Three Pictures of High Energy Lepton-Proton Collisions

Infinite momentum frame **Parton Model**

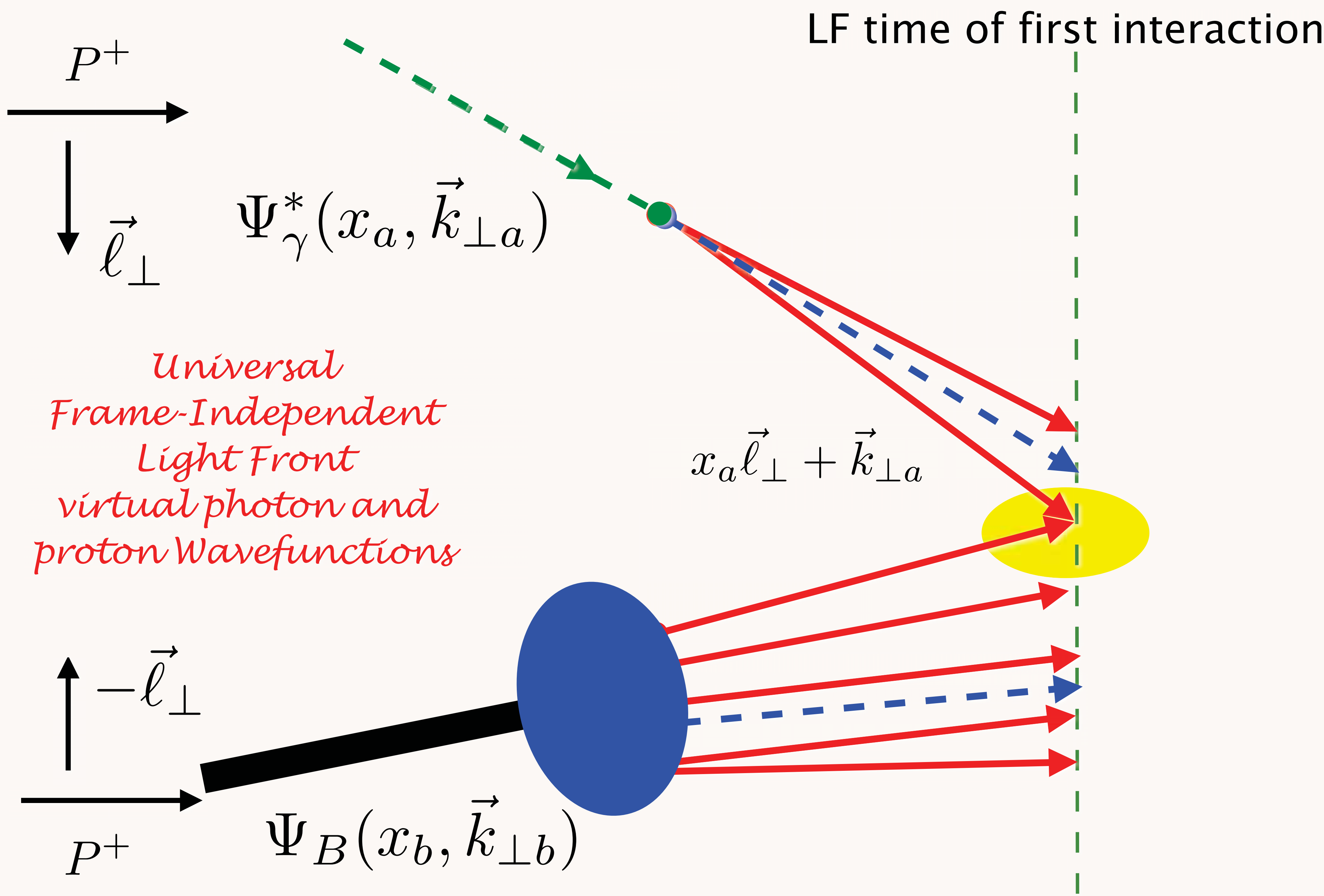
Simple Virtual Photon Probes Complex Evolved Proton

Proton Rest Frame **Color-Dipole Model**

Color Dipole of Virtual Photon Scatters on a Static Proton

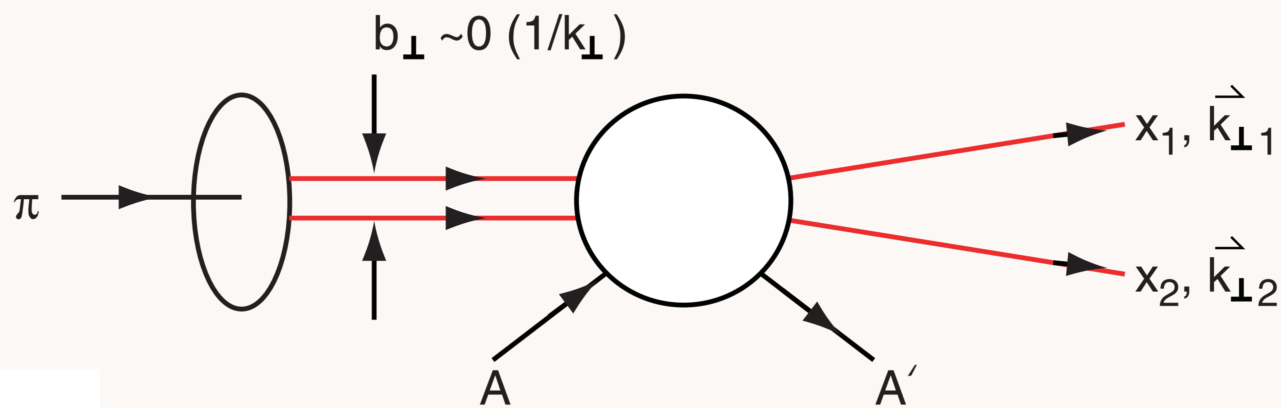
Frame-Independent **Light-Front HamiltonianTheory**

Collision of Light-Front Wavefunctions of Virtual Photon and Proton


LF time of first interaction
P^+
$\vec{\ell}_\perp$
$\Psi^*_\gamma(x_a, \vec{k}_{\perp a})$
Universal
Frame-Independent
Light Front
virtual photon and
proton Wavefunctions
$x_a\vec{\ell}_\perp + \vec{k}_{\perp a}$
$-\vec{\ell}_\perp$
P^+
$\Psi_B(x_b, \vec{k}_{\perp b})$

Diffractive Dissociation of Pion into Quark Jets

E791 Ashery et al.



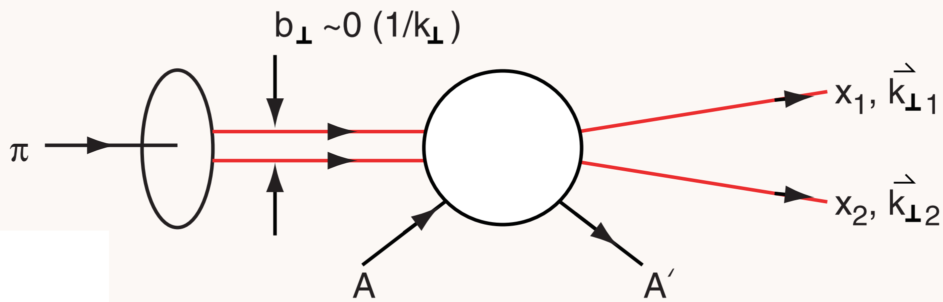
$$M \propto \frac{\partial^2}{\partial^2 k_\perp} \psi_\pi(x, k_\perp)$$

Measure Light-Front Wavefunction of Pion

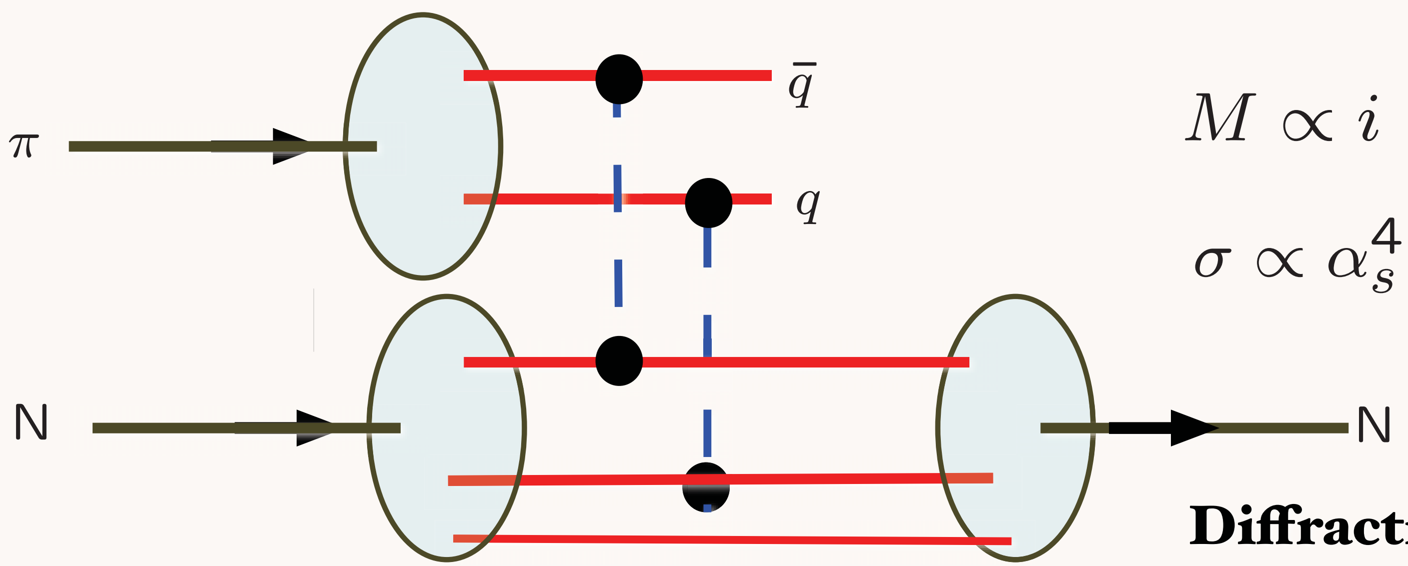
Minimal momentum transfer to nucleus

Nucleus left Intact!

Key Ingredients in Ashery Experiment



Two-gluon exchange gives imaginary amplitude proportional to energy, constant diffractive cross sections



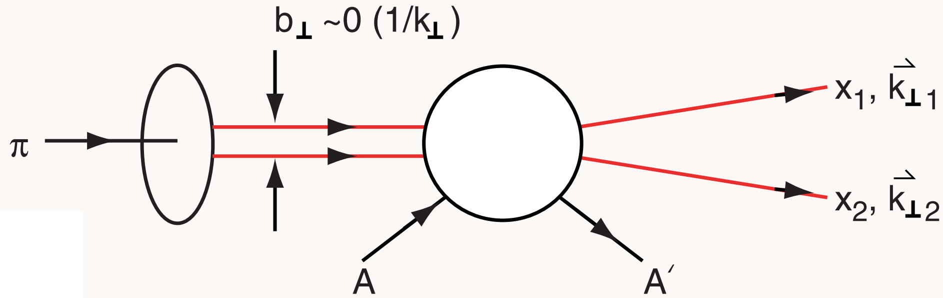
$$M \propto i\ s\ \alpha_s^2\ b_\perp^\pi\ b_\perp^N$$

$$\sigma \propto \alpha_s^4\ (b_\perp^\pi)^2\ (b_\perp^N)^2$$

Target left intact

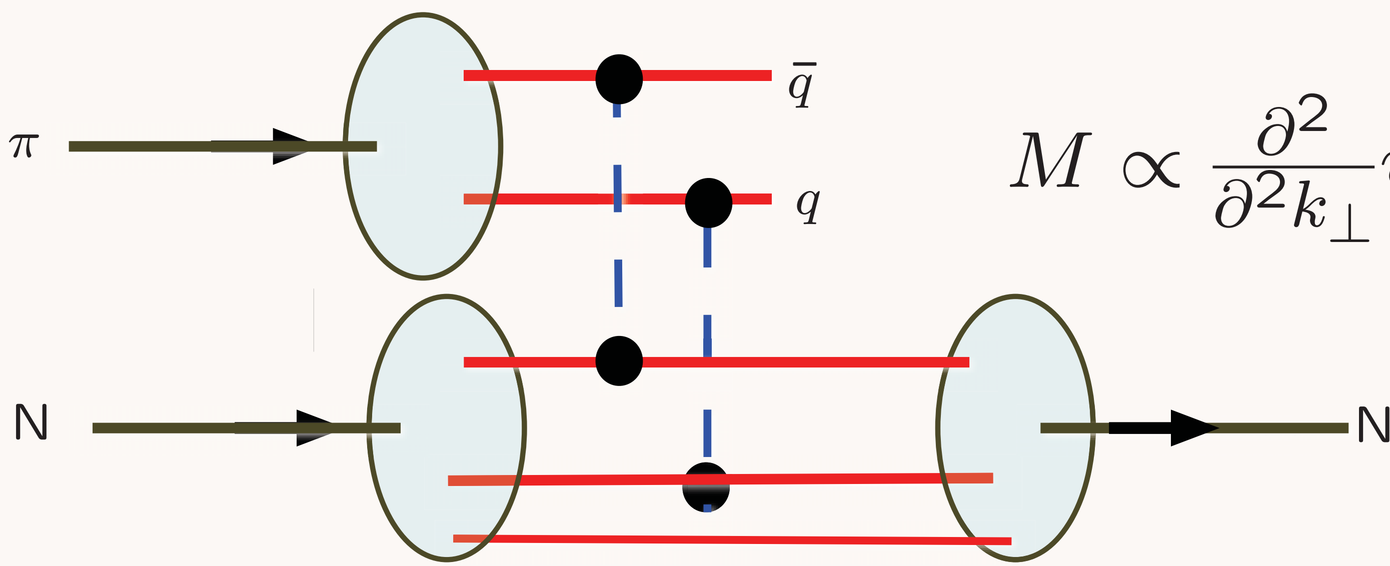
Diffraction, Rapidity gap

E791 FNAL Diffractive DiJet

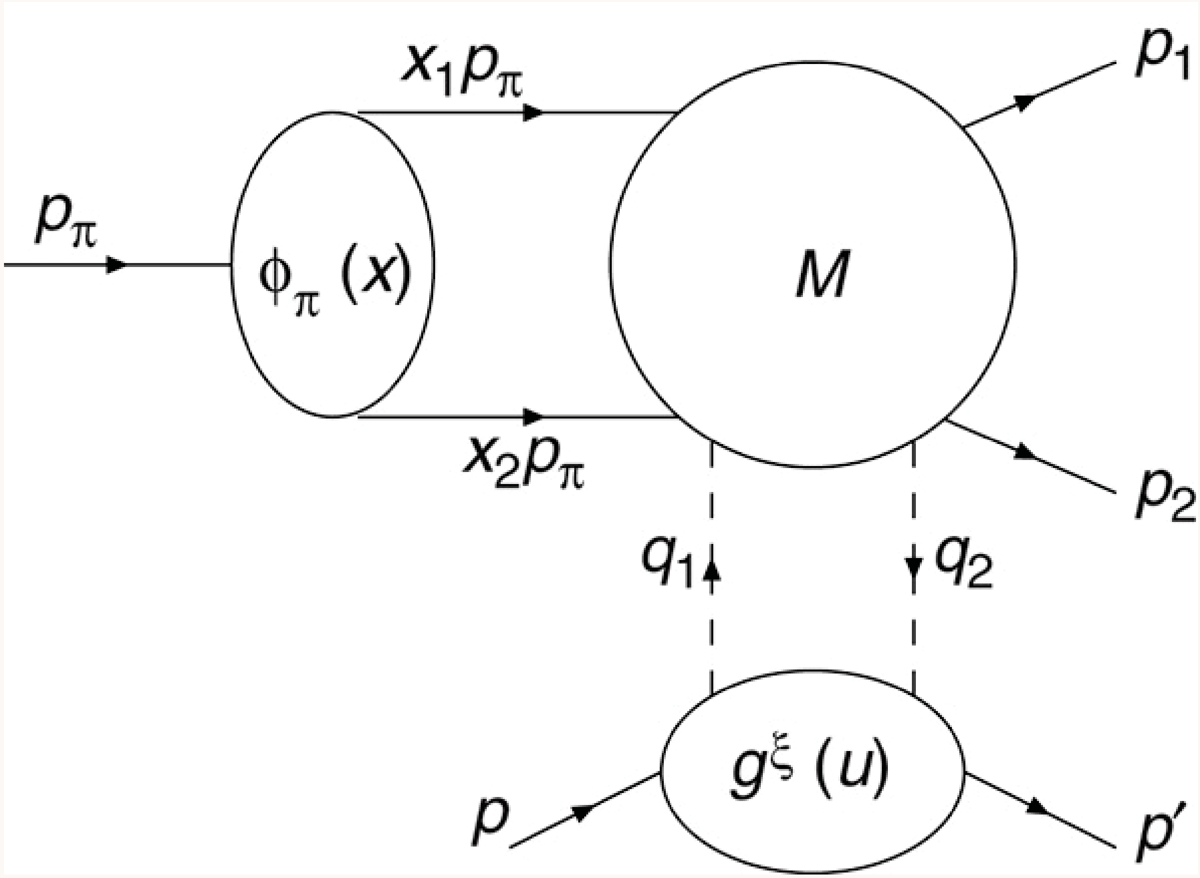


Gunion, Frankfurt, Mueller, Strikman, sjb
Frankfurt, Miller, Strikman

Two-gluon exchange measures the second derivative of the pion light-front wavefunction



$$M \propto \frac{\partial^2}{\partial^2 k_\perp}\psi_\pi(x, k_\perp)$$



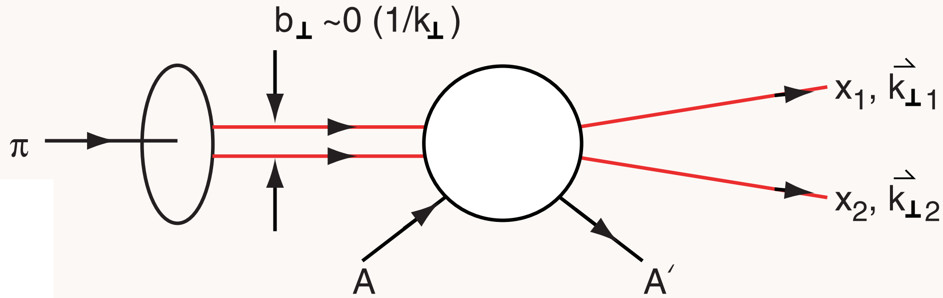
x

1-x

gluons measure size of color dipole

$$\frac{d\sigma}{dk_t^2} \propto |\alpha_s(k_t^2) x_N G(u, k_t^2)|^2 \left| \frac{\partial^2}{\partial k_t^2} \psi(x, k_t) \right|^2$$

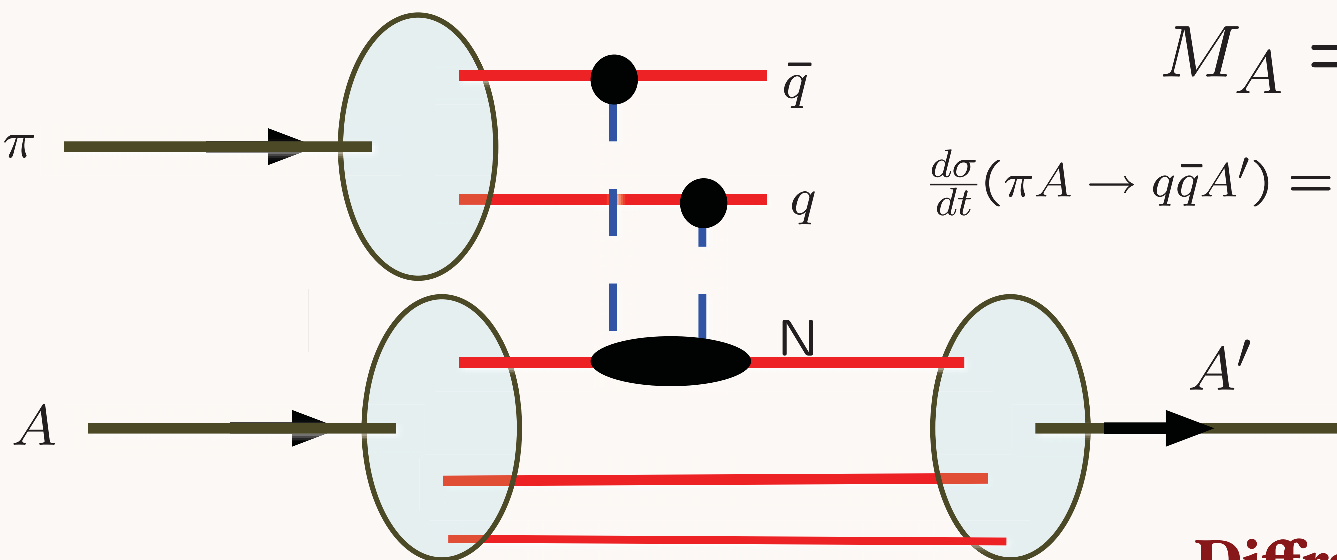
Key Ingredients in E791 Experiment



Brodsky Mueller
Frankfurt Miller Strikman

Small color-dipole moment pion not absorbed; interacts with each nucleon coherently

QCD COLOR Transparency



$$M_A = A\ M_N$$

$$\frac{d\sigma}{dt}(\pi A \to q\bar{q}A') = A^2\ \frac{d\sigma}{dt}(\pi N \to q\bar{q}N')\ F_A^2(t)$$

Target left intact

Diffraction, Rapidity gap

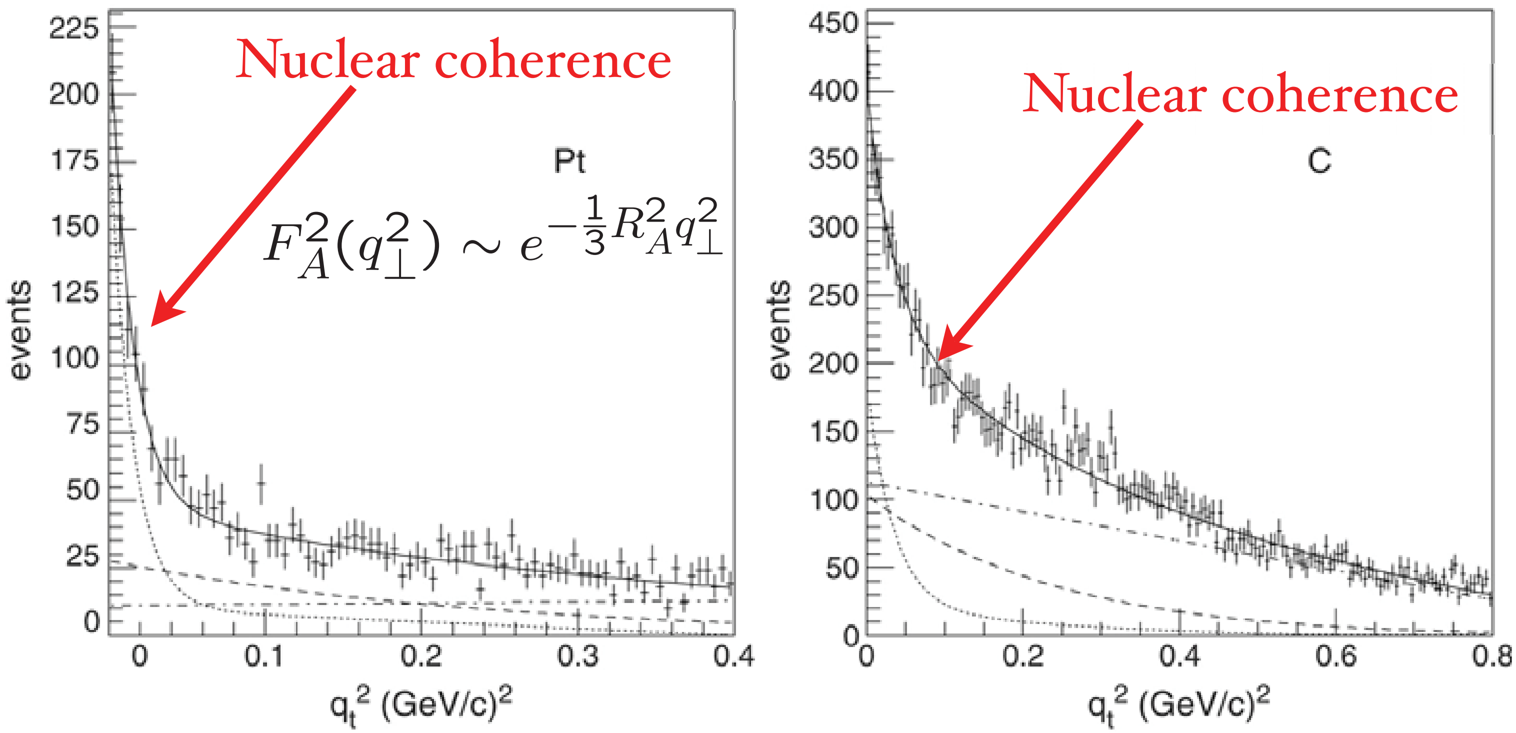
- Fully coherent interactions between pion and nucleons.

- Emerging Di-Jets do not interact with nucleus.

$$\mathcal{M}(\mathcal{A}) = \mathcal{A} \cdot \mathcal{M}(\mathcal{N})$$

$$\underline{\frac{d\sigma}{dq_t^2} \propto A^2 \quad q_t^2 \sim 0}$$

$$\underline{\sigma \propto A^{4/3}}$$



Mueller, sjb; Bertsch et al;
Frankfurt, Miller, Strikman

Measure pion LFWF in diffractive dijet production
Confirmation of color transparency

A-Dependence results: $\sigma \propto A^{\alpha}$

k_t range (GeV/c)	α	α (CT)
$1.25 < k_t < 1.5$	1.64 +0.06 -0.12	1.25
$1.5 < k_t < 2.0$	1.52 ± 0.12	1.45
$2.0 < k_t < 2.5$	1.55 ± 0.16	1.60

Ashery E791

α (Incoh.) $= 0.70 \pm 0.1$

Conventional Glauber Theory Ruled Out !

Factor of 7

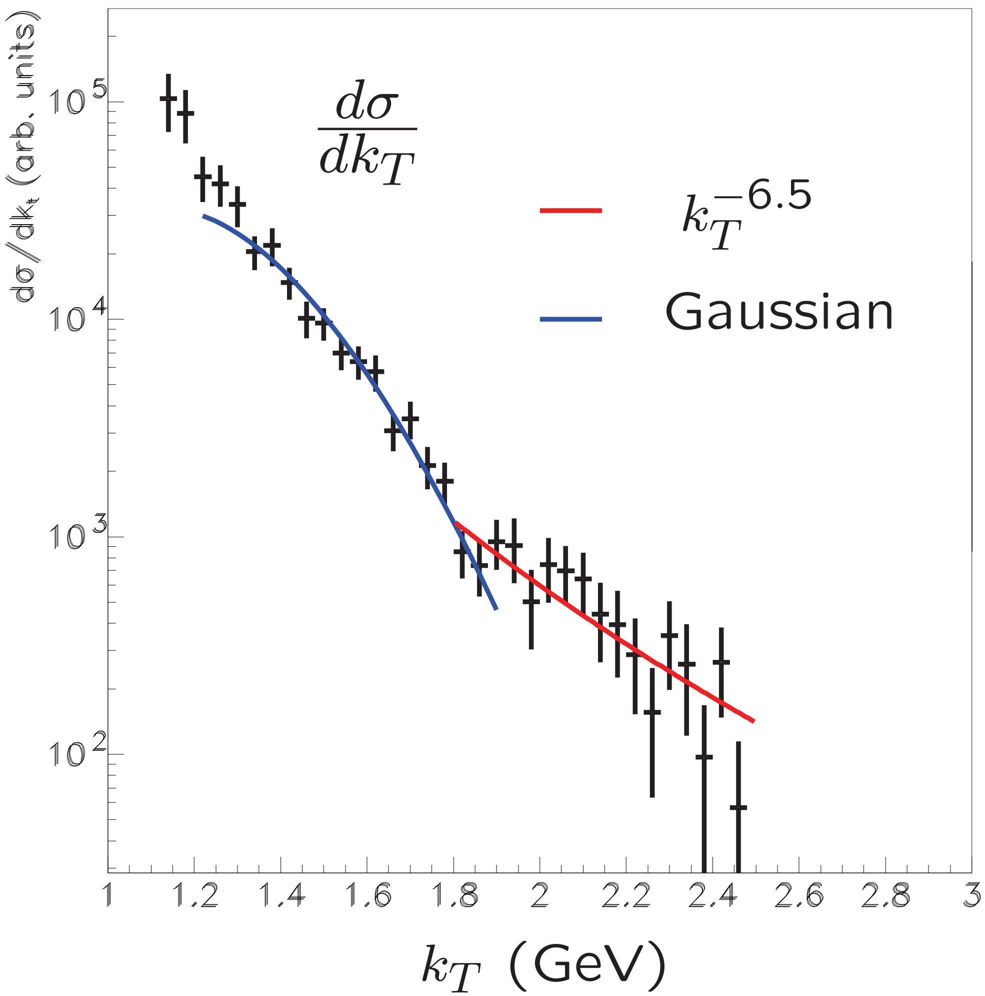
Color Transparency

Bertsch, Gunion, Goldhaber, sjb

A. H. Mueller, sjb

- Fundamental test of gauge theory in hadron physics
- Small color dipole moments interact weakly in nuclei
- Complete coherence at high energies
- Clear Demonstration of CT from Diffractive Di-Jets

E791 Diffractive Di-Jet transverse momentum distribution



Two Components

High Transverse momentum dependence $k_T^{-6.5}$ *consistent with PQCD, ERBL Evolution*

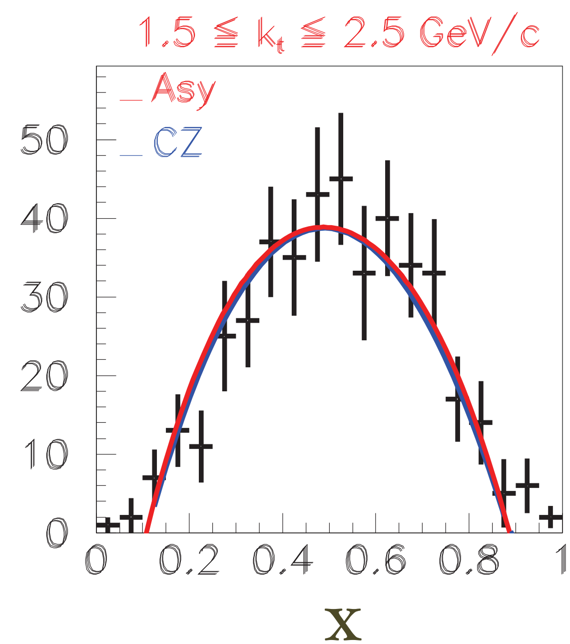
Gaussian component at small k_T *similar to AdS/CFT LFWF*

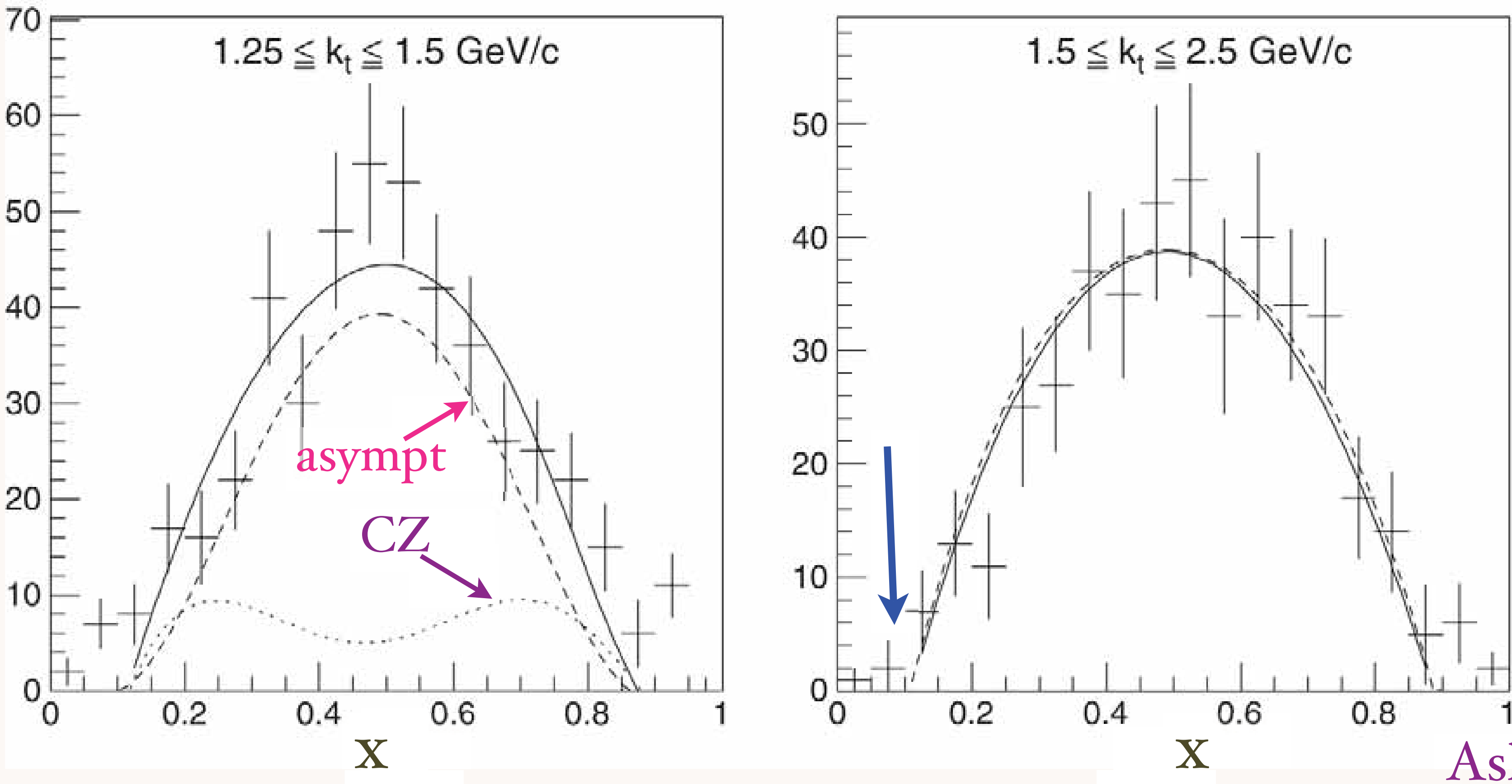
Diffractive Dissociation of a Pion into Dijets

$$\pi A \rightarrow Jet\,Jet\,A'$$

$$\psi^{\pi}_{q\bar{q}}(x, \vec{k}_\perp)$$

- E791 Fermilab Experiment Ashery et al
- 500 GeV pions collide on nuclei keeping it intact
- Measure momentum of two jets
- Study momentum distributions of pion LF wavefunction

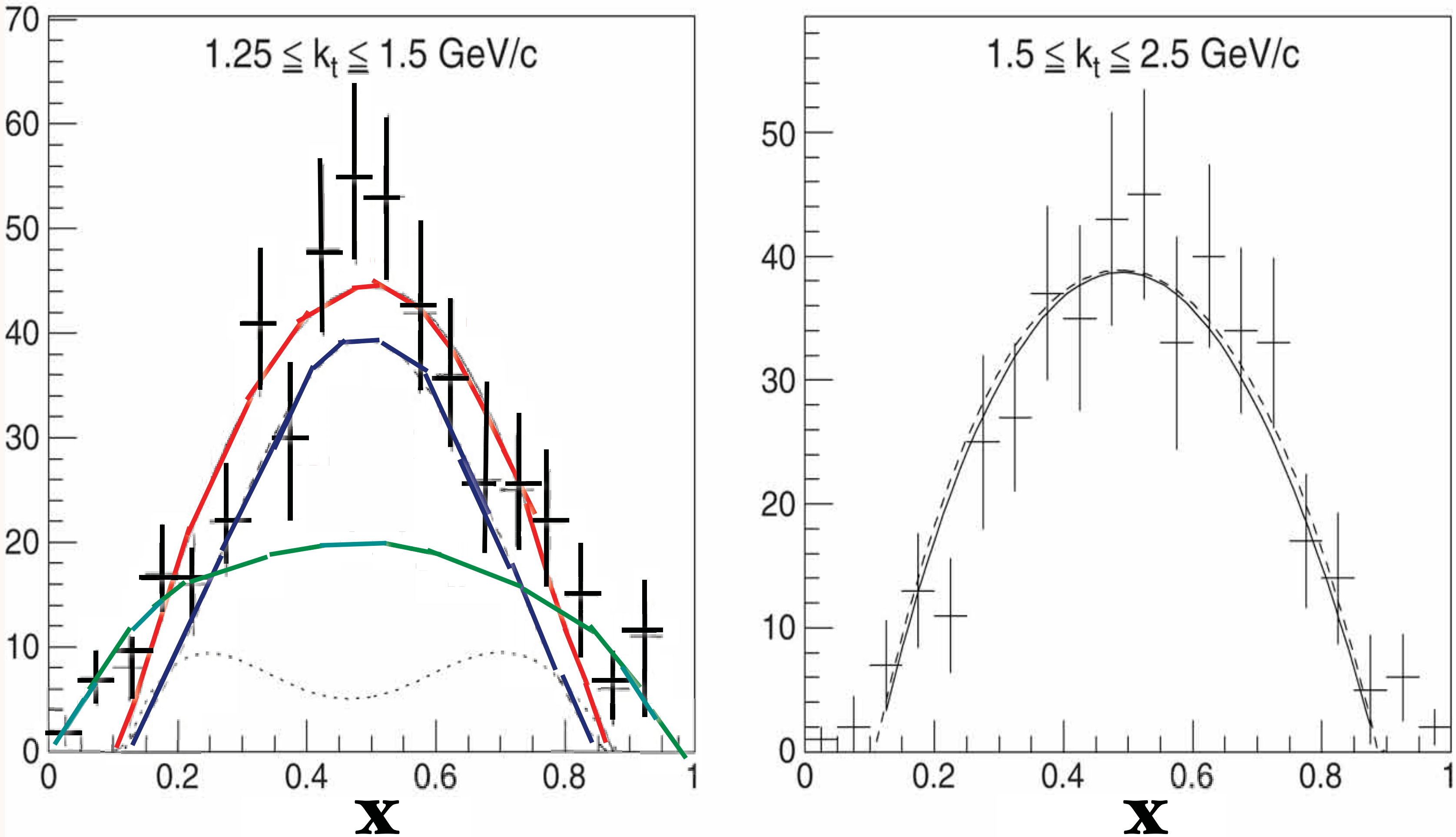




Ashery E791

Narrowing of x distribution at high jet transverse momentum

x distribution of diffractive dijets from the platinum target for $1.25 \leq k_t \leq 1.5$ GeV/c (left) and for $1.5 \leq k_t \leq 2.5$ GeV/c (right). The solid line is a fit to a combination of the asymptotic and CZ distribution amplitudes. The dashed line shows the contribution from the asymptotic function and the dotted line that of the CZ function.



Ashery
E791

Possibly two components:

Perturbative (ERBL) + Nonperturbative (AdS/CFT)

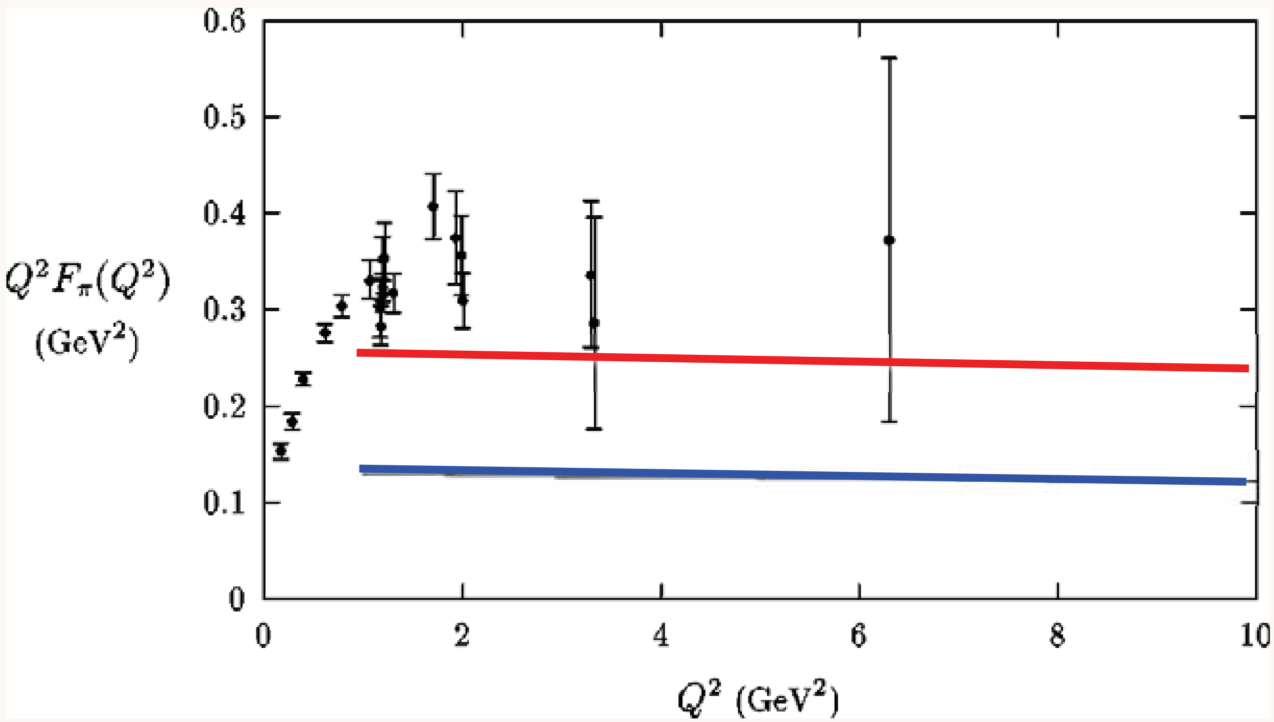
$$\phi(x) = A_{\rm pert}(k_\perp^2)x(1-x) + B_{\rm nonpert}(k_\perp^2)\sqrt{x(1-x)}$$

Narrowing of x distribution at high jet transverse momentum

Lepage, sjb

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

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



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

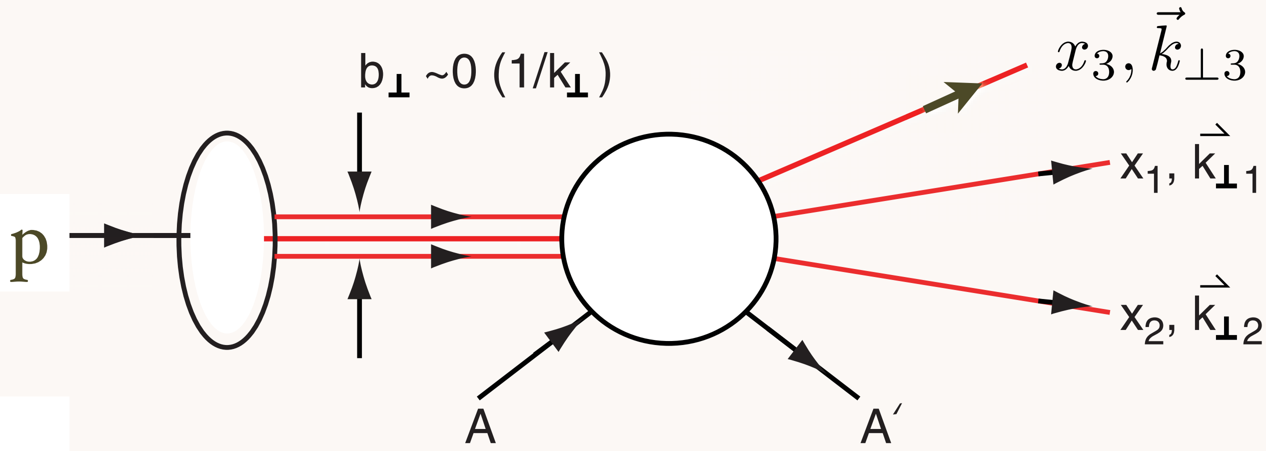
$\phi_{asymptotic} \propto x(1-x)$

Normalized to f_π

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

Diffractive Dissociation of Proton into Quark Jets

Frankfurt, Miller, Strikman



Measure Light-Front Wavefunction of Proton

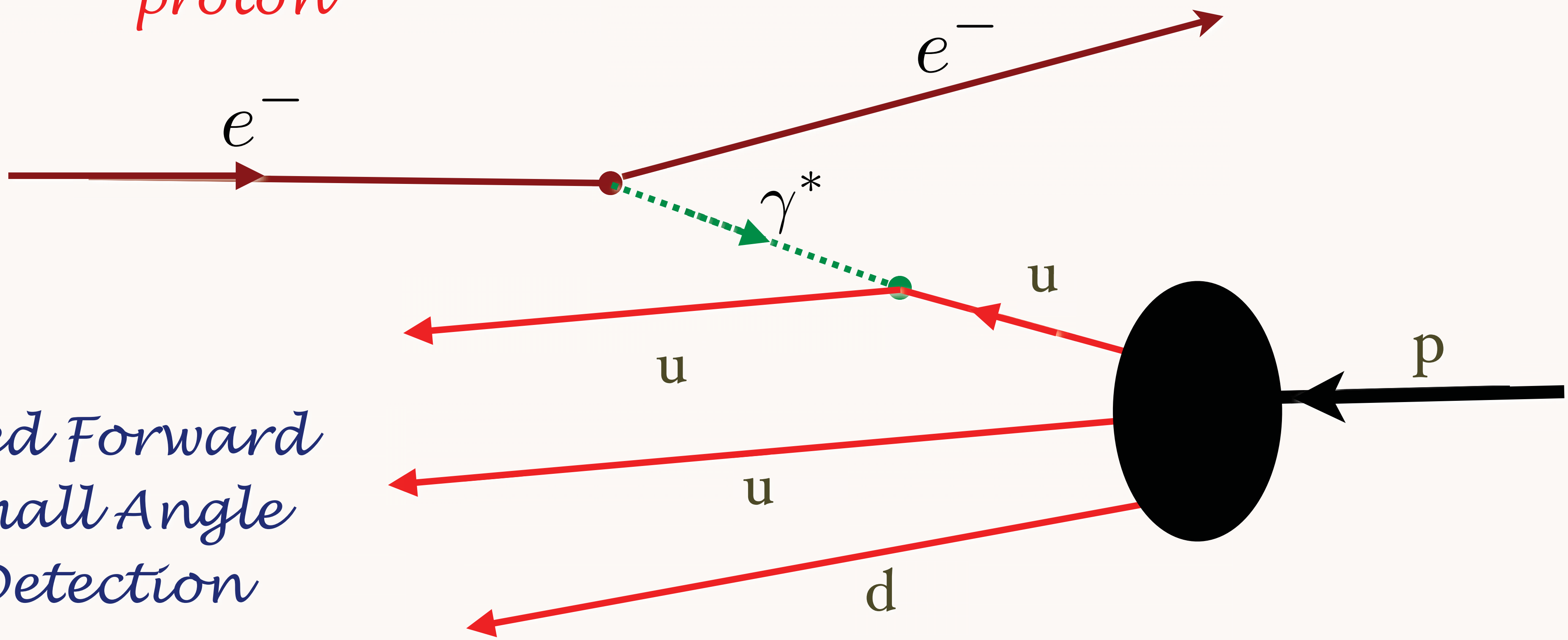
Minimal momentum transfer to nucleus
Nucleus left Intact!

Electromagnetic Tri-Jet Excitation of Proton

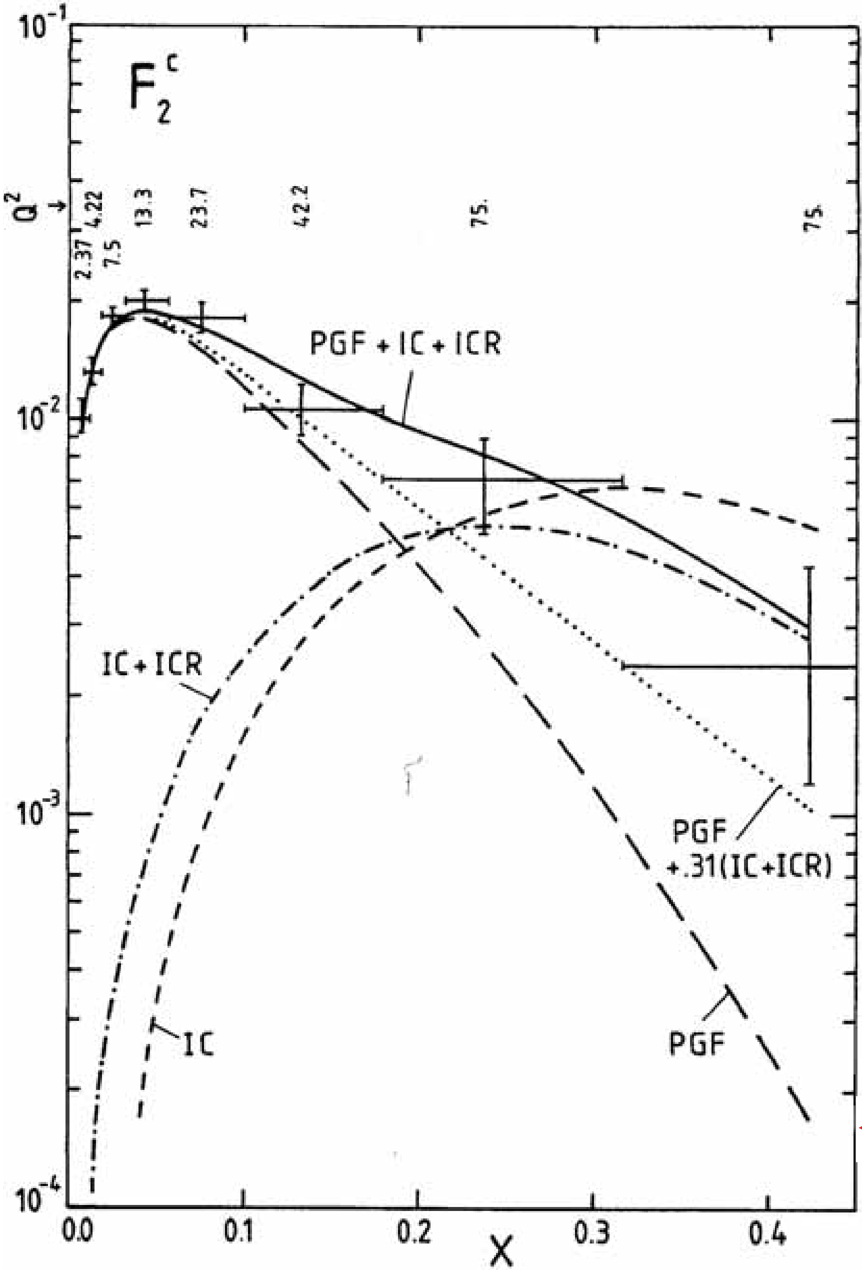
$$ep \to e \text{ jet jet jet}$$

Measure light-front wavefunction of proton

$$\frac{\partial}{\partial k_\perp} \Psi^p_{n=3}(x_i, \vec{k}_{\perp i}, \lambda_i)$$



Need Forward Small Angle Detection

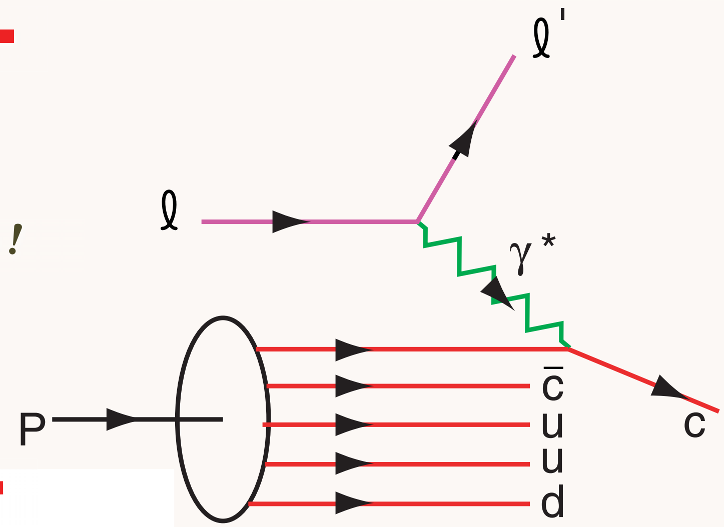


Measurement of Charm Structure Function

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

factor of 30 !



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

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

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

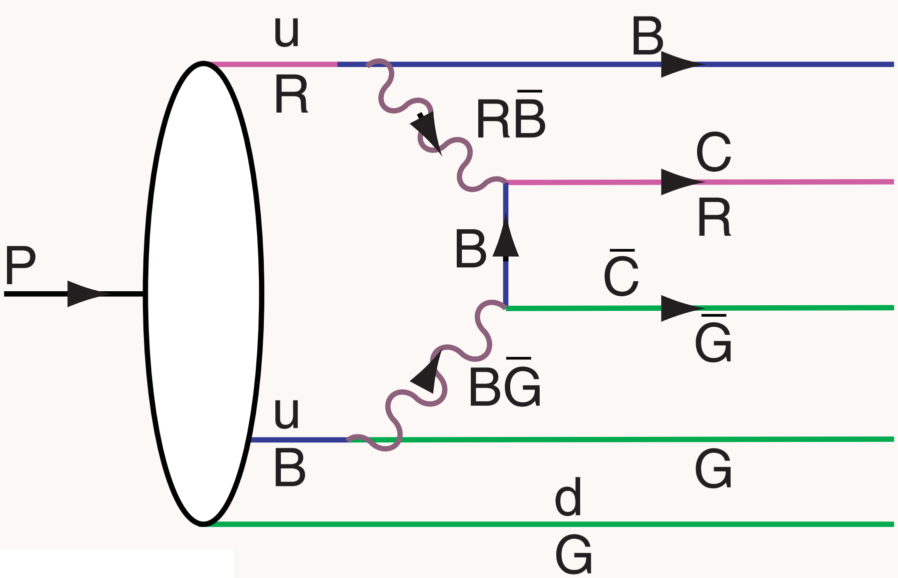
- High x_F $pp \to J/\psi J/\psi X$

- 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 Test of QCD



$|uudc\bar{c}>$ 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

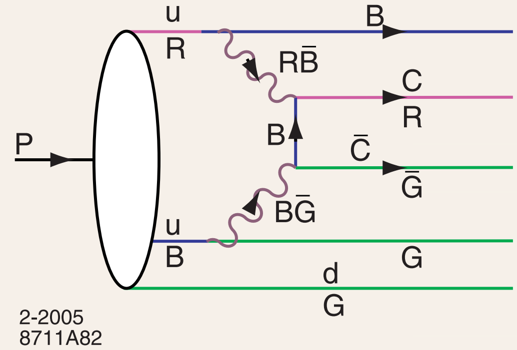
$$\hat{x}_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

High x charm!

Hoyer, Peterson, Sakai, sjb

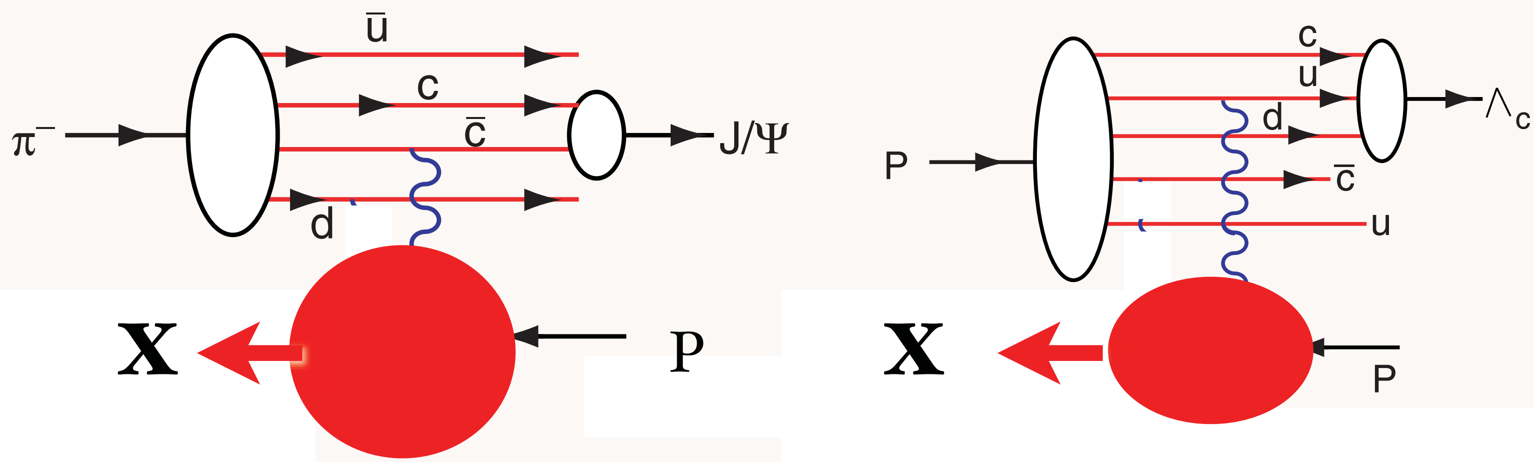
Hoyer, Peterson, Sakai, sjb

Intrinsic Heavy-Quark Fock States



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

Leading Hadron Production from Intrinsic Charm

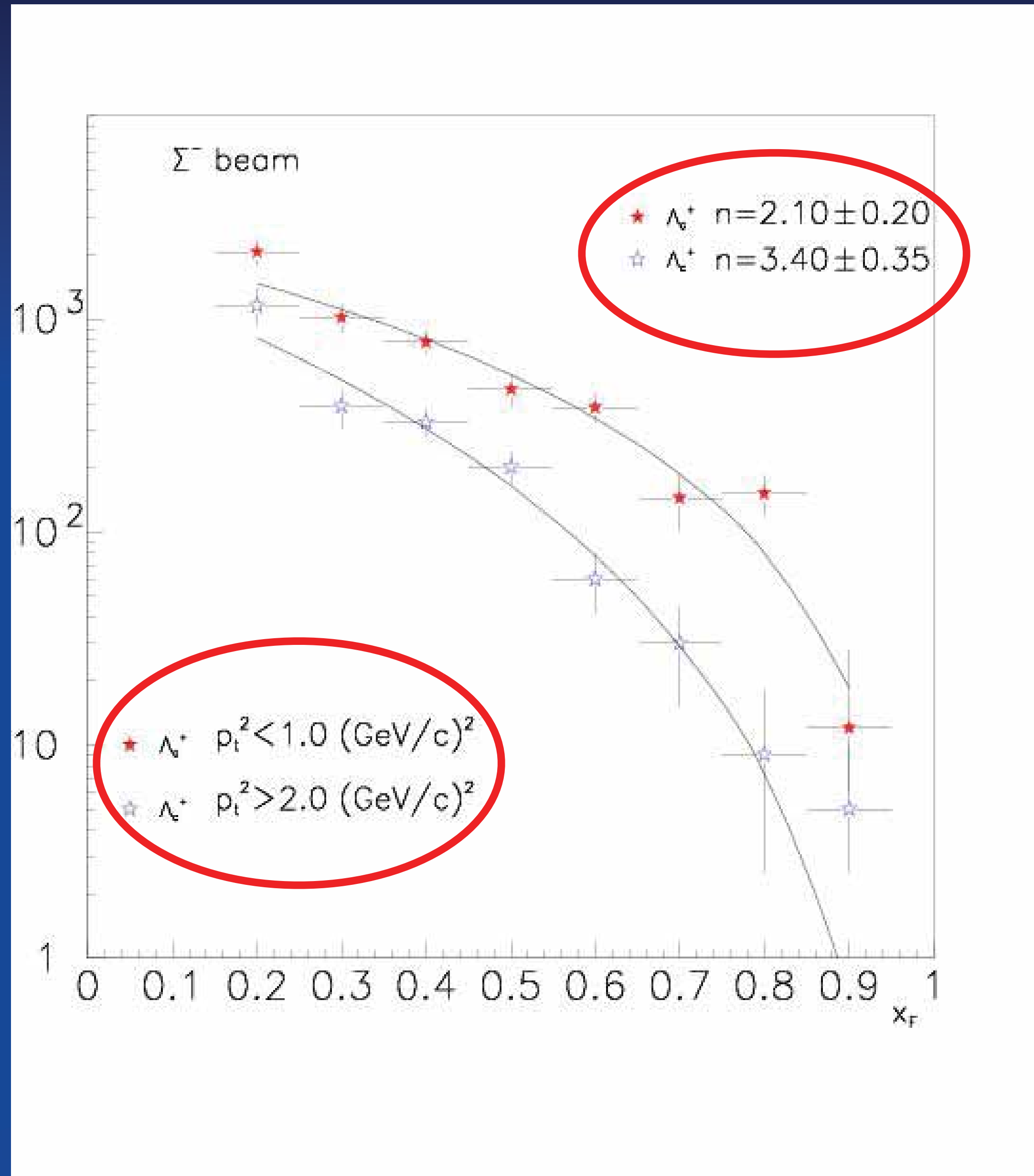


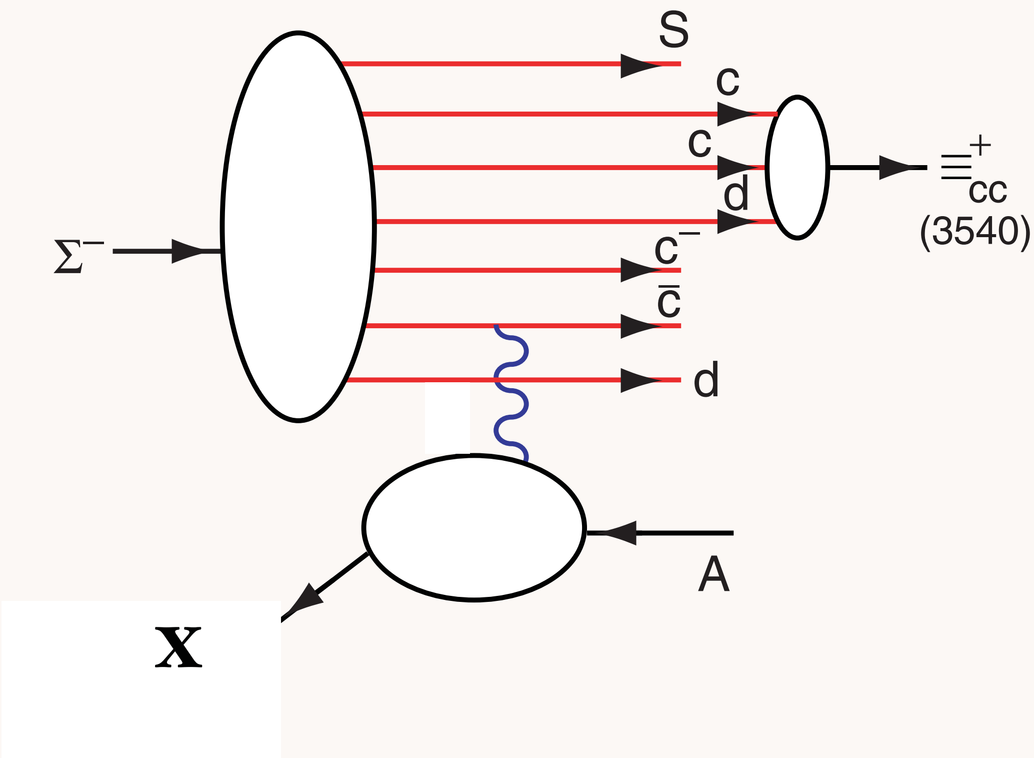
Coalescence of Comoving Charm and Valence Quarks Produce J/ψ, Λ_c and other Charm Hadrons at High x_F

SELEX Λ_c^+ Studies – p_T Dependence

- Λ_c^+ production by Σ^- vs x_F shows harder spectrum at low p_T - consistent with an intrinsic charm picture.

(Vogt, Brodsky and Hoyer, Nucl. Phys. B383,683 (1992))

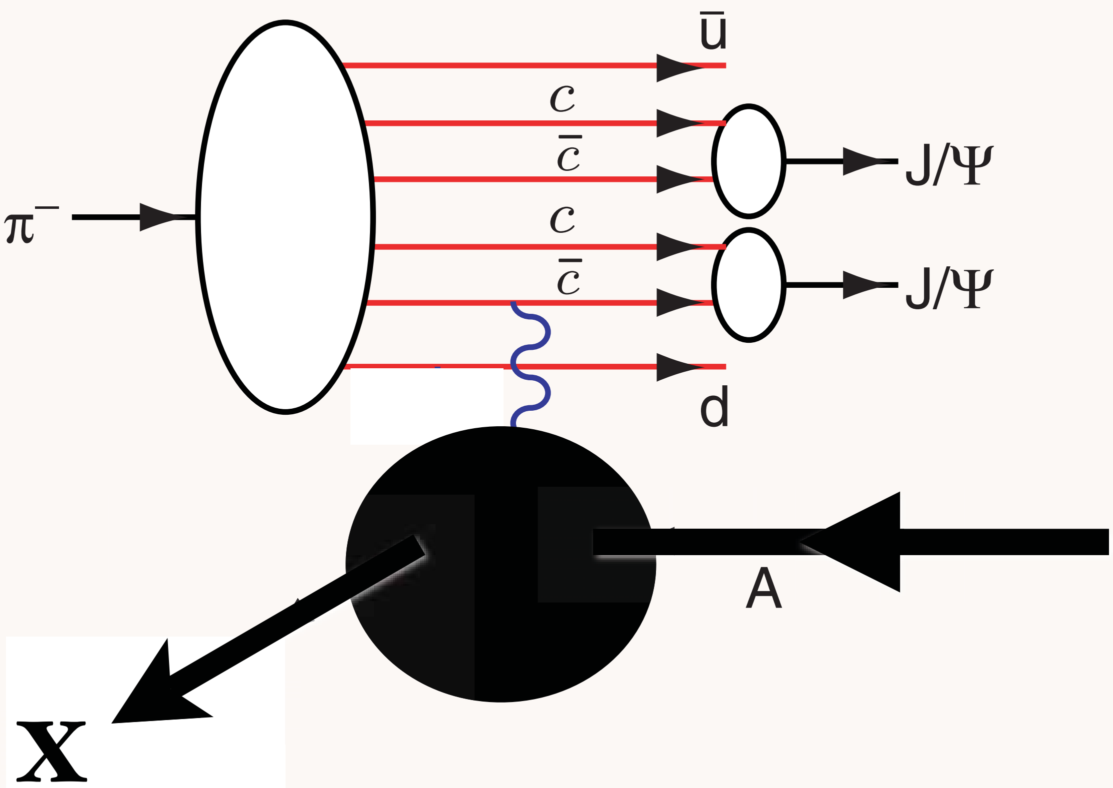




Production of a Double-Charm Baryon

SELEX high x_F $\quad < x_F >= 0.33$

Production of Two Charmonia at High x_F



All events have $x^F_{\psi\psi} > 0.4$!

Excludes `color drag' model

$\pi A \to J/\psi J/\psi X$

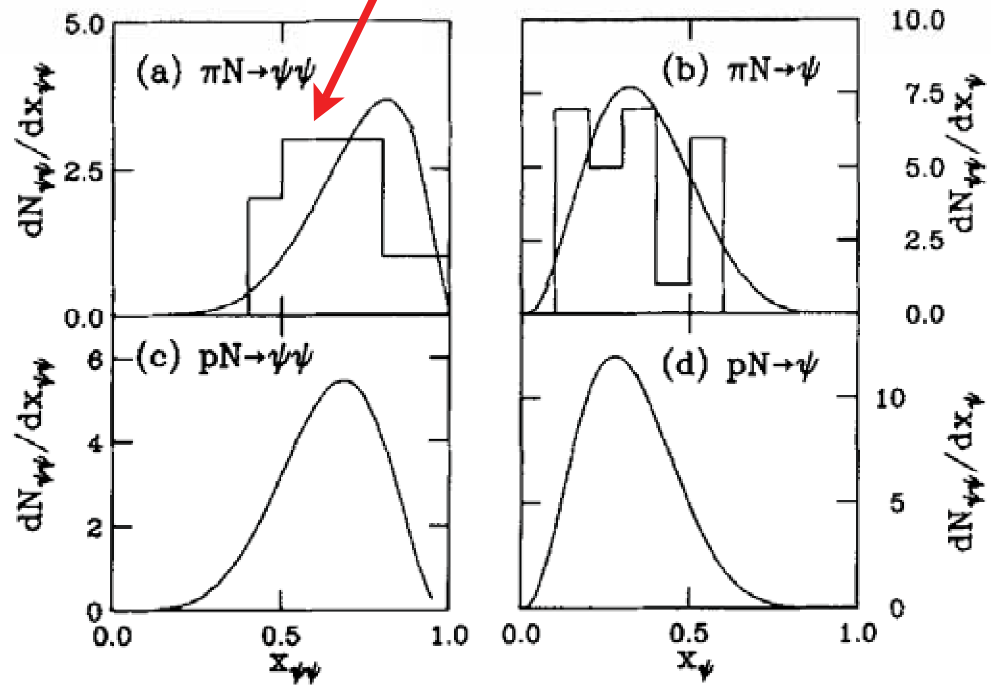


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized to the number of pairs from both pion beams (a) and the number of pairs from the 400 GeV proton measurement (c). The number of single J/ψ's is twice the number of pairs.

NA3 Data

Intrinsic charm contribution to double quarkonium hadroproduction ★

R. Vogt [a], S.J. Brodsky [b]

The probability distribution for a general n-parti intrinsic $c\bar{c}$ Fock state as a function of x and $\boldsymbol{k}_T$ written as

$$\frac{dP_{\rm ic}}{\prod_{i=1}^n dx_i d^2k_{T,i}} = N_n \alpha_s^4(M_{c\bar{c}}) \frac{\delta(\sum_{i=1}^n \boldsymbol{k}_{T,i})\delta(1-\sum_{i=1}^n x_i)}{(m_h^2 - \sum_{i=1}^n (m_{T,i}^2/x_i))^2},$$

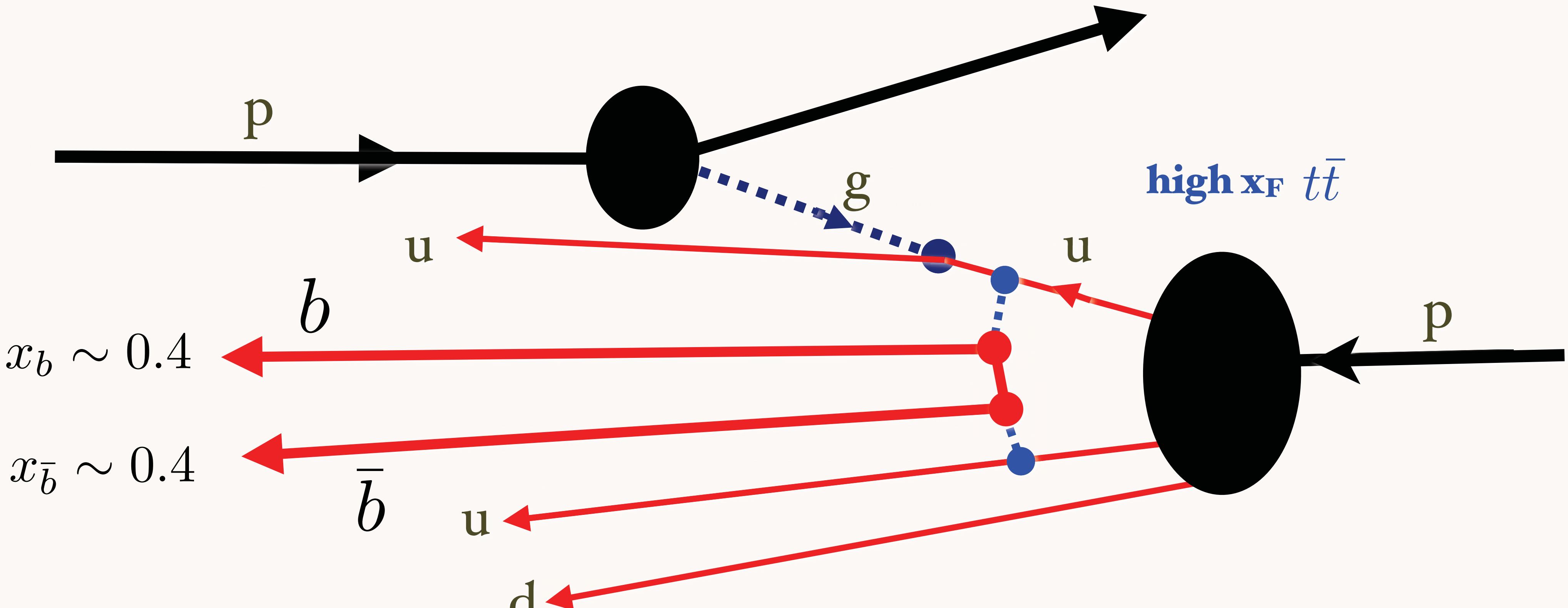
Excitation of Intrinsic Heavy Quarks in Proton

Amplitude maximal at small invariant mass, equal rapidity

$$x_i \sim \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

Produce forward, high x_F

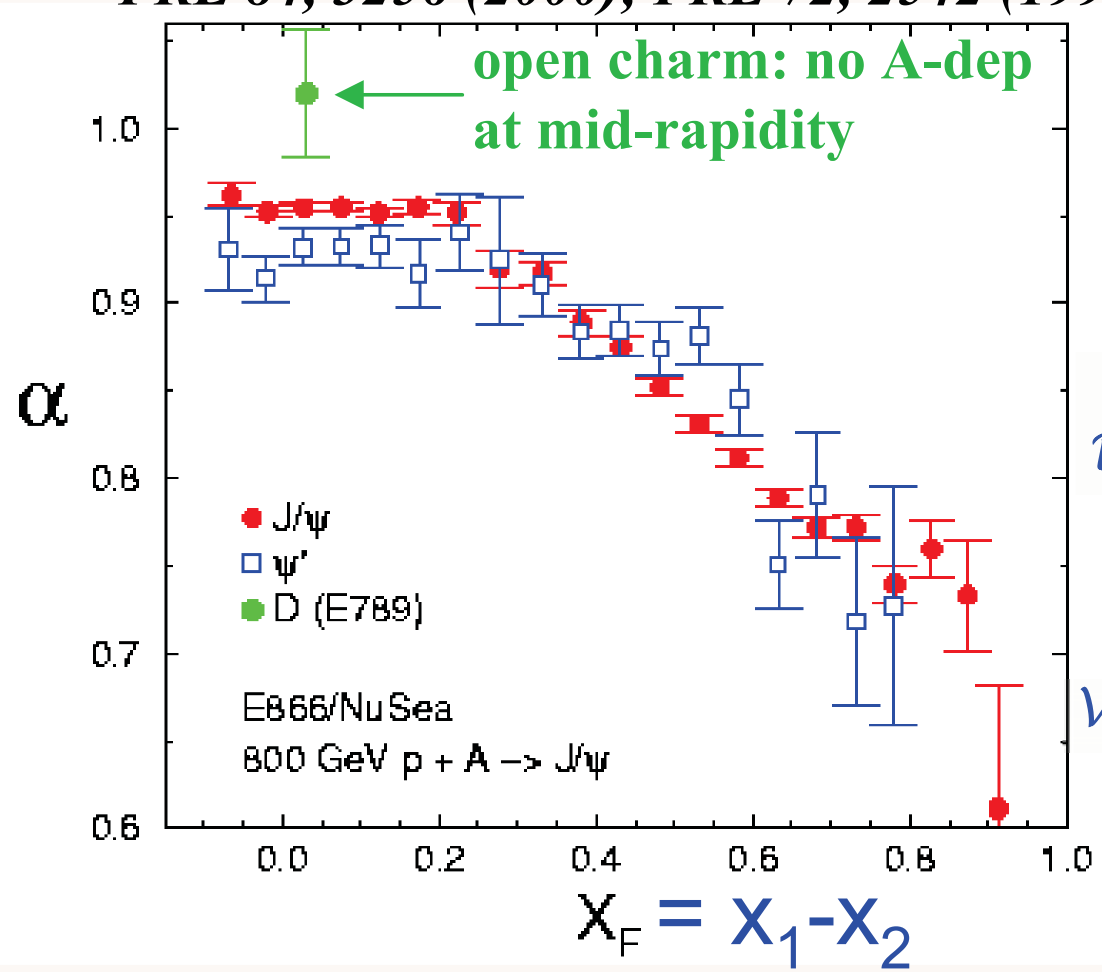
$\Upsilon(b\bar{b}), \Lambda_b(bud), B^+(\bar{b}u), B^0(\bar{b}d)$



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.

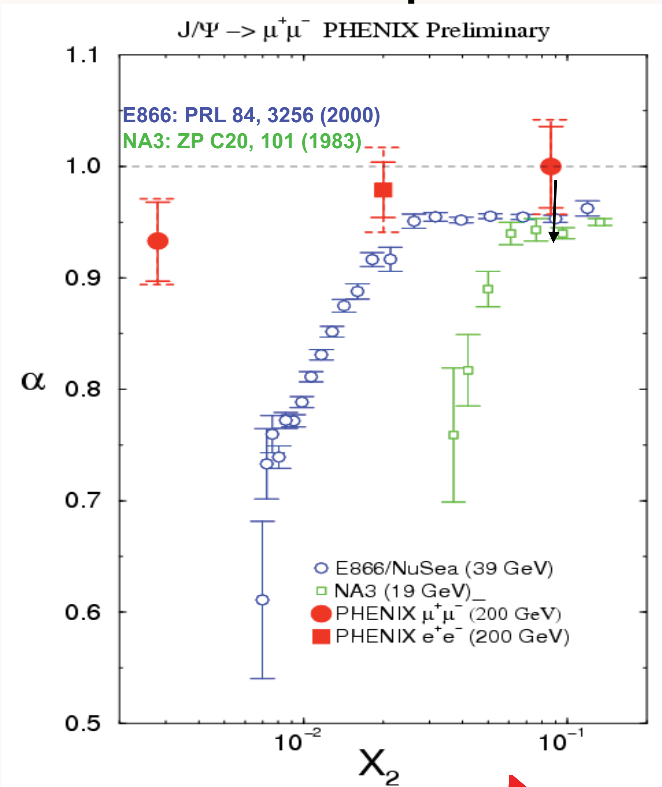
P. Hoyer, M. Vanttinen (Helsinki U.) , U. Sukhatme (Illinois U., Chicago) . HU-TFT-90-14, May 1990. 7pp.

Published in Phys.Lett.B246:217-220,1990

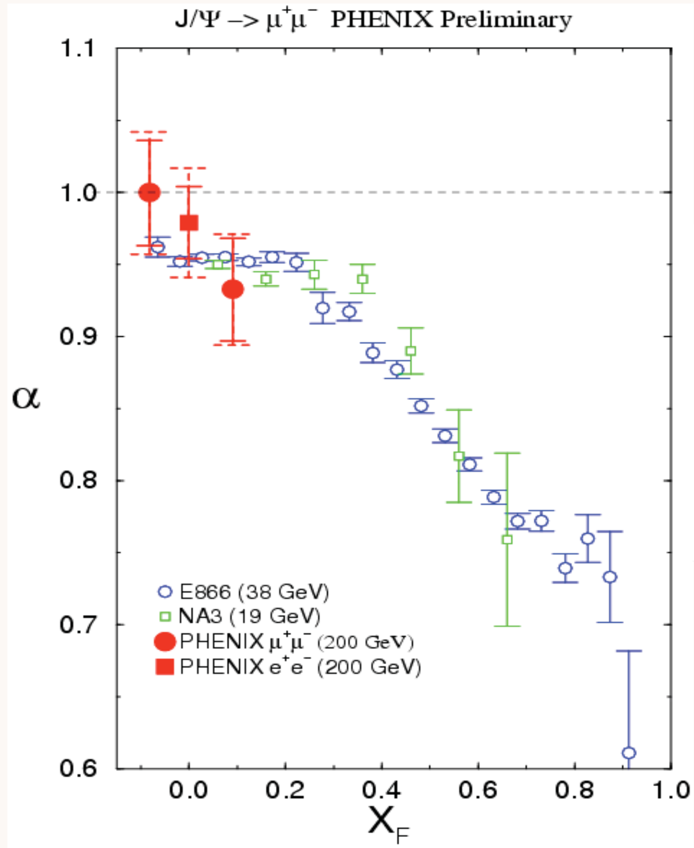
J/ψ nuclear dependence vrs rapidity, x_{Au}, x_F

M.Leitch

PHENIX compared to lower energy measurements



Klein,Vogt, PRL 91:142301,2003
Kopeliovich, NP A696:669,2001

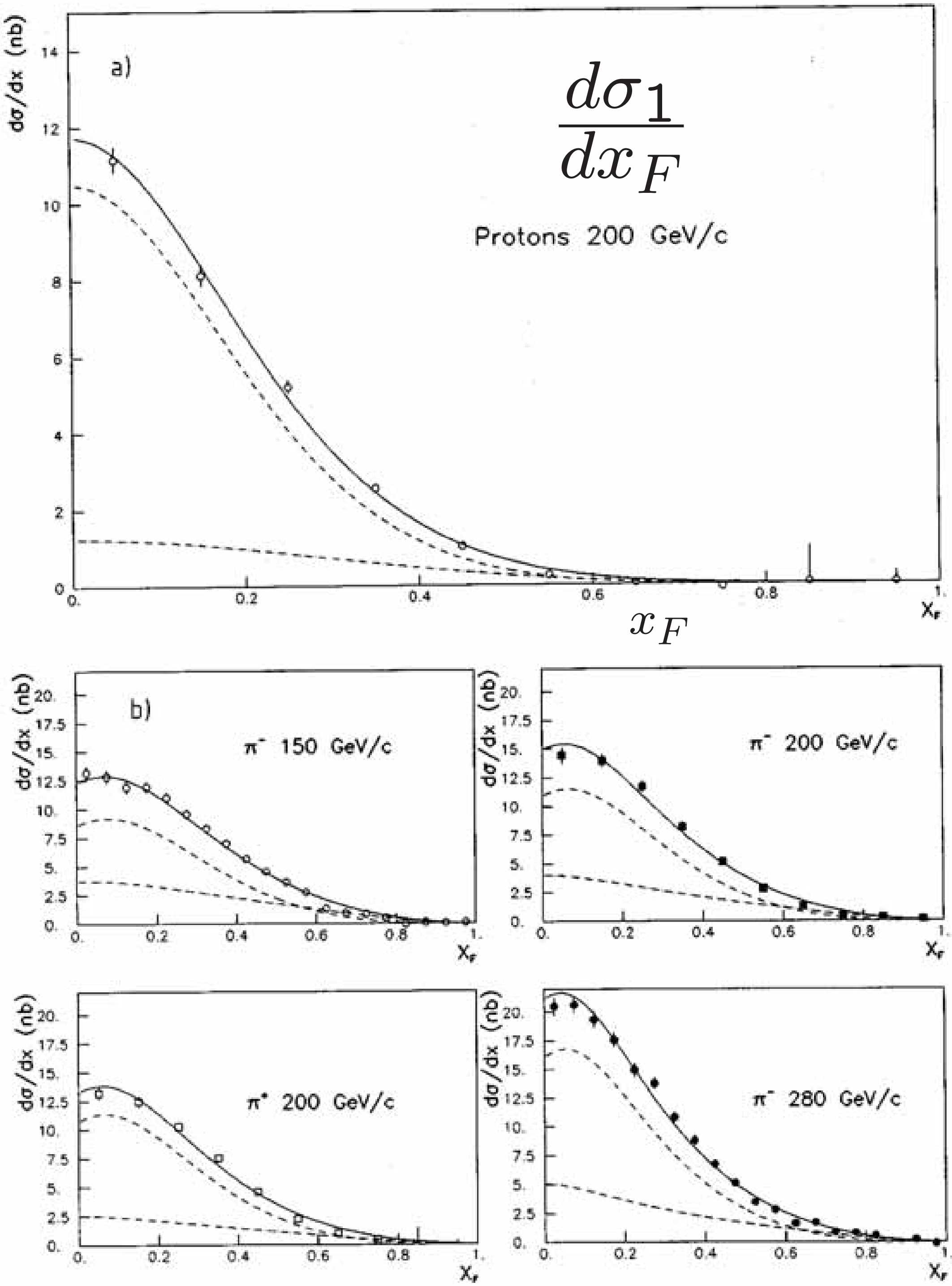


Huge "absorption" effect at large xF

Violates PQCD factorization!

$$\frac{d\sigma}{dx_F}(pA \to J/\psi X)$$

Hoyer, Sukhatme, Vanttinen



J. Badier et al, NA3

Two Components

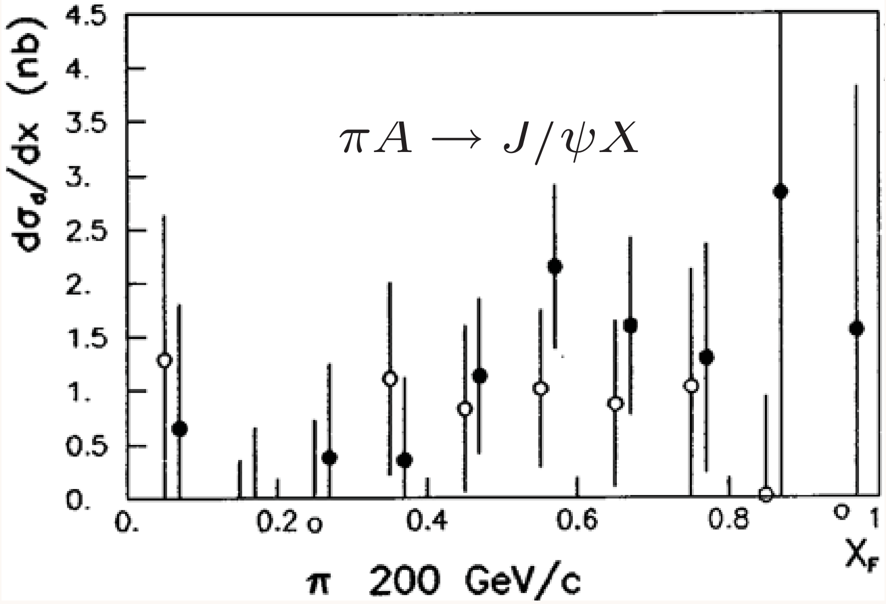
$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^1 \frac{d\sigma_1}{dx_F} + A^{2/3}\frac{d\sigma_{2/3}}{dx_F}$$

A^1 component

Identify with Fusion

Conventional PQCD subprocesses

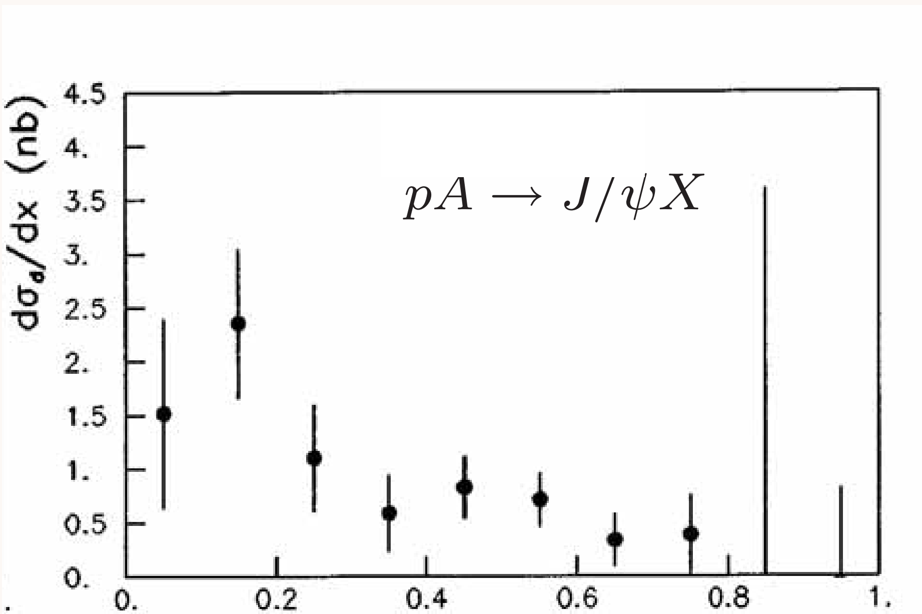
$$\frac{d\sigma_1}{dx_F}(\pi A \to J/\psi X)$$



J. Badier et al, NA3

$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^1 \frac{d\sigma_1}{dx_F} + A^{2/3}\frac{d\sigma_{2/3}}{dx_F}$$

$A^{2/3}$ component



p 200 GeV/c

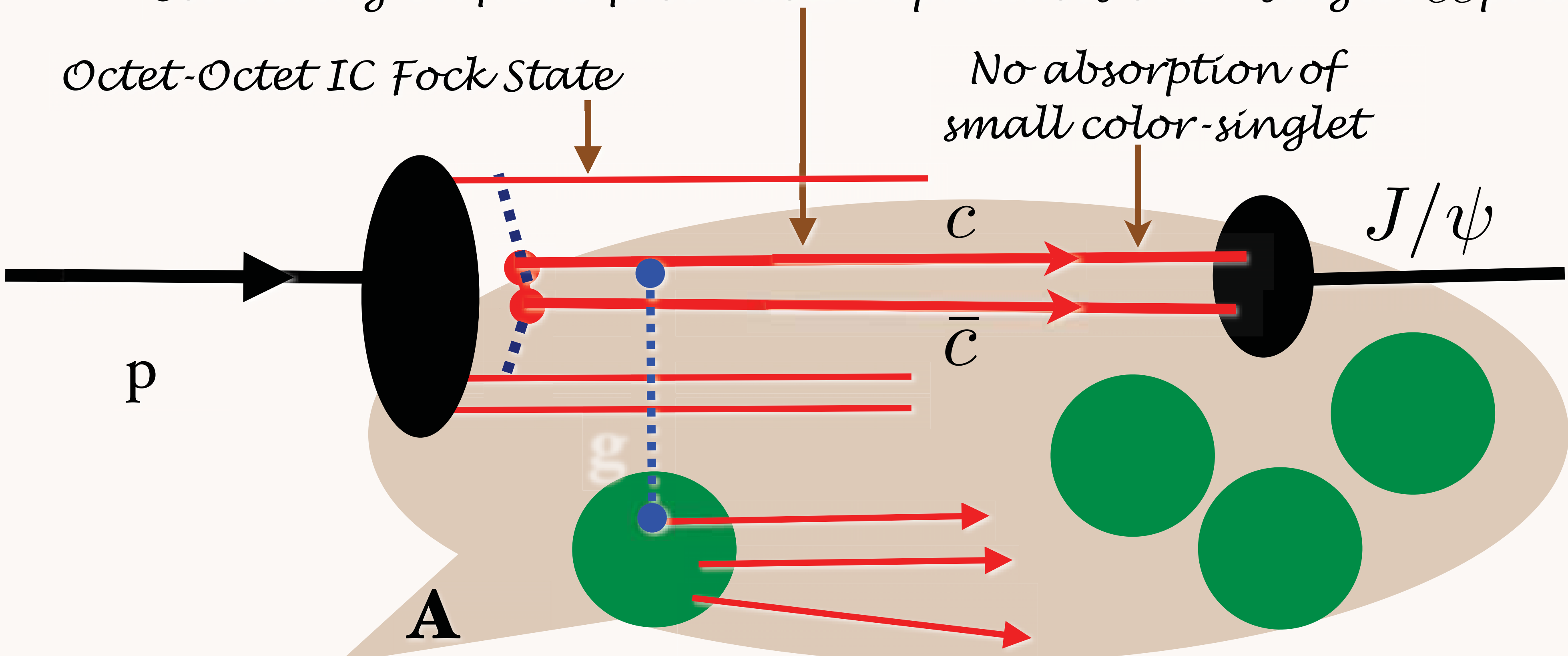
Identify with IC
High x_F

Remarkably Flat Distribution

Excess beyond conventional PQCD subprocesses

Kopeliovich, Schmidt, Soffer, sjb

Color-Opaque IC Fock state interacts on nuclear front surface

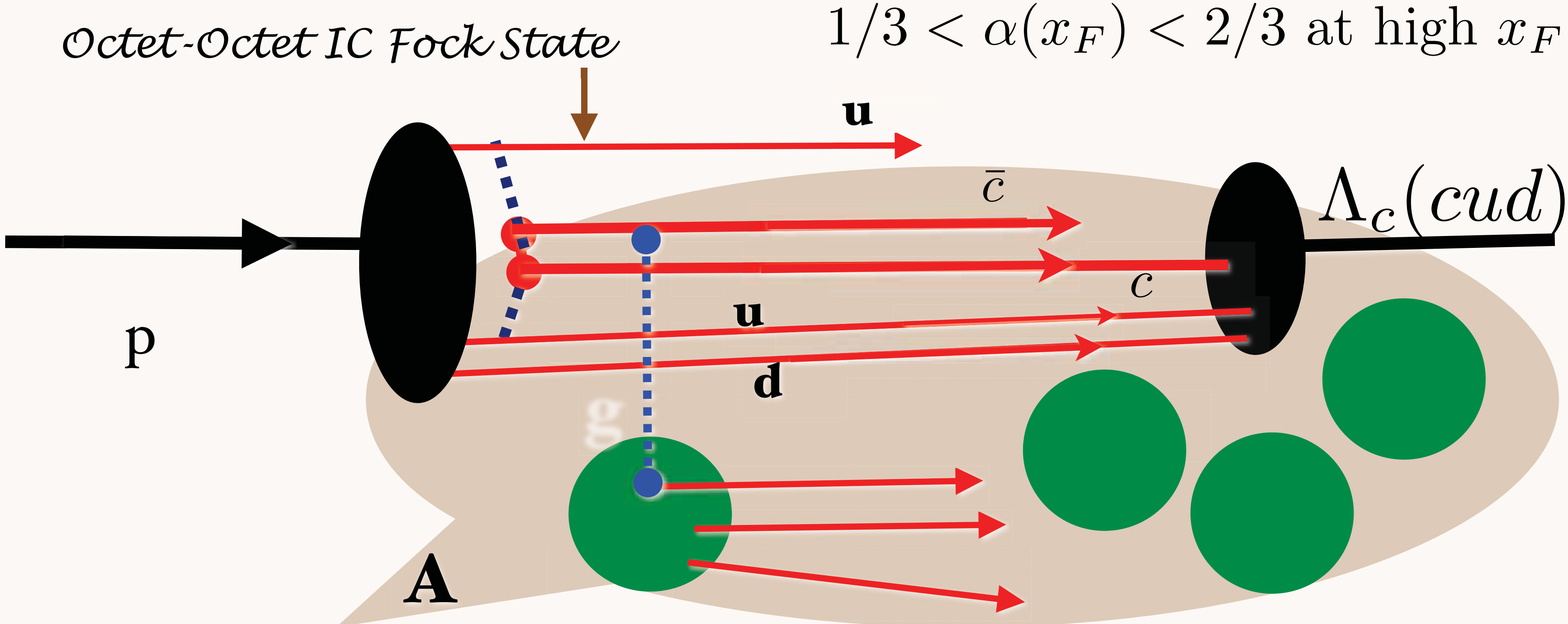


$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$

Color-Opaque IC Fock state interacts on nuclear front surface

$$\frac{d\sigma}{dx_F}(pA \to \Lambda_c X) = A^{\alpha(x_F)} \frac{d\sigma}{dx_F}(pN \to \Lambda_c X)$$

$1/3 < \alpha(x_F) < 2/3$ at high x_F



Reconciles ISR and Fixed Target Measurements!

- IC Explains Anomalous $\alpha(x_F)$ not $\alpha(x_2)$ dependence of $pA \to J/\psi X$ (Mueller, Gunion, Tang, SJB)

- Color Octet IC Explains $A^{2/3}$ behavior at high x_F (NA3, Fermilab) (Kopeliovitch, Schmidt, Soffer, SJB)

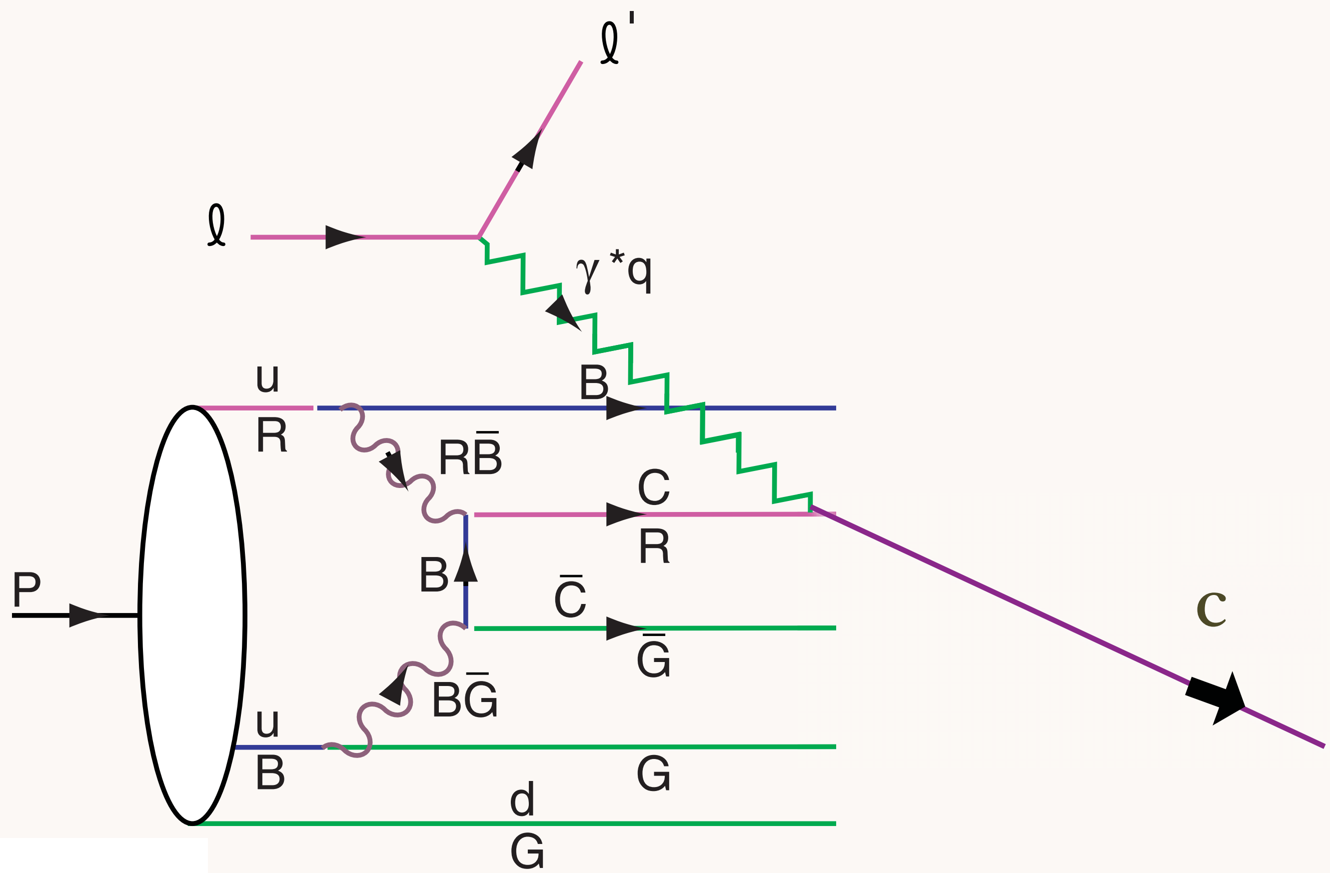
Color Opaqueness

- IC Explains $J/\psi \to \rho\pi$ puzzle (Karliner, SJB)

- IC leads to new effects in B decay (Gardner, SJB)

Higgs production at x_F = 0.8

Measure c(x) in Deep Inelastic Lepton-Proton Scattering



Hoyer, Peterson, SJB

Why is Intrinsic Charm Important for Flavor Physics?

- New perspective on fundamental nonperturbative hadron structure
- Charm structure function at high x
- Dominates high x_F charm and charmonium production
- Hadroproduction of new heavy quark states such as ccu, ccd at high x_F
- Intrinsic charm -- long distance contribution to penguin mechanisms for weak decay
- Novel Nuclear Effects from color structure of IC, Heavy Ion Collisions
- New mechanisms for high x_F Higgs hadroproduction
- Dynamics of b production: LHCb
- Fixed target program at LHC: produce bbb states

PHYSICAL REVIEW D **73**, 113005 (2006)

Diffractive Higgs production from intrinsic heavy flavors in the proton

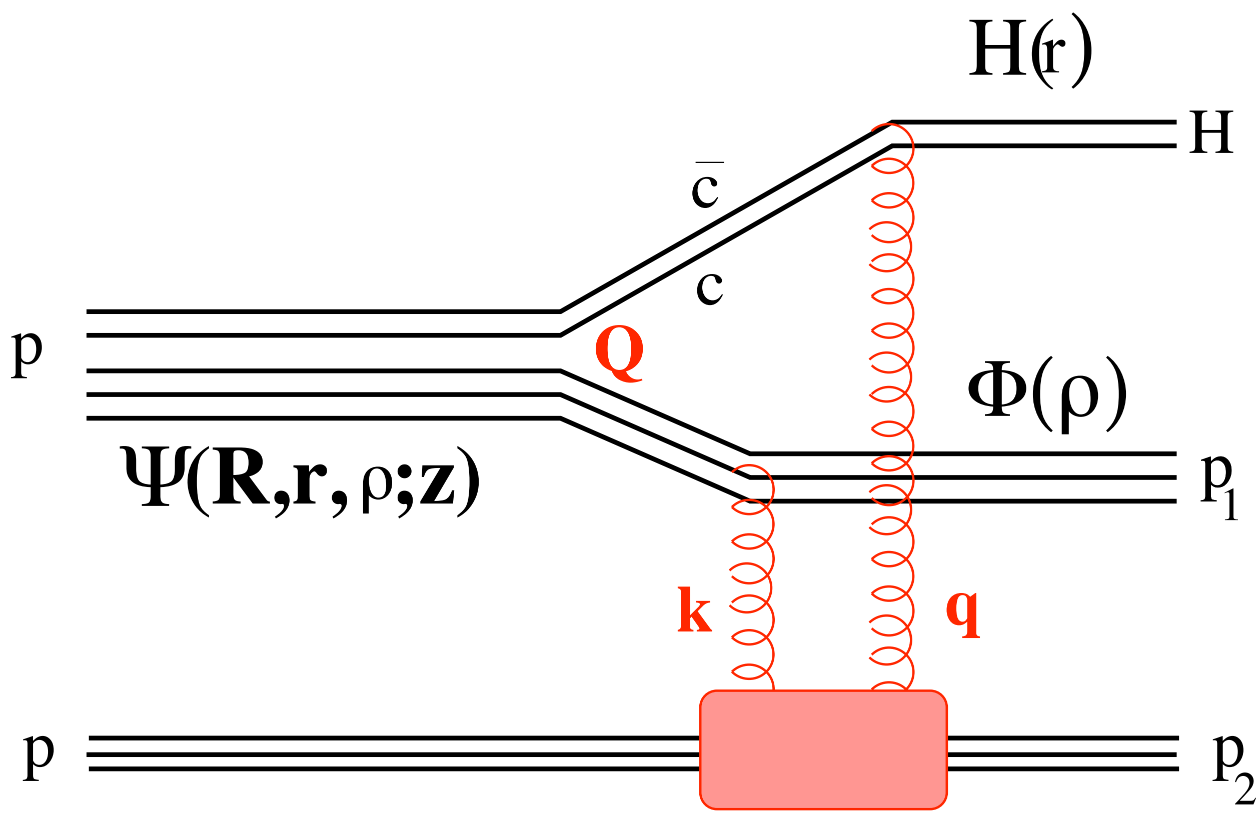
Stanley J. Brodsky,[1,*] Boris Kopeliovich,[2,†] Ivan Schmidt,[2,‡] and Jacques Soffer[3,§]

Higgs Hadroproduction at Large Feynman x

Stanley J. Brodsky[*a], Alfred Scharff Goldhaber[†a,b], Boris Z. Kopeliovich[‡c,d], Ivan Schmidt[§c]

To be published in Nuclear Physics B

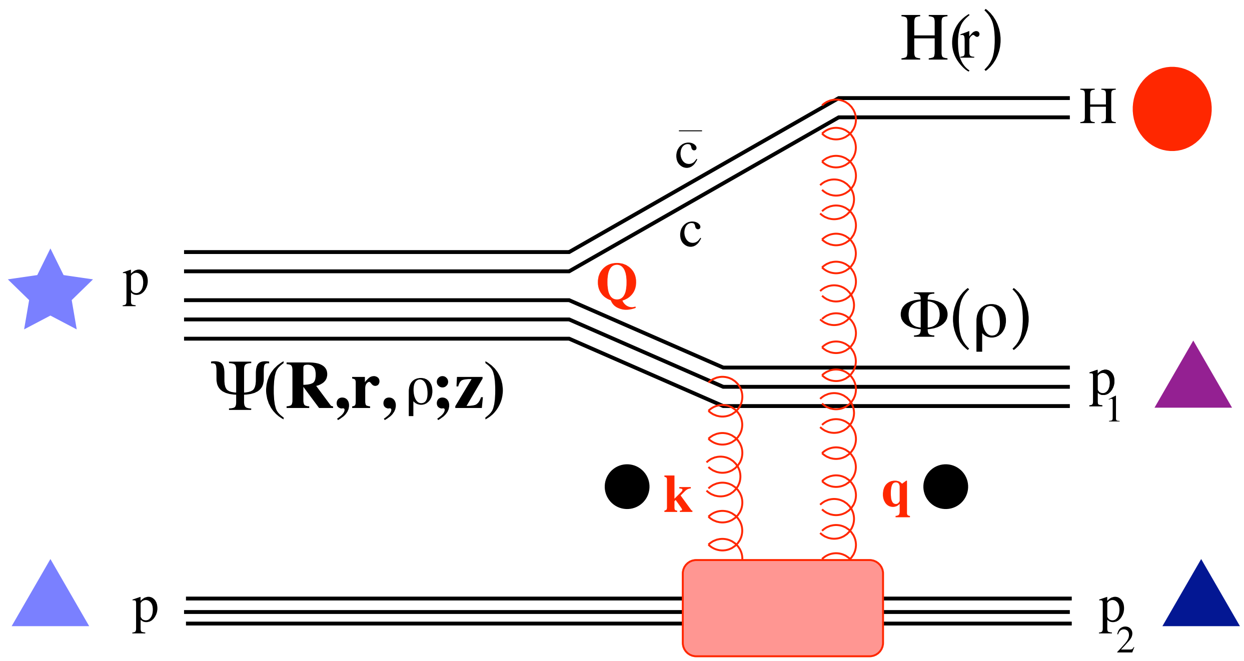
$$\frac{d\sigma(pp \to ppH)}{dx_2 d^2 p_1 d^2 p_2} = \frac{1}{(1-x_2)16\pi^2} |A(x_2, \vec{p}_1, \vec{p}_2)|^2$$



$$A(x_2, \vec{p}_1, \vec{p}_2) = \frac{8}{3\sqrt{2}} \int d^2Q \frac{d^2q}{q^2} \frac{d^2k}{k^2} \alpha_s(q^2)\alpha_s(k^2)\delta(\vec{q} + \vec{p}_2 + \vec{k})\delta(\vec{k} - \vec{p}_1 - \vec{Q})$$

$$\times \int d^2\boldsymbol{\tau} |\Phi_p(\boldsymbol{\tau})|^2 [e^{i(\vec{k}+\vec{q})\cdot\vec{\tau}/2} - e^{i(\vec{q}-\vec{k})\cdot\vec{\tau}/2}]$$

$$\times \int d^2R d^2r d^2\rho H^\dagger(\vec{r}) e^{i\vec{q}\cdot\vec{r}/2}(1 - e^{-i\vec{q}\cdot\vec{r}})\Phi_p^\dagger(\vec{\rho}) e^{i\vec{k}\cdot\vec{\rho}/2}(1 - e^{-i\vec{k}\cdot\vec{\rho}})\Psi_p(\vec{R}, \vec{r}, \vec{\rho}, z) e^{i\vec{Q}\cdot\vec{R}}.$$

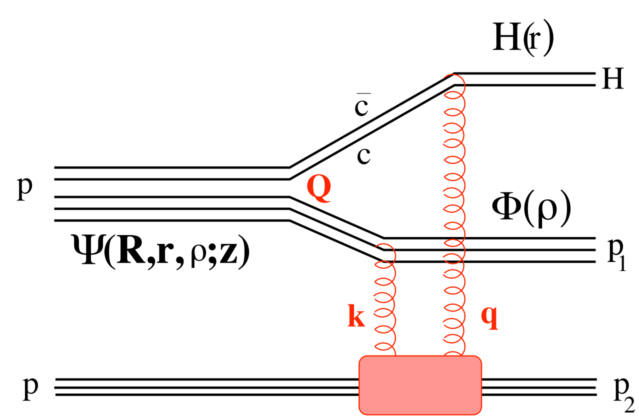


$$\Psi_p(\vec{R}, \vec{r}, \vec{\rho}, z) = \Psi_{\mathrm{IC}}(\vec{R}, z)\Psi_{\bar{c}c}(\vec{r})\Psi_{3q}(\vec{\rho}).$$

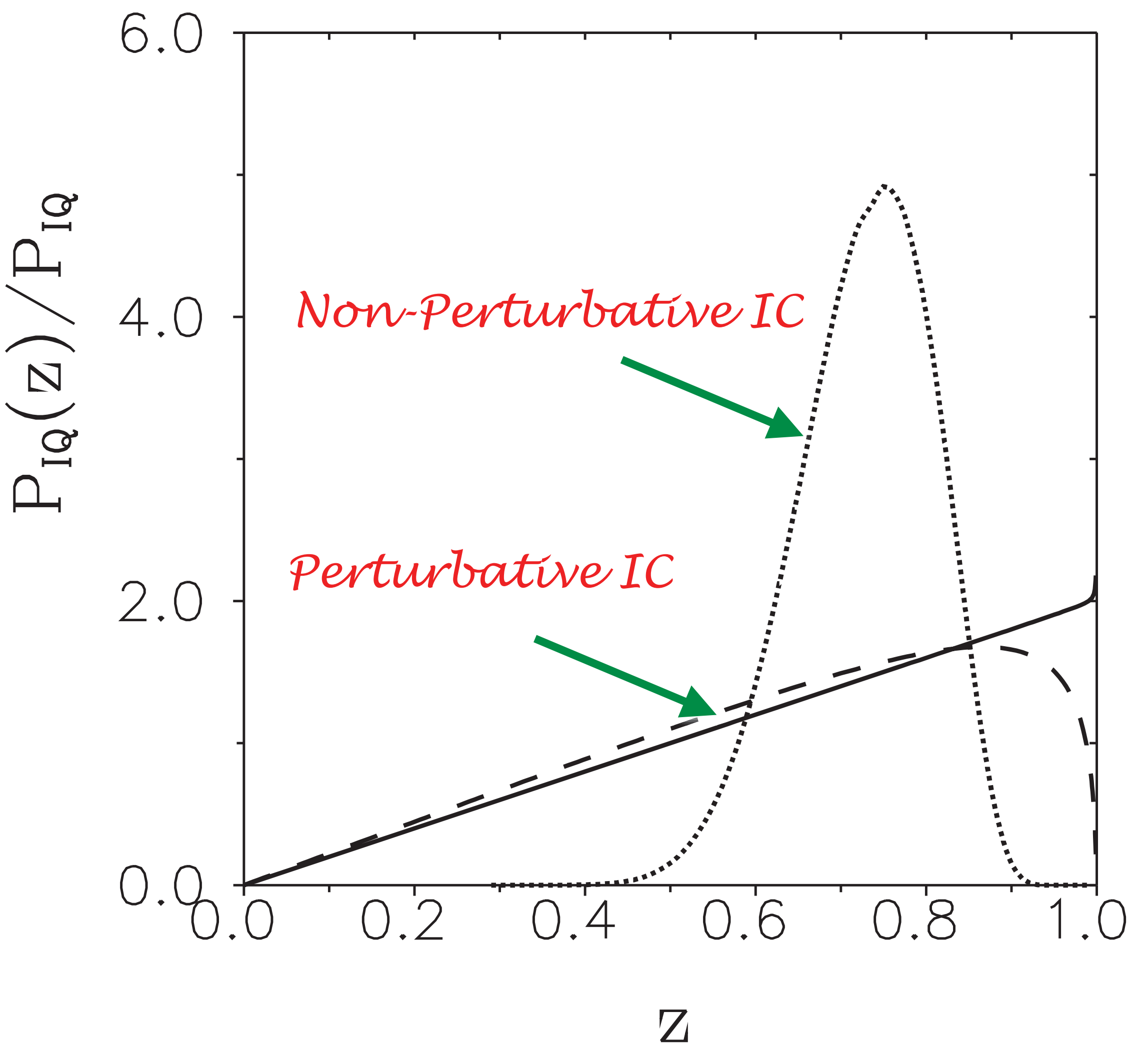
$$\int_0^1 dz \int d^2R d^2r d^2\rho |\Psi_p(\vec{R}, \vec{r}, \vec{\rho}, z)|^2 = P_{\mathrm{IC}},$$

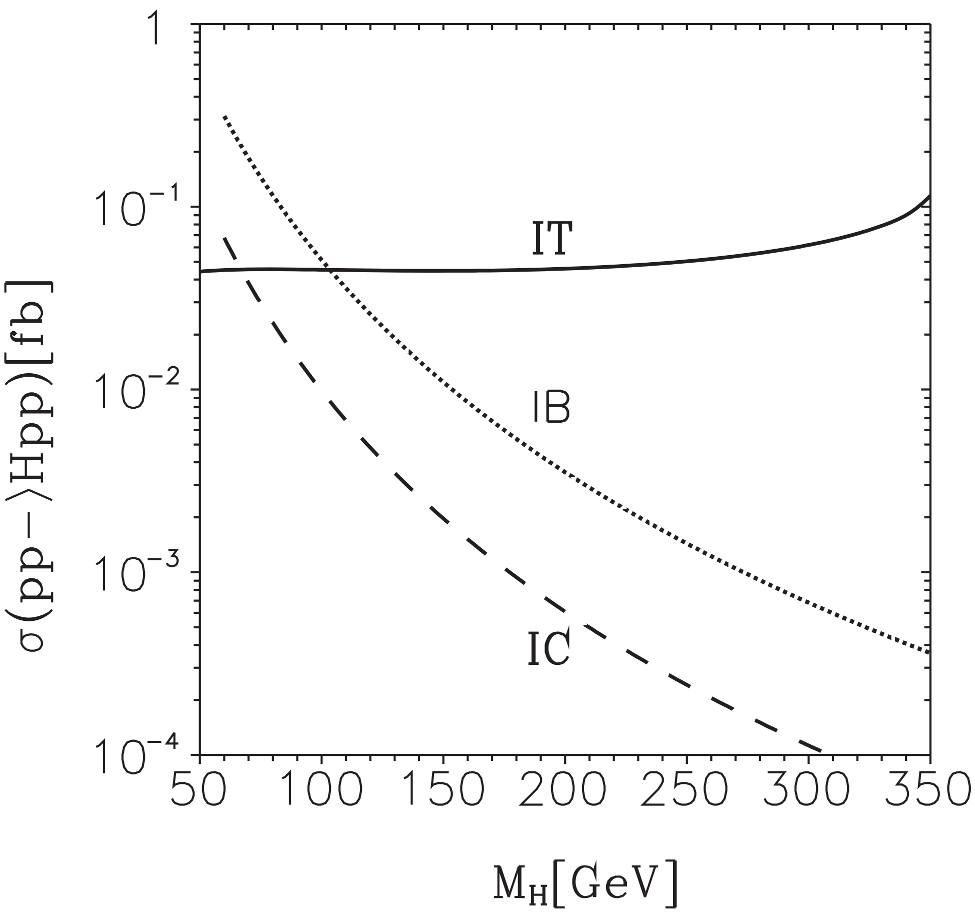
$$\Psi_{\mathrm{IQ}}(Q, z, \kappa) \propto \frac{z(1-z)}{Q^2 + z^2 m_p^2 + M_{\bar{Q}Q}^2(1-z)}.$$

$$H(\vec{r}) = i\frac{\sqrt{N_c G_F}}{2\pi} m_c \bar{\chi}\, \vec{\sigma}\, \chi \frac{\vec{r}}{r}\left[\epsilon Y_1(\epsilon r) - \frac{ir}{2}\Gamma_H M_H Y_0(\epsilon r)\right]$$



The distribution of produced Higgs particles over the fraction of the proton beam momentum. The dotted, dashed, and solid curves correspond to Higgs production from nonperturbative IC ($\beta = 1$), perturbative IC ($\beta = 0$), and IT, respectively.

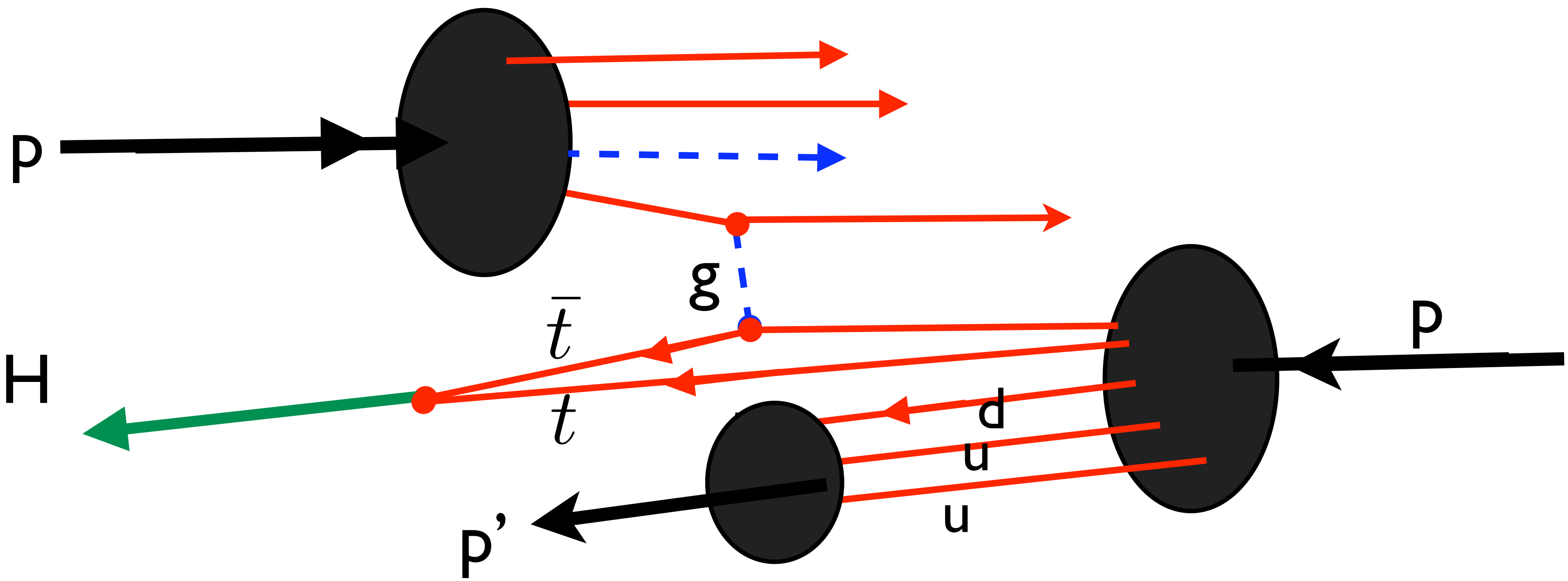


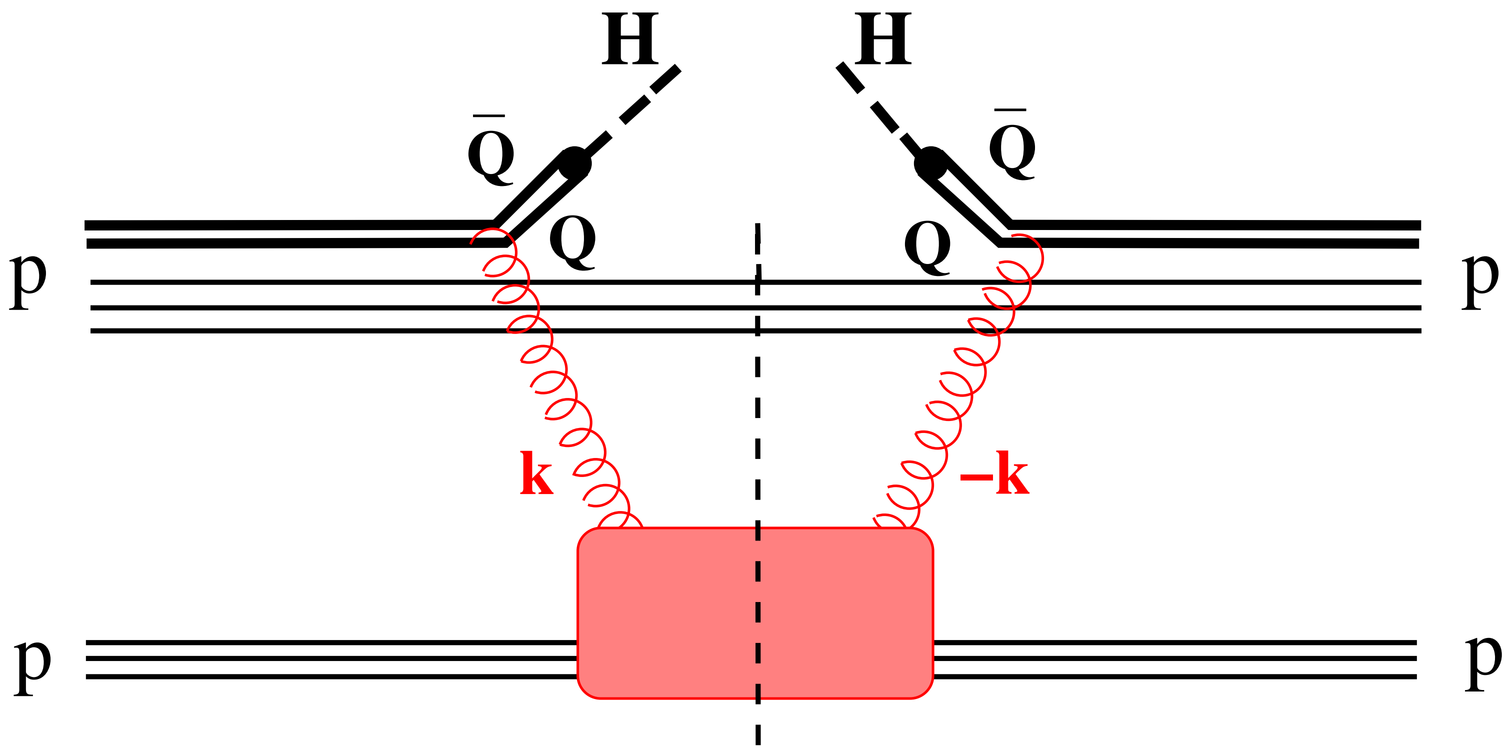


The cross section of the reaction $pp \rightarrow Hp + p$ as a function of the Higgs mass. Contributions of IC (dashed line), IB (dotted line), and IT (solid line).

Goldhaber, Kopeliovich, Schmidt, SJB

Higgs Hadroproduction at High x_F from Intrinsic Heavy Quarks




H
H
$\bar{Q}$
$\bar{Q}$
Q
Q
p
p
p
p
k
−k

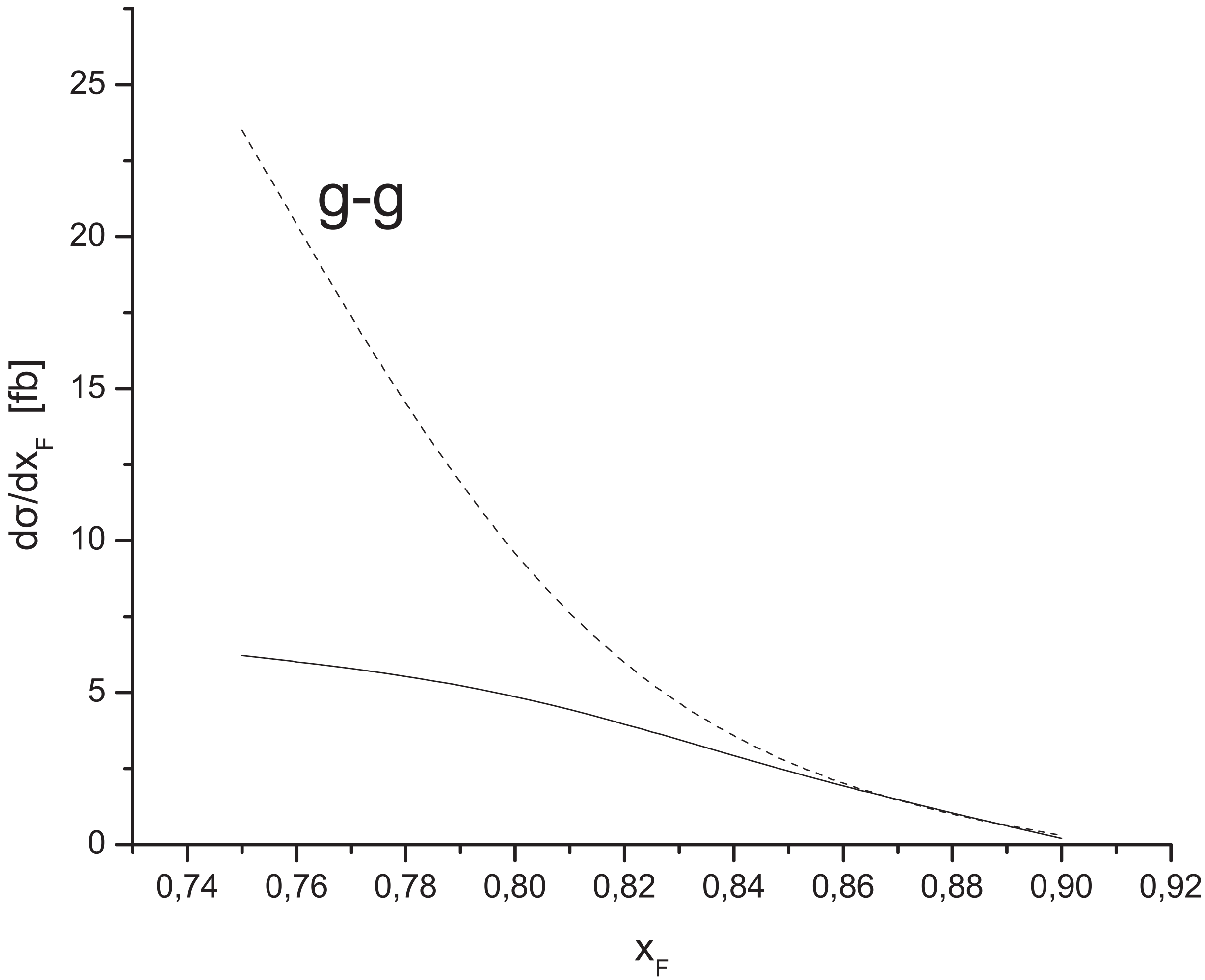
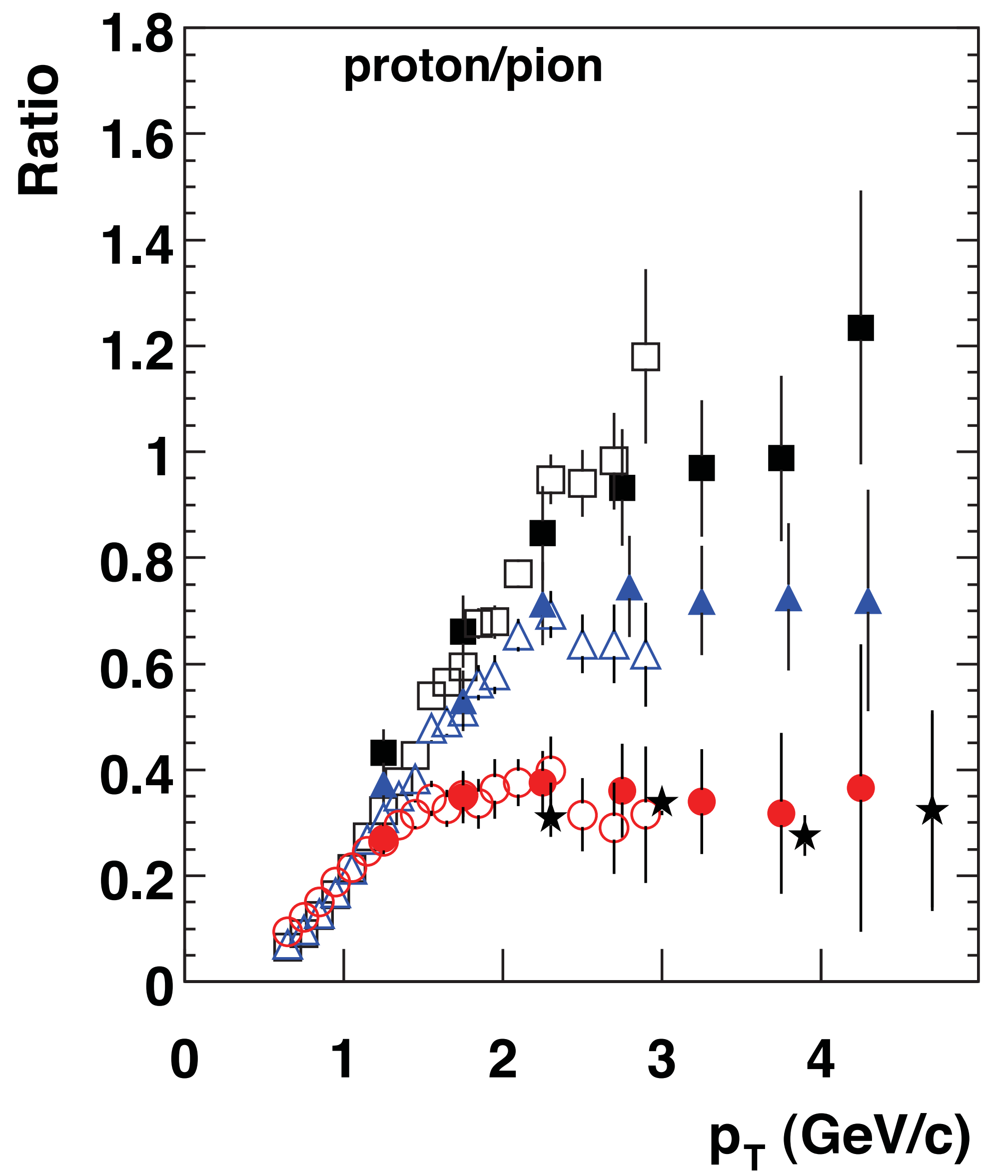


Figure 2: The cross section of inclusive Higgs production in f b, coming from the non-perturbative intrinsic charm distribution, at LHC ($\sqrt{s}$ = 14 TeV) energies. For comparison we show also an estimate of the cross section for gluon-gluon fusion.

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**

Au+Au 0-10%

Au+Au 20-30%

Au+Au 60-92%

p+p, $\sqrt{s}$ = 53 GeV, ISR

e^+e^-, gluon jets, DELPHI

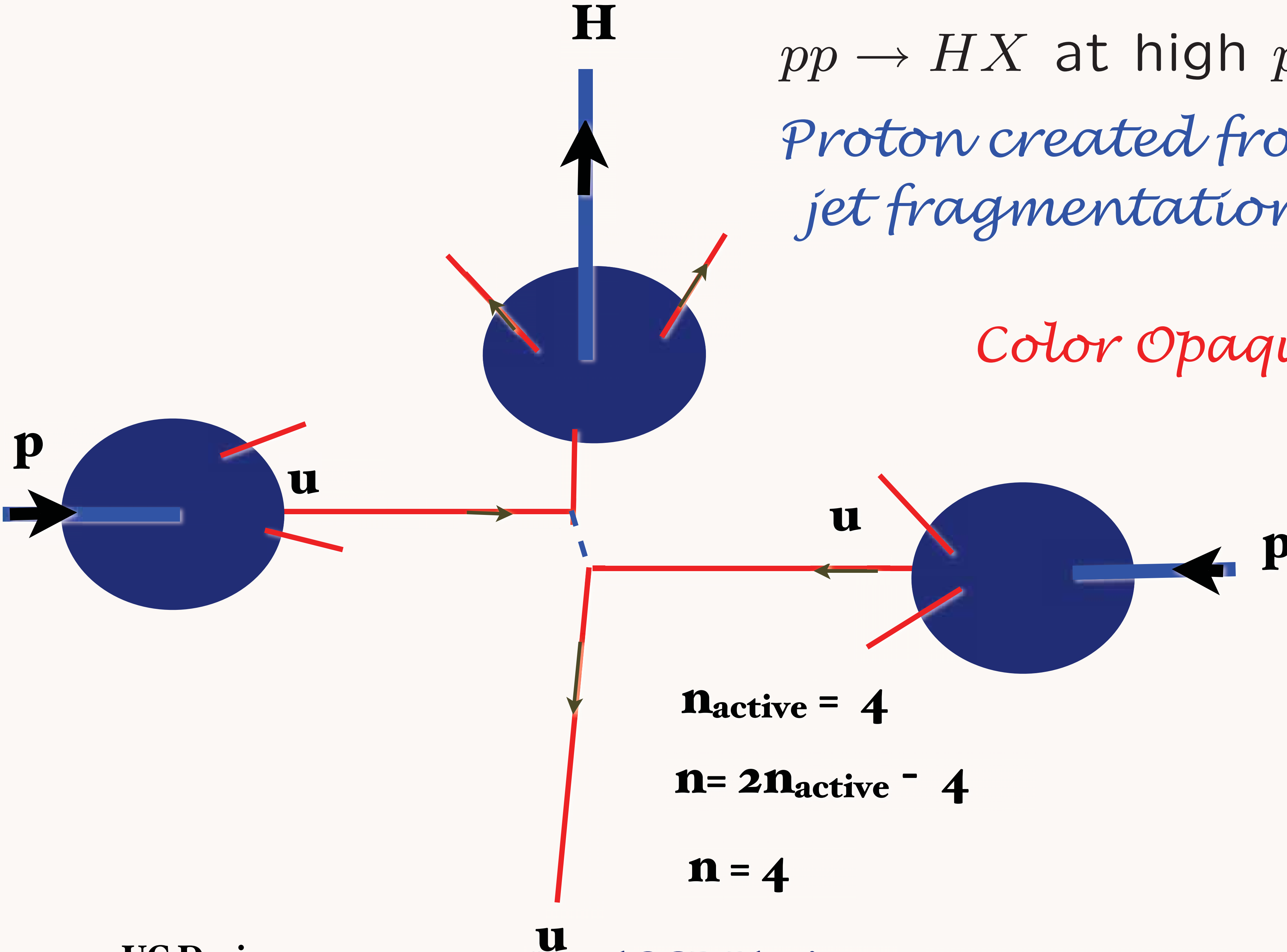
e^+e^-, quark jets, DELPHI

← **Peripheral**

$pp \to HX$ 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

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

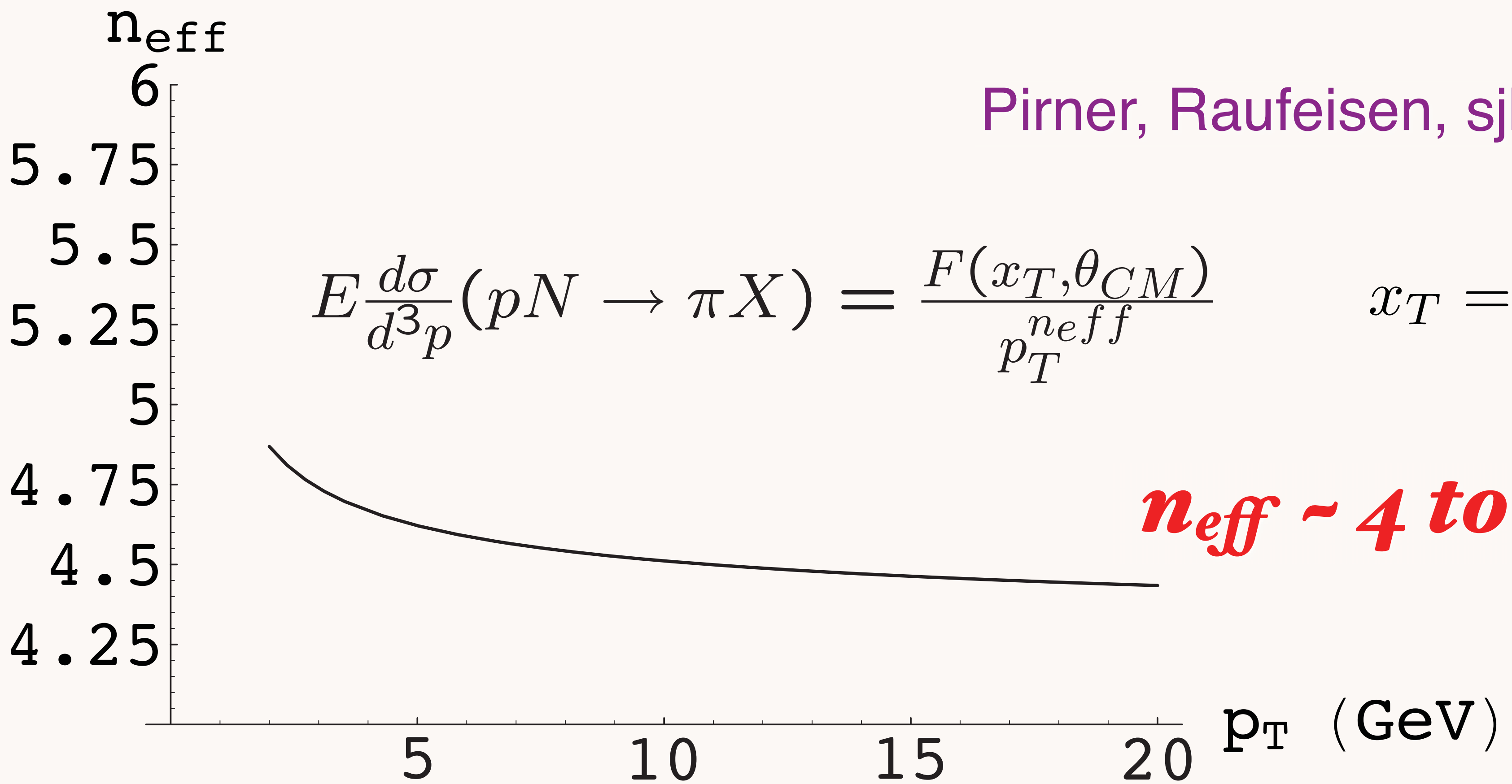
$$E\frac{d\sigma}{d^3p}(pN \to \pi X) = \frac{F(x_T,\theta_{CM})}{p_T^{n_{eff}}}$$

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

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

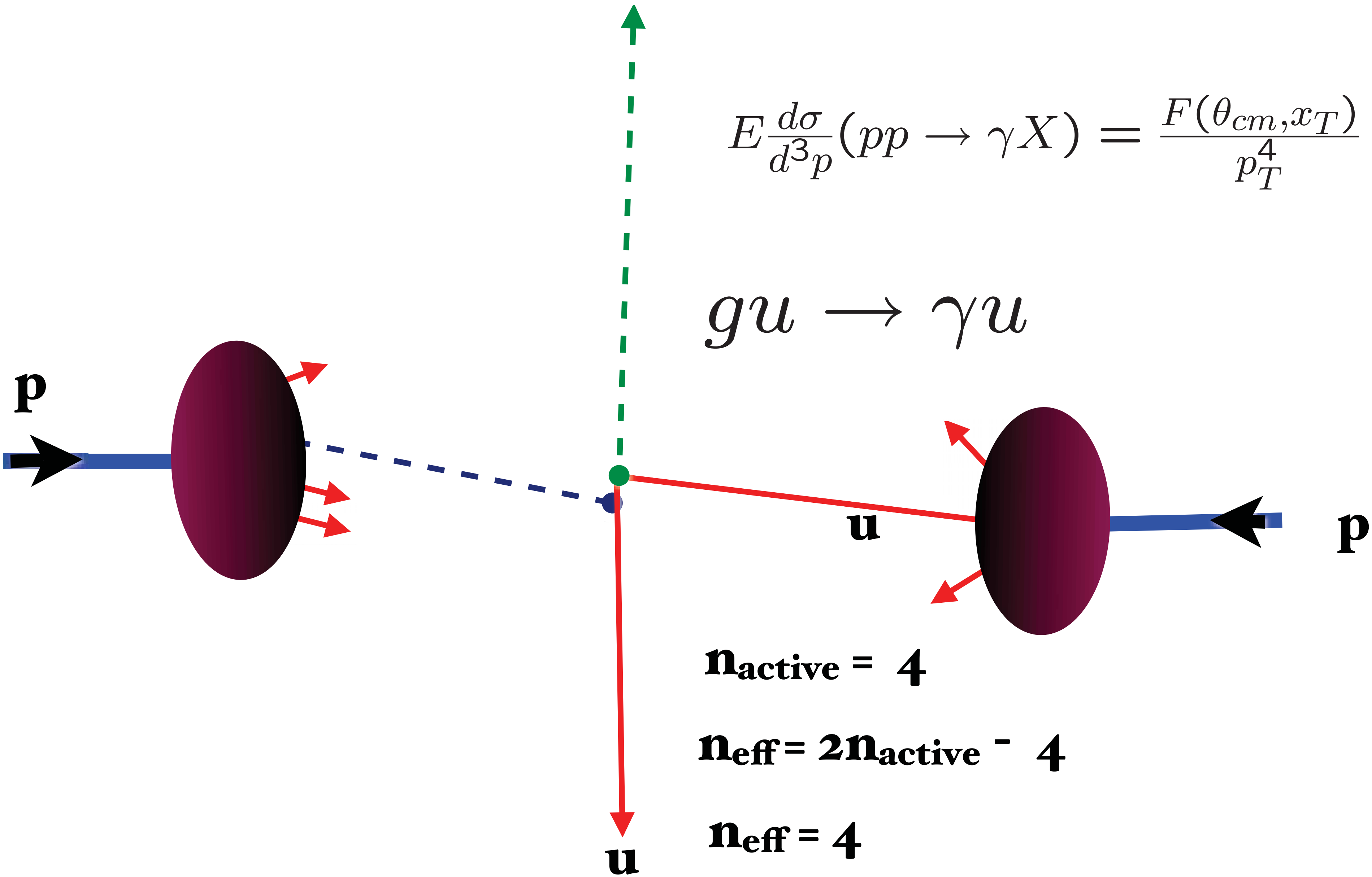
n_{eff} ~ 4 to 5

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

$$pp \longrightarrow \gamma X$$

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

$$gu \longrightarrow \gamma u$$



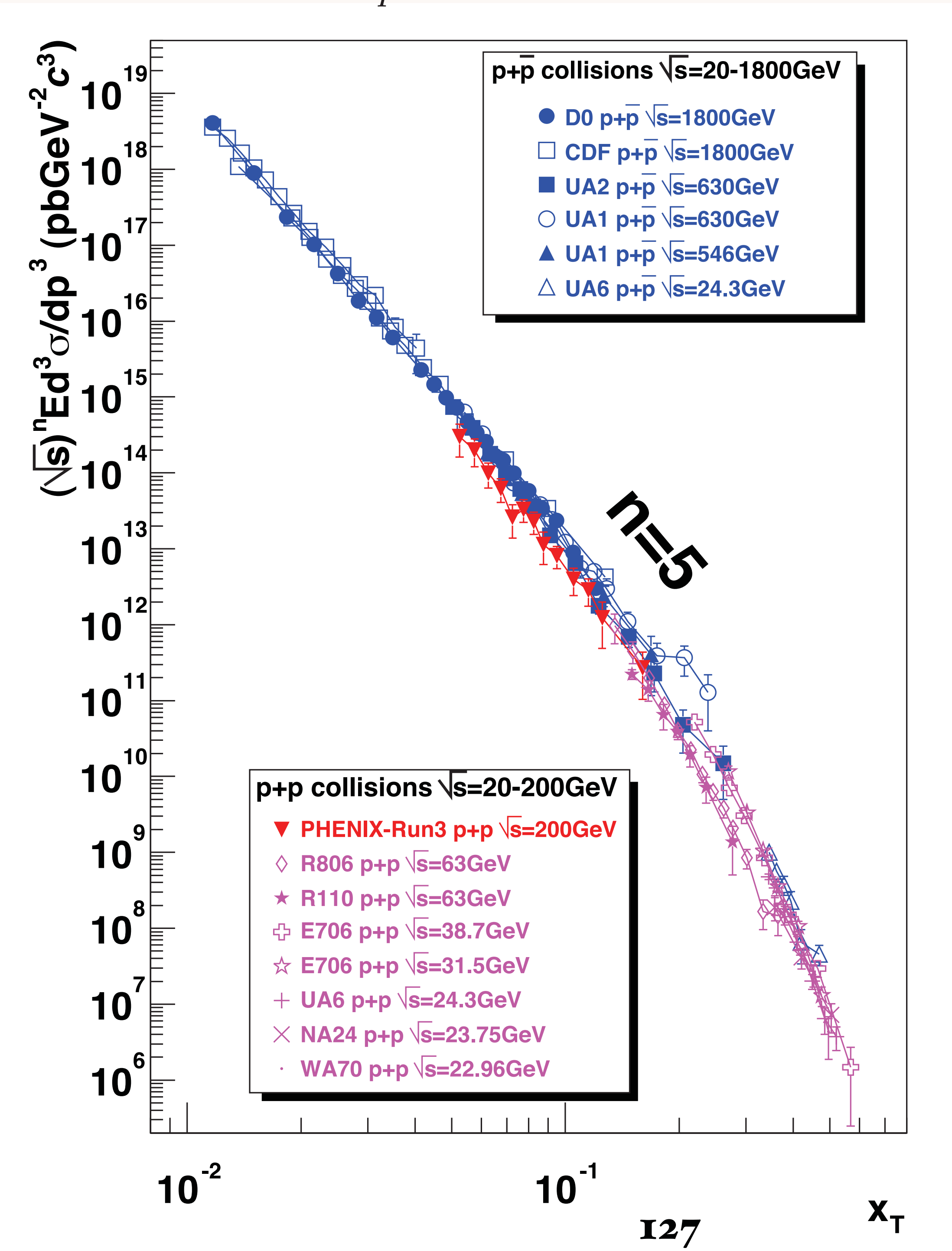
$n_{active} = 4$

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

$n_{eff} = 4$

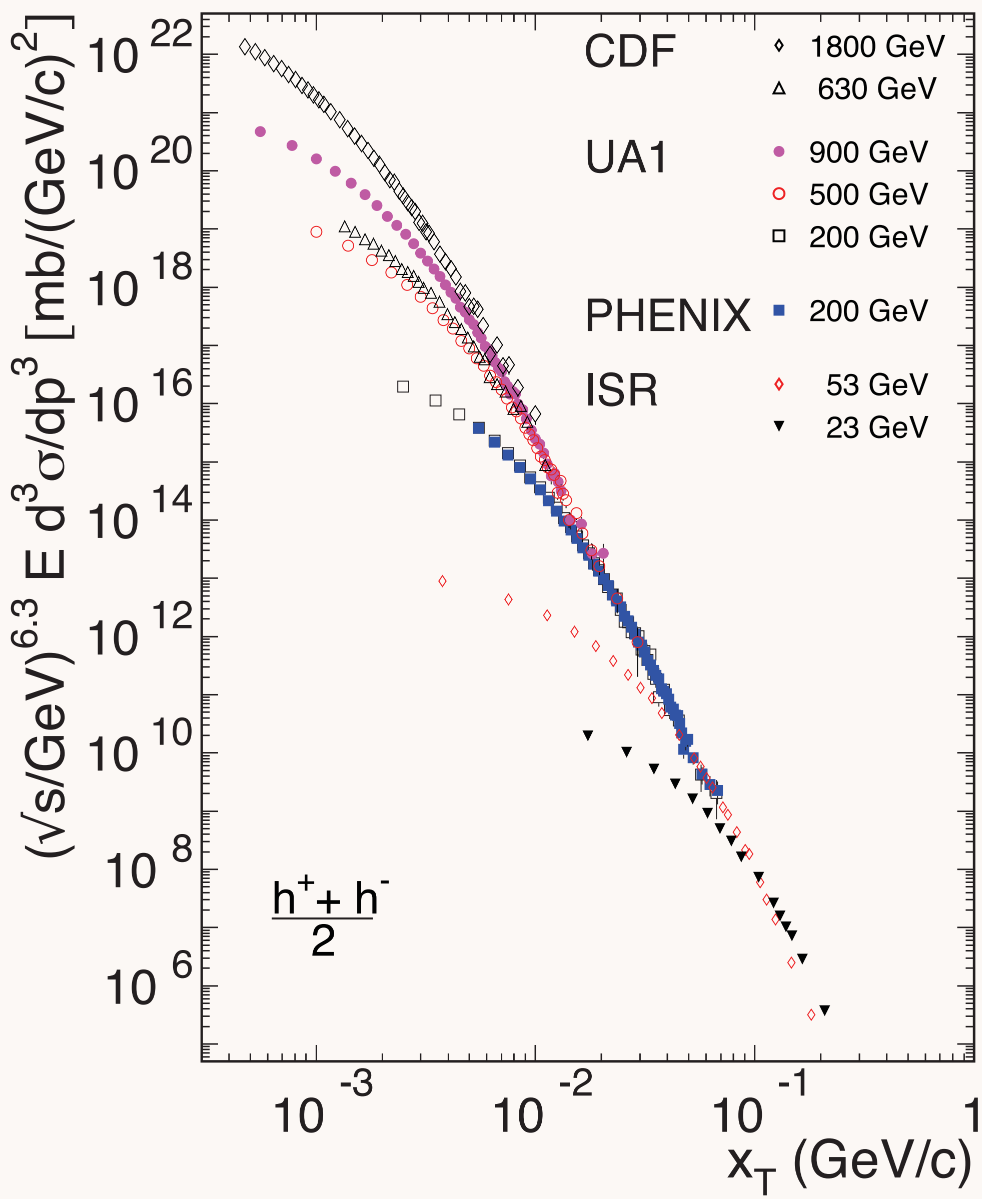
$\sqrt{s}^n E \frac{d\sigma}{d^3p}(pp \to \gamma X)$ at fixed x_T

Tannenbaum



Scaling of direct photon production consistent with PQCD

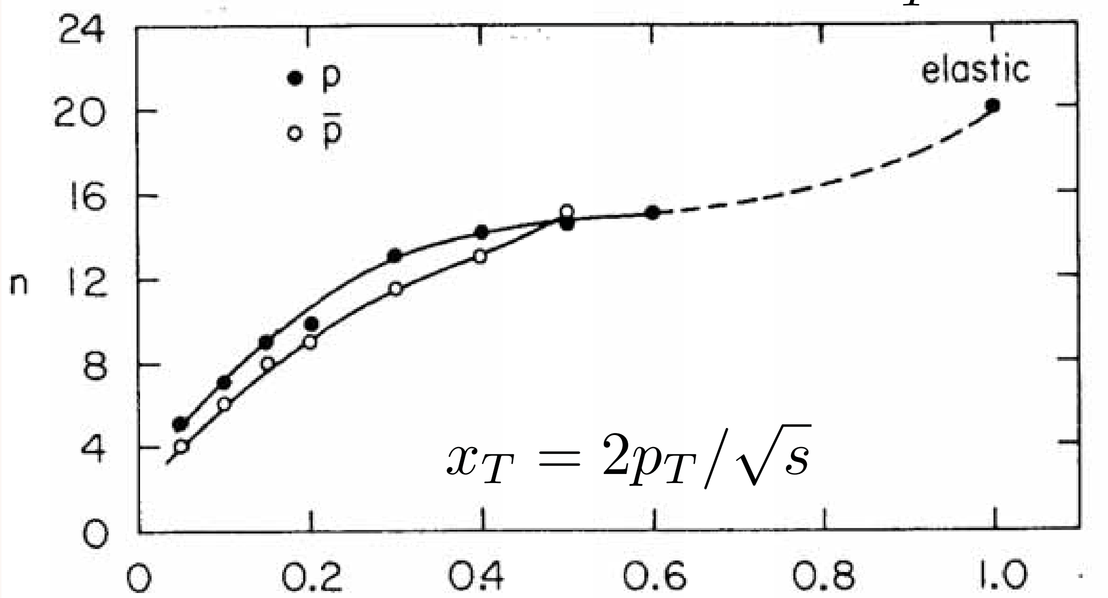
$\sqrt{s}^{6.3} \times E\frac{d\sigma}{d^3p}(pp \to H^{\pm}X)$ at fixed x_T



Tannenbaum

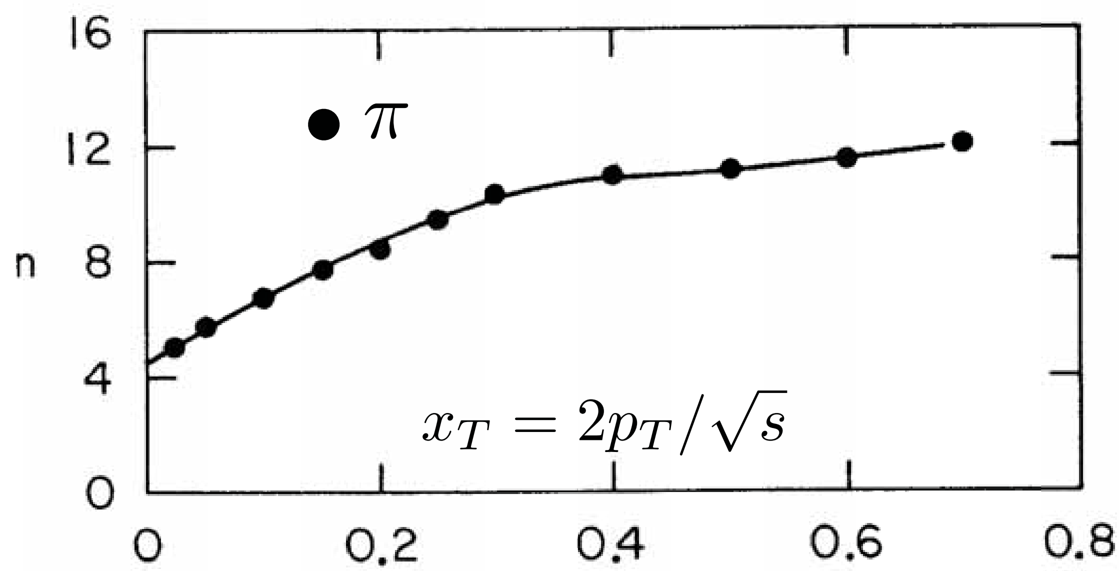
Scaling inconsistent with PQCD

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



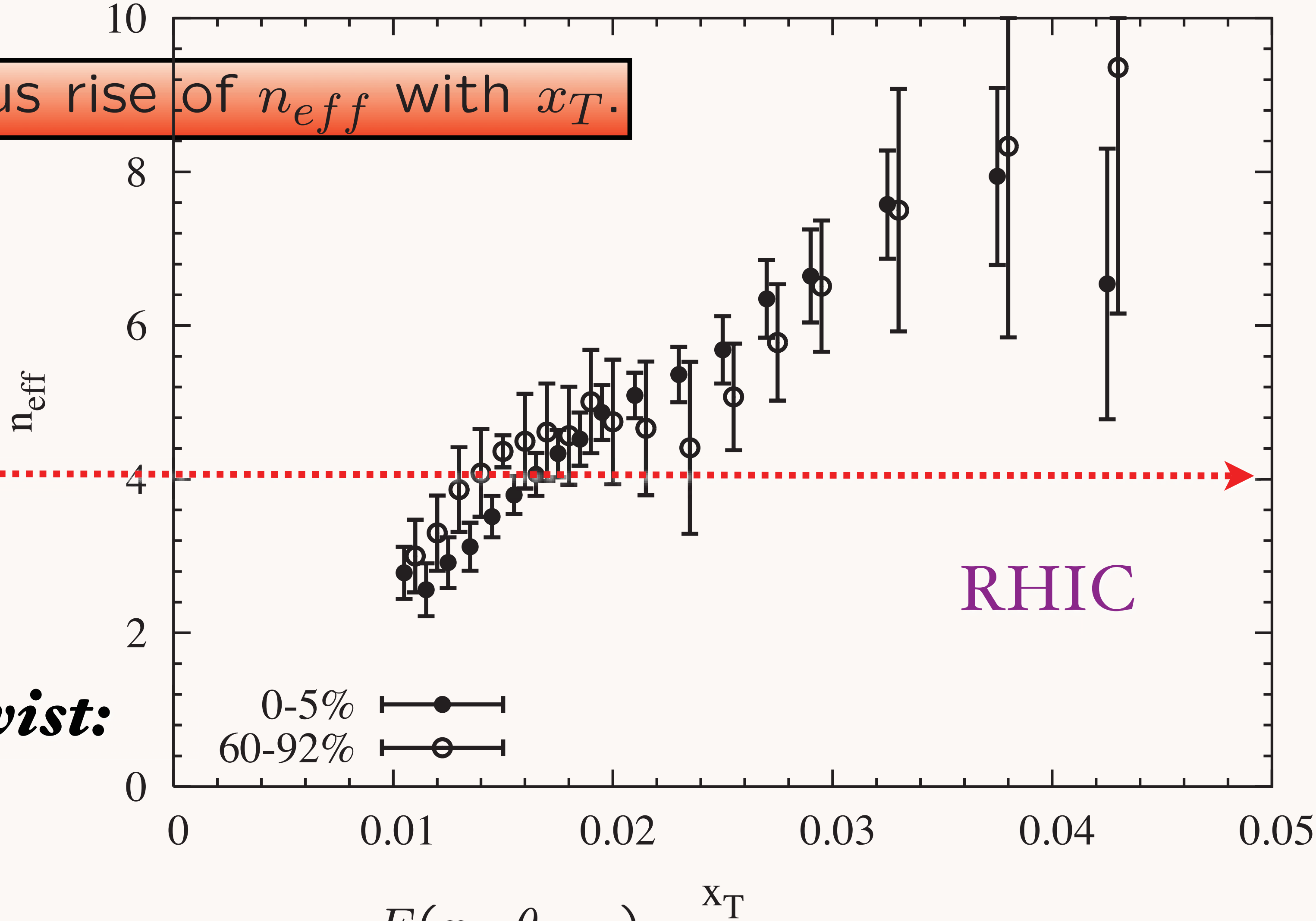
Clear evidence for higher-twist contributions

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.

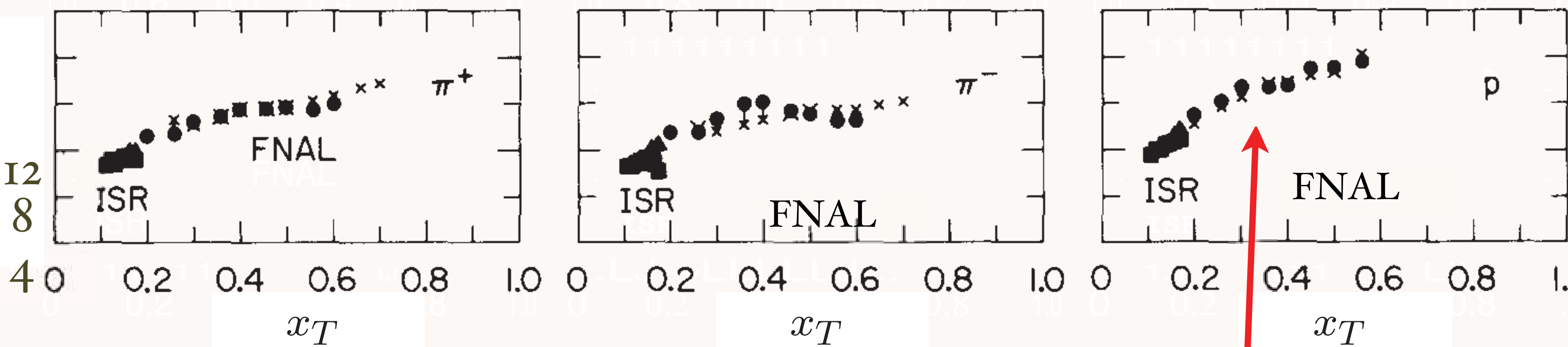


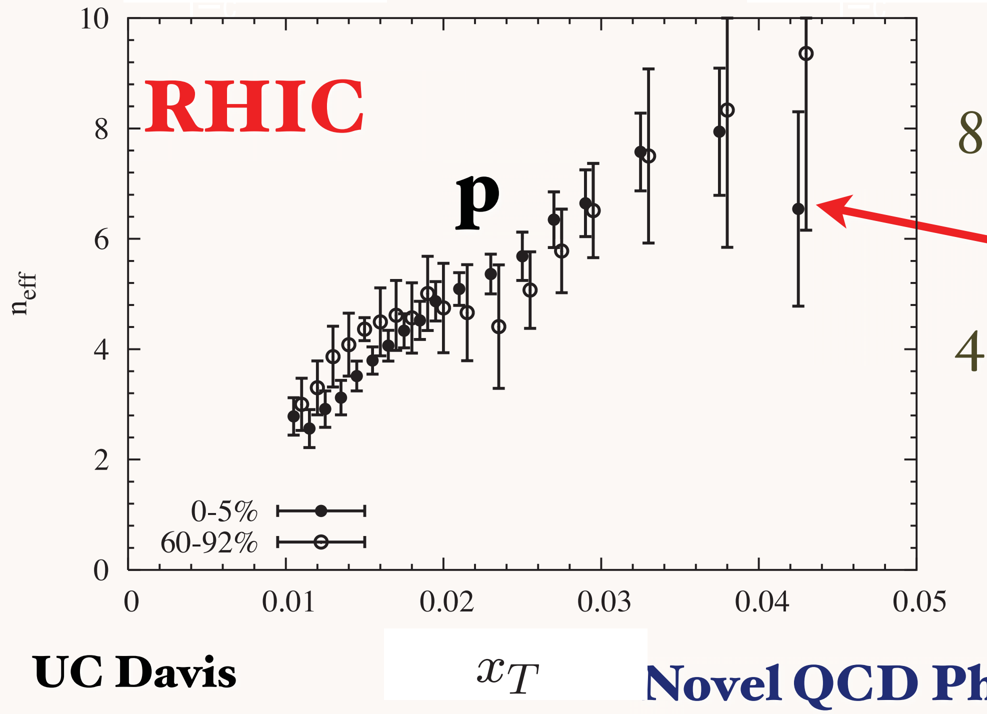
$n_{eff} = 4$

Leading twist:

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

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





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

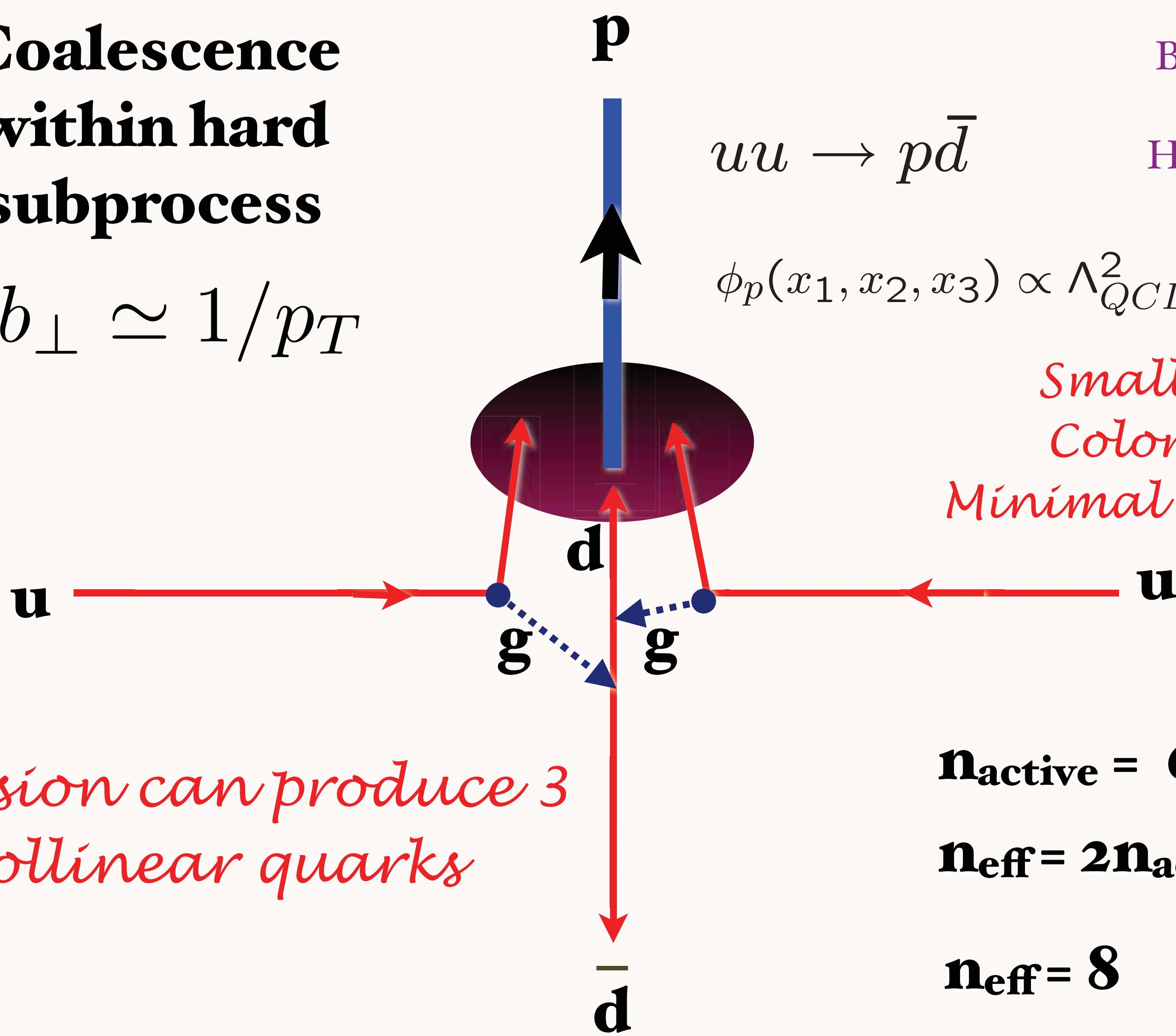
$$E\frac{d\sigma}{d^3p}(pp \to pX) = \frac{F(x_T, \theta_{CM})}{p_T^{8}}$$

Trend consistent with RHIC at small x_T

Baryon can be made directly within hard subprocess

Coalescence within hard subprocess

$$b_\perp \simeq 1/p_T$$



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

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

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

Small color-singlet
Color Transparent
Minimal same-side energy

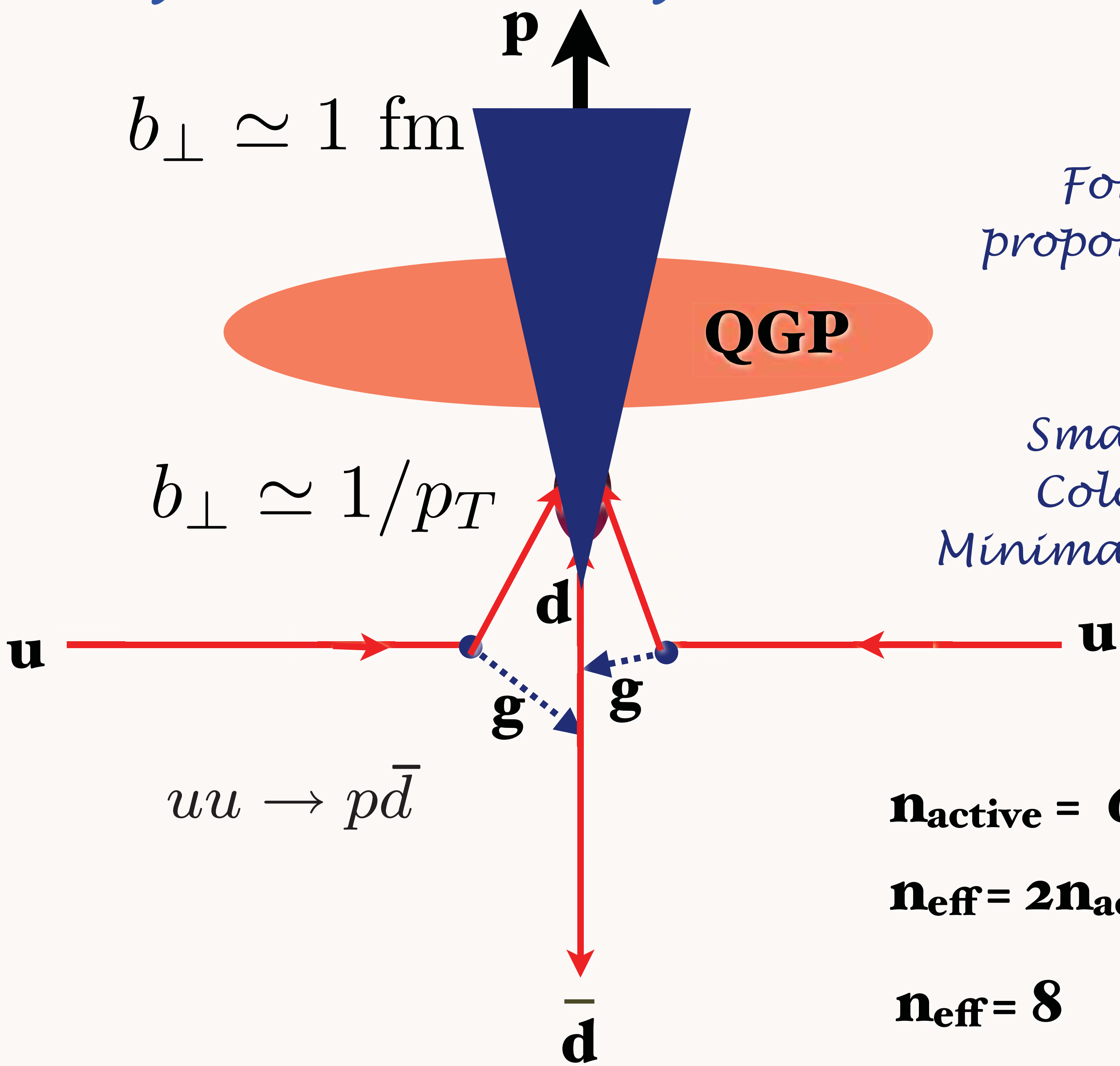
Collision can produce 3 collinear quarks

$n_{active} = 6$

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

$n_{eff} = 8$

Baryon made directly within hard subprocess



Formation Time proportional to Energy

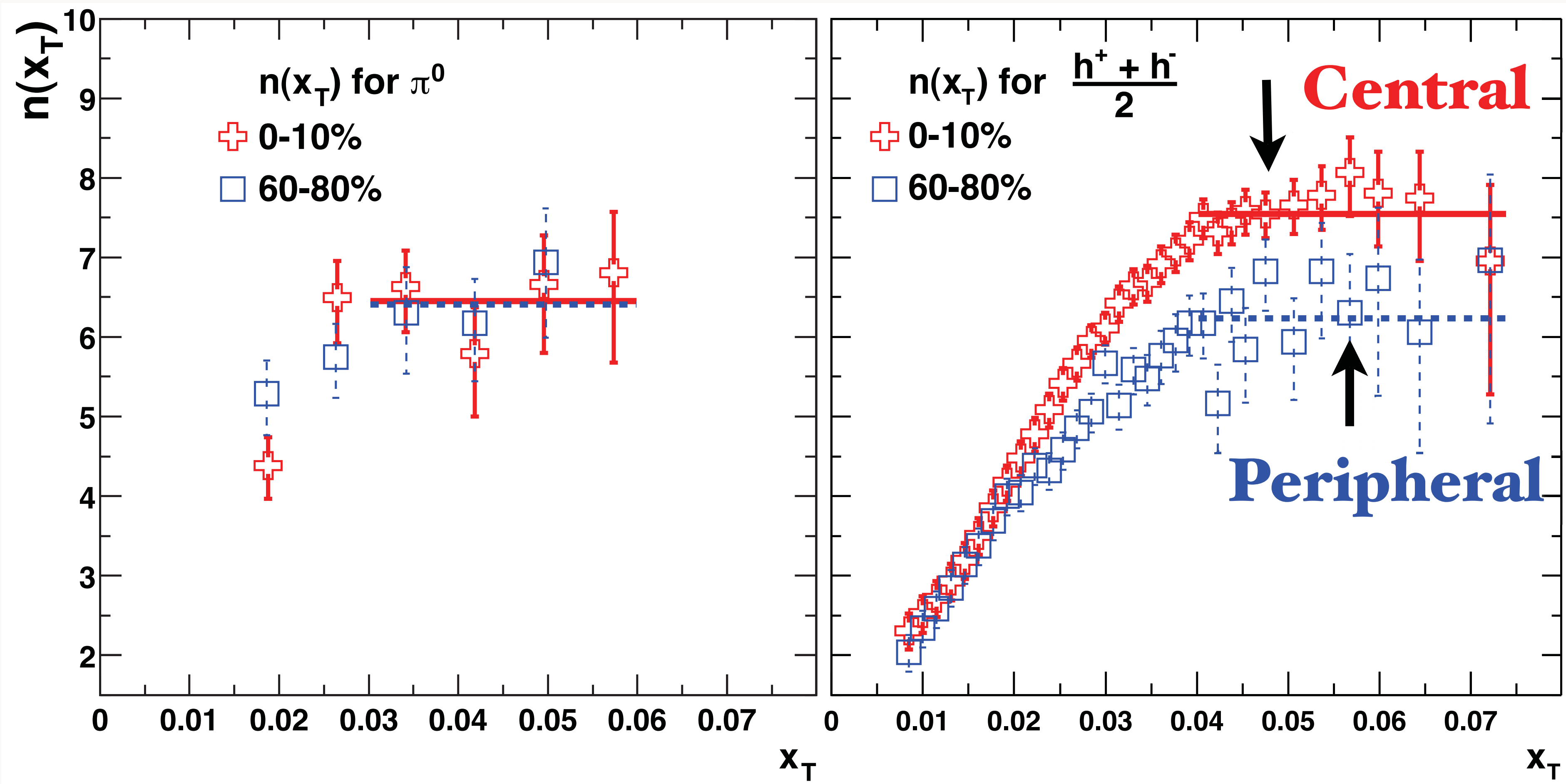
Small color-singlet
Color Transparent
Minimal same-side energy

$n_{active} = 6$

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

$n_{eff} = 8$

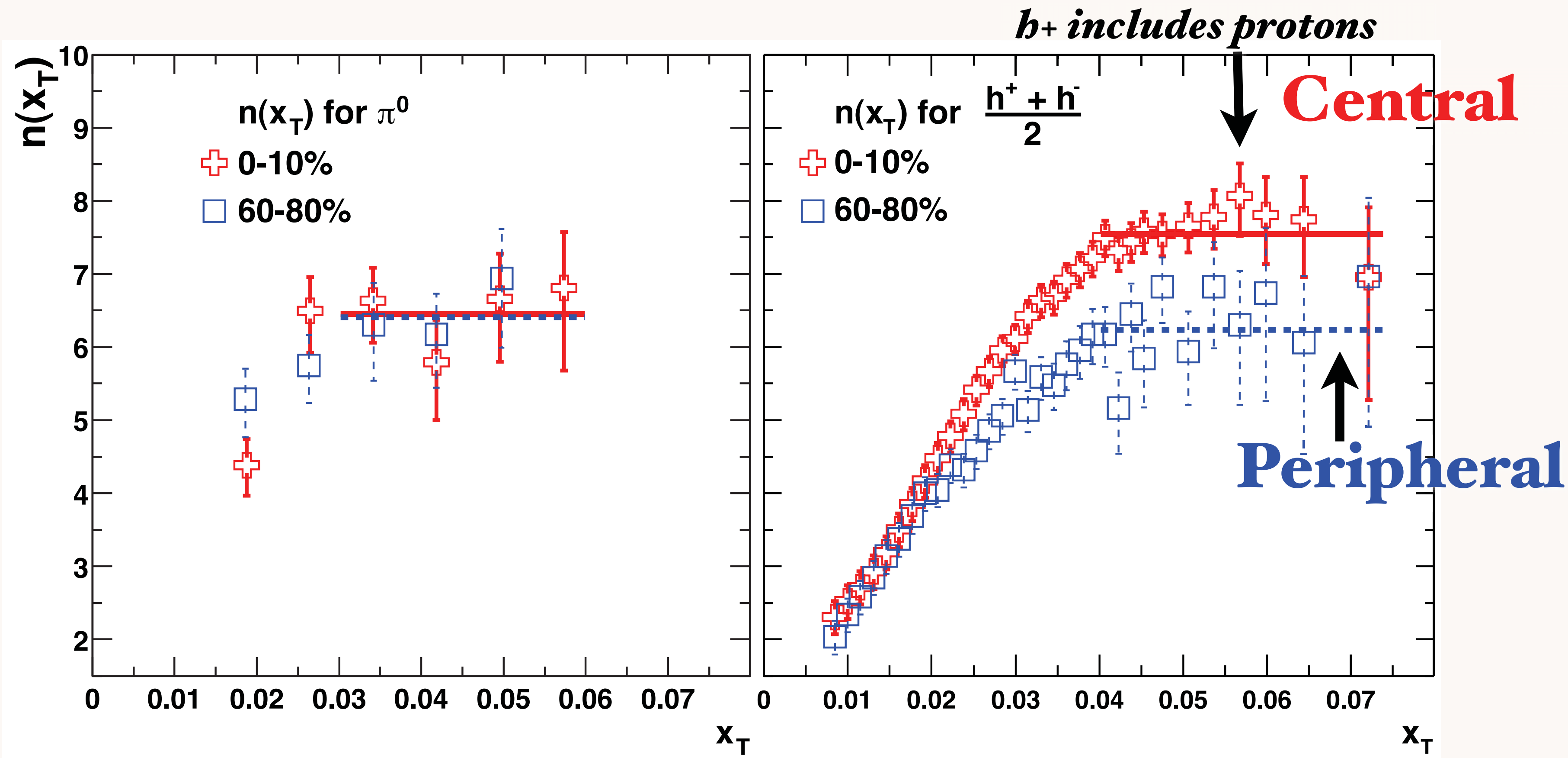
$$\sqrt{s_{NN}} = 130 \text{ and } 200 \text{ GeV}$$



Proton power changes with centrality !

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`].

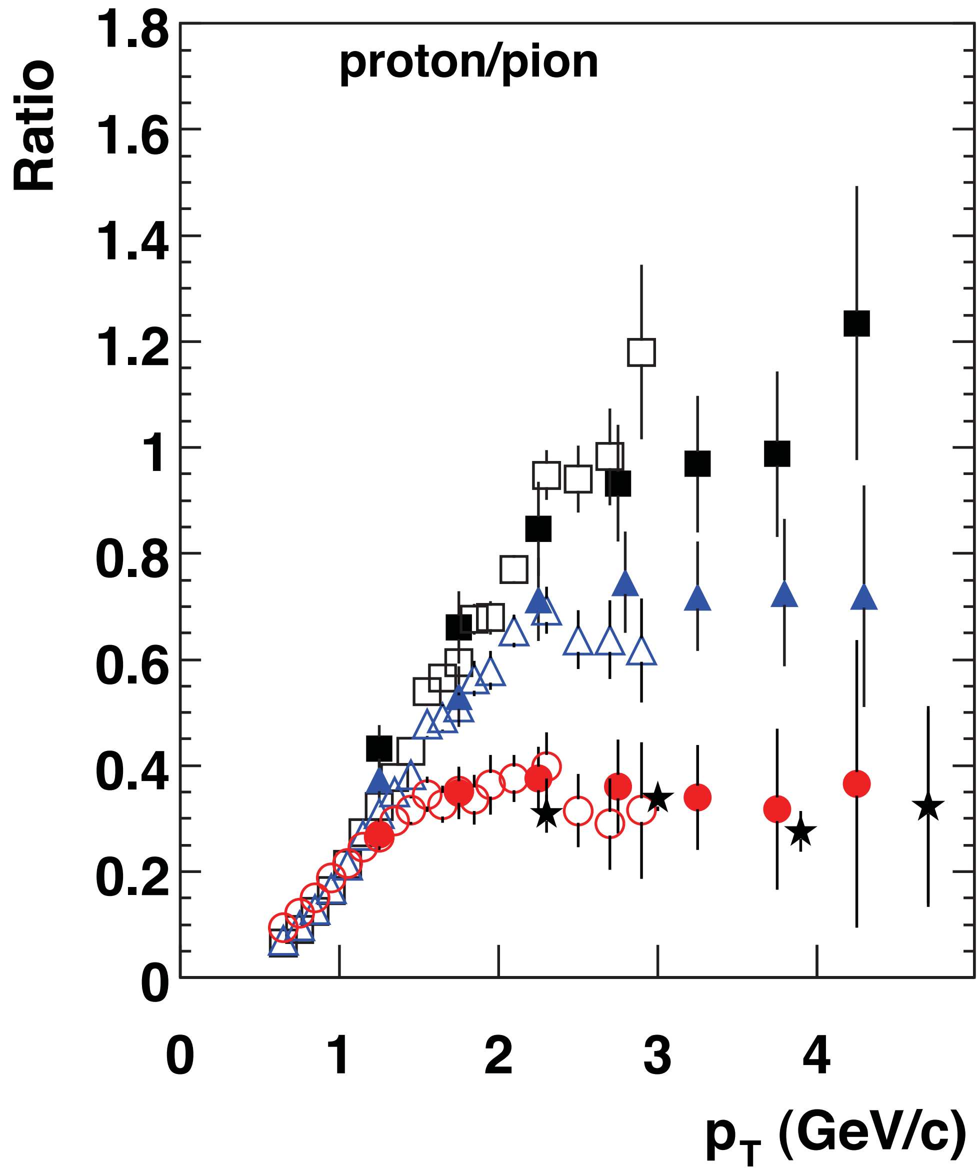


Proton power changes with centrality !

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

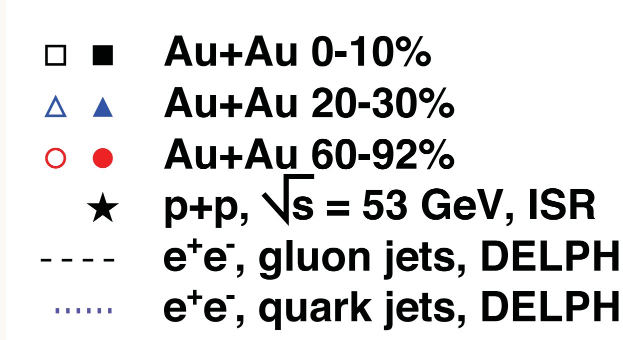
S. S. Adler *et al.* PHENIX Collaboration *Phys. Rev. Lett.* **91**, 172301 (2003).

Particle ratio changes with centrality!



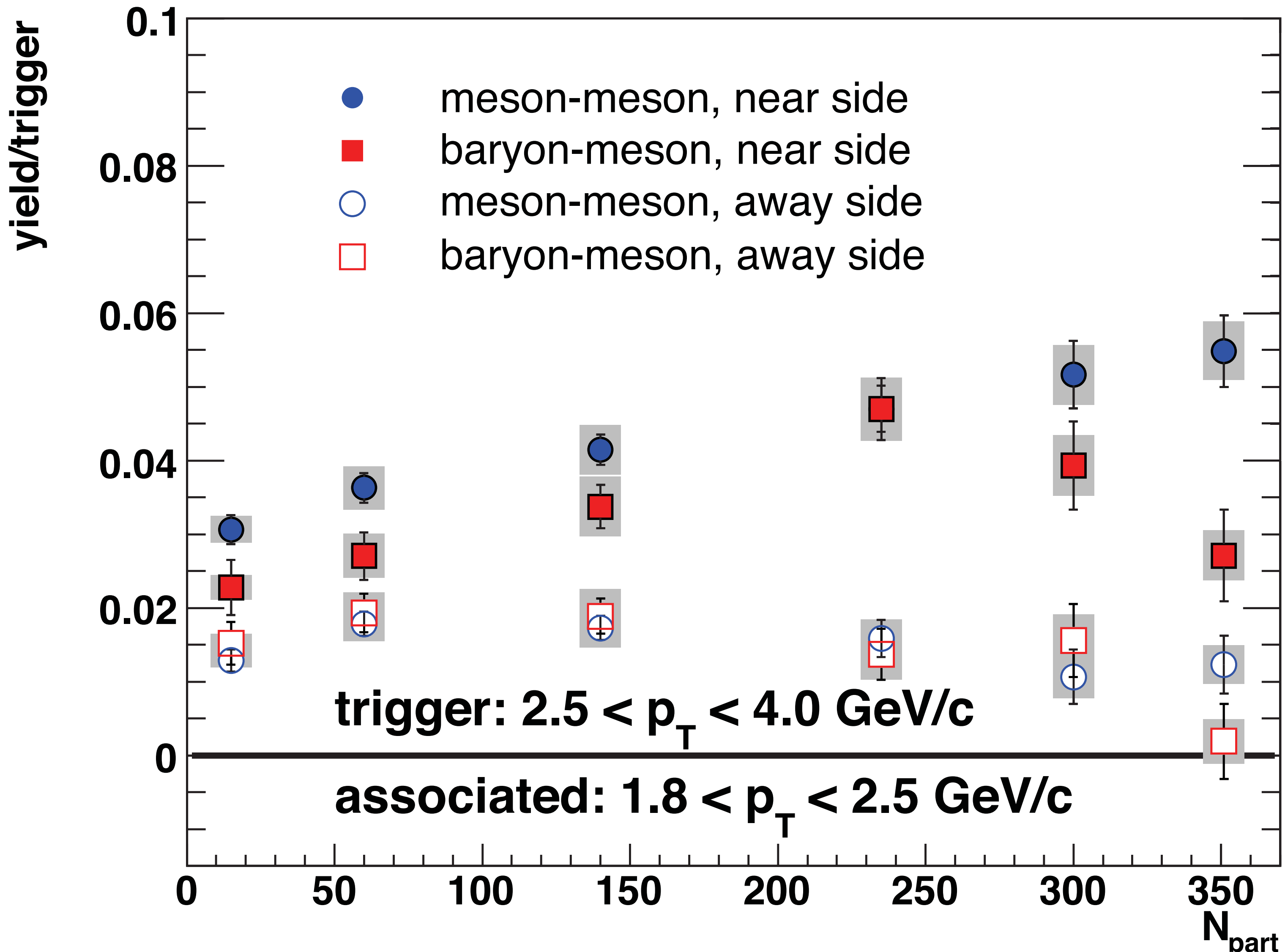
Protons less absorbed in nuclear collisions than pions because of dominant color transparent higher twist process

← **Central**



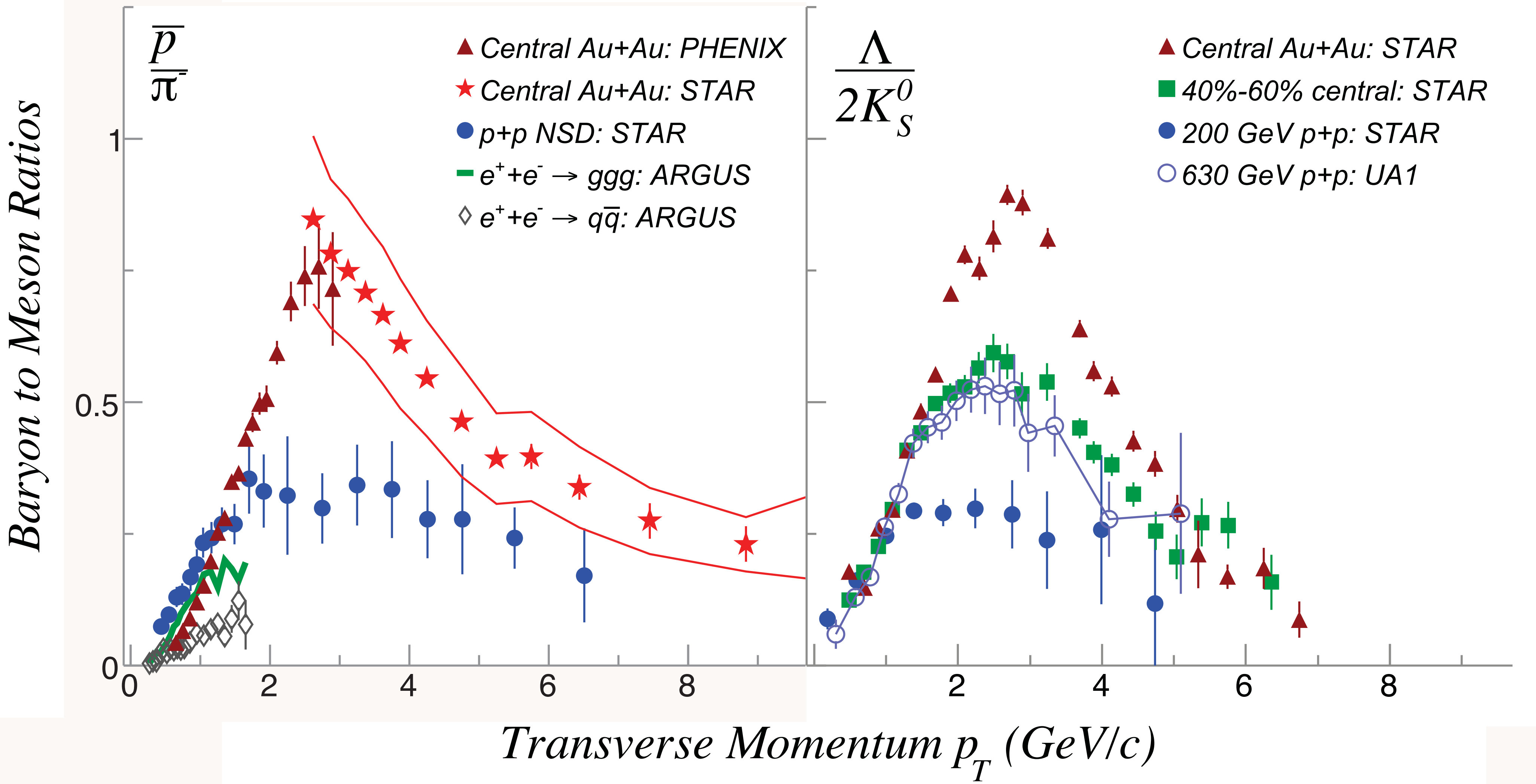
← **Peripheral**

Anne Sickles



proton trigger: # same-side particles decreases with centrality

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

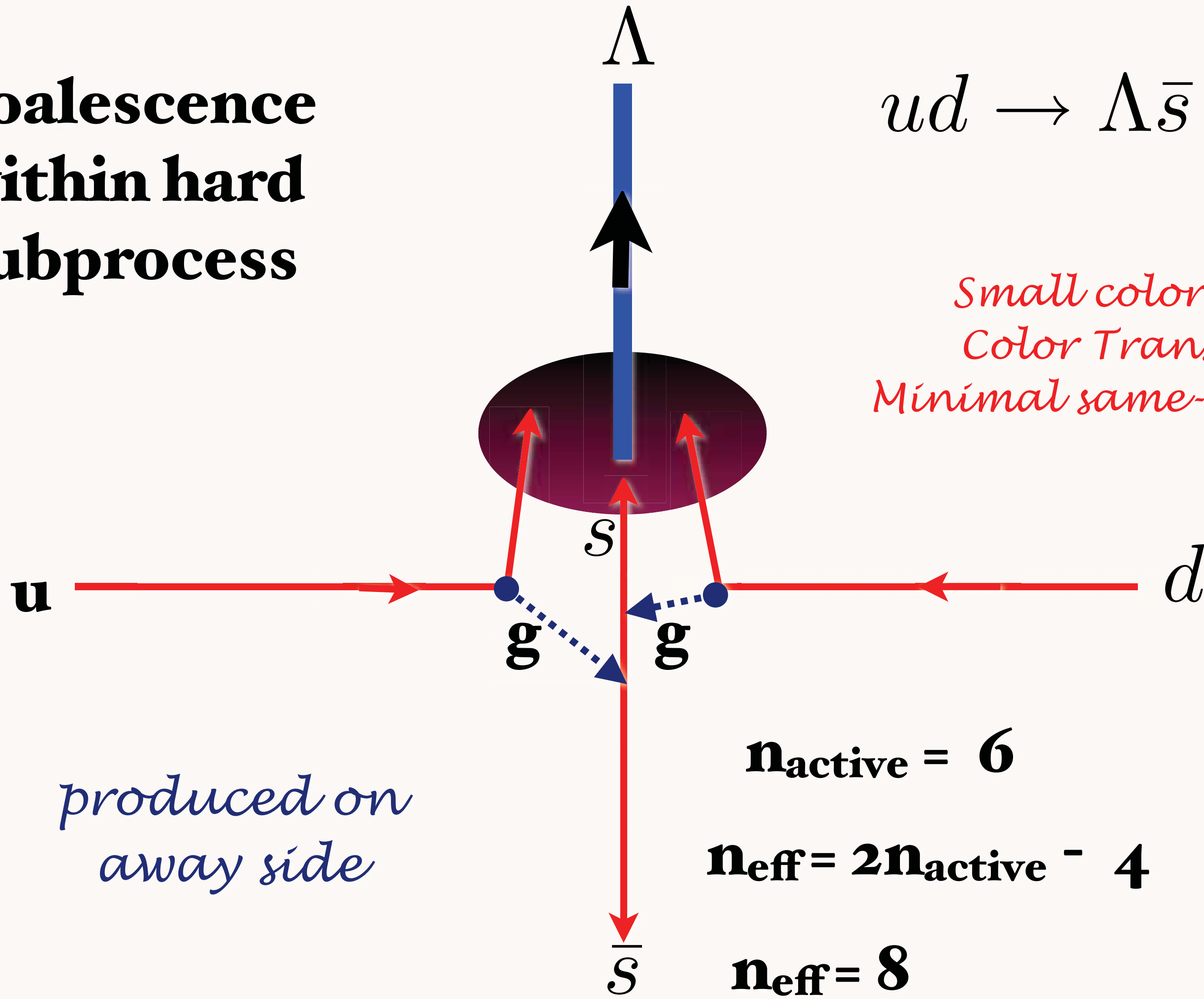

Baryon to Meson Ratios
$\frac{\bar{p}}{\pi^-}$
Central Au+Au: PHENIX
Central Au+Au: STAR
p+p NSD: STAR
$e^+ + e^- \rightarrow ggg$: ARGUS
$e^+ + e^- \rightarrow q\bar{q}$: ARGUS
$\frac{\Lambda}{2K_S^0}$
Central Au+Au: STAR
40%-60% central: STAR
200 GeV p+p: STAR
630 GeV p+p: UA1
1
0.5
0
0
2
4
6
8
2
4
6
8
Transverse Momentum p_T (GeV/c)

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

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

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

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

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 $x_T = 1$**

Novel Aspects of QCD in ep scattering

- Clash of DGLAP and BFKL with unitarity: saturation phenomena; off-shell effects at high x
- Heavy quark distributions do not derive exclusively from DGLAP or gluon splitting -- component intrinsic to hadron wavefunction:
  Intrinsic c(x,Q), b(x,Q), t(x,Q):
- Hidden-Color of Nuclear Wavefunction
- Antishadowing is quark specific!
- Polarized u(x) and d(x) at large x; duality
- Virtual Compton scattering : DVCS, DVMS, GPDs; J=0 fixed pole reflects elementary source of electromagnetic current
- Initial-and Final-State Interactions: leading twist SSA, DDIS
- Direct Higher-Twist Processes; Color Transparency

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

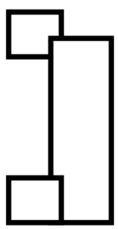
Conventional wisdom in QCD concerning scale setting

- 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-Electron Scattering in QED

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



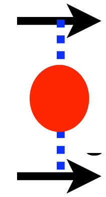
$$\alpha(t) = \frac{\alpha(0)}{1 - \Pi(t)}$$

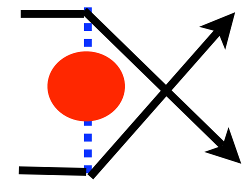
Gell Mann-Low Effective Charge

Electron-Electron Scattering in QED

- No renormalization scale ambiguity!

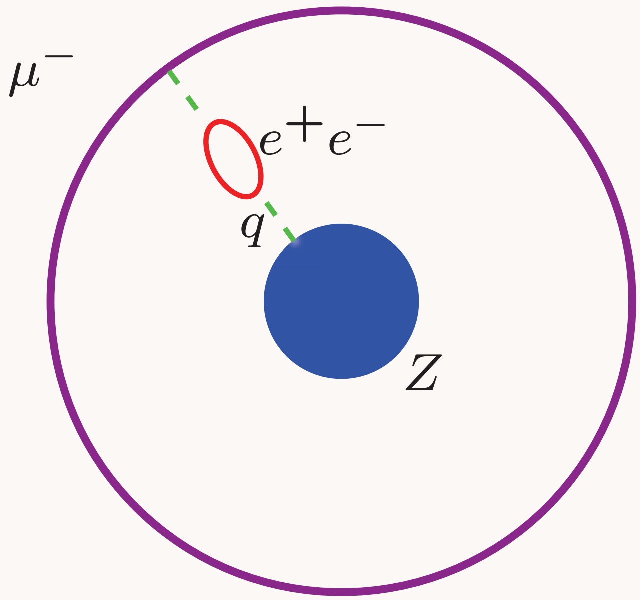
$$\mathcal{M}_{ee\to ee}(++;++) = \frac{8\pi s}{t}\,\alpha(t) + \frac{8\pi s}{u}\,\alpha(u)$$





- 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
- Sums all vacuum polarization, non-zero beta terms into running coupling.
- If one chooses a different scale, one must sum an infinite number of graphs -- but then recover same result!
- Number of active leptons correctly set
- Analytic: reproduces correct behavior at lepton mass thresholds

Another Example in QED: Muonic Atoms



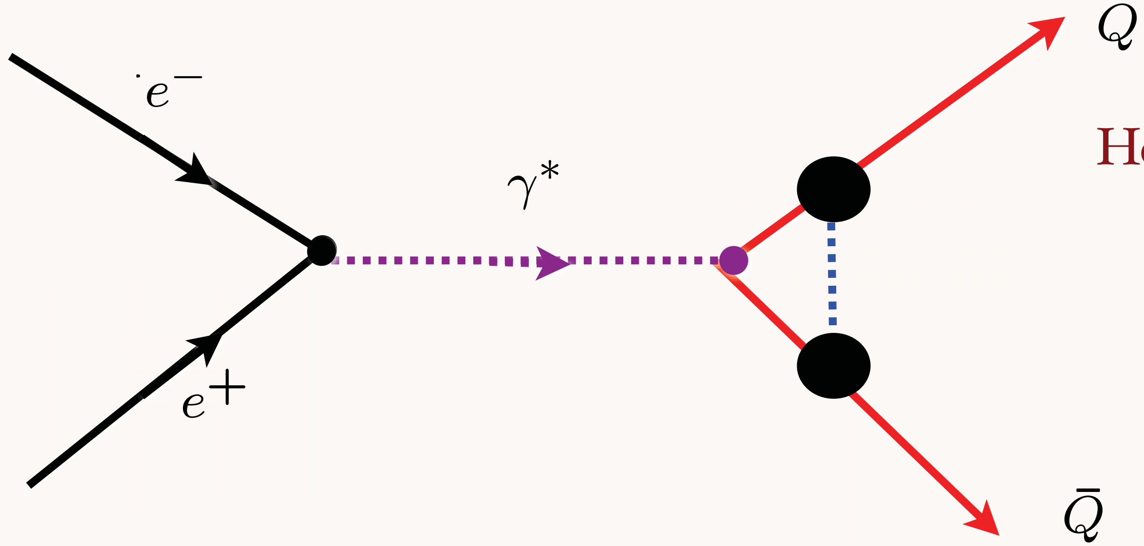
$$V(q^2) = -\frac{Z\alpha_{QED}(q^2)}{q^2}$$

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

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

Scale is unique: Tested to ppm

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



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.

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!

Novel Aspects of QCD

- Heavy quark distributions do not derive exclusively from DGLAP or gluon splitting -- component intrinsic to hadron wavefunction: Higgs at high x_F

- Initial and final-state interactions are not power suppressed in hard QCD reactions

- 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

- DDIS and Sivers Effect: Breakdown of Leading-Twist Factorization
- Physics of Hard Pomeron
- Measure Fundamental Hadron Wavefunction via Di-jet and Tri-jet Fragmentation
- Origin of Leading Twist Shadowing
- Non-Universal Antishadowing
- Heavy quark structure functions at high x
- Higgs production at large xF
- Hadroproduction of new heavy quark states such as ccu, ccd at high x_F
- Novel Nuclear Effects from color structure of IC
- Fixed target program at LHC: produce bbb states
- Direct Hadroproduction at high pT

String Theory

↓

AdS/CFT

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

↓

AdS/QCD

Goal: First Approximant to QCD

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

Conformal behavior at short distances
+ Confinement at large distance

↓

Semi-Classical QCD / Wave Equations

↓

Holography

Boost Invariant 3+1 Light-Front Wave Equations

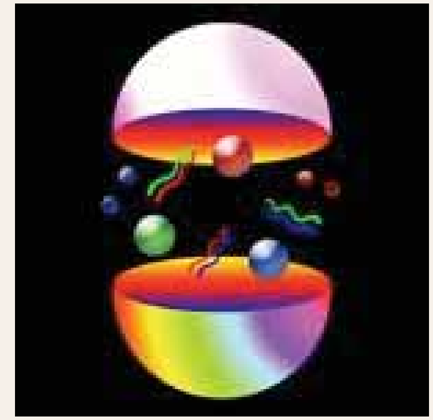
↓

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

Integrable!

Hadron Spectra, Wavefunctions, Dynamics

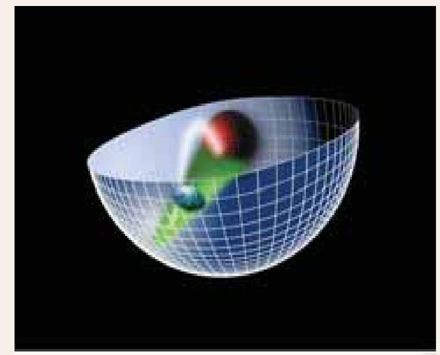
- Quarks and Gluons:
Fundamental constituents of hadrons and nuclei



- *Quantum Chromodynamics (QCD)*

- New Insights from higher space-time dimensions: *AdS/QCD*

- *Light-Front Holography*



- *Hadronization at the Amplitude Level*

- *Light Front Wavefunctions:* analogous to the Schrodinger wavefunctions of atomic physics

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