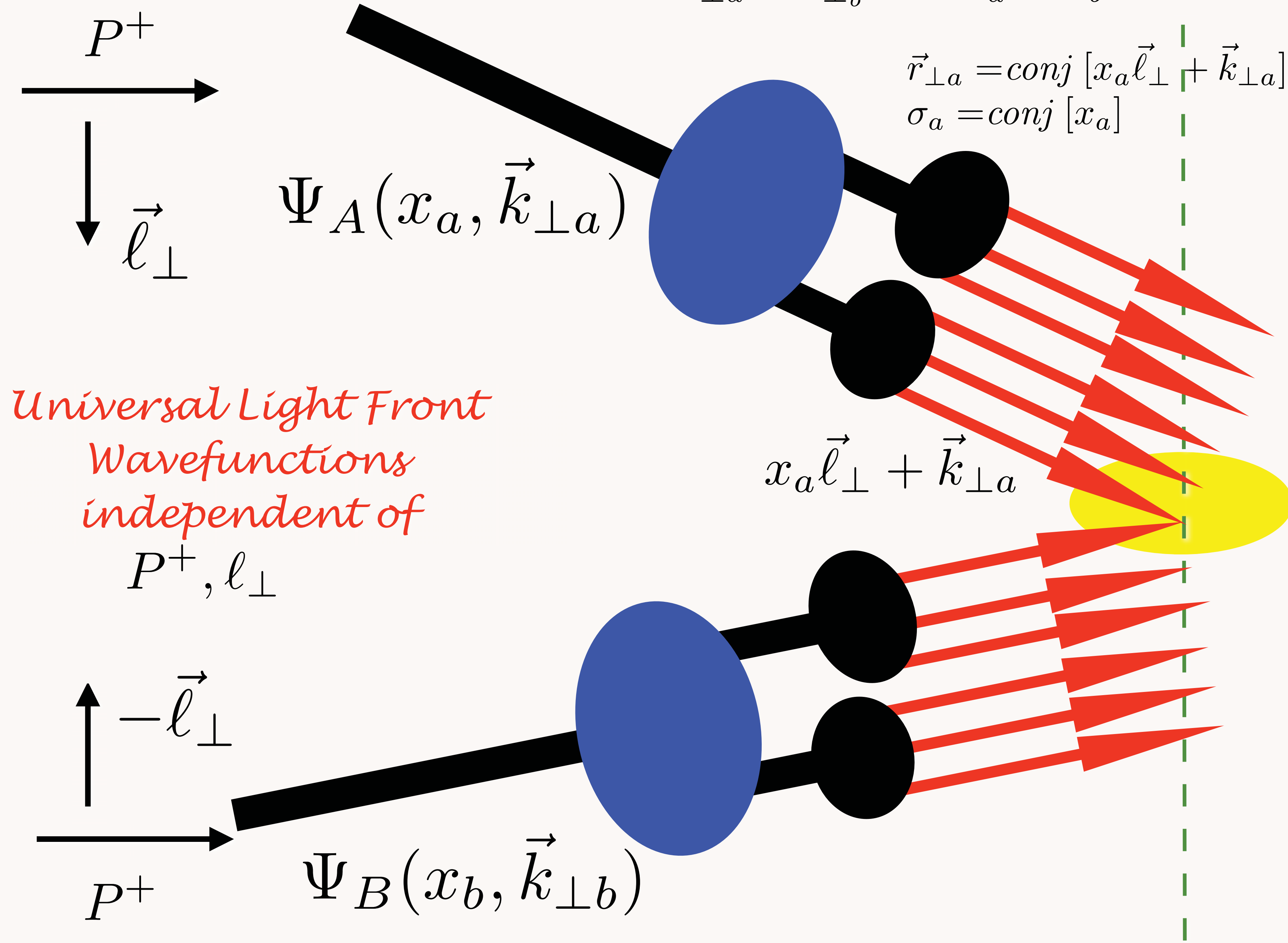
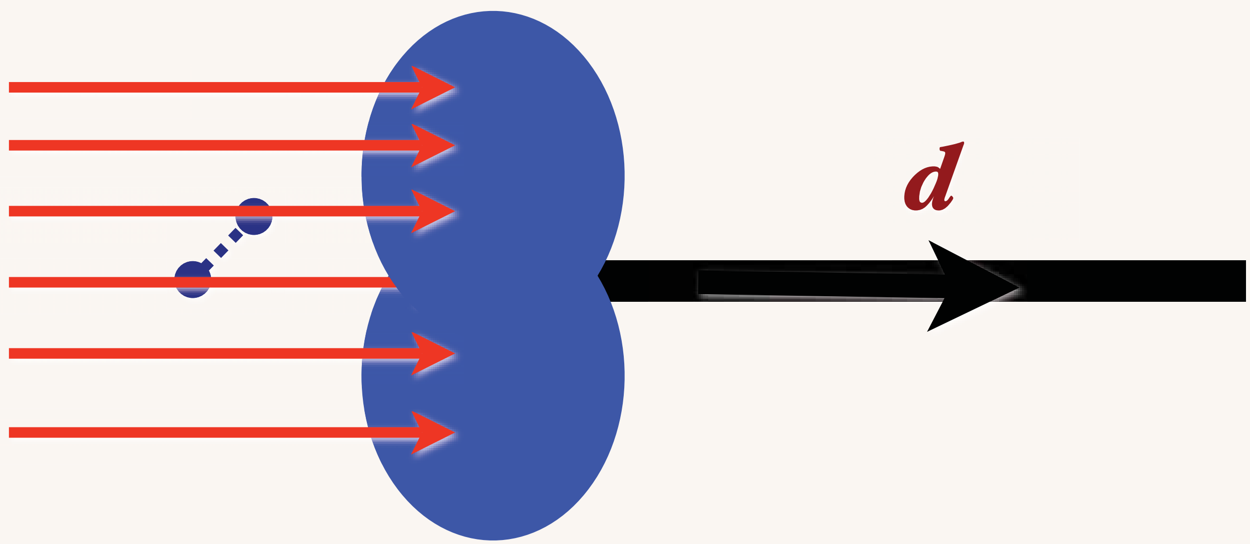
Interaction of a and b when $\vec{r}_{\perp a} \simeq \vec{r}_{\perp b}$ and $\sigma_a \simeq \sigma_b$



Features of LF T-Matrix Formalism
"Event Amplitude Generator"

- Hidden Color: Six-quark color-singlet Fock states of deuteron from hard gluon exchange:

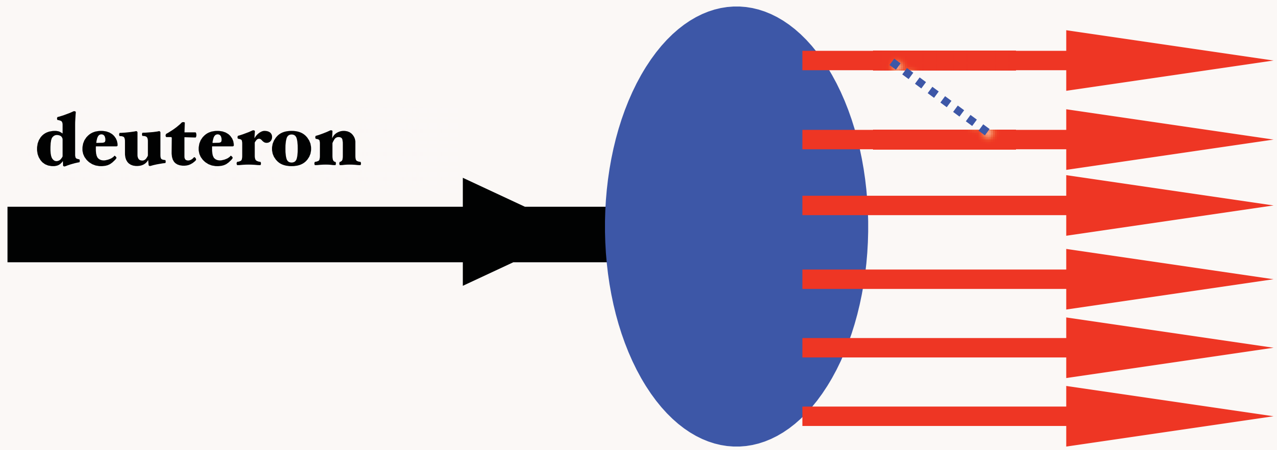
- Deuteron LFWF not always product of nucleon clusters



Hidden Color of Deuteron

Evolution of 5 color-singlet Fock states

$$\Psi^{\mathbf{d}}_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



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

$\sum_i^n x_i = 1$

$$\Phi_n(x_i, Q) = \int^{k^2_{\perp i} < Q^2} \Pi' d^2 k_{\perp j} \psi_n(x_i, \vec{k}_{\perp j})$$

Ji, Lepage, sjb

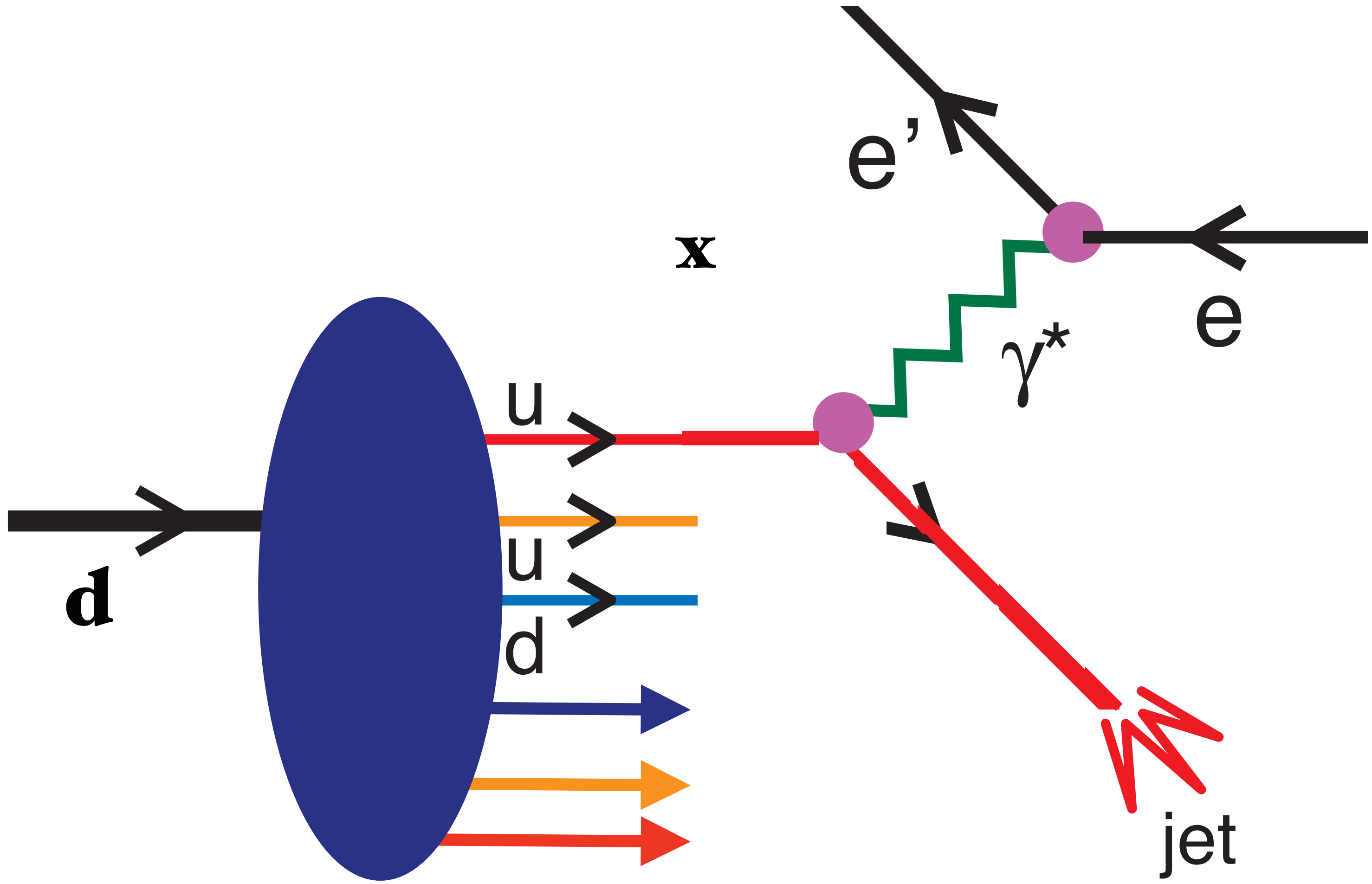
5 X 5 Matrix Evolution Equation for deuteron distribution amplitude

Hidden Color in QCD

Lepage, Ji, sjb

- Deuteron six quark wavefunction:
- 5 color-singlet combinations of 6 color-triplets -- one state is |n p>
- Components evolve towards equality at short distances
- Hidden color states dominate deuteron form factor and photodisintegration at high momentum transfer
- Predict $\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-}) \simeq \frac{d\sigma}{dt}(\gamma d \to pn)$ at high Q^2

Deep Inelastic Electron-Deuteron Scattering

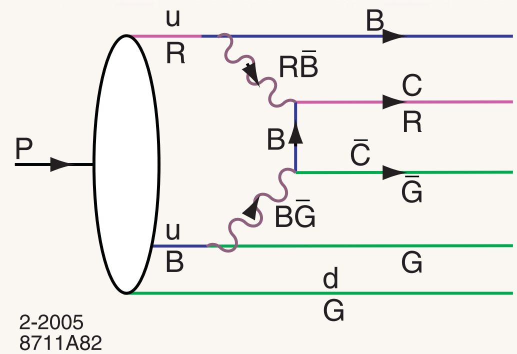


Hidden color: excited target spectator system

No nucleon spectator

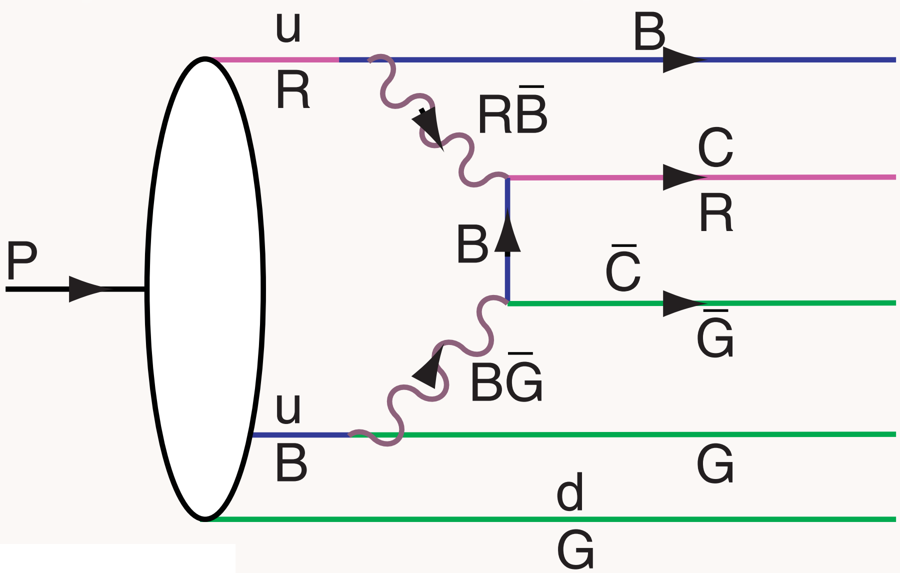
Hoyer, Peterson, Sakai, sjb

Intrinsic Heavy-Quark Fock States



- Rigorous prediction of QCD, OPE
- Color-Octet Color-Octet Fock State!
- Probability $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- Large Effect at high x
- 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

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.

$$< p|\frac{G^3_{\mu\nu}}{m^2_Q}|p > \text{ vs. } < p|\frac{F^4_{\mu\nu}}{m^4_\ell}|p >$$

$c\bar{c}$ 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*

Electron-Electron Scattering in QED

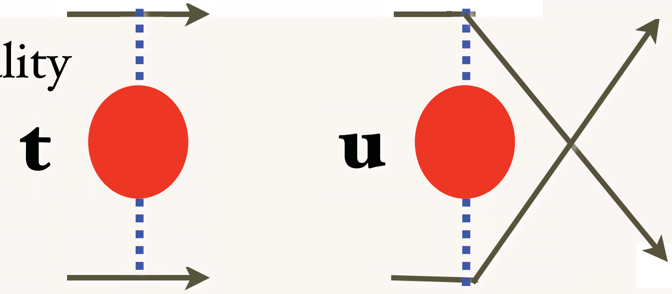
$$\mathcal{M}_{ee\to ee}(++;++) = \frac{8\pi s}{t}\ \alpha(t) + \frac{8\pi s}{u}\ \alpha(u)$$

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

Gell Mann-Low Effective Charge

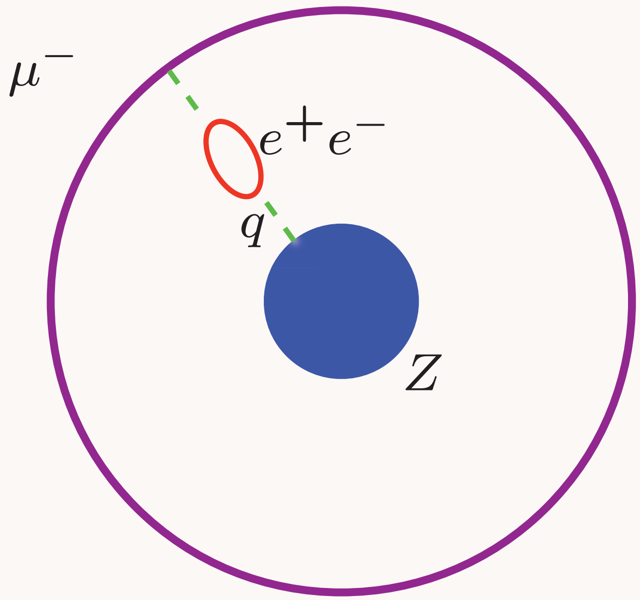
Electron-Electron Scattering in QED

$$\mathcal{M}_{ee\to ee}(++;++) = \frac{8\pi s}{t}\,\alpha(t) + \frac{8\pi s}{u}\,\alpha(u)$$



- 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!

Another Example in QED: Muonic Atoms



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

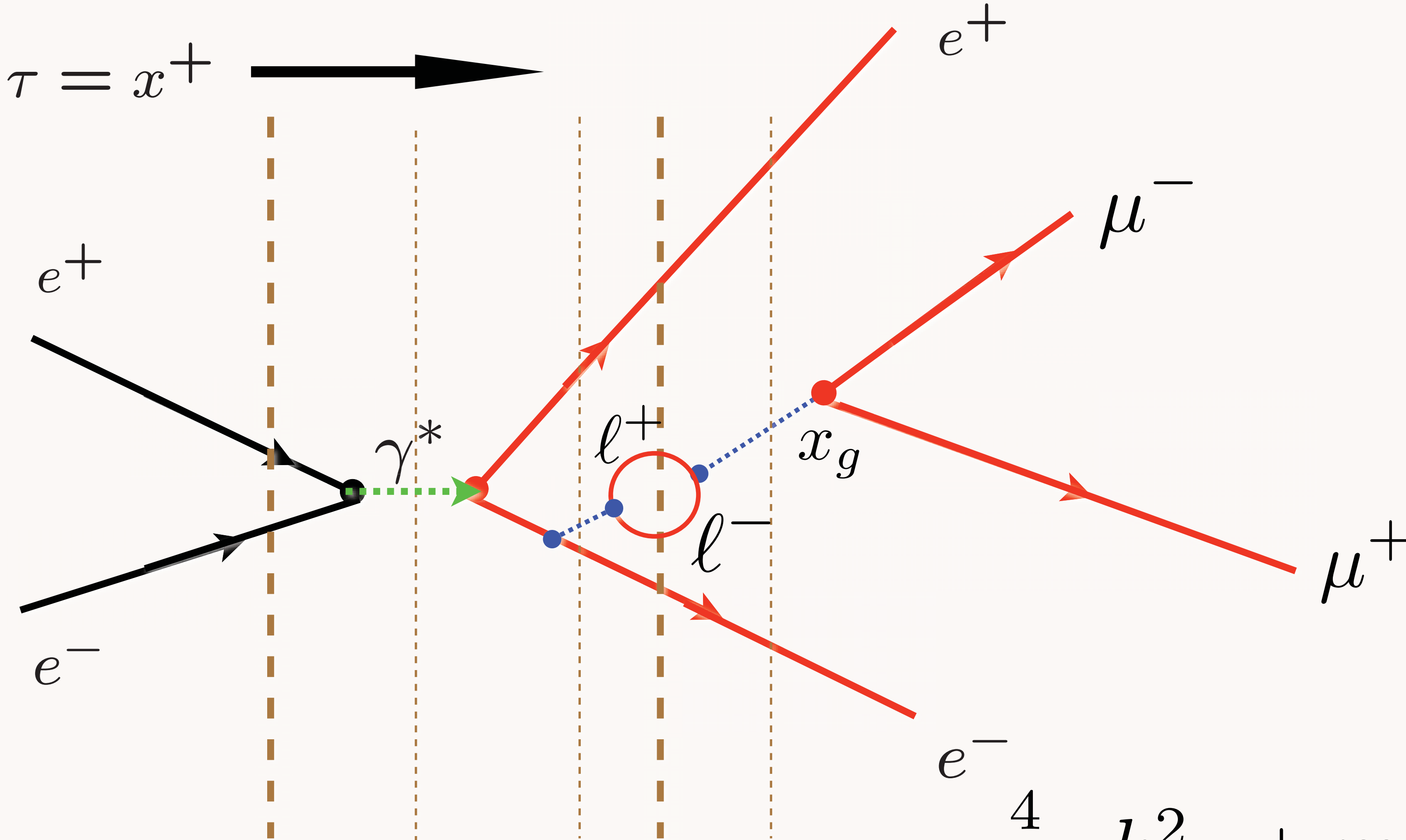
$$\mu_R^2 \equiv q^2$$

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

Scale is unique: Tested to ppm

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

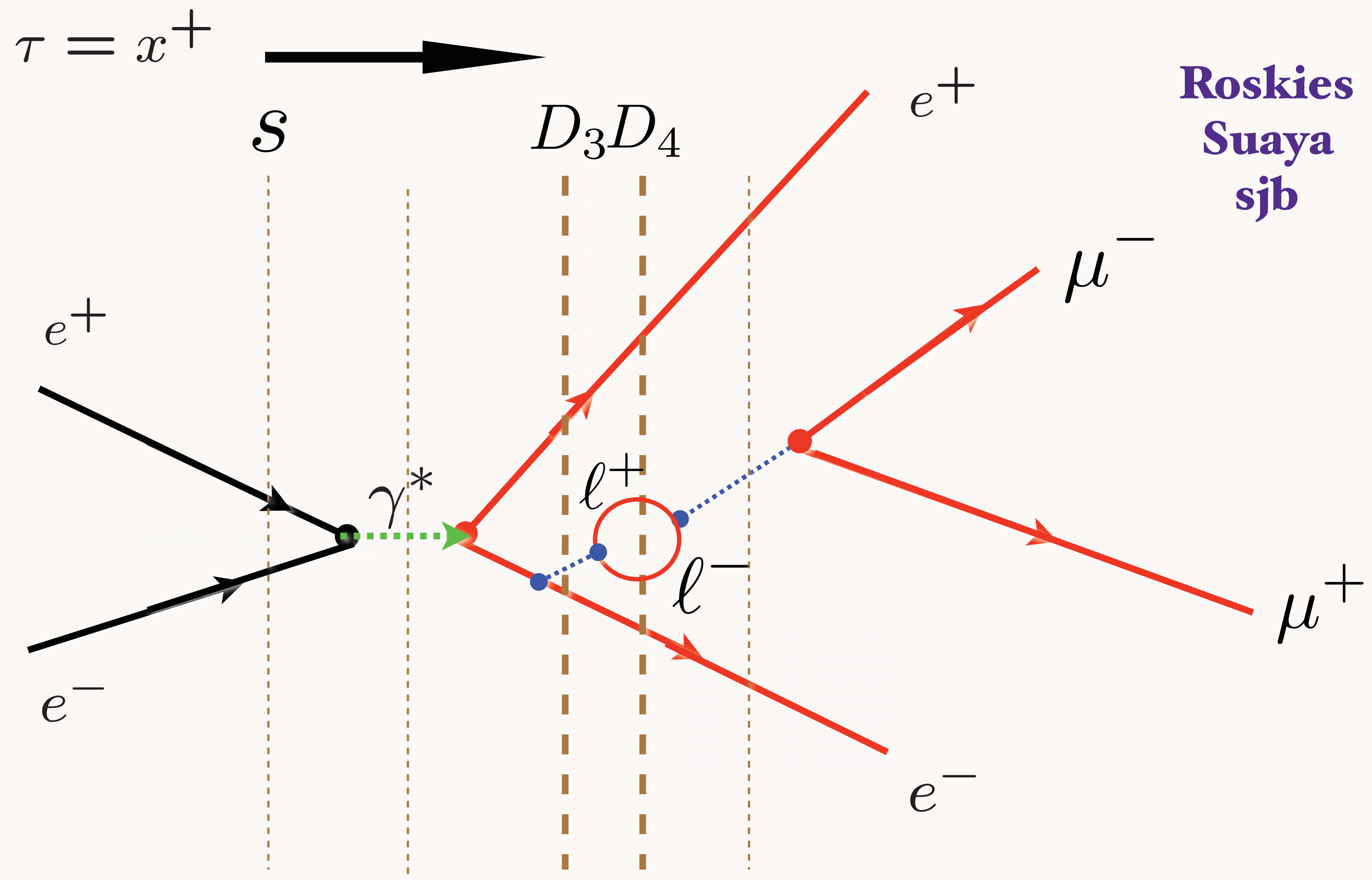
QED Renormalization
Scale Setting in LFPth



$$\alpha(\mu^2 = x_g D_4) \qquad D_4 = s - \sum_{i=1}^{4} \frac{k_{\perp i}^2 + m_i^2}{x_i}$$

Scale sets effective # leptons

Alternate Denominator: UV Subtraction Method



Roskies
Suaya
sjb

$$T_{ren}: \frac{1}{s - D_4} \rightarrow \frac{1}{s - D_4} - \frac{1}{D_3 - D_4}$$

$$D_4 = s - \sum_{i=1}^{4} \frac{k_{\perp i}^2 + m_i^2}{x_i}$$

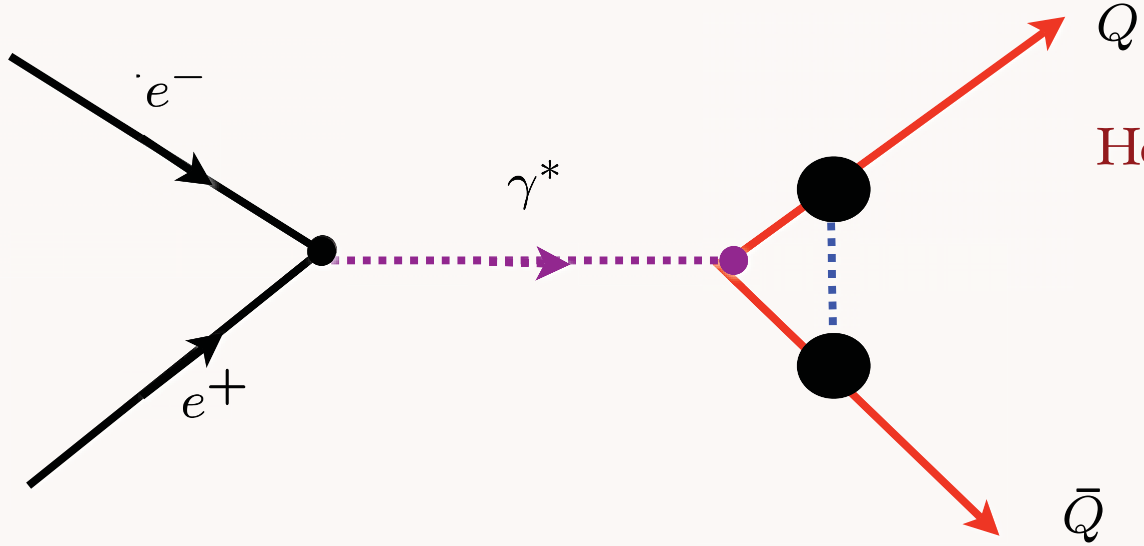
Huet, sjb

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

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

Analytic Feature of SU(Nc) Gauge Theory

Scale-Setting procedure for QCD must be applicable to QED



Hoang, Kuhn, Teubner, sjb

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

Example of Multiple BLM Scales

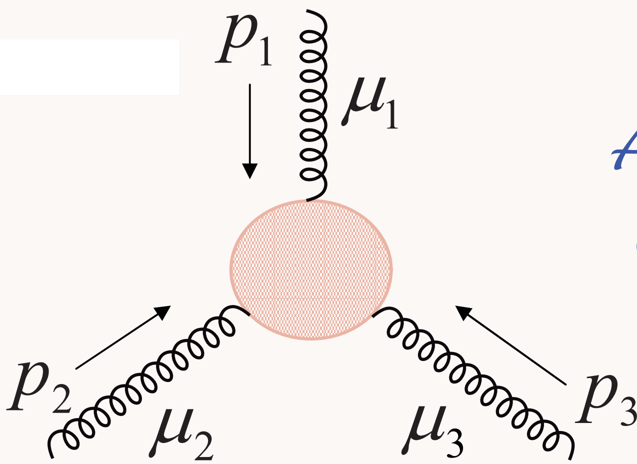
Angular distributions of massive quarks and leptons close to threshold.

General Structure of the Three-Gluon Vertex

"THE FORM-FACTORS OF THE GAUGE-INVARIANT THREE-GLUON VERTEX"

M. Binger, sjb

$$\hat{\Gamma}_{\mu_1\mu_2\mu_3} =$$

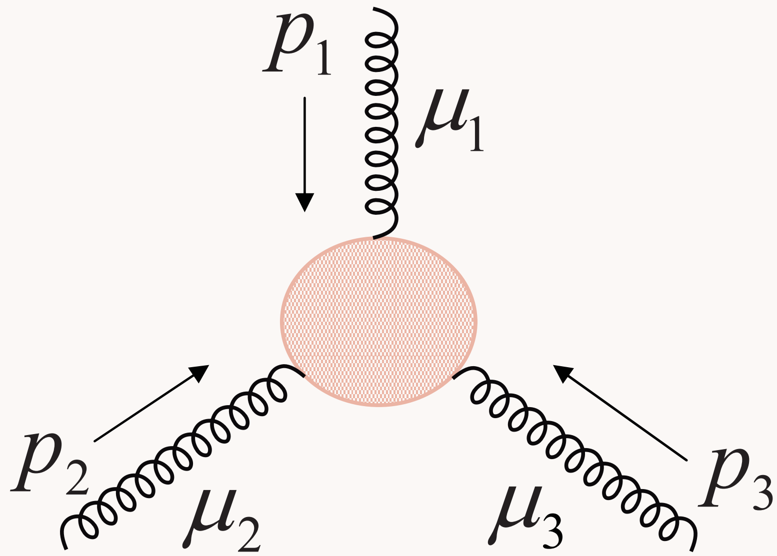


Analytic calculation: general masses, spin

3 index tensor $\hat{\Gamma}_{\mu_1\mu_2\mu_3}$ built out of $g_{\mu\nu}$ and p_1, p_2, p_3 with $p_1 + p_2 + p_3 = 0$

⇨ 14 basis tensors and form factors

$$\hat{\Gamma}_{\mu_1\mu_2\mu_3} =$$



H. J. Lu

$$\mu_R^2 \simeq \frac{p_{min}^2 p_{med}^2}{p_{max}^2}$$

Properties of the Effective Scale

$$Q^2_{eff}(a,b,c) = Q^2_{eff}(-a,-b,-c)$$

$$Q^2_{eff}(\lambda a, \lambda b, \lambda c) = |\lambda| Q^2_{eff}(a,b,c)$$

$$Q^2_{eff}(a,a,a) = |a|$$

$$Q^2_{eff}(a,-a,-a) \approx 5.54|a|$$

$$Q^2_{eff}(a,a,c) \approx 3.08|c| \quad \text{for} \quad |a| >> |c|$$

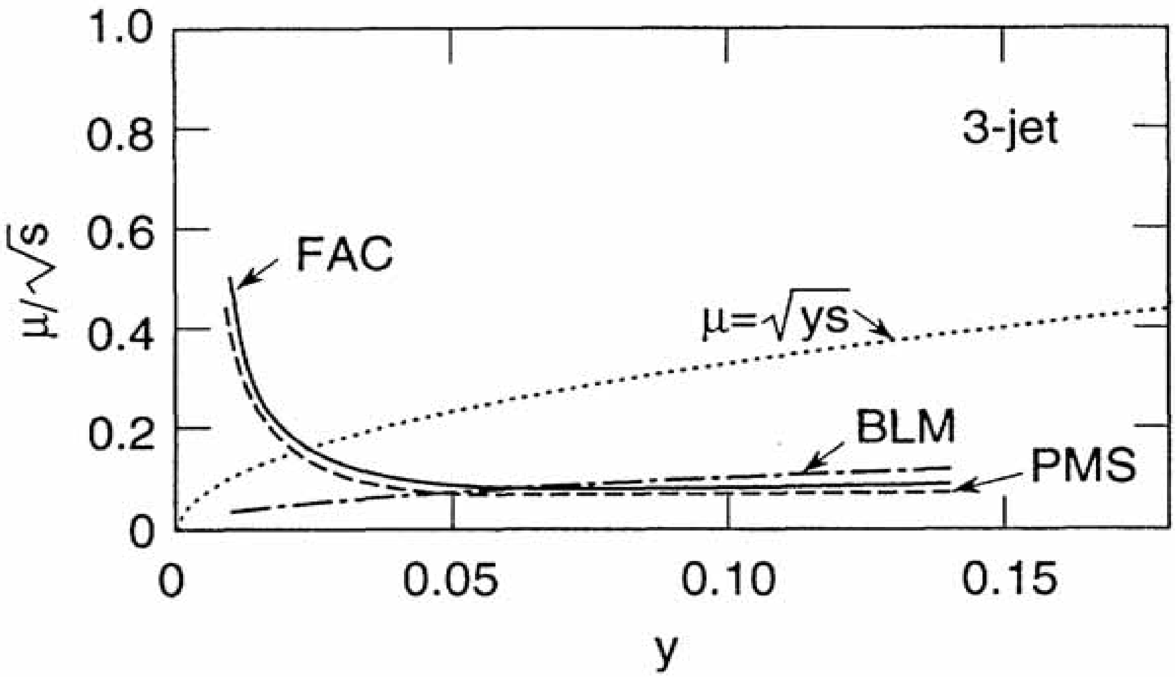
$$Q^2_{eff}(a,-a,c) \approx 22.8|c| \quad \text{for} \quad |a| >> |c|$$

$$Q^2_{eff}(a,b,c) \approx 22.8\frac{|bc|}{|a|} \quad \text{for} \quad |a| >> |b|,|c|$$

Surprising dependence on Invariants

BLM Method

- Satisfies Transitivity, all aspects of Renormalization Group; scheme independent
- Analytic at Flavor Thresholds
- Preserves Underlying Conformal Template
- Physical Interpretation of Scales; Multiple Scales
- Correct Abelian Limit ($N_C = 0$)
- Eliminates unnecessary source of imprecision of PQCD predictions
- Commensurate Scale Relations: Fundamental Tests of QCD free of renormalization scale and scheme ambiguities
- BLM used in many applications, QED, LGTH, BFKL, ...



Kramer & Lampe

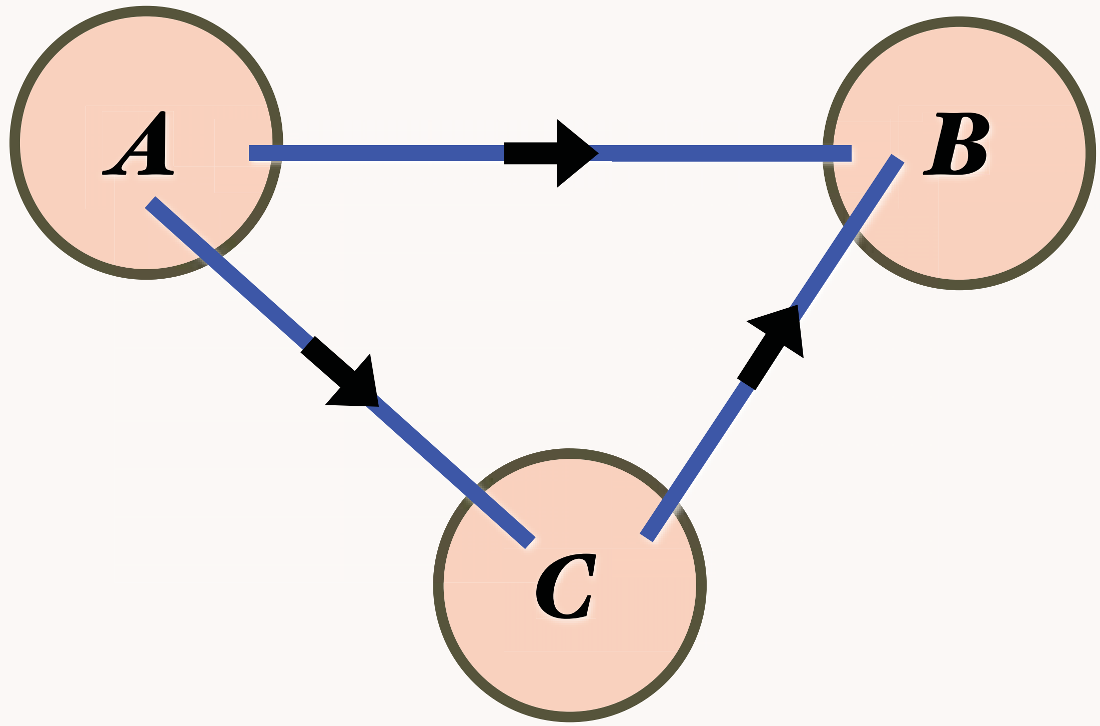
Three-Jet Rate

The scale $\mu/\sqrt{s}$ according to the BLM (dashed-dotted), PMS (dashed), FAC (full), and $\sqrt{y}$ (dotted) procedures for the three-jet rate in e^+e^- annihilation, as computed by Kramer and Lampe [10]. Notice the strikingly different behavior of the BLM scale from the PMS and FAC scales at low y. In particular, the latter two methods predict increasing values of μ as the jet invariant mass $\mathcal{M} < \sqrt{(ys)}$ decreases.

Rathsman

Other Jet Observables:

Transitivity Property of Renormalization Group

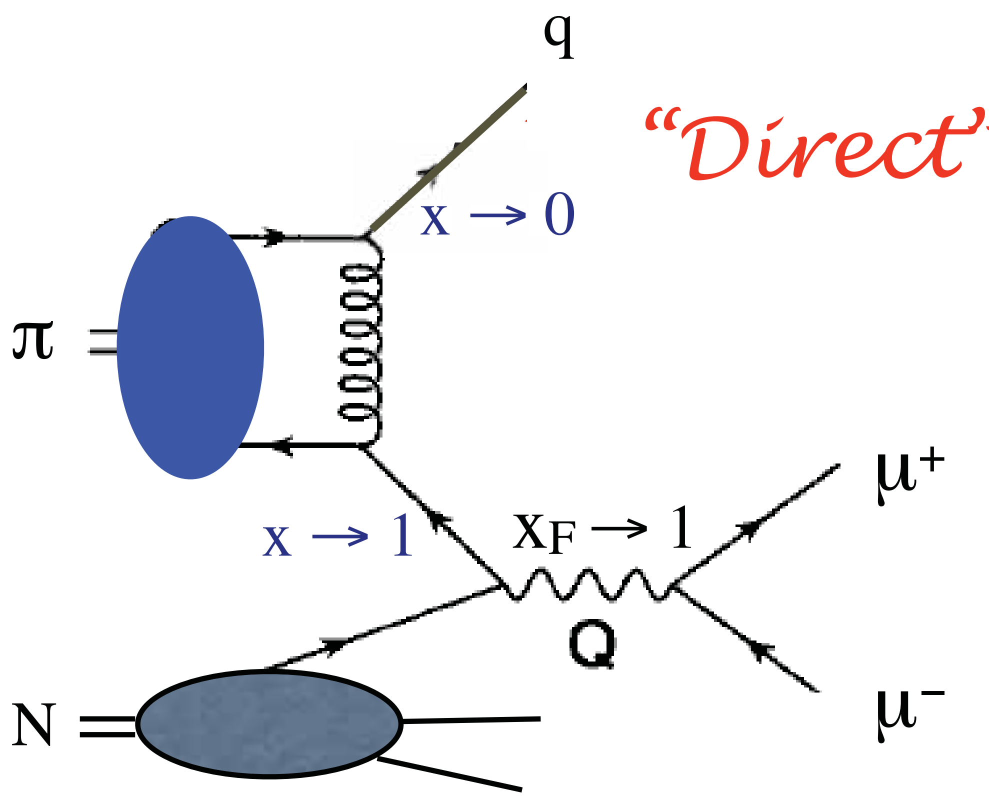


A→C   C→B   *identical to*   A→B

Relation of observables independent of intermediate scheme C

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

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



Berger and Brodsky, PRL 42 (1979) 940

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

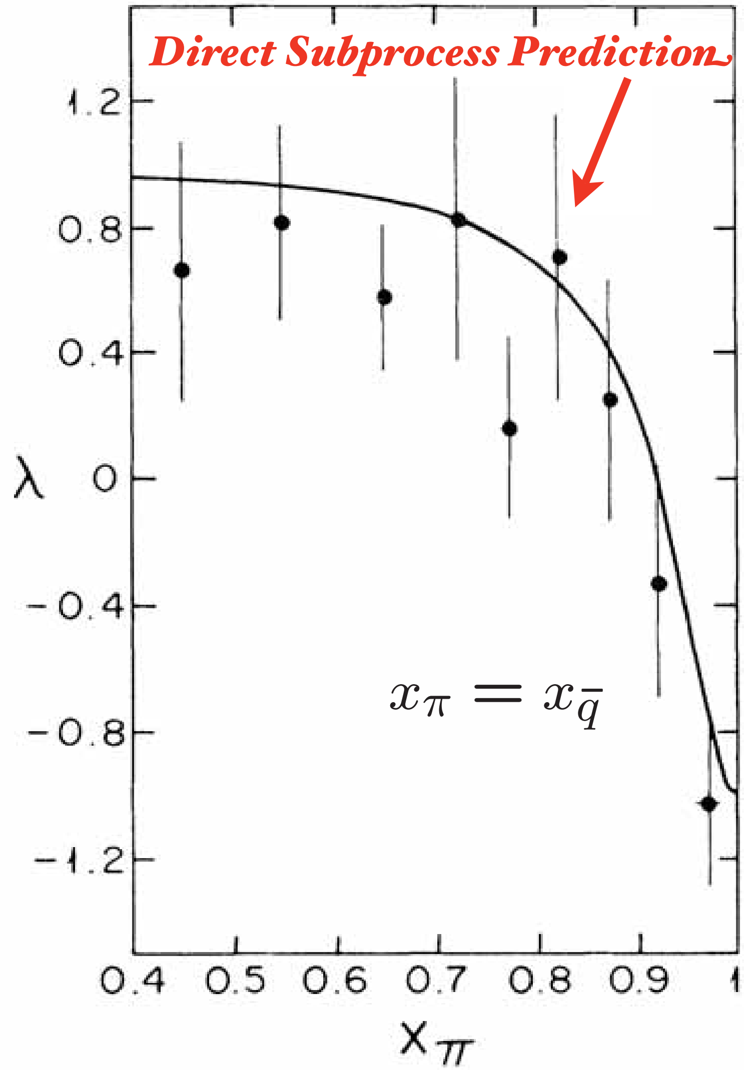
$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \rho \sin 2\theta \cos\phi + \omega \sin^2\theta \cos 2\phi .$$

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

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

Dramatic change in angular distribution at large x_F

Example of a higher-twist direct subprocess

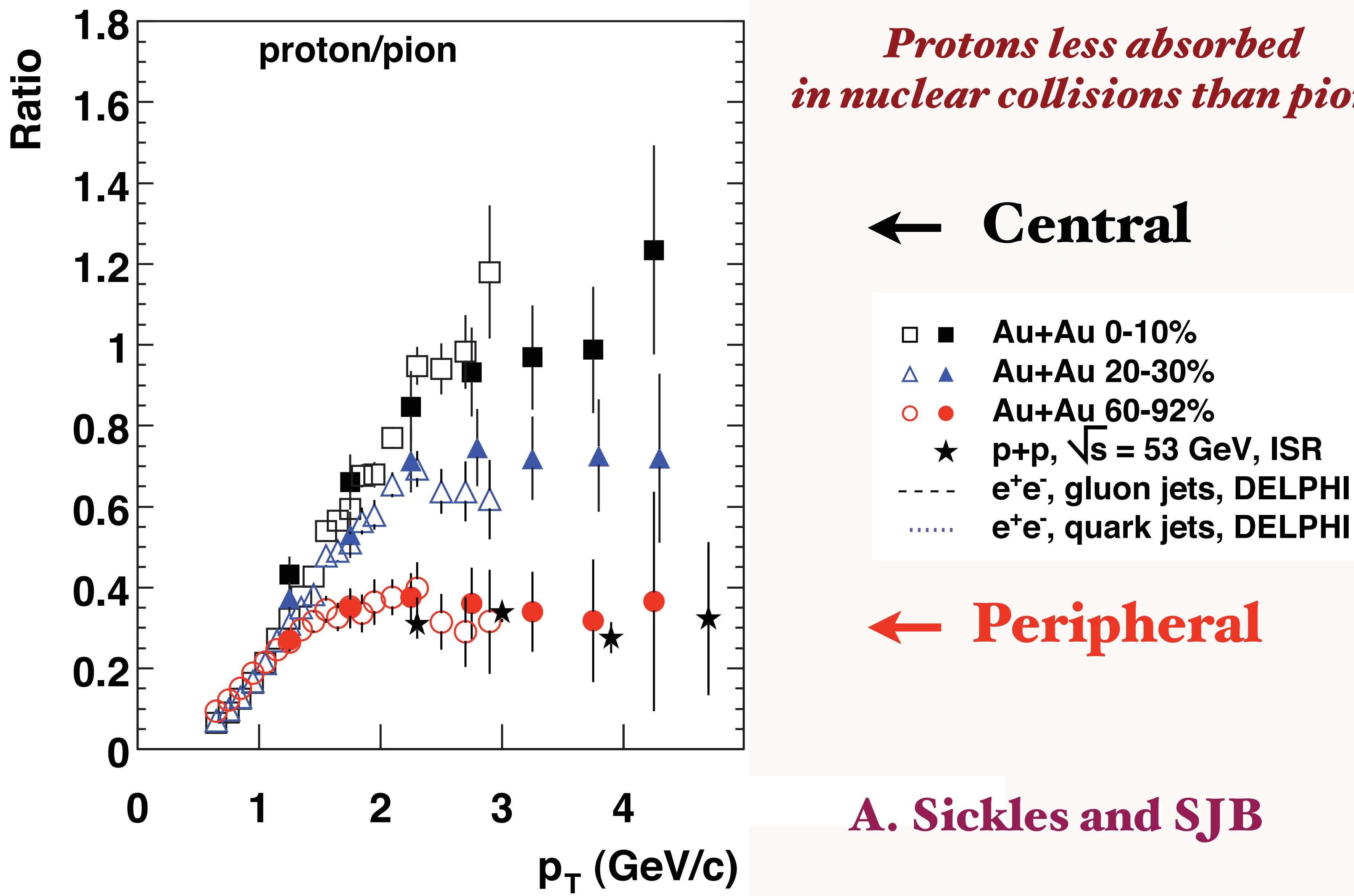


Chicago-Princeton Collaboration

Phys.Rev.Lett.55:2649,1985

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

← **Central**

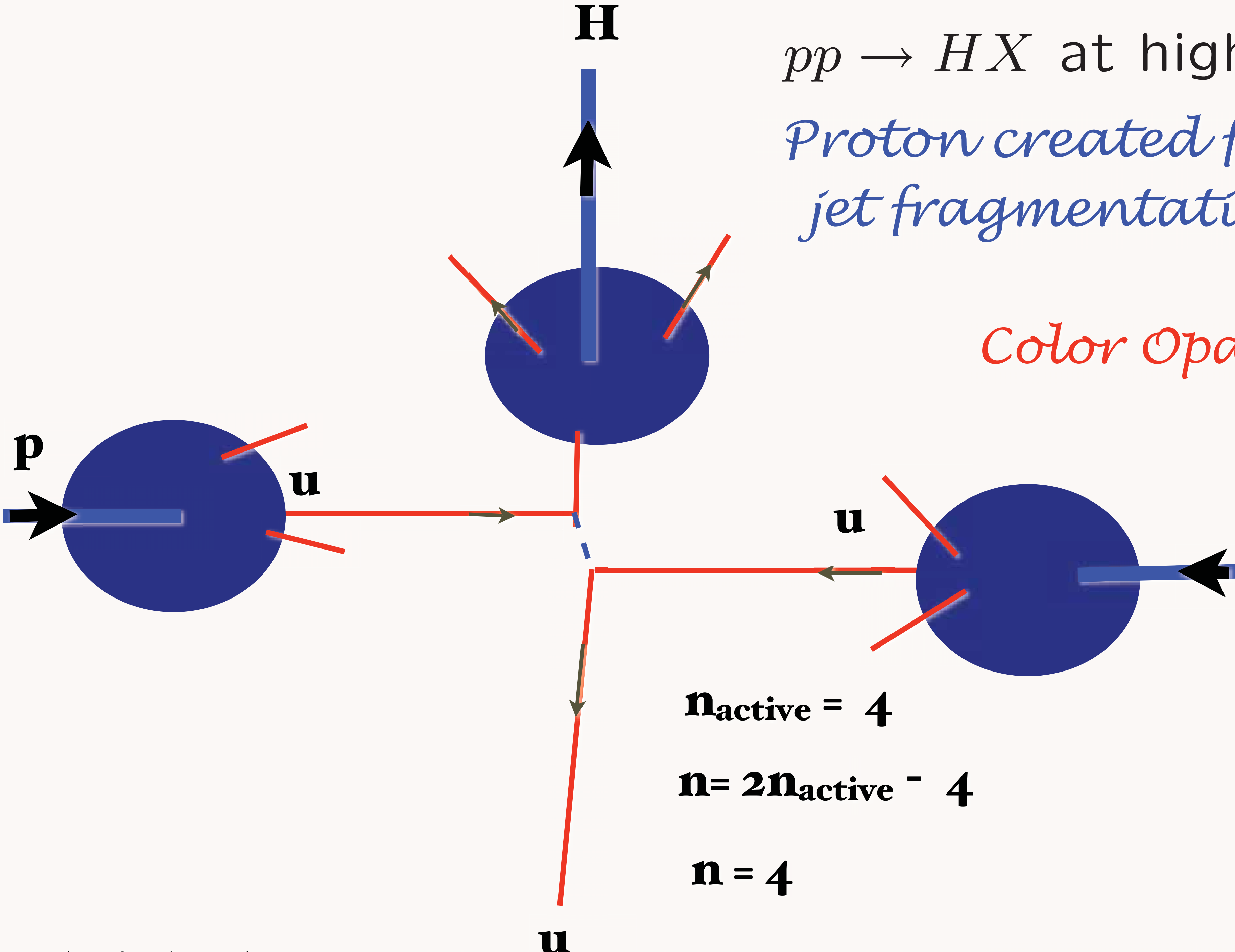
← **Peripheral**

A. Sickles and SJB

$pp \to HX$ 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

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

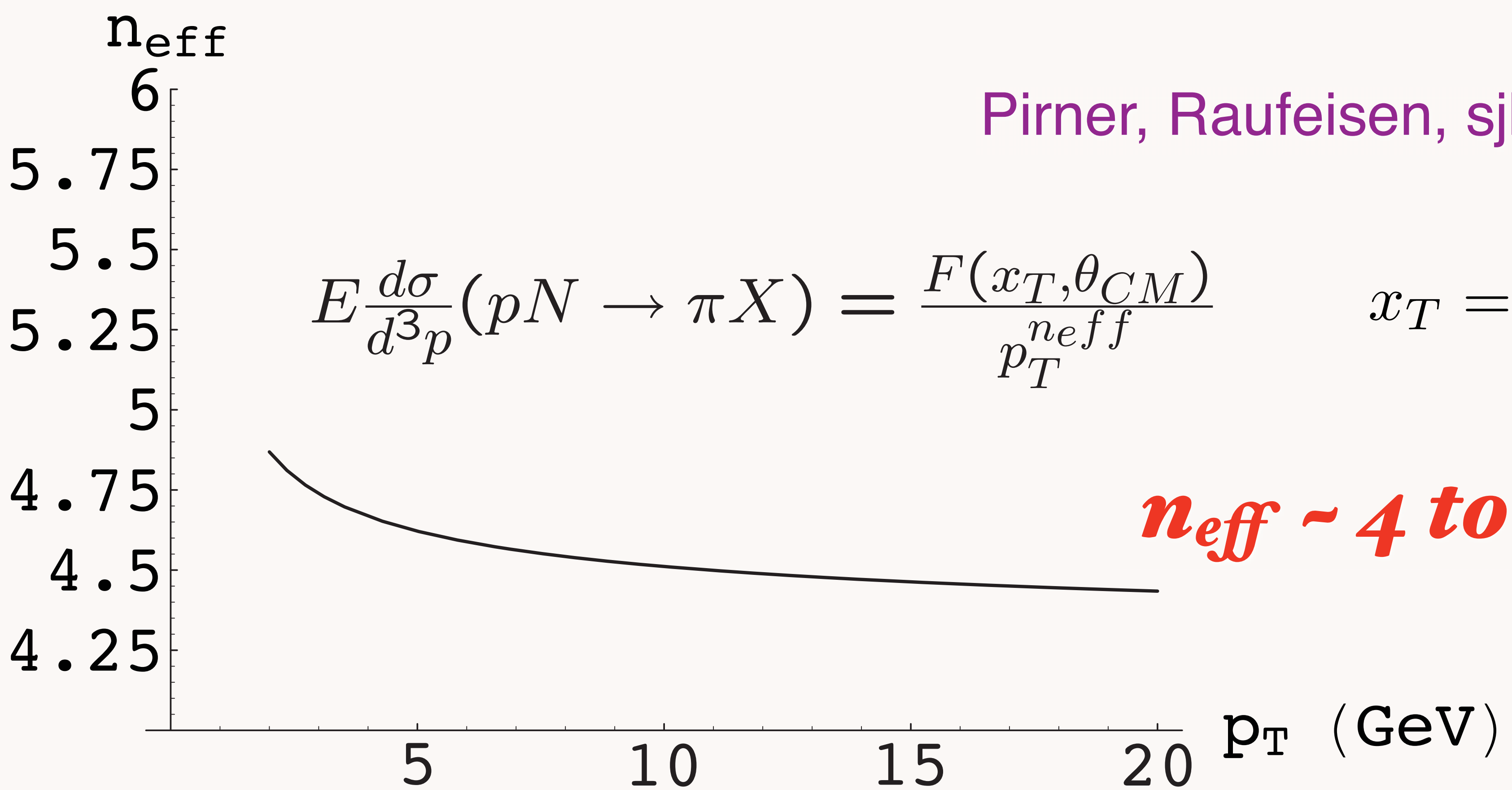
$$E\frac{d\sigma}{d^3p}(pN \to \pi X) = \frac{F(x_T,\theta_{CM})}{p_T^{neff}}$$

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



Pirner, Raufeisen, sjb

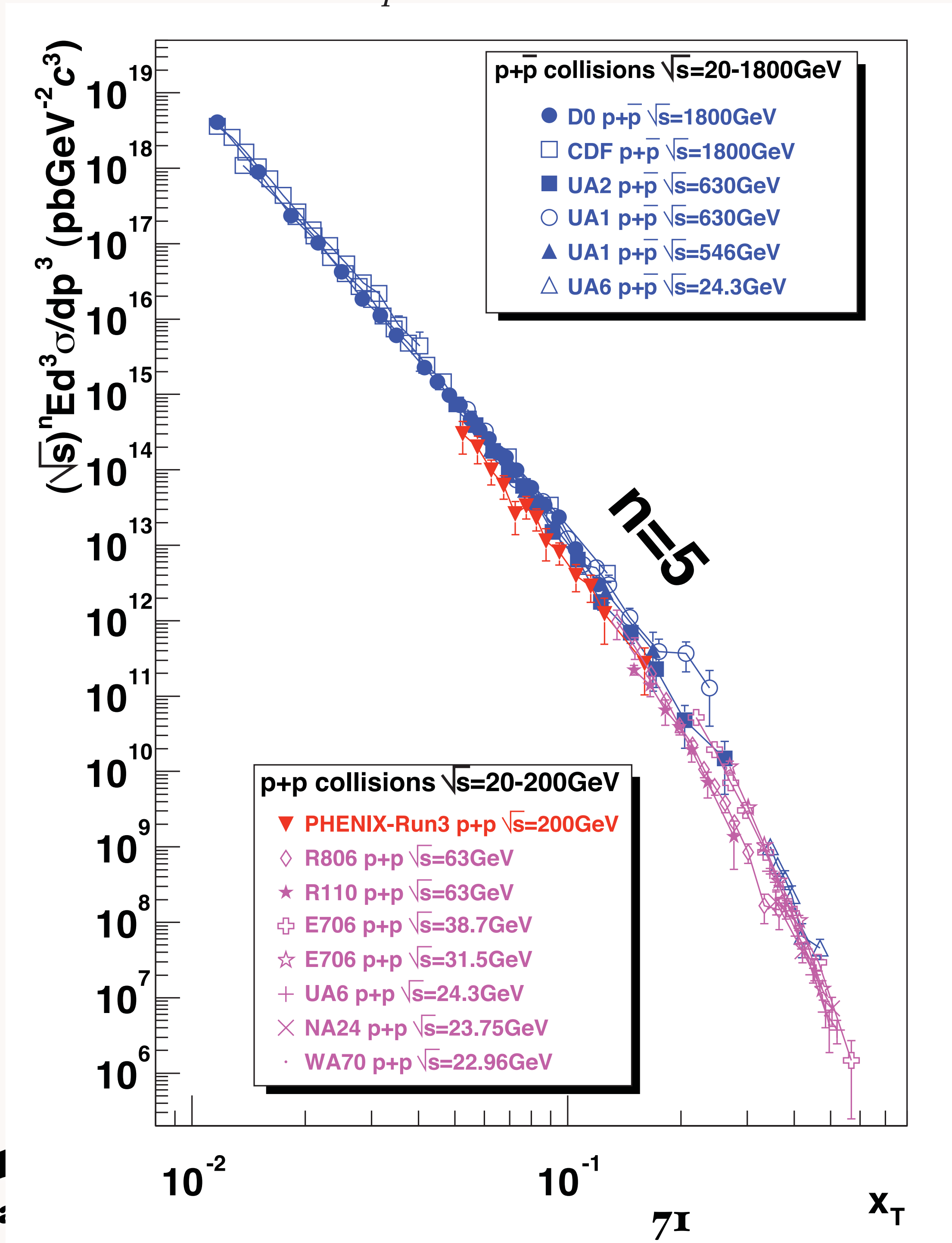
$$E\frac{d\sigma}{d^3p}(pN \to \pi X) = \frac{F(x_T,\theta_{CM})}{p_T^{n_{eff}}} \qquad x_T = \frac{2p_T}{\sqrt{s}}$$

$n_{eff} \sim 4$ to 5

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

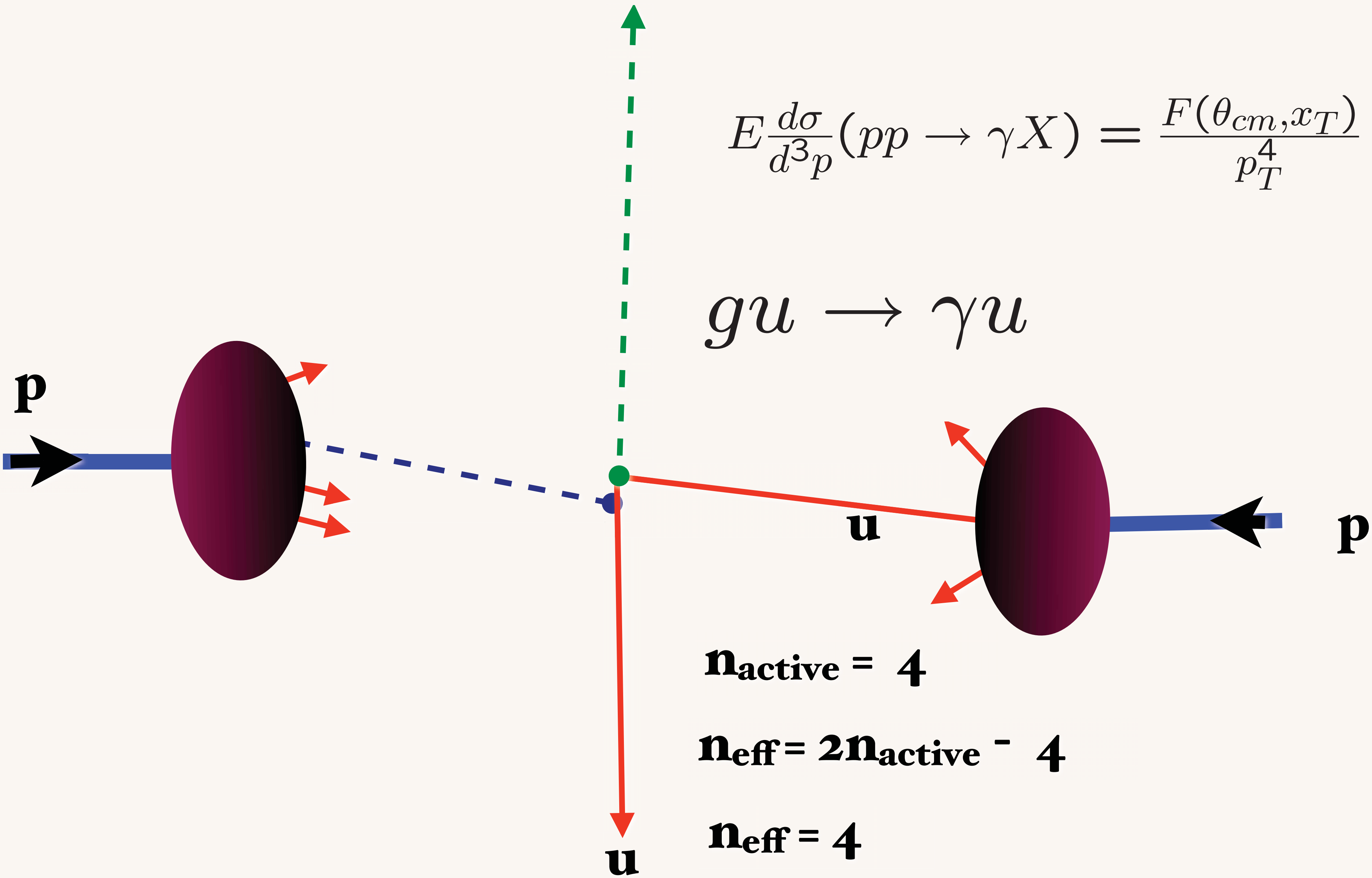
$\sqrt{s}^n E \frac{d\sigma}{d^3p}(pp \to \gamma X)$ at fixed x_T

Tannenbaum

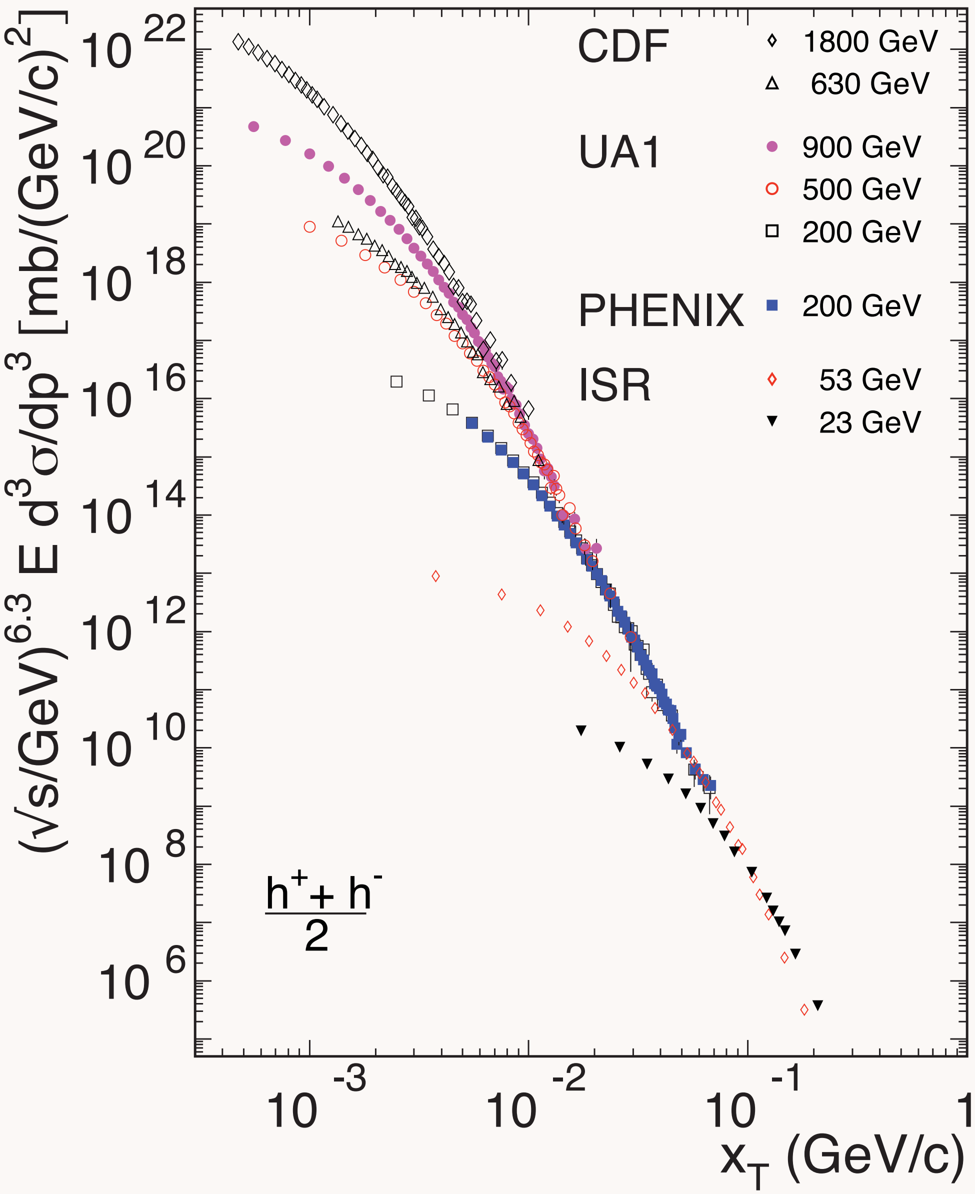


Scaling of direct photon production consistent with PQCD

$$pp \longrightarrow \gamma X$$



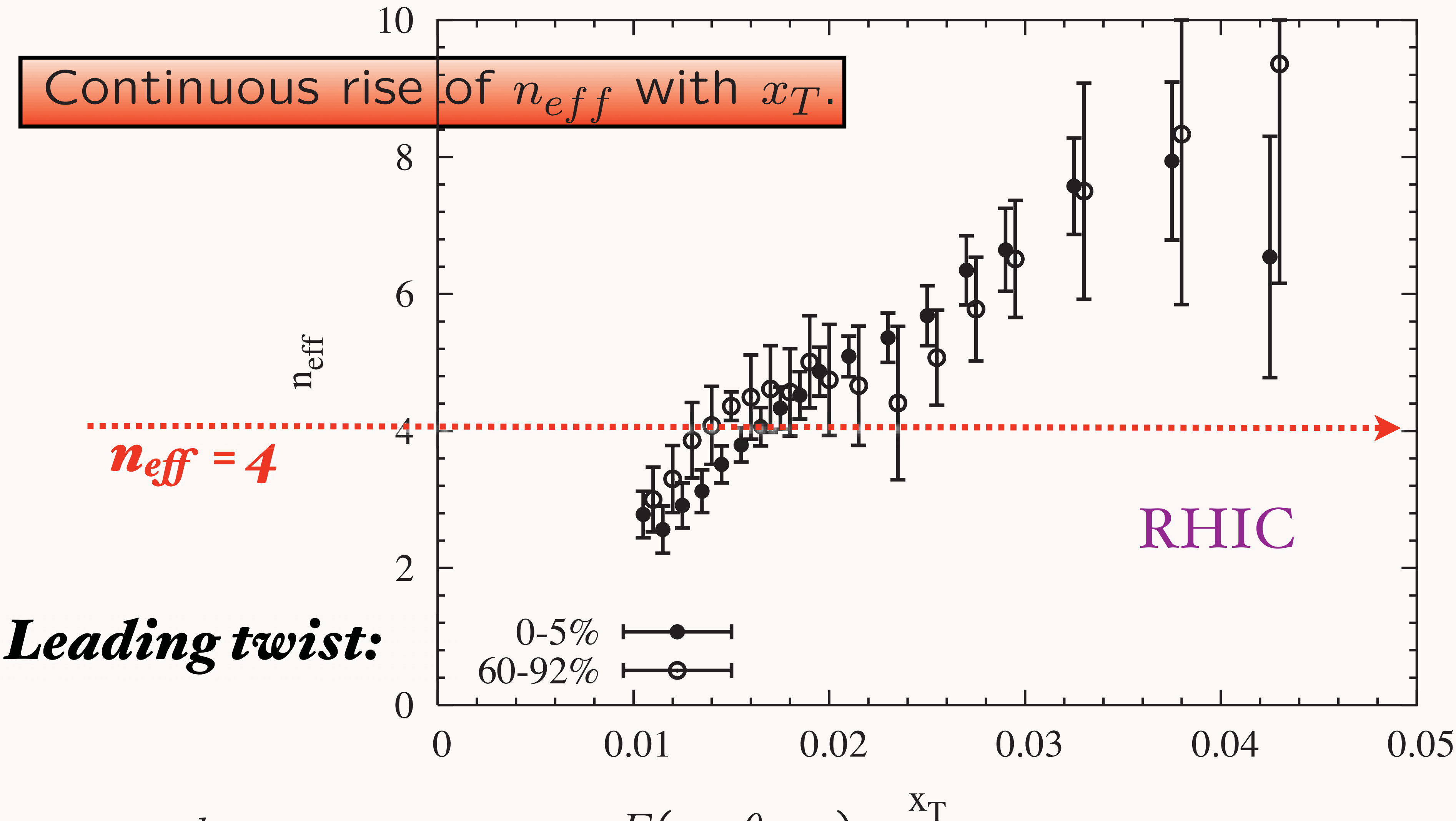
$\sqrt{s}^{6.3} \times E\frac{d\sigma}{d^3p}(pp \to H^{\pm}X)$ at fixed x_T



Tannenbaum

Scaling inconsistent with PQCD

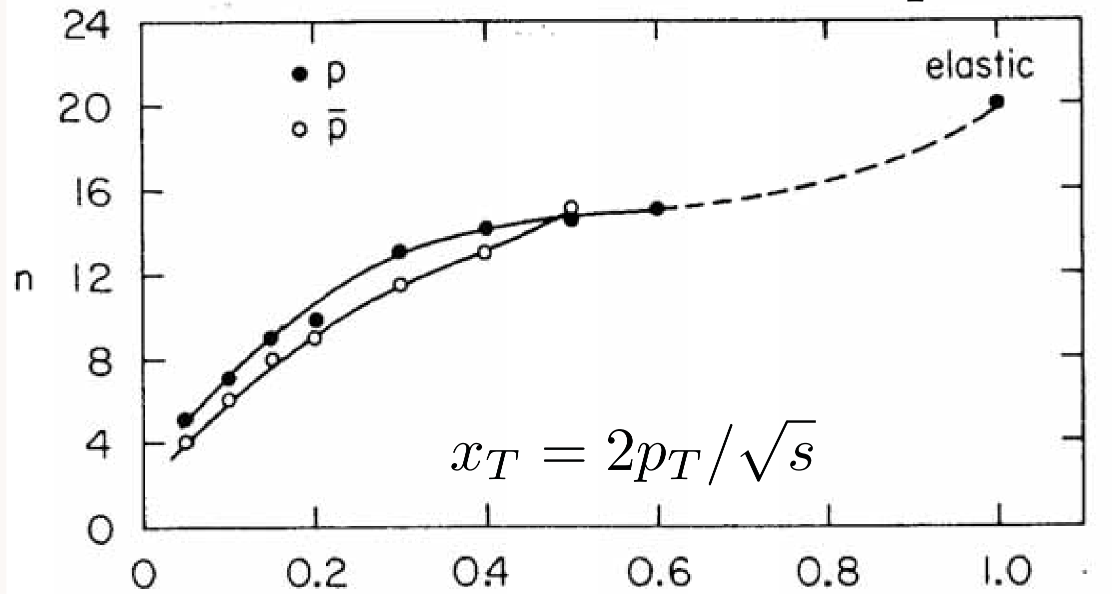
Protons produced in AuAu collisions at RHIC do not exhibit clear scaling properties in the available p_T range. Shown are data for central $(0-5\%)$ and for peripheral $(60-90\%)$ collisions.



Leading twist:

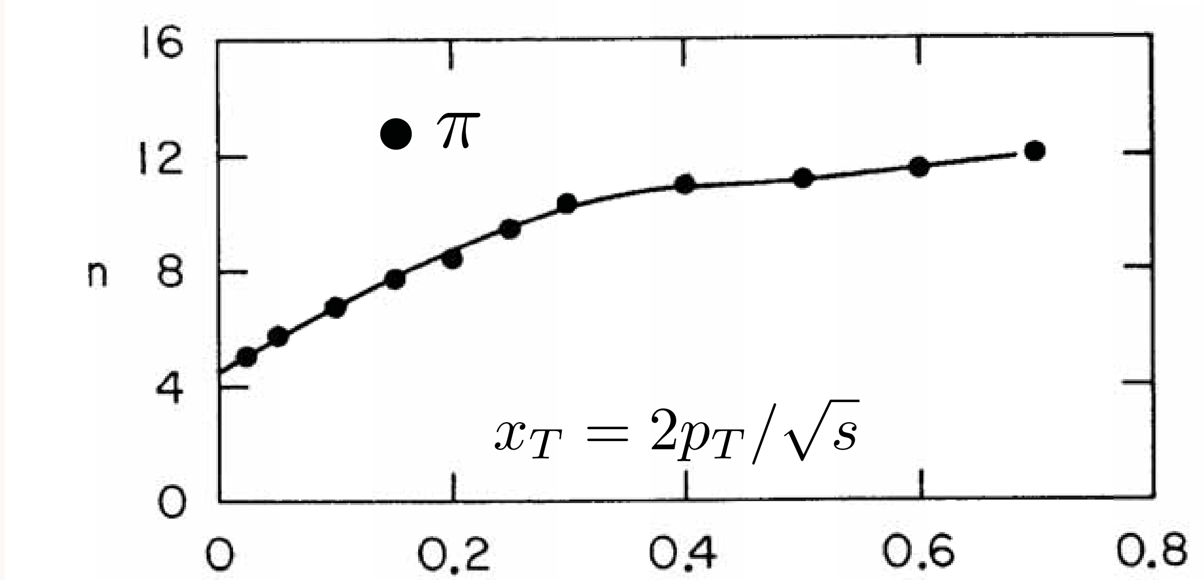
$$E\frac{d\sigma}{d^3p}(pN \to pX) = \frac{F(x_T,\theta_{CM})}{p_T^{n_{eff}}}$$

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

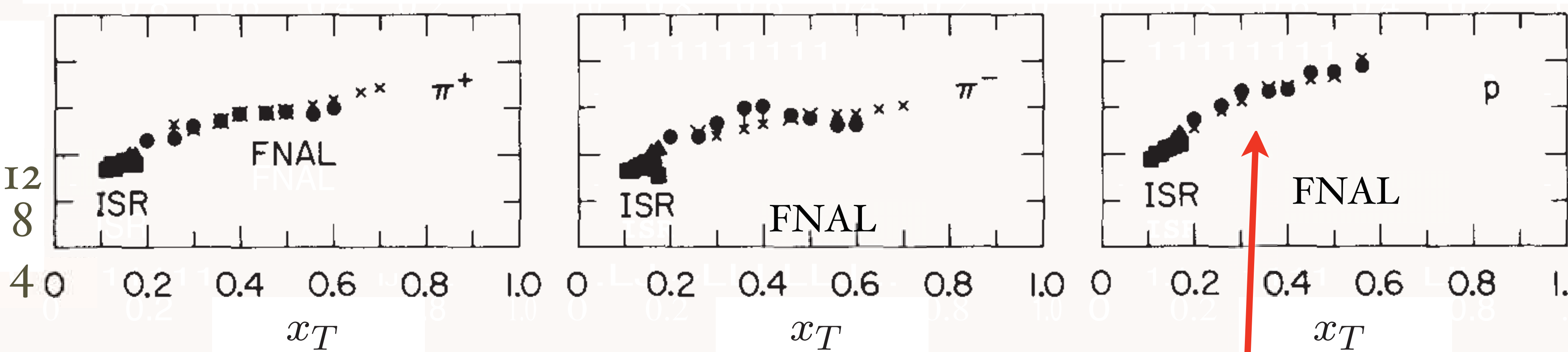


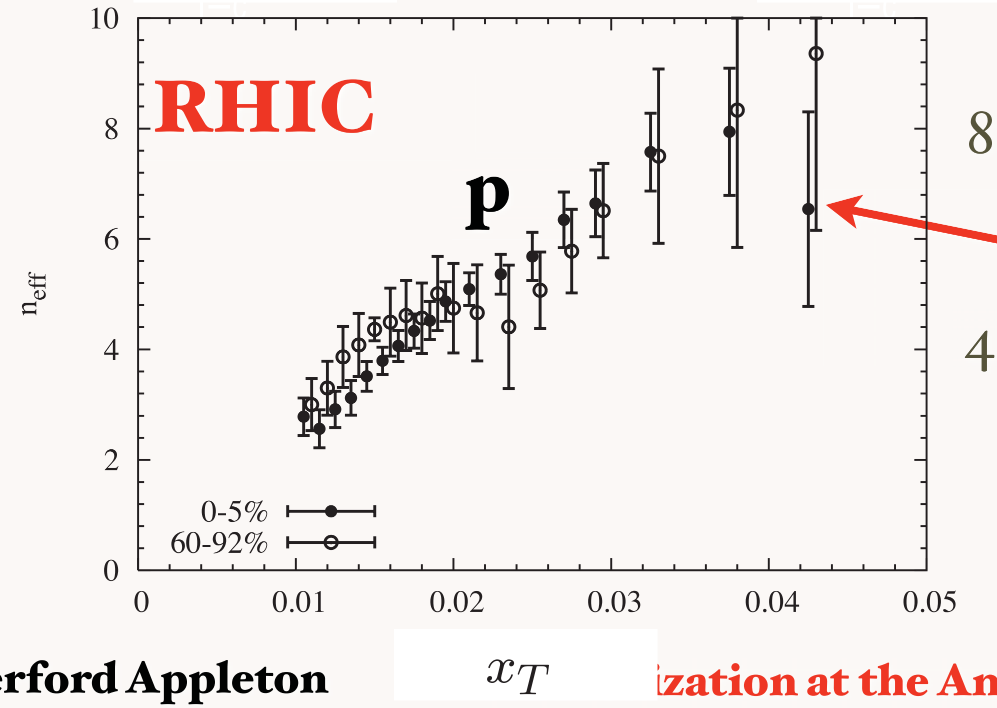
Clear evidence for higher-twist contributions

J. W. Cronin, SSI 1974



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



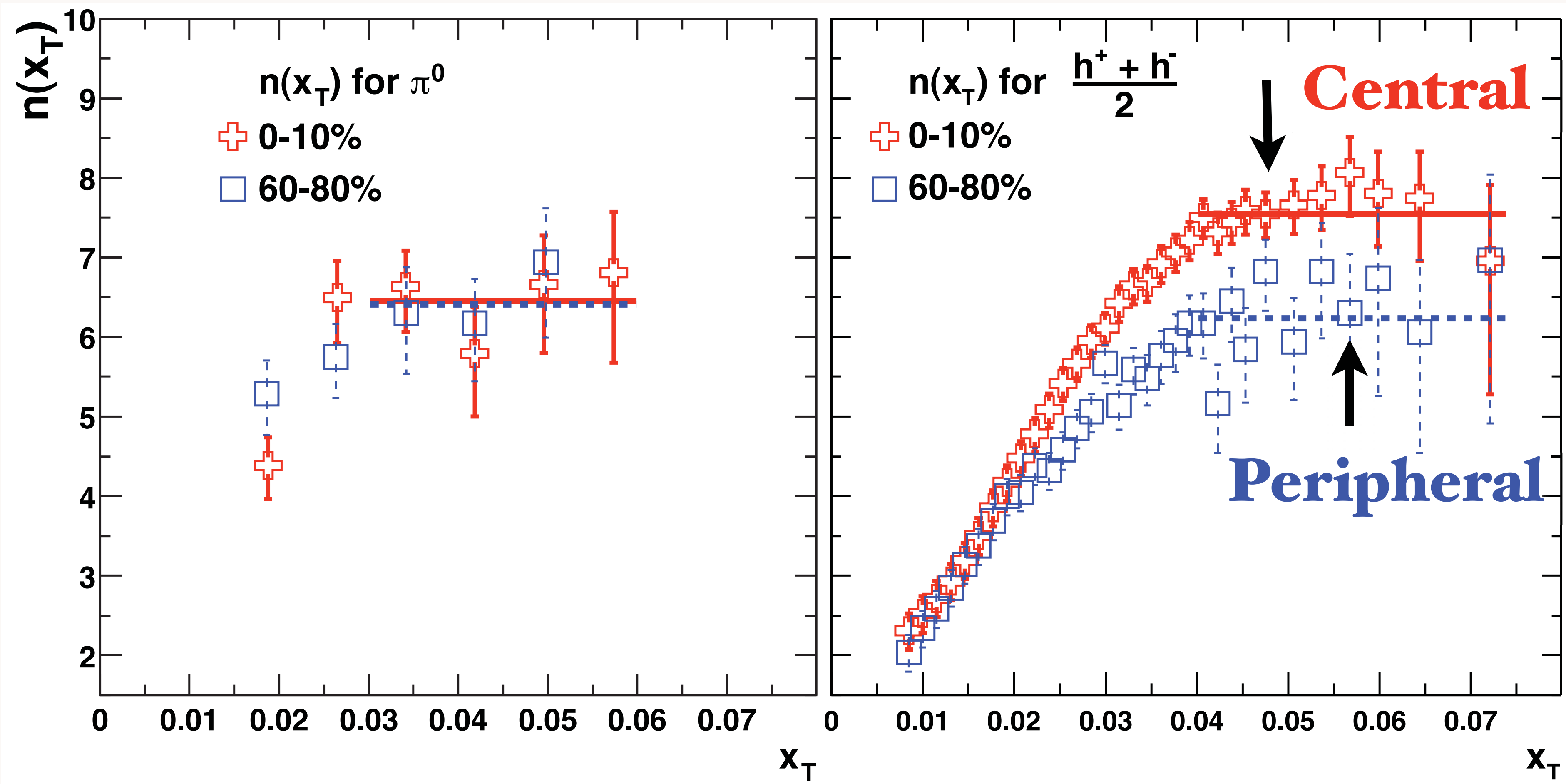


$$E\frac{d\sigma}{d^3p}(pp \to pX) = \frac{F(x_T,\theta_{CM})}{p_T^{12}}$$

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

Trend consistent with RHIC at small x_T

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

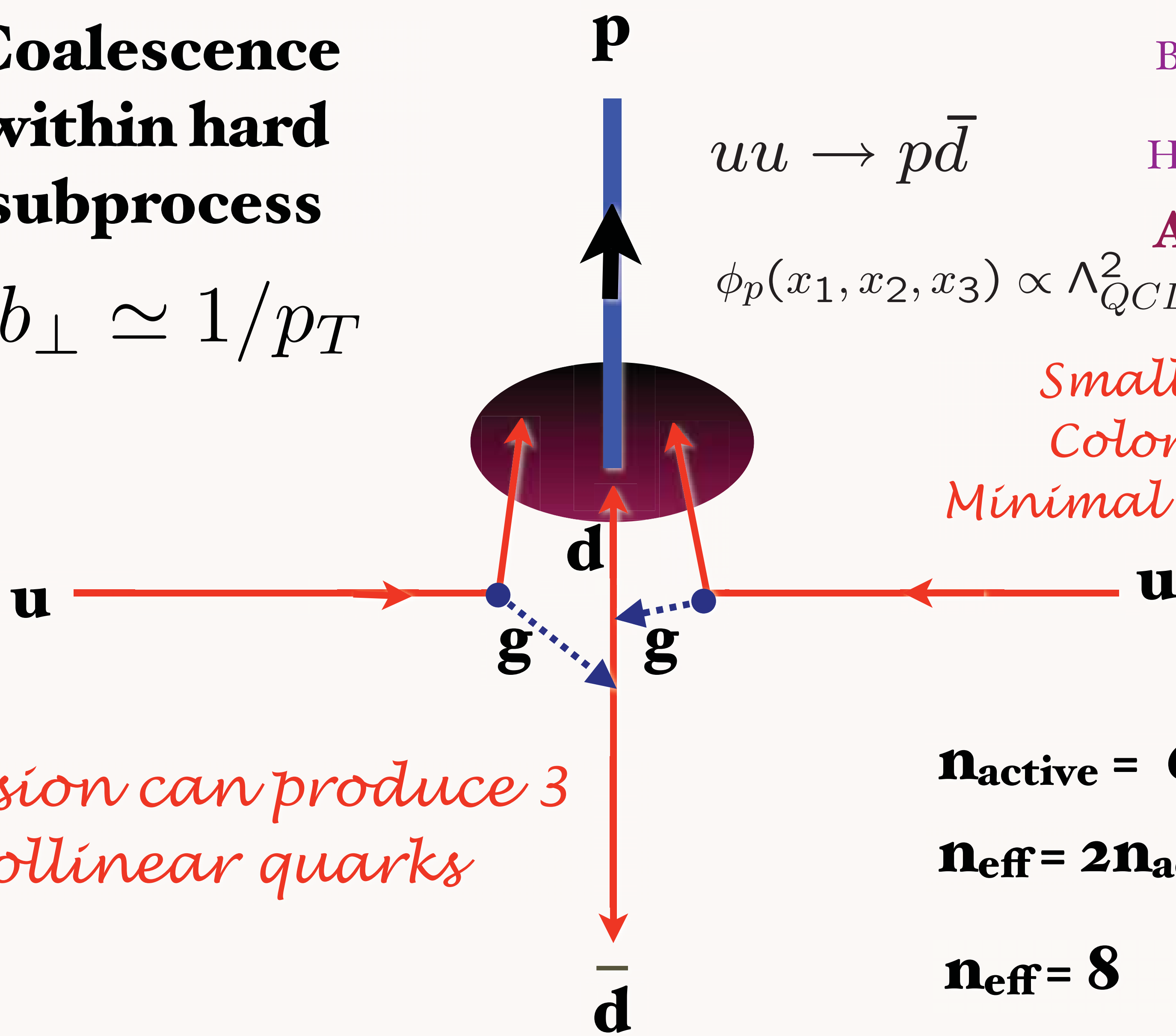


Proton power changes with centrality !

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

A. Sickles and SJB

Small color-singlet
Color Transparent
Minimal same-side energy

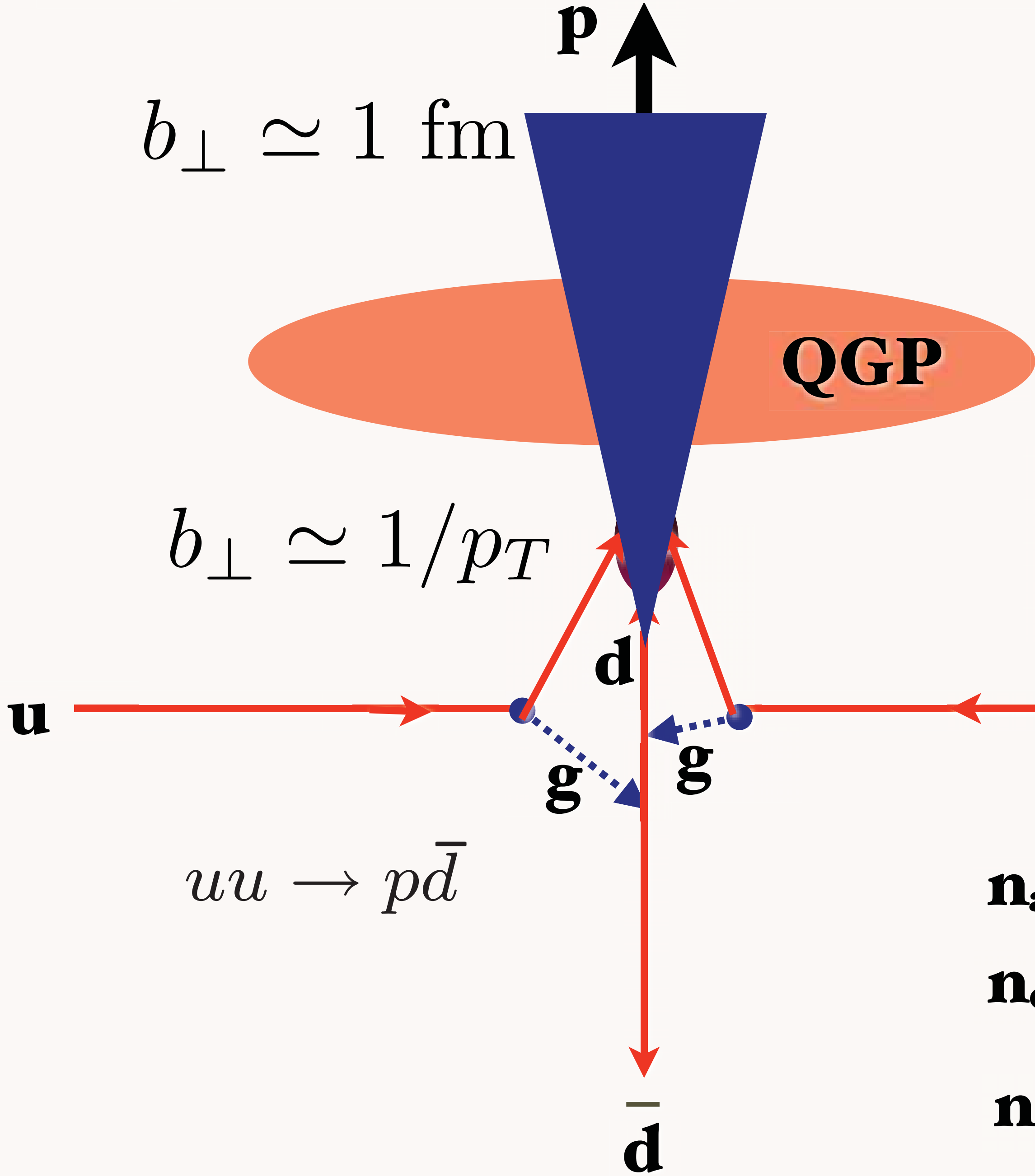
Collision can produce 3 collinear quarks

$n_{active} = 6$

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

$n_{eff} = 8$

Baryon made directly within hard subprocess



Formation Time proportional to Energy

Small color-singlet
Color Transparent
Minimal same-side energy

$n_{active} = 6$

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

$n_{eff} = 8$

A. Sickles and SJB

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

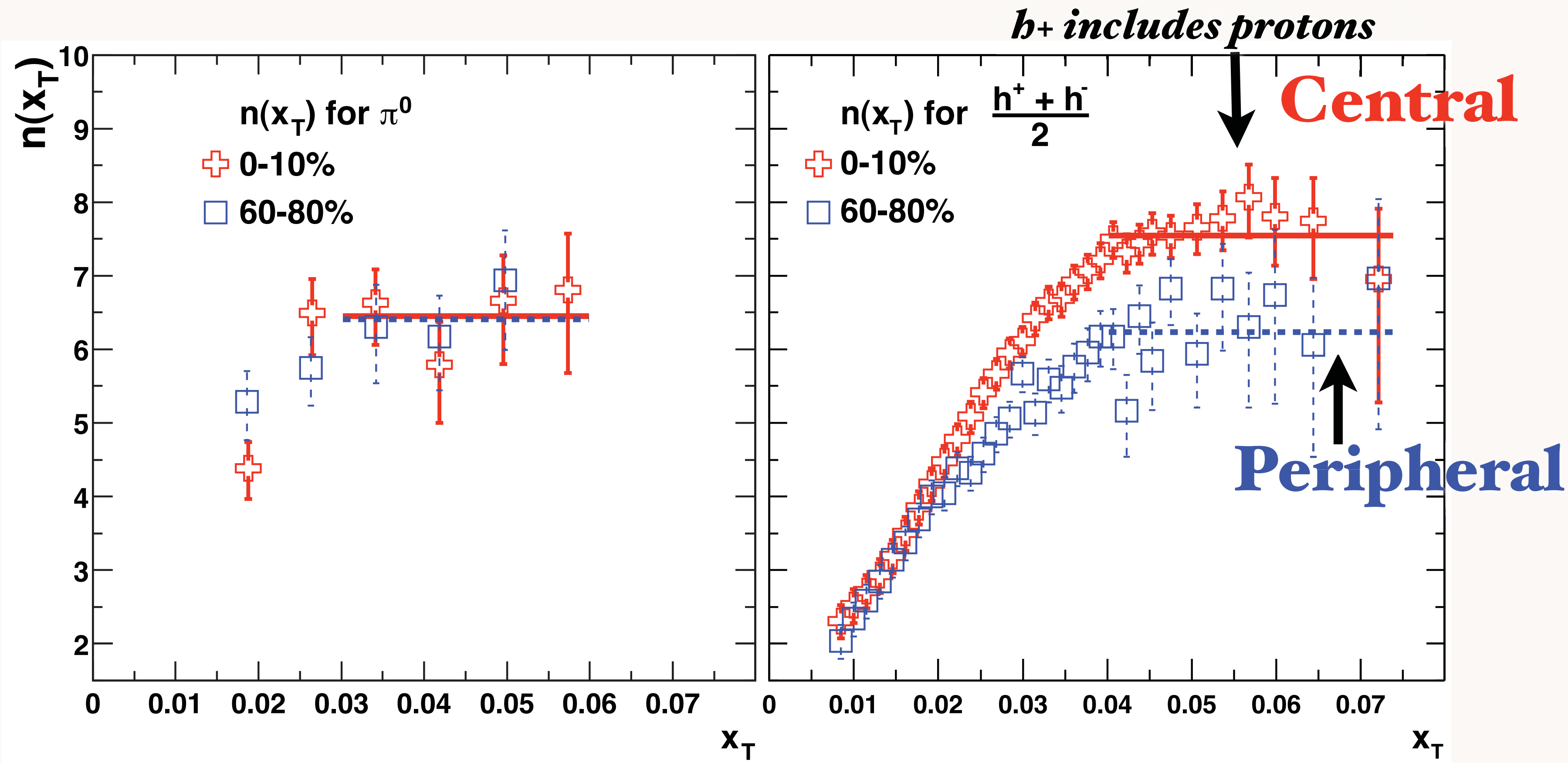
$$\frac{d\sigma}{d^3p/E}(pp \to pX) = A\frac{(1-x_T)^{11}}{p_T^4} + B\frac{(1-x_T)^7}{p_T^8}$$

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

Small color-singlet
Color Transparent
Minimal same-side energ

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

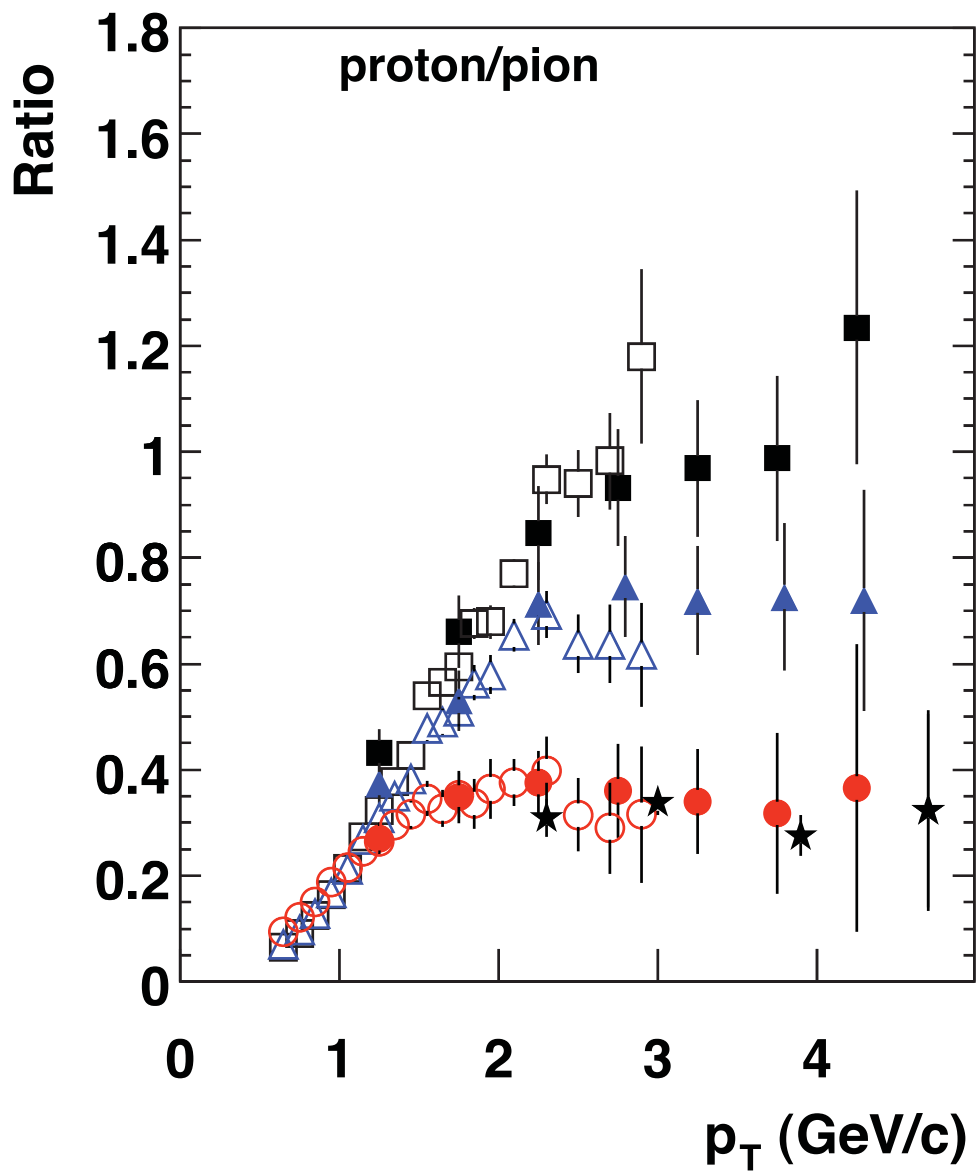
S. S. Adler, *et al.*, PHENIX Collaboration, *Phys. Rev.* C **69**, 034910 (2004) [`nucl-ex/0308006`].



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

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

Particle ratio changes with centrality!

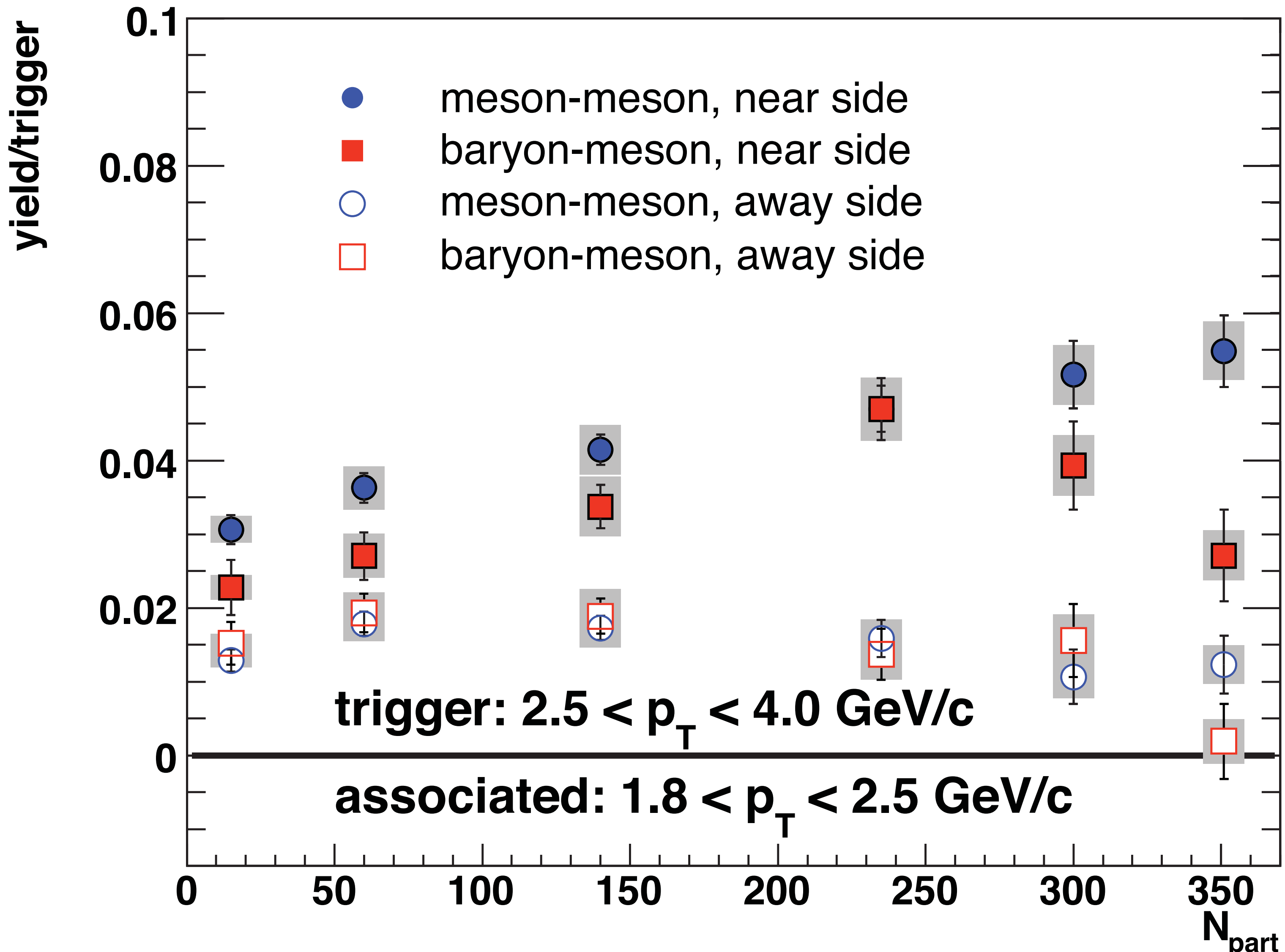


Protons less absorbed in nuclear collisions than pions because of dominant color transparent higher twist process

← **Central**

← **Peripheral**

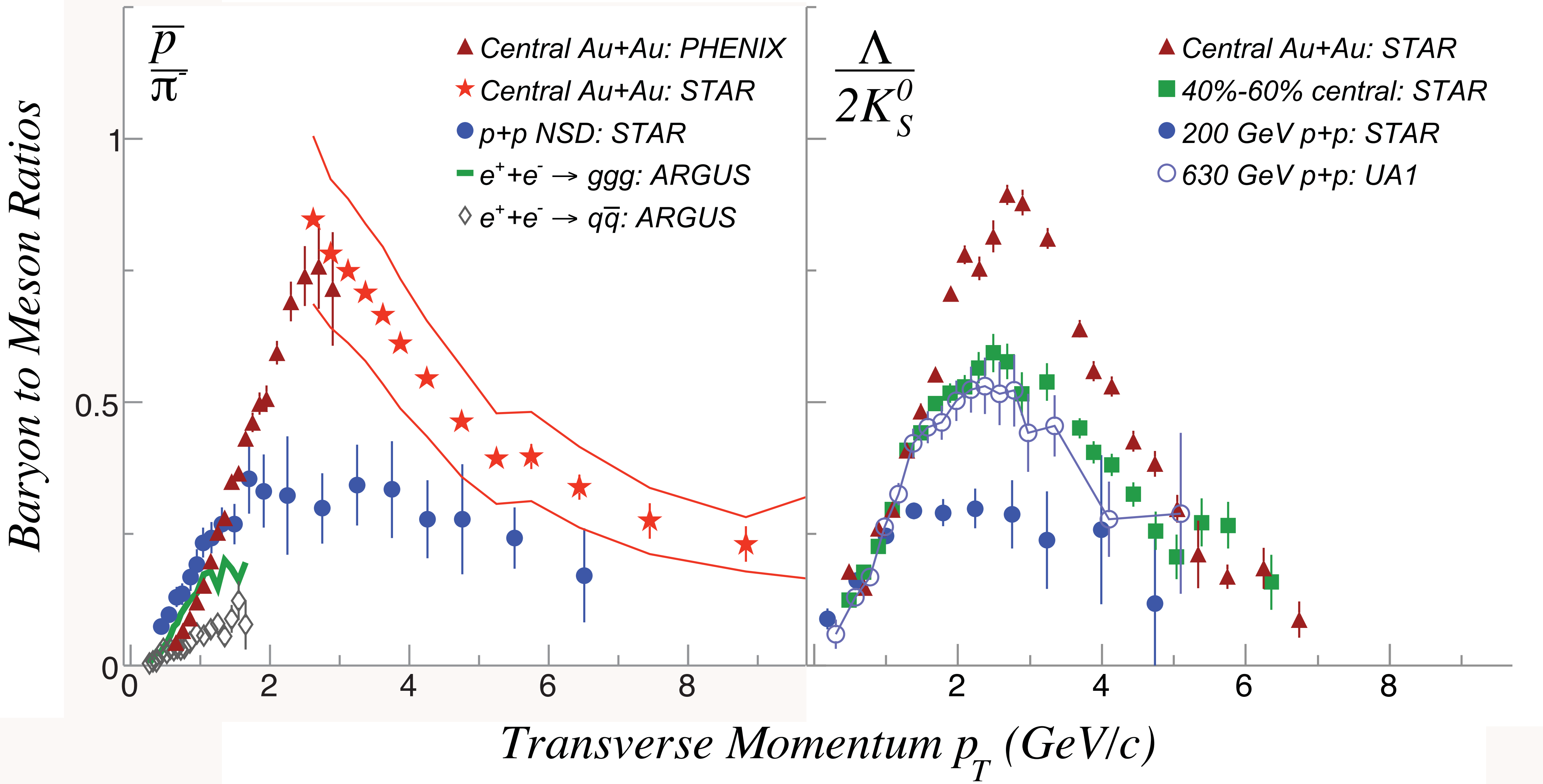
Anne Sickles



proton trigger: # same-side particles decreases with centrality

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

Paul Sorensen

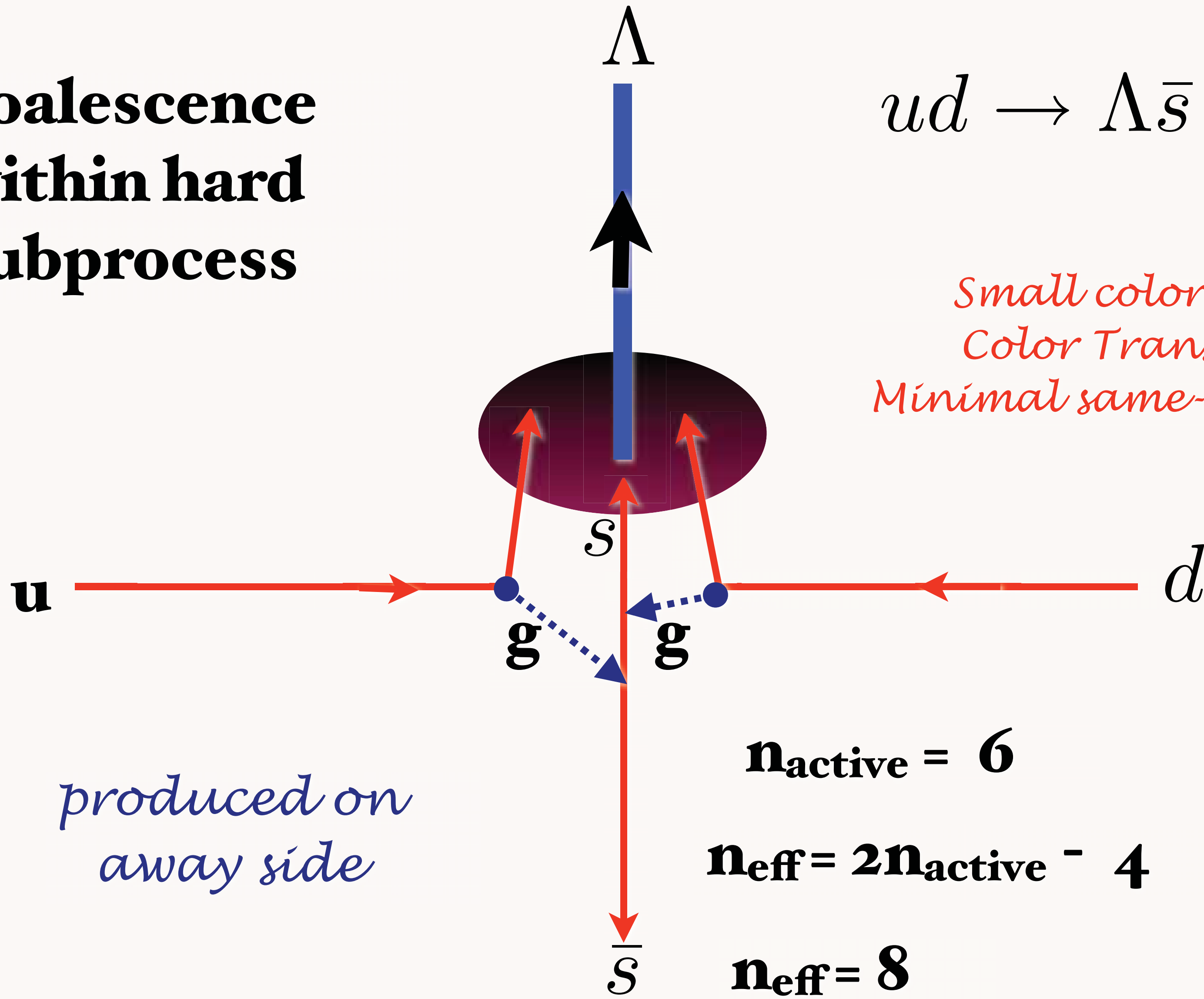


Lambda can be made directly within hard subprocess

Coalescence within hard subprocess

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

Small color-singlet
Color Transparent
Minimal same-side energy



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

$n_{active} = 6$

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

$n_{eff} = 8$

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 $x_T = 1$

- Renormalization scale is not arbitrary; multiple scales, unambiguous at given order
- Heavy quark distributions do not derive exclusively from DGLAP or gluon splitting -- component intrinsic to hadron wavefunction
- Initial and final-state interactions are not always power suppressed in a hard QCD reaction
- LFWFS are universal, but measured nuclear parton distributions are not universal -- antishadowing is flavor dependent
- Hadroproduction at large transverse momentum does not derive exclusively from 2 to 2 scattering subprocesses
- Hadronization at the Amplitude Level