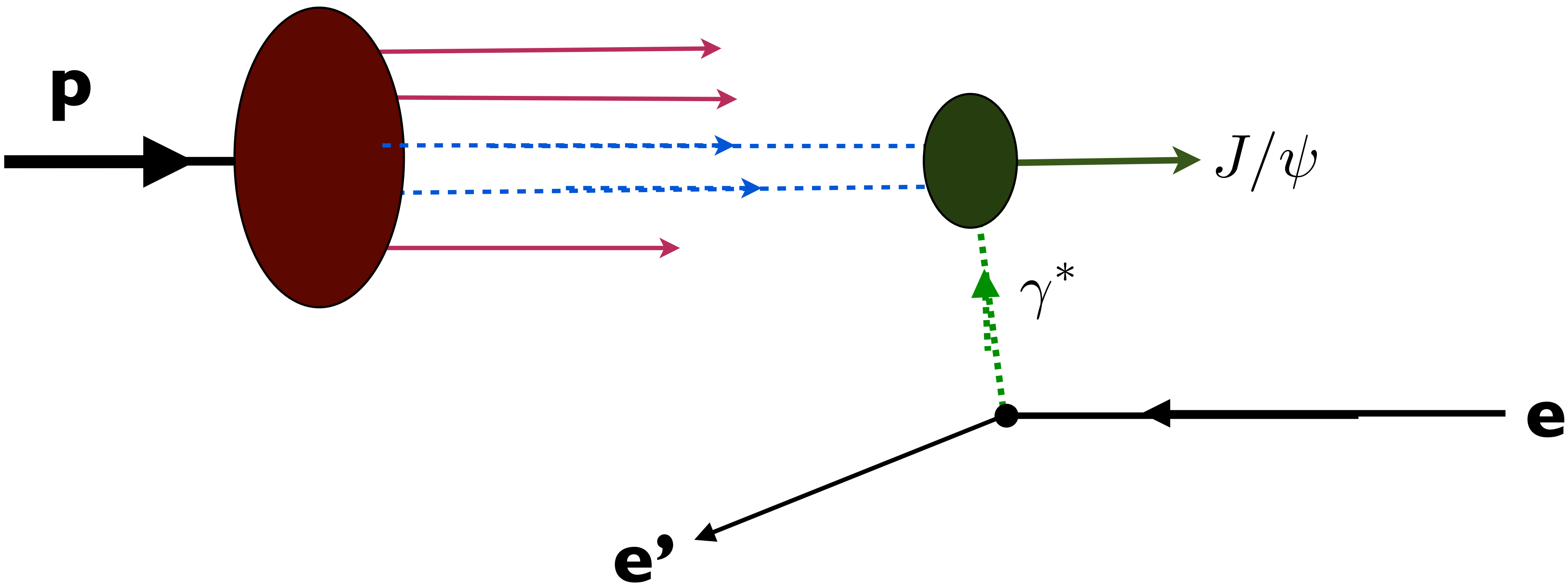
Dominant near threshold

Phase space factor β cancelled by gluonic final-state interactions

Sommerfeld-Schwinger-Sakharov Effect

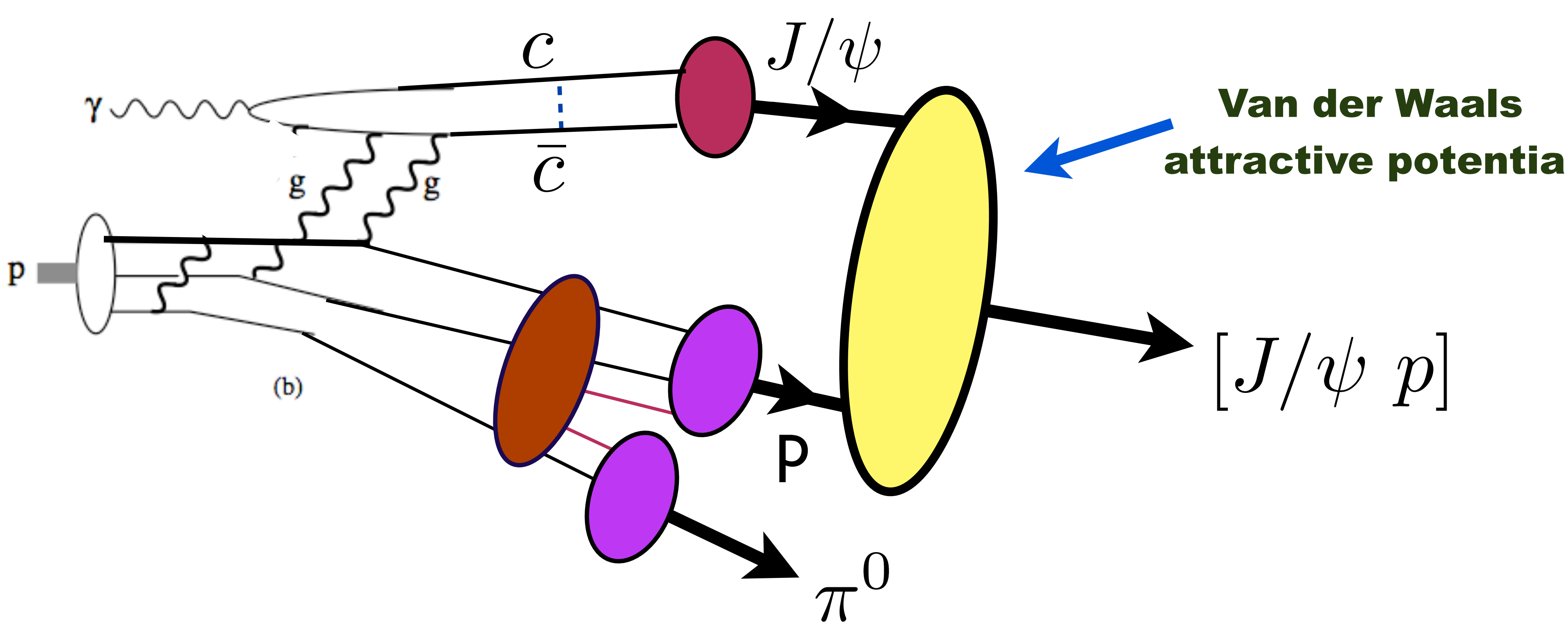
$$\gamma^* p \to J/\psi X$$

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



Digluon-initiated subprocess in ep and γp collisions

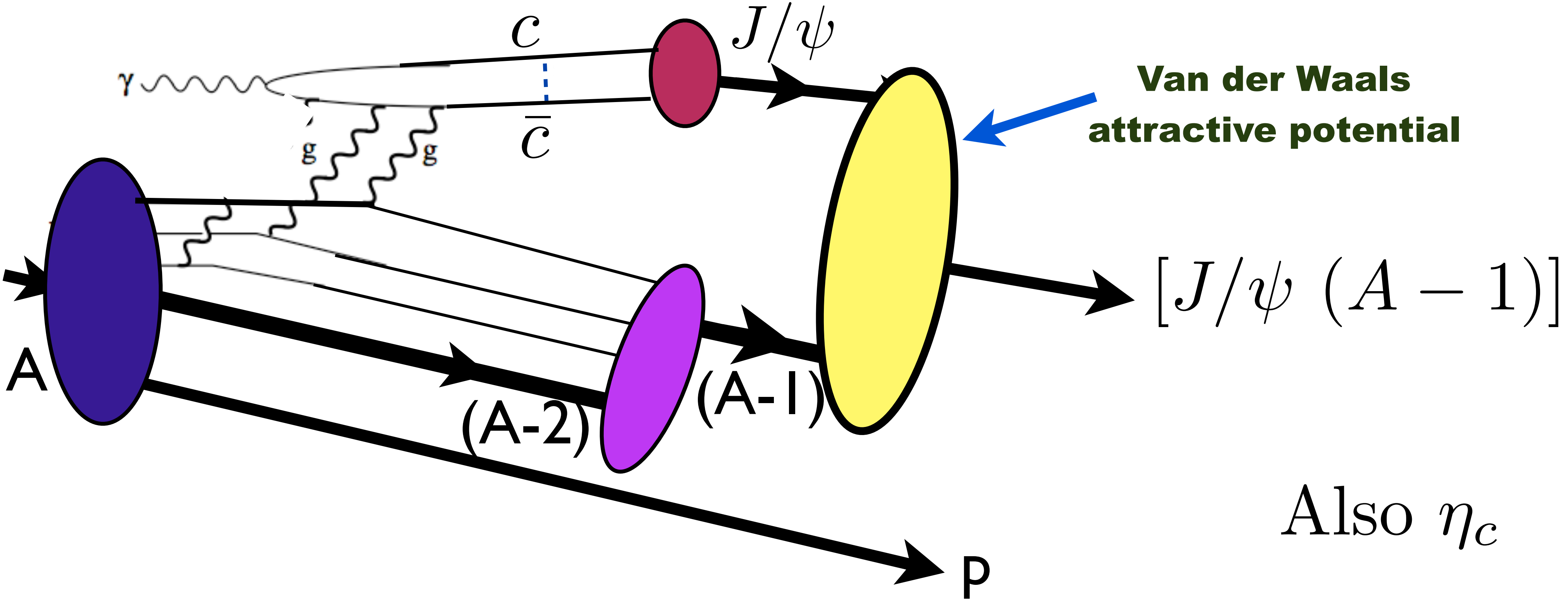
Charmonium Production at Threshold



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

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!

$$\gamma^* p \to J/\psi + p \text{ threshold}$$

$$\text{at } \sqrt{s} \simeq 4 \text{ GeV}, \ E_{\rm lab}^{\gamma^*} \simeq 7.5 \text{ GeV}.$$

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

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

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

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

$$\gamma^* d \to J/\psi + d \text{ threshold}$$

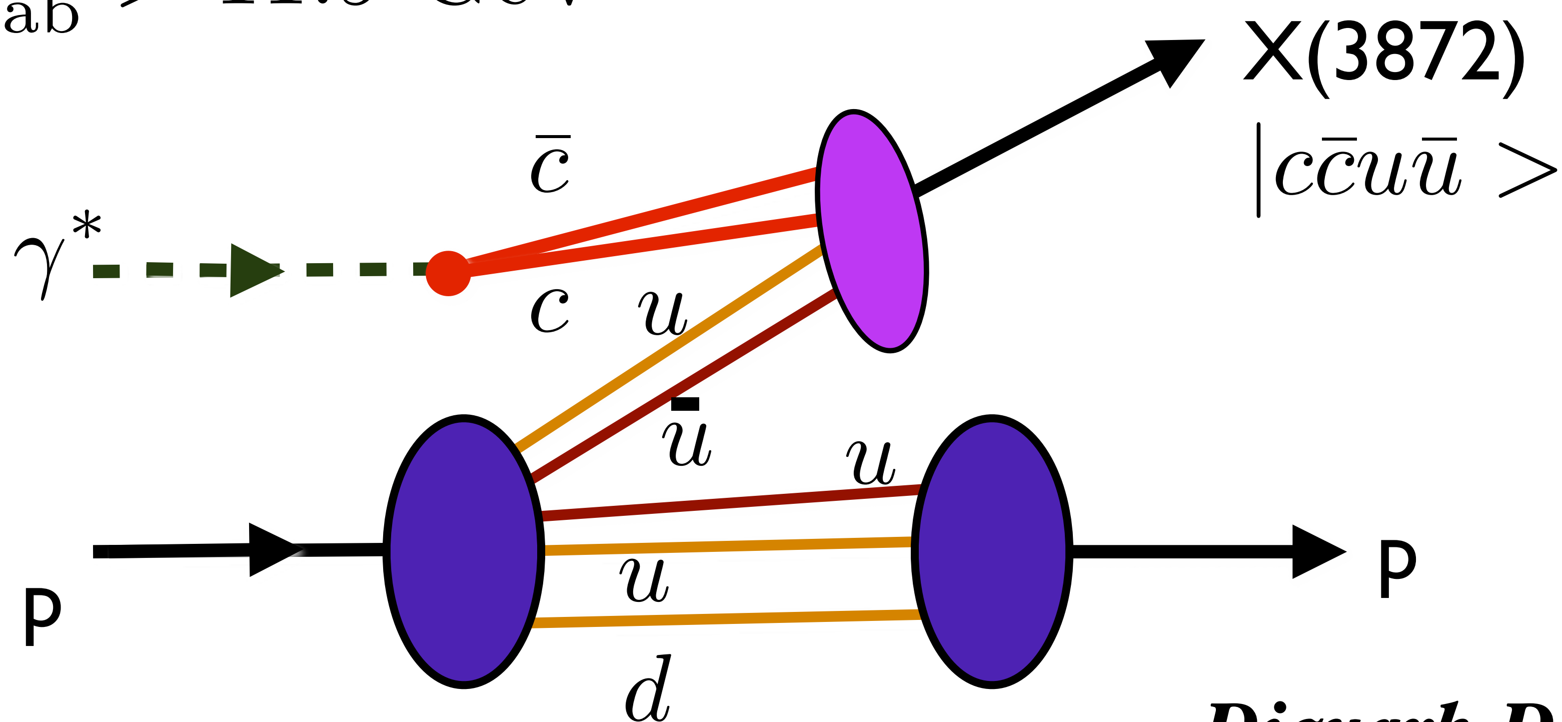
$$\text{at } \sqrt{s} \simeq 5 \text{ GeV}, \ E_{\rm lab}^{\gamma^*} \simeq 6 \text{ GeV}.$$

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?

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

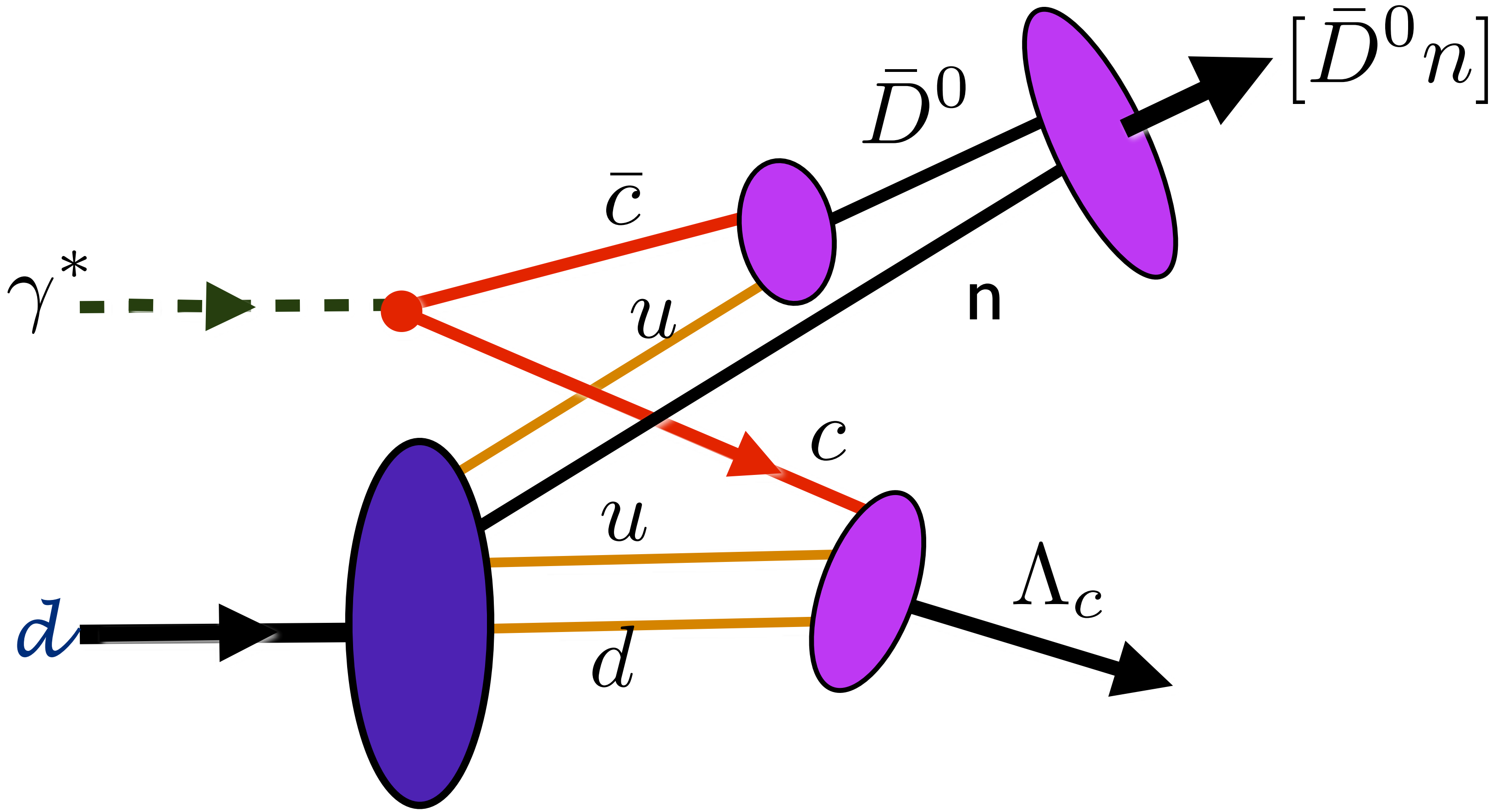
$$|c\bar{c}q\bar{q}>$$

New approach to hadronic decays

Dominance of Ψ' vs J/Ψ decays

Lebed, Hwang, sjb

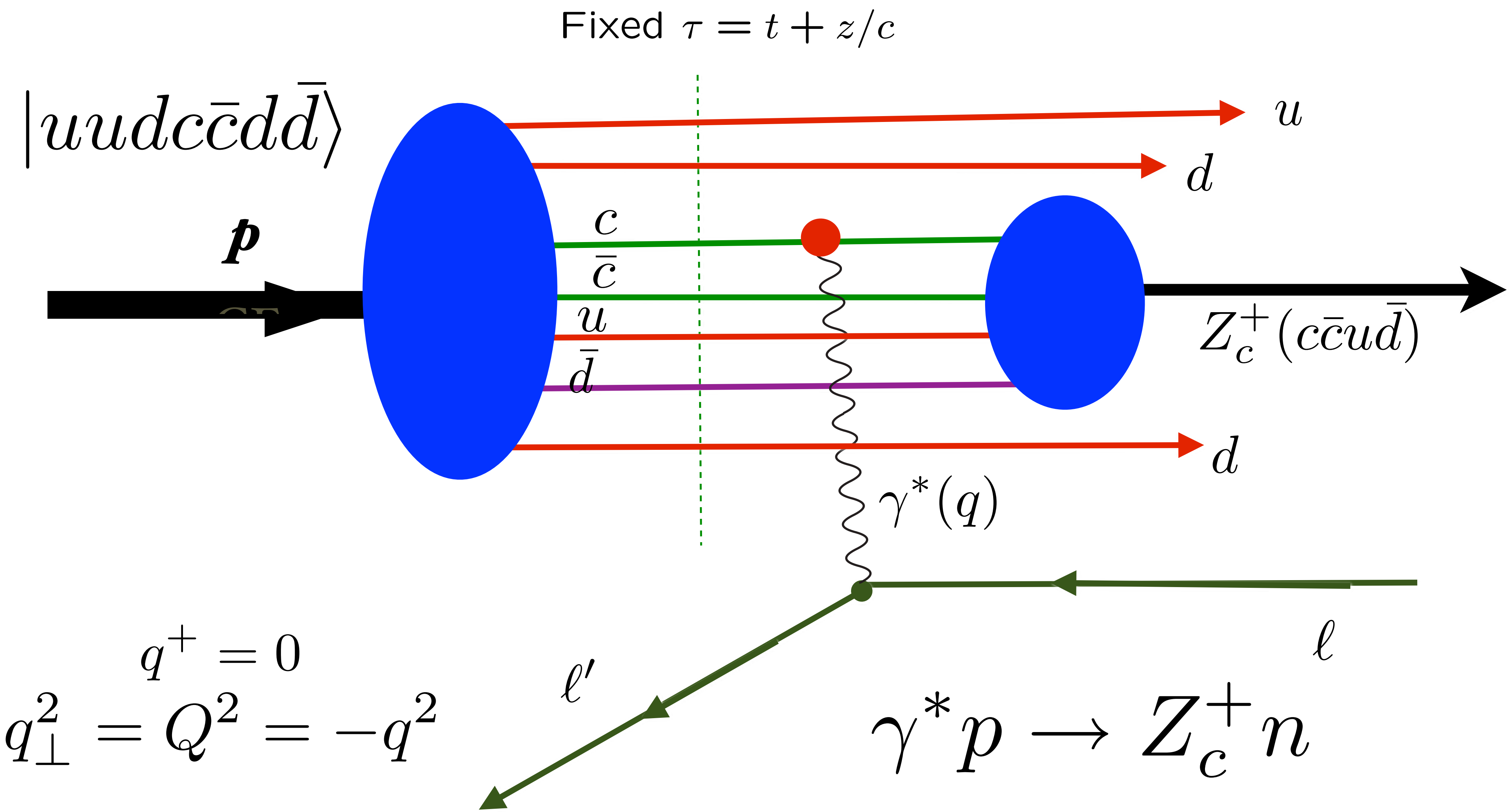
Open Charm Production at Threshold



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

Create pentaquark on deuteron at low relative velocity

Light-Front Wavefunctions and Heavy-Quark Electroproduction

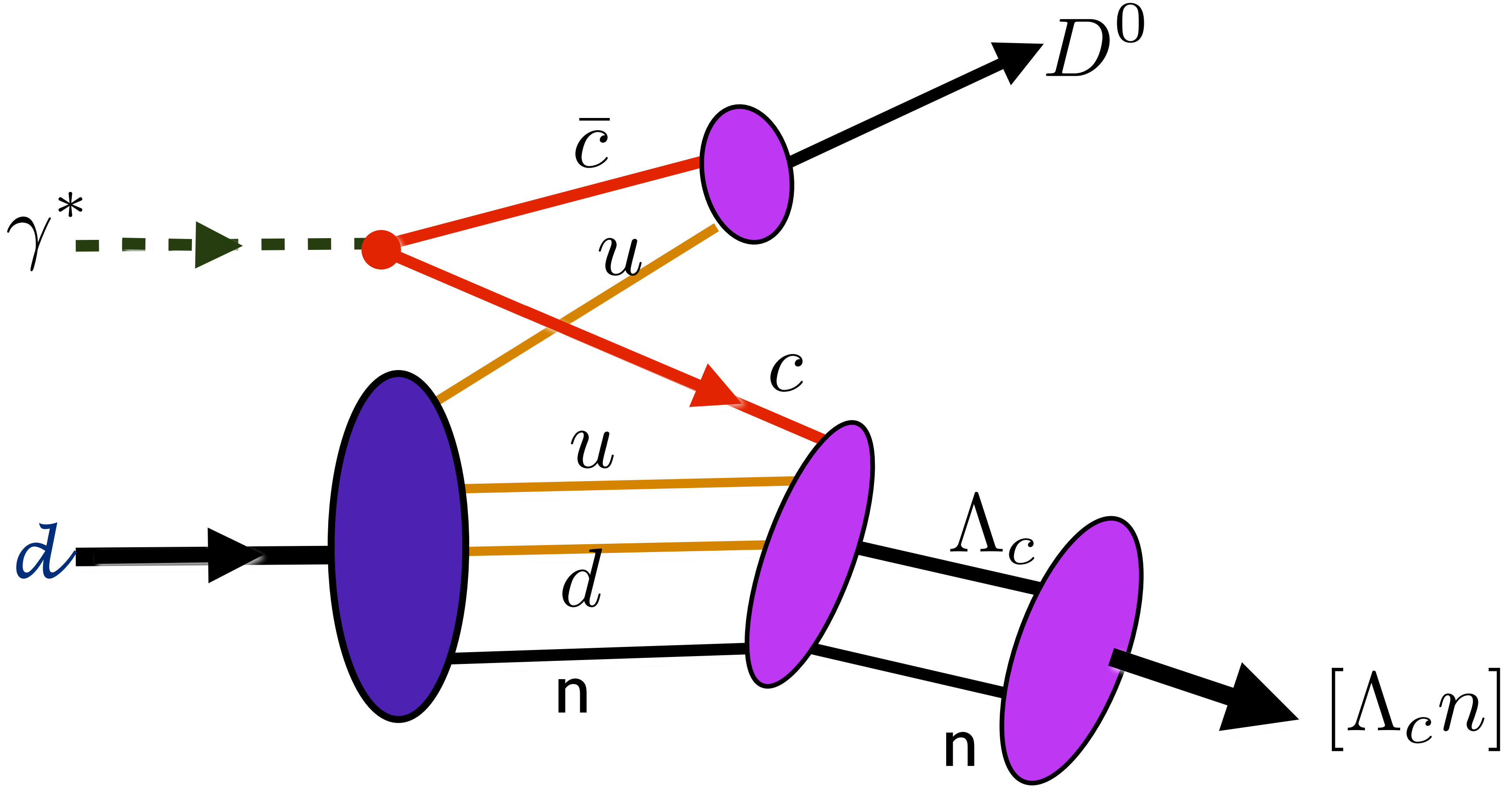


Produce Charged Tetraquarks at JLab!

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

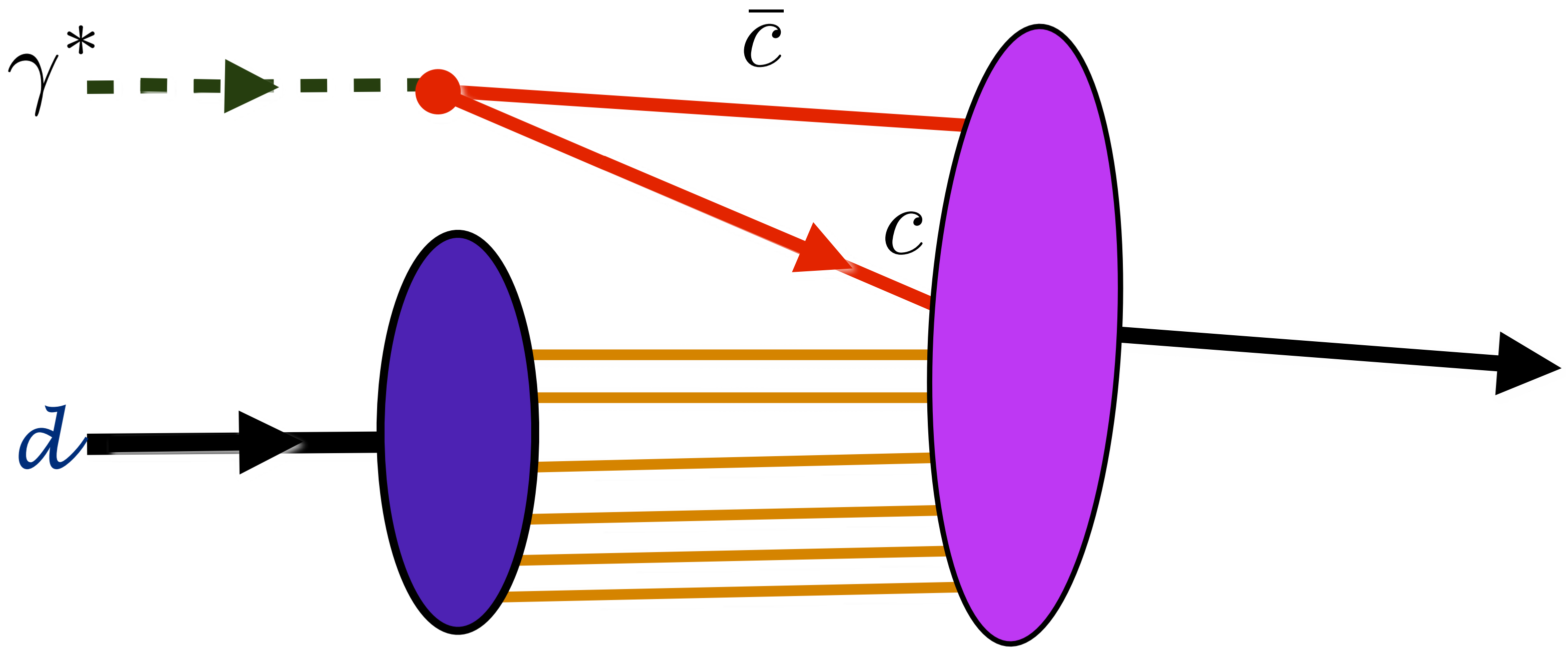
$$\gamma d \to [B=+2, Q=+4]\pi^- \pi^- \pi^-$$

Discover at JLab!

Bashkanov, Clement, sjb

Octoquark Production at Threshold

$$M_{\mathrm{octoquark}} \sim 5\ \mathrm{GeV}$$



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

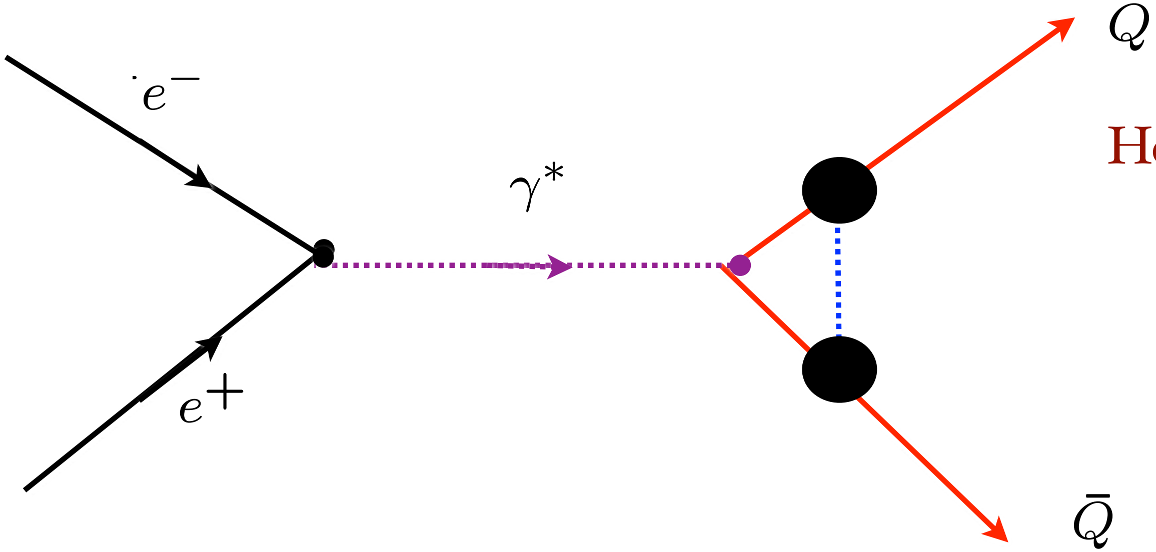
Explains Krisch Effect!

JLab 12 GeV: An Exotic Charm Factory!

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

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

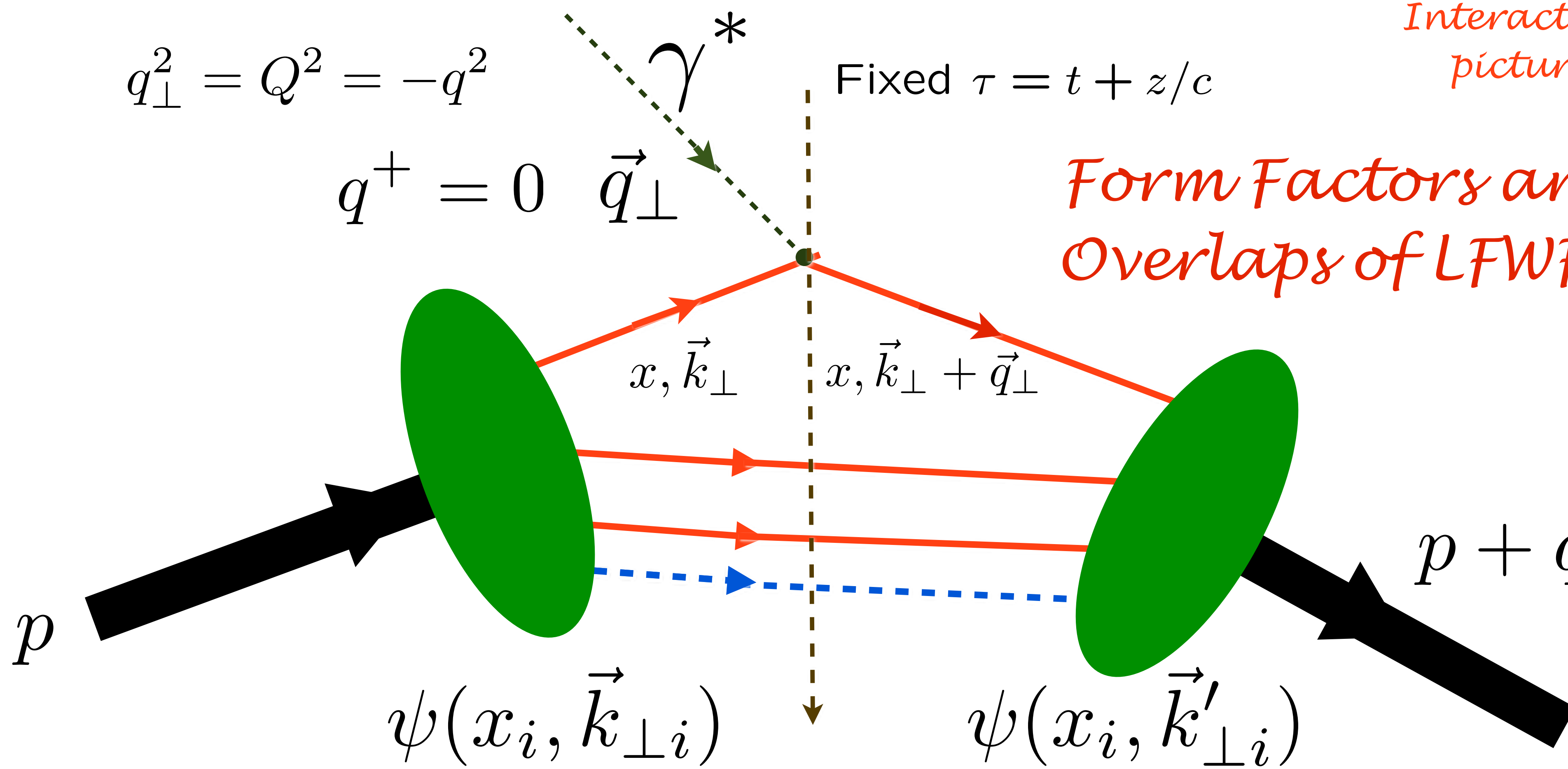
Properties of Hard Exclusive Reactions

- **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**

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

Front Form

Interaction picture



Form Factors are Overlaps of LFWFs

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

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

Drell &Yan, West
Exact LF formula!

Drell, sjb

Lepton sees quarks at same LF time τ

Exact LF Formula for Pauli Form Factor

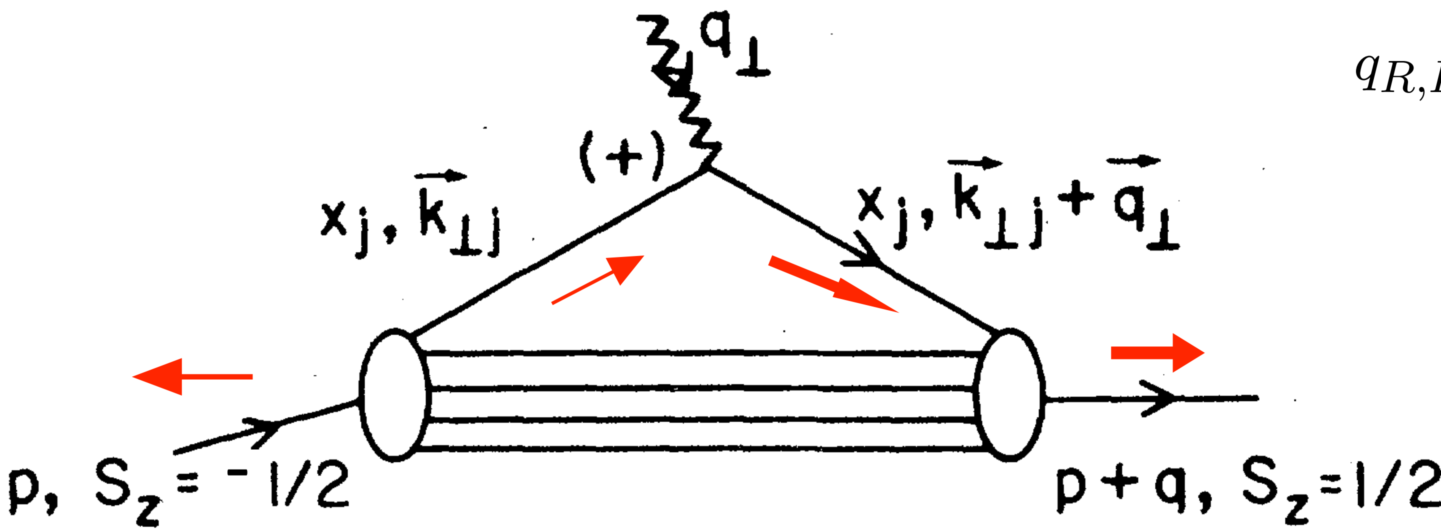
$$\frac{F_2(q^2)}{2M} = \sum_a \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp] \sum_j e_j \, \frac{1}{2} \times$$

Drell, sjb

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

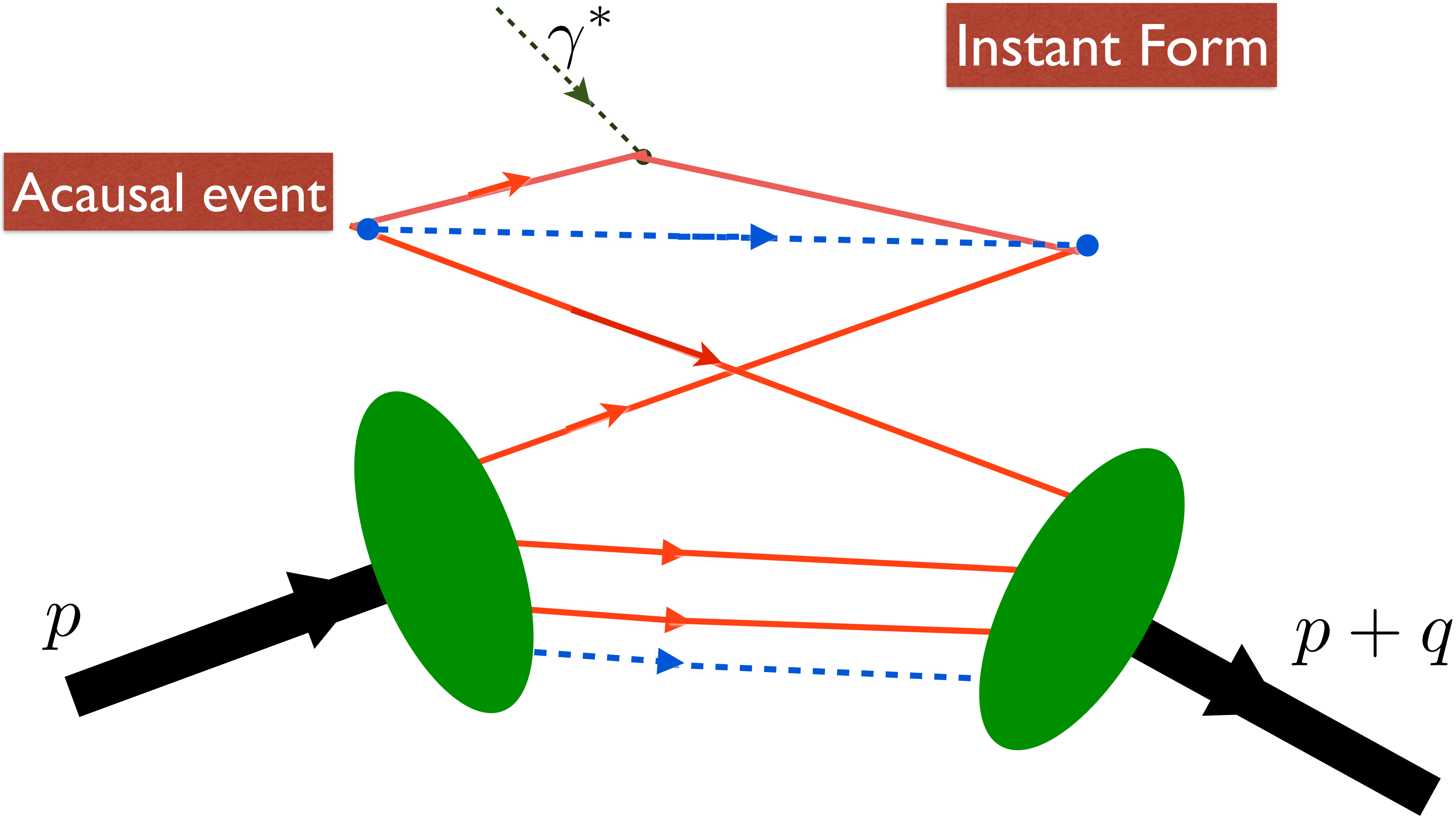
$$\mathbf{k}'_{\perp i} = \mathbf{k}_{\perp i} - x_i \mathbf{q}_\perp \qquad \mathbf{k}'_{\perp j} = \mathbf{k}_{\perp j} + (1 - x_j)\mathbf{q}_\perp$$

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



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

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

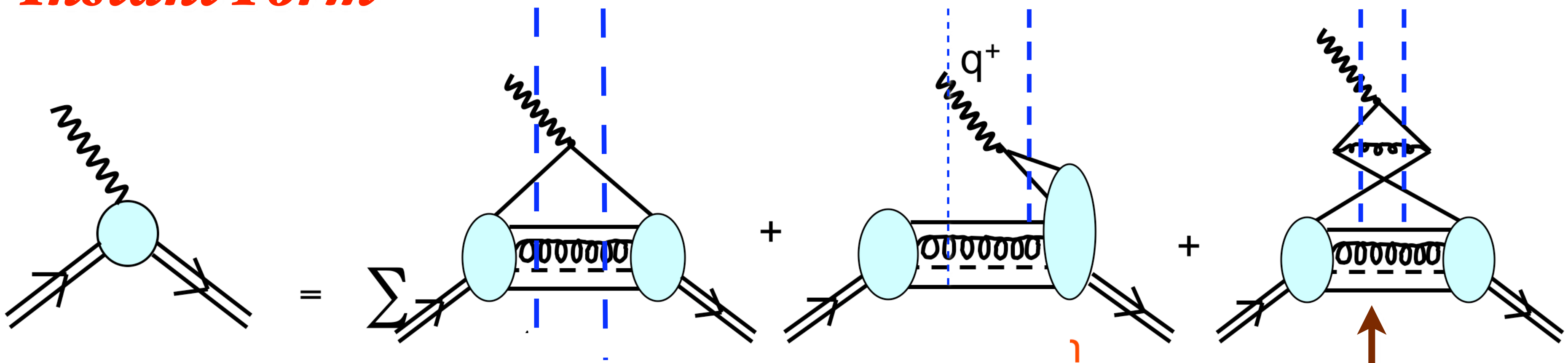


Must include vacuum-induced currents to compute form factors and other current matrix elements in instant form

Boost are dynamical in instant form

Calculation of Form Factors in Equal-Time Theory

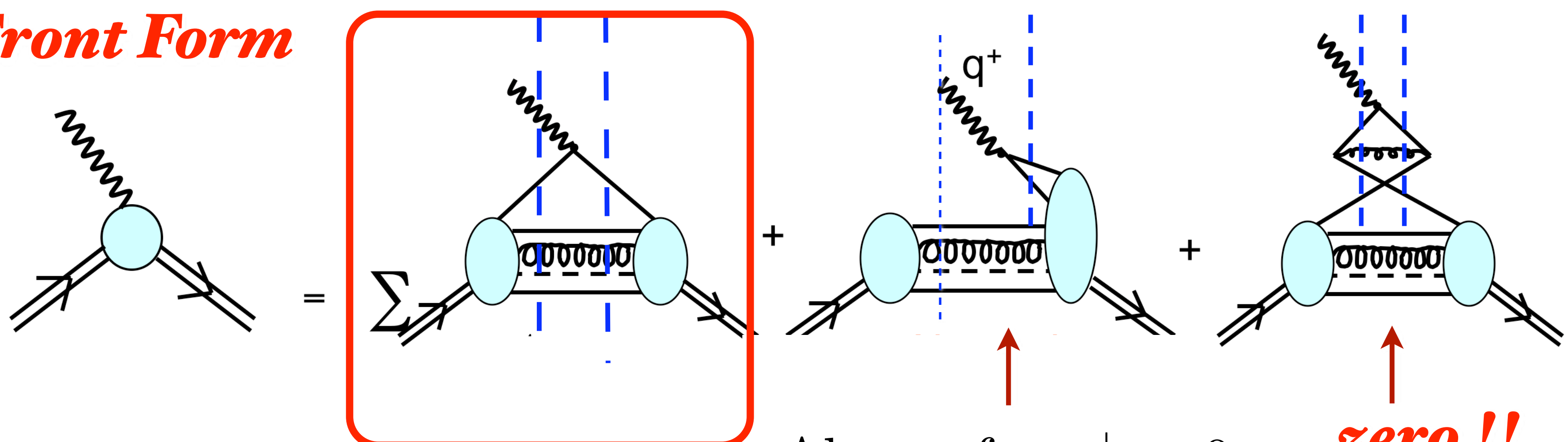
Instant Form



Need vacuum-induced currents

Calculation of Form Factors in Light-Front Theory

Front Form



Exact Answer!

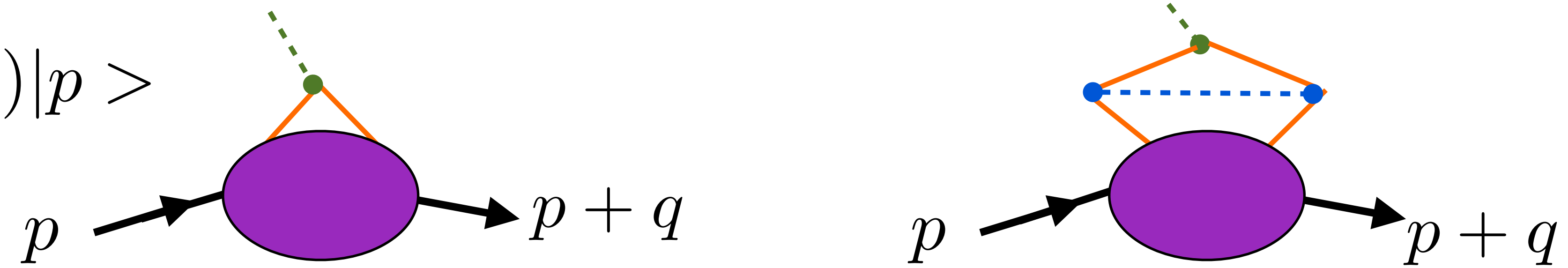
Absent for $q^+ = 0$

zero !!

No vacuum graphs

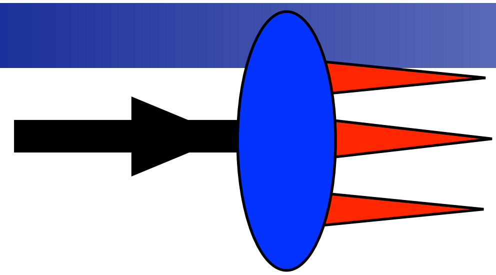
Calculation of proton form factor in Instant Form

$$< p+q|J^\mu(0)|p >$$



- **Need to boost proton wavefunction from p to p+q: Extremely complicated dynamical problem; even the particle number changes**
- **Need to couple to all currents arising from vacuum!! Remains even after normal-ordering**
- **Each time-ordered contribution is frame-dependent**
- **Divide by disconnected vacuum diagrams**
- **Instant form: Violates causality**

- *Light Front Wavefunctions:*



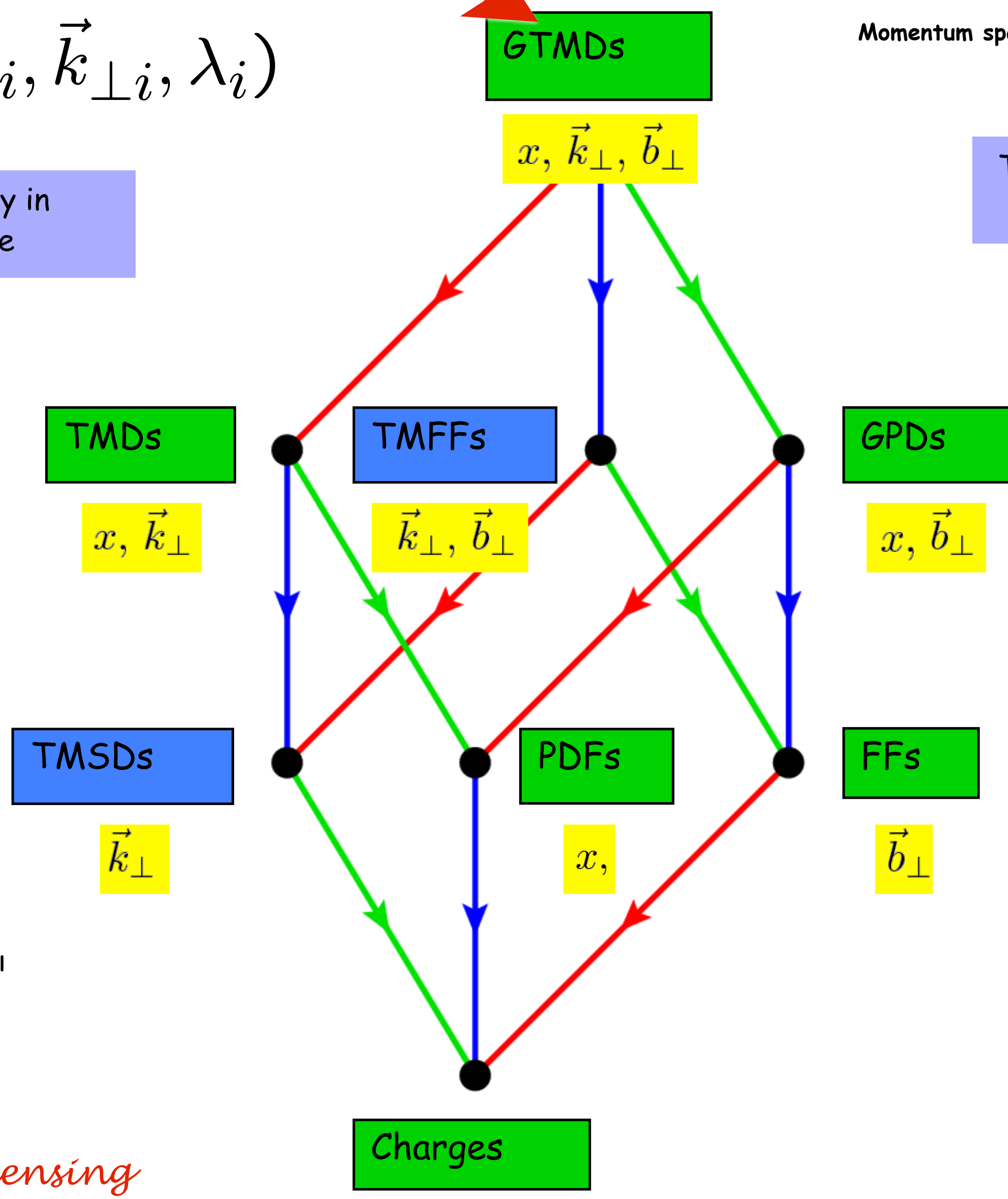
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

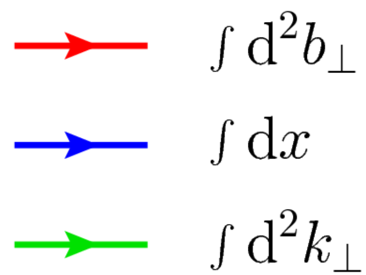
Momentum space $\vec{k}_\perp \leftrightarrow \vec{z}_\perp$ Position space

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

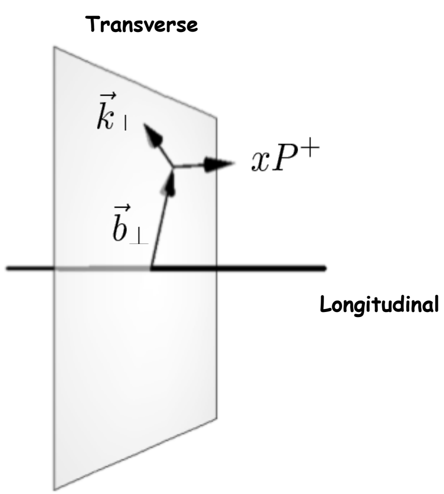
Transverse density in momentum space

Transverse density in position space





Lorce, Pasquini



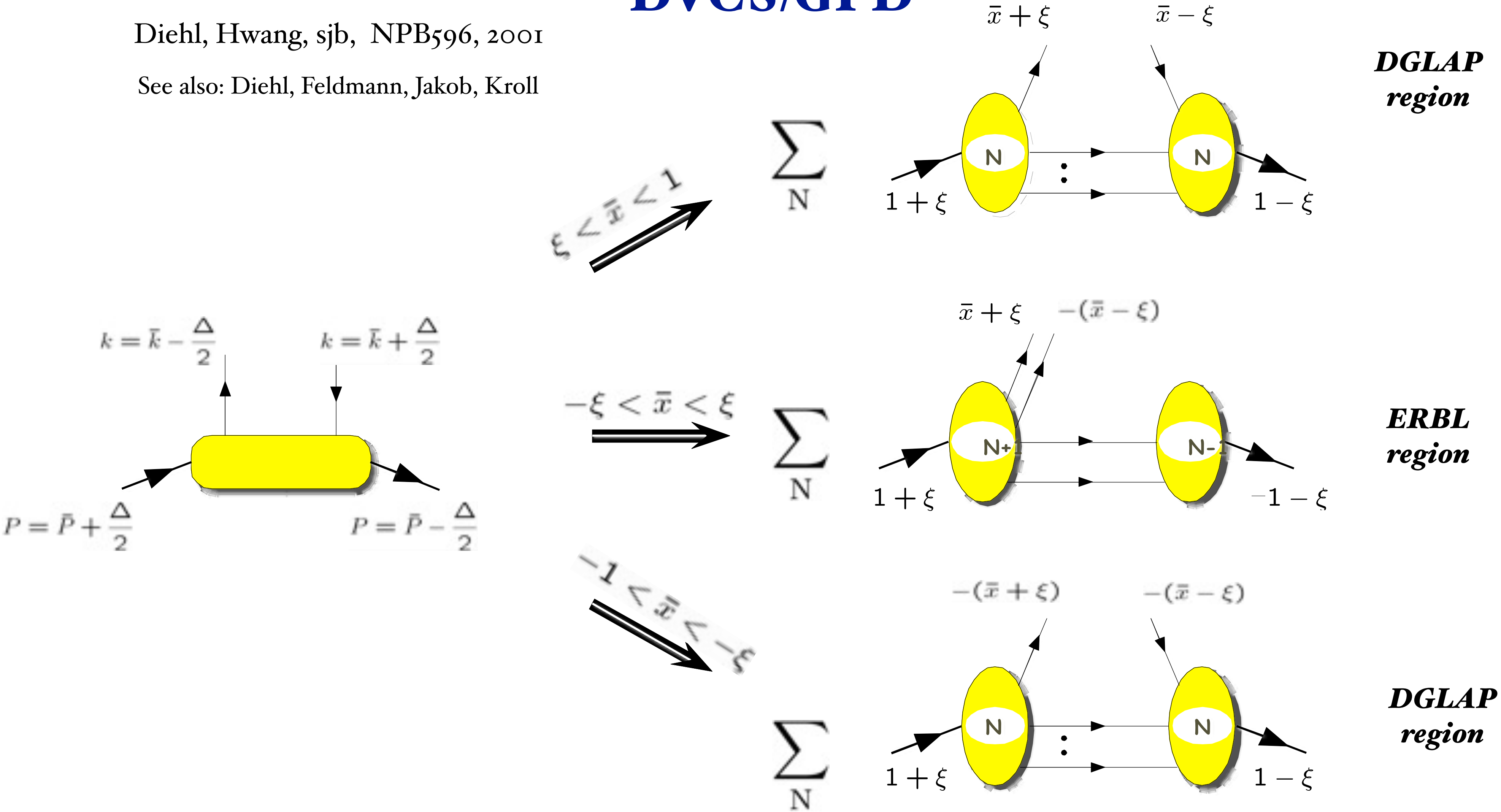
Sivers, T-odd from lensing

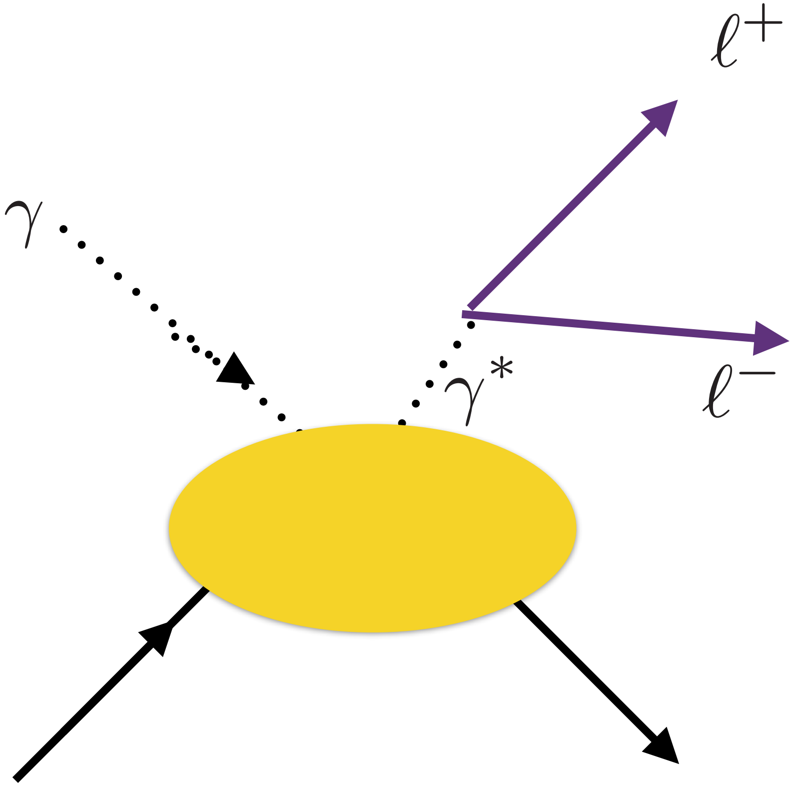
Light-Front Wave Function Overlap Representation

DVCS/GPD

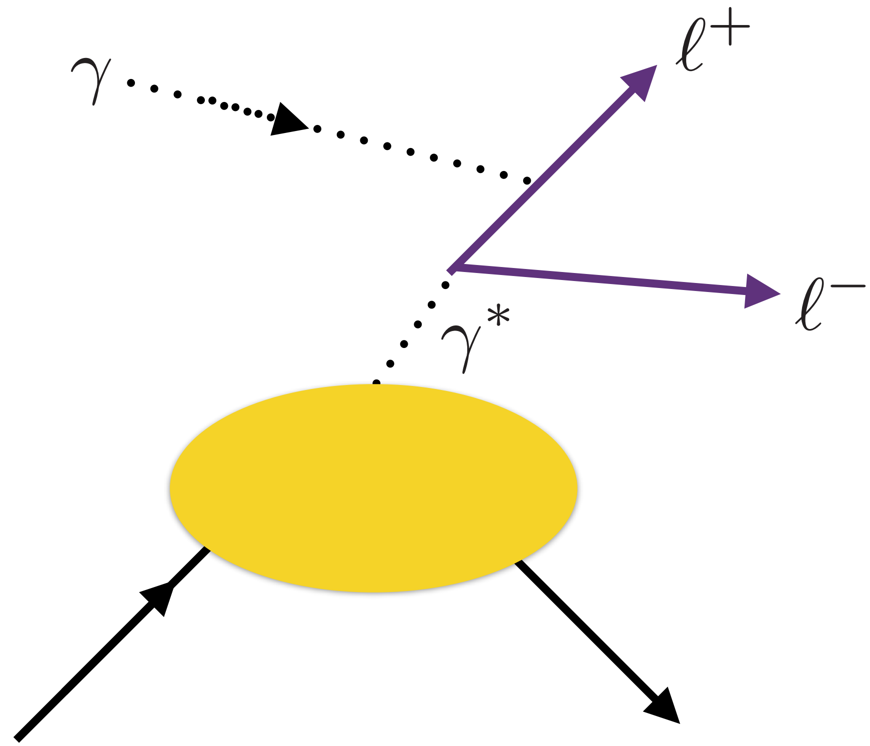
Diehl, Hwang, sjb, NPB596, 2001

See also: Diehl, Feldmann, Jakob, Kroll





Virtual Compton



Bethe-Heitler

Interference produces ℓ^+ vs. ℓ^- asymmetry

Close, Gunion, sjb

Measures Real Part of Compton Amplitude

- **Timelike virtual photon couples to product of timelike VM poles**

"Handbag" Approximation

- **Parton model: assume current-current correlator carried by single quark propagator at high photon virtuality**

- **Imaginary Part of Virtual Forward Compton Amplitude gives DIS structure Functions**

- **Leading-Twist Dominance — Motivated by the Operator Product Expansion**

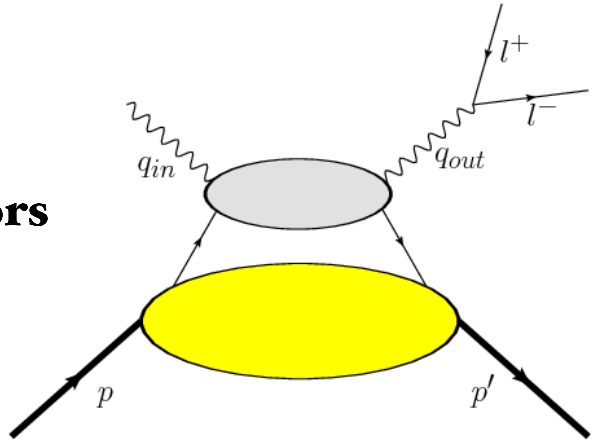
- **Predicts Momentum and Baryon Number Sum Rules**

- **Real Part: J=0 Fixed Pole from local two-photon operators**

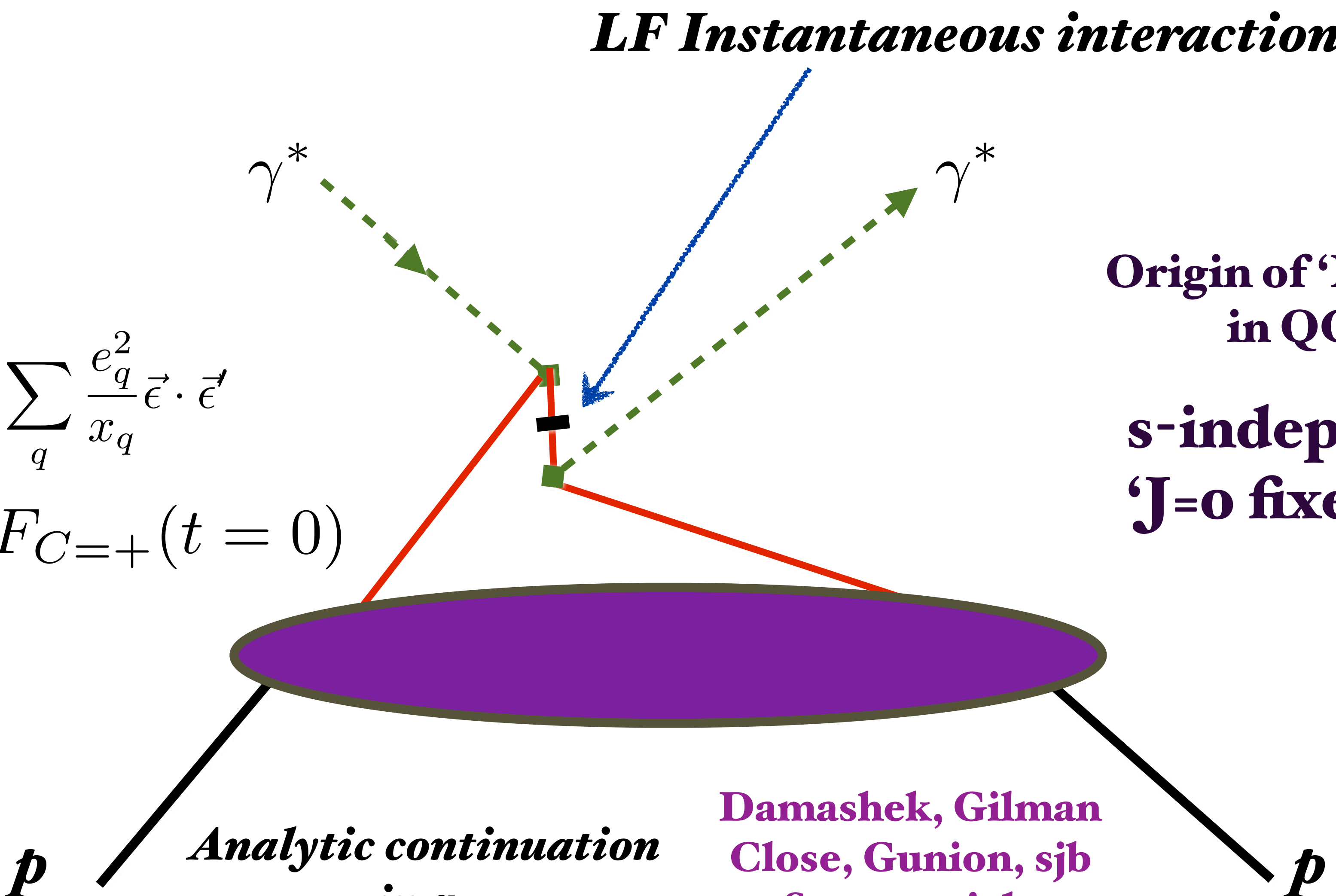
- **Regge Behavior of Compton Amplitude**

- **Timelike virtual photon couples to product of timelike VM poles**

- **High t, s: Counting rules, hadron helicity conservation, ERBL evolution; quark interchange; distribution amplitudes, color transparency ...**



Leading-Twist Contribution to Real Part of DVCS



$$T = -2 \sum_q \frac{e_q^2}{x_q} \vec{\epsilon} \cdot \vec{\epsilon}'$$

$$T \propto s^0 F_{C=+}(t=0)$$

Origin of 'D-Term' in QCD

s-independent 'J=0 fixed pole'

Analytic continuation in α_R

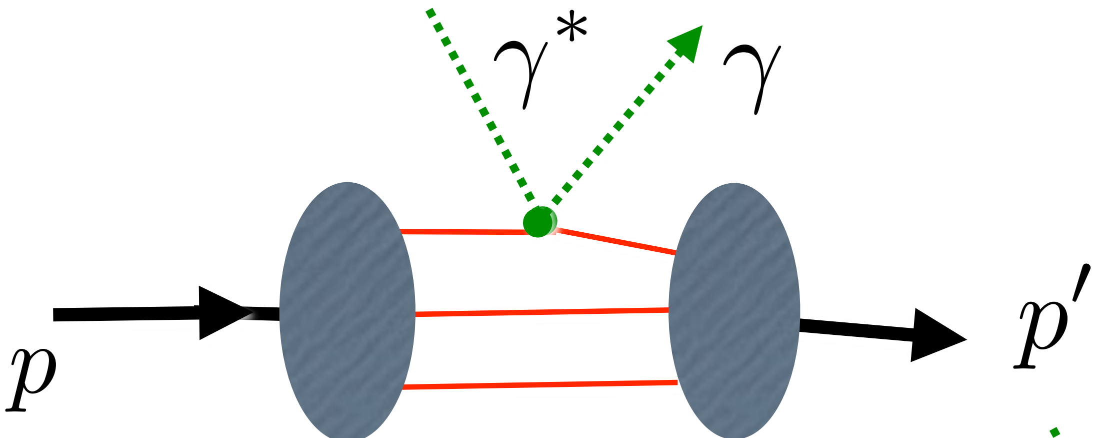
Damashek, Gilman
Close, Gunion, sjb
Szczepaniak, Llanes Estrada, sjb

J=0 Fixed Pole Contribution to DVCS

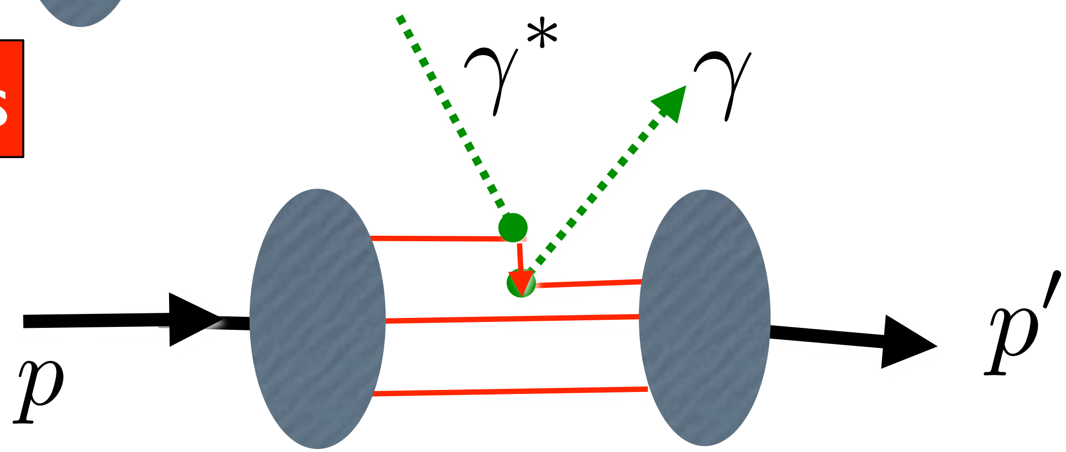
- J=0 fixed pole -- direct test of QCD locality -- from seagull or instantaneous contribution to Feynman propagator

Szczepaniak, Llanes-Estrada, sjb

Close, Gunion, sjb



squarks

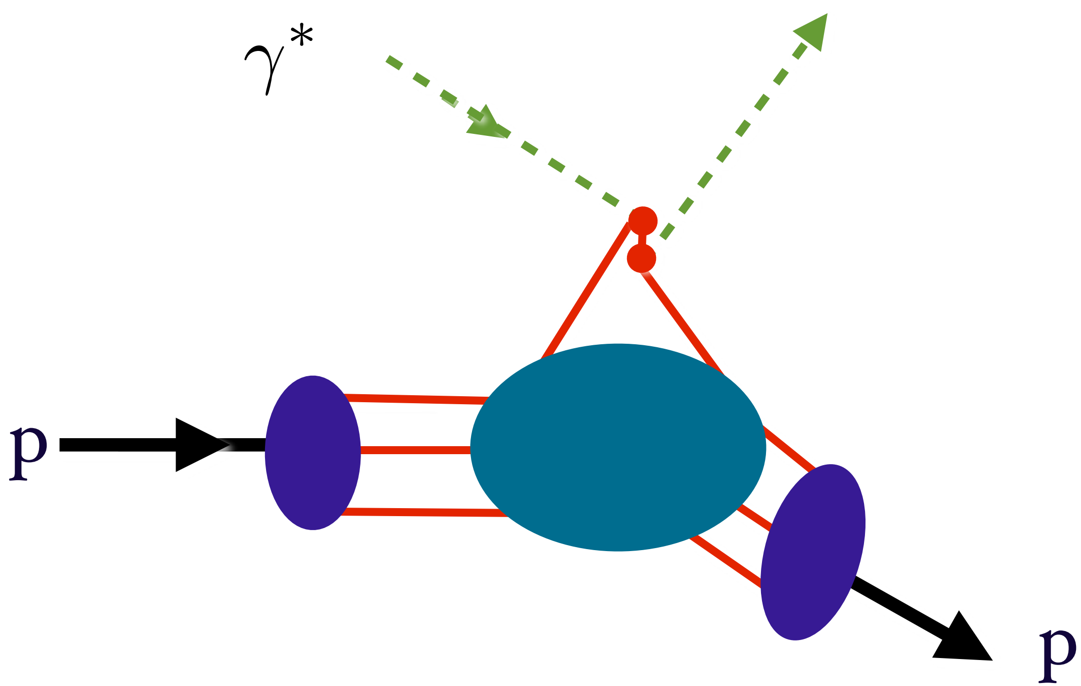


Real amplitude, independent of Q^2 at fixed t

quarks

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

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

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

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

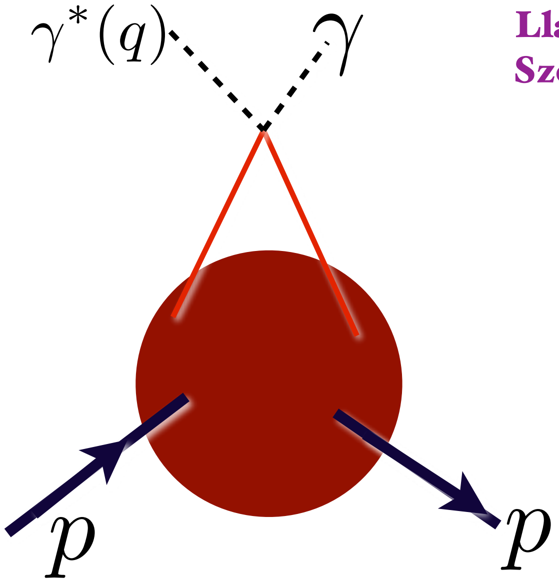
Real phase

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

Independent of Q^2 at fixed t

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

Fundamental test of local gauge theory



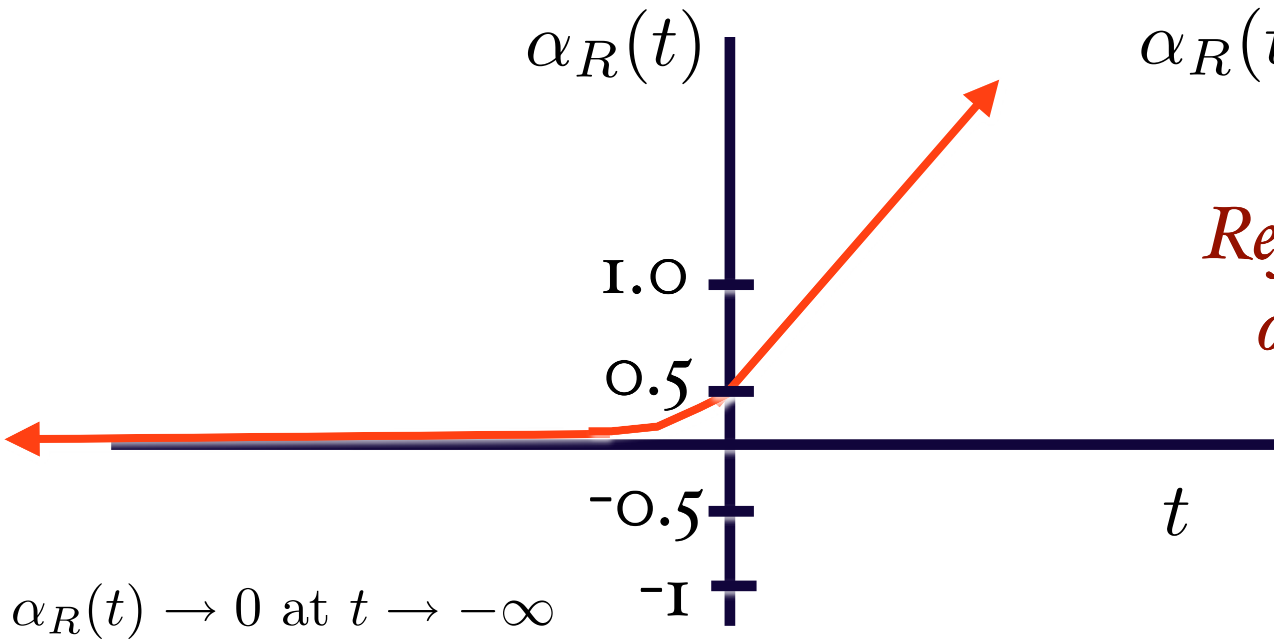
Q^2-independent contribution to Real DVCS amplitude

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

independent of s

Regge domain

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



$$\alpha_R(t) \to 0 \text{ at } t \to -\infty$$

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

"Handbag" Approximation

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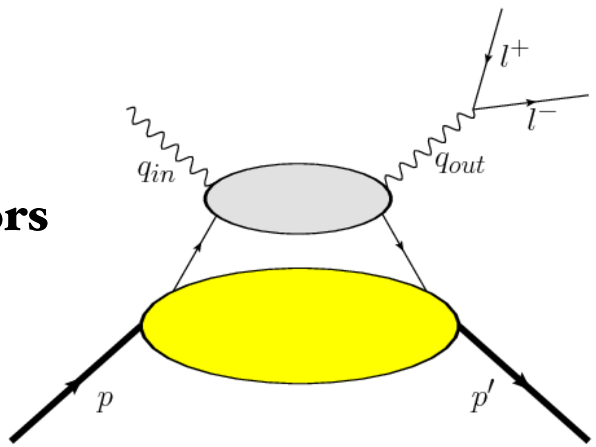
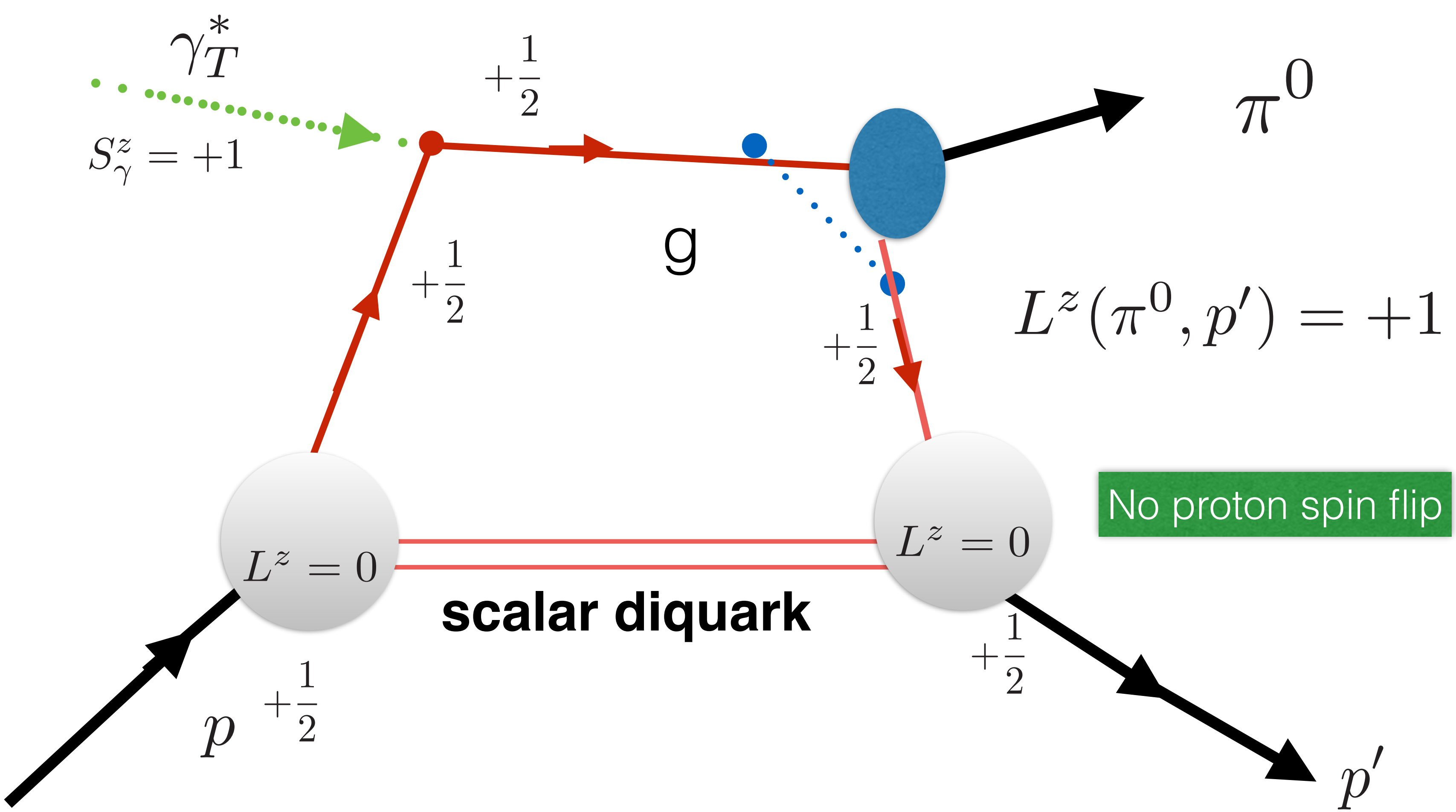


$$\gamma^* p \to \pi^0 p'$$

No quark chiral flip

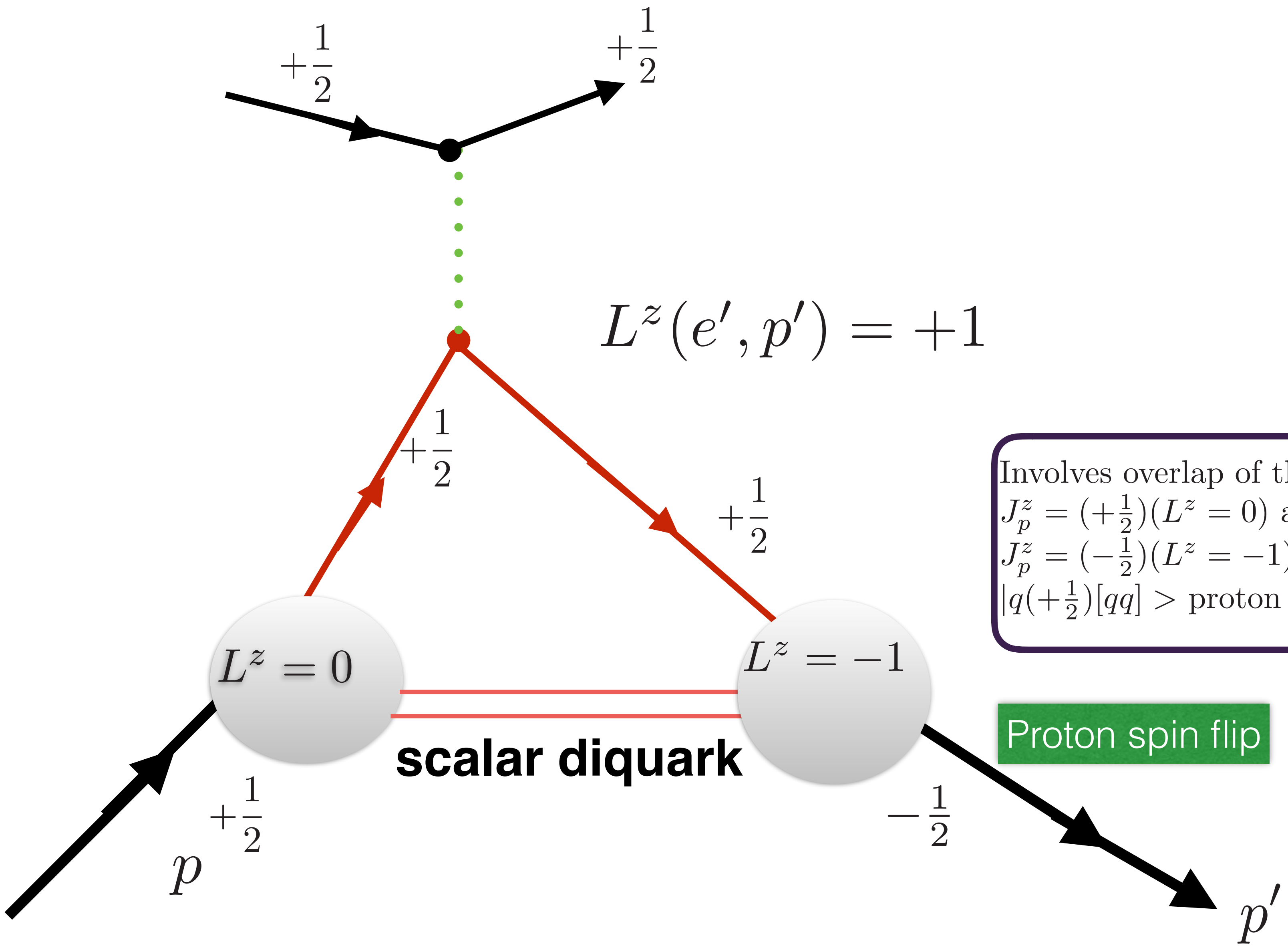
Uses dominant twist-2 pion distribution amplitude

Vanishes at $t = 0$ because of $L^z \neq 0$



$$ep \to ep'$$

Pauli Form Factor: Amplitude vanishes at t=0.



Involves overlap of the
$J_p^z = (+\frac{1}{2})(L^z = 0)$ and
$J_p^z = (-\frac{1}{2})(L^z = -1)$
$|q(+\frac{1}{2})[qq] >$ proton LF Fock states.

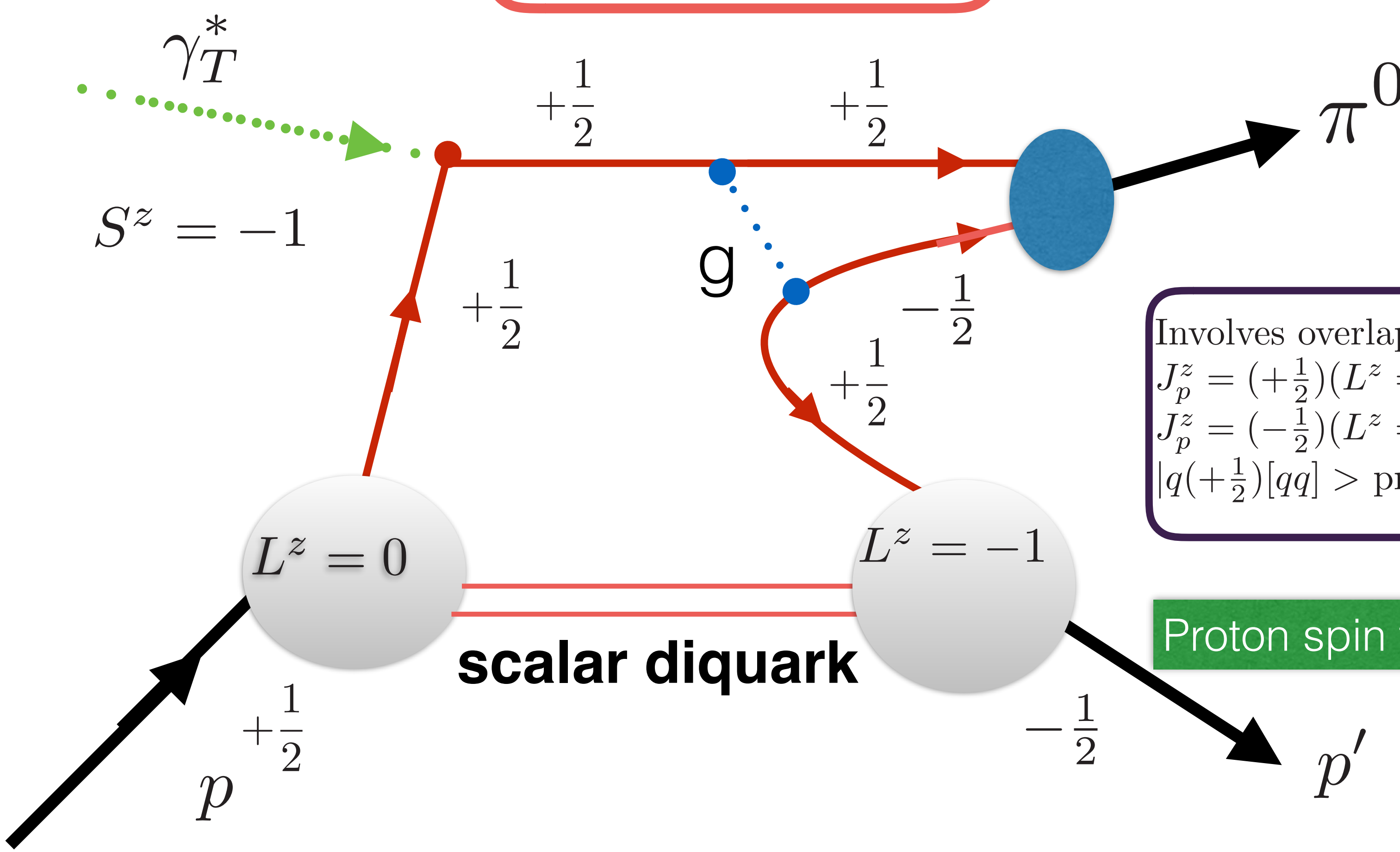
$$\gamma^* p \to \pi^0 p'$$

No quark chiral flip

$$J^z_{init} = (-\tfrac{1}{2}) = -1 + (+\tfrac{1}{2}) \to 0 + (-\tfrac{1}{2}) = (-\tfrac{1}{2}) = J^z_{final}$$

Uses dominant twist-2 pion distribution amplitude

$\boxed{\text{Finite at } t = 0}$ $\quad L^z(\pi^0, p') = 0$



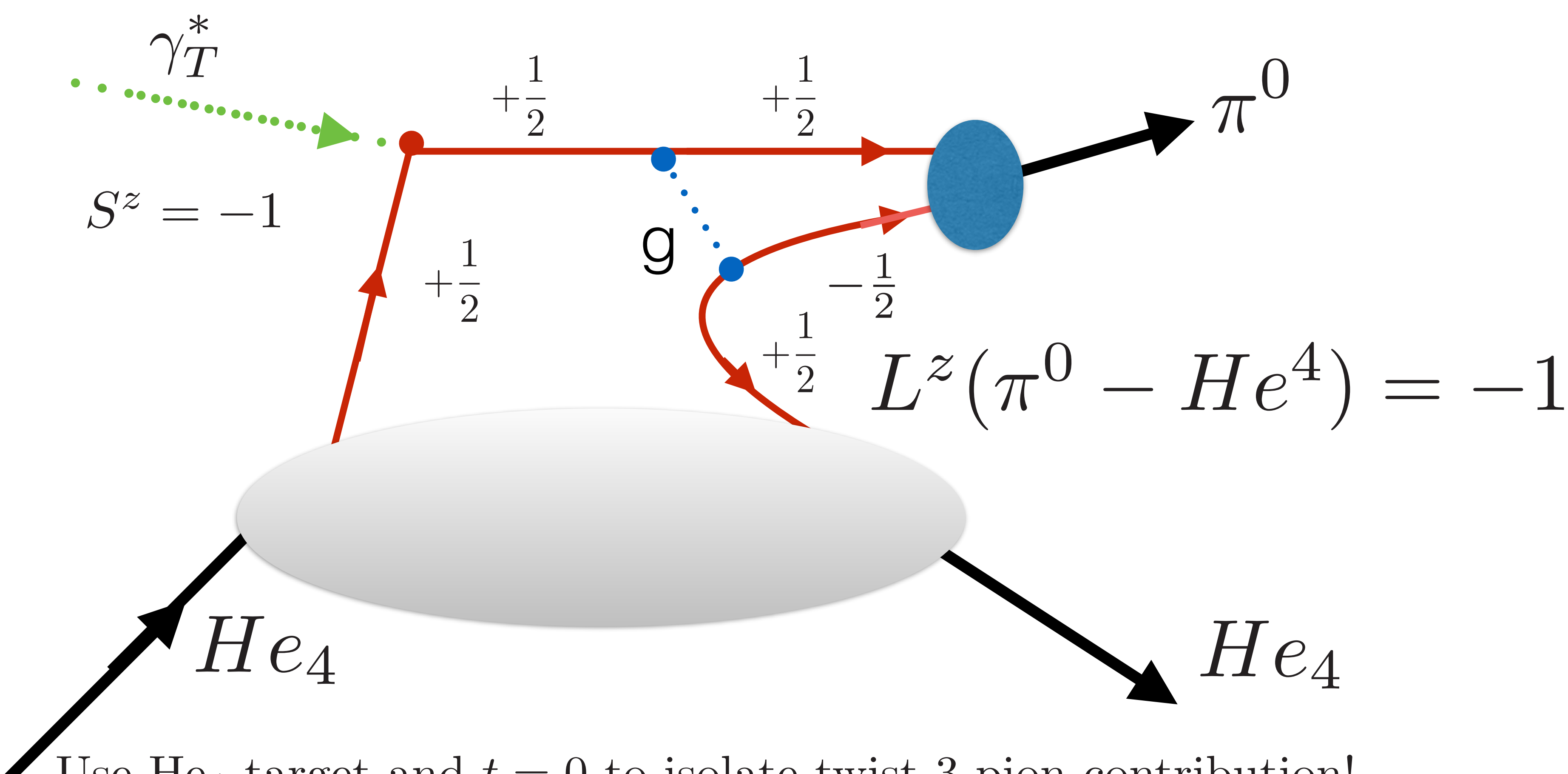
Involves overlap of the
$J^z_p = (+\frac{1}{2})(L^z = 0)$ and
$J^z_p = (-\frac{1}{2})(L^z = -1)$
$|q(+\frac{1}{2})[qq] >$ proton LF Fock states.

$$\gamma_T^* He_4 \to \pi_0 He_4$$

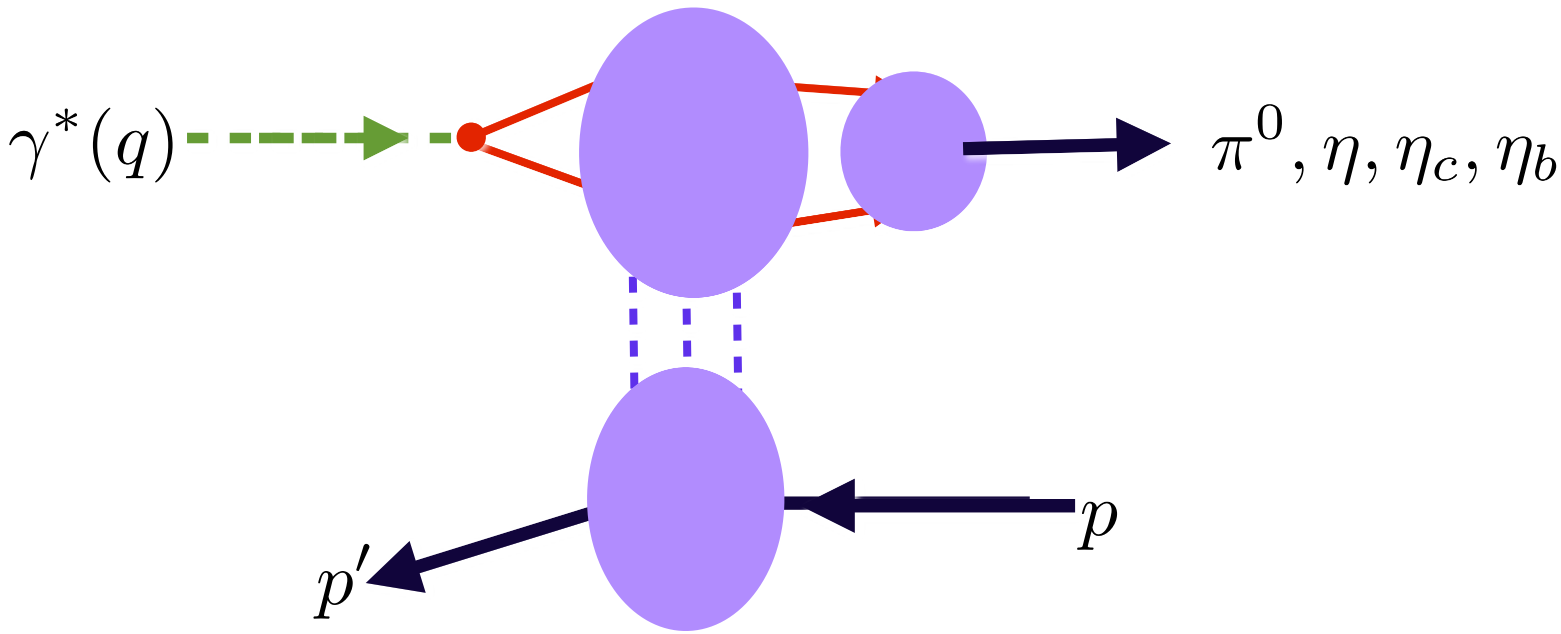
No quark chiral flip

Uses dominant twist-2 pion distribution amplitude

Vanishes at t =0



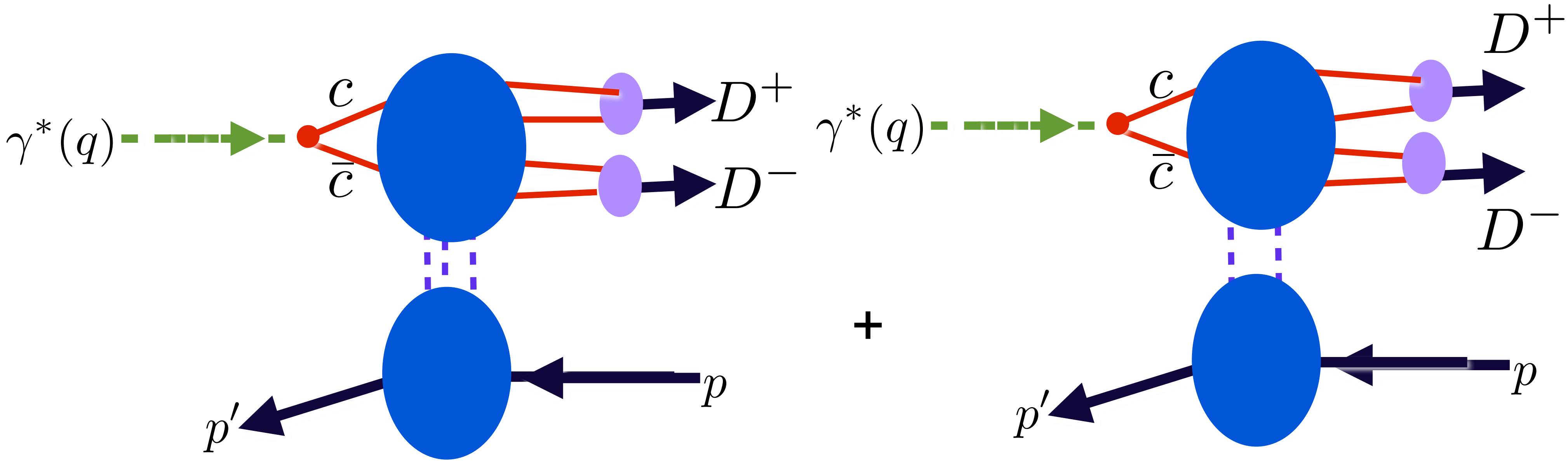
Use He_4 target and $t = 0$ to isolate twist-3 pion contribution!



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

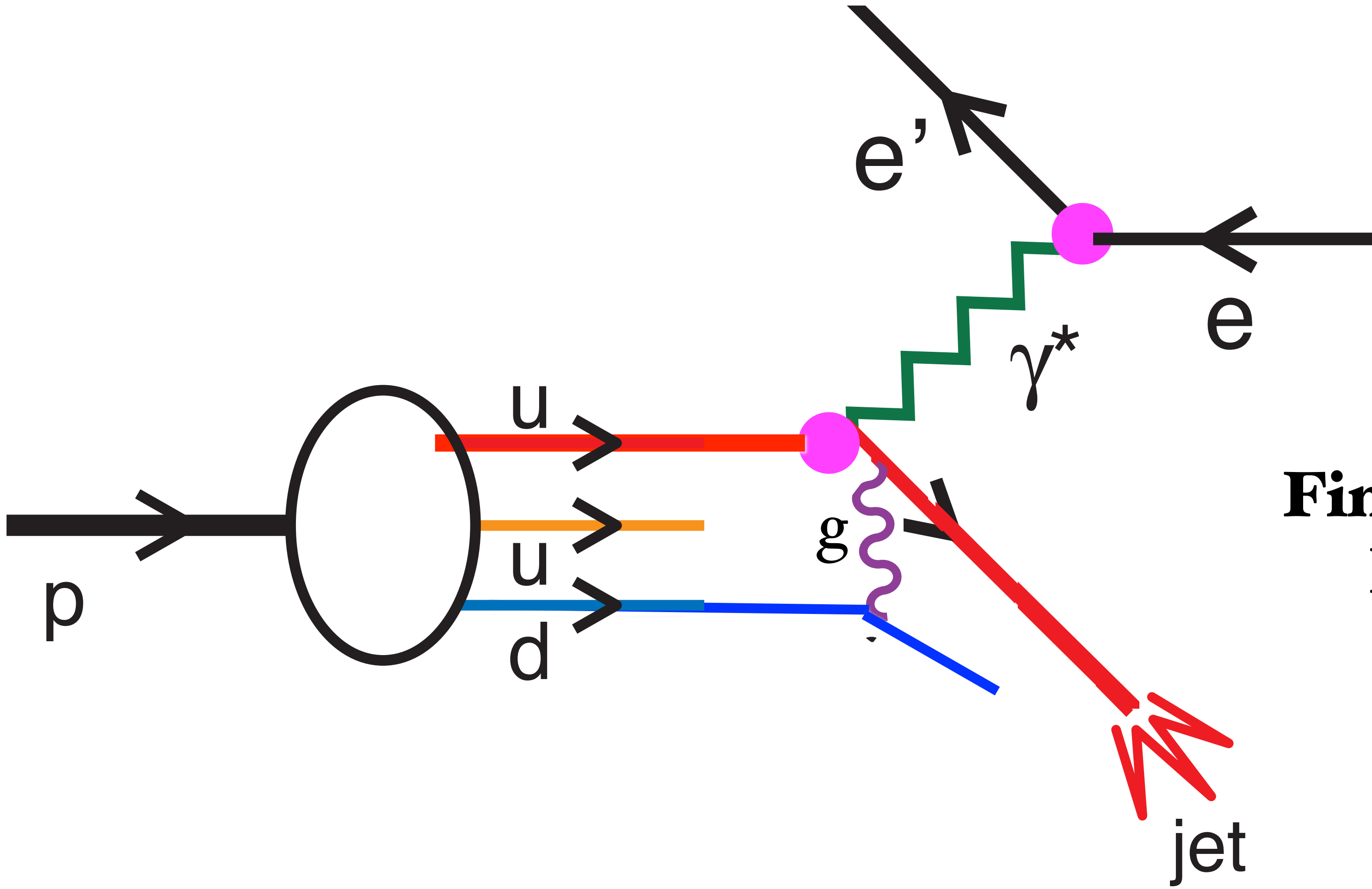
Merino, Rathsman, sjb

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

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

Hoang, Kuhn, sjb

Deep Inelastic Electron-Proton Scattering



Final-State QCD Interaction

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

Single-spin asymmetries

Leading Twist Sivers Effect

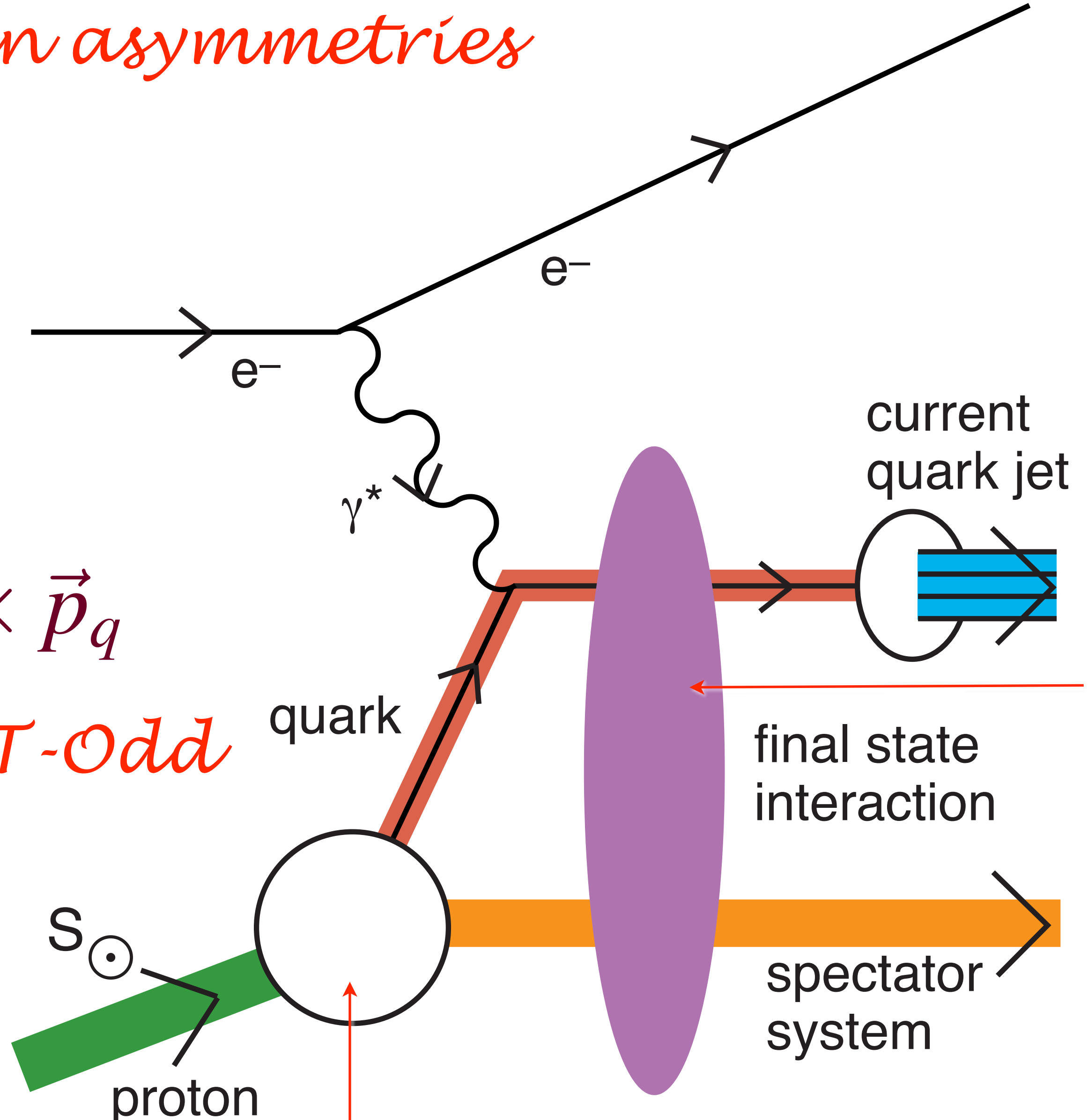
Hwang, Schmidt, sjb

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

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

Pseudo- T-Odd

"Lensing" involves soft scales



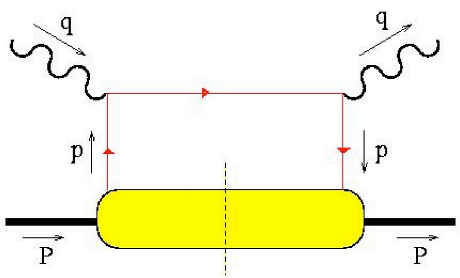
Light-Front Wavefunction S and P- Waves!

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

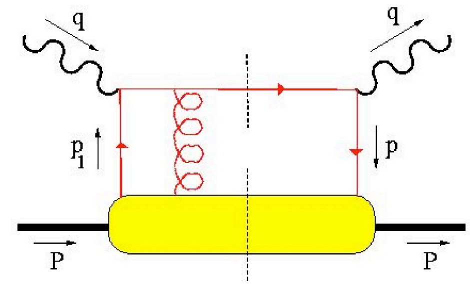
"Lensing Effect"

Leading-Twist Rescattering Violates pQCD Factorization!

Sign reversal in DY!



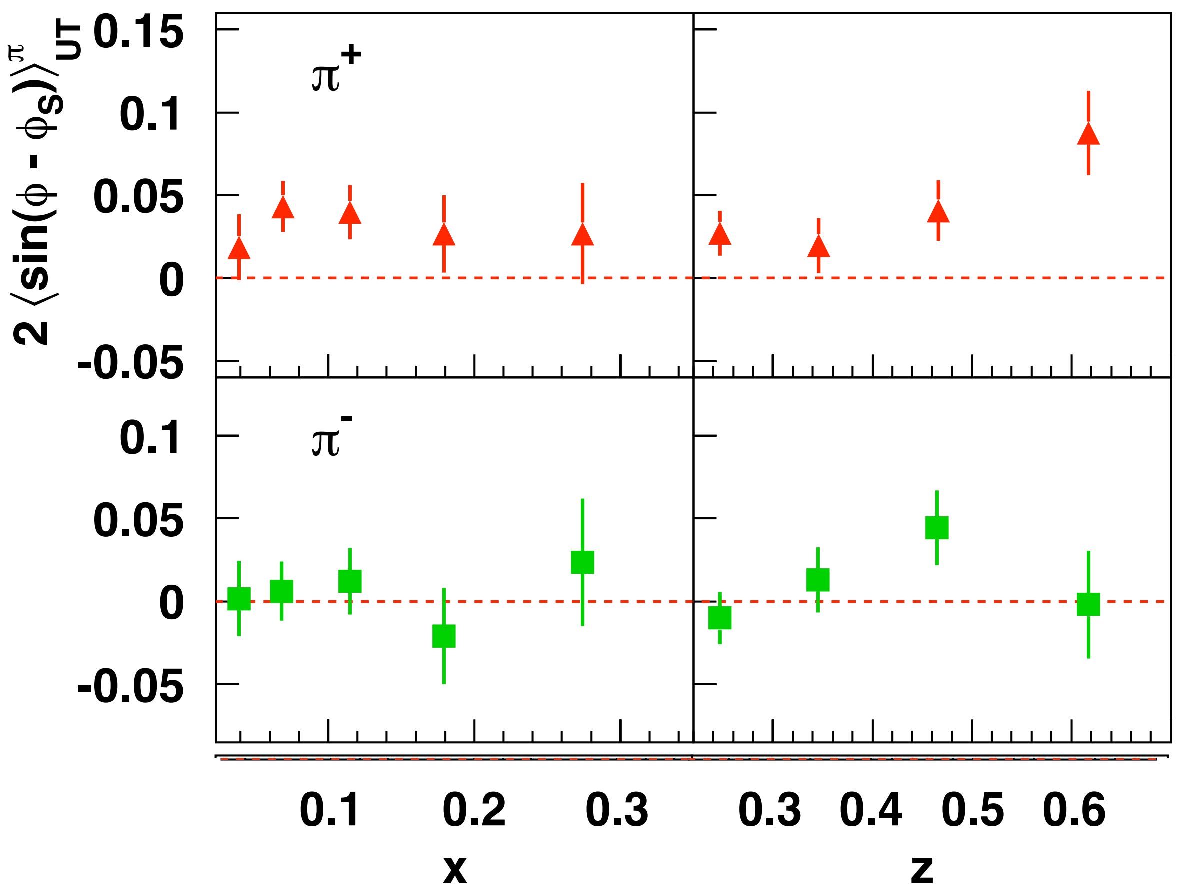
can interfere
with



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

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

Sivers asymmetry from HERMES



- First evidence for non-zero Sivers function!
- $\Rightarrow$ presence of non-zero **quark orbital angular momentum**!
- Positive for **π^+**...
  Consistent with zero for **π^-**...

Gamberg: Hermes
data compatible with BHS model

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

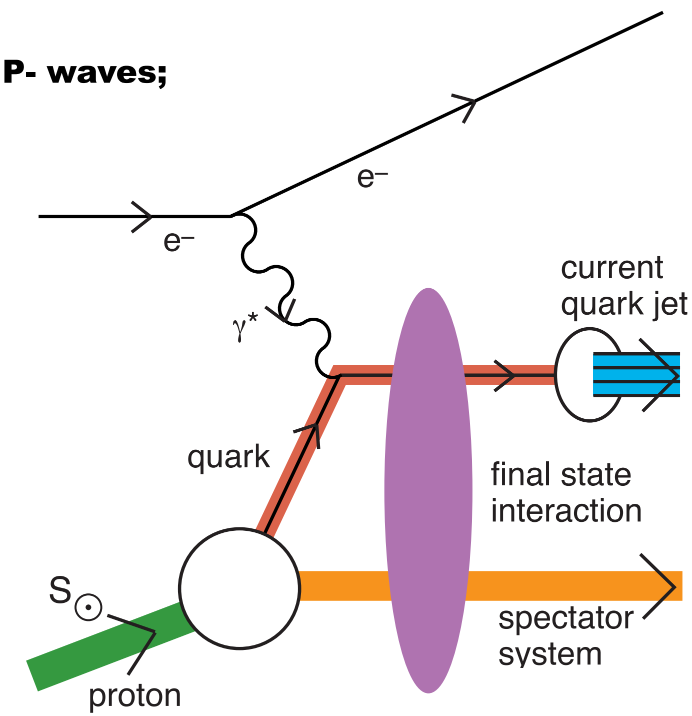
Final-State Interactions Produce Pseudo T-Odd (Sivers Effect)

Hwang, Schmidt, sjb
Collins

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

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

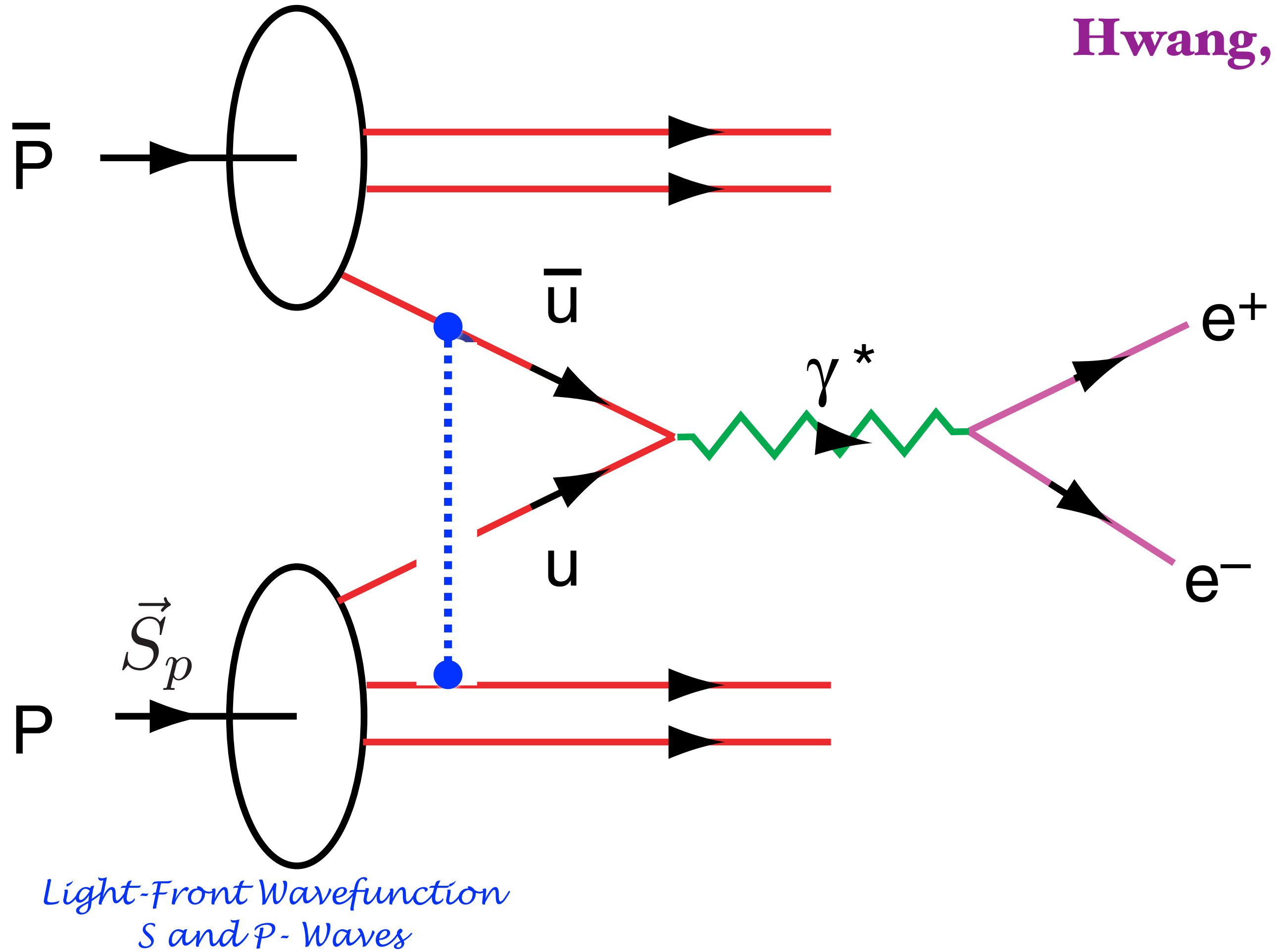
Dae Sung Hwang, Yuri V. Kovchegov,
Ivan Schmidt, Matthew D. Sievert, sjb



Pasquini, Xiao, Yuan, sjb

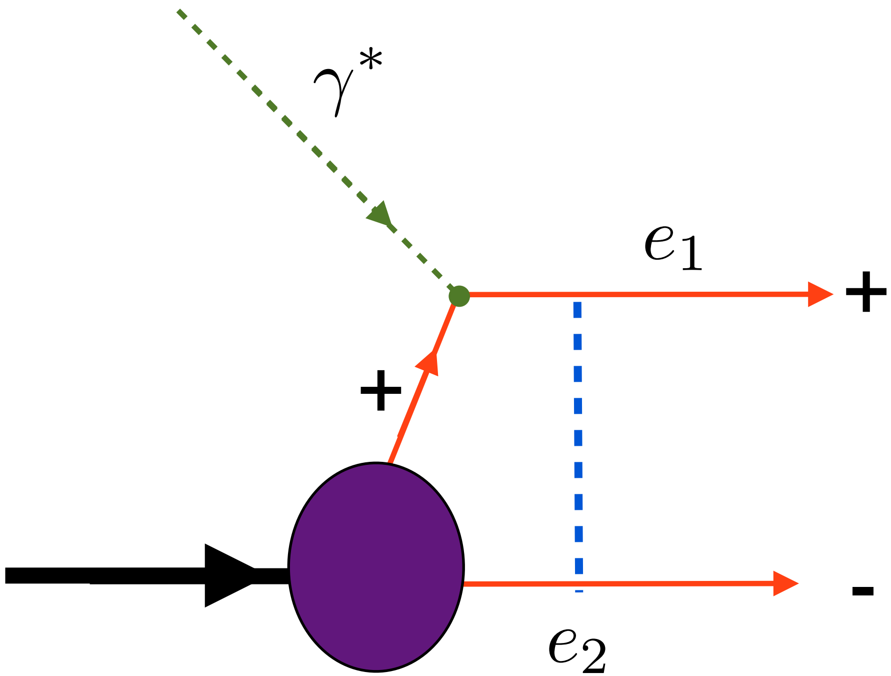
Mulders, Boer **Qiu, Sterman**

Collins
Hwang, Schmidt, sjb



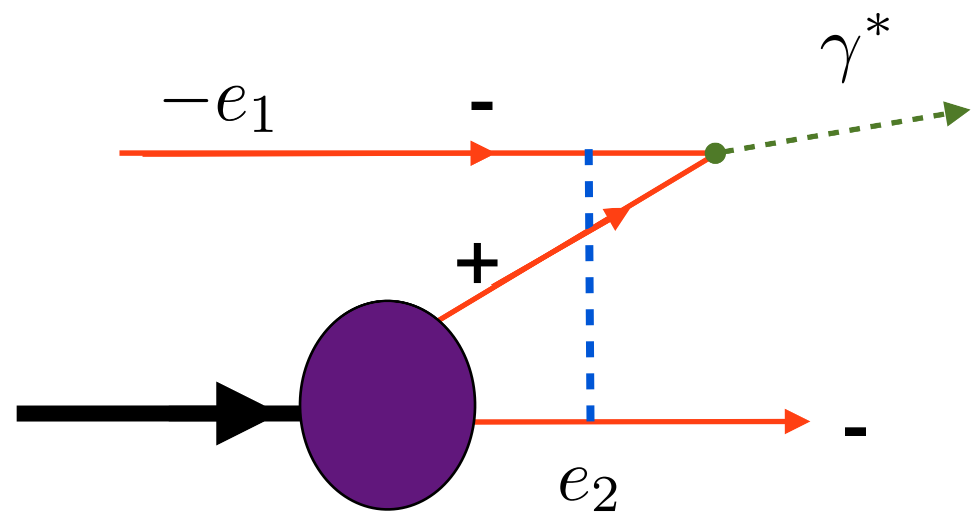
Pseudo-Odd Correlation $i\ \vec{S}_p \cdot \vec{q} \times \vec{p}_{\bar{p}}$

Sivers Effect in Di-Lepton Production is Predicted to have Opposite Sign compared to SIDIS



DIS

Attractive, opposite-sign rescattering potential



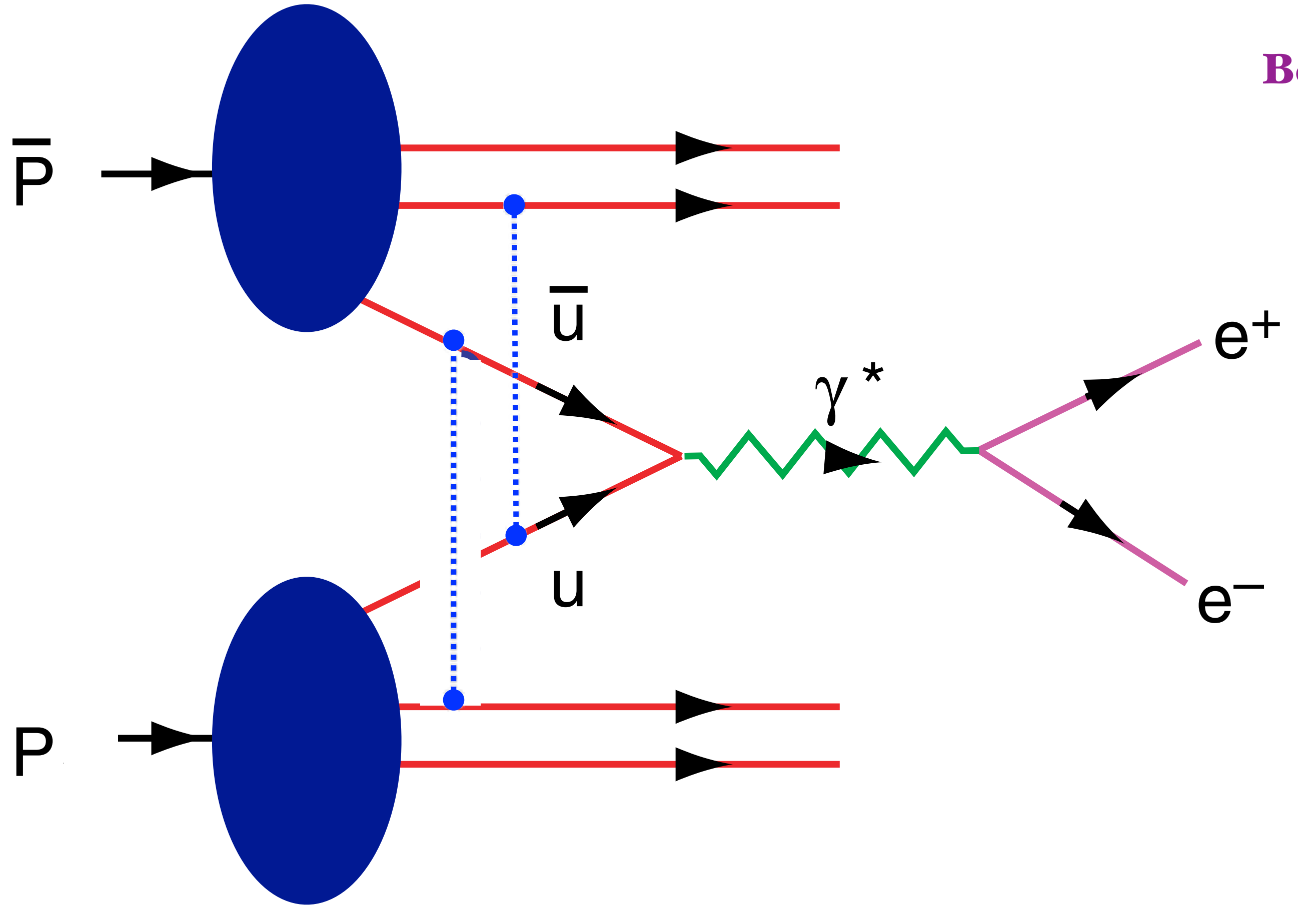
DY

Repulsive, same-sign scattering potential

Dae Sung Hwang, Yuri V. Kovchegov, Ivan Schmidt, Matthew D. Sievert, sjb

Example of Leading-Twist Lensing Correction

Boer, Hwang, sjb



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

Product of Boer - Mulders Functions

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

Violates Lam-Tung relation!

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

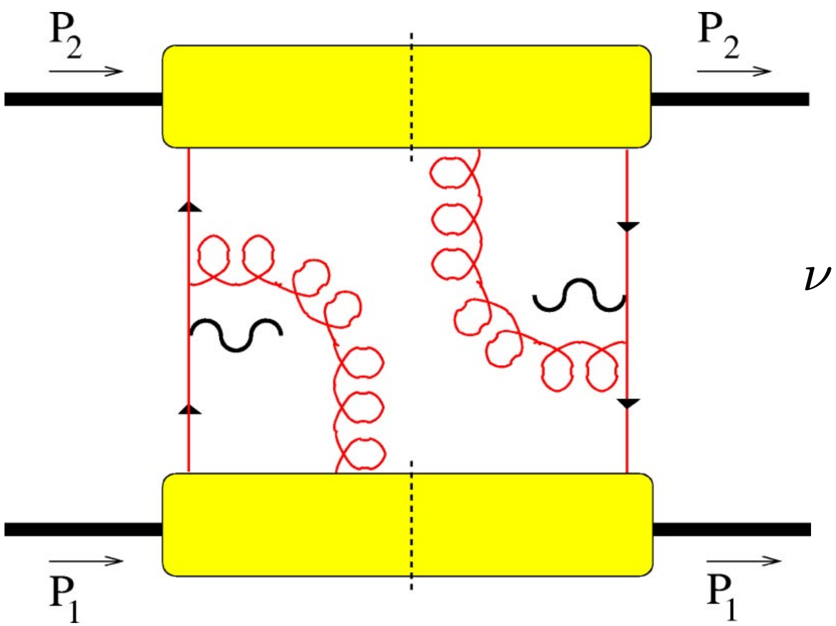
Boer, Hwang, sjb

Drell-Yan planar correlations

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

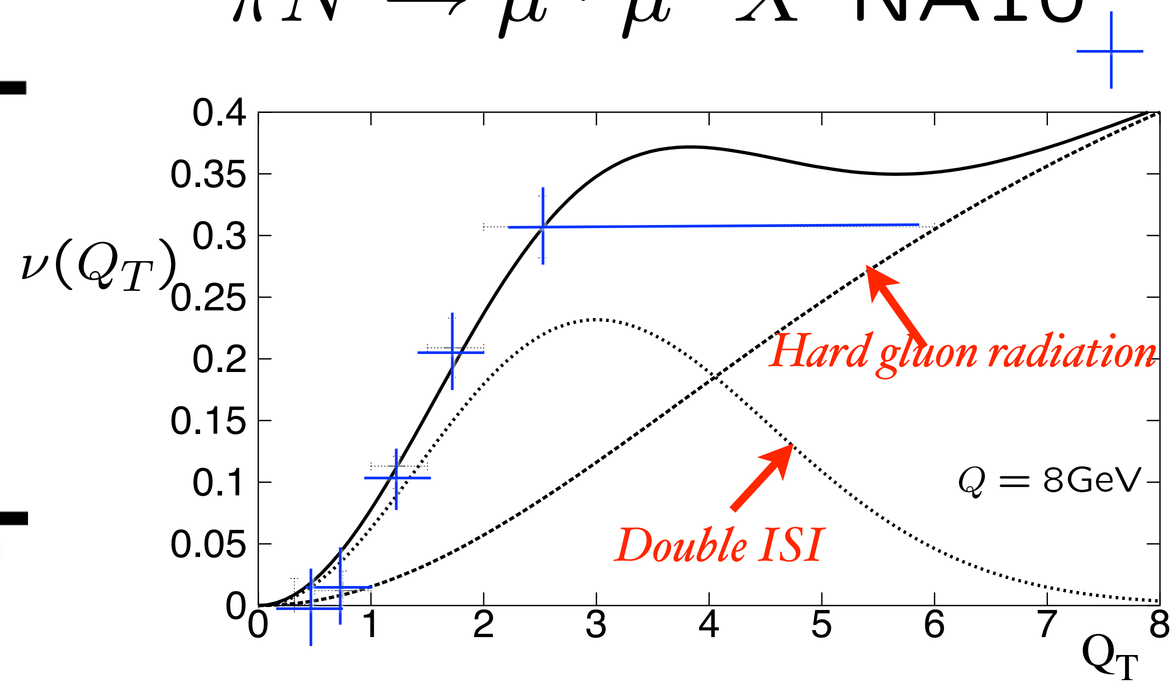
PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

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



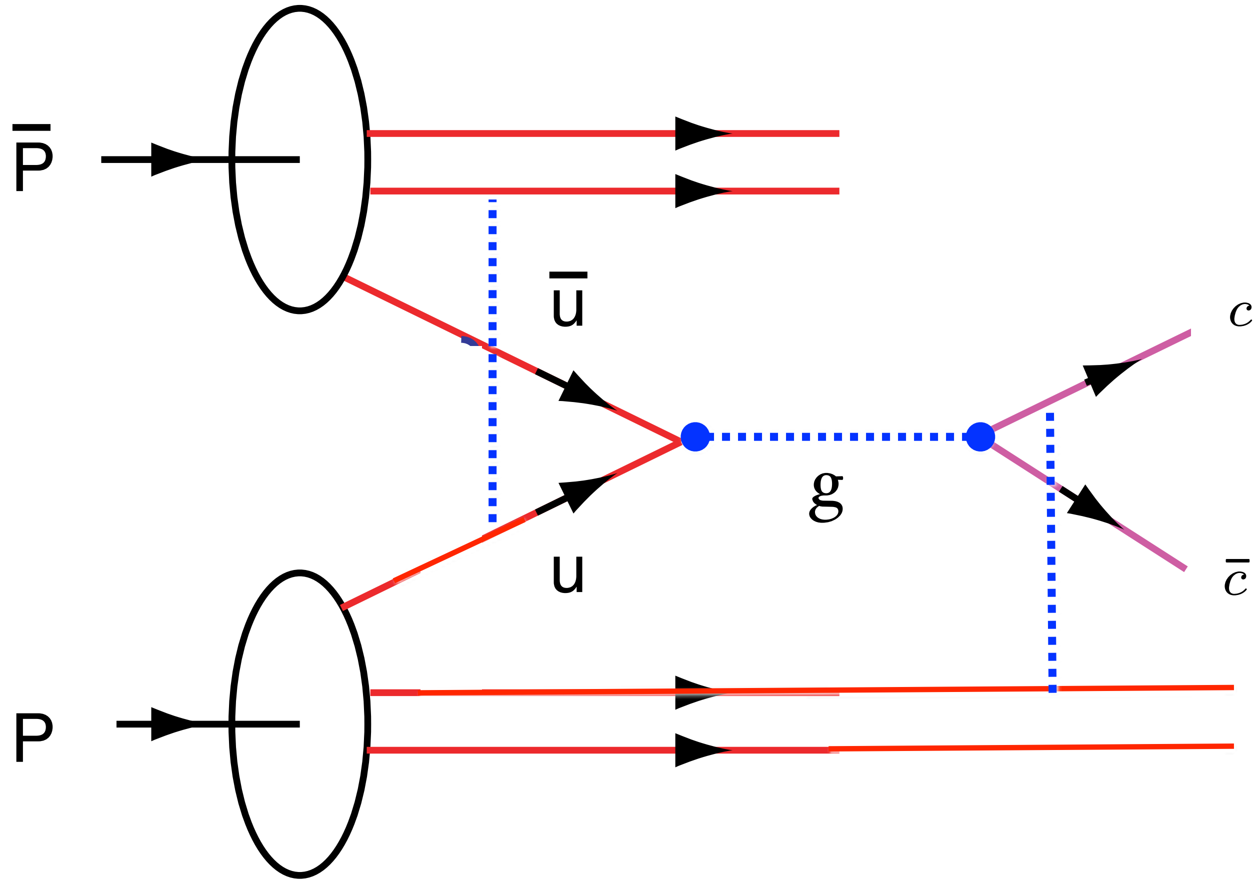
Violates Lam-Tung relation!

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



Model: Boer,

See also: Collins and Qiu

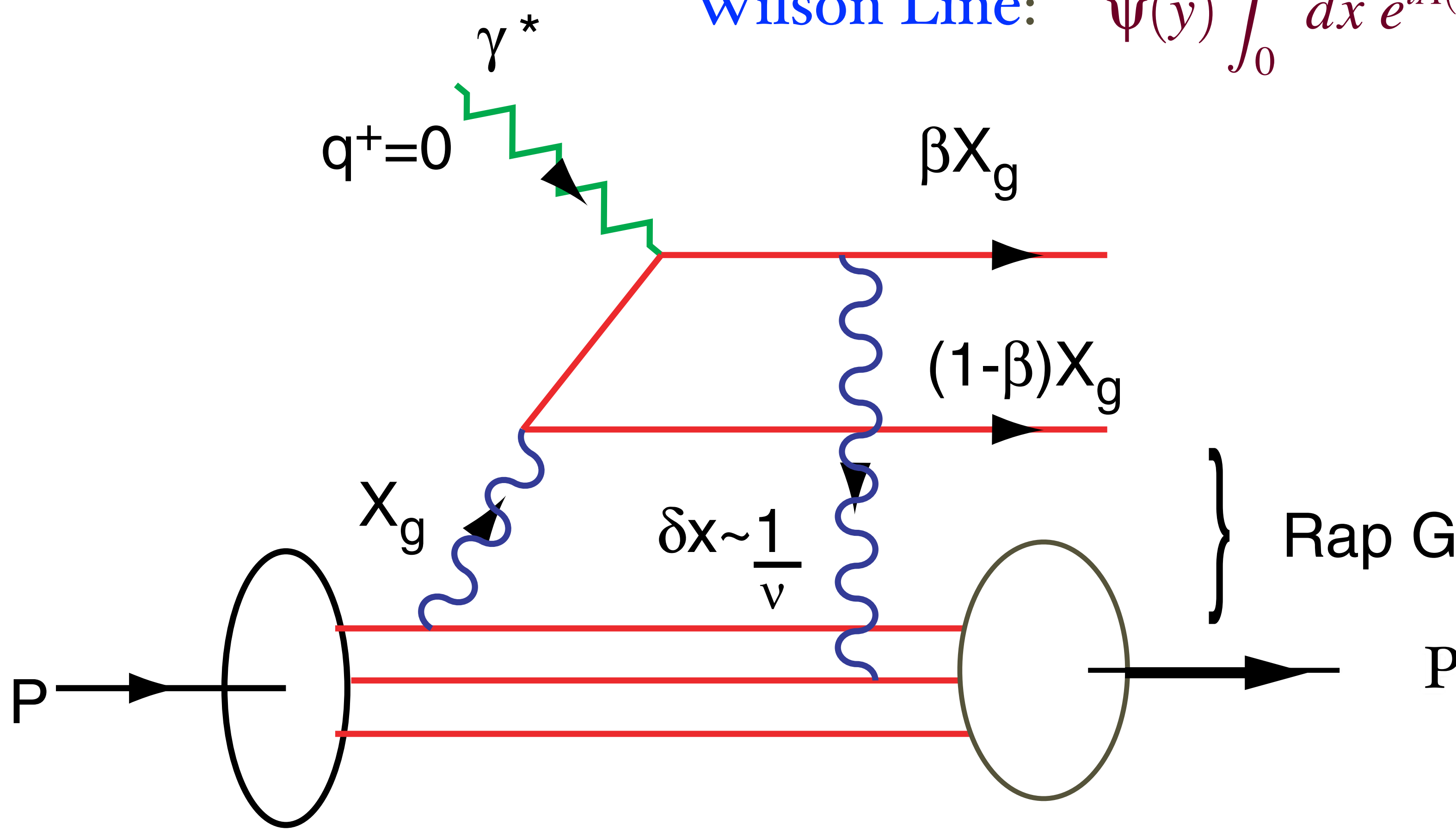


Problem for factorization when both ISI and FSI occur

Hoyer, Marchal, Peigne, Sannino, sjb

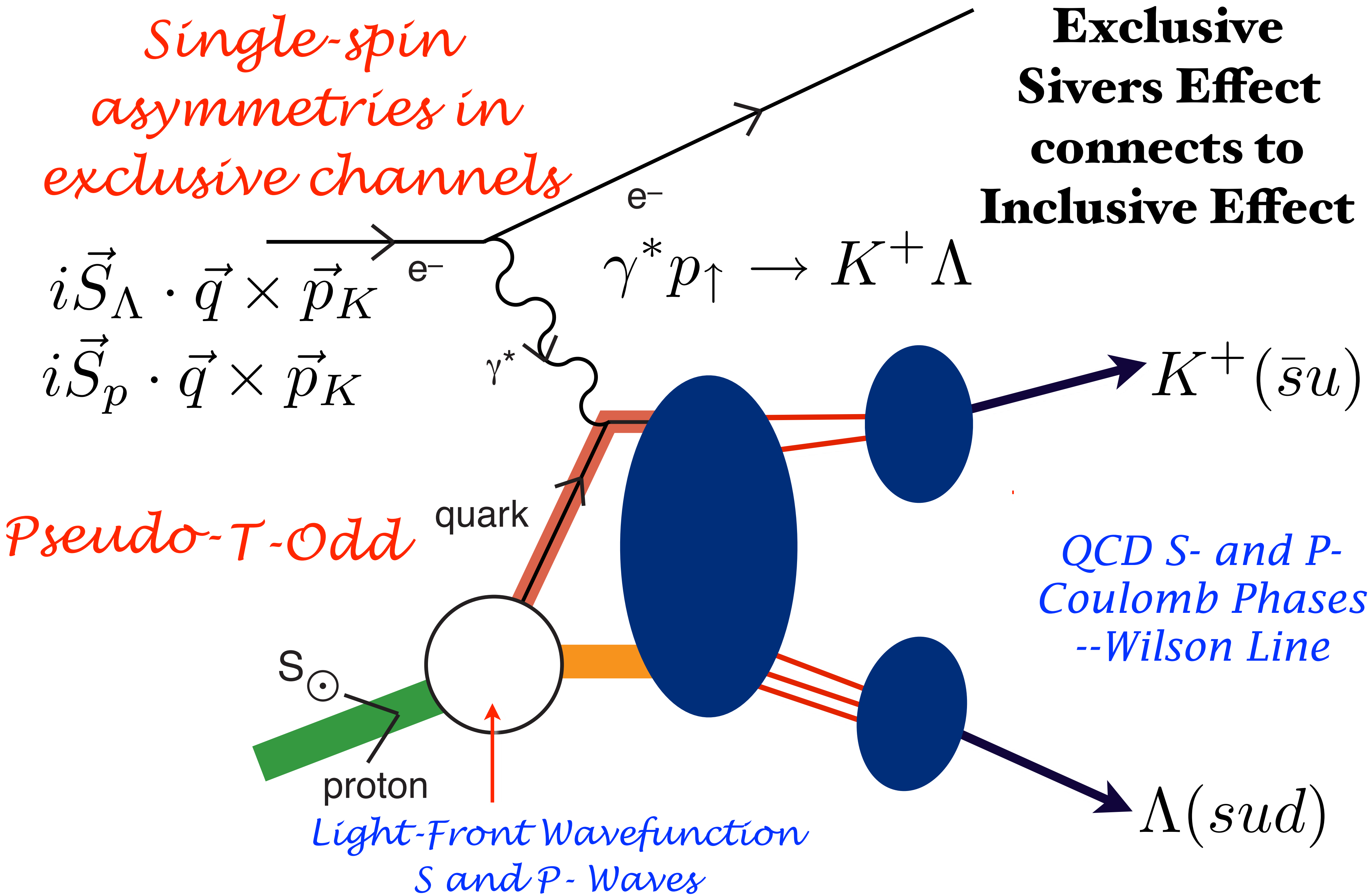
QCD Mechanism for Rapidity Gaps

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



Reproduces lab-frame color dipole approach

DDIS: Input for leading twist nuclear shadowing



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,

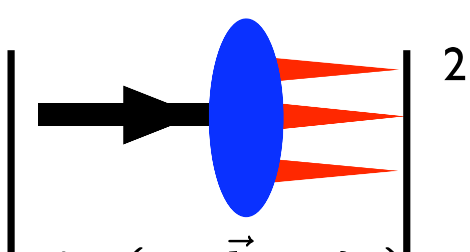
Mulders, Boer

Qiu, Sterman

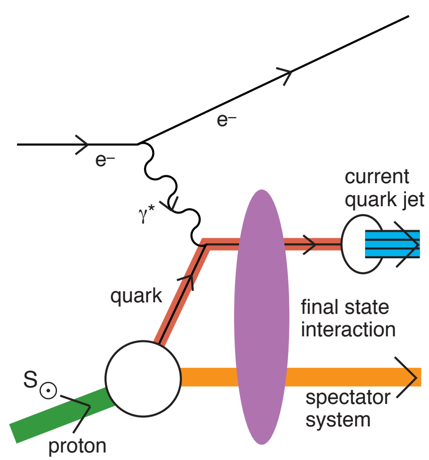
Collins, Qiu

Pasquini, Xiao, Yuan, sjb

Liuti, sjb

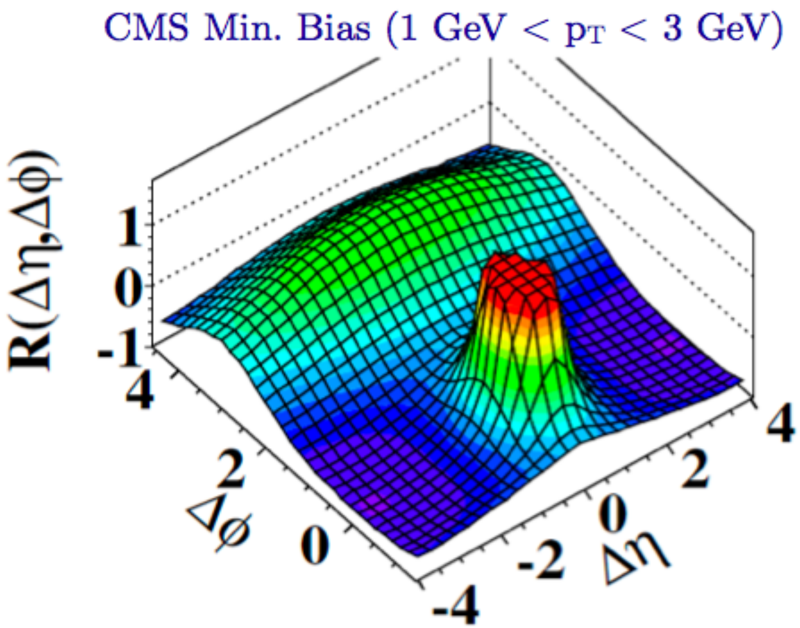


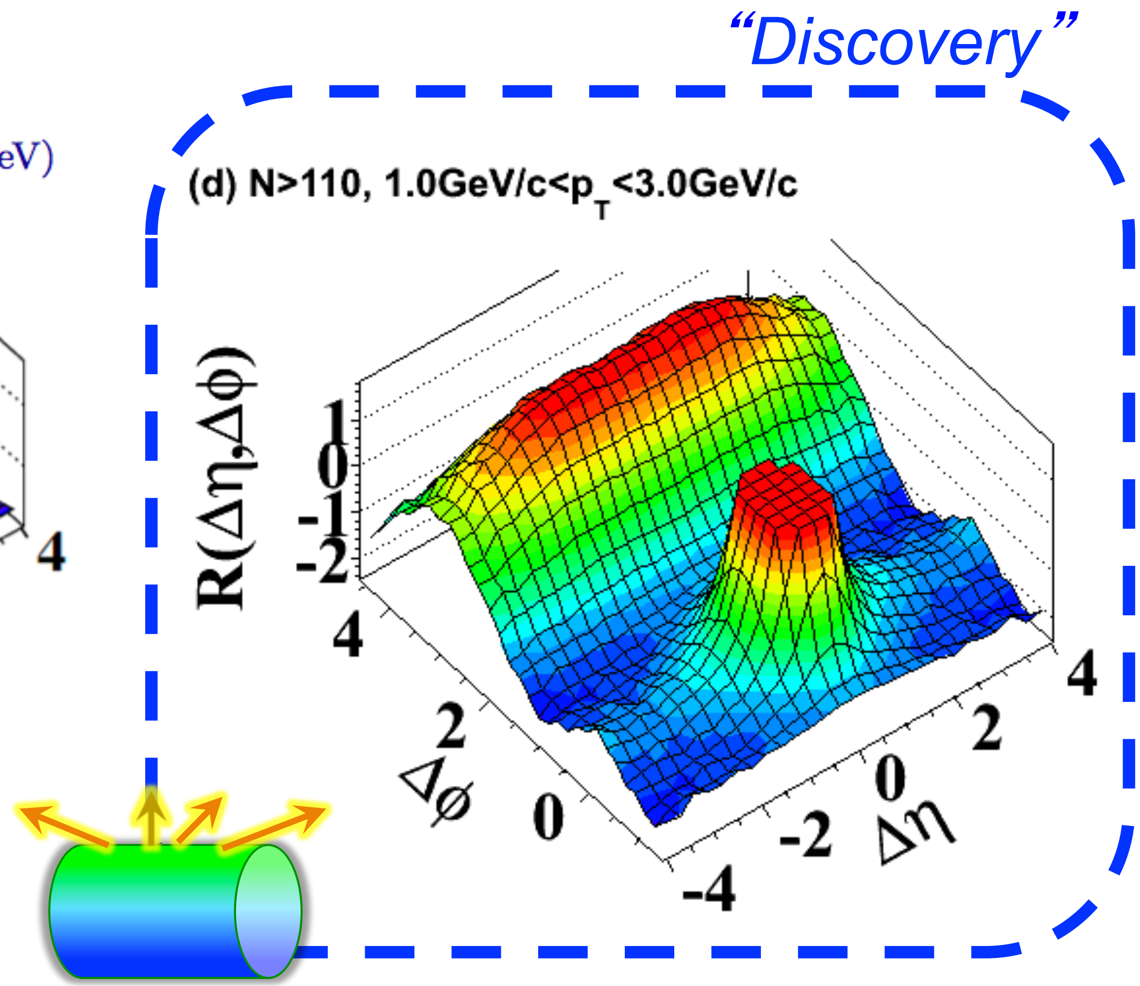
$$\left| \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) \right|^2$$



Ridge in high-multiplicity p p collisions

Two-particle correlations: CMS results

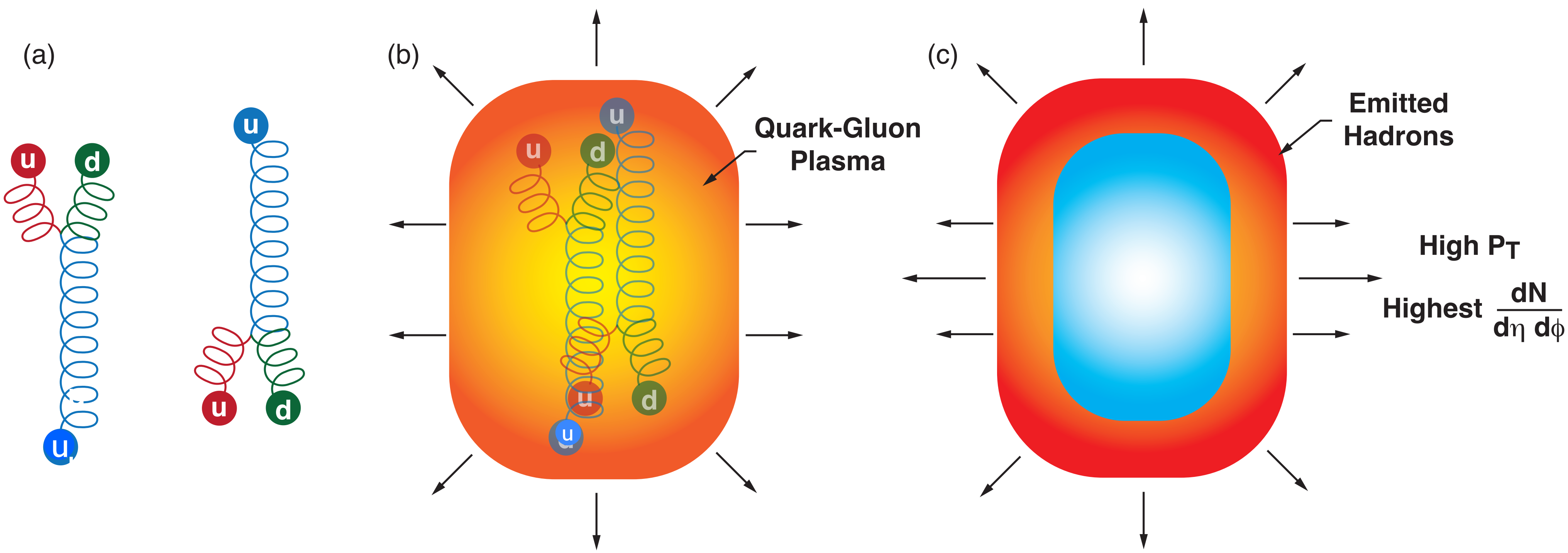




- **Ridge: Distinct long range correlation in η collimated around ΔΦ≈ 0 for two hadrons in the intermediate $1 < p_T, q_T < 3$ GeV**

Raju Venugopalan

Ridge may reflect collision of aligned flux tubes

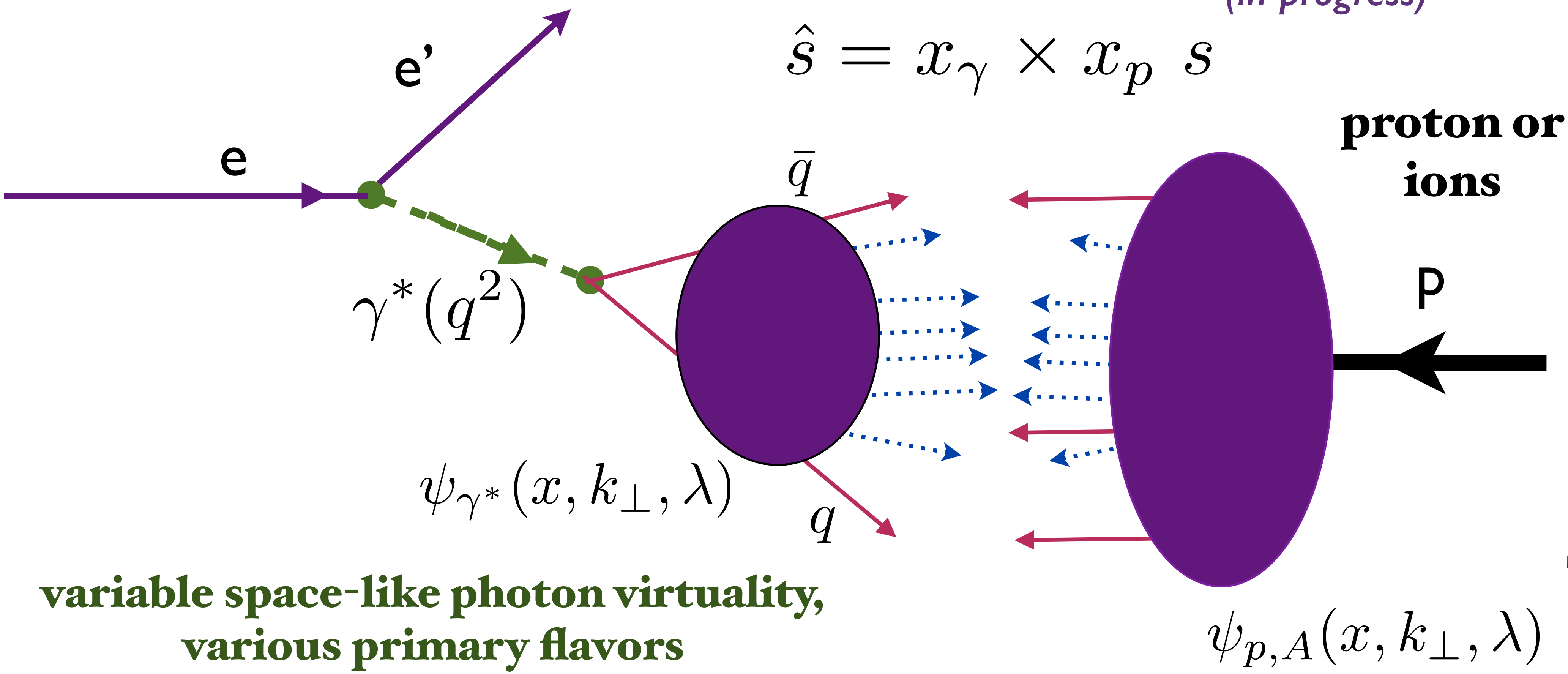


Bjorken, Goldhaber, sjb

Electron-Ion Collider: Virtual Photon-Ion Collider

Perspective from the e-p collider frame

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



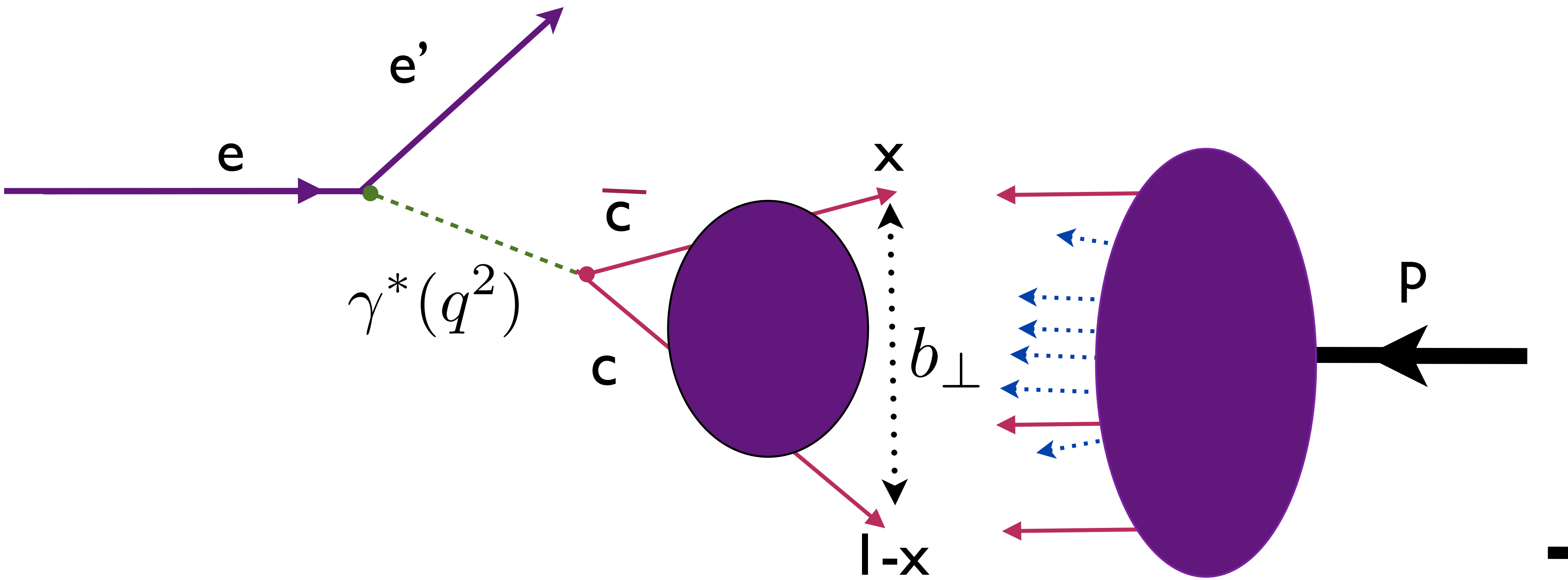
variable space-like photon virtuality, various primary flavors

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

Front-surface dynamics: shadowing/antishadowing

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

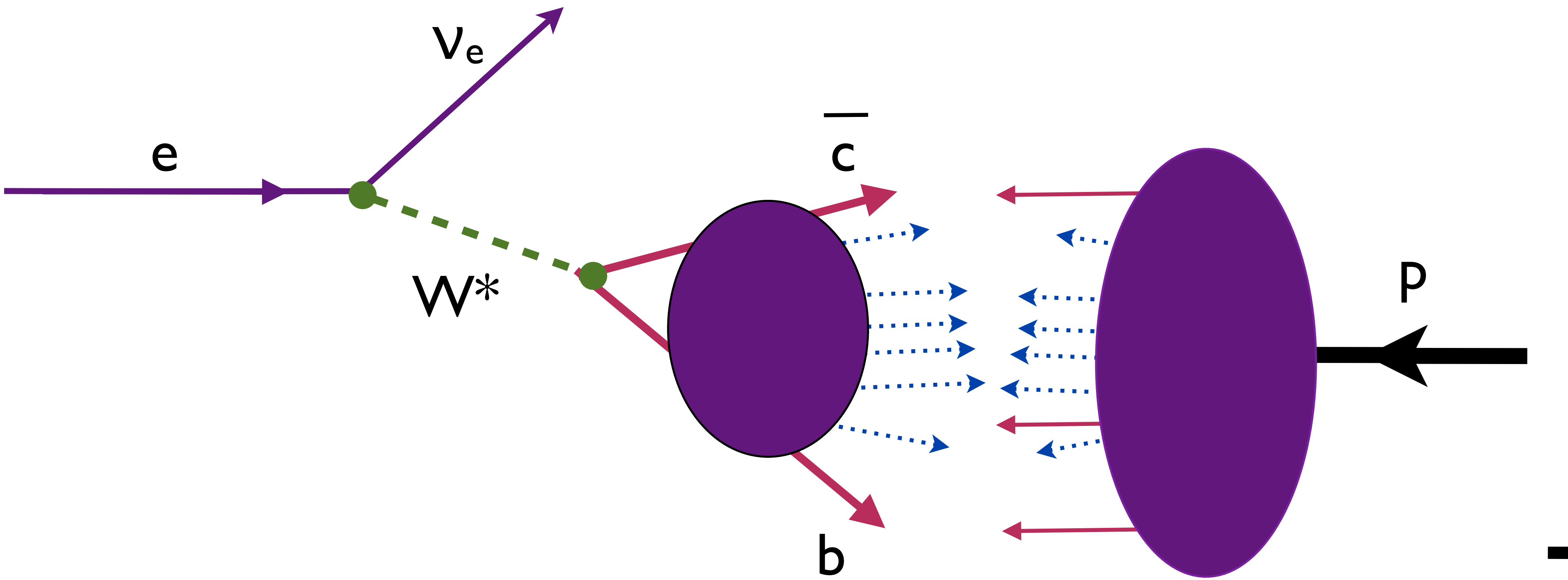
$$< b_\perp^2 > \sim \frac{1}{Q^2 x(1-x) + m_c^2}$$



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



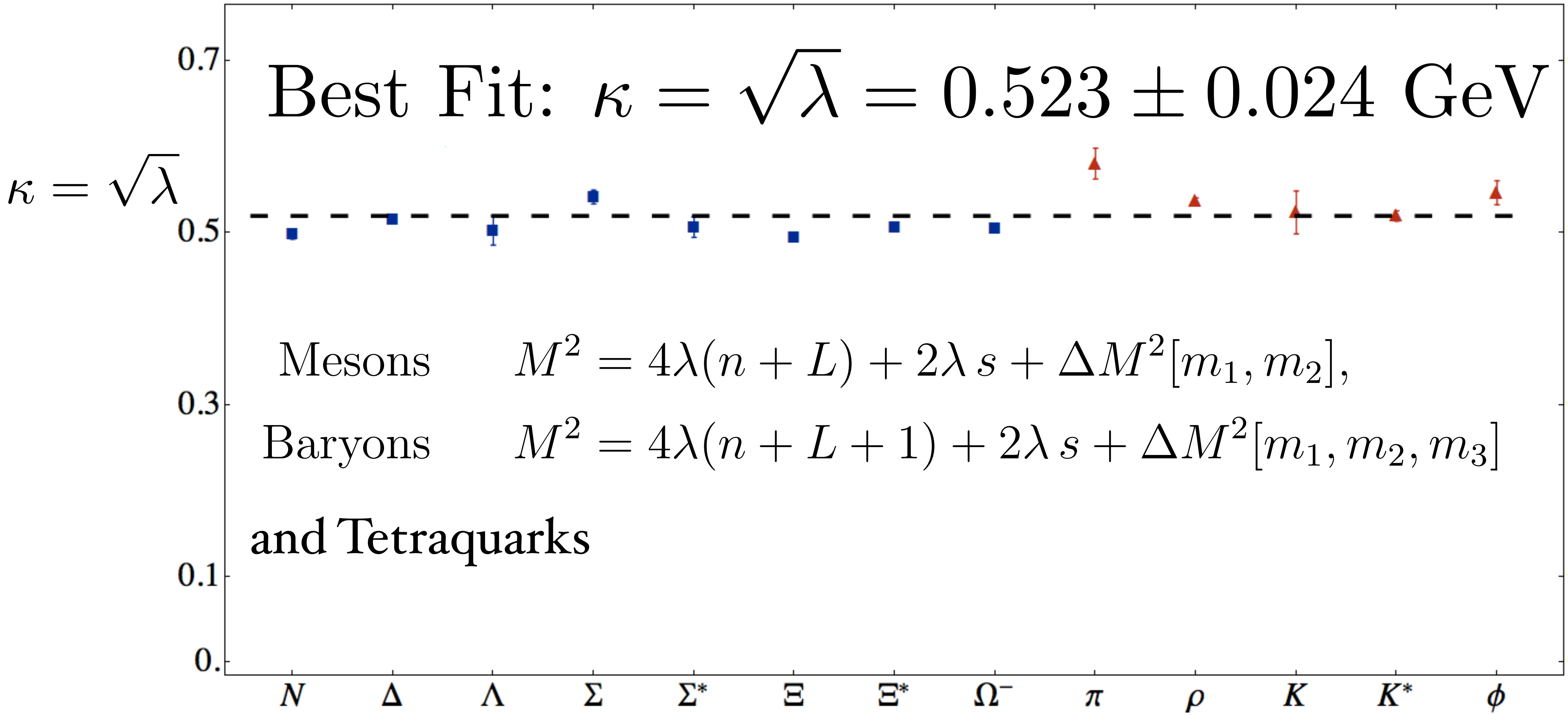
variable W* virtuality, variable flavors

proton or ions

- Universal Regge slopes

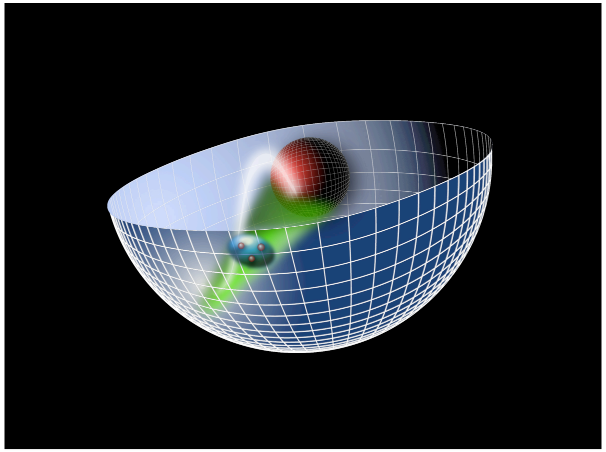
Dosch, de Teramond, Lorce, sjb

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



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.

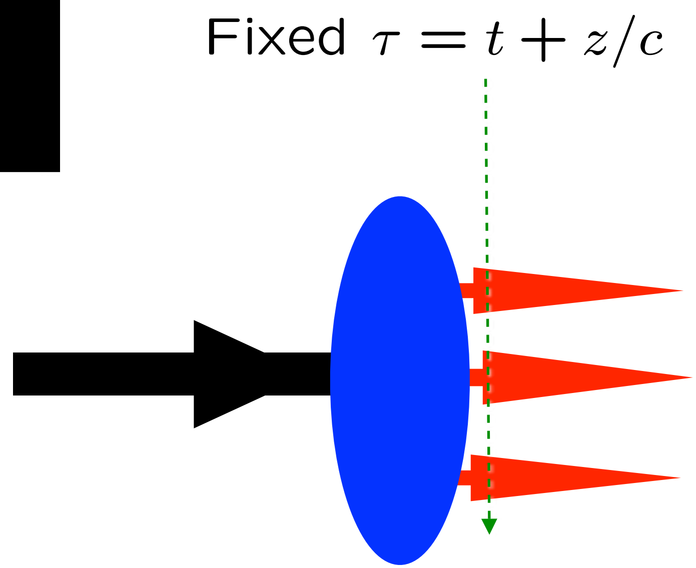
$\phi(z)$



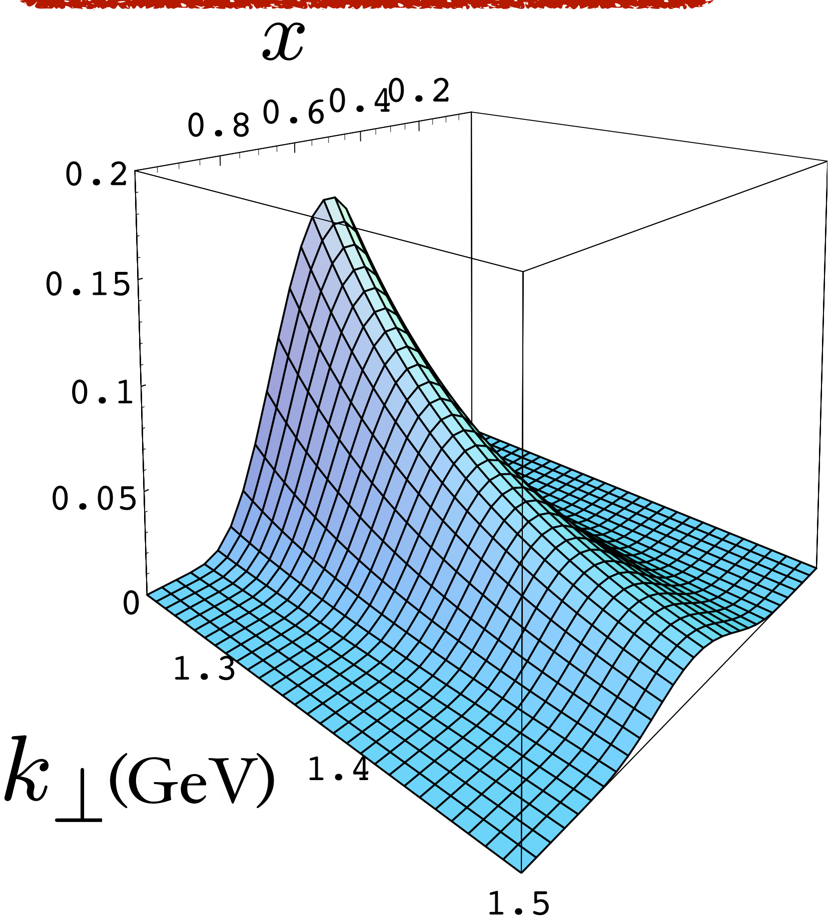
AdS5: Conformal Template for QCD

- *Light-Front Holography*

Duality of AdS$_5$ 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

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

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

Classical Chiral Lagrangian is Conformally Invariant

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

How does color confinement arise?

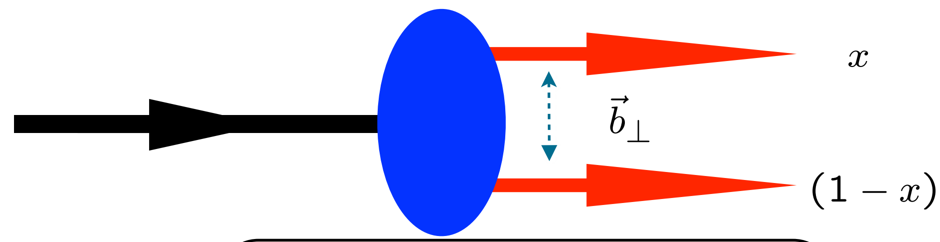
- **de Alfaro, Fubini, Furlan:**

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

Unique confinement potential!

Light-Front QCD

Fixed $\tau = t + z/c$



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

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

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

Coupled Fock states

Eliminate higher Fock states and retarded interactions

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

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

$$\zeta, \phi$$

$$m_q = 0$$

AdS/QCD:

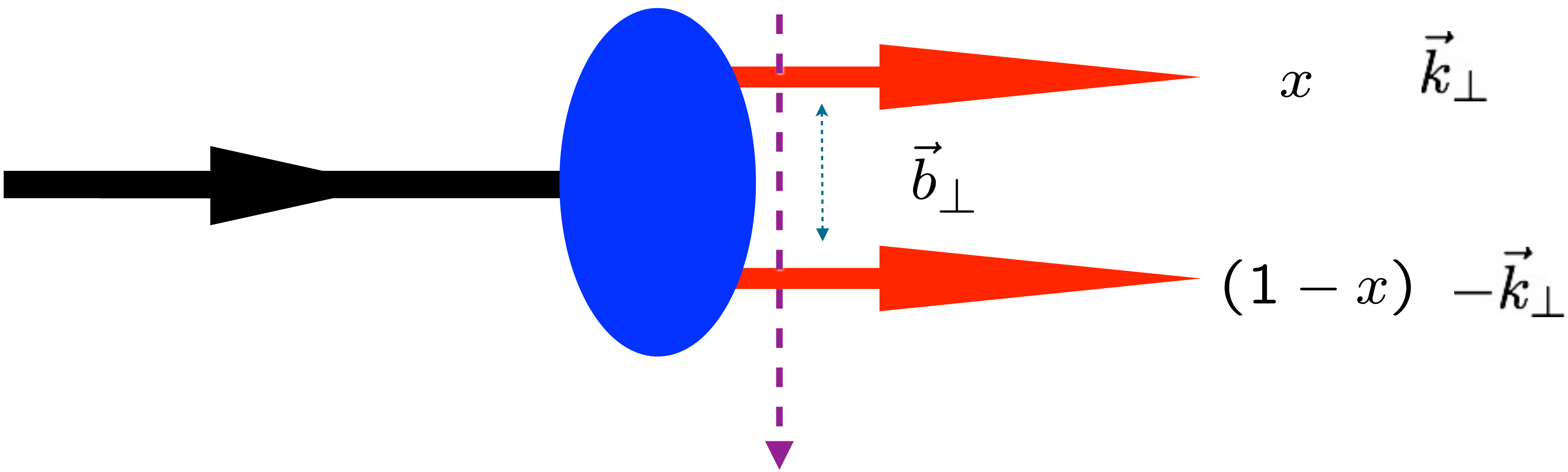
$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L+S-1)$$

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

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

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

QCD Lagrangian

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

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

Classical Chiral Lagrangian is Conformally Invariant

Where does the QCD Mass Scale come from?

QCD does not know what MeV units mean!
Only Ratios of Masses Determined

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

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

Unique confinement potential!

Need a First Approximation to QCD

Comparable in simplicity to Schrödinger Theory in Atomic Physics

Relativistic, Frame-Independent, Color-Confining

Origin of hadronic mass scale if m_q=0

Semi-Classical Approximation to QCD

AdS/QCD
Light-Front Holography
BLFQ

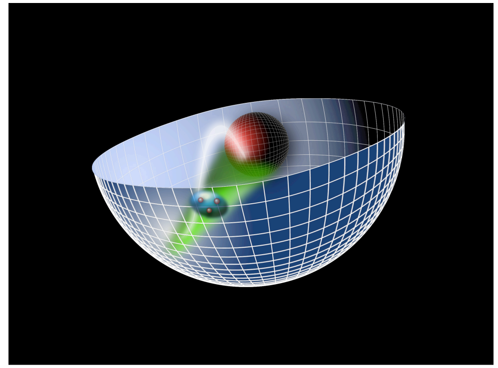
$\hbar \to 0$
(Hoyer)

de Tèramond, Dosch, sjb

AdS/QCD
Soft-Wall Model

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

Single scheme-independent fundamental mass scale



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

Light-Front Holography

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

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

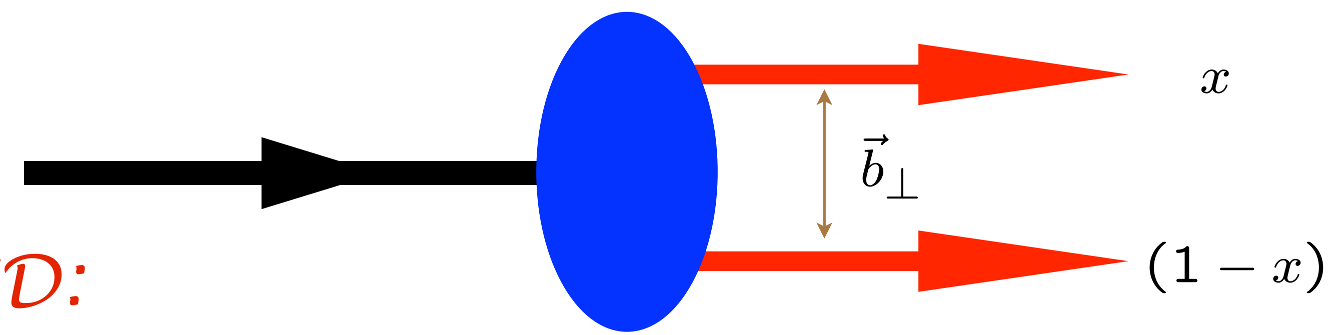
Relativistic LF single-variable radial equation for QCD & QED

Frame Independent!

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

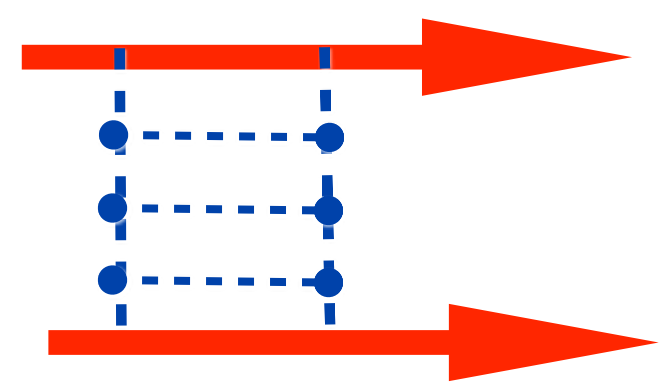
$$m_q \sim 0$$

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



AdS/QCD:

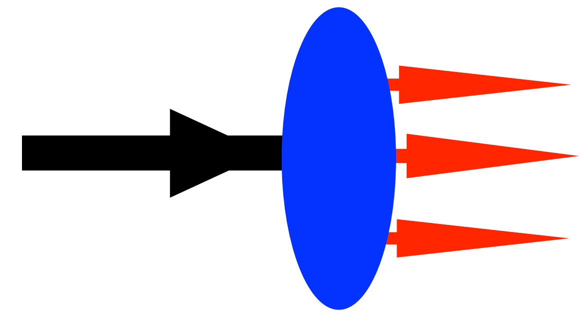
$$U(\zeta, S, L) = \kappa^2 \zeta^2 + \kappa^2 (L + S - 1/2)$$



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



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

- Hadron Spectroscopy and LF Dynamics
- Color Confinement Potential
- Running QCD Coupling $\alpha(Q^2)$ at All Scales Q^2
- What sets the QCD Mass Scale?
- Connection of Hadron Masses to $\Lambda_{\overline{MS}}$

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

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

- Color Confinement

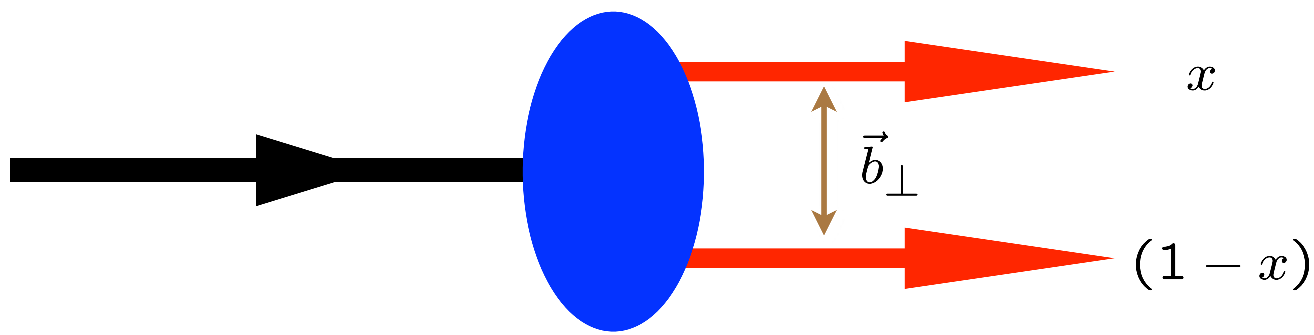
- Introduces confinement scale κ

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

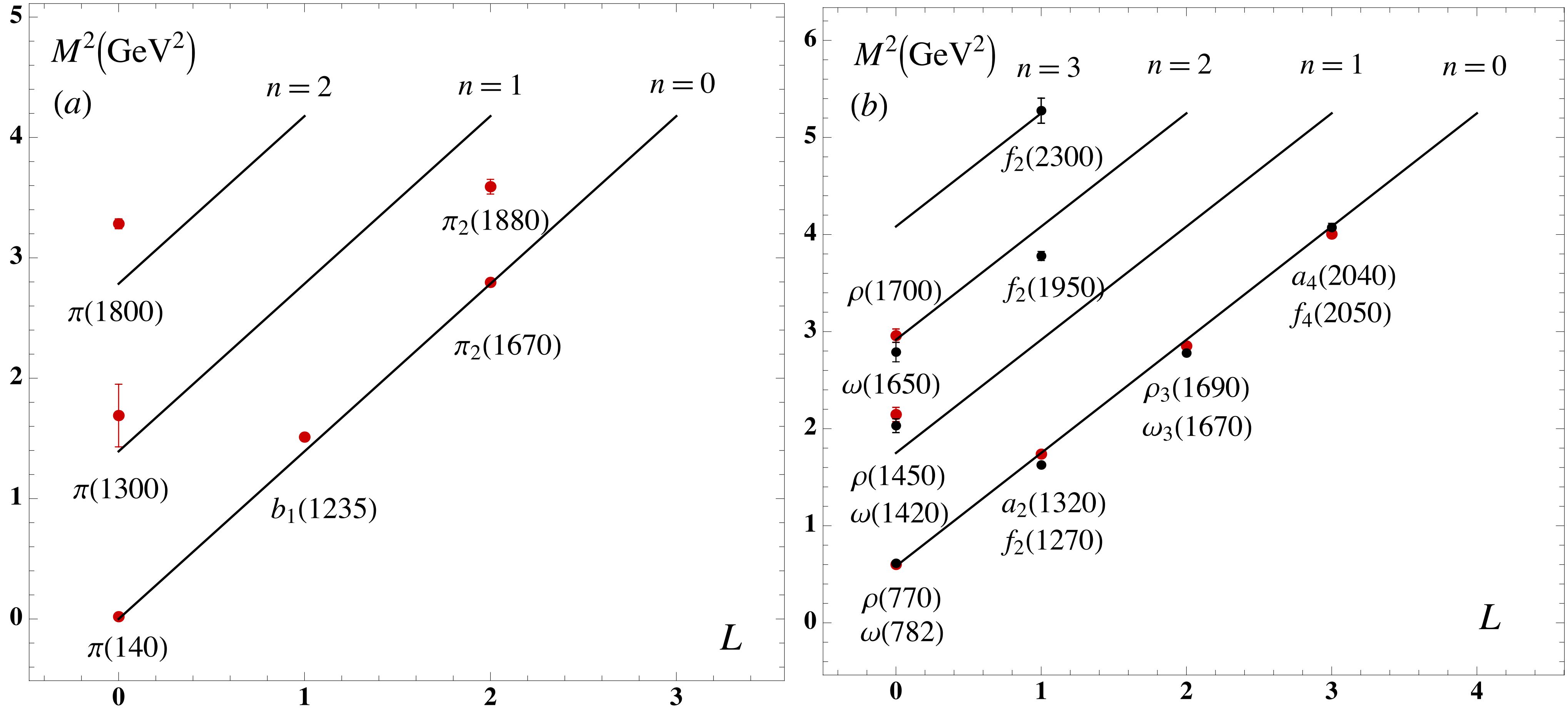
$$\phi_{n,L}(\zeta) = \kappa^{1+L}\sqrt{\frac{2n!}{(n+L)!}}\,\zeta^{1/2+L} e^{-\kappa^2\zeta^2/2} L_n^L(\kappa^2\zeta^2)$$

- Eigenvalues

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

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

Prediction from AdS/QCD



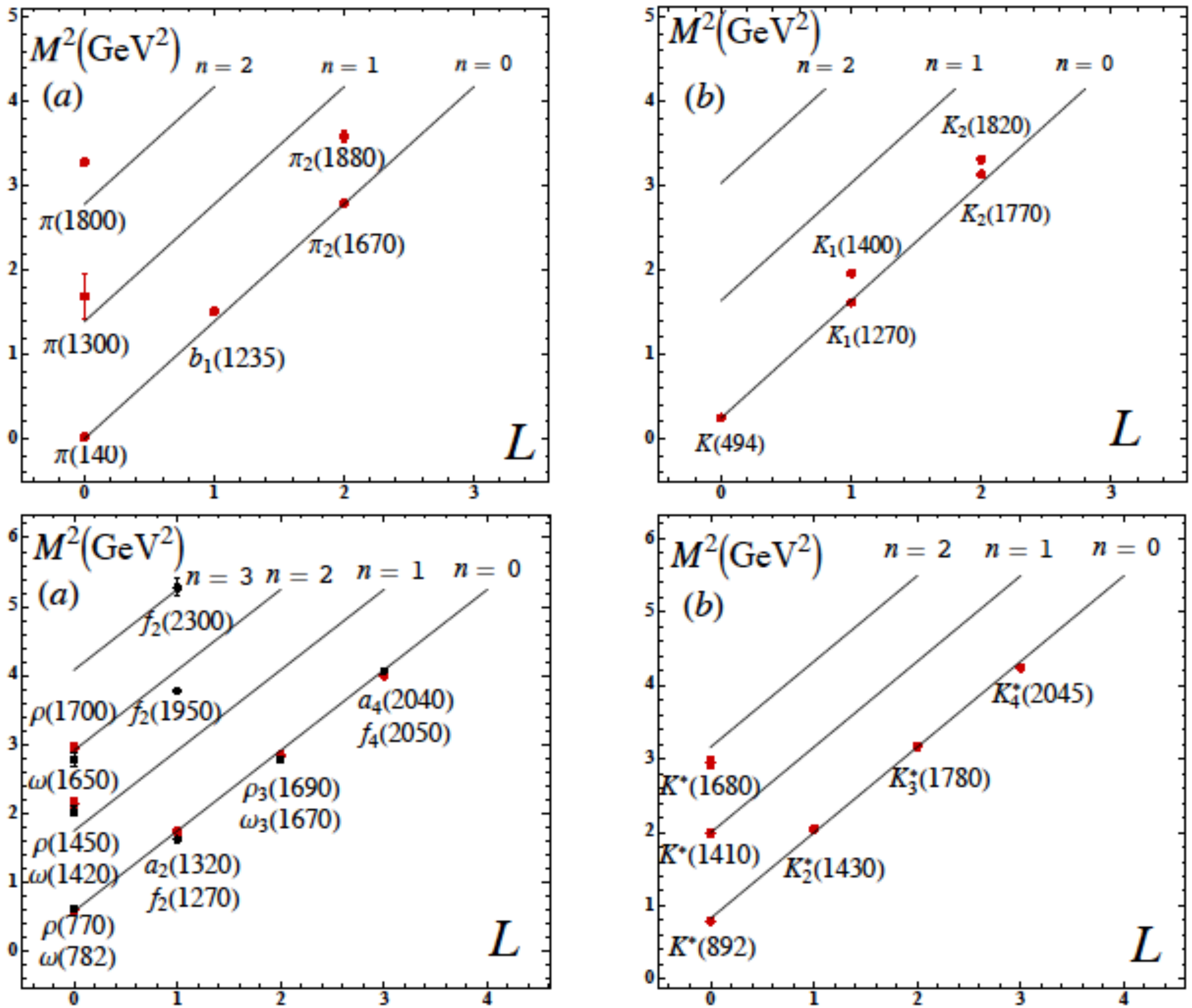
$$m_u = m_d = 0$$

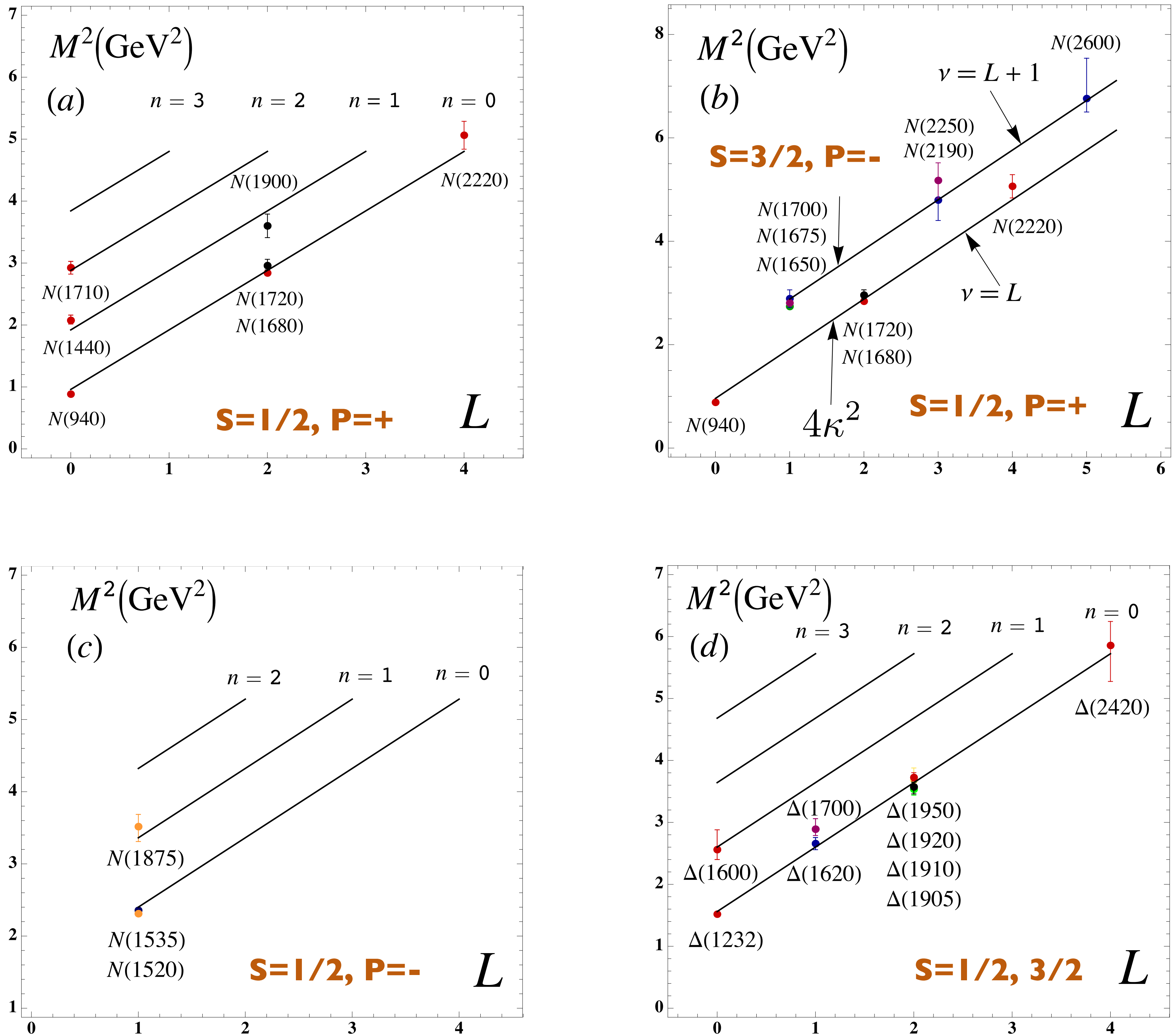
$$M^2(n, L, S) = 4\kappa^2(n + L + S/2)$$

De Tèramond, Dosch, sjb

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

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



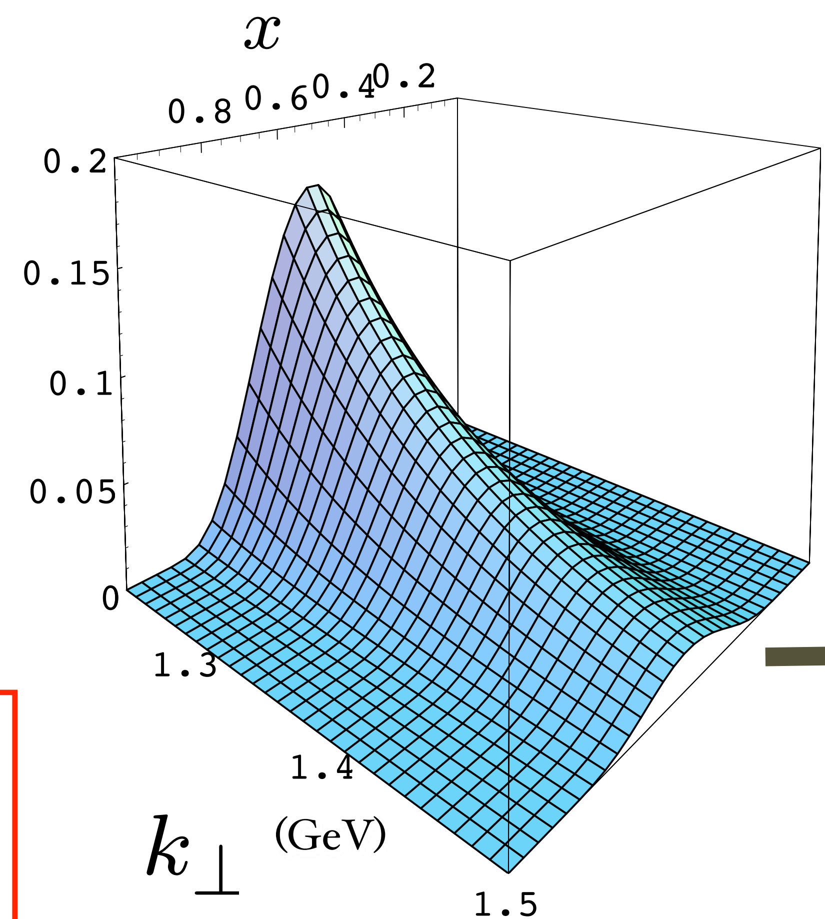


$M^2(\mathrm{GeV}^2)$
(a)
$n=3$ $n=2$ $n=1$ $n=0$
$N(1900)$
$N(2220)$
$N(1710)$
$N(1440)$
$N(1720)$
$N(1680)$
$N(940)$
S=1/2, P=+
L
$M^2(\mathrm{GeV}^2)$
(b)
$N(2600)$
$\nu = L+1$
$N(2250)$
$N(2190)$
S=3/2, P=-
$N(1700)$
$N(1675)$
$N(1650)$
$N(2220)$
$\nu = L$
$N(1720)$
$N(1680)$
$N(940)$
$4\kappa^2$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

Prediction from AdS/QCD: Meson LFWF

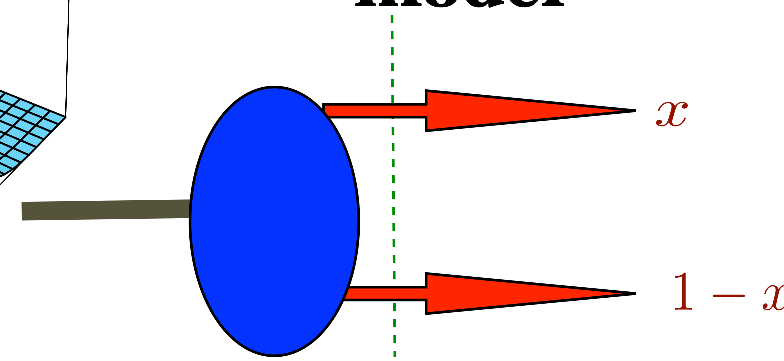
$$e^{\varphi(z)} = e^{+\kappa^2 z}$$

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



de Teramond, Cao, sjb

"Soft Wall" model



massless quarks

Note coupling

$$k_\perp^2, x$$

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

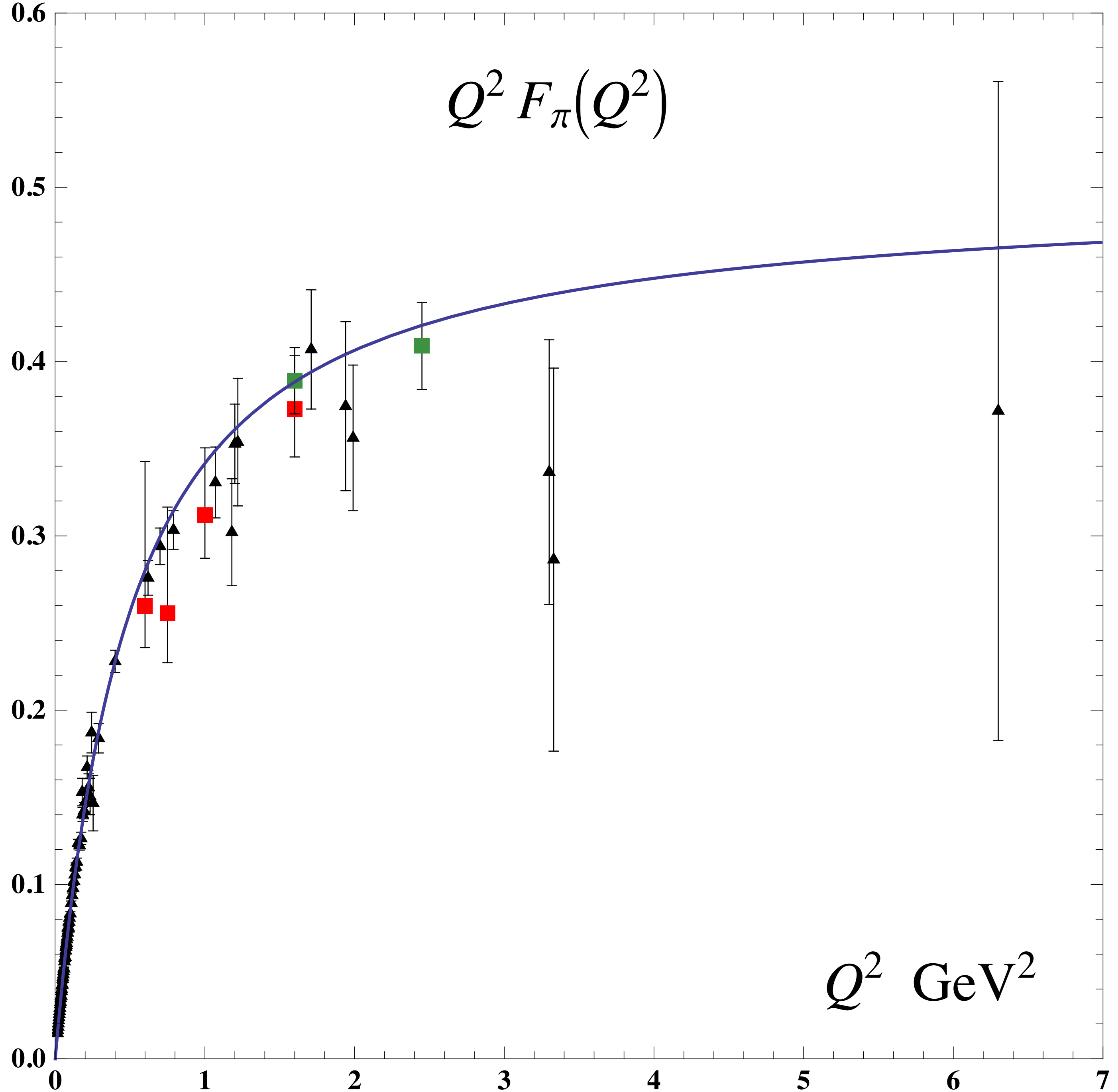
$$\boxed{\phi_\pi(x) = \frac{4}{\sqrt{3}\pi} f_\pi \sqrt{x(1-x)}}$$

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

Same as DSE!

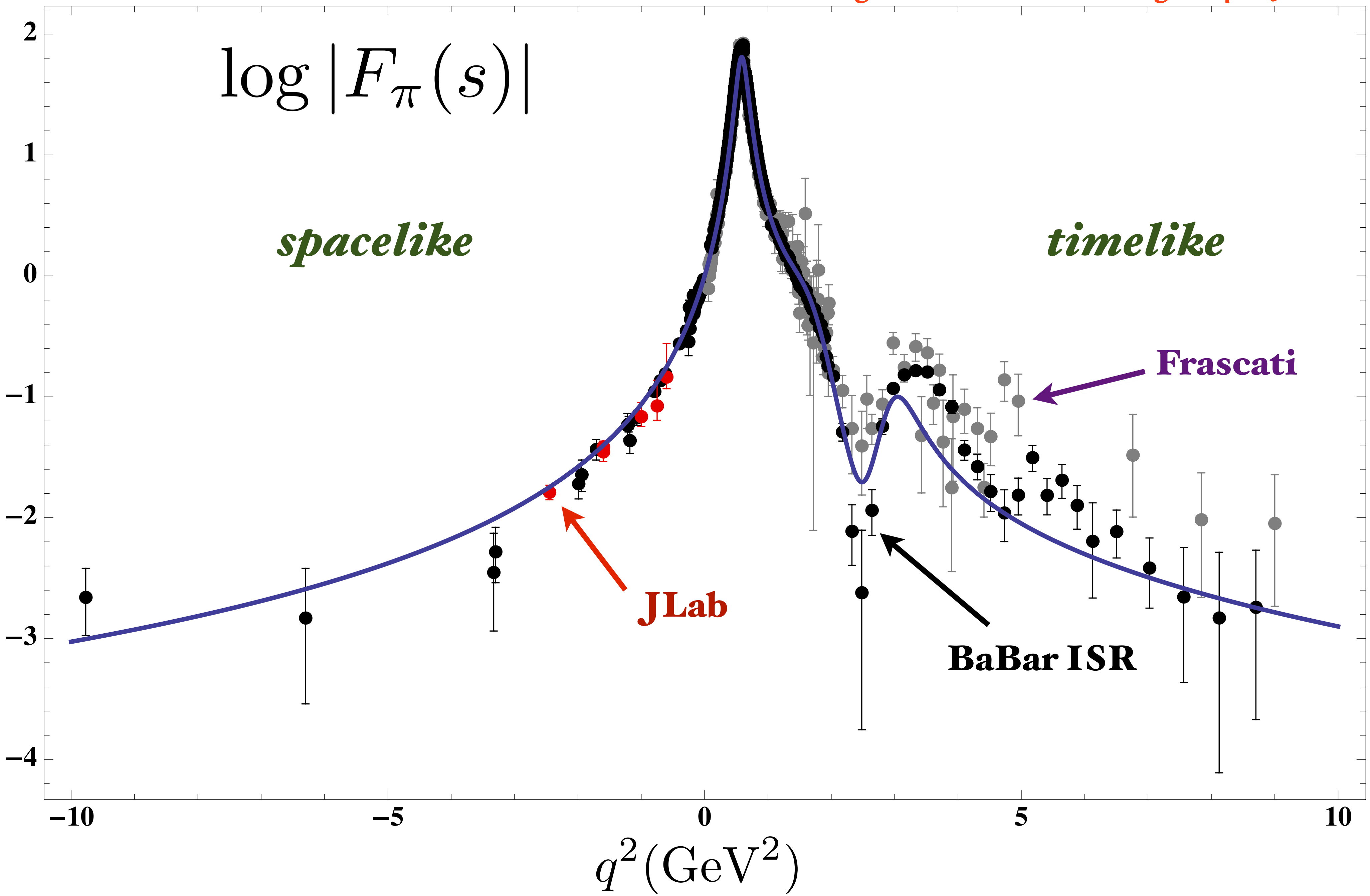
Provides Connection of Confinement to Hadron Structure

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

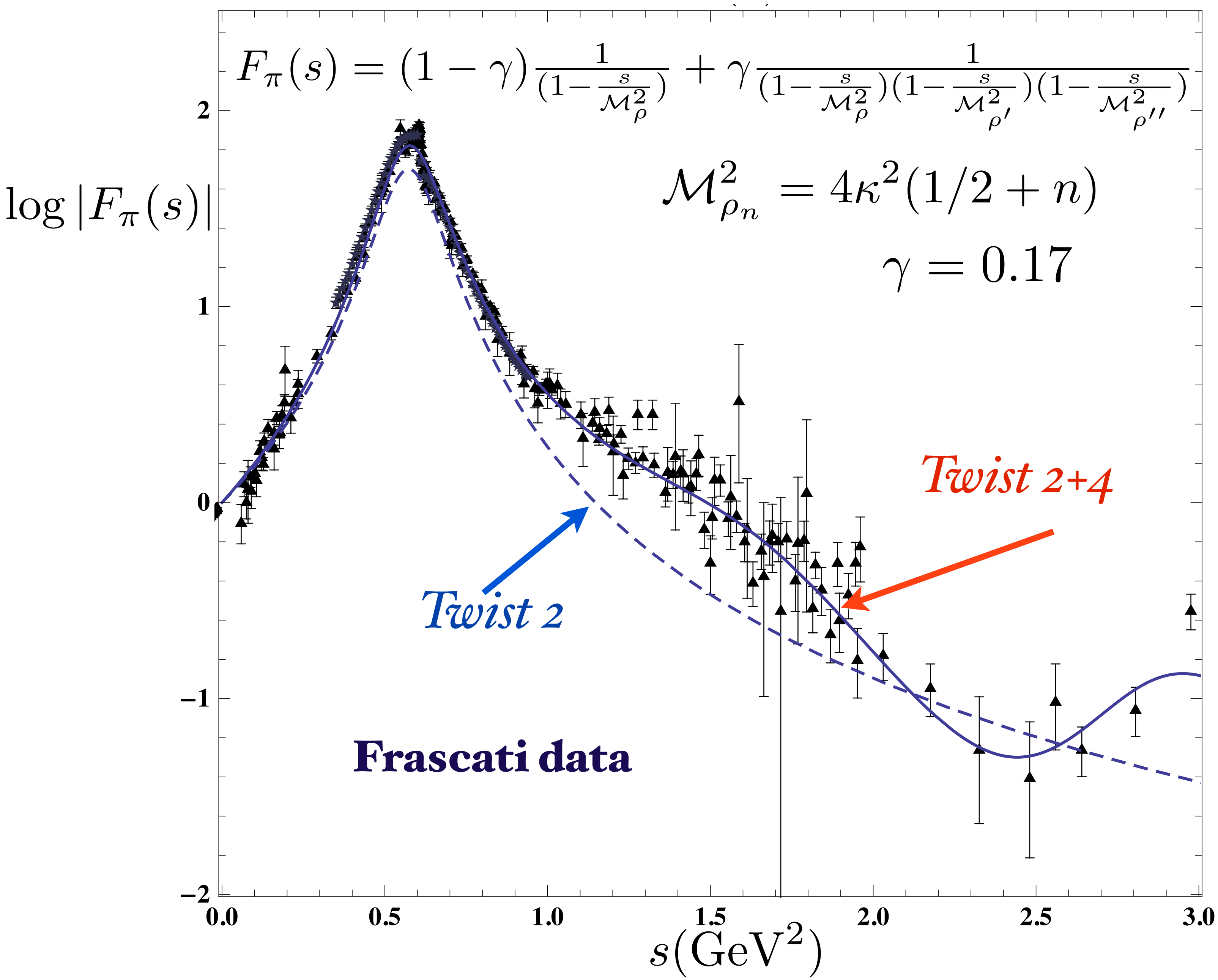


Counting Rules from Leading Twist Obeyed

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

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

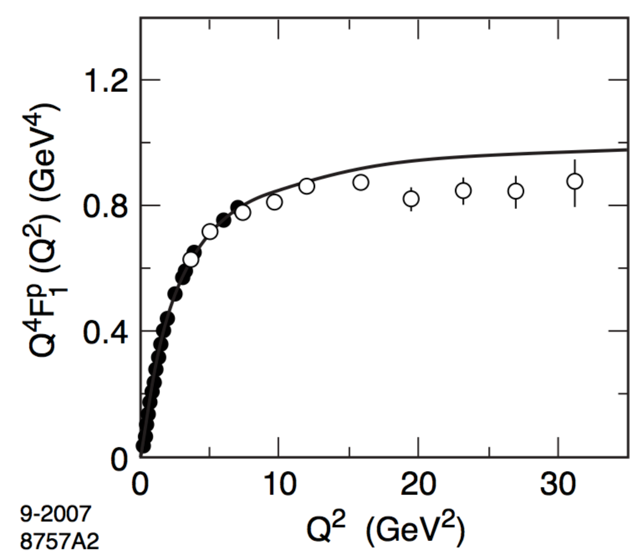
- Bulk-to-boundary propagator [Grigoryan and Radyushkin (2007)]

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

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



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

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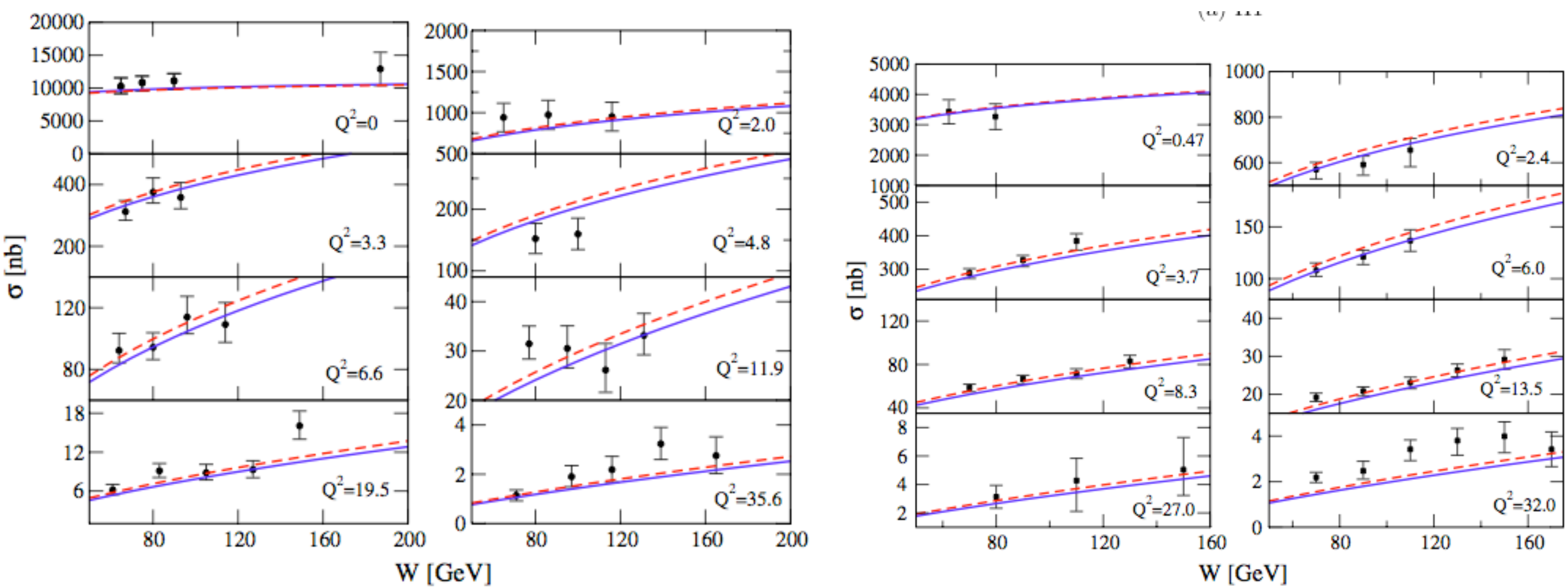
(Received 5 April 2012; published 20 August 2012)

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

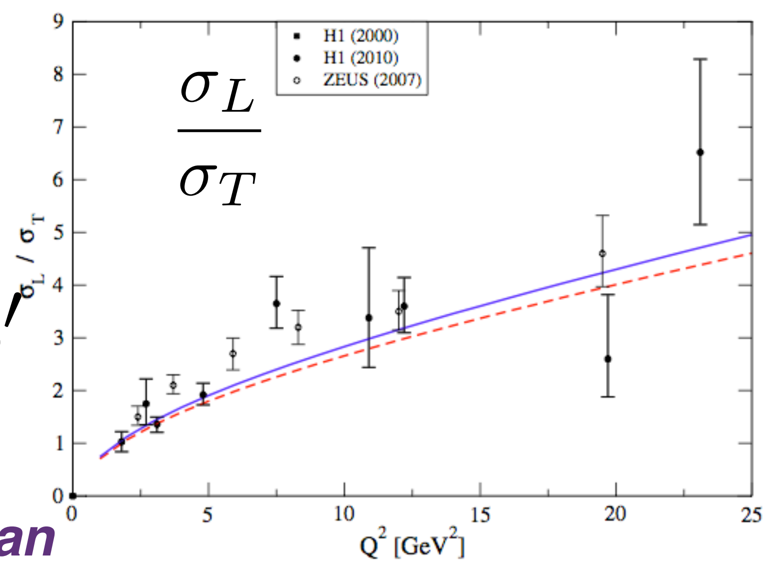
AdS/QCD Holographic Wave Function for the ρ Meson and Diffractive ρ Meson Electroproduction



(b) ZEUS

J. R. Forshaw, R. Sandapen

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



Prediction from Light-Front Holography

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

Nuclear effects: Sergey Gevorkyan

LF Holography

Baryon Equation

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

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

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

S=1/2, P=+

both chiralities

Meson Equation

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

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

Same κ!

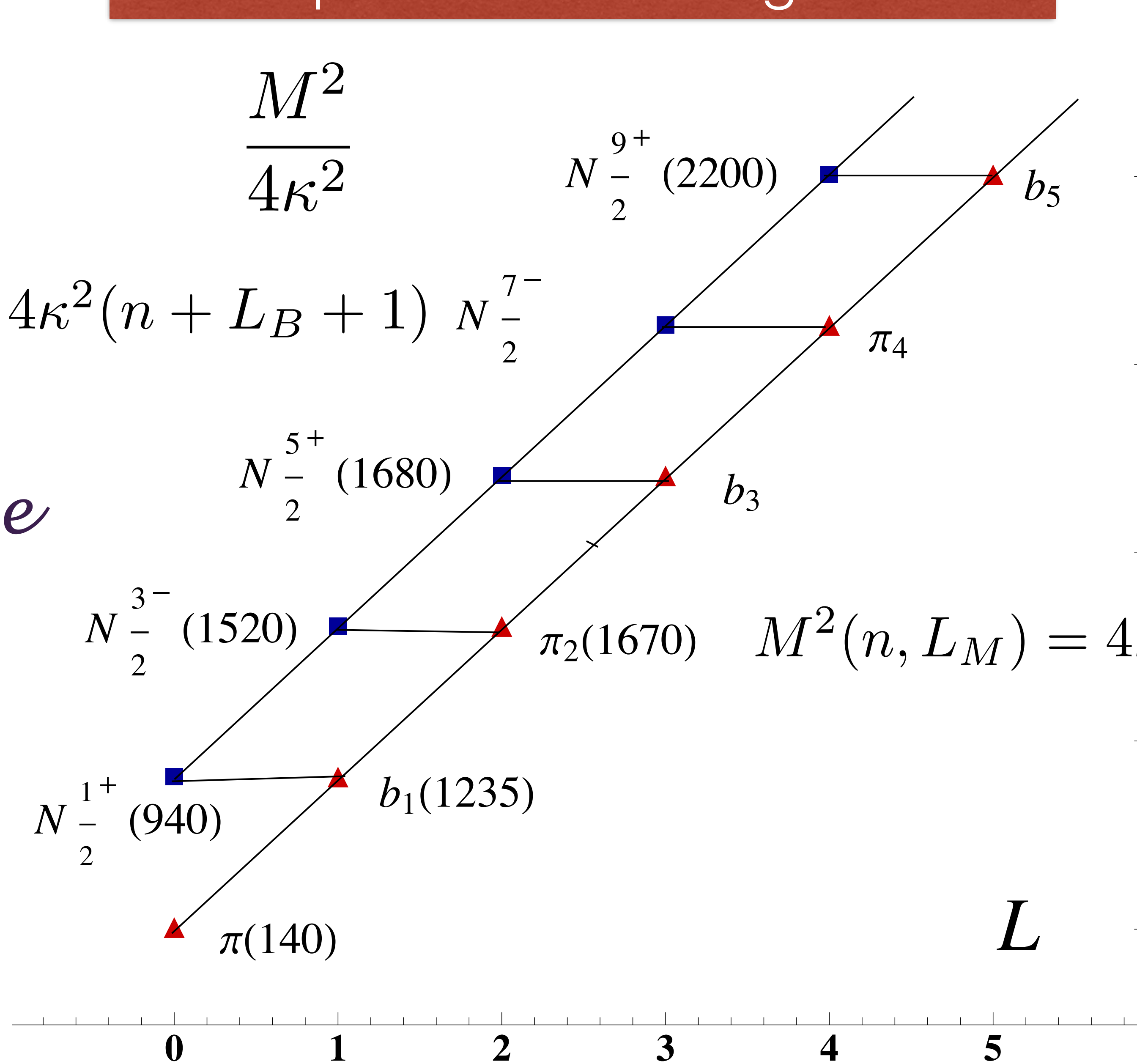
S=0, I=1 Meson is superpartner of S=1/2, I=1 Baryon

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

Superconformal Algebra

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

Same slope

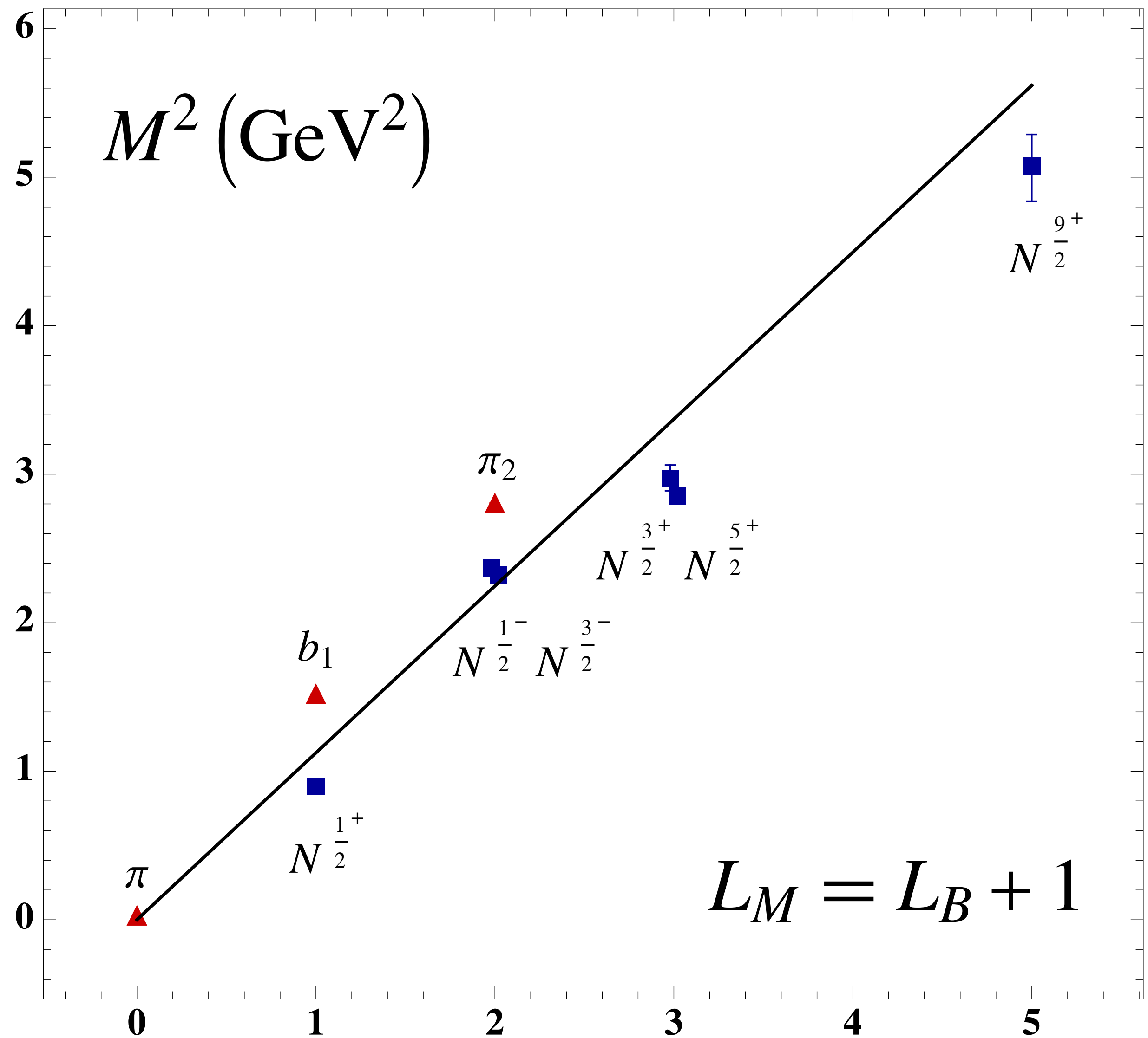


$$M^2(n, L_M) = 4\kappa^2(n + L_M)$$

Meson-Baryon Mass Degeneracy for L_M=L_B+1

Dosch, de Teramond, sjb

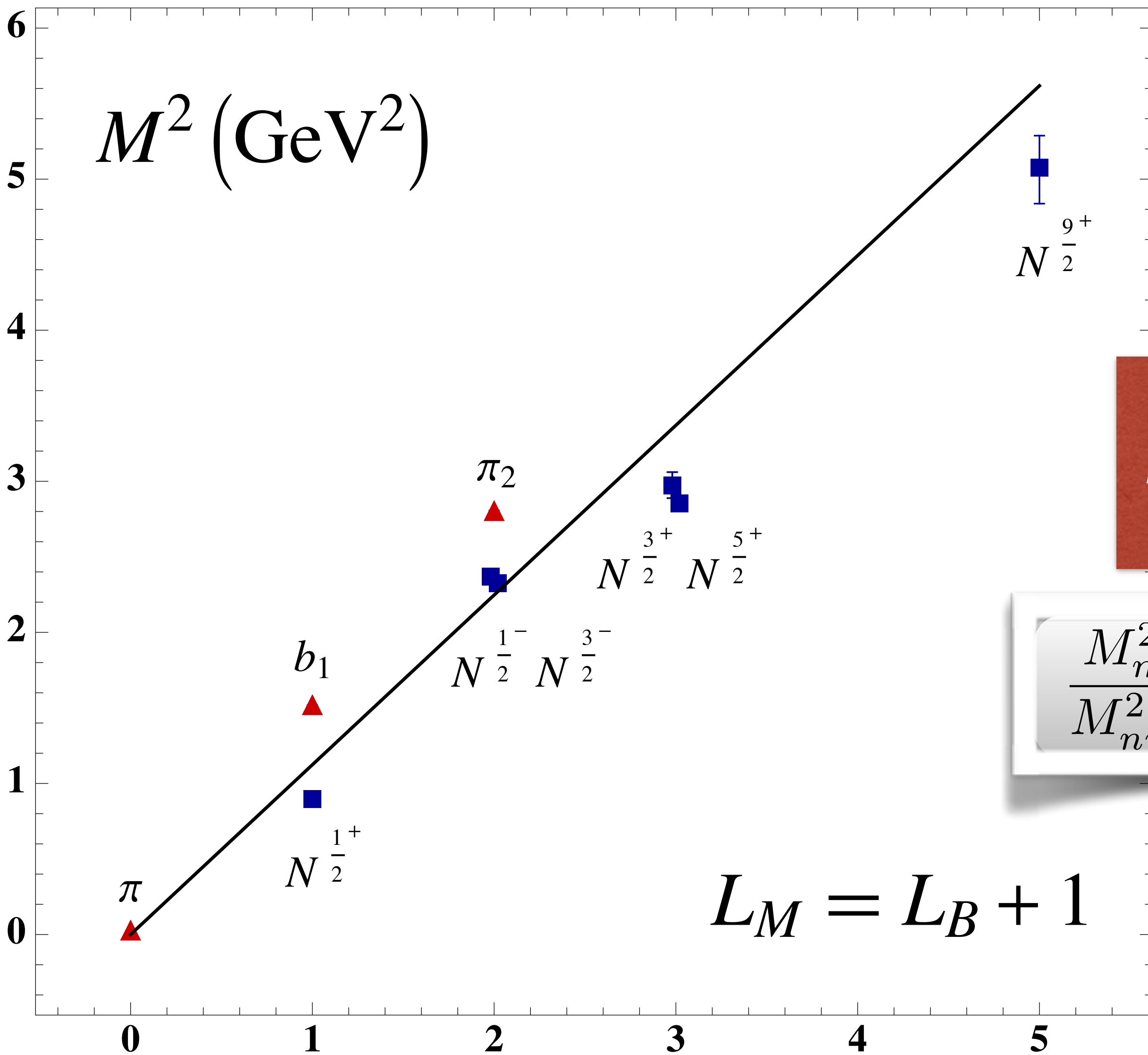
Superconformal AdS Light-Front Holographic QCD (LFHQCD): Identical meson and baryon spectra!



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

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

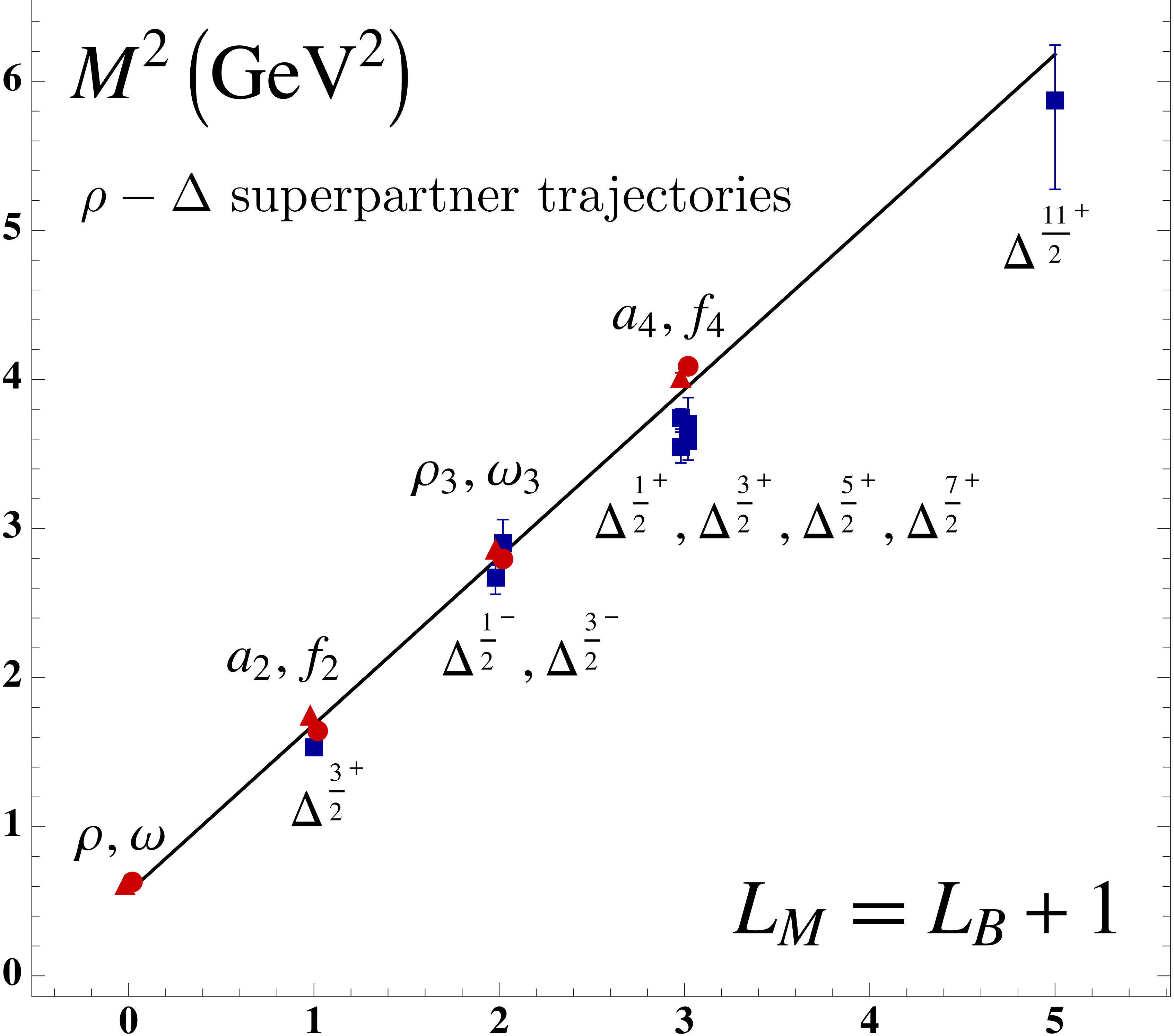
Superconformal AdS Light-Front Holographic QCD (LFHQCD): Identical meson and baryon spectra!



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

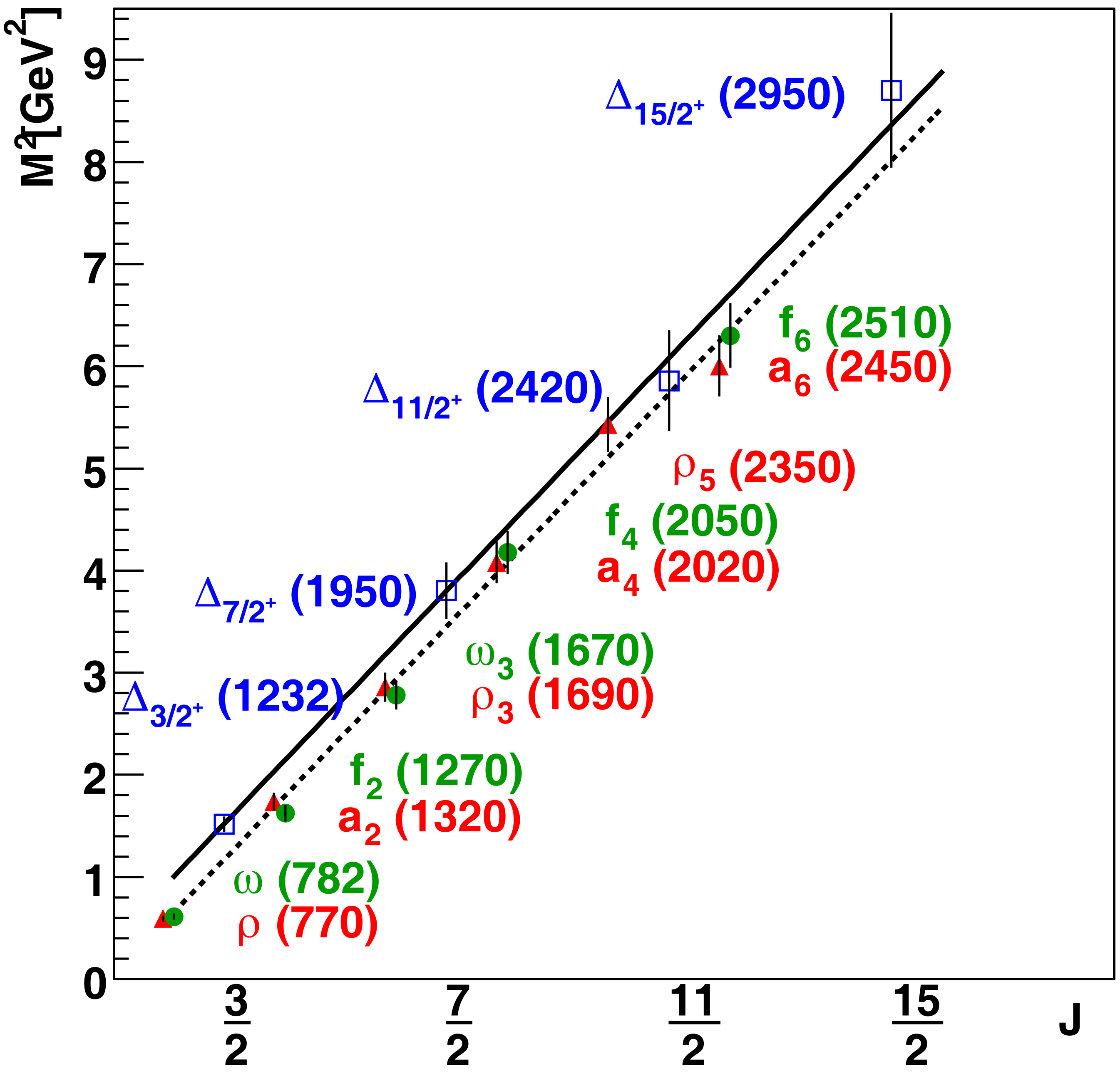
$$\frac{M^2_{meson}}{M^2_{nucleon}} = \frac{n + L_M}{n + L_B + 1}$$

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

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

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

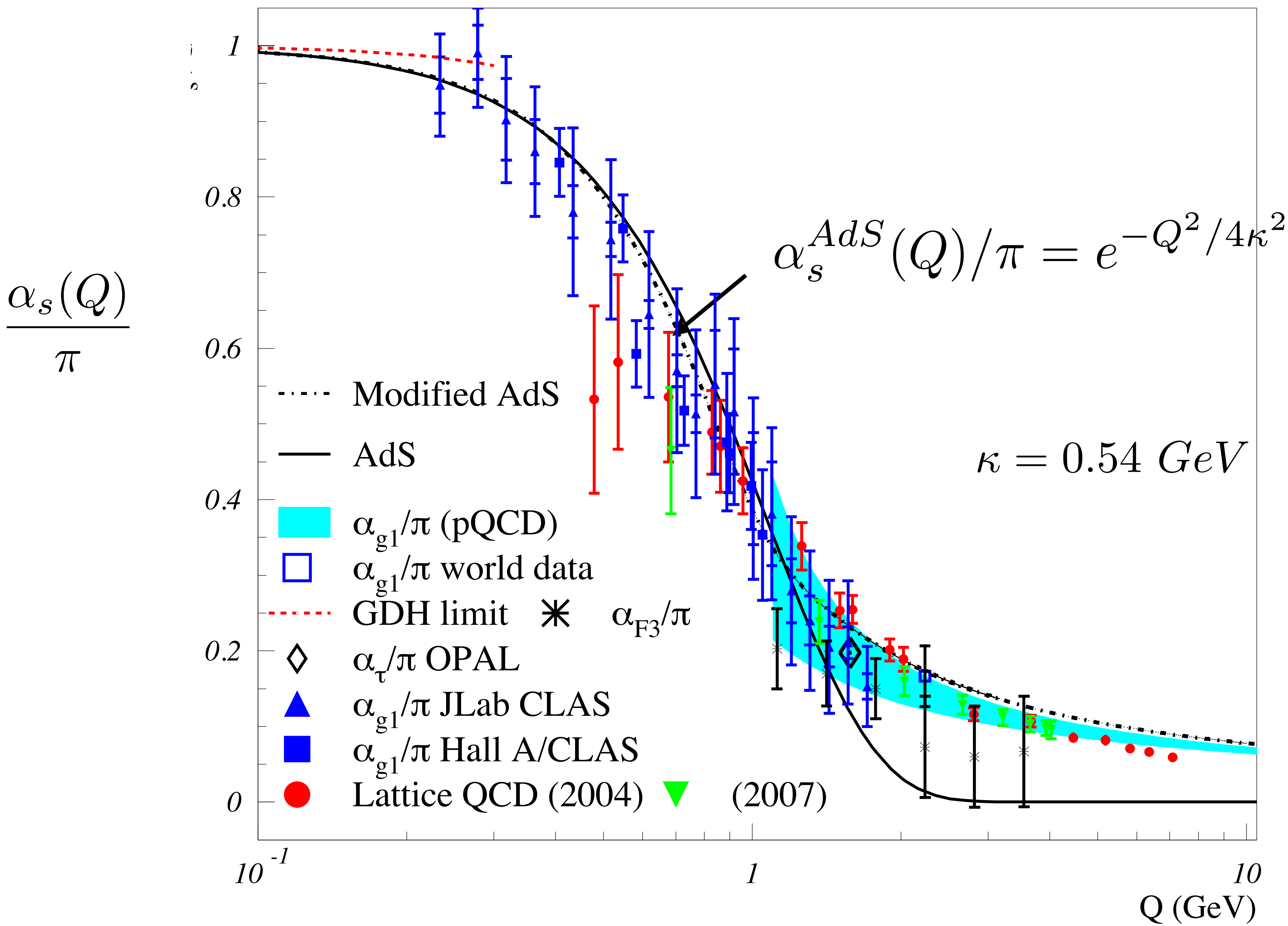
- Solution

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

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

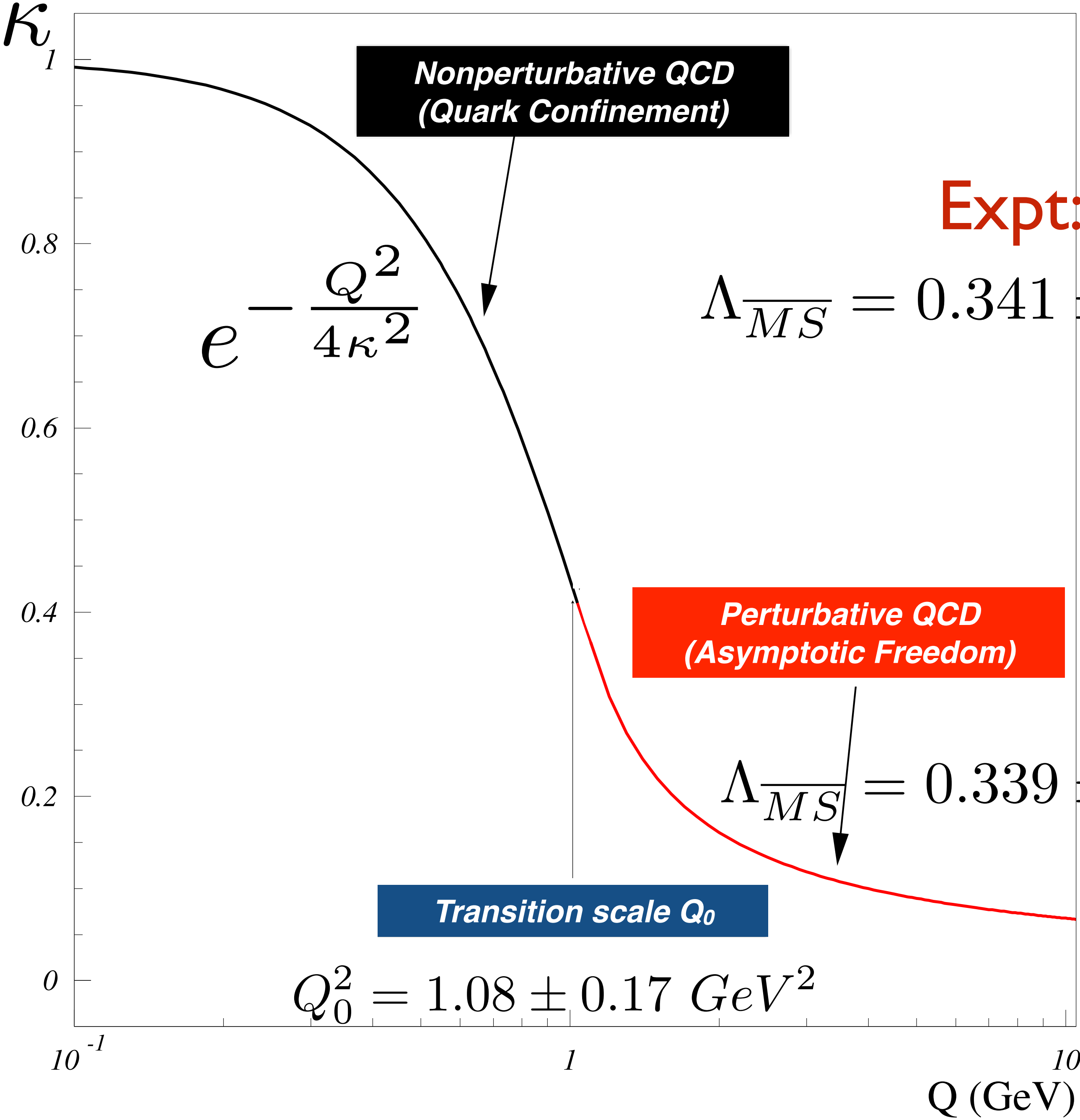
$$m_\rho = \sqrt{2}\kappa$$

$$m_p = 2\kappa$$

All-Scale QCD Coupling

Deur, de Tèramond, sjb

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



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

Expt:

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

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

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

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

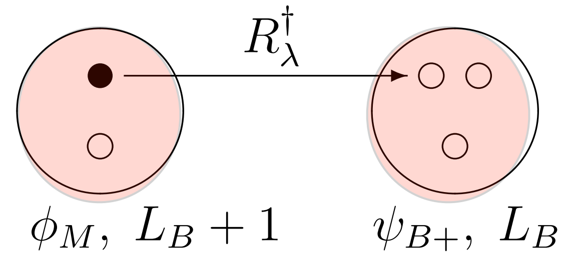
de Tèramond, Dosch, Lorce, sjb

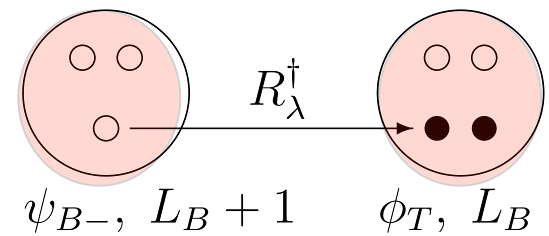
Superconformal Algebra

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 $\quad \lambda = \kappa^2$





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

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

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

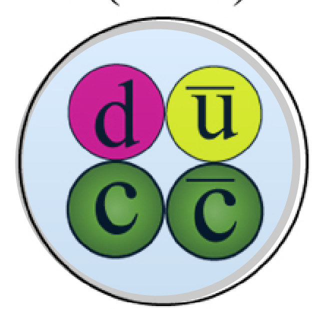
Complete Regge spectrum in n, L

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

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

Q= +2

Z(4430)



Q= - 1

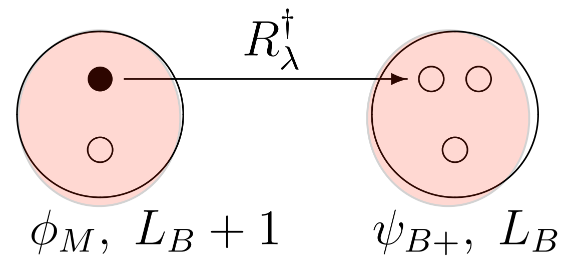
de Tèramond, Dosch, Lorce, sjb

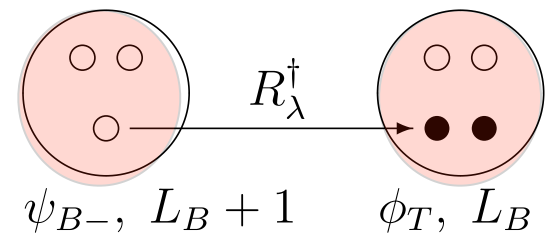
Superconformal Algebra

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 $\lambda = \kappa^2$





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

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

Universal Hadronic Decomposition

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

$\lambda = \kappa^2$

Equal: Virial Theorem

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

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

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

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

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

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

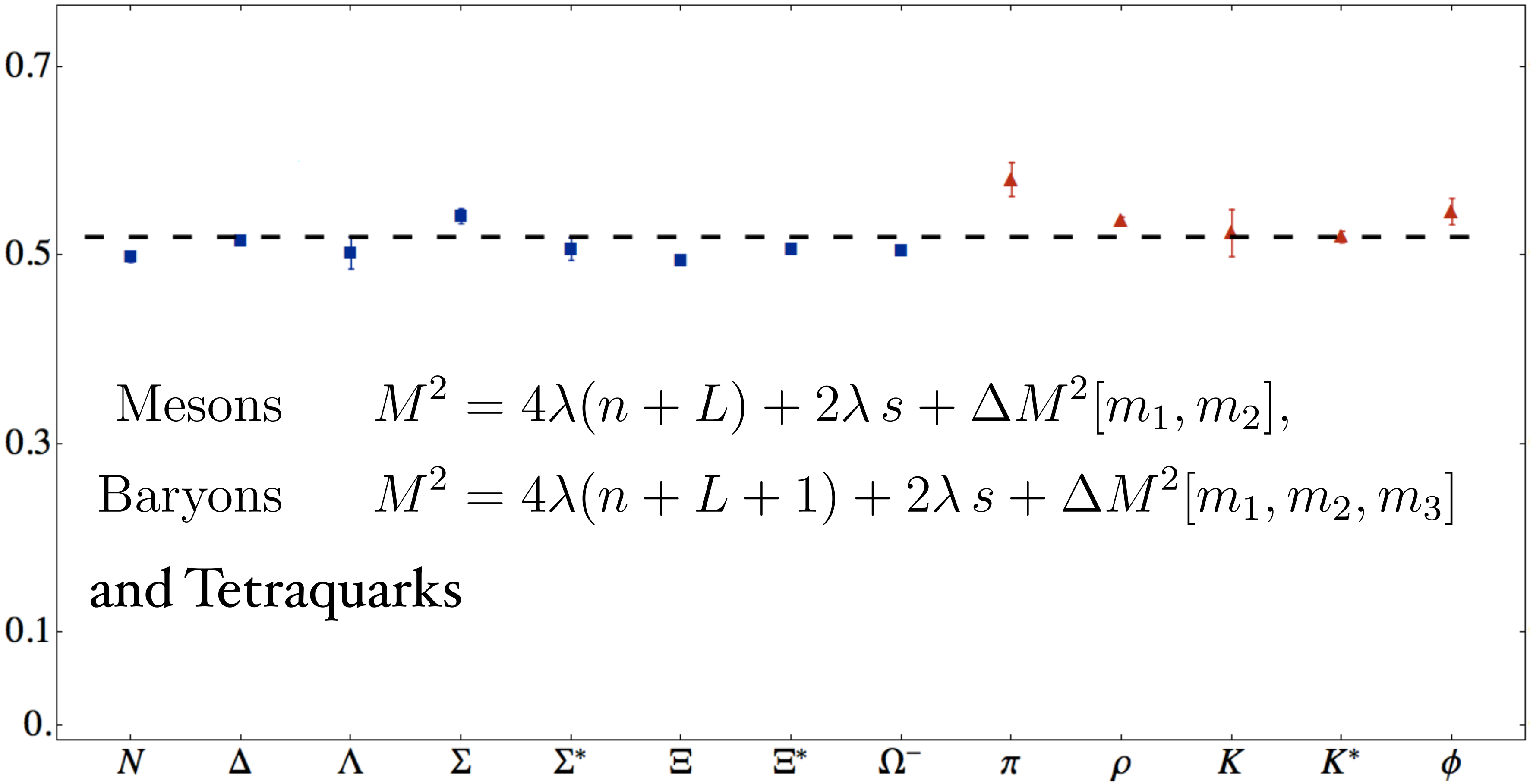
hyperfine spin-spin

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

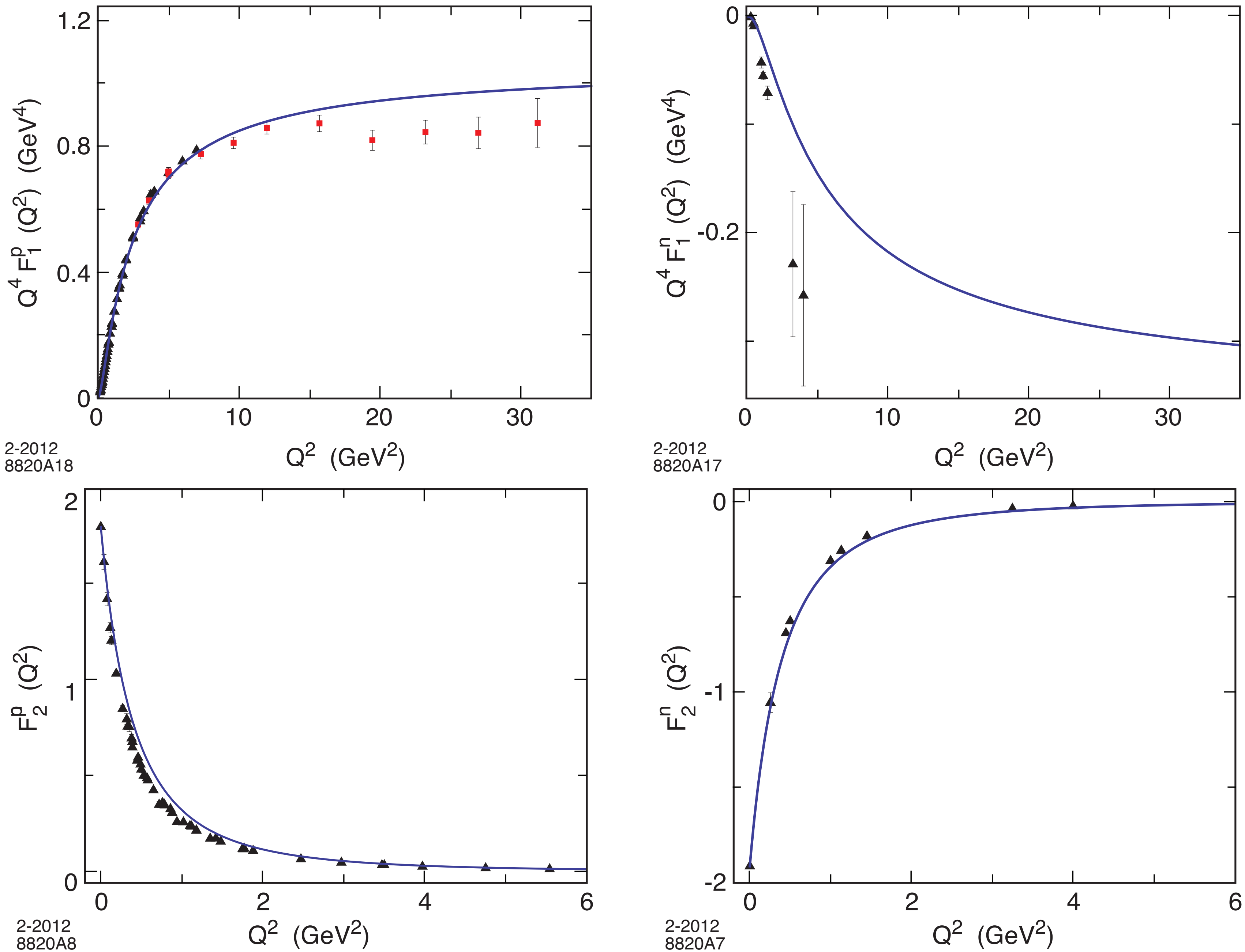
and Tetraquarks

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

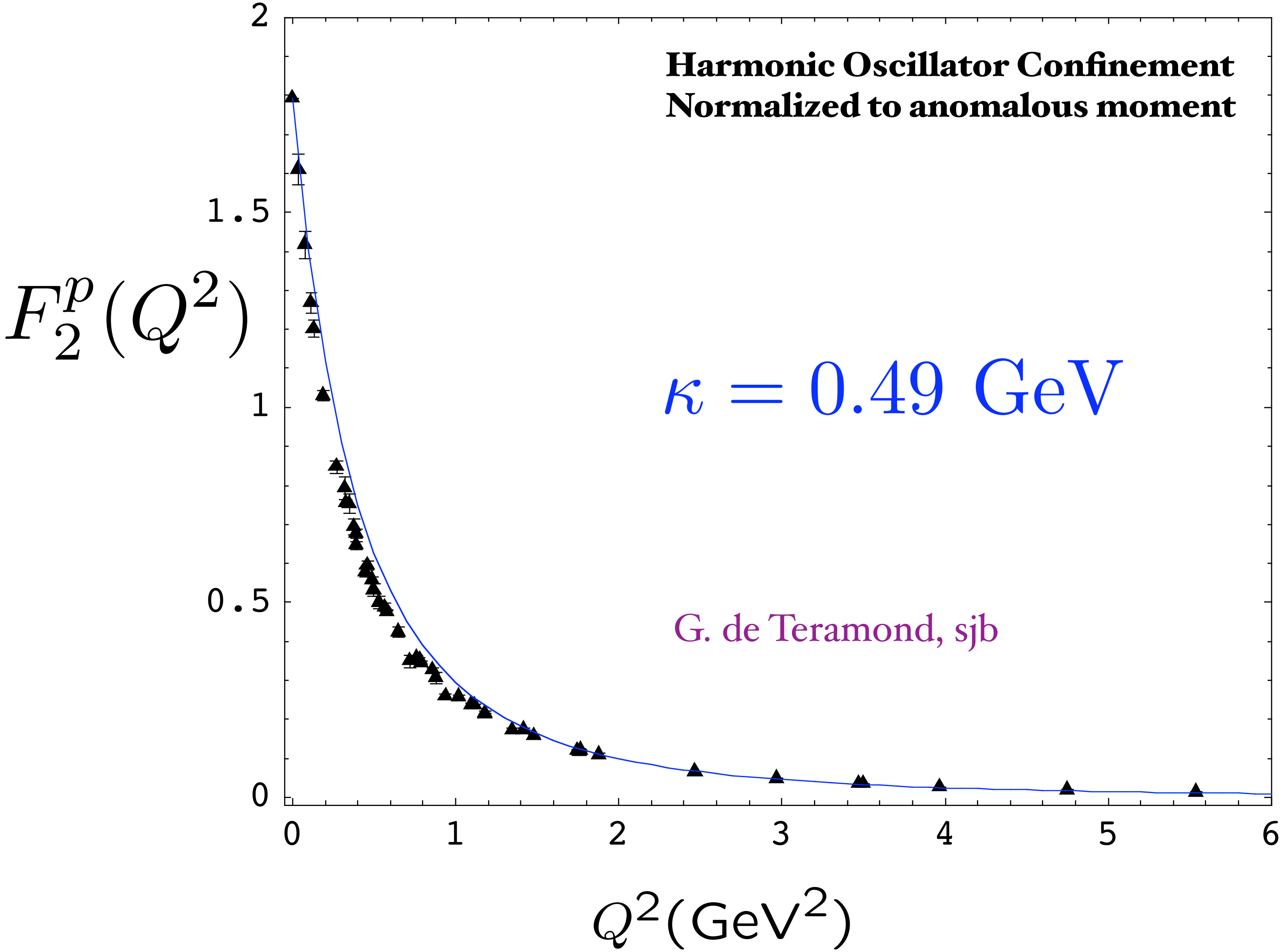
$$\kappa = \sqrt{\lambda}$$

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

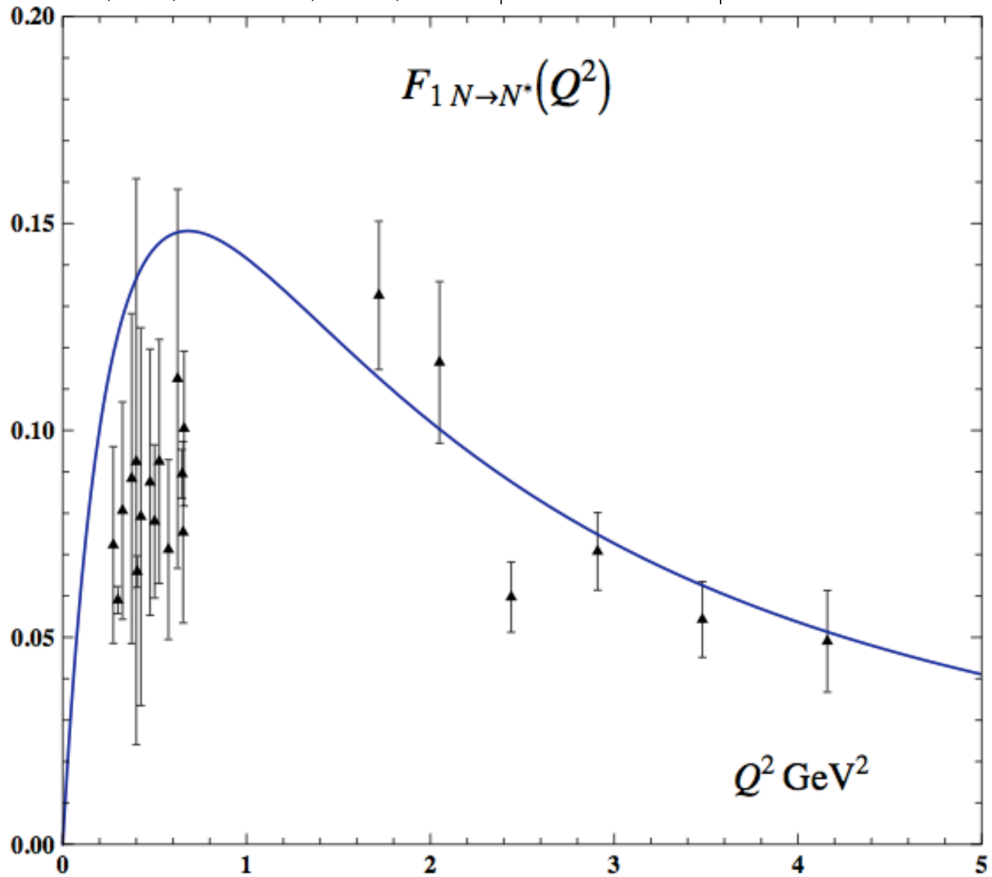


Spacelike Pauli Form Factor

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



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



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

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

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

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

- Regge Spectroscopy
- Same slope in n, L

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

- LFWFs, Distribution Amplitudes
- Form Factors, Structure Functions, GPDs

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

- Non-perturbative running coupling
- Meson-Baryon Supersymmetry for $L_M = L_B + 1$

$$\lambda = \kappa^2$$

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

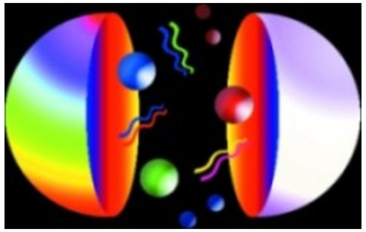
Tests of AdS/QCD and LF Holography JLab 12 GeV

- 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

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

- 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 $\varkappa$!

$\boxed{\text{Counting Rules Obeyed}}$

AdS/QCD and Light-Front Holography

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

- **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**

  $[Q^2]^{n-1} F(Q^2) \rightarrow \mathrm{const}$
- **Space-like and Time-like Meson and Baryon Form Factors**
- **Running Coupling for NPQCD** $\quad \alpha_s(Q^2) \propto e^{-\frac{Q^2}{4\kappa^2}}$
- **Meson Distribution Amplitude** $\quad \phi_\pi(x) \propto f_\pi \sqrt{x(1-x)}$

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?:** $[qq]_{\bar{3}C}[\bar{q}\bar{q}]_{3C}$

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

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.

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

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

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."

$$(m_q = 0)$$
$$m_\pi = 0$$

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

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

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 $\Lambda_{\overline{MS}}$

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 ...

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

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

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

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

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

$Conformal\ Series$

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

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

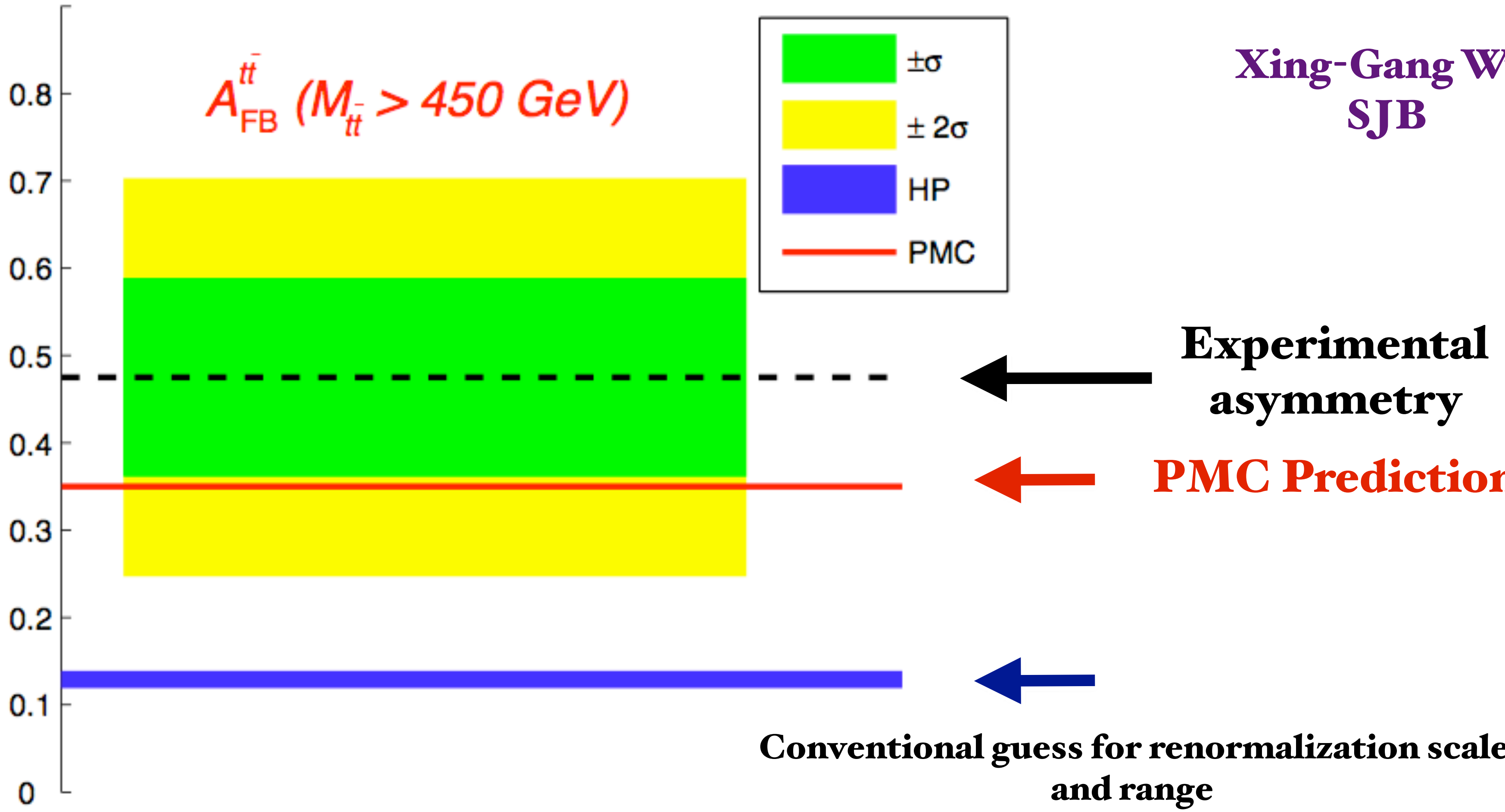
Eliminates unnecessary systematic uncertainty

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)



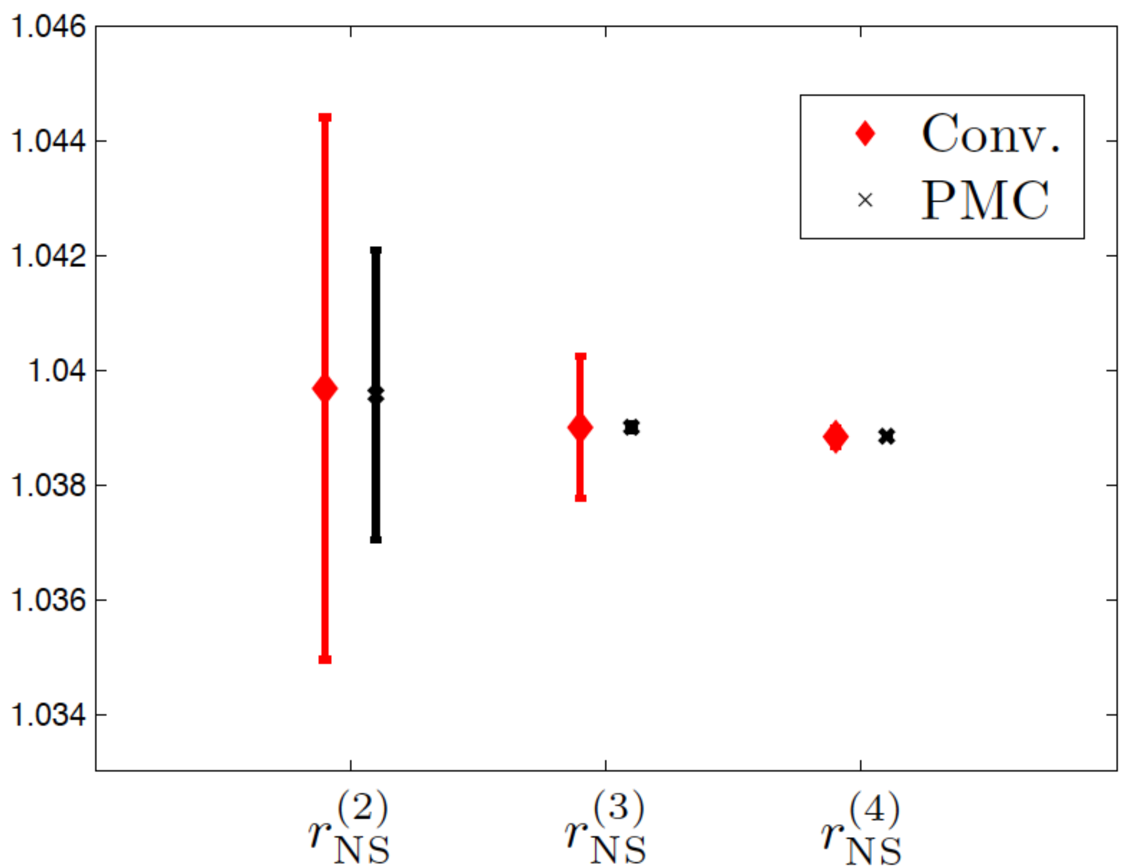
Xing-Gang Wu
SJB

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

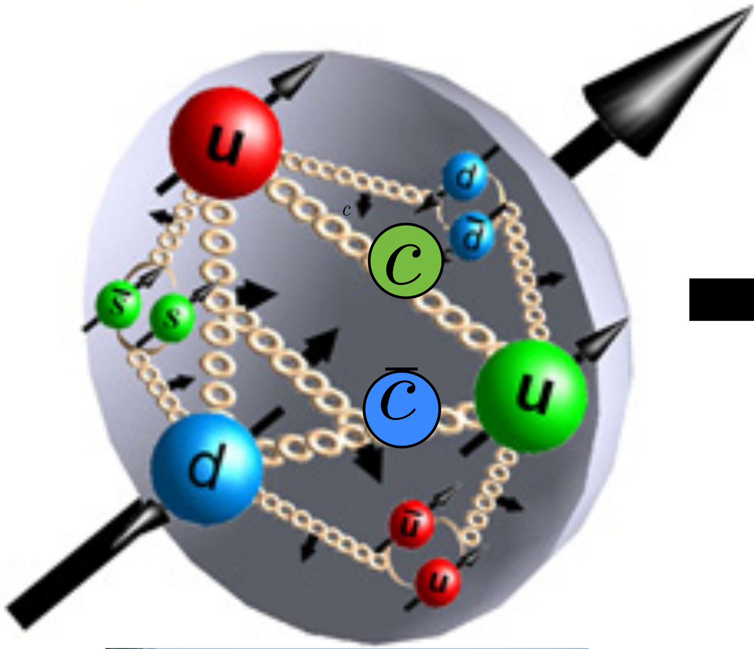
S-Q Wang, X-G Wu, sjb

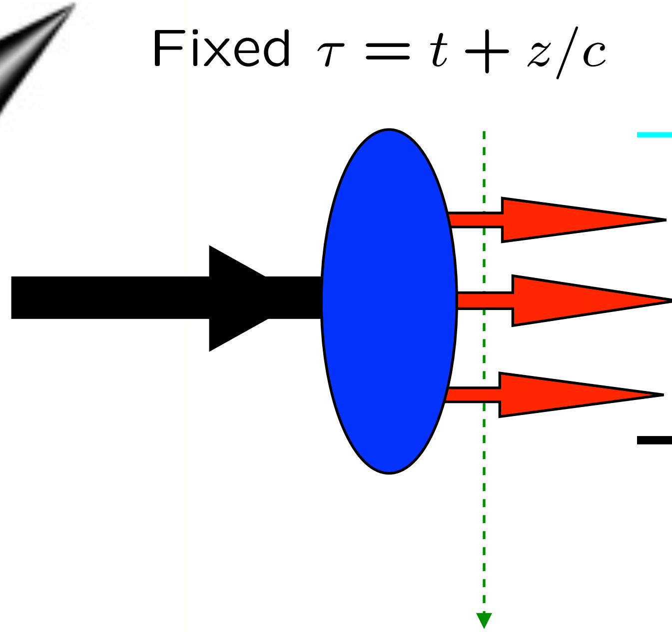
P.A. Baikov, K.G. Chetyrkin, J.H. Kuhn, and J. Rittinger, Phys. Rev. Lett. 108, 222003 (2012).

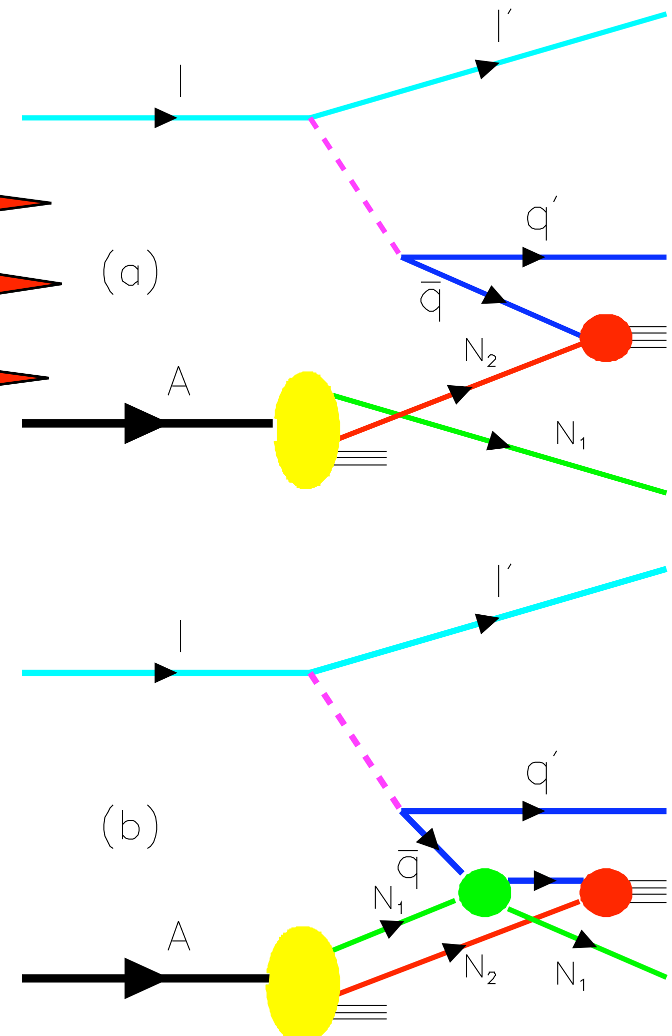


The values of $r_{\rm NS}^{(n)} = 1 + \sum_{i=1}^{n} C_i^{\rm NS} a_s^i$ and their errors $\pm|C_n^{\rm NS} a_s^n|_{\rm MAX}$. The diamonds and the crosses are for conventional (Conv.) and PMC scale settings, respectively. The central values assume the initial scale choice $\mu_r^{\rm init} = M_Z$.

Novel QCD Features of Hadrons and Nuclei







Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

with Guy de Tèramond, Hans Günter Dosch, Cedric Lorce, Kelly Chiu, and Alexandre Deur

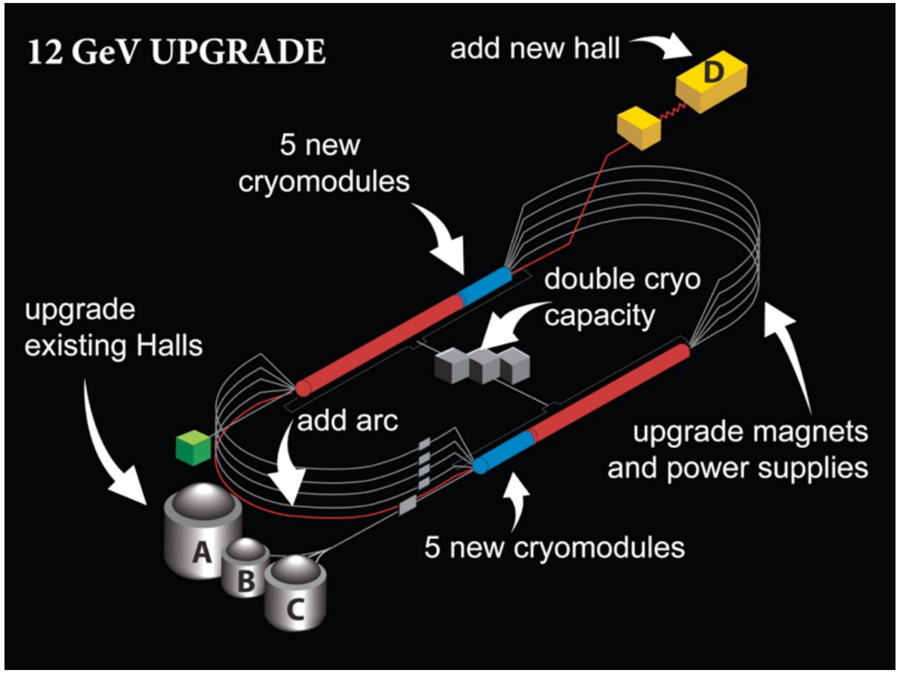
CDR QCD: Partons and Nuclei **Orsay** **June 1, 2017**

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

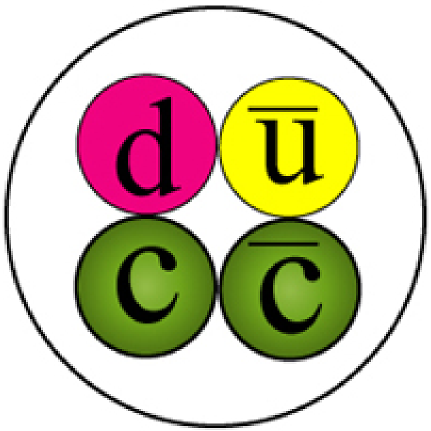
- *Intrinsic Heavy Quarks*
- *Charm at Threshold*
- *Novel Heavy Quark Resonances at Threshold*
- *Nuclear-Bound Quarkonium*
- *Exclusive and Inclusive Sivers Effect.*
- *Breakdown of pQCD Leading-Twist Factorization*
- *Non-universal antishadowing*
- *Hidden Color*
- *J=0 Fixed pole in DVCS*

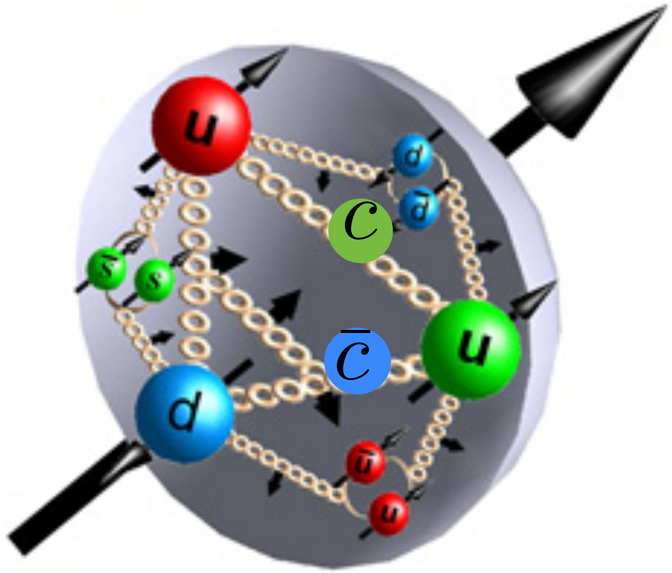


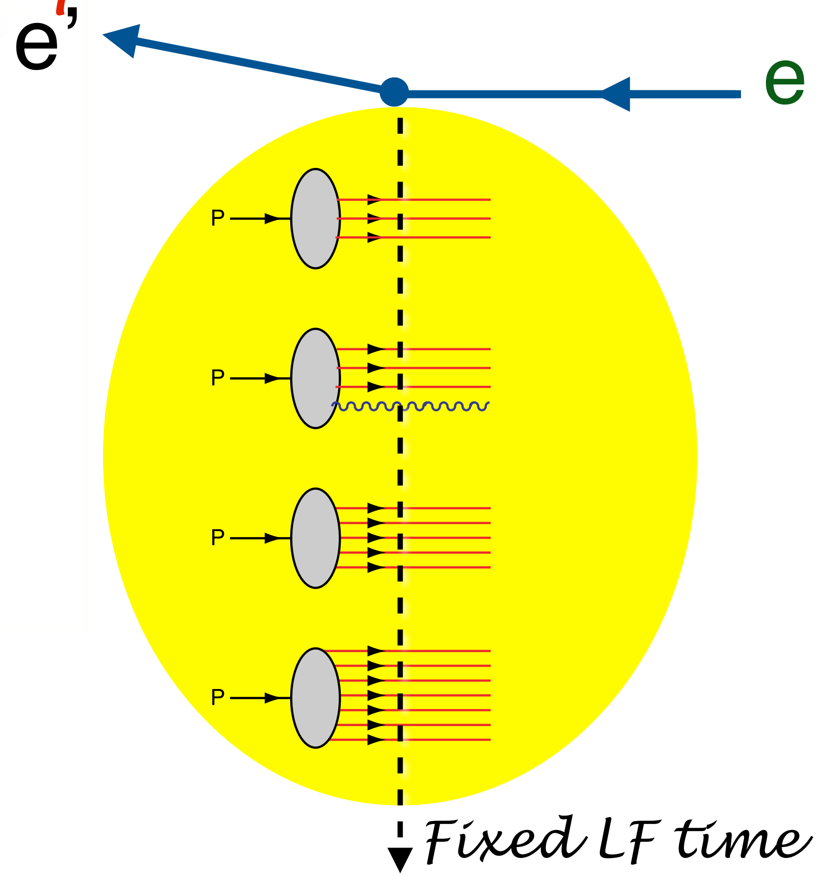
Illuminate New Hadronic Physics

Novel QCD Phenomena in Nuclear Photo - and Electroproduction

Exotic Hadrons







$\tau = t + z/c$

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Jefferson Lab

April 29, 2016