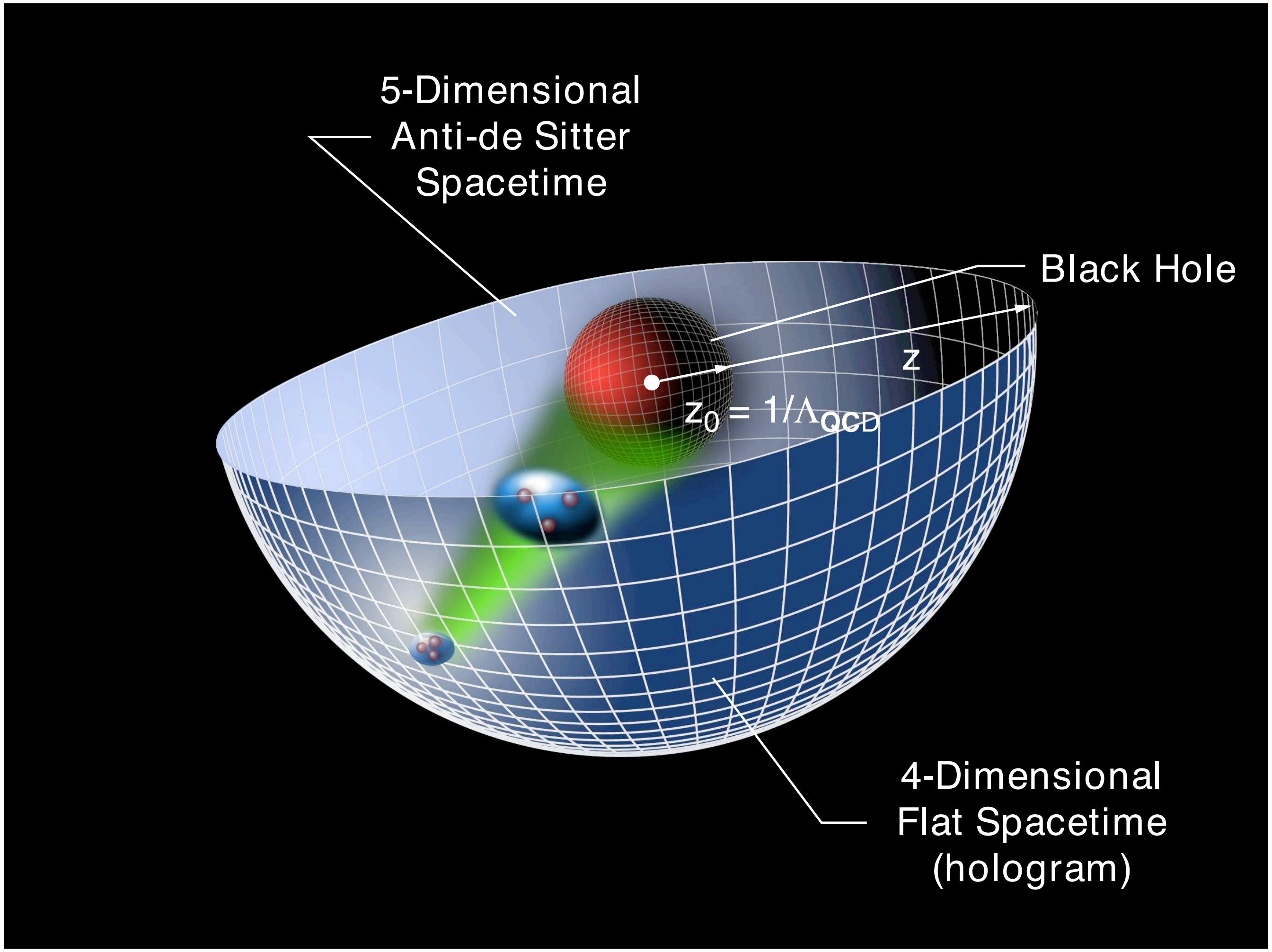
AdS/CFT and Novel QCD Phenomena

Stan Brodsky, SLAC

Small-x and Diffraction Workshop March 28-30, 2007 **Fermilab**

AdS/QCD



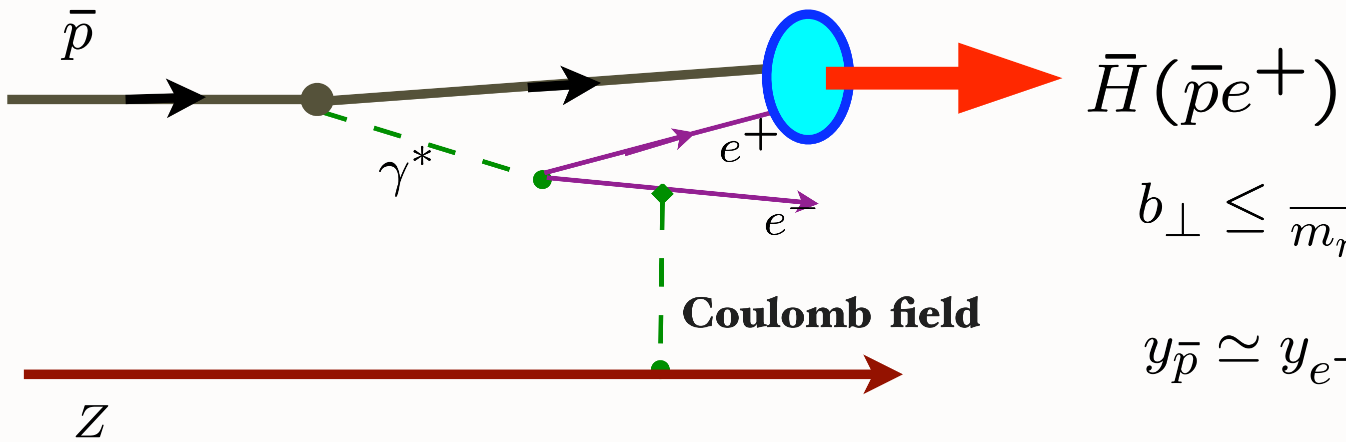
Changes in length scale mapped to evolution in the 5th dimension z

in collaboration with Guy de Teramond

Formation of Relativistic Anti-Hydrogen

Measured at CERN-LEAR and FermiLab

Munger, Schmidt, sjb



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

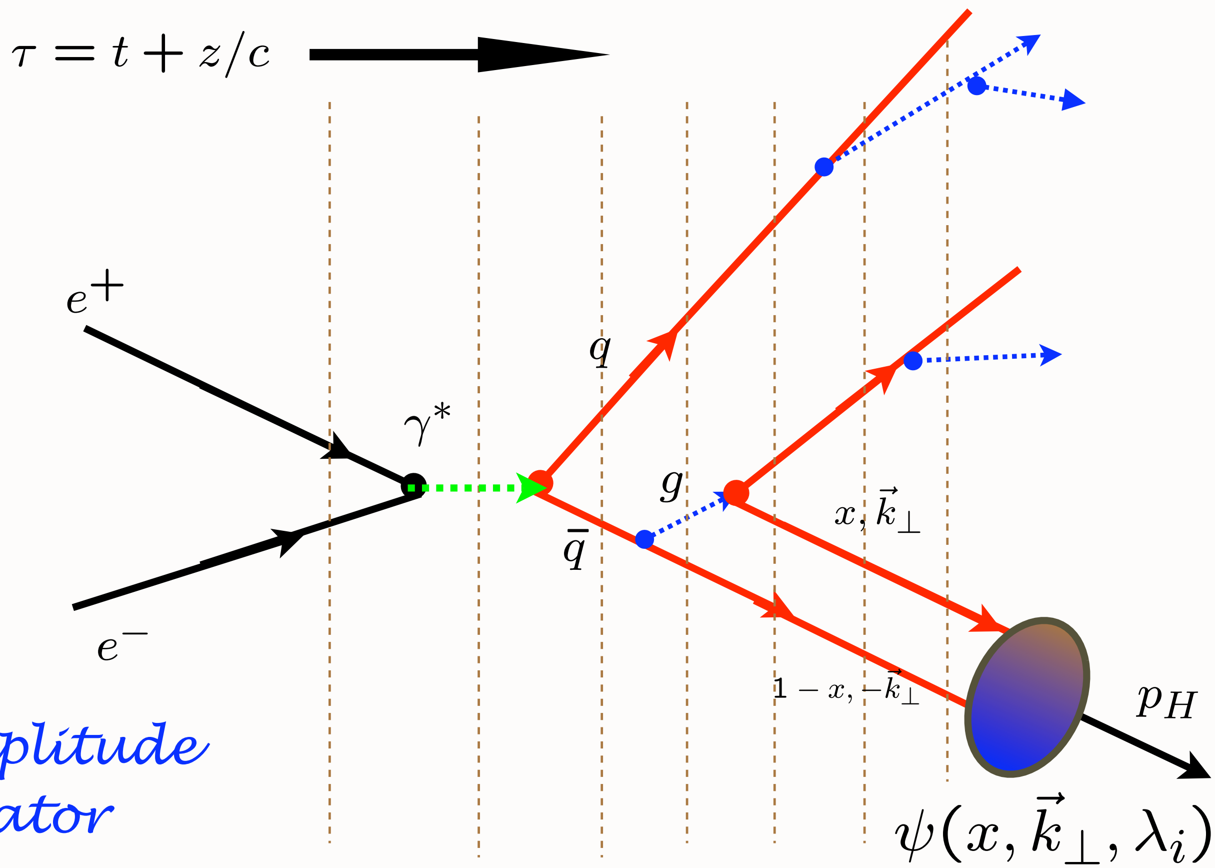
$y_{\bar{p}} \simeq y_{e^+}$

Coalescence of off-shell co-moving positron and antiproton

Wavefunction maximal at small impact separation and equal rapidity

"Hadronization" at the Amplitude Level

Hadronization at the Amplitude Level



Event amplitude generator

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

Light-Front Wavefunctions

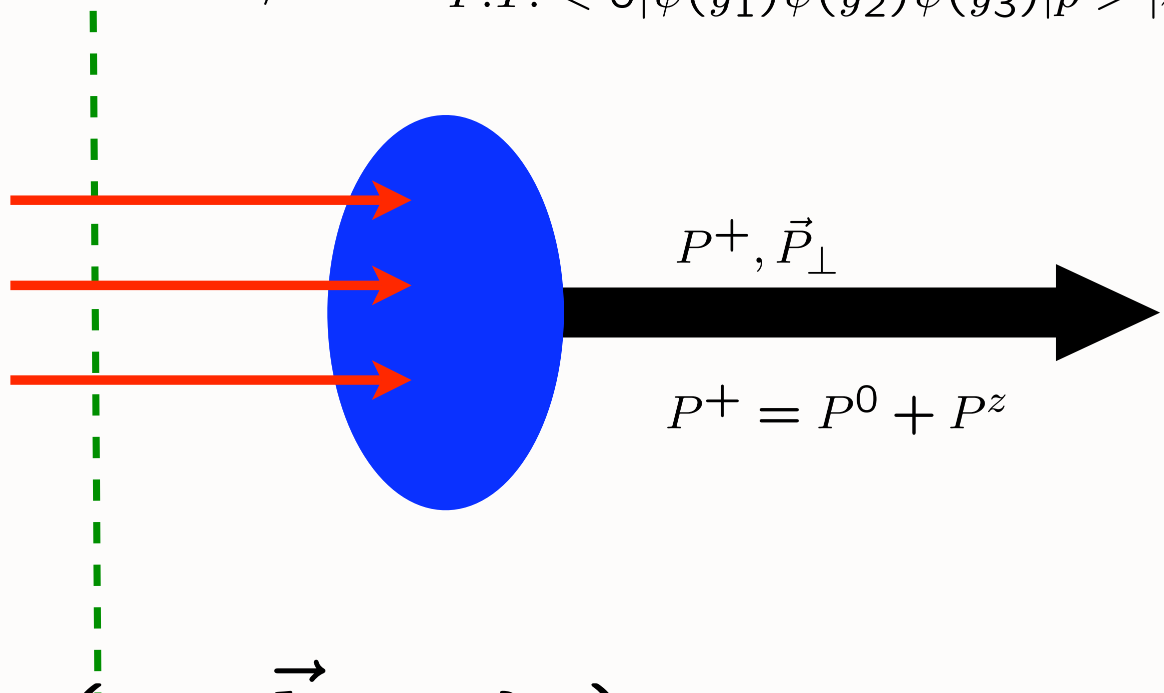
Fixed $\tau = t + z/c$

$F.T. < 0|\psi(y_1)\psi(y_2)\psi(y_3)|p > |_{\tau_i=0}$

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

$\sum_i^n x_i = 1$

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



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

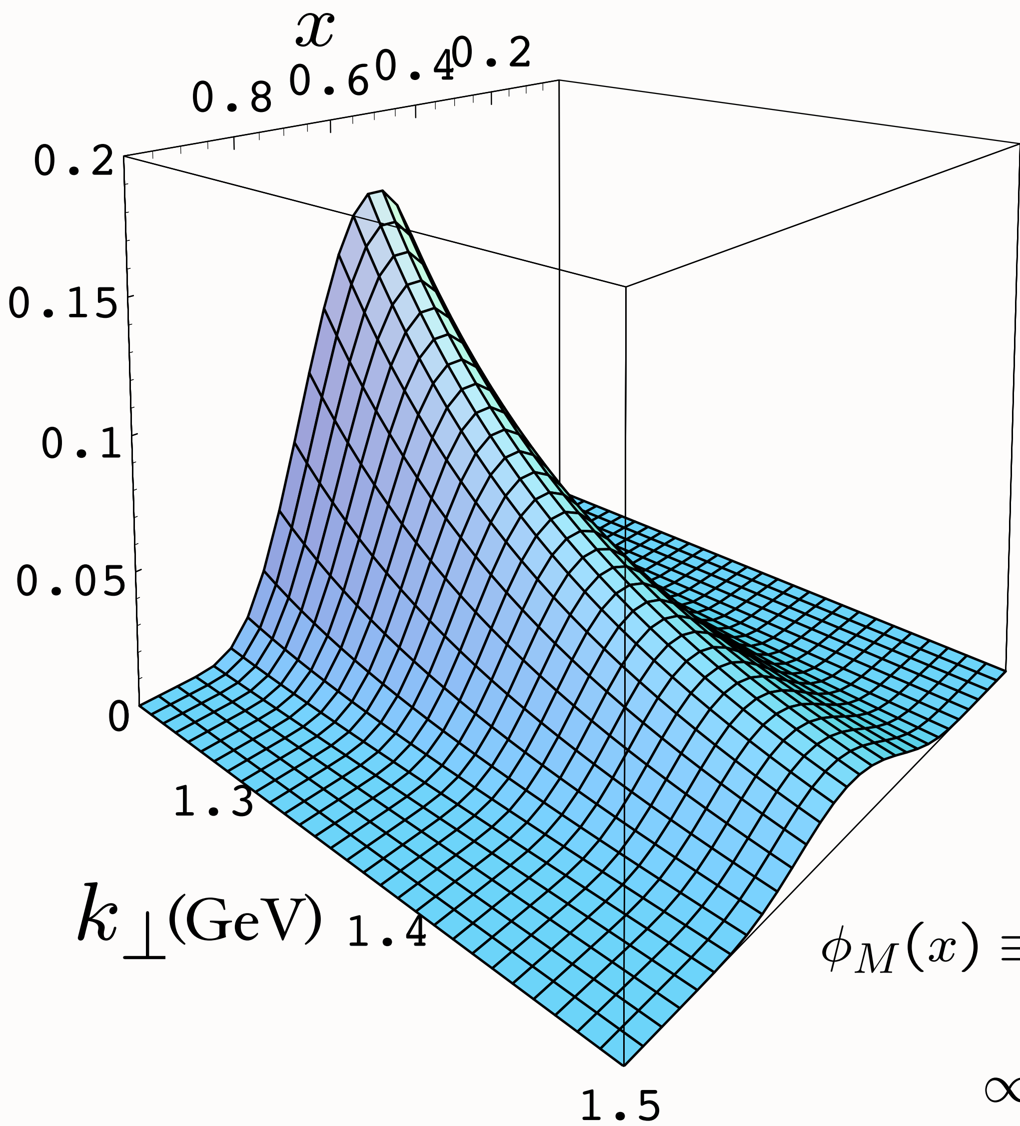
Invariant under boosts! Independent of P^μ

Creating Hadrons

- Coalescence of co-moving quarks
- Maximal probability at minimum off-shellness
- Hadronization formation at a given light-front time described by light-front wavefunction $\psi_n^H(x_i, k_{\perp i}, \lambda_i)$
- Example in QED: Formation of anti-hydrogen
- Exclusive amplitudes controlled by LFWS
- LFWFs predicted by AdS/CFT

Prediction from AdS/CFT: Meson Light Front WF

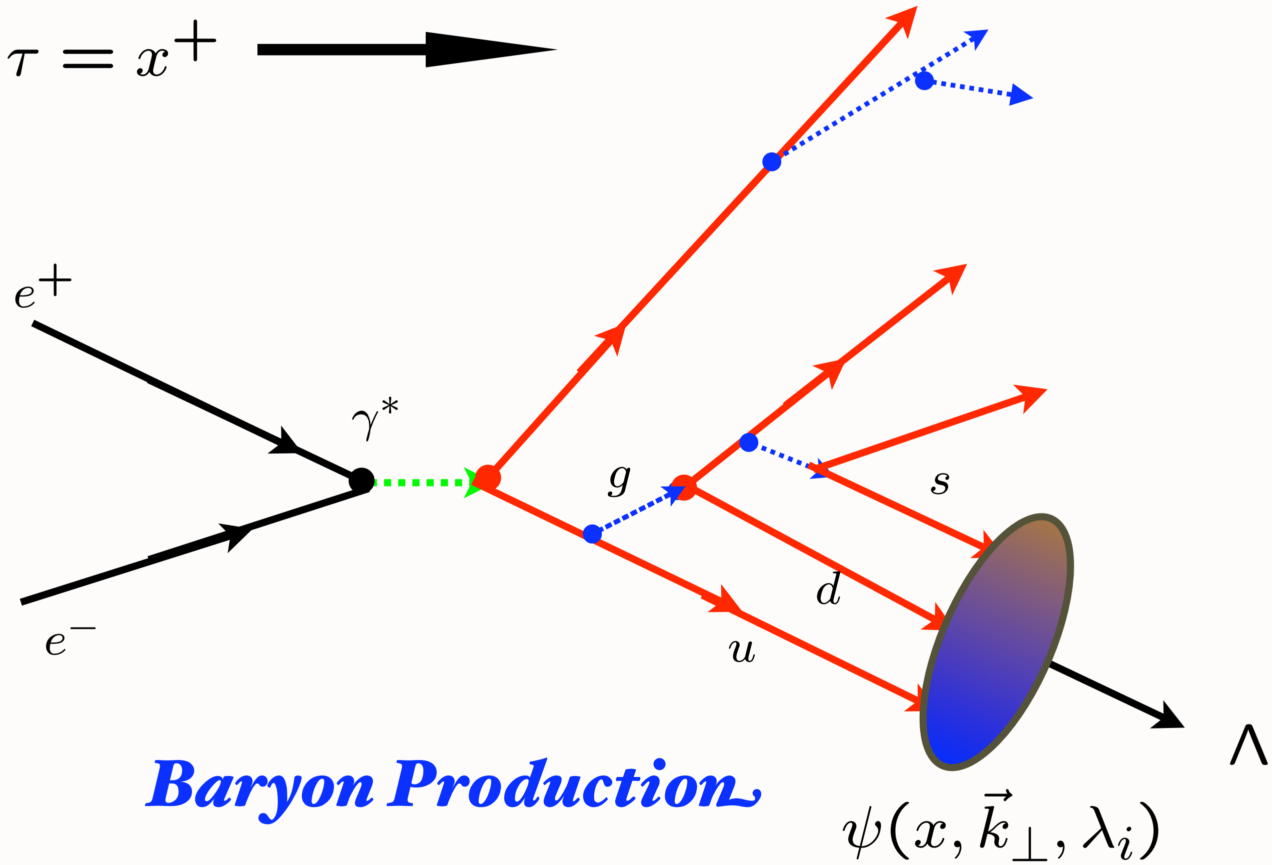
de Teramond, sjb



$$\phi_M(x) \equiv \int d^2k_\perp \psi_M(x, \vec{k}_\perp)$$

$$\propto f_M \sqrt{x(1-x)}$$

Hadronization at the Amplitude Level

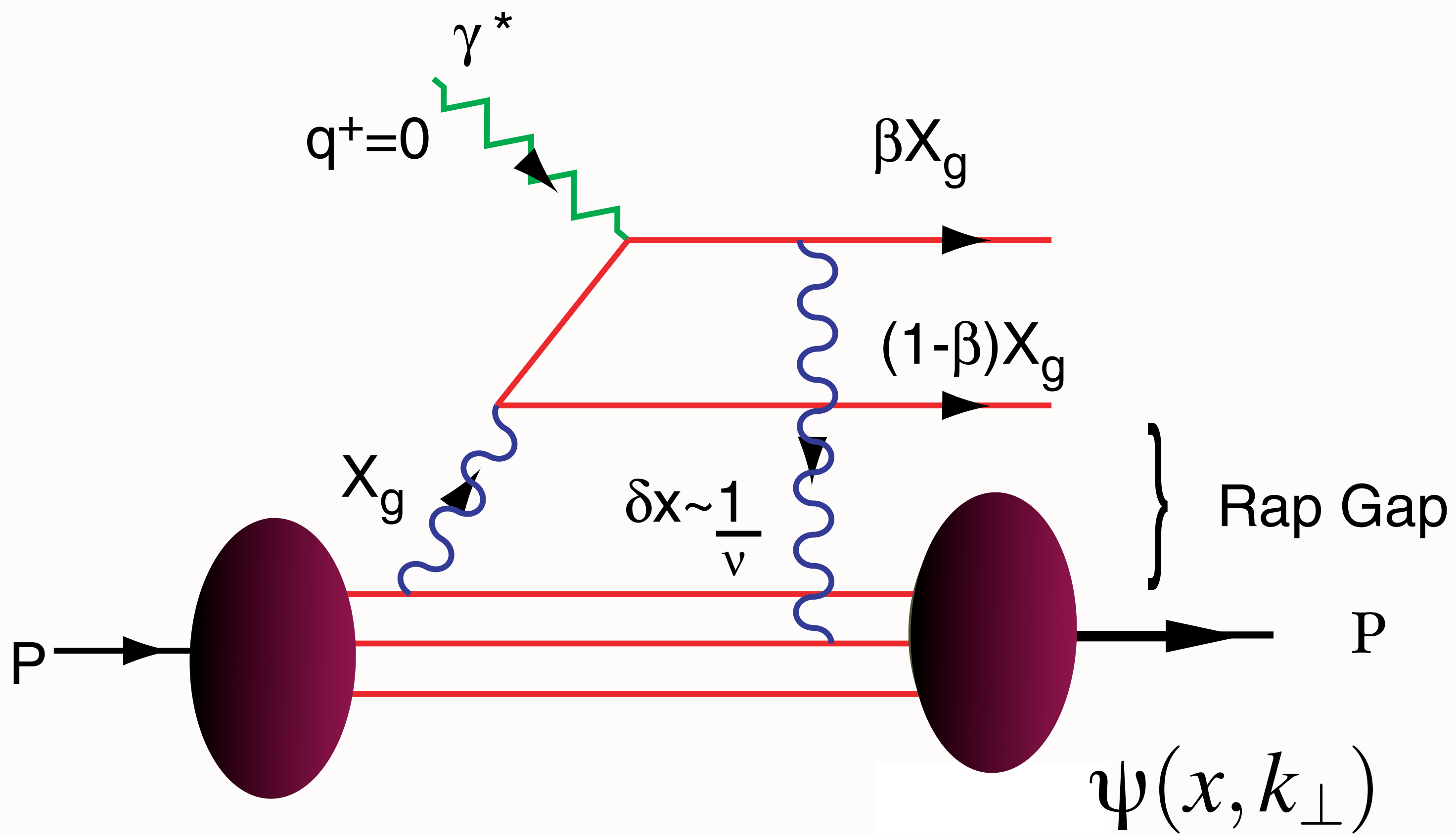


Baryon Production

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

Hoyer, Marchal, Peigne, Sannino, sjb

QCD Mechanism for Rapidity Gaps



Light-Front Wavefunctions

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

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

$$x_i = \frac{k_i^+}{P^+}$$

Invariant under boosts. Independent of P^μ

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

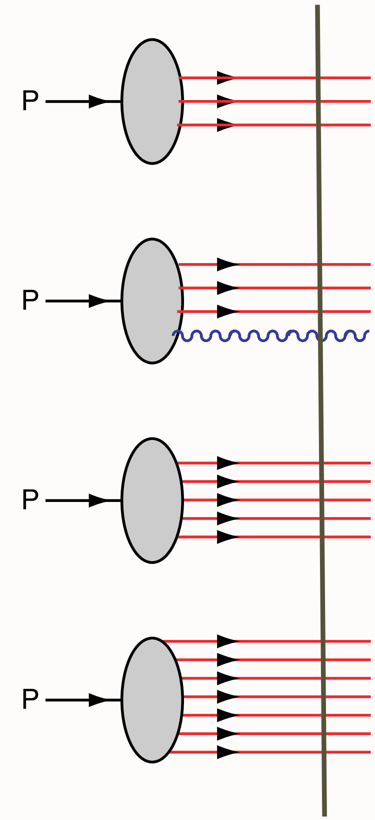
Remarkable new insights from AdS/CFT, the duality between conformal field theory and Anti-de Sitter Space

Light-Front Wavefunctions

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

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

$$x_i = \frac{k_i^+}{P^+}$$

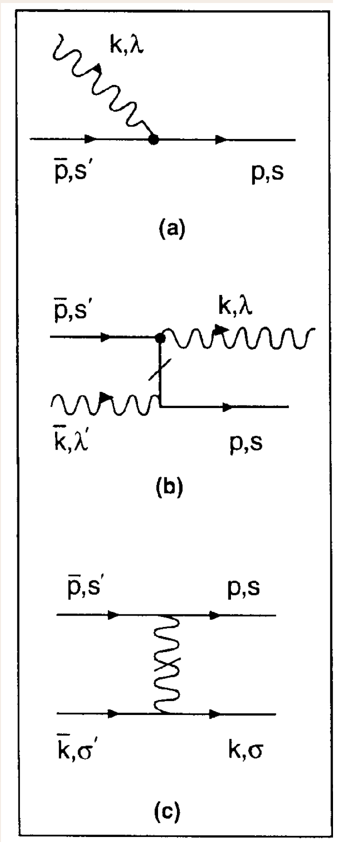


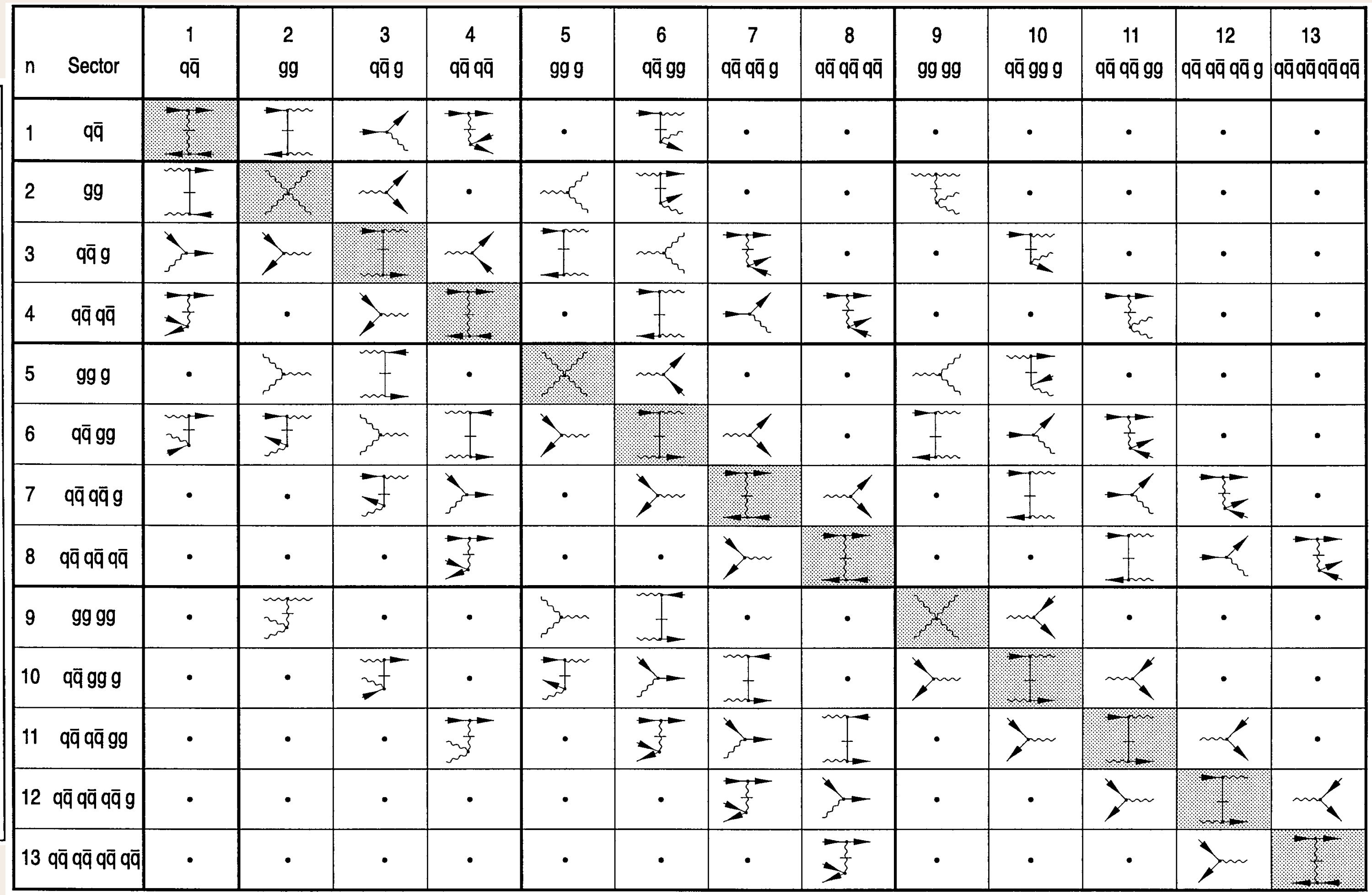
$$\mathrm{H}_{LF}^{QCD}|\psi> = M^2|\psi>$$

Invariant under boosts. Independent of P^μ

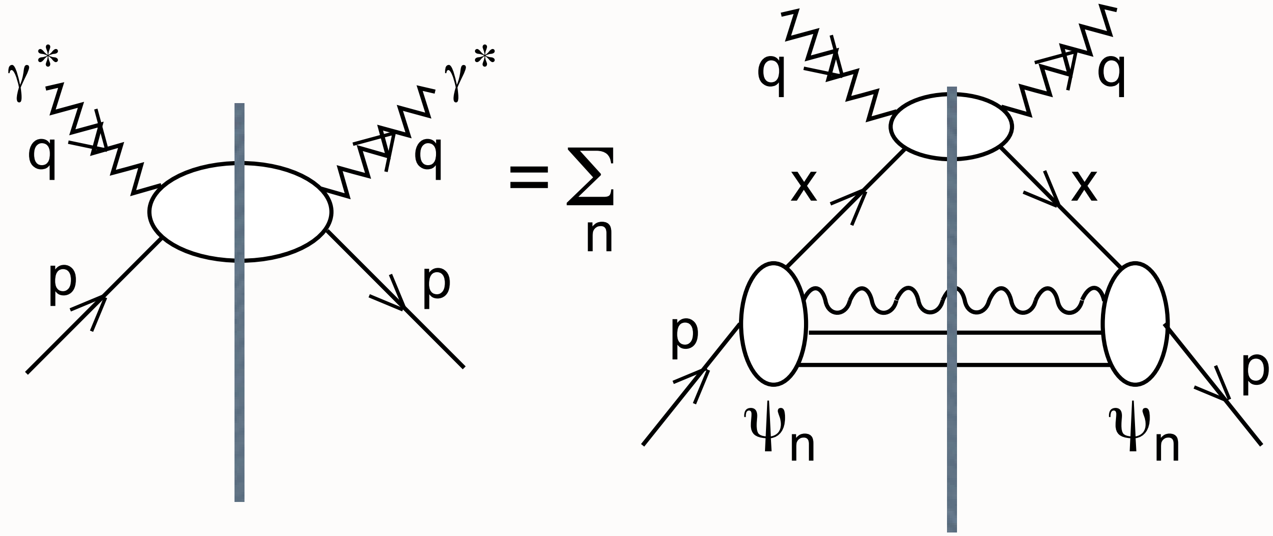
Light-Front QCD Heisenberg Equation

$$H_{LC}^{QCD} |\Psi_h\rangle = \mathcal{M}_h^2 \; |\Psi_h\rangle$$





Deep Inelastic Lepton Proton Scattering

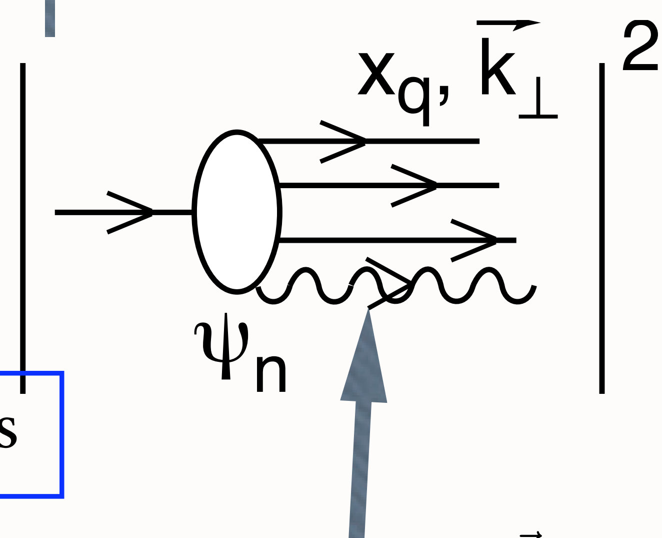


Imaginary Part of
Forward Virtual Compton Amplitude

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

$x = x_q$

All spin, flavor distributions



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

Angular Momentum on the Light-Front

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

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

Conserved
LF Fock state by Fock State

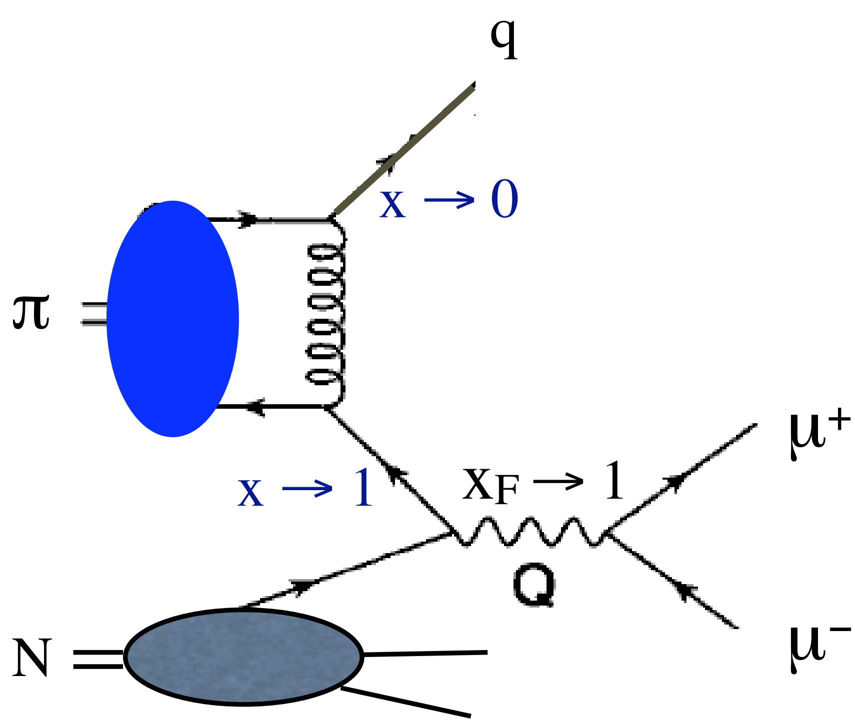
$$l_j^z = -\mathrm{i}\left(k_j^1 \frac{\partial}{\partial k_j^2} - k_j^2 \frac{\partial}{\partial k_j^1}\right)$$

n-1 orbital angular momenta

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

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

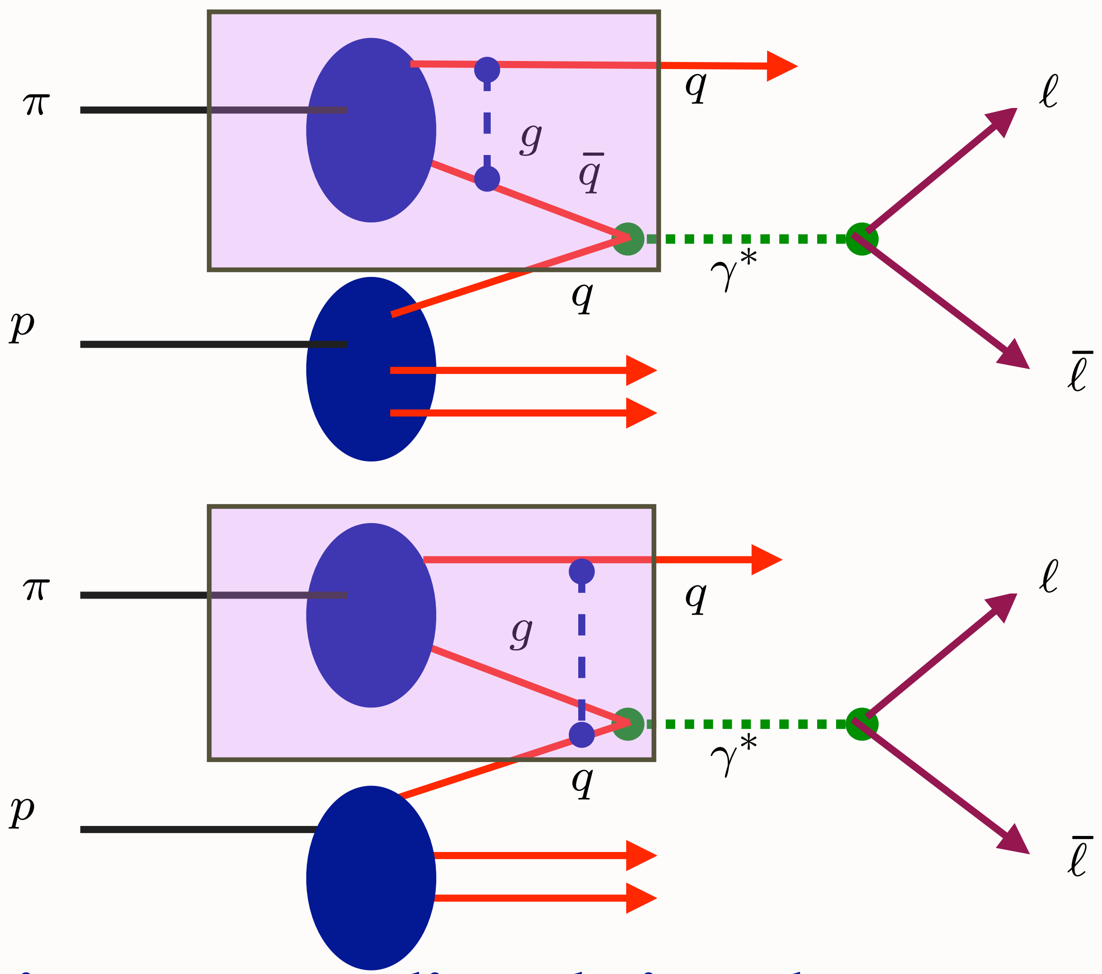
Entire pion wf contributes to hard process



Virtual photon is longitudinally polarized

Berger and Brodsky, PRL 42 (1979) 940

Berger, Lepage, sjb



$$\pi q \to \gamma^* q$$

Pion appears directly in subprocess at large x_F

All of the pion momentum transferred to the lepton pair

Lepton Pair produced longitudinally polarized

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

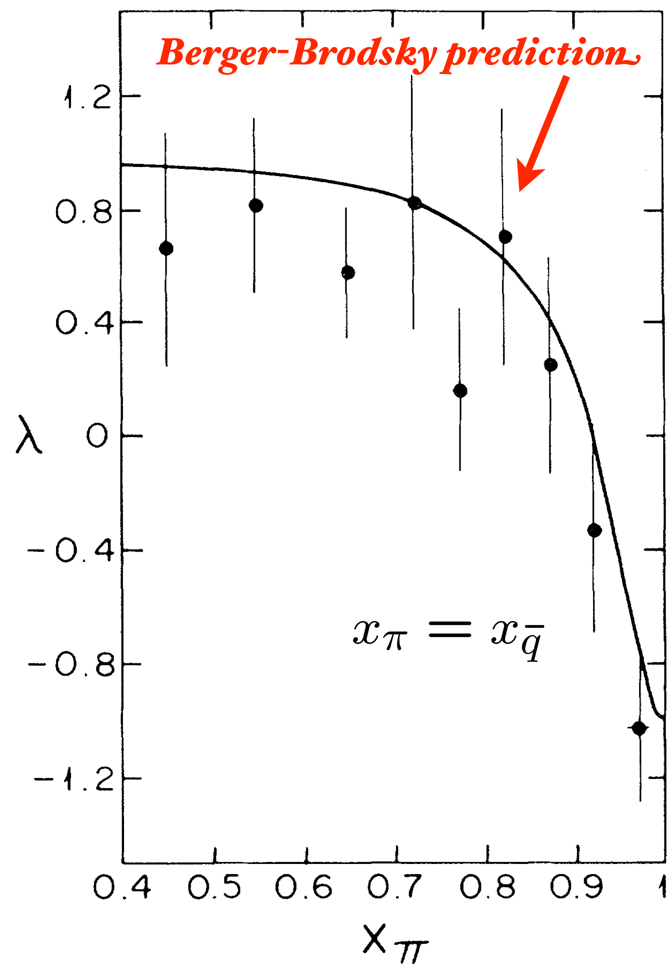
$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \rho \sin 2\theta \cos\phi + \omega \sin^2\theta \cos 2\phi.$$

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

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

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

Direct Subprocesses

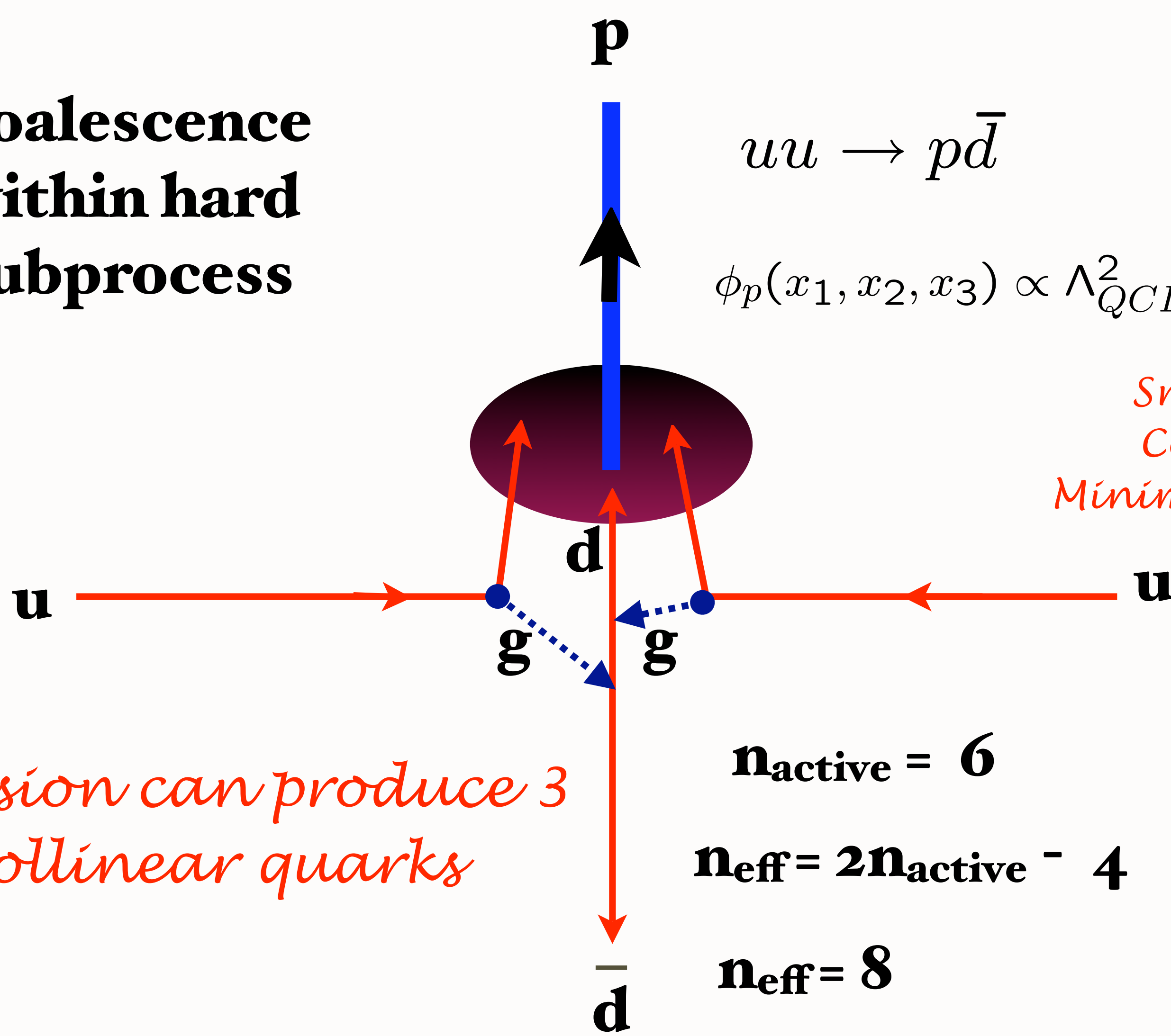
- Hadron produced directly in subprocess
- Hadronic amplitude physics encompassed in LFWF
- Higher twist in $1/Q^2$, but dominant at large x or z
- Observed in Drell-Yan reactions at large x_F: dramatic change in lepton angular distribution
- Merges with exclusive processes at exclusive boundary
- Strength amplified by trigger-bias effect in single-particle triggers
- Color transparent

Berger, Brodsky, Lepage

Brodsky, Hoyer, Mueller, Tang

Baryon can be made directly within hard subprocess

Coalescence within hard subprocess



$uu \rightarrow p\bar{d}$

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

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

Small color-singlet
Color Transparent
Minimal same-side energy

Collision can produce 3 collinear quarks

$\mathbf{n_{active} = 6}$

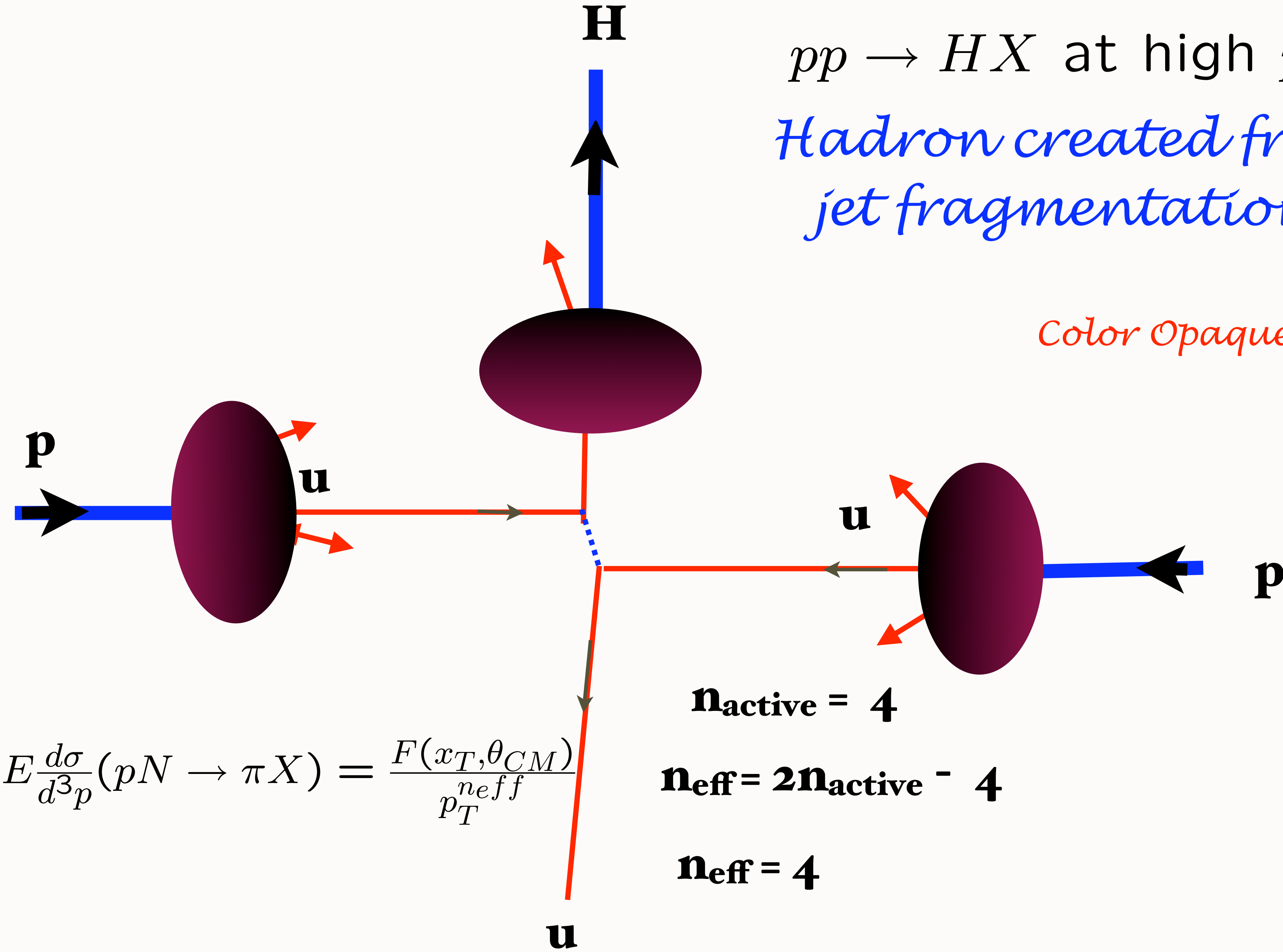
$\mathbf{n_{eff} = 2n_{active} - 4}$

$\mathbf{n_{eff} = 8}$

$qq \rightarrow B\bar{q}$

$pp \rightarrow HX$ at high p_T

Hadron created from jet fragmentation



Color Opaque

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

$n_{active} = 4$

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

$n_{eff} = 4$

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

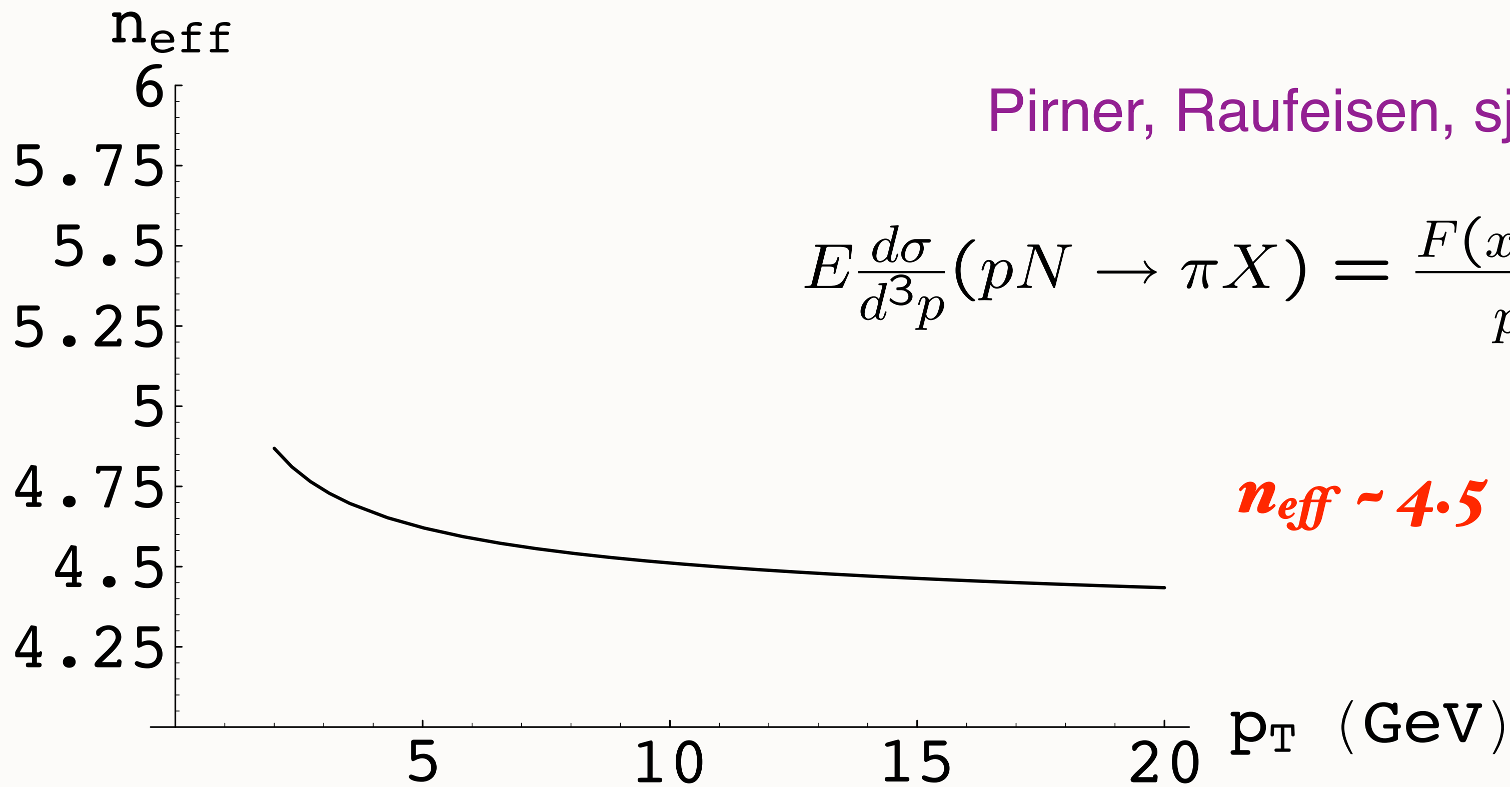
$$E\frac{d\sigma}{d^3p}(pN \to \pi X) = \frac{F(x_T,\theta_{CM})}{p_T^{neff}}$$

n_{eff} = 4

Bjorken scaling

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

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} ~ 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

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

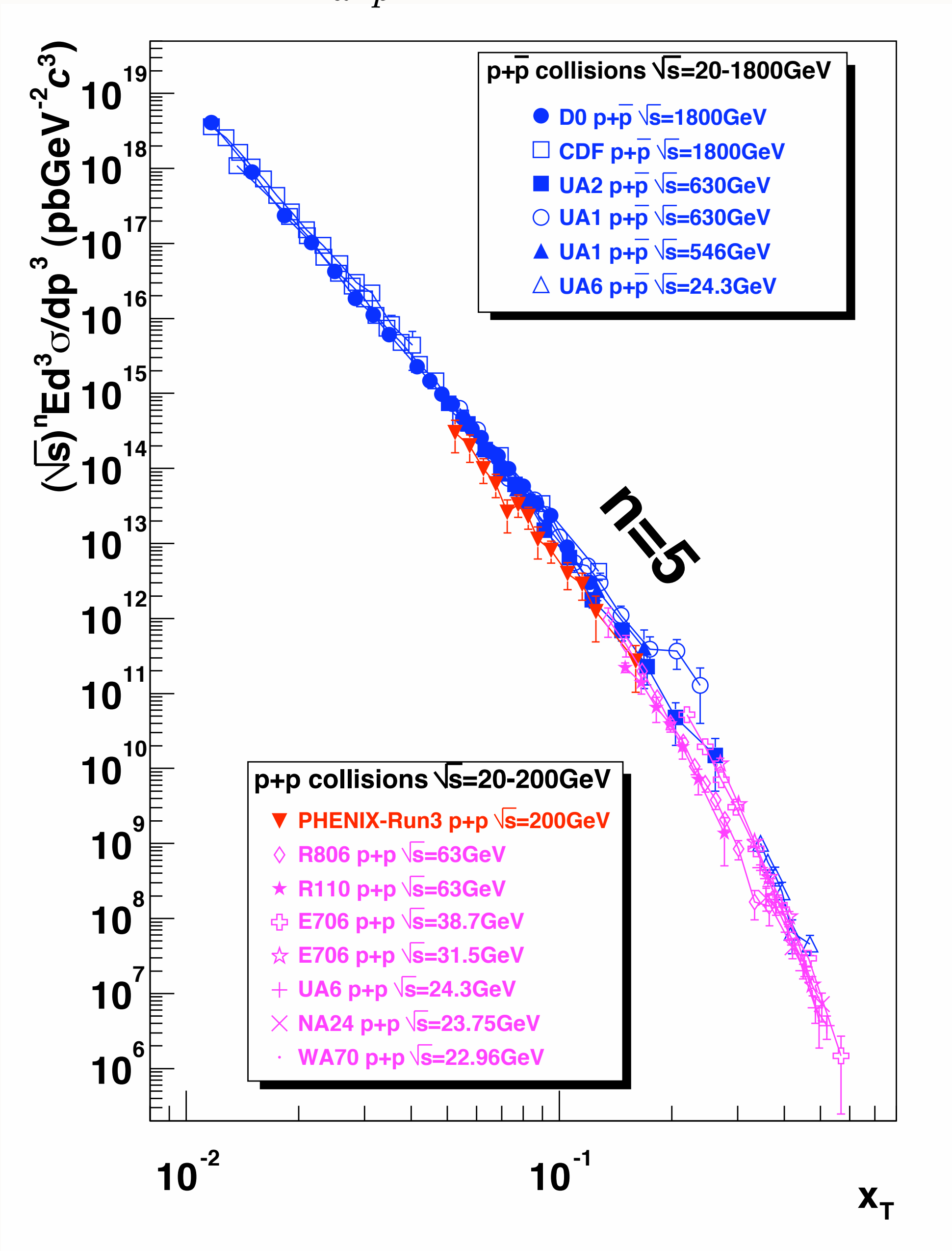
$n_{eff} \sim 4.5$

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

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

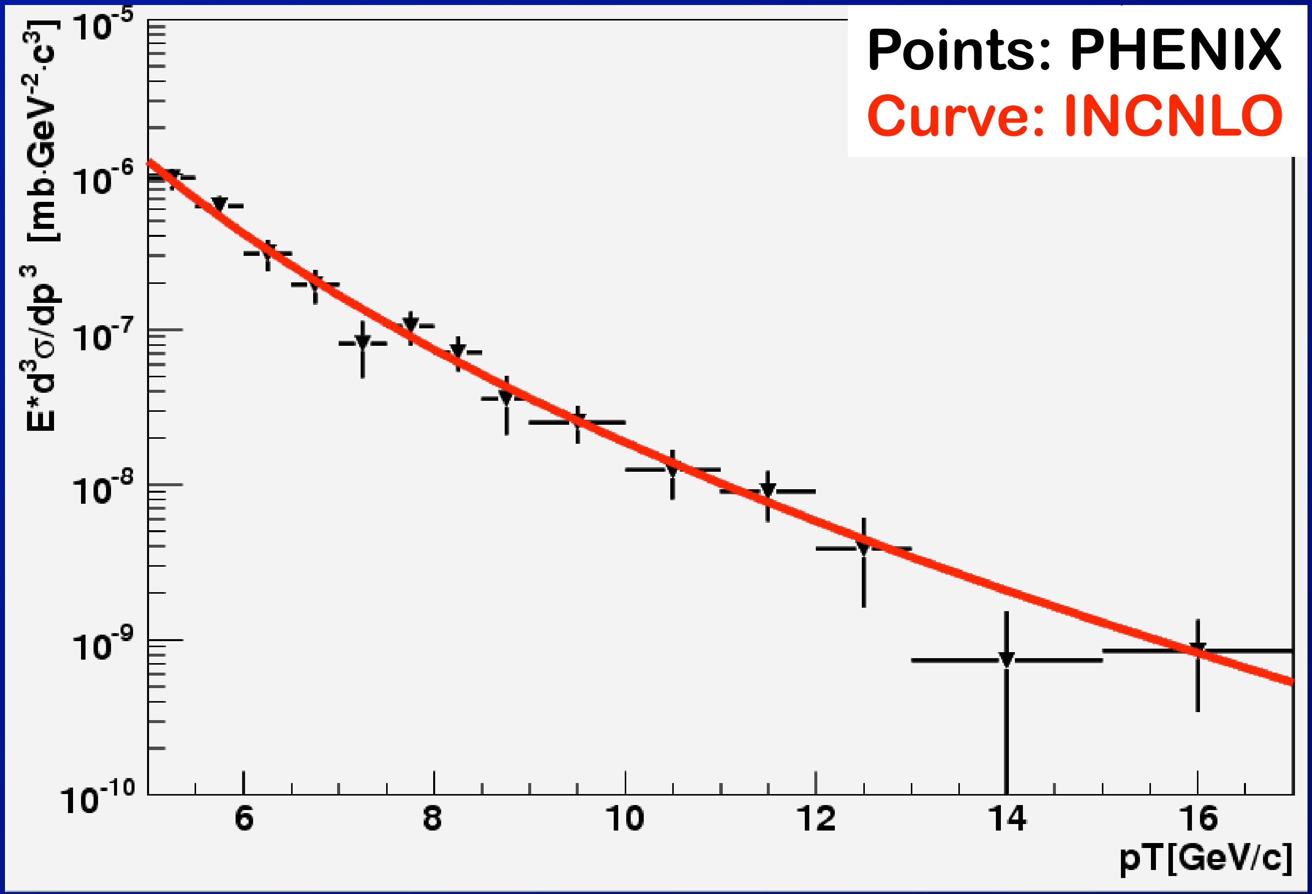
$\sqrt{s}^n E \frac{d\sigma}{d^3p}(pp \to \gamma X)$ at fixed x_T

Tannenbaum



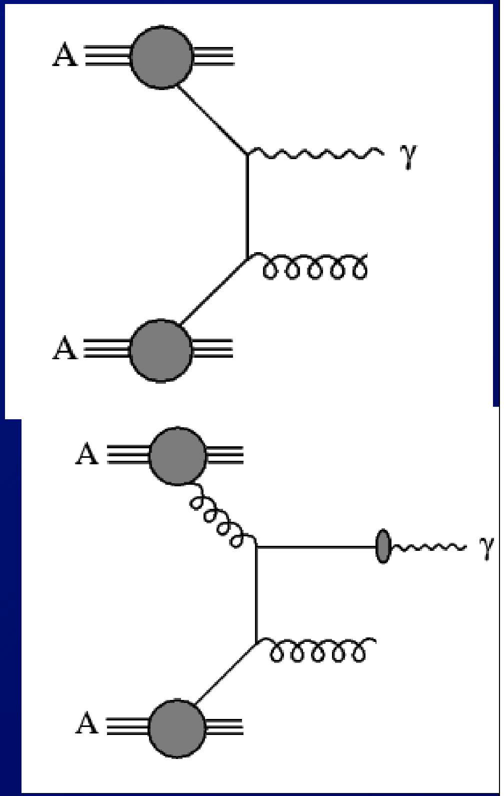
Scaling of direct photon production consistent with PQCD

PHENIX Prompt γ: Comparison to pQCD



INCNLO (1.4):

NLO pQCD + NLL photon frag. func.



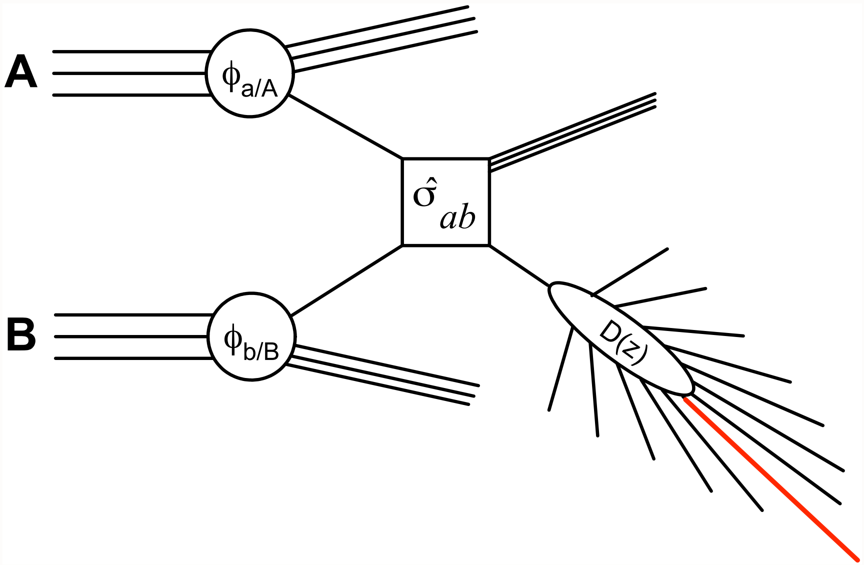
- No K factors, no fudge factors, absolute comparison
- Completely independent calculation.
  - Good control over pQCD prompt photon calculation @ RHIC.

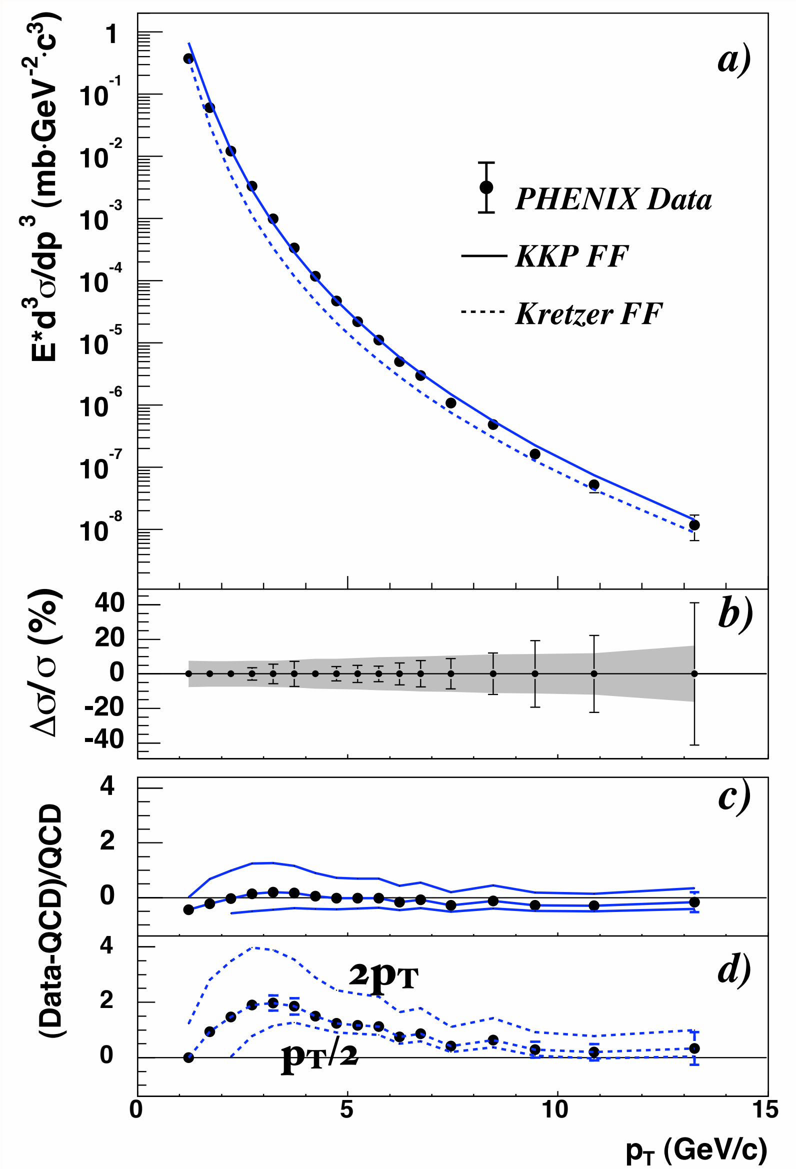
Cole

$$E \frac{d\sigma}{d^3p}(pp \to \pi^0 X)$$

$\sqrt{s} = 200\,\mathrm{GeV}$

Tannenbaum

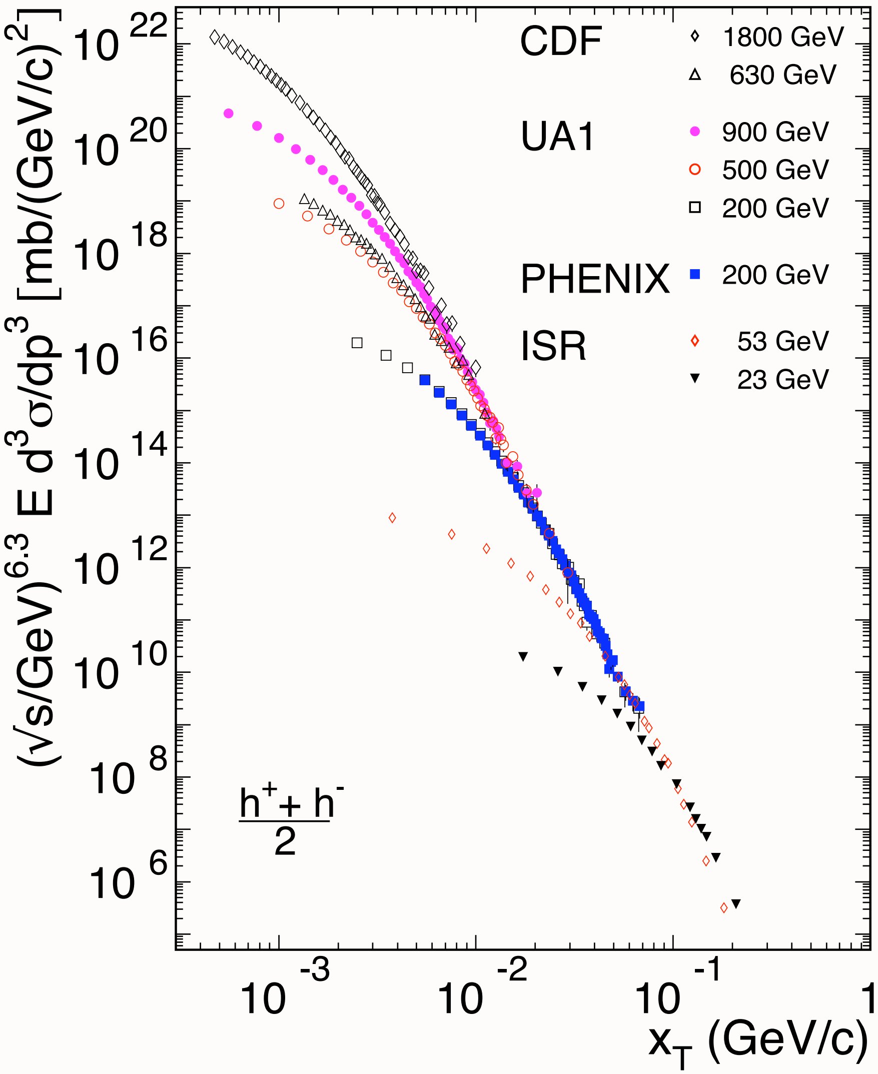




NLO pQCD predictions
Vogelsang

Assumes equal factorization and renormalization scales: $p_T/2$, p_T, $2p_T$

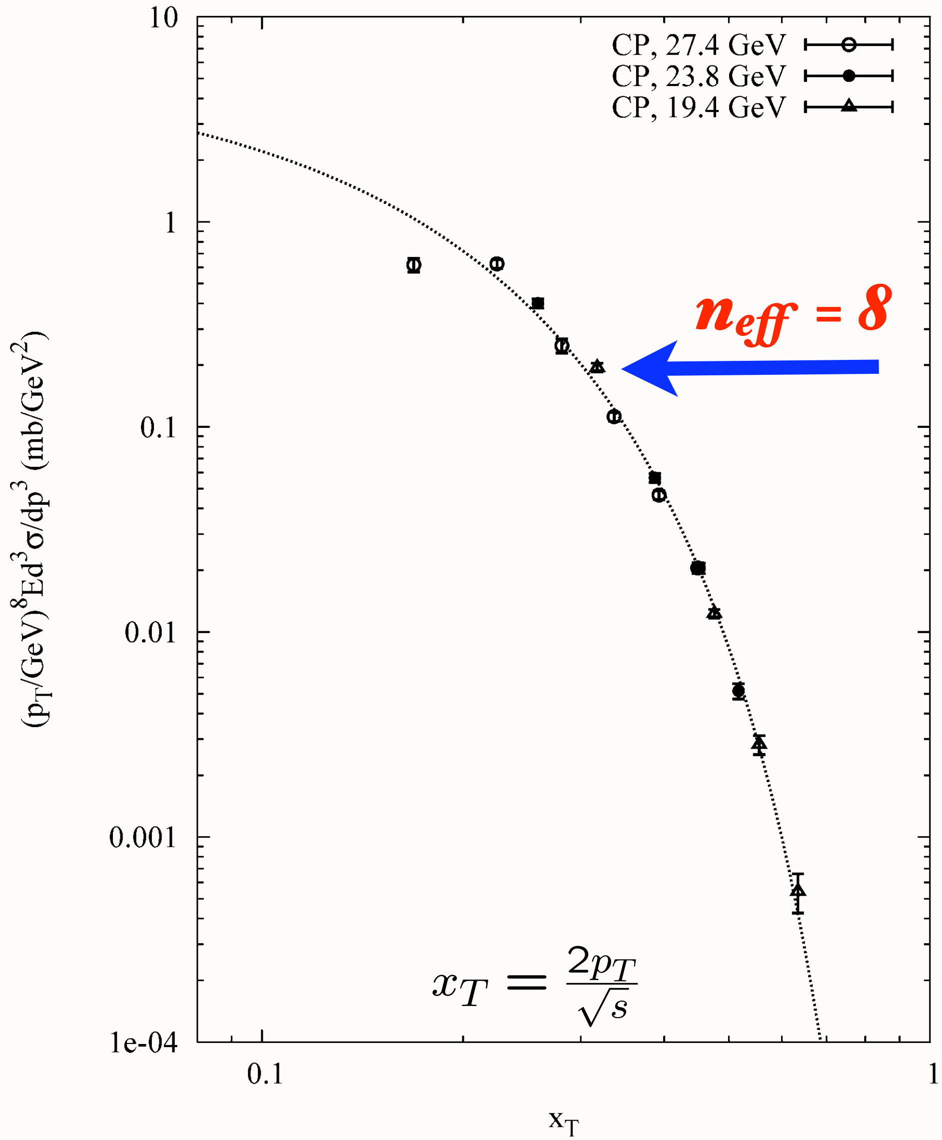
$\sqrt{s}^{6.3} \times E\frac{d\sigma}{d^3p}(pp \to H^{\pm}X)$ at fixed x_T



Tannenbaum

No Single Scaling Inconsistent with PQCD

Invariant cross sections for $pp \to (\pi^+ + \pi^-)/2 + X$



Chicago-Princeton FermiLab Measurements

Far from PQCD leading twist

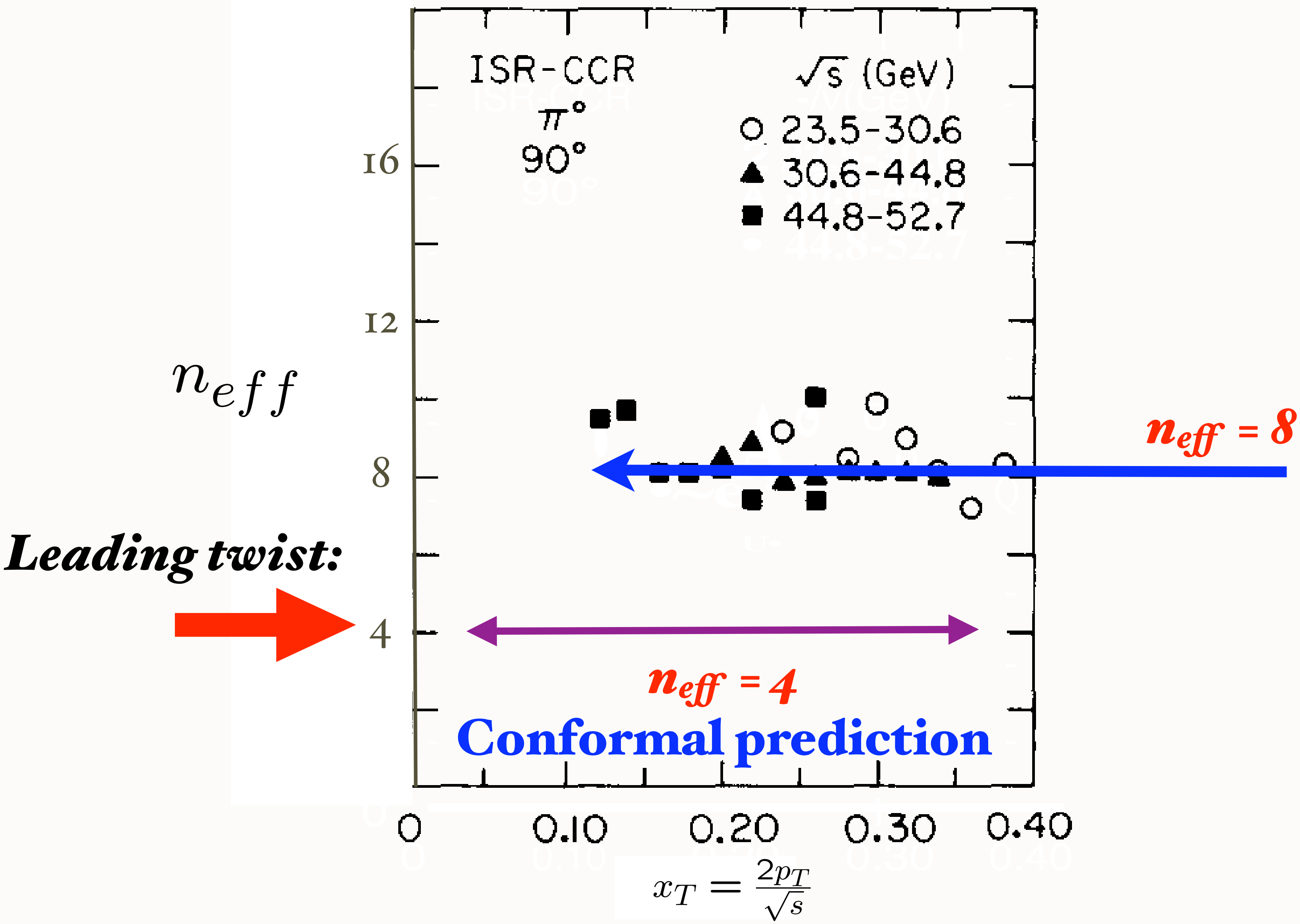
$$p_T{}^n \times E\frac{d\sigma}{d^3p}(pp \to \pi X)$$

at fixed x_T, $\theta_{CM} = \frac{\pi}{2}$

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

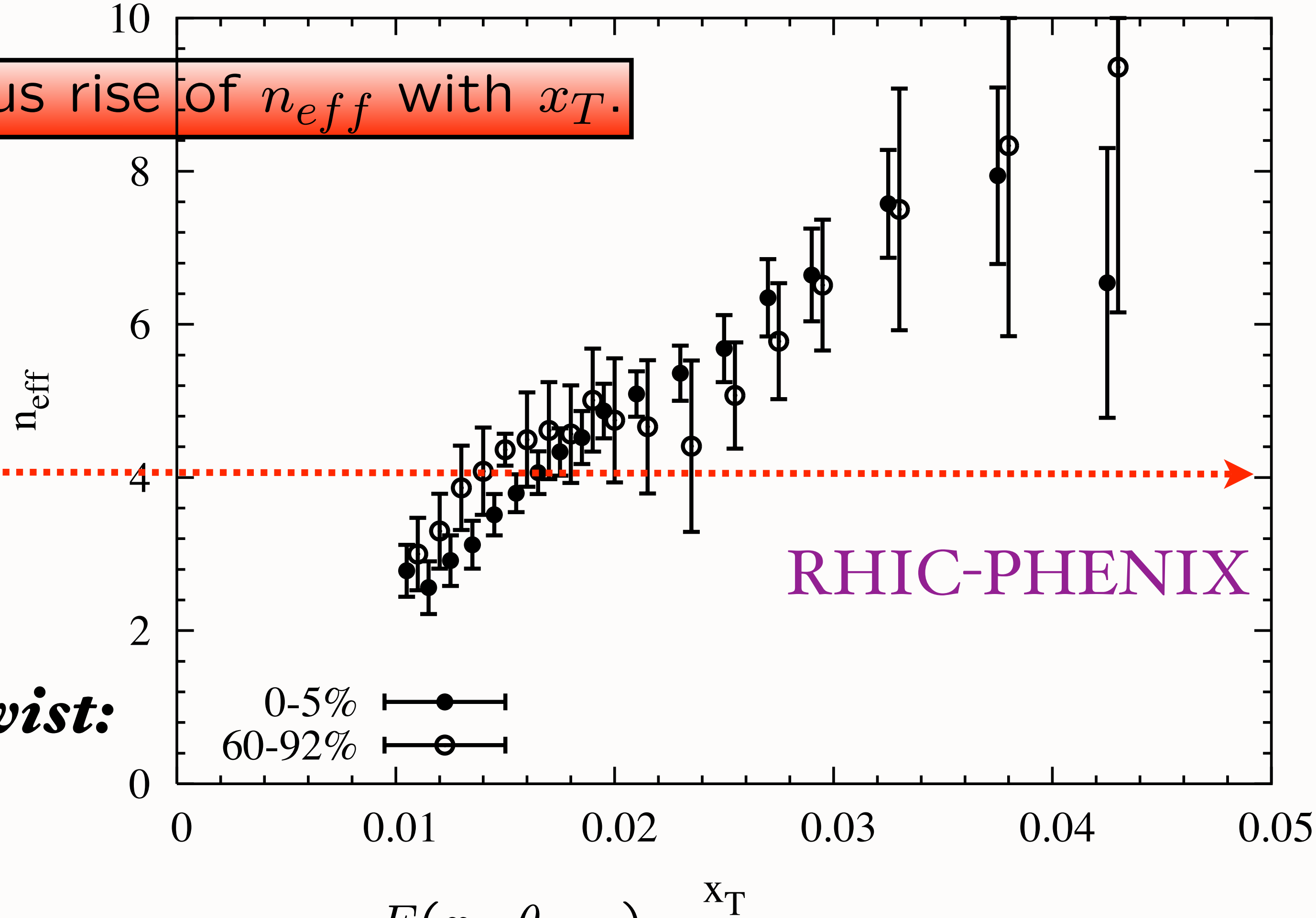
$$F(x_T, \theta_{CM} = \pi/2) = C(1 - x_T)^9$$

$$E\frac{d\sigma}{d^3p}(pp \to \pi^0 X) = \frac{F(x_T, \theta_{CM})}{p_T^{n_{eff}}}$$



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

Continuous rise of n_{eff} with x_T.



$n_{eff} = 4$

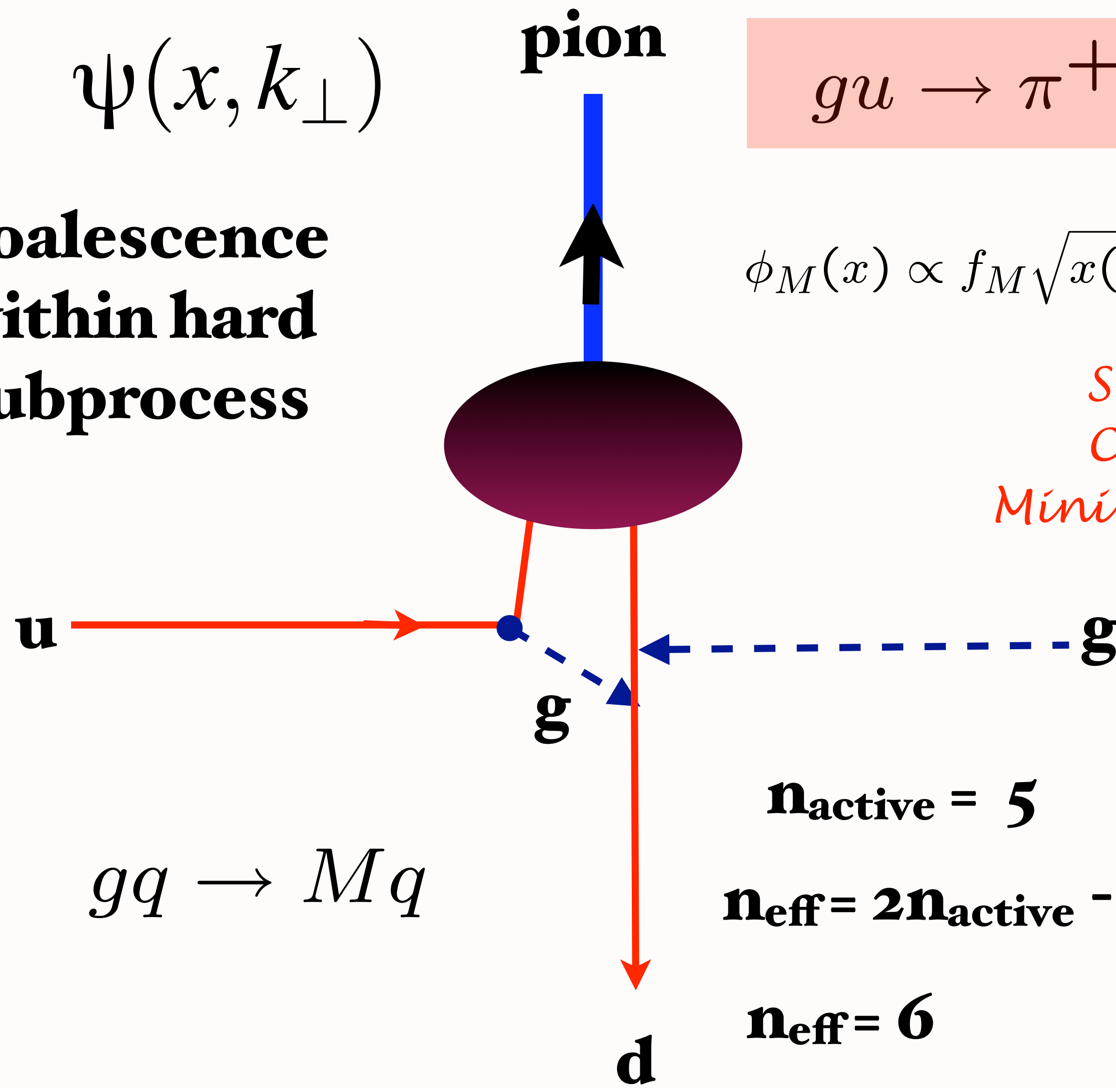
Leading twist:

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

Meson can be made directly within hard subprocess

$\psi(x, k_\perp)$

Coalescence within hard subprocess



$$gu \rightarrow \pi^+ d$$

$$\phi_M(x) \propto f_M \sqrt{x(1-x)} \propto \Lambda_{QCD}$$

Small color-singlet
Color Transparent!
Minimal same-side energy

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

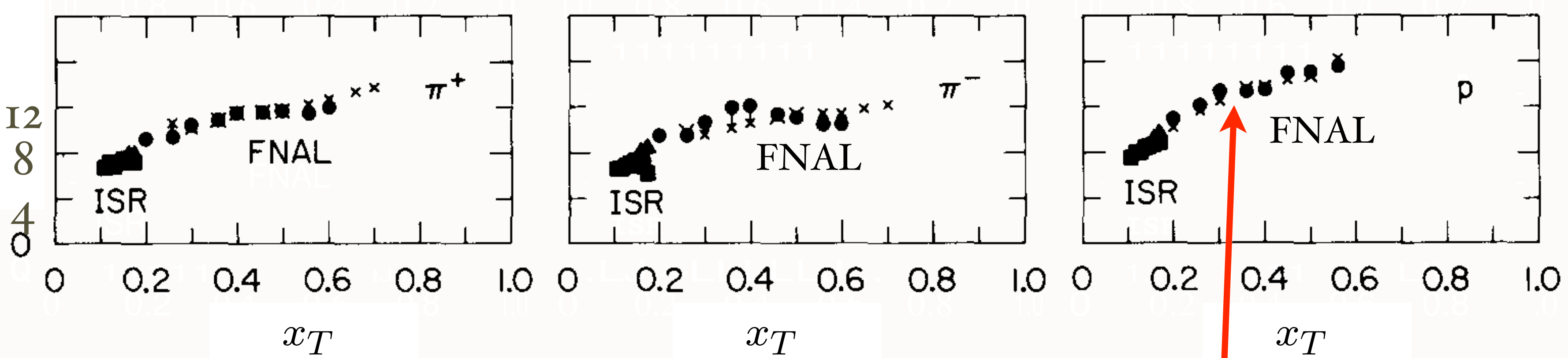
$$gq \rightarrow Mq$$

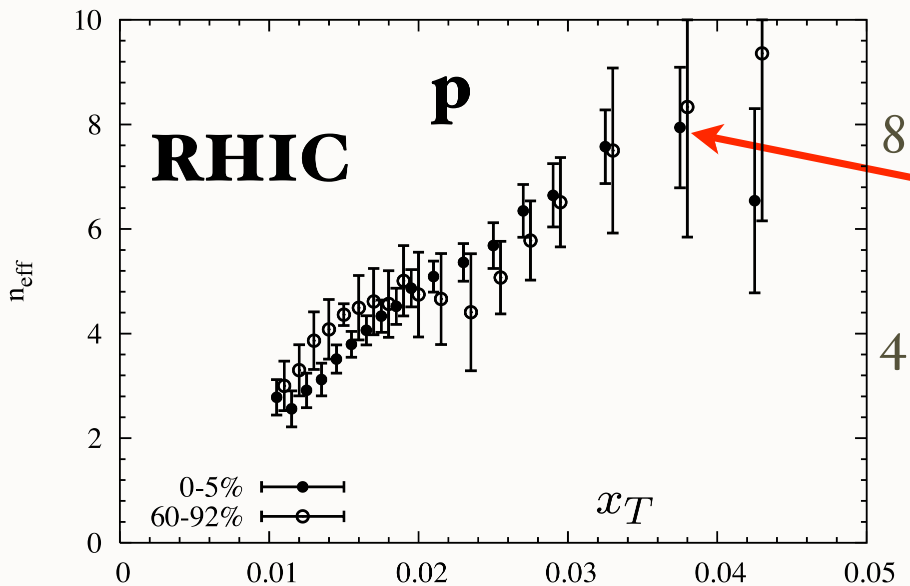
$n_{active} = 5$

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

$n_{eff} = 6$

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





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

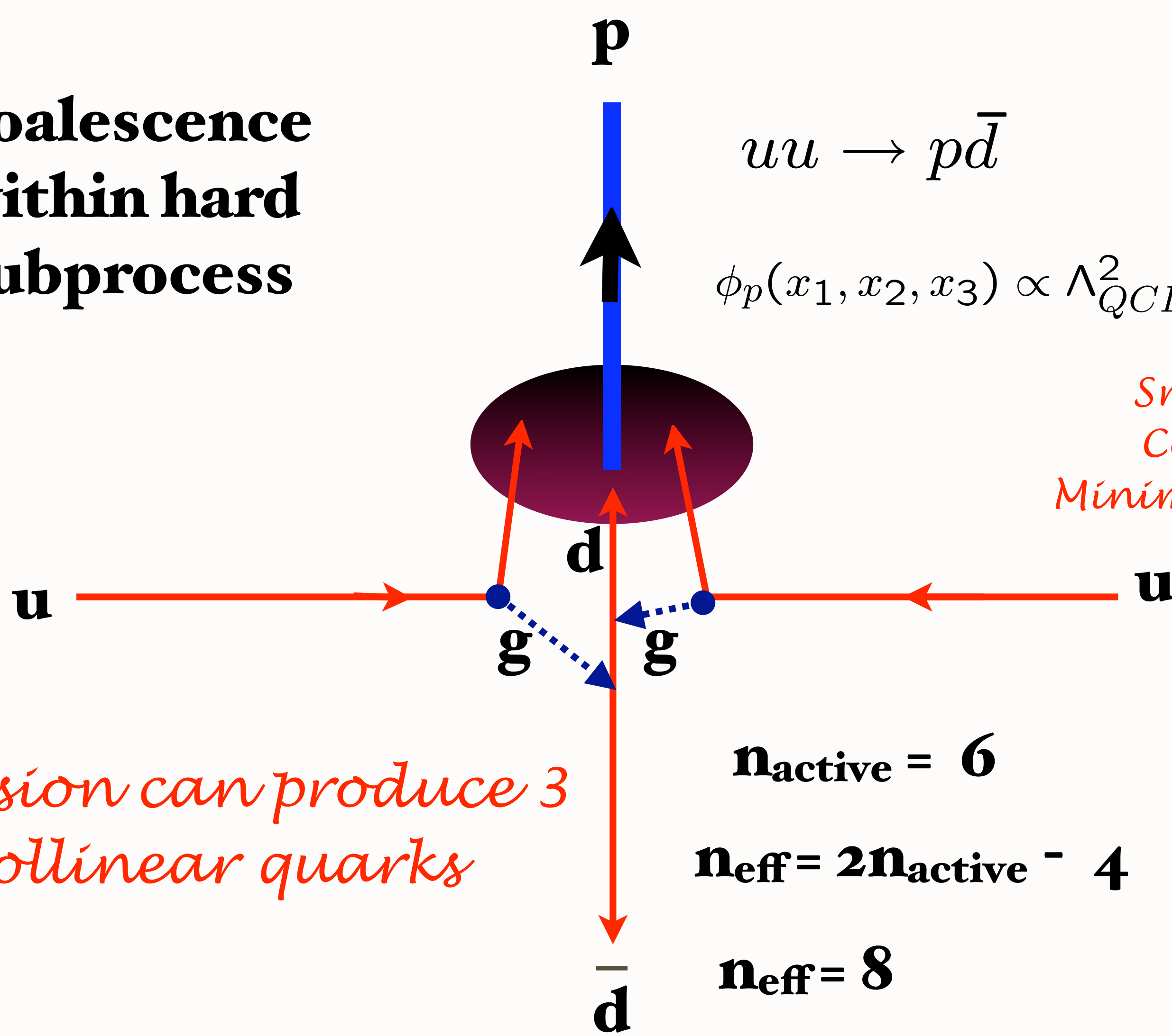
$$E\frac{d\sigma}{d^3p}(pp \to pX) = \frac{F(x_T,\theta_{CM})}{p_T^{8}}$$

Trend consistent with RHIC at small x_T

Baryon can be made directly within hard subprocess

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

Coalescence within hard subprocess



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

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

Small color-singlet
Color Transparent
Minimal same-side energy

Collision can produce 3 collinear quarks

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

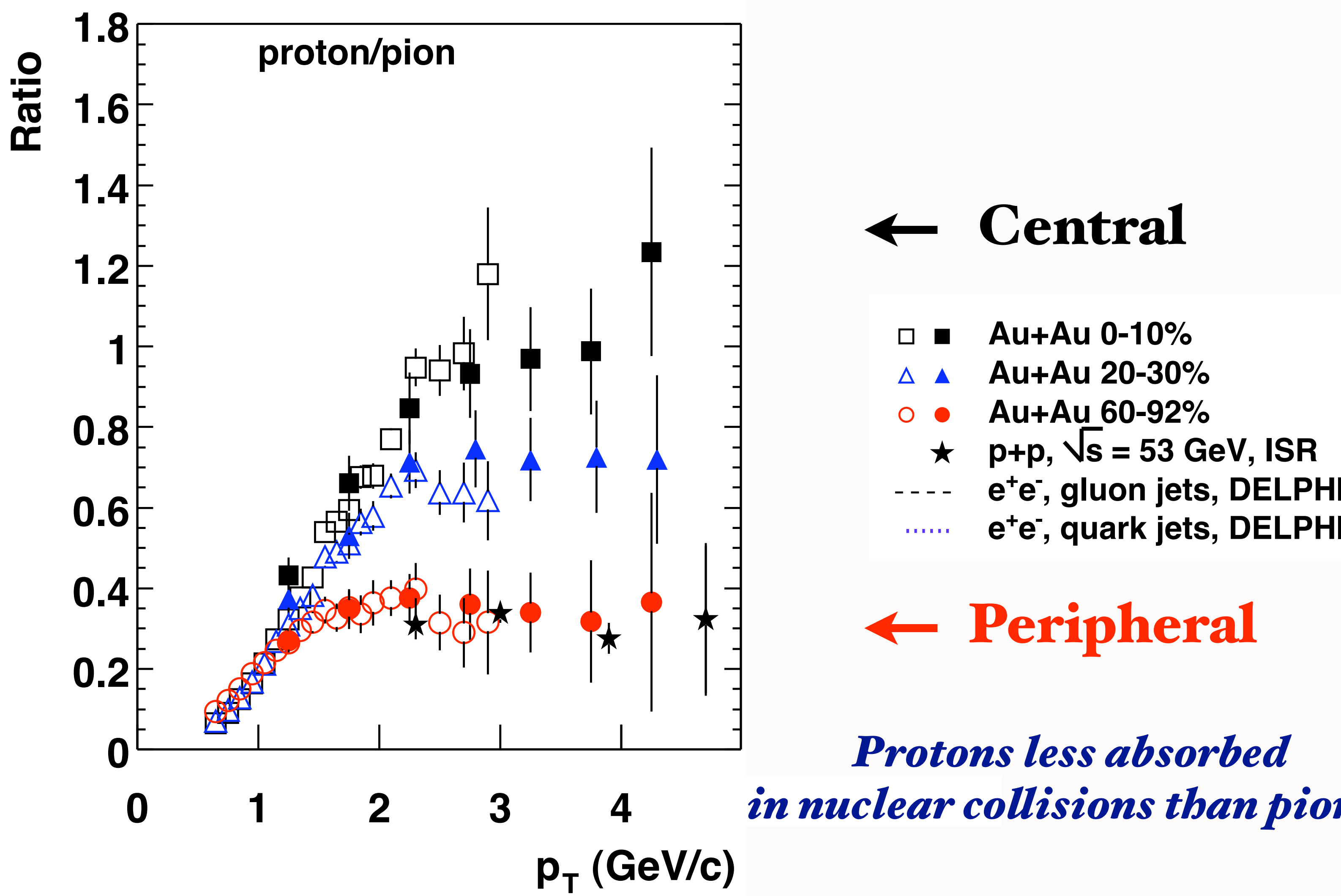
$n_{active} = 6$

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

$n_{eff} = 8$

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

Particle ratio changes with centrality!

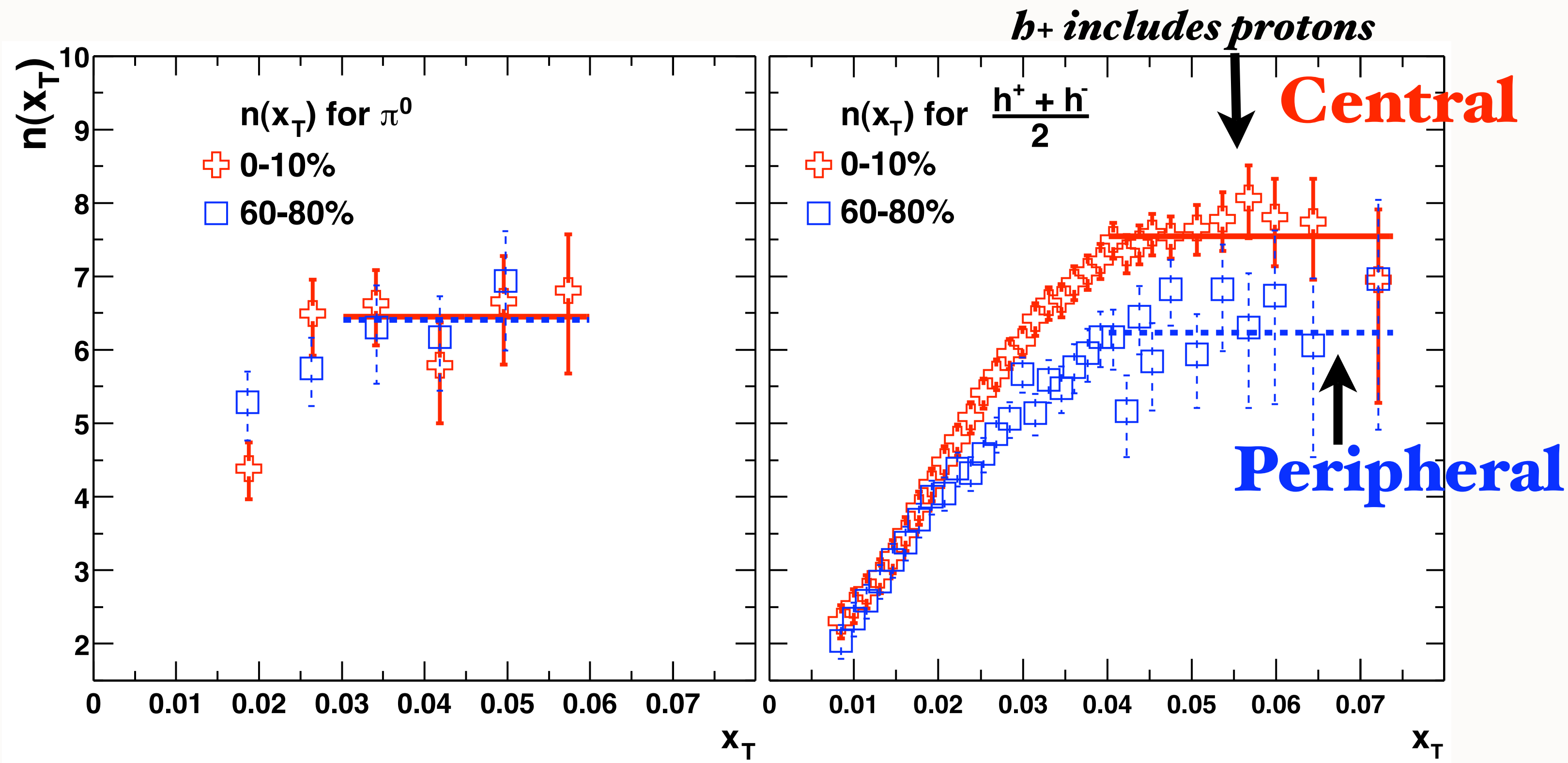


Protons less absorbed in nuclear collisions than pions!

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

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

Evidence for Direct, Higher-Twist Subprocesses

- Anomalous power behavior at fixed x_T
- Protons more likely to come from direct 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
- Exclusive-inclusive connection at $x_T = 1$

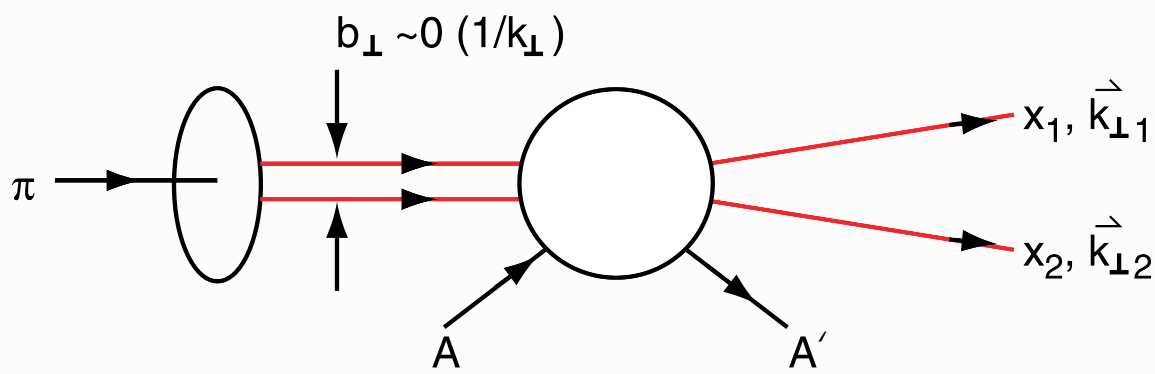
Role of higher twist in hard inclusive reactions

Semi-Exclusive Reactions -BHMT

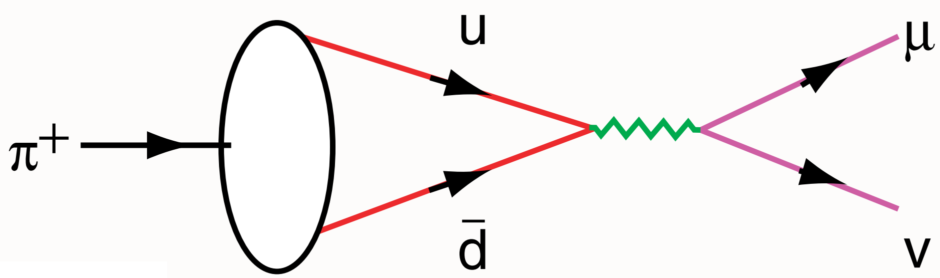
Hoyer, Mueller, Tang, sjb

- 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

Fluctuation of a Pion to a Compact Color Dipole State



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



Same Fock State Determines Weak Decay