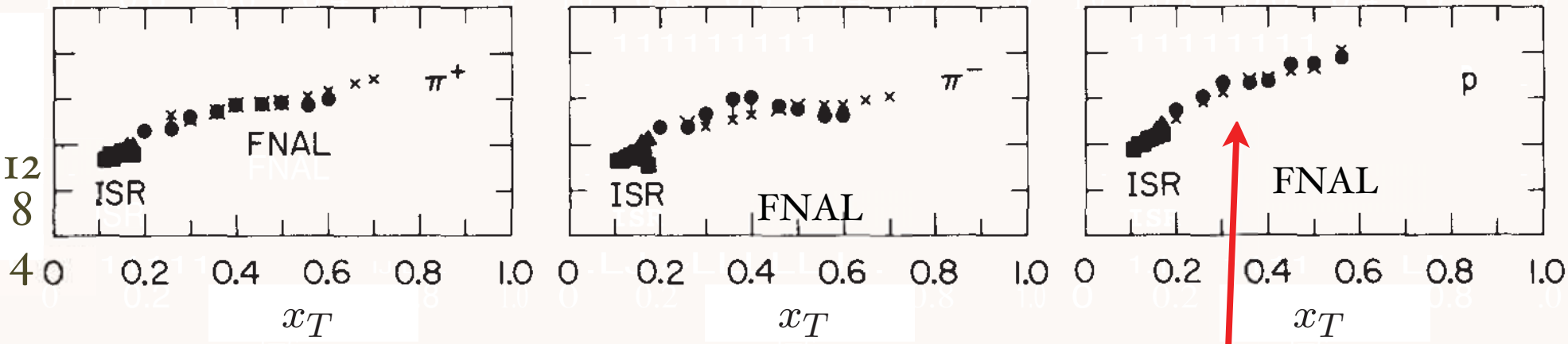
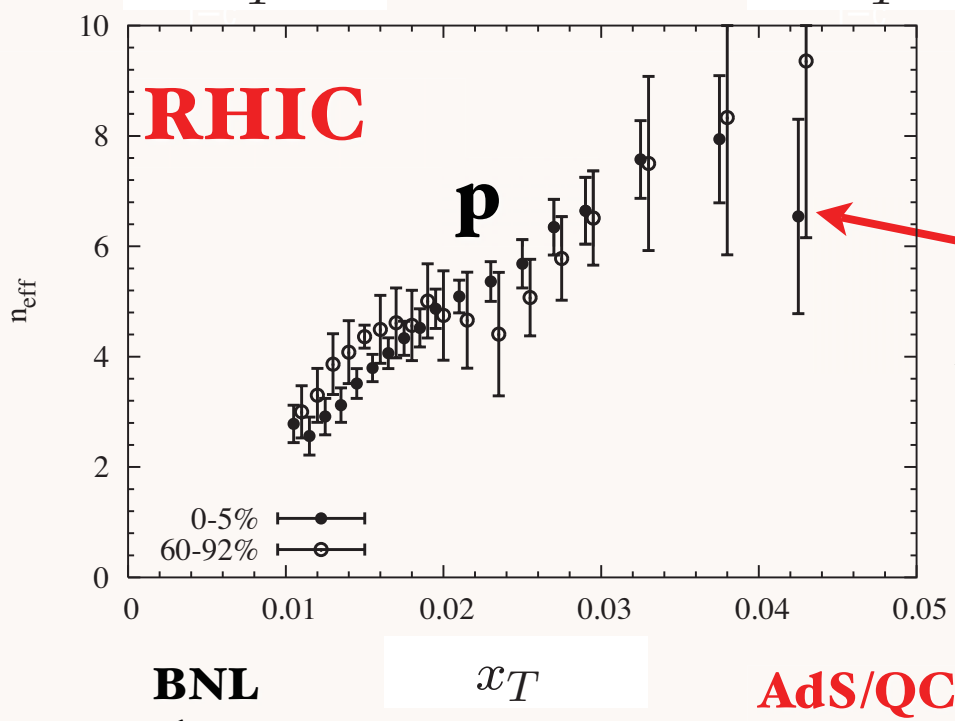
$$E\frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T,\theta_{CM})}{p_T^{n_{eff}}}$$




8

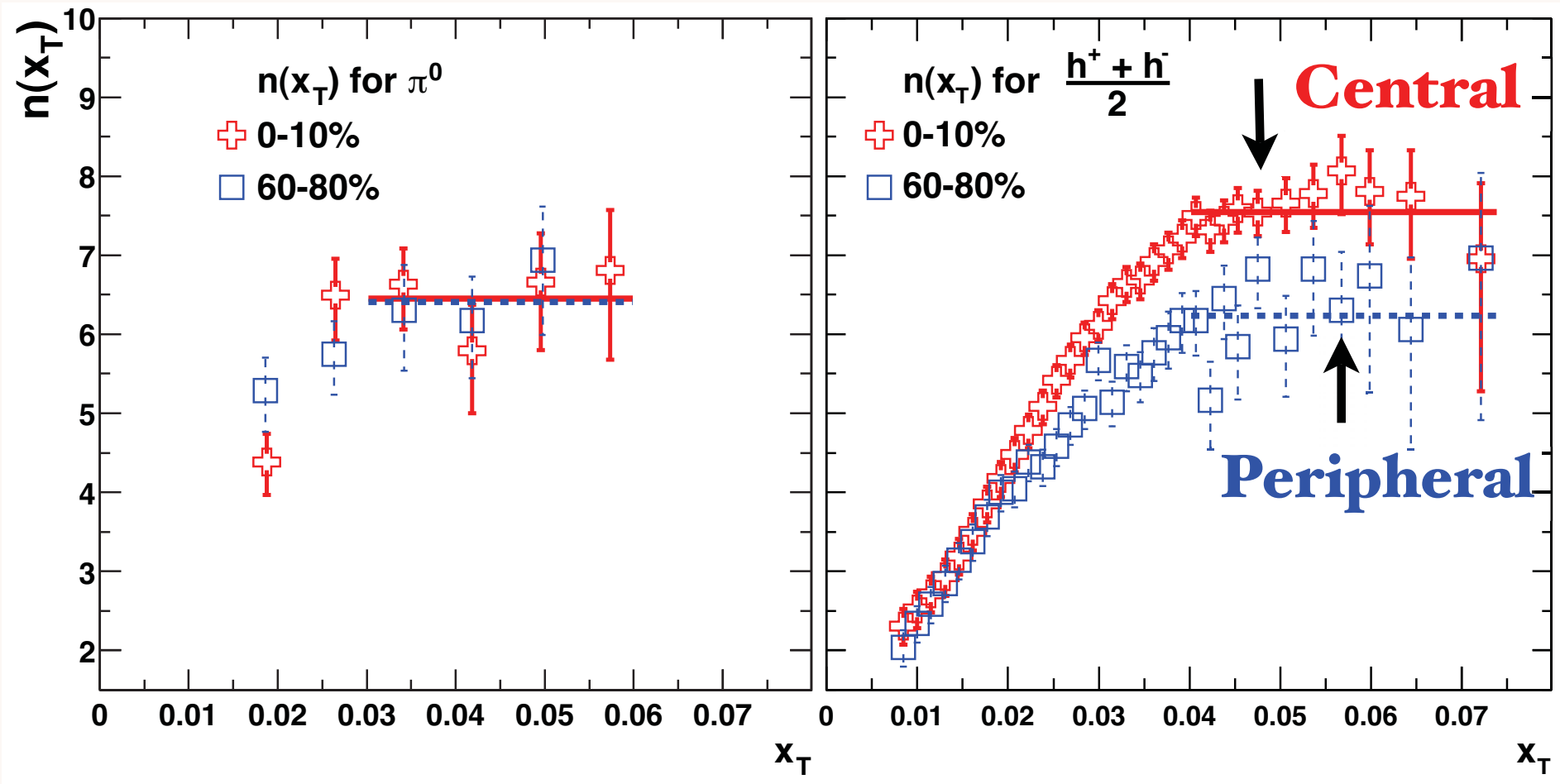
4

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

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

*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

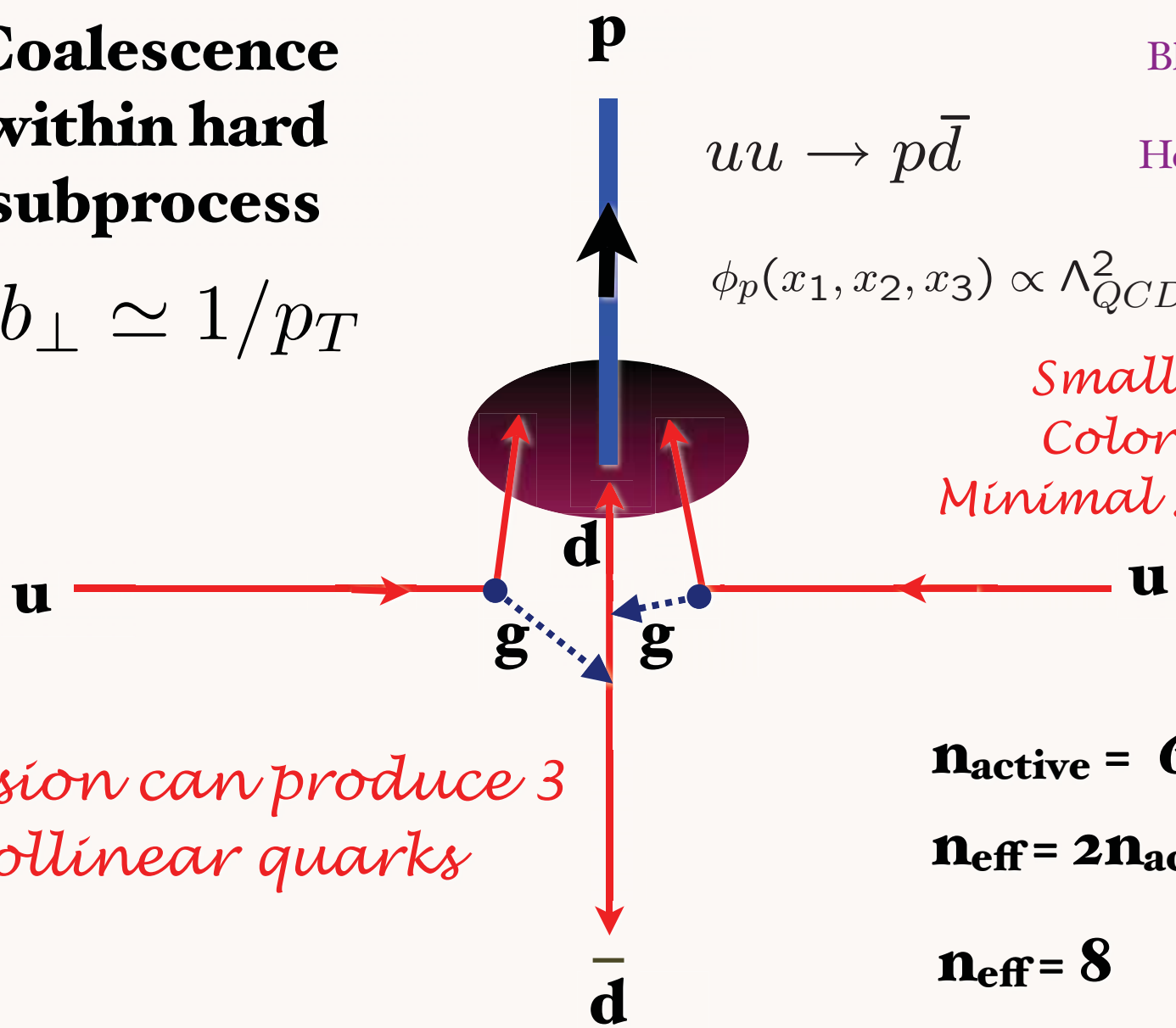
**Coalescence within hard subprocess**

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

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

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

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




Small color-singlet
Color Transparent
Minimal same-side energy

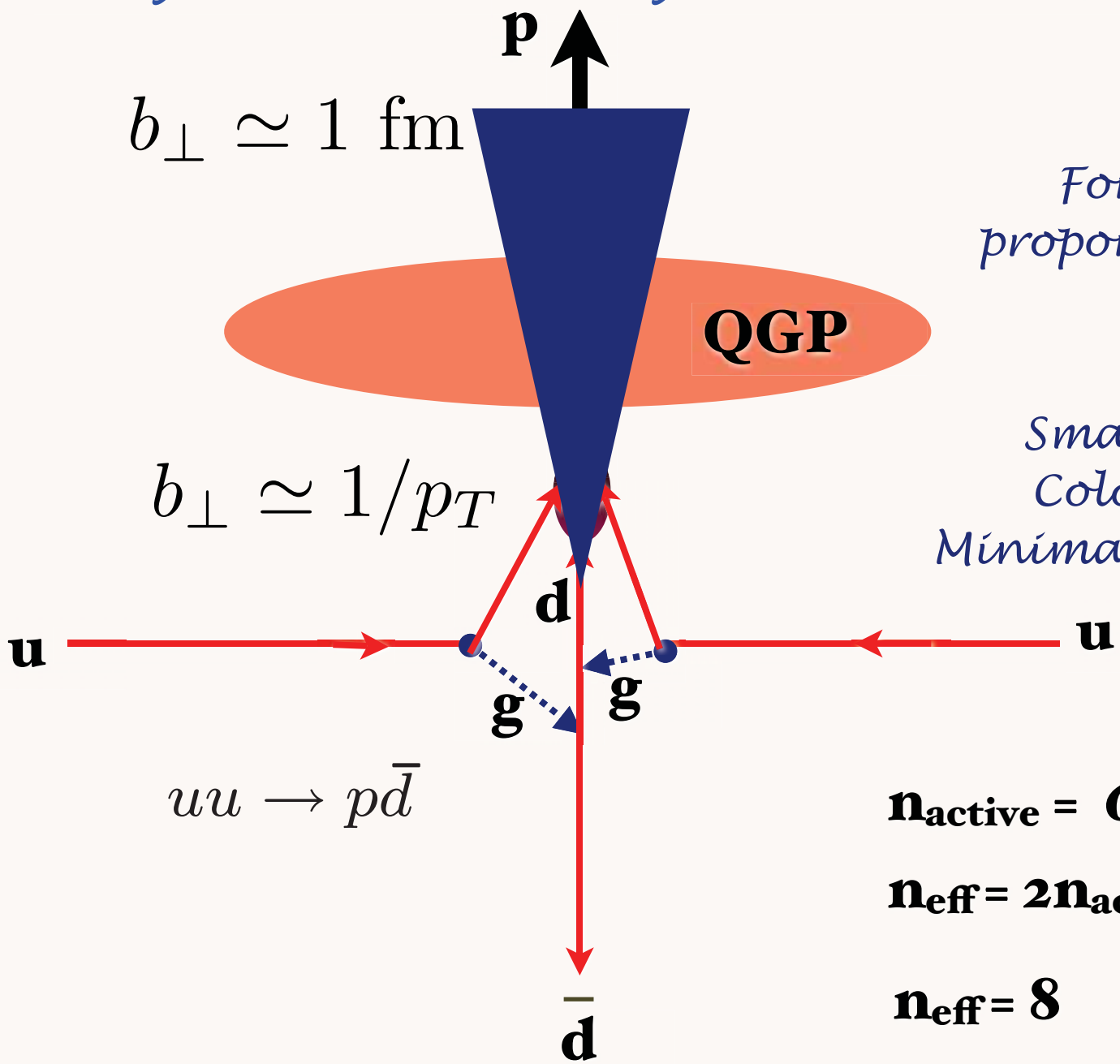
Collision can produce 3 collinear quarks

$n_{active} = 6$

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

$n_{eff} = 8$

# Baryon made directly within hard subprocess




Formation Time
proportional to Energy

Small color-singlet
Color Transparent
Minimal same-side energy

$n_{active} = 6$

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

$n_{eff} = 8$

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

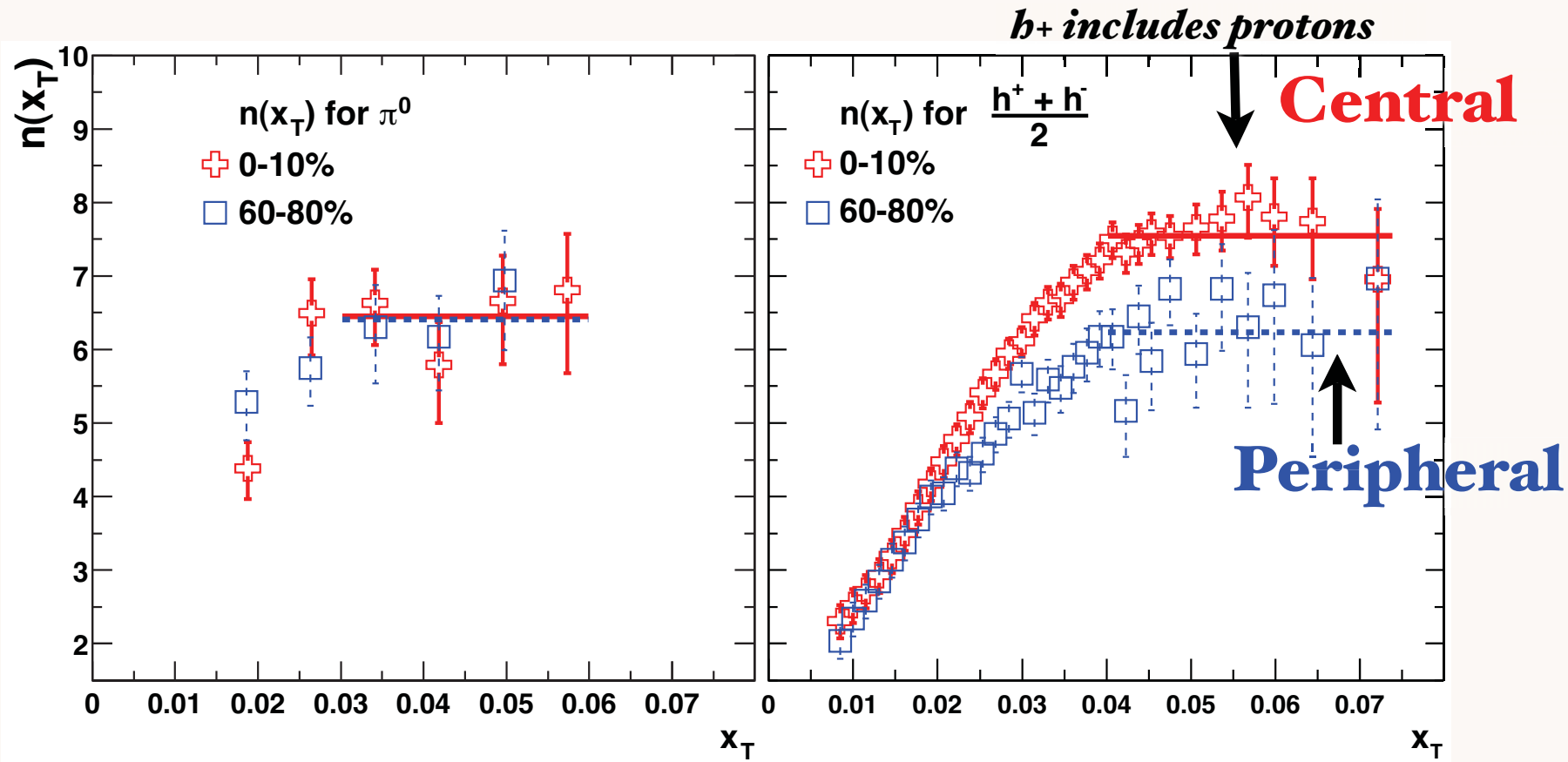
$$\frac{d\sigma}{d^3p/E}(pp \to pX) = A\frac{(1-x_T)^{11}}{p_T^4} + B\frac{(1-x_T)^7}{p_T^8}$$

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

Small color-singlet
Color Transparent
Minimal same-side energy

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

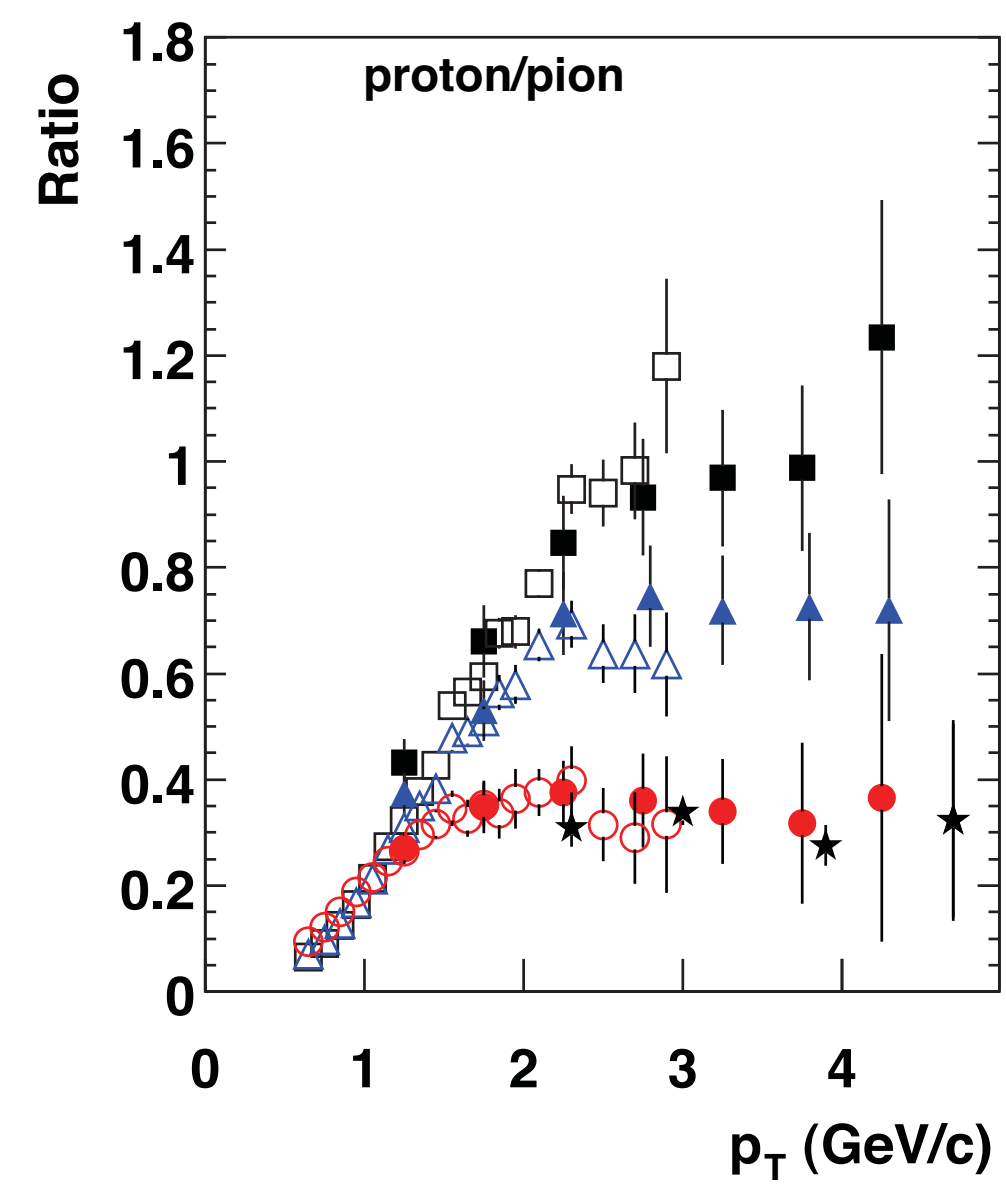
S. S. Adler, *et al.*, PHENIX Collaboration, *Phys. Rev.* C **69**, 034910 (2004) [nucl-ex/0308006].




*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!



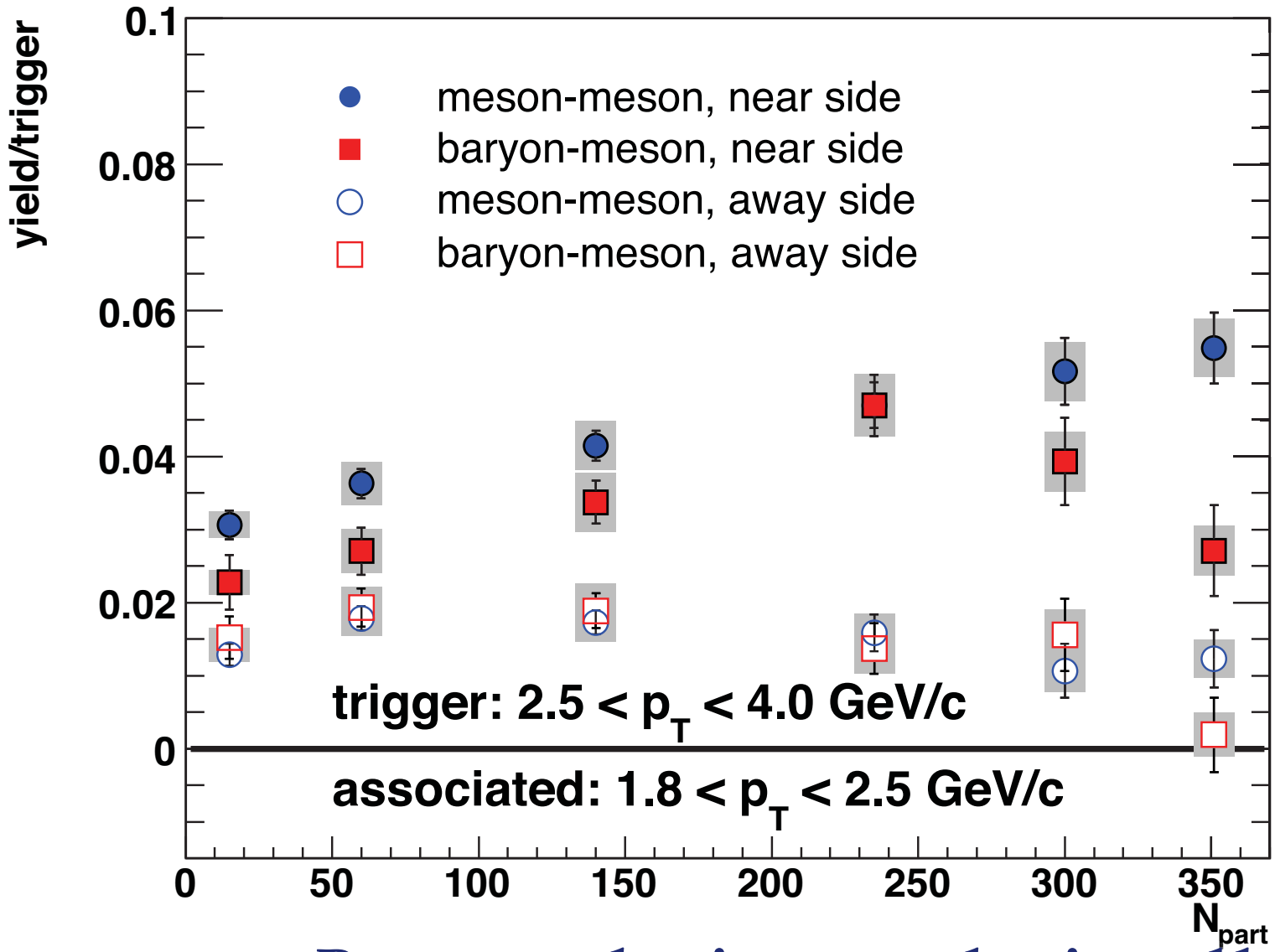

***Protons less absorbed in nuclear collisions than pions because of dominant color transparent higher twist process***

← **Central**

- □ ■ 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

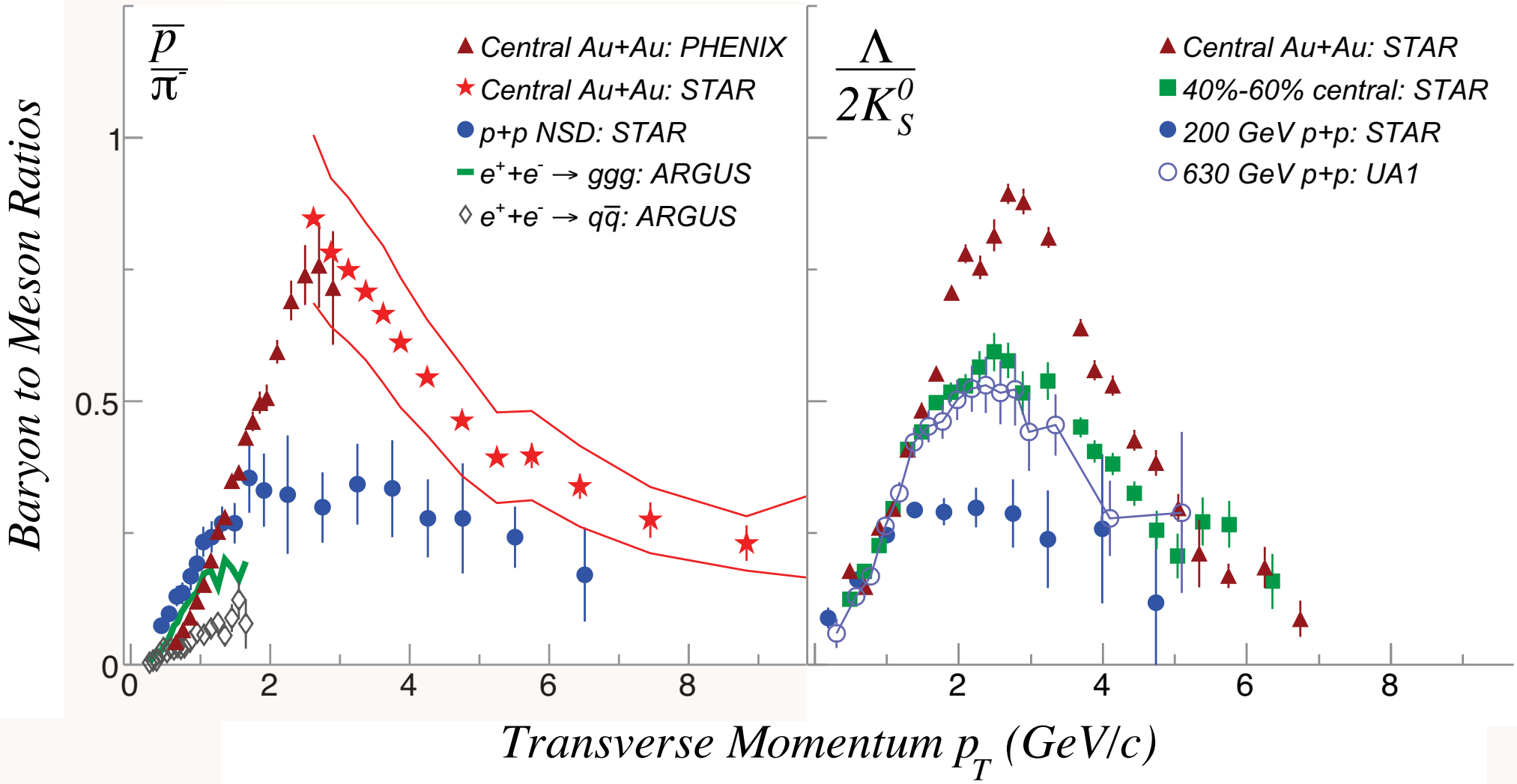
← **Peripheral**

Anne Sickles




*proton trigger: # same-side particles decreases with centrality*

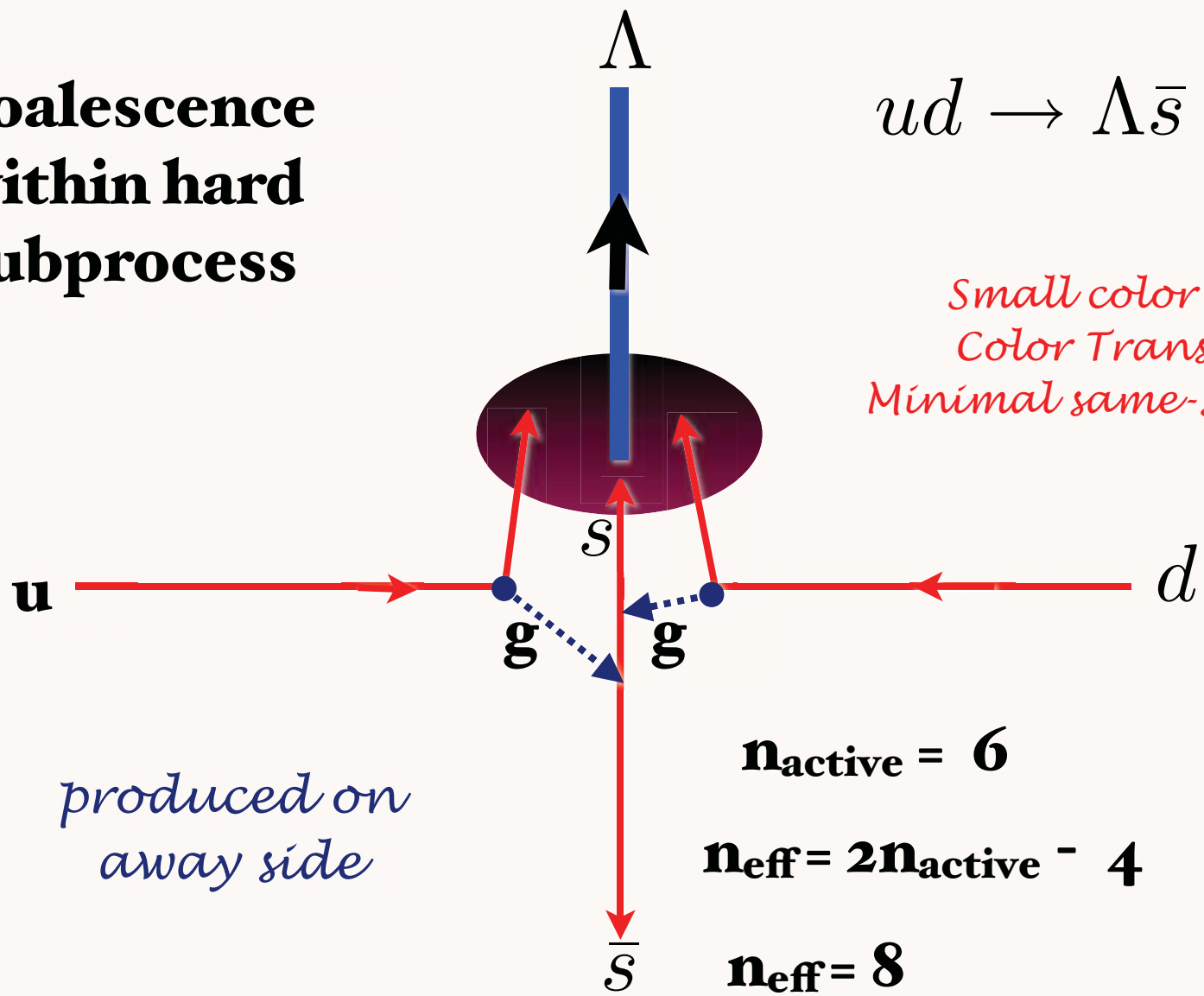
**Proton production more dominated by color-transparent direct high-$n_{eff}$ subprocesses**


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
0
0.5
1
0
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

$n_{active} = 6$

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

$n_{eff} = 8$

# 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 $x_T = 1$

# Role of higher twist in hard inclusive reactions

- **Hadron can be produced directly in hard subprocess as in exclusive reactions**

*"Semi-Exclusive Reactions"*

Hoyer, Mueller, Tang, sjb

- **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**

# Holographic Connection between LF and AdS/CFT

- Predictions for hadronic spectra, light-front wavefunctions, interactions
- Deduce meson and baryon wavefunctions, distribution amplitude, structure function from holographic constraint
- Identification of Orbital Angular Momentum Casimir for SO(2): LF Rotations
- Extension to massive quarks

$$|p, S_z> = \sum_{n=3} \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) |n; \vec{k}_{\perp_i}, \lambda_i>$$

*sum over states with n=3, 4, ...constituents*

The Light Front Fock State Wavefunctions

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

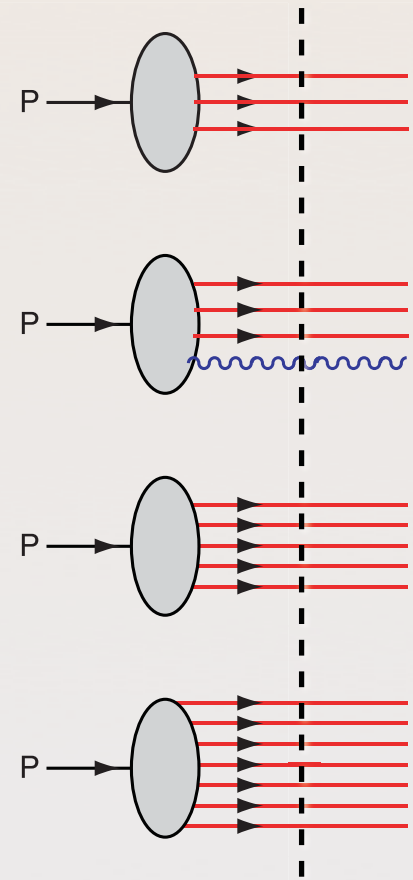
are boost invariant; they are independent of the hadron's energy and momentum $P^\mu$.

The light-cone momentum fraction

$$x_i = \frac{k_i^+}{p^+} = \frac{k_i^0 + k_i^z}{P^0 + P^z}$$

are boost invariant.

$$\sum_i^n k_i^+ = P^+, \ \sum_i^n x_i = 1, \ \sum_i^n \vec{k}_i^\perp = \vec{0}^\perp.$$




*Fixed LF time*

**Intrinsic heavy quarks** $\bar{u}(x) \neq \bar{d}(x)$

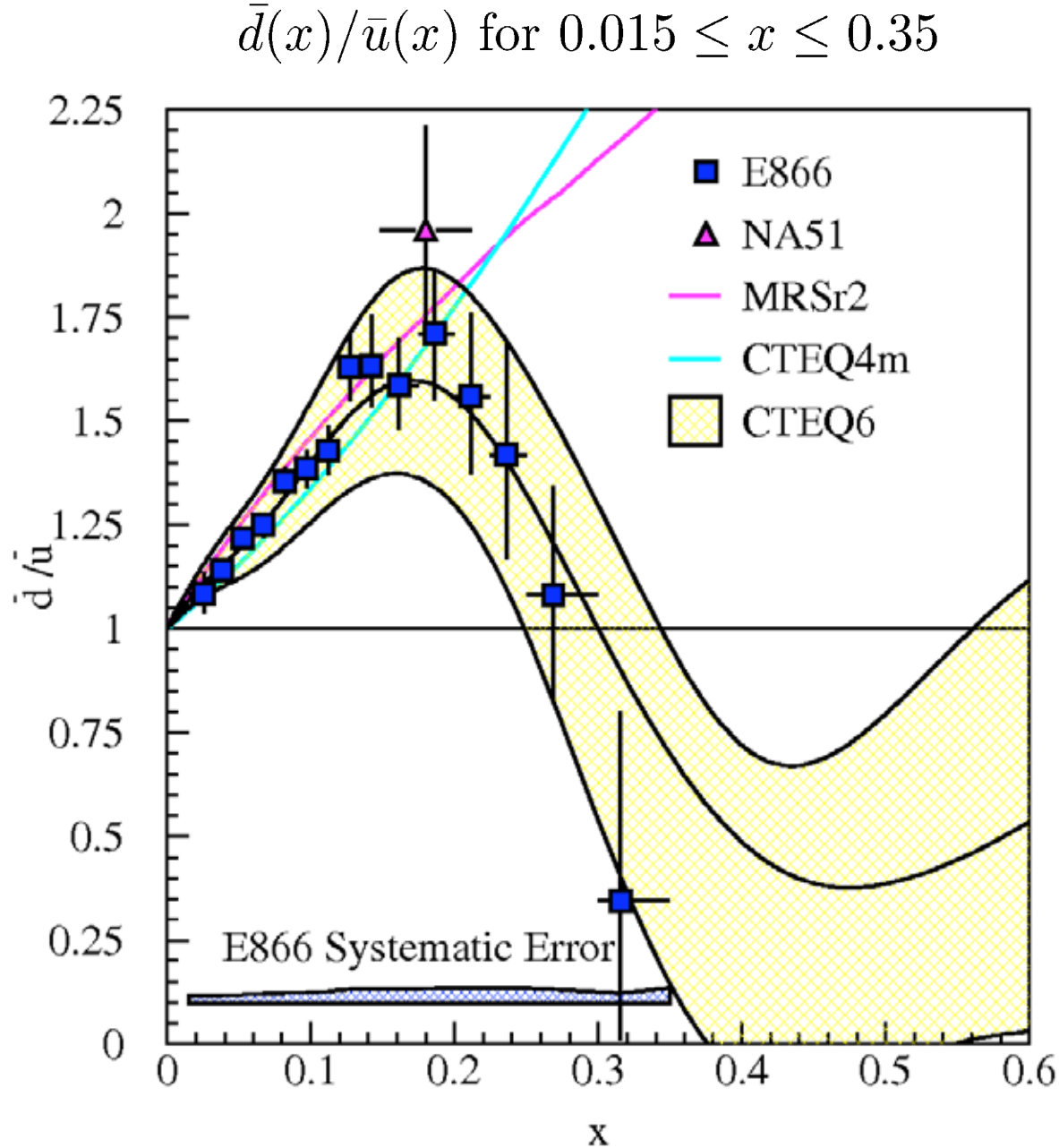
**Mueller: BFKL DYNAMICS** $\bar{s}(x) \neq s(x)$

# Light Antiquark Flavor Asymmetry

- Naïve Assumption from gluon splitting:

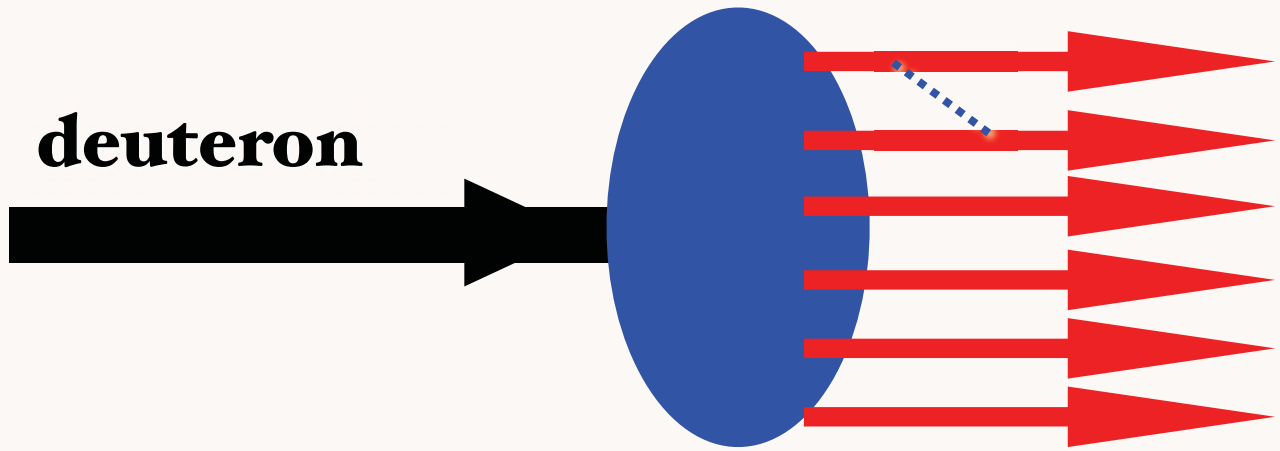
$$\bar{d}(x) = \bar{u}(x)$$

- E866/NuSea (Drell-Yan)



# Evolution of 5 color-singlet Fock states

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



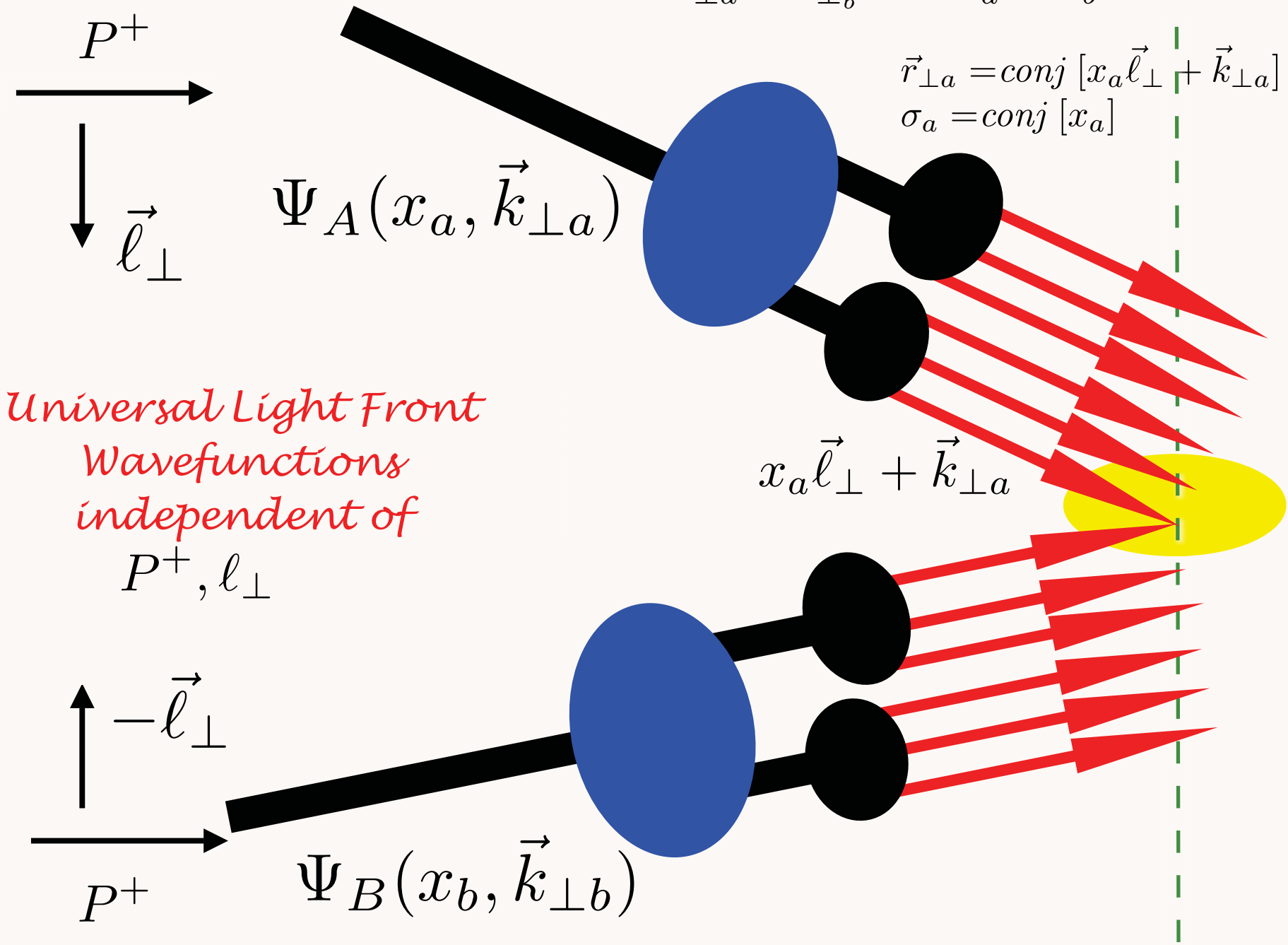

$$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$$

$$\sum_i^n x_i = 1$$

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

*5 X 5 Matrix Evolution Equation for deuteron distribution amplitude*

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




Universal Light Front Wavefunctions independent of $P^+, \ell_\perp$

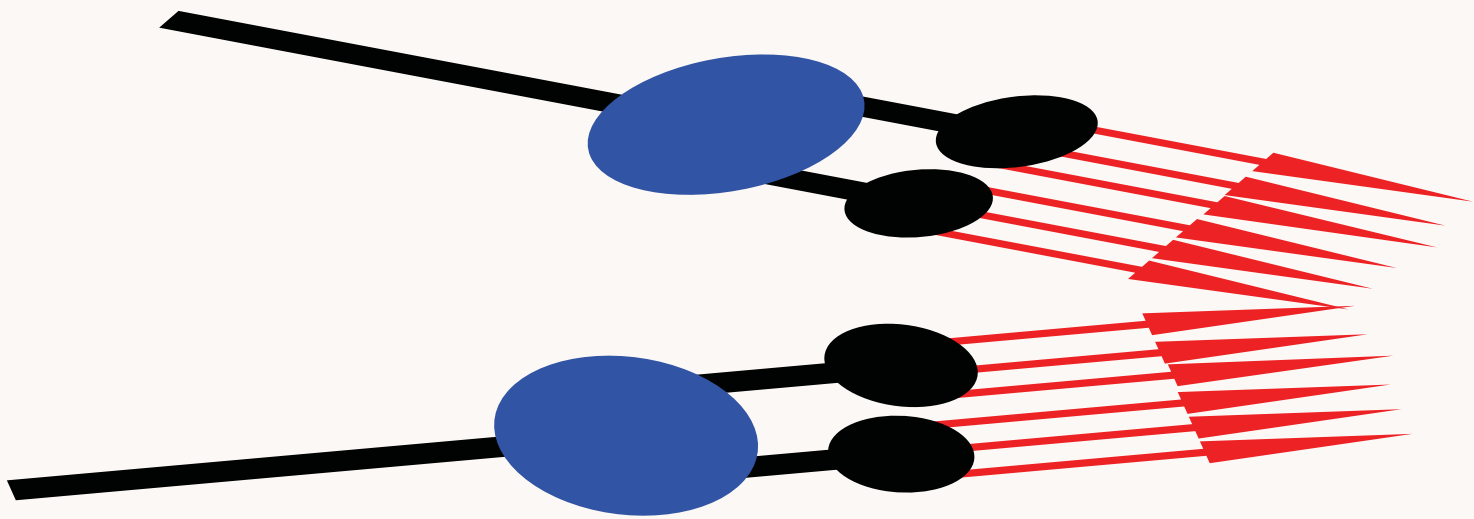
$$p_A = (P^+, \frac{M_A^2 + \ell_\perp^2}{P^+}, \vec{\ell}_\perp)$$

$$p_B = (P^+, \frac{M_B^2 + \ell_\perp^2}{P^+}, -\vec{\ell}_\perp)$$

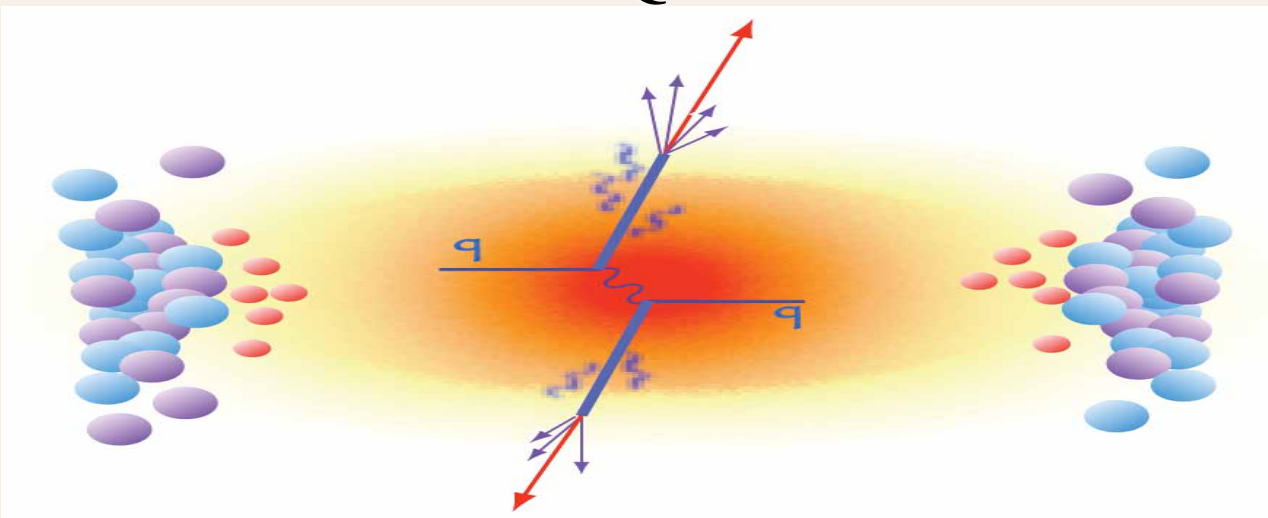
Both beams move along the positive z direction, and $s = (p_A + p_B)^2 = 2M_A^2 + 2M_B^2 + 4\ell_\perp^2$ is represented by the oppositely directed transverse momenta $\pm\vec{\ell}_\perp$ of the colliding nuclei.

Note that the value of $P^+$ is irrelevant.

As $\tau$ progresses, the constituents from A and B each interact as their coordinates $\sigma_i$ and $\vec{b}_{\perp i}$ overlap.



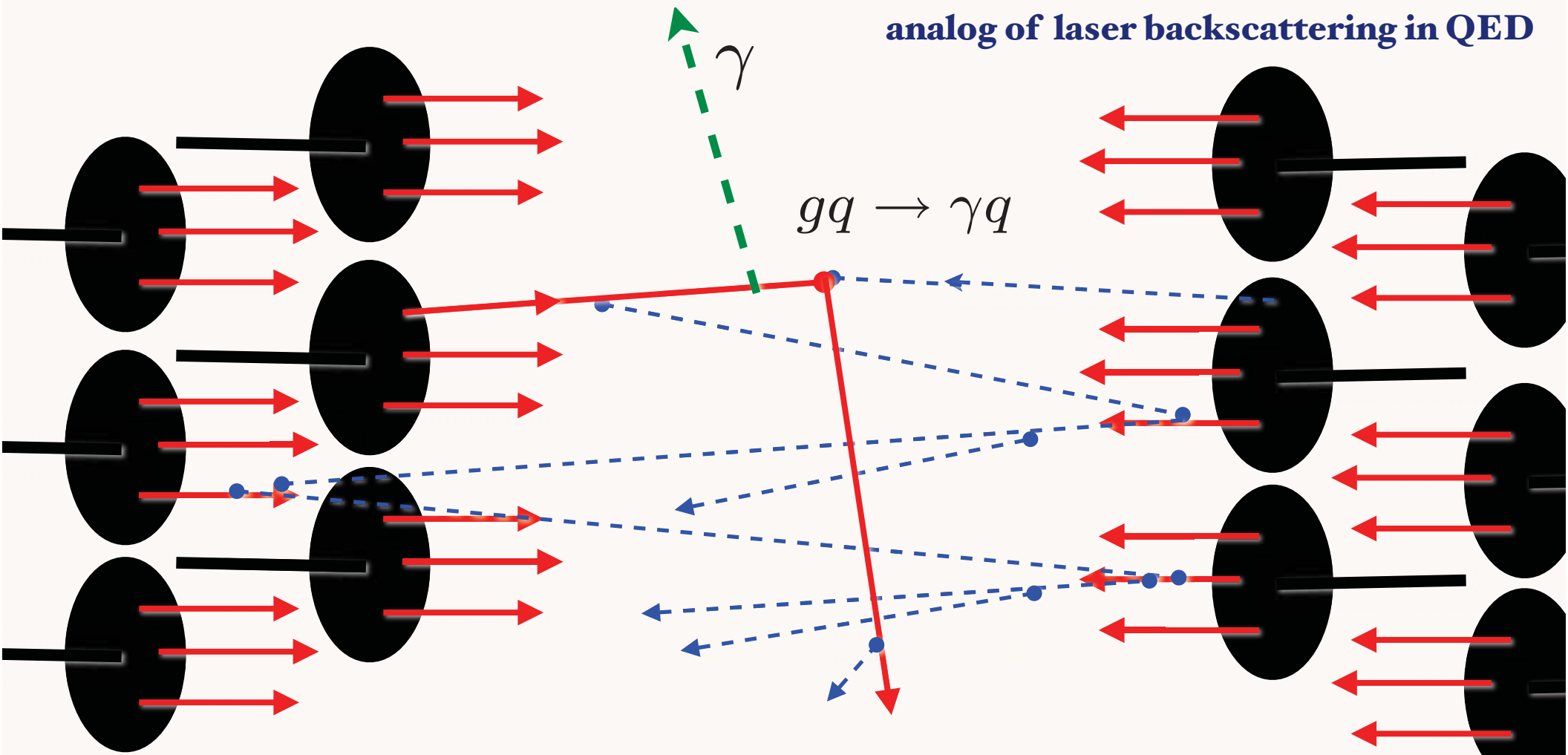
# What is the dynamical mechanism which creates the QGP?




- How do the parameters of the QGP depend on the initial and final state conditions?
- A dynamical model: "Gluonic Laser"

# Gluonic Laser

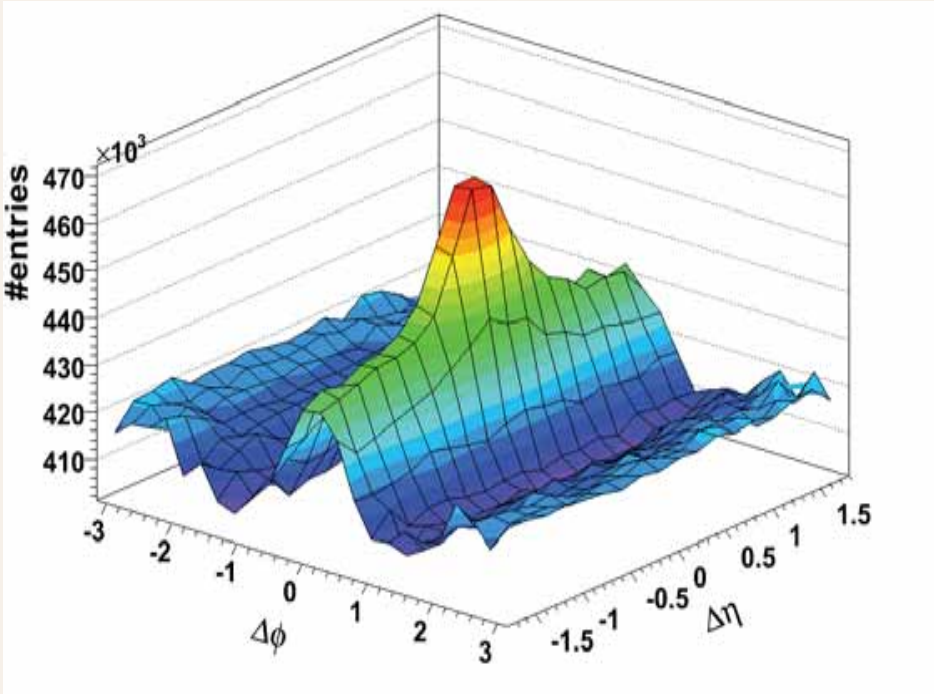
**Gluonic bremsstrahlung from initial hard scattering backscatters on nuclear ``mirrors"**

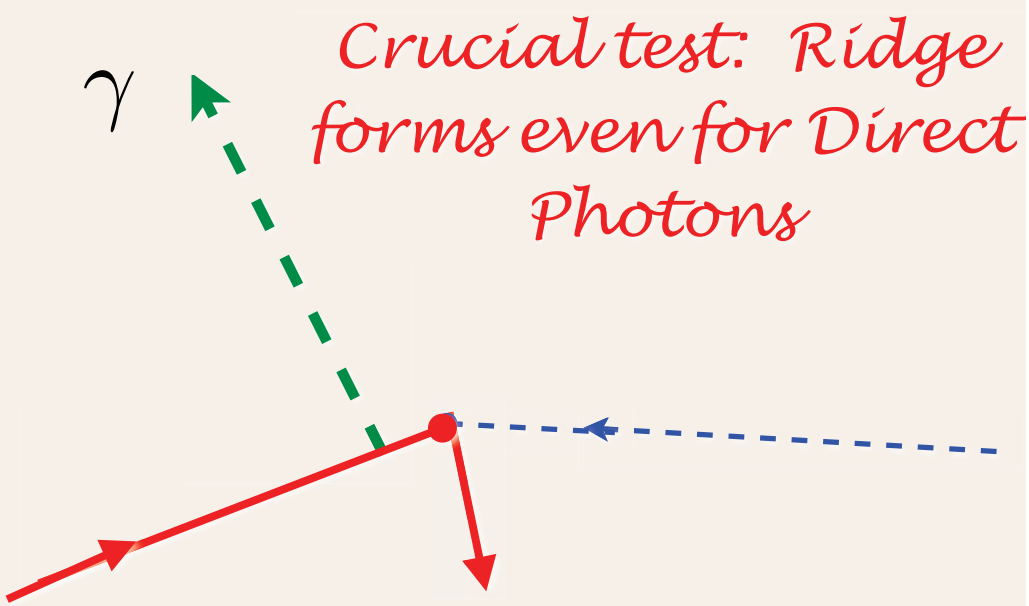



**QCD cascade mechanism for forming quark-gluon plasma inside overlap ellipse**

***energy loss from stimulated radiation of away-side jet***

# Consequences of Gluon Laser Mechanism




**Ridge created by trigger bias (Cronin effect)**

**Momenta of initial colored partons biased towards trigger**

**Soft gluon radiation from initial state partons emitted in plane of production; fills rapidity**

# Possible time sequence of a RHIC Ion-Ion Collision

- **Nuclei collide; nucleons overlap within an ellipse**
- **Initial hard collision between quarks and/or gluons producing high $p_T$ trigger hadron or photon**
- **Induced gluon radiation radiated from initial parton collision**
- **collinear radiation back-scatters on other incoming partons**
- **Cascading gluons creates multi-parton quark-gluon plasma within ellipse, thermalization**
- **Stimulated radiation contributes to energy loss of away-side jet**
- **Sidewise pressure creates hadronic energy along minor axis -- yields planar $\cos 2\phi$ correlation: $v_2$**
- **Same final state for high $p_T$ direct photons and mesons**
- **Baryons formed in higher-twist double-scattering process at high $x_T$; double induced radiation and thus double $v_2$.**

$$|p, S_z> = \sum_{n=3} \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) |n; \vec{k}_{\perp_i}, \lambda_i>$$

*sum over states with n=3, 4, ...constituents*

The Light Front Fock State Wavefunctions

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

are boost invariant; they are independent of the hadron's energy and momentum $P^\mu$.

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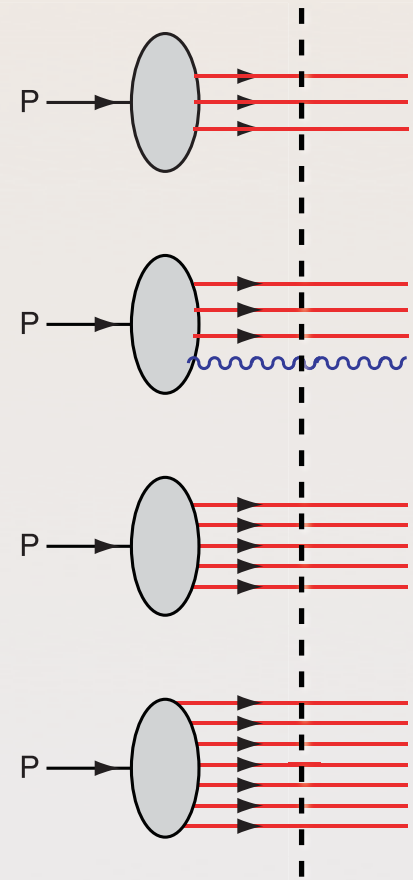
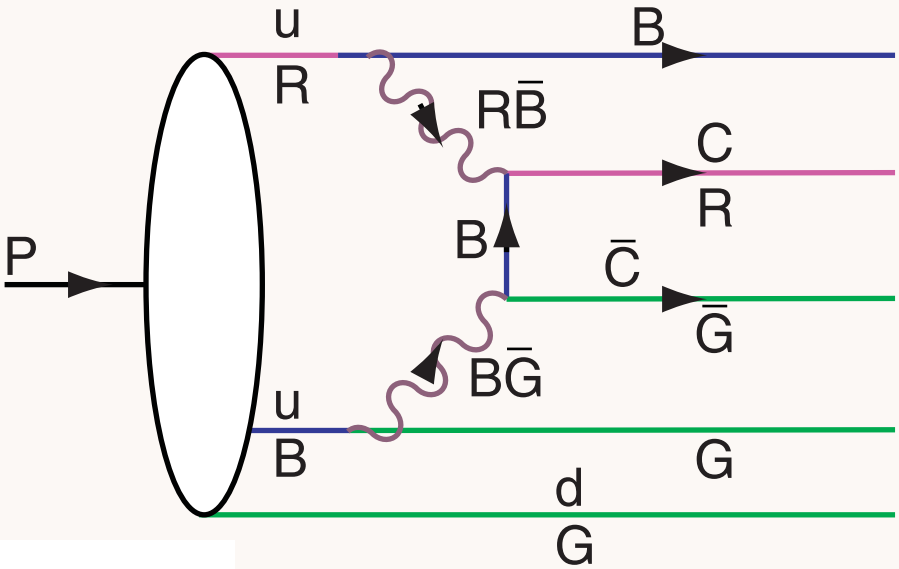



*Fixed LF time*

**Intrinsic heavy quarks** $\bar{u}(x) \neq \bar{d}(x)$

**Mueller: BFKL DYNAMICS** $\bar{s}(x) \neq s(x)$




$|uudc\bar{c}>$ 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.

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

$c\bar{c}$ in Color Octet

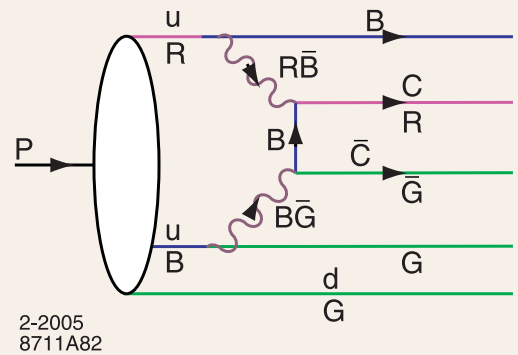
Distribution peaks at equal rapidity (velocity)
Therefore heavy particles carry the largest momentum fractions

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

*High x charm!*

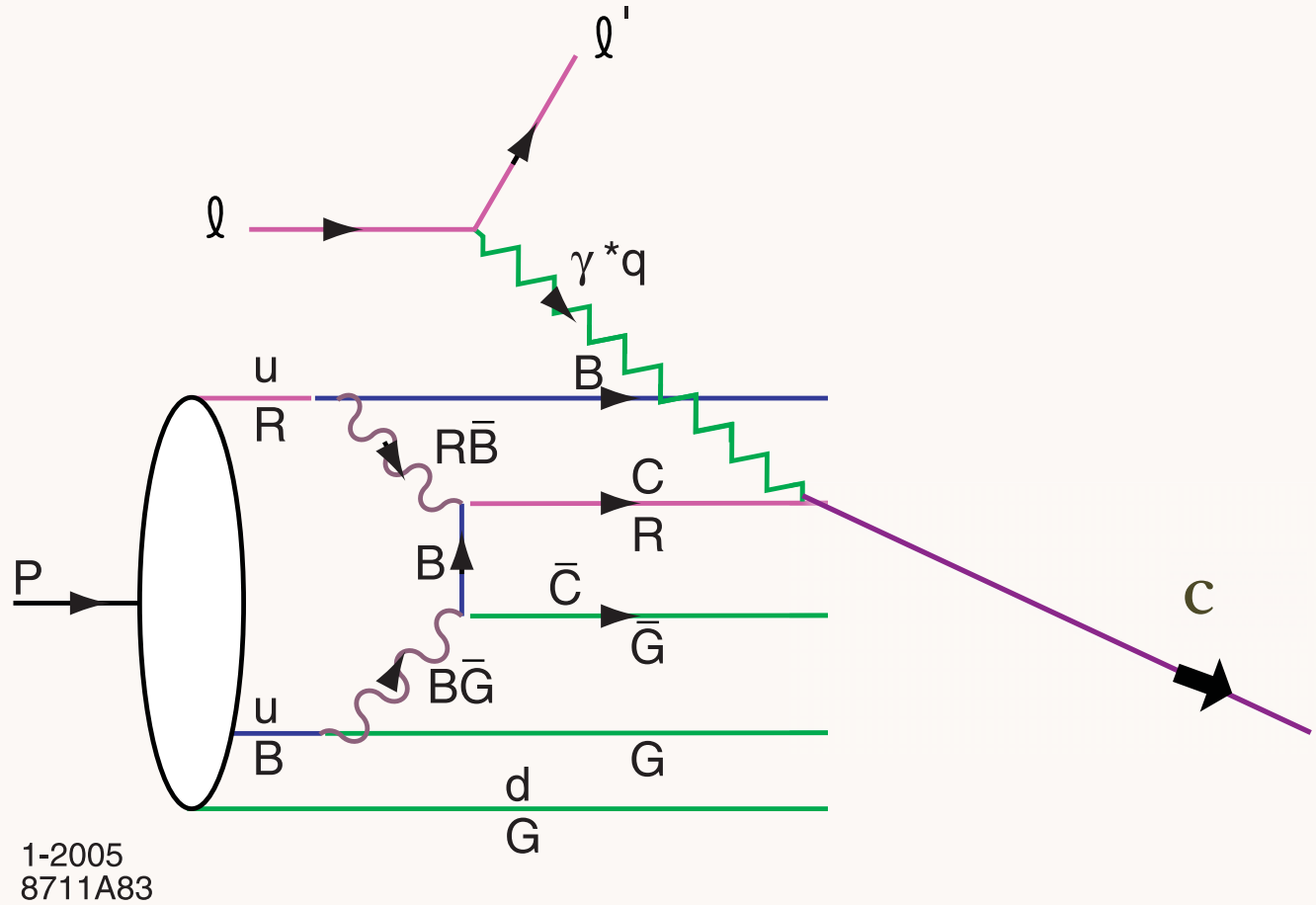
Hoyer, Peterson, Sakai, sjb

# 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

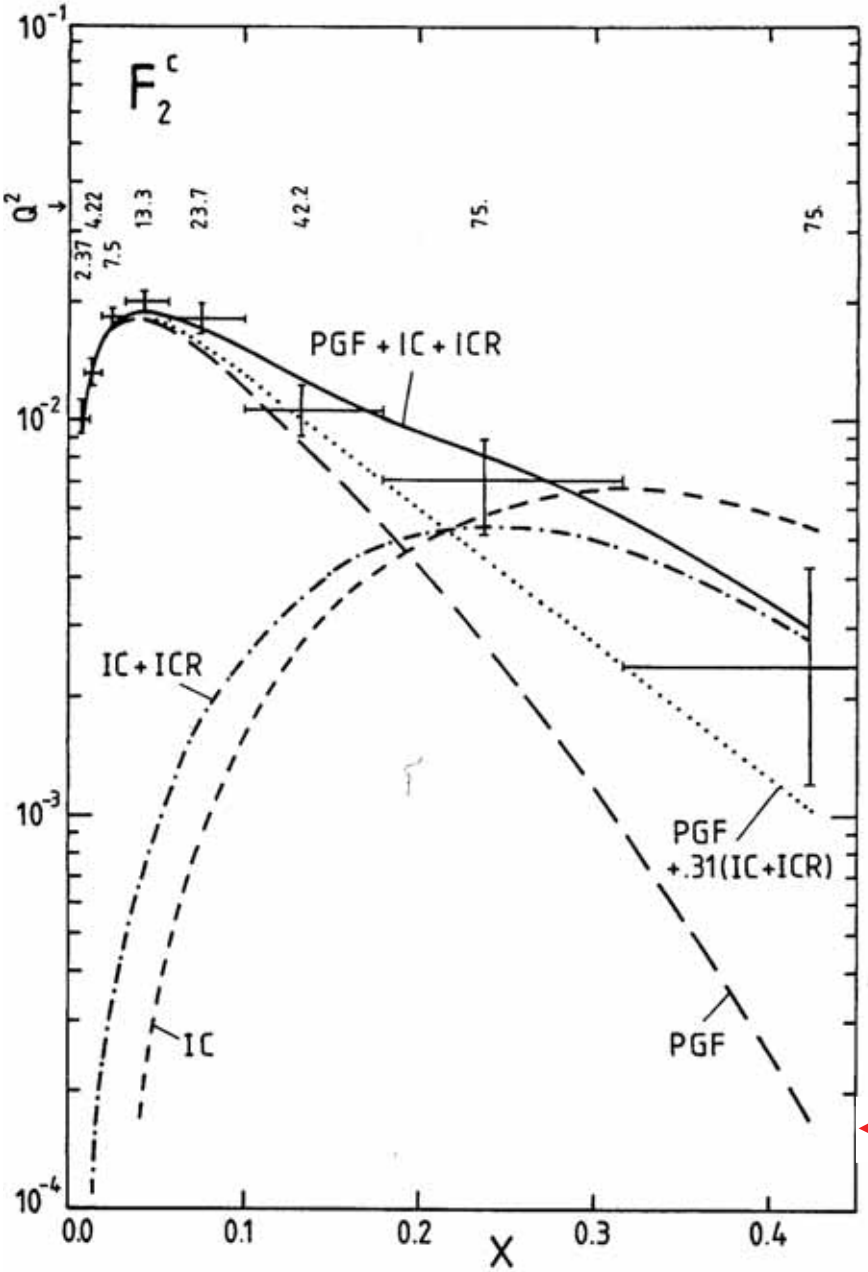
# Measure c(x) in Deep Inelastic Lepton-Proton Scattering




Hoyer, Peterson, SJB

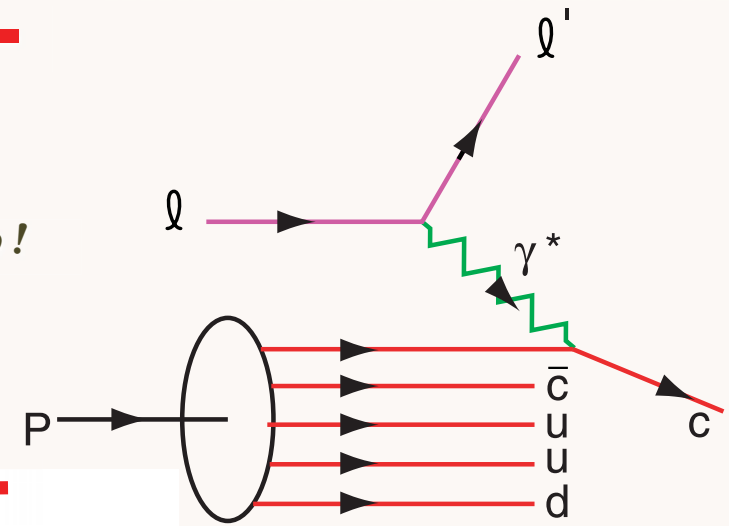
# Measurement of Charm Structure Function

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 $x_F$ $pp \to \Lambda_c X$

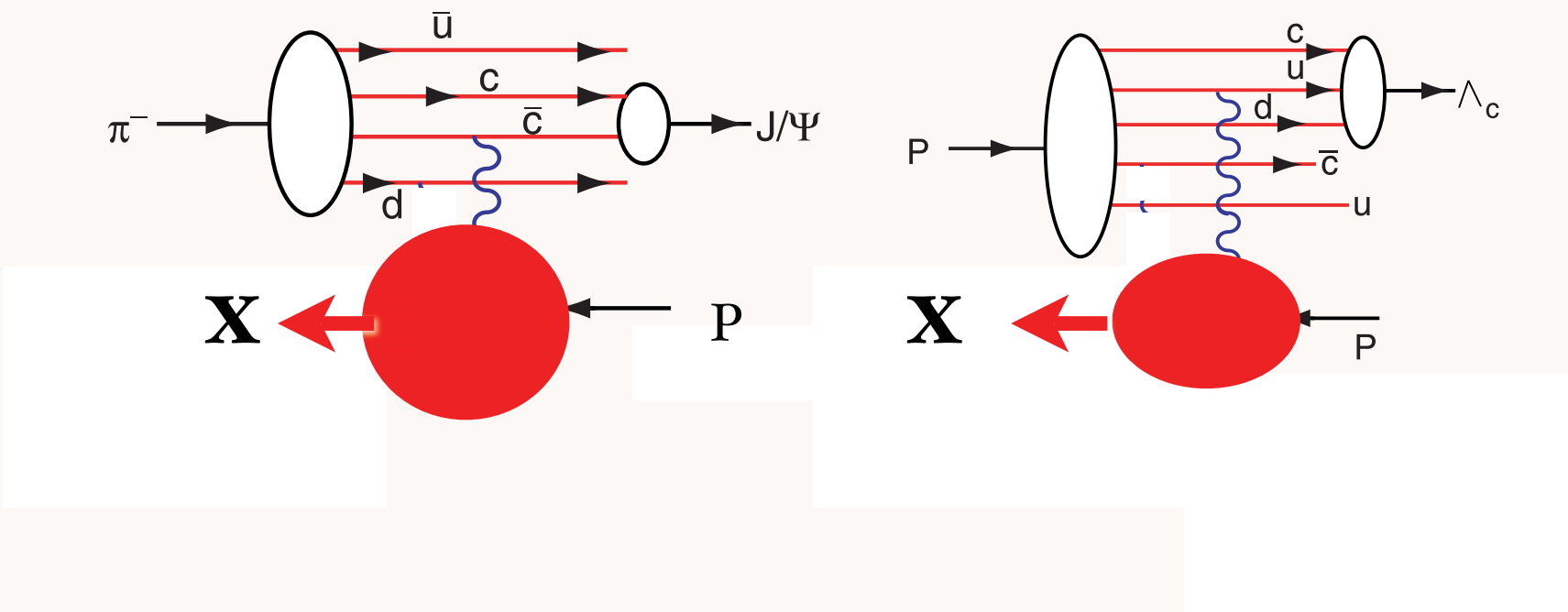
- High $x_F$ $pp \to \Lambda_b X$

- High $x_F$ $pp \to \Xi(ccd) X$ (SELEX)

Test intrinsic high-$x$ $c(x)$ and $b(x)$ at RHIC

$$pp \to c, bX \text{ at high } p_T, x_F$$

# Leading Hadron Production from Intrinsic Charm

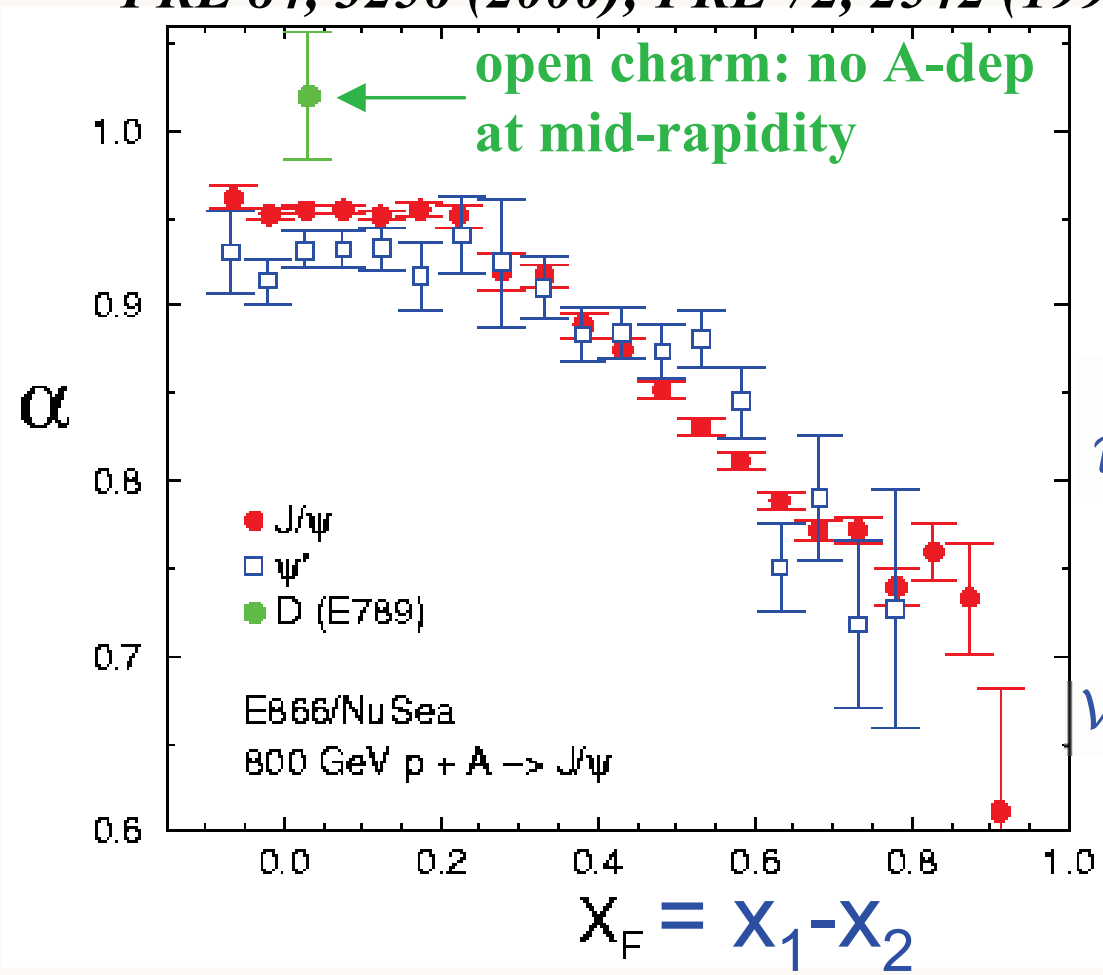



Coalescence of Comoving Charm and Valence Quarks Produce $J/\psi$, $\Lambda_c$ and other Charm Hadrons at High $x_F$

**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*

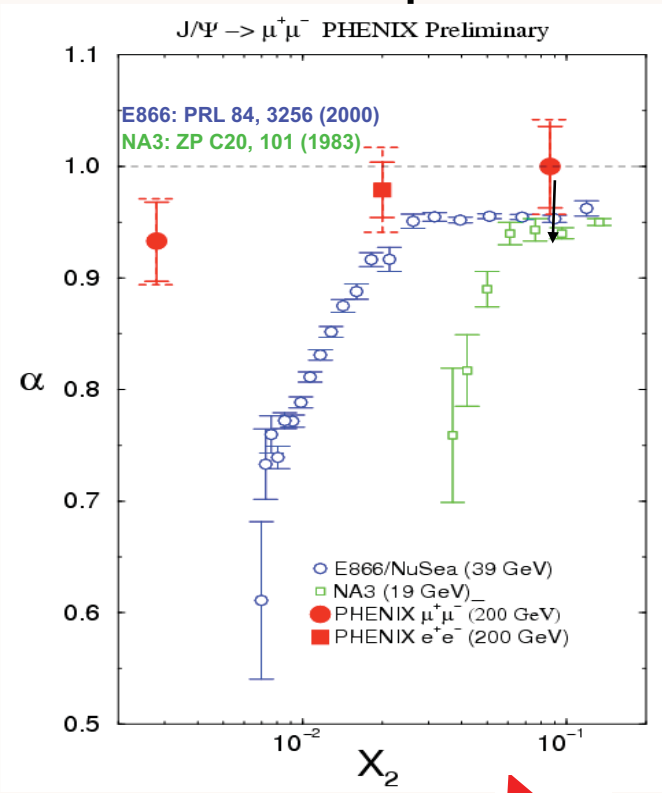
*Violation of PQCD Factorization!*

**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

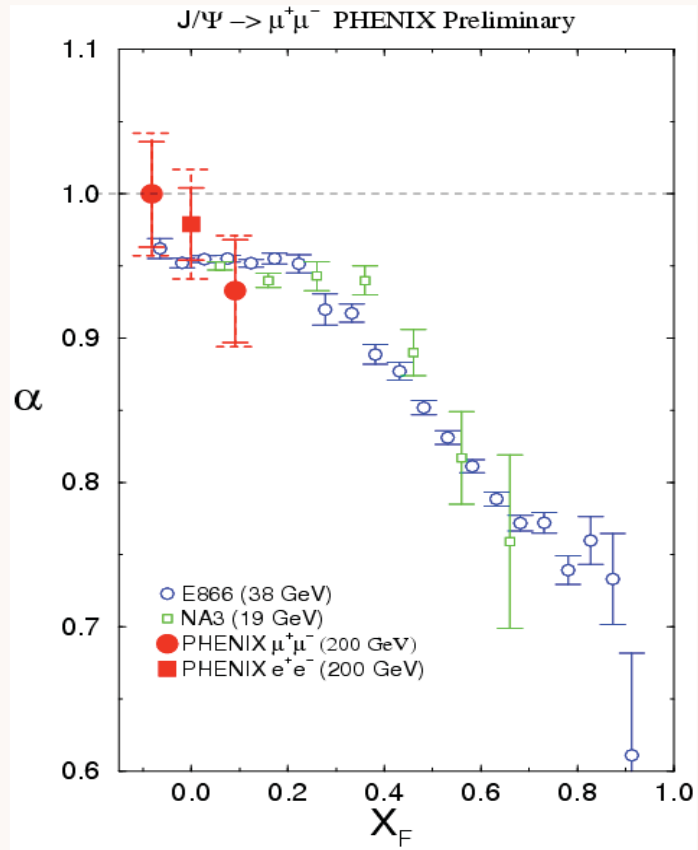
# J/ψ nuclear dependence vrs rapidity, $x_{Au}$, $x_F$

M.Leitch

## PHENIX compared to lower energy measurements




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

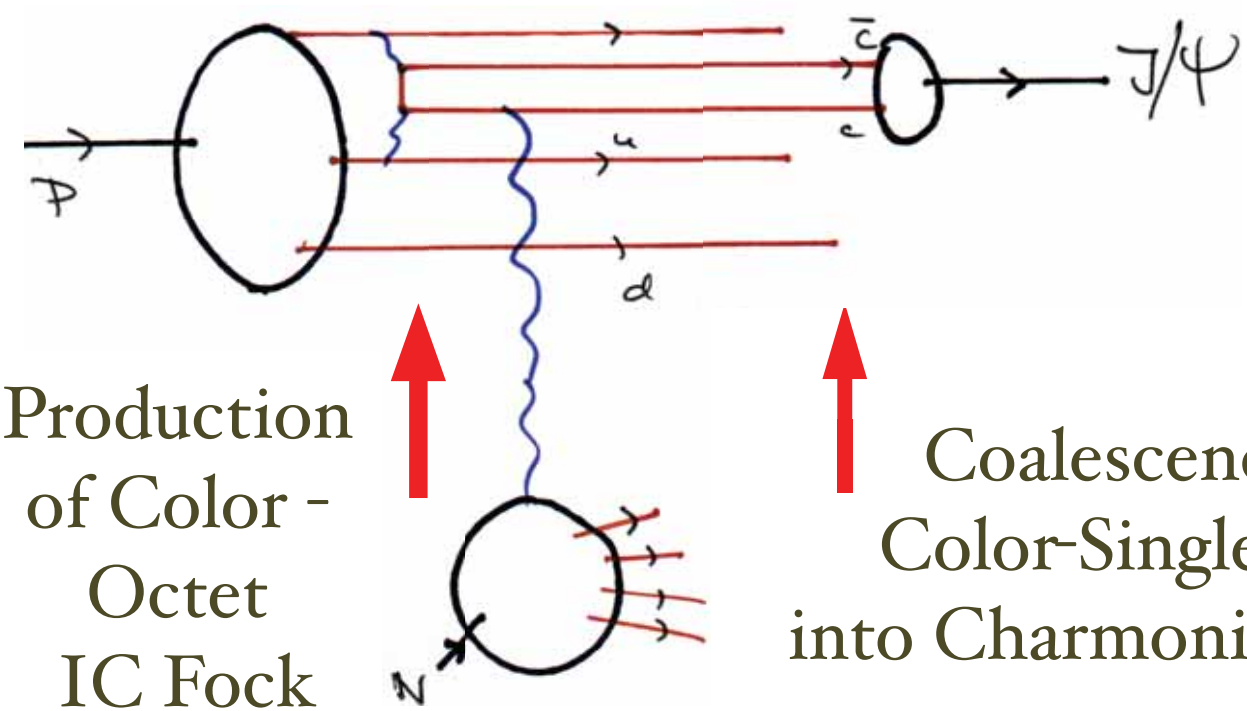



*Huge "absorption" effect*

*Violates PQCD factorization!*

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

Hoyer, Sukhatme, Vanttinen



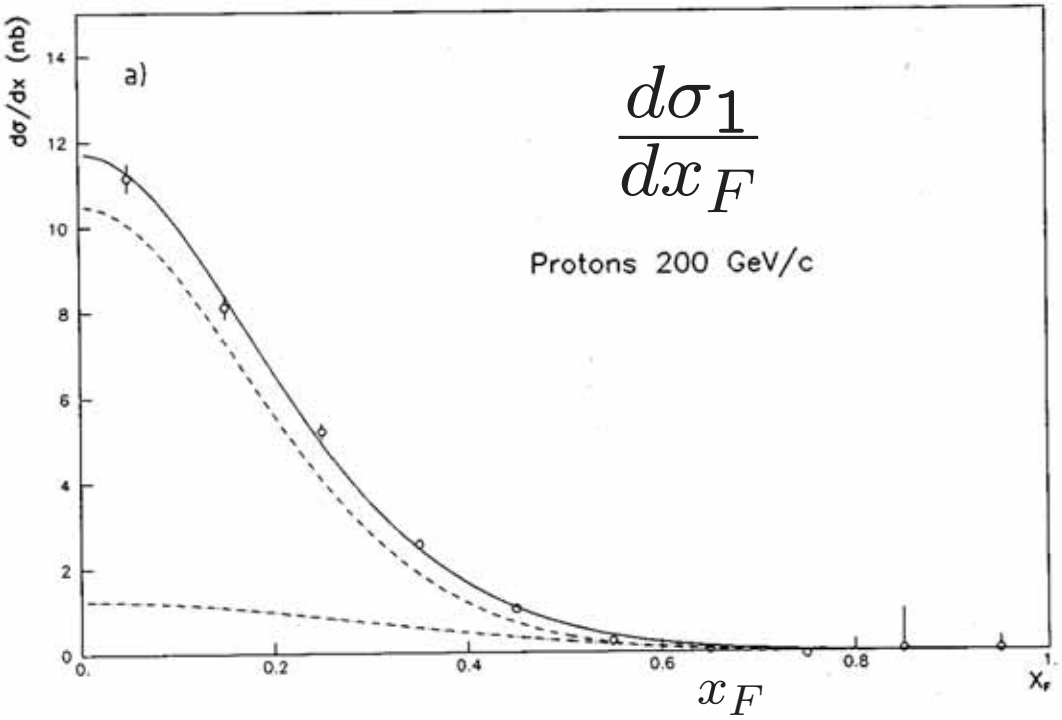

Production of Color - Octet IC Fock State

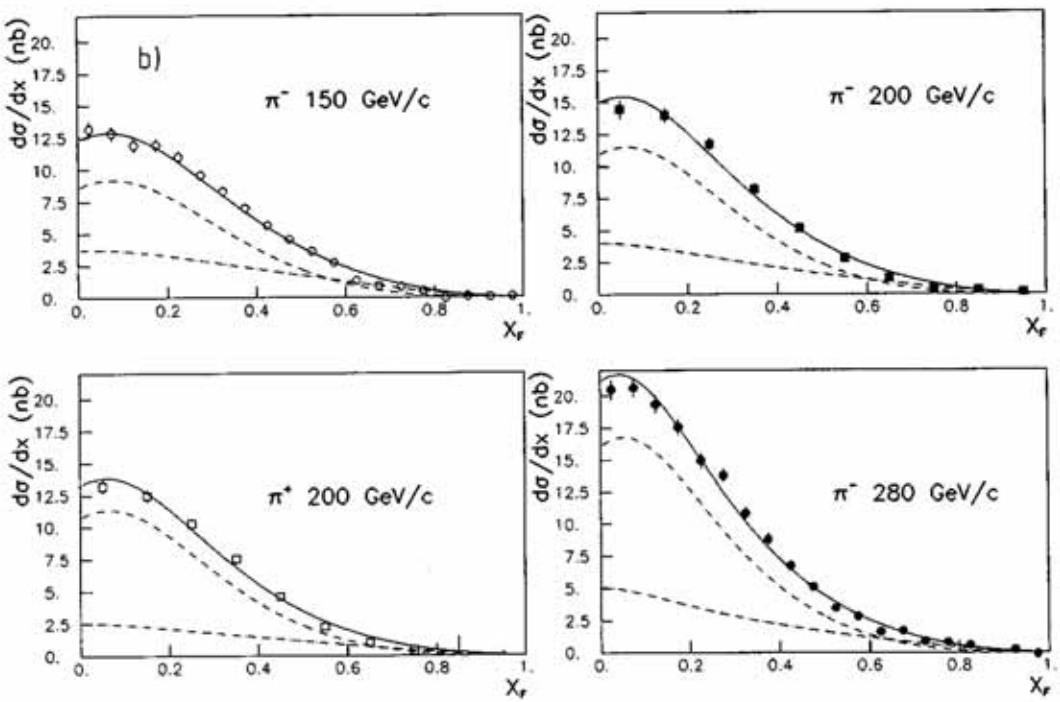
Coalescence of Color-Singlet Pair into Charmonium State

Scattering on Nucleon via one Gluon

**Color-Octet IC Fock state interacts on nuclear front surface**

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




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

J. Badier et al, NA3

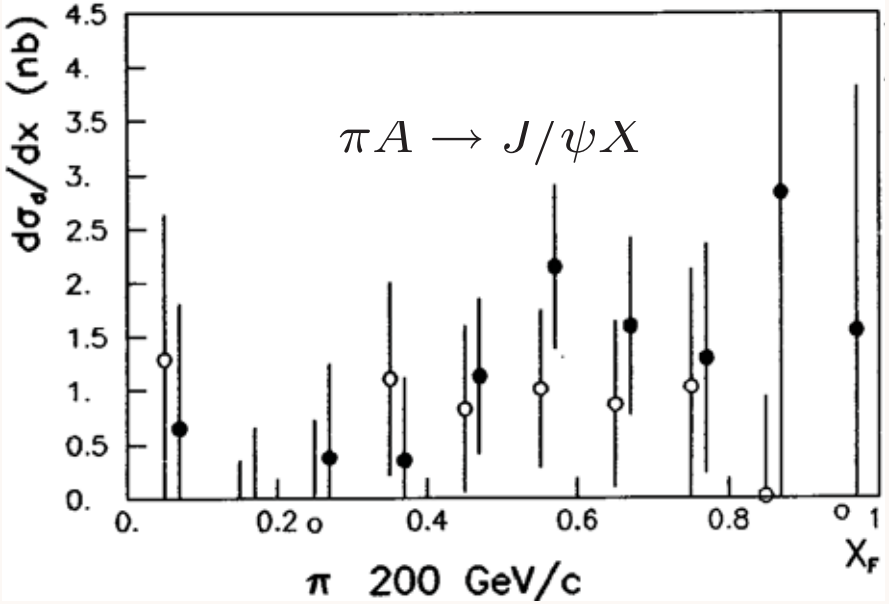
*Two Components*

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

$A^1$ component

*Identify with Fusion*

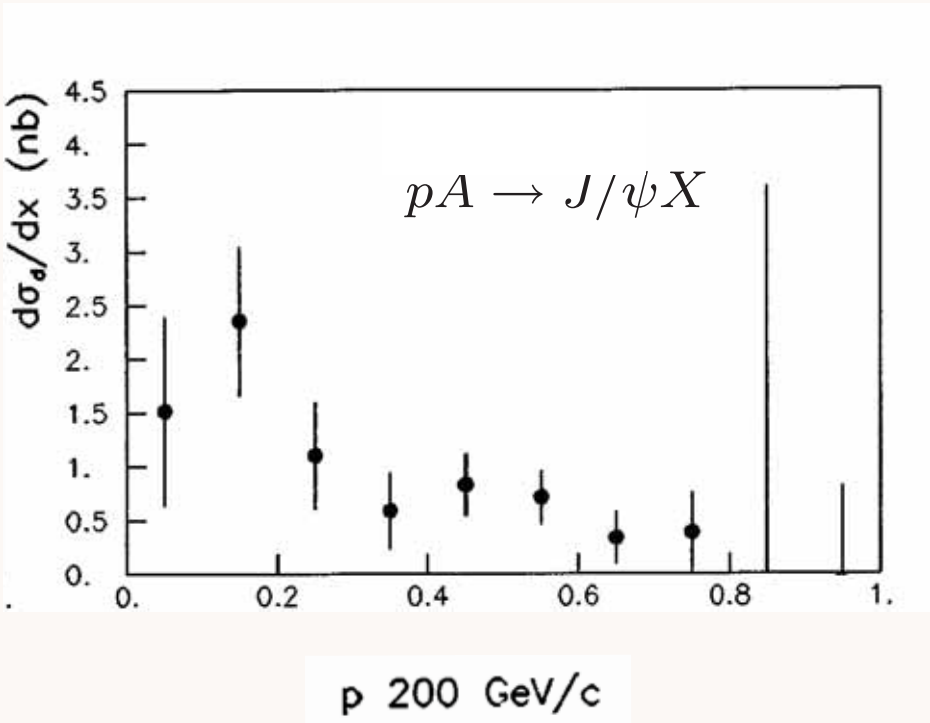
**Conventional PQCD subprocesses**




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




*Identify with IC High $x_F$*

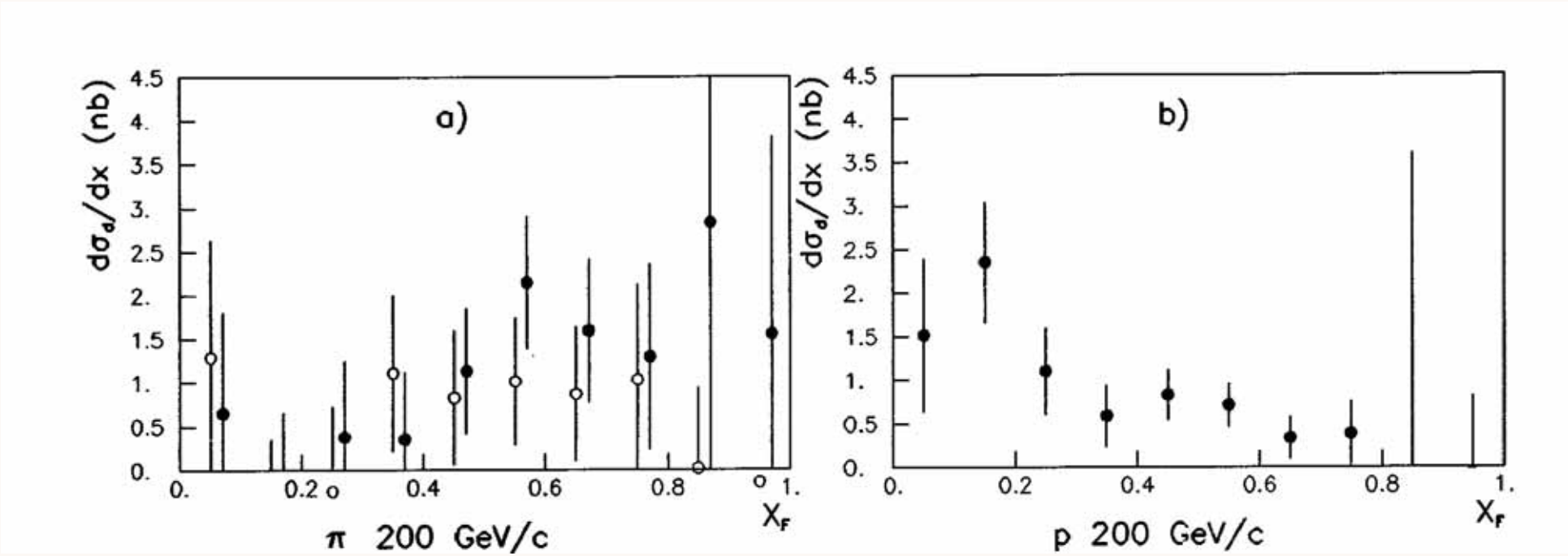
*Remarkably Flat Distribution*

**Excess beyond conventional PQCD subprocesses**

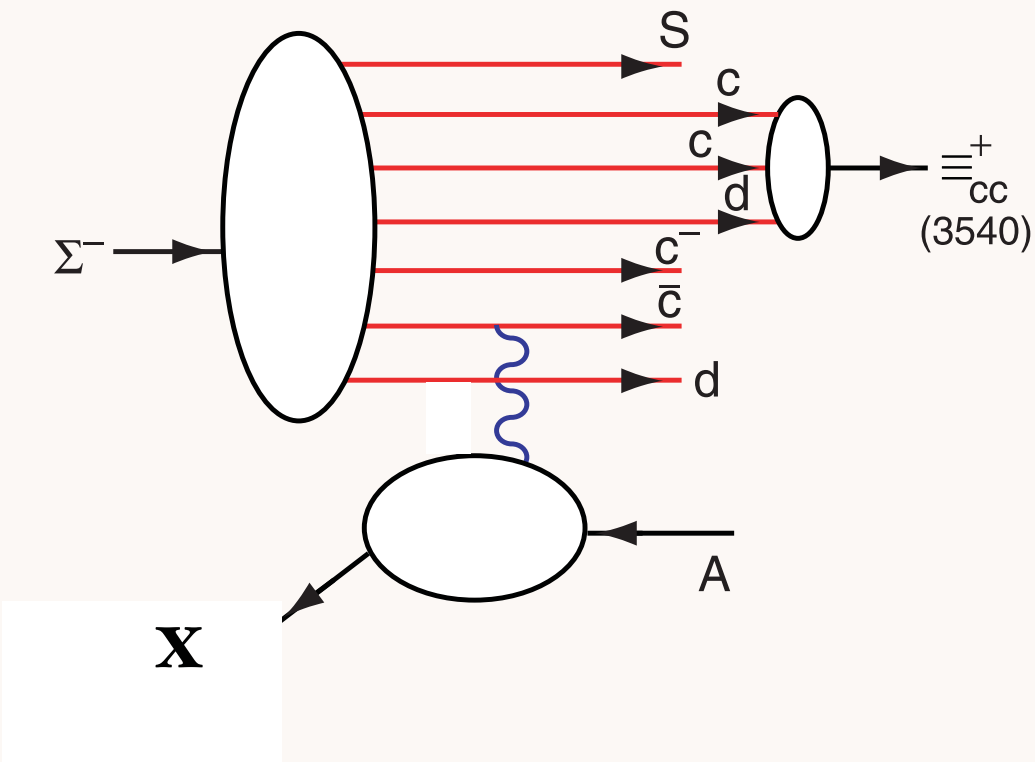
EXPERIMENTAL J/ψ HADRONIC PRODUCTION FROM 150 TO 280 GeV/c

NA3 COLLABORATION

CERN-EP/83-86
June 29th, 1983



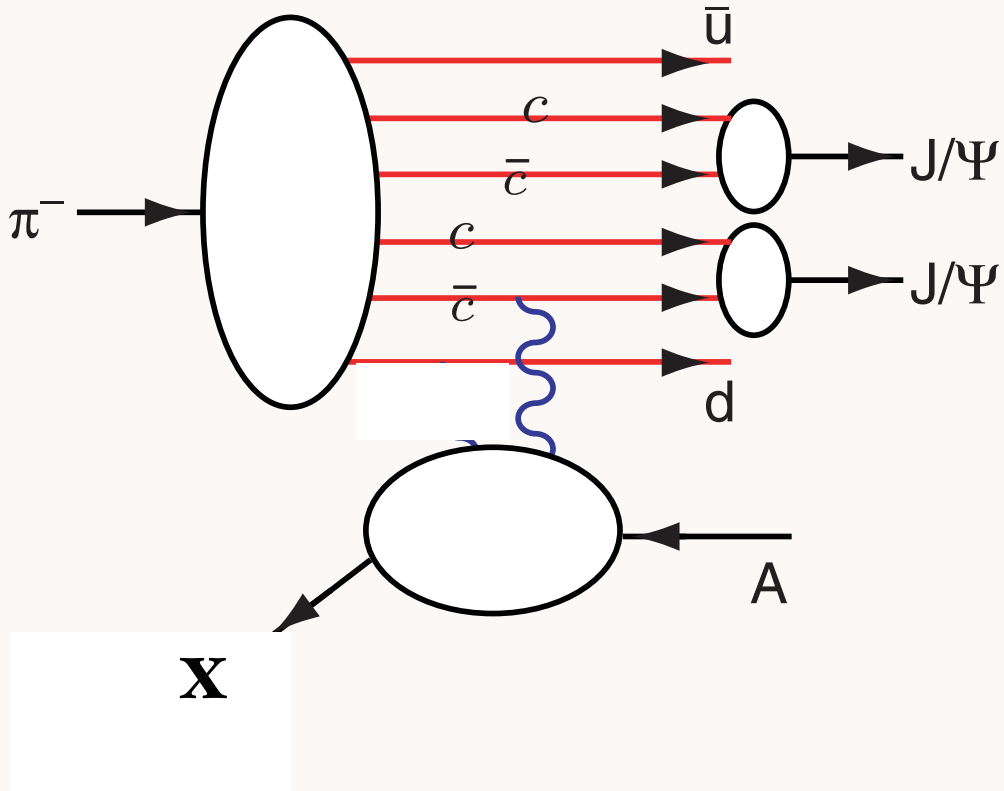

$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^1 \frac{d\sigma_{fusion}}{dx_F}(pA \to J/\psi X) + A^{2/3} \frac{d\sigma_{non-fusion}}{dx_F}(pA \to J/\psi X)$$




# Production of a Double-Charm Baryon

**SELEX high $x_F$** $< x_F >= 0.33$

# Production of Two Charmonia at High $x_F$



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

# Excludes `color drag' model

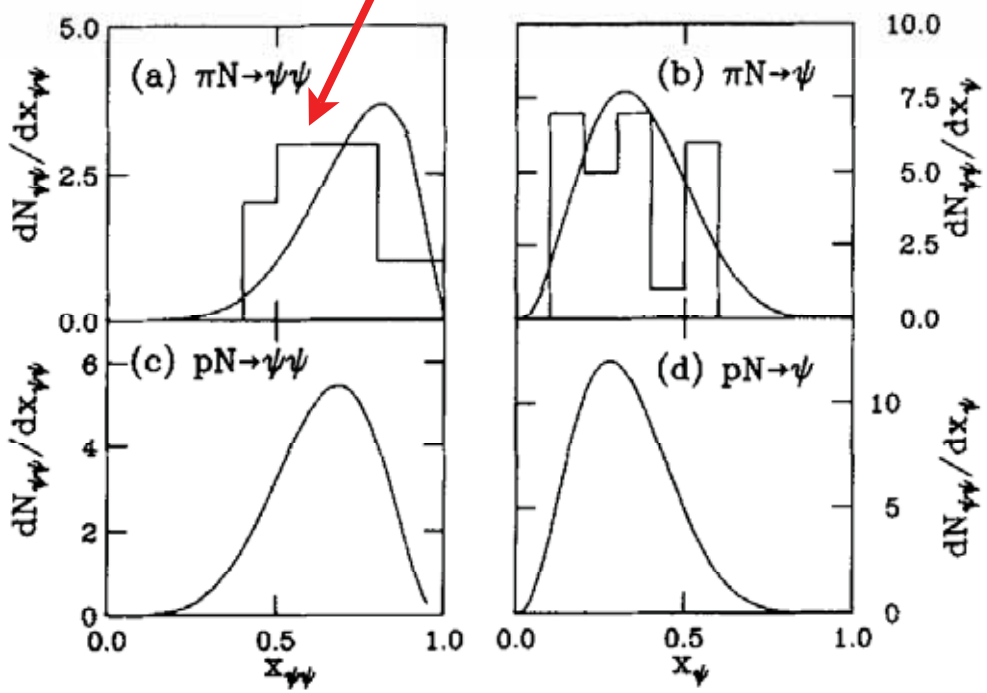



Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of $J/\psi$'s from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/$c$ [1]. The $x_{\psi\psi}$ distributions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

## NA3 Data

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

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 $k_T$ written as

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

# Heavy Quark Anomalies

Nuclear dependence of $J/\psi$ hadroproduction

Violates PQCD Factorization: $A^\alpha(x_F)$ not $A^\alpha(x_2)$

Huge $A^{2/3}$ effect at large $x_F$

- 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)

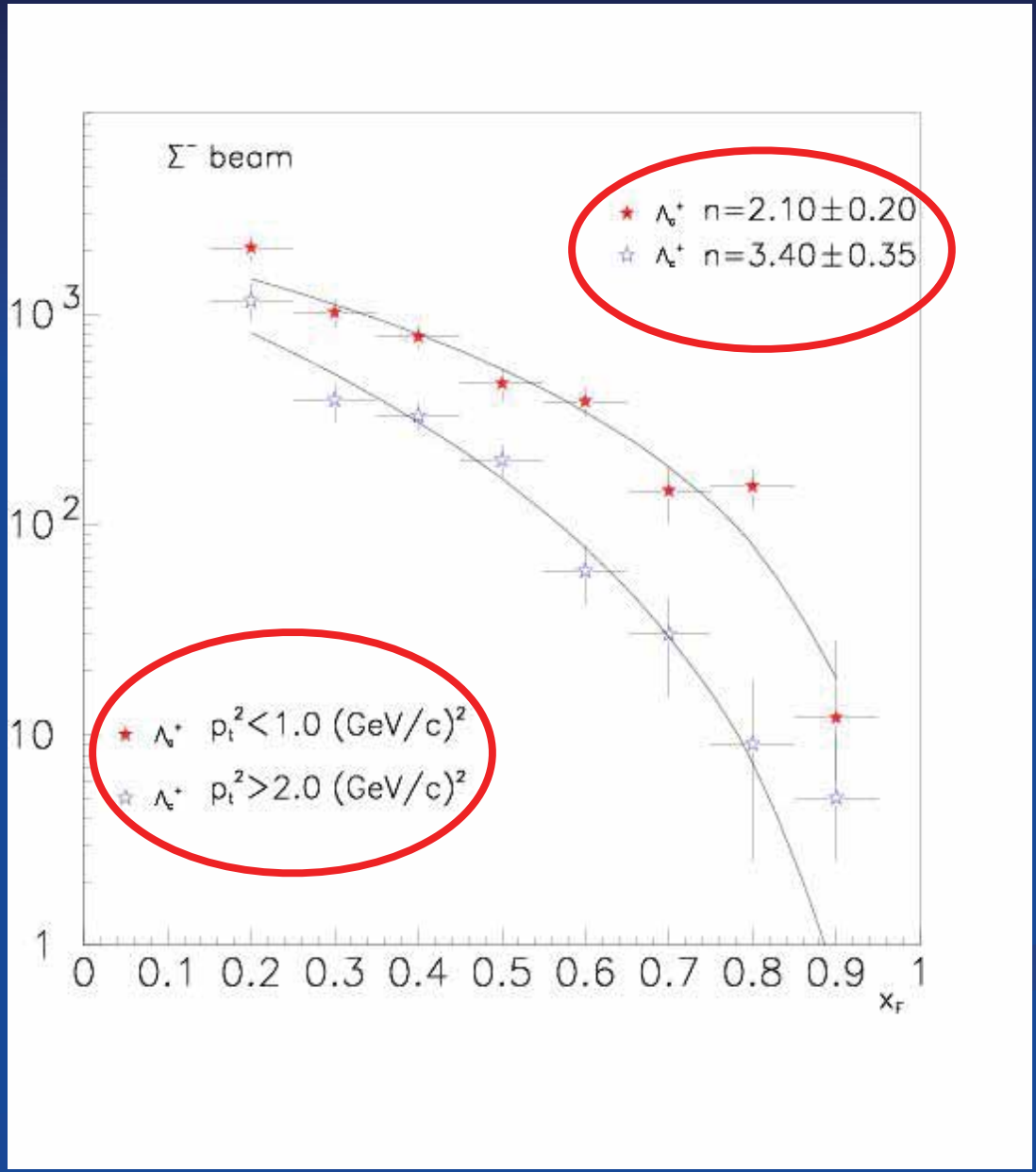
- IC leads to new effects in $B$ decay (Gardner, SJB)

**Higgs production at $x_F$ = 0.8**

# SELEX $\Lambda_c^+$ Studies – $p_T$ Dependence

- $\Lambda_c^+$ production by $\Sigma^-$ 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))



# Heavy Quark Anomalies

$J/\psi \to \rho\pi$ puzzle

**BR = 1.27 +/- 0.09 %**

*Largest two-body decay channel*

Violates hadron helicity conservation

$\psi'$ almost never decays to $\rho\ \pi$ $< 8.3 \times 10^{-5}$

Solution: Intrinsic charm Fock states in $\rho, \pi$

Karliner, 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

# Hadron Dynamics at the Amplitude Level

- LFWFS are the universal hadronic amplitudes which underlie structure functions, GPDs, exclusive processes, distribution amplitudes, direct subprocesses, hadronization.
- Relation of spin, momentum, and other distributions to physics of the hadron itself.
- Connections between observables, orbital angular momentum
- Role of FSI and ISIs--Sivers effect