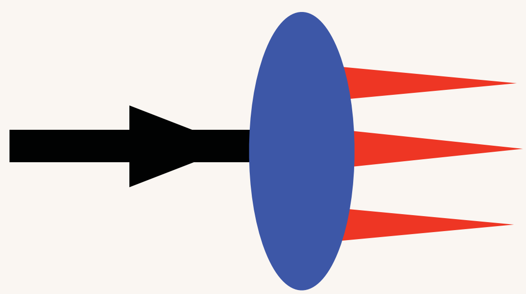
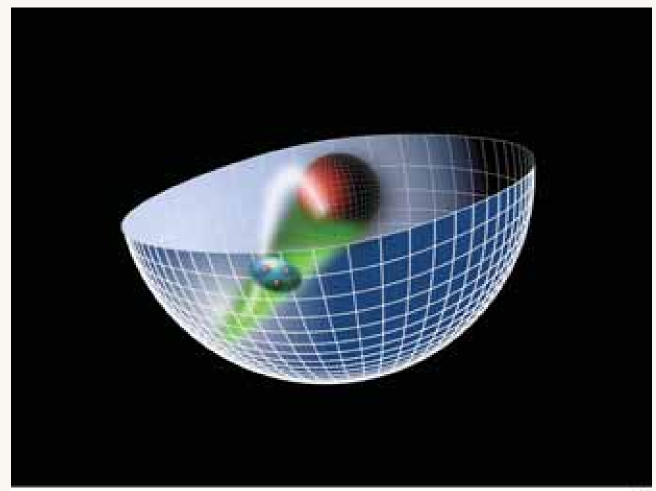
New Horizons in QCD

From Particles and Fields to Nuclei and Fields:
An International Symposium in Celebration of Al Mueller's 70th Birthday

Columbia University October 23, 2009



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



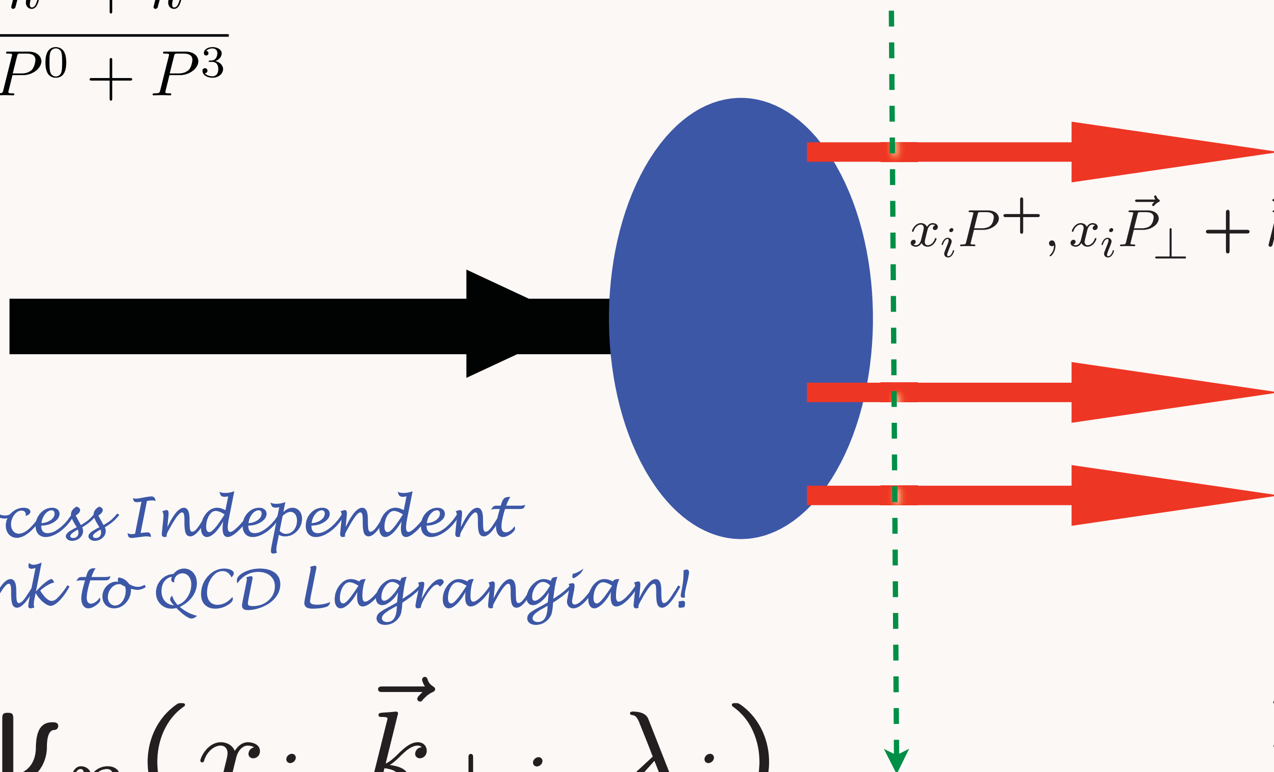
Stan Brodsky, SLAC National Accelerator Laboratory

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

Fixed $\tau = t + z/c$

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

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



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

Process Independent

Direct Link to QCD Lagrangian!

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

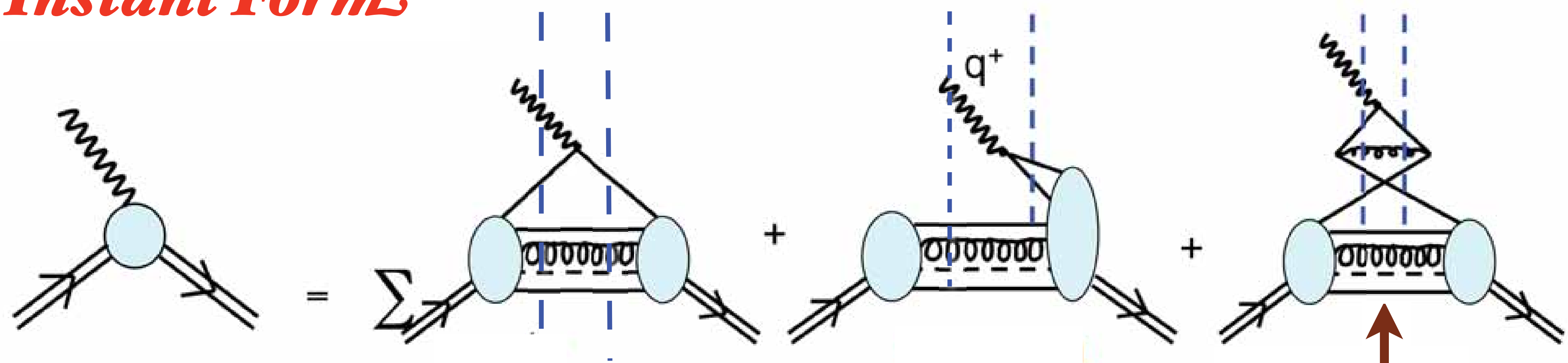
$\sum_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

Calculation of Form Factors in Equal-Time Theory

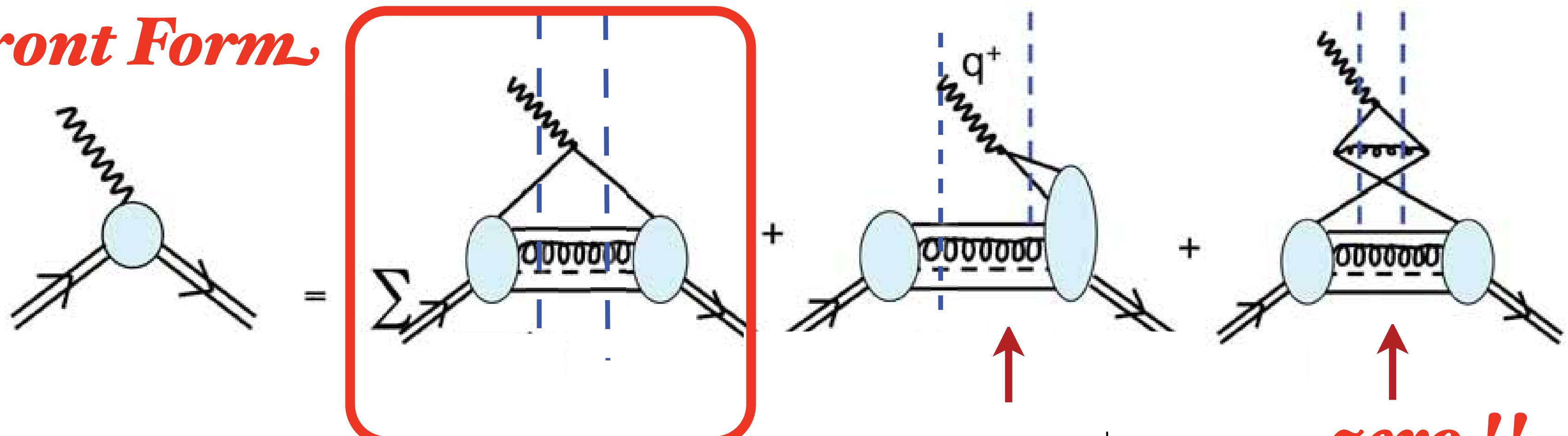
Instant Form



Need vacuum-induced currents

Calculation of Form Factors in Light-Front Theory

Front Form



Complete Answer

Absent for $q^+ = 0$

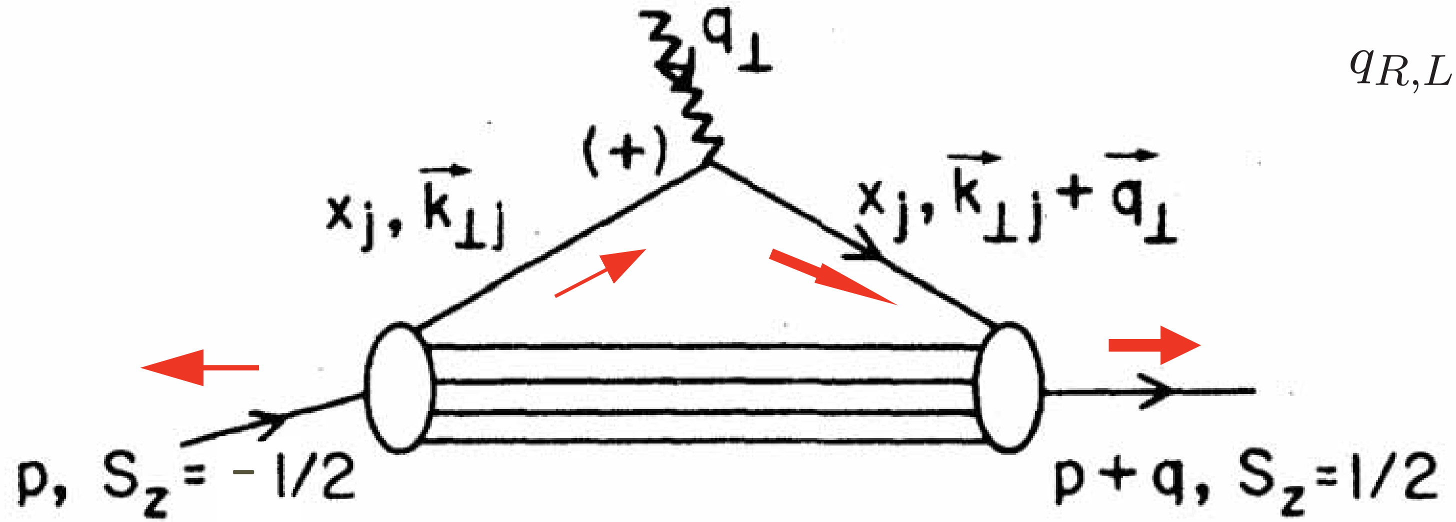
zero !!

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

Drell, sjb

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

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



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

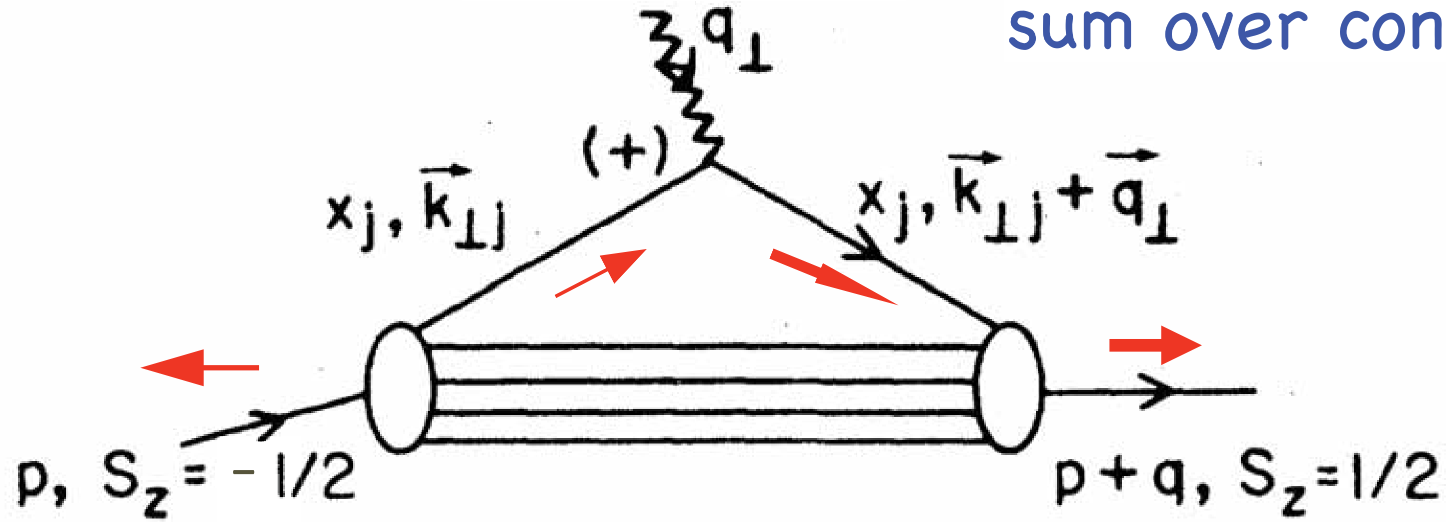
Must have $\Delta \ell_z = \pm 1$ to have nonzero $F_2(q^2)$

Same matrix elements appear in Sivers effect
-- connection to quark anomalous moments

Anomalous gravitomagnetic moment B(0)

Terayev, Okun, et al: *B(0) Must vanish because of Equivalence Theorem*

graviton



sum over constituents

Hwang, Schmidt, sjb; Holstein et al

$B(0) = 0$

Each Fock State

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

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

The Light Front Fock State Wavefunctions

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

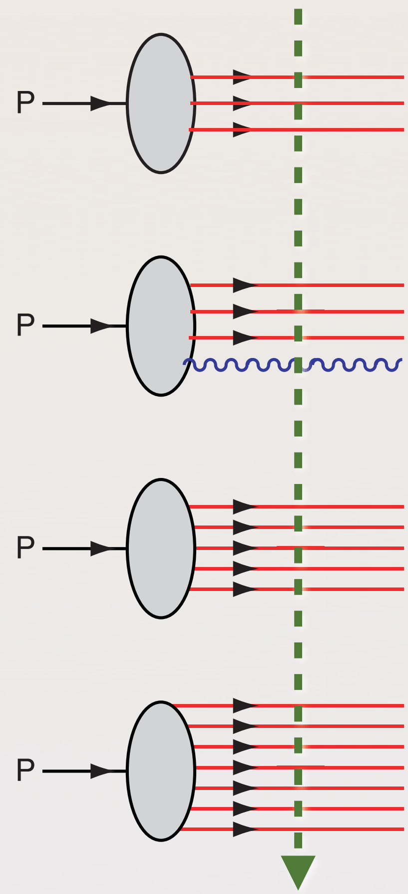
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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

$c(x), b(x)$ at high x

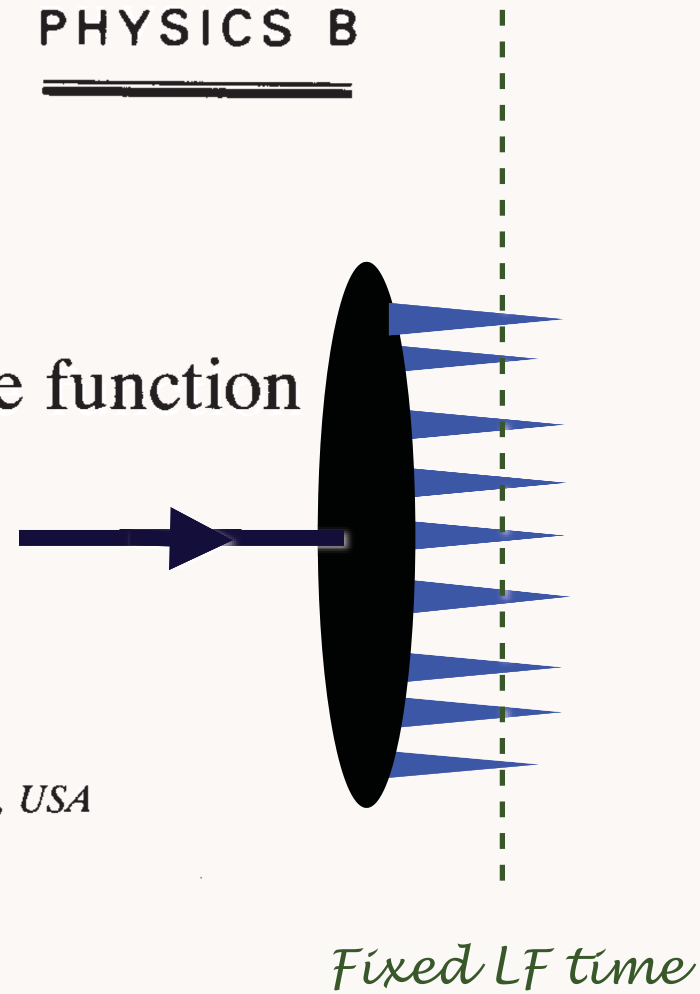
$\bar{s}(x) \neq s(x)$

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

Nuclear Physics B415 (1994) 373–385
North-Holland

NUCLEAR
PHYSICS B

Soft gluons in the infinite-momentum wave function and the BFKL pomeron *



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Received 27 August 1993
Accepted for publication 8 November 1993

We construct the infinite-momentum wave function for arbitrary numbers of soft gluons in a heavy quark–antiquark, onium, state. The soft gluon part of the wave function is constructed exactly within the leading logarithmic and large-N_c limits. The BFKL pomeron emerges when gluon number densities are evaluated.

INTRINSIC CHEVROLETS AT THE SSC

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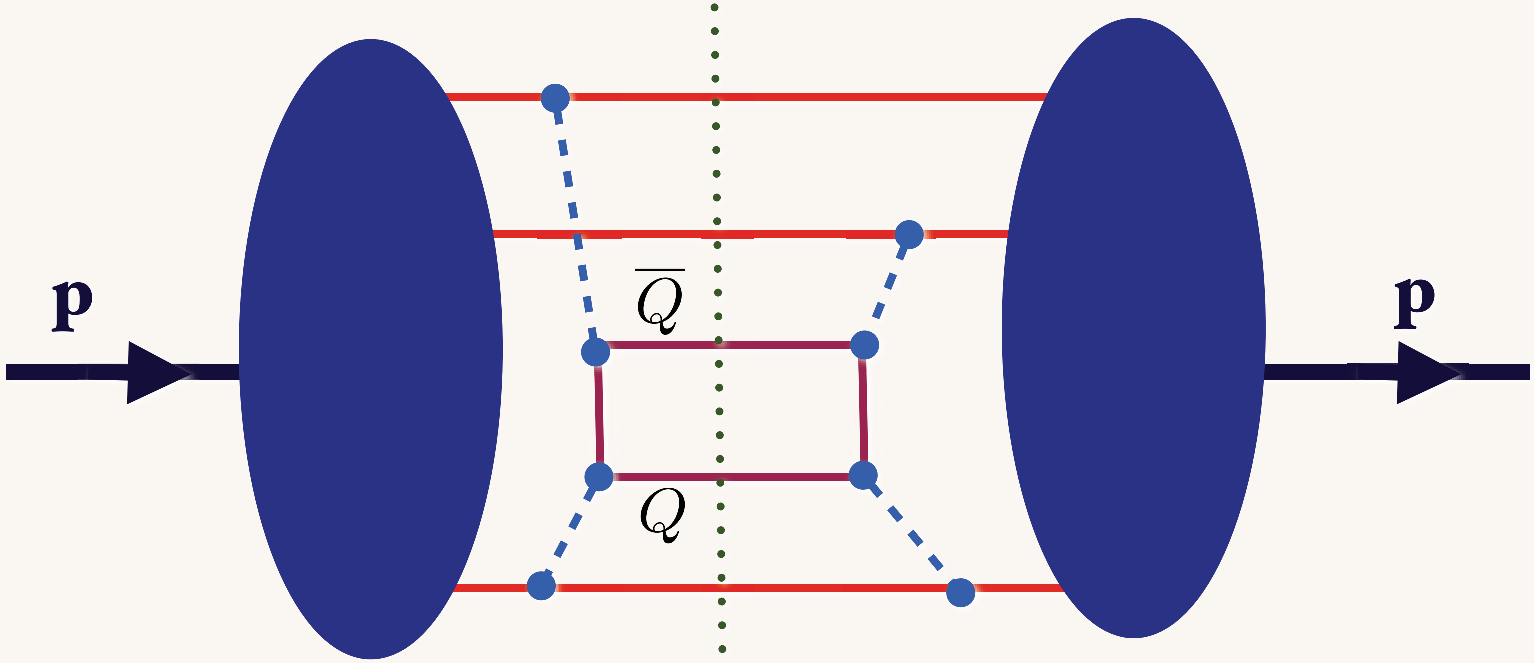
$$\mathcal{L}^{eff}_{QCD} = -\frac{1}{4} F_{\mu\nu a} F^{\mu\nu a} - \frac{g^2 N_C}{120\pi^2 M_Q^2} D_\alpha F_{\mu\nu a} D^\alpha F^{\mu\nu a} + C \frac{g^2 N_C}{120\pi^2 M_Q^2} F_\mu^{a\nu} F_\nu^{b\tau} F_\tau^{c\mu} f_{abc} + \mathcal{O}(\frac{1}{M_Q^4})$$

Probability of Intrinsic Heavy Quarks ~ $1/M^2_Q$

Published in Snowmass Summer Study 1984:0227 (QCD184:S7:1984)

Proton Self Energy
Intrinsic Heavy Quarks

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



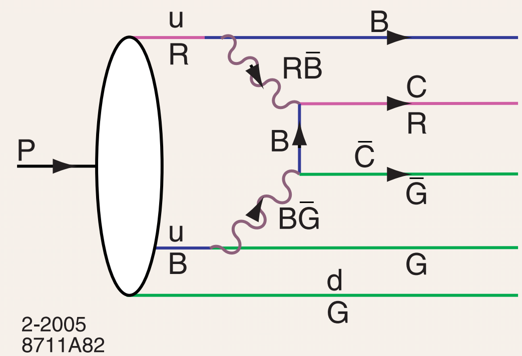
Probability (QED) $\propto \frac{1}{M_\ell^4}$

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

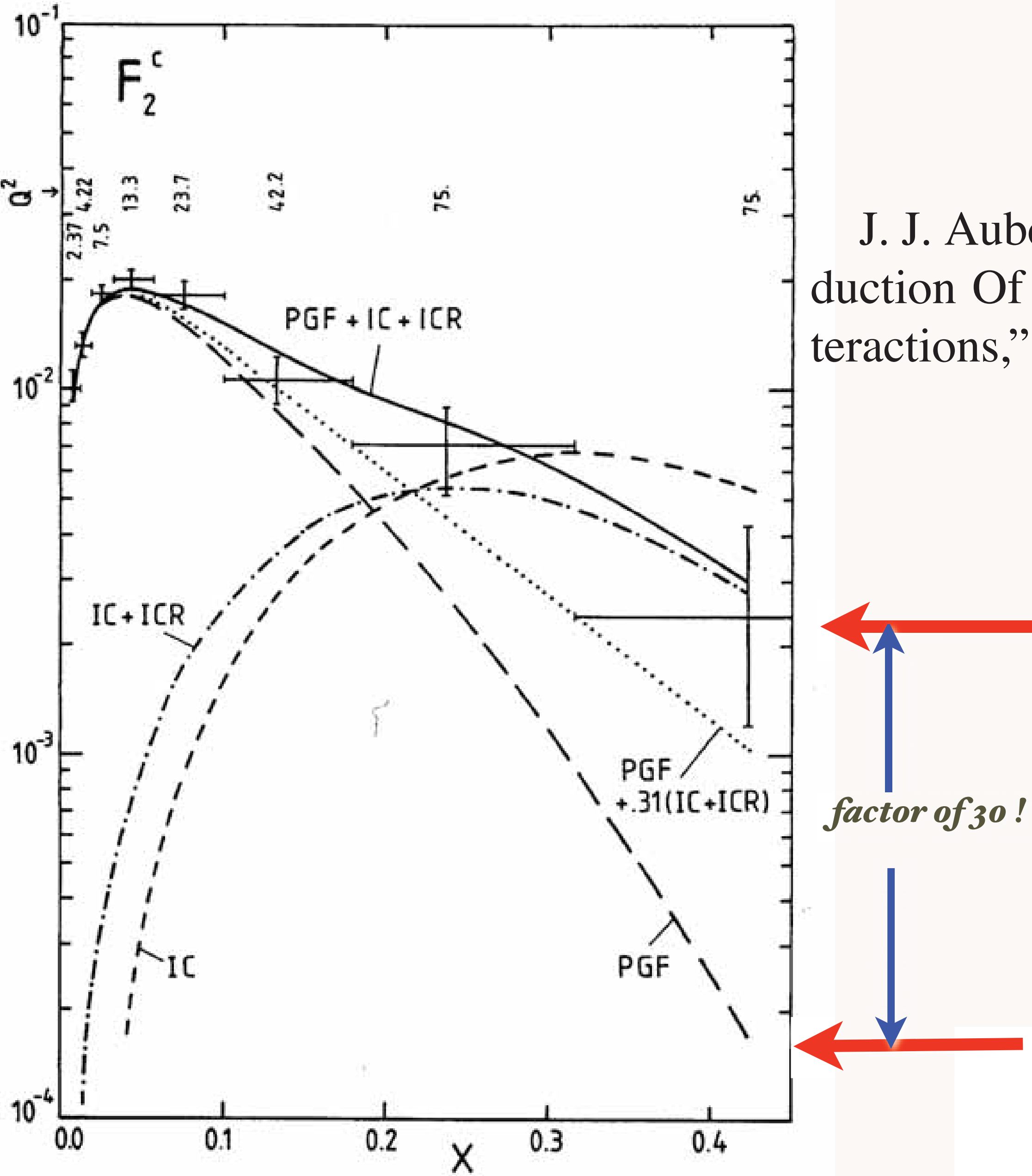
Collins, Ellis, Gunion, Mueller, sjb

Hoyer, Peterson, Sakai, sjb

Intrinsic Heavy-Quark Fock States



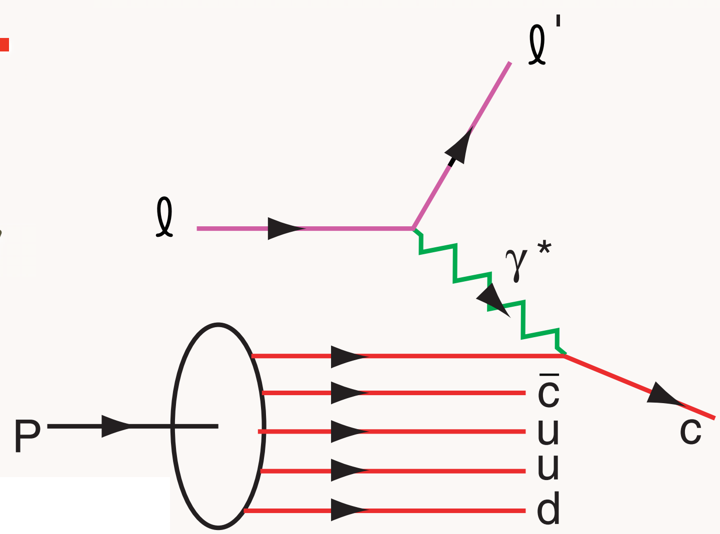
- Rigorous prediction of QCD, OPE
- Color-Octet Color-Octet Fock State!
- Probability $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- Large Effect at high x **Collins, Ellis, Gunion, Mueller, sjb**
- Greatly increases kinematics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



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)

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.

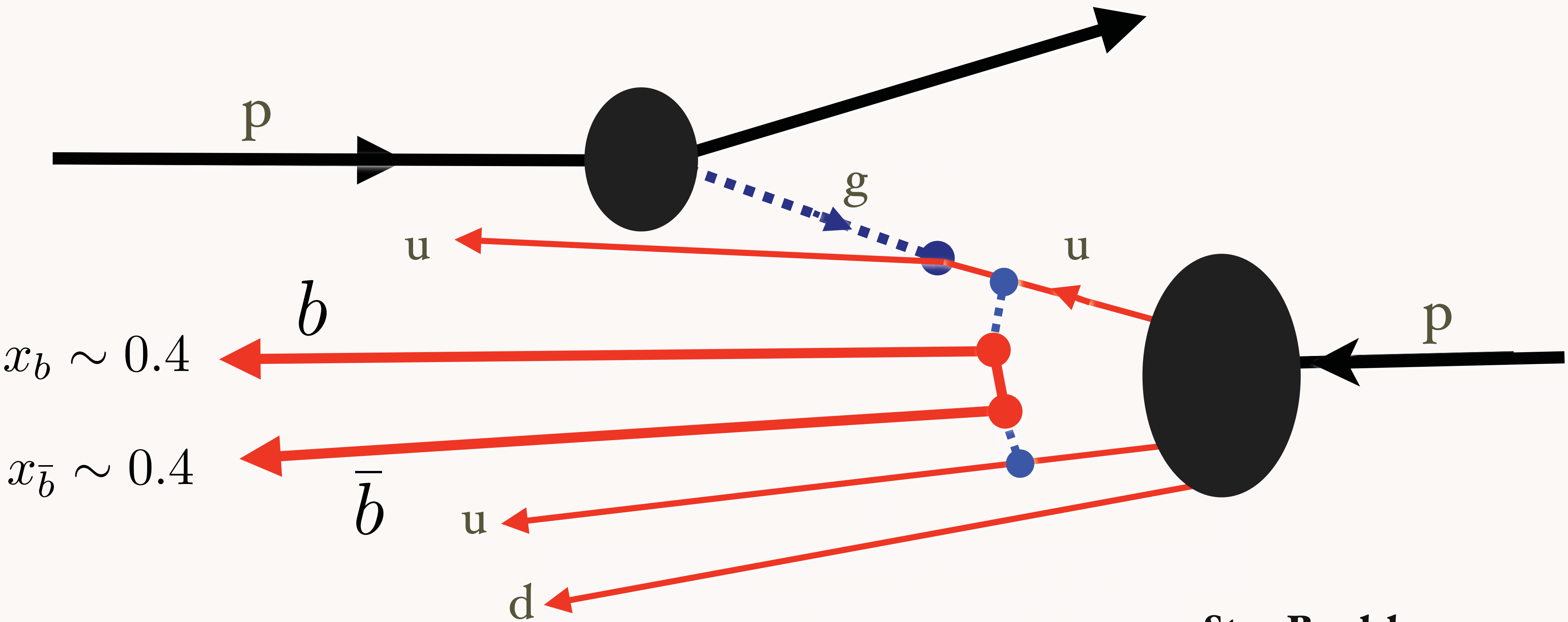
Excitation of Intrinsic Heavy Quarks in Proton

Amplitude maximal at small invariant mass, equal rapidity

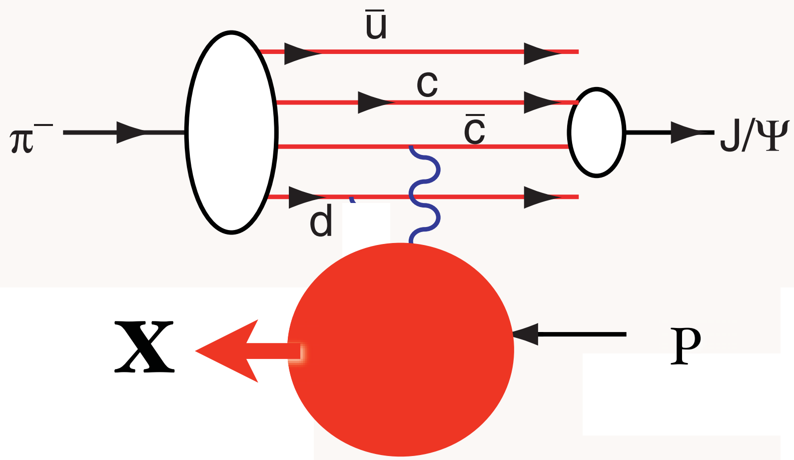
$$x_i \sim \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

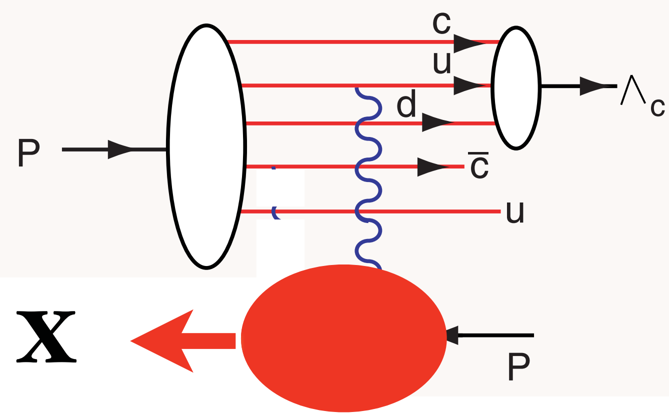
Produce forward, high x_F

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



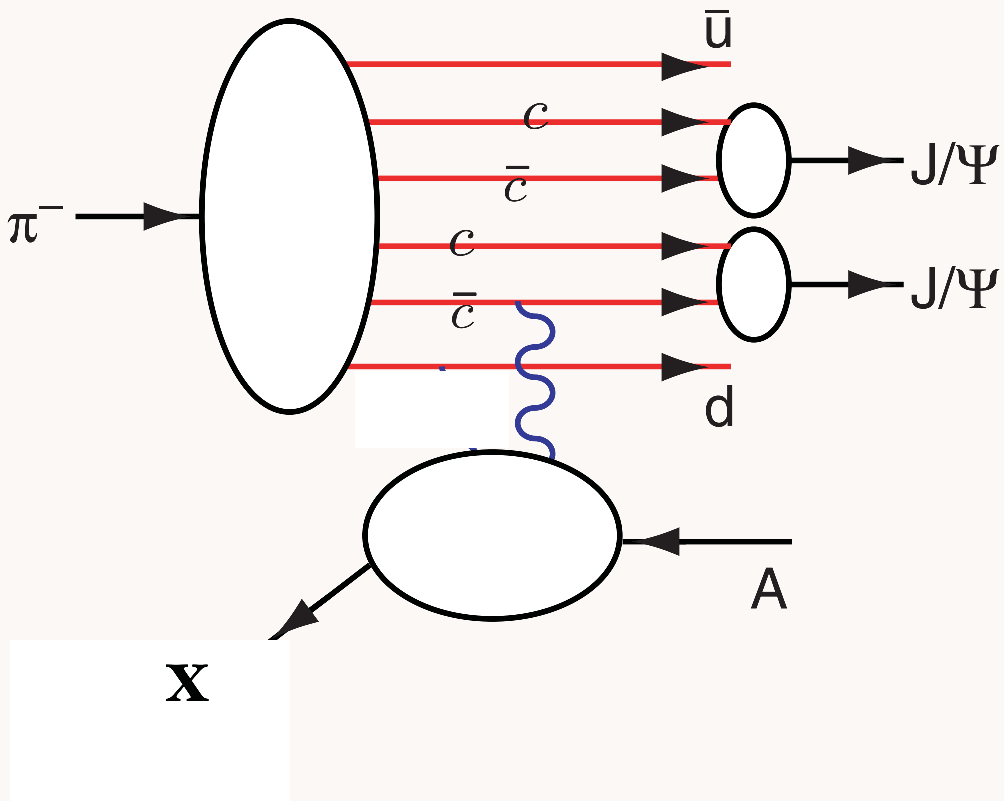
Leading Hadron Production from Intrinsic Charm





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

Production of Two Charmonia at High x_F



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

Excludes color drag model

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

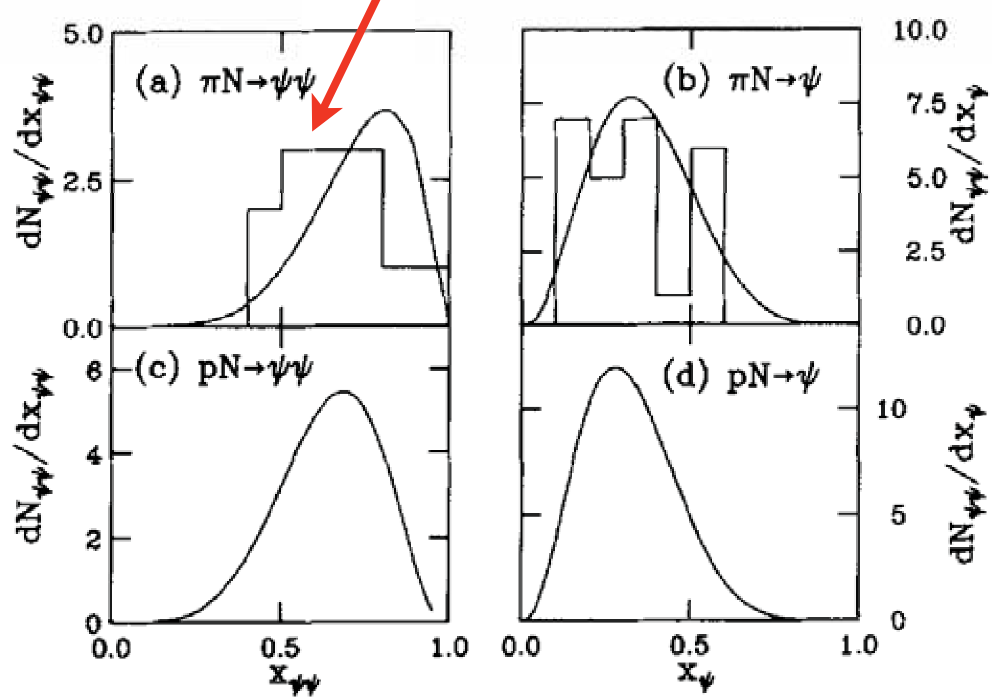


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized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

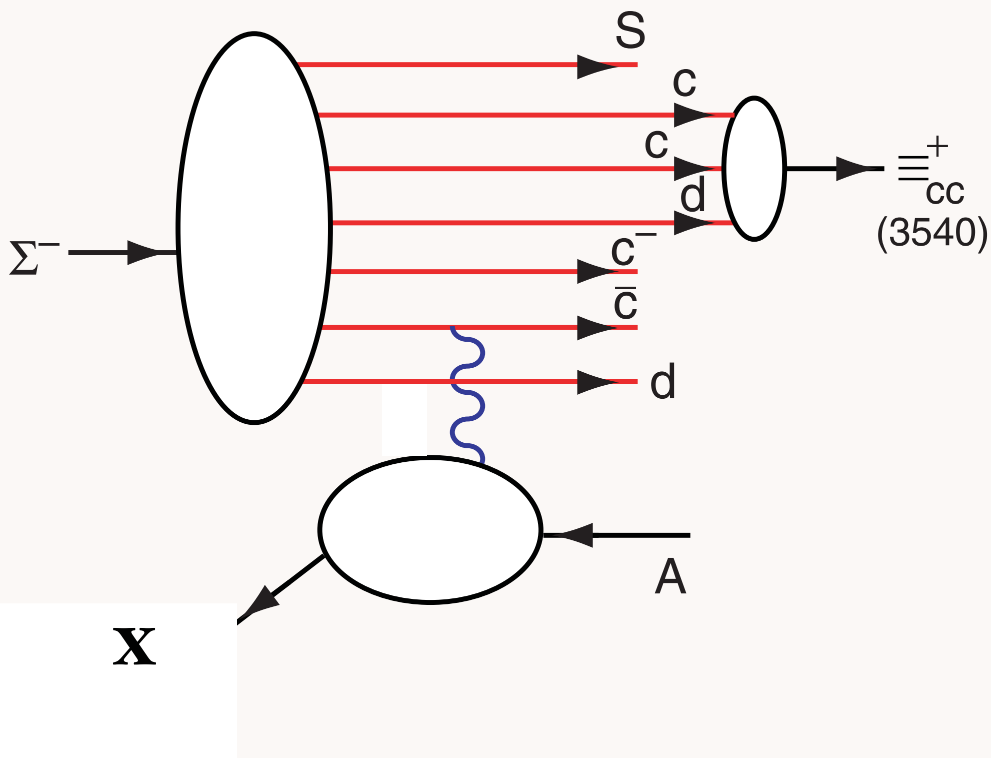
NA3 Data

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

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



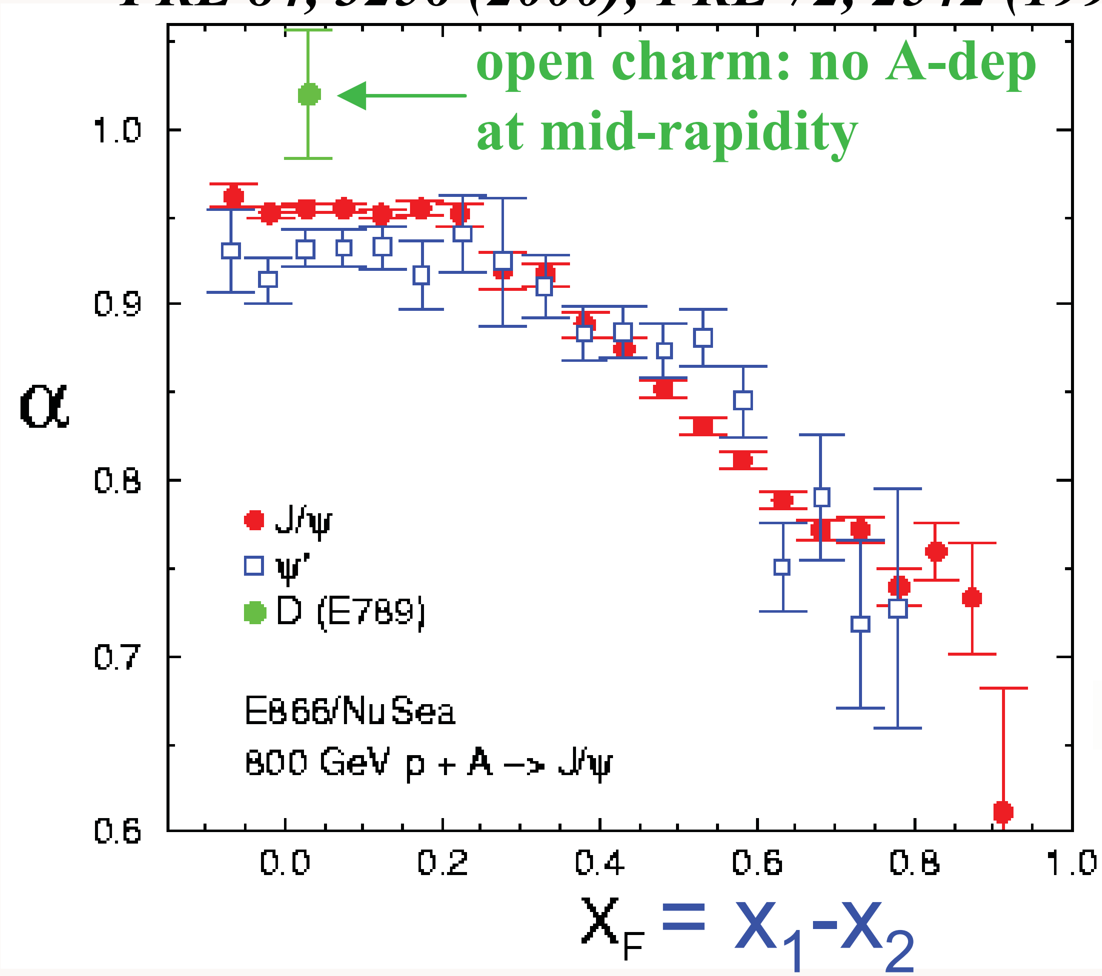
Production of a Double-Charm Baryon

SELEX high x_F $< x_F >= 0.33$

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

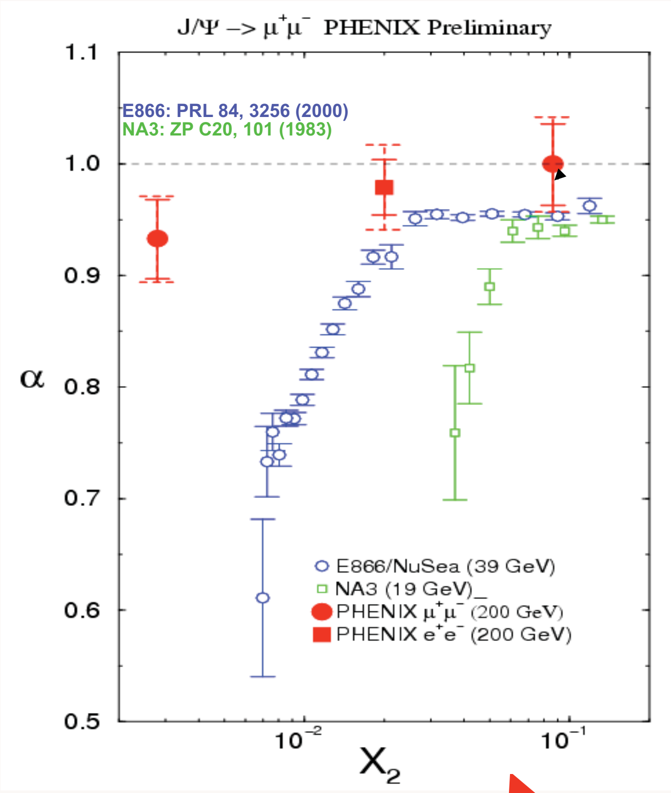
Violation of PQCD Factorization!

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

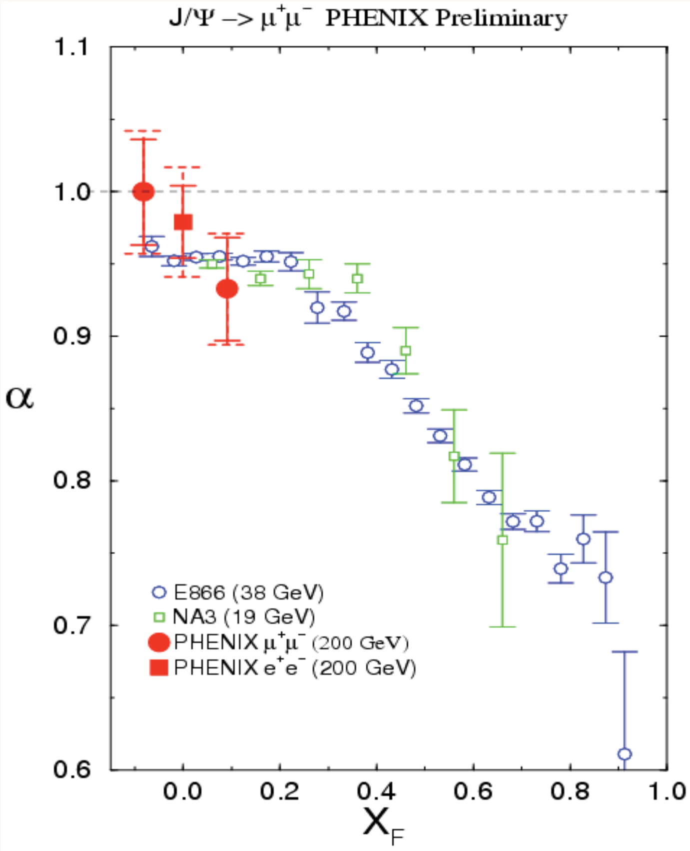
J/ψ nuclear dependence vrs rapidity, x_{Au}, x_F

M.Leitch

PHENIX compared to lower energy measurements



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

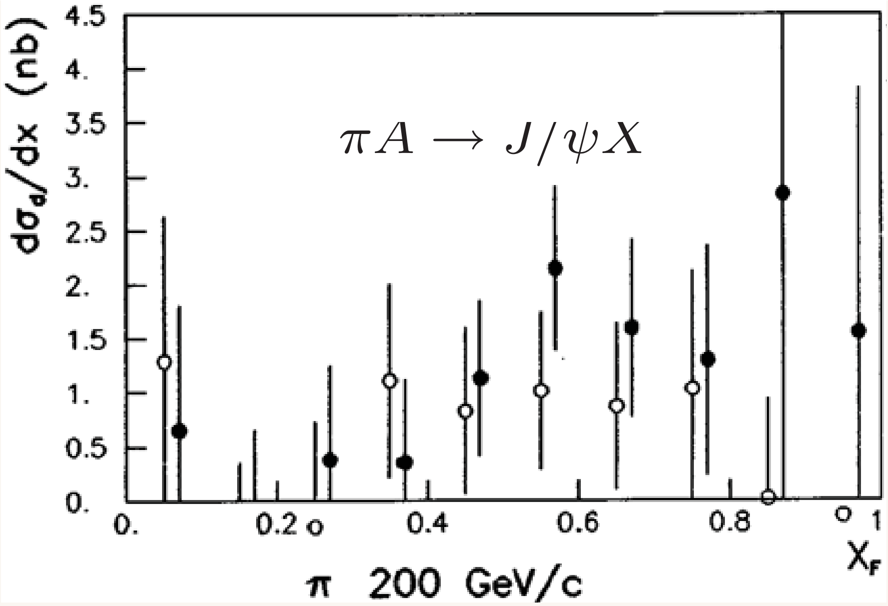


Huge "absorption" effect

Violates PQCD factorization!

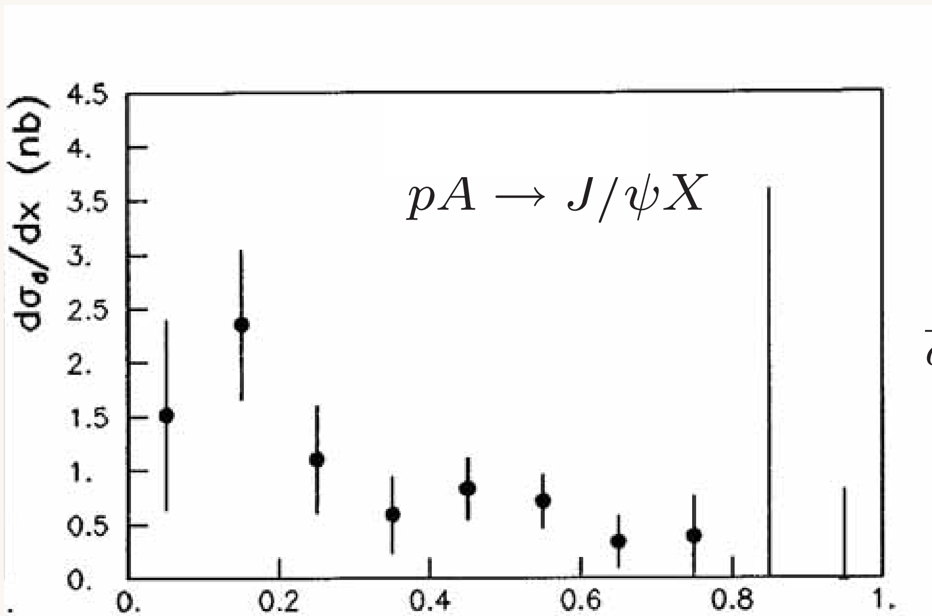
$$\frac{d\sigma}{dx_F}(pA \to J/\psi X)$$

Hoyer, Sukhatme, Vanttinen



J. Badier et al, NA3

$A^{2/3}$ component



p 200 GeV/c

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

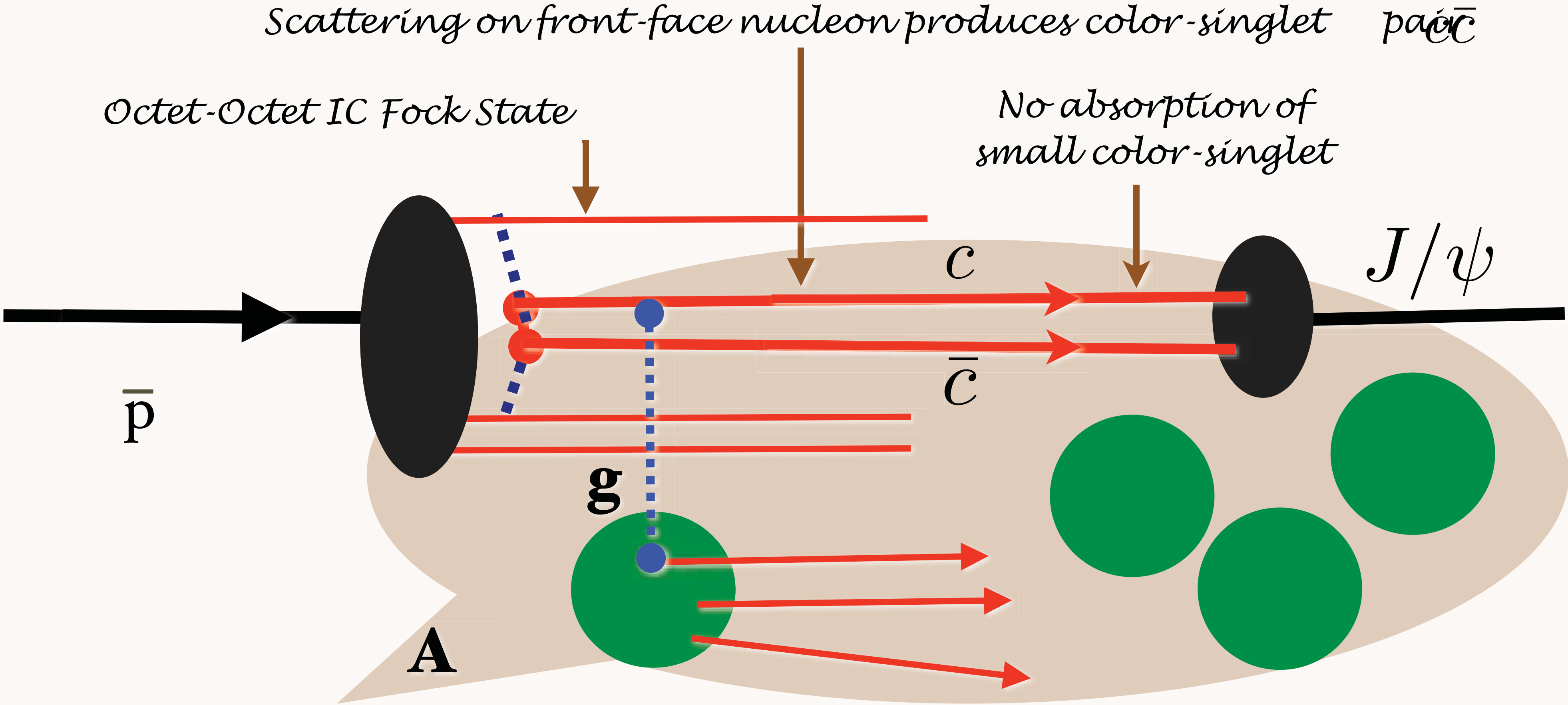
g g fusion

Intrinsic charm

Excess beyond conventional PQCD subprocesses

Kopeliovich, Schmidt, Soffer, sjb

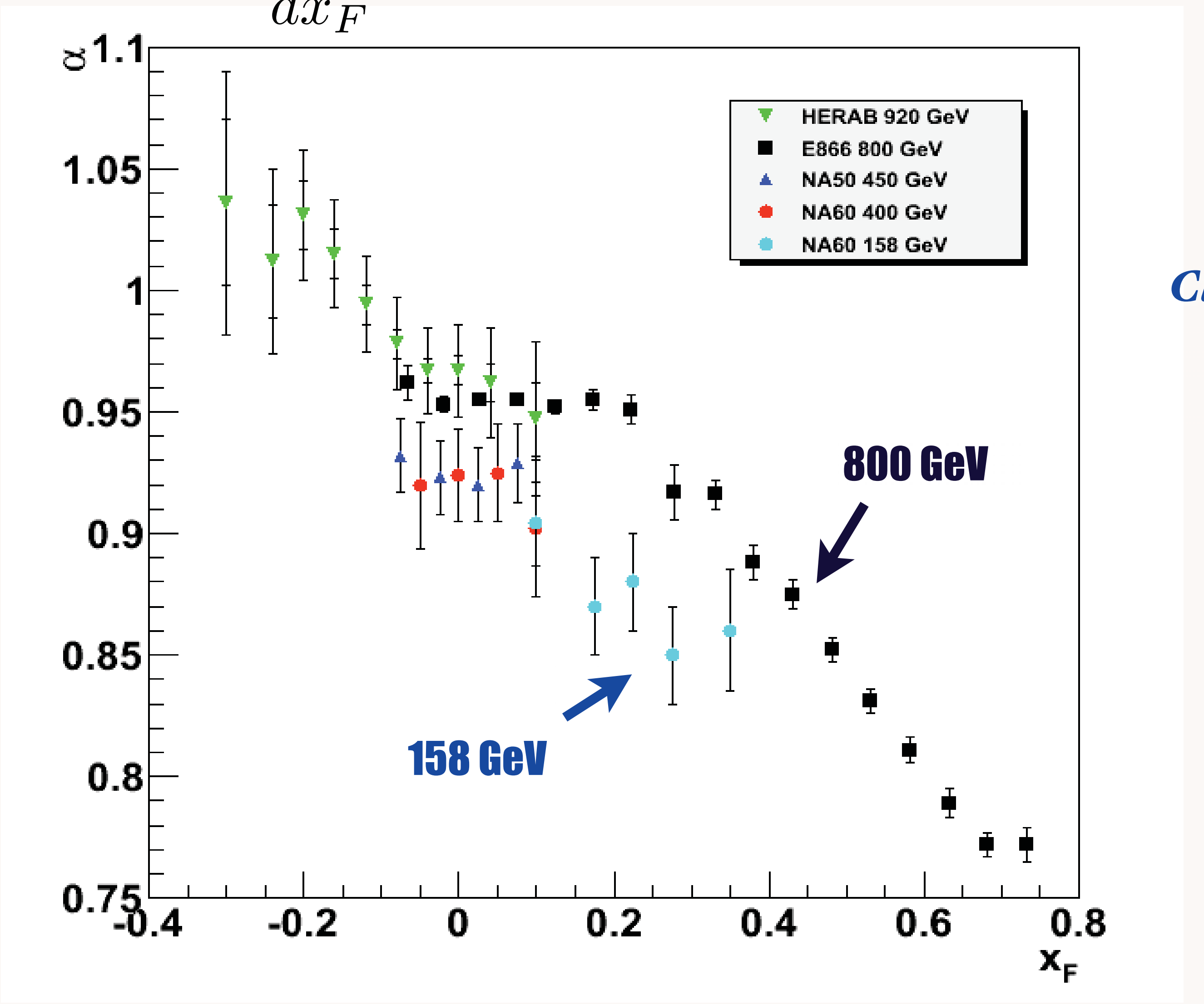
Color-Opaque IC Fock state interacts on nuclear front surface



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

NA60 pA data @ 158GeV

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



Clear dependence on x_F and beam energy

- 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

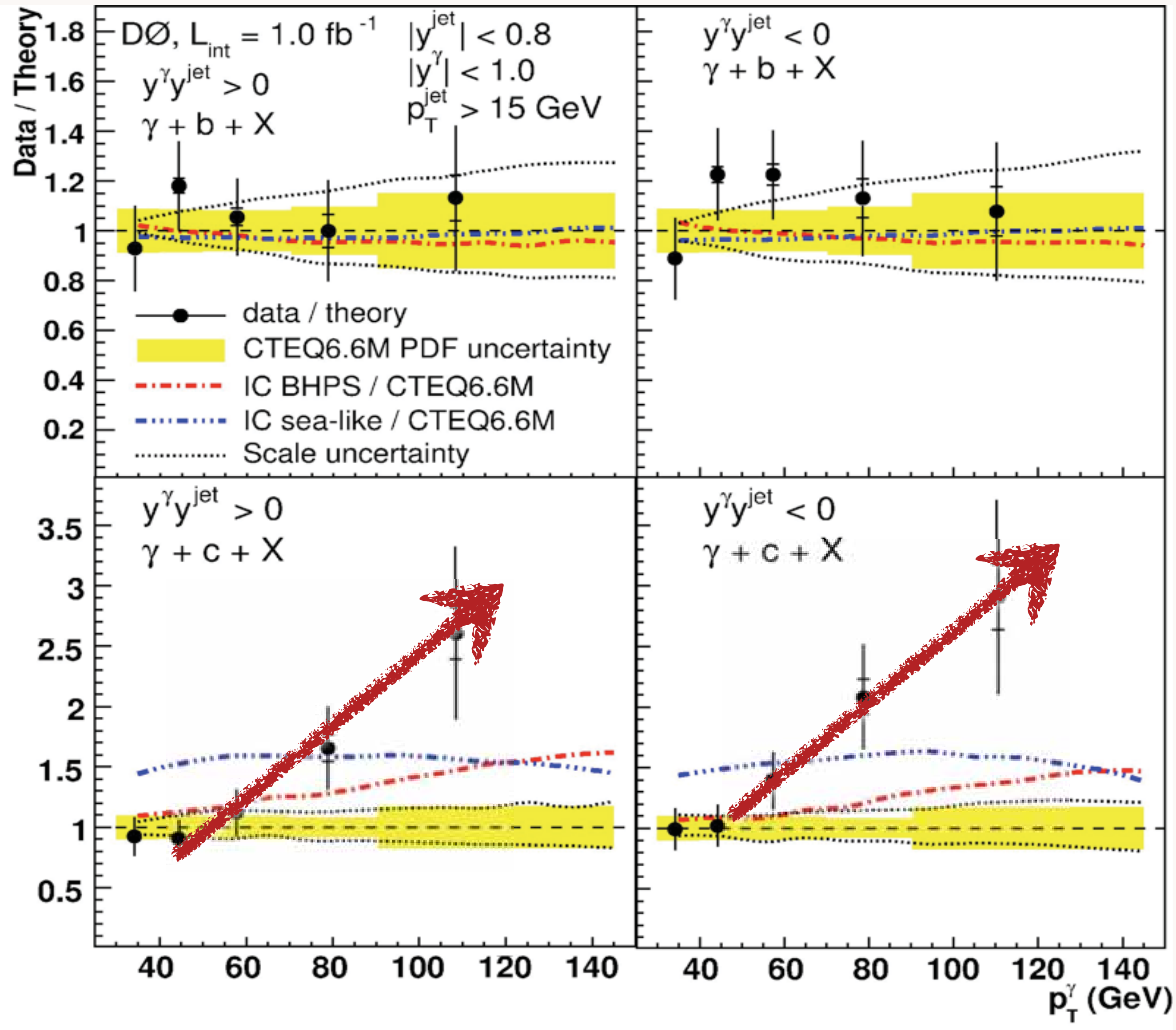
- IC Explains $J/\psi \to \rho\pi$ puzzle (Karliner, SJB)

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

Higgs production at $x_F = 0.8$

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

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

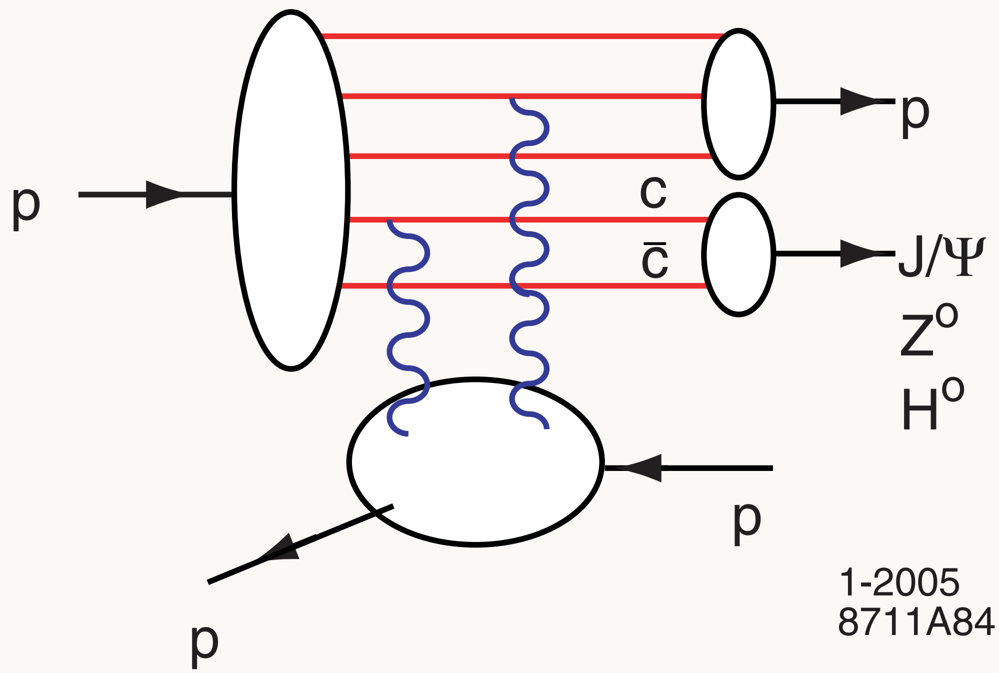


$$\frac{\Delta\sigma(\bar{p}p \to \gamma c X)}{\Delta\sigma(\bar{p}p \to \gamma b X)}$$

Ratio insensitive to gluon PDF, scales

Signal for significant IC at x > 0.1 ?

Intrinsic Charm Mechanism for Exclusive Diffraction Production



$$\mathrm{p\,p} \to J/\psi\; p\; p$$

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

Exclusive Diffractive and Non-Diffractive High-X_F Higgs Production

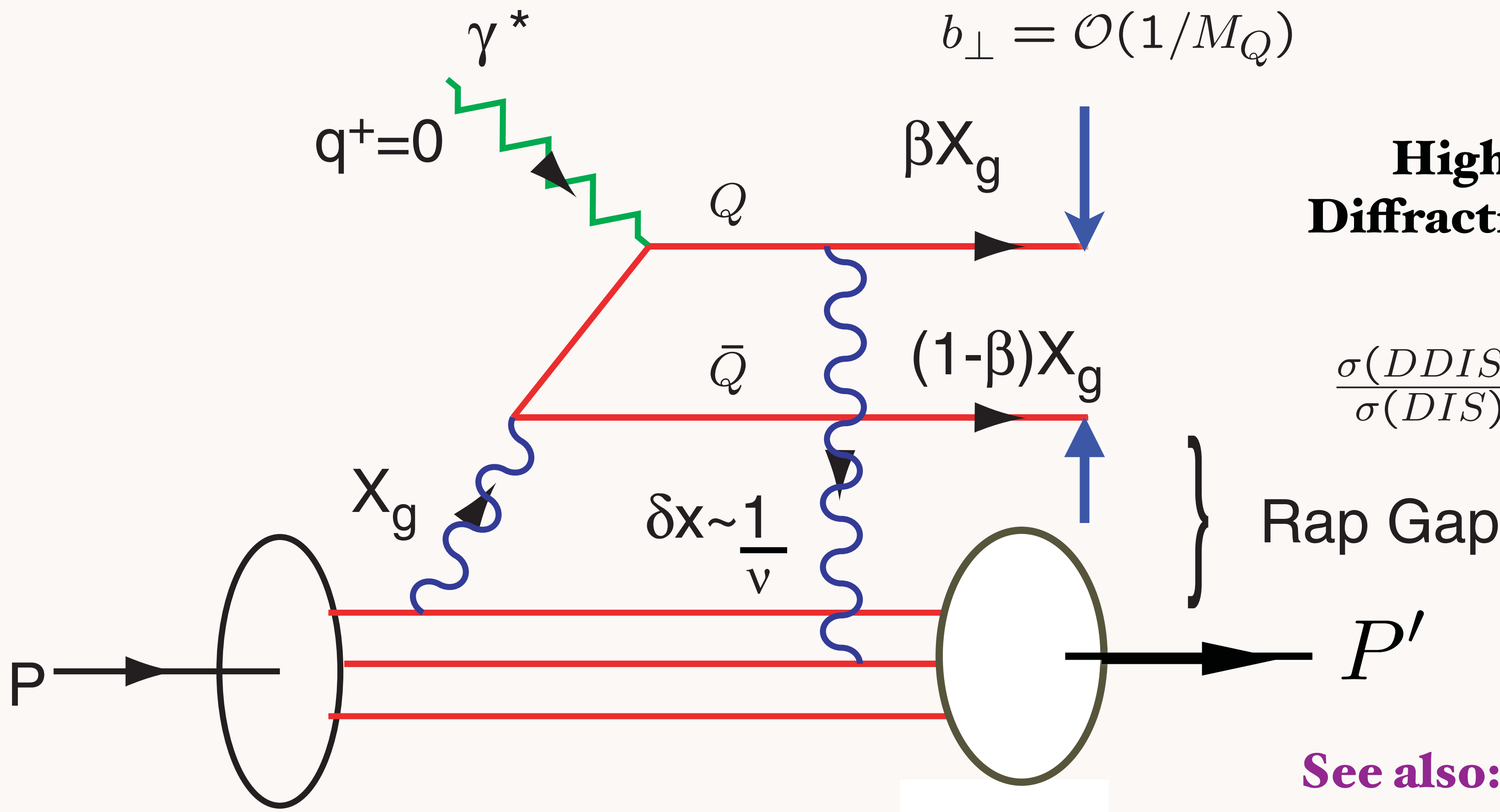
Goldhaber, Kopeliovitch, Schmidt, Soffer, sjb

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

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

Reproduces lab-frame color dipole approach

Nuclear Physics B 369 (1992) 519–542
North-Holland

NUCLEAR
PHYSICS B

New QCD production mechanisms for hard processes at large x *

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Received 12 August 1991
Accepted for publication 24 September 1991

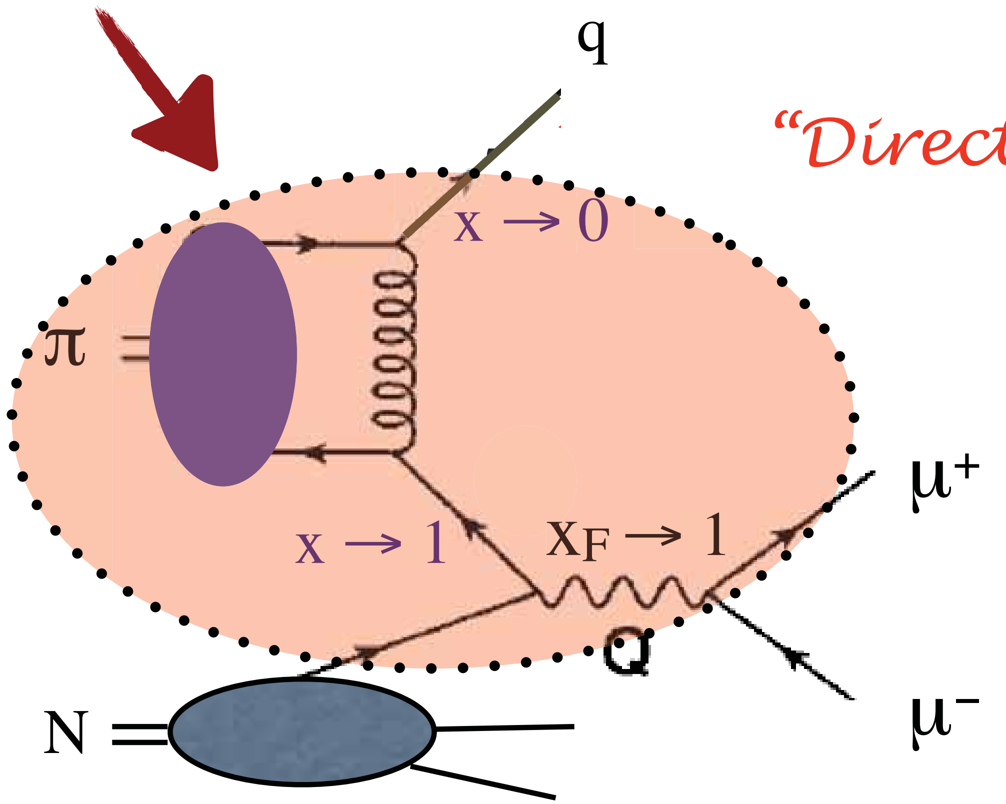
We study the QCD production mechanisms for lepton and quark pairs of high mass $\mathcal{M}$ that carry a large fraction x of the projectile momentum. We show that the dominant contribution comes from peripheral processes in which low-x spectator quarks interact with the target, with the hardness scale of the collision being given by $Q^2 = \mathcal{M}^2(1-x)$. In the high-$\mathcal{M}^2$ limit with fixed $\mathcal{M}^2(1-x)$ we identify new leading-order perturbative contributions from the hadron wave function which involve more than one constituent. These "intrinsic" contributions cannot be expressed in terms of the usual single-parton structure functions, implying a breakdown of QCD factorization. In a numerical study of a simple gauge theory model, we show that such contributions can dominate the standard single-parton factorizable terms. These results appear to explain several anomalies seen in the data: the excess production and the anomalous nuclear-number of dependence of open and bound charm at large x; the "cumulative" effects ($x > 1$) observed in hadron production from nuclei; and the large target-polarization asymmetry observed for hadron production at high x. The intrinsic multi-parton processes provide new mechanisms for the hadro-production of the J/ψ directly in a color-singlet state and also for the production of heavy flavor systems in lepto-production at high momentum.

$\pi N \to \mu^+ \mu^- X$ at high x_F

In the limit where $(1-x_F)Q^2$ is fixed as $Q^2 \to \infty$

Light-Front Wavefunctions from AdS/CFT

Entire pion wf contributes to hard process



"Direct" Subprocess

Virtual photon is longitudinally polarized

Berger, sjb

Hoyer, Mueller, Tang, sjb

Khoze, Brandenburg, Muller, sjb

$$\pi^- N \to \mu^+ \mu^- X \text{ at } 80 \text{ GeV}/c$$

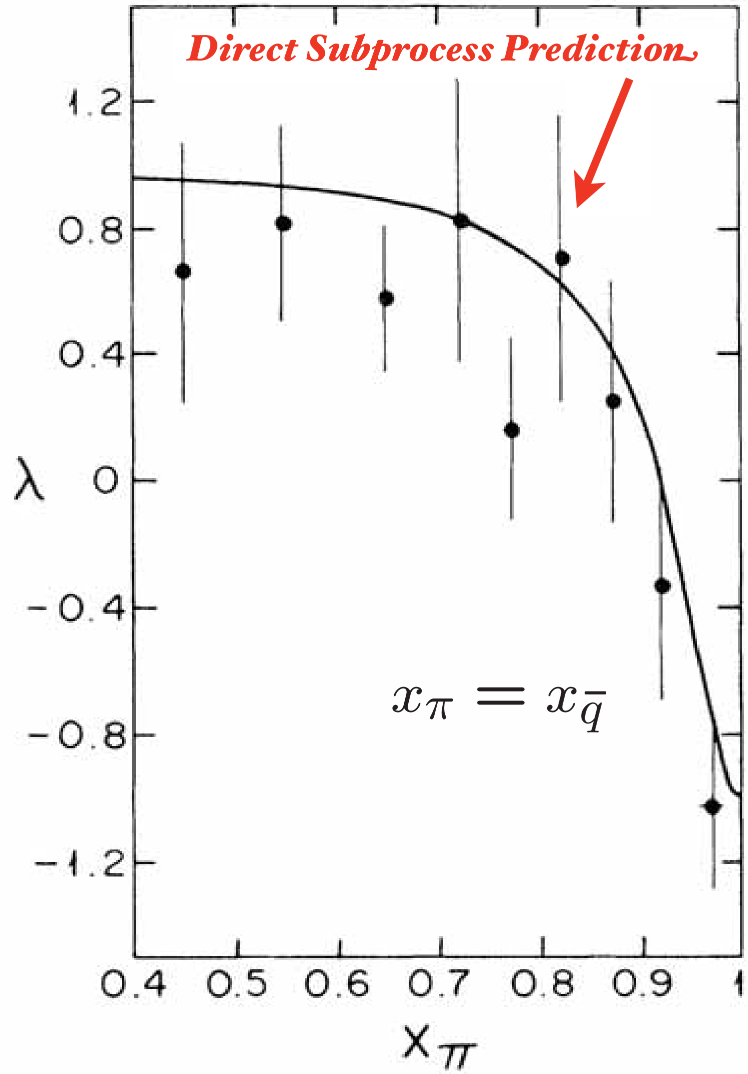
$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \rho \sin 2\theta \cos\phi + \omega \sin^2\theta \cos 2\phi .$$

$$\frac{d^2\sigma}{dx_\pi d\cos\theta} \propto x_\pi \left[(1-x_\pi)^2 (1+\cos^2\theta) + \frac{4}{9} \frac{\langle k_T^2 \rangle}{M^2} \sin^2\theta \right]$$

$$\langle k_T^2 \rangle = 0.62 \pm 0.16 \ \text{GeV}^2/c^2$$

$$Q^2 = M^2$$

Dramatic change in angular distribution at large x_F



Chicago-Princeton Collaboration

Phys.Rev.Lett.55:2649,1985

Example of a higher-twist direct subprocess

Volume 206, number 4 PHYSICS LETTERS B 2 June 1988

USING NUCLEI TO PROBE HADRONIZATION IN QCD

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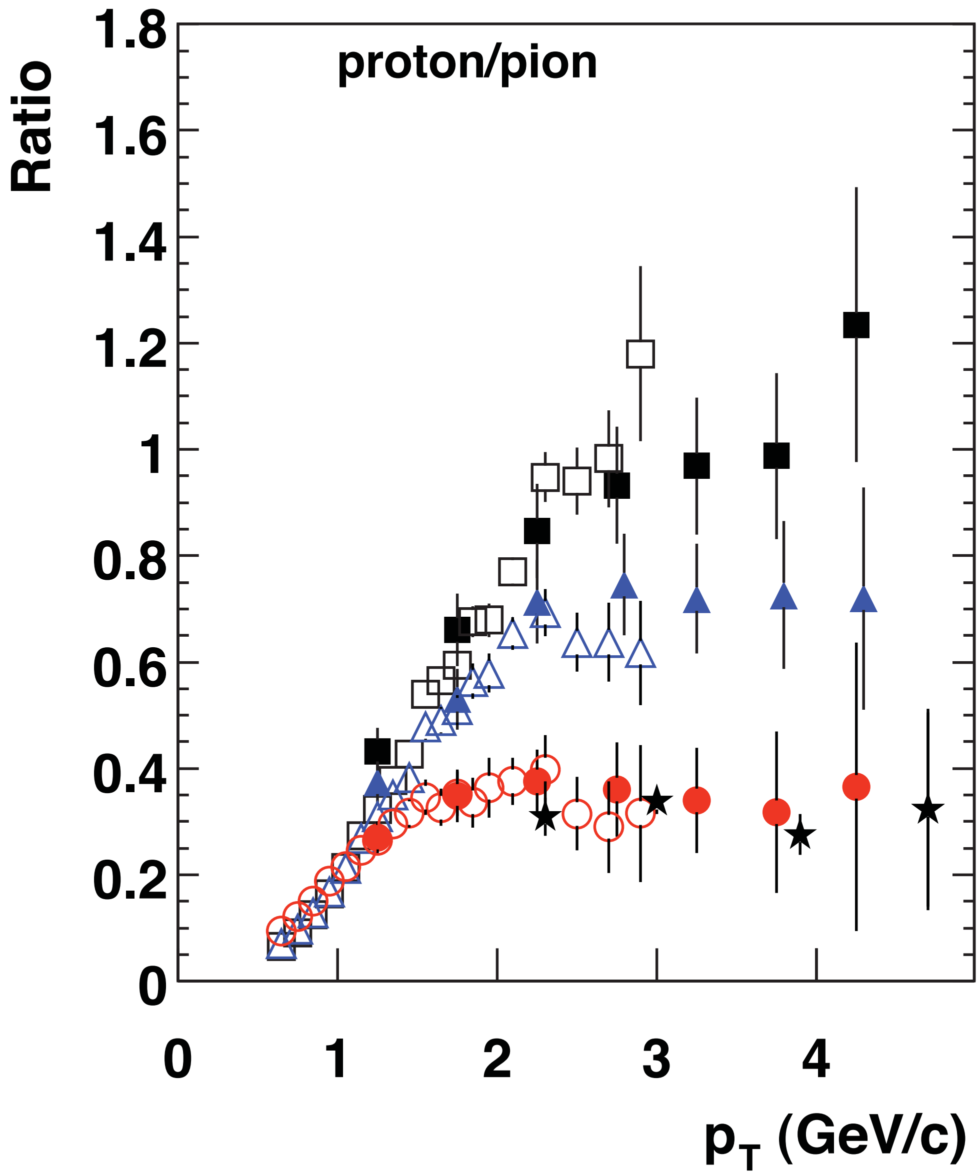
Received 15 March 1988

The behavior of quasi-exclusive and inclusive ρ and J/ψ photoproduction, electroproduction and hadroproduction in nuclei are discussed for small and large $p_{\perp}$. In particular we argue that J/ψ production in ion–ion collisions is likely to be suppressed relative to the background lepton pair production, independent of whether or not a QCD plasma is formed. We point out that previous extractions of the J/ψ inelastic cross section do not actually measure the cross section for the interaction of physical J/ψ's with nucleons.

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

Baryon Anomaly: Particle ratio changes with centrality!



Protons less absorbed in nuclear collisions than pions

← **Central**

□ ■	Au+Au 0-10%
△ ▲	Au+Au 20-30%
○ ●	Au+Au 60-92%
★	p+p, $\sqrt{s}$ = 53 GeV, ISR
- - - -	e^+e^-, gluon jets, DELPHI
......	e^+e^-, quark jets, DELPHI

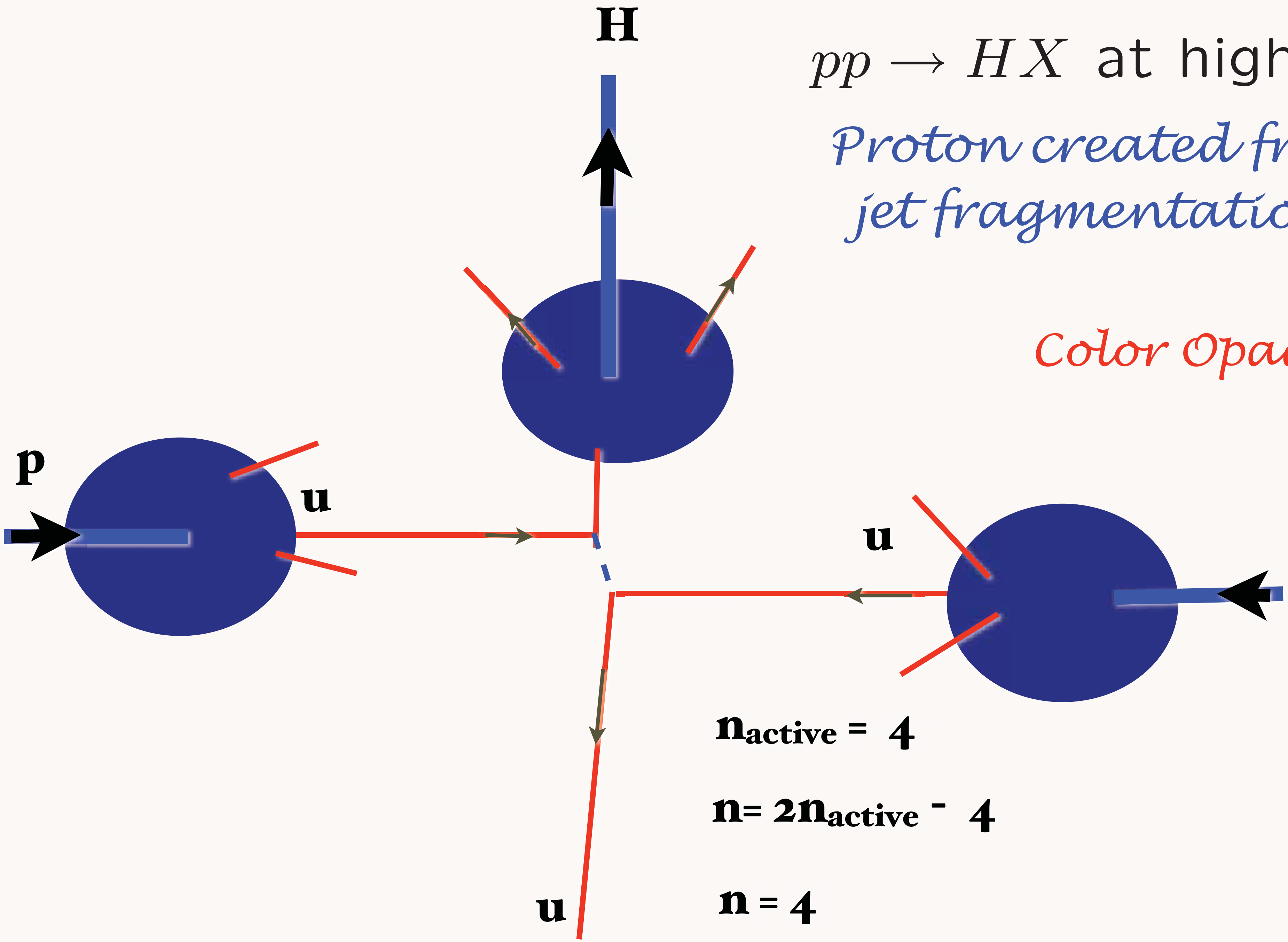
← **Peripheral**

Sickles, sjb

$pp \to HX$ at high p_T

Proton created from jet fragmentation

Color Opaque



$n_{active} = 4$

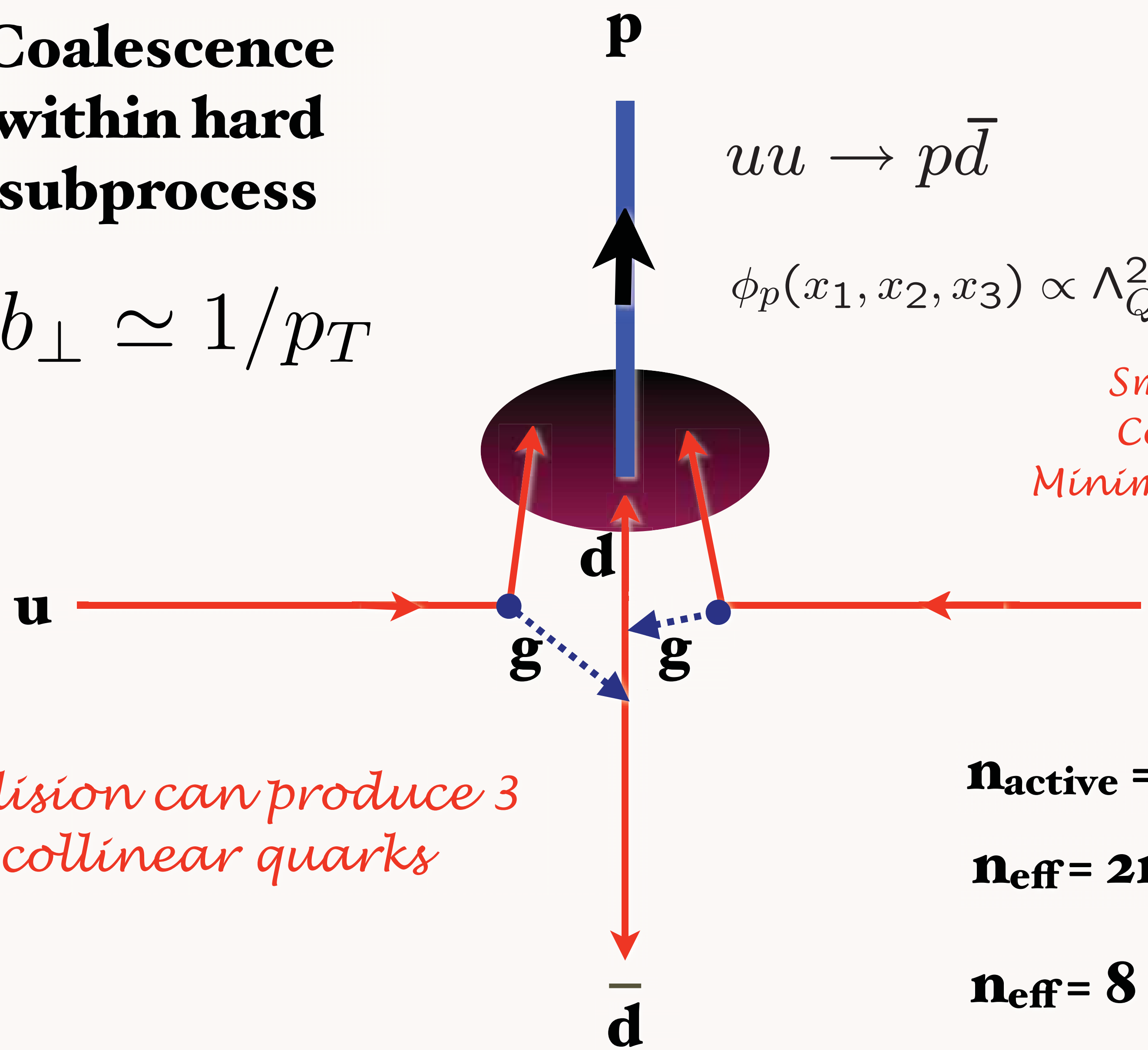
$n = 2n_{active} - 4$

$n = 4$

Baryon can be made directly within hard subprocess

Coalescence within hard subprocess

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



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

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

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

Sickles, sjb

Small color-singlet
Color Transparent
Minimal same-side energy

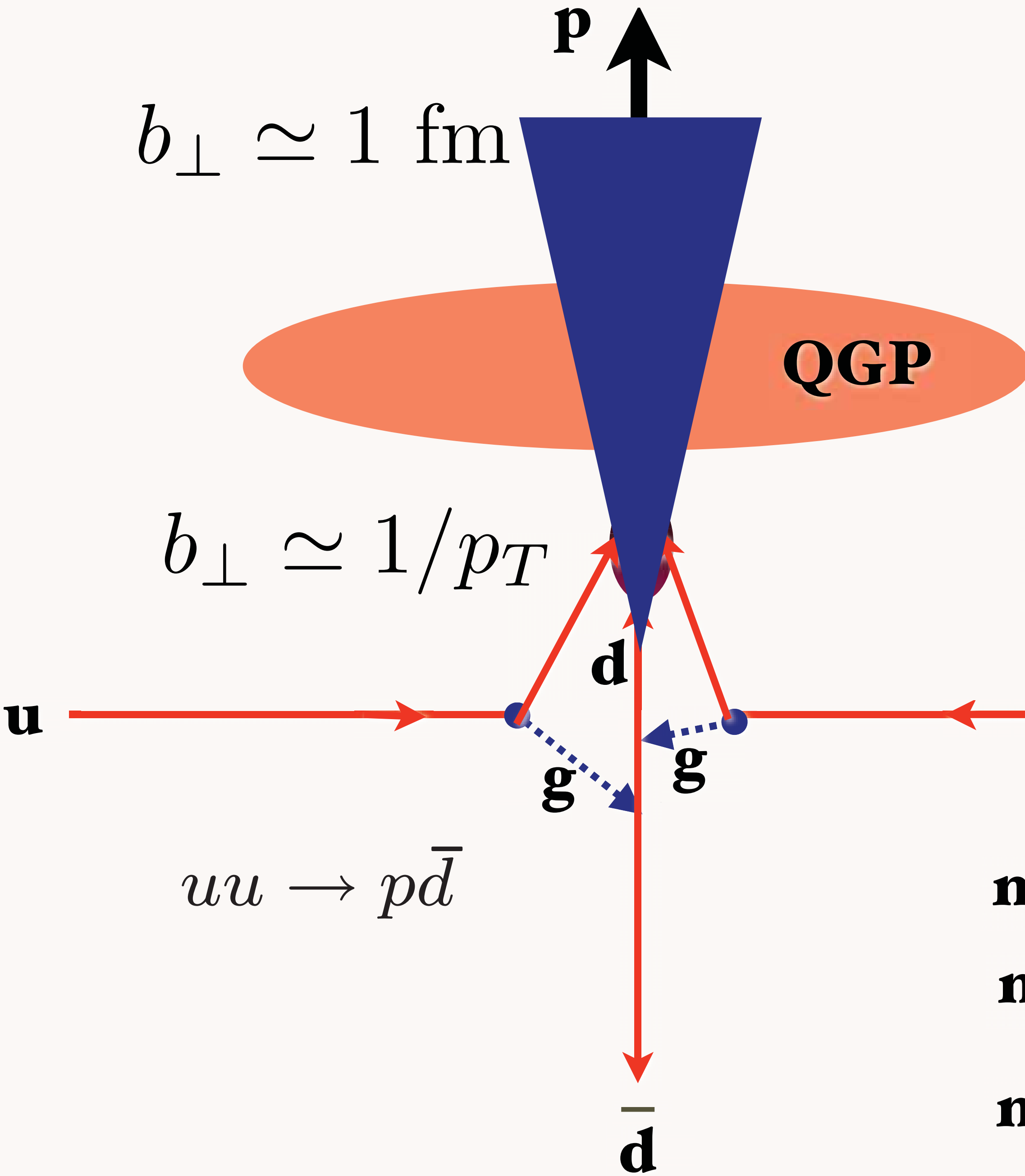
Collision can produce 3 collinear quarks

$n_{active} = 6$

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

$n_{eff} = 8$

Baryon made directly within hard subprocess



Formation Time proportional to Energy

Small color-singlet
Color Transparent
Minimal same-side energy

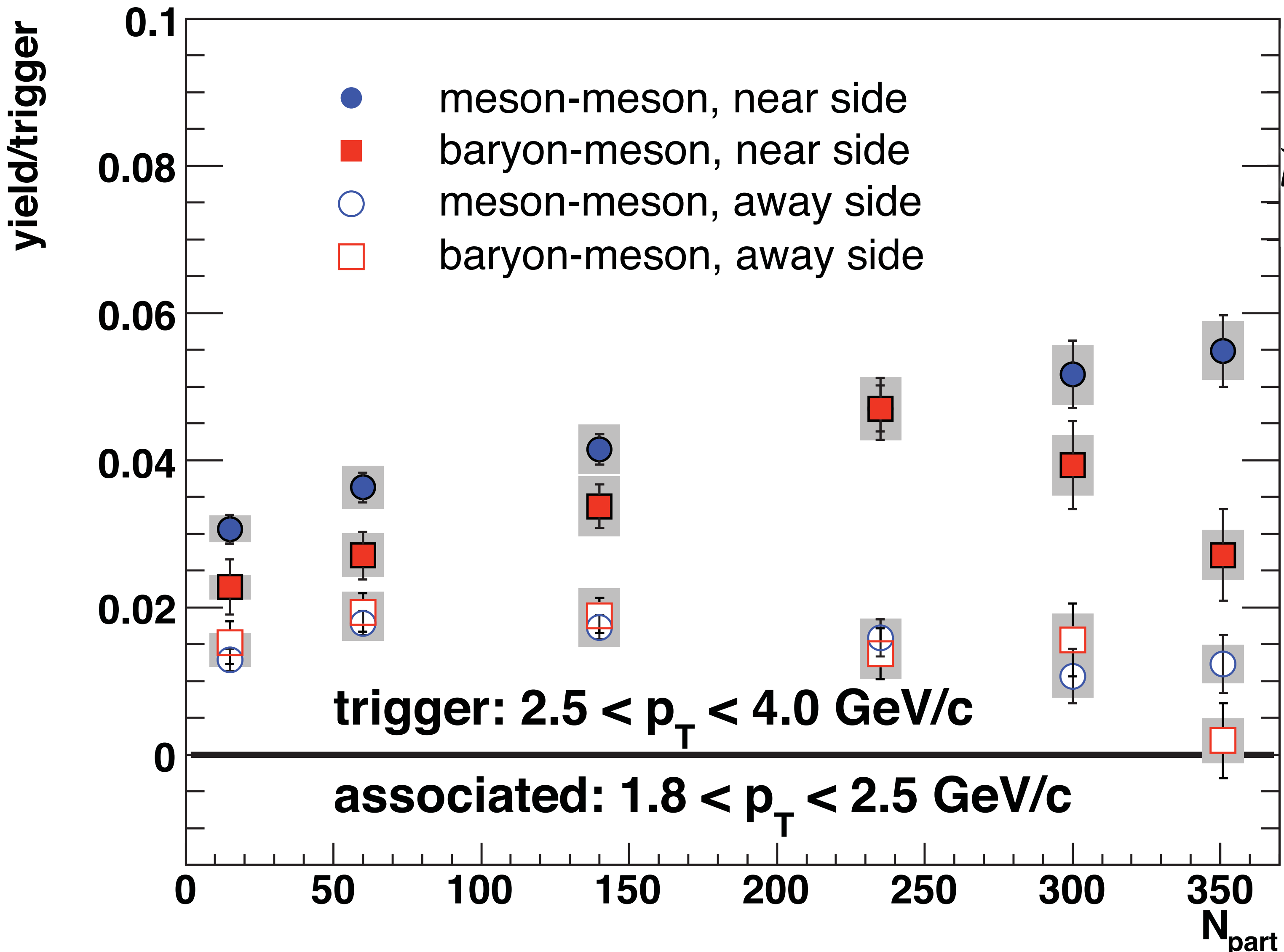
Mueller, sjb

$n_{active} = 6$

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

$n_{eff} = 8$

Anne Sickles

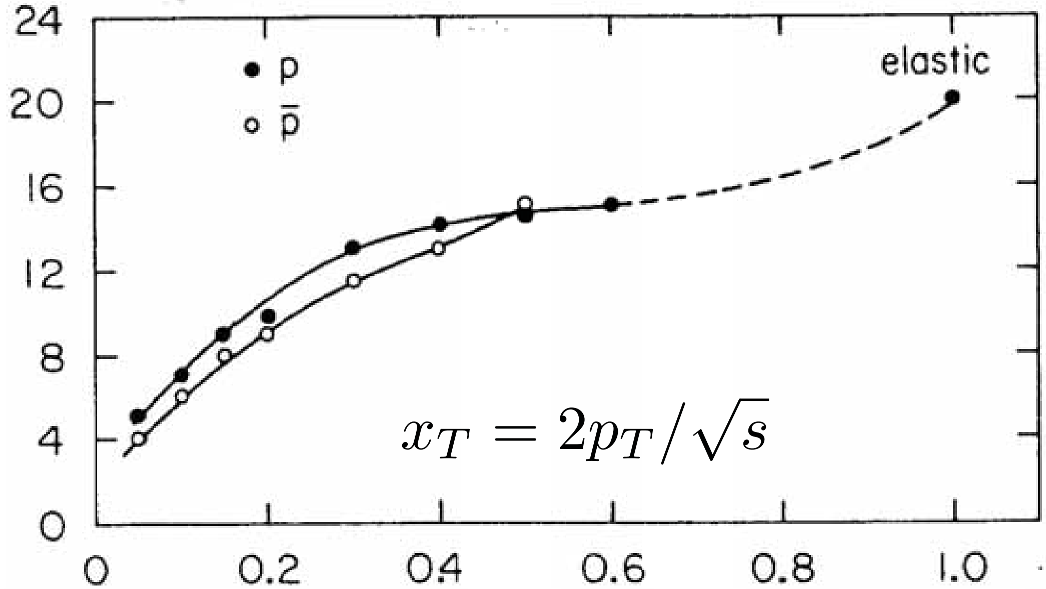


proton trigger: # same-side particles decreases with centrality

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

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

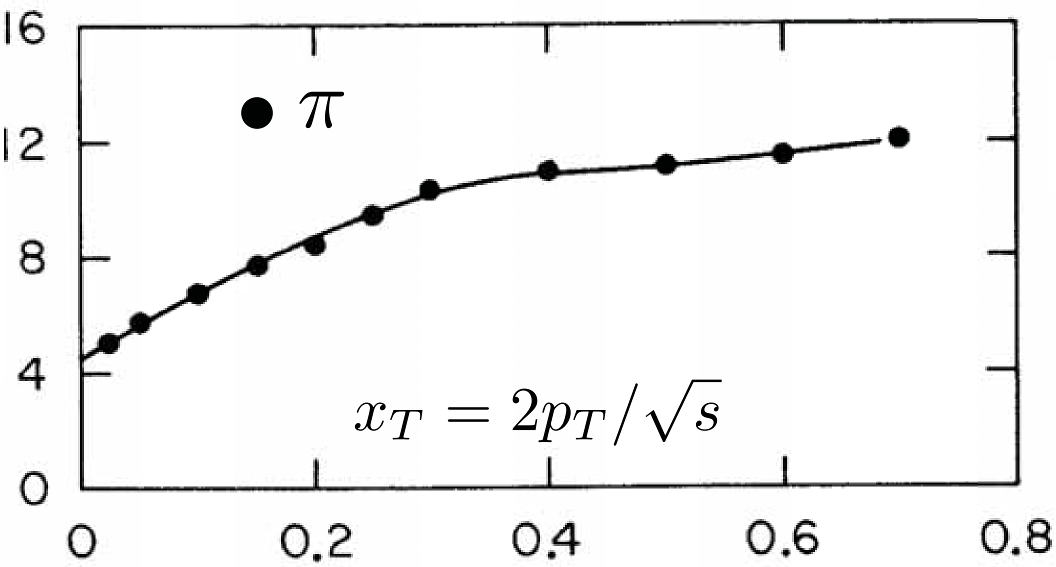
$n_{\rm eff}$



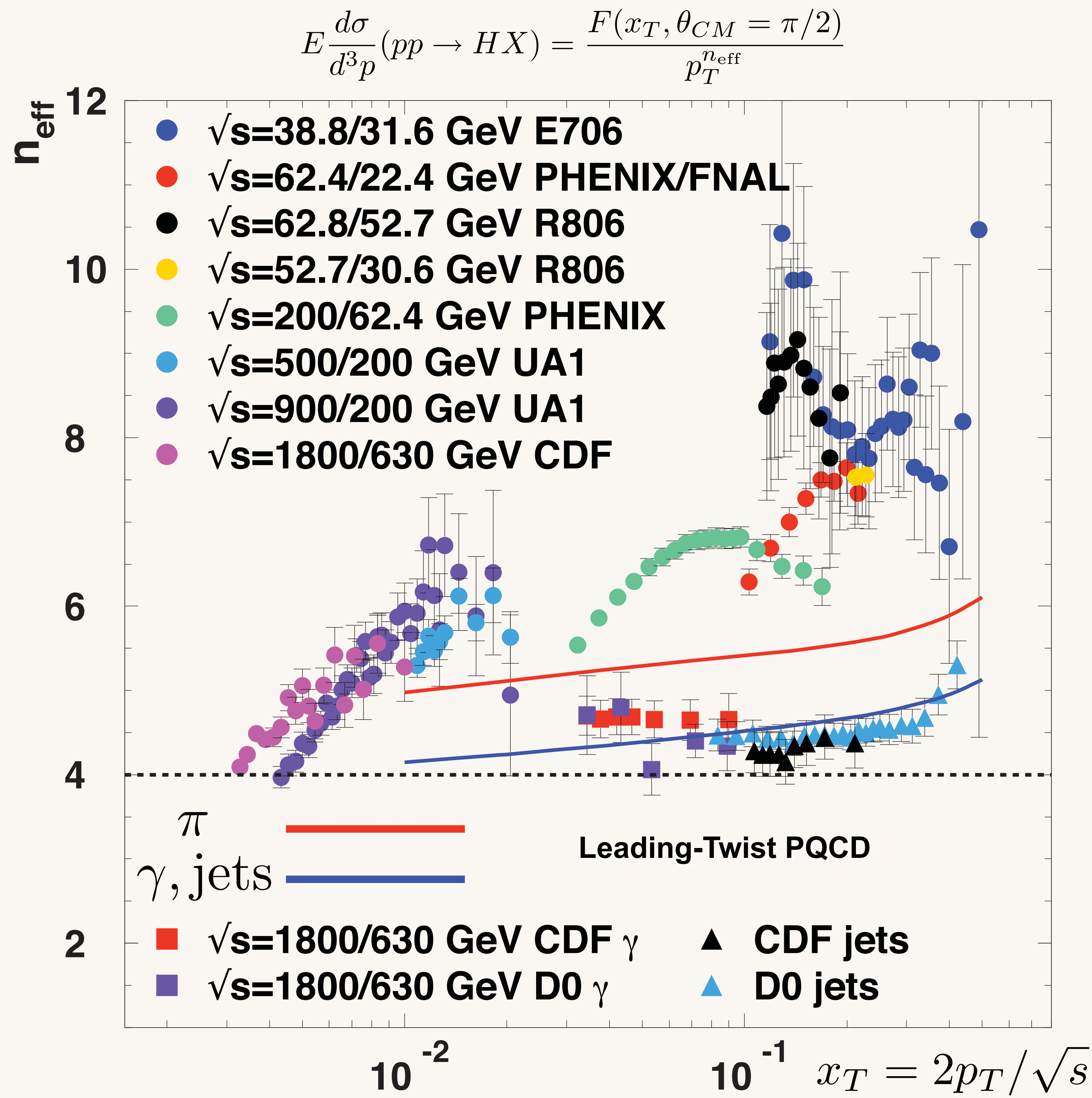
Clear evidence for higher-twist contributions

Fermilab, ISR data

$n_{\rm eff}$



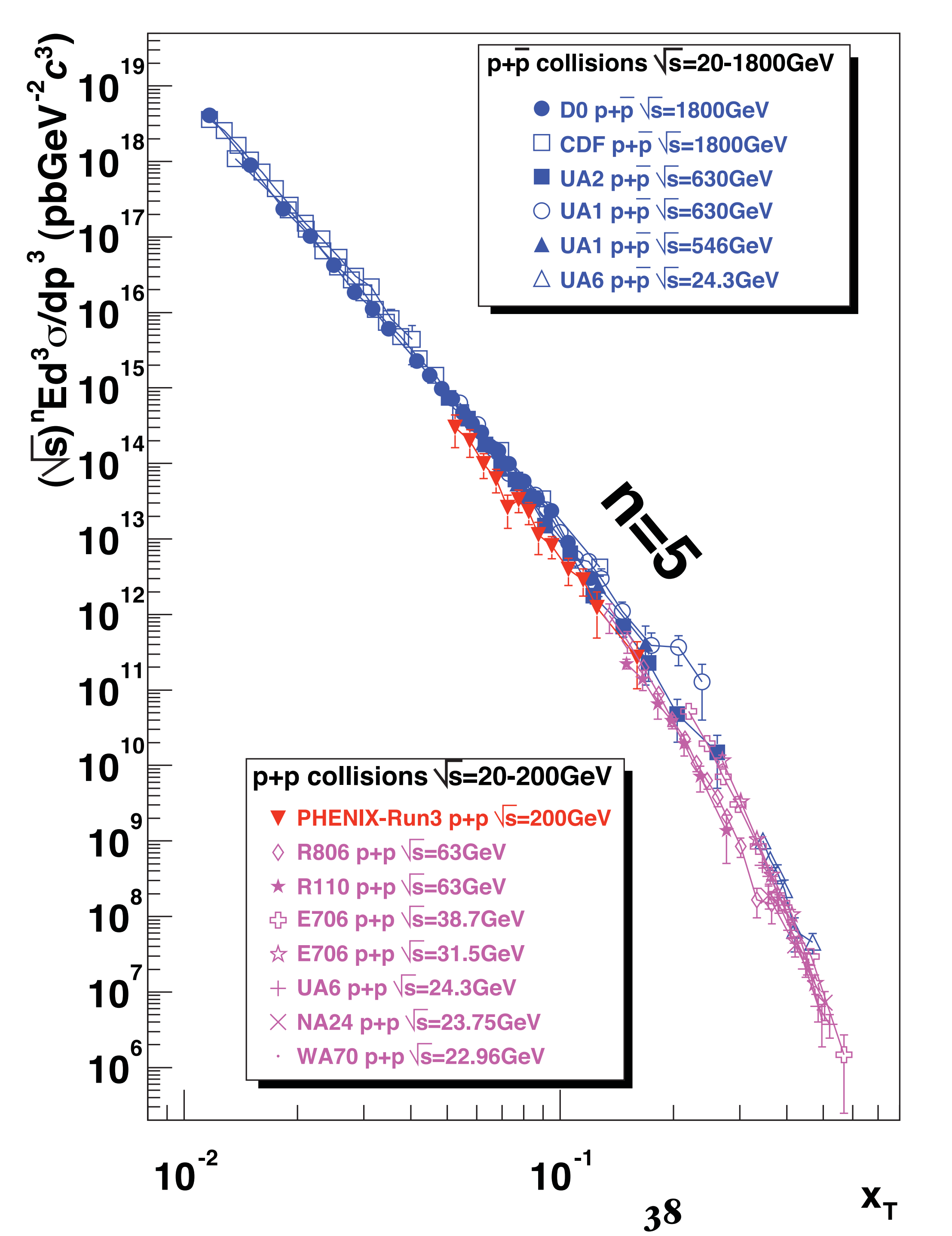
Continuous Rise of $n_{\rm eff}$



$E\frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T, \theta_{CM} = \pi/2)}{p_T^{n_{\rm eff}}}$
$n_{\rm eff}$
√s=38.8/31.6 GeV E706
√s=62.4/22.4 GeV PHENIX/FNAL
√s=62.8/52.7 GeV R806
√s=52.7/30.6 GeV R806
√s=200/62.4 GeV PHENIX
√s=500/200 GeV UA1
√s=900/200 GeV UA1
√s=1800/630 GeV CDF
π
γ, jets
Leading-Twist PQCD
√s=1800/630 GeV CDF γ
√s=1800/630 GeV D0 γ
CDF jets
D0 jets
$x_T = 2p_T/\sqrt{s}$

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

Tannenbaum

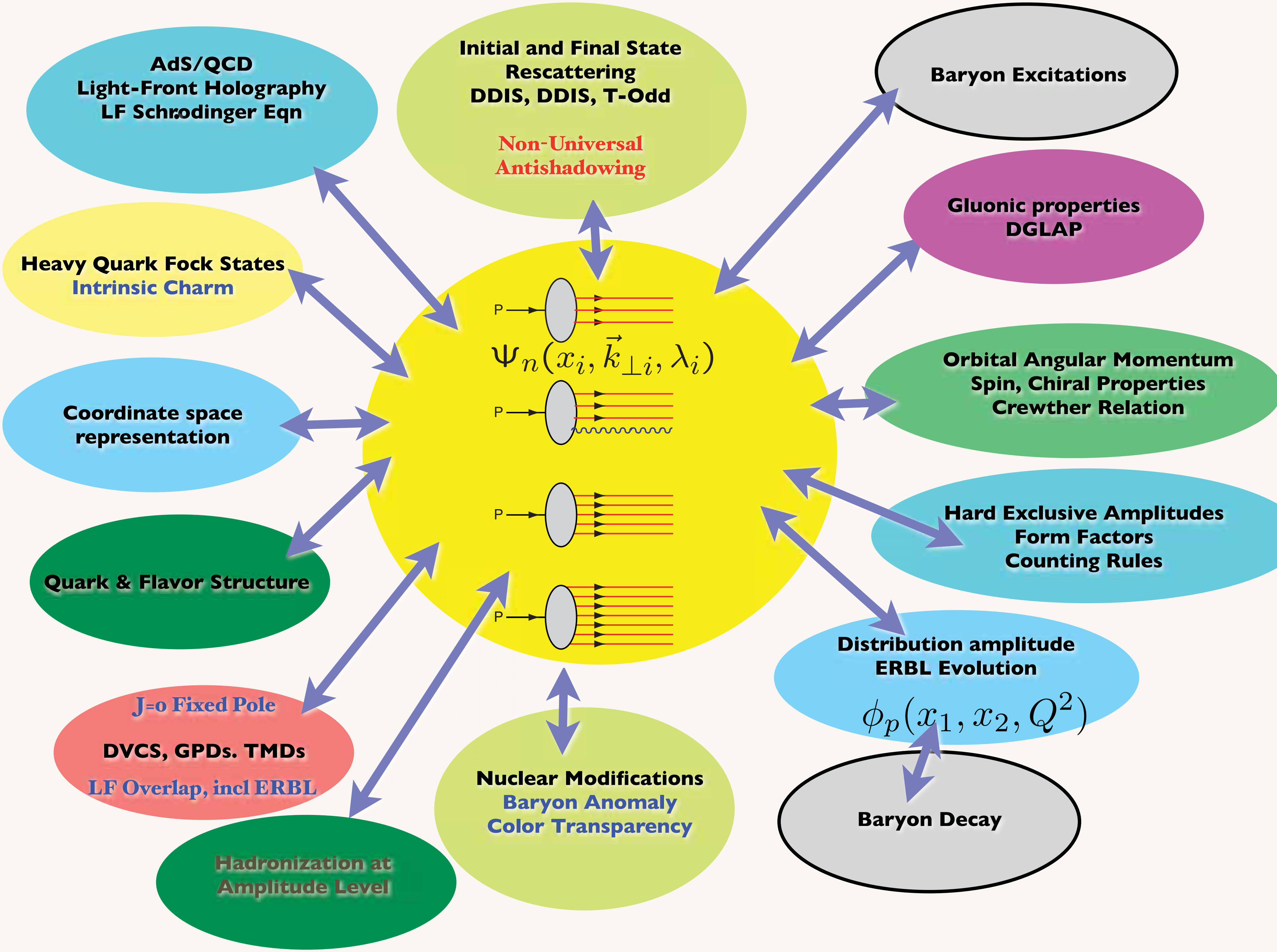


Scaling of direct photon production consistent with PQCD

Light-Front QCD Features and Phenomenology

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

QCD and the LF Hadron Wavefunctions



Single-spin asymmetries

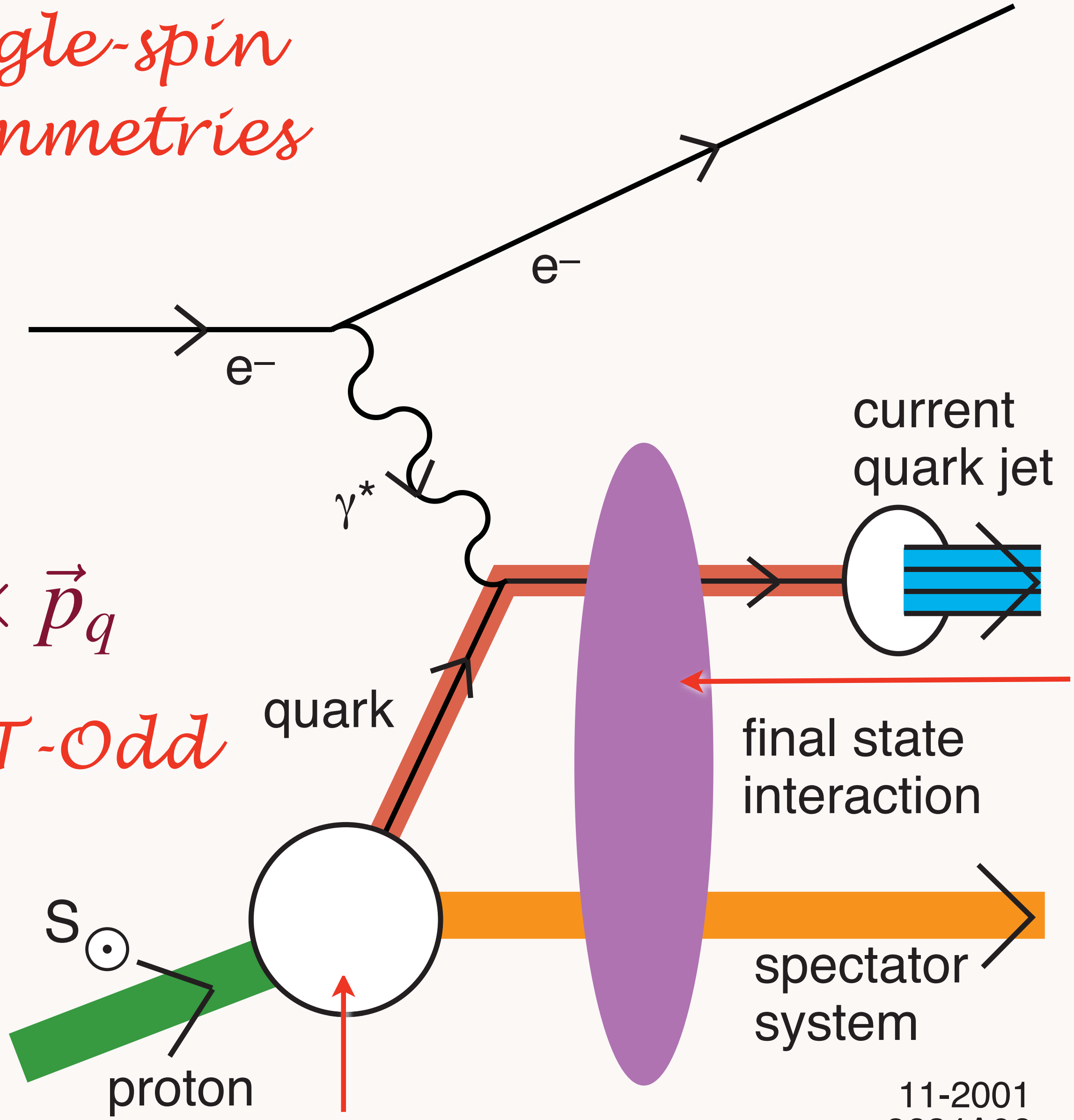
Leading Twist Sivers Effect

Hwang, Schmidt, sjb

Collins, Burkardt Ji, Yuan

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

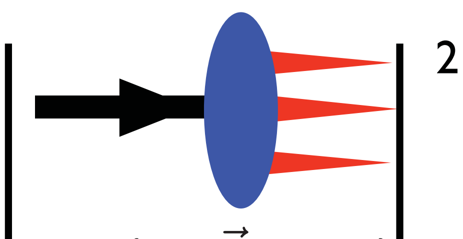
Pseudo- T-Odd



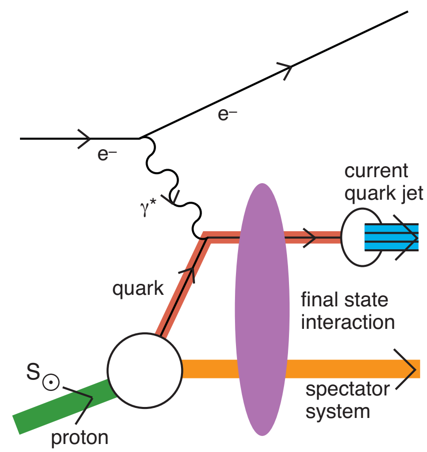
QCD S- and P- Coulomb Phases --Wilson Line

Light-Front Wavefunction S and P- Waves

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



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



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

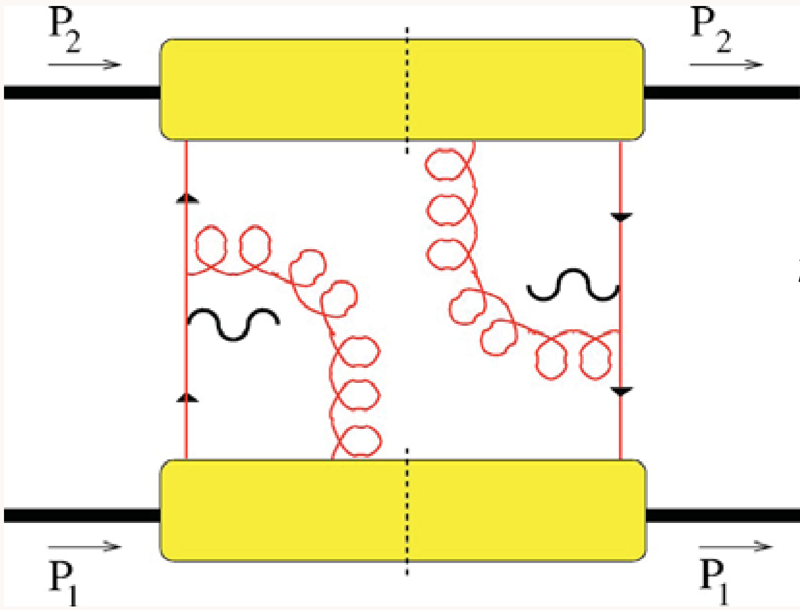
Boer, Hwang, sjb

Drell-Yan planar correlations

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

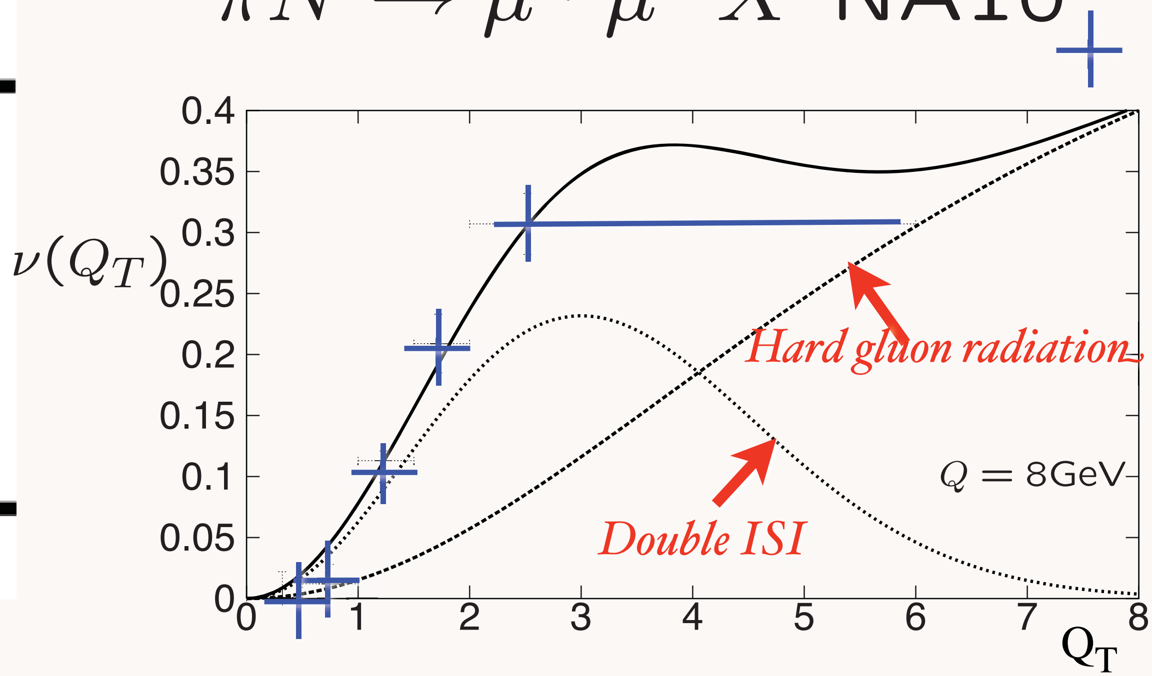
PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

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

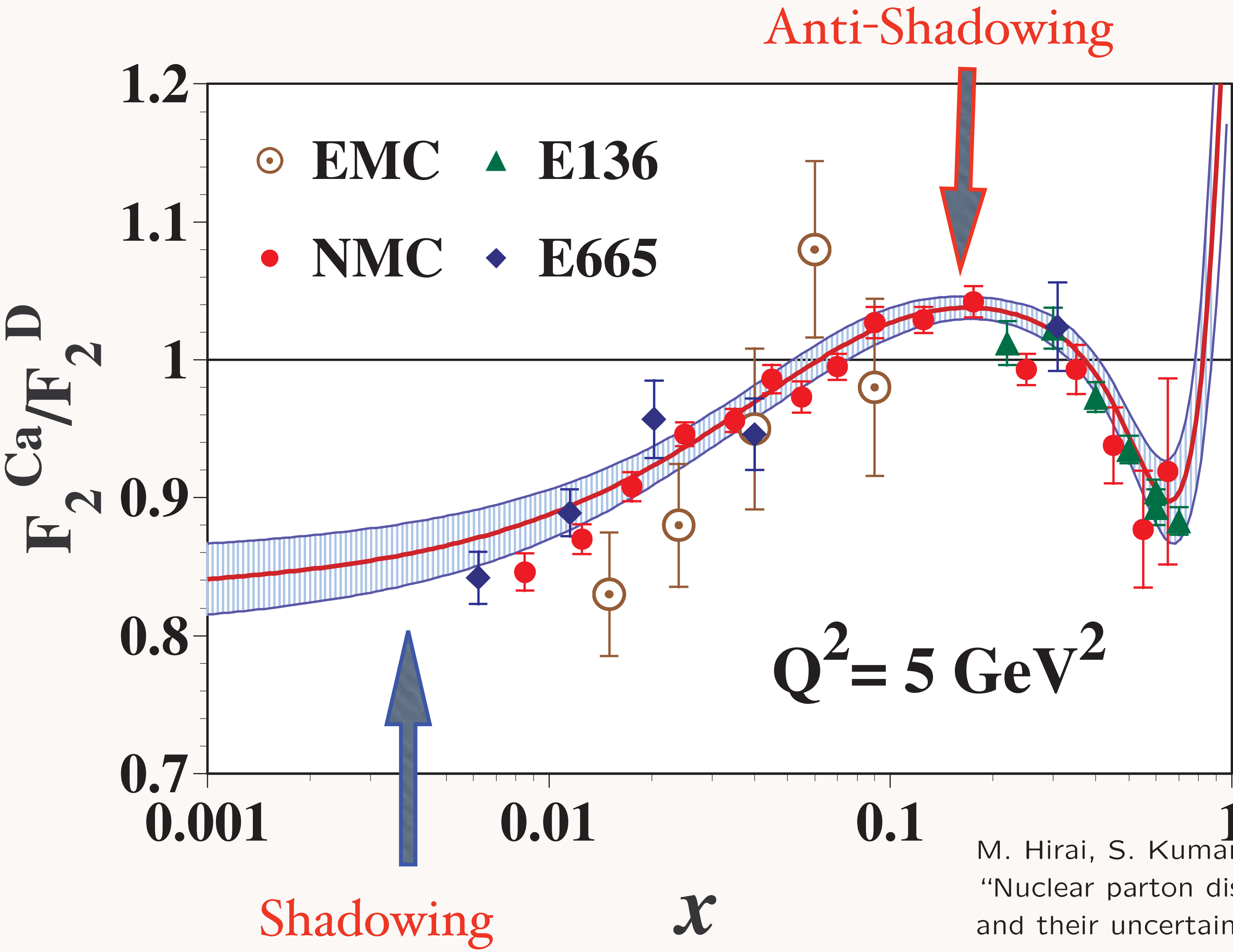


Violates Lam-Tung relation!

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



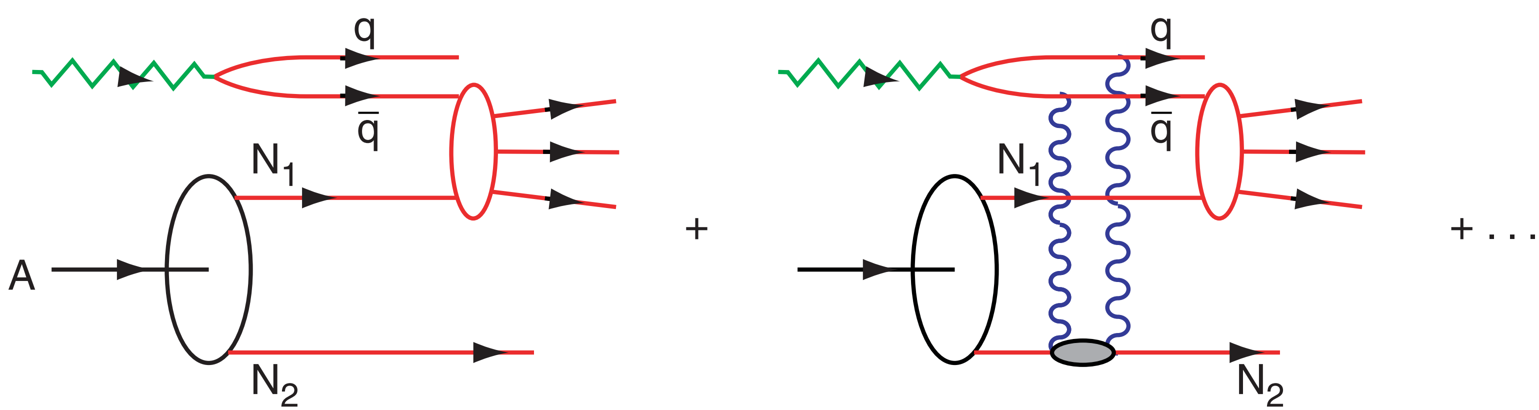
Model: Boer,



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
Mueller

Nuclear Shadowing in QCD



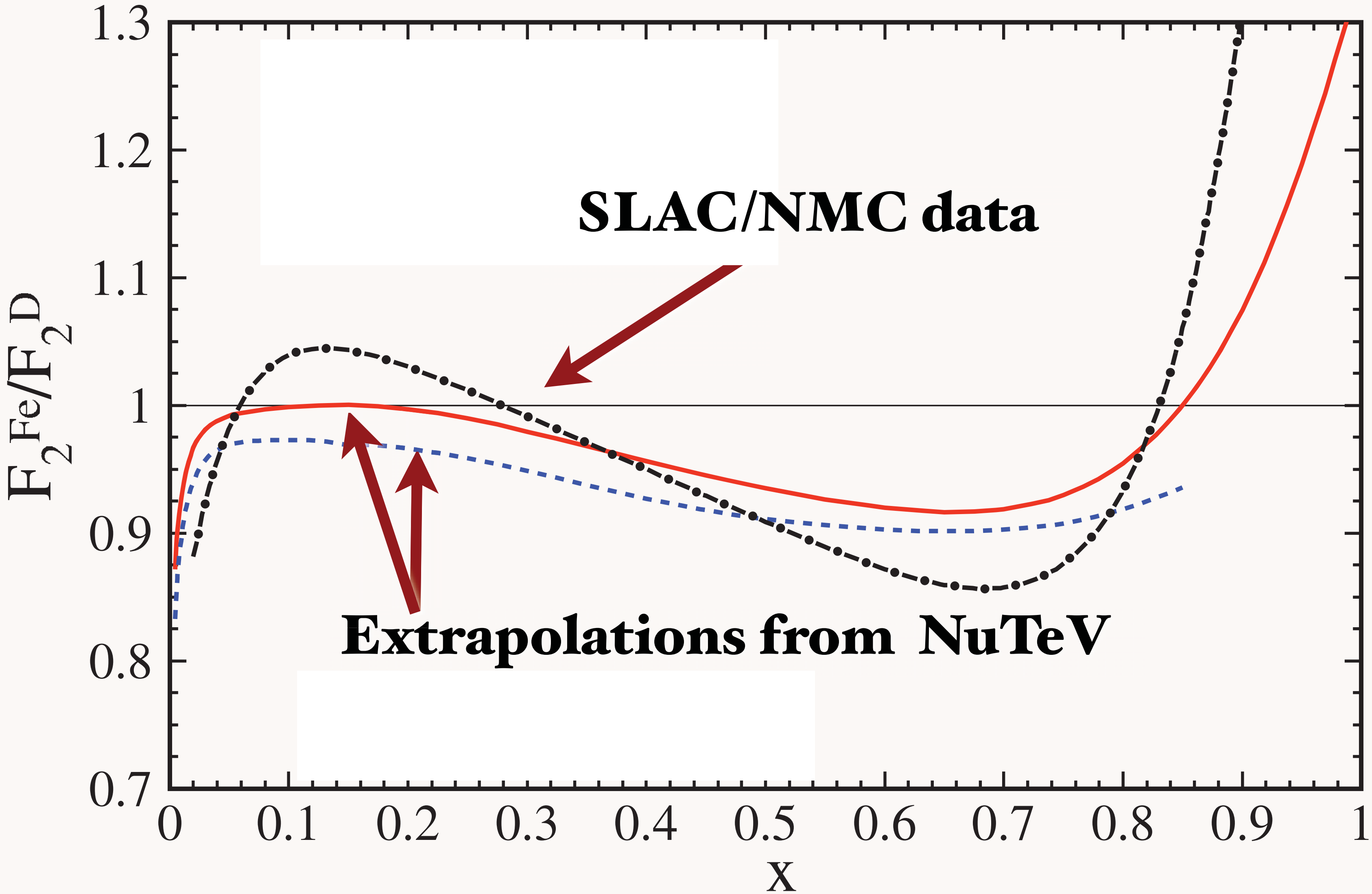
Shadowing depends on understanding leading twist-diffraction in DIS

Nuclear Shadowing not included in nuclear LFWF !

Dynamical effect due to virtual photon interacting in nucleus

Antishadowing (Reggeon exchange) is not universal!

$Q^2 = 5\ \mathrm{GeV}^2$

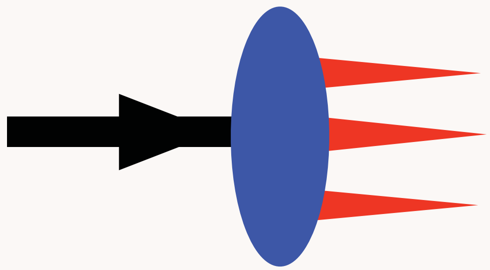


Scheinbein, Yu, Keppel, Morfin, Olness, Owens

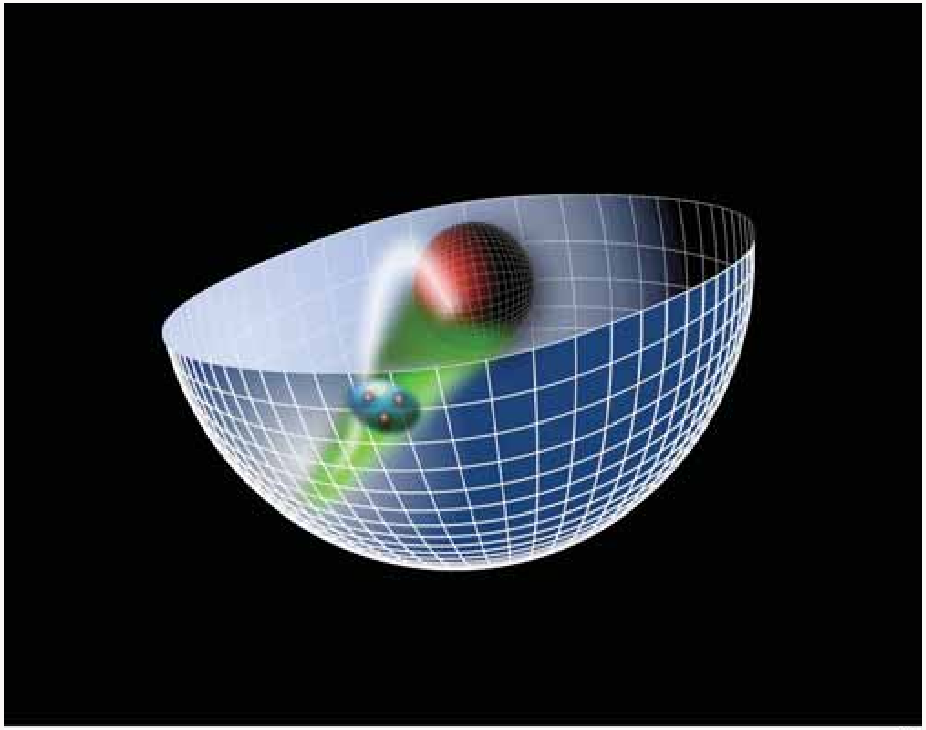
Light-Front Holography and Non-Perturbative QCD

Goal:
Use AdS/QCD duality to construct a first approximation to QCD

Hadron Spectrum
Light-Front Wavefunctions,
Form Factors, DVCS, etc

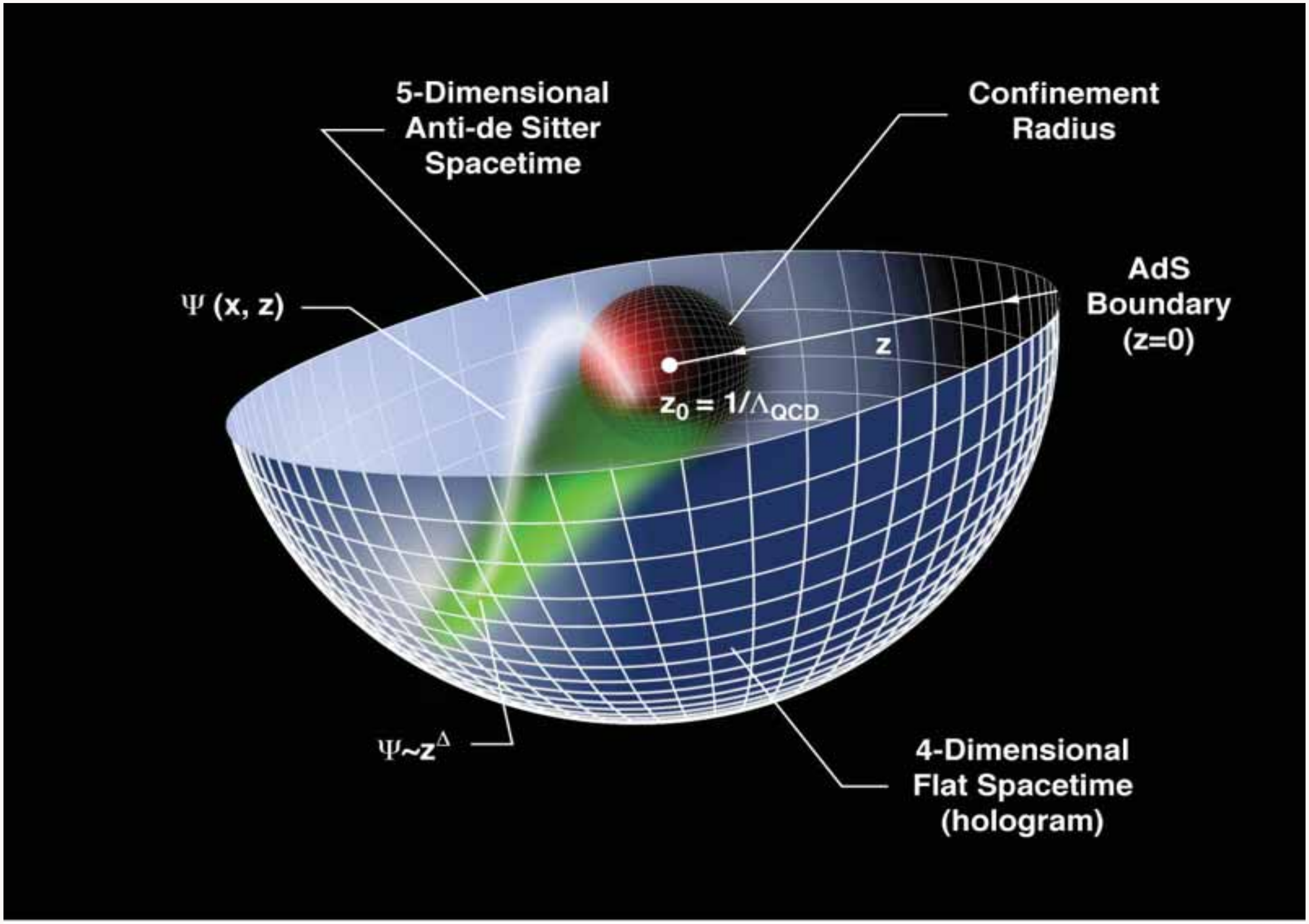


$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



in collaboration with
Guy de Teramond

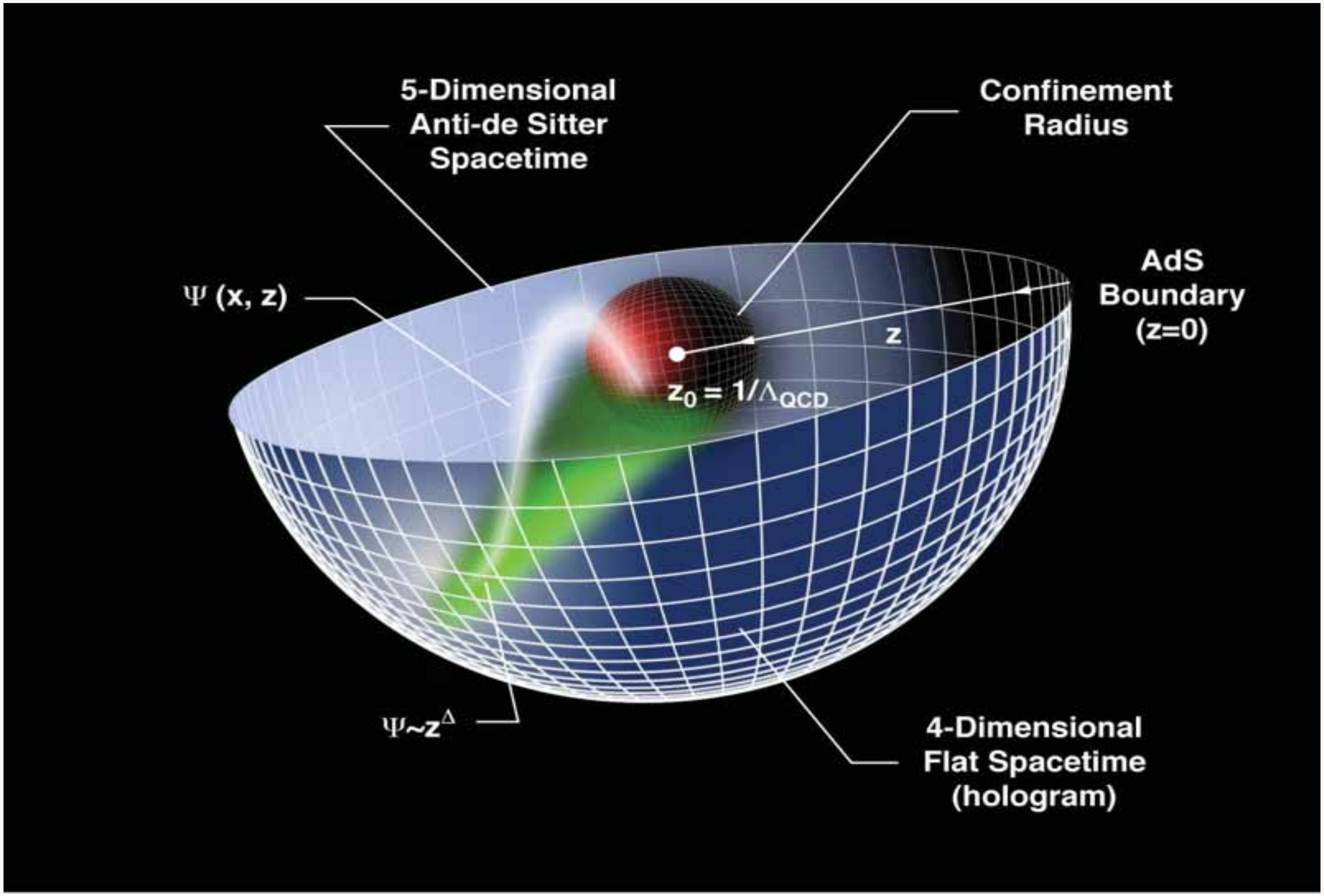
Applications of AdS/CFT to QCD



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

in collaboration with Guy de Teramond

Applications of AdS/CFT to QCD



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

String Theory

Bottom-Up

Top-Down

Goal:

- **Use AdS/CFT to provide an approximate, covariant, and analytic model of hadron structure with confinement at large distances, conformal behavior at short distances**

- **Analogous to the Schrodinger Theory for Atomic Physics**

- *AdS/QCD Light-Front Holography*

- *Hadronic Spectra and Light-Front Wavefunctions*

Conformal Theories are invariant under the Poincare and conformal transformations with

$$\mathbf{M}^{\mu\nu}, \mathbf{P}^{\mu}, \mathbf{D}, \mathbf{K}^{\mu},$$

the generators of SO(4,2)

SO(4,2) has a mathematical representation on AdS5

Scale Transformations

- Isomorphism of $SO(4,2)$ of conformal QCD with the group of isometries of AdS space

$$ds^2 = \frac{R^2}{z^2}(\eta_{\mu\nu}dx^\mu dx^\nu - dz^2),$$

invariant measure

$x^\mu \to \lambda x^\mu, \; z \to \lambda z$, maps scale transformations into the holographic coordinate z.

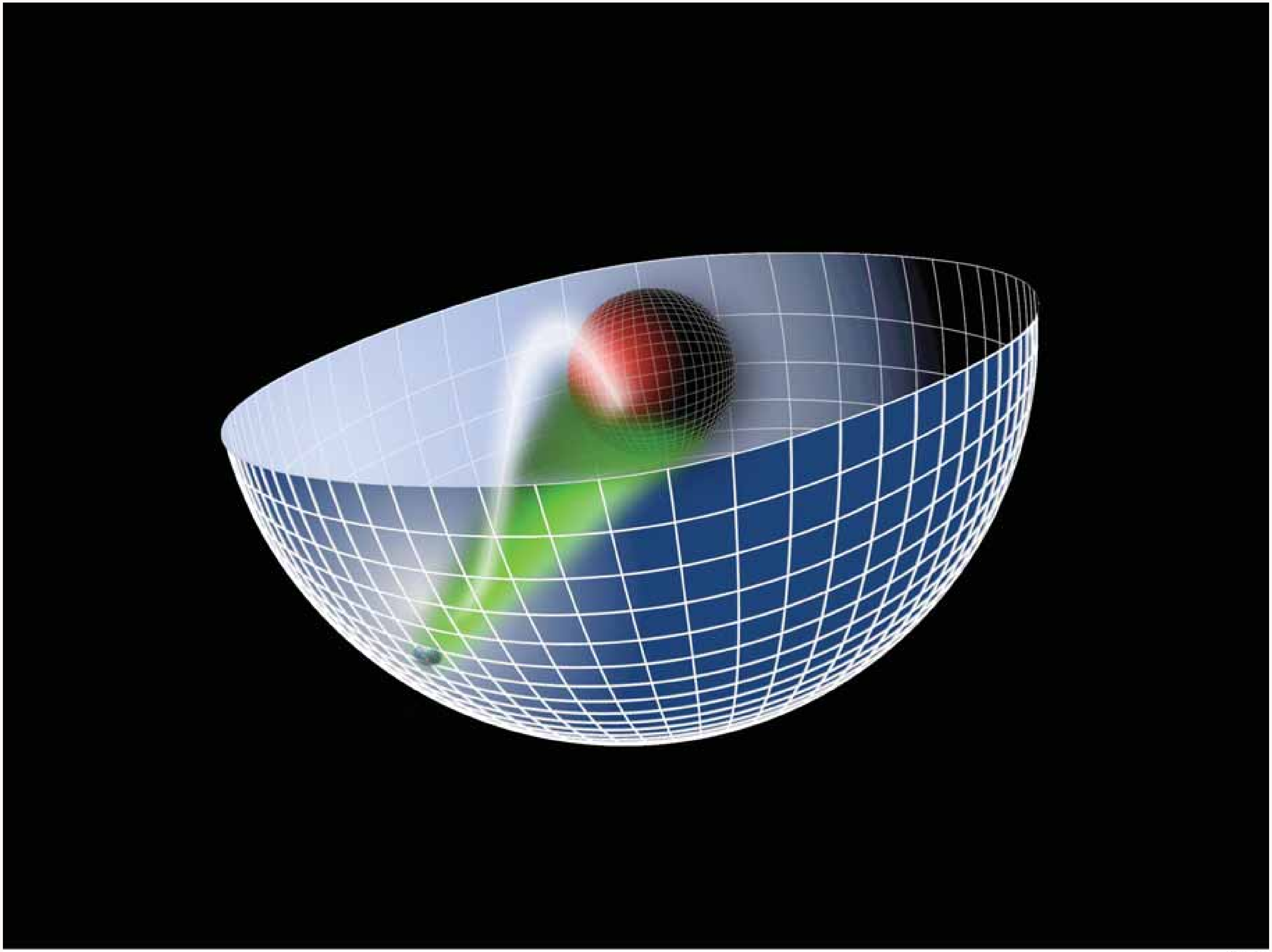
- AdS mode in z is the extension of the hadron wf into the fifth dimension.

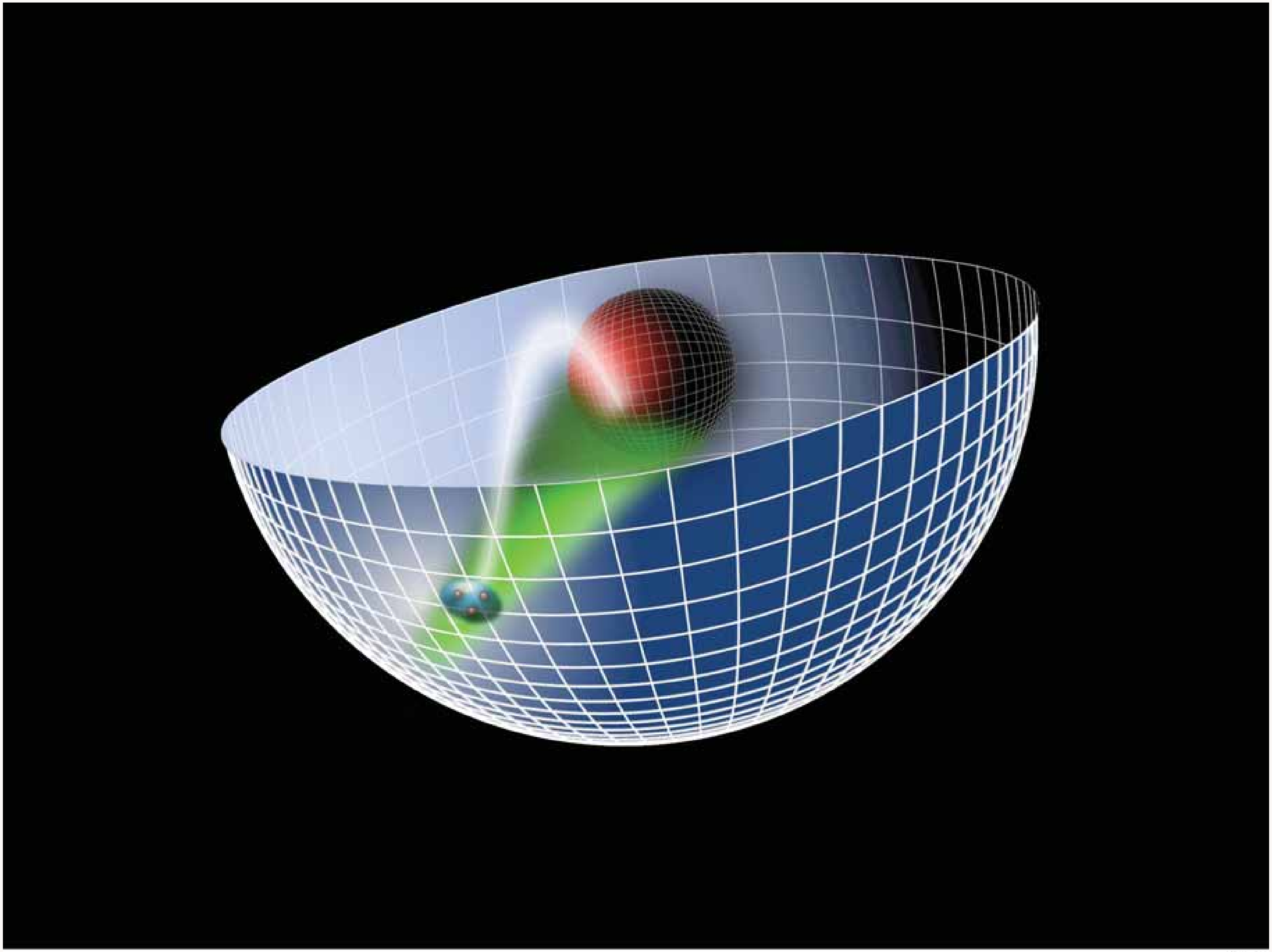
- Different values of z correspond to different scales at which the hadron is examined.

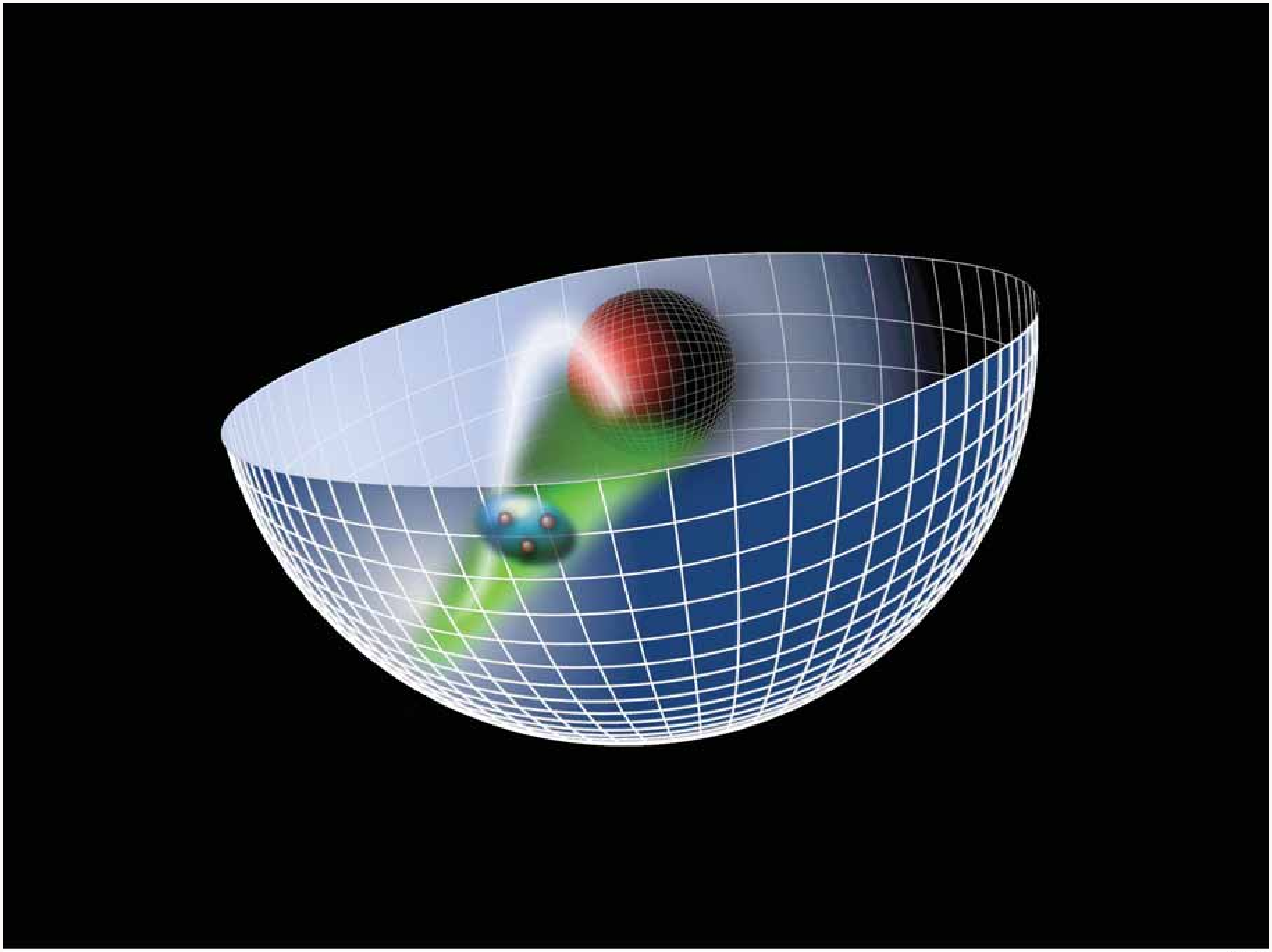
$$x^2 \to \lambda^2 x^2, \quad z \to \lambda z.$$

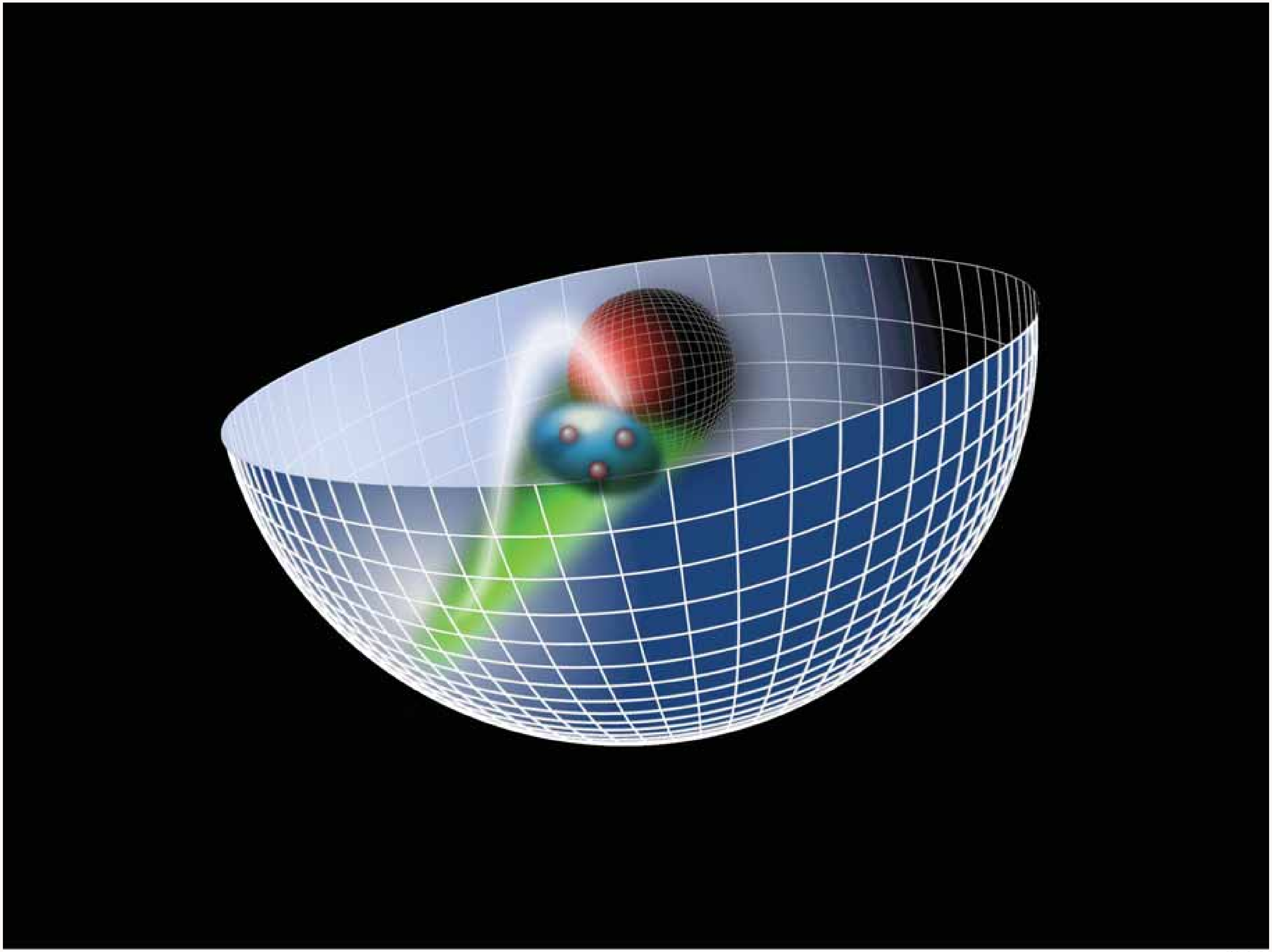
$x^2 = x_\mu x^\mu$: invariant separation between quarks

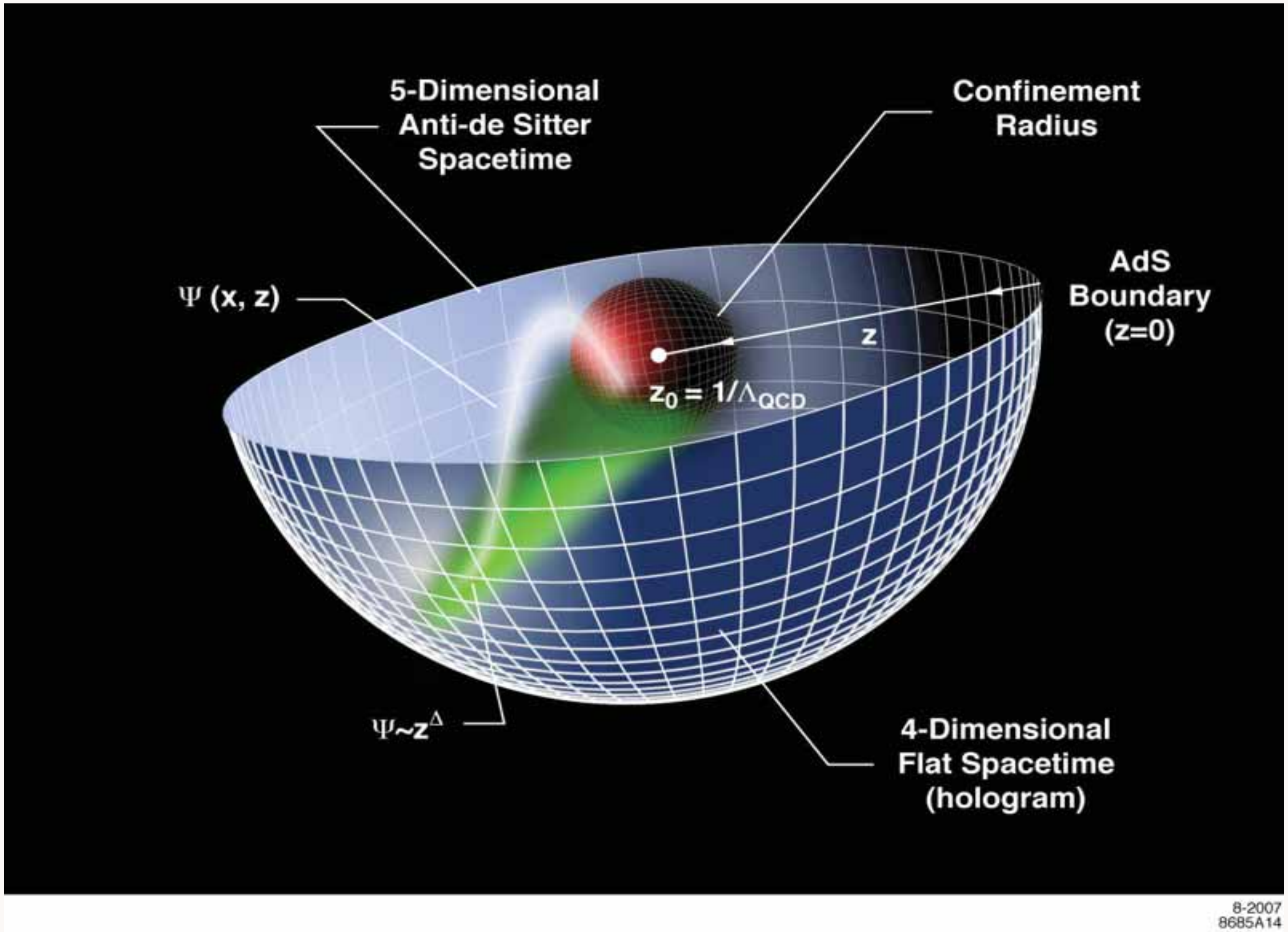
- The AdS boundary at $z \to 0$ correspond to the $Q \to \infty$, UV zero separation limit.









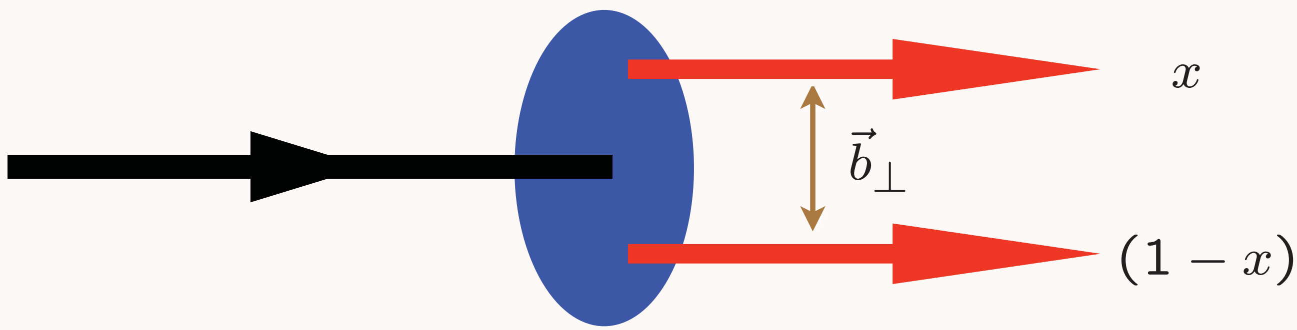


- Truncated AdS/CFT (Hard-Wall) model: cut-off at $z_0 = 1/\Lambda_{\rm QCD}$ breaks conformal invariance and allows the introduction of the QCD scale (Hard-Wall Model) Polchinski and Strassler (2001).
- Smooth cutoff: introduction of a background dilaton field $\varphi(z)$ – usual linear Regge dependence can be obtained (Soft-Wall Model) Karch, Katz, Son and Stephanov (2006).

LF(3+1) AdS$_5$

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

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



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

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

AdS/CFT: Anti-de Sitter Space / Conformal Field Theory

Maldacena:

Map AdS_5 X S_5 to conformal N=4 SUSY

- **QCD is not conformal**; however, it has manifestations of a scale-invariant theory: Bjorken scaling, dimensional counting for hard exclusive processes

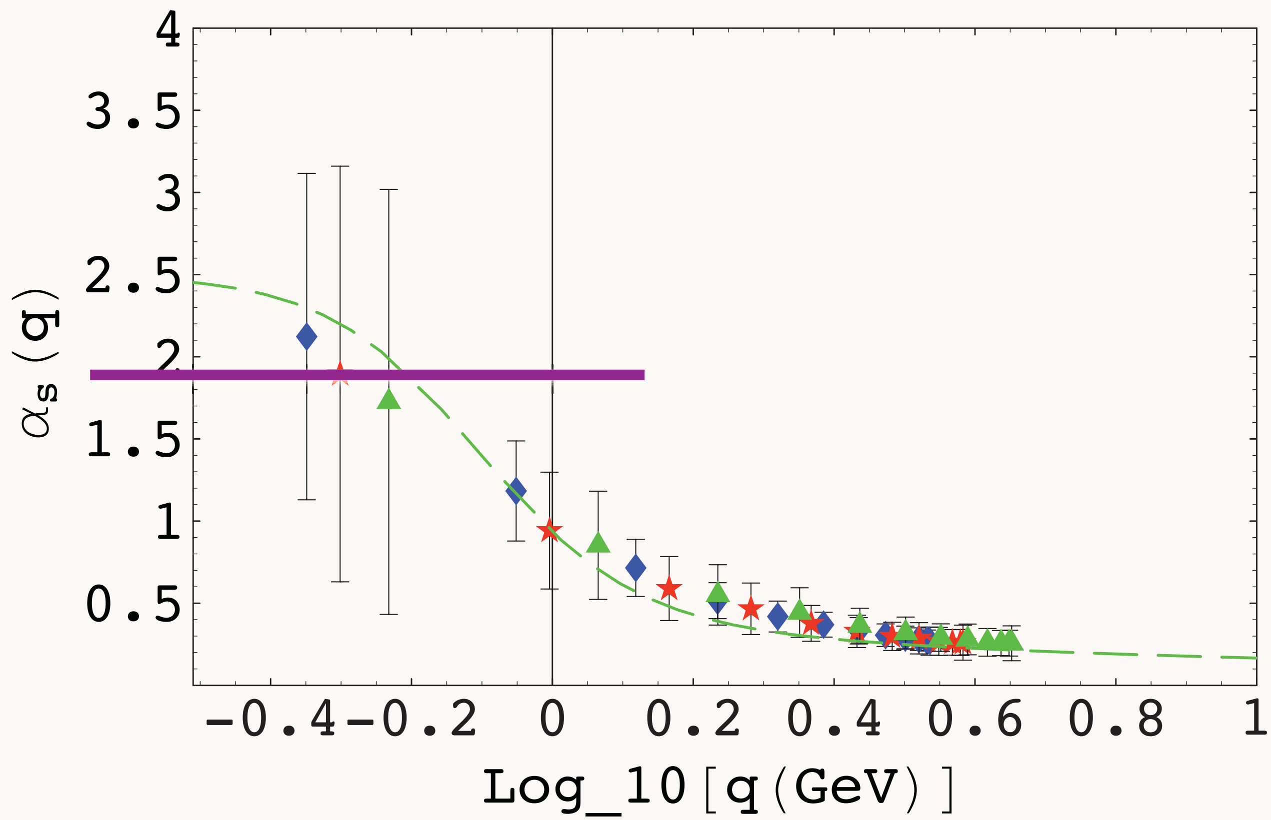
- **Conformal window:** $\alpha_s(Q^2) \simeq \text{const at small } Q^2$

- **Use mathematical mapping of the conformal group SO(4,2) to AdS5 space**

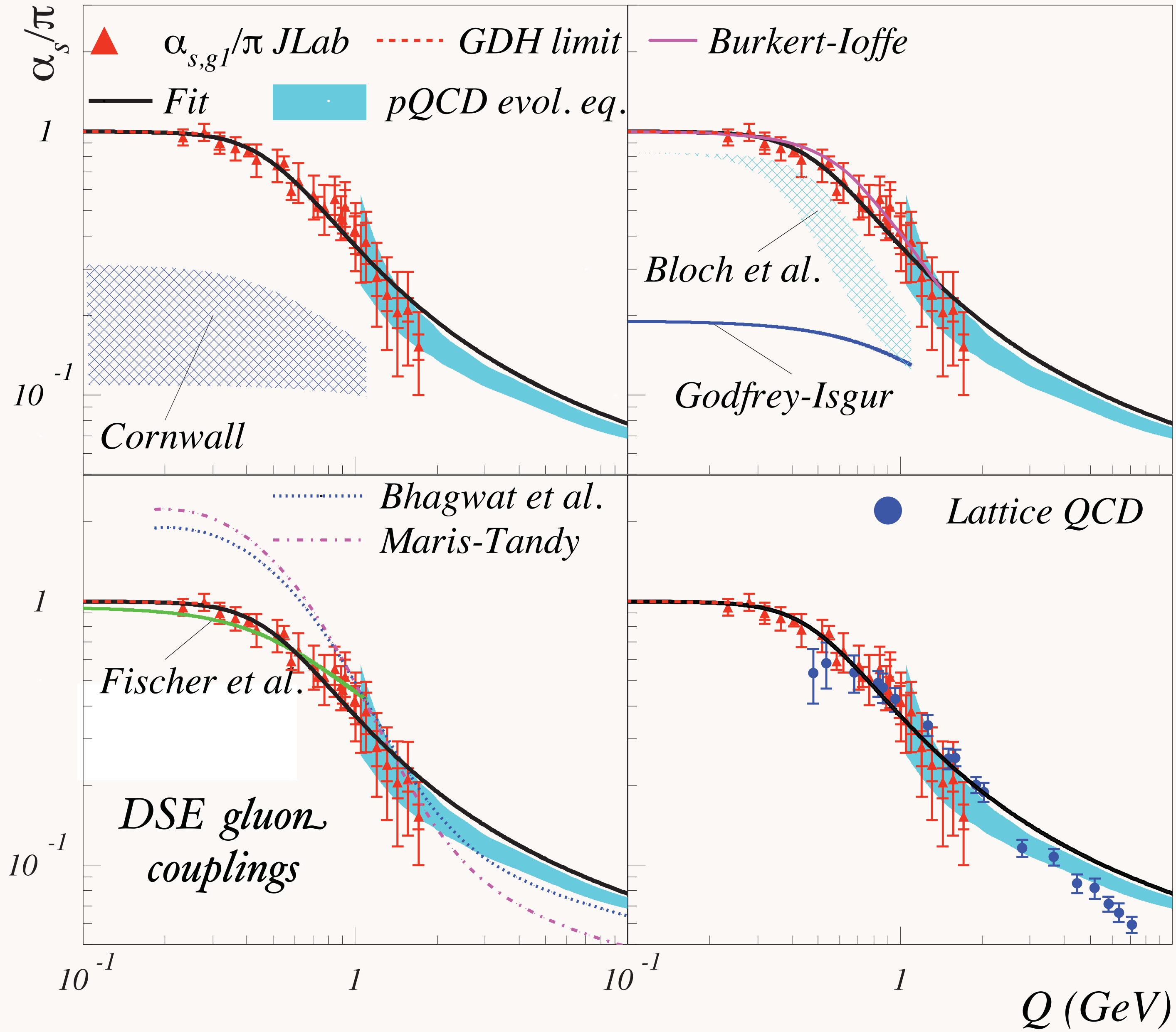
Conformal QCD Window in Exclusive Processes

- Does α_s develop an IR fixed point? Dyson–Schwinger Equation Alkofer, Fischer, LLanes-Estrada, Deur . . .

- Recent lattice simulations: evidence that α_s becomes constant and is not small in the infrared Furui and Nakajima, hep-lat/0612009 (Green dashed curve: DSE).



Deur, Korsch, et al.



Maximal Wavelength of Confined Fields

- **Colored fields confined to finite domain** $(x-y)^2 < \Lambda^{-2}_{QCD}$
- **All perturbative calculations regulated in IR**
- **High momentum calculations unaffected**
- **Bound-state Dyson-Schwinger Equation**
- **Analogous to Bethe's Lamb Shift Calculation**

Quark and Gluon vacuum polarization insertions decouple: IR fixed Point

Shrock, sjb

J. D. Bjorken,
SLAC-PUB 1053
Cargese Lectures 1989

A strictly-perturbative space-time region can be defined as one which has the property that any straight-line segment lying entirely within the region has an invariant length small compared to the confinement scale (whether or not the segment is spacelike or timelike).

IR Conformal Window for QCD

- *Dyson-Schwinger Analysis:* **QCD gluon coupling has IR Fixed Point**

- *Evidence from Lattice Gauge Theory*

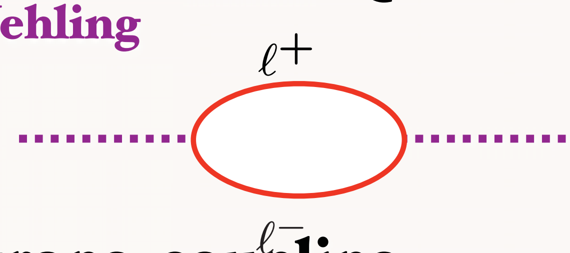
- *Stability of* $\Upsilon \to ggg$ Shrock, sjb

- Define coupling from observable: **indications of IR fixed point for QCD effective charges** Deur, Chen, Burkert, Korsch,

- Confined gluons and quarks have maximum wavelength: **Decoupling of QCD vacuum polarization at small Q^2**

Serber-Uehling

$$\Pi(Q^2) \to \frac{\alpha}{15\pi}\frac{Q^2}{m^2} \qquad Q^2 << 4m^2$$



- **Justifies application of AdS/CFT in strong-coupling conformal window**

AdS/CFT

- Use mapping of conformal group SO(4,2) to AdS5
- Scale Transformations represented by wavefunction in 5th dimension $x_\mu^2 \to \lambda^2 x_\mu^2$ $z \to \lambda z$
- Match solutions at small z to conformal twist dimension of hadron wavefunction at short distances $\psi(z) \sim z^\Delta$ at $z \to 0$
- Hard wall model: Confinement at large distances and conformal symmetry in interior
- Truncated space simulates "bag" boundary conditions

$$0 < z < z_0 \qquad \psi(z_0) = 0 \qquad z_0 = \frac{1}{\Lambda_{QCD}}$$

AdS Schrodinger Equation for bound state of two scalar constituents:

$$[-\frac{d^2}{dz^2} - \frac{1-4L^2}{4z^2}]\phi(z) = \mathcal{M}^2\phi(z)$$

L: light-front orbital angular momentum

Derived from variation of Action in AdS_5

Hard wall model: truncated space

$$\phi(z = z_0 = \frac{1}{\Lambda_c}) = 0.$$

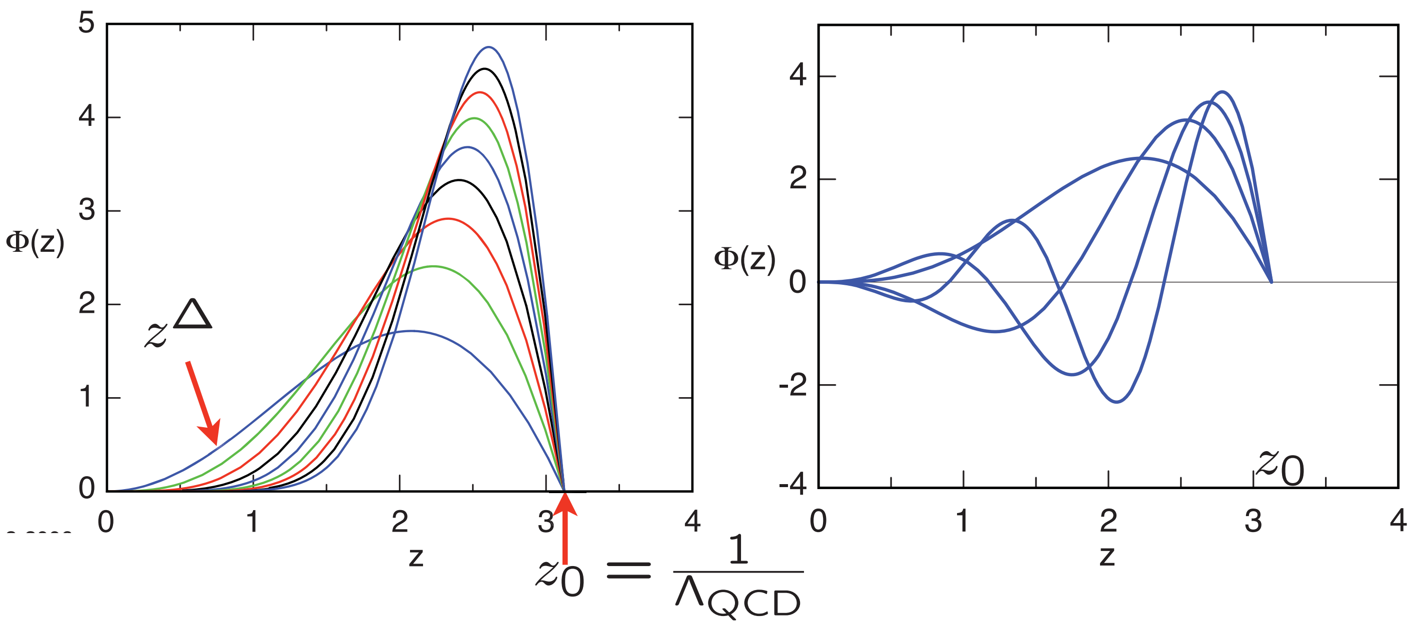
Match fall-off at small z to conformal twist-dimension at short distances

twist

- Pseudoscalar mesons: $\mathcal{O}_{2+L} = \overline{\psi}\gamma_5 D_{\{\ell_1} \dots D_{\ell_m\}}\psi$ ($\Phi_\mu = 0$ gauge). $\Delta = 2 + L$

- 4-d mass spectrum from boundary conditions on the normalizable string modes at $z = z_0$, $\Phi(x, z_o) = 0$, given by the zeros of Bessel functions $\beta_{\alpha,k}$: $\mathcal{M}_{\alpha,k} = \beta_{\alpha,k}\Lambda_{QCD}$

- Normalizable AdS modes $\Phi(z)$



$S = 0$ Meson orbital and radial AdS modes for $\Lambda_{QCD} = 0.32$ GeV.

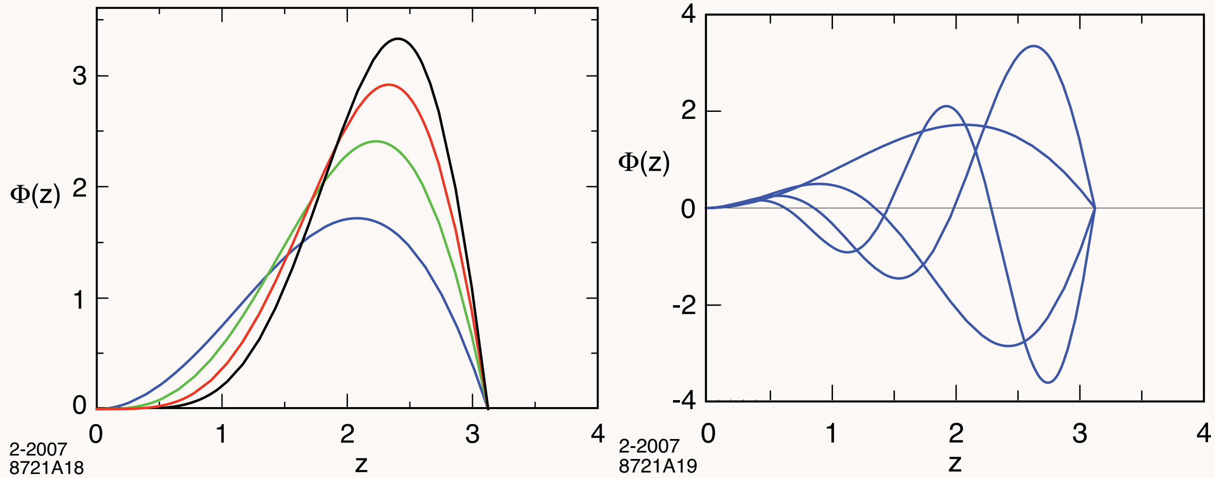


Fig: Orbital and radial AdS modes in the hard wall model for $\Lambda_{\rm QCD}$ = 0.32 GeV .

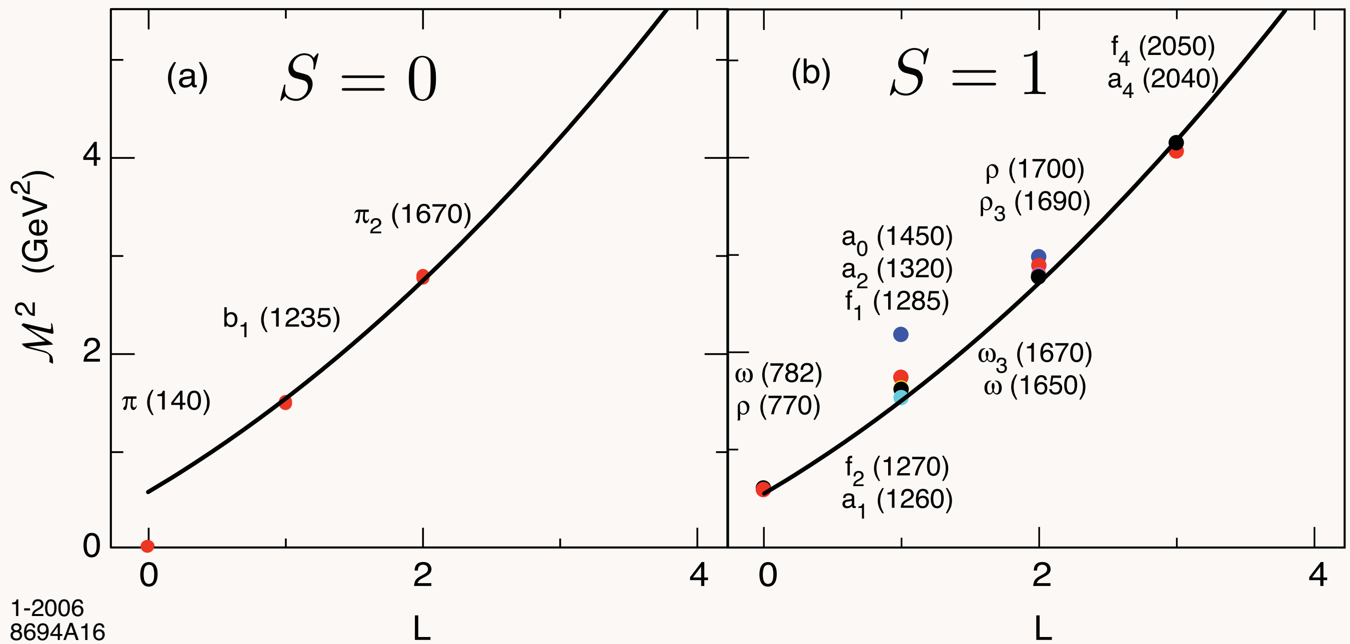


Fig: Light meson and vector meson orbital spectrum $\Lambda_{QCD} = 0.32$ GeV

Soft-Wall Model

- Soft-wall model [Karch, Katz, Son and Stephanov (2006)] retain conformal AdS metrics but introduce smooth cutoff wich depends on the profile of a dilaton background field $\varphi(z) = \pm\kappa^2 z^2$

$$S = \int d^d x \, dz \, \sqrt{g} \, e^{\varphi(z)} \mathcal{L},$$

- Equation of motion for scalar field $\mathcal{L} = \frac{1}{2}\left(g^{\ell m}\partial_\ell \Phi \partial_m \Phi - \mu^2 \Phi^2\right)$

$$\left[z^2 \partial_z^2 - \left(d - 1 \mp 2\kappa^2 z^2\right) z \, \partial_z + z^2 \mathcal{M}^2 - (\mu R)^2\right] \Phi(z) = 0$$

with $(\mu R)^2 \geq -4$. See also [Metsaev (2002), Andreev (2006)] **+ sign: Fen Zuo(2009**

- LH holography requires 'plus dilaton' $\varphi = +\kappa^2 z^2$. Lowest possible state $(\mu R)^2 = -4$

$$\mathcal{M}^2 = 4\kappa^2 n, \quad \Phi_n(z) \sim z^2 e^{-\kappa^2 z^2} L_n(\kappa^2 z^2)$$

$\Phi_0(z)$ a chiral symmetric bound state of two massless quarks with scaling dimension 2: the pion

Massless pion