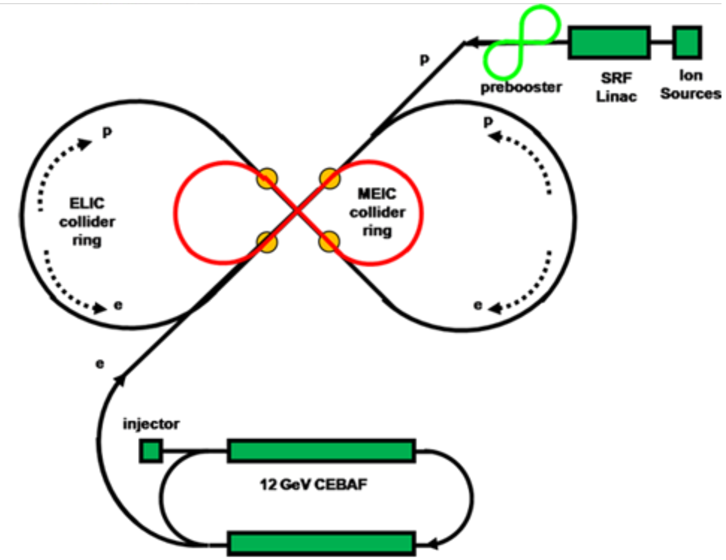
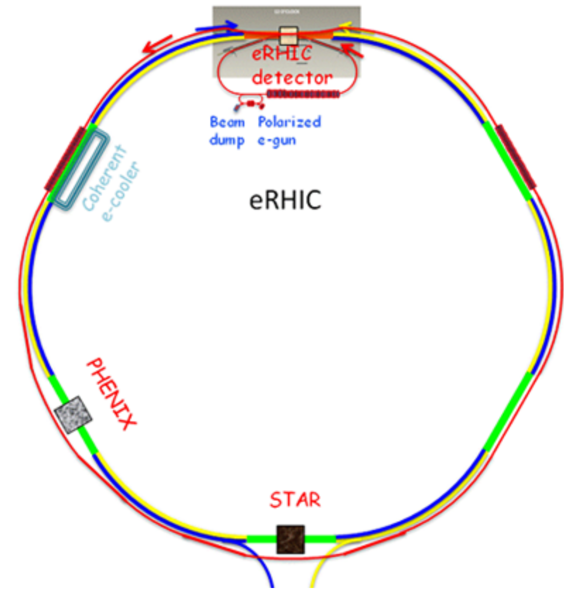
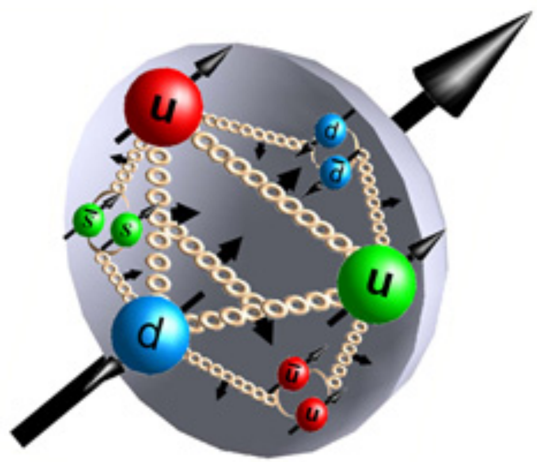
Intrinsic Heavy Quark Phenomena at the EIC and Fixed Target Facilities

AFTER @ LHC







Stan Brodsky

CP³ - Origins
Particle Physics & Origin of Mass

SLAC
NATIONAL ACCELERATOR LABORATORY

Fall meeting of the GDR PH-QCD: Nucleon and Nucleus Structure Studies with a LHC fixed-target experiment and Electron-Ion Collider

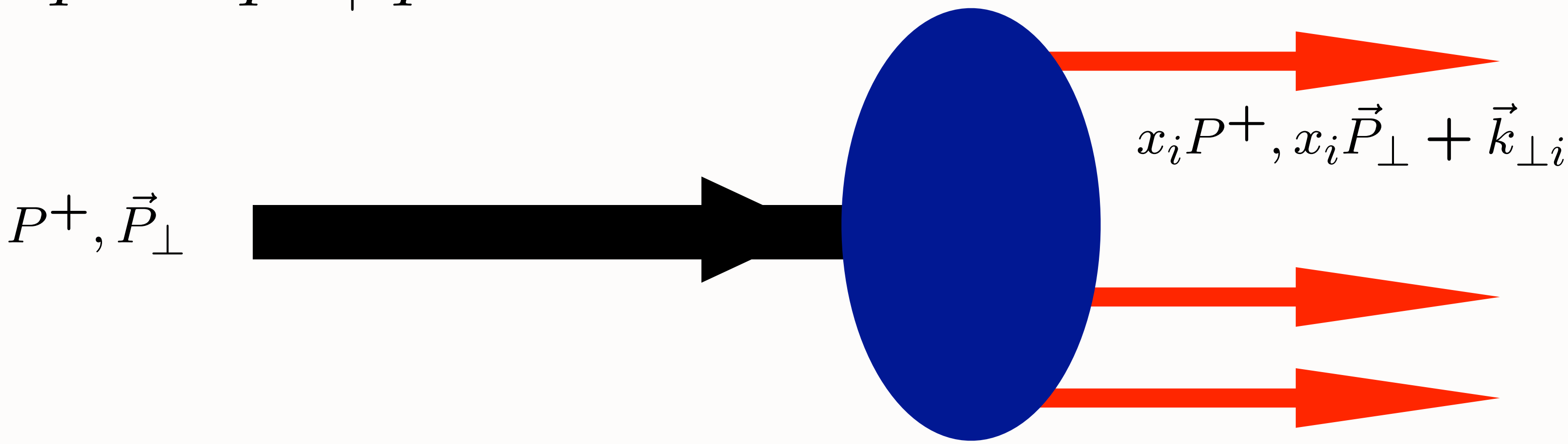
The France-Stanford Center for Interdisciplinary Studies

October 18, 2011

IPN
INSTITUT DE PHYSIQUE NUCLÉAIRE

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

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



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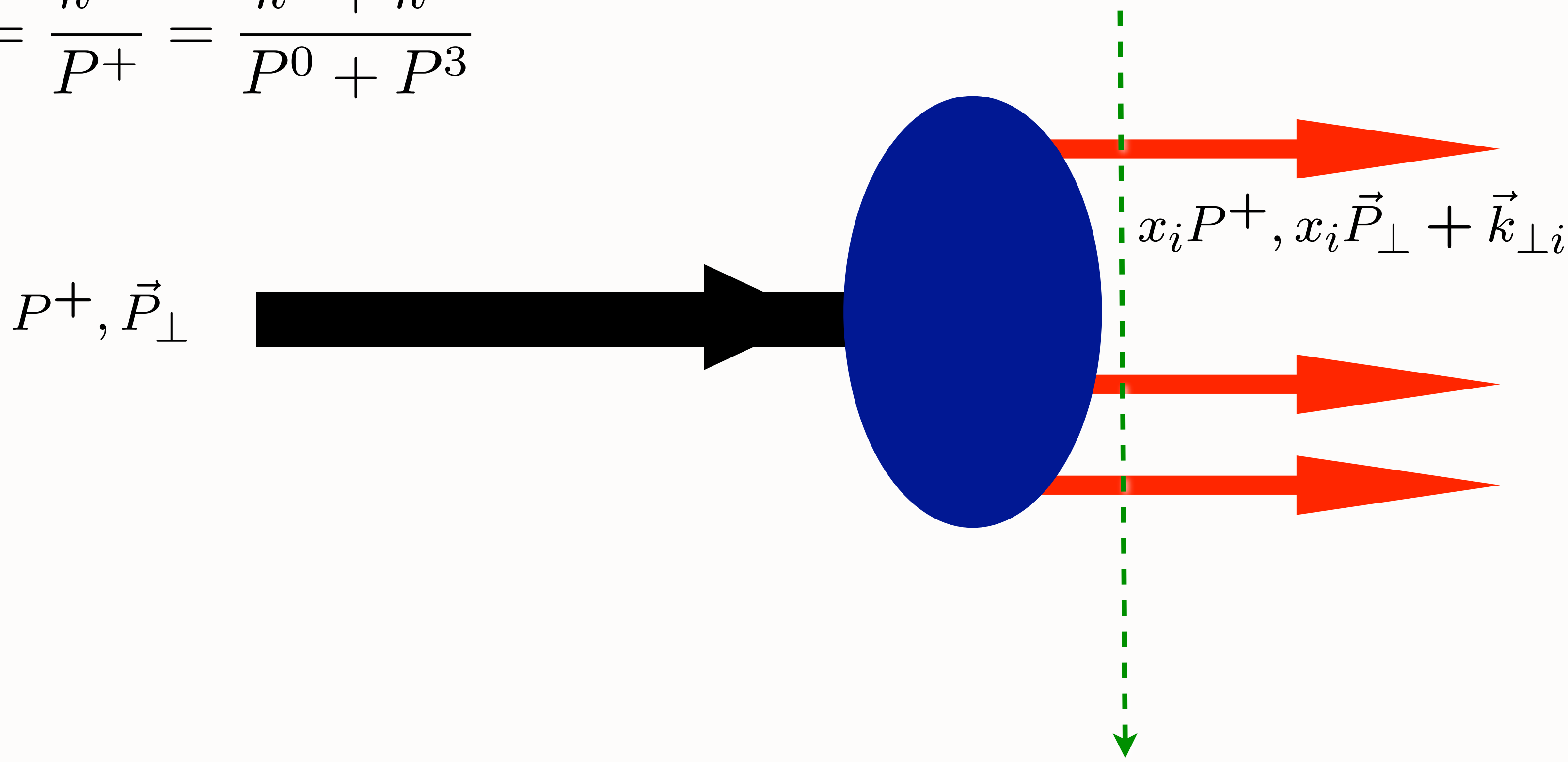

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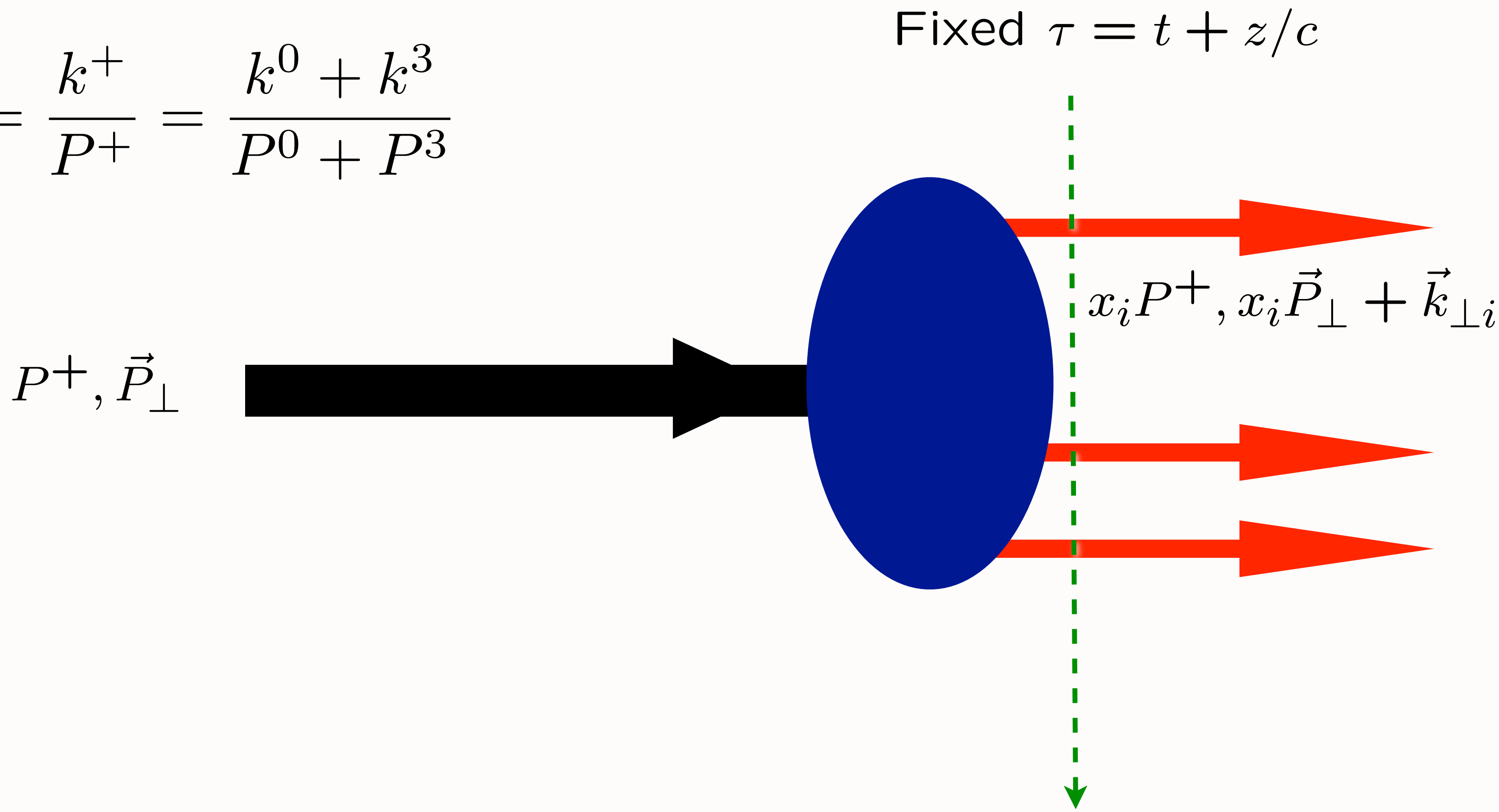

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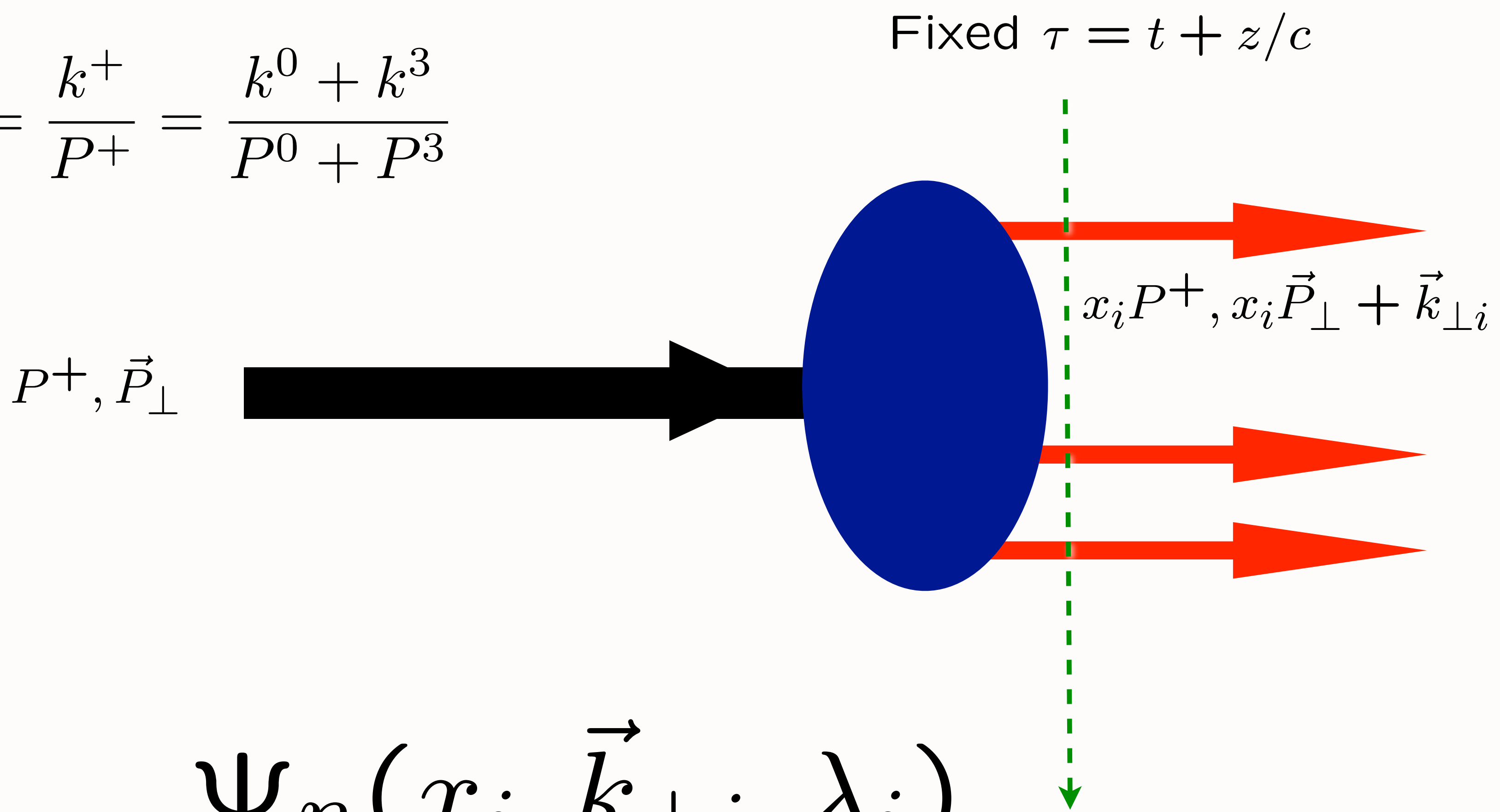

$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

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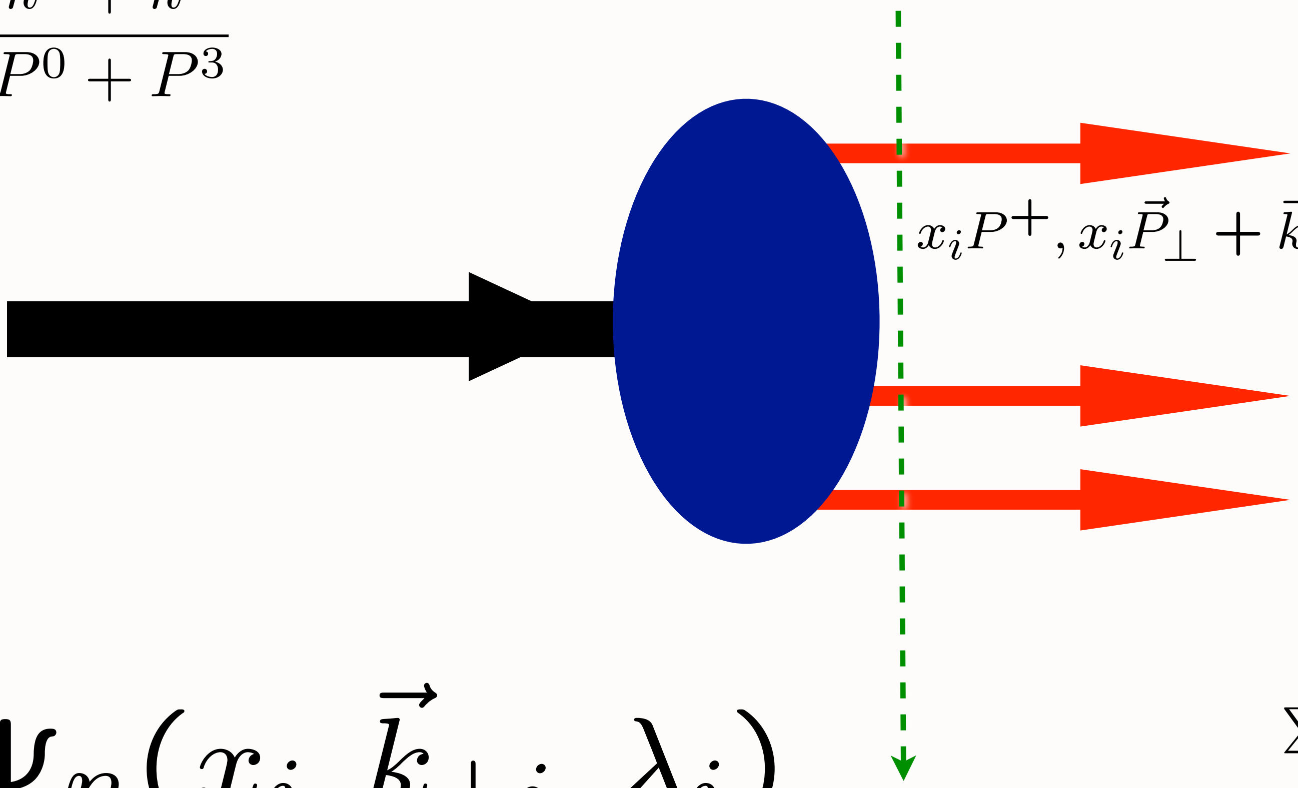
Fixed $\tau = t + z/c$

$P^+, \vec{P}_\perp$



$x_i P^+, x_i \vec{P}_\perp + \vec{k}_{\perp i}$

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$\sum_i^n x_i = 1$

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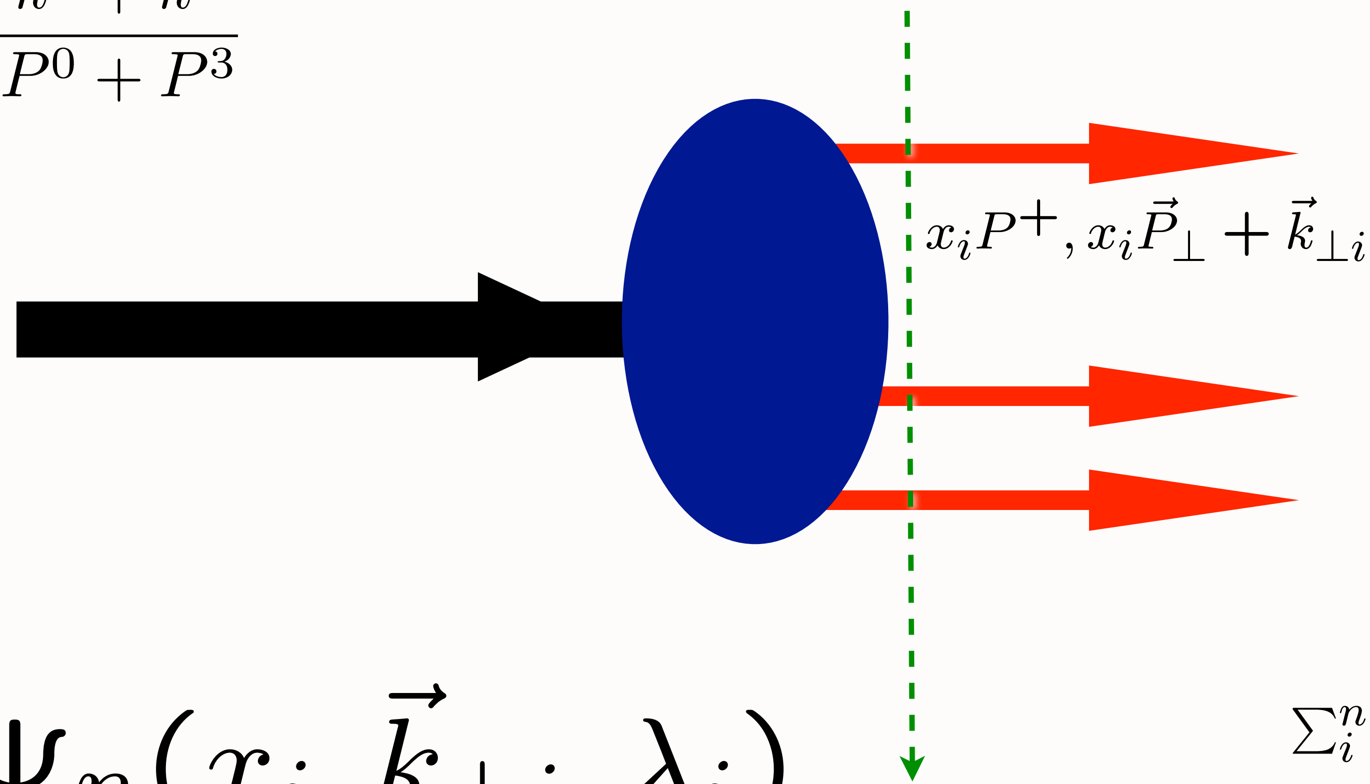

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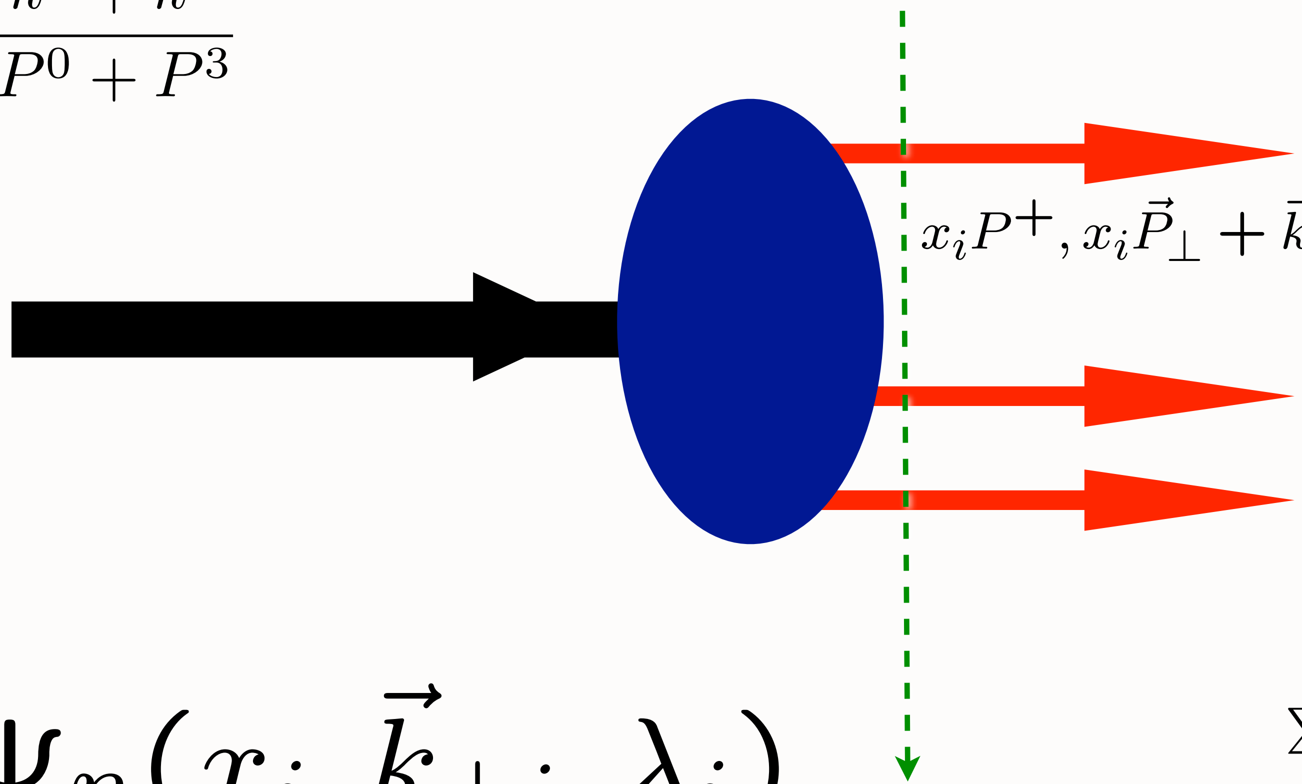

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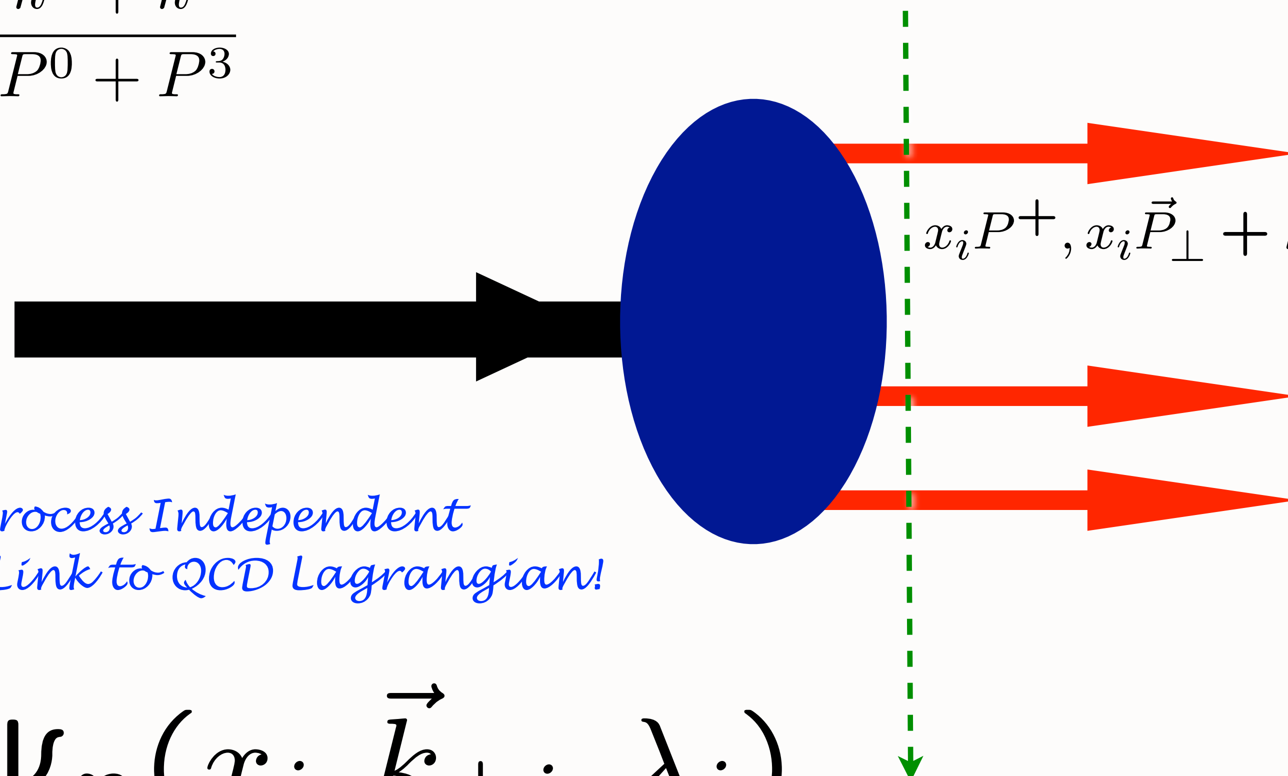

$P^+, \vec{P}_\perp$

$x_i P^+, x_i \vec{P}_\perp + \vec{k}_{\perp i}$

Process Independent
Direct Link to QCD Lagrangian!

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Each element of flash photograph illuminated at same LF time

$$\tau = t + z/c$$

HELEN BRADLEY - PHOTOGRAPHY

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Evolve in LF time

$$P^- = i\frac{d}{d\tau}$$

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Eigenstate -- independent of τ

HELEN BRADLEY - PHOTOGRAPHY

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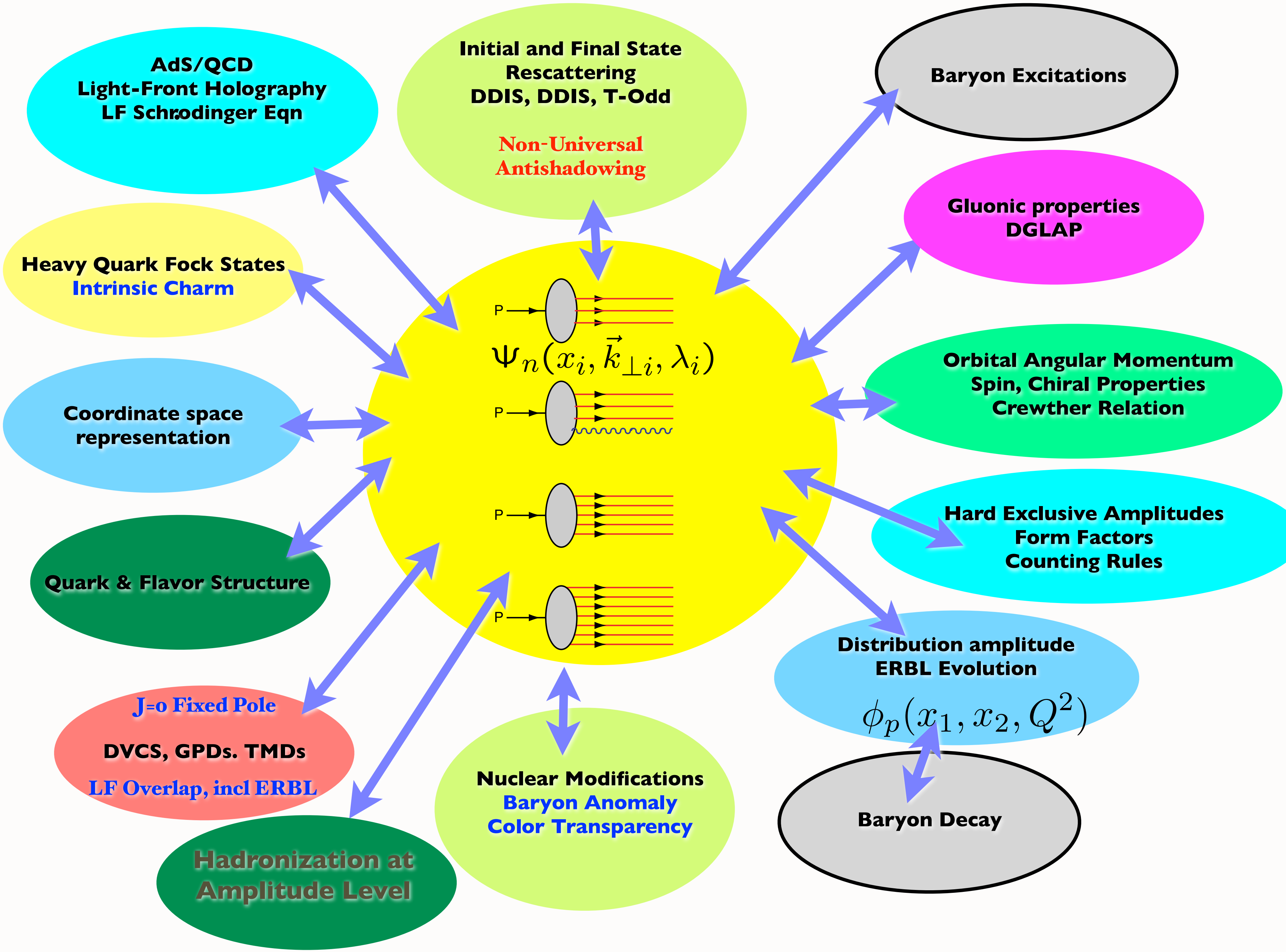
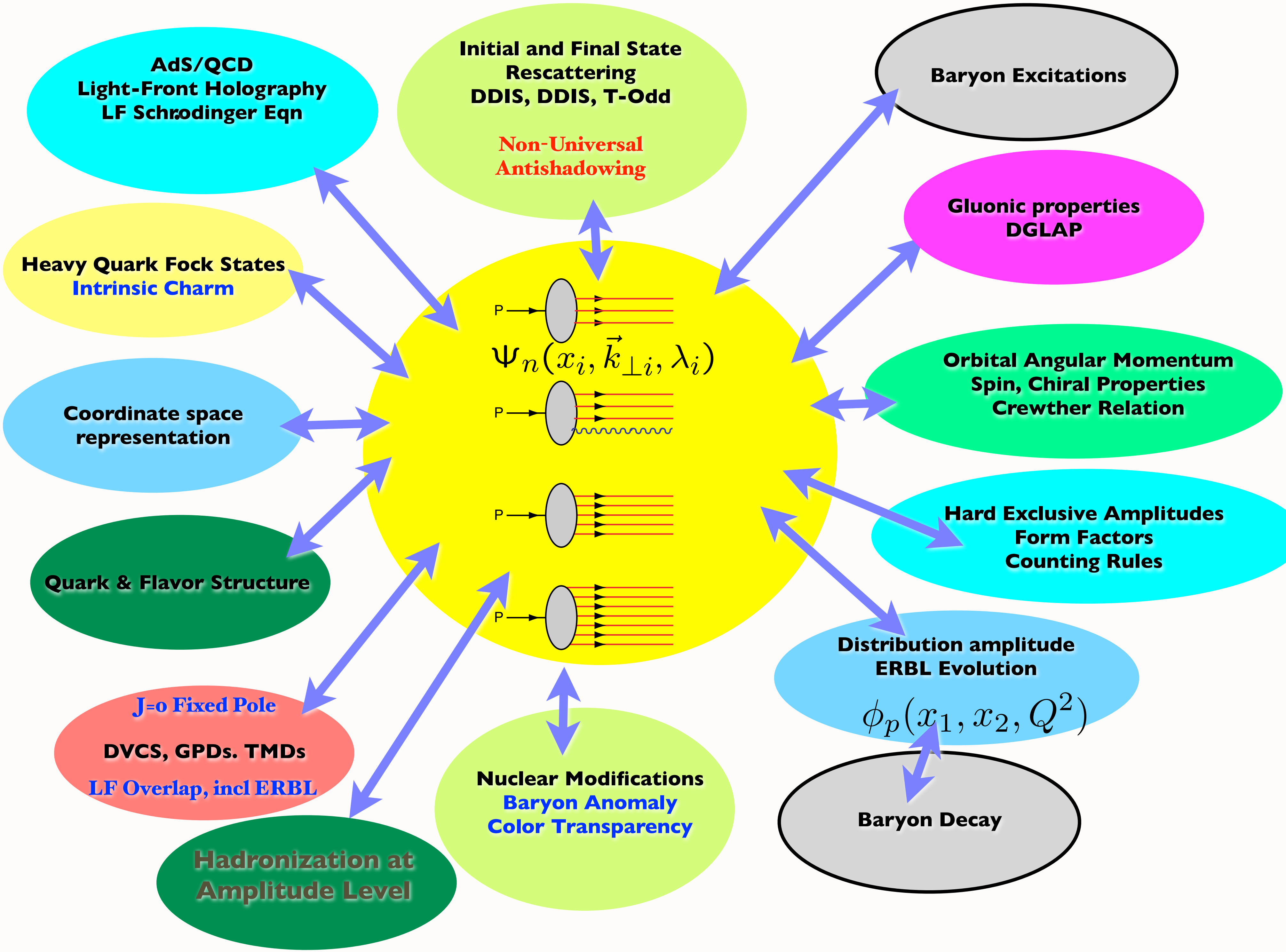
HELEN BRADLEY - PHOTOGRAPHY

QCD and the LF Hadron Wavefunctions



QCD and the LF Hadron Wavefunctions



Lorce

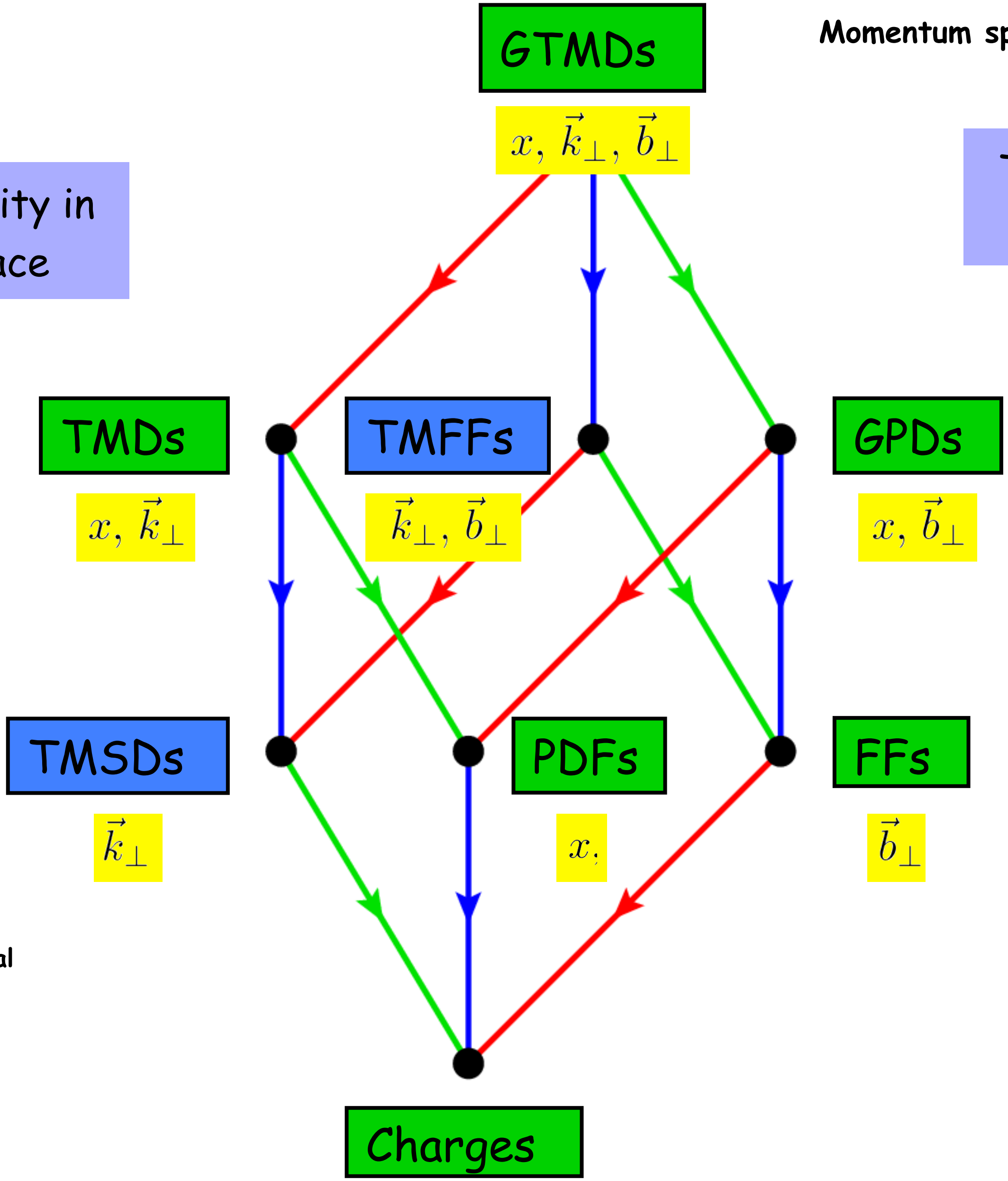
$\xi = 0$

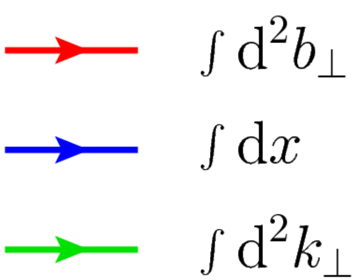
Momentum space $\vec{k}_\perp \leftrightarrow \vec{z}_\perp$ Position space

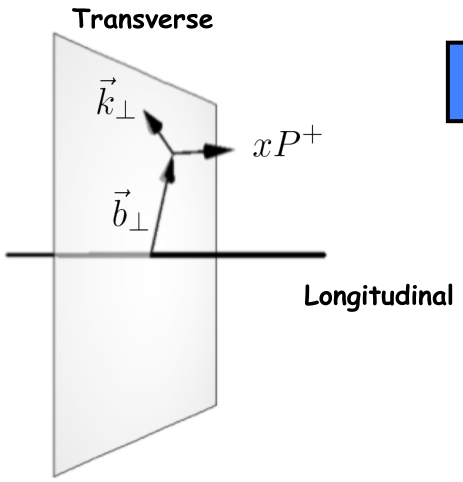
$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$

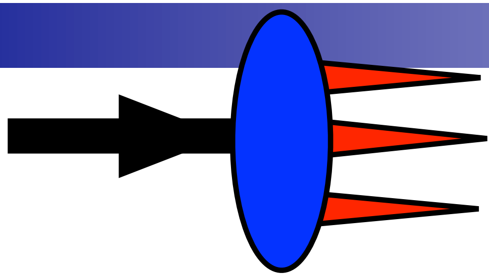
Transverse density in momentum space

Transverse density in position space









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

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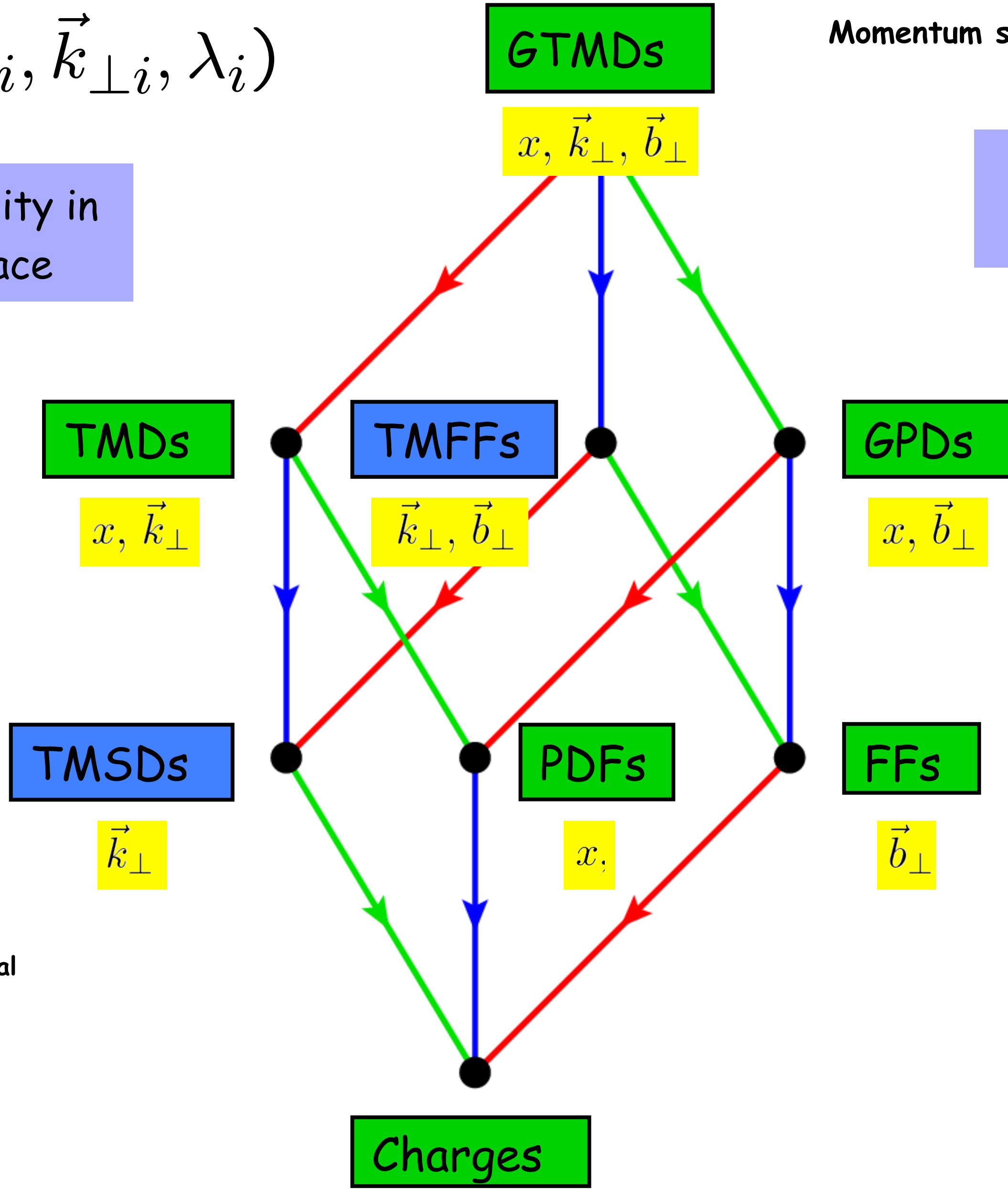

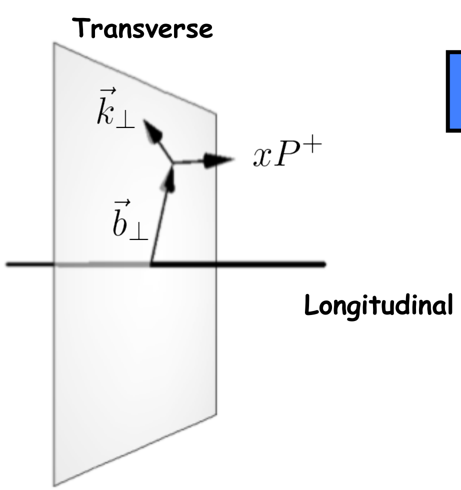

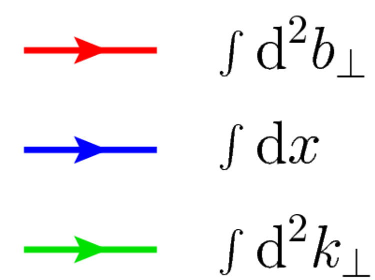

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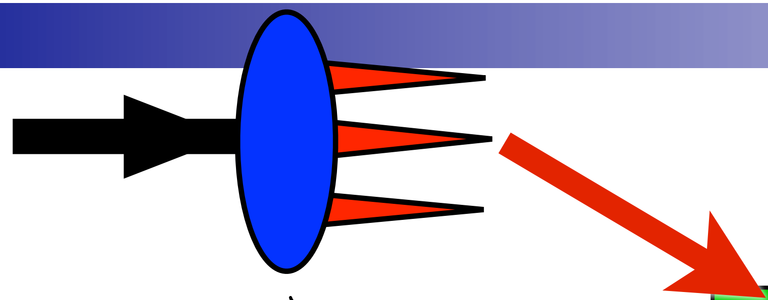

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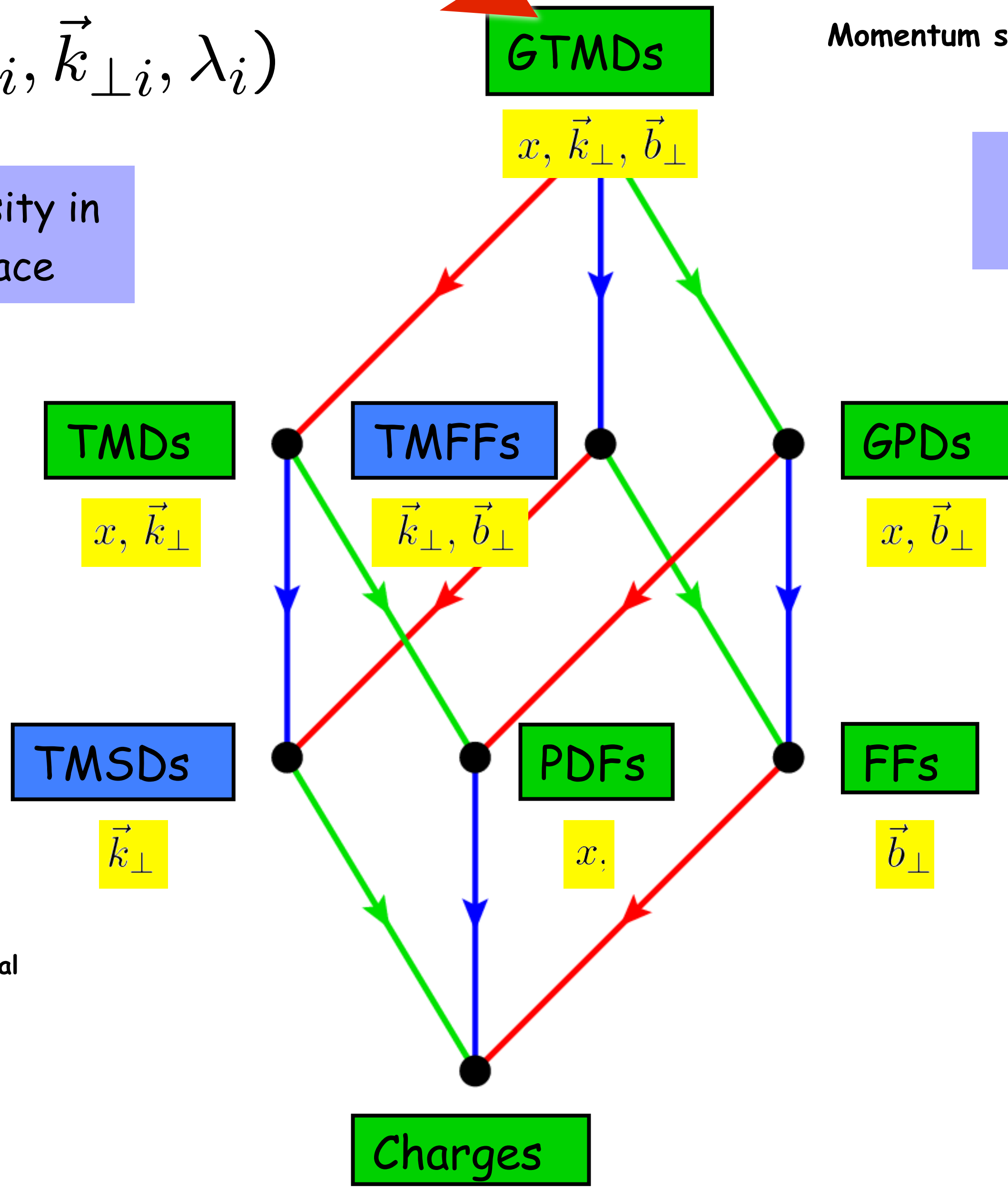
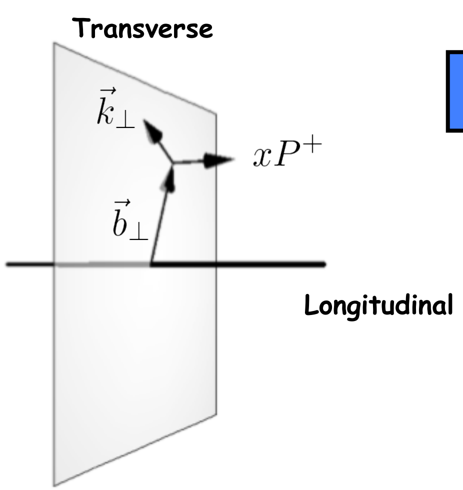
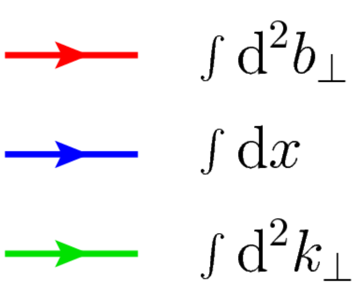
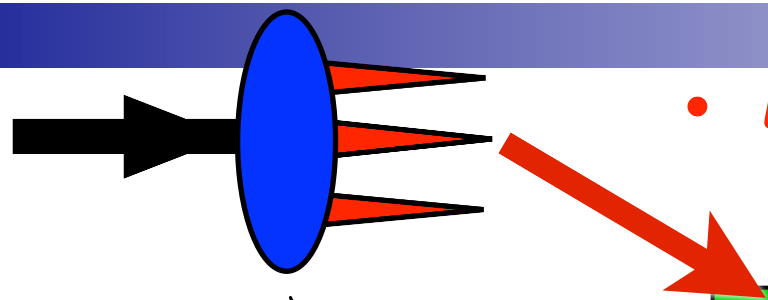






• *Light Front Wavefunctions:*



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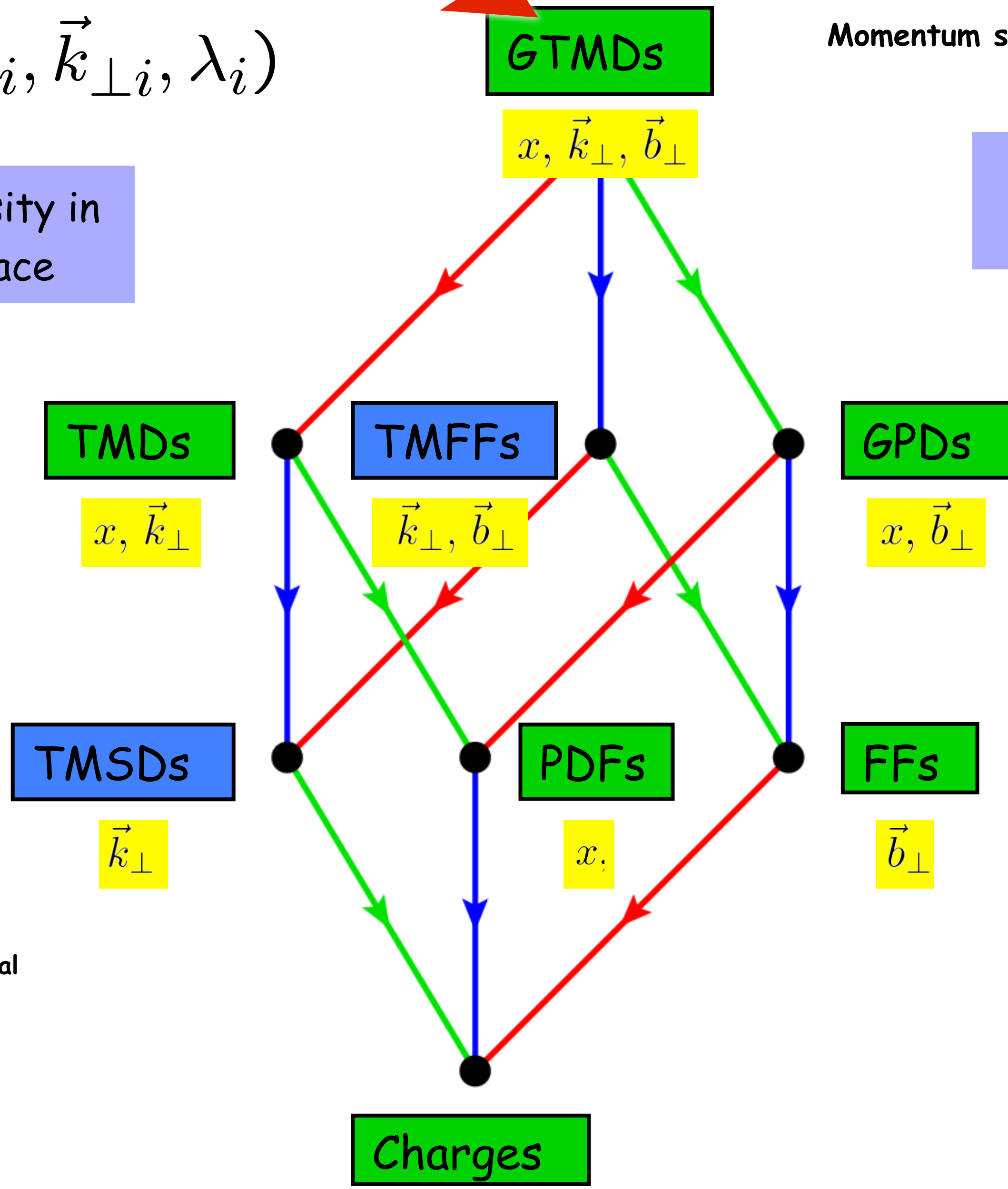

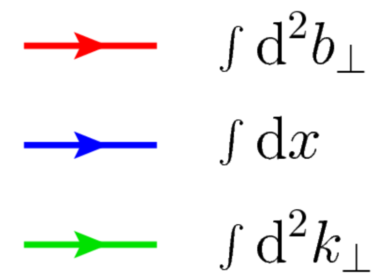

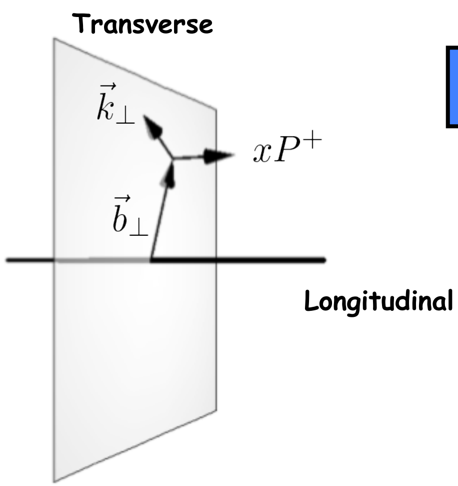

$$|p, S_z> = \sum_{n=3} \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) |n; \vec{k}_{\perp_i}, \lambda_i>$$

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

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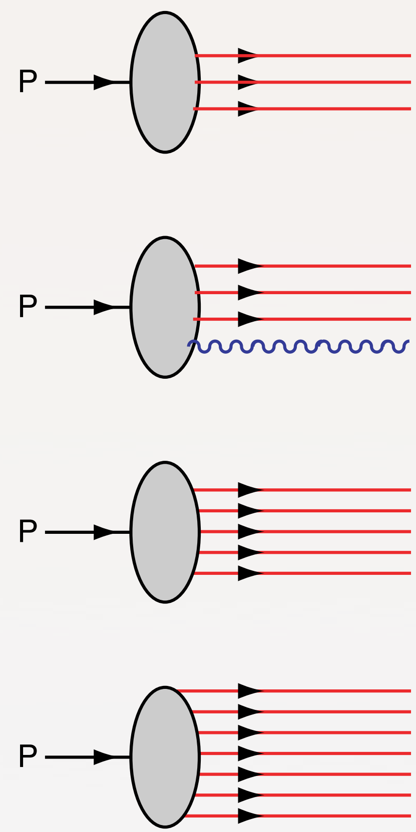

Intrinsic heavy quarks $\bar{s}(x) \neq s(x)$

c(x), b(x) at high x ! $\bar{u}(x) \neq \bar{d}(x)$

Mueller: gluon Fock states BFKL

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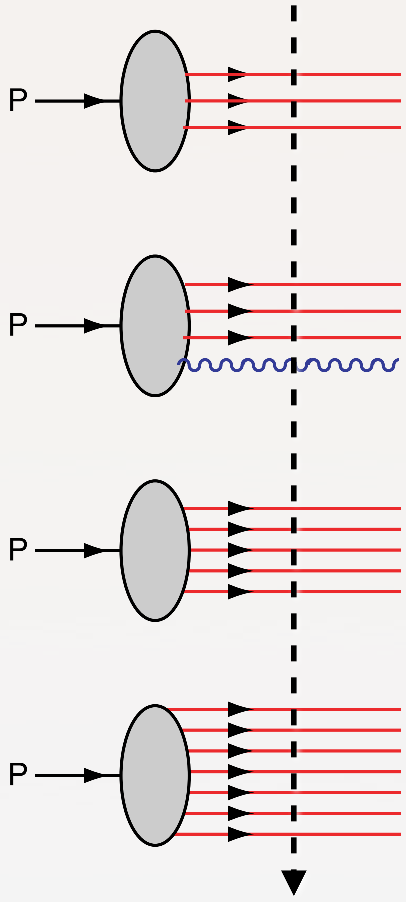

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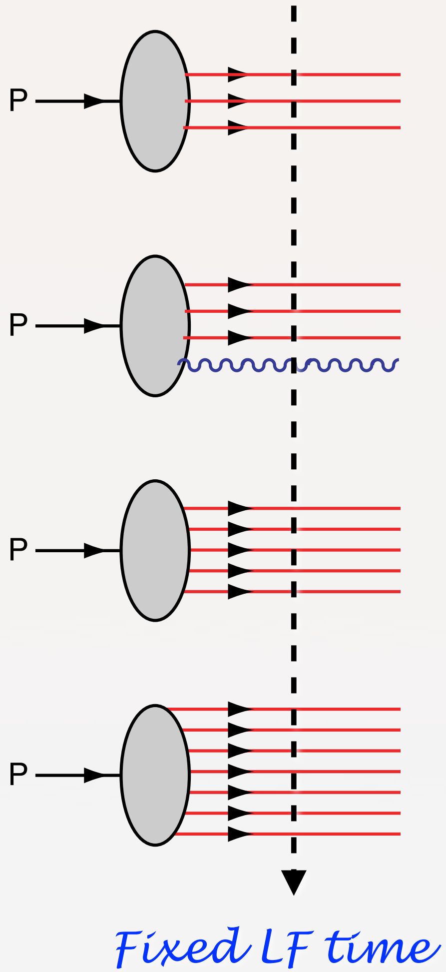

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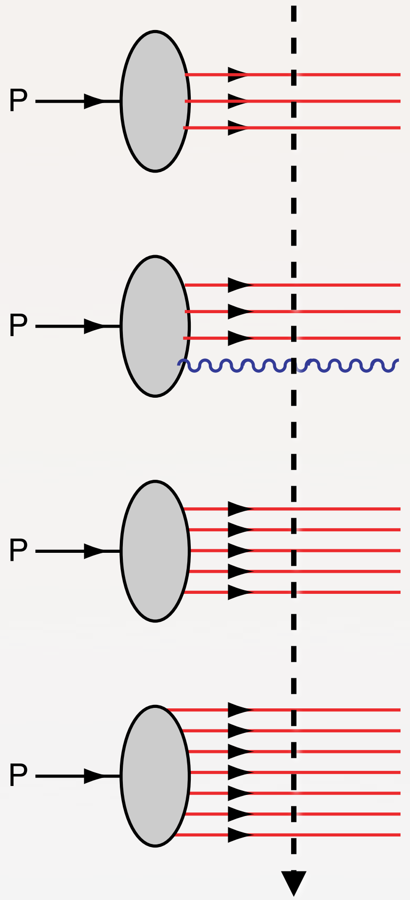

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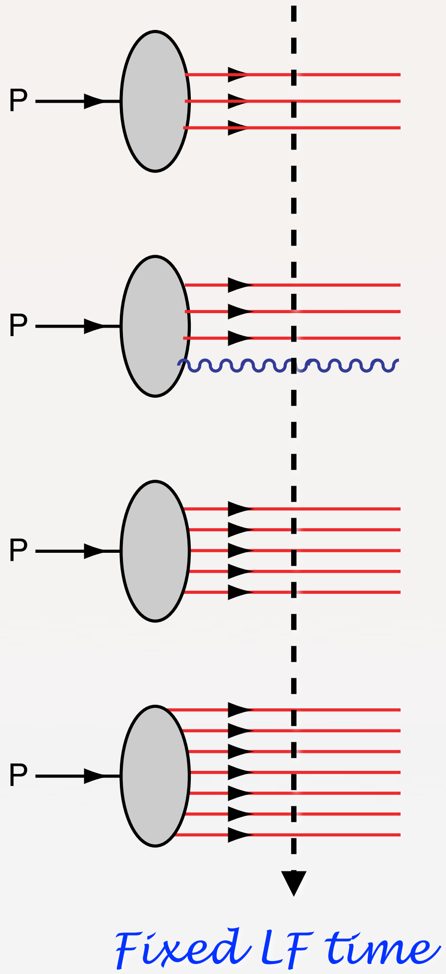

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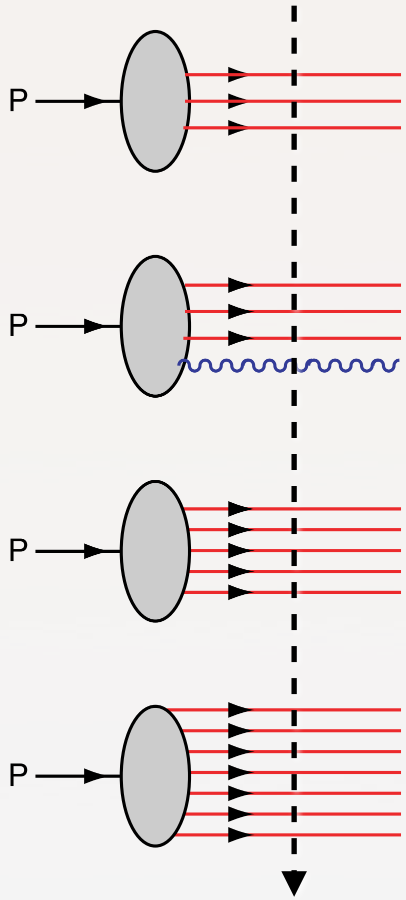

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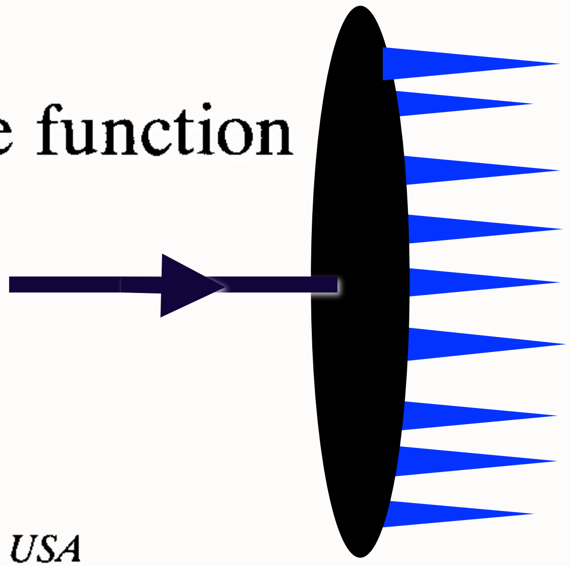
Nuclear Physics B415 (1994) 373–385
North-Holland

NUCLEAR
PHYSICS B

Soft gluons in the infinite-momentum wave function and the BFKL pomeron *



A.H. Mueller

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and

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Received 27 August 1993
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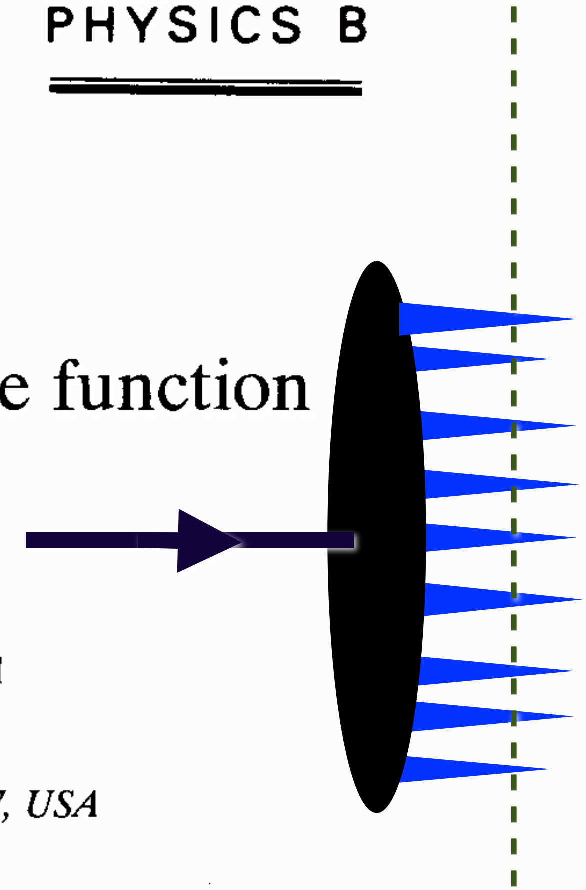

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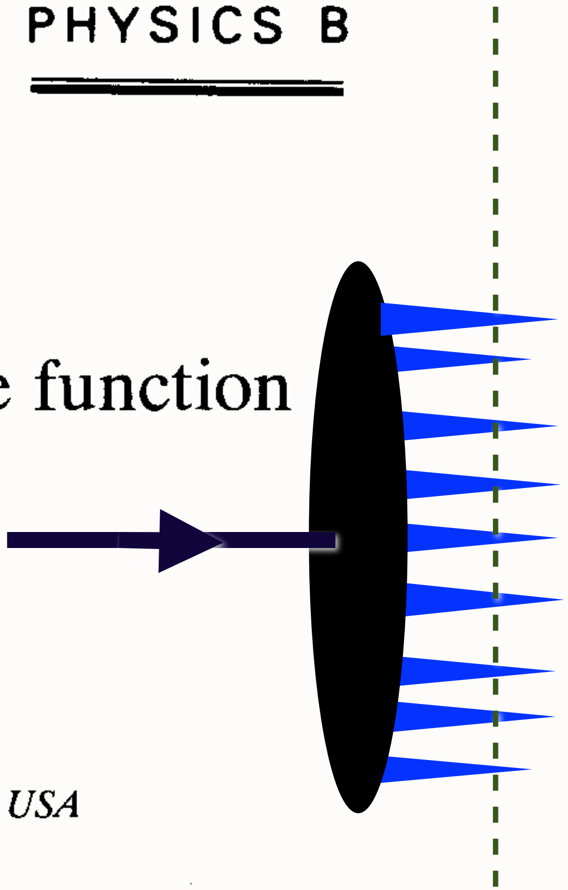

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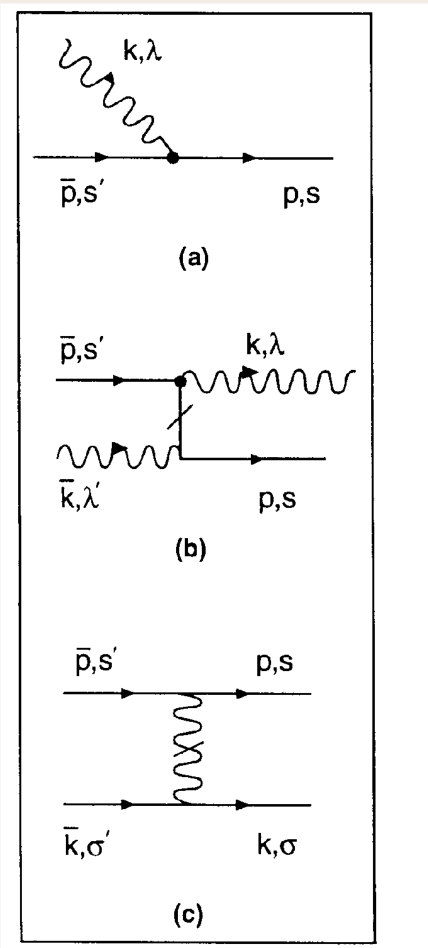

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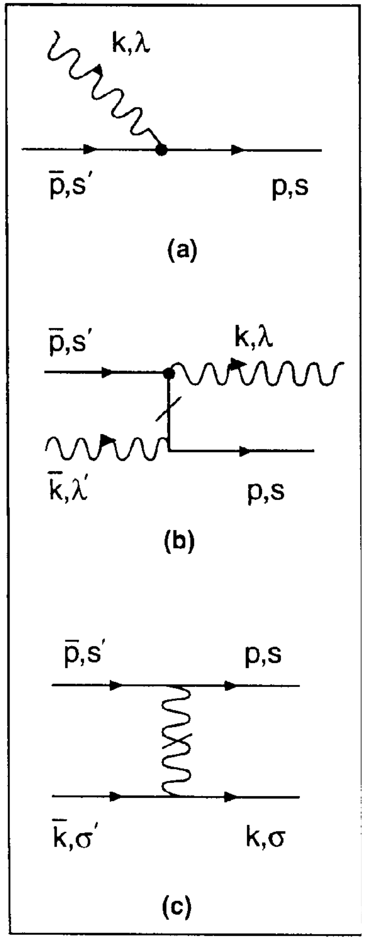
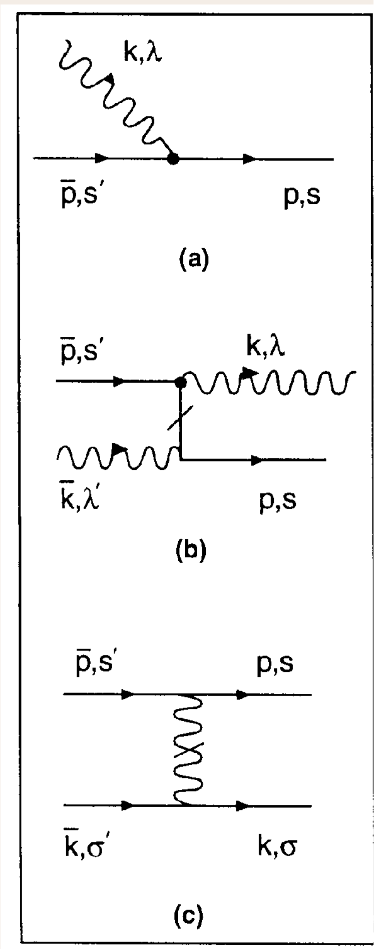
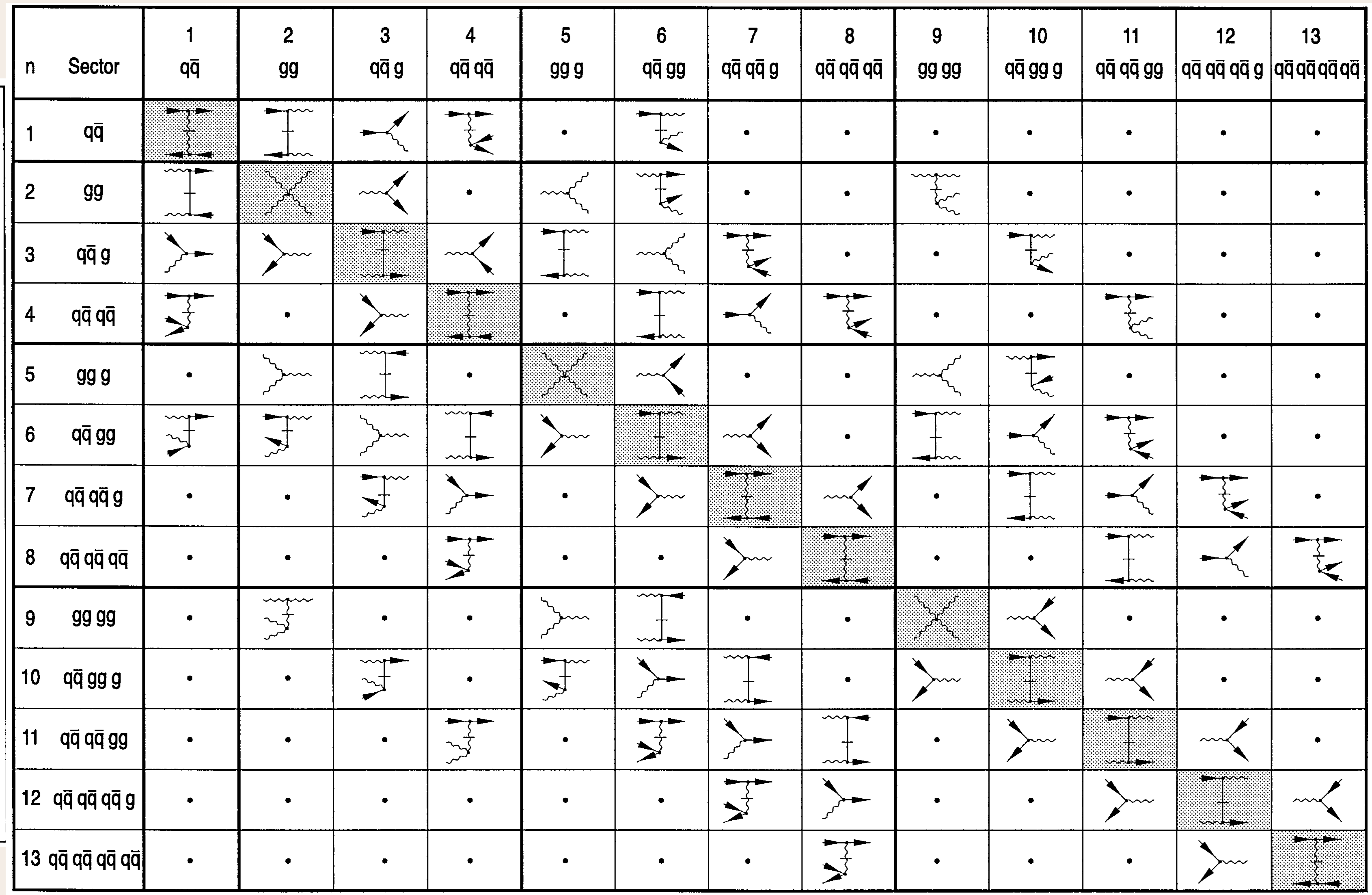


n	Sector	1 $q\bar{q}$	2 gg	3 $q\bar{q}\,g$	4 $q\bar{q}\,q\bar{q}$	5 $gg\,g$	6 $q\bar{q}\,gg$	7 $q\bar{q}\,q\bar{q}\,g$	8 $q\bar{q}\,q\bar{q}\,q\bar{q}$	9 $gg\,gg$	10 $q\bar{q}\,gg\,g$	11 $q\bar{q}\,q\bar{q}\,gg$	12 $q\bar{q}\,q\bar{q}\,q\bar{q}\,g$	13 $q\bar{q}\,q\bar{q}\,q\bar{q}\,q\bar{q}$
1	$q\bar{q}$					•		•	•	•	•	•	•	•
2	gg				•			•	•		•	•	•	•
3	$q\bar{q}\,g$								•	•		•	•	•
4	$q\bar{q}\,q\bar{q}$		•			•				•	•		•	•
5	$gg\,g$	•			•			•	•			•	•	•
6	$q\bar{q}\,gg$								•				•	•
7	$q\bar{q}\,q\bar{q}\,g$	•	•			•				•				•
8	$q\bar{q}\,q\bar{q}\,q\bar{q}$	•	•	•		•	•			•	•			
9	$gg\,gg$	•		•	•			•	•			•	•	•
10	$q\bar{q}\,gg\,g$	•	•		•				•				•	•
11	$q\bar{q}\,q\bar{q}\,gg$	•	•	•		•				•				•
12	$q\bar{q}\,q\bar{q}\,q\bar{q}\,g$	•	•	•	•	•	•			•	•			
13	$q\bar{q}\,q\bar{q}\,q\bar{q}\,q\bar{q}$	•	•	•	•	•	•	•		•	•	•		

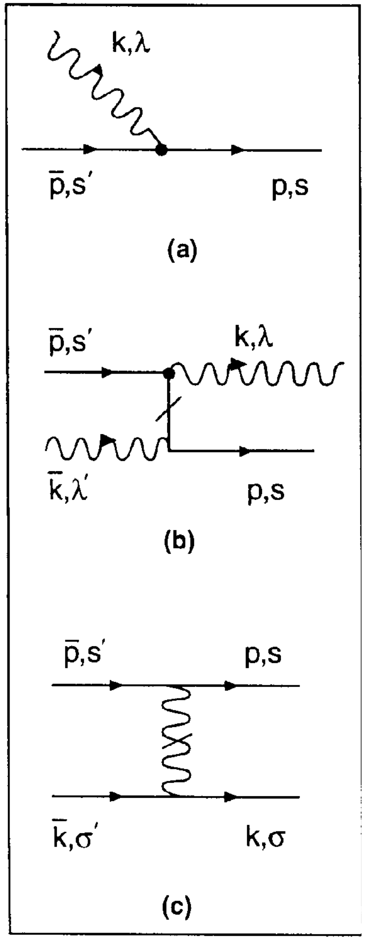
$$H_{LC}^{QCD} |\Psi_h\rangle = \mathcal{M}_h^2 \, |\Psi_h\rangle$$

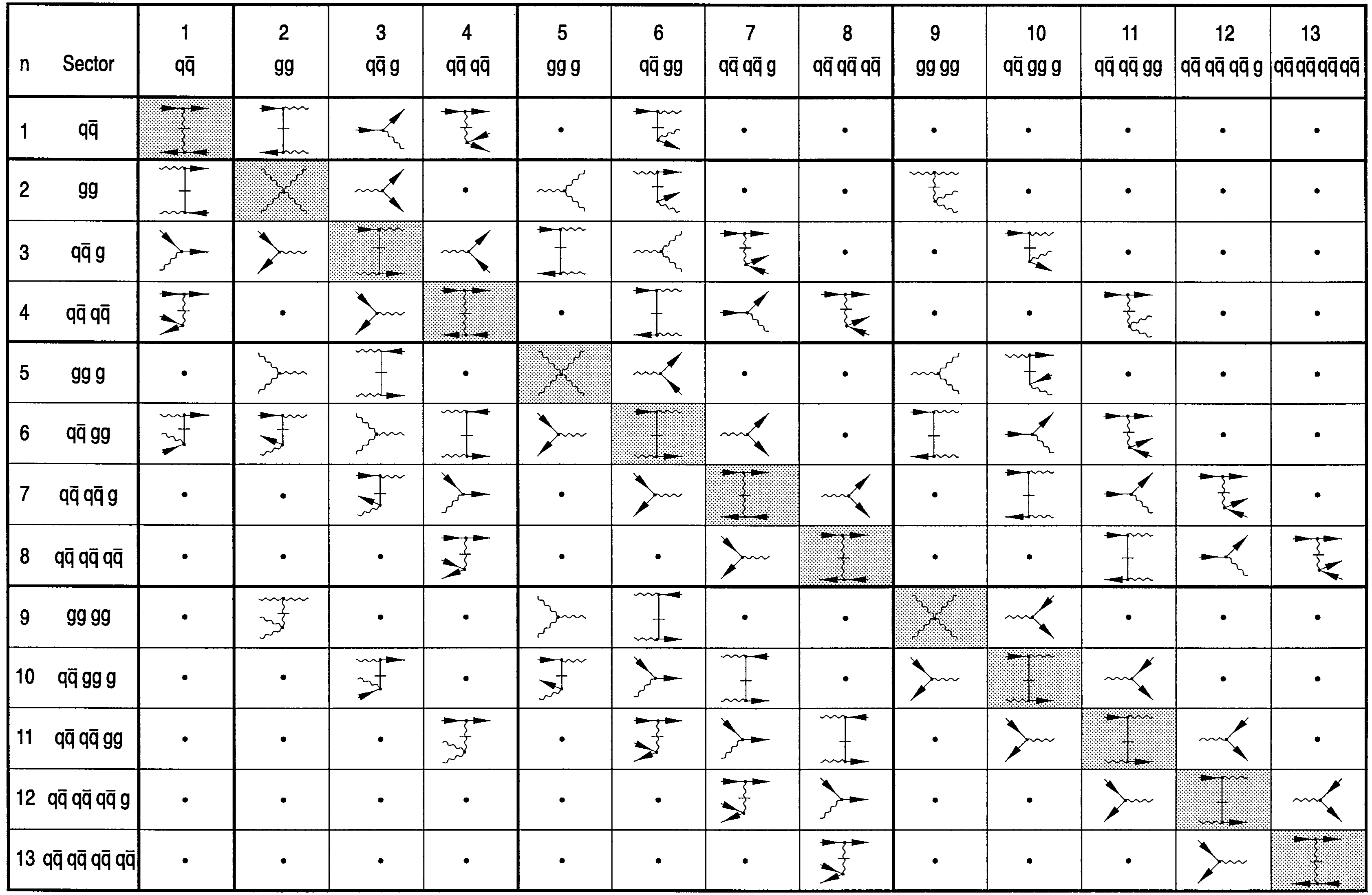




Light-Front QCD

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

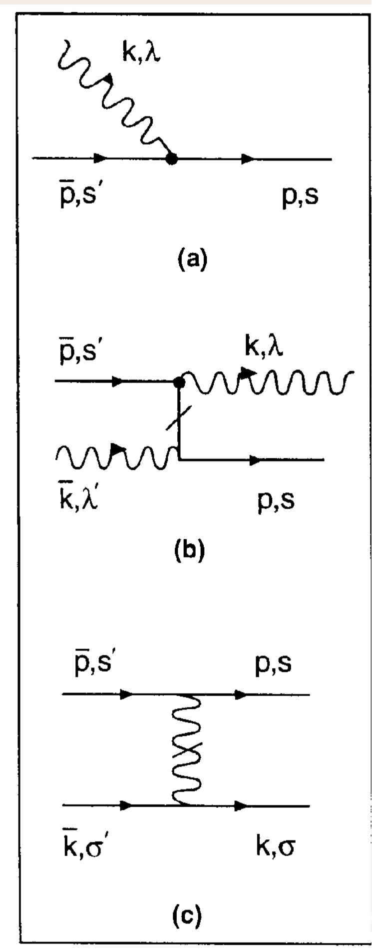


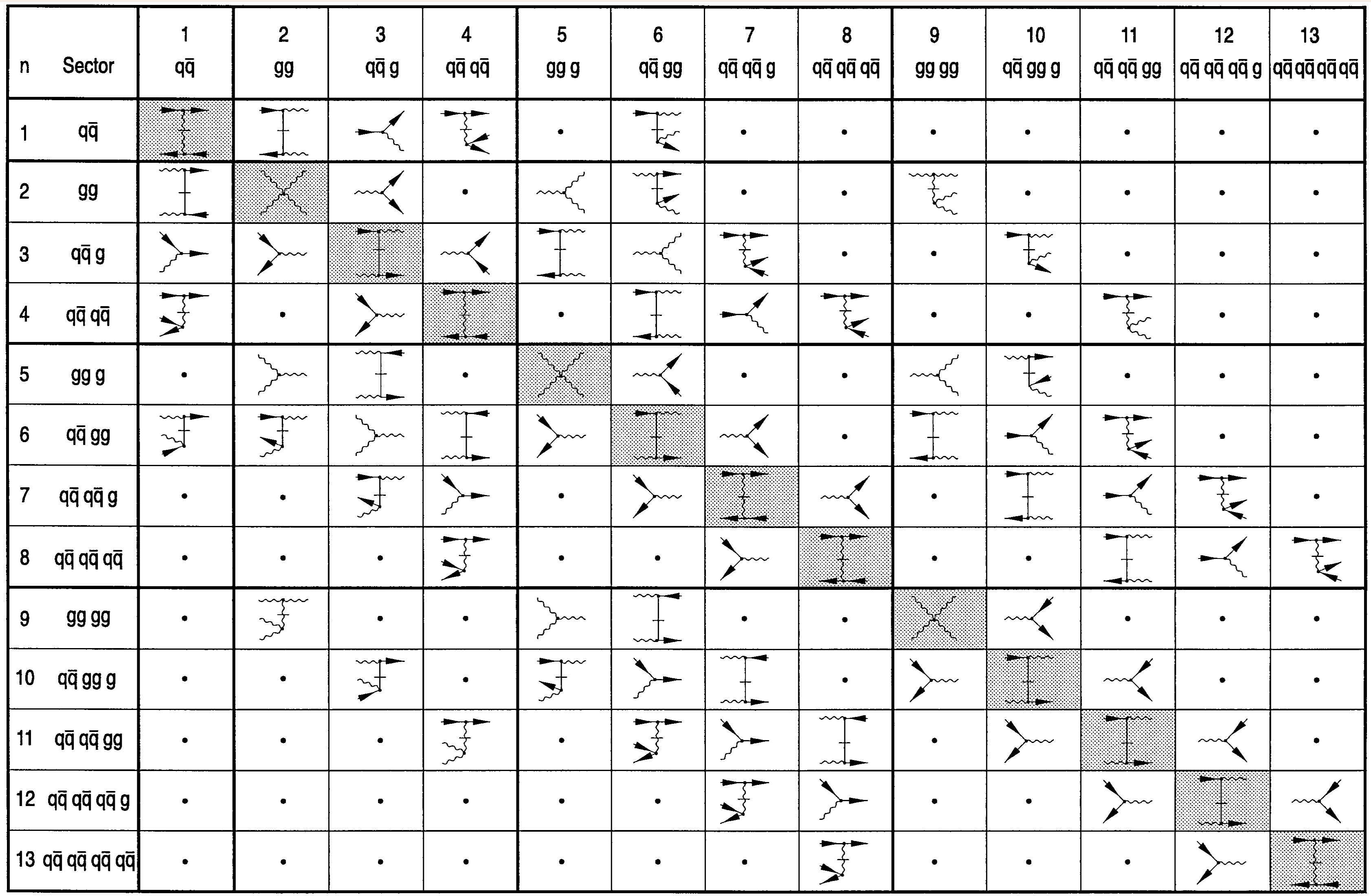


n	Sector	1 qq̄	2 gg	3 qq̄ g	4 qq̄ qq̄	5 gg g	6 qq̄ gg	7 qq̄ qq̄ g	8 qq̄ qq̄ qq̄	9 gg gg	10 qq̄ gg g	11 qq̄ qq̄ gg	12 qq̄ qq̄ qq̄ g	13 qq̄ qq̄ qq̄ qq̄
1	qq̄					•		•	•	•	•	•	•	•
2	gg				•			•	•		•	•	•	•
3	qq̄ g								•	•		•	•	•
4	qq̄ qq̄		•			•				•	•		•	•
5	gg g	•			•			•	•			•	•	•
6	qq̄ gg								•				•	•
7	qq̄ qq̄ g	•	•			•				•				•
8	qq̄ qq̄ qq̄	•	•	•		•	•			•	•			
9	gg gg	•		•	•			•	•			•	•	•
10	qq̄ gg g	•	•		•				•				•	•
11	qq̄ qq̄ gg	•	•	•		•				•				•
12	qq̄ qq̄ qq̄ g	•	•	•	•	•	•			•	•			
13	qq̄ qq̄ qq̄ qq̄	•	•	•	•	•	•	•		•	•	•		

Light-Front QCD Heisenberg Equation

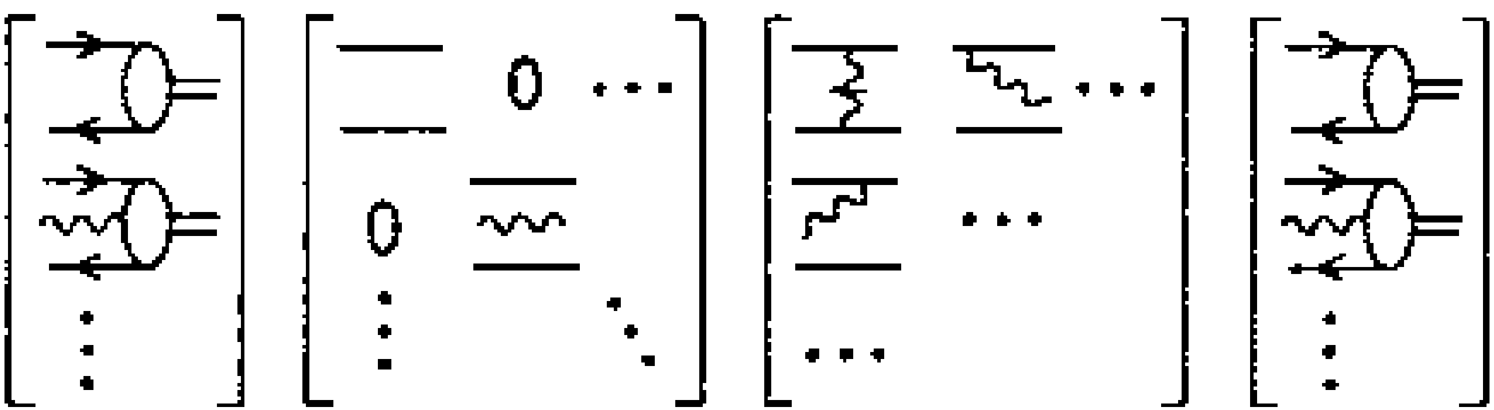
$$H_{LC}^{QCD}|\Psi_h\rangle = \mathcal{M}_h^2\,|\Psi_h\rangle$$





LIGHT-FRONT SCHRODINGER EQUATION

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



G.P. Lepage, sjb

$A^+ = 0$

Remarkable Features of Hadron Structure

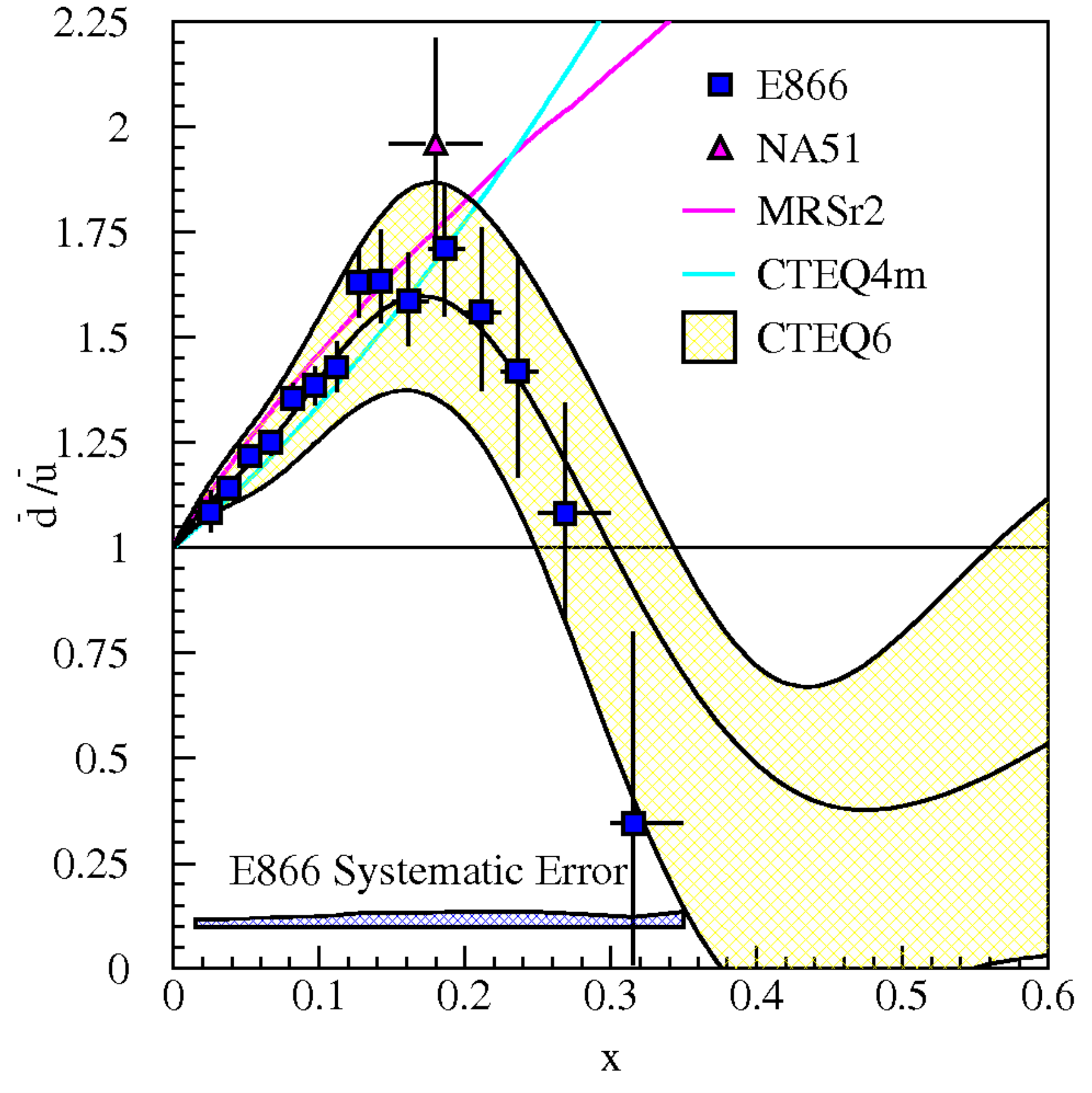
- Valence quark helicity represents less than half of the proton's spin and momentum
- Non-zero quark orbital angular momentum!
- Asymmetric sea: $\bar{u}(x) \neq \bar{d}(x)$ relation to meson cloud
- Non-symmetric strange and antistrange sea $\bar{s}(x) \neq s(x)$

  $\Delta s(x) \neq \Delta \bar{s}(x)$
- Intrinsic charm and bottom at high x
- Hidden-Color Fock states of the Deuteron

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

- E866/NuSea (Drell-Yan)

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

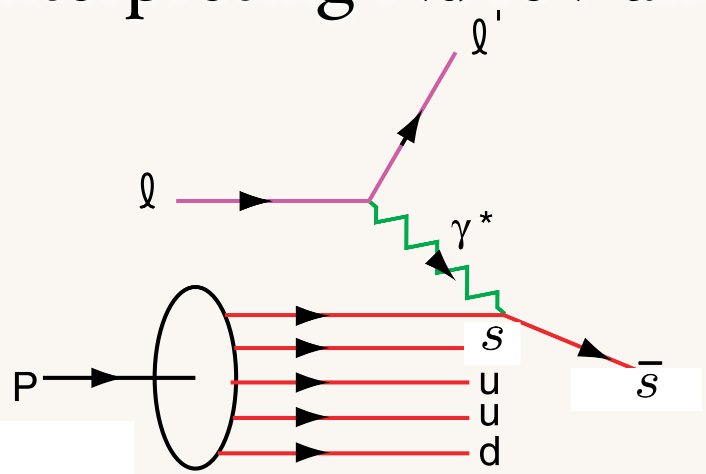


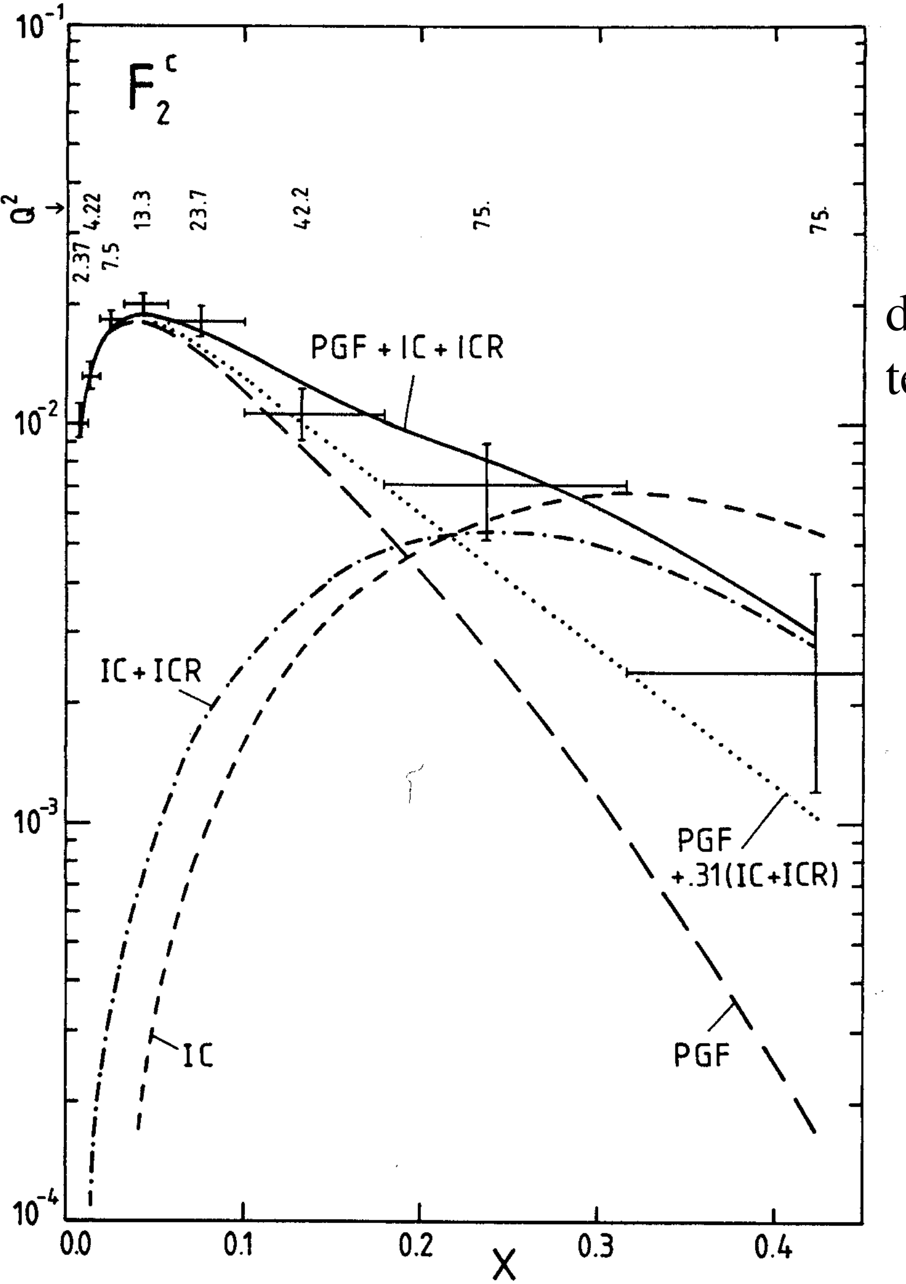
Intrinsic glue, sea, heavy quarks

Measure strangeness distribution from DIS at EIC

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

- Non-symmetric strange and antistrange sea
- Non-perturbative input; e.g $|uuds\bar{s}> \simeq |\Lambda(uds)K^+(\bar{s}u)>$
- Crucial for interpreting NuTeV anomaly





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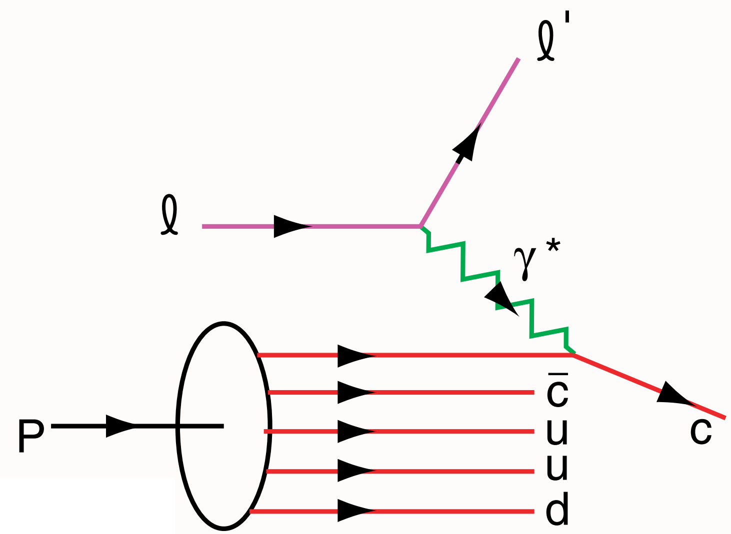

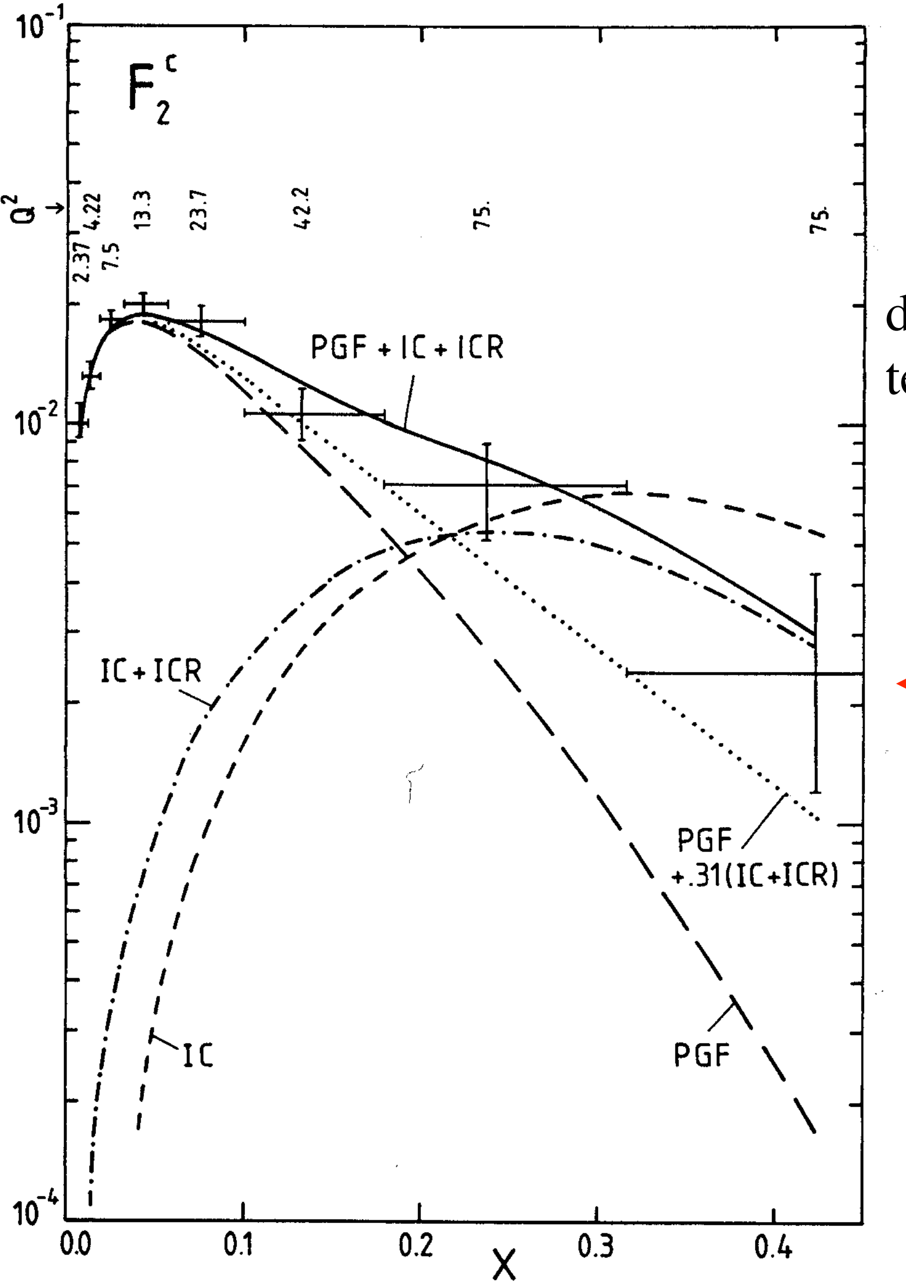

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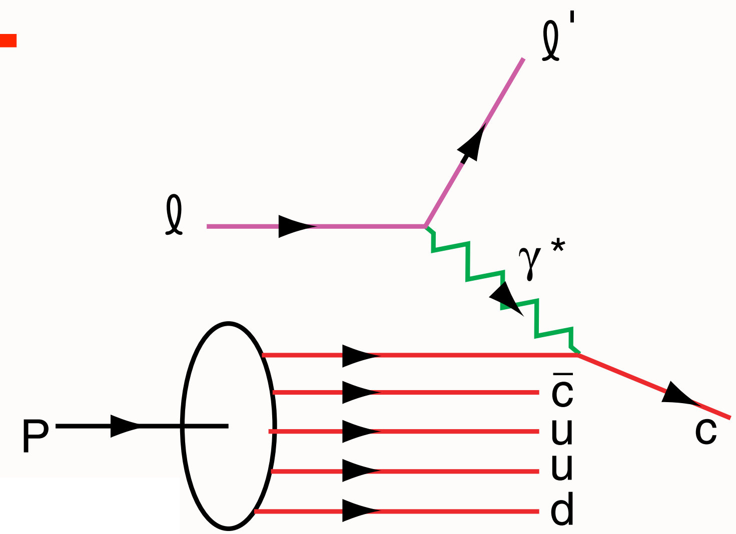

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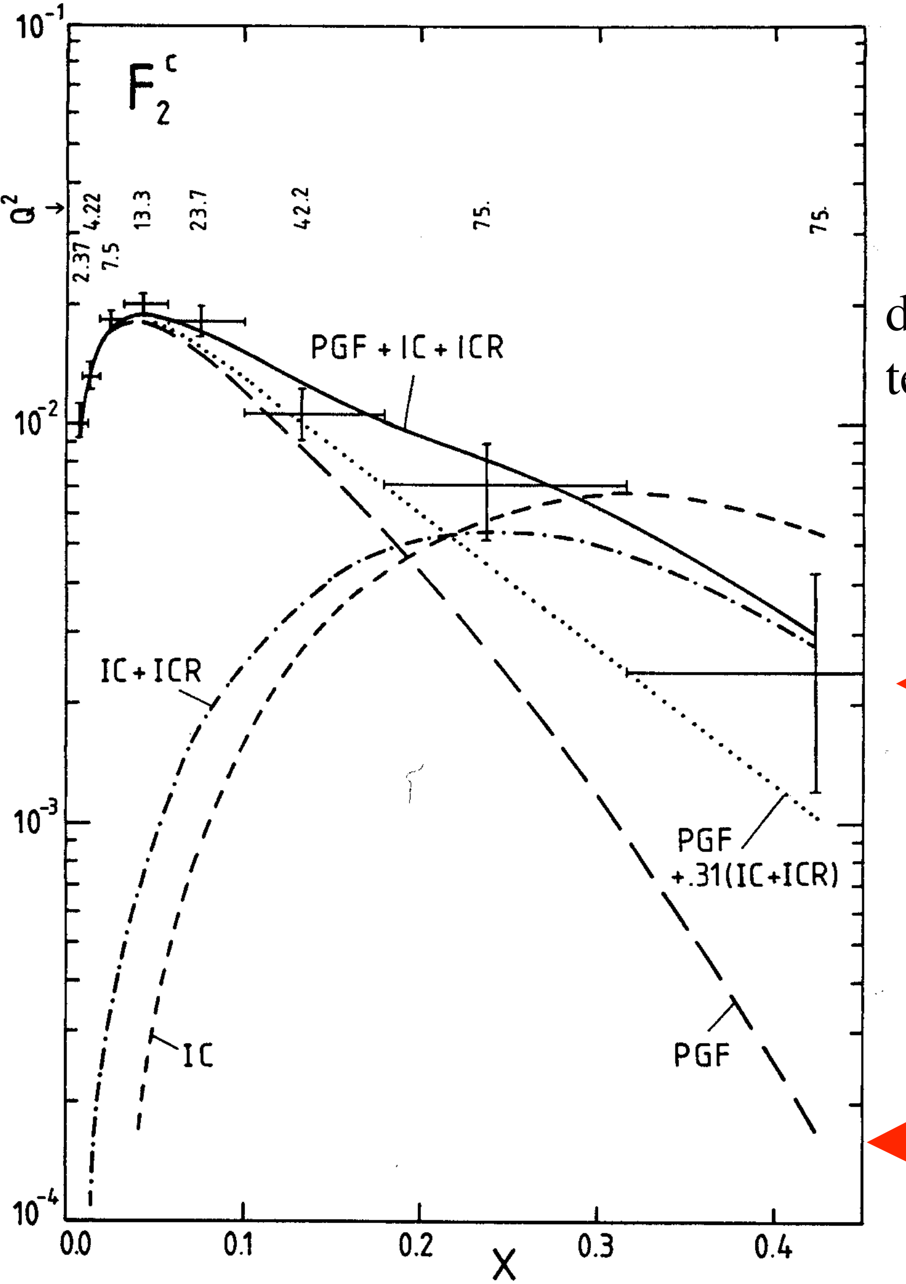

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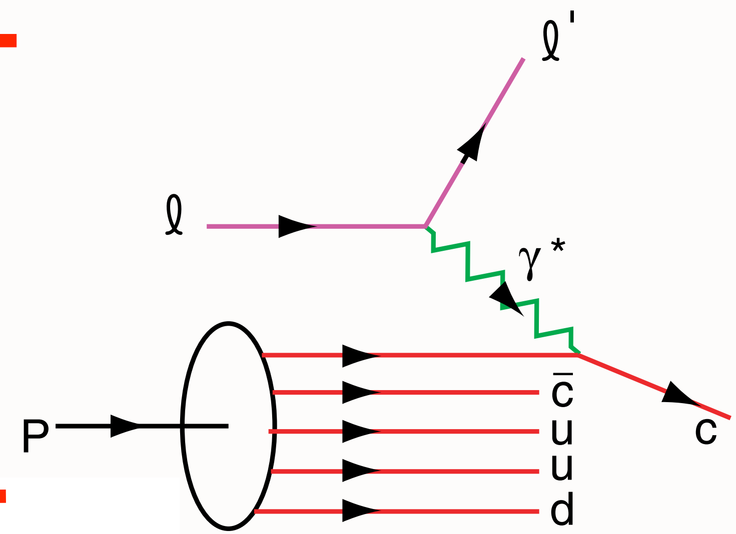

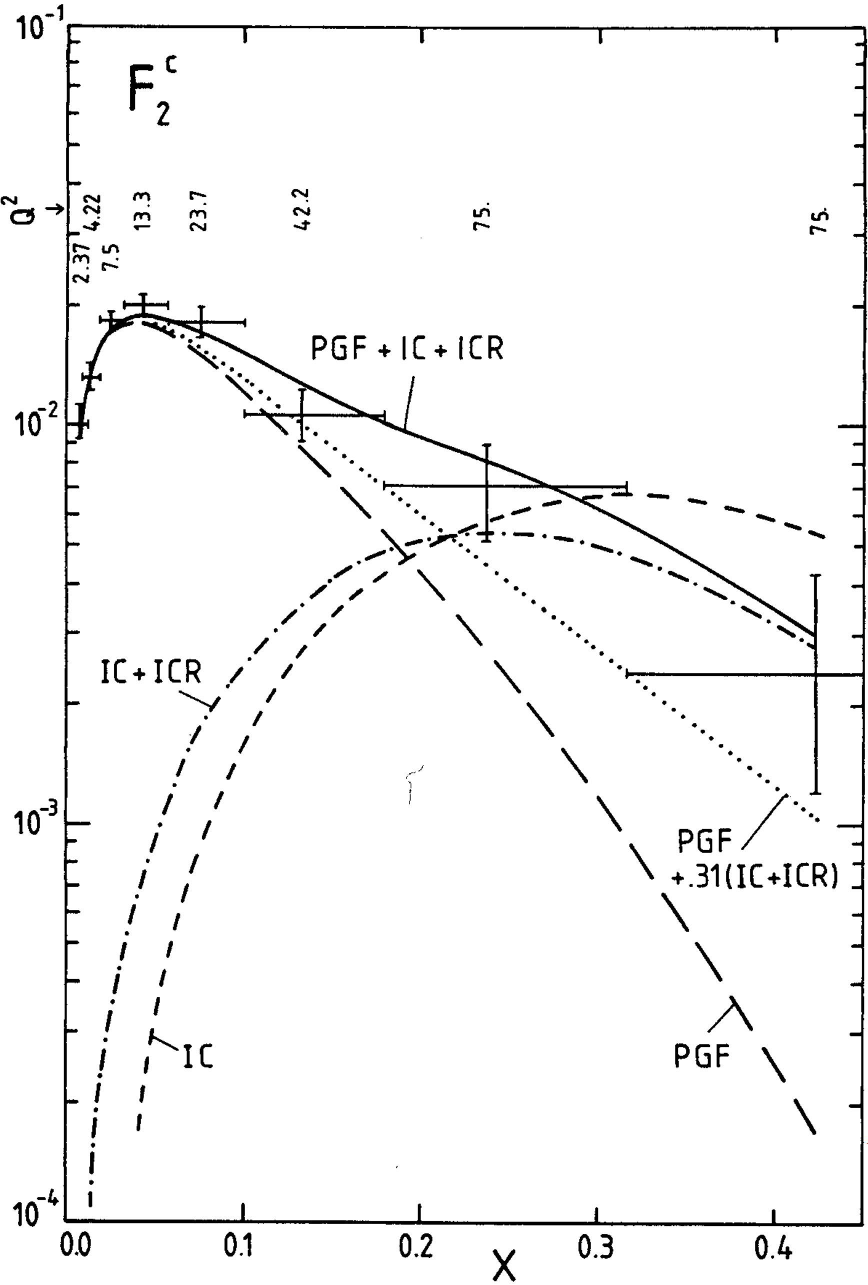

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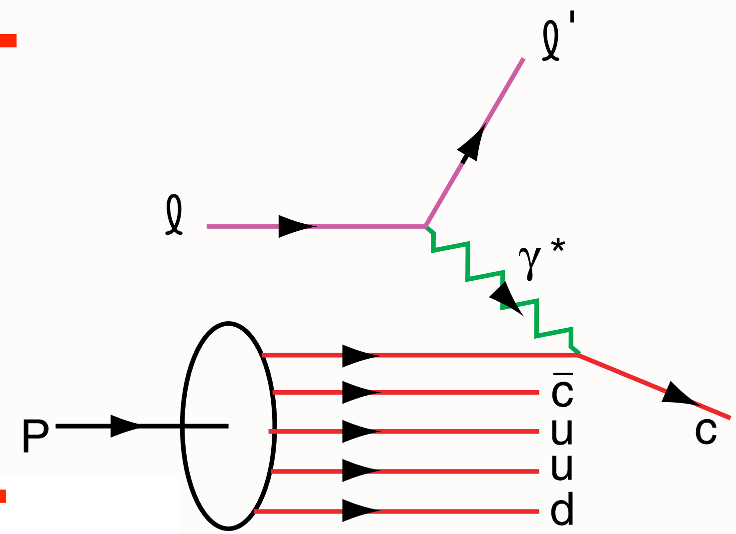

DGLAP / Photon-Gluon Fusion: factor of 30 too small

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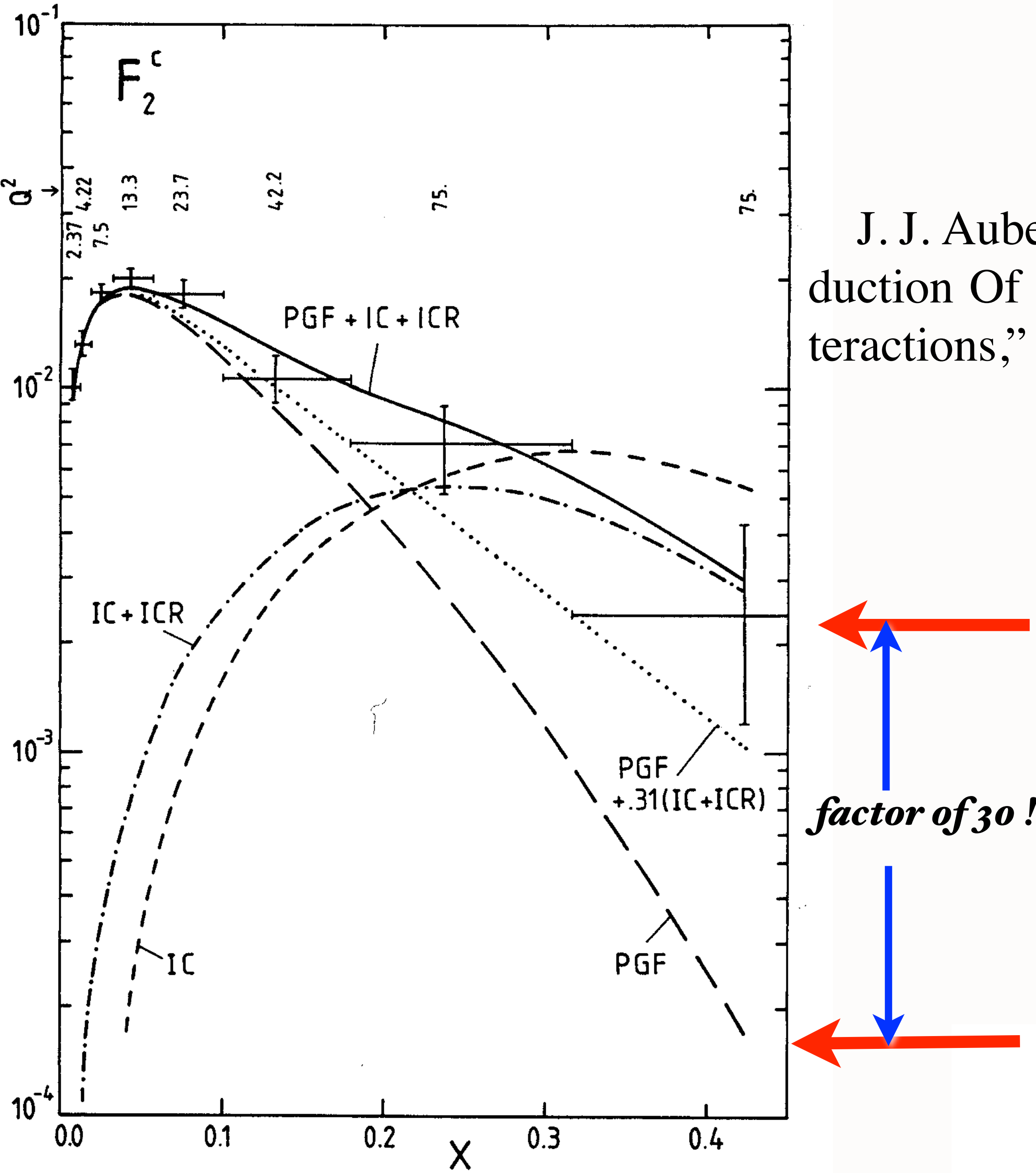

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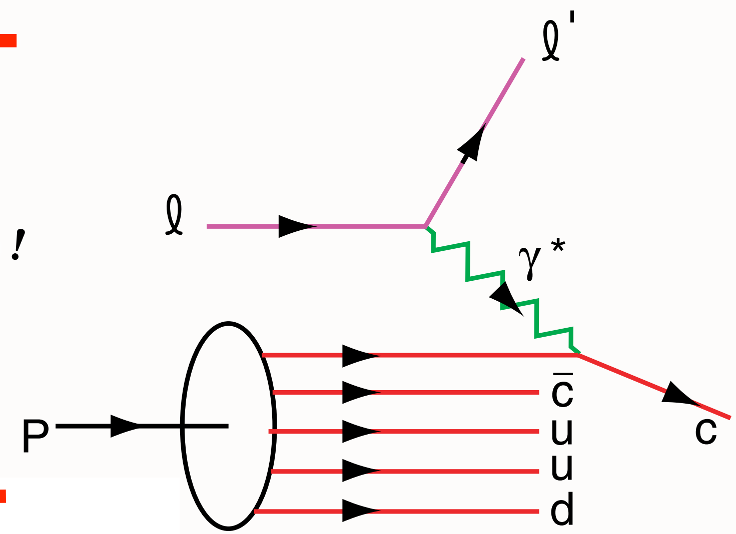


DGLAP / Photon-Gluon Fusion: factor of 30 too small

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!

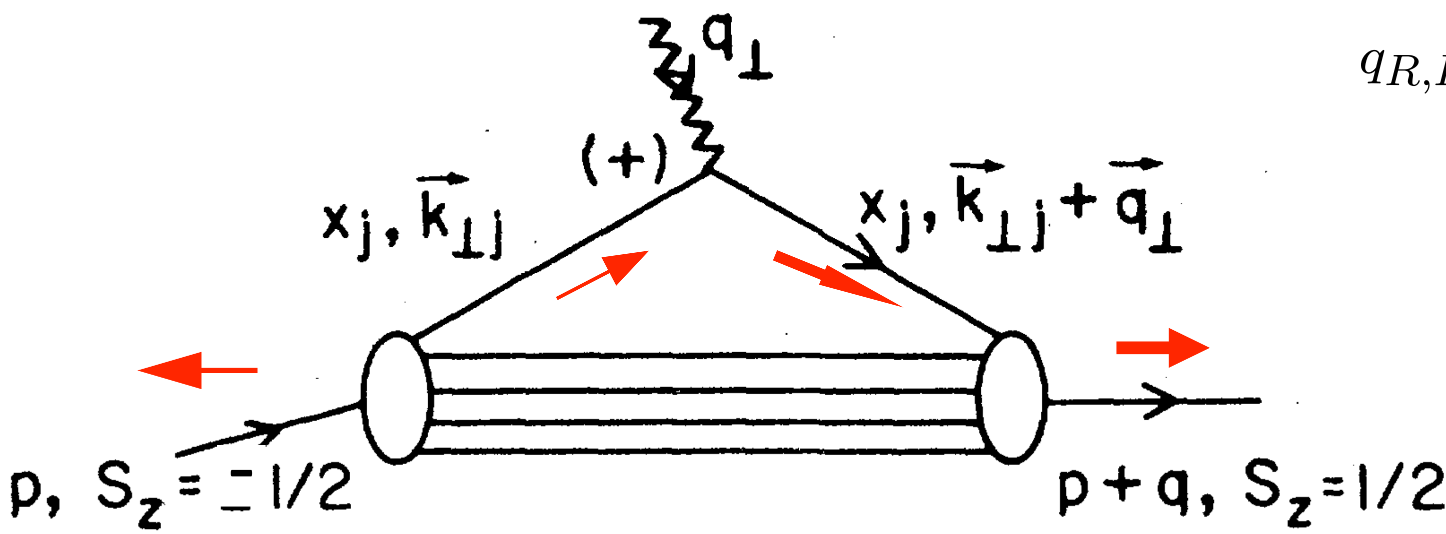
$$\frac{F_2(q^2)}{2M} = \sum_a \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp] \sum_j e_j \, \frac{1}{2} \times$$

Drell, sjb

$$\left[-\frac{1}{q^L}\psi_a^{\uparrow *}(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\, \psi_a^{\downarrow}(x_i, \mathbf{k}_{\perp i}, \lambda_i) + \frac{1}{q^R}\psi_a^{\downarrow *}(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\, \psi_a^{\uparrow}(x_i, \mathbf{k}_{\perp i}, \lambda_i) \right]$$

$$\mathbf{k}'_{\perp i} = \mathbf{k}_{\perp i} - x_i \mathbf{q}_\perp \qquad \mathbf{k}'_{\perp j} = \mathbf{k}_{\perp j} + (1 - x_j)\mathbf{q}_\perp$$

$$q_{R,L} = q^x \pm i q^y$$

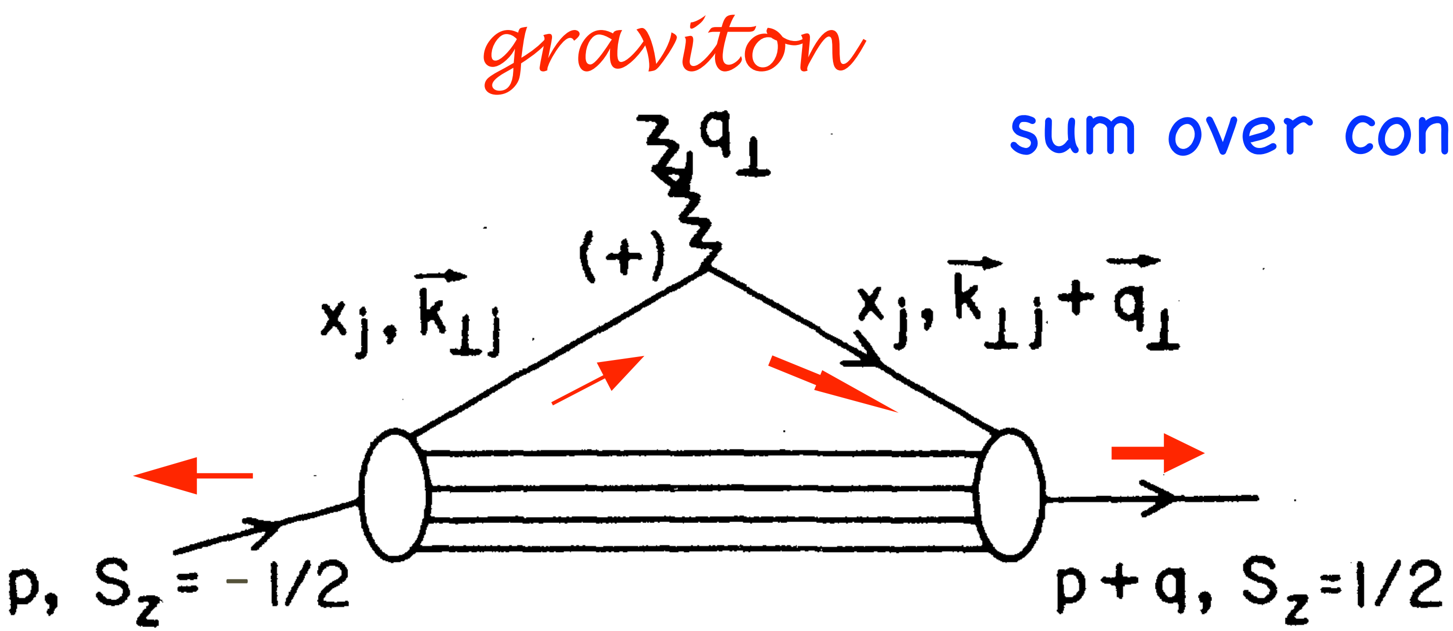


Must have $\Delta\ell_z = \pm 1$ to have nonzero $F_2(q^2)$

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

Anomalous gravitomagnetic moment B(0)

Okun et al: *B(0) Must vanish because of Equivalence Theorem*



Hwang, Schmidt, sjb; Holstein et al

B(0) = 0

Each Fock State

Anomalous gravitomagnetic moment B(0)

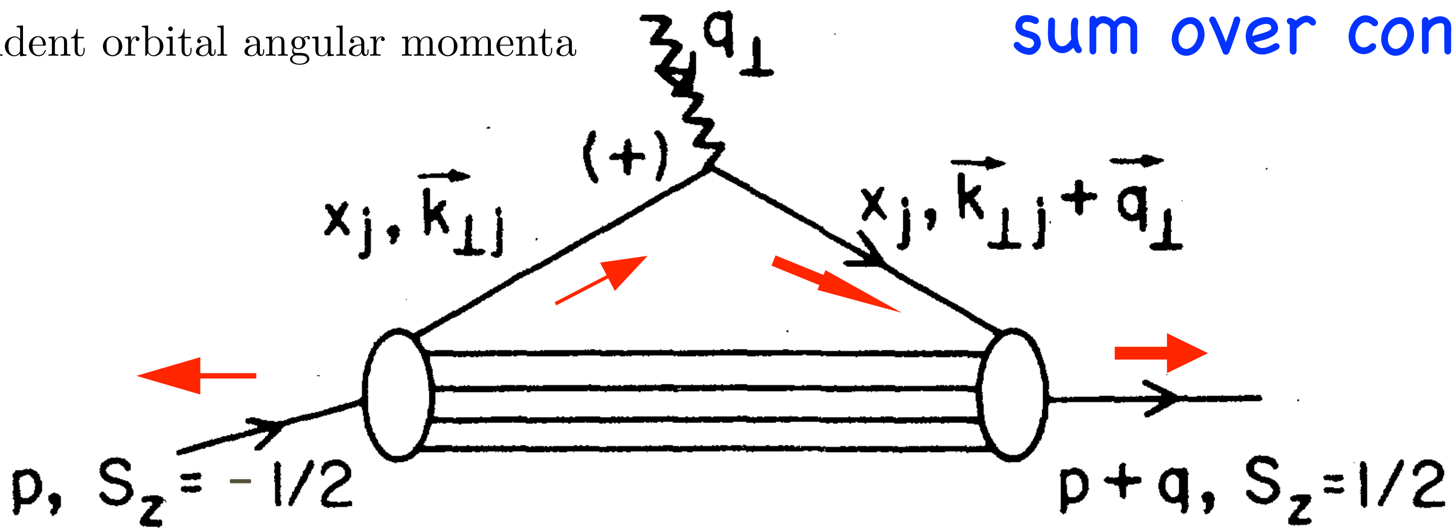
Okun et al: *B(0) Must vanish because of Equivalence Theorem*

graviton

$\sum_{i=1}^{n} L_i = 0$

$n - 1$ independent orbital angular momenta

sum over constituents



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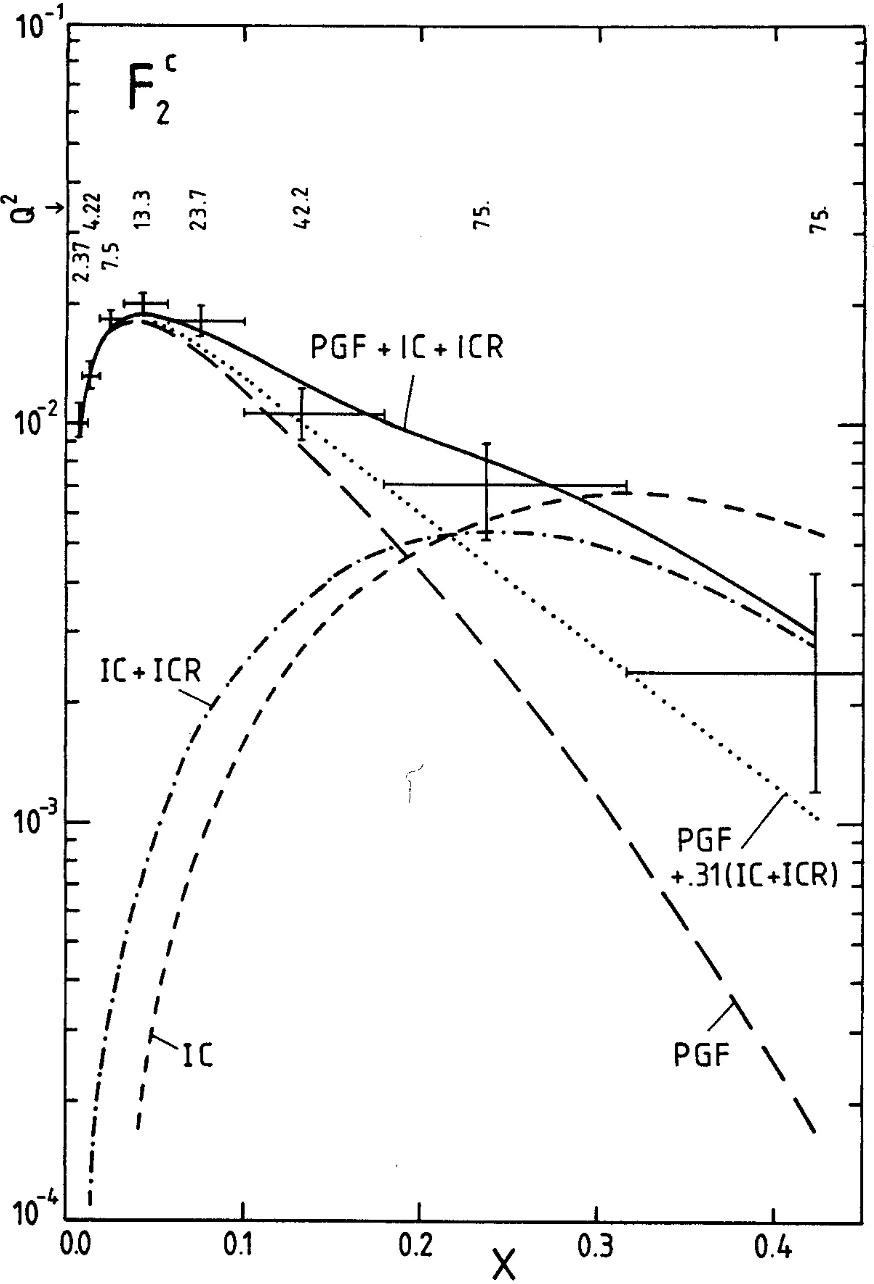

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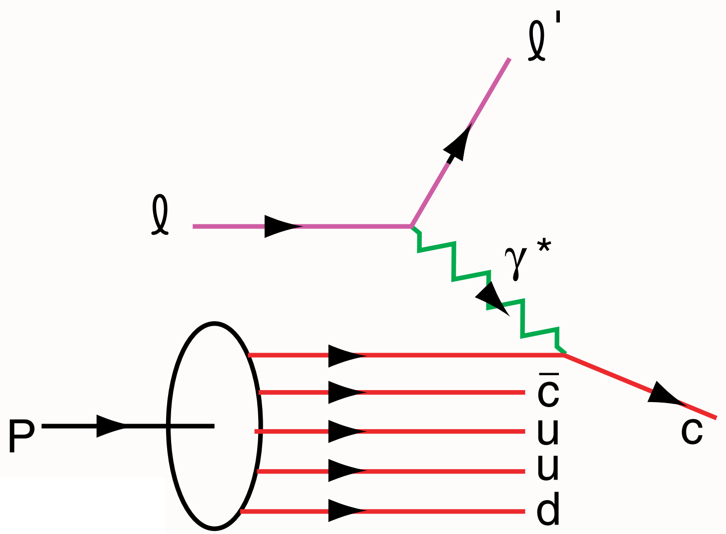

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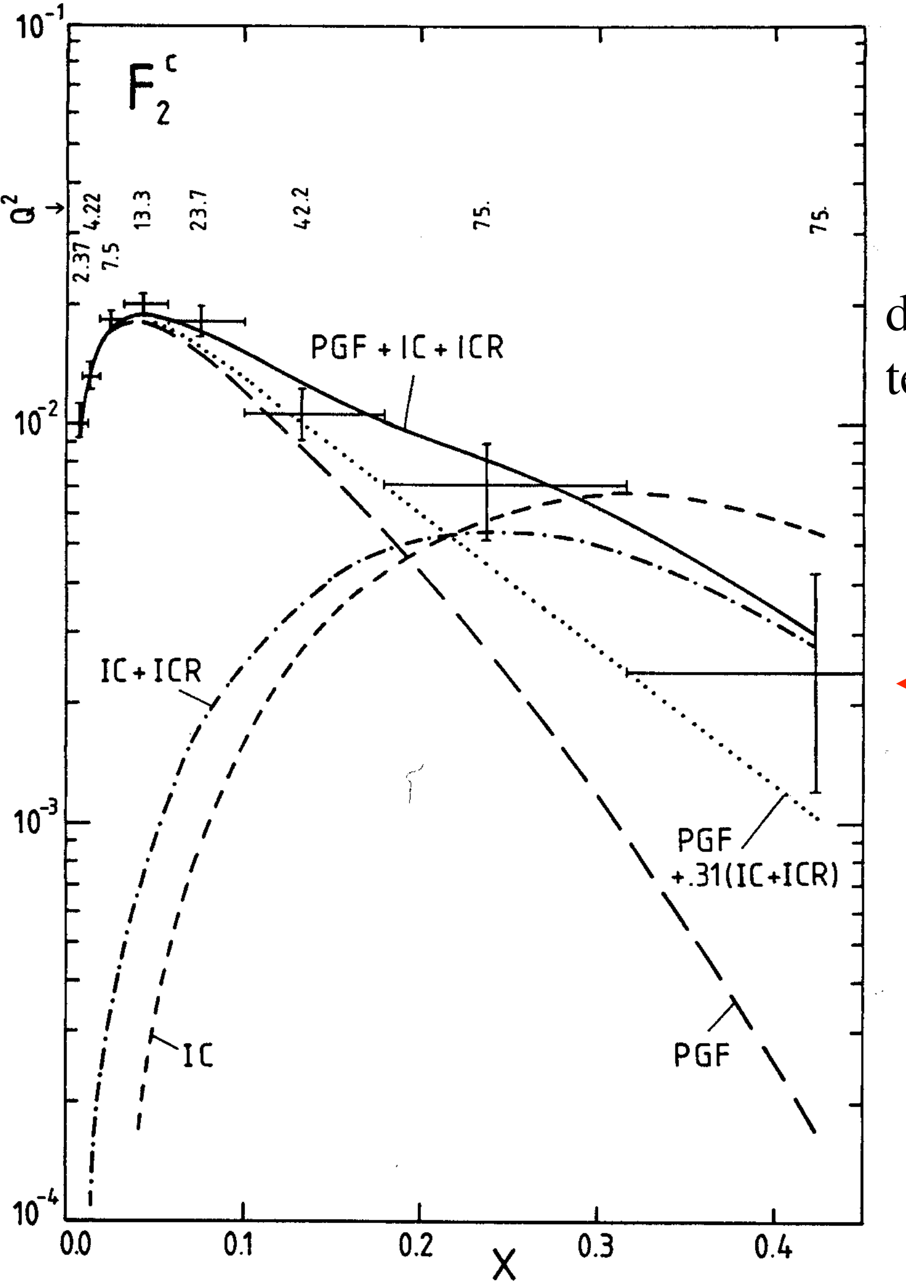

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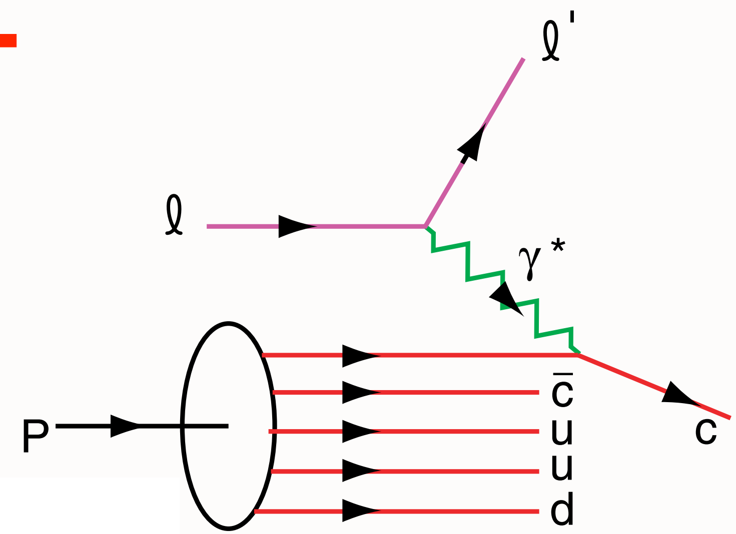

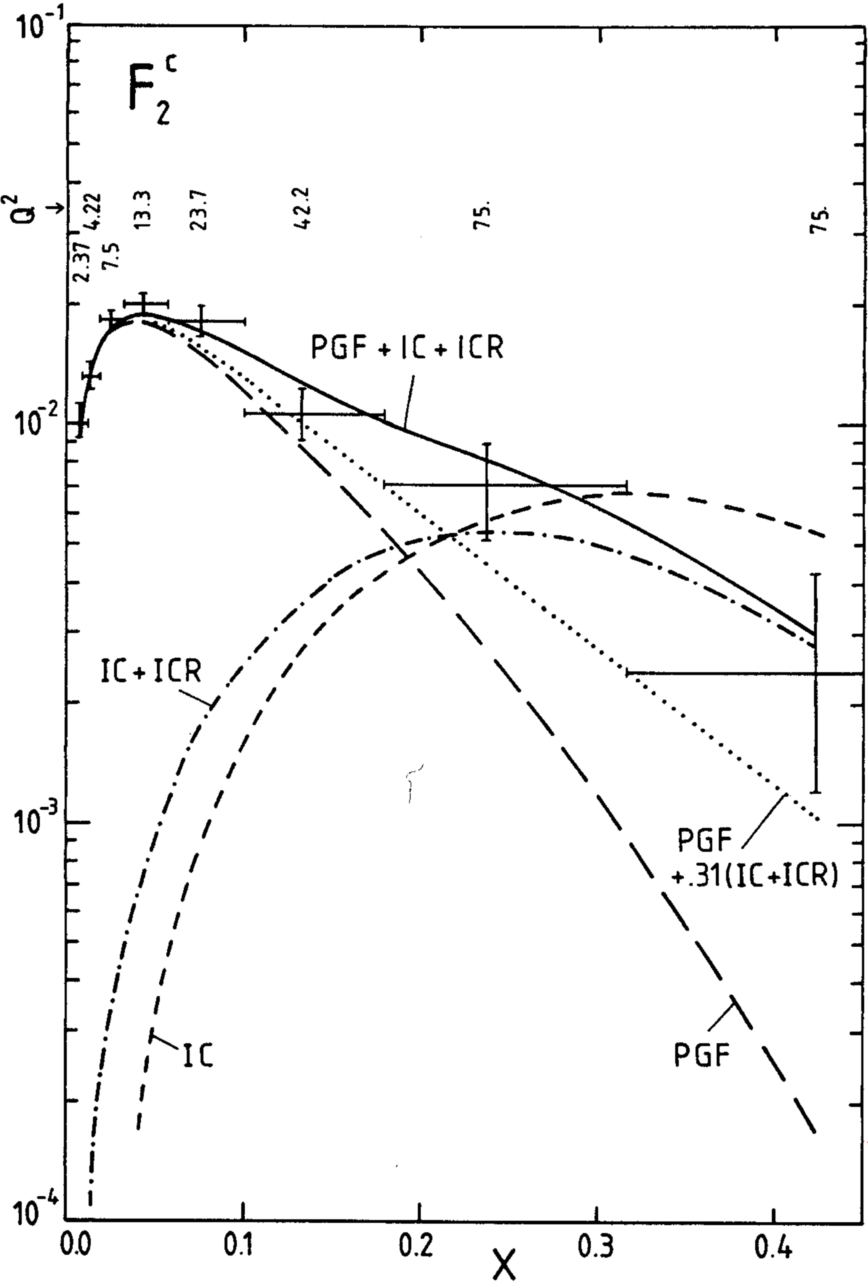

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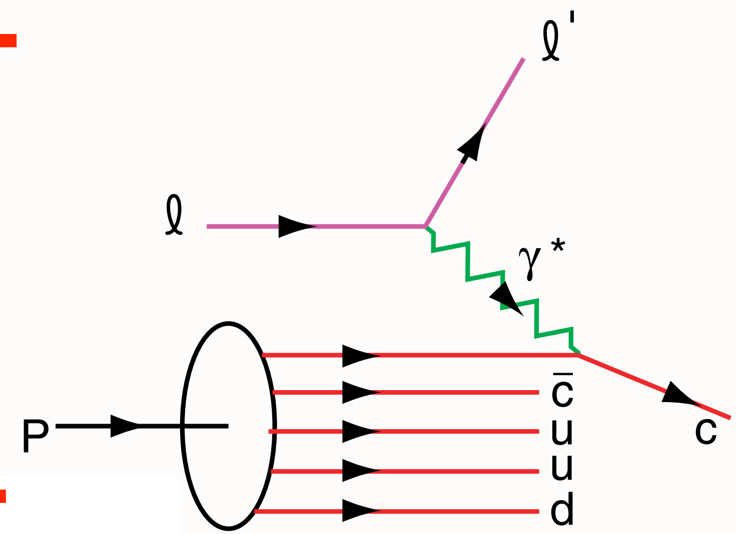

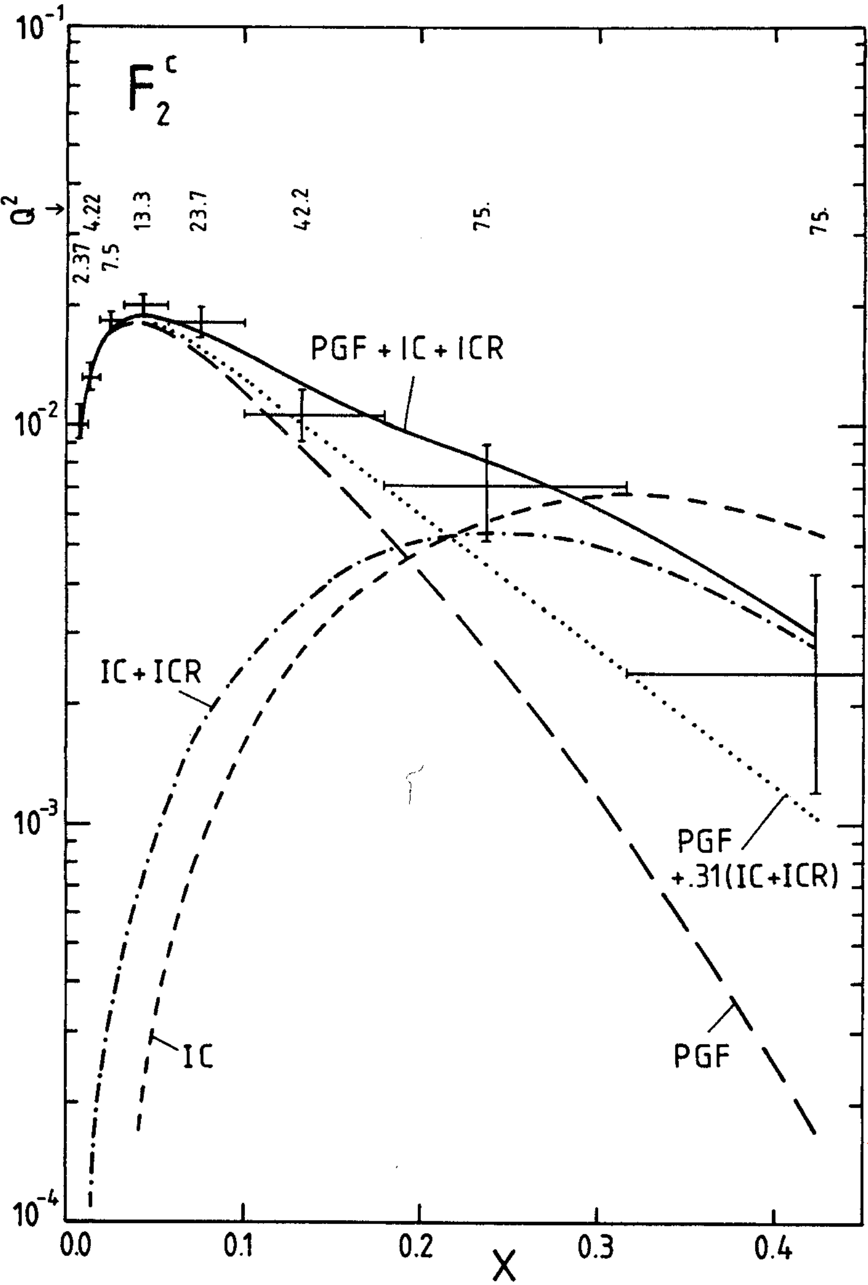

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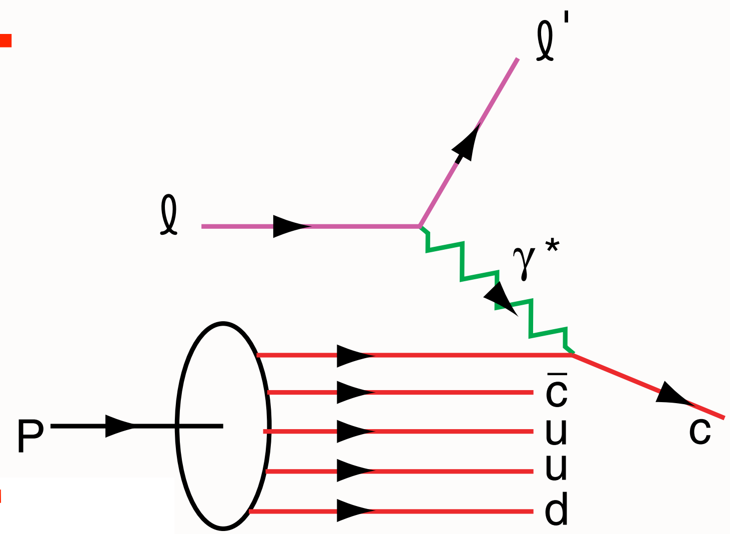

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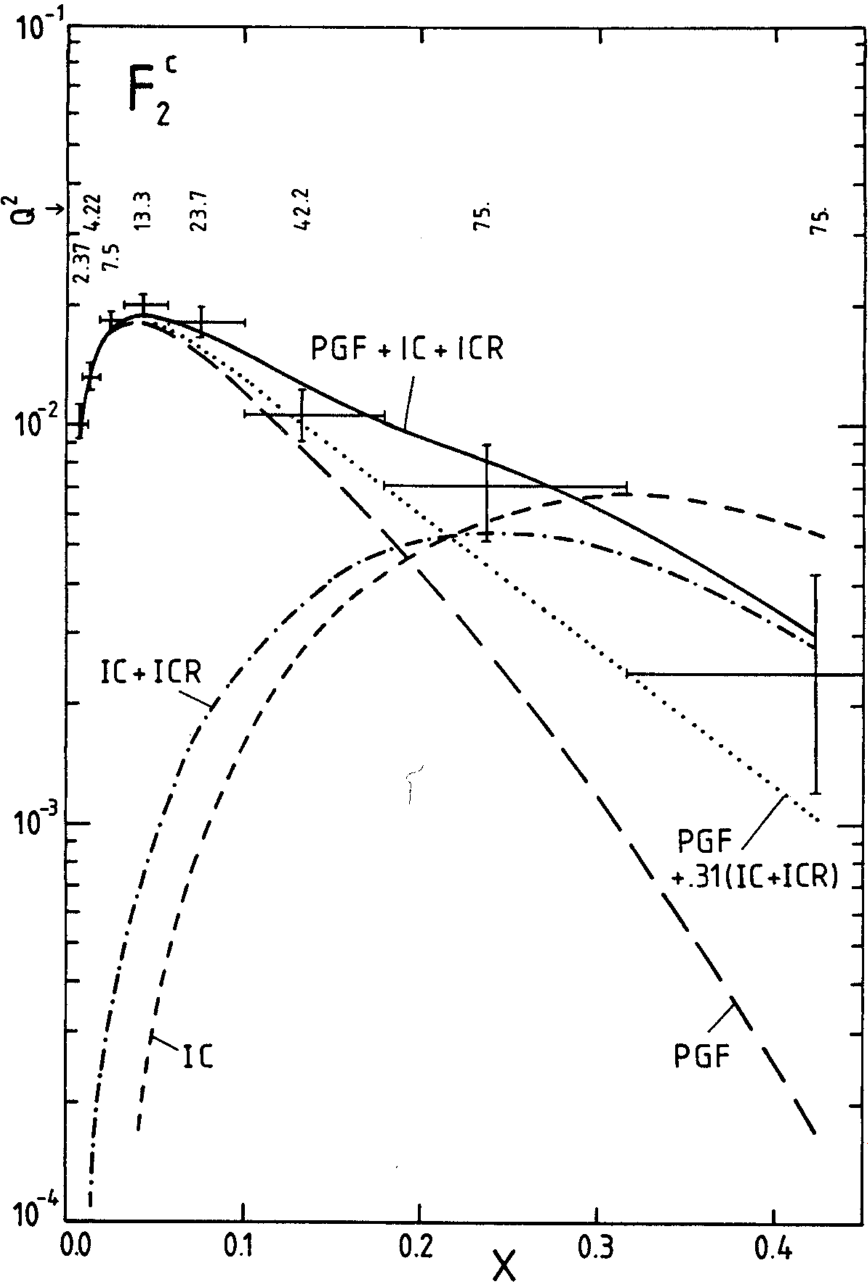

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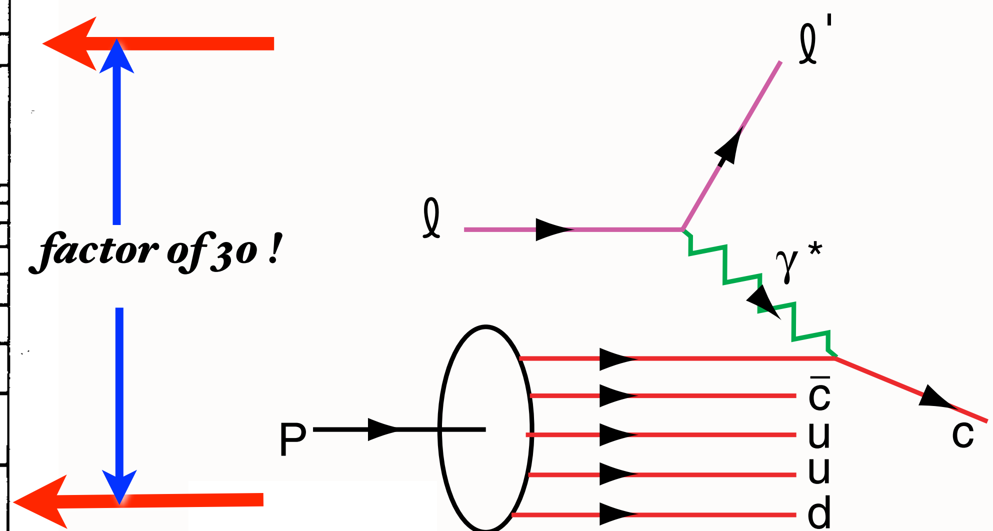

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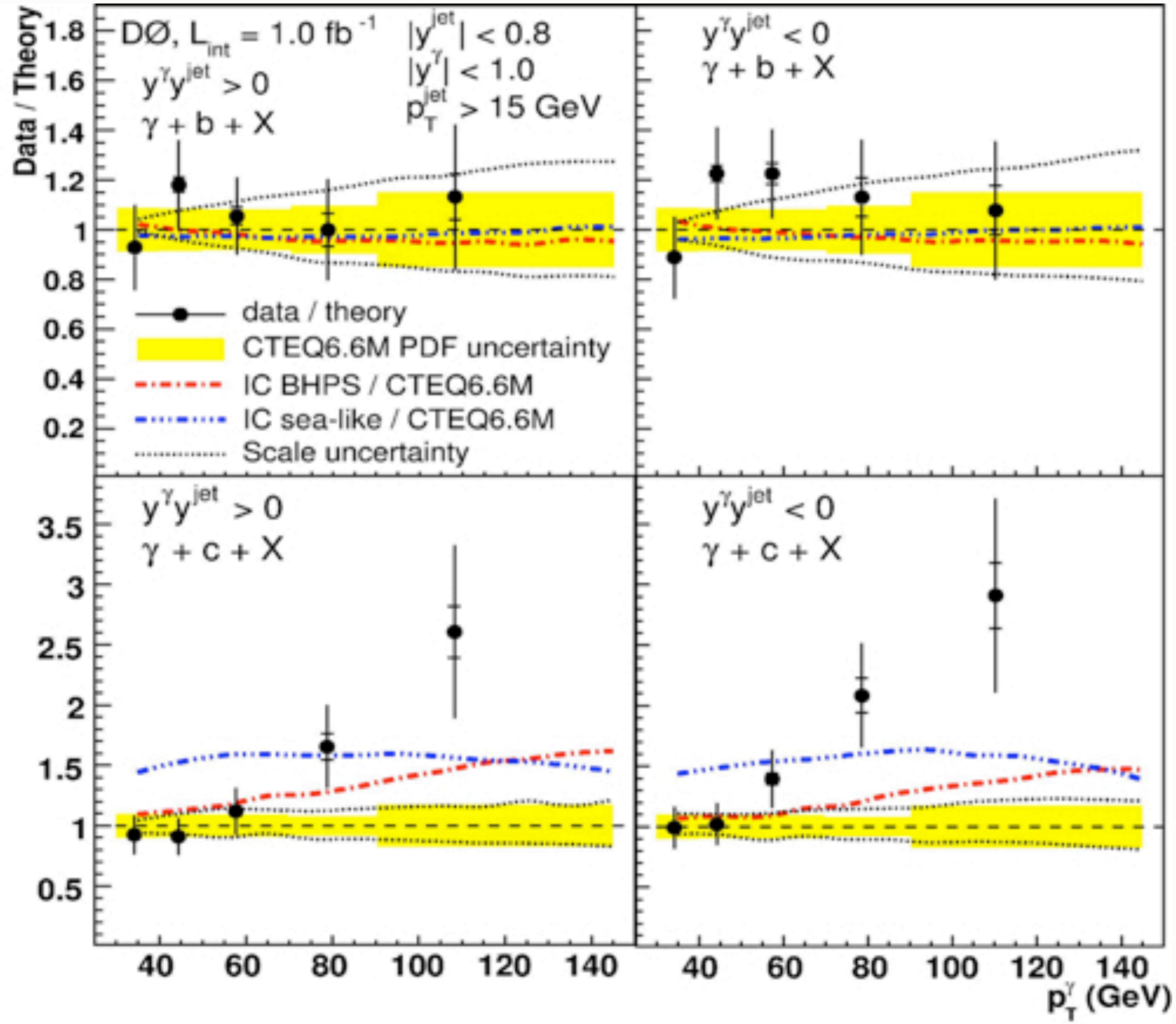
PRL 102, 192002 (2009) PHYSICAL REVIEW LETTERS week ending 15 MAY 2009

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 ?

DGLAP evolution issues?

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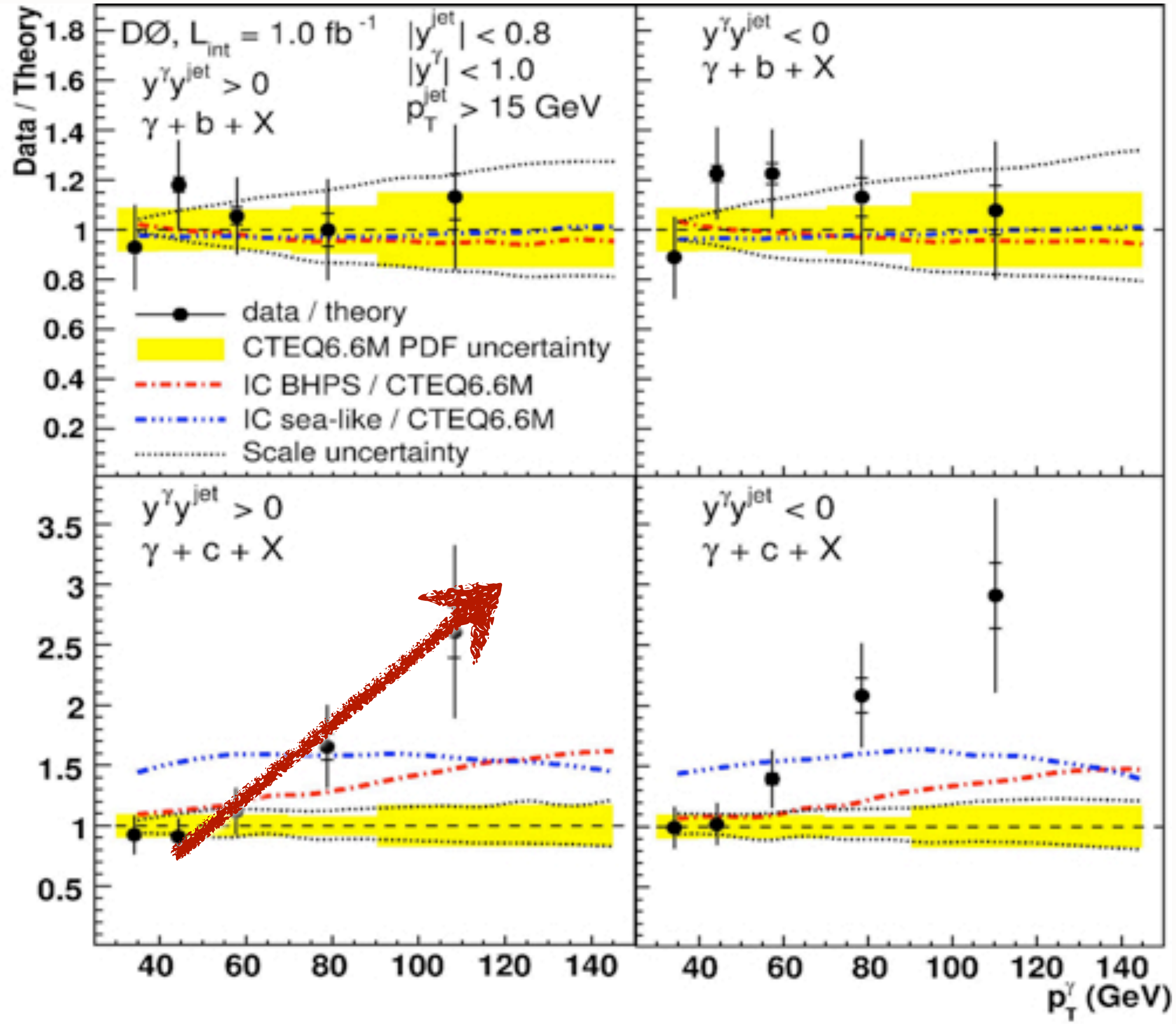

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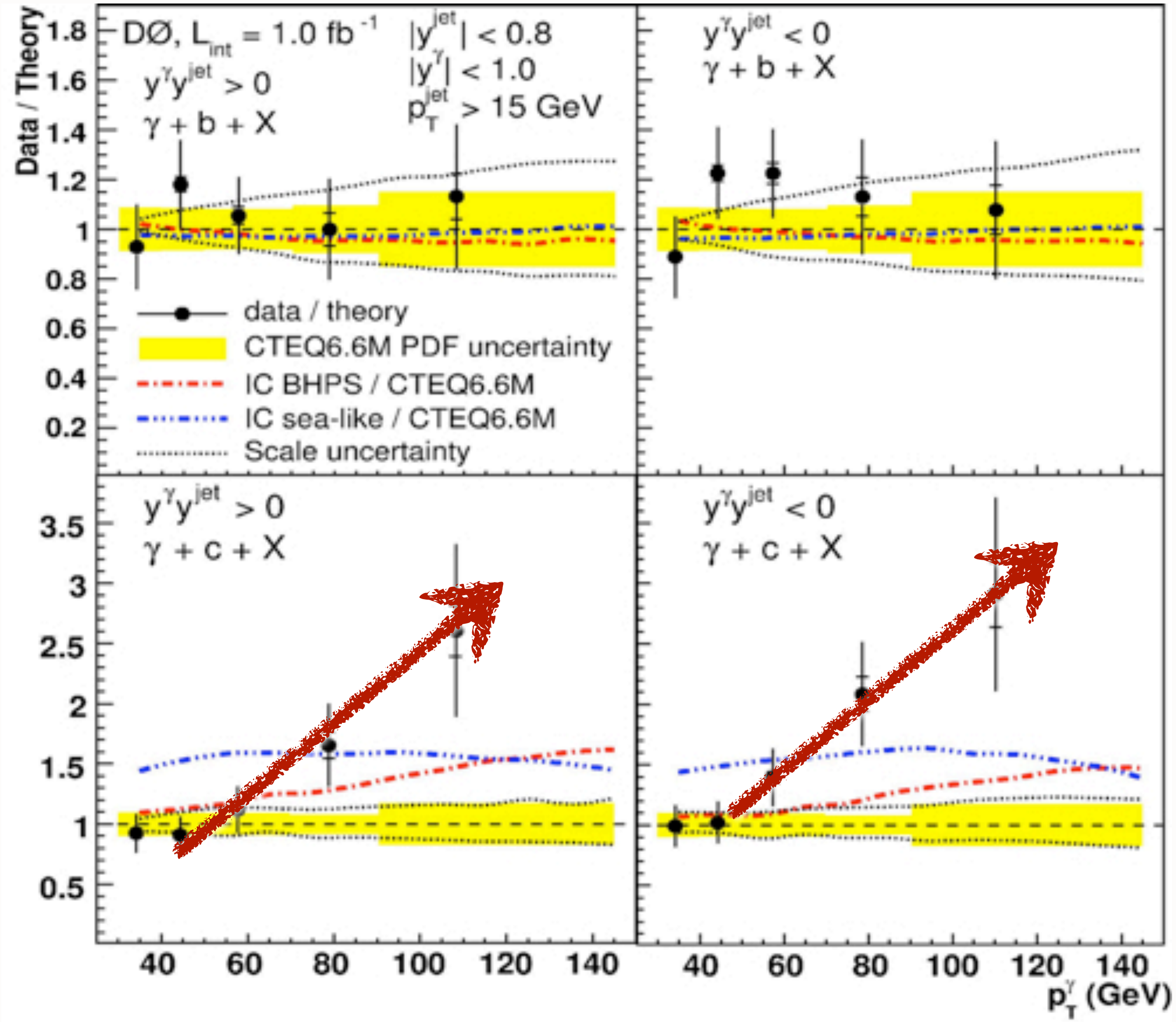

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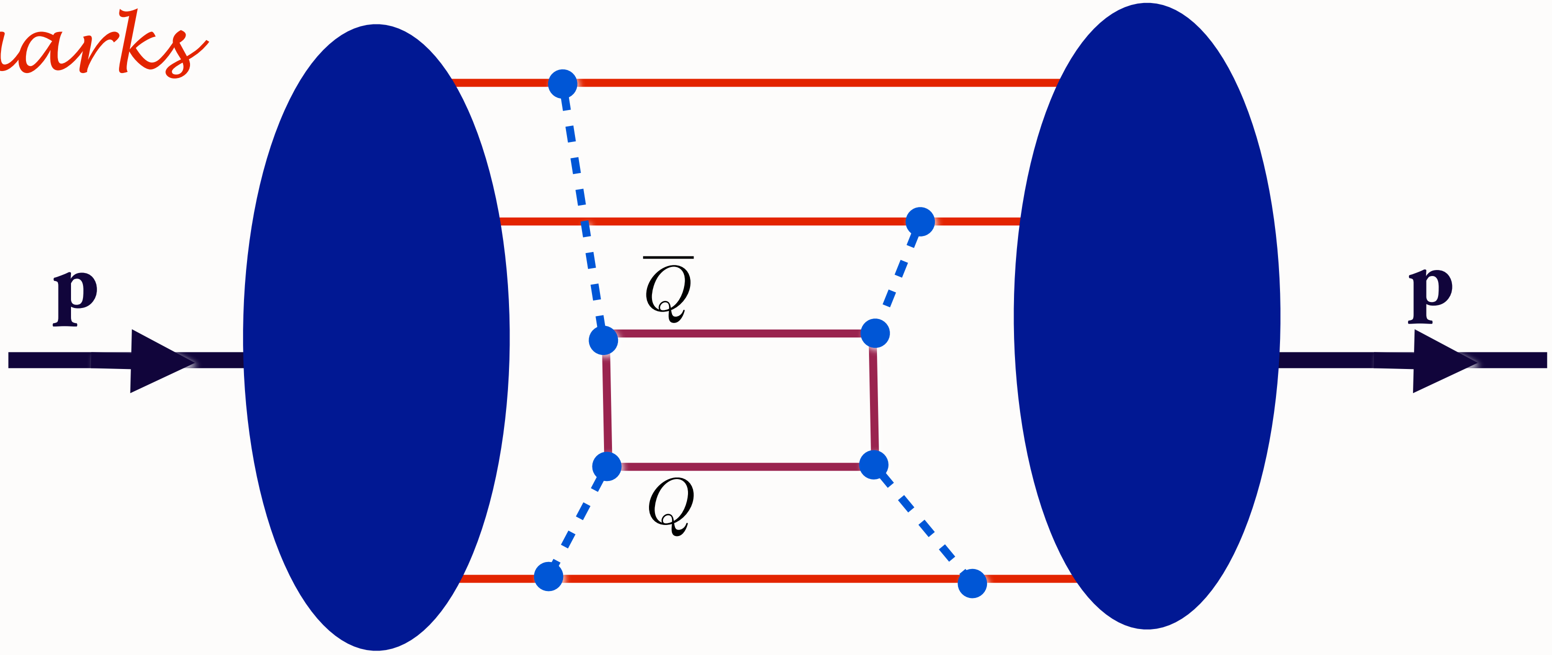
Proton Self Energy Intrinsic Heavy Quarks

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



Probability (QED) $\propto \frac{1}{M_\ell^4}$ Probability (QCD) $\propto \frac{1}{M_Q^2}$

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

Proton Self Energy
Intrinsic Heavy
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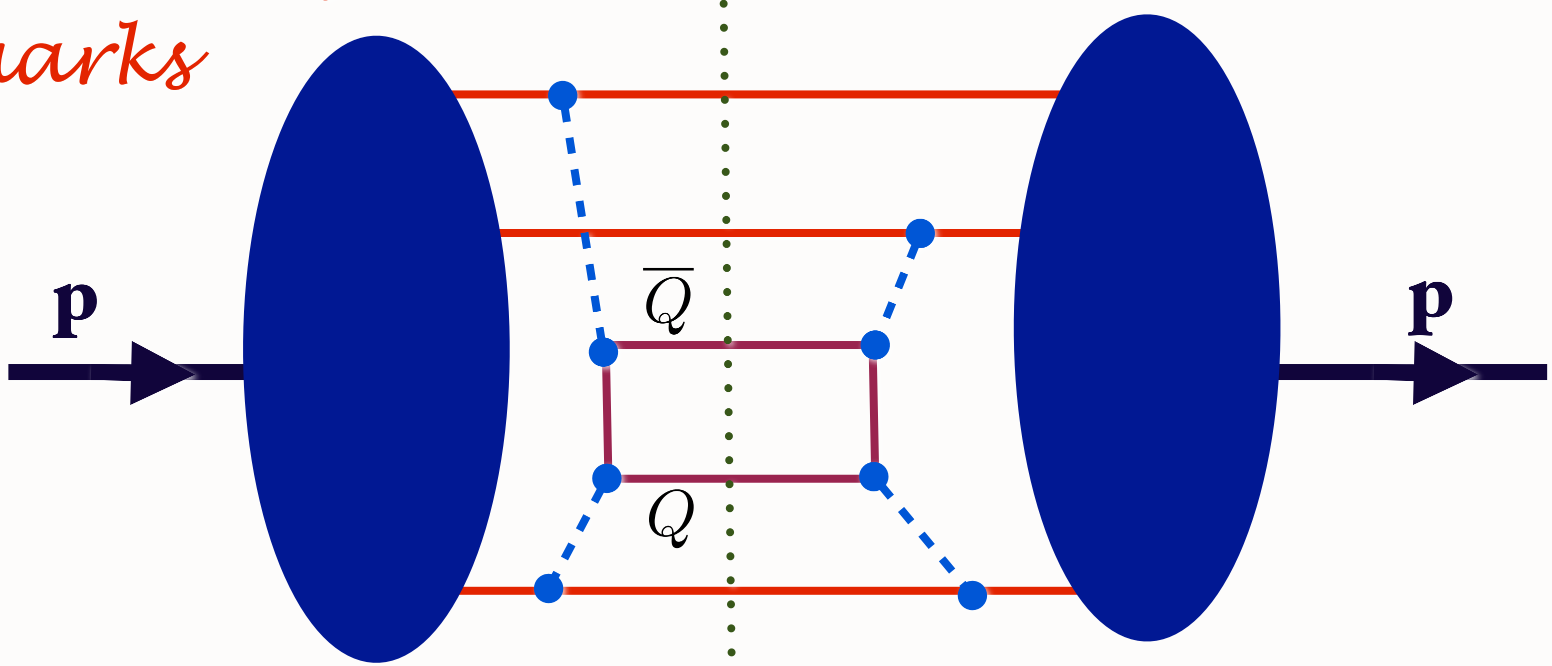

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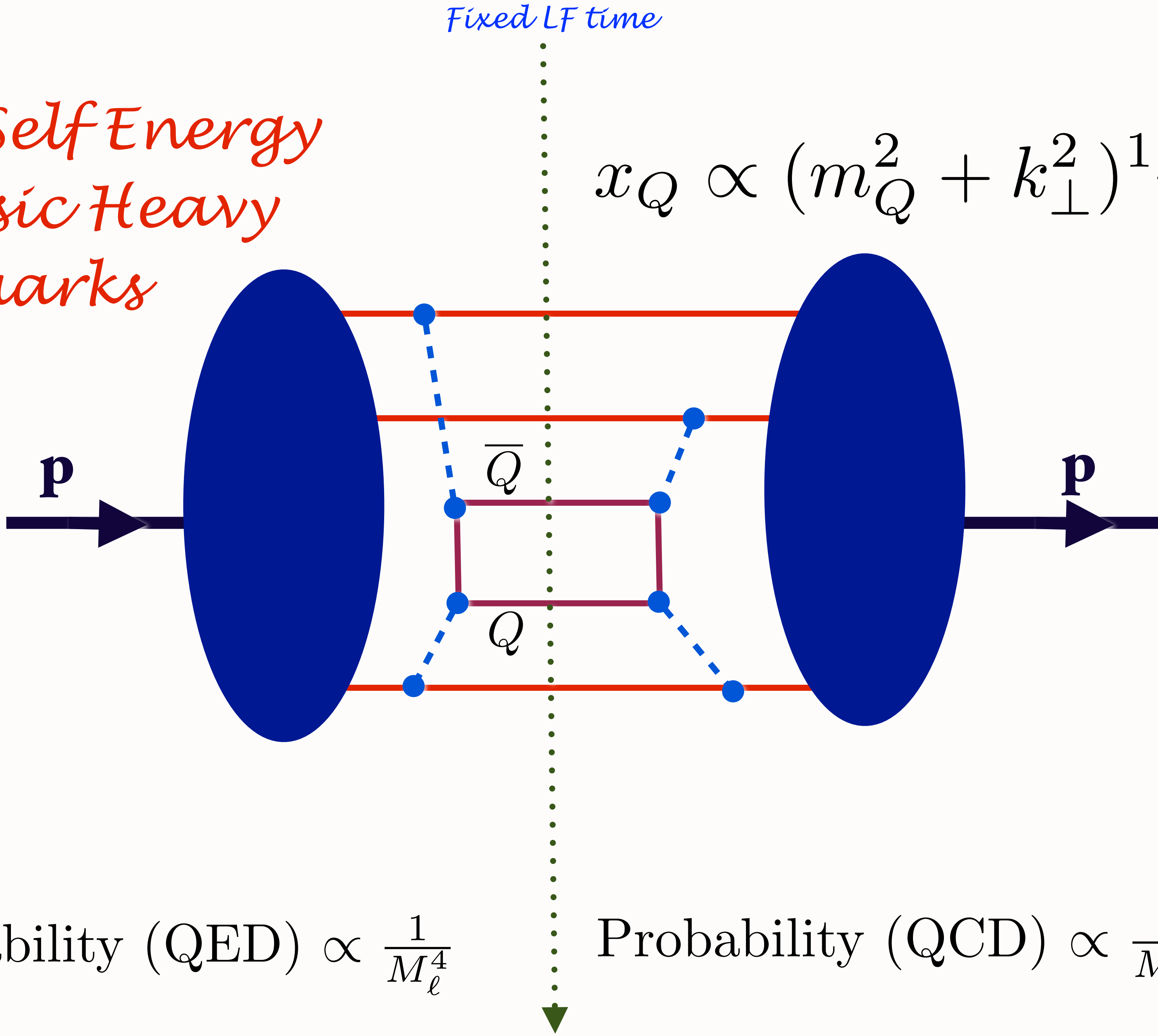

Probability (QED) $\propto \frac{1}{M_\ell^4}$

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

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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

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

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

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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

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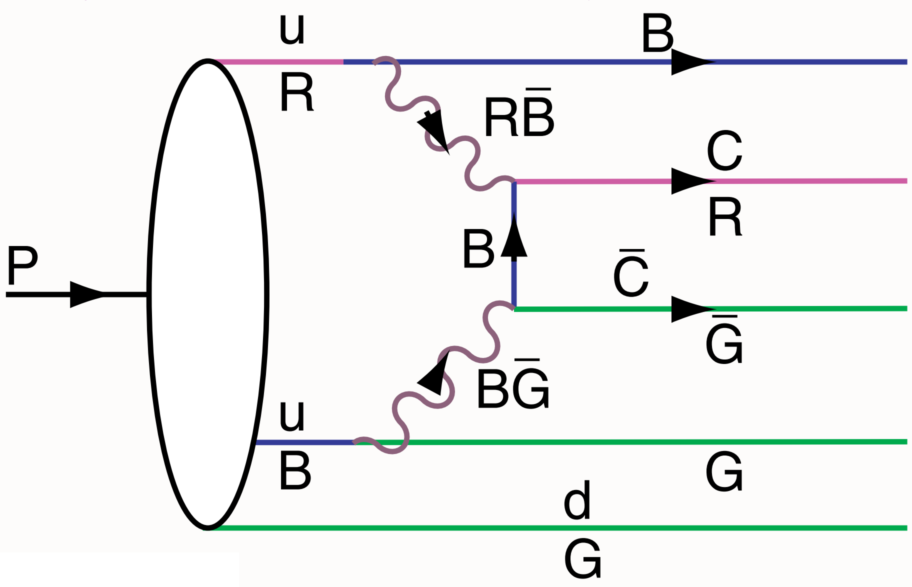
Abstract: We review the technique of heavy quark mass expansion of various operators made of heavy quark fields using a semiclassical approximation. It corresponds to an operator product expansion in the form of series in the inverse heavy quark mass. This technique applied recently to the axial current 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.

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

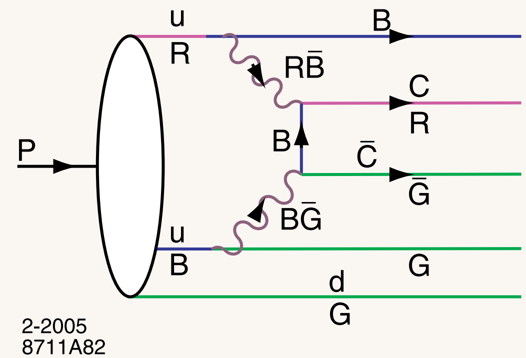
$$\hat{x}_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

High x charm! *Charm at Threshold*

Action Principle: Minimum KE, maximal potential

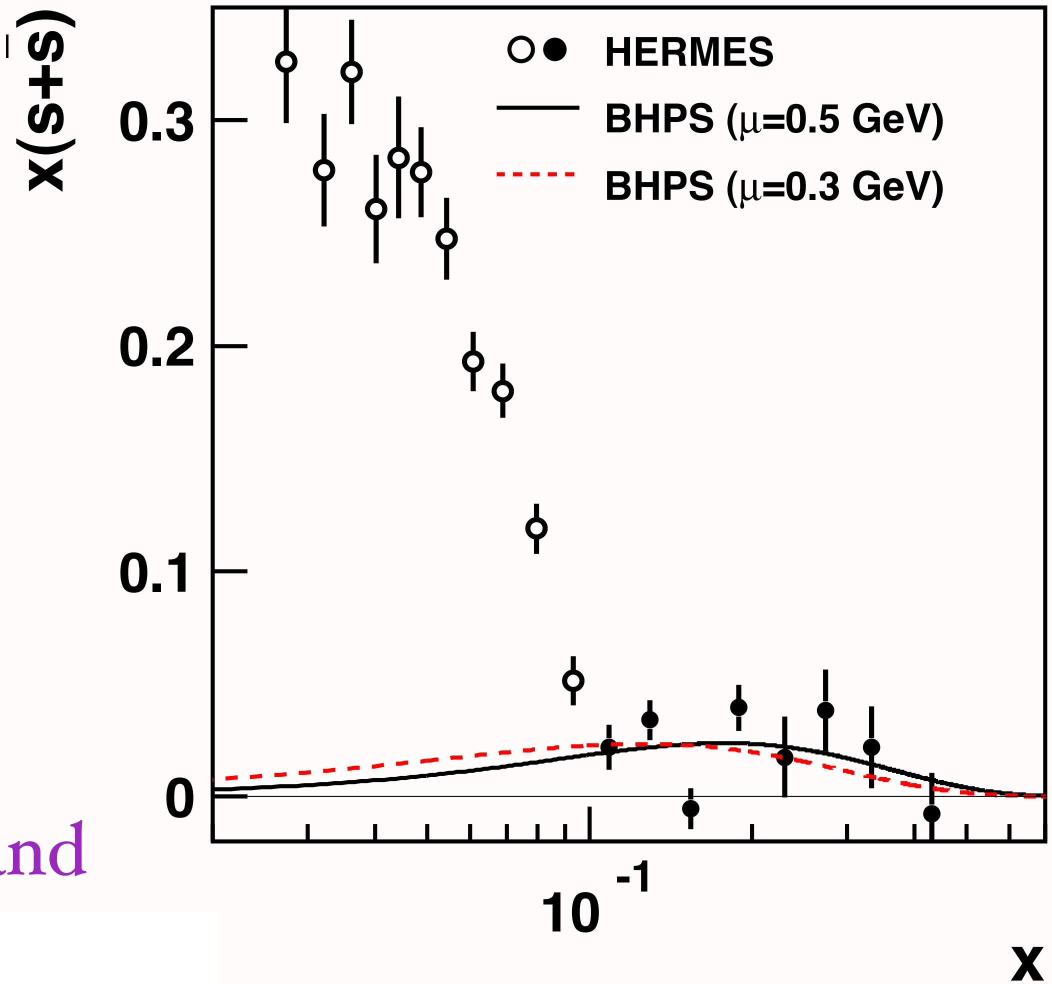
Hoyer, Peterson, Sakai, sjb

Intrinsic Heavy-Quark Fock States

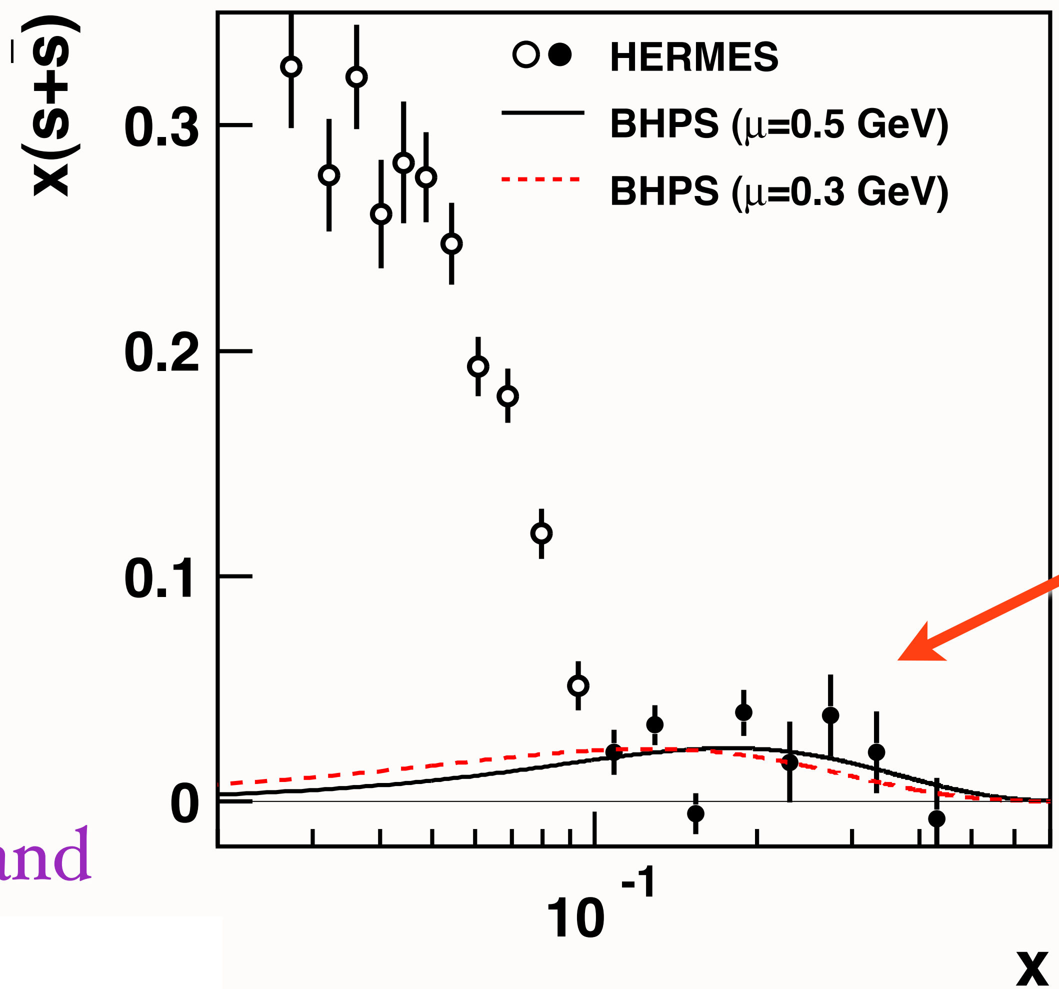


- ***Rigorous*** prediction of QCD, OPE
- Color-Octet Color-Octet Fock State!
- Probability $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- Large Effect at high x
- Greatly increases kinematics of colliders such as Higgs production (Kopeliovich, Schmidt, Soffer, sjb)
- Severely underestimated in conventional parameterizations of heavy quark distributions (Pumplin, Tung)
- Many empirical tests

W. C. Chang and J.-C. Peng



Comparison of the HERMES $x(s(x)+\bar{s}(x))$ data with the calculations based on the BHPS model. The solid and dashed curves are obtained by evolving the BHPS result to $Q^2 = 2.5$ GeV^2 using $\mu = 0.5$ GeV and $\mu = 0.3$ GeV, respectively. The normalizations of the calculations are adjusted to fit the data at $x > 0.1$ with statistical errors only, denoted by solid circles.



Intrinsic strangeness

W. C. Chang and J.-C. Peng

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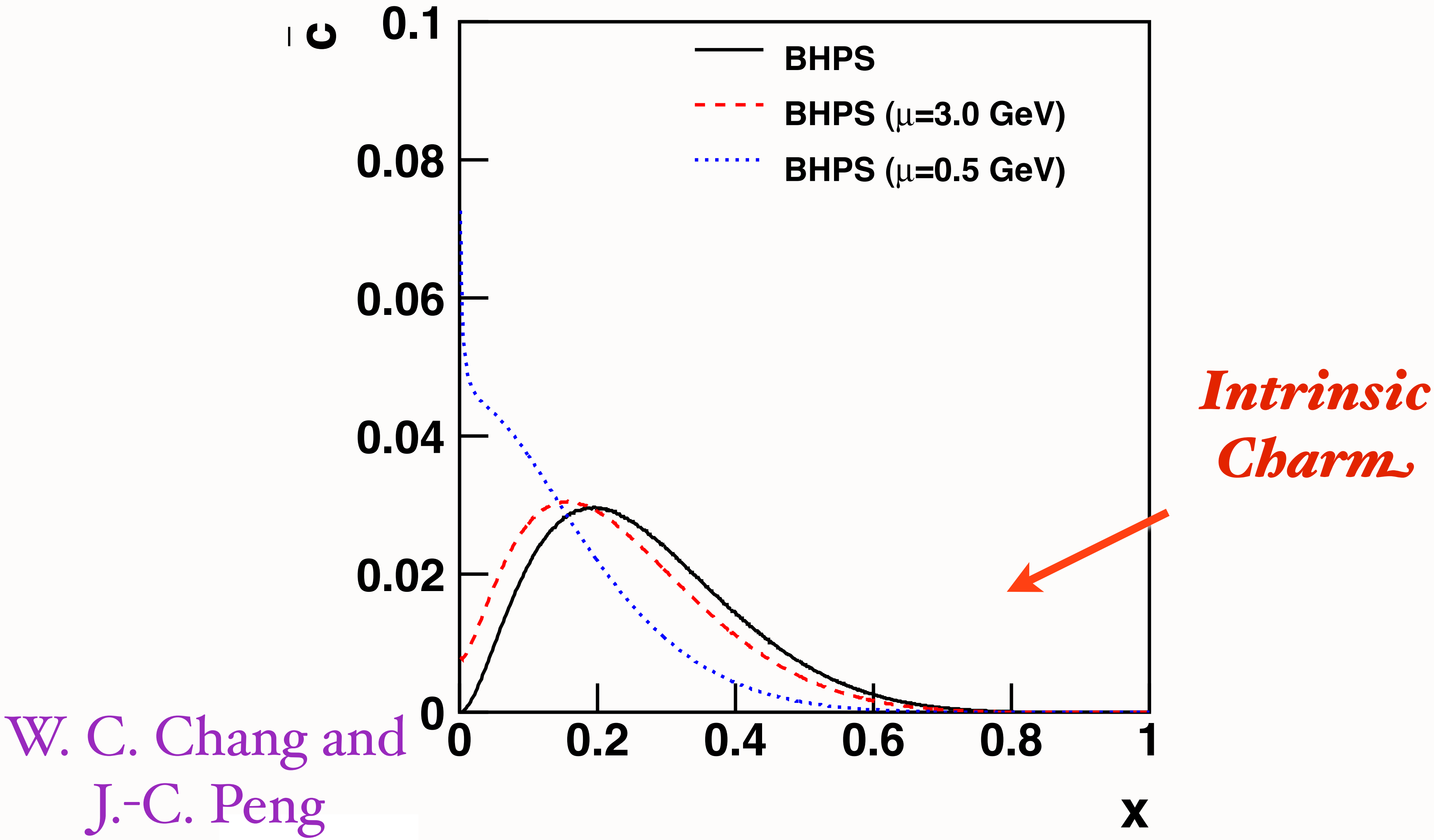
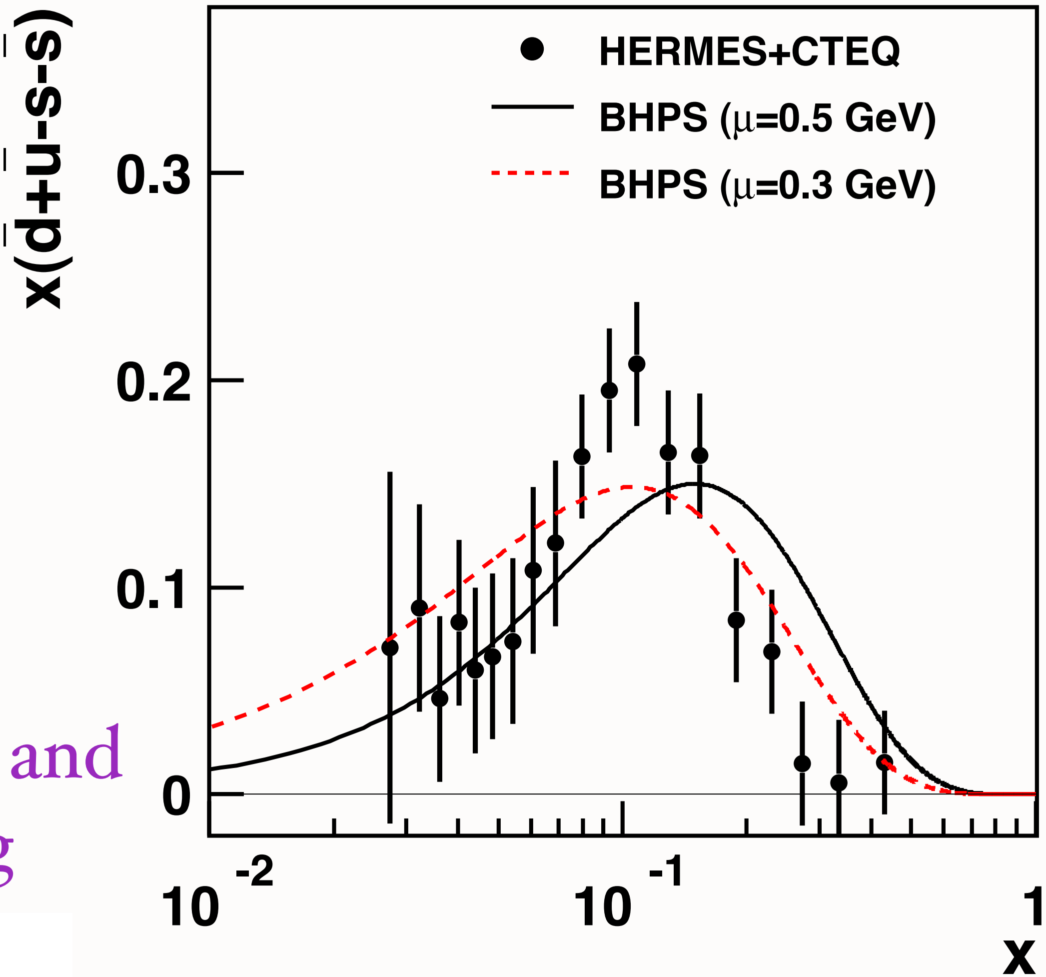


Calculations of the $\bar{c}(x)$ distributions based on the BHPS model. The solid curve corresponds to the calculation using Eq. 1 and the dashed and dotted curves are obtained by evolving the BHPS result to $Q^2 = 75$ GeV^2 using $\mu = 3.0$ GeV, and $\mu = 0.5$ GeV, respectively. The normalization is set at $\mathcal{P}_5^{c\bar{c}} = 0.01$.



W. C. Chang and J.-C. Peng

Comparison of the $x(\bar{d}(x)+\bar{u}(x)-s(x)-\bar{s}(x))$ data with the calculations based on the BHPS model. The values of $x(s(x)+\bar{s}(x))$ are from the HERMES experiment [6], and those of $x(\bar{d}(x)+\bar{u}(x))$ are obtained from the PDF set CTEQ6.6 [11]. The solid and dashed curves are obtained by evolving the BHPS result to $Q^2 = 2.5$ GeV^2 using $\mu = 0.5$ GeV and $\mu = 0.3$ GeV, respectively. The normalization of the calculations are adjusted to fit the data.

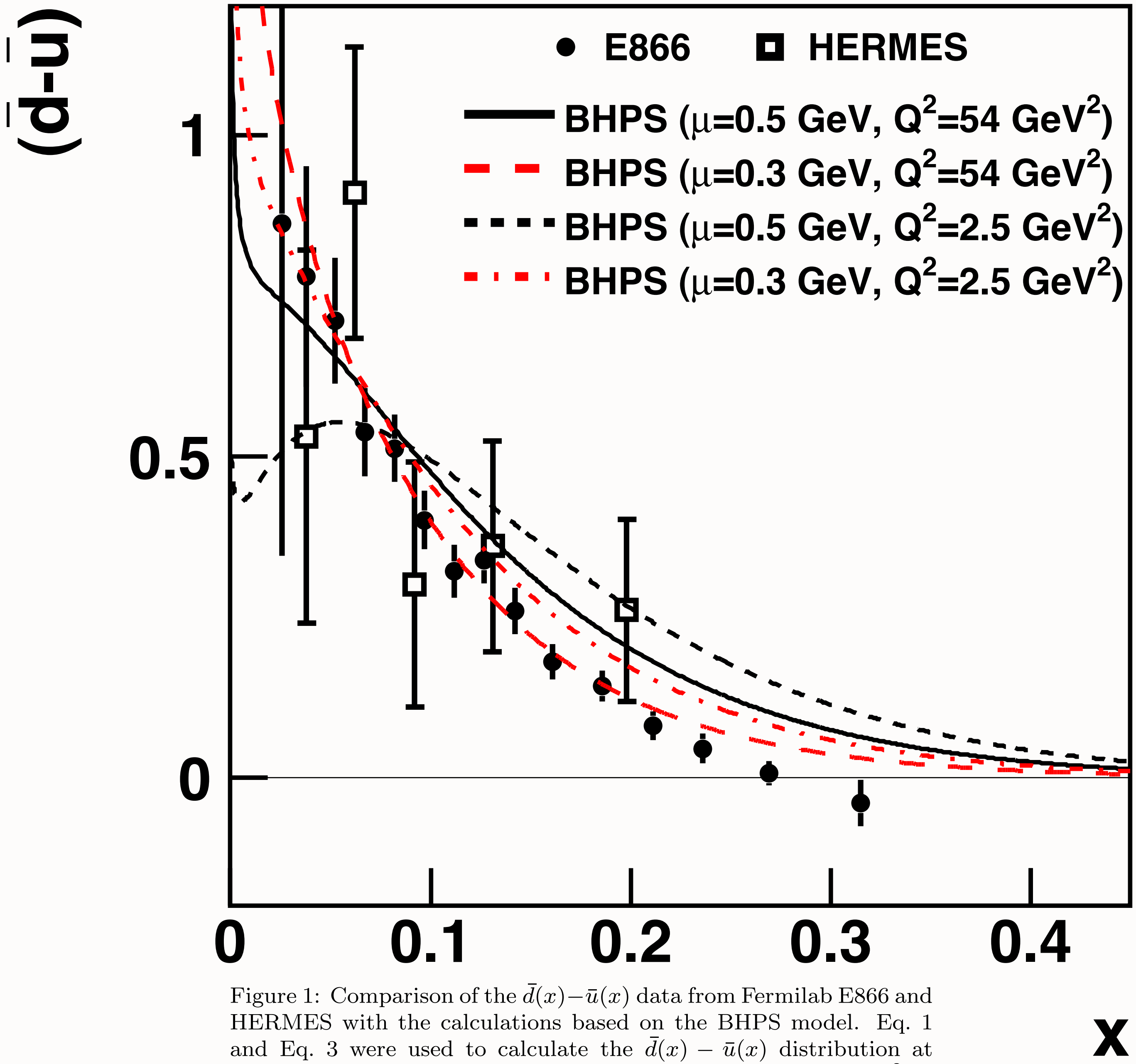
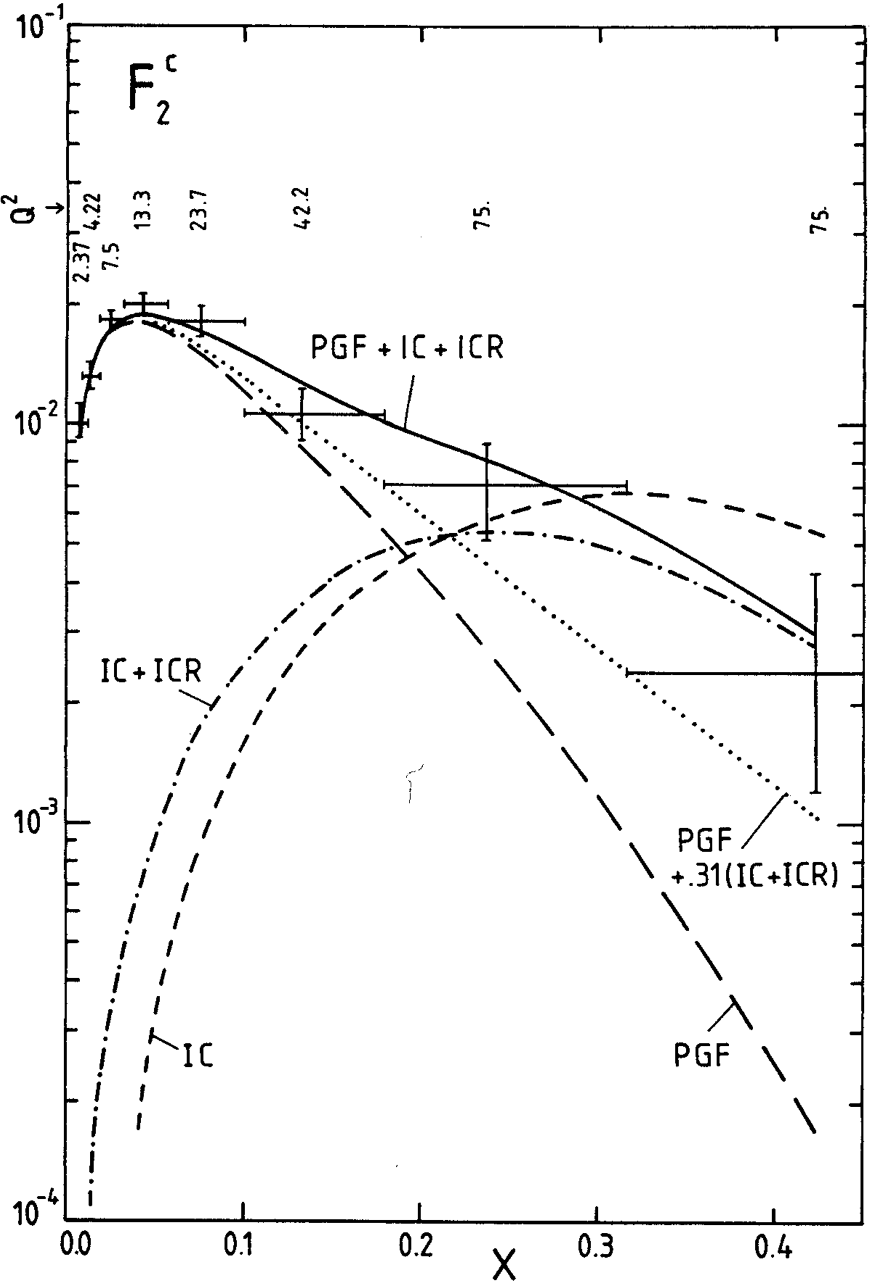


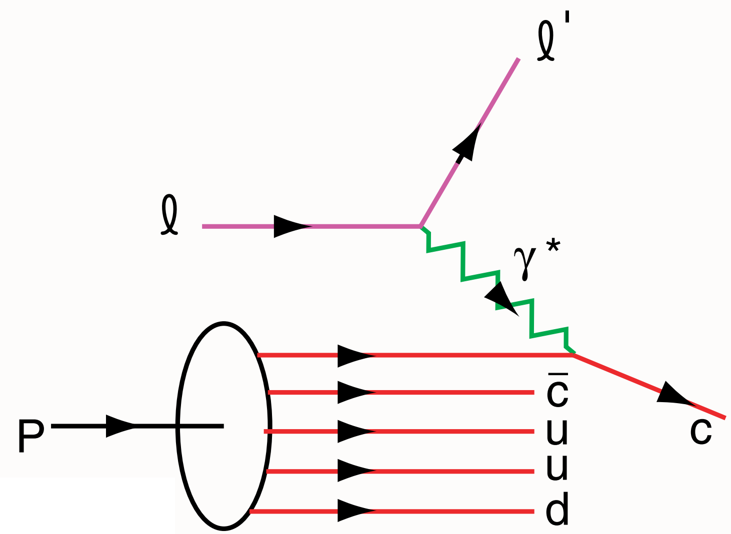
Figure 1: Comparison of the $\bar{d}(x) - \bar{u}(x)$ data from Fermilab E866 and HERMES with the calculations based on the BHPS model. Eq. 1 and Eq. 3 were used to calculate the $\bar{d}(x) - \bar{u}(x)$ distribution at the initial scale. The distribution was then evolved to the Q^2 of the experiments and shown as various curves. Two different initial scales, $\mu = 0.5$ and 0.3 GeV, were used for the E866 calculations in order to illustrate the dependence on the choice of the initial scale.



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



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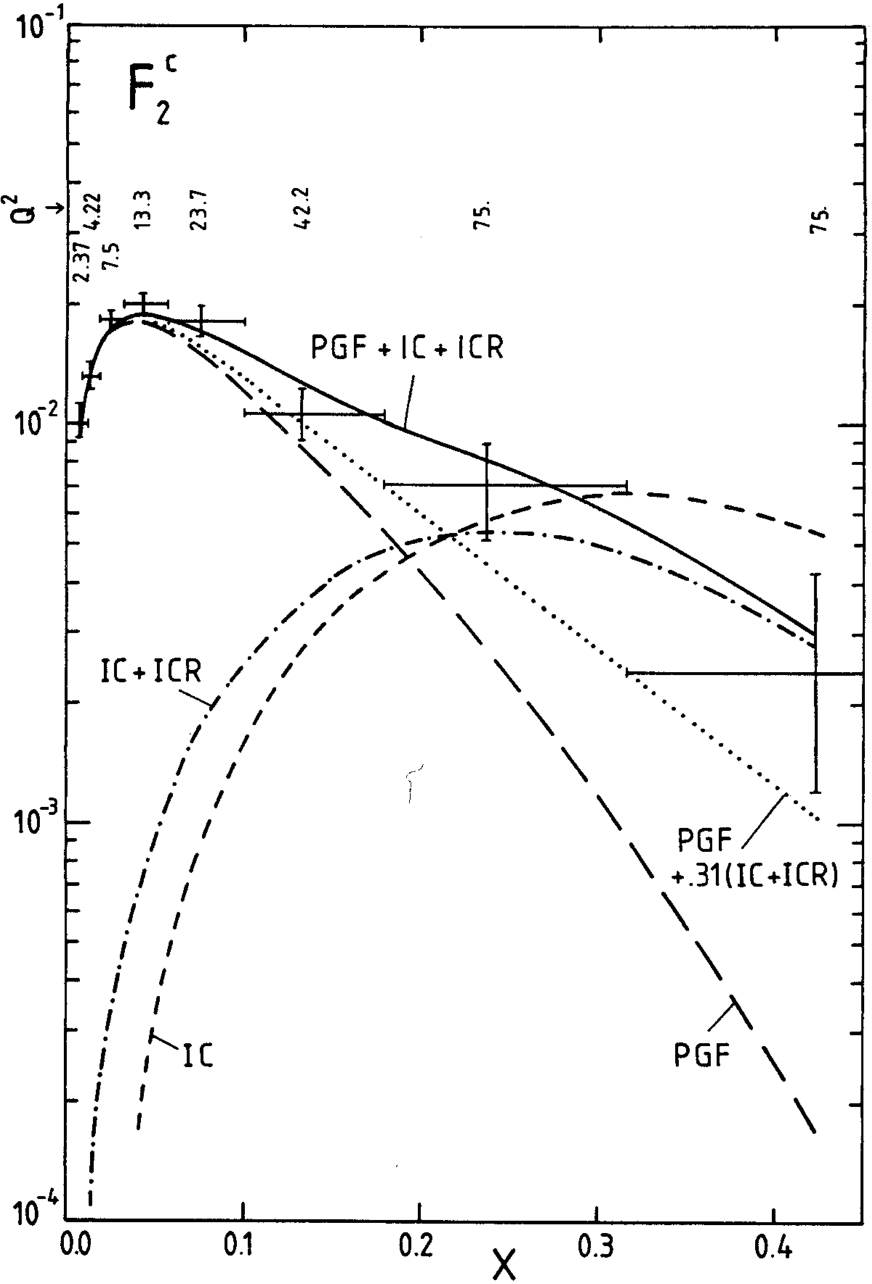

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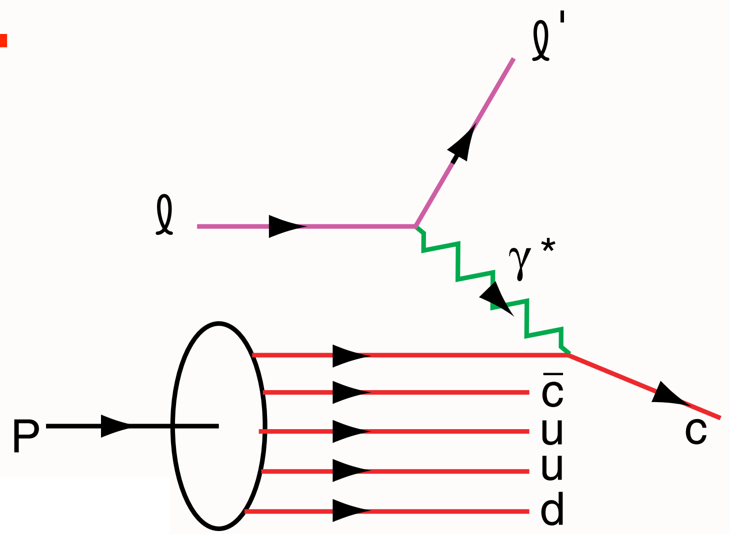

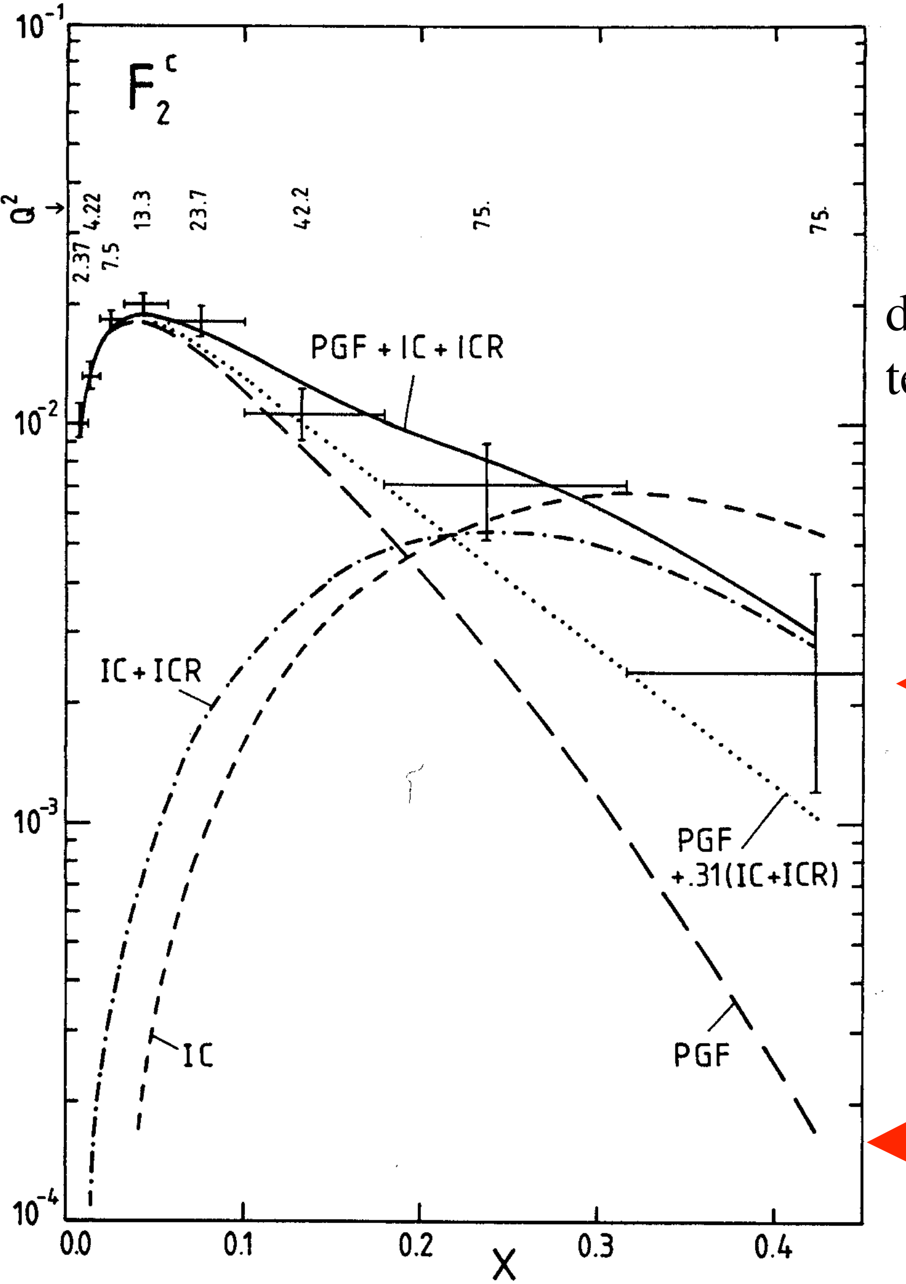

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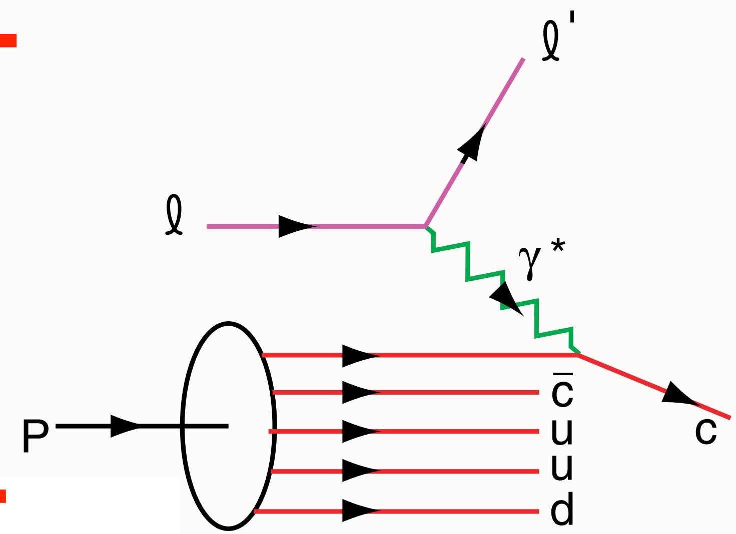
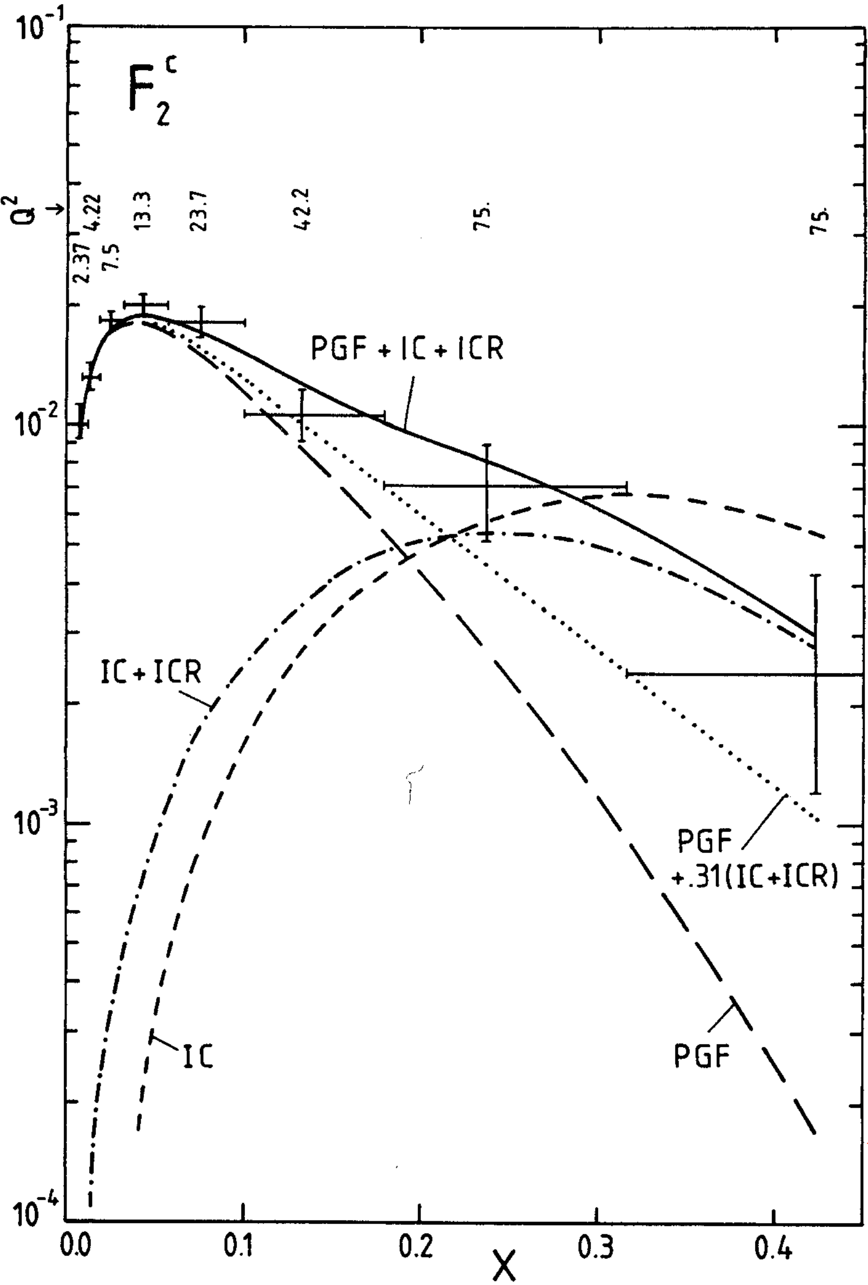


Measurement of Charm Structure Function



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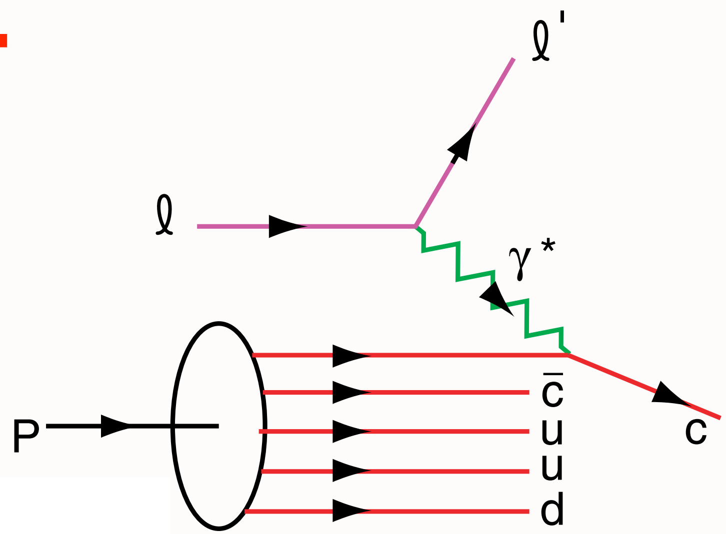

DGLAP / Photon-Gluon Fusion: factor of 30 too small

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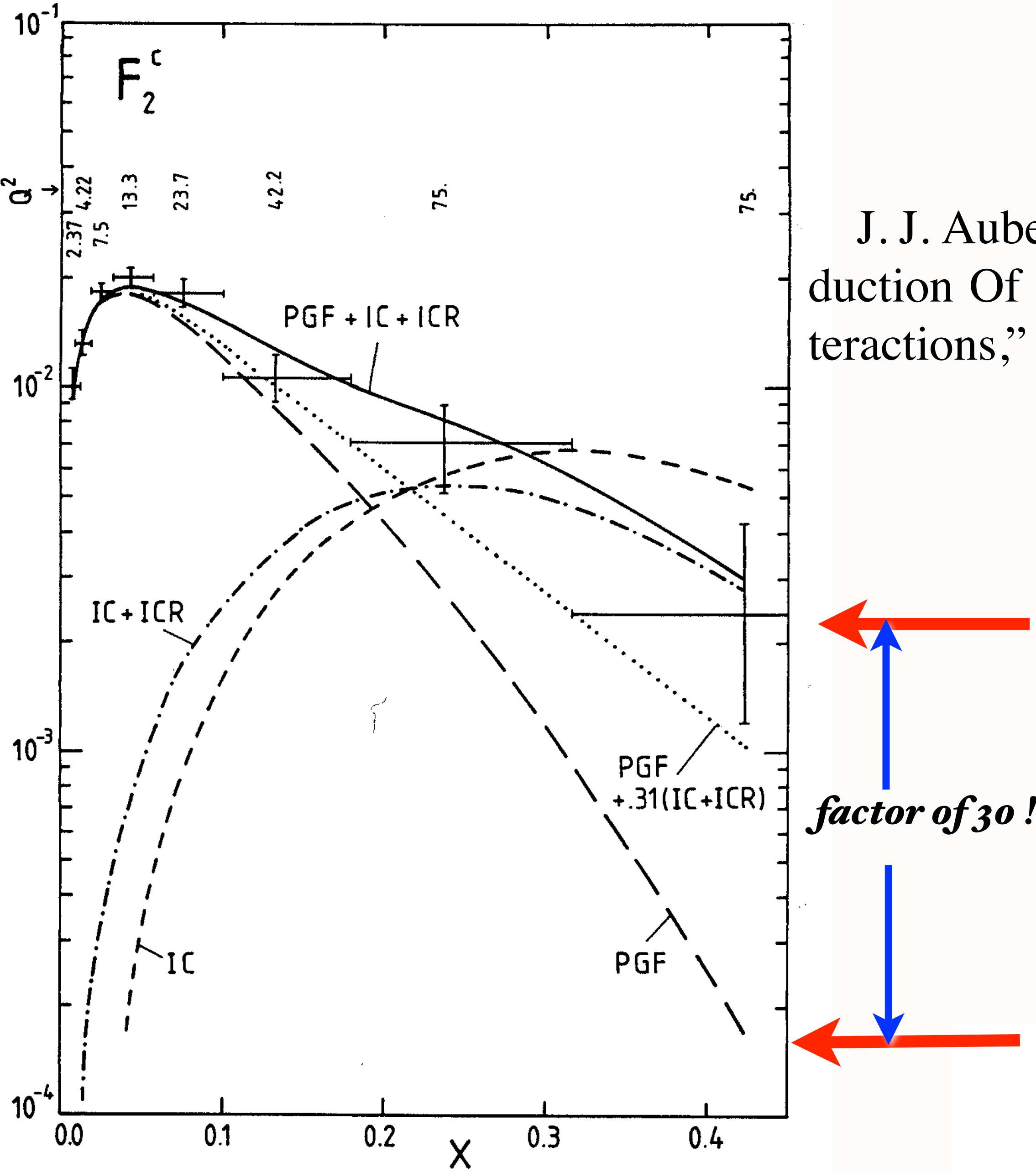
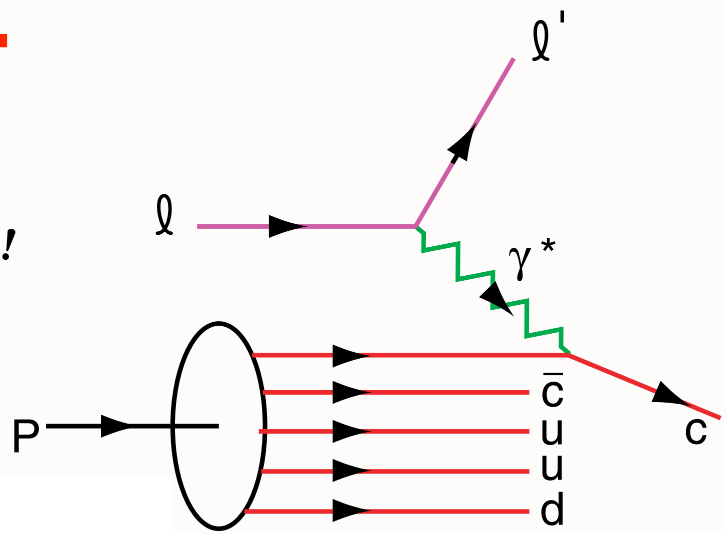


First Evidence for Intrinsic Charm



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 $pp \to J/\psi J/\psi X$

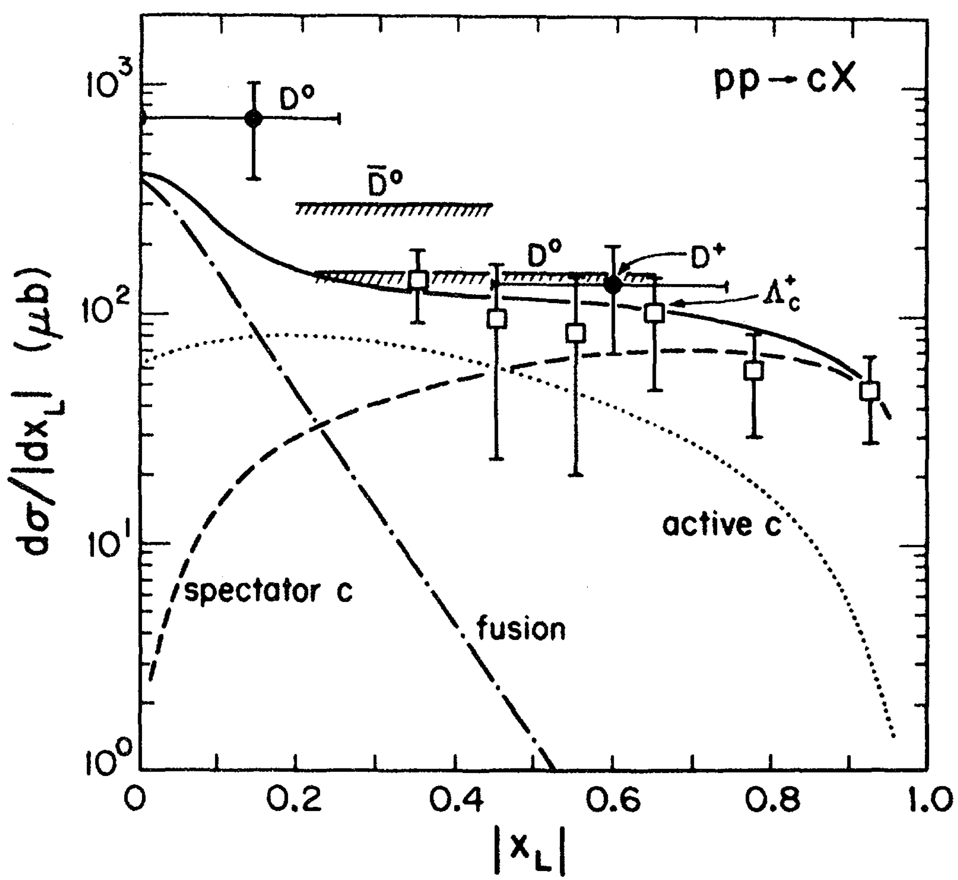
- High x_F $pp \to \Lambda_c X$

- High x_F $pp \to \Lambda_b X$

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

IC Structure Function: Critical Measurement for EIC

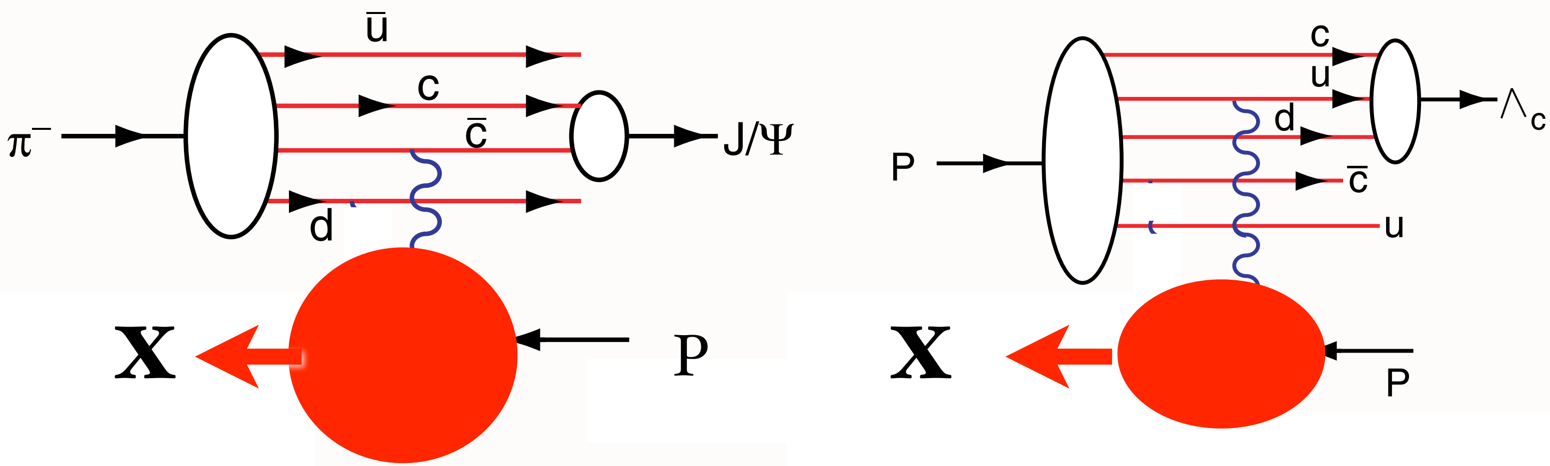
Many interesting spin, charge asymmetry, spectator effects



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).

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

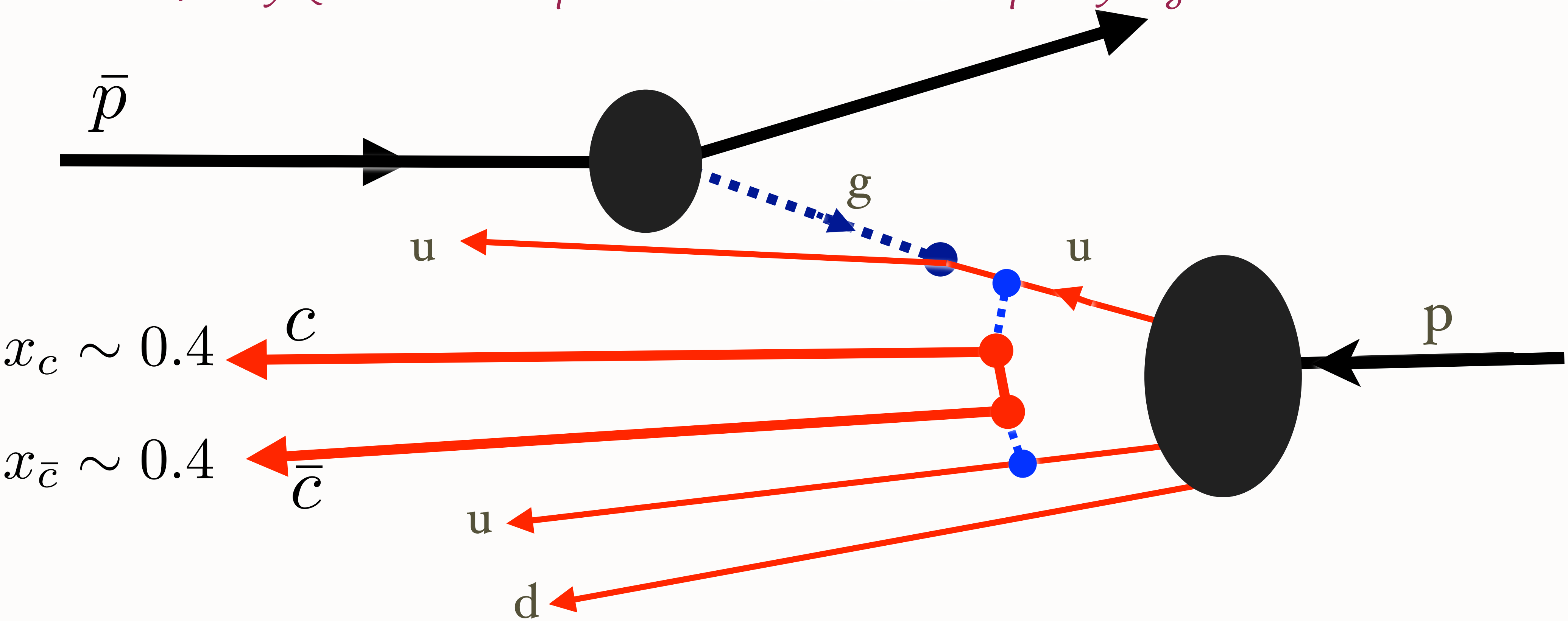
Excitation of Intrinsic Heavy Quarks in Proton

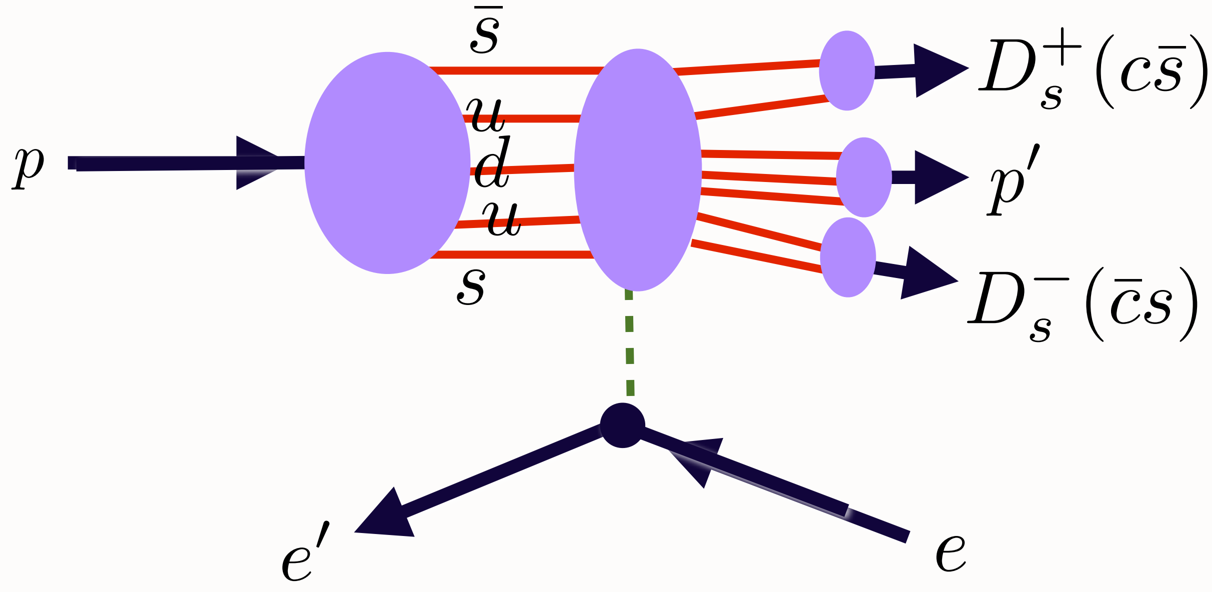
Amplitude maximal at small invariant mass, equal rapidity

$$x_i \sim \frac{m_{\perp i}}{\sum_j^n m_{\perp j}} \qquad \frac{d\sigma}{dy_{J/\psi}}(\bar{p}p \to J/\psi X)$$

J-P Lansberg, sjb

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



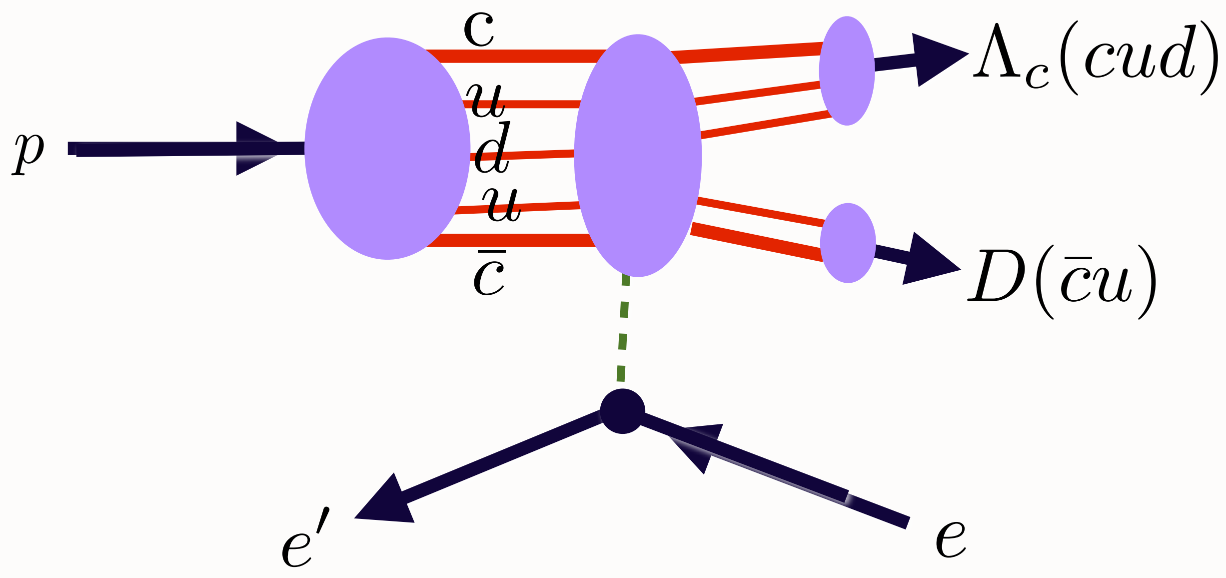


Look for $D_s^-(\bar{c}s)$ vs. $D_s^+(c\bar{s})$ asymmetry

Reflects s vs. $\bar{s}$ asymmetry in proton $|uuds\bar{s} >$ Fock LF state.

Asymmetry natural from $|K^+\Lambda >$ excitation **Ma, sjb**

Assumes symmetric charm and anti-charm distributions

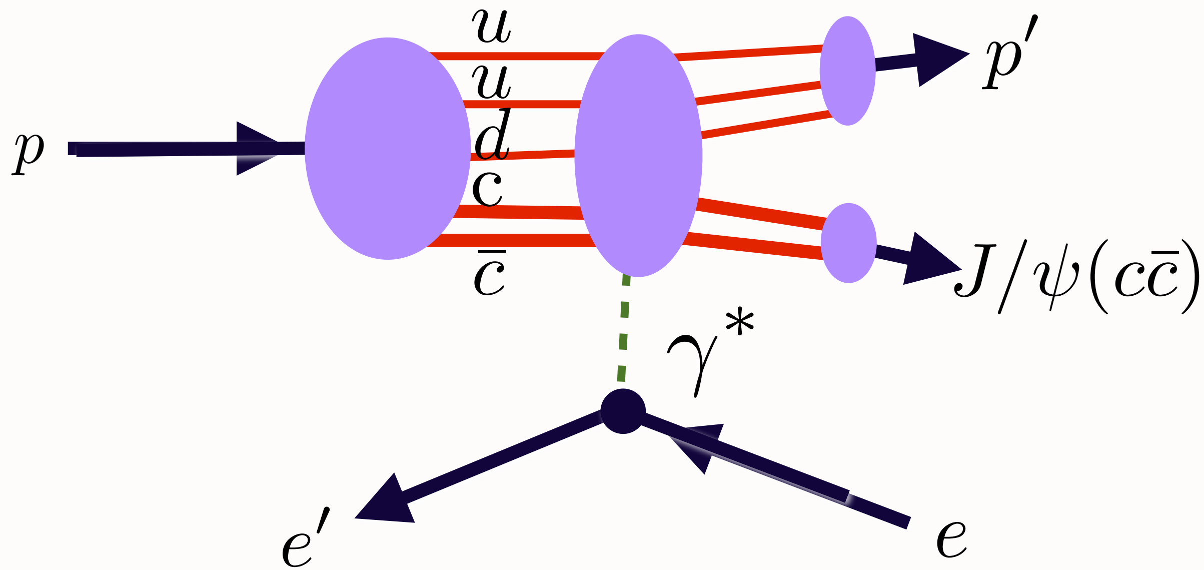


EIC
Experiment

Dissociate proton to high x_F heavy-quark pair

$$\gamma^* p \to \Lambda_c(cdd) + D(\bar{c}u), \gamma^* p \to \Lambda_b(bud) B^+(\bar{b}u)$$

Test intrinsic charm, bottom

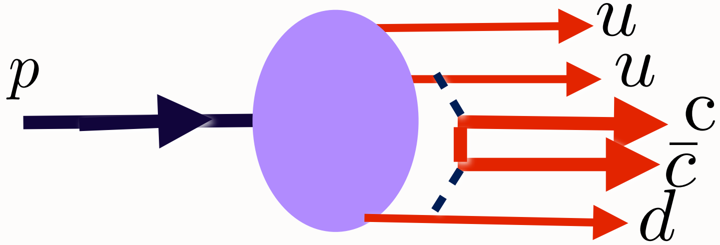


Lansberg, sjb

Dissociate proton to high x_F Quarkonium:

$$\gamma^* p \to J/\psi + p'$$

$$\gamma^* p \to \Upsilon + p'$$



But possibly disfavored since

$$|p> \simeq |(uud)_{8_C} (c\bar{c})_{8C}>$$

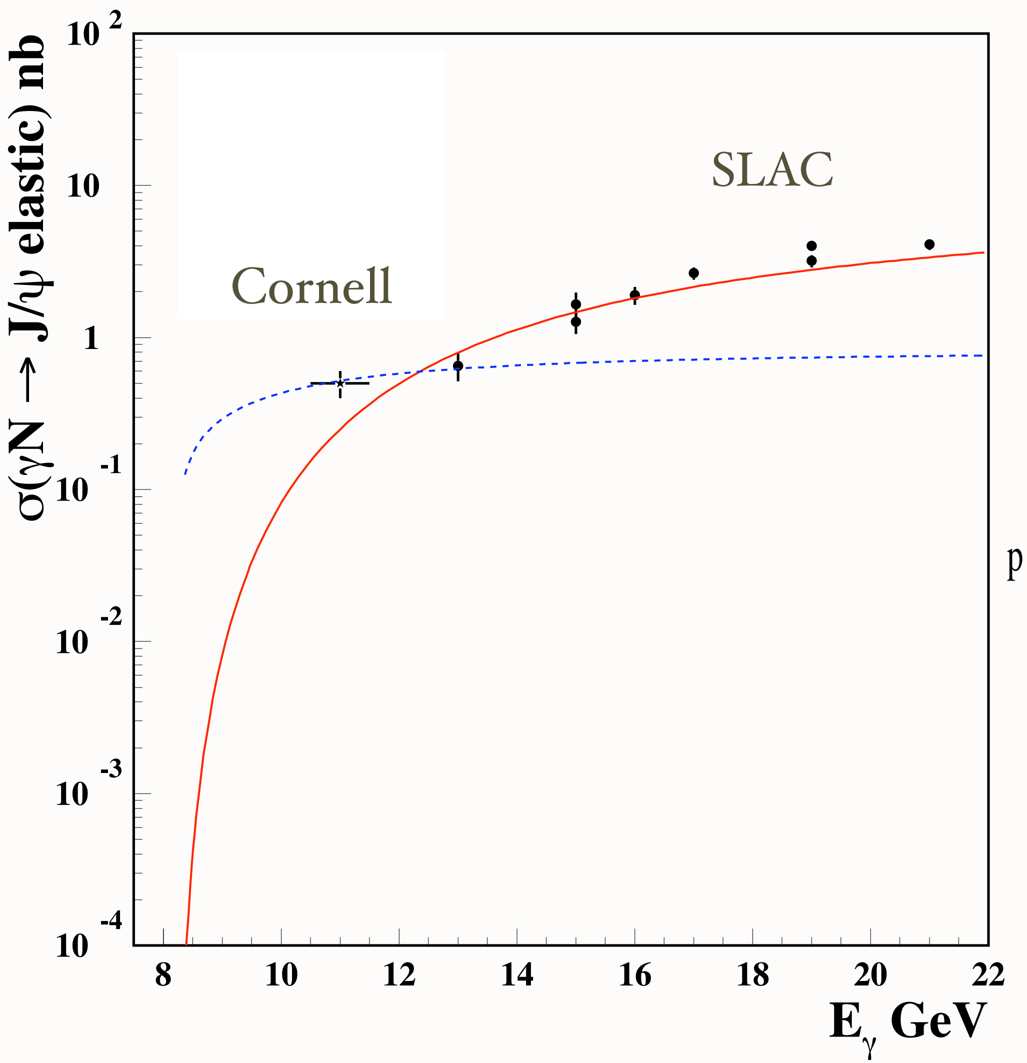
Collins, Ellis, Gunion, Mueller, sjb

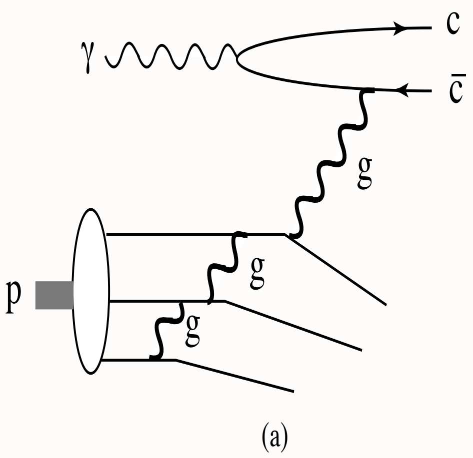
M. Polyakov et al.

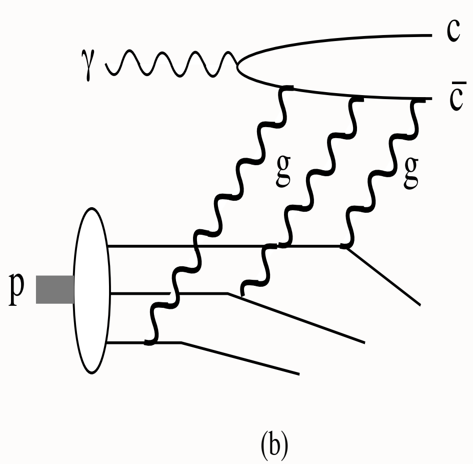
Test intrinsic charm, bottom

$$\gamma p \to J/\psi p$$

Chudakov, Hoyer, Laget, sjb







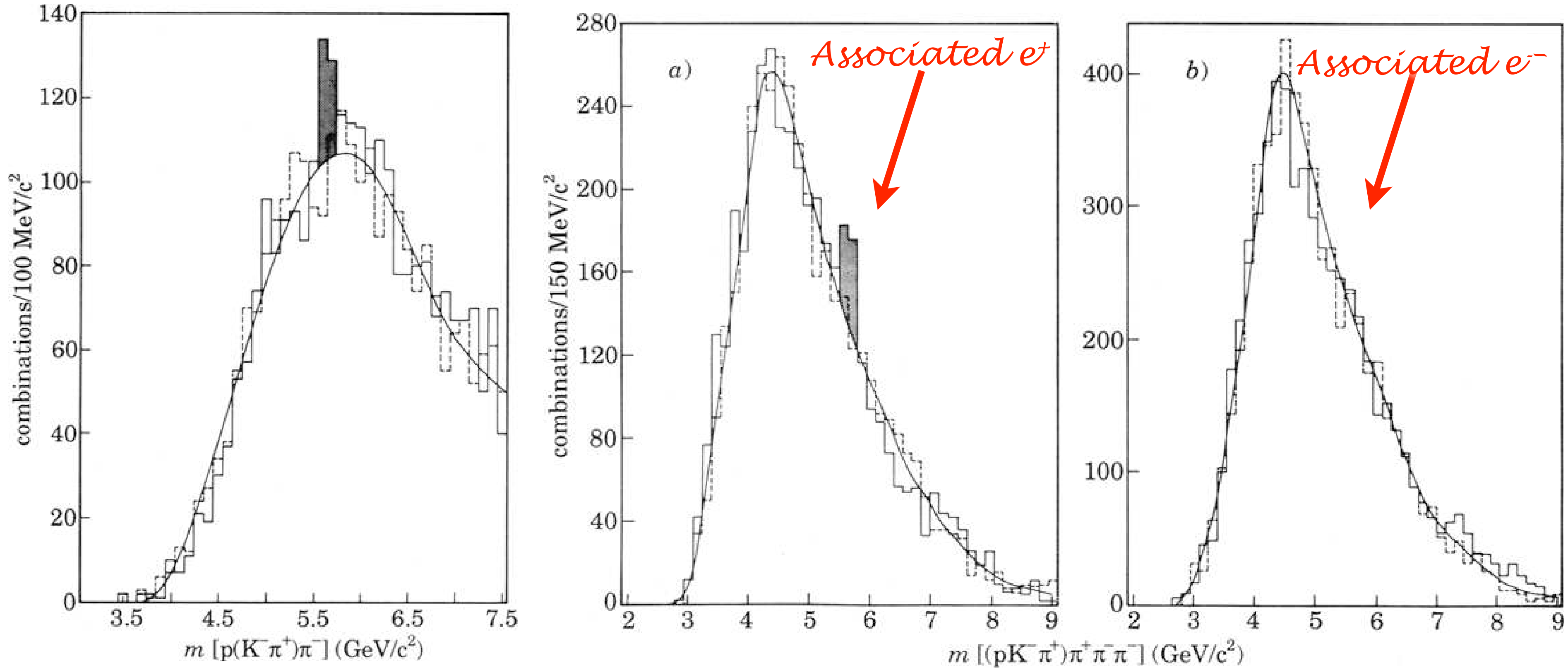
Leading twist contribution

Dominant near threshold

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

$pp \to \Lambda_b(bud)B(\bar{b}q)X$ 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]

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

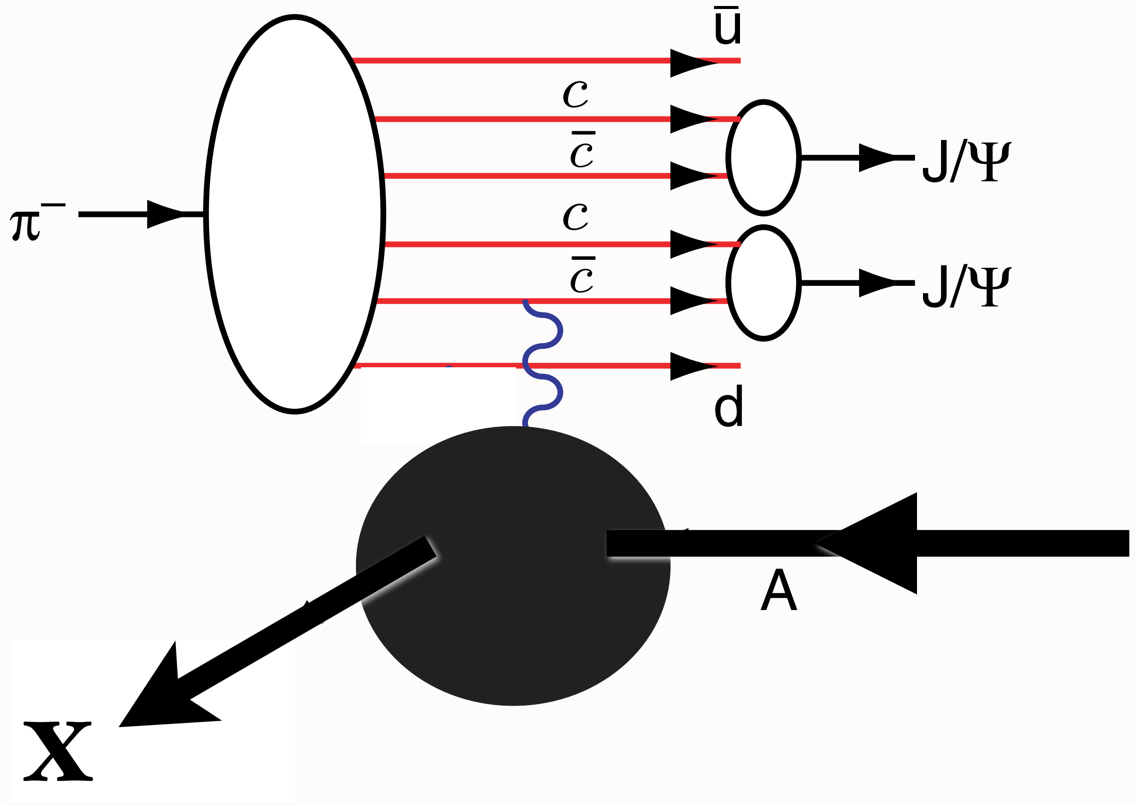
G. Bari, M. Basile, G. Bruni, G. Cara Romeo, R. Casaccia, L. Cifarelli, F. Cindolo, A. Contin, G. D'Alì, C. Del Papa, S. De Pasquale, P. Giusti, G. Iacobucci, G. Maccarrone, T. Massam, R. Nania, F. Palmonari, G. Sartorelli, G. Susinno, L. Votano and A. Zichichi

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



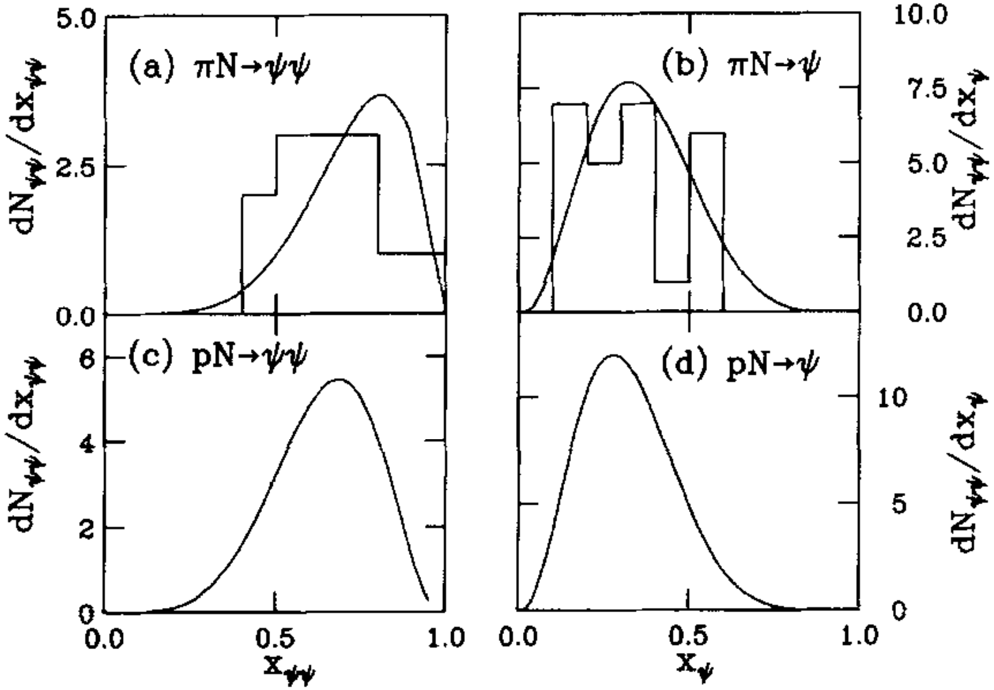


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized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

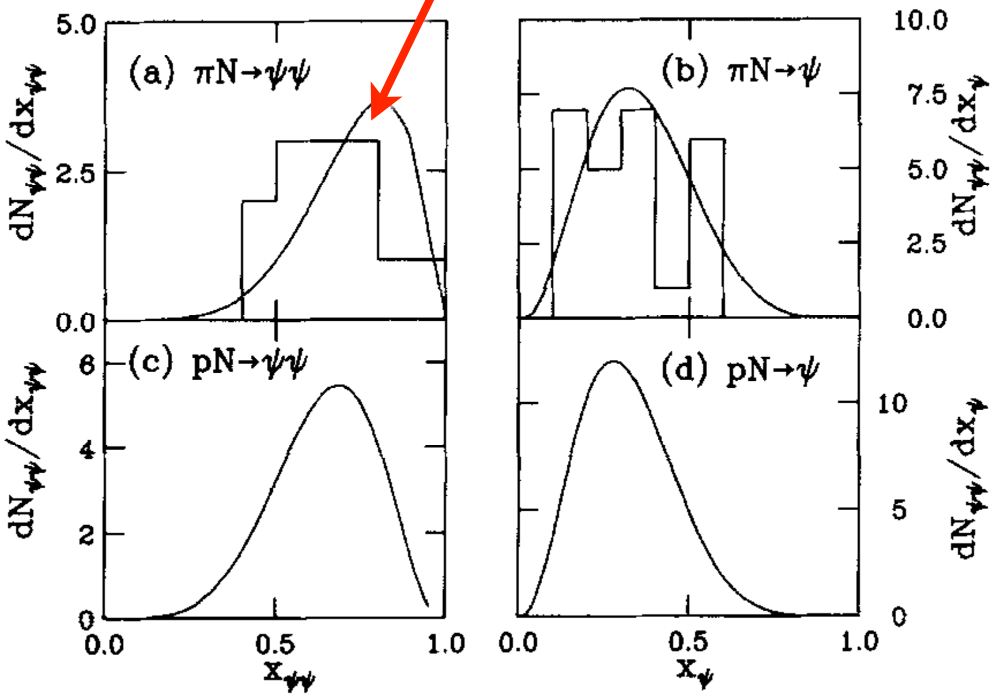
$\pi A \to J/\psi J/\psi X$

R, Vogt, sjb

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

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

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



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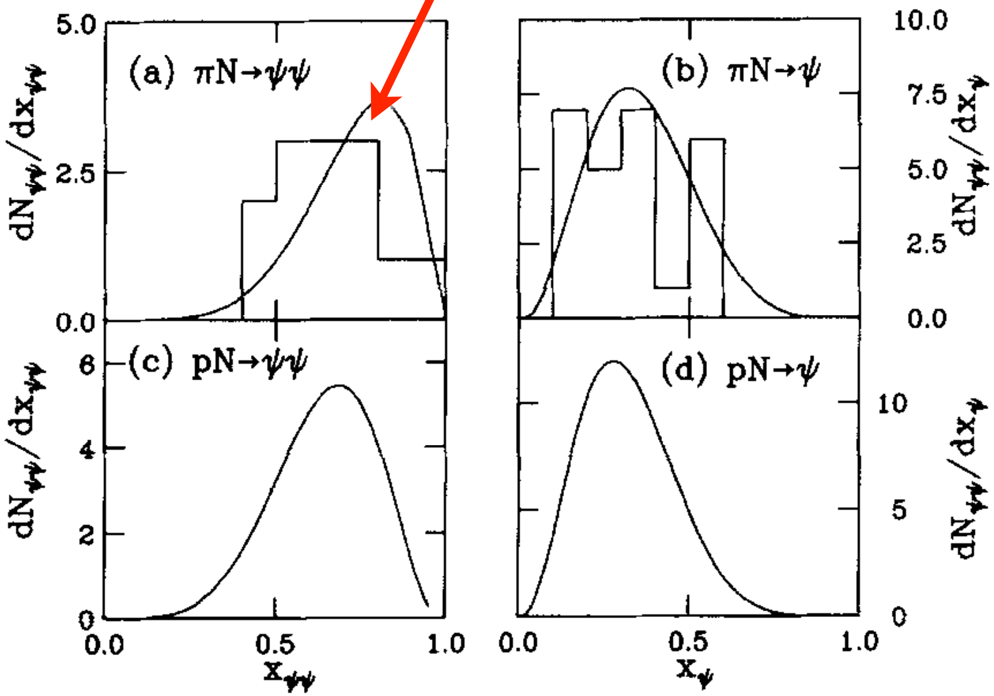
All events have $x^F_{\psi\psi} > 0.4$!

Excludes `color drag' model

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

R, Vogt, sjb



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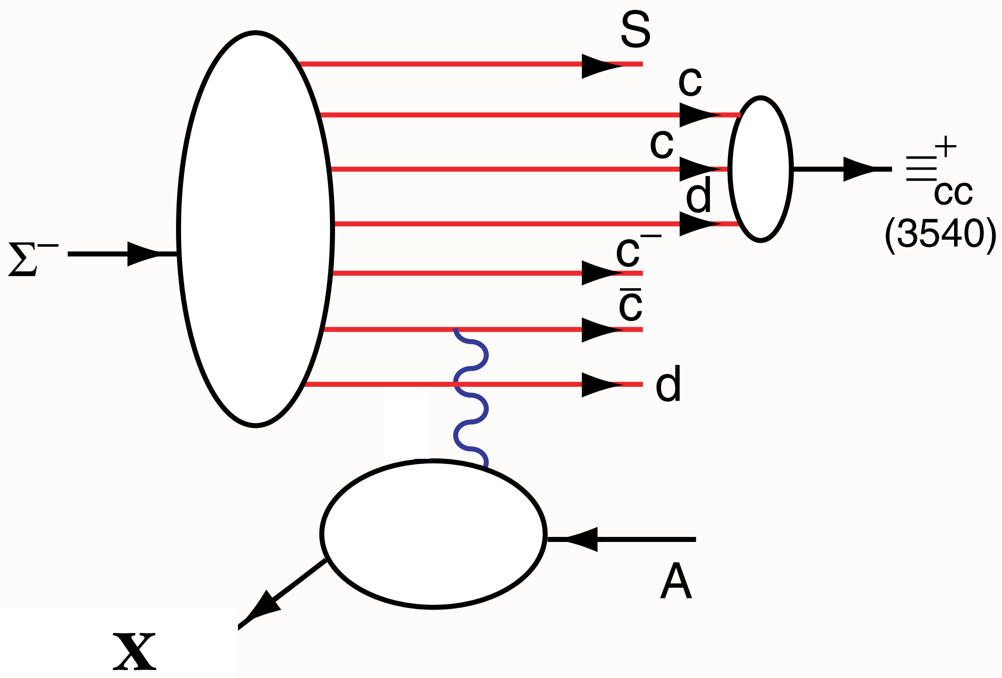
$$\frac{dP_{\rm ic}}{\prod_{i=1}^n dx_i d^2 k_{T,i}} = N_n \alpha_s^4(M_{c\bar{c}}) \frac{\delta(\sum_{i=1}^n \boldsymbol{k}_{T,i})\delta(1-\sum_{i=1}^n x_i)}{(m_h^2 - \sum_{i=1}^n (m_{T,i}^2/x_i))^2},$$

NA3 Data



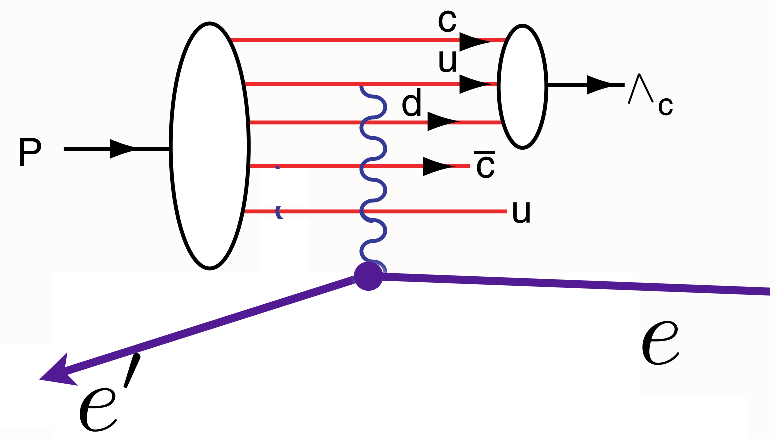
Production of a Double-Charm Baryon

SELEX high x_F $< x_F >= 0.33$

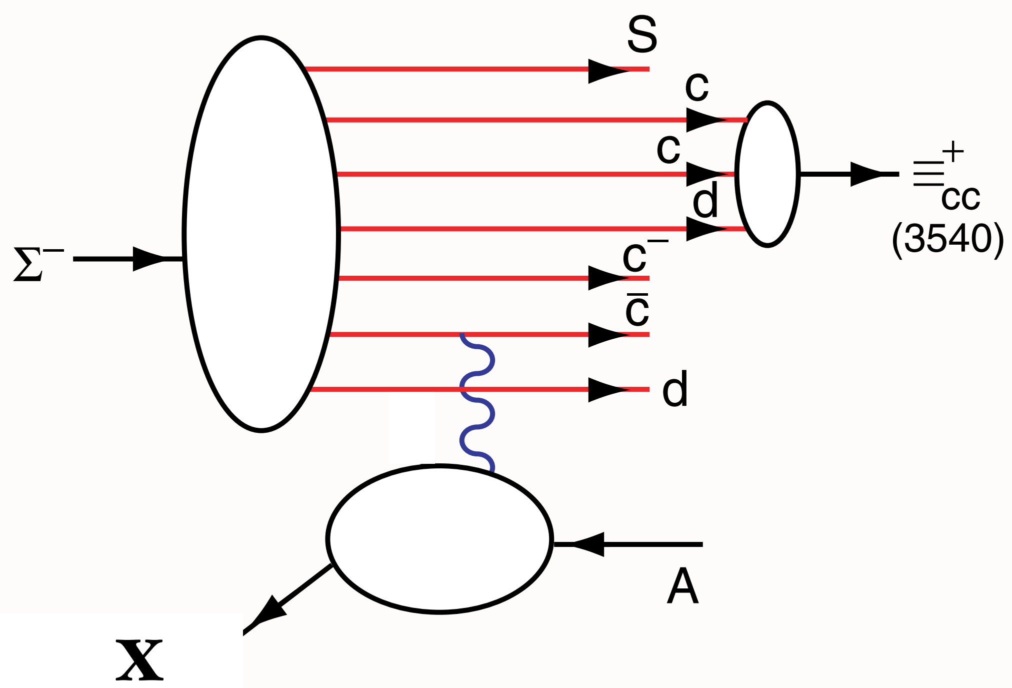
Leading charm production in proton fragmentation region at the EIC

Intrinsic charm and bottom quarks have same rapidity as valence quarks

Produce $\Xi(ccd), B(\bar{b}u), \Lambda(cbu), \Xi(bbu)$



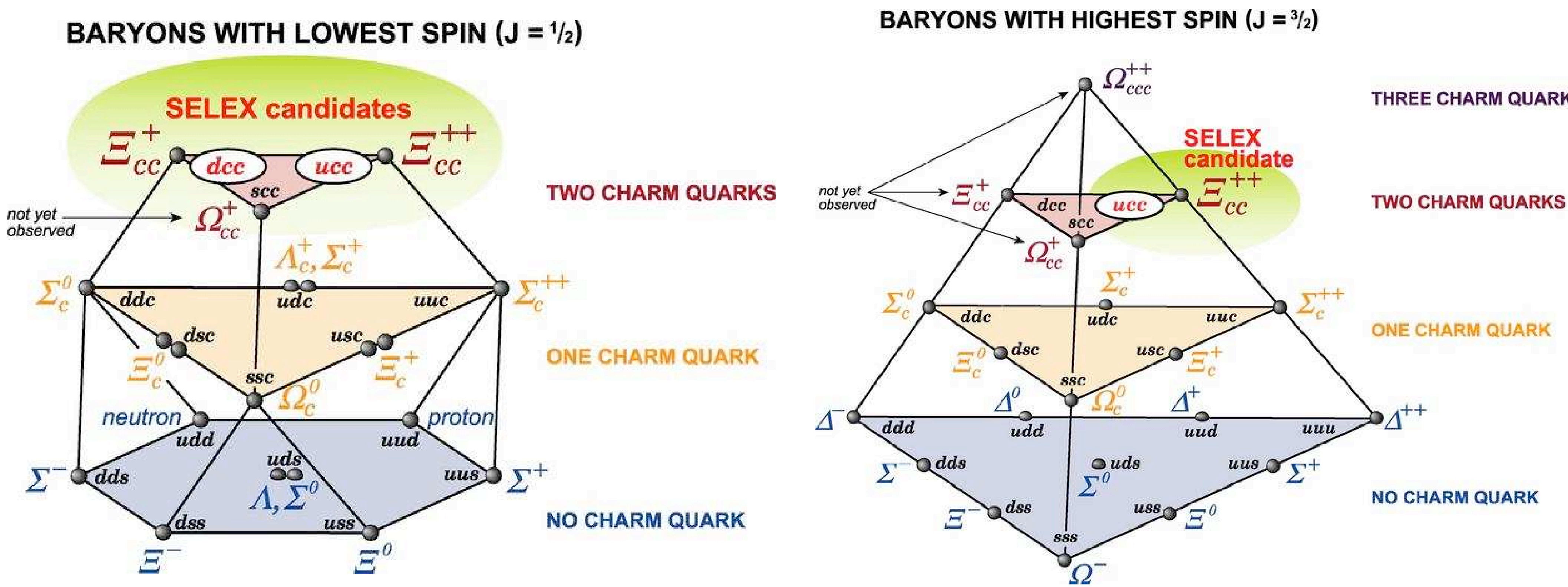
Coalescence of Comoving Charm and Valence Quarks Produce J/ψ, Λ_c and other Charm Hadrons at High x_F



Production of a Double-Charm Baryon

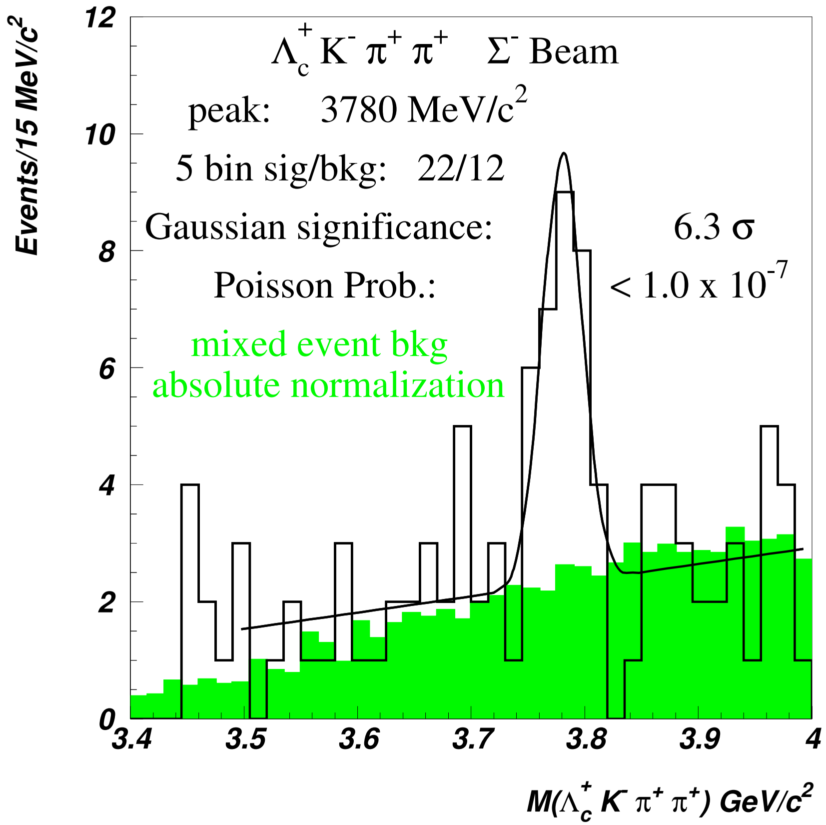
SELEX high $\mathbf{x_F}$ $< x_F > = 0.33$

Doubly Charmed Baryons



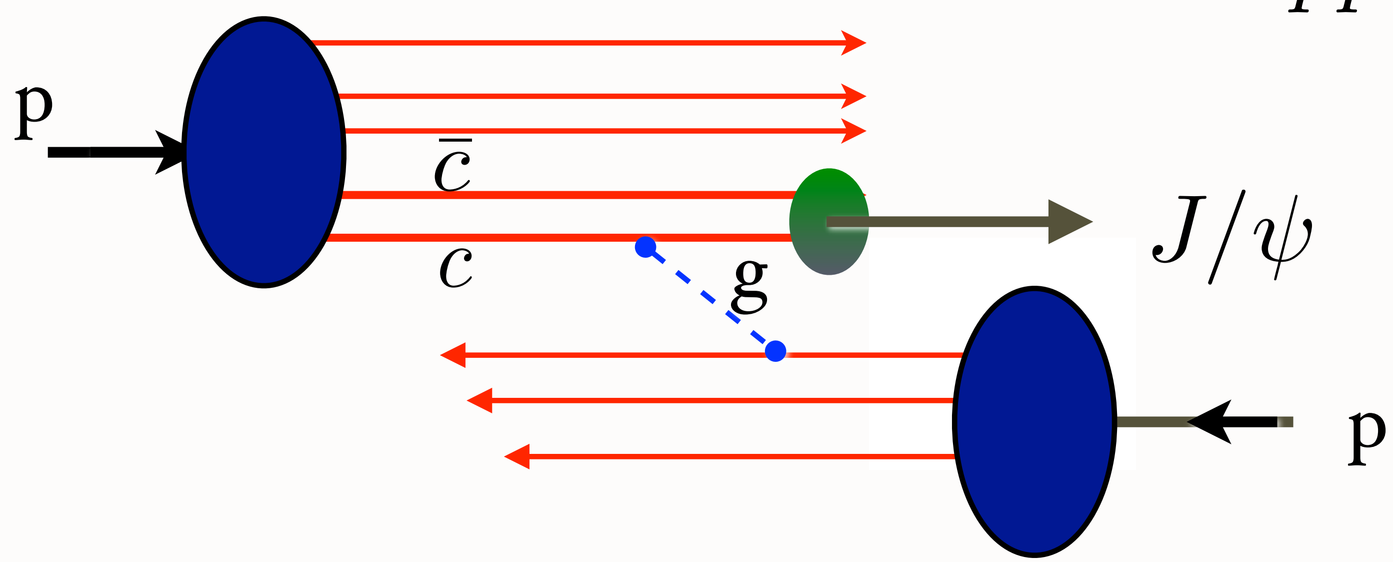
$\Xi_{cc}(3780)^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

- 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 Inclusive High-X_F Quarkonium Production

$$pp \to J/\psi X$$



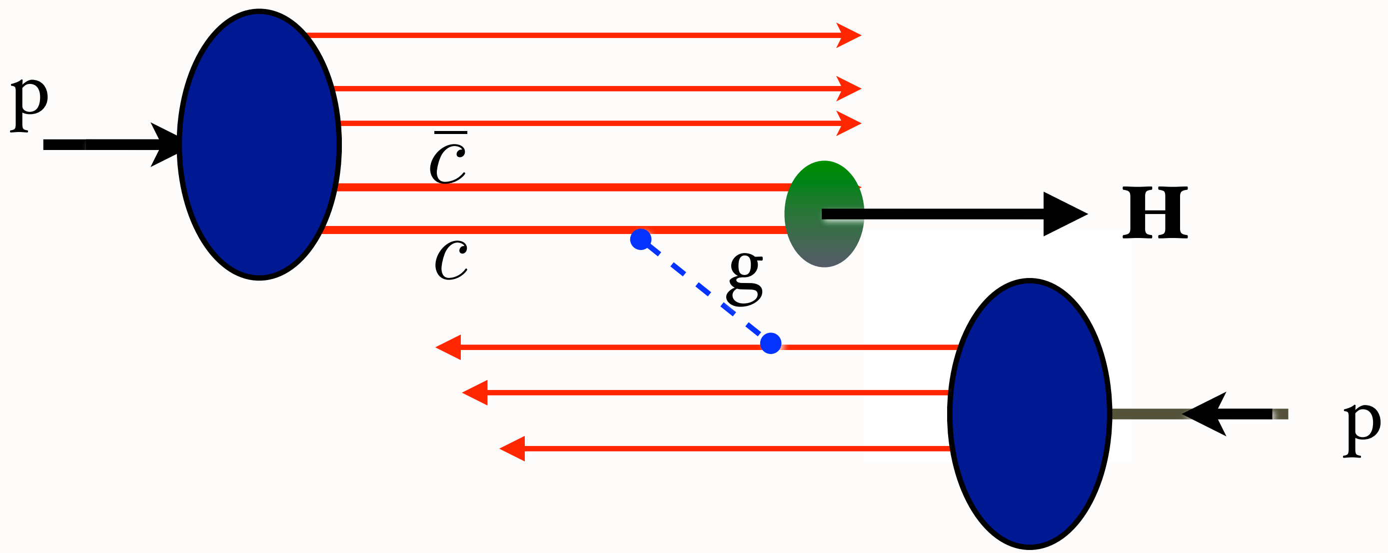
Goldhaber, Kopeliovich, Soffer, Schmidt, sjb

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

Intrinsic Charm Mechanism for Inclusive High-X_F Higgs Production



$$pp \to HX$$

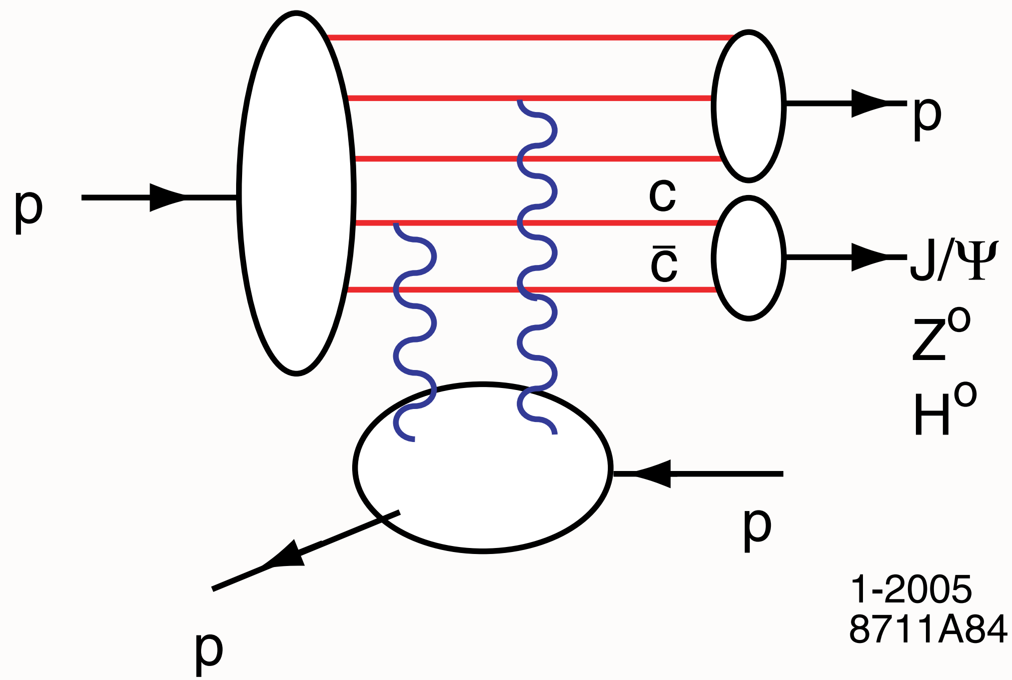
Goldhaber, Kopeliovich, Schmidt, sjb

Also: intrinsic bottom, top

Higgs can have 80% of Proton Momentum!

New search strategy for Higgs

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

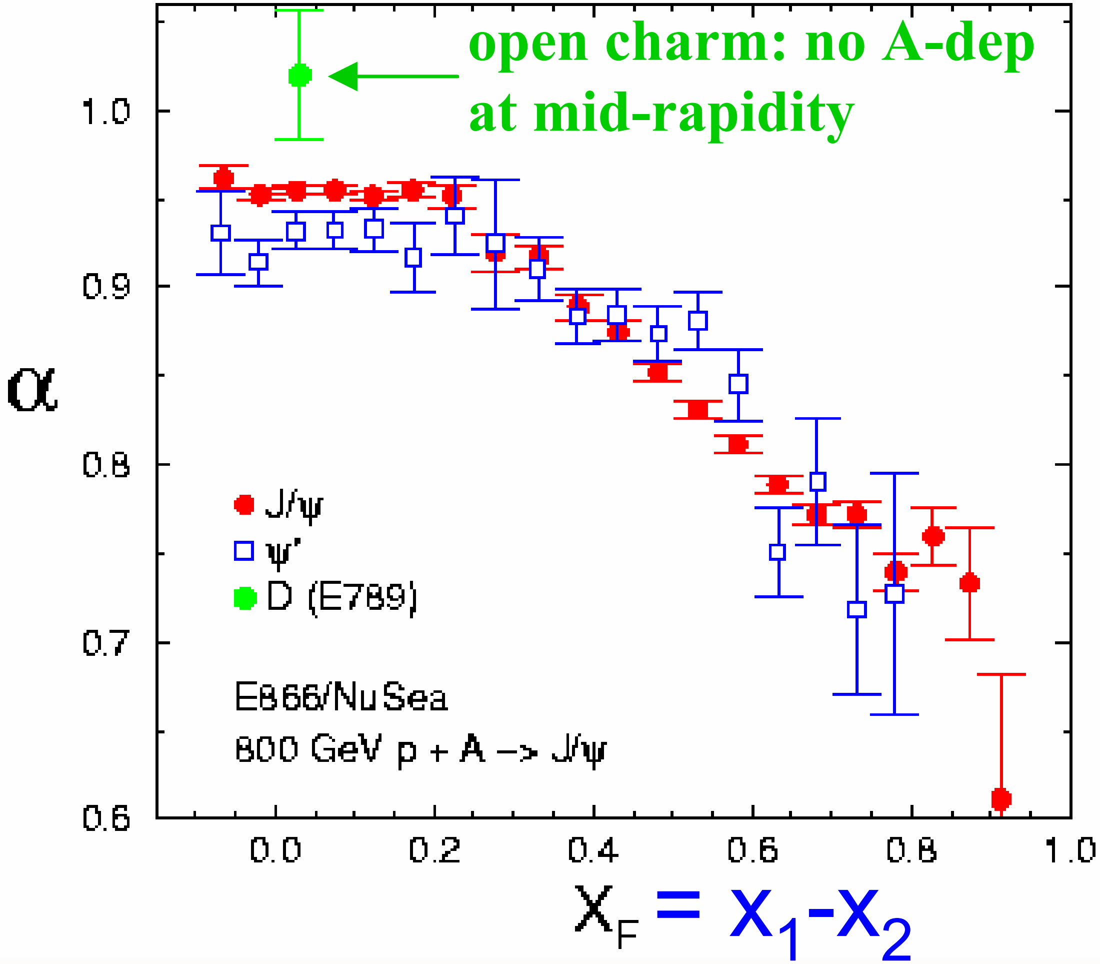
Collision produces color-singlet J/ψ through color exchange

RHIC Experiment

800 GeV p-A (FNAL) $\sigma_A = \sigma_p * A^{\alpha}$

PRL 84, 3256 (2000); PRL 72, 2542 (1994)

M. Leitch



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

800 GeV p-A (FNAL) $\sigma_A = \sigma_p * A^{\alpha}$

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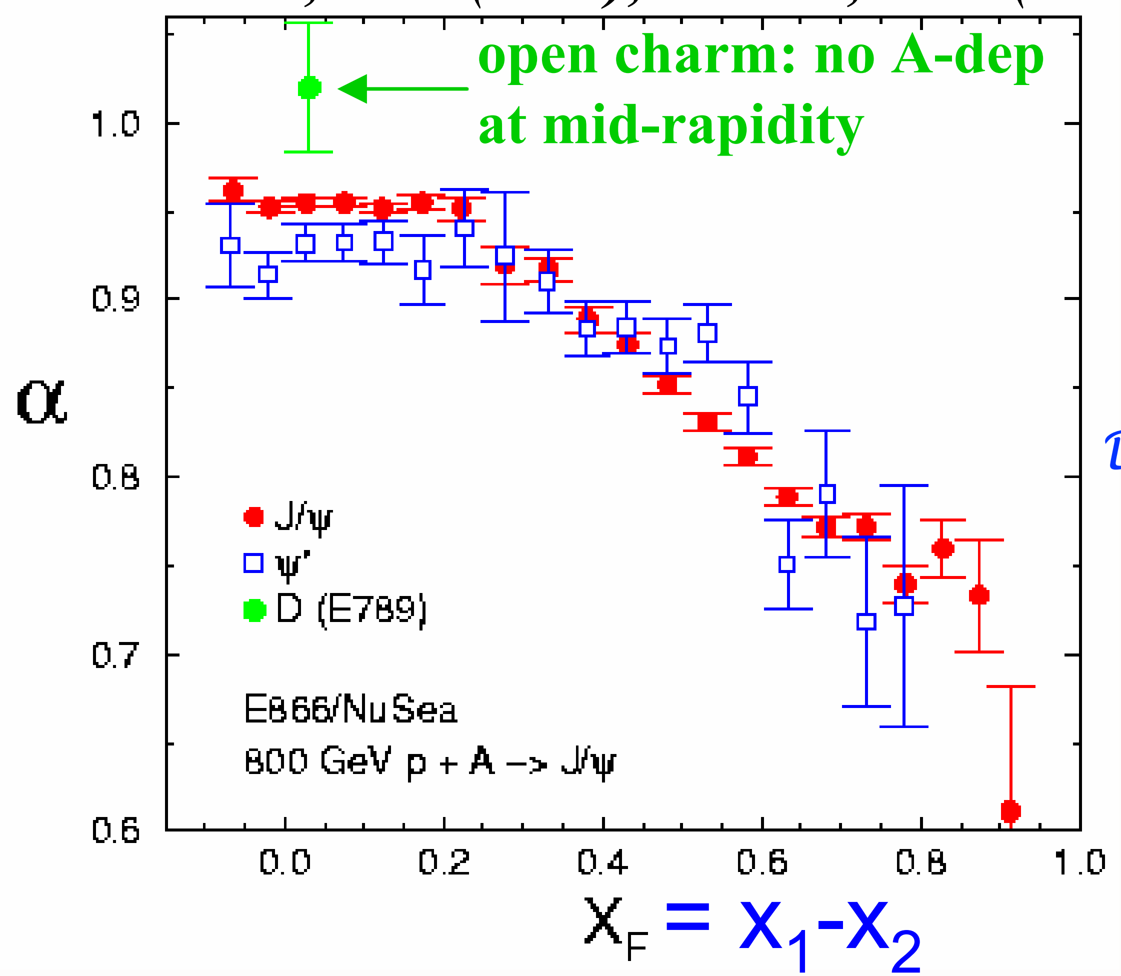

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Remarkably Strong Nuclear Dependence for Fast Charmonium

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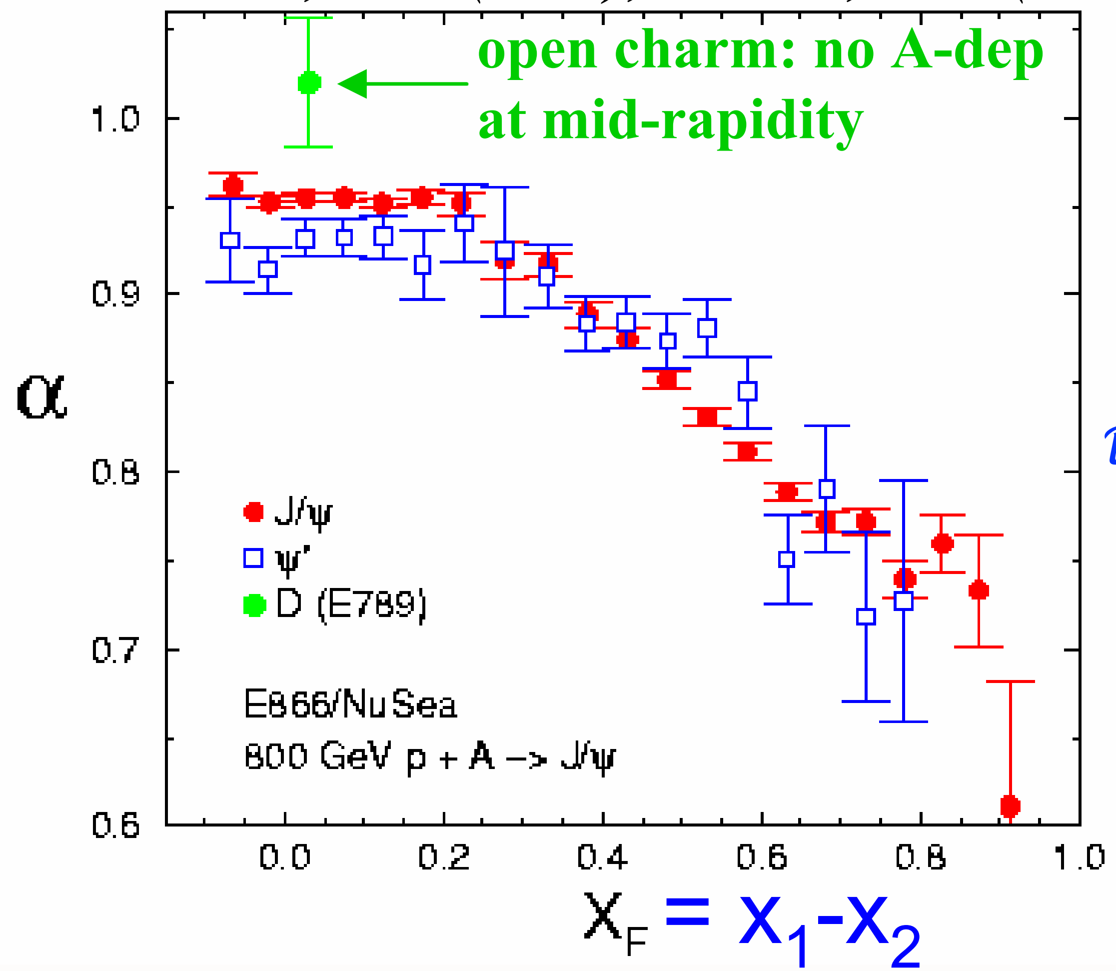

$$\frac{d\sigma}{dx_F}(pA \rightarrow J/\psi X)$$

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

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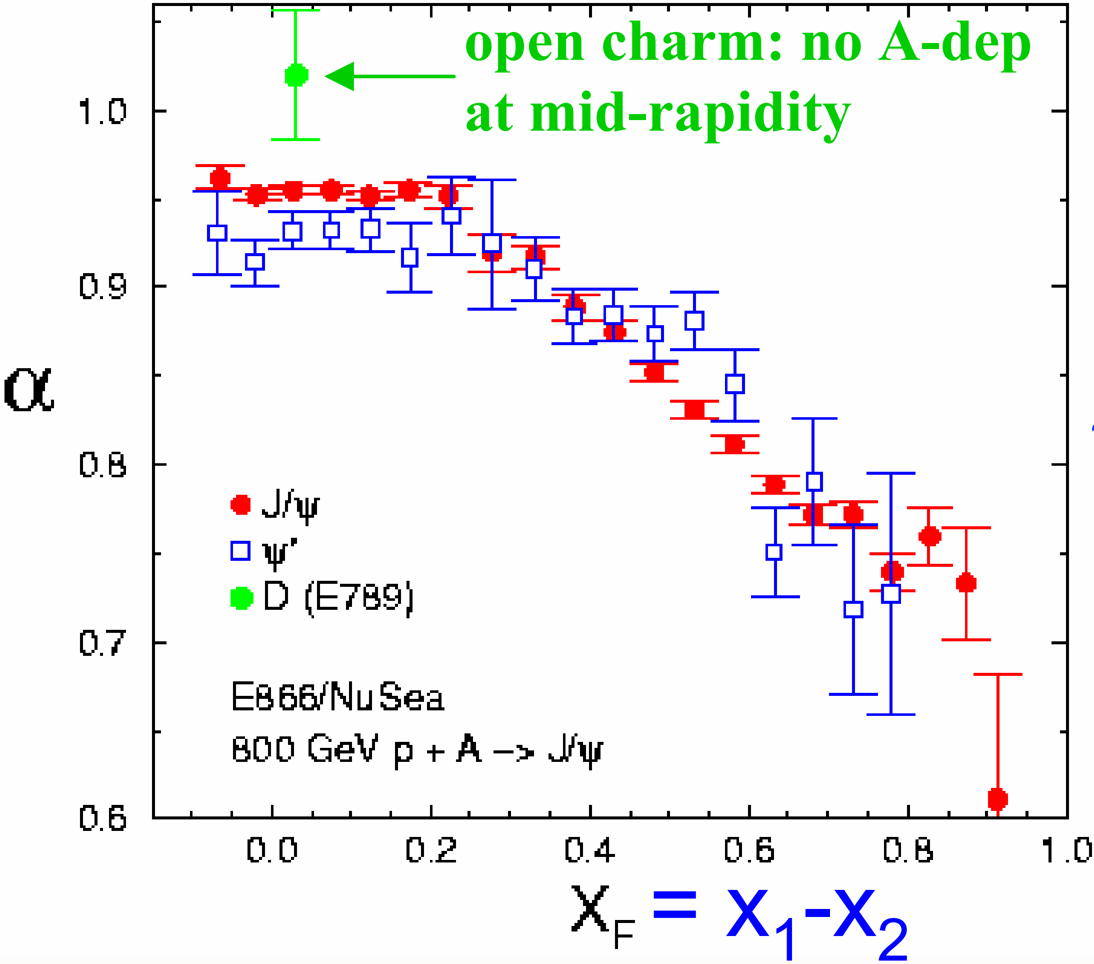

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IC Explains large excess of quarkonia at large x_F, A-dependence

Heavy Quark Anomalies

Nuclear dependence of J/ψ hadroproduction

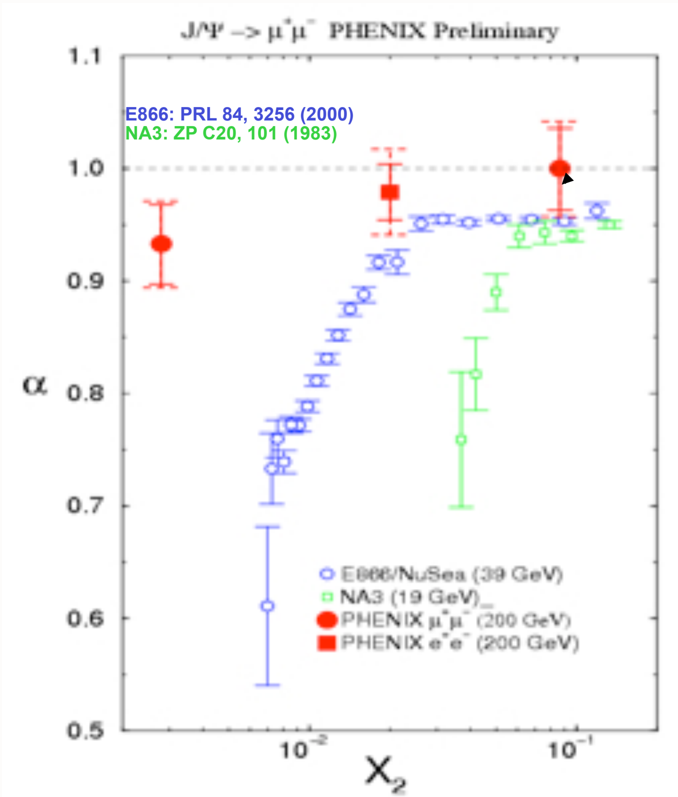
Violates PQCD Factorization: $A^{\alpha}(x_F)$ not $A^{\alpha}(x_2)$

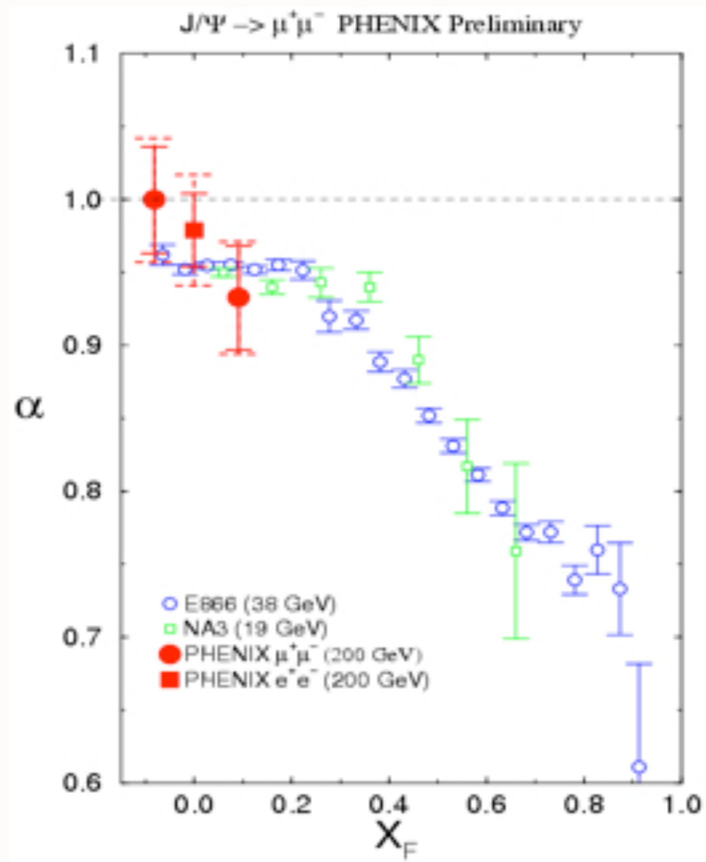
Huge $A^{2/3}$ effect at large x_F

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

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

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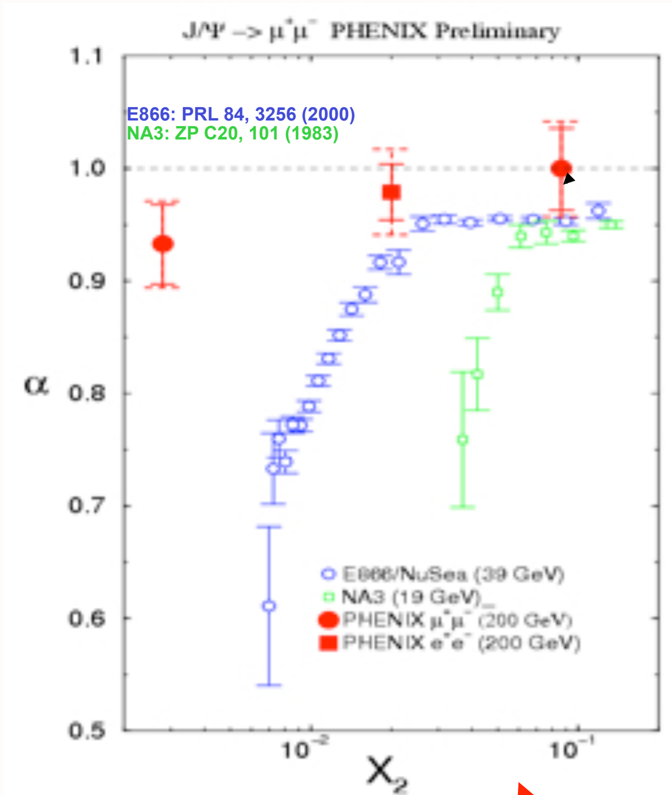

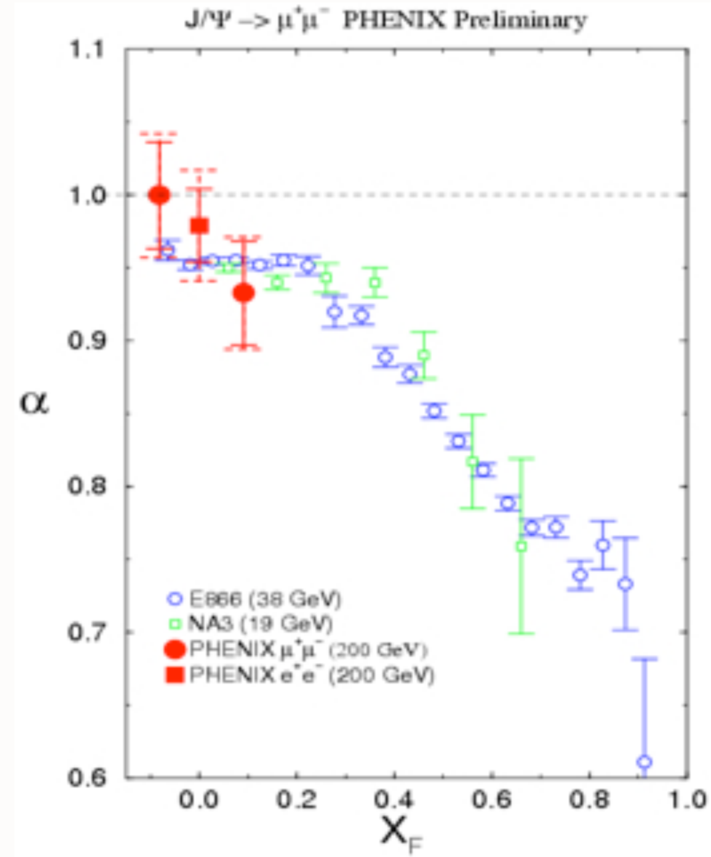

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Violates PQCD factorization!

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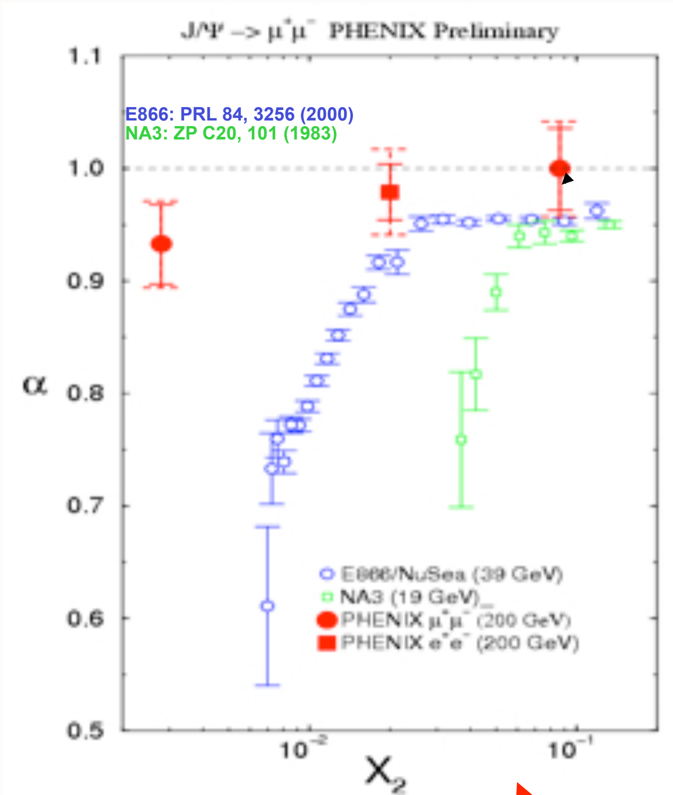

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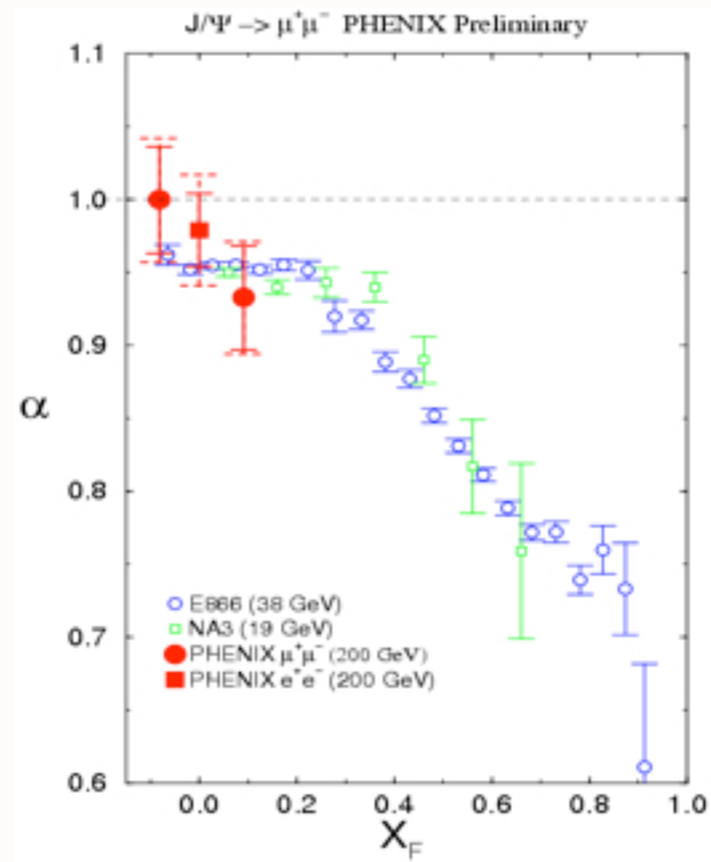


Huge "absorption" effect

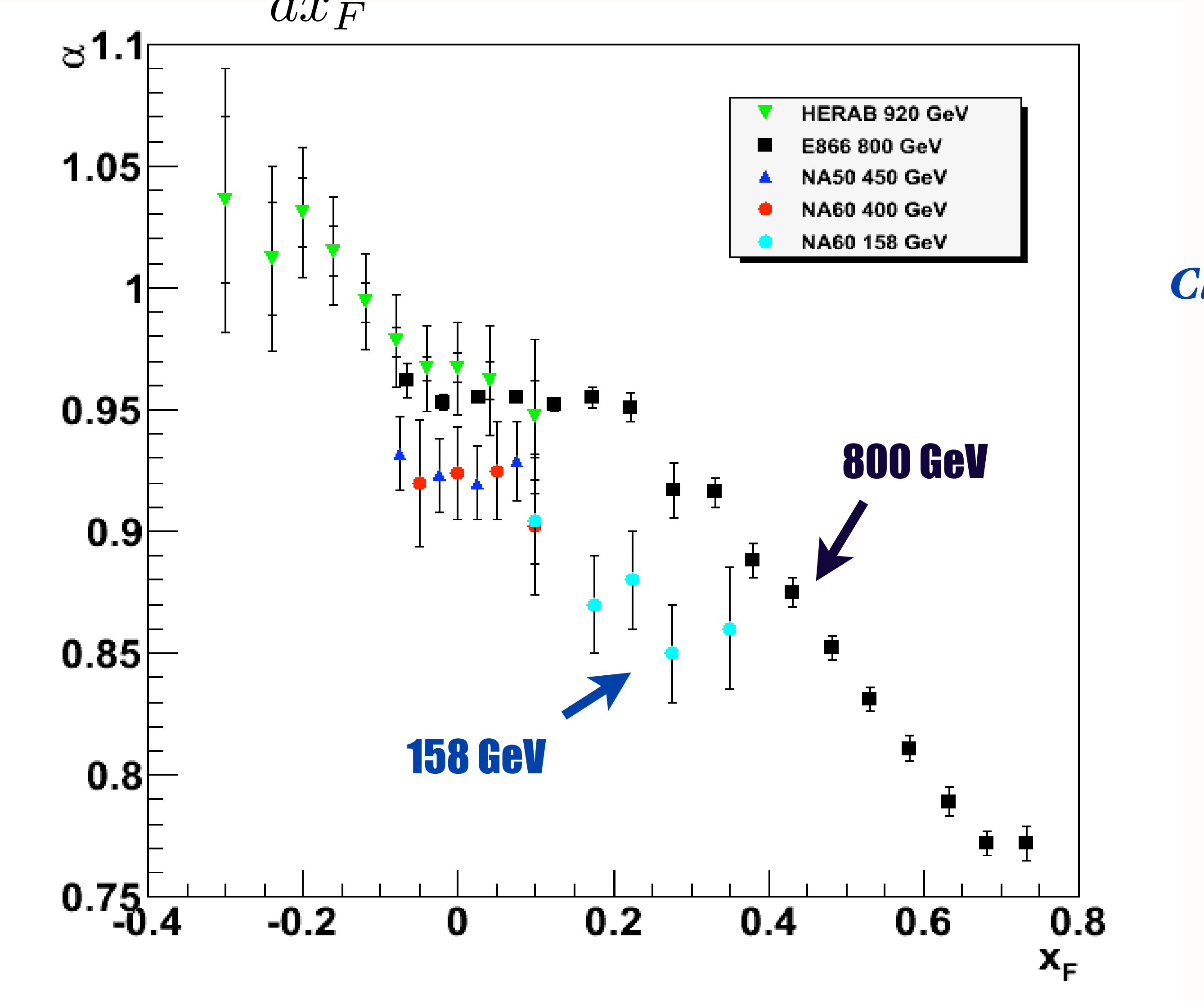
Violates PQCD factorization!

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

Hoyer, Sukhatme, Vanttinen

NA60 pA data @ 158GeV

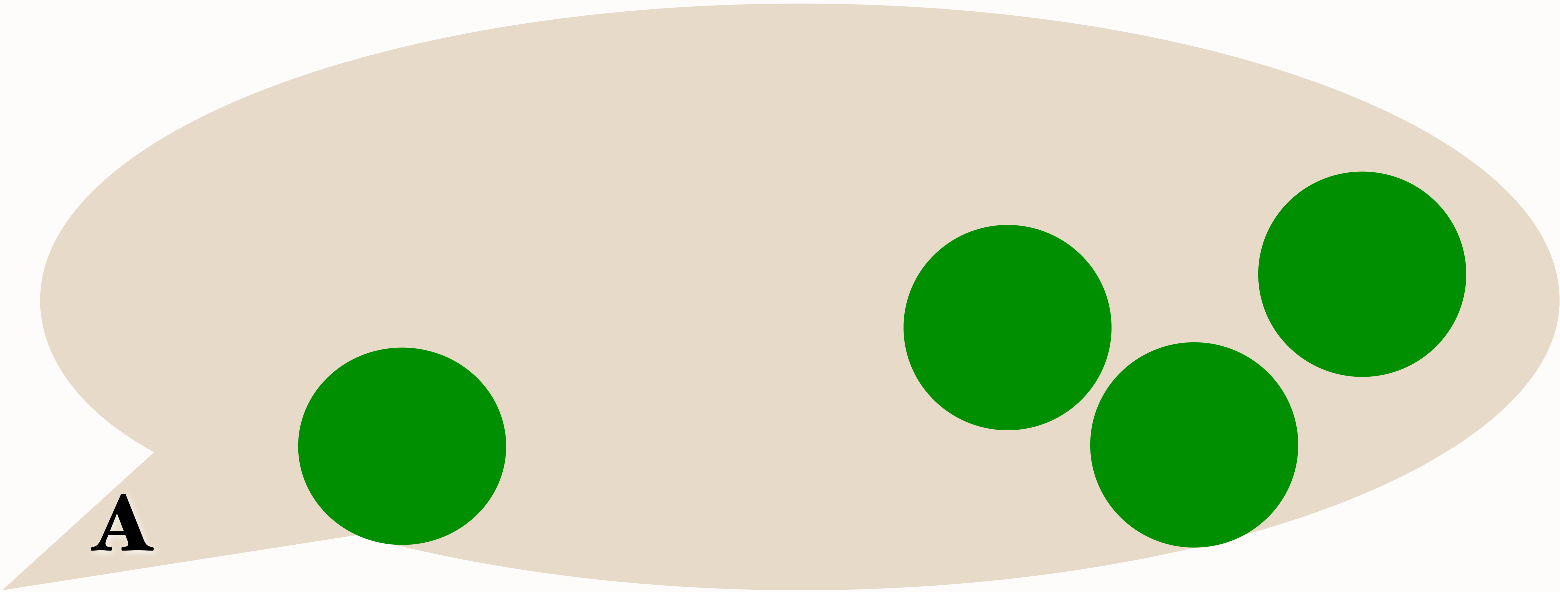
$$\frac{d\sigma}{dx_F}(pA \rightarrow J/\psi X) \propto A^{\alpha}$$



Clear dependence on x_F and beam energy

Color-Opaque IC Fock state interacts on nuclear front surface

Kopeliovich, Schmidt, Soffer, sjb



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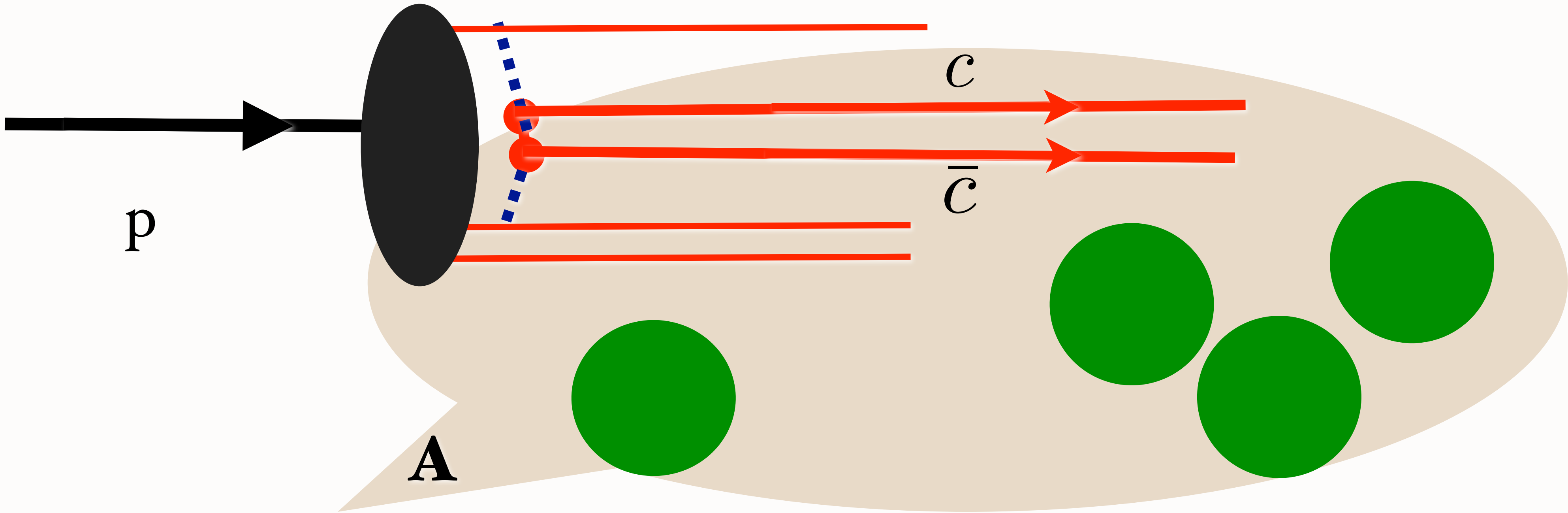

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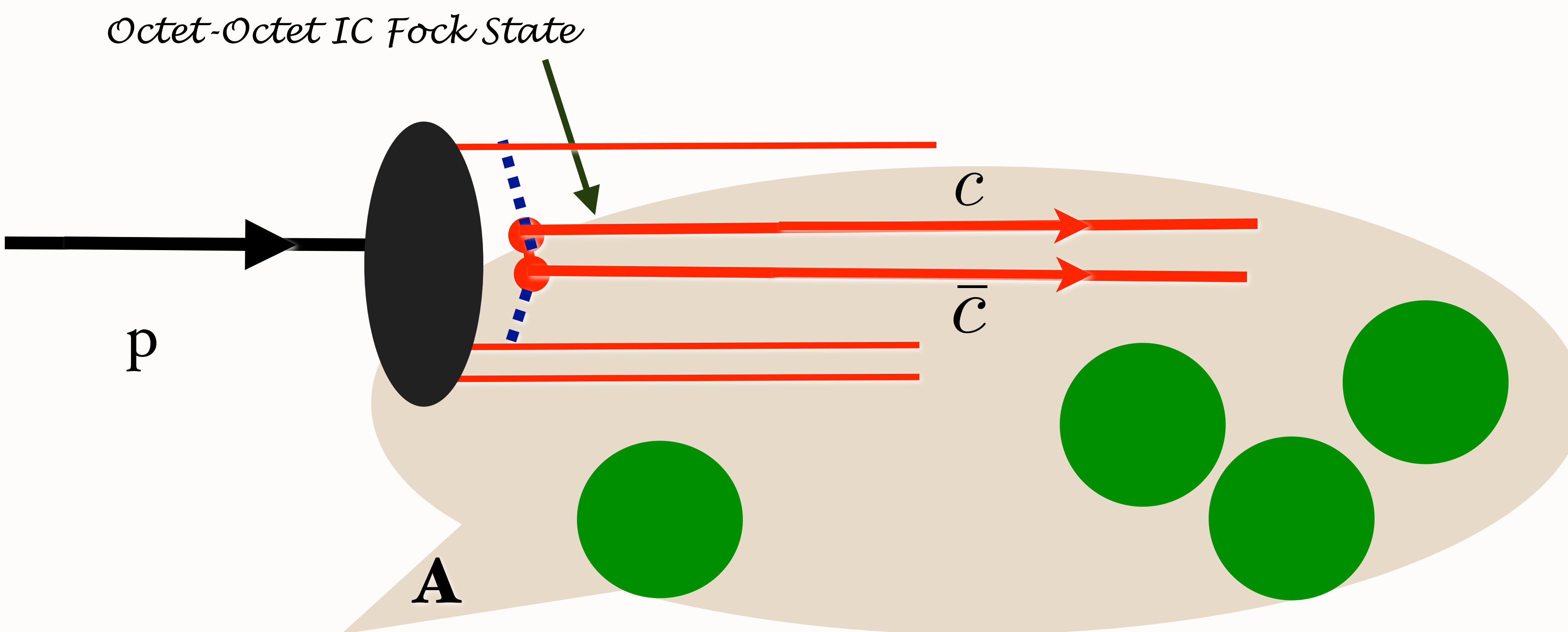

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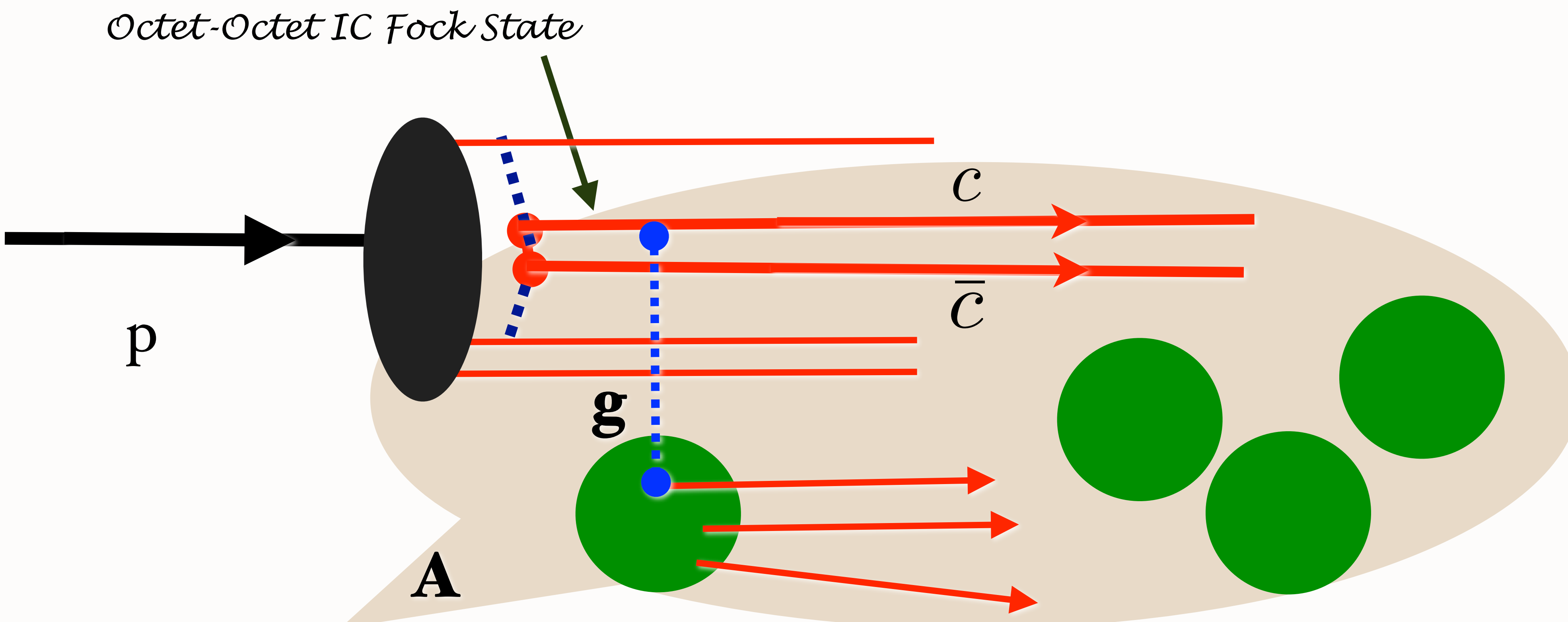

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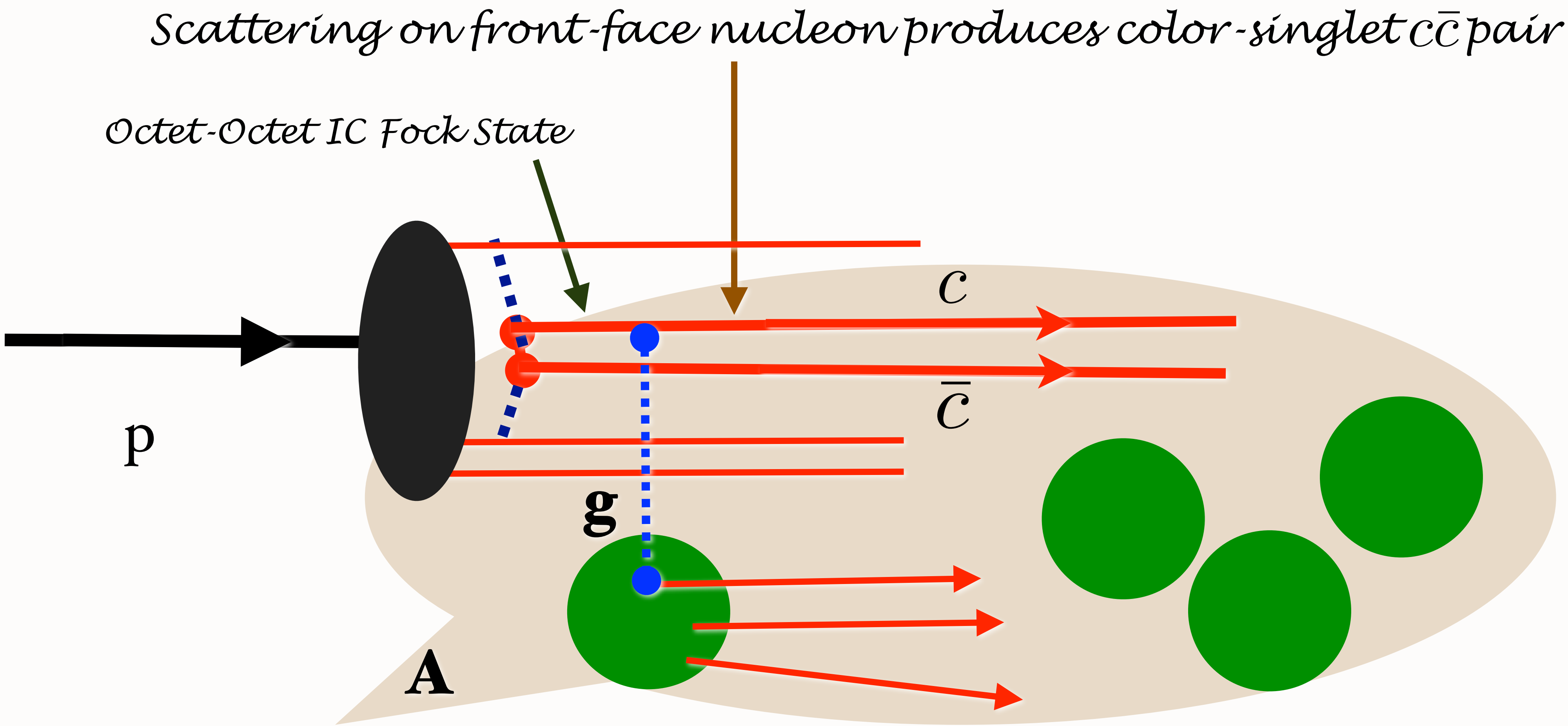

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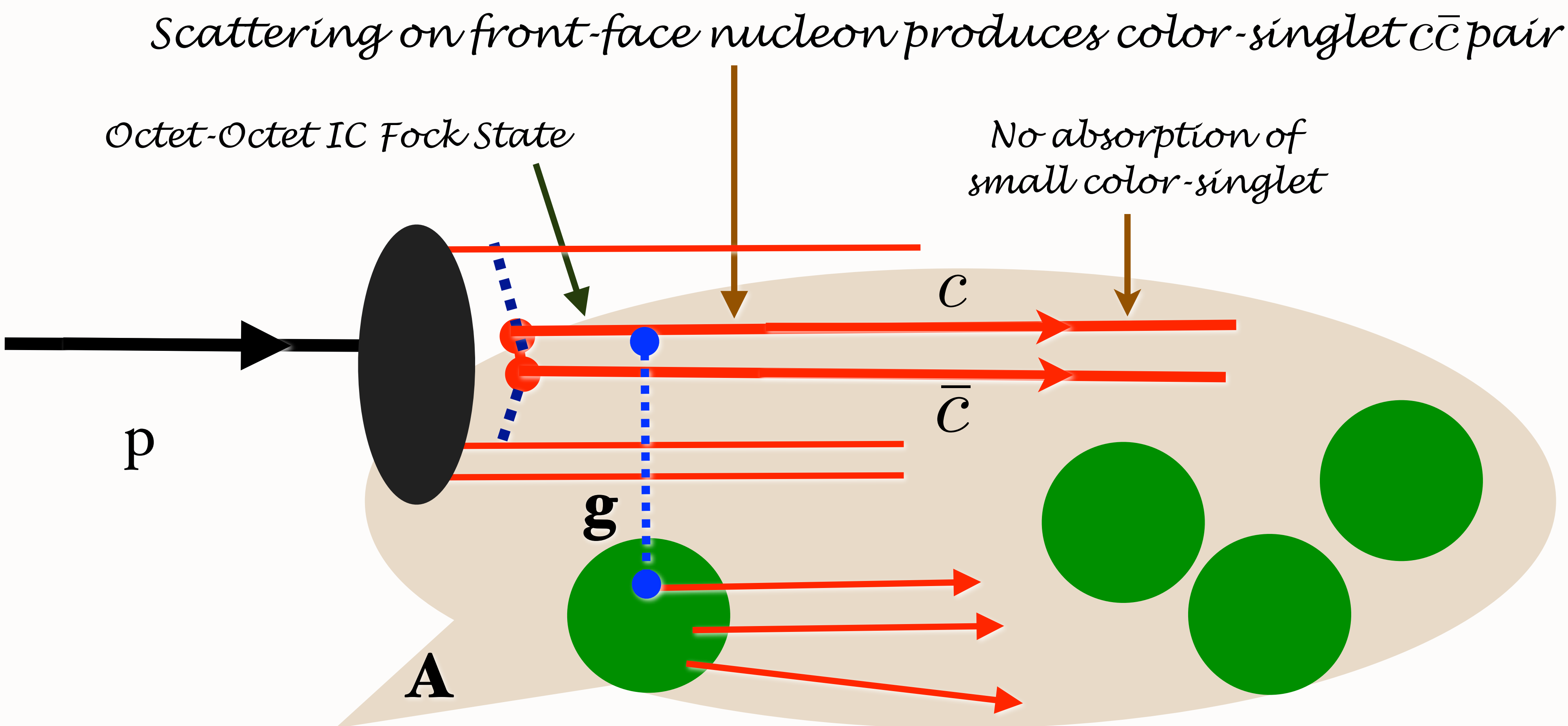

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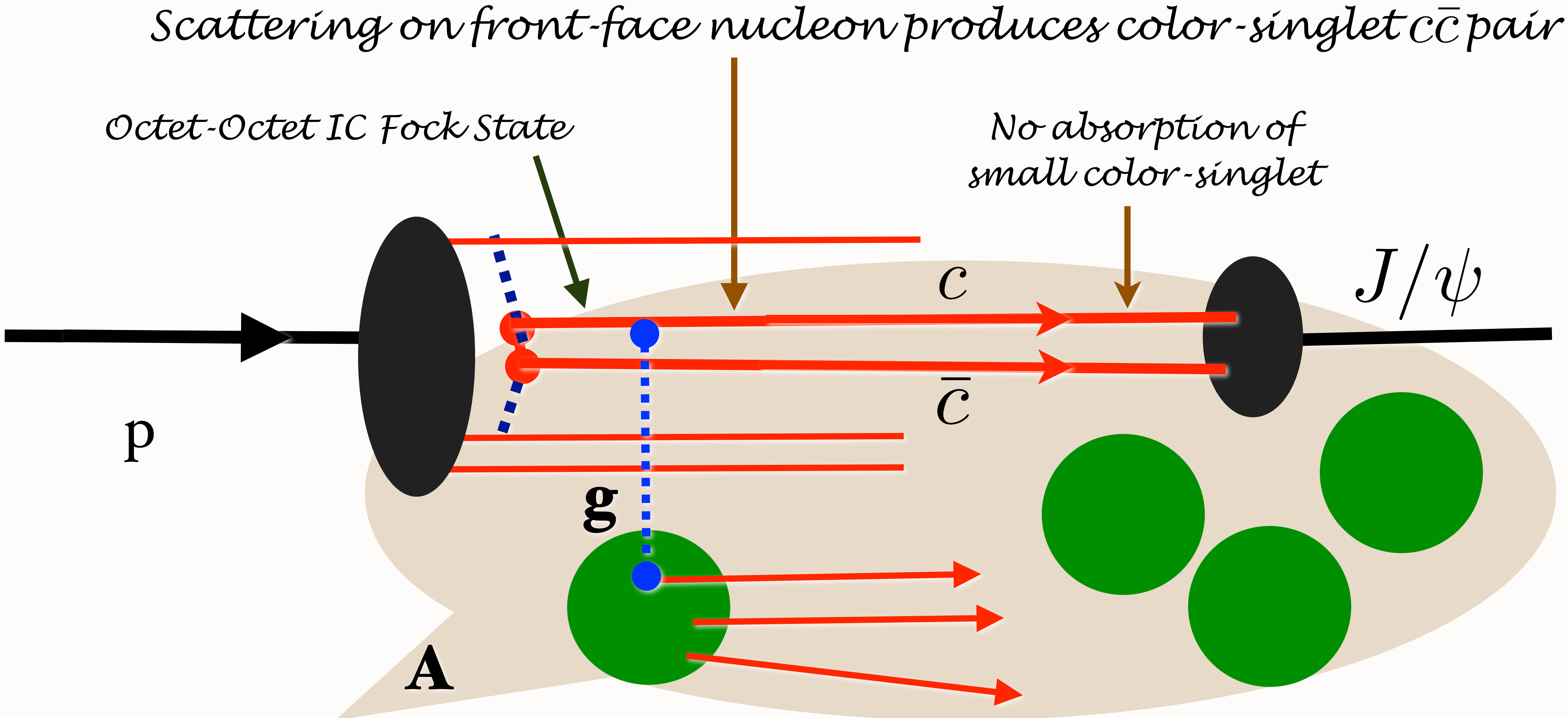

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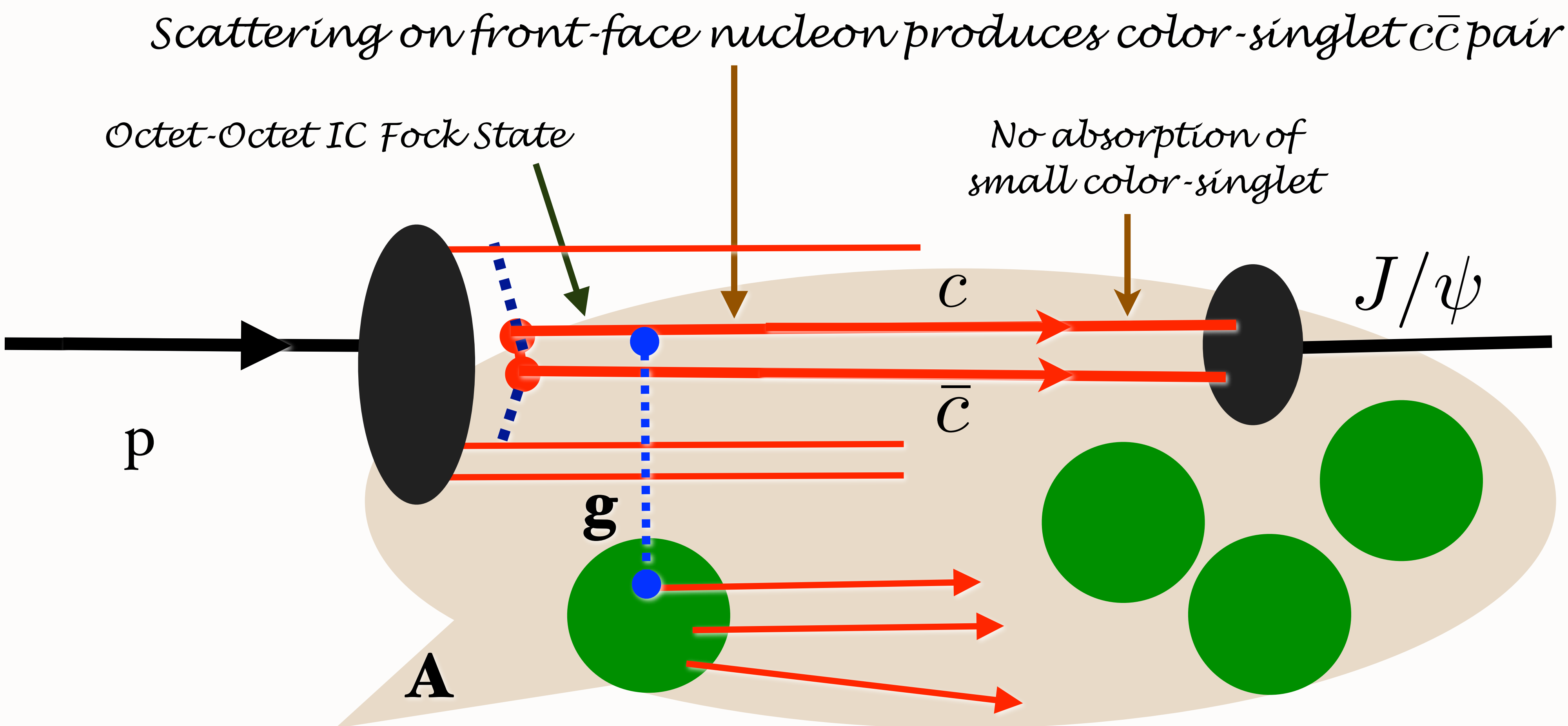
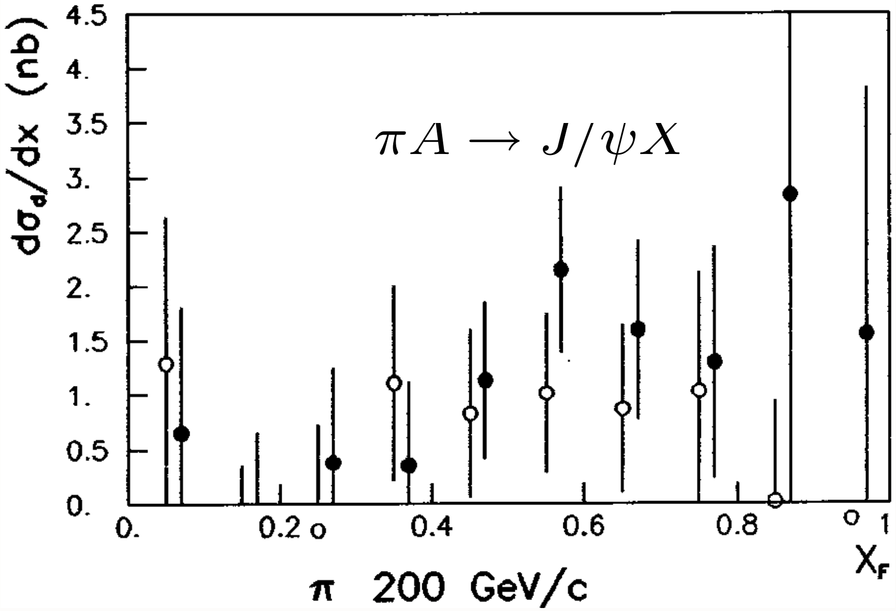
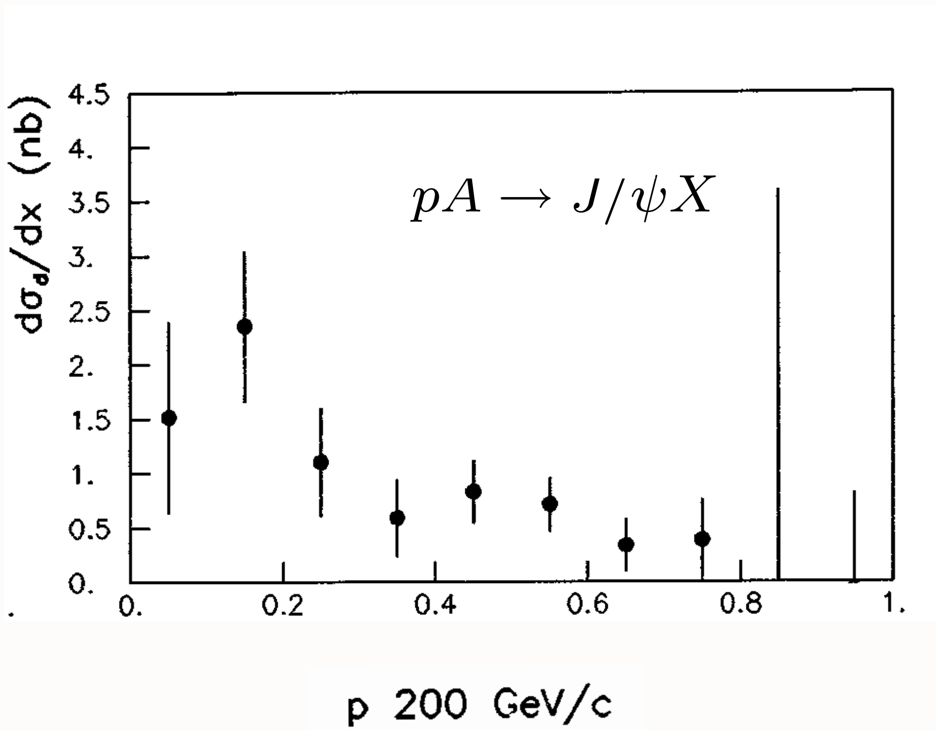


$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$



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

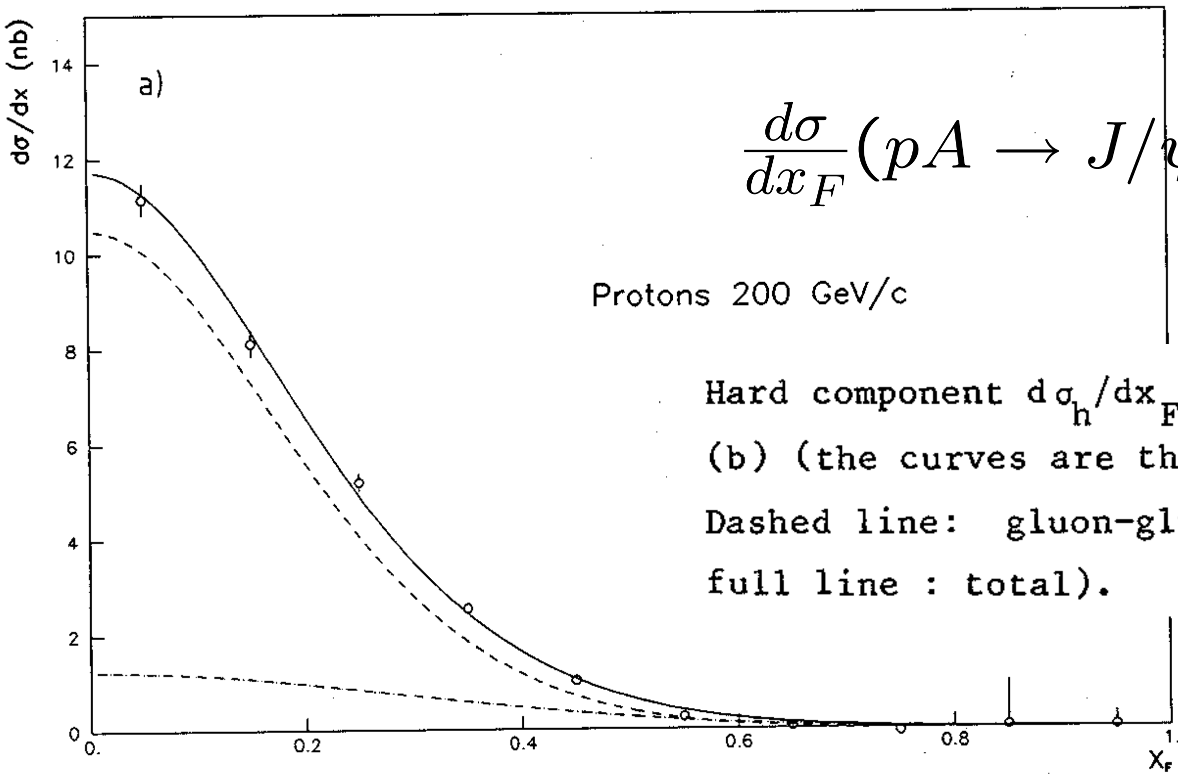
$A^{2/3}$ component



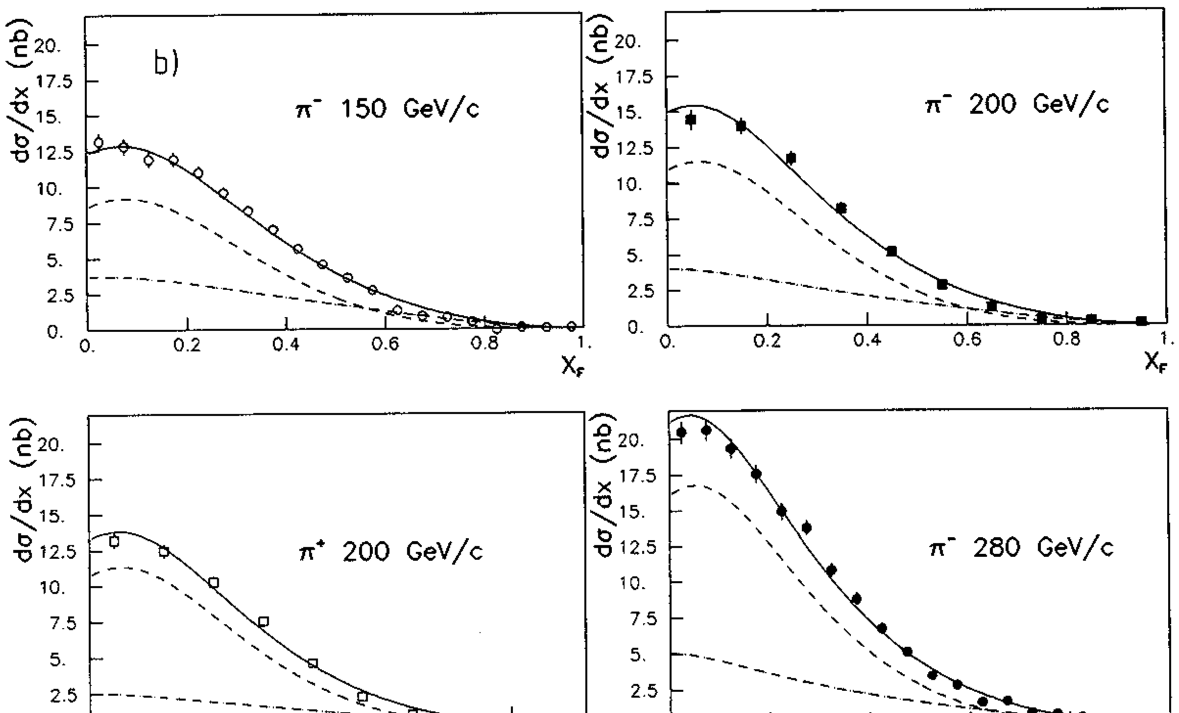
J. Badier et al, NA3

Excess beyond conventional PQCD subprocesses

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



Hard component $d\sigma_h/dx_F$ for incident protons (a) and pions (b) (the curves are the result of the fit described in the text. Dashed line: gluon-gluon fusion; dash-dotted line : $q\bar{q}$ fusion; full line : total).



A^1 component consistent with sum of gg and $\bar{q}q$ fusion

ELSEVIER

Nuclear Physics B441 (1995) 197–214

NUCLEAR PHYSICS B

QCD constraints on the shape of polarized quark and gluon distributions ☆

Stanley J. Brodsky [a], Matthias Burkardt [b,1], Ivan Schmidt [c]

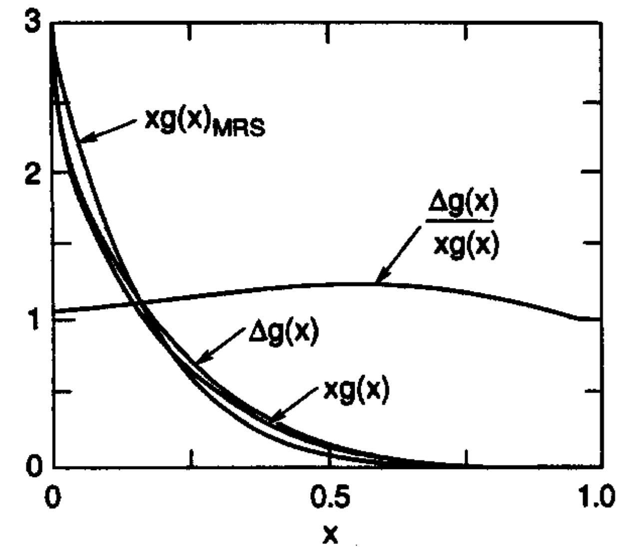
[a] Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, USA
[b] Center for Theoretical Physics, Laboratory for Nuclear Science, and Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[c] Universidad Federico Santa María, Casilla 110-V, Valparaiso, Chile

The limiting power-law behavior at $x \to 1$ of the helicity-dependent distributions derived from the minimally connected graphs

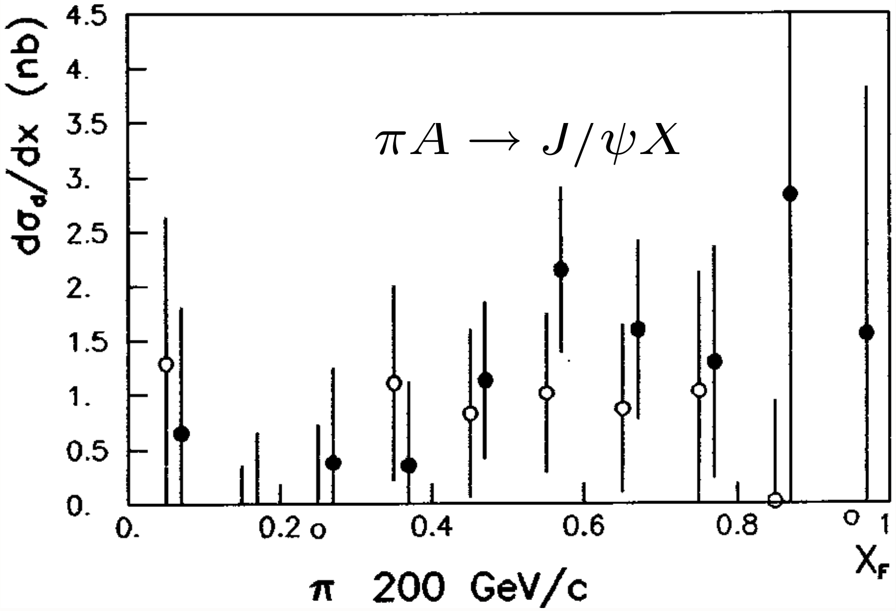
$$G_{q/H} \sim (1-x)^p,$$

where

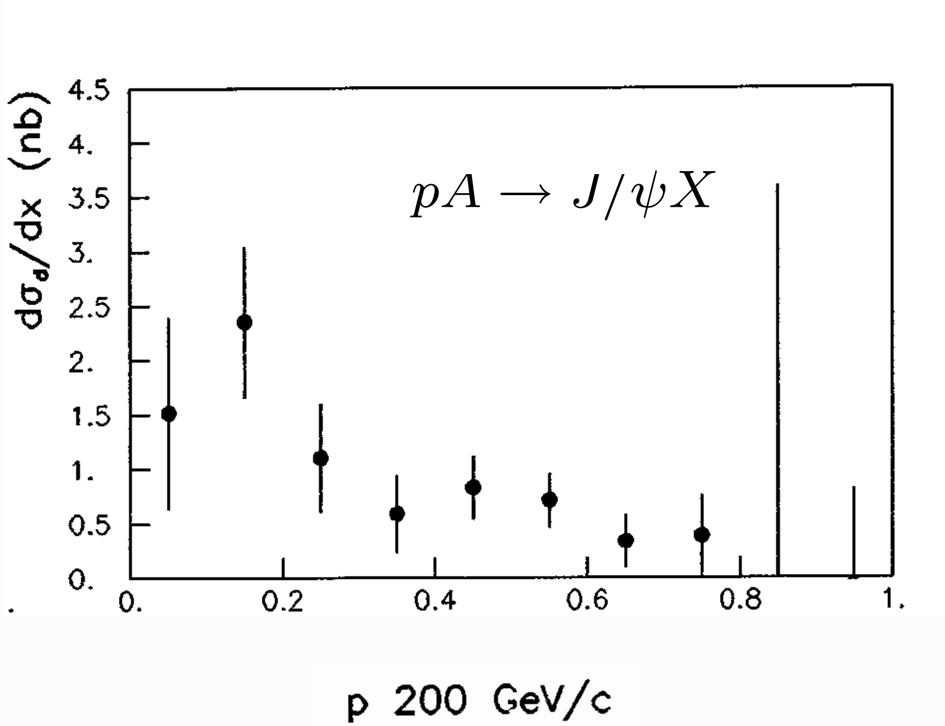
$$p = 2n - 1 + 2\Delta S_z .$$



J. Badier et al, NA3



$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^1 \frac{d\sigma_1}{dx_F} + A^{2/3} \frac{d\sigma_2/}{dx_F}$$



$A^{2/3}$ component

High x_F

consistent with

color octet

intrinsic charm

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, bcc, bbb, at high x_F**
- **Intrinsic charm -- long distance contribution to penguin mechanisms for weak decay** *Gardner, sjb*
- $J/\psi \to \rho\pi$ **puzzle explained** *Karliner , sjb*
- **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**

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

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

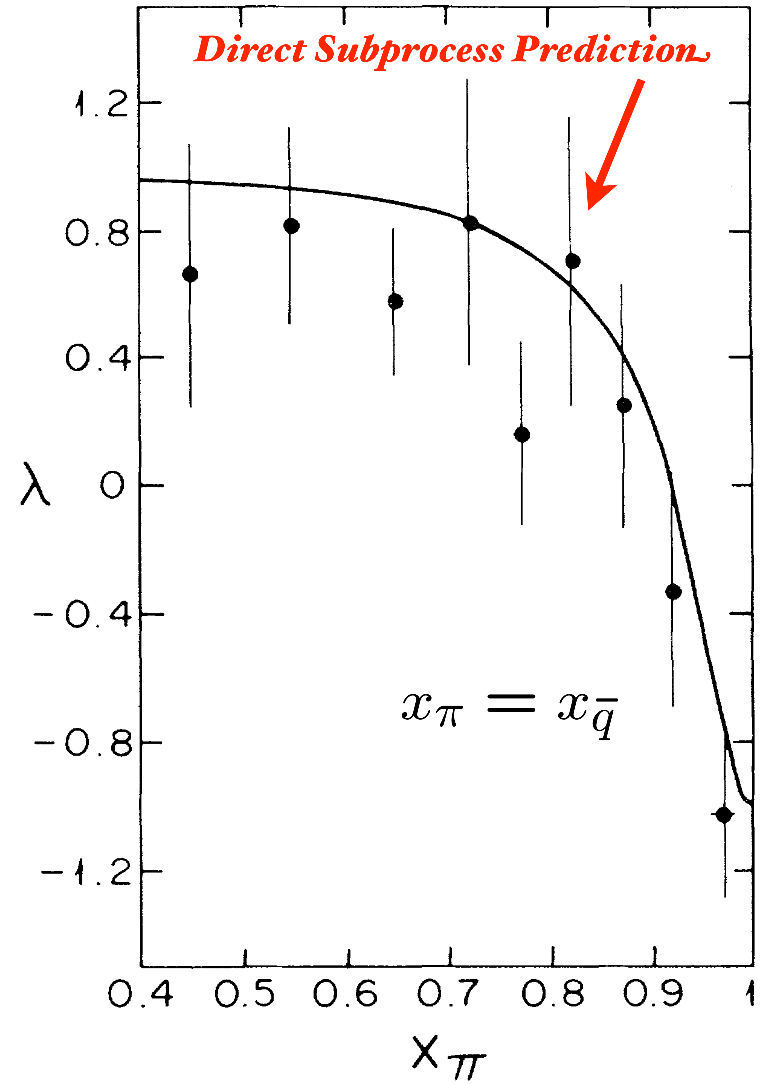
$$\frac{d^2\sigma}{dx_\pi d\cos\theta} \propto x_\pi \left[(1-x_\pi)^2 (1+\cos^2\theta) + \frac{4}{9} \frac{\langle k_T^2 \rangle}{M^2} \sin^2\theta \right]$$

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

$$Q^2 = M^2$$

Dramatic change in angular distribution at large x_F

Example of a higher-twist direct subprocess



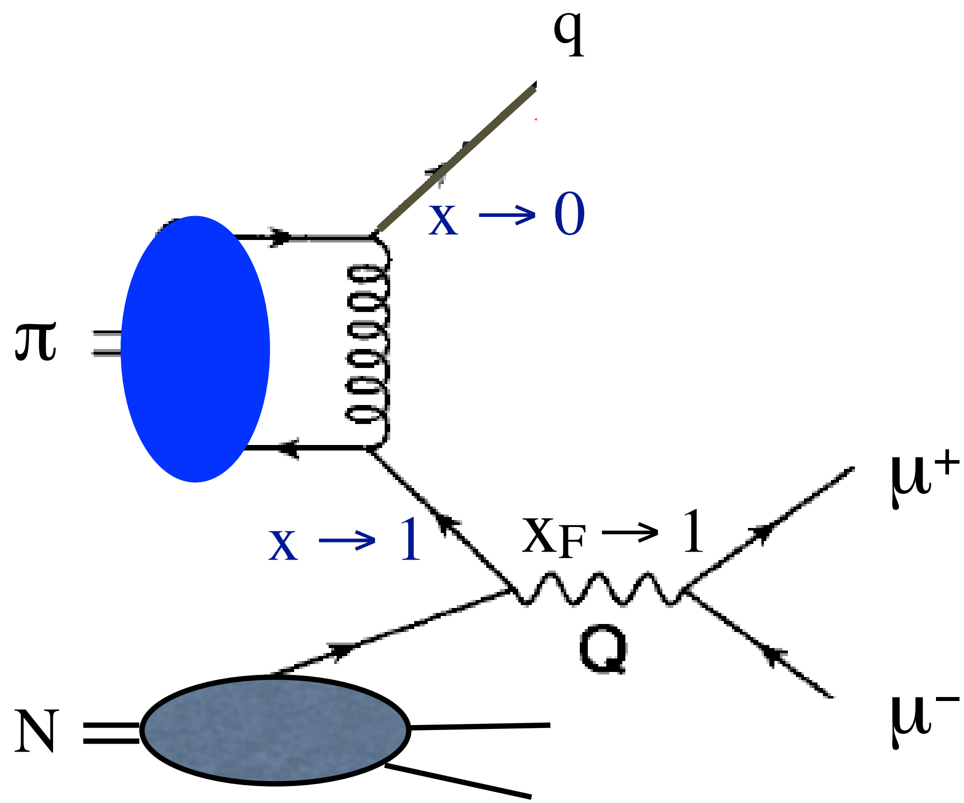
Chicago-Princeton Collaboration

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 $Q^2 \to \infty$

Entire pion wf contributes to hard process



Virtual photon is longitudinally polarized

Berger, sjb
Khoze, Brandenburg, Muller, sjb

Hoyer Vanttinen

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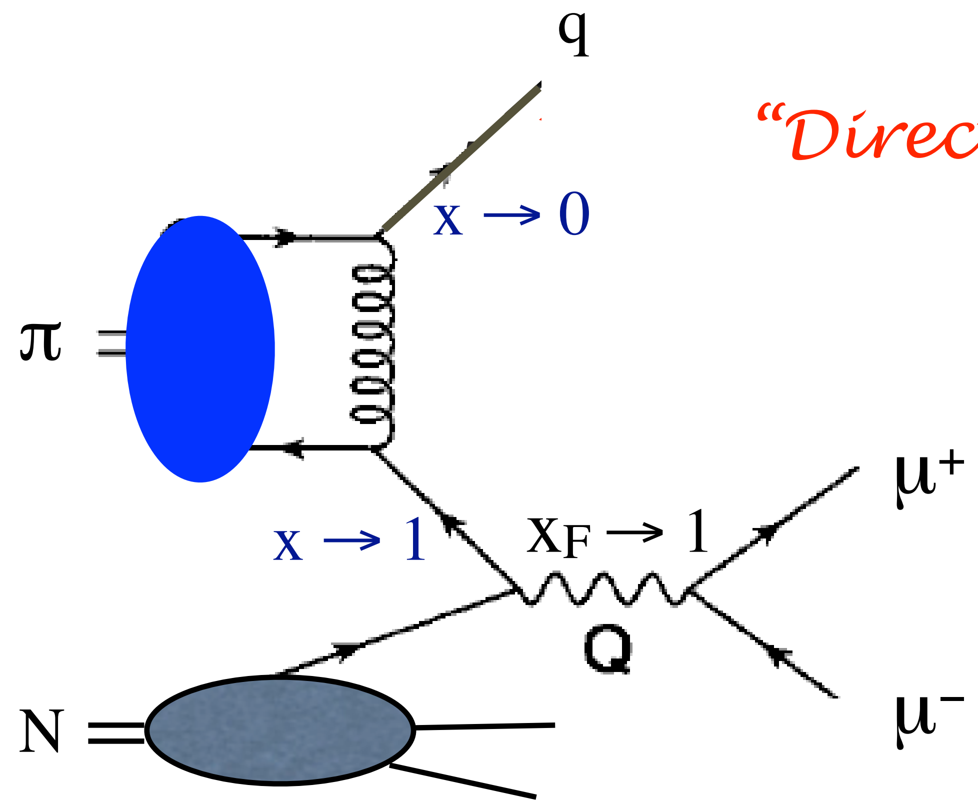

"Direct" Subprocess

Virtual photon is longitudinally polarized

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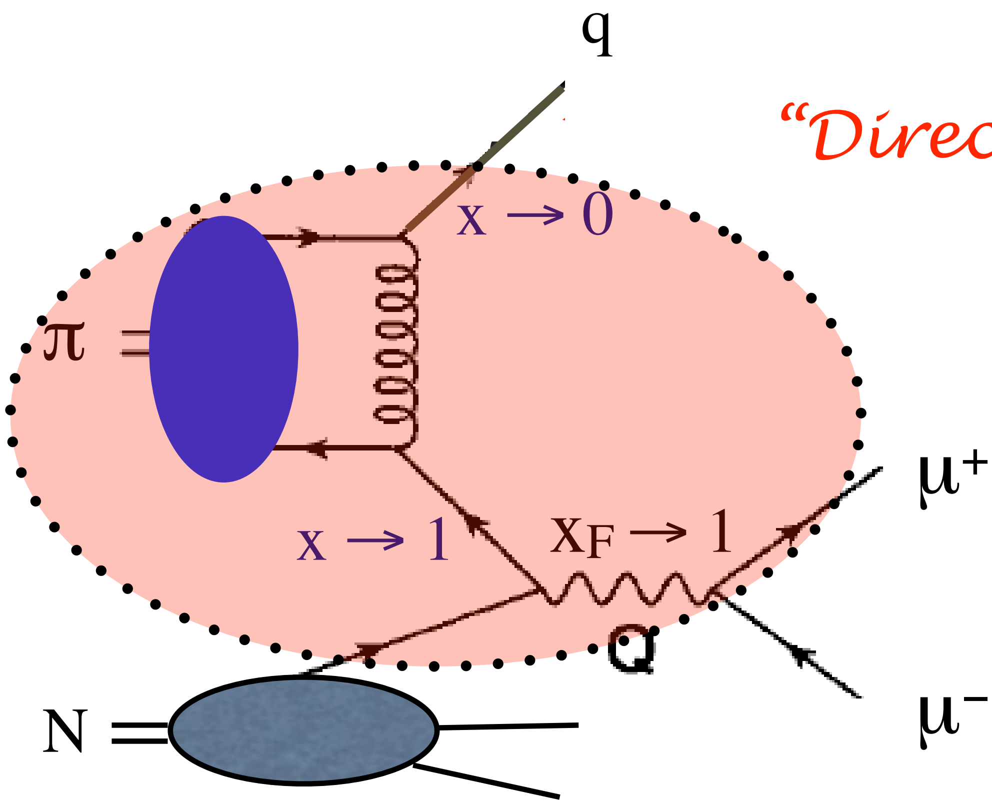

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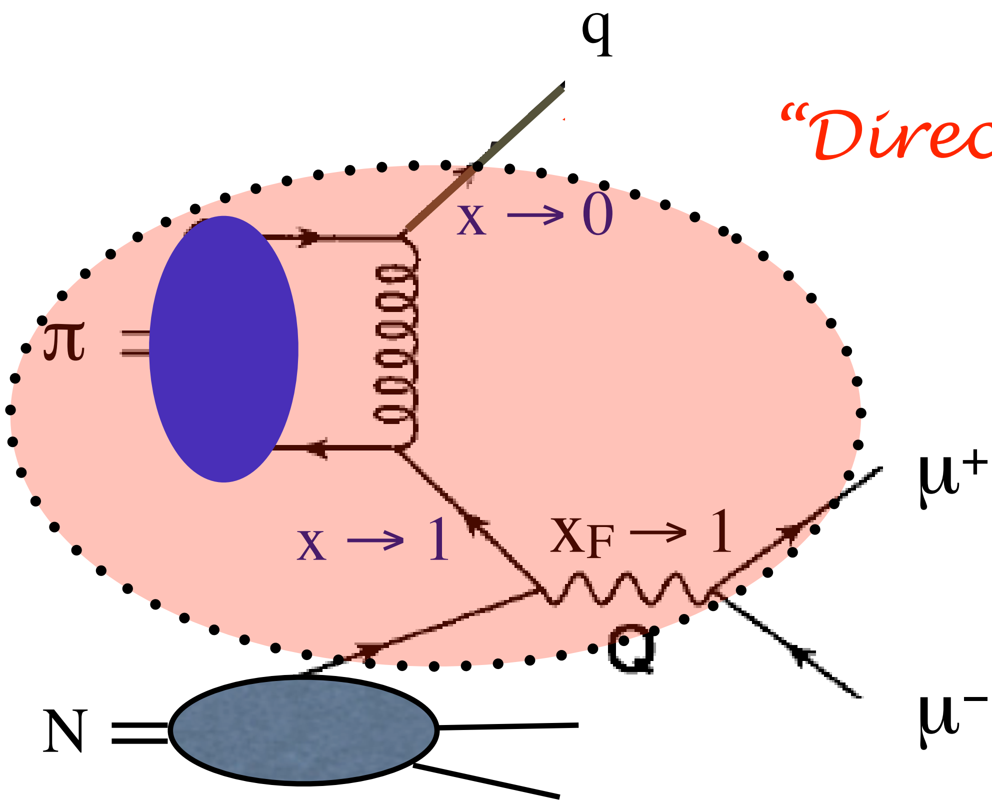
Distribution amplitude from AdS/CFT

Entire pion wf contributes to hard process



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Distribution amplitude from AdS/CFT

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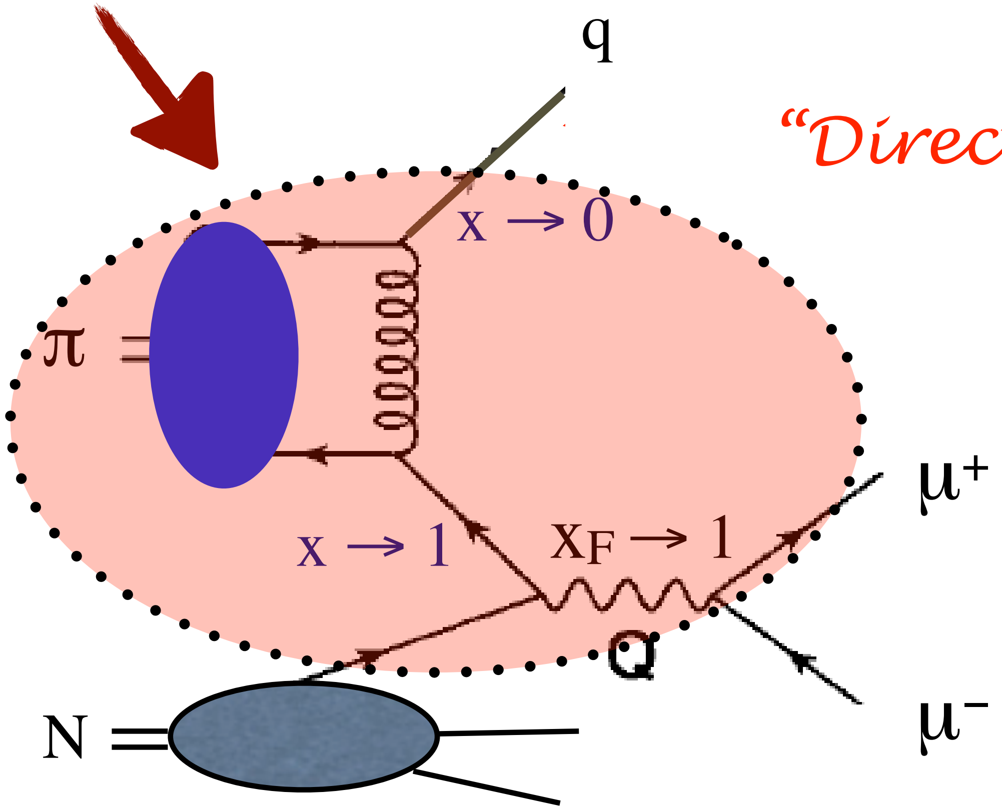

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Khoze, Brandenburg, Muller, sjb

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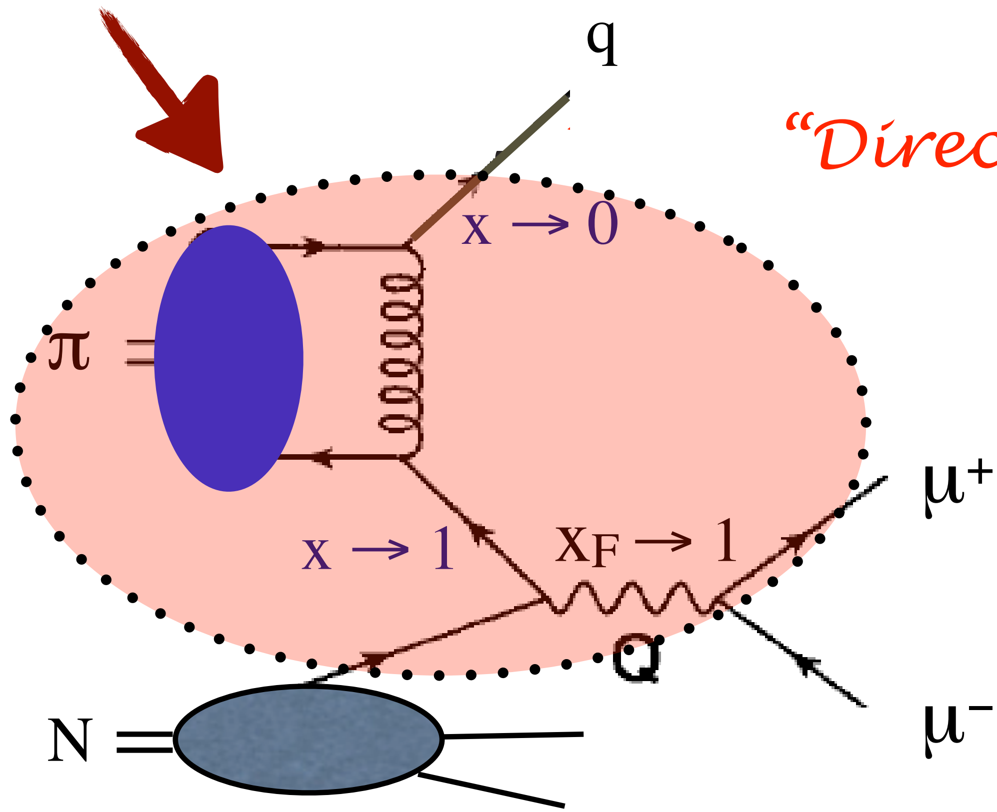


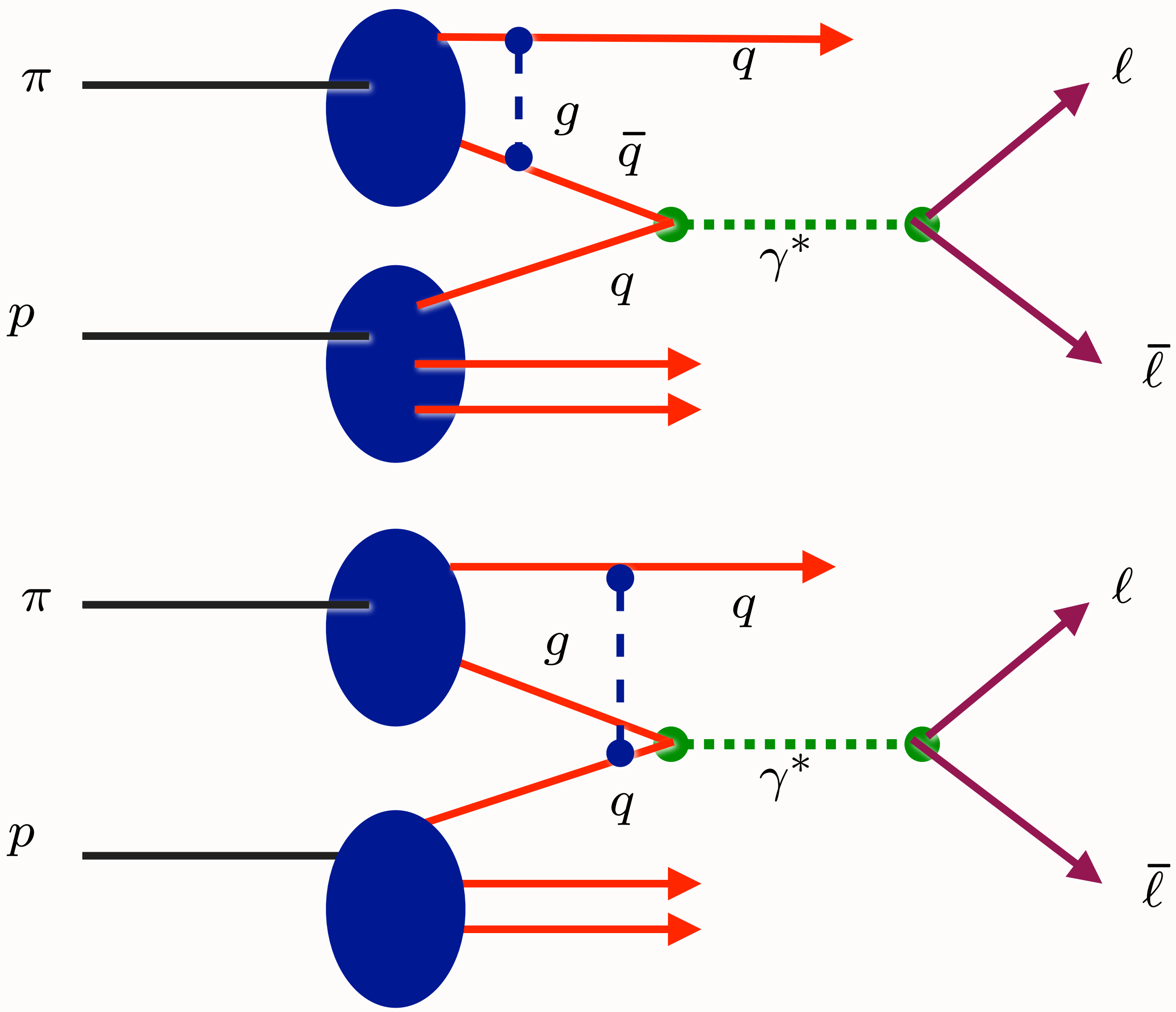
"Direct" Subprocess

Virtual photon is longitudinally polarized

Similar higher twist terms in jet hadronization at large z

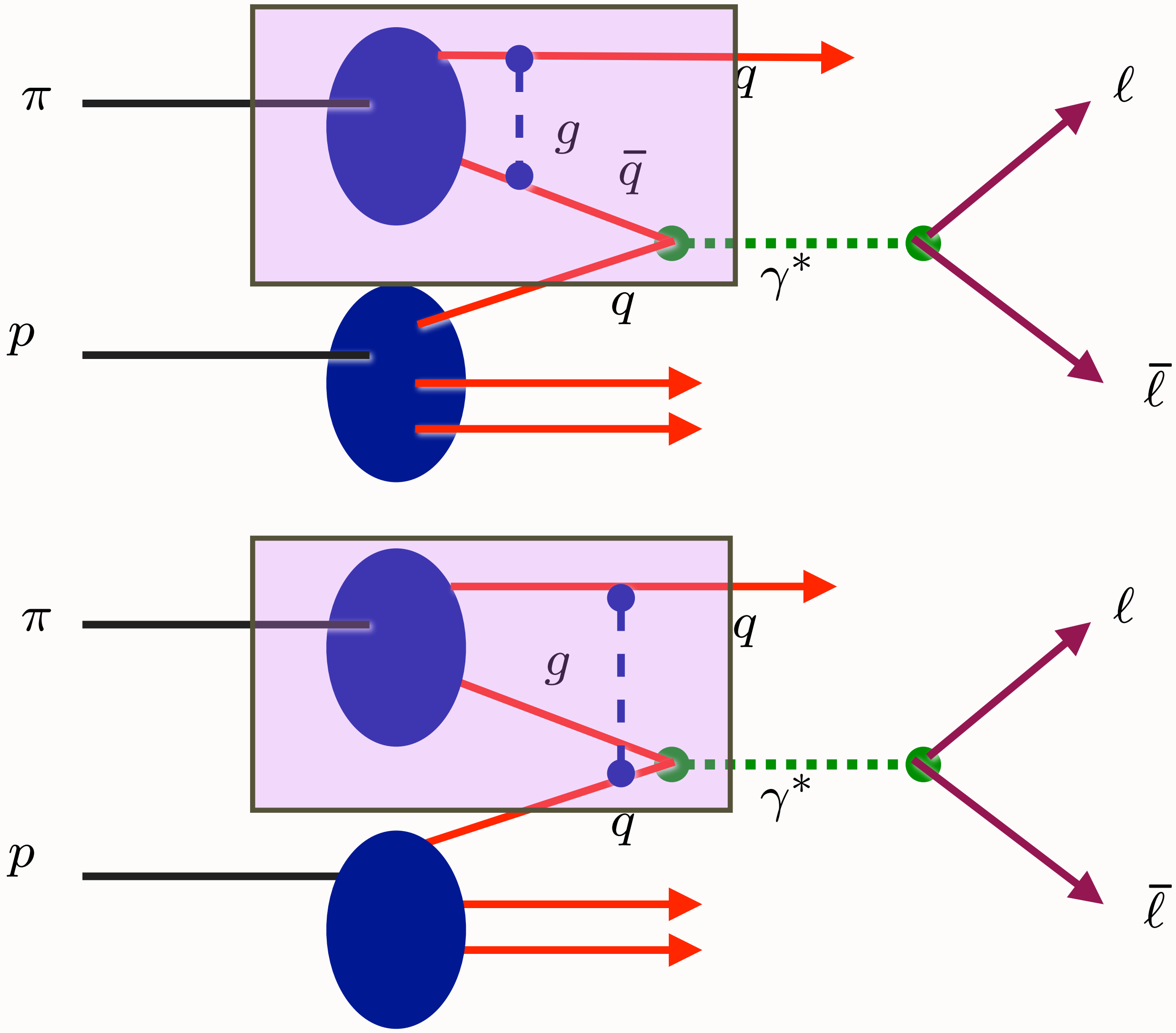
Berger, sjb
Khoze, Brandenburg, Muller, sjb
Hoyer Vanttinen

Berger, Lepage, sjb



Initial State Interaction

Berger, Lepage, sjb

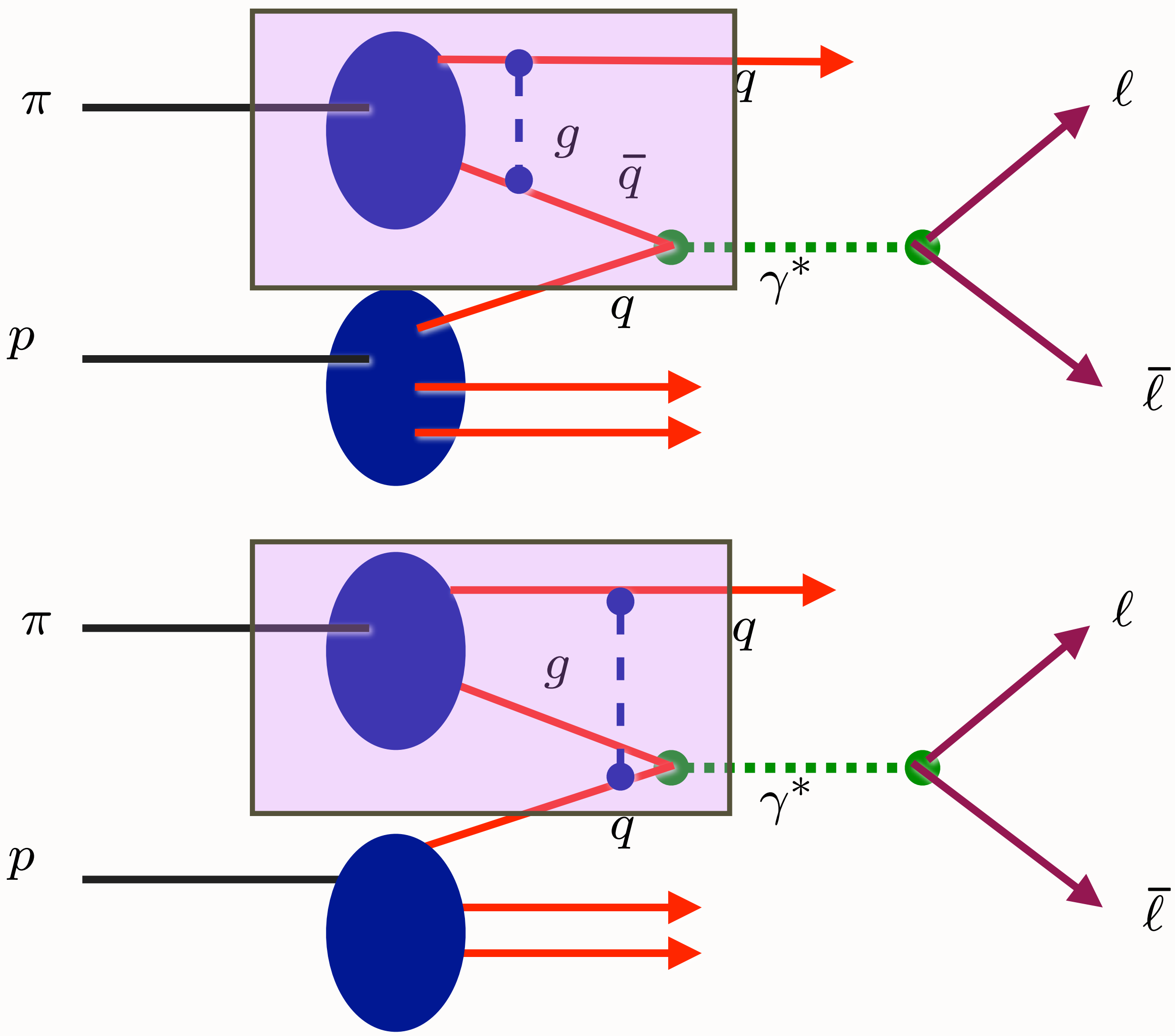


$$\pi q \to \gamma^* q$$

Initial State Interaction

Pion appears directly in subprocess at large x_F

Berger, Lepage, sjb



$$\pi q \to \gamma^* q$$

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

Bjorken, Kogut, Soper; Blankenbecler, Gunion, sjb; Blankenbecler, Schmidt

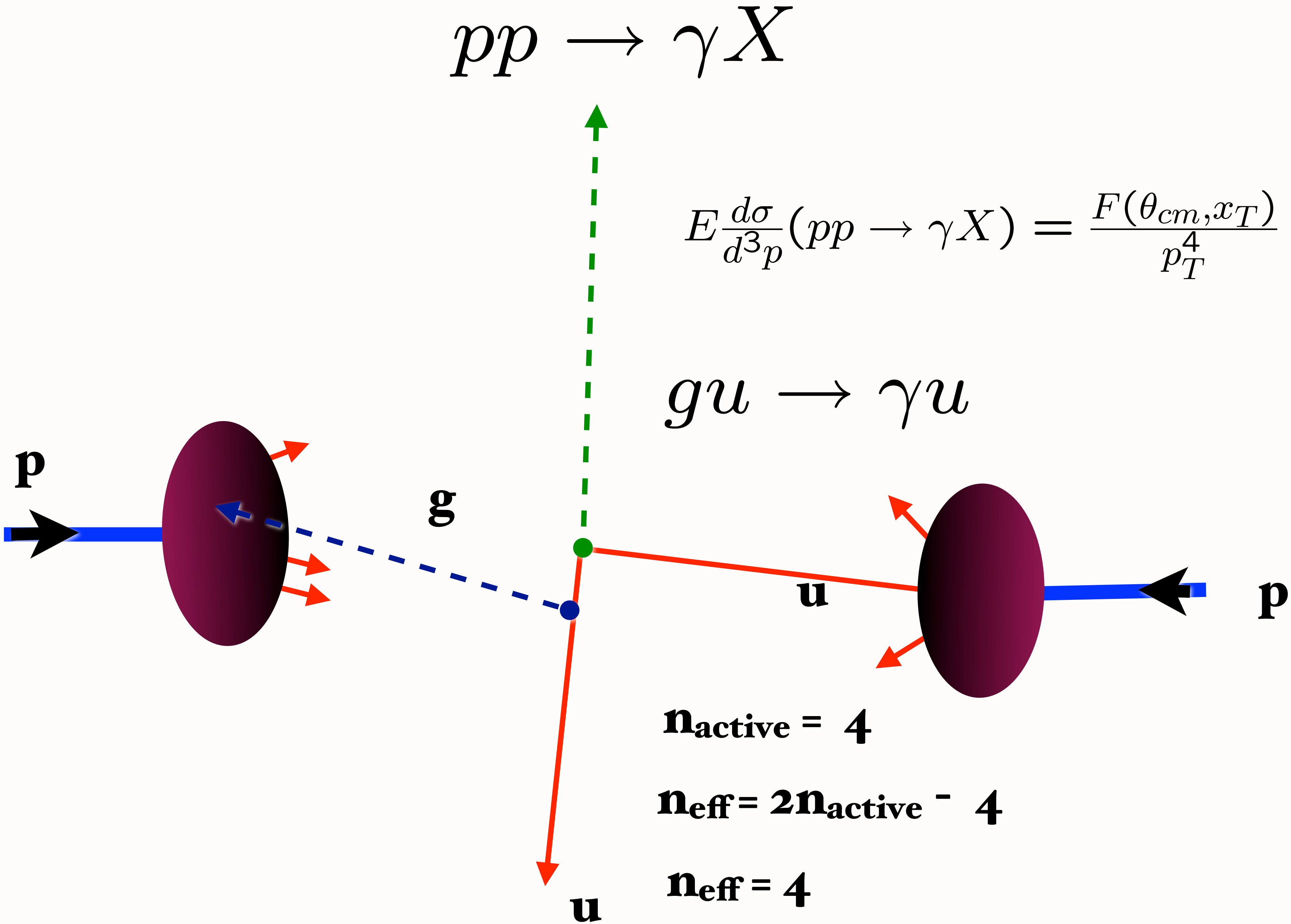
Crucial Test of Leading -Twist QCD: Scaling at fixed x_T

$$E\frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T, \theta_{cm})}{p_T^{n_{\rm eff}}} \qquad x_T = \frac{2p_T}{\sqrt{s}}$$

Parton model: n_{eff} = 4

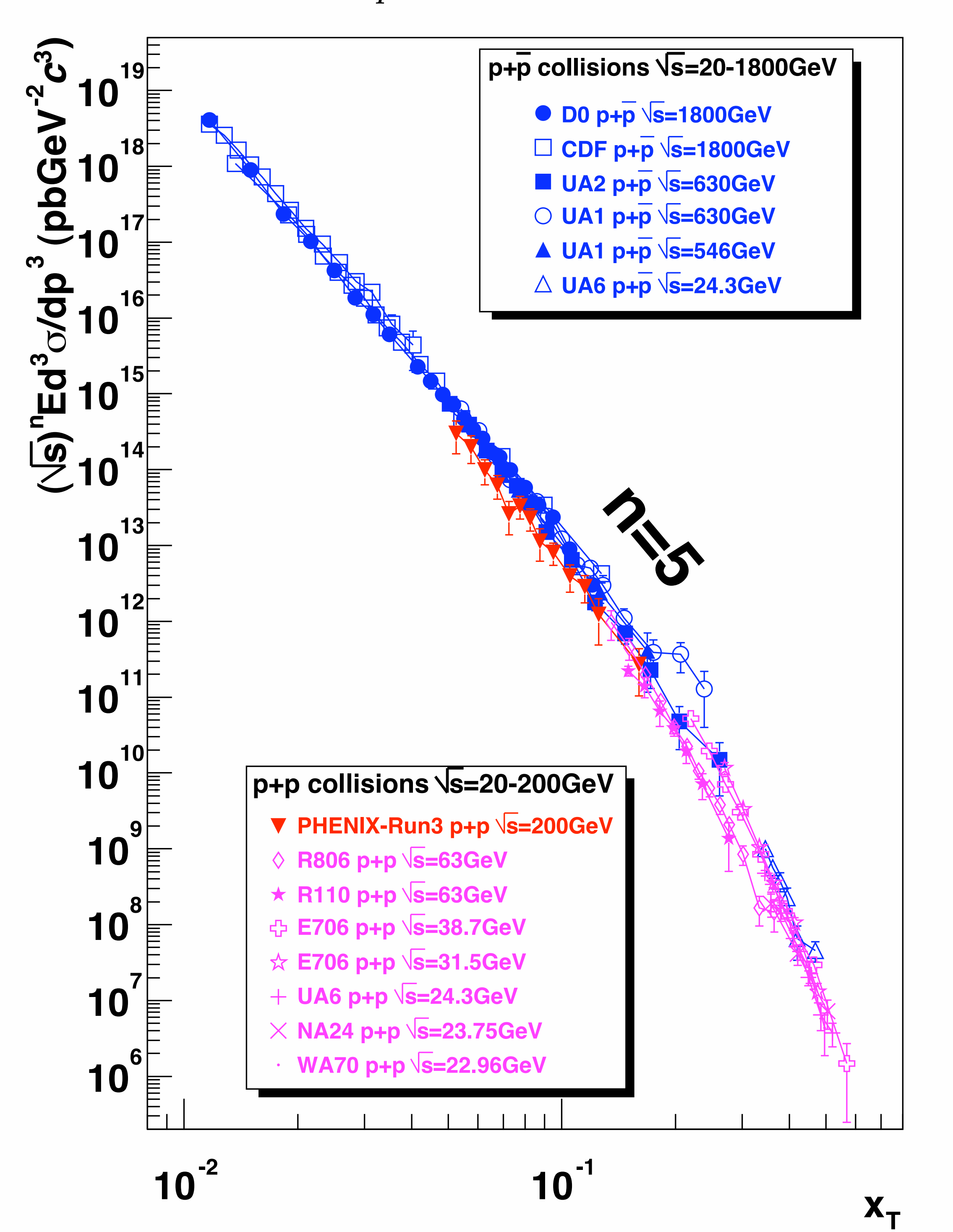
As fundamental as Bjorken scaling in DIS

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


$pp \to \gamma X$
$E\frac{d\sigma}{d^3p}(pp \to \gamma X) = \frac{F(\theta_{cm}, x_T)}{p_T^4}$
$gu \to \gamma u$
p
g
u
p
u
$n_{active} = 4$
$n_{eff} = 2n_{active} - 4$
$n_{eff} = 4$

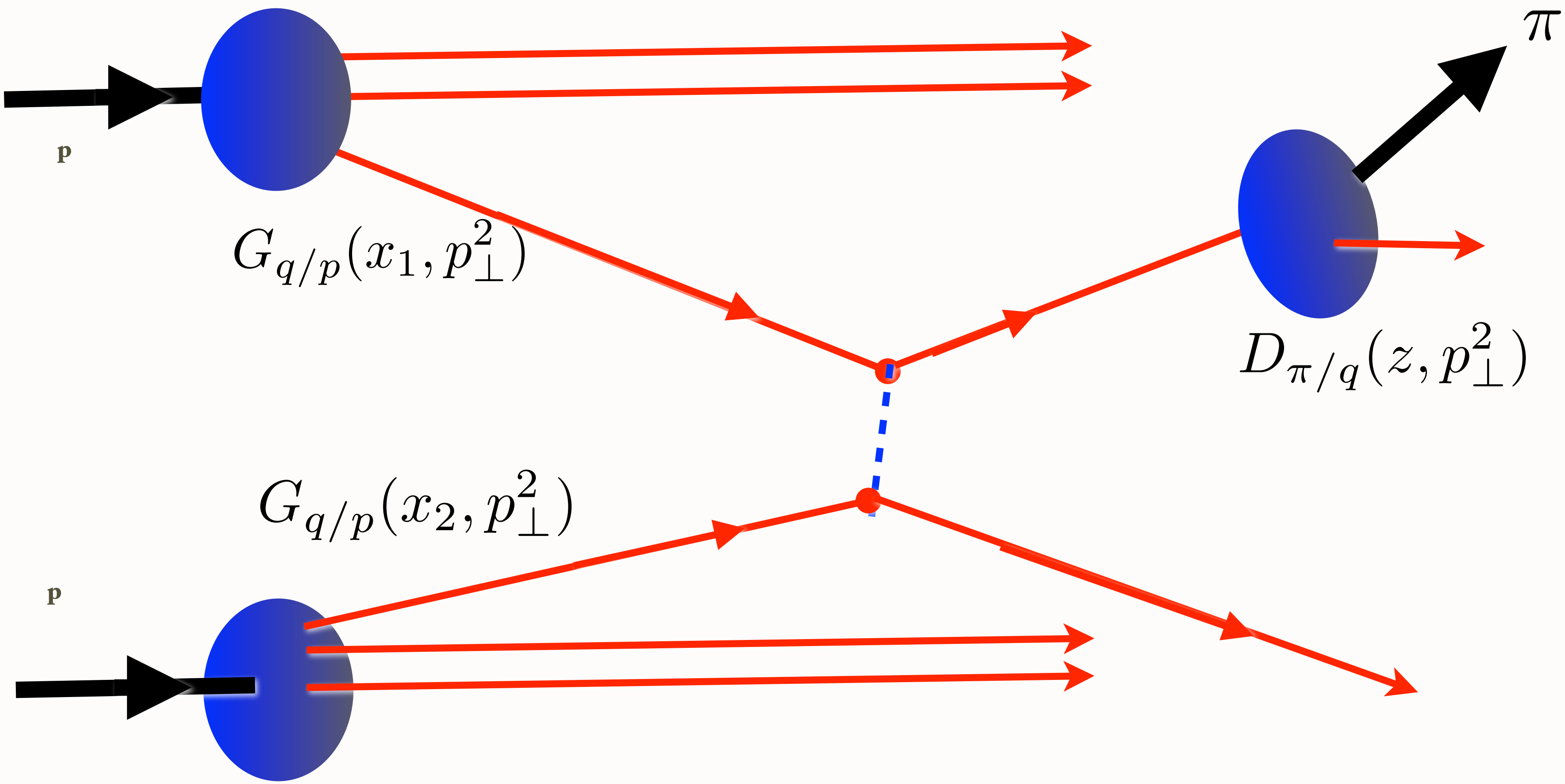
$\sqrt{s}^n E \frac{d\sigma}{d^3p}(pp \to \gamma X)$ at fixed x_T

Tannenbaum



x_T-scaling of direct photon production: consistent with PQCD

Leading-Twist Contribution to Hadron Production

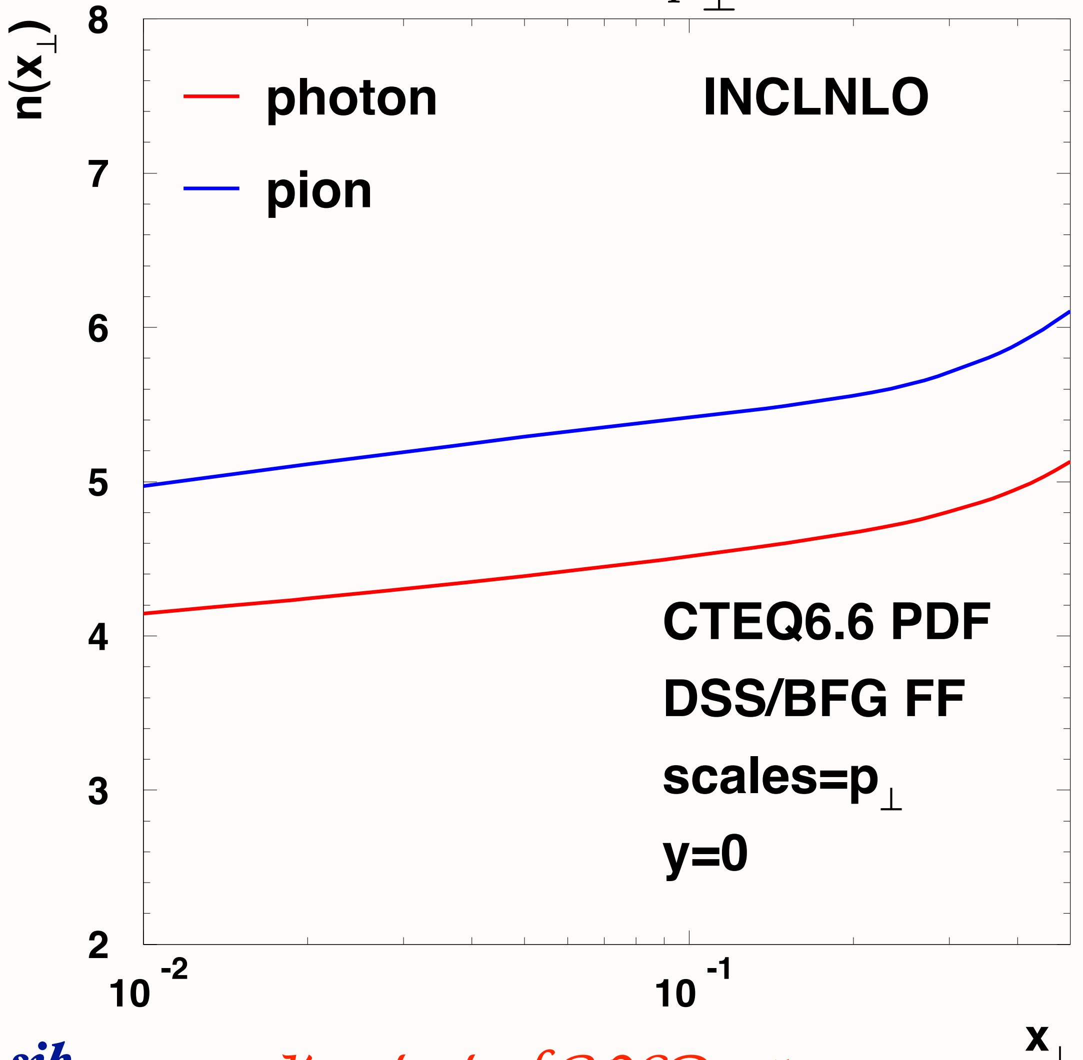


Parton model and Conformal Scaling:

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

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

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



$$pp \to \pi X$$

$$pp \to \gamma X$$

$5 < p_\perp < 20\ GeV$

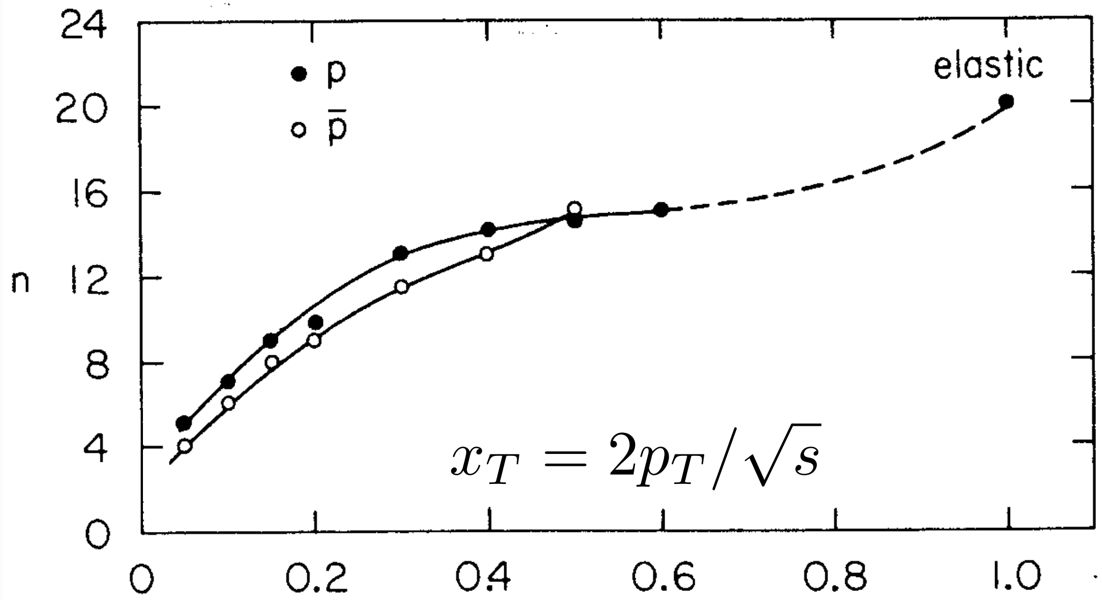
$70\ GeV < \sqrt{s} < 4\ TeV$

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

Arleo, Hwang, Sickles, sjb

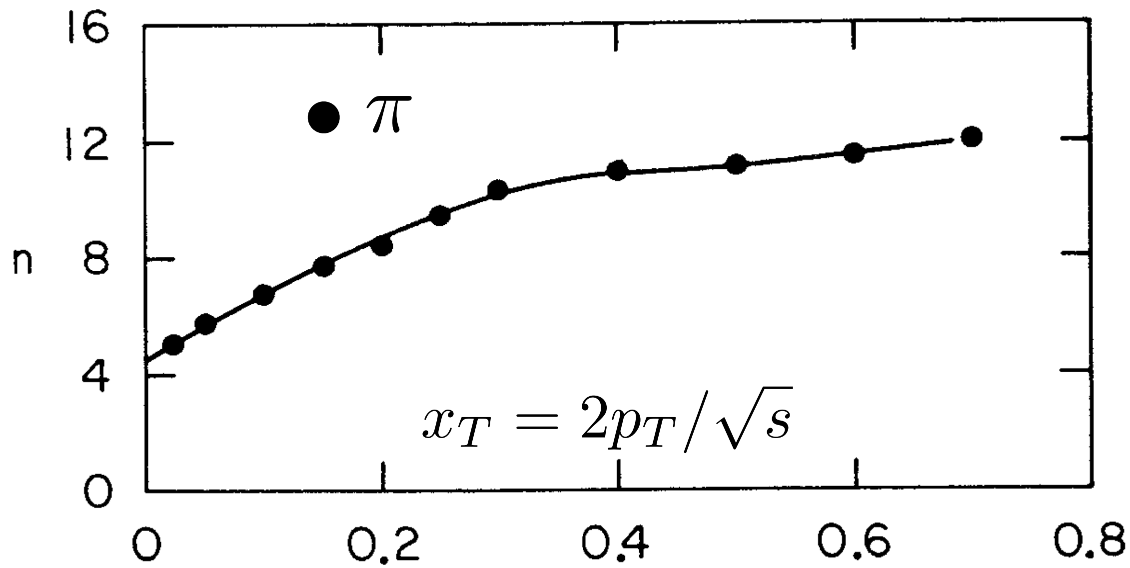
Pirner, Raufeisen, sjb

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



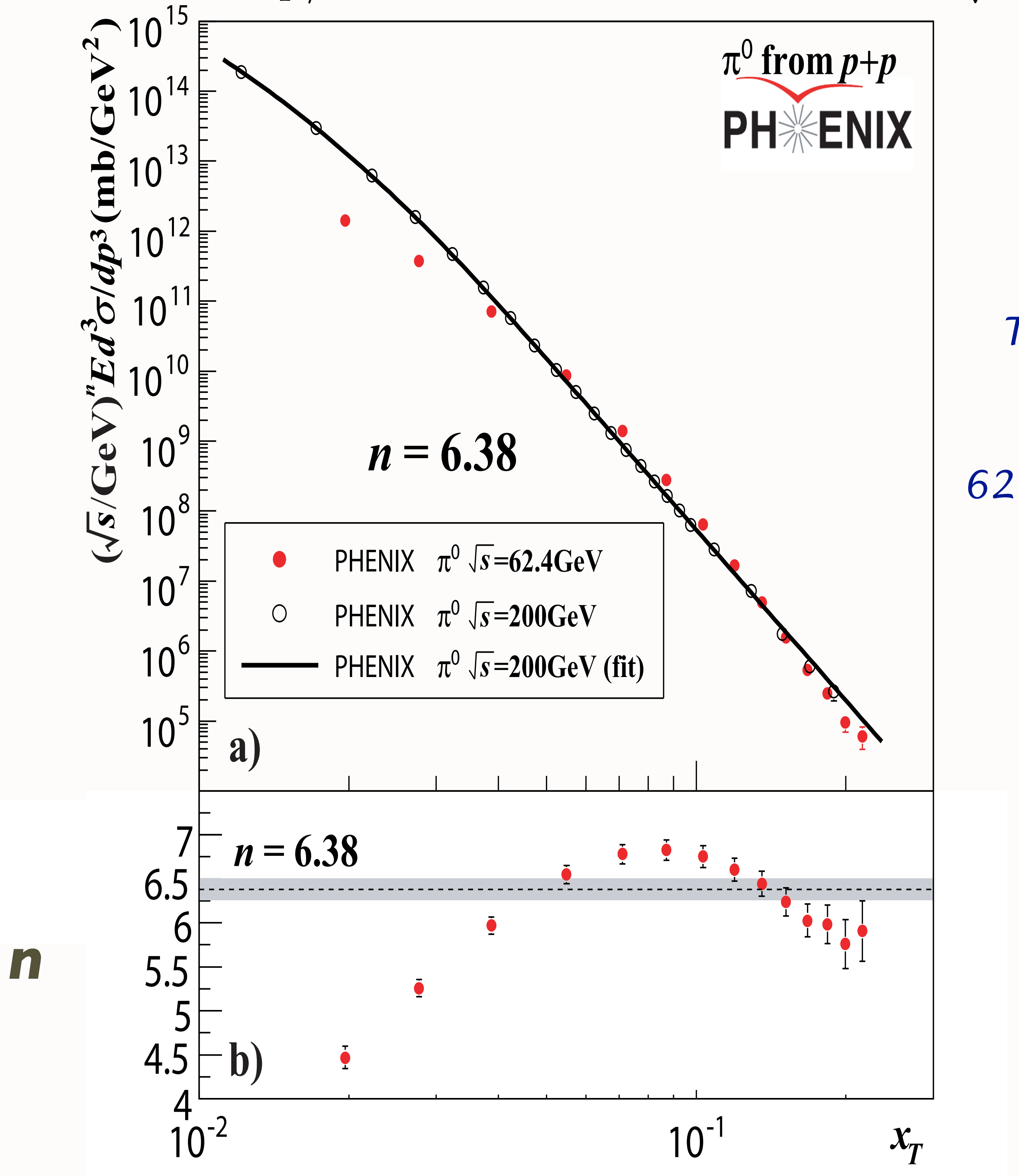
Clear evidence for higher-twist contributions

J. W. Cronin, SSI 1974



Chicago-Princeton FNAL

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

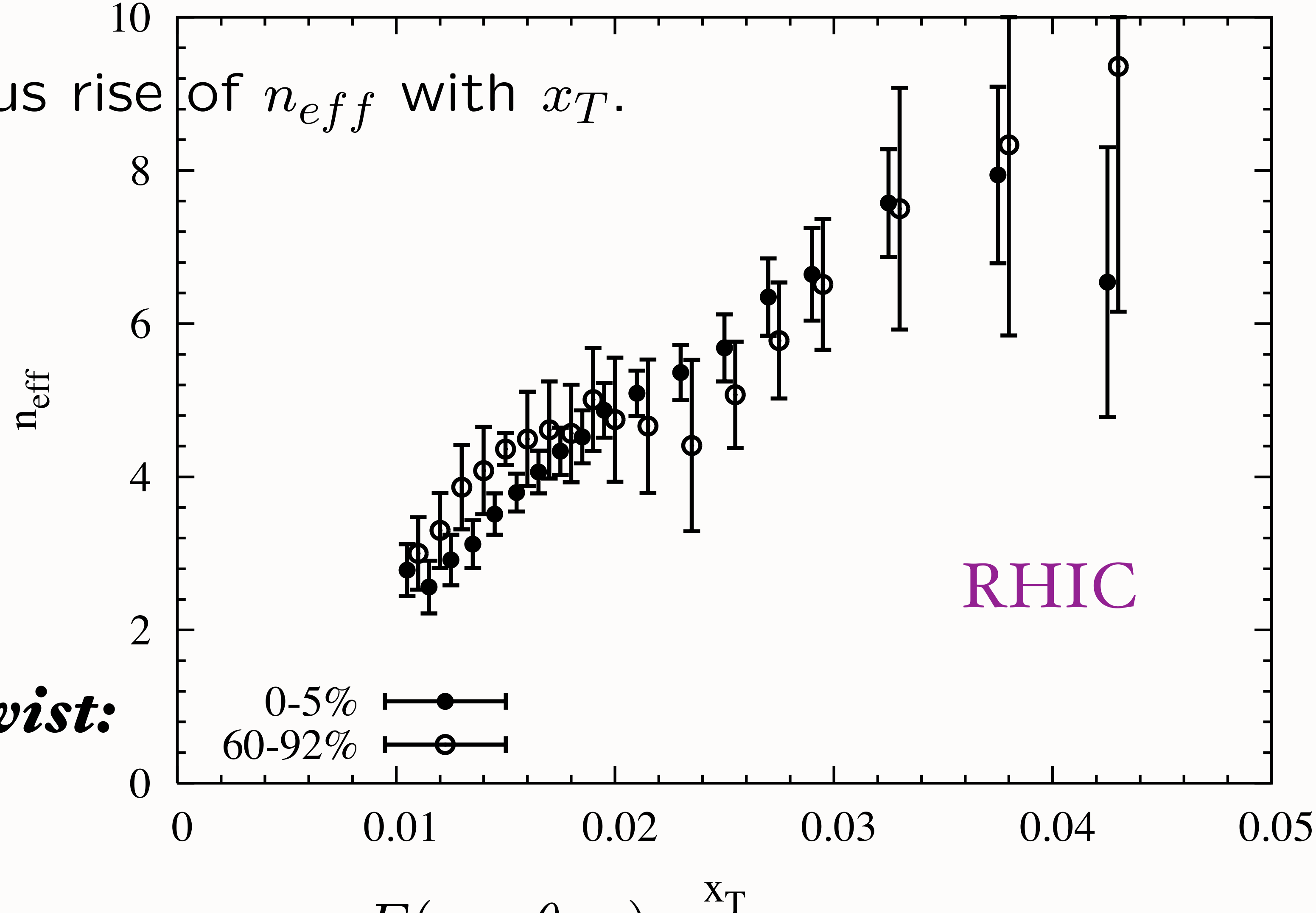


M. J. Tannenbaum

PHENIX 62.4 and 200 GeV data

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.



Leading twist:

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

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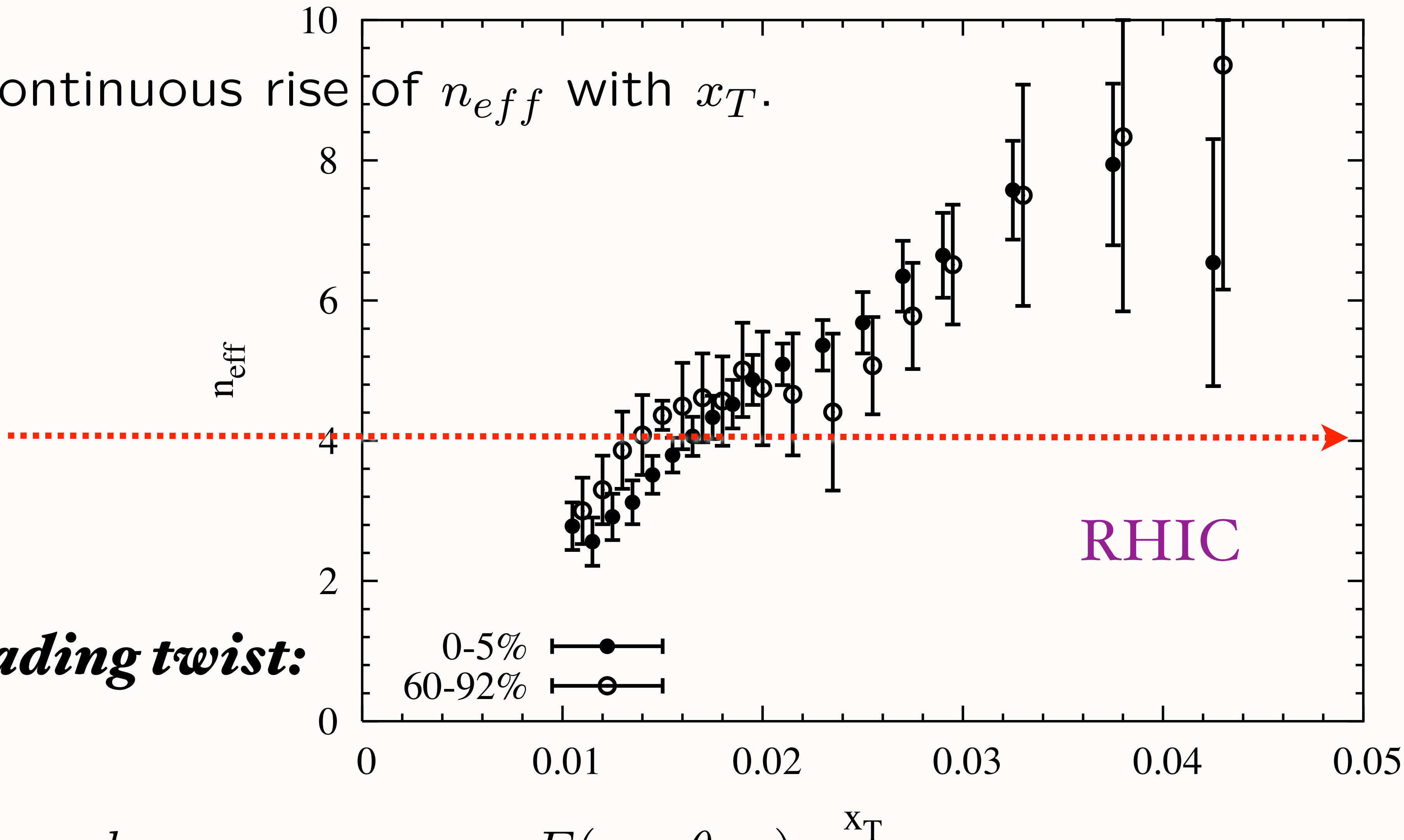

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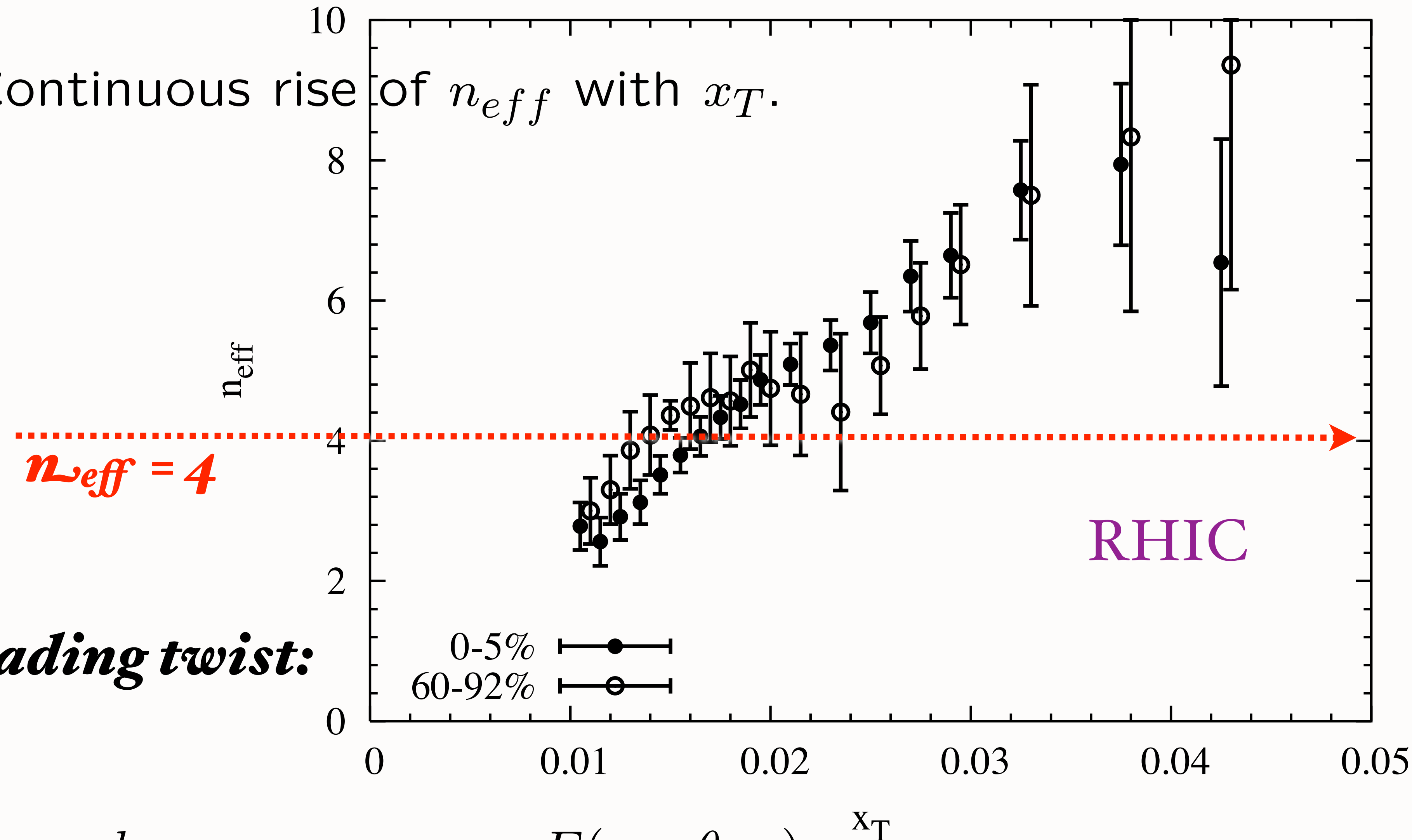

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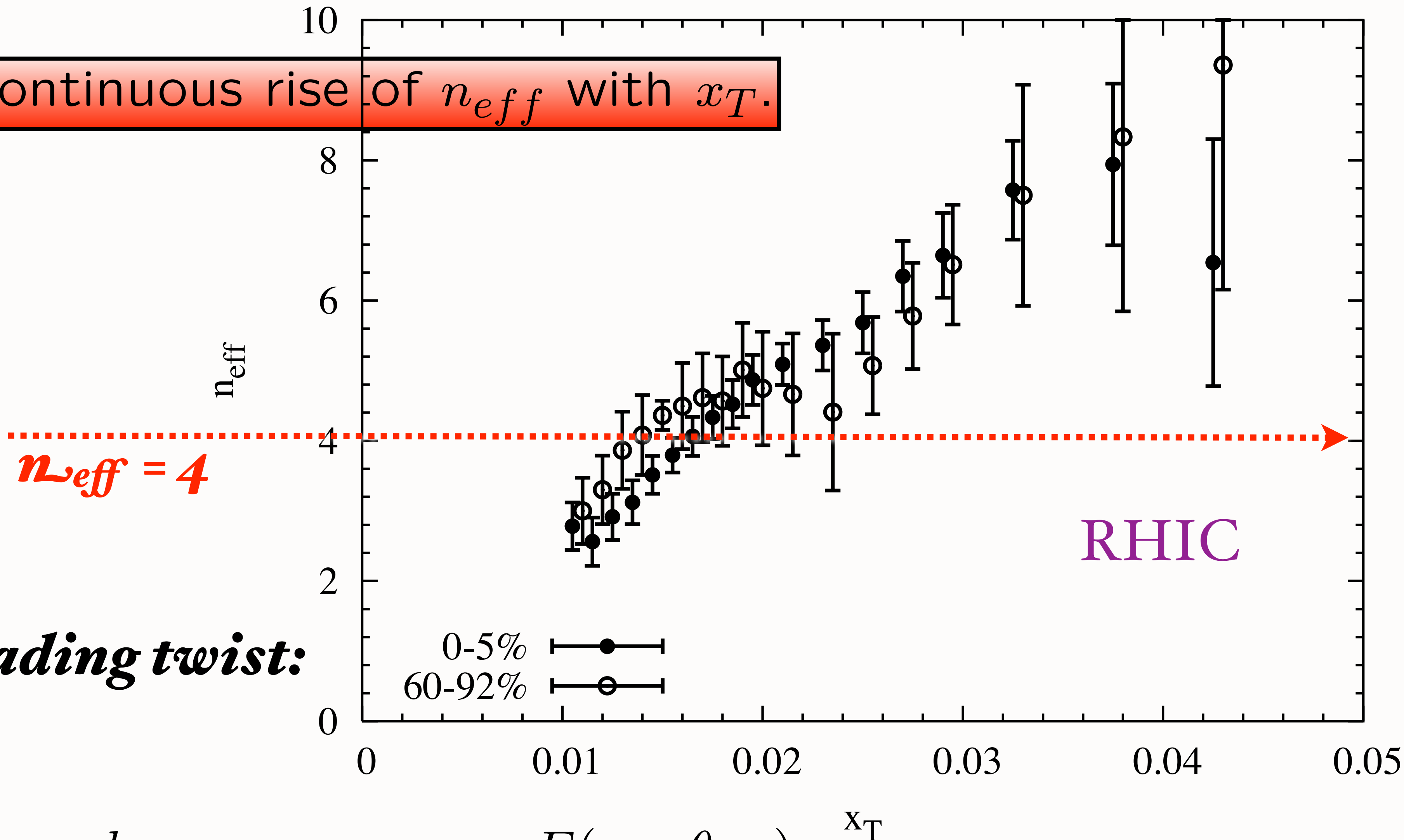

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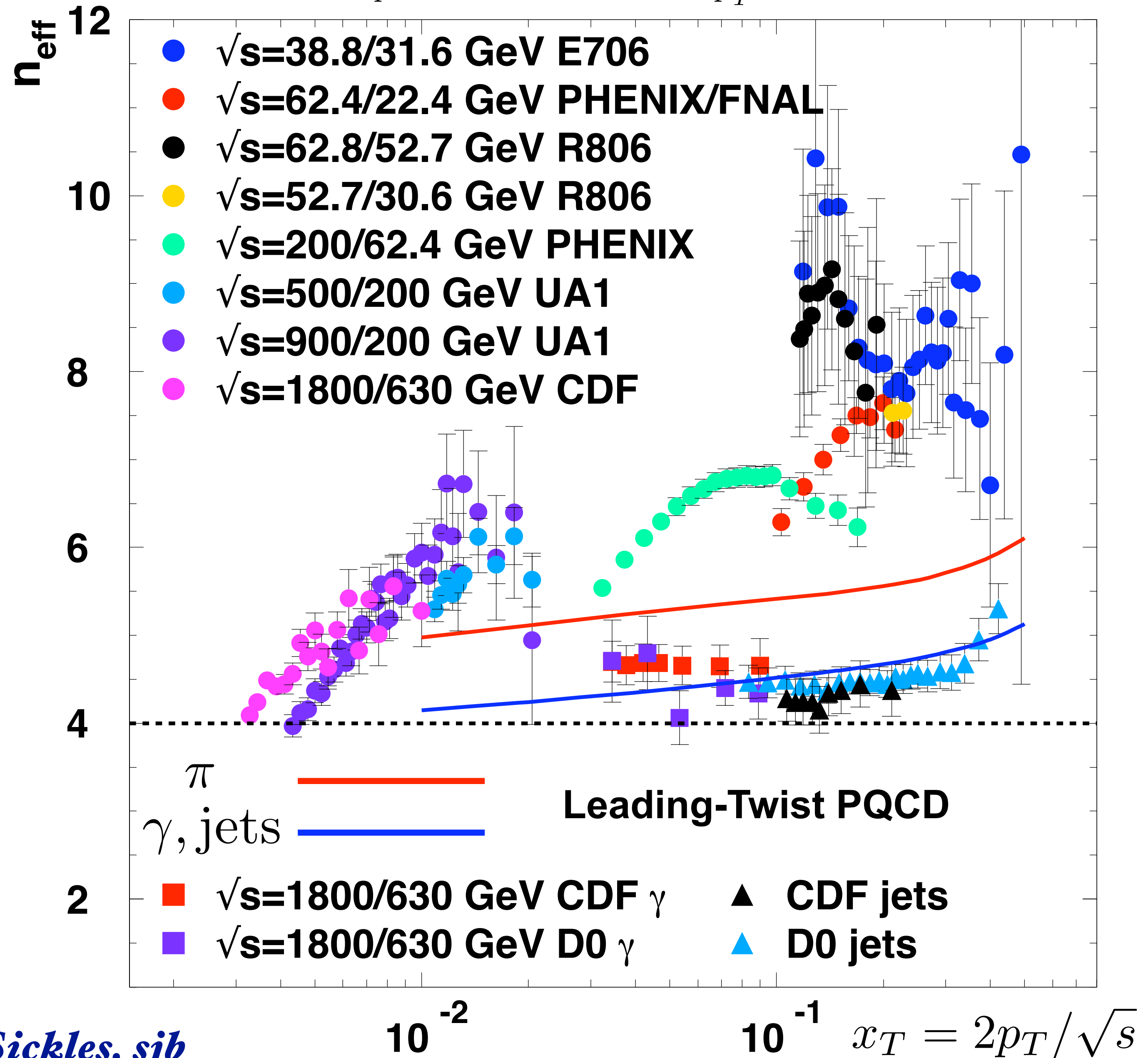
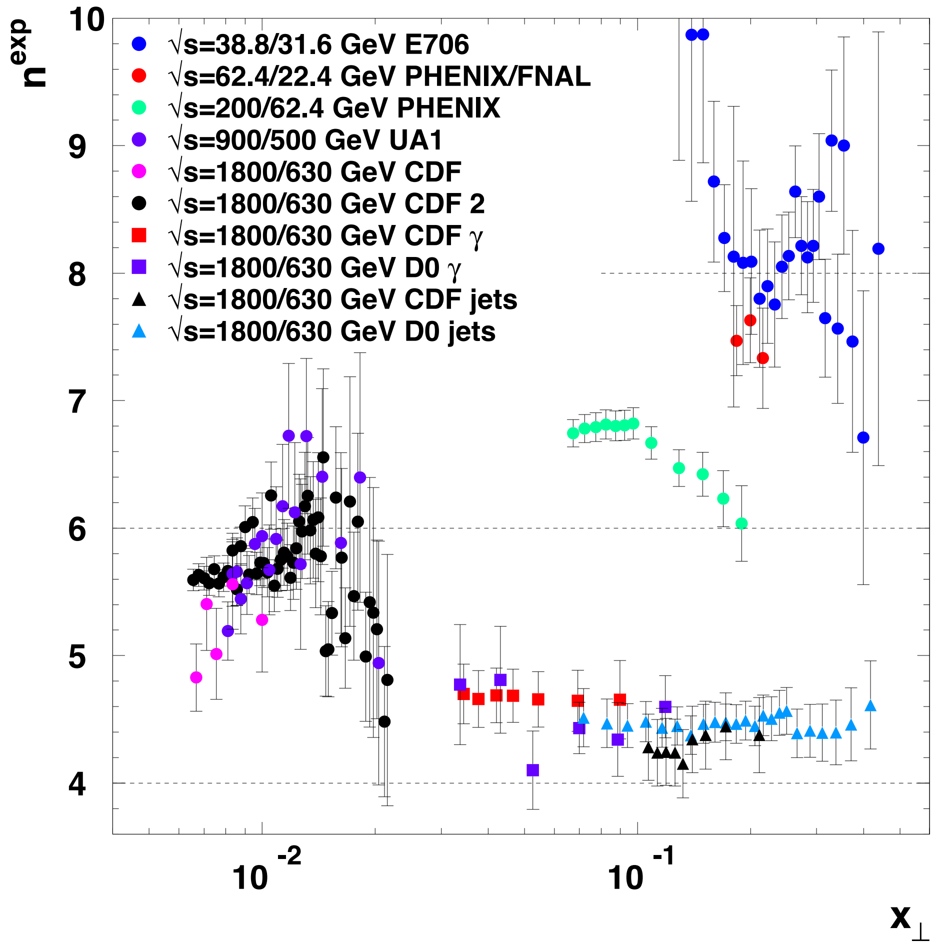
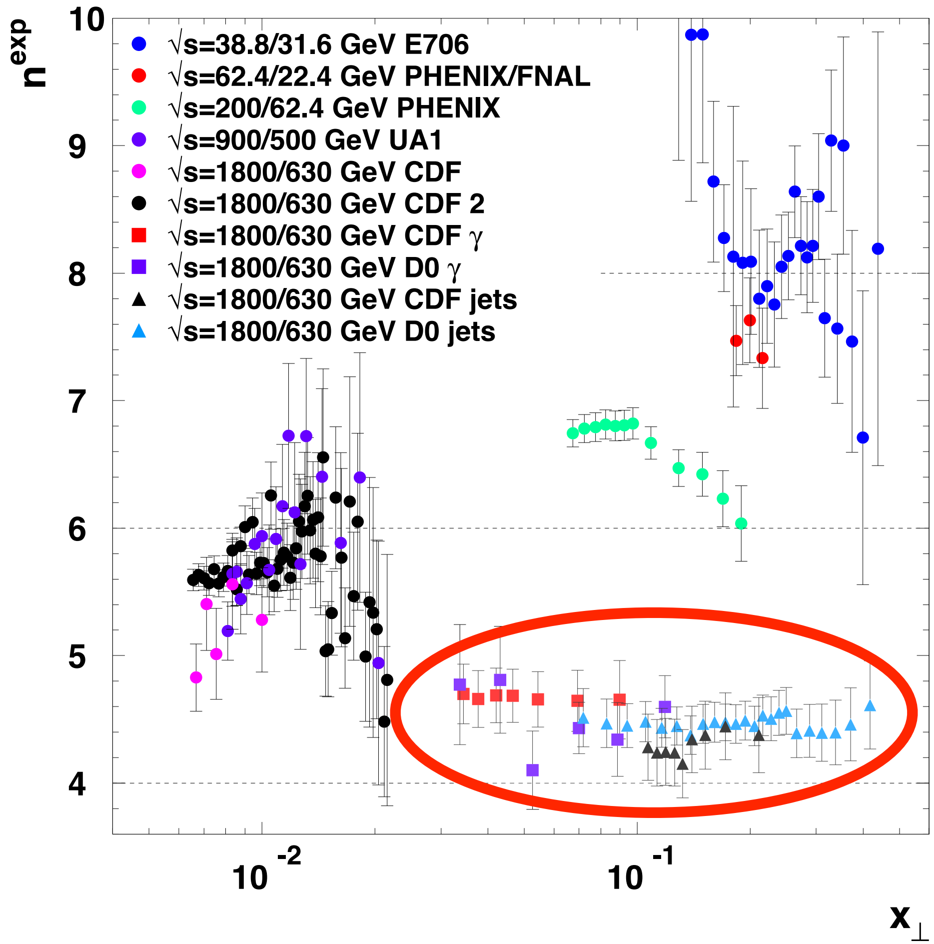


Arleo, Hwang, Sickles, sjb



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



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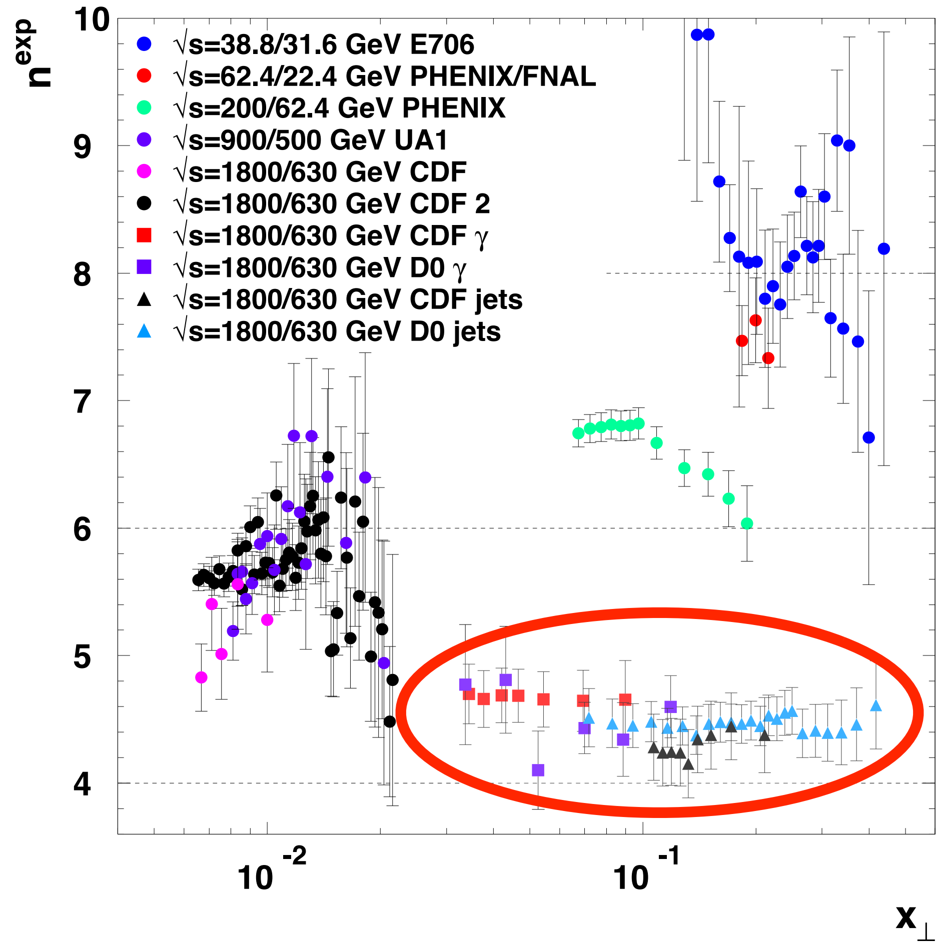

Photons and Jets agree with PQCD x_T scaling
Hadrons do not!

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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.

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Small color-singlet
Color Transparent
Minimal same-side energ

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

Scale dependence

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

2-component toy-model

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

Define effective exponent

$$\begin{aligned} n_{\rm eff}(x_\perp, p_\perp, B/A) &\equiv -\frac{\partial \ln \sigma^{\rm model}}{\partial \ln p_\perp} + n^{\rm NLO}(x_\perp, p_\perp) - 4 \\ &= \frac{2B/A}{p_\perp^2 + B/A} + n^{\rm NLO}(x_\perp, p_\perp) \end{aligned}$$

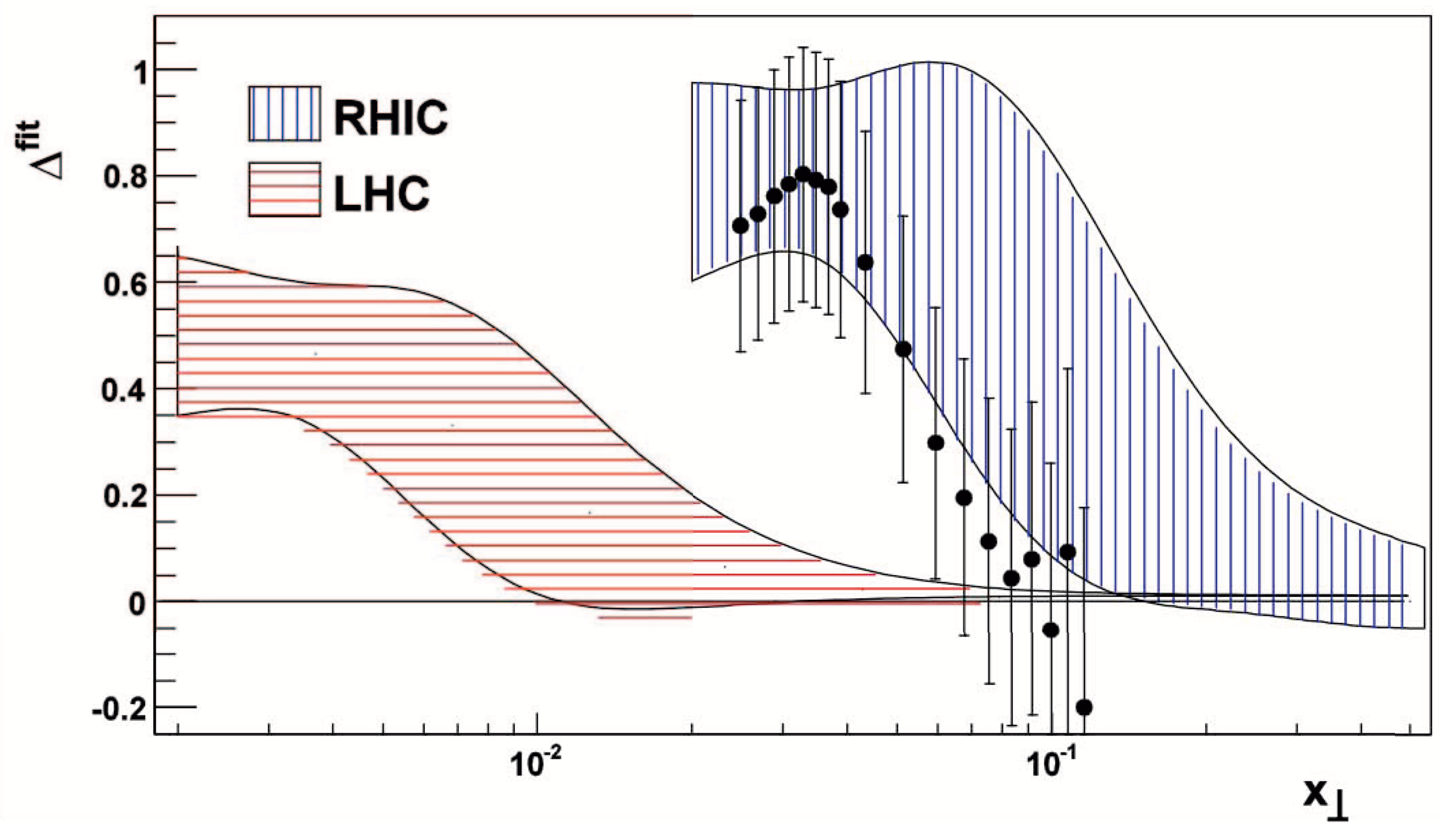
Arleo,Hwang, Sickles, sjb

RHIC/LHC predictions

PHENIX results

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

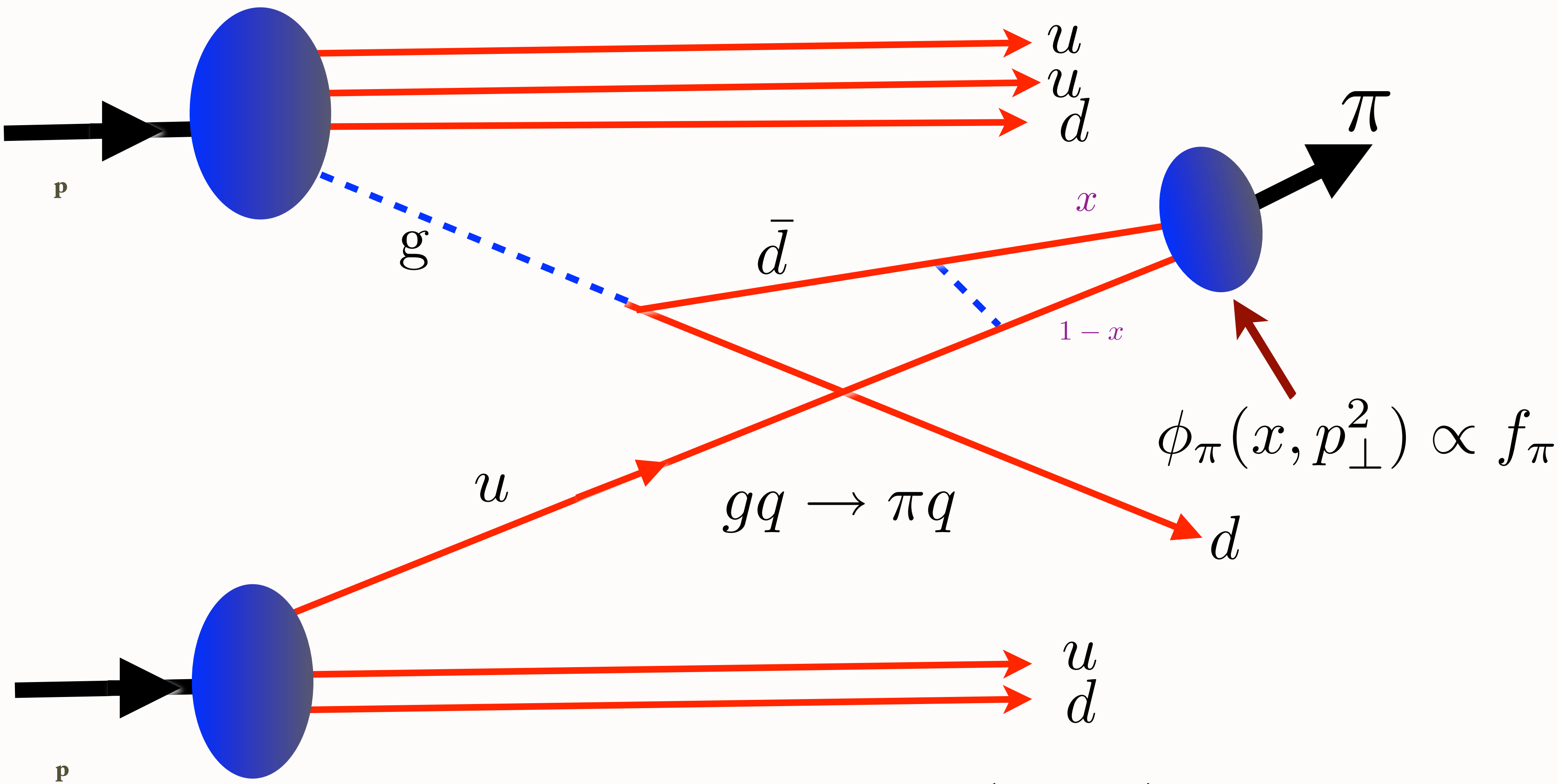
[A. Bezilevsky, APS Meeting]



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

Arleo,Hwang, Sickles, sjb

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

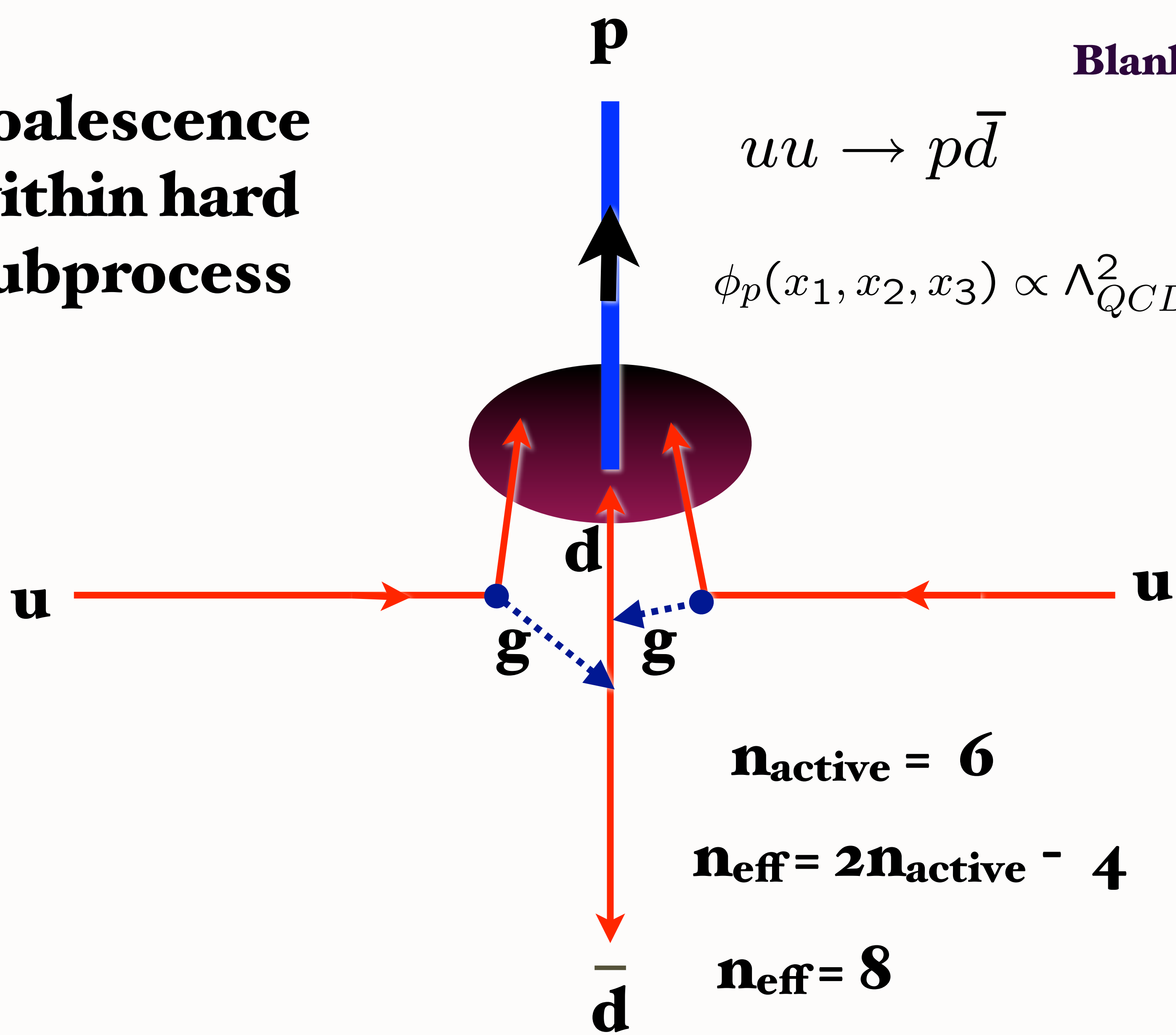
Baryon can be made directly within hard subprocess

Bjorken
Blankenbecler, Gunion, sjb
Berger, sjb
Sickles, Sjb

Coalescence within hard subprocess

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

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



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Arleo, Hwang, Sickles, sjb

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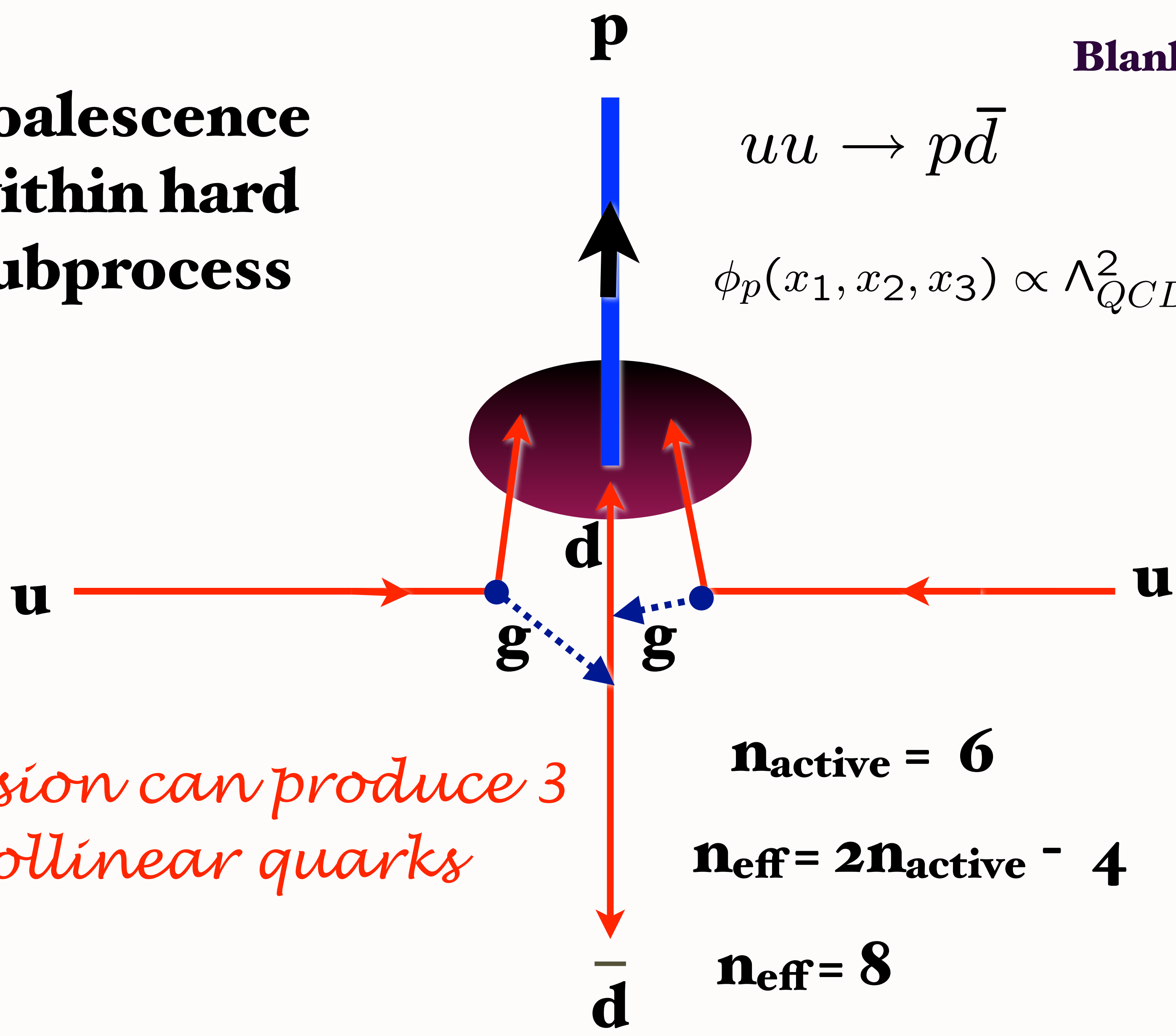

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Bjorken
Blankenbecler, Gunion, sjb
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Collision can produce 3 collinear quarks

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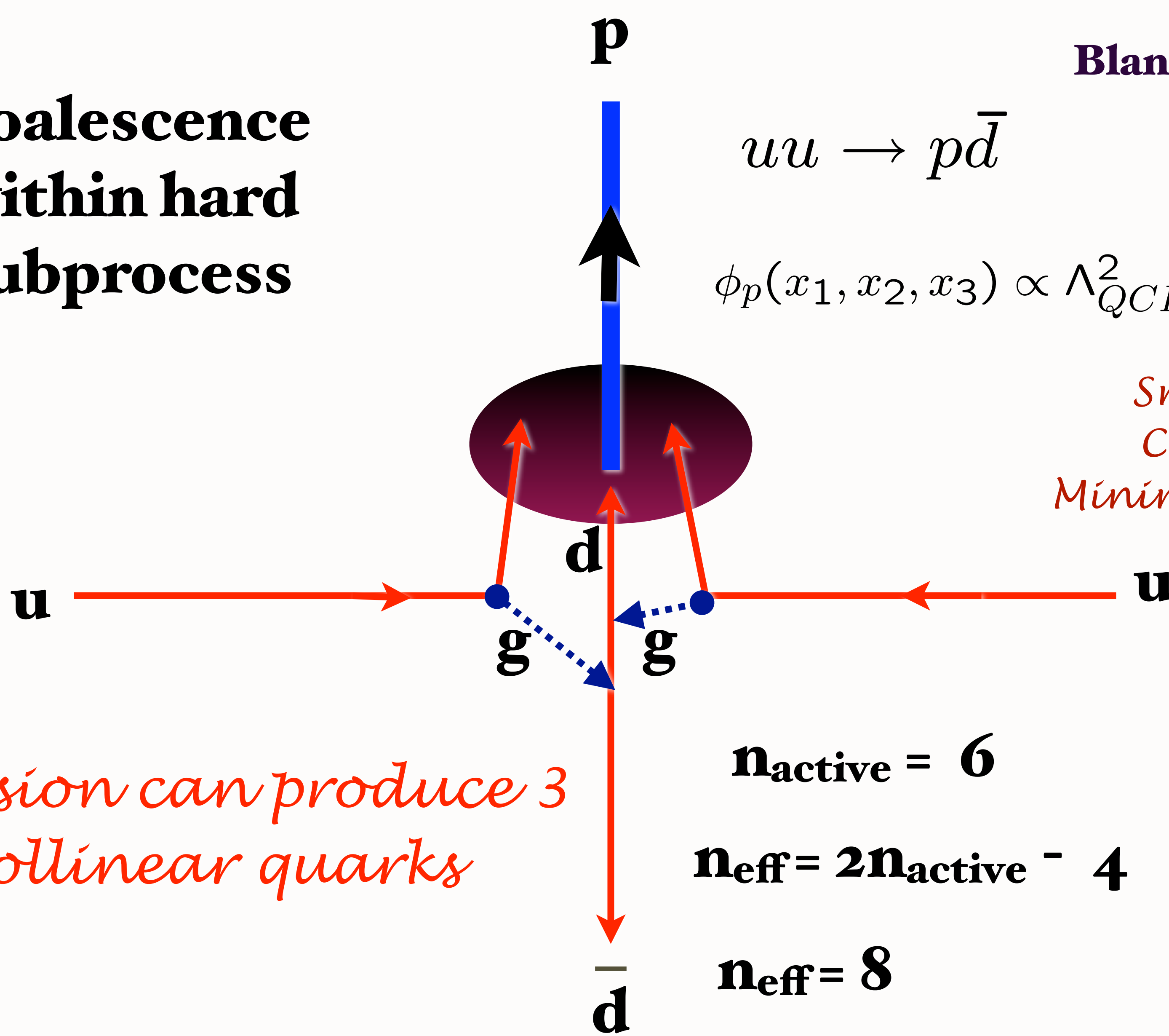

Small color-singlet
Color Transparent
Minimal same-side energy

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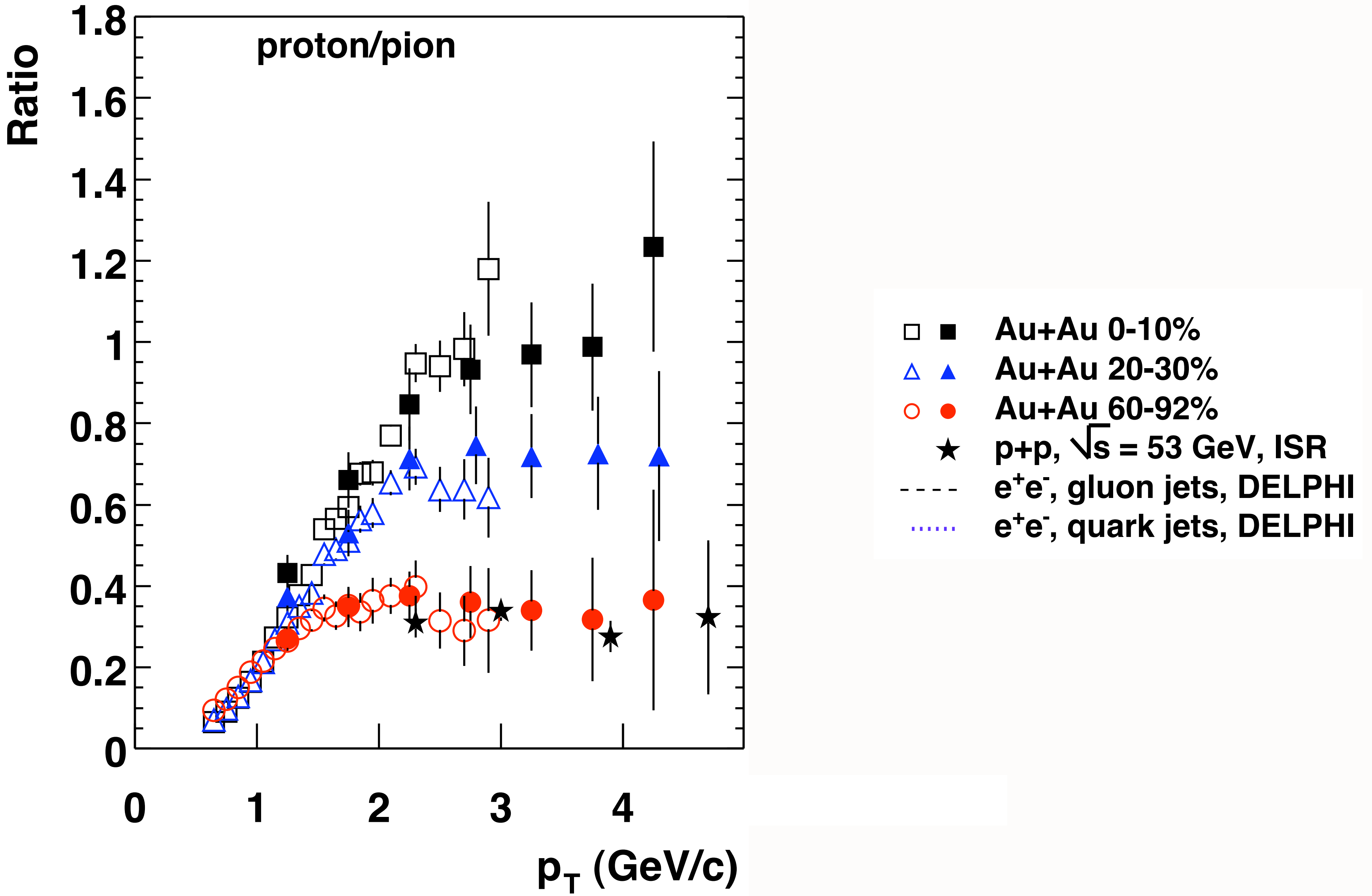
Arleo, Hwang, Sickles, sjb

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

Particle ratio changes with centrality!



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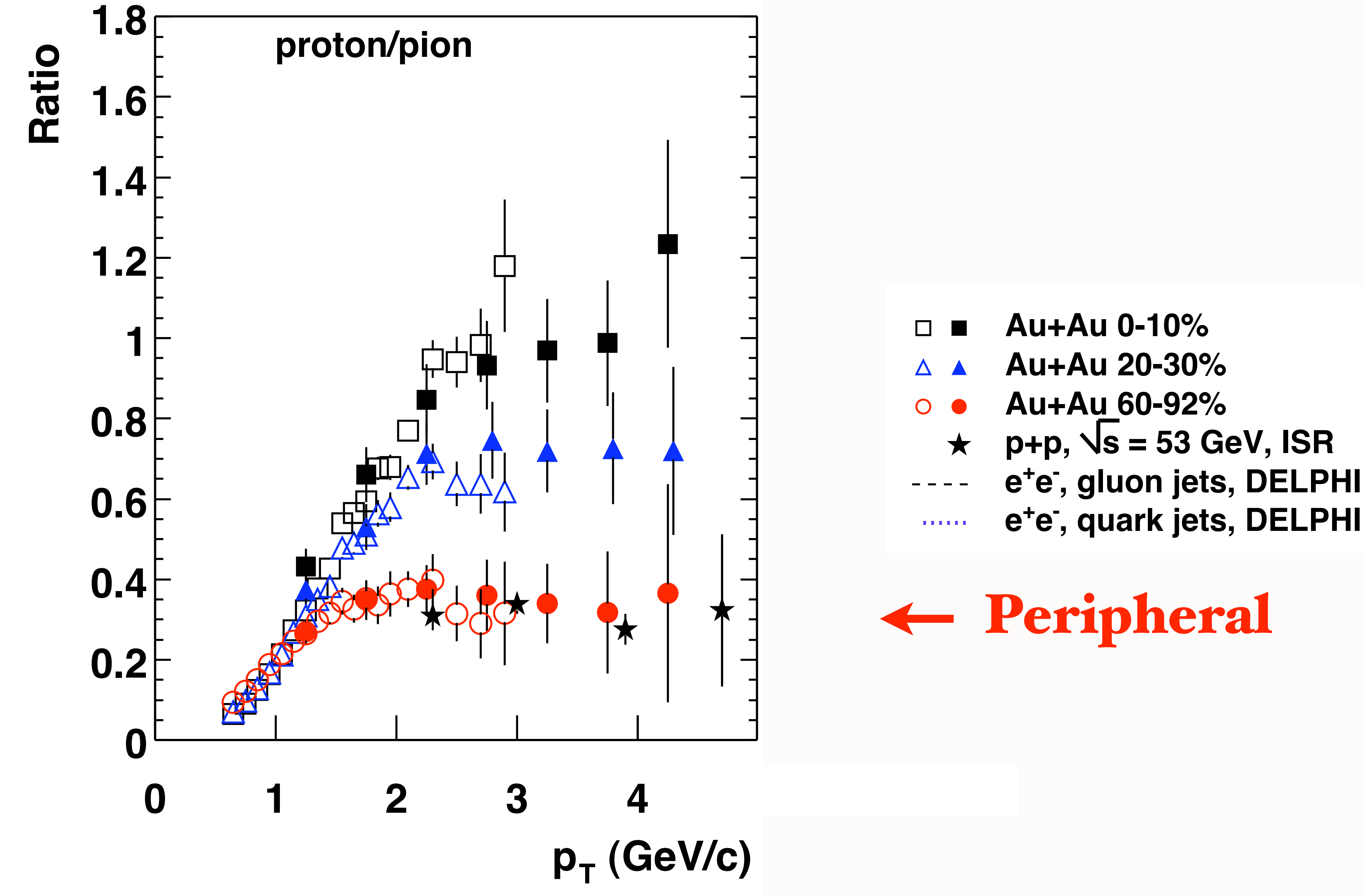

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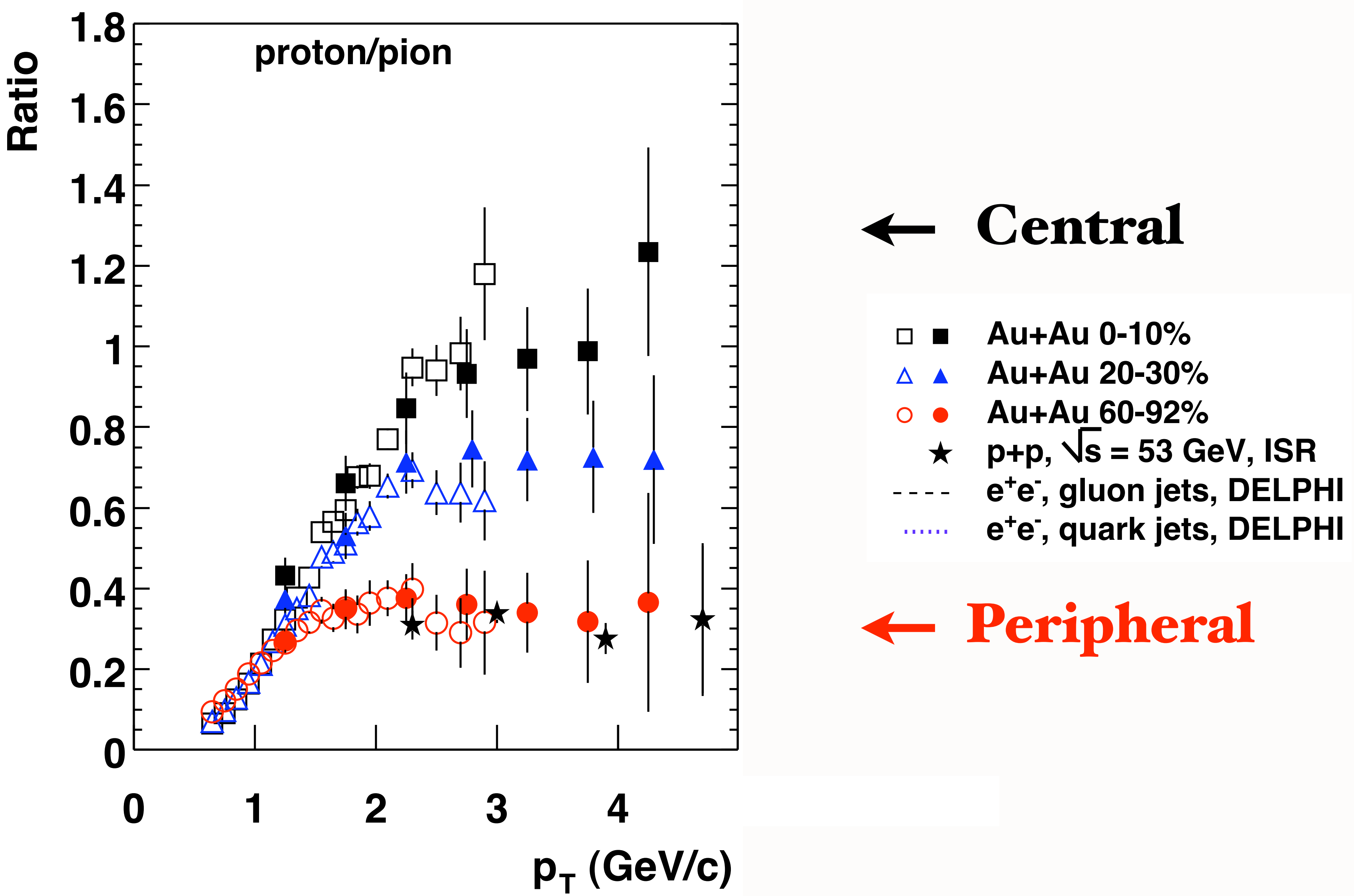

← **Central**

← **Peripheral**

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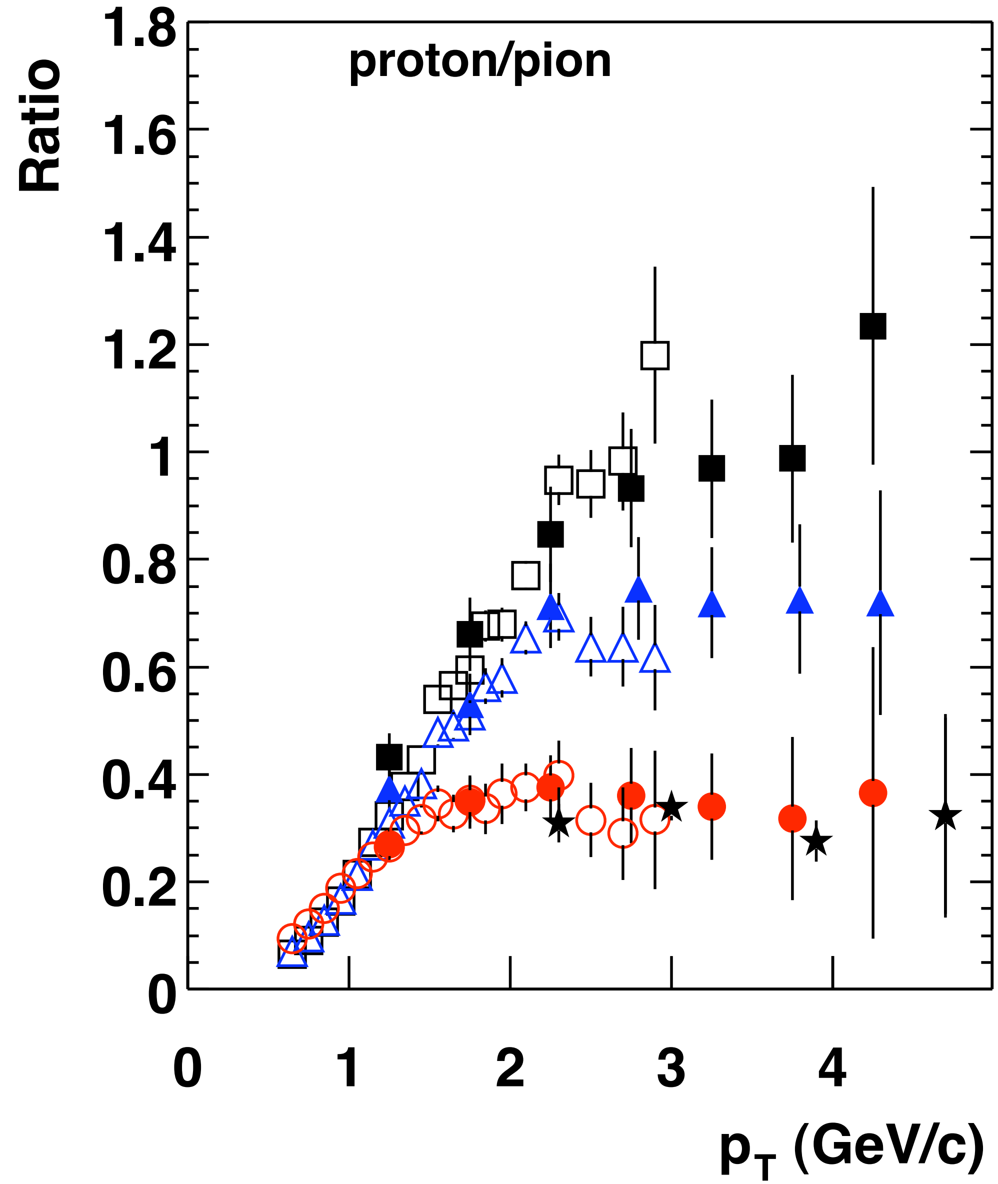

Protons less absorbed in nuclear collisions than pions because of dominant color transparent higher twist process

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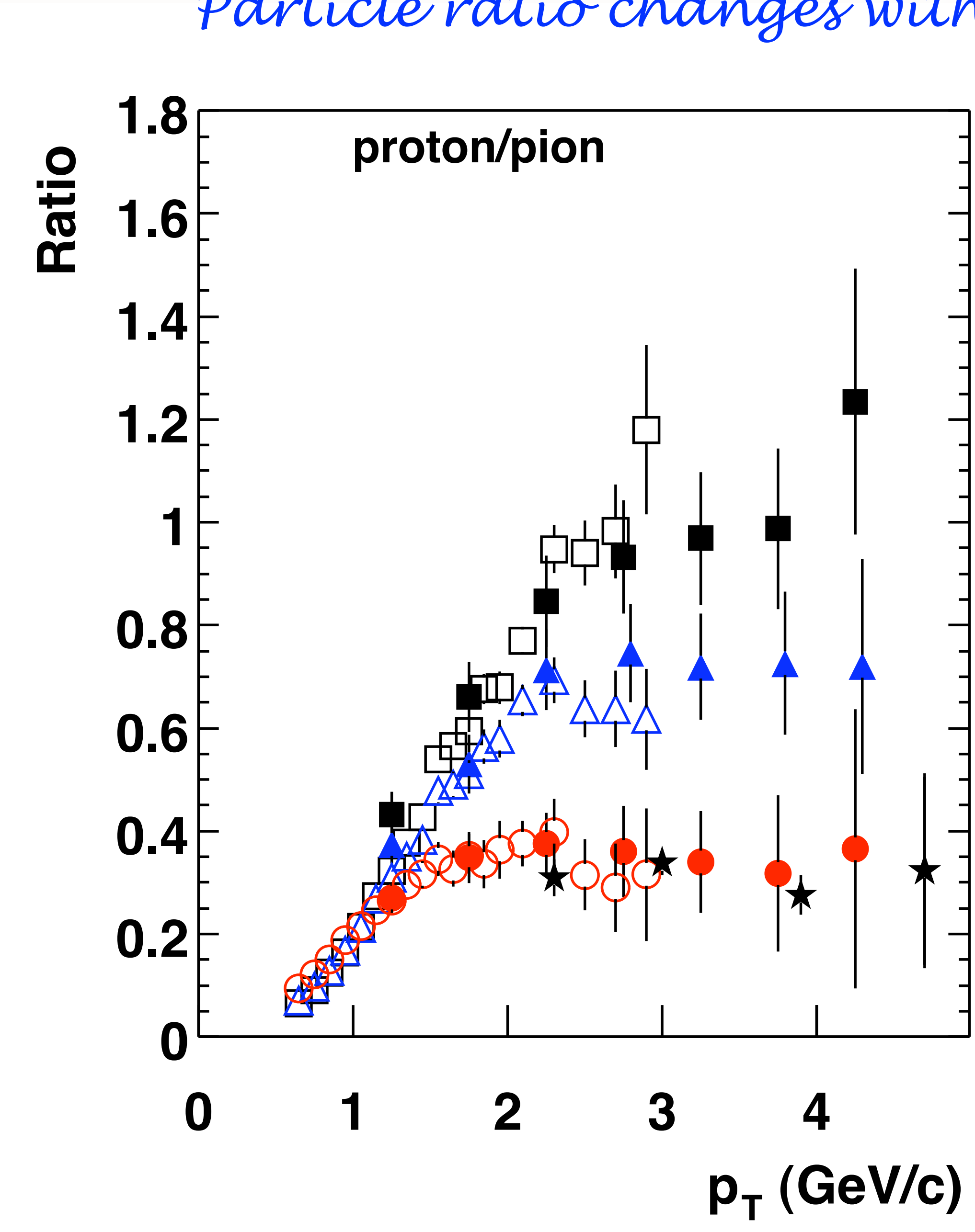

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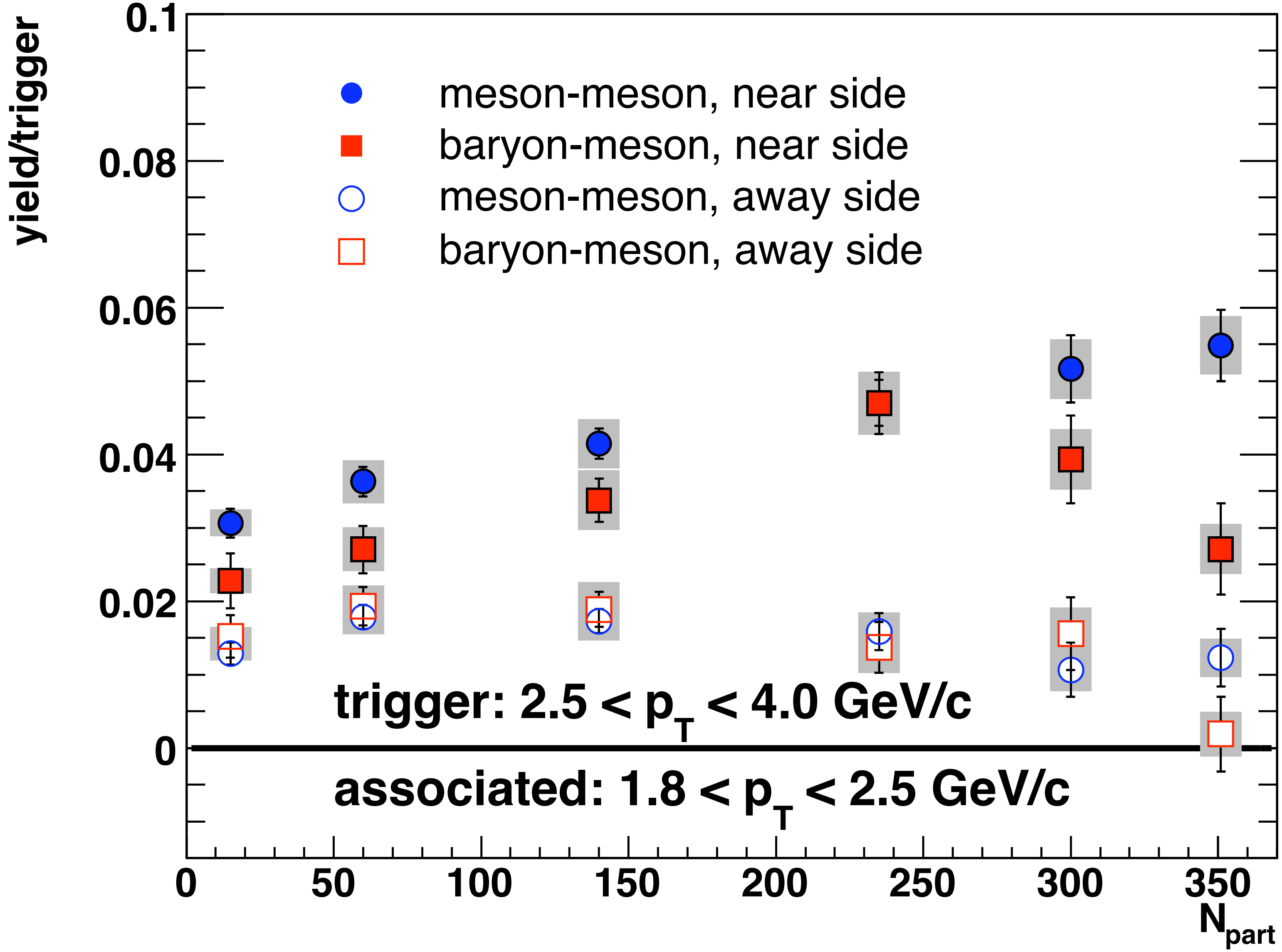
Tannenbaum:

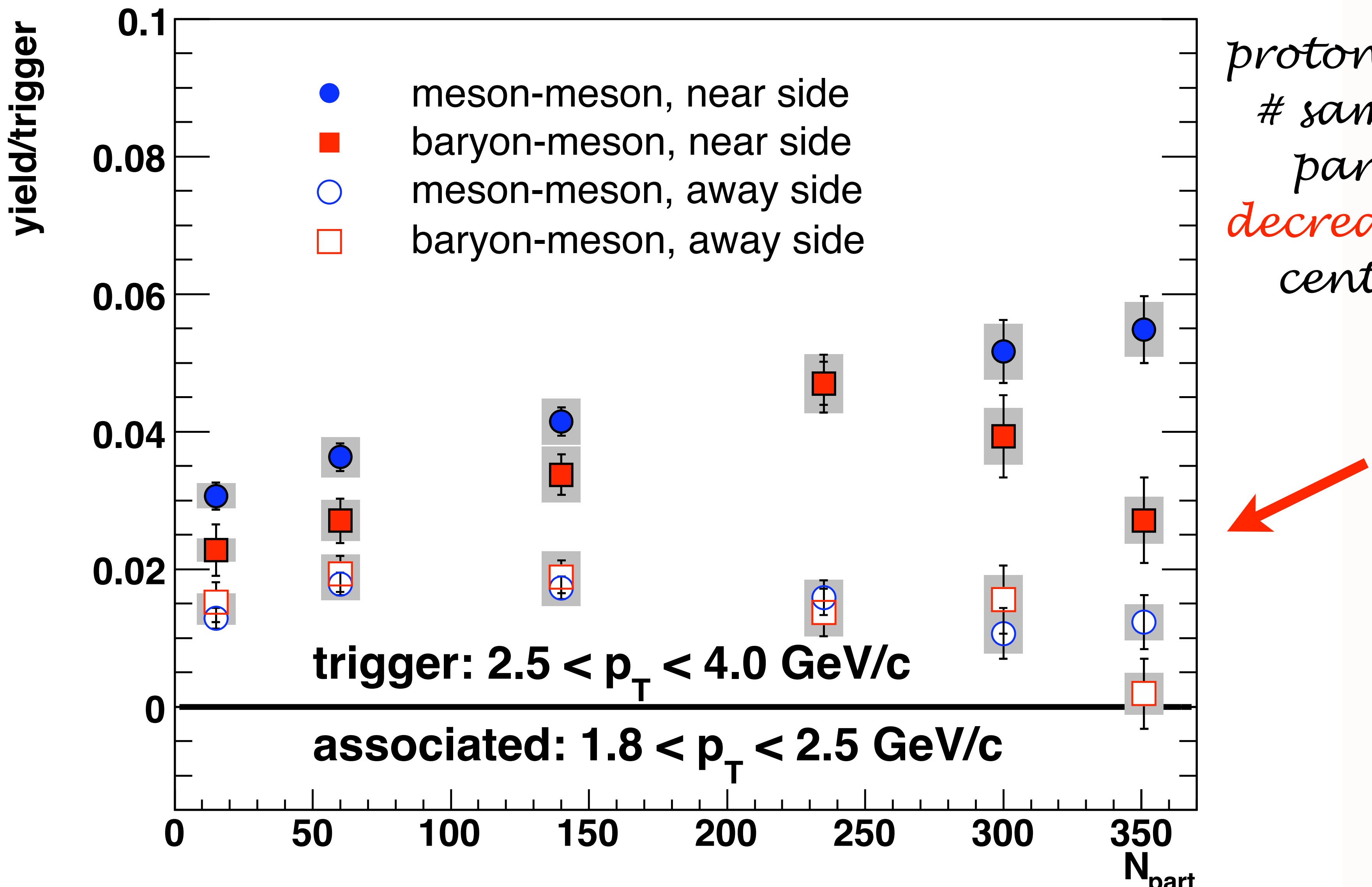
Baryon Anomaly:

Anne Sickles



proton trigger: # same-side particles decreases with centrality

Anne Sickles



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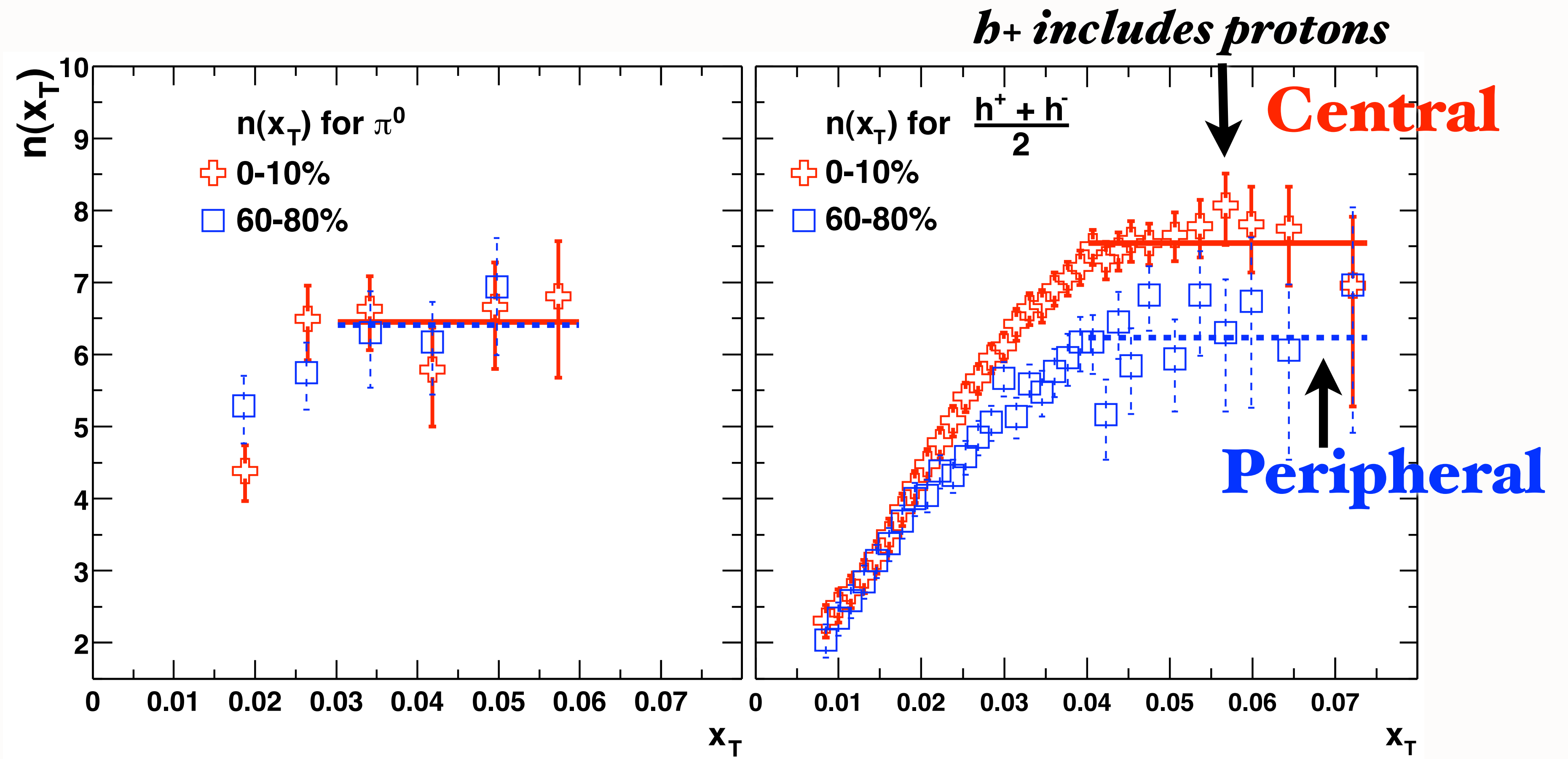
Proton production more dominated by color-transparent direct high-n_{eff} subprocesses

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`].



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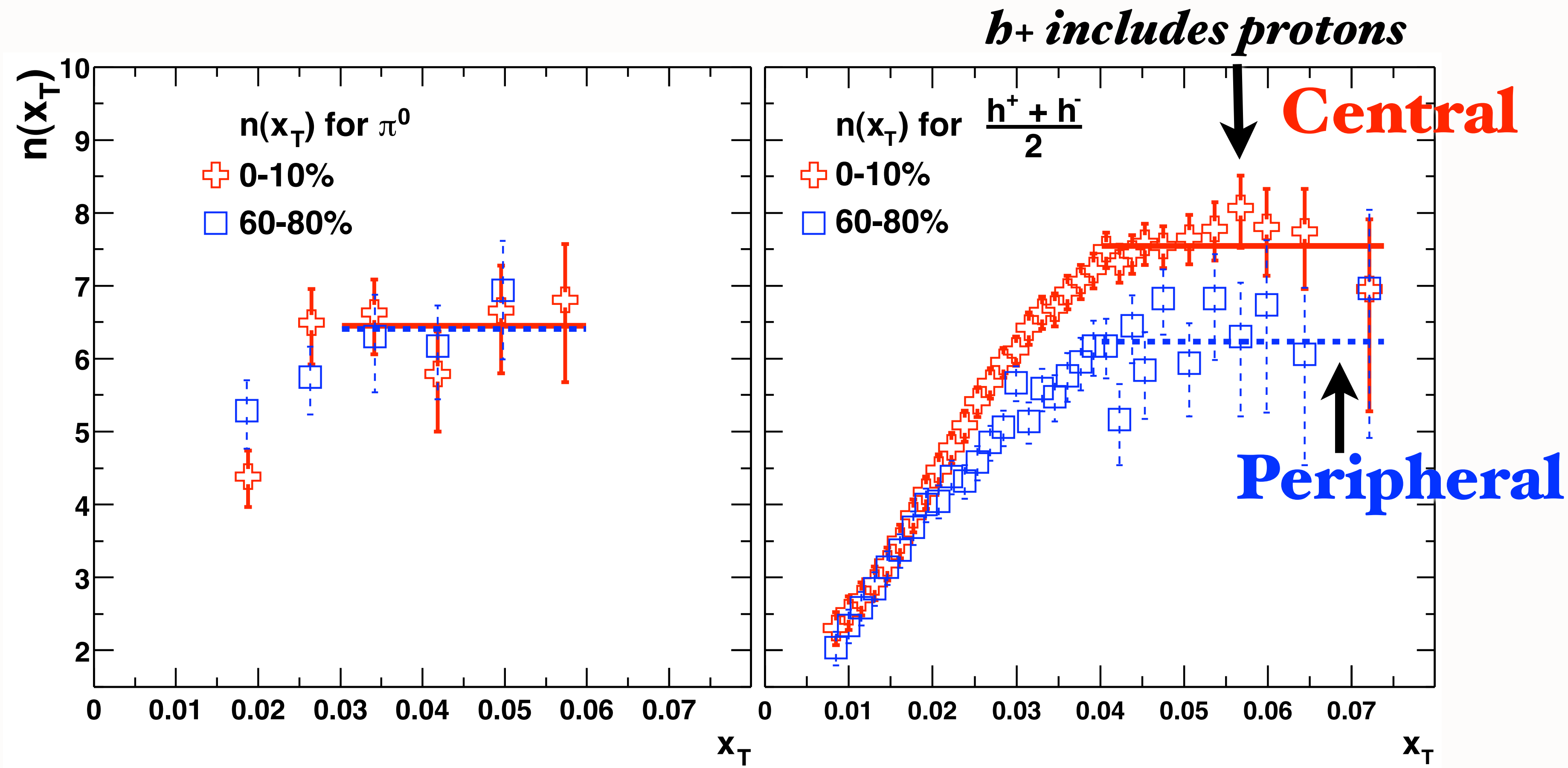

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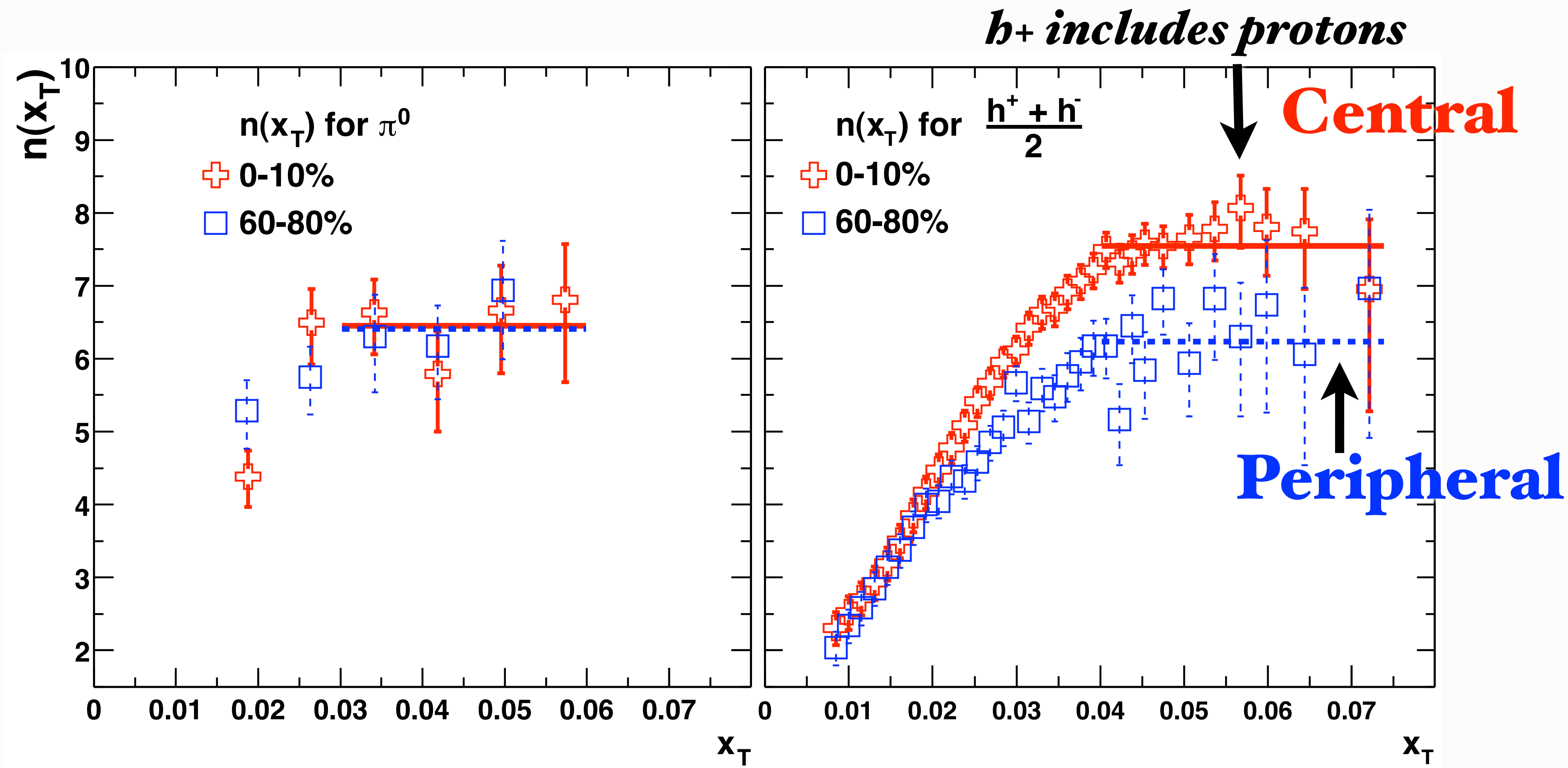

Proton power changes with centrality !

Proton production dominated by
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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 $x_T = 1$**

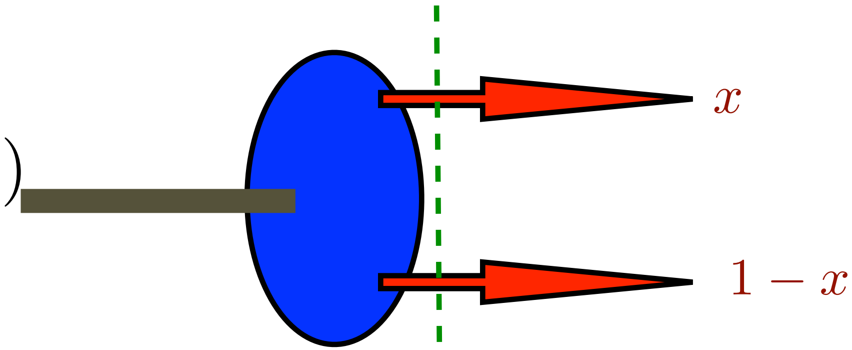
Arleo,Hwang, Sickles, sjb

Direct Higher Twist Processes

- QCD predicts that hadrons can be produced 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

Hadron Distribution Amplitudes

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



$k_\perp^2 < Q^2$

$\sum_i x_i = 1$

Fixed $\tau = t + z/c$

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

Lepage, Huang, sjb

Efremov, Radyushkin

- **ERBL Evolution Equations from PQCD, OPE,**
- **Conformal Invariance**

Sachrajda, Frishman Lepage, Braun, Gardi

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

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!
- renormalization scale cannot be fixed
- QCD condensates are vacuum effects
- Infrared Slavery
- Nuclei are composites of nucleons only
- Real part of DVCS arbitrary
- heavy quarks only from gluon splitting

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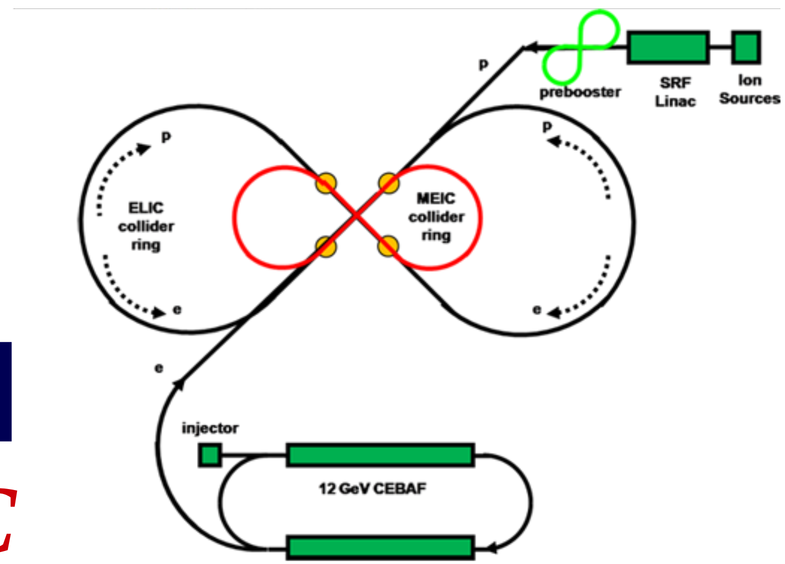
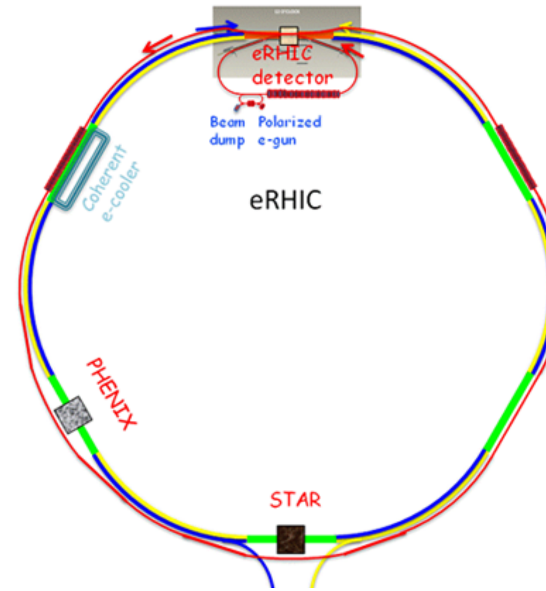
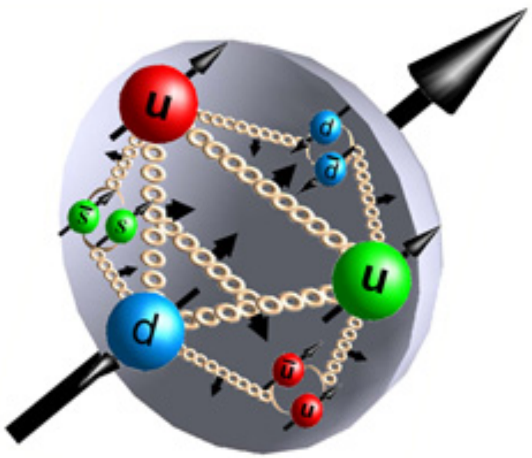
Intrinsic Heavy Quark Phenomena at the EIC and Fixed Target Facilities

AFTER @ LHC







Stan Brodsky

CP³ - Origins
Particle Physics & Origin of Mass

SLAC NATIONAL ACCELERATOR LABORATORY

Fall meeting of the GDR PH-QCD: Nucleon and Nucleus Structure Studies with a LHC fixed-target experiment and Electron-Ion Collider

The France-Stanford Center for Interdisciplinary Studies

October 18, 2011

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