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

$x^\mu \rightarrow \lambda x^\mu, \; z \rightarrow \lambda z$, 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.

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

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

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

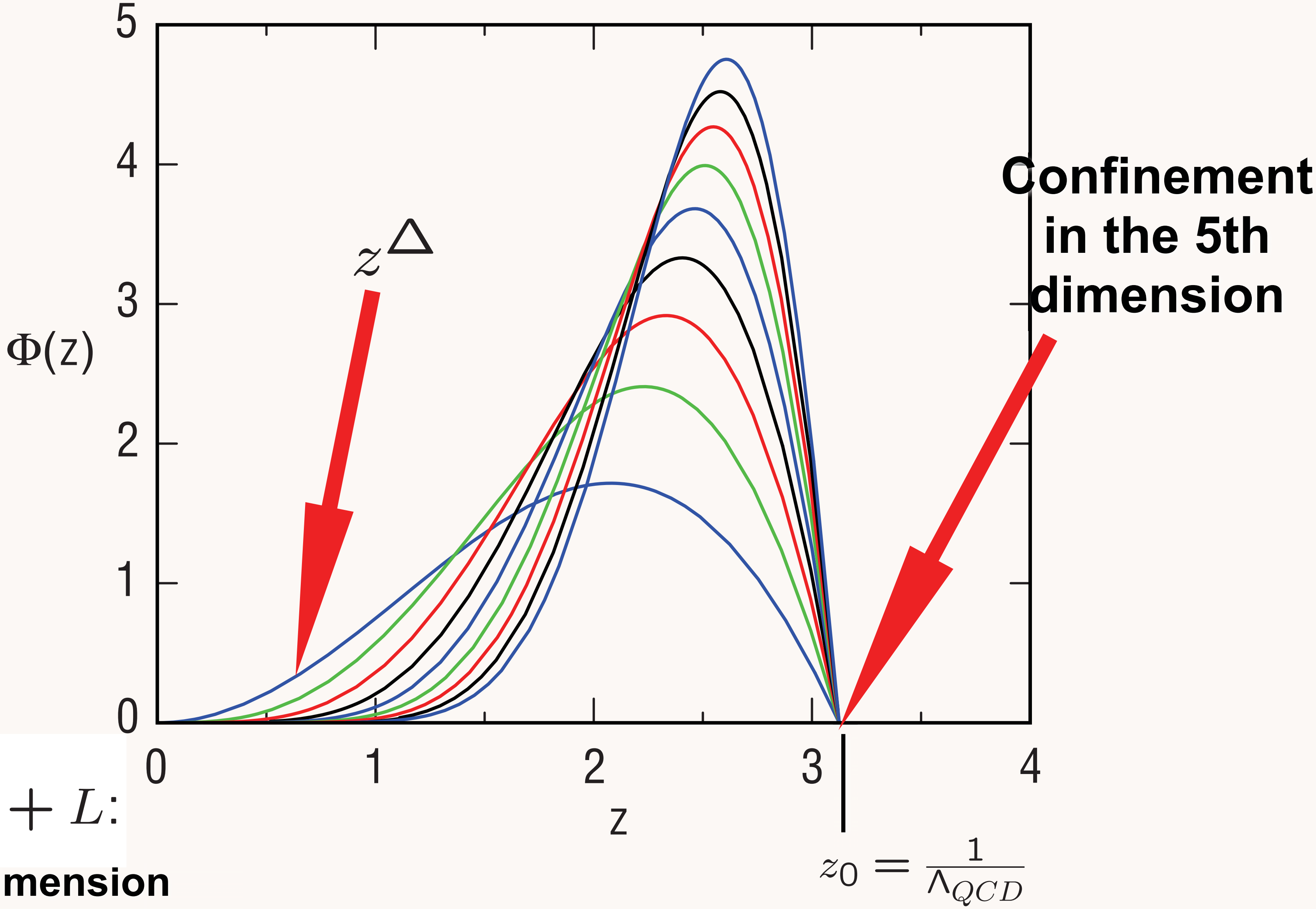
Guy de Teramond
SJB

AdS/CFT

- Use mapping of conformal group SO(4,2) to AdS5
- Scale Transformations represented by wavefunction $\psi(z)$ in 5th dimension $x_\mu^2 \to \lambda^2 x_\mu^2$ $z \to \lambda z$
- Holographic model: Confinement at large distances and conformal symmetry in interior $0 < z < z_0$
- Match solutions at small z to conformal dimension of hadron wavefunction at short distances $\psi(z) \sim z^\Delta$ at $z \to 0$
- Truncated space simulates "bag" boundary conditions

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

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



$\Delta = 3 + L$:

Twist dimension of baryon

de Teramond, sjb

$$\Phi(z) = z^{3/2}\phi(z)$$

AdS Schrodinger Equation for bound state of two scalar constituents

$$[-\frac{d^2}{dz^2} + V(z)]\phi(z) = M^2\phi(z)$$

Truncated space

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

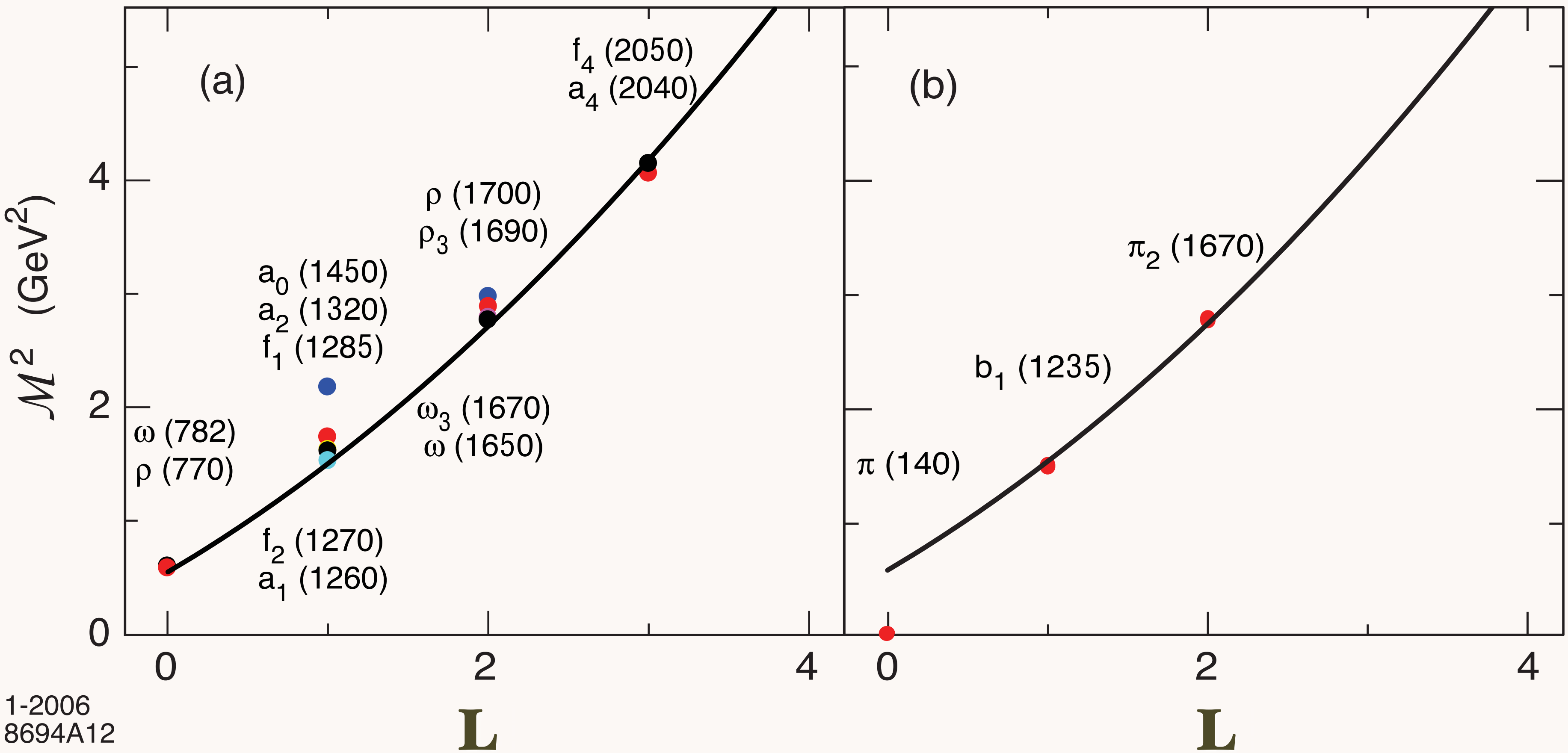
$$\phi(z = z_0 = \frac{1}{\Lambda_c}) = 0.$$

Alternative: Harmonic oscillator confinement

$$V(z) = -\frac{1-4L^2}{4z^2} + \kappa^4 z^2$$

Karch, et al.

Derived from variation of Action in AdS_5



Light meson orbital spectrum $\Lambda_{QCD} = 0.32 \text{ GeV}$

Guy de Teramond
SJB

Baryon Spectrum

- Baryon: twist-three, dimension $\frac{9}{2} + L$

$$\mathcal{O}_{\frac{9}{2}+L} = \psi D_{\{\ell_1} \dots D_{\ell_q} \psi D_{\ell_{q+1}} \dots D_{\ell_m\}} \psi, \qquad L = \sum_{i=1}^{m} \ell_i.$$

Wave Equation: $$\boxed{\left[z^2\, \partial_z^2 - 3z\, \partial_z + z^2 \mathcal{M}^2 - \mathcal{L}_\pm^2 + 4\right] f_\pm(z) = 0}$$

with $\mathcal{L}_+ = L + 1$, $\mathcal{L}_- = L + 2$, and solution

$$\Psi(x, z) = C e^{-iP\cdot x} z^2 \Big[J_{1+L}(z\mathcal{M})\, u_+(P) + J_{2+L}(z\mathcal{M})\, u_-(P) \Big]$$

- 4-d mass spectrum $\Psi(x, z_o)^\pm = 0 \quad \Longrightarrow$ parallel Regge trajectories for baryons !

$$\mathcal{M}^+_{\alpha,k} = \beta_{\alpha,k} \Lambda_{QCD}, \qquad \mathcal{M}^-_{\alpha,k} = \beta_{\alpha+1,k} \Lambda_{QCD}.$$

- Ratio of eigenvalues determined by the ratio of zeros of Bessel functions !

Prediction from AdS/QCD

Only one parameter!

Entire light quark baryon spectrum

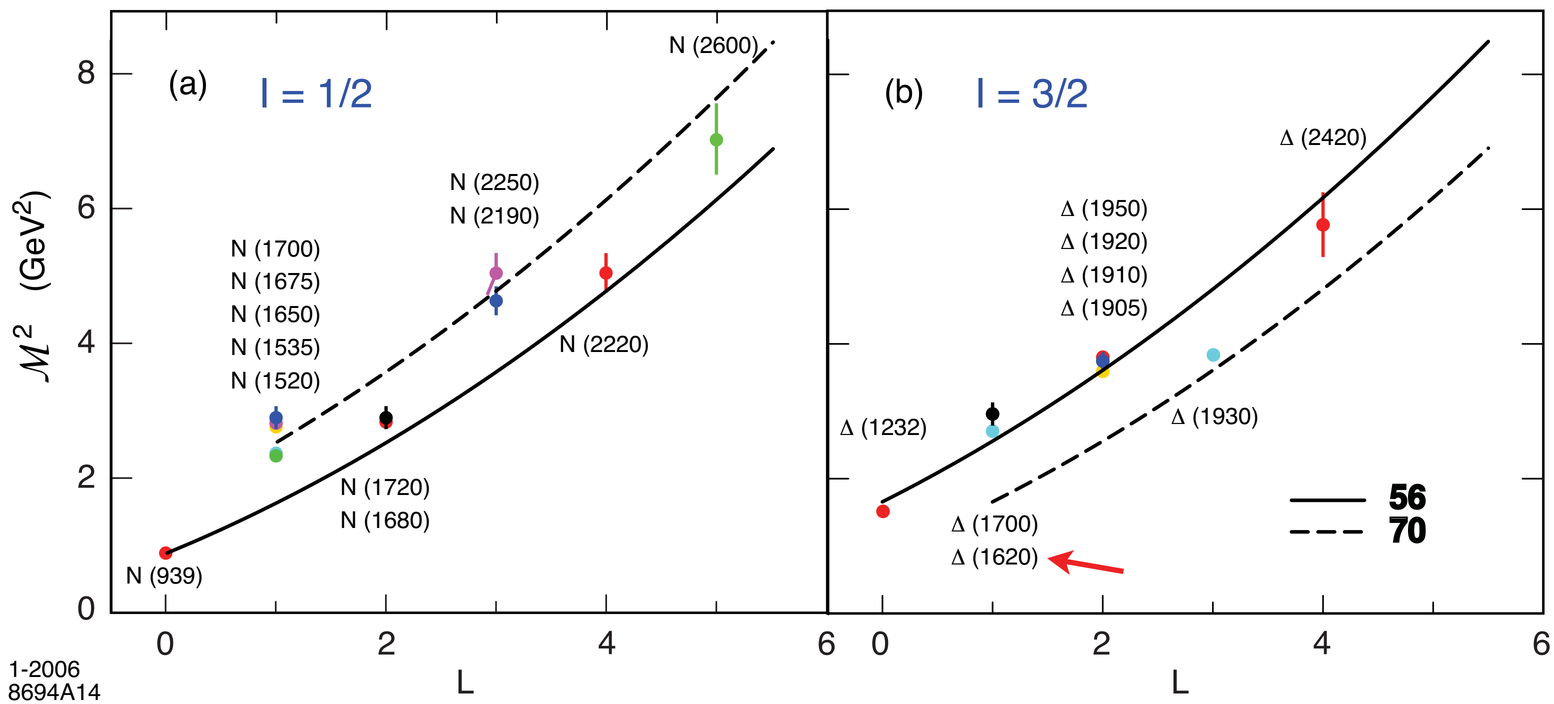


Fig: Predictions for the light baryon orbital spectrum for Λ_{QCD} = 0.25 GeV. The $\mathbf{56}$ trajectory corresponds to L even $P = +$ states, and the $\mathbf{70}$ to L odd $P = -$ states.

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

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

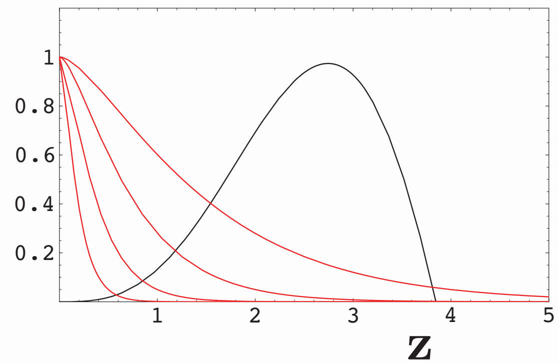
Hadron Form Factors from AdS/CFT

- Propagation of external perturbation suppressed inside AdS. $J(Q,z) = zQK_1(zQ)$
- At large Q^2 the important integration region is $z \sim 1/Q$.

$$F(Q^2)_{I \to F} = \int \frac{dz}{z^3} \Phi_F(z) J(Q,z) \Phi_I(z)$$

$\mathbf{J}(\mathbf{Q}, \mathbf{z}), \quad \mathbf{\Phi}(\mathbf{z})$

High Q^2
from
small z ~ 1/Q



Polchinski, Strassler
de Teramond, sjb

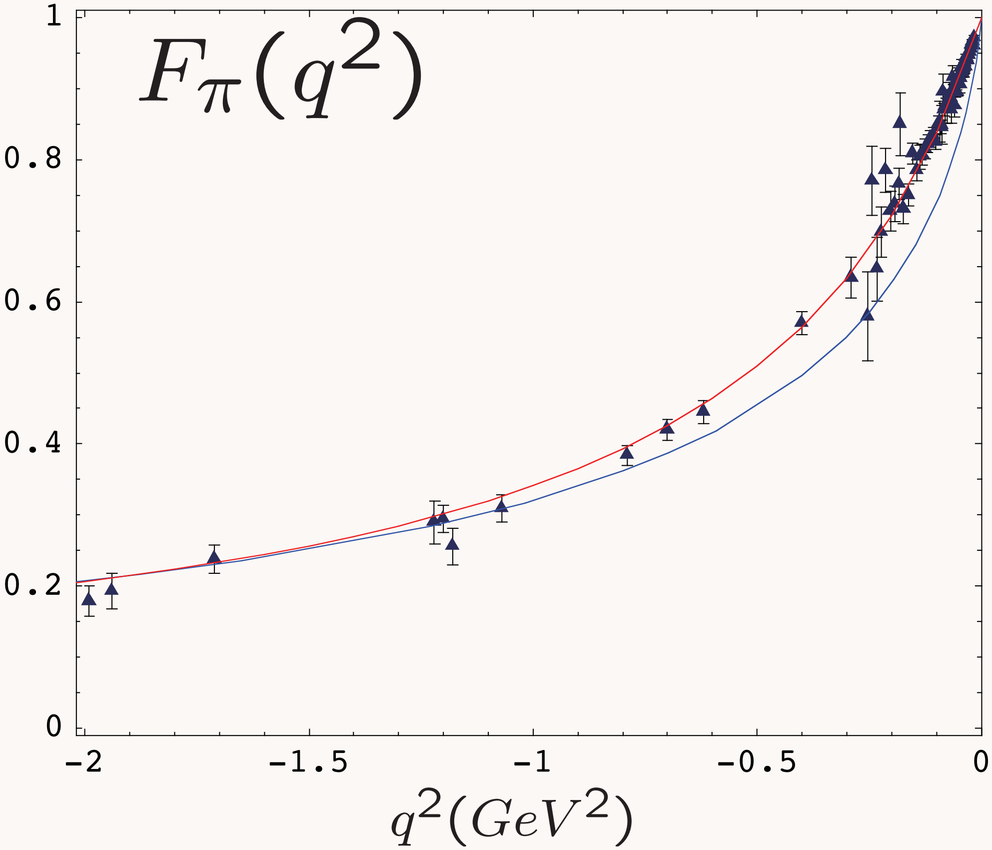
- Consider a specific AdS mode $\Phi^{(n)}$ dual to an n partonic Fock state $|n\rangle$. At small z, $\Phi^{(n)}$ scales as $\Phi^{(n)} \sim z^{\Delta_n}$. Thus:

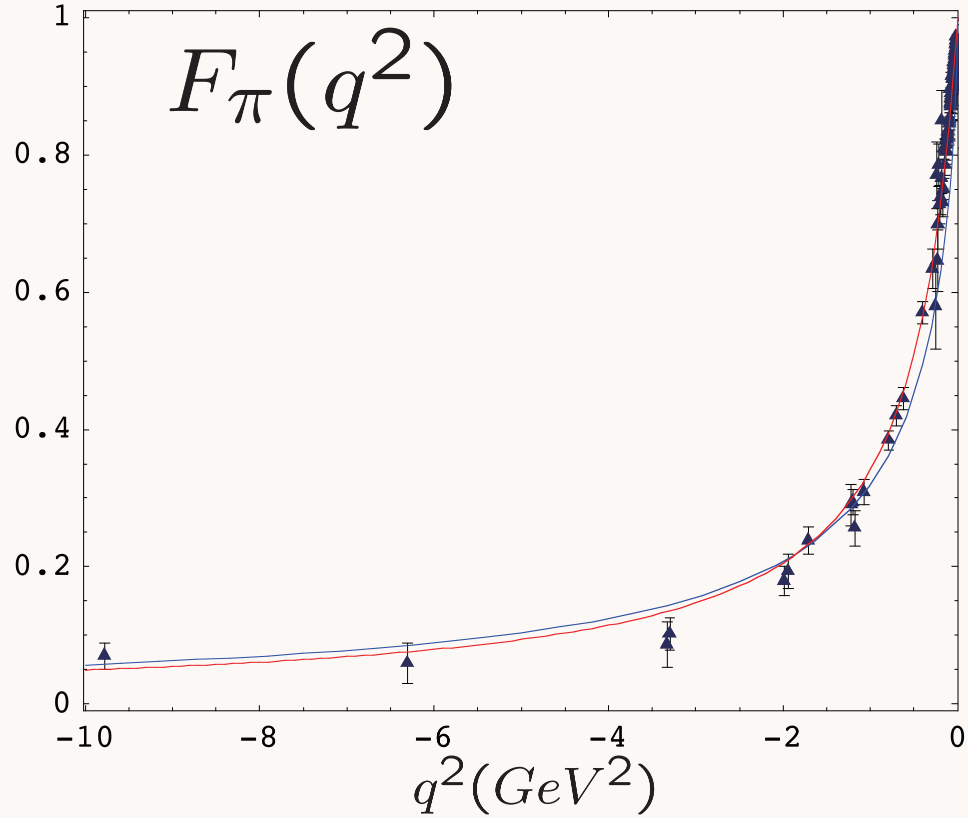
$$F(Q^2) \to \left[\frac{1}{Q^2}\right]^{\tau - 1},$$

Dimensional Quark Counting Rules: General result from AdS/CFT

where $\tau = \Delta_n - \sigma_n$, $\sigma_n = \sum_{i=1}^{n} \sigma_i$. The twist is equal to the number of partons, $\tau = n$.

Spacelike pion form factor from AdS/CFT





Data Compilation from Baldini, Kloe and Volmer

Harmonic Oscillator Confinement

Truncated Space Confinement

One parameter - set by pion decay constant

de Teramond, sjb
See also: Radyushkin

Nucleon Form Factors

- Consider the spin non-flip form factors in the infinite wall approximation

$$F_+(Q^2) = g_+ R^3 \int \frac{dz}{z^3} \, J(Q,z) \, |\psi_+(z)|^2,$$
$$F_-(Q^2) = g_- R^3 \int \frac{dz}{z^3} \, J(Q,z) \, |\psi_-(z)|^2,$$

where the effective charges g_+ and g_- are determined from the spin-flavor structure of the theory.

- Choose the struck quark to have $S^z = +1/2$. The two AdS solutions $\psi_+(z)$ and $\psi_-(z)$ correspond to nucleons with $J^z = +1/2$ and $-1/2$.

- For $SU(6)$ spin-flavor symmetry

$$F_1^p(Q^2) = R^3 \int \frac{dz}{z^3} \, J(Q,z) |\psi_+(z)|^2,$$
$$F_1^n(Q^2) = -\frac{1}{3} R^3 \int \frac{dz}{z^3} \, J(Q,z) \left[|\psi_+(z)|^2 - |\psi_-(z)|^2 \right],$$

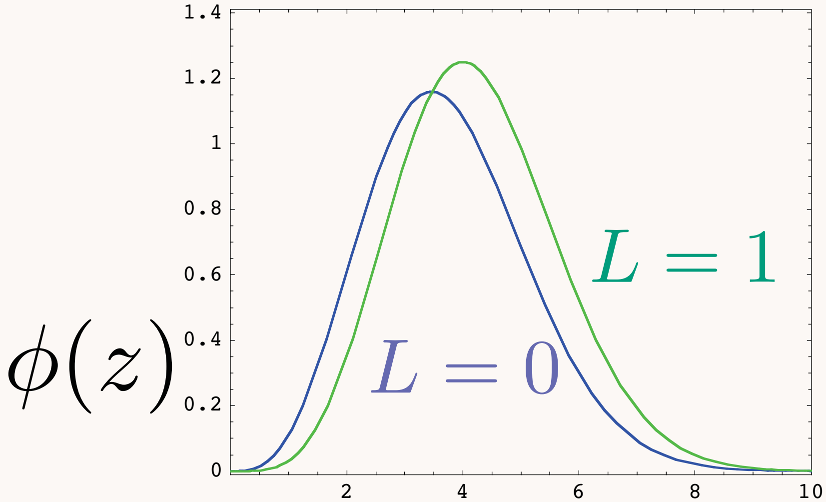
where $F_1^p(0) = 1, \; F_1^n(0) = 0$.

- Large Q power scaling: $F_1(Q^2) \to \left[1/Q^2\right]^2$.

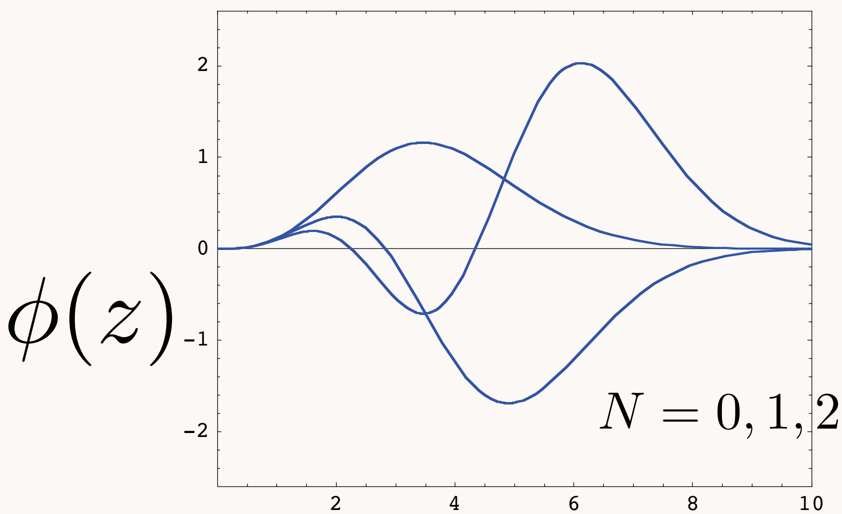
G. de Teramond, sjb

AdS/QCD

Guy de Teramond
SJB



Proton Wavefunctions needed for Dirac and Pauli Form Factors

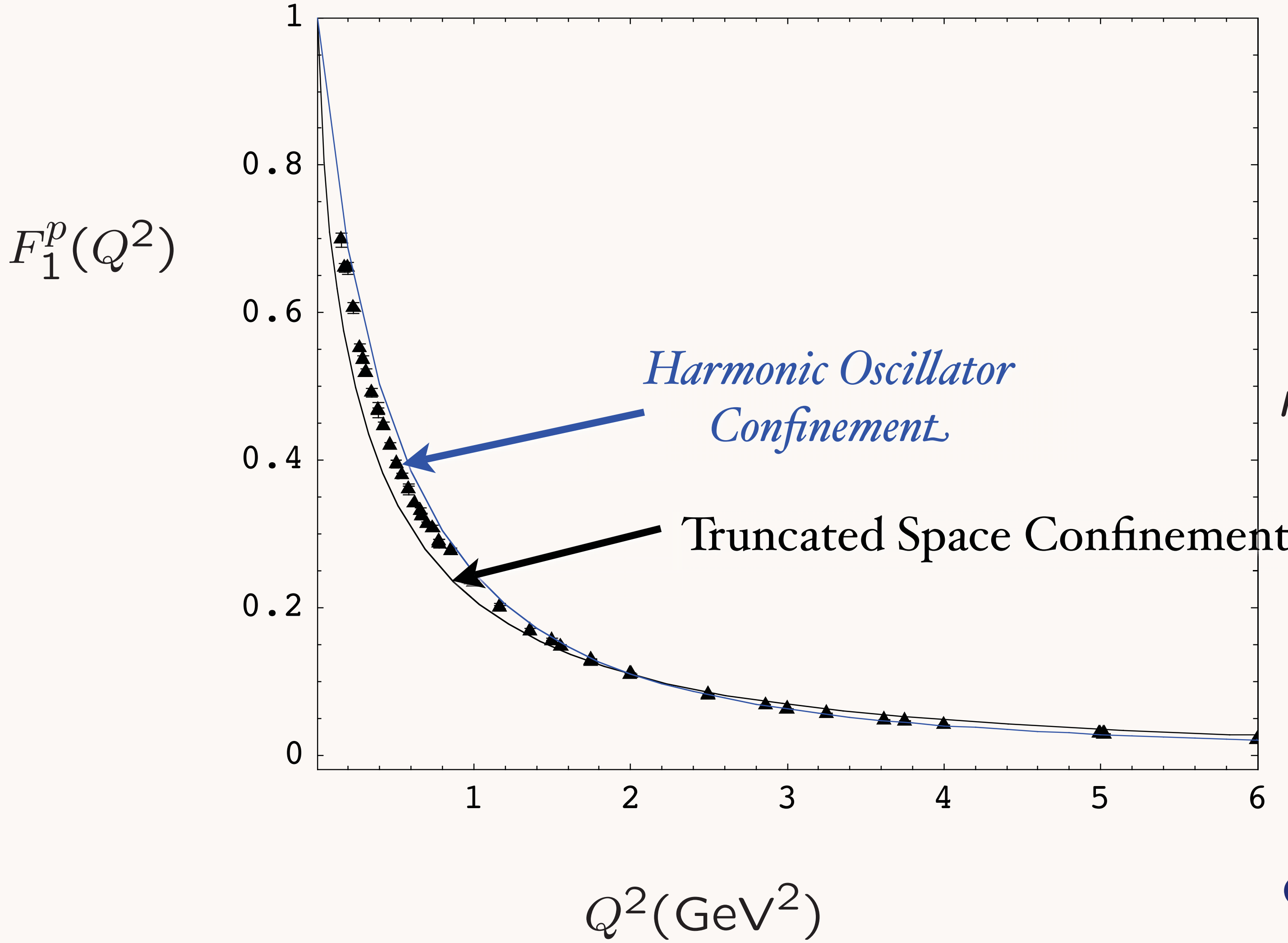


Harmonic Oscillator "Soft Wall" Model

$$\Phi(\zeta) = \kappa^{2+L}\sqrt{\frac{2n!}{(n+L+1)!}}\, z^{3+L} e^{-\kappa^2\zeta^2/2} L_n^{L+1}(\kappa^2\zeta^2)$$

G. de Teramond, sjb

Preliminary



$\kappa = 0.424$ GeV

$\Lambda = 0.2$ GeV

Current modified by metric

$$F_1(Q^2)_{I\to F} = \int \frac{dz}{z^3}\Phi^{\uparrow}_F(z)J(Q,z)\Phi^{\uparrow}_I(z)$$

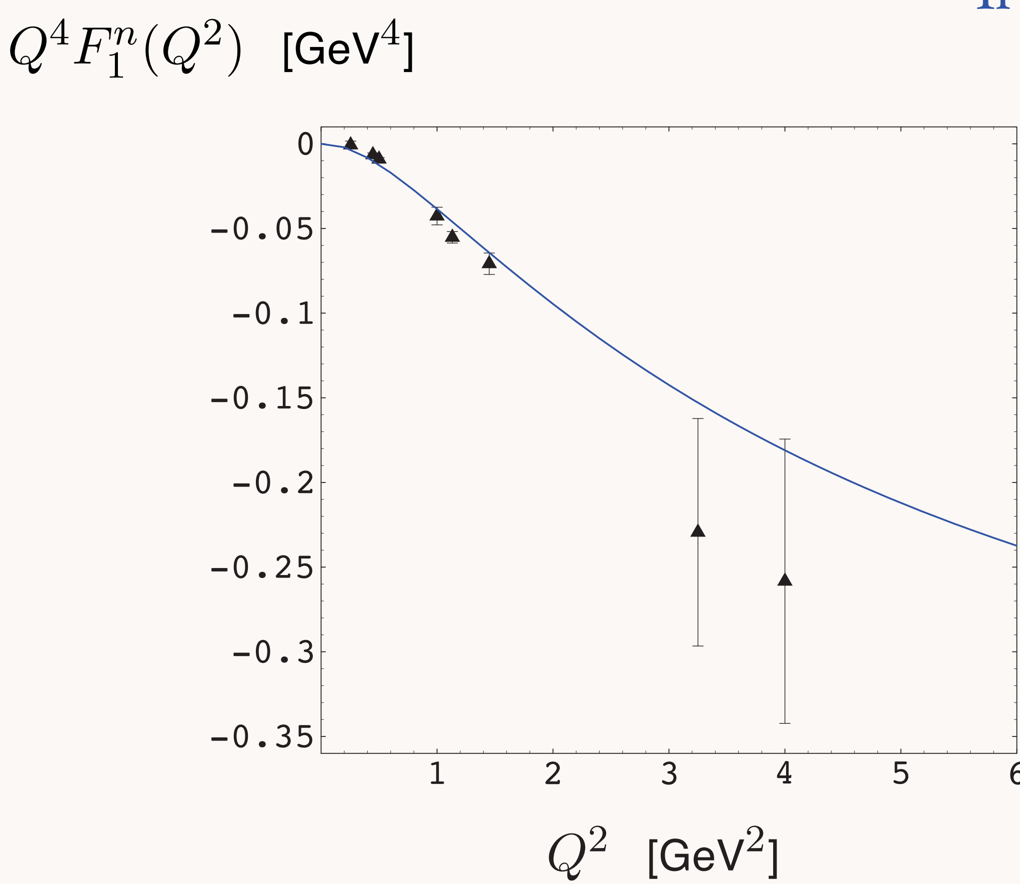
G. de Teramond, sjb

Preliminary

Dirac Neutron Form Factor

(Valence Approximation)

Truncated Space Confinement

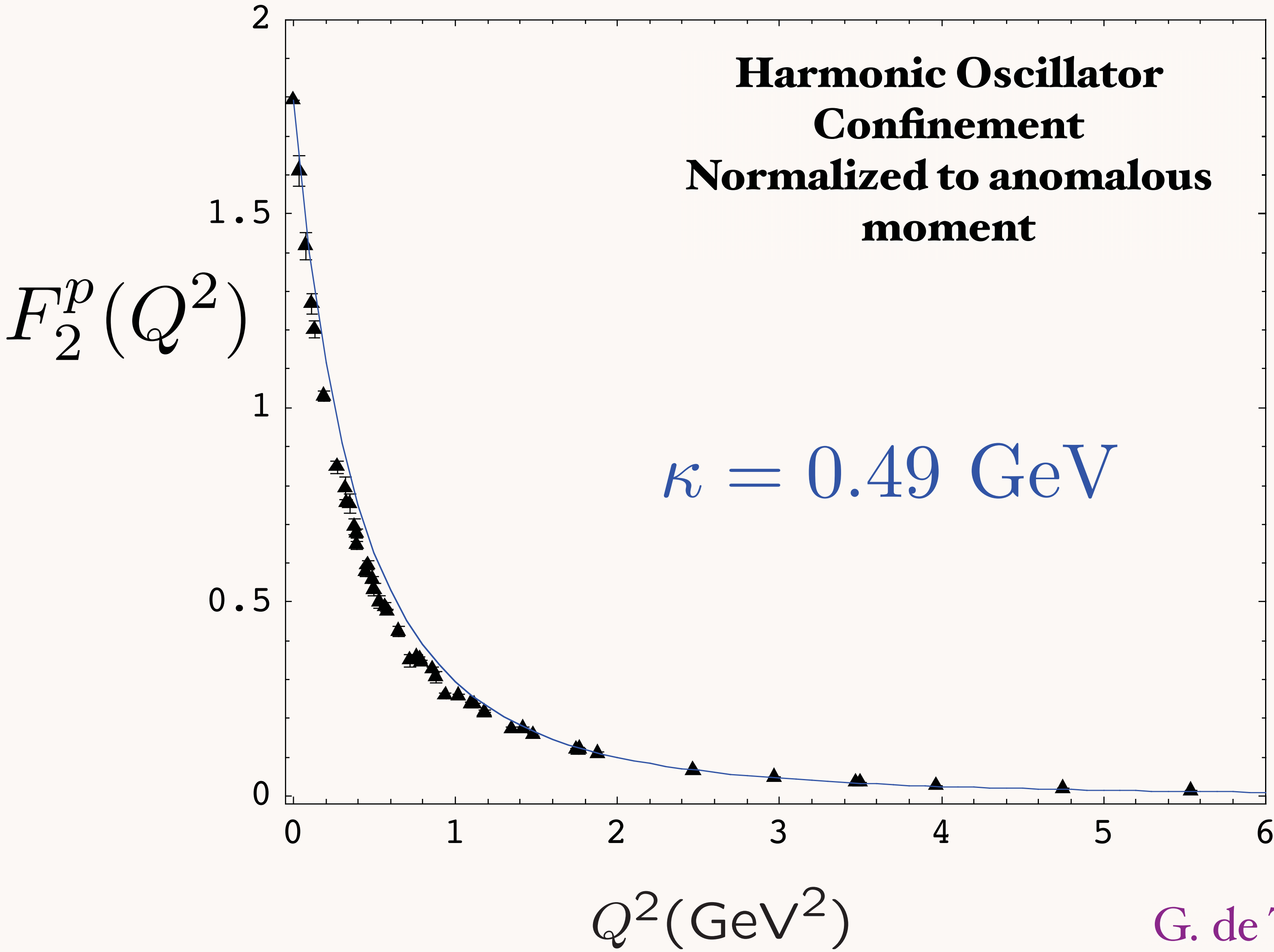


Prediction for $Q^4 F_1^n(Q^2)$ for $\Lambda_{QCD} = 0.21$ GeV in the hard wall approximation. Data analysis from Diehl (2005).

Spacelike Pauli Form Factor

Preliminary

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



G. de Teramond, sjb

Hadronic Form Factor in Space and Time-Like Regions

- The form factor in AdS/QCD is the overlap of the normalizable modes dual to the incoming and outgoing hadron Φ_I and Φ_F and the non-normalizable mode J, dual to the external source (hadron spin σ):

$$F(Q^2)_{I\to F} = R^{3+2\sigma}\int_0^\infty \frac{dz}{z^{3+2\sigma}}\, e^{(3+2\sigma)A(z)}\Phi_F(z)\, J(Q,z)\, \Phi_I(z)$$
$$\simeq R^{3+2\sigma}\int_0^{z_o} \frac{dz}{z^{3+2\sigma}}\, \Phi_F(z)\, J(Q,z)\, \Phi_I(z),$$

- $J(Q,z)$ has the limiting value 1 at zero momentum transfer, $F(0)=1$, and has as boundary limit the external current, $A^\mu = \epsilon^\mu e^{iQ\cdot x} J(Q,z)$. Thus:

$$\lim_{Q\to 0} J(Q,z) = \lim_{z\to 0} J(Q,z) = 1.$$

- Solution to the AdS Wave equation with boundary conditions at $Q=0$ and $z\to 0$:

$$J(Q,z) = zQK_1(zQ).$$

Polchinski and Strassler, hep-th/0209211; Hong, Yong and Strassler, hep-th/0409118.

Light-Front Representation of Two-Body Meson Form Factor

- Drell-Yan-West form factor

$$F(q^2) = \sum_q e_q \int_0^1 dx \int \frac{d^2\vec{k}_\perp}{16\pi^3} \, \psi^*_{P'}(x, \vec{k}_\perp - x\vec{q}_\perp) \, \psi_P(x, \vec{k}_\perp).$$

- Fourrier transform to impact parameter space $\vec{b}_\perp$

$$\psi(x, \vec{k}_\perp) = \sqrt{4\pi} \int d^2\vec{b}_\perp \, e^{i\vec{b}_\perp \cdot \vec{k}_\perp} \widetilde{\psi}(x, \vec{b}_\perp)$$

- Find ($b = |\vec{b}_\perp|$) :

$$F(q^2) = \int_0^1 dx \int d^2\vec{b}_\perp \, e^{ix\vec{b}_\perp \cdot \vec{q}_\perp} \left|\widetilde{\psi}(x, b)\right|^2$$

$$= 2\pi \int_0^1 dx \int_0^\infty b \, db \, J_0(bqx) \, \left|\widetilde{\psi}(x, b)\right|^2,$$

Soper

Identical DYW and AdS5 Formulae: Two-parton case

- Change the integration variable $\zeta = |\vec{b}_\perp|\sqrt{x(1-x)}$

$$F(Q^2) = 2\pi \int_0^1 \frac{dx}{x(1-x)} \int_0^{\zeta_{max}=\Lambda^{-1}_{\rm QCD}} \zeta\, d\zeta\, J_0\left(\frac{\zeta Q x}{\sqrt{x(1-x)}}\right) \left|\widetilde{\psi}(x,\zeta)\right|^2,$$

- Compare with AdS form factor for arbitrary Q. Find:

Same result for LF and AdS5

$$J(Q,\zeta) = \int_0^1 dx J_0\left(\frac{\zeta Q x}{\sqrt{x(1-x)}}\right) = \zeta Q K_1(\zeta Q),$$

$\zeta \leftrightarrow \mathbf{z}$

the solution for the electromagnetic potential in AdS space, and

$$\widetilde{\psi}(x,\vec{b}_\perp) = \frac{\Lambda_{\rm QCD}}{\sqrt{\pi} J_1(\beta_{0,1})} \sqrt{x(1-x)} J_0\left(\sqrt{x(1-x)}|\vec{b}_\perp|\beta_{0,1}\Lambda_{QCD}\right) \theta\left(\vec{b}_\perp^{\,2} \le \frac{\Lambda^{-2}_{\rm QCD}}{x(1-x)}\right)$$

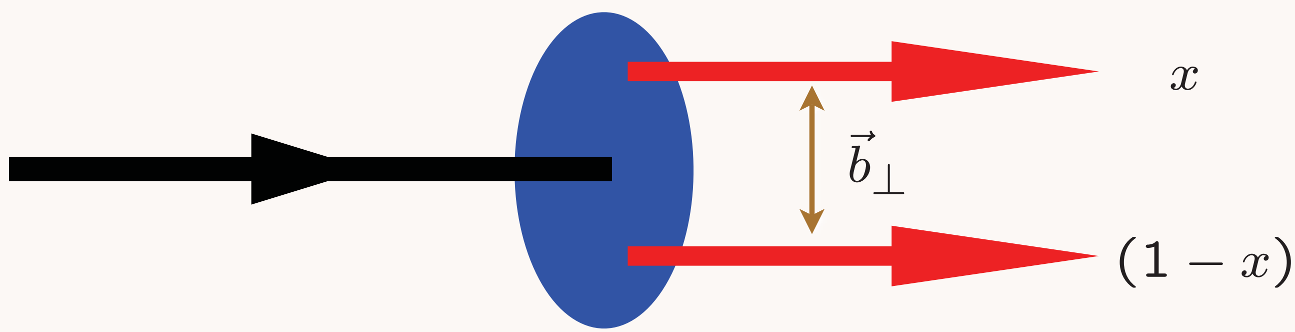
the holographic LFWF for the valence Fock state of the pion $\psi_{\overline{q}q/\pi}$.

- The variable ζ, $0 \le \zeta \le \Lambda^{-1}_{QCD}$, represents the scale of the invariant separation between quarks and is also the holographic coordinate $\zeta = z$!

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

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

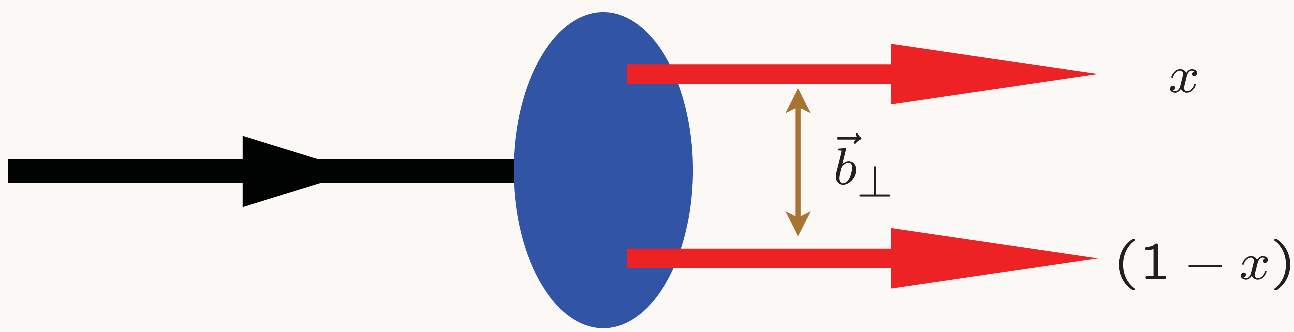
Relativistic LF radial equation

Frame Independent

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

G. de Teramond, sjb

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



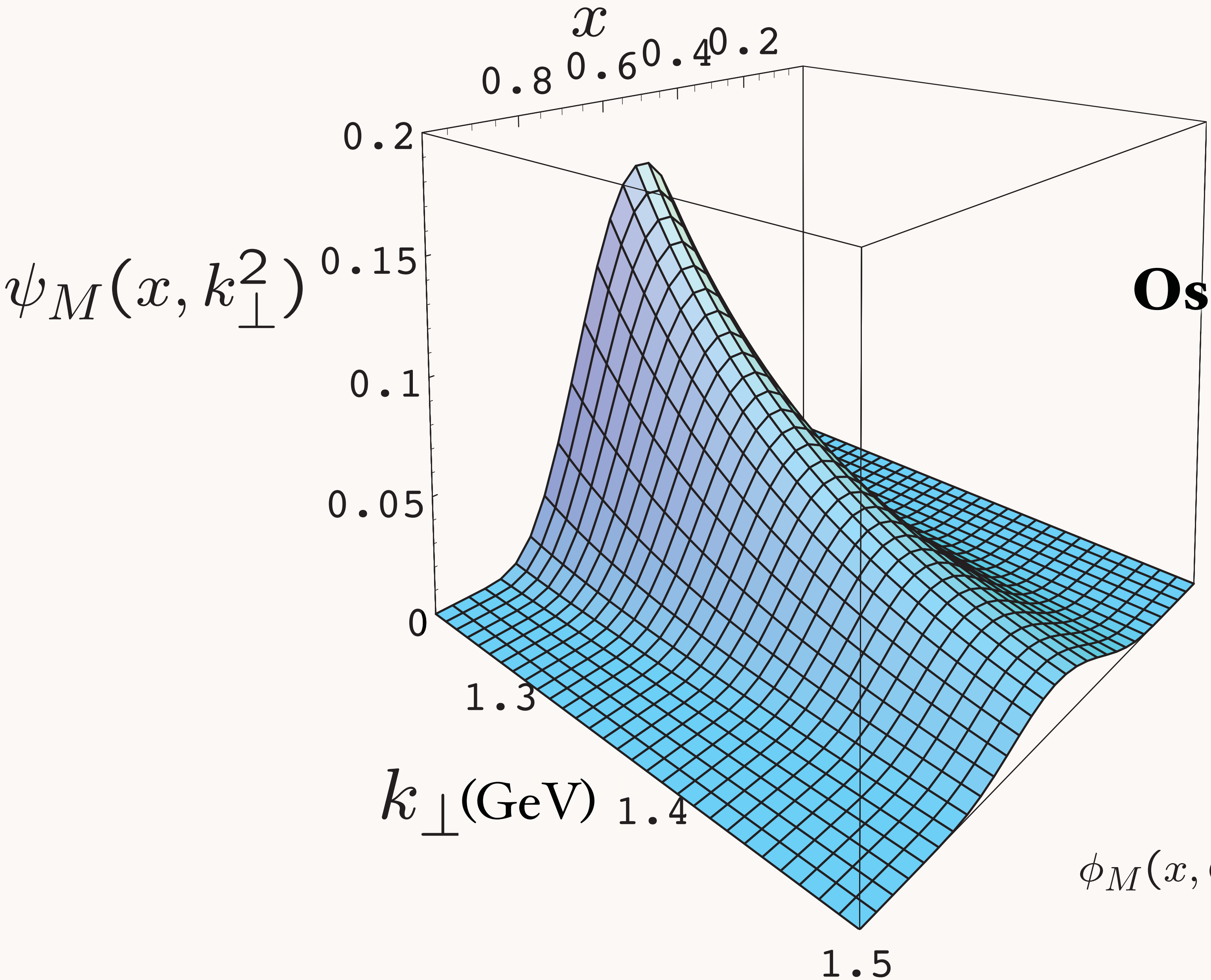
Effective conformal potential:

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

$$+\kappa^4\zeta^2$$

Soft wall harmonic oscillator potential:

Prediction from AdS/CFT: Meson LFWF

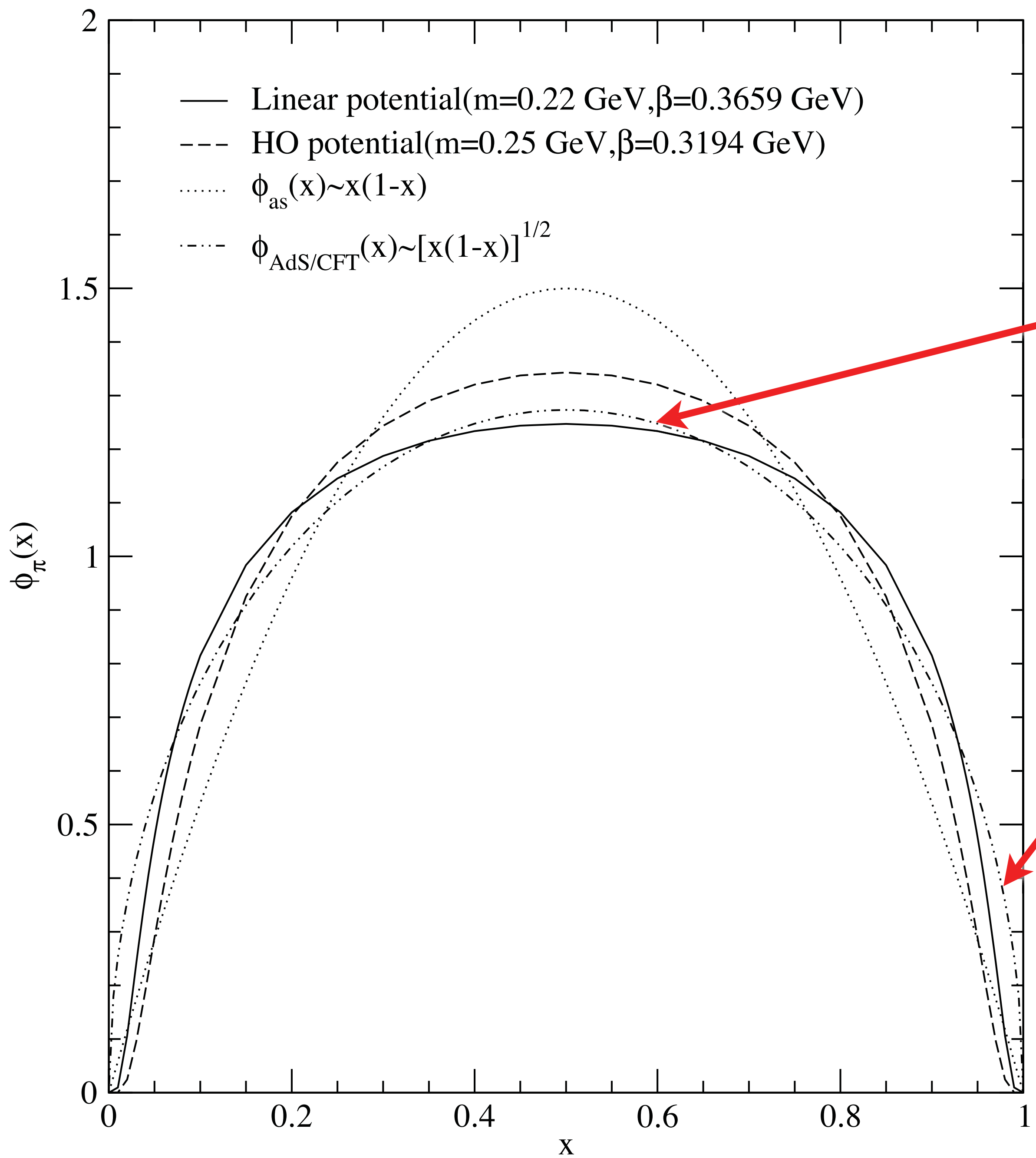


Harmonic Oscillator model

de Teramond, sjb

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

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



AdS/CFT:

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

Increases PQCD leading twist predictio
$F_\pi(Q^2)$ by factor 16/9

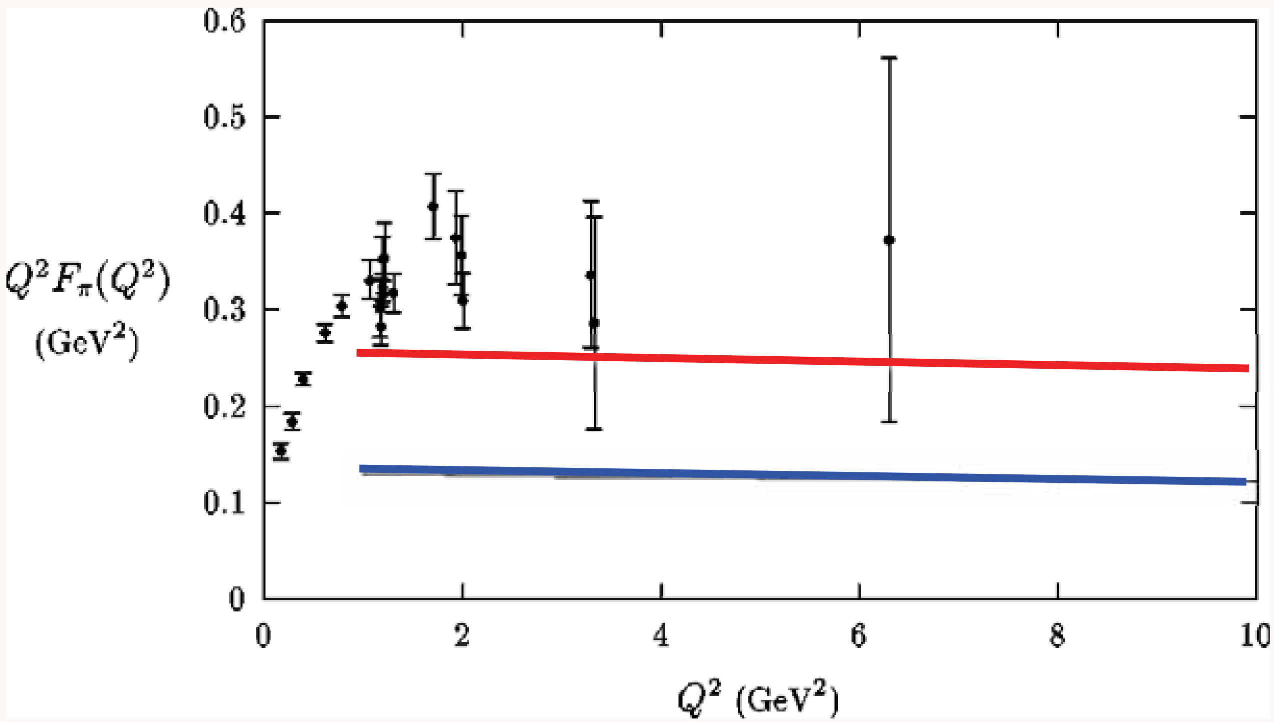
/QCD

Stan Brodsky, SLAC

Lepage, sjb

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

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



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

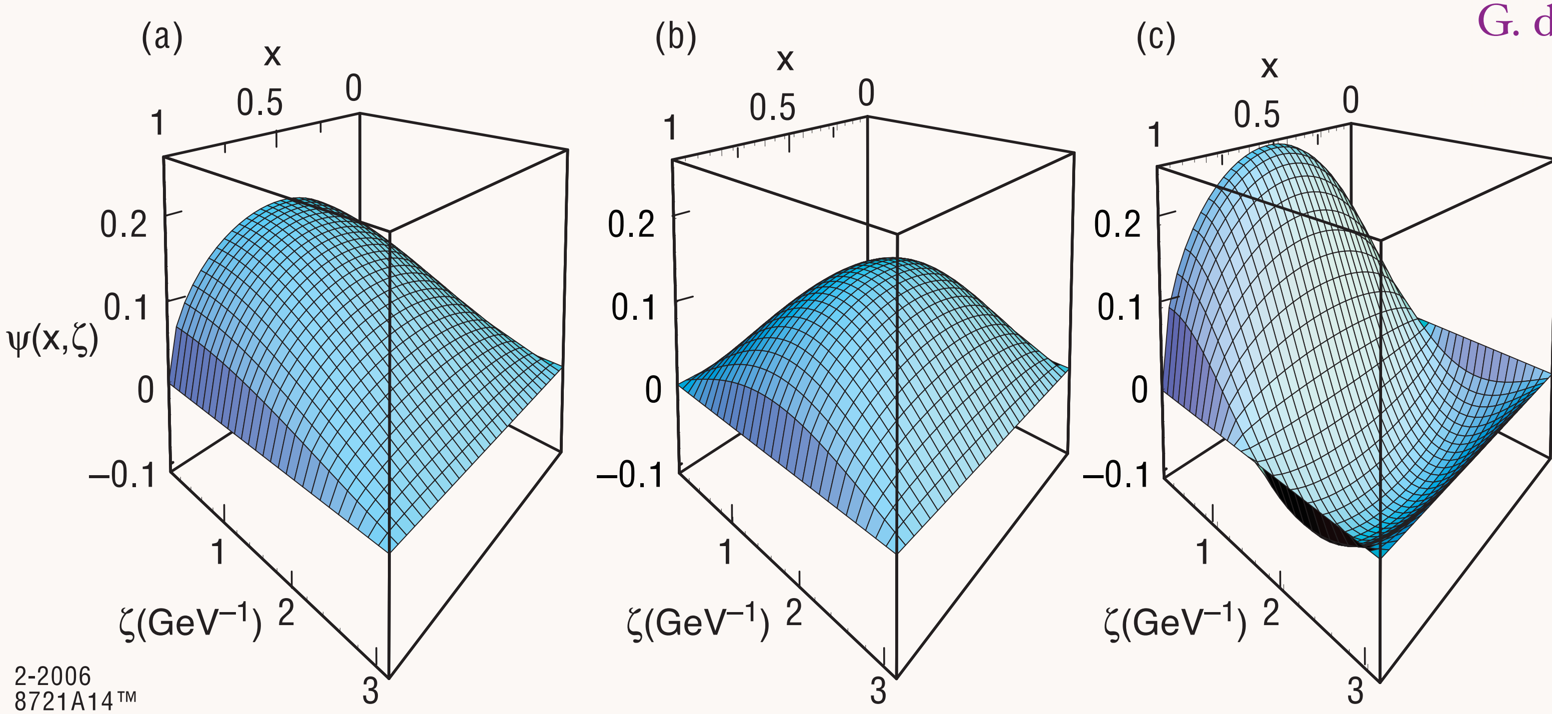
$\phi_{asymptotic} \propto x(1-x)$

Normalized to f_π

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

AdS/CFT Prediction for Meson LFWF

G. de Teramond
SJB



Two-parton holographic LFWF in impact space $\widetilde{\psi}(x,\zeta)$ for $\Lambda_{QCD} = 0.32$ GeV: (a) ground state $L=0,\ k=1$; (b) first orbital exited state $L=1,\ k=1$; (c) first radial exited state $L=0,\ k=2$. The variable ζ is the holographic variable $z = \zeta = |b_\perp|\sqrt{x(1-x)}$.

String Theory

↓

AdS/CFT

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

↓

Goal: First Approximant to QCD

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

AdS/QCD

Conformal behavior at short distances
+ Confinement at large distance

↓

Semi-Classical QCD / Wave Equations

↓ Holography

Boost Invariant 3+1 Light-Front Wave Equations

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

↓ Integrable!

Hadron Spectra, Wavefunctions, Dynamics

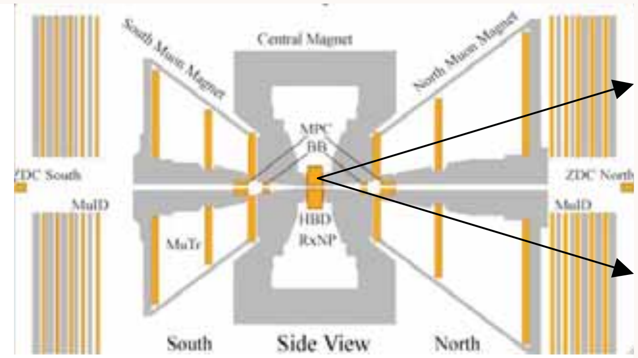
New Perspectives on QCD Phenomena from AdS/CFT

- AdS/CFT: Duality between string theory in Anti-de Sitter Space and Conformal Field Theory
- New Way to Implement Conformal Symmetry
- Holographic Model: Conformal Symmetry at Short Distances, Confinement at large distances
- Remarkable predictions for hadronic spectra, wavefunctions, interactions
- AdS/CFT provides novel insights into the quark structure of hadrons

New Perspectives for QCD from AdS/CFT

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

Heavy quark production: J/Ψ



Why heavy quark and J/Ψ?

- Minimize Collins' effects
  - J/Ψ production dominated by gluon gluon fusion at RHIC energy

    Pythia 6.1 simulation

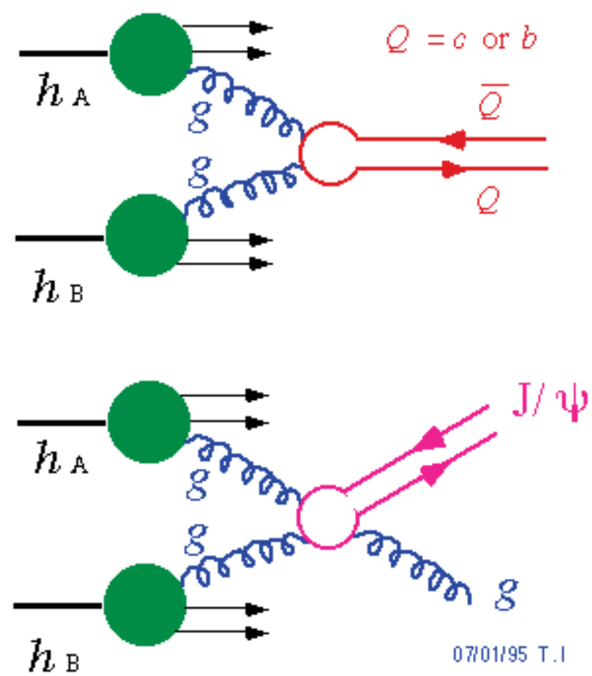
$c\bar{c}$:	$gg \to c\bar{c}$	95%
$b\bar{b}$:	$gg \to b\bar{b}$	85%

  - gluon has zero transversity

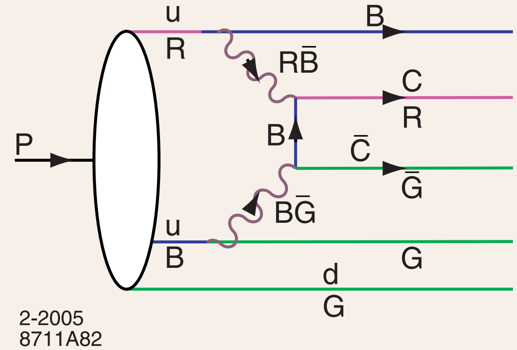
- A golden channel for gluon Sivers function

Wrong predictions at large x_F

Gluon Fusion



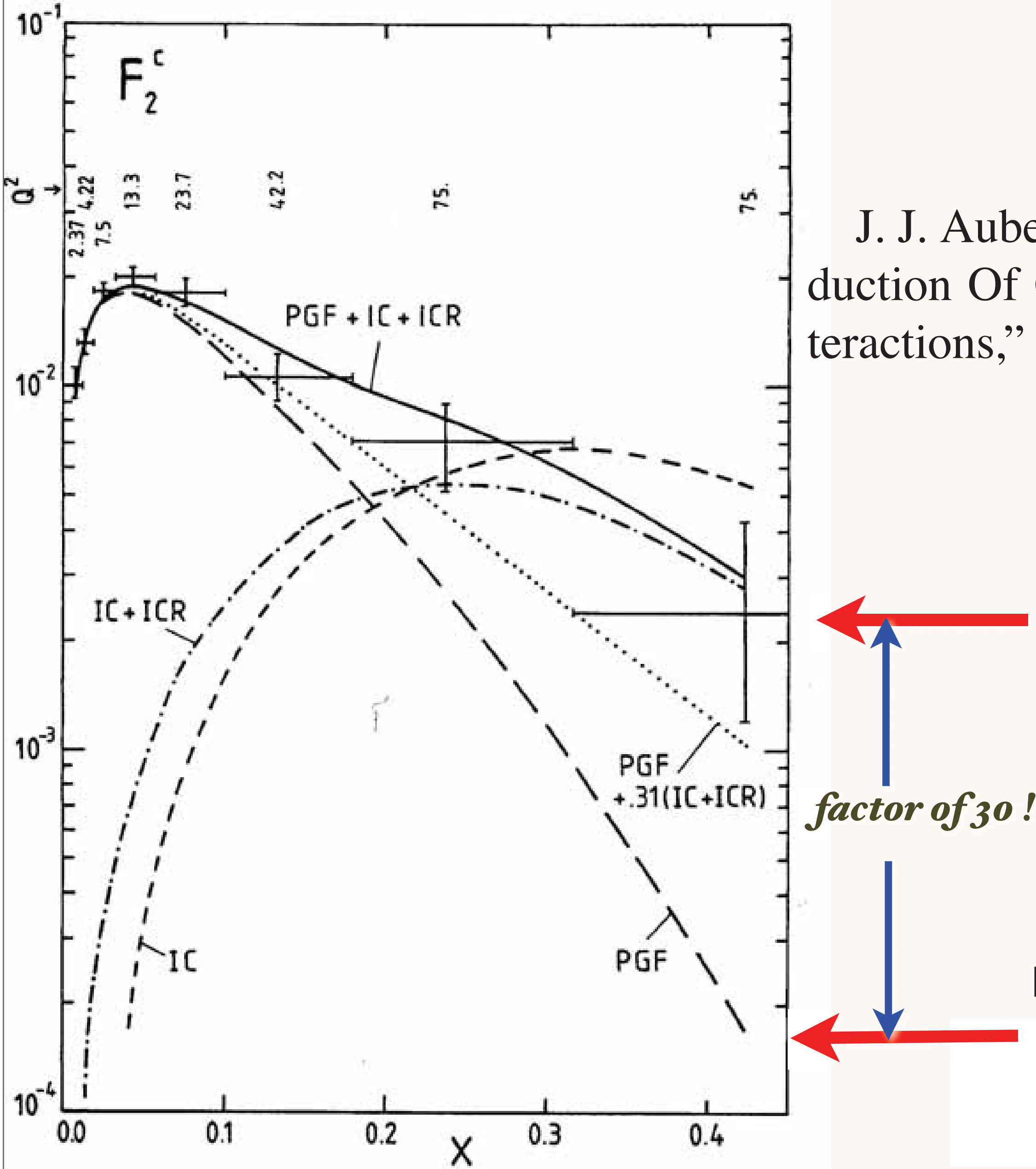
Intrinsic Heavy-Quark Fock States



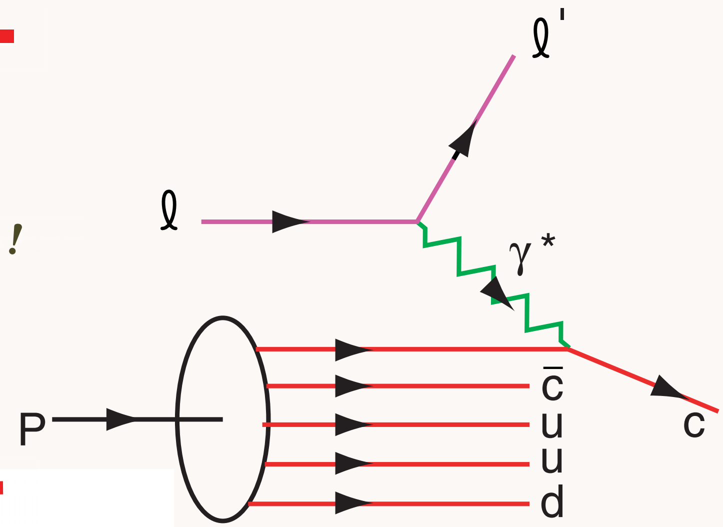
- Rigorous prediction of QCD, OPE
- Color-Octet Color-Octet Fock State!
- Probability $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- Large Effect at high x
- Greatly increases kinematics of colliders such as Higgs production (Kopeliovich, 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).

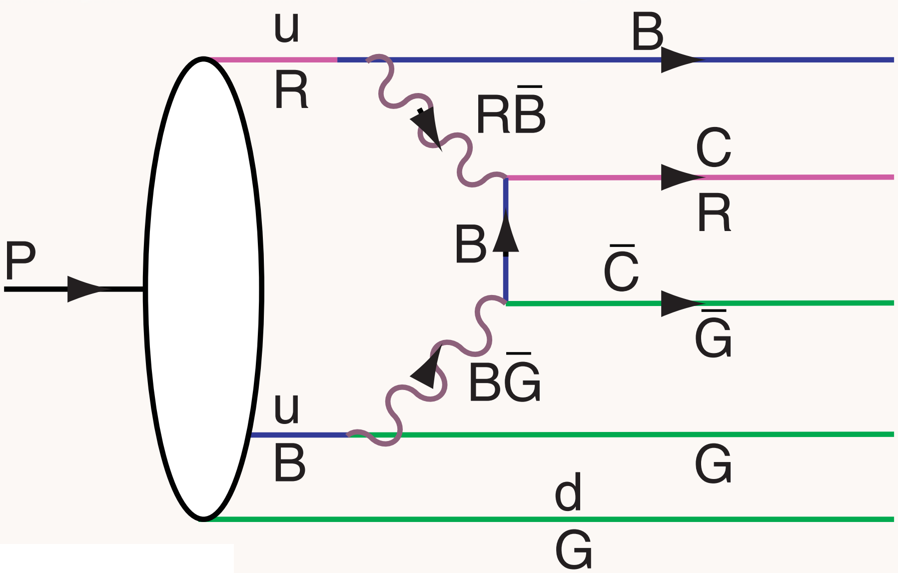


First Evidence for Intrinsic Charm



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

Hoyer, Peterson, Sakai, sjb



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

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

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

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

OPE derivation - M.Polyakov et al.

$< p|\frac{G^3_{\mu\nu}}{m^2_Q}|p >$ 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

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

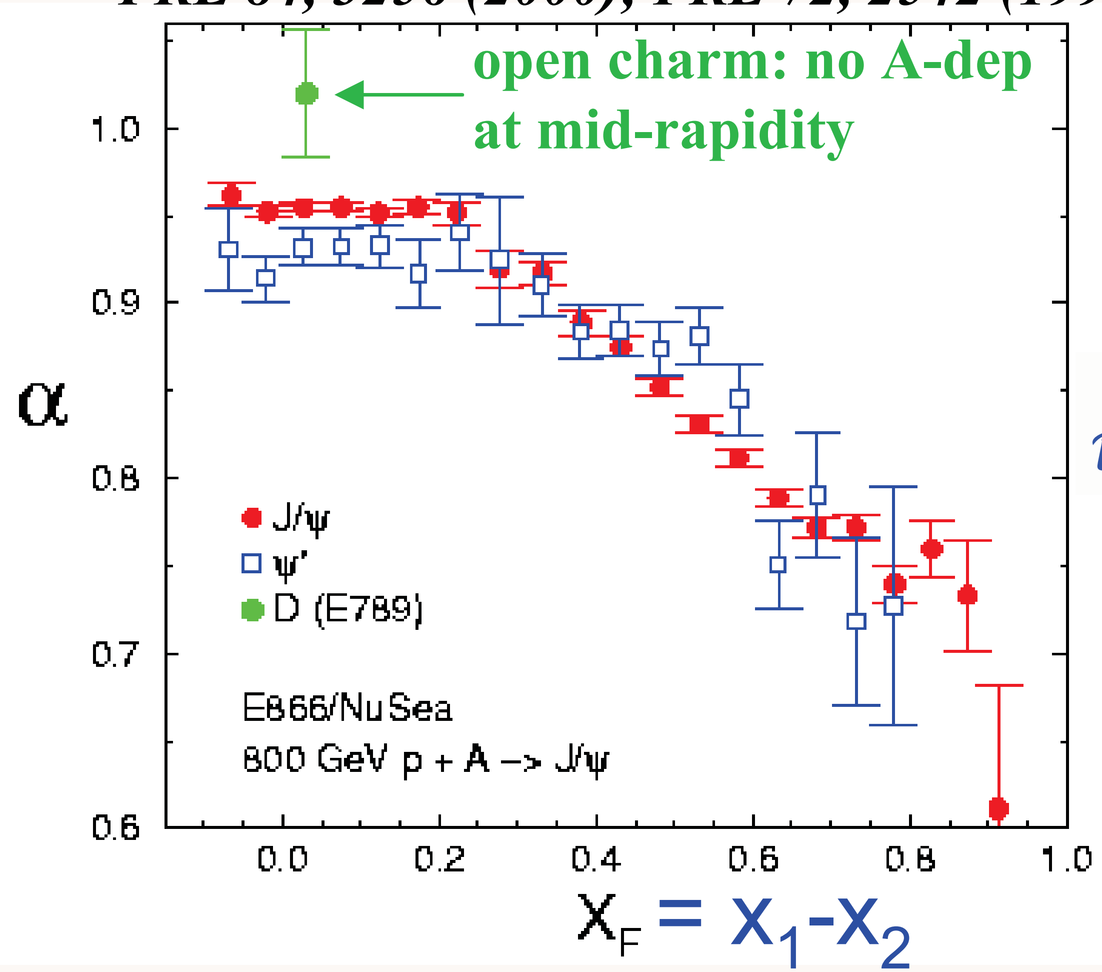
High x charm!

Charm at Threshold

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

IC Explains large excess of quarkonia at large x_F, A-dependence

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

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

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

- High x_F $pp \to \Lambda_c X$

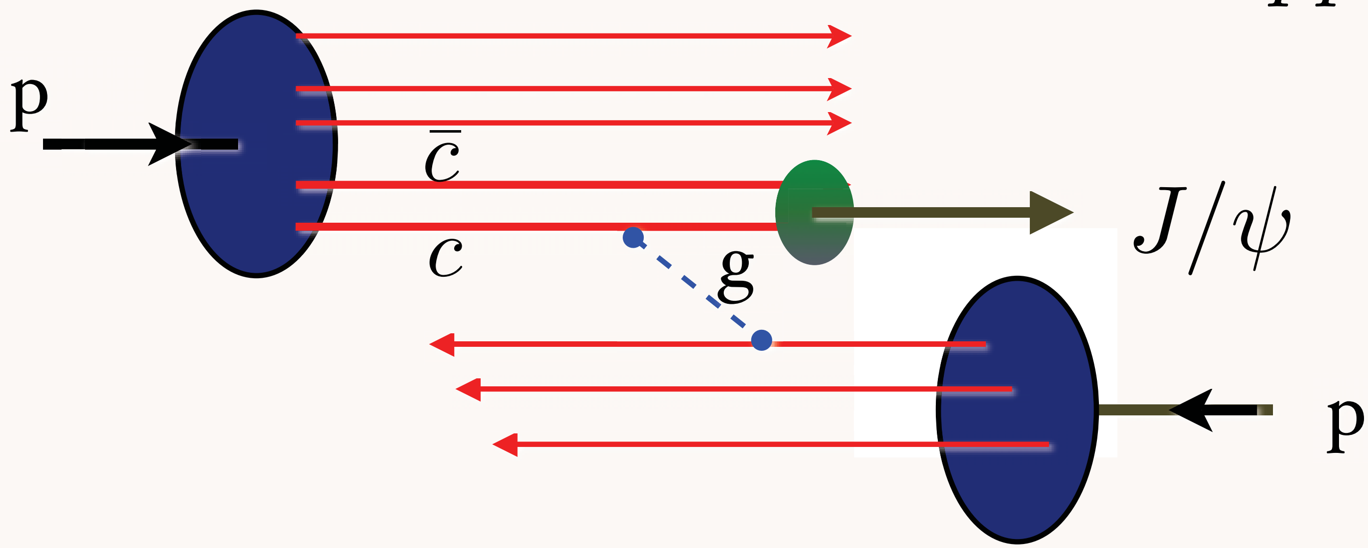
- High x_F $pp \to \Lambda_b X$

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

IC Structure Function: Critical Measurement for COMPASS

Intrinsic Charm Mechanism for Inclusive High-X_F Quarkonium Production

$$pp \to J/\psi X$$



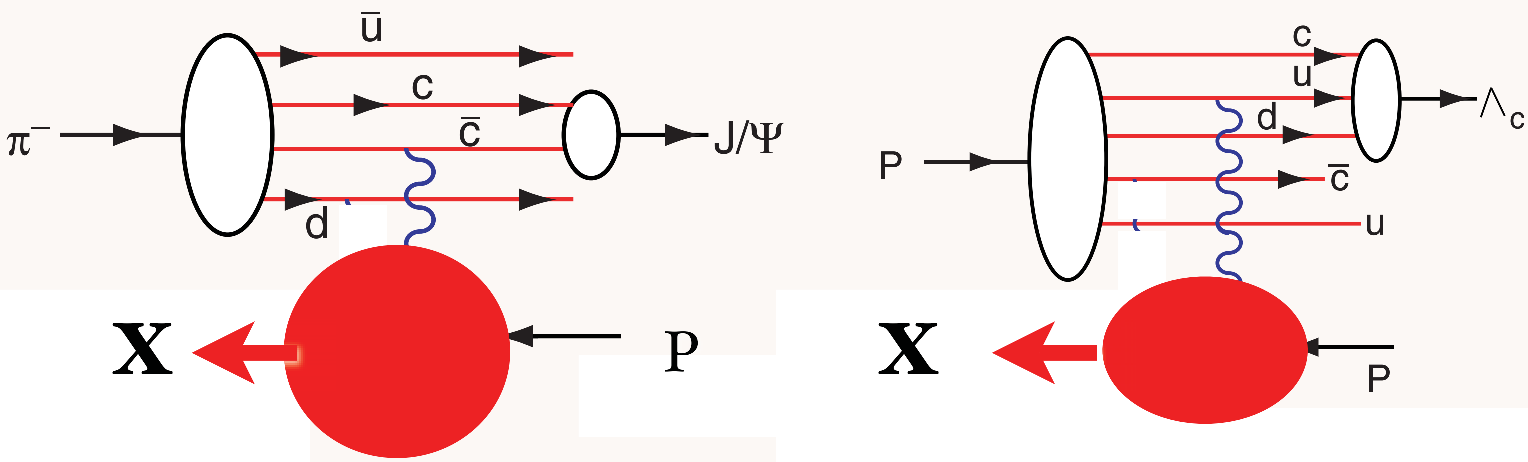
Goldhaber, Kopeliovich, Soffer, Schmidt, sjb

Quarkonia can have 80% of Proton Momentum!

Color-octet IC interacts at front surface of nucleus

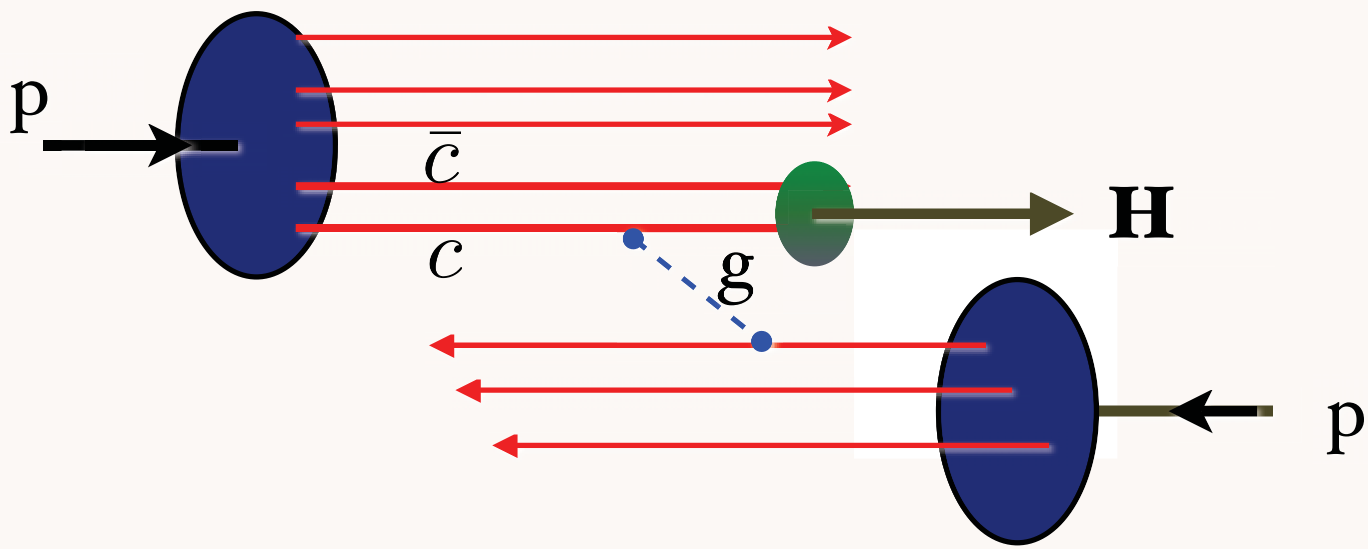
IC can explains large excess of quarkonia at large x_F, A-dependence

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

Intrinsic Charm Mechanism for Inclusive High-X_F Higgs Production



$pp \to HX$

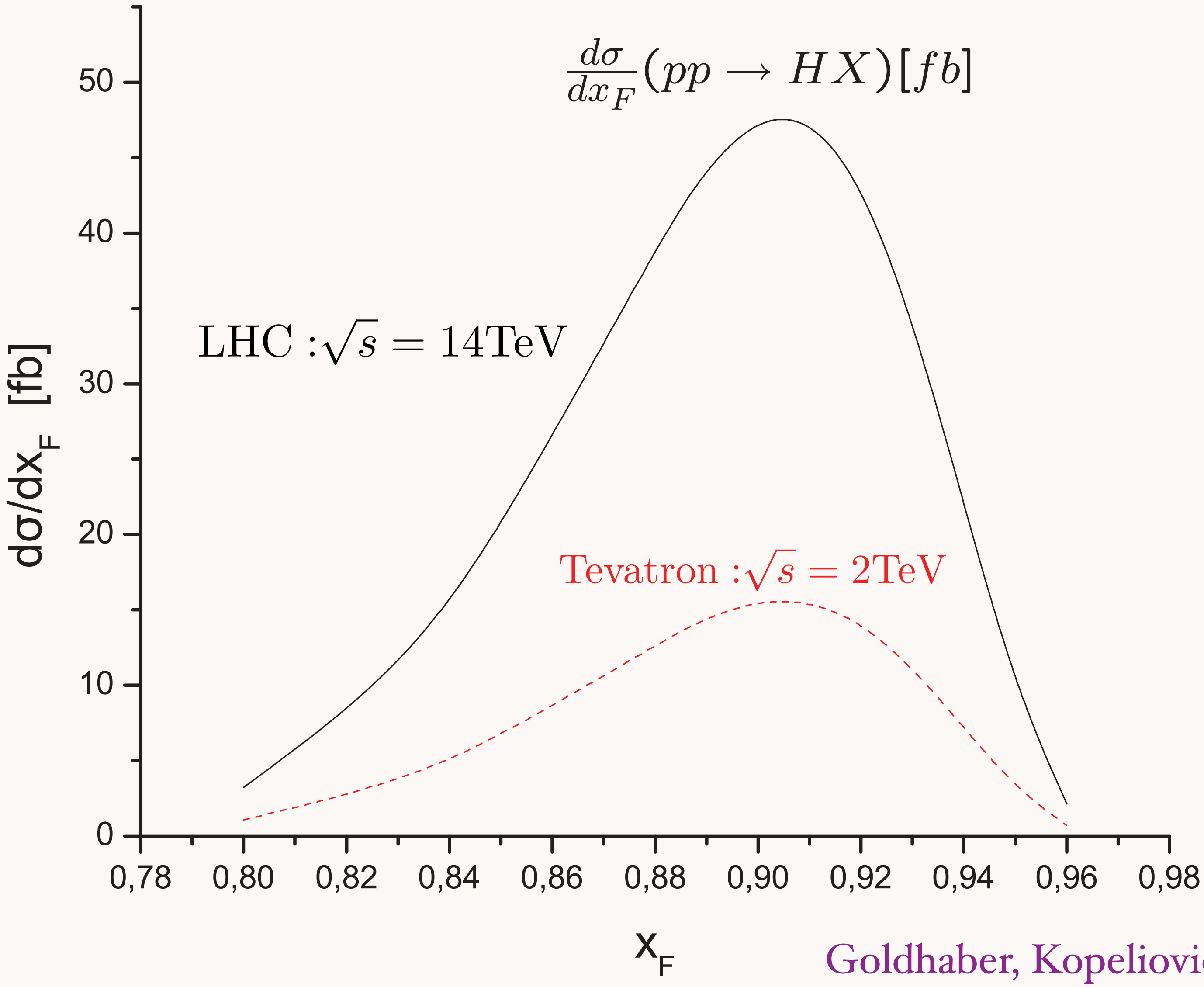
Goldhaber, Kopeliovich, Schmidt, sjb

Also: intrinsic bottom, top

Higgs can have 80% of Proton Momentum!

New search strategy for Higgs

Intrinsic Bottom Contribution to Inclusive Higgs Production



Goldhaber, Kopeliovich, Schmidt, sjb
preliminary

Use extreme caution when using $\gamma g \to c\bar{c}$ or $gg \to \bar{c}c$ to tag gluon dynamics

Contalbrigo

Elastic Scattering

Low-E $\bar{p}p$, $\bar{p}d$ at AD

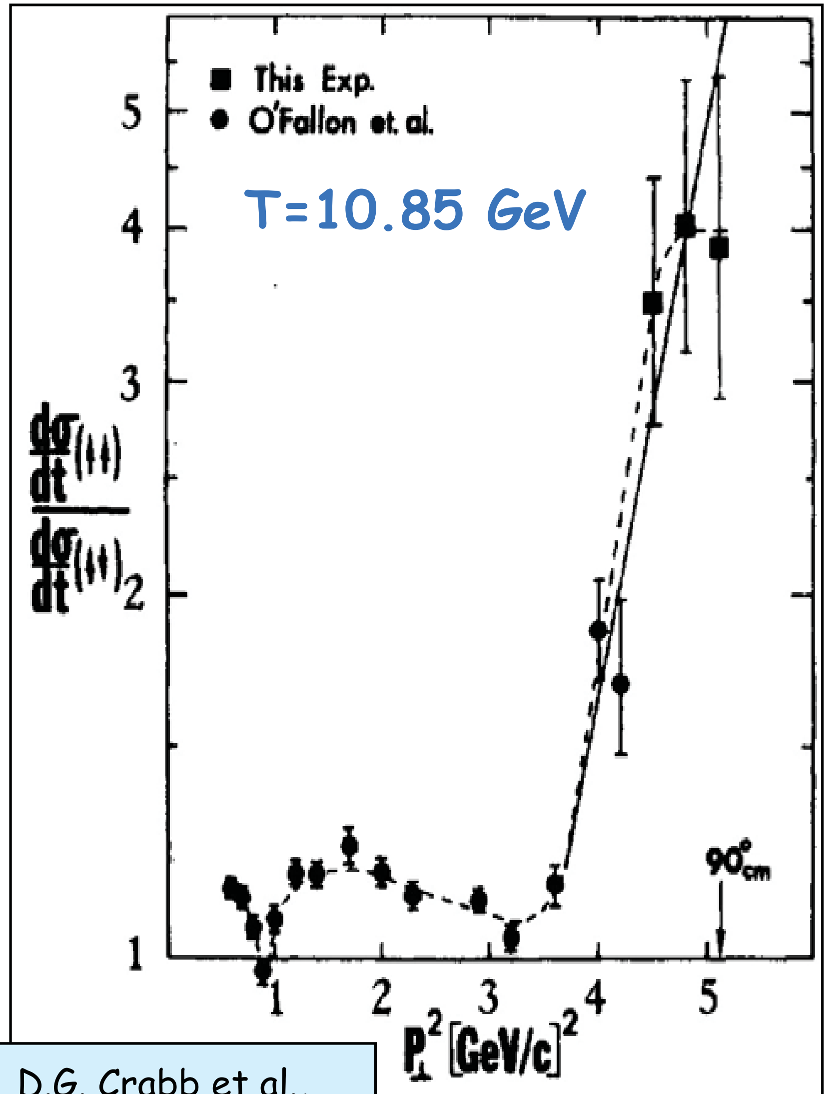
Polarization build-up studies

High-t pp from ZGS, AGS

Spin-dependence at large-$P_\perp$ ($90°_{cm}$):

Hard scattering takes place only with spins ↑↑.

Similar studies in $p\bar{p}$ elastic scattering



D.G. Crabb et al., PRL 41, 1257 (1978)

A. Krisch, Sci. Am. 257 (1987)
"The results challenge the prevailing theory that describes the proton's structure and forces"

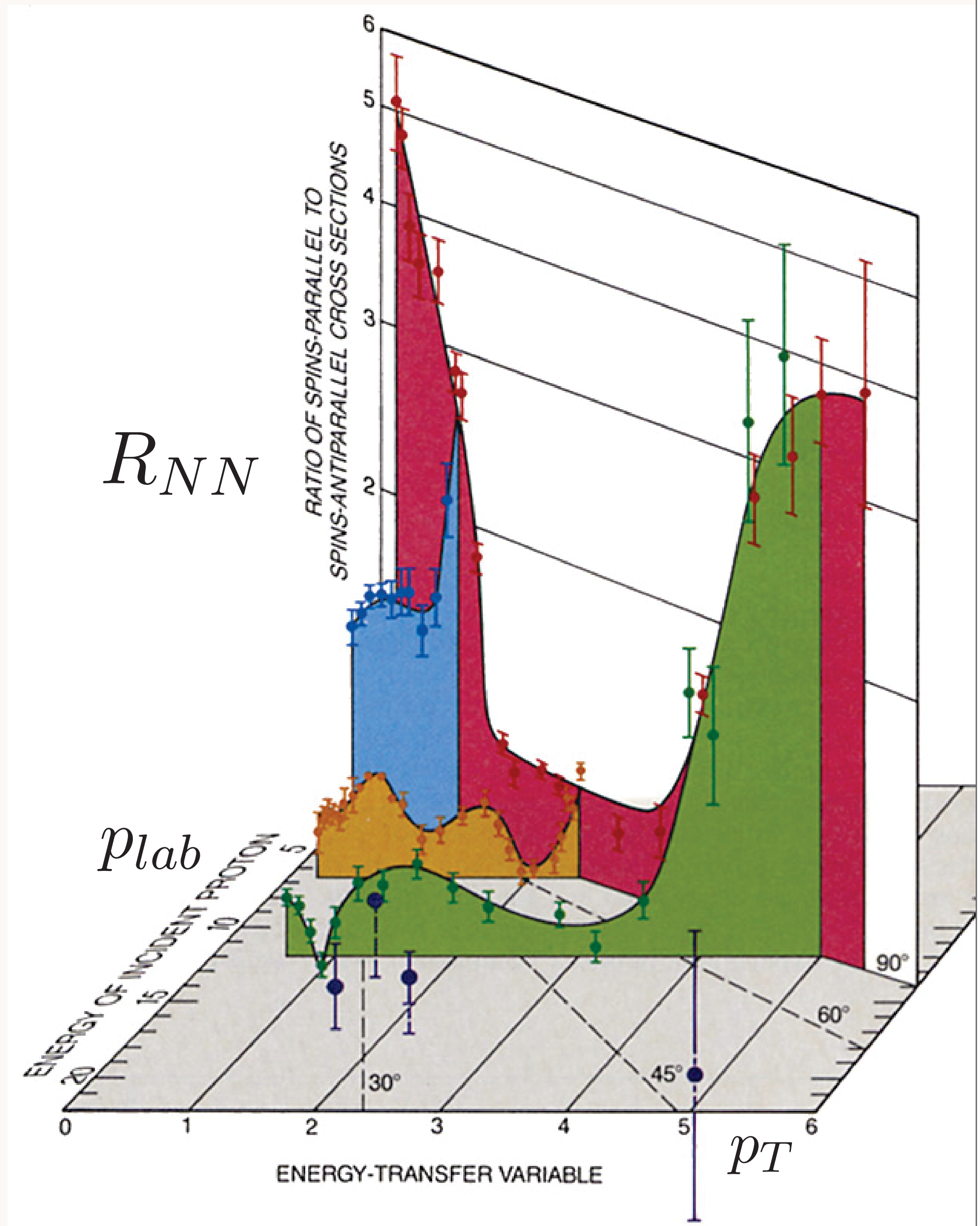
"Exclusive Transversity"

Spin-dependence at large-P_T ($90°_{cm}$):

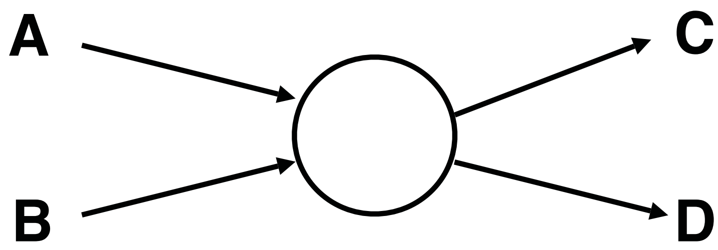
Hard scattering takes place only with spins ↑↑

Coincidence?: Quenching of Color Transparency

Coincidence?: Charm and Strangeness Thresholds



Constituent Counting Rules



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

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

$$n_{tot} = n_A + n_B + n_C + n_D$$

Fixed t/s or $\cos\theta_{cm}$

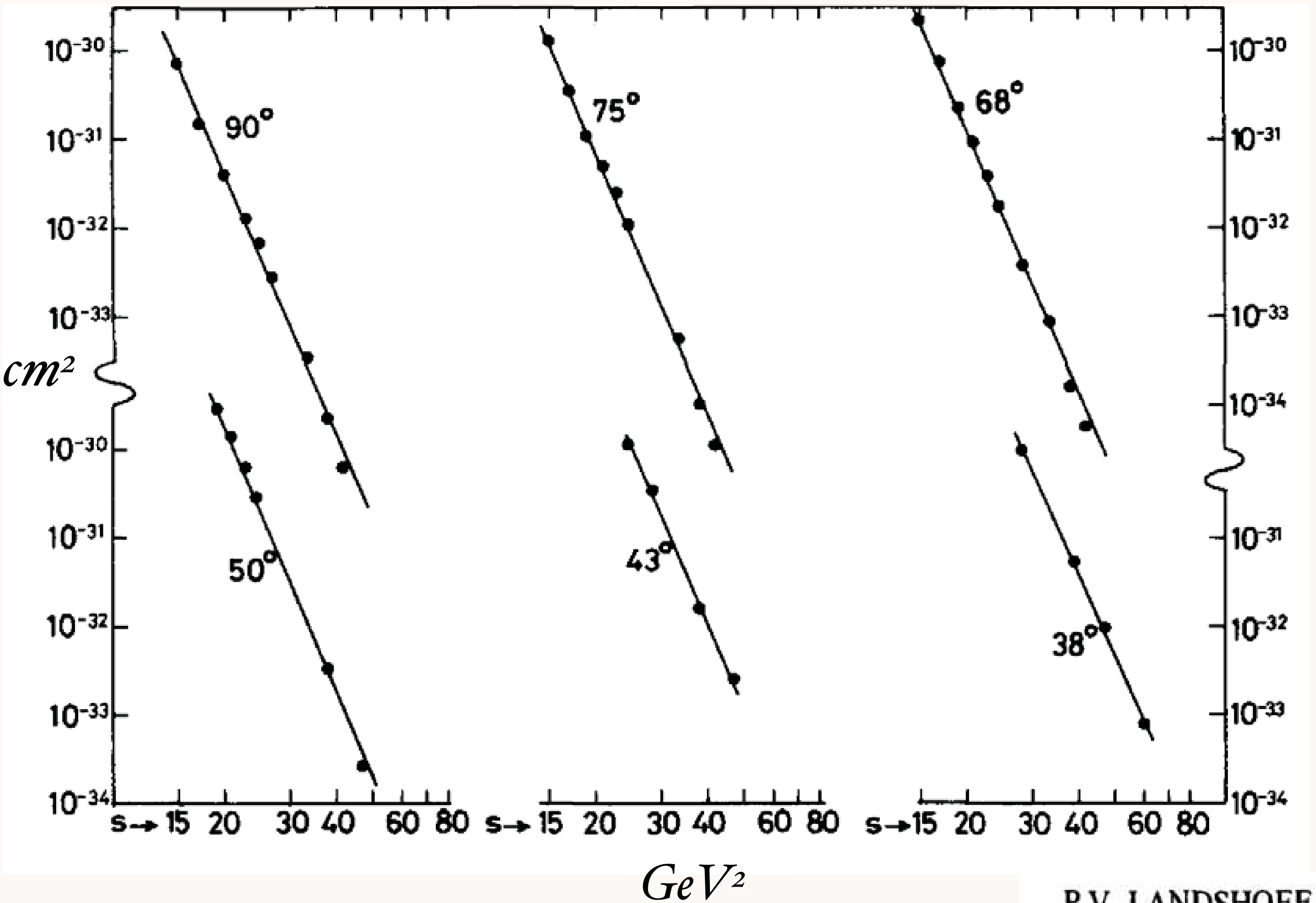
Farrar & sjb; Matveev, Muradyan, Tavkhelidze

Conformal symmetry and PQCD predict leading-twist scaling behavior of fixed-CM angle exclusive amplitudes

Characteristic scale of QCD: 300 MeV

Many new J-PARC, GSI, J-Lab, Belle, Babar tests

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

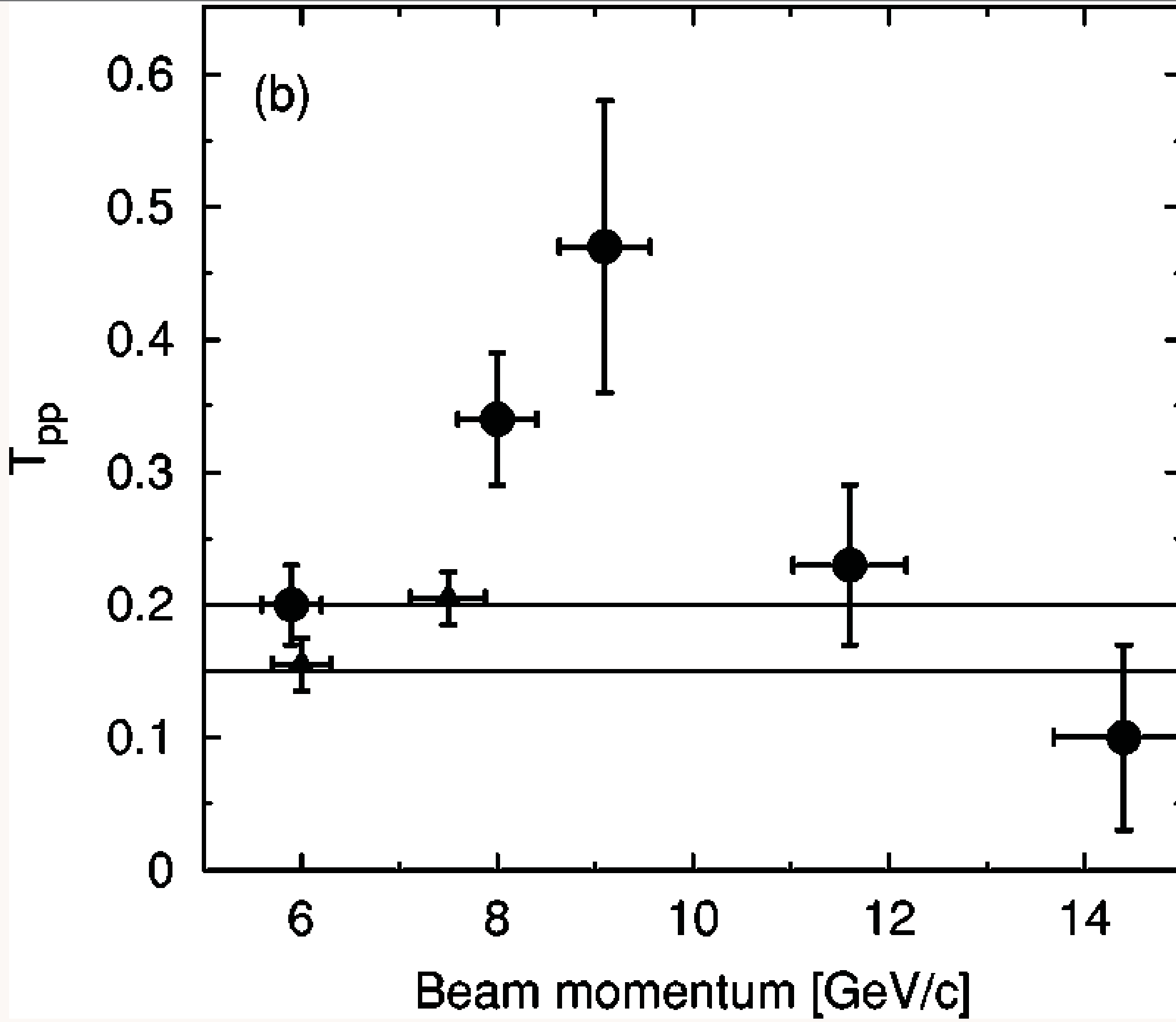


P.V. LANDSHOFF and J.C. POLKINGHORNE

Best Fit

$n = 9.7 \pm 0.5$

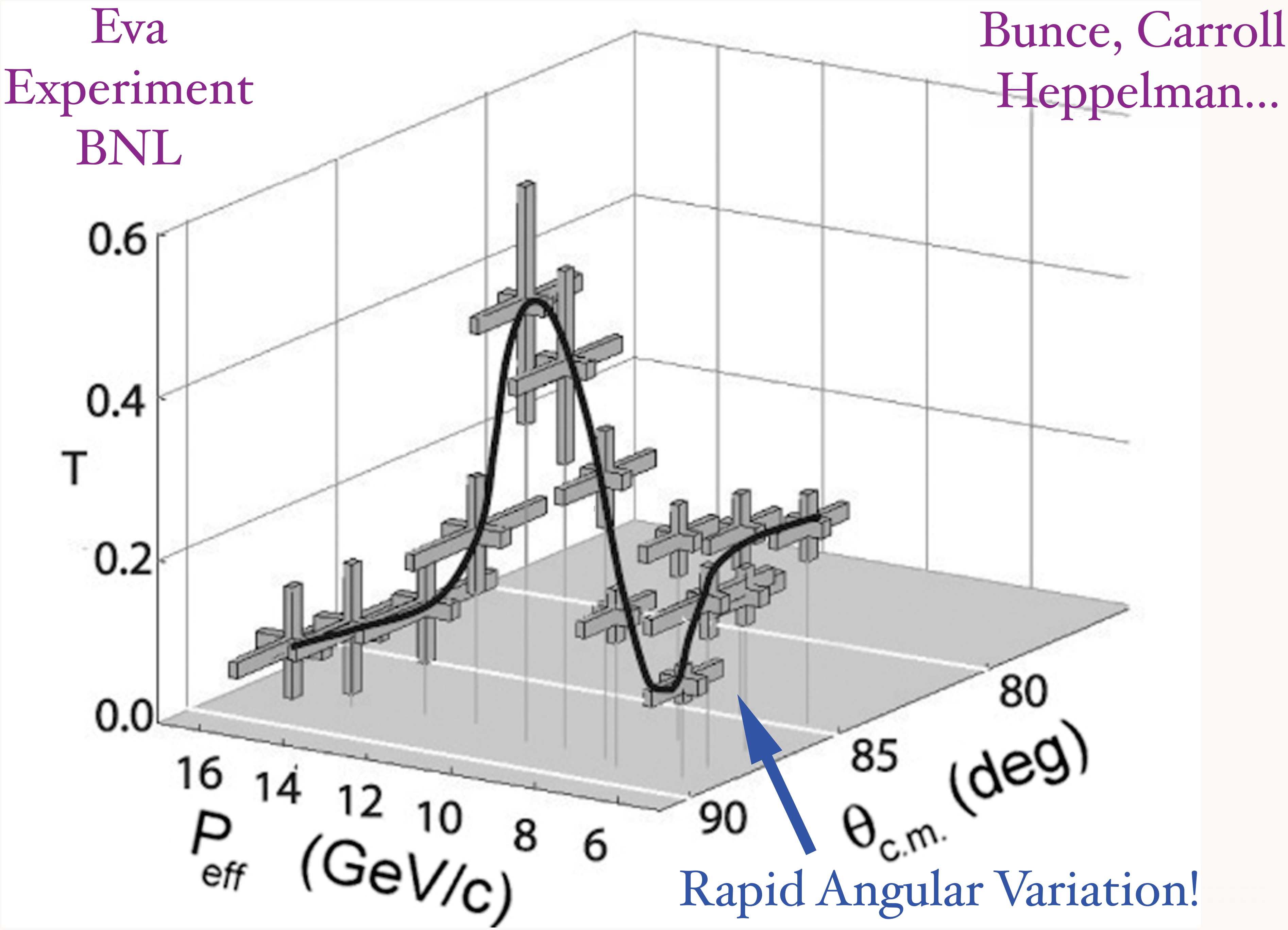
Reflects underlying conformal scale-free interactions



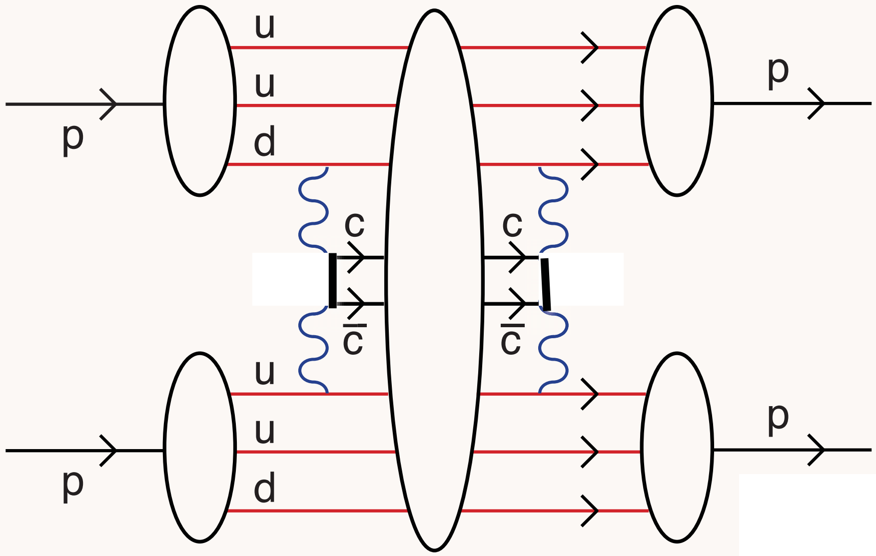
PHYSICAL REVIEW C **70**, 015208 (2004)

Nuclear transparency in $90^{\circ}_{c.m.}$ quasielastic $A(p,2p)$ reactions

J. Aclander,[7] J. Alster,[7] G. Asryan,[1,*] Y. Averiche,[5] D. S. Barton,[1] V. Baturin,[2,†] N. Buktoyarova,[1,†] G. Bunce,[1]
A. S. Carroll,[1,‡] N. Christensen,[3,§] H. Courant,[3] S. Durrant,[2] G. Fang,[3] K. Gabriel,[2] S. Gushue,[1] K. J. Heller,[3] S. Heppelmann,[2]
I. Kosonovsky,[7] A. Leksanov,[2] Y. I. Makdisi,[1] A. Malki,[7] I. Mardor,[7] Y. Mardor,[7] M. L. Marshak,[3] D. Martel,[4]
E. Minina,[2] E. Minor,[2] I. Navon,[7] H. Nicholson,[8] A. Ogawa,[2] Y. Panebratsev,[5] E. Piasetzky,[7] T. Roser,[1] J. J. Russell,[4]
A. Schetkovsky,[2,†] S. Shimanskiy,[5] M. A. Shupe,[3,‖] S. Sutton,[8] M. Tanaka,[1,¶] A. Tang,[6] I. Tsetkov,[5] J. Watson,[6] C. White,[3]
J-Y. Wu,[2] and D. Zhalov[2]


Eva
Experiment
BNL
Bunce, Carroll,
Heppelman...
0.6
0.4
T
0.2
0.0
16
14
12
10
8
6
P_{eff} (GeV/c)
90
85
80
$\theta_{c.m.}$ (deg)
Rapid Angular Variation!

- New QCD physics in proton-proton elastic scattering at the charm threshold
- Anomalously large charm photoproduction at threshold?
- Octoquark resonances?
- Color Transparency disappears at charm threshold
- Huge transversity correlation at charm threshold



QCD Schwinger-Sommerfeld Enhancement at Heavy Quark Threshold

Hebecker, Kuhn, sjb

S. J. Brodsky and G. F. de Teramond, "Spin Correlations, QCD Color Transparency And Heavy Quark Thresholds In Proton Proton Scattering," Phys. Rev. Lett. **60**, 1924 (1988).

$pp \to (c\bar{c}uuduud) \to pp$

Strong distortion, resonance phenomena at threshold

$\sqrt{s_{\rm threshold}} \simeq 3+2 = 5$ GeV, $p_{lab} \sim 12$ GeV

$(c\bar{c}uuduud)$ S-wave resonance, odd parity

$A_{NN} = 1$ for $J = L = S = 1$

$p^{\uparrow}p^{\uparrow}$ only

Interferes with PQCD quark-interchange amplitude

Test at $\sqrt{s} = 3, 5, 12$ GeV, $\theta_{cm} = \pi/2$

$\sigma(pp \to cX) \simeq 1\ \mu b$ near charm threshold

Key QCD Experiment at GSI

Open Charm

$$\bar{p}p \to \bar{\Lambda}_c(\overline{cud})D^0(\bar{c}u)p$$

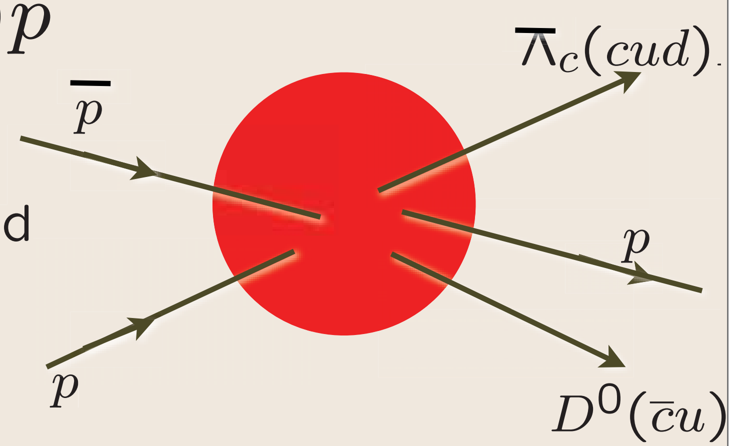
Total open charm cross section at threshold

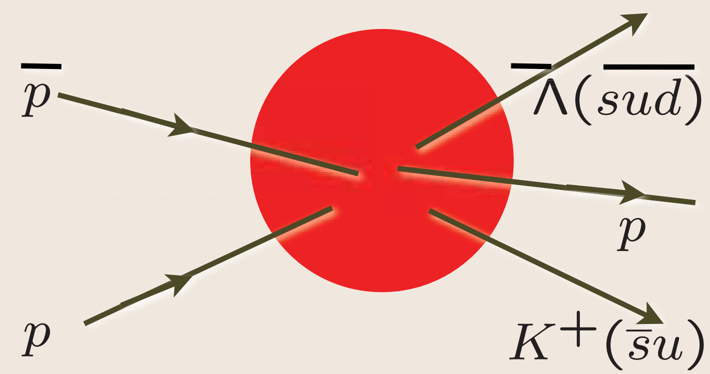
$$\sigma(pp \to cX) \simeq 1\mu b$$

needed to explain Krisch A_{NN}

Compare with strangeness channels

$$pp \to \Lambda(sud)K^+(\bar{s}u)p$$





Lu, Kataev, Gabadadze, Sjb

Generalized Crewther Relation

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

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

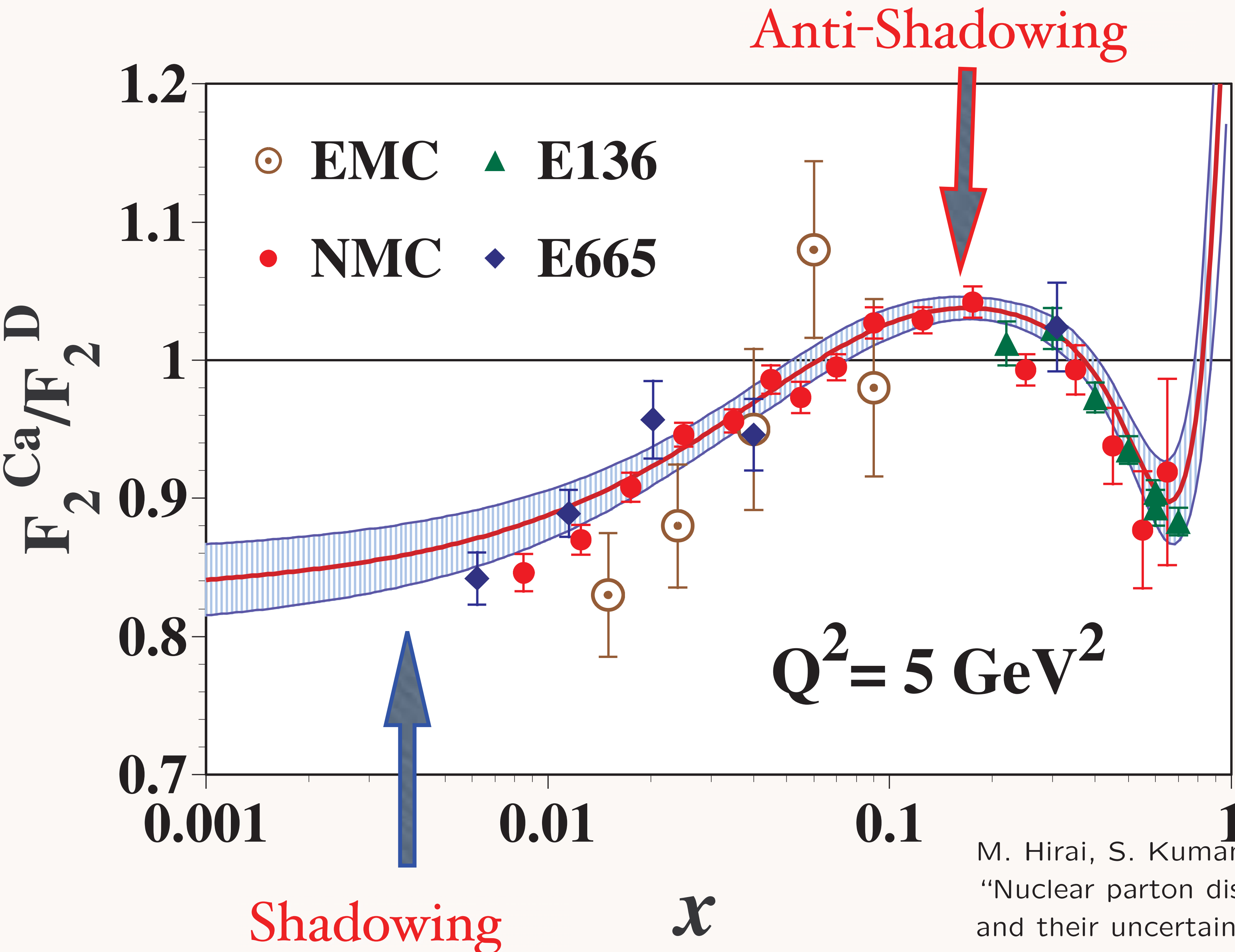
Conformal relation true to all orders in perturbation theory

No radiative corrections to axial anomaly

Nonconformal terms set relative scales (BLM)

Analytic matching at quark thresholds

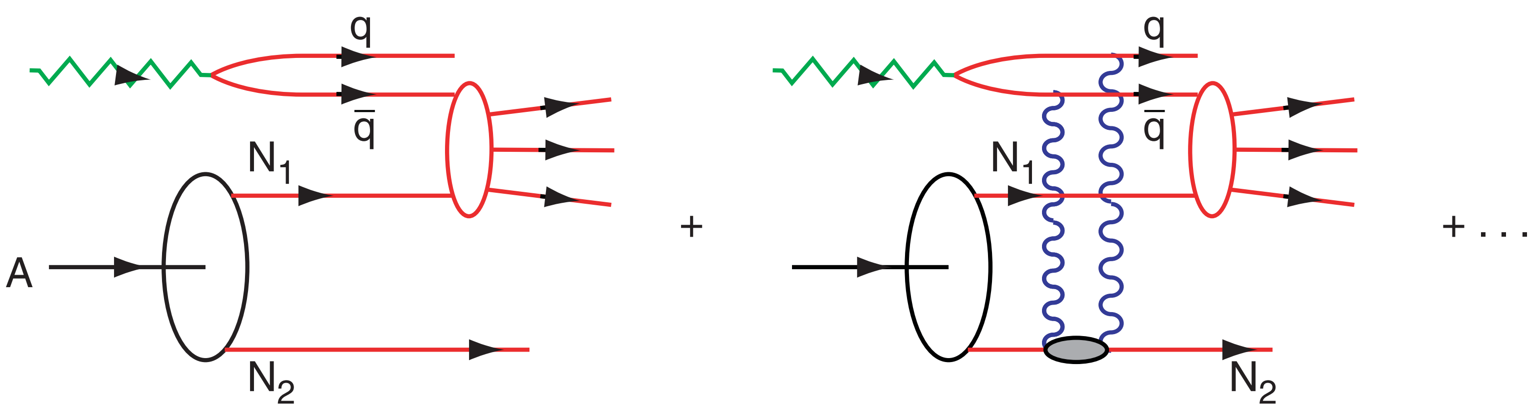
No renormalization scale ambiguity!



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

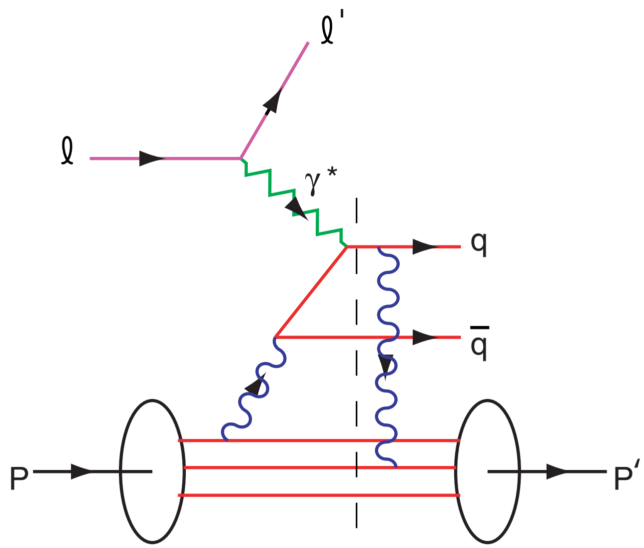
Nuclear Shadowing in QCD



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 understanding leading-twist-diffraction in DIS

Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate Pomeron

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

Physics of FSI not in Wavefunction of Target

Antishadowing (Reggeon exchange) is not universal!

New physics at high x_F

Direct subprocesses

Dominance of higher-twist subprocesses in some domains

Reggeon (multiquark) exchange in both exclusive and inclusive reactions

Intrinsic Heavy Quarks

Why such large neutron asymmetries?

- A_N is produced via interference of spin non-flip and spin-flip amplitudes
- In Regge theory

  -- A spin non-flip amplitude contribution can be described due to Reggeon and Pomeron exchange

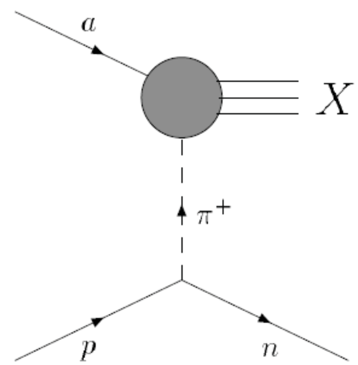
  -- We need spin-flip amplitude –> one pion exchange amplitude

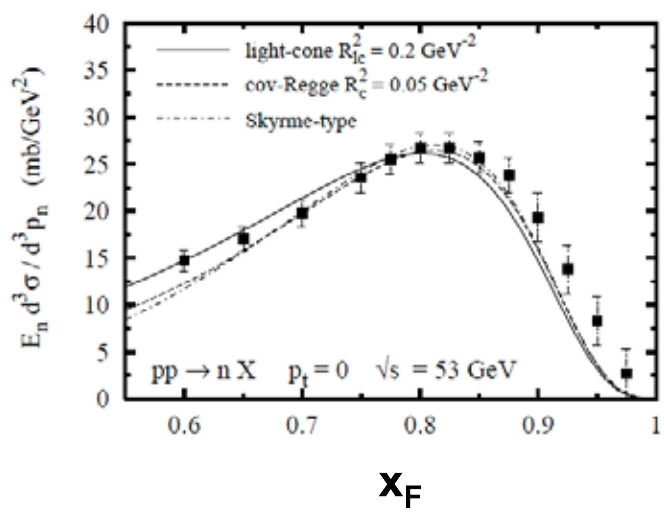
- One pion exchange model (OPE) may explain the result

  -- OPE has been used to describe exclusive diffractive neutron production

  -- The cross-section at ISR is well described by spin-flip OPE

Eur.Phys.J.A7:109-119,2000

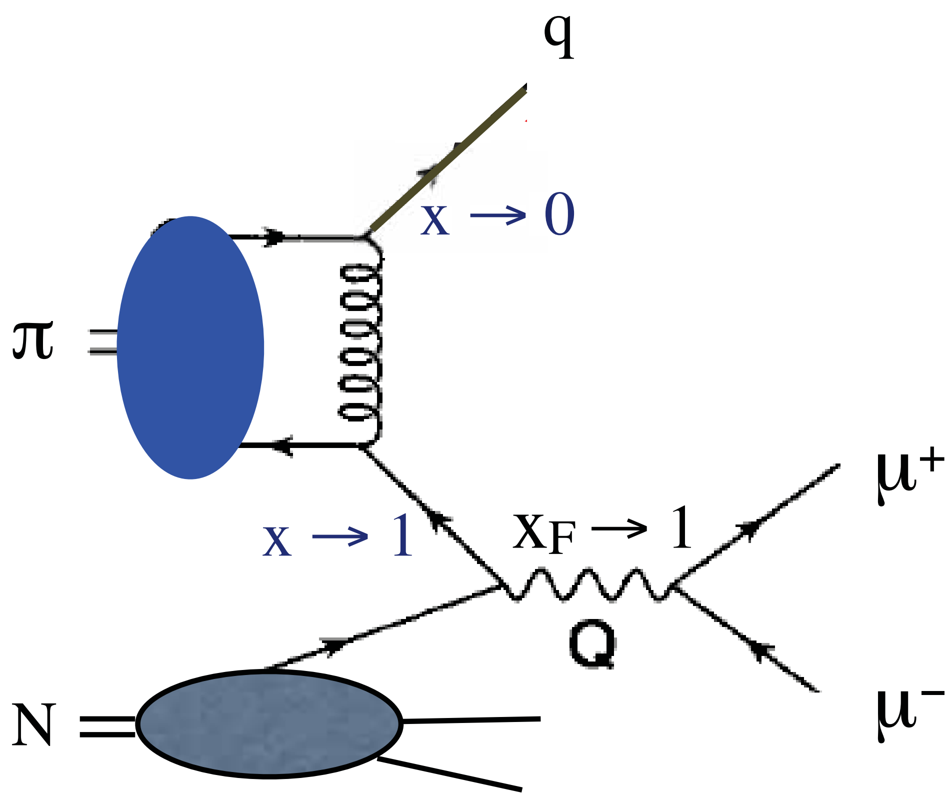




$\pi N \to \mu^+ \mu^- X$ at high x_F

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

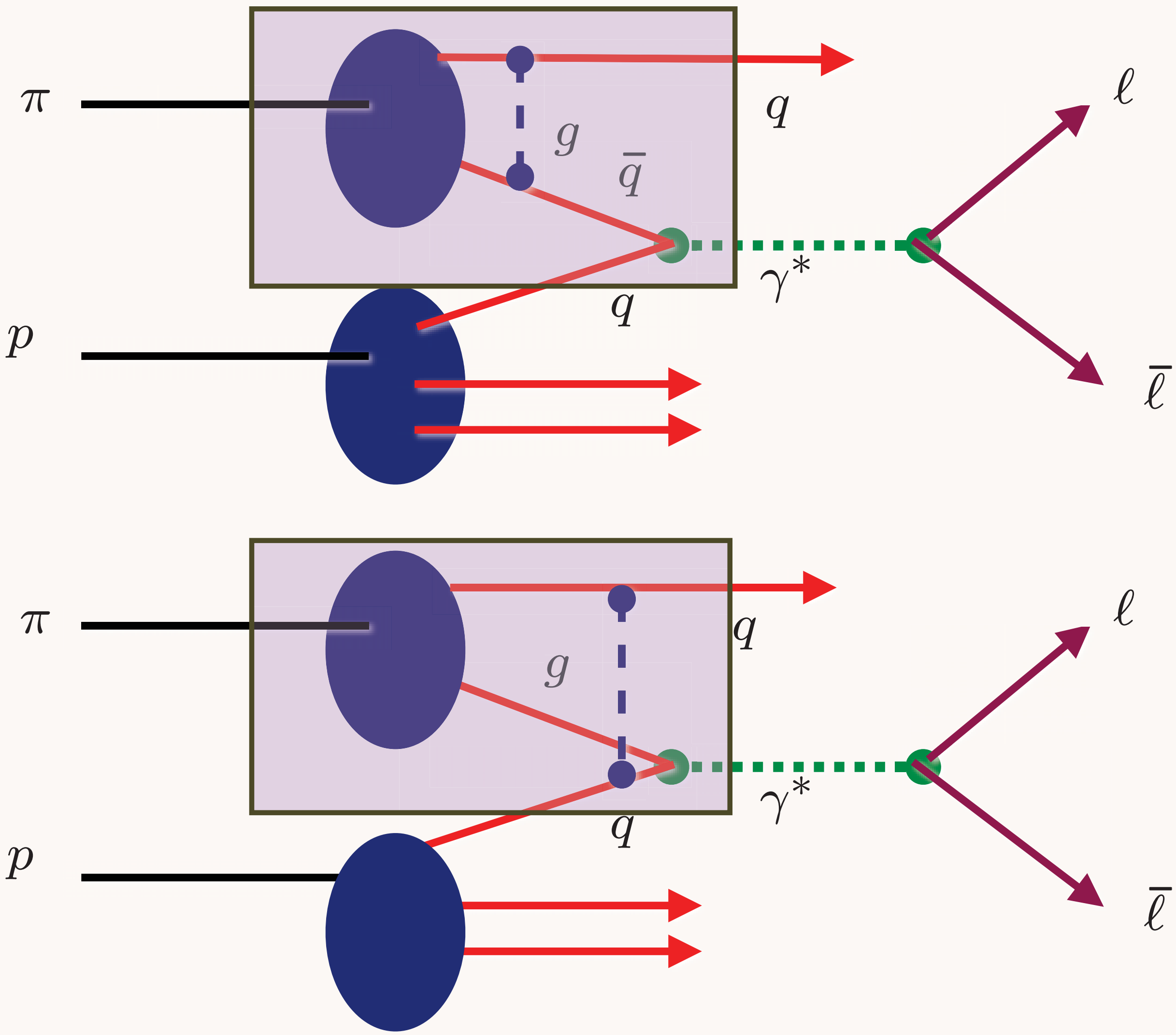
Entire pion wf contributes to hard process



Virtual photon is longitudinally polarized

Berger and Brodsky, PRL 42 (1979) 940

Berger, Lepage, sjb



$$\pi q \rightarrow \gamma^* q$$

Pion appears directly in subprocess at large x_F

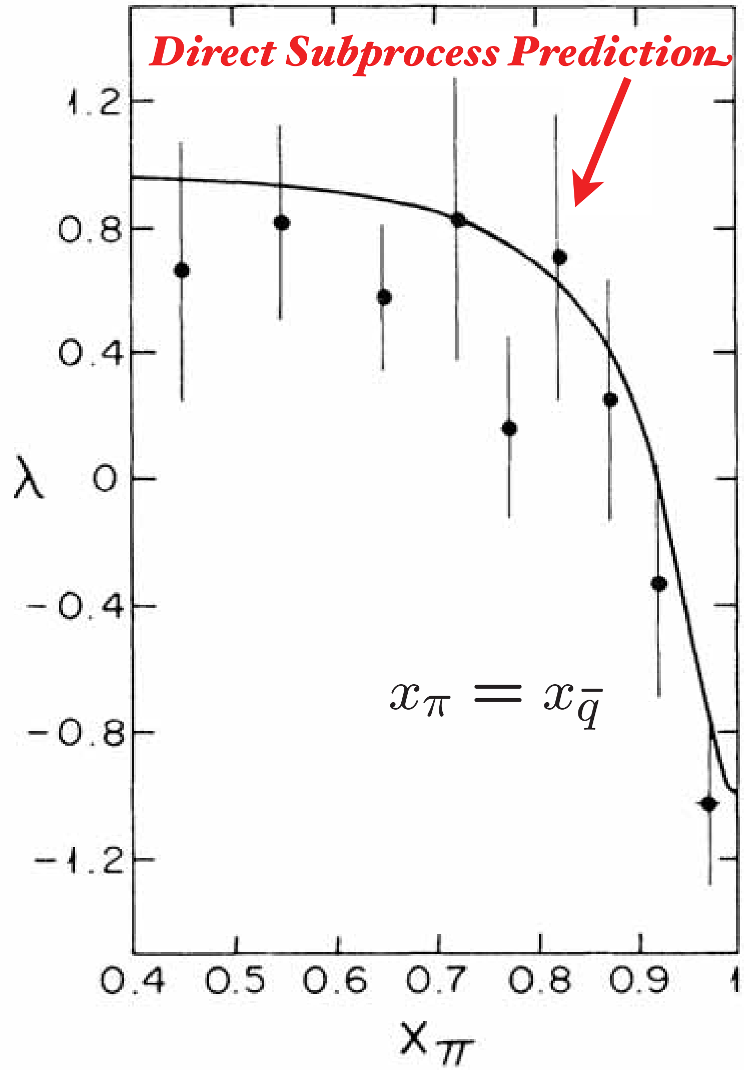
All of the pion's momentum is transferred to the lepton pair
Lepton Pair is produced longitudinally polarized

$\pi^- N \rightarrow \mu^+ \mu^- X$ at 80 GeV/c

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

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

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



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

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

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

$n_{eff} = 4$

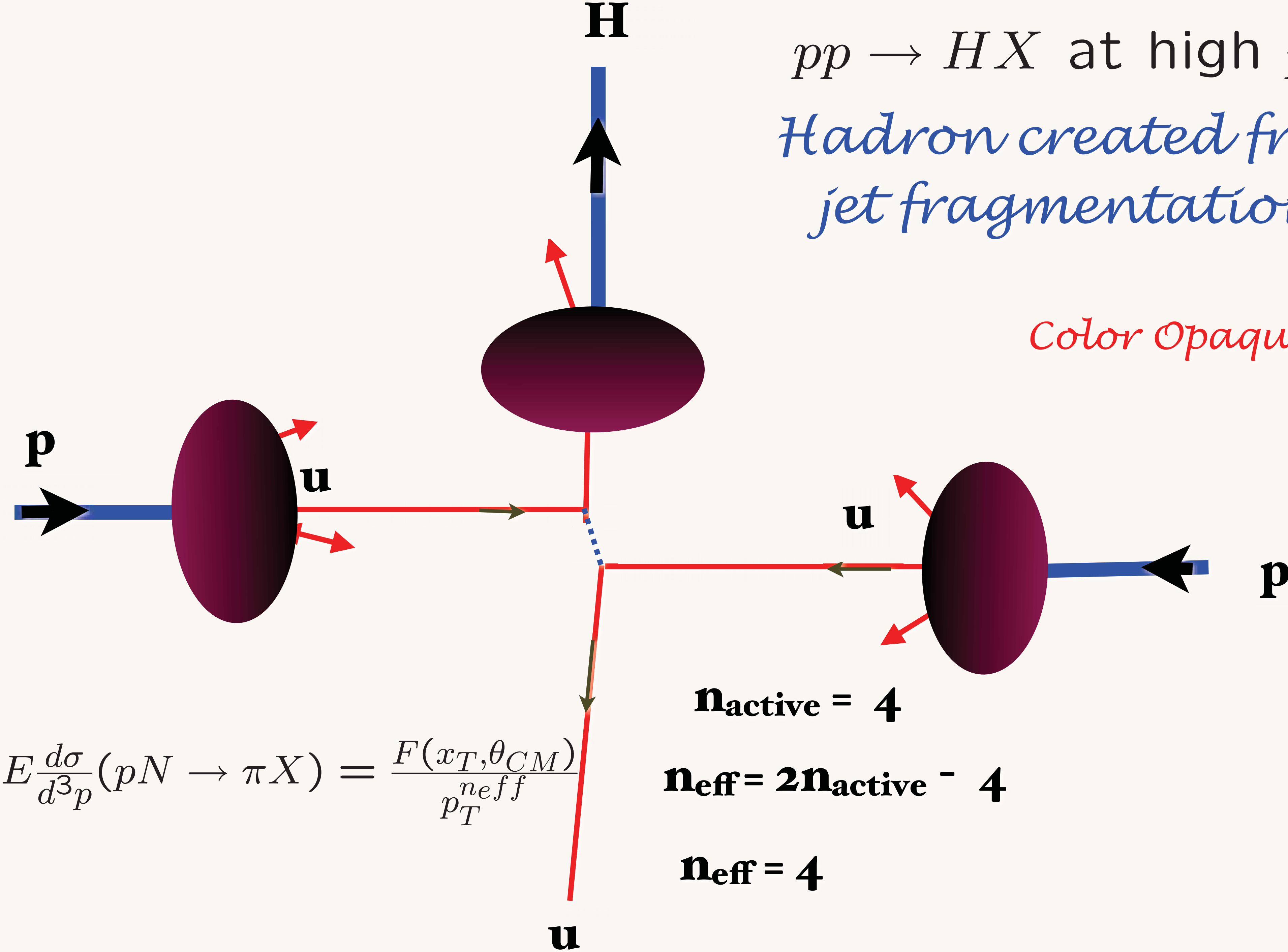
Bjorken scaling

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

Power increased by running coupling, DGLAP evolution

$pp \to HX$ at high p_T

Hadron created from jet fragmentation



Color Opaque

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

$n_{active} = 4$

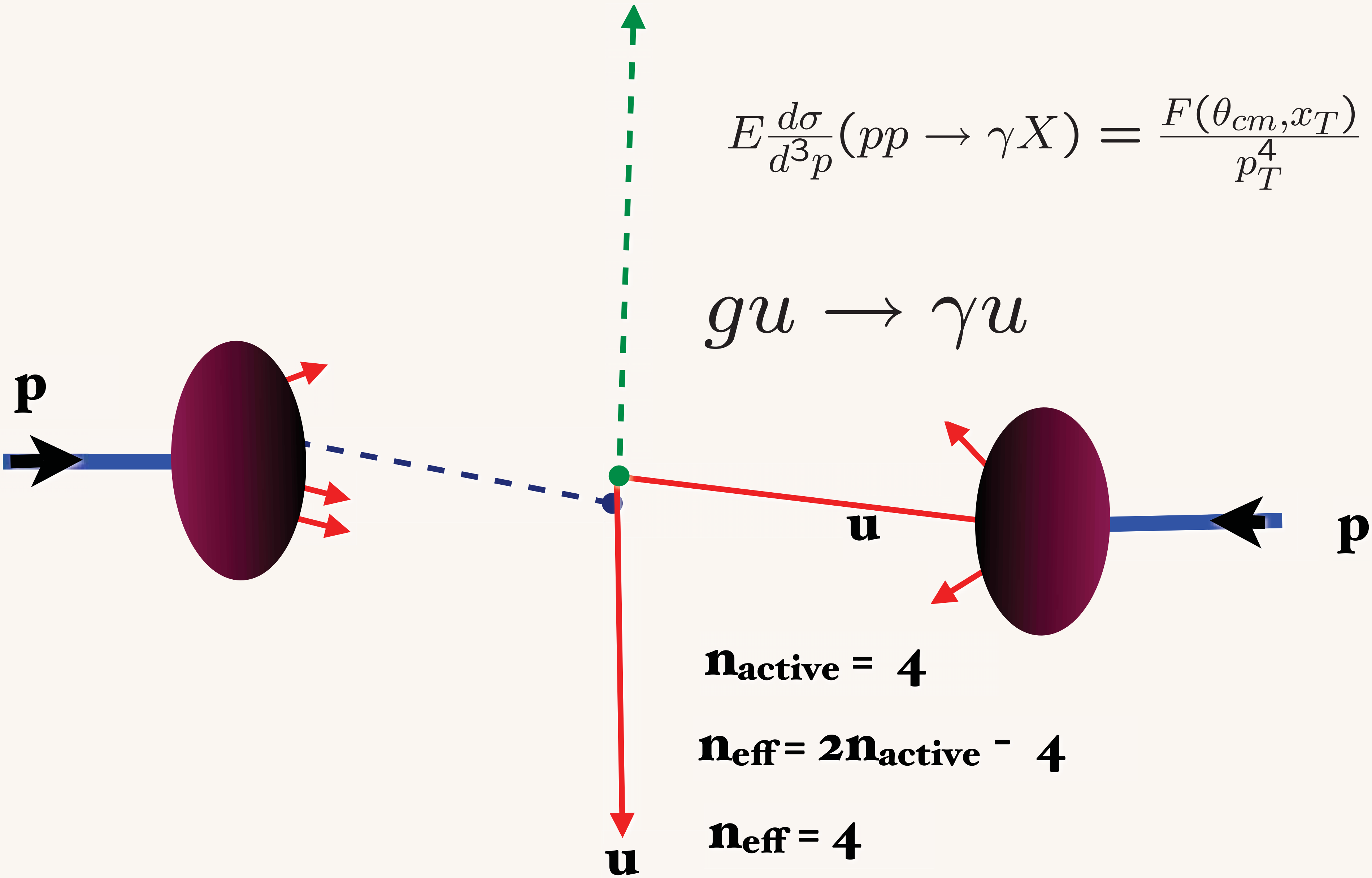
$n_{eff} = 2n_{active} - 4$

$n_{eff} = 4$

$$pp \to \gamma X$$

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

$$gu \to \gamma u$$

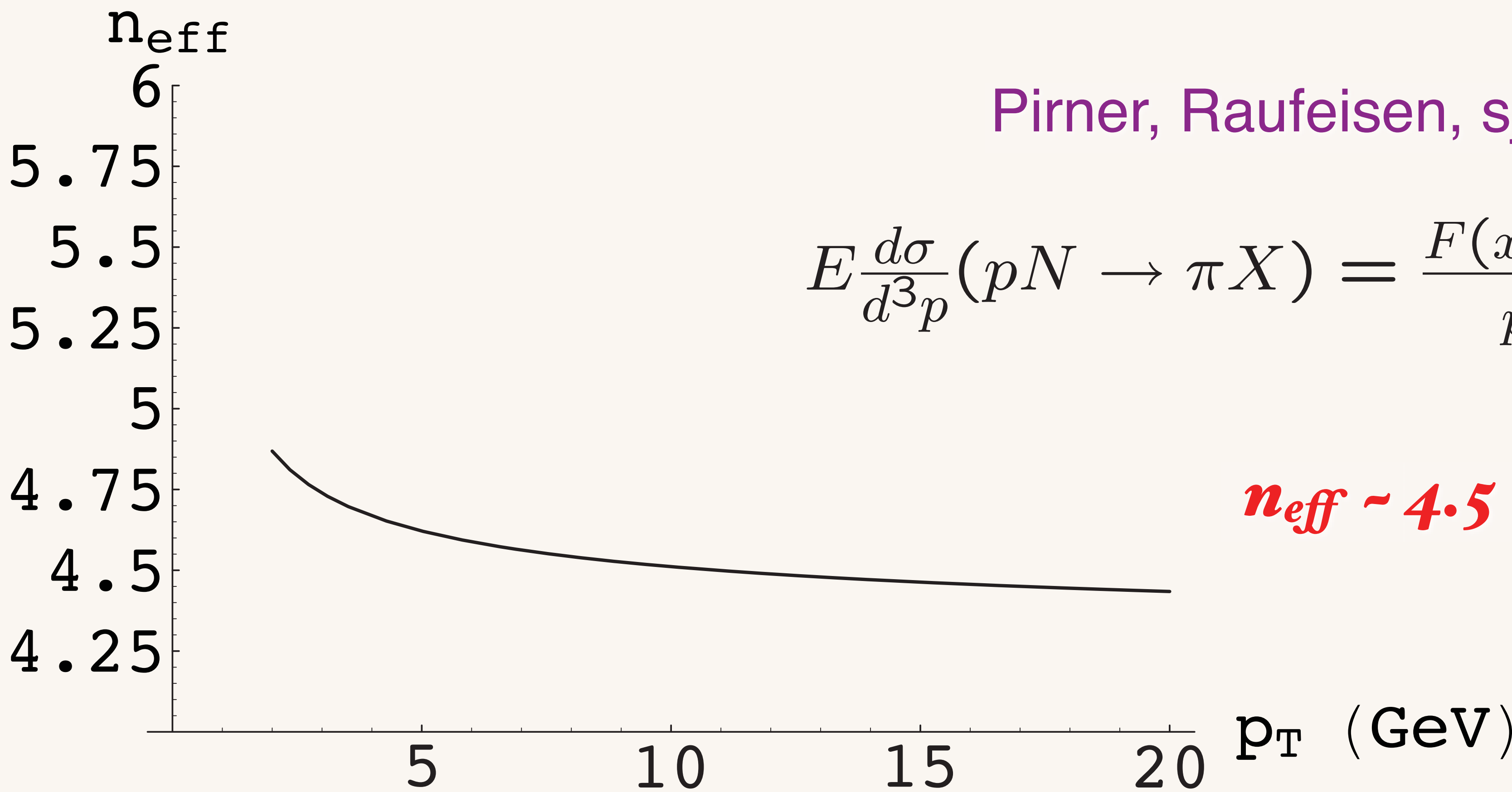


$n_{active} = 4$

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

$n_{eff} = 4$

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



Pirner, Raufeisen, sjb

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

$n_{eff} \sim 4.5$

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

$$d\sigma(h_a h_b \to hX) = \sum_{abc} G_{a/h_a}(x_a) G_{b/h_b}(x_b) dx_a dx_b \frac{1}{2\hat{s}} \left|A_{fi}\right|^2 dX_f D_{h/c}(z_c) dz_c.$$

$$E\frac{d^3\sigma(h_a h_b \to hX)}{d^3p} = \frac{F(y, x_R)}{p_T^{n(y,x_R)}}.$$

$$n = 2n_{active} - 4,$$

Pirner, Raufeisen, sjb

$$n_{eff}(p_T) = -\frac{d \ln E \frac{d^3\sigma(h_a h_b \to hX)}{d^3p}}{d \ln(p_T)}$$

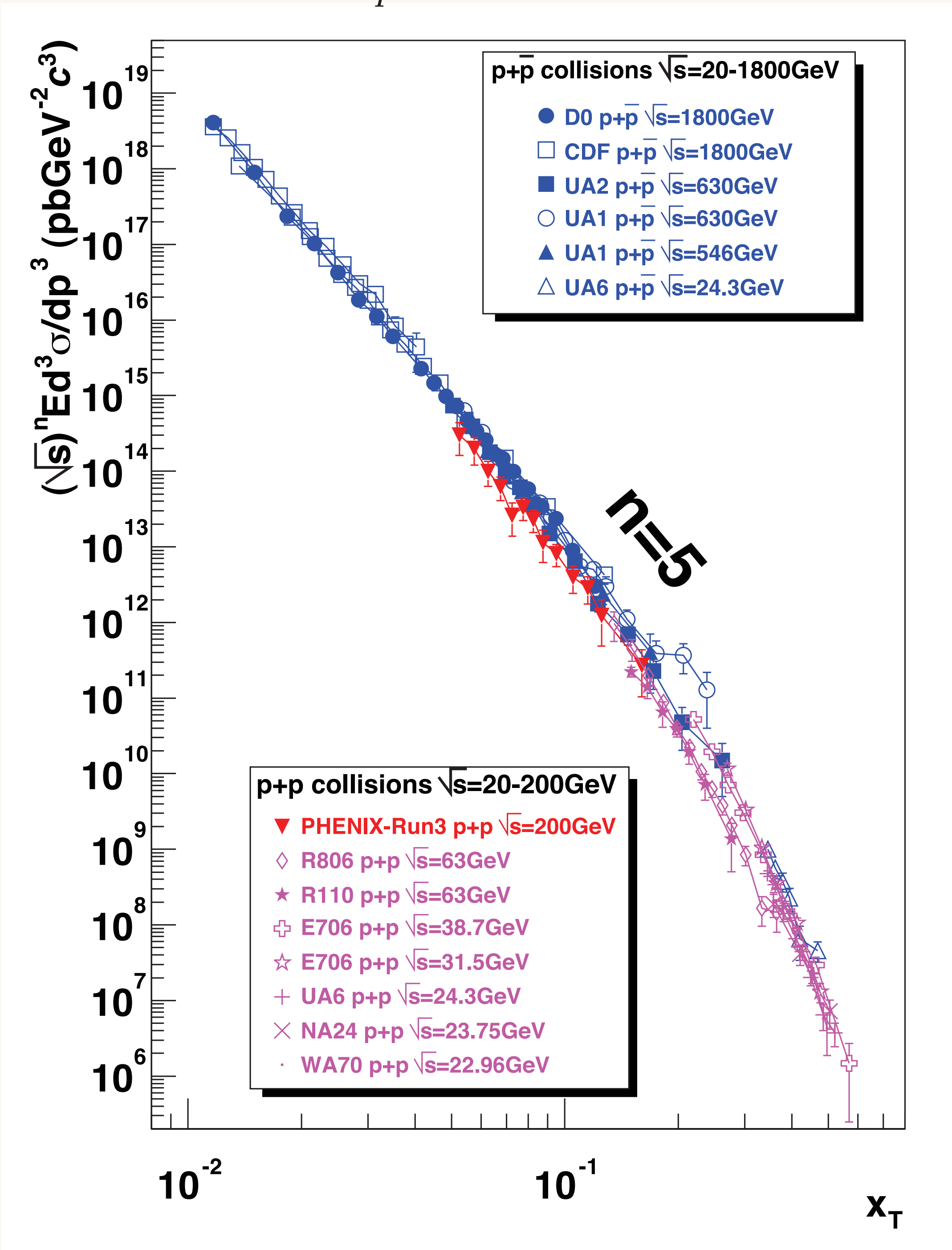
$n_{eff} \sim 4.5$

$$E\frac{d^3\sigma(h_a h_b \to hX)}{d^3p} = \left[\frac{\alpha_s(p_T^2)}{p_T^2}\right]^{n_{active}-2} \frac{(1-x_R)^{2n_s-1+3\xi(p_T)}}{x_R^{\lambda(p_T)}} \alpha_s^{2n_s}(k_{x_R}^2) f(y).$$

$$\xi(p_T) = \frac{C_R}{\pi} \int_{k_{x_R}^2}^{p_T^2} \frac{dk_\perp^2}{k_\perp^2} \alpha_s(k_\perp^2) = \frac{4C_R}{\beta_0} \ln \frac{\ln(p_T^2/\Lambda_{QCD}^2)}{\ln(k_{x_R}^2/\Lambda_{QCD}^2)}.$$

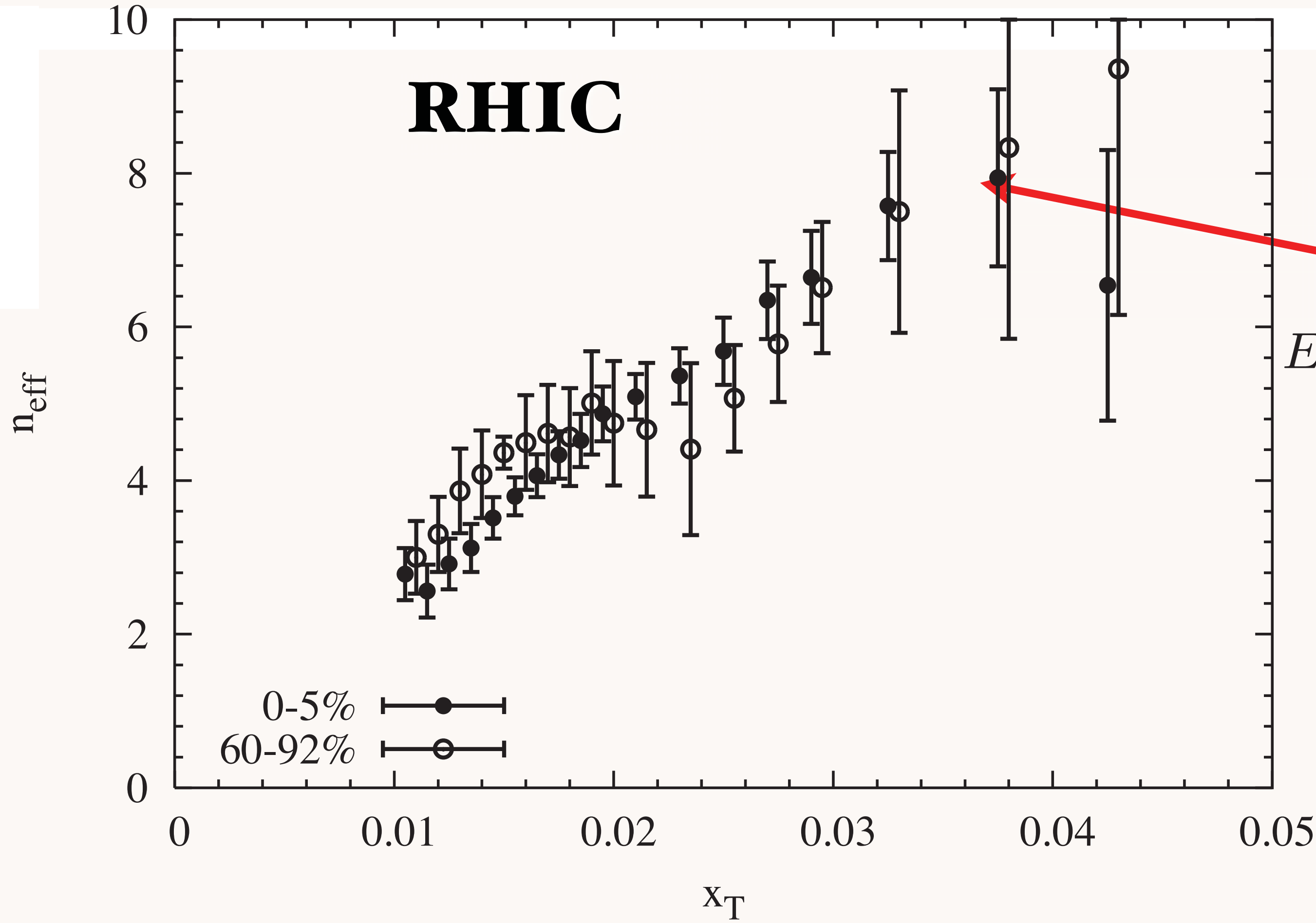
$\sqrt{s}^n E\frac{d\sigma}{d^3p}(pp \to \gamma X)$ at fixed x_T

Tannenbaum



x_T-scaling of direct photon production is consistent with PQCD

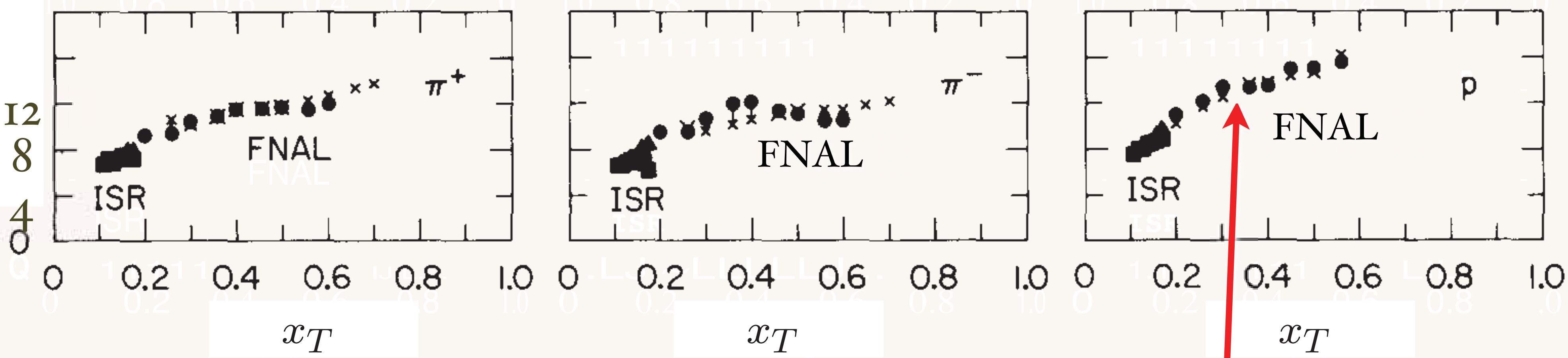
$$E\frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T,\theta_{CM})}{p_T^{n_{eff}}}$$

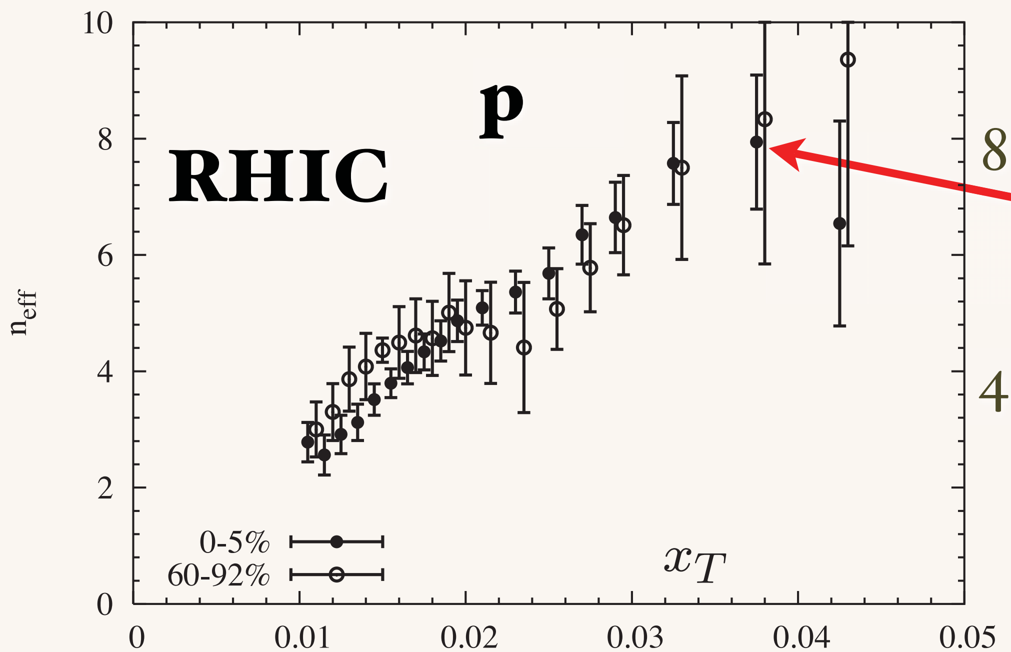


$$E\frac{d\sigma}{d^3p}(pp \to pX) = \frac{F(x_T,\theta_{CM})}{p_T^8}$$

Proton production at RHIC far from leading-twist

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





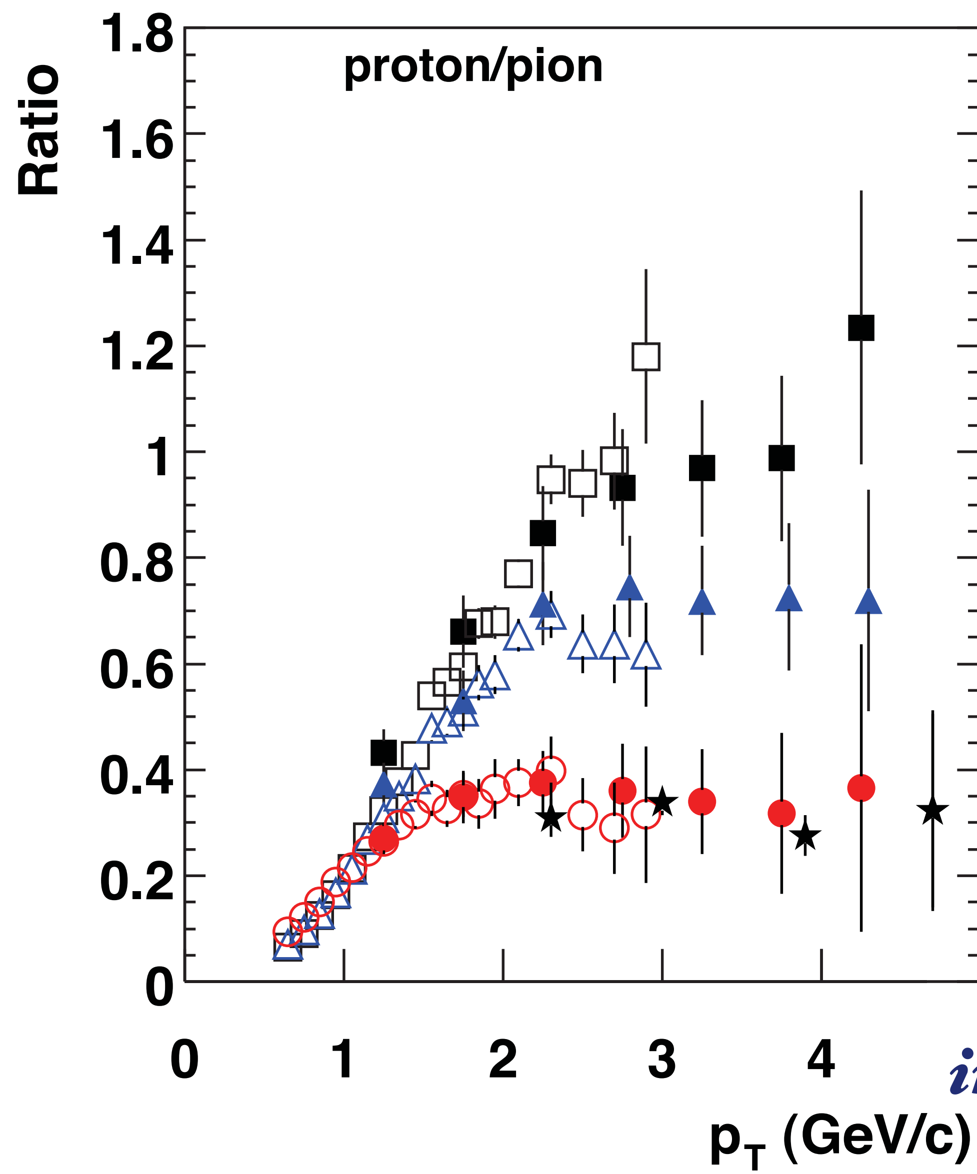
$$E\frac{d\sigma}{d^3p}(pp \to pX) = \frac{F(x_T,\theta_{CM})}{p_T^{12}}$$

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

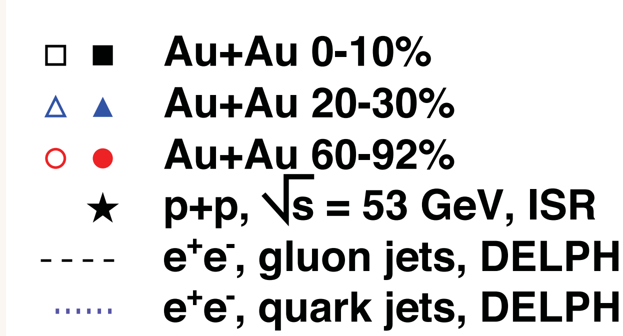
ISR/FNA consistent with RHIC at small x_T

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

Particle ratio changes with centrality!



← **Central**



← **Peripheral**

Protons less absorbed in nuclear collisions than pions!

Open (filled) points are for $\pi^{\pm}$ (π^0), respectively.

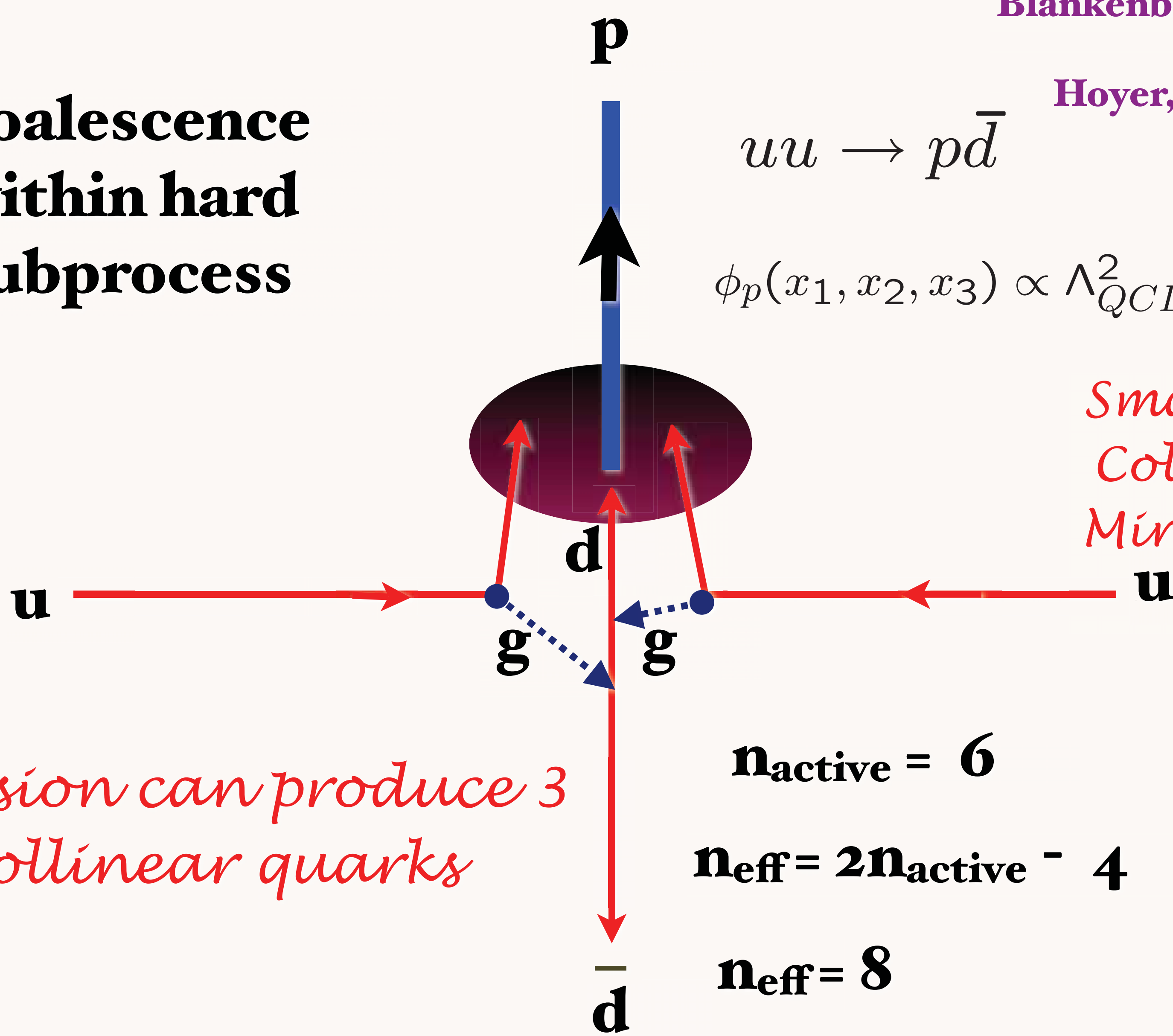
Baryon can be made directly within hard subprocess

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

Coalescence within hard subprocess

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

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



Small color-singlet
Color Transparent
Minimal same-side energy

Collision can produce 3 collinear quarks

$n_{active} = 6$

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

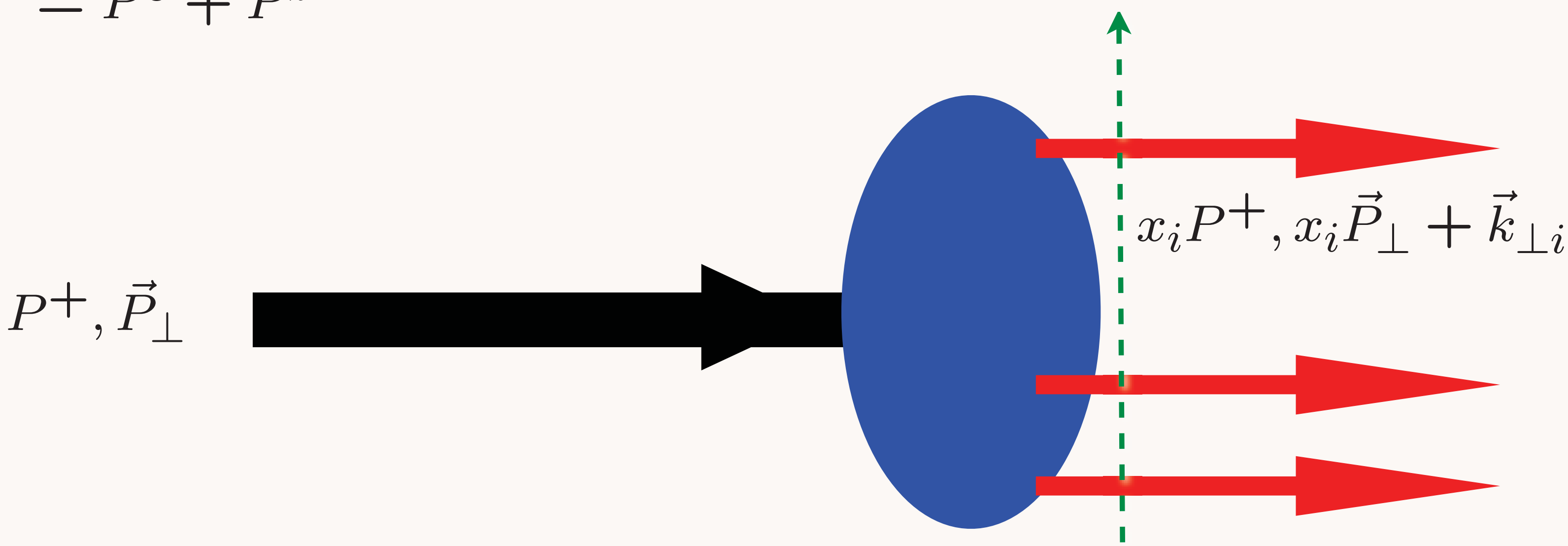
$n_{eff} = 8$

$$qq \rightarrow B\bar{q}$$

Light-Front Wavefunctions

Fixed $\tau = t + z/c$

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



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

$\sum_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

Hadron Dynamics at the Amplitude Level

- LFWFS are the universal hadronic amplitudes which underlie structure functions, GPDs, exclusive processes, distribution amplitudes, direct subprocesses, hadronization.

- Relation of spin, momentum, and other distributions to physics of the hadron itself.

- Connections between observables, orbital angular momentum

- Role of FSI and ISIs--Sivers effect

PACSPIN '07:

Strong Experimental and Theoretical Progress in Hadron Spin Physics

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