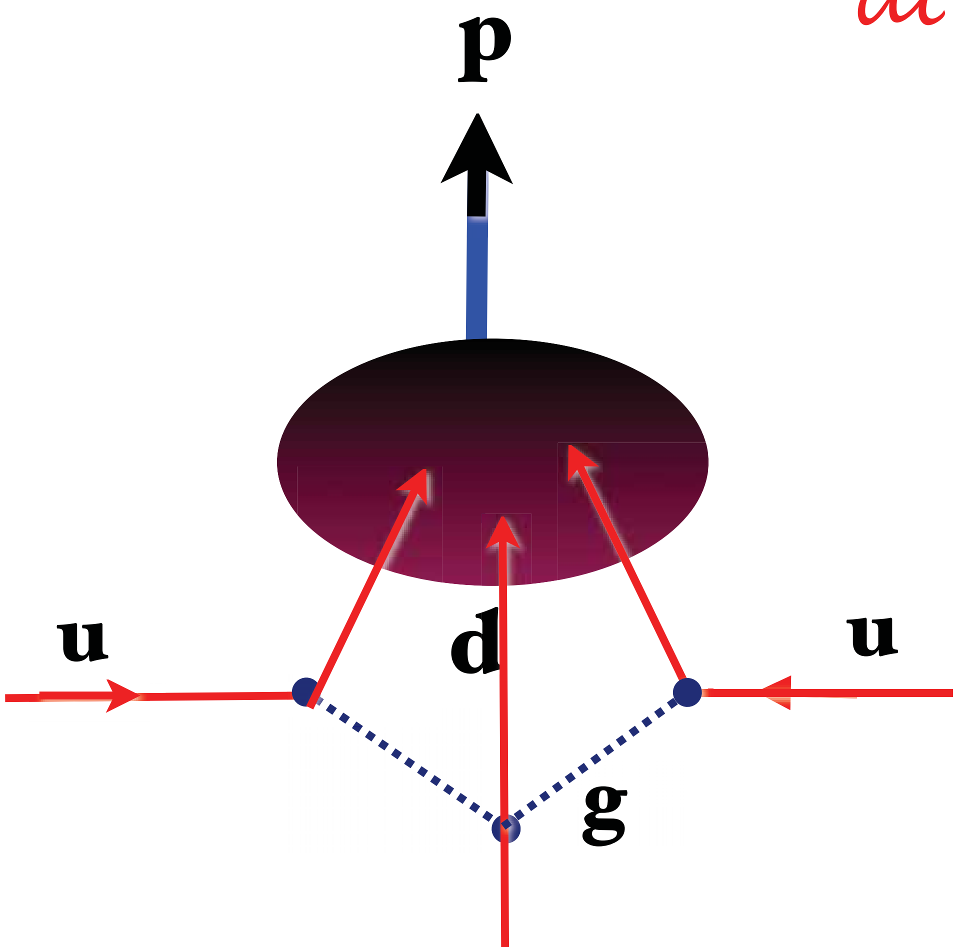
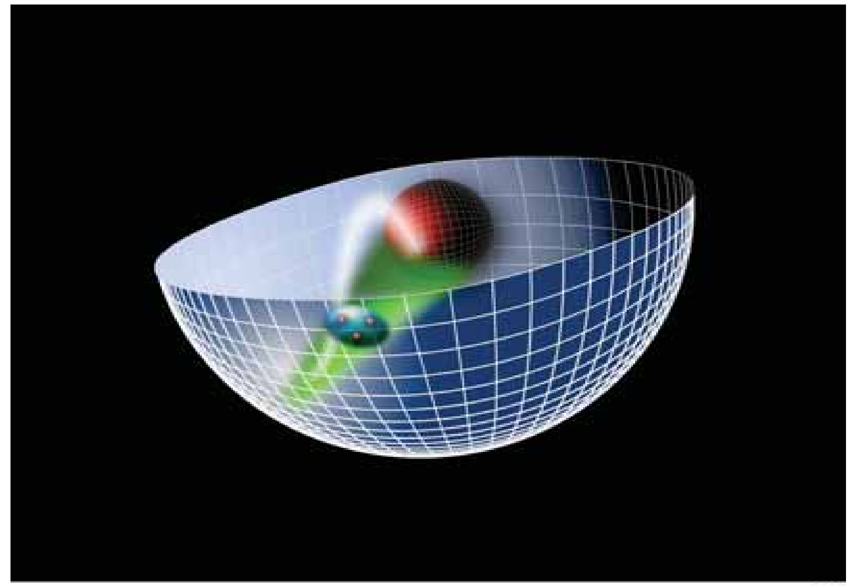
Novel High Transverse Momentum Phenomena at the LHC



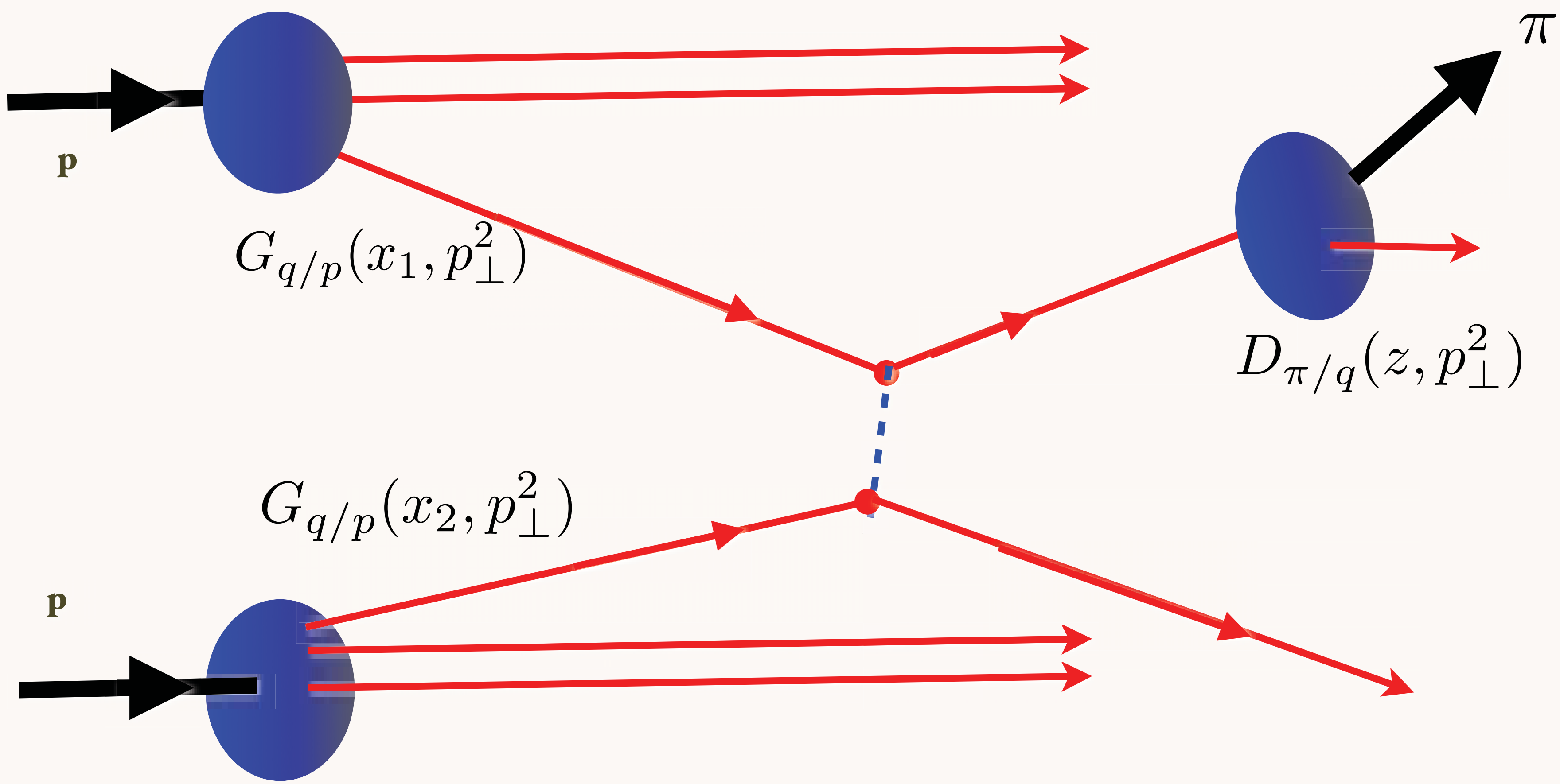


4th International Workshop
High-pT physics at the LHC

Prague February 5, 2009

Stan Brodsky, SLAC

Leading-Twist Contribution to Hadron Production



Parton model and Conformal Scaling:

$$\frac{d\sigma}{d^3p/E} = \alpha_s^2 \frac{F(x_\perp, y)}{p_\perp^4}$$

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

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

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

Parton model: $n_{eff} = 4$

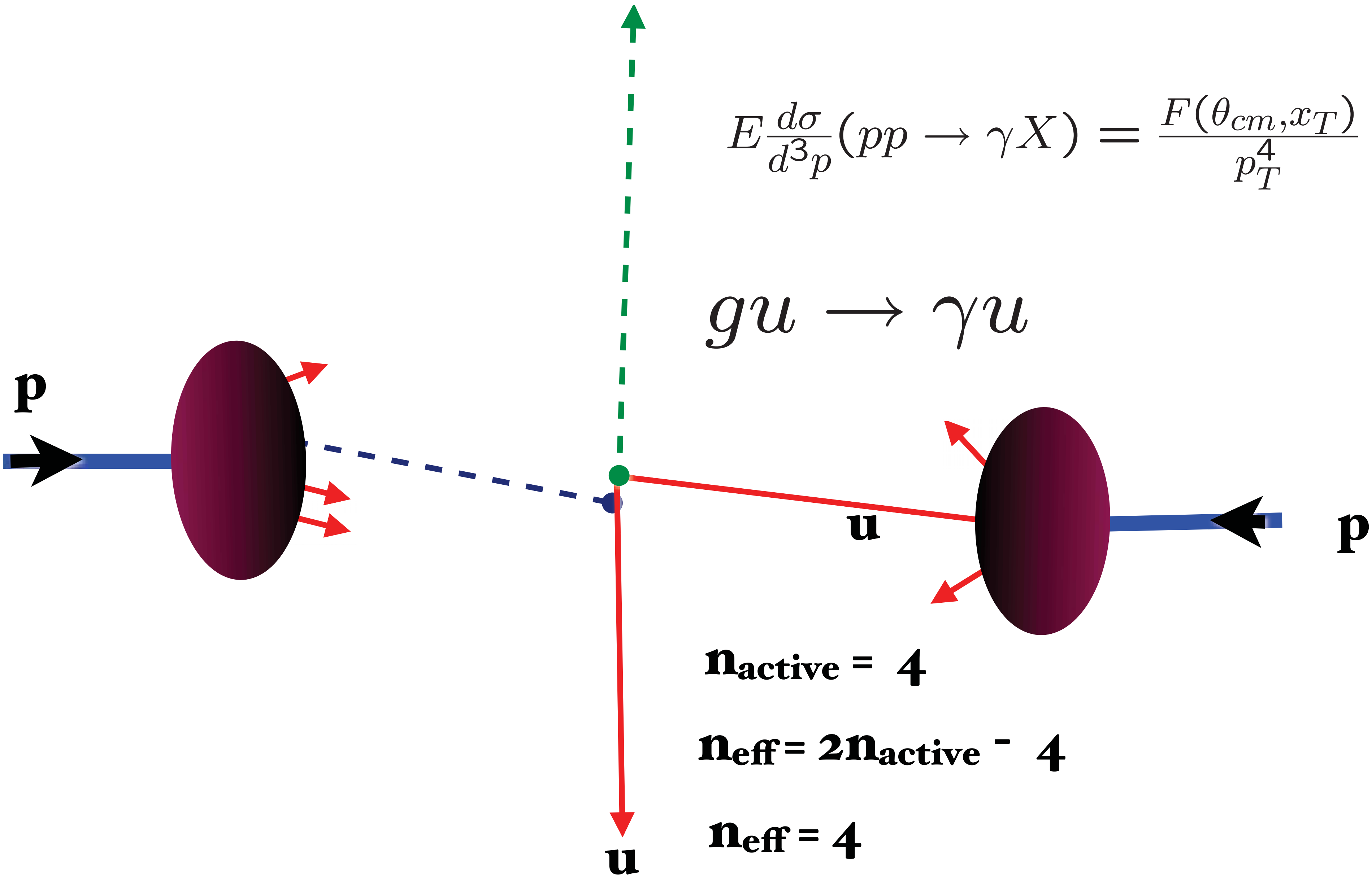
As fundamental as Bjorken scaling in DIS

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

$$pp \longrightarrow \gamma X$$

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

$$gu \longrightarrow \gamma u$$



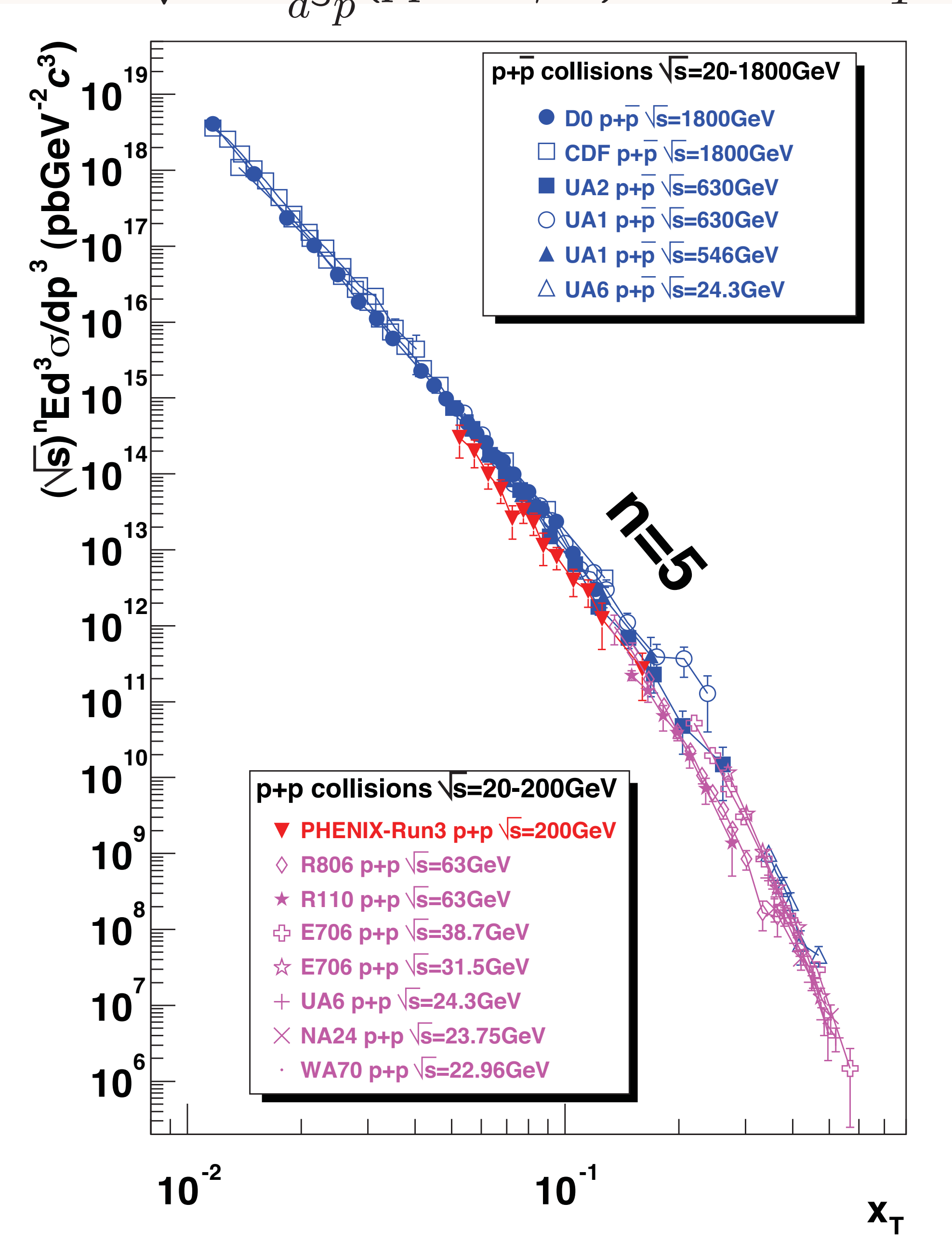
$n_{active} = 4$

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

$n_{eff} = 4$

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

Tannenbaum

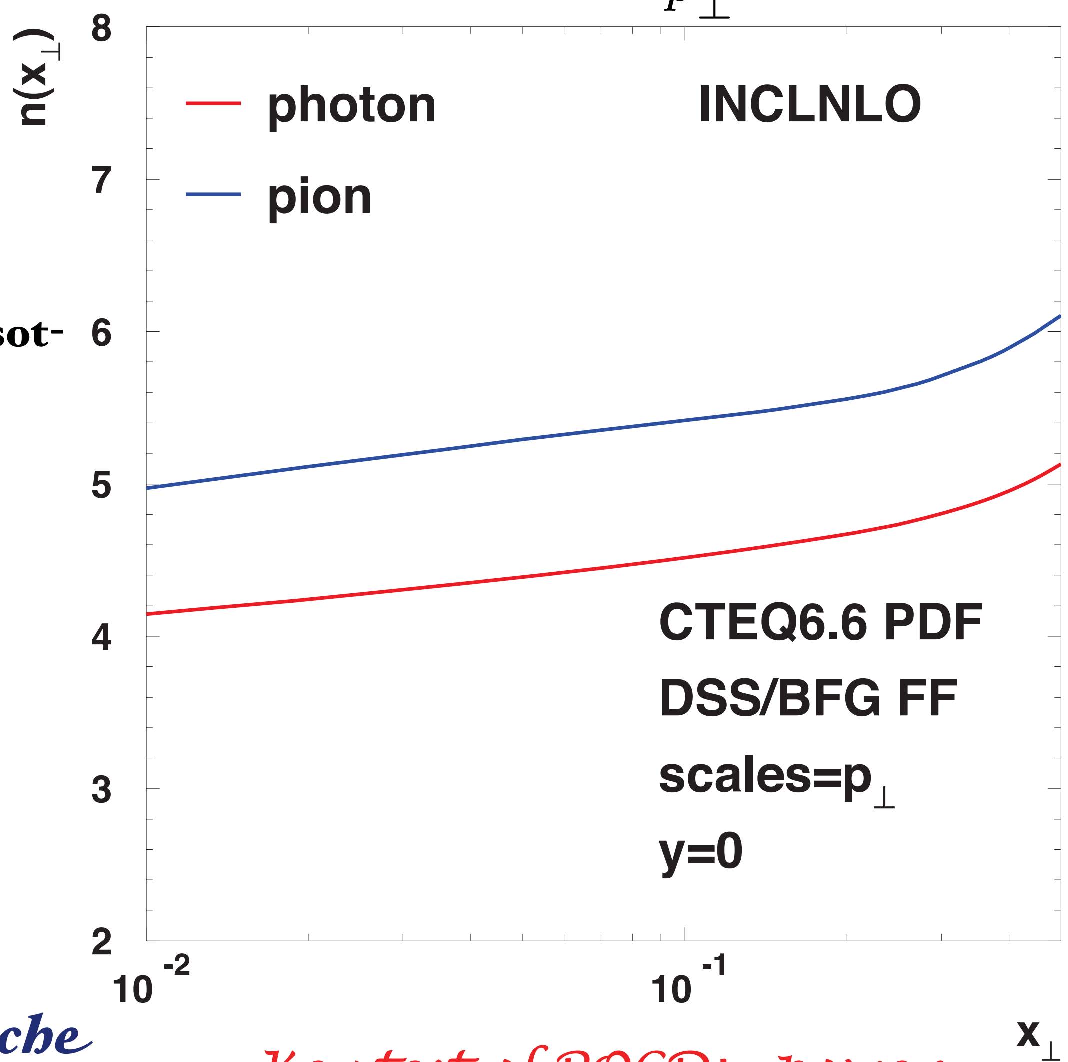


Scaling of direct photon production consistent with PQCD

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

$$\frac{d\sigma}{d^3p/E} = \frac{F(x_\perp, y)}{p_\perp^{n(x_\perp)}}$$

DSS
(De Florian-Sassot-Stratmann)



$$pp \to \pi X$$

$$pp \to \gamma X$$

$$5 < p_\perp < 20 \ GeV$$

$$70 \ GeV < \sqrt{s} < 4 \ TeV$$

Arleo, Aurenche
Pirner, Raufeisen, sjb

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

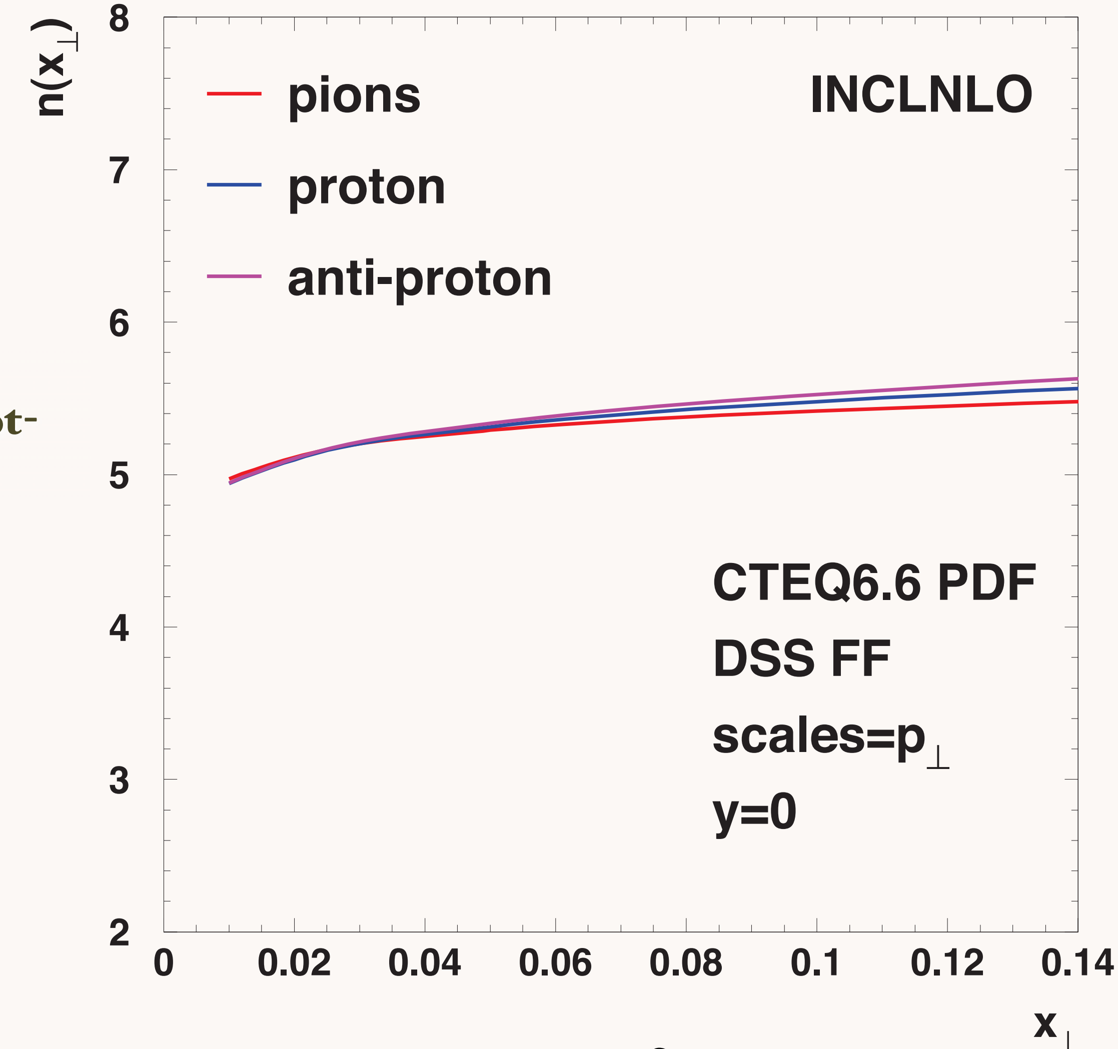
$5 < p_\perp < 20\ GeV \quad 70\ GeV < \sqrt{s} < 4\ TeV$

$pp \to \pi X$

$pp \to pX$

$pp \to \bar{p}X$

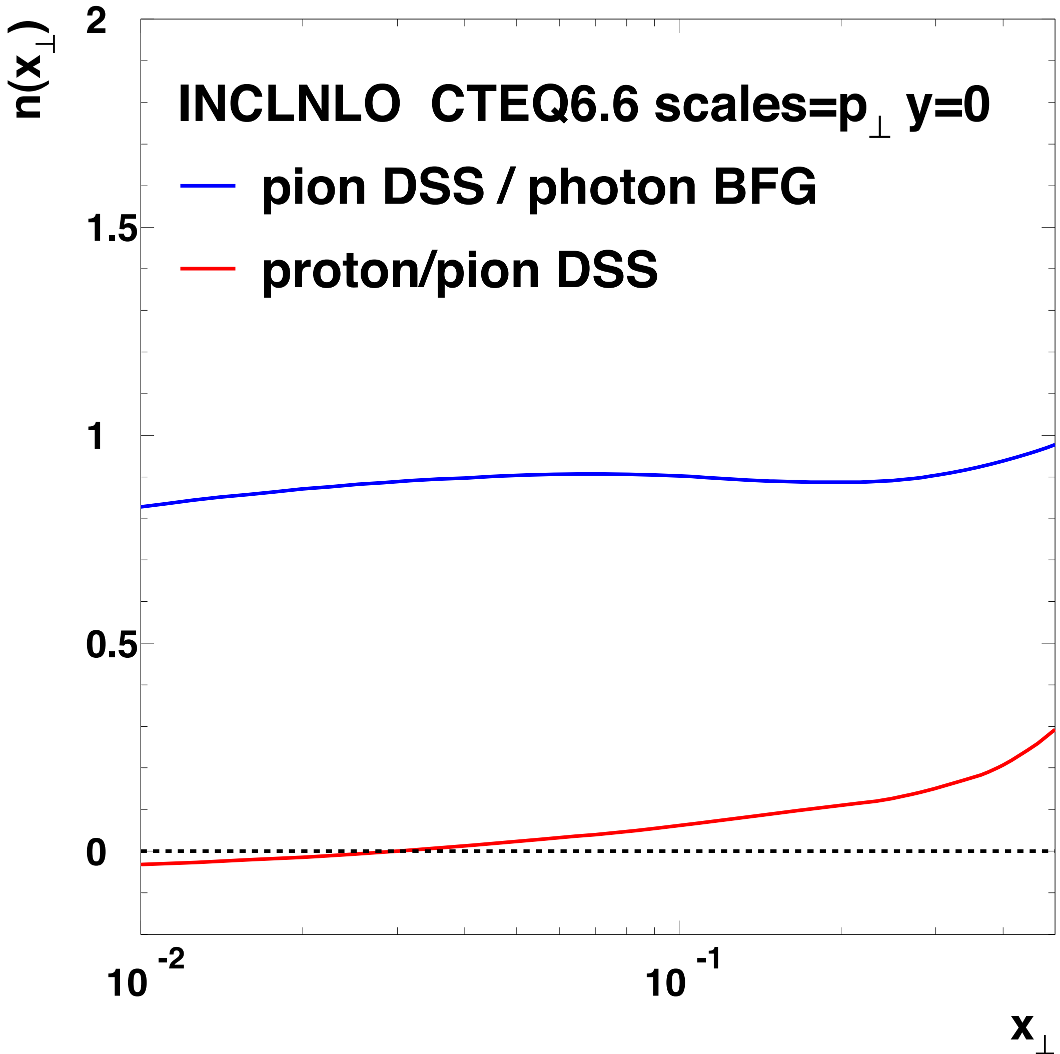
DSS
(De Florian-Sassot-Stratmann)



$$\frac{d\sigma}{d^3p/E} = \frac{F(x_\perp, y)}{p_\perp^{n(x_\perp)}}$$

Arleo, Aurenche

$$x_\perp = \frac{2p_\perp}{\sqrt{s}}$$



DSS
(De Florian-Sassot-Stratmann)

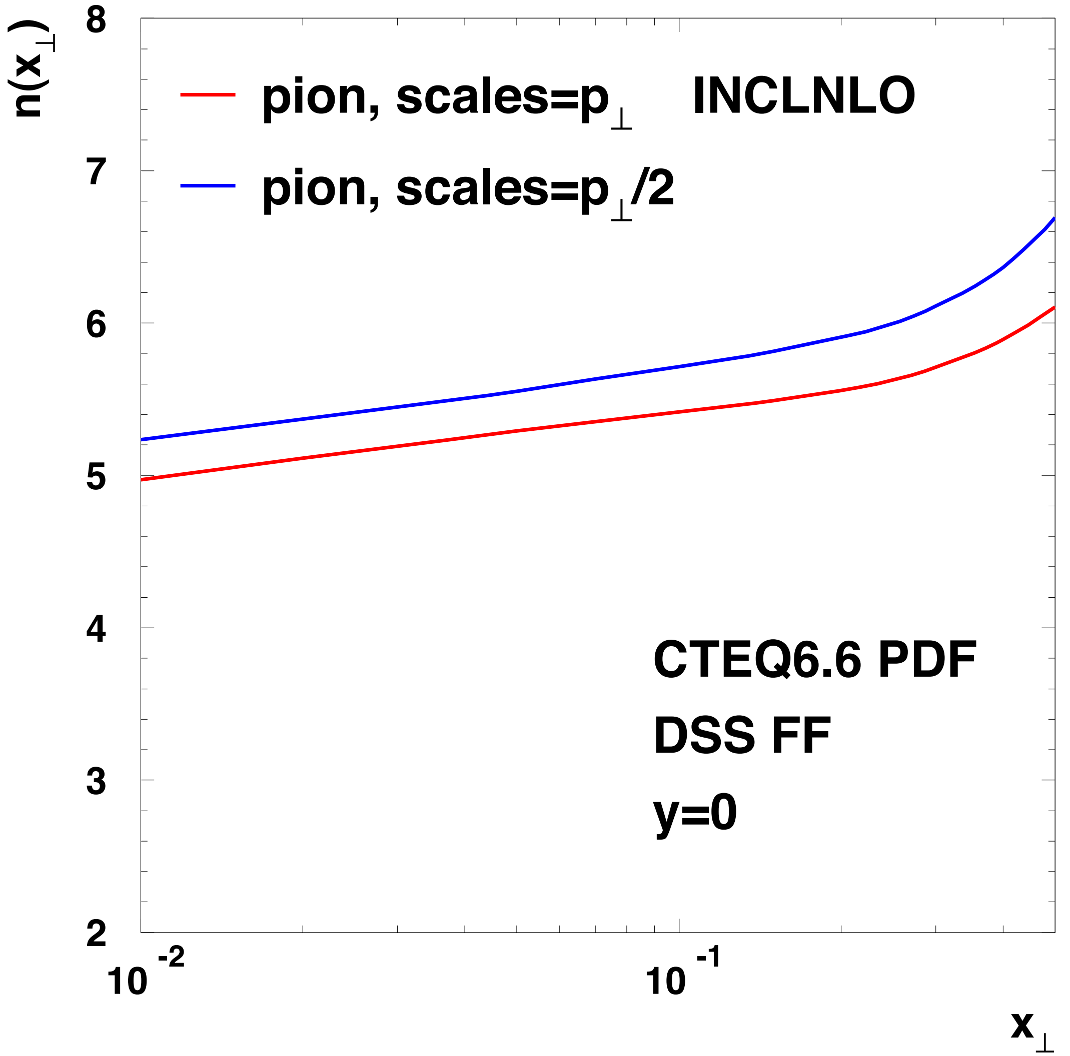
$$\frac{\frac{d\sigma(pp\to\pi X)}{d^3p/E}}{\frac{d\sigma(pp\to\gamma X)}{d^3p/E}} = \frac{F(x_\perp, y)}{p_\perp^{n(x_\perp)}}$$

$$\frac{\frac{d\sigma(pp\to p X)}{d^3p/E}}{\frac{d\sigma(pp\to\pi X)}{d^3p/E}} = \frac{F(x_\perp, y)}{p_\perp^{n(x_\perp)}}$$

Arleo, Aurenche

$$\frac{d\sigma}{d^3p/E} = \frac{F(x_\perp, y)}{p_\perp^{n(x_\perp)}}$$

DSS
(De Florian-Sassot-Stratmann)



Some scale dependence

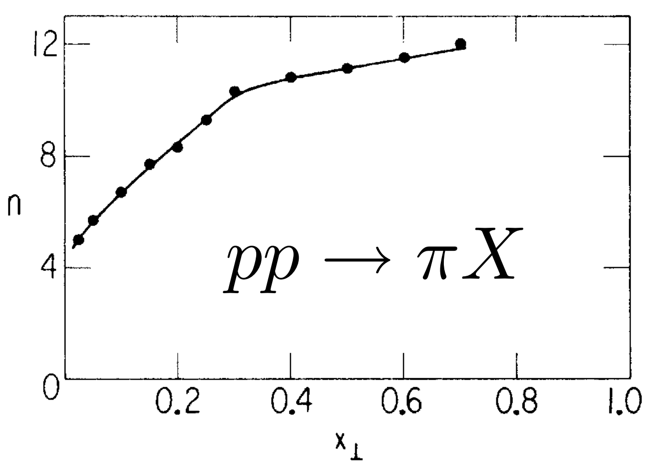
Arleo, Aurenche

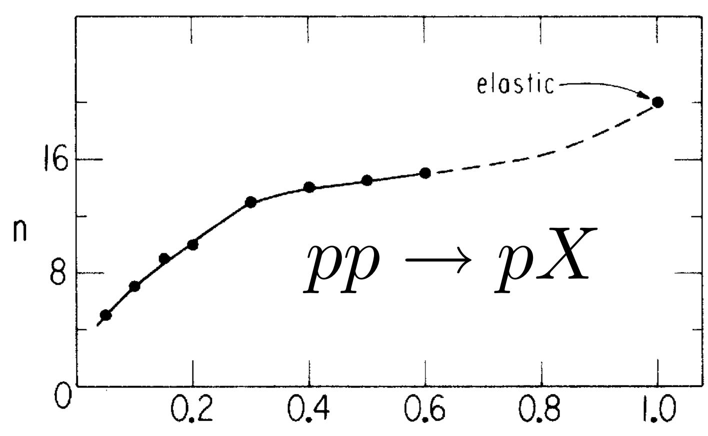
PHYSICAL REVIEW D VOLUME 11, NUMBER 11 1 JUNE 1975

Production of hadrons at large transverse momentum at 200, 300, and 400 GeV *

J. W. Cronin, H. J. Frisch, and M. J. Shochet
The Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637

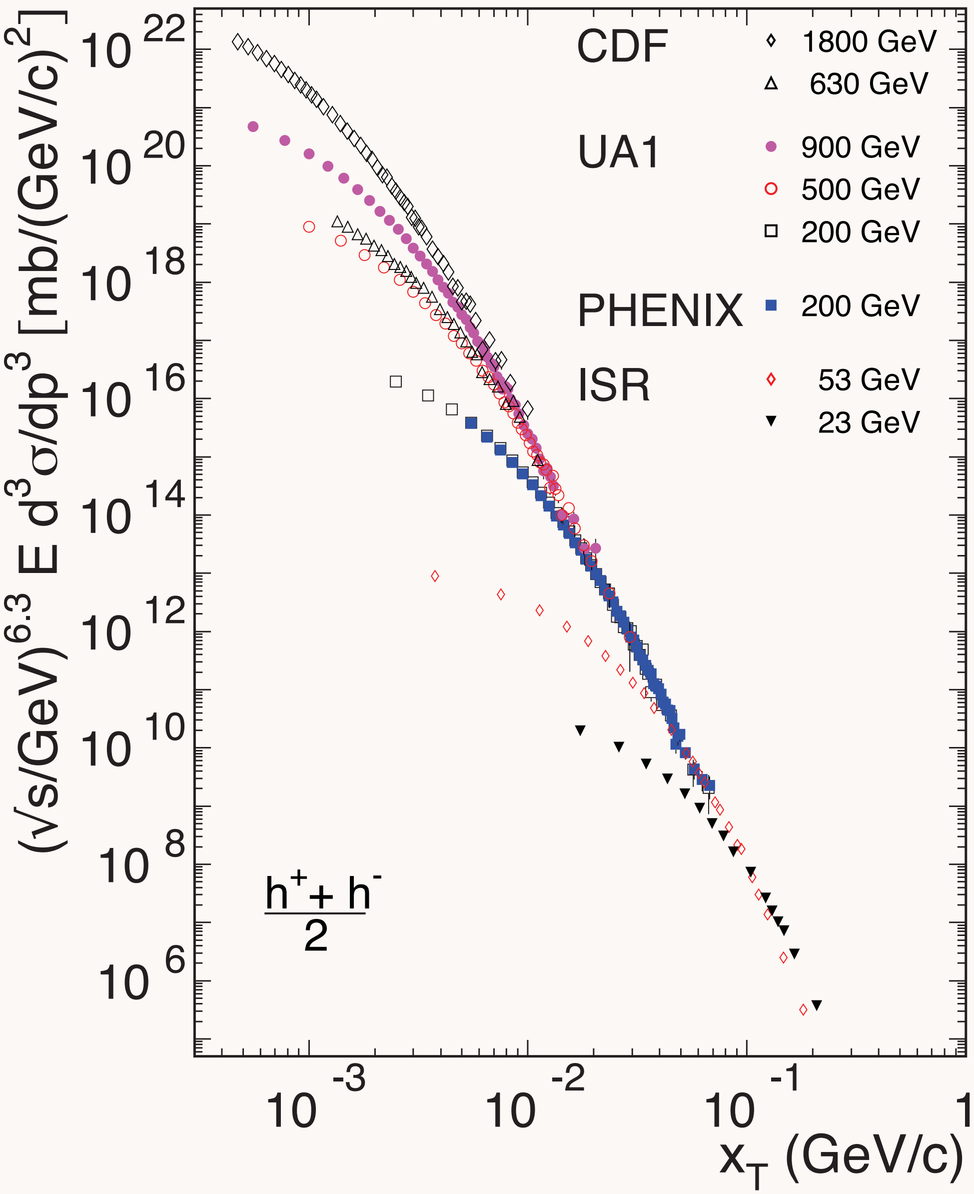
J. P. Boymond, P. A. Piroué, and R. L. Sumner
Department of Physics, Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540





$$\frac{d\sigma}{d^3p/E} = \frac{F(x_\perp, y)}{p_\perp^{n(x_\perp)}}$$

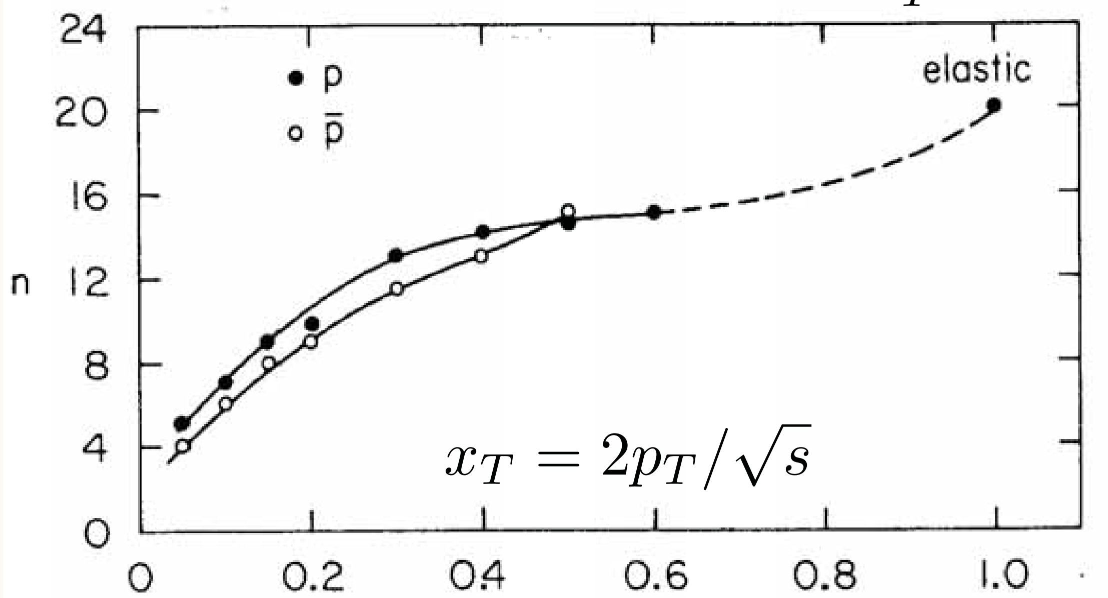
$$\sqrt{s}^{6.3} \times E\frac{d\sigma}{d^3p}(pp \to H^{\pm}X) \text{ at fixed } x_T$$



Tannenbaum

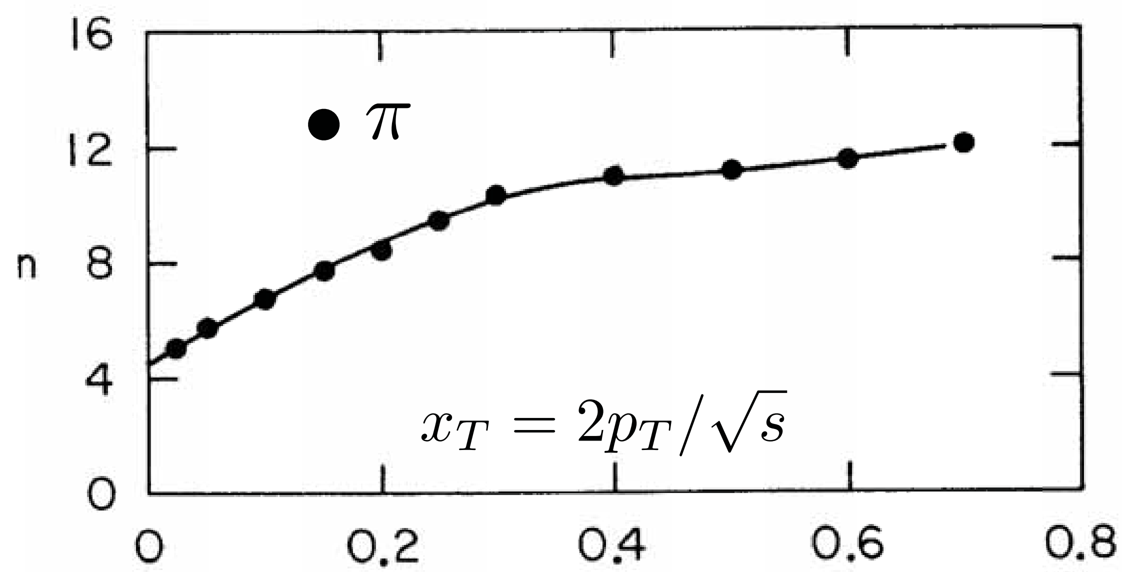
Scaling inconsistent with PQCD

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



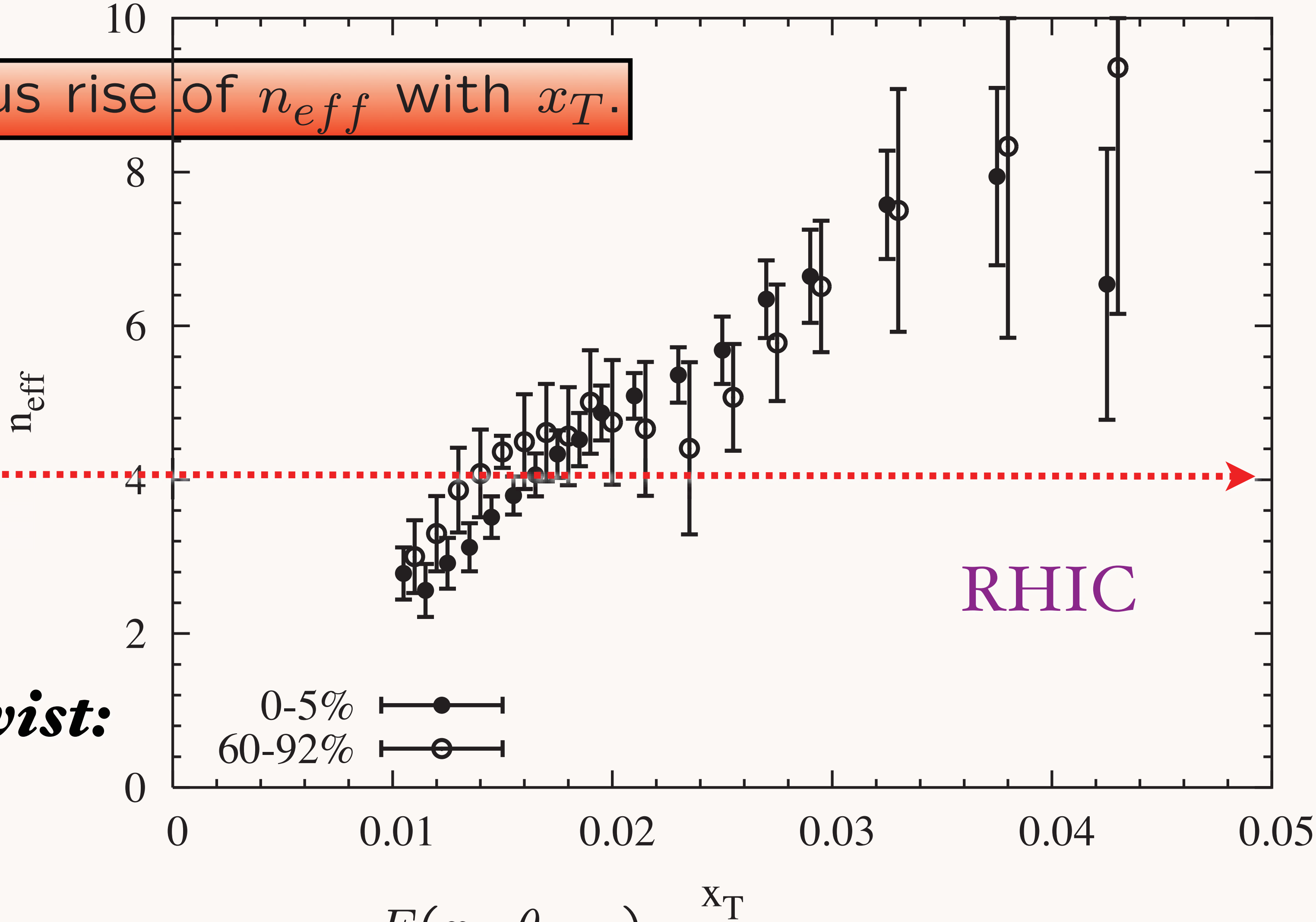
Clear evidence for higher-twist contributions

J. W. Cronin, SSI 1974



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

Continuous rise of n_{eff} with x_T.

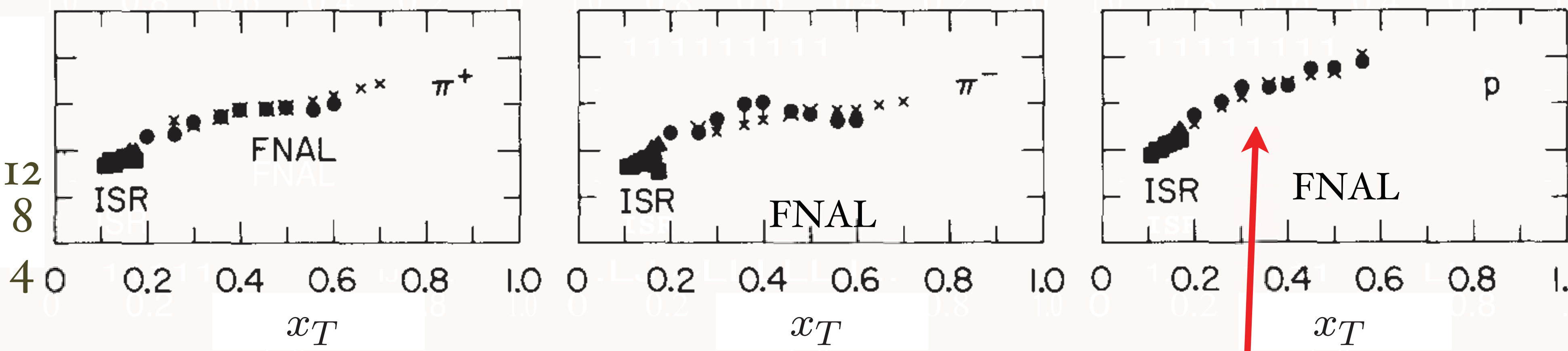


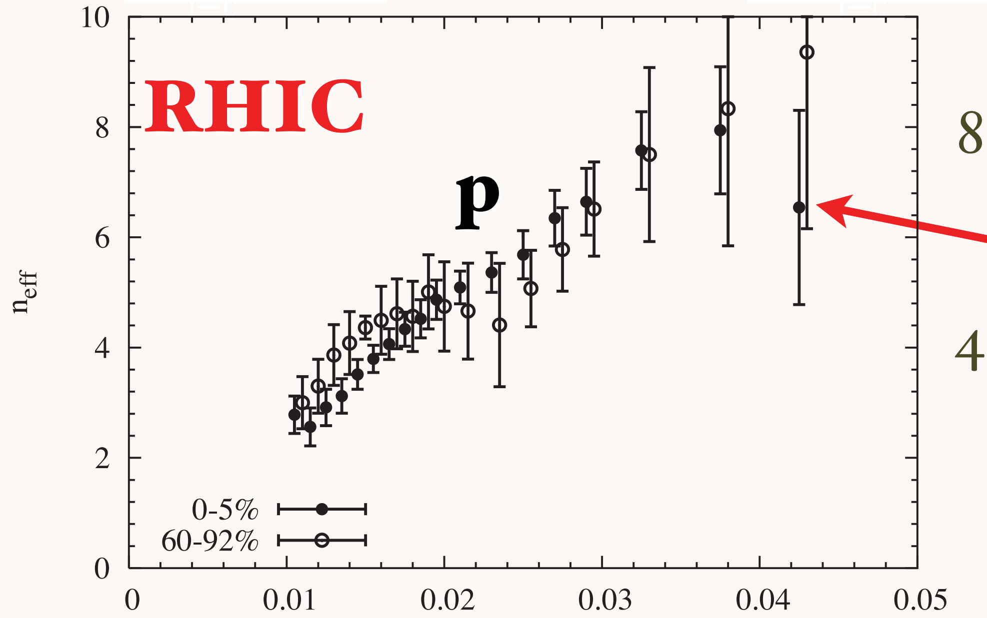
$n_{eff} = 4$

Leading twist:

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

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



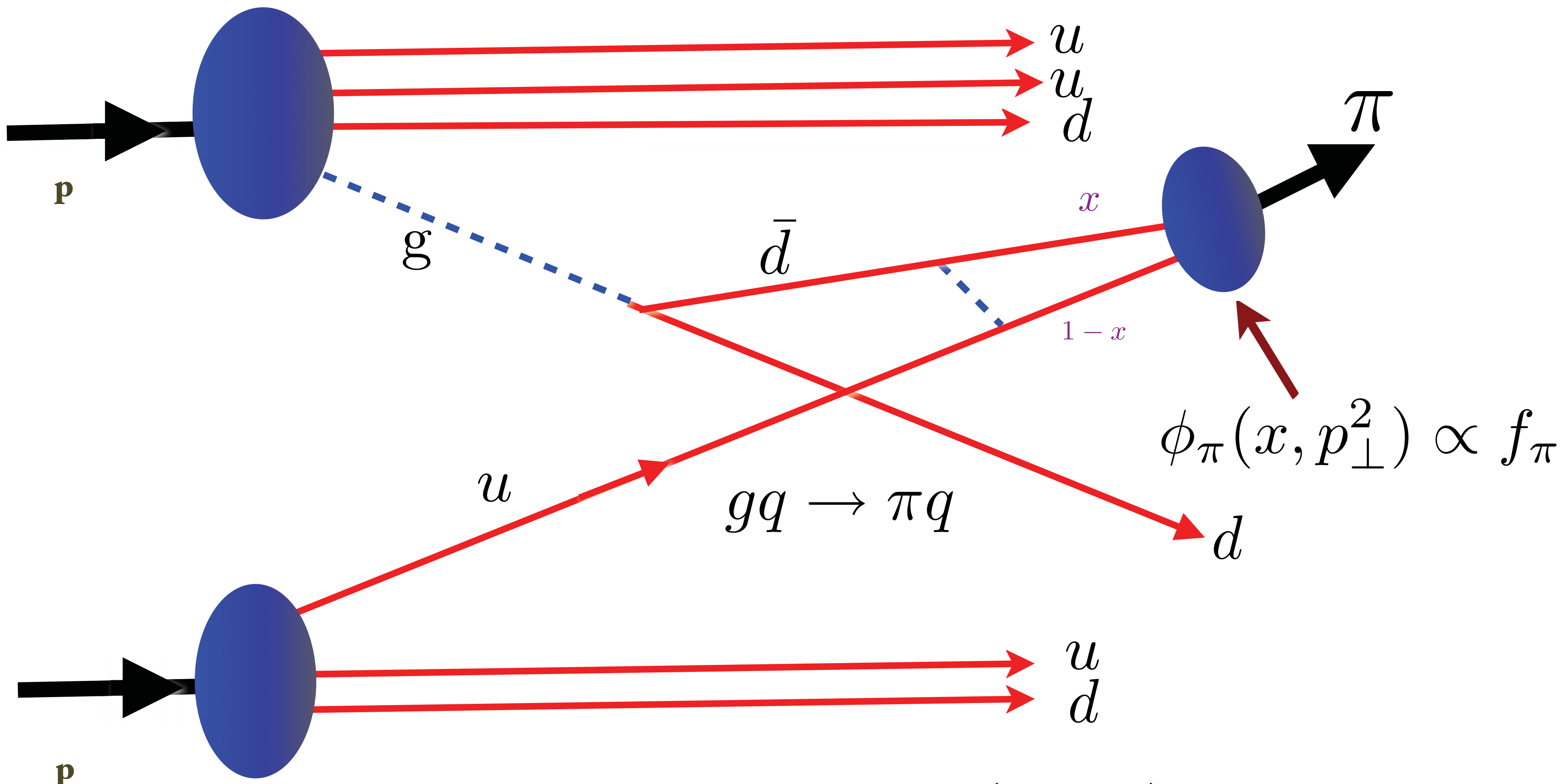


$$E\frac{d\sigma}{d^3p}(pp \to pX) = \frac{F(x_T,\theta_{CM})}{p_T^{12}}$$

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

Trend consistent with RHIC at small x_T

Higher-Twist Contribution to Hadron Production

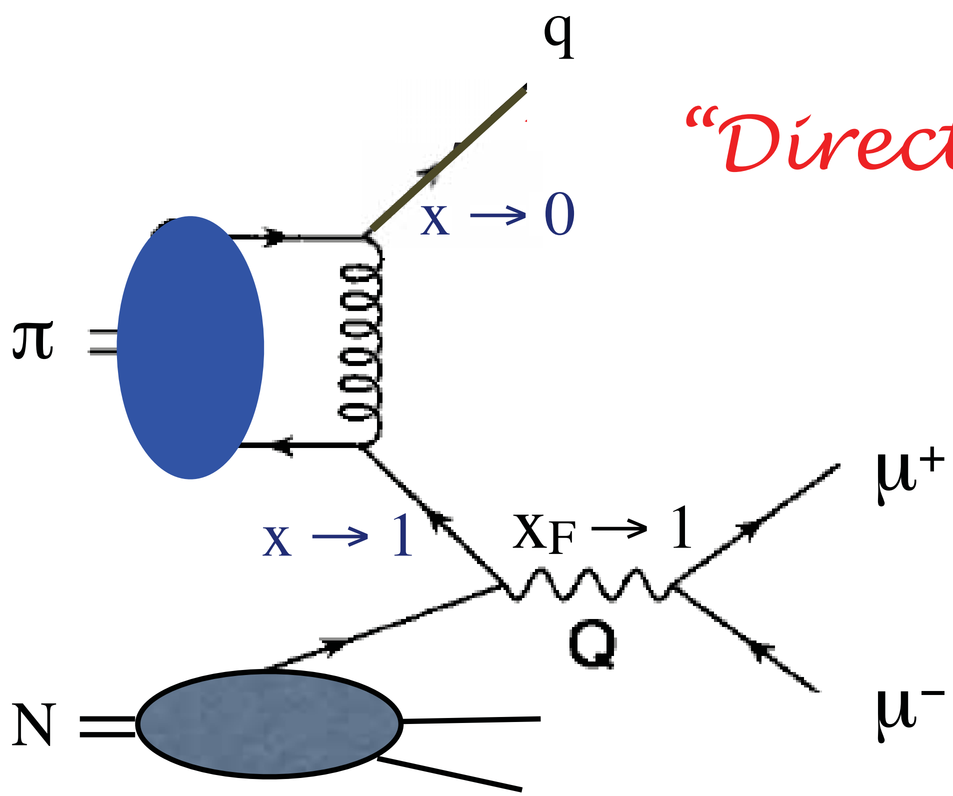


$$\frac{d\sigma}{d^3p/E} = \alpha_s^3 f_\pi^2 \frac{F(x_\perp, y)}{p_\perp^6}$$

No Fragmentation Function

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

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



"Direct" Subprocess

Entire pion wf contributes to hard process

Virtual photon is longitudinally polarized

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

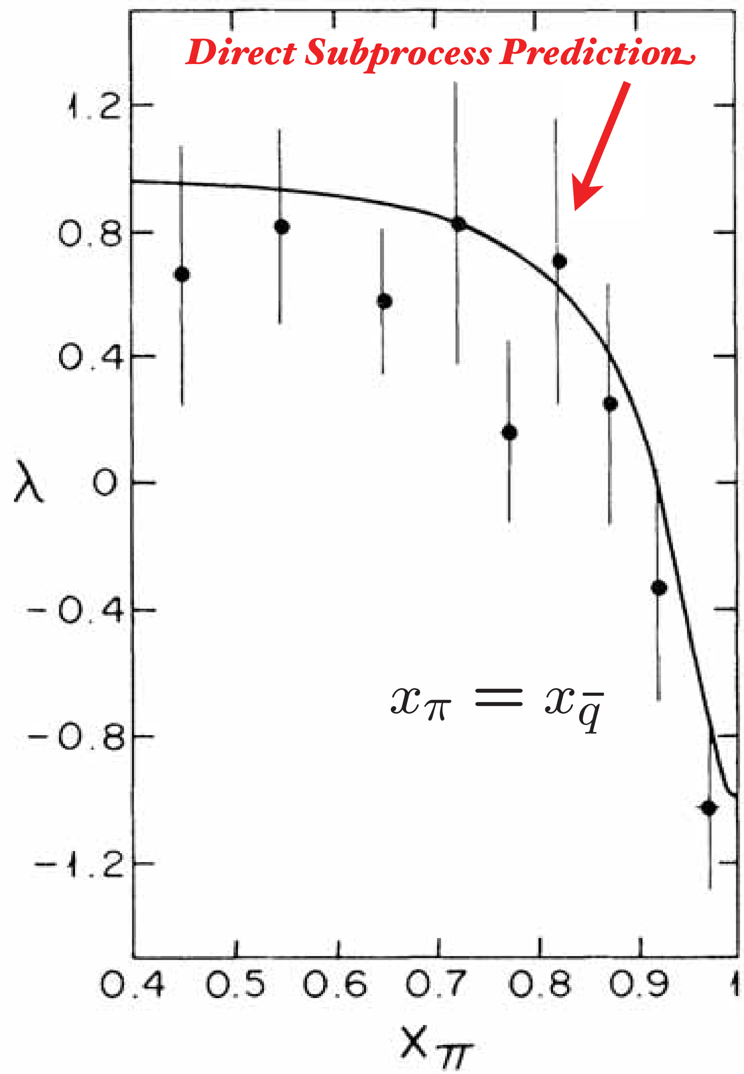
$$\pi^- N \to \mu^+ \mu^- X \text{ at } 80 \text{ GeV}/c$$

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

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

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

Dramatic change in angular distribution at large x_F



Chicago-Princeton Collaboration

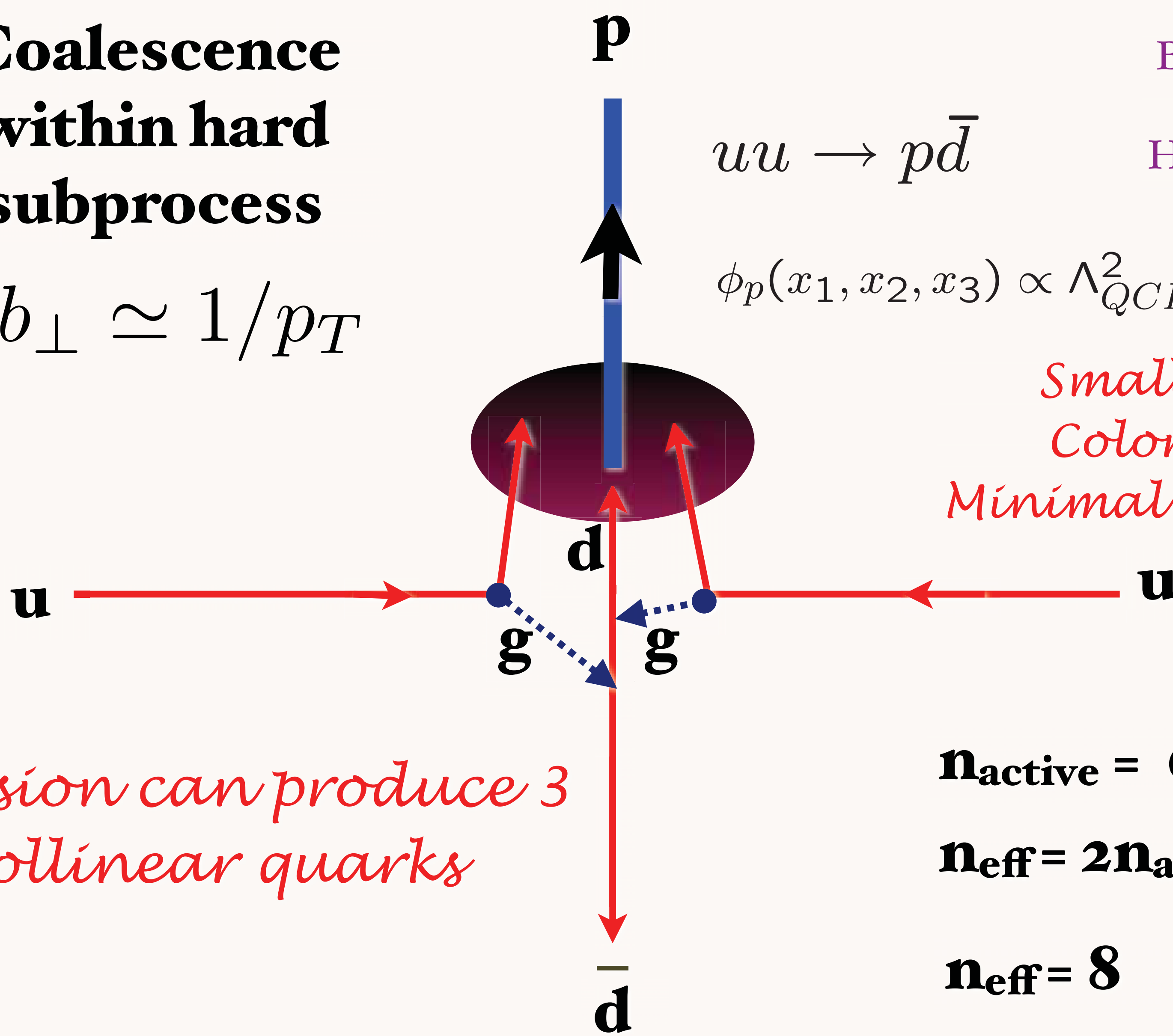
Phys.Rev.Lett.55:2649,1985

Example of a higher-twist direct subprocess

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

Anne Sickles, sjb

Small color-singlet
Color Transparent
Minimal same-side energy

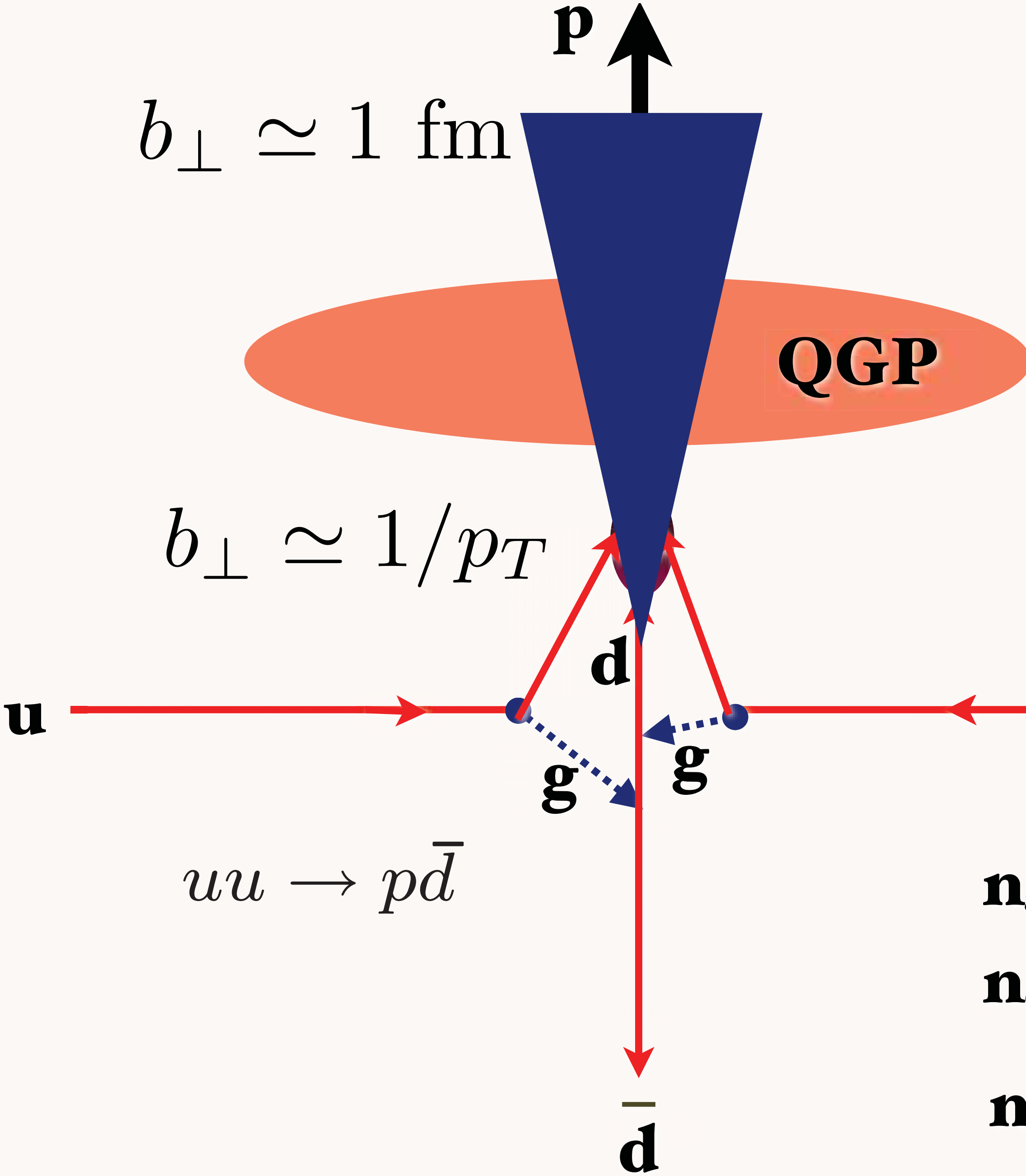
Collision can produce 3 collinear quarks

$n_{active} = 6$

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

$n_{eff} = 8$

Baryon made directly within hard subprocess



Anne Sickles, sjb

Formation Time proportional to Energy

Small color-singlet
Color Transparent
Minimal same-side energy

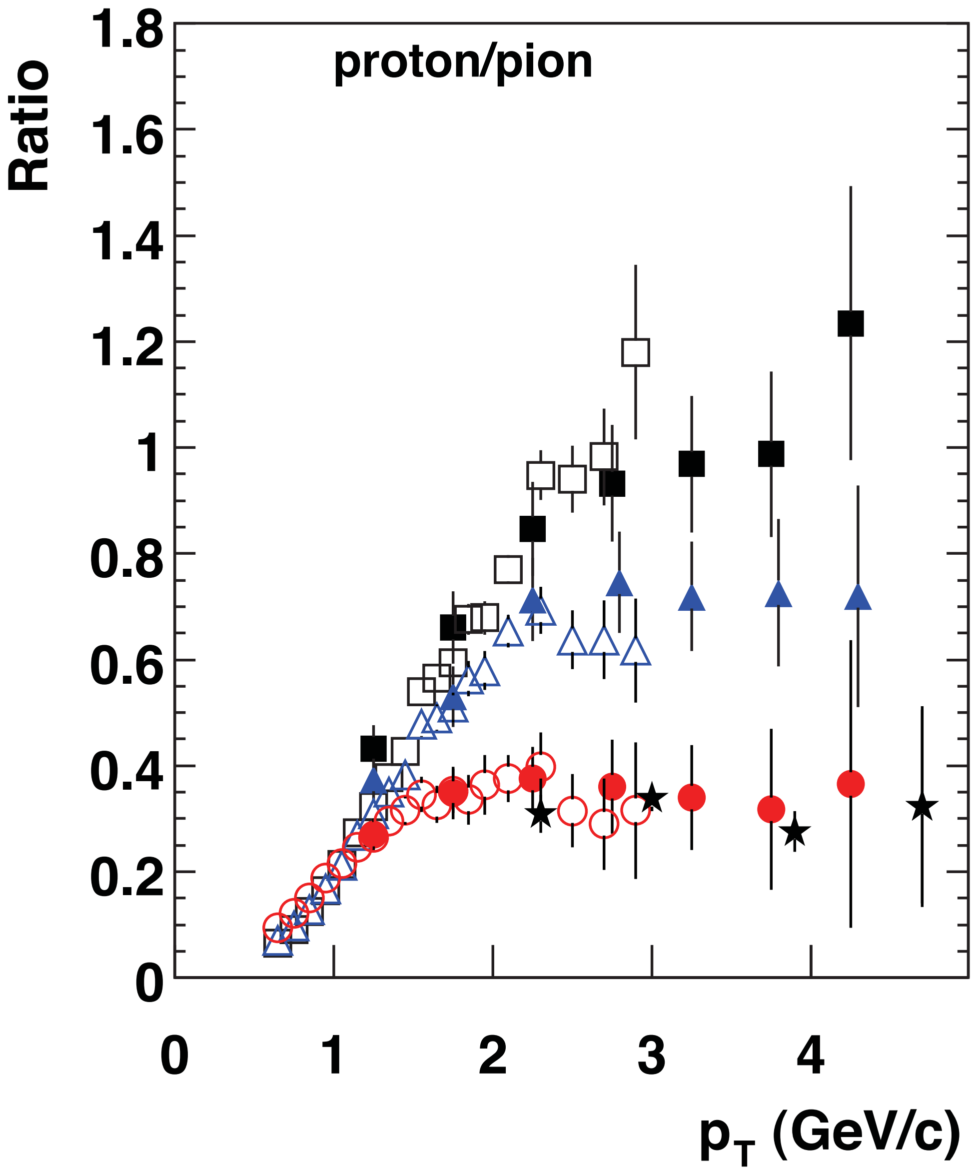
$n_{active} = 6$

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

$n_{eff} = 8$

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

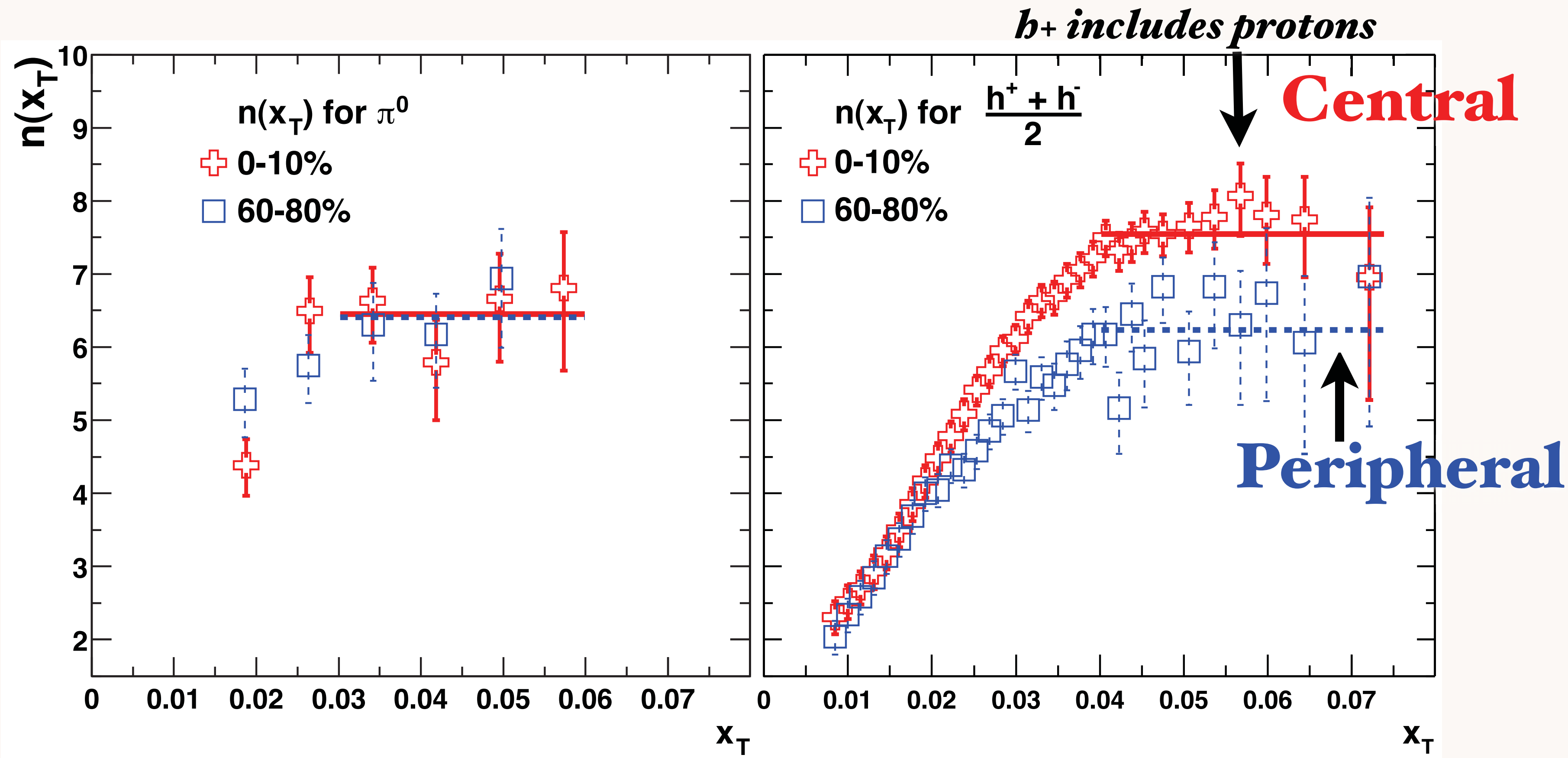
← **Central**

← **Peripheral**

Tannenbaum: Baryon Anomaly:

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

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



Proton power changes with centrality !

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

Dimensional counting rules provide a simple rule-of-thumb guide for the power-law fall-off of the inclusive cross section in both p_T and $(1-x_T)$ due to a given subprocess:

$$E\frac{d\sigma}{d^3p}(AB \to CX) \propto \frac{(1-x_T)^{2n_{spectator}-1}}{{p_T}^{2n_{active-4}}}$$

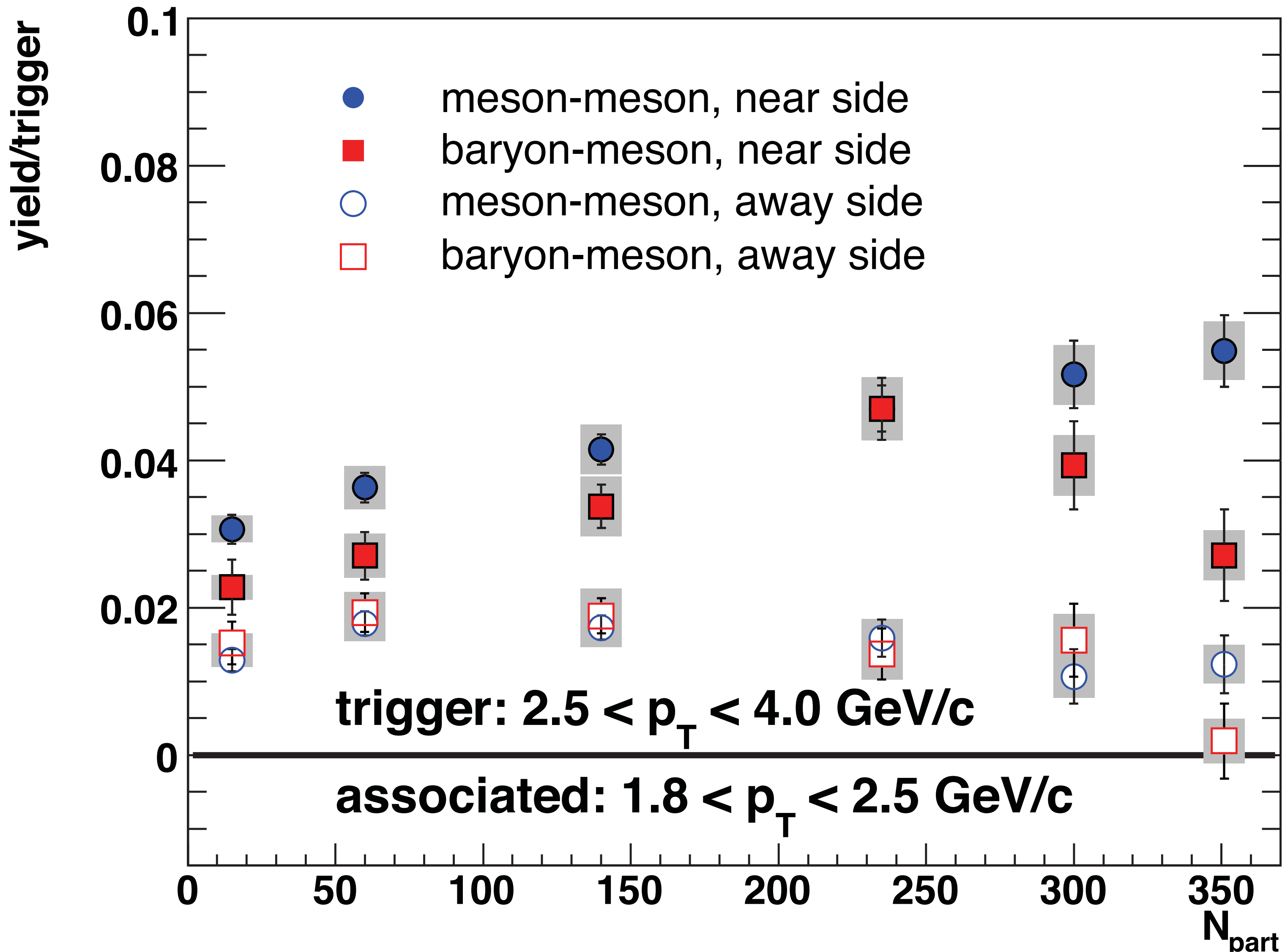
where n_{active} is the "twist", i.e., the number of elementary fields participating in the hard subprocess, and $n_{spectator}$ is the total number of constituents in A, B and C not participating in the hard-scattering subprocess. For example, consider $pp \to pX$. The leading-twist contribution from $qq \to qq$ has $n_{active} = 4$ and $n_{spectator} = 6$. The higher-twist subprocess $qq \to p\bar{q}$ has $n_{active} = 6$ and $n_{spectator} = 4$. This simplified model provides two distinct contributions to the inclusive cross section

$$\frac{d\sigma}{d^3p/E}(pp \to pX) = A\frac{(1-x_T)^{11}}{p_T^4} + B\frac{(1-x_T)^7}{p_T^8}$$

and $n = n(x_T)$ increases from 4 to 8 at large x_T.

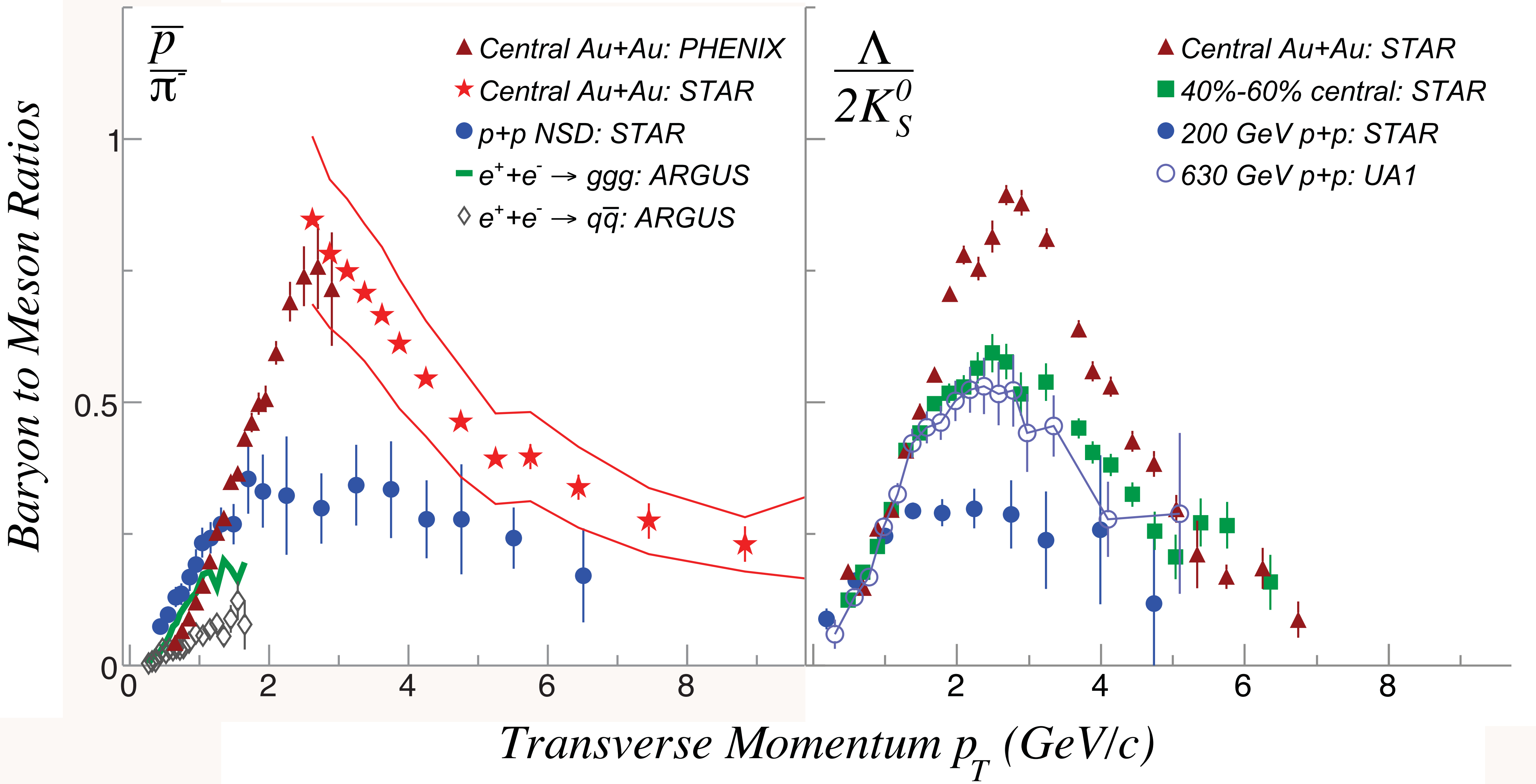
Small color-singlet
Color Transparent
Minimal same-side energ

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
$\bar{p}/\pi^-$
Central Au+Au: PHENIX
Central Au+Au: STAR
p+p NSD: STAR
$e^+ + e^- \rightarrow ggg$: ARGUS
$e^+ + e^- \rightarrow q\bar{q}$: ARGUS
$\Lambda / 2K_S^0$
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 p_T (GeV/c)

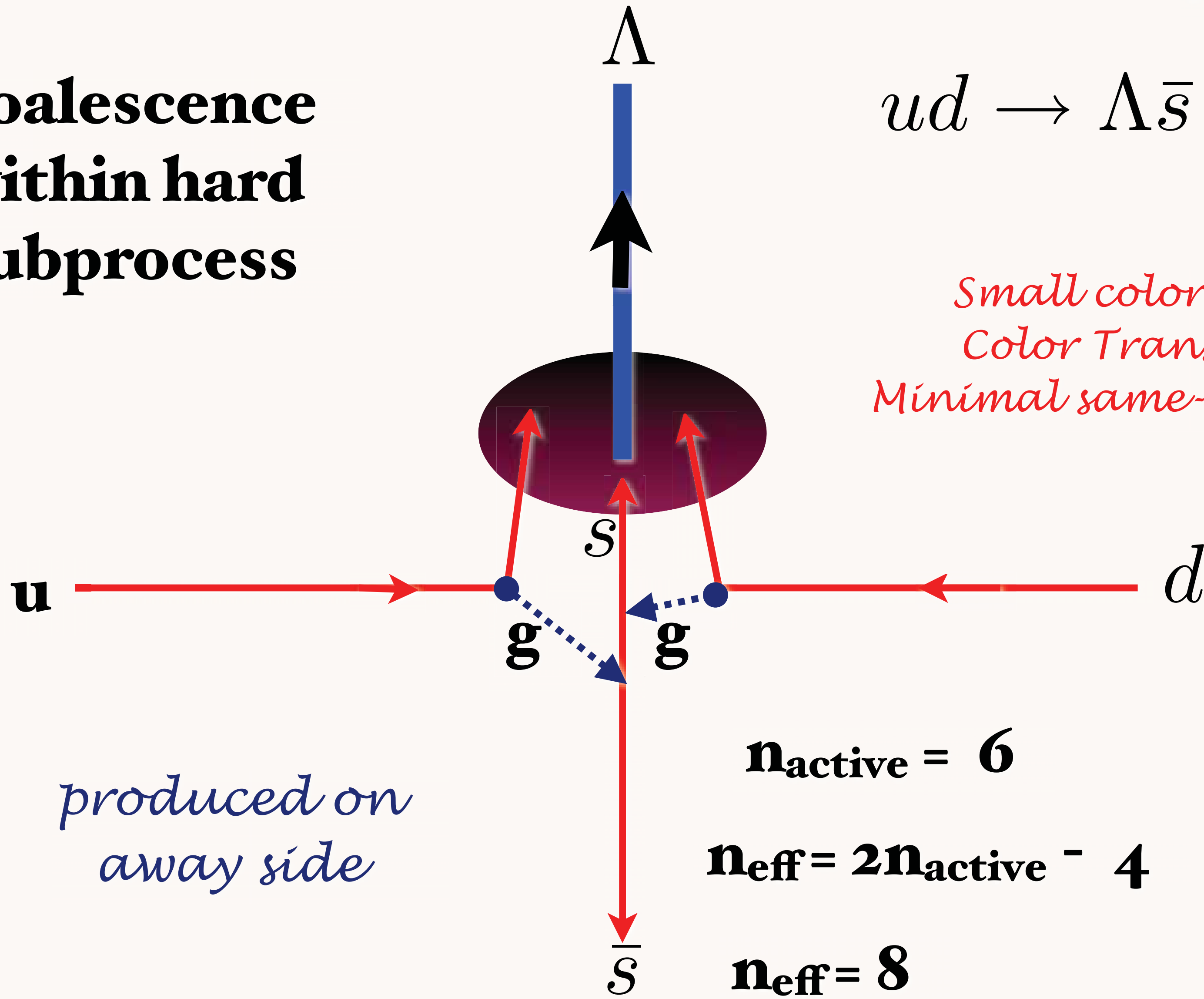
Lambda can be made directly within hard subprocess

Anne Sickles, sjb

Coalescence within hard subprocess

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

Small color-singlet
Color Transparent
Minimal same-side energy



$\bar{s}$ *produced on away side*

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

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

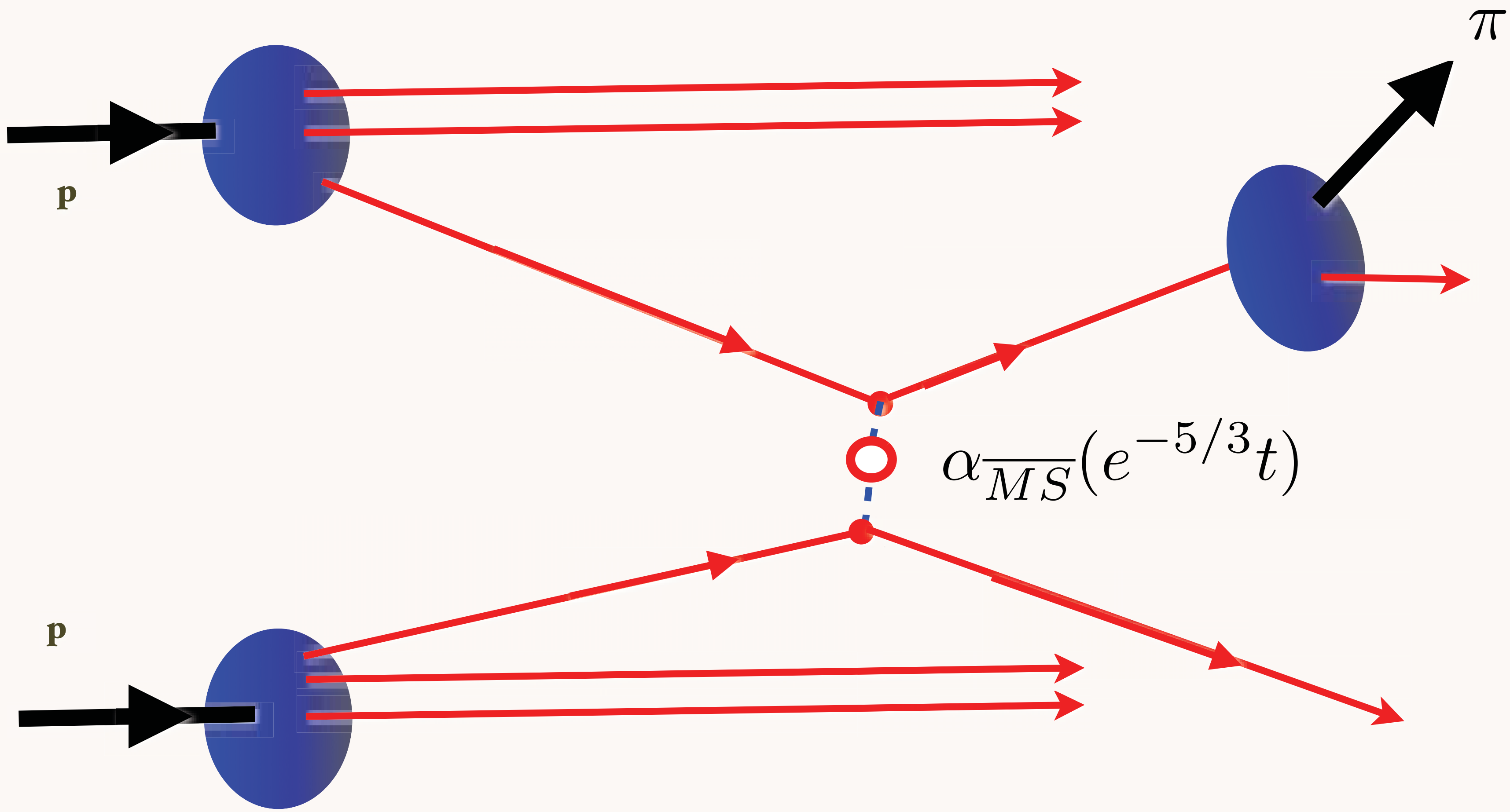
$\mathbf{n_{eff}} = 8$

Baryon Anomaly: Evidence for Direct, Higher-Twist Subprocesses

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

Anne Sickles, sjb

Renormalization Scale-Setting Not Ambiguous



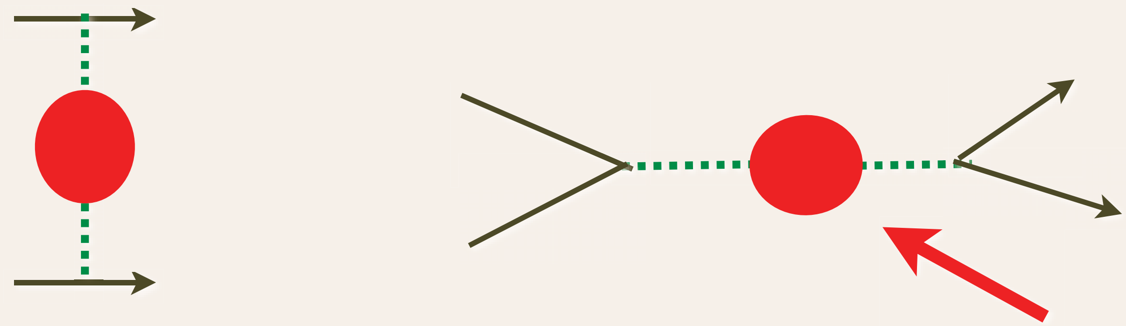
Conventional wisdom in QCD concerning scale setting

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

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

Electron-Positron Scattering in QED

$$M_{e^+e^-\to e^+e^-}(s,t) = \frac{8\pi s}{t}\alpha(t) + \frac{8\pi t}{s}\alpha(s)$$

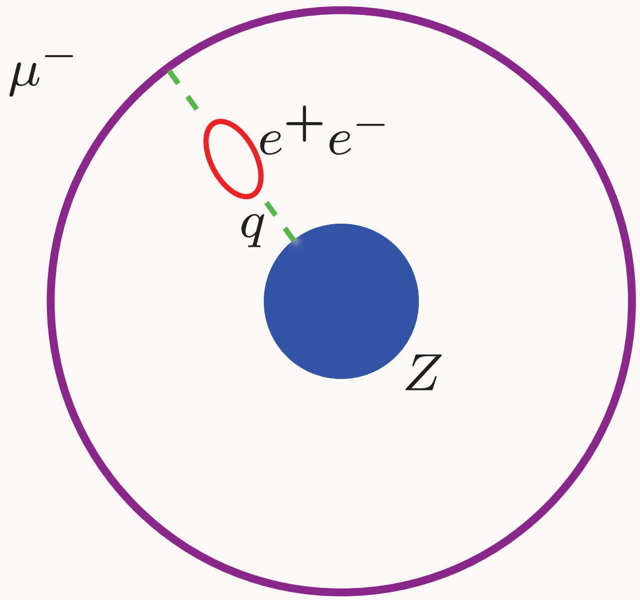


Running Coupling is Complex for Timelike Argument

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

Gell Mann-Low Running Charge sums all vacuum polarization insertions

Another Example in QED: Muonic Atoms



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

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

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

Scale is unique: Tested to ppm

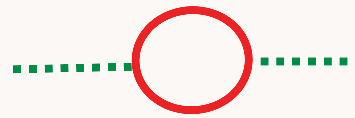
Gyulassy: Higher Order VP verified to 0.1% precision in μ Pb

Scale-Setting in QED

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

Must recover QED result using $\alpha_S^{\overline{MS}}(\mu^2)$

$$\alpha(q^2) = \alpha(q_0^2)\frac{(1-\Pi(q_0^2))}{(1-\Pi(q^2))} \quad \text{where } \Pi(q^2=0)=0$$

$$\Pi(q^2) =$$ 

Identical QED result if

$$\ln(-\frac{\mu^2}{m^2}) = 6\int_0^1 d\alpha[\alpha(1-\alpha)]\ln(1-\frac{q_0^2\alpha(1-\alpha)}{m^2})$$

Dae Sung Hwang, sjb

$$\mu^2 = q_0^2 e^{-5/3} \quad \text{at large } q_0^2$$

q^2_0: Normalization point

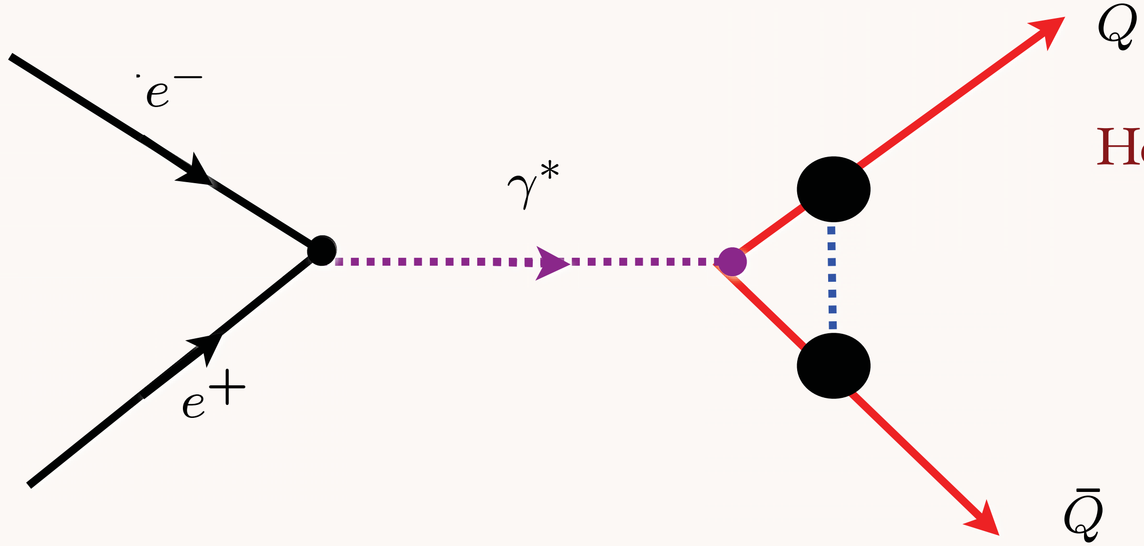
Huet, sjb

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

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

Analytic Feature of SU(Nc) Gauge Theory

Scale-Setting procedure for QCD must be applicable to QED



Hoang, Kuhn, Teubner, sjb

BLM: Lepage, Mackenzie, sjb

β : *Relative Velocity*

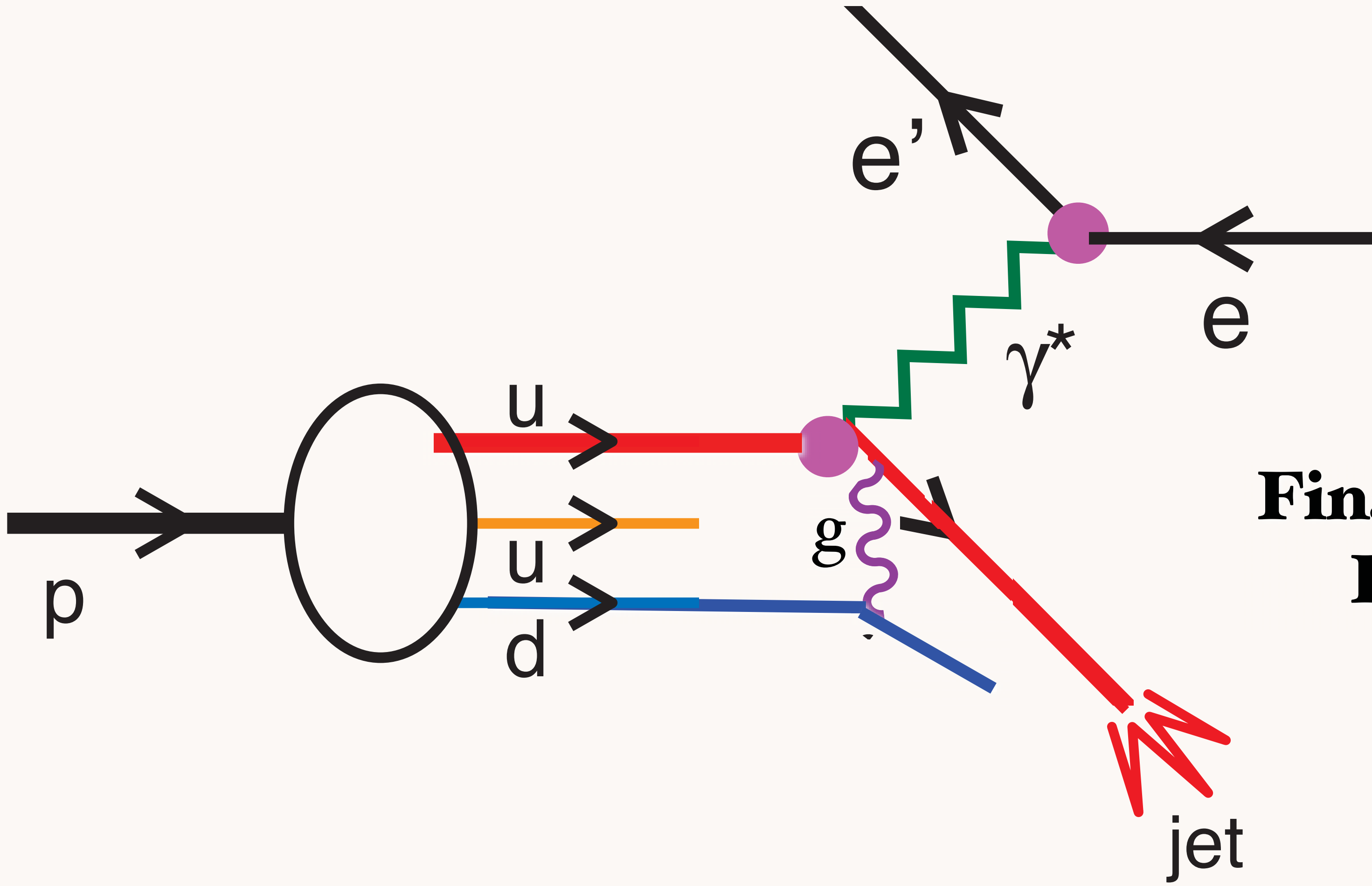
$$F_1 + F_2 = 1 + \frac{\alpha(s\,\beta^2)\,\pi}{4\,\beta} - 2\,\frac{\alpha(s\,e^{3/4}/4)}{\pi}$$

$$\cong \left(1 - 2\,\frac{\alpha(s\,e^{3/4}/4)}{\pi}\right)\left(1 + \frac{\alpha(s\,\beta^2)\,\pi}{4\,\beta}\right)$$

Example of Multiple BLM Scales

Angular distributions of massive quarks and leptons close to threshold.

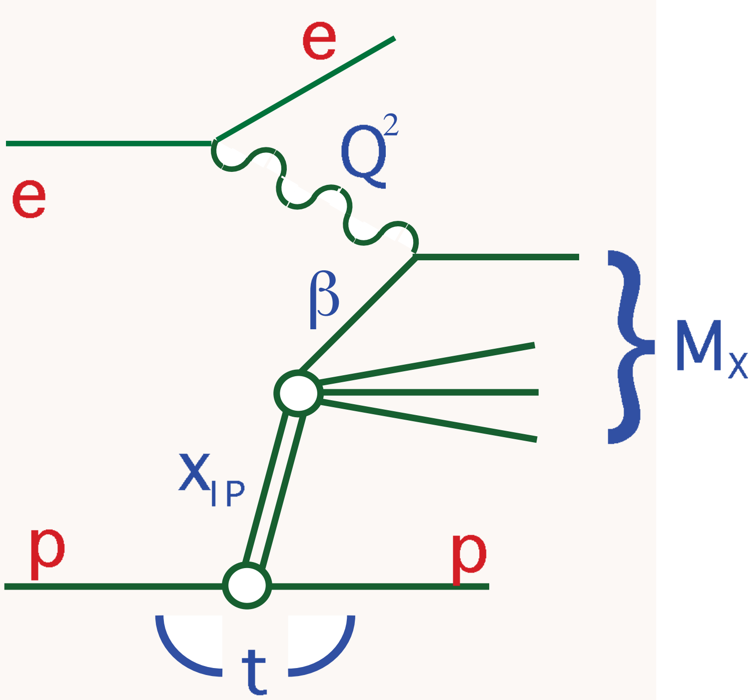
Deep Inelastic Electron-Proton Scattering



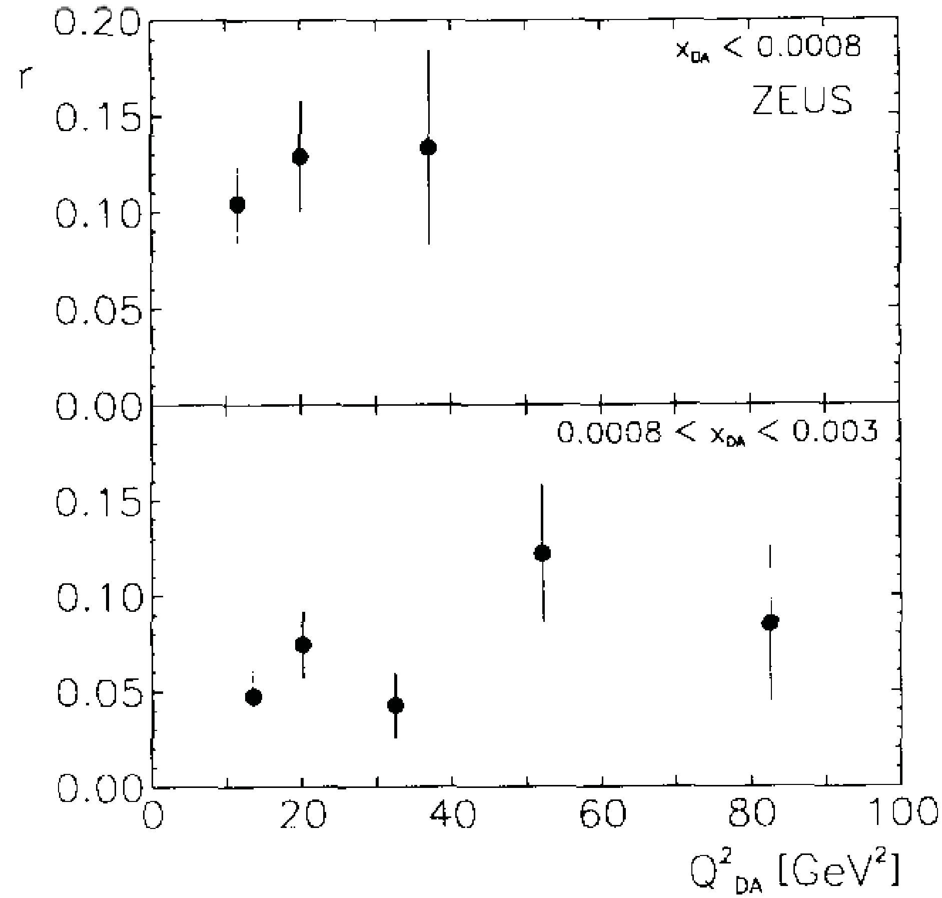
Final-State QCD Interaction

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

Remarkable observation at HERA



10% to 15% of DIS events are diffractive !

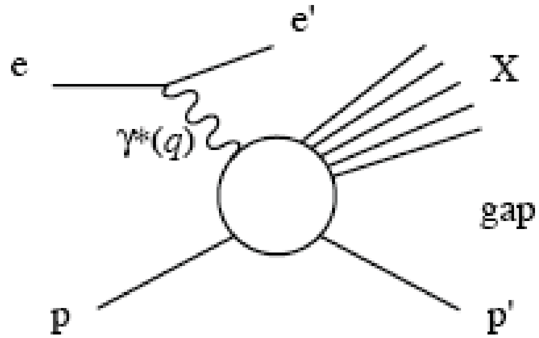


Fraction r of events with a large rapidity gap, $\eta_{\max} < 1.5$, as a function of Q^2_{DA} for two ranges of x_{DA}. No acceptance corrections have been applied.

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

DDIS

Diffractive Deep Inelastic Lepton-Proton Scattering



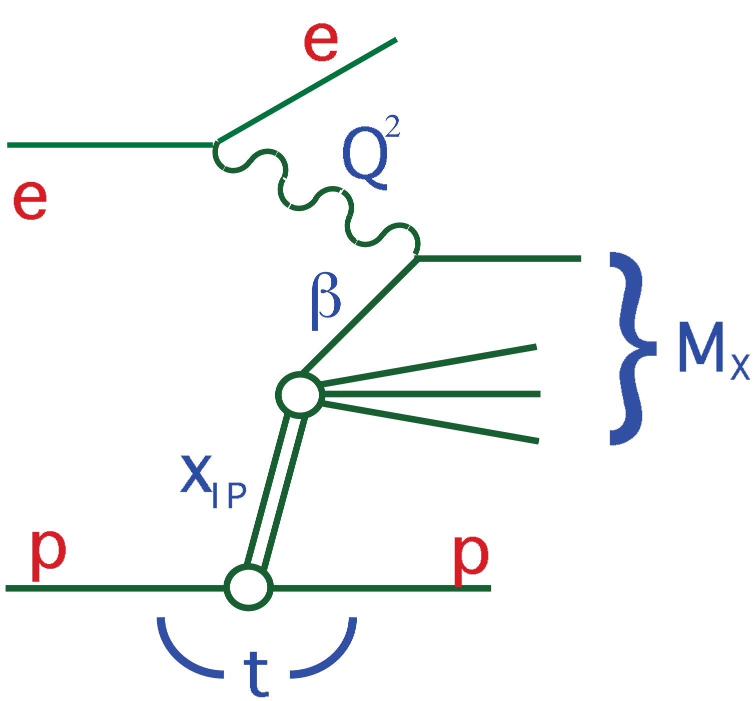
- In a large fraction ($\sim$ 10–15%) of DIS events, the proton escapes intact, keeping a large fraction of its initial momentum
- This leaves a large *rapidity gap* between the proton and the produced particles
- The t-channel exchange must be *color singlet* $\rightarrow$ a pomeron

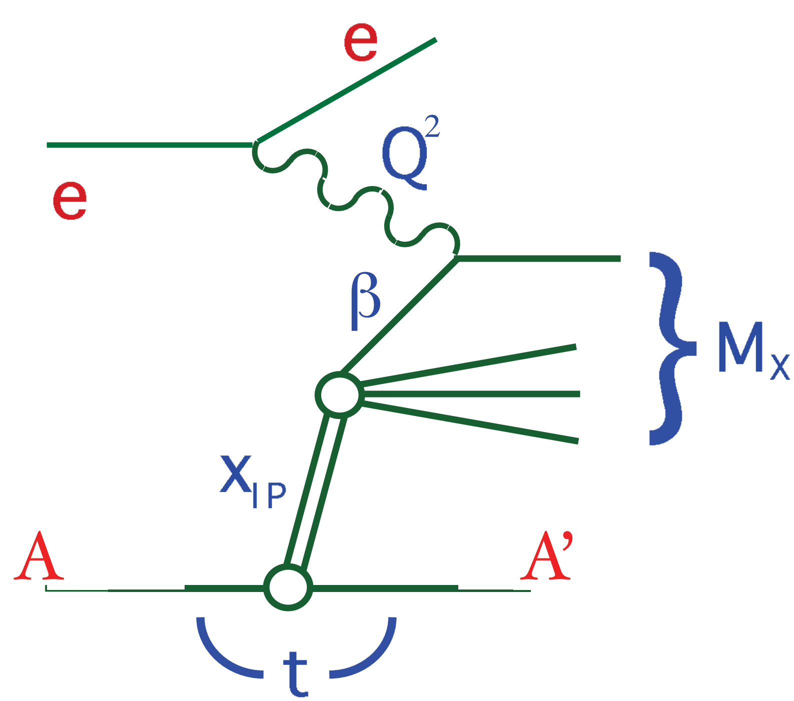
Profound effect: target stays intact despite production of a massive system X

Diffractive Deep Inelastic Scattering

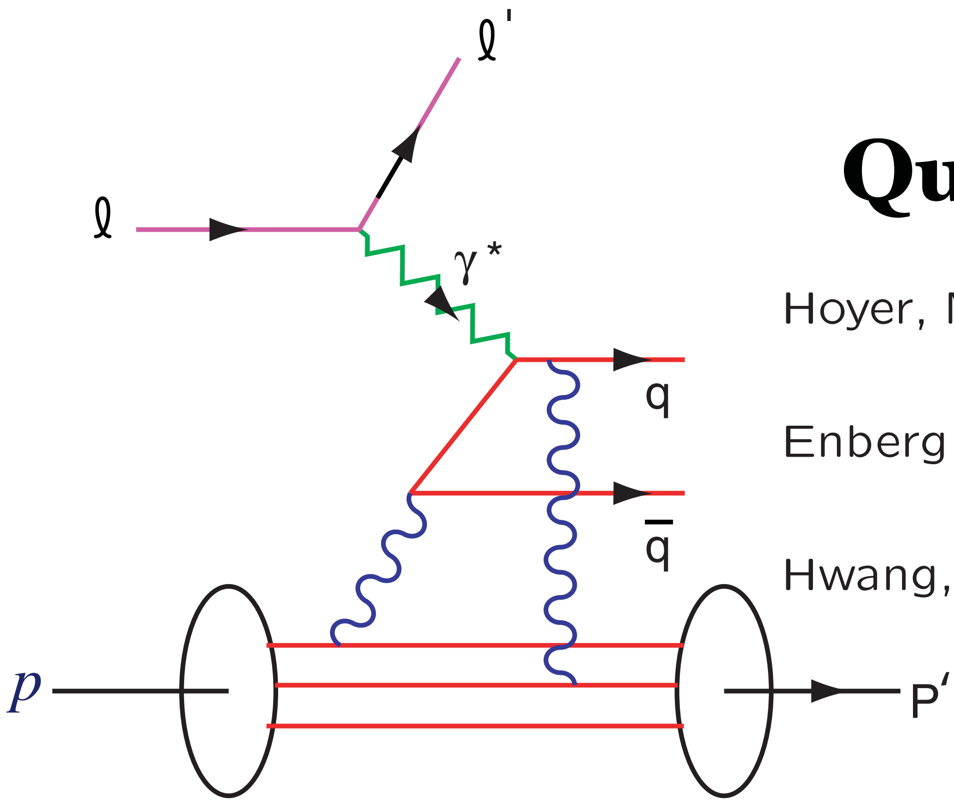
Diffractive DIS $ep \to epX$ where there is a large rapidity gap and the target nucleon remains intact probes the final state interaction of the scattered quark with the spectator system via gluon exchange.

Diffractive DIS on nuclei $eA \to e'AX$ and hard diffractive reactions such as $\gamma^* A \to VA$ can occur coherently leaving the nucleus intact.





Final-State QCD Interaction Produces Diffractive DIS



Quark Rescattering

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

Enberg, Hoyer, Ingelman, SJB

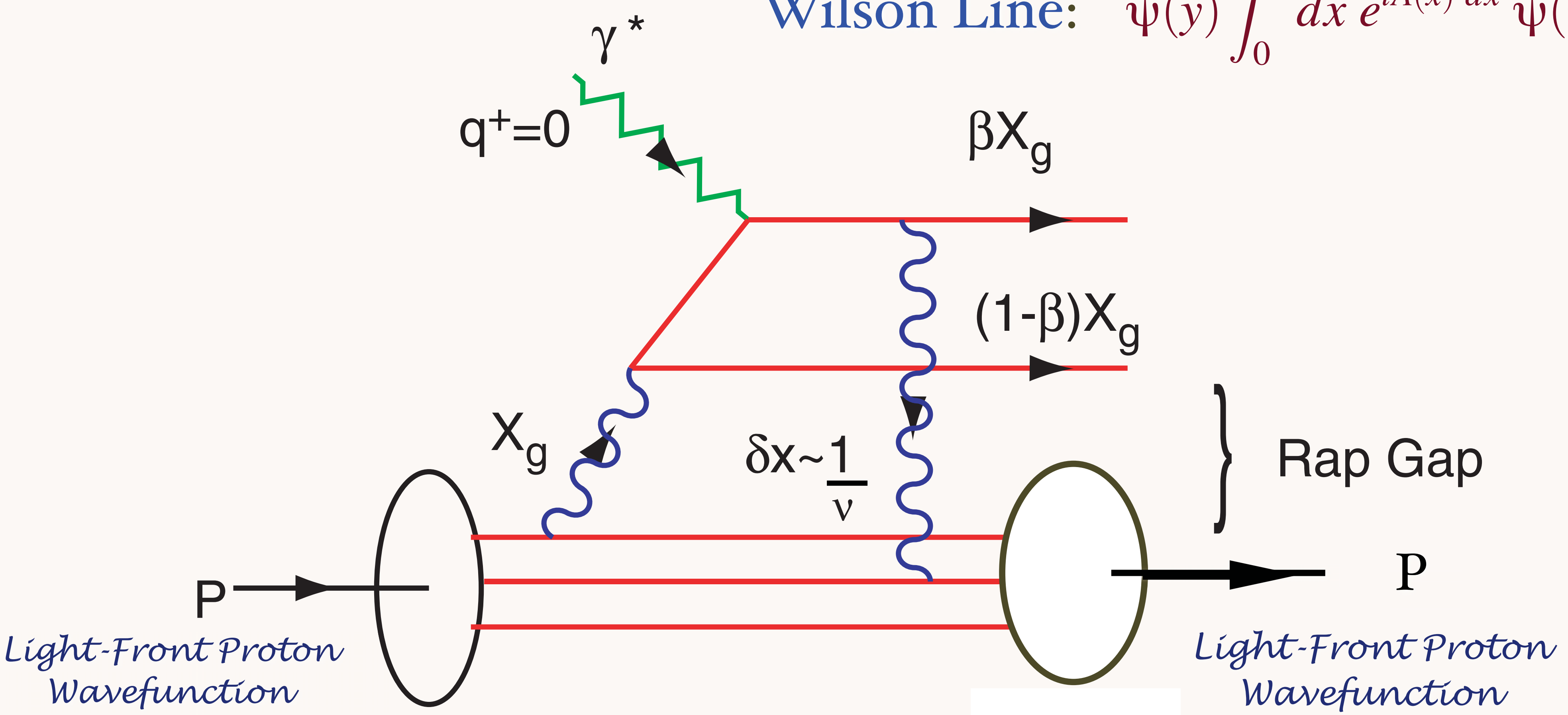
Hwang, Schmidt, SJB

Low-Nussinov model of Pomeron

Hoyer, Marchal, Peigne, Sannino, sjb

QCD Mechanism for Rapidity Gaps

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



Reproduces lab-frame color dipole approach