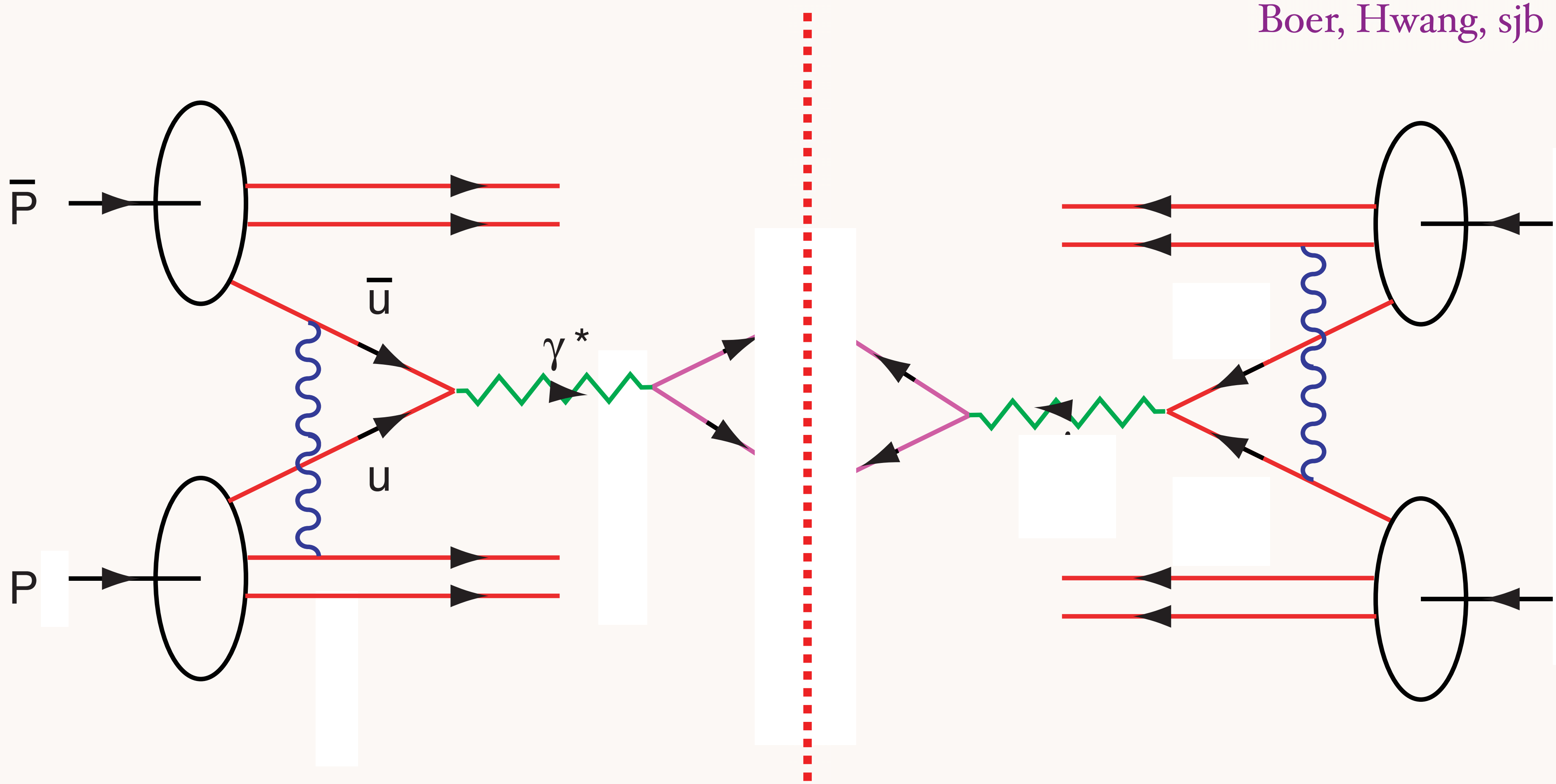
Boer, Hwang, sjb



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

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

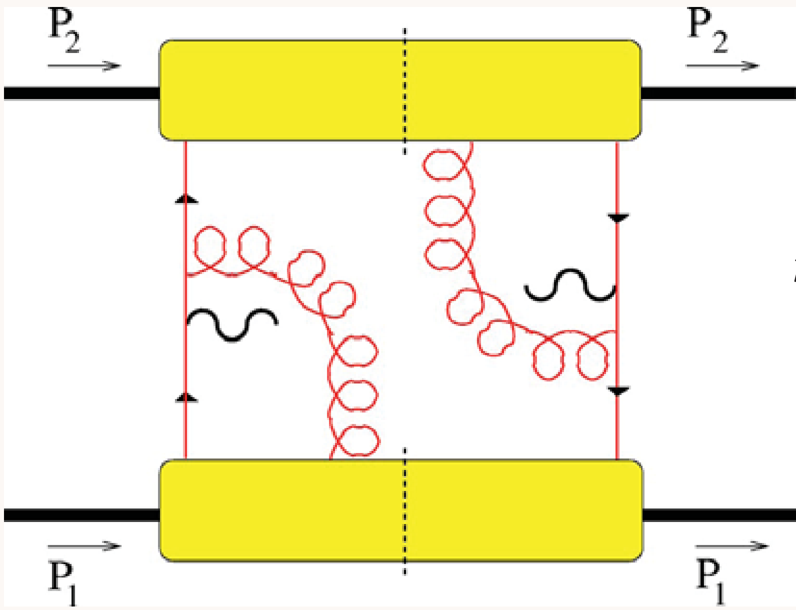
Boer, Hwang, sjb

Drell-Yan planar correlations

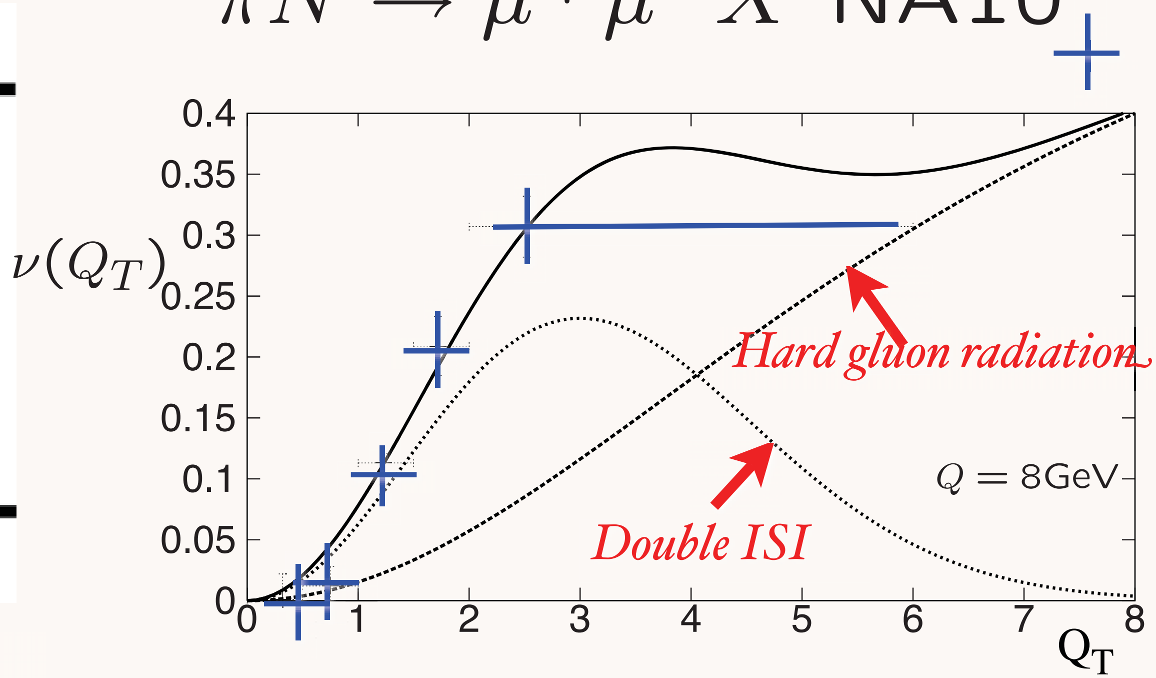
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \left(1 + \lambda\cos^2\theta + \mu\sin 2\theta\,\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right)$$

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

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



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



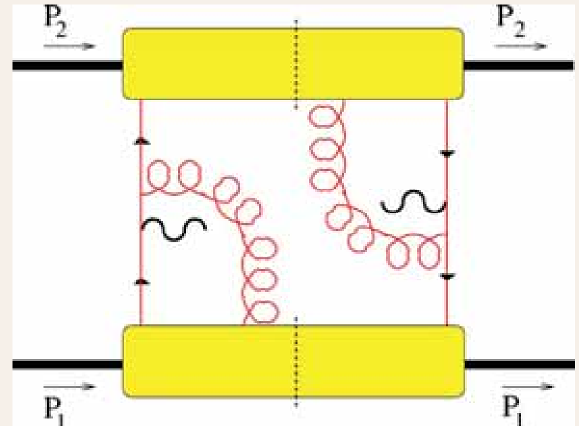
Violates Lam-Tung relation!

Model: Boer,

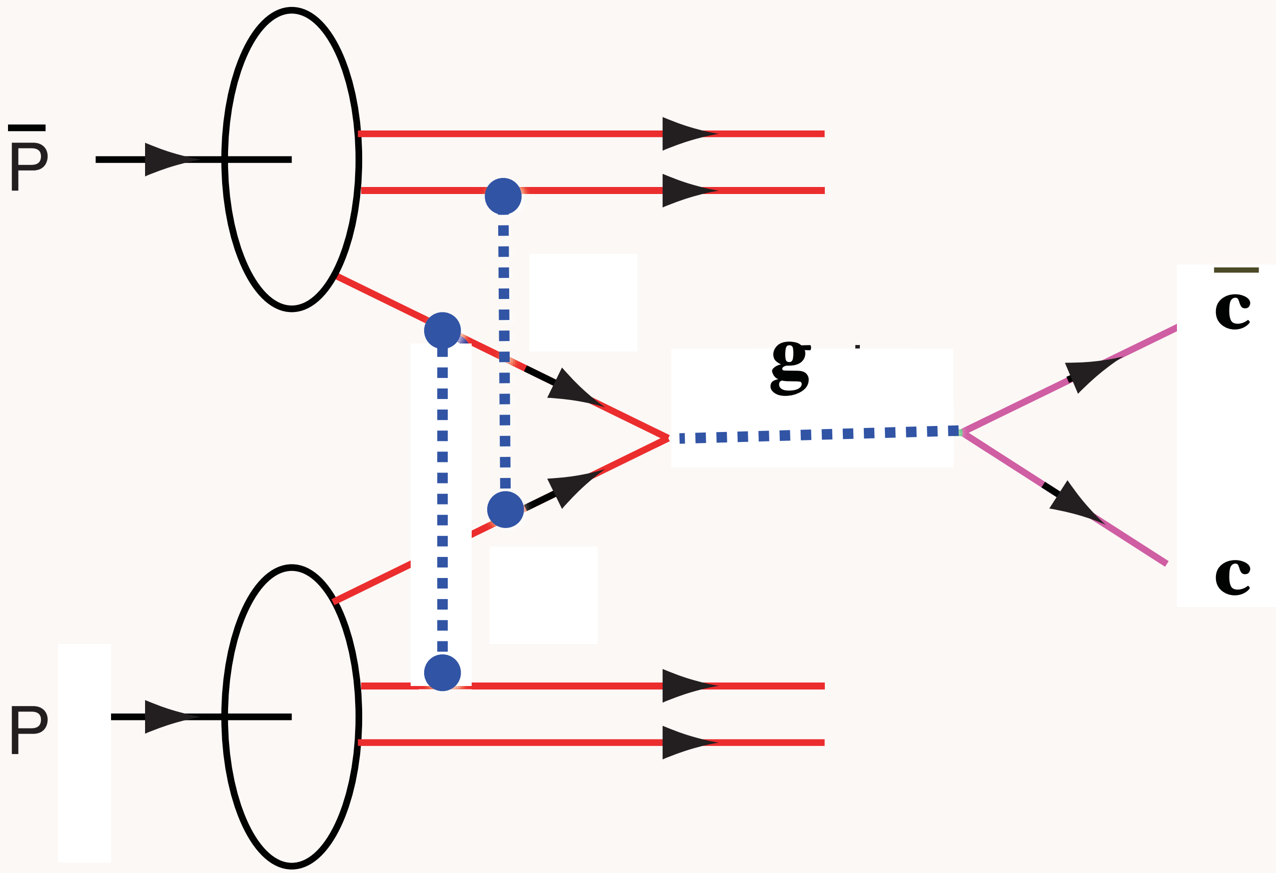
Anomalous effect from Double ISI in Massive Lepton Production

Boer, Hwang, sjb

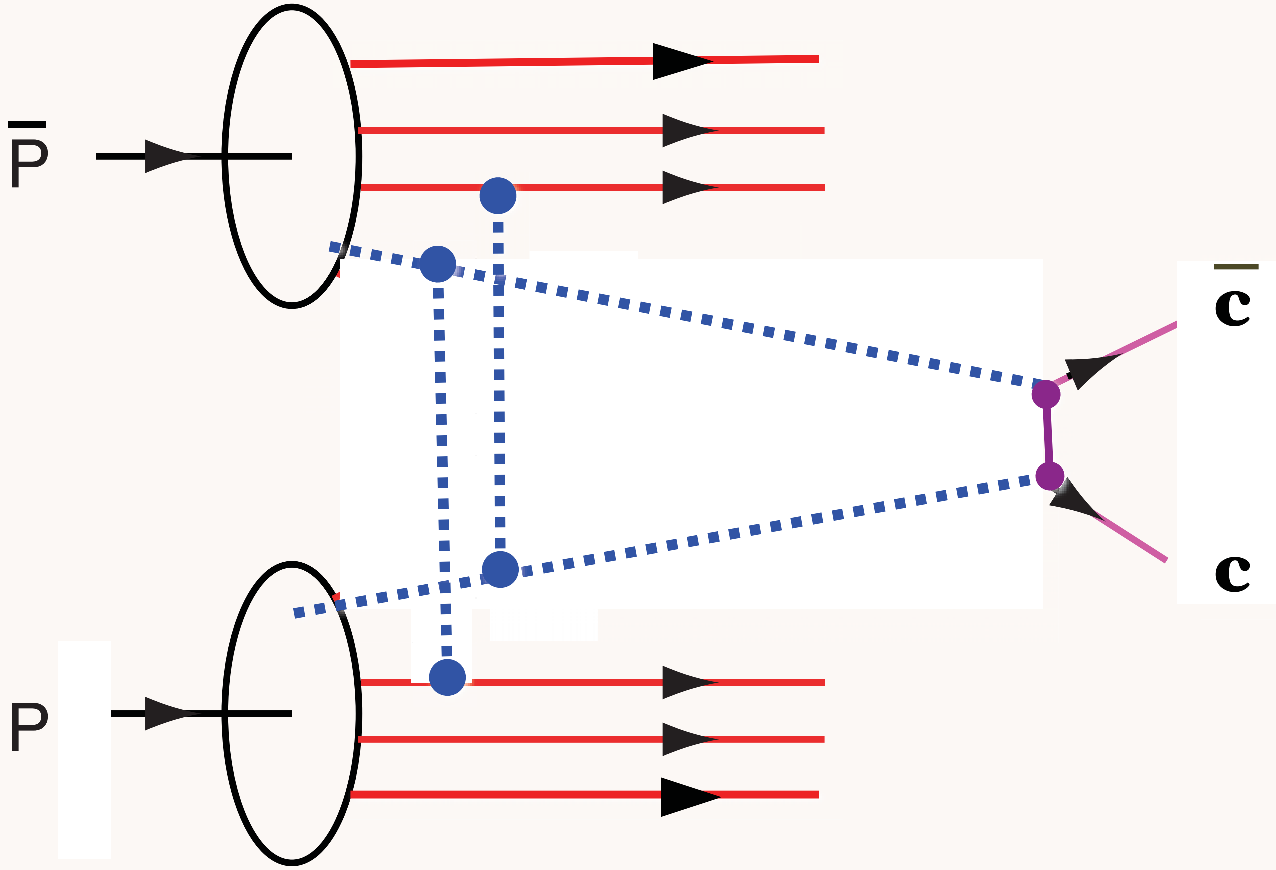
$\cos 2\phi$ correlation



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

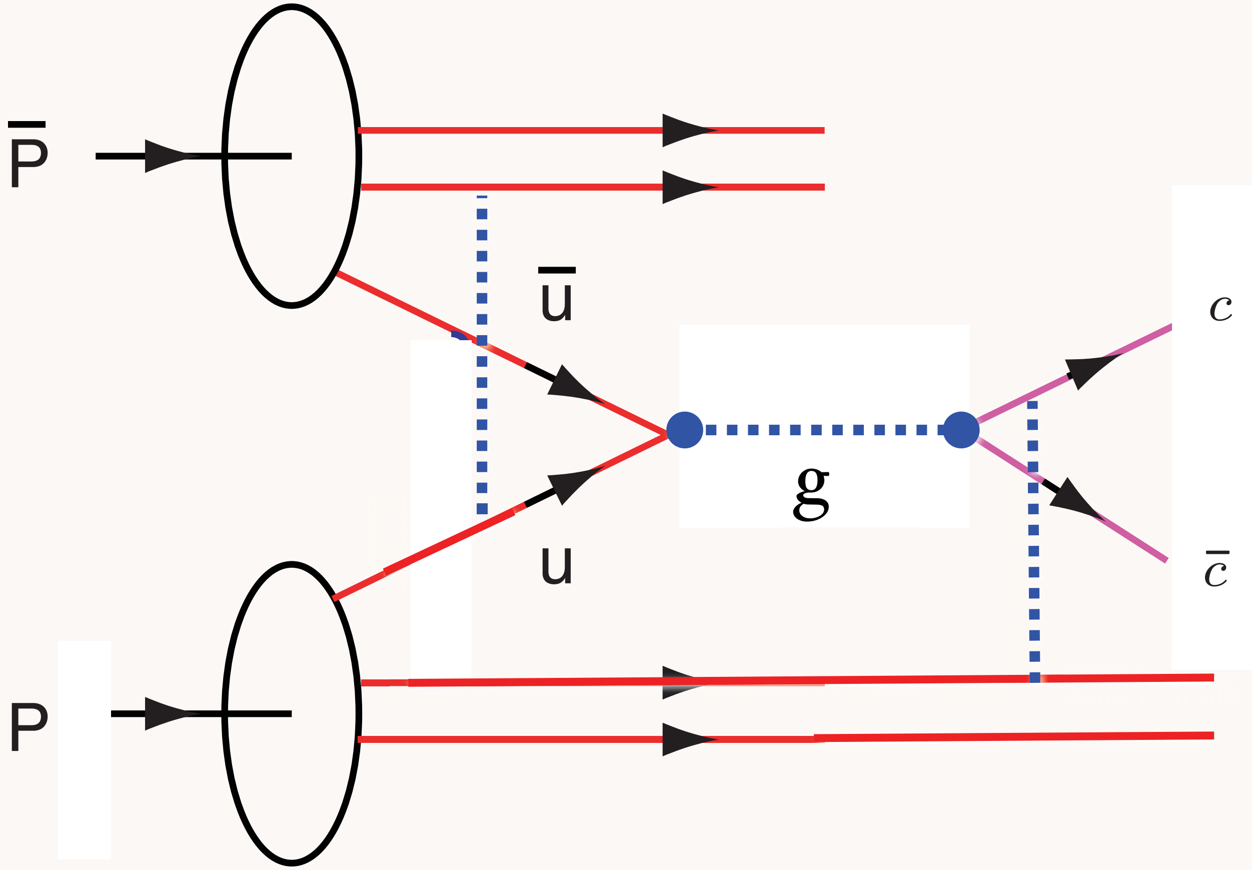


$\cos 2\phi$ **correlation for quarkonium production at leading twist from double ISI**



$\cos 2\phi$ **correlation for quarkonium production at leading twist from double ISI**

Enhanced by gluon color charge

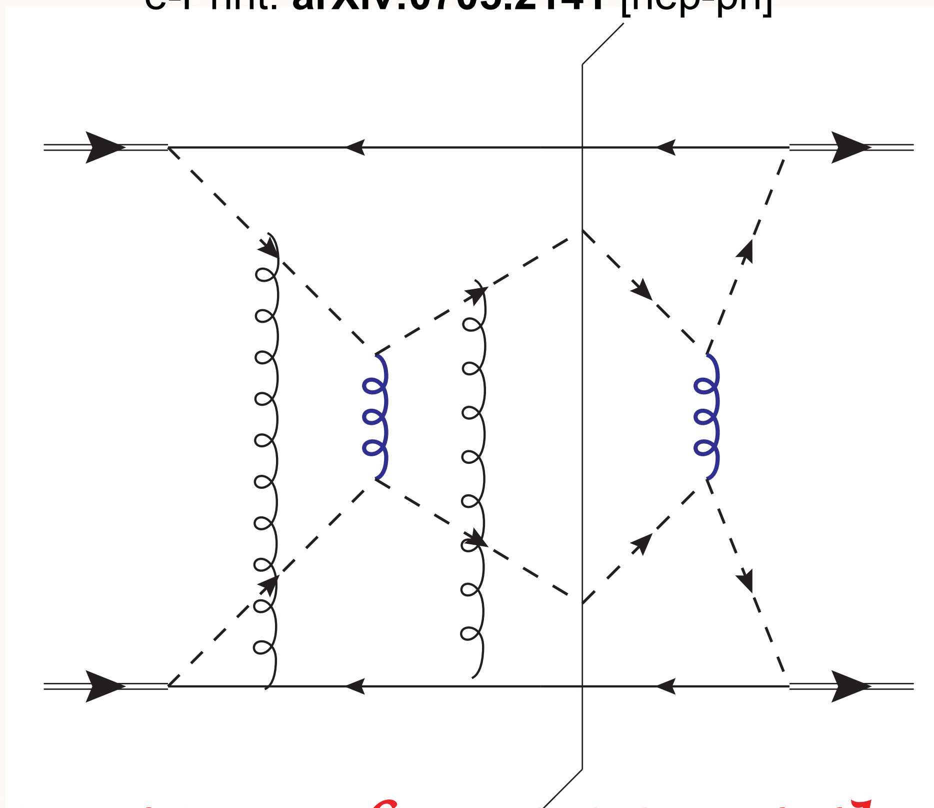


Problem for factorization when both ISI and FSI occur

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]



Implications for QCD at the LHC

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

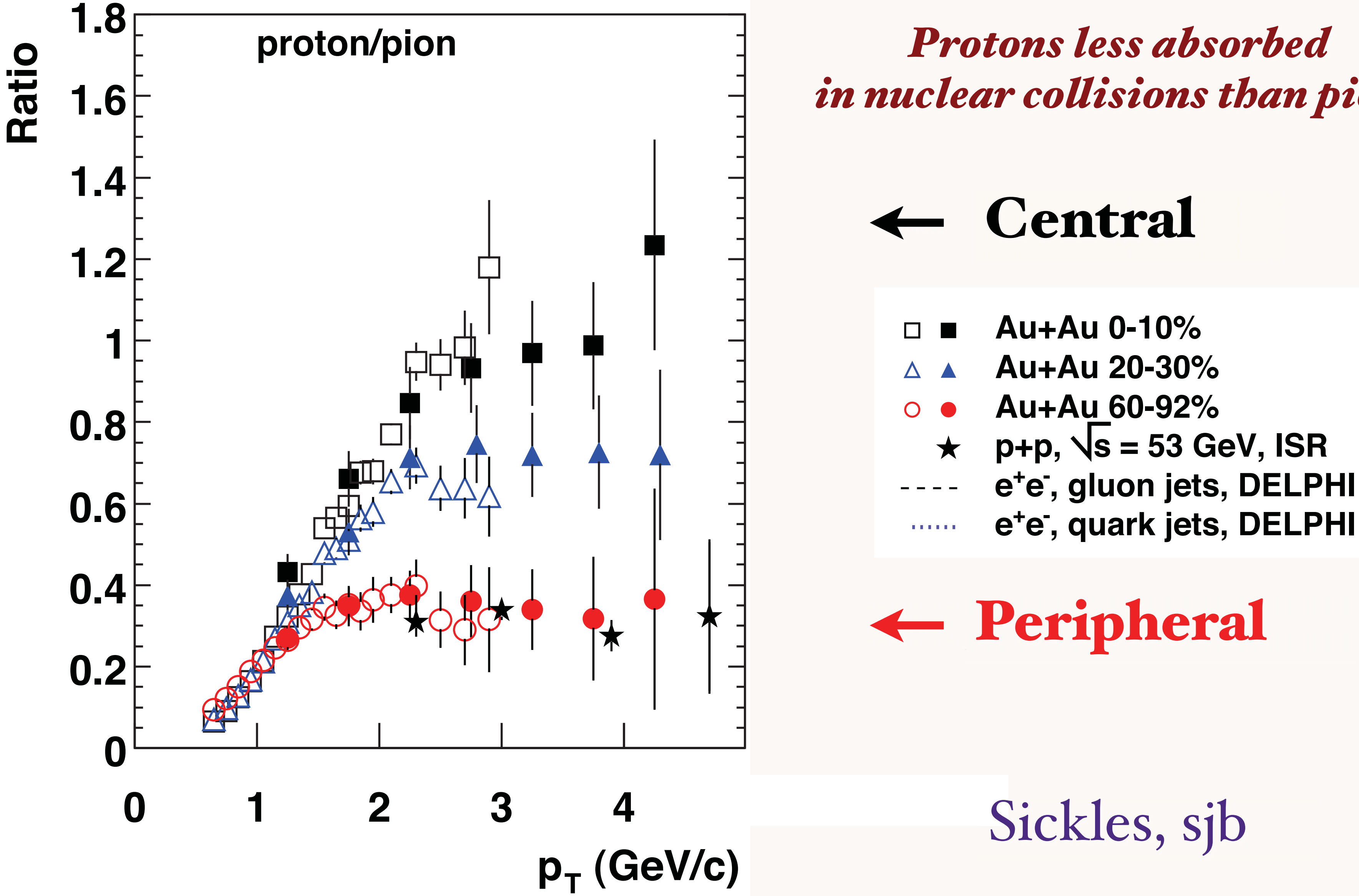
- Although we know the QCD Lagrangian, we have only begun to understand its remarkable properties and features.

- 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, dangling gluons, shadowing, antishadowing, QGP, CGC, ...

Truth is stranger than fiction, but it is because Fiction is obliged to stick to possibilities. —*Mark Twain*

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

Baryon Anomaly: Particle ratio changes with centrality!



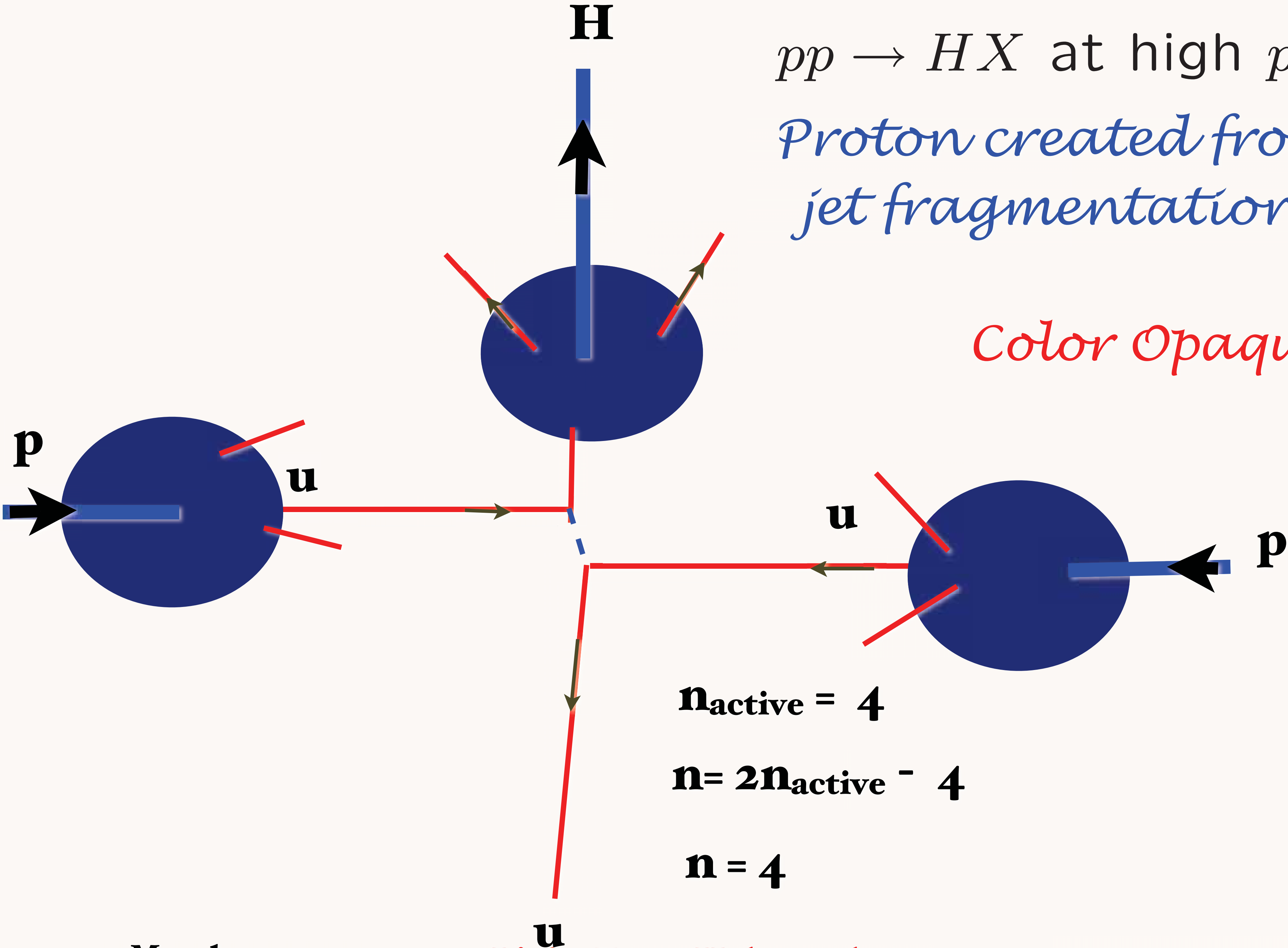
Protons less absorbed in nuclear collisions than pions

Sickles, sjb

$pp \rightarrow HX$ 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

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

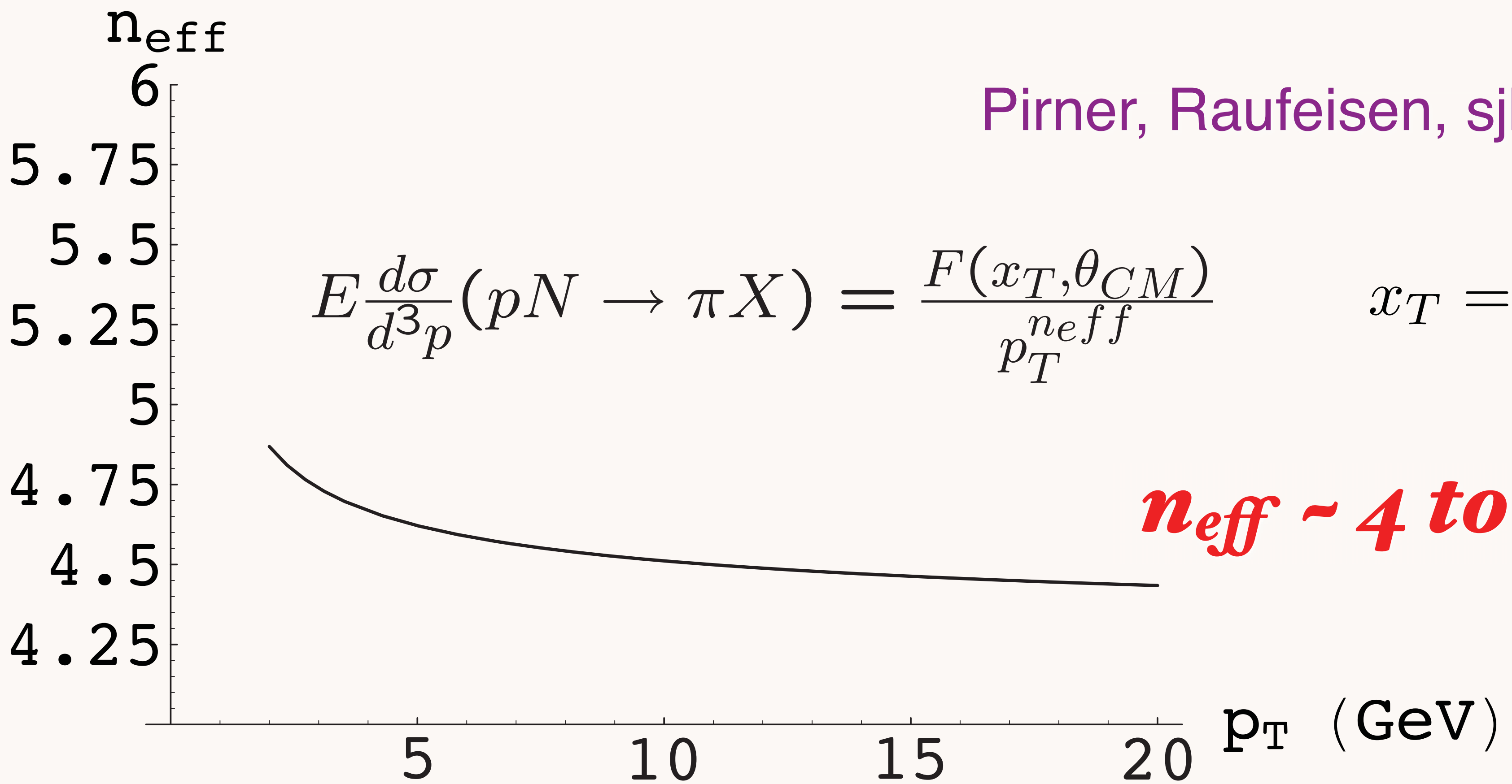
$$E\frac{d\sigma}{d^3p}(pN \to \pi X) = \frac{F(x_T,\theta_{CM})}{p_T^{neff}}$$

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



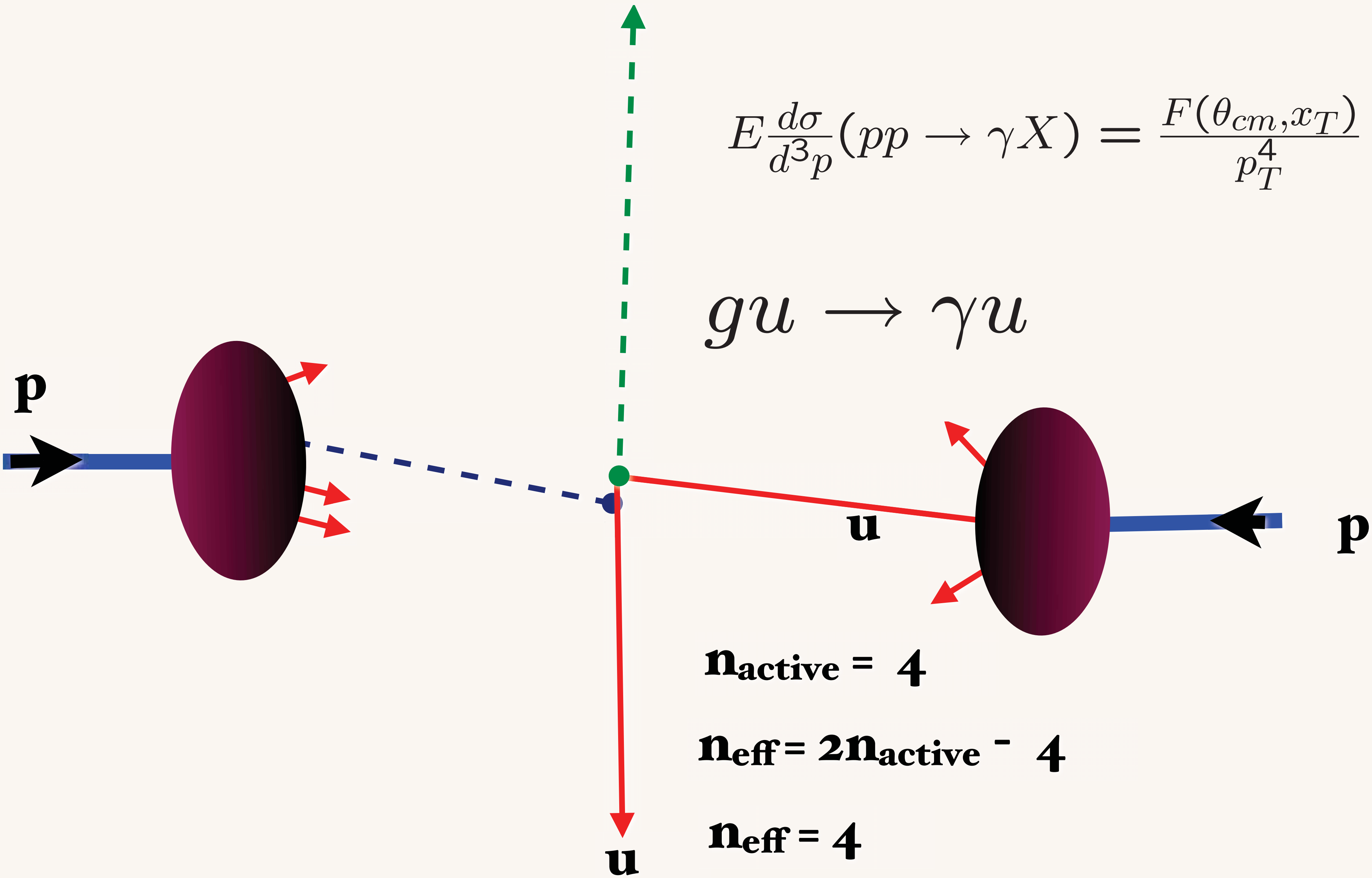
$$E\frac{d\sigma}{d^3p}(pN \to \pi X) = \frac{F(x_T, \theta_{CM})}{p_T^{n_{eff}}} \qquad x_T = \frac{2p_T}{\sqrt{s}}$$

n_{eff} ~ 4 to 5

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

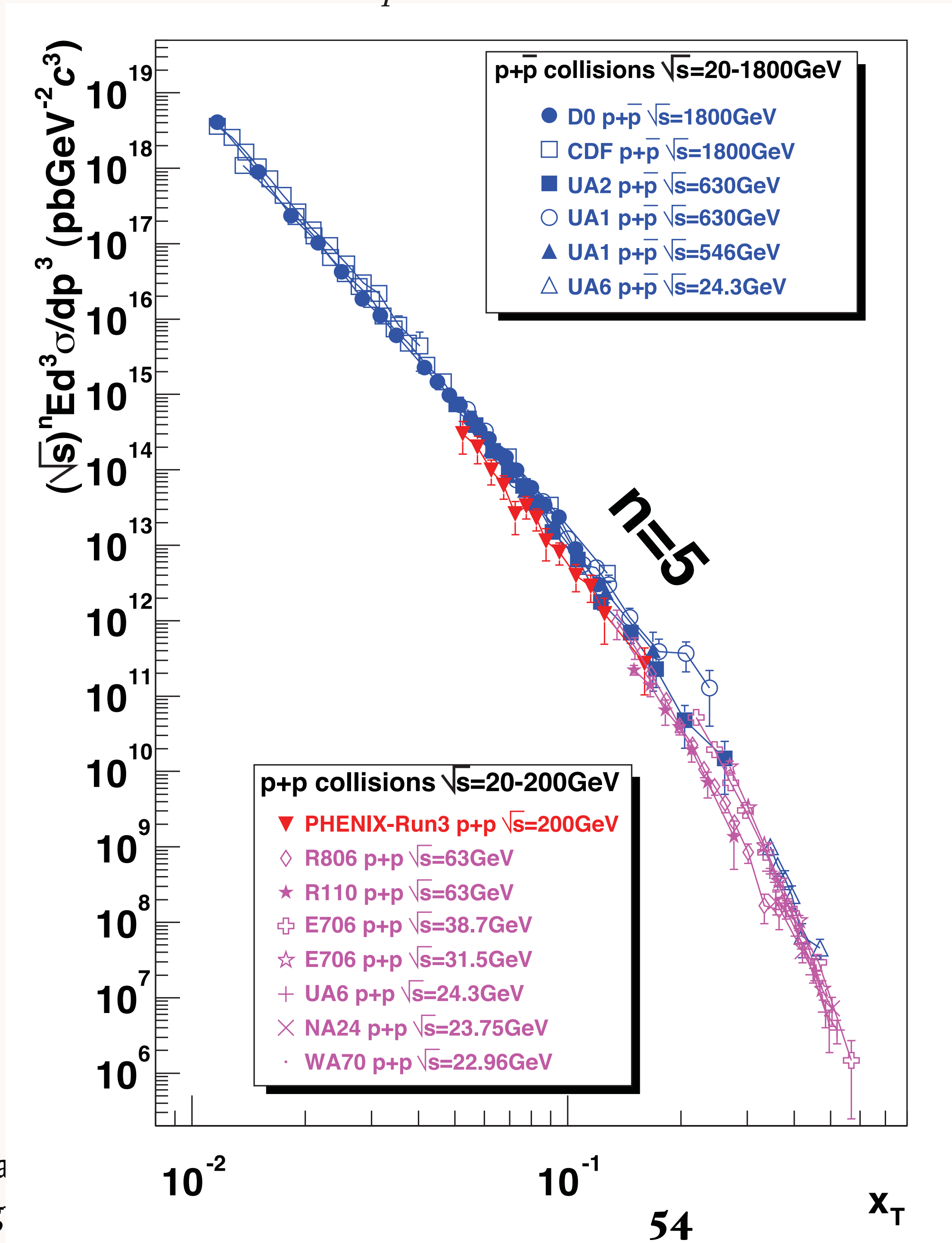
$$pp \longrightarrow \gamma X$$

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



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

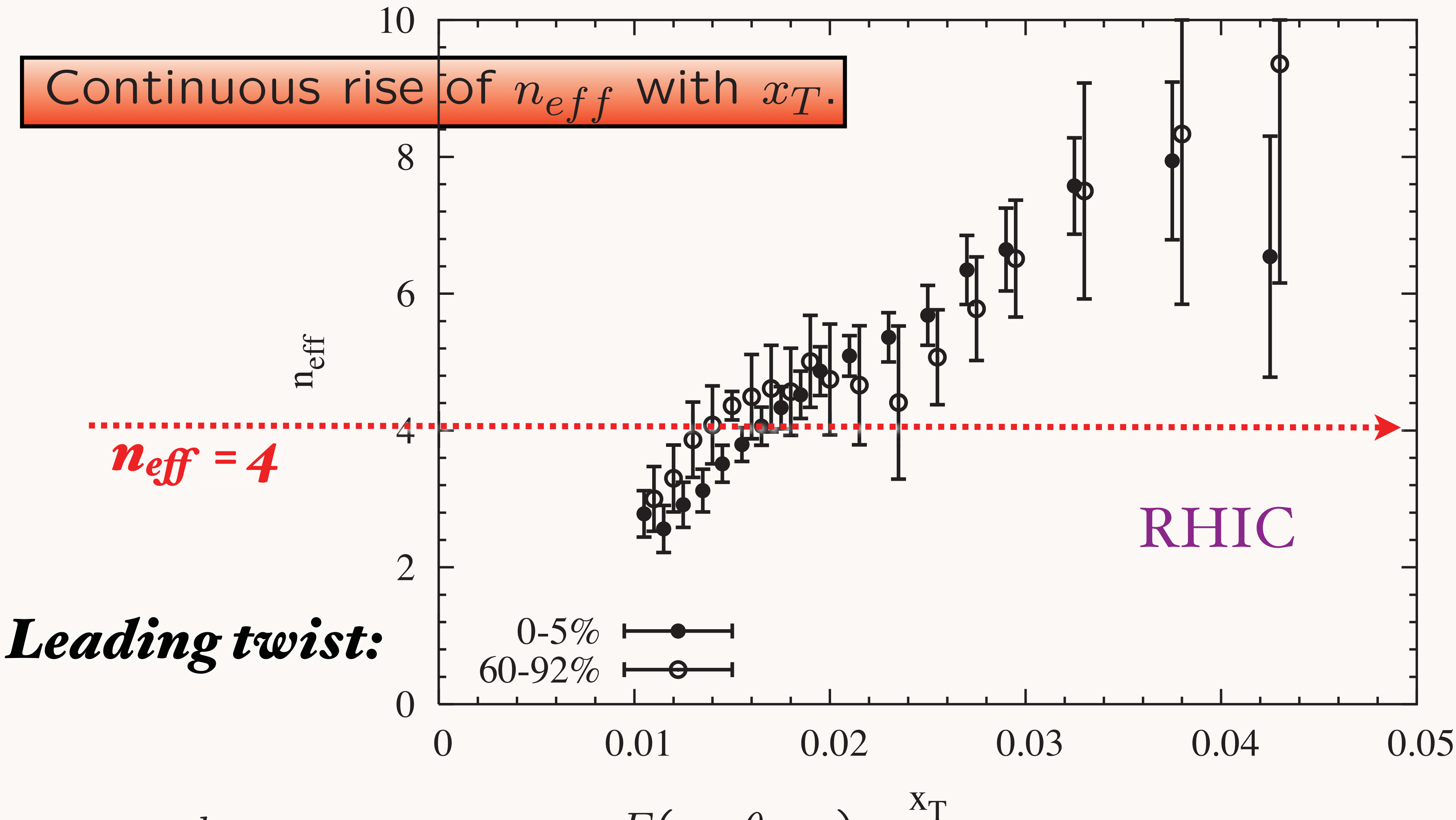
Tannenbaum



Scaling of direct photon production consistent with PQCD

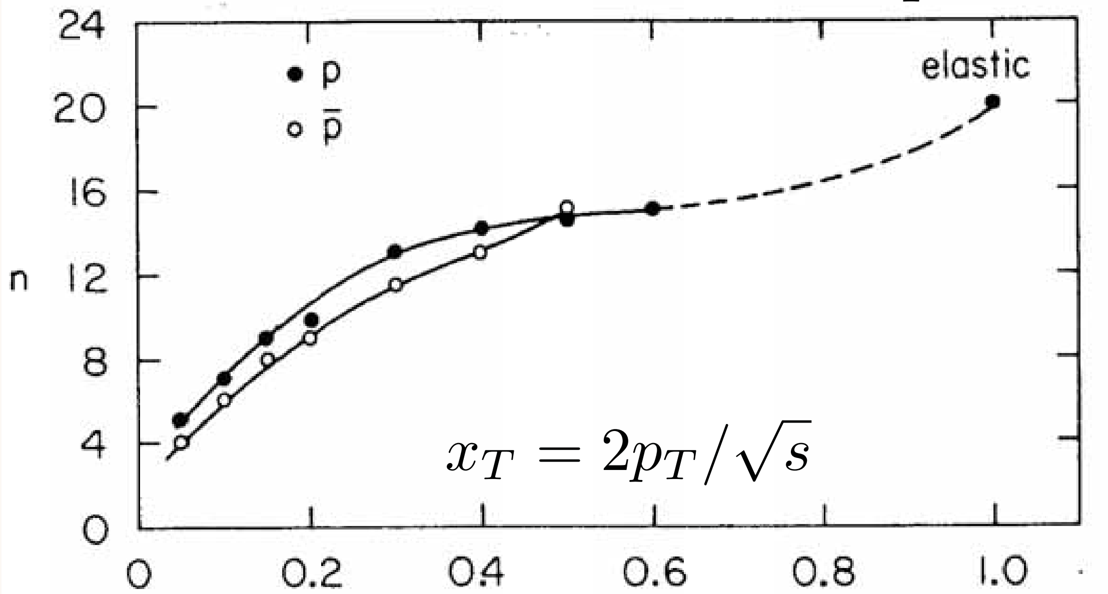
Stan Brodsky
SLAC & IPPP

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.



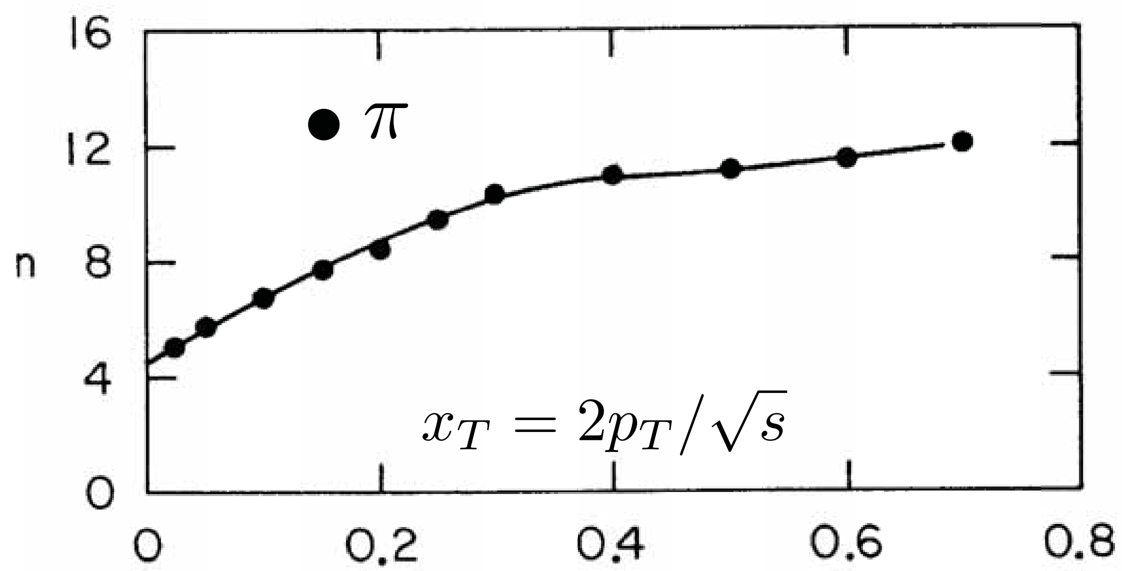
$$E\frac{d\sigma}{d^3p}(pN \to pX) = \frac{F(x_T,\theta_{CM})}{p_T^{n_{eff}}}$$

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

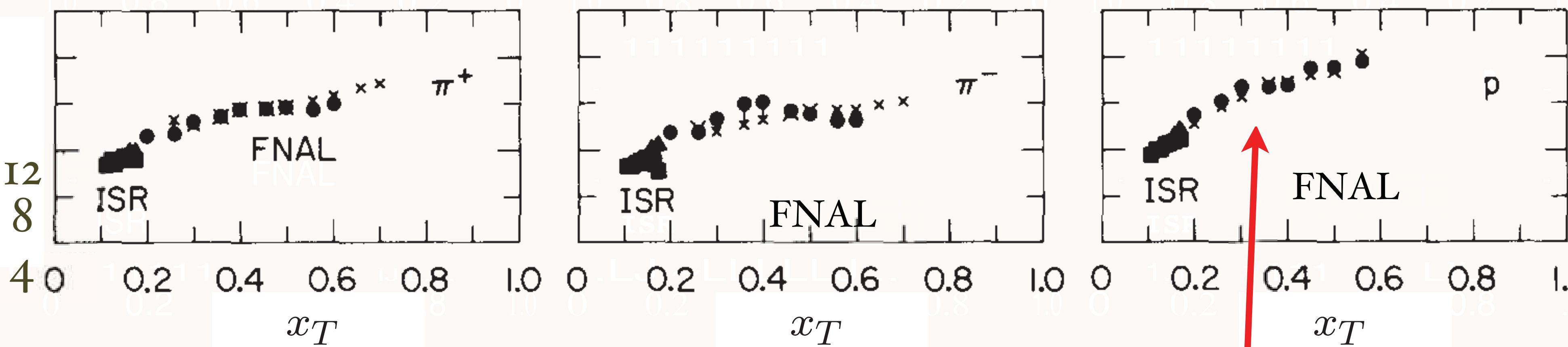


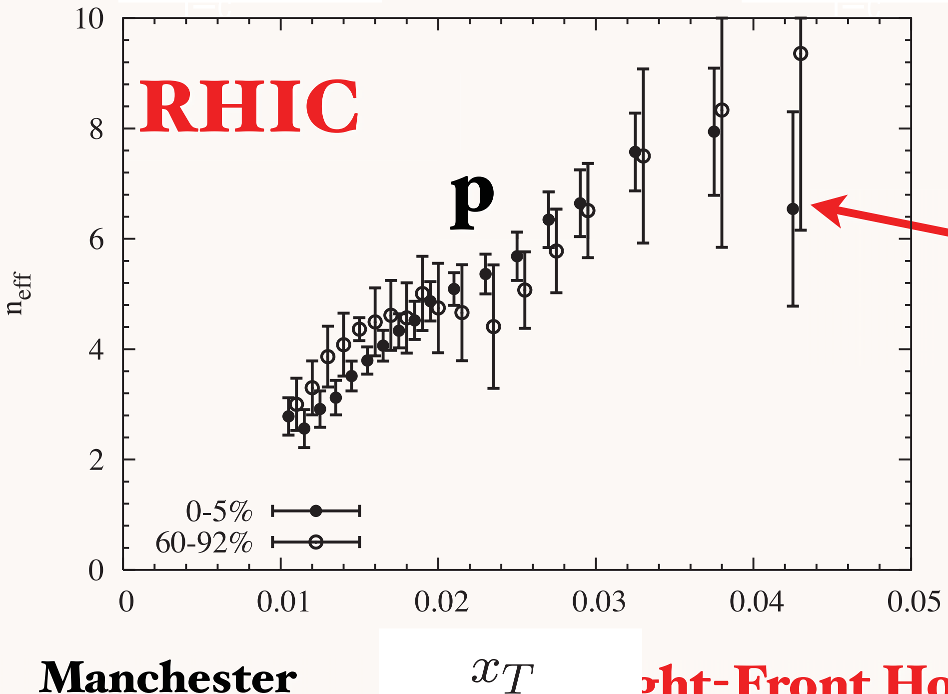
Clear evidence for higher-twist contributions

Fermilab, ISR data



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



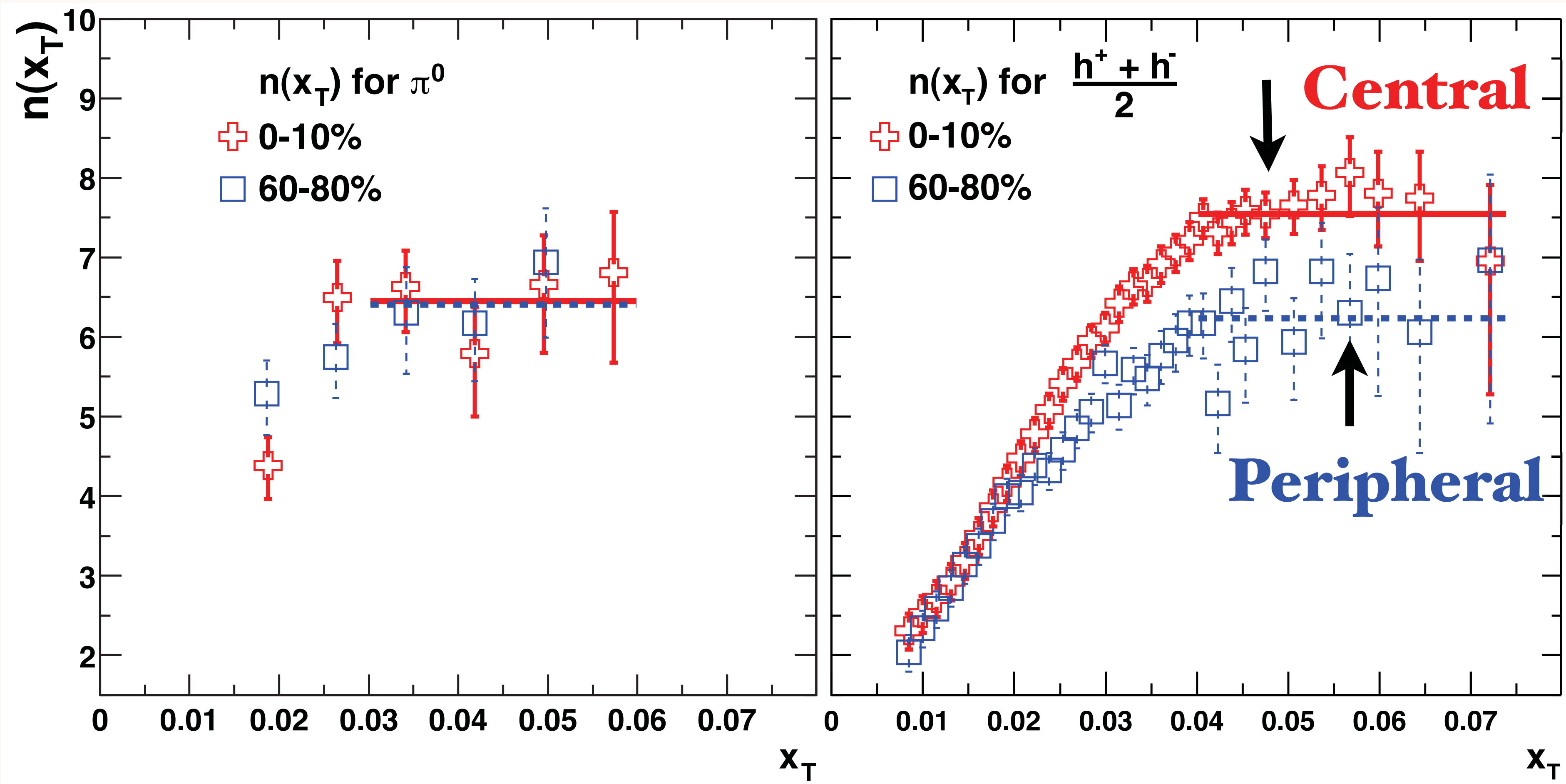


$$E\frac{d\sigma}{d^3p}(pp \to pX) = \frac{F(x_T, \theta_{CM})}{p_T^{12}}$$

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

Trend consistent with RHIC at small x_T

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

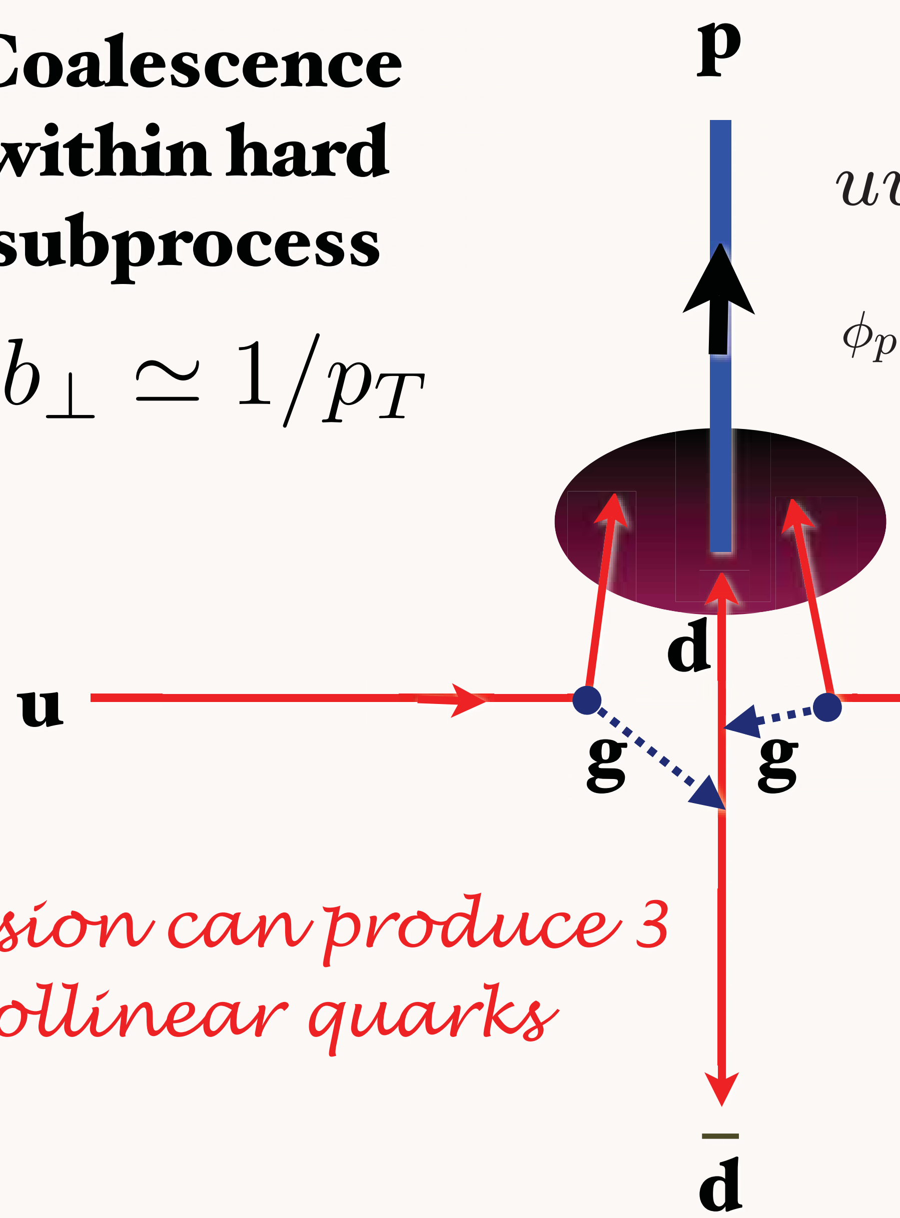


Proton power changes with centrality !

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

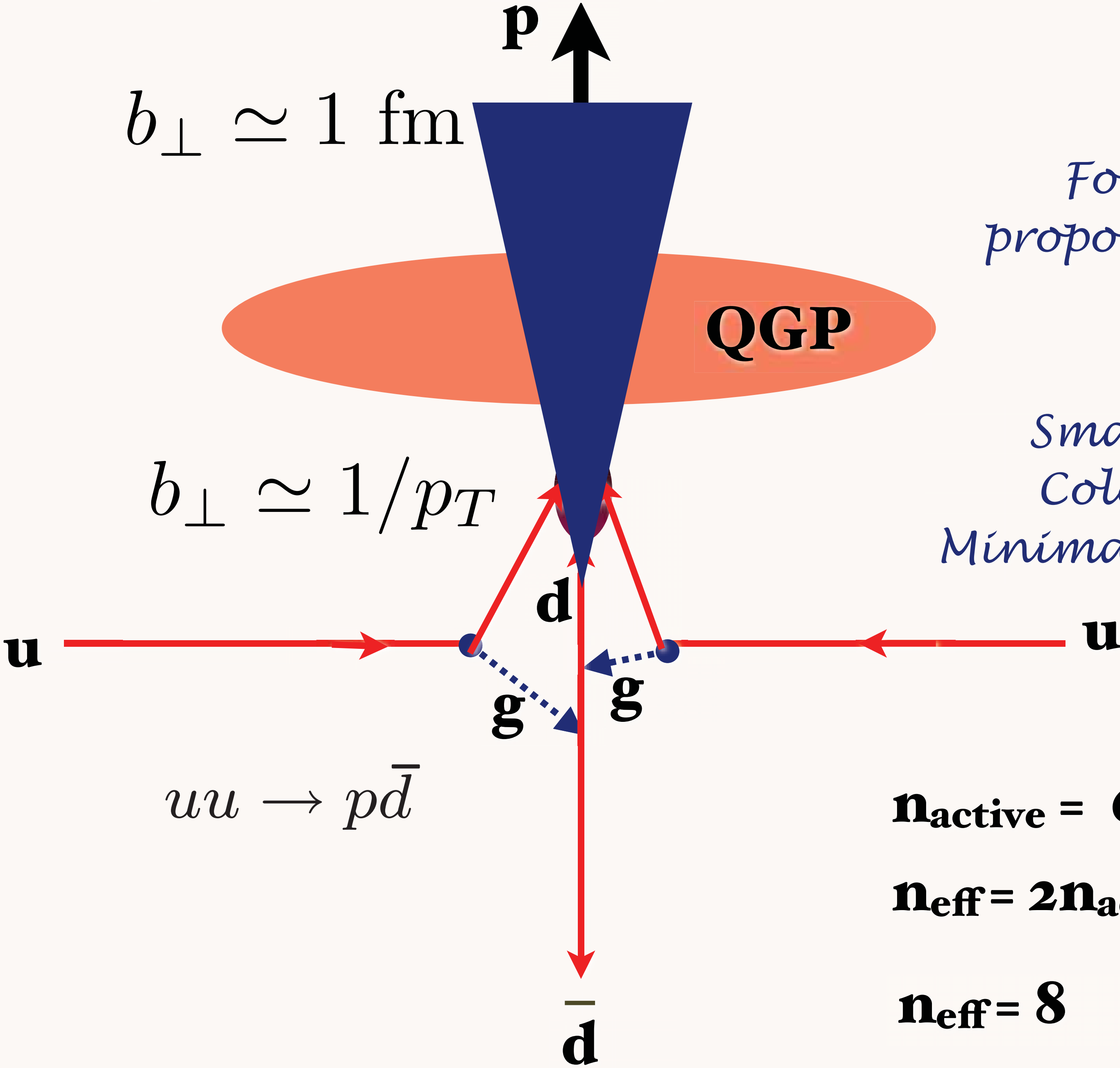
Collision can produce 3 collinear quarks

$n_{active} = 6$

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

$n_{eff} = 8$

Baryon made directly within hard subprocess



Formation Time proportional to Energy

Small color-singlet
Color Transparent
Minimal same-side energy

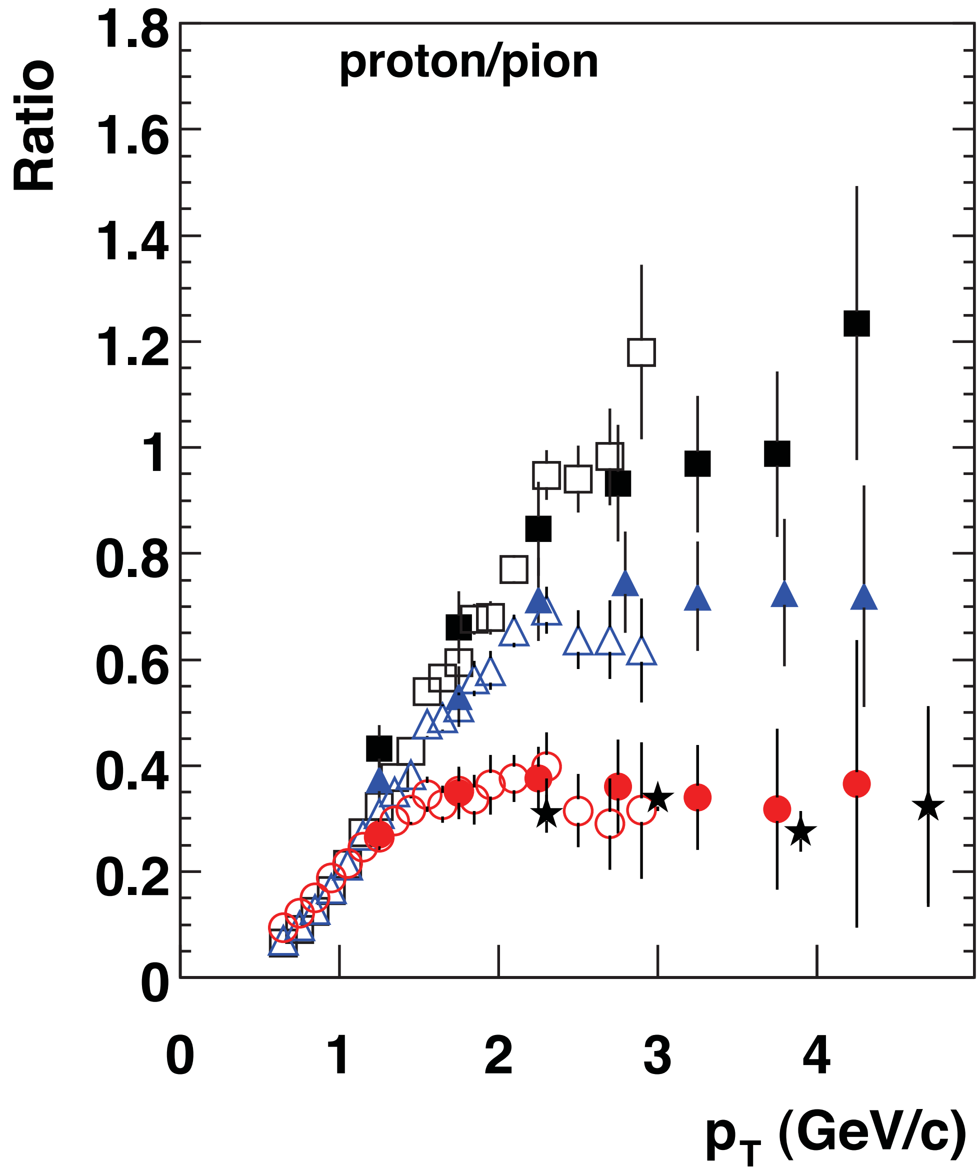
$n_{active} = 6$

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

$n_{eff} = 8$

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

Particle ratio changes with centrality!

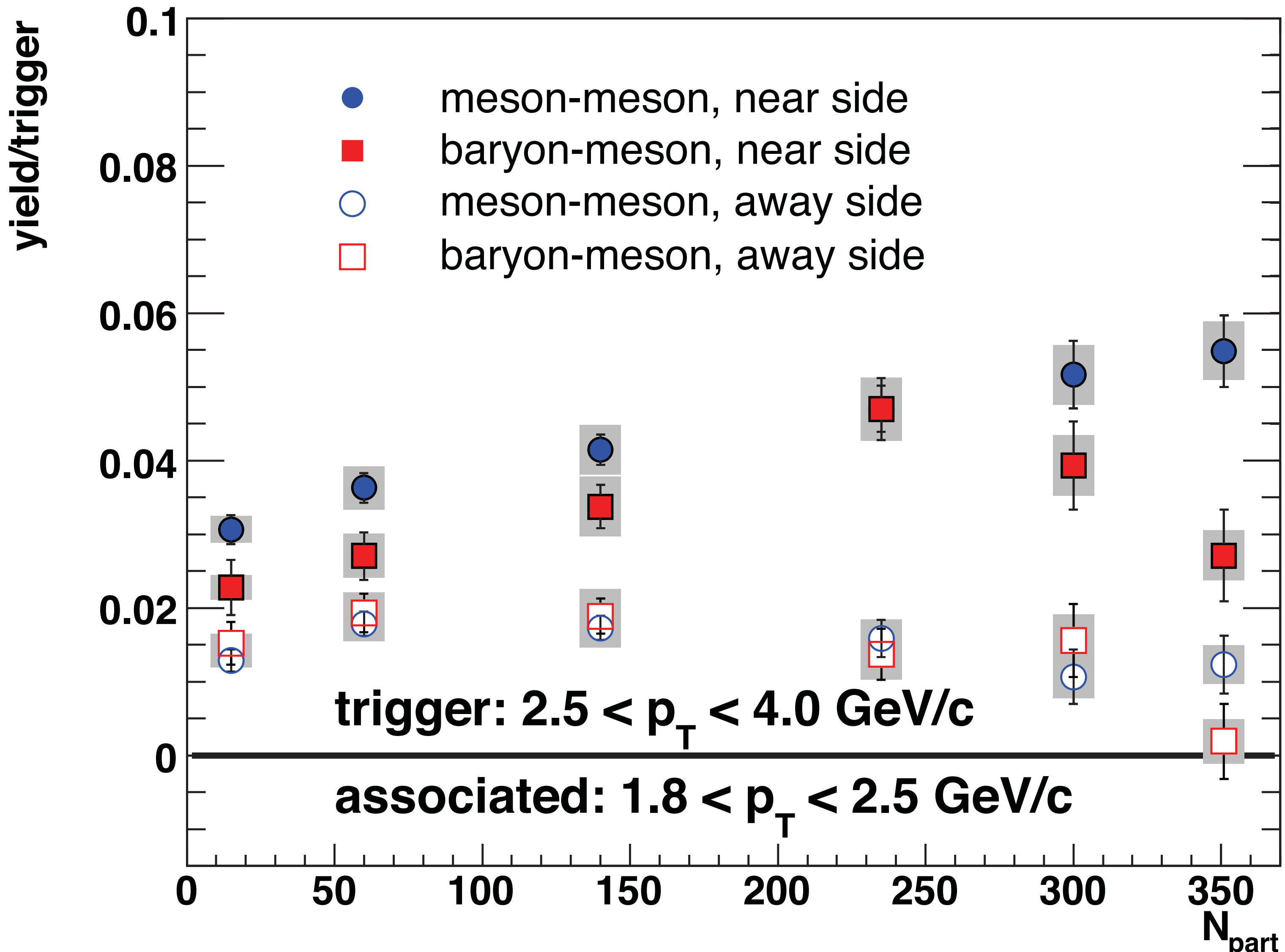


Protons less absorbed in nuclear collisions than pions because of dominant color transparent higher twist process

← Central

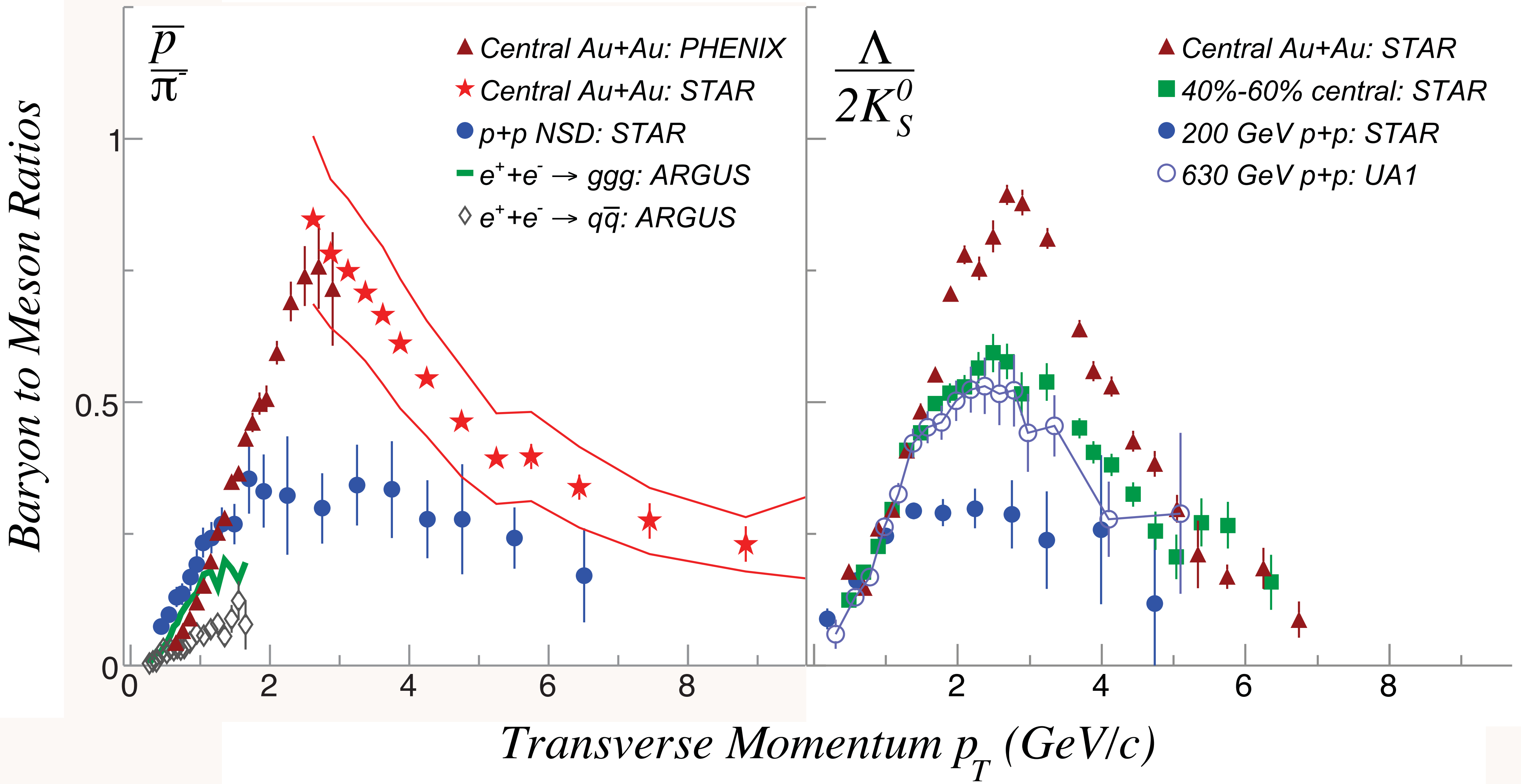
← Peripheral

Anne Sickles



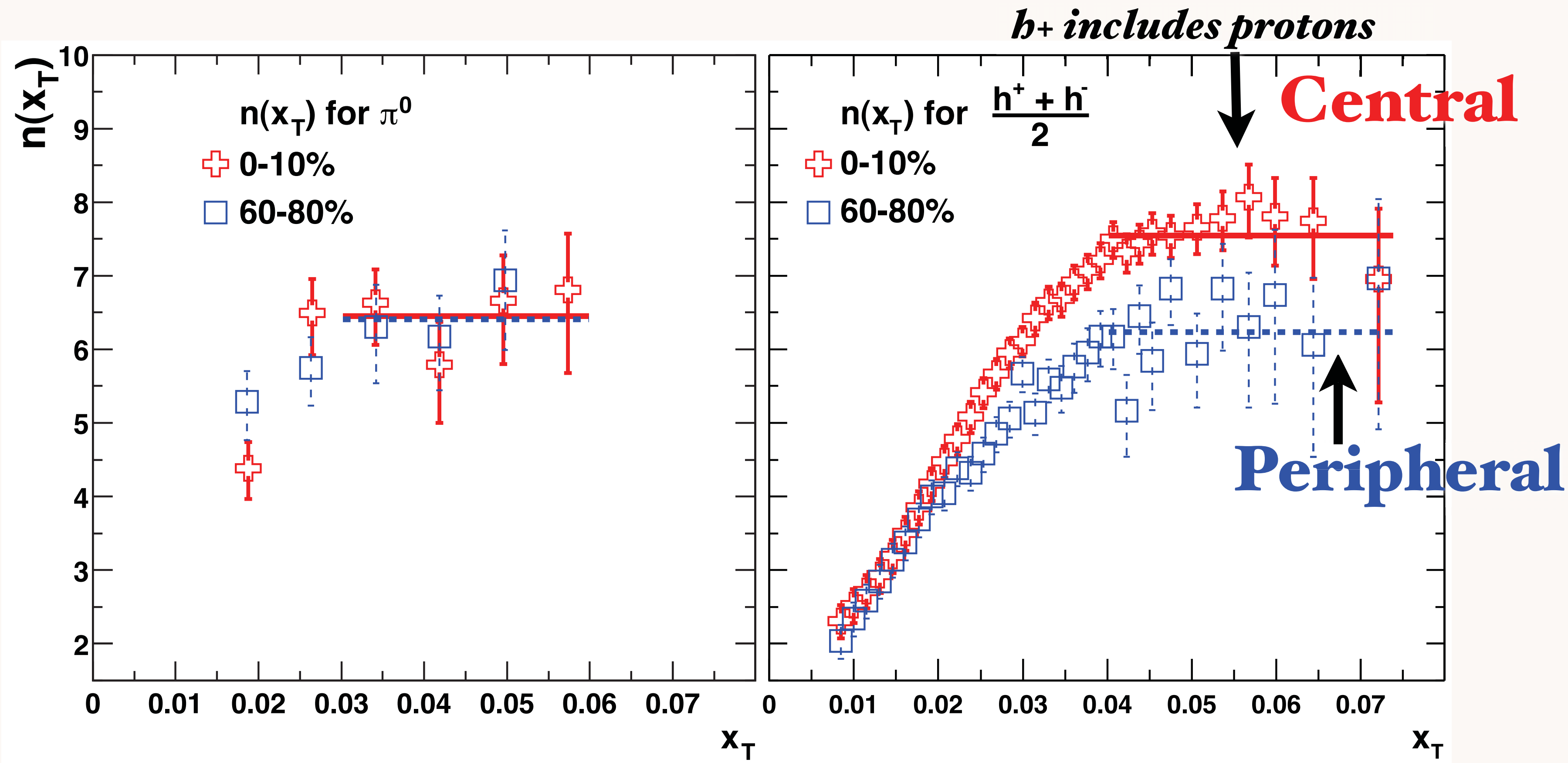
proton trigger: # same-side particles decreases with centrality

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


Baryon to Meson Ratios
p̄ / π⁻
Central Au+Au: PHENIX
Central Au+Au: STAR
p+p NSD: STAR
e⁺+e⁻ → ggg: ARGUS
e⁺+e⁻ → qq̄: ARGUS
Λ / 2K⁰S
Central Au+Au: STAR
40%-60% central: STAR
200 GeV p+p: STAR
630 GeV p+p: UA1
0
0.5
1
0
2
4
6
8
Transverse Momentum pT (GeV/c)

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

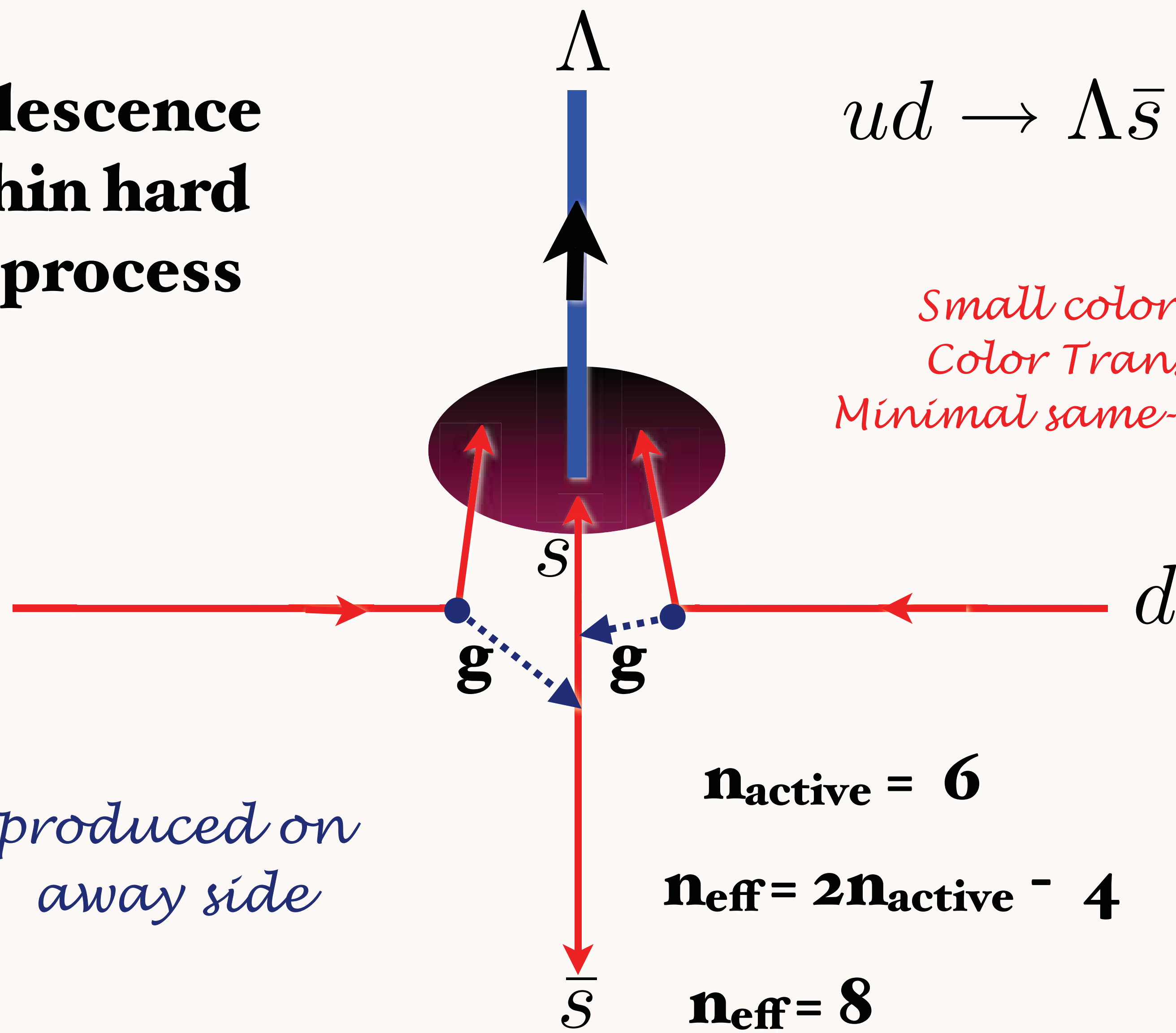
S. S. Adler, *et al.*, PHENIX Collaboration, *Phys. Rev.* C **69**, 034910 (2004) [`nucl-ex/0308006`].



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

Lambda can be made directly within hard subprocess

Coalescence within hard subprocess



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

Small color-singlet
Color Transparent
Minimal same-side energy

$\bar{s}$ produced on away side

$n_{active} = 6$

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

$n_{eff} = 8$

Sickles, sjb

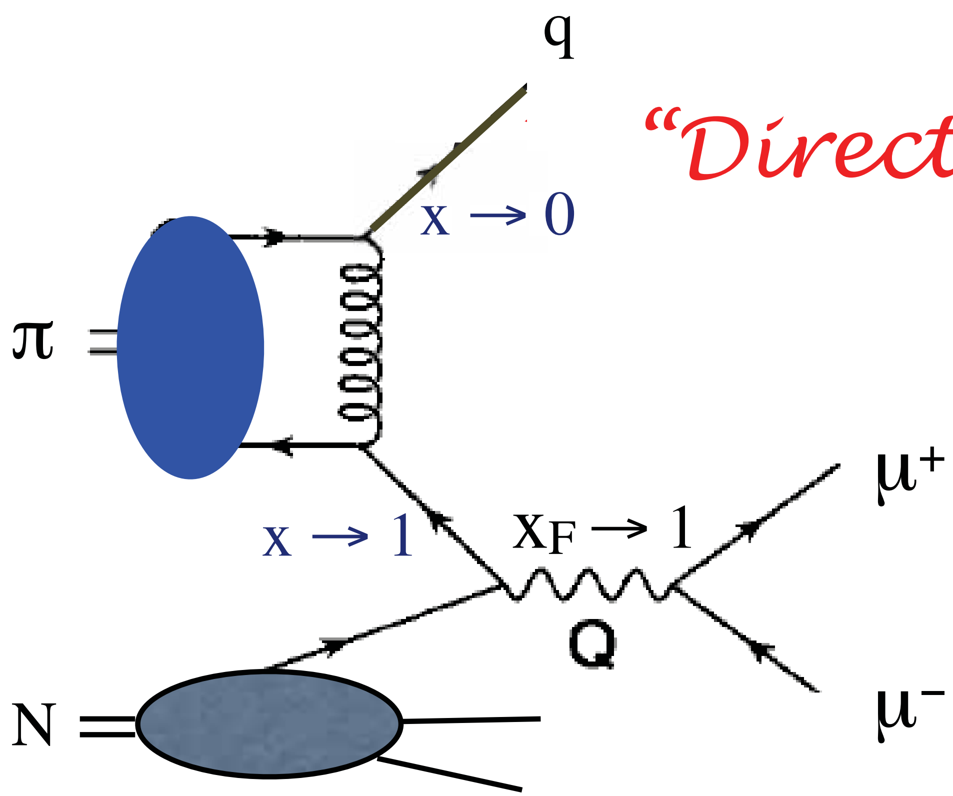
Baryon Anomaly: Evidence for Direct, Higher-Twist Subprocesses

- 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 $x_T = 1$

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

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

Entire pion wf contributes to hard process



"Direct" Subprocess

Virtual photon is longitudinally polarized

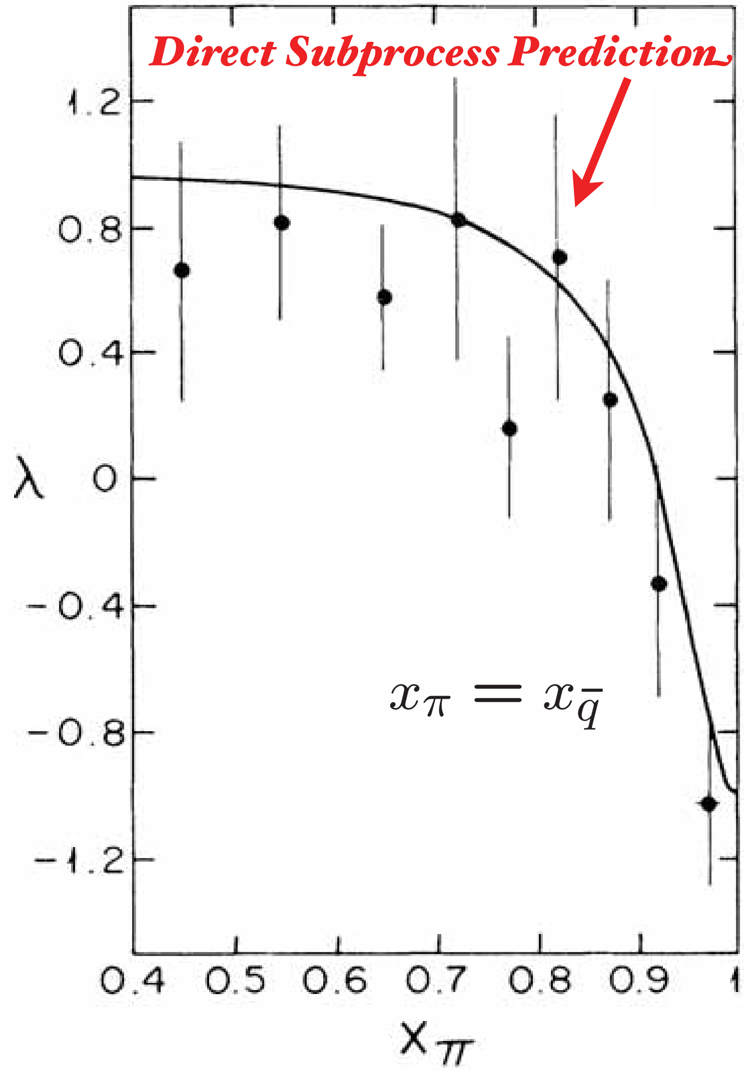
Berger, sjb
Khoze, Brandenburg, Muller, sjb
Hoyer Vanttinen

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

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

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

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



Dramatic change in angular distribution at large x_F

Example of a higher-twist direct subprocess

Chicago-Princeton Collaboration

Phys.Rev.Lett.55:2649,1985

Role of higher twist in hard inclusive reactions

- Hadron can be produced directly in hard subprocess as in exclusive reactions
- Sum over reactions
- Trigger bias: No wasted same-side energy
- Exclusive - inclusive connection important at high x_T
- Explanation of $n_{eff} = 8, 12$ observed at ISR, Fermilab: Chicago-Princeton experiments
- Direct Hadron Production -- color transparency and reduced same side absorption
- Critical to plot data at fixed x_T
- Interpretation of RHIC data is modified if higher twist subprocesses play an important role

QCD Lagrangian

gluon dynamics | quark kinetic energy + quark-gluon dynamics | mass term

$$L_{QCD} = -\frac{1}{4g^2}\,\mathrm{Tr}(G^{\mu\nu}G_{\mu\nu}) + \sum_{f=1}^{nf} i\,\overline{\psi}_f\, D_\mu \gamma^\mu \psi_f + \sum_{f=1}^{nf} m_f\, \overline{\psi}_f\, \psi_f$$

QCD color charge | field strength tensor | covariant derivative | quark field

Yang-Mills Gauge Principle: Invariance under Color Rotation and Phase Change at Every Point of Space and Time

Dimensionless Coupling
Renormalizable
Asymptotic Freedom
Color Confinement

$$L_{QCD} \to H^{LF}_{QCD} \to \psi^{LF}_{n/H}(x_i, \vec{k}_{\perp i}, \lambda_i)$$

Light-Front QCD

Heisenberg Matrix Formulation

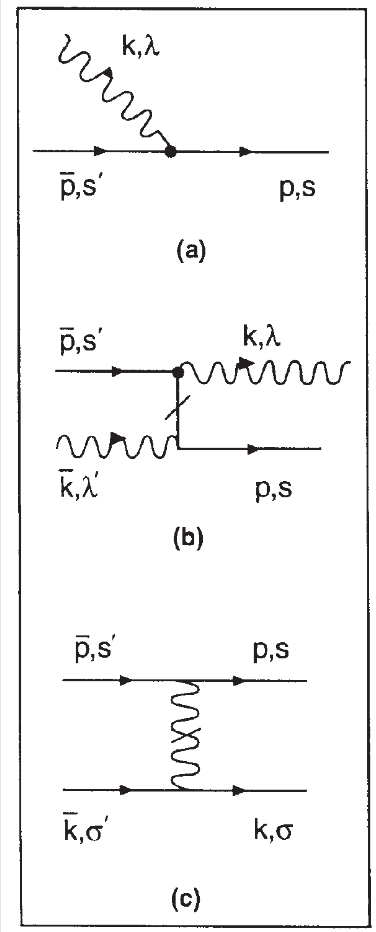
Physical gauge: $A^+ = 0$

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

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

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

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

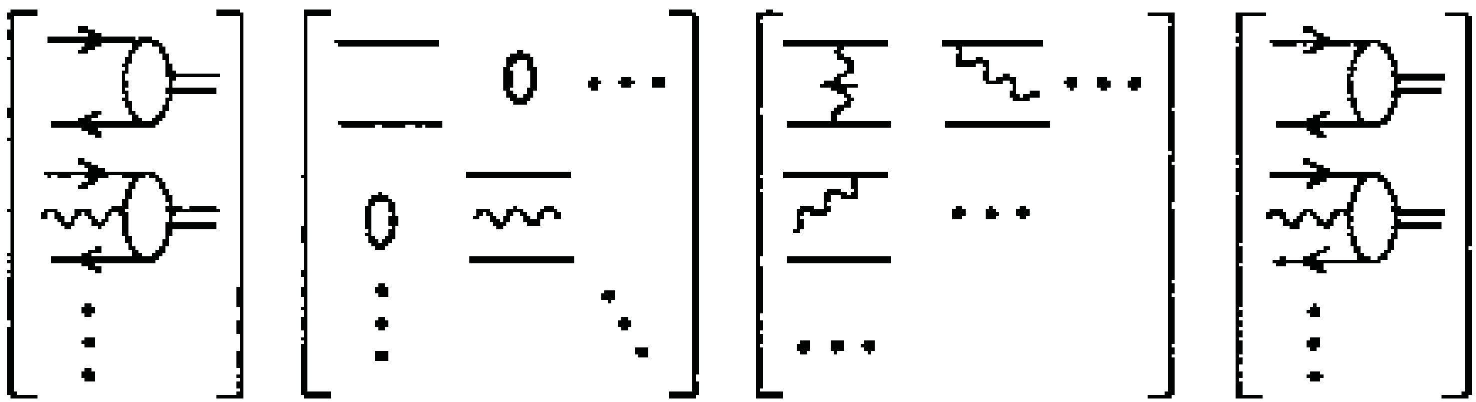


Eigenvalues and Eigensolutions give Hadron Spectrum and Light-Front wavefunctions

DLCQ: Periodic BC in x^-. Discrete k^+; frame-independent truncation

LIGHT-FRONT SCHRODINGER EQUATION

$$\left(M_\pi^2 - \sum_i \frac{\vec{k}_{\perp i}^{\,2} + m_i^2}{x_i}\right) \begin{bmatrix} \psi_{q\bar{q}/\pi} \\ \psi_{q\bar{q}g/\pi} \\ \vdots \end{bmatrix} = \begin{bmatrix} \langle q\bar{q}|\, V\, |q\bar{q}\rangle & \langle q\bar{q}|\, V\, |q\bar{q}g\rangle & \cdots \\ \langle q\bar{q}g|\, V\, |q\bar{q}\rangle & \langle q\bar{q}g|\, V\, |q\bar{q}g\rangle & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix} \begin{bmatrix} \psi_{q\bar{q}/\pi} \\ \psi_{q\bar{q}g/\pi} \\ \vdots \end{bmatrix}$$



$A^+ = 0$

G.P. Lepage, sjb

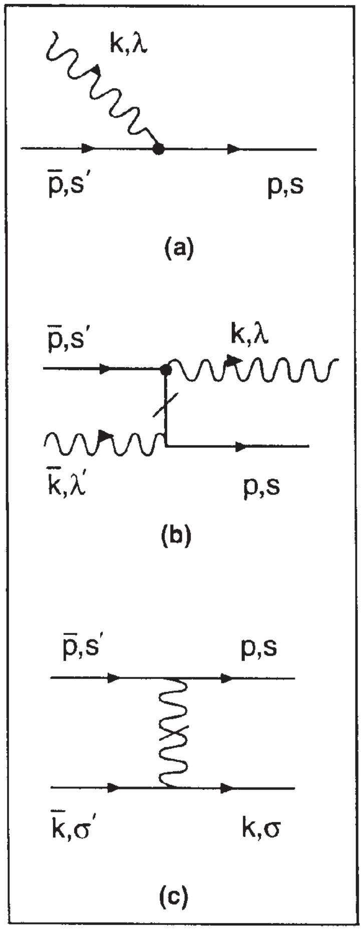
Light-Front QCD

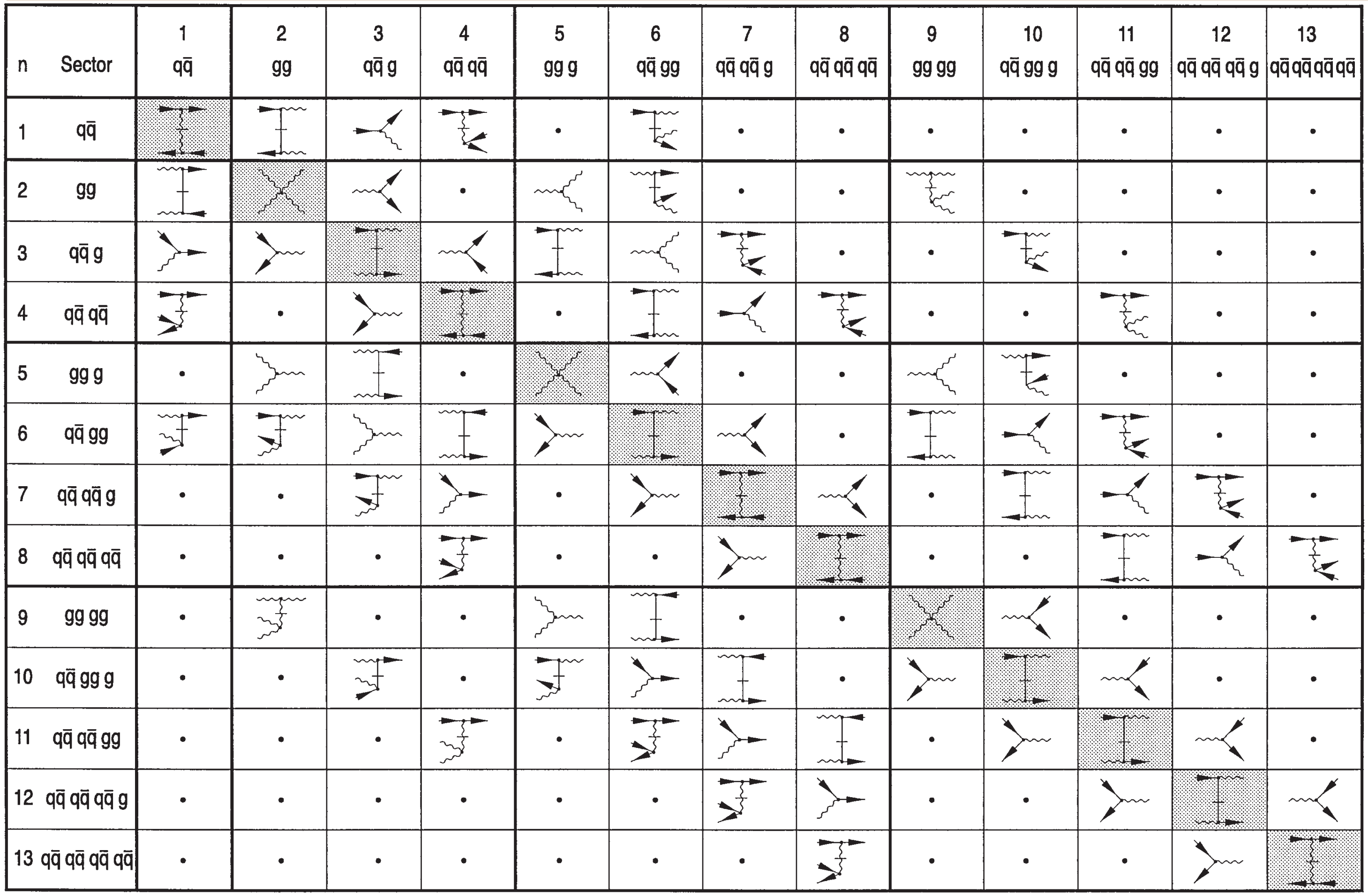
Heisenberg Matrix Formulation

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

H.C. Pauli & sjb

Discretized Light-Cone Quantization





Eigenvalues and Eigensolutions give Hadron Spectrum and Light-Front wavefunctions

DLCQ: Frame-independent, No fermion doubling; Minkowski Space

DLCQ: Periodic BC in x^-. Discrete k^+; frame-independent truncation

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.

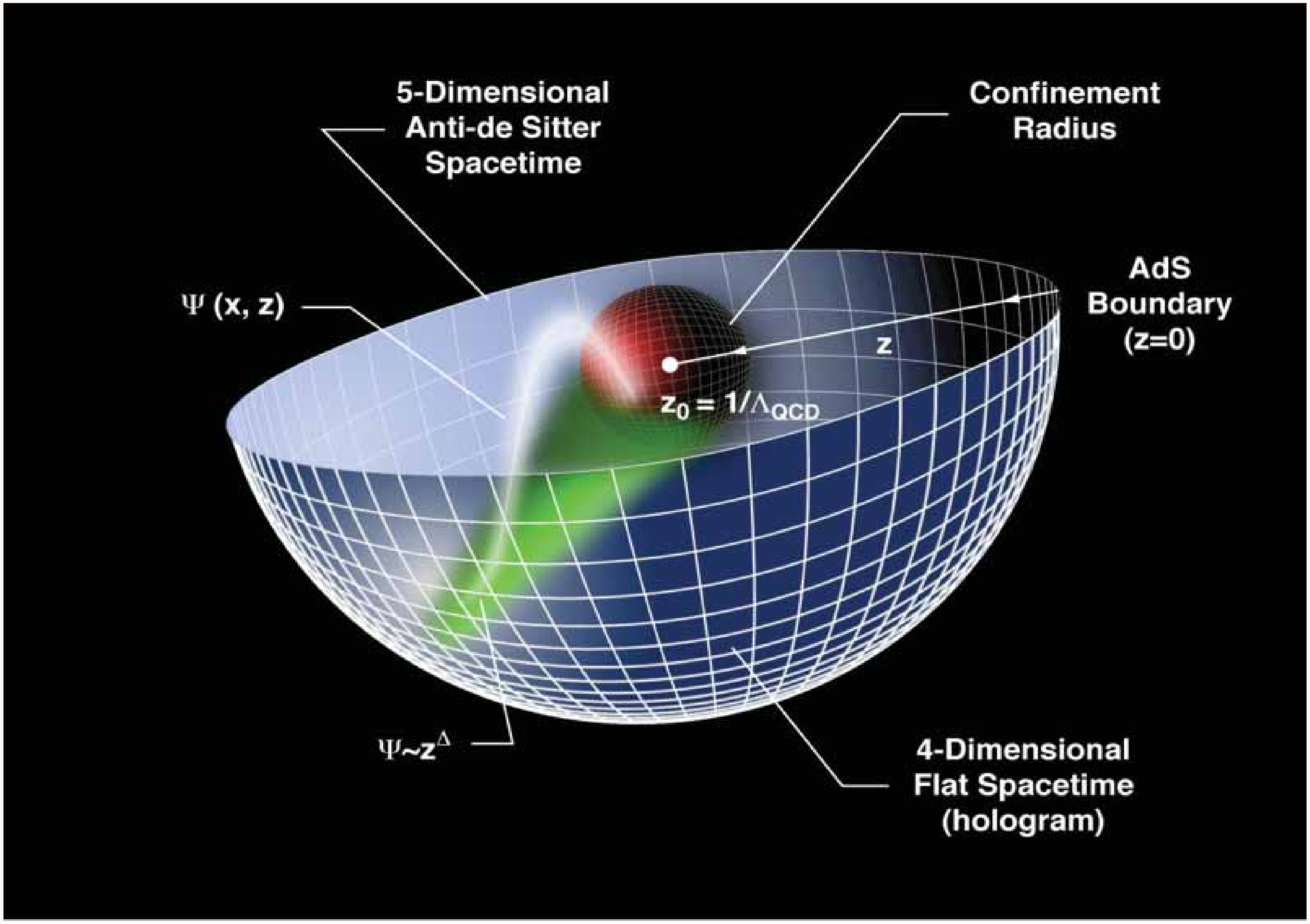
- Different values of z correspond to different scales at which the hadron is examined.

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

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

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

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