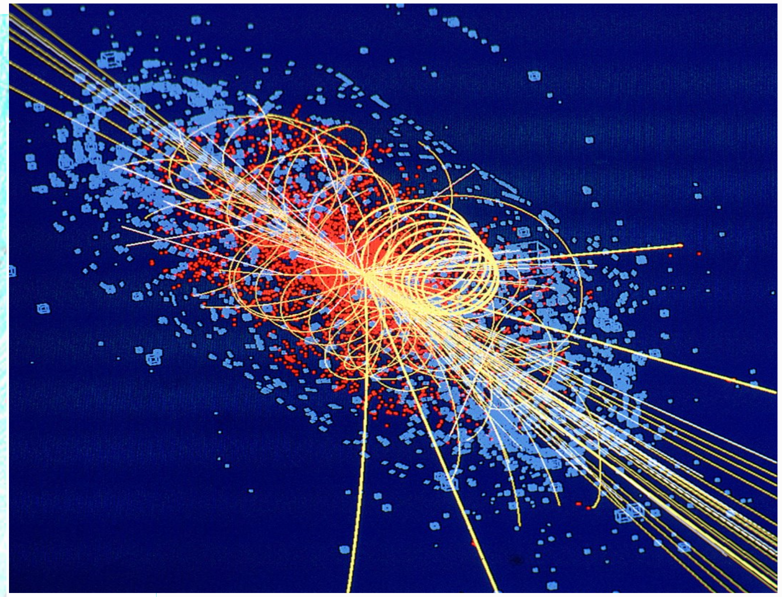
Novel QCD Phenomena at the LHC (I)



Stan Brodsky
SLAC

September 30, 2010

HIGH ENERGY
Instituto de Ciencias Nucleares
MÉXICO, CITY
SEPTEMBER 27th-OCTOBER 1st

MÉXICO 2010
Bicentenario Independencia
Centenario Revolución

UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO

UNAM

5th Workshop on High p-T Physics at LHC

SMF

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

Dimensional analysis

Scattering amplitude $1\ 2 \cdots \to \ldots n$ has dimension

$$\mathcal{M} \sim [\text{length}]^{n-4}$$

Consequence

In a conformal theory (no intrinsic scale), scaling of inclusive particle production

$$E\,\frac{d\sigma}{d^3p}(A\ B\ \to C\ X) \sim \frac{|\mathcal{M}|^2}{s^2} = \frac{F(x_\perp, \vartheta^{\text{cm}})}{p_\perp^{2n_{\text{active}}-4}}$$

where n_{active} is the number of fields participating to the hard process

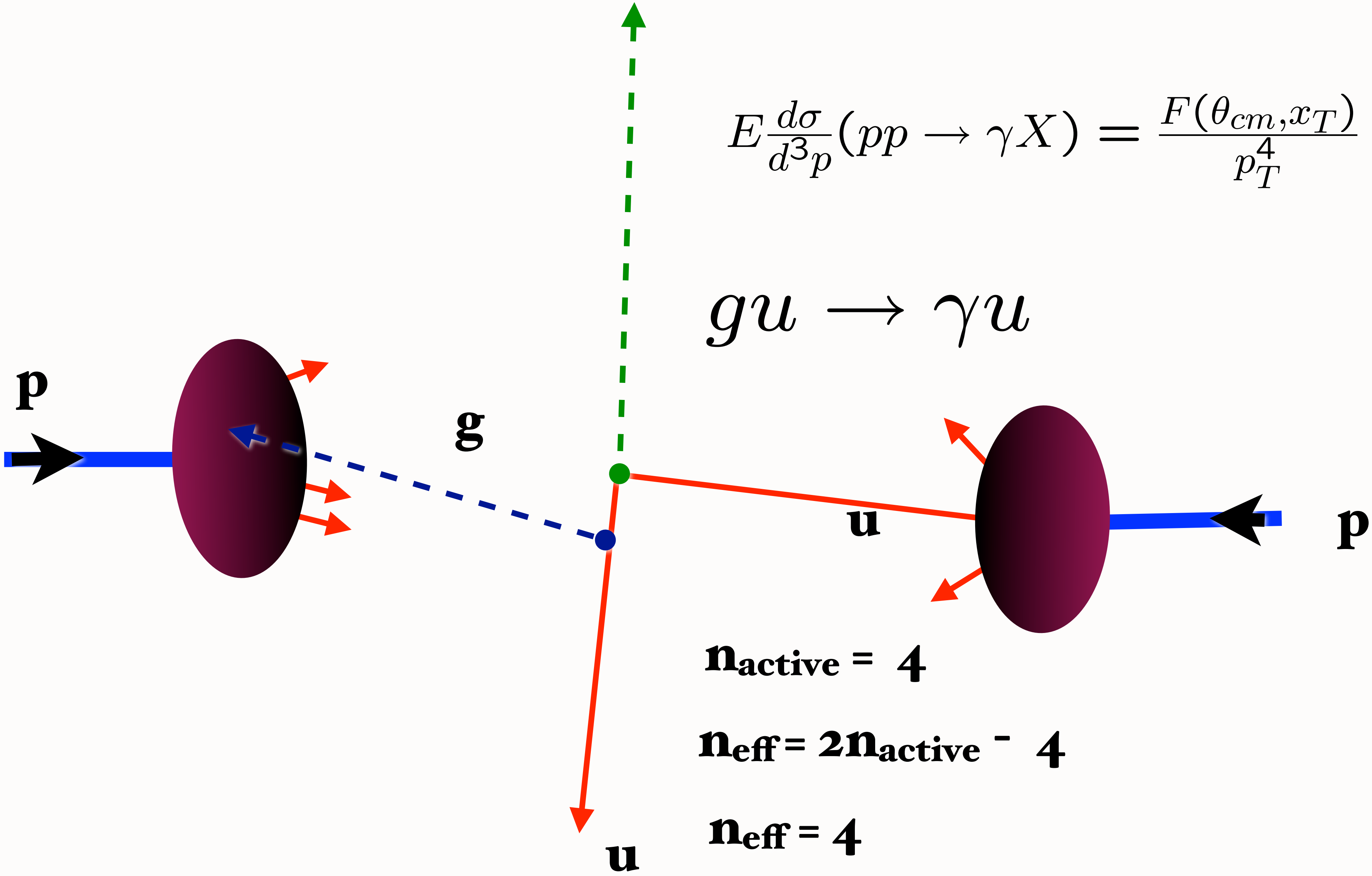
$x_\perp = 2p_\perp/\sqrt{s}$ and ϑ^{cm}: ratios of invariants

$$n_{active} = 4 \to n_{eff} = 4$$

$$pp \to \gamma X$$

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

$$gu \to \gamma u$$

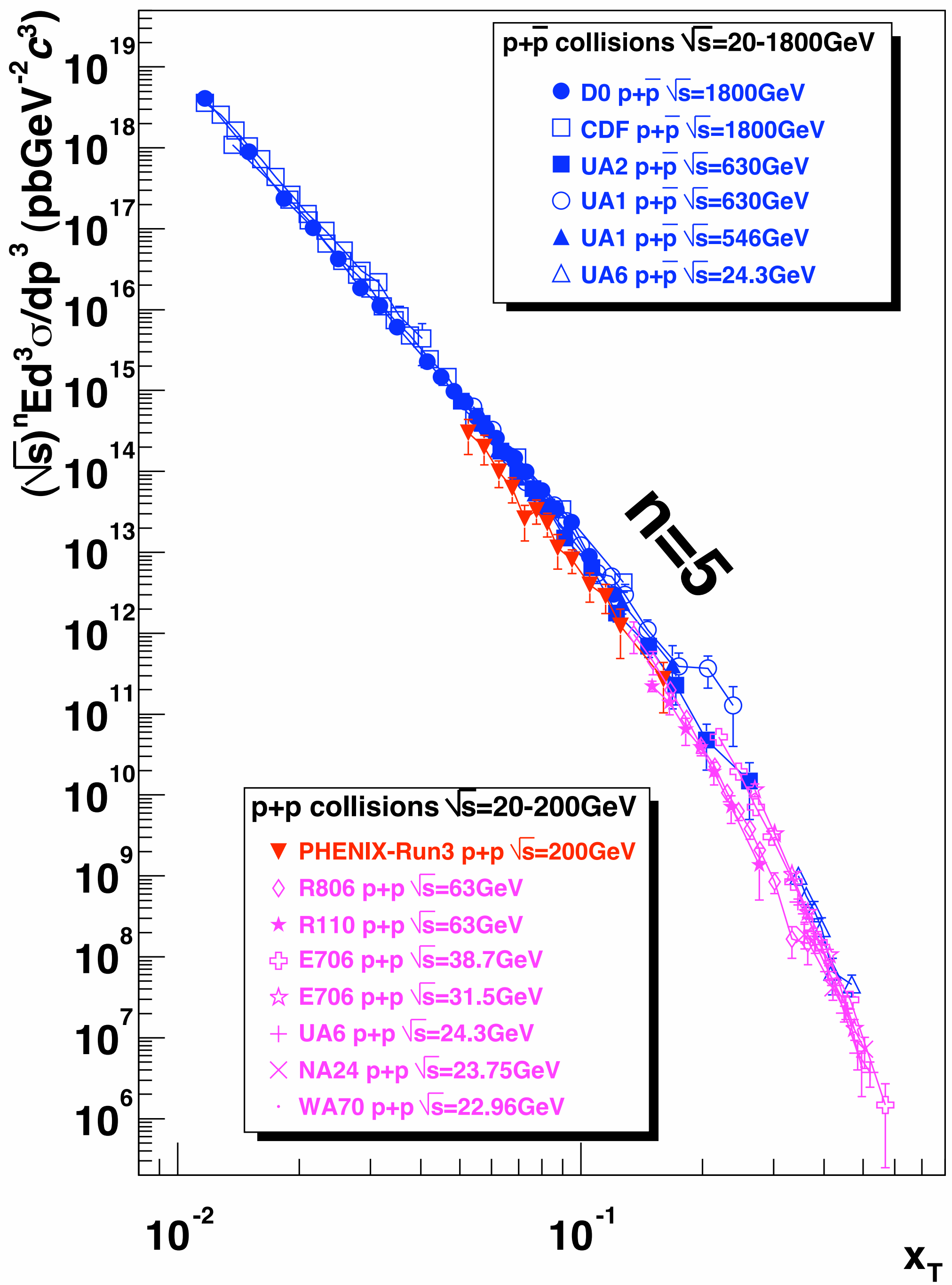


$n_{active} = 4$

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

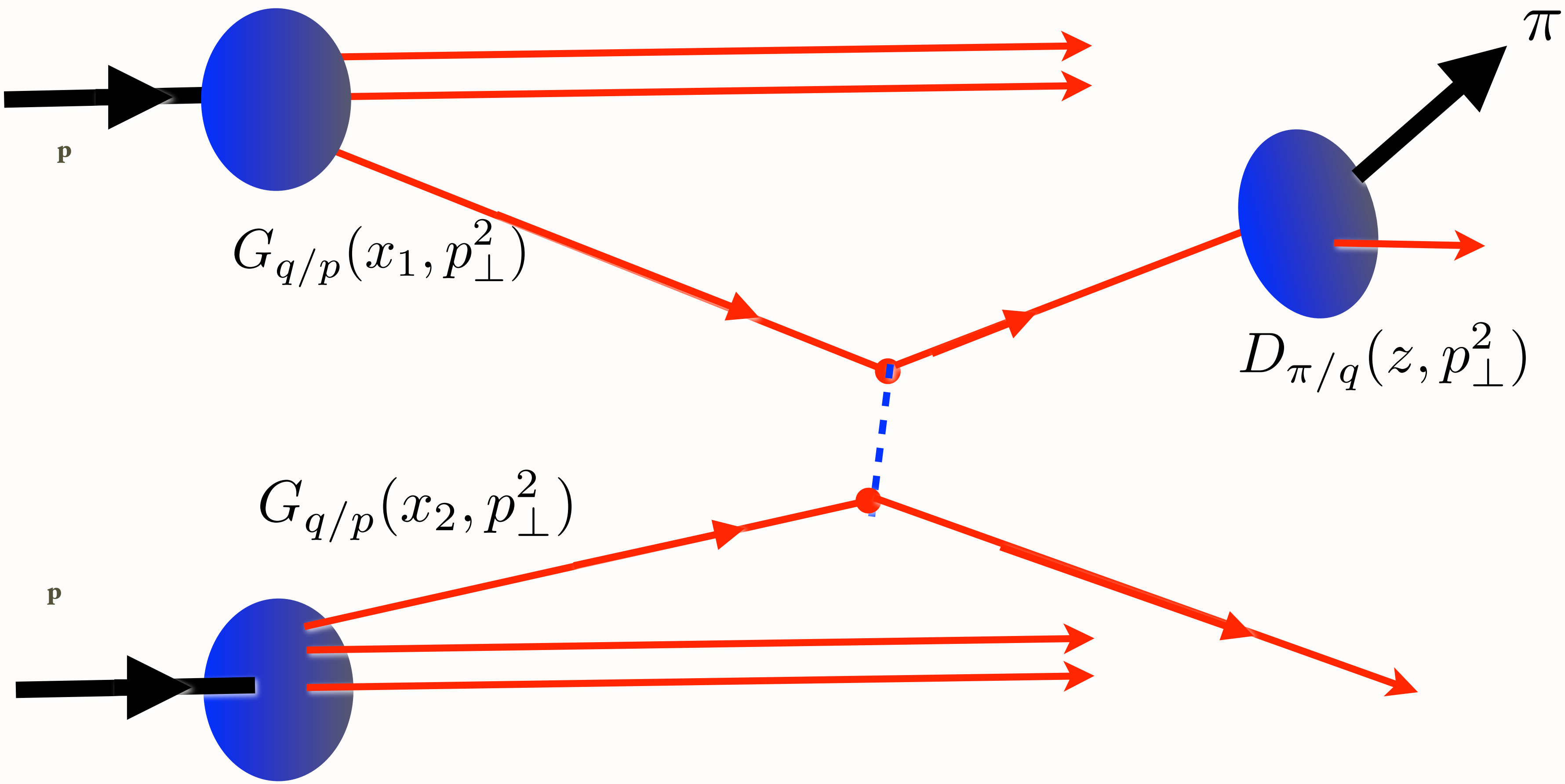
$n_{eff} = 4$

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



x_T-scaling of direct photon production: consistent with PQCD

Leading-Twist Contribution to Hadron Production

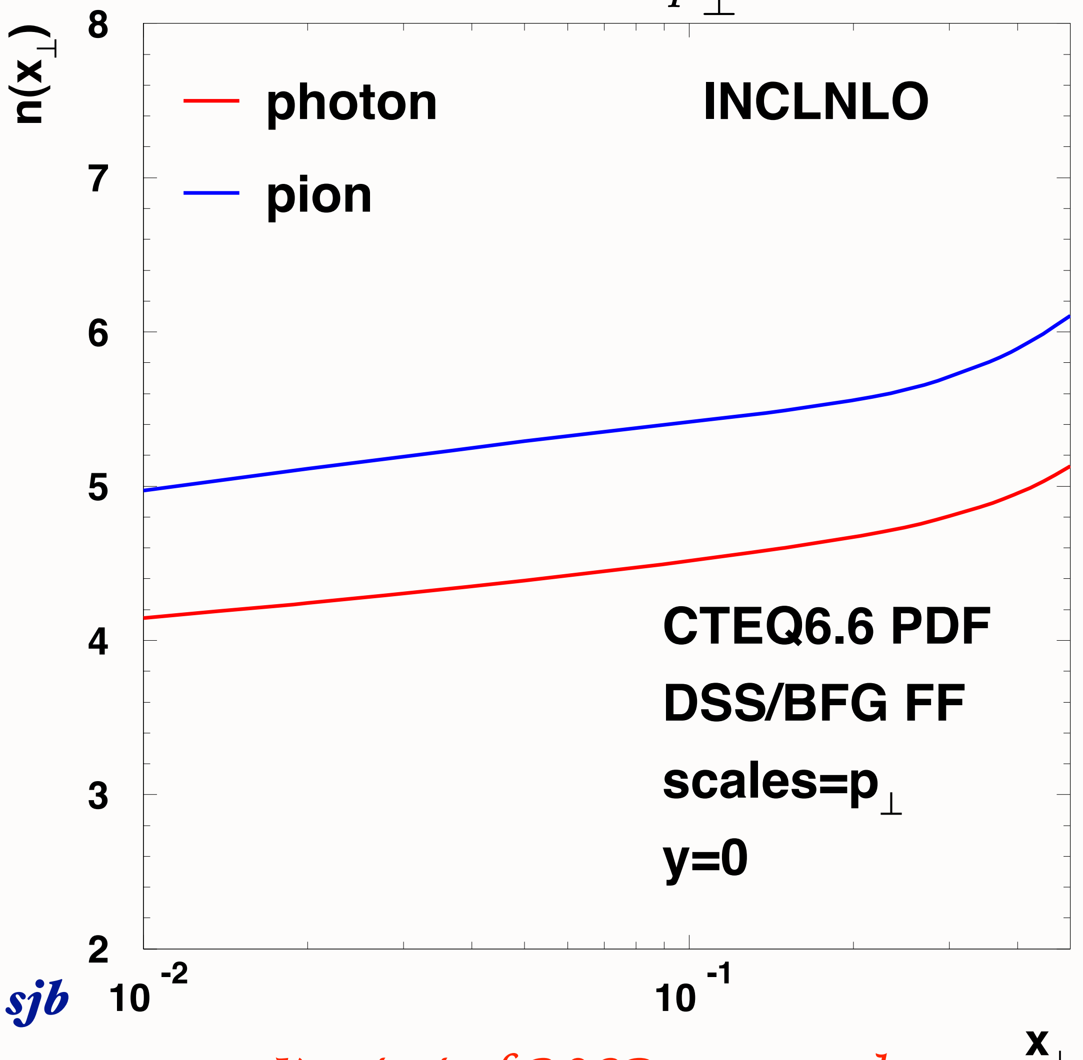


Parton model and Conformal Scaling:

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

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

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



$$pp \rightarrow \pi X$$

$$pp \rightarrow \gamma X$$

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

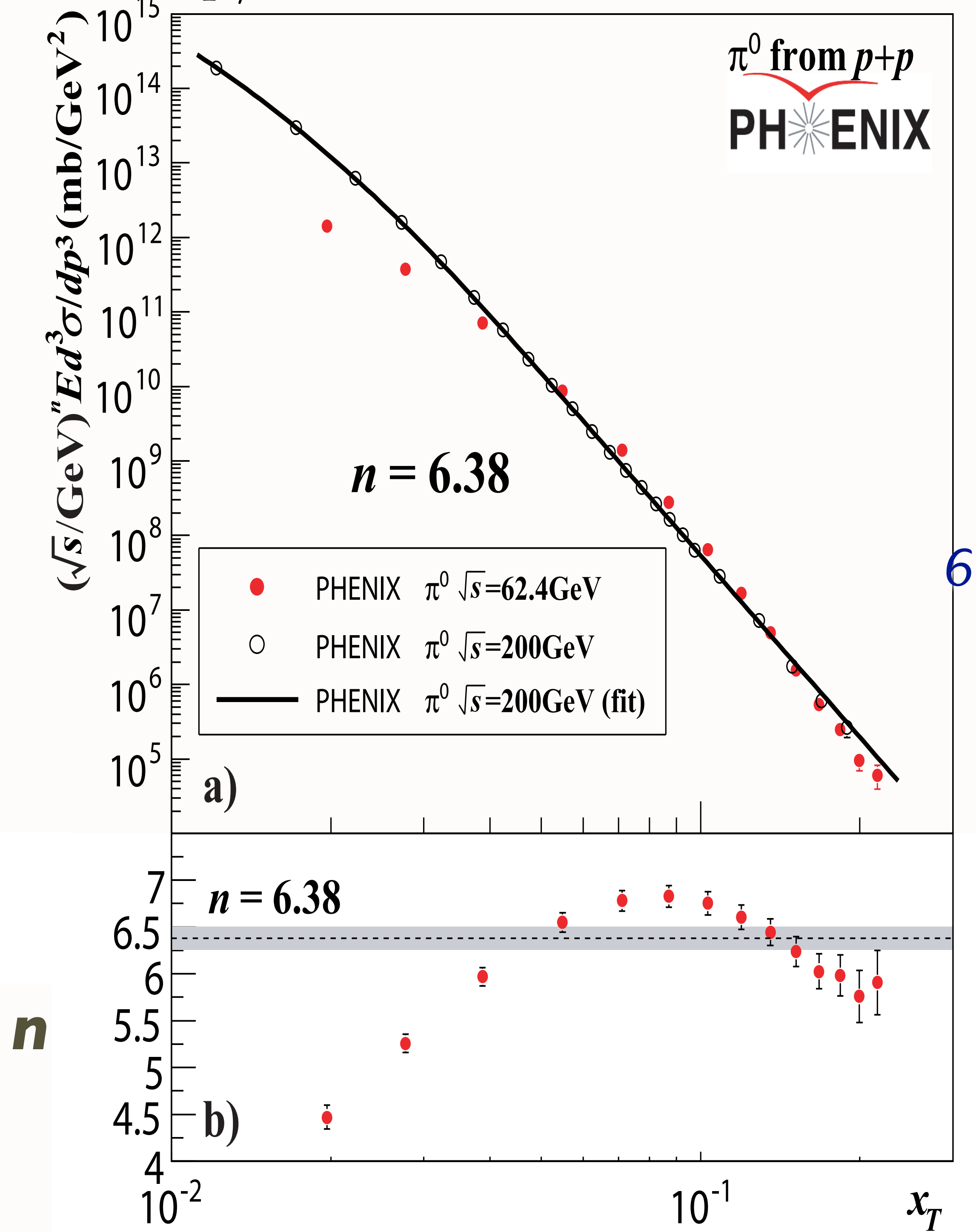
$$70 \ GeV < \sqrt{s} < 4 \ TeV$$

Arleo, Hwang, Sickles, sjb

Pirner, Raufeisen, sjb

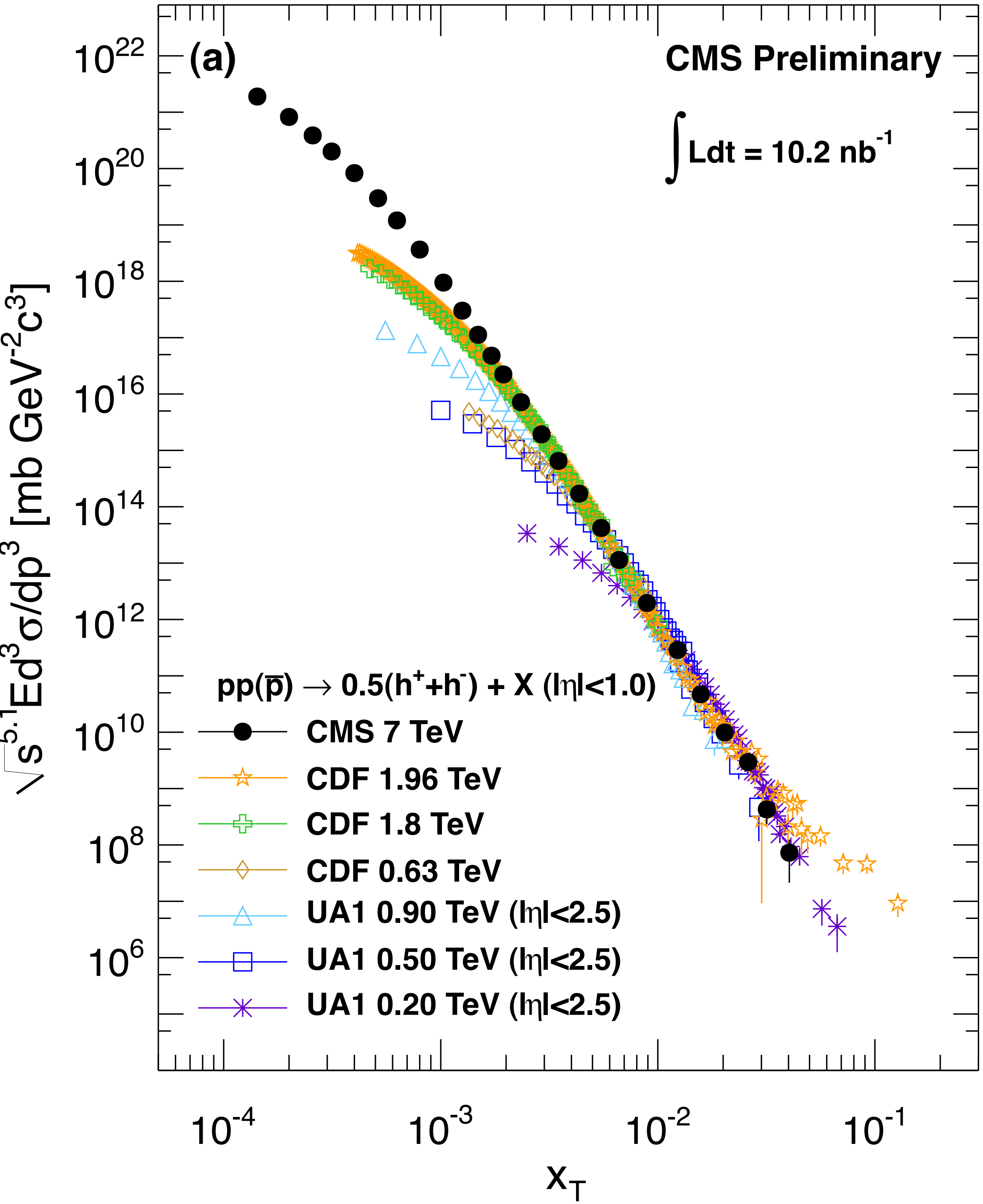
Key test of PQCD: power-law fall-off at fixed x_T

$$[\sqrt{s}]^n \frac{d\sigma}{d^3p/E}(pp \to \pi^0 X) \text{ at fixed } x_T = \frac{2p_T}{\sqrt{s}}$$



M. J. Tannenbaum

PHENIX 62.4 and 200 GeV data



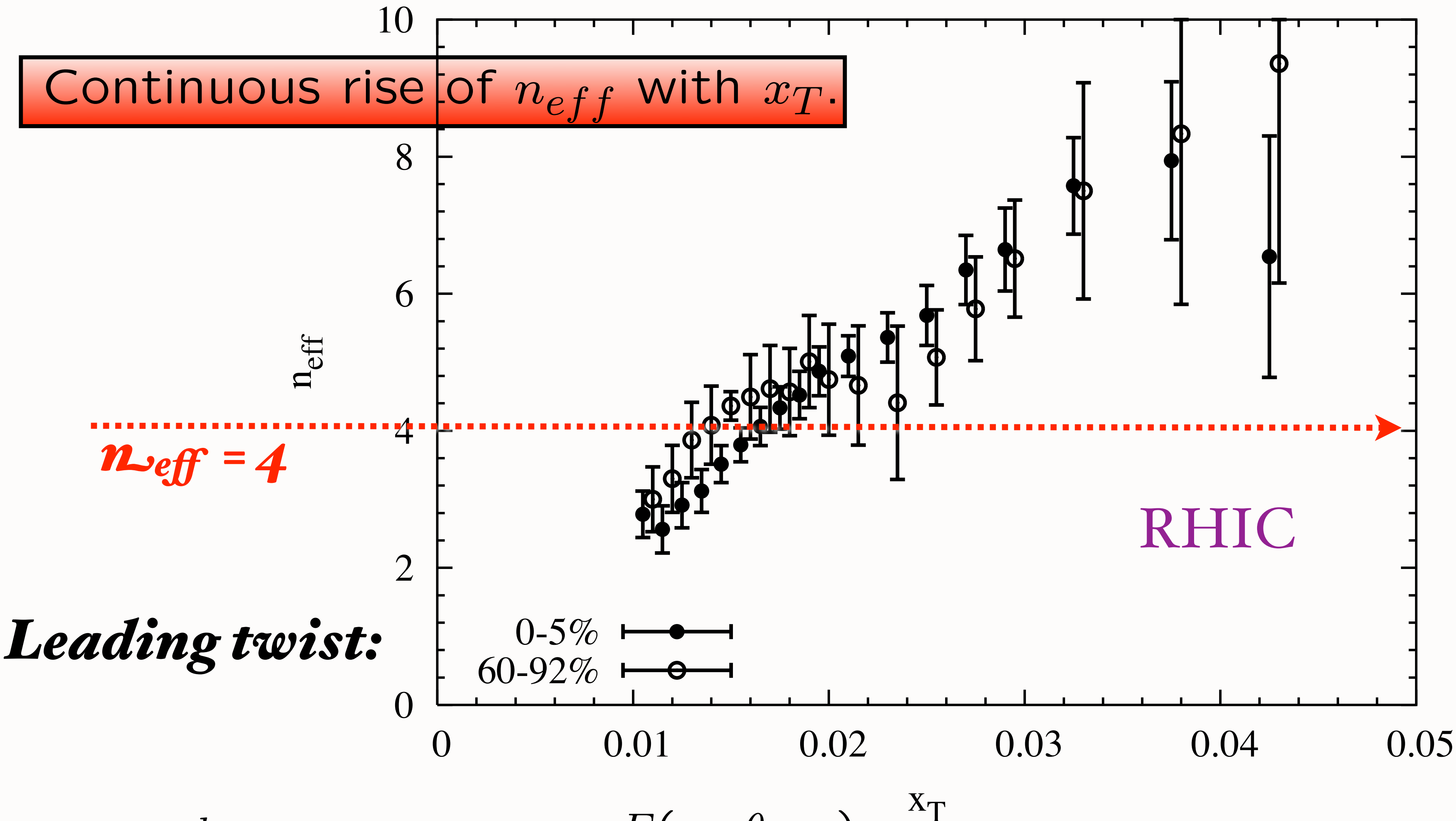
Jet-triggered charged particle transverse momentum spectra in pp collisions at 7 TeV

The CMS Collaboration

x_T scaling fails

Inclusive invariant cross sections, scaled by $\sqrt{s}^{5.1}$

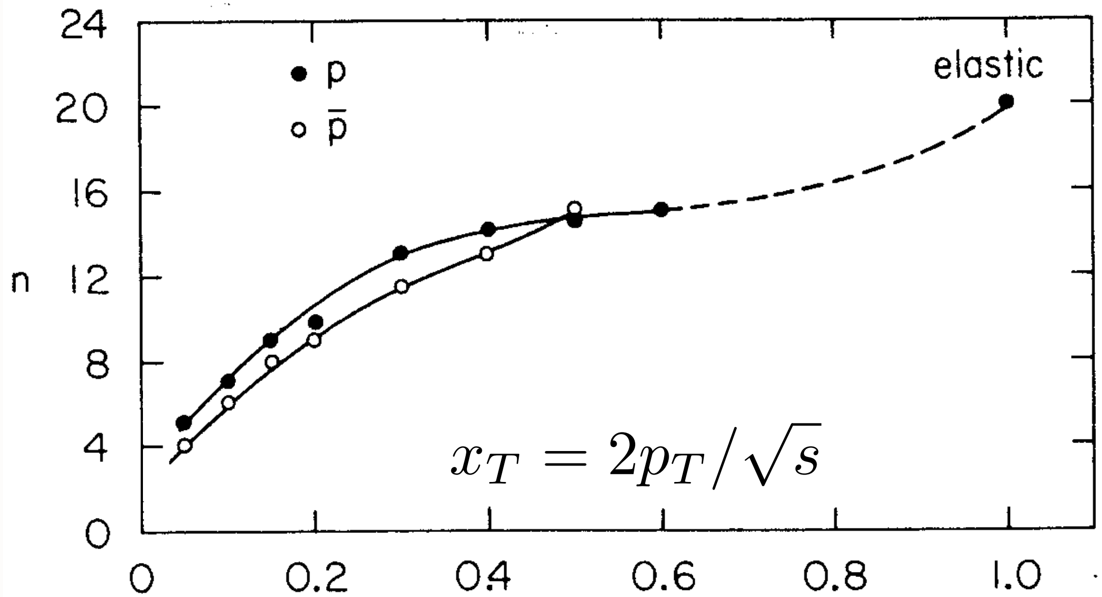
Protons produced in AuAu collisions at RHIC do not exhibit clear scaling properties in the available p_T range. Shown are data for central $(0-5\%)$ and for peripheral $(60-90\%)$ collisions.



Leading twist:

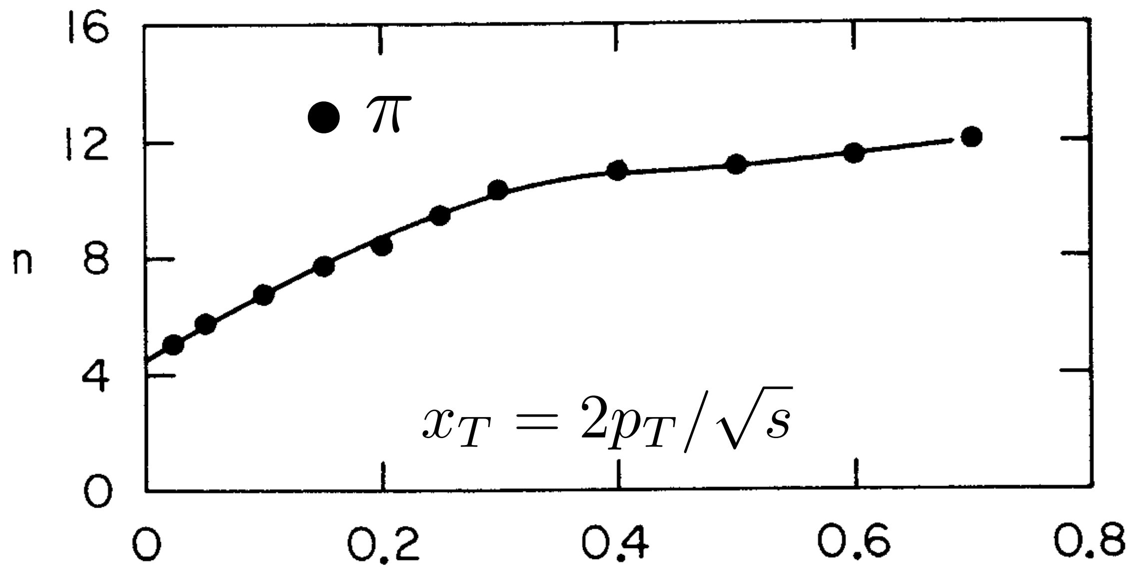
$$E\frac{d\sigma}{d^3p}(pN \to pX) = \frac{F(x_T,\theta_{CM})}{p_T^{n_{eff}}}$$

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



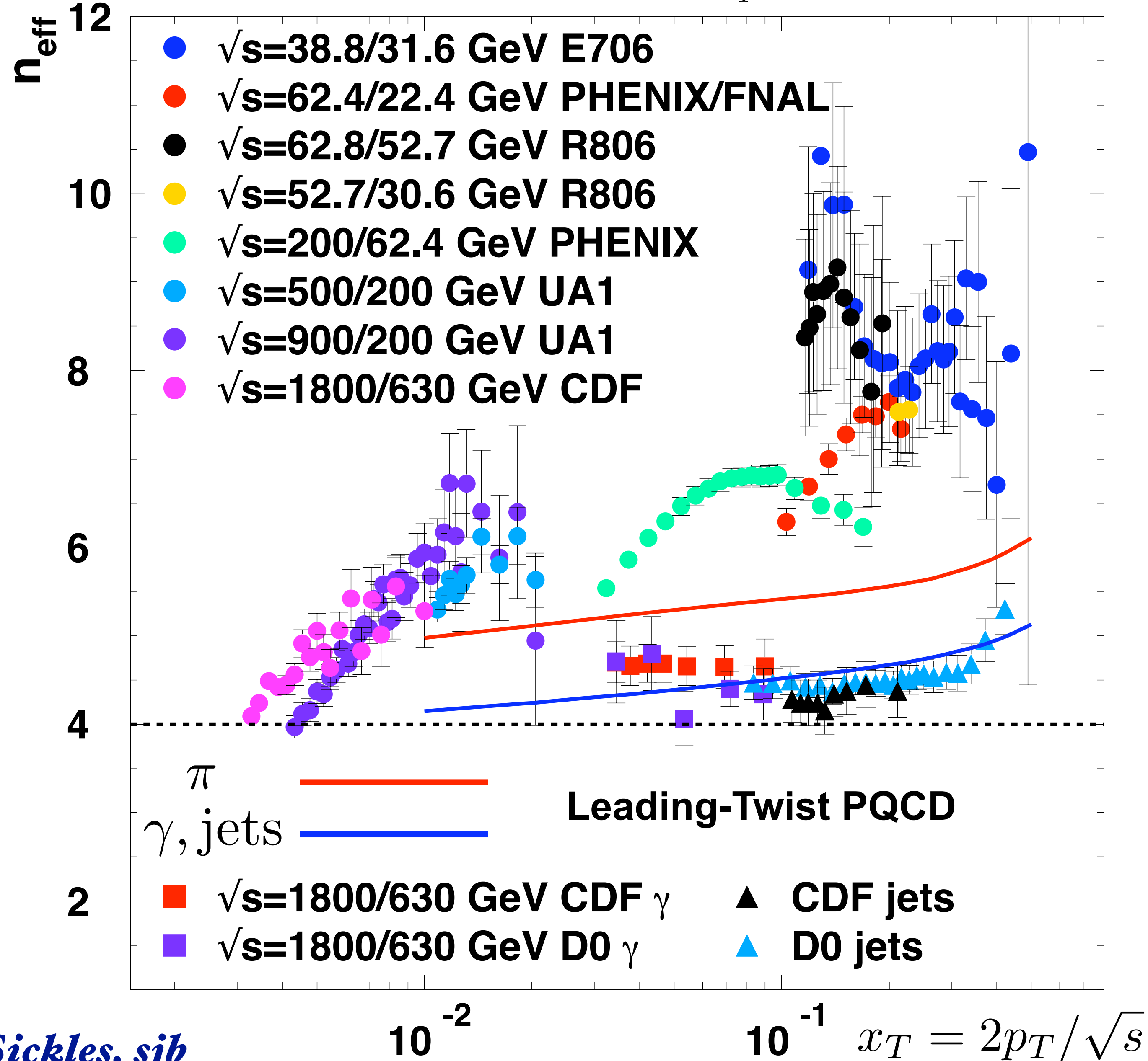
Clear evidence for higher-twist contributions

J. W. Cronin, SSI 1974

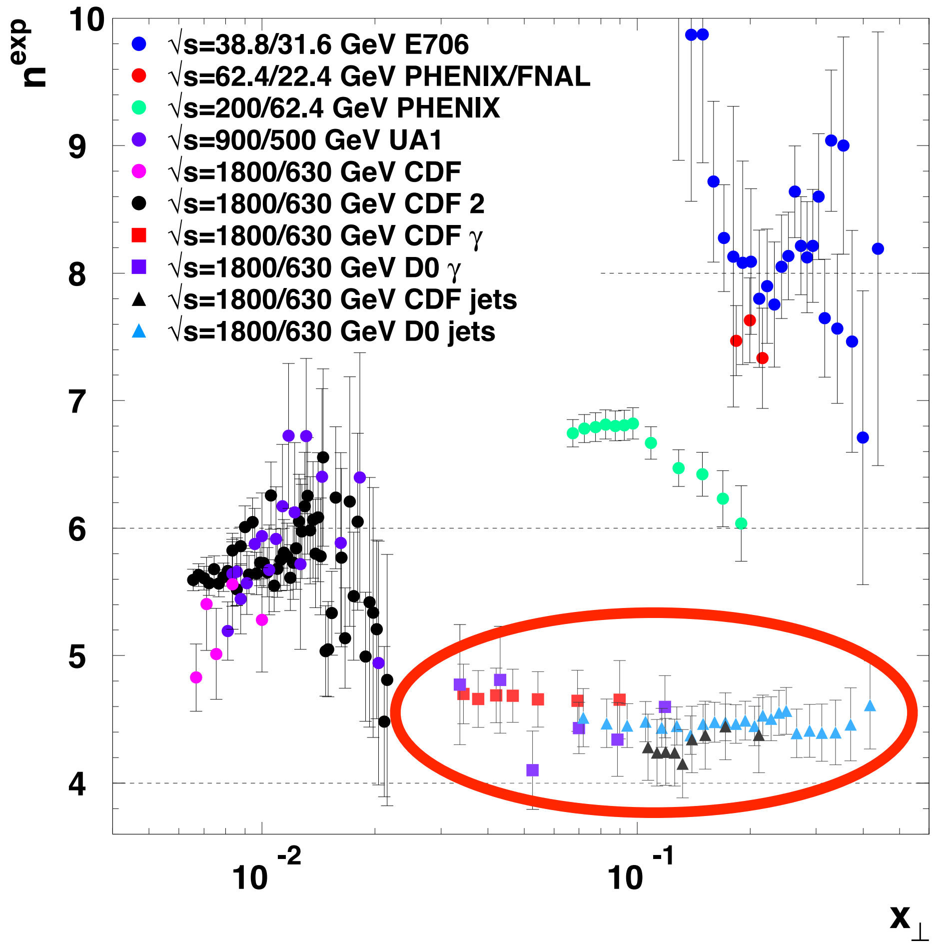


Chicago-Princeton FNAL

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



Arleo, Hwang, Sickles, sjb

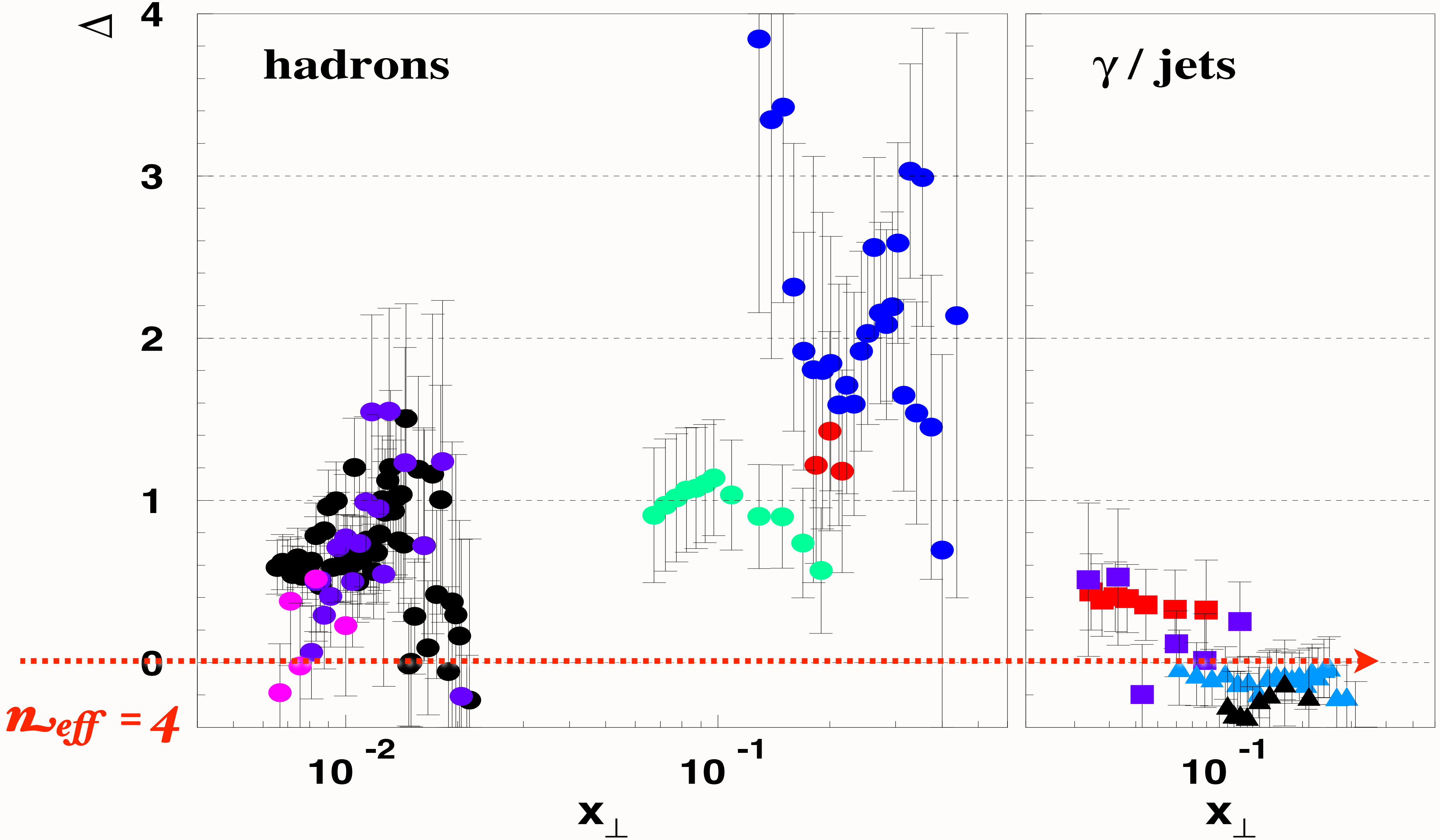


Photons and Jets agree with PQCD x_T scaling

Hadrons do not!

- Significant increase of the hadron n^{exp} with $x_\perp$
  - $n^{\text{exp}} \simeq 8$ at large $x_\perp$
- Huge contrast with photons and jets !
  - n^{exp} constant and slight above 4 at all $x_\perp$

Arleo, Hwang, Sickles, sjb



$$\Delta(x_\perp) = n^{\exp}(x_\perp) - n^{\mathrm{NLO}}(x_\perp)$$

Data analysis

- Scaling exponent extracted by comparing $x_\perp$ spectra at two $\sqrt{s}$

$$n^{\mathrm{exp}}(x_\perp) \equiv -\frac{\ln\left[\sigma^{\mathrm{inv}}(x_\perp, \sqrt{s_1}) / \sigma^{\mathrm{inv}}(x_\perp, \sqrt{s_2})\right]}{\ln\left(\sqrt{s_1}/\sqrt{s_2}\right)}$$

  within the same experiment in order to reduce systematic errors
- Particle production at mid-rapidity
  - hadrons (π and $h^\pm$), prompt photons, jets
- Data sets
  - most recent measurements: CDF, D0, E706, PHENIX
  - ...as well as older ISR data

Scale dependence

Pion scaling exponent extracted vs. $p_\perp$ at fixed $x_\perp$

2-component toy-model

$$\sigma^{\rm model}(pp \to \pi \ {\rm X}\,) \propto \frac{A(x_\perp)}{p_\perp^4} + \frac{B(x_\perp)}{p_\perp^6}$$

Define effective exponent

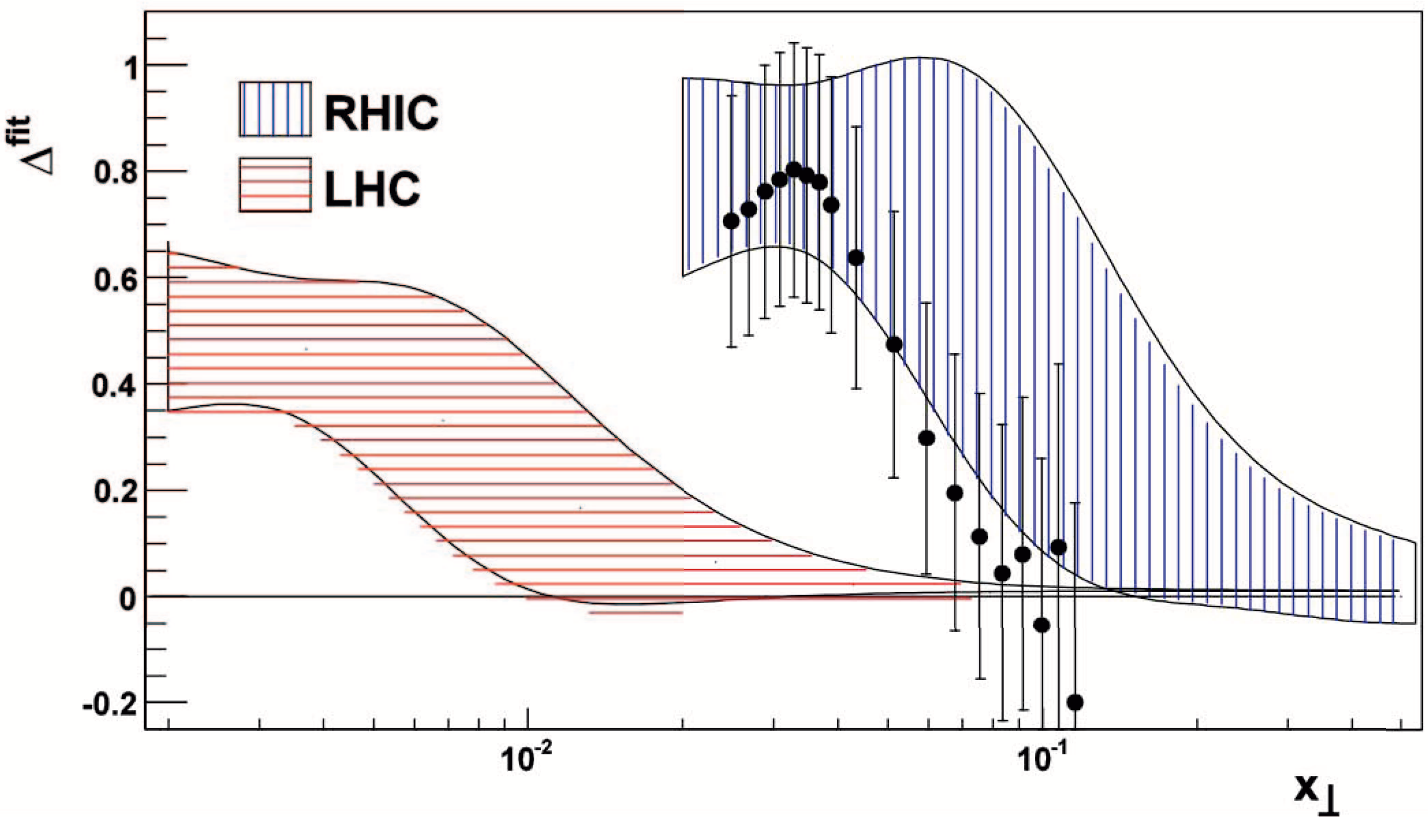
$$\begin{aligned} n_{\rm eff}(x_\perp, p_\perp, B/A) &\equiv -\frac{\partial \ln \sigma^{\rm model}}{\partial \ln p_\perp} + n^{\rm NLO}(x_\perp, p_\perp \\ &= \frac{2B/A}{p_\perp^2 + B/A} + n^{\rm NLO}(x_\perp, p_\perp) \end{aligned}$$

RHIC/LHC predictions

PHENIX results

Scaling exponents from $\sqrt{s} = 500$ GeV preliminary data

[A. Bezilevsky, APS Meeting]



- Magnitude of Δ and its $x_{\perp}$-dependence consistent with predictions

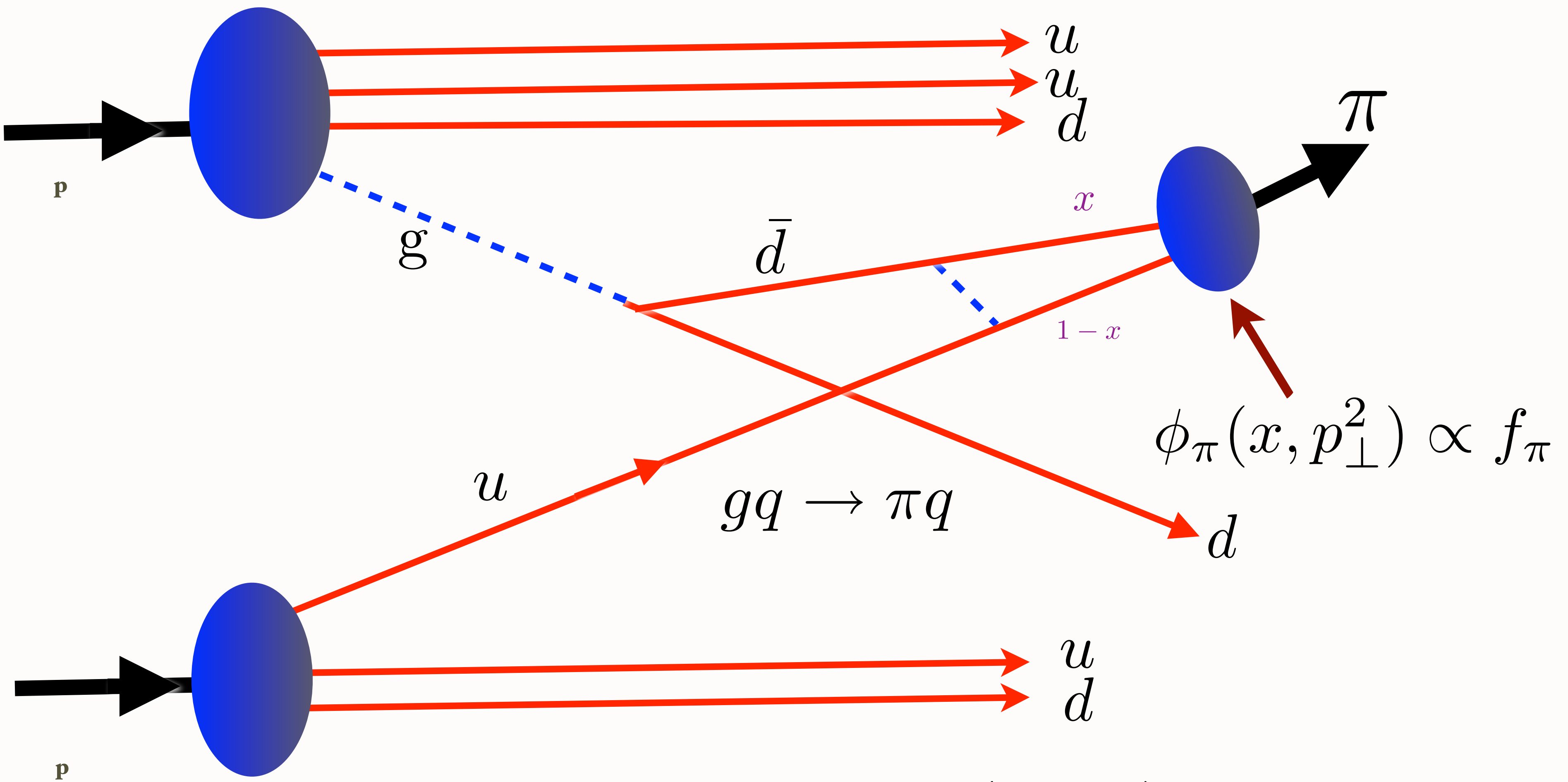
Direct Higher Twist Processes

- QCD predicts that hadrons can interact directly within hard subprocesses
- Exclusive and quasi-exclusive reactions
- Form factors, deeply virtual meson scattering
- Controlled by the hadron distribution amplitude

$$\phi_H(x_i, Q)$$

- Satisfies ERBL evolution

Direct Contribution to Hadron Production



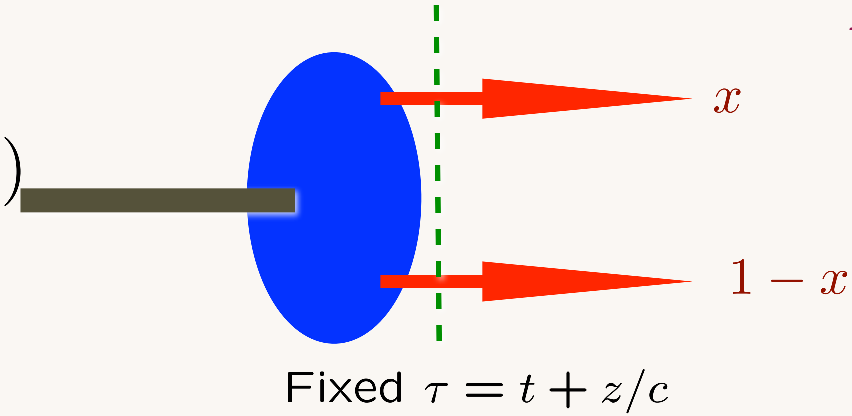
$$\frac{d\sigma}{d^3p/E} = \alpha_s^3 f_\pi^2 \frac{F(x_\perp, y)}{p_\perp^6}$$

No Fragmentation Function

Hadron Distribution Amplitudes

Lepage, sjb

$$\phi_M(x,Q) = \int^Q d^2\vec{k}\ \psi_{q\bar{q}}(x,\vec{k}_\perp)$$



$k_\perp^2 < Q^2$

$$\sum_i x_i = 1$$

- Fundamental gauge invariant non-perturbative input to hard exclusive processes, heavy hadron decays. Defined for Mesons, Baryons

Lepage, sjb
Efremov, Radyushkin

- Evolution Equations from PQCD, OPE,

Sachrajda, Frishman Lepage, sjb
Braun, Gardi

- Conformal Invariance

Kirchbach

- Compute from valence light-front wavefunction in light-cone gauge

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

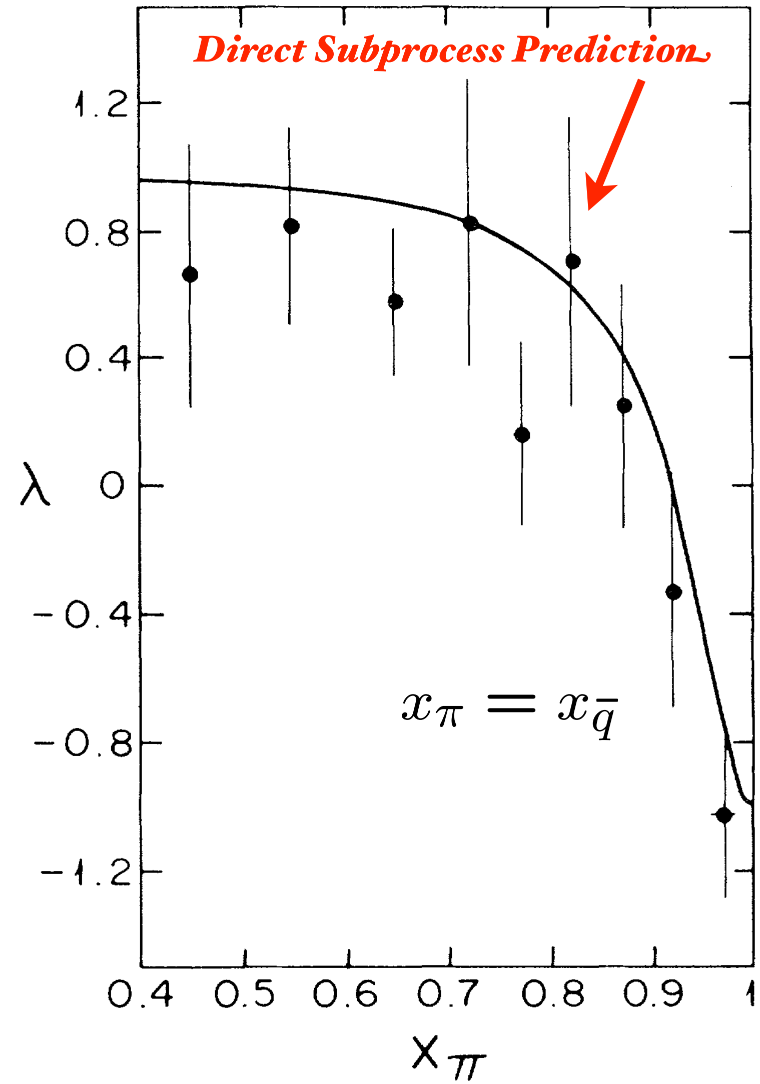
$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \rho \sin 2\theta \cos\phi + \omega \sin^2\theta \cos 2\phi .$$

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

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

$$Q^2 = M^2$$

Dramatic change in angular distribution at large x_F



Example of a higher-twist direct subprocess

Chicago-Princeton Collaboration

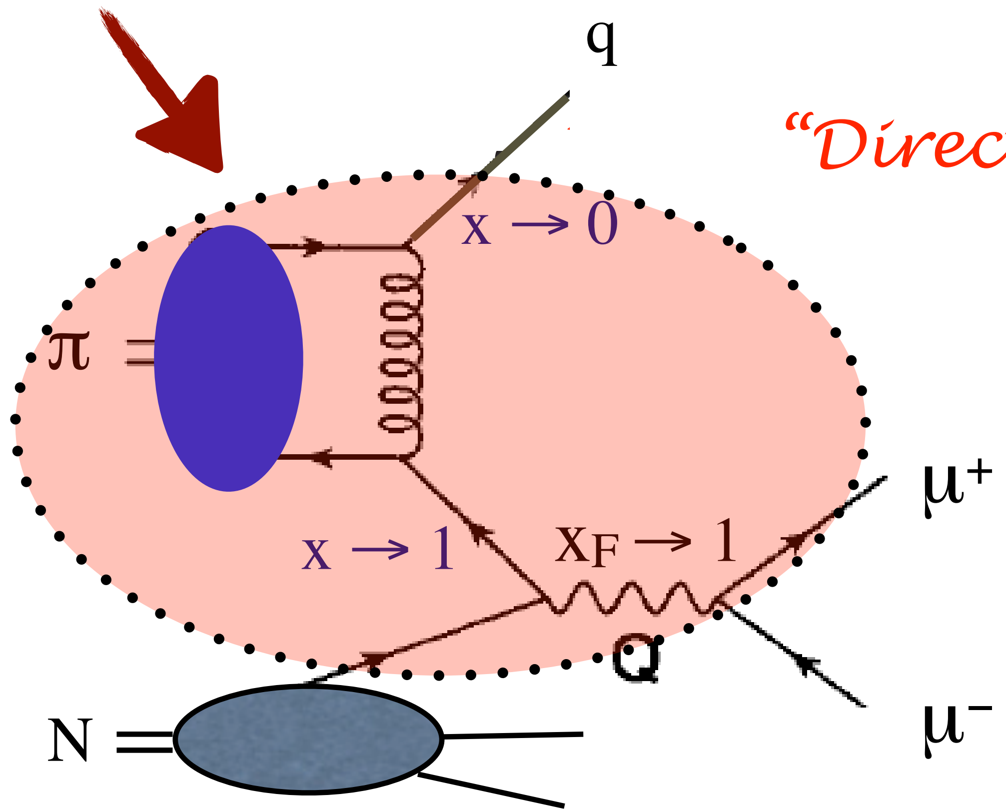
Phys.Rev.Lett.55:2649,1985

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

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

Distribution amplitude from AdS/CFT

Entire pion wf contributes to hard process



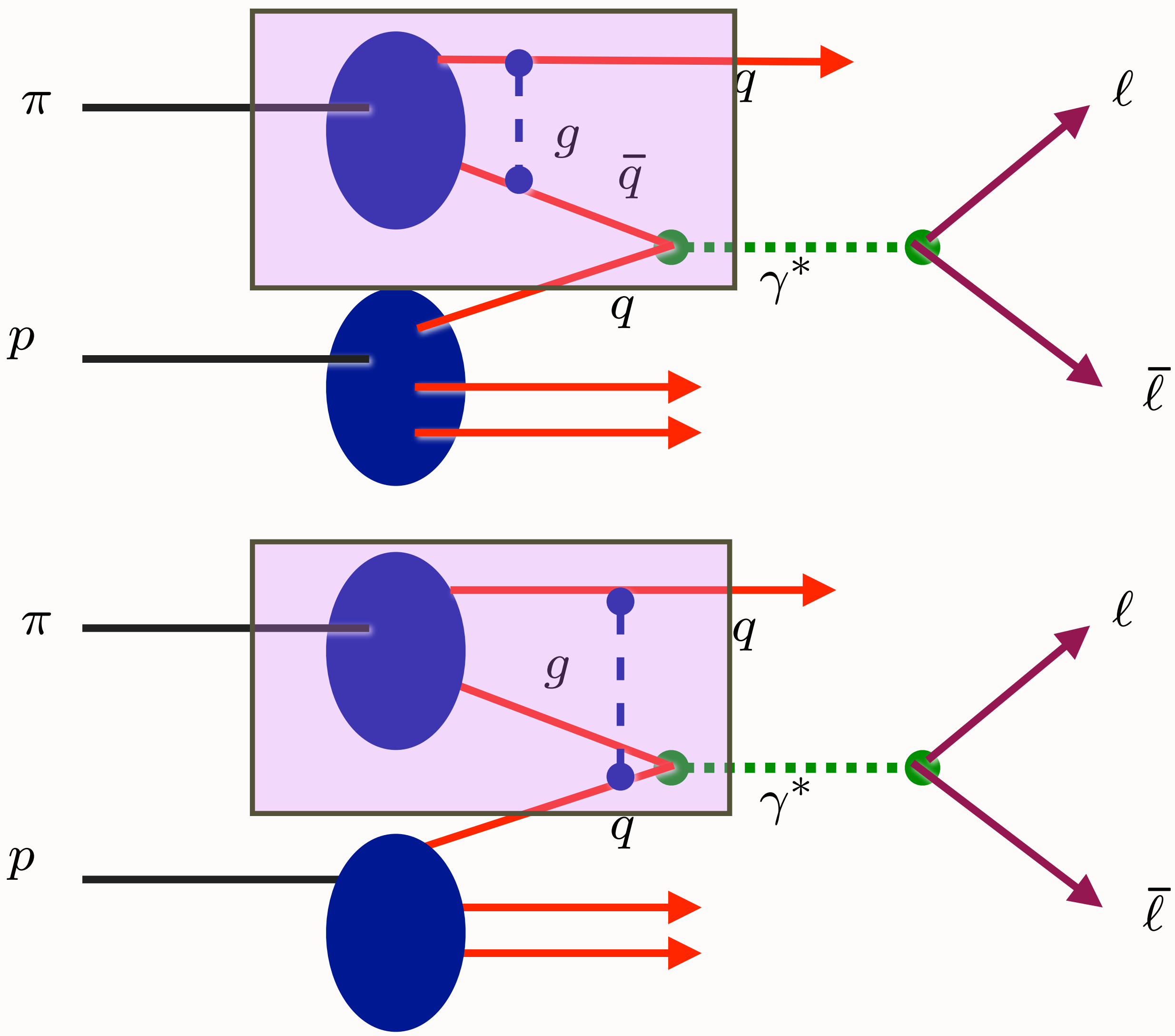
Virtual photon is longitudinally polarized

Similar higher twist terms in jet hadronization at large z

Berger, sjb
Khoze, Brandenburg, Muller, sjb

Hoyer Vanttinen

Berger, Lepage, sjb



$$\pi q \rightarrow \gamma^* q$$

Initial State Interaction

Pion appears directly in subprocess at large x_F

All of the pion's momentum is transferred to the lepton pair

Lepton Pair is produced longitudinally polarized

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

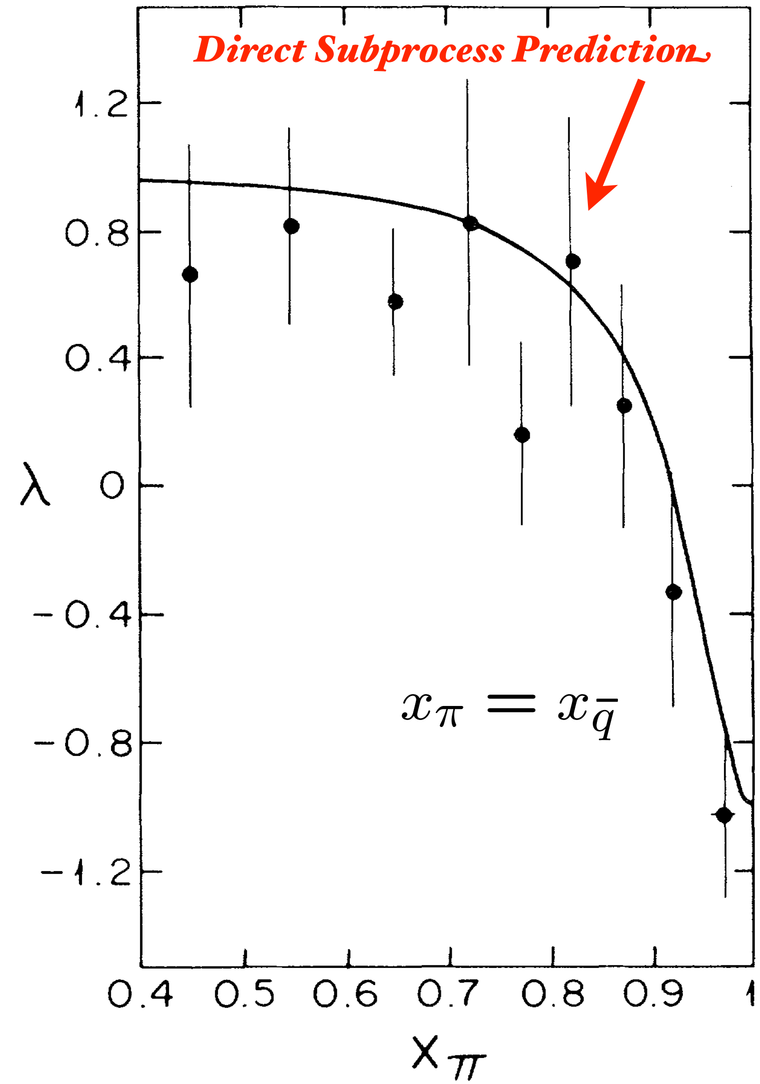
$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \rho \sin 2\theta \cos\phi + \omega \sin^2\theta \cos 2\phi.$$

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

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

$$Q^2 = M^2$$

Dramatic change in angular distribution at large x_F



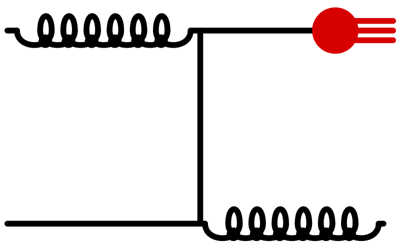
Chicago-Princeton Collaboration

Phys.Rev.Lett.55:2649,1985

Example of a higher-twist direct subprocess

Scaling laws in inclusive pion production

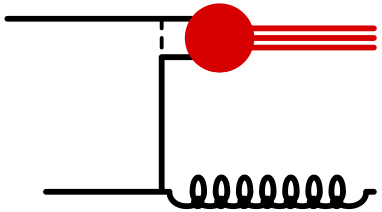
- Conventional pQCD picture (leading twist): $2 \to 2$ process followed by fragmentation into a pion on long time scales



$$n_{\rm active} = 4 \to n = 4 \; (= 2 \times 4 - 4)$$

$$E\,\frac{d\sigma}{d^3p}(p\,p \to \pi\,X) \sim \frac{F(x_\perp, \vartheta^{\rm cm})}{p_\perp^4}$$

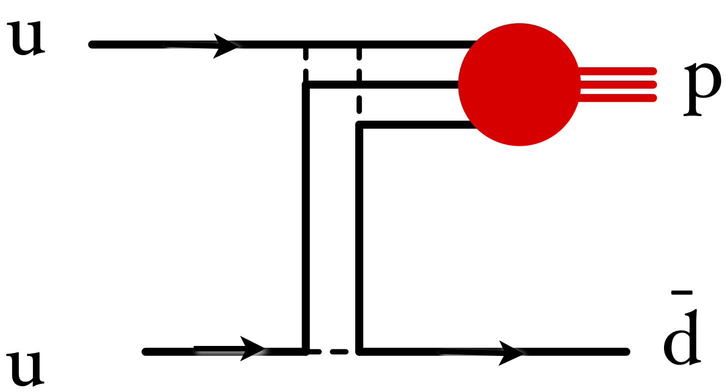
- Direct higher-twist picture: pion produced directly in the hard process



$$n_{\rm active} = 5 \to n = 6 \; (= 2 \times 5 - 4)$$

$$E\,\frac{d\sigma}{d^3p}(p\,p \to \pi\,X) \sim \frac{F'(x_\perp, \vartheta^{\rm cm})}{p_\perp^6}$$

Direct Proton Production



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

$$E \frac{d\sigma}{d^3p}(p\ p \to p\ X) \sim \frac{F(x_\perp, \vartheta^{\mathrm{cm}})}{p_\perp^8}$$

Explains "Baryon anomaly" at RHIC!

Sickles, 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

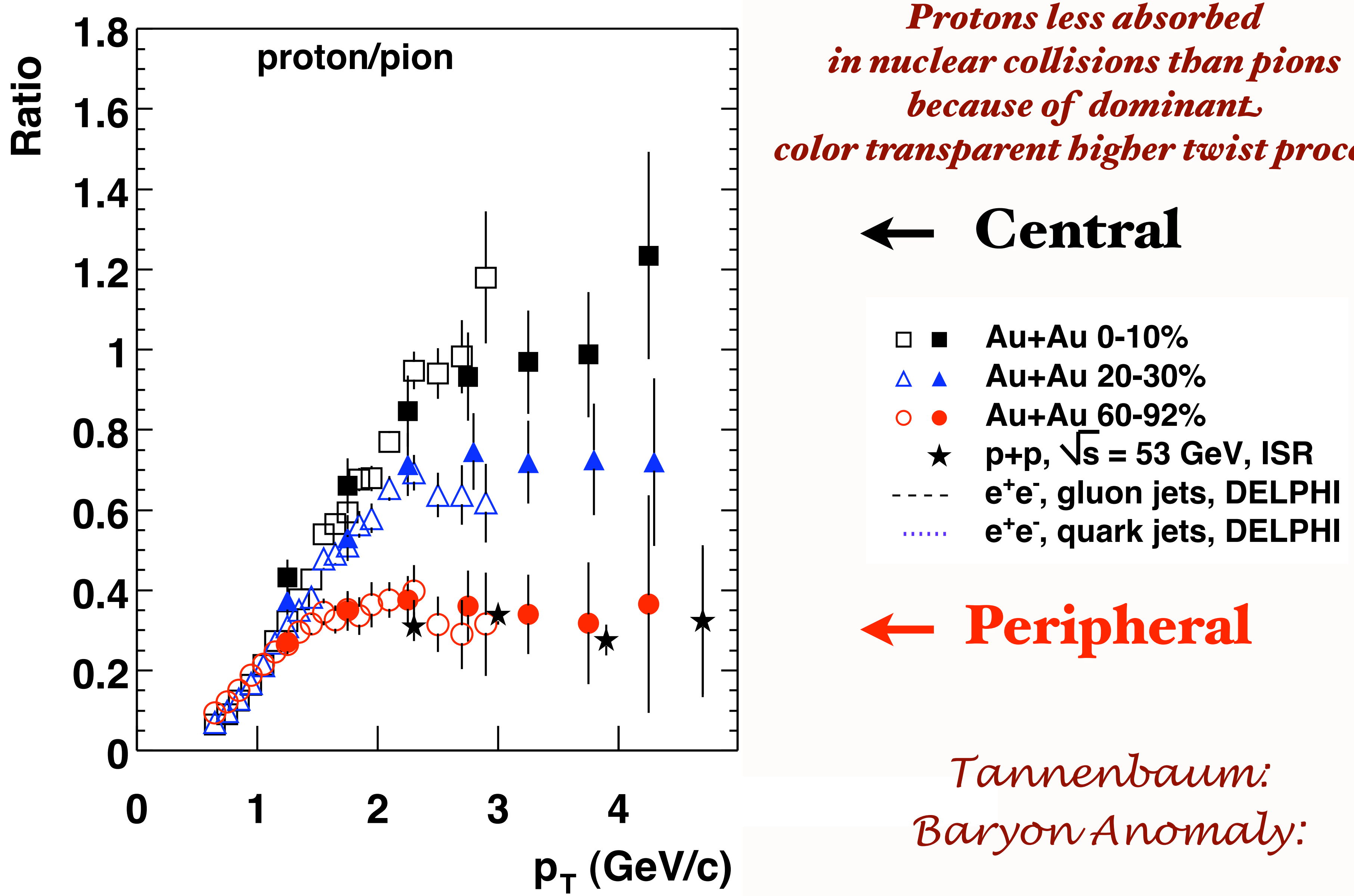
$$\frac{d\sigma}{d^3p/E}(pp \to pX) = A\frac{(1-x_T)^{11}}{p_T^4} + B\frac{(1-x_T)^7}{p_T^8}$$

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

Small color-singlet
Color Transparent
Minimal same-side energ

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**

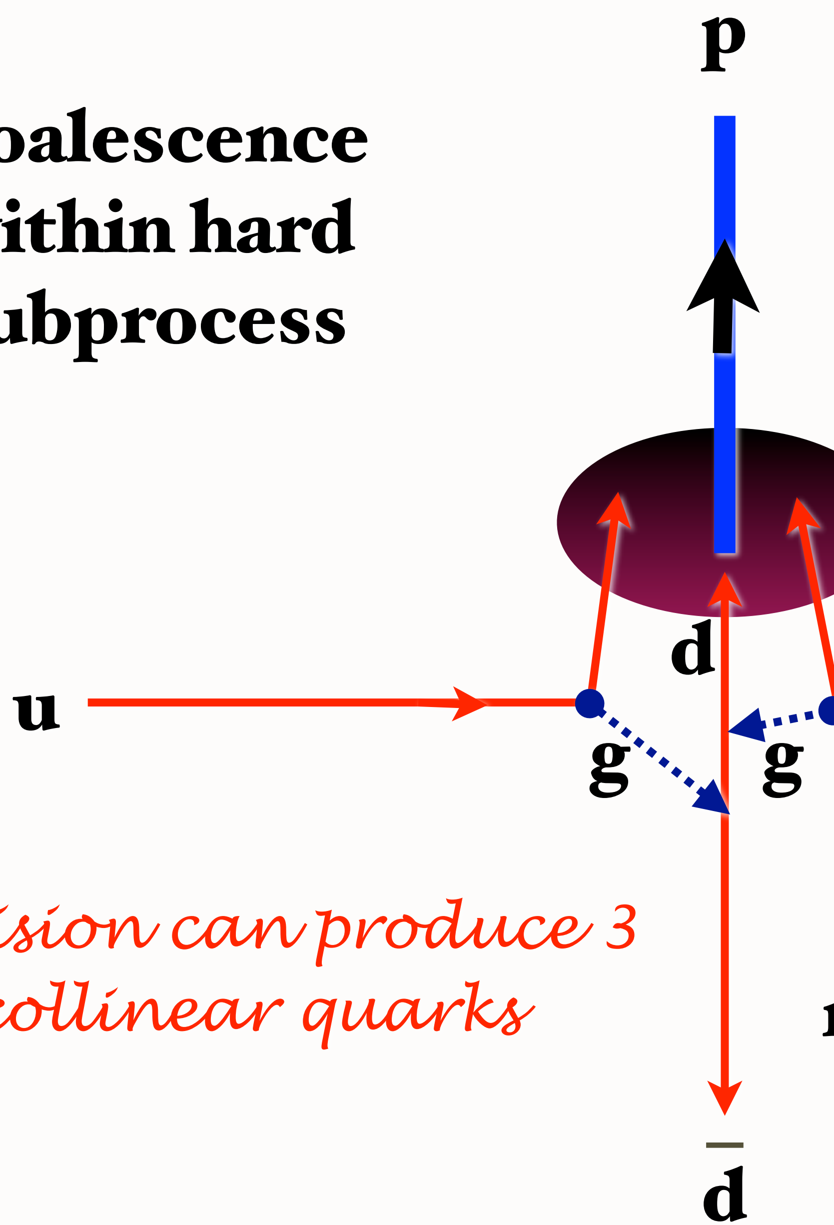
← **Peripheral**

Tannenbaum:

Baryon Anomaly:

Baryon can be made directly within hard subprocess!

Coalescence within hard subprocess



$uu \to p\bar{d}$

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

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

Sickles; sjb

Small color-singlet
Color Transparent
Minimal same-side energy

Baryon anomaly

$qq \to B\bar{q}$

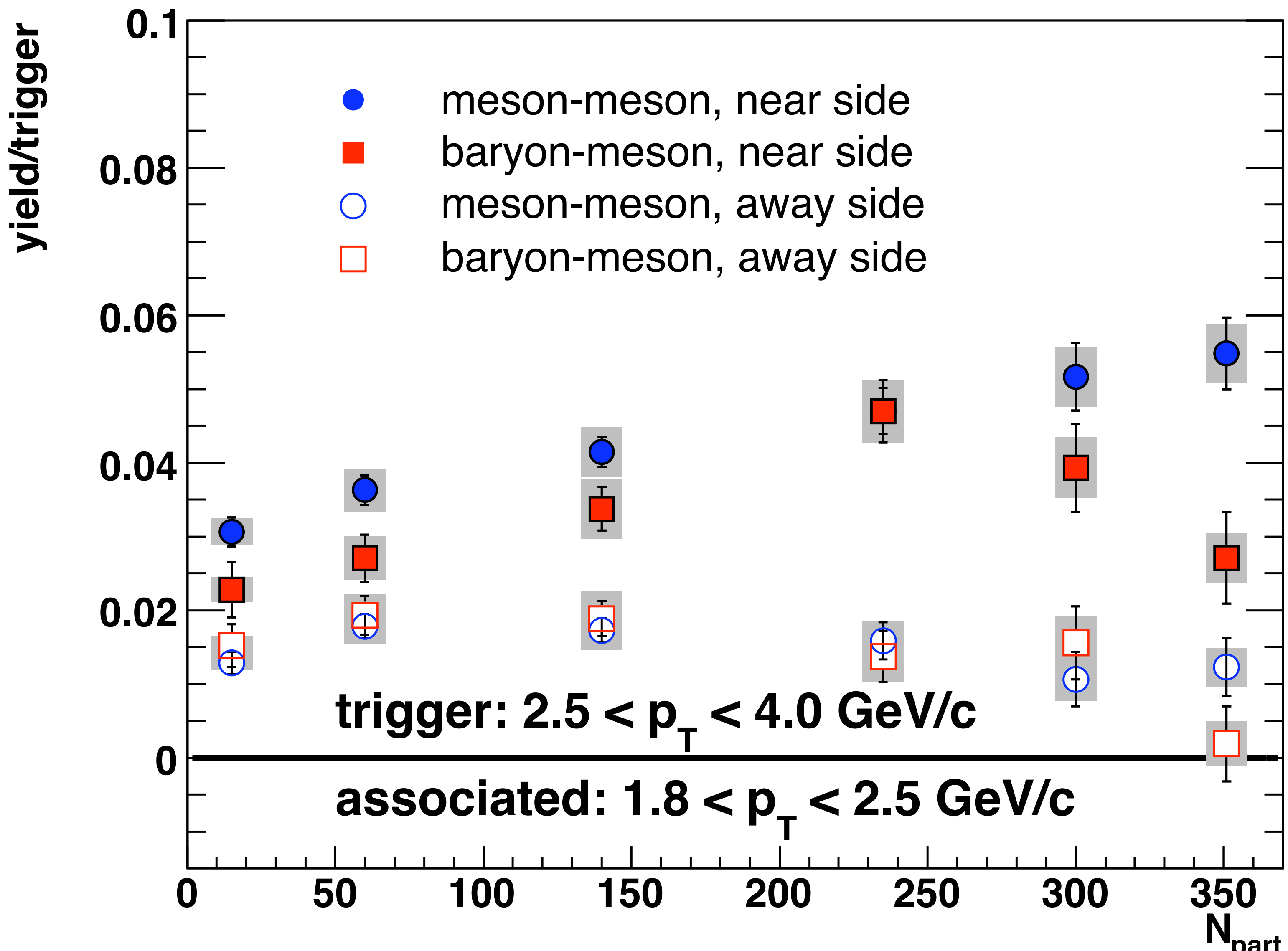
Collision can produce 3 collinear quarks

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

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

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

Anne Sickles

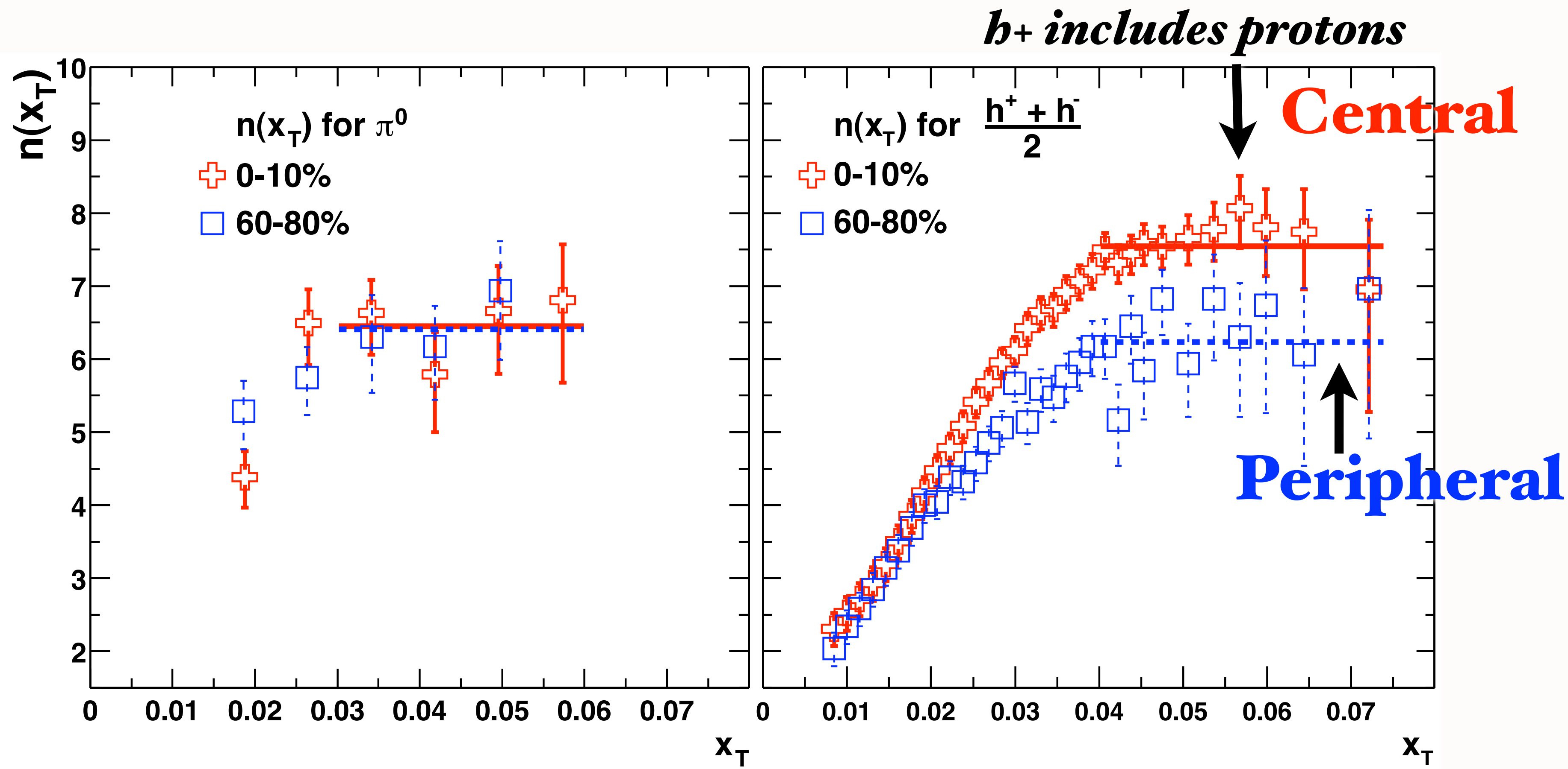


proton trigger: # same-side particles decreases with centrality

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

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].

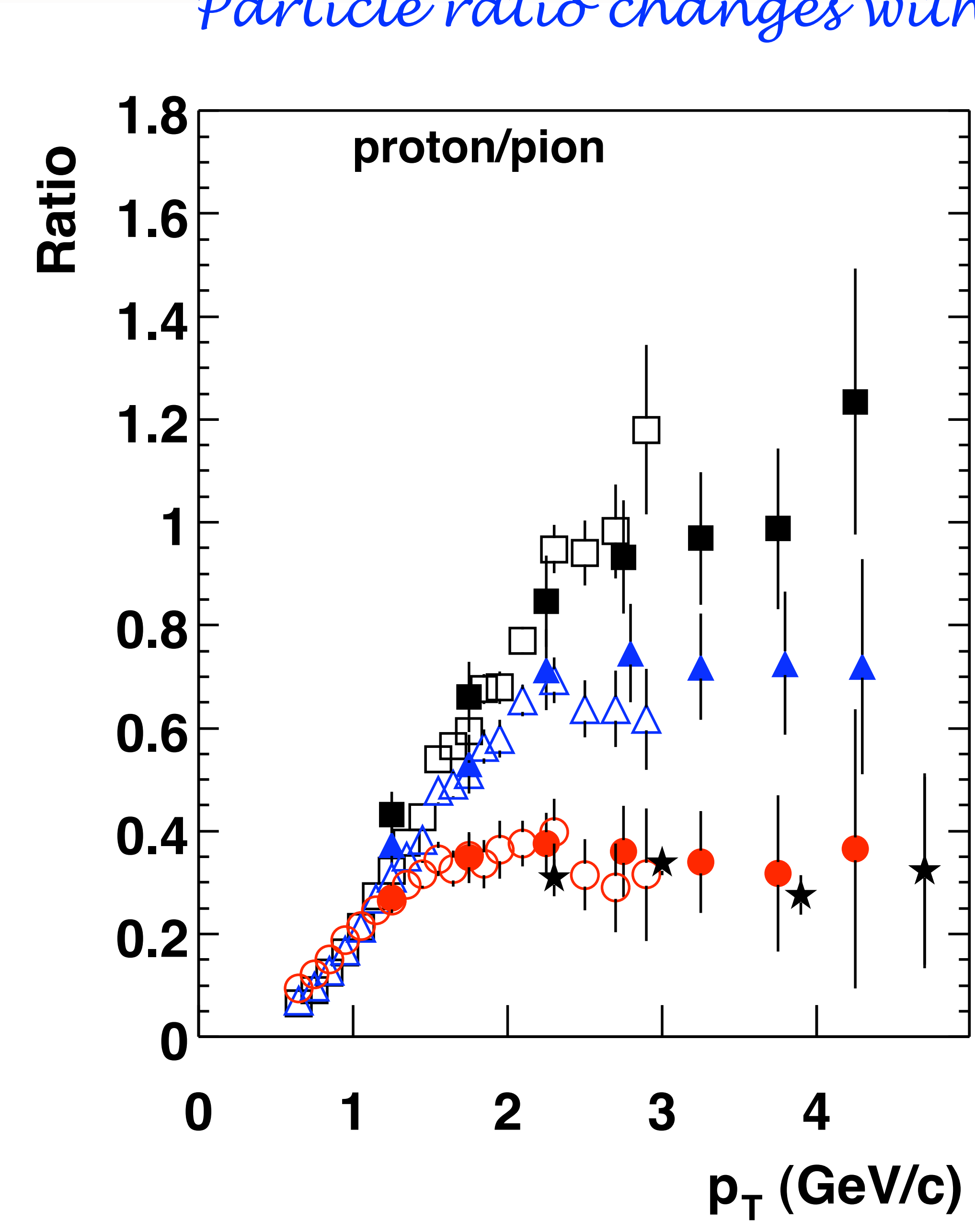


Proton power changes with centrality !

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**

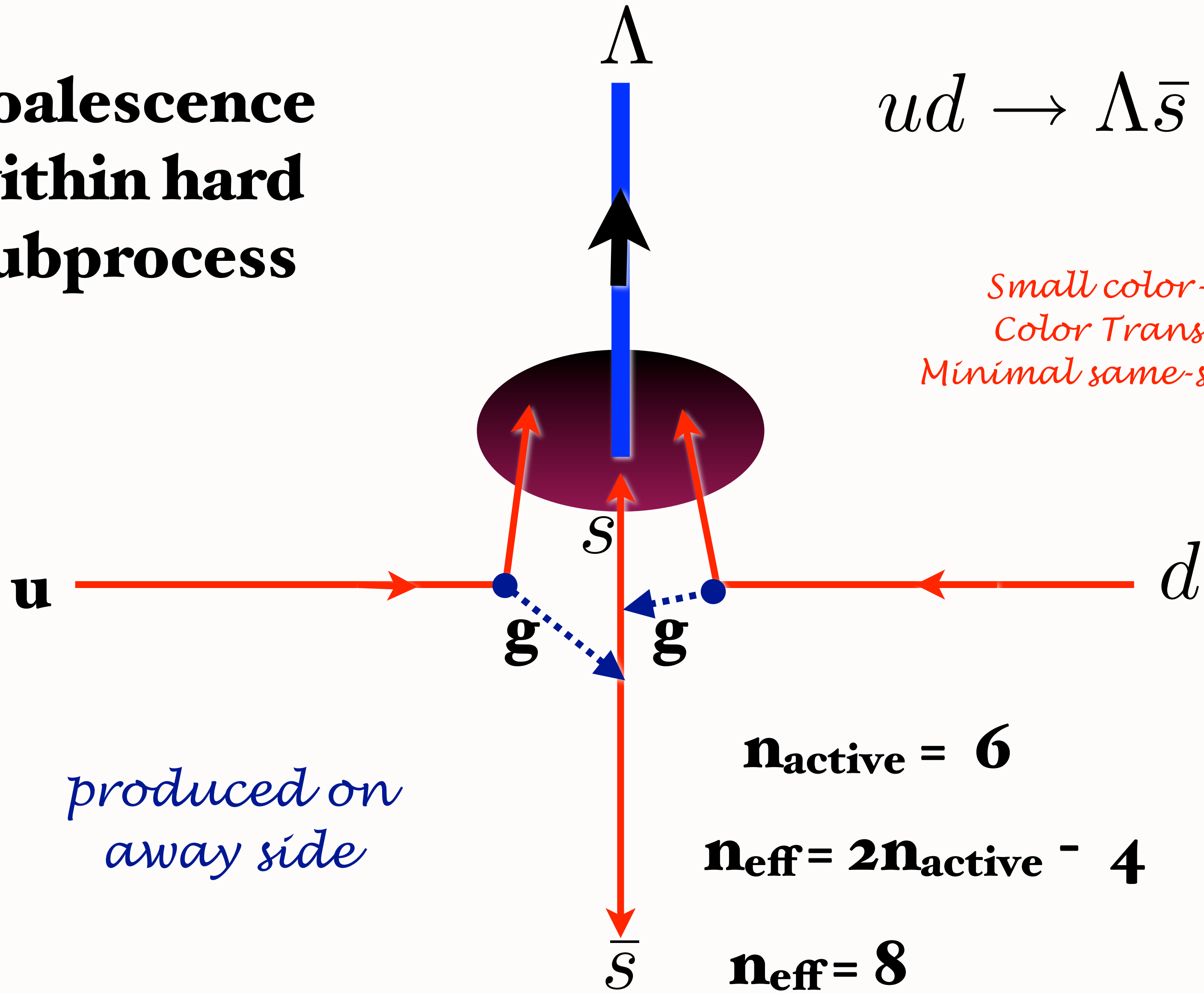
← **Peripheral**

Tannenbaum: Baryon Anomaly:

Lambda can be made directly within hard subprocess

Anne Sickles, sjb

Coalescence within hard subprocess



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

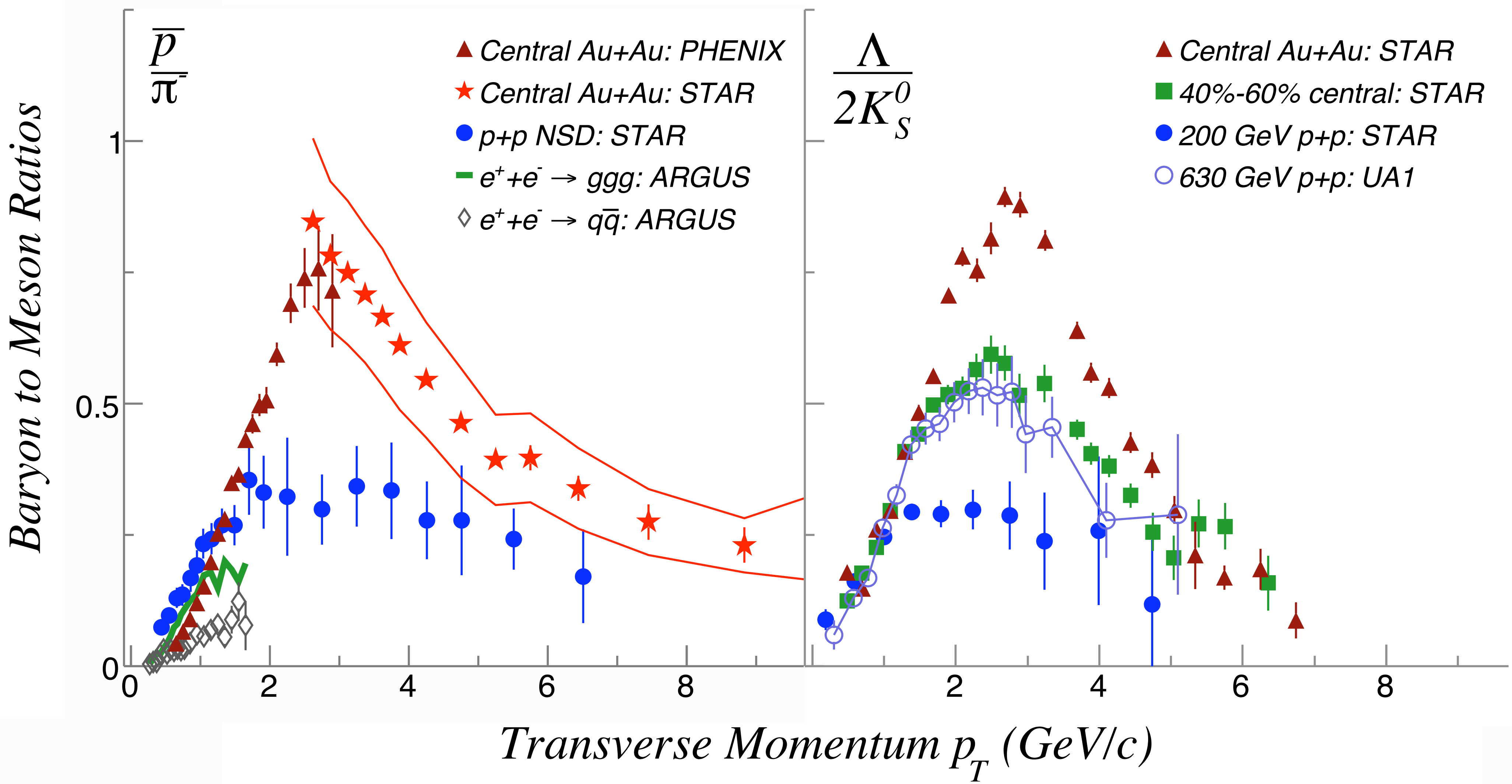
Small color-singlet
Color Transparent
Minimal same-side energy

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

$n_{active} = 6$

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

$n_{eff} = 8$


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

Higher Twist at the LHC

- Fixed x_T: powerful analysis of PQCD
- Insensitive to modeling
- Higher twist terms energy efficient since no wasted fragmentation energy
- Evaluate at minimal x_1 and x_2 where structure functions are maximal
- Higher Twist competitive despite faster fall-off in p_T
- Direct processes can confuse new physics searches

Isolated hadrons

Leading twist

Hadrons accompanied by a significant hadronic activity $\Rightarrow$ inside jets

Higher twist

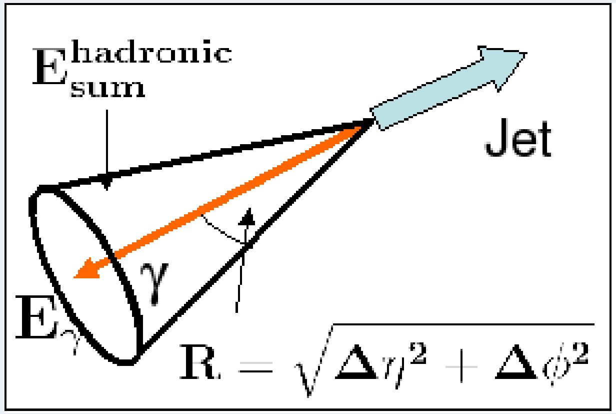
Color-singlet produced in the hard process $\Rightarrow$ "isolated" hadrons

Idea: use isolation criteria to filter the leading twist component

$$E_\perp^{\rm had} \leq E_\perp^{\rm max} = \varepsilon\ p_\perp^h$$

for particles inside a cone

$$(\eta - \eta_\gamma)^2 + (\phi - \phi_\gamma)^2 \leq R^2$$



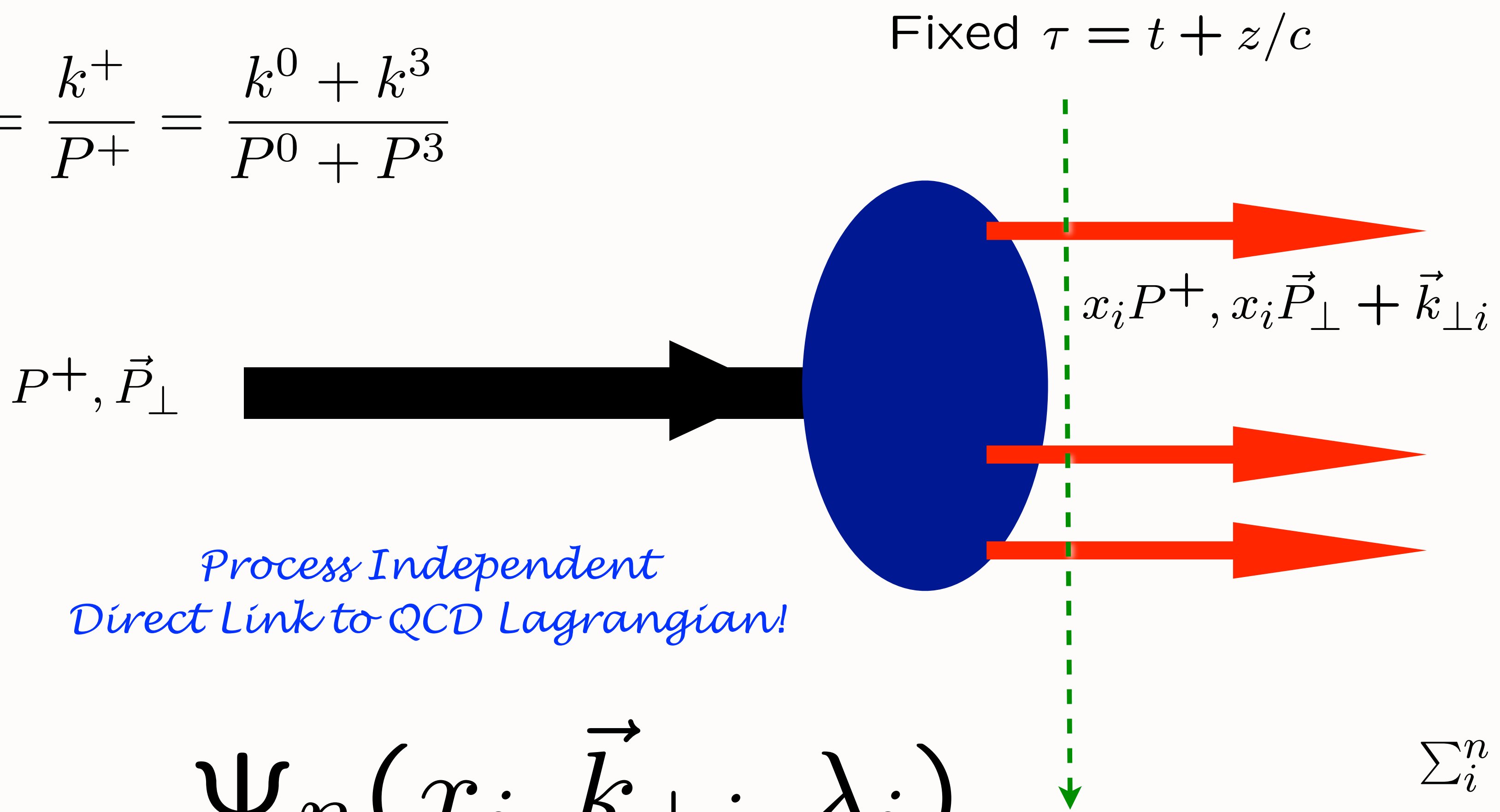
Consequence

Enhanced scaling exponent for isolated hadrons

$$n^h_{\rm isolated} > n^h_{\rm inclusive}$$

Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$



Process Independent
Direct Link to QCD Lagrangian!

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

$\sum_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

Angular Momentum on the Light-Front

LC gauge

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

Conserved
LF Fock state by Fock State

Gluon orbital angular momentum defined in physical lc gauge

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

n-1 orbital angular momenta

Orbital Angular Momentum is a property of LFWFS

Nonzero Anomalous Moment -->
Nonzero quark orbital angular momentum!

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

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

The Light Front Fock State Wavefunctions

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

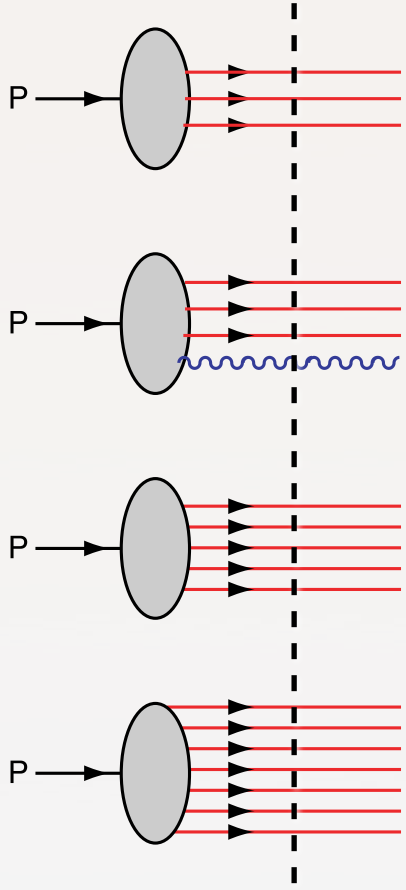
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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.

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



Intrinsic heavy quarks
c(x), b(x) at high x !

$\bar{s}(x) \neq s(x)$
$\bar{u}(x) \neq \bar{d}(x)$

Mueller: gluon Fock states $_{40}$**BFKL**

Hidden Color

Remarkable Features of Hadron Structure

- Valence quark helicity represents less than half of the proton's spin and momentum
- Non-zero quark orbital angular momentum!
- Asymmetric sea: $\bar{u}(x) \neq \bar{d}(x)$ relation to meson cloud
- Non-symmetric strange and antistrange sea $\bar{s}(x) \neq s(x)$
- Intrinsic charm and bottom at high x $\Delta s(x) \neq \Delta \bar{s}(x)$
- Hidden-Color Fock states of the Deuteron

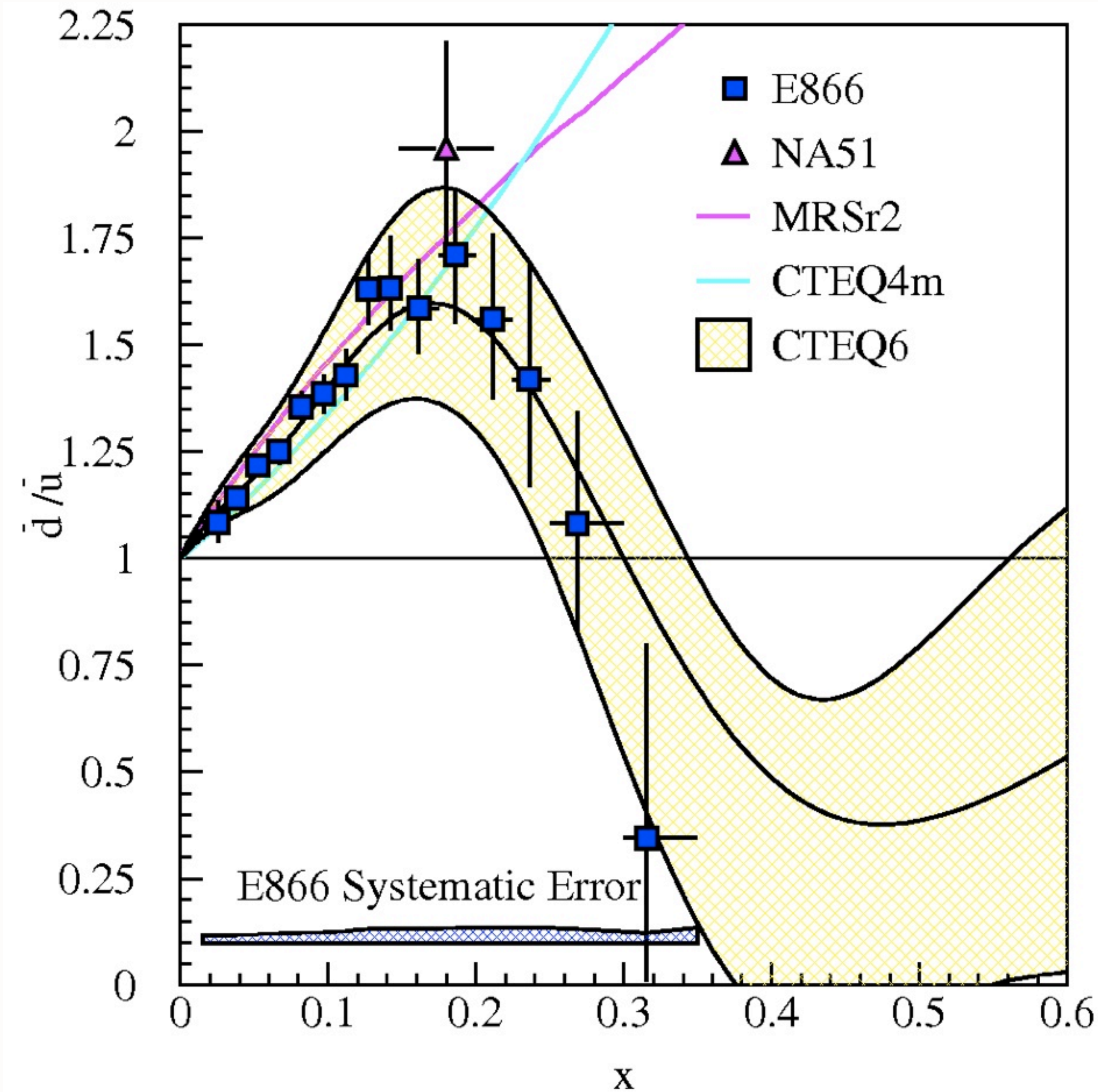
■ E866/NuSea (Drell-Yan)

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

$$s(x) \neq \bar{s}(x)$$

Intrinsic glue, sea, heavy quarks

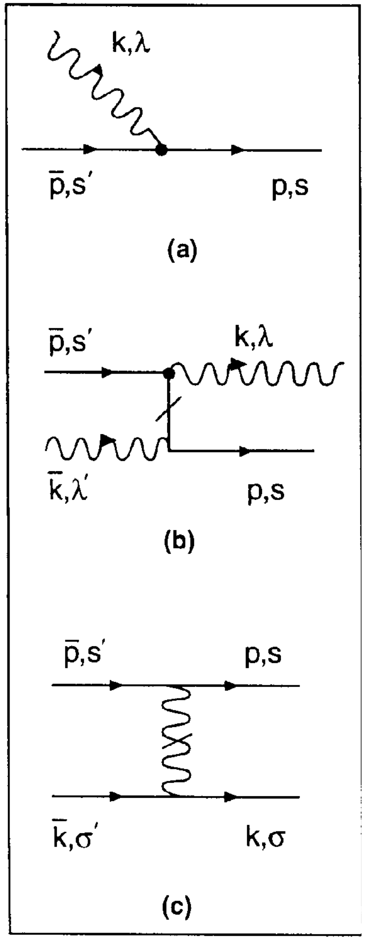
$\bar{d}(x)/\bar{u}(x)$ for $0.015 \leq x \leq 0.35$

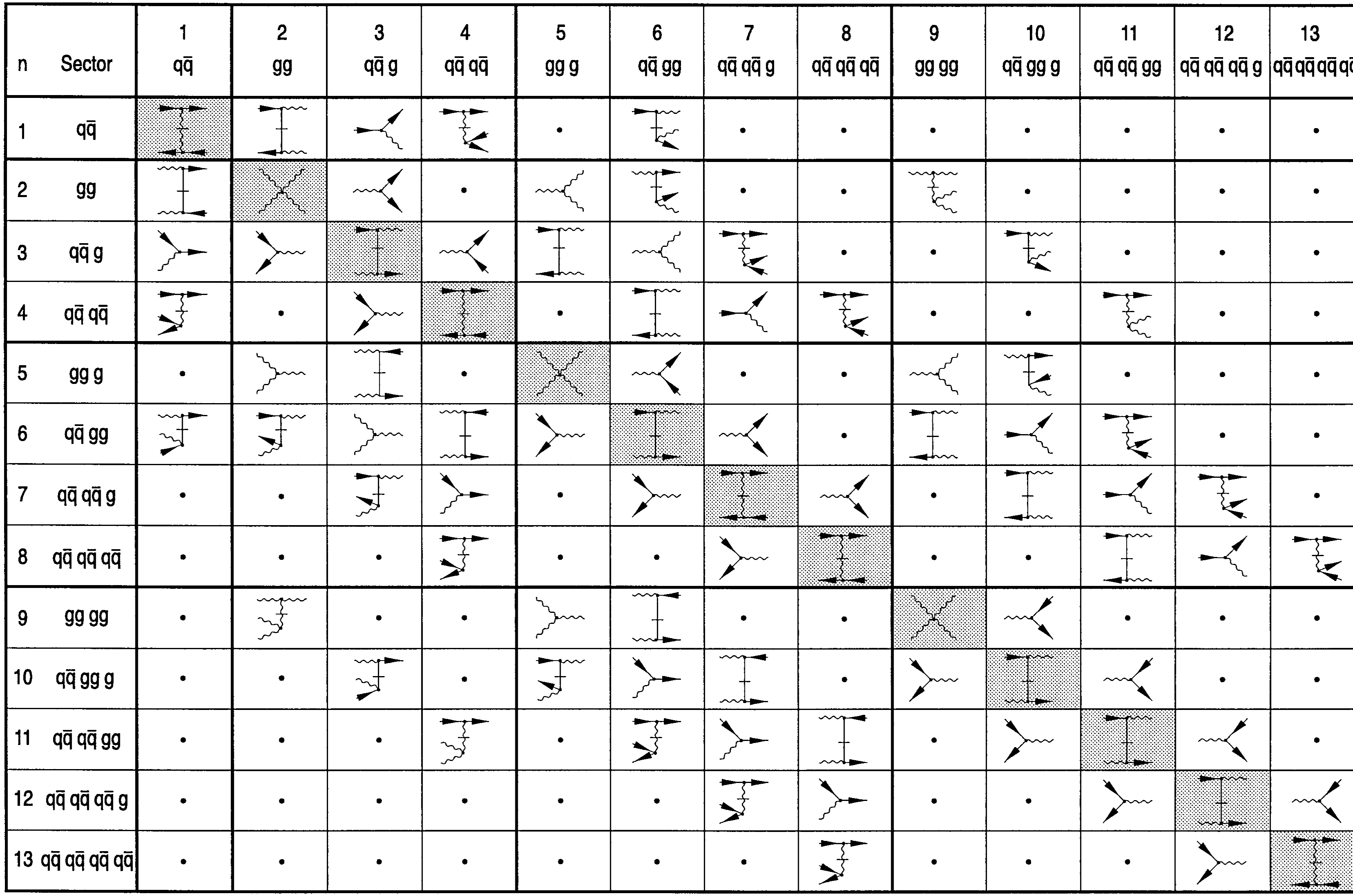


Light-Front QCD

Heisenberg Equation

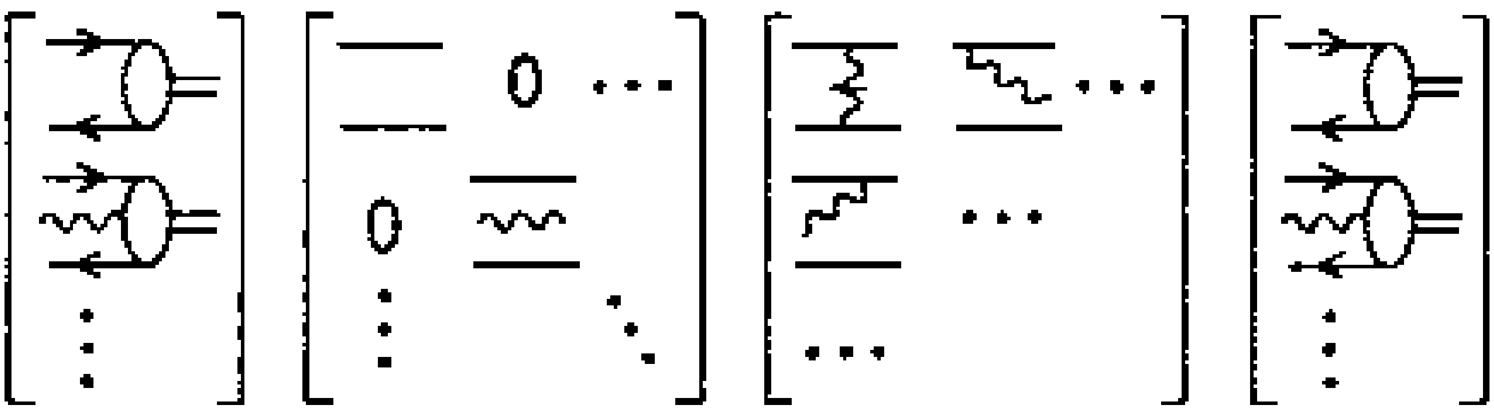
$$H_{LC}^{QCD}|\Psi_h\rangle = \mathcal{M}_h^2 \, |\Psi_h\rangle$$





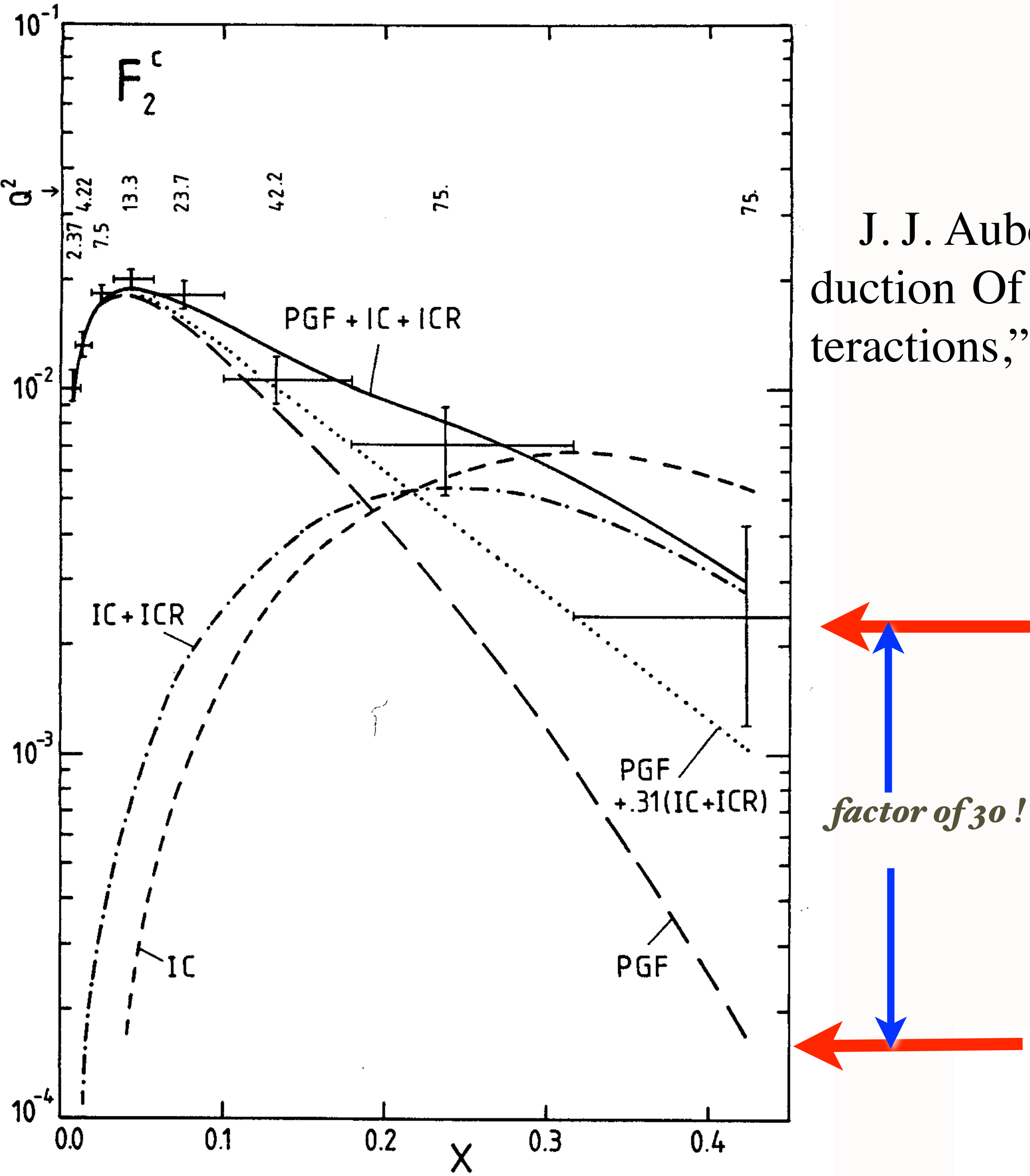
LIGHT-FRONT SCHRODINGER EQUATION

$$\left(M_\pi^2 - \sum_i \frac{\vec{k}_{\perp i}^{\,2} + m_i^2}{x_i}\right) \begin{bmatrix} \psi_{q\bar{q}/\pi} \\ \psi_{q\bar{q}g/\pi} \\ \vdots \end{bmatrix} = \begin{bmatrix} \langle q\bar{q}|\, V \,|q\bar{q}\rangle & \langle q\bar{q}|\, V \,|q\bar{q}g\rangle & \cdots \\ \langle q\bar{q}g|\, V \,|q\bar{q}\rangle & \langle q\bar{q}g|\, V \,|q\bar{q}g\rangle & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix} \begin{bmatrix} \psi_{q\bar{q}/\pi} \\ \psi_{q\bar{q}g/\pi} \\ \vdots \end{bmatrix}$$



$A^+ = 0$

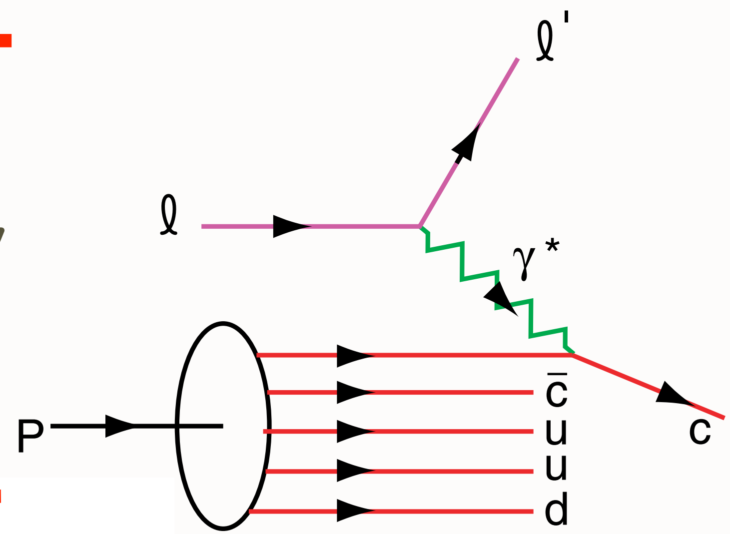
G.P. Lepage, sjb



Measurement of Charm Structure Function

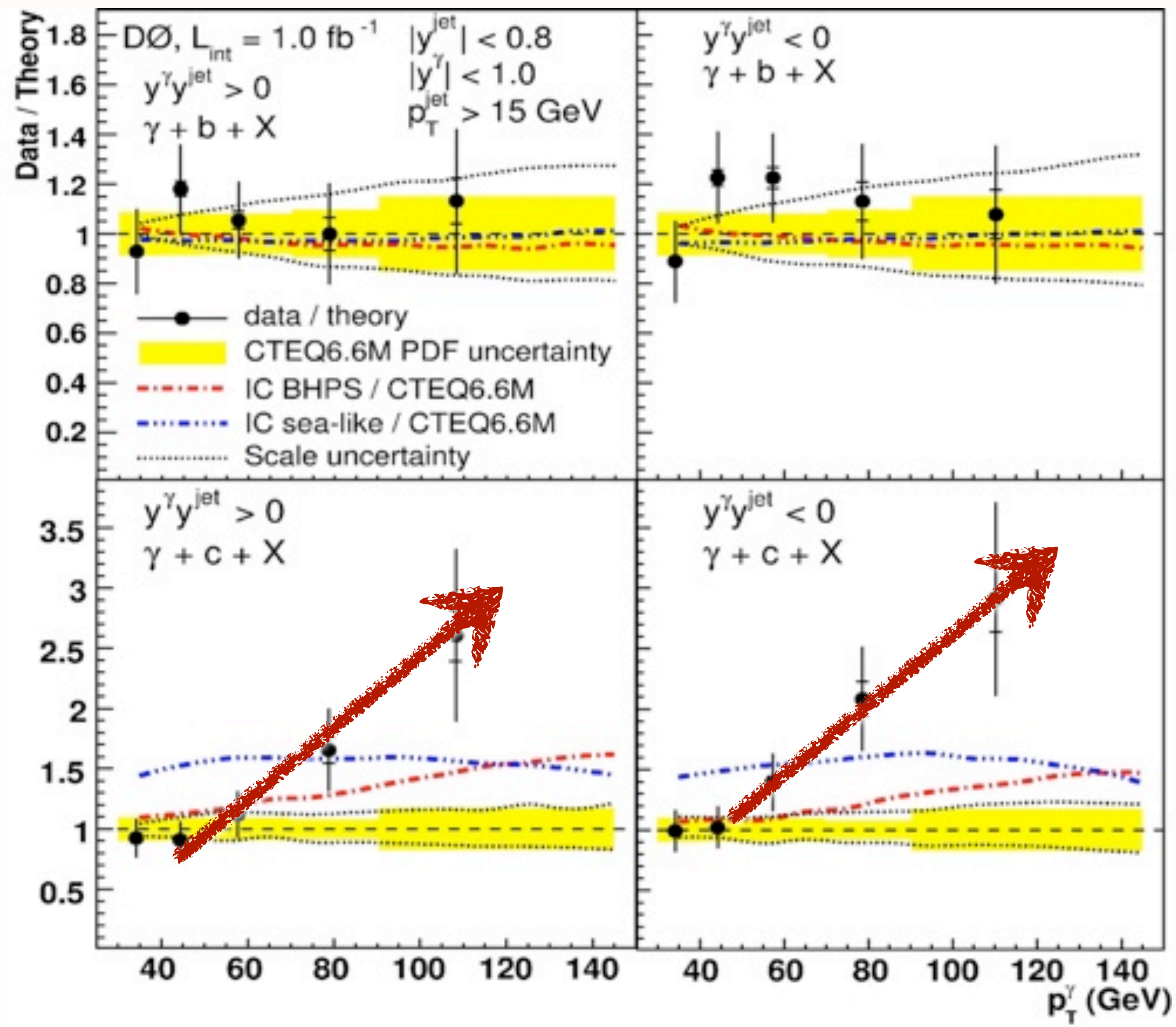
J. J. Aubert et al. [European Muon Collaboration], "Production Of Charmed Particles In 250-Gev Mu+ - Iron Interactions," Nucl. Phys. B 213, 31 (1983).

First Evidence for Intrinsic Charm



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

Measurement of $\gamma + b + X$ and $\gamma + c + X$ Production Cross Sections in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

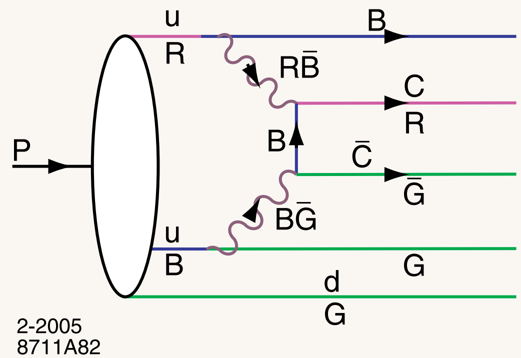


$$\frac{\Delta\sigma(\bar{p}p \to \gamma c X)}{\Delta\sigma(\bar{p}p \to \gamma b X)}$$

Ratio insensitive to gluon PDF, scales

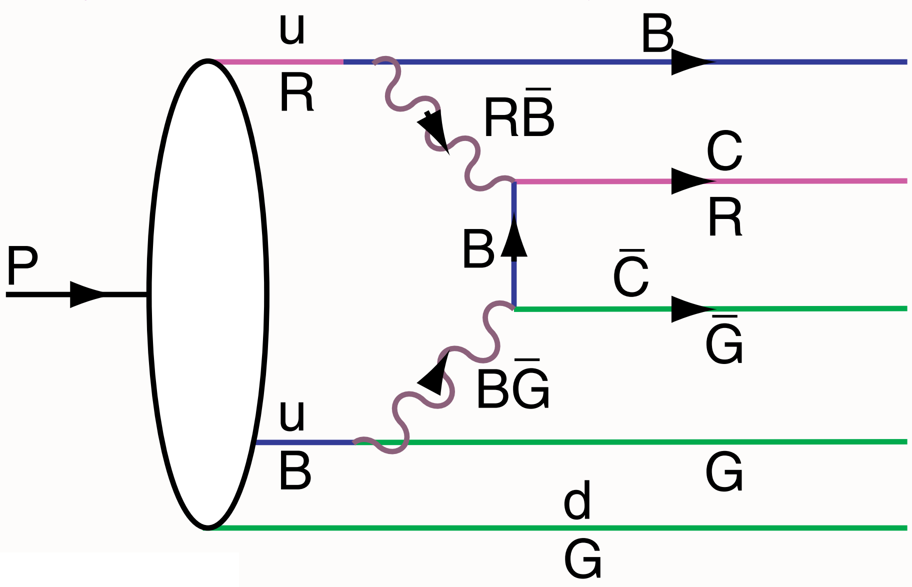
Signal for significant IC at x > 0.1 ?

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.

$< p|\frac{G^3_{\mu\nu}}{m^2_Q}|p >$ 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

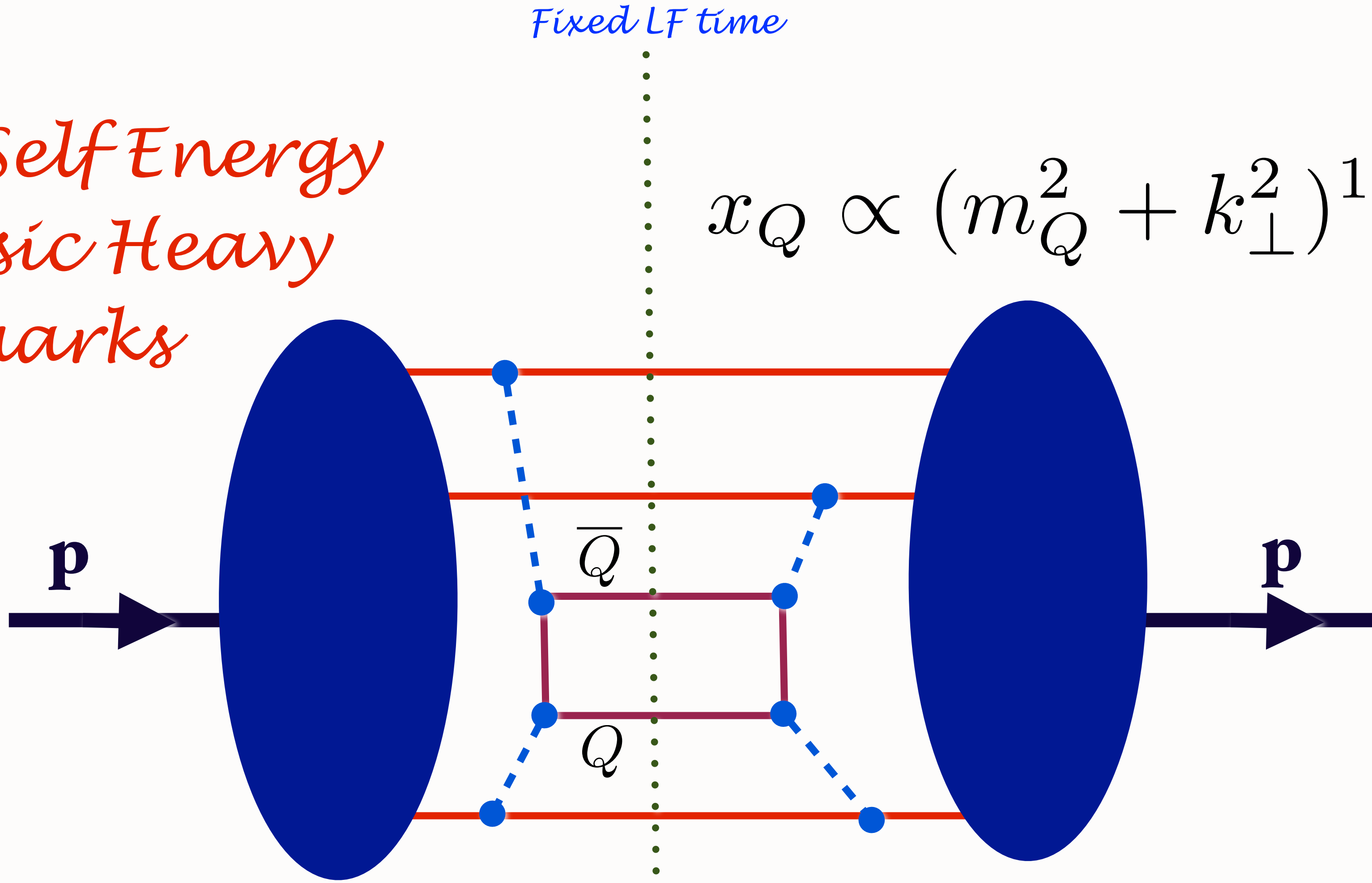
$$\hat{x}_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

High x charm! *Charm at Threshold*

Action Principle: Minimum KE, maximal potential

Proton Self Energy
Intrinsic Heavy Quarks

$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$



Probability (QED) $\propto \frac{1}{M_\ell^4}$

Probability (QCD) $\propto \frac{1}{M_Q^2}$

Collins, Ellis, Gunion, Mueller, sjb
M. Polyakov

INTRINSIC CHEVROLETS AT THE SSC

Stanley J. Brodsky

Stanford Linear Accelerator Center, Stanford University, Stanford CA 94305

John C. Collins

Department of Physics, Illinois Institute of Technology, Chicago IL 60616
and
High Energy Physics Division, Argonne National Laboratory, Argonne IL 60439

Stephen D. Ellis

Department of Physics, FM-15, University of Washington, Seattle WA 98195

John F. Gunion

Department of Physics, University of California, Davis CA 95616

Alfred H. Mueller

Department of Physics, Columbia University, New York NY 10027

$$\mathcal{L}^{eff}_{QCD} = -\frac{1}{4}F_{\mu\nu a}F^{\mu\nu a} - \frac{g^2 N_C}{120\pi^2 M_Q^2} D_\alpha F_{\mu\nu a} D^\alpha F^{\mu\nu a} + C\frac{g^2 N_C}{120\pi^2 M_Q^2} F^{a\nu}_{\mu} F^{b\tau}_{\nu} F^{c\mu}_{\tau} f_{abc} + \mathcal{O}(\frac{1}{M_Q^4})$$

Probability of Intrinsic Heavy Quarks ~ $1/M^2_Q$

Published in Snowmass Summer Study 1984:0227 (QCD184:S7:1984)

Heavy quark mass expansion and intrinsic charm in light hadrons.

M. Franz (Ruhr U., Bochum), Maxim V. Polyakov (Ruhr U., Bochum & St. Petersburg, INP), K. Goeke (Ruhr U., Bochum).

Feb 2000

Phys.Rev. D62 (2000) 074024
e-Print: **hep-ph/0002240**

Abstract: We review the technique of heavy quark mass expansion of various operators made of heavy quark fields using a semiclassical approximation. It corresponds to an operator product expansion in the form of series in the inverse heavy quark mass. This technique applied recently to the axial current is used to estimate the charm content of the η, η' mesons and the intrinsic charm contribution to the proton spin. The derivation of heavy quark mass expansion for $\bar{Q}\gamma_5 Q$ is given here in detail and the expansions of the scalar, vector and tensor current and of a contribution to the energy-momentum tensor are presented as well. The obtained results are used to estimate the intrinsic charm contribution to various observables.

- 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 $pp \to \Lambda_c X$

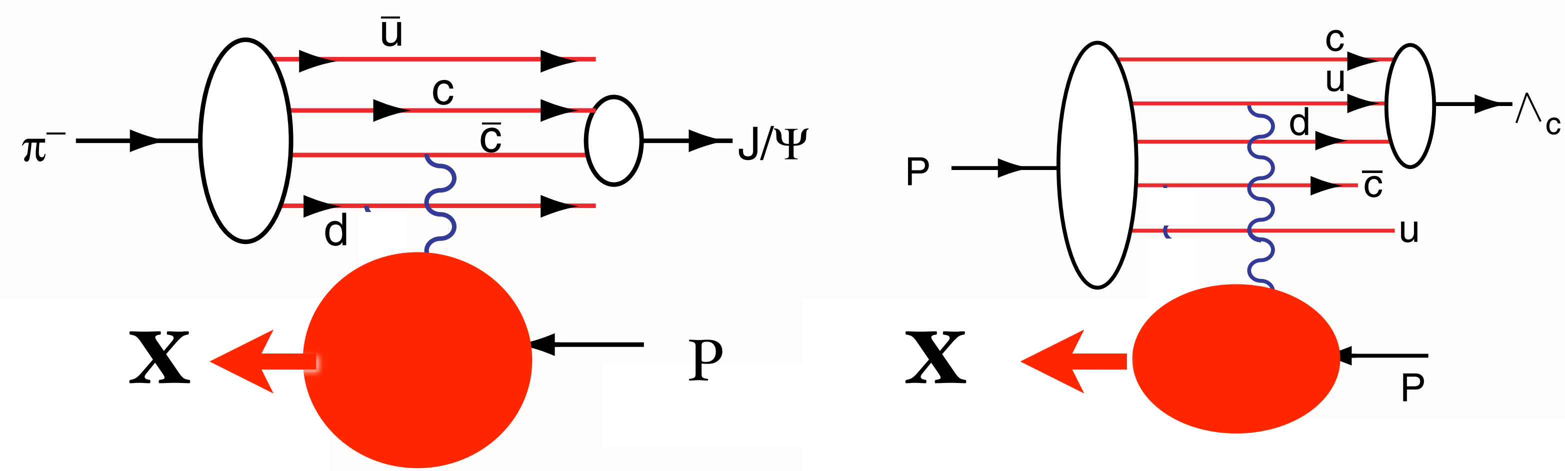
- High x_F $pp \to \Lambda_b X$

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

IC Structure Function: Critical Measurement for EIC

Many interesting spin, charge asymmetry, spectator effects

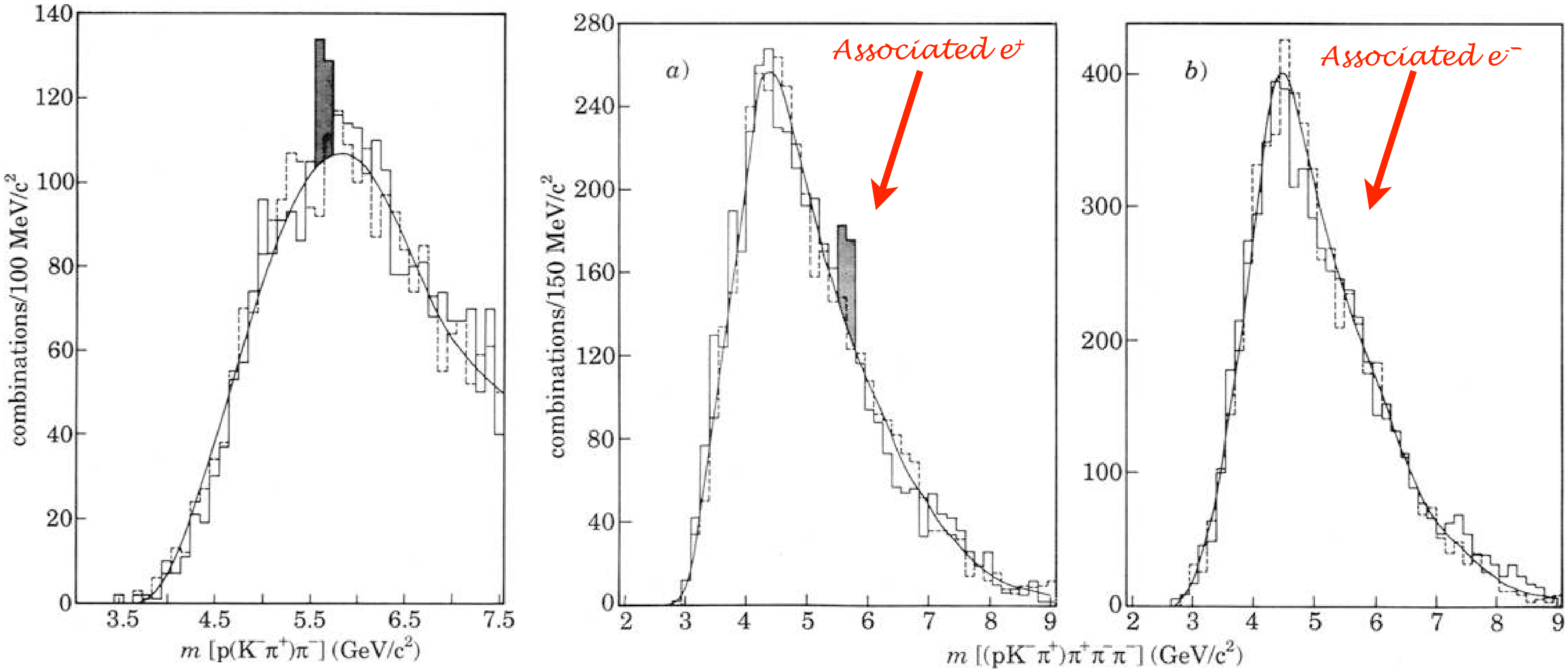
Leading Hadron Production from Intrinsic Charm



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

$pp \to \Lambda_b(bud)B(\bar{b}q)X$ at large x_F

CERN-ISR R422 (Split Field Magnet), 1988/1991



$\Lambda_b^0 \to pD^0\pi^-$

$\Lambda_b^0 \to \Lambda_c^+\pi^+\pi^-\pi^-$

Il Nuovo Cimento 104, 1787

[redacted]

CM-P00063074

Preprint DFUB-91/5
27 May 1991

THE Λ_b^o BEAUTY BARYON PRODUCTION IN PROTON-PROTON INTERACTIONS AT $\sqrt{s}$=62 GeV: A SECOND OBSERVATION

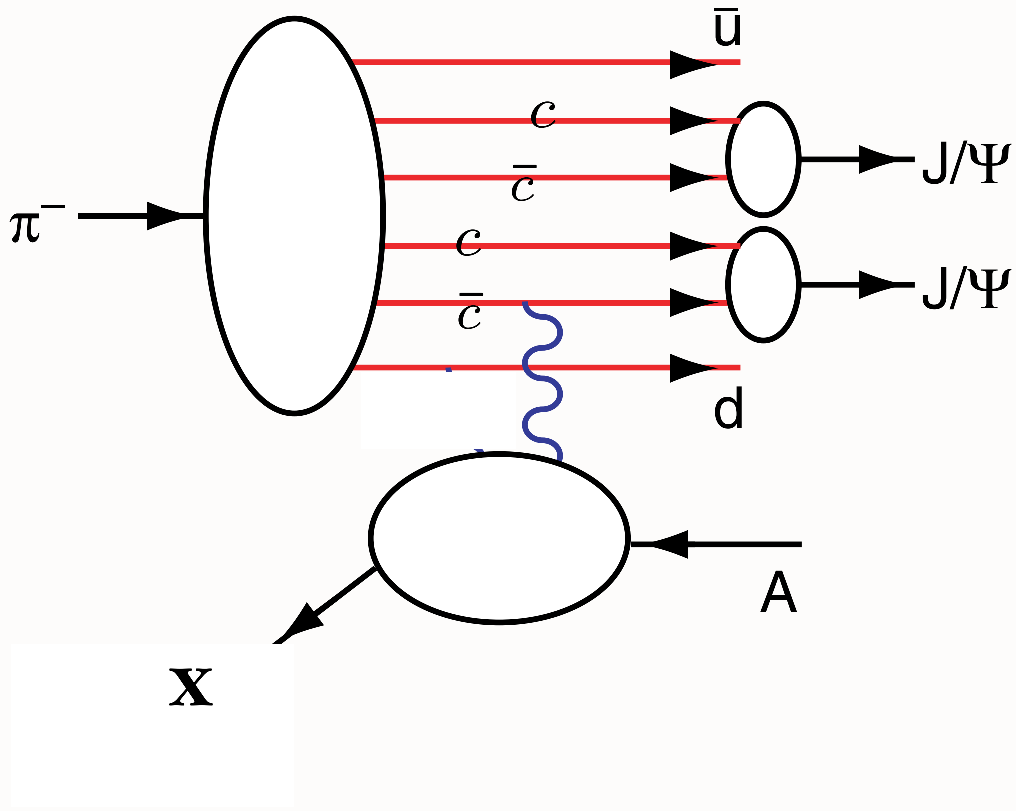
G. Bari, M. Basile, G. Bruni, G. Cara Romeo, R. Casaccia, L. Cifarelli, F. Cindolo, A. Contin, G. D'Alì, C. Del Papa, S. De Pasquale, P. Giusti, G. Iacobucci, G. Maccarrone, T. Massam, R. Nania, F. Palmonari, G. Sartorelli, G. Susinno, L. Votano and A. Zichichi

CERN, Geneva, Switzerland
Dipartimento di Fisica dell'Università, Bologna, Italy
Dipartimento di Fisica dell'Università, Cosenza, Italy
Istituto di Fisica dell'Università, Palermo, Italy
Istituto Nazionale di Fisica Nucleare, Bologna, Italy
Istituto Nazionale di Fisica Nucleare, LNF, Frascati, Italy

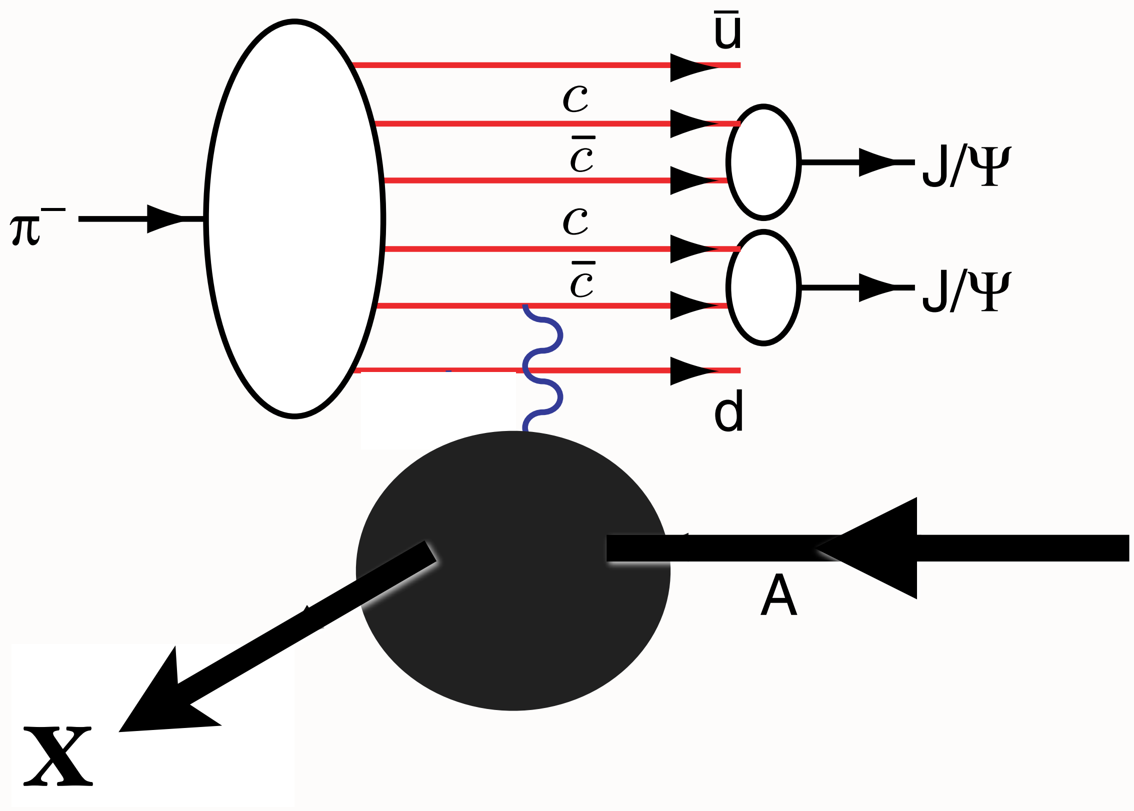
Abstract

Another decay mode of the Λ_b^o (open-beauty baryon) state has been observed: $\Lambda_b^o \rightarrow \Lambda_c^+\pi^+\pi^-\pi^-$. In addition, new results on the previously observed decay channel, $\Lambda_b^o \rightarrow pD^o\pi^-$, are reported. These results confirm our previous findings on Λ_b^o production at the ISR. The mass value (5.6 GeV/c^2) is found to be in good agreement with theoretical predictions. The production mechanism is found to be "leading".

Production of Two Charmonia at High x_F



Production of Two Charmonia at High x_F



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

Excludes `color drag' model

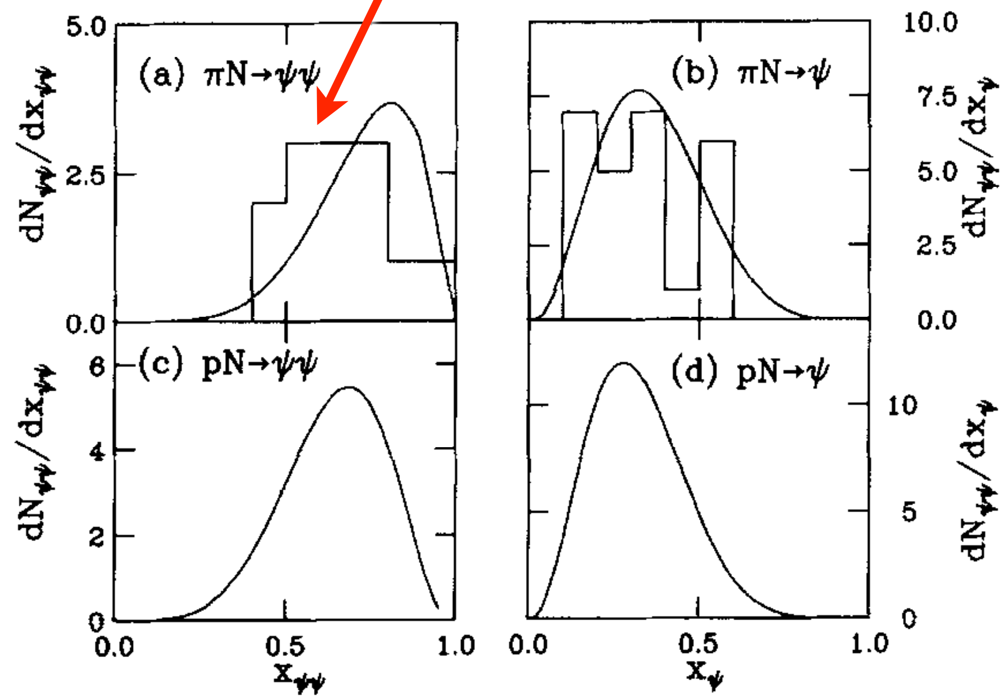


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized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

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

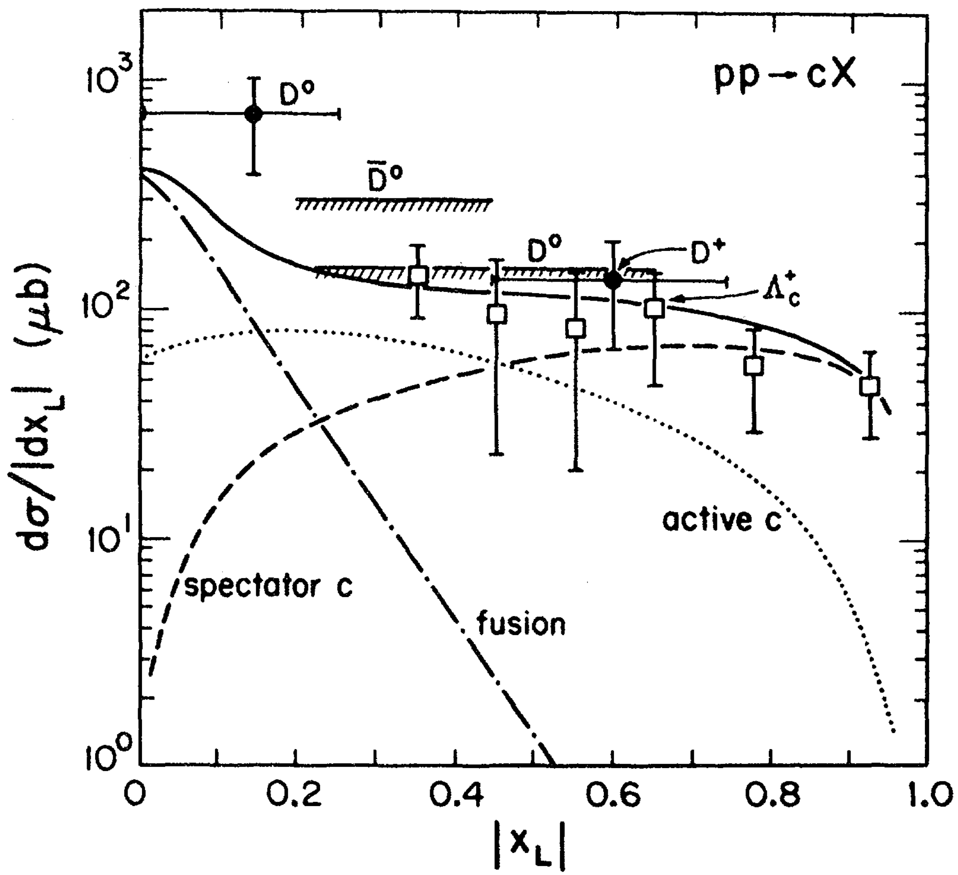
Intrinsic charm contribution to double quarkonium hadroproduction ★

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

$$\frac{dP_{\rm ic}}{\prod_{i=1}^n dx_i d^2k_{T,i}}$$

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



Model similar to Intrinsic Charm

V. D. Barger, F. Halzen and W. Y. Keung,
"The Central And Diffractive Components Of Charm Production,"
Phys. Rev. D 25, 112 (1982).

Excitation of Intrinsic Heavy Quarks in Proton

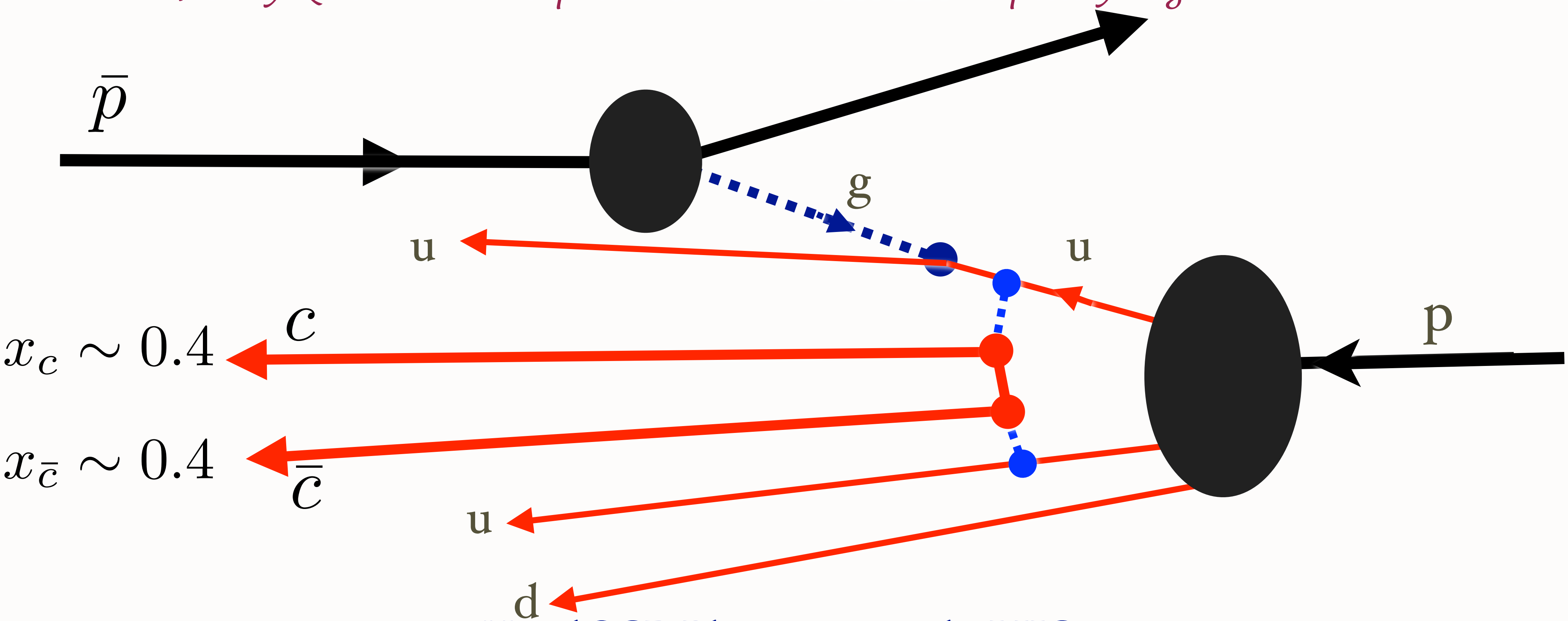
Amplitude maximal at small invariant mass, equal rapidity

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

$$\frac{d\sigma}{dy_{J/\psi}}(\bar{p}p \to J/\psi X)$$

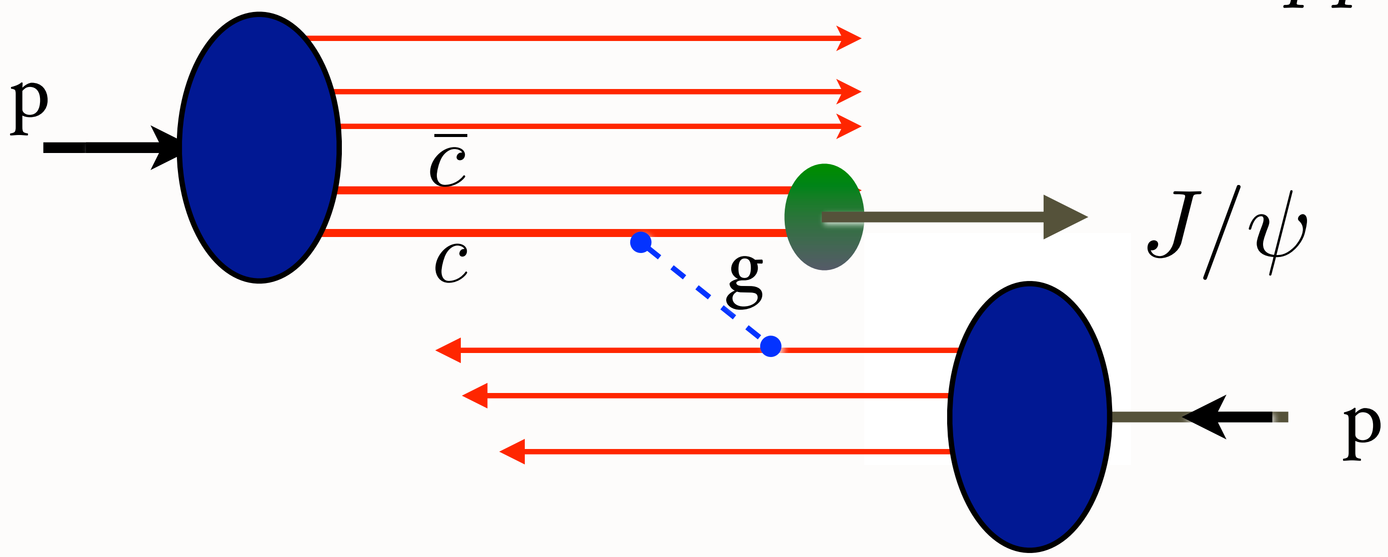
J-P Lansberg, sjb

Heavy Quarkonium produced in **TARGET** *rapidity region*



Intrinsic Charm Mechanism for Inclusive High-X_F Quarkonium Production

$$pp \rightarrow J/\psi X$$

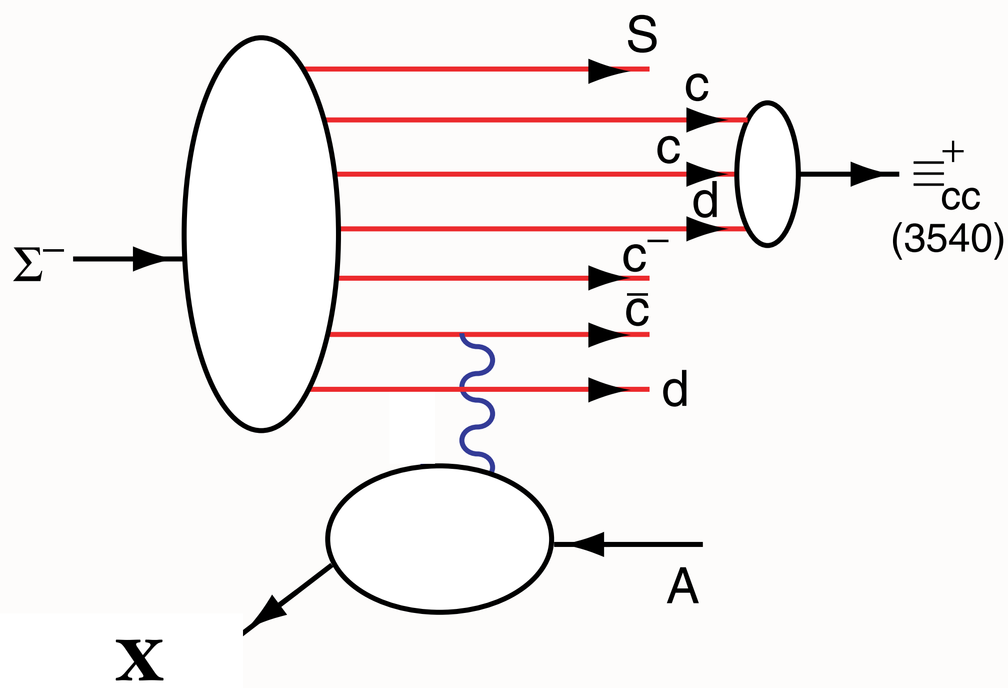


Goldhaber, Kopeliovich, Soffer, Schmidt, sjb

Quarkonia can have 80% of Proton Momentum!

Color-octet IC interacts at front surface of nucleus

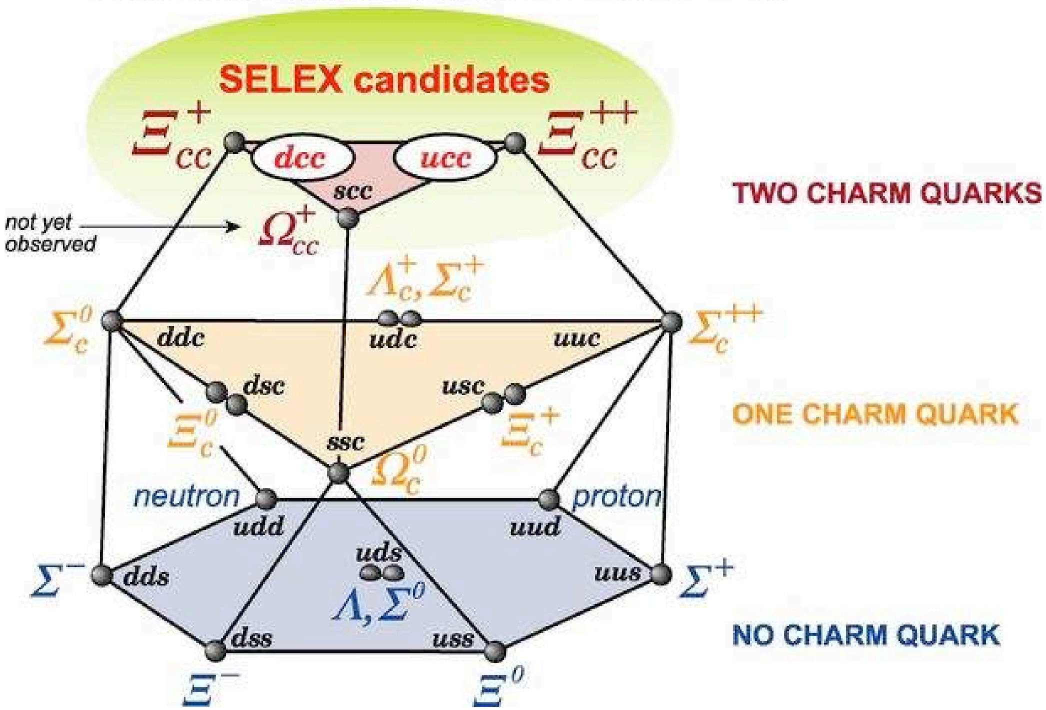
IC can explains large excess of quarkonia at large x_F, A-dependence

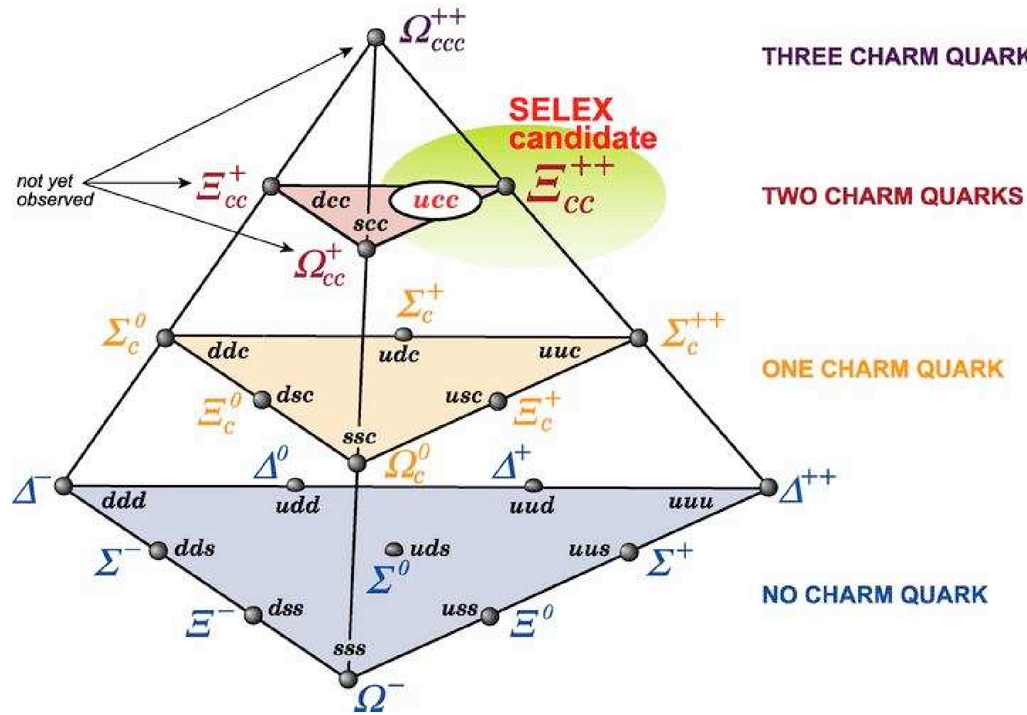


Production of a Double-Charm Baryon

SELEX high x_F $< x_F >= 0.33$

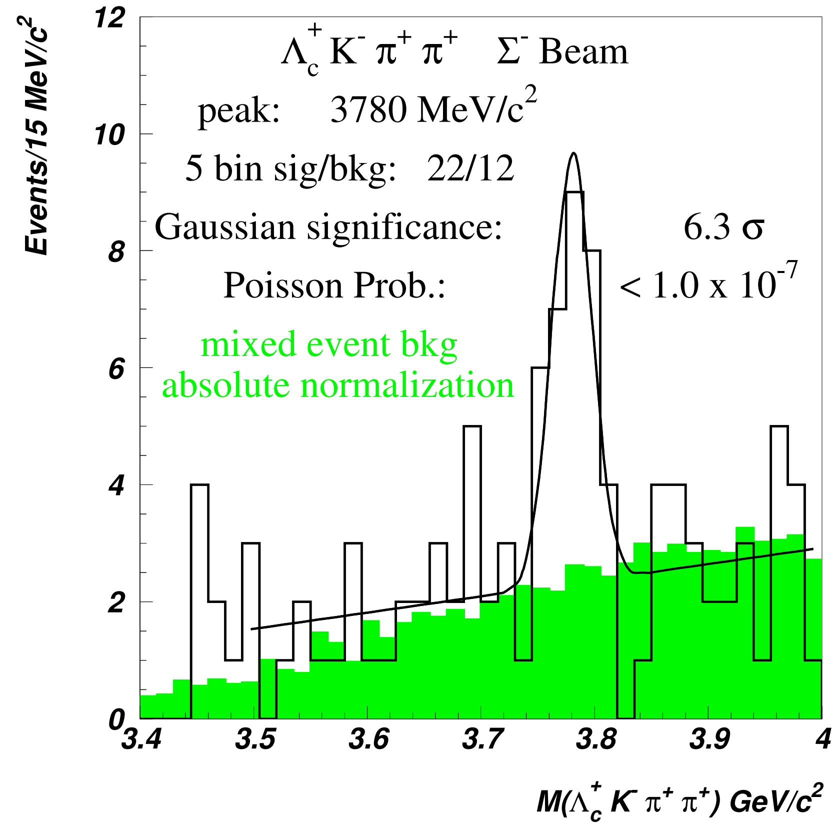
Doubly Charmed Baryons



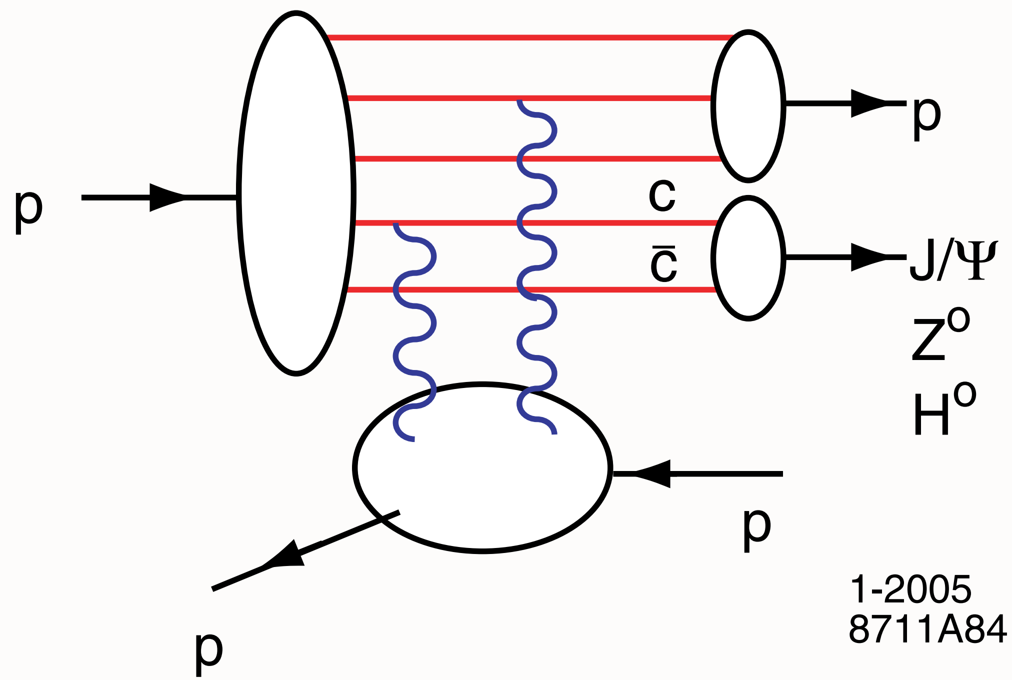


$\Xi_{cc}(3780)^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

- Re-Analyzed Data
- Restrict to Σ^-–Beam
- Peak wider than Resolution
- Half decay to $\Xi_{cc}^+(3520)$
- Still working on Details



Intrinsic Charm Mechanism for Exclusive Diffraction Production



$$p\,p \to J/\psi\; p\; p$$

$$x_{J/\psi} = x_c + x_{\bar{c}}$$

Exclusive Diffractive
High-X_F Higgs Production

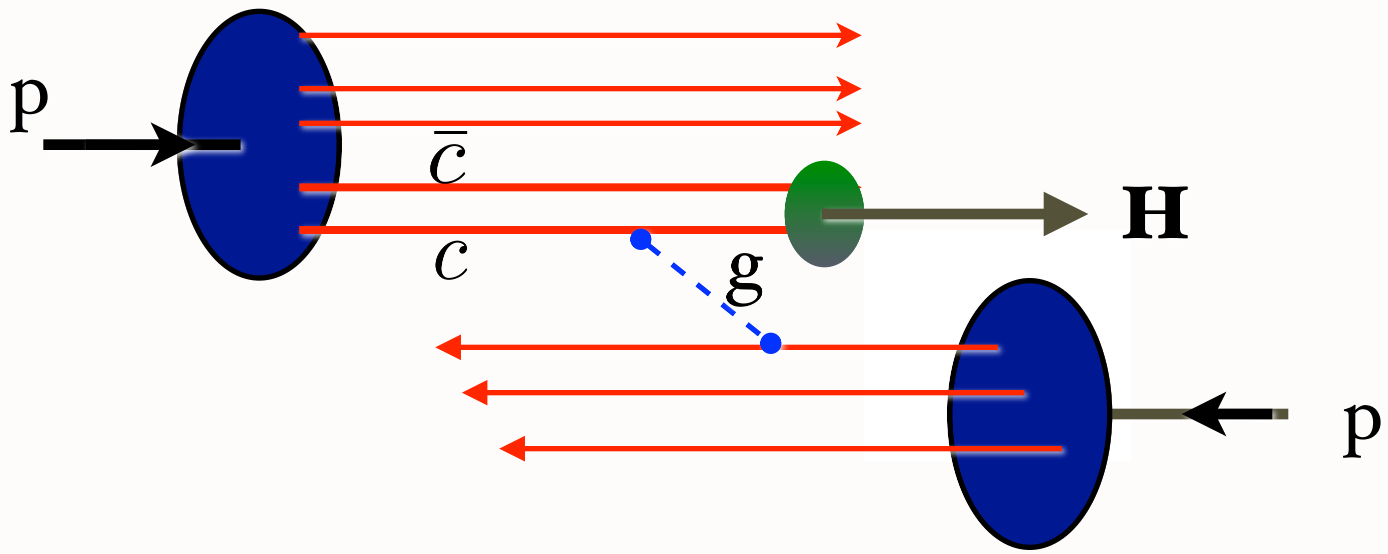
Kopeliovitch, Schmidt, Soffer, sjb

Intrinsic $c\bar{c}$ pair formed in color octet 8_C in proton wavefunction Large Color Dipole

Collision produces color-singlet J/ψ through color exchange

RHIC Experiment

Intrinsic Charm Mechanism for Inclusive High-X_F Higgs Production



$$pp \rightarrow HX$$

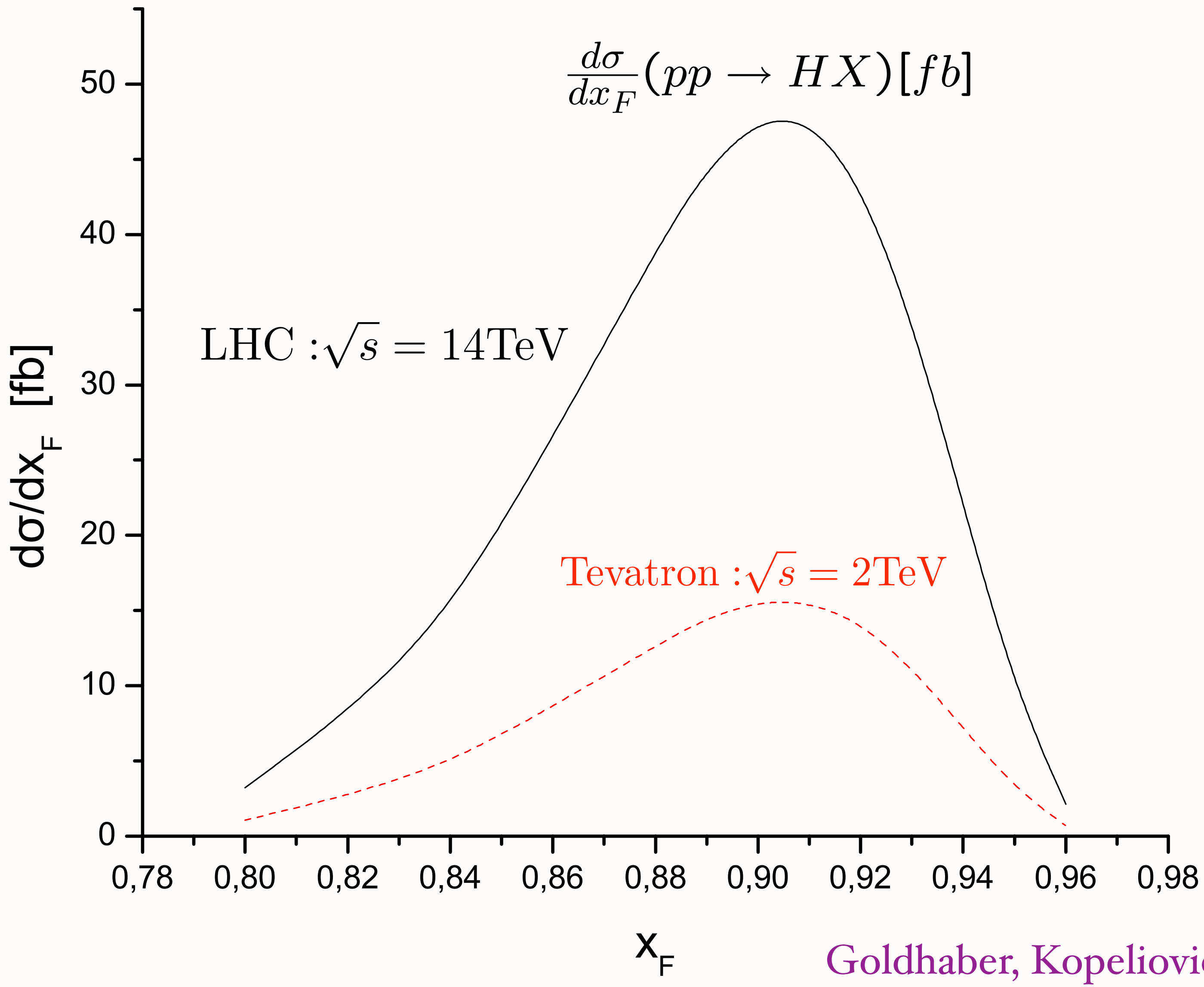
Goldhaber, Kopeliovich, Schmidt, sjb

Also: intrinsic bottom, top

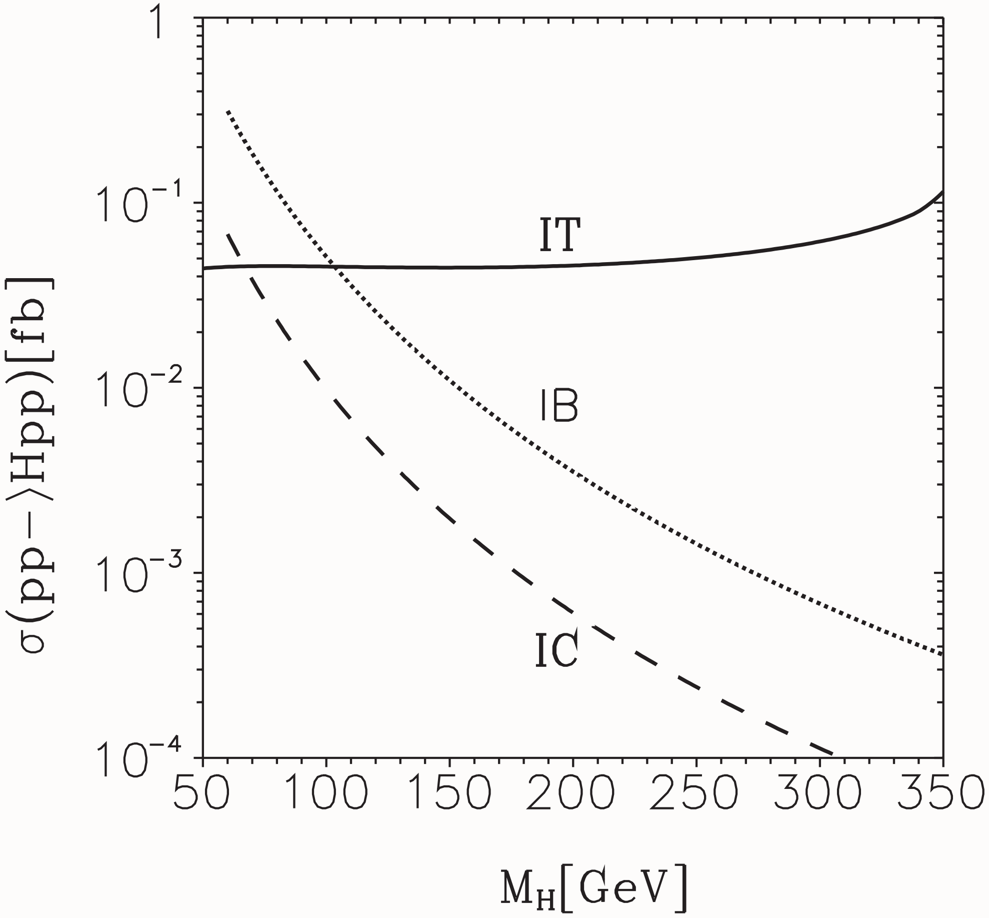
Higgs can have 80% of Proton Momentum!

New search strategy for Higgs

Intrinsic Bottom Contribution to Inclusive Higgs Production



Goldhaber, Kopeliovich, Schmidt, sjb



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).

Heavy Quark Anomalies

Nuclear dependence of J/ψ hadroproduction

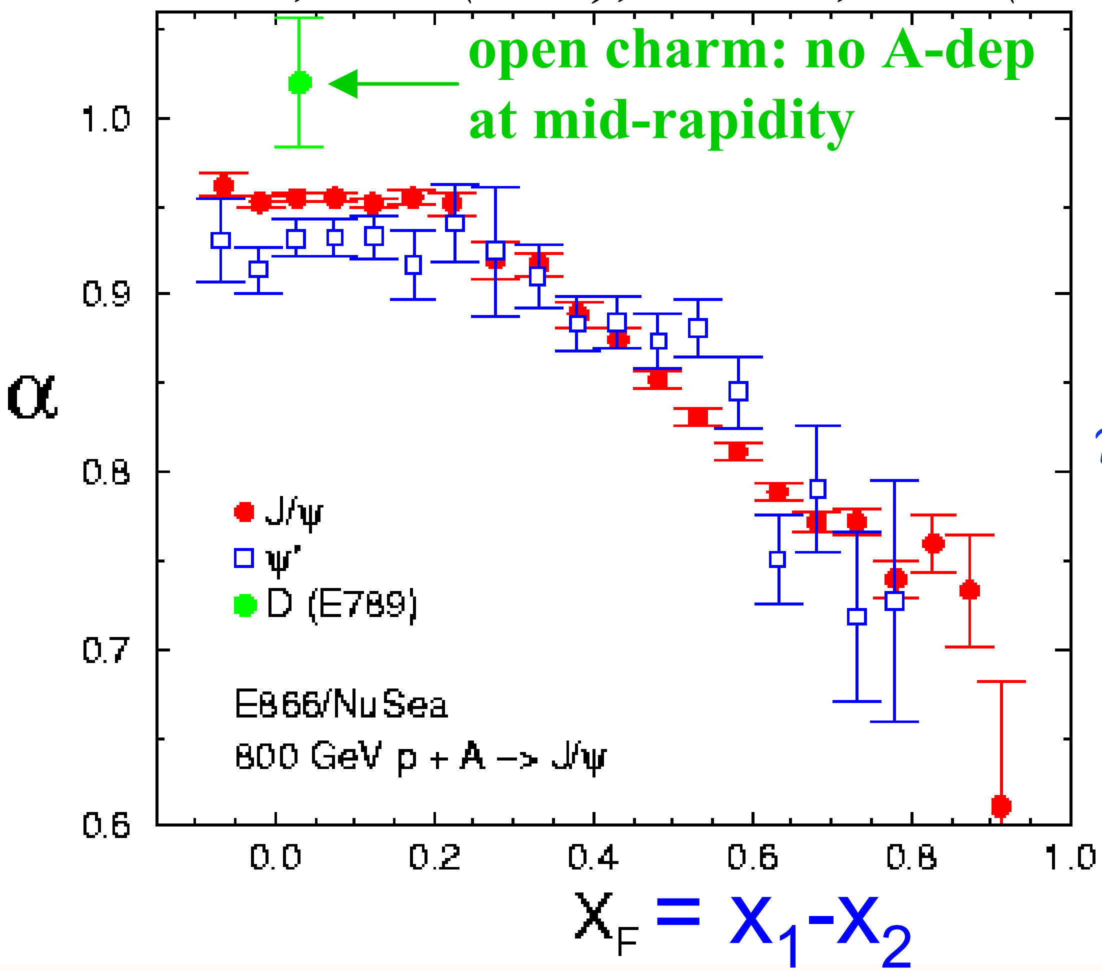
Violates PQCD Factorization: $A^{\alpha}(x_F)$ not $A^{\alpha}(x_2)$

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

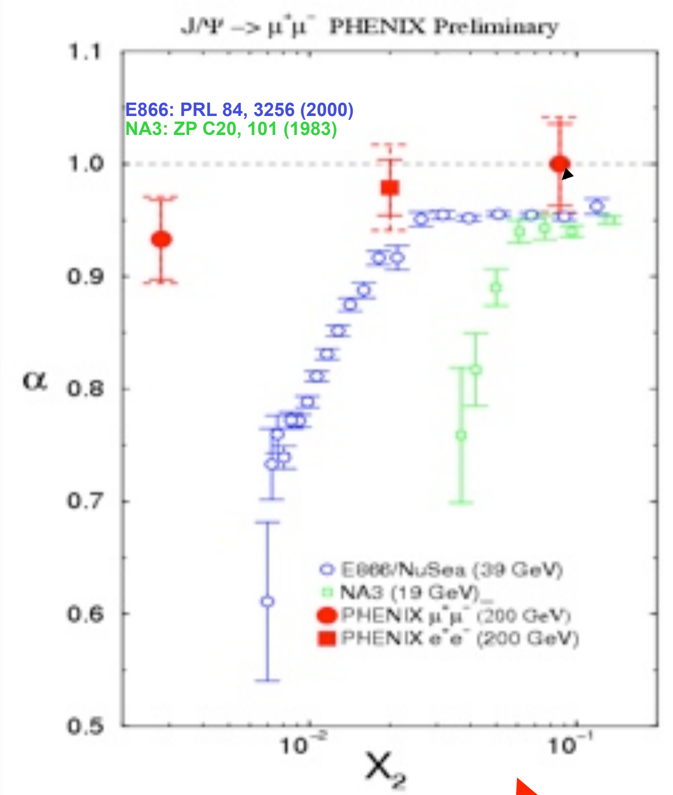
Published in Phys.Lett.B246:217-220,1990

IC Explains large excess of quarkonia at large x_F, A-dependence

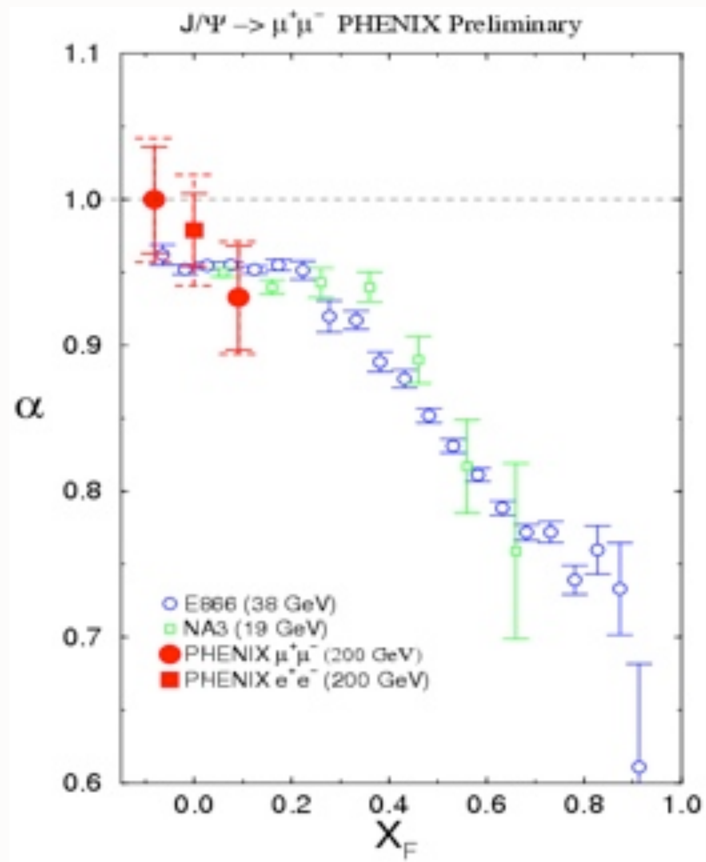
M.Leitch

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

PHENIX compared to lower energy measurements



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



Huge "absorption" effect

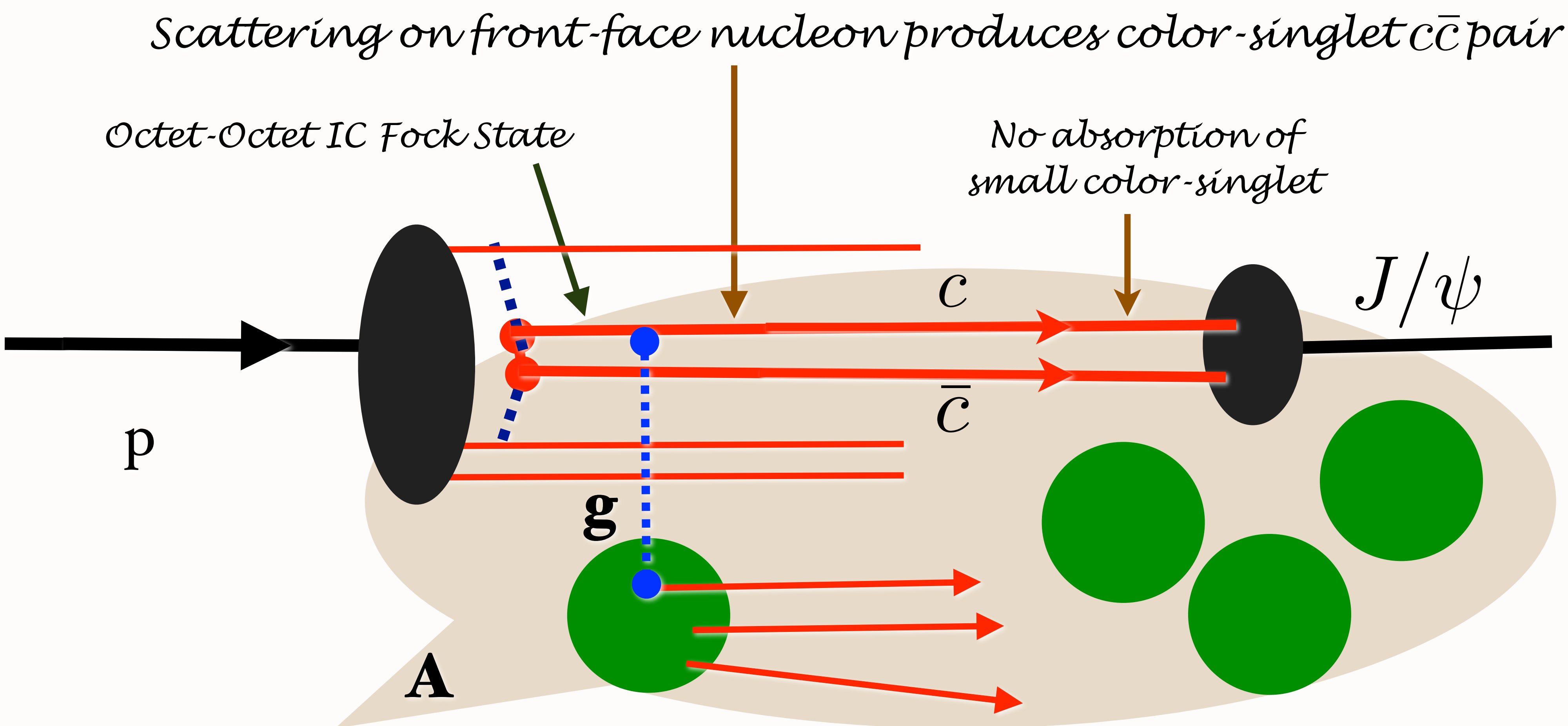
Violates PQCD factorization!

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

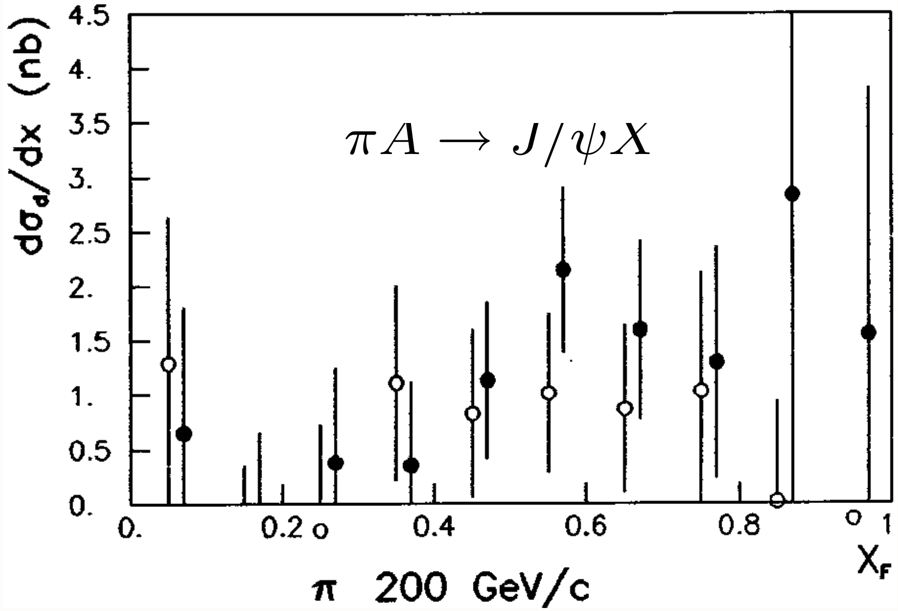
Hoyer, Sukhatme, Vanttinen

Color-Opaque IC Fock state interacts on nuclear front surface

Kopeliovich, Schmidt, Soffer, sjb

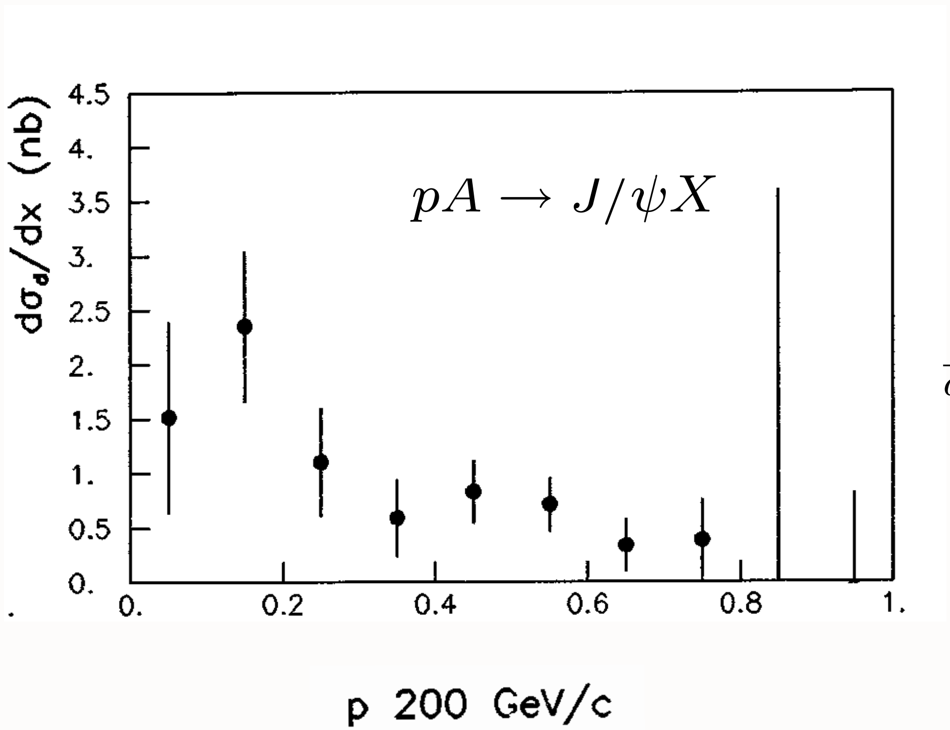


$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$



$A^{2/3}$ component

J. Badier et al, NA3



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

Excess beyond conventional PQCD subprocesses

- 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)

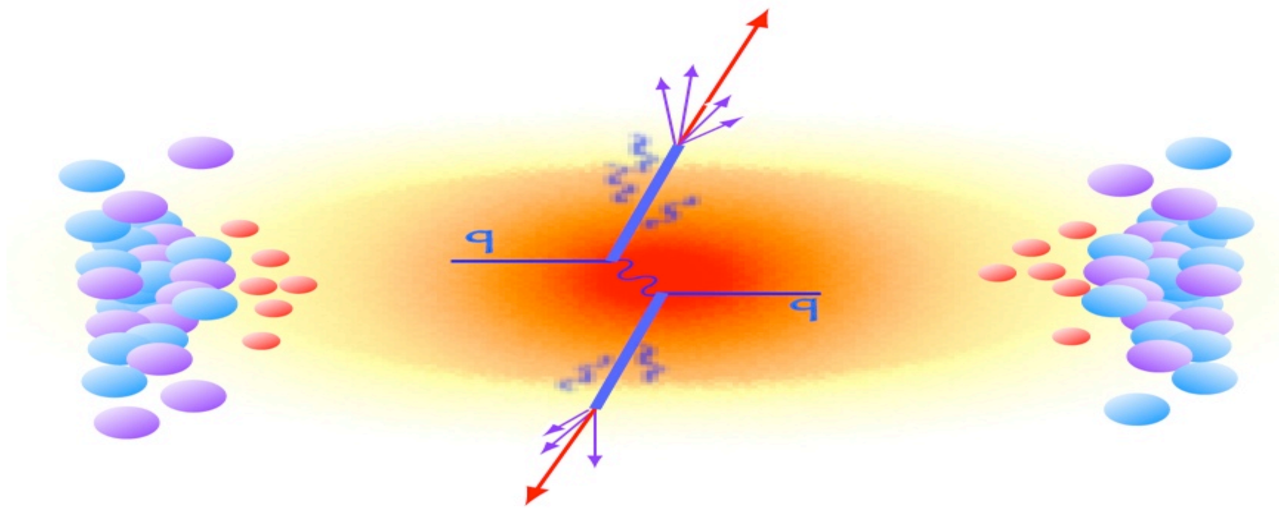
Higgs production at $x_F = 0.8$

Why is Intrinsic Charm Important for Flavor Physics?

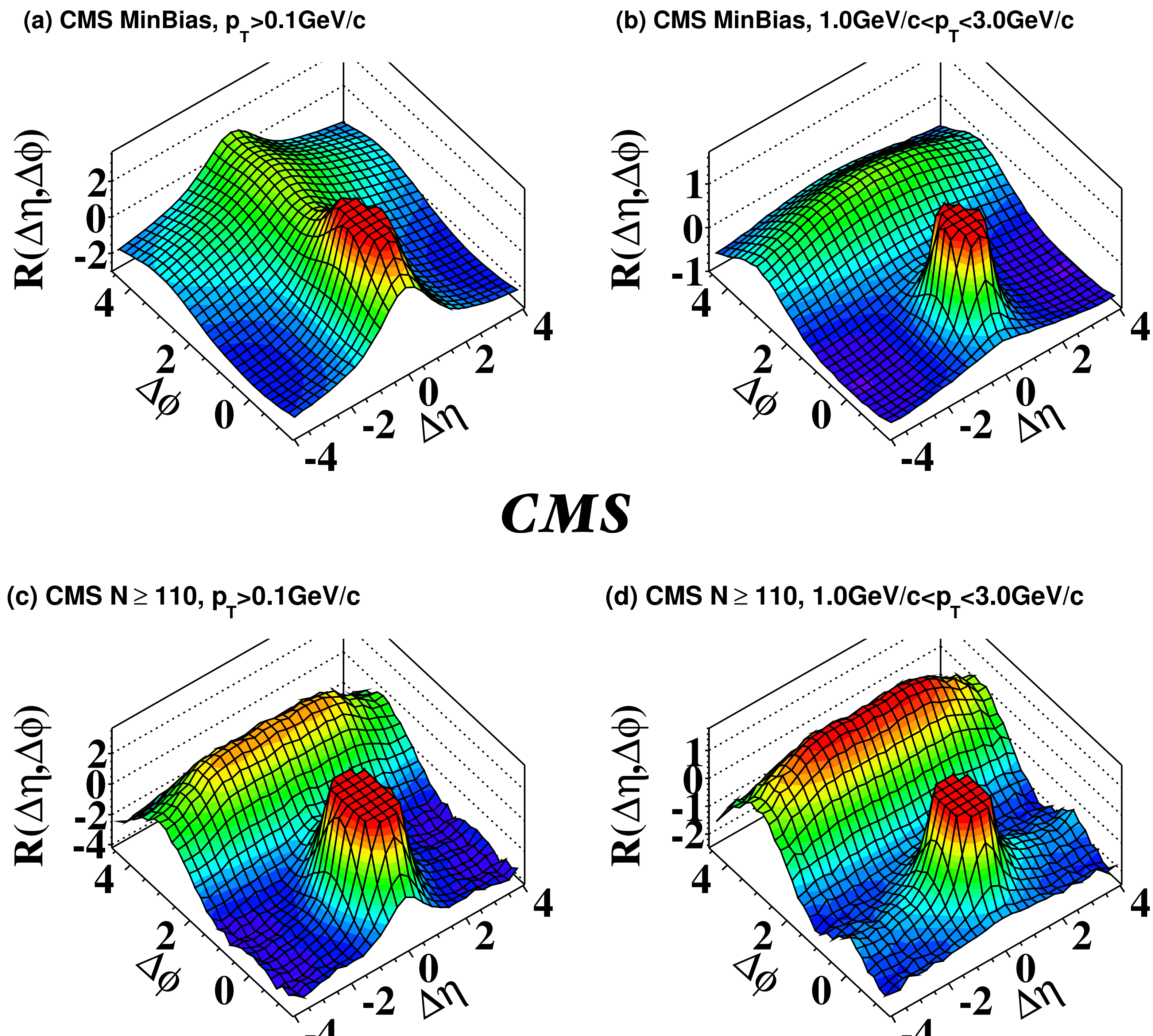
- **New perspective on fundamental nonperturbative hadron structure**
- **Charm structure function at high x**
- **Dominates high x_F charm and charmonium production**
- **Hadroproduction of new heavy quark states such as ccu, ccd at high x_F**
- **Intrinsic charm -- long distance contribution to penguin 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**

Use extreme caution when using $\gamma g \to c\bar{c}$ or $gg \to \bar{c}c$ to tag gluon dynamics

What is the dynamical mechanism which creates the QGP?



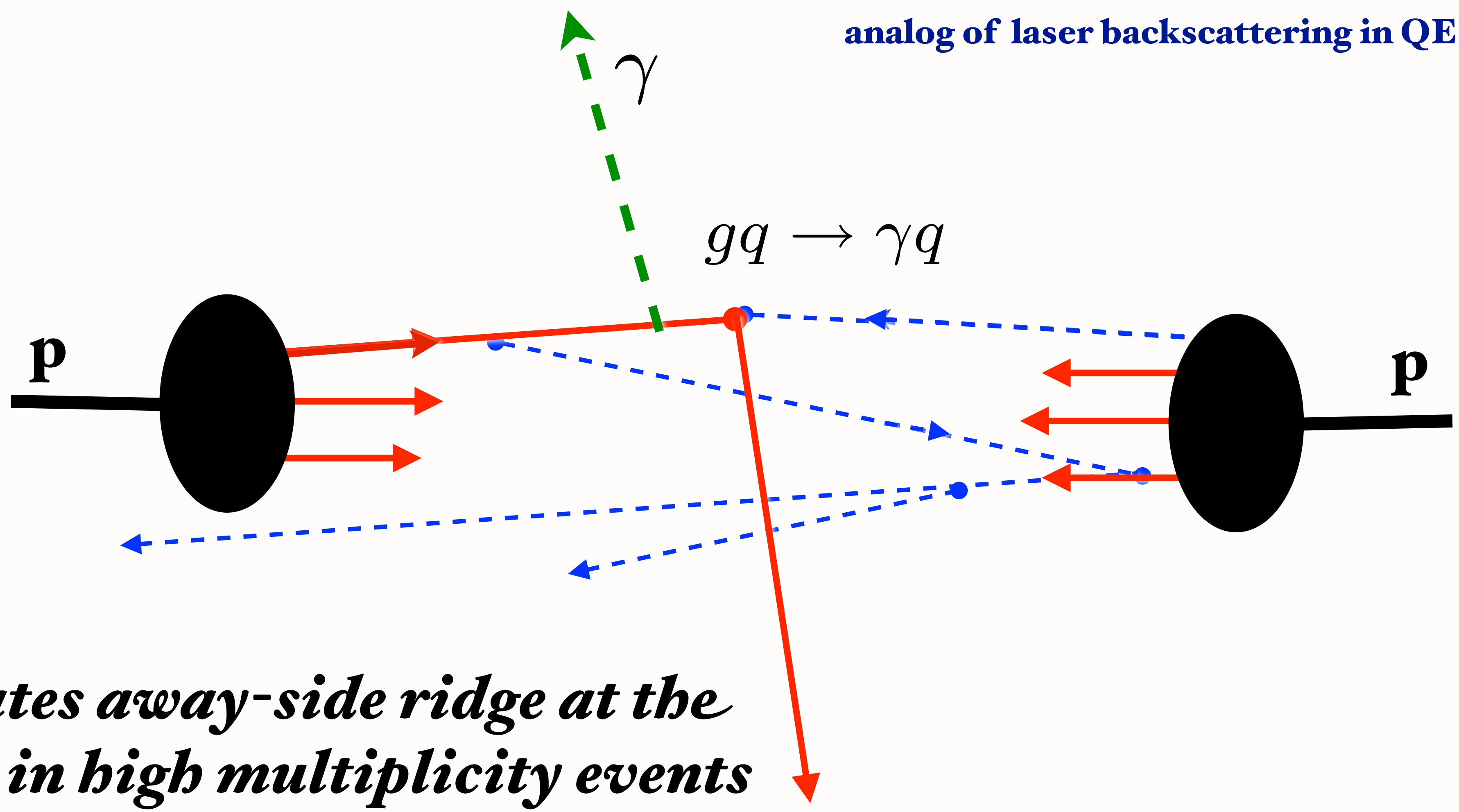
- How do the parameters of the QGP depend on the initial and final state conditions?
- A dynamical model: "Gluonic Laser"


(a) CMS MinBias, p_T>0.1GeV/c
(b) CMS MinBias, 1.0GeV/c<p_T<3.0GeV/c
CMS
(c) CMS N ≥ 110, p_T>0.1GeV/c
(d) CMS N ≥ 110, 1.0GeV/c<p_T<3.0GeV/c
R(Δη,Δϕ)
Δϕ
Δη

Gluonic Laser

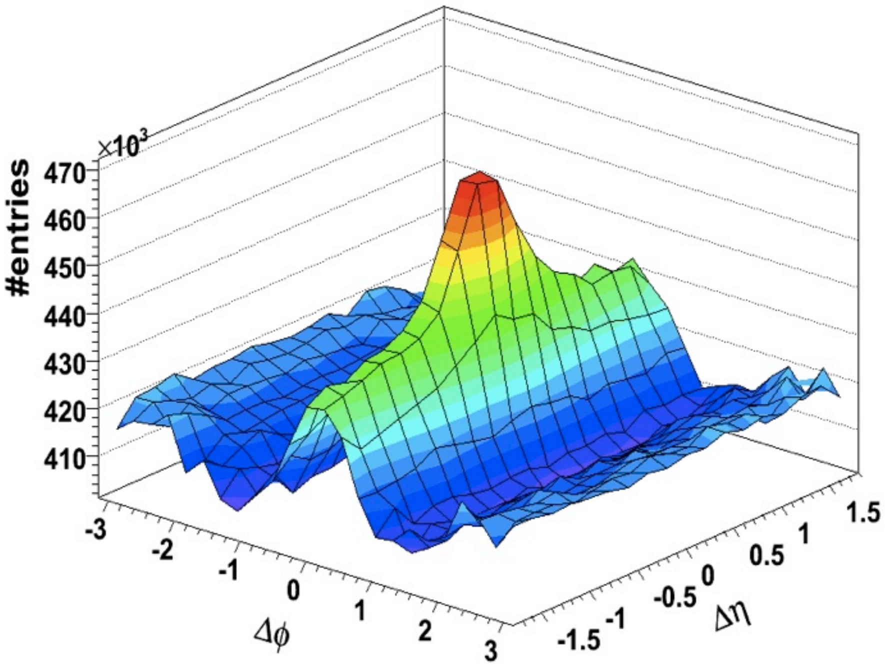
Gluonic bremsstrahlung from initial hard scattering backscatters on nucleon spectators

analog of laser backscattering in QED

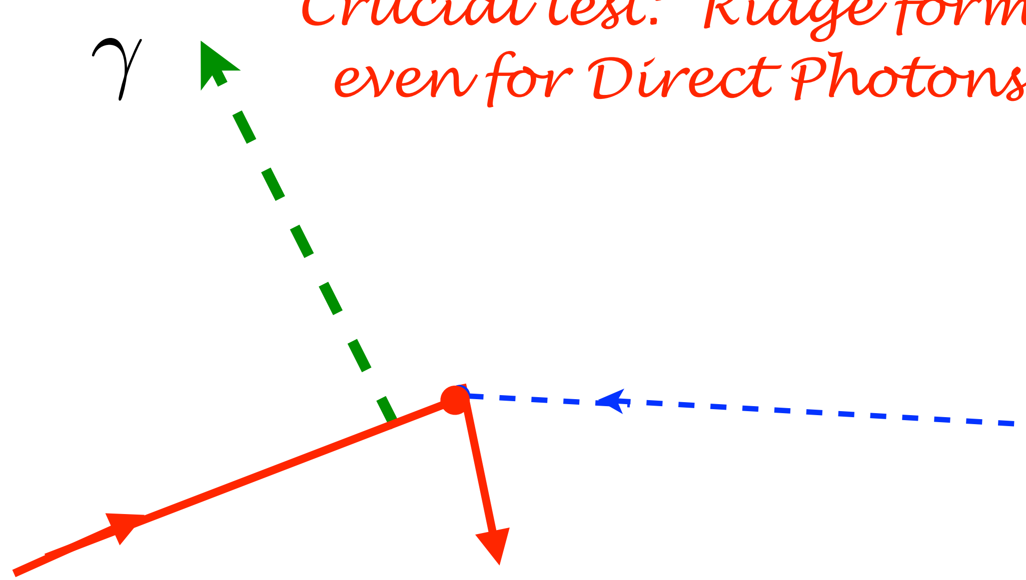


Creates away-side ridge at the LHC in high multiplicity events

Consequences of Gluon Laser Mechanism



Crucial test: Ridge forms even for Direct Photons



Ridge created by trigger bias (Cronin effect)
Momenta of initial colored partons biased towards trigger

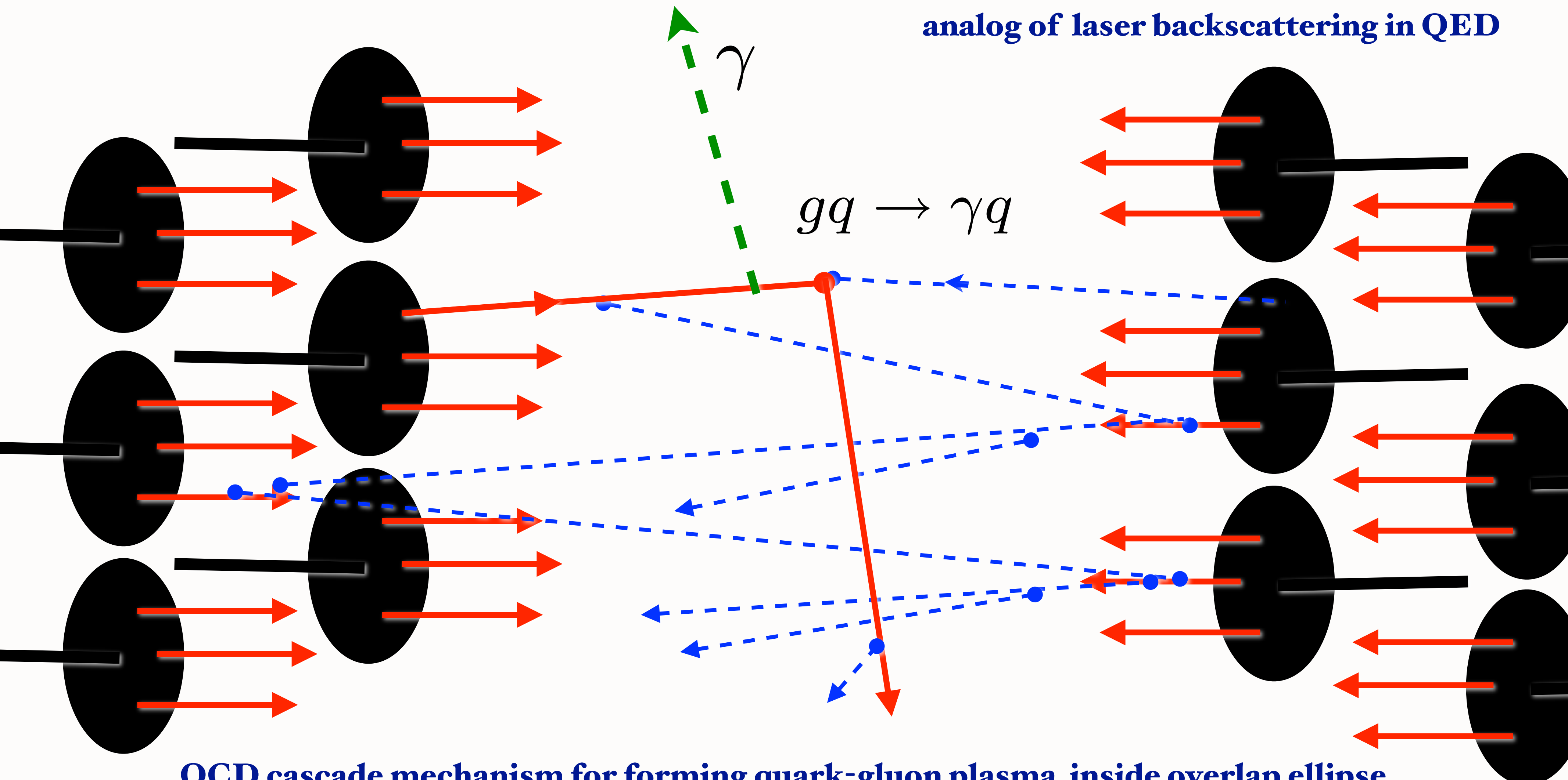
Soft gluon radiation from initial state partons emitted in plane of production; fills rapidity

Quantum Coherent

Gluonic Laser in Central Heavy Ion Collisions

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

analog of laser backscattering in QED



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

Coherence

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**
- **Coherence creates hadronic momentum along minor axis**
- **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.**

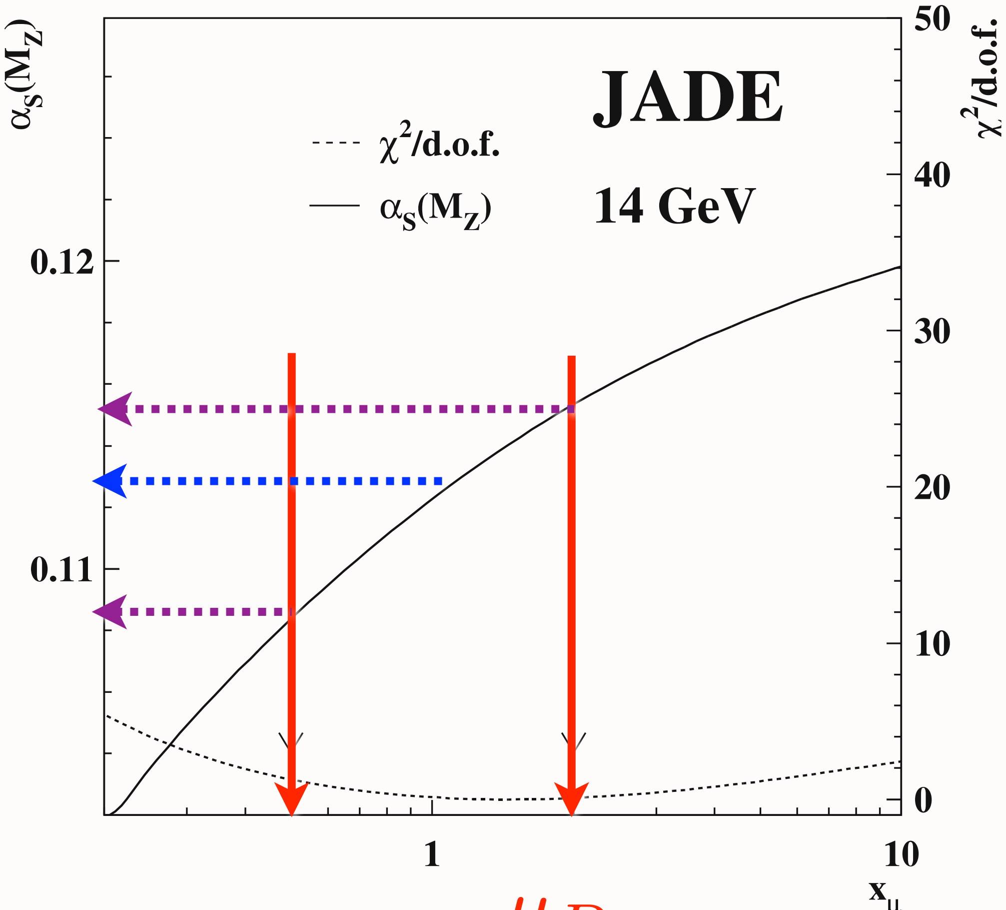
Pervasive Myth in PQCD

- ***Renormalization Scale is Arbitrary***

Measurement of the strong coupling α_S from the four-jet rate in e^+e^- annihilation using JADE data

J. Schieck[1,a], S. Bethke[1], O. Biebel[2], S. Kluth[1], P.A.M. Fernández[3], C. Pahl[1], The JADE Collaboration[b]

Eur. Phys. J. C 48, 3–13 (2006)



$$x_\mu = \frac{\mu_R}{\sqrt{s}}$$

The theoretical uncertainty, associated with missing higher order terms in the theoretical prediction, is assessed by varying the renormalization scale factor x_μ. The predictions of a complete QCD calculation would be independent of x_μ, but a finite-order calculation such as that used here retains some dependence on x_μ. The renormalization scale factor x_μ is set to 0.5 and two. The larger deviation from the default value of α_S is taken as systematic uncertainty.

$\alpha_S(M_{Z^0})$ and the χ^2/d.o.f. of the fit to the four-jet rate as a function of the renormalization scale x_μ for $\sqrt{s} = 14$ GeV to 43.8 GeV. The arrows indicate the variation of the renormalization scale factor used for the determination of the systematic uncertainties

PMS & FAC inapplicable

Conventional wisdom 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

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

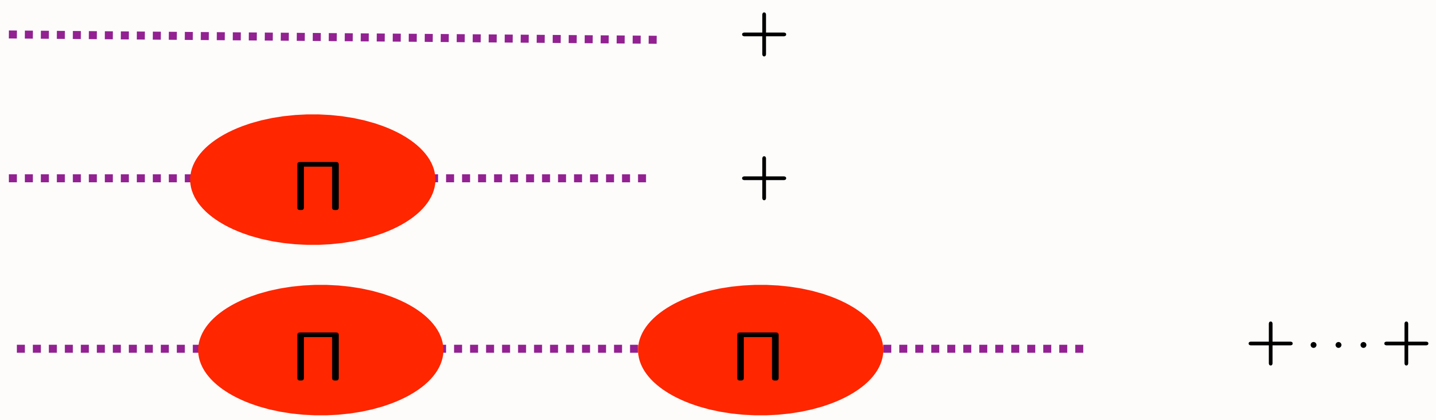
$$\alpha(t) = \frac{\alpha(0)}{1-\Pi(t)}$$

Gell Mann-Low Effective Charge

QED Effective Charge

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

All-orders lepton loop corrections to dressed photon propagator



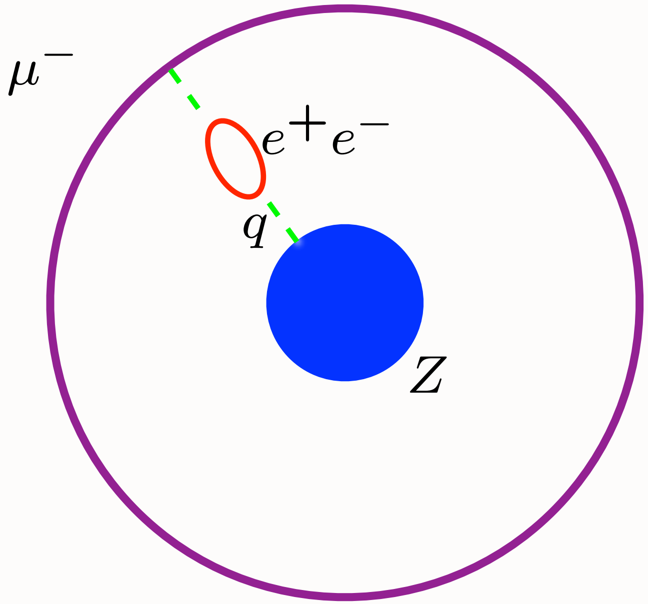
$$\alpha(t) = \frac{\alpha(t_0)}{1-\Pi(t,t_0)}$$

$$\Pi(t,t_0) = \frac{\Pi(t)-\Pi(t_0)}{1-\Pi(t_0)}$$

Initial scale t_0 is arbitrary -- Variation gives RGE Equations

Physical renormalization scale t not arbitrary

Another Example in QED: Muonic Atoms



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

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

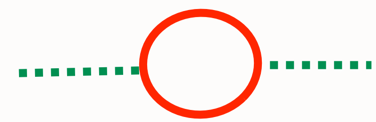
$$\alpha_{QED}(q^2) = \frac{\alpha_{QED}(0)}{1-\Pi(q^2)}$$

Scale is unique: Tested to ppm

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

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

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

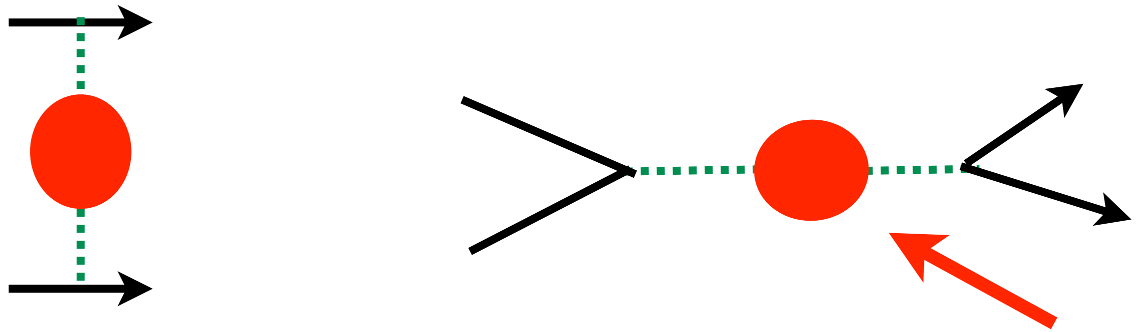
Dae Sung Hwang, sjb

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

q^2_0: Normalization point

Electron-Positron Scattering in QED

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

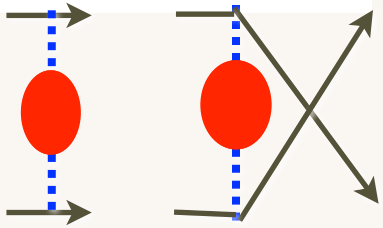


$$\alpha(t) = \frac{\alpha(0)}{1-\Pi(t)}$$

Gell Mann-Low Running Charge sums all vacuum polarization insertions

Electron-Electron Scattering in QED

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



- No renormalization scale ambigui
- 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! Scheme independent.
- 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.

Huet, sjb

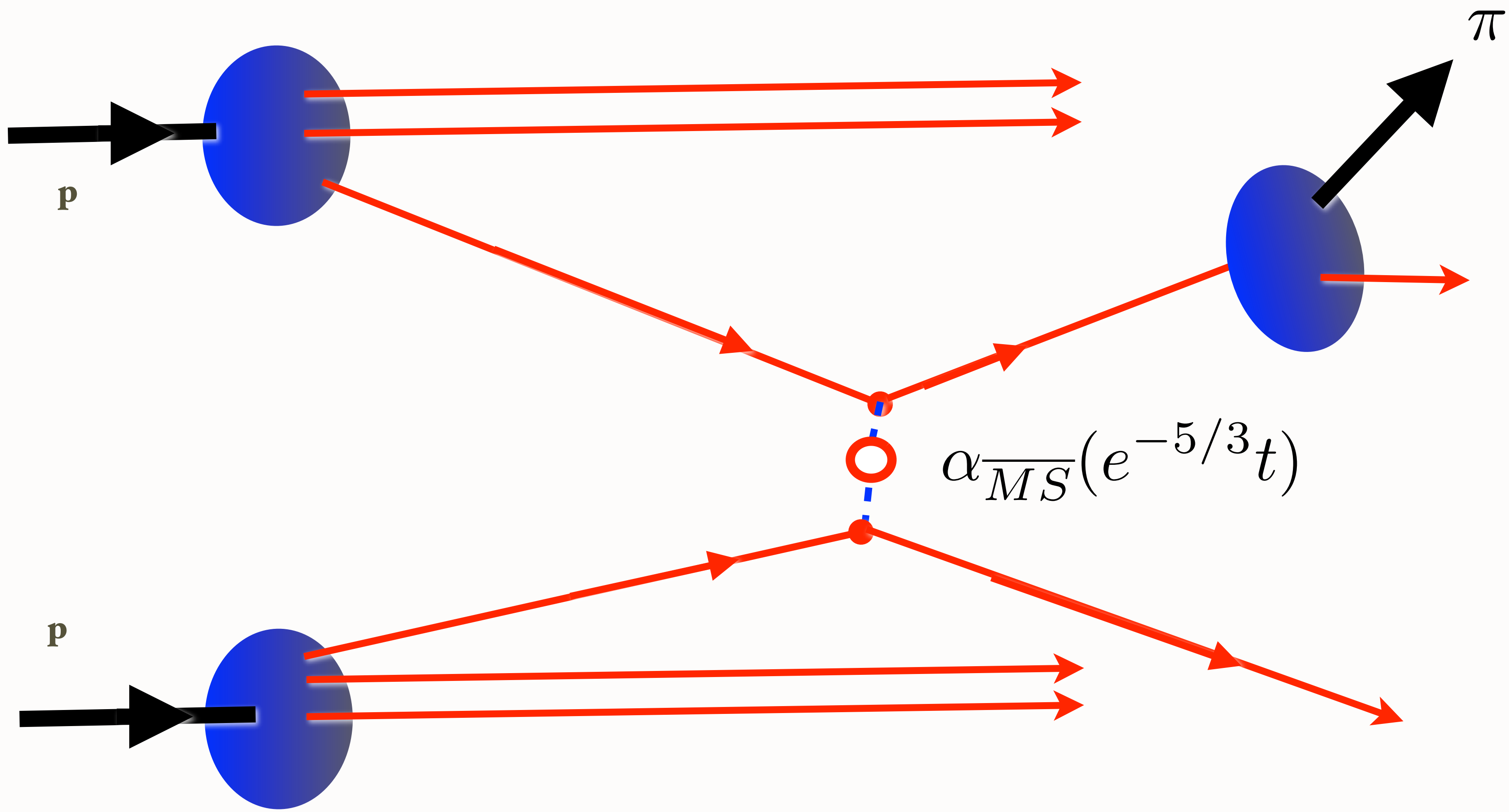
$$\lim N_C \to 0 \text{ at fixed } \alpha = C_F \alpha_s, n_\ell = n_F / C_F$$

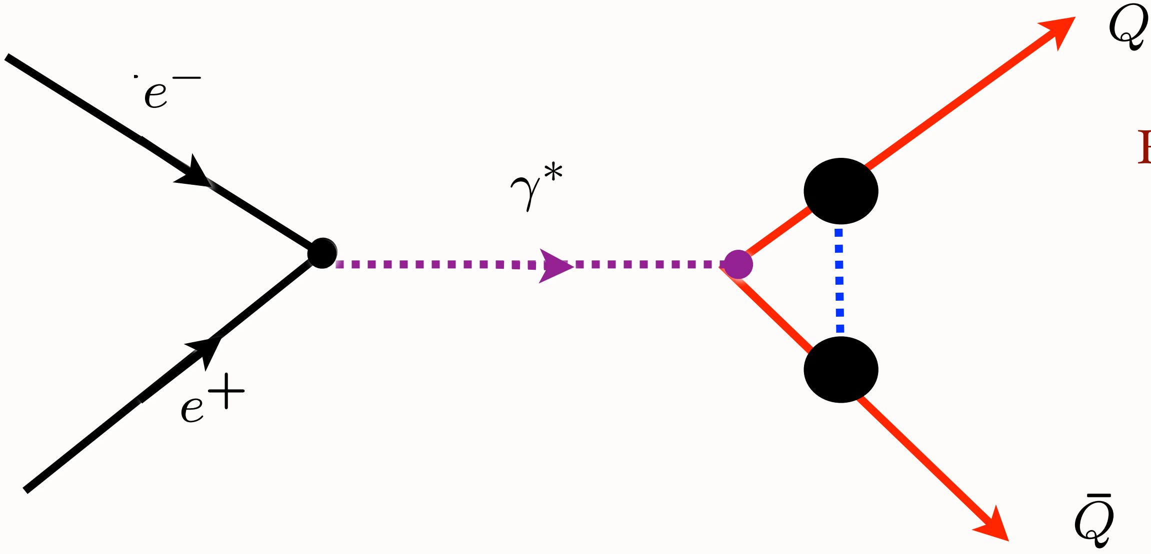
$$\text{QCD} \to \text{Abelian Gauge Theory}$$

Analytic Feature of SU(Nc) Gauge Theory

Scale-Setting procedure for QCD must be applicable to QED

Renormalization Scale-Setting Not Ambiguous





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.

PHYSICAL REVIEW D VOLUME 28, NUMBER 1 1 JULY 1983

On the elimination of scale ambiguities in perturbative quantum chromodynamics

Stanley J. Brodsky
Institute for Advanced Study, Princeton, New Jersey 08540
*and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305**

G. Peter Lepage
Institute for Advanced Study, Princeton, New Jersey 08540
*and Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853**

Paul B. Mackenzie
Fermilab, Batavia, Illinois 60510
(Received 23 November 1982)

We present a new method for resolving the scheme-scale ambiguity that has plagued perturbative analyses in quantum chromodynamics (QCD) and other gauge theories. For Abelian theories the method reduces to the standard criterion that only vacuum-polarization insertions contribute to the effective coupling constant. Given a scheme, our procedure automatically determines the coupling-constant scale appropriate to a particular process. This leads to a new criterion for the convergence of perturbative expansions in QCD. We examine a number of well known reactions in QCD, and find that perturbation theory converges well for all processes other than the gluonic width of the Υ. Our analysis calls into question recent determinations of the QCD coupling constant based upon Υ decay.

BLM: Choose μ_R in α_s to absorb all β terms

BLM Scale Setting

$\beta_0 = 11 - \frac{2}{3} n_f$

$$\rho = C_0 \alpha_{\overline{MS}}(Q) \left[1 + \frac{\alpha_{\overline{MS}}(Q)}{\pi} \left(-\tfrac{3}{2} \beta_0 A_{VP} + \tfrac{33}{2} A_{VP} + B \right) + \cdots \right]$$

n_f dependent coefficient identifies quark loop VP contribution

by

$$\rho = C_0 \alpha_{\overline{MS}}(Q^*) \left[1 + \frac{\alpha_{\overline{MS}}(Q^*)}{\pi} C_1^* + \cdots \right] ,$$

Conformal coefficient - independent of β

where

$$Q^* = Q \exp(3 A_{VP}) ,$$

$$C_1^* = \tfrac{33}{2} A_{VP} + B .$$

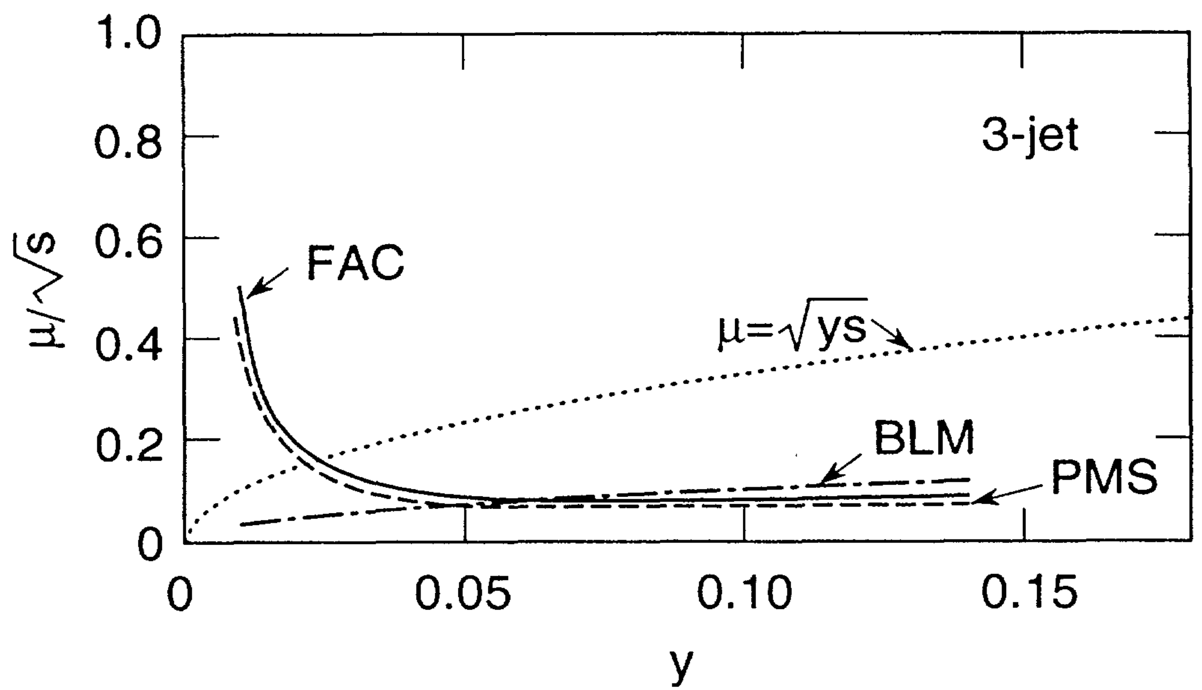
The term $33 A_{VP}/2$ in C_1^* serves to remove that part of the constant B which renormalizes the leading-order coupling. The ratio of these gluonic corrections to the light-quark corrections is fixed by $\beta_0 = 11 - \frac{2}{3} n_f$.

Use skeleton expansion:

Gardi, Grunberg, Rathsman, sjb

Features of BLM Scale

- **All terms associated with nonzero beta function summed into running coupling**
- **BLM Scale Q* sets the number of active flavors**
- **Only n_f dependence required to determine renormalization scale at NLO**
- **Result is scheme independent: Q* has exactly the correct dependence to compensate for change of scheme**
- **Result independent of starting scale**
- **Correct Abelian limit**
- **Resulting series identical to conformal series!**
- **Renormalon n! growth of PQCD coefficients from beta function eliminated!**



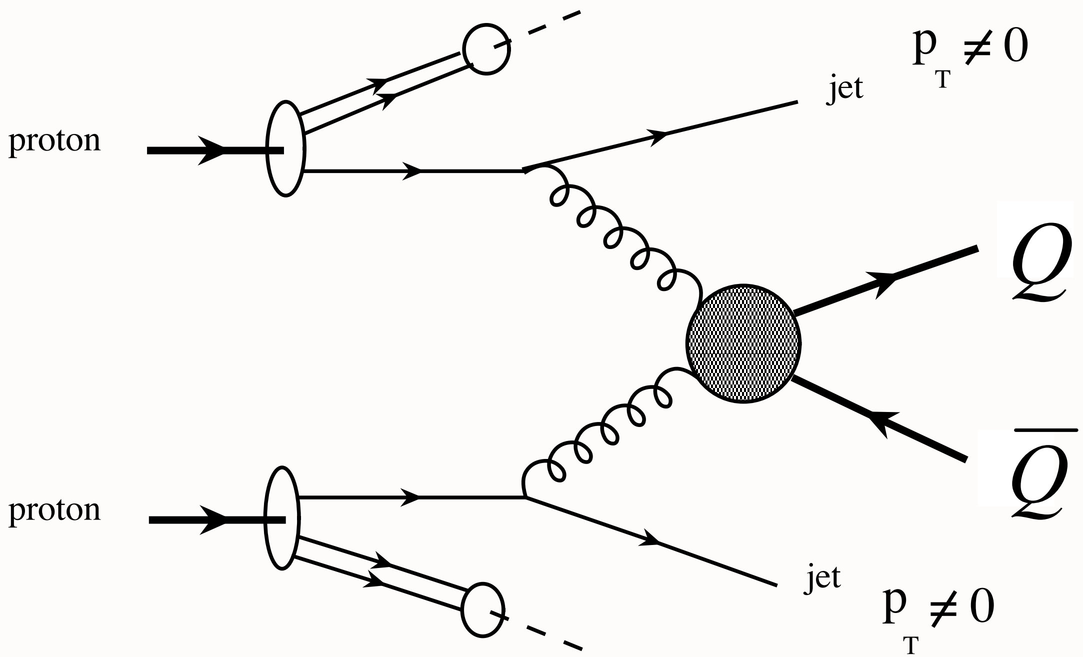
Kramer & Lampe

Three-Jet rate in electron-positron annihilation

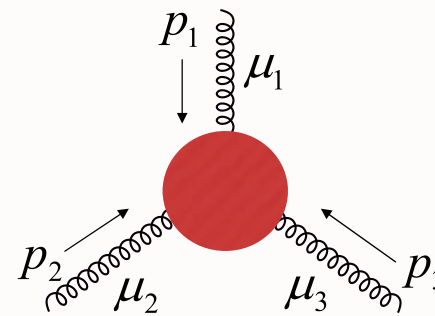
The scale $\mu/\sqrt{s}$ according to the BLM (dashed-dotted), PMS (dashed), FAC (full), and $\sqrt{y}$ (dotted) procedures for the three-jet rate in e^+e^- annihilation, as computed by Kramer and Lampe [10]. Notice the strikingly different behavior of the BLM scale from the PMS and FAC scales at low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

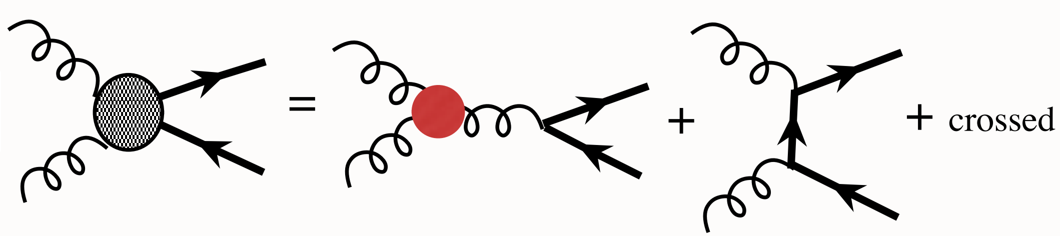
Other Jet Observables: Rathsman

Heavy Quark Hadroproduction



3-gluon coupling depends on 3 physical scales





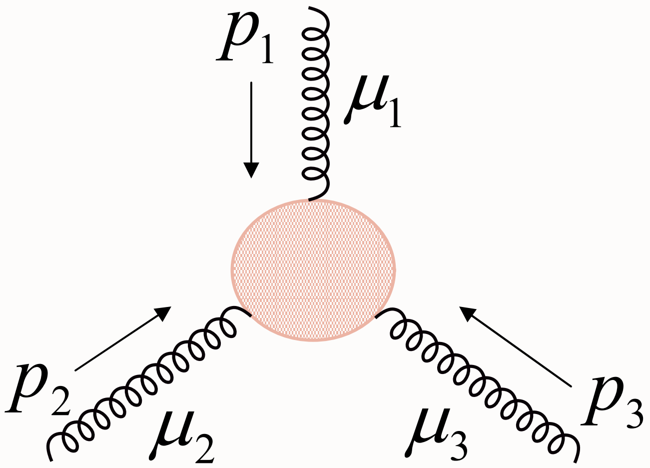
The Renormalization Scale Problem

$$\rho(Q^2) = C_0 + C_1\alpha_s(\mu_R) + C_2\alpha_s^2(\mu_R) + \cdots$$

$$\mu_R^2 = CQ^2$$

Is there a way to set the renormalization scale μ_R *?*

What happens if there are multiple physical scales ?



Relate Observables to Each Other

- Eliminate intermediate scheme
- No scale ambiguity
- Transitive!
- Commensurate Scale Relations
- Example: Generalized Crewther Relation

Define QCD Coupling from Observable

Grunberg

$$R_{e^+e^-\to X}(s) \equiv 3\Sigma_q e_q^2 \; [1 + \frac{\alpha_R(s)}{\pi}]$$

$$\Gamma(\tau \to X e \nu)(m_\tau^2) \equiv \Gamma_0(\tau \to u\bar{d} e \nu) \times [1 + \frac{\alpha_\tau(m_\tau^2)}{\pi}]$$

Commensurate scale relations:
Relate observable to observable at commensurate scales

Effective Charges: analytic at quark mass thresholds, finite at small momenta

H.Lu, Rathsman, sjb

Pinch scheme: Cornwall, et al

Relate Observables to Each Other

- Eliminate intermediate scheme
- No scale ambiguity
- Transitive!
- Commensurate Scale Relations
- Conformal Template
- Example: Generalized Crewther Relation

$$R_{e^+e^-}(Q^2) \equiv 3 \sum_{\text{flavors}} e_q^{\,2} \left[1 + \frac{\alpha_R(Q)}{\pi} \right] .$$

$$\int_0^1 dx \left[g_1^{ep}(x, Q^2) - g_1^{en}(x, Q^2) \right] \equiv \frac{1}{3} \left| \frac{g_A}{g_V} \right| \left[1 - \frac{\alpha_{g_1}(Q)}{\pi} \right]$$

$$\frac{\alpha_R(Q)}{\pi} = \frac{\alpha_{\overline{MS}}(Q)}{\pi} + \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^2 \left[\left(\frac{41}{8} - \frac{11}{3}\zeta_3\right) C_A - \frac{1}{8}C_F + \left(-\frac{11}{12} + \frac{2}{3}\zeta_3\right) f\right]$$
$$+ \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^3 \left\{\left(\frac{90445}{2592} - \frac{2737}{108}\zeta_3 - \frac{55}{18}\zeta_5 - \frac{121}{432}\pi^2\right) C_A^2 + \left(-\frac{127}{48} - \frac{143}{12}\zeta_3 + \frac{55}{3}\zeta_5\right) C_A C_F - \frac{23}{32}C_F^2\right.$$
$$+ \left[\left(-\frac{970}{81} + \frac{224}{27}\zeta_3 + \frac{5}{9}\zeta_5 + \frac{11}{108}\pi^2\right) C_A + \left(-\frac{29}{96} + \frac{19}{6}\zeta_3 - \frac{10}{3}\zeta_5\right) C_F\right] f$$
$$\left. + \left(\frac{151}{162} - \frac{19}{27}\zeta_3 - \frac{1}{108}\pi^2\right) f^2 + \left(\frac{11}{144} - \frac{1}{6}\zeta_3\right) \frac{d^{abc}d^{abc}}{C_F d(R)} \frac{\left(\sum_f Q_f\right)^2}{\sum_f Q_f^2}\right\}.$$

$$\frac{\alpha_{g_1}(Q)}{\pi} = \frac{\alpha_{\overline{MS}}(Q)}{\pi} + \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^2 \left[\frac{23}{12}C_A - \frac{7}{8}C_F - \frac{1}{3}f\right]$$
$$+ \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^3 \left\{\left(\frac{5437}{648} - \frac{55}{18}\zeta_5\right) C_A^2 + \left(-\frac{1241}{432} + \frac{11}{9}\zeta_3\right) C_A C_F + \frac{1}{32}C_F^2\right.$$
$$\left. + \left[\left(-\frac{3535}{1296} - \frac{1}{2}\zeta_3 + \frac{5}{9}\zeta_5\right) C_A + \left(\frac{133}{864} + \frac{5}{18}\zeta_3\right) C_F\right] f + \frac{115}{648} f^2\right\}.$$

Eliminate MSbar,
Find Amazing Simplification

$$R_{e^+e^-}(Q^2) \equiv 3 \sum_{\text{flavors}} e_q^2 \left[1 + \frac{\alpha_R(Q)}{\pi} \right].$$

$$\int_0^1 dx \left[g_1^{ep}(x,Q^2) - g_1^{en}(x,Q^2) \right] \equiv \frac{1}{3} \left| \frac{g_A}{g_V} \right| \left[1 - \frac{\alpha_{g_1}(Q)}{\pi} \right]$$

$$\frac{\alpha_{g_1}(Q)}{\pi} = \frac{\alpha_R(Q^*)}{\pi} - \left(\frac{\alpha_R(Q^{**})}{\pi} \right)^2 + \left(\frac{\alpha_R(Q^{***})}{\pi} \right)^3$$

Geometric Series in Conformal QCD

Generalized Crewther Relation

Lu, Kataev, Gabadadze, Sjb

Lu, Kataev, Gabadadze, Sjb

Generalized Crewther Relation

$$[1 + \frac{\alpha_R(s^*)}{\pi}][1 - \frac{\alpha_{g_1}(q^2)}{\pi}] = 1$$

$$\sqrt{s^*} \simeq 0.52 Q$$

Conformal relation true to all orders in perturbation theory

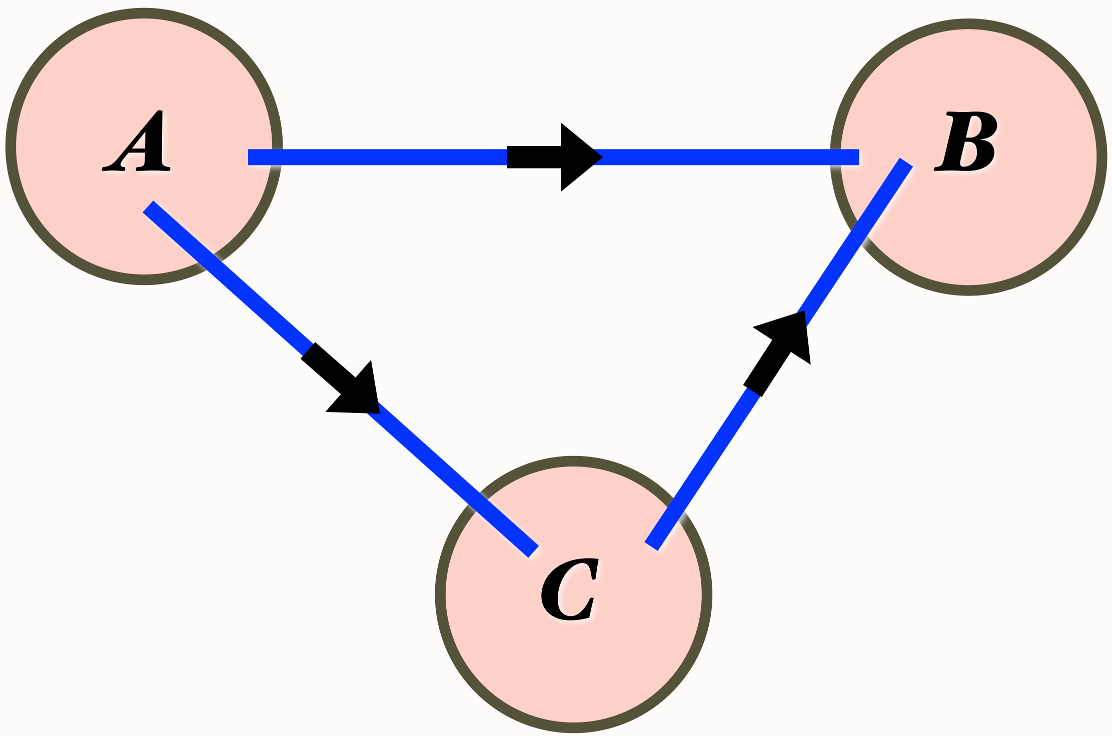
No radiative corrections to axial anomaly

Nonconformal terms set relative scales (BLM)

Analytic matching at quark thresholds

No renormalization scale ambiguity!

Transitivity Property of Renormalization Group



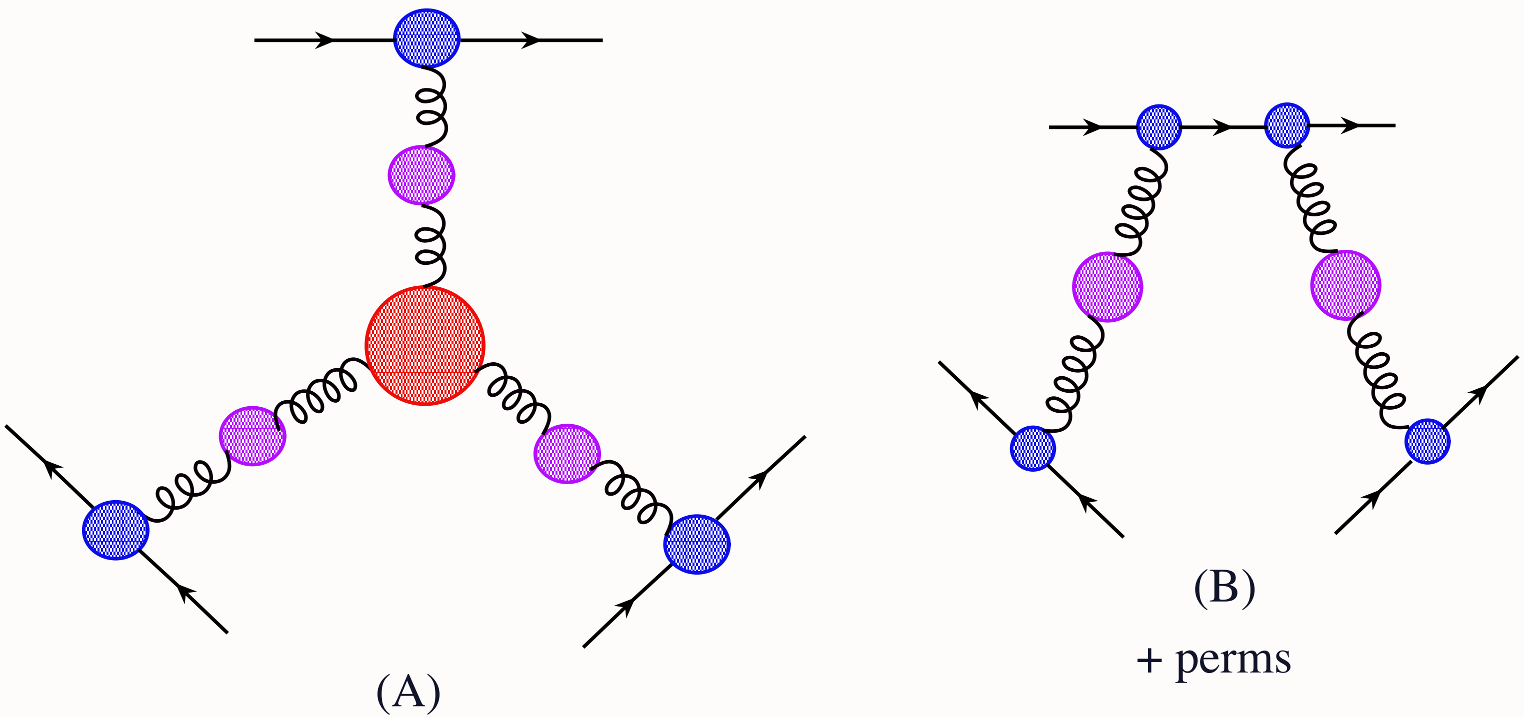
A* → *C   ***C* → *B***   ***identical to*** ***A* → *B***

Relation of observables independent of intermediate scheme C

3 Gluon Vertex In Scattering Amplitudes

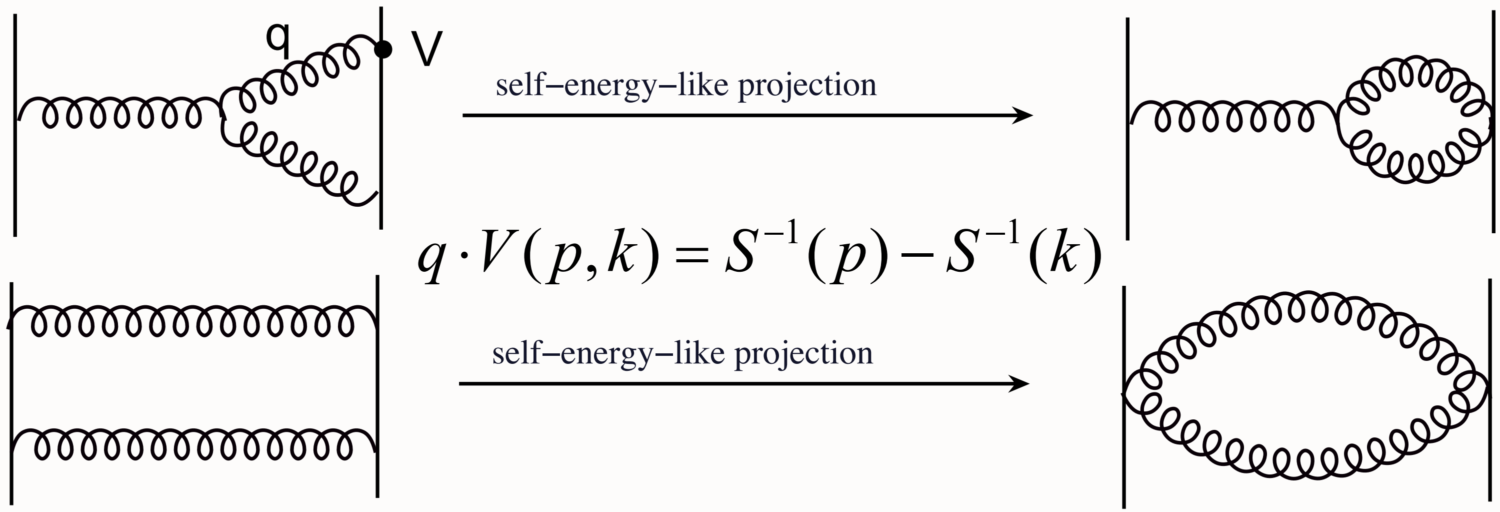
Pinch-Technique approach :

fully dress with gauge-invariant Green's functions

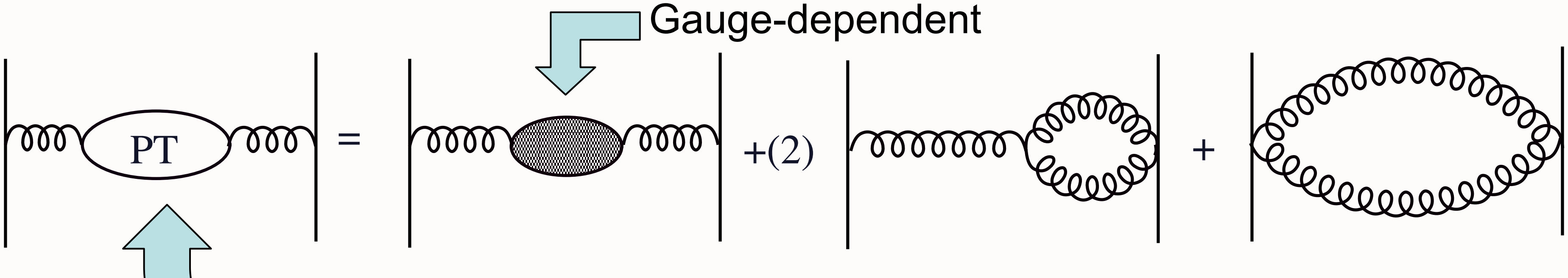


The Pinch Technique

(Cornwall, Papavassiliou)



$$q \cdot V(p,k) = S^{-1}(p) - S^{-1}(k)$$



Gauge-invariant gluon self-energy!

13

natural generalization of QED charge

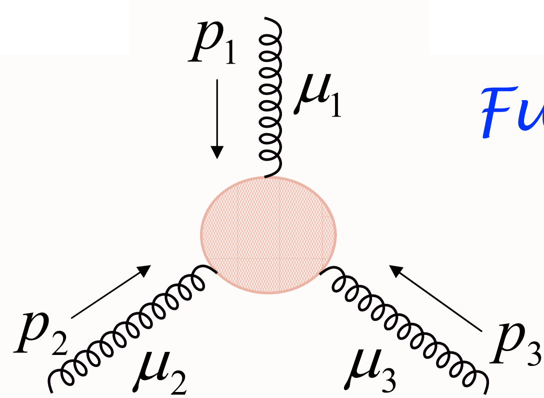
Pinch Scheme (PT)

- J. M. Cornwall, Phys. Rev. D 26, 345 (1982)
- Equivalent to Background Field Method in Feynman gauge
- Effective Lagrangian Scheme of Kennedy & Lynn
- Rearrange Feynman diagrams to satisfy Ward Identities
- Longitudinal momenta from triple-gluon coupling, etc. hit vertices which cancel ("pinch") propagators
- Two-point function: Uniqueness, analyticity, unitarity, optical theorem
- Defines analytic coupling with smooth threshold behavior

Binger, sjb

General Structure of the Three-Gluon Vertex

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



Full analytic calculation, general masses, spin
Pinch Scheme

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 $p_1 + p_2 + p_3 = 0$

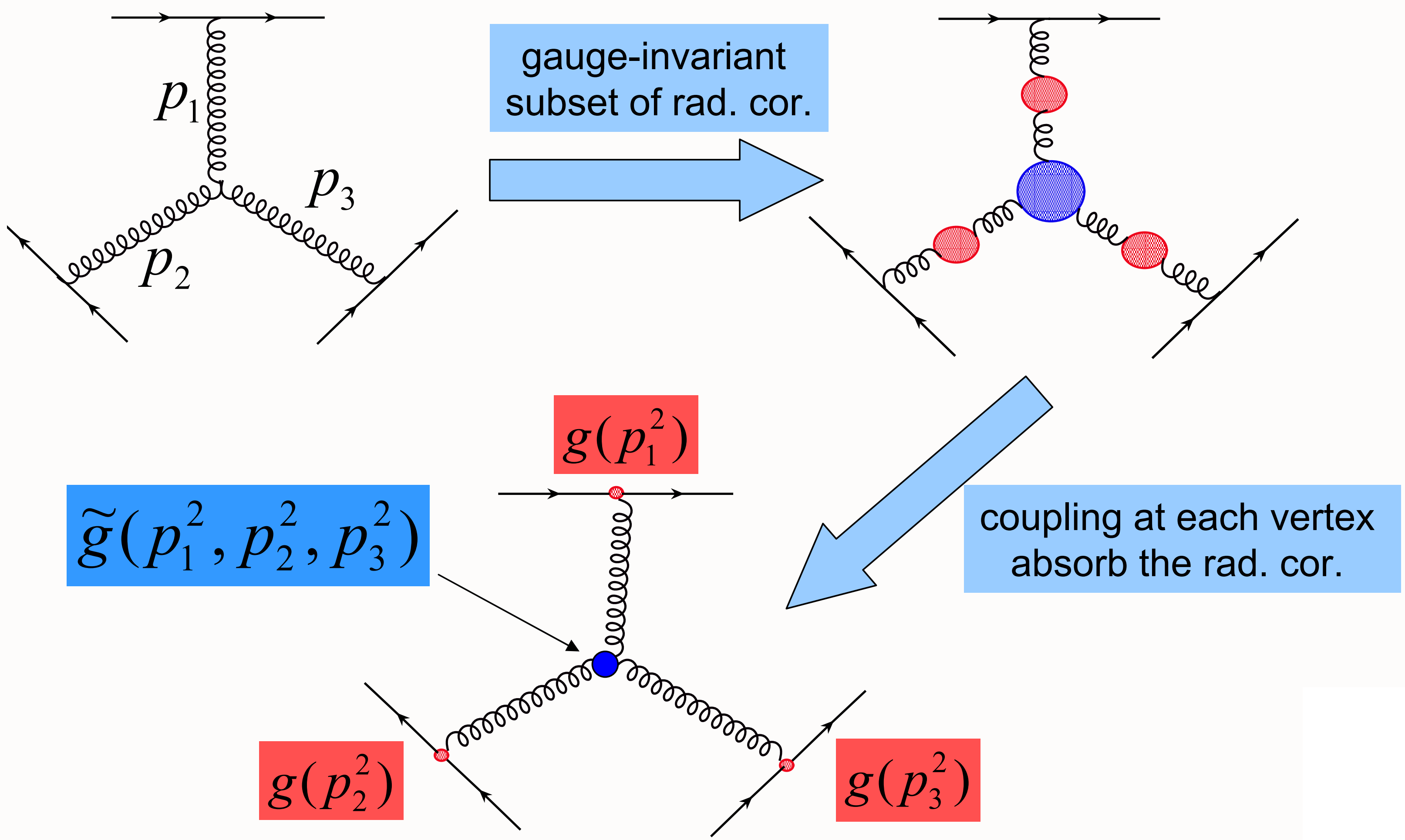
⇒ 14 basis tensors and form factors

PHYSICAL REVIEW D 74, 054016 (2006)

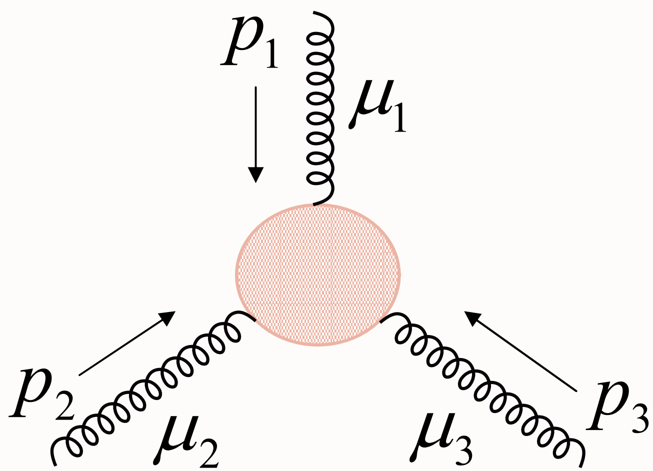
Form factors of the gauge-invariant three-gluon vertex

Michael Binger[*] and Stanley J. Brodsky[†]

Multi-scale Renormalization of the Three-Gluon Vertex



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



H. J. Lu

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

Properties of the Effective Scale

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

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

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

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

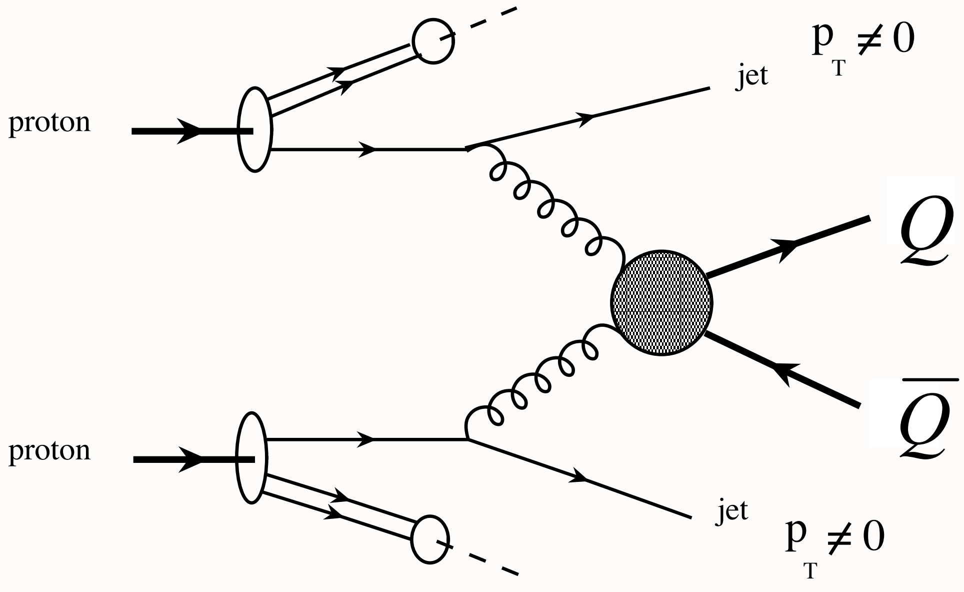
$$Q^2_{eff}(a,a,c) \approx 3.08\,|c| \quad \text{for} \quad |a| >> |c|$$

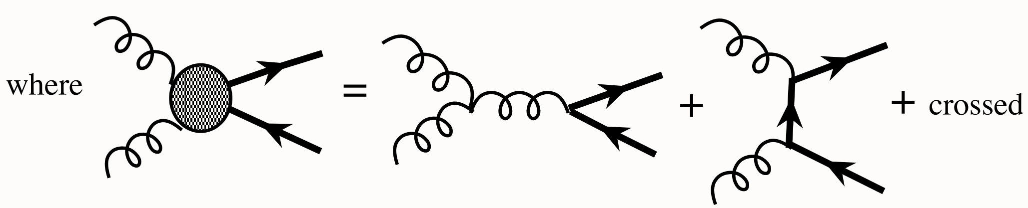
$$Q^2_{eff}(a,-a,c) \approx 22.8\,|c| \quad \text{for} \quad |a| >> |c|$$

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

Surprising dependence on Invariants

Heavy Quark Hadro-production





- Preliminary calculation using (massless) results for tree level form factor
- Very low effective scale

→ much larger cross section than $\overline{MS}$ with scale $\mu_R = M_{Q\overline{Q}}$ or M_Q

- Future : repeat analysis using the full mass-dependent results and include all form factors

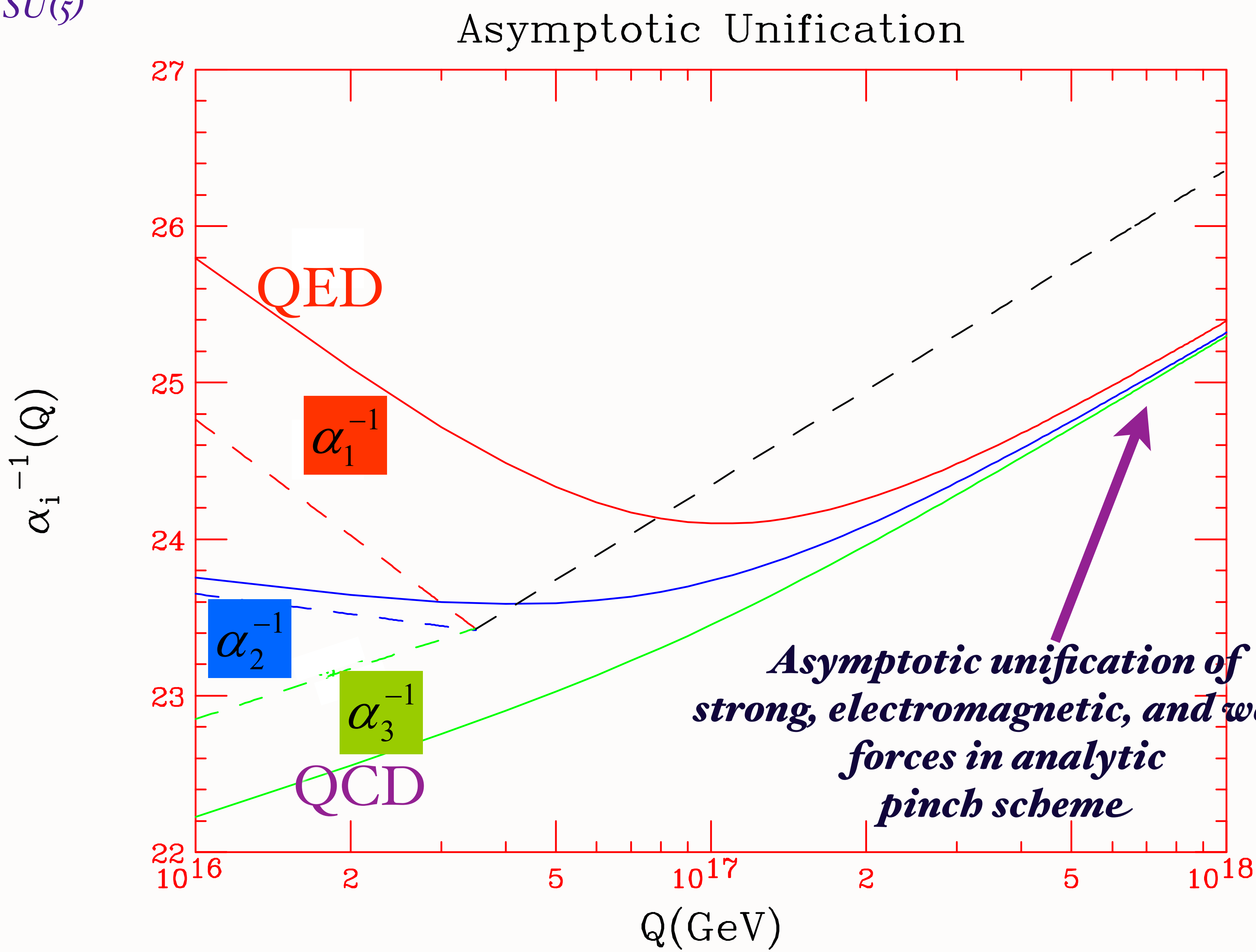
Expect that this approach accounts for most of the one-loop corrections

Unification in Physical Schemes

- Smooth analytic threshold behavior with automatic decoupling
- More directly reflects the unification of the forces
- Higher "unification" scale than usual

Supersymmetric SU(5)

Binger, sjb



Asymptotic unification of strong, electromagnetic, and weak forces in analytic pinch scheme

QCD Myths

- Anti-Shadowing is Universal
- ISI and FSI are higher twist effects and universal
- High transverse momentum hadrons arise only from jet fragmentation -- baryon anomaly!
- heavy quarks only from gluon splitting
- renormalization scale cannot be fixed
- QCD condensates are vacuum effects
- Infrared Slavery
- Nuclei are composites of nucleons only
- Real part of DVCS arbitrary