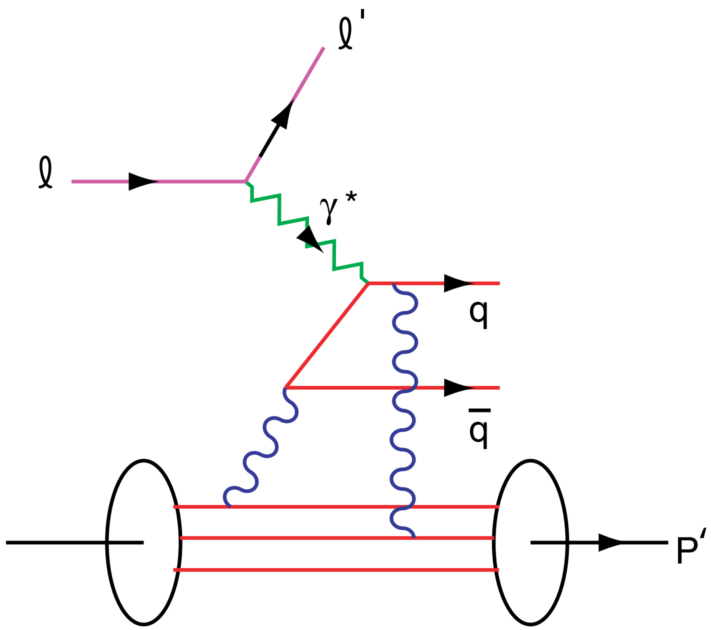
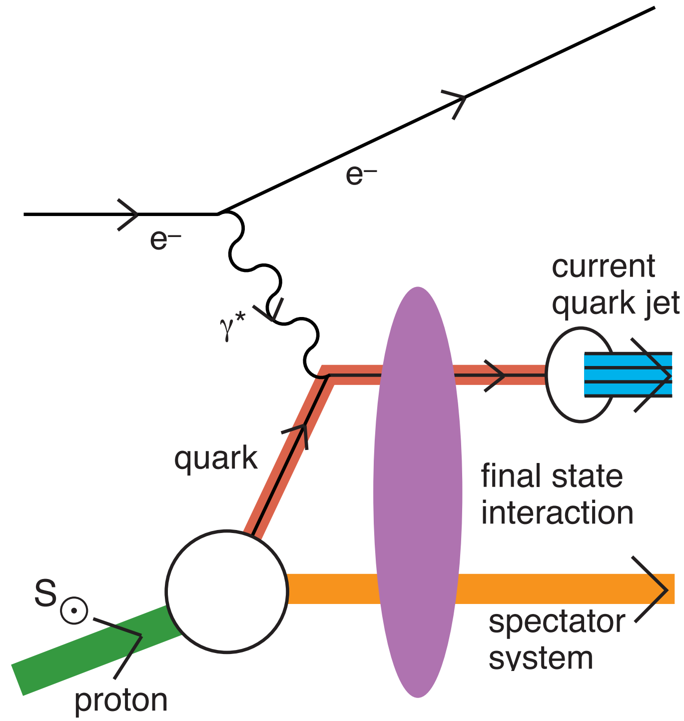
Novel QCD Phenomenology

Stan Brodsky, SLAC/IPPP

Queen guitarist Brian May has handed in his astronomy PhD thesis - 36 years after abandoning it to join the band.



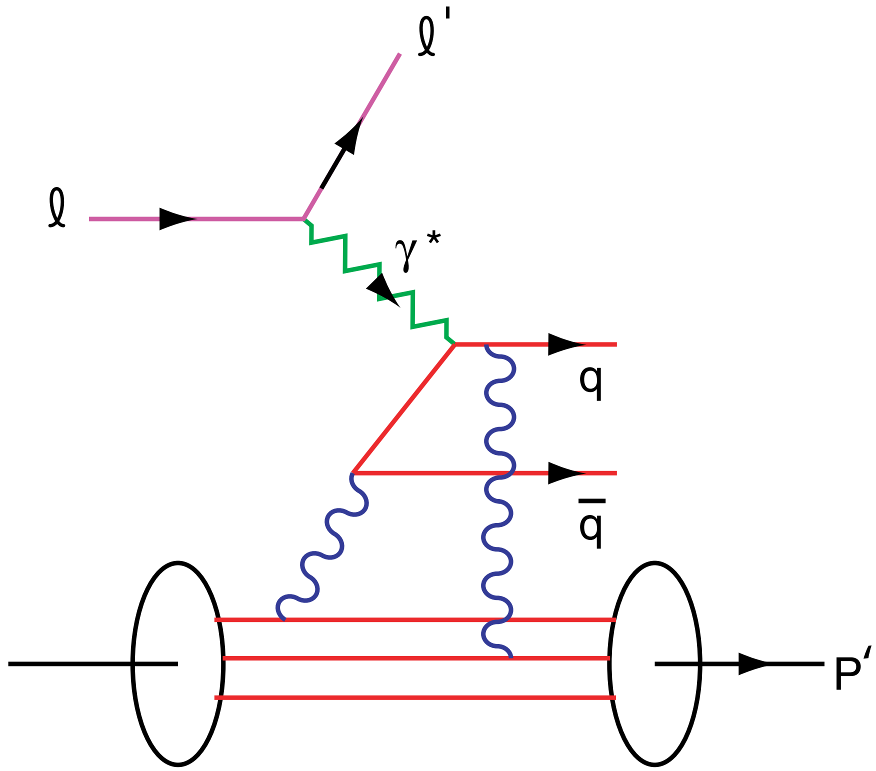


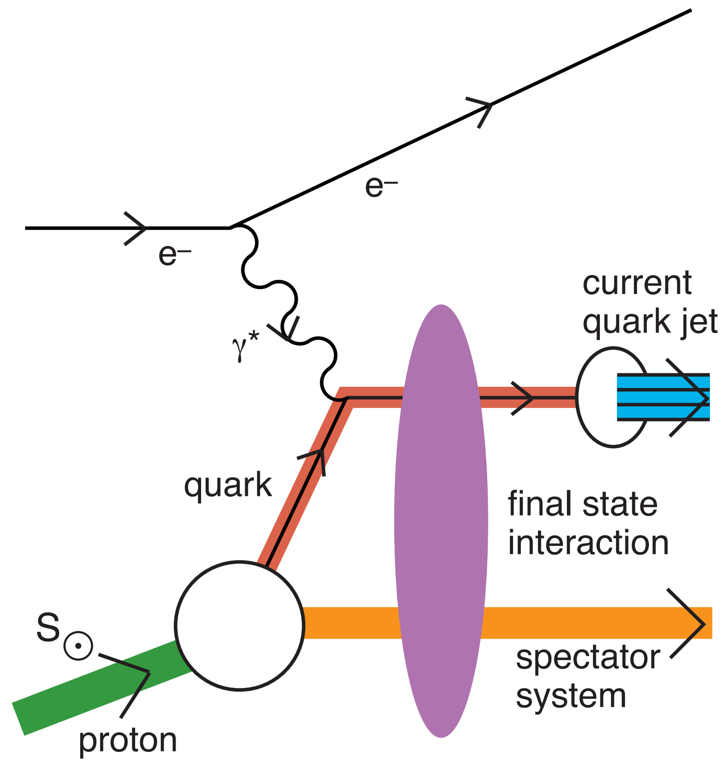
Imperial College, London

16 Sep 2008

Novel QCD Phenomenology

Stan Brodsky, SLAC/IPPP





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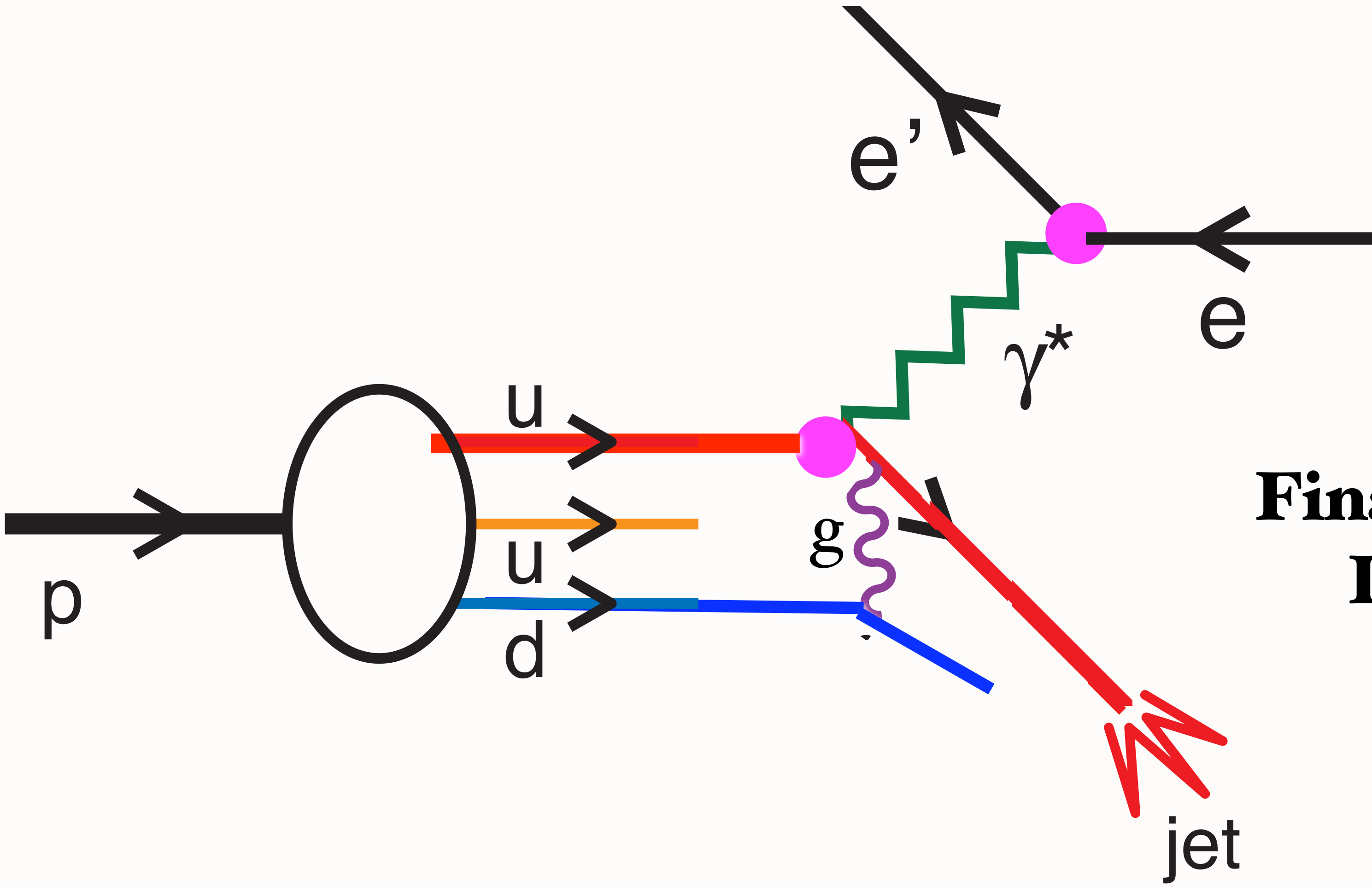
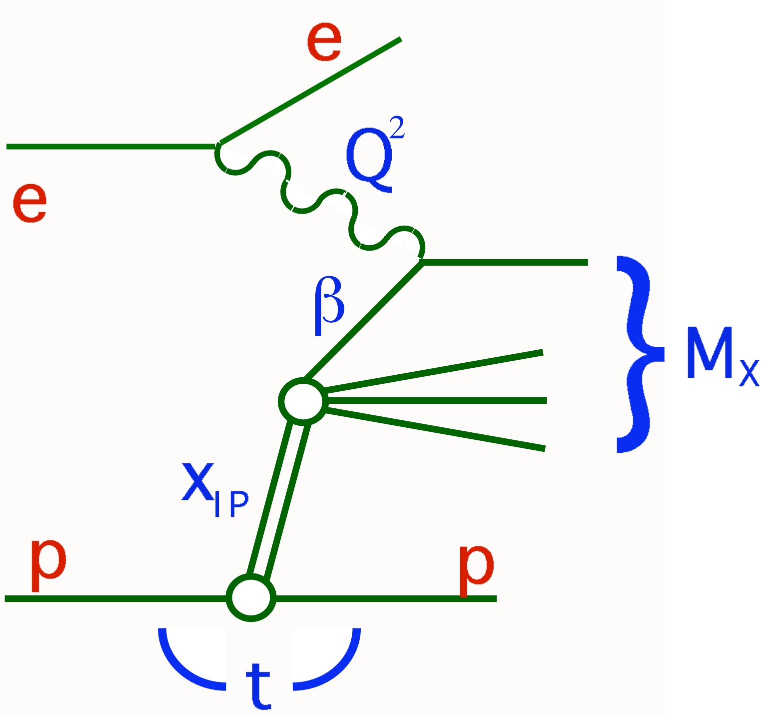
Deep Inelastic Electron-Proton Scattering



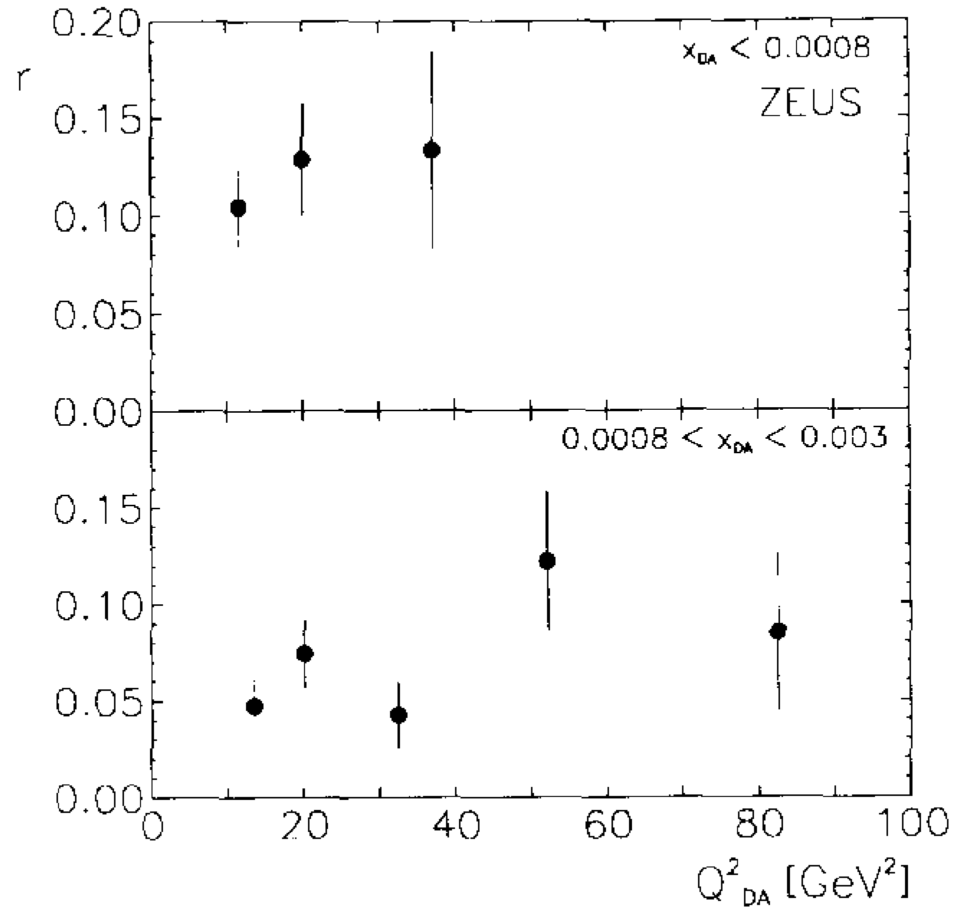
Final-State QCD Interaction

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

Remarkable observation at HERA



10% to 15% of DIS events are diffractive !

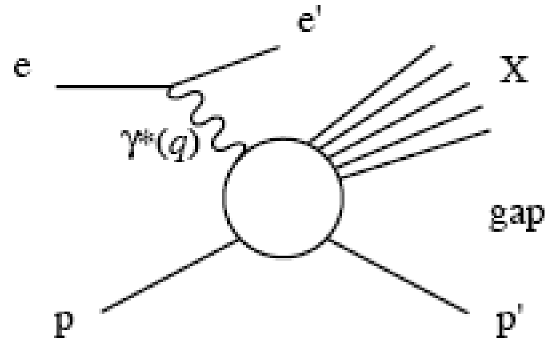


Fraction r of events with a large rapidity gap, $\eta_{\max} < 1.5$, as a function of Q^2_{DA} for two ranges of x_{DA}. No acceptance corrections have been applied.

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

DDIS

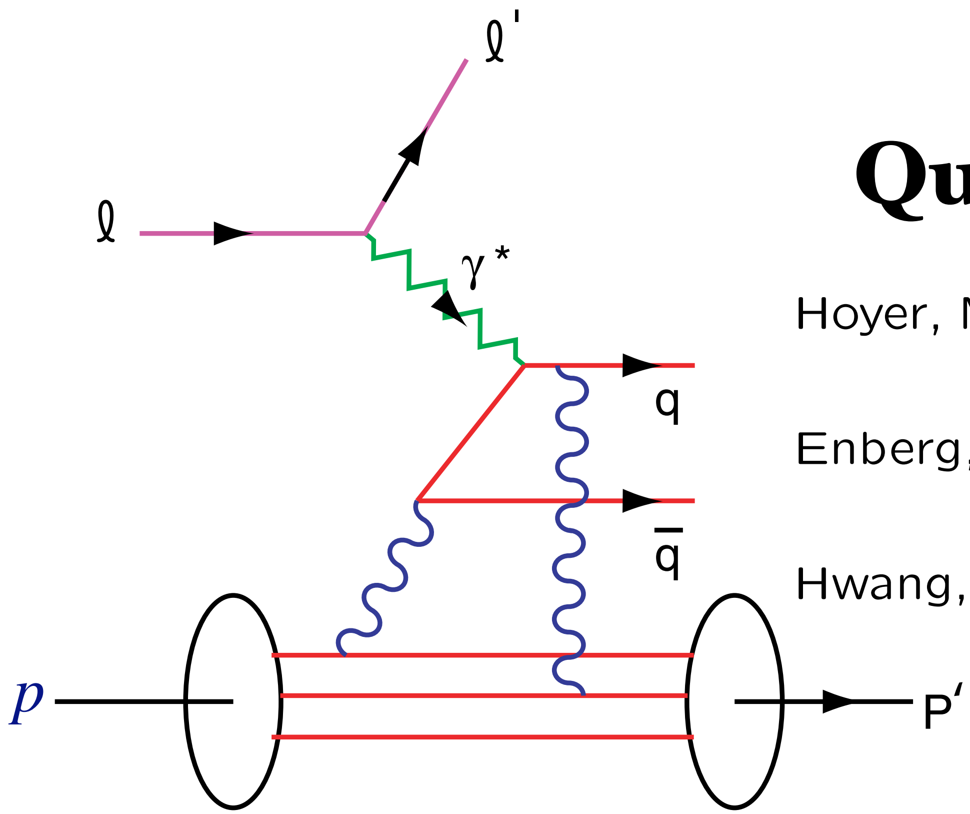
Diffractive Deep Inelastic Lepton-Proton Scattering



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

Profound effect: target stays intact despite production of a massive system X

Final-State QCD Interaction Produces Diffractive DIS



Quark Rescattering

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

Enberg, Hoyer, Ingelman, SJB

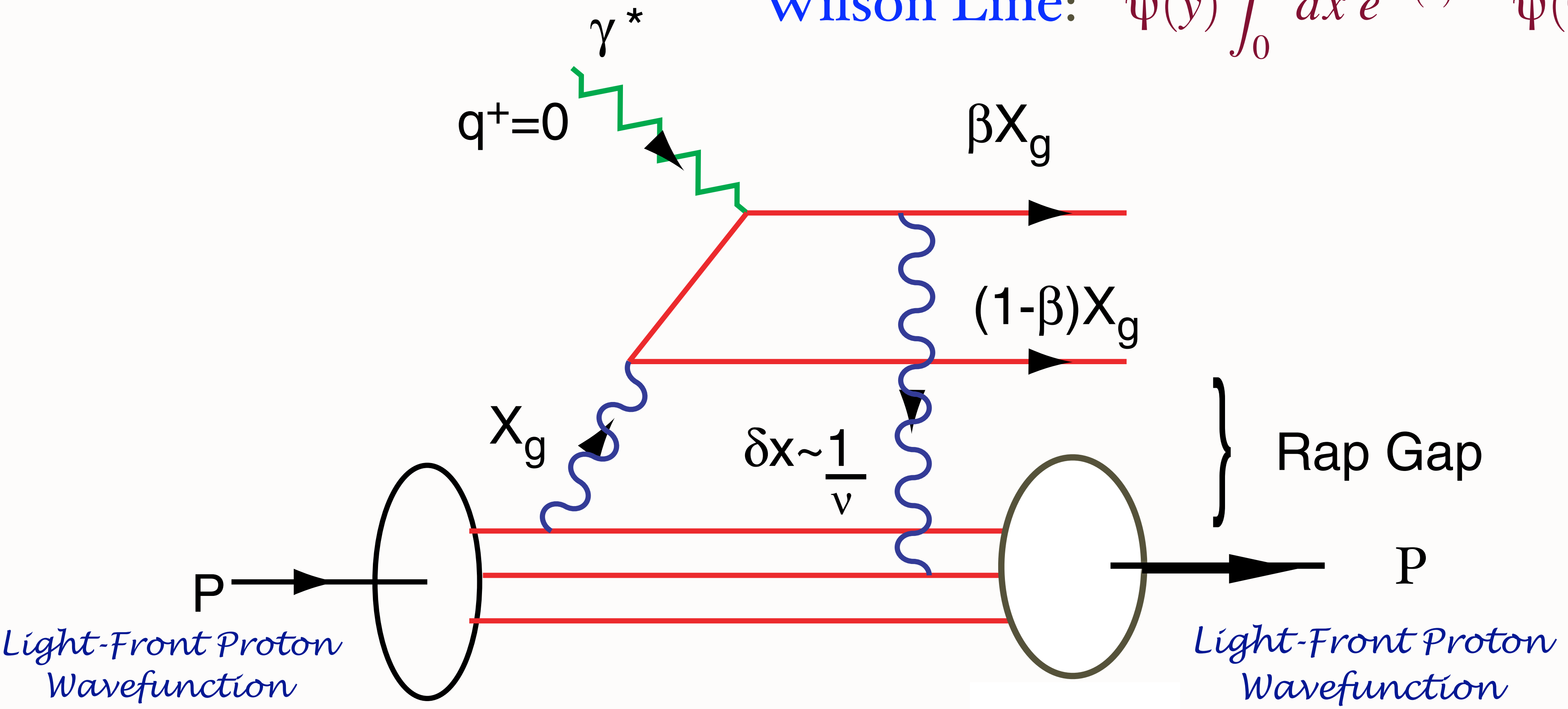
Hwang, Schmidt, SJB

Low-Nussinov model of Pomeron

Hoyer, Marchal, Peigne, Sannino, sjb

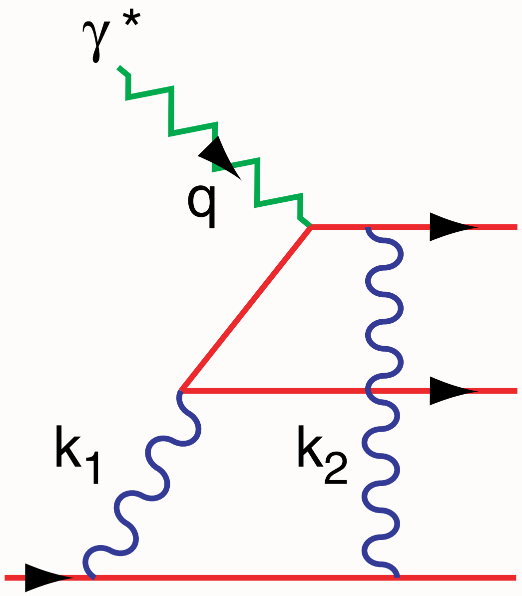
QCD Mechanism for Rapidity Gaps

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

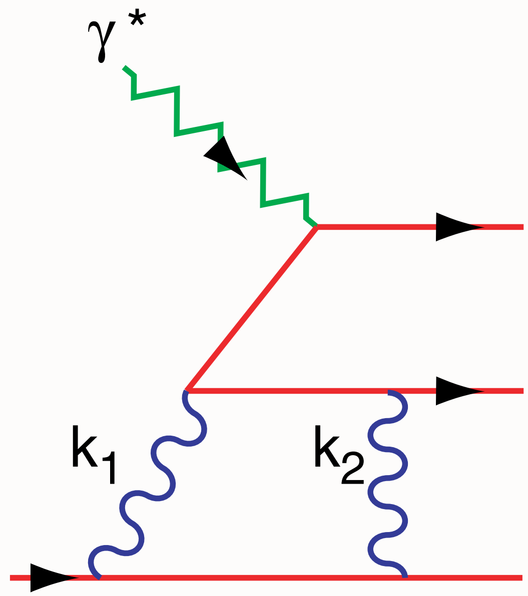


Reproduces lab-frame color dipole approach

Final State Interactions in QCD

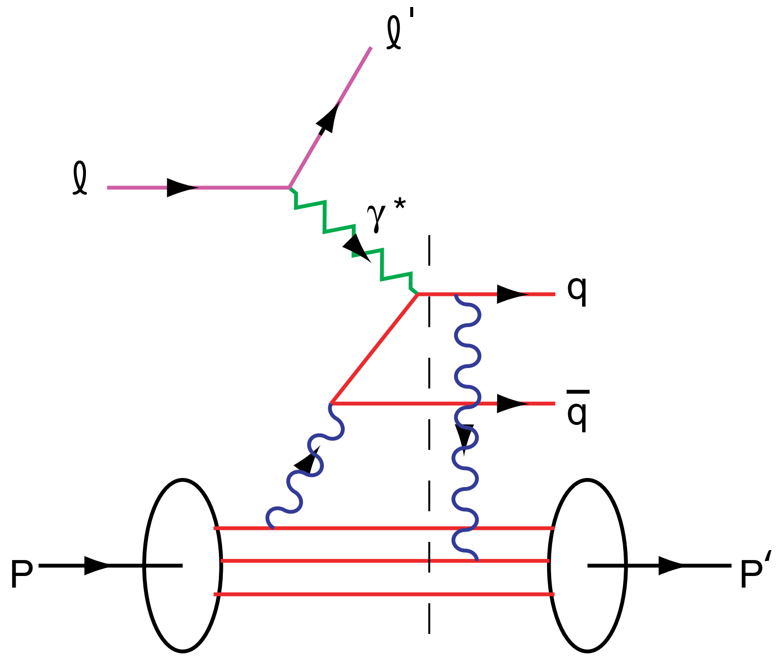


Feynman Gauge



Light-Cone Gauge

Result is Gauge Independent

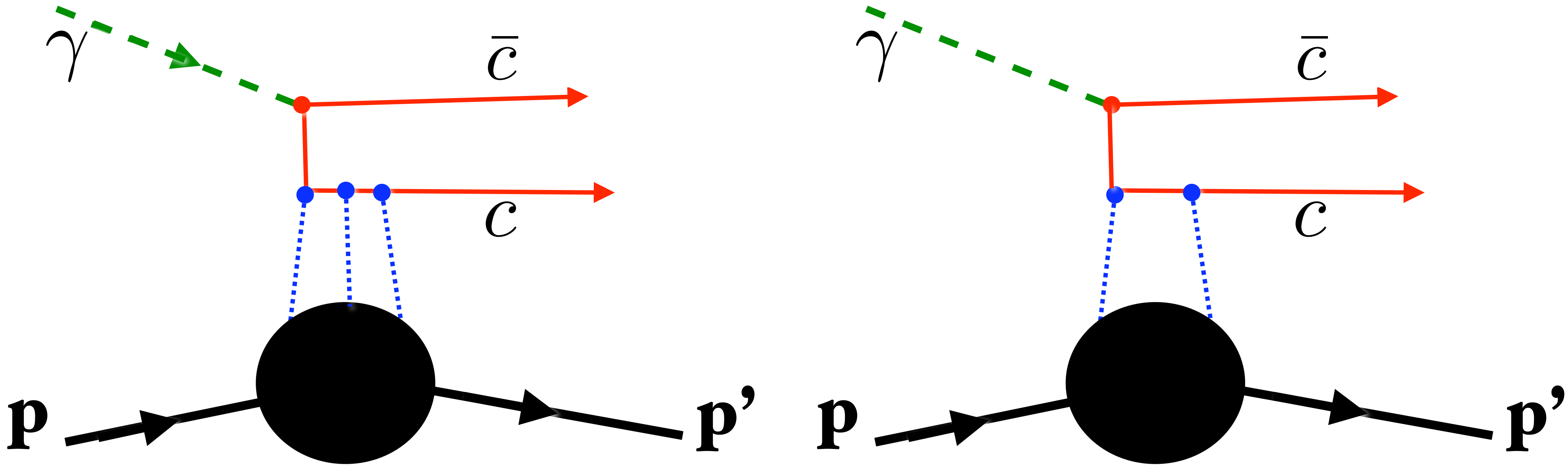


Integration over on-shell domain produces phase i

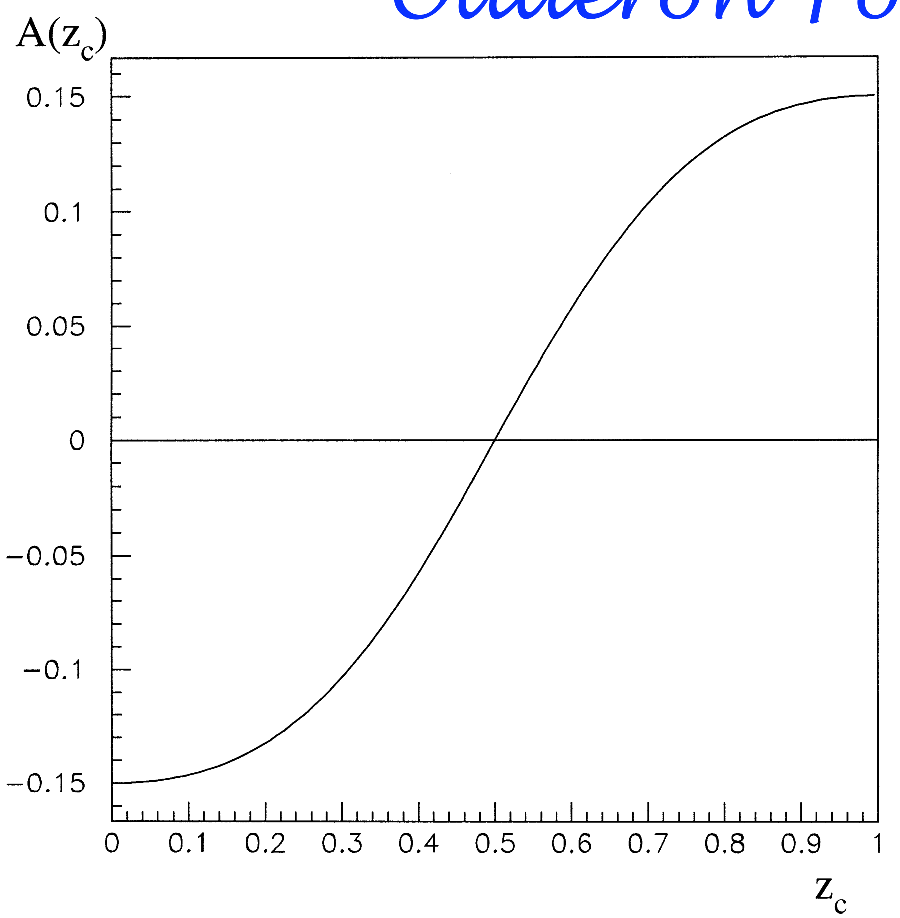
Need Imaginary Phase to Generate Pomeron

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

Physics of FSI not in Wavefunction of Target



Odderon-Pomeron Interference!



$$\frac{d\sigma}{dz_c}(\gamma p \to c\bar{c}p')$$

$$\mathscr{A}\left(t \simeq 0, M_X^2, z_c\right) \simeq 0.45\left(\frac{s_{\gamma p}}{M_X^2}\right)^{-0.25} \frac{2z_c - 1}{z_c^2 + (1-z_c)^2}$$

Measure charm momentum asymmetry in photon fragmentation region

Only one charm quark needs to be measured

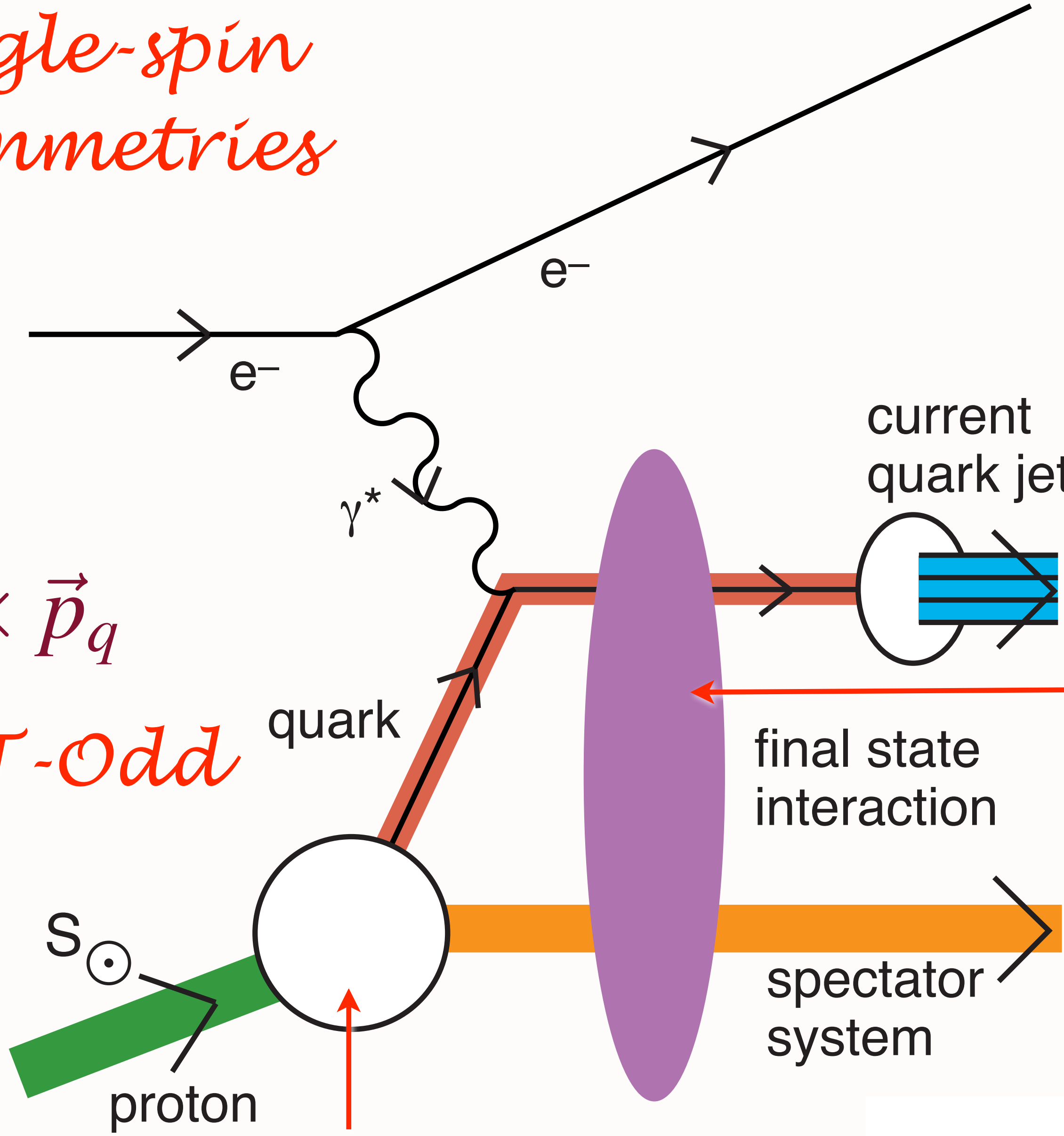
Merino, Rathsman, sjb

Leading Twist Sivers Effect

Single-spin asymmetries

Hwang, Schmidt, sjb

Collins, Burkardt Ji, Yuan

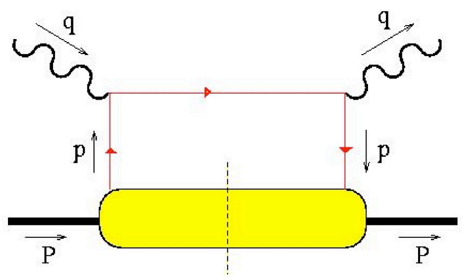


$$i\, \vec{S}_p \cdot \vec{q} \times \vec{p}_q$$

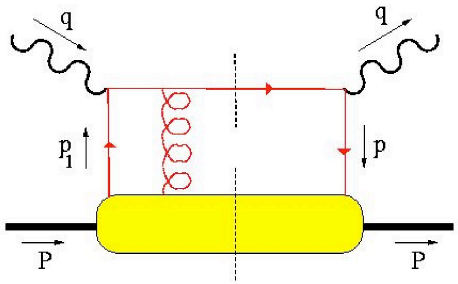
Pseudo-T-Odd

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

Light-Front Wavefunction S and P- Waves



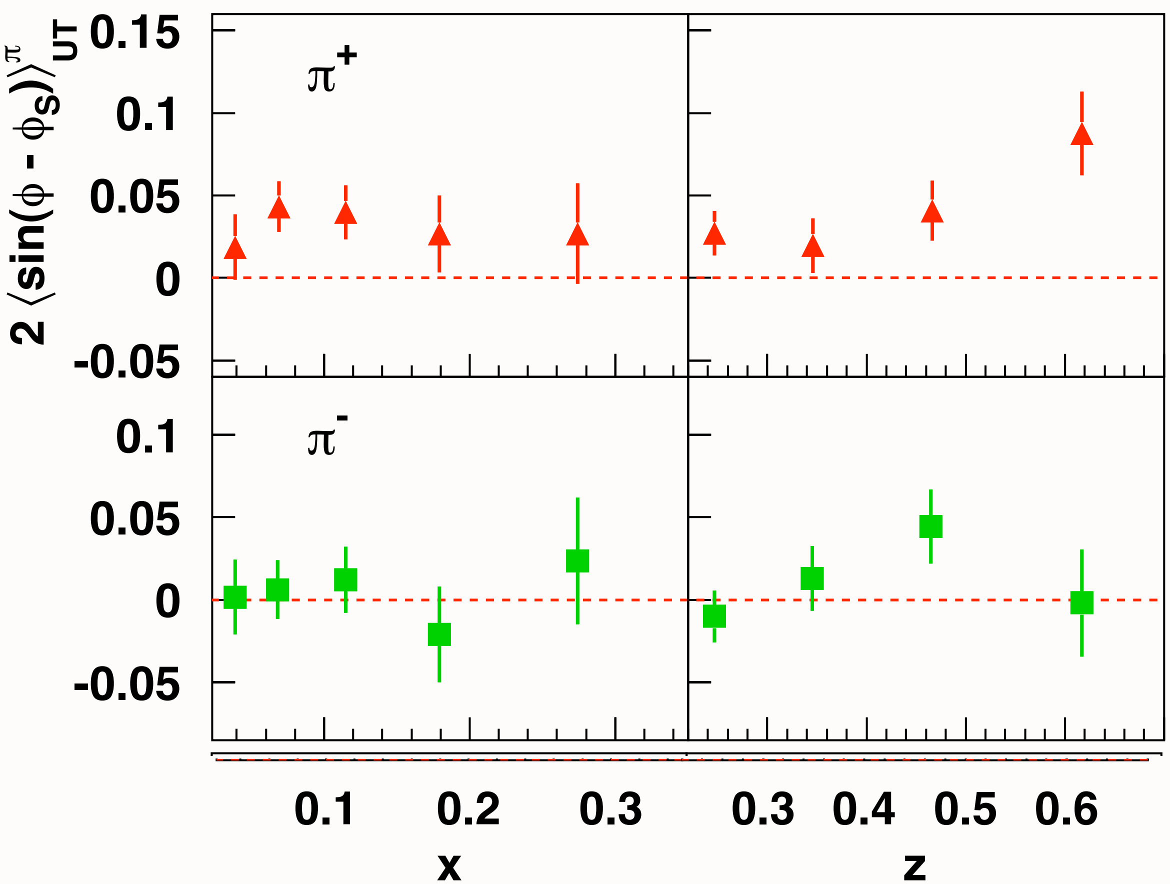
can interfere with



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

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

Sivers asymmetry from HERMES



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

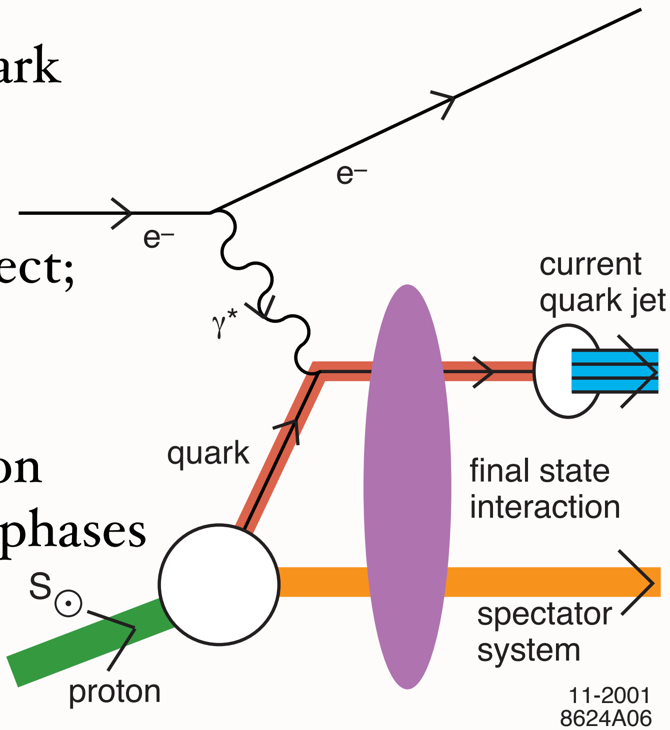
Gamberg: Hermes data compatible with BHS model

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

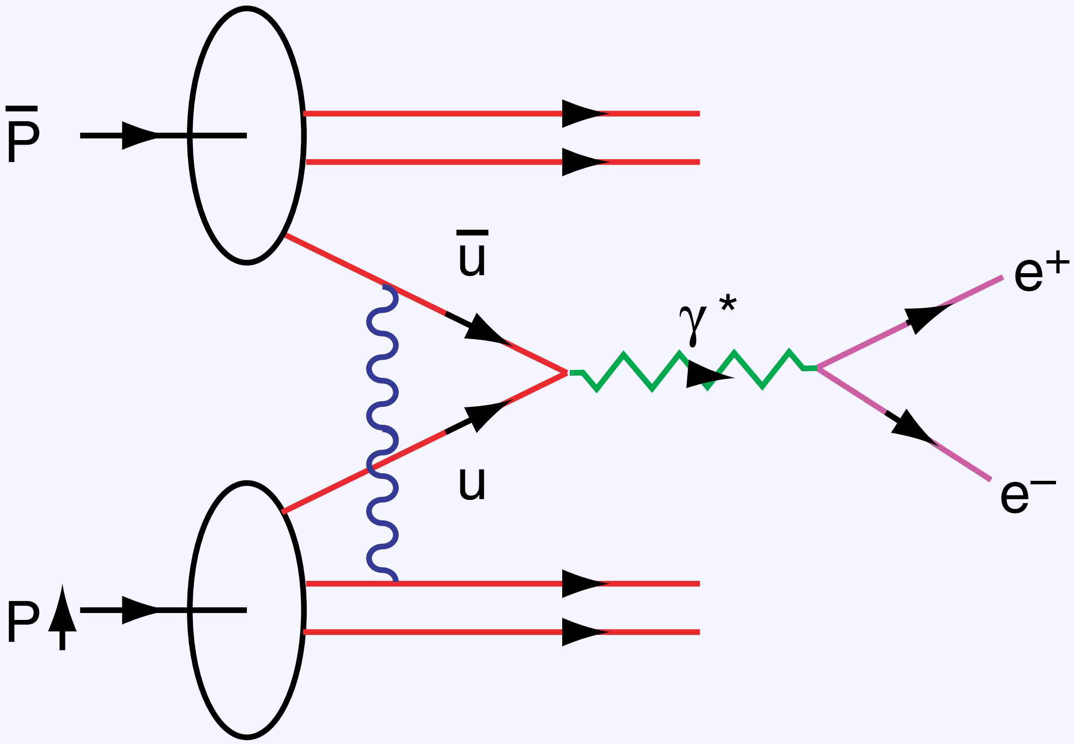
Final-State Interactions Produce Pseudo T-Odd (Sivers Effect)

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

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



Predict Opposite Sign SSA in DY !



Collins;
Hwang, Schmidt.
sjb

Single Spin Asymmetry In the Drell Yan Process

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

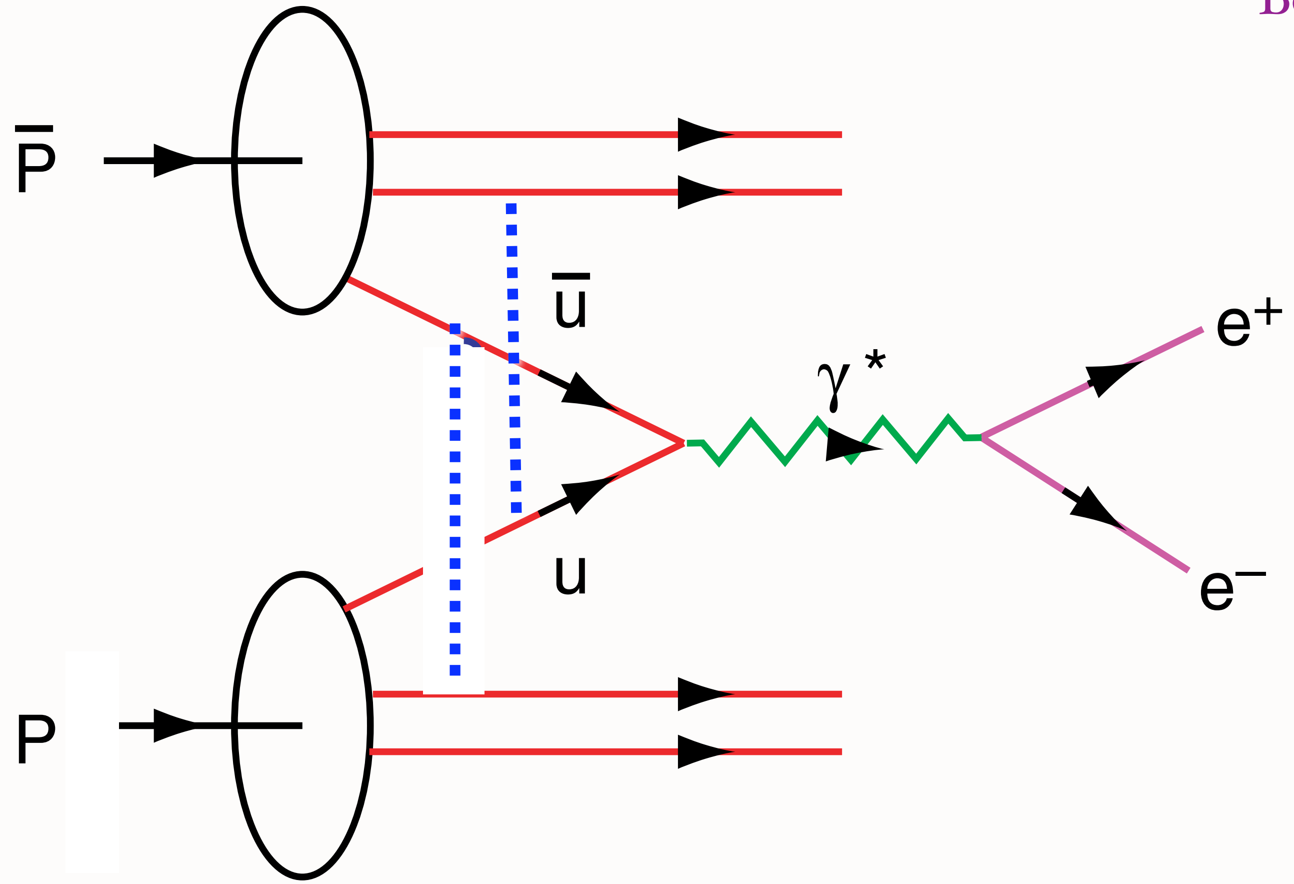
Quarks Interact in the Initial State

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

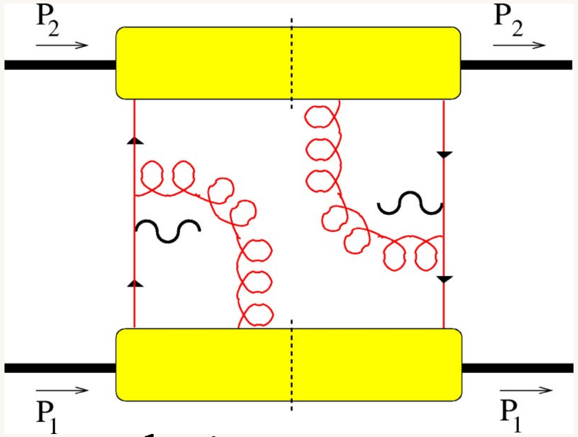


DY $\cos 2\phi$ **correlation at leading twist from double ISI**

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

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

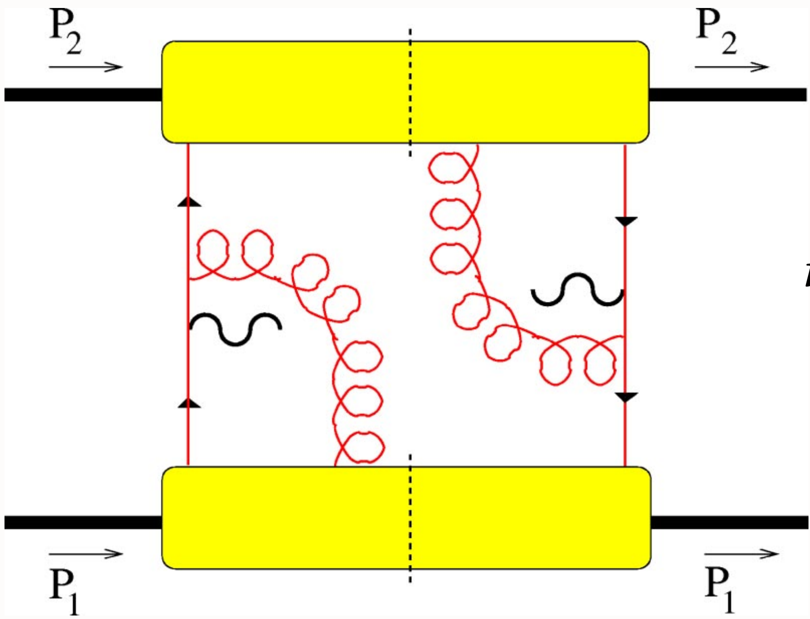
Boer, Hwang, sjb

Drell-Yan planar correlations

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

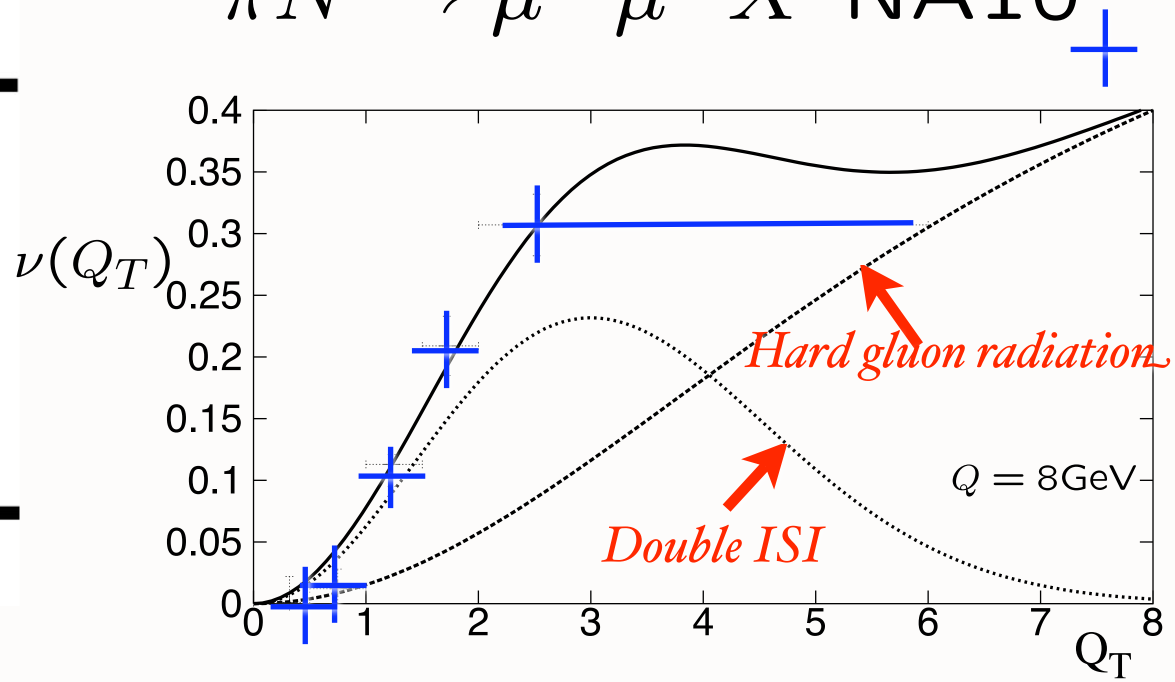
PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

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

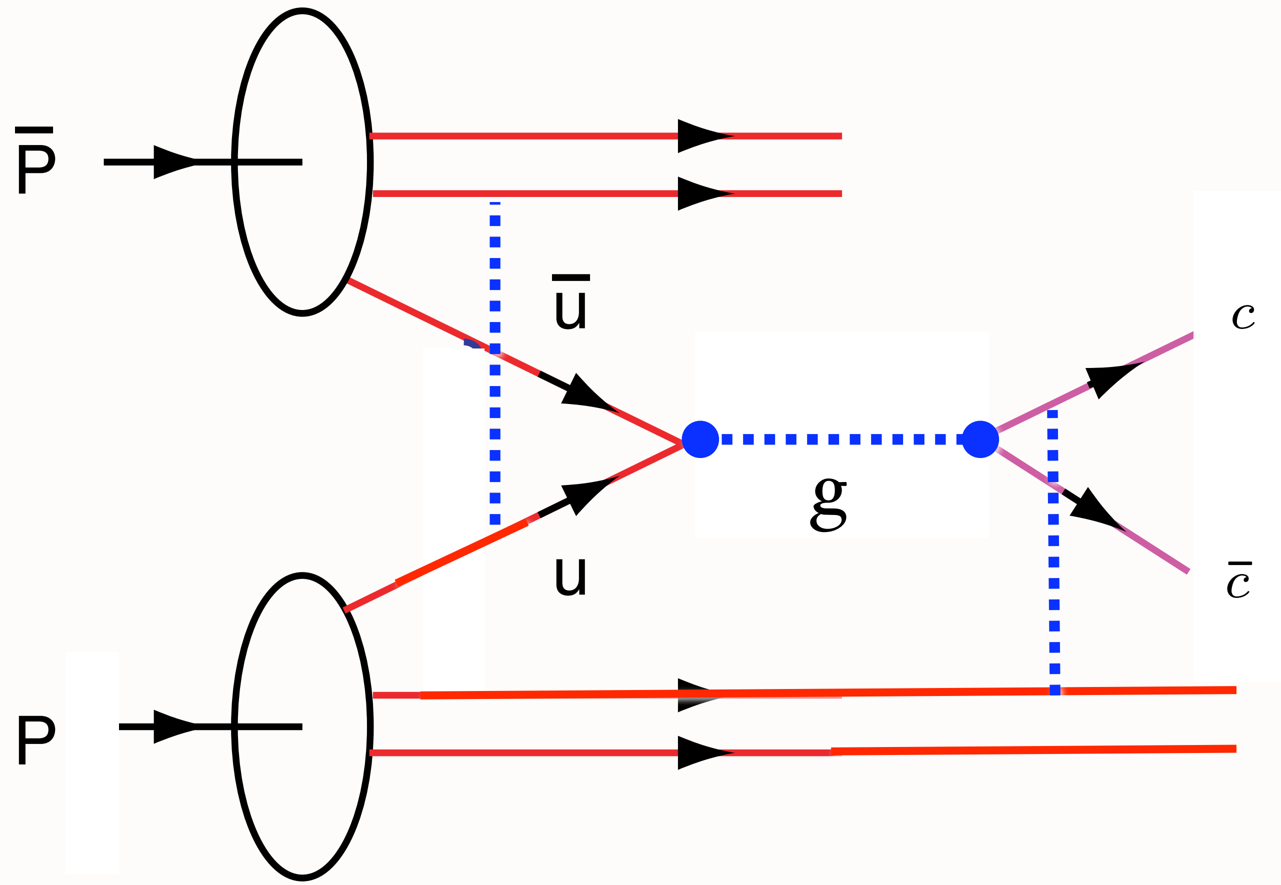


Violates Lam-Tung relation!

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



Model: Boer,

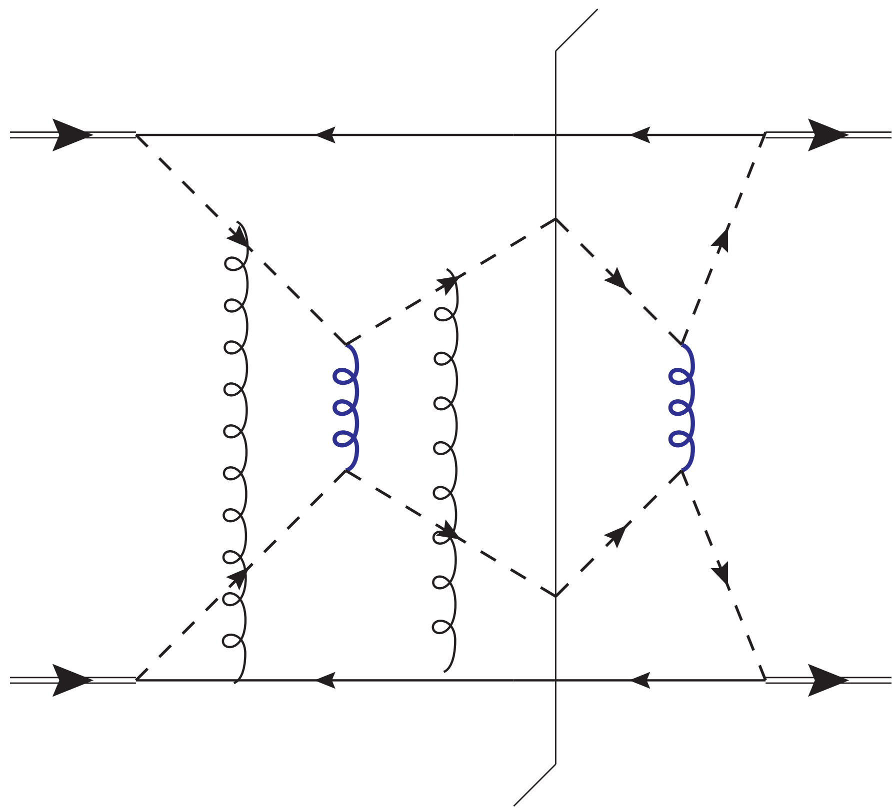


Problem for factorization when both ISI and FSI occur

Factorization is violated in production of high-transverse-momentum particles in hadron-hadron collisions

John Collins, Jian-Wei Qiu . ANL-HEP-PR-07-25, May 2007.

e-Print: **arXiv:0705.2141** [hep-ph]



The exchange of two extra gluons, as in this graph, will tend to give non-factorization in unpolarized cross sections.

Novel Aspects of QCD in ep scattering

- Initial and final-state interactions are not power suppressed DIS; Wilson line correction to handbag diagram in DVCS

- Leading-twist Bjorken-scaling single-spin asymmetry:

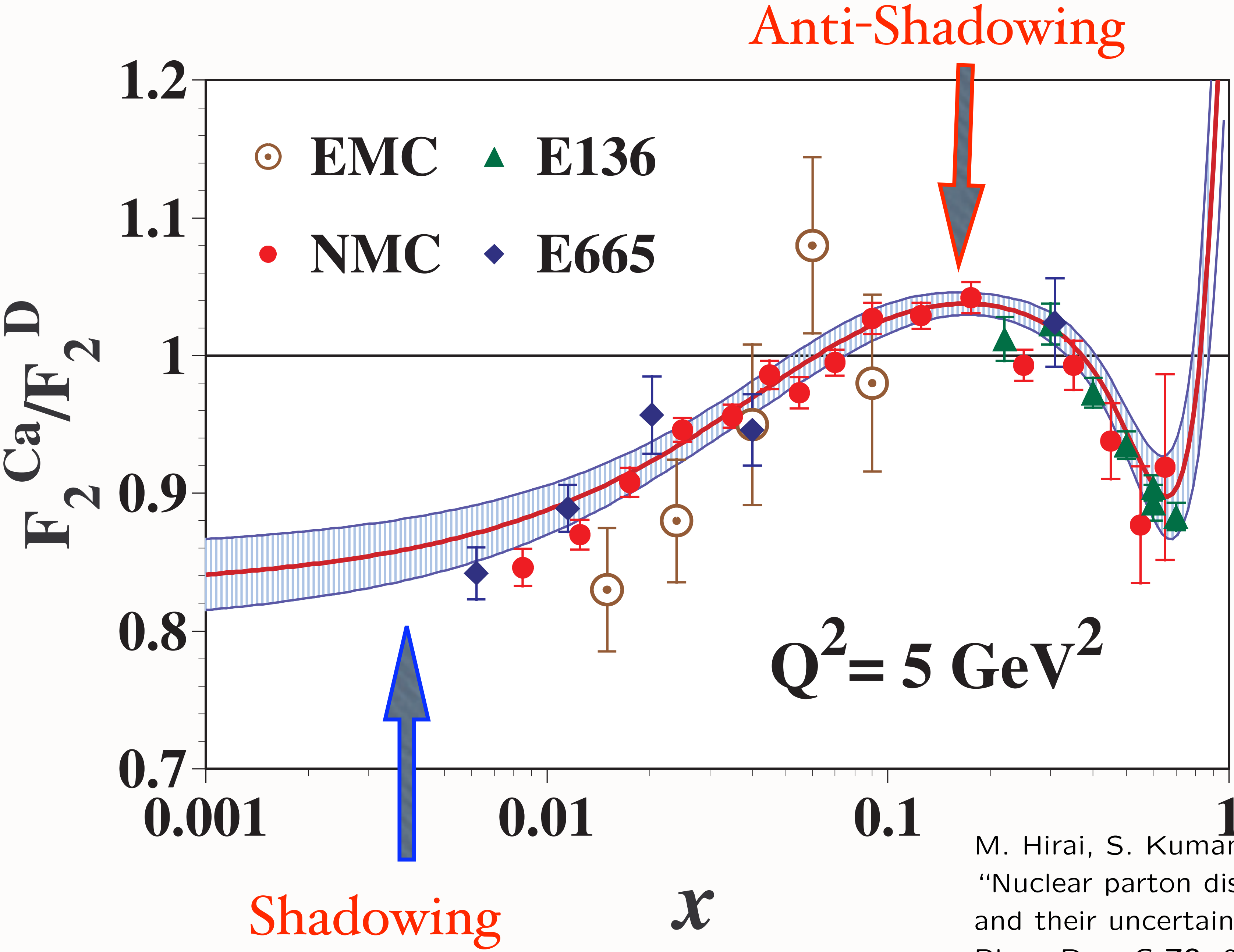
- Leading-twist Bjorken-scaling Diffractive DIS

- Diffractive Electroproduction; Color Transparency

- DIS at high energy reflects interactions of color-dipole of virtual photon with proton and nucleus: shadowing, saturation:

- Breakdown of parton model concepts: Structure functions are not probability distributions

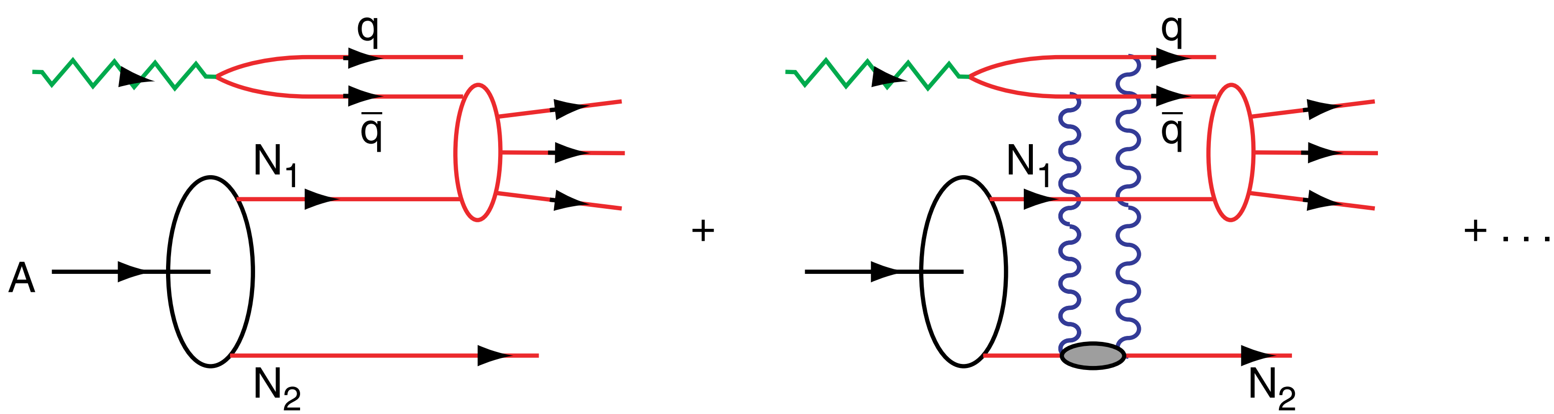
- Nuclear LFWFS are universal, but the measured nuclear parton distributions are not universal -- antishadowing is flavor-dependent



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].

Stodolsky
Pumplin, sjb
Gribov

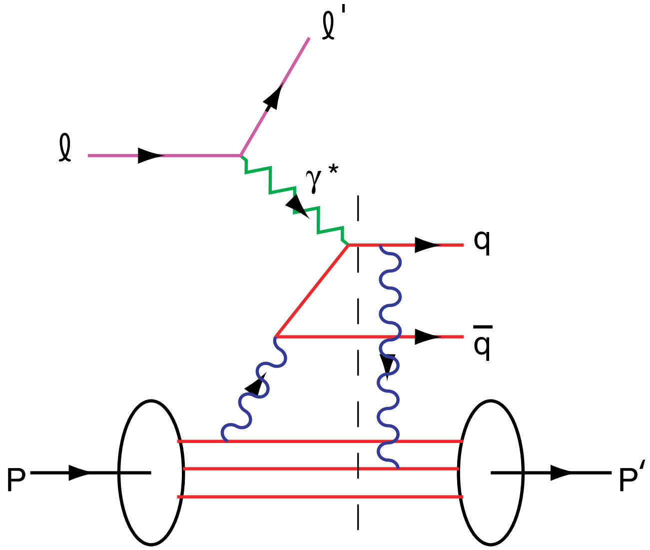
Nuclear Shadowing in QCD



Shadowing depends on understanding leading twist-diffraction in DIS

Nuclear Shadowing not included in nuclear LFWF !

Dynamical effect due to virtual photon interacting in nucleus



Shadowing depends on leading-twist DDIS

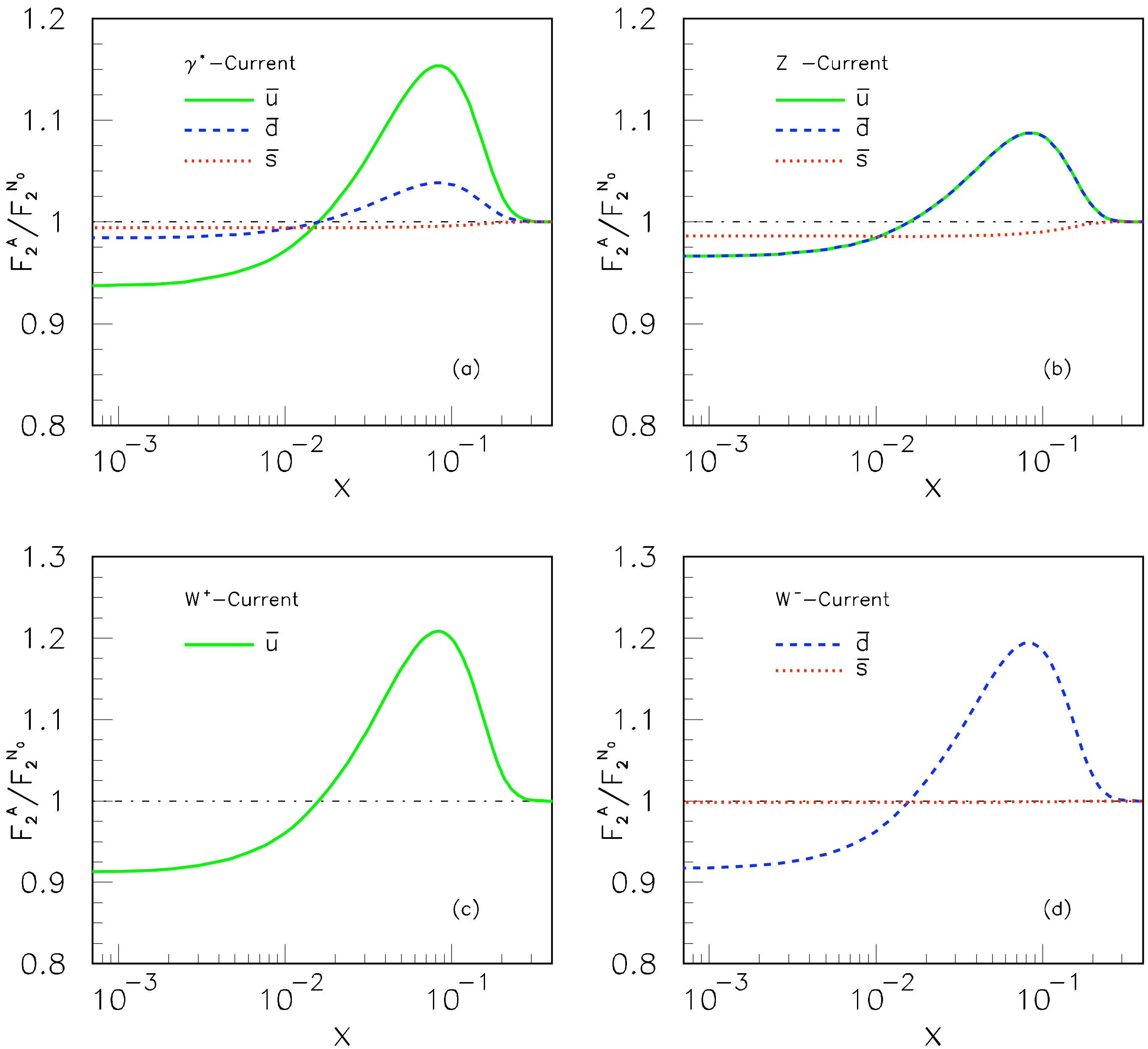
Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate Pomeron

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

Physics of FSI not in Wavefunction of Target

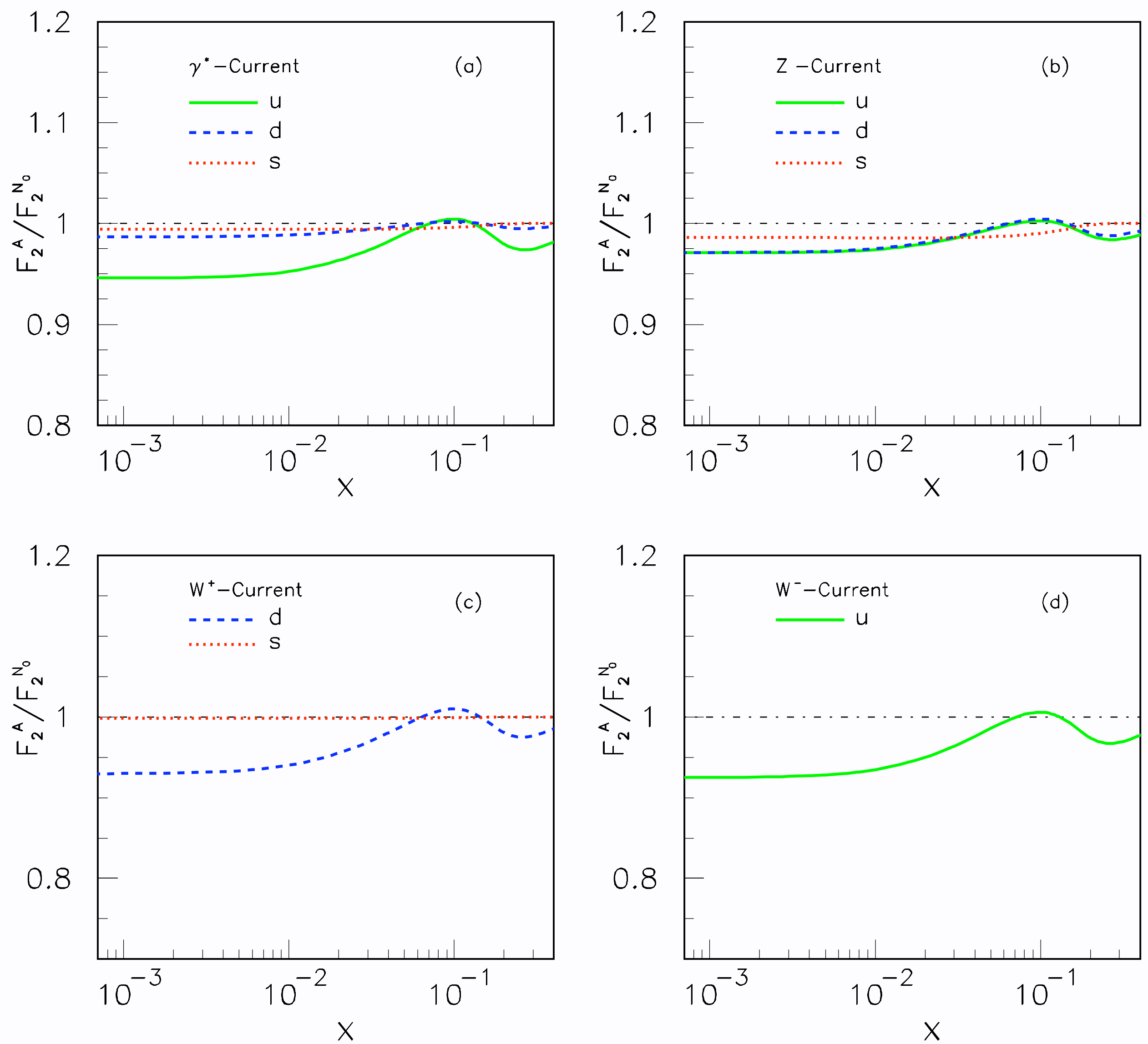
Antishadowing (Reggeon exchange) is not universal!



Schmidt, Yang; sjb

Nuclear Antishadowing not universal !

Shadowing and Antishadowing of DIS Structure Functions



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

Modifies NuTeV extraction of $\sin^2\theta_W$

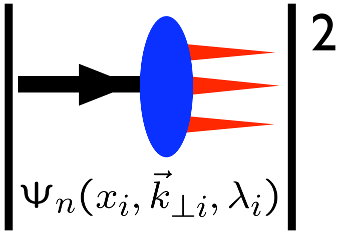
Test in flavor-tagged lepton-nucleus collisions

Physics of Rescattering

- Diffractive DIS
- Non-Unitary Correction to DIS: Structure functions are not probability distributions
- Nuclear Shadowing, Antishadowing- Not in Target WF
- Single Spin Asymmetries -- opposite sign in DY and DIS
- DY angular distribution at leading twist from double ISI-- not given by PQCD factorization -- breakdown of factorization!
- Wilson Line Effects not 1 even in LCG
- Must correct hard subprocesses for initial and final-state soft gluon attachments
- Corrections to Handbag Approximation in DVCS

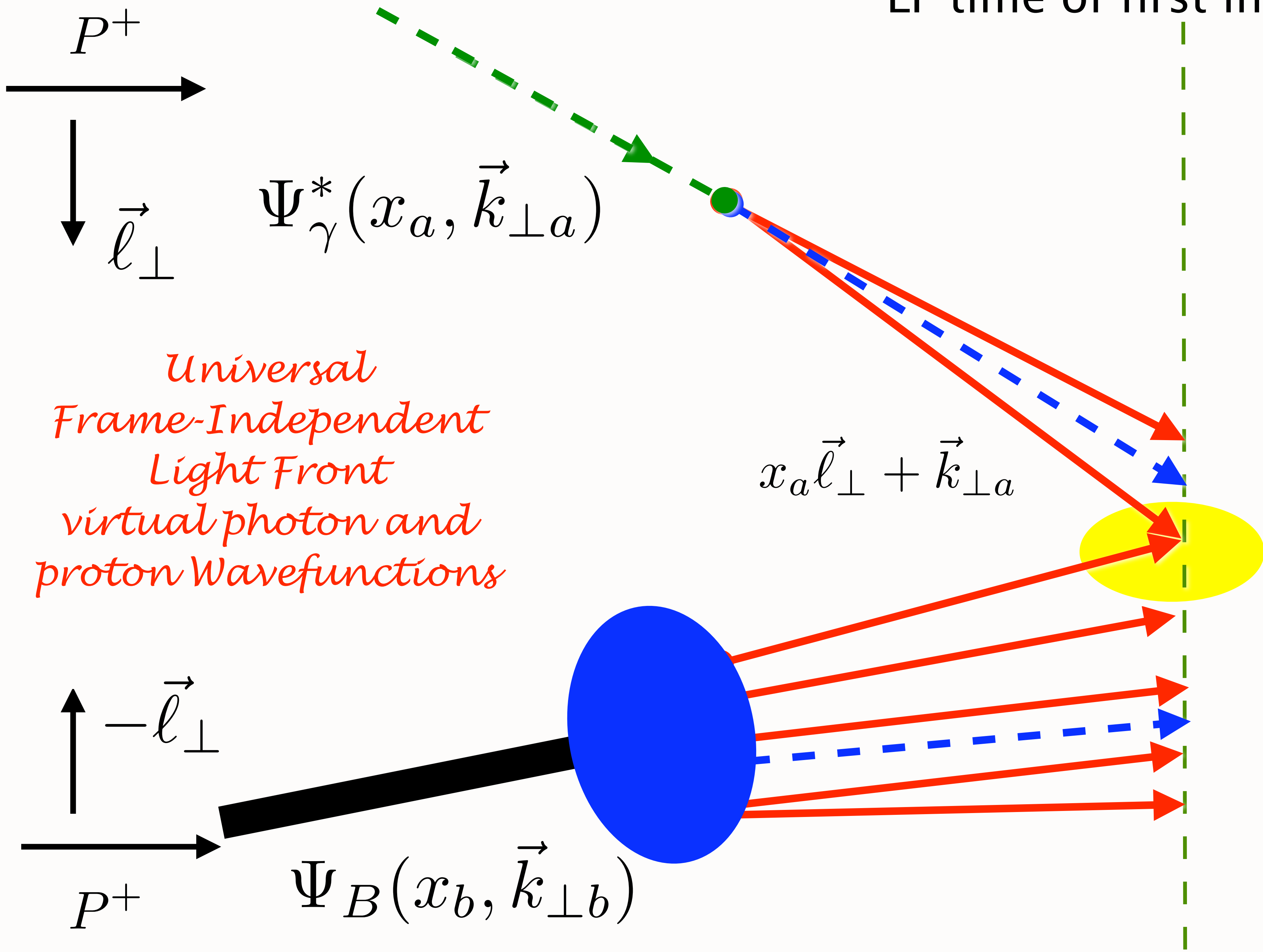
Hoyer, Marchal, Peigne, Sannino, sjb

Static vs. Dynamic Structure Functions



Static	Dynamic
Square of Target LFWFs	Modified by Rescattering: ISI & FSI
No Wilson Line	Contains Wilson Line, Phases
Probability Distributions	No Probabilistic Interpretation
Process-Independent	Process-Dependent - From Collision
T-even Observables	T-Odd (Sivers, Boer-Mulders, etc.)
No Shadowing, Anti-Shadowing	Shadowing, Anti-Shadowing, Saturation
Sum Rules: Momentum and J^z	Not Proven
DGLAP Evolution; mod. at large x	DGLAP Evolution
No Diffractive DIS	Hard Pomeron and Odderon: DDIS

LF time of first interaction

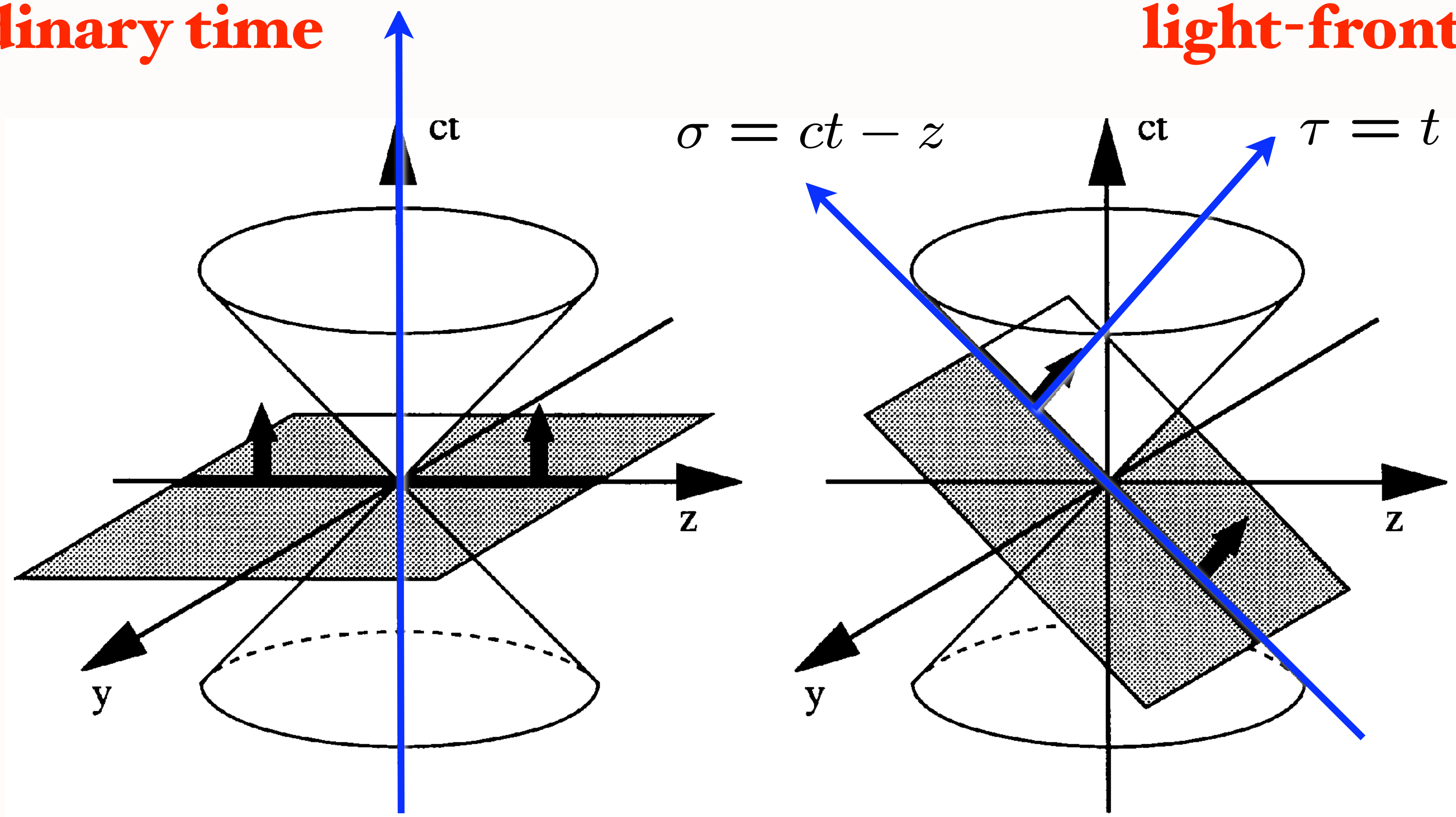


P.A.M Dirac, Rev. Mod. Phys. 21, 392 (1949)

Dirac's Amazing Idea: The Front Form

Evolve in ordinary time

Evolve in light-front time!



Instant Form **Front Form**

Each element of flash photograph illuminated at same LF time

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

Evolve in LF time

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

Eigenstate -- independent of τ

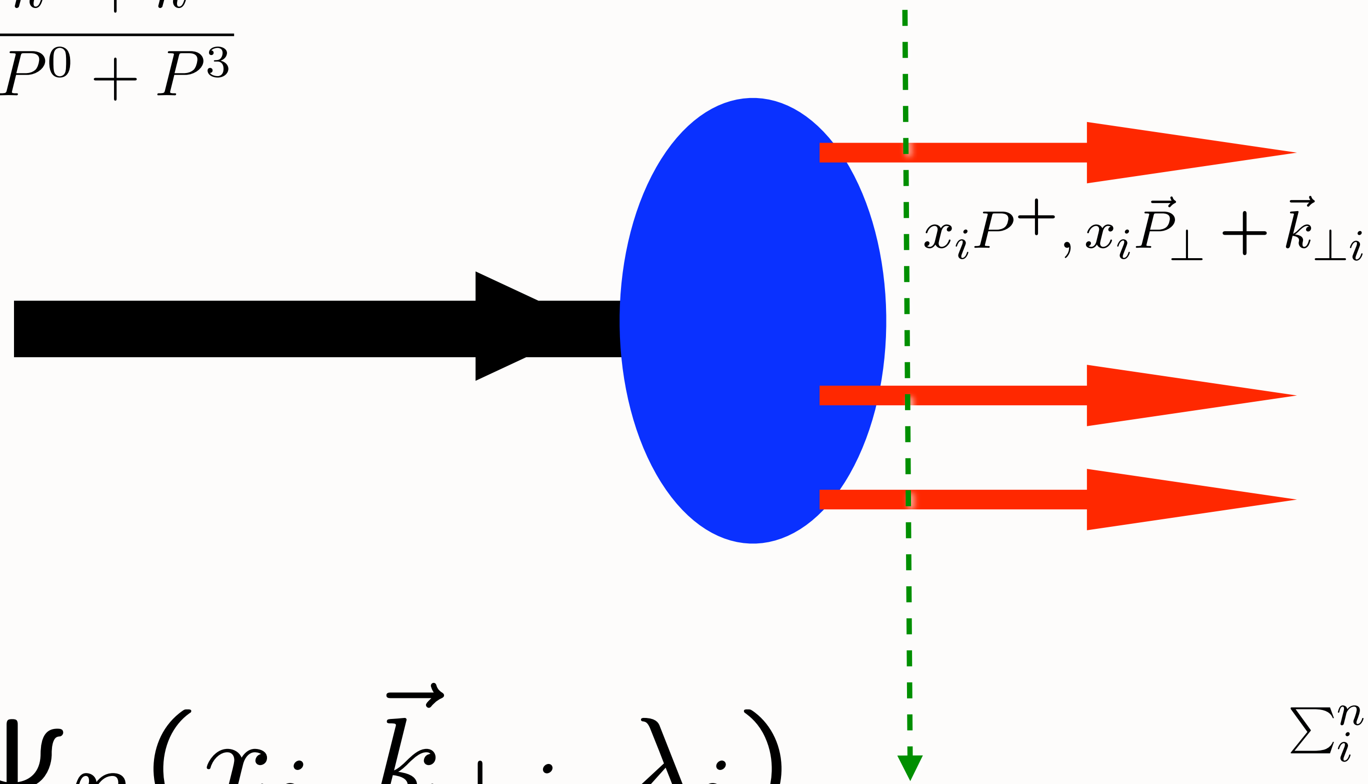
HELEN BRADLEY - PHOTOGRAPHY

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

Fixed $\tau = t + z/c$

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

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



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

$\sum_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

Light-Front Wavefunctions

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

$$\psi(x, k_\perp) \qquad x_i = \frac{k_i^+}{P^+}$$

Invariant under boosts. Independent of P^μ

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

Direct connection to QCD Lagrangian

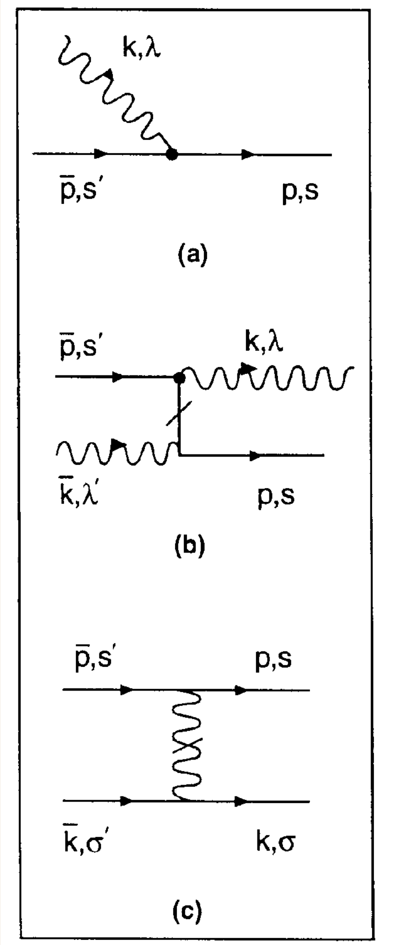
Remarkable new insights from AdS/CFT, the duality between conformal field theory and Anti-de Sitter Space

Light-Front QCD

Heisenberg Matrix Formulation

Physical gauge: $A^+ = 0$

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



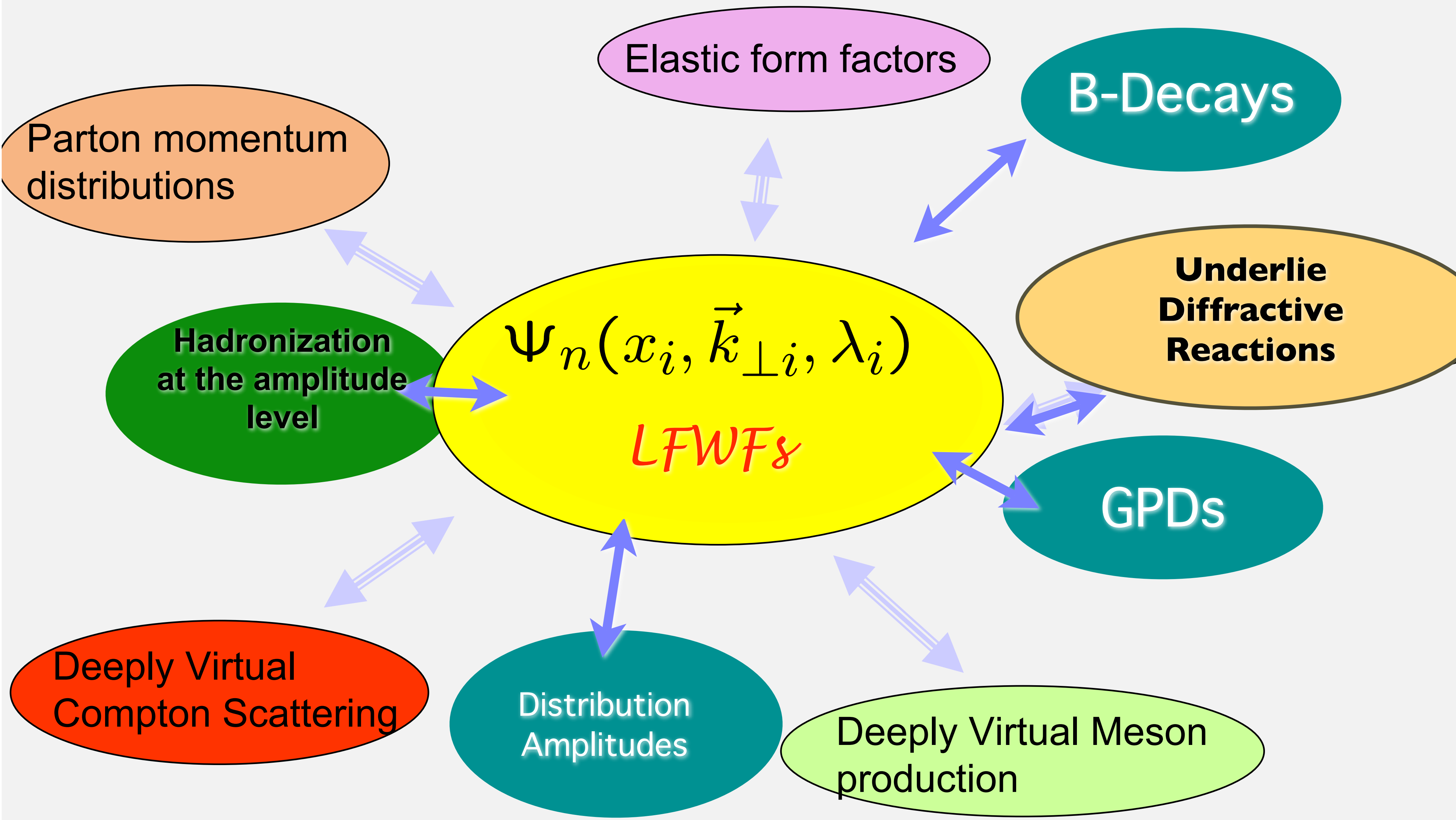
$$H^{QCD}_{LF} = \sum_i [\frac{m^2 + k^2_\perp}{x}]_i + H^{int}_{LF}$$

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

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

Eigenvalues and Eigensolutions give Hadron Spectrum and Light-Front wavefunctions

A Unified Description of Hadron Structure



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

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

The Light Front Fock State Wavefunctions

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

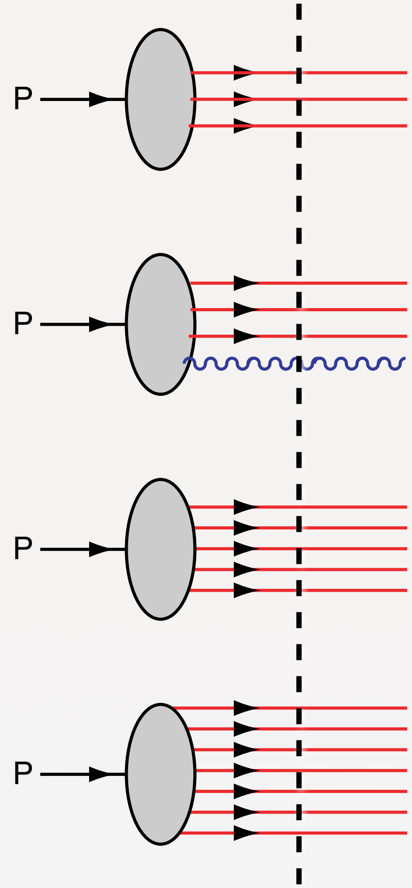
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

The light-cone momentum fraction

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

are boost invariant.

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



Fixed LF time

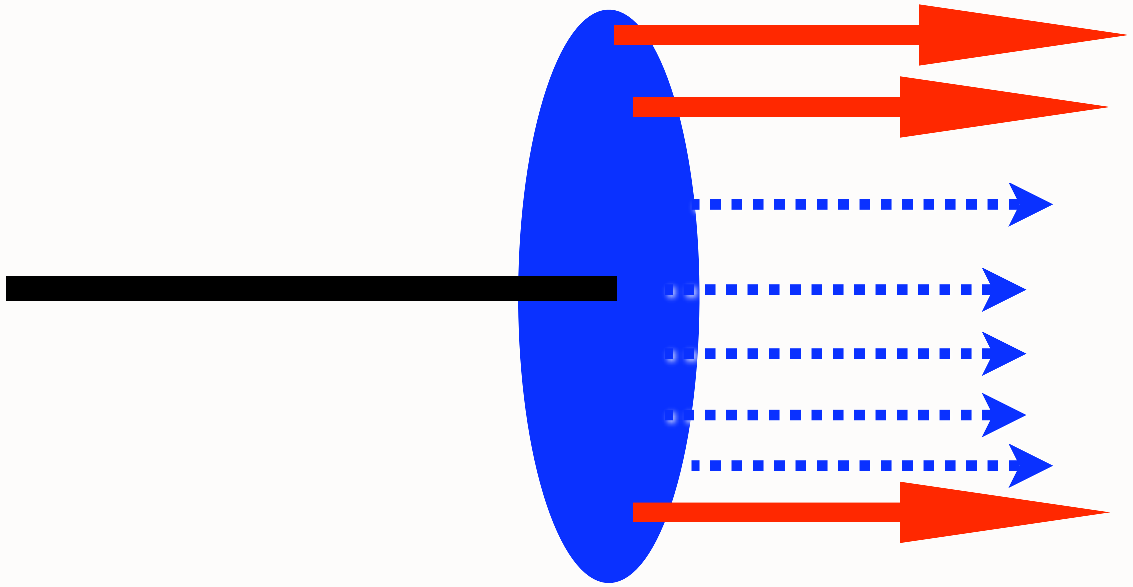
Intrinsic heavy quarks,

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

Soft gluons in the infinite momentum wave function and the BFKL **pomeron.**
Alfred H. Mueller (SLAC & Columbia U.) . SLAC-PUB-10047, CU-TP-609, Aug 1993. 12pp.
Published in **Nucl.Phys.B415:373-385,1994**.

Light cone wave functions at small x.
F. Antonuccio (Heidelberg, Max Planck Inst. & Heidelberg U.) , S.J. Brodsky (SLAC) , S. Dalley (CERN) .
Phys.Lett.B412:104-110,1997.
e-Print: **hep-ph/9705413**

Mueller: BFKL derived from multi-gluon Fock State



Antonuccio, Dalley, sjb: Ladder Relations

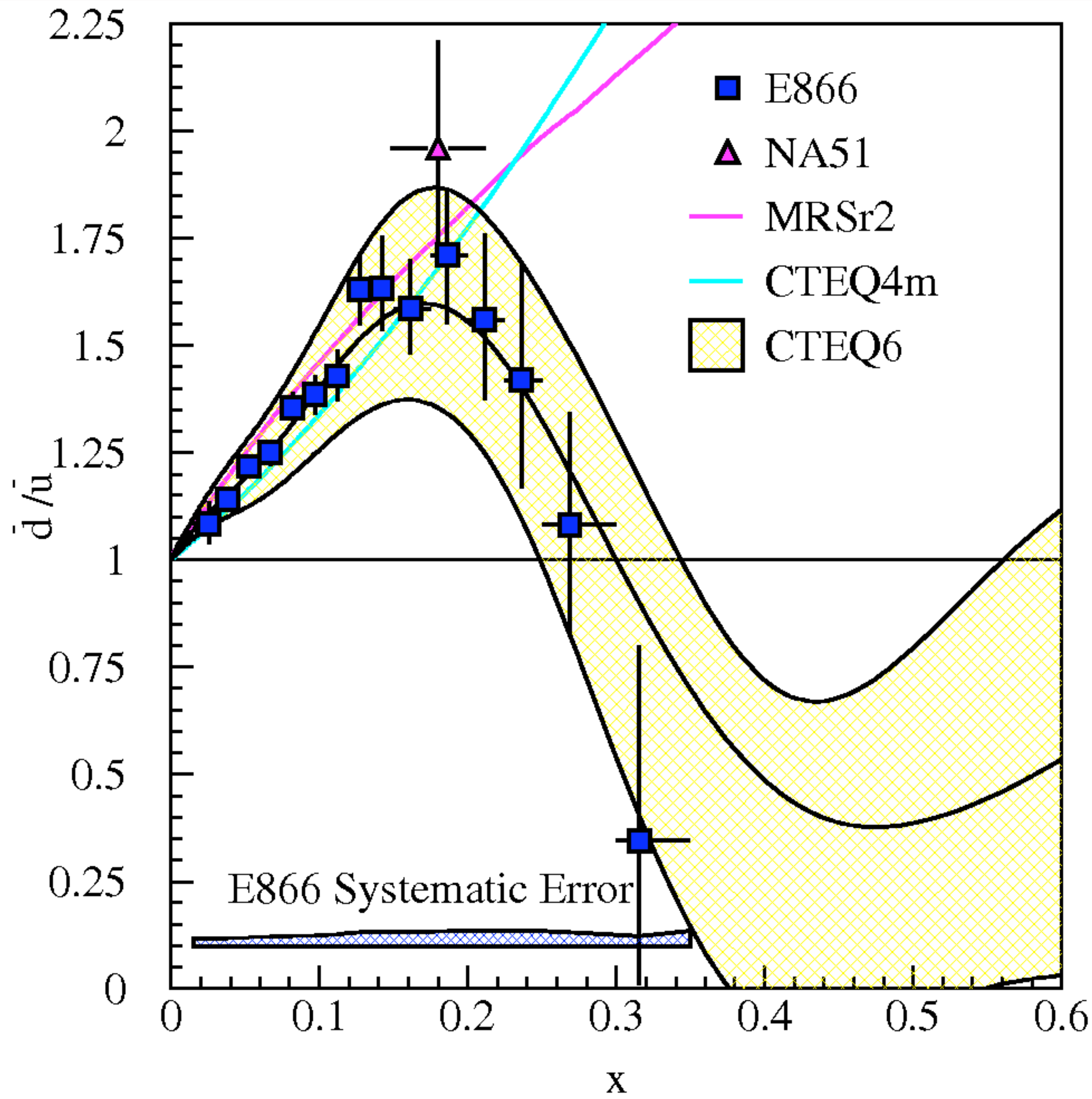
$\bar{d}(x)/\bar{u}(x)$ for $0.015 \leq x \leq 0.35$

- E866/NuSea (Drell-Yan)

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

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

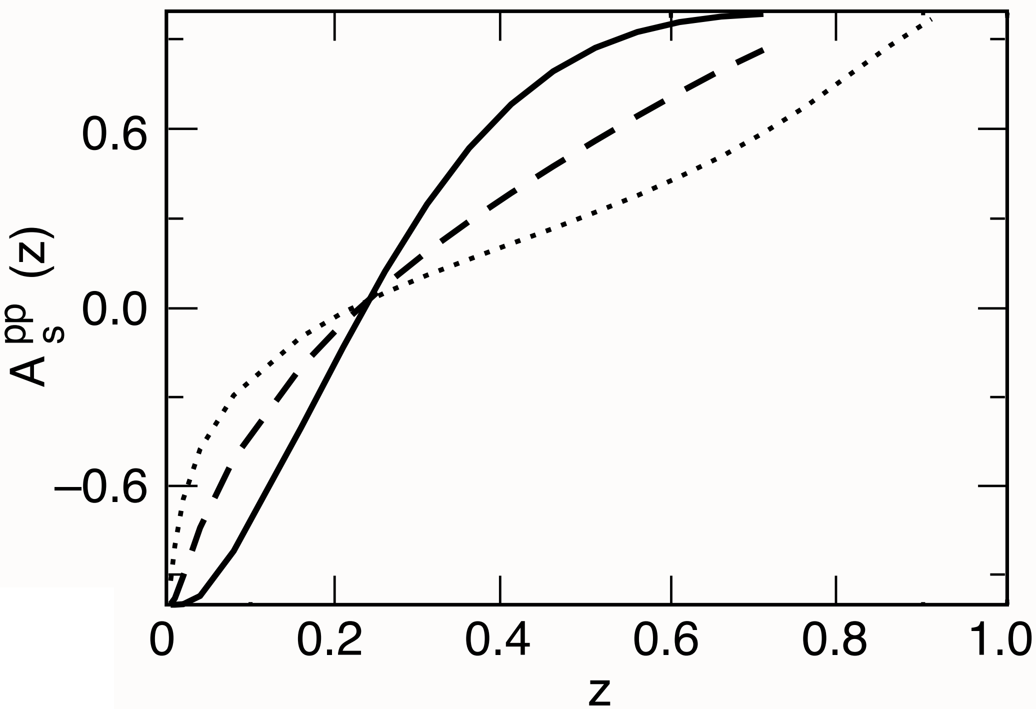
Intrinsic glue, sea, heavy quarks



Compare protons versus anti-proton in $\bar{s}$ current quark fragmentation

$$D_{s\to p}(z) \neq D_{s\to\bar{p}}(z)$$

Tag s quark via high x_F Λ production in proton fragmentation region.



B.Q. Ma and sjb

$$A_s^{p\bar{p}}(z) = \frac{D_{s\to p}(z) - D_{s\to\bar{p}}(z)}{D_{s\to p}(z) + D_{s\to\bar{p}}(z)}$$

Consequence of $s_p(x) \neq \bar{s}_p(x)$ $\quad |uuds\bar{s}> \simeq |K^+\Lambda>$

Angular Momentum on the Light-Front

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

Conserved
LF Fock state by Fock State

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

n-1 orbital angular momenta

Nonzero Anomalous Moment -->Nonzero orbital angular momentum

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

Drell, sjb

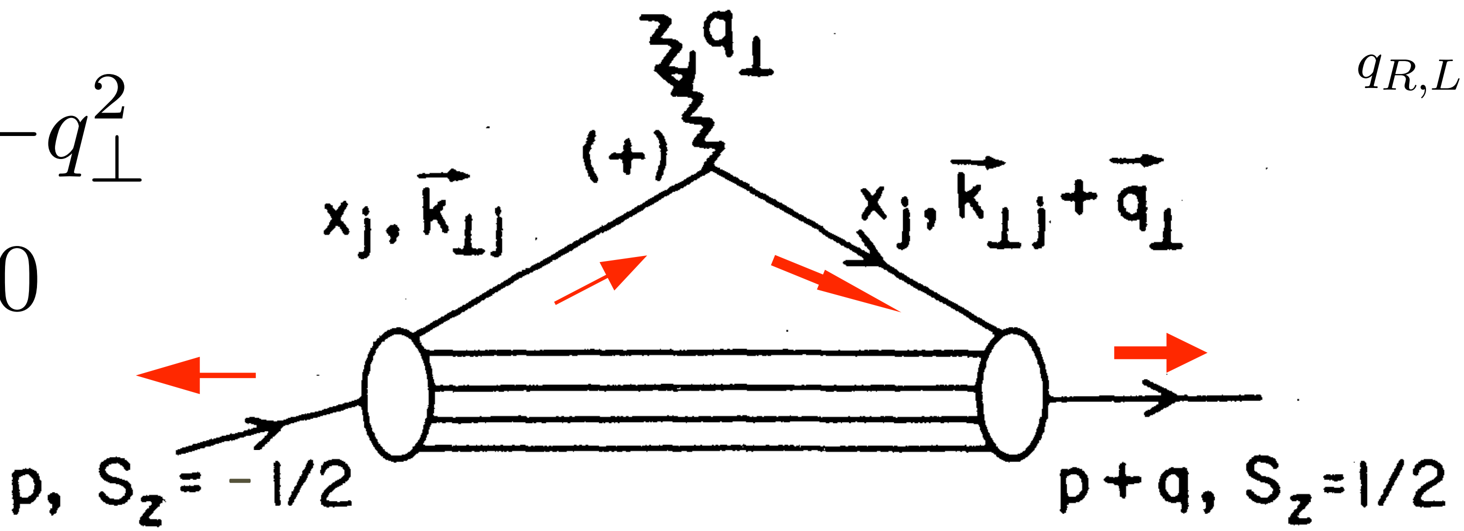
$$\left[-\frac{1}{q^L}\psi_a^{\uparrow *}(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\, \psi_a^{\downarrow}(x_i, \mathbf{k}_{\perp i}, \lambda_i) + \frac{1}{q^R}\psi_a^{\downarrow *}(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\, \psi_a^{\uparrow}(x_i, \mathbf{k}_{\perp i}, \lambda_i) \right]$$

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

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

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

$$q^+ = 0$$

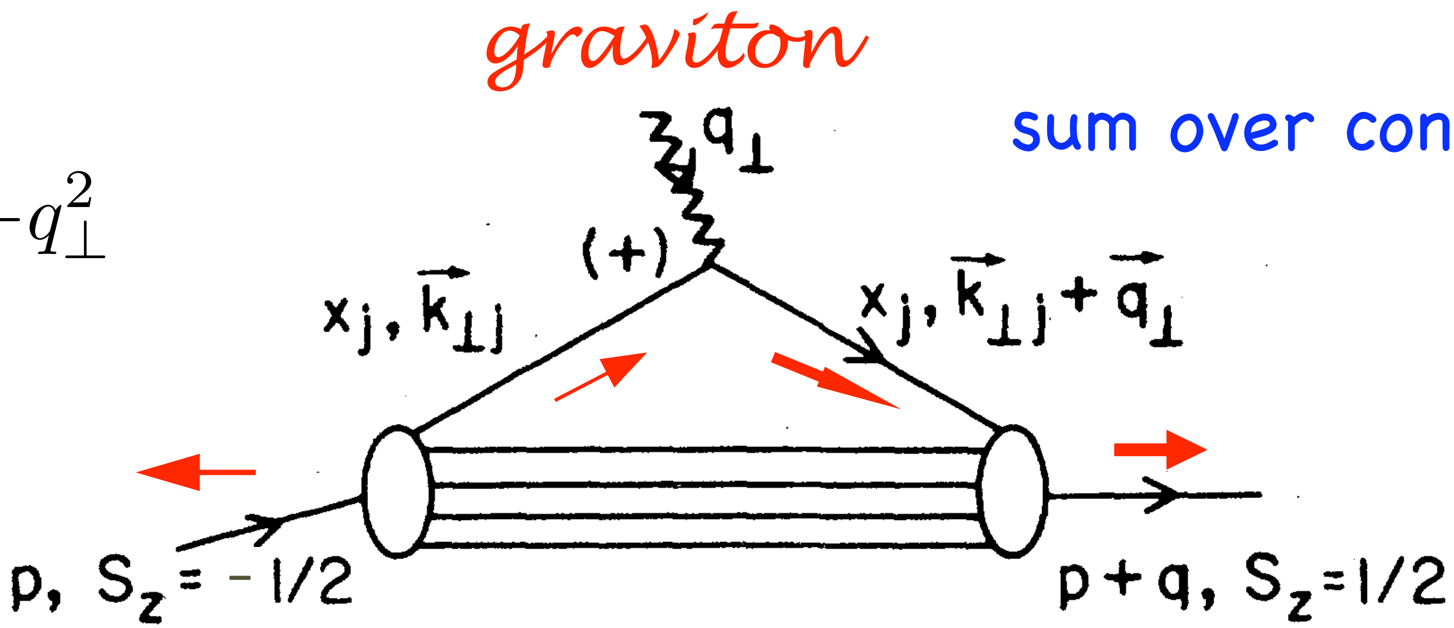


$\boxed{\text{Must have } \Delta\ell_z = \pm 1 \text{ to have nonzero } F_2(q^2)}$

Anomalous gravitomagnetic moment B(0)

Okun, Kobzarev, Teryaev: B(0) Must vanish because of Equivalence Theorem

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



sum over constituents

Hwang, Schmidt, sjb;
Holstein et al

$\boxed{B(0) = 0}$

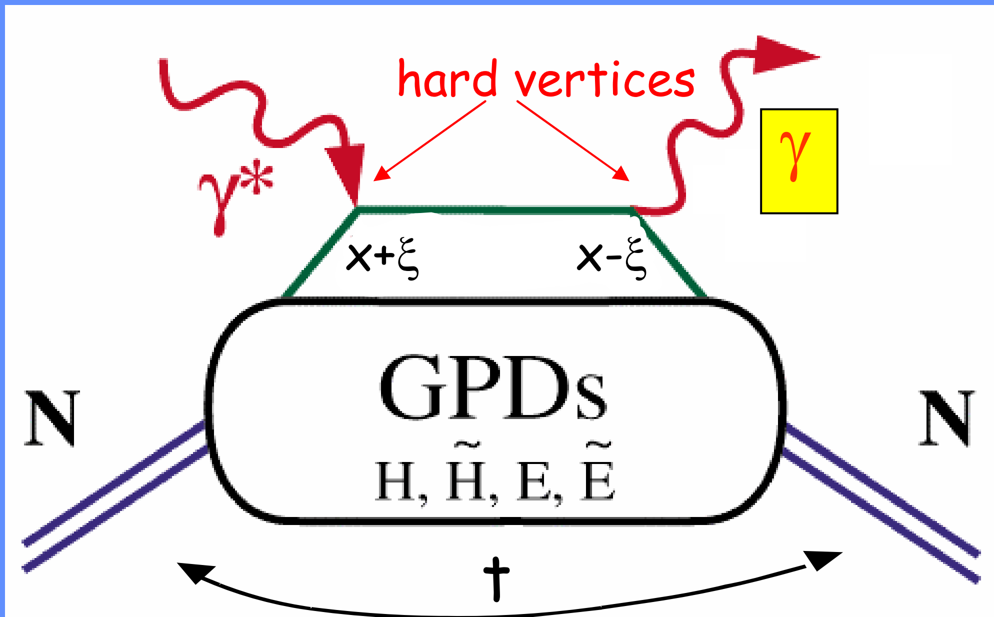
Each Fock State

Some Applications of Light-Front Wavefunctions

- Exact formulae for form factors, quark and gluon distributions; vanishing anomalous gravitational moment; edm connection to anm
- Deeply Virtual Compton Scattering, generalized parton distributions, angular momentum sum rules
- Exclusive weak decay amplitudes
- Single spin asymmetries: Role of ISI and FSI
- Factorization theorems, DGLAP, BFKL, ERBL Evolution
- Quark interchange amplitude
- Relation of spin, momentum, and other distributions to physics of the hadron itself.

GPDs & Deeply Virtual Exclusive Processes
- New Insight into Nucleon Structure

Deeply Virtual Compton Scattering (DVCS)



x – quark momentum fraction

ξ– longitudinal momentum transfer

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

$H(x,\xi,t), E(x,\xi,t), \ldots$ "Generalized Parton Distributions"

Quark angular momentum (Ji sum rule)

$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^{1} x\,dx \left[H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$

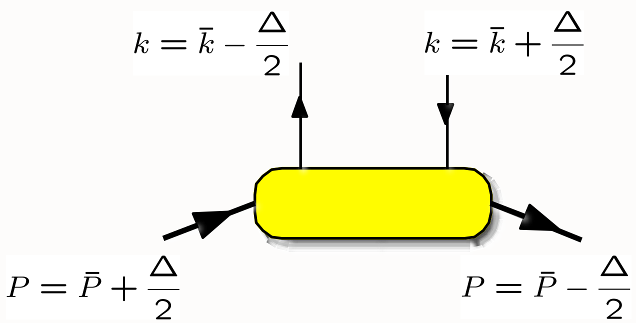
X. Ji, Phy.Rev.Lett.78,610(1997)

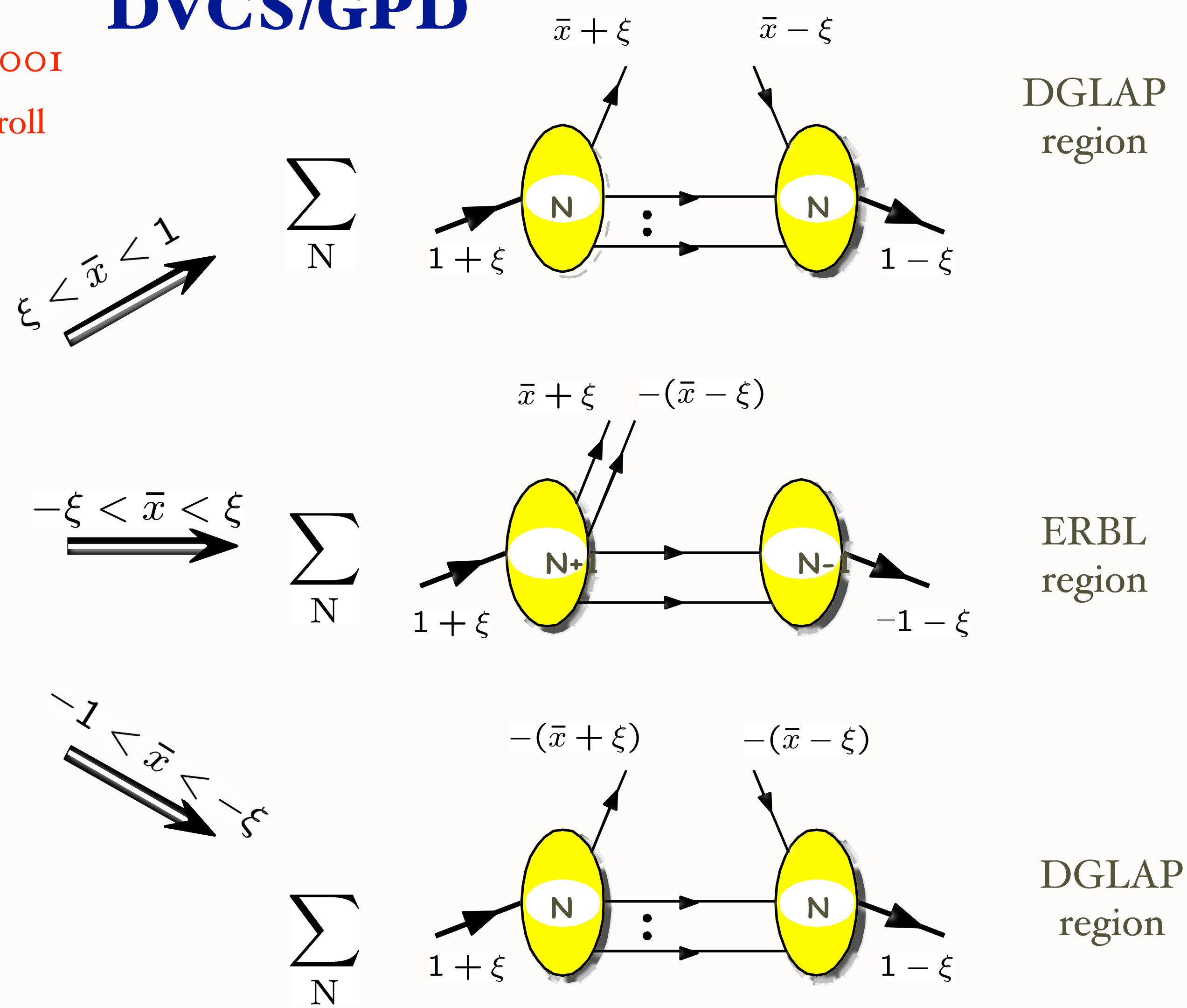
Light-Front Wave Function Overlap Representation

DVCS/GPD

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

Link to DIS and Elastic Form Factors

DIS at $\xi = t = 0$

$$H^q(x,0,0) = q(x), \quad -\bar{q}(-x)$$

$$\tilde{H}^q(x,0,0) = \Delta q(x), \quad \Delta\bar{q}(-x)$$

Form factors (sum rules)

$$\int_{-1}^{1} dx \sum_q \left[H^q(x,\xi,t)\right] = F_1(t) \quad \text{Dirac f.f.}$$

$$\int_{-1}^{1} dx \sum_q \left[E^q(x,\xi,t)\right] = F_2(t) \quad \text{Pauli f.f.}$$

$$\int_{-1}^{1} dx\, \tilde{H}^q(x,\xi,t) = G_{A,q}(t), \quad \int_{-1}^{1} dx\, \tilde{E}^q(x,\xi,t) = G_{P,q}(t)$$

$$H^q, E^q, \tilde{H}^q, \tilde{E}^q(x,\xi,t)$$

Verified using LFWFs
Diehl, Hwang, sjb

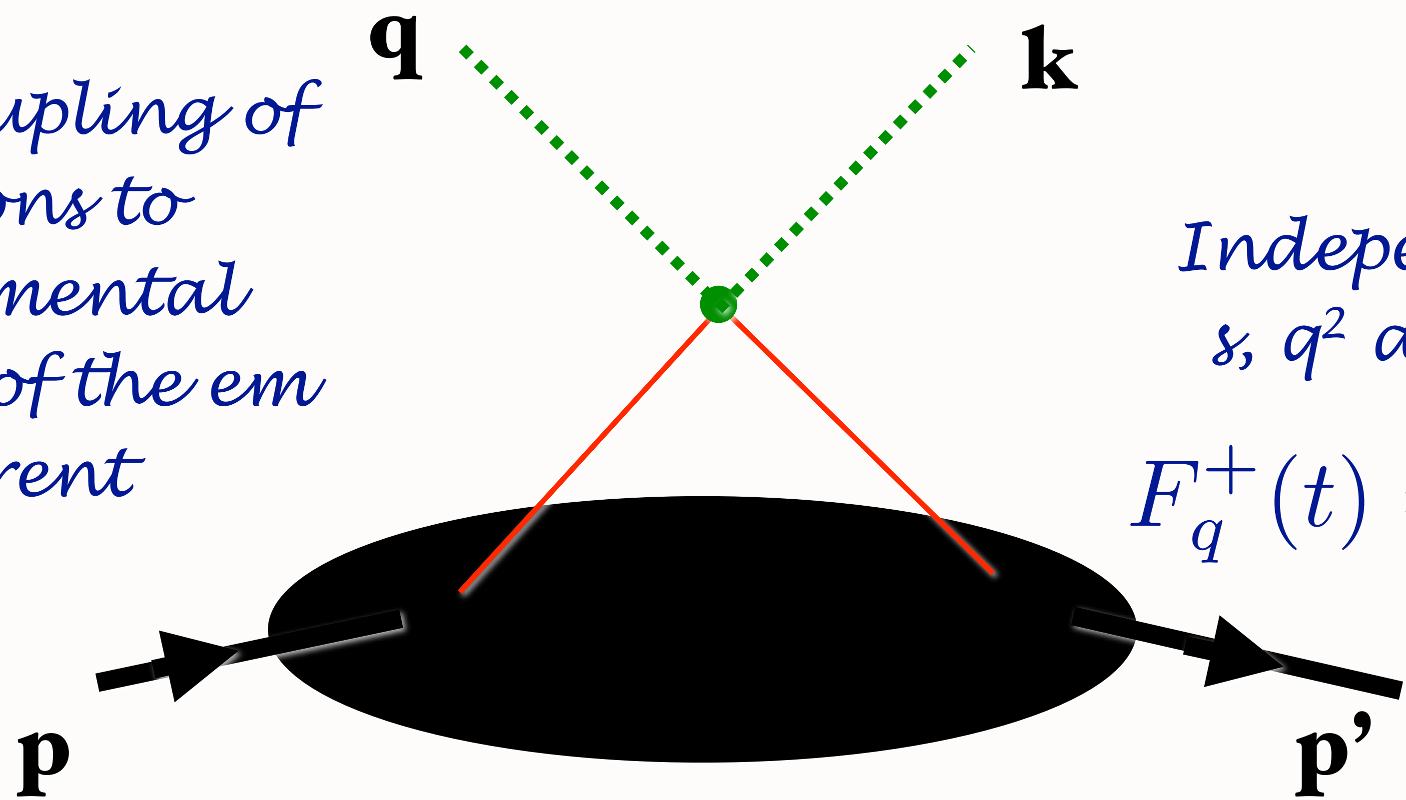
Quark angular momentum (Ji's sum rule)

$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^{1} x\,dx \left[H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$

X. Ji, Phy.Rev.Lett.78,610(1997)

'Seagull' contribution to real and virtual Compton scattering

Local coupling of photons to fundamental carriers of the em current

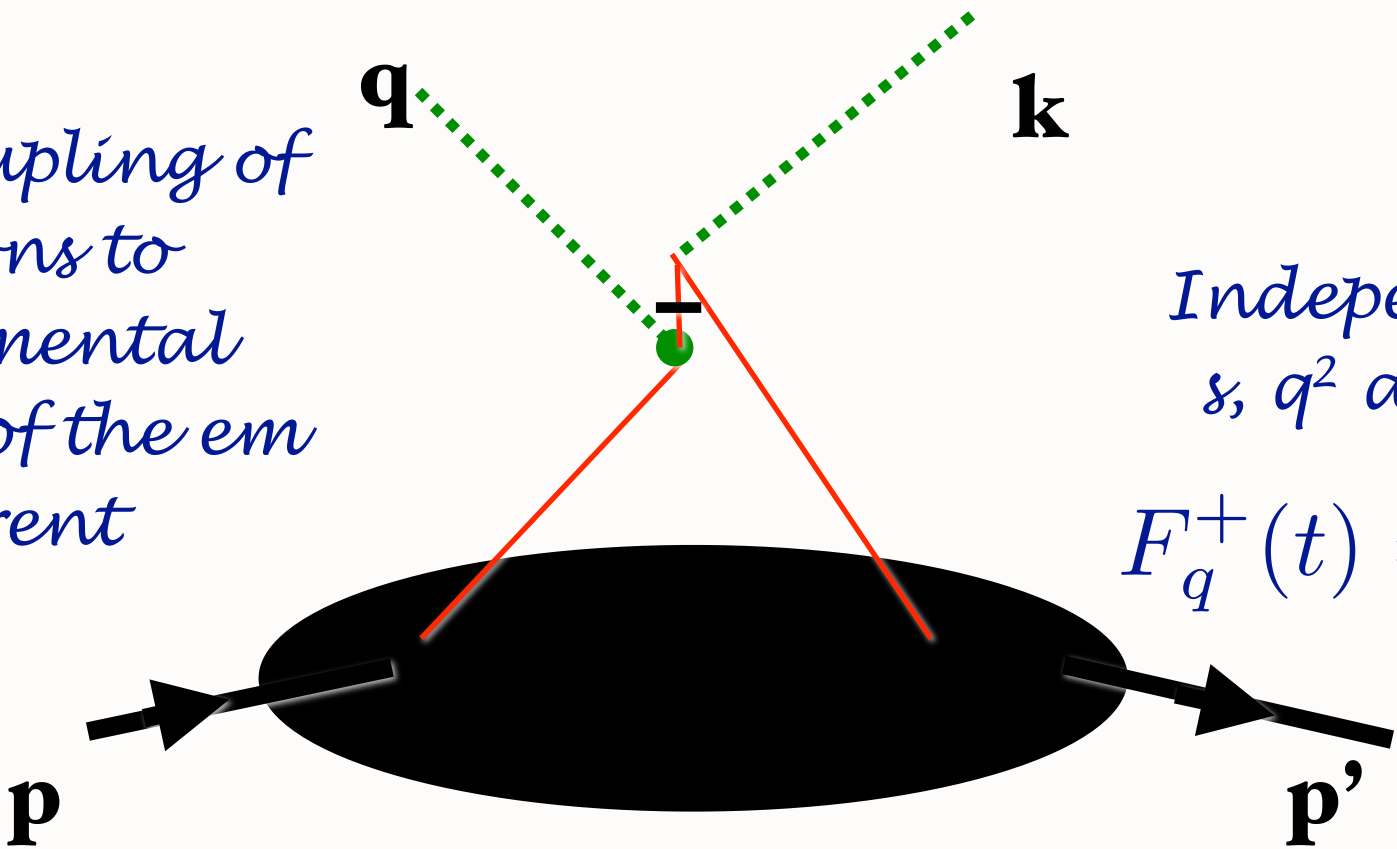


Independent of s, q^2 at fixed t

$$F_q^+(t) = < \frac{1}{x} >$$

$$M = -2 \sum_{q/p} e_q^2 F_q^+(t) \vec{\epsilon} \cdot \vec{\epsilon}'$$

Instantaneous fermion exchange contribution to real and virtual Compton scattering

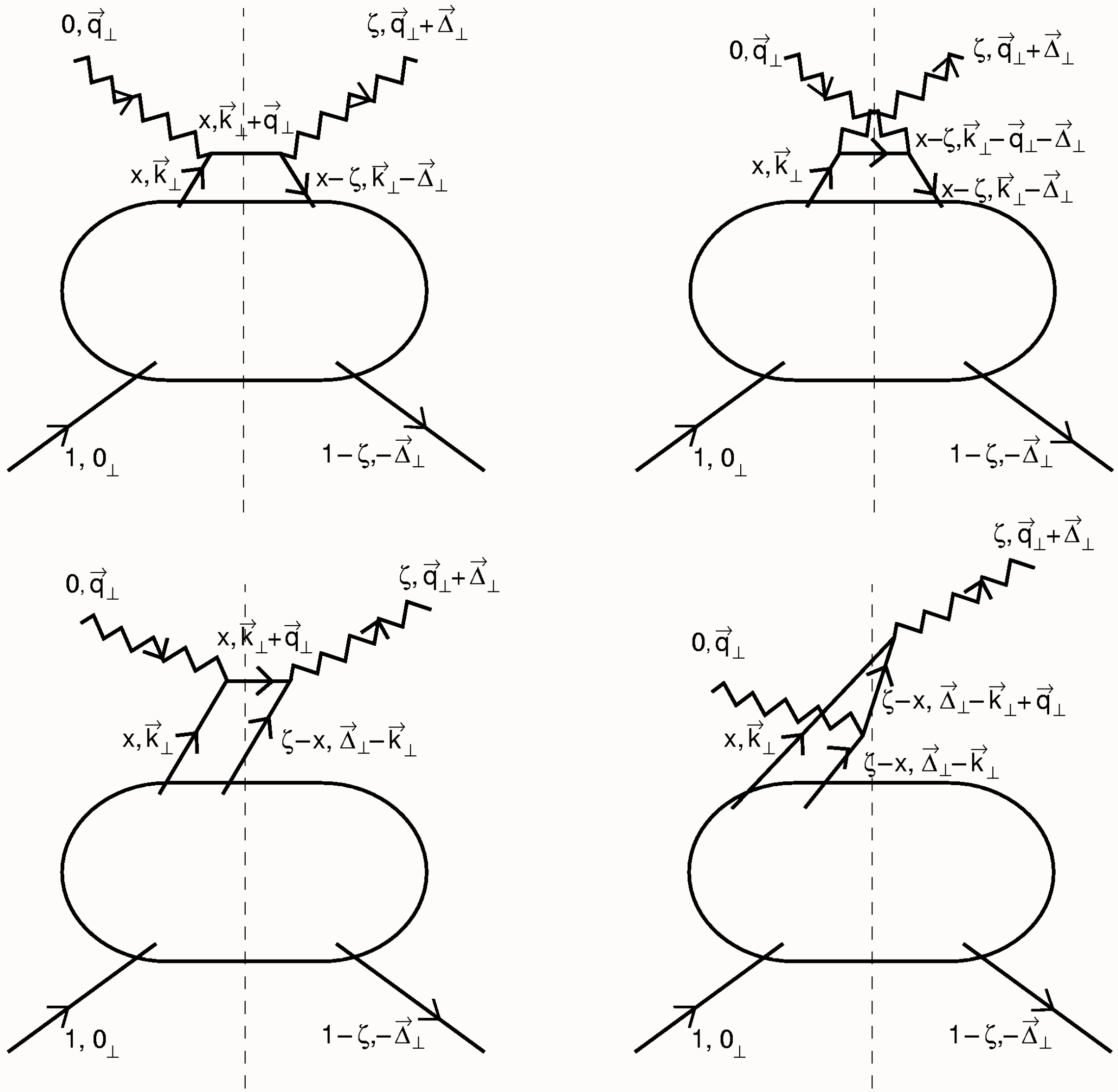


Local coupling of photons to fundamental carriers of the em current

Independent of s, q² at fixed t

$$F_q^+(t) = < \frac{1}{x} >$$

$$M = -2 \sum_{q/p} e_q^2 F_q^+(t) \vec{\epsilon} \cdot \vec{\epsilon}'$$



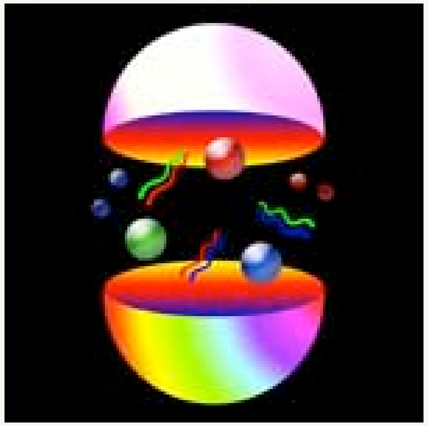
$$A_{J=0} \sim e_q^2 s^0 F(t)$$

Local J=0 fixed pole contribution

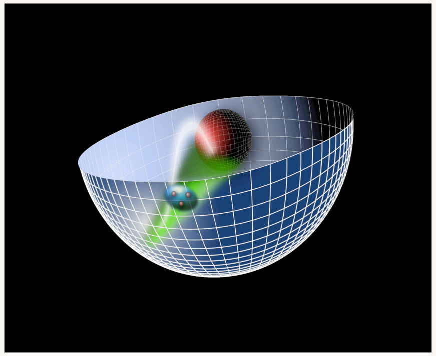
Close, Gunion, sjb; Szczepaniak, Llanes-Estrada, sjb

Light-cone wavefunction representation of deeply virtual Compton scattering ☆

Stanley J. Brodsky [a], Markus Diehl [a,1], Dae Sung Hwang [b]

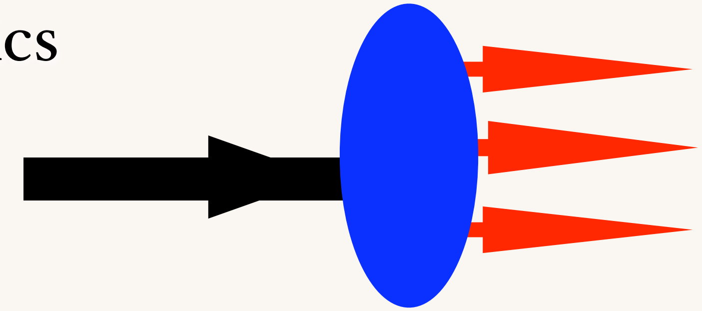


- Quarks and Gluons:
  Fundamental constituents of hadrons and nuclei
- *Quantum Chromodynamics (QCD)*
- New Insights from higher space-time dimensions: *AdS/QCD*

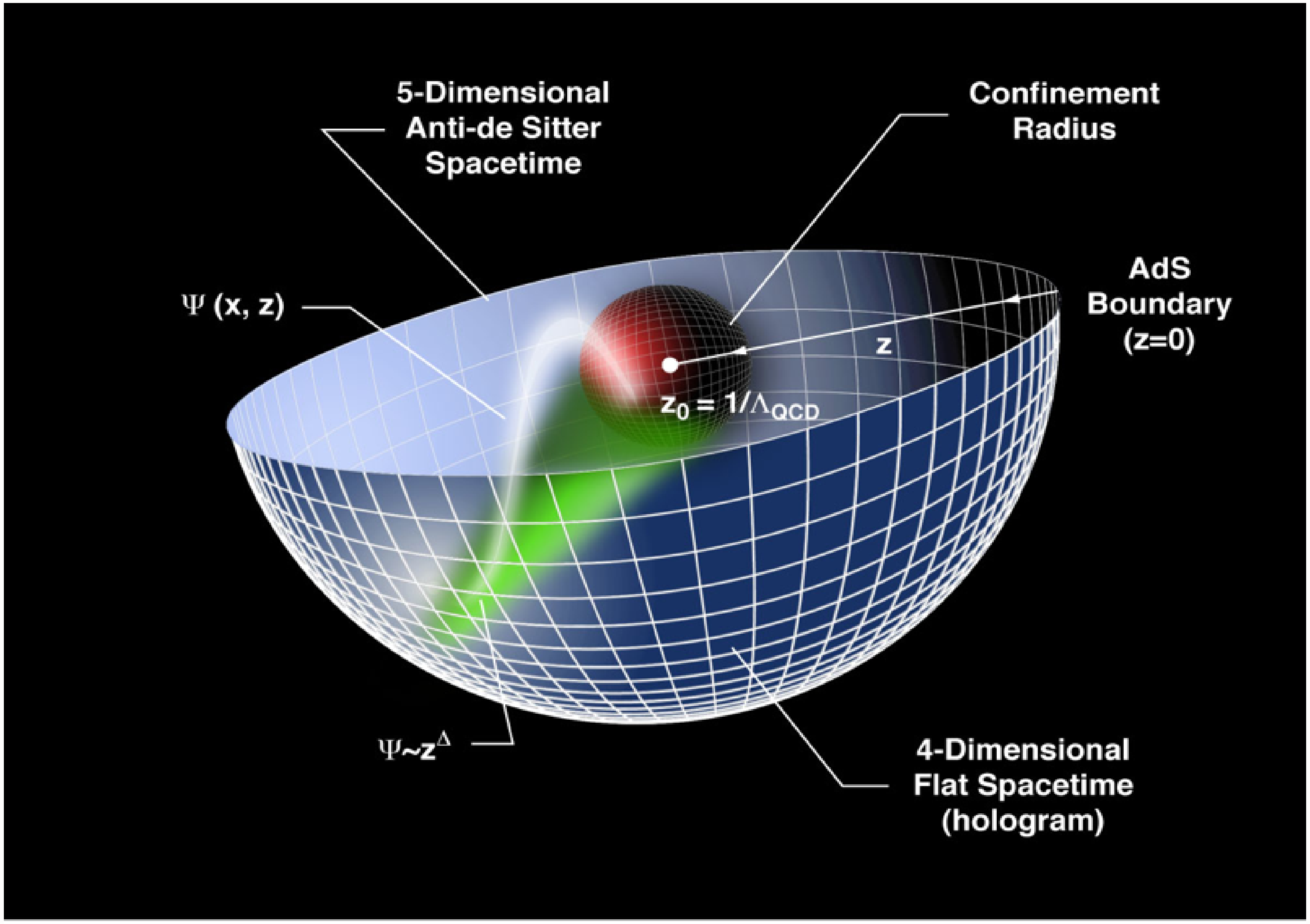


- *Light-Front Holography*
- *Hadronization at the Amplitude Level*
- *Light Front Wavefunctions:* analogous to the Schrodinger wavefunctions of atomic physics

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



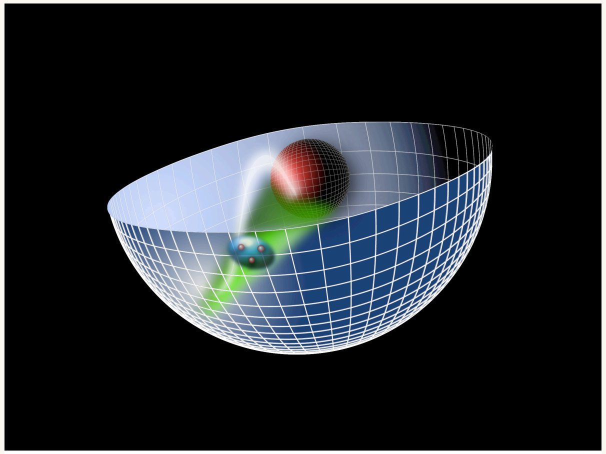
Applications of AdS/CFT to QCD



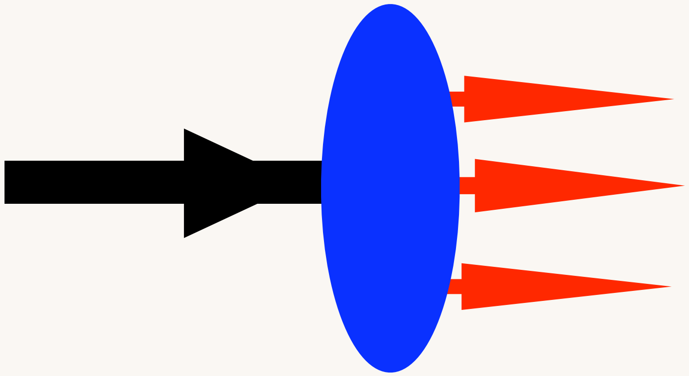
Changes in physical length scale mapped to evolution in the 5th dimension z

in collaboration with Guy de Teramond

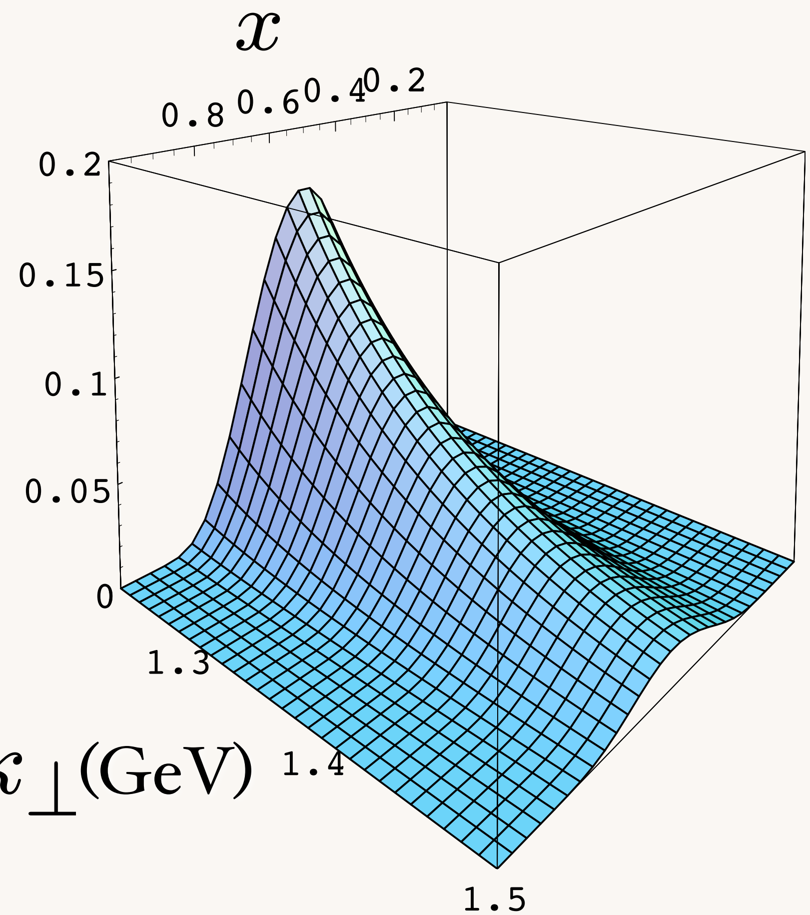
$\phi(z)$



- *Light-Front Holography*



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



- *Light Front Wavefunctions:*

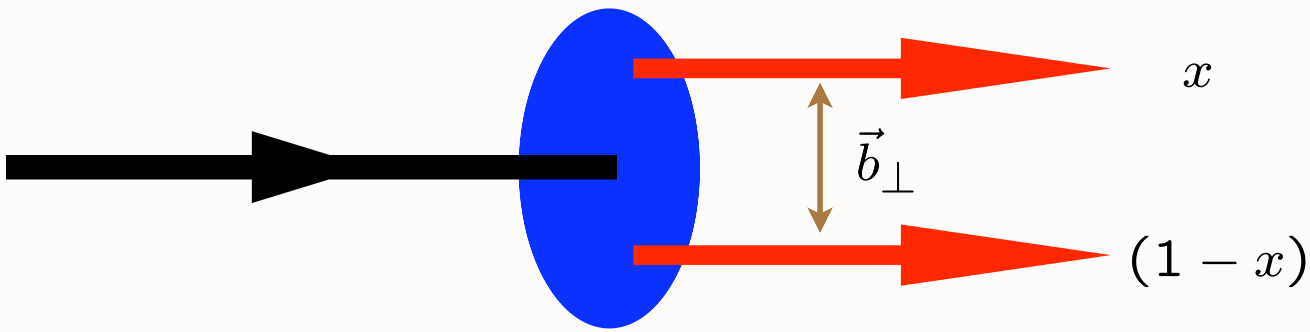
  Schrödinger Wavefunctions
  of Hadron Physics

LF(3+1) AdS5

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

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

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



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

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

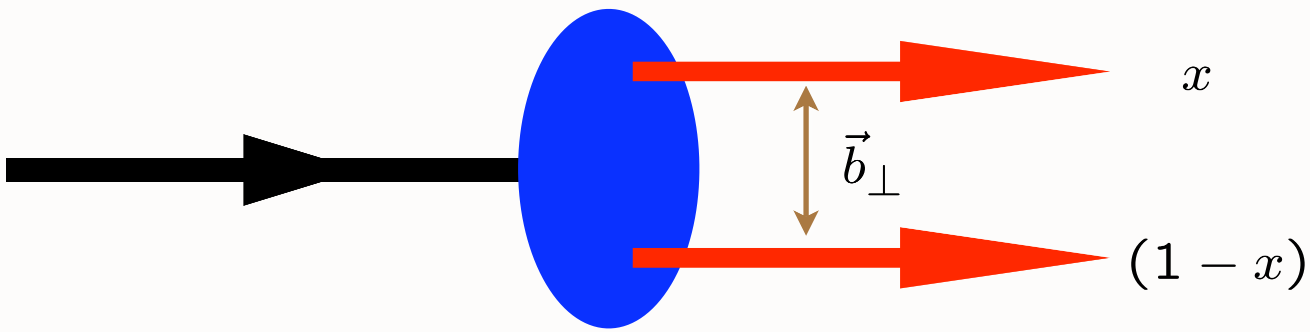
Light-Front Holography: Map AdS/CFT to 3+1 LF Theory

Relativistic LF radial equation

Frame Independent

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

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



$$U(\zeta)=\kappa^4\zeta^2$$

soft wall confining potential:

G. de Teramond, sjb

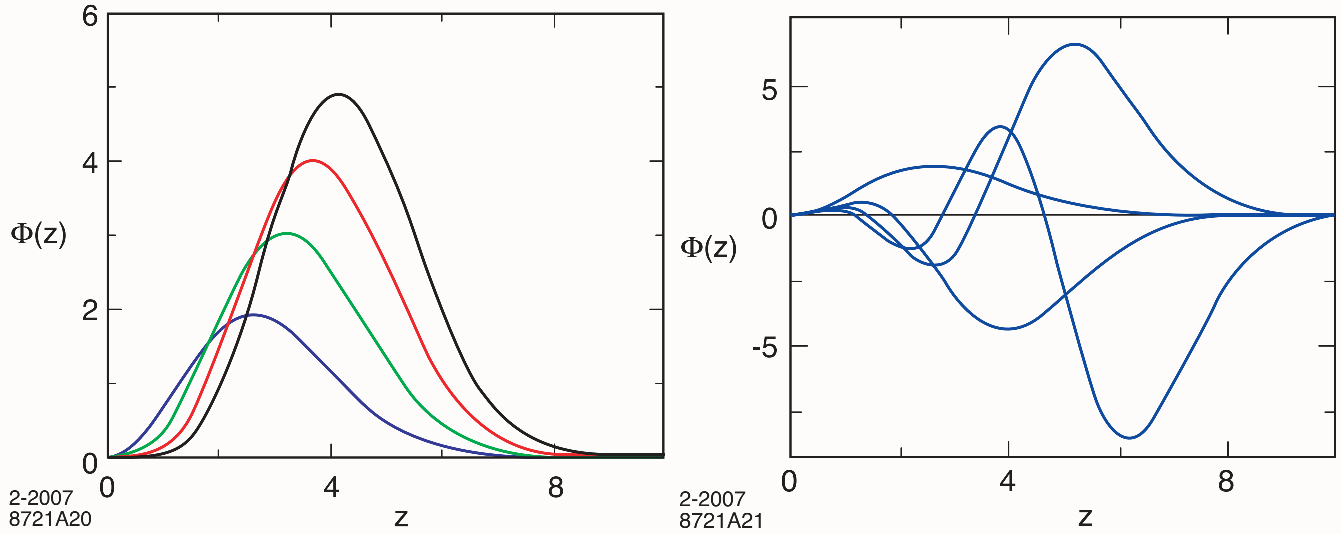
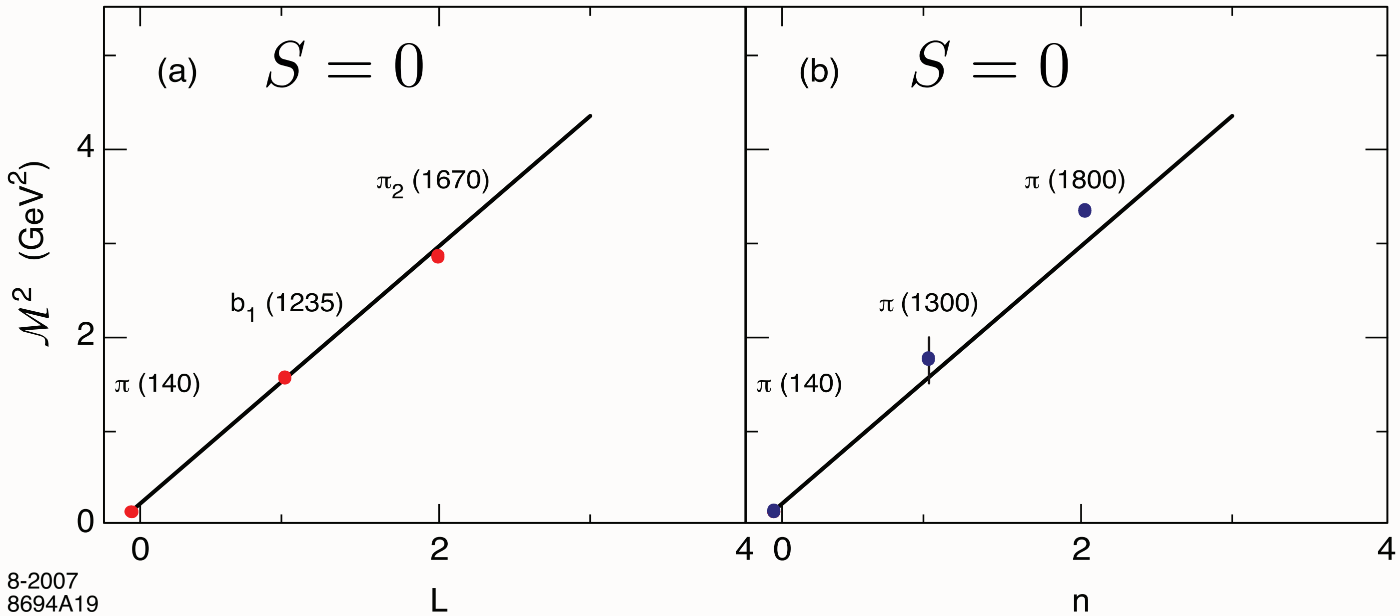


Fig: Orbital and radial AdS modes in the soft wall model for κ = 0.6 GeV .

Soft Wall Model



Light meson orbital (a) and radial (b) spectrum for $\kappa = 0.6$ GeV.

Soft-wall model

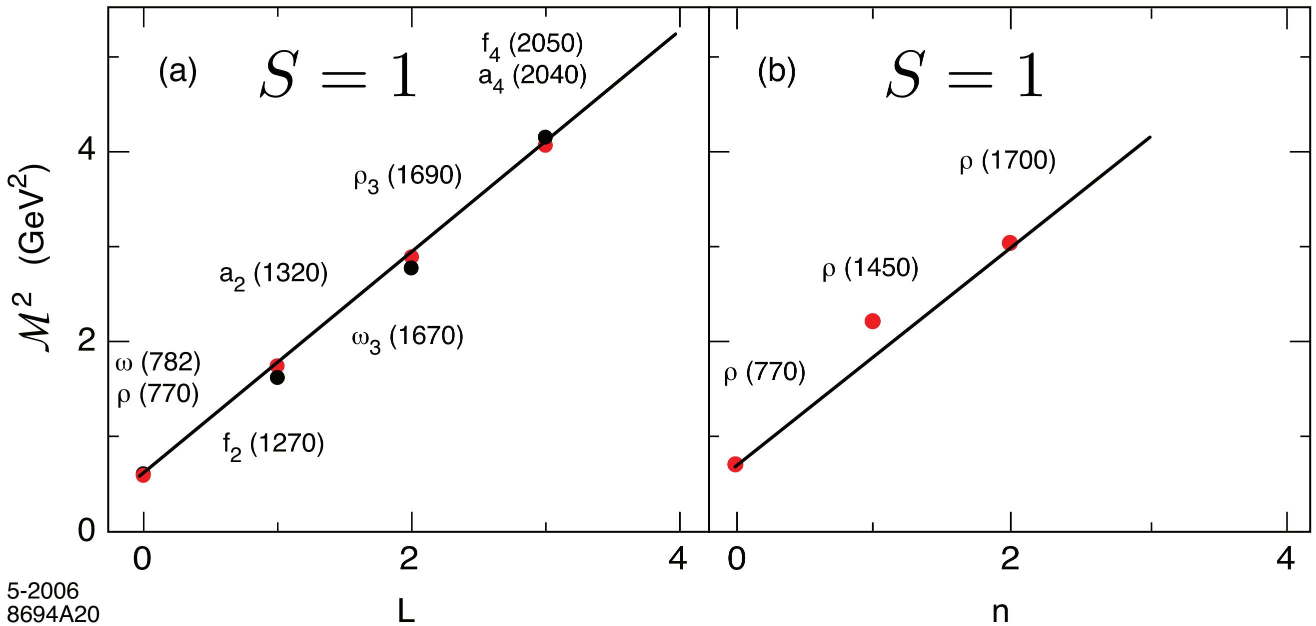
- Effective LF Schrödinger wave equation

$$\left[-\frac{d^2}{dz^2} - \frac{1-4L^2}{4z^2} + \kappa^4 z^2 + 2\kappa^2(L+S-1)\right]\phi_S(z) = \mathcal{M}^2\phi_S(z)$$

with eigenvalues $\mathcal{M}^2 = 2\kappa^2(2n+2L+S)$.

Same slope in n and L

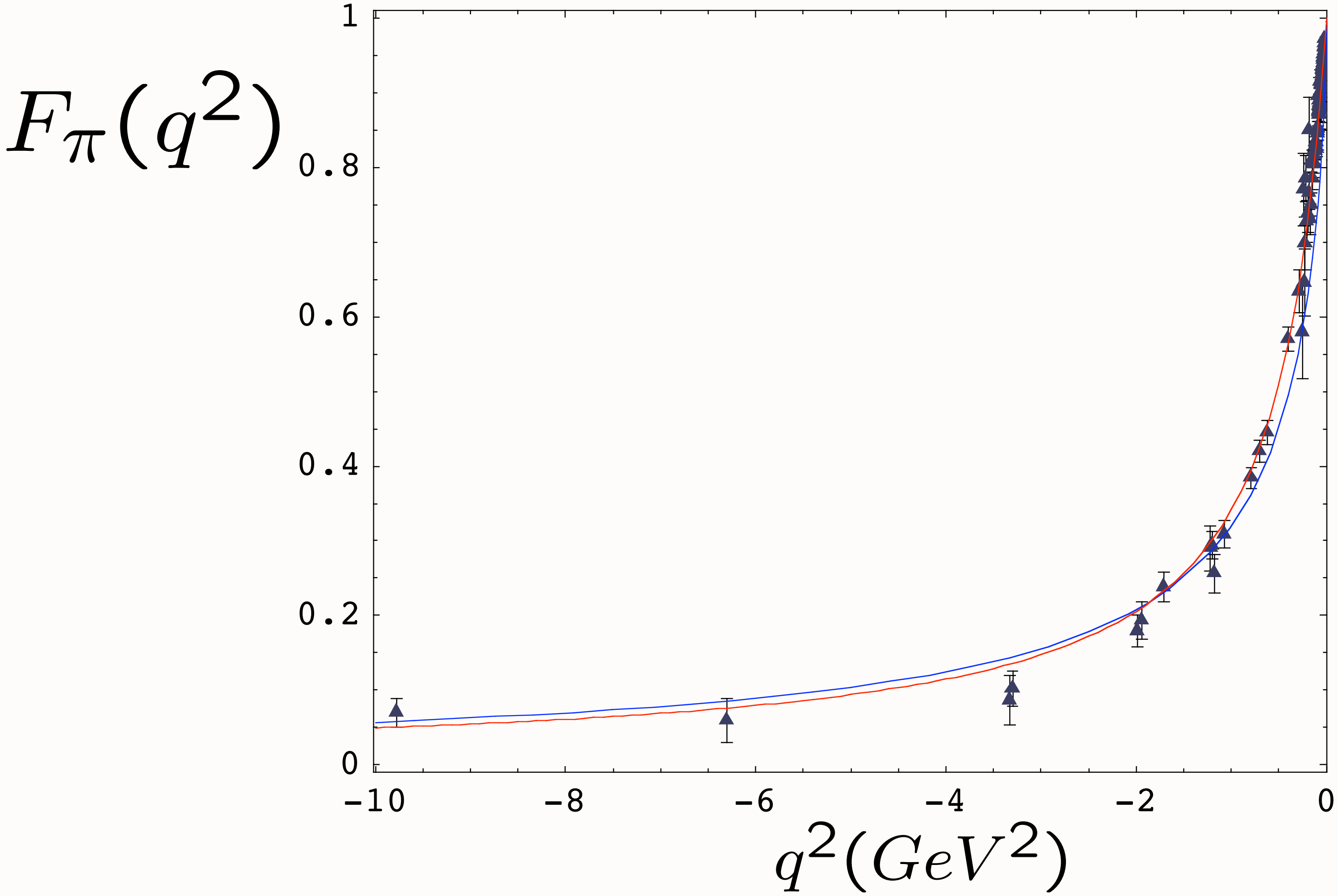
- Compare with Nambu string result (rotating flux tube): $M_n^2(L) = 2\pi\sigma\left(n+L+1/2\right)$.



Vector mesons orbital (a) and radial (b) spectrum for $\kappa = 0.54$ GeV.

- Glueballs in the bottom-up approach: (HW) Boschi-Filho, Braga and Carrion (2005); (SW) Colangelo, De Facio, Jugeau and Nicotri(2007).

Spacelike pion form factor from AdS/CFT



Data Compilation
Baldini, Kloe and Volmer

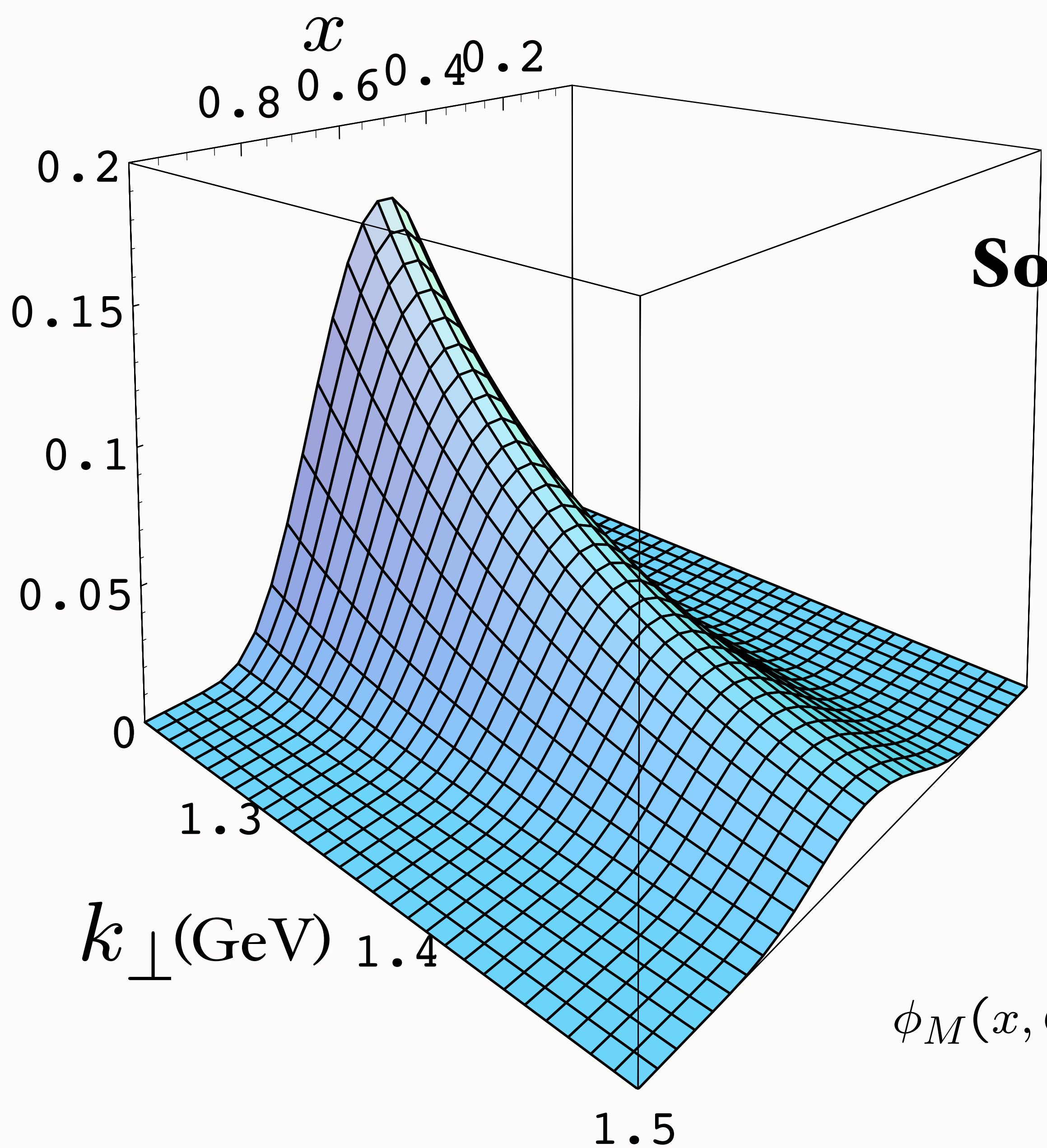
Soft Wall: Harmonic Oscillator Confinement

Hard Wall: Truncated Space Confinement

One parameter - set by pion decay constant

de Teramond, sjb
See also: Radyushkin

Prediction from AdS/CFT: Meson LFWF



Soft Wall Model

de Teramond, sjb

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

Increases PQCD prediction for $F_\pi(Q^2)$ by 16/9

Second Moment of Pion Distribution Amplitude

$$< \xi^2 >= \int_{-1}^{1} d\xi \; \xi^2 \phi(\xi)$$

$$\xi = 1 - 2x$$

$$< \xi^2 >_\pi = 1/5 = 0.20 \qquad \phi_{asympt} \propto x(1-x)$$

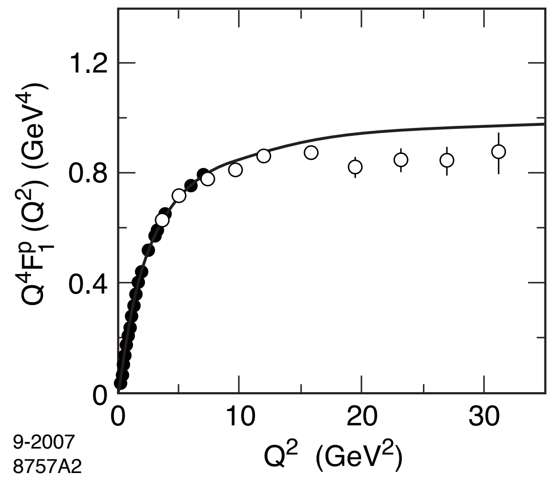
$$< \xi^2 >_\pi = 1/4 = 0.25 \qquad \phi_{AdS/QCD} \propto \sqrt{x(1-x)}$$

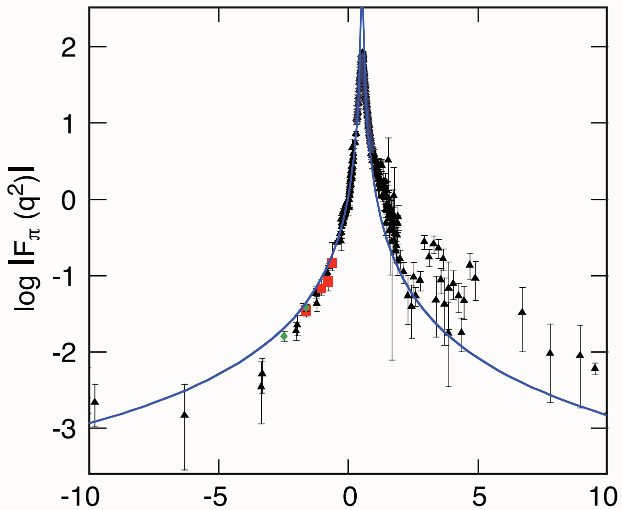
$\text{Lattice (I)} \;\; < \xi^2 >_\pi = 0.28 \pm 0.03$ Donnellan et al.

$\text{Lattice (II)} \; < \xi^2 >_\pi = 0.269 \pm 0.039$ Braun et al.

Other Applications of Light-Front Holography

- Light baryon spectrum
- Light meson spectrum
- Nucleon form-factors: space-like region
- Pion form-factors: space and time-like regions
- Gravitational form factors of composite hadronss
- n-parton holographic mapping
- Heavy flavor mesons





hep-th/0501022

hep-ph/0602252

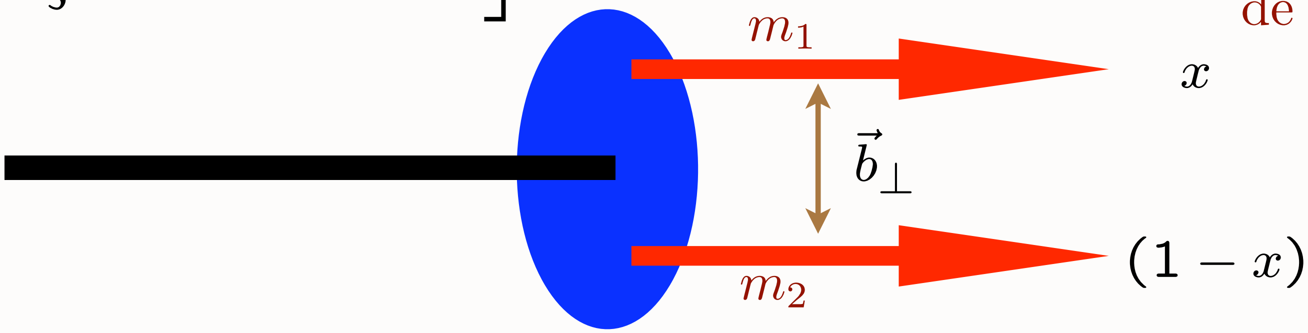
arXiv:0707.3859

arXiv:0802.0514

arXiv:0804.0452

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

de Teramond, sjb



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

Holographic Variable

$$-\frac{d}{d\zeta^2} \equiv \frac{k_\perp^2}{x(1-x)}$$

LF Kinetic Energy in momentum space

Assume LFWF is a dynamical function of the quark-antiquark invariant mass squared

$$-\frac{d}{d\zeta^2} \to -\frac{d}{d\zeta^2} + \frac{m_1^2}{x} + \frac{m_2^2}{1-x} \equiv \frac{k_\perp^2 + m_1^2}{x} + \frac{k_\perp^2 + m_2^2}{1-x}$$

Result: Soft-Wall LFWF for massive constituents

$$\psi(x,\mathbf{k}_\perp) = \frac{4\pi c}{\kappa\sqrt{x(1-x)}} e^{-\frac{1}{2\kappa^2}\left(\frac{\mathbf{k}_\perp^2}{x(1-x)} + \frac{m_1^2}{x} + \frac{m_2^2}{1-x}\right)}$$

LF WF in impact space: soft-wall model with massive quarks

$$\psi(x,\mathbf{b}_\perp) = \frac{c\,\kappa}{\sqrt{\pi}}\sqrt{x(1-x)}\,e^{-\frac{1}{2}\kappa^2 x(1-x)\mathbf{b}_\perp^2 - \frac{1}{2\kappa^2}\left[\frac{m_1^2}{x} + \frac{m_2^2}{1-x}\right]}$$

$$z \to \zeta \to \chi$$

$$\chi^2 = b^2 x(1-x) + \frac{1}{\kappa^4}\left[\frac{m_1^2}{x} + \frac{m_2^2}{1-x}\right]$$

J/ψ

LFWF peaks at

$$x_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

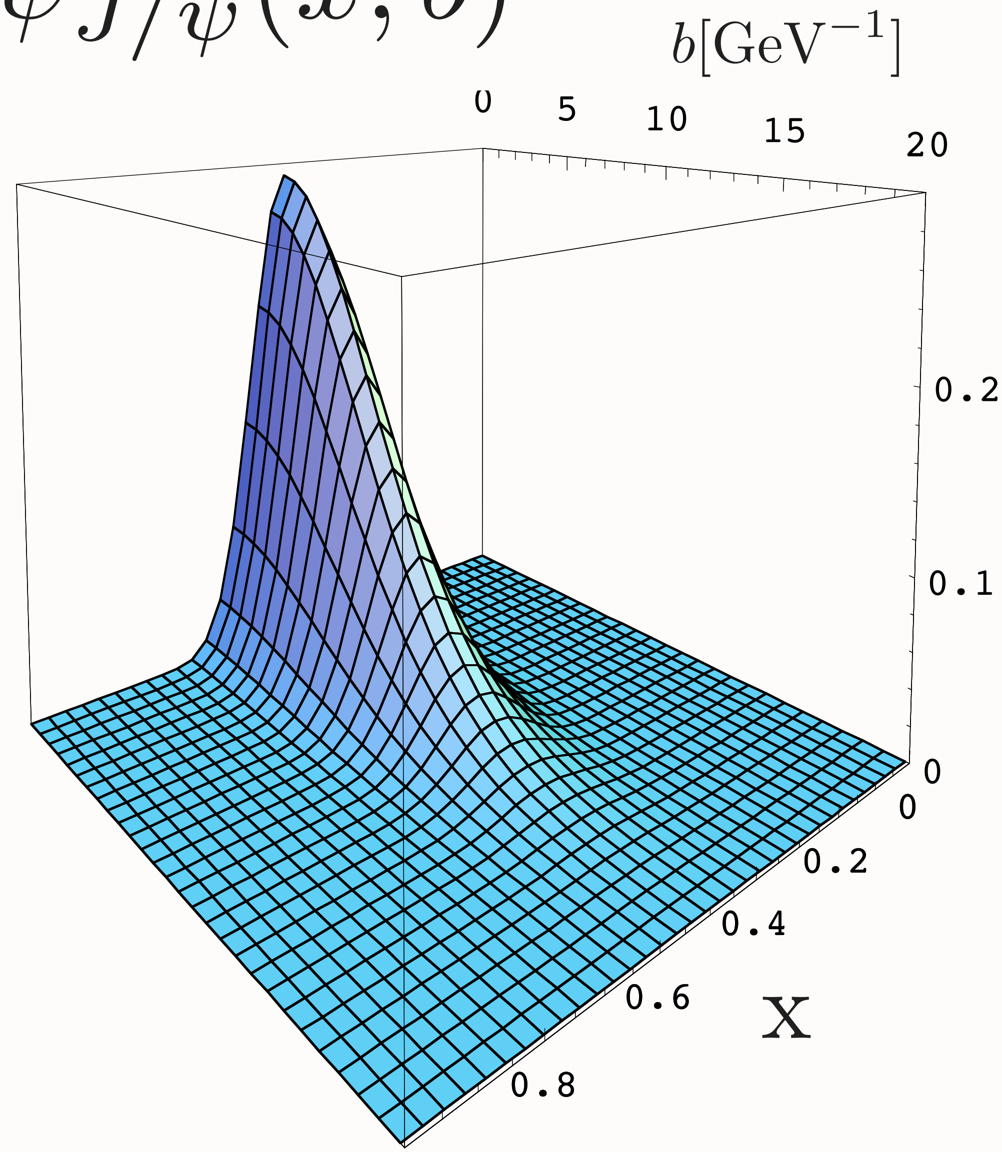
where

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

minimum of LF energy denominator

$$\kappa = 0.375 \text{ GeV}$$

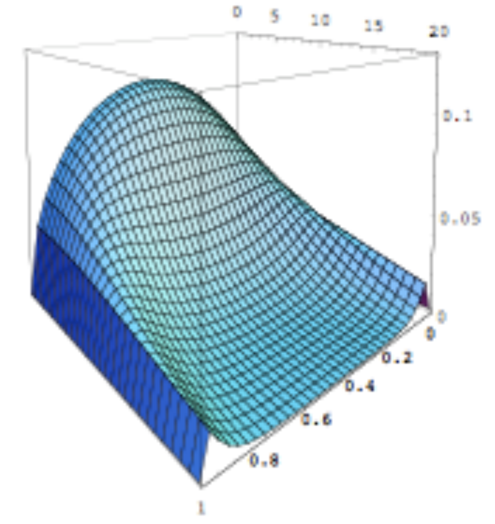
$$\psi_{J/\psi}(x, b)$$

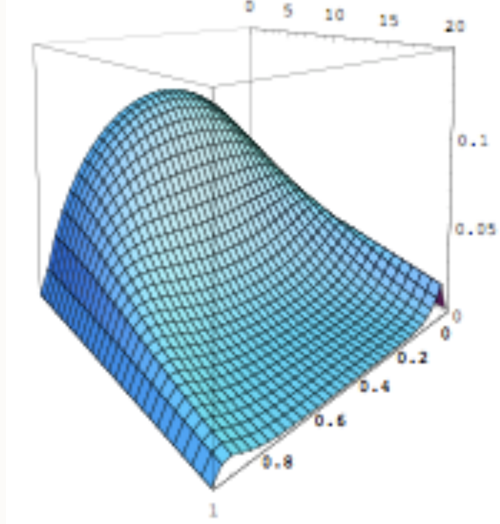


$$m_a = m_b = 1.25 \text{ GeV}$$

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

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



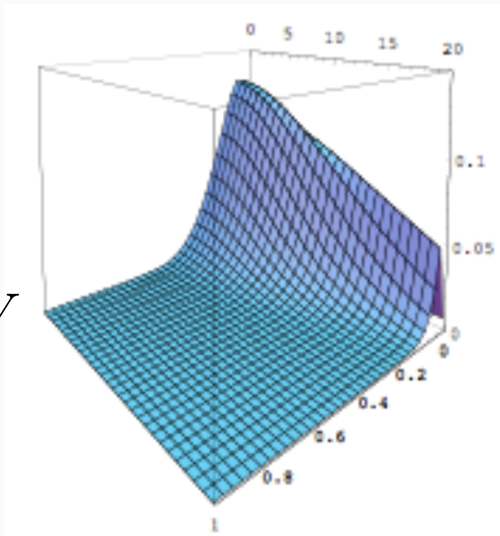


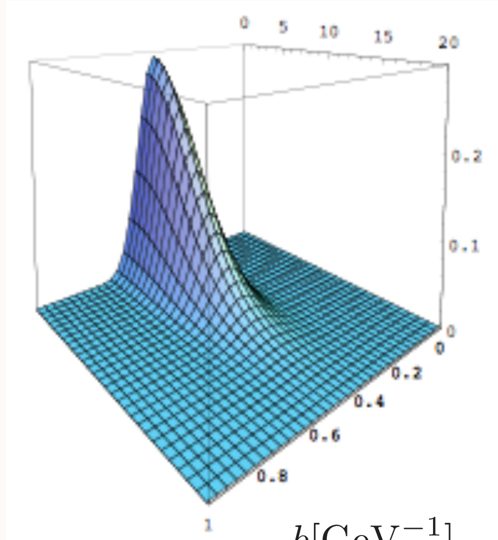
$$|K^+ >= |u\bar{s}>$$

$$m_s = 95\ MeV$$

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

$$m_c = 1.25\ GeV$$

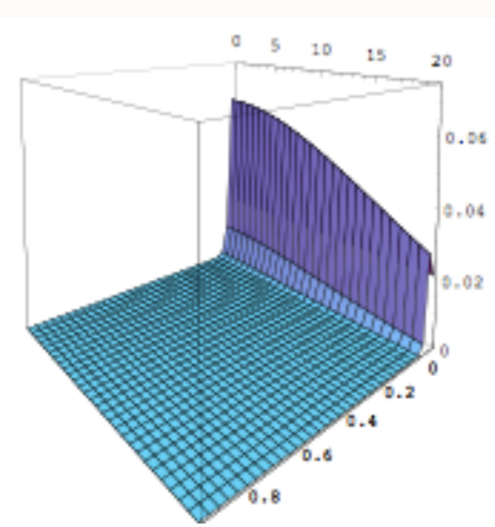


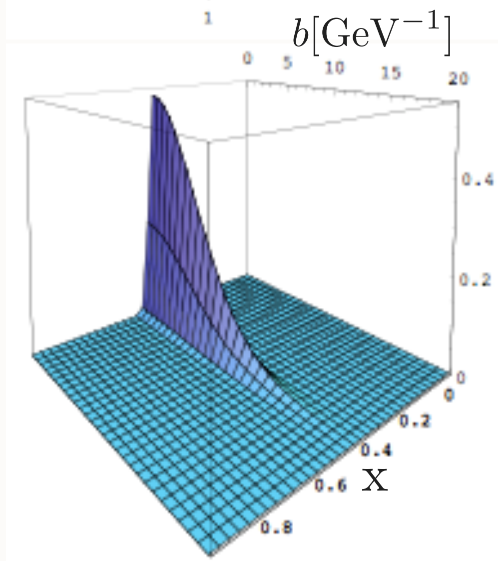


$$|\eta_c >= |c\bar{c}>$$

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

$$m_b = 4.2\ GeV$$





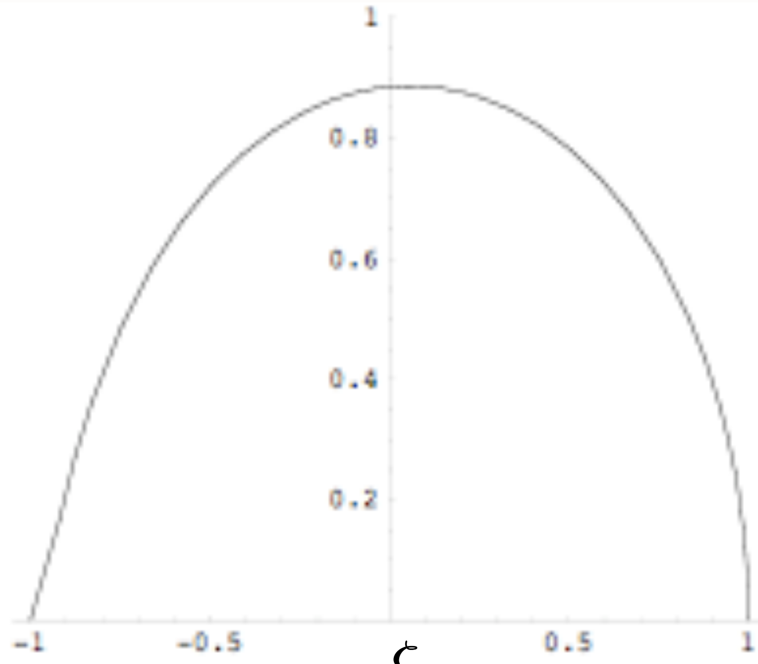
$$|\eta_b >= |b\bar{b}>$$

$$\kappa = 375\ MeV$$

First Moment of Kaon Distribution Amplitude

$$< \xi >= \int_{-1}^{1} d\xi \; \xi \; \phi(\xi)$$

$$\xi = 1 - 2x$$



$$< \xi >_K = 0.04 \pm 0.02 \qquad \kappa = 375 \; MeV$$

Range from $m_s = 65 \pm 25$ MeV (PDG)

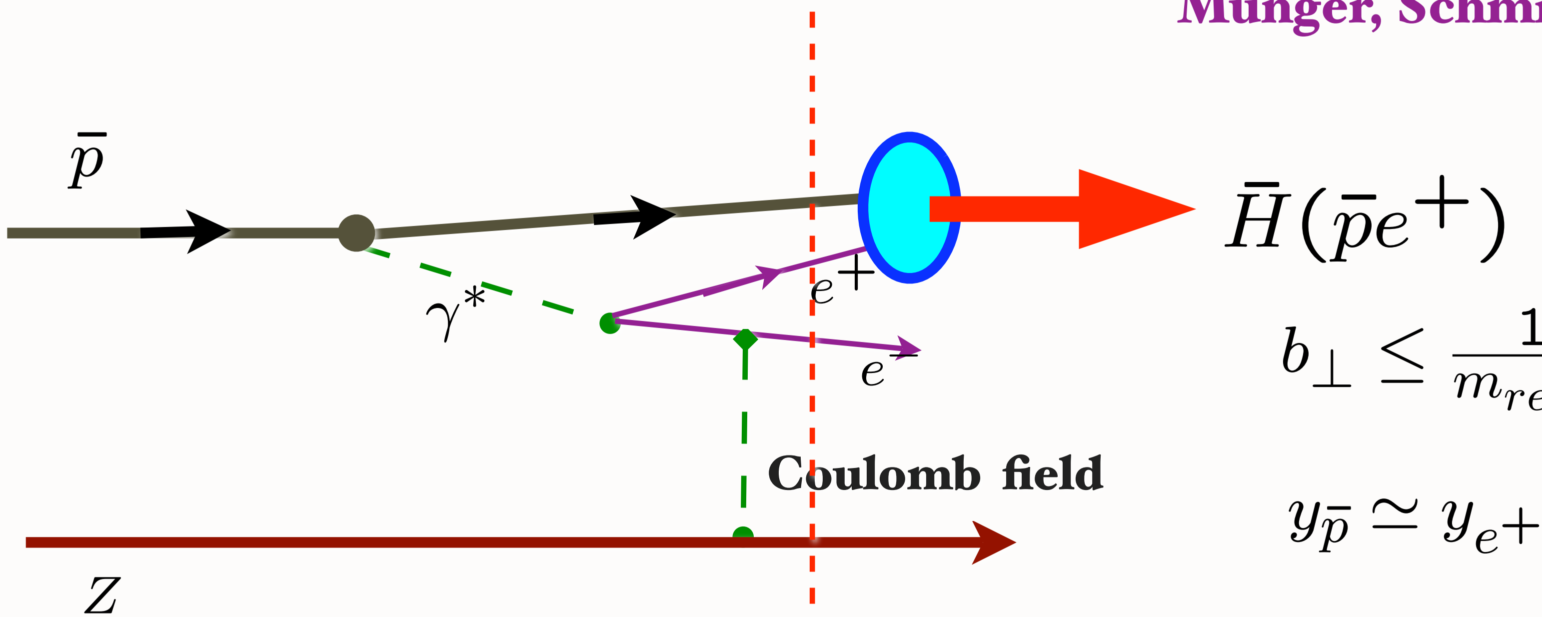
$< \xi >_K = 0.029 \;\pm 0.002$ Donnellan et al.

$< \xi >_K = 0.0272 \pm 0.0005$ Braun et al.

Formation of Relativistic Anti-Hydrogen

Measured at CERN-LEAR and FermiLab

Munger, Schmidt, sjb



$$b_\perp \leq \frac{1}{m_{red}\alpha}$$

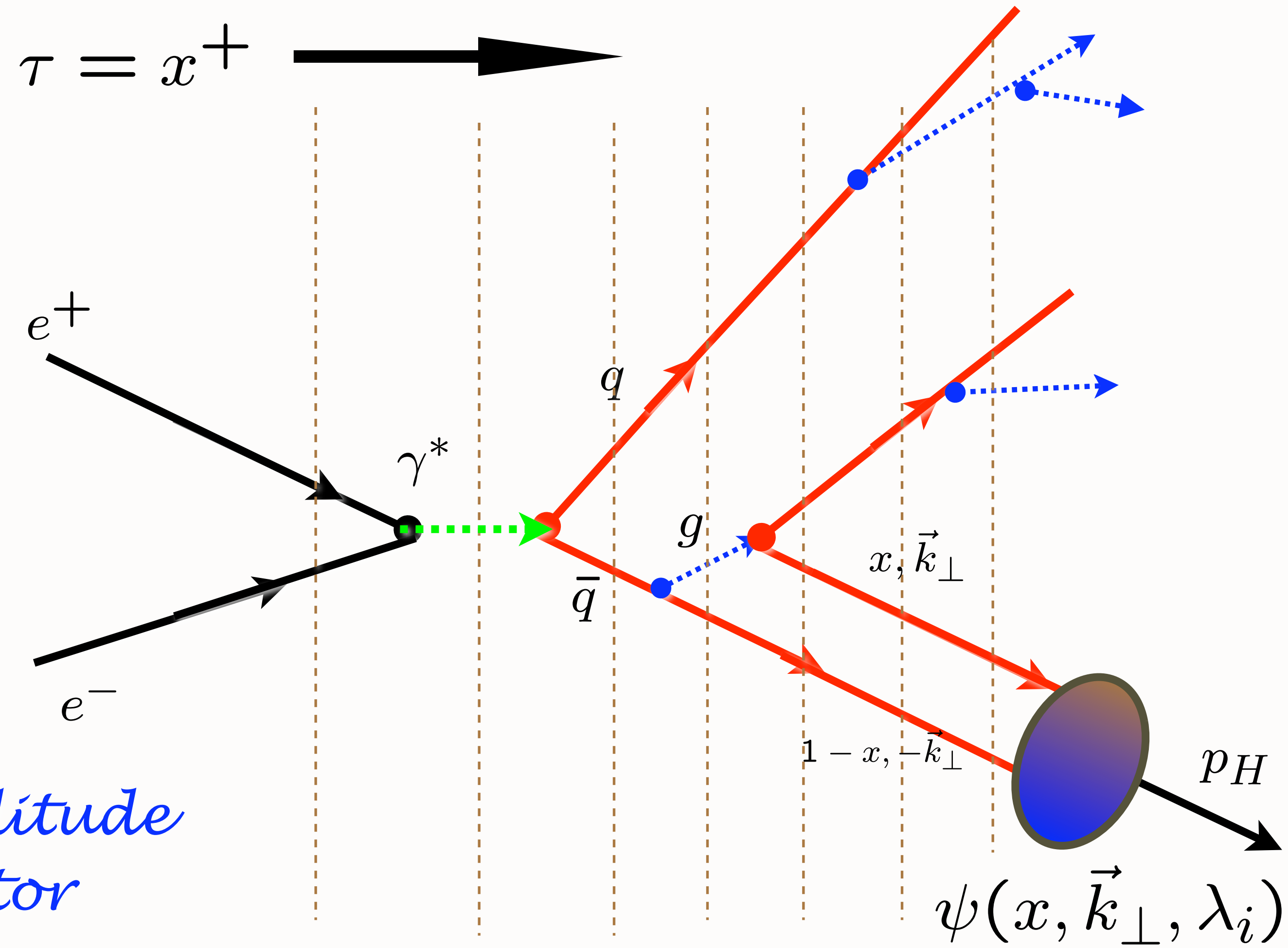
$$y_{\bar{p}} \simeq y_{e^+}$$

Coalescence of off-shell co-moving positron and antiproton

Wavefunction maximal at small impact separation and equal rapidity

"Hadronization" at the Amplitude Level

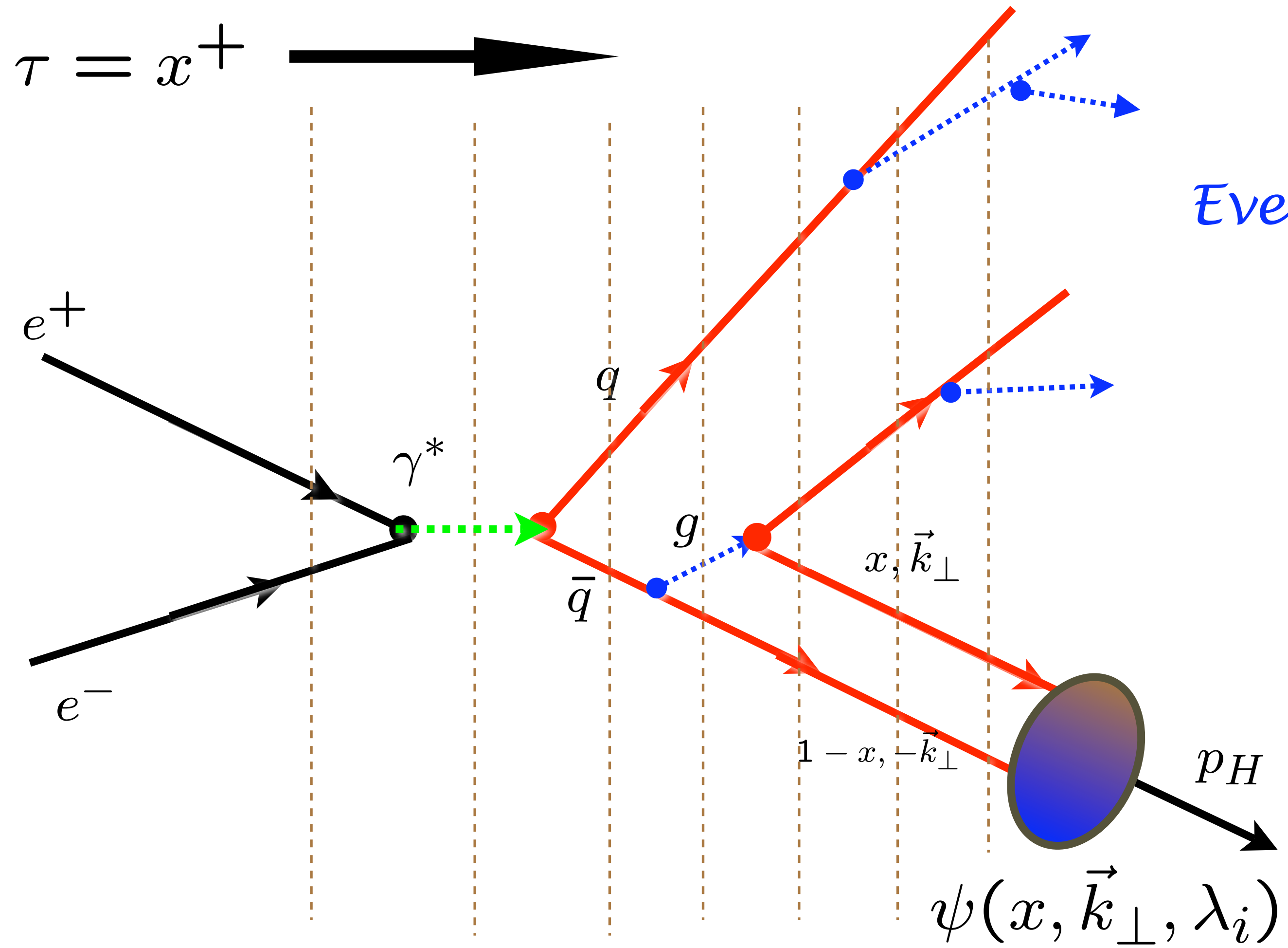
Hadronization at the Amplitude Level



Event amplitude generator

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

Hadronization at the Amplitude Level



Event amplitude generator

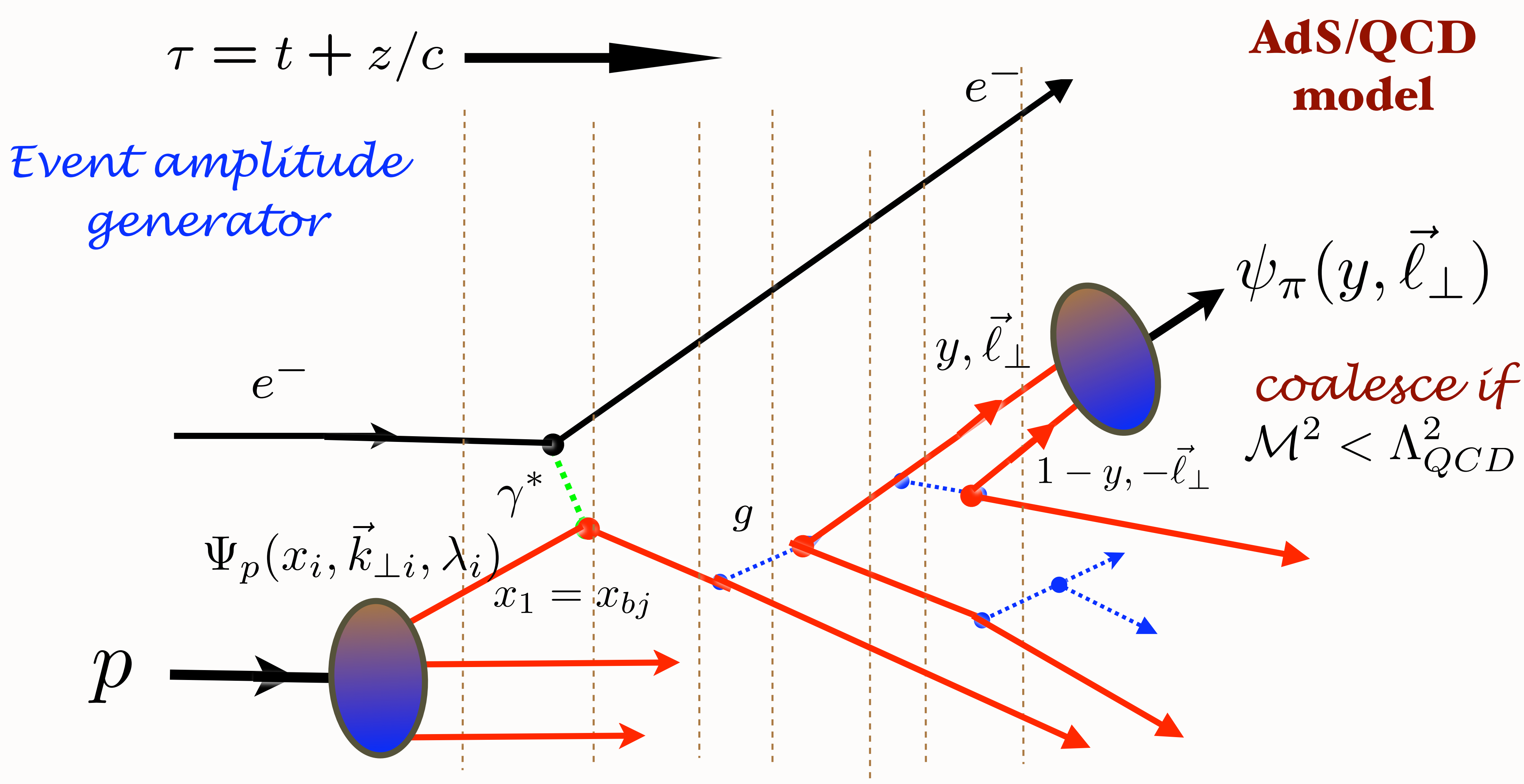
AdS/QCD Hard Wall Confinement:

Capture if $\zeta^2 = x(1-x)b_\perp^2 > \frac{1}{\Lambda^2_{QCD}}$

i.e.,

$\mathcal{M}^2 = \frac{k_\perp^2}{x(1-x)} < \Lambda^2_{QCD}$

Jet Hadronization at the Amplitude Level



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

Three Pictures of High Energy Lepton-Proton Collisions

Infinite momentum frame **Parton Model**

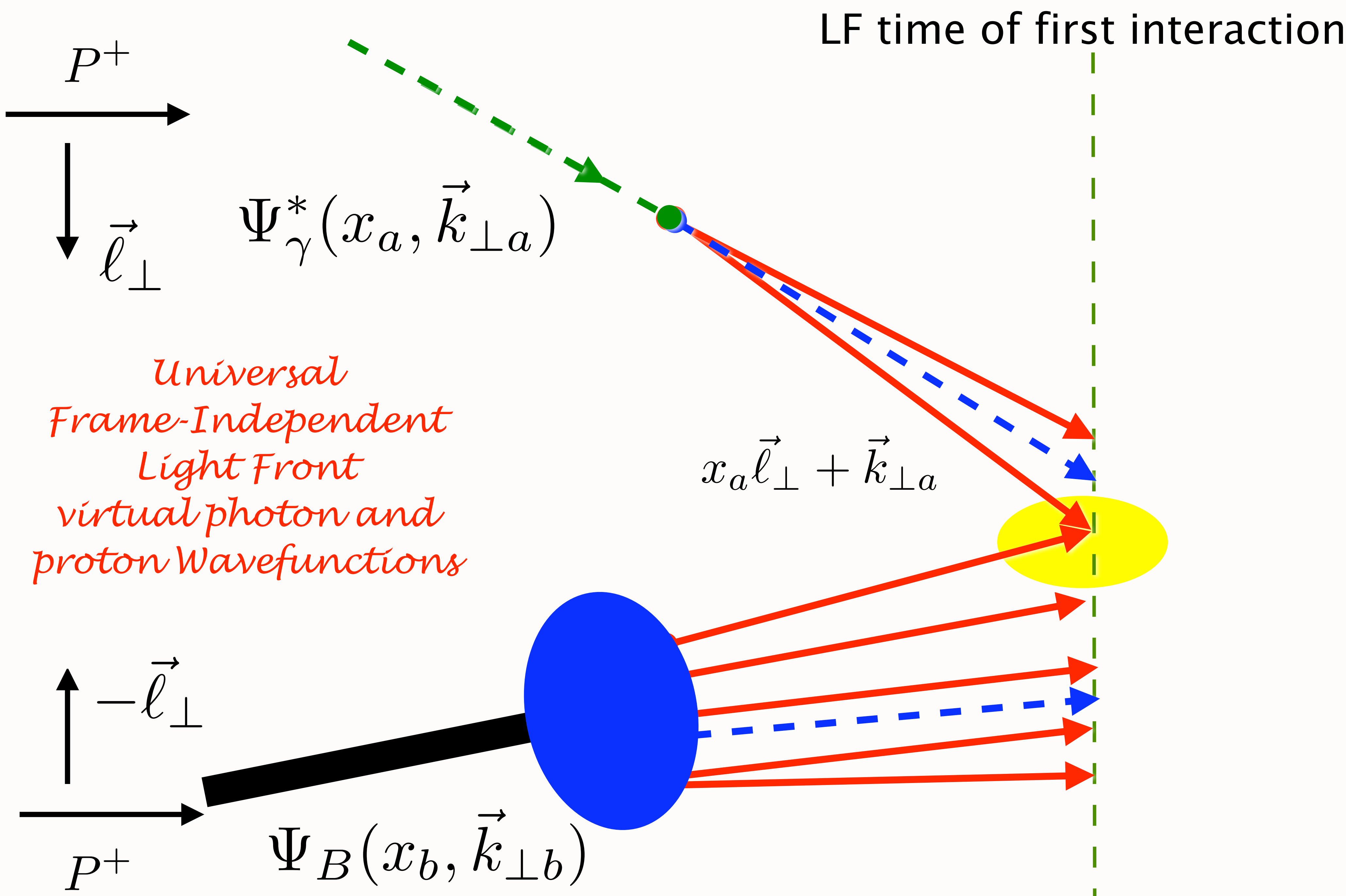
Simple Virtual Photon Probes Complex Evolved Proton

Proton Rest Frame **Color-Dipole Model**

Color Dipole of Virtual Photon Scatters on a Static Proton

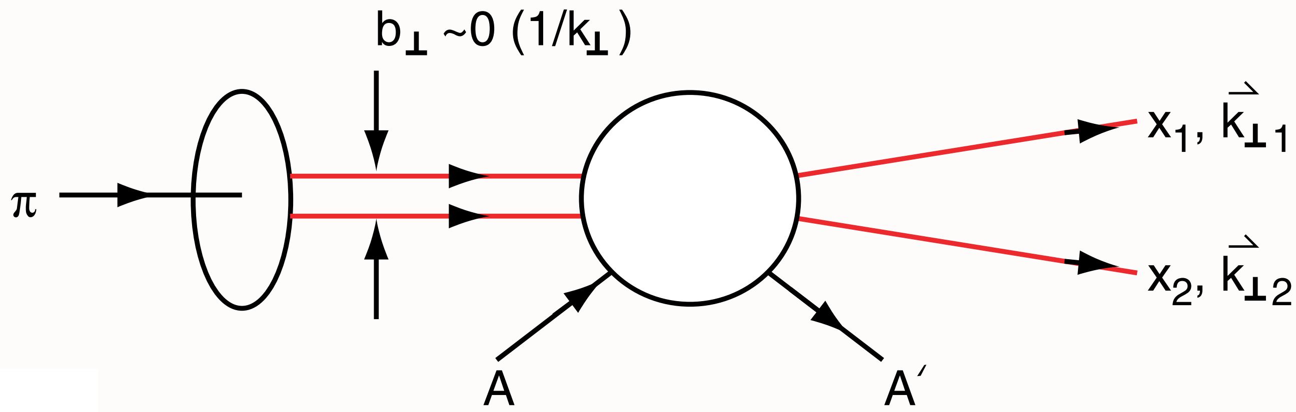
Frame-Independent **Light-Front HamiltonianTheory**

Collision of Light-Front Wavefunctions of Virtual Photon and Proton


LF time of first interaction
P^+
$\vec{\ell}_\perp$
$\Psi^*_\gamma(x_a, \vec{k}_{\perp a})$
Universal
Frame-Independent
Light Front
virtual photon and
proton Wavefunctions
$x_a\vec{\ell}_\perp + \vec{k}_{\perp a}$
$-\vec{\ell}_\perp$
P^+
$\Psi_B(x_b, \vec{k}_{\perp b})$

Diffractive Dissociation of Pion into Quark Jets

E791 Ashery et al.



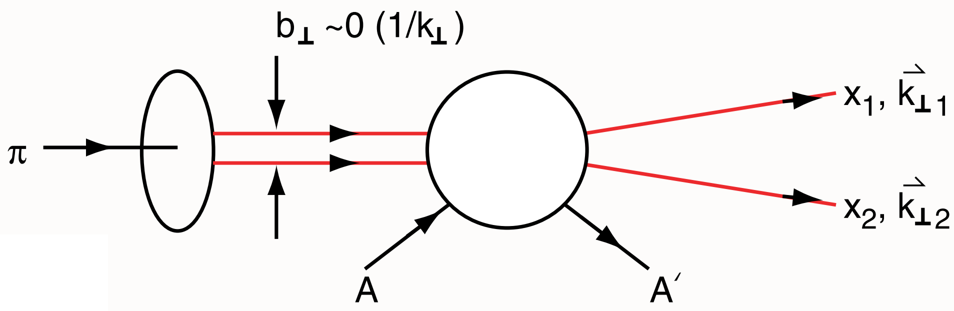
$$M \propto \frac{\partial^2}{\partial^2 k_\perp} \psi_\pi(x, k_\perp)$$

Measure Light-Front Wavefunction of Pion

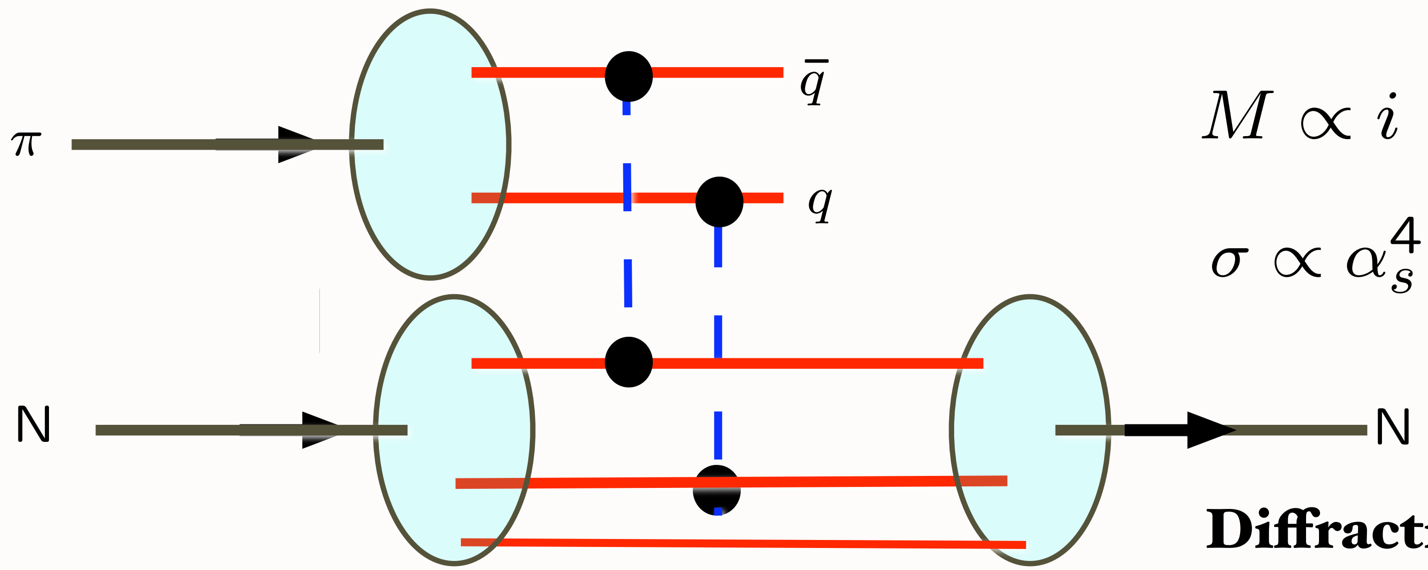
Minimal momentum transfer to nucleus

Nucleus left Intact!

Key Ingredients in Ashery Experiment



Two-gluon exchange gives imaginary amplitude proportional to energy, constant diffractive cross sections



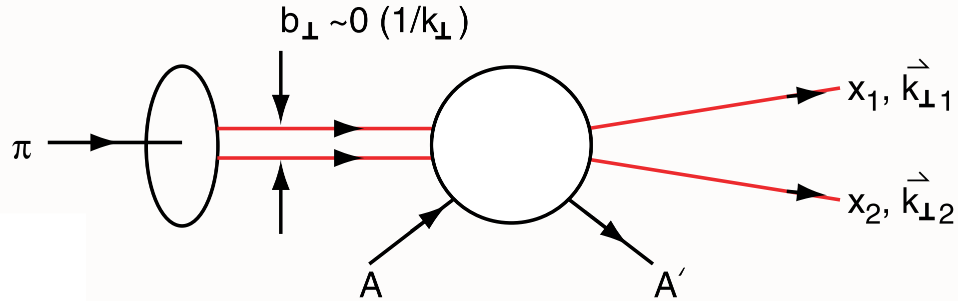
$$M \propto i \; s \; \alpha_s^2 \; b_\perp^\pi \; b_\perp^N$$

$$\sigma \propto \alpha_s^4 \; (b_\perp^\pi)^2 \; (b_\perp^N)^2$$

Target left intact

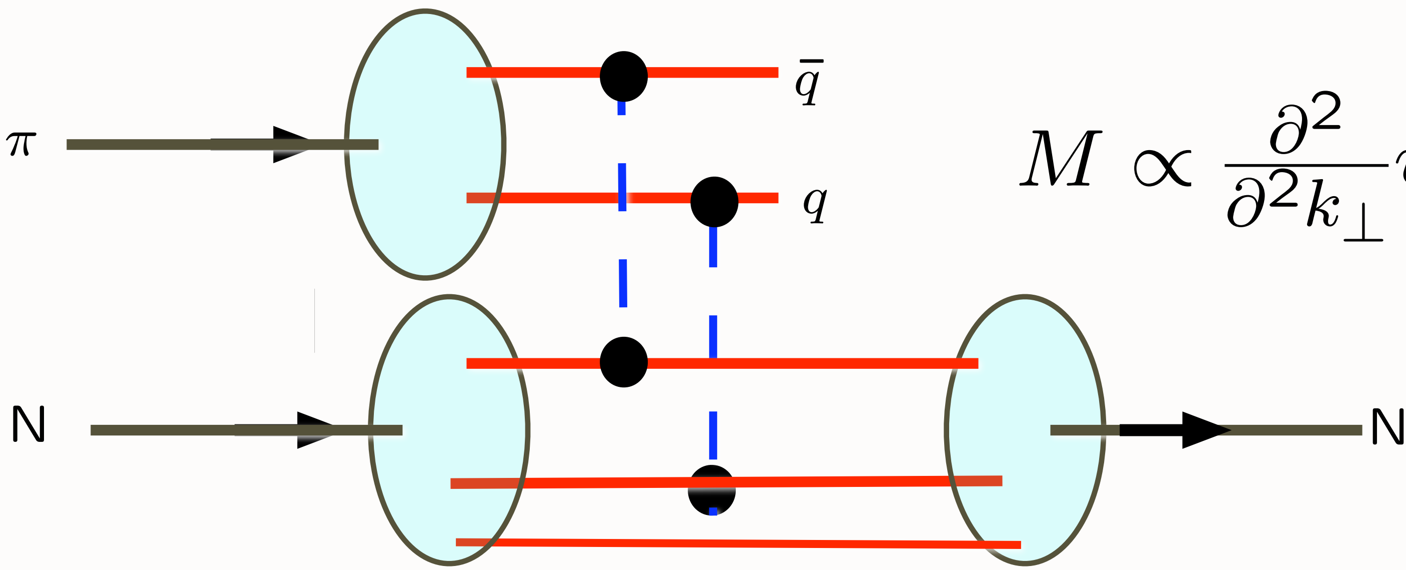
Diffraction, Rapidity gap

E791 FNAL Diffractive DiJet

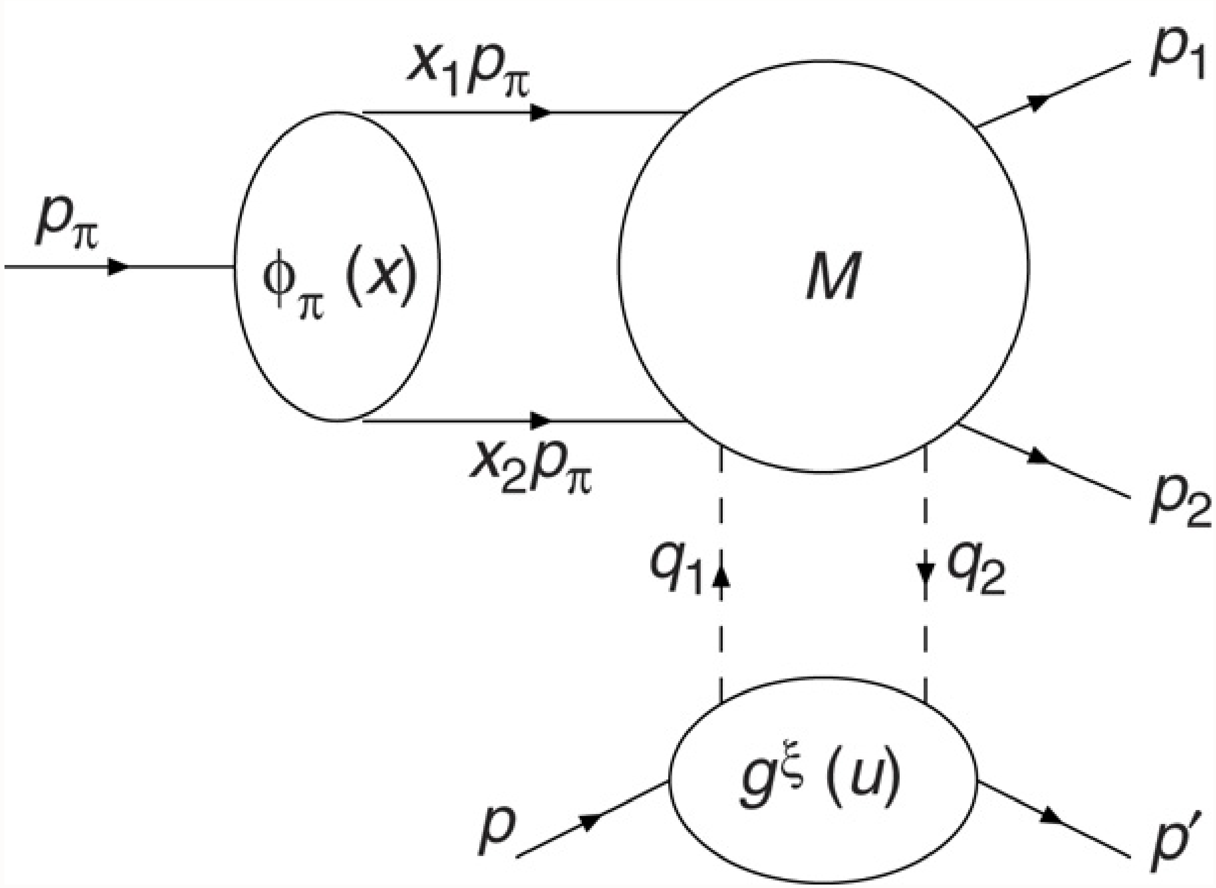


Gunion, Frankfurt, Mueller, Strikman, sjb
Frankfurt, Miller, Strikman

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



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



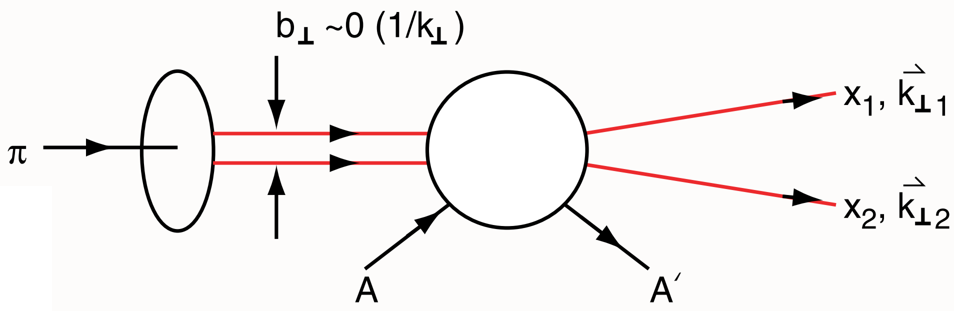
x

1-x

gluons measure size of color dipole

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

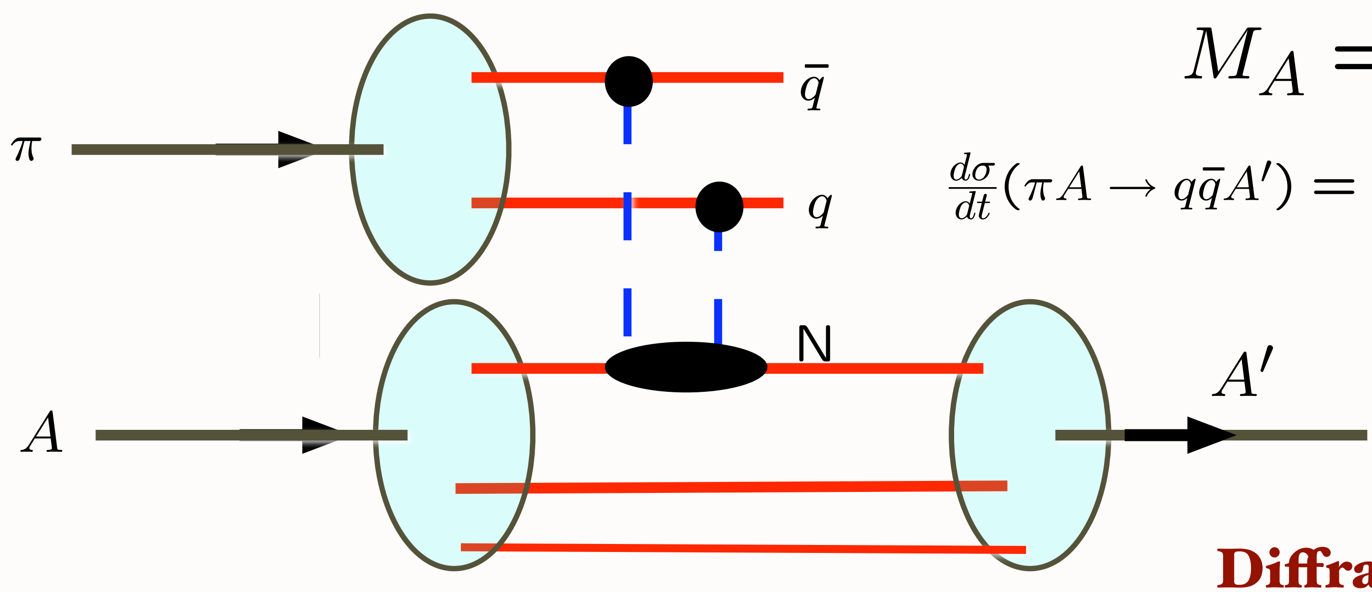
Key Ingredients in E791 Experiment



Brodsky Mueller
Frankfurt Miller Strikman

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

QCD COLOR Transparency



$$M_A = A\ M_N$$

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

Target left intact

Diffraction, Rapidity gap

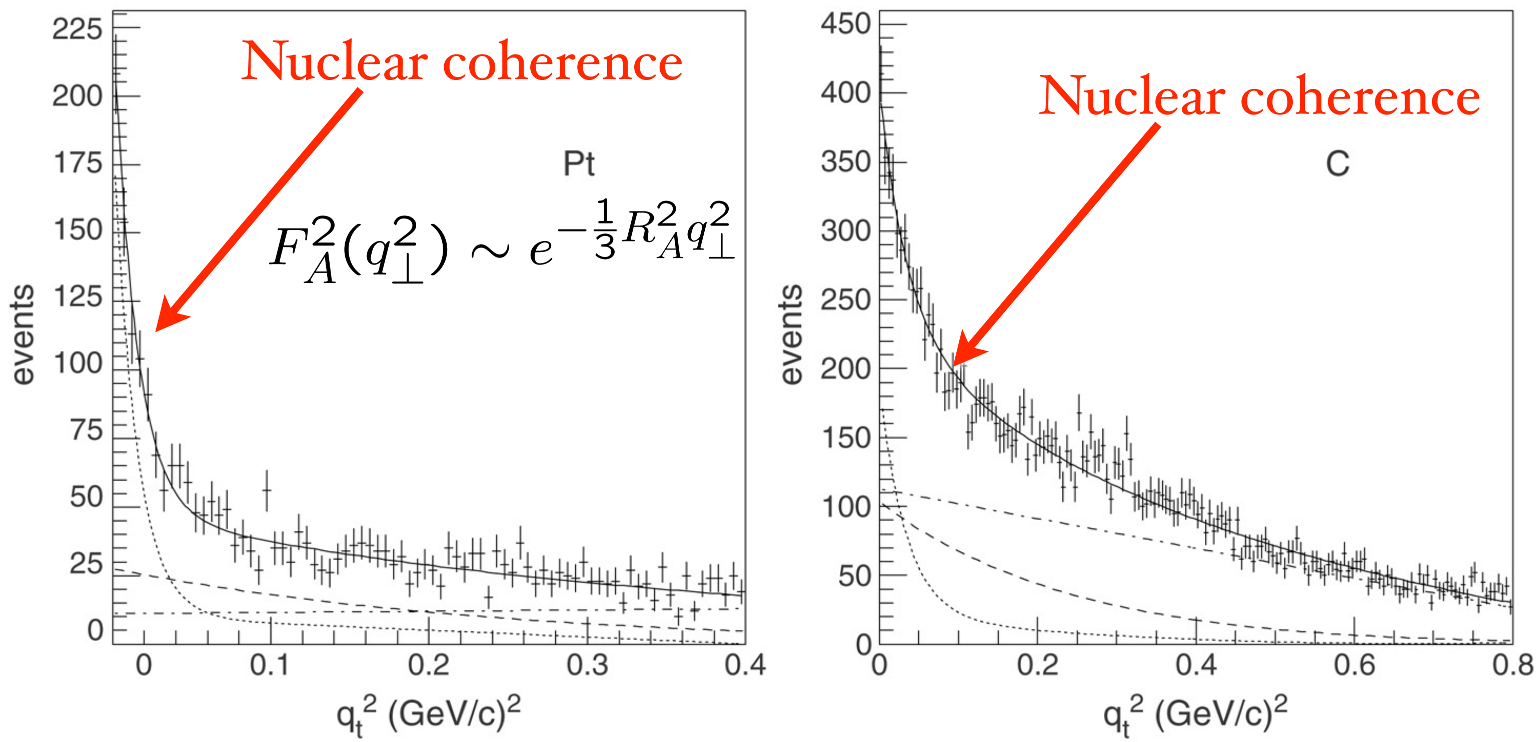
- Fully coherent interactions between pion and nucleons.

- Emerging Di-Jets do not interact with nucleus.

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

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

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



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

Measure pion LFWF in diffractive dijet production
Confirmation of color transparency

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

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

Ashery E791

α (Incoh.) $= 0.70 \pm 0.1$

Conventional Glauber Theory Ruled Out !

Factor of 7

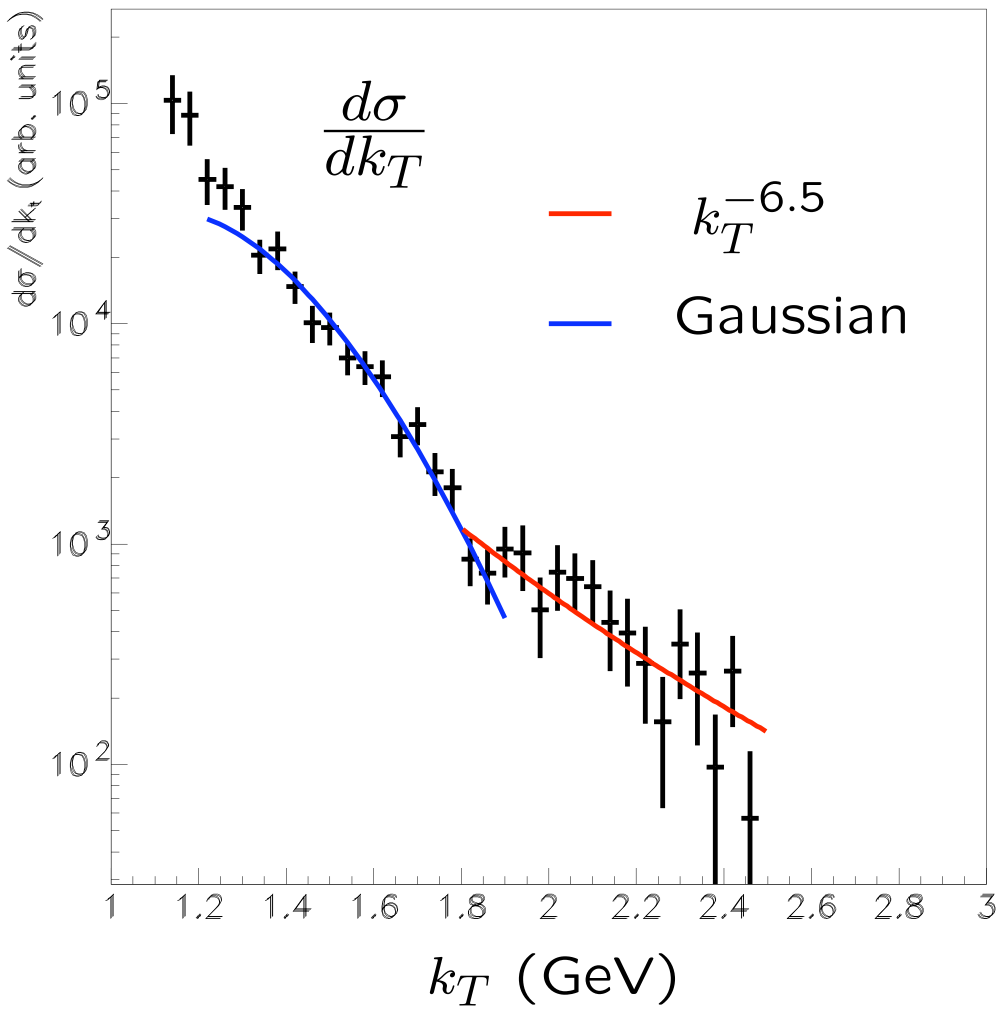
Color Transparency

Bertsch, Gunion, Goldhaber, sjb

A. H. Mueller, sjb

- 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

E791 Diffractive Di-Jet transverse momentum distribution



Two Components

High Transverse momentum dependence $k_T^{-6.5}$ consistent with PQCD, ERBL Evolution

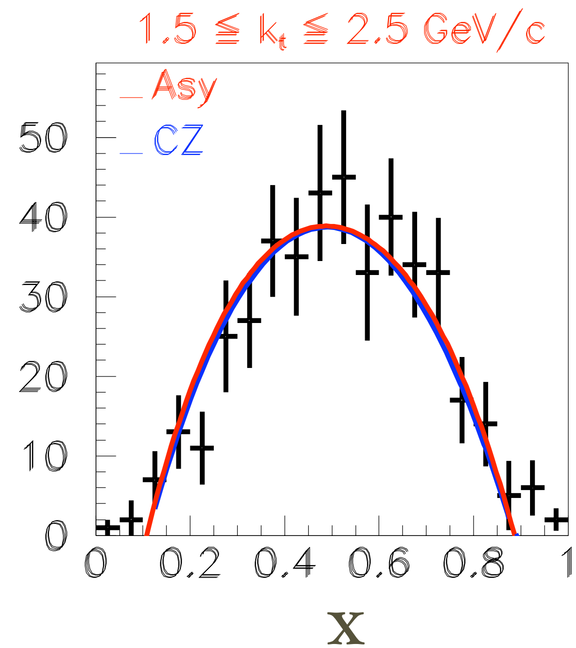
Gaussian component at small k_T similar to AdS/CFT LFWF

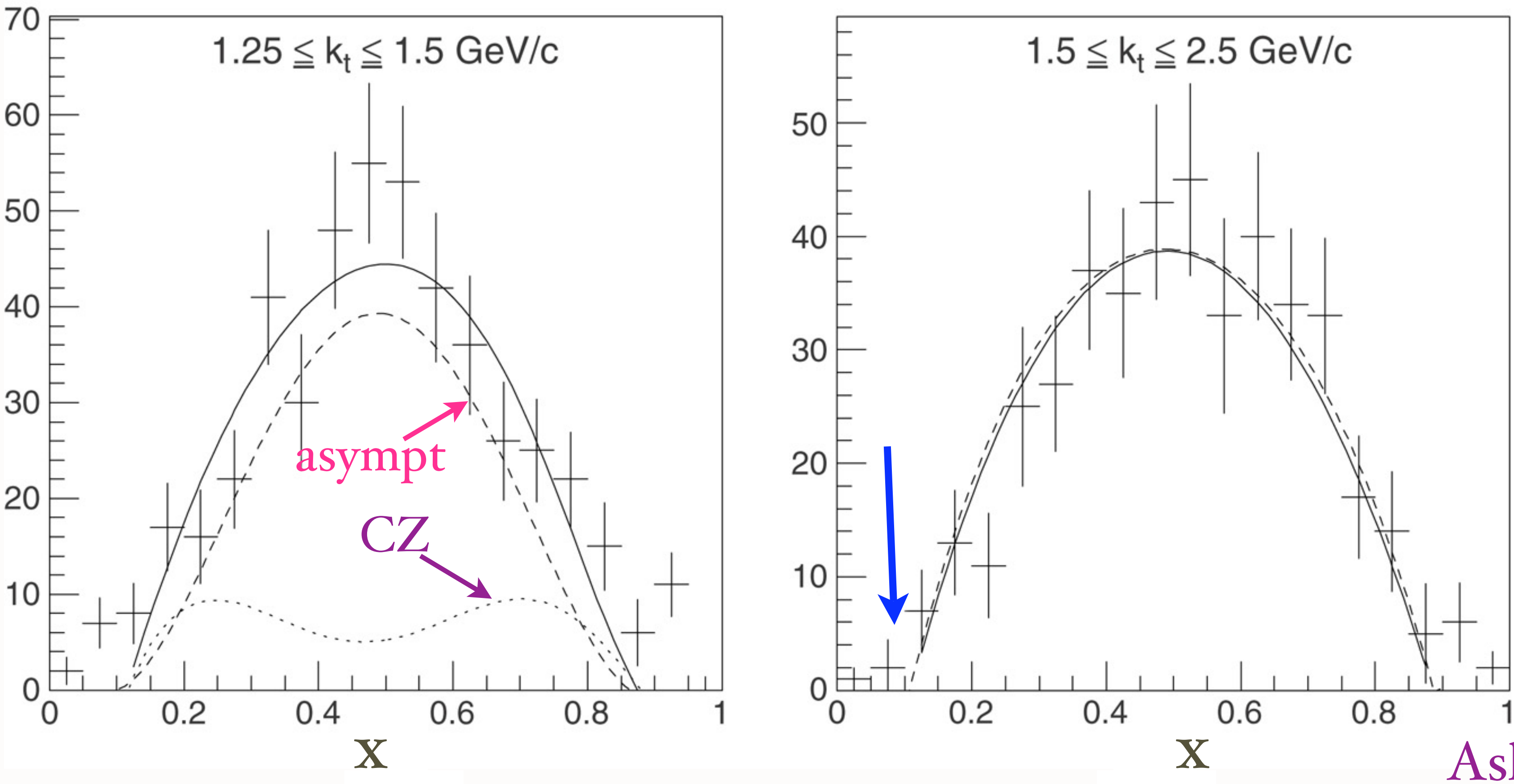
Diffractive Dissociation of a Pion into Dijets

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

- E791 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

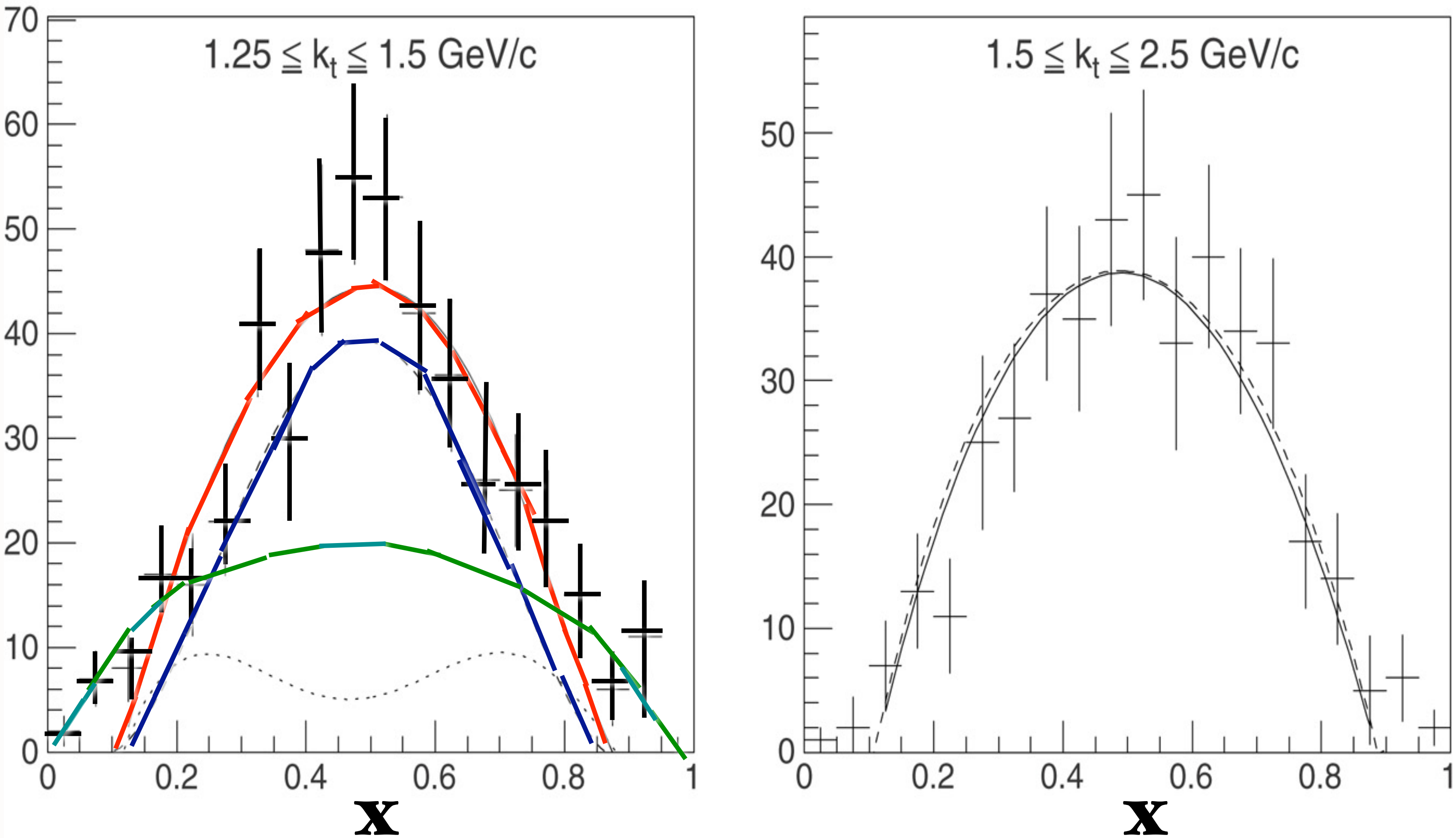
$$\psi^{\pi}_{q\bar{q}}(x, \vec{k}_\perp)$$





Narrowing of x distribution at high jet transverse momentum

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.



Ashery
E791

Possibly two components:

Perturbative (ERBL) + Nonperturbative (AdS/CFT)

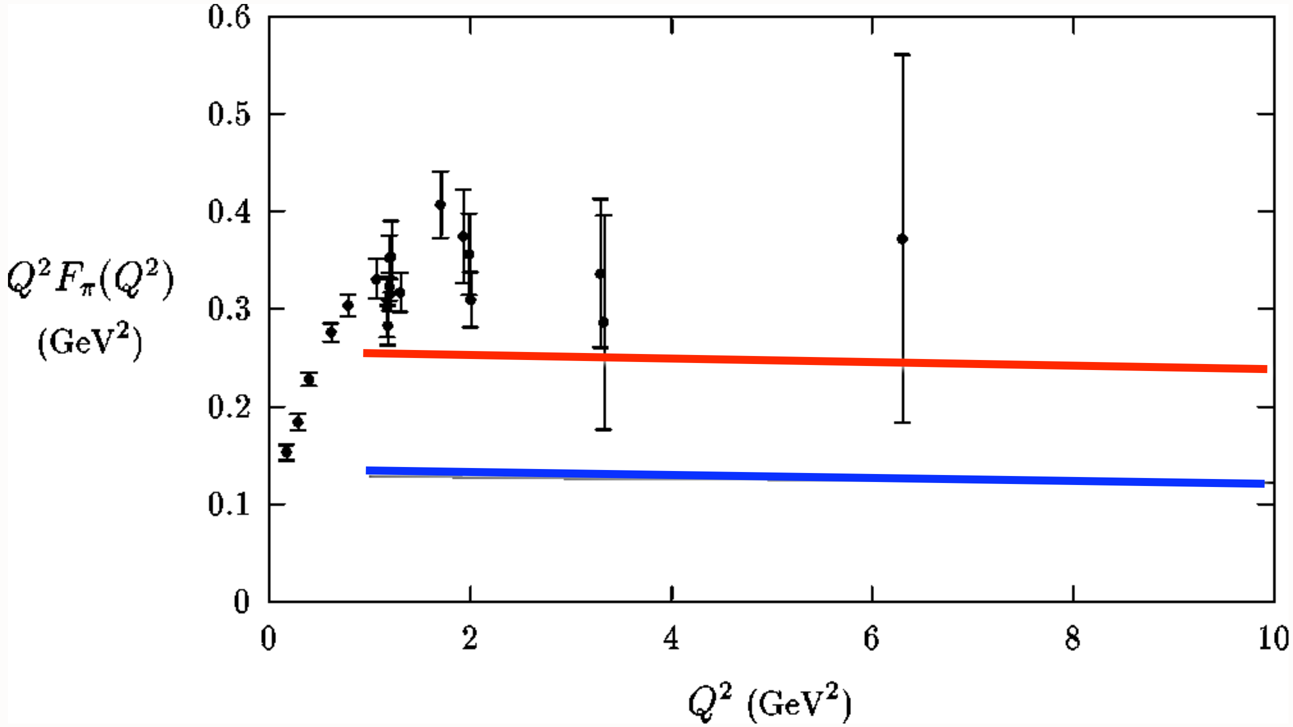
$$\phi(x) = A_{\rm pert}(k^2_\perp) x(1-x) + B_{\rm nonpert}(k^2_\perp)\sqrt{x(1-x)}$$

Narrowing of x distribution at high jet transverse momentum

Lepage, sjb

C. Ji, A. Pang, D. Robertson, sjb
Choi, Ji

$$F_\pi(Q^2) = \int_0^1 dx\, \phi_\pi(x) \int_0^1 dy\, \phi_\pi(y) \frac{16\pi C_F \alpha_V(Q_V)}{(1-x)(1-y)Q^2}$$



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

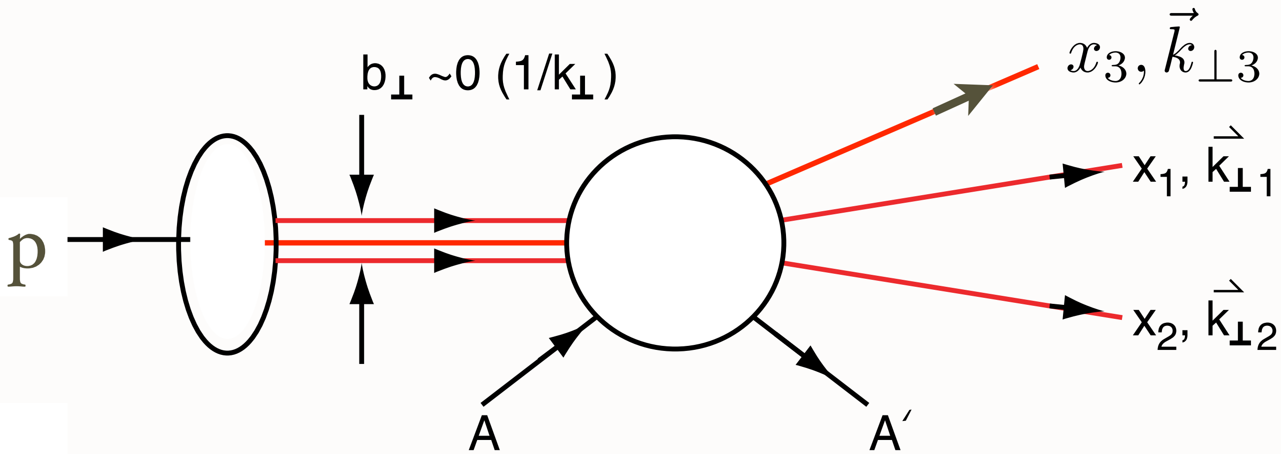
$\phi_{asymptotic} \propto x(1-x)$

Normalized to f_π

AdS/CFT: Increases PQCD leading twist prediction for $F_\pi(Q^2)$ by factor 16/9

Diffractive Dissociation of Proton into Quark Jets

Frankfurt, Miller, Strikman



Measure Light-Front Wavefunction of Proton

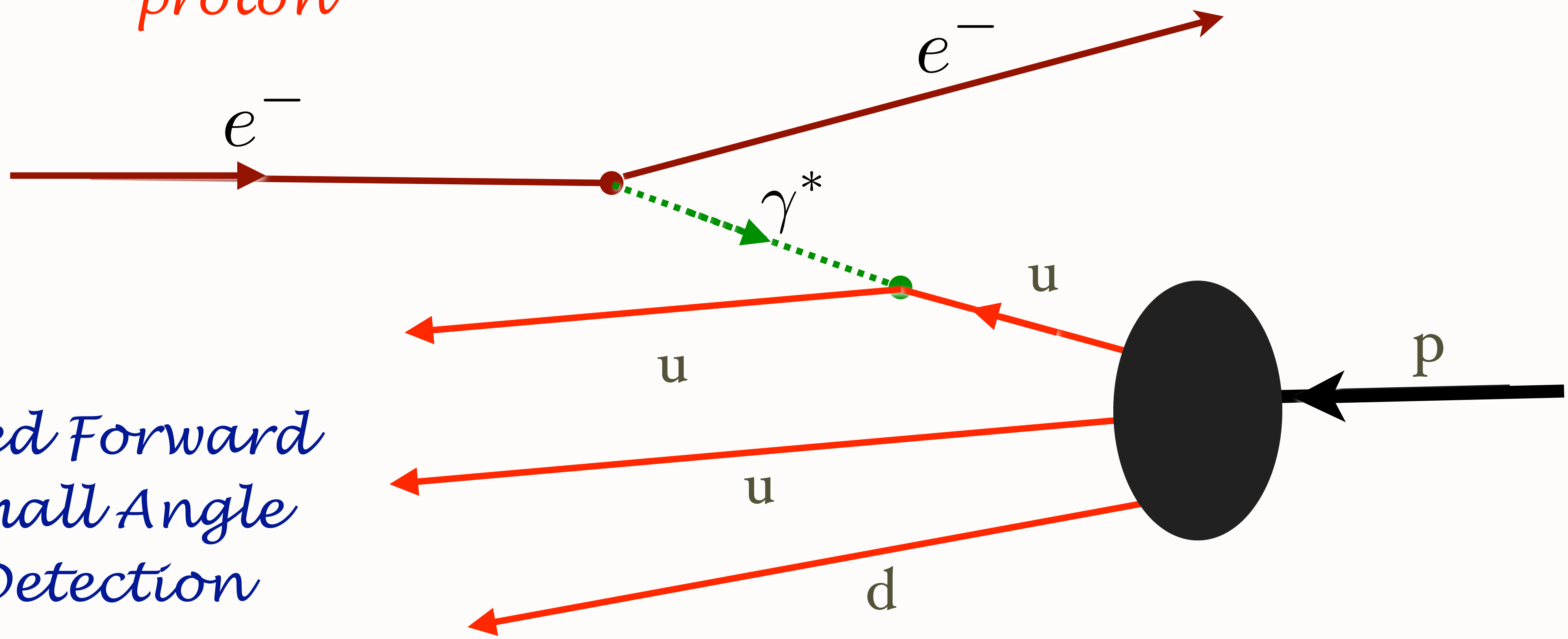
Minimal momentum transfer to nucleus
Nucleus left Intact!

Electromagnetic Tri-Jet Excitation of Proton

$$ep \to e \text{ jet jet jet}$$

Measure light-front wavefunction of proton

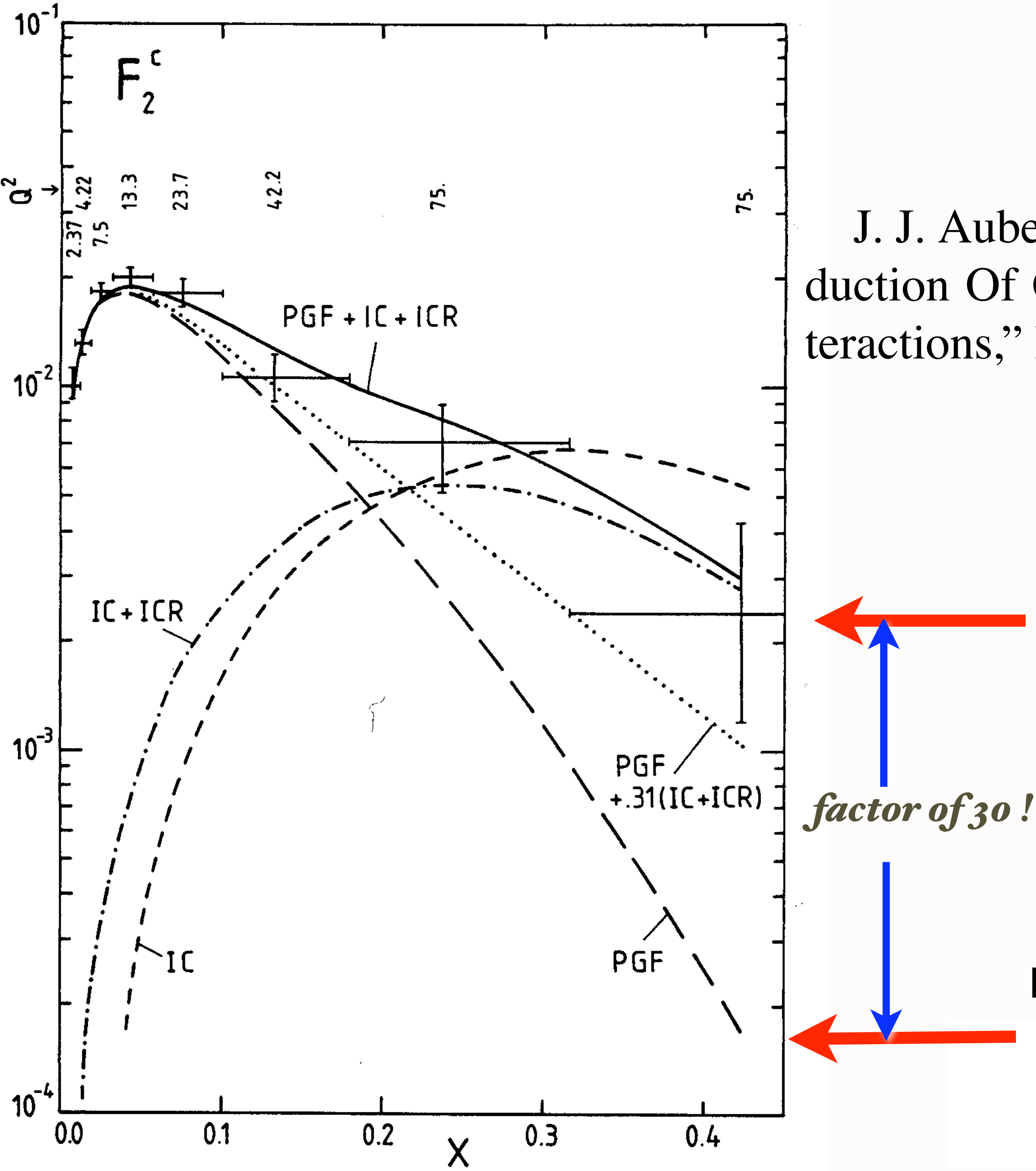
$$\frac{\partial}{\partial k_\perp} \Psi^p_{n=3}(x_i, \vec{k}_{\perp i}, \lambda_i)$$



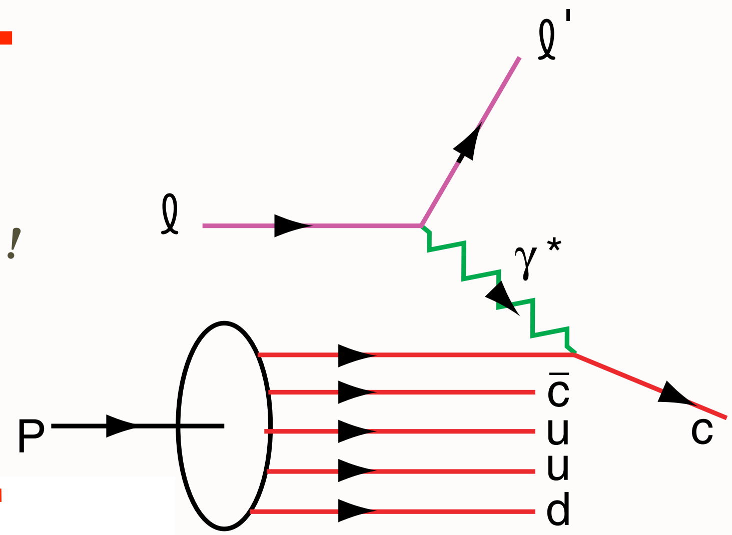
Need Forward Small Angle Detection

Measurement of Charm Structure Function

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



First Evidence for Intrinsic Charm



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

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

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

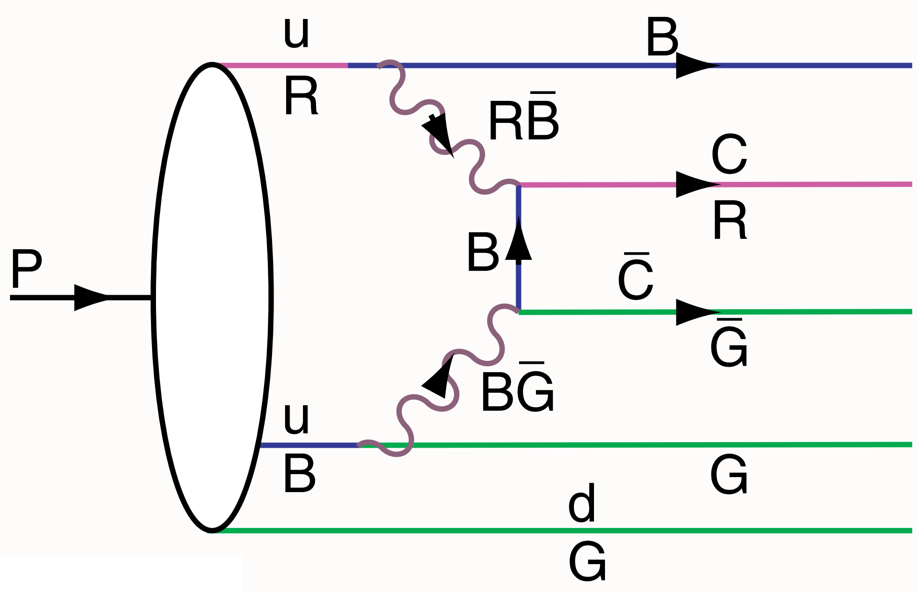
- High x_F $pp \to J/\psi J/\psi X$

- 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)

IC Structure Function: Critical Test of QCD



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

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

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

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

OPE derivation - M.Polyakov et al.

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

$c\bar{c}$ in Color Octet

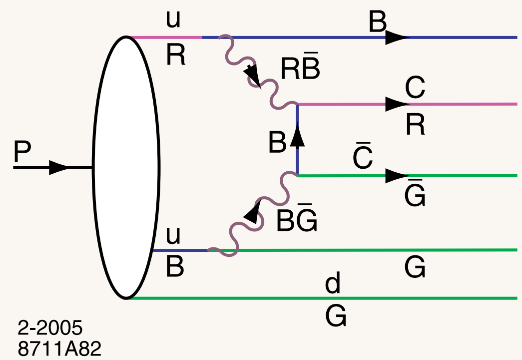
Distribution peaks at equal rapidity (velocity)
Therefore heavy particles carry the largest momentum fractions

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

High x charm!

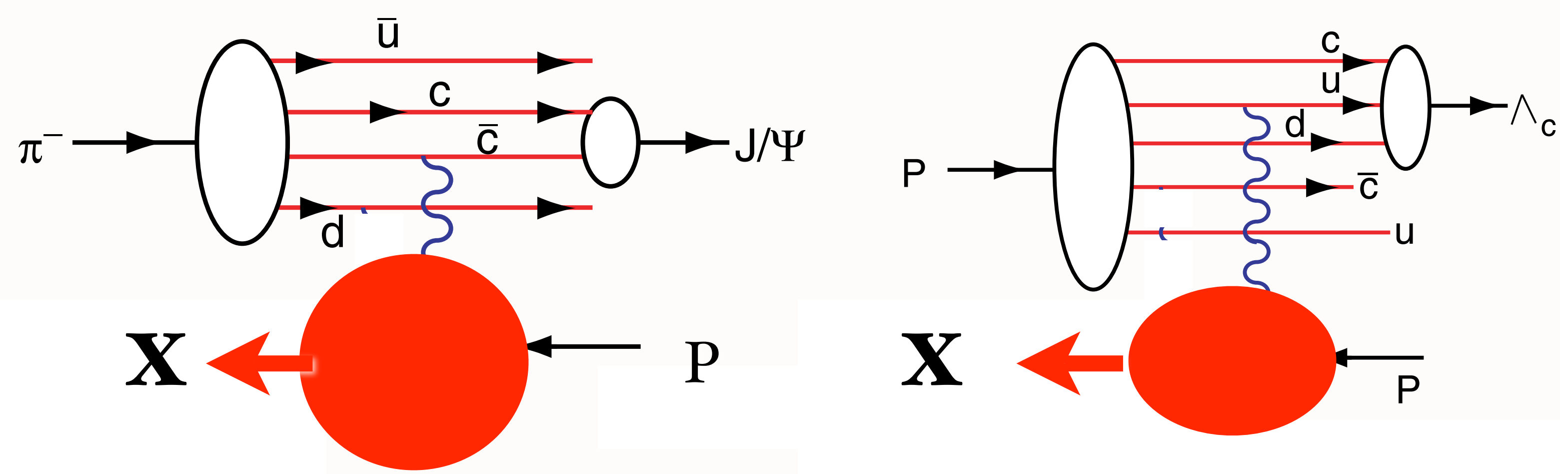
Hoyer, Peterson, Sakai, sjb

Intrinsic Heavy-Quark Fock States



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

Leading Hadron Production from Intrinsic Charm



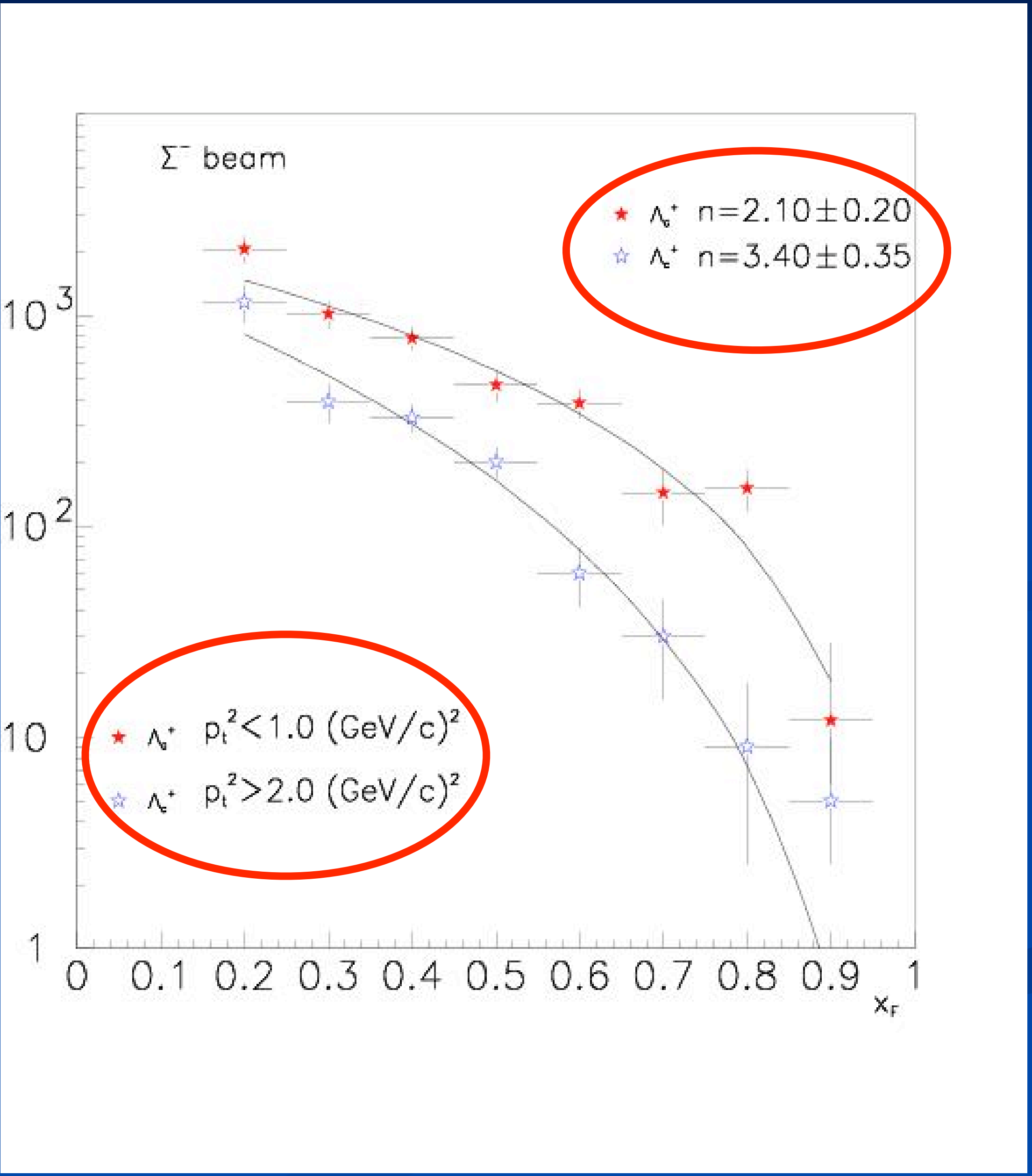
Coalescence of Comoving Charm and Valence Quarks Produce J/ψ, Λ_c and other Charm Hadrons at High x_F

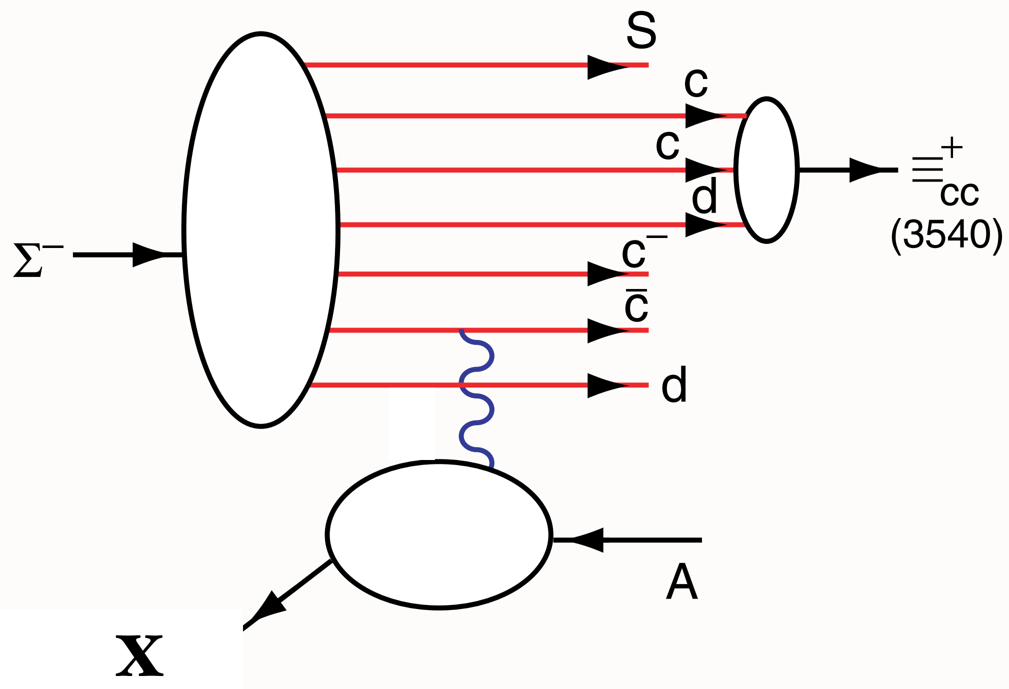
SELEX Λ_c^+ Studies – p_T Dependence

- 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))

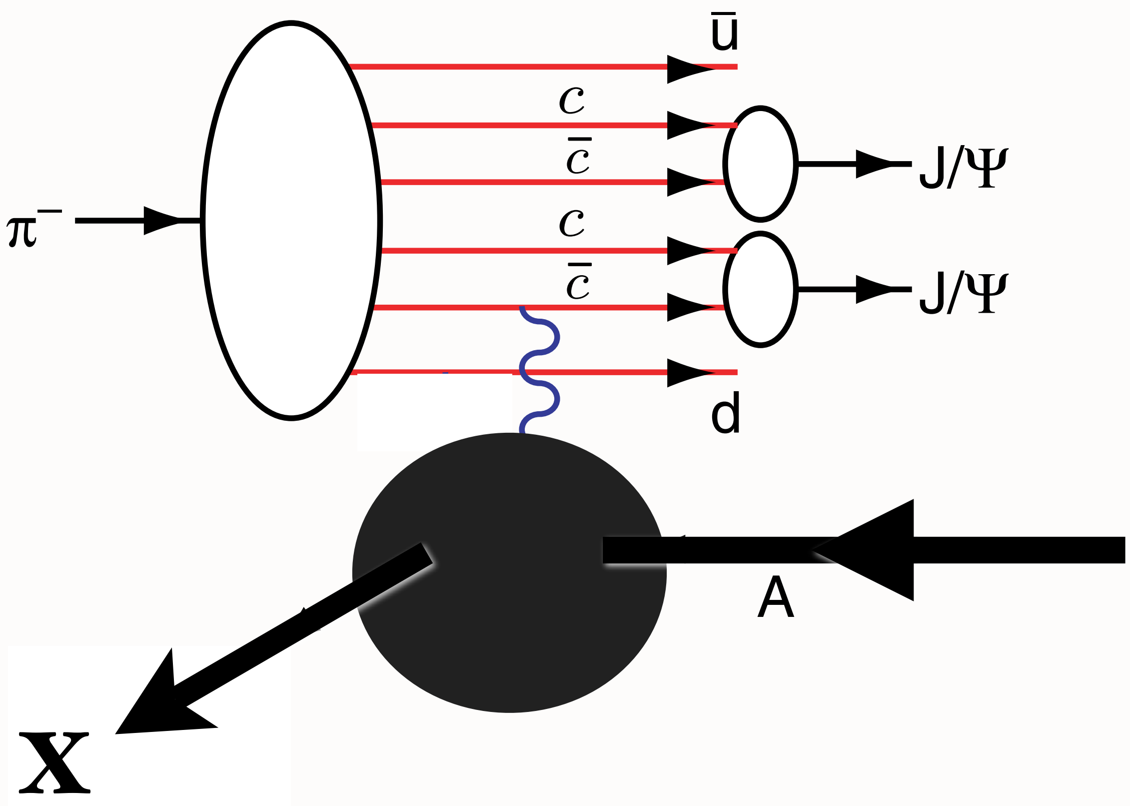




Production of a Double-Charm Baryon

SELEX high x_F $< x_F >= 0.33$

Production of Two Charmonia at High x_F



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

Excludes `color drag' model

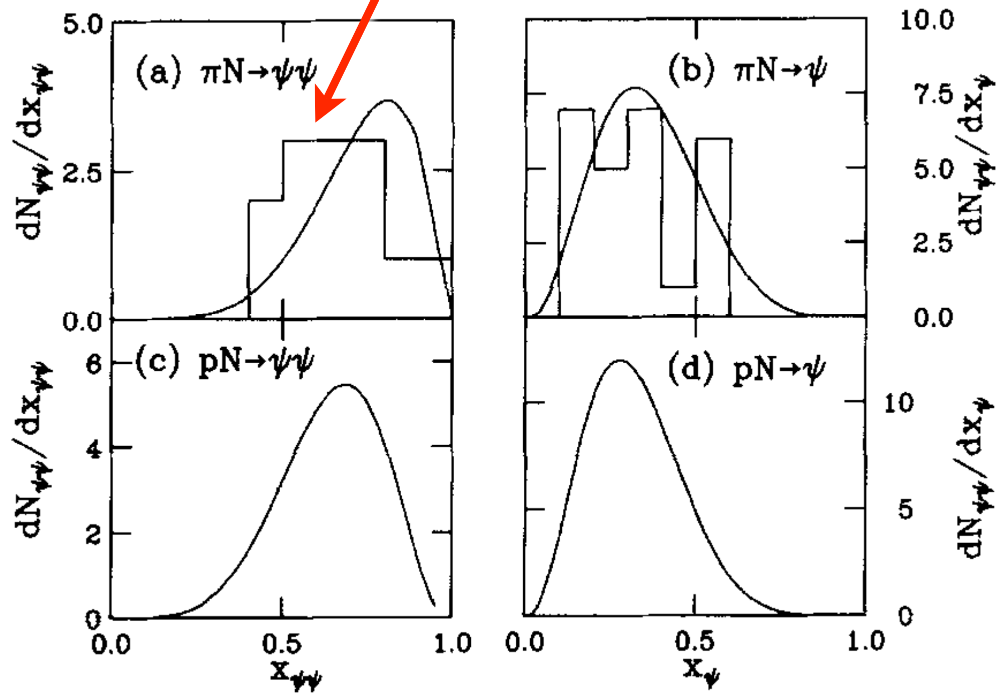


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized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

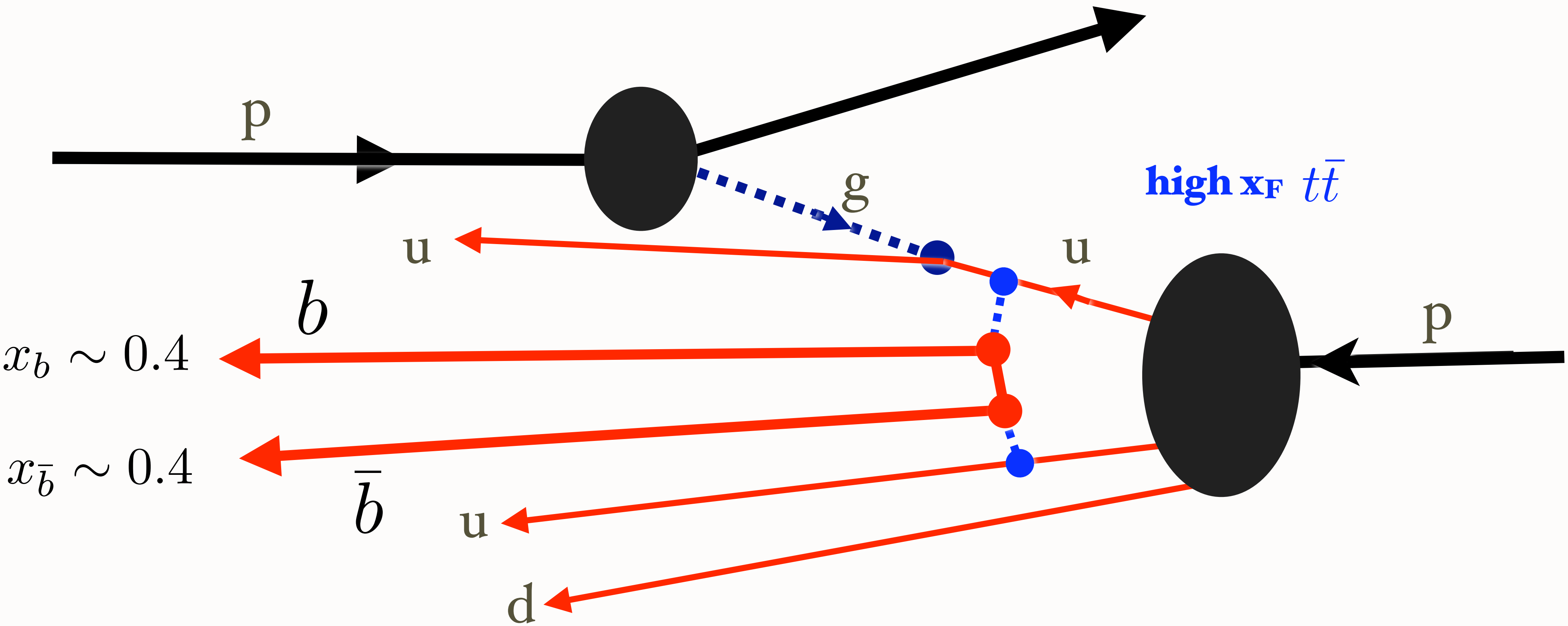
$$\frac{dP_{\rm ic}}{\prod_{i=1}^n dx_i d^2 k_{T,i}} = N_n \alpha_s^4(M_{c\bar{c}}) \frac{\delta(\sum_{i=1}^n \boldsymbol{k}_{T,i})\delta(1-\sum_{i=1}^n x_i)}{(m_h^2 - \sum_{i=1}^n (m_{T,i}^2/x_i))^2},$$

Excitation of Intrinsic Heavy Quarks in Proton

Amplitude maximal at small invariant mass, equal rapidity

$$x_i \sim \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

Produce forward, high x_F
$\Upsilon(b\bar{b}), \Lambda_b(bud), B^+(\bar{b}u), B^0(\bar{b}d)$

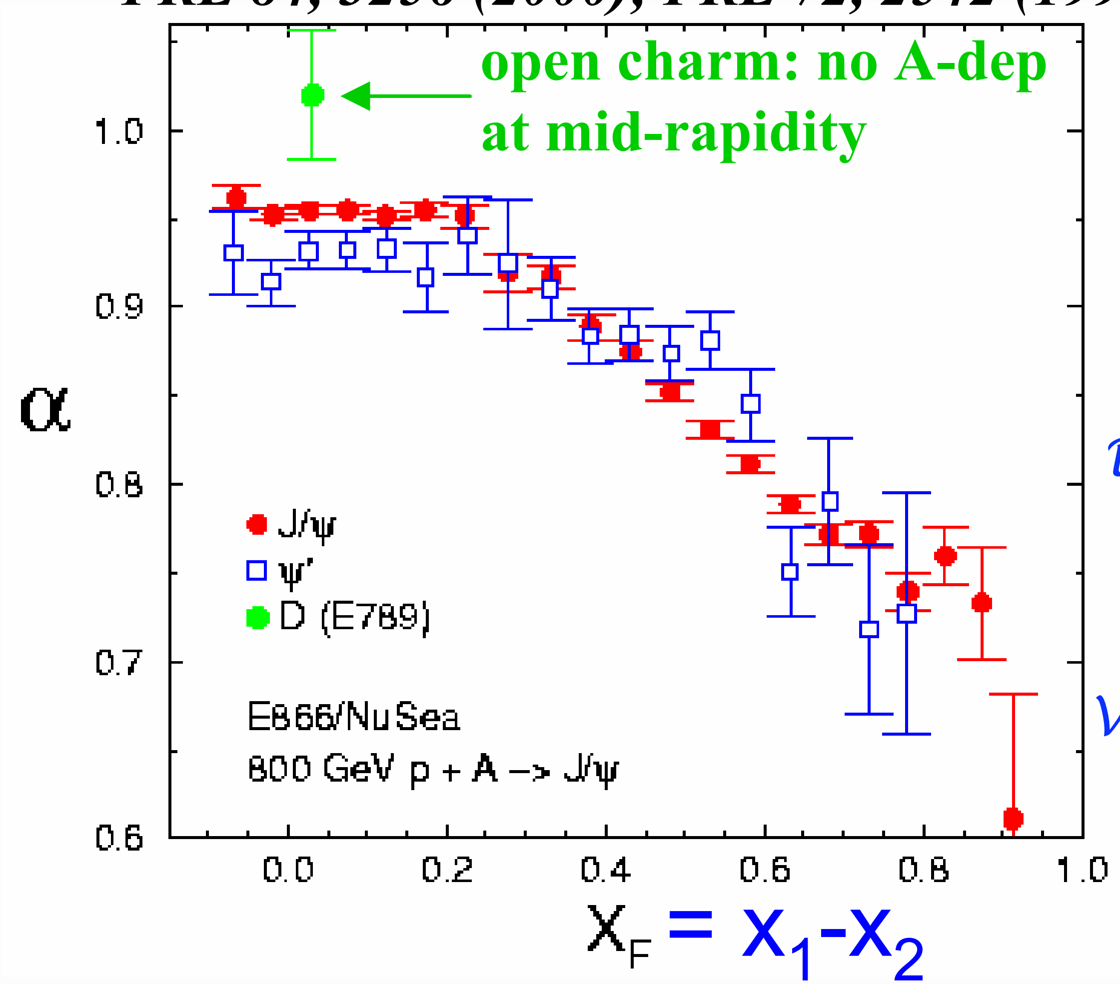


800 GeV p-A (FNAL) $\sigma_A = \sigma_p * A^{\alpha}$

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

M. Leitch

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



Remarkably Strong Nuclear Dependence for Fast Charmonium

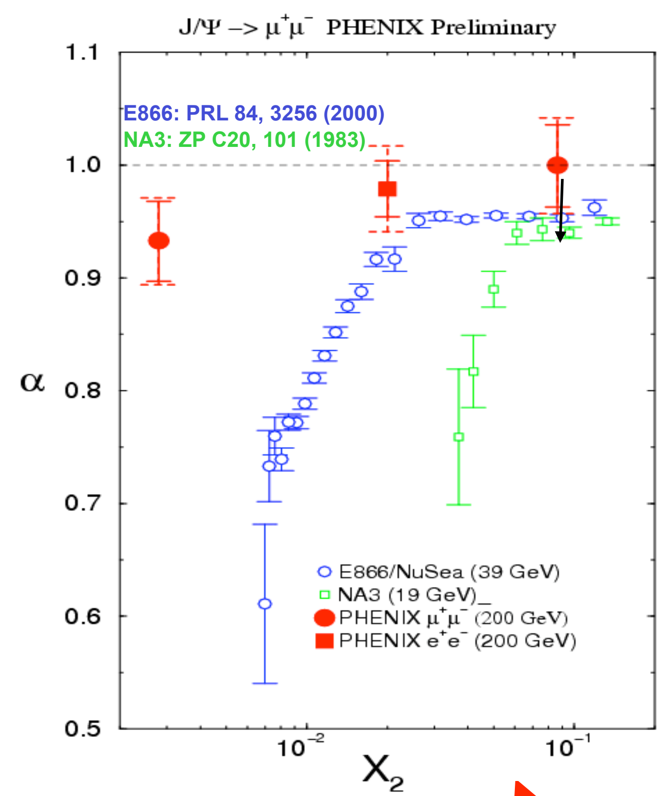
Violation of PQCD Factorization!

Violation of factorization in charm hadroproduction.
P. Hoyer, **M. Vanttinen** (**Helsinki U.**) , **U. Sukhatme** (**Illinois U., Chicago**) **. HU-TFT-90-14, May 1990. 7pp.**
Published in Phys.Lett.B246:217-220,1990

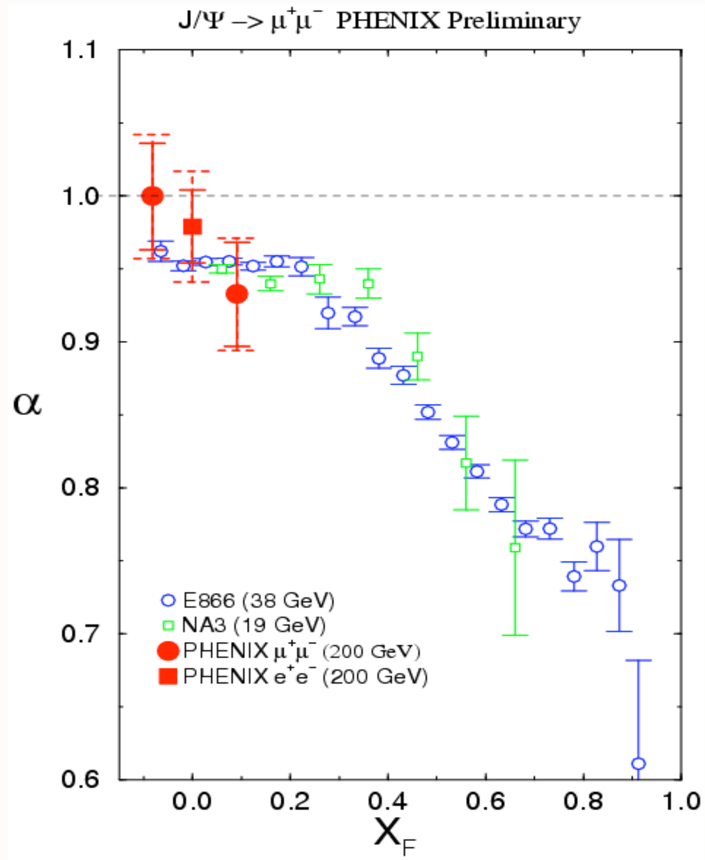
J/ψ nuclear dependence vrs rapidity, x_{Au}, x_F

M.Leitch

PHENIX compared to lower energy measurements



Klein,Vogt, PRL 91:142301,2003
Kopeliovich, NP A696:669,2001

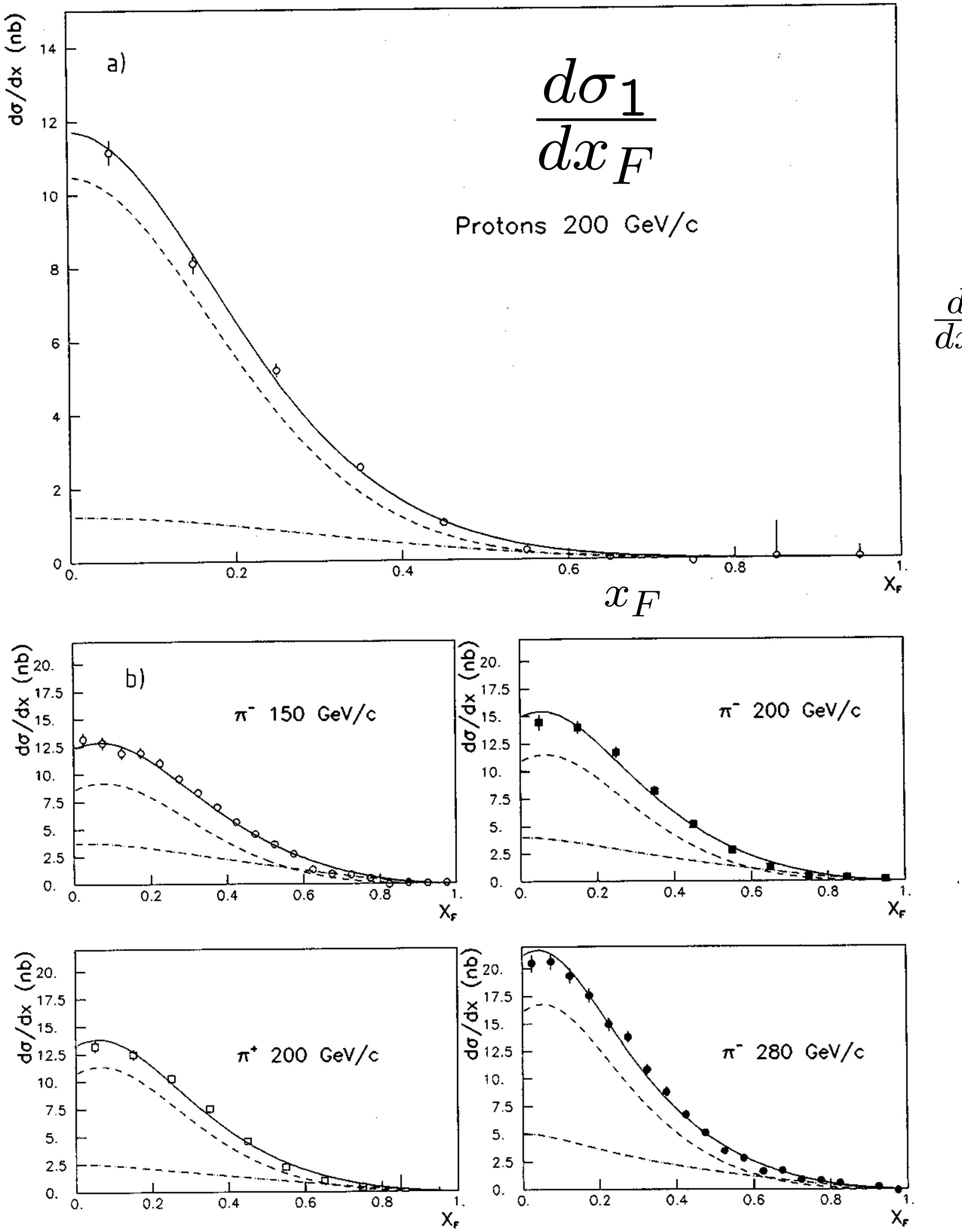


Huge "absorption" effect at large xF

Violates PQCD factorization!

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

Hoyer, Sukhatme, Vanttinen



J. Badier et al, NA3

Two Components

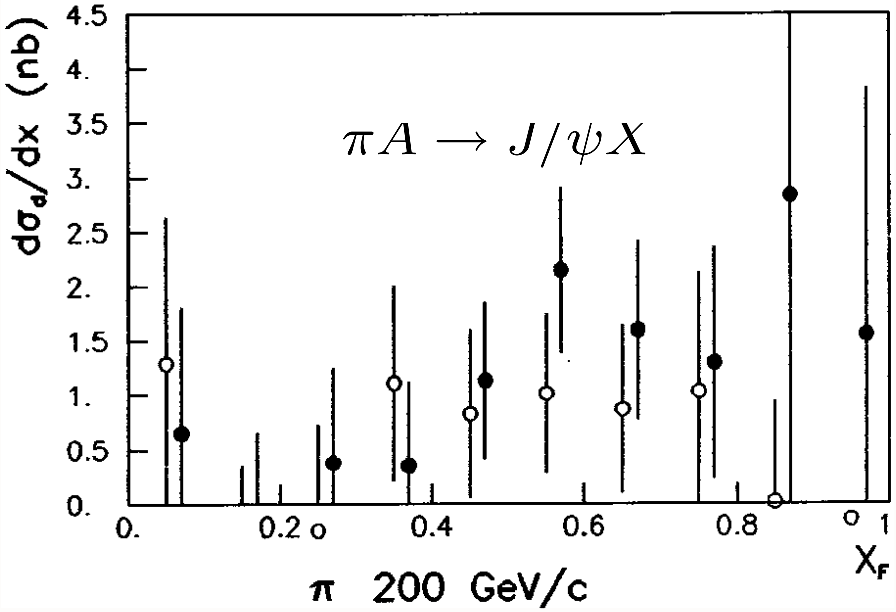
$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^1 \frac{d\sigma_1}{dx_F} + A^{2/3}\frac{d\sigma_{2/3}}{dx_F}$$

A^1 component

Identify with Fusion

Conventional PQCD subprocesses

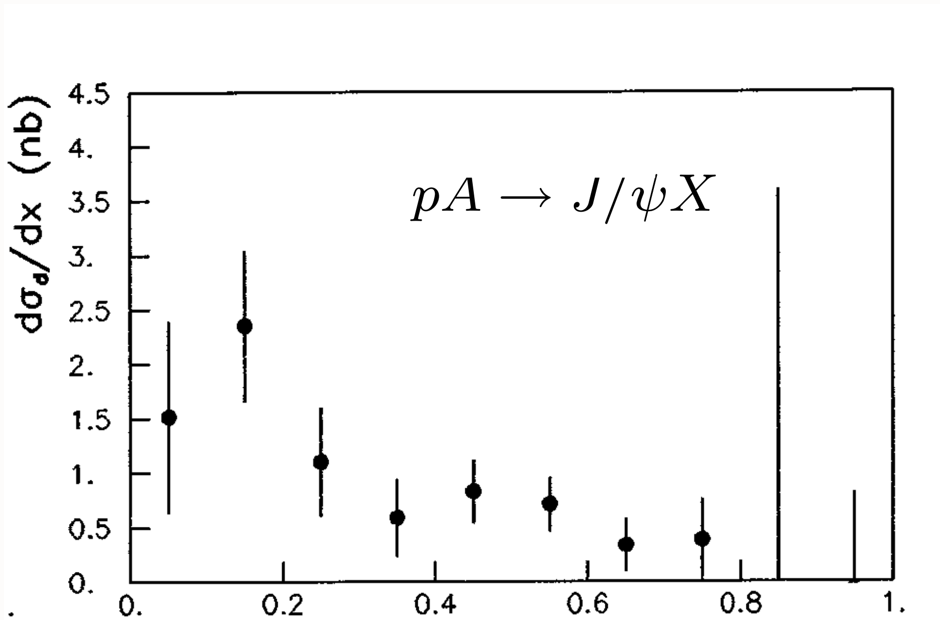
$$\frac{d\sigma_1}{dx_F}(\pi A \to J/\psi X)$$



J. Badier et al, NA3

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

$A^{2/3}$ component



p 200 GeV/c

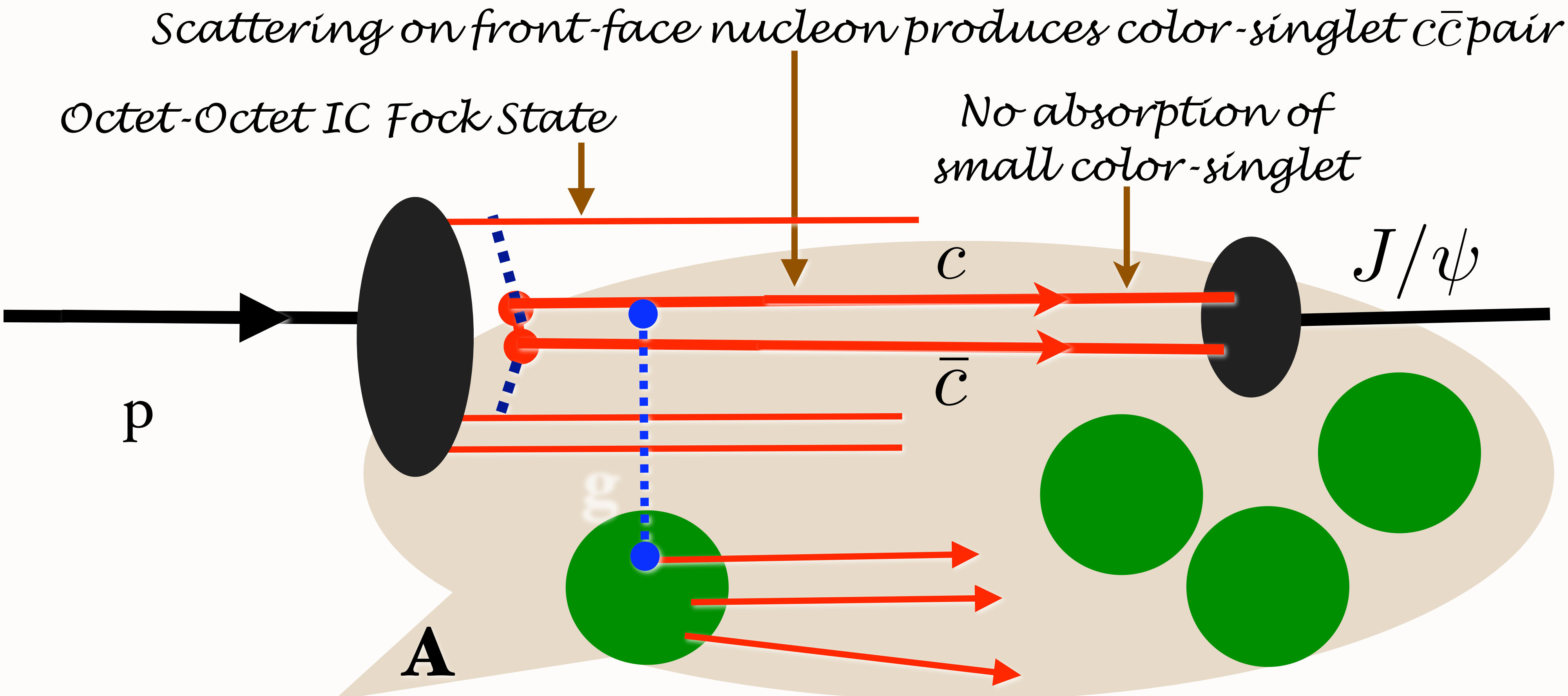
Identify with IC
High x_F

Remarkably Flat Distribution

Excess beyond conventional PQCD subprocesses

Kopeliovich, Schmidt,
Soffer, sjb

Color-Opaque IC Fock state interacts on nuclear front surface

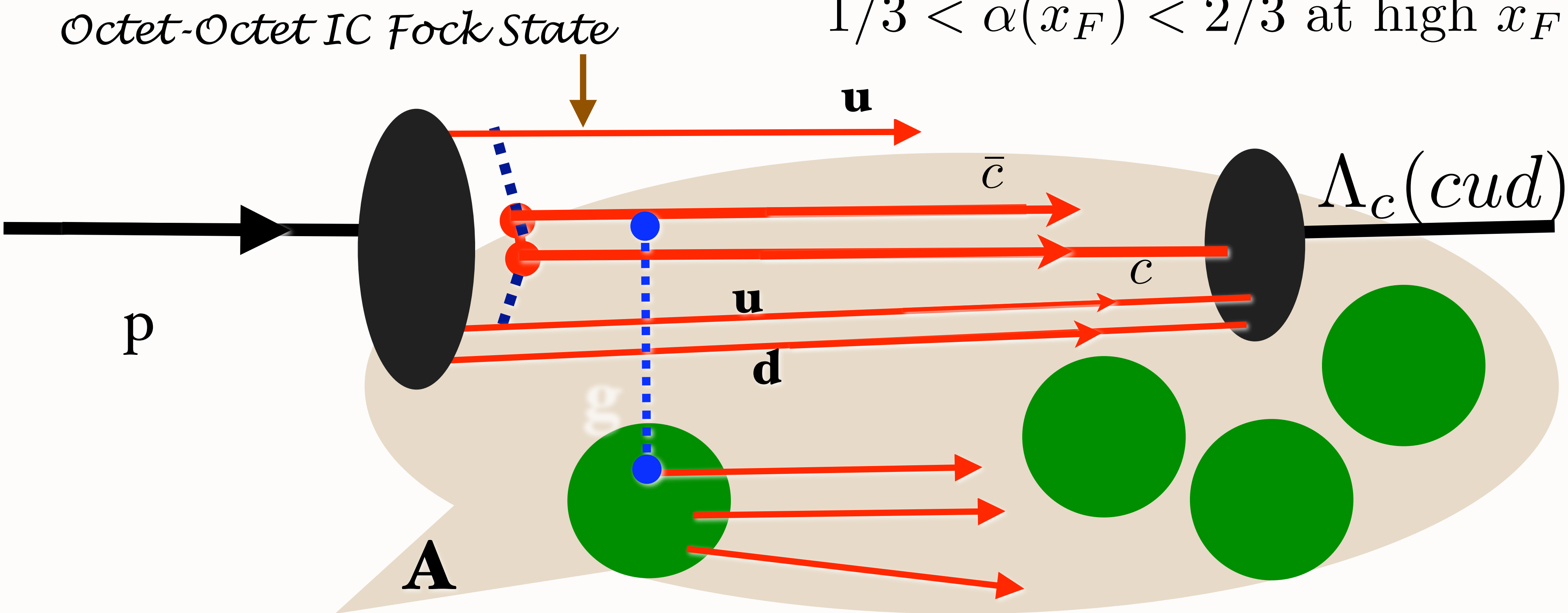


$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$

Color-Opaque IC Fock state interacts on nuclear front surface

$$\frac{d\sigma}{dx_F}(pA \to \Lambda_c X) = A^{\alpha(x_F)} \frac{d\sigma}{dx_F}(pN \to \Lambda_c X)$$

$1/3 < \alpha(x_F) < 2/3$ at high x_F



Reconciles ISR and Fixed Target Measurements!

- 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)

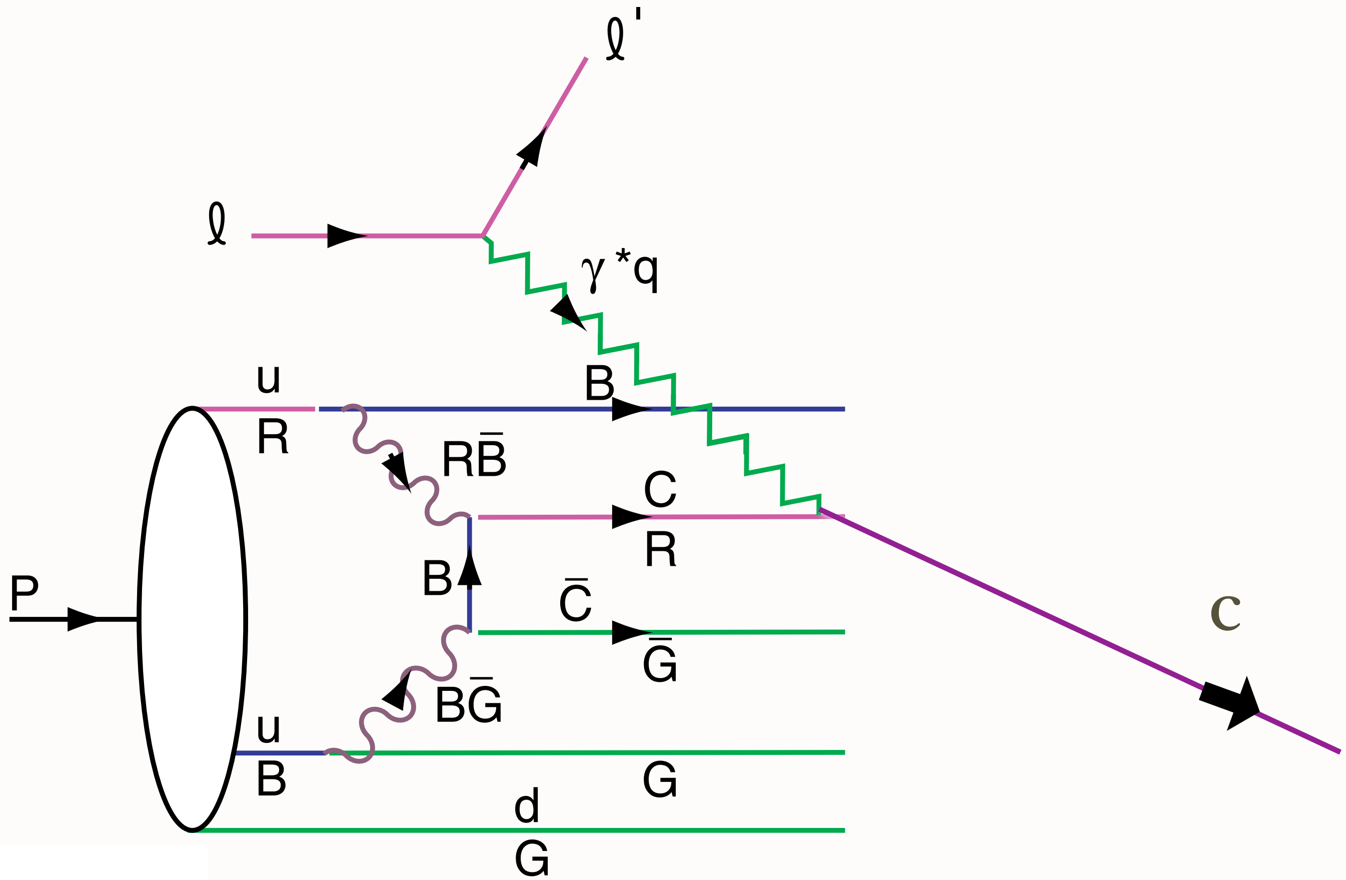
Color Opaqueness

- 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

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



Hoyer, Peterson, SJB

Why is Intrinsic Charm Important for Flavor Physics?

- New perspective on fundamental nonperturbative hadron structure
- Charm structure function at high x
- Dominates high x_F charm and charmonium production
- Hadroproduction of new heavy quark states such as ccu, ccd at high x_F
- Intrinsic charm -- long distance contribution to penguin mechanisms for weak decay
- Novel Nuclear Effects from color structure of IC, Heavy Ion Collisions
- New mechanisms for high x_F Higgs hadroproduction
- Dynamics of b production: LHCb
- Fixed target program at LHC: produce bbb states

PHYSICAL REVIEW D **73,** 113005 (2006)

Diffractive Higgs production from intrinsic heavy flavors in the proton

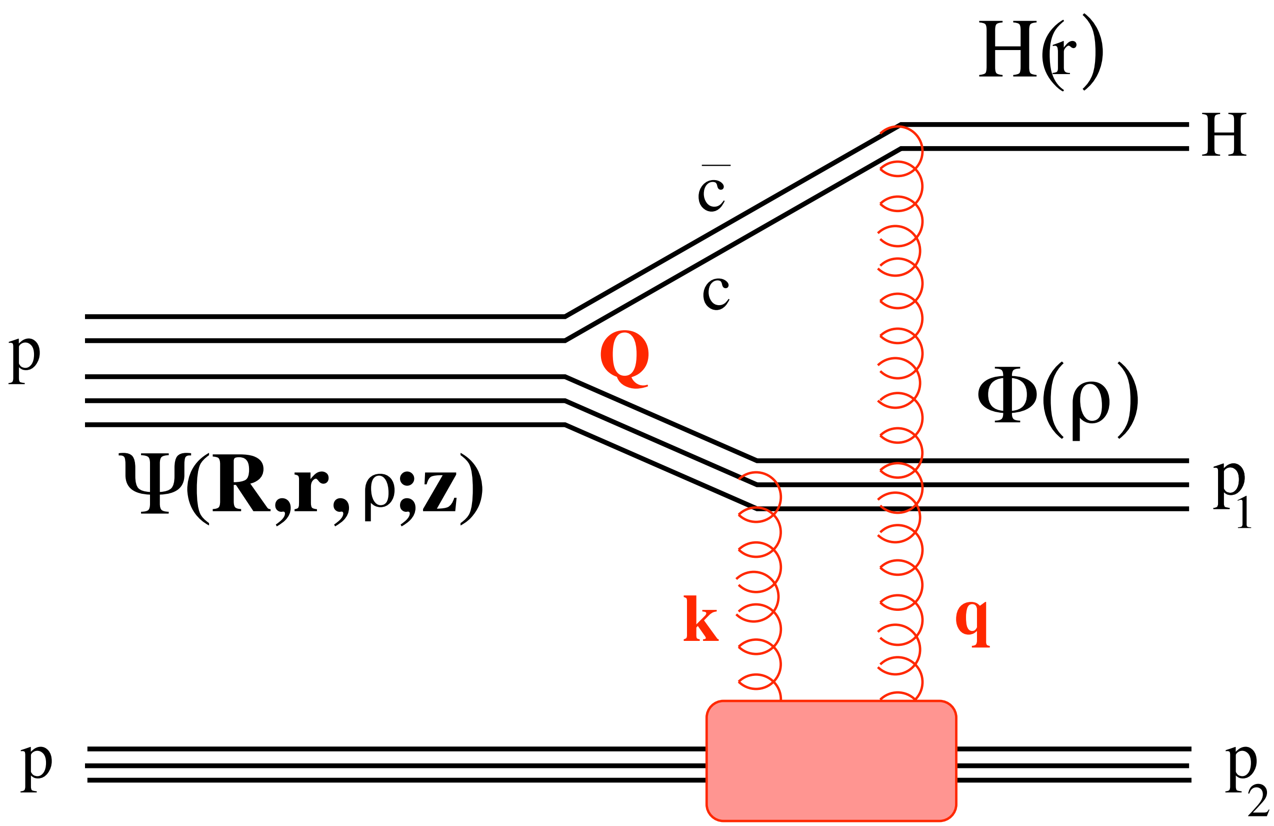
Stanley J. Brodsky,[1,*] Boris Kopeliovich,[2,†] Ivan Schmidt,[2,‡] and Jacques Soffer[3,§]

Higgs Hadroproduction at Large Feynman x

Stanley J. Brodsky[*a], Alfred Scharff Goldhaber[†a,b], Boris Z. Kopeliovich[‡c,d], Ivan Schmidt[§c]

To be published in Nuclear Physics B

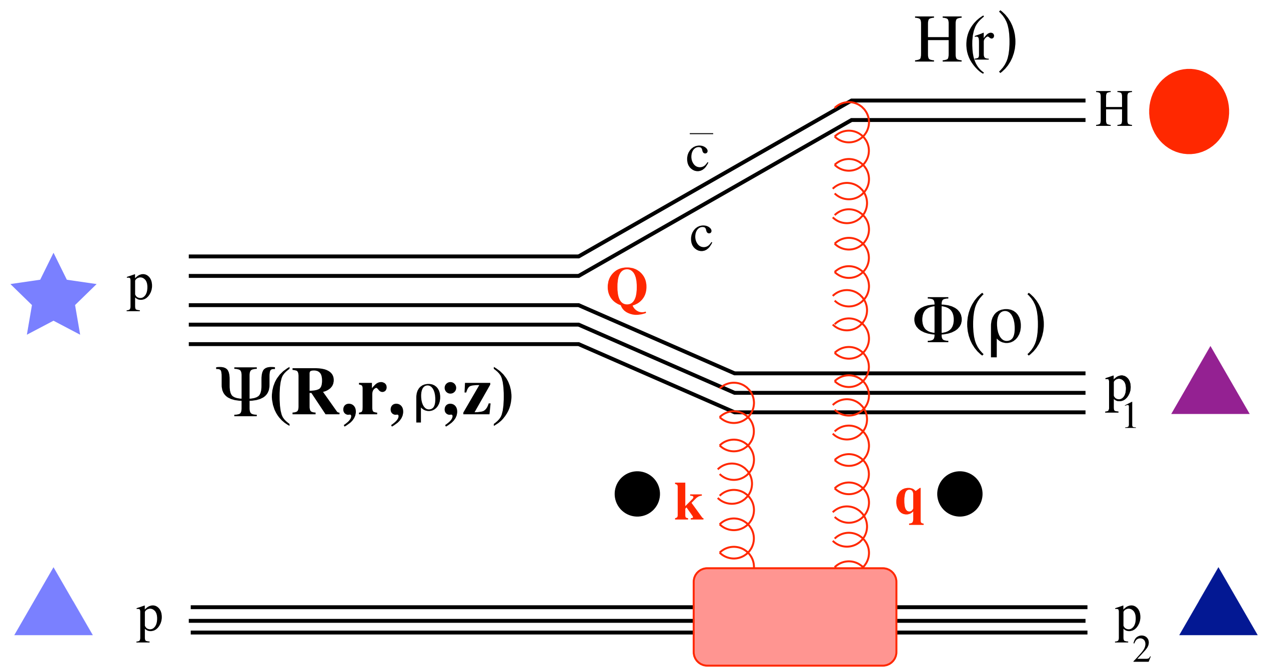
$$\frac{d\sigma(pp \rightarrow \ ppH)}{dx_2 d^2 p_1 d^2 p_2} = \frac{1}{(1-x_2)16\pi^2} |A(x_2, \vec{p}_1, \vec{p}_2)|^2$$



$$A(x_2, \vec{p}_1, \vec{p}_2) = \frac{8}{3\sqrt{2}} \int d^2Q \frac{d^2q}{q^2} \frac{d^2k}{k^2} \alpha_s(q^2)\alpha_s(k^2)\delta(\vec{q} + \vec{p}_2 + \vec{k})\delta(\vec{k} - \vec{p}_1 - \vec{Q})$$

$$\times \int d^2\tau |\Phi_p(\tau)|^2 [e^{i(\vec{k}+\vec{q})\cdot\vec{\tau}/2} - e^{i(\vec{q}-\vec{k})\cdot\vec{\tau}/2}]$$

$$\times \int d^2R d^2r d^2\rho H^\dagger(\vec{r}) e^{i\vec{q}\cdot\vec{r}/2}(1 - e^{-i\vec{q}\cdot\vec{r}})\Phi_p^\dagger(\vec{\rho}) e^{i\vec{k}\cdot\vec{\rho}/2}(1 - e^{-i\vec{k}\cdot\vec{\rho}})\Psi_p(\vec{R}, \vec{r}, \vec{\rho}, z) e^{i\vec{Q}\cdot\vec{R}}.$$

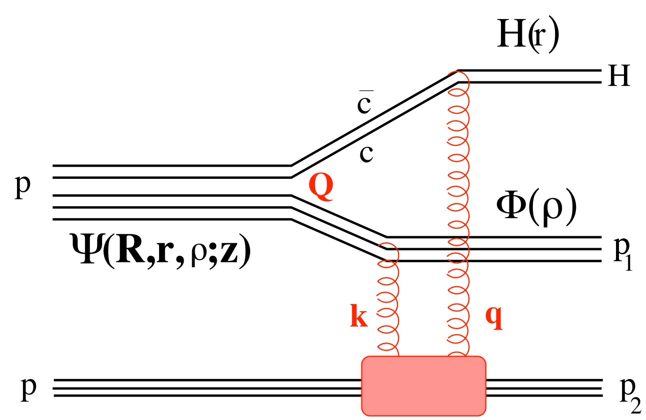


$$\Psi_p(\vec{R}, \vec{r}, \vec{\rho}, z) = \Psi_{\mathrm{IC}}(\vec{R}, z)\Psi_{\bar{c}c}(\vec{r})\Psi_{3q}(\vec{\rho}).$$

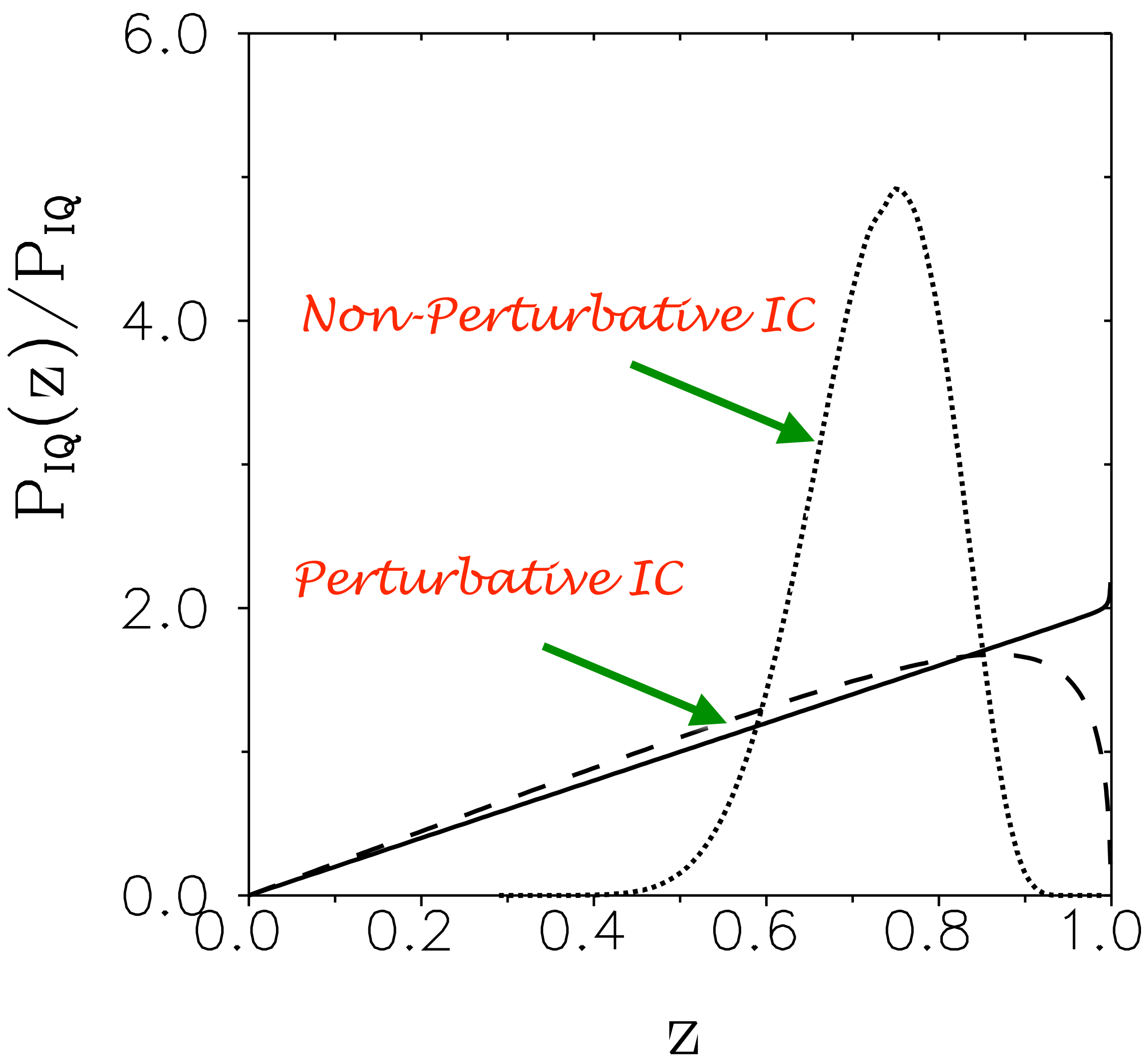
$$\int_0^1 dz \int d^2R d^2r d^2\rho |\Psi_p(\vec{R}, \vec{r}, \vec{\rho}, z)|^2 = P_{\mathrm{IC}},$$

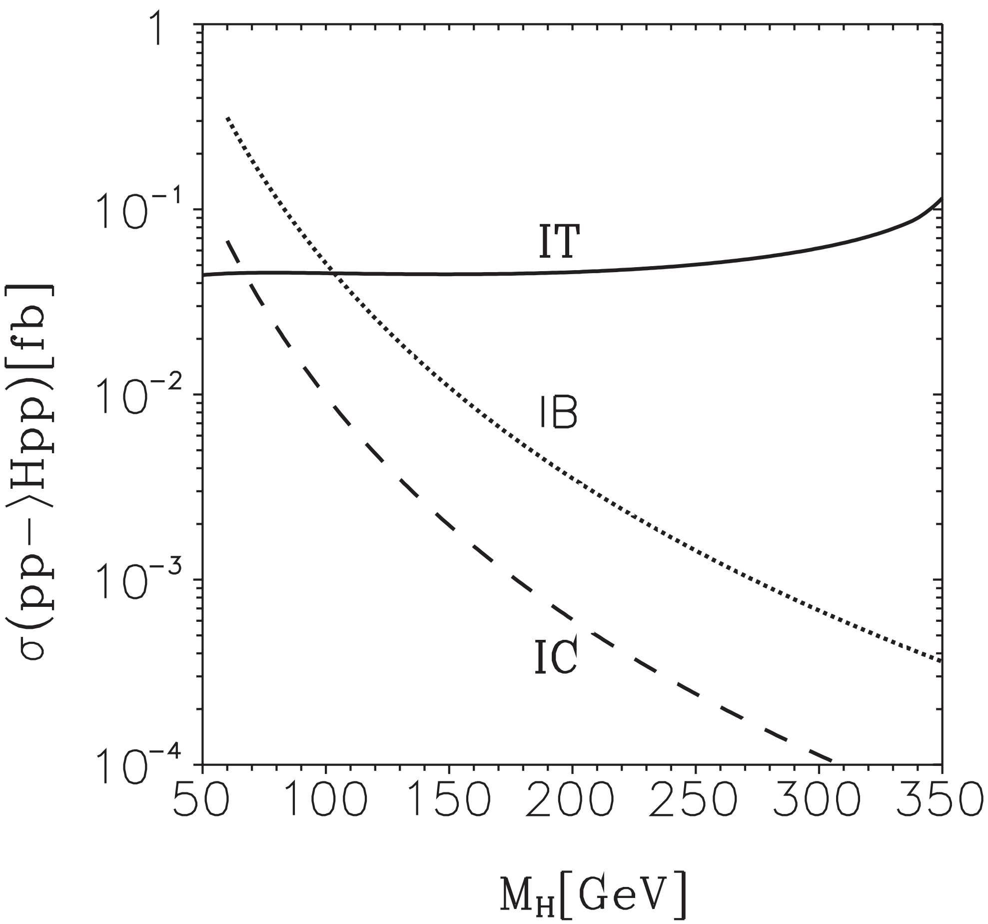
$$\Psi_{\mathrm{IQ}}(Q, z, \kappa) \propto \frac{z(1-z)}{Q^2 + z^2 m_p^2 + M^2_{\bar{Q}Q}(1-z)}.$$

$$H(\vec{r}) = i\frac{\sqrt{N_c G_F}}{2\pi} m_c \bar{\chi}\, \vec{\sigma}\, \chi \frac{\vec{r}}{r}\left[\epsilon Y_1(\epsilon r) - \frac{ir}{2}\Gamma_H M_H Y_0(\epsilon r)\right]$$



The distribution of produced Higgs particles over the fraction of the proton beam momentum. The dotted, dashed, and solid curves correspond to Higgs production from nonperturbative IC ($\beta = 1$), perturbative IC ($\beta = 0$), and IT, respectively.

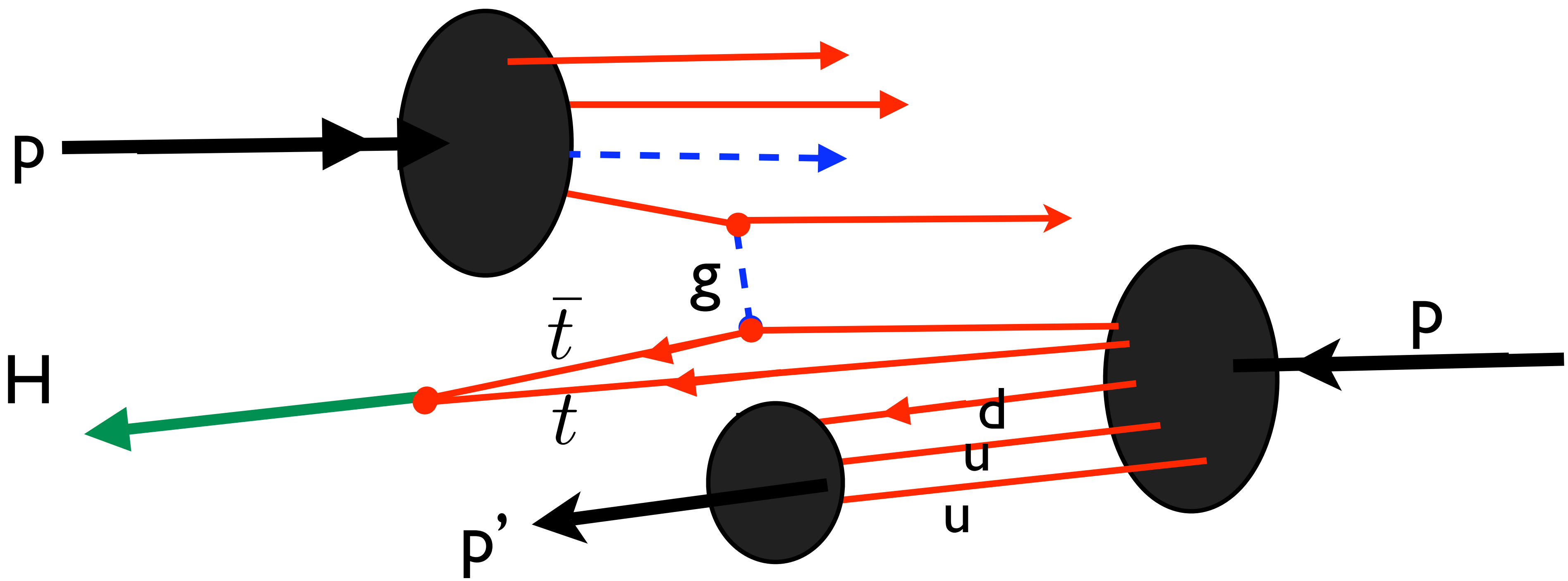


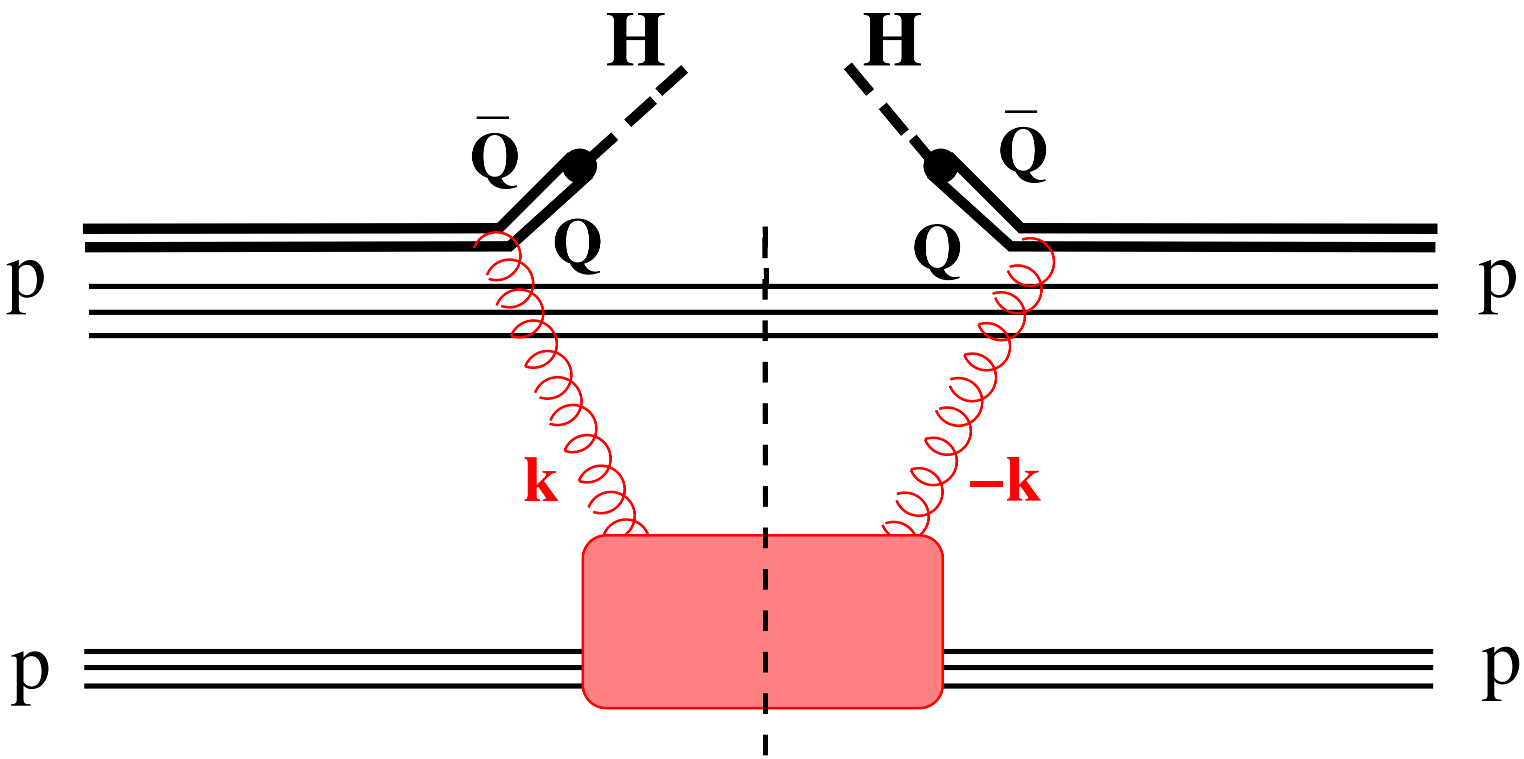


The cross section of the reaction $pp \rightarrow Hp + p$ as a function of the Higgs mass. Contributions of IC (dashed line), IB (dotted line), and IT (solid line).

Goldhaber, Kopeliovich, Schmidt, SJB

Higgs Hadroproduction at High x_F from Intrinsic Heavy Quarks




H
H
$\bar{Q}$
$\bar{Q}$
Q
Q
p
p
k
−k
p
p

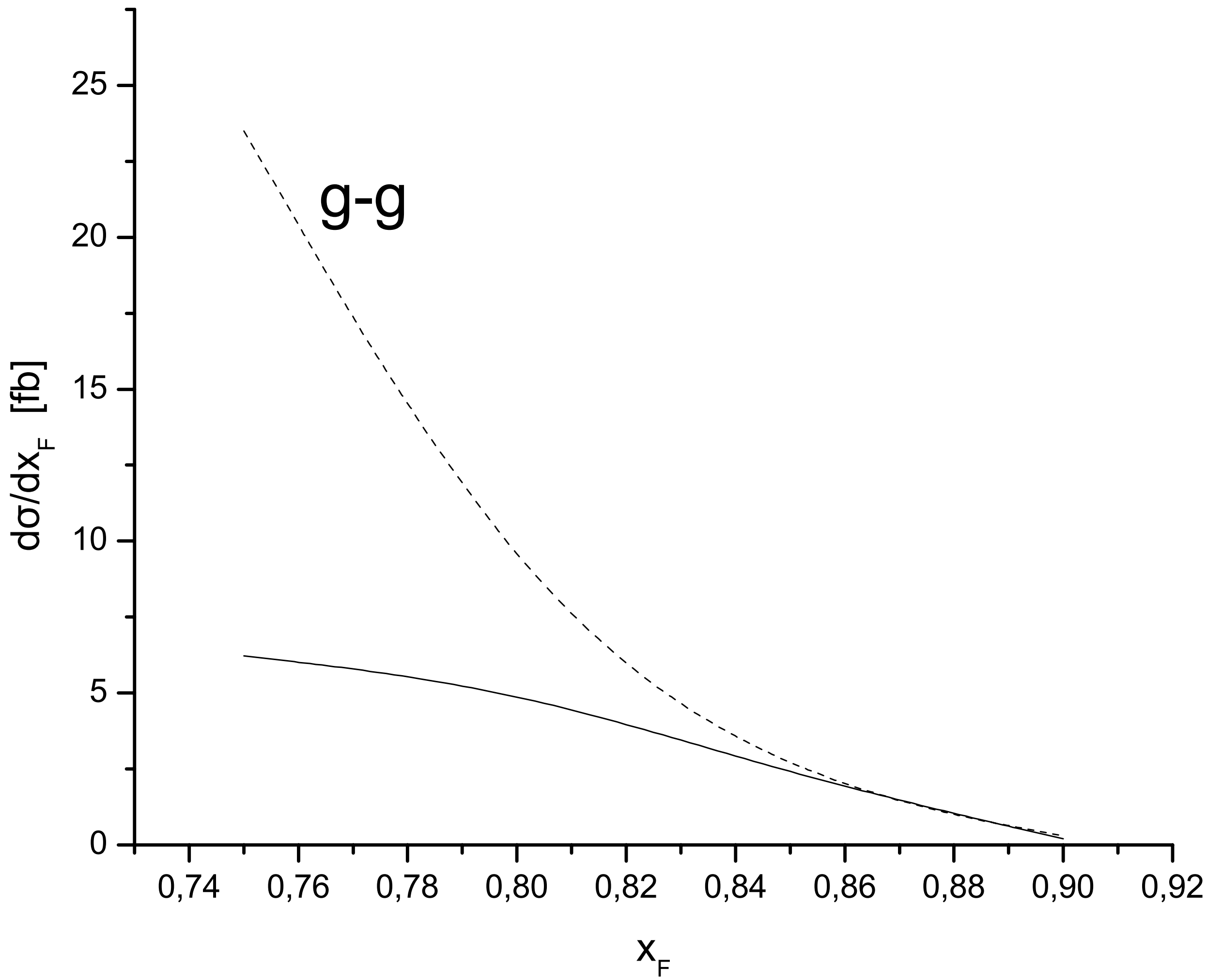
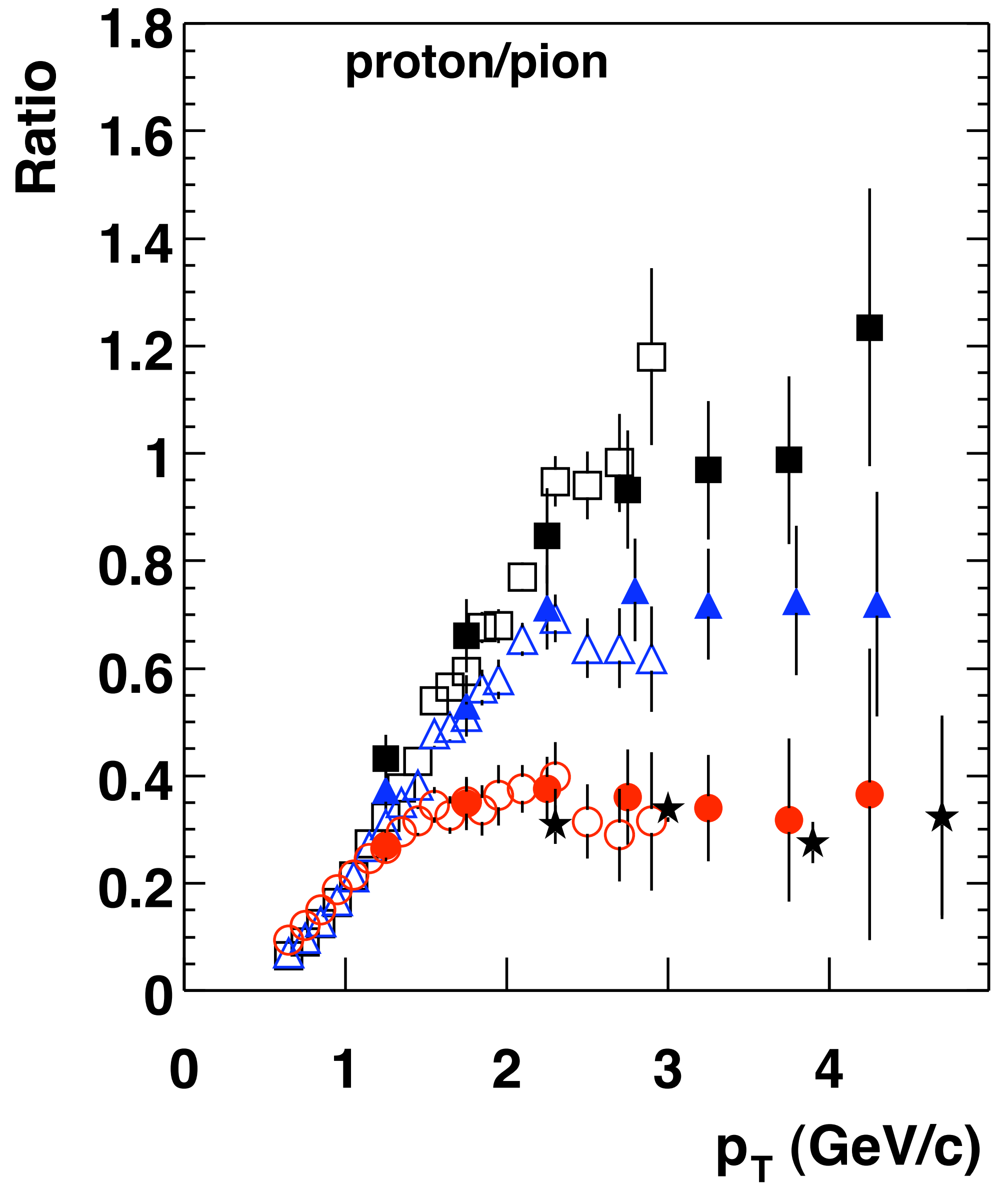


Figure 2: The cross section of inclusive Higgs production in f b, coming from the non-perturbative intrinsic charm distribution, at LHC ($\sqrt{s}$ = 14 TeV) energies. For comparison we show also an estimate of the cross section for gluon-gluon fusion.

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

Particle ratio changes with centrality!



Protons less absorbed in nuclear collisions than pions

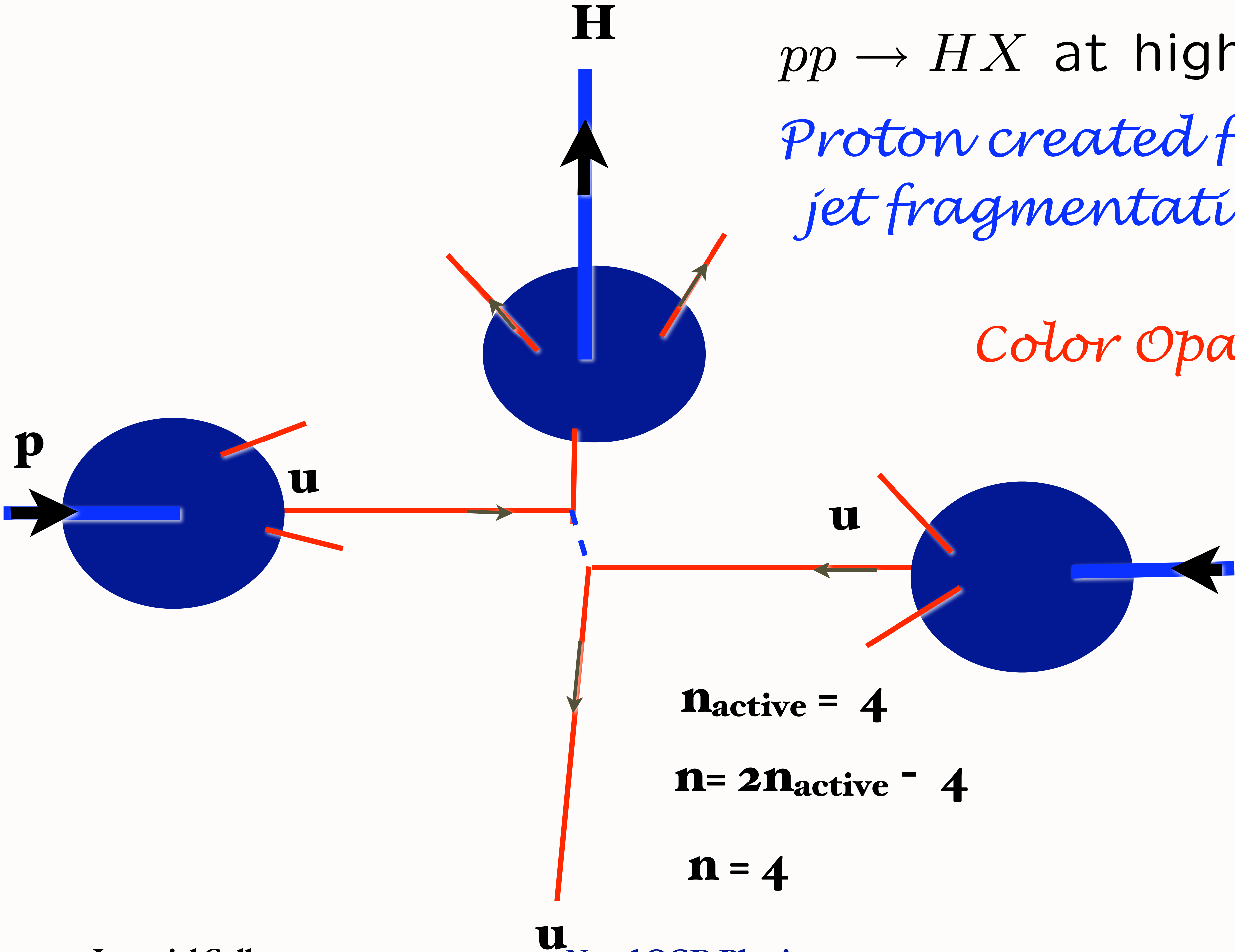
← **Central**

← **Peripheral**

$pp \to HX$ at high p_T

Proton created from jet fragmentation

Color Opaque



$n_{active} = 4$

$n = 2n_{active} - 4$

$n = 4$

Crucial Test of Leading -Twist QCD: Scaling at fixed x_T

$$x_T = \frac{2p_T}{\sqrt{s}}$$

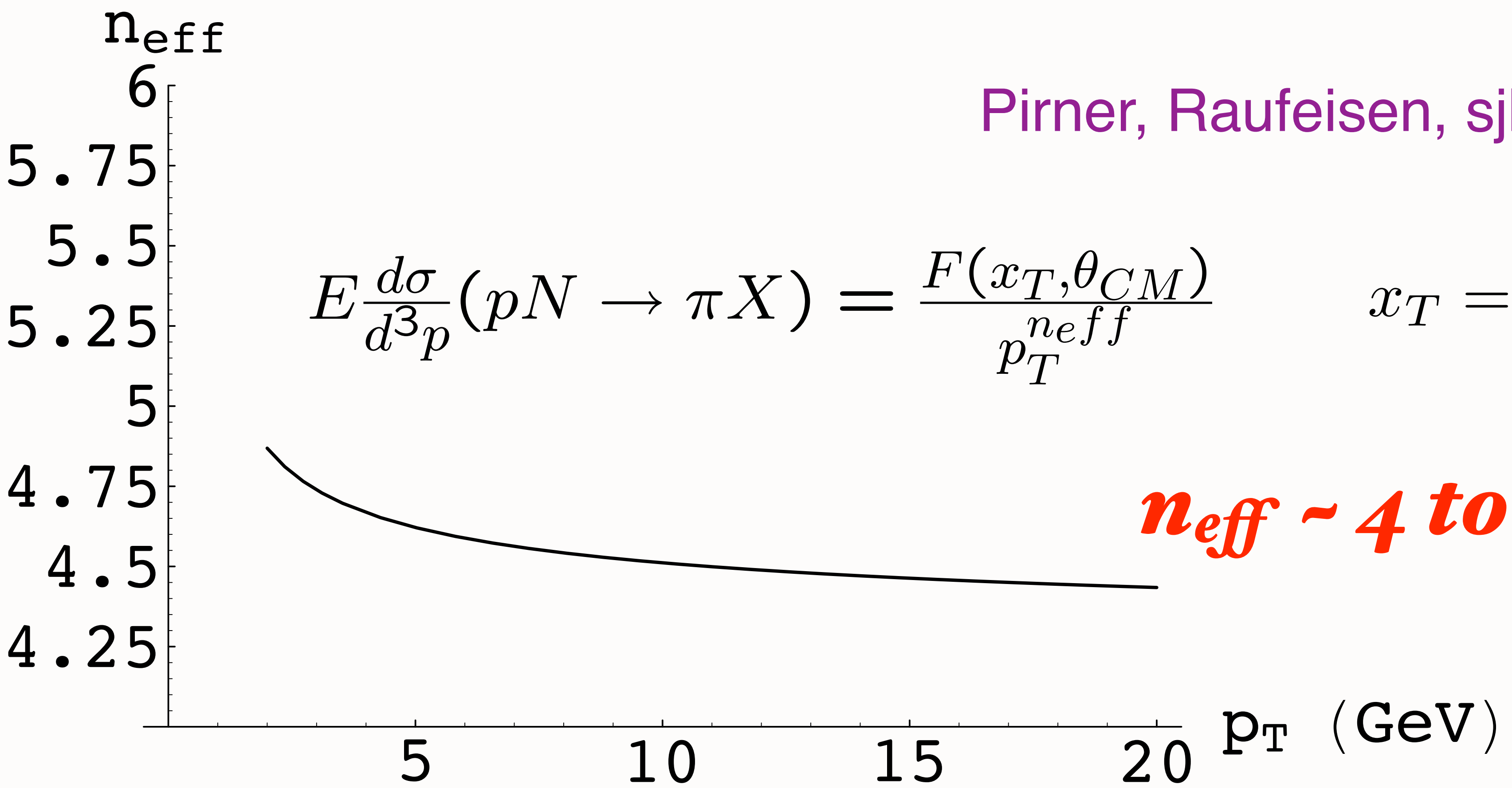
$$E\frac{d\sigma}{d^3p}(pN \to \pi X) = \frac{F(x_T,\theta_{CM})}{p_T^{neff}}$$

Parton model: $n_{eff} = 4$

As fundamental as Bjorken scaling in DIS

Conformal scaling: $n_{eff} = 2\, n_{active} - 4$

QCD prediction: Modification of power fall-off due to DGLAP evolution and the Running Coupling



Pirner, Raufeisen, sjb

$$E\frac{d\sigma}{d^3p}(pN \to \pi X) = \frac{F(x_T, \theta_{CM})}{p_T^{n_{eff}}} \qquad x_T = \frac{2p_T}{\sqrt{s}}$$

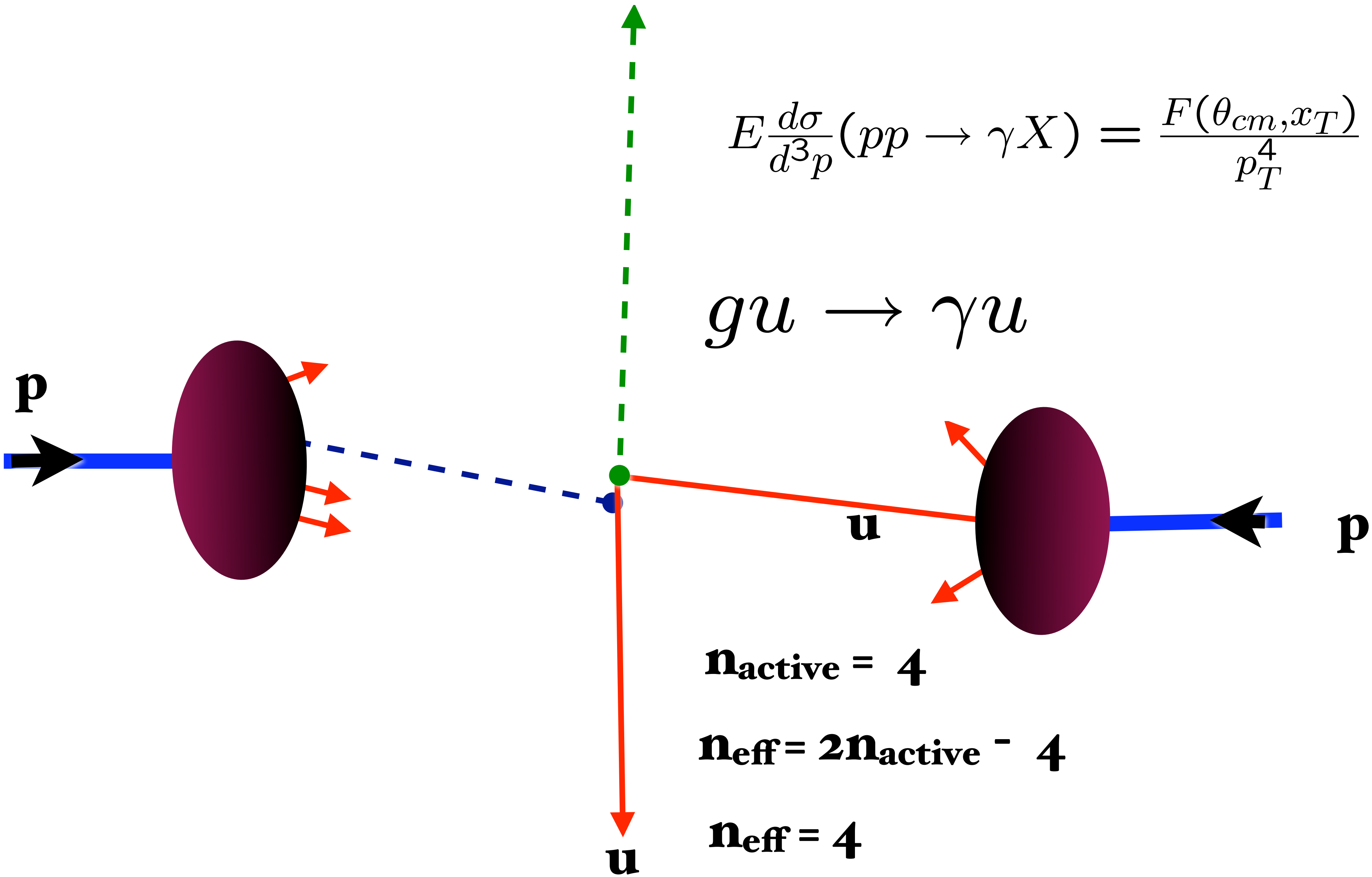
$n_{eff} \sim 4$ to 5

Key test of PQCD: power-law fall-off at fixed x_T

$$pp \longrightarrow \gamma X$$

$$E\frac{d\sigma}{d^3p}(pp \to \gamma X) = \frac{F(\theta_{cm}, x_T)}{p_T^4}$$

$$gu \longrightarrow \gamma u$$



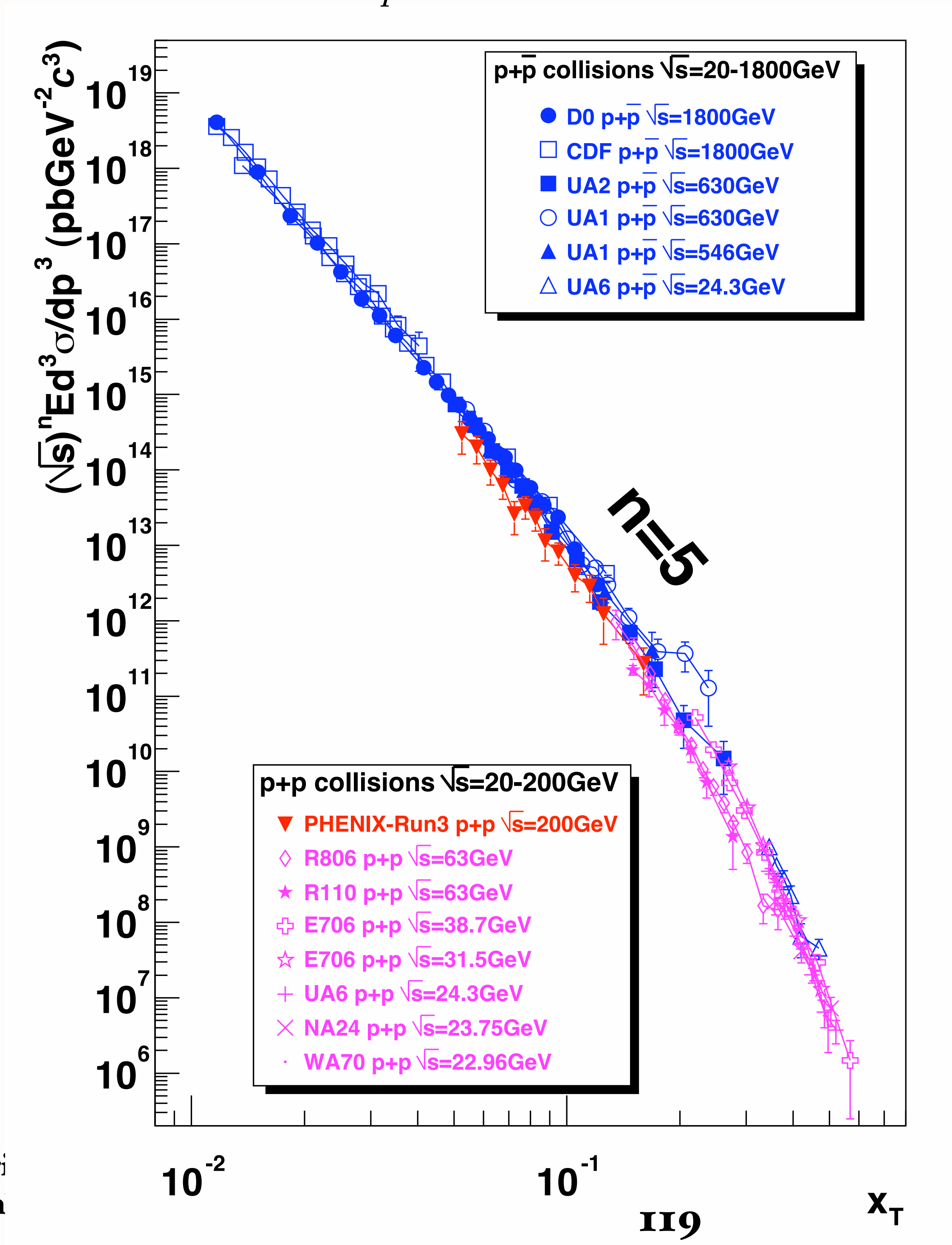
$\mathbf{n_{active}} = 4$

$\mathbf{n_{eff}} = 2\mathbf{n_{active}} - 4$

$\mathbf{n_{eff}} = 4$

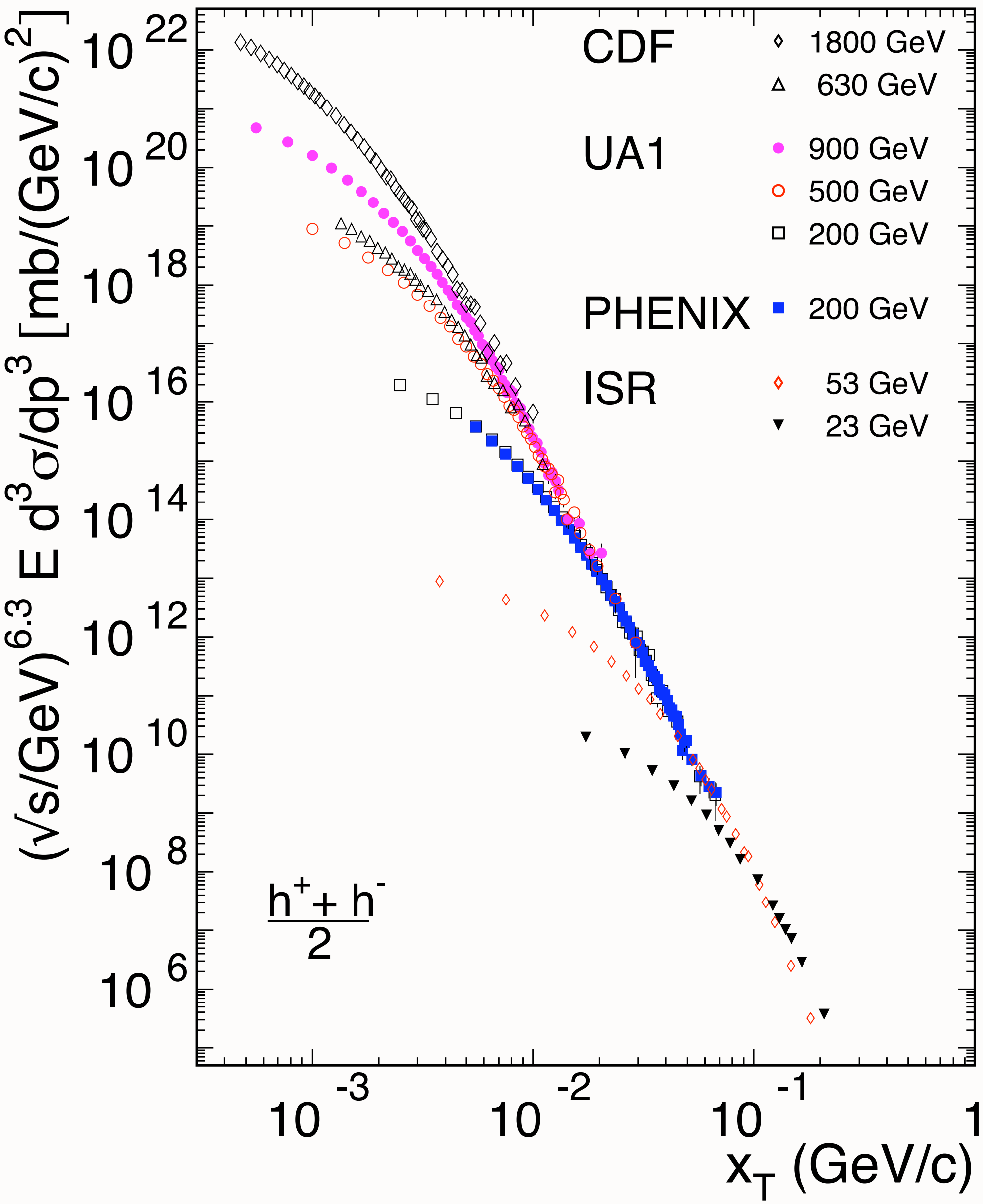
$\sqrt{s}^n E \frac{d\sigma}{d^3p}(pp \to \gamma X)$ at fixed x_T

Tannenbaum



Scaling of direct photon production consistent with PQCD

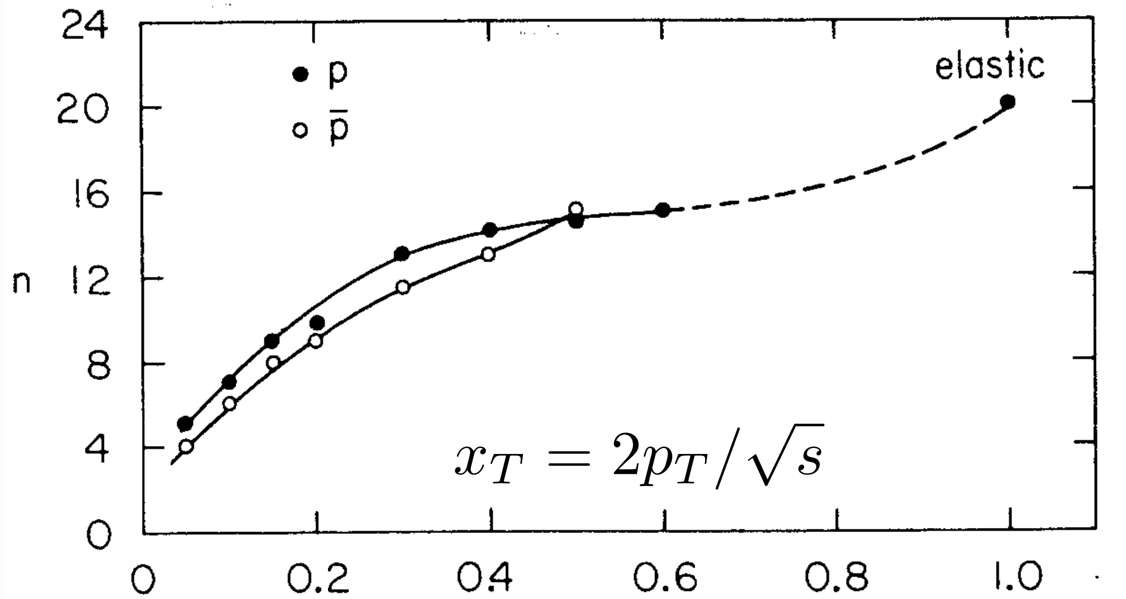
$$\sqrt{s}^{6.3} \times E\frac{d\sigma}{d^3p}(pp \to H^{\pm}X) \text{ at fixed } x_T$$



Tannenbaum

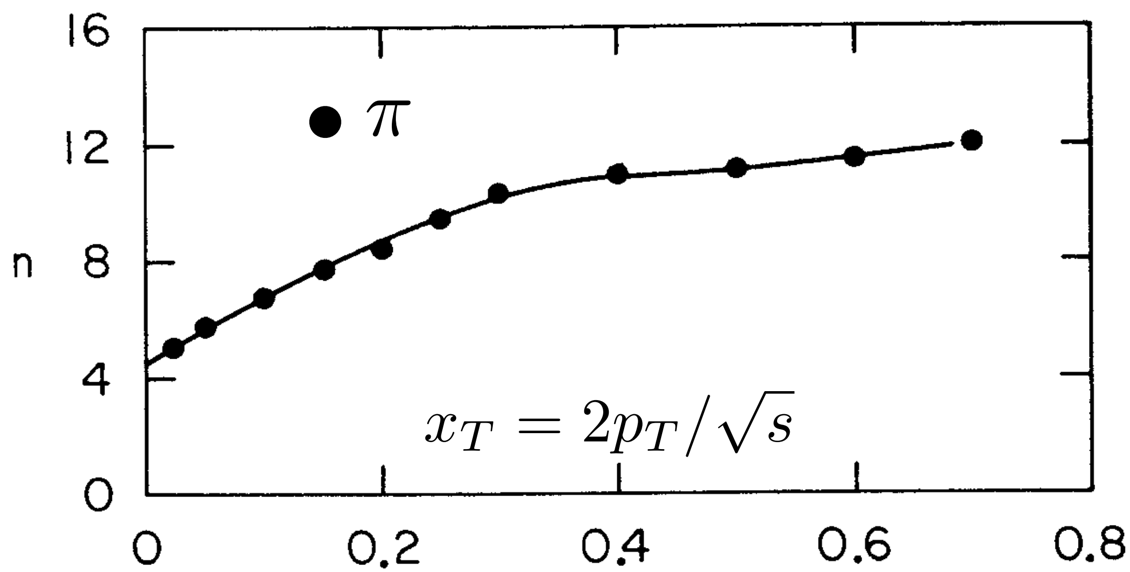
Scaling inconsistent with PQCD

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



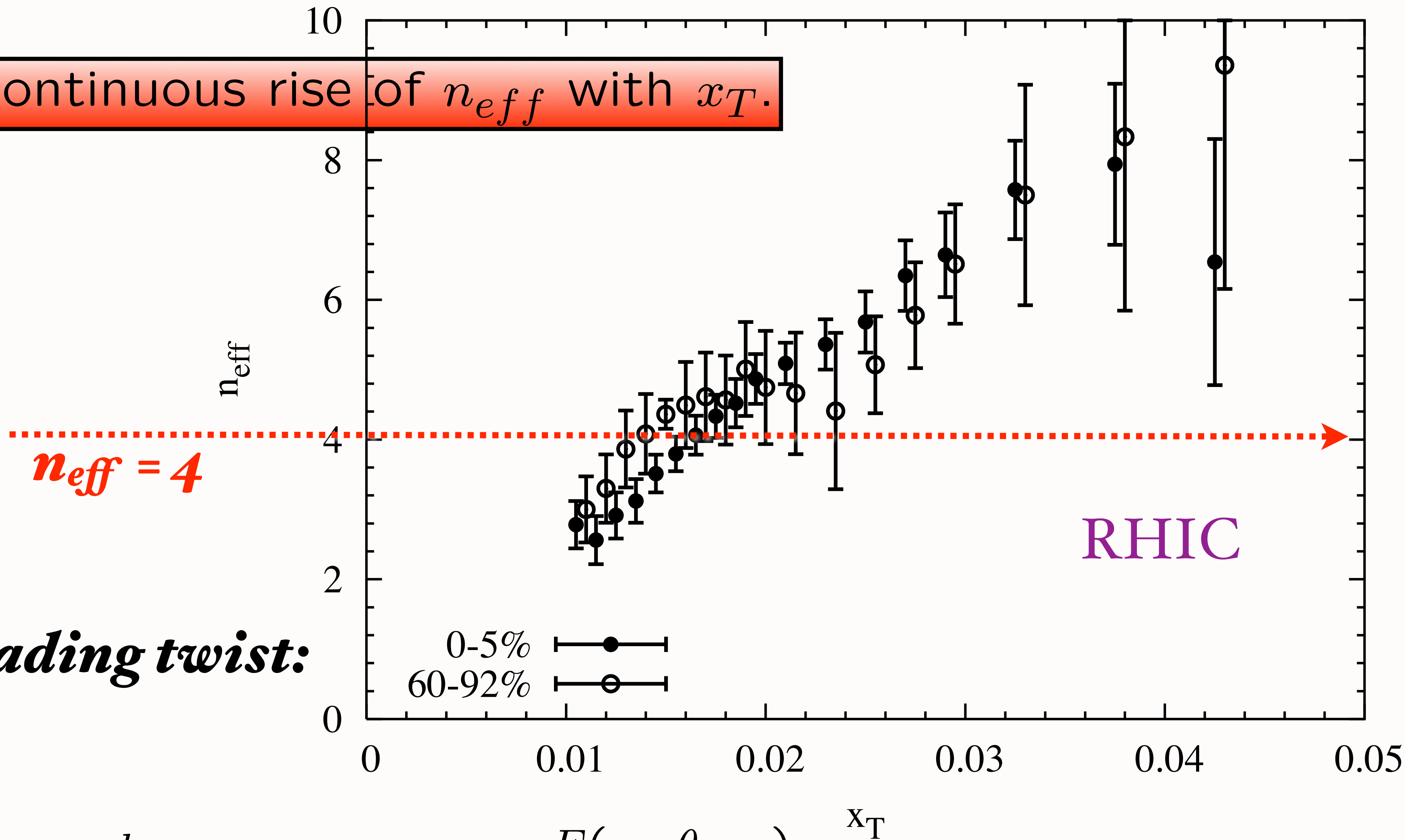
Clear evidence for higher-twist contributions

J. W. Cronin, SSI 1974



Protons produced in AuAu collisions at RHIC do not exhibit clear scaling properties in the available p_T range. Shown are data for central $(0-5\%)$ and for peripheral $(60-90\%)$ collisions.

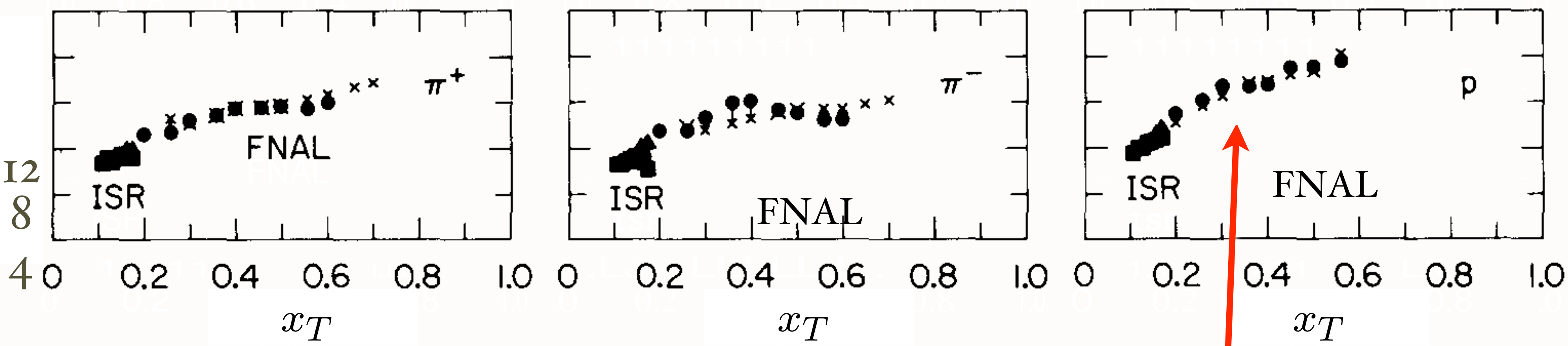
Continuous rise of n_{eff} with x_T.

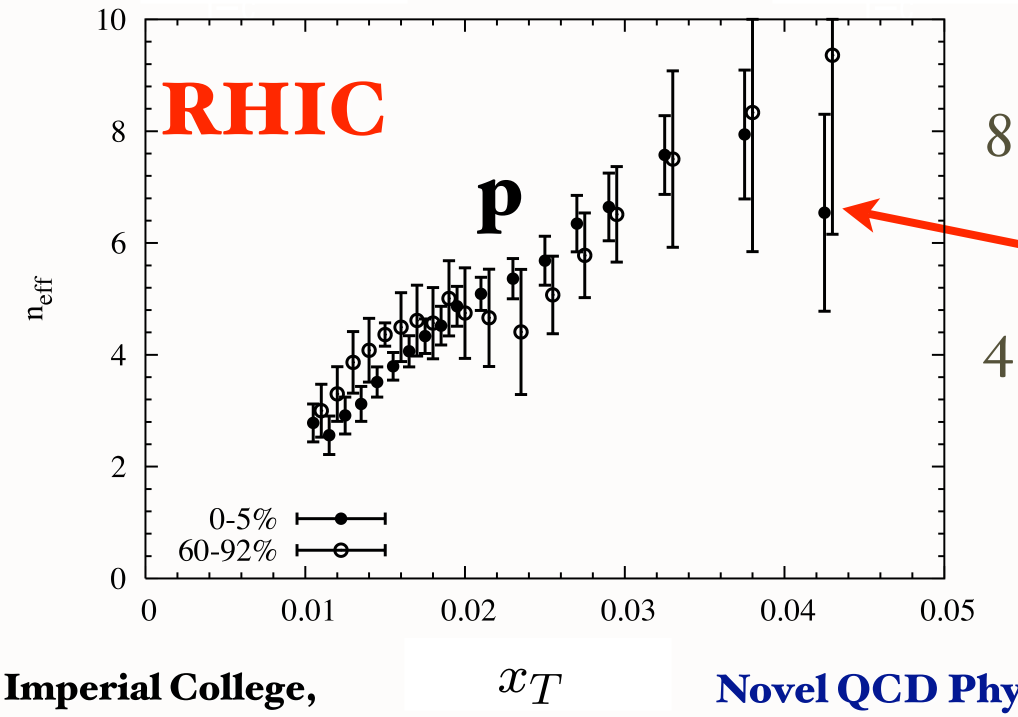


Leading twist:

$$E\frac{d\sigma}{d^3p}(pN \to pX) = \frac{F(x_T,\theta_{CM})}{p_T^{n_{eff}}}$$

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





$$E\frac{d\sigma}{d^3p}(pp \to pX) = \frac{F(x_T, \theta_{CM})}{p_T^{12}}$$

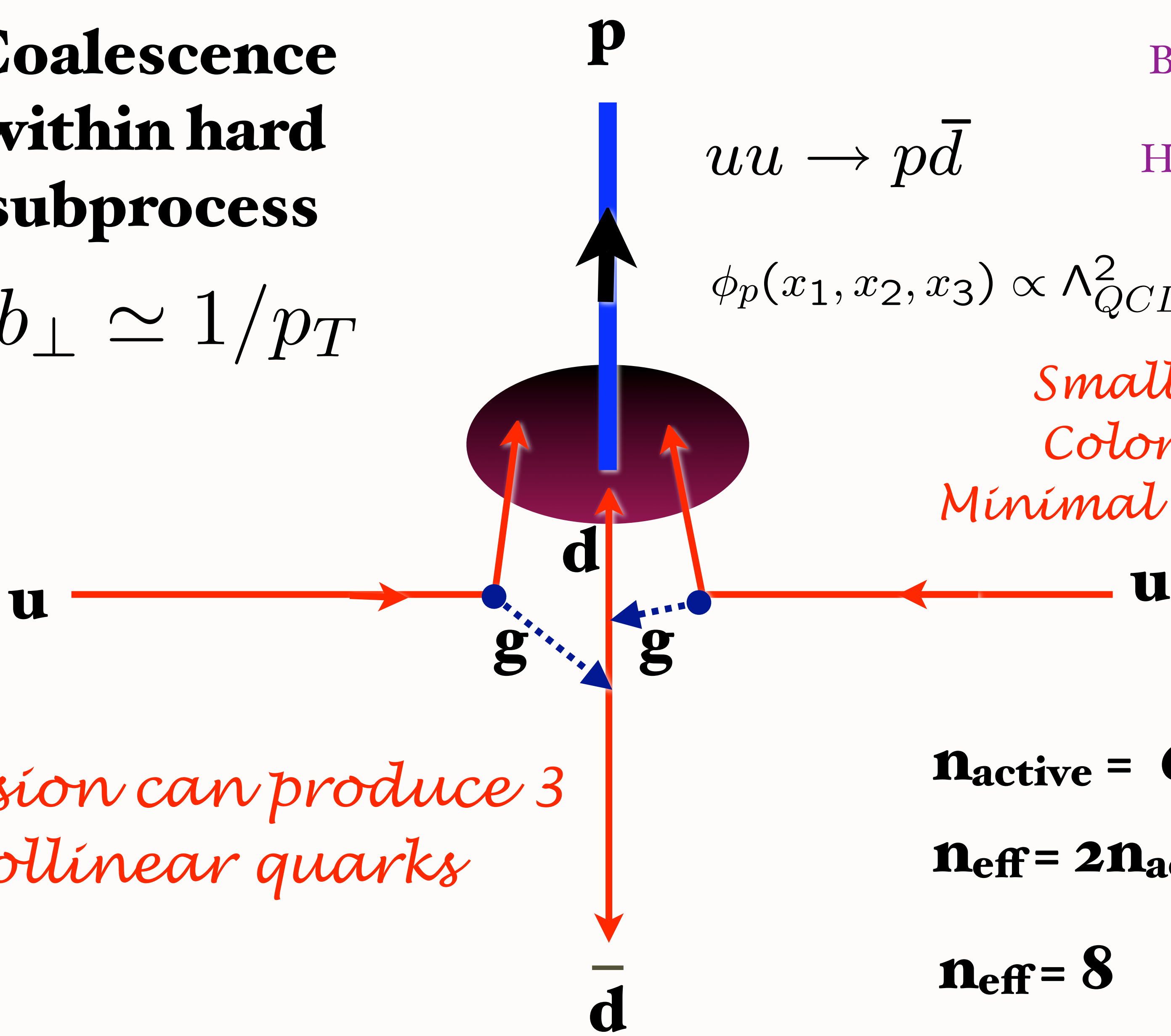
$$E\frac{d\sigma}{d^3p}(pp \to pX) = \frac{F(x_T, \theta_{CM})}{p_T^{8}}$$

Trend consistent with RHIC at small x_T

Baryon can be made directly within hard subprocess

Coalescence within hard subprocess

$$b_\perp \simeq 1/p_T$$



$$uu \rightarrow p\bar{d}$$

$$\phi_p(x_1, x_2, x_3) \propto \Lambda^2_{QCD}$$

Bjorken
Blankenbecler, Gunion, sjb
Berger, sjb
Hoyer, et al: Semi-Exclusive

Small color-singlet
Color Transparent
Minimal same-side energy

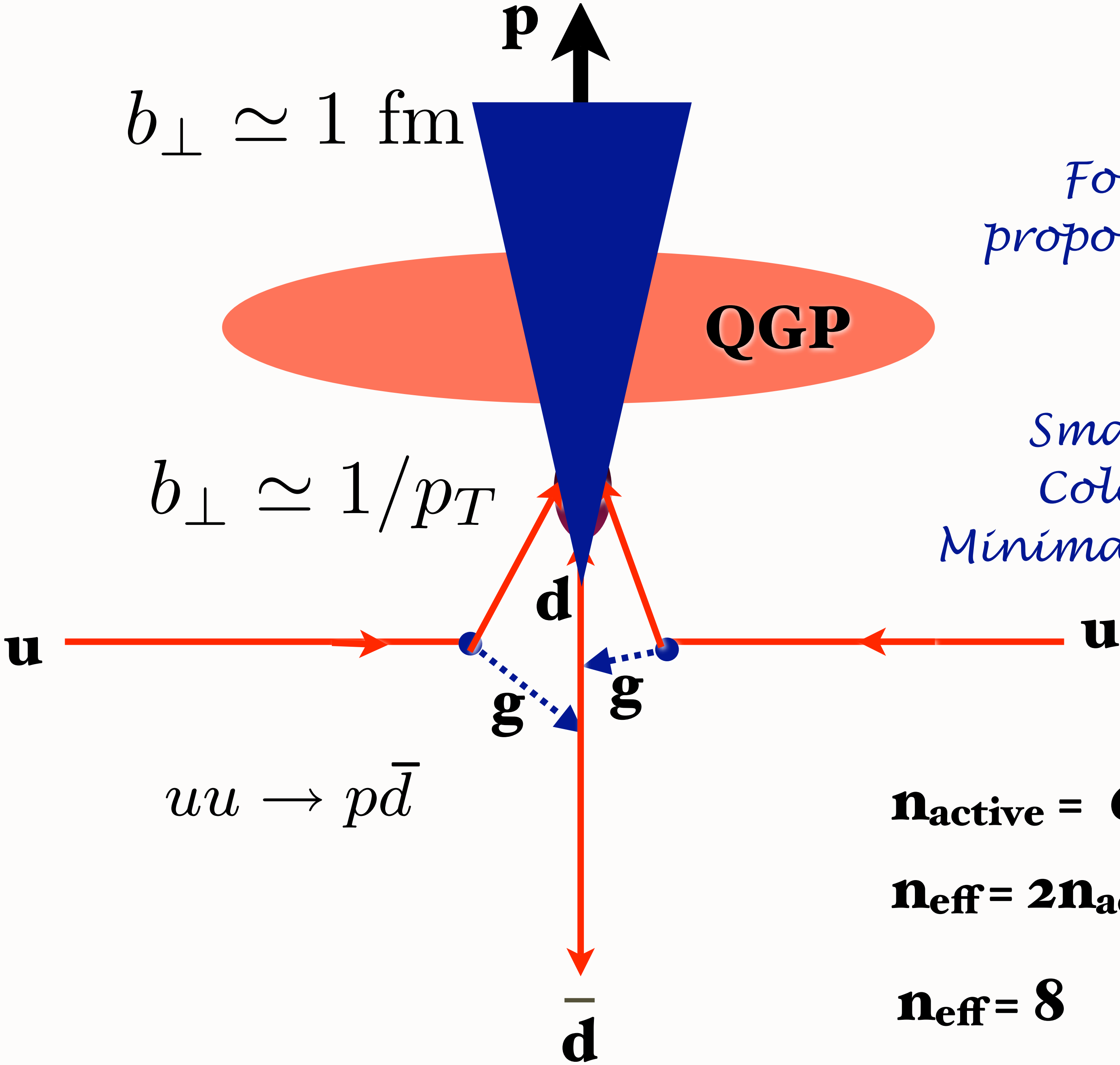
Collision can produce 3 collinear quarks

$n_{active} = 6$

$n_{eff} = 2n_{active} - 4$

$n_{eff} = 8$

Baryon made directly within hard subprocess



Formation Time
proportional to Energy

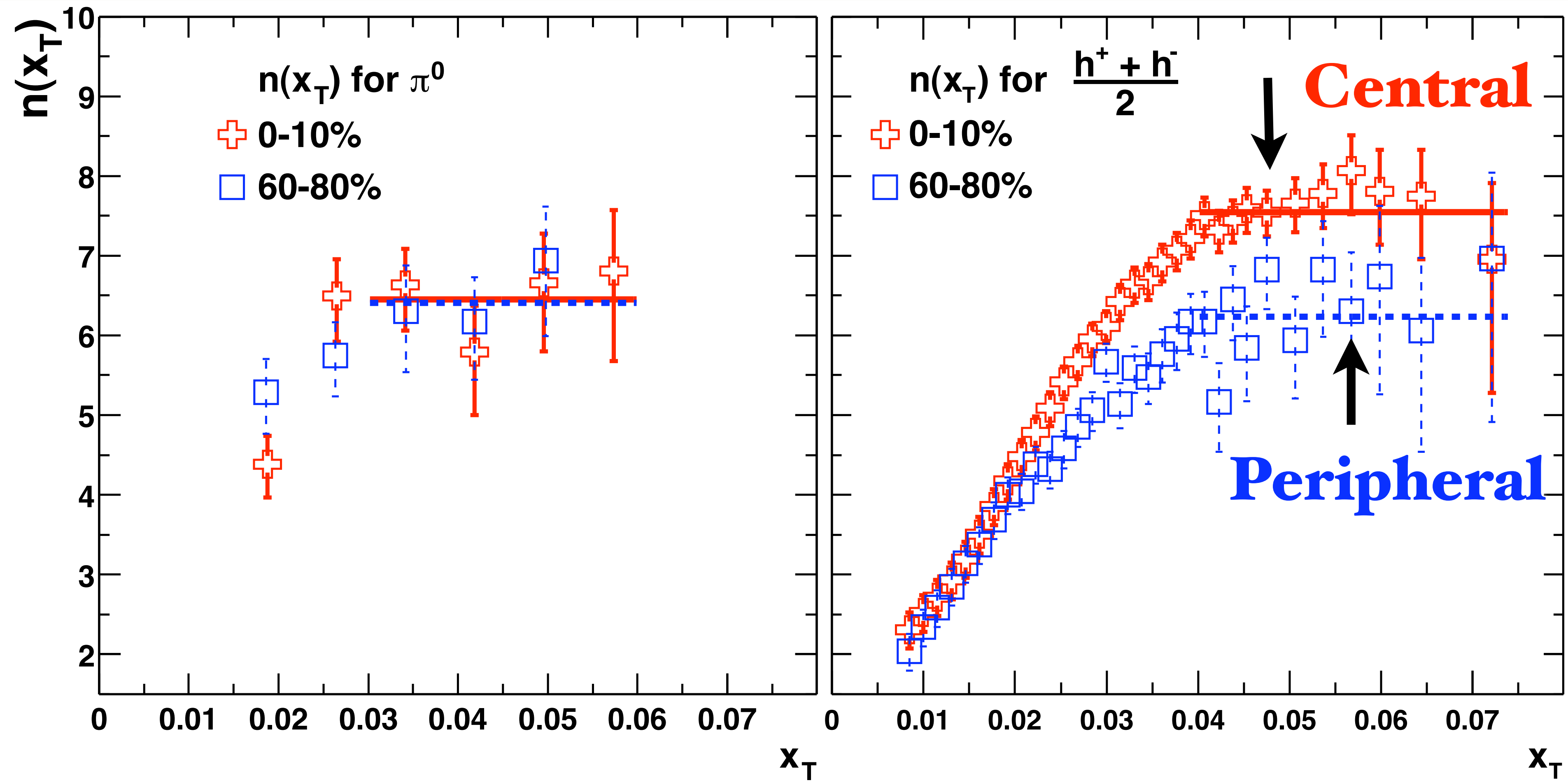
Small color-singlet
Color Transparent
Minimal same-side energy

$n_{active} = 6$

$n_{eff} = 2n_{active} - 4$

$n_{eff} = 8$

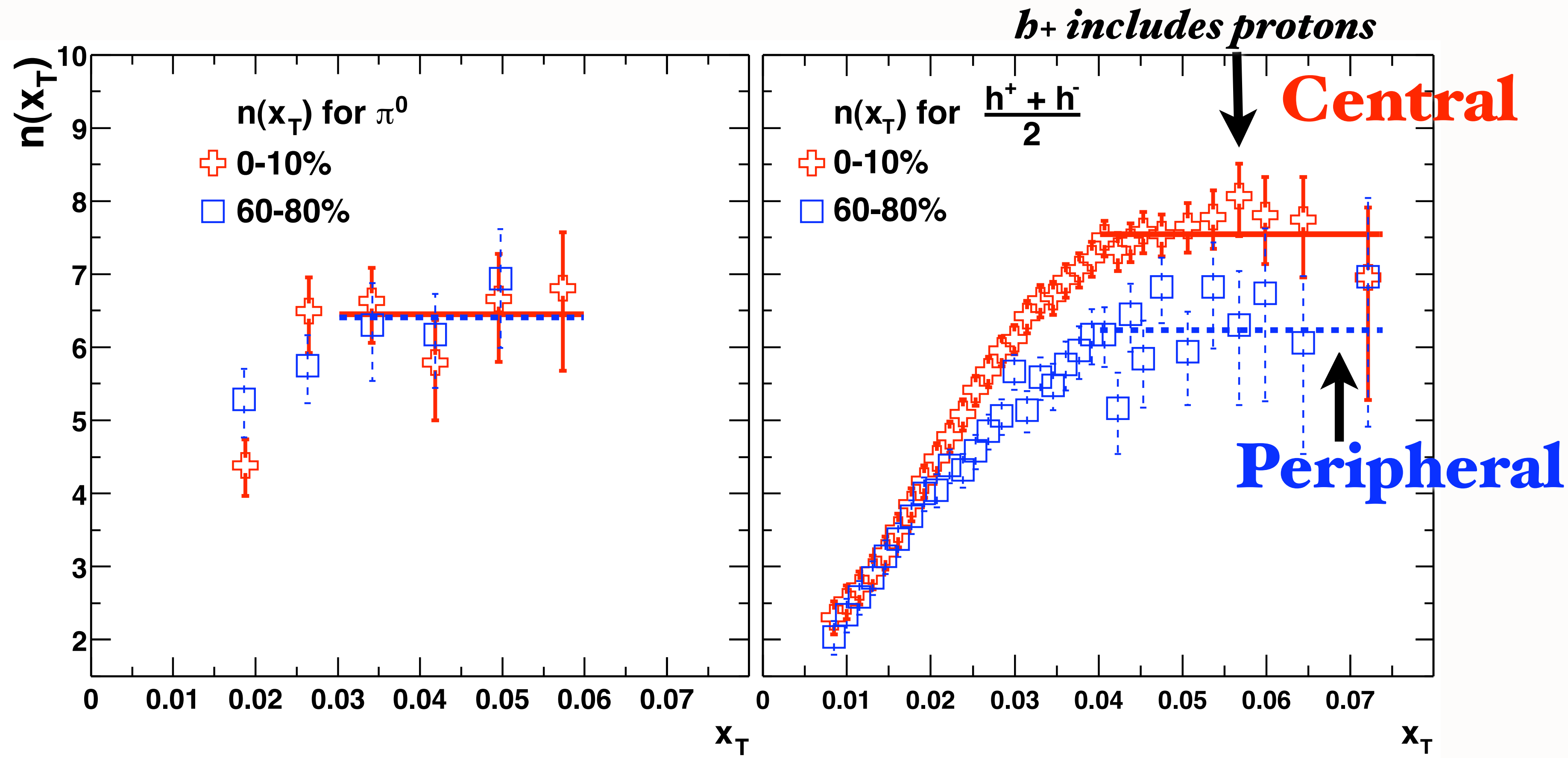
$$\sqrt{s_{NN}} = 130 \text{ and } 200 \text{ GeV}$$



Proton power changes with centrality !

Power-law exponent $n(x_T)$ for π^0 and h spectra in central and peripheral Au+Au collisions at $\sqrt{s_{NN}} = 130$ and 200 GeV

S. S. Adler, *et al.*, PHENIX Collaboration, *Phys. Rev.* C **69**, 034910 (2004) [nucl-ex/0308006].

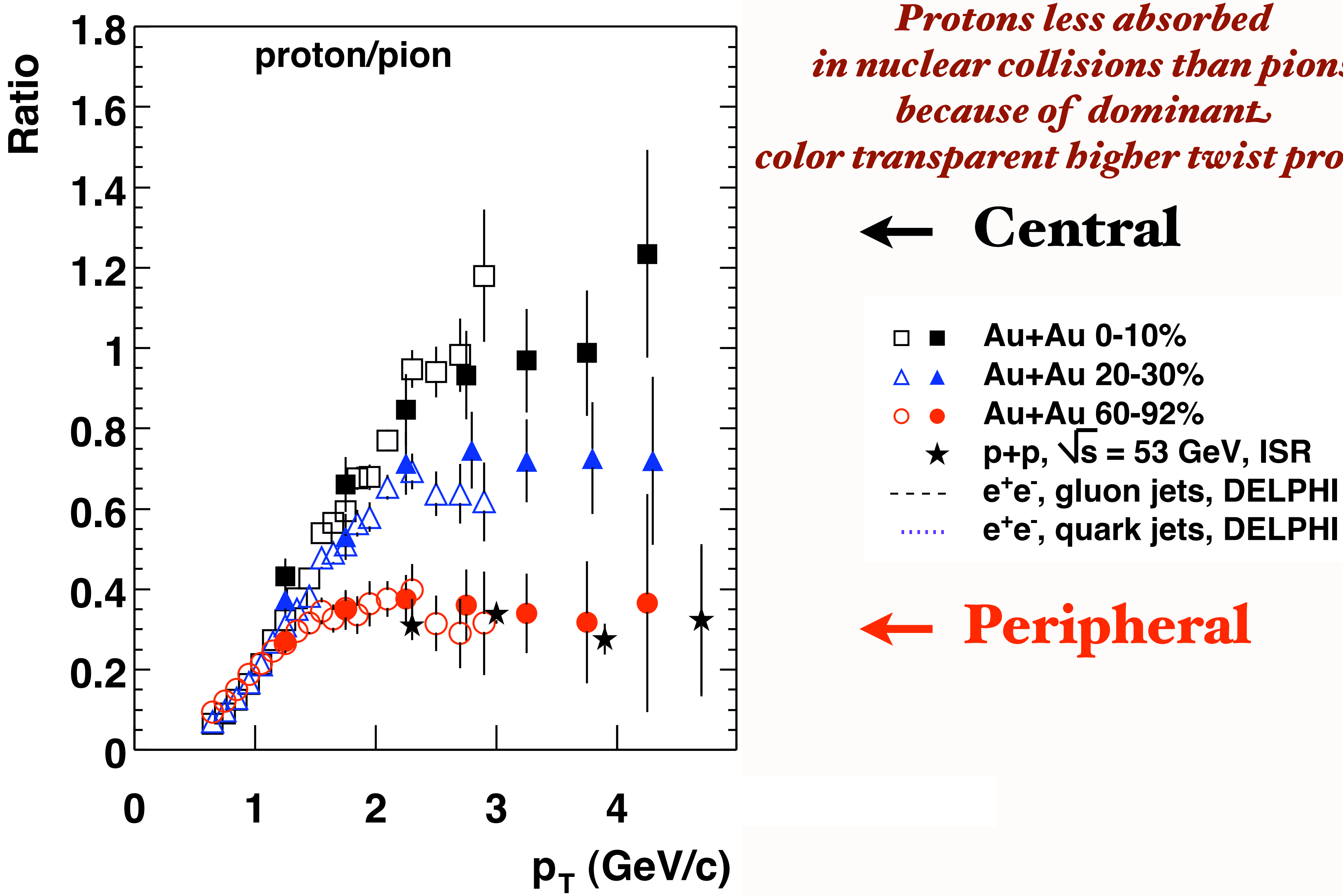


Proton power changes with centrality !

Proton production dominated by color-transparent direct high n_{eff} subprocesses

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

Particle ratio changes with centrality!

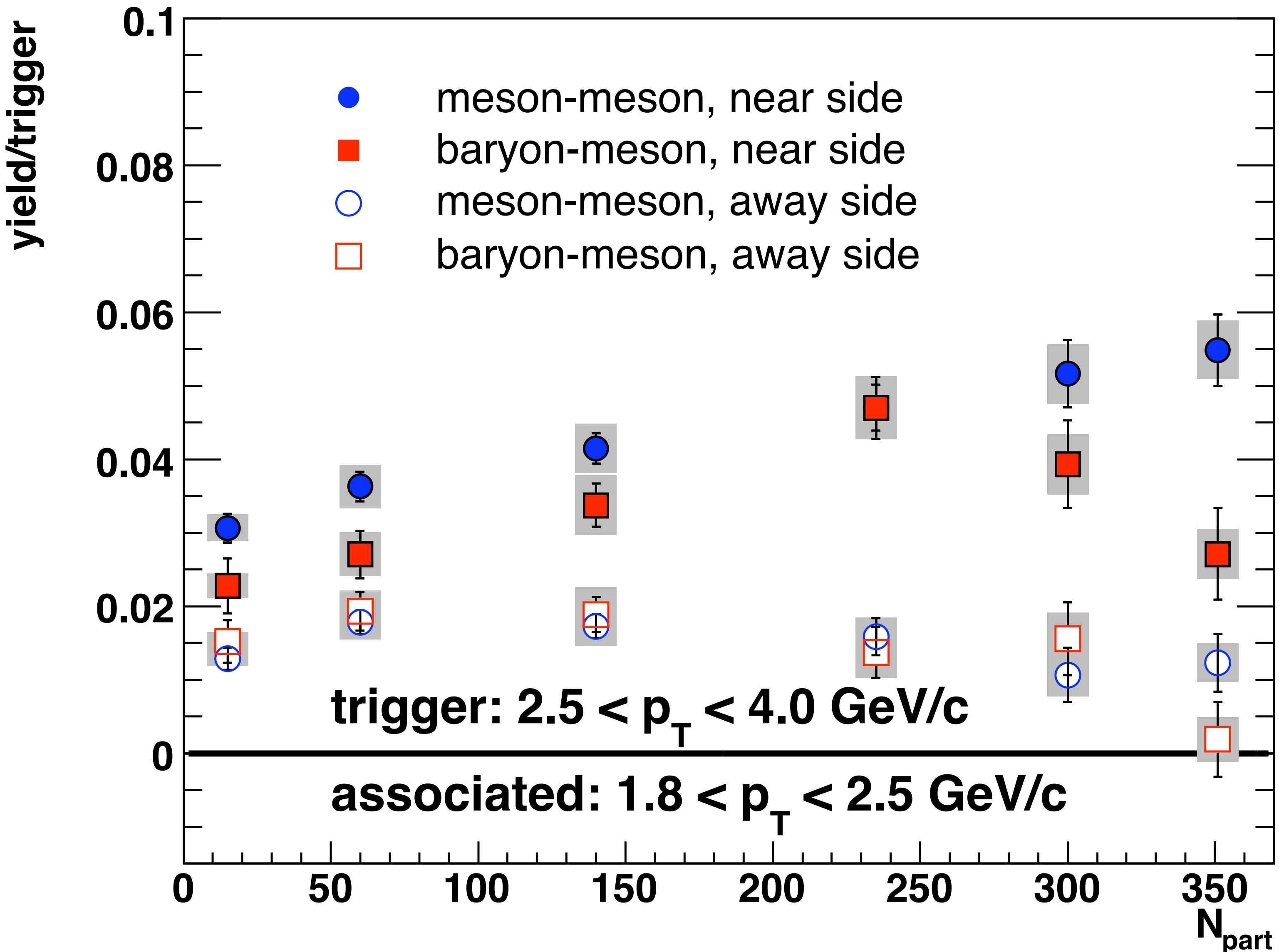


Protons less absorbed in nuclear collisions than pions because of dominant color transparent higher twist process

← **Central**

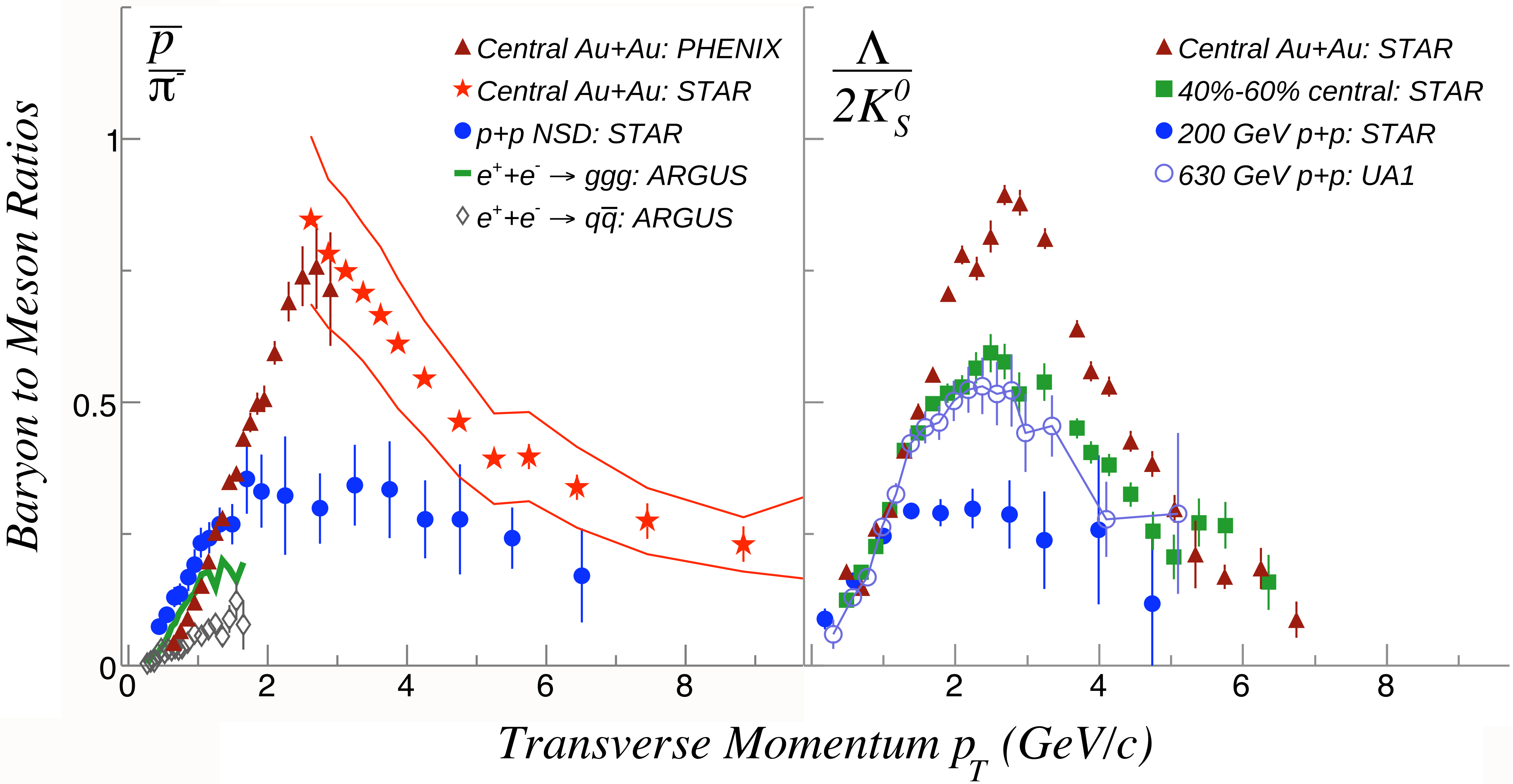
← **Peripheral**

Anne Sickles



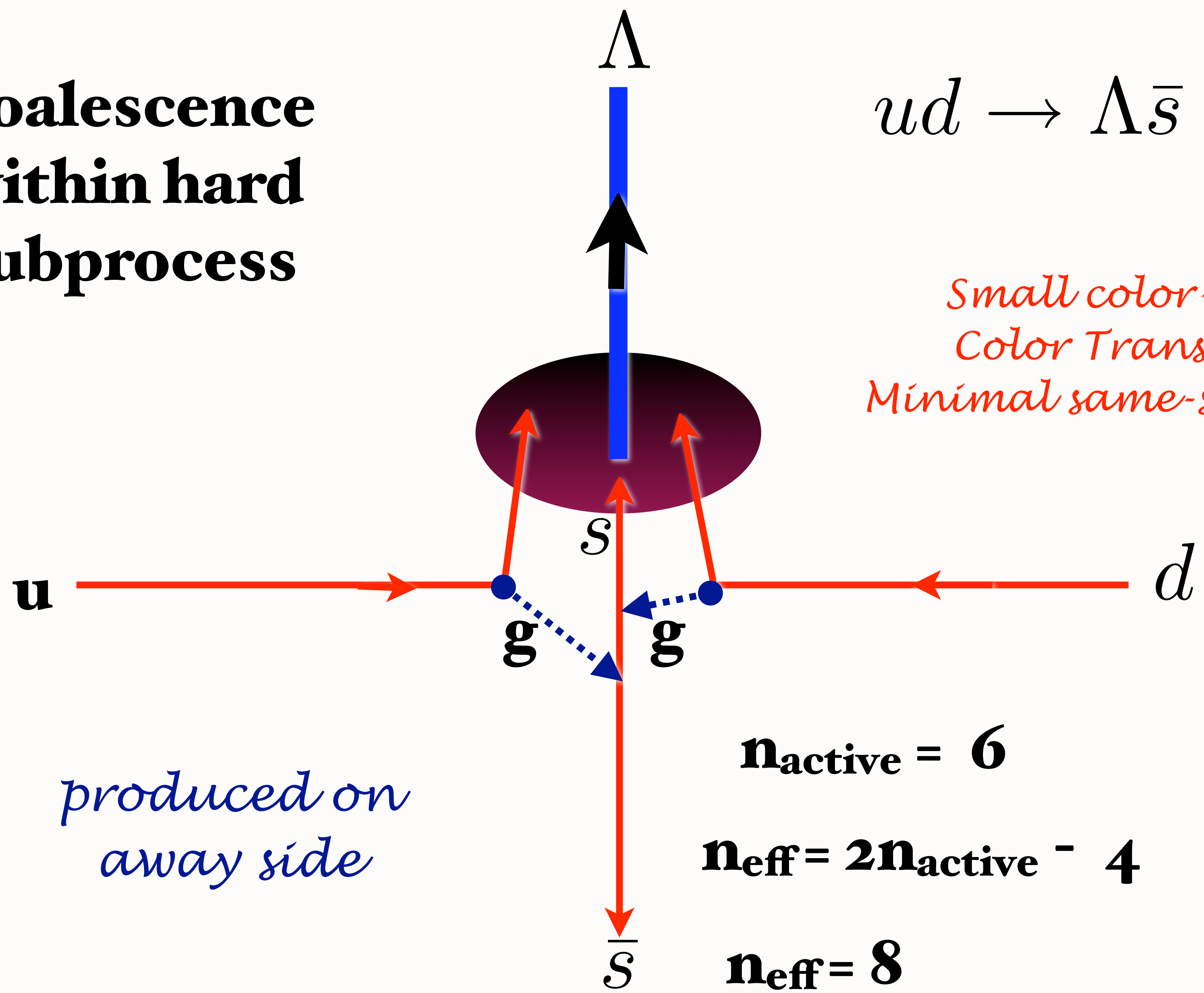
proton trigger: # same-side particles decreases with centrality

Proton production more dominated by color-transparent direct high-n_{eff} subprocesses


$\frac{\overline{p}}{\pi^-}$
Central Au+Au: PHENIX
Central Au+Au: STAR
p+p NSD: STAR
$e^+ + e^- \rightarrow ggg$: ARGUS
$e^+ + e^- \rightarrow q\overline{q}$: ARGUS
$\frac{\Lambda}{2K_S^0}$
Central Au+Au: STAR
40%-60% central: STAR
200 GeV p+p: STAR
630 GeV p+p: UA1
Baryon to Meson Ratios
Transverse Momentum p_T (GeV/c)
0
0.5
1
0
2
4
6
8

Lambda can be made directly within hard subprocess

Coalescence within hard subprocess



$ud \rightarrow \Lambda \bar{s}$

Small color-singlet
Color Transparent
Minimal same-side energy

$\bar{s}$ produced on away side

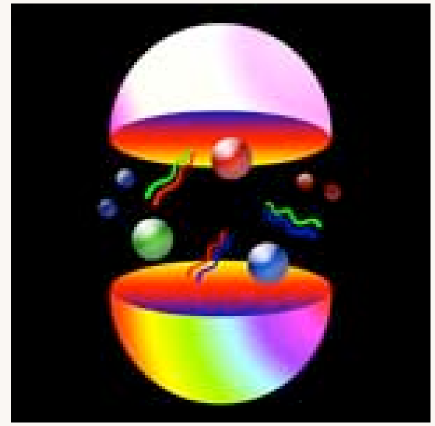
$n_{active} = 6$

$n_{eff} = 2n_{active} - 4$

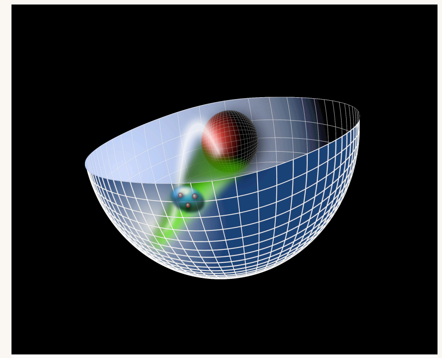
$n_{eff} = 8$

Baryon Anomaly: Evidence for Direct, Higher-Twist Subprocesses

- **Explains anomalous power behavior at fixed x_T**
- **Protons more likely to come from direct higher-twist subprocess than pions**
- **Protons less absorbed than pions in central nuclear collisions because of color transparency**
- **Predicts increasing proton to pion ratio in central collisions**
- **Proton power n_{eff} increases with centrality since leading twist contribution absorbed**
- **Fewer same-side hadrons for proton trigger at high centrality**
- **Exclusive-inclusive connection at $x_T = 1$**

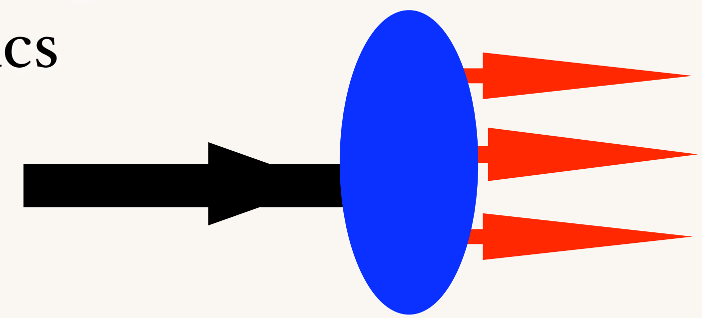


- Quarks and Gluons:
  Fundamental constituents of hadrons and nuclei
- *Quantum Chromodynamics (QCD)*
- New Insights from higher space-time dimensions: *AdS/QCD*



- *Light-Front Holography*
- *Hadronization at the Amplitude Level*
- *Light Front Wavefunctions:* analogous to the Schrodinger wavefunctions of atomic physics

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



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Novel Aspects of QCD in ep scattering

- Clash of DGLAP and BFKL with unitarity: saturation phenomena; off-shell effects at high x
- Heavy quark distributions do not derive exclusively from DGLAP or gluon splitting -- component intrinsic to hadron wavefunction:
  Intrinsic c(x,Q), b(x,Q), t(x,Q):
- Hidden-Color of Nuclear Wavefunction
- Antishadowing is quark specific!
- Polarized u(x) and d(x) at large x; duality
- Virtual Compton scattering : DVCS, DVMS, GPDs; J=0 fixed pole reflects elementary source of electromagnetic current
- Initial-and Final-State Interactions: leading twist SSA, DDIS
- Direct Higher-Twist Processes; Color Transparency

Huet, sjb

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

$$\text{QCD} \to \text{Abelian Gauge Theory}$$

Analytic Feature of SU(Nc) Gauge Theory

Scale-Setting procedure for QCD must be applicable to QED

Conventional wisdom in QCD concerning scale setting

- Renormalization scale "unphysical": No optimal physical scale
- Can ignore possibility of multiple physical scales
- Accuracy of PQCD prediction can be judged by taking arbitrary guess $\mu_R = Q$
- with an arbitrary range $Q/2 < \mu_R < 2Q$
- Factorization scale should be taken equal to renormalization scale $\mu_F = \mu_R$

These assumptions are untrue in QED and thus they cannot be true for QCD!

Electron-Electron Scattering in QED

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

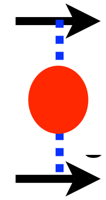
$$\alpha(t) = \frac{\alpha(0)}{1-\Pi(t)}$$

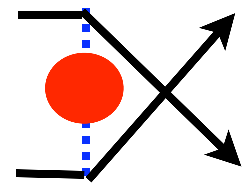
Gell Mann-Low Effective Charge

Electron-Electron Scattering in QED

- No renormalization scale ambiguity!

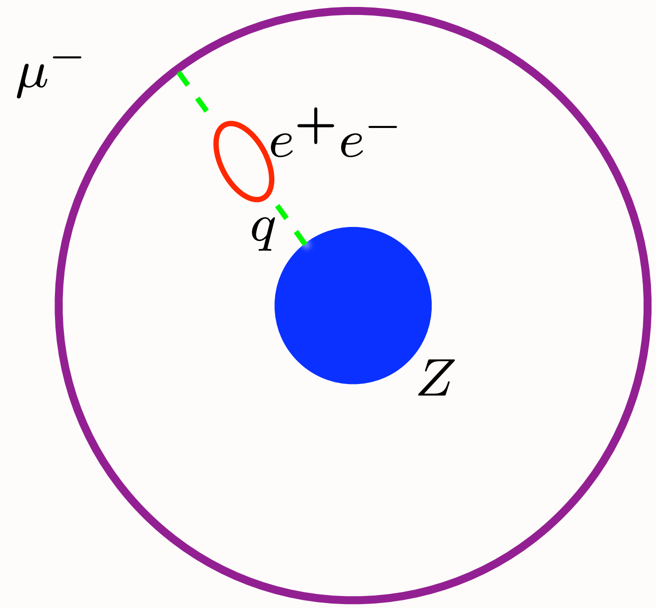
$$\mathcal{M}_{ee\to ee}(++;++) = \frac{8\pi s}{t}\,\alpha(t) + \frac{8\pi s}{u}\,\alpha(u)$$





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

Another Example in QED: Muonic Atoms



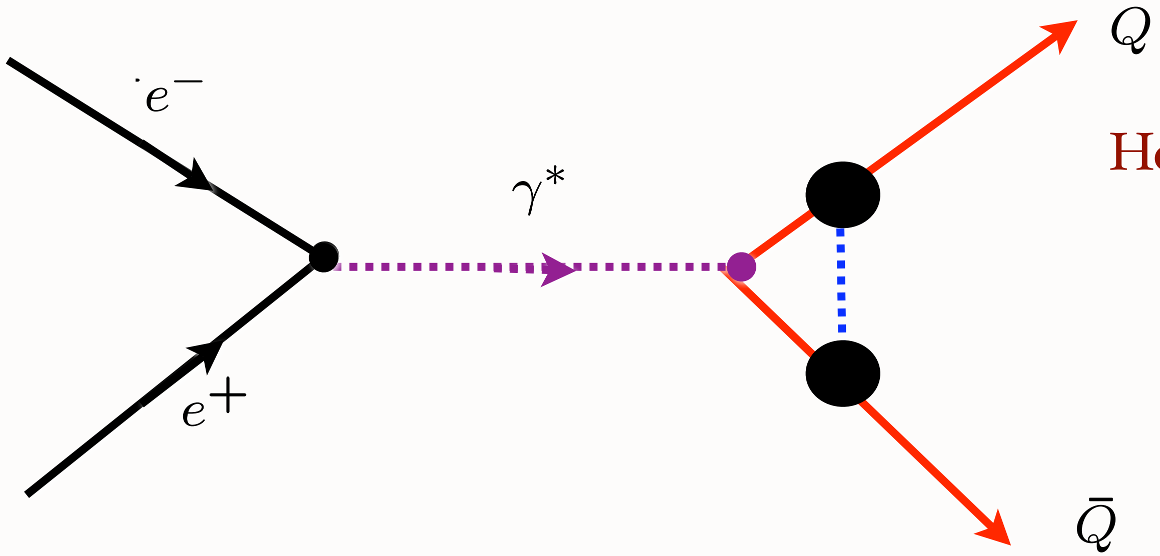
$$V(q^2) = -\frac{Z\alpha_{QED}(q^2)}{q^2}$$

$$\mu_R^2 \equiv q^2$$

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

Scale is unique: Tested to ppm

Gyulassy: Higher Order VP verified to 0.1% precision in μ Pb



Hoang, Kuhn, Teubner, sjb

$$
\begin{aligned}
F_1 + F_2 &= 1 + \frac{\alpha(s\,\beta^2)\,\pi}{4\,\beta} - 2\,\frac{\alpha(s\,e^{3/4}/4)}{\pi} \\
&\cong \left(1 - 2\,\frac{\alpha(s\,e^{3/4}/4)}{\pi}\right)\left(1 + \frac{\alpha(s\,\beta^2)\,\pi}{4\,\beta}\right)
\end{aligned}
$$

Example of Multiple BLM Scales

Angular distributions of massive quarks and leptons close to threshold.

Novel Aspects of QCD

- **Heavy quark distributions do not derive exclusively from DGLAP or gluon splitting -- component intrinsic to hadron wavefunction: Higgs at high x_F**
- **Initial and final-state interactions are not power suppressed in hard QCD reactions**
- **LFWFS are universal, but measured nuclear parton distributions are not universal -- antishadowing is flavor dependent**
- **Hadroproduction at large transverse momentum does not derive exclusively from 2 to 2 scattering subprocesses**

- **DDIS and Sivers Effect: Breakdown of Leading-Twist Factorization**
- **Physics of Hard Pomeron**
- **Measure Fundamental Hadron Wavefunction via Di-jet and Tri-jet Fragmentation**
- **Origin of Leading Twist Shadowing**
- **Non-Universal Antishadowing**
- **Heavy quark structure functions at high x**
- **Higgs production at large xF**
- **Hadroproduction of new heavy quark states such as ccu, ccd at high x_F**
- **Novel Nuclear Effects from color structure of IC**
- **Fixed target program at LHC: produce bbb states**
- **Direct Hadroproduction at high pT**

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

- Novel QCD Phenomena: hidden color, color transparency, strangeness asymmetry, intrinsic charm, anomalous heavy quark phenomena, anomalous spin effects, single-spin asymmetries, odderon, diffractive deep inelastic scattering, initial and final-state interaction effects, shadowing, antishadowing ...

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

—Mark Twain