QCD Phenomenology and Nucleon Structure

Stan Brodsky, SLAC

Lecture IV

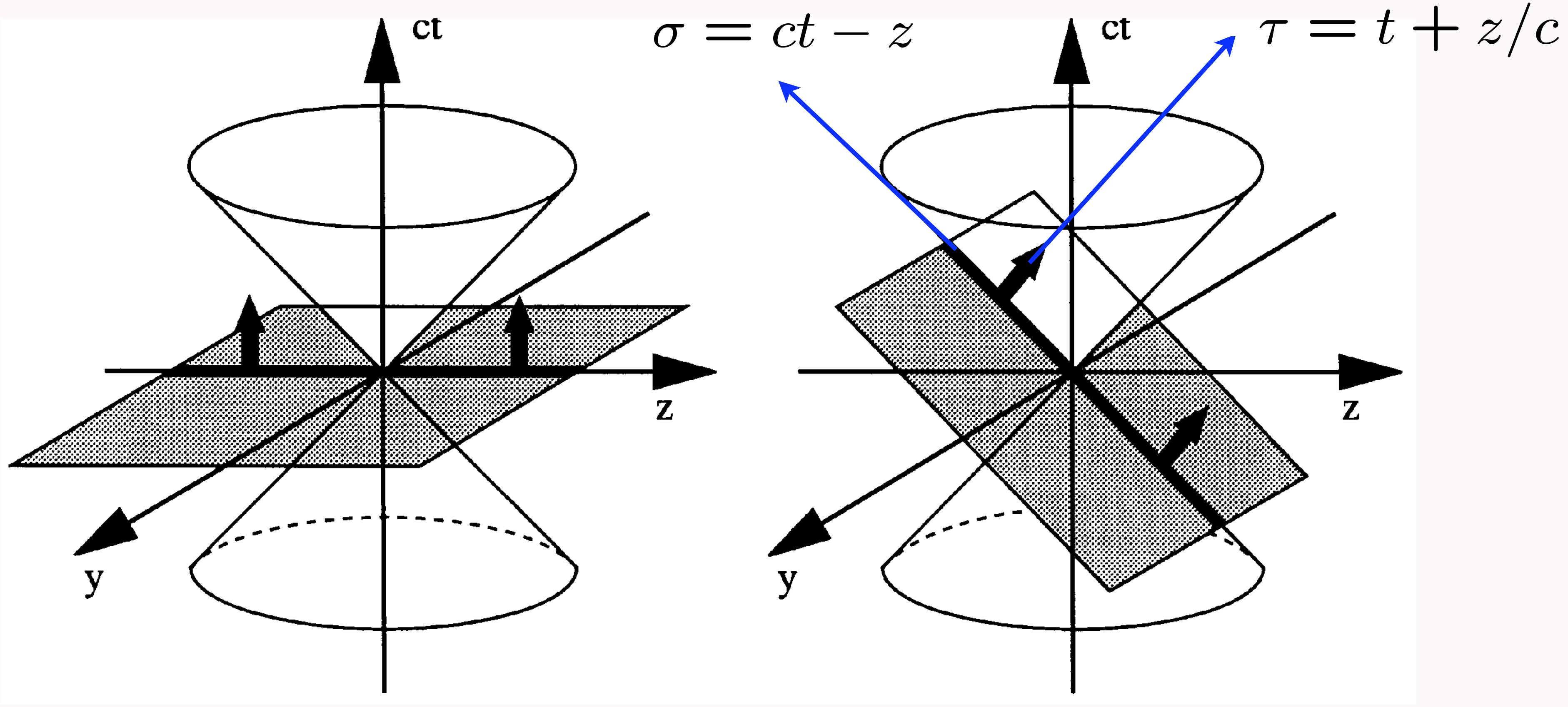
National Nuclear Physics Summer School

Hadron Dynamics at the Amplitude Level

- DIS studies have primarily focussed on probability distributions: integrated and unintegrated.
- Test QCD at the amplitude level: Phases, multi-parton correlations, spin, angular momentum, exclusive amplitudes
- Impact of ISI and FSI: Single Spin Asymmetries, Diffractive Deep Inelastic Scattering, Shadowing, Antishadowing
- Wavefunctions on the light front: fundamental QCD dynamics of hadrons, nuclei
- Remarkable new insights from AdS/CFT, the duality between conformal field theory and Anti-de Sitter Space

Dirac's Amazing Idea: The "Front Form"

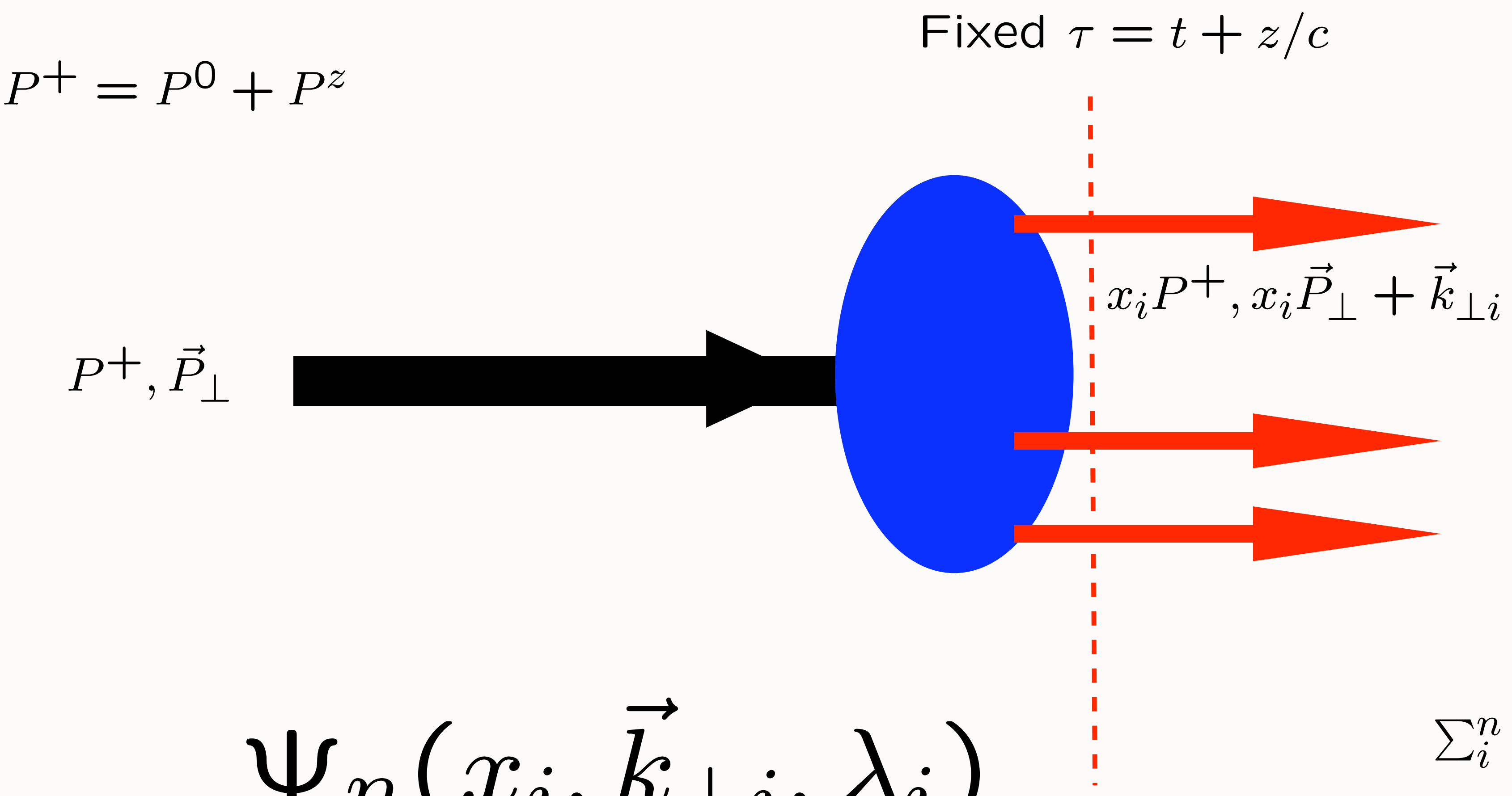
Evolve in light-cone time!



Instant Form

Front Form

Light-Front Wavefunctions



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

$\sum_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

'Tis a mistake / Time flies not
It only hovers on the wing
Once born the moment dies not
'tis an immmortal thing

Montgomery

Light-Front Wavefunctions

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

$$\psi(x, k_\perp)$$

Invariant under boosts. Independent of P^μ

$$x_i = \frac{k_i^+}{P^+}$$

$$H_{LF}^{QCD}|\psi> = M^2|\psi>$$

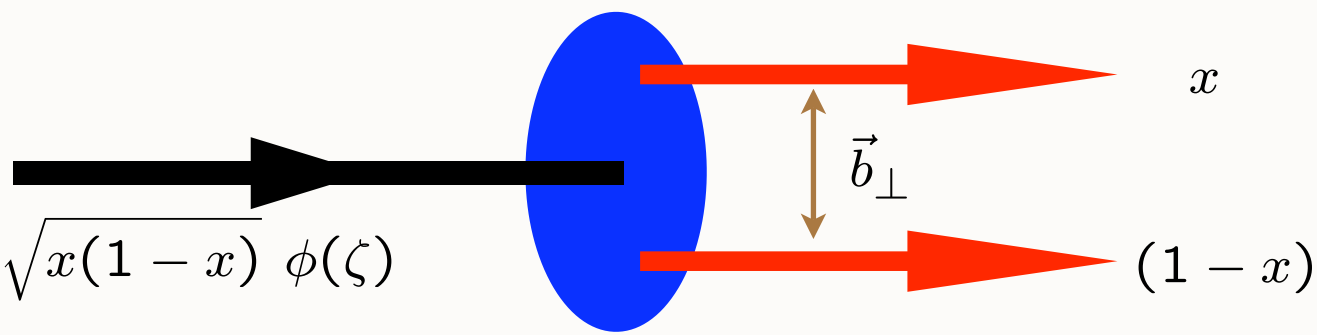
Remarkable new insights from AdS/CFT, the duality between conformal field theory and Anti-de Sitter Space

Mapping between LF(3+1) and AdS_5

LF(3+1) — AdS_5

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

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



$$\psi(x, \vec{b}_\perp) = \sqrt{x(1-x)}\ \phi(\zeta)$$

G. de Teramond and sjb

Map AdS/CFT to 3+1 LF Theory

Effective radial equation:

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

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

Effective conformal potential:

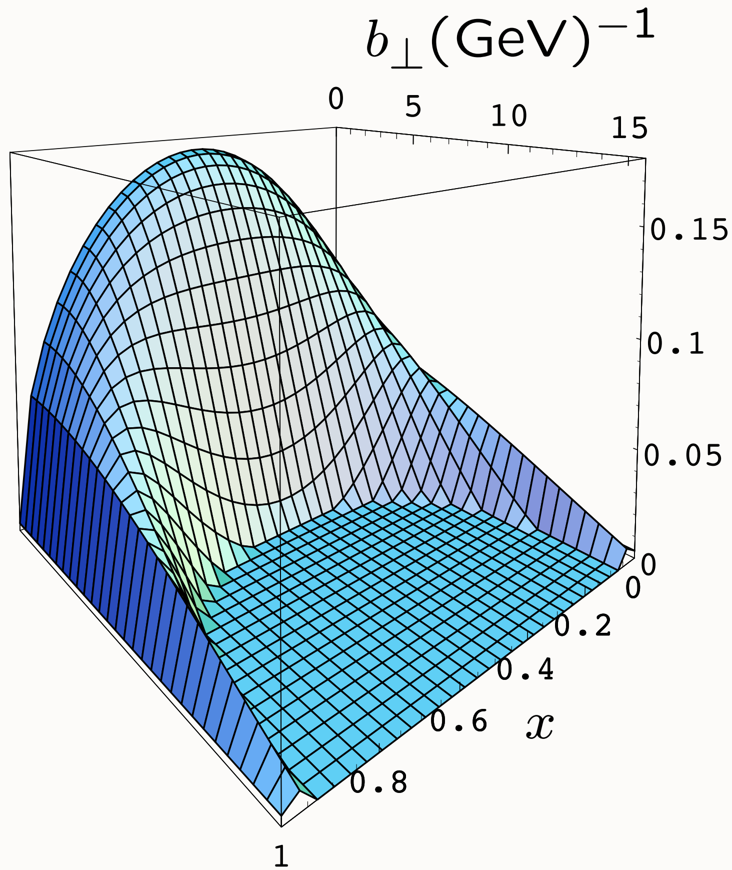
$$V(\zeta) = -\frac{1-4L^2}{4\zeta^2}.$$

General solution:

$$\widetilde{\psi}_{L,k}(x,\vec{b}_\perp) = B_{L,k}\sqrt{x(1-x)}$$

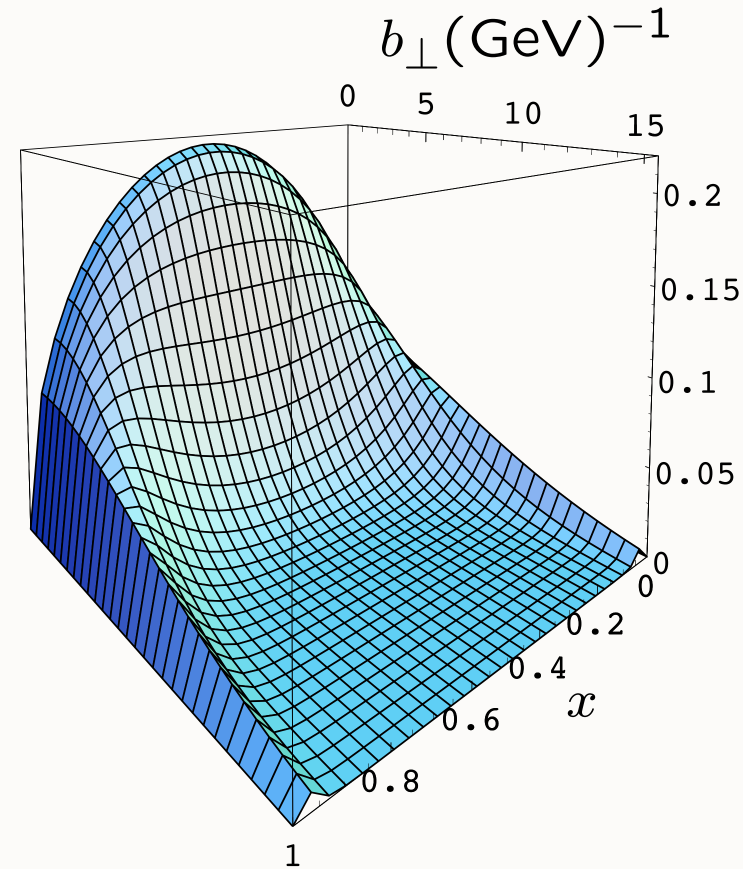
$$J_L\left(\sqrt{x(1-x)}|\vec{b}_\perp|\beta_{L,k}\Lambda_{\rm QCD}\right)\theta\left(\vec{b}_\perp^{\,2} \le \frac{\Lambda_{\rm QCD}^{-2}}{x(1-x)}\right),$$

AdS/CFT Predictions for Meson LFWF $\psi(x, b_\perp)$



$\Lambda_{QCD} = 0.32$ GeV

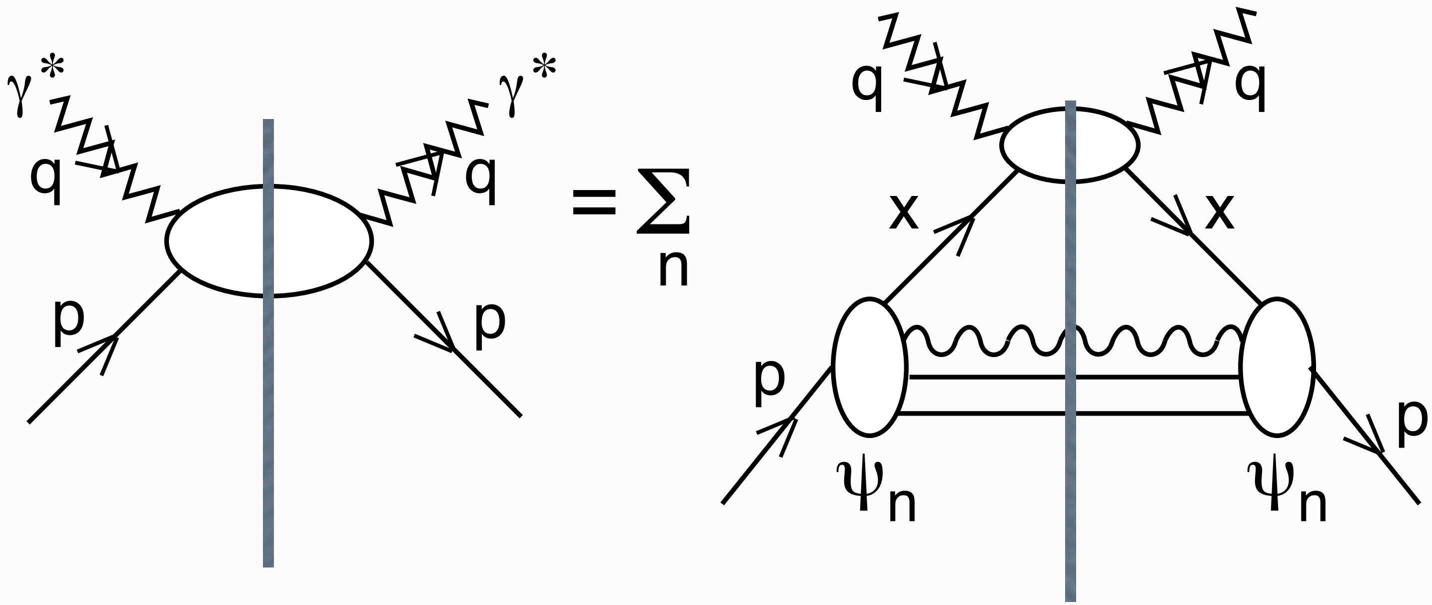
Truncated Space



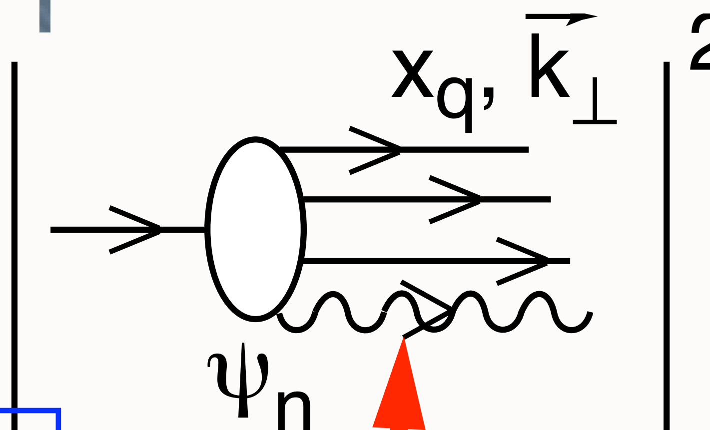
$\kappa = 0.76$ GeV.

Harmonic Oscillator

Deep Inelastic Lepton Proton Scattering



Imaginary Part of
Forward Virtual Compton Amplitude

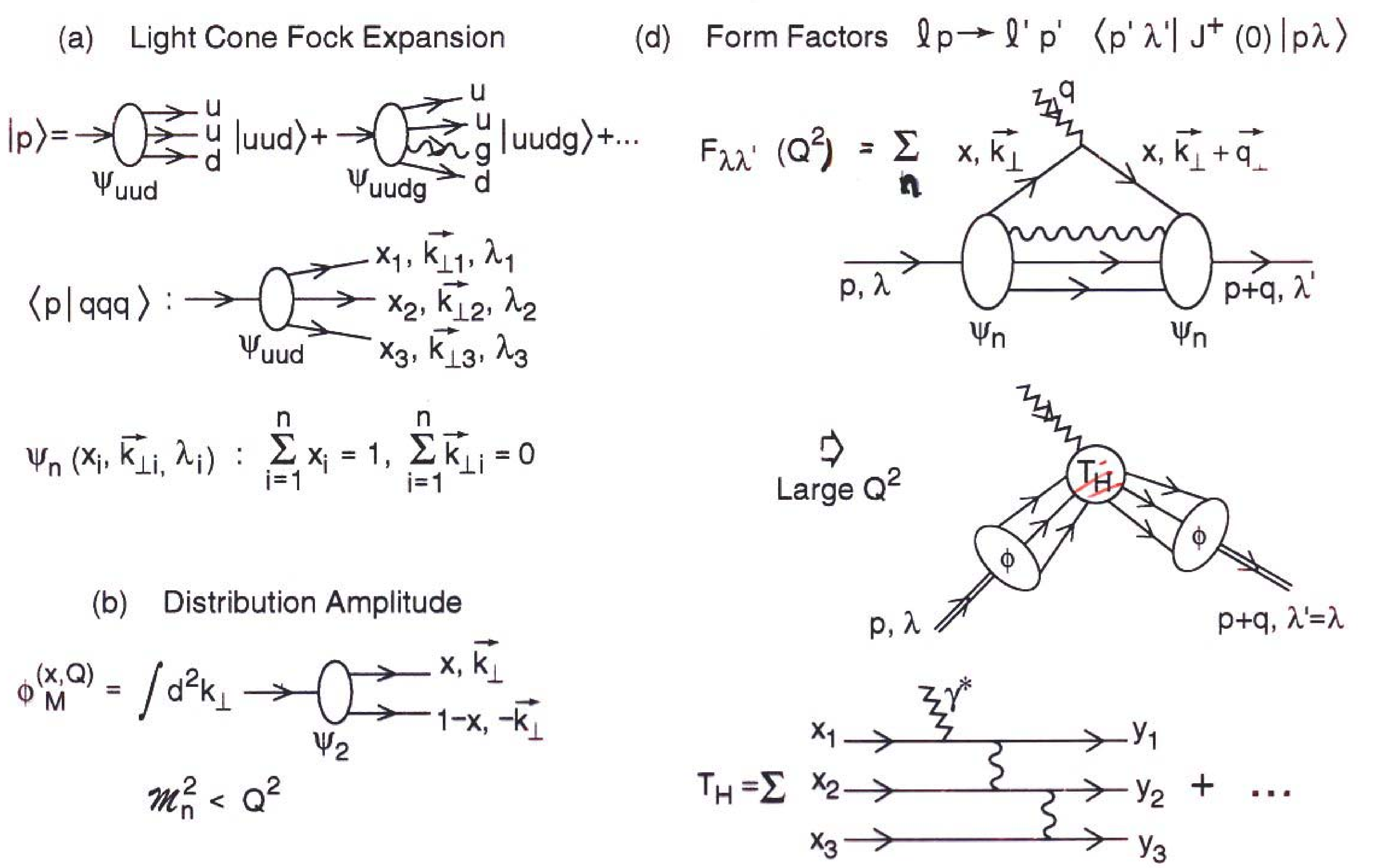


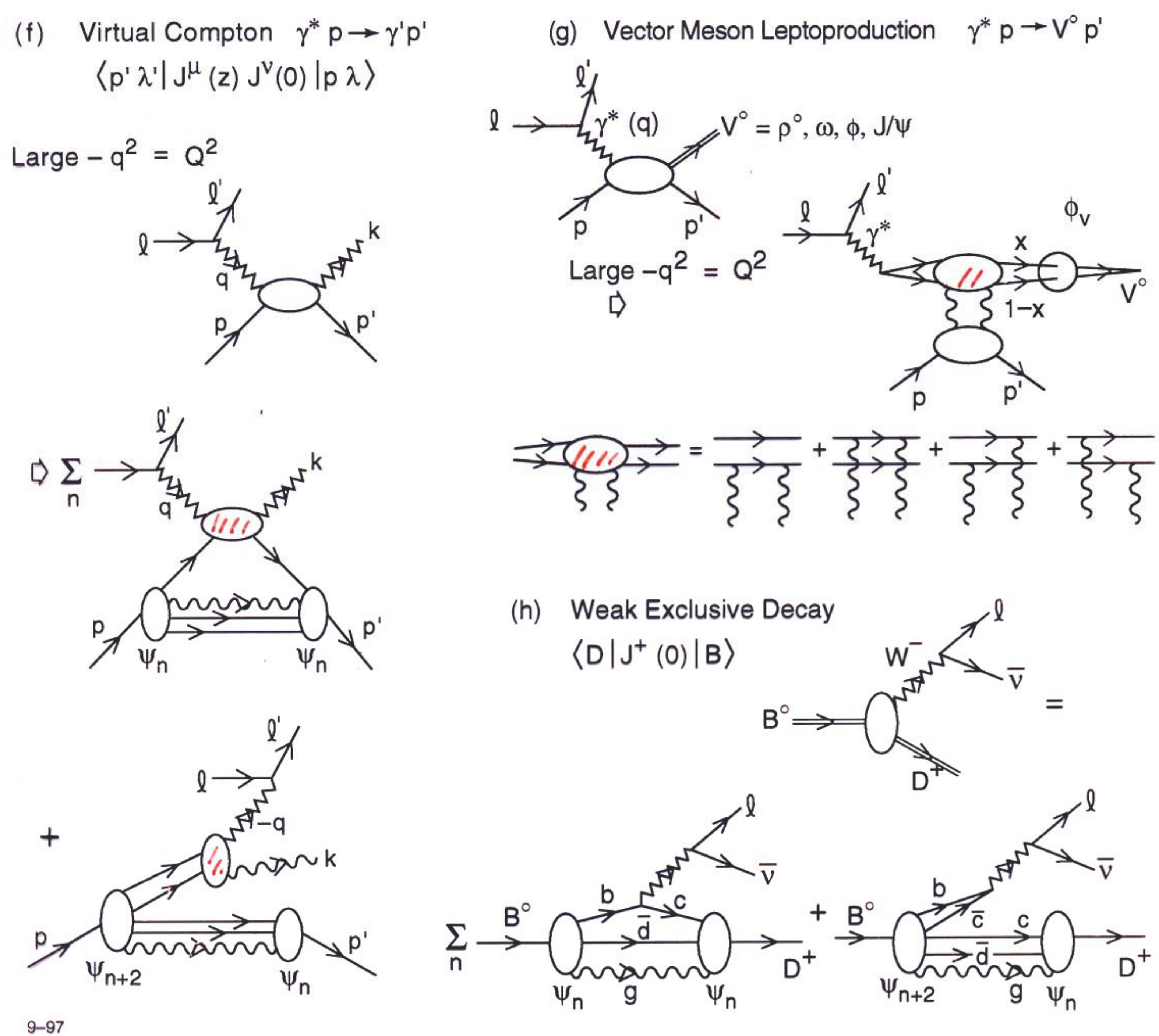
$q(x, Q^2) = \sum_n \int^{k_\perp^2 \leq Q^2 \perp} d^2 k_\perp \, |\Psi_n(x, k_\perp)|^2$

$x = x_q$

All spin, flavor distributions

Light-Front Wave Functions $\psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$

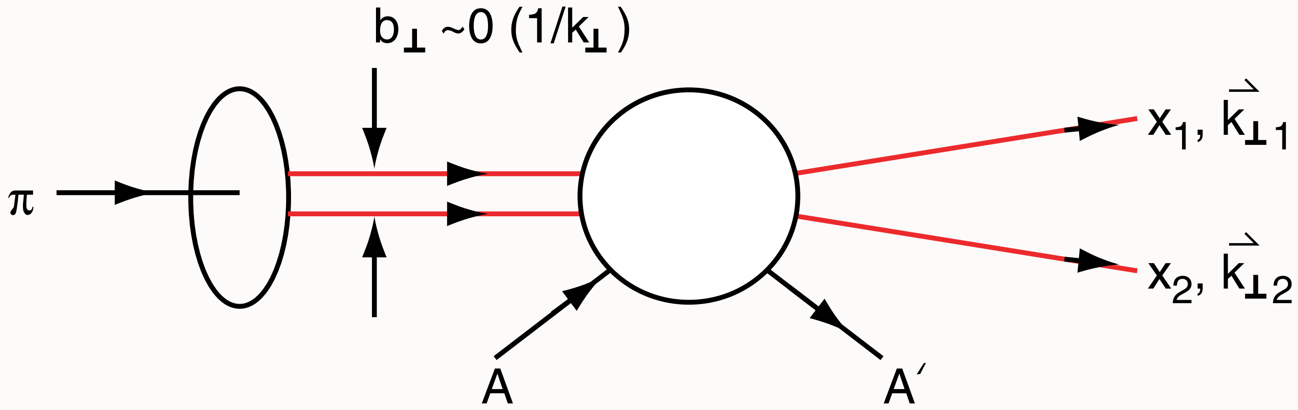

(a) Light Cone Fock Expansion
|p⟩= ψuud |uud⟩+ ψuudg |uudg⟩+...
⟨p|qqq⟩ : ψuud
x1, k⊥1, λ1
x2, k⊥2, λ2
x3, k⊥3, λ3
ψn (xi, k⊥i, λi) : Σ xi = 1, Σ k⊥i = 0
(b) Distribution Amplitude
φM(x,Q) = ∫d²k⊥ ψ2
x, k⊥
1−x, −k⊥
m²n < Q²
(d) Form Factors ℓp → ℓ' p' ⟨p' λ'| J⁺ (0) |pλ⟩
Fλλ' (Q²) = Σn
x, k⊥
x, k⊥ + q⊥
q
p, λ
p+q, λ'
ψn
ψn
Large Q²
TH
φ
φ
p, λ
p+q, λ'=λ
γ*
TH =Σ
x1
x2
x3
y1
y2
y3
+ ...


(f) Virtual Compton γ* p → γ'p'
⟨p' λ'| J^μ (z) J^ν(0) |p λ⟩
Large − q² = Q²
(g) Vector Meson Leptoproduction γ* p → V° p'
V° = ρ°, ω, φ, J/ψ
Large −q² = Q²
φ_V
x
1−x
(h) Weak Exclusive Decay
⟨D | J⁺ (0) | B⟩
W⁻
B°
D⁺
ψ_n
ψ_{n+2}
9–97

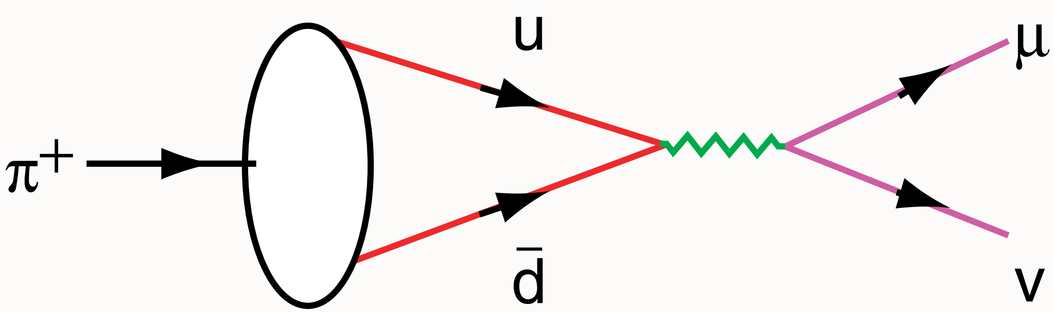
Use Diffraction to Resolve Hadron Substructure

- Measure Light-Front Wavefunctions
- Test AdS/CFT predictions
- Novel Aspects of Hadron Wavefunctions: Intrinsic Charm, Hidden Color, Color Transparency/Opaqueness
- Diffractive Di-Jet Production
- Nuclear Shadowing and Antishadowing
- New Mechanism for Higgs Production

Fluctuation of a Pion to a Compact Color Dipole State



Color-Transparent Fock State For High Transverse Momentum Di-Jets



Same Fock State Determines Weak Decay

Evaluation of QCD Matrix Elements: Example f_π

- Pion decay constant defined by the matrix element of EW current J_W^+:

$$\left\langle 0 \left| \overline{\psi}_u \gamma^+ (1-\gamma_5) \psi_d \right| \pi^- \right\rangle = i\sqrt{2} P^+ f_\pi ,$$

with

$$\left| \pi^- \right\rangle = |d\overline{u}\rangle = \frac{1}{\sqrt{N_C}} \frac{1}{\sqrt{2}} \sum_{c=1}^{N_C} \left(b^\dagger_{c\, d\downarrow} d^\dagger_{c\, u\uparrow} - b^\dagger_{c\, d\uparrow} d^\dagger_{c\, u\downarrow} \right) |0\rangle .$$

- Use light-cone expression:

$$f_\pi = 2\sqrt{N_C} \int_0^1 dx \int \frac{d^2 \vec{k}_\perp}{16\pi^3} \, \psi_{\overline{q}q/\pi}(x, k_\perp).$$

Lepage and Brodsky, Phys. Rev. D **22**, 2157 (1980)

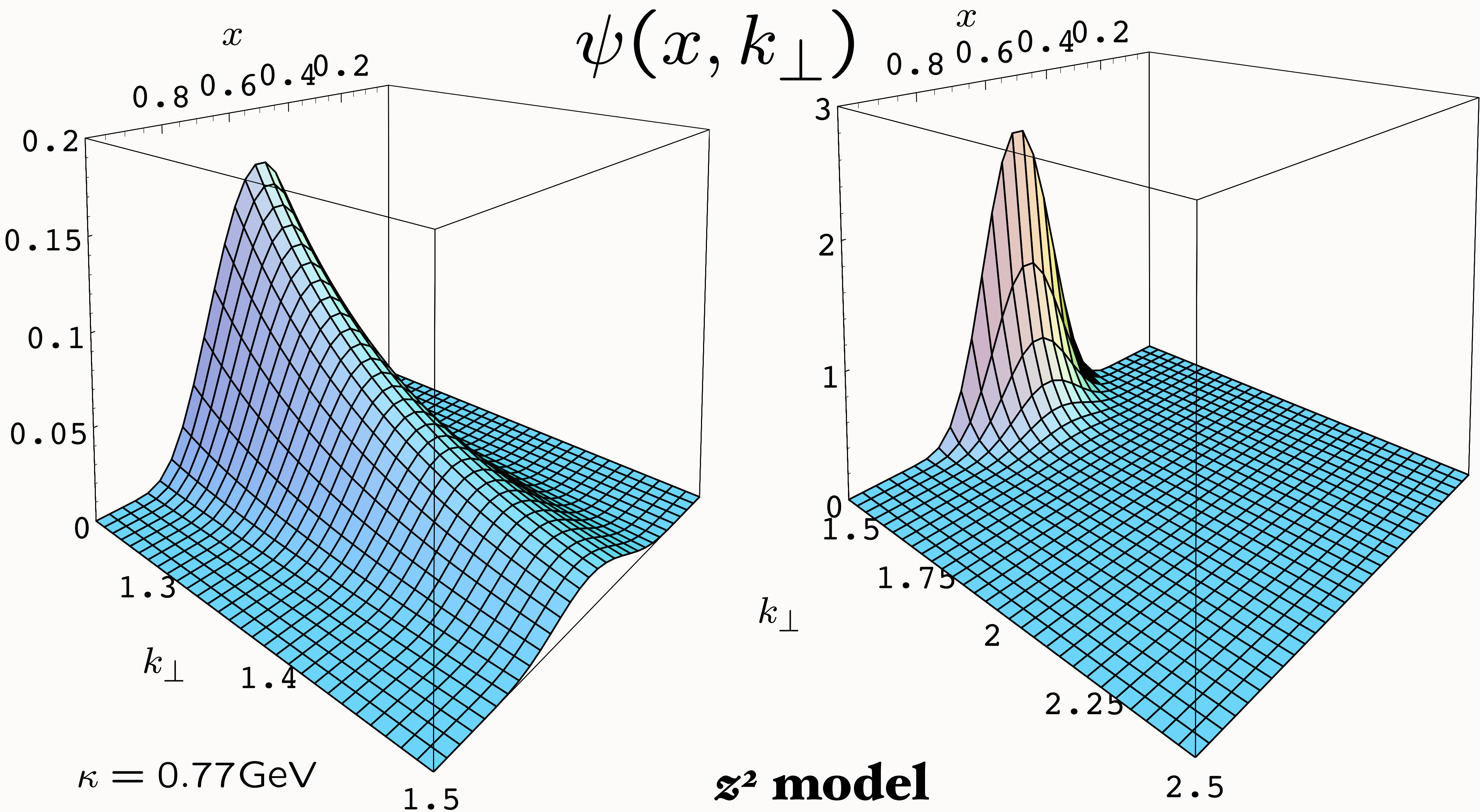
- Find:

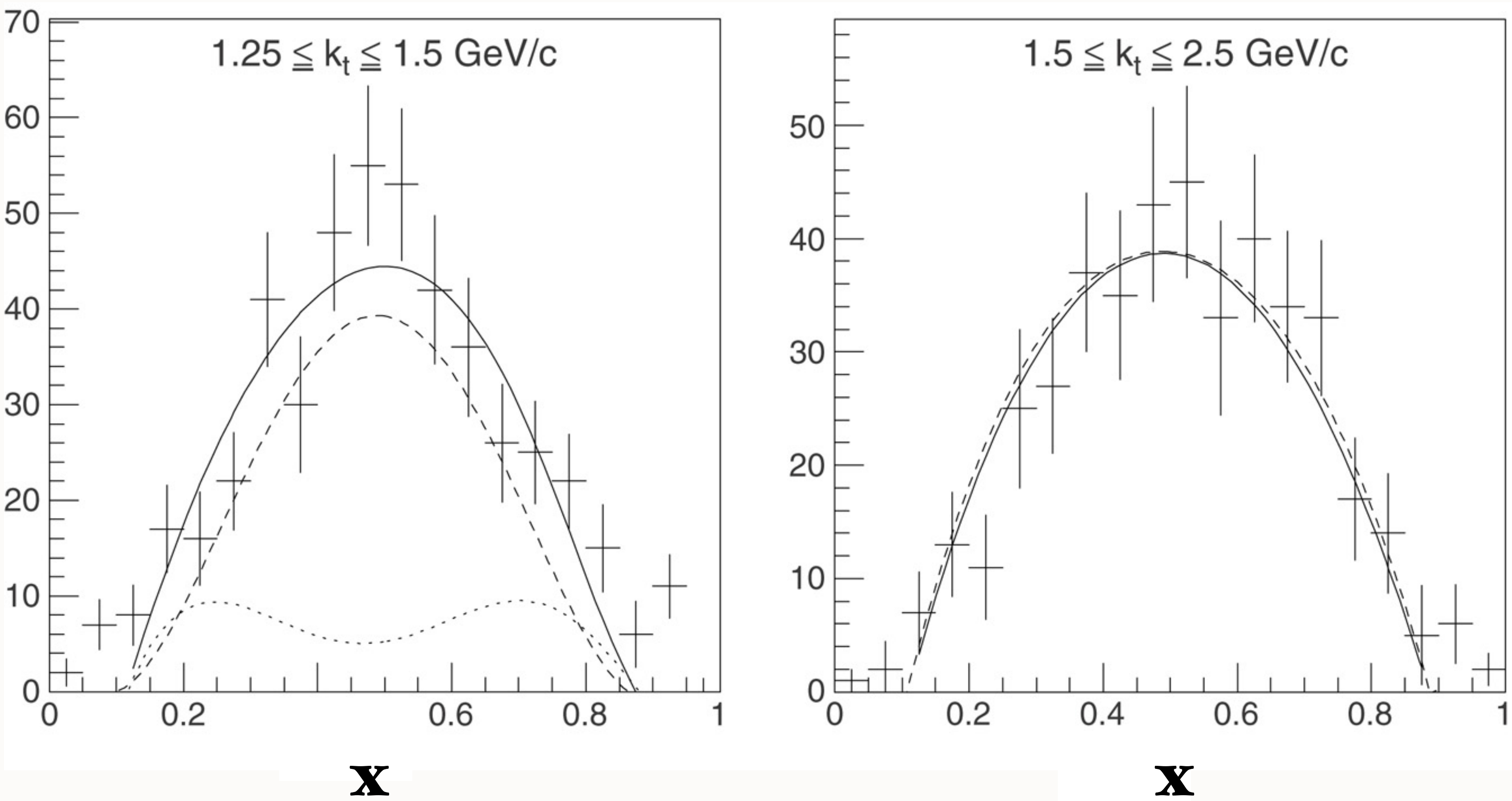
$$f_\pi = \frac{\sqrt{3}\Lambda_{\rm QCD}}{8 J_1(\beta_{0,1})} = 83.4 \,\mathrm{Mev},$$

for $\Lambda_{\rm QCD} = 0.2$ GeV.

Experiment: $f_\pi = 92.4$ Mev.

Predictions from AdS/CFT





The **x** distribution of diffractive dijets from the platinum target for $1.25 \leq k_t \leq 1.5$ GeV/c (left) and for $1.5 \leq k_t \leq 2.5$ GeV/c (right). The solid line is a fit to a combination of the asymptotic and CZ distribution amplitudes. The dashed line shows the contribution from the asymptotic function and the dotted line that of the CZ function.

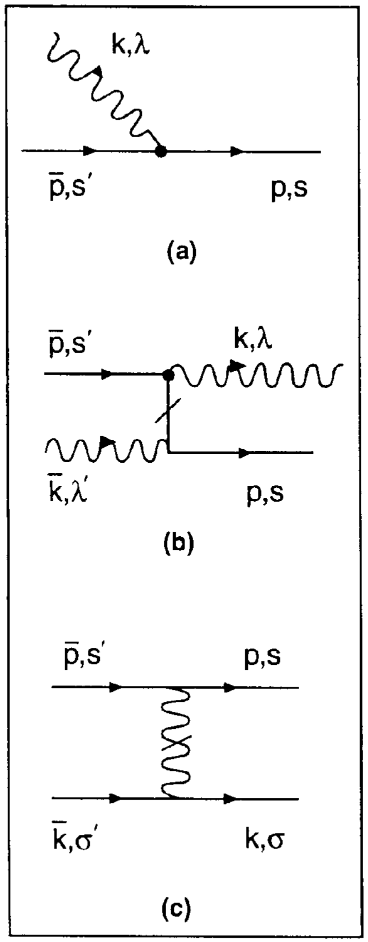
Solving the LF Heisenberg Eqn.

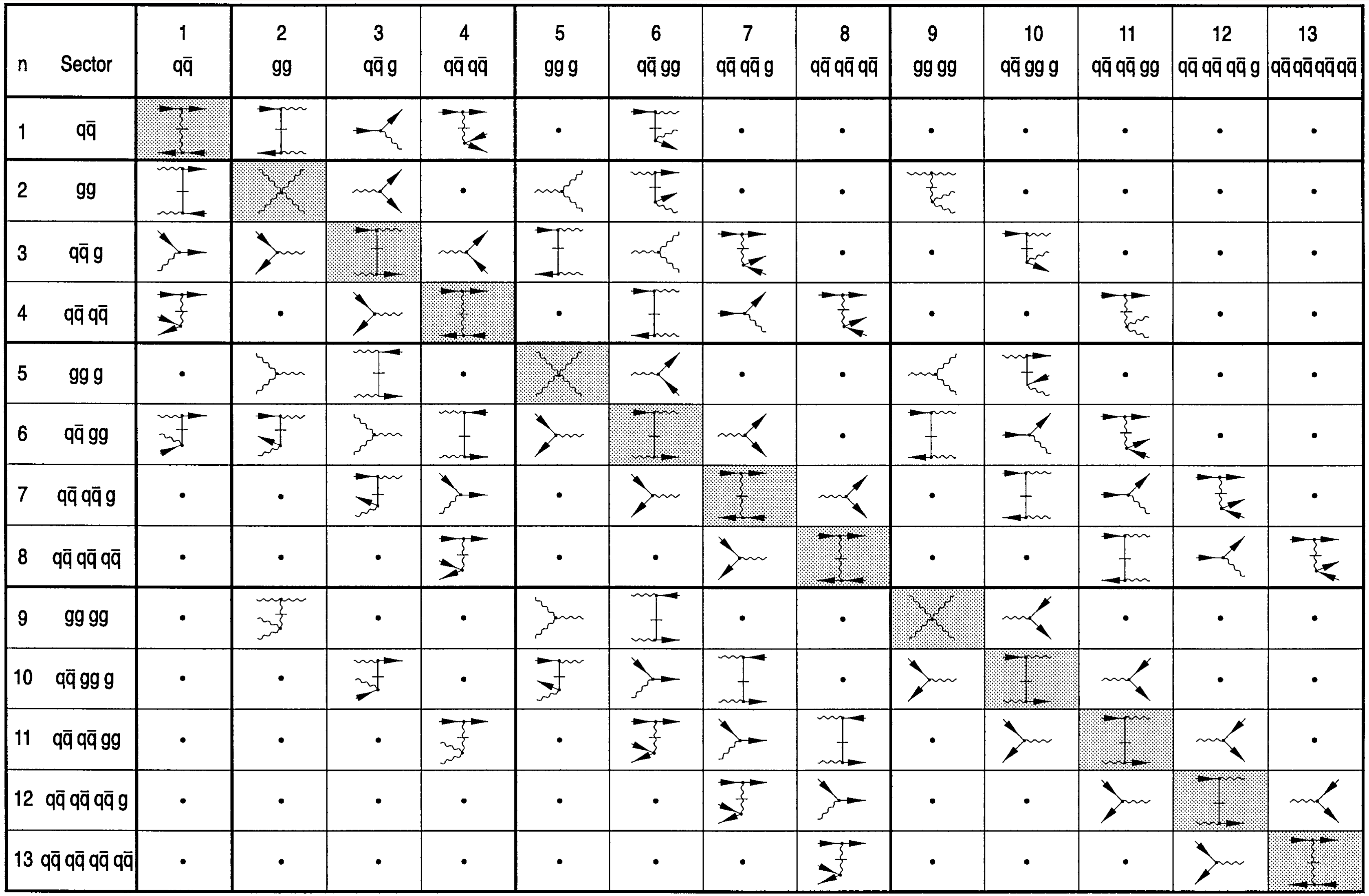
- Discretized Light-Cone Quantization (DLCQ) Pauli, sjb
  Minkowski space !
- Many 1+1 model field theories completely solved using DLCQ Hornbostel, Pauli, sjb; Klebanov
- UV Regularization: 3+ 1 Pauli Villars Hiller, McCartor, sjb
- Transverse Lattice Bardeen, Peterson,Rabinovici, Burkardt, Dalley
- Bethe-Salpeter/Dyson-Schwinger at fixed LF time
- Angular Structure of Solutions known Karmanov, Hwang, sjb
- **Use AdS/CFT model solutions and AdS/LF Equations as starting point**! Vary, de Teramond sjb

Light-Front QCD Heisenberg Equation

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

DLCQ

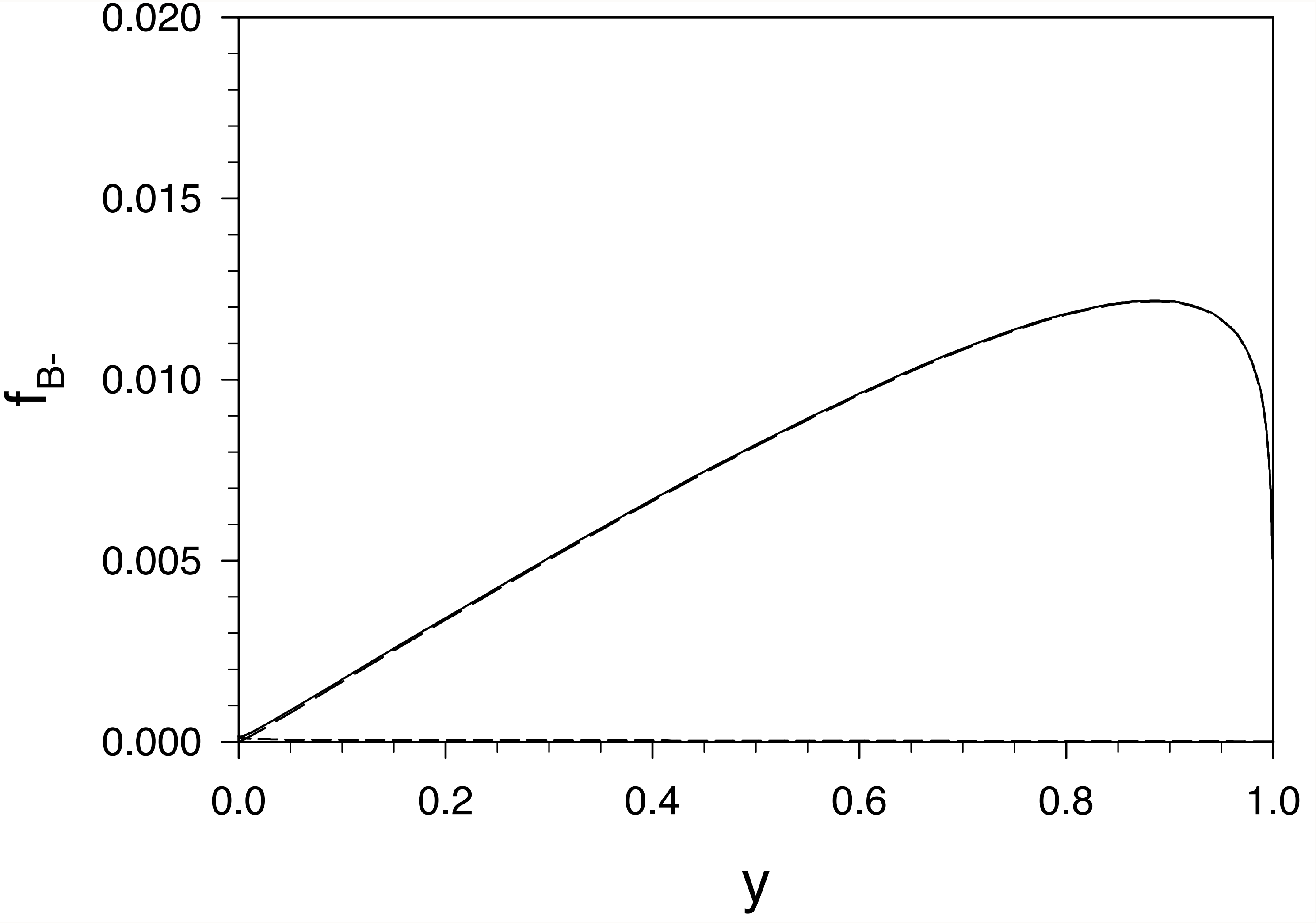




Pauli, Pinsky, sjb

Structure function of boson constituent in 3+1 Yukawa theory

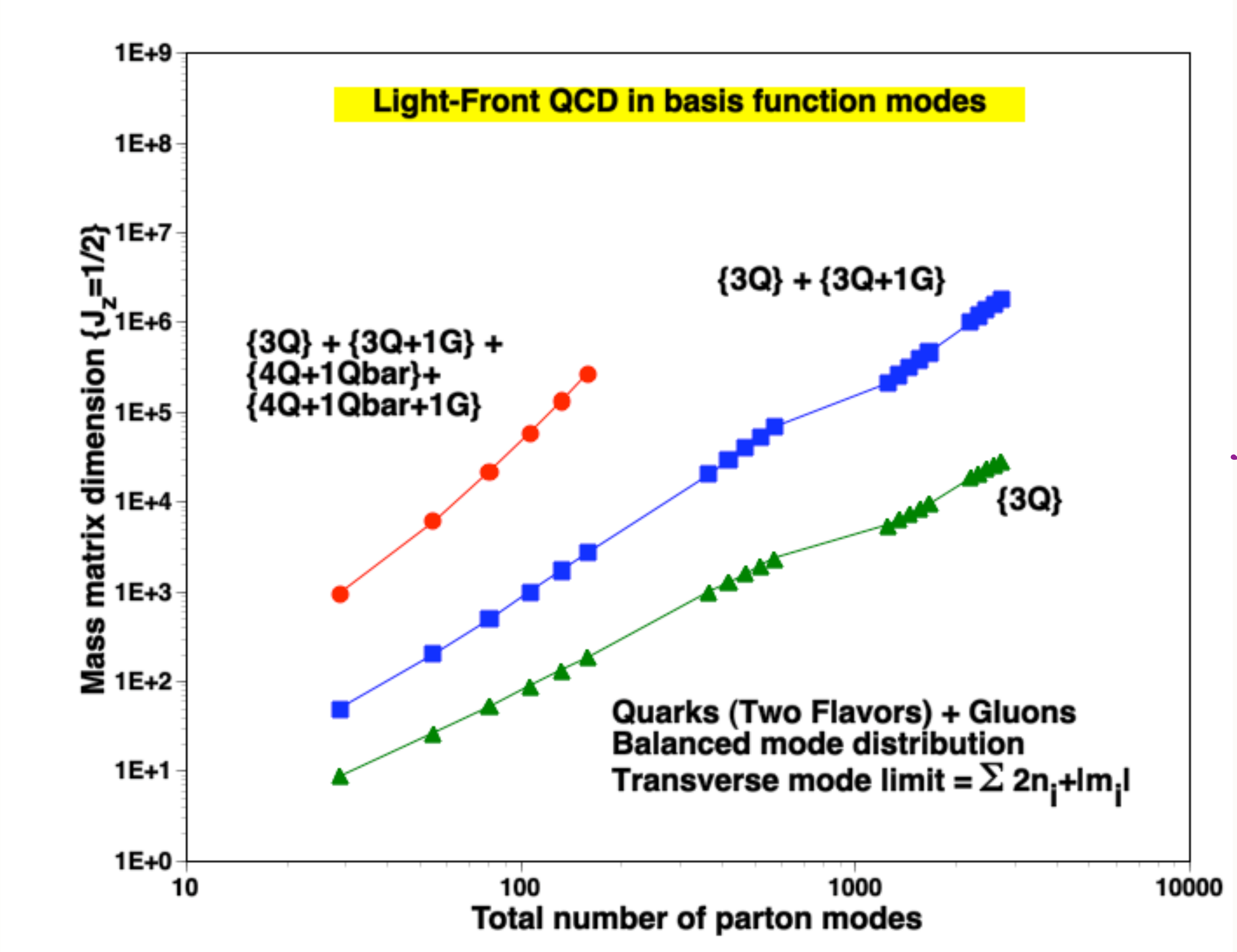
Three-particle Fock state truncation



Pauli-Villars Regularization

Hiller, McCartor, sjb

Use AdS/CFT basis (complete and orthonormal) to diagonalize LF QCD Hamiltonian

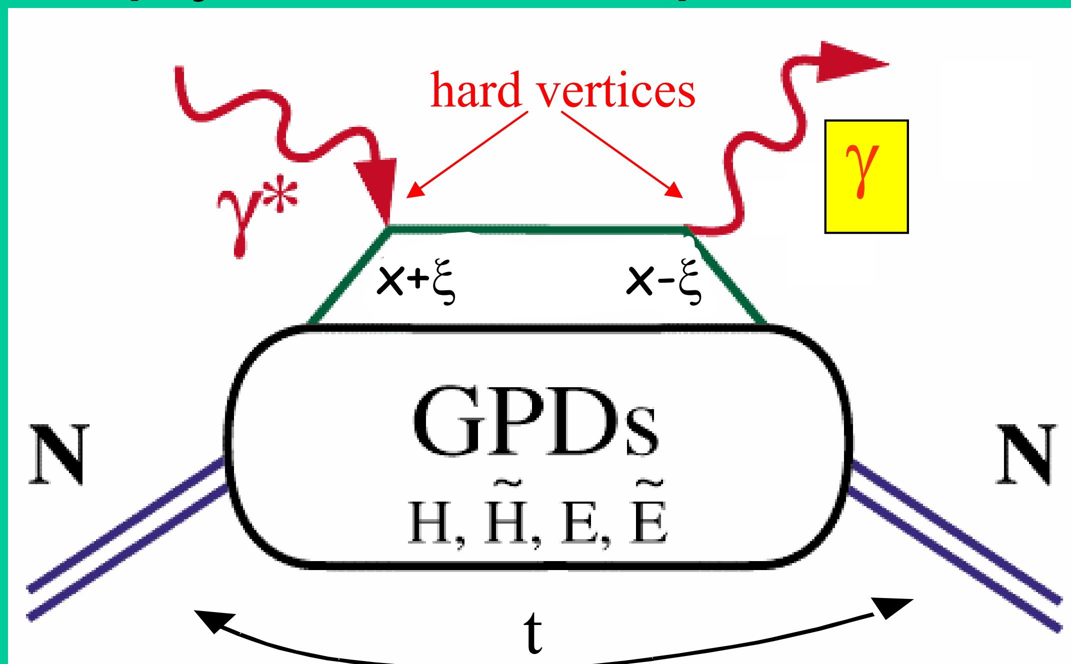


J. Vary et al

GPDs & Deeply Virtual Exclusive Processes

"handbag" mechanism

Deeply Virtual Compton Scattering (DVCS)



x – longitudinal quark momentum fraction

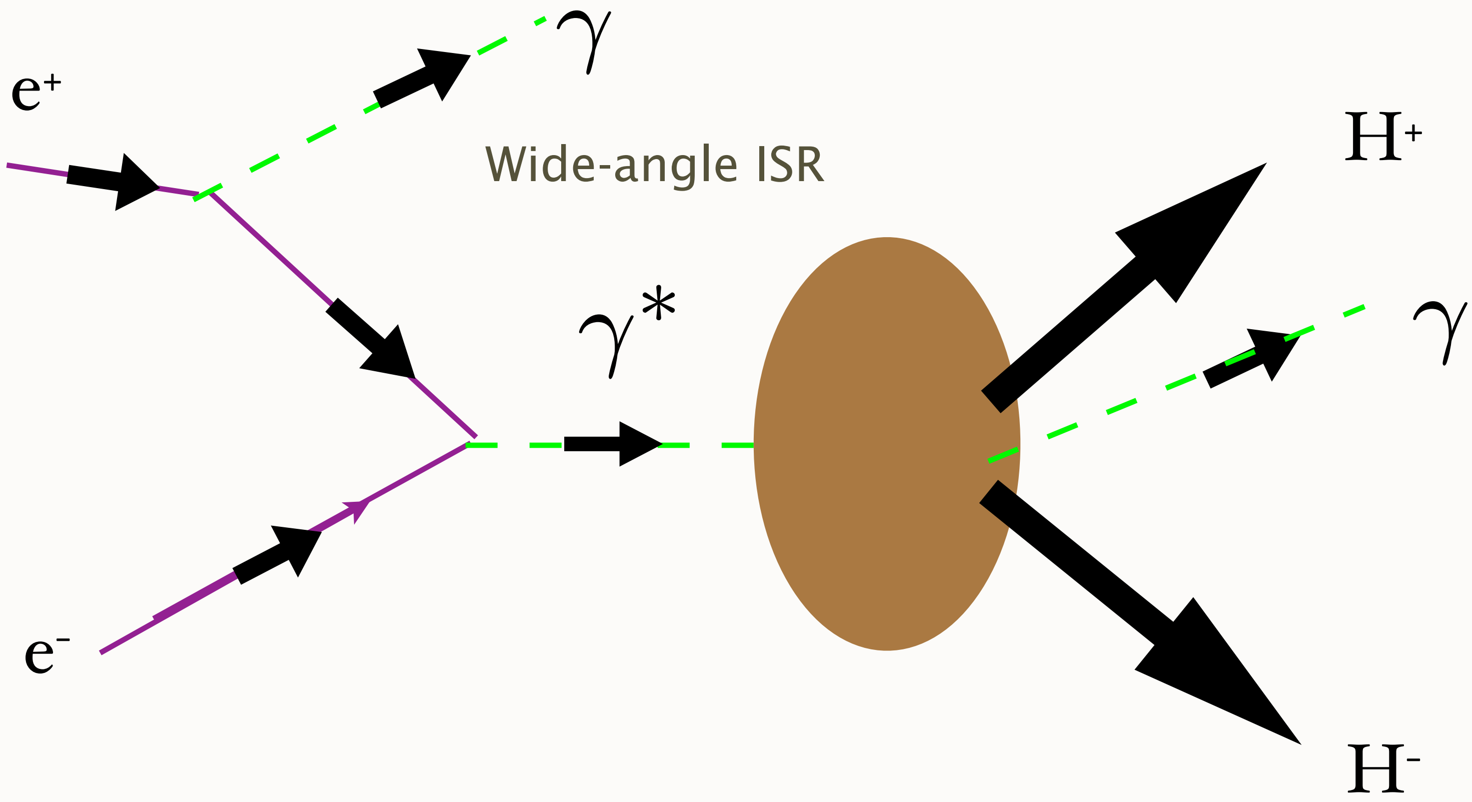
2ξ – longitudinal momentum transfer

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

$H(x,\xi,t), E(x,\xi,t), \ldots$

$$\xi = \frac{x_B}{2-x_B}$$

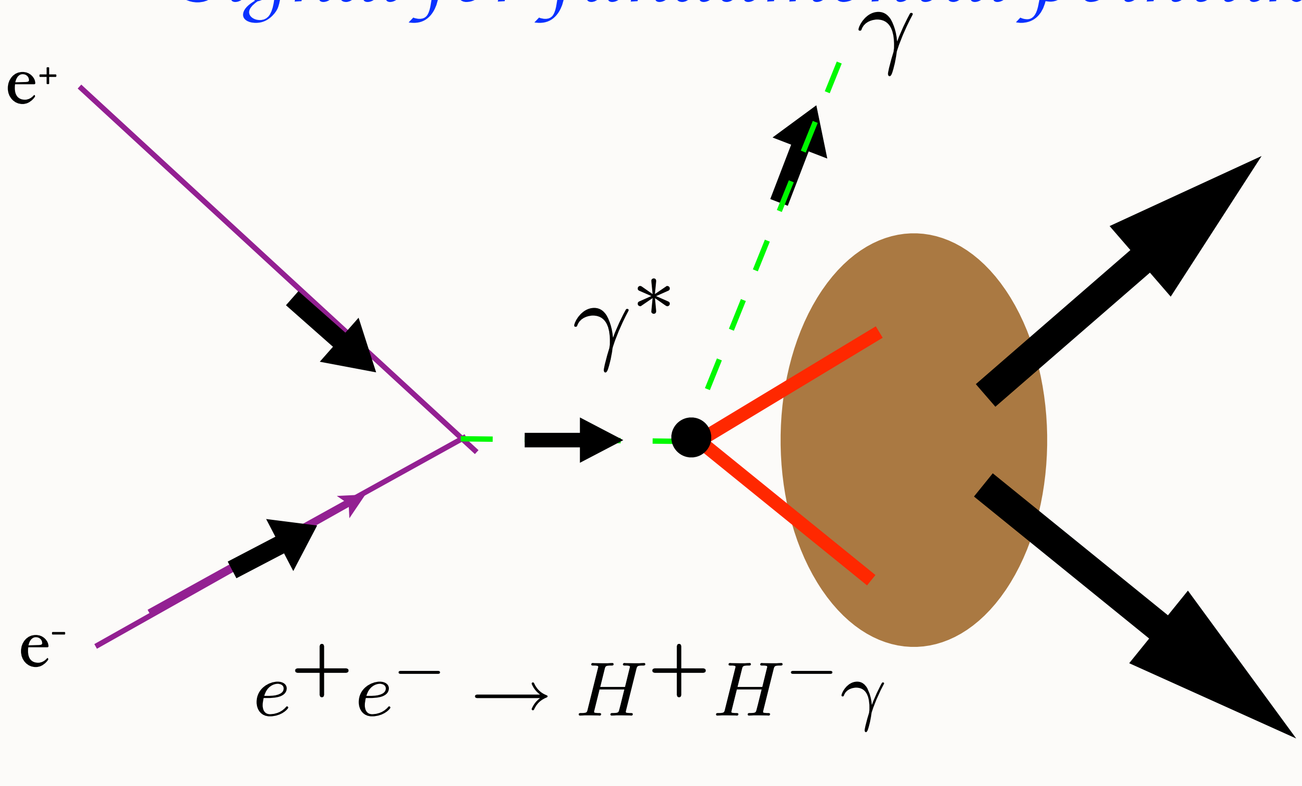
Time-like Deeply Virtual Compton Scattering
Time-like Generalized Parton Distributions



Interference of timelike DVCS amplitude $T(\gamma^* \to H^+ H^- \gamma)$
with timelike form factor produces charge asymmetry

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

Time-like Deeply Virtual Compton Scattering
J=0 Fixed Pole
Signal for fundamental pointlike structure



Instantaneous quark exchange

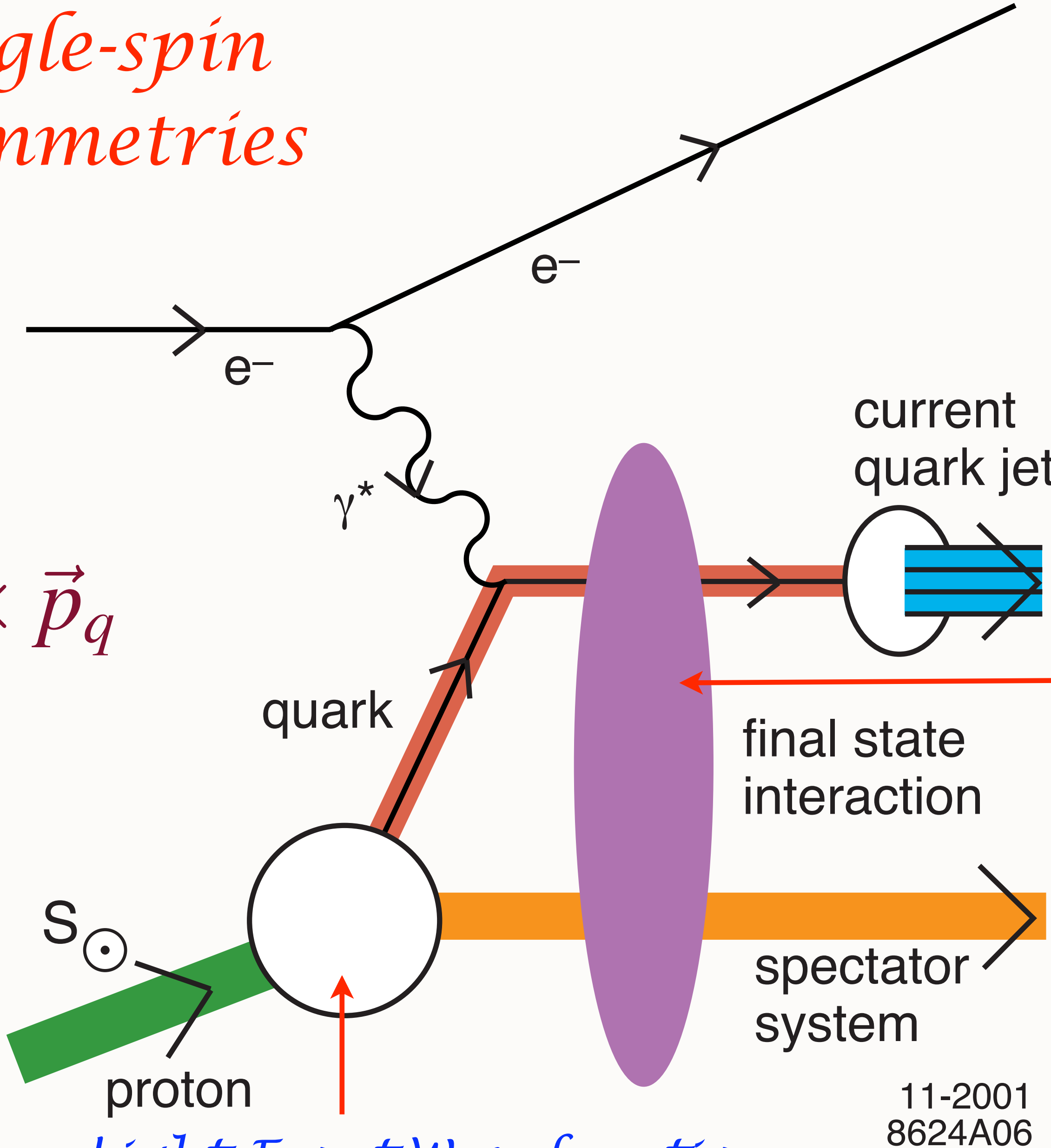
$$T_{\text{seagull}} = F(M^2_{H\bar{H}})$$

Local "seagull" interaction of two photons at same point produces isotropic real amplitude, independent of photon virtuality at fixed pair mass

Single-spin asymmetries

Sivers Effect

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



QCD S- and P-Coulomb Phases

Light-Front Wavefunction S and P- Waves

Hwang, Schmidt.
sjb

Final State Interactions Produce T-Odd (Sivers Effect)

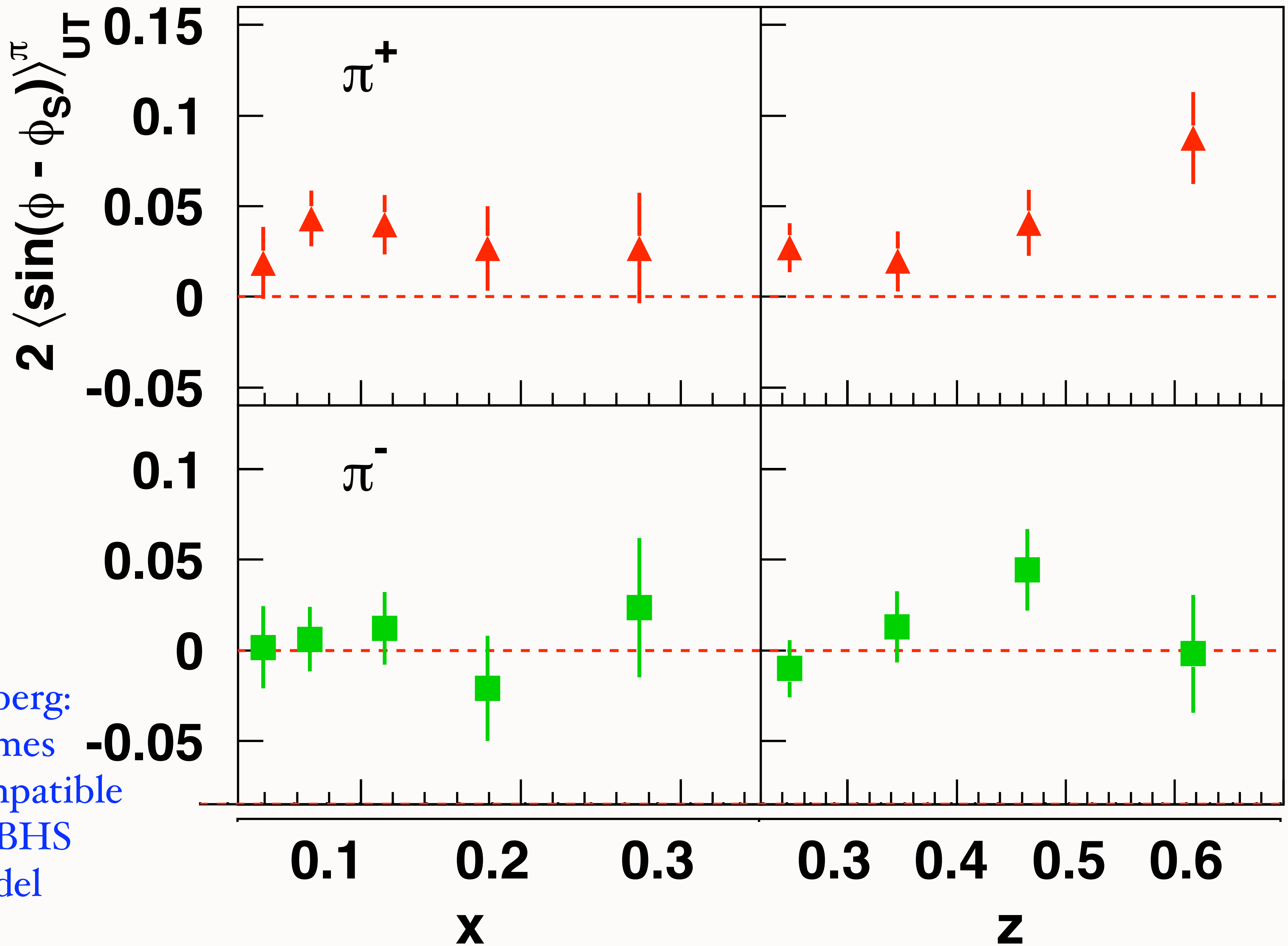
- Bjorken Scaling!
- Arises from Interference of Final-State Coulomb Phases in S and P waves
- Relate to the quark contribution to the target proton anomalous magnetic moment
- Sum of Sivers Functions for all quarks and gluons vanishes. (Zero gravitoanomalous magnetic moment)

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

Hwang, Schmidt. sjb; Burkardt

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

Sivers asymmetry from HERMES



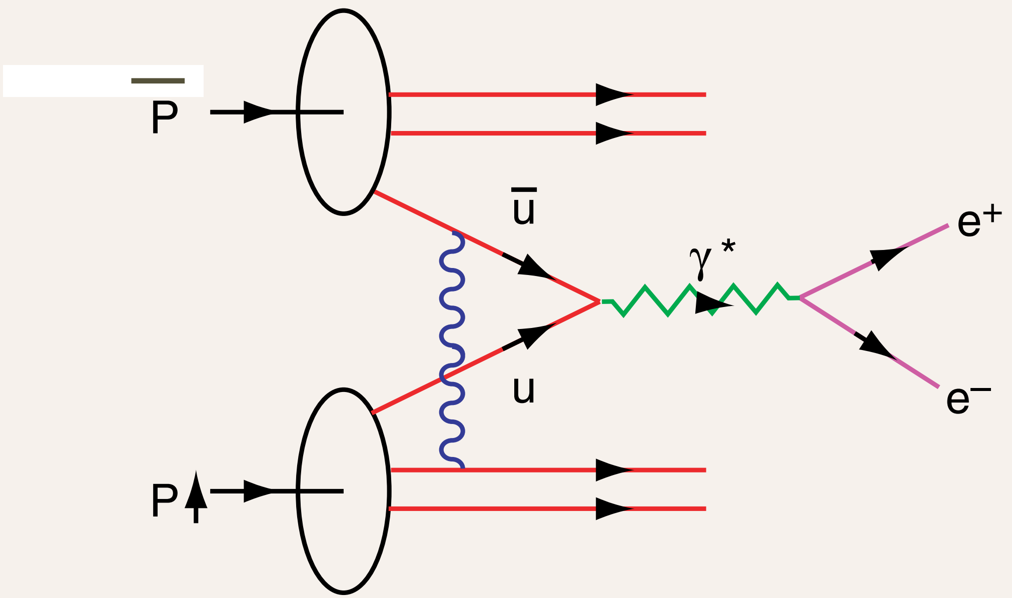
Gamberg:
Hermes
data compatible
with BHS
model

Key QCD Experiment at GSI

Measure single-spin asymmetry A_N in Drell-Yan reactions

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

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



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

$$Q^2 = x_1 x_2 s$$

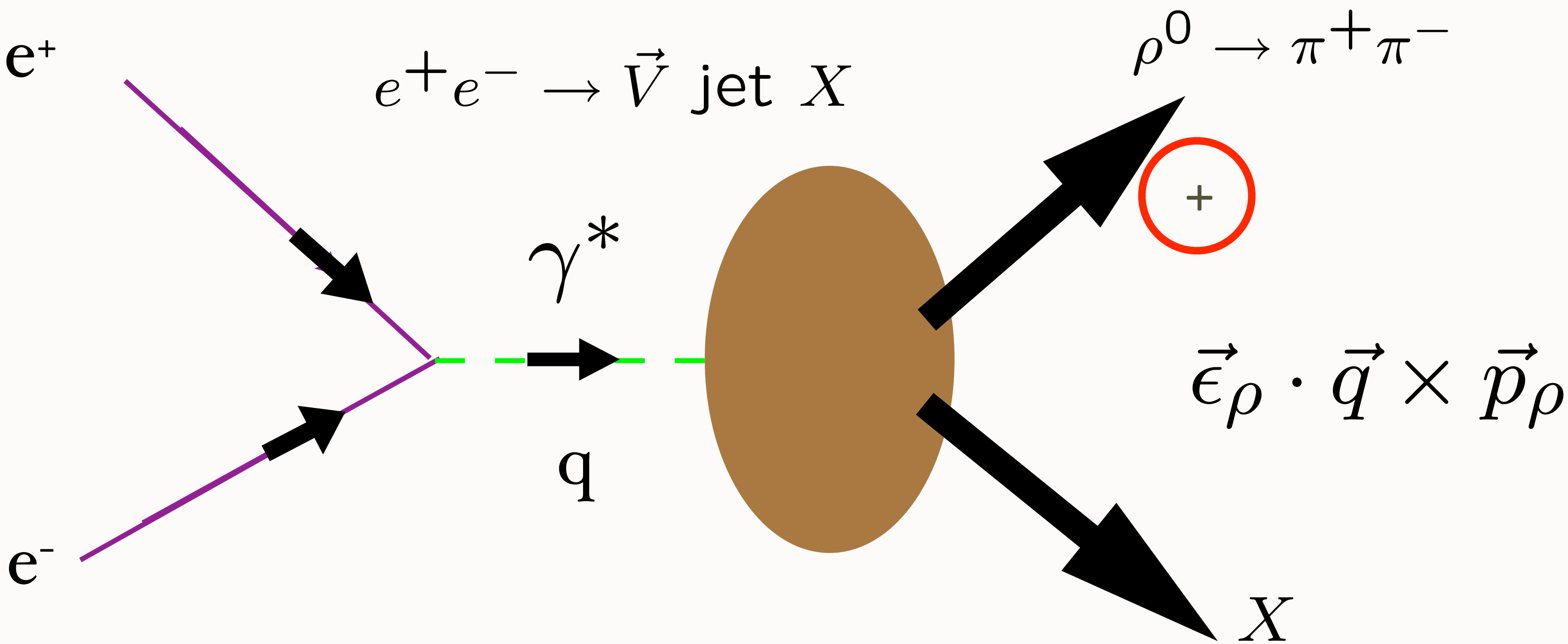
$$Q^2 = 4 \text{ GeV}^2, s = 80 \text{ GeV}^2$$

$$x_1 x_2 = .05, x_F = x_1 - x_2$$

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

Measure Time-like T-odd SSA

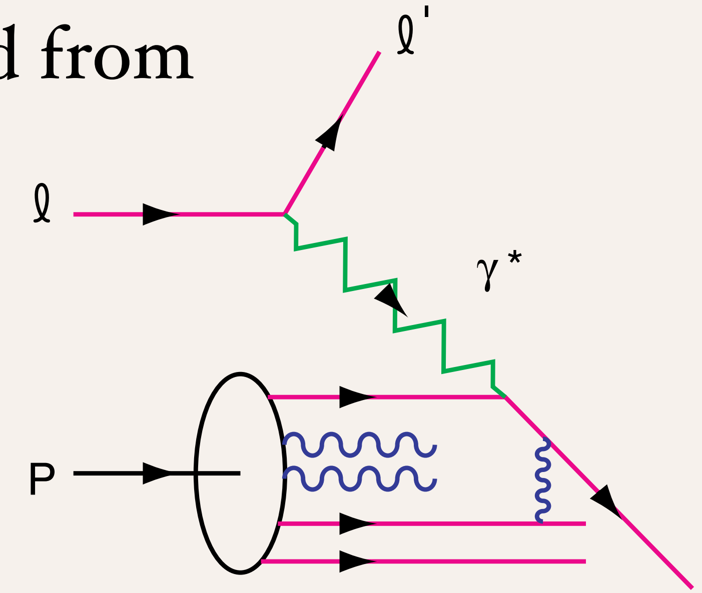
Test both Sivers and Collins Effect in Quark Fragmentation



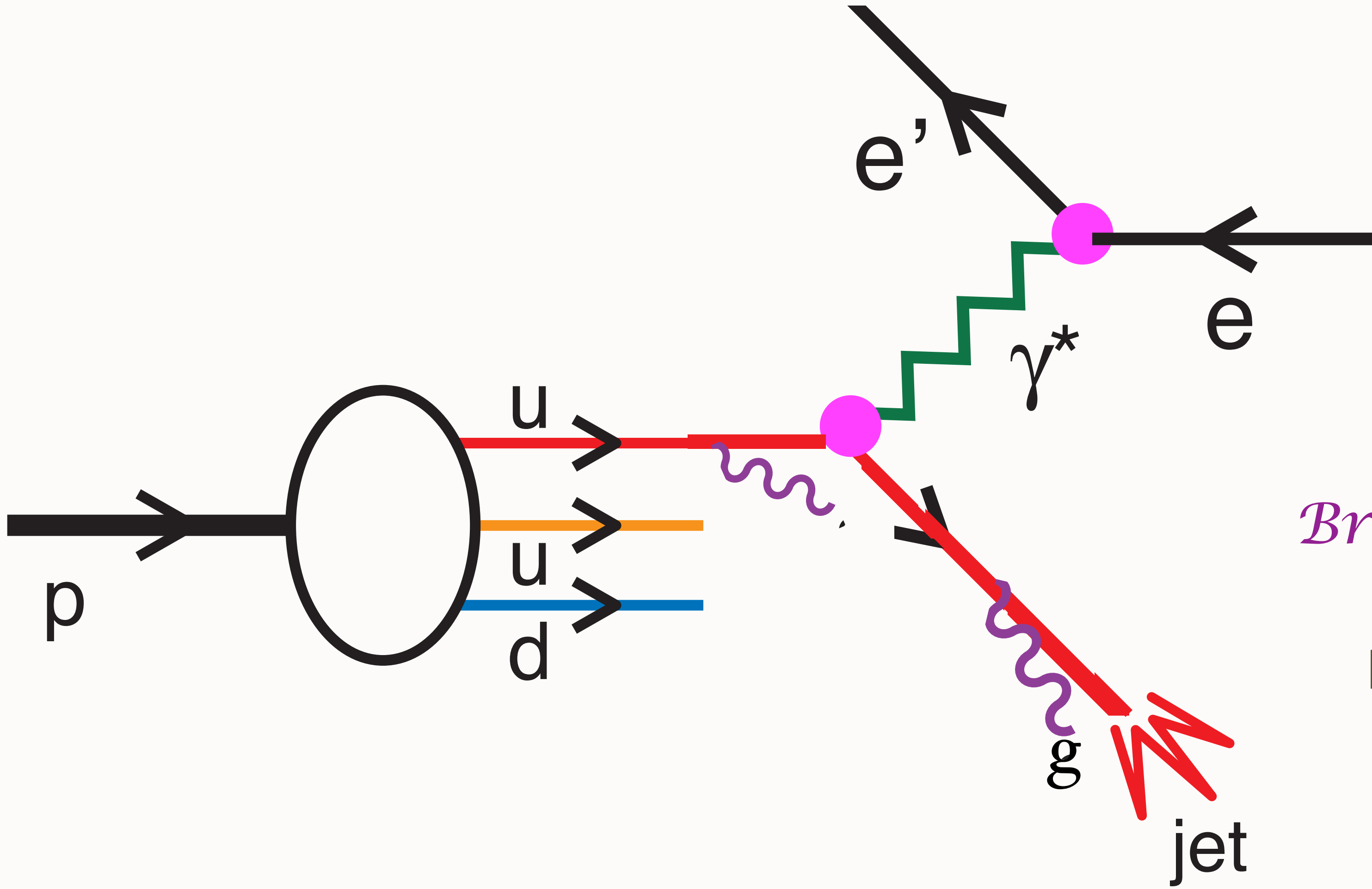
$$\epsilon_{\mu\nu\sigma\tau} \; \epsilon_V^\mu \; p_V^\nu \; p_{\text{jet}}^\sigma \; q^\tau$$

Measure spin projection of detected hadron normal to production plane; use asymmetric B-factory

- Quarks Reinteract in Final State
- Analogous to Coulomb phases, but not unitary
- Observable effects: DDIS, SSI, shadowing, antishadowing
- Structure functions cannot be computed from LFWFs computed in isolation
- Wilson line not 1 even in lcg



First Evidence for Quark Structure of Matter

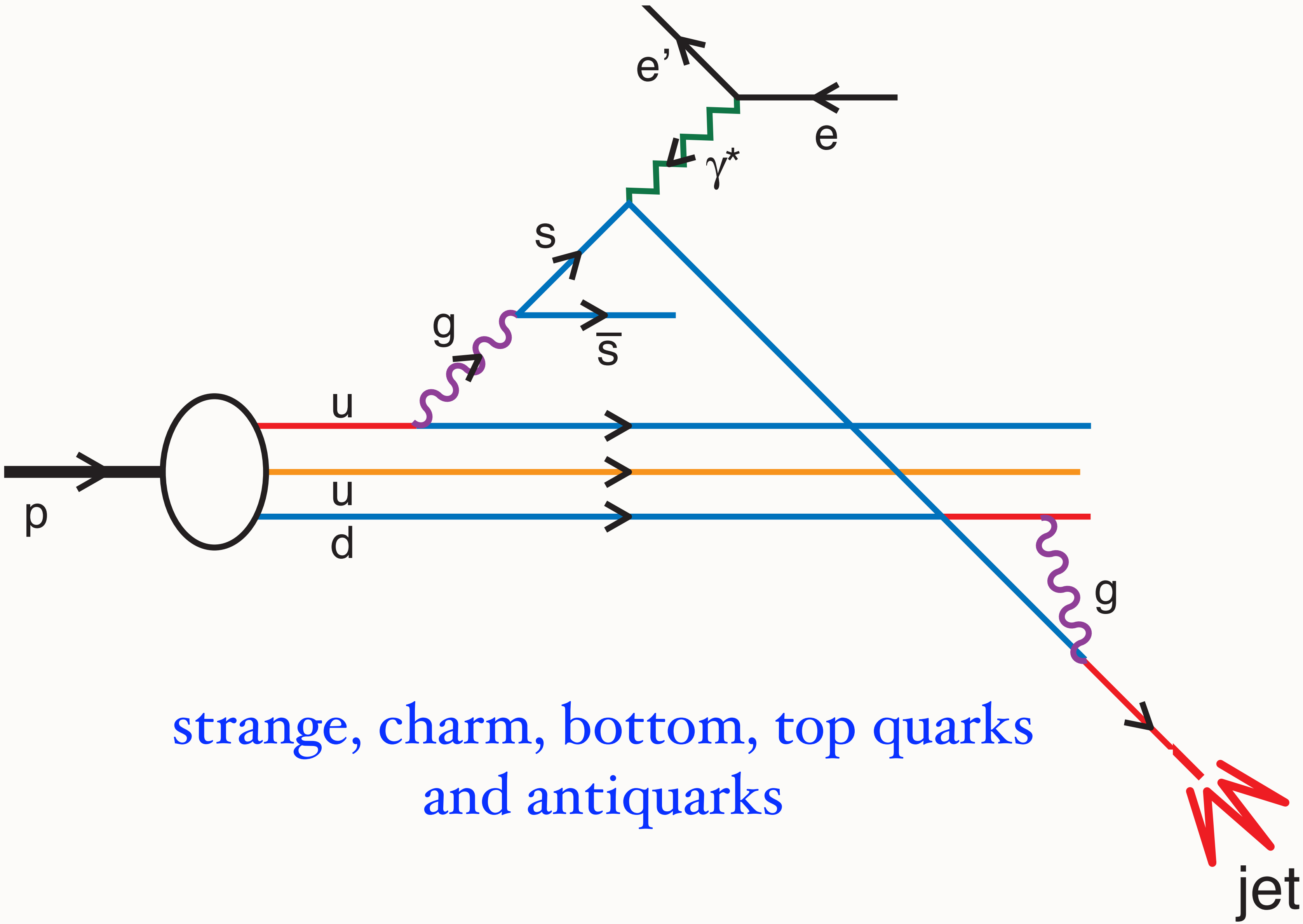


Gluonic Bremmstrahlung

DGLAP Evolution

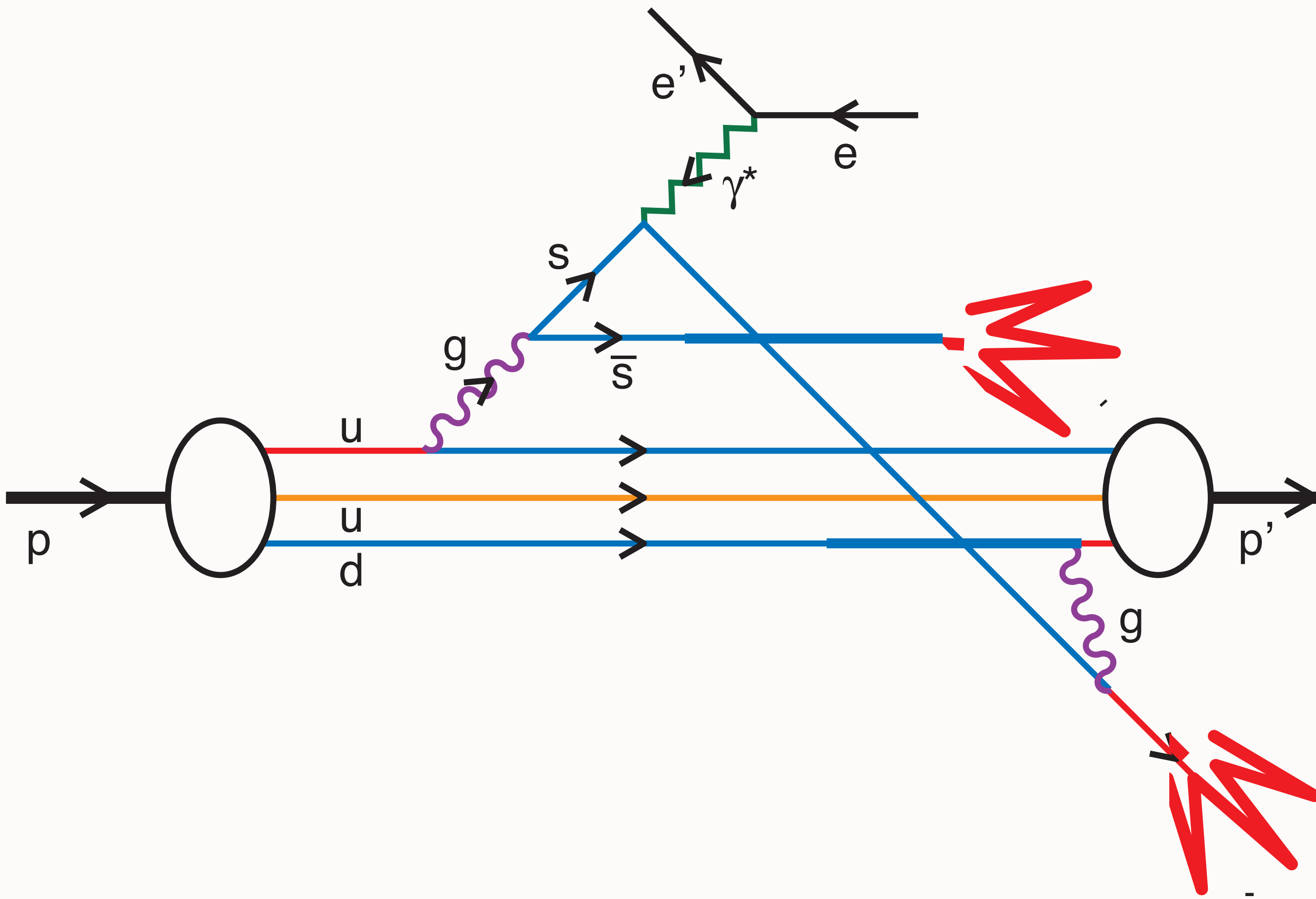
Deep Inelastic Electron-Proton Scattering

Production of new types of quarks from quantum fluctuations



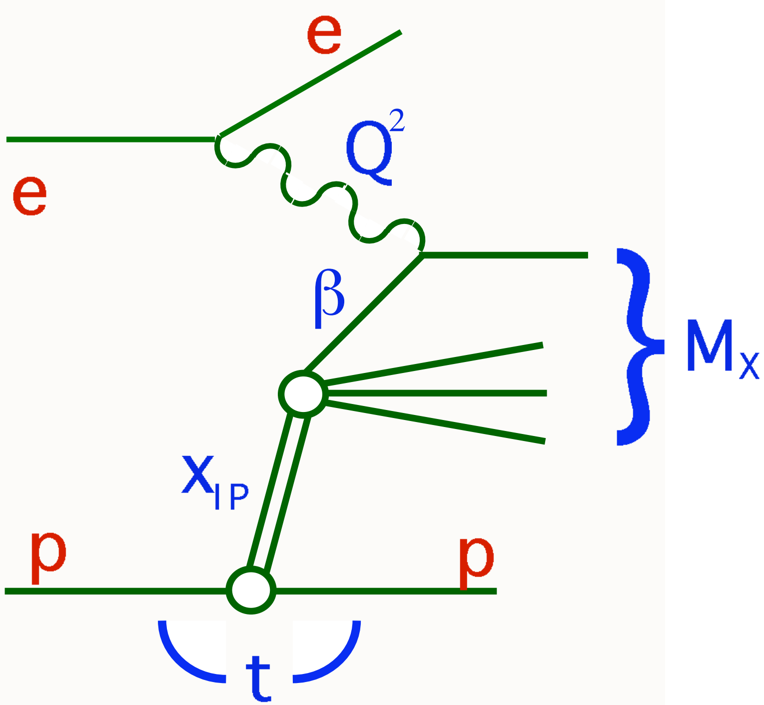
strange, charm, bottom, top quarks
and antiquarks

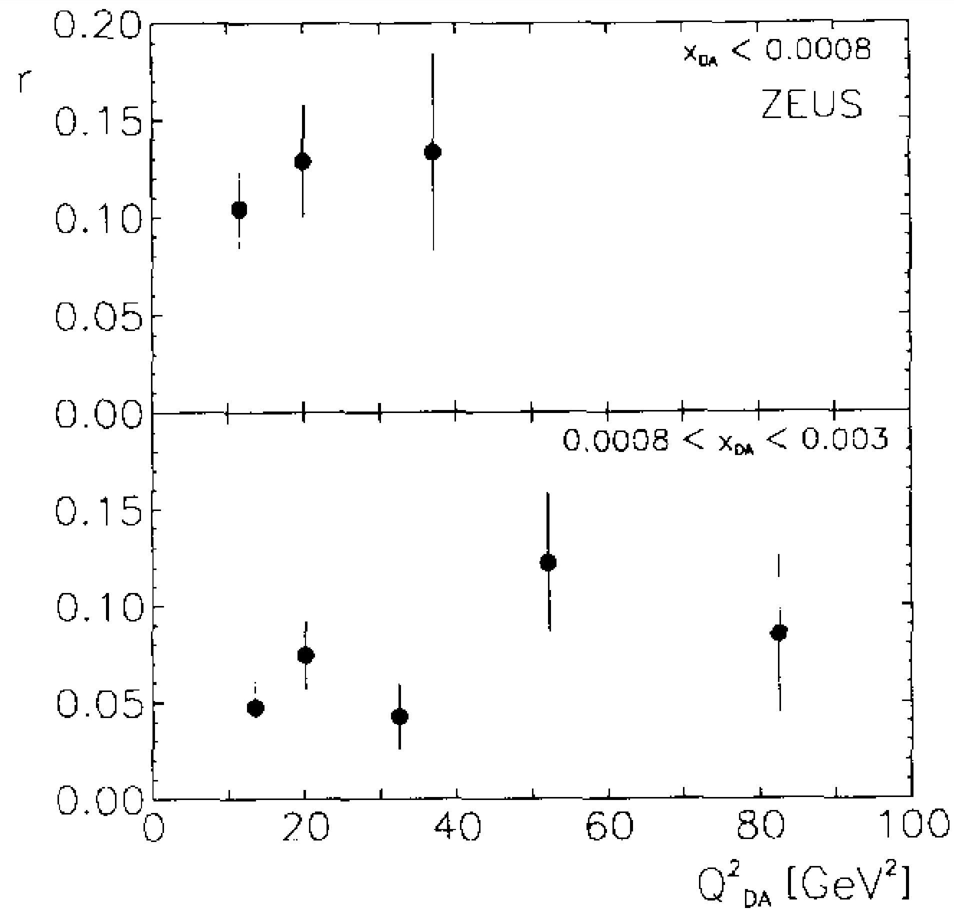
Diffractive Deep Inelastic Scattering



Proton Remains Intact in Final State

Remarkable observation at HERA



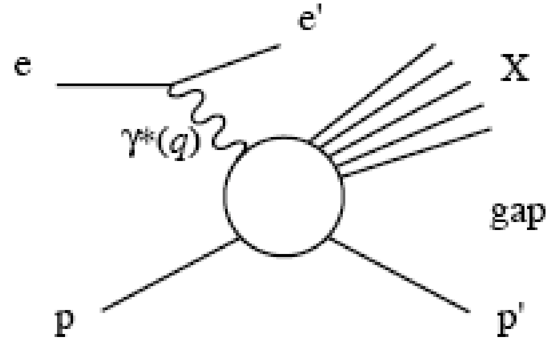


Fraction r of events with a large rapidity gap, $\eta_{\max} < 1.5$, as a function of Q^2_{DA} for two ranges of x_{DA}. No acceptance corrections have been applied.

10% to 15% of DIS events are diffractive !

M. Derrick et al. [ZEUS Collaboration], Phys. Lett. B 315, 481 (1993).

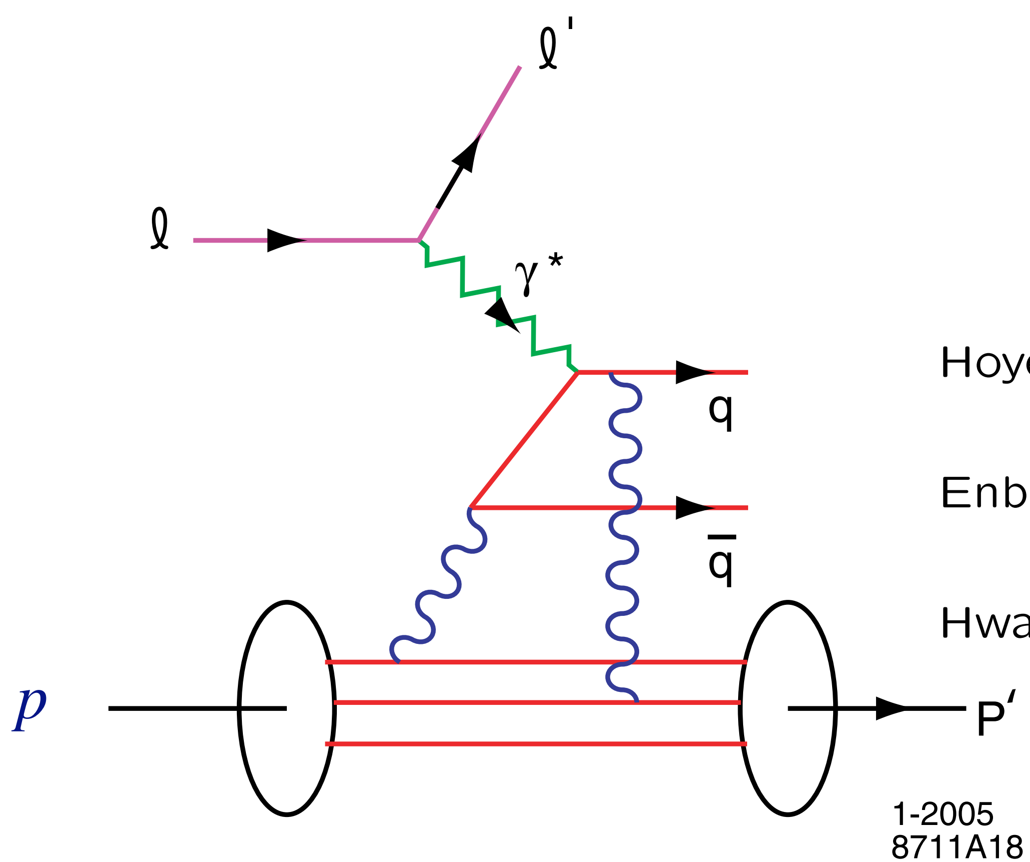
DDIS



- In a large fraction ($\sim$ 10–15%) of DIS events, the proton escapes intact, keeping a large fraction of its initial momentum
- This leaves a large *rapidity gap* between the proton and the produced particles
- The t-channel exchange must be *color singlet* $\rightarrow$ a pomeron??

Diffractive Deep Inelastic Lepton-Proton Scattering

Final State Interaction Produces Diffractive DIS



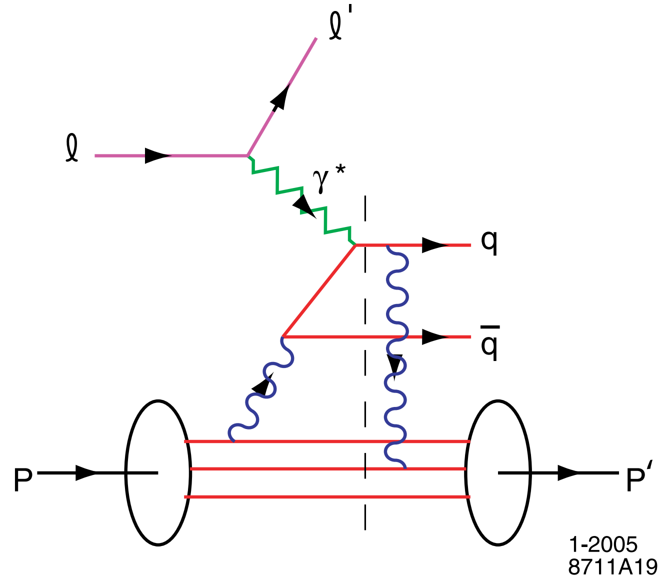
Quark Rescattering

Hoyer, Marchal, Peigne, Sannino, SJB (BHM

Enberg, Hoyer, Ingelman, SJB

Hwang, Schmidt, SJB

Low-Nussinov model of Pomeron



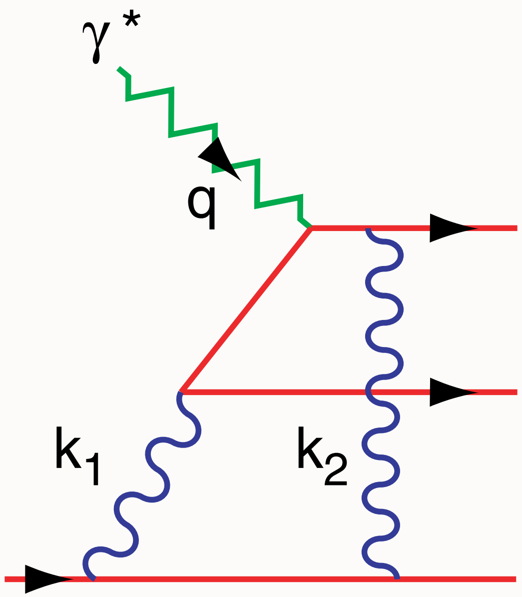
Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate
Pomeron

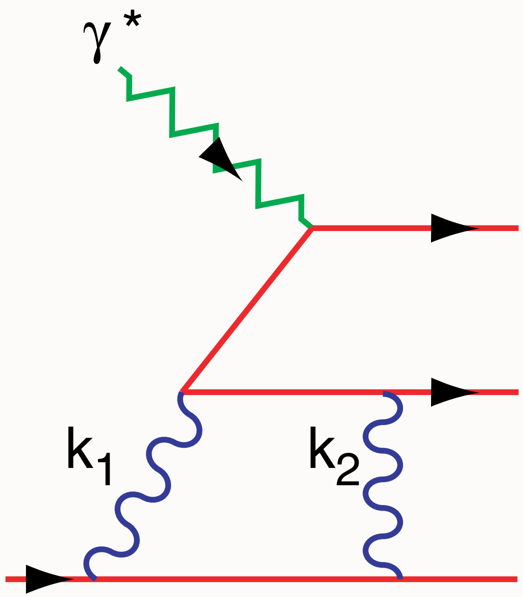
Need Imaginary Phase to Generate
T-Odd Single-Spin Asymmetry

Physics of FSI not in Wavefunction of Target

Final State Interactions in QCD



Feynman Gauge

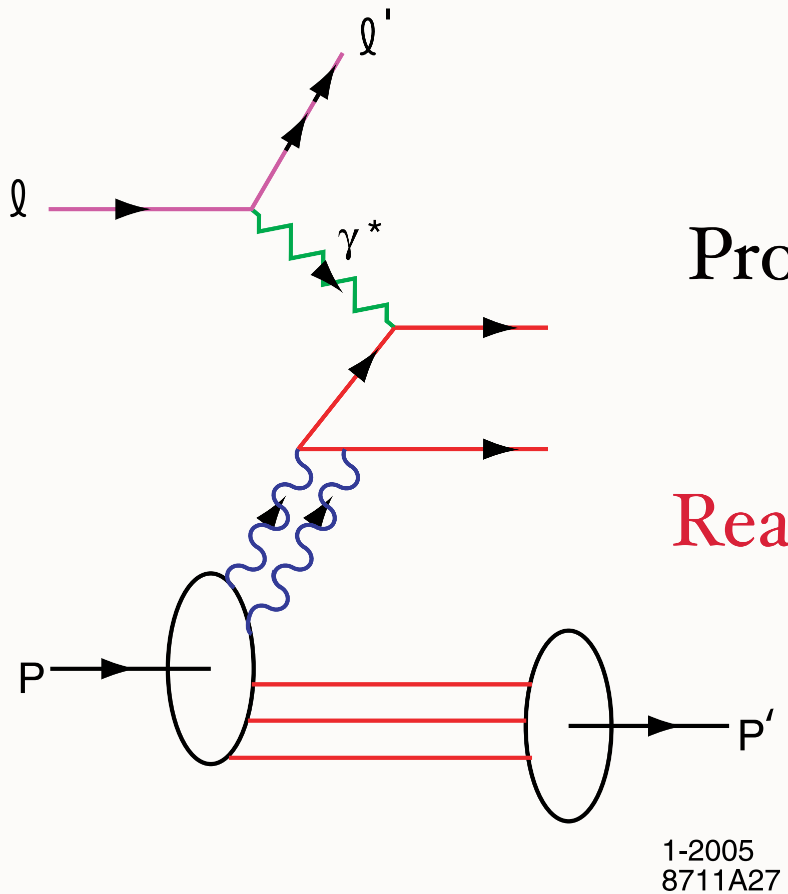


Light-Cone Gauge

Result is Gauge Independent

Problem: Wrong Phase

Conventional Model:
Pomeron acts as constituent of proton



Real; must be imaginary

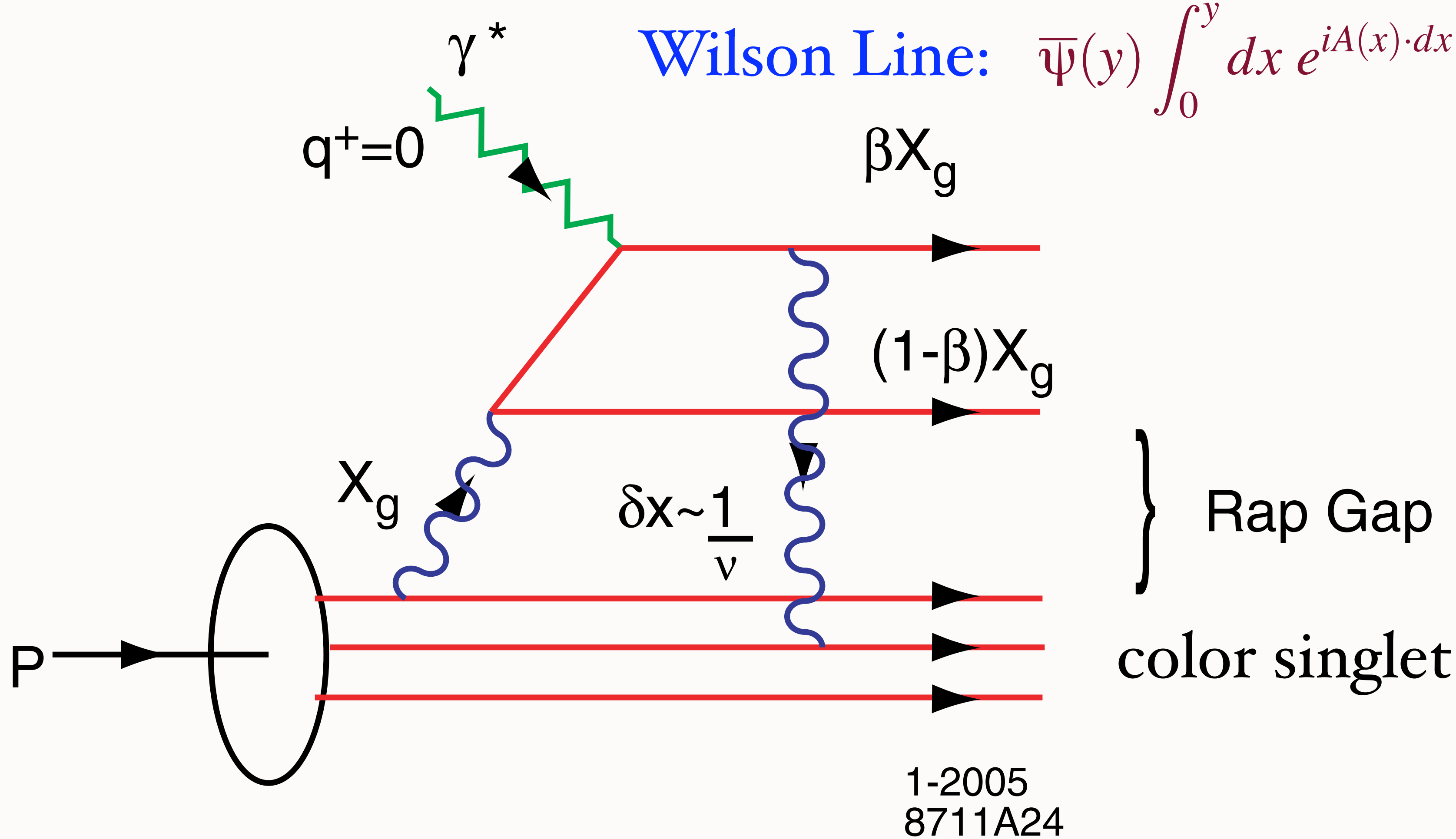
Need Final State Interactions !

Hoyer, Marchal. Peigne, Sannino, sjb

Enberg, Hoyer, Ingelman, sjb

QCD Mechanism for Rapidity Gaps

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



Consequences for DDIS

- Underlying hard scattering sub-process is the same in diffractive and non-diffractive events
- Same Q^2 dependence of diffractive and inclusive PDFs (remember: hard radiation not resolved)
- and same energy (W or x_B) dependence

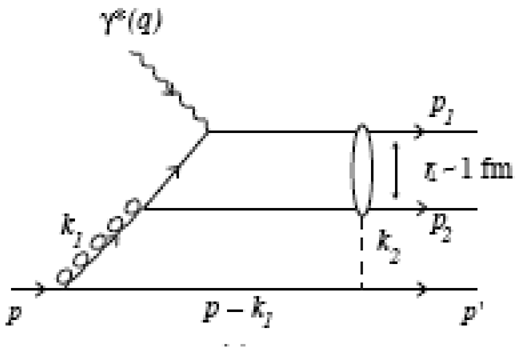
$\Rightarrow \frac{\sigma_{\text{diff}}}{\sigma_{\text{tot}}}$ independent of x_B and Q^2 (as in data)

Also describes: vector meson leptoproduction

BGMFS

- Note:
  - In pomeron models the ratio depends on $x_B^{1-\alpha_{I\!P}}$ *which is ruled out*
  - In a two-gluon model with two hard gluons, the diffractive cross section depends on $[f_{g/p}(x_B, Q^2)]^2$

- Rescattering gluons have small momenta
  $\Rightarrow$ β dependence of diffractive PDFs arises from underlying (non-perturbative) $g \to q\bar{q}$ and $g \to gg$



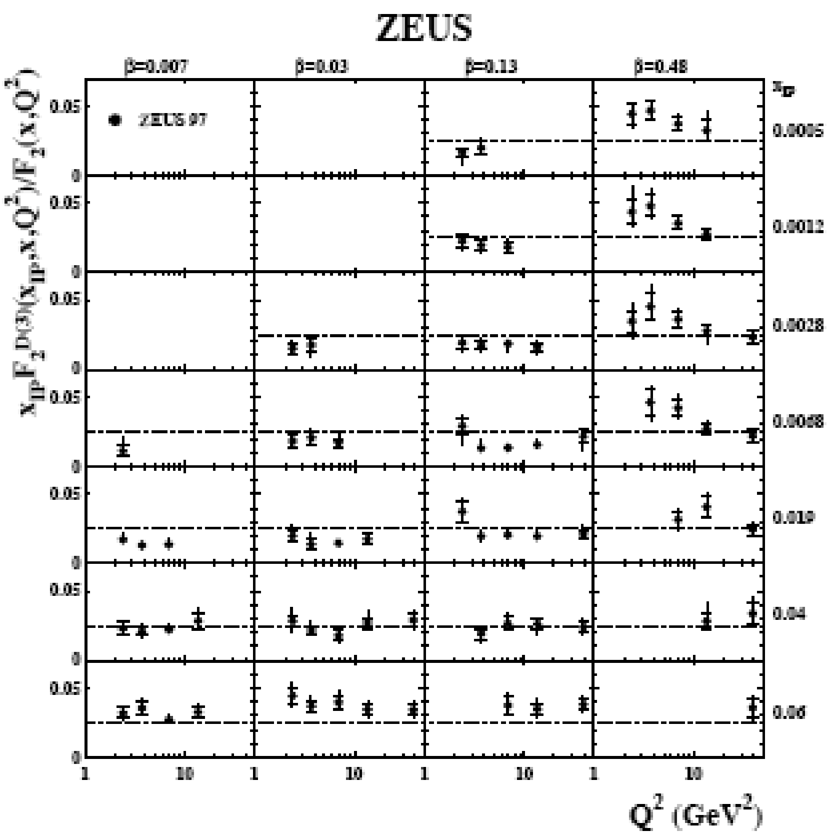
- *Effective* $I\!P$ distribution and quark structure function:

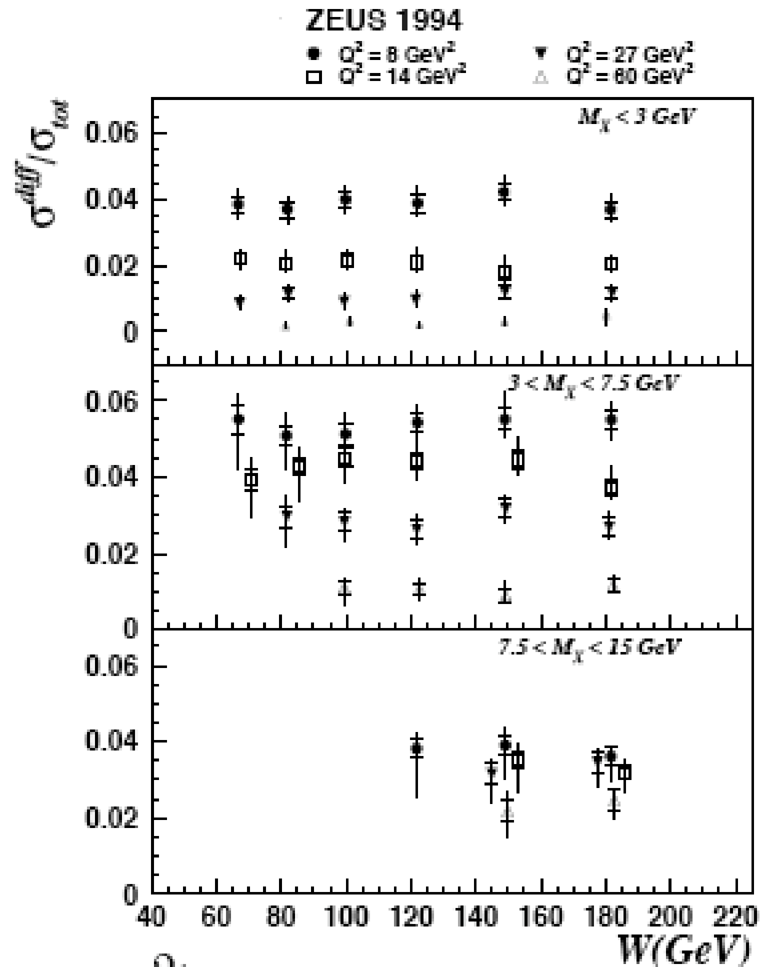
$$f_{I\!P/p}(x_{I\!P}) \propto g(x_{I\!P}, Q_0^2)$$
$$f_{q/I\!P}(\beta, Q_0^2) \propto \beta^2 + (1-\beta)^2$$

- Diffractive amplitudes from rescattering are dominantly *imaginary* — as expected for diffraction (Ingelman–Schlein $I\!P$ model has real amplitudes)

S. J. Brodsky, P. Hoyer, N. Marchal, S. Peigne and F. Sannino, Phys. Rev. D 65, 114025 (2002) [arXiv:hep-ph/0104291].
S. J. Brodsky, R. Enberg, P. Hoyer and G. Ingelman, arXiv:hep-ph/0409119.

ZEUS data on cross section ratios



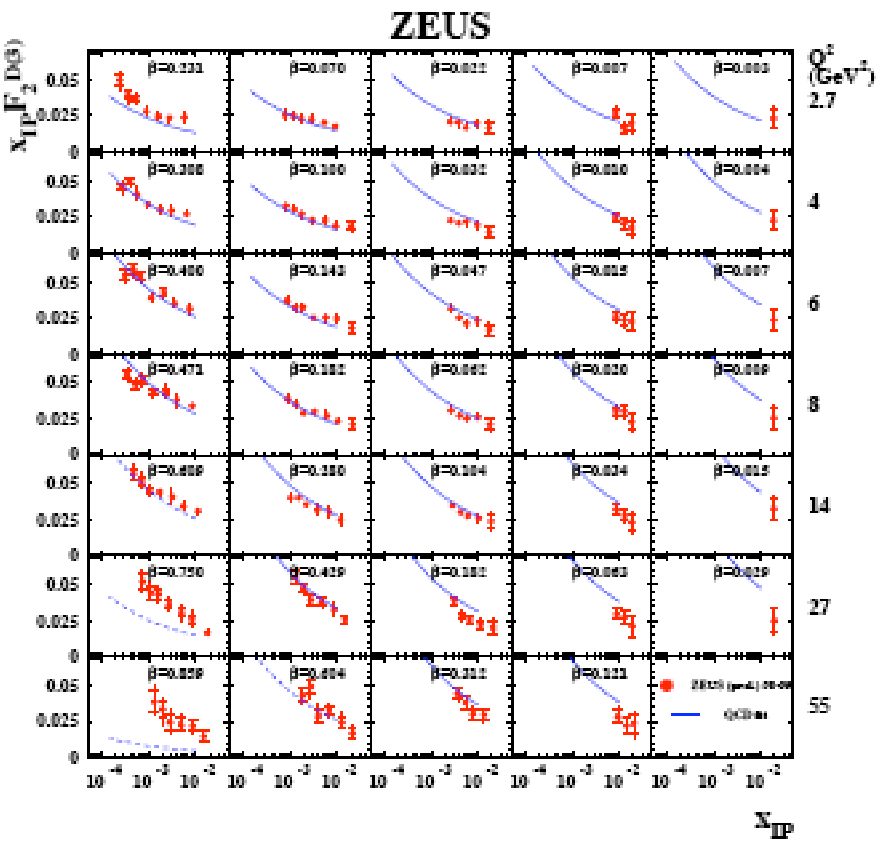


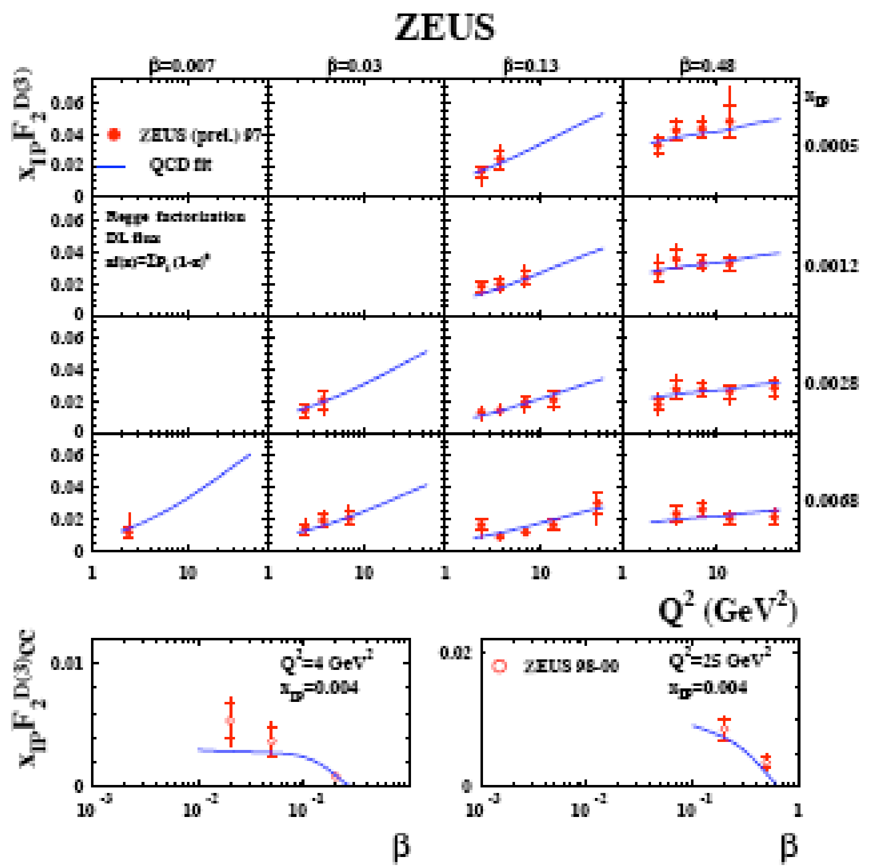
$$\frac{d\sigma^{DDIS}}{d\beta dQ^2 dx_{\mathbb{P}}} \Big/ \frac{d\sigma^{DIS}}{dx dQ^2} = \frac{x_{\mathbb{P}} F_2^D(x_{\mathbb{P}}, x, Q^2)}{F_2(x_{\mathbb{P}}, x, Q^2)}$$

Same W dependence

The Pomeron formalism

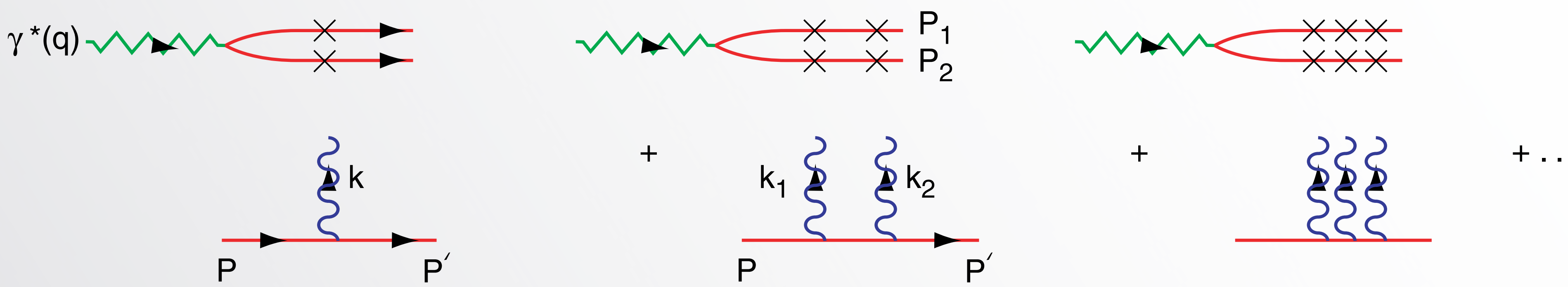
F_2^D is fitted to HERA data $\longrightarrow$ good description





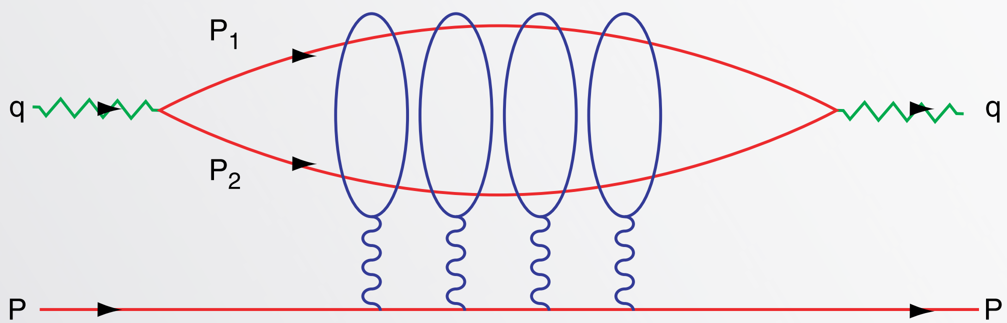
Lines given by fit with NLO QCD evolution

Lab Frame Picture

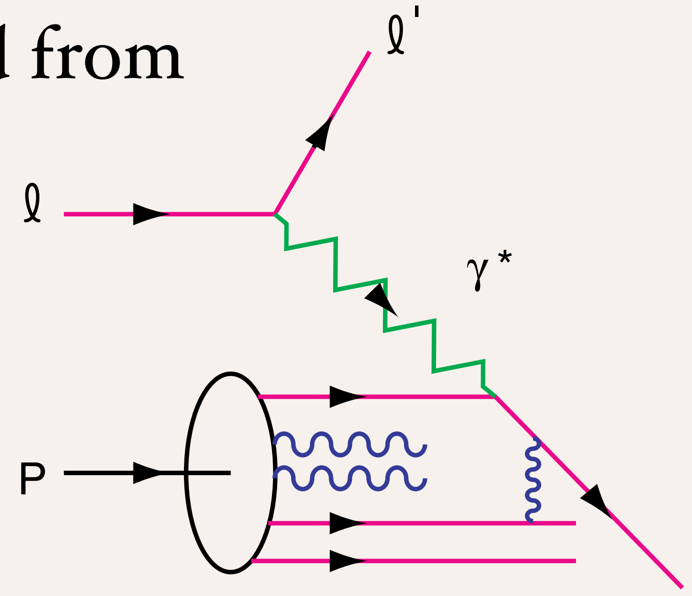


Sum Eikonal Interactions

Similar to Color Dipole Model



- Quarks Reinteract in Final State
- Analogous to Coulomb phases, but not unitary
- Observable effects: DDIS, SSI, shadowing, antishadowing
- Structure functions cannot be computed from LFWFs computed in isolation
- Wilson line not 1 even in lcg



$$Q^4 \frac{d\sigma}{dQ^2\, dx_B} = \frac{\alpha_{\rm em}}{16\pi^2} \frac{1-y}{y^2} \frac{1}{2M\nu} \int \frac{dp_2^-}{p_2^-} d^2\vec{r}_T\, d^2\vec{R}_T\, |\tilde{M}|^2$$

where

$$|\tilde{M}(p_2^-, \vec{r}_T, \vec{R}_T)| = \left| \frac{\sin\left[g^2\, W(\vec{r}_T, \vec{R}_T)/2\right]}{g^2\, W(\vec{r}_T, \vec{R}_T)/2} \tilde{A}(p_2^-, \vec{r}_T, \vec{R}_T) \right|$$

is the resummed result. The Born amplitude is

$$\tilde{A}(p_2^-, \vec{r}_T, \vec{R}_T) = 2eg^2 MQp_2^-\, V(m_{||} r_T) W(\vec{r}_T, \vec{R}_T)$$

where $m_{||}^2 = p_2^- M x_B + m^2$ and

FSI not Unitary Phase!

$$V(m\, r_T) \equiv \int \frac{d^2\vec{p}_T}{(2\pi)^2} \frac{e^{i\vec{r}_T\cdot\vec{p}_T}}{p_T^2 + m^2} = \frac{1}{2\pi} K_0(m\, r_T).$$

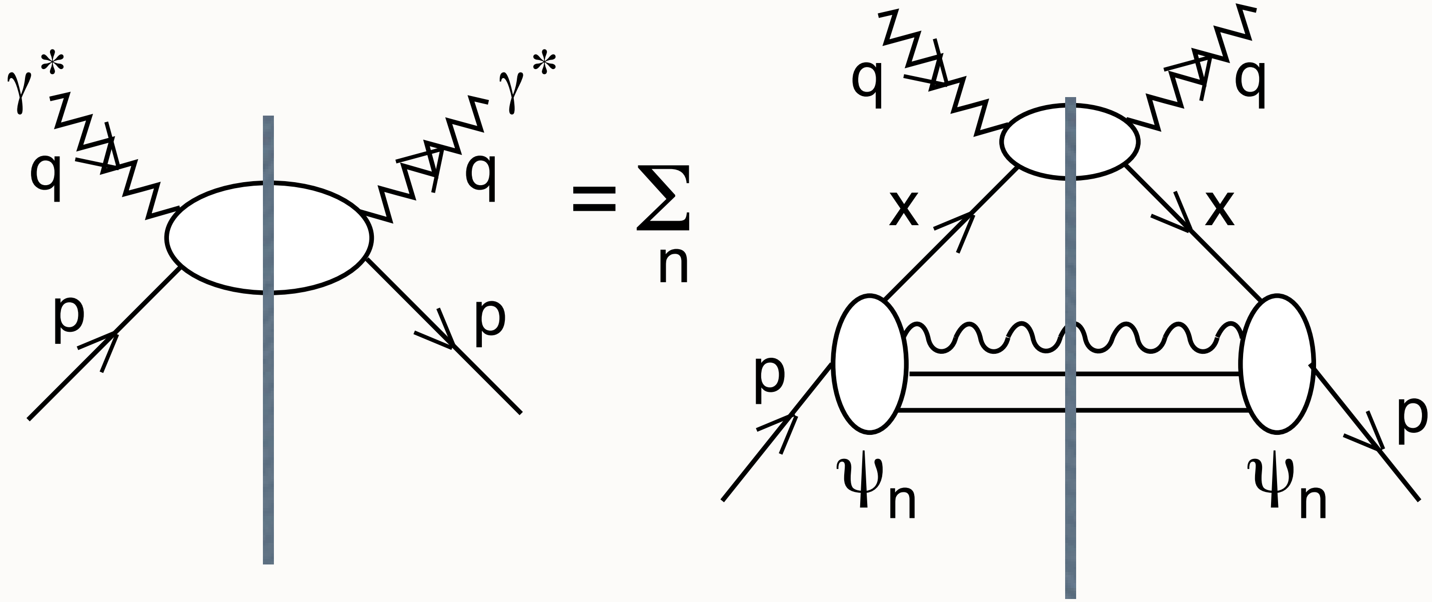
The rescattering effect of the dipole of the $q\overline{q}$ is controlled by

$$W(\vec{r}_T, \vec{R}_T) \equiv \int \frac{d^2\vec{k}_T}{(2\pi)^2} \frac{1 - e^{i\vec{r}_T\cdot\vec{k}_T}}{k_T^2} e^{i\vec{R}_T\cdot\vec{k}_T} = \frac{1}{2\pi} \log\left(\frac{|\vec{R}_T + \vec{r}_T|}{R_T}\right).$$

Precursor of Nuclear Shadowing

BHMPS

Deep Inelastic Lepton Proton Scattering

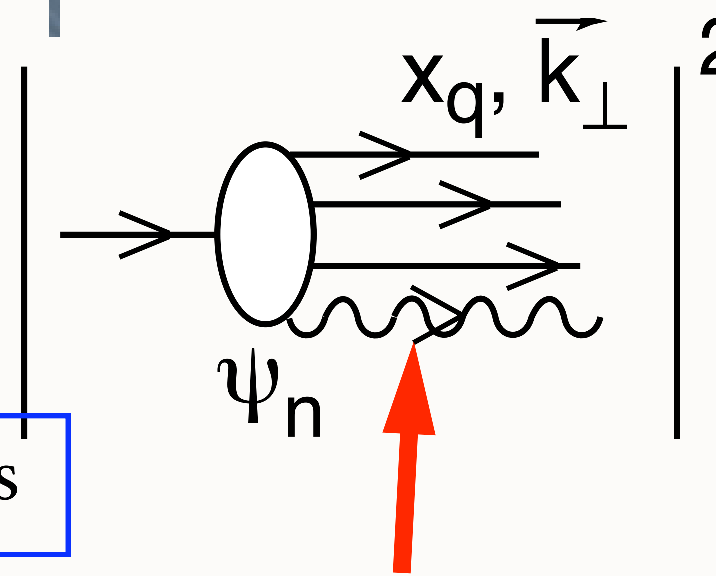


Imaginary Part of
Forward Virtual Compton Amplitude

$q(x,Q^2) = \sum_n \int^{k_\perp^2 \leq Q^2 \perp} d^2k_\perp \, |\Psi_n(x,k_\perp)|^2$

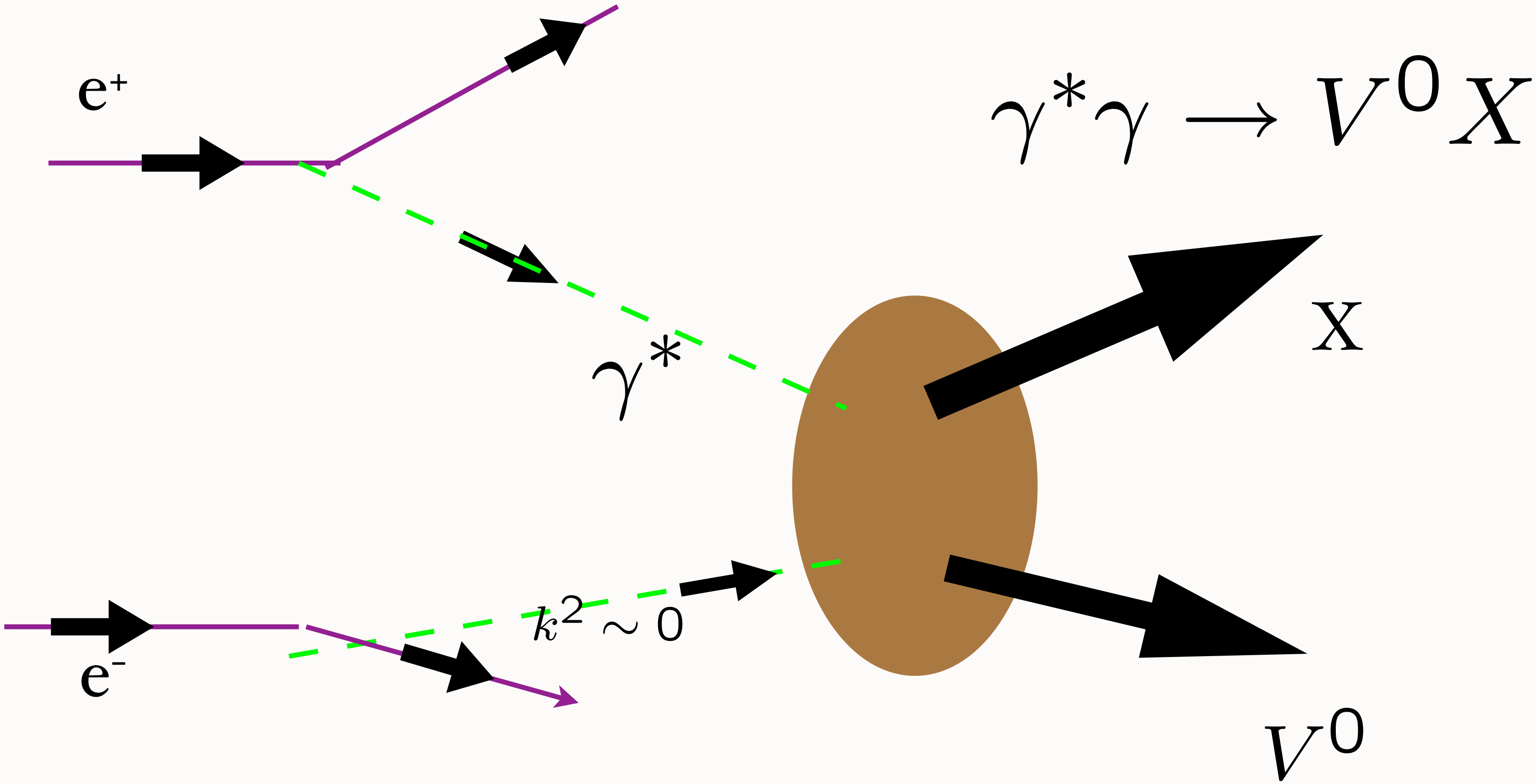
$x = x_q$

All spin, flavor distributions



Light-Front Wave Functions $\psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$

Photon Diffractive Structure Function

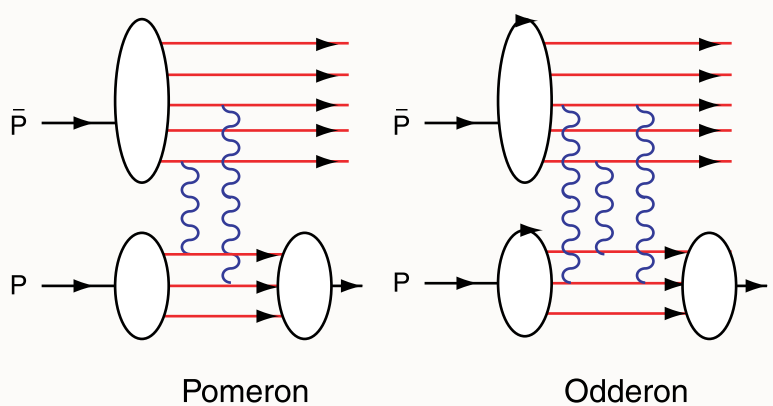


Diffractive deep inelastic scattering on a photon target

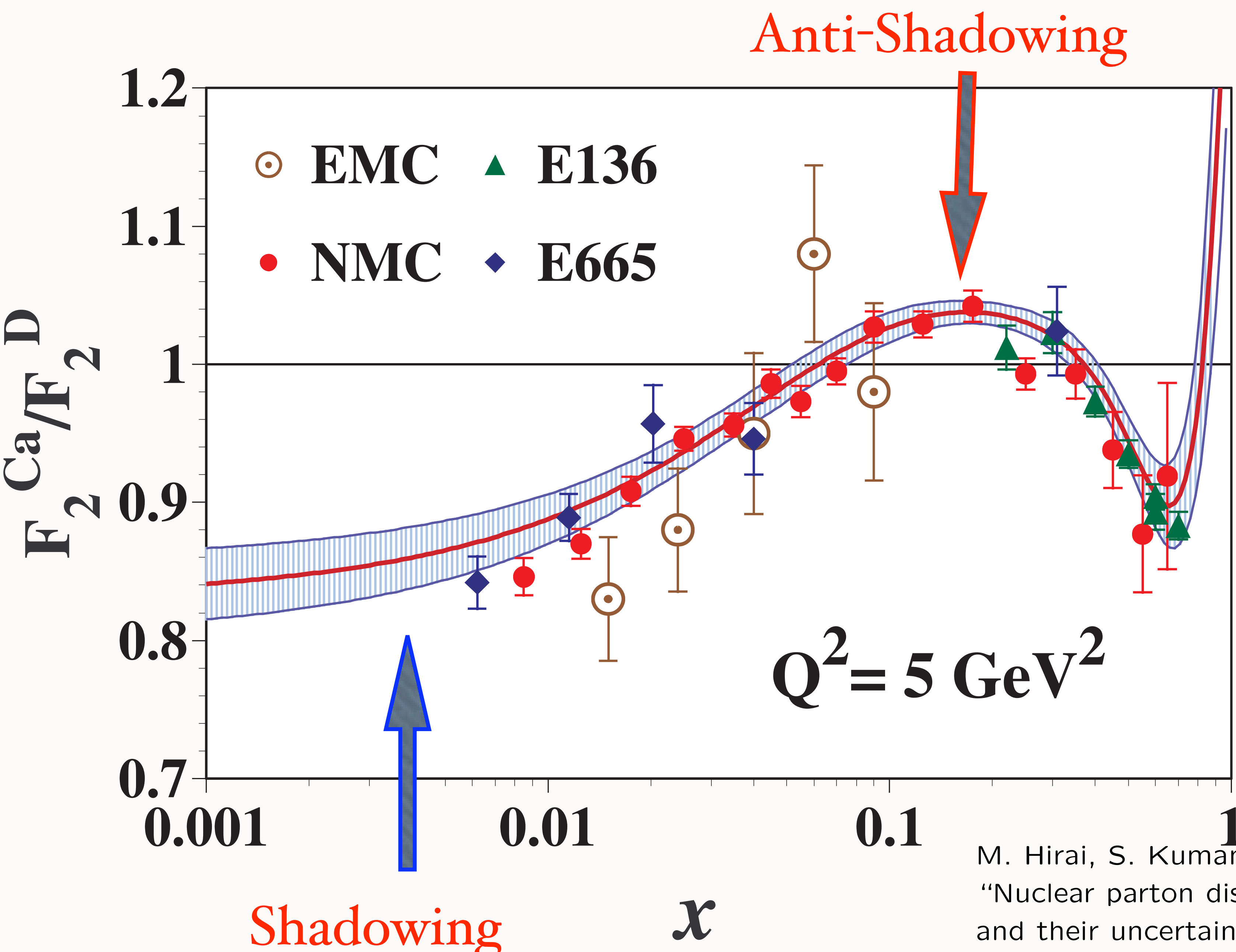
The Odderon

Merino, Rathsman, sjb

- Three-Gluon Exchange, C= -, J=1, Nearly Real Phase *BFKL*
- Interference of 2-gluon and 3-gluon exchange leads to matter/ antimatter asymmetries
- Asymmetry in jet asymmetry in $\gamma p \longrightarrow c\bar{c}p$ *e-p collider test*
- Analogous to lepton energy and angle asymmetry $\gamma Z \to e^+ e^- Z$
- Pion Asymmetry in $\gamma p \longrightarrow \pi^+ \pi^- p$



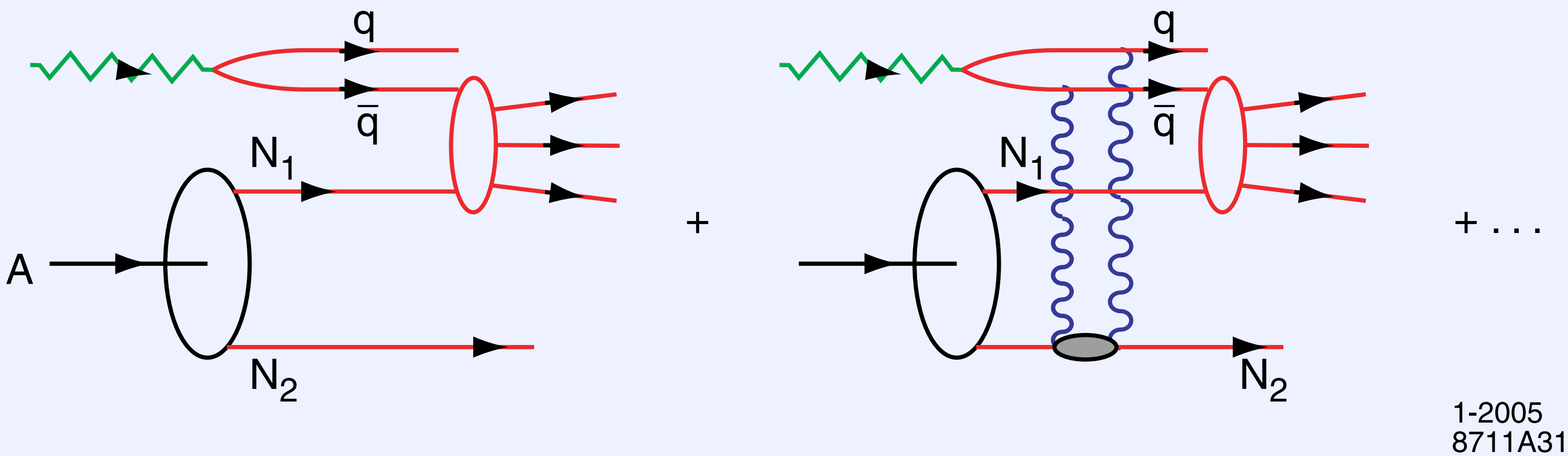
Odderon: Another source of antishadowing



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].

Pumplin, sjb
Gribov

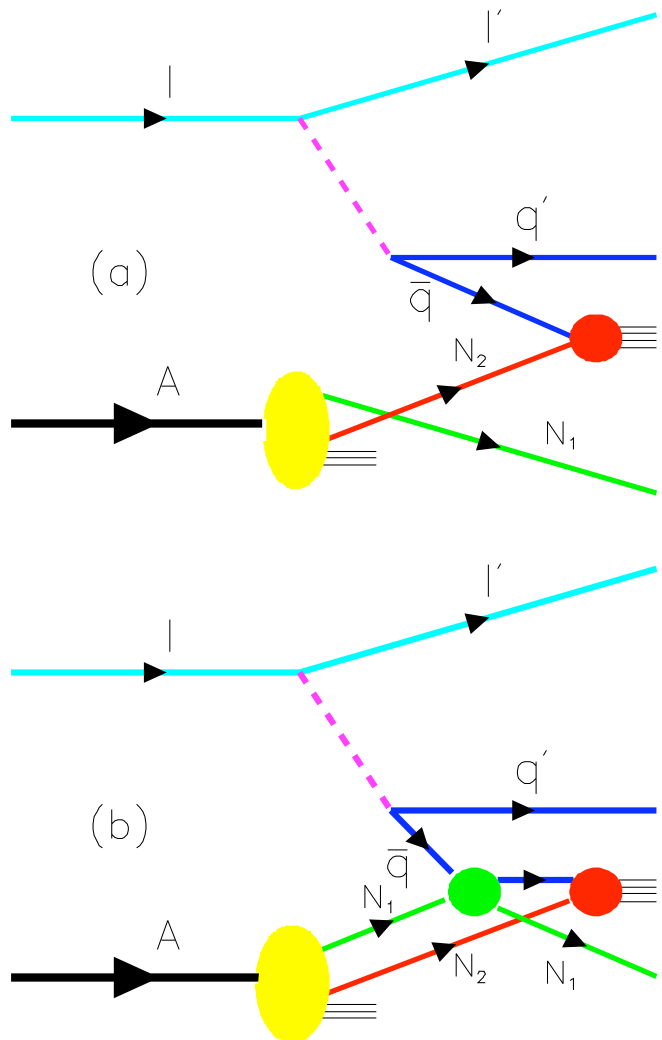
Nuclear Shadowing in QCD



Shadowing depends on understanding diffraction in DIS

Nuclear Shadowing not included in nuclear LFWF !

Dynamical effect due to virtual photon interacting in nucleus



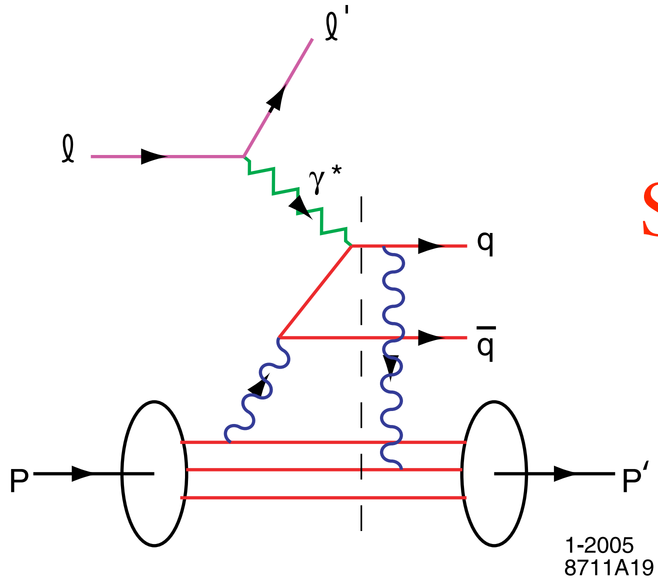
The one-step and two-step processes in DIS on a nucleus.

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

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

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

HERA DDIS produces observed nuclear shadowing



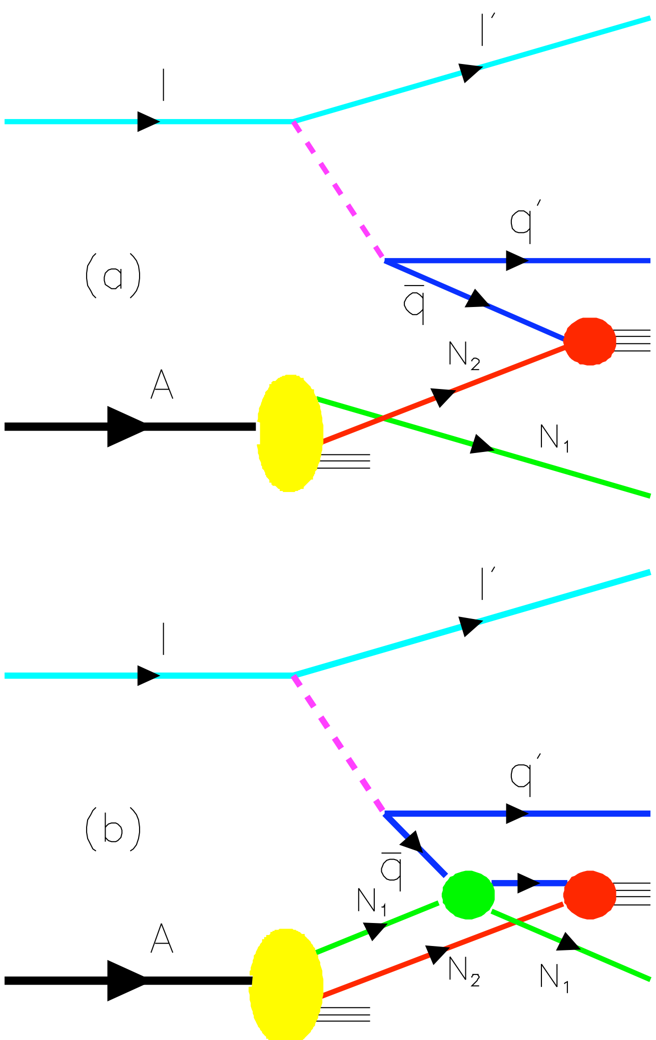
Shadowing depends on understanding diffraction in DIS

Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate Pomeron

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

Physics of FSI not in Wavefunction of Target



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

If the scattering on nucleon N_1 is via $C=-$ Reggeon or Odderon exchange, the one-step and two-step amplitudes are **constructive in phase, enhancing** the $\overline{q}$ flux reaching N_2

$\rightarrow$ Antishadowing of the DIS nuclear structure functions

Reggeon Exchange

Phase of two-step amplitude relative to one step:

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

Constructive Interference

Depends on quark flavor!

Thus antishadowing is not universal

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

Shadowing and Antishadowing in Lepton-Nucleus Scattering

- Shadowing: Destructive Interference
of Two-Step and One-Step Processes
Pomeron Exchange

- Antishadowing: Constructive Interference
of Two-Step and One-Step Processes!
Reggeon and Odderon Exchange

- Antishadowing is Not Universal!
Electromagnetic and weak currents:
different nuclear effects !
Potentially significant for NuTeV Anomaly}

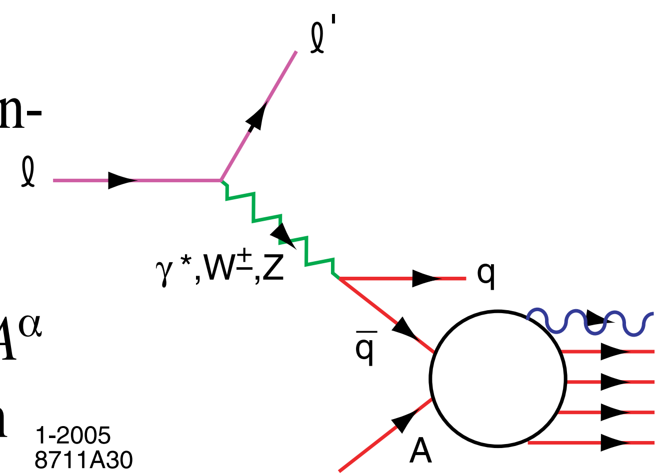
Origin of Nuclear Shadowing and Regge Behavior of Deep Inelastic Structure Functions

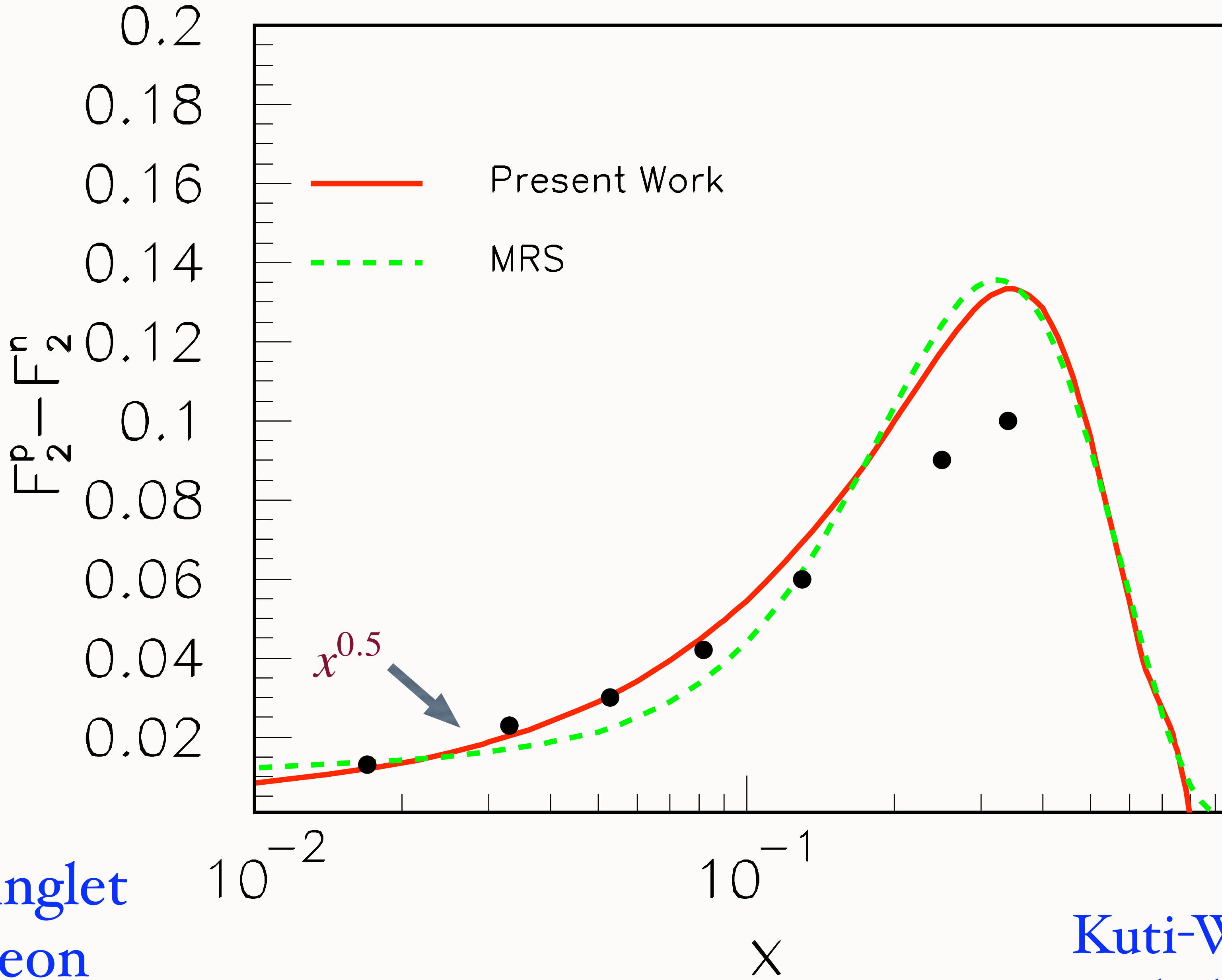
in light-cone gauge

Antiquark Interacts with Target Nucleus at Effective Energy $\hat{s} \propto 1/x_{Bj}$

$\sigma_{\bar{q}N} \sim \hat{s}^{\alpha_R - 1} \rightarrow F_{2N}(x_{bj}) \sim x^{1-\alpha_R}$ at small x_{bj}

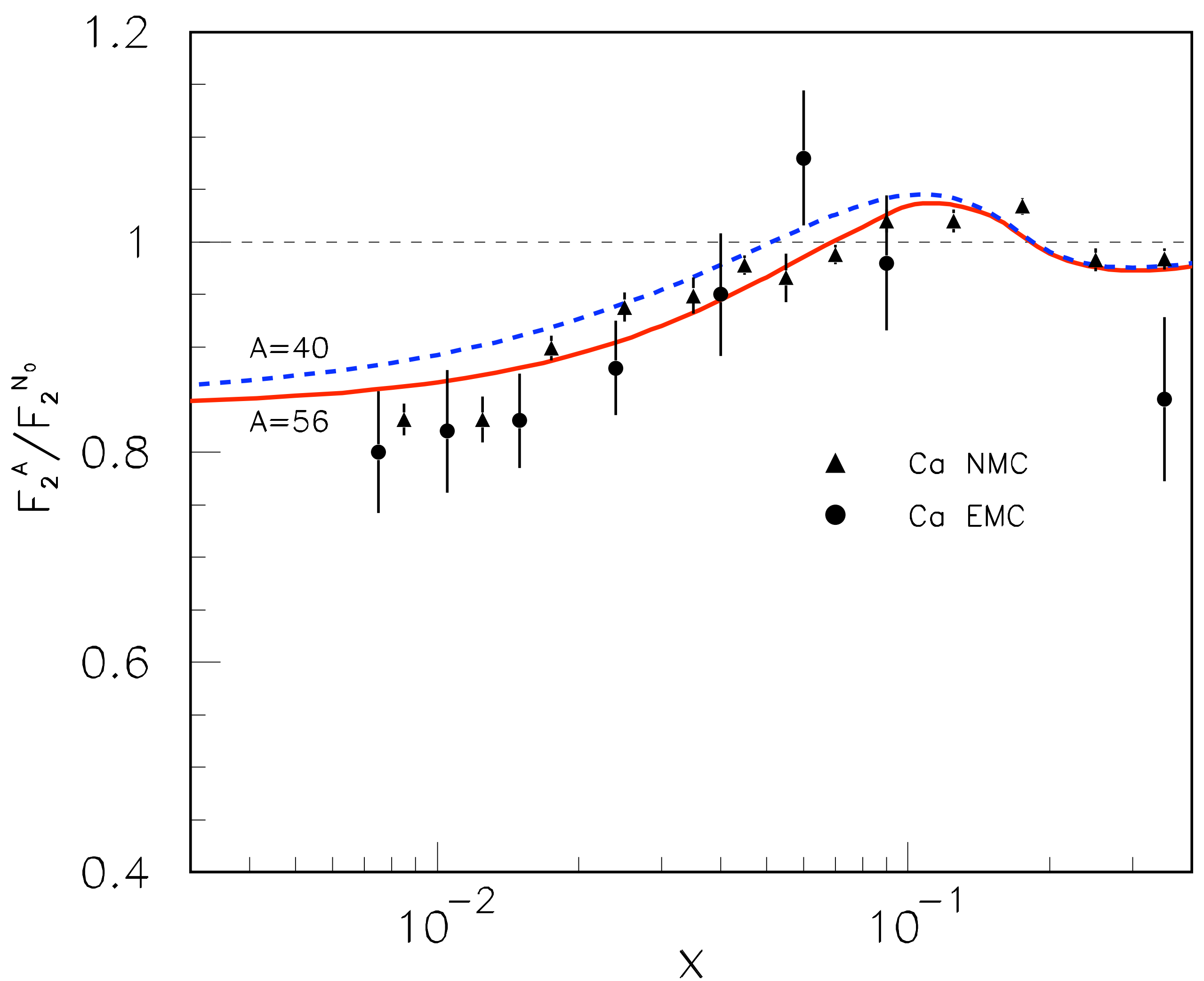
Shadowing of antiquark-nucleus cross section $\sigma_{\bar{q}A} \sim A^{\alpha}$ produces same A dependence of nuclear structure function





Non-singlet Reggeon Exchange

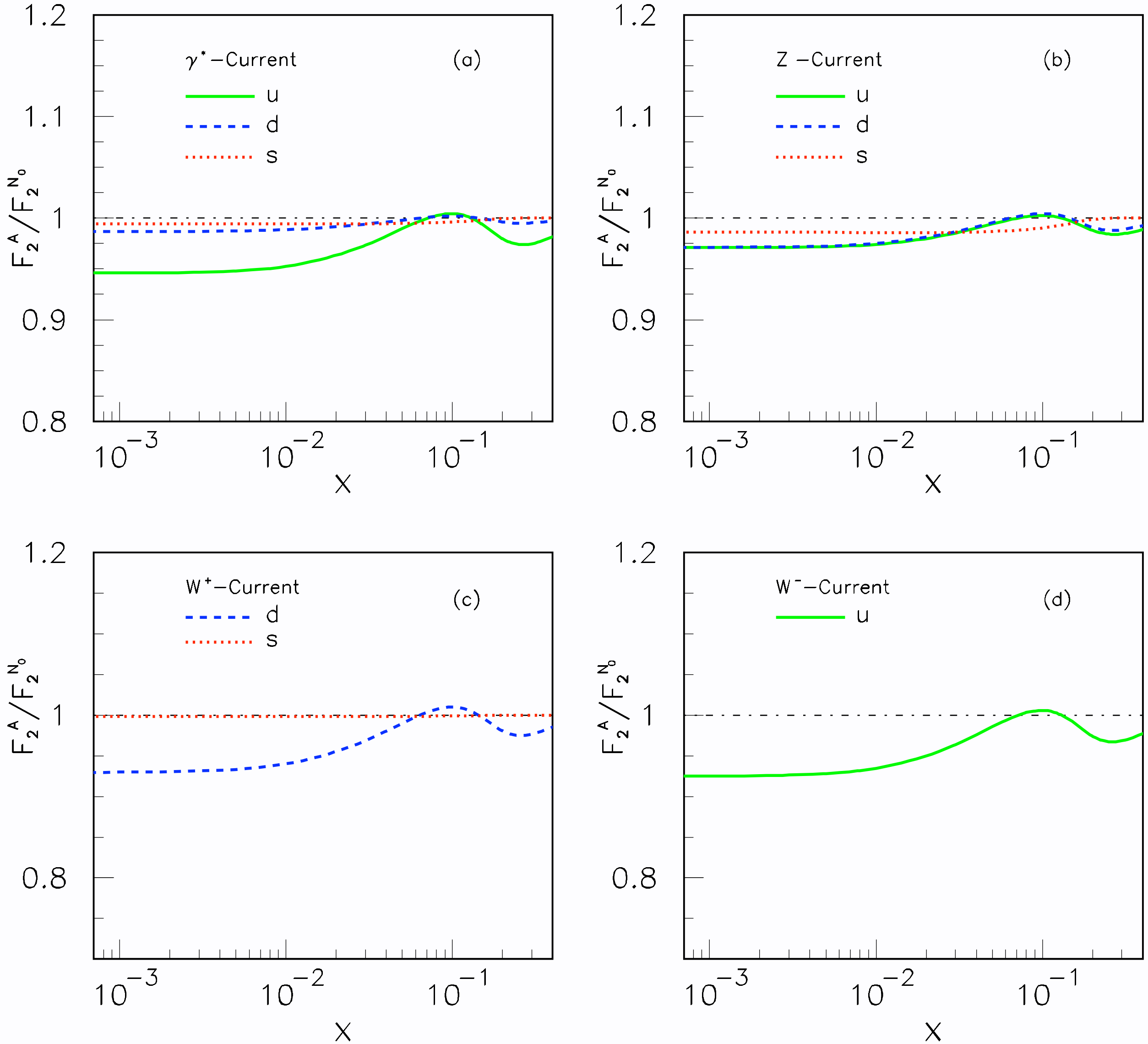
Kuti-Weisskopf behavior



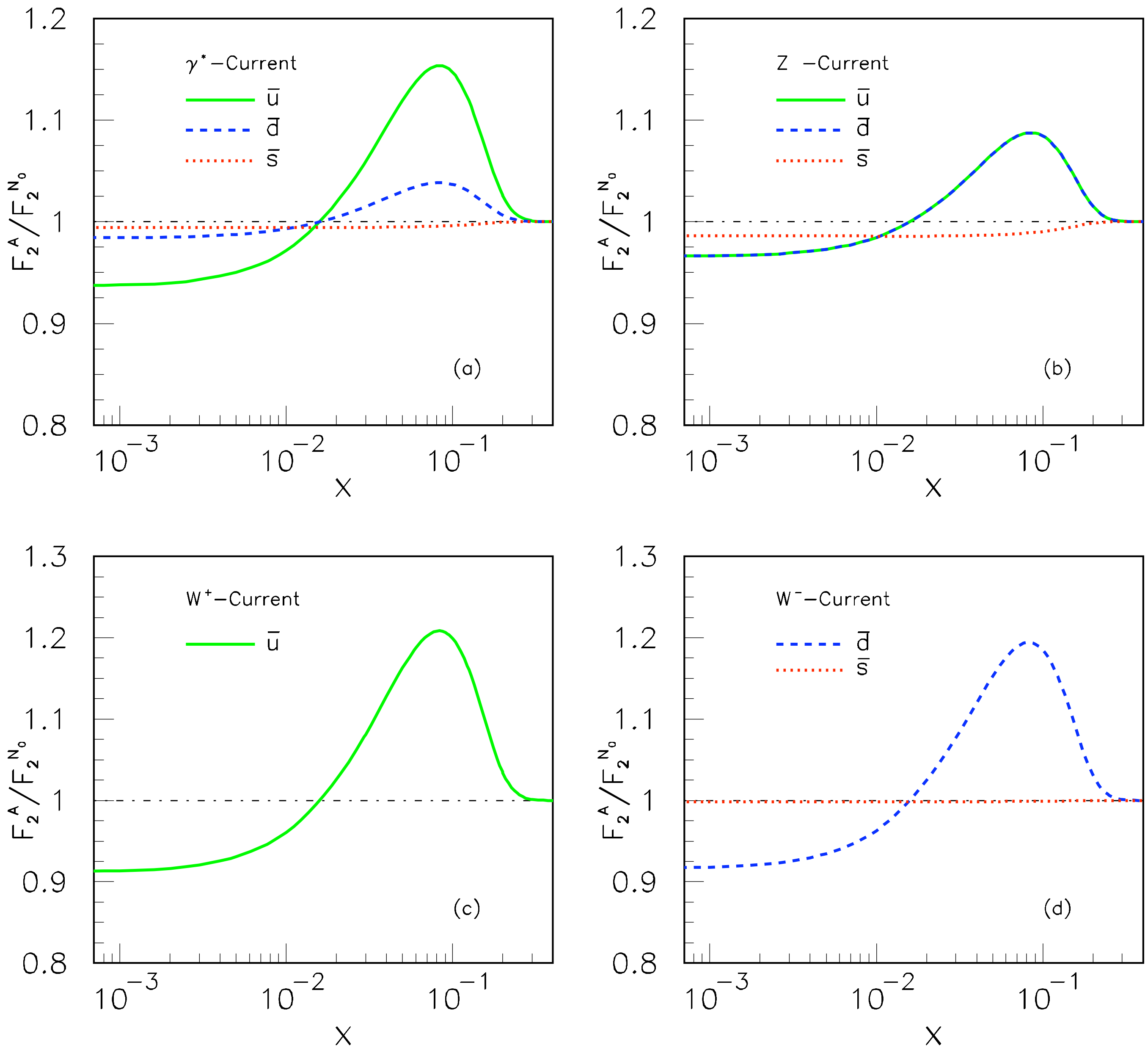
The nuclear shadowing and antishadowing effects at $\langle Q^2 \rangle = 1 \text{ GeV}^2$

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].

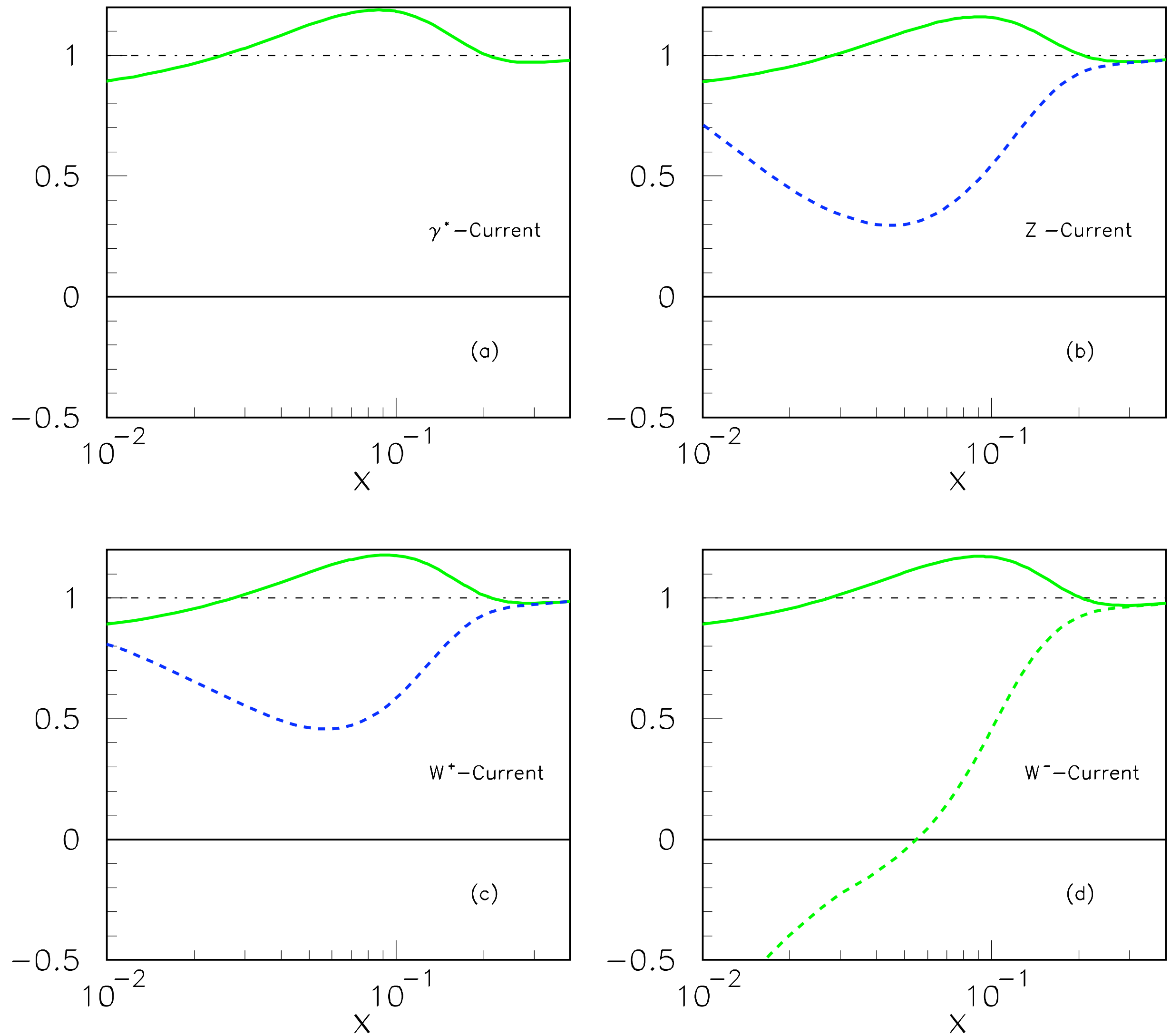
Shadowing and Antishadowing of DIS Structure Functions



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].

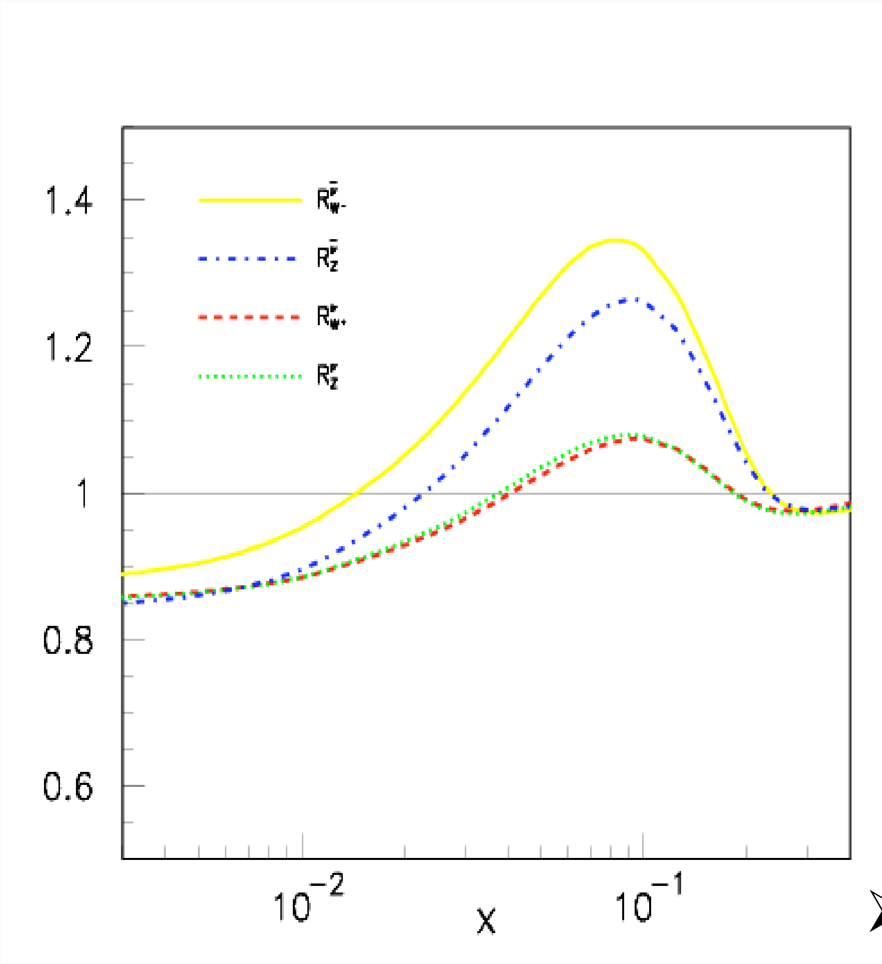


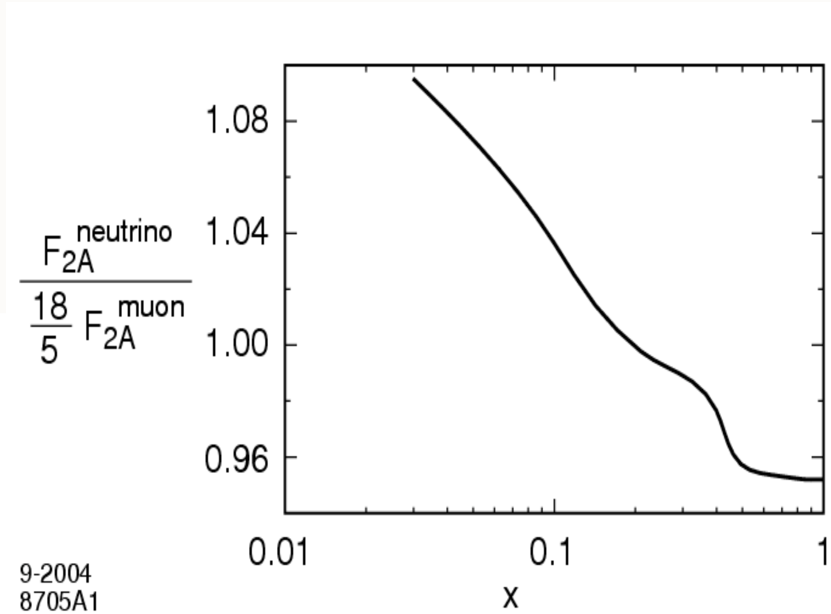
Nuclear Effect not Universal !



Ratios $F_2^A/F_2^{N^0}$ (solid curves) and $F_3^A/F_3^{N^0}$ (dashed curves)

Model predictions





$$R_Z^{\nu}(x) = \frac{d\sigma(\nu_\mu + A \to \nu_\mu + X)/dx}{d\sigma(\nu_\mu + N \to \nu_\mu + X)/dx}$$

- Bigger antishadowing for $\bar{\nu}$
- Different NC-CC effects only for $\bar{\nu}$

Coherence of multiscattering nuclear processes → { Shadowing, Antishadowing }

Different antishadowing for → { Neutral currents, Charged currents, Electromagnetic currents }

Estimate 20% effect on extraction of $\sin^2\theta_W$ for NuTeV

Need new experimental studies of antishadowing in

- Parity-violating DIS
- Spin Dependent DIS
- Charged and Neutral Current DIS

Nuclear Shadowing and Anti-Shadowing in QCD

- Relation to Diffractive DIS and Final-State Interactions
- Novel Color Effects
- Non-Universality of Antishadowing
- Implications for NuTeV

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

H. J. Lu and SJB "Shadowing And Antishadowing Of Nuclear Structure Functions," Phys. Rev. Lett. **64**, 1342 (1990).

Jian-Jun Yang

Ivan Schmidt

Hung Jung Lu

Hard Diffraction from Rescattering

Unification:

- Diffractive Deep Inelastic Scattering (DDIS)
- Nuclear Shadowing & Antishadowing
- Single Spin Asymmetries (Sivers Effect)
- Diffractive Di-jets, Tri-jets
- Fundamental Features of Gauge Theory, Color

Novel Diffractive Phenomena and New Insights Into QCD from AdS/CFT

- Ashery Diffractive Di-Jet Production:

- First measurement of hadron wavefunction

- Verification of QCD Color Transparency

- Related phenomena: Diffractive deep inelastic scattering and vector meson electroproduction

- Nuclear shadowing and antishadowing

- New "Exclusive Diffractive Mechanism" for high x_F Higgs Production

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

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

The Light Front Fock State Wavefunctions

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

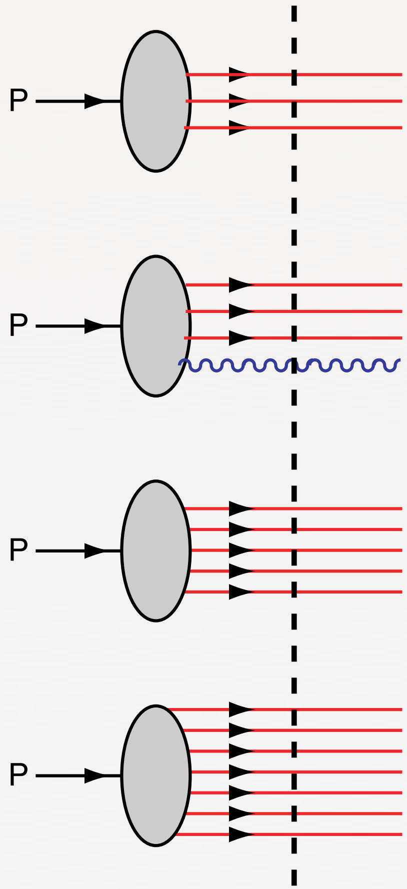
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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.

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



Intrinsic glue, sea quarks, charm, bottom

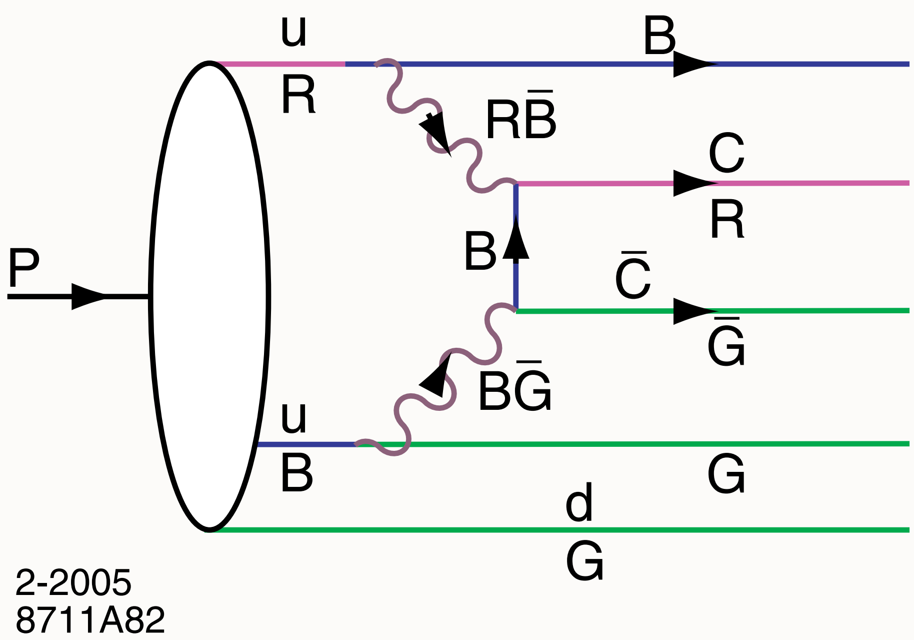
Fixed LF time

Hadrons Fluctuate in Particle Number

- Proton Fock States

  $|uud>, |uudg>, |uuds\bar{s}>, |uudc\bar{c}>, |uudb\bar{b}> \cdots$
- Strange and Anti-Strange Quarks not Symmetric

  $s(x) \neq \bar{s}(x)$
- "Intrinsic Charm": High momentum heavy quarks
- "Hidden Color": Deuteron not always p + n
- Orbital Angular Momentum Fluctuations - Anomalous Magnetic Moment



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

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

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

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

OPE derivation - M.Polyakov et al.

$c\bar{c}$ in Color Octet

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

High x charm!

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

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

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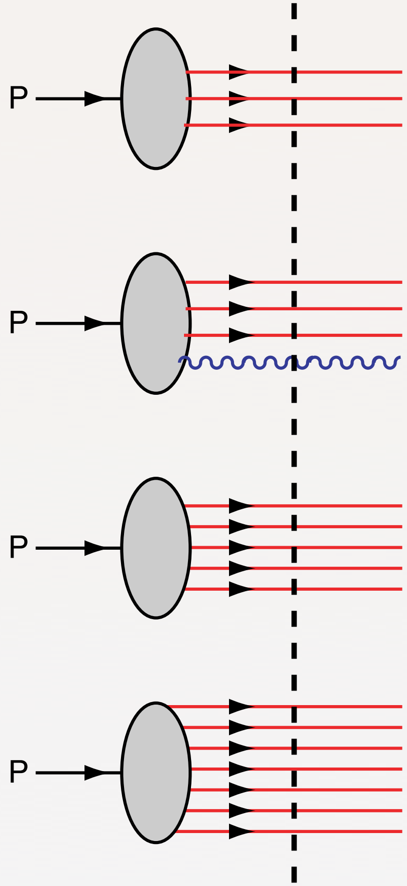
are boost invariant.

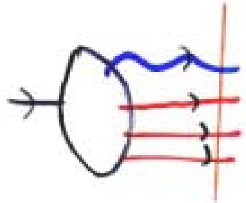
$$\sum_i^n k_i^+ = P^+, \; \sum_i^n x_i = 1, \; \sum_i^n \vec{k}_i^\perp = \vec{0}^\perp.$$

Intrinsic glue, sea quarks, charm, bottom

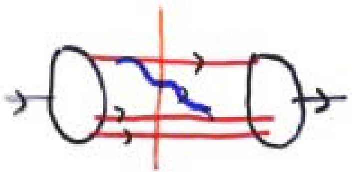


Fixed LF time

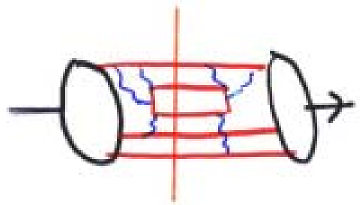
Hadrons: complex relativistic systems



fluctuations in particle no., size, spin, color



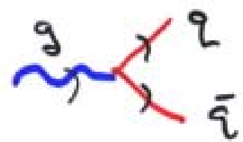
gluons intrinsic to hadron structure



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

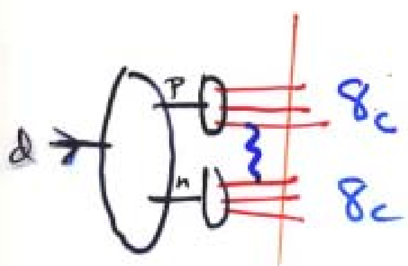
$s(x) \neq \bar{s}(x)$?

∴ sea not from pQCD gluon splitting alone



$q(x) = \bar{q}(x)$

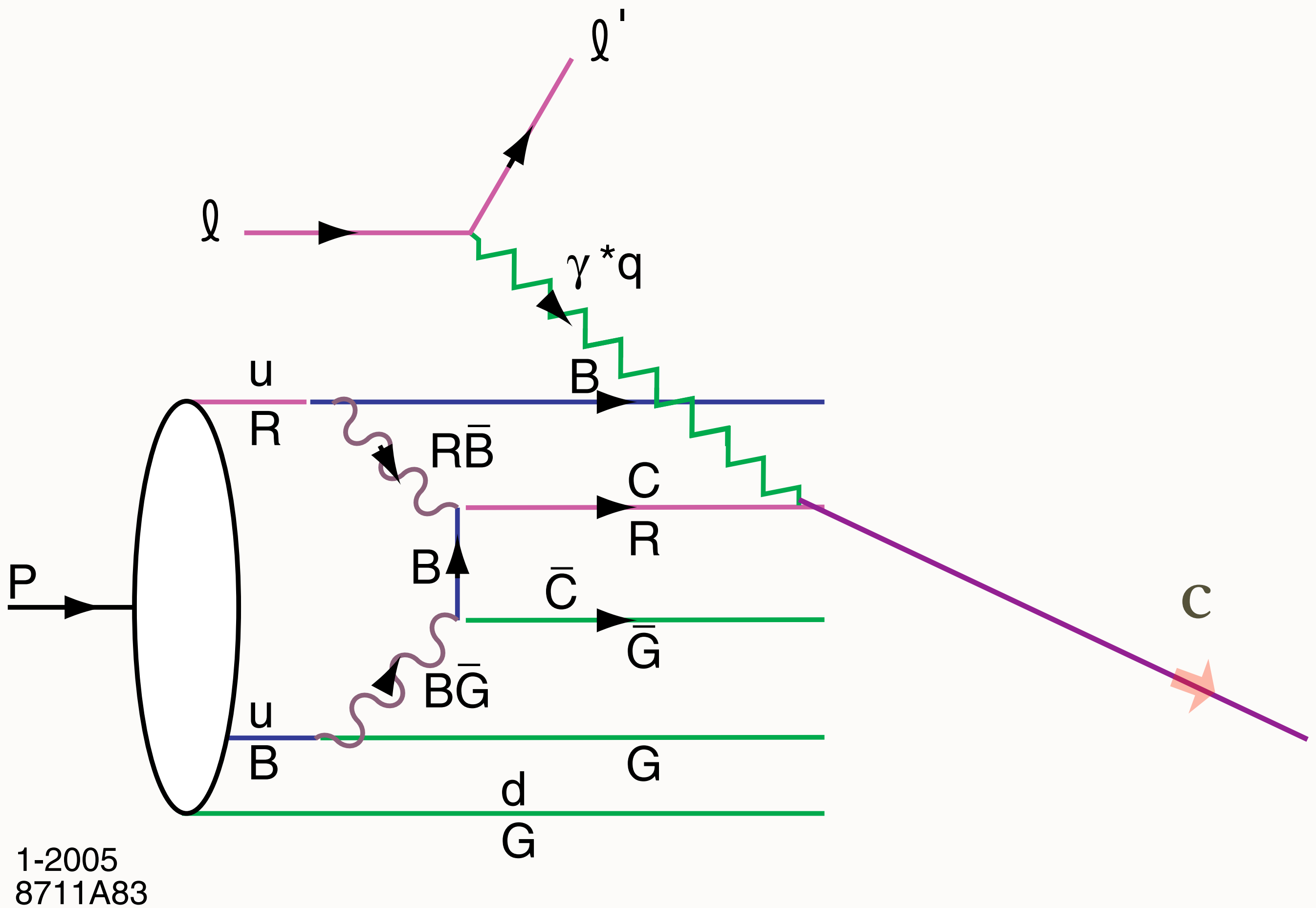
$\bar{u}(x) = \bar{d}(x)$



"Hidden color" in nuclei,

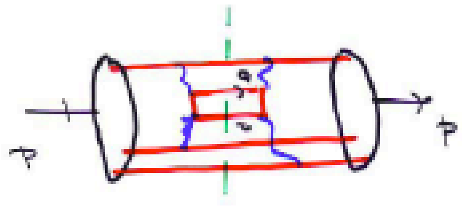
$\Psi_d \neq \Psi_n \otimes \Psi_p$

Measure c(x) in Deep Inelastic Lepton-Proton Scattering



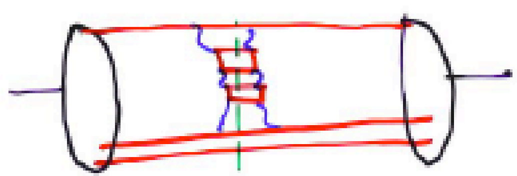
Hoyer, Peterson, SJB

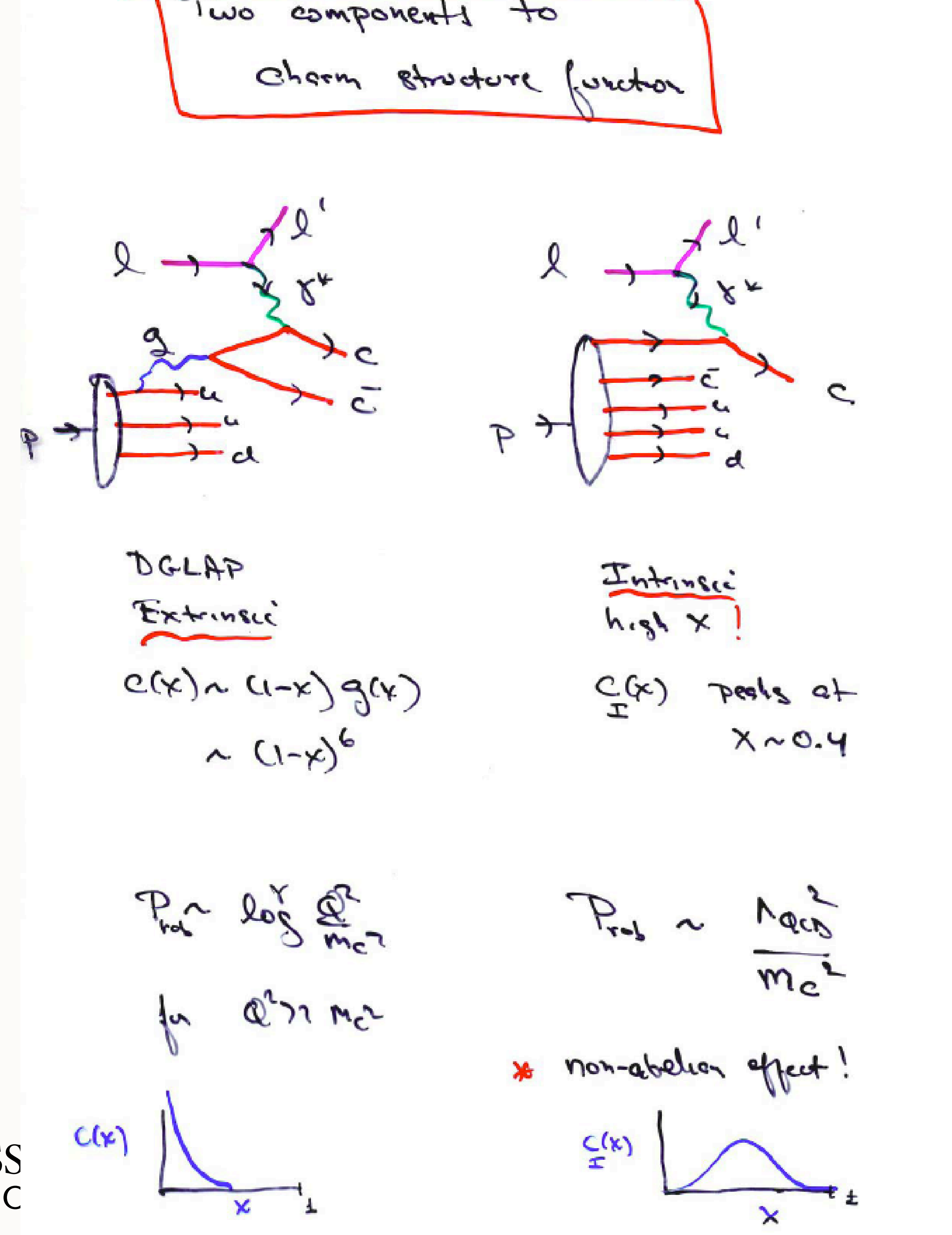
Heavy Quark Fluctuations

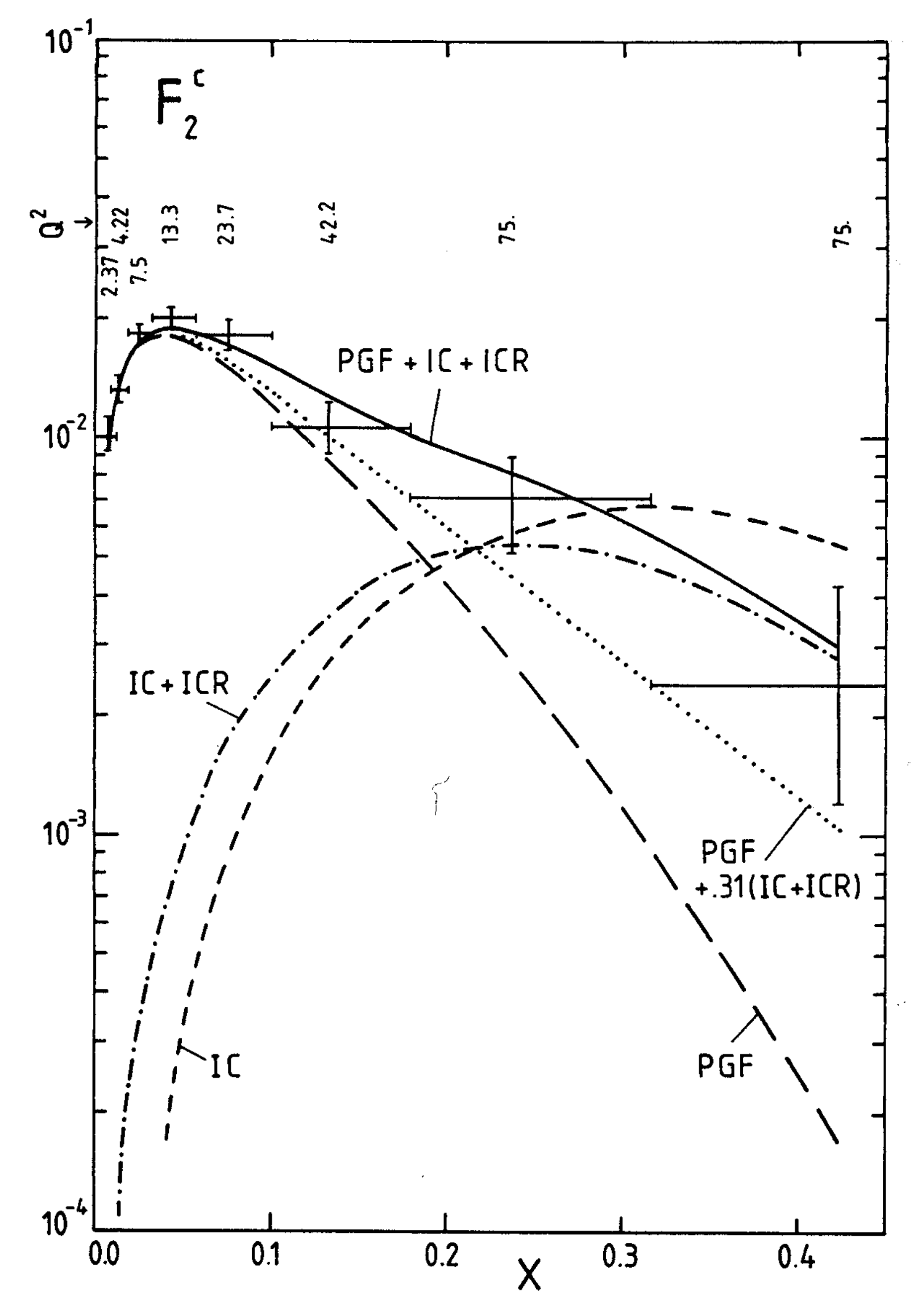


$|uud\, Q\bar{Q}\rangle$

* $Q(x) \neq \bar{Q}(x)$ — "Coulomb effects"
* $P_{Q\bar{Q}} \sim \frac{1}{M^2_{Q\bar{Q}}}$ — (non-Abelian) Eff op $G^2_{\mu\nu}$
* $x_Q \sim \frac{m_{Q\perp}}{\sum_{i=1}^{n} m_{\perp i}}$ — large momentum fract. carried by heavy partons
* $P_{Q\bar{Q}Q\bar{Q}} \sim \frac{1}{M^2_{Q\bar{Q}Q\bar{Q}}}$!



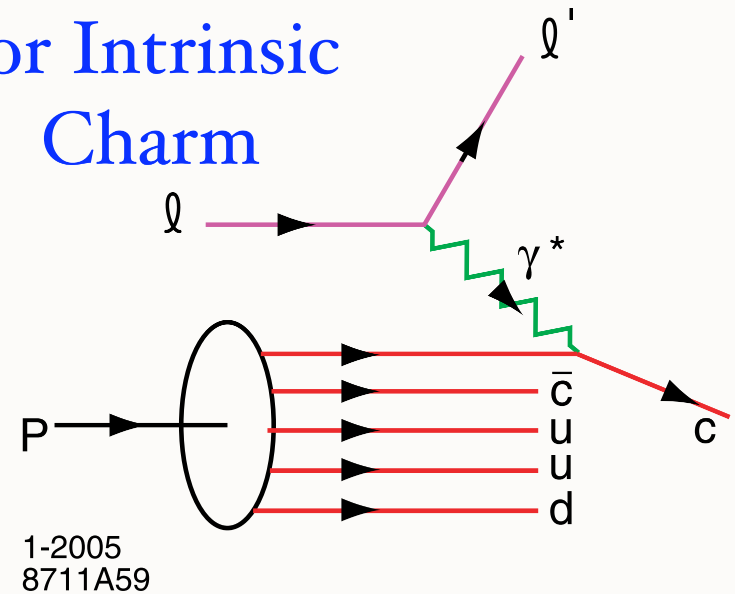

Two components to
charm structure function
l
l'
γ*
g
c
c̄
u
u
d
p
l
l'
γ*
c
c̄
u
u
d
P
DGLAP
Extrinsic
c(x) ~ (1-x) g(x)
~ (1-x)^6
Intrinsic
high x !
C_I(x) peaks at
x ~ 0.4
Prob ~ log^γ Q^2/mc^2
for Q^2 >> mc^2
Prob ~ Λ_QCD^2 / mc^2
* non-abelian effect !
c(x)
x
1
C_I(x)
x
1



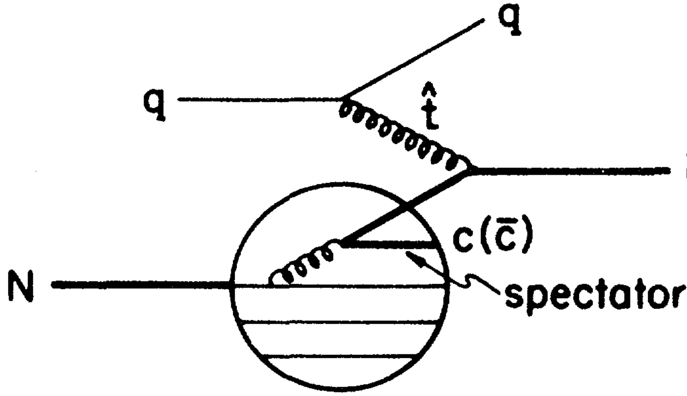
Measurement of Charm Structure Function

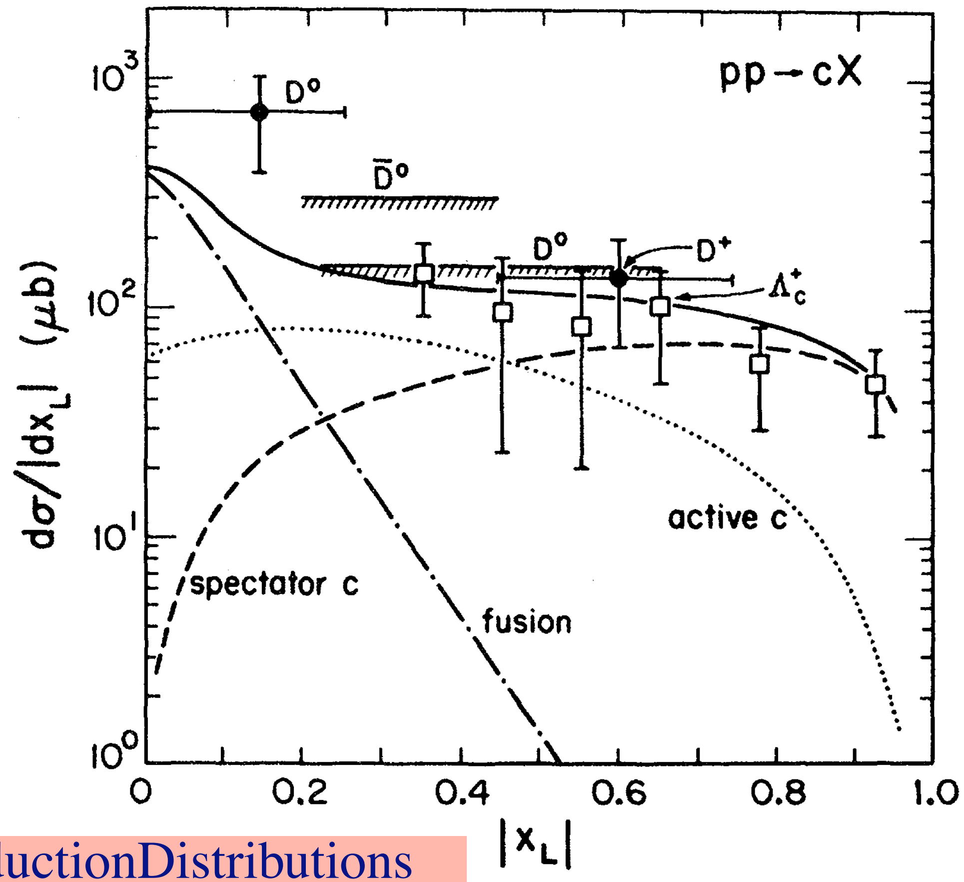
J. J. Aubert et al. [European Muon Collaboration], "P
duction Of Charmed Particles In 250-Gev Mu+ - Iron
teractions," Nucl. Phys. B 213, 31 (1983).

Evidence for Intrinsic Charm



DGLAP / Photon-Gluon Fusion Factor of 30 too small





Predictions for Inclusive Charm ProductionDistributions at the ISR. Assumes active and spectator charm distribution in proton patterned on IC, plus coalescence of valence and charm quarks.

V. D. Barger, F. Halzen and W. Y. Keung,
"The Central And Diffractive Components Of Charm Production,"
Phys. Rev. D 25, 112 (1982).

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

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

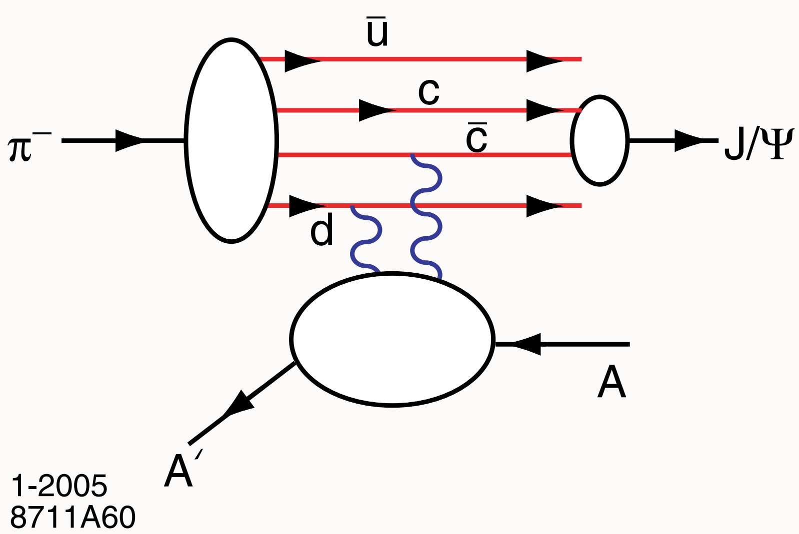
- High x_F $pp \rightarrow J/\psi J/\psi X$

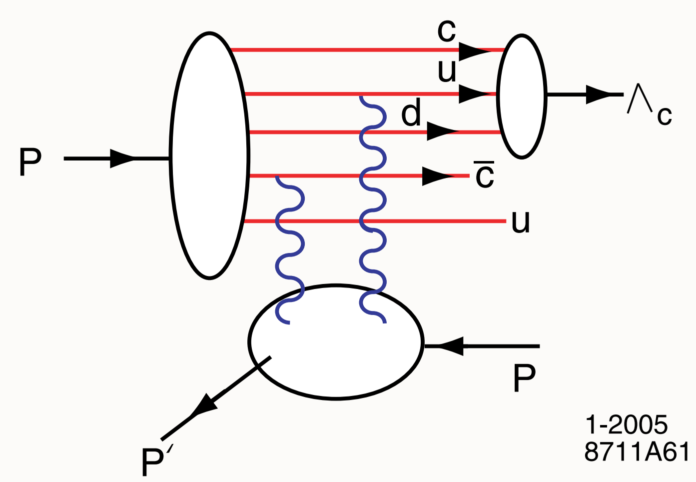
- High x_F $pp \rightarrow \Lambda_c X$

- High x_F $pp \rightarrow \Lambda_b X$

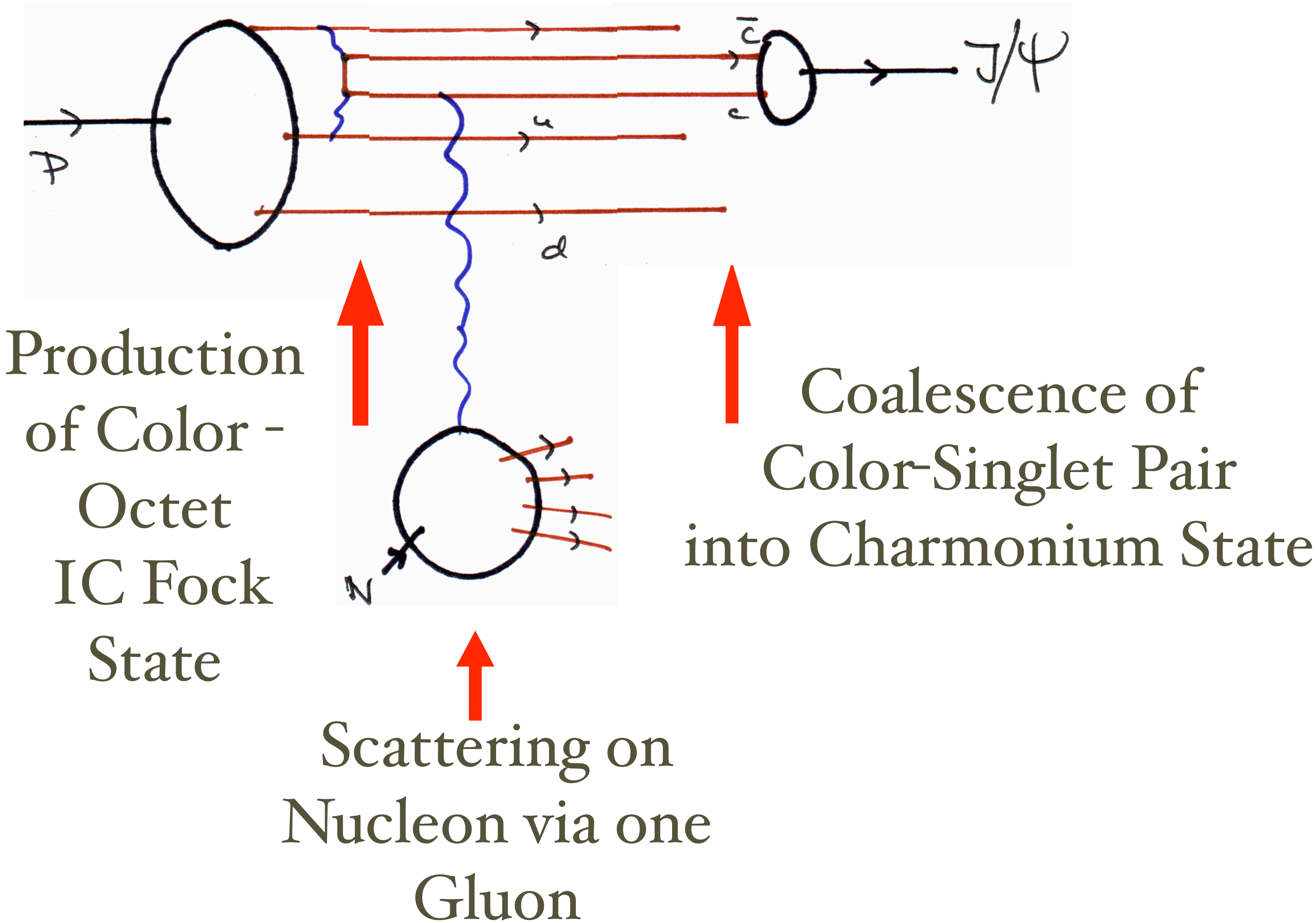
- High x_F $pp \rightarrow \Xi(ccd) X$ (SELEX)

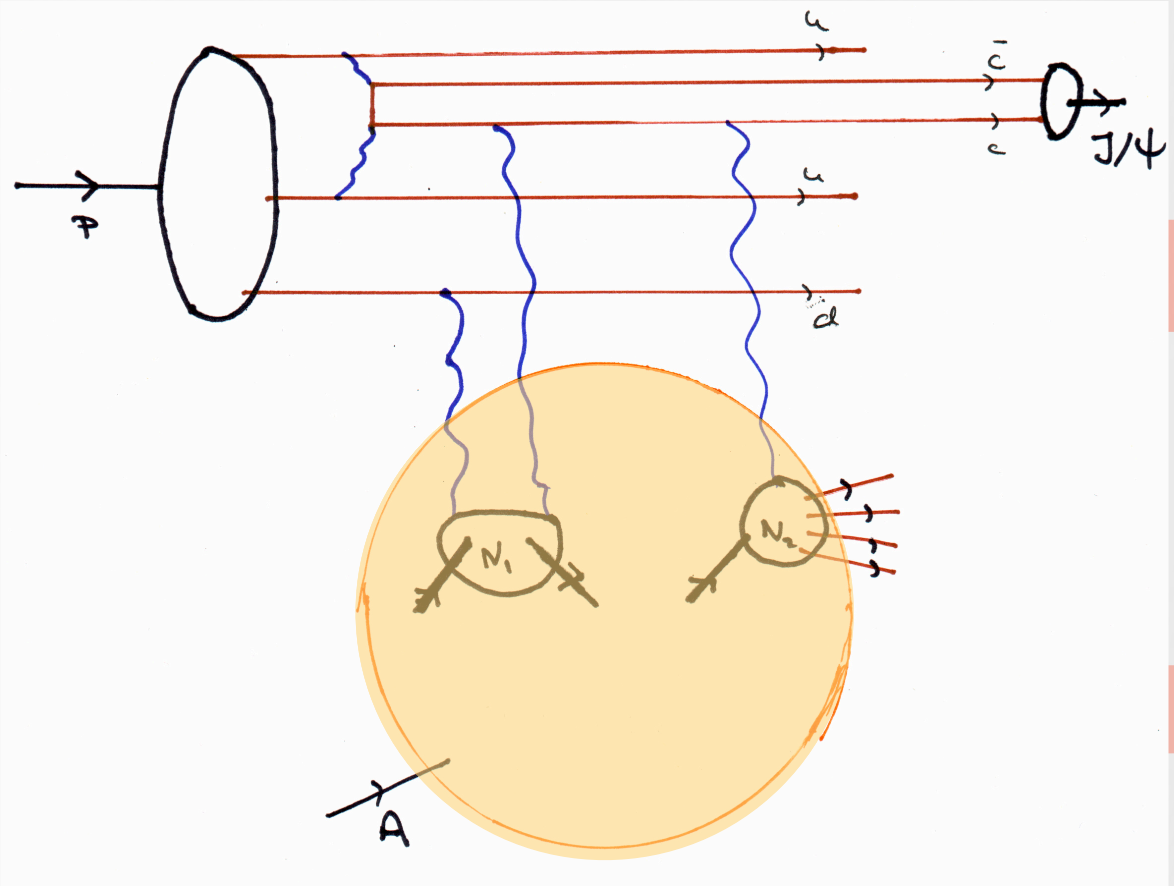
Diffractive Dissociation of Intrinsic Charm





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


P
c̄
c
u
d
J/ψ
N
Production of Color - Octet IC Fock State
Coalescence of Color-Singlet Pair into Charmonium State
Scattering on Nucleon via one Gluon



Shadowing of $pA \to J/\Psi X$

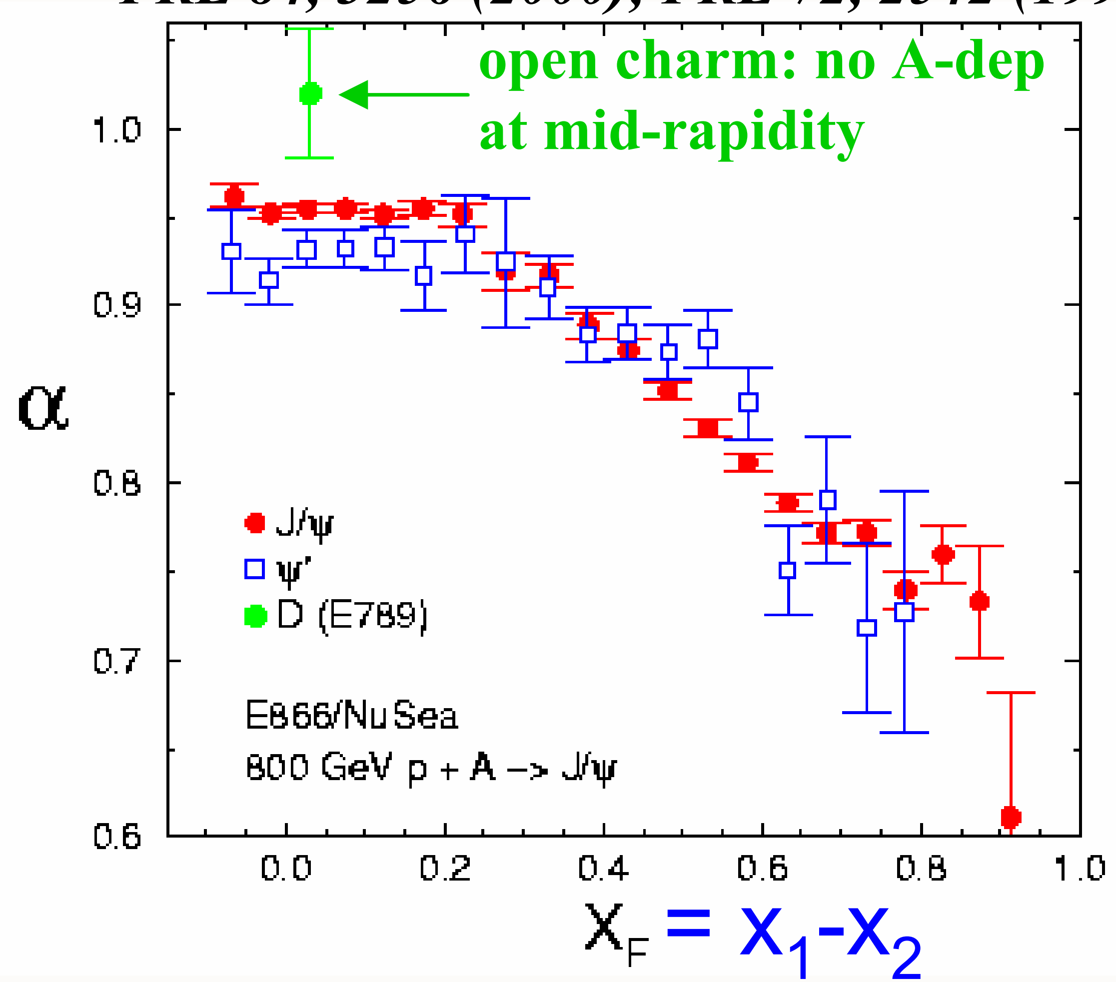
J/Ψ Production on Front Surface
No Absorption of Propagating J/Ψ
$\sigma(p + A \to J/\Psi + X) \propto A^{2/3}$

Elastic scattering of IC Fock state:
$|[uud]_{8_C}[c\bar{c}]_{8_C} > + N_1 \to |[uud]_{8_C}[c\bar{c}]_{8_C} > + N_1$
followed by:
$|[uud]_{8_C}[c\bar{c}]_{8_C} > + N_2 \to J/\Psi + X$
Depleted flux on downstream nucleons

Color-Opaque
Color-Octet Intrinsic Charm!

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

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



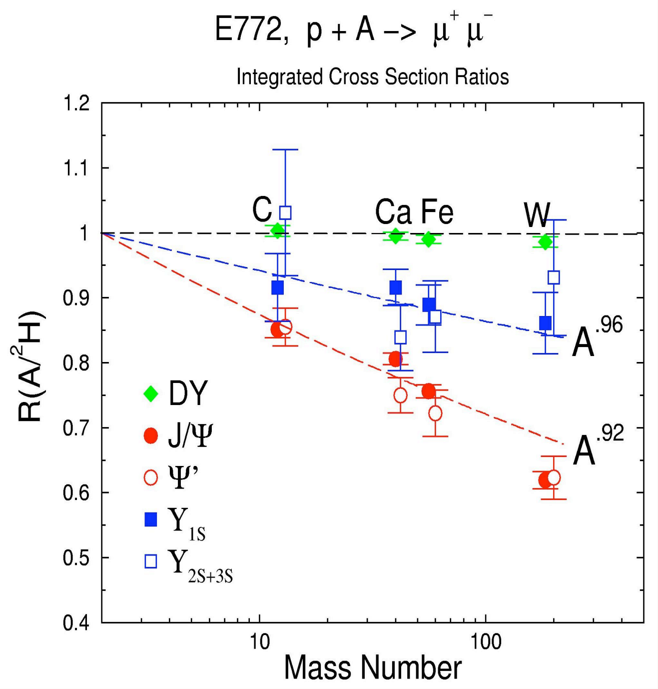
Remarkably Strong Nuclear Dependence for Fast Charmonium

M. Leitch

Nuclear effects in Quarkonium production

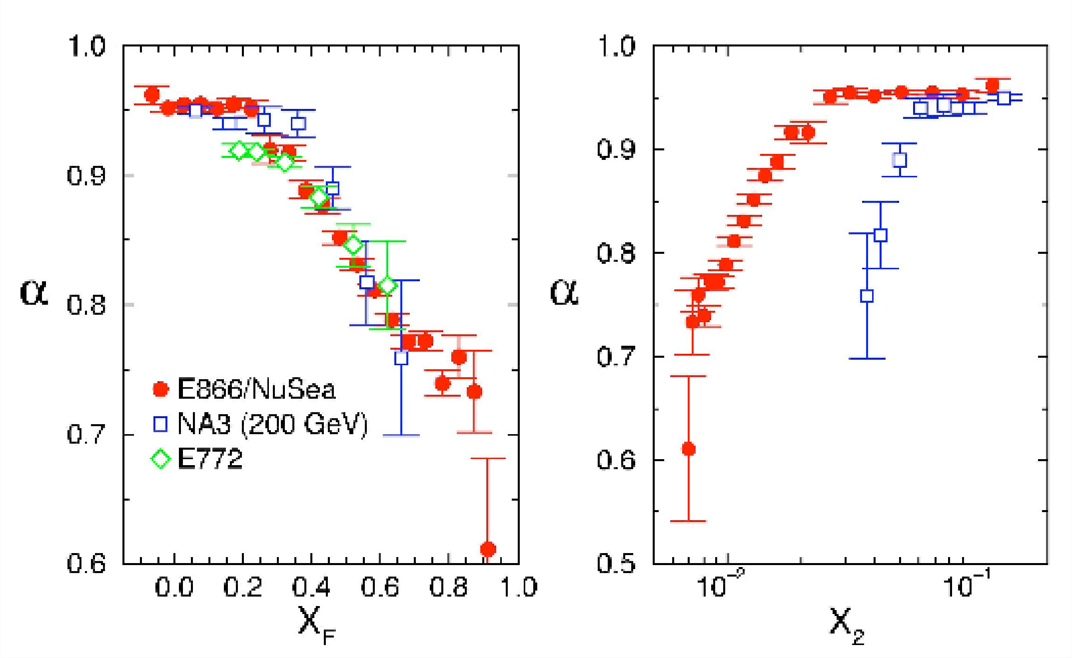
p + A at $s^{1/2}$ = 38.8 GeV

E772 data



$\sigma(p+A) = A^{\alpha}\,\sigma(p+N)$

Strong x_F - dependence



Nuclear effects scale with x_F, not x_2 !!!

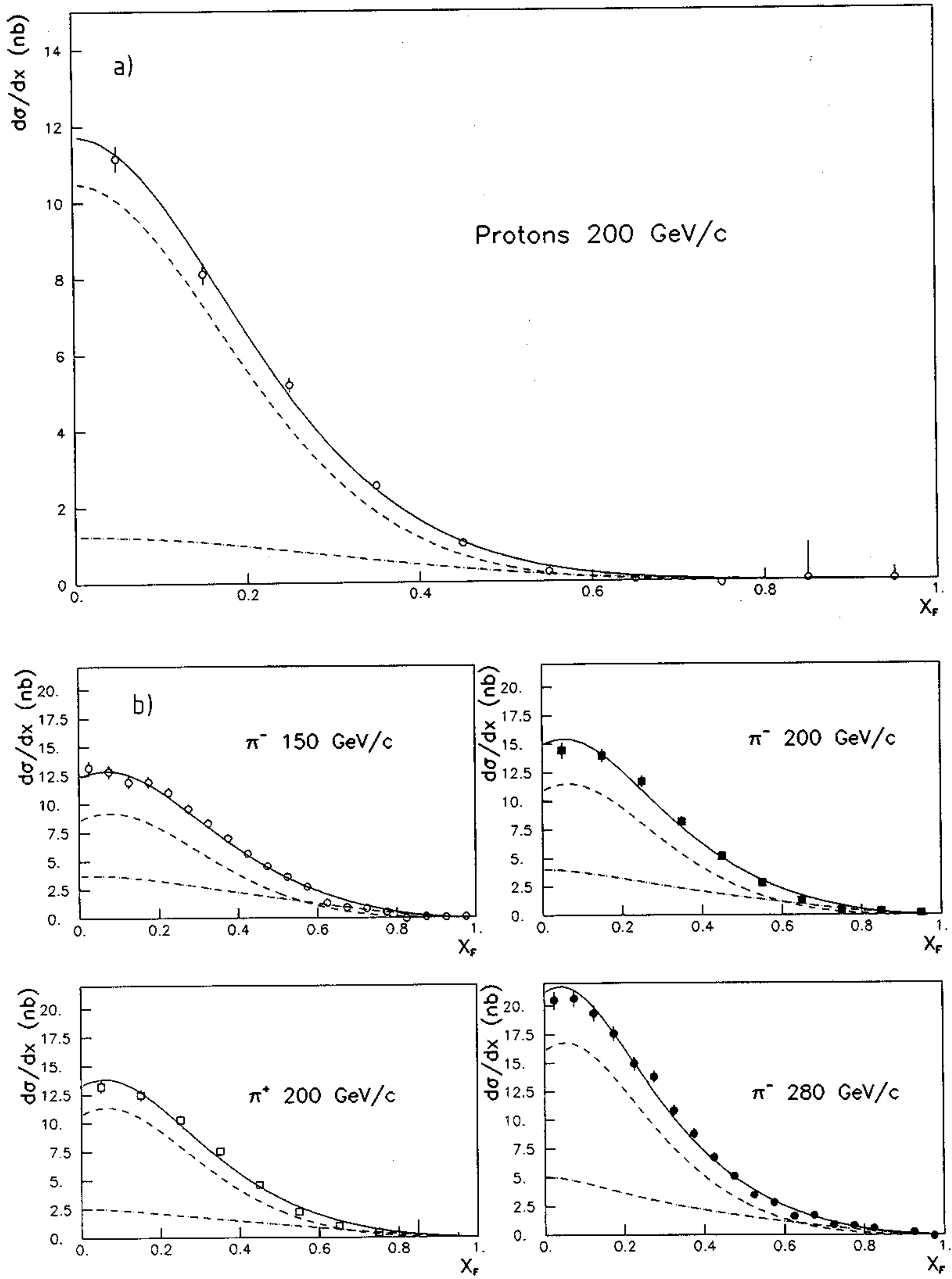
M.Leitch

Nuclear Dependence of Quarkonium Production

NA3 data for $\frac{d\sigma}{dx_F}(p(\pi)A \to J/\psi X)$: hard A^1 and "diffractive" $A^{2/3}$ components

Diffractive contribution extends to large x_F

$A^{\alpha(x_F)}$ not $A^{\alpha(x_2)}$: PQCD Factorization Violated!



Hard Component $\frac{d\sigma}{dx_F}(p(\pi)A \to J/\psi X)$

The fit: gg fusion (dashed)

$q\bar{q}$ fusion (dashed-dot)

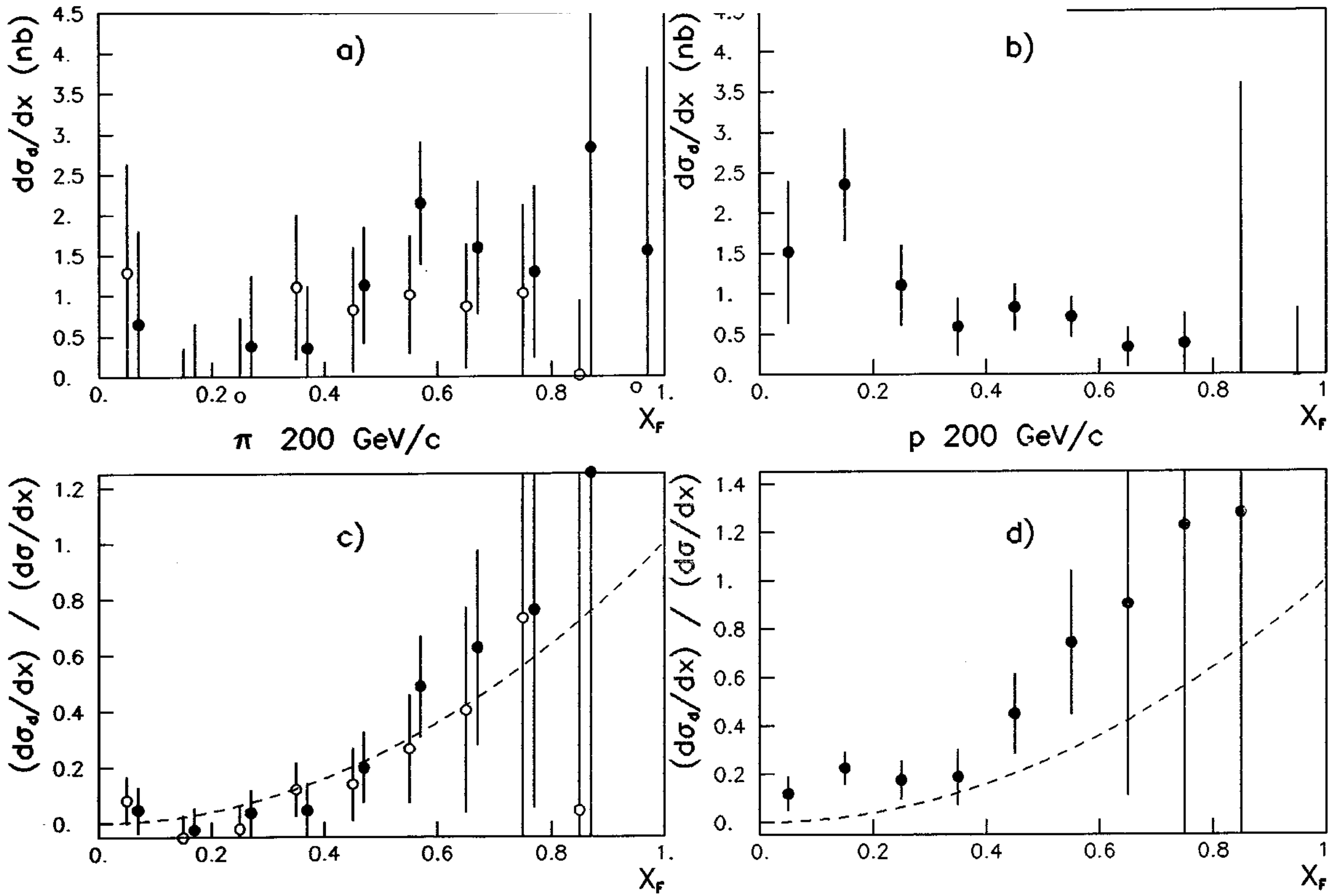
total (solid)

A^1 Component

EXPERIMENTAL J/ψ HADRONIC PRODUCTION FROM 150 TO 280 GeV/c

NA3 COLLABORATION

CERN-EP/83-86
June 29th, 1983



$A^{2/3}$ Component

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

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

Color Opaqueness

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

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

Double Charmonium Production

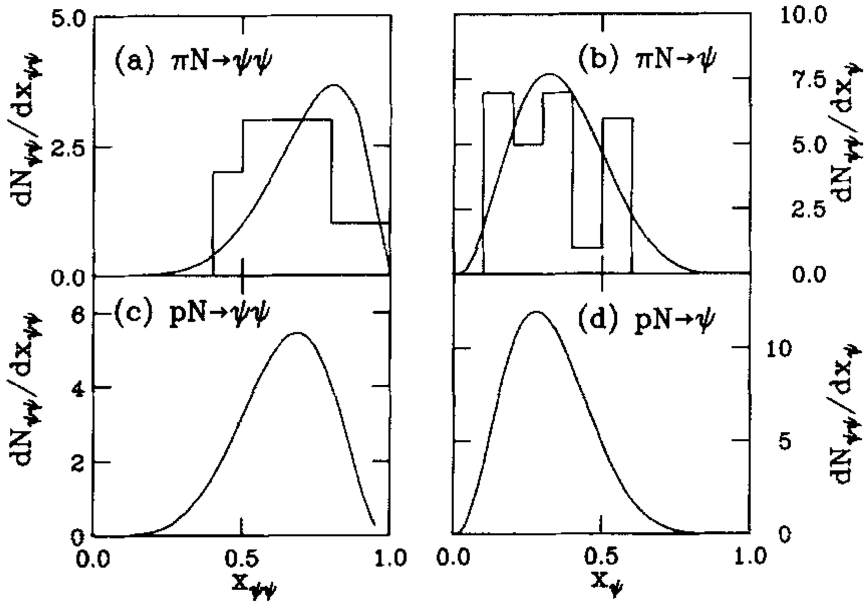


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized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

NA3 Data

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

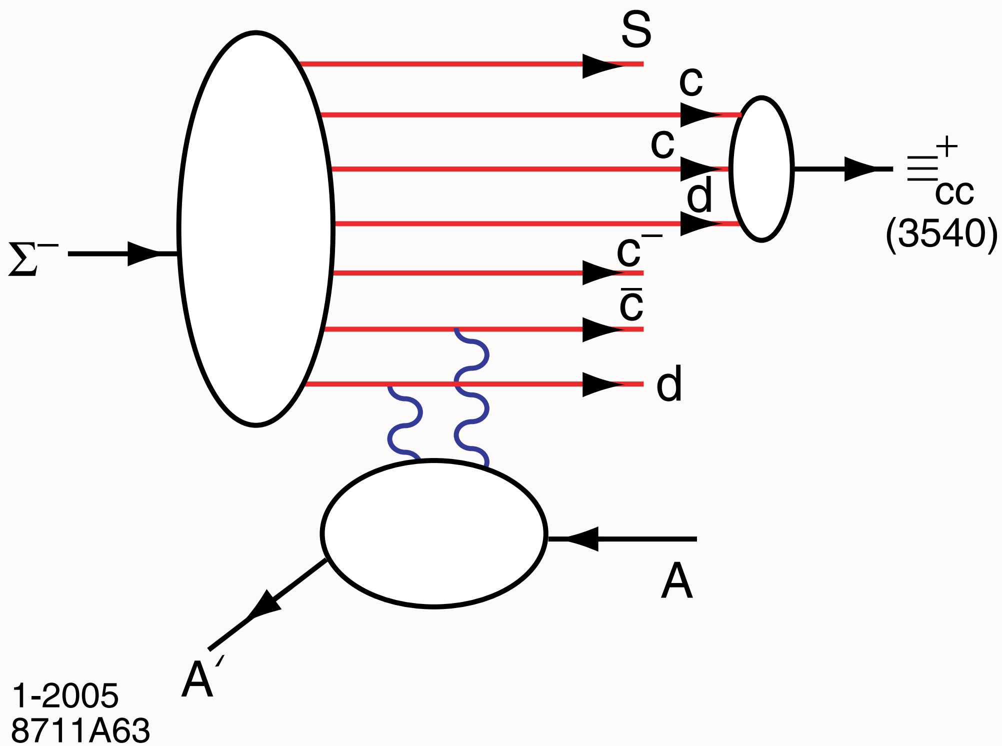
Intrinsic charm contribution to double quarkonium hadroproduction ★

R. Vogt [a], S.J. Brodsky [b]

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

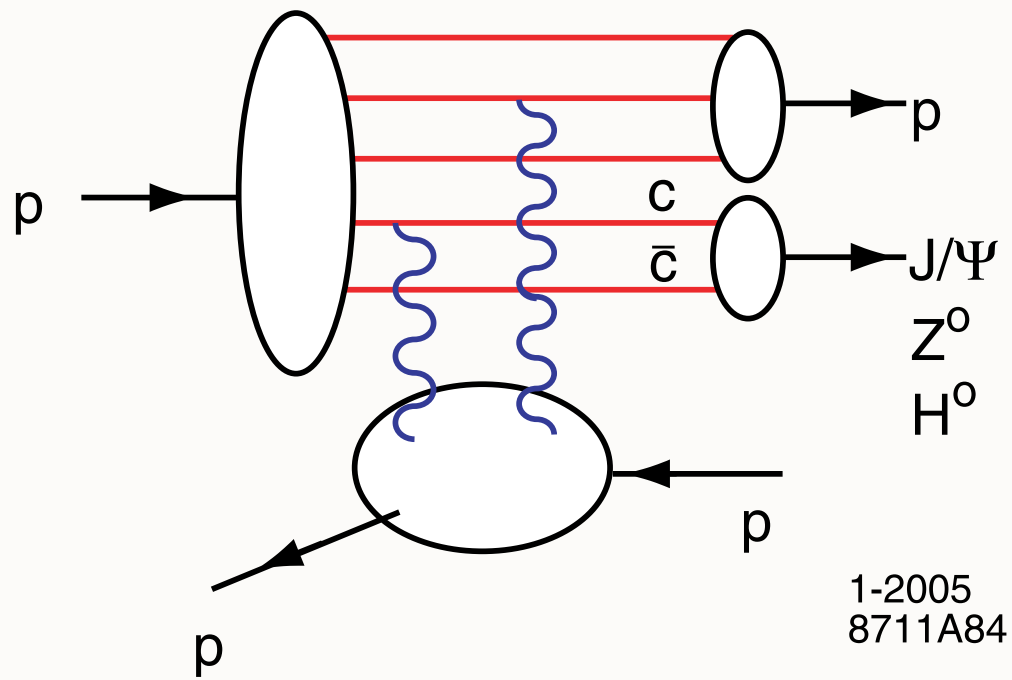
$$\frac{dP_{\rm ic}}{\prod_{i=1}^{n} dx_i d^2 k_{T,i}} = N_n \alpha_s^4 (M_{c\bar{c}}) \frac{\delta(\sum_{i=1}^{n} \boldsymbol{k}_{T,i})\,\delta(1 - \sum_{i=1}^{n} x_i)}{(m_h^2 - \sum_{i=1}^{n} (m_{T,i}^2 / x_i))^2} ,$$

Double Intrinsic Charm



Production of a Double-Charm Baryon

Intrinsic Charm Mechanism for Exclusive Diffraction Production



$$p\,p \rightarrow J/\psi\, p\, p$$

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

Exclusive Diffractive
High-X_F Higgs Production

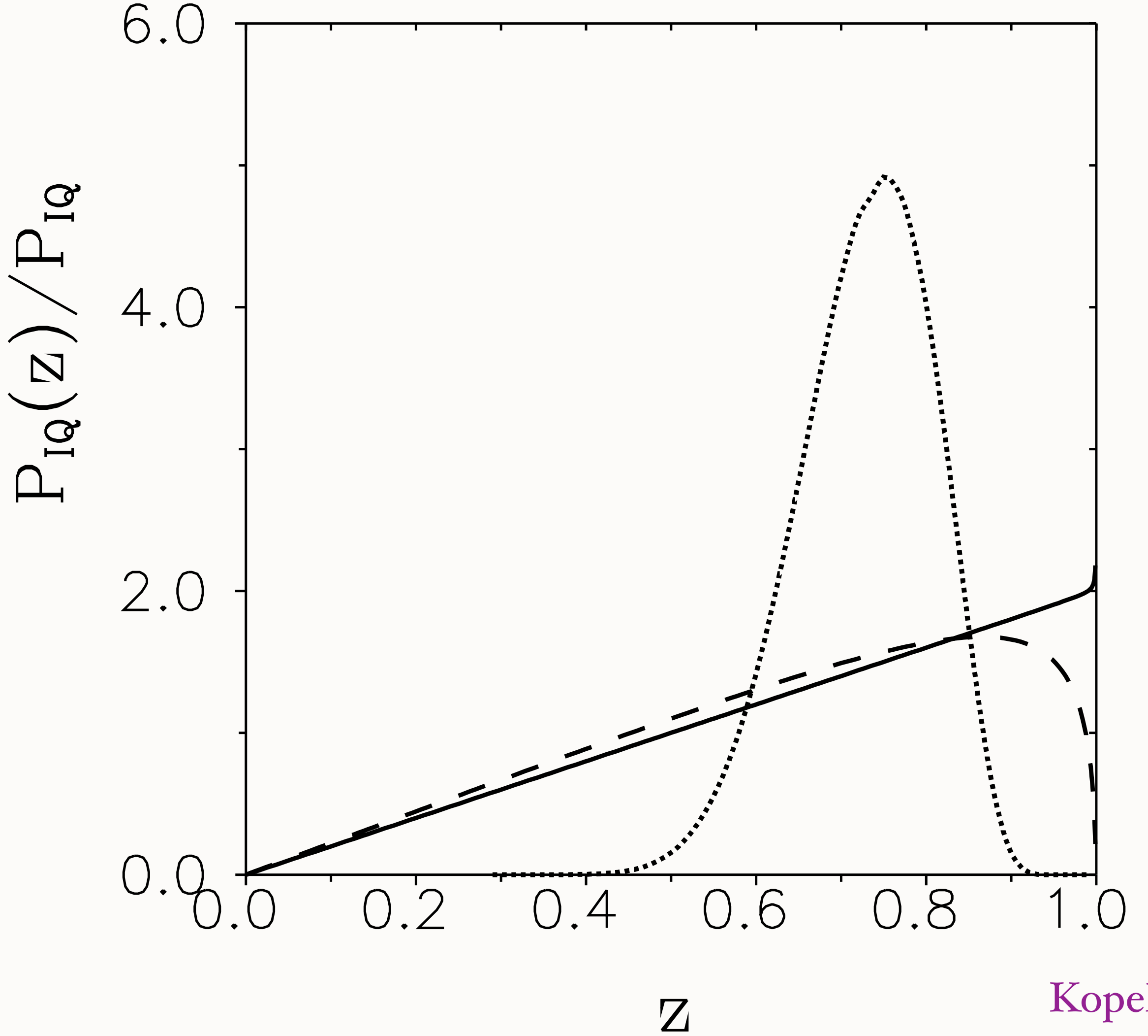
Kopeliovitch, Schmidt, Soffer, sjb

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

Collision produces color-singlet J/ψ through color exchange

RHIC Experiment

Intrinsic Charm Mechanism for Exclusive Diffraction Production



Kopeliovitch, Schmidt, Soffer, sjb

Anomalous QCD Effects

- Hidden Color of Nuclear Wavefunction
- Odderon Trajectory: Charm jet asymmetry
- Anomalous Regge Behavior: J=0 Fixed Pole
- Proton-Proton Scattering:
  Color Transparency Breakdown and A_{NN}
- Non-Universality of Antishadowing
- Intrinsic Heavy Quarks at large x
- Anomalous scaling of single-particle inclusive at high p_T

Conformal symmetry: Template for QCD

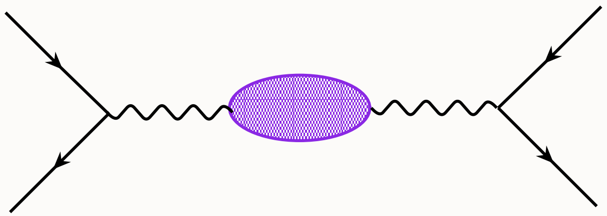
- Initial approximation to PQCD; then correct for non-zero beta function and quark masses
- Commensurate scale relations: relate observables at corresponding scales: Generalized Crewther Relation
- Arguments for Infrared fixed-point for α_s Alhofer, et al.
- Effective Charges: analytic at quark mass thresholds, finite at small momenta
- Eigensolutions of Evolution Equation of distribution amplitudes

The Renormalization Scale Problem

$$\rho = C_0 \alpha_s(Q) \left[1 + C_1(Q) \frac{\alpha_s(Q)}{\pi} + C_2(Q) \frac{\alpha_s{}^2(Q)}{\pi^2} + \cdots \right].$$

How does one set renormalization scale Q?

$$e^+e^- \to \mu^+\mu^-$$



$$\mu^2 \equiv s$$

Scale of $\alpha_{QED}(\mu^2)$ unique!

The QED Effective Charge

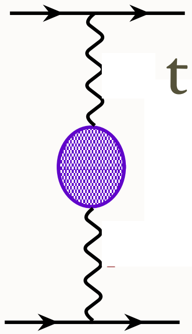
- Complex
- Analytic through mass thresholds
- Distinguishes between timelike and spacelike momenta

Analyticity essential !

Electron-Electron Scattering in QED

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

- No renormalization scale ambiguity!
- Two separate physical scales.
- Gauge Invariant. Dressed photon propagator
- Sums all vacuum polarization, non-zero beta terms into running coupling.
- If one chooses a different scale, one must sum an infinite number of graphs -- but then recover same result!
- Number of active leptons correctly set
- Analytic: reproduces correct behavior at lepton mass thresholds



The Renormalization Scale Problem

M. Binger, sjb

- No renormalization scale ambiguity in QED
- Gell Mann-Low-Dyson QED Coupling defined from physical observable;
- Sums all Vacuum Polarization Contributions
- Renormalization Scale in QED scheme: Identical to Photon Virtuality
- Analytic: Reproduces lepton-pair thresholds
- Examples: muonic atoms, g-2, Lamb Shift
- Time-like and Space-like QED Coupling related by analyticity
- Uses Dressed Skeleton Expansion

Lessons from QED : Summary

- Effective couplings are complex analytic functions with the correct threshold structure expected from unitarity

- Multiple “renormalization” scales appear

- The scales are unambiguous since they are physical kinematic invariants

- Optimal improvement of perturbation theory

Features of BLM Scale Setting

On The Elimination Of Scale Ambiguities In Perturbative Quantum Chromodynamics.

Lepage, Mackenzie, sjb   **Phys.Rev.D28:228,1983**

- All terms associated with nonzero beta function summed into running coupling
- Resulting series identical to conformal series
- Renormalon n! growth of PQCD coefficients from beta function eliminated!
- In general, BLM scale depends on all invariants

BLM Scale Setting

$$\rho = C_0 \alpha_{\overline{MS}}(Q) \left[1 + \frac{\alpha_{\overline{MS}}(Q)}{\pi} \left(-\tfrac{3}{2}\beta_0 A_{VP} + \tfrac{33}{2} A_{VP} + B \right) + \cdots \right]$$

Use n_f dependence at NLO to identify A_{VP}

by

$$\rho = C_0 \alpha_{\overline{MS}}(Q^*) \left[1 + \frac{\alpha_{\overline{MS}}(Q^*)}{\pi} C_1^* + \cdots \right],$$

Conformal Coefficient

where

$$Q^* = Q \exp(3A_{VP}),$$

$$C_1^* = \tfrac{33}{2} A_{VP} + B .$$

The term $33A_{VP}/2$ in C_1^* serves to remove that part of the constant B which renormalizes the leading-order coupling. The ratio of these gluonic corrections to the light-quark corrections is fixed by $\beta_0 = 11 - \frac{2}{3} n_f$.

Use skeleton expansion
Gardi, Rathsman, sjb

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

$$R_{e^+e^-}(Q^2) = 3 \sum_q e_q^2 \left[1 + \frac{\alpha_{\overline{MS}}(Q)}{\pi} + \frac{\alpha_{\overline{MS}}^2}{\pi^2}(1.98 - 0.115 n_f) + \cdots \right]$$

$$\to 3 \sum_q e_q^2 \left[1 + \frac{\alpha_{\overline{MS}}(Q^*)}{\pi} + \frac{\alpha_{\overline{MS}}^2(Q^*)}{\pi^2} 0.08 + \cdots \right],$$

$Q^* = 0.710Q.$ Notice that $\alpha_R(Q)$ differs from $\alpha_{\overline{MS}}(Q^*)$ by only $0.08\alpha_{\overline{MS}}/\pi$, so that $\alpha_R(Q)$ and $\alpha_{\overline{MS}}(0.71Q)$ are effectively interchangeable (for any value of n_f).

Deep-inelastic scattering. The moments of the nonsinglet structure function $F_2(x,Q^2)$ obey the evolution equation

$$Q^2\frac{d}{dQ^2}\ln M_n(Q^2)$$

$$=-\frac{\gamma_n^{(0)}}{8\pi}\alpha_{\overline{\rm MS}}(Q)\left[1+\frac{\alpha_{\overline{\rm MS}}}{4\pi}\,\frac{2\beta_0\beta_n+\gamma_n^{(1)}}{\gamma_n^{(0)}}+\cdots\right]$$

$$\to -\frac{\gamma_n^{(0)}}{8\pi}\alpha_{\overline{\rm MS}}(Q_n^*)\left[1-\frac{\alpha_{\overline{\rm MS}}(Q_n^*)}{\pi}C_n+\cdots\right],$$

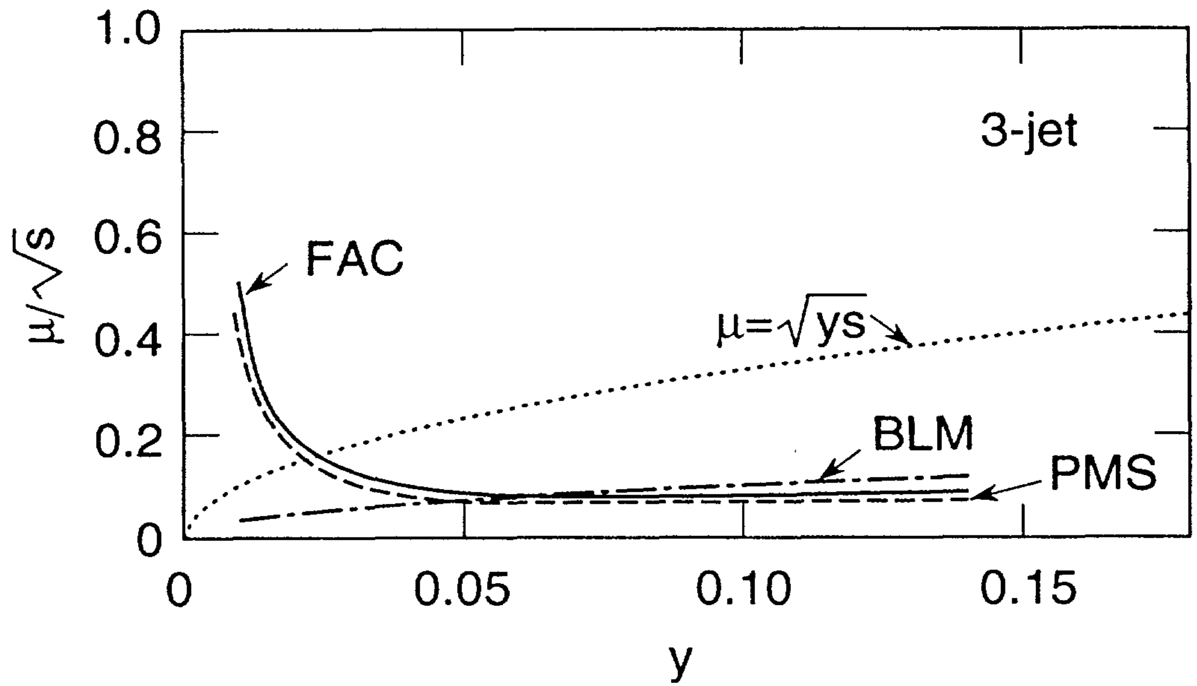
where, for example,

$$Q_2^*=0.48Q,\quad C_2=0.27\ ,$$

$$Q_{10}^*=0.21Q,\quad C_{10}=1.1\ .$$

For n very large, the effective scale here becomes $Q_n^*\sim Q/\sqrt{n}$

BLM scales for DIS moments



Kramer & Lampe

Three-Jet Rate

The scale $\mu/\sqrt{s}$ according to the BLM (dashed-dotted), PMS (dashed), FAC (full), and $\sqrt{y}$ (dotted) procedures for the three-jet rate in e^+e^- annihilation, as computed by Kramer and Lampe [10]. Notice the strikingly different behavior of the BLM scale from the PMS and FAC scales at low y. In particular, the latter two methods predict increasing values of μ as the jet invariant mass $\mathcal{M} < \sqrt{(ys)}$ decreases.

Rathsman

Other Jet Observables:

Features of BLM Scale Setting

- All terms associated with nonzero beta function summed into running coupling
- Conformal series preserved
- BLM Scale Q* sets the number of active flavors
- Correct analytic dependence in the quark mass
- Only n_f dependence required to determine renormalization scale at NLO
- Result is scheme independent: Q* has exactly the correct dependence to compensate for change of scheme
- Correct Abelian limit!

$$\lim N_C \to 0 \text{ at fixed } \alpha = C_F \alpha_s, n_\ell = n_F / C_F$$

QCD → Abelian Gauge Theory

Analytic Feature of SU(Nc) Gauge Theory

Huet, sjb

Relate Observables to Each Other

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

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

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

Apply BLM, Eliminate MSbar, Find Amazing Simplification

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

$$\frac{\alpha_{g_1}(Q)}{\pi} = \frac{\alpha_R(Q^*)}{\pi} - \left(\frac{\alpha_R(Q^{**})}{\pi}\right)^2 + \left(\frac{\alpha_R(Q^{***})}{\pi}\right)^3$$

Geometric Series in Conformal QCD

Generalized Crewther Relation

add Light-by-Light

Lu, Kataev, Gabadadze, Sjb

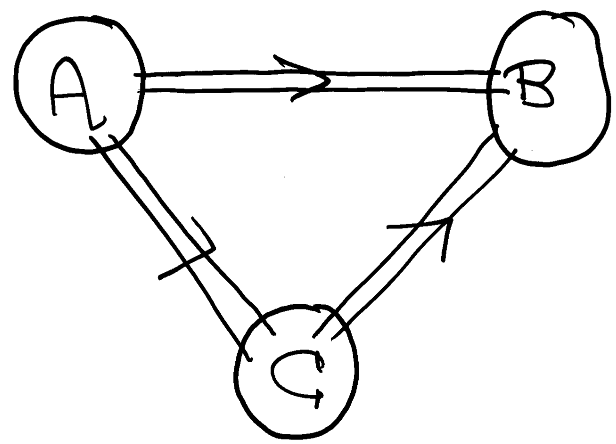
Generalized Crewther Relation

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

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

Conformal relation true to all orders in perturbation theory

Transitivity property – Renormalization Group



$A \Rightarrow C \Rightarrow B$

same as $A \Rightarrow B$

indep of C

Relation between observables $A \Leftrightarrow B$

independent of choice of C

independent of scheme or theoretical convention!

PMS violates transitivity

Commensurate Scale Relation:

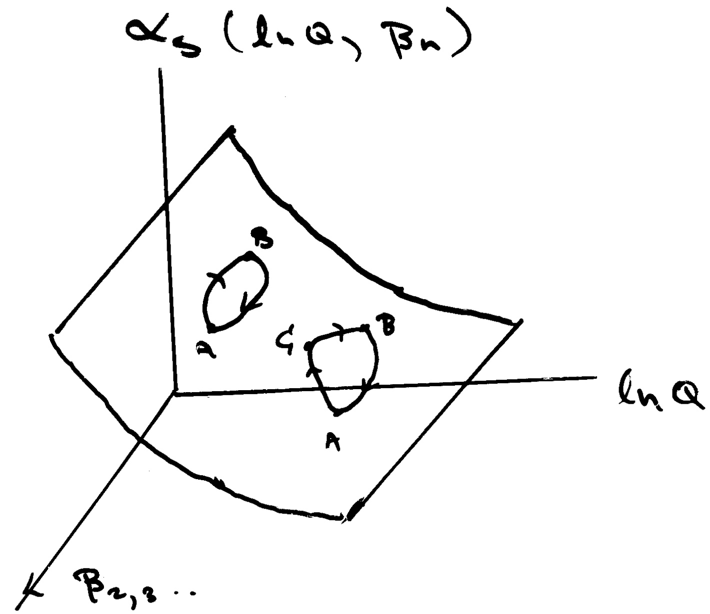
$$* \quad \alpha_B(Q_B) = \alpha_A(Q_A)\left[1 + C^{(1)}_{A/B}\,\frac{\alpha_A}{\pi} + \cdots\right]$$

↑ conformal coeff.

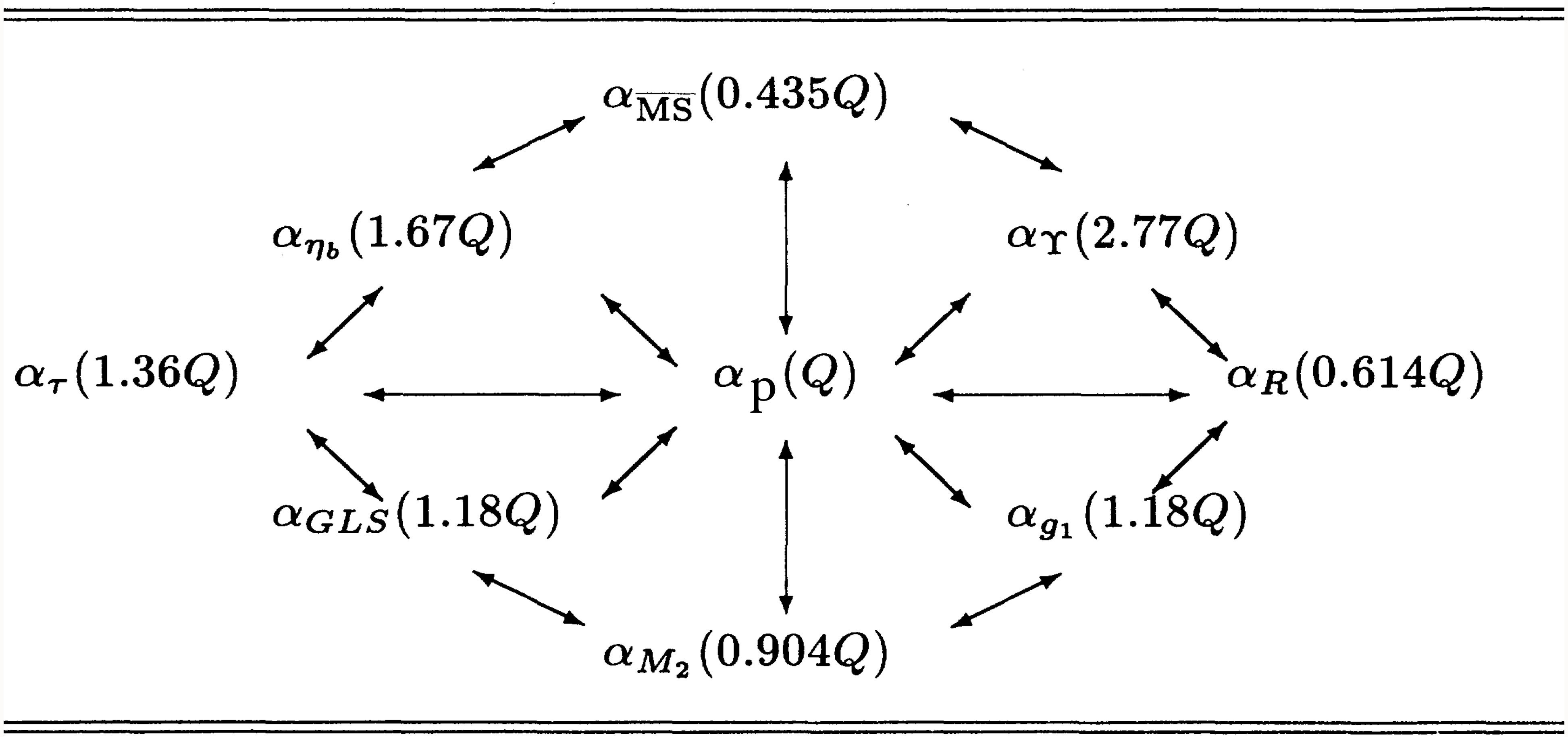
$$Q_B/Q_A = \lambda_{B/A}$$

Peterman Stückelberg "Renormalization Group"

$\lambda_{B/A} = \lambda_{B/C}/\lambda_{A/C}$	transitive
$\lambda_{B/A} = \lambda^{-1}_{A/B}$	symmetry
$\lambda_{A/A} = I$	identity

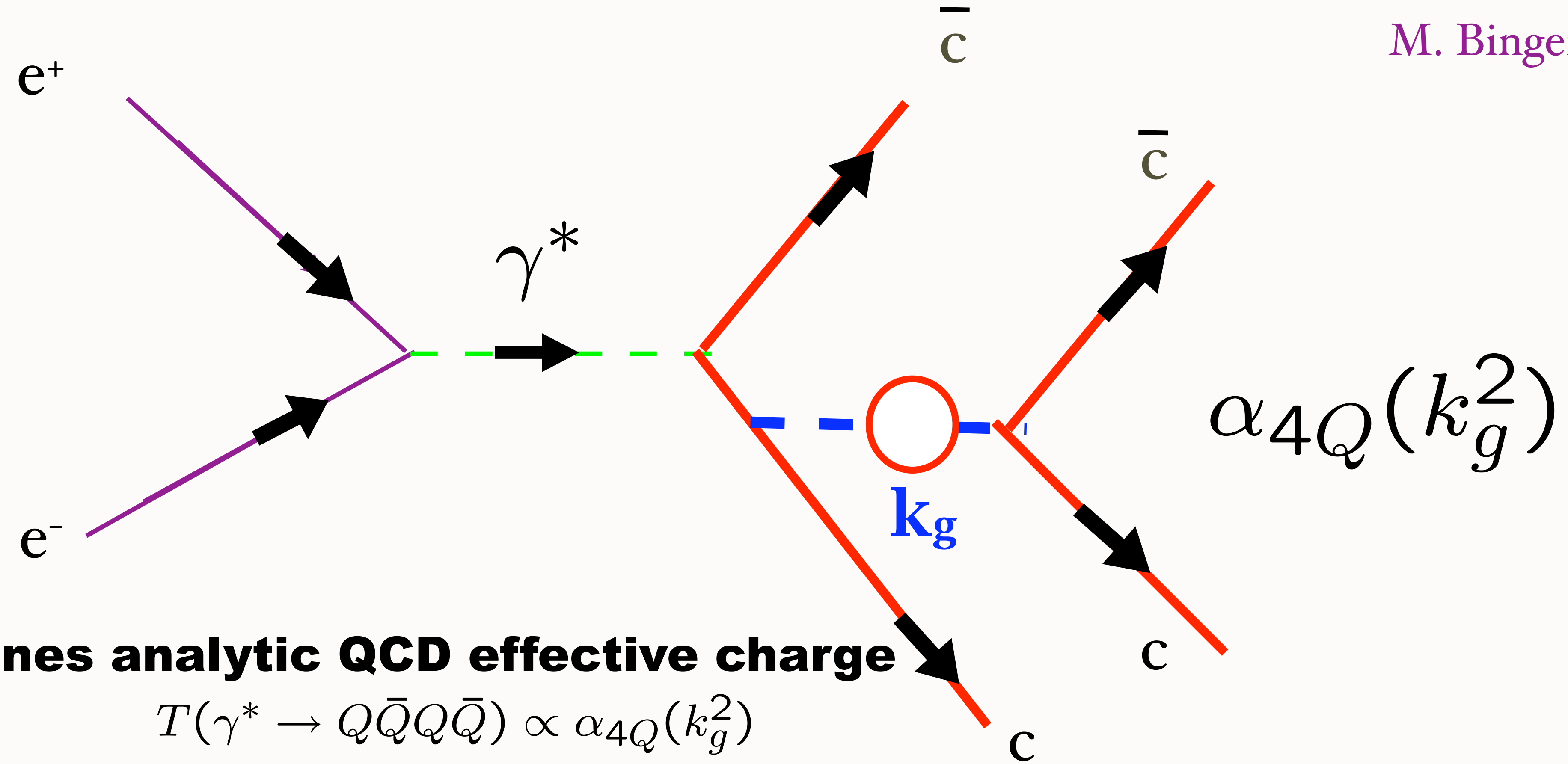


Leading Order Commensurate Scales



Translate between schemes at LO

Production of four heavy-quark jets



M. Binger, sjb

Defines analytic QCD effective charge

$$T(\gamma^* \to Q\bar{Q}Q\bar{Q}) \propto \alpha_{4Q}(k_g^2)$$

time-like values not same as space-like

coupling similar to "pinch" scheme

complex for time-like argument

Unification in Physical Schemes

"PHYSICAL RENORMALIZATION SCHEMES AND GRAND UNIFICATION"
M.B. and Stanley J. Brodsky. **Phys.Rev.D69:095007,2004**

$$\alpha_i(Q) = \frac{\alpha_i(Q_0)}{1+\hat{\Pi}_i(Q)-\hat{\Pi}_i(Q_0)}$$

i=1,2,3

$$\hat{\Pi}_i(Q) = \frac{\alpha_i}{4\pi}\sum_p \beta_i^{(p)}\left(L_{s(p)}(Q^2/m_p^2)+\cdots\right)$$

"log-like" function:

$$L_{s(p)} \approx \log(e^{\eta_p}+Q^2/m_p^2)$$

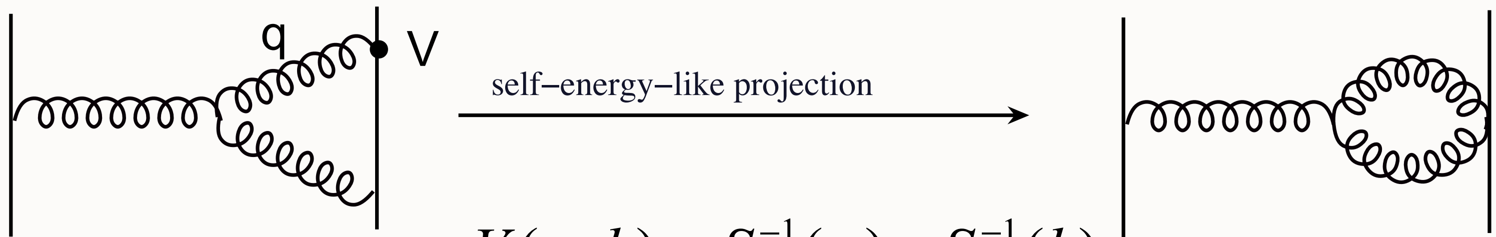
$$\eta_p = 8/3,\, 5/3,\, 40/21$$

For spin s(p) = 0, ½, and 1

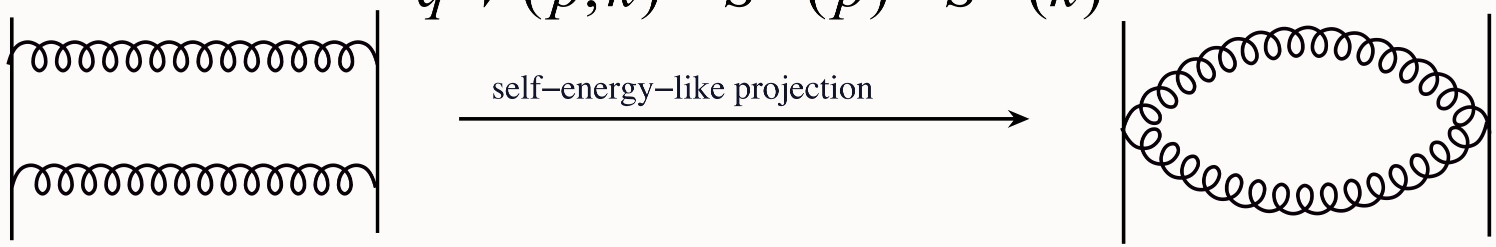
⇒ Elegant and natural formalism for all threshold effects

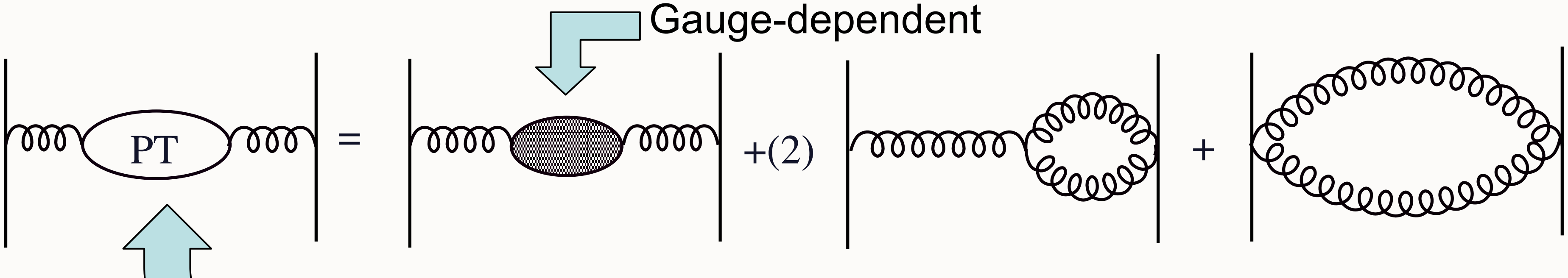
The Pinch Technique

(Cornwall, Papavassiliou)



$$q \cdot V(p,k) = S^{-1}(p) - S^{-1}(k)$$

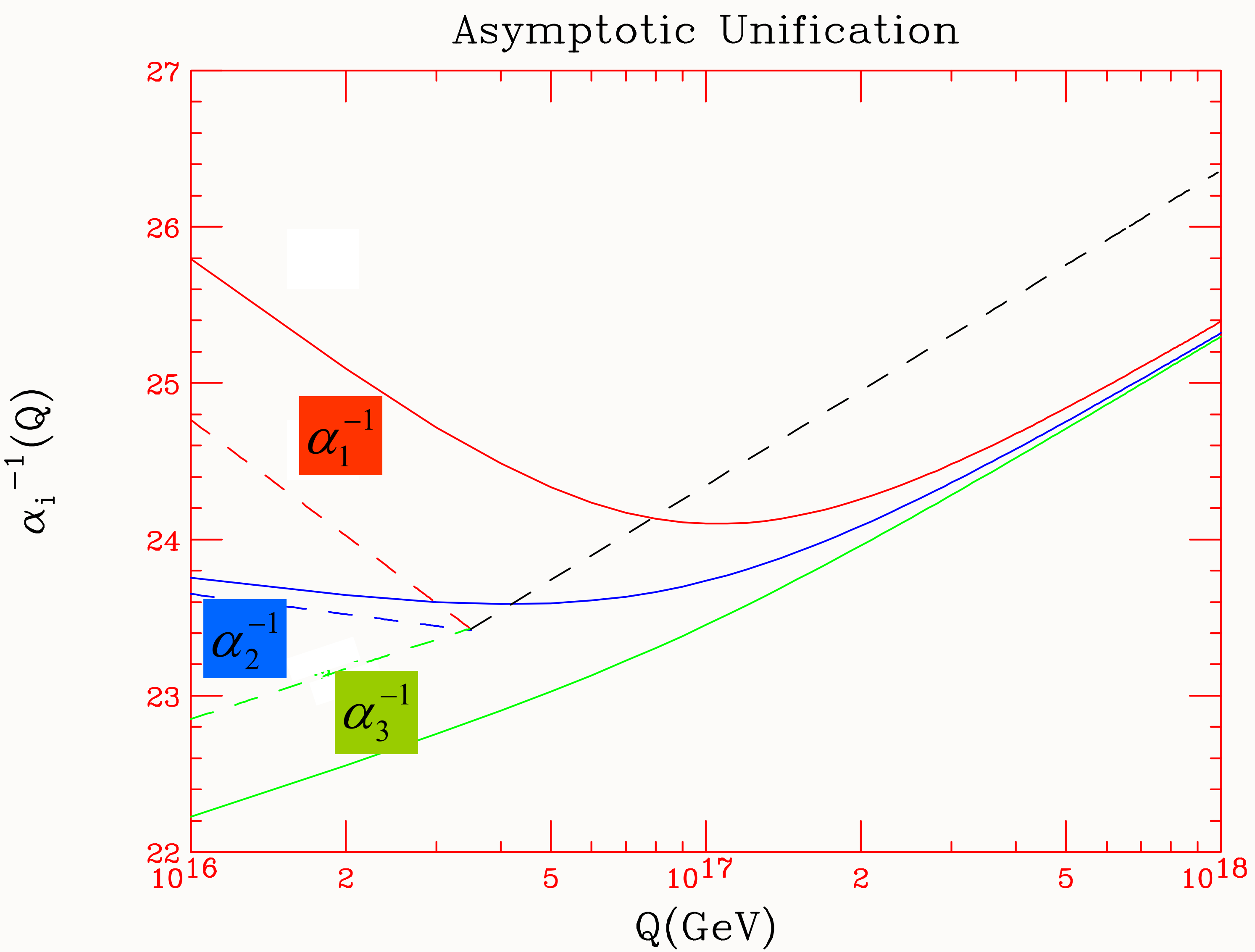




Gauge-invariant gluon self-energy!

13

natural generalization of QED charge


Asymptotic Unification
$\alpha_i^{-1}(Q)$
Q(GeV)
α_1^{-1}
α_2^{-1}
α_3^{-1}
27
26
25
24
23
22
10^{16}
2
5
10^{17}
2
5
10^{18}

Binger, sjb

Analyticity and Mass Thresholds

$\overline{MS}$ does not have automatic decoupling of heavy particles

→ Must define a set of schemes in each desert region and match

$$\alpha_s^{(f)}(M_Q) = \alpha_s^{(f+1)}(M_Q)$$

- The coupling has discontinuous derivative at the matching point
- At higher orders the coupling itself becomes discontinuous!
- Does not distinguish between spacelike and timelike momenta

"AN ANALYTIC EXTENSION OF THE MS-BAR RENORMALIZATION SCHEME"
S. Brodsky, M. Gill, M. Melles, J. Rathsman. **Phys.Rev.D58:116006,1998**

Unification in Physical Schemes

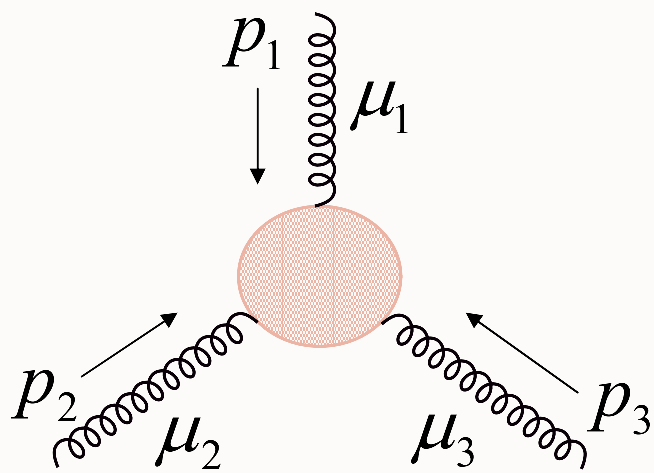
- Smooth analytic threshold behavior with automatic decoupling
- More directly reflects the unification of the forces
- Higher "unification" scale than usual

General Structure of the Three-Gluon Vertex

"THE FORM-FACTORS OF THE GAUGE-INVARIANT THREE-GLUON VERTEX"

Binger, sjb hep-ph/0602199.

$$\hat{\Gamma}_{\mu_1\mu_2\mu_3} =$$



Full calculation, general masses, spin

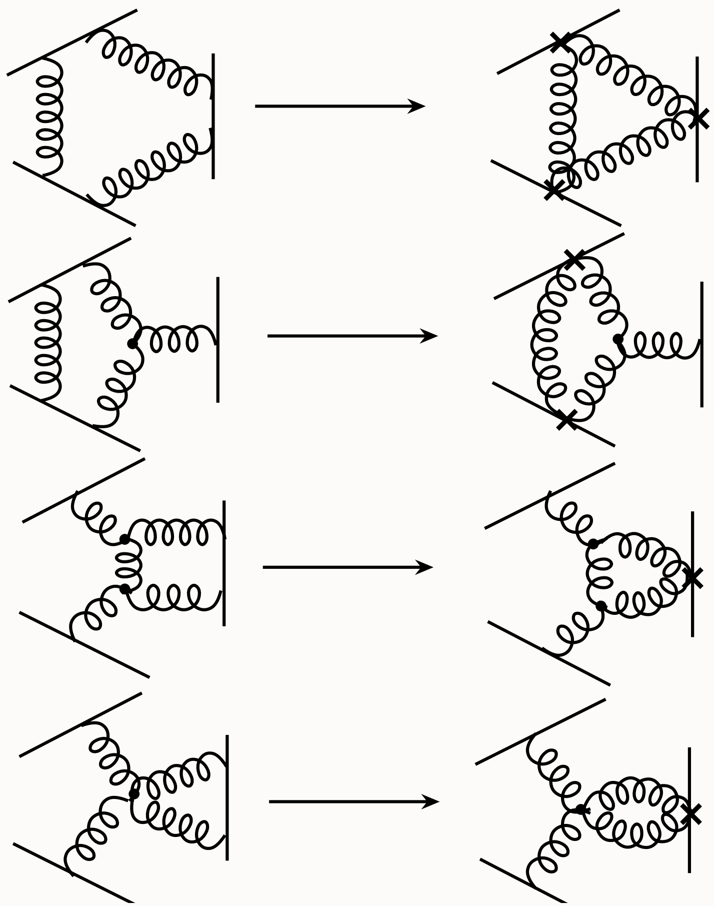
3 index tensor $\hat{\Gamma}_{\mu_1\mu_2\mu_3}$ built out of $g_{\mu\nu}$ and p_1, p_2, p_3

with $p_1 + p_2 + p_3 = 0$

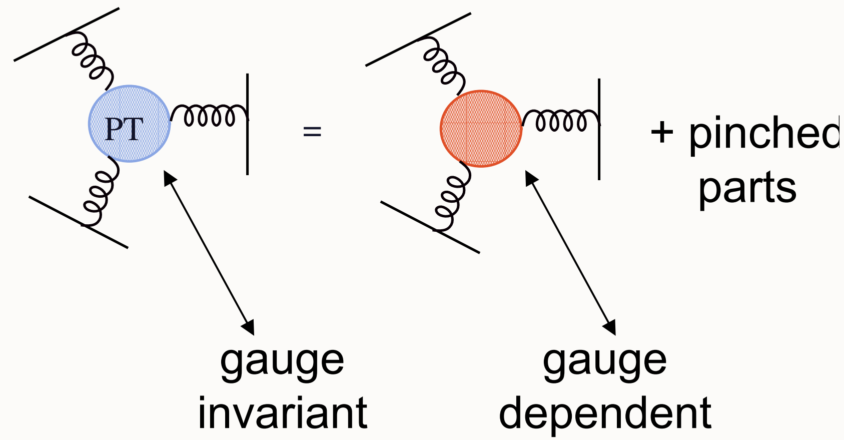
⇒ 14 basis tensors and form factors

The Gauge Invariant Three Gluon Vertex

Cornwall and Papavassiliou performed the PT construction :



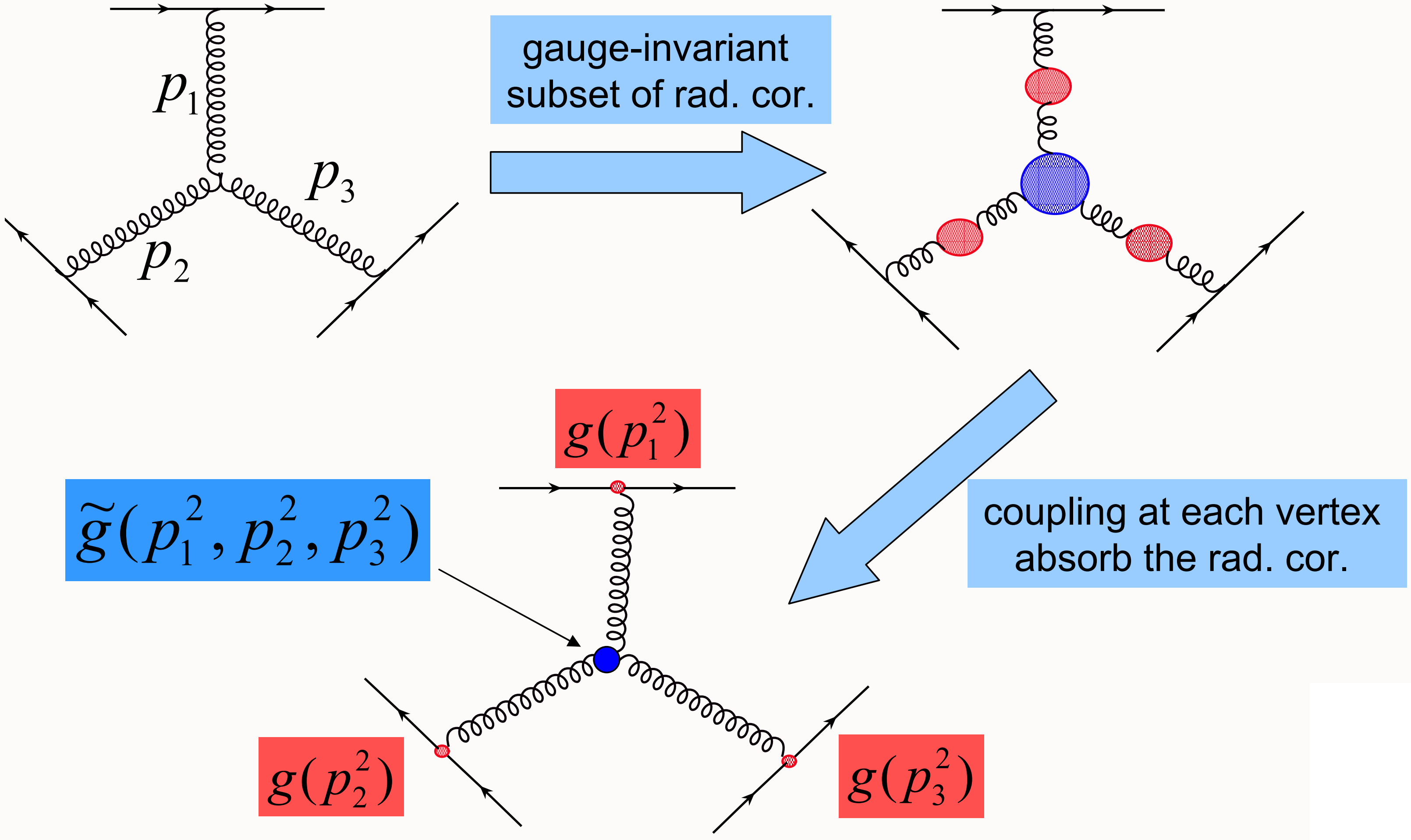
The “pinched” parts are added to the “regular” 3 gluon vertex



Summary of Supersymmetric Relations

Massless	Massive
$F_G + 4F_Q + (10-d)F_S = 0$	$F_{MG} + 4F_{MQ} + (9-d)F_{MS} = 0$
$\Sigma_{QG}(F) \equiv \frac{d-2}{2}F_Q + F_G$	$\Sigma_{MQG}(F) \equiv \frac{d-1}{2}F_{MQ} + F_{MG}$
= simple	= simple

Multi-scale Renormalization of the Three-Gluon Vertex



3 Scale Effective Charge

$$\tilde{\alpha}(a,b,c) \equiv \frac{\tilde{g}^2(a,b,c)}{4\pi}$$

(First suggested by H.J. Lu)

$$\frac{1}{\tilde{\alpha}(a,b,c)} = \frac{1}{\alpha_{bare}} + \frac{1}{4\pi}\beta_0\left(L(a,b,c) - \frac{1}{\varepsilon} + \cdots\right)$$

$$\frac{1}{\tilde{\alpha}(a,b,c)} = \frac{1}{\tilde{\alpha}(a_0,b_0,c_0)} + \frac{1}{4\pi}\beta_0\left[L(a,b,c) - L(a_0,b_0,c_0)\right]$$

L(a,b,c) = 3-scale “log-like” function

L(a,a,a) = log(a)

3 Scale Effective Scale

$$L(a,b,c) \equiv \log\left(Q^2_{eff}(a,b,c)\right) + i\,\mathrm{Im}\,L(a,b,c)$$

Governs strength of the three-gluon vertex

$$\frac{1}{\widetilde{\alpha}(a,b,c)} = \frac{1}{\widetilde{\alpha}(a_0,b_0,c_0)} + \frac{1}{4\pi}\beta_0\left[L(a,b,c) - L(a_0,b_0,c_0)\right]$$

$$\hat{\Gamma}_{\mu_1\mu_2\mu_3} \propto \sqrt{\widetilde{\alpha}(a,b,c)}$$

Generalization of BLM Scale to 3-Gluon Vertex

Properties of the Effective Scale

$$Q^2_{eff}(a,b,c) = Q^2_{eff}(-a,-b,-c)$$

$$Q^2_{eff}(\lambda a, \lambda b, \lambda c) = |\lambda| Q^2_{eff}(a,b,c)$$

$$Q^2_{eff}(a,a,a) = |a|$$

$$Q^2_{eff}(a,-a,-a) \approx 5.54 |a|$$

$$Q^2_{eff}(a,a,c) \approx 3.08 |c| \quad \text{for} \quad |a| >> |c|$$

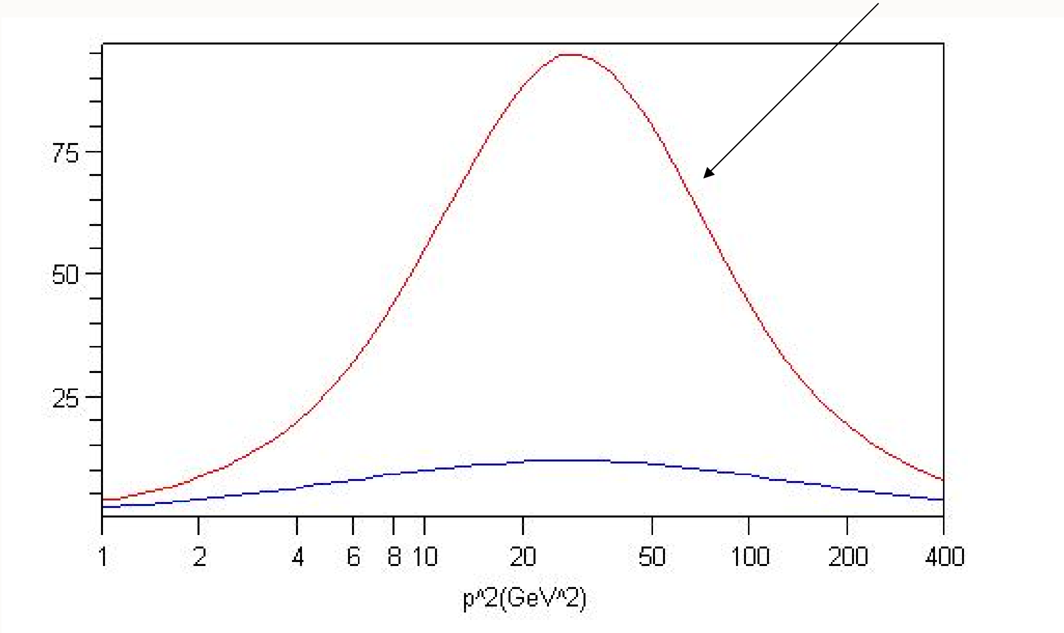
$$Q^2_{eff}(a,-a,c) \approx 22.8 |c| \quad \text{for} \quad |a| >> |c|$$

$$Q^2_{eff}(a,b,c) \approx 22.8 \frac{|bc|}{|a|} \quad \text{for} \quad |a| >> |b|, |c|$$

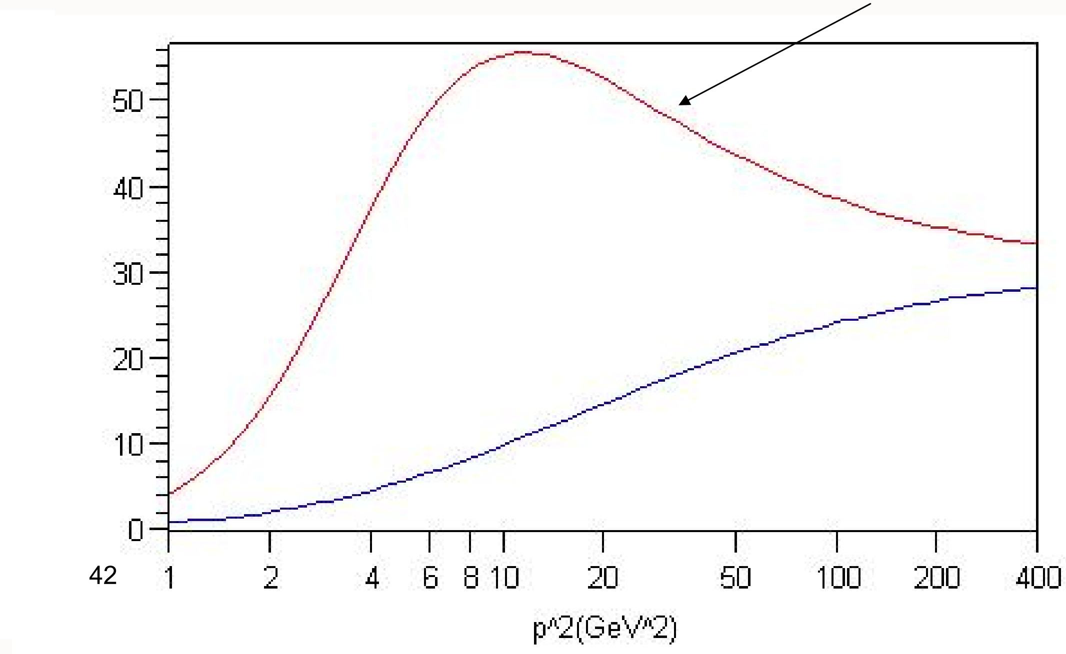
Surprising dependence on Invariants

The Effective Scale

$Q^2_{eff}\left(10\,\mathrm{GeV}^2, 10\,\mathrm{GeV}^2, p^2\right)$ $Q^2_{eff}\left(-10\,\mathrm{GeV}^2, -10\,\mathrm{GeV}^2, p^2\right)$

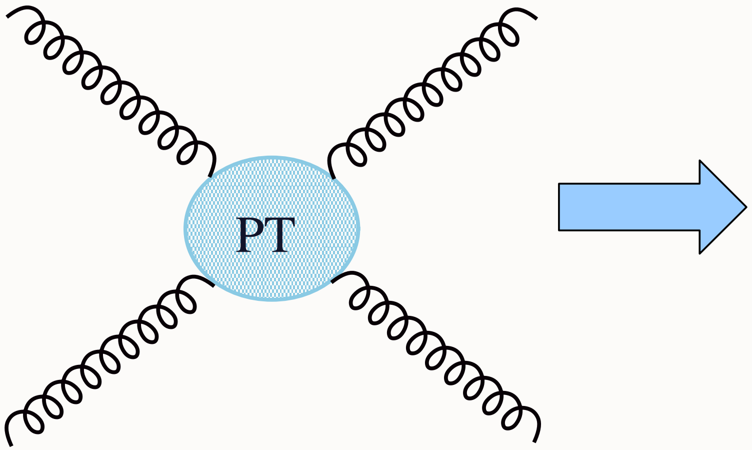


$Q^2_{eff}\left(10\,\mathrm{GeV}^2, p^2, p^2\right)$ $Q^2_{eff}\left(-10\,\mathrm{GeV}^2, p^2, p^2\right)$



Future Directions

Gauge-invariant four gluon vertex



$$L_4(p_1, p_2, p_3, p_4)$$

$$Q^2_{4\,eff}(p_1, p_2, p_3, p_4)$$

Hundreds of form factors!

Summary and Future

- ***Multi-scale analytic*** renormalization based on ***physical, gauge-invariant*** Green's functions

- ***Optimal*** improvement of perturbation theory with ***no scale-ambiguity*** since physical kinematic invariants are the arguments of the (multi-scale) couplings

Conventional renormalization scale-setting method:

- Guess arbitrary renormalization scale and take arbitrary range. Wrong for QED and Precision Electroweak.
- Prediction depends on choice of renormalization scheme
- Variation of result with respect to renormalization scale only sensitive to nonconformal terms; no information on genuine (conformal) higher order terms
- Conventional procedure has no scientific basis.
- FAC and PMS give unphysical results.
- Renormalization scale not arbitrary: Analytic constraint from flavor thresholds

Use Physical Scheme to Characterize QCD Coupling

- Use Observable to define QCD coupling or Pinch Scheme
- Analytic: Smooth behavior as one crosses new quark threshold
- New perspective on grand unification

Binger, Sjb

Factorization scale

$$\mu_{\text{factorization}} \neq \mu_{\text{renormalization}}$$

- Arbitrary separation of soft and hard physics
- Dependence on factorization scale not associated with beta function - present even in conformal theory
- Keep factorization scale separate from renormalization scale

$$\frac{d\mathcal{O}}{d\mu_{\text{factorization}}} = 0$$

- Residual dependence when one works in fixed order in perturbation theory.

Use BLM!

- Satisfies Transitivity, all aspects of Renormalization Group; scheme independent
- Analytic at Flavor Thresholds
- Preserves Underlying Conformal Template
- Physical Interpretation of Scales; Multiple Scales
- Correct Abelian Limit ($N_C = 0$)
- Eliminates unnecessary source of imprecision of PQCD predictions
- Commensurate Scale Relations: Fundamental Tests of QCD free of renormalization scale and scheme ambiguities
- BLM used in many applications, QED, LGTH, BFKL, ...

Light-Front QCD Phenomenology

- Hidden color, Intrinsic glue, sea, Color Transparency
- Near Conformal Behavior of LFWFs at Short Distances; PQCD constraints
- Vanishing anomalous gravitomagnetic moment
- Relation between edm and anomalous magnetic moment
- Cluster Decomposition Theorem for relativistic systems
- OPE: DGLAP, ERBL evolution; invariant mass scheme

New Perspectives for QCD from AdS/CFT

- LFWFs: Fundamental description of hadrons at amplitude level
- Holographic Model from AdS/CFT : Confinement at large distances and conformal behavior at short distances
- Model for LFWFs, meson and baryon spectra: many applications!
- New basis for diagonalizing Light-Front Hamiltonian
- Physics similar to MIT bag model, but covariant. No problem with support $0 < x < 1$.
- Quark Interchange dominant force at short distances

Essential to test QCD

- J-PARC
- GSI antiprotons
- 12 GeV Jlab
- BaBar/Belle: ISR, two-gamma, timelike DVCS
- RHIC/LHC Nuclear Collisions; LHCb
- electron-proton, electron-nucleus collisions

Novel Tests of QCD at GSI

Polarized antiproton Beam   Secondary Beams

- Characteristic momentum scale of QCD: 300 MeV
- Many Tests of AdS/CFT predictions possible
- Exclusive channels: Conformal scaling laws, quark-interchange
- $\bar{p}p$ scattering: fundamental aspects of nuclear force
- Color transparency: Coherent color effects
- Nuclear Effects, Hidden Color, Anti-Shadowing
- Anomalous heavy quark phenomena
- Spin Effects: A_N, A_{NN}

Hadron Dynamics at the Amplitude Level

- DIS studies have primarily focussed on probability distributions: integrated and unintegrated.
- Test QCD at the amplitude level: Phases, multi-parton correlations, spin, angular momentum, exclusive amplitudes
- Impact of ISI and FSI: Single Spin Asymmetries, Diffractive Deep Inelastic Scattering, Shadowing, Antishadowing
- Hadron wavefunctions: Fundamental QCD Dynamics
- Remarkable new insights from AdS/CFT, the duality between conformal field theory and Anti-de Sitter Space