Trento ECT*

Photonic and Diffractive Phenomena in QCD

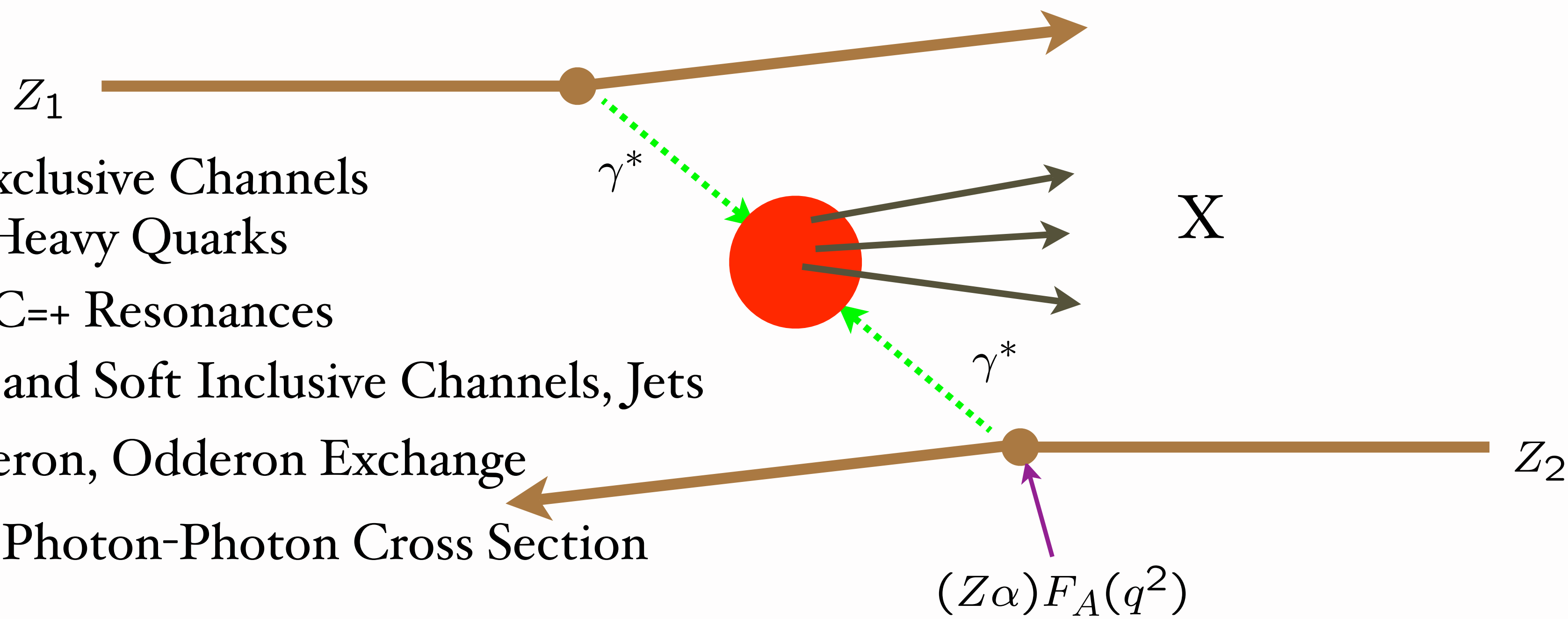
Stan Brodsky, SLAC

LHC Photoproduction Workshop
January 16, 2007

Study Two-Photon Processes in Peripheral Heavy Ion Collisions

$$Z_1 Z_2 \to X + Z_1 + Z_2 \qquad \gamma\gamma \to \eta_c, \eta_b, Z^0, W^+W^-, H^0, \dots$$

Exclusive Channels
Heavy Quarks
C=+ Resonances
Hard and Soft Inclusive Channels, Jets
Pomeron, Odderon Exchange
Total Photon-Photon Cross Section

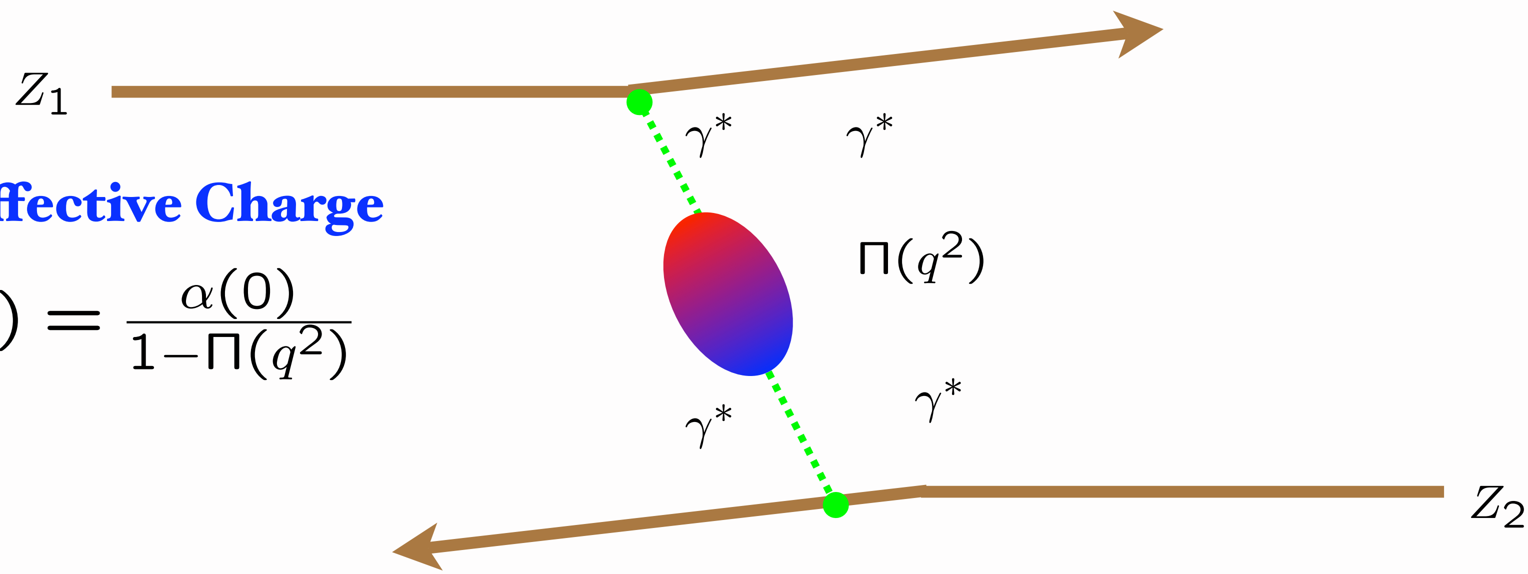


High masses accessible at the LHC

Elastic Scattering of Heavy Ions

Coulomb scattering of heavy charges

$Q^2 = -q^2 = -t << M_A^2$



QED Effective Charge

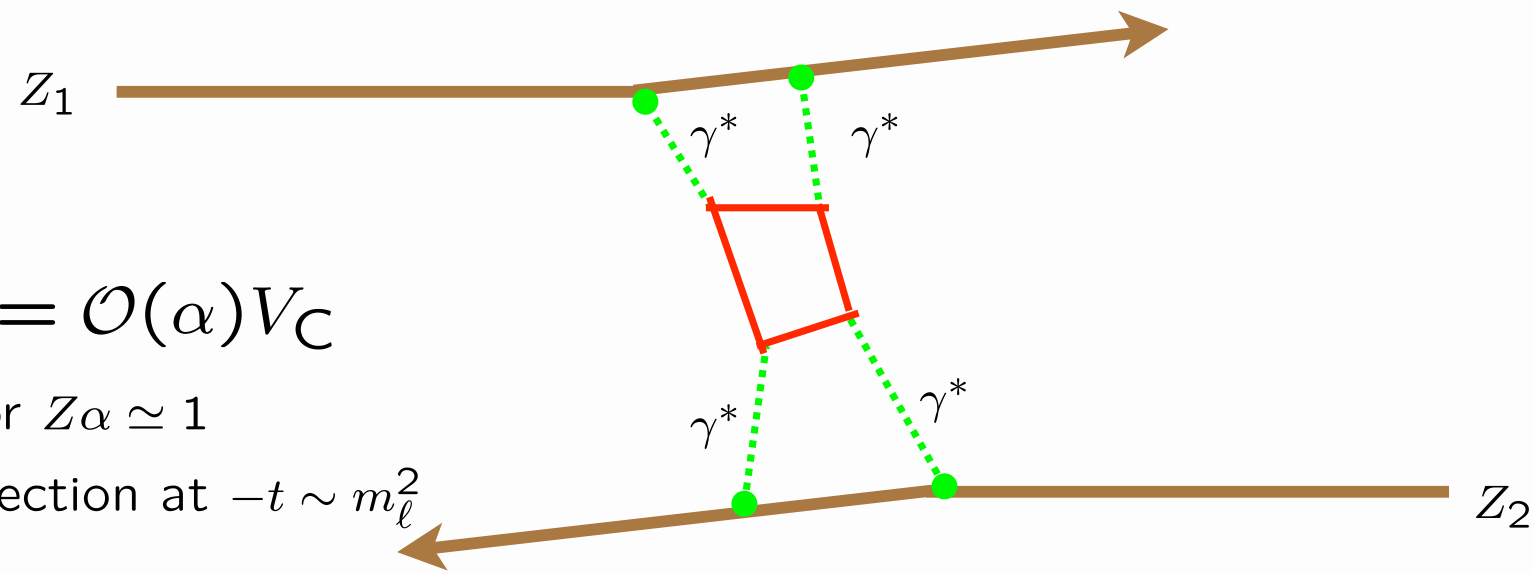
$$\alpha(q^2) = \frac{\alpha(0)}{1-\Pi(q^2)}$$

Calculate Lippmann-Schwinger T Matrix from effective potential

$$V_C = Z_1 Z_2 \frac{\alpha(q^2)}{q^2} F_{A_1}(q^2) F_{A_2}(q^2)$$

Elastic Scattering of Heavy Ions

Significant correction to Coulomb scattering from light-by-light scattering



$$V_{\mathrm{LL}} = \mathcal{O}(\alpha) V_{\mathrm{C}}$$

For $Z\alpha \simeq 1$

1% correction at $-t \sim m_\ell^2$

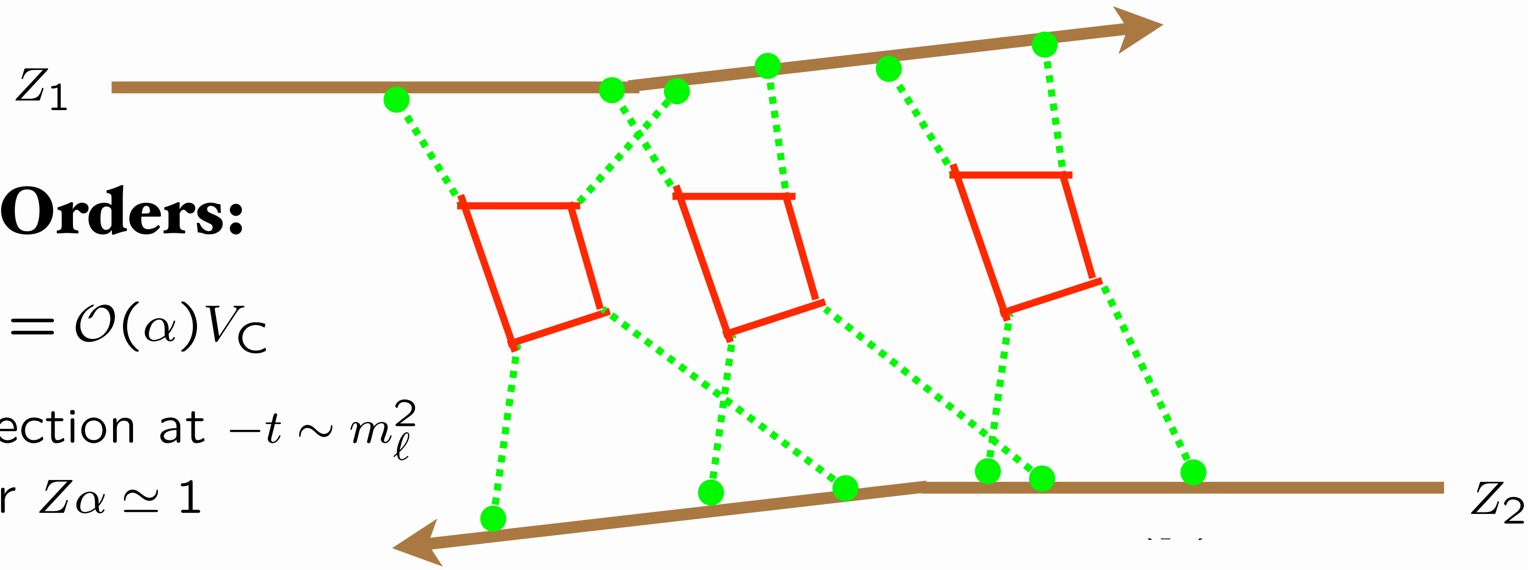
Effective Schrödinger potential $V_{\mathrm{C}} + V_{\mathrm{LL}}$

$$V_{\mathrm{C}} = Z_1 Z_2 \frac{\alpha(q^2)}{q^2} F_{A_1}(q^2) F_{A_2}(q^2) \qquad V_{\mathrm{LL}} = Z_1^2 Z_2^2 \alpha^4 \mathcal{T} F_{A_1} F_{A_2}$$

Elastic Scattering of Heavy Ions

Multiple Light-by-Light scattering

Cross graphs become eikonal at high mass



All Orders:

$V_{LL} = \mathcal{O}(\alpha) V_C$

1% correction at $-t \sim m_\ell^2$

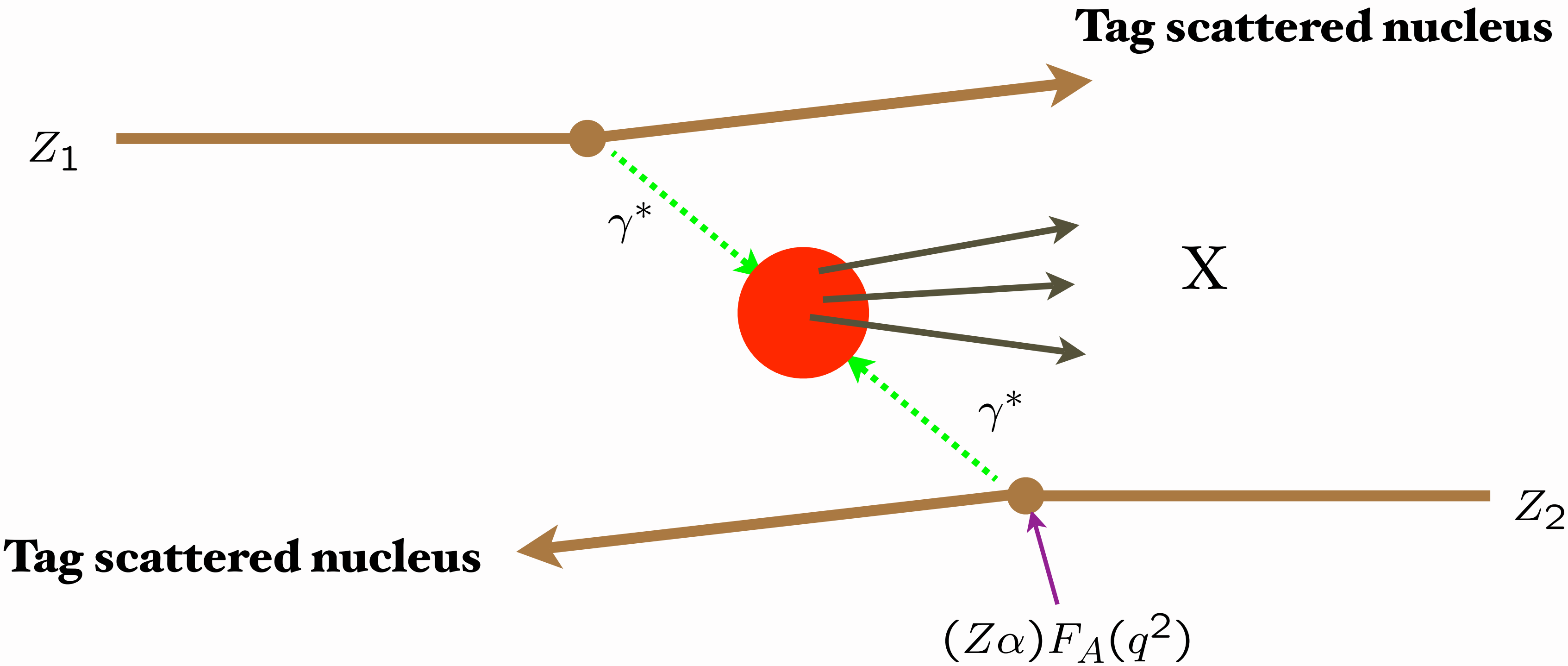
For $Z\alpha \simeq 1$

Calculate Lippmann-Schwinger T Matrix from $V_{eff} = V_C + V_{LL}$

$$V_C = Z_1 Z_2 \frac{\alpha(q^2)}{q^2} F_{A_1}(q^2) F_{A_2}(q^2) \qquad V_{LL} = Z_1^2 Z_2^2 \alpha^4 \mathcal{T} F_{A_1} F_{A_2}$$

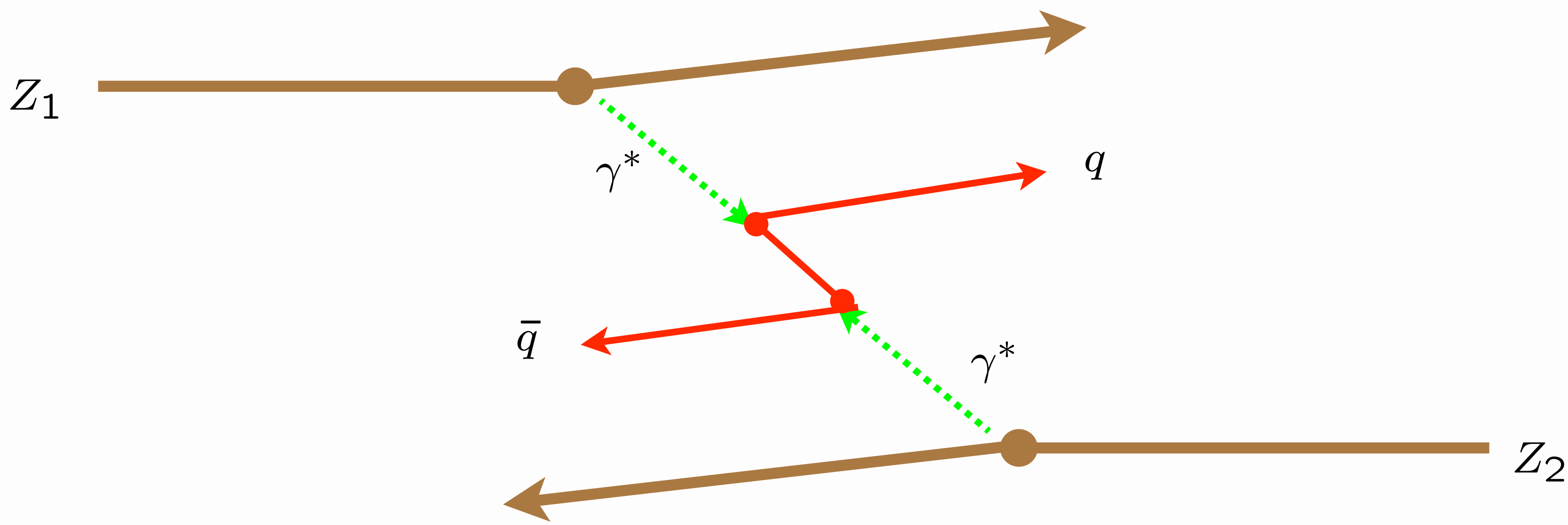
Study Two-Photon Processes in Peripheral Heavy Ion Collisions

$$Z_1 Z_2 \to X + Z_1 + Z_2$$



Study Jet Production in Peripheral Heavy Ion Collisions

$$Z_1 Z_2 \to \text{Jet Jet} + Z_1 + Z_2$$



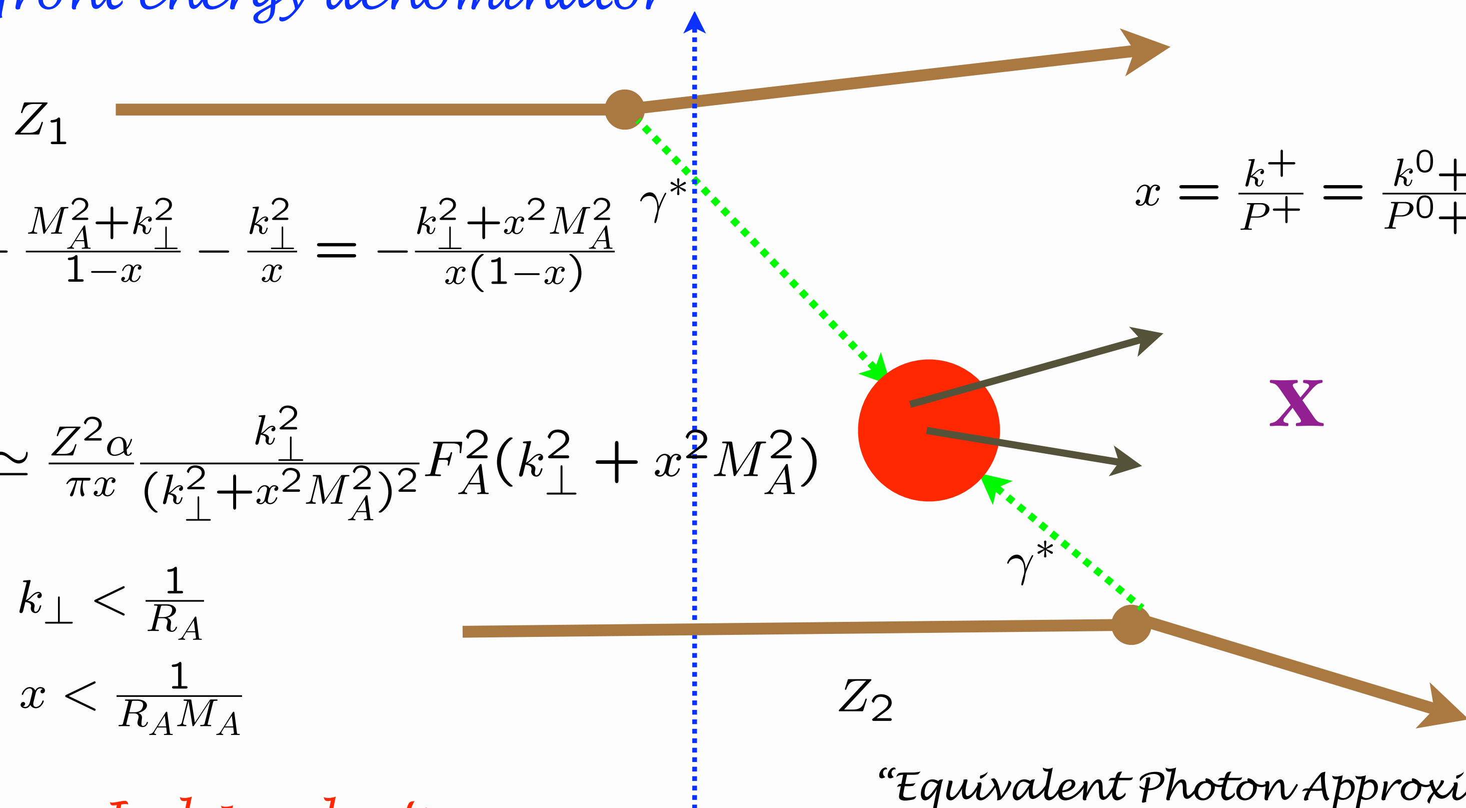
$$\sigma(\gamma\gamma \to X) = N_C \sum e_q^4 \sigma(\gamma\gamma \to \mu^+\mu^-)$$

Rule out Han-Nambu quark charges

Study Two-Photon Processes in Peripheral Heavy Ion Collisions

$$Z_1 Z_2 \rightarrow X + Z_1 + Z_2$$

Light-front energy denominator



$$M_A^2 - \frac{M_A^2 + k_\perp^2}{1-x} - \frac{k_\perp^2}{x} = -\frac{k_\perp^2 + x^2 M_A^2}{x(1-x)}$$

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

$$\frac{dN_\gamma}{dx\,dk_\perp^2} \simeq \frac{Z^2 \alpha}{\pi x} \frac{k_\perp^2}{(k_\perp^2 + x^2 M_A^2)^2} F_A^2(k_\perp^2 + x^2 M_A^2)$$

$$k_\perp < \frac{1}{R_A}$$

$$x < \frac{1}{R_A M_A}$$

Frame-Independent Coherence Condition

"Equivalent Photon Approximation": PQCD Factorization

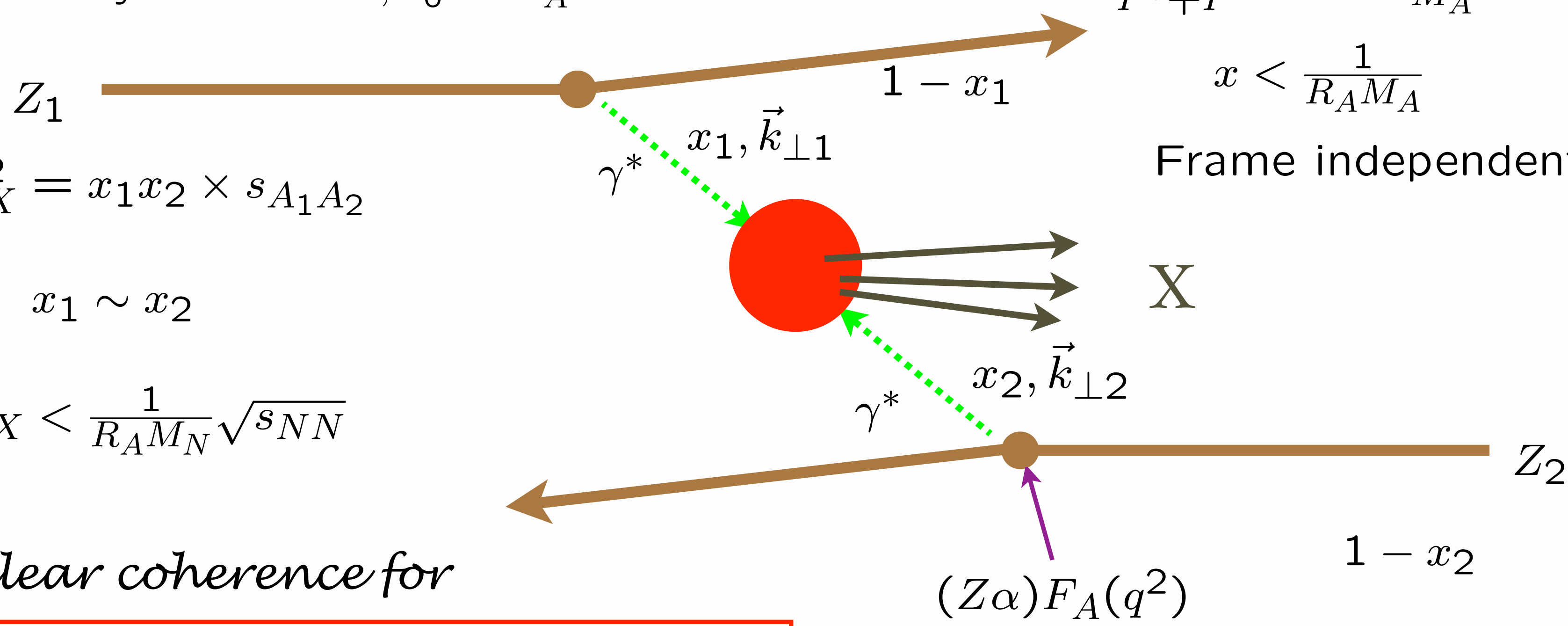
Study Two-Photon Processes in Peripheral Heavy Ion Collisions

in rest system $P^z = 0, P_0 = M_A$

$$1 - x = \frac{P'^0 + P'^z}{P^0 + P^z} \simeq 1 - \frac{P'^z}{M_A}$$

$$x < \frac{1}{R_A M_A}$$

Frame independent



$$\mathcal{M}_X^2 = x_1 x_2 \times s_{A_1 A_2}$$

$$x_1 \sim x_2$$

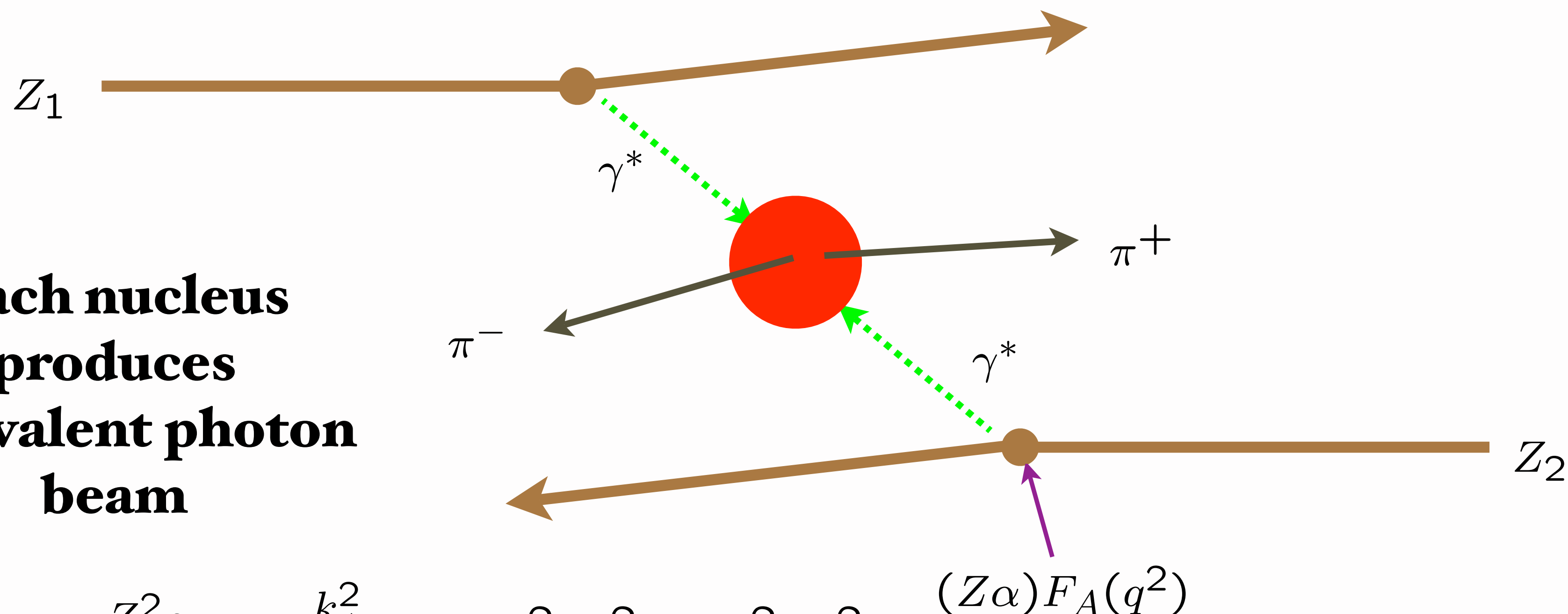
$$\mathcal{M}_X < \frac{1}{R_A M_N}\sqrt{s_{NN}}$$

Nuclear coherence for

$$\mathcal{M}_X < \frac{\sqrt{s_{NN}}}{5A^{1/3}} \sim 0.5 \text{ TeV at the LHC}$$

Study Exclusive Two-Photon Processes in Peripheral Heavy Ion Collisions

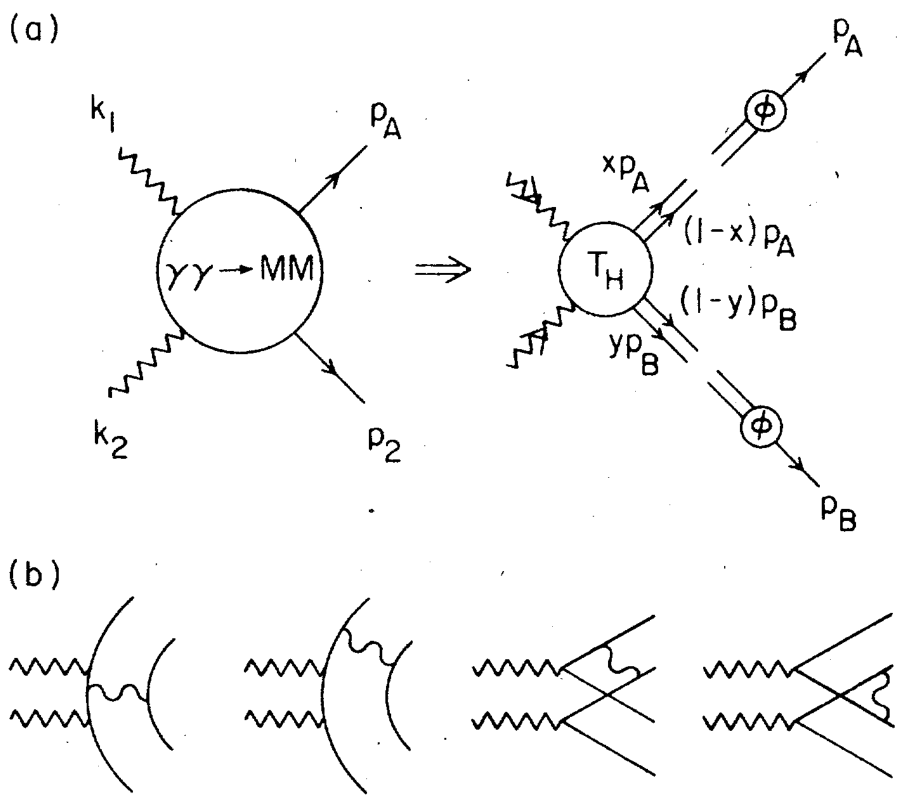
$$Z_1 Z_2 \to \pi^+ \pi^- + Z_1 + Z_2$$

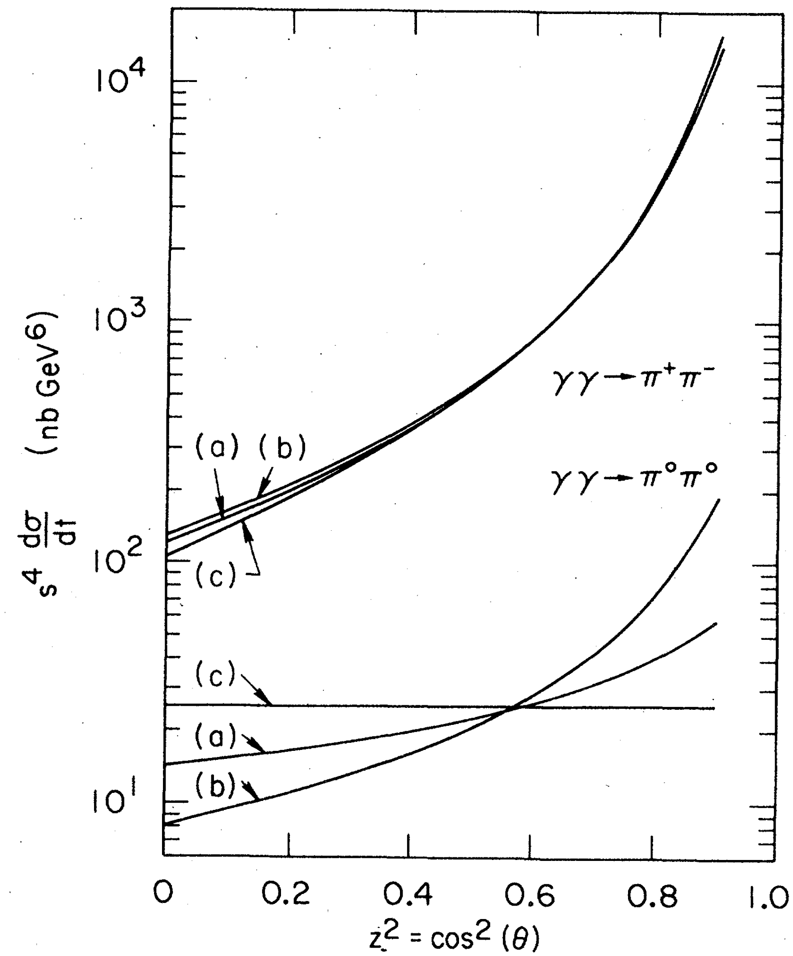


Each nucleus produces equivalent photon beam

$$\frac{dN_\gamma}{dx dk_\perp^2} \simeq \frac{Z^2 \alpha}{x} \frac{k_\perp^2}{(k_\perp^2 + x^2 M_A^2)^2} F_A^2(k_\perp^2 + x^2 M_A^2)$$

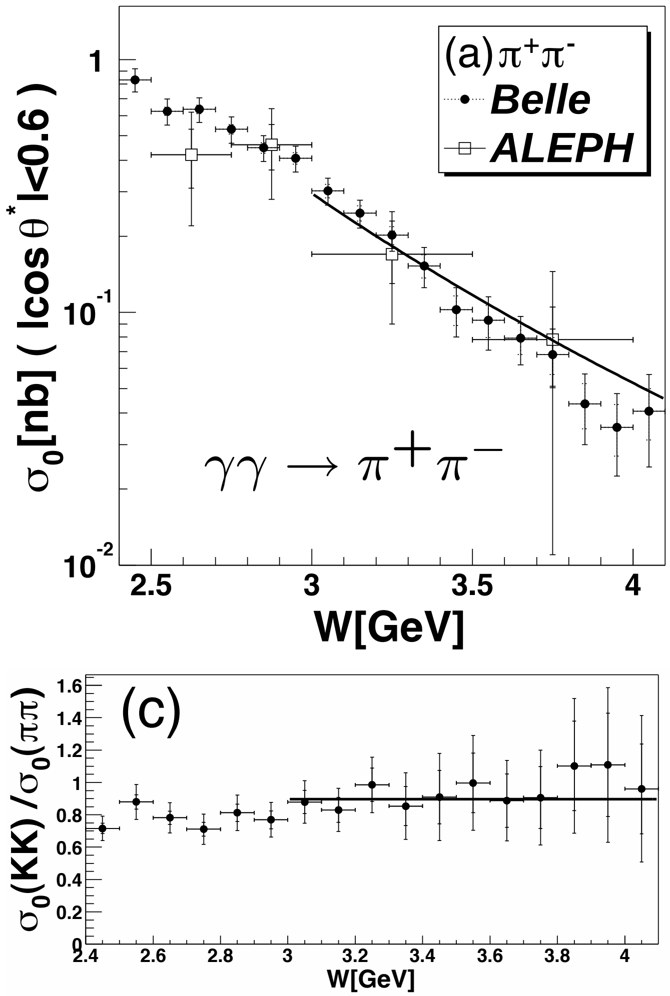
+ higher-order Coulomb corrections





$$\frac{\frac{d\sigma}{dt}(\gamma\gamma\to\pi^+\pi^-)}{\frac{d\sigma}{dt}(\gamma\gamma\to\mu^+\mu^-)} \sim \frac{4\,|F_\pi(s)|^2}{1-\cos^4\theta_{c.m.}}$$

Crucial test: $\gamma\gamma \to \pi^0\pi^0$



Possible extension to very high invariant mass using LHC UPC

$$s = E^2_{cm} = W^2 = Q^2$$

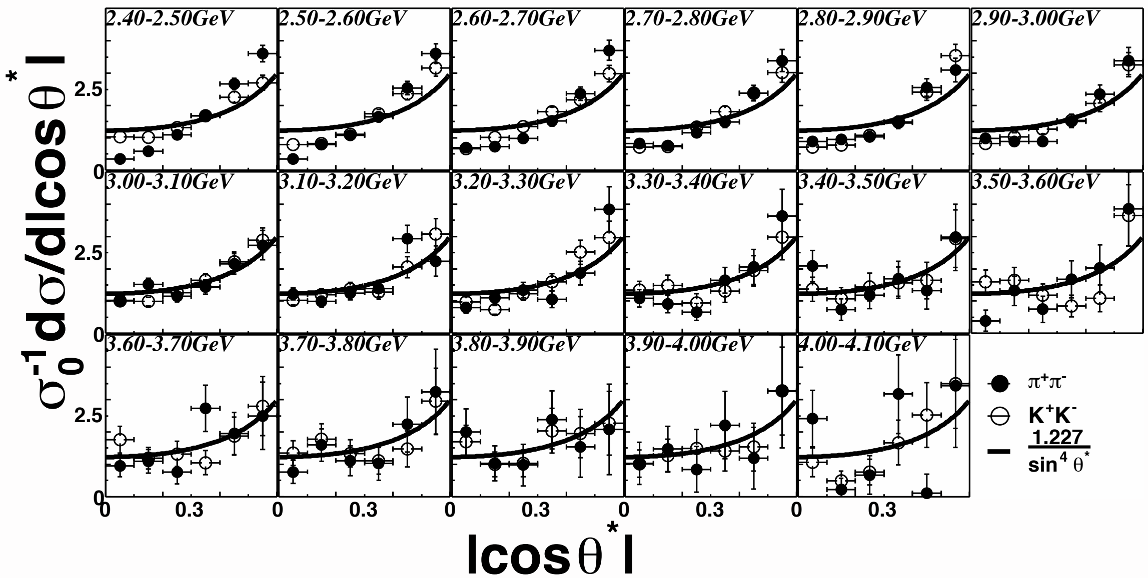
PQCD, AdS/CFT:

$$\Delta\sigma(\gamma\gamma \to \pi^+\pi^-, K^+, K^-) \sim 1/W^6$$

$$|\cos(\theta_{CM})| < 0.6$$

Fig. 5. Cross section for (a) $\gamma\gamma\to\pi^+\pi^-$, (b) $\gamma\gamma\to K^+K^-$ in the c.m. angular region $|\cos\theta^*| < 0.6$ together with a W^{-6} dependence line derived from the fit of $s|R_M|$. (c) shows the cross section ratio. The solid line is the result of the fit for the data above 3 GeV. The errors indicated by short ticks are statistical only.

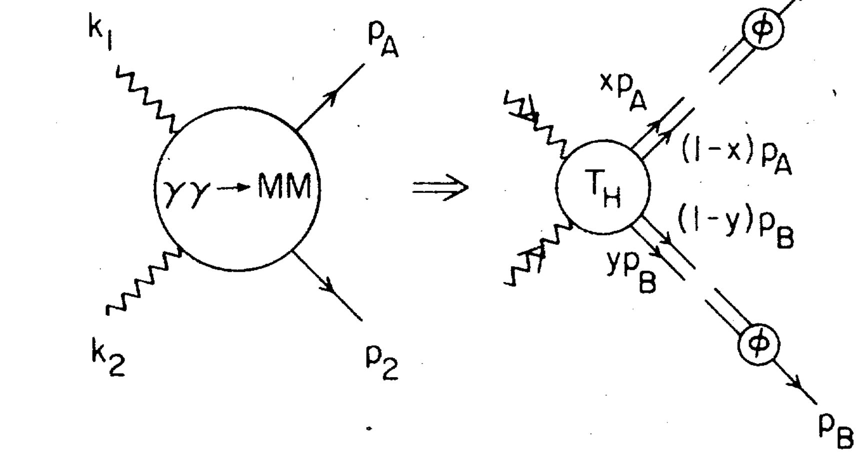
$$\frac{d\sigma}{d|\cos\theta^*|}(\gamma\gamma \to M^+M^-) \approx \frac{16\pi\alpha^2}{s}\frac{|F_M(s)|^2}{\sin^4\theta^*},$$

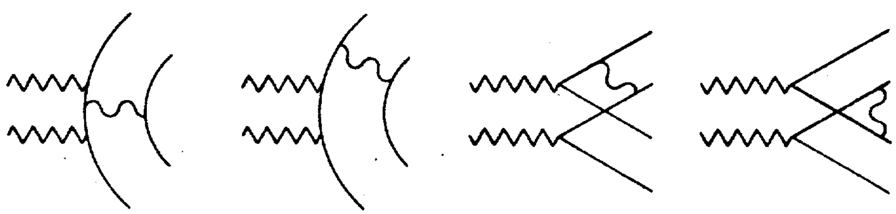


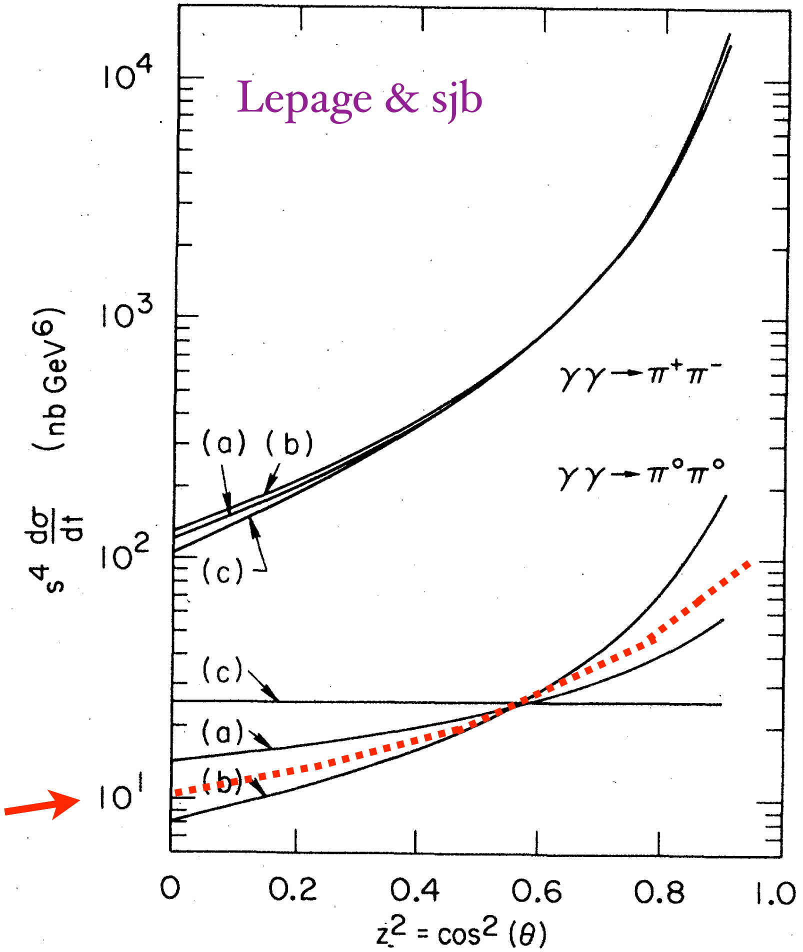
Measurement of the $\gamma\gamma \to \pi^+\pi^-$ and $\gamma\gamma \to K^+K^-$ processes at energies of 2.4–4.1 GeV

Belle Collaboration

Fig. 4. Angular dependence of the cross section, $\sigma_0^{-1} d\sigma/d|\cos\,\theta^*|$, for the $\pi^+\pi^-$(closed circles) and K^+K^-(open circles) processes. The curves are $1.227 \times \sin^{-4}\theta^*$. The errors are statistical only.







Neutral pair angular distribution sensitive to AdS/CFT distribution!

$$\phi_\pi^{AdS/QCD}(x) \propto [x(1-x)]^{1/2}$$

(a): $\phi_\pi(x) \propto x(1-x)$

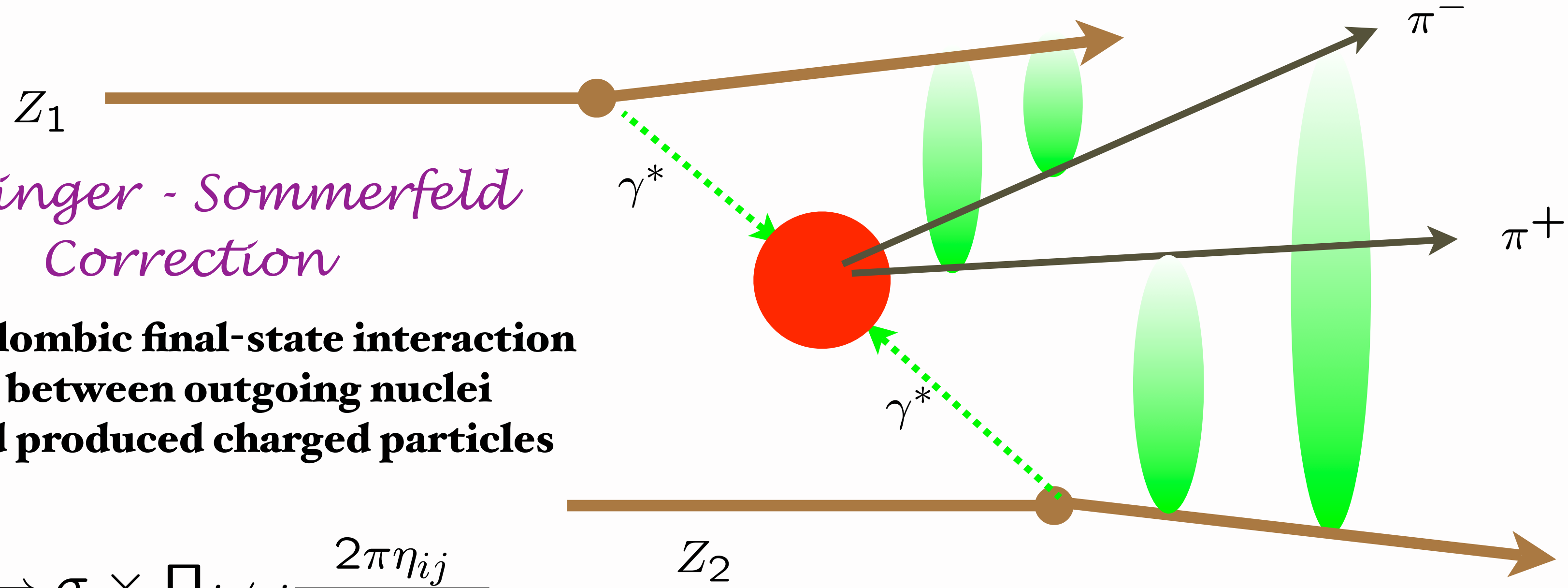
(b): $\phi_\pi(x) \propto [x(1-x)]^{1/4}$

(c): $\phi_\pi(x) \propto \delta(x-1/2)$

de Teramond & sjb

Final-State Coulomb Corrections

$$Z_1 Z_2 \to \pi^+\pi^- + Z_1 + Z_2$$



Schwinger - Sommerfeld Correction

Coulombic final-state interaction between outgoing nuclei and produced charged particles

$$\sigma \to \sigma \times \Pi_{i \neq j} \frac{2\pi\eta_{ij}}{e^{2\pi\eta_{ij}} - 1}$$

$$\eta_{ij} = \frac{\pi Z_i q_j \alpha}{\beta_{ij}}$$

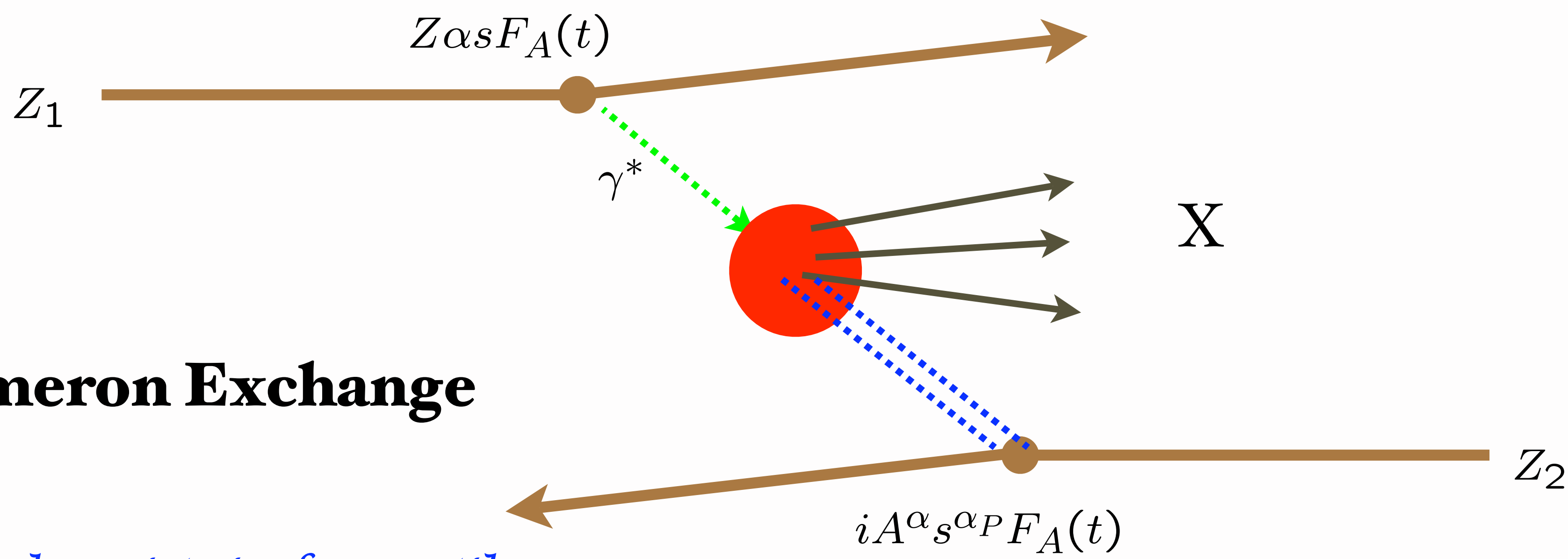
Strong final-state interactions at small relative velocity

Schwinger-Sommerfeld Correction

- Final-state Coulombic interactions of nuclei with charged hadrons distort trajectories
- Not unitarity $\sigma \to \sigma \times \Pi_{i \neq j} \frac{2\pi\eta_{ij}}{e^{2\pi\eta_{ij}} - 1}$ $\eta_{ij} = \frac{\pi Z_i q_j \alpha}{\beta_{ij}}$
- Generate charge asymmetries and single-spin asymmetries -- opposite charges attract
- Use QED lepton production as reference

Study Two-Photon Processes in Peripheral Heavy Ion Collisions

$$Z_1 Z_2 \to X + Z_1 + Z_2$$



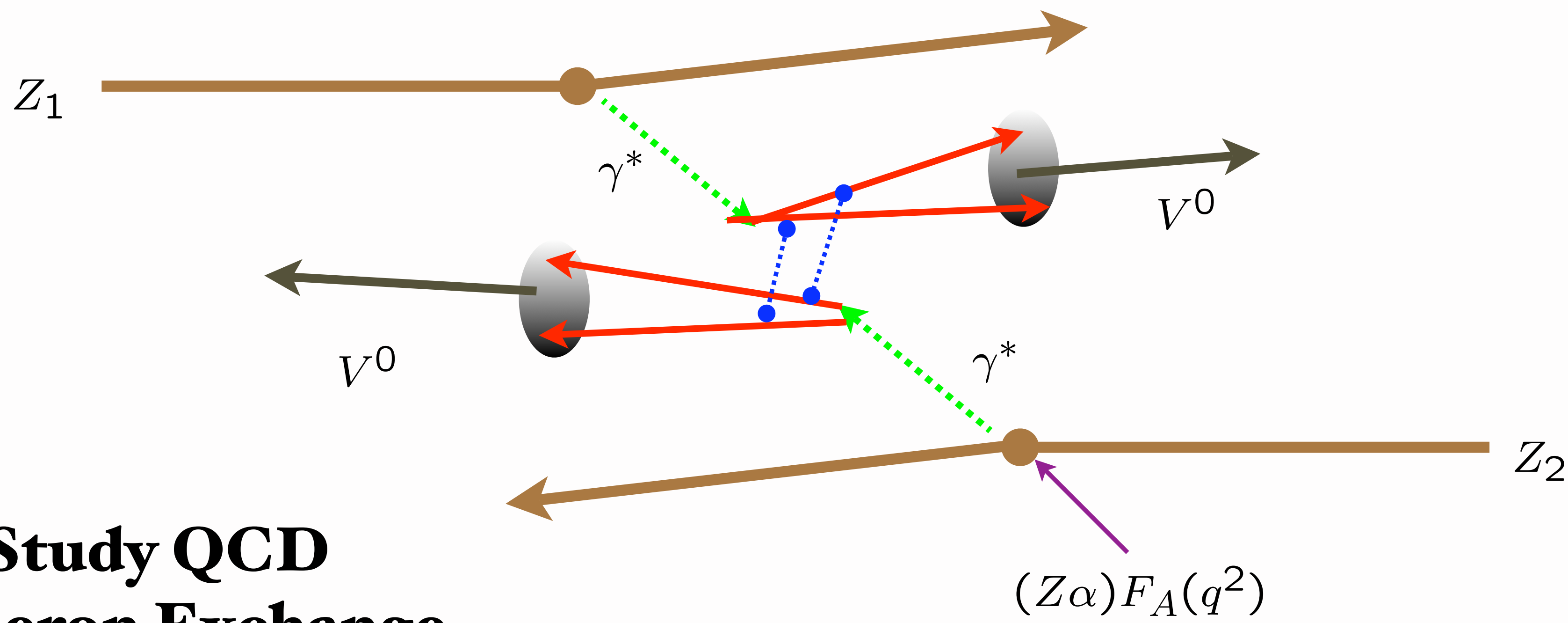
Pomeron Exchange

Real part interferes with
Coulomb exchange
Charge asymmetries
Single-Spin Asymmetries

$\alpha \sim 1/3$ to $\alpha = 1.$

Study Doubly Diffractive C= - Vector Meson Photoproduction in Peripheral Heavy Ion Collisions

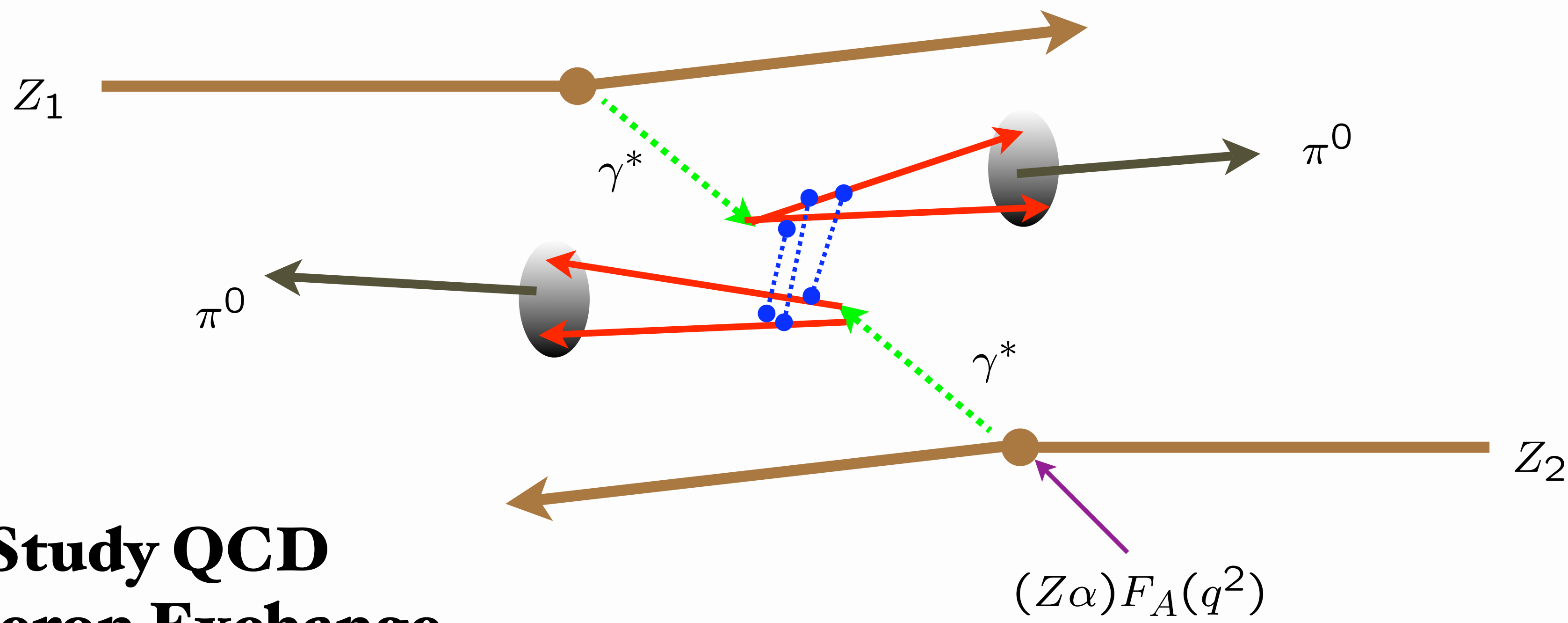
$$Z_1 Z_2 \to V^0 V^0 + Z_1 + Z_2$$



Study QCD Pomeron Exchange

Study Doubly C=+ Meson Production in Peripheral Heavy Ion Collisions

$$Z_1 Z_2 \to \pi^0 \pi^0 + Z_1 + Z_2$$

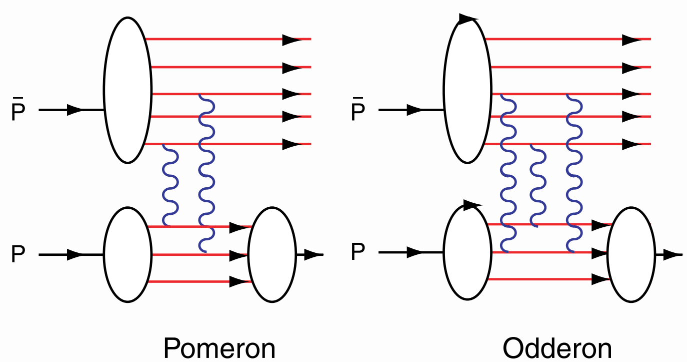


Study QCD Odderon Exchange

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 $\gamma p \to c\bar{c} p$ *e-p collider test*
- Analogous to lepton energy and angle asymmetry $\gamma Z \to e^+ e^- Z$
- Pion Asymmetry in $\gamma p \to \pi^+ \pi^- p$



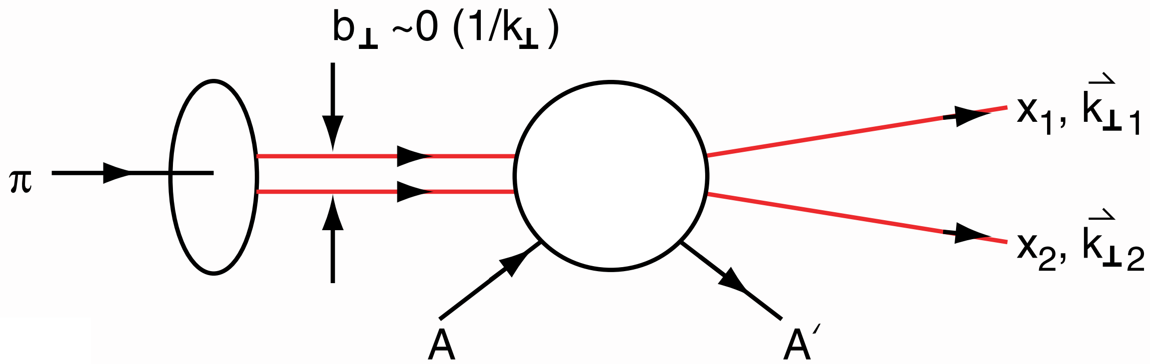
Odderon: Another source of antishadowing

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, Tri-Jet Production
- Nuclear Shadowing and Antishadowing
- Novel QCD Mechanism for Higgs Production

Diffractive Dissociation of Pion into Quark Jets

E791 Ashery et al.



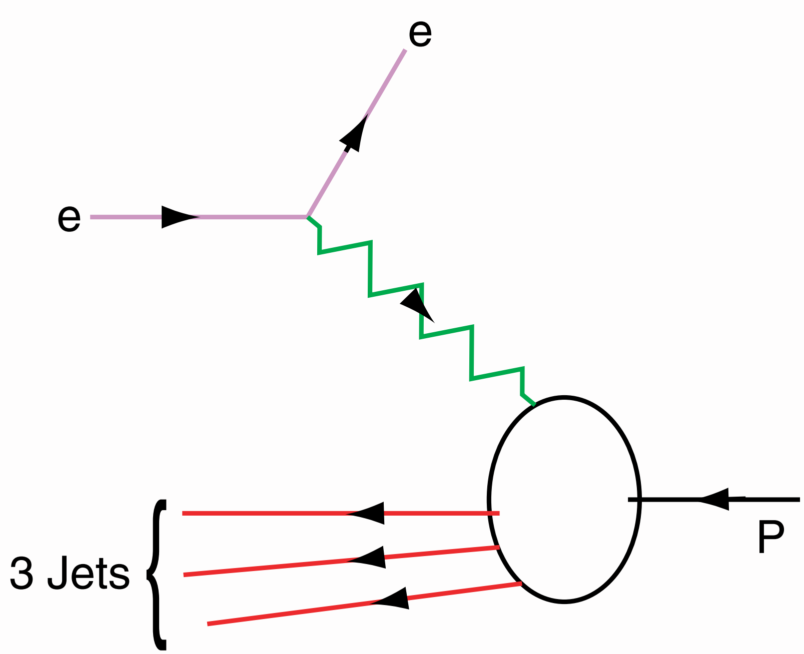
$$M \propto \frac{\partial^2}{\partial^2 k_\perp} \psi_\pi(x, k_\perp)$$

Measure Light-Front Wavefunction of Pion

Minimal momentum transfer to nucleus

Nucleus left Intact!

Coulomb- or Hadron -Dissociate Proton to Three Jets



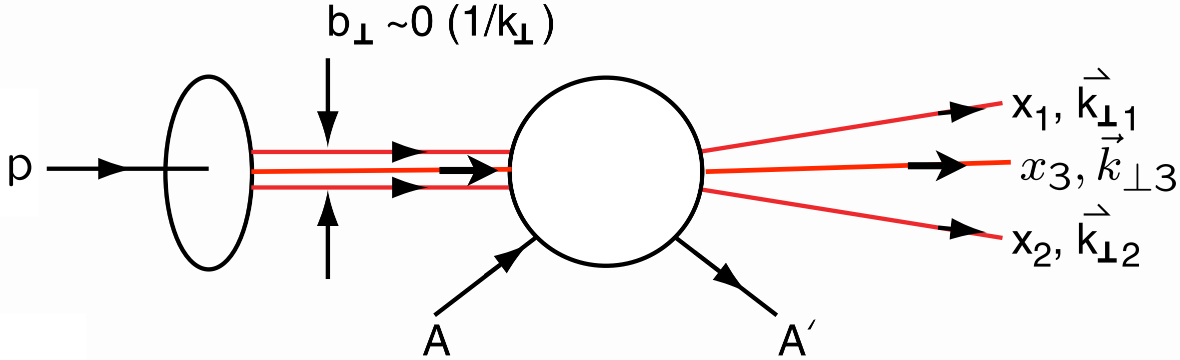
Frankfurt
Miller
Strikman

Measure $\Psi_{qqq}(x_i, \vec{k}_{\perp i})$ valence wavefunction of proton

Polarized proton: Spin correlations

Diffractive Dissociation of Proton into Quark Jets

Frankfurt, Miller, Strikman



Measure Light-Front Wavefunction of proton

Minimal momentum transfer to nucleus

Nucleus left Intact

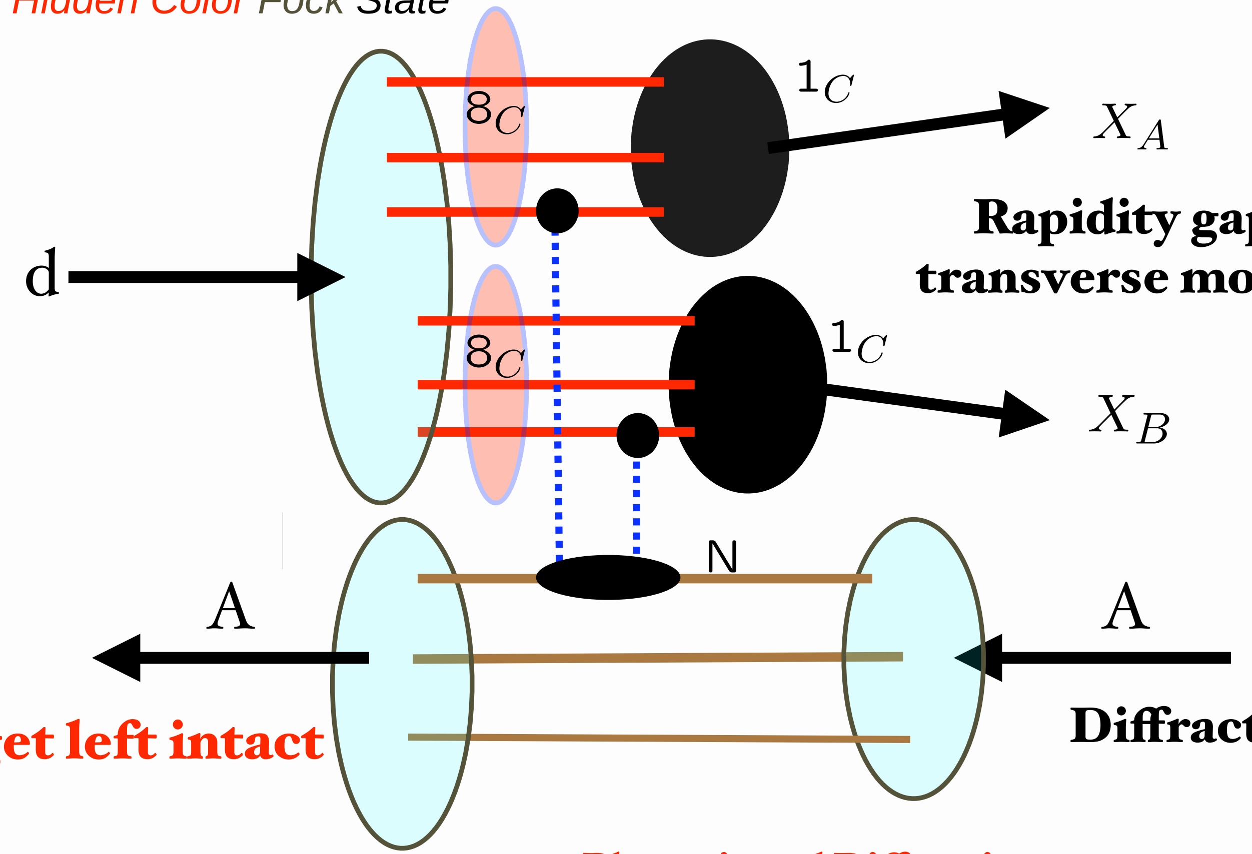
$$M \propto \sum_{ij}^{3} \frac{\partial^2}{\partial \vec{k}_{\perp i} \partial \vec{k}_{\perp j}} \psi_3^p(x_i, \vec{k}_{\perp i})$$

conformal invariance - AdS/CFT

$$\psi_3^p(x_i, \vec{k}_{\perp i}) \simeq \frac{F_p^2}{\mathcal{M}^4} \qquad \mathcal{M}^2 = \sum_i \frac{k_{\perp i}^2}{x_i}$$

LHC with forward acceptance

Diffractive dissociation of color-octet deuteron to two high tranverse momentum clusters

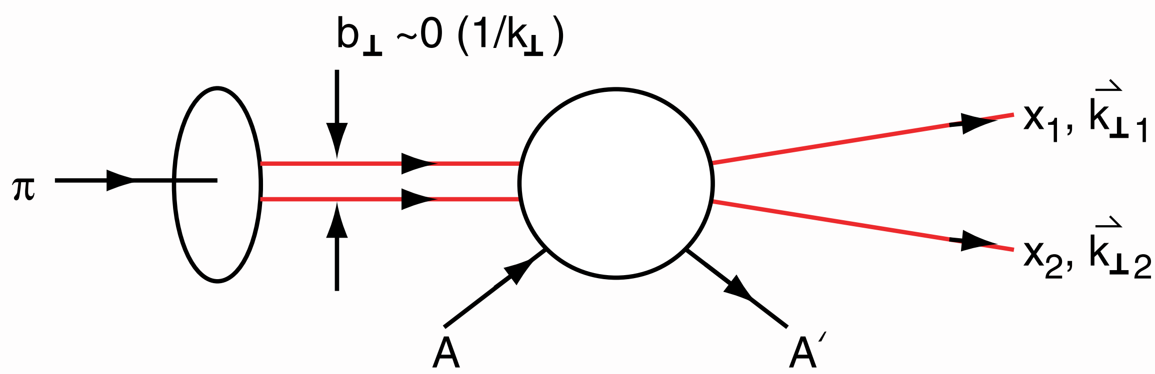


Rapidity gap between high transverse momentum clusters

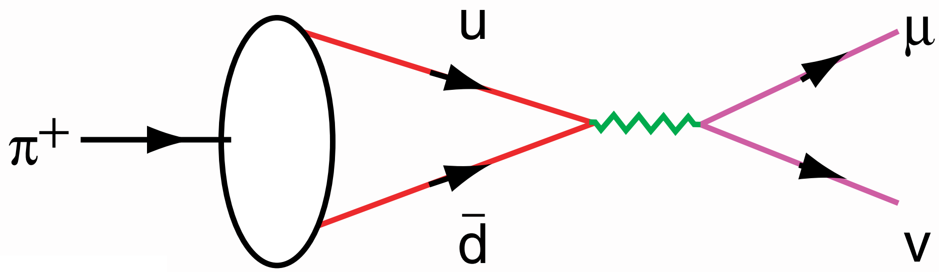
Target left intact

Diffraction, Rapidity gap

Fluctuation of a Pion to a Compact Color Dipole State

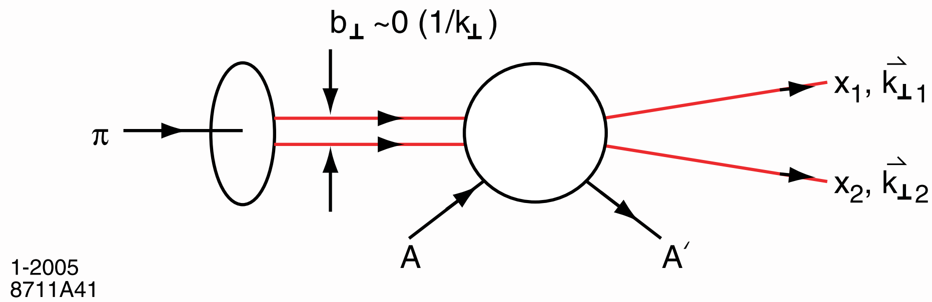


Color-Transparent Fock State For High Transverse Momentum Di-Jets

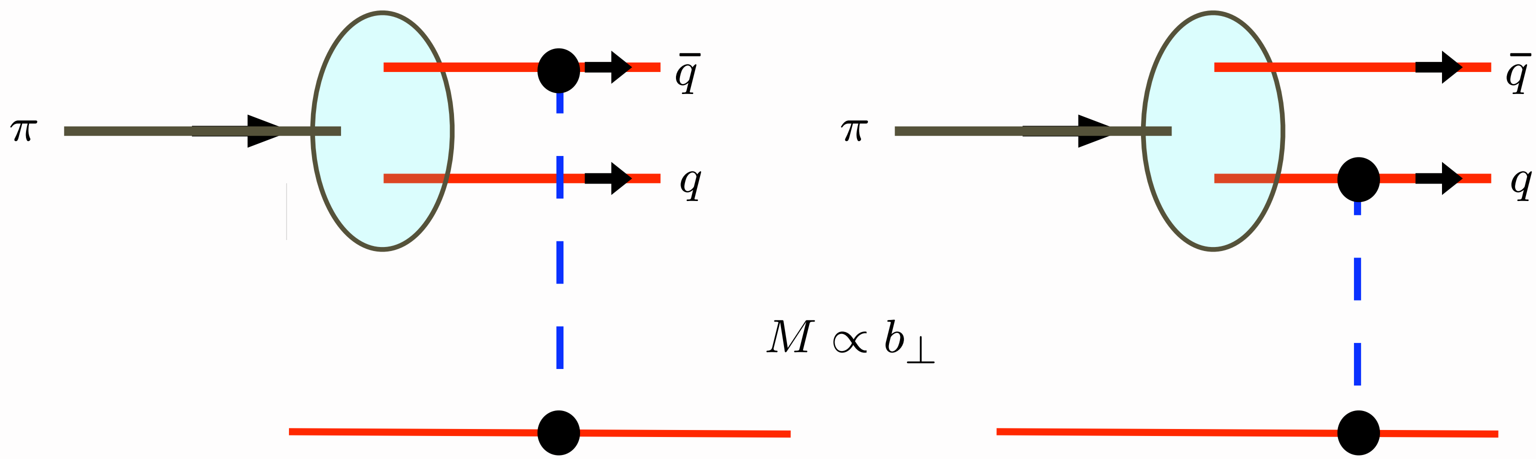


Same Fock State Determines Weak Decay

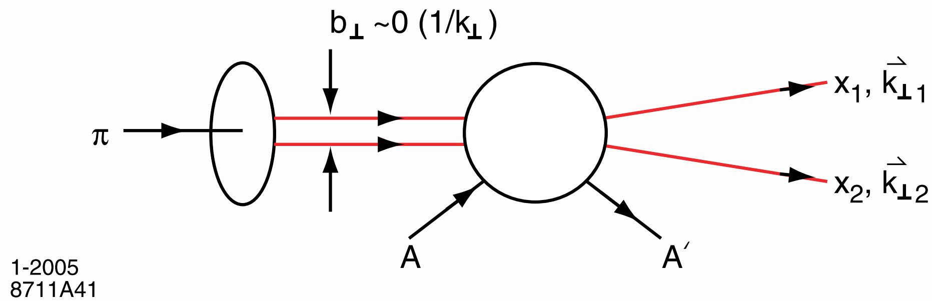
Key Ingredients in Ashery Experiment



Local gauge-theory interactions measure transverse size of color dipole



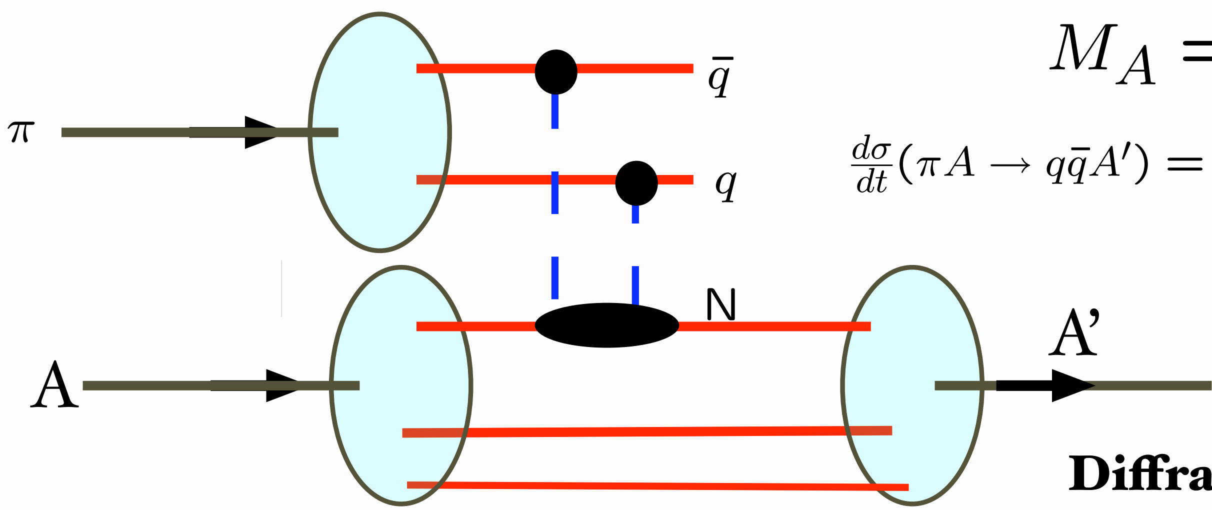
Key Ingredients in Ashery Experiment



Brodsky Mueller
Frankfurt Miller Strikman

Small color-dipole moment pion not absorbed; interacts with <u>each</u> nucleon coherently

<u>QCD COLOR Transparency</u>



$$M_A = A \ M_N$$

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

Target left intact

Diffraction, Rapidity gap

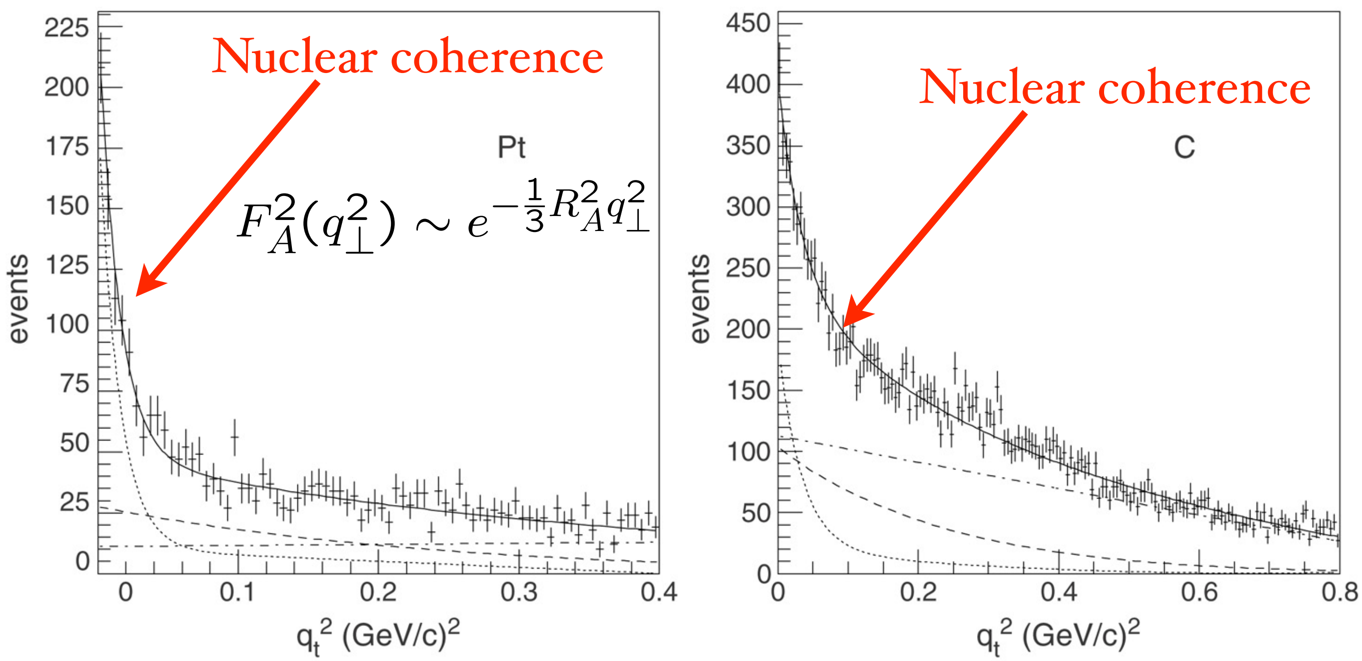
- **Fully coherent interactions between pion and nucleons.**

- **Emerging Di-Jets do not interact with nucleus.**

$$\mathcal{M}(\mathcal{A}) = \mathcal{A} \cdot \mathcal{M}(\mathcal{N})$$

$$\frac{d\sigma}{dq_t^2} \propto A^2 \quad q_t^2 \sim 0$$

$$\sigma \propto A^{4/3}$$



Ashery E791: Measure of pion LFWF in diffractive dijet production Confirmation of color transparency, gauge theory of strong interactions

Theory predictions; Frankfurt, Miller, Strikman

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

α (Incoh.) = 0.70 ± 0.1

Is there an additional contribution from Coulomb exchange?

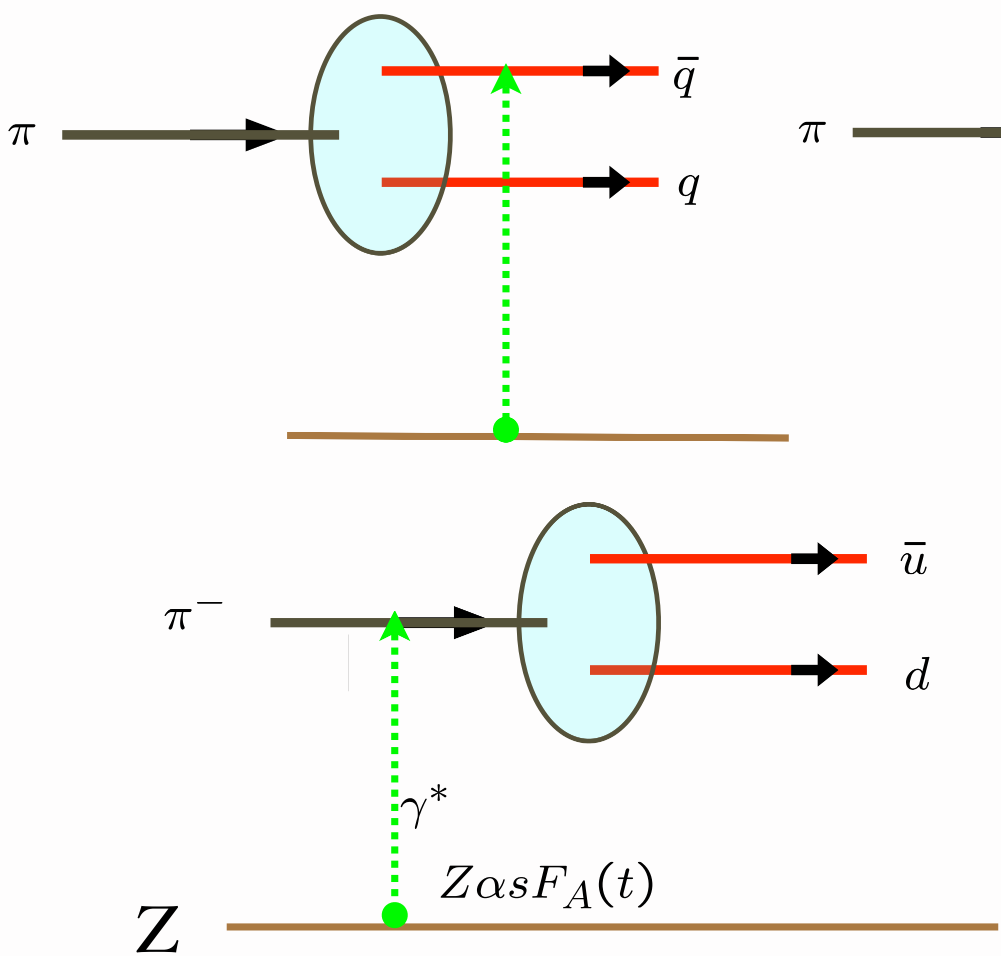
Conventional Glauber Theory Ruled Out !

Factor of 7

Coulomb Contribution to Diffractive Dijet Production

Electric Dipole Contribution to Coulomb Scattering

$$M \propto b_\perp$$



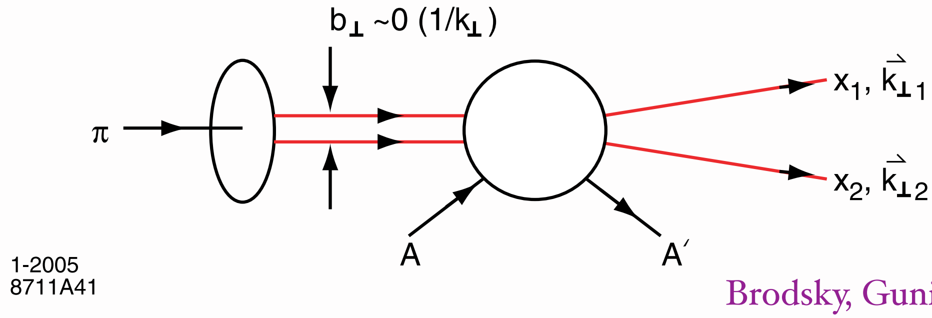
Real Phase
Charge asymmetries from HO Coulomb and interference with Pomeron

Color Transparency

A. H. Mueller, sjb
Bertsch, Gunion, Goldhaber, sjb
Frankfurt, Miller, Strikman

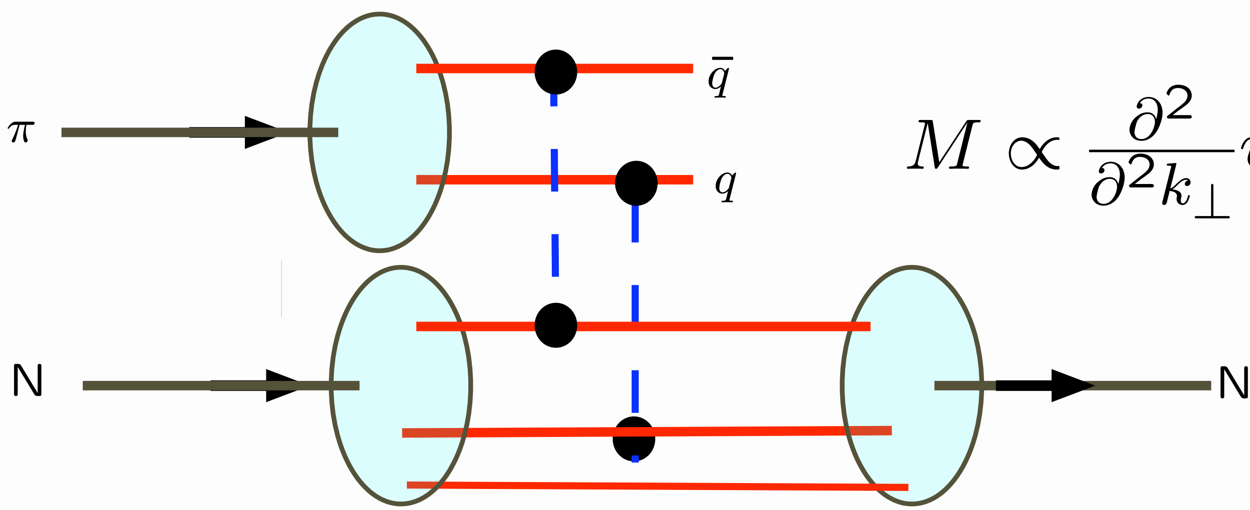
- Fundamental test of gauge theory in hadron physics
- Small color dipole moments interact weakly in nuclei
- Complete coherence at high energies
- Clear Demonstration of CT from Diffractive Di-Jets

Key Ingredients in Ashery Experiment

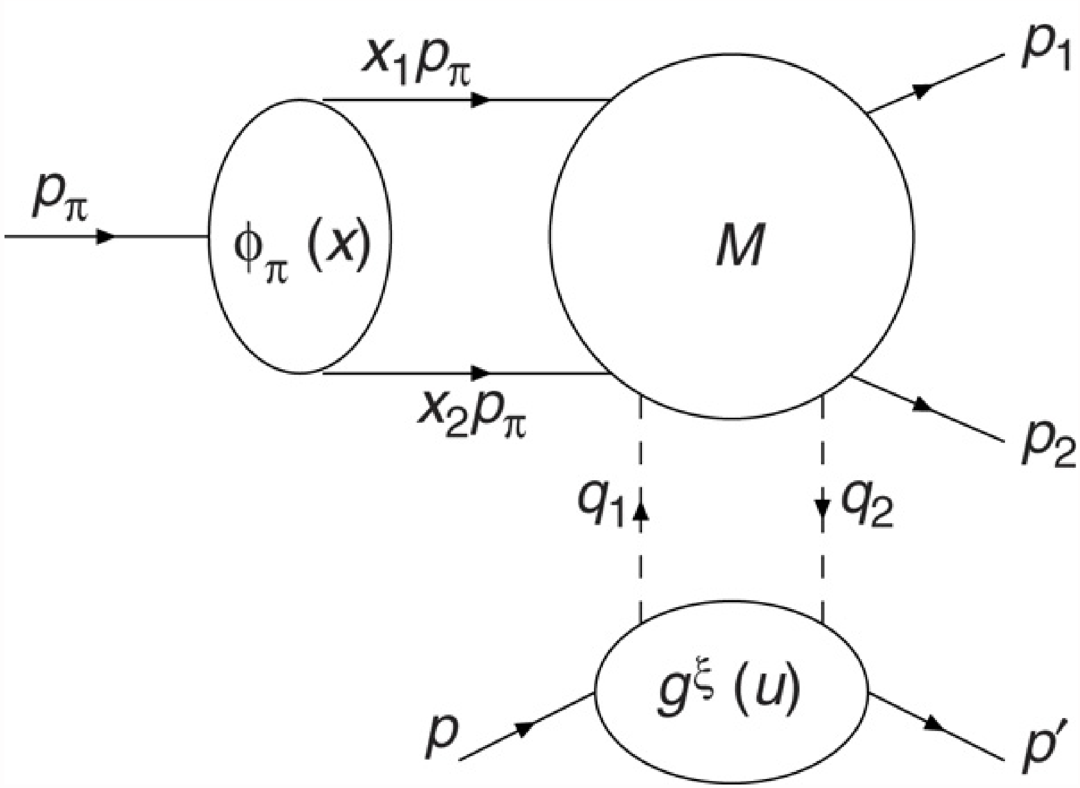


Brodsky, Gunion, Frankfurt, Mueller, Strikman
Frankfurt, Miller, Strikman

Two-gluon exchange measures the second derivative of the pion light-front wavefunction



$$M \propto \frac{\partial^2}{\partial^2 k_\perp} \psi_\pi(x, k_\perp)$$



x

1-x

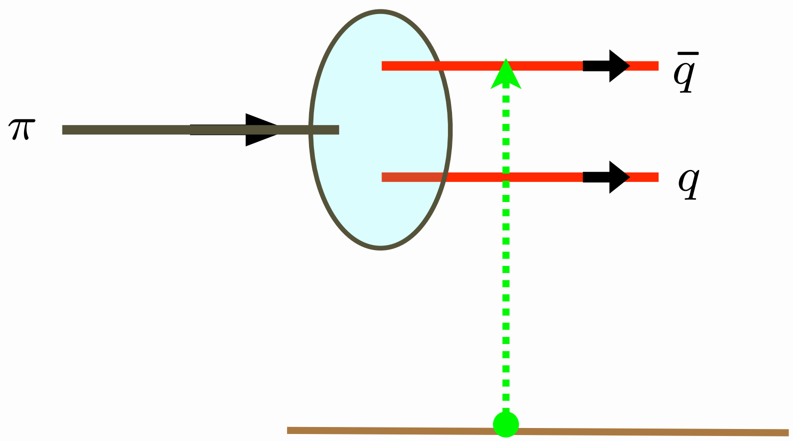
gluons measure size of color dipole

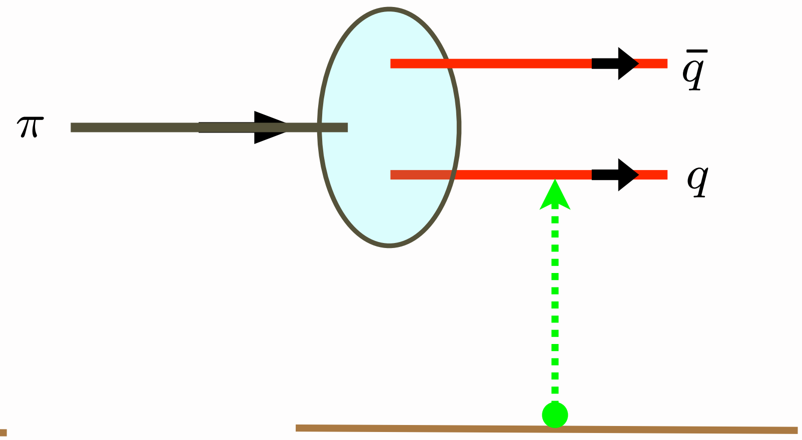
$$\frac{d\sigma}{dk_t^2} \propto |\alpha_s(k_t^2) x_N G(u, k_t^2)|^2 \left| \frac{\partial^2}{\partial k_t^2} \psi(x, k_t) \right|^2$$

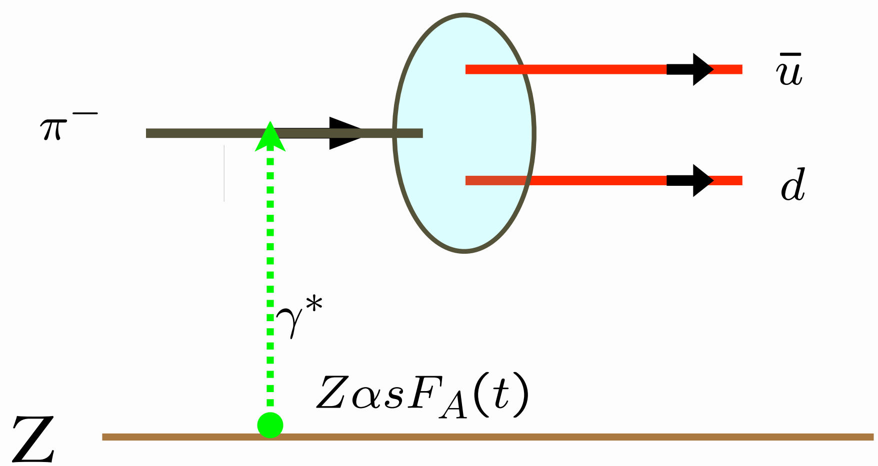
Coulomb Contribution to Diffractive Dijet Production

Electric Dipole Contribution to Coulomb Scattering

$$M \propto b_\perp$$





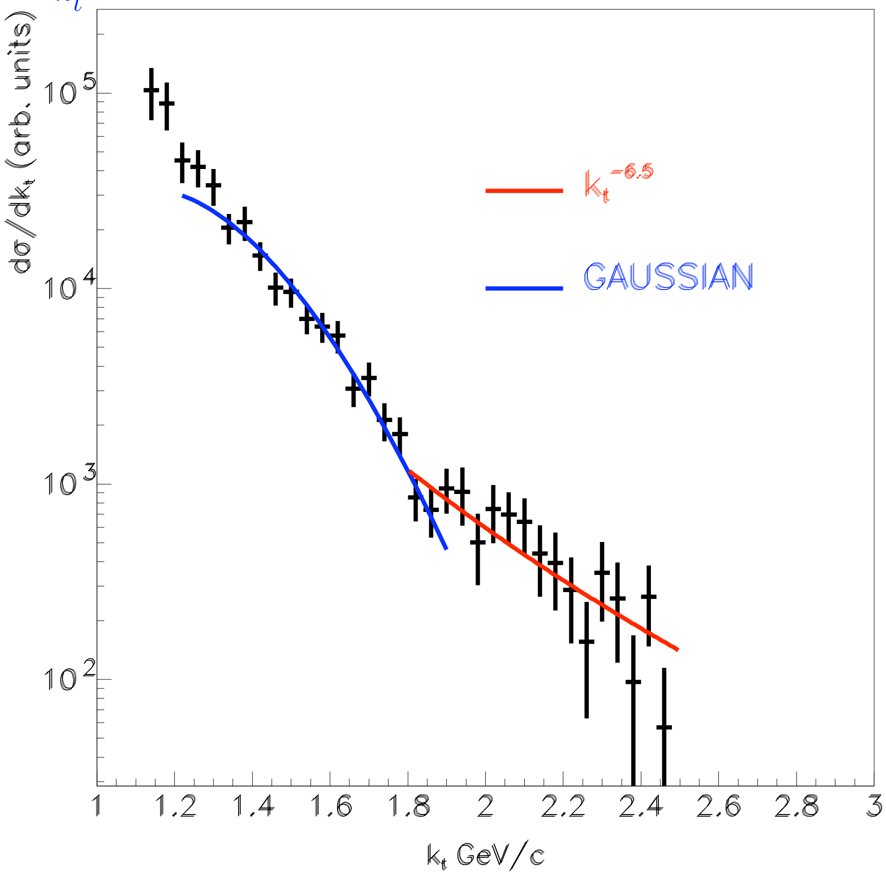


Real Phase
Charge asymmetries from HO Coulomb and interference with Pomeron

THE k_t DEPENDENCE OF DI-JETS YIELD

$$\frac{d\sigma}{dk_t^2} \propto \left|\alpha_s(k_t^2) G(x,k_t^2)\right|^2 \left|\frac{\partial^2}{\partial k_t^2}\psi(u,k_t)\right|^2$$

With $\psi \sim \frac{\phi}{k_t^2}$, weak $\phi(k_t^2)$ and $\alpha_s(k_t^2)$ dependences and $G(x,k_t^2) \sim k_t^{1/2}$: $\frac{d\sigma}{dk_t} \sim k_t^{-6}$



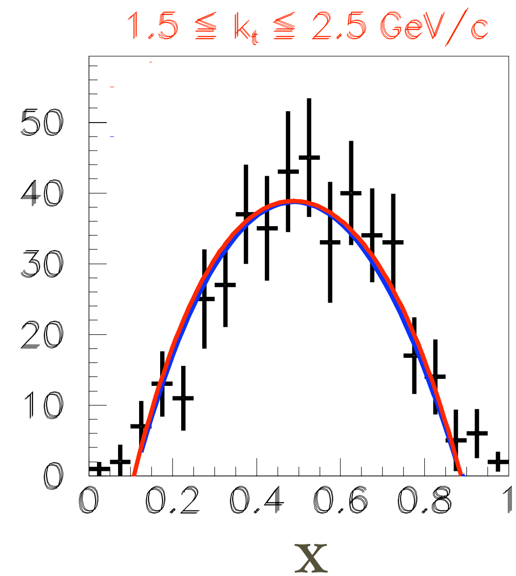
High Transverse momentum dependence consistent with PQCD, ERBL Evolution

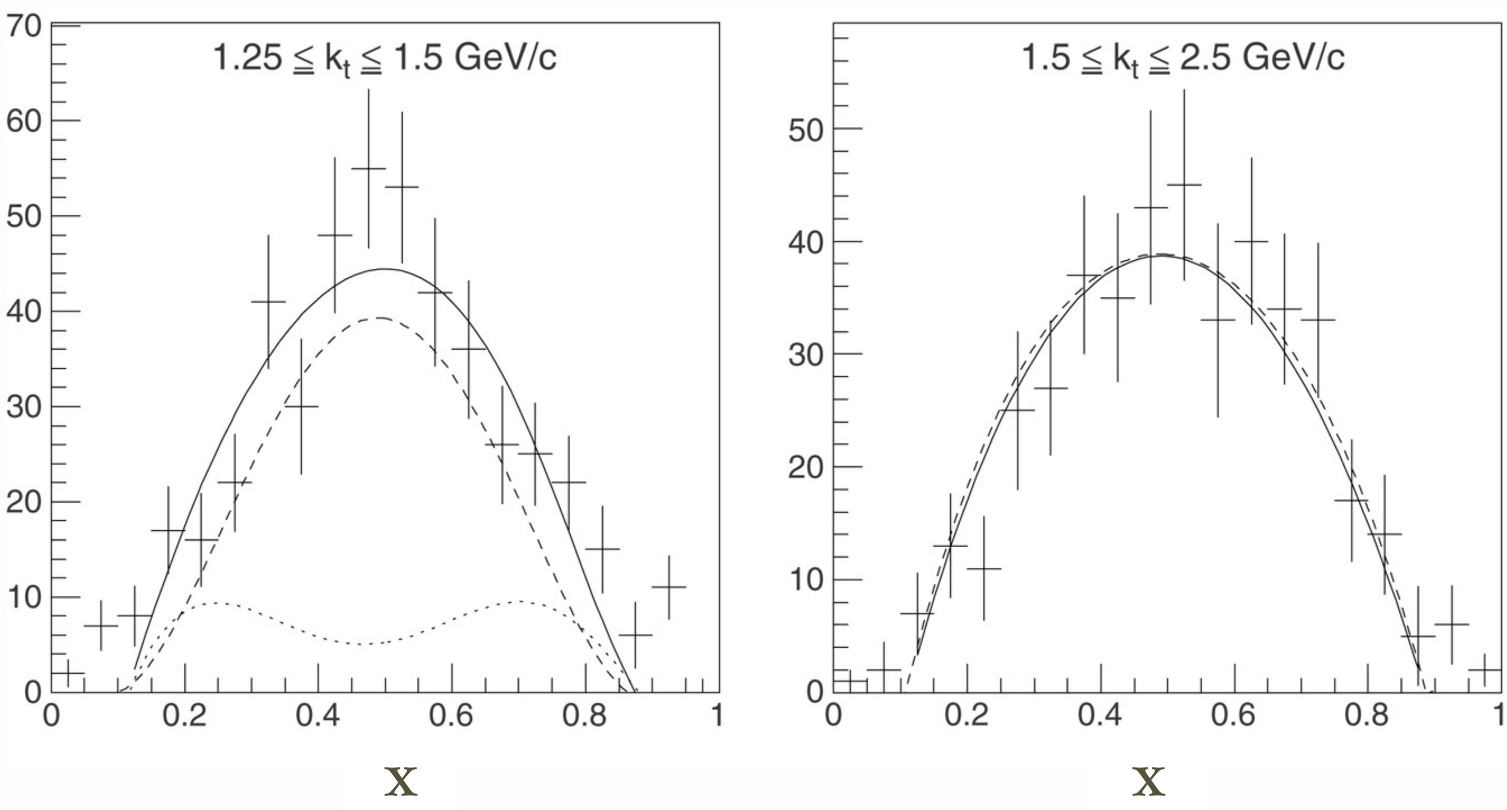
Diffractive Dissociation of a Pion into Dijets

$$\pi A \rightarrow Jet\,Jet\,A'$$

- E789 Fermilab Experiment Ashery et al
- 500 GeV pions collide on nuclei keeping it intact
- Measure momentum of two jets
- Study momentum distributions of pion LF wavefunction

$$\psi^{\pi}_{q\bar{q}}(x, \vec{k}_{\perp})$$



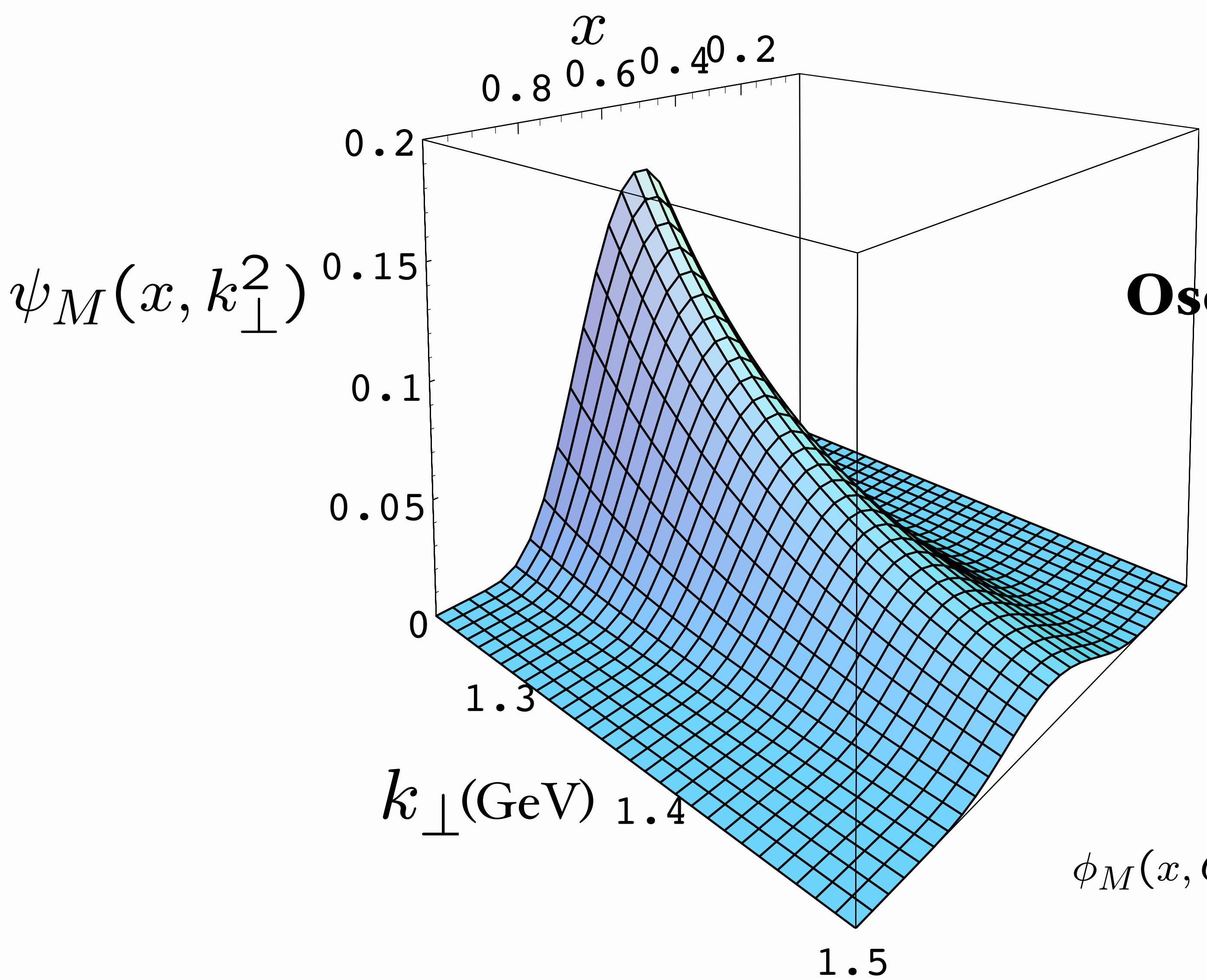


x: distribution of diffractive dijets from the platinum target for $1.25 \leq k_t \leq 1.5$ GeV/c (left) and for $1.5 \leq k_t \leq 2.5$ GeV/c (right). The solid line is a fit to a combination of the asymptotic and CZ distribution amplitudes. The dashed line shows the contribution from the asymptotic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

Narrowing of x distribution at higher jet transverse momentum

ERBL evolution

Prediction from AdS/CFT: Meson LFWF



Harmonic Oscillator model

$\kappa = 0.77 \text{GeV}$

de Teramond, sjb

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

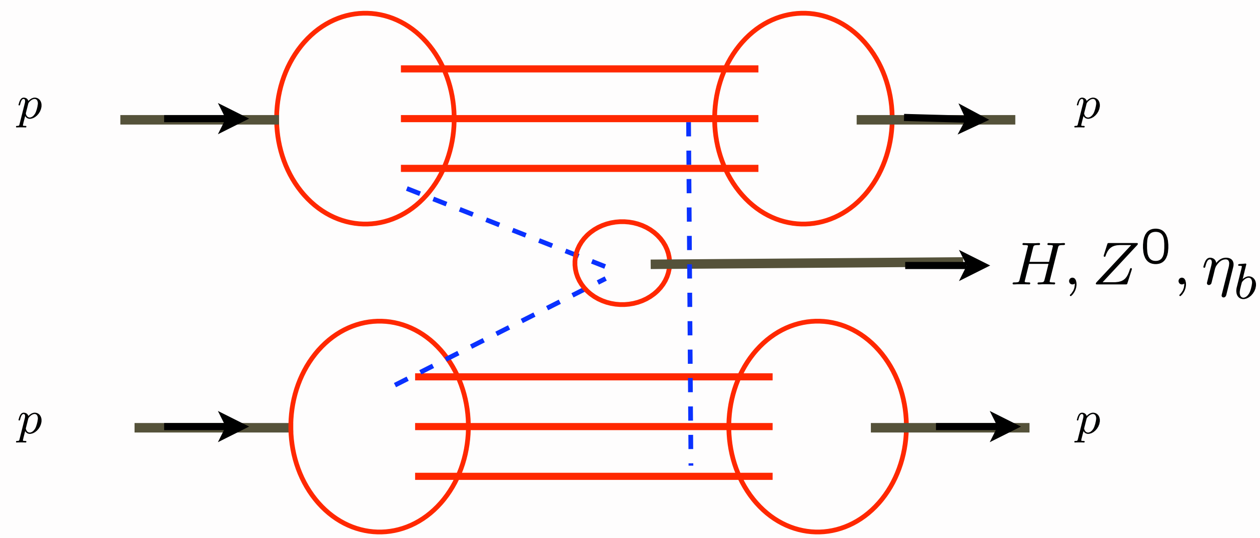
Diffractive Hadron-Hadron Hard Collisions

- Single diffractive + high P_T
- Double diffractive + high P_T
- Heavy quarks diffractive
- Higgs Production!
- Lepton pair diffractive
- Nuclear dependence

Doubly diffractive Higgs production

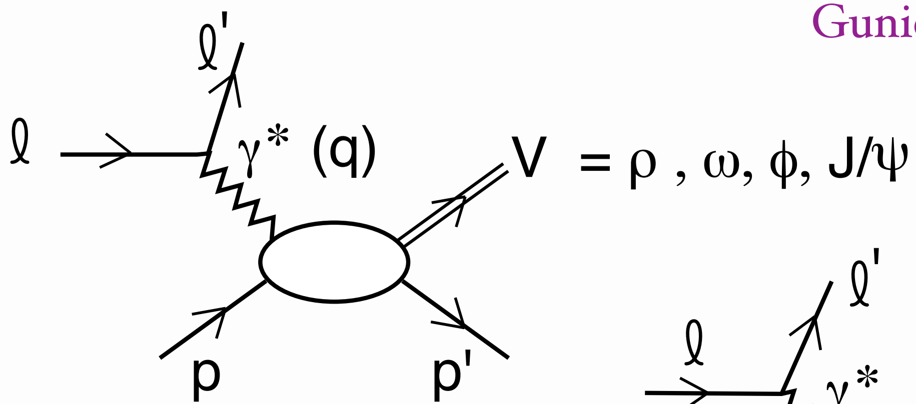
$$pp \to p + H + p$$

Nucleus-Nucleus at the LHC



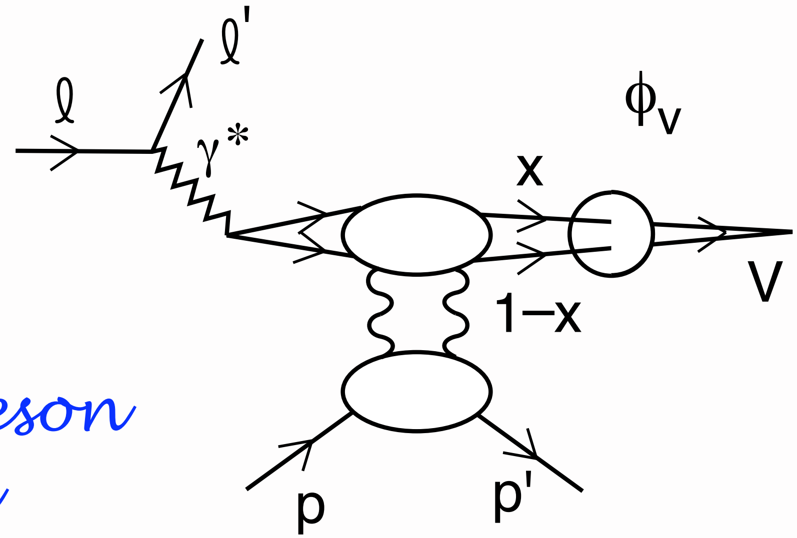
De Roeck, V.A. Khoze, A.D.Martin, R.Orava M.G.Ryskin,

Gunion, Frankfurt, Mueller, Strikman, sjb

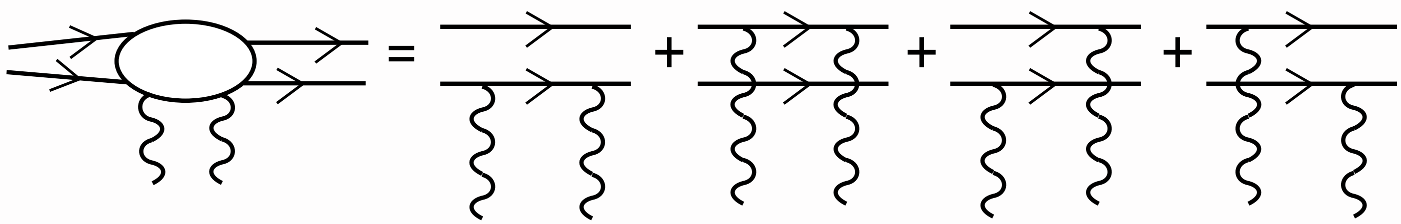


Large $-q^2 = Q^2$

⇨



Diffractive Vector Meson Leptoproduction

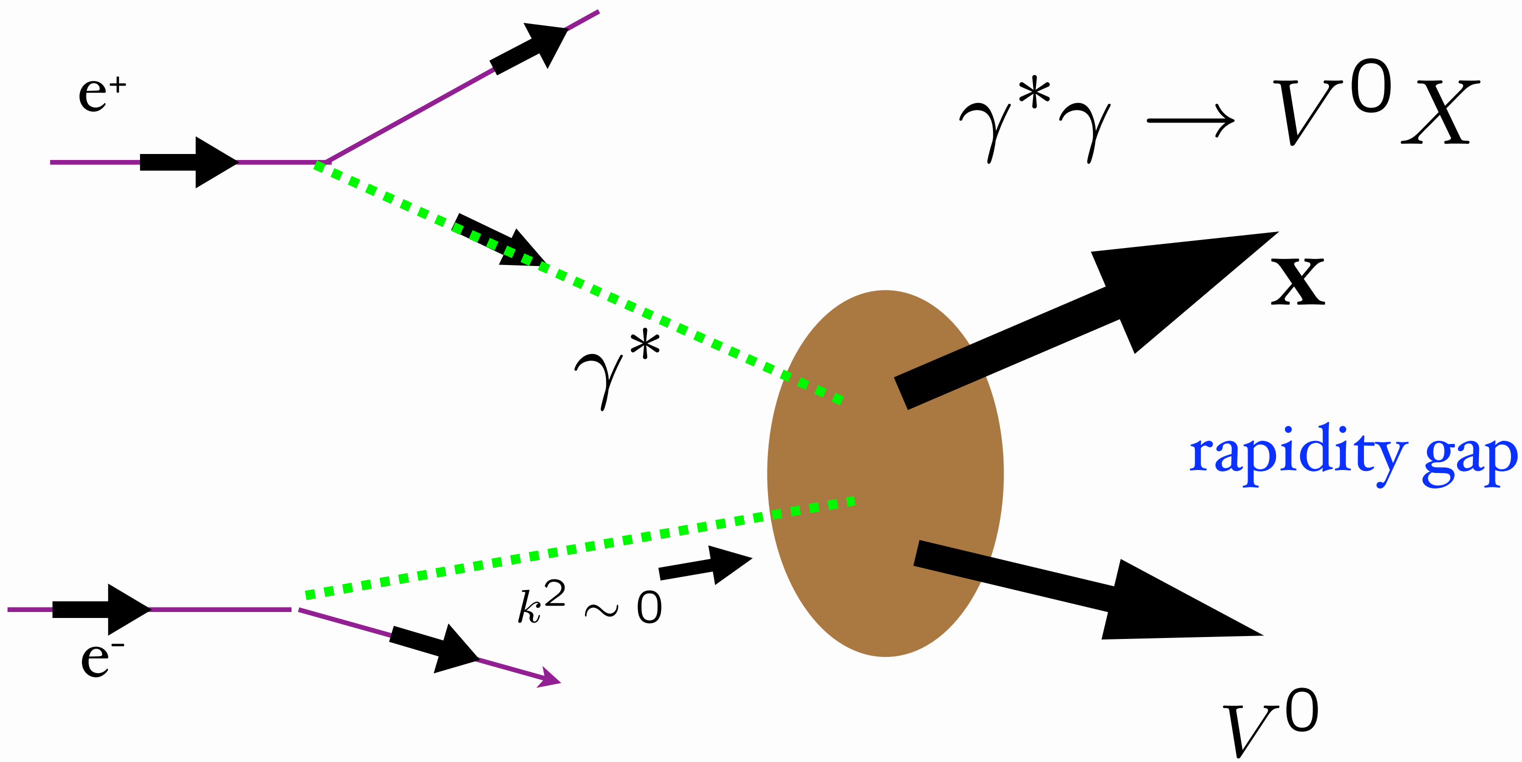


$$M \propto \frac{\partial^2}{\partial^2 k_\perp}\psi_{\gamma^*}(x,k_\perp)$$

Convolute with

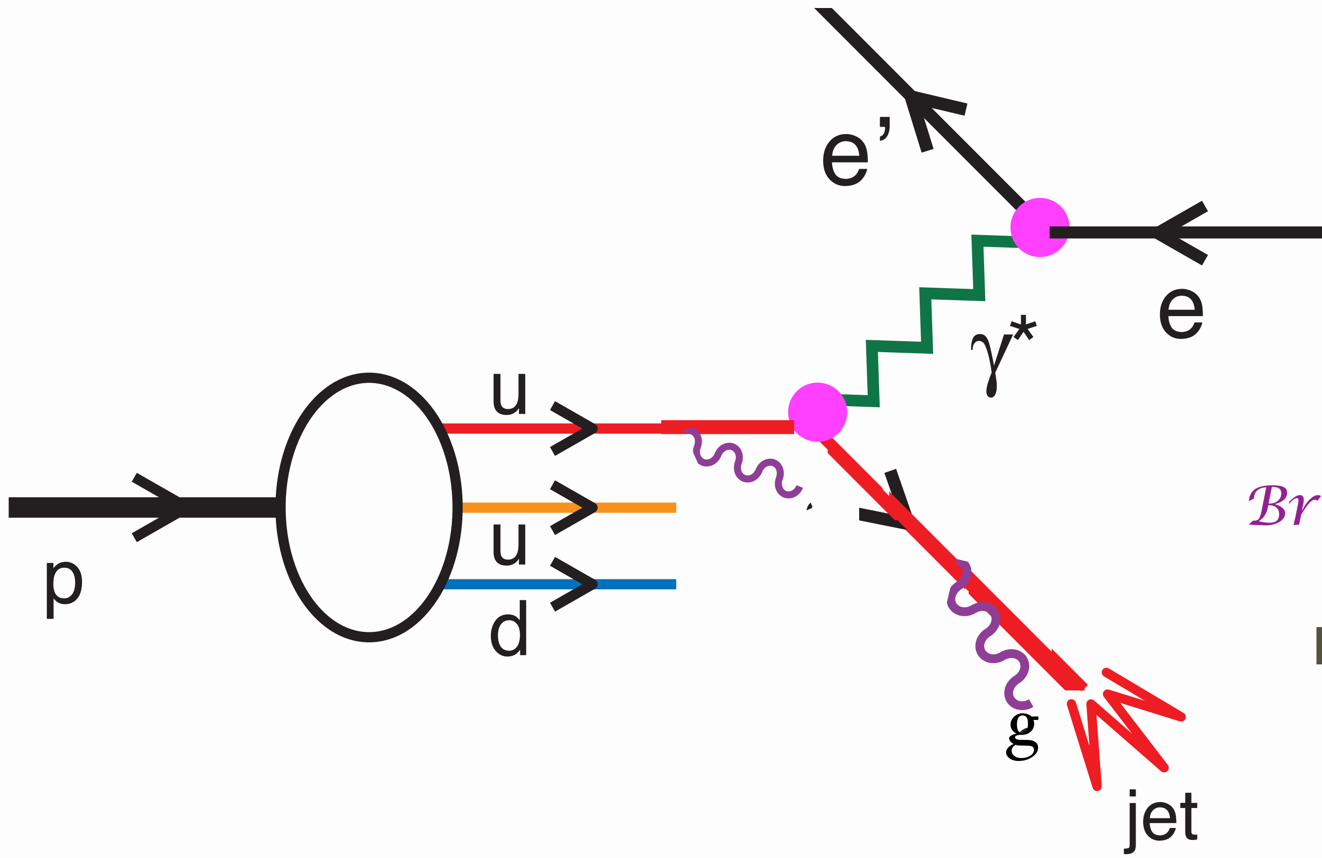
$$\phi(x,Q) = \int d^2k_\perp \Psi_{q\bar{q}}(x,\vec{k}_\perp)$$

Photon Diffractive Structure Function



Diffractive deep inelastic scattering on a photon target

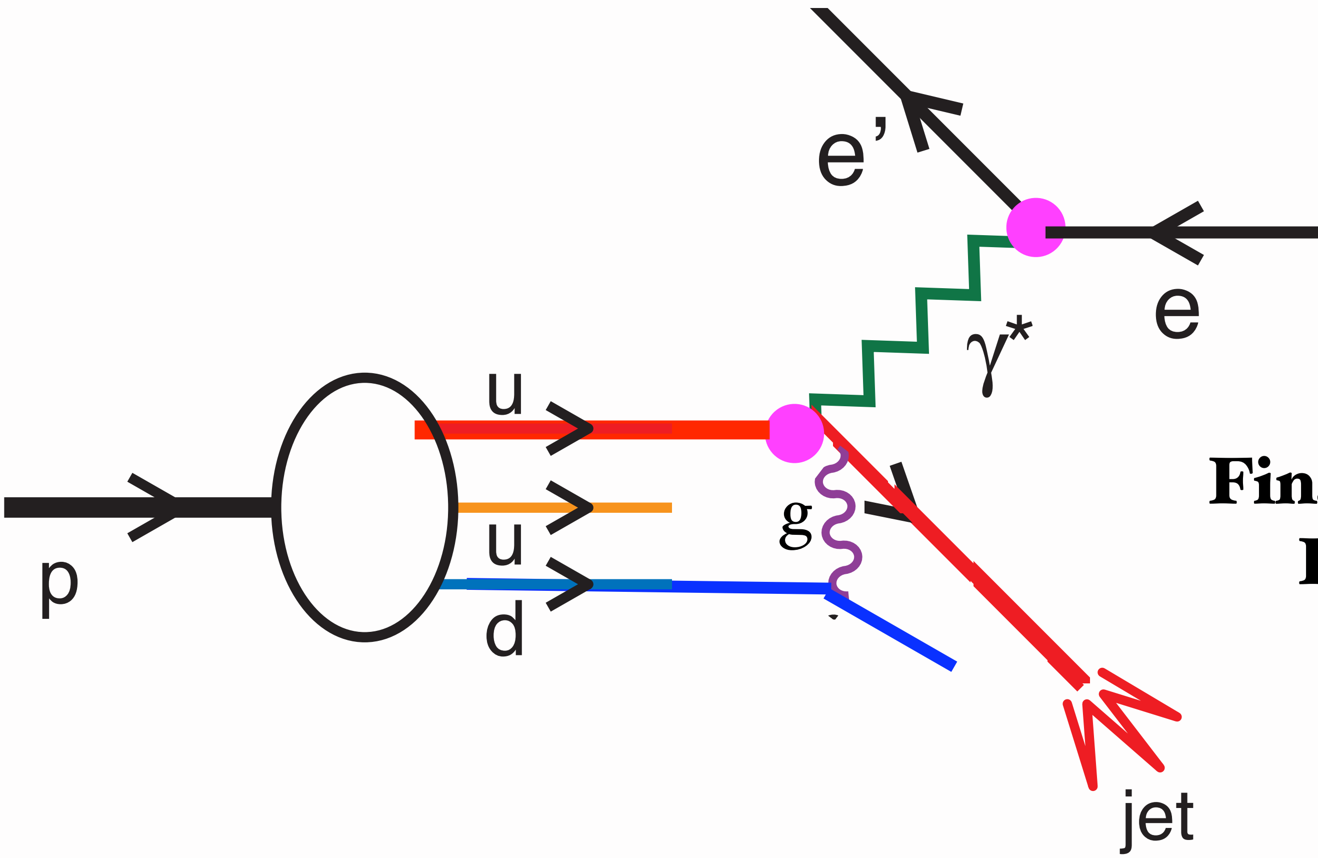
Deep Inelastic Electron-Proton Scattering



Gluonic Bremmstrahlung

DGLAP Evolution

Deep Inelastic Electron-Proton Scattering



Final-State QCD Interaction

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

Initial- and Final-State Interactions

- Diffractive Deep Inelastic Scattering -- Bjorken Scaling!
- Non-Unitary Correction to DIS: Structure functions are not probability distributions
- Nuclear Shadowing, Antishadowing
- T-Odd Single Spin Asymmetries -- Leading Twist -- opposite sign in DY and DIS --
- DY $\cos 2\phi$ correlation at leading twist from double ISI-- not given by standard PQCD factorization
- Wilson Line Effects nonzero even in LCG
- Must correct hard subprocesses for initial and final-state soft gluon attachments

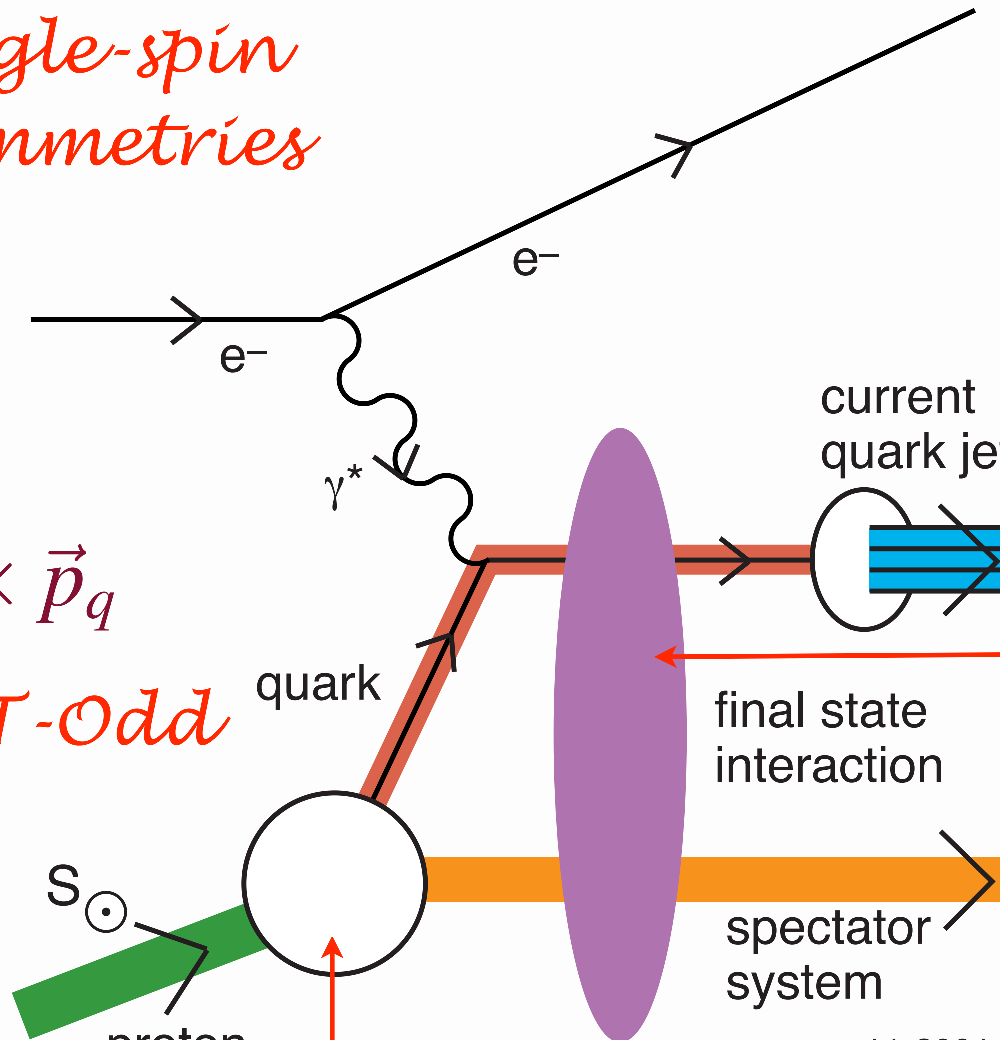
Hoyer, Marchal, Peigne, Sannino, sjb   Bodwin, Lepage, sjb

Single-spin asymmetries

Leading Twist Sivers Effect

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

Pseudo-T-Odd



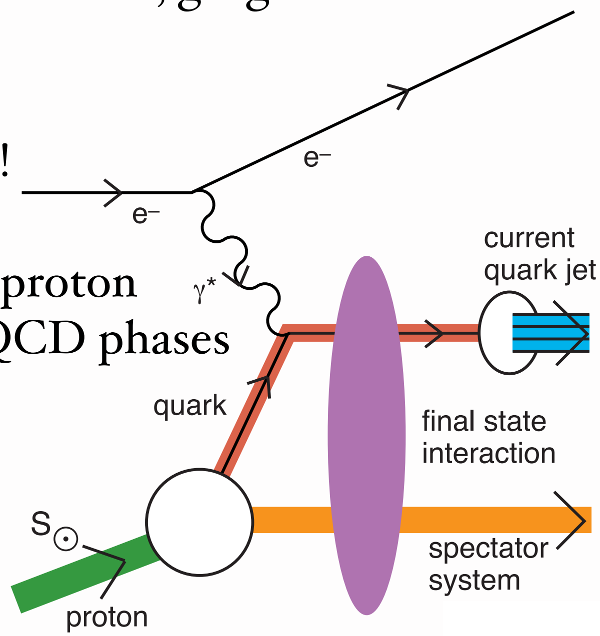
QCD S- and P-Coulomb Phases

Light-Front Wavefunction S and P- Waves

D. S. Hwang, I. A. Schmidt, sjb

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

- Leading-Twist Bjorken Scaling!
- Requires nonzero orbital angular momentum of quark! $\mathbf{i}\ \vec{S}\cdot\vec{p}_{jet}\times\vec{q}$
- Arises from the interference of Final-State QCD Coulomb phases in S- and P- waves; Wilson line effect; gauge independent
- Unexpected QCD Effect -- thought to be zero!
- Relate to the quark contribution to the target proton anomalous magnetic moment and final-state QCD phases
- QCD Coulomb phase at soft scale
- Measure in jet trigger or leading hadron
- Sum of Sivers Functions for all quarks and gluons vanishes. (Zero gravito-anomalous magnetic moment: B(0)= 0)

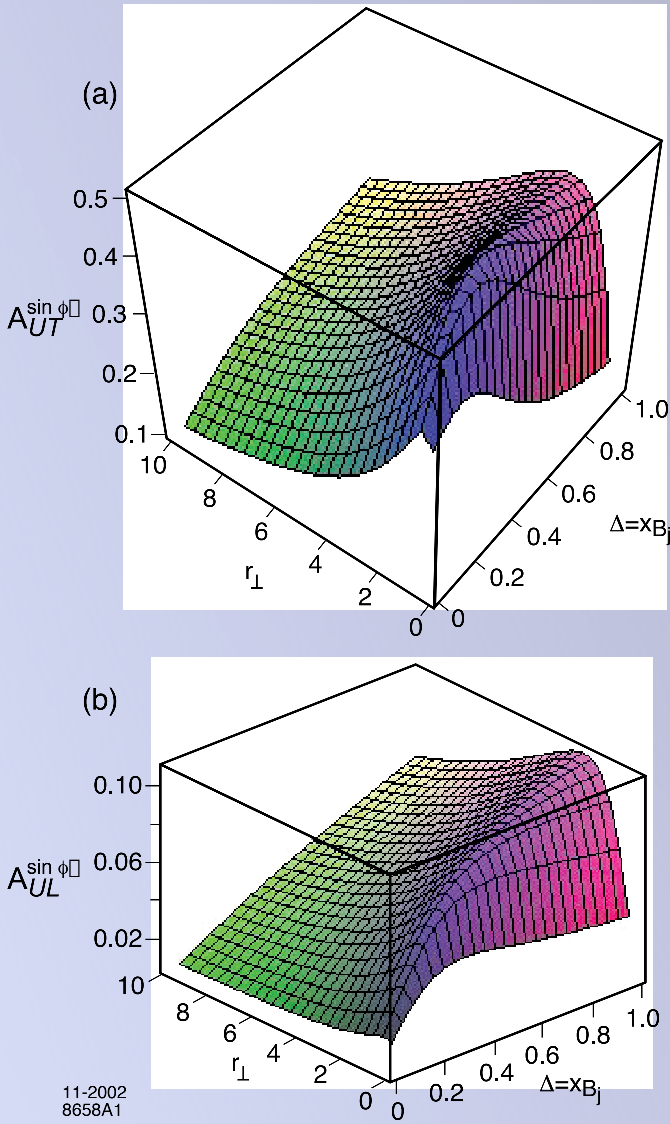


Final-State Interactions Produce Pseudo T-Odd (Sivers Effect)

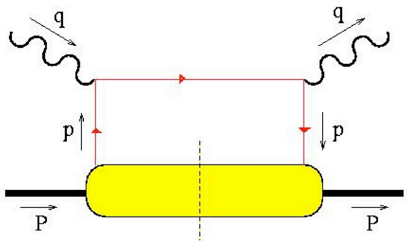
$$\mathbf{i}\ \vec{S} \cdot \vec{p}_{jet} \times \vec{q}$$

- Leading-Twist Bjorken Scaling!
- Requires nonzero orbital angular momentum of quark!
- Arises from the interference of Final-State QCD and QED Coulomb phases in S- and P- waves; Wilson line effect; gauge independent
- Many Tests in UPC at the LHC
- QCD Coulomb phase at soft scale
- Measure in jet trigger or leading hadron
- Lambda production

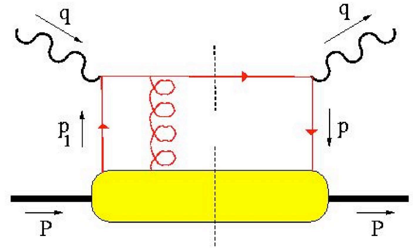
Prediction for Single-Spin Asymmetry



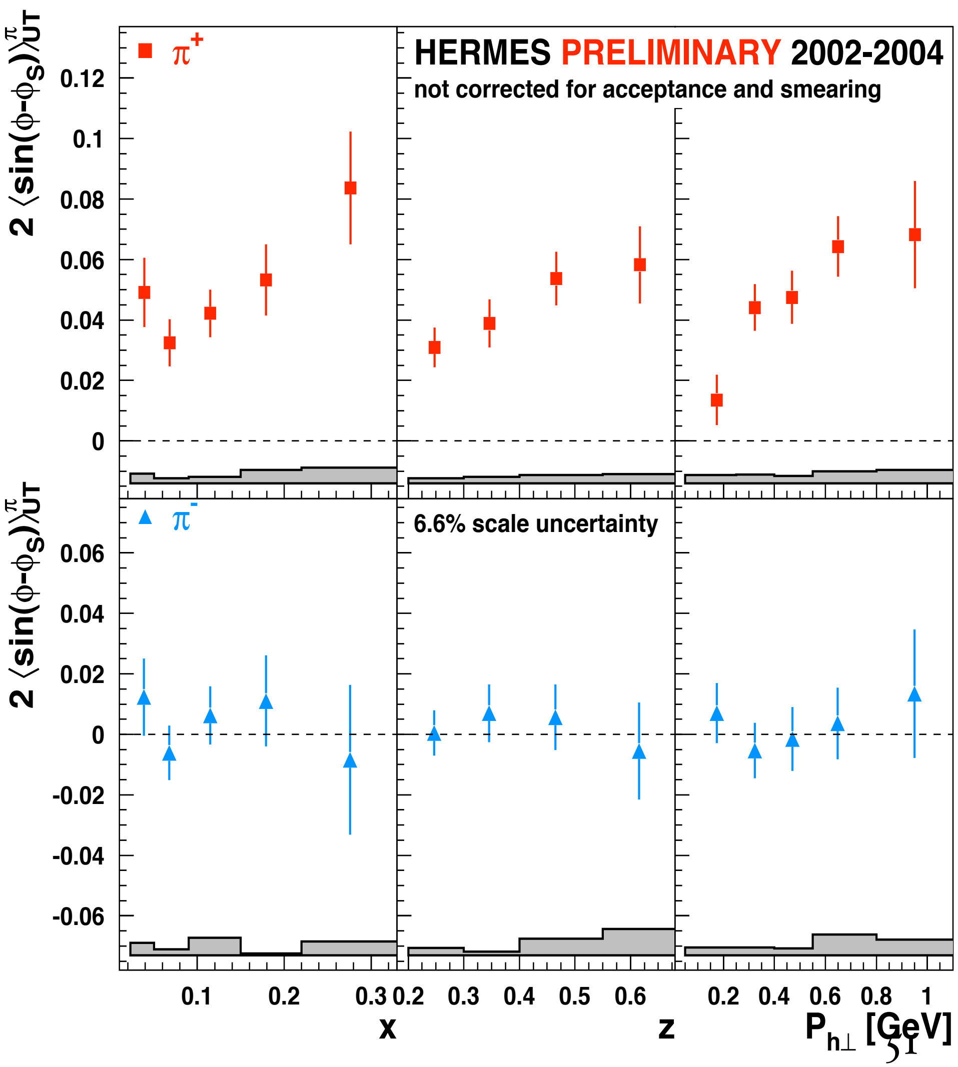
Hwang, Schmidt, sjb



can interfere with



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



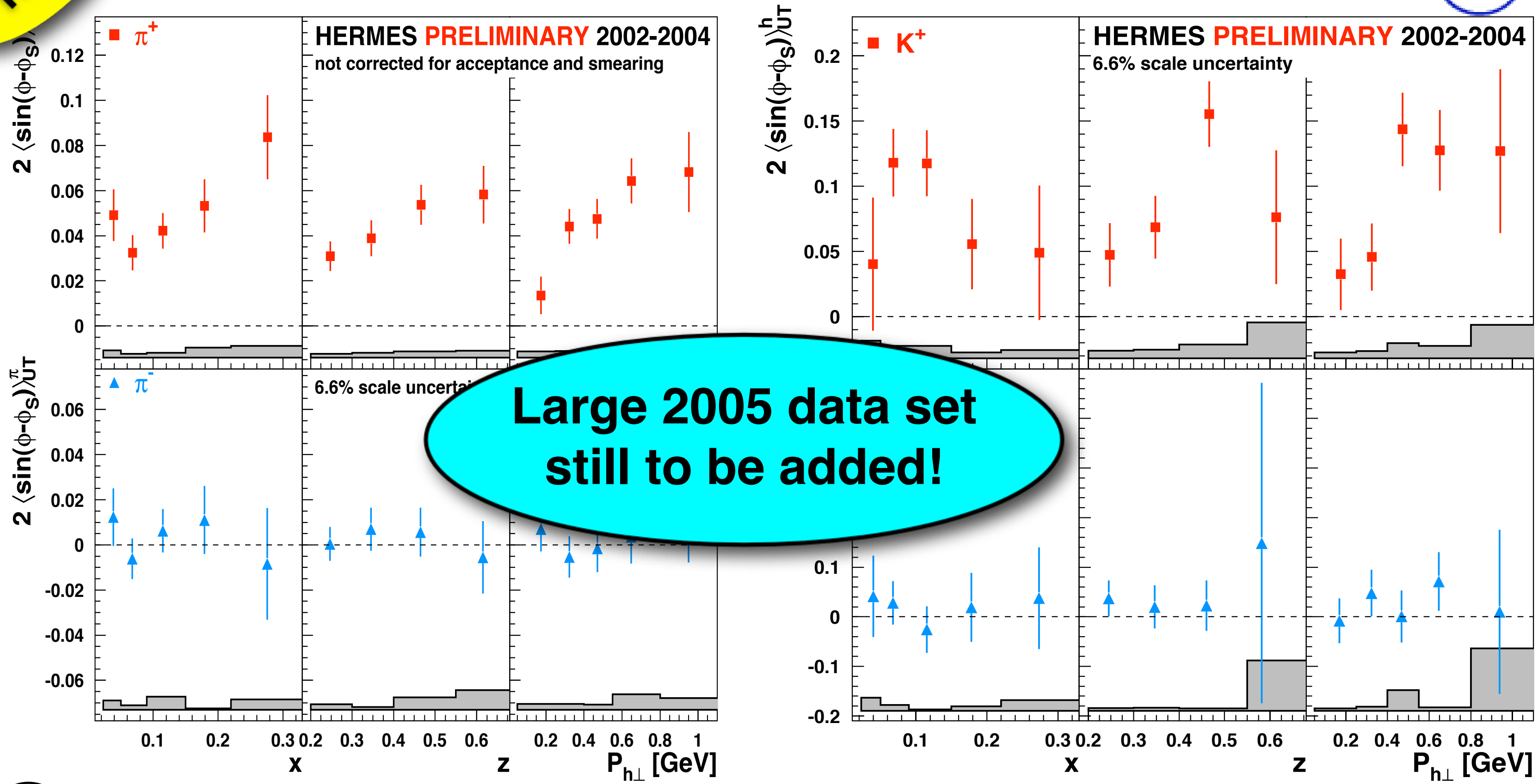
- First evidence for non-zero Sivers function!
- ⇒ presence of non-zero **quark orbital angular momentum**!
- Positive for **π+**...
  Consistent with zero for **π−**...

Gamberg: Hermes data compatible with BHS model

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

NEW!

Sivers Moments for Kaons from 2002–2004 Data



– Effect about **equal** for $K^- = s\bar{u}$ and $\pi^- = d\bar{u}$ → note: same antiquark ...

\+ Effect *seems* ***larger*** for $K^+ = u\bar{s}$ than $\pi^+ = u\bar{d}$ at $x \approx 0.1$ ... !

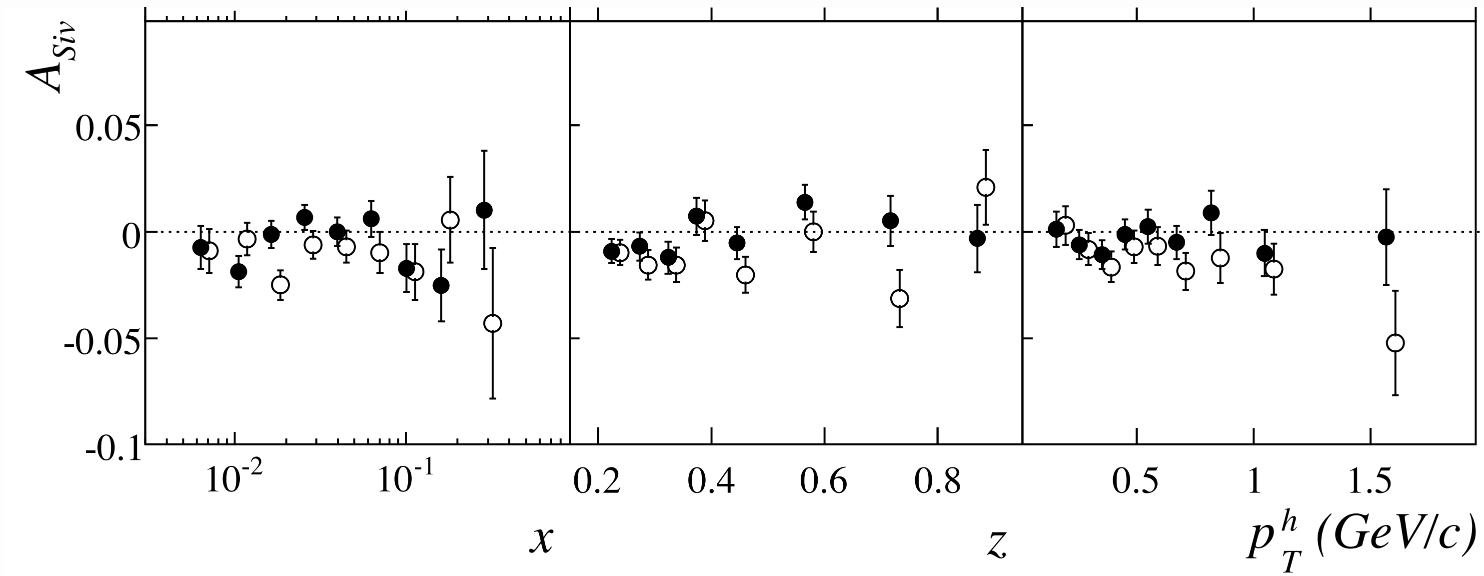
N. Makins

Schmidt, Lu:
pattern follows quark contributions to anomalous moment

A new measurement of the Collins and Sivers asymmetries on a transversely polarised deuteron target

The COMPASS Collaboration

hep-ex/0610068



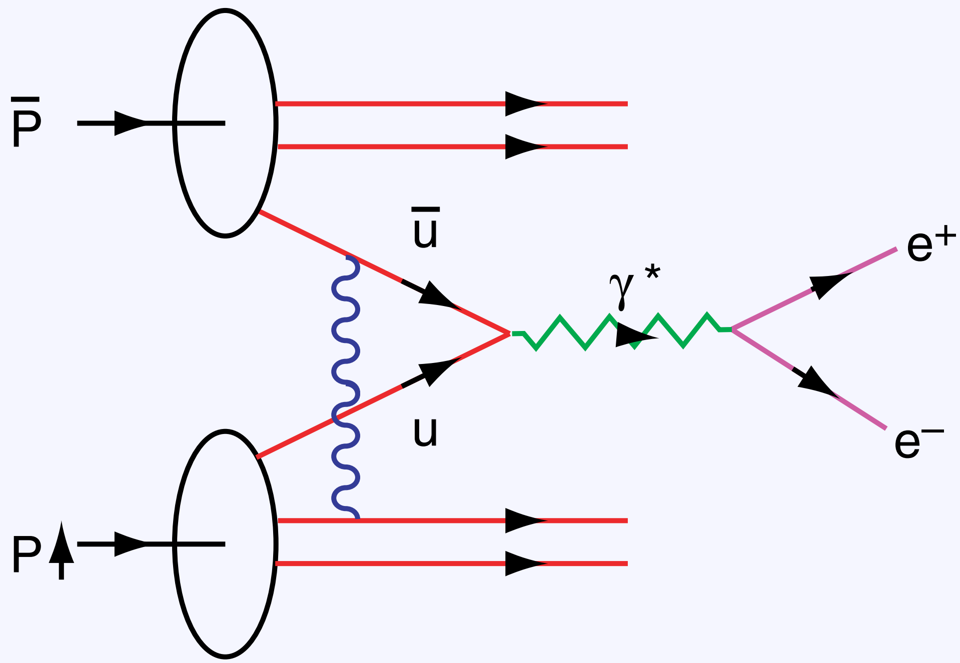
Sivers SSA cancels on an isospin zero target --

gluon contribution to the Sivers asymmetry small

small gluon contribution to orbital angular momentum of nucleon

Gardner, sjb

Predict Opposite Sign SSA in DY !



Collins;
Hwang, Schmidt.
sjb

Single Spin Asymmetry In the Drell Yan Process

$\vec{S}_p \cdot \vec{p} \times \vec{q}_{\gamma^*}$

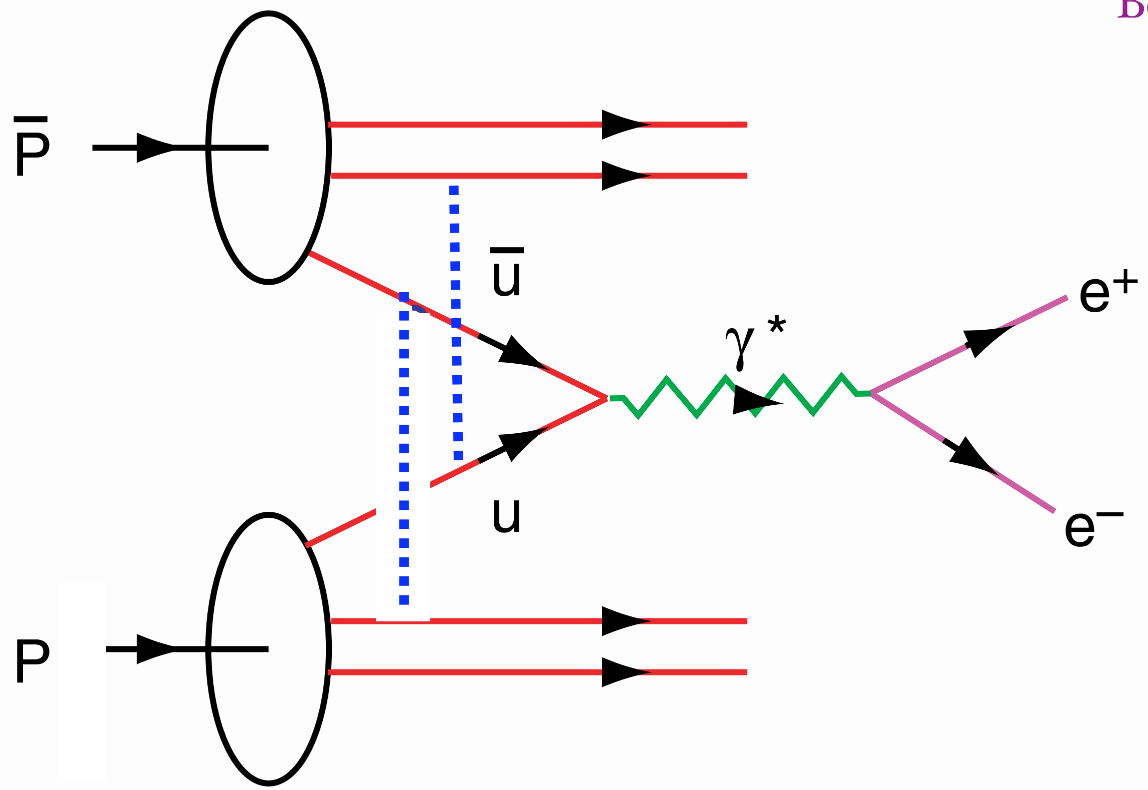
Quarks Interact in the Initial State

Interference of Coulomb Phases for *S* and *P* states

Produce Single Spin Asymmetry [Siver's Effect]Proportional to the Proton Anomalous Moment and α_s.

Opposite Sign to DIS! No Factorization

Boer, Hwang, sjb



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

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

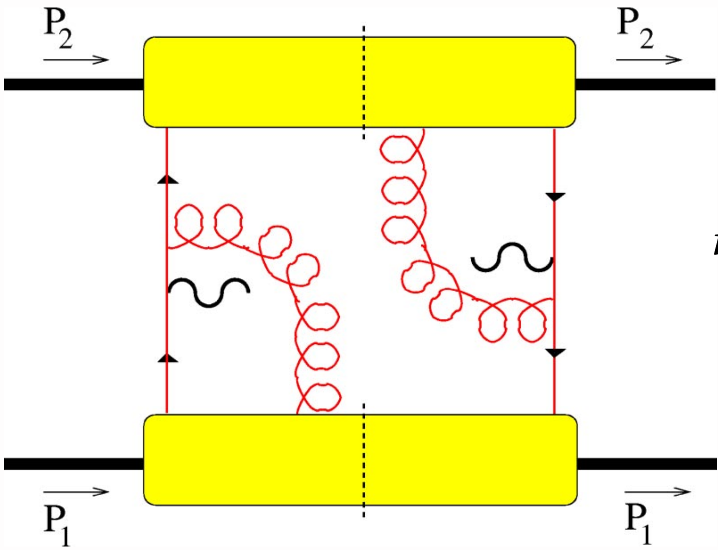
Boer, Hwang, sjb

Drell-Yan planar correlations

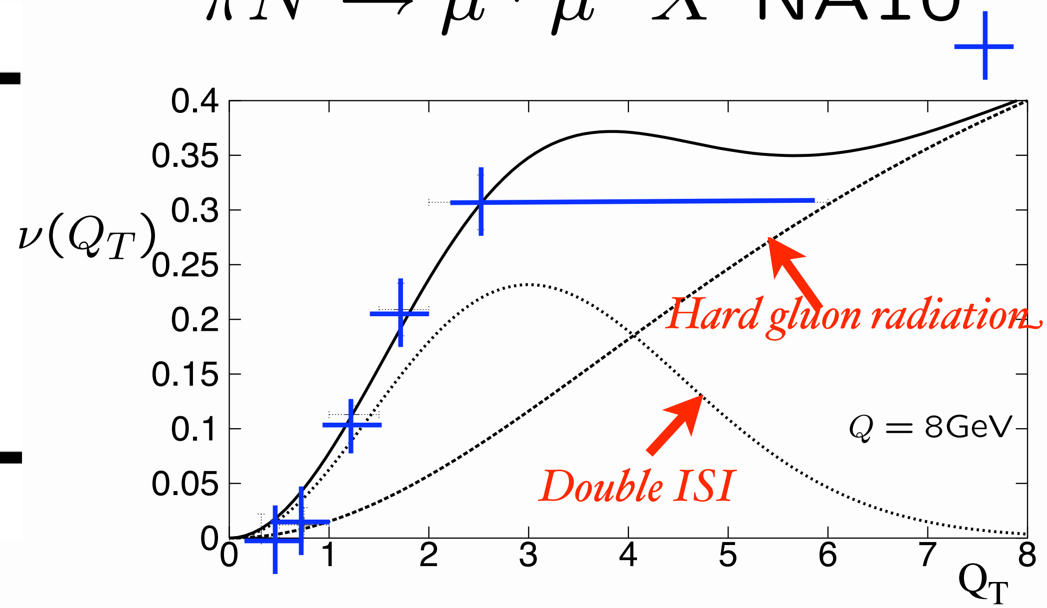
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \left(1 + \lambda \cos^2\theta + \mu \sin 2\theta \, \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi\right)$$

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

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



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



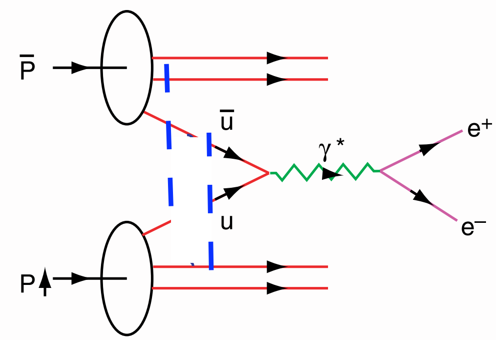
Violates Lam-Tung relation!

Model: Boer,

Anomalous effect from Double ISI in Massive Lepton Production

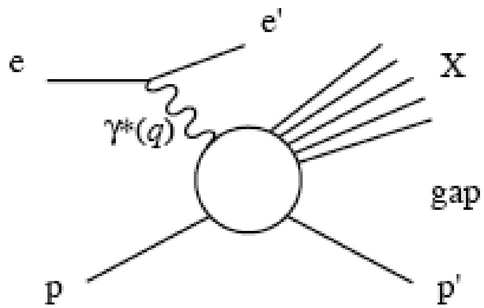
Boer, Hwang, sjb

$\cos 2\phi$ correlation



- Leading Twist, valence quark dominated
- Violates Lam-Tung Relation!
- Not obtained from standard PQCD subprocess analysis
- Normalized to the square of the single spin asymmetry in semi-inclusive DIS
- No polarization required
- Challenge to standard picture of PQCD Factorization

DDIS

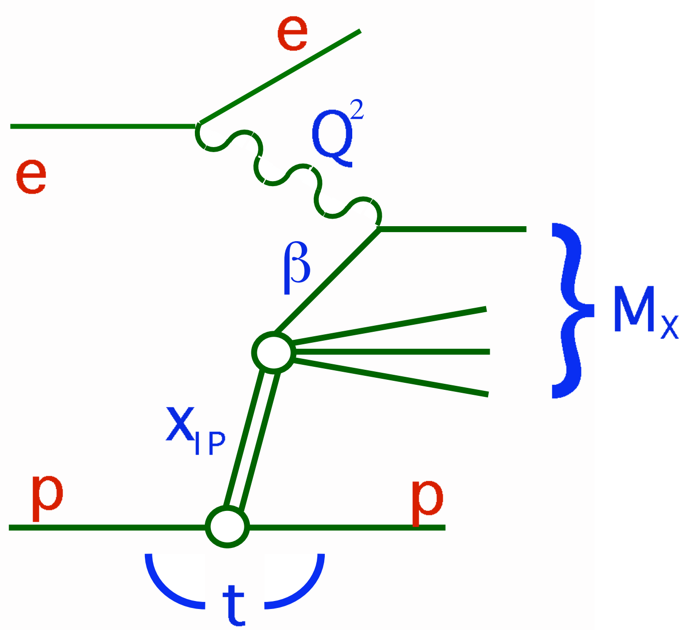


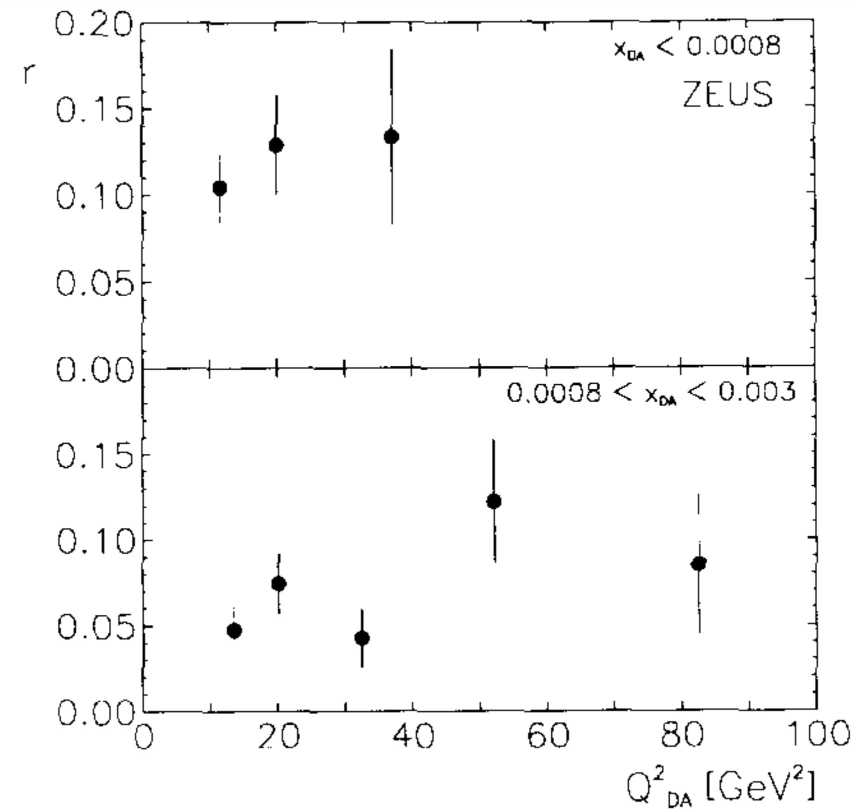
- In a large fraction ($\sim$ 10–15%) of DIS events, the proton escapes intact, keeping a large fraction of its initial momentum
- This leaves a large *rapidity gap* between the proton and the produced particles
- The t-channel exchange must be *color singlet*

"Pomeron structure function"

Diffractive Deep Inelastic Lepton-Proton Scattering

Remarkable observation at HERA



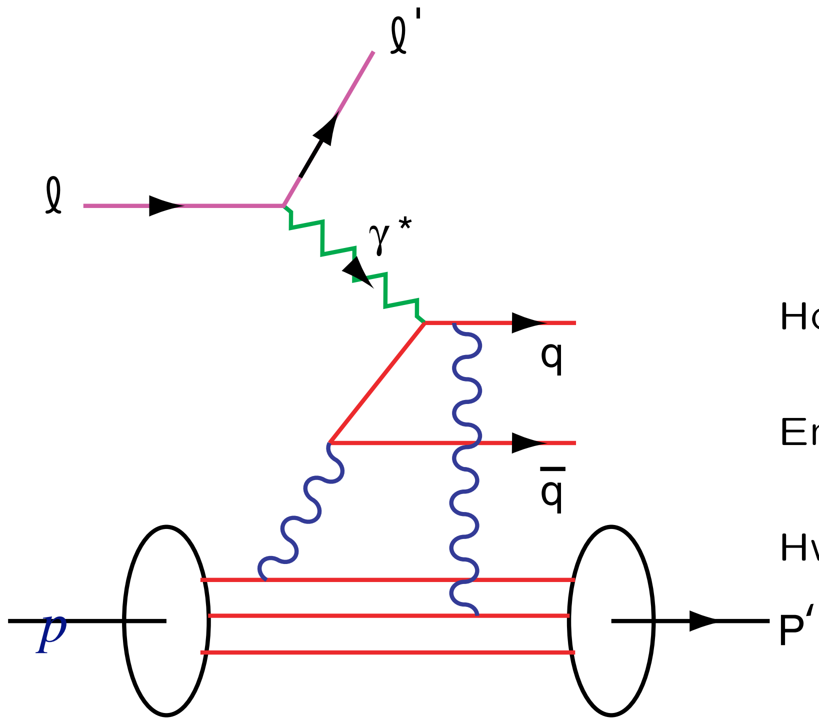


Fraction r of events with a large rapidity gap, $\eta_{\max} < 1.5$, as a function of $Q^2_{\rm DA}$ for two ranges of $x_{\rm DA}$. No acceptance corrections have been applied.

10% to 15% of DIS events are diffractive !

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

Final-State Interaction Produces Diffractive DIS



Quark Rescattering

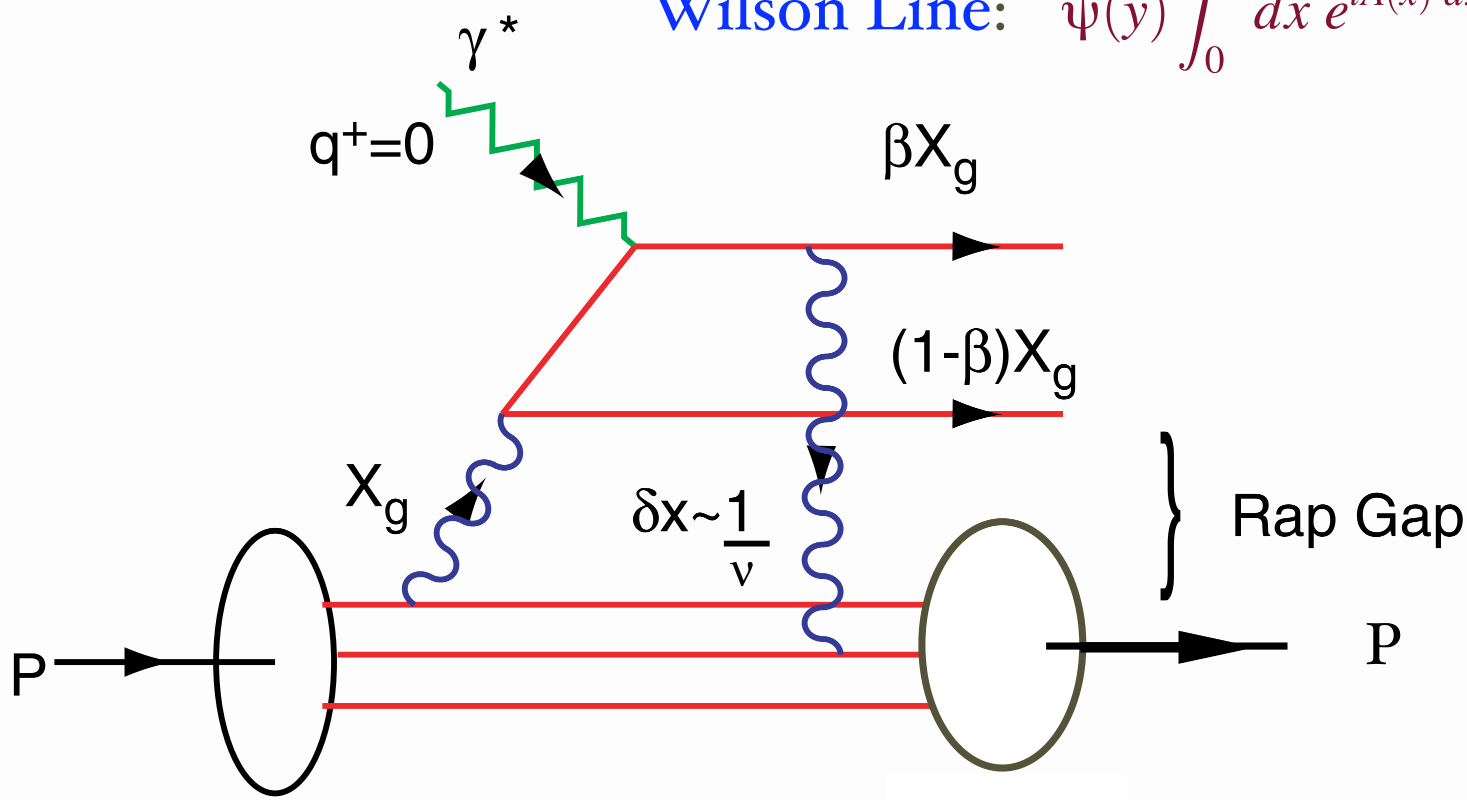
Hoyer, Marchal, Peigne, Sannino, SJB (BHMPS)

Enberg, Hoyer, Ingelman, SJB

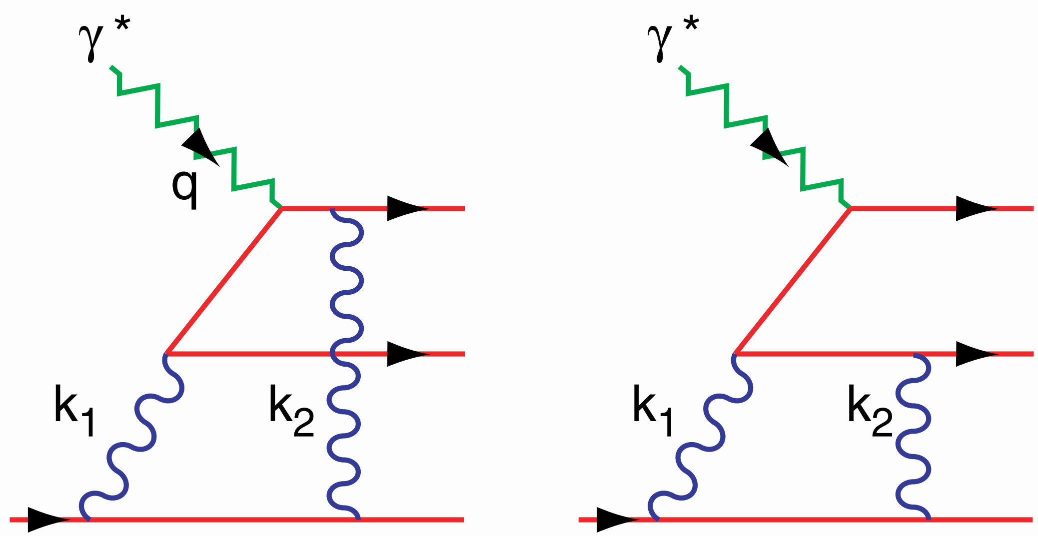
Hwang, Schmidt, SJB

QCD Mechanism for Rapidity Gaps

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



Final-State Interactions in QCD



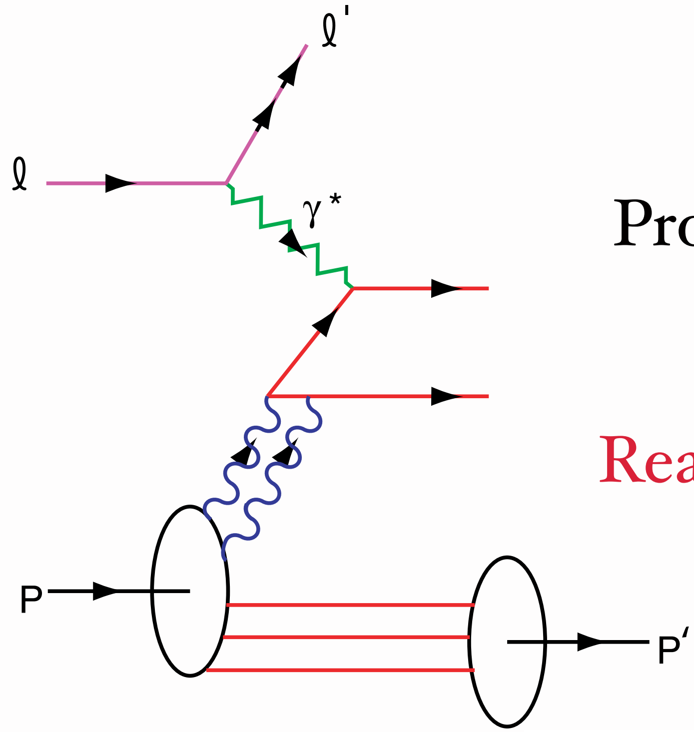
Feynman Gauge Light-Cone Gauge

Result is Gauge Independent

FSI nonzero even in LCG

Conventional Model:

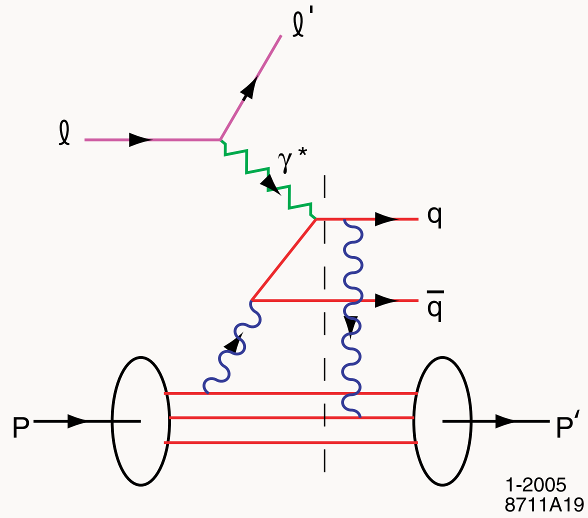
Pomeron acts as constituent of proton



Problem: Wrong Phase

Real; must be imaginary

Need Final-State Interactions !



Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate
Pomeron Exchange

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

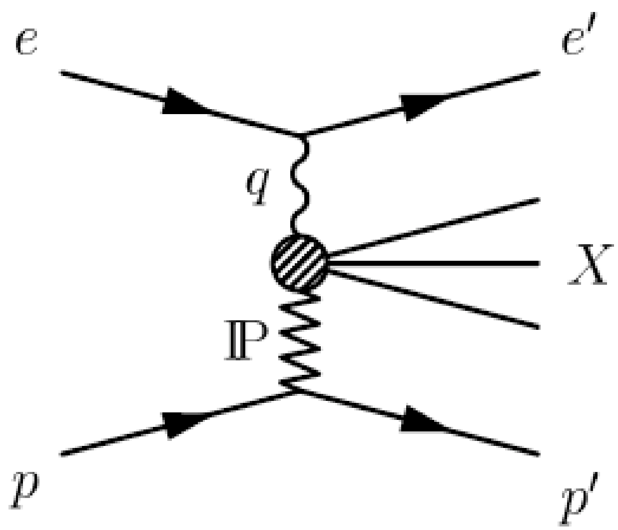
Physics of FSI not in (Real) Wavefunction of Target

The Pomeron formalism

Cross section for Diffractive DIS:

$$\frac{d\sigma}{dx\,dQ^2\,dx_{I\!P}\,dt} = \frac{4\pi\alpha^2}{\beta Q^4}\left(1 - y + \frac{y^2}{2}\right) F_2^{D(4)}$$

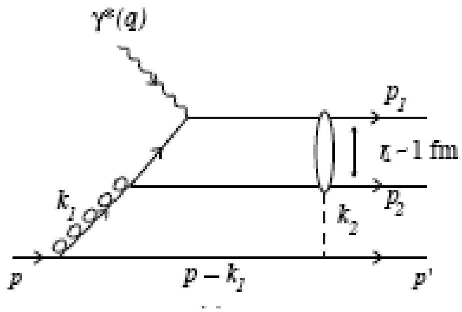
Assuming DIS on a hadronic "pomeron" radiated from the proton, the diffractive structure function is Regge factorized



$$F_2^{D(4)}(x, Q^2, x_{I\!P}, t) = \underbrace{f(x_{I\!P}, t)}_{I\!P \text{ flux}} \; \underbrace{F_2^{I\!P}(\beta, Q^2)}_{I\!P \text{ structure}}$$

The pomeron flux is taken from Regge theory

- 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:

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

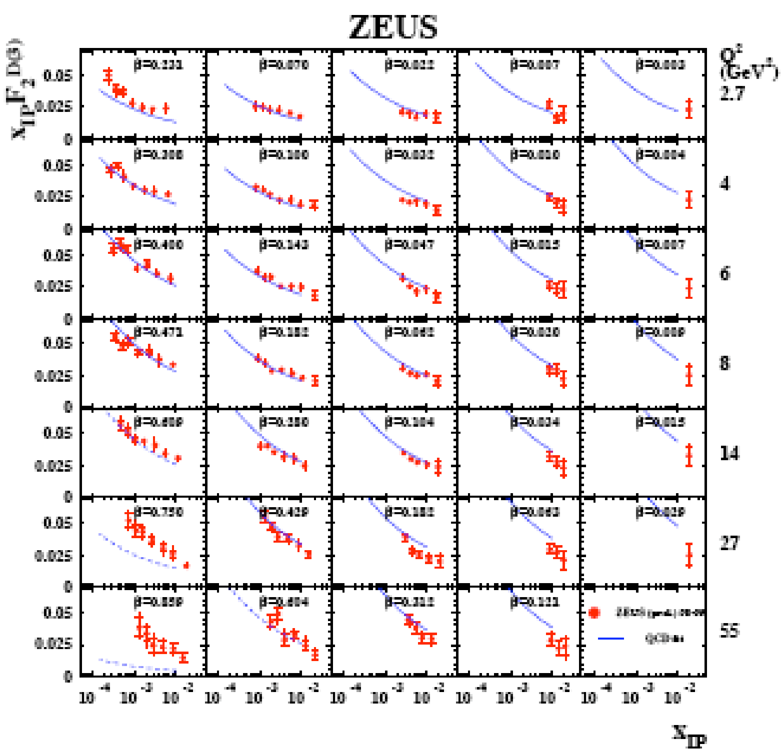
- Diffractive amplitudes from rescattering are dominantly *imaginary* — as expected for diffraction (Ingelman–Schlein $I\!P$ model has real amplitudes)

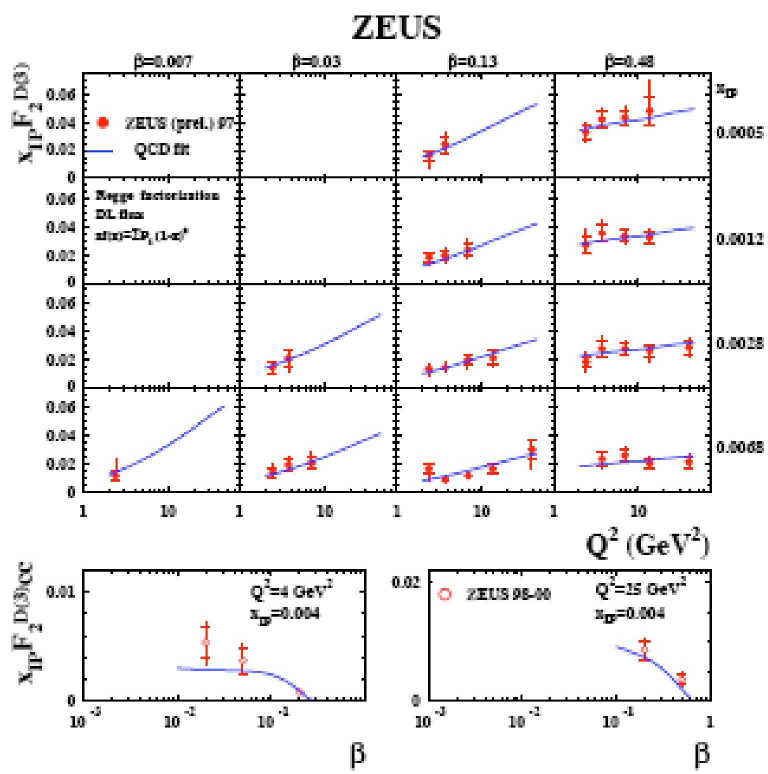
S. J. Brodsky, P. Hoyer, N. Marchal, S. Peigne and F. Sannino, Phys. Rev. D 65, 114025 (2002) [arXiv:hep-ph/0104291].
S. J. Brodsky, R. Enberg, P. Hoyer and G. Ingelman, arXiv:hep-ph/0409119.

Enberg, Hoyer, Ingelman, sjb

The Pomeron formalism

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





Lines given by fit with NLO QCD evolution

Consequences for DDIS

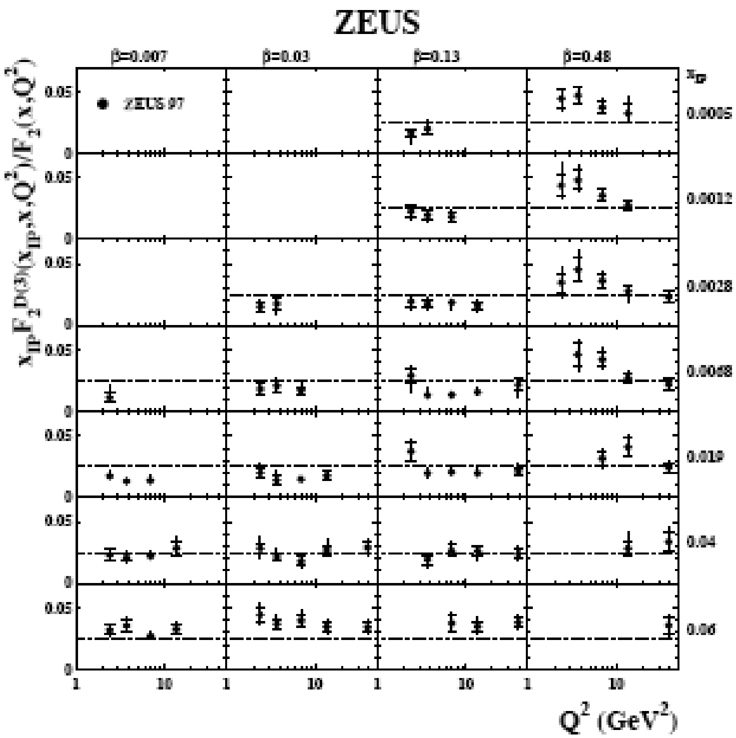
- Underlying hard scattering sub-process is the same in diffractive and non-diffractive events
- Same Q^2 dependence of diffractive and inclusive PDFs (remember: hard radiation not resolved)
- and same energy (W or x_B) dependence

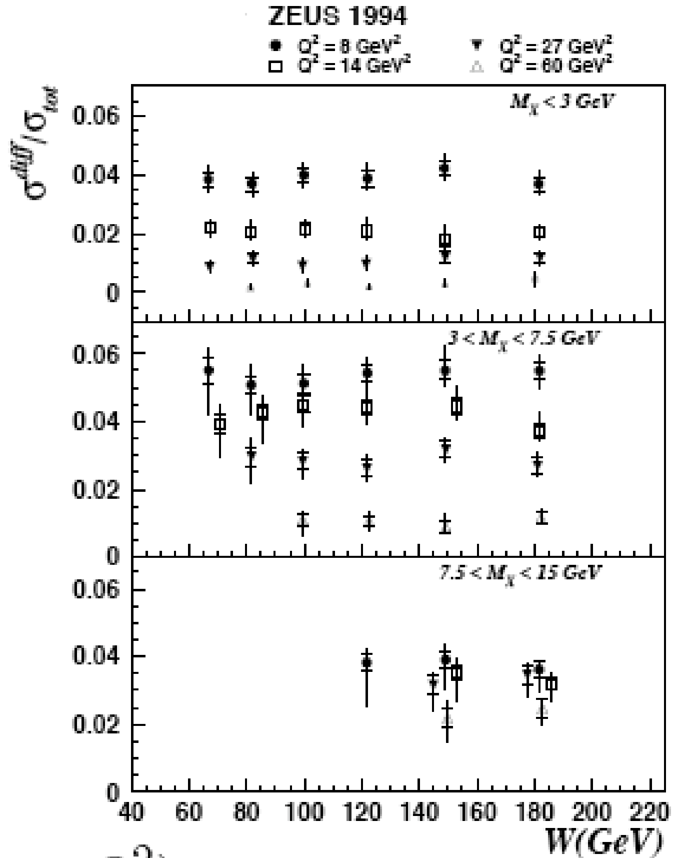
$\Rightarrow \frac{\sigma_{\text{diff}}}{\sigma_{\text{tot}}}$ independent of x_B and Q^2 (as in data)

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 $[f_{g/p}(x_B, Q^2)]^2$

ZEUS data on cross section ratios

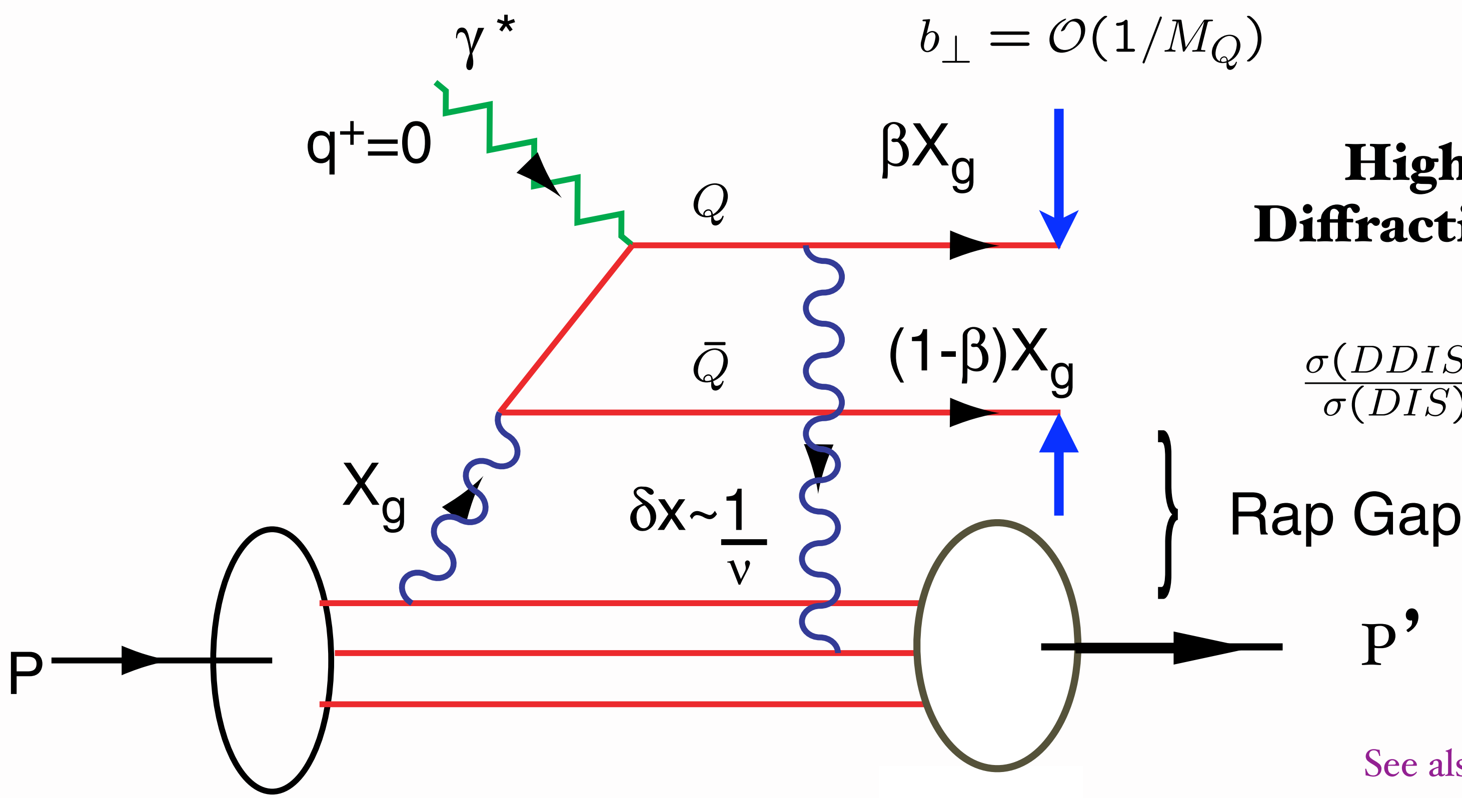




$$\frac{d\sigma^{DDIS}}{d\beta dQ^2 dx_{I\!P}} \Big/ \frac{d\sigma^{DIS}}{dx dQ^2} = \frac{x_{I\!P} F_2^D(x_{I\!P}, x, Q^2)}{F_2(x_{I\!P}, x, Q^2)}$$

Same W dependence

Predict: Reduced DDIS/DIS for Heavy Quarks



Higher Twist Diffraction Fraction

$$\frac{\sigma(DDIS)}{\sigma(DIS)} \simeq \frac{\Lambda^2_{QCD}}{M^2_Q}$$

See also: Bartels et al

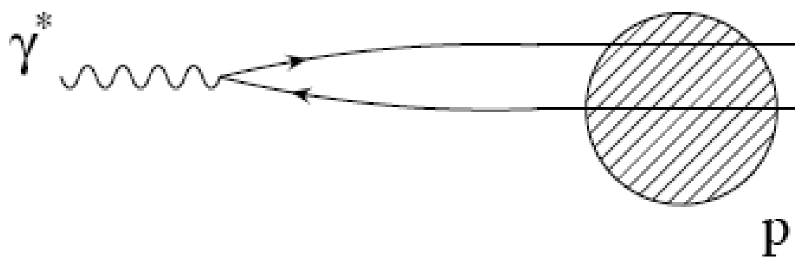
Kopeliovitch, Schmidt, sjb

Dipole models

Many models are based on using the dipole frame

→ Use proton's rest frame, or more generally, a frame where the photon has very large lightcone q^+ momentum

Then the photon fluctuates into a *color dipole* before hitting the proton



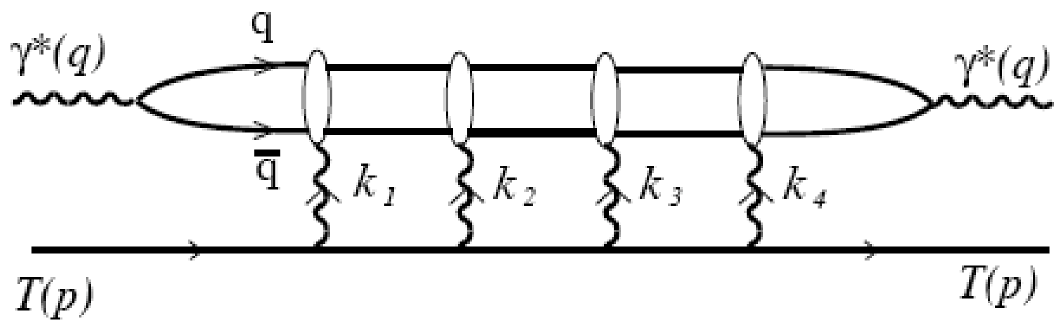
At small x_B the fluctuation is very long-lived and the $q\bar{q}$ pair of the dipole is transversely frozen during the interaction.

Very useful in small-x physics!

Kopeliovitch, Bartels

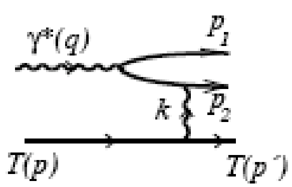
Rescattering toy model

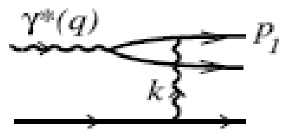
BHMPS: Toy model — scalar abelian gauge theory:



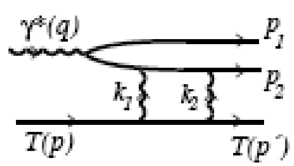
$x_B \to 0$: on-shell intermediate states $\to$ imag. 2-gluon ampl.

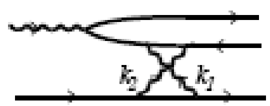
as required for pomeron from crossing symmetry





$$\propto g^2 K_0(m r_\perp) \log\left(\frac{|\boldsymbol{R}_\perp + \boldsymbol{r}_\perp|}{|\boldsymbol{R}_\perp|}\right)$$





$$\propto i g^4 K_0(m r_\perp) \left[\log\left(\frac{|\boldsymbol{R}_\perp + \boldsymbol{r}_\perp|}{|\boldsymbol{R}_\perp|}\right)\right]^2$$

Rescattering factorizes in coordinate space!

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

where

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

FSI not Unitary Phase!

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

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

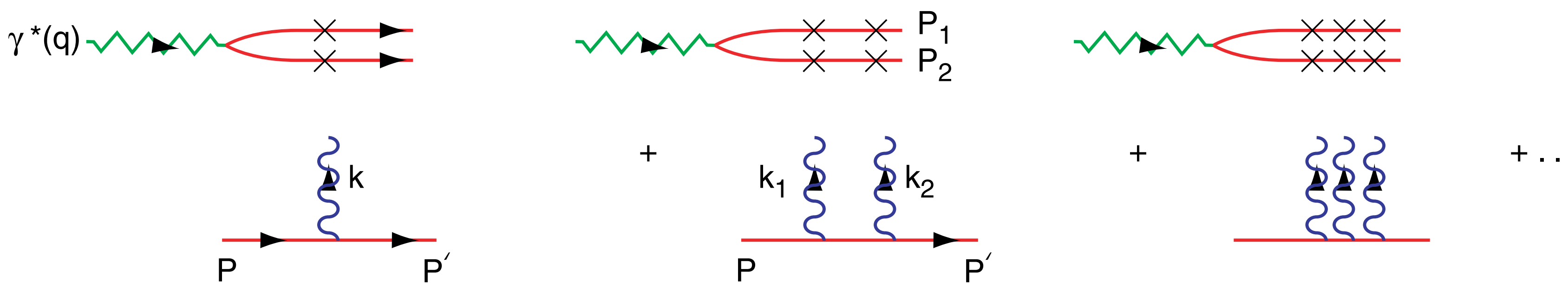
The rescattering effect of the dipole of the $q\overline{q}$ is controlled by

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

Precursor of Nuclear Shadowing

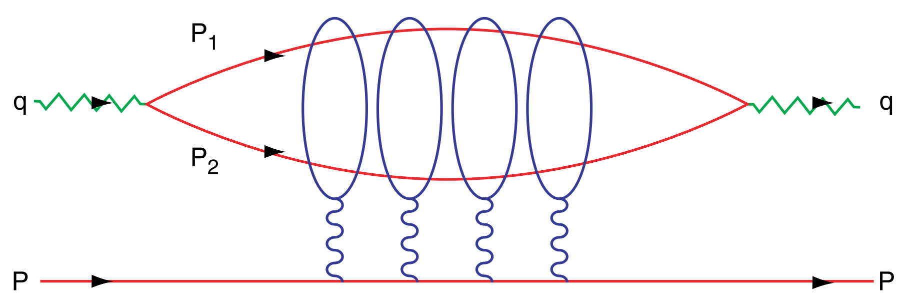
BHMPS

Same result obtained in Lab or Parton q+=0 Frame

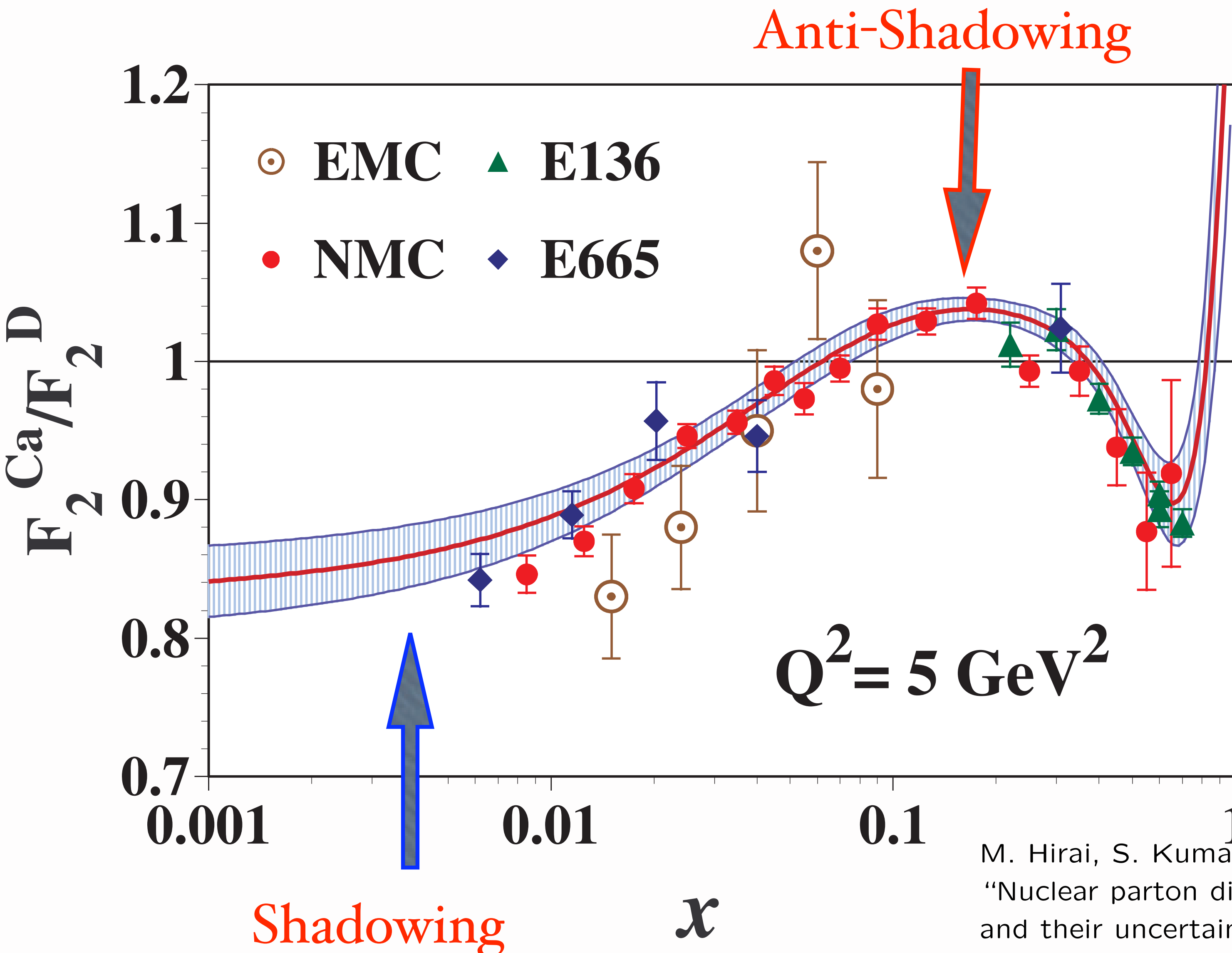


Sum Eikonal Interactions

Similar to Color-Dipole Model



Final-state interactions included



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].

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

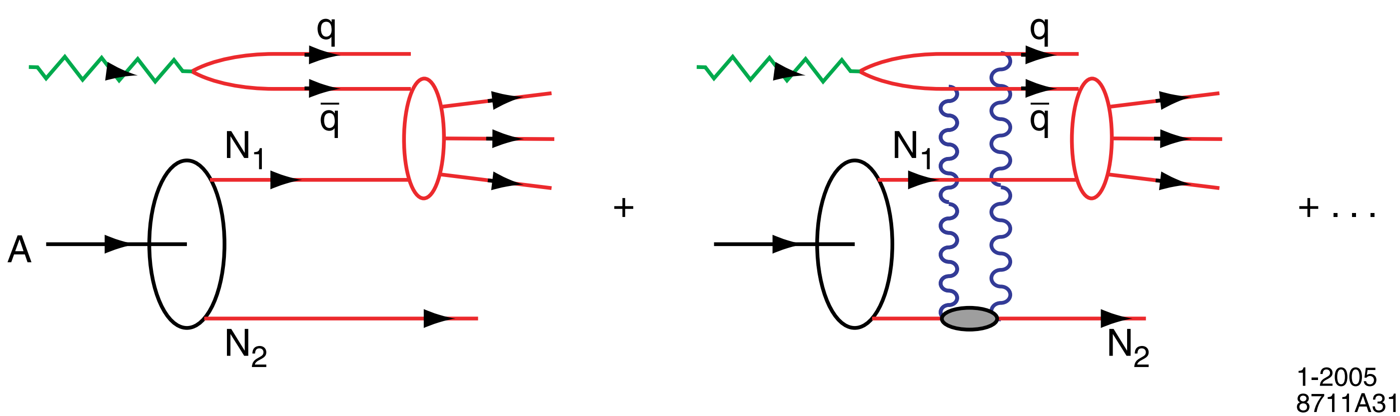
Ivan Schmidt

Hung Jung Lu

sjb

Stodolsky
Pumplin, sjb
Gribov

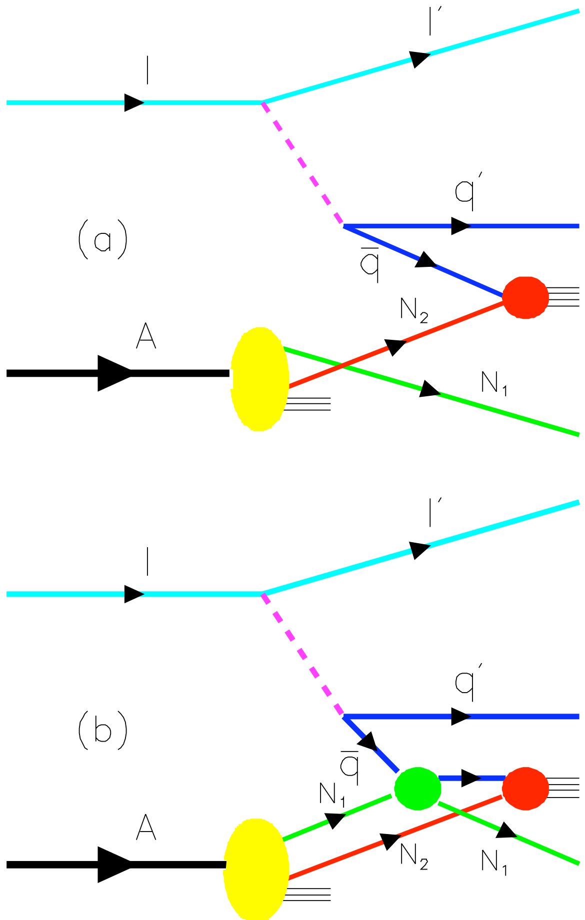
Nuclear Shadowing in QCD



Shadowing depends on understanding diffraction in DIS

Nuclear Shadowing not included in nuclear LFWF !

Dynamical effect due to virtual photon interacting in nucleus



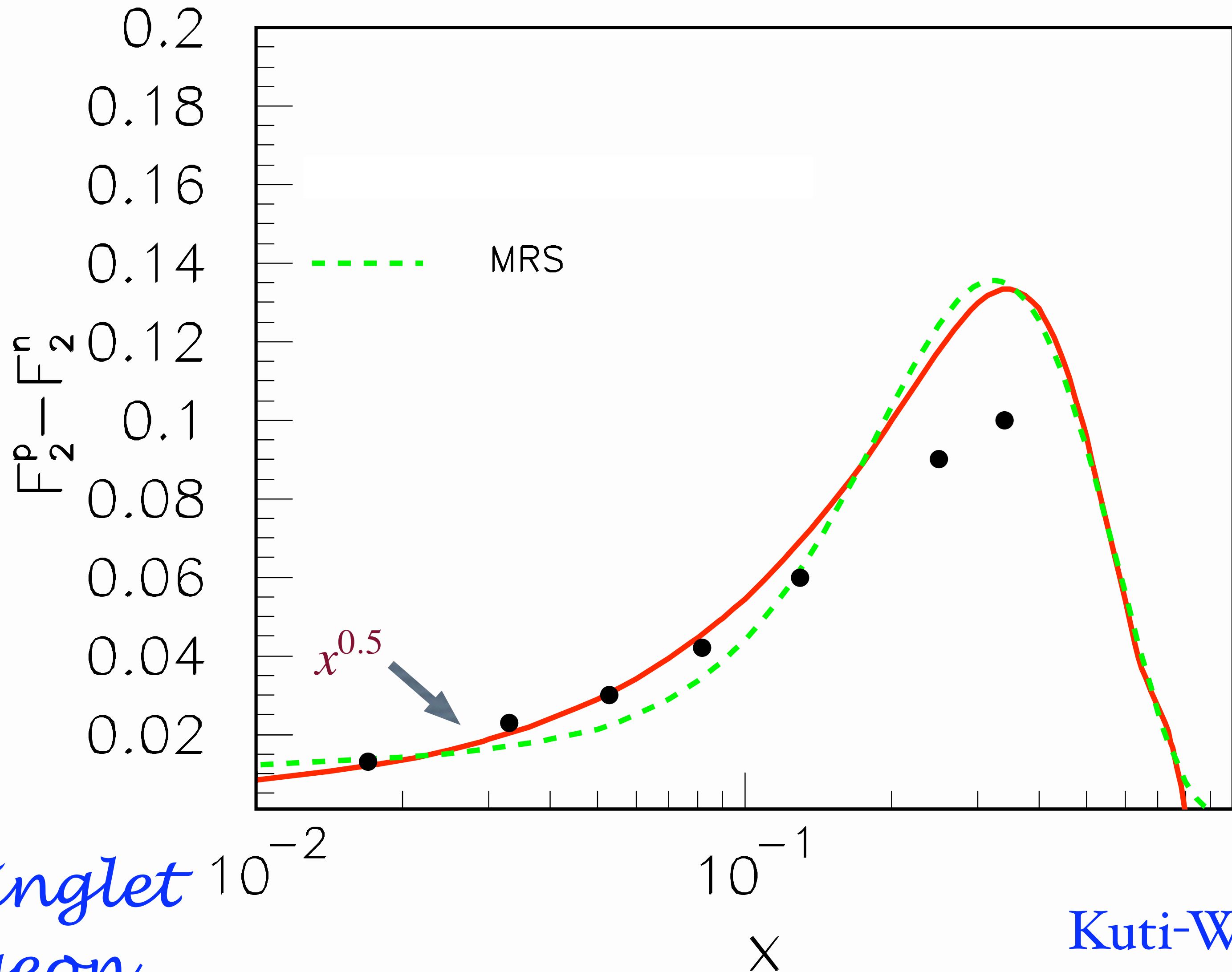
The one-step and two-step processes in DIS on a nucleus.

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 $\overline{q}$ flux reaching N_2.

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

Observed HERA DDIS produces nuclear shadowing



Non-singlet Reggeon Exchange

Kuti-Weisskopf behavior

Reggeon Exchange

Phase of two-step amplitude relative to one step:

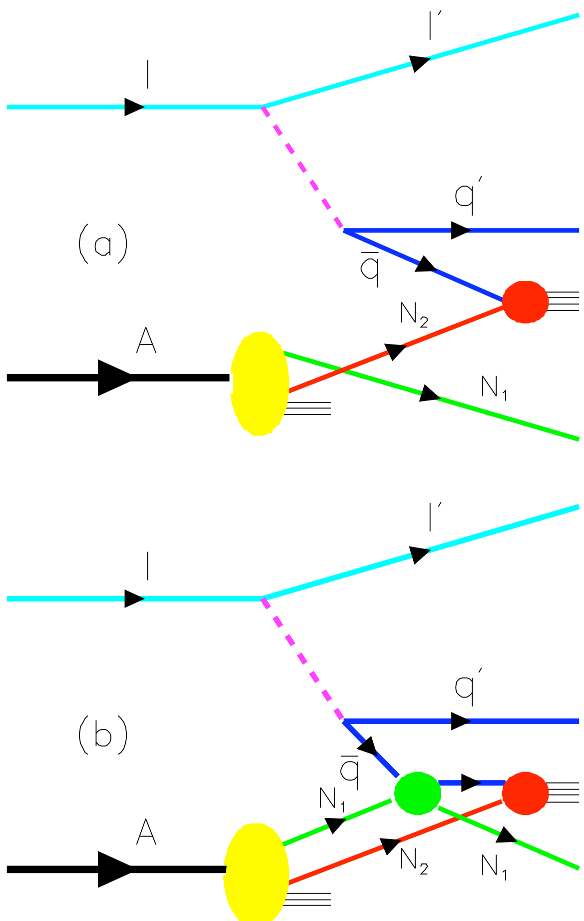
$$\frac{1}{\sqrt{2}}(1-i) \times i = \frac{1}{\sqrt{2}}(i+1)$$

Constructive Interference

Depends on quark flavor!

Thus antishadowing is not universal

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

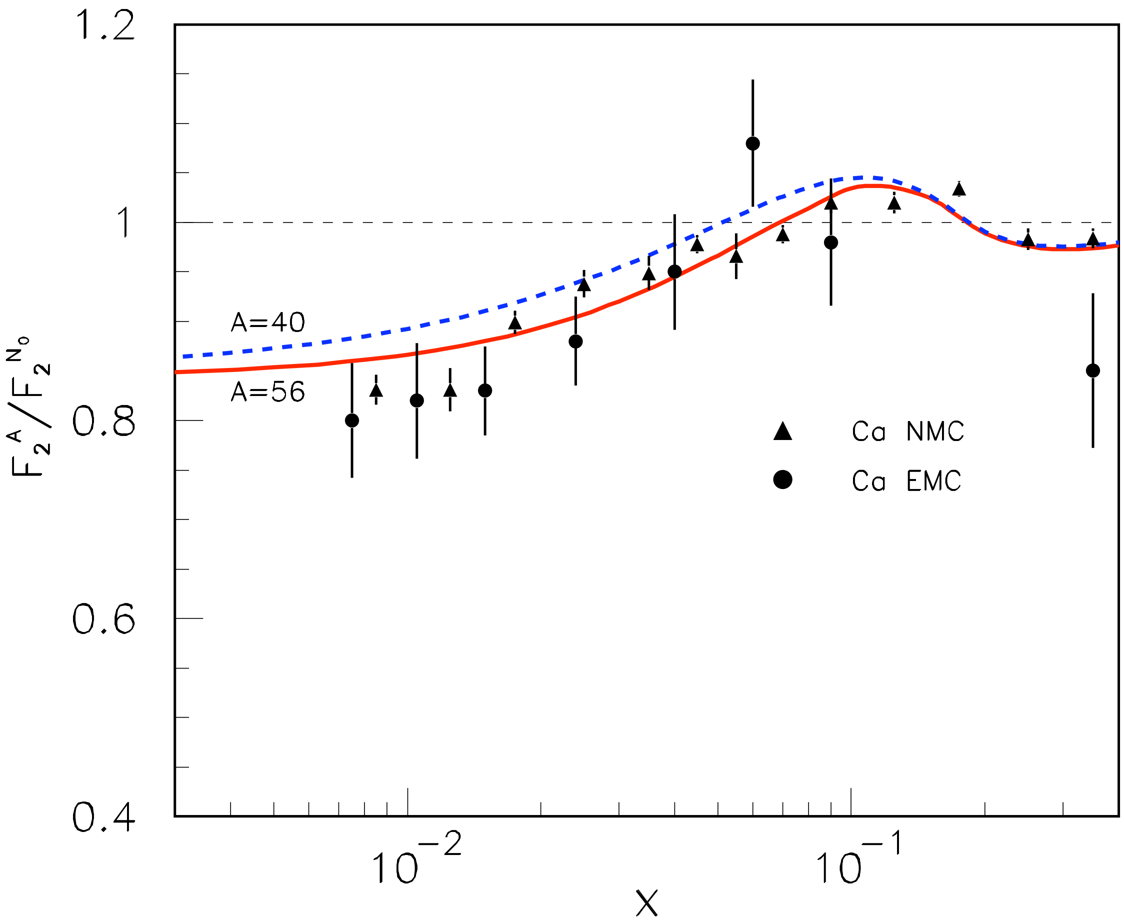


The one-step and two-step processes in DIS on a nucleus.

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 $\bar{q}$ flux reaching N_2

$\rightarrow$ Antishadowing of the DIS nuclear structure functions

H. J. Lu, sjb
Schmidt, Yang, sjb



Predicted nuclear shadowing and and antishadowing at $Q^2 = 1\ \text{GeV}^2$

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].

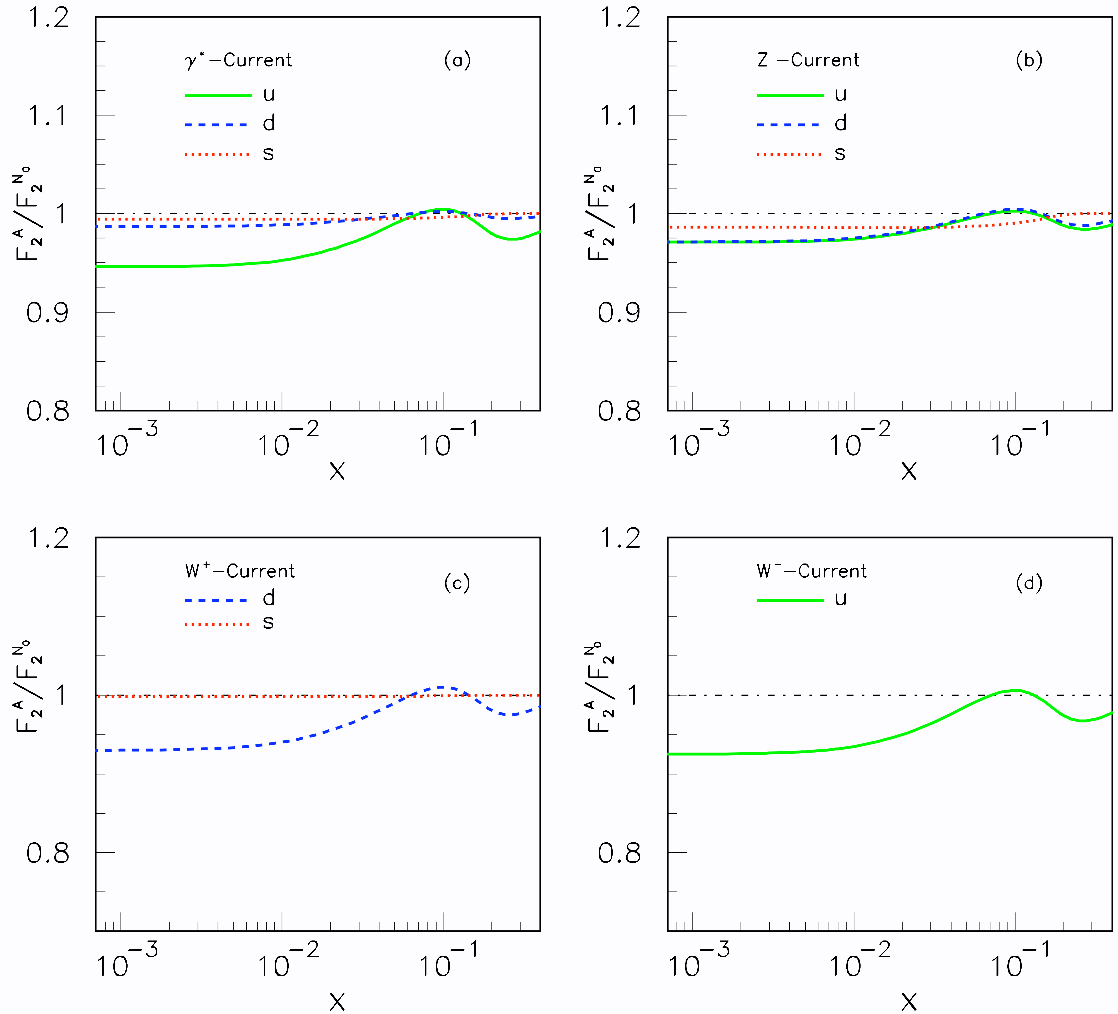
Shadowing and Antishadowing in Lepton-Nucleus Scattering

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

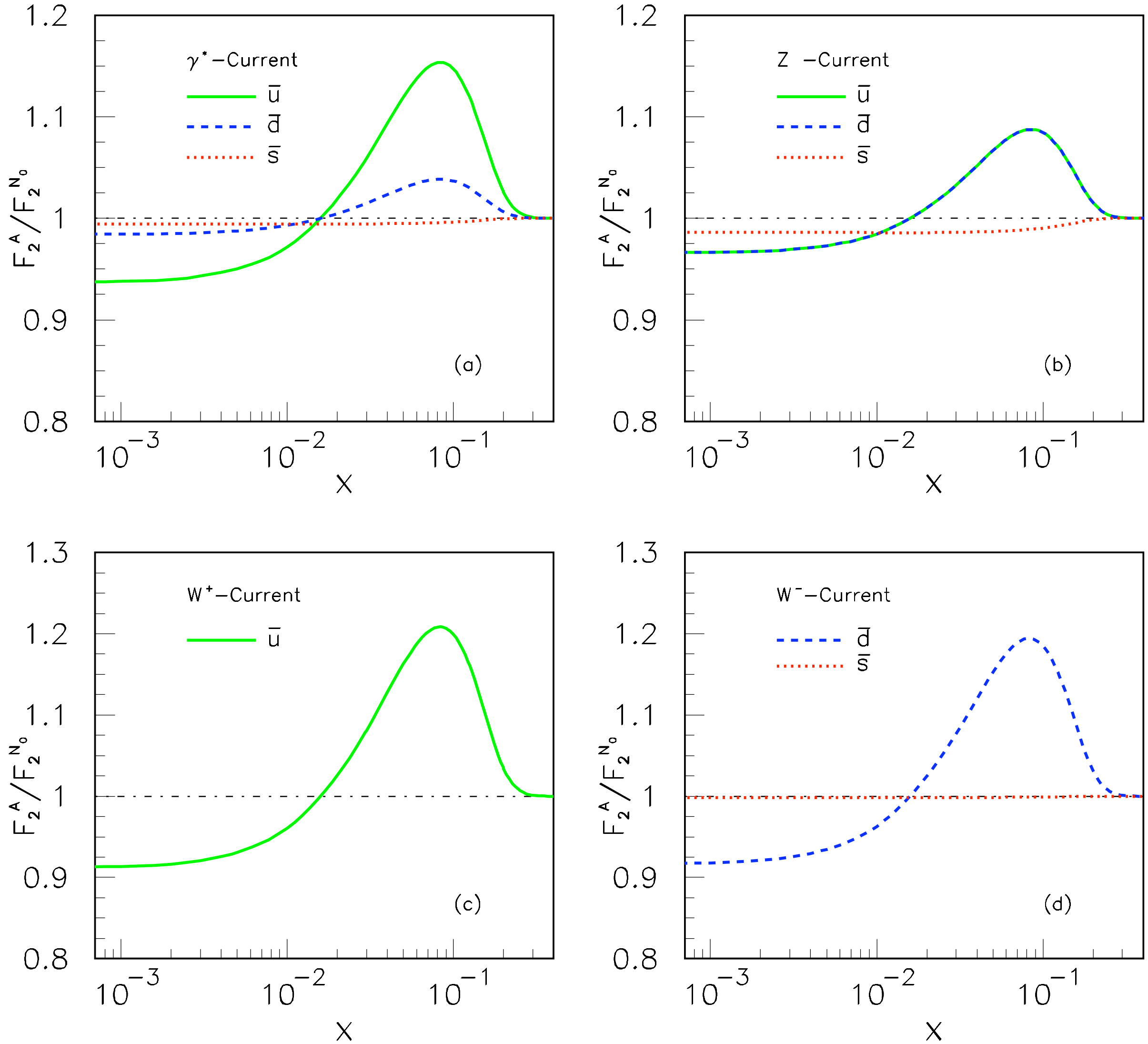
- Antishadowing: Constructive Interference
of Two-Step and One-Step Processes!
Reggeon and Odderon Exchange

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

Shadowing and Antishadowing of DIS Structure Functions

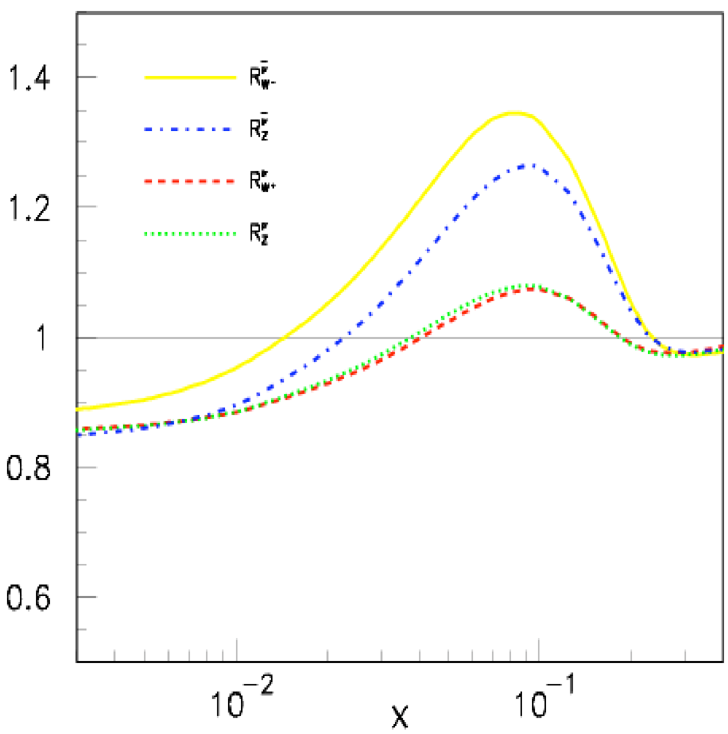


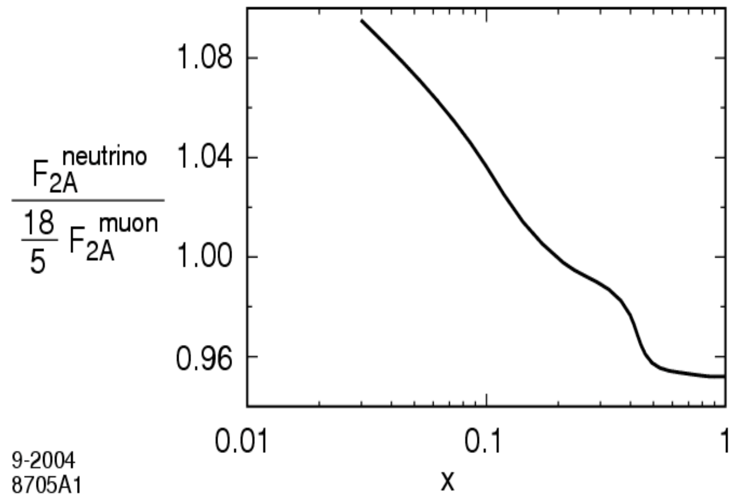
S. J. Brodsky, I. Schmidt and J. J. Yang, "Nuclear Antishadowing in Neutrino Deep Inelastic Scattering," Phys. Rev. D 70, 116003 (2004) [arXiv:hep-ph/0409279].



Nuclear Effect not Universal !

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

Lu, Schmidt, Yang, sjb

Need new experimental studies of antishadowing in

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

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

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.

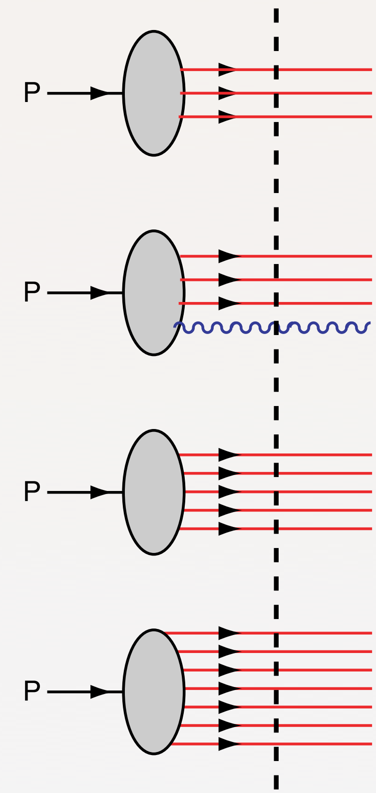
The light-cone momentum fraction

$$x_i = \frac{k_i^+}{p^+} = \frac{k_i^0 + k_i^z}{P^0 + P^z}$$

are boost invariant.

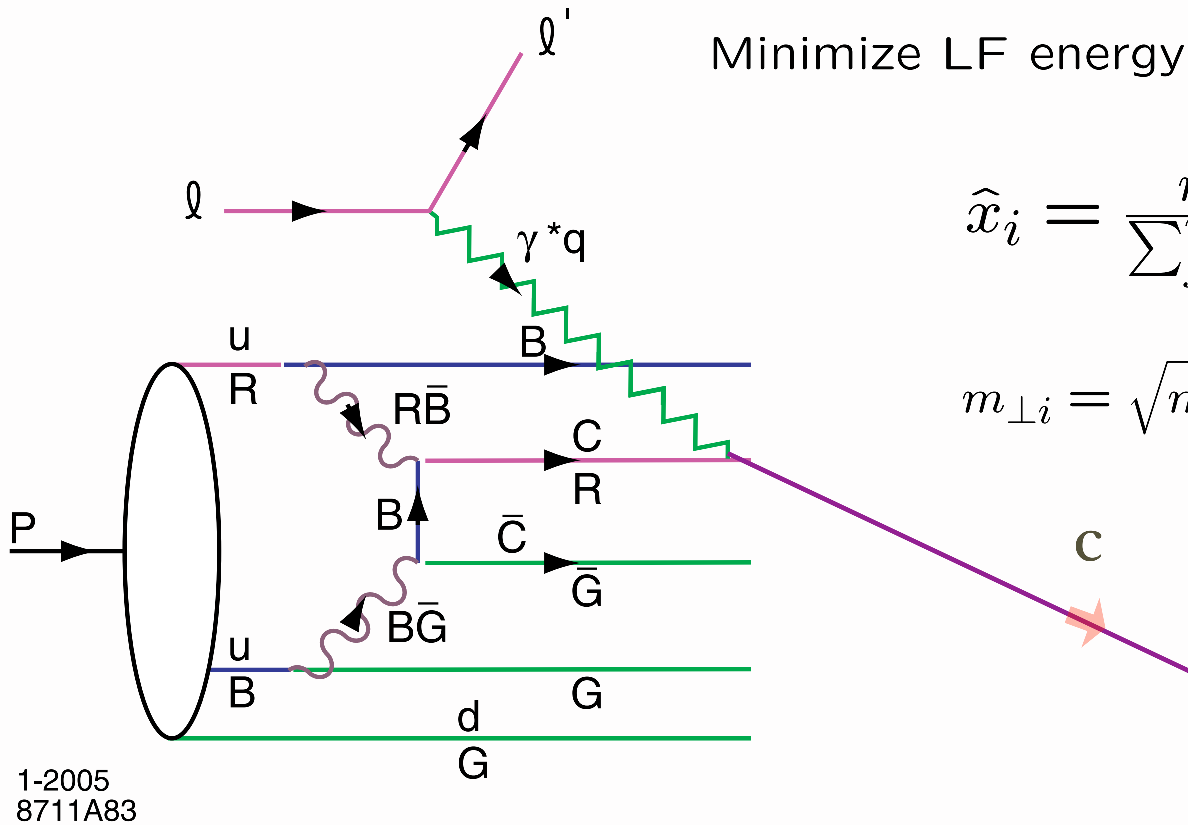
$$\sum_i^n k_i^+ = P^+, \ \sum_i^n x_i = 1, \ \sum_i^n \vec{k}_i^\perp = \vec{0}^\perp.$$

Intrinsic heavy quarks, $\bar{s}(x) \neq s(x)$



Fixed LF time

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



Minimize LF energy denominator

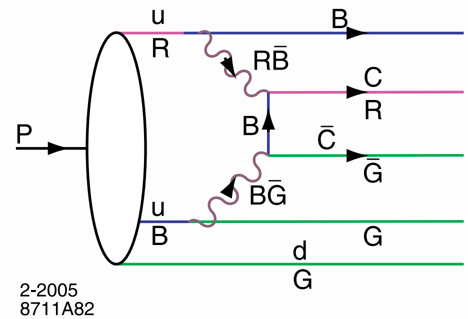
$$\hat{x}_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

$$m_{\perp i} = \sqrt{m_i^2 + k_{\perp i}^2}$$

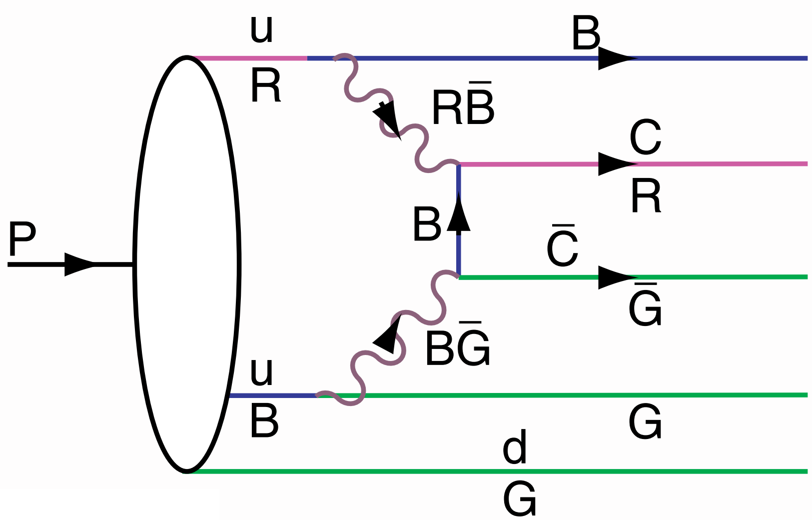
Hoyer, Peterson, SJB

Hoyer, Peterson, Sakai, sjb

Intrinsic Heavy-Quark Fock States



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



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

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

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

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

OPE derivation - M.Polyakov et al.

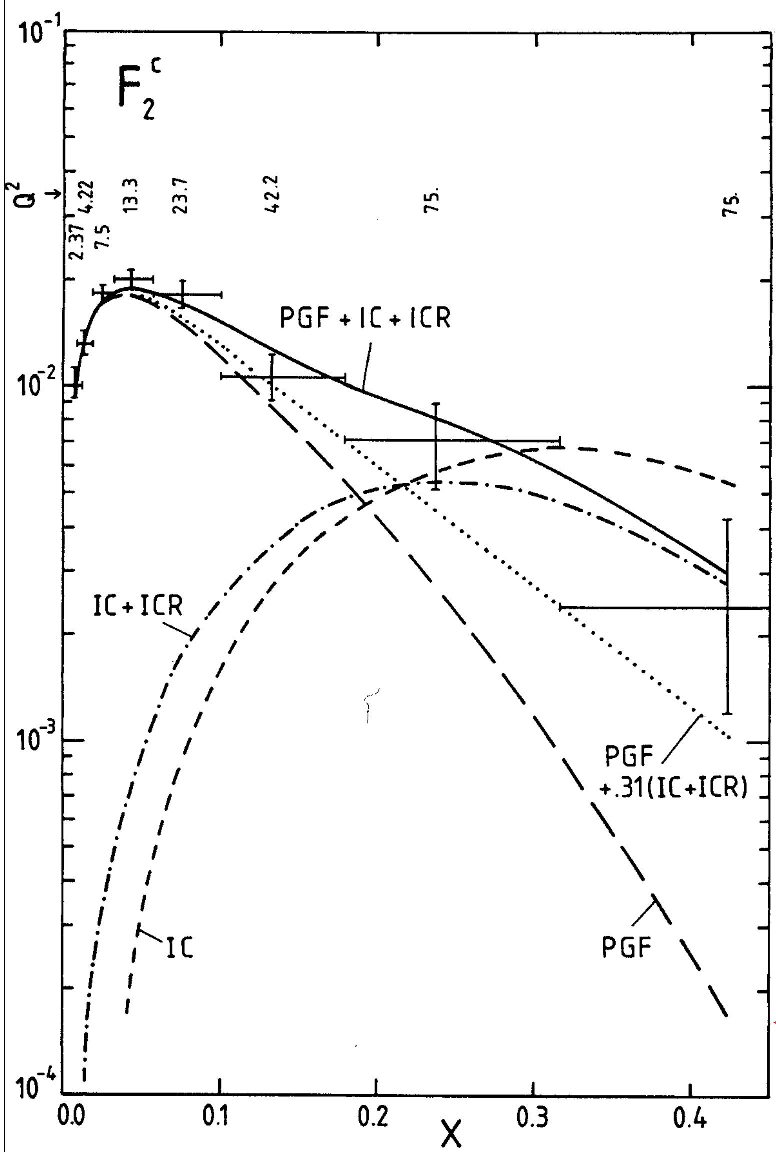
$c\bar{c}$ in Color Octet

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

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

High x charm!

Hoyer, Peterson, Sakai, sjb

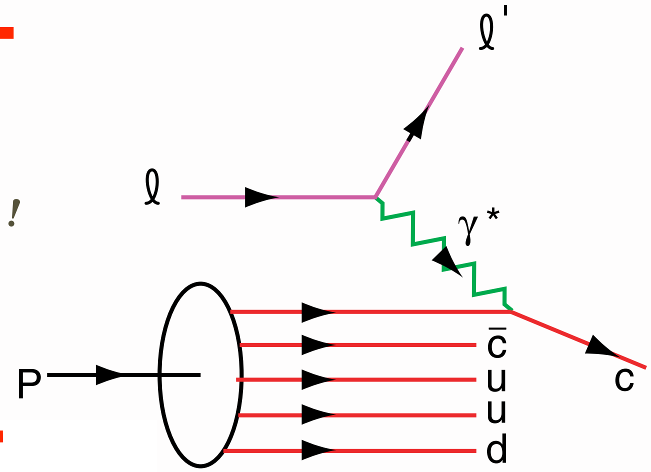


Measurement of Charm Structure Function

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

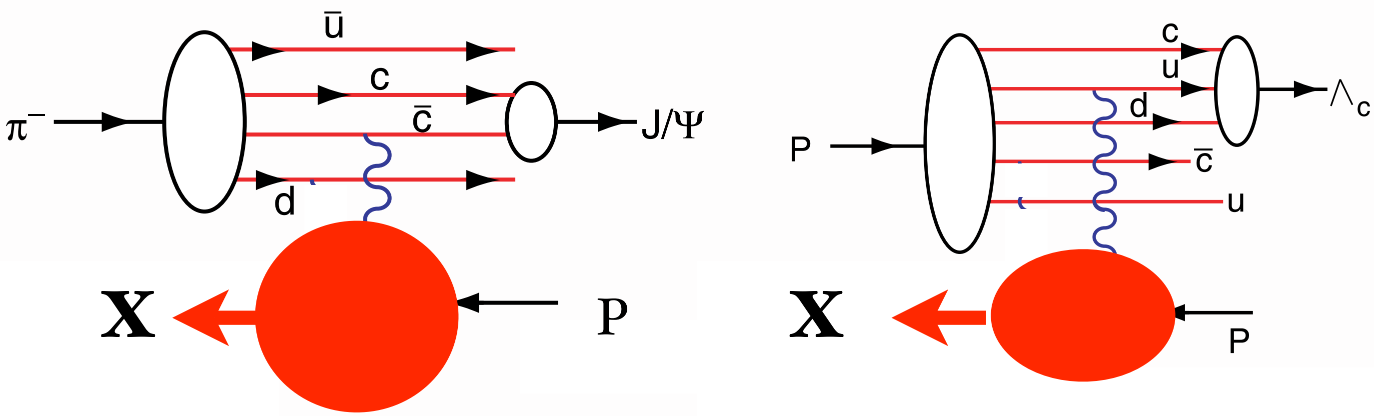
First Evidence for Intrinsic Charm

factor of 30 !



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

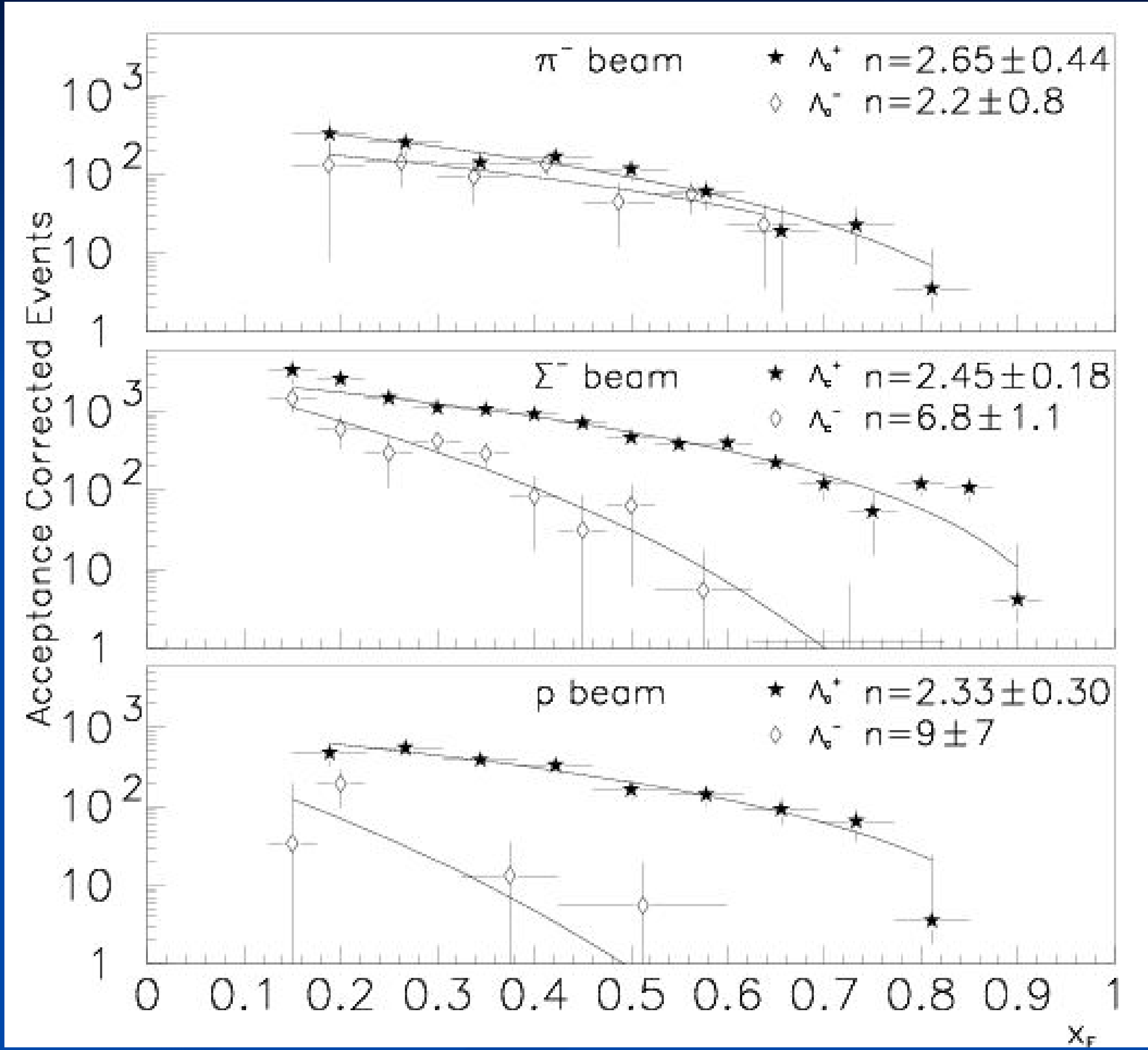
Leading Hadron Production from Intrinsic Charm



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

SELEX Λ_c^+ Studies – Momentum Dependence

- Production similar for baryon, antibaryon from π beam at all x_F
- Baryon beams make antibaryons chiefly at small x_F but not large x_F: *not* simply fragmentation
- High statistics Σ data suggest cross section enhancement at very large x_F – idea originally from Pythia color drag.

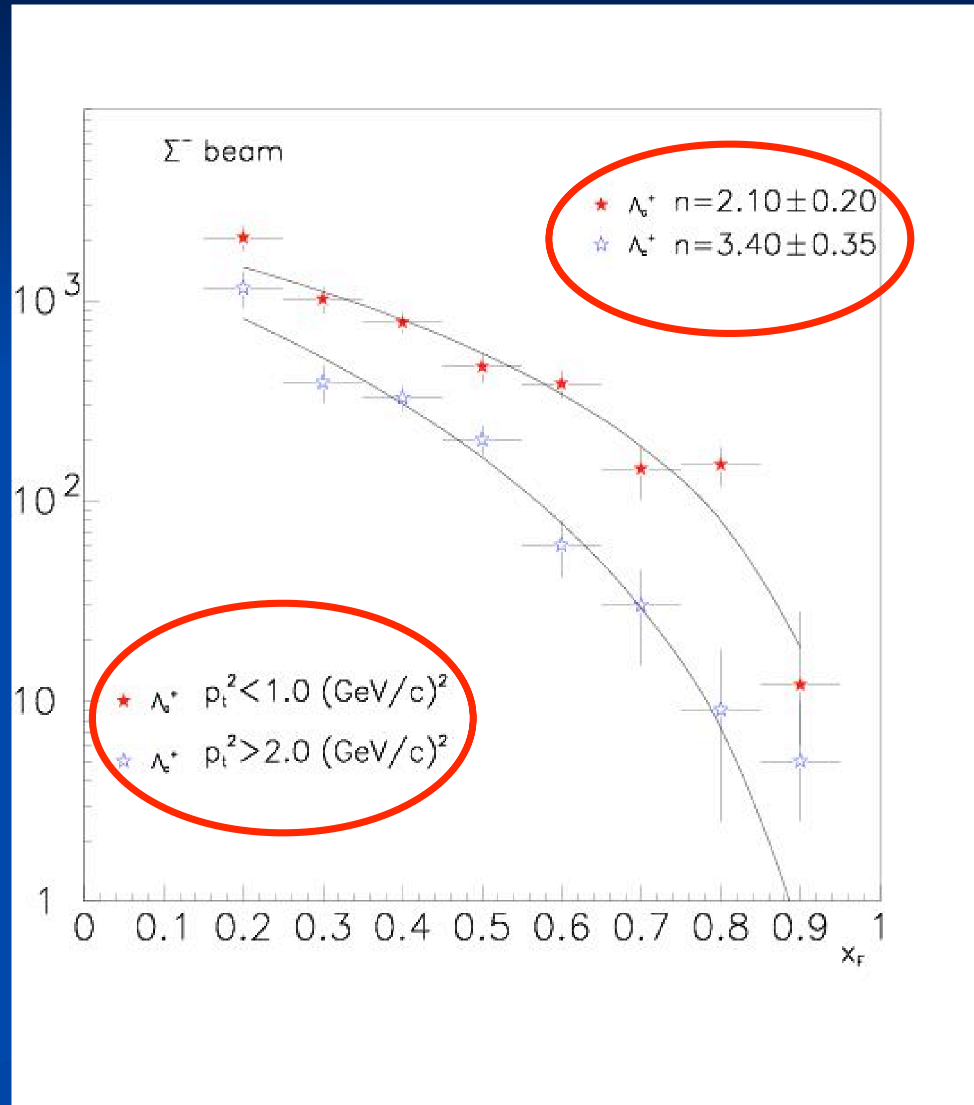


SELEX Λ_c^+ Studies – p_T Dependence

- Λ_c^+ production by Σ^- vs x_F

shows harder spectrum at low p_T - consistent with an intrinsic charm picture.

(Vogt, Brodsky and Hoyer, Nucl. Phys. B383,683 (1992))



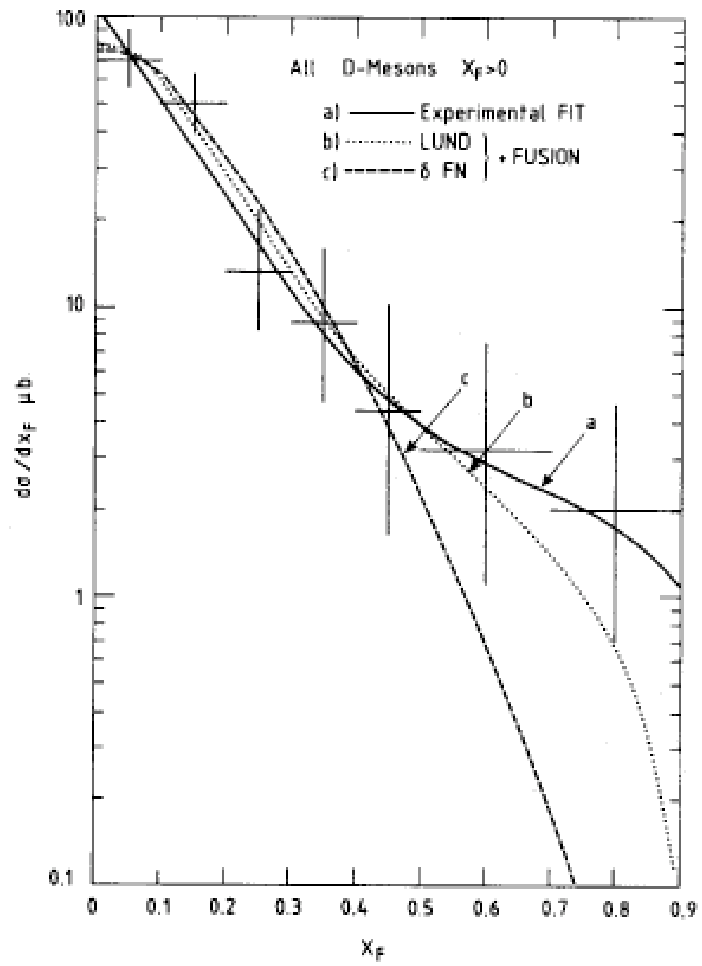
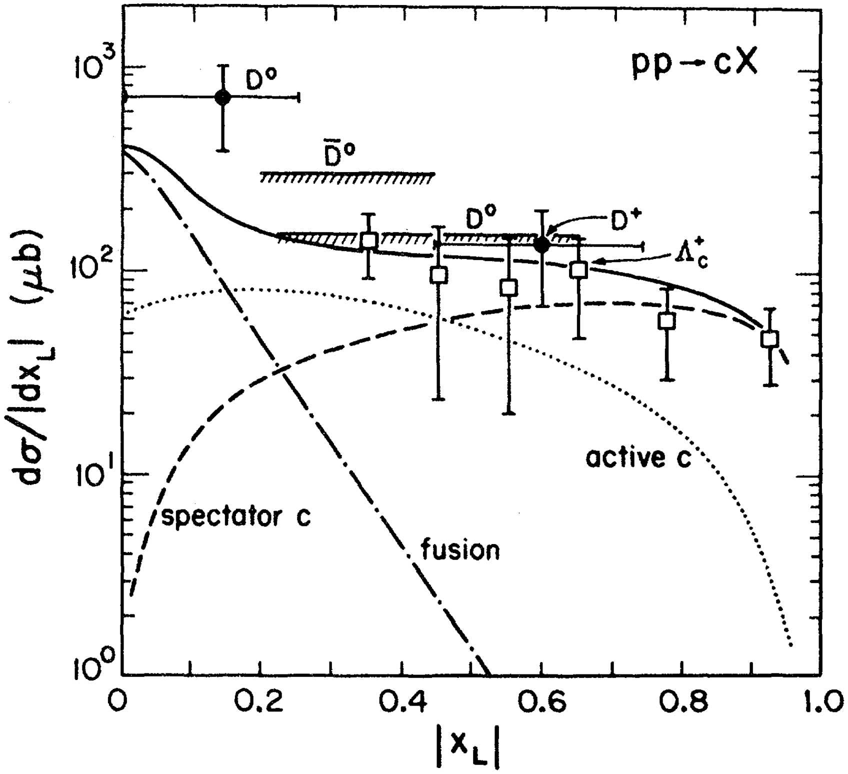


Fig. 1. The differential distribution x_F for all D mesons having $x_F > 0$. Curve (a) is the two-component fit to the data as described in the text. Curve (b) is the prediction of the Lund fusion calculation. Curve (c) is the prediction of the bare QCD fusion calculation (δ-function fragmentation). Note that both theoretical curves have been normalised to the observed total cross section for $x_F > 0$.

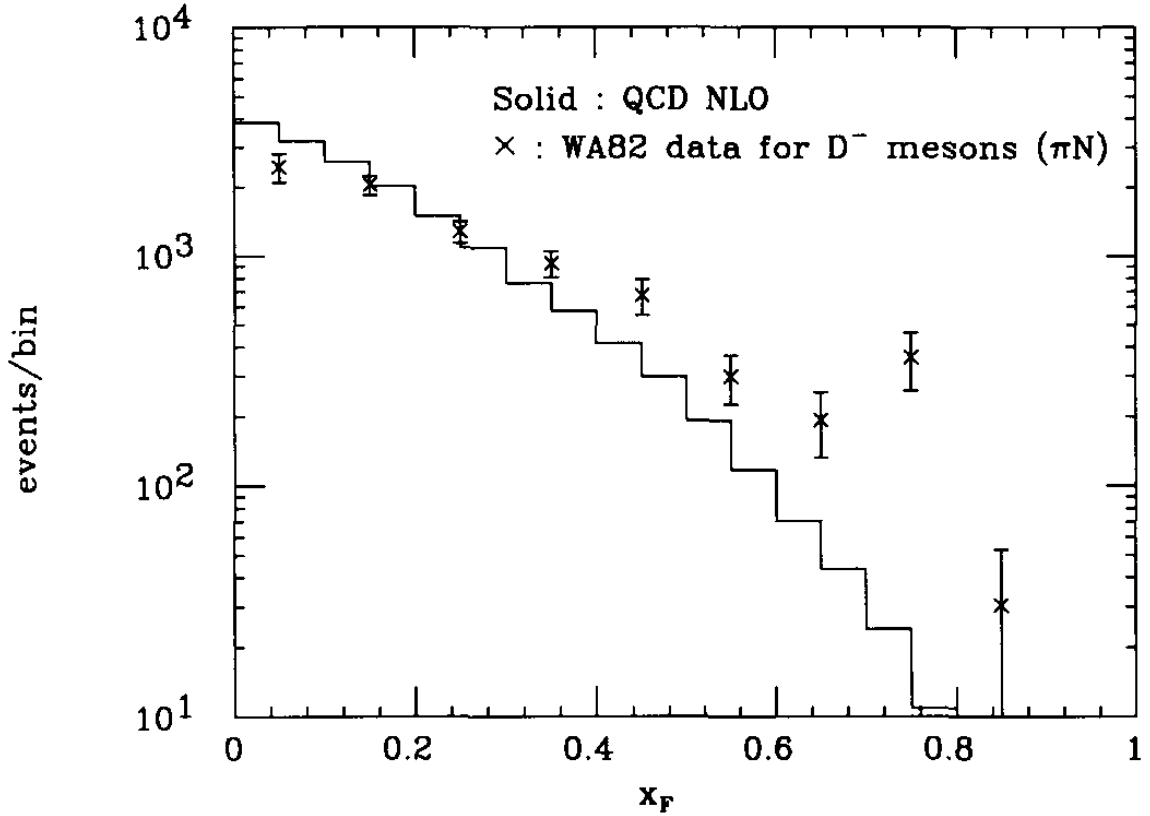
M. Aguilar-Benitez et al.
[NA27 Collaboration],
"Inclusive Properties Of *D* Mesons
Produced In 360-GeV πp Interaction
Phys. Lett. B 161, 400 (1985).



Model similar to Intrinsic Charm

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).



S. Frixione, M. L. Mangano, P. Nason and G. Ridolfi, "Heavy-Quark Production," Adv. Ser. Direct. High Energy Phys. 15, 609 (1998) [arXiv:hep-ph/9702287].

- 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 $pp \to \Lambda_c X$

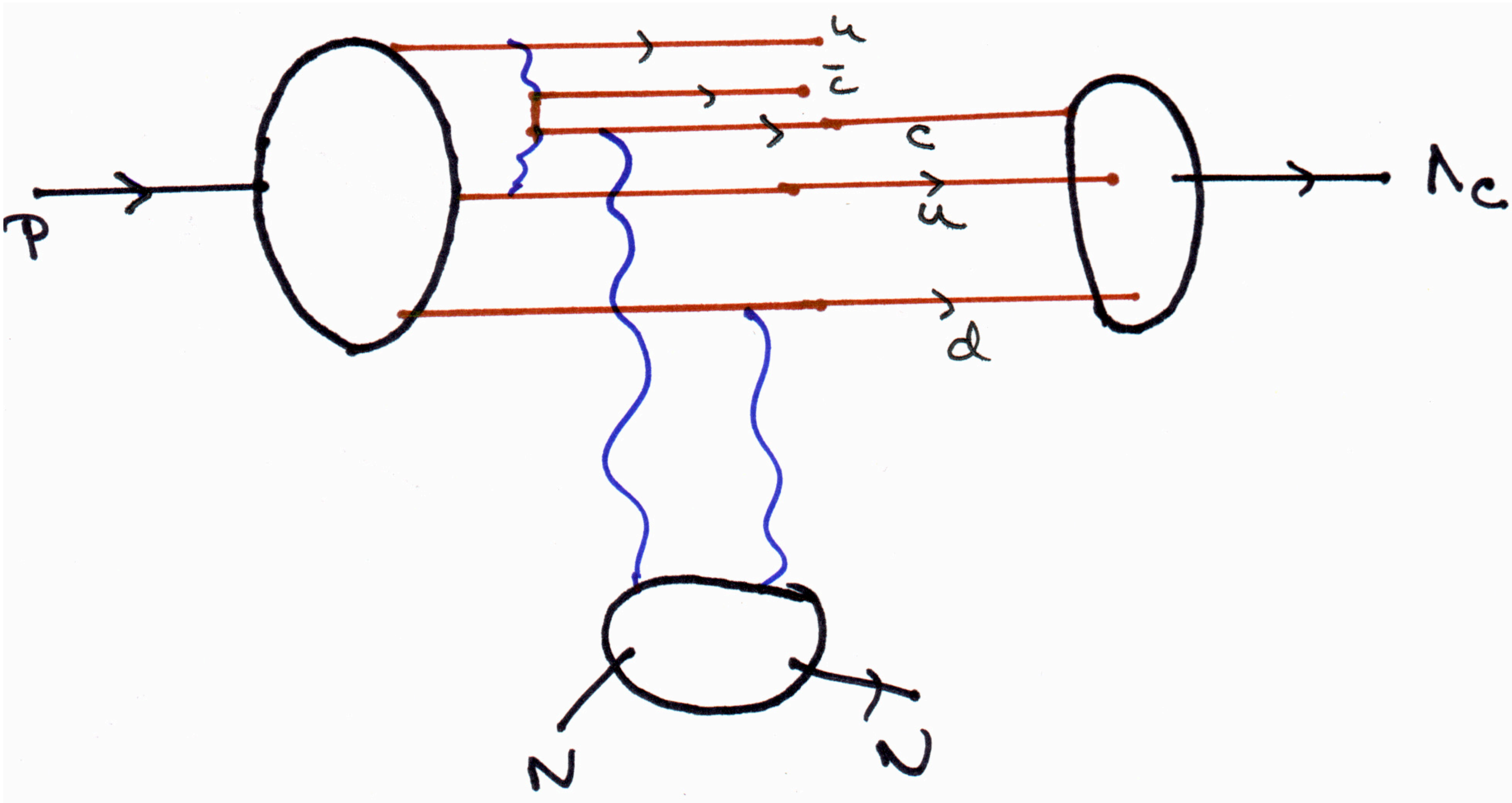
- High x_F $pp \to \Lambda_b X$

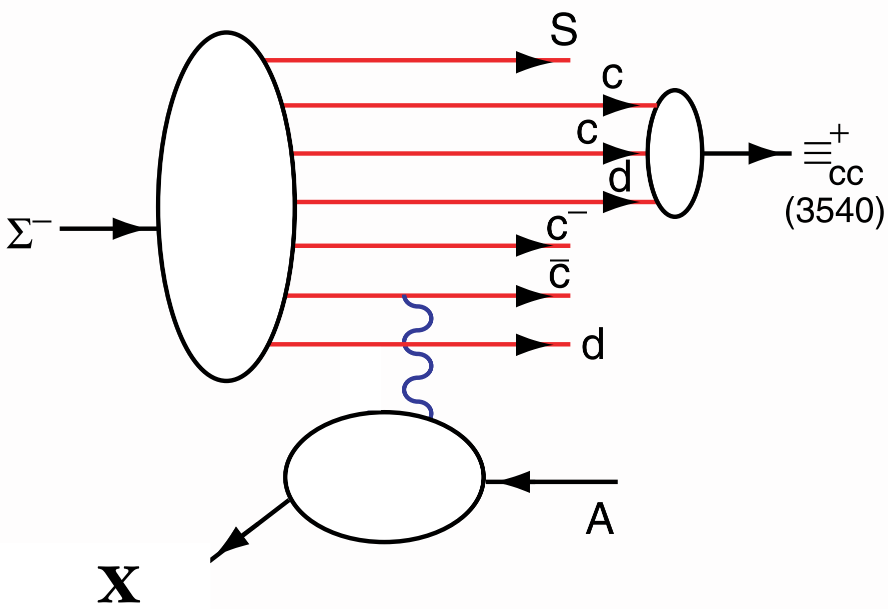
- High x_F $pp \to \Xi(ccd) X$ (SELEX)

C.H. Chang, J.P. Ma, C.F. Qiao and X.G.Wu,
Hadronic production of the doubly charmed baryon Xi/cc with intrinsic charm," arXiv:hep-ph/0610205.

$p\,p \to p \Lambda_c X$

Diffractive Dissociation of Intrinsic Charm





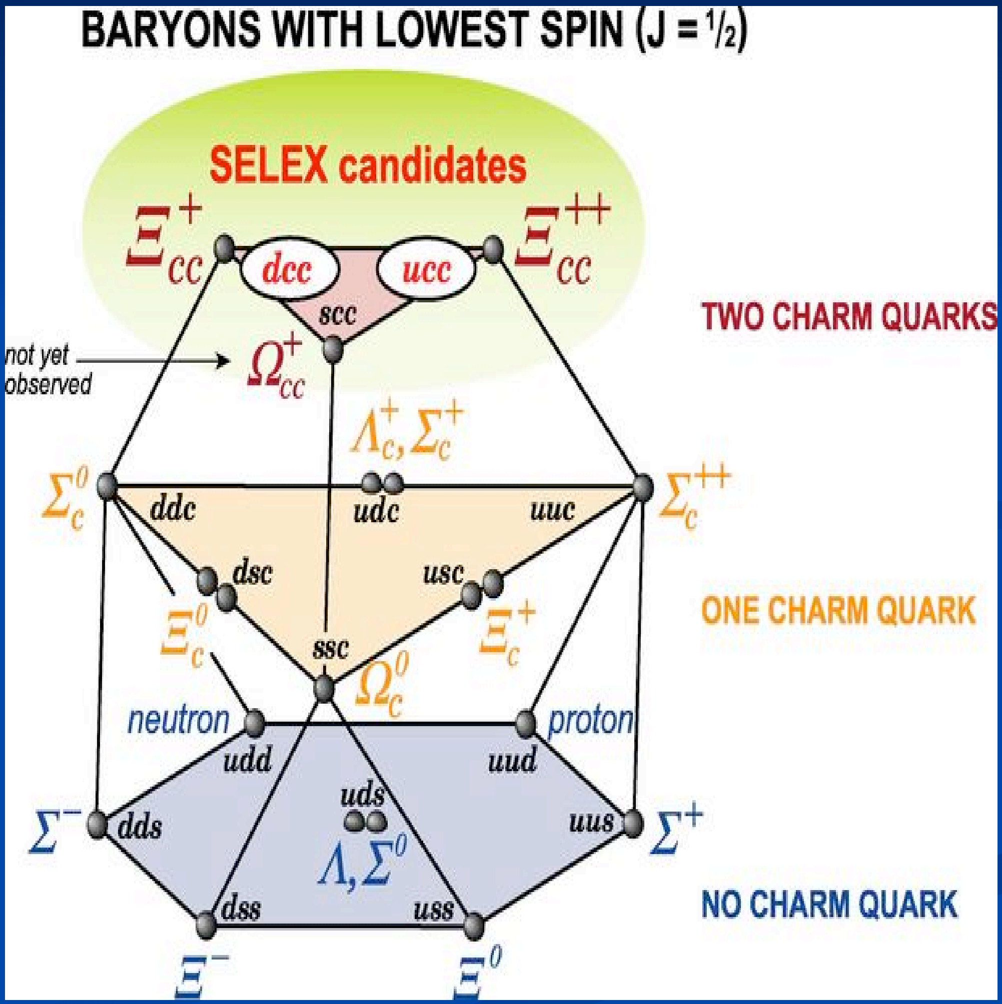
Production of a Double-Charm Baryon

SELEX high x_F $< x_F >= 0.33$

Double Charm Baryons: SU(4)

- QCD: isodoublet of (ccq) baryons
- Models agree: ground state ~ 3.5-3.6 GeV/c^2
- Lattice concurs:
  Flynn, et al., hep-lat/030710

⟹

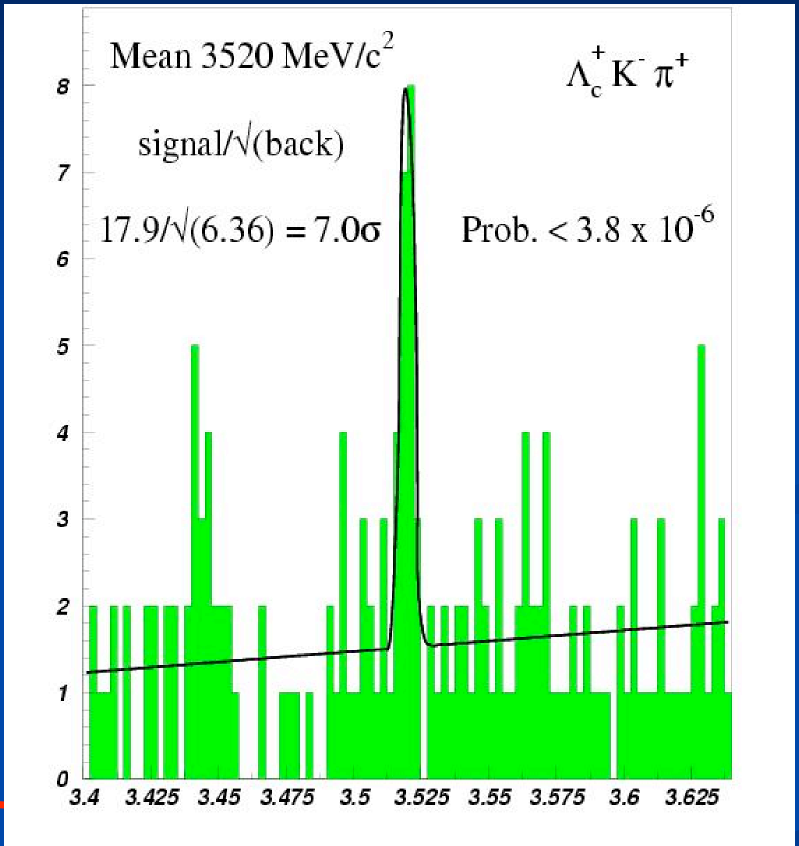


Features of First SELEX Ξ_{cc}^{+} Observation

Phys Rev Lett 89 (2002)112001

First candidate for new baryon comes from baryon beam experiment:

- $(ccd)^{+} \rightarrow \Lambda_c^{+} K^{-} \pi^{+}$ Cabibbo-favored spectator mode
- mass agrees very well with potential models
- state seen from Σ^{-}, p but not π^{-}
- lifetime is very short – < 35 ps at 90% confidence. Disagrees with prediction from HQ single charm lifetime hierarchy.

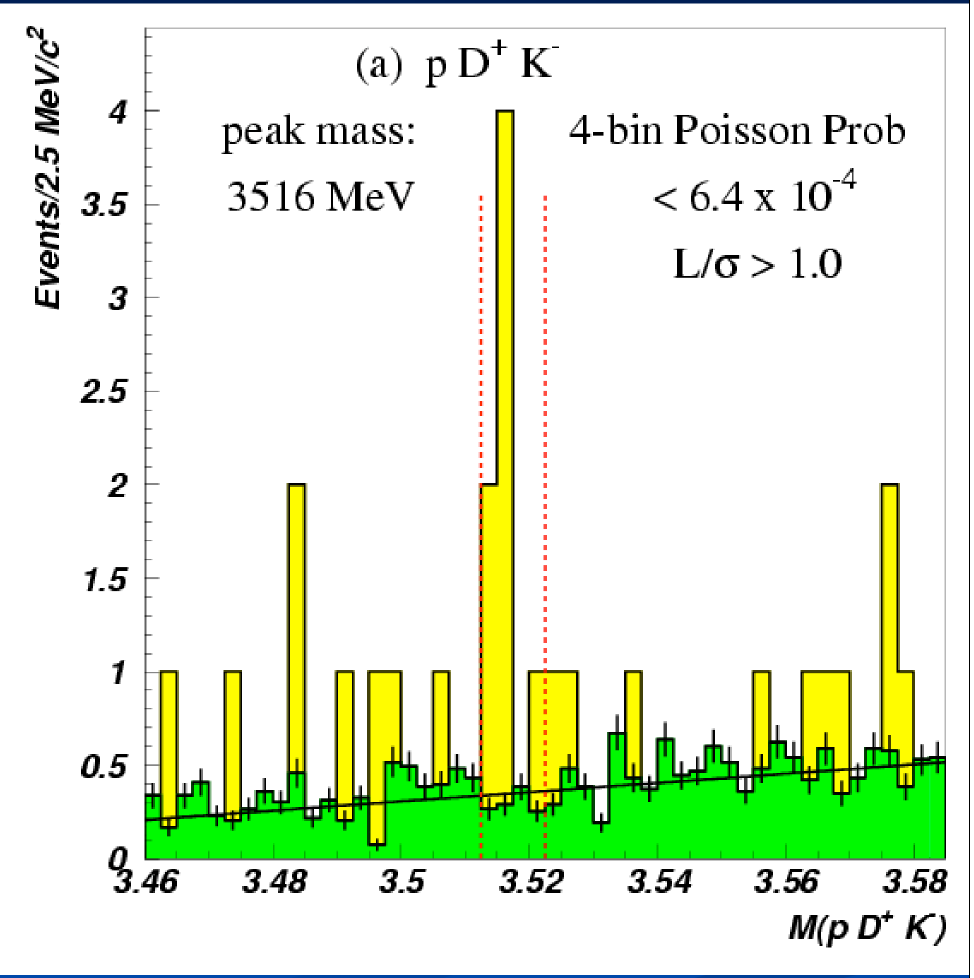


- Cross section is *large*! Involves 40% of SELEX Λ_c^{+} production. Fragmentation predictions are 10,000 times smaller.

Application: New Ξ_{cc}^+ Decay Mode

$\Xi_{cc}^+ \rightarrow pD^+K^-$ is quark rearrangement from $\Lambda_c^+K^-\pi^+$

- Q-value of decay is smaller than that for $\Lambda_c^+K^-\pi^+ \Rightarrow$ low rate
- Check physics background with wrong sign pD^-K^+ – no peaks
- Event-mixed background (green) matches background fit to data (solid line) – confirms signal.
- Mass matches within 1 MeV of $\Lambda_c^+K^-\pi^+$ value



Phys. Lett. **B**628(2005) 18

SELEX Summary II – Double Charm

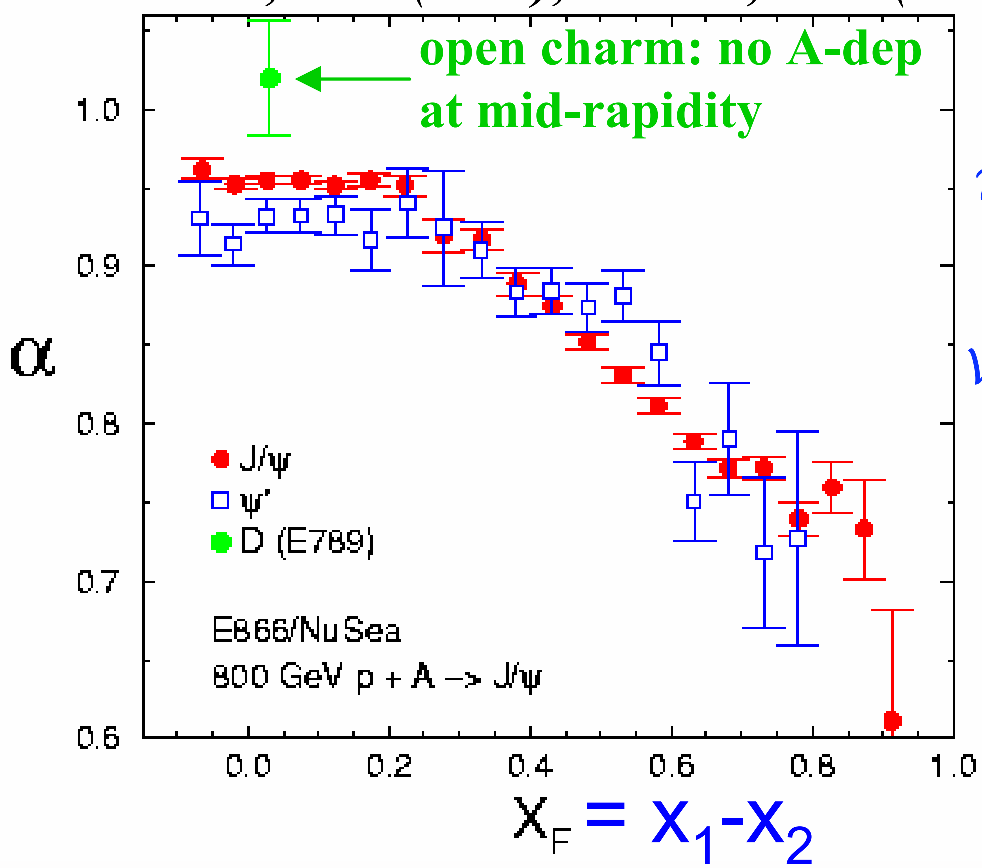
- Double charm here to stay
  - Ξ_{cc}^{+}(3520) seen decaying into three different single charm states
  - Double charm production comes only from baryon-baryon interactions with VERY large cross section – totally inconsistent with fragmentation production. SELEX cross section consistent with intrinsic charm prediction
  - Q=2 excited state shows chain decay via pion emission.
  - Double charm baryons NOT seen in fragmentation processes at Belle, BaBar – consistent with SELEX baryon-only production.
  - No report yet on the third double charm baryon, the Ω_{CC}^{+}

SELEX is 10 years young and not yet ready to stop producing surprises.

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

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

M. Leitch



Remarkably Strong Nuclear Dependence for Fast Charmonium

Violation of PQCD Factorization!

Violation of factorization in charm hadroproduction.

P. Hoyer, **M. Vanttinen** (**Helsinki U.**) , **U. Sukhatme** (**Illinois U., Chicago**) **. HU-TFT-90-14, May 1990. 7pp.**

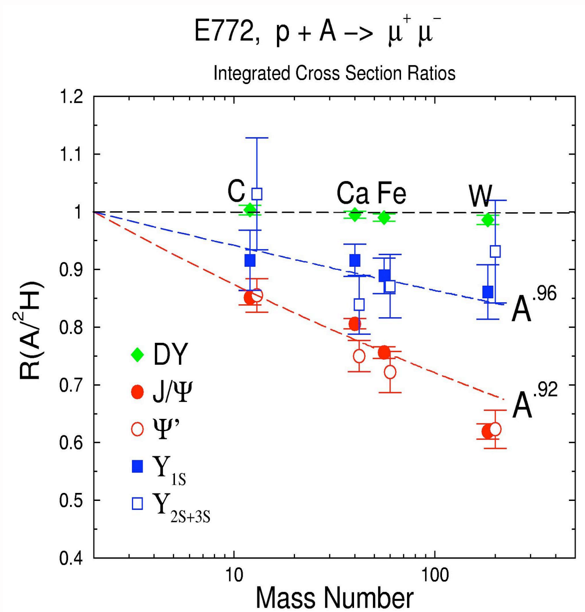
Published in Phys.Lett.B246:217-220,1990

Nuclear effects in Quarkonium production

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

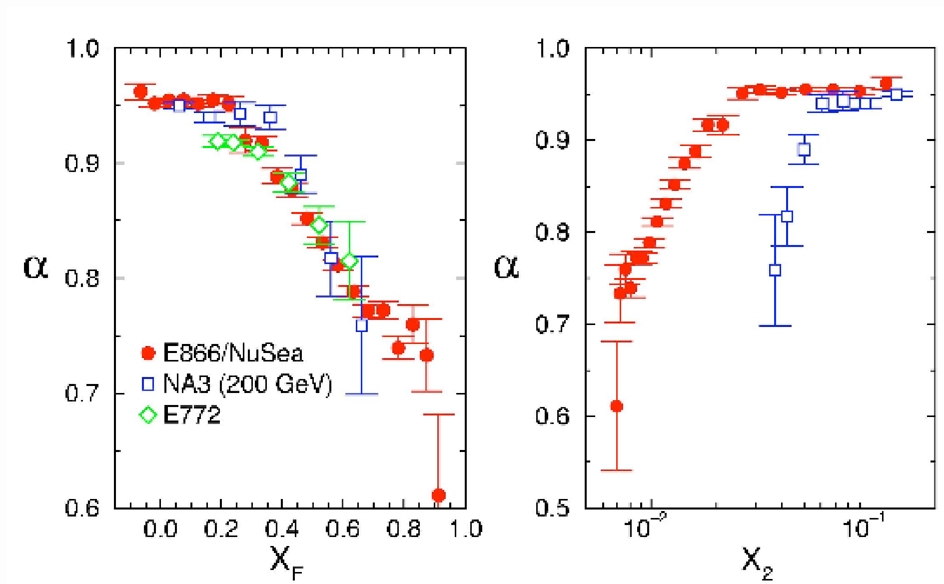
M.Leitch

E772 data



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

Strong x_F - dependence



Nuclear effects scale with x_F, not x_2 !!!

Violation of factorization in charm hadroproduction.

P. Hoyer, **M. Vanttinen** (**Helsinki U.**) , **U. Sukhatme** (**Illinois U., Chicago**) **. HU-TFT-90-14, May 1990. 7pp.**

Published in Phys.Lett.B246:217-220,1990

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

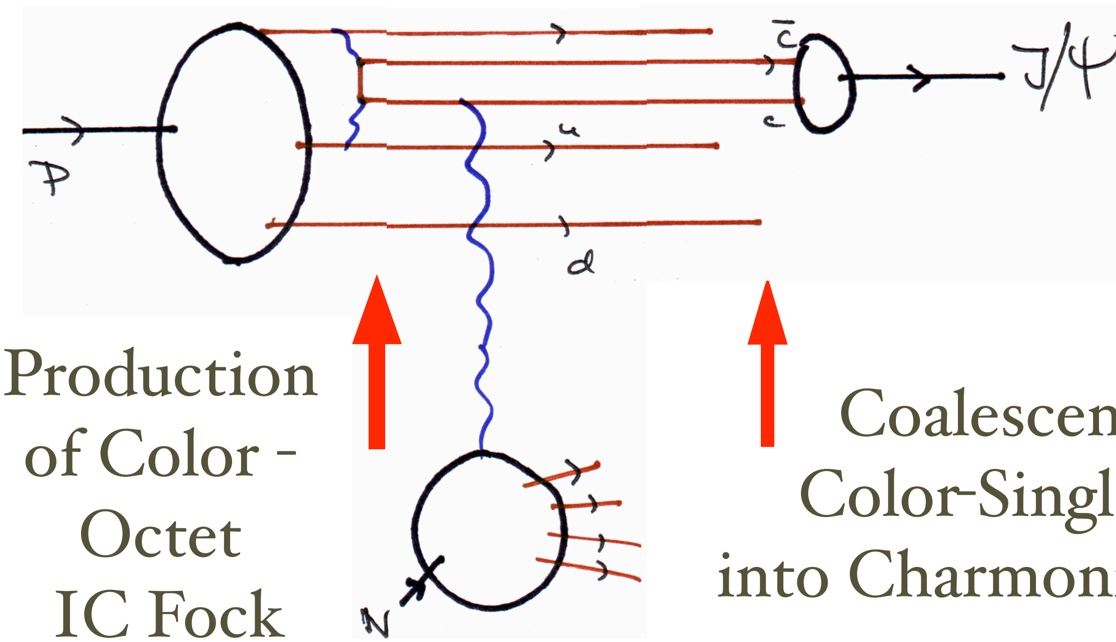
- Color Octet IC Explains $A^{2/3}$ behavior at high x_F (NA3, Fermilab) (Kopeliovitch, Schmidt, Soffer, SJB)

Color Opaqueness

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

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

Higgs production at x_F = 0.8



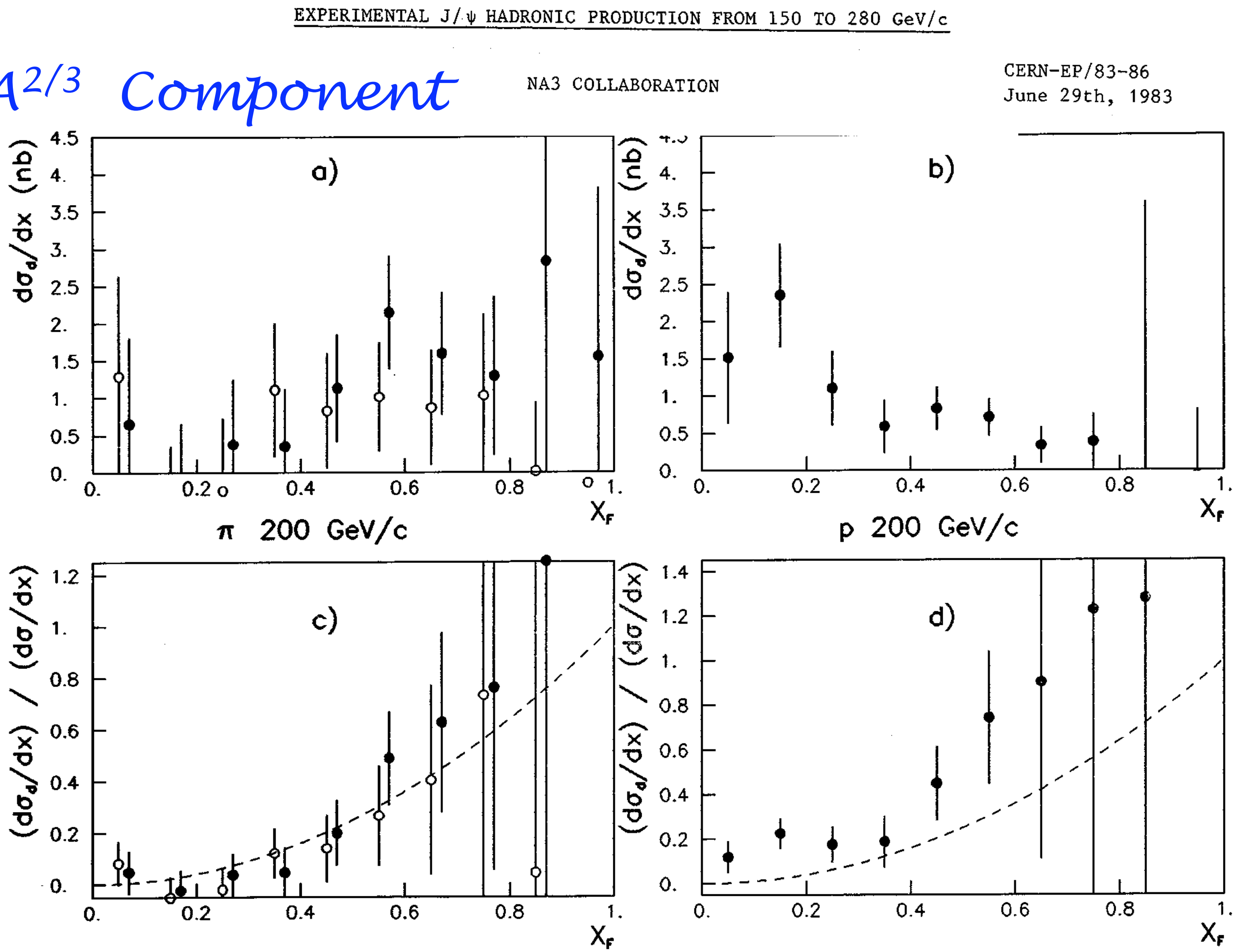
Production of Color - Octet IC Fock State

Coalescence of Color-Singlet Pair into Charmonium State

Scattering on Nucleon via one Gluon

In nuclear case,
IC Fock state absorbed on front surface

$A^{2/3}$ Component



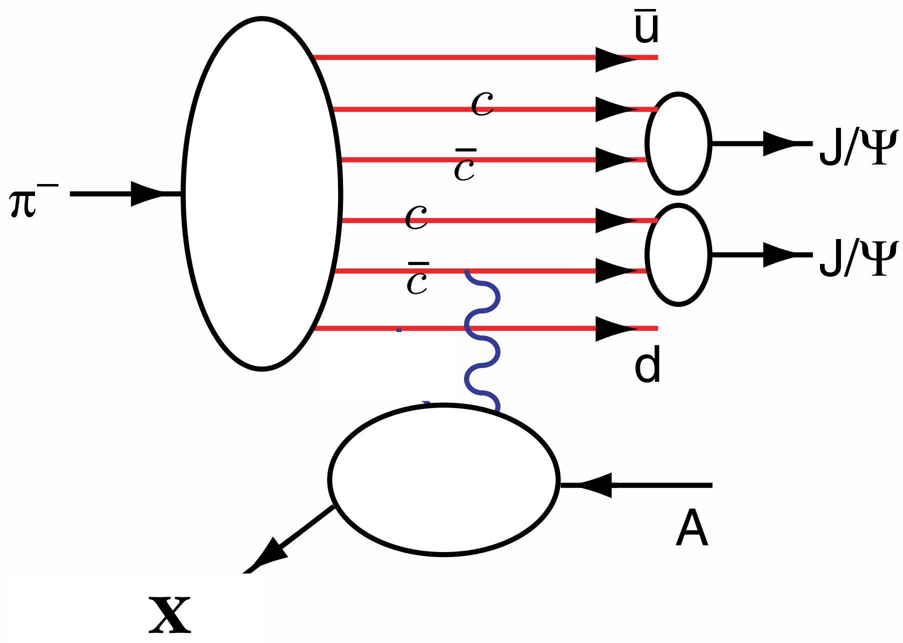
Nuclear Dependence of Quarkonium Production

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!

Production of Two Charmonia at High x_F



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

Excludes color drag model

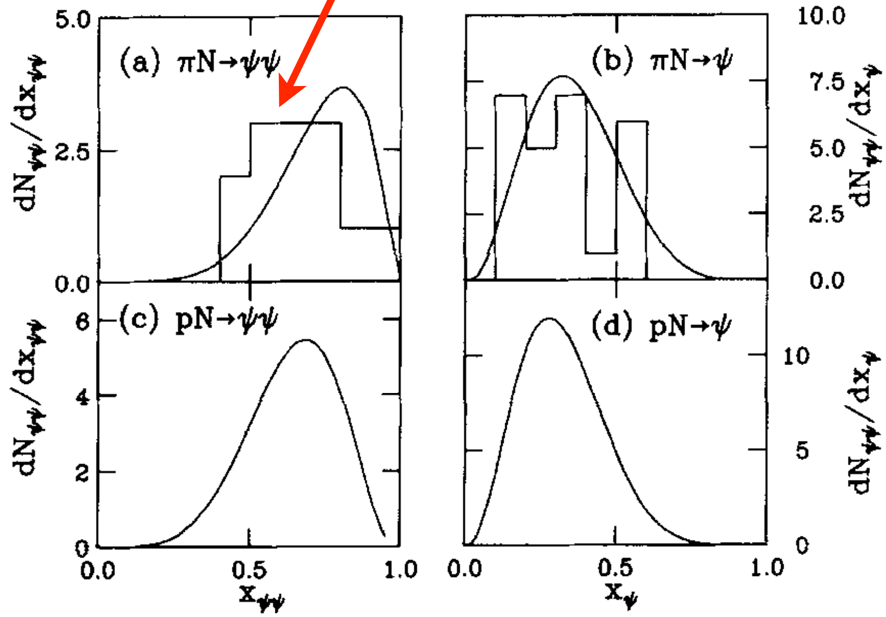


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized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

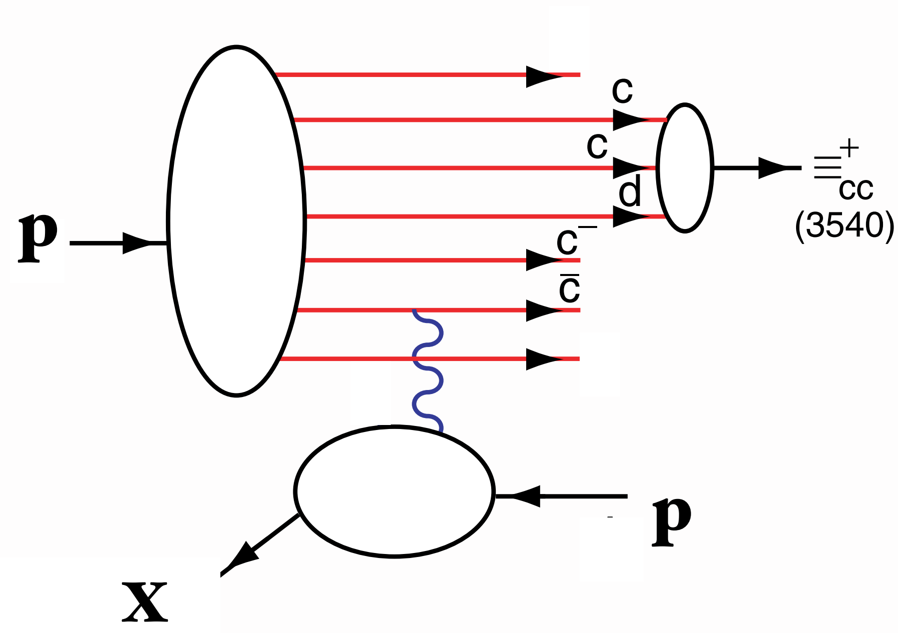
$$\pi A \to J/\psi J/\psi X$$

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 k_T written as

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

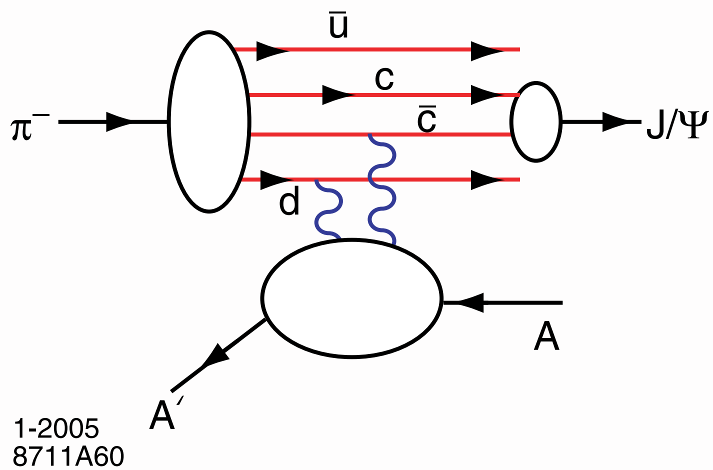


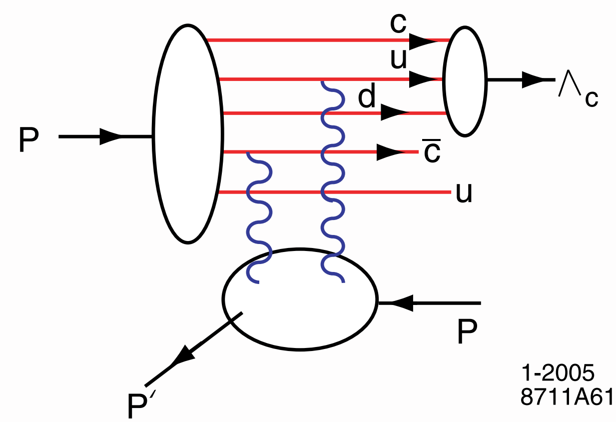
Production of a Double-Charm Baryon

LHCb high x_F

Also: Charm-Bottom Hadrons, ...

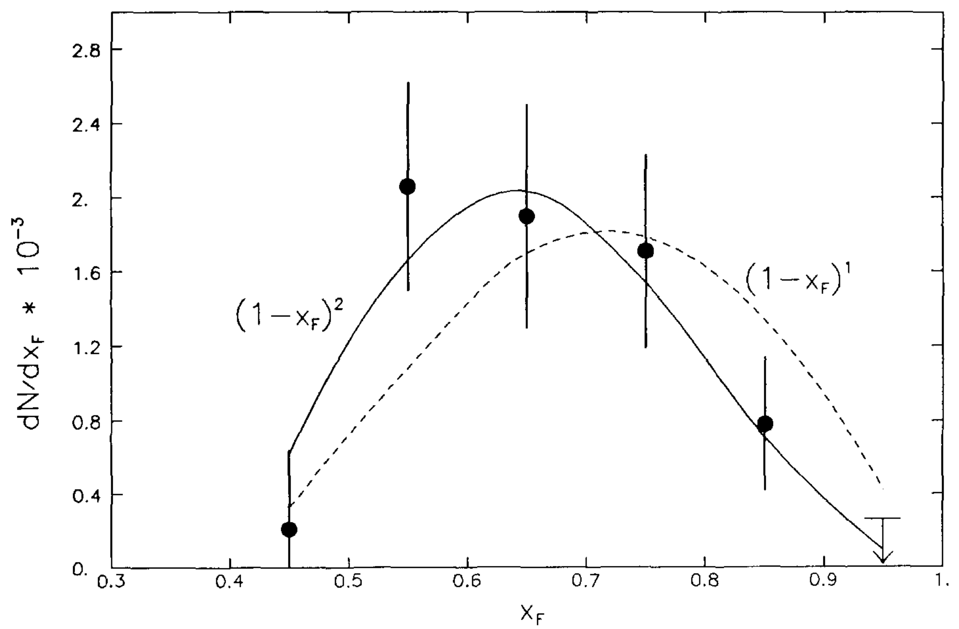
Diffractive Dissociation of Intrinsic Charm





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

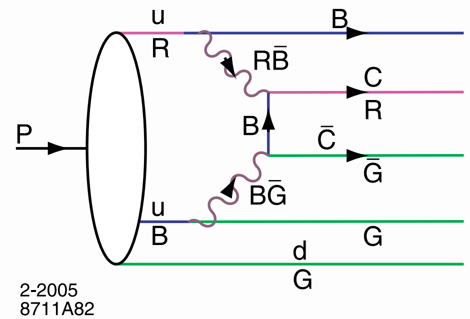
Diffractive Production of Charm Hadrons at the ISR



P. M. Chauvat et al. [R608 Collaboration],
"Production of Λ_C With Large x_F At The ISR,"
Phys. Lett. B 199, 304 (1987).
$pp \to p\Lambda_C X$

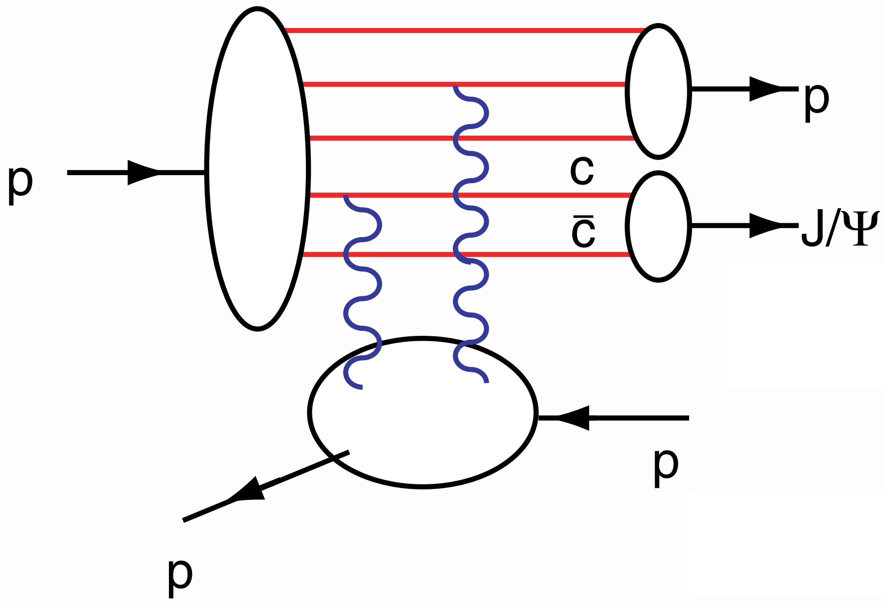
Hoyer, Peterson, Sakai, sjb

Intrinsic Heavy-Quark Fock States



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

Intrinsic Charm Mechanism for Exclusive Diffraction Production



$$pp \to p + J/\psi + p$$

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

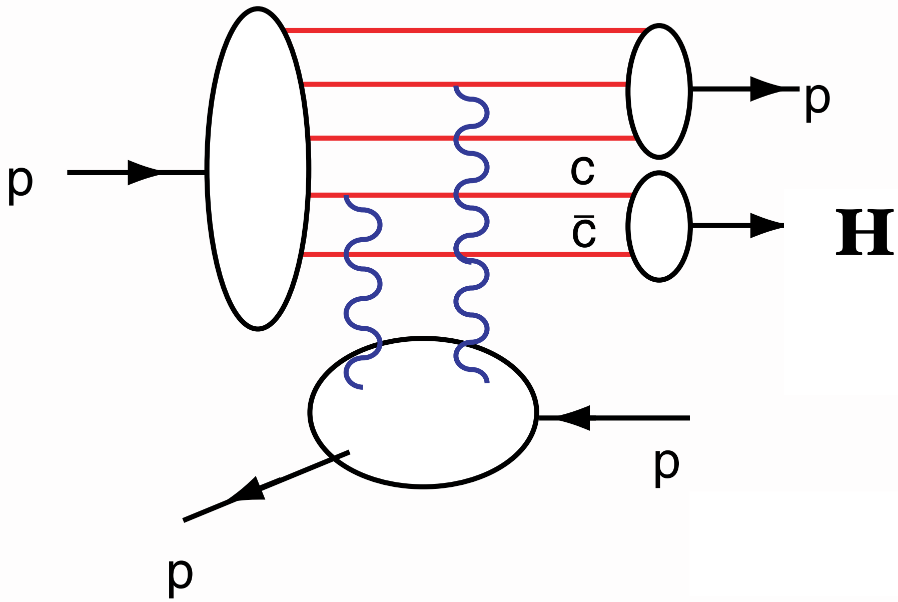
Kopeliovitch, Schmidt, Soffer, sjb

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 Diffractive High-X_F Higgs Production



$$pp \to p + H + p$$

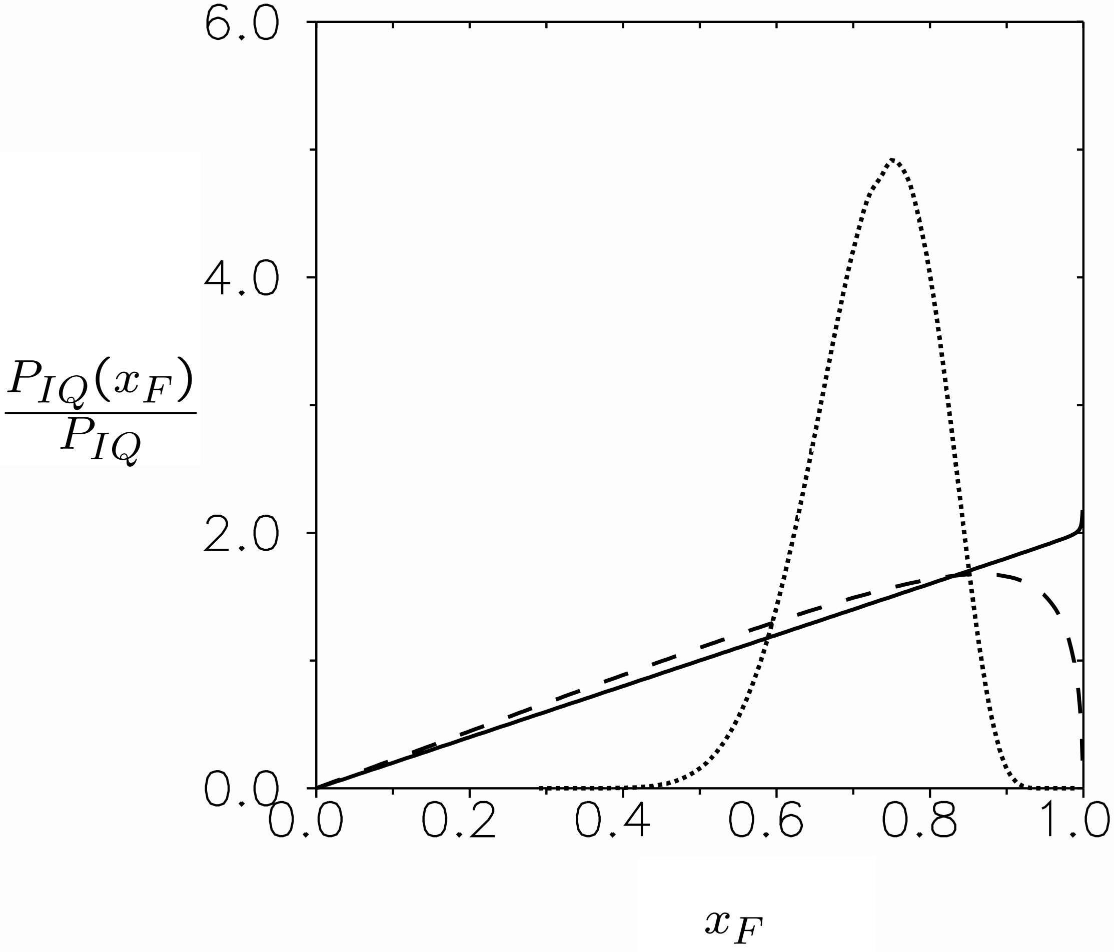
Also: intrinsic bottom, top

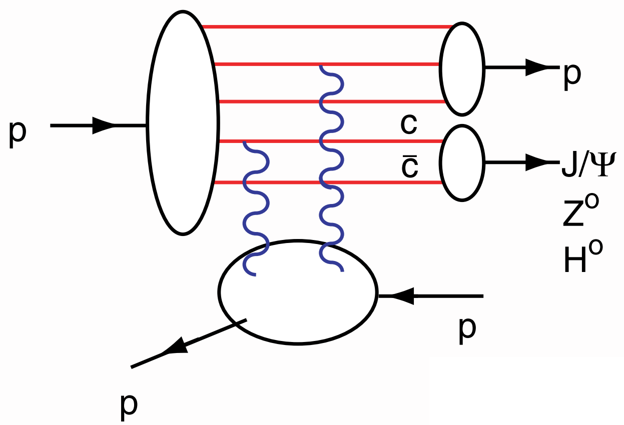
Kopeliovitch, Schmidt, Soffer, sjb

Higgs can have 80% of Proton Momentum!

RHIC Experiment

Intrinsic Charm Mechanism for Exclusive Diffraction Production



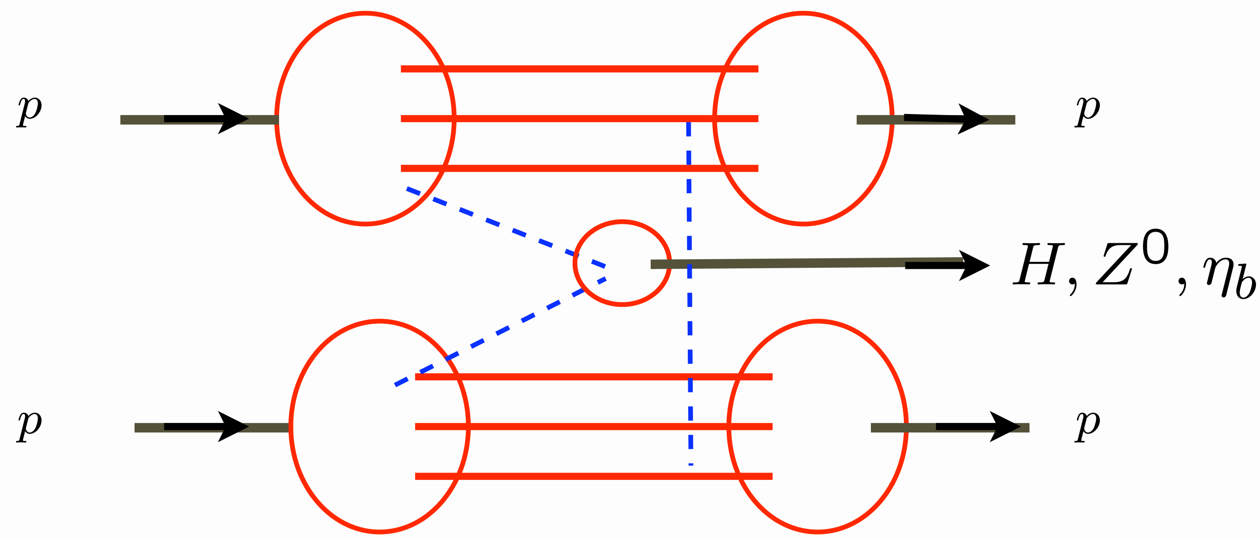


Kopeliovitch, Schmidt, Soffer, sjb

Doubly diffractive Higgs production

$$pp \to p + H + p$$

Nucleus-Nucleus at the LHC



De Roeck, V.A. Khoze, A.D.Martin, R.Orava M.G.Ryskin,

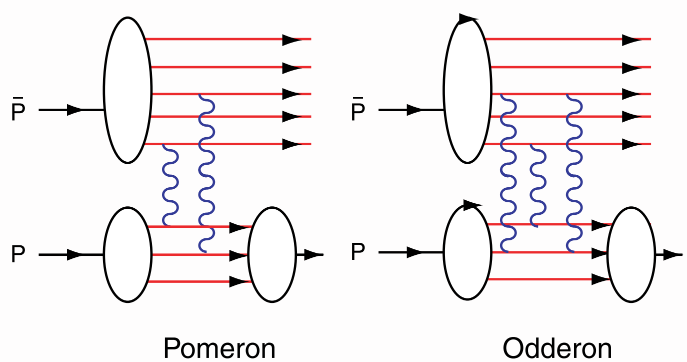
“Dangling Gluons”

- Diffractive DIS
- Non-Unitary Correction to DIS: Structure functions are not probability distributions
- Nuclear Shadowing, Antishadowing
- Single Spin Asymmetries -- opposite sign in DY and DIS
- DY $\cos 2\phi$ correlation at leading twist from double ISI-- not given by standard PQCD factorization
- Wilson Line Effects persist even in LCG
- Must correct hard subprocesses for initial and final-state soft gluon attachments -- Ji gauge link, Kovchegov gauge

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 $\gamma p \to c\bar{c}p$ — *e-p collider test*
- Analogous to lepton energy and angle asymmetry $\gamma Z \to e^+e^-Z$
- Pion Asymmetry in $\gamma p \to \pi^+\pi^- p$



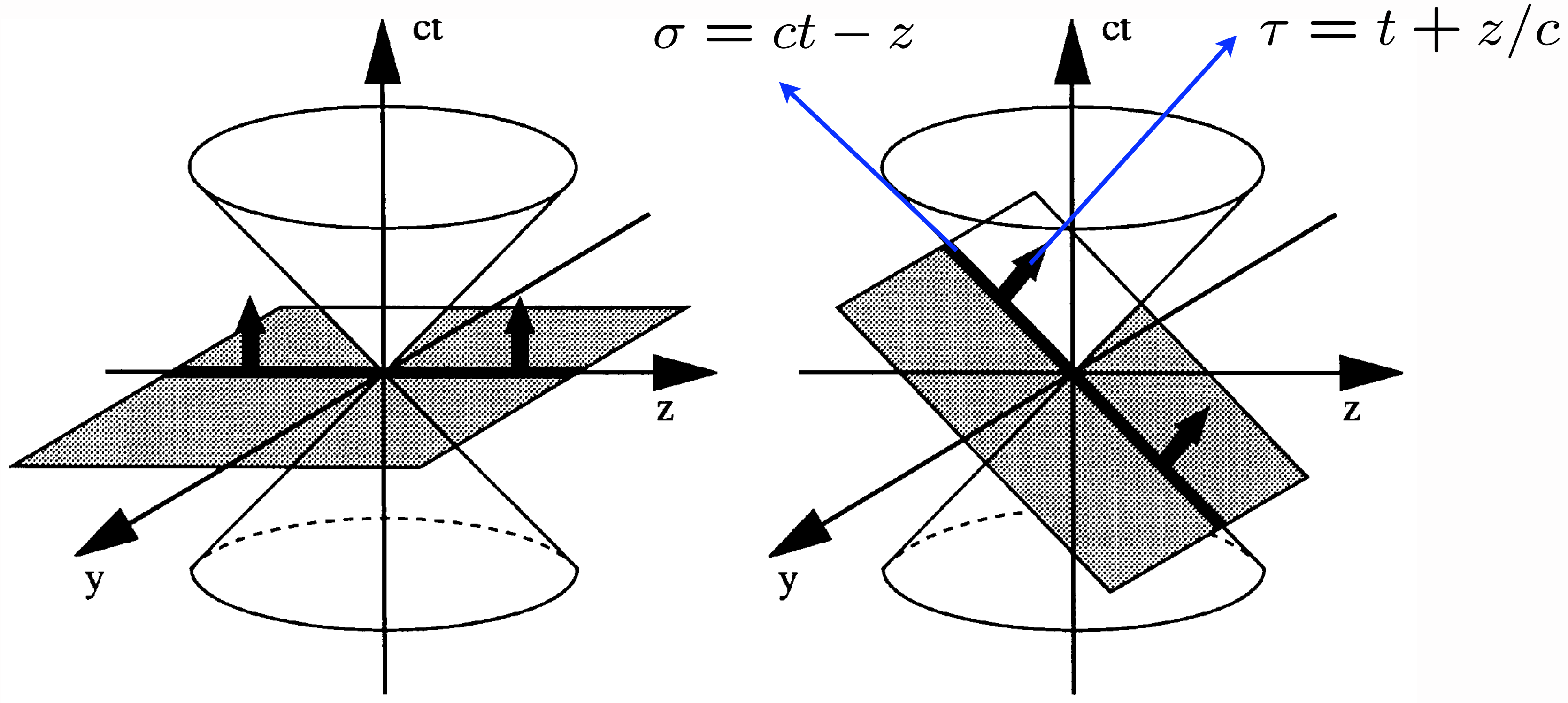
Odderon: Another source of antishadowing

Hadron Dynamics at the Amplitude Level

- LFWFS are the universal hadronic amplitudes which underlie structure functions, GPDs, exclusive processes.
- Relation of spin, momentum, and other distributions to physics of the hadron itself.
- Connections between observables, orbital angular momentum
- Role of FSI and ISIs--Sivers effect

Dirac's Amazing Idea: The "Front Form"

Evolve in light-front time!



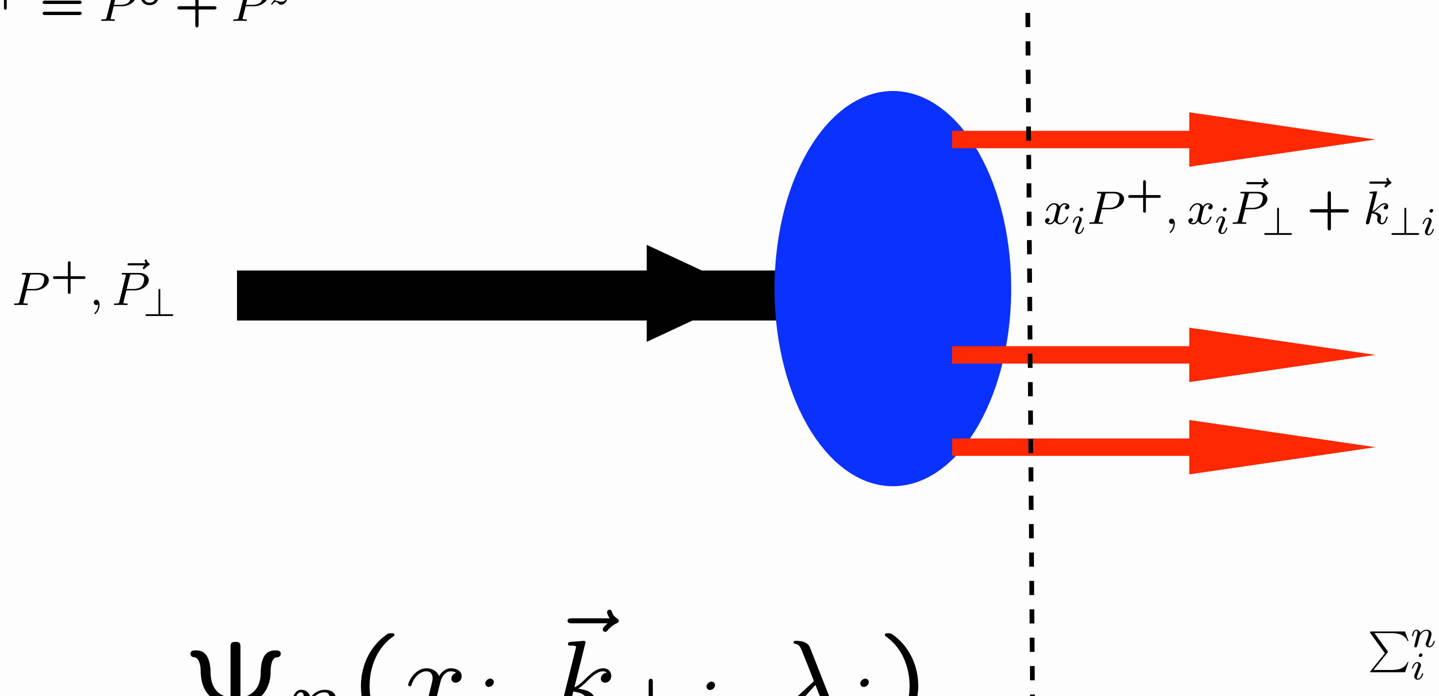
Instant Form

Front Form

Light-Front Wavefunctions

Fixed $\tau = t + z/c$

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



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

$\sum_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

Light-Front Wavefunctions

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

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

Invariant under boosts. Independent of P^μ $\quad x_i = \frac{k_i^+}{P^+}$

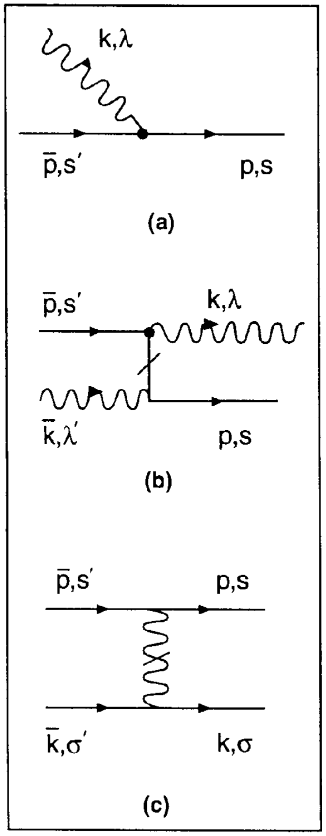
$$H_{LF}^{QCD}|\psi> = M^2|\psi>$$

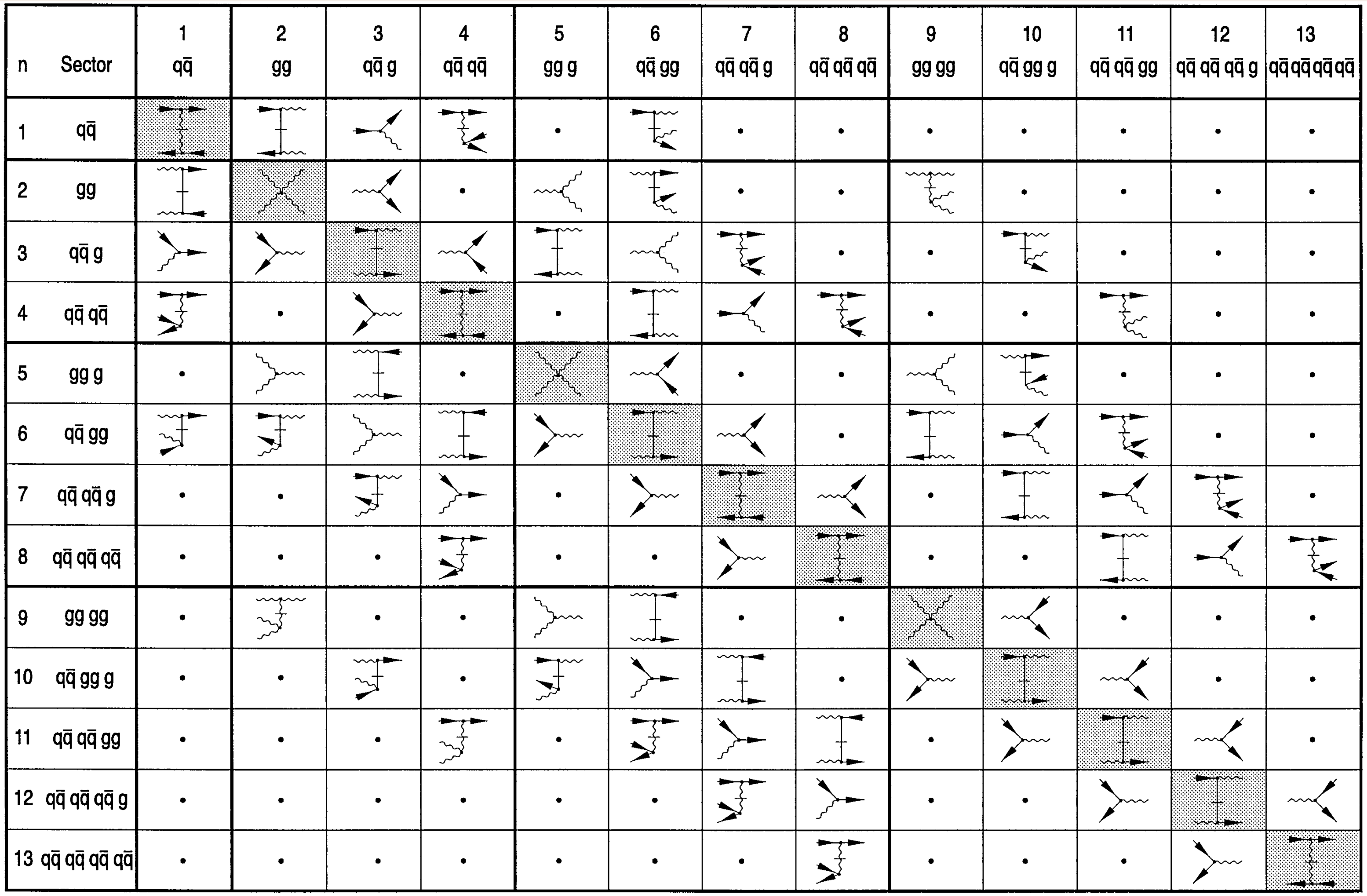
Remarkable new insights from AdS/CFT, the duality between conformal field theory and Anti-de Sitter Space

Light-Front QCD Heisenberg Equation

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

DLCQ





Use AdS/QCD basis functions

Pauli, Pinsky, sjb

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

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

The Light Front Fock State Wavefunctions

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

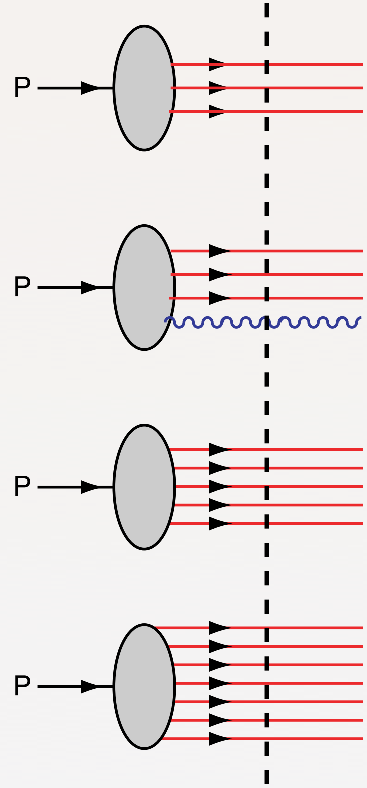
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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

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

Montgomery

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

Angular Momentum on the Light-Front

A^+=0 gauge: No unphysical degrees of freedom

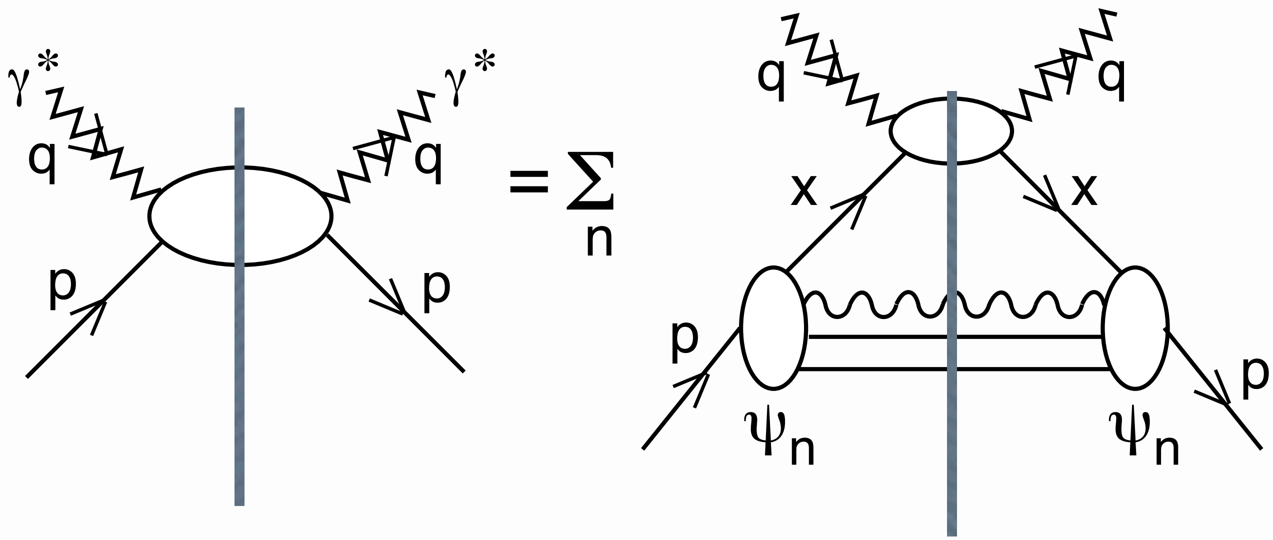
$$J^z = \sum_{i=1}^{n} s_i^z + \sum_{j=1}^{n-1} l_j^z.$$

Conserved
LF Fock state by Fock State

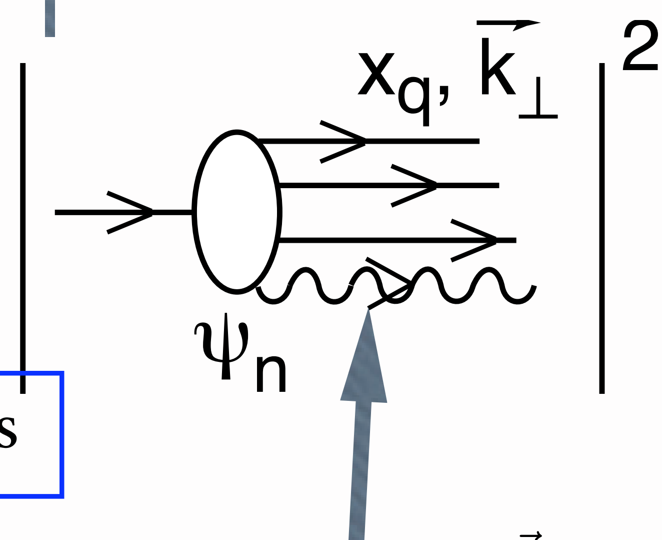
$$l_j^z = -\mathrm{i}\left(k_j^1 \frac{\partial}{\partial k_j^2} - k_j^2 \frac{\partial}{\partial k_j^1}\right)$$

n-1 orbital angular momenta

Deep Inelastic Lepton Proton Scattering and LFWFs



Imaginary Part of
Forward Virtual Compton Amplitude



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

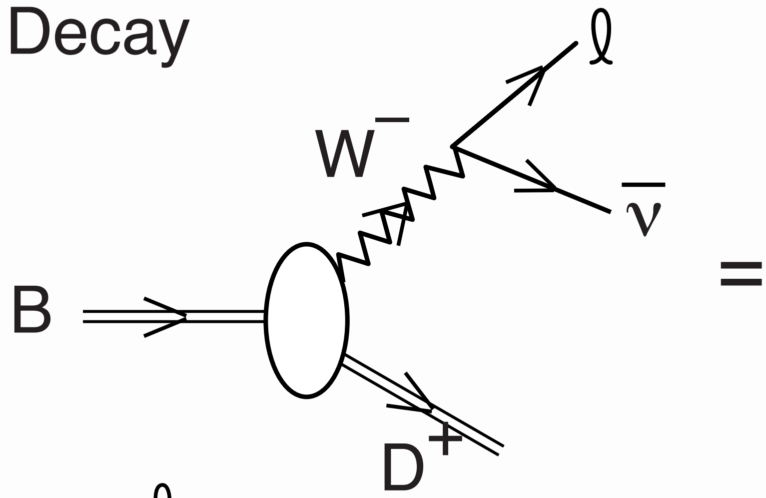
$x = x_q$

All spin, flavor distributions

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

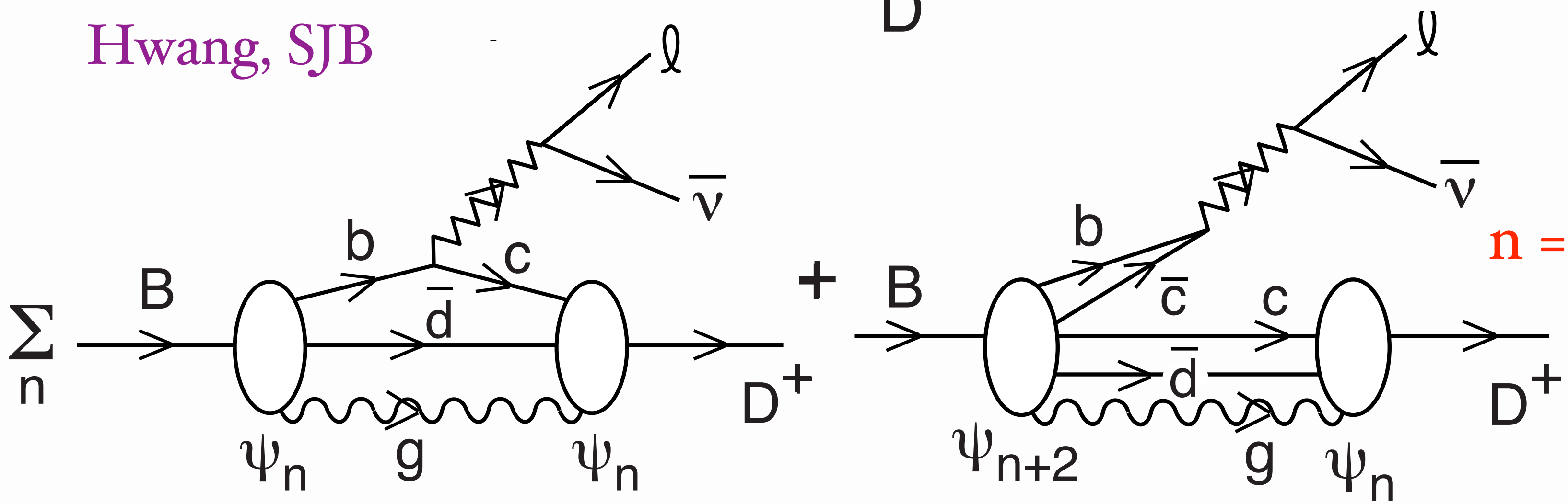
Weak Exclusive Decay

$\langle D \,|\, J^{+}(0) \,|\, B \rangle$



Exact Formula

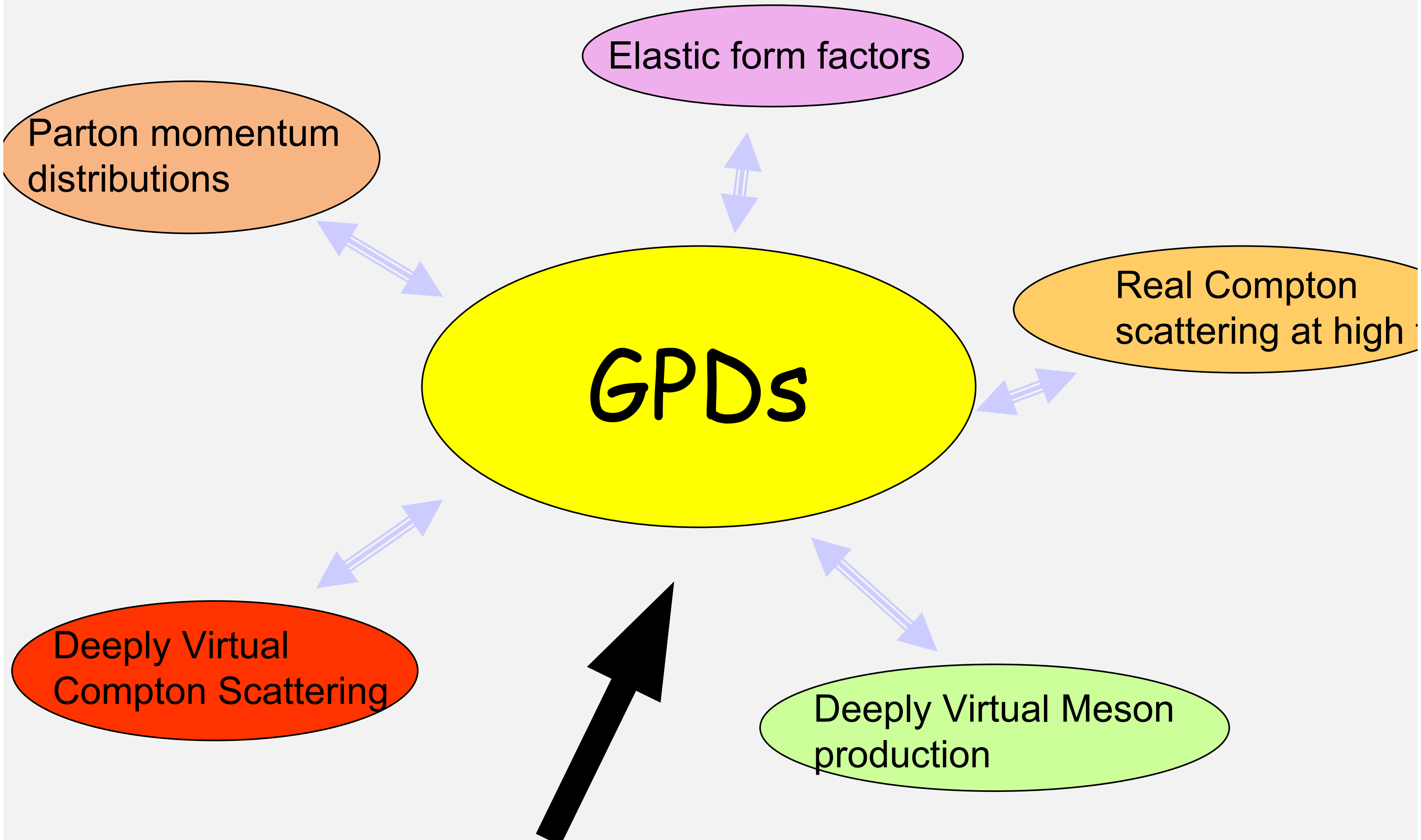
Hwang, SJB



$n = n' + 2$

Annihilation amplitude needed for Lorentz Invariance

A Unified Description of Hadron Structure

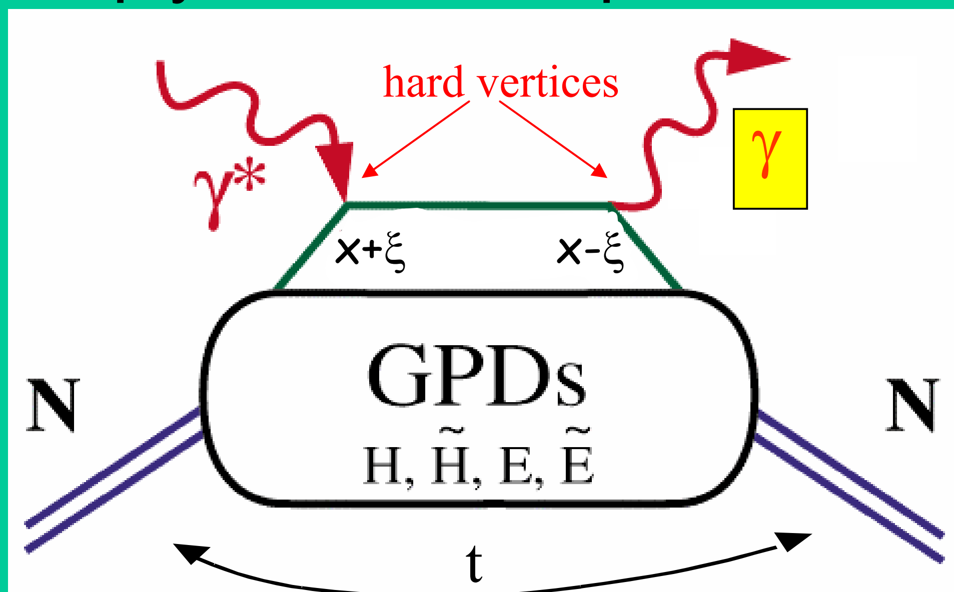


Light Front Wavefunctions

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,ξ,t), E(x,ξ,t), . .

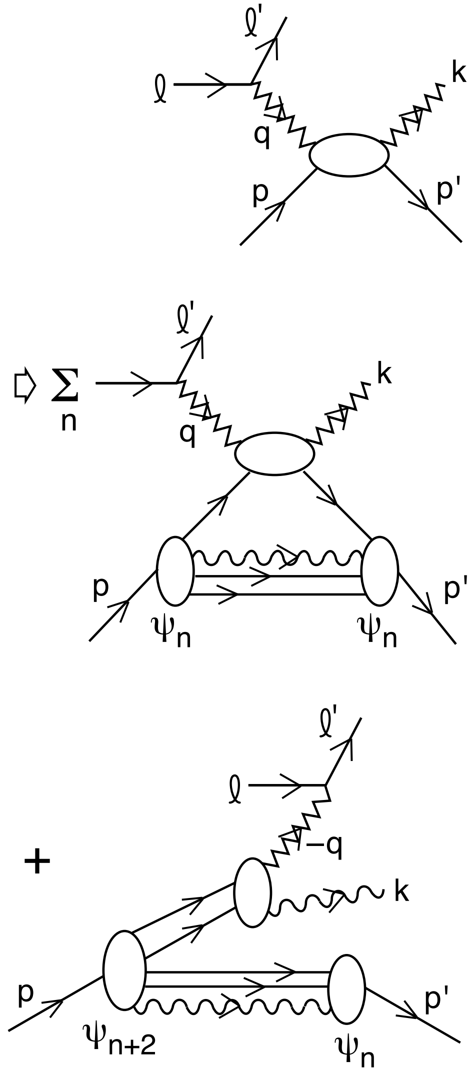
$$\xi = \frac{x_B}{2 - x_B}$$

$$\langle p'\,\lambda' |\, J^{\mu}(z)\, J^{\nu}(0)\, | p\,\lambda \rangle$$

$\text{Large} - q^2 = Q^2$

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

Deeply Virtual Compton Scattering



Given LFWFs, compute all GPDs !

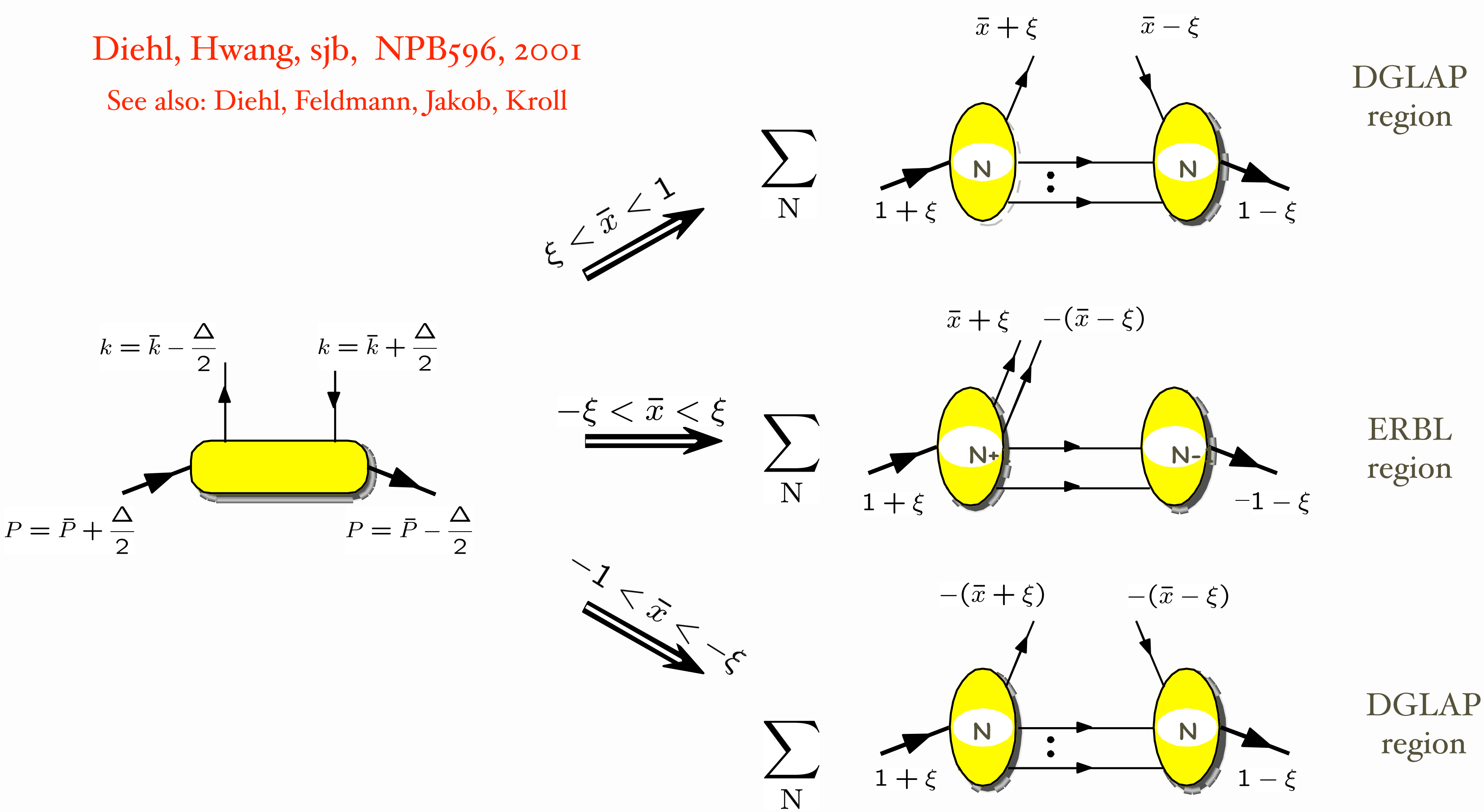
ERBL Evolution

n = n' + 2
Required for Lorentz Invariance

Light-Front Wave Function Overlap Representation

Diehl, Hwang, sjb, NPB596, 2001

See also: Diehl, Feldmann, Jakob, Kroll



N=3 VALENCE QUARK ⇒ Light-cone Constituent quark model

N=5 VALENCE QUARK + QUARK SEA ⇒ Meson-Cloud model

Pasquini

The Generalized Parton Distribution $E(x, \zeta, t)$

The generalized form factors in virtual Compton scattering $\gamma^*(q) + p(P) \to \gamma^*(q') + p(P')$ with $t = \Delta^2$ and $\Delta = P - P' = (\zeta P^+, \boldsymbol{\Delta}_\perp, (t + \boldsymbol{\Delta}_\perp^2)/\zeta P^+)$, have been constructed in the light-front formalism. [Brodsky, Diehl, Hwang, 2001]

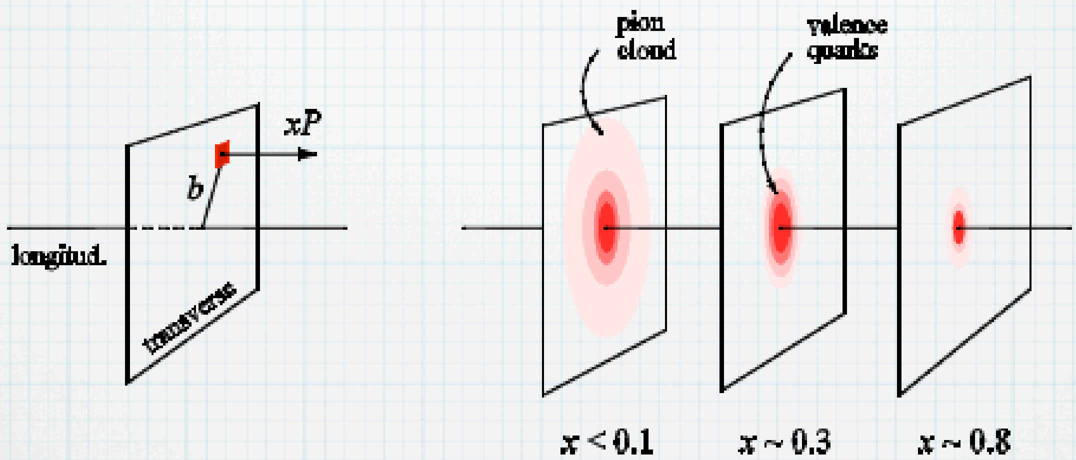
We find, under $\boldsymbol{q}_\perp \to \boldsymbol{\Delta}_\perp$, for $\zeta \le x \le 1$,

$$\frac{E(x, \zeta, 0)}{2M} = \sum_a (\sqrt{1-\zeta})^{1-n} \sum_j \delta(x - x_j) \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp] \times \psi_a^*(x_i', \mathbf{k}_{\perp i}, \lambda_i) \mathbf{S}_\perp \cdot \mathbf{L}_\perp^{\mathbf{q_j}} \psi_a(x_i, \mathbf{k}_{\perp i}, \lambda_i) \, ,$$

with $x_j' = (x_j - \zeta)/(1-\zeta)$ for the struck parton j and $x_i' = x_i/(1-\zeta)$ for the spectator parton i.

The E distribution function is related to a $\mathbf{S}_\perp \cdot \mathbf{L}_\perp^{\mathbf{q_j}}$ matrix element at finite ζ as well.

Can obtain 3D image of proton



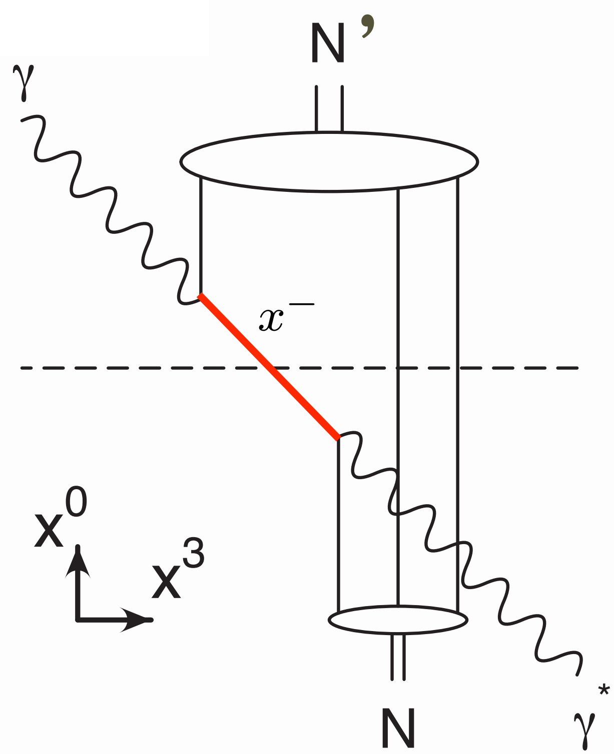
find distributions of quarks w.r.t. longitudinal momentum x P and transverse position b

We can also Fourier transform the skewness distribution

Space-time picture of DVCS

P. Hoyer

$\sigma = \frac{1}{2}x^- P^+$

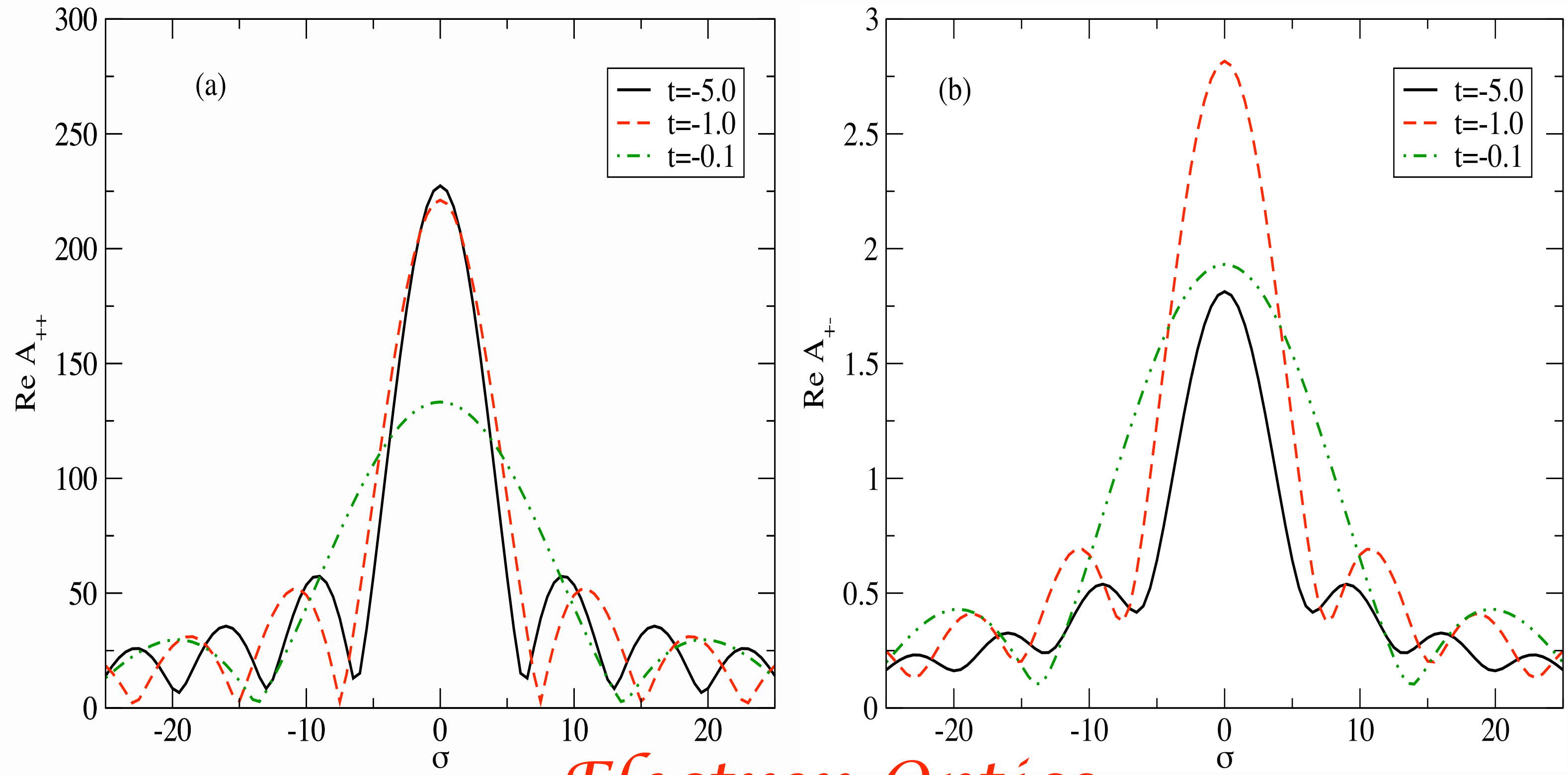


$x^+ = \mathbf{x}_\perp = 0$

The position of the struck quark differs by x^- in the two wave functions

Determine x- distribution from FT of skewness, the longitudinal momentum transfer $\zeta = \frac{Q^2}{2p\cdot q}$

S. J. Brodsky[a], D. Chakrabarti[b], A. Harindranath[c], A. Mukherjee[d], J. P. Vary[e,a,f]



Electron Optics

Fourier spectrum of the real part of the DVCS amplitude of an electron vs. σ for $M = 0.51$ MeV, $m = 0.5$ MeV, $\lambda = 0.02$ MeV, (a) when the electron helicity is not flipped; (b) when the helicity is flipped. The parameter t is in MeV^2.

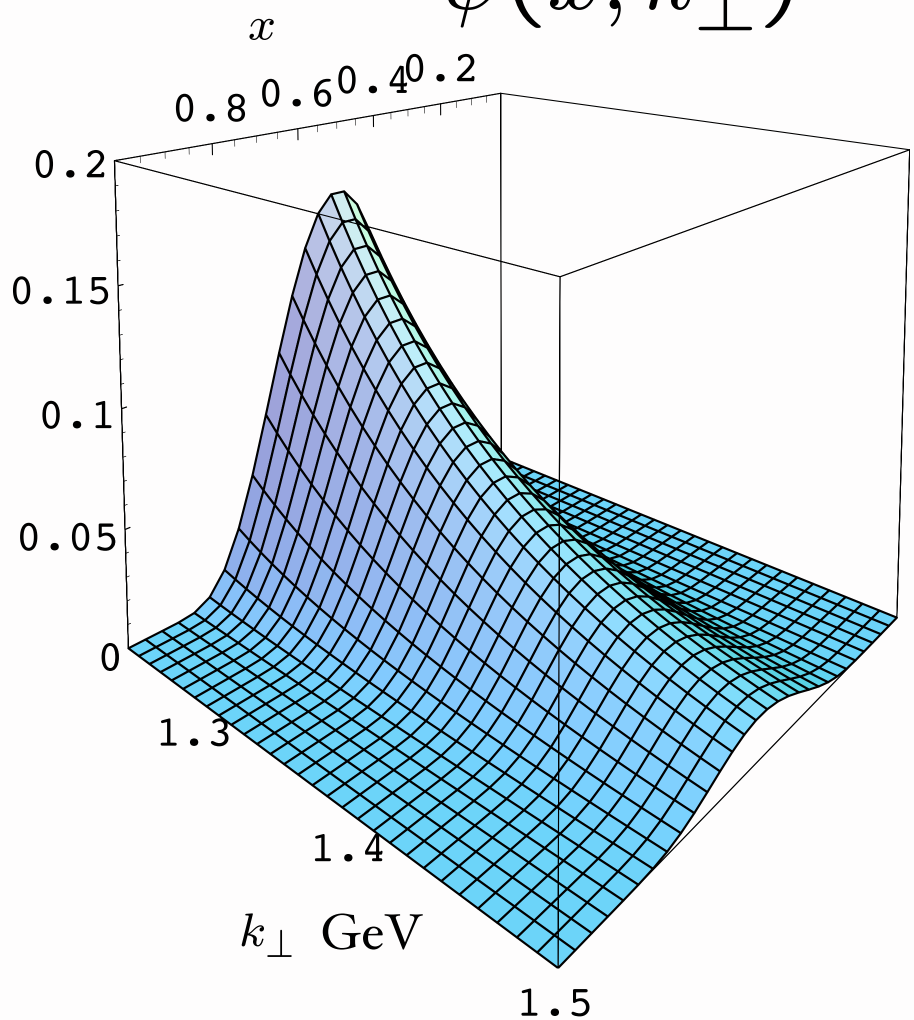
$$\sigma = \frac{1}{2} x^- P^+$$

$$A(\sigma, \Delta_\perp) = \frac{1}{2\pi} \int d\zeta e^{\frac{i}{2}\sigma\zeta} M(\zeta, \Delta_\perp)$$

$$\zeta = \frac{Q^2}{2p \cdot q}$$

Predictions from AdS/CFT
Pion LFWF

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



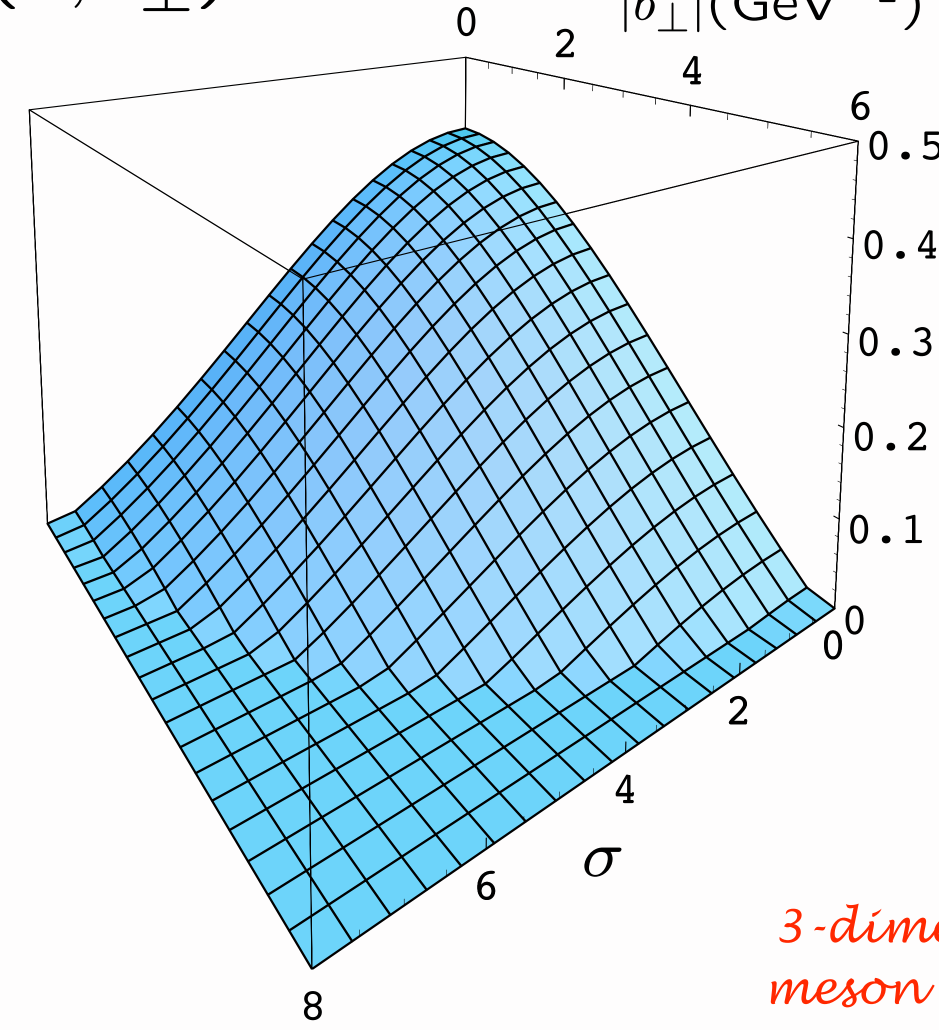
Harmonic Oscillator model

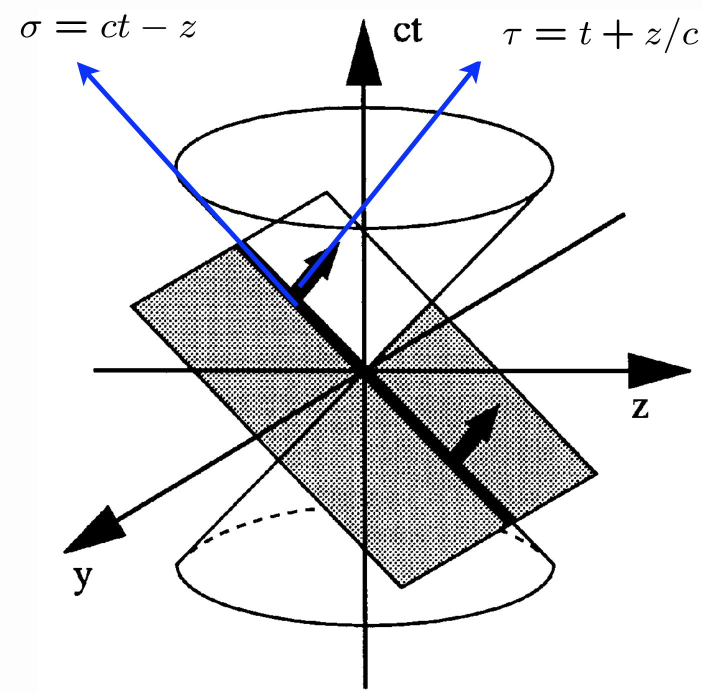
$\kappa = 0.77$GeV

AdS/CFT Holographic Model

G. de Teramond
SJB

$\psi(\sigma, b_\perp)$





The front form

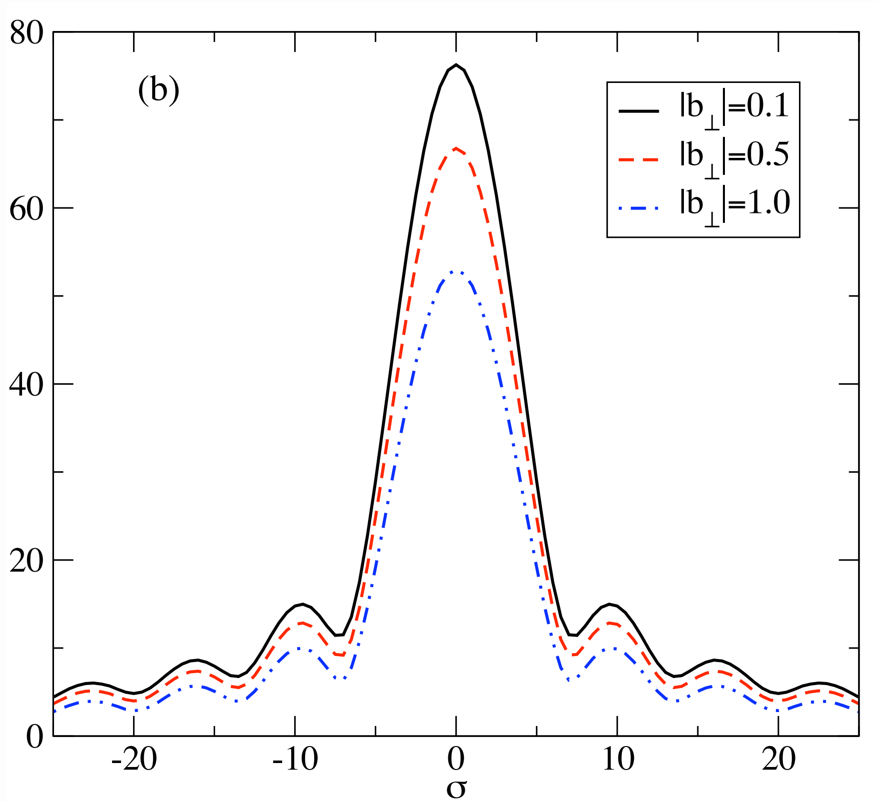
3-dimensional photograph: meson LFWF at fixed LF Time

S. J. Brodsky[a], D. Chakrabarti[b], A. Harindranath[c], A. Mukherjee[d], J. P. Vary[e,a,f]

Hadron Optics

$$A(\sigma, b_\perp) = \frac{1}{2\pi}\int d\zeta e^{i\sigma\zeta}\tilde{A}(b_\perp, \zeta)$$

$$\sigma = \tfrac{1}{2}x^- P^+ \qquad \zeta = \frac{Q^2}{2p\cdot q}$$

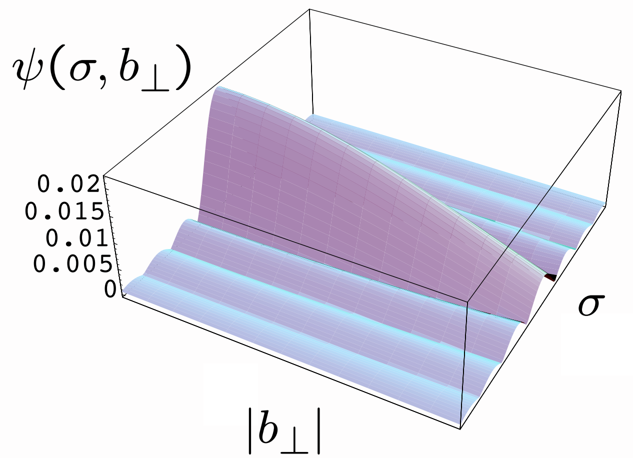


The Fourier Spectrum of the DVCS amplitude in σ space for different fixed values of $|b_\perp|$.

GeV units

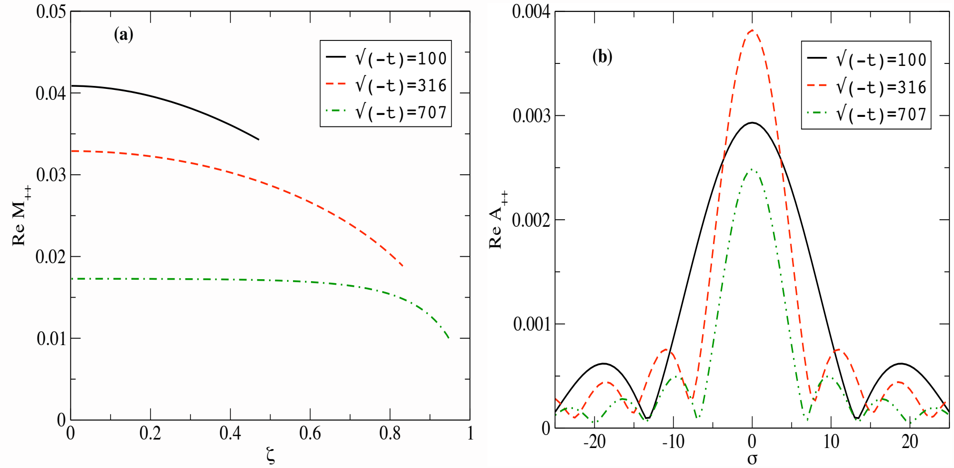
DVCS Amplitude using holographic QCD meson LFWF

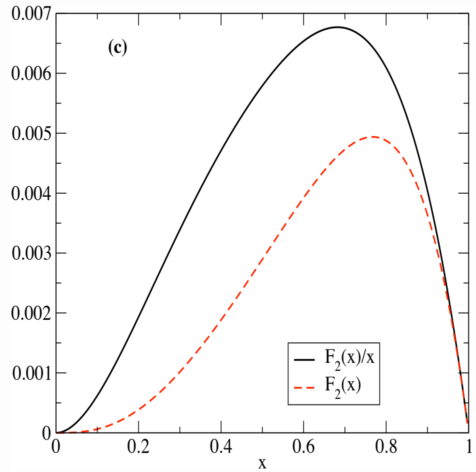
$$\Lambda_{QCD} = 0.32$$



S. J. Brodsky[a], D. Chakrabarti[b], A. Harindranath[c], A. Mukherjee[d], J. P. Vary[e,a,f]

Hadron Optics from the Fourier Transform of DVCS amplitudes





$$A(\sigma, \Delta_\perp) = \frac{1}{2\pi} \int d\zeta e^{\frac{i}{2}\sigma\zeta} M(\zeta, \Delta_\perp)$$

Real part of the DVCS amplitude for the simulated meson-like bound state. The parameters are $M = 150, m = \lambda = 300$ MeV. (a) Helicity non-flip amplitude vs. ζ, (b) Fourier spectrum of the same vs. σ, (c) Structure function vs. x. The parameter t is in MeV^2.

LFWFS provide a fundamental description of hadron observables

- LFWFS underly structure functions and generalized parton distributions.
- Parton number not conserved: n=n' & n=n'+2 at nonzero skewness
- GPDs are not densities or probability distributions
- Nonperturbative QCD: Lattice, DLCQ, Bethe-Salpeter, AdS/CFT

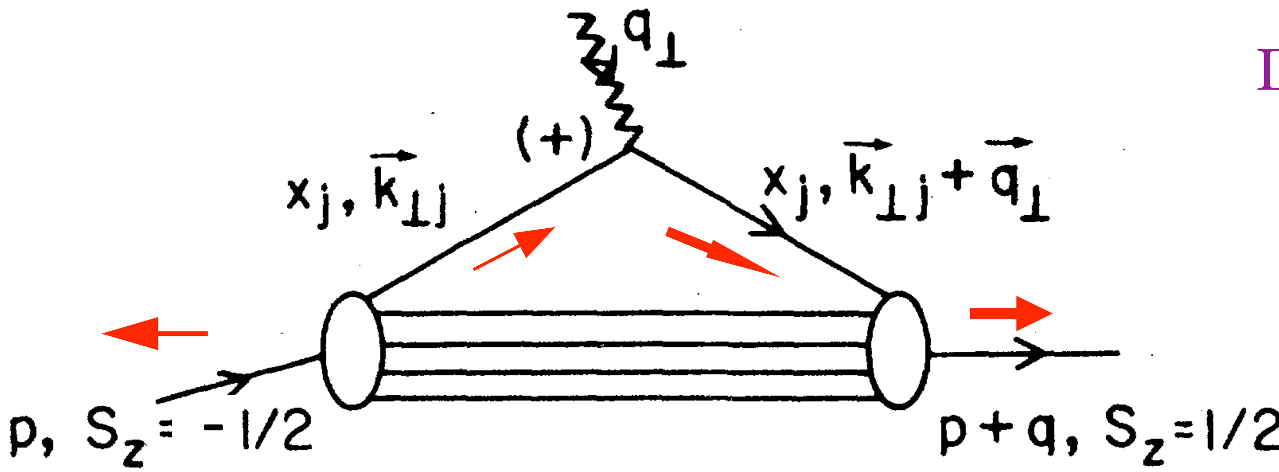
Exact formula for Pauli Form Factor

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

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

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

Drell, sjb



Must have $\Delta L_z = \pm 1$ to have nonzero F_2

LFWFs of Electron (n=2)

$J_z = +\frac{1}{2}$

Gives Schwinger Anomalous Moment $\frac{\alpha}{2\pi}$

$$\left\{\begin{array}{l}
\psi^{\uparrow}_{+\frac{1}{2}\,+1}(x,\vec{k}_{\perp}) = -\sqrt{2}\frac{(-k^1+ik^2)}{x(1-x)}\,\varphi\ , \\
\psi^{\uparrow}_{+\frac{1}{2}\,-1}(x,\vec{k}_{\perp}) = -\sqrt{2}\frac{(+k^1+ik^2)}{1-x}\,\varphi\ , \\
\psi^{\uparrow}_{-\frac{1}{2}\,+1}(x,\vec{k}_{\perp}) = -\sqrt{2}(M-\frac{m}{x})\,\varphi\ , \\
\psi^{\uparrow}_{-\frac{1}{2}\,-1}(x,\vec{k}_{\perp}) = 0\ ,
\end{array}\right.$$

$L_z = -1$

$L_z = 1$

$L_z = 0$

where

$$\varphi = \varphi(x,\vec{k}_{\perp}) = \frac{e/\sqrt{1-x}}{M^2-(\vec{k}_{\perp}^2+m^2)/x-(\vec{k}_{\perp}^2+\lambda^2)/(1-x)}\ .$$

$M \to m + \lambda$

Spin-1 mass λ

Spin-1/2 mass m

$$\left\{\begin{array}{l}
\psi^{\downarrow}_{+\frac{1}{2}\,+1}(x,\vec{k}_{\perp}) = 0\ , \\
\psi^{\downarrow}_{+\frac{1}{2}\,-1}(x,\vec{k}_{\perp}) = -\sqrt{2}(M-\frac{m}{x})\,\varphi\ , \\
\psi^{\downarrow}_{-\frac{1}{2}\,+1}(x,\vec{k}_{\perp}) = -\sqrt{2}\frac{(-k^1+ik^2)}{1-x}\,\varphi\ , \\
\psi^{\downarrow}_{-\frac{1}{2}\,-1}(x,\vec{k}_{\perp}) = -\sqrt{2}\frac{(+k^1+ik^2)}{x(1-x)}\,\varphi\ .
\end{array}\right.$$

Drell, sjb

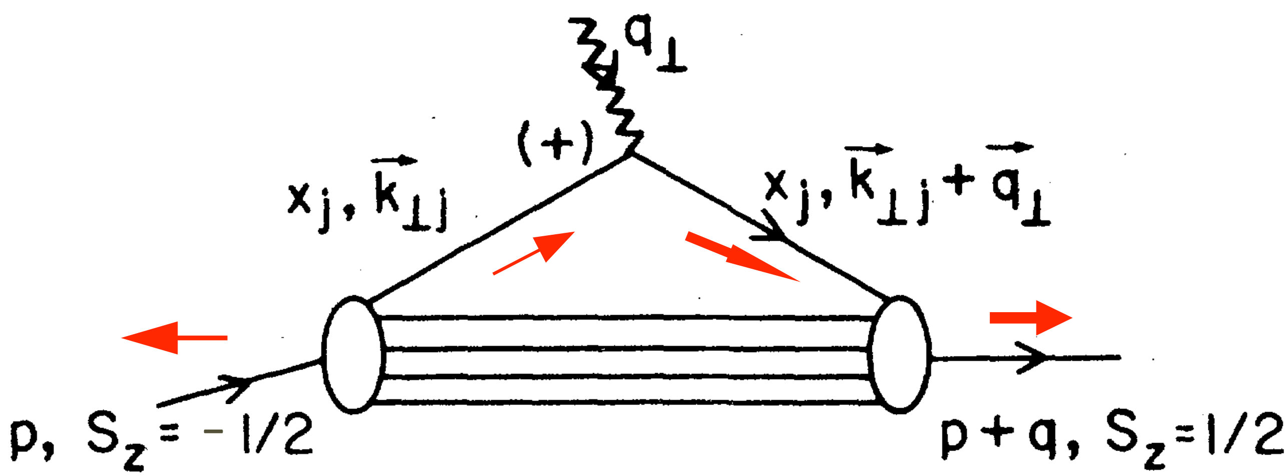
Hwang, Schmidt, sjb

Anomalous gravitomagnetic moment B(o)

Equivalence theorem: B(o)=o

graviton

sum over constituents



B(0) = 0

Each Fock State

Anomalous moment and charge radius determines the orbital angular momentum of quarks in the proton

Use charge radius $R^2 = -6F_1'(0)$ and anomalous moment $\kappa = F_2(0)$

to determine $< L_z^2 >_q \sim 0.15.$

C. E. Carlson and sjb

$SU(6)$ symmetry: $u^\uparrow :: u^\downarrow :: d^\uparrow :: d^\downarrow = 5/3 :: 1/3 :: 1/3 :: 2/3.$

$S^z = 1/2, L^z = 0$ $\qquad$ $S^z = -1/2, L^z = +1$

$< L_z^2 >_d = 2 < L_z^2 >_u$ $\qquad$ $< L_z^2 >_d = 2/9, < L_z^2 >_u = 1/9$ $\qquad$ $< L_z^2 >_q = 1/3$

If the valence state has a 45% probability, and the higher Fock states have no orbital angular momentum

$< L_z^2 >_q = 0.15.$

$< L_z^2 >_d = 0.10, < L_z^2 >_u = 0.05.$

(Reversed for the neutron.)

CP-violating phase

$$F_3(q^2) = F_2(q^2) \times \tan\phi$$

Fock state by Fock state

Gardner, Hwang, sjb,

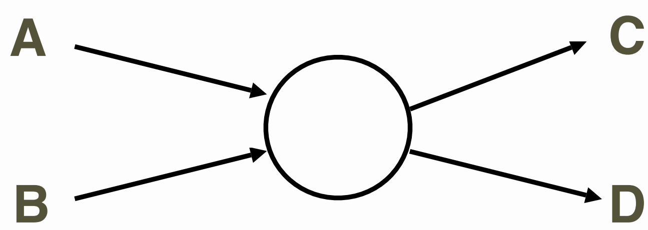
Advantages of Light-Front Quantization

- Frame independent; J_z kinematical
- Minkowski space; no fermion doubling
- Physical degrees of freedom; physical polarization
- Trivial vacuum; zero modes
- LF Quantization of Standard Model: Zero mode not vacuum expectation value
- **B(0) =0**; Exact formula for current matrix elements
- DLCQ; covariant truncation of Fock space
- LFWFs, spectra, physics at the amplitude level, phases\
- AdS/CFT predictions

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, Tri-Jet Production
- Nuclear Shadowing and Antishadowing
- Novel QCD Mechanism for Higgs Production

Constituent Counting Rules



$$\frac{d\sigma}{dt}(s,t) = \frac{F(\theta_{\rm cm})}{s^{[n_{\rm tot}-2]}} \qquad s = E^2_{\rm cm}$$

$$F_H(Q^2) \sim [\frac{1}{Q^2}]^{n_H-1} \qquad -t = Q^2$$

Farrar & sjb; Matveev et al

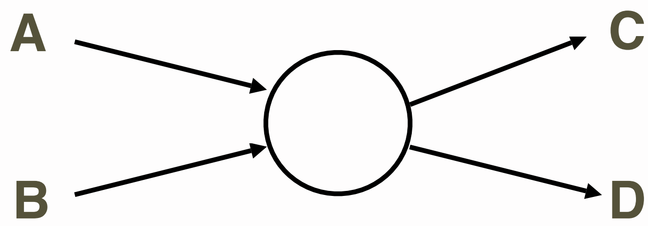
Conformal symmetry and PQCD predicts leading-twist power behavior

Characteristic scale of QCD: 300 MeV

Scaling cannot be postponed!

New J-PARC, GSI, J-Lab, Belle, Babar tests

Constituent Counting Rules



$$\frac{d\sigma}{dt}(s,t) = \frac{F(\theta_{\rm cm})}{s^{[n_{\rm tot}-2]}} \qquad s = E^2_{\rm cm}$$

$$F_H(Q^2) \sim [\frac{1}{Q^2}]^{n_H - 1} \qquad -t = Q^2$$

- Point-like quark and gluon constituents plus scale-invariant interactions

Farrar, sjb; Matveev et al

- Fall-off of Amplitude measures degree of compositeness (twist)
- Reflects near-Conformal Invariance of QCD
- PQCD: Logarithmic Modification by running coupling and ERBL Evolution

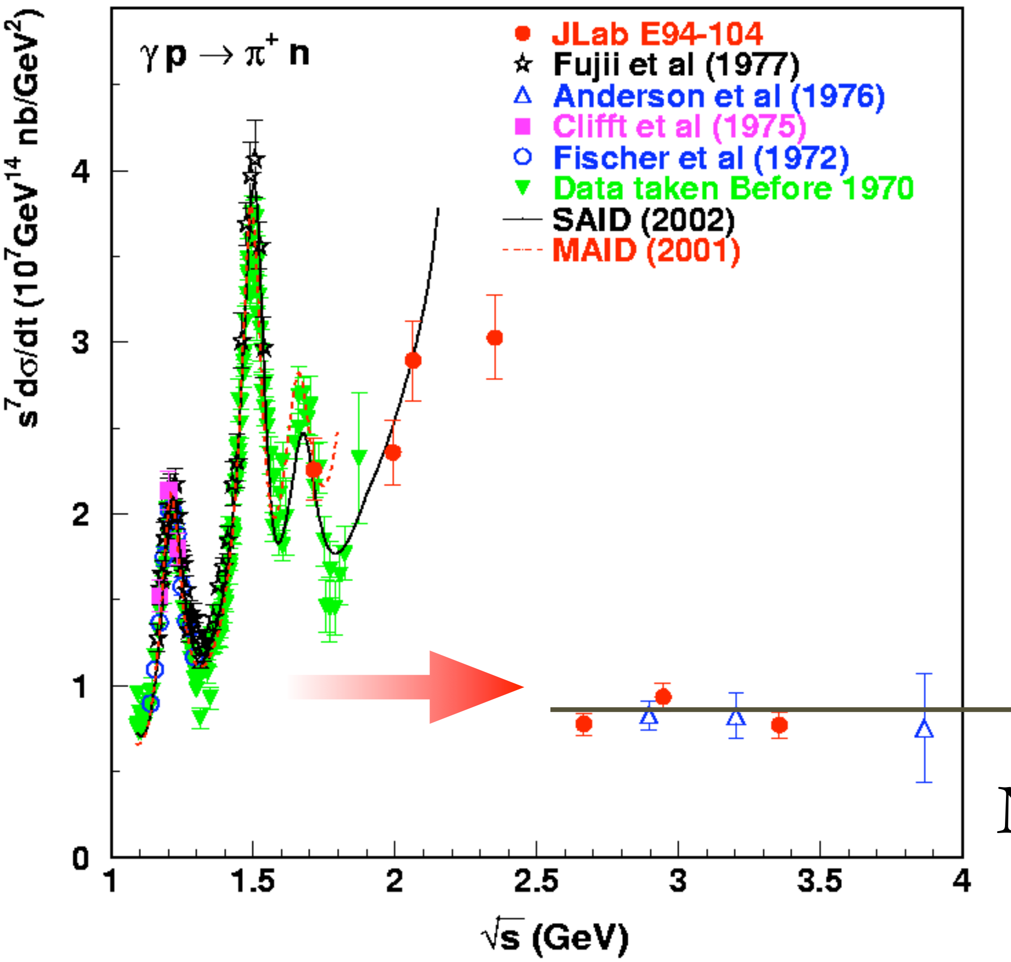
Lepage, sjb; Efremov, Radyushkin

- Angular and Spin Dependence -- Fundamental Wavefunctions: Hadron Distribution Amplitudes $\phi_H(x_i, Q)$

Test of PQCD Scaling

Constituent counting rules

Farrar, sjb; Muradyan, Matveev, Taveklidze



$s^7 d\sigma/dt(\gamma p \to \pi^+ n) \sim const$
fixed θ_{CM} scaling

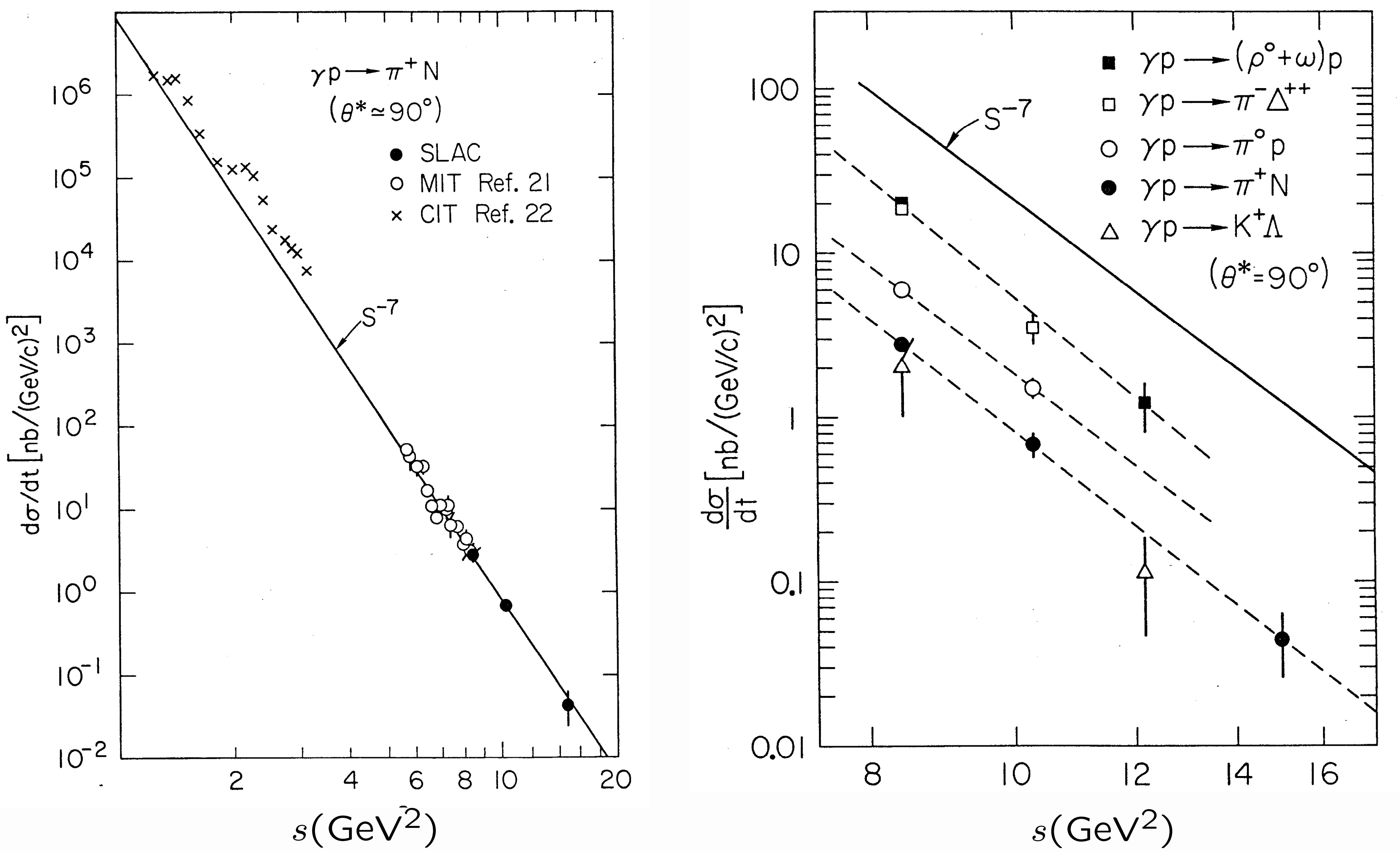
PQCD and AdS/CFT:

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

$s^7\frac{d\sigma}{dt}(\gamma p \to \pi^+ n) = F(\theta_{CM})$
$n_{tot} = 1+3+2+3 = 9$

No sign of running coupling

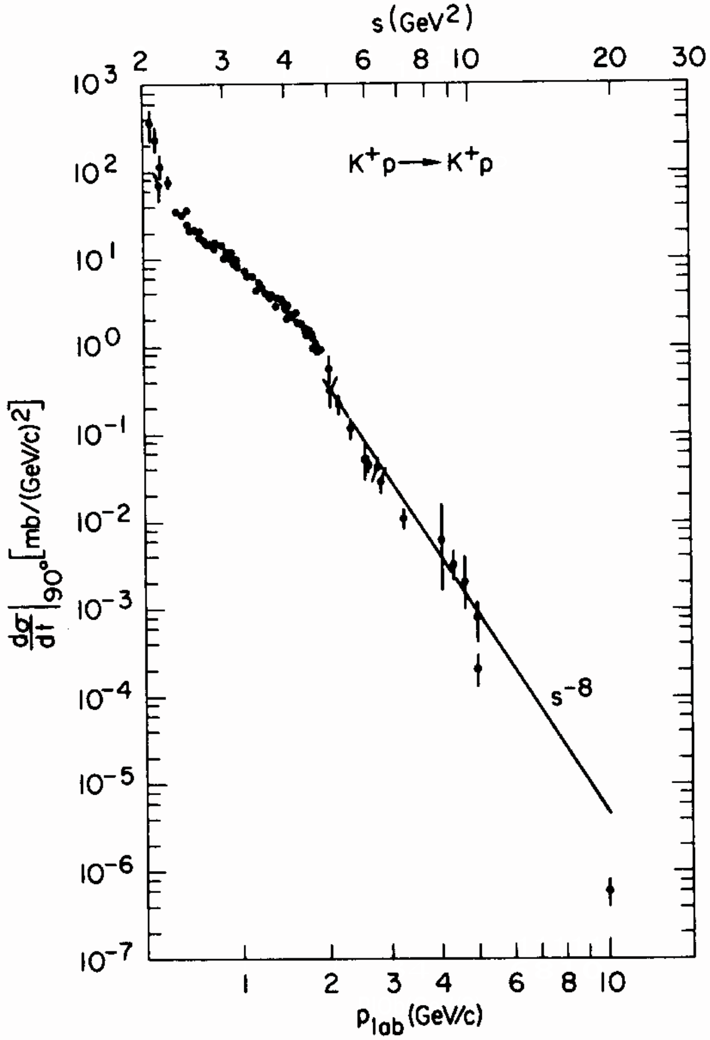
Conformal invariance at high momentum transfers!



Conformal Invariance:

$$\frac{d\sigma}{dt}(\gamma p \to MB) = \frac{F(\theta_{cm})}{s^7}$$

Quark-Counting

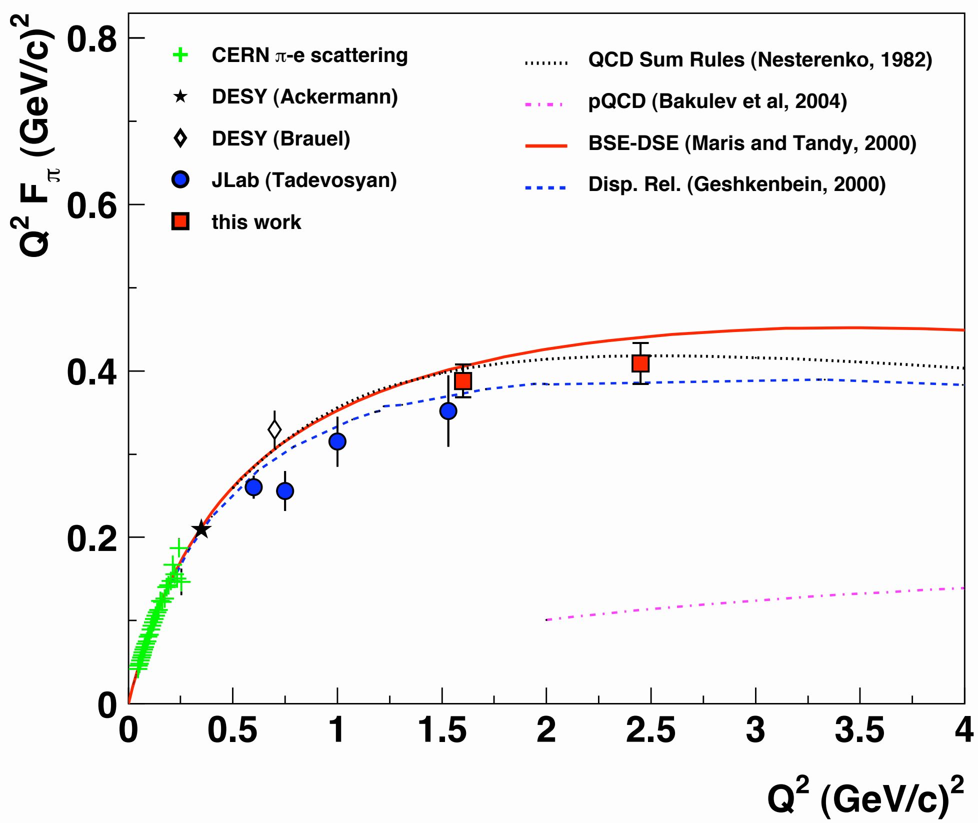


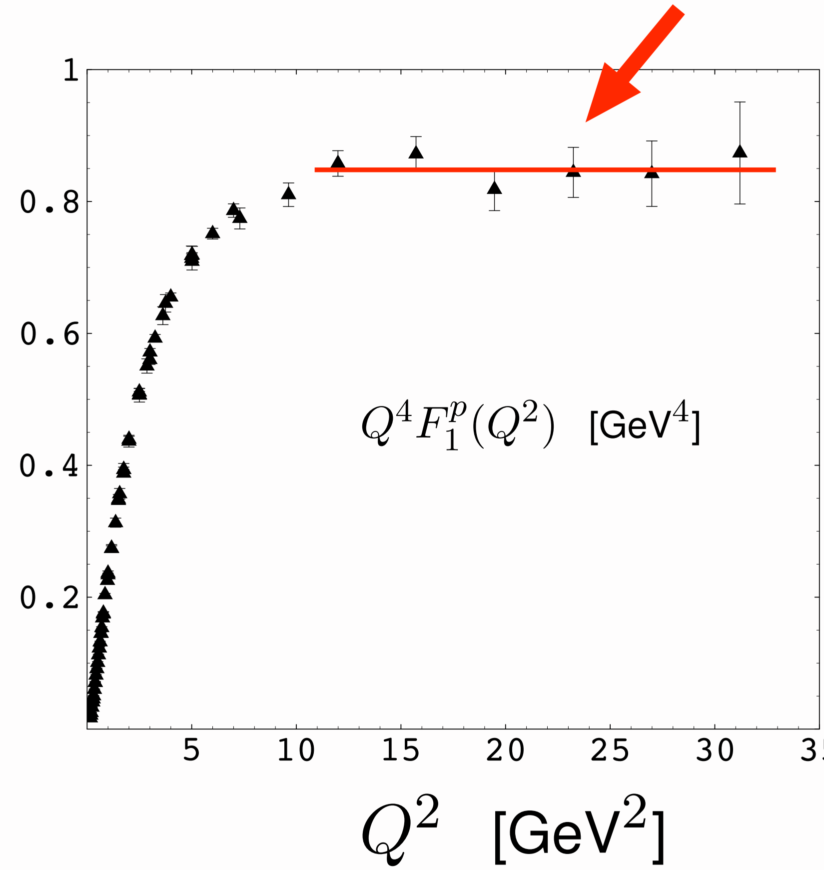
$$\frac{d\sigma}{dt}(K^+p \to K^+p) = \frac{F(\theta_{CM})}{s^8}$$

$$n = 2 \times 3 + 2 \times 2 - 2 = 8$$

Conformal behavior: $Q^2 F_\pi(Q^2) \to$ const

$Q^4 F_1(Q^2) \to$ const



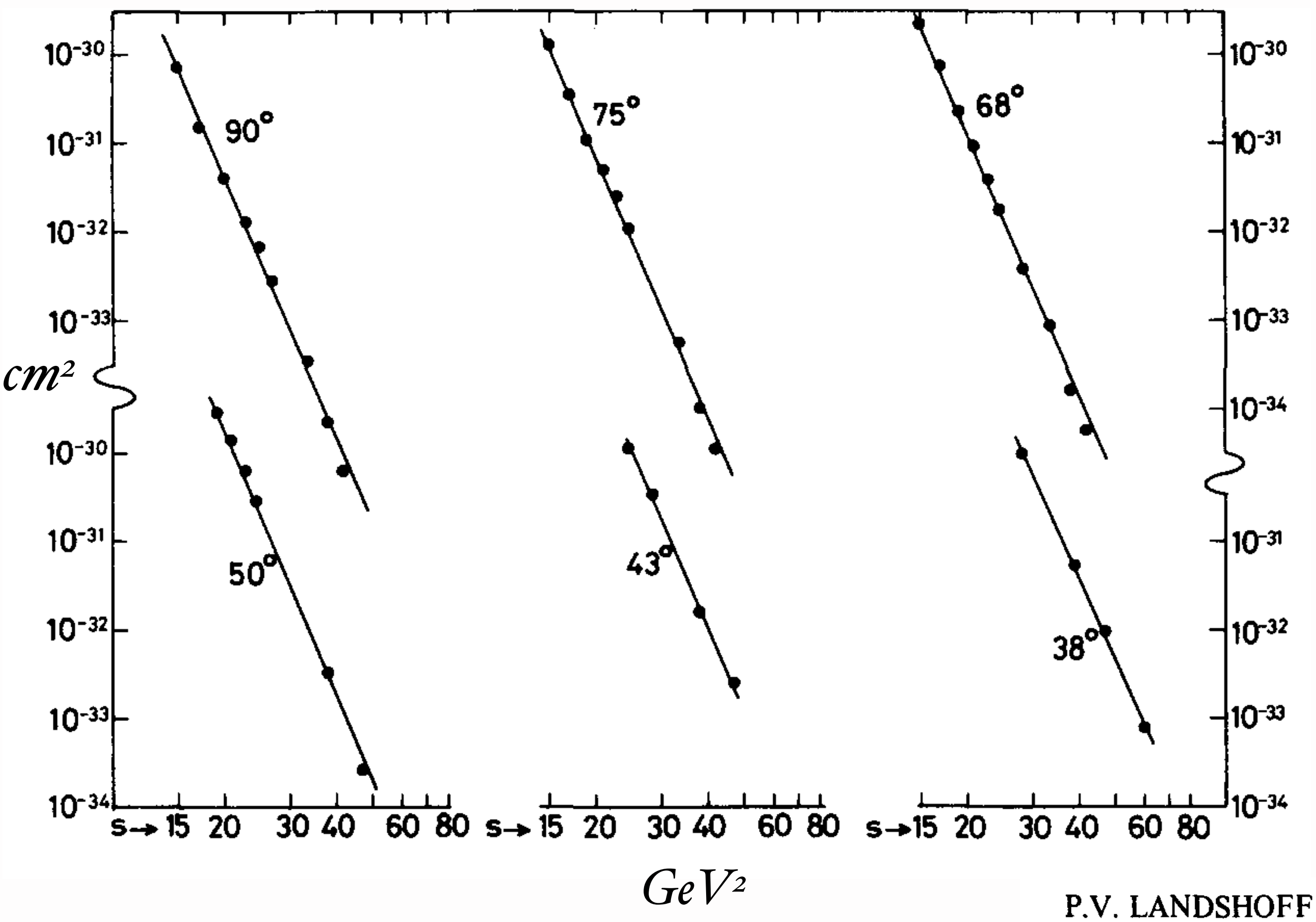


Determination of the Charged Pion Form Factor at Q2=1.60 and 2.45 (GeV/c)2.
By Fpi2 Collaboration (T. Horn *et al.*). Jul 2006. 4pp.
e-Print Archive: **nucl-ex/0607005**

Generalized parton distributions from nucleon form-factor da
M. Diehl (**DESY**) , **Th. Feldmann** (**CERN**) , **R. Jakob**, **P. Kroll** (**W**
DESY-04-146, CERN-PH-04-154, WUB-04-08, Aug 2004. 68pp.
Published in Eur.Phys.J.C39:1-39,2005
e-Print Archive: **hep-ph/0408173**

G. Huber

Quark-Counting : $\frac{d\sigma}{dt}(pp \to pp) = \frac{F(\theta_{CM})}{s^{10}}$ $n = 4 \times 3 - 2 = 10$



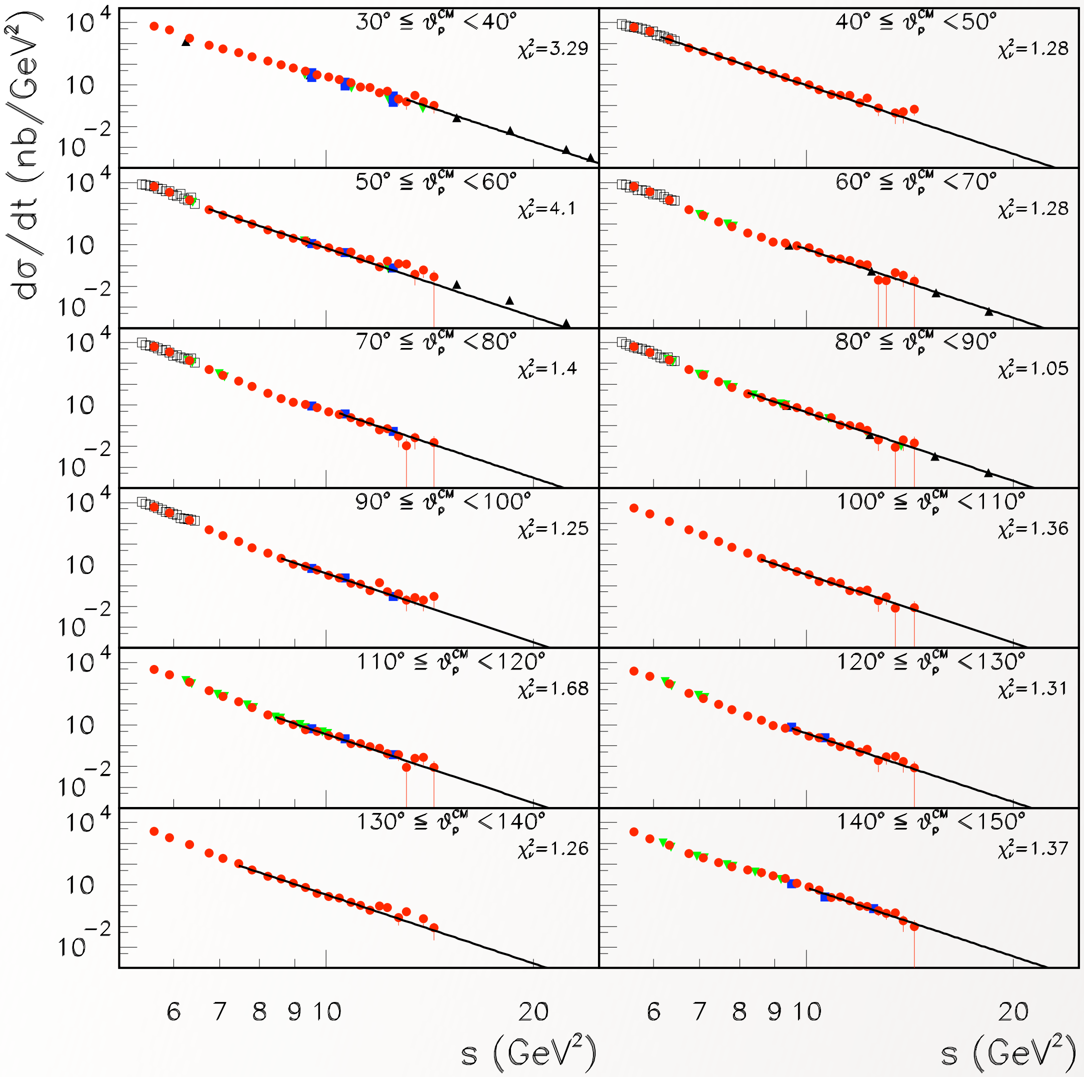
P.V. LANDSHOFF and J.C. POLKINGHORNE

Best Fit

$n = 9.7 \pm 0.5$

Reflects underlying conformal scale-free interactions

Deuteron Photodisintegration



J-Lab

PQCD and AdS/CFT:

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

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

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

Conformal invariance
at high momentum transfers!

Why do dimensional counting rules work so well?

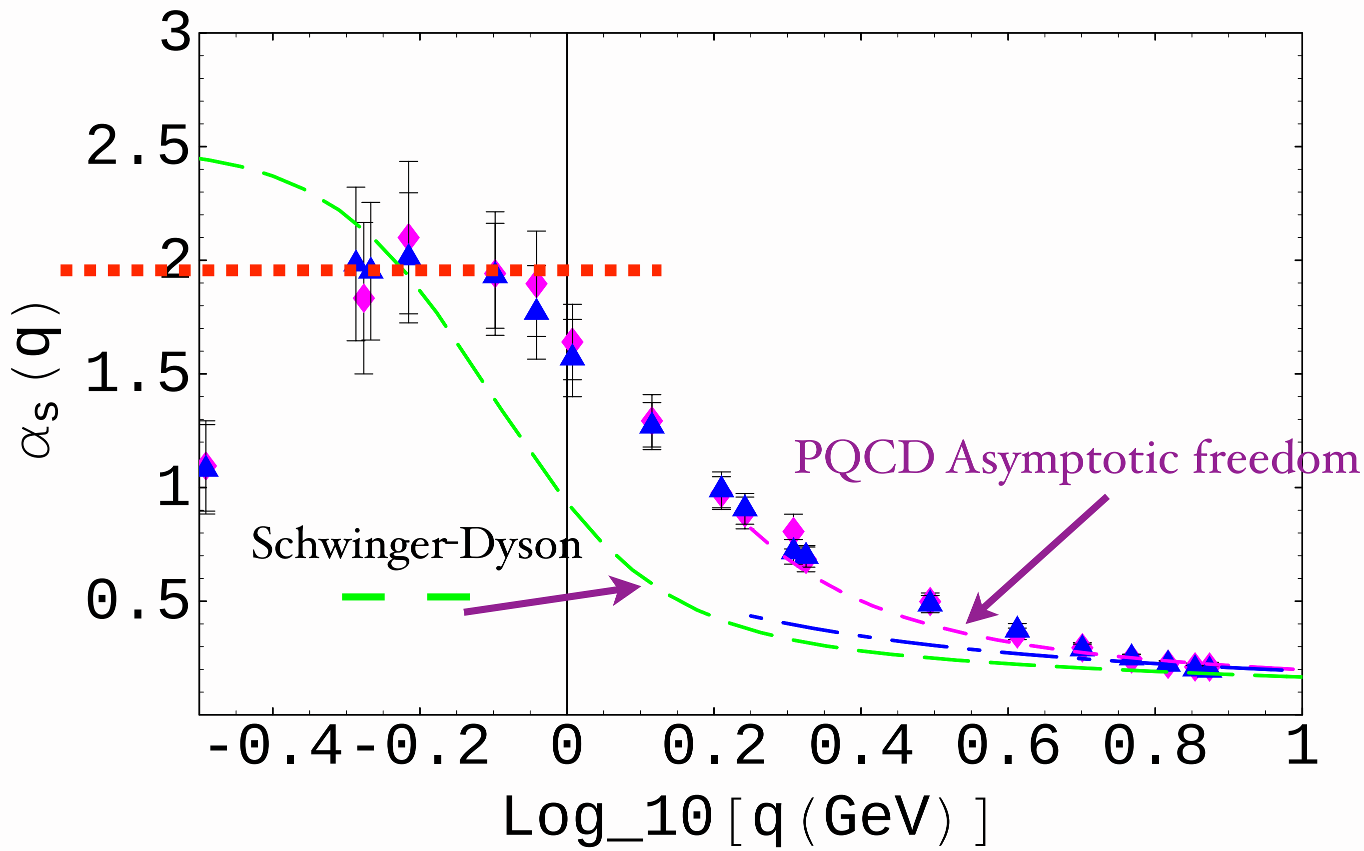
- **PQCD predicts log corrections from powers of α_s, logs, pinch contributions** Lepage, sjb; Efremov, Radyushkin

- **DSE: QCD coupling (mom scheme) has IR Fixed point!** Alkofer, Fischer, von Smekal et al.

- **Lattice results show similar flat behavior** Furui, Nakajima

- **PQCD exclusive amplitudes dominated by integration regime where α_s is large and flat**

Infrared-Finite QCD Coupling?



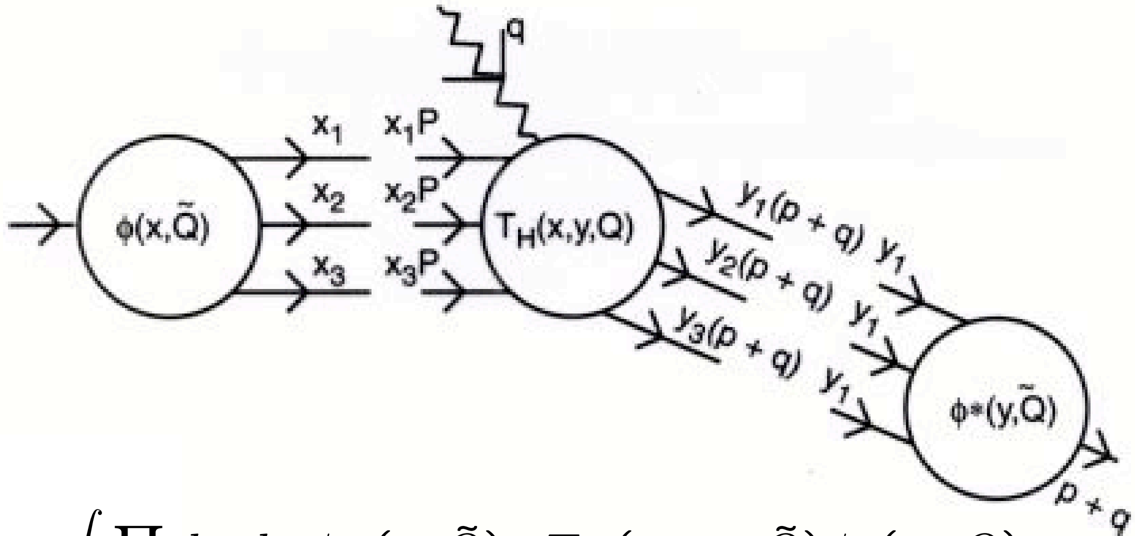
Lattice simulation (MILC)

Furui, Nakajima

DSE: Alkofer, Fischer, von Smekal et al.

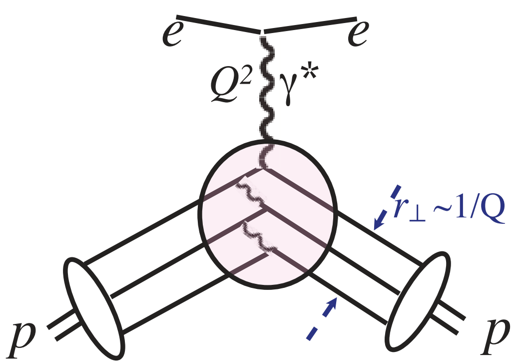
Leading-Twist PQCD Factorization

Lepage, sjb



$$M = \int \prod dx_i dy_i \phi_F(x,\tilde{Q}) \times T_H(x_i,y_i,\tilde{Q}) \phi_I(y_i,Q)$$

Exclusive



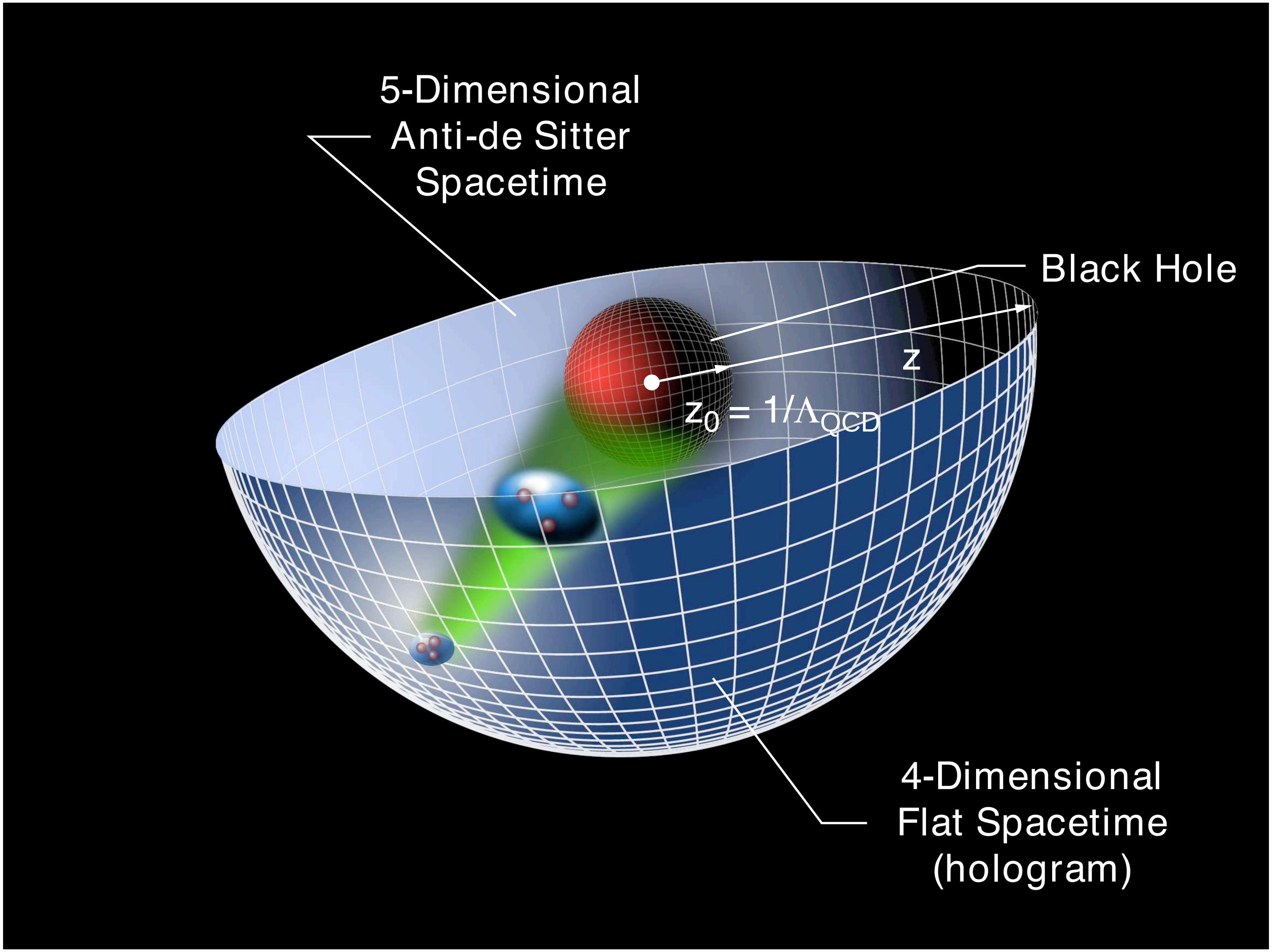
If $\alpha_s(\tilde{Q}^2) \simeq$ constant

$Q^4 F_1(Q^2) \simeq$ constant

AdS/CFT and QCD

Mapping of Poincare' and
Conformal SO(4,2) symmetries of
3+1 space to AdS5 space

- Representation of Semi-Classical QCD
- Confinement at Long Distances and Conformal Behavior at short distances
- Non-Perturbative Derivation of Dimensional Counting Rules
- Hadron Spectra, Regge Trajectories, Light-Front Wavefunctions; QCD at the amplitude level
- Goal: A first approximant to physical QCD



5-Dimensional
Anti-de Sitter
Spacetime
Black Hole
z
$z_0 = 1/\Lambda_{QCD}$
4-Dimensional
Flat Spacetime
(hologram)

String Theory

↓

AdS/CFT

Mapping of Poincare' and Conformal SO(4,2) symmetries of 3+1 space to AdS5 space

↓

Goal: First Approximant to QCD

Counting rules for Hard Exclusive Scattering
Regge Trajectories
QCD at the Amplitude Level

AdS/QCD

Conformal behavior at short distances
+ Confinement at large distance

↓

Semi-Classical QCD / Wave Equations

↓ Holography

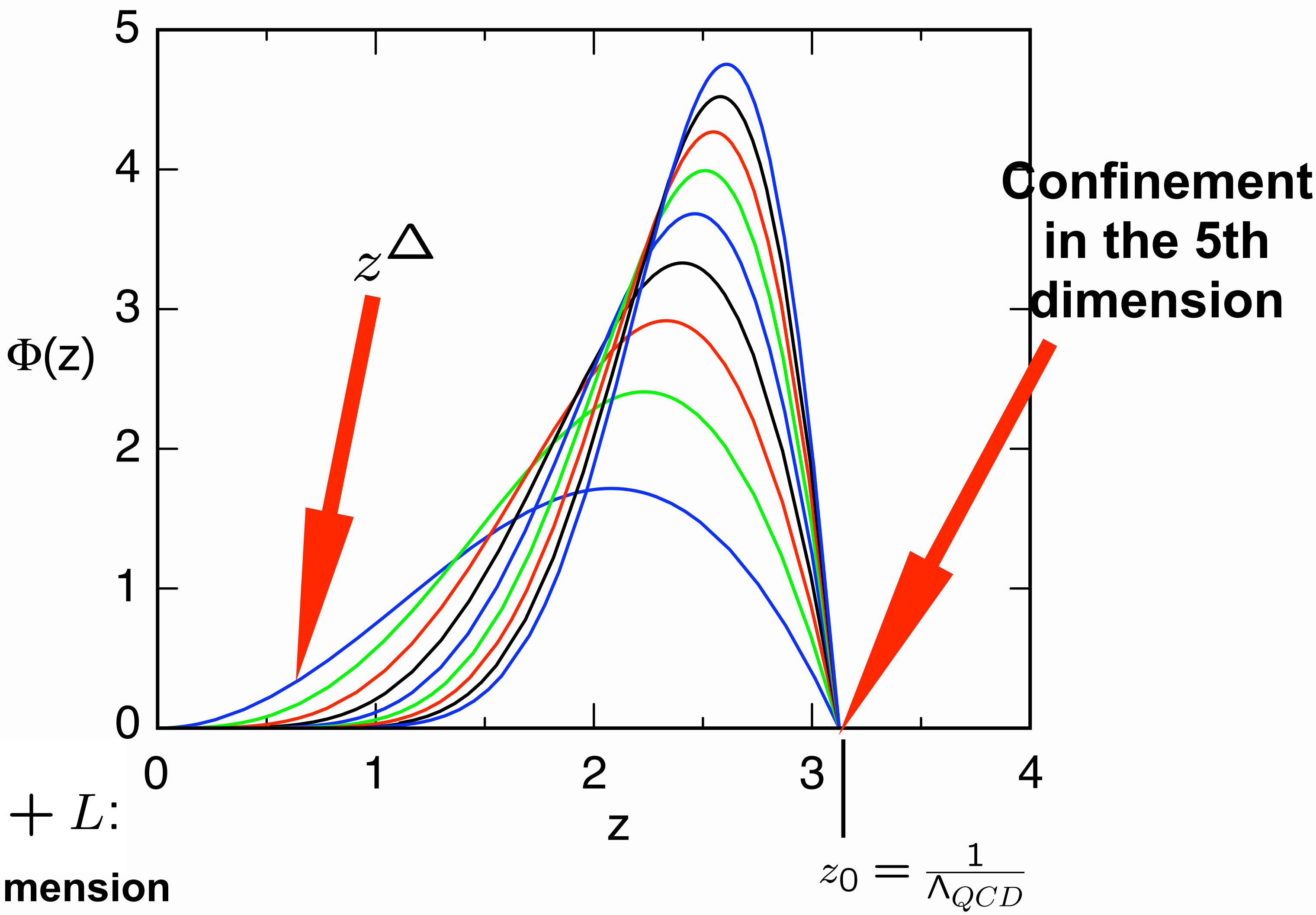
Boost Invariant 3+1 Light-Front Wave Equations

J =0,1,1/2,3/2 plus L

↓ Integrable!

Hadron Spectra, Wavefunctions, Dynamics

Identify hadron by its interpolating operator at z -- > 0



$\Delta = 3 + L$:

Twist dimension of baryon

de Teramond, sjb

Prediction from AdS/QCD

Only one parameter!

Entire light quark baryon spectrum

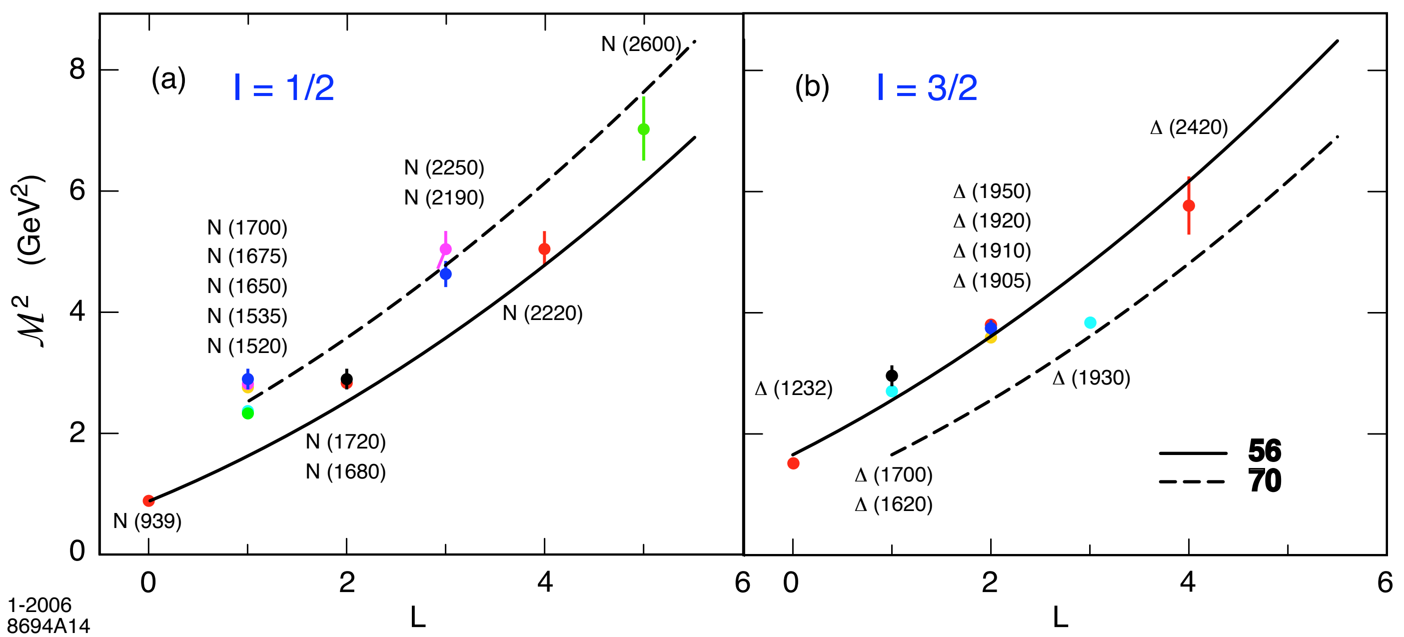
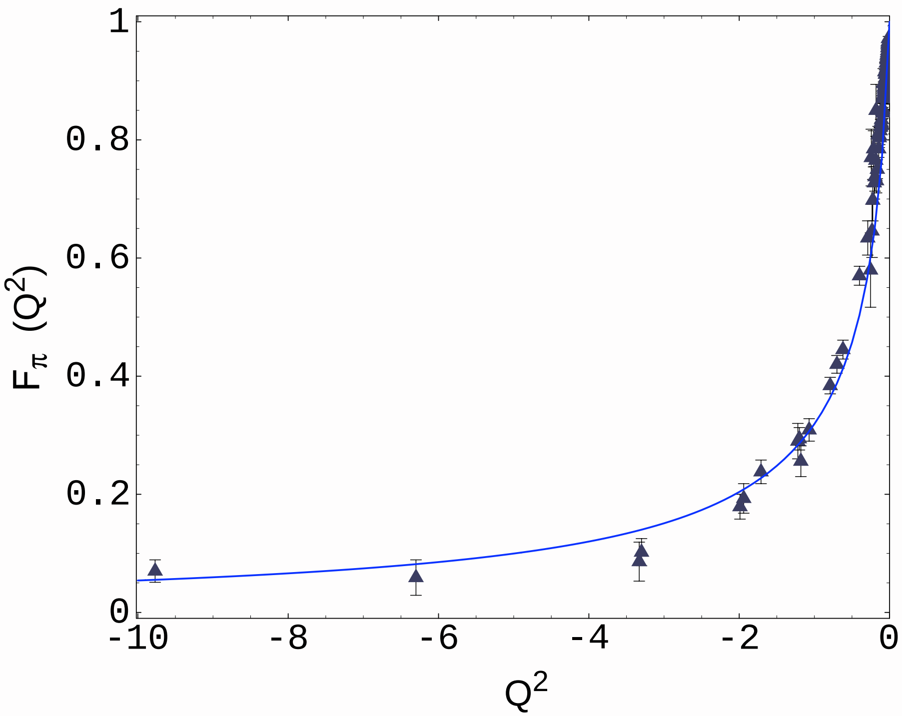


Fig: Predictions for the light baryon orbital spectrum for Λ_{QCD} = 0.25 GeV. The $\mathbf{56}$ trajectory corresponds to L even $P = +$ states, and the $\mathbf{70}$ to L odd $P = -$ states.

Guy de Teramond
SJB

- $SU(6)$ multiplet structure for N and Δ orbital states, including internal spin S and L.

$SU(6)$	S	L	Baryon State
56	$\frac{1}{2}$	0	$N\frac{1}{2}^+(939)$
	$\frac{3}{2}$	0	$\Delta\frac{3}{2}^+(1232)$
70	$\frac{1}{2}$	1	$N\frac{1}{2}^-(1535)$ $N\frac{3}{2}^-(1520)$
	$\frac{3}{2}$	1	$N\frac{1}{2}^-(1650)$ $N\frac{3}{2}^-(1700)$ $N\frac{5}{2}^-(1675)$
	$\frac{1}{2}$	1	$\Delta\frac{1}{2}^-(1620)$ $\Delta\frac{3}{2}^-(1700)$
56	$\frac{1}{2}$	2	$N\frac{3}{2}^+(1720)$ $N\frac{5}{2}^+(1680)$
	$\frac{3}{2}$	2	$\Delta\frac{1}{2}^+(1910)$ $\Delta\frac{3}{2}^+(1920)$ $\Delta\frac{5}{2}^+(1905)$ $\Delta\frac{7}{2}^+(1950)$
70	$\frac{1}{2}$	3	$N\frac{5}{2}^-$ $N\frac{7}{2}^-$
	$\frac{3}{2}$	3	$N\frac{3}{2}^-$ $N\frac{5}{2}^-$ $N\frac{7}{2}^-(2190)$ $N\frac{9}{2}^-(2250)$
	$\frac{1}{2}$	3	$\Delta\frac{5}{2}^-(1930)$ $\Delta\frac{7}{2}^-$
56	$\frac{1}{2}$	4	$N\frac{7}{2}^+$ $N\frac{9}{2}^+(2220)$
	$\frac{3}{2}$	4	$\Delta\frac{5}{2}^+$ $\Delta\frac{7}{2}^+$ $\Delta\frac{9}{2}^+$ $\Delta\frac{11}{2}^+(2420)$
70	$\frac{1}{2}$	5	$N\frac{9}{2}^-$ $N\frac{11}{2}^-$
	$\frac{3}{2}$	5	$N\frac{7}{2}^-$ $N\frac{9}{2}^-$ $N\frac{11}{2}^-(2600)$ $N\frac{13}{2}^-$

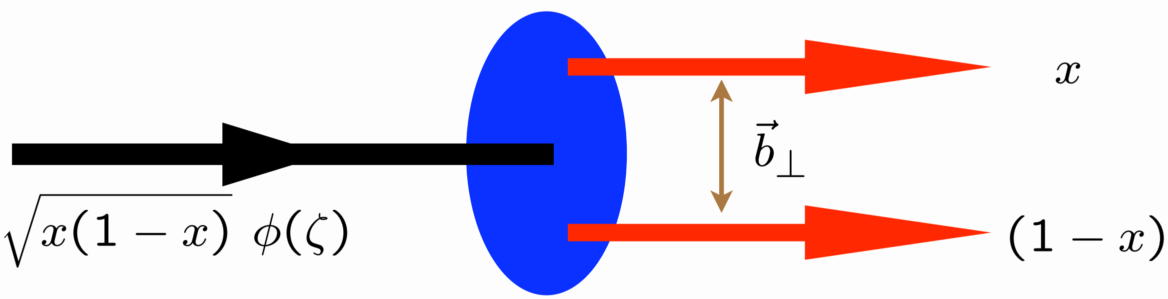


Space-like pion form factor in holographic model for $\Lambda_{QCD} = 0.2$ GeV.

Data Compilation from Baldini, Kloe and Volmer

Mapping between LF(3+1) and AdS_5

LF(3+1)		AdS_5
$\psi(x, \vec{b}_\perp)$	⟷	$\phi(z)$
$\zeta = \sqrt{x(1-x)\vec{b}_\perp^2}$	⟷	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:

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

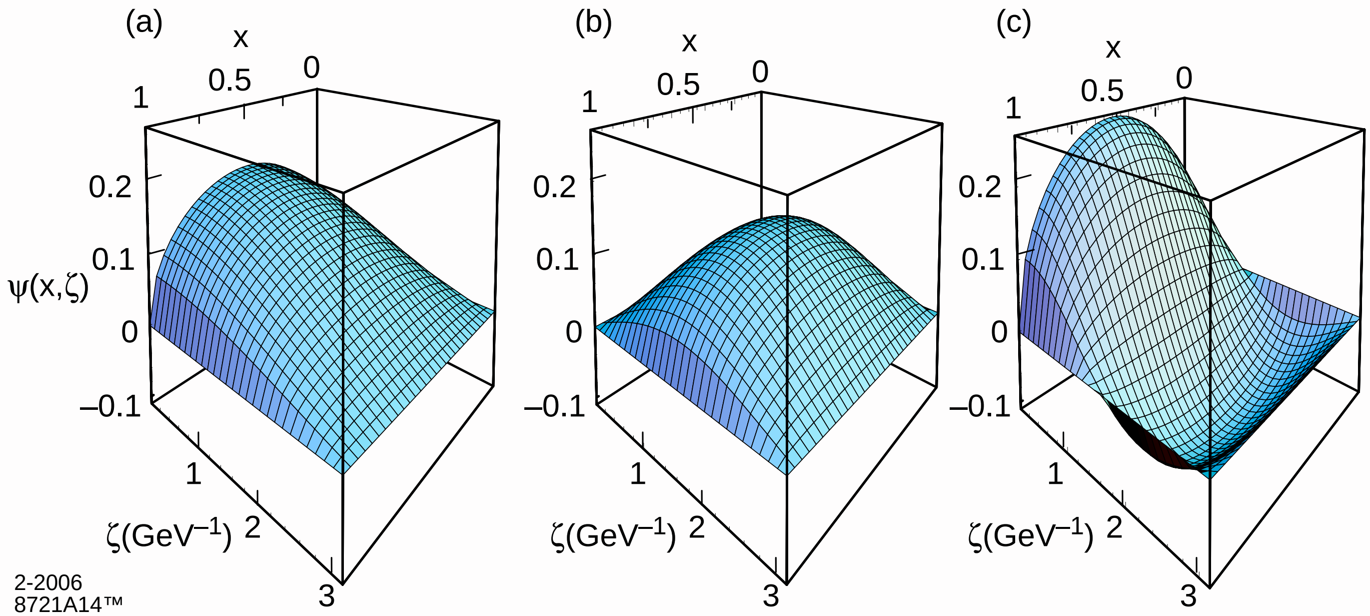
General solution:

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

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

Two parton LFWF bound state:

$$\widetilde{\psi}_{\overline{q}q/\pi}(x,\zeta) = B_{L,k}\sqrt{x(1-x)}J_L\left(\zeta\beta_{L,k}\Lambda_{\rm QCD}\right)\theta\big(z \le \Lambda_{\rm QCD}^{-1}\big),$$

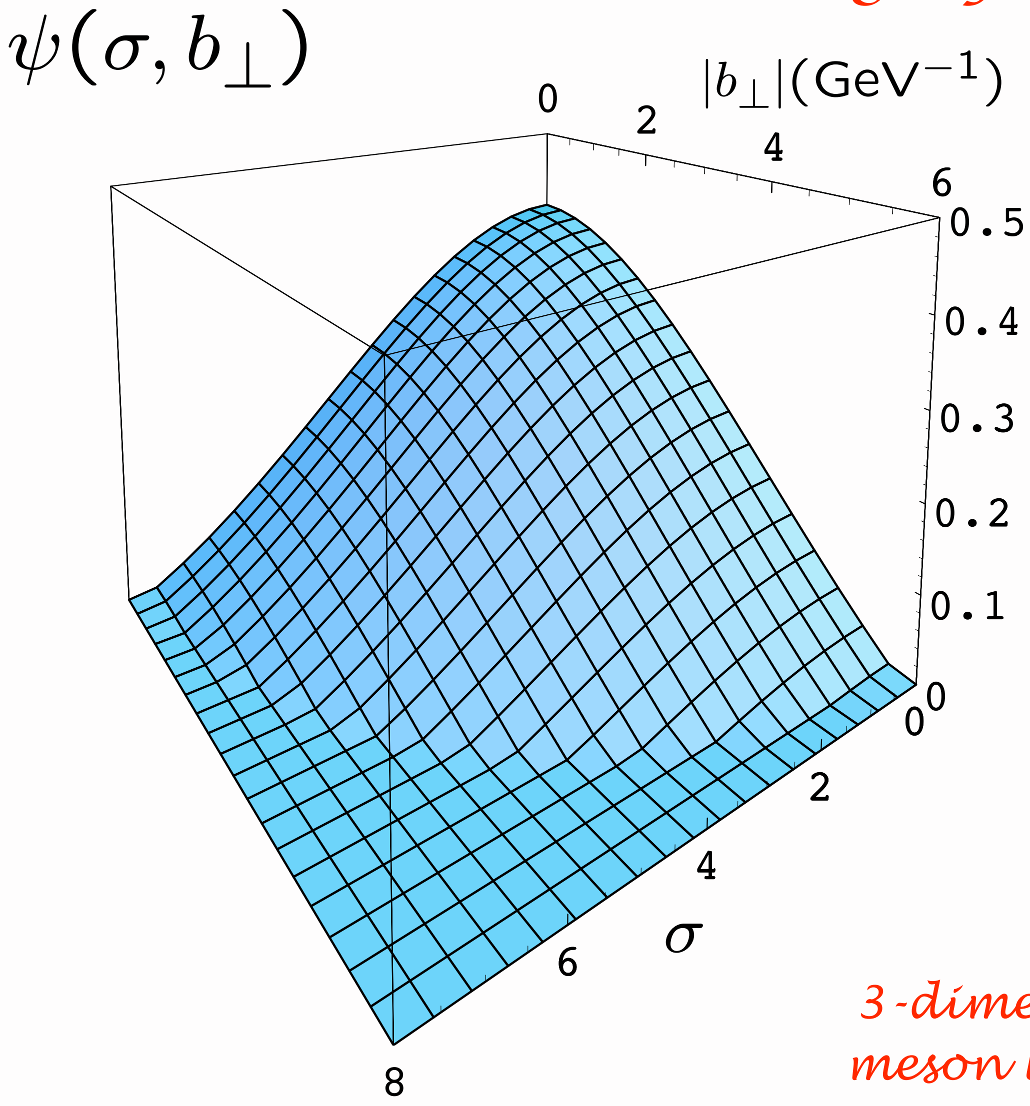


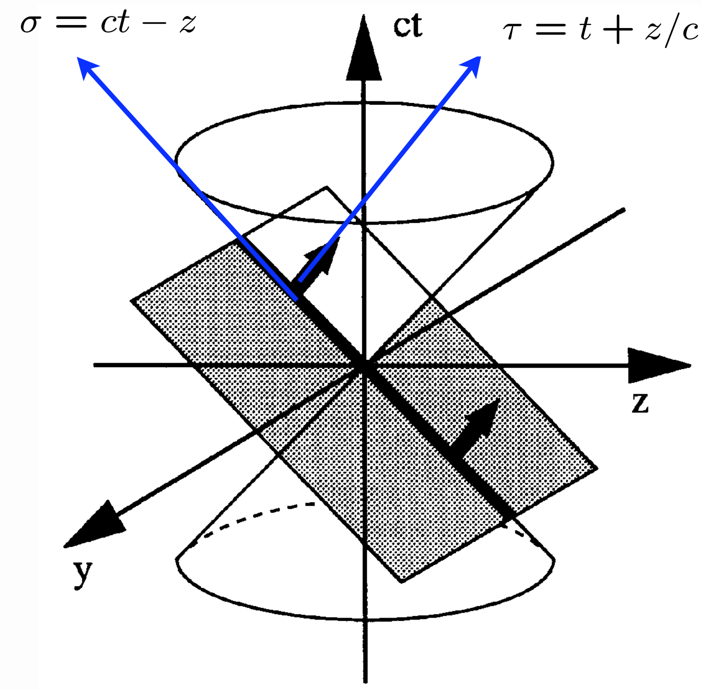
(a) ground state $L=0$, $k=1$, (b) first orbital $L=1$, $k=1$, (c) first radial $L=0$, $k=2$.

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

AdS/CFT Holographic Model

G. de Teramond
SJB





The front form

3-dimensional photograph: meson LFWF at fixed LF Time

Physics of Rescattering

- Diffractive DIS: New Insights into Final State Interactions in QCD
- Origin of Hard Pomeron
- Structure Functions not Probability Distributions!
- T-odd SSAs, Shadowing, Antishadowing
- Diffractive dijets/ trijets, doubly diffractive Higgs
- Novel Effects: Color Transparency, Color Opaqueness, Intrinsic Charm, Odderon

"Dangling Gluons"

- Diffractive DIS
- Non-Unitary Correction to DIS: Structure functions are not probability distributions
- Nuclear Shadowing, Antishadowing
- Single Spin Asymmetries -- opposite sign in DY and DIS
- DY $\cos 2\phi$ correlation at leading twist from double ISI-- not given by standard PQCD factorization
- Wilson Line Effects persist even in LCG
- Must correct hard subprocesses for initial and final-state soft gluon attachments -- Ji gauge link, Kovchegov gauge

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

- Novel QCD Phenomena: diffraction, hidden color, color transparency, shadowing, anti-shadowing, intrinsic charm, anomalous heavy quark phenomena, anomalous spin effects, odderon, anomalous Regge behavior ...

- Remarkable Predictions of AdS/QCD

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

—Mark Twain