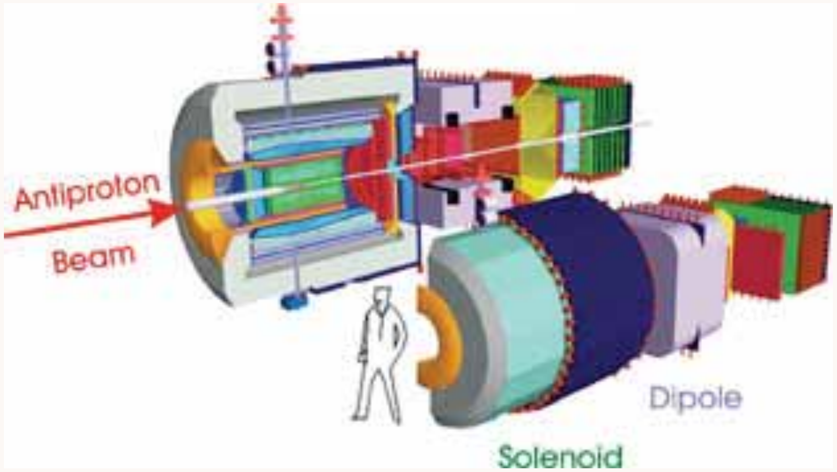
Novel QCD and Nuclear Physics at FAIR

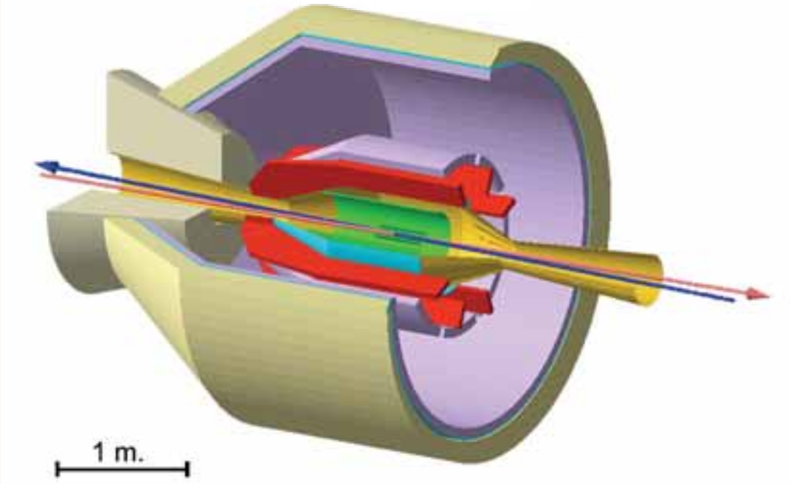
Stan Brodsky, SLAC

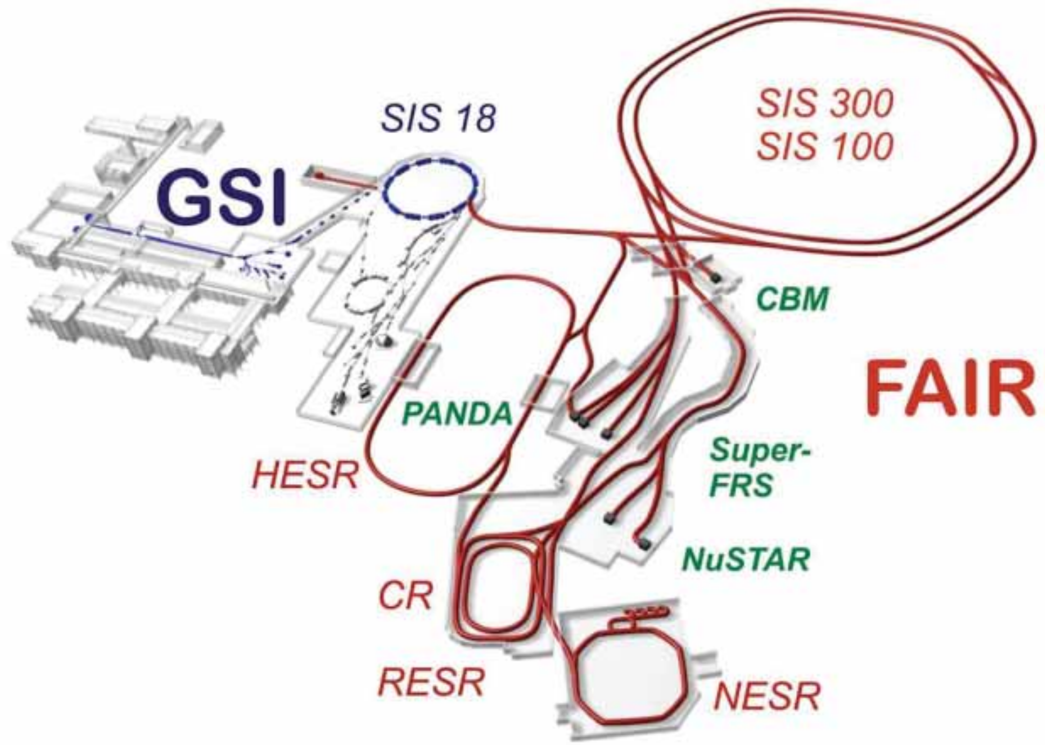
GSI-FAIR Workshop, Prerow, Germany October 11, 2009

Panda


Antiproton
Beam
Dipole
Solenoid

PAX


1 m.


SIS 18
GSI
SIS 300
SIS 100
CBM
FAIR
PANDA
HESR
Super-
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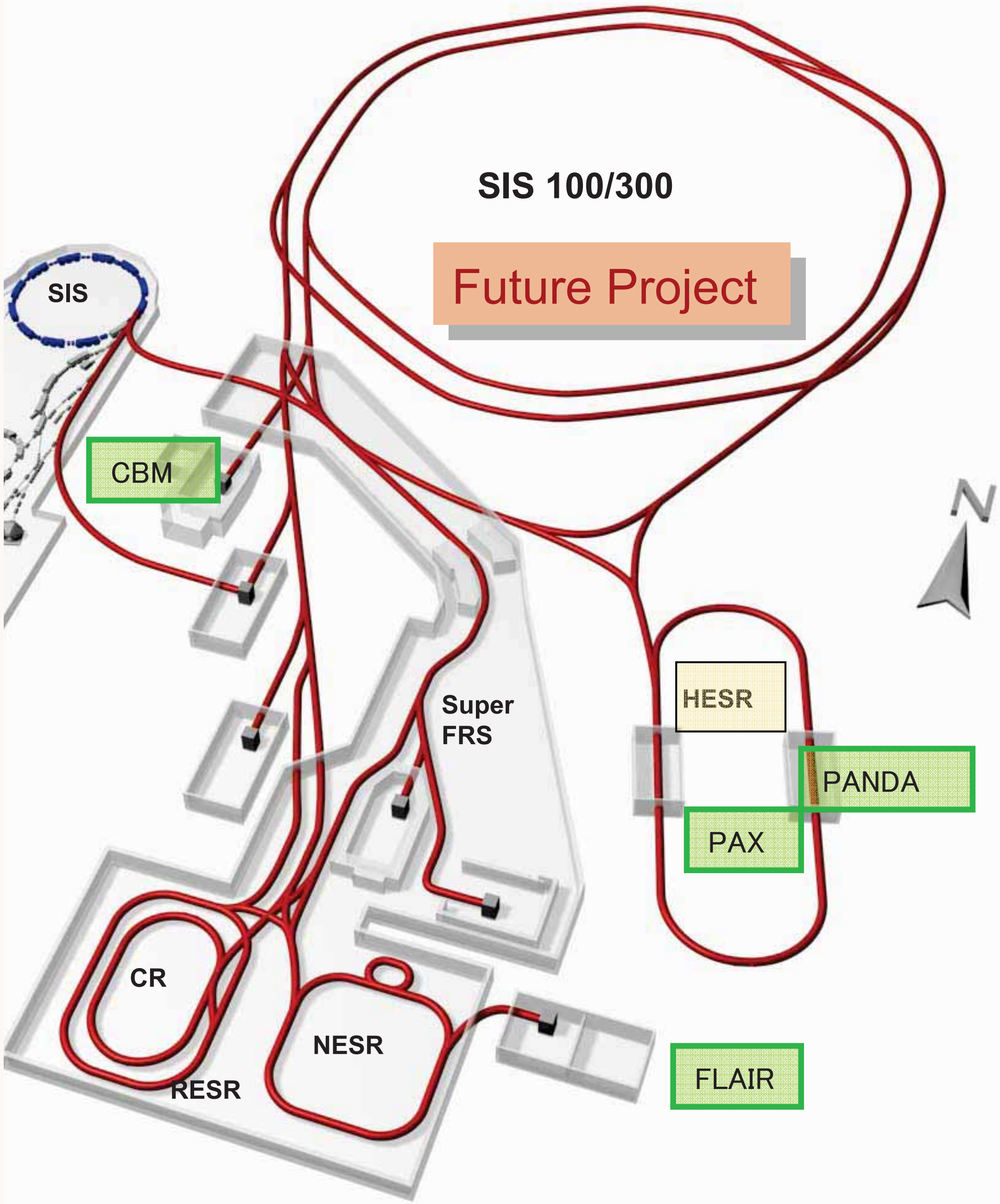
NuSTAR
CR
RESR
NESR



Facility for Antiproton and Ion Research

Primary Beams

- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
- 10^{10}/s $^{238}U^{73+}$ up to 35 GeV/u
- $3x10^{13}$/s 30 GeV protons

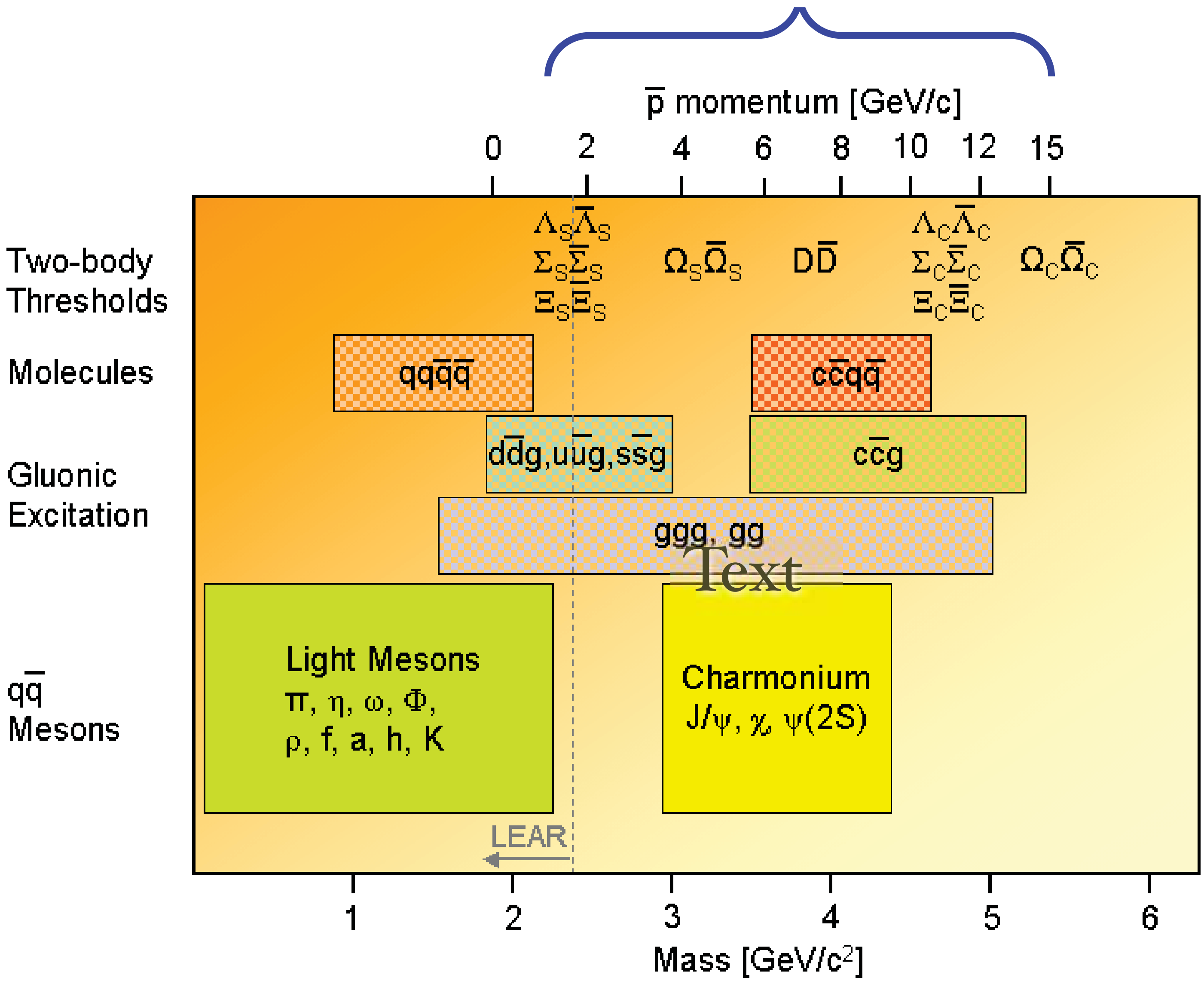
Secondary Beams

- broad range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 higher in intensity than presently
- antiprotons 3 - 30 GeV

Storage and Cooler Rings

- radioactive beams
- 10^{11} antiprotons 1 - 15 GeV/c, stored and cooled

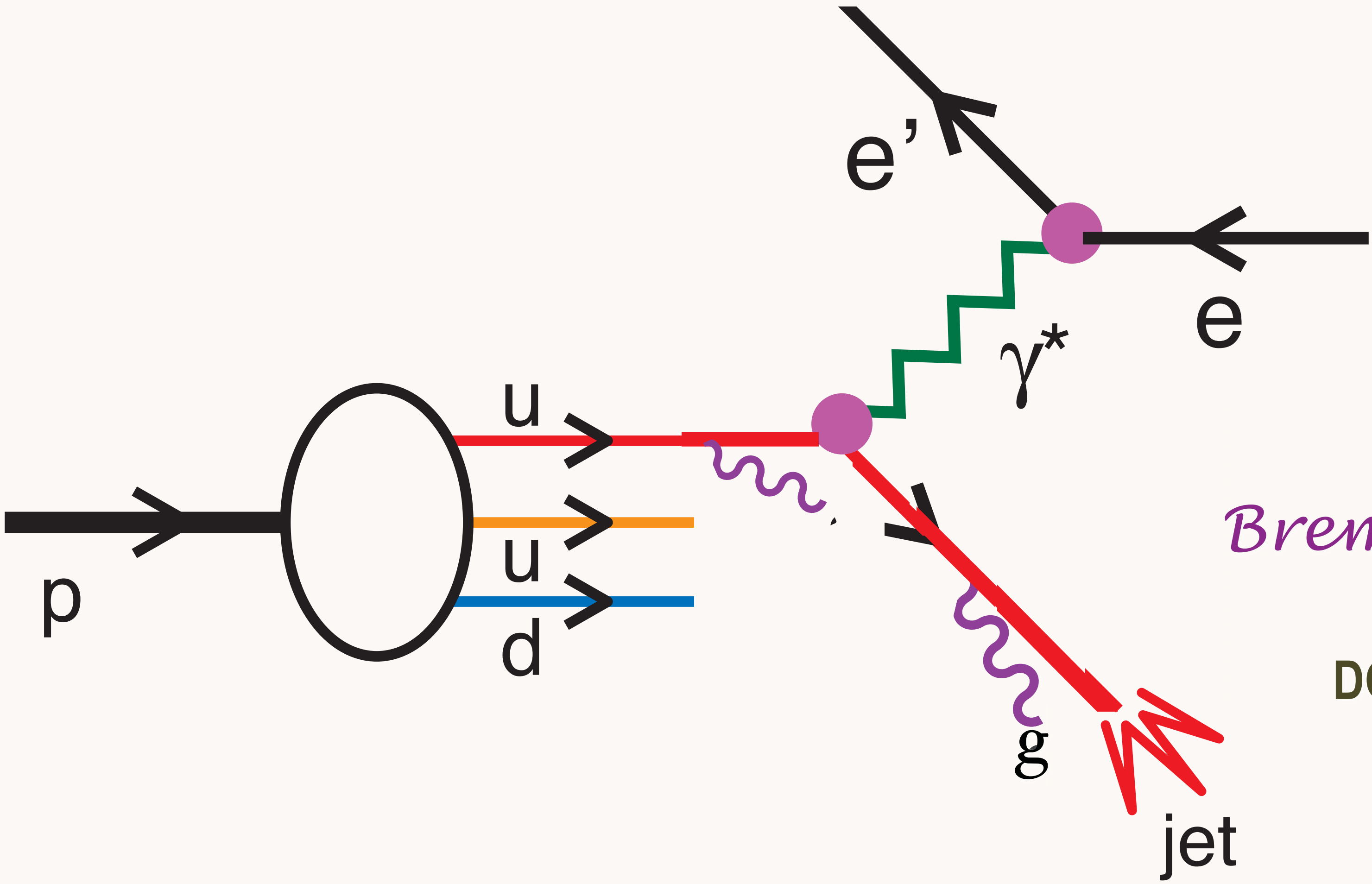
Mass and Anti-Proton Momentum Range at PAX, PANDA



- Production of open charm
- Charmed hybrids
- Glueballs
- Charmonium

Michael Düren

Deep Inelastic Electron-Proton Scattering



Gluonic Bremmstrahlung

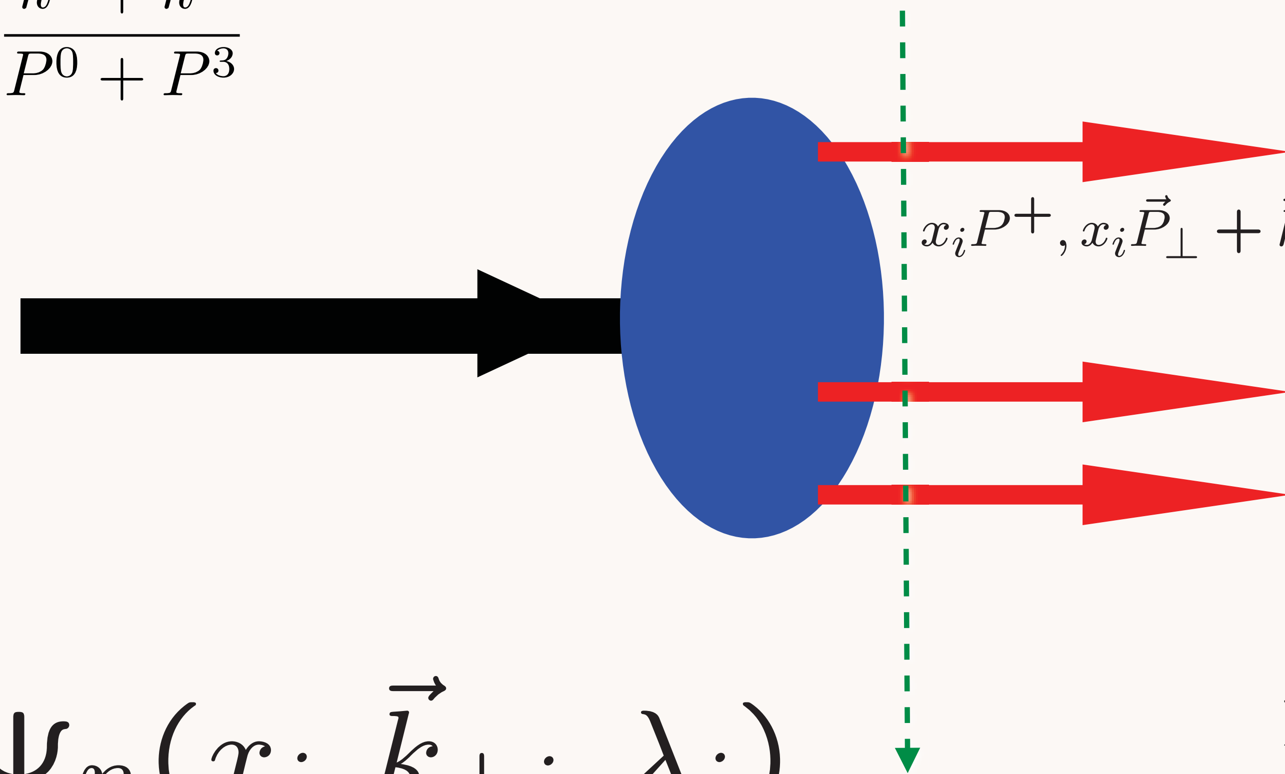
DGLAP Evolution

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

Fixed $\tau = t + z/c$

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

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



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

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

$\sum_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

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

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

The Light Front Fock State Wavefunctions

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

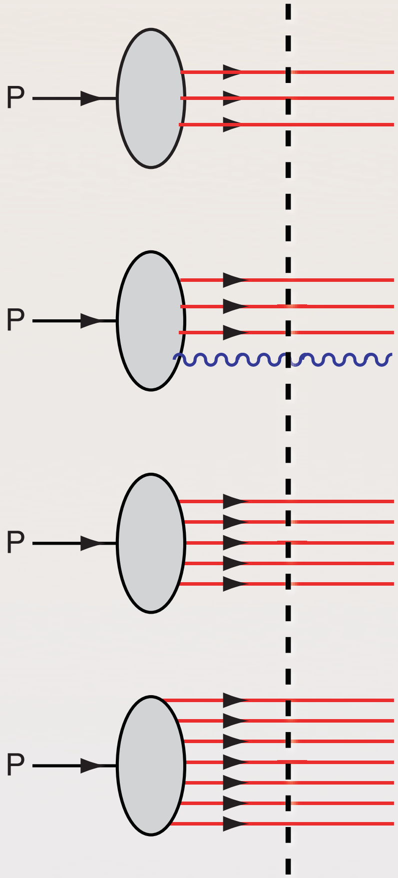
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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.

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

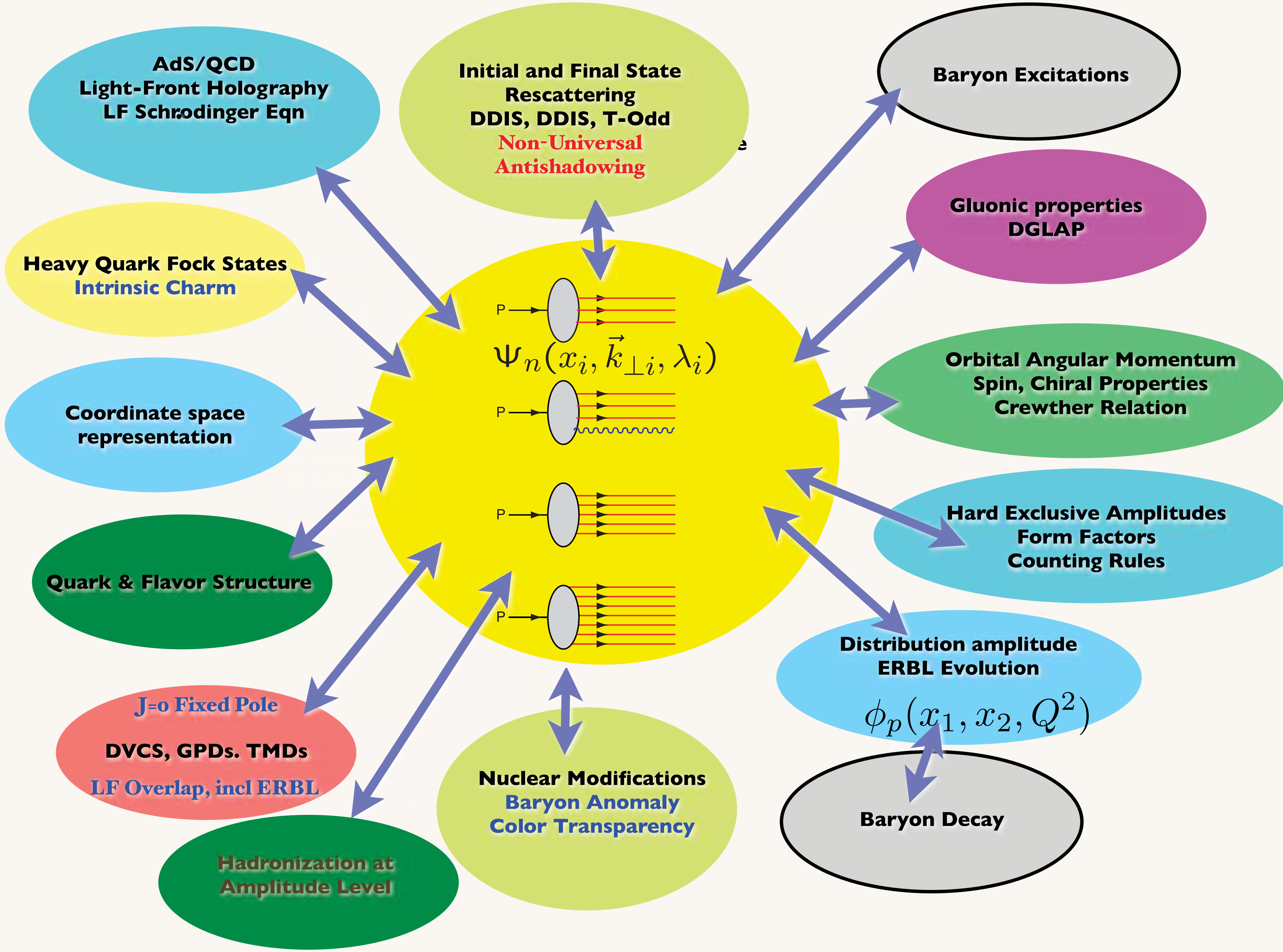


Fixed LF time

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

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

QCD and the LF Hadron Wavefunctions

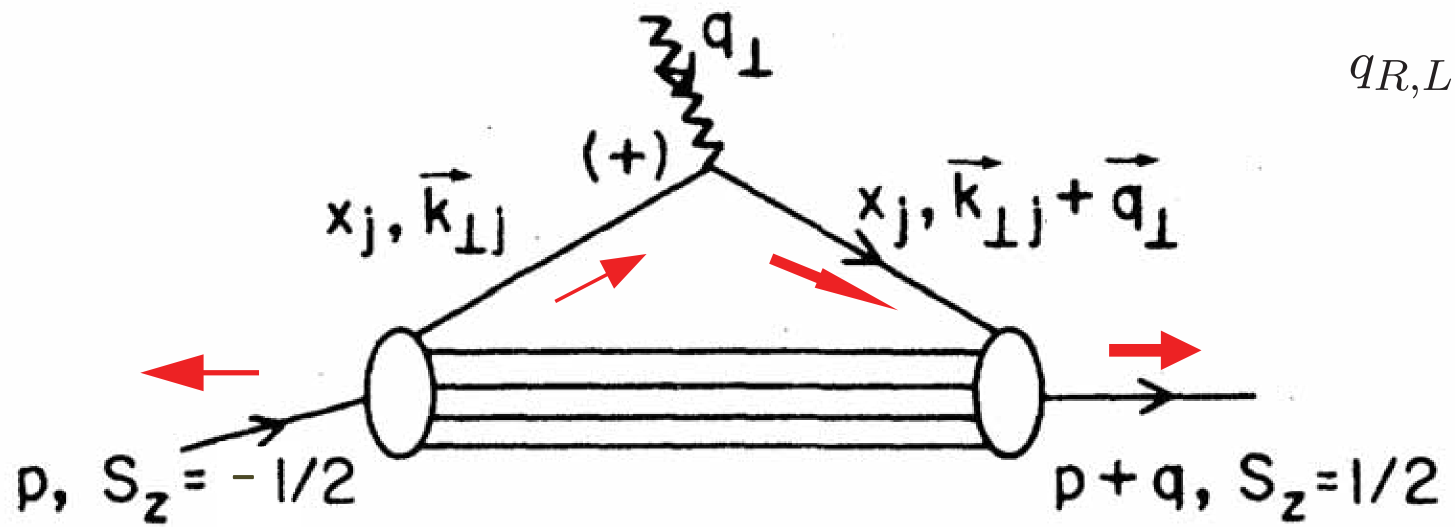


$$\frac{F_2(q^2)}{2M} = \sum_a \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp] \sum_j e_j \, \frac{1}{2} \times$$

Drell, sjb

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

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

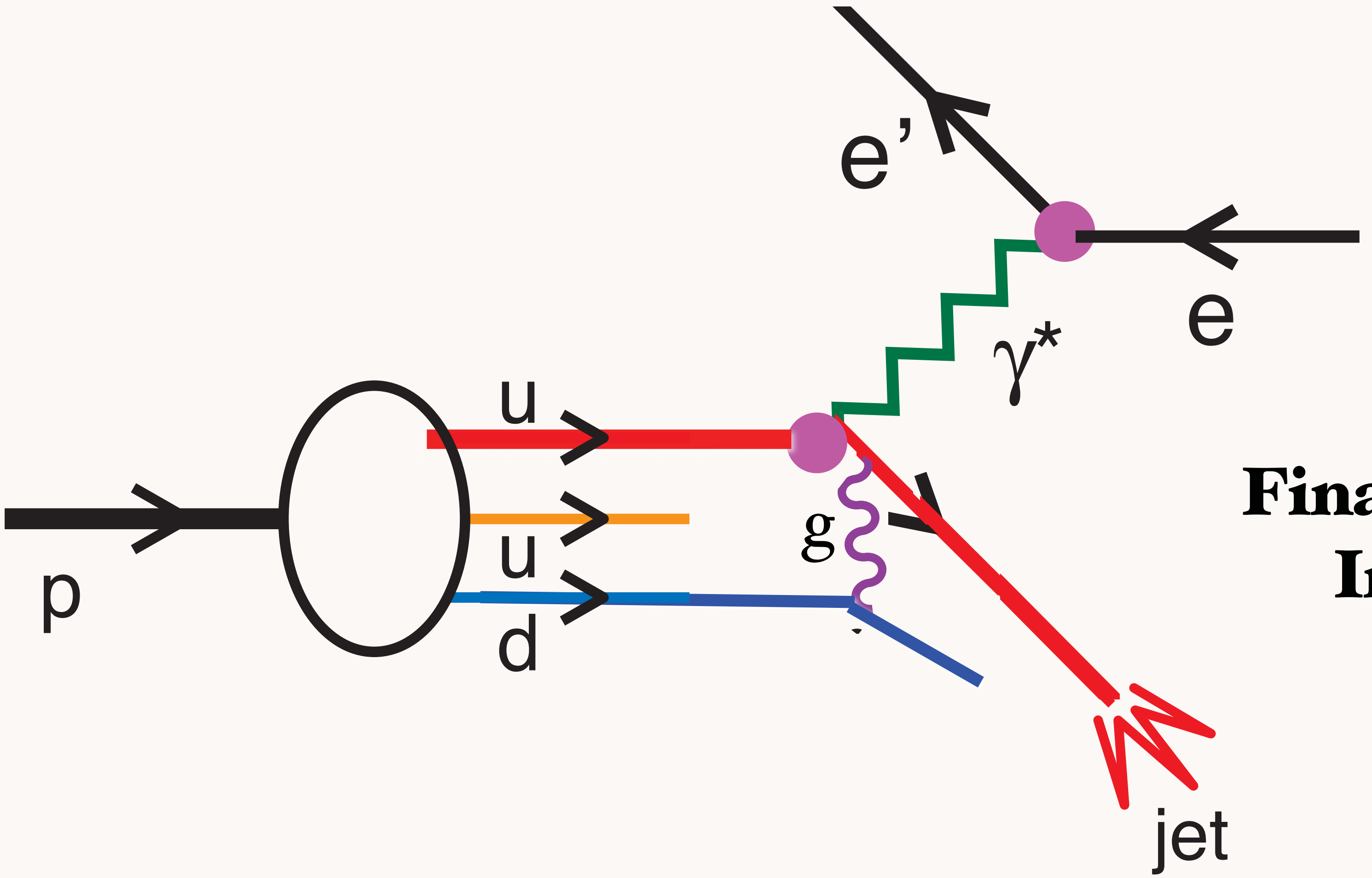


$$q_{R,L} = q^x \pm i q^y$$

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

Same matrix elements appear in Sivers effect
-- connection to quark anomalous moments

Deep Inelastic Electron-Proton Scattering



Final-State QCD Interaction

Conventional wisdom:

Final-state interactions of struck quark can be neglected

Leading Twist Sivers Effect

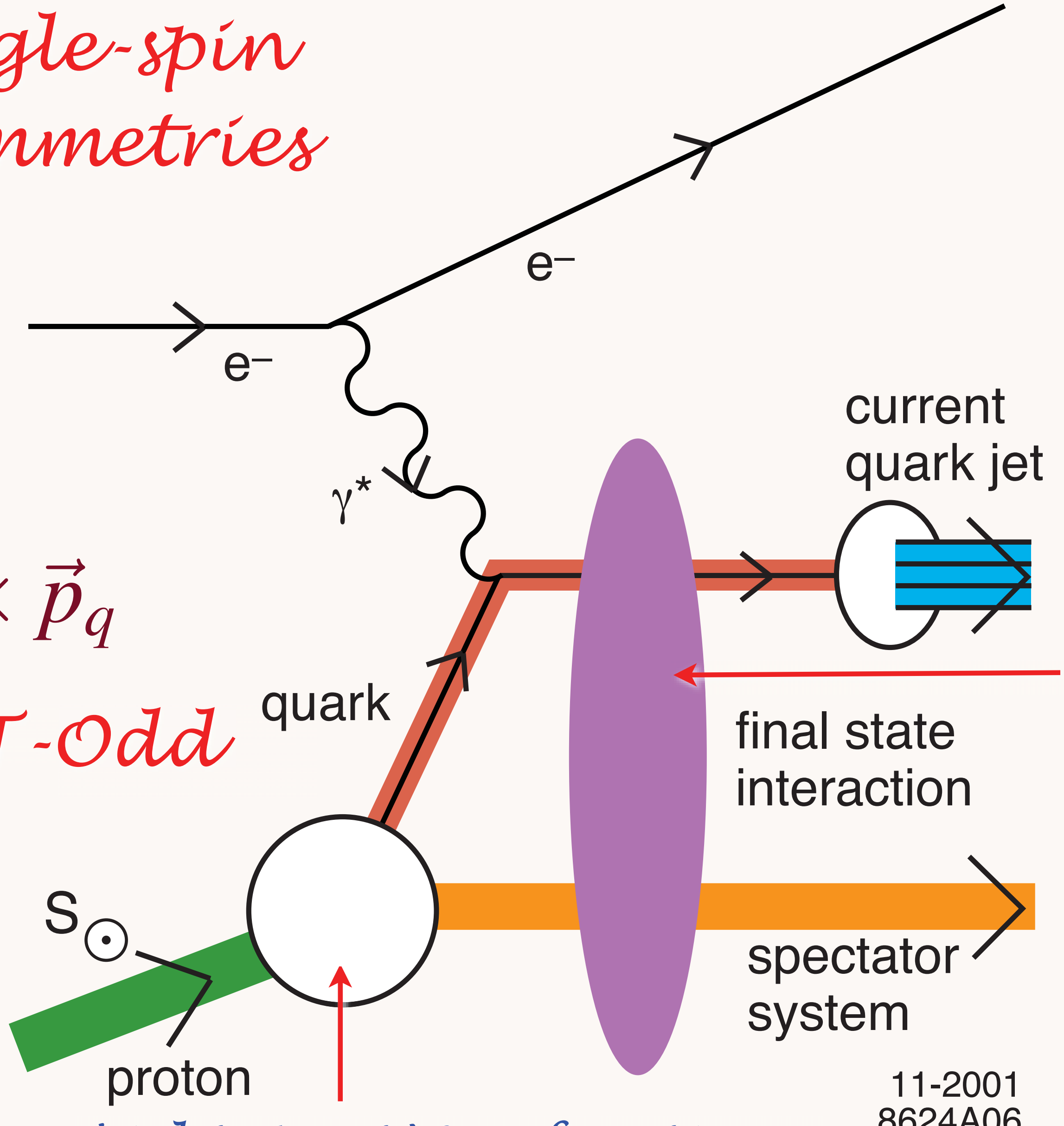
Single-spin asymmetries

Hwang, Schmidt, sjb

Collins, Burkardt
Ji, Yuan

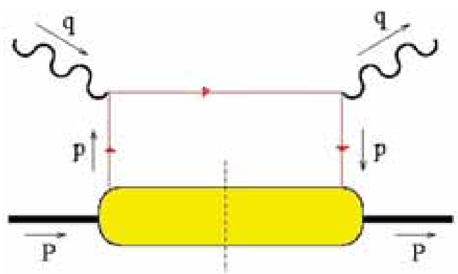
$$i\ \vec{S}_p \cdot \vec{q} \times \vec{p}_q$$

Pseudo-T-Odd

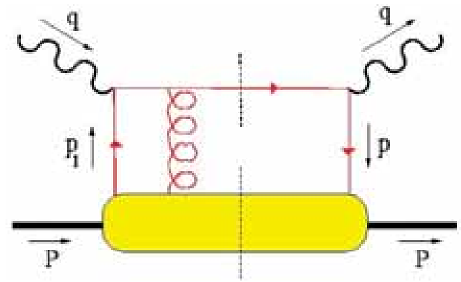


*QCD S- and P-
Coulomb Phases
--Wilson Line*

*Light-Front Wavefunction
S and P- Waves*



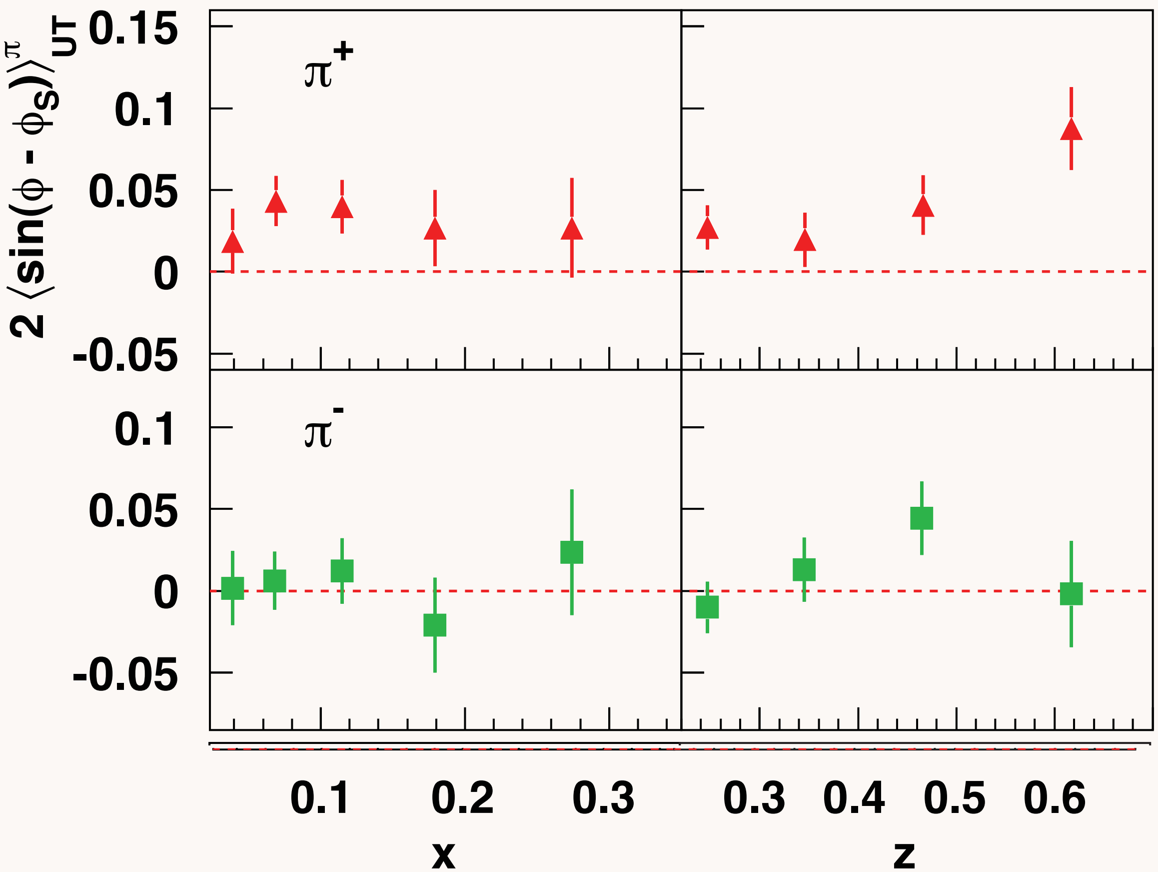
can interfere
with



and produce
a T-odd effect!
(also need $L_z \neq 0$)

HERMES coll., A. Airapetian et al., Phys. Rev. Lett. 94 (2005) 012002.

Sivers asymmetry from HERMES



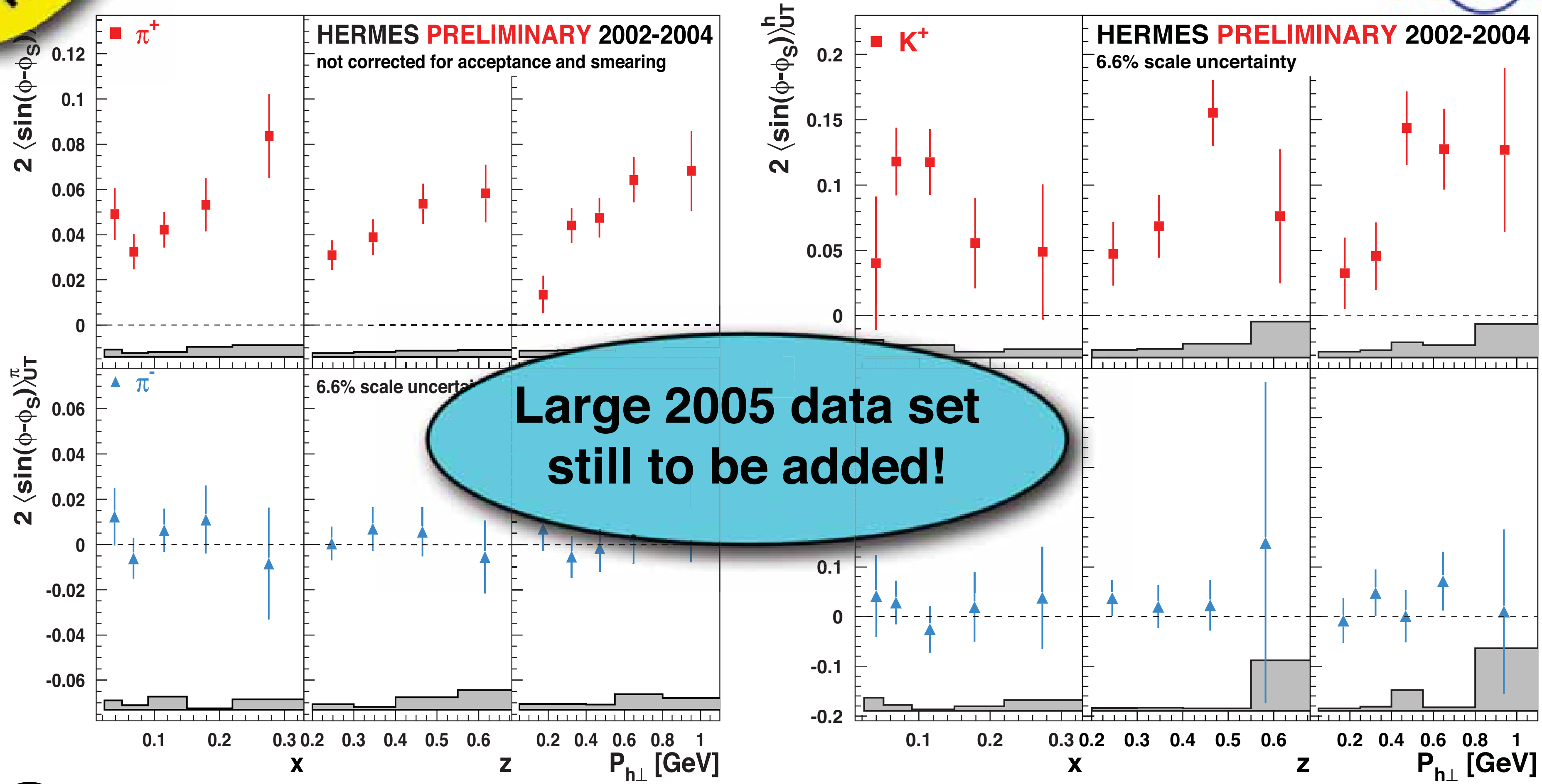
- First evidence for non-zero Sivers function!
- ⇒ presence of non-zero **quark orbital angular momentum**!
- Positive for **π^+**...
  Consistent with zero for **π^-**...

Gamberg: Hermes data compatible with BHS model

Schmidt, Lu: Hermes charge pattern follow quark contributions to anomalous moment

NEW!

Sivers Moments for Kaons from 2002–2004 Data



- Effect about **equal** for $K^- = s\bar{u}$ and $\pi^- = d\bar{u}$ → note: same antiquark ...
- Effect *seems* ***larger*** for $K^+ = u\bar{s}$ than $\pi^+ = u\bar{d}$ at $x \approx 0.1$ ... !

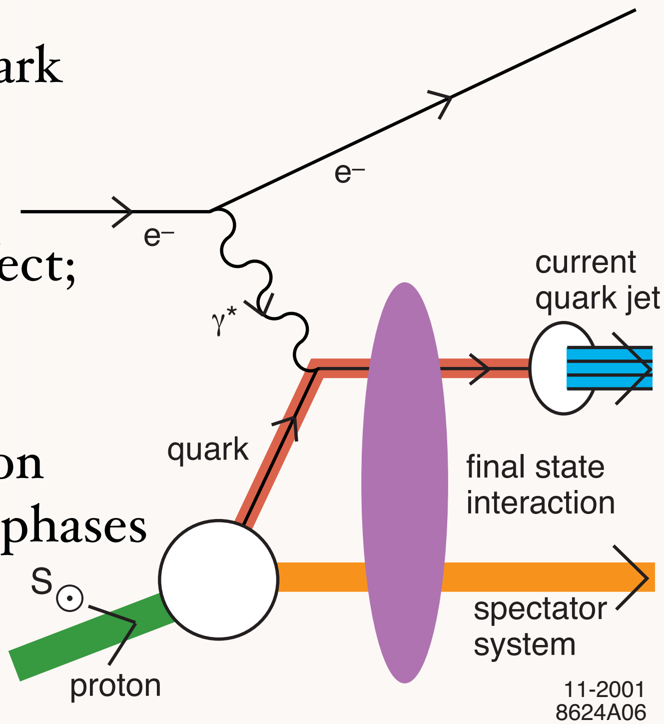
N. Makins

Schmidt, Lu: pattern follows quark contributions to anomalous moment

Final-State Interactions Produce Pseudo T-Odd (Sivers Effect)

$$\mathbf{i}\, \vec{S} \cdot \vec{p}_{jet} \times \vec{q}$$

- Leading-Twist Bjorken Scaling!
- Requires nonzero orbital angular momentum of quark
- Arises from the interference of Final-State QCD Coulomb phases in S- and P- waves; Wilson line effect; gauge independent
- Relate to the quark contribution to the target proton anomalous magnetic moment and final-state QCD phases
- QCD phase at soft scale: IR Fixed Point?



- New window to QCD coupling and running gluon mass in the IR
- QED S and P Coulomb phases infinite -- difference of phases finite

Single-spin asymmetries

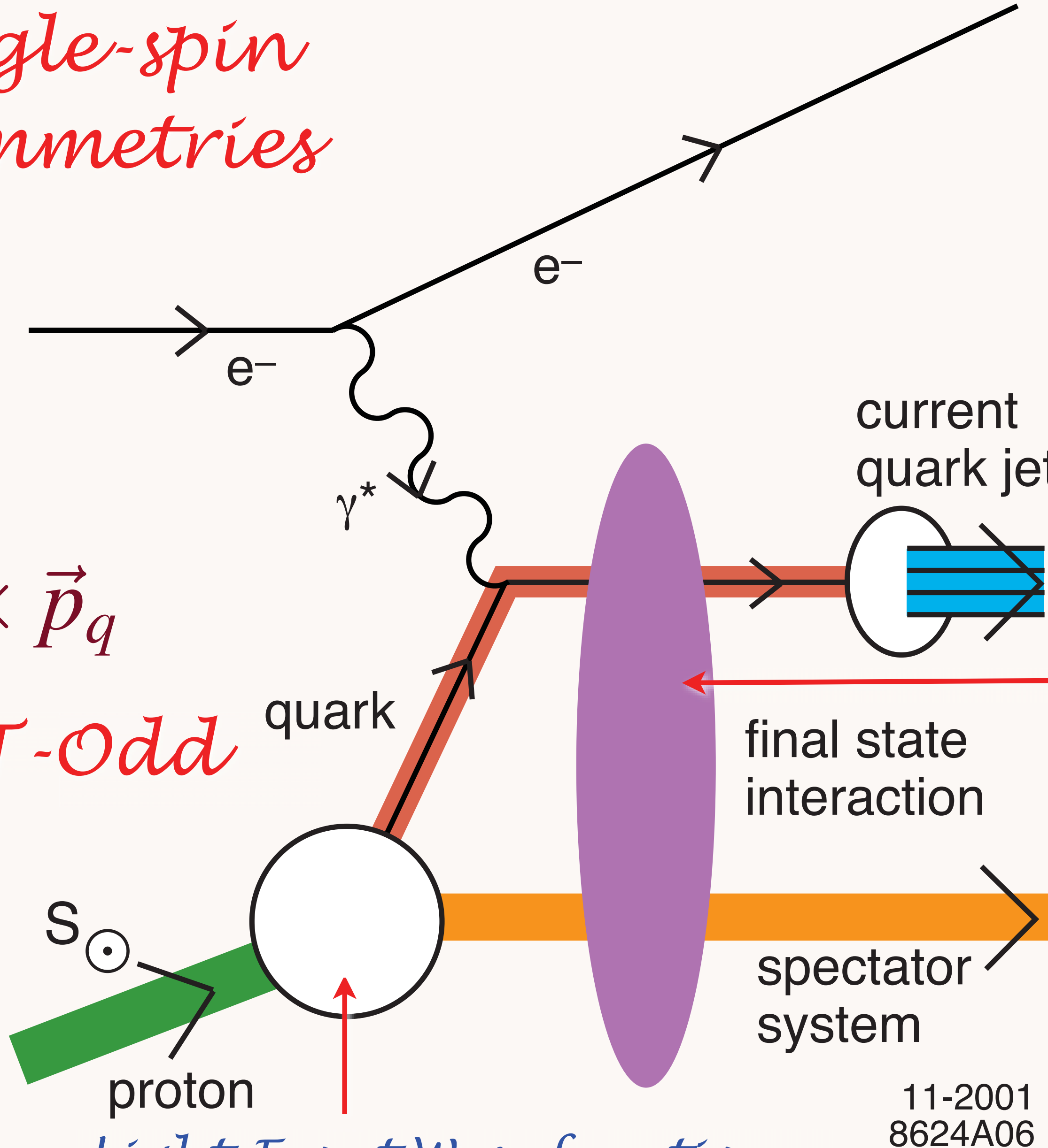
Leading Twist Sivers Effect

Hwang, Schmidt, sjb

Collins, Burkardt Ji, Yuan

$i\,\vec{S}_p \cdot \vec{q} \times \vec{p}_q$

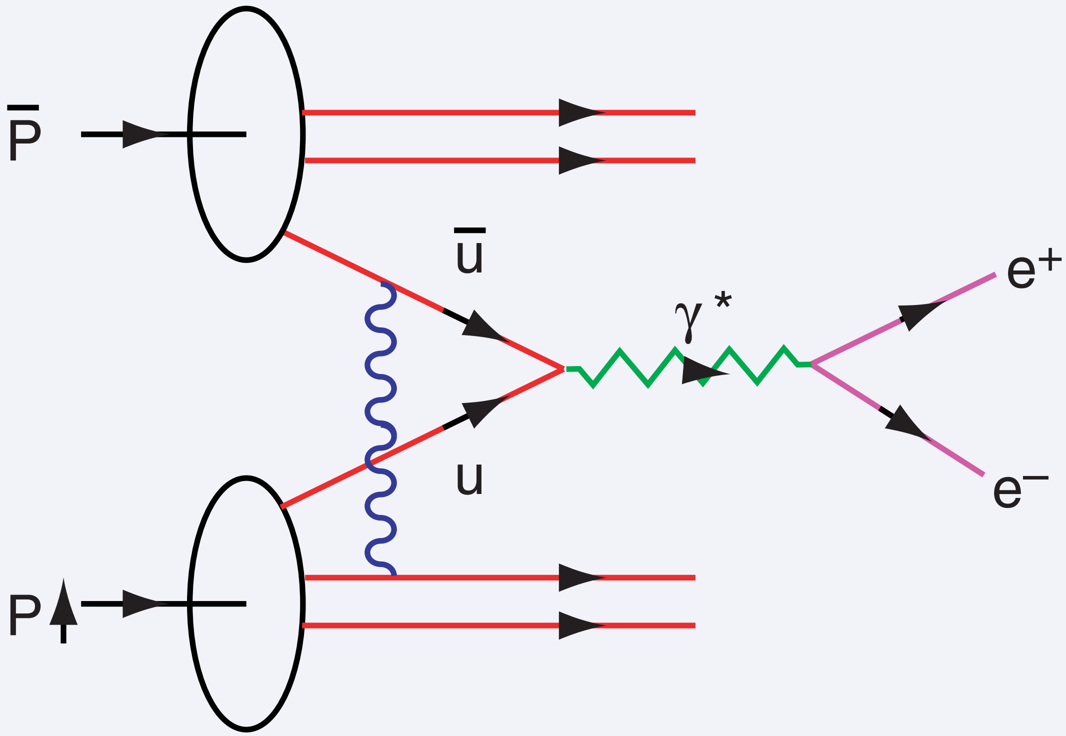
Pseudo-T-Odd



QCD S- and P-Coulomb Phases --Wilson Line

Light-Front Wavefunction S and P- Waves

Predict Opposite Sign SSA in DY !



Collins; Hwang, Schmidt. sjb

Single Spin Asymmetry In the Drell Yan Process

$\vec{S}_p \cdot \vec{\bar{p}} \times \vec{q}_{\gamma^*}$

Quarks Interact in the Initial State

Interference of Coulomb Phases for S and P states

Produce Single Spin Asymmetry [Siver's Effect]Proportional to the Proton Anomalous Moment and α_s.

Opposite Sign to DIS! No Factorization

Key QCD FAIR Experiment

Measure single-spin asymmetry A_N in Drell-Yan reactions

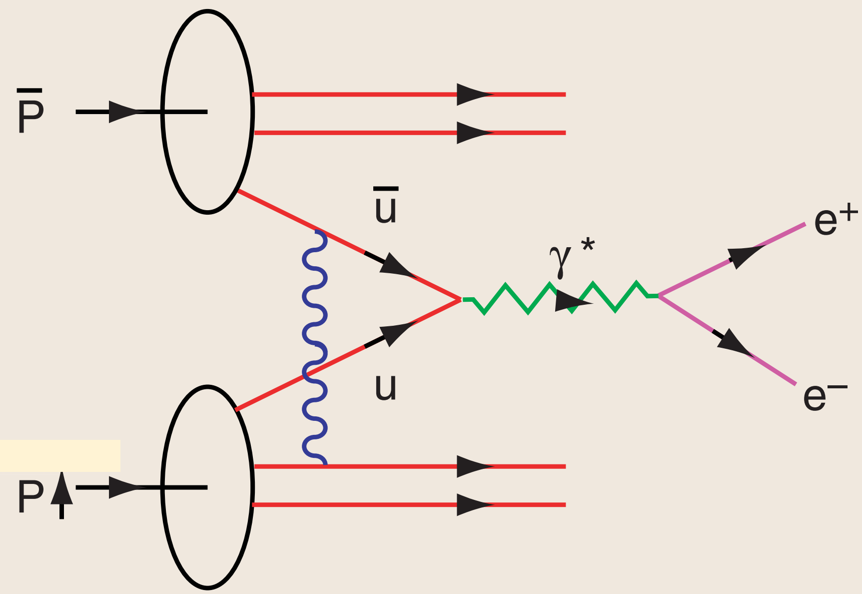
Leading-twist Bjorken-scaling A_N from S, P-wave initial-state gluonic interactions

Predict: $A_N(DY) = -A_N(DIS)$
Opposite in sign!

$Q^2 = x_1 x_2 s$

$Q^2 = 4$ GeV^2, $s = 80$ GeV^2

$x_1 x_2 = .05, x_F = x_1 - x_2$



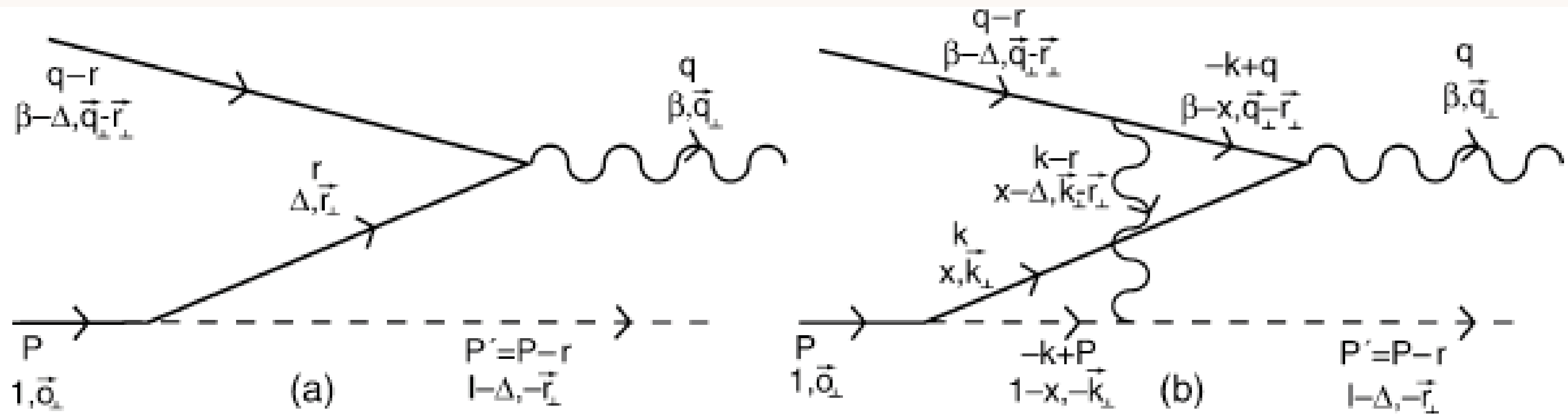
$\bar{p} p_\uparrow \to \ell^+ \ell^- X$

$\vec{S} \cdot \vec{q} \times \vec{p}$ correlation

Initial-state interactions and single-spin asymmetries in Drell–Yan processes ☆

Stanley J. Brodsky [a], Dae Sung Hwang [a,b], Ivan Schmidt [c]

Nuclear Physics B 642 (2002) 344–356

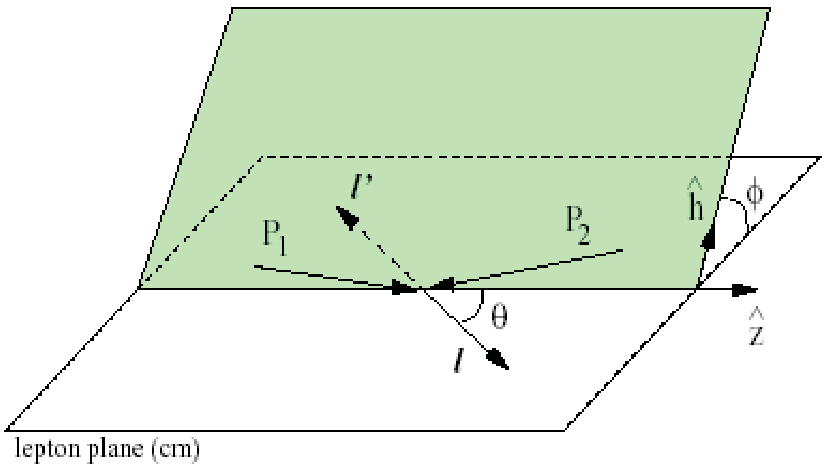


$$\mathcal{P}_y = -\frac{e_1 e_2}{8\pi}\frac{2(\Delta M + m) r^1}{[(\Delta M + m)^2 + \vec{r}_\perp^{\,2}]}\left[\vec{r}_\perp^{\,2} + \Delta(1-\Delta)\left(-M^2 + \frac{m^2}{\Delta} + \frac{\lambda^2}{1-\Delta}\right)\right]$$

$$\times \frac{1}{\vec{r}_\perp^{\,2}} \ln \frac{\vec{r}_\perp^{\,2} + \Delta(1-\Delta)(-M^2 + \frac{m^2}{\Delta} + \frac{\lambda^2}{1-\Delta})}{\Delta(1-\Delta)(-M^2 + \frac{m^2}{\Delta} + \frac{\lambda^2}{1-\Delta})}.$$

Here $\Delta = \frac{q^2}{2P\cdot q} = \frac{q^2}{2M\nu}$ where ν is the energy of the lepton pair in the target rest frame.

Drell-Yan angular distribution



Unpolarized DY

- Experimentally, a violation of the Lam-Tung sum rule is observed by sizeable cos2Φ moments
- Several model explanations
  - higher twist
  - spin correlation due to non-triva QCD vacuum
  - Non-zero Boer Mulders function

$$\text{Lam} - \text{Tung SR}: \ 1 - \lambda = 2\nu$$

$$\text{NLO pQCD}: \lambda \approx 1 \ \mu \approx 0 \ \nu \approx 0$$

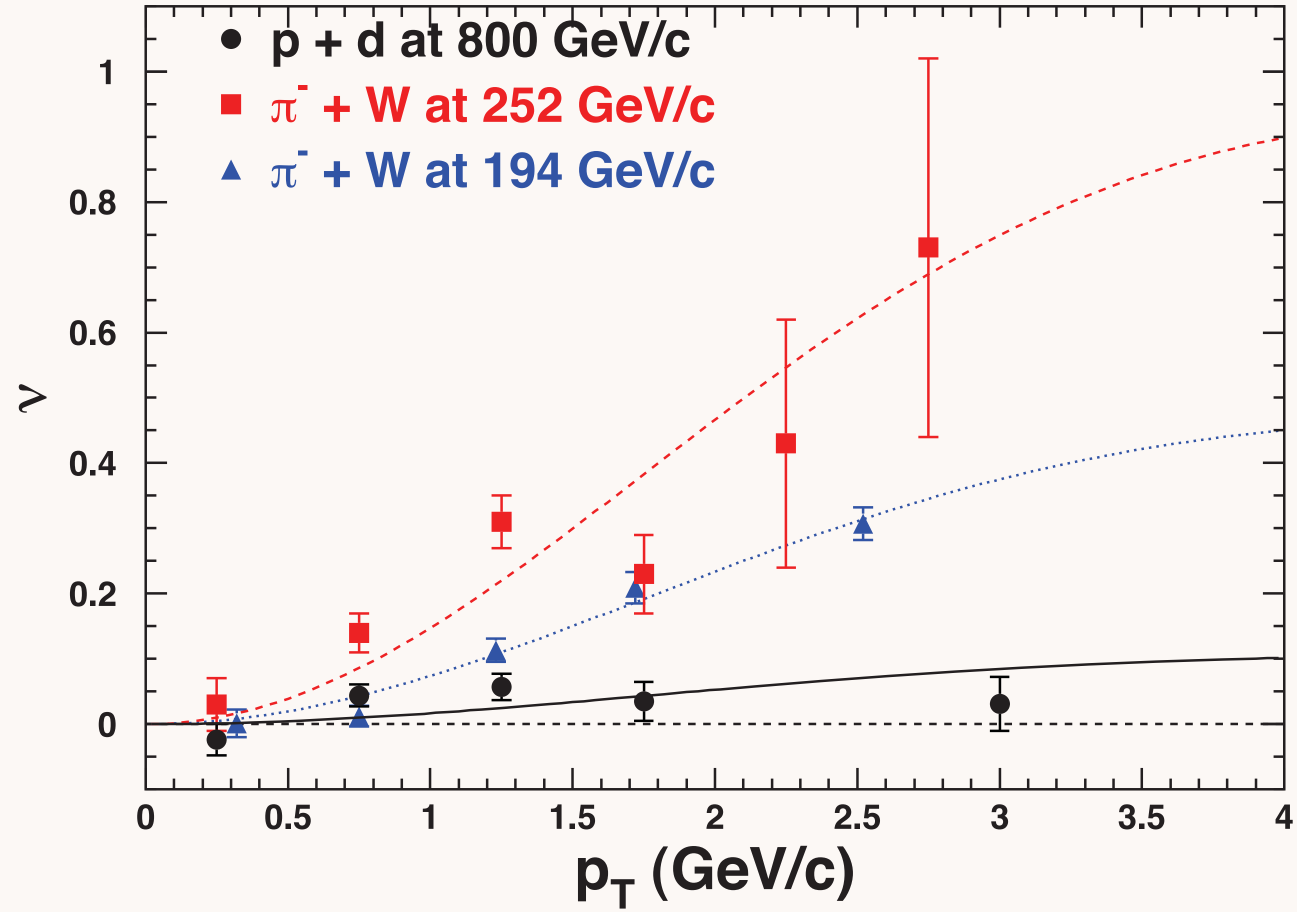
$$\text{experiment}: \ \nu \approx 0.3$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right)$$

B. Seitz

Measurement of Angular Distributions of Drell-Yan Dimuons in $p + d$ Interaction at 800 GeV/c

(FNAL E866/NuSea Collaboration)

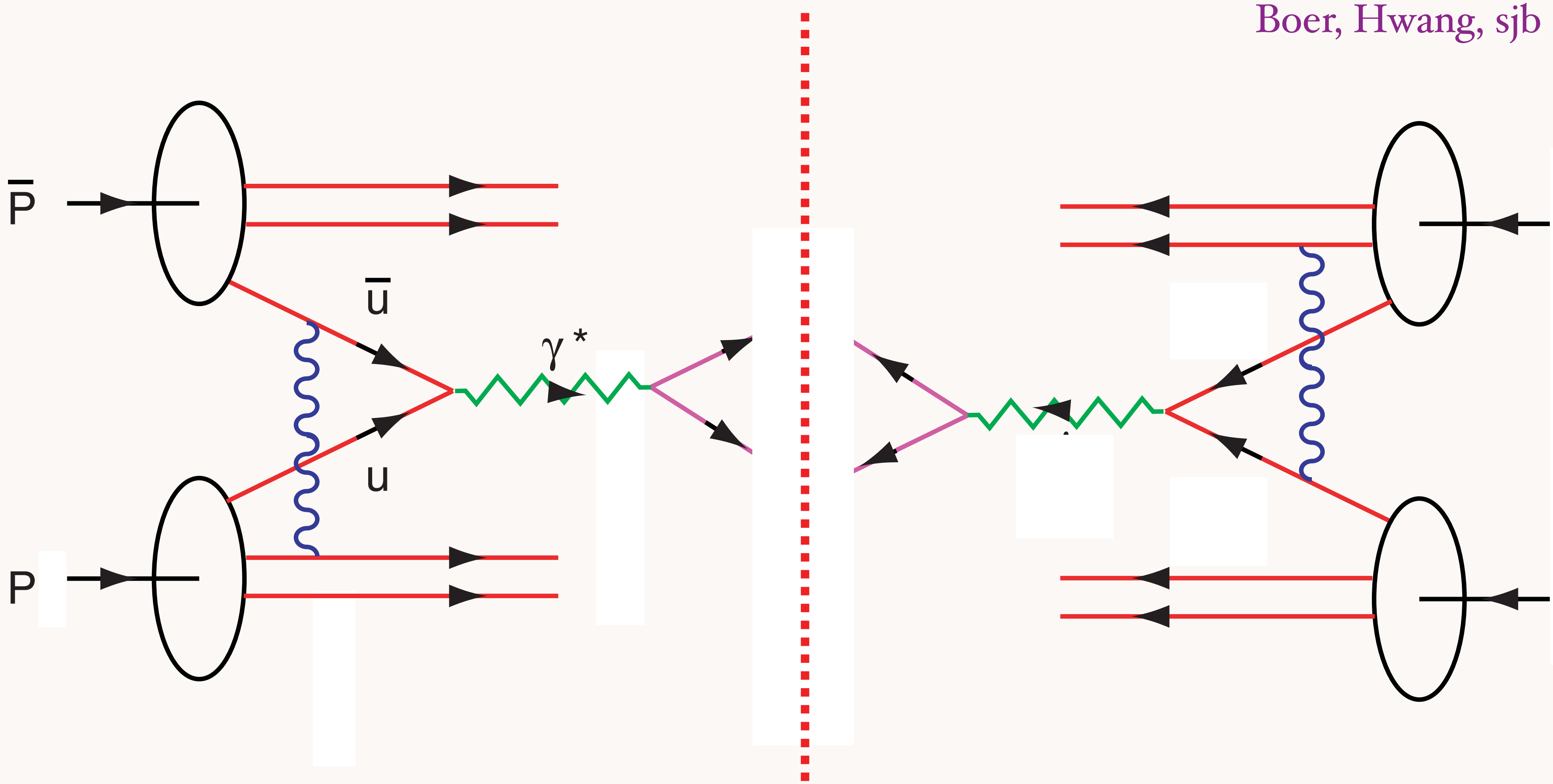


Huge Effect in $\pi W \to \mu^+ \mu^- X$

Negligible Effect $pd \to \mu^+ \mu^- X$

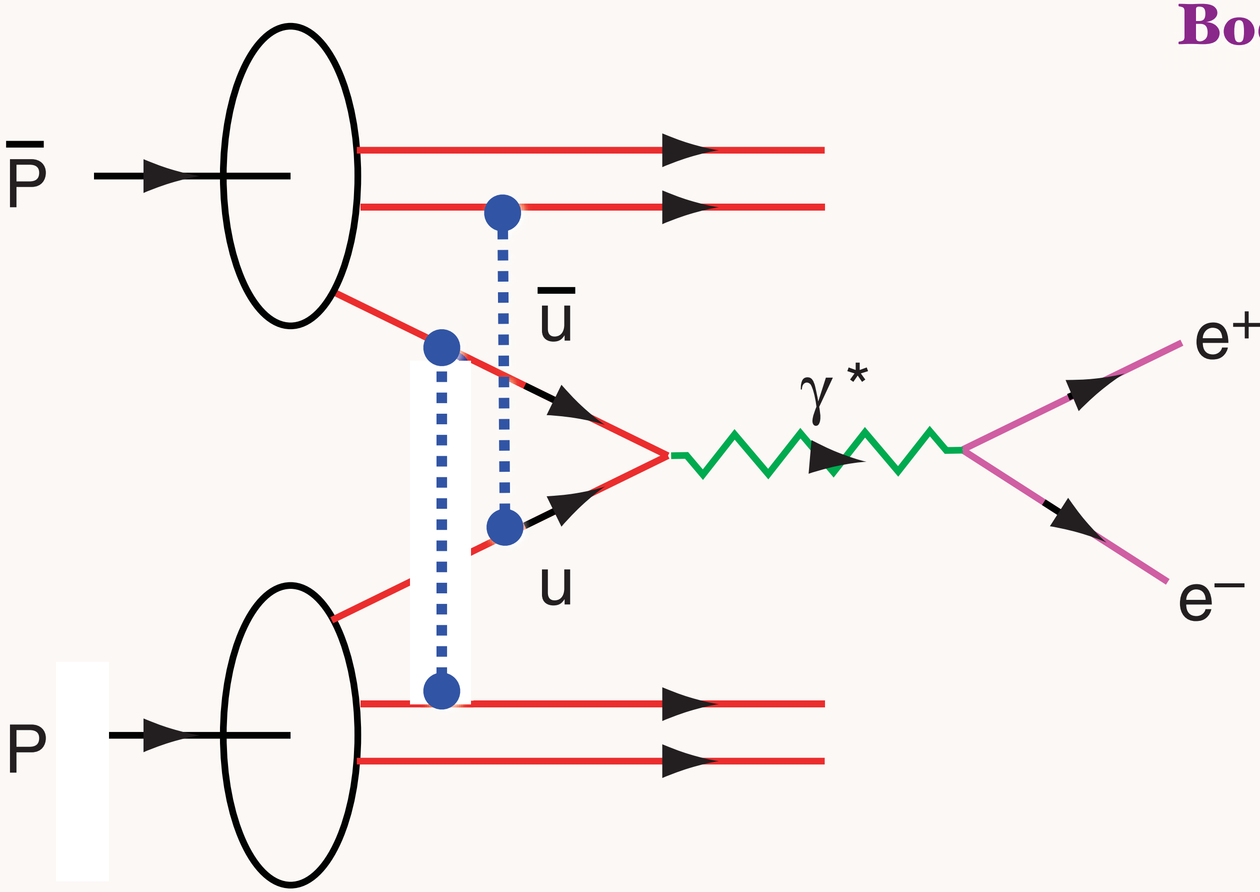
Parameter ν vs. p_T in the Collins-Soper frame for three Drell-Yan measurements. Fits to the data using Eq. 3 and $M_C = 2.4$ GeV/c^2 are also shown.

Boer, Hwang, sjb



DY $\cos 2\phi$ correlation at leading twist from double ISI

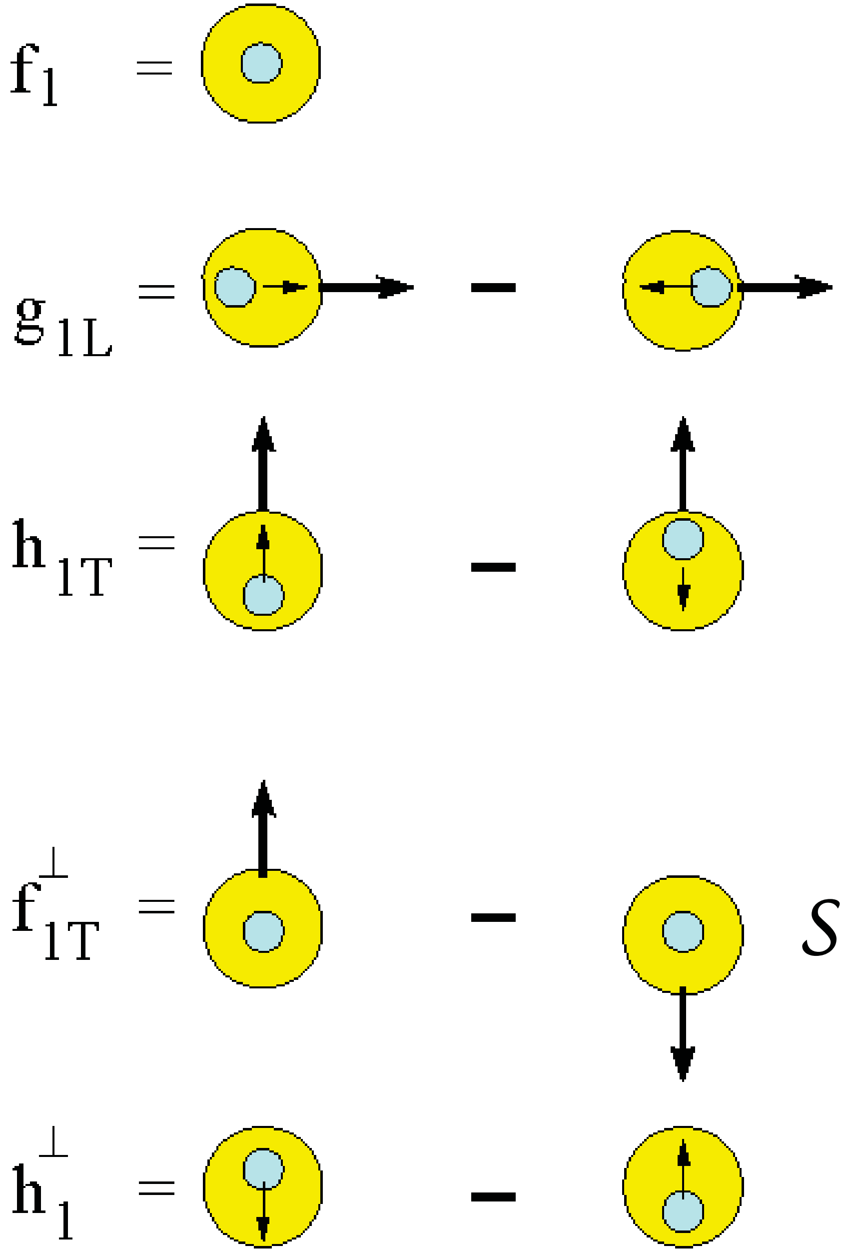
Boer, Hwang, sjb



DY $\cos 2\phi$ correlation at leading twist from double ISI

Product of Boer - Mulders Functions

$$h_1^{\perp}(x_1, \boldsymbol{p}_{\perp}^2) \times \bar{h}_1^{\perp}(x_2, \boldsymbol{k}_{\perp}^2)$$



Unpolarized Distribution

Bj Sum Rule

Transversity

Sivers Function

Boer-Mulders Function

T-Odd:
Require ISI or FSI

Double Initial-State Interactions generate anomalous $\cos 2\phi$

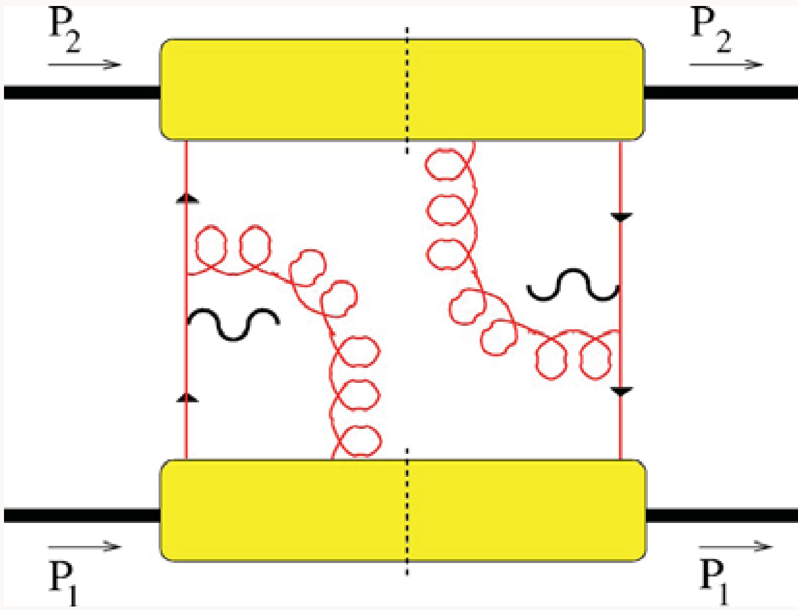
Boer, Hwang, sjb

Drell-Yan planar correlations

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \left(1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2}\sin^2\theta \cos 2\phi\right)$$

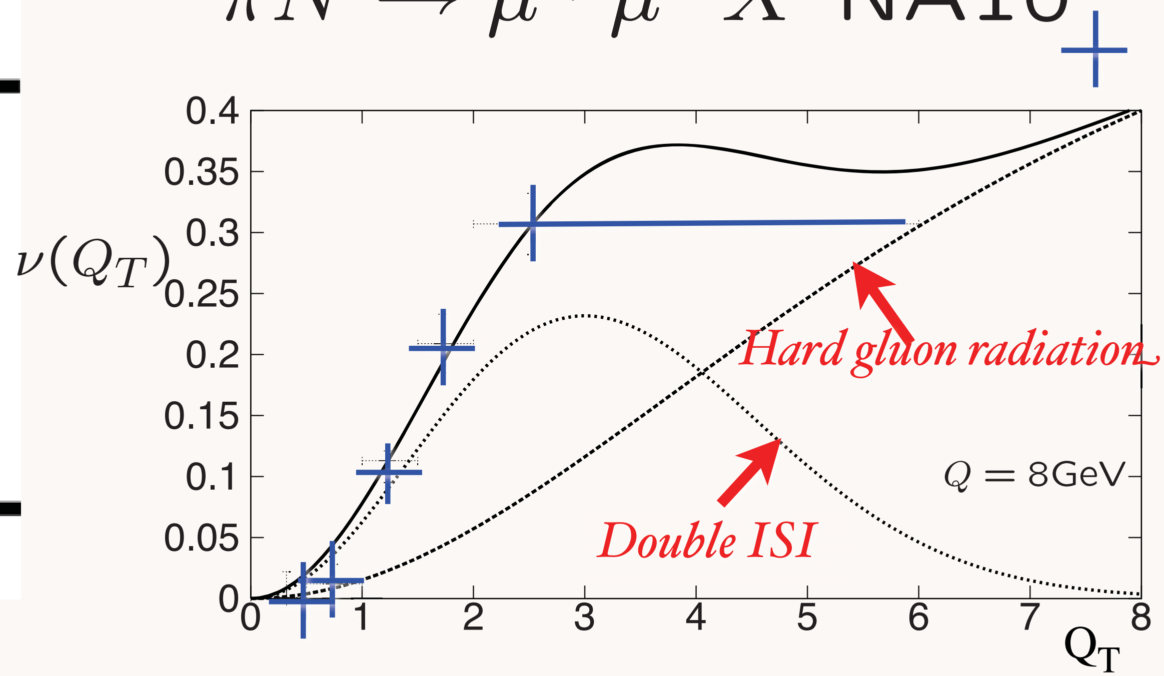
PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

$$\frac{\nu}{2} \propto h_1^{\perp}(\pi)\, h_1^{\perp}(N)$$



Violates Lam-Tung relation!

$\pi N \to \mu^+\mu^- X$ NA10

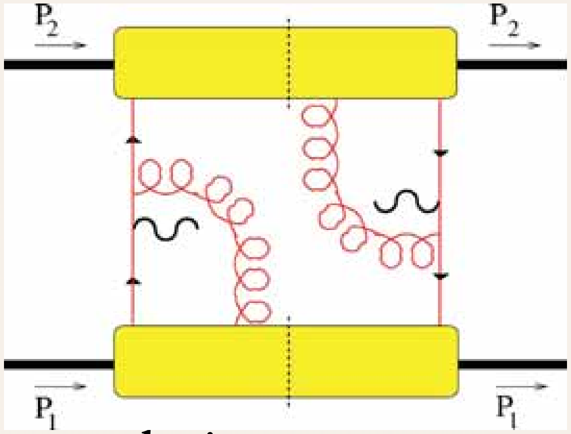


Model: Boer,

Anomalous effect from Double ISI in Massive Lepton Production

Boer, Hwang, sjb

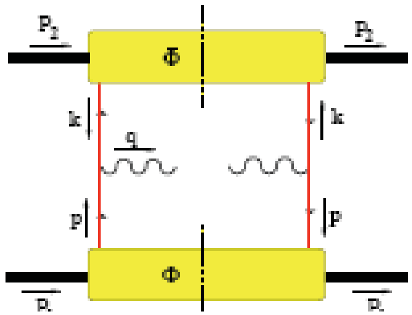
$\cos 2\phi$ correlation

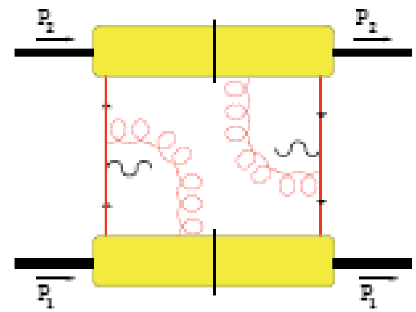


- Leading Twist, valence quark dominated
- Violates Lam-Tung Relation!
- Not obtained from standard PQCD subprocess analysis
- Normalized to the square of the single spin asymmetry in semi-inclusive DIS
- No polarization required
- Challenge to standard picture of PQCD Factorization

Key QCD FAIR Experiment

$\cos 2\phi$ correlation in DY from double ISI

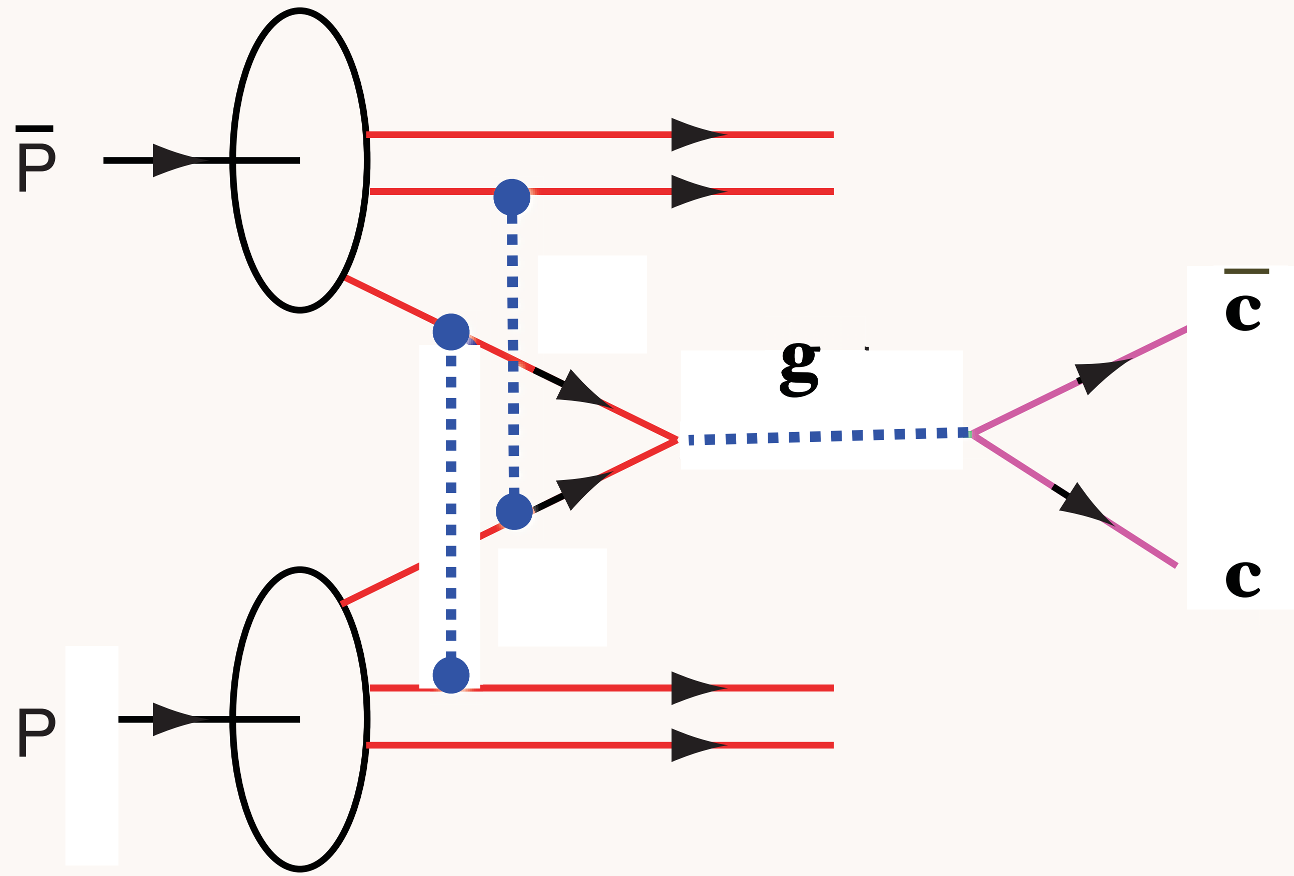




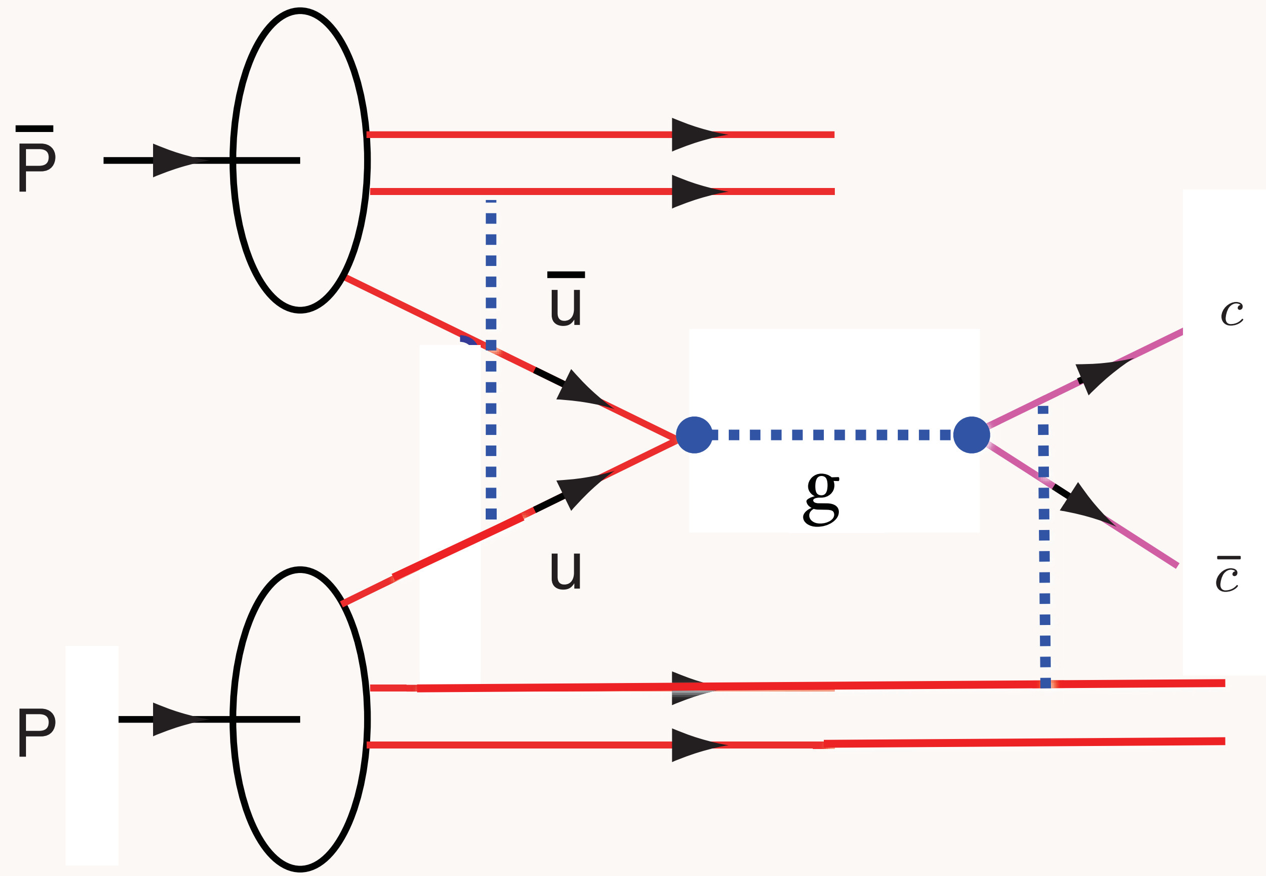
Boer, Hwang, sjb

Abstract

We show that initial-state interactions contribute to the $\cos 2\phi$ distribution in unpolarized Drell-Yan lepton pair production $p\,p$ and $p\overline{p} \to \ell^+\ell^- X$, without suppression. The asymmetry is expressed as a product of chiral-odd distributions $h_1^\perp(x_1, \boldsymbol{p}_\perp^2) \times \overline{h}_1^\perp(x_2, \boldsymbol{k}_\perp^2)$, where the quark-transversity function $h_1^\perp(x, \boldsymbol{p}_\perp^2)$ is the transverse momentum dependent, light-cone momentum distribution of transversely polarized quarks in an *unpolarized* proton. We compute this (naive) T-odd and chiral-odd distribution function and the resulting $\cos 2\phi$ asymmetry explicitly in a quark-scalar diquark model for the proton with initial-state gluon interaction. In this model the function $h_1^\perp(x, \boldsymbol{p}_\perp^2)$ equals the T-odd (chiral-even) Sivers effect function $f_{1T}^\perp(x, \boldsymbol{p}_\perp^2)$. This suggests that the single-spin asymmetries in the SIDIS and the Drell-Yan process are closely related to the $\cos 2\phi$ asymmetry of the unpolarized Drell-Yan process, since all can arise from the same underlying mechanism. This provides new insight regarding the role of quark and gluon orbital angular momentum as well as that of initial- and final-state gluon exchange interactions in hard QCD processes.



$\cos 2\phi$ correlation for charm pair production at leading twist from double ISI

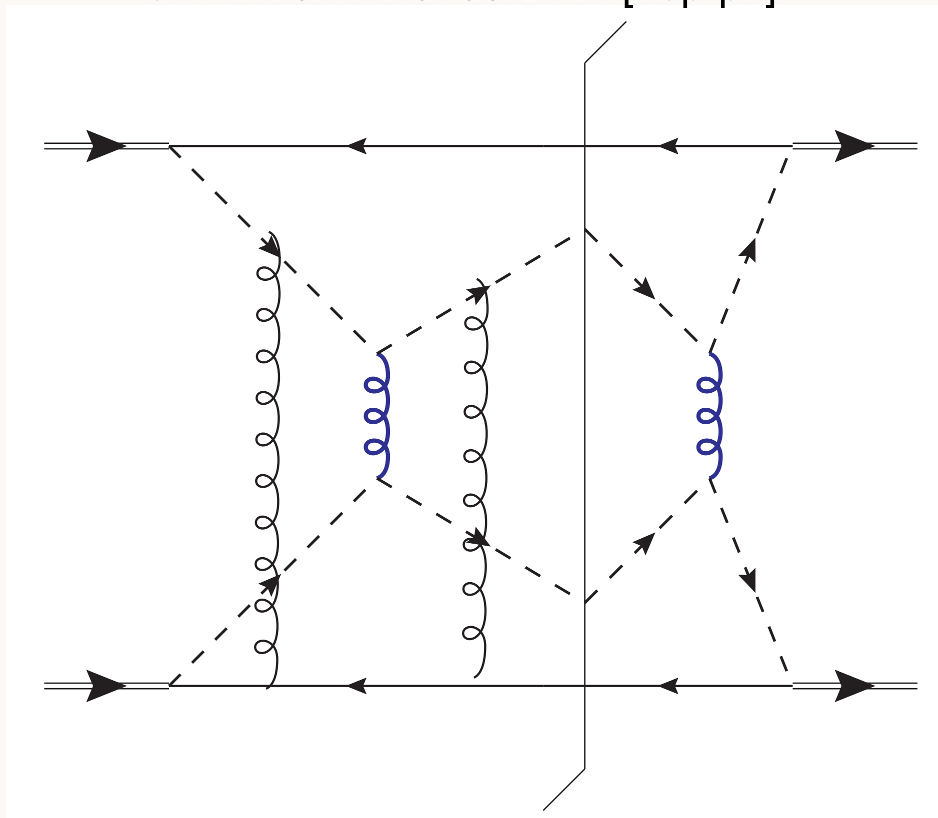


Problem for factorization when both ISI and FSI occur

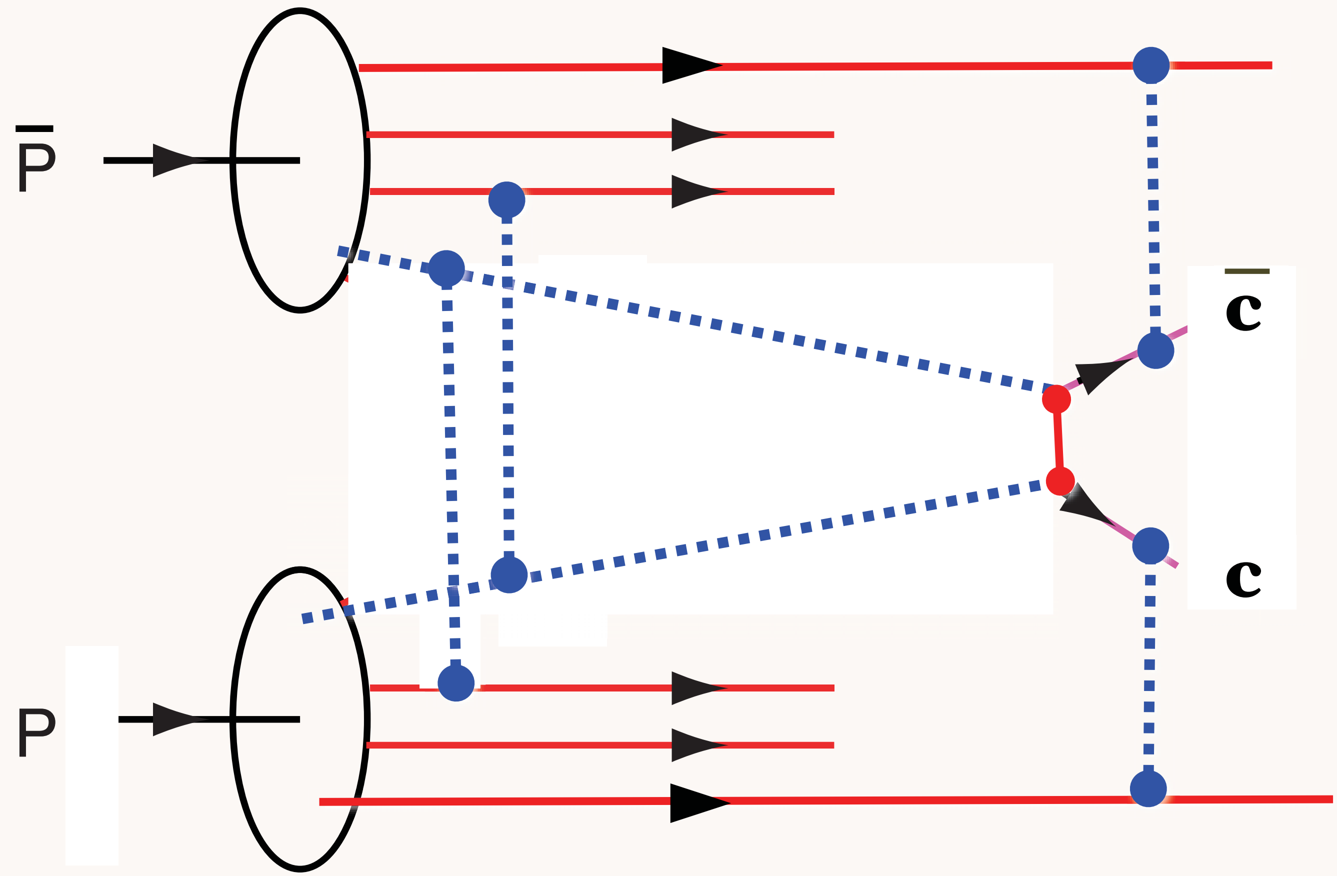
Factorization is violated in production of high-transverse-momentum particles in hadron-hadron collisions

John Collins, Jian-Wei Qiu . ANL-HEP-PR-07-25, May 2007.

e-Print: **arXiv:0705.2141** [hep-ph]

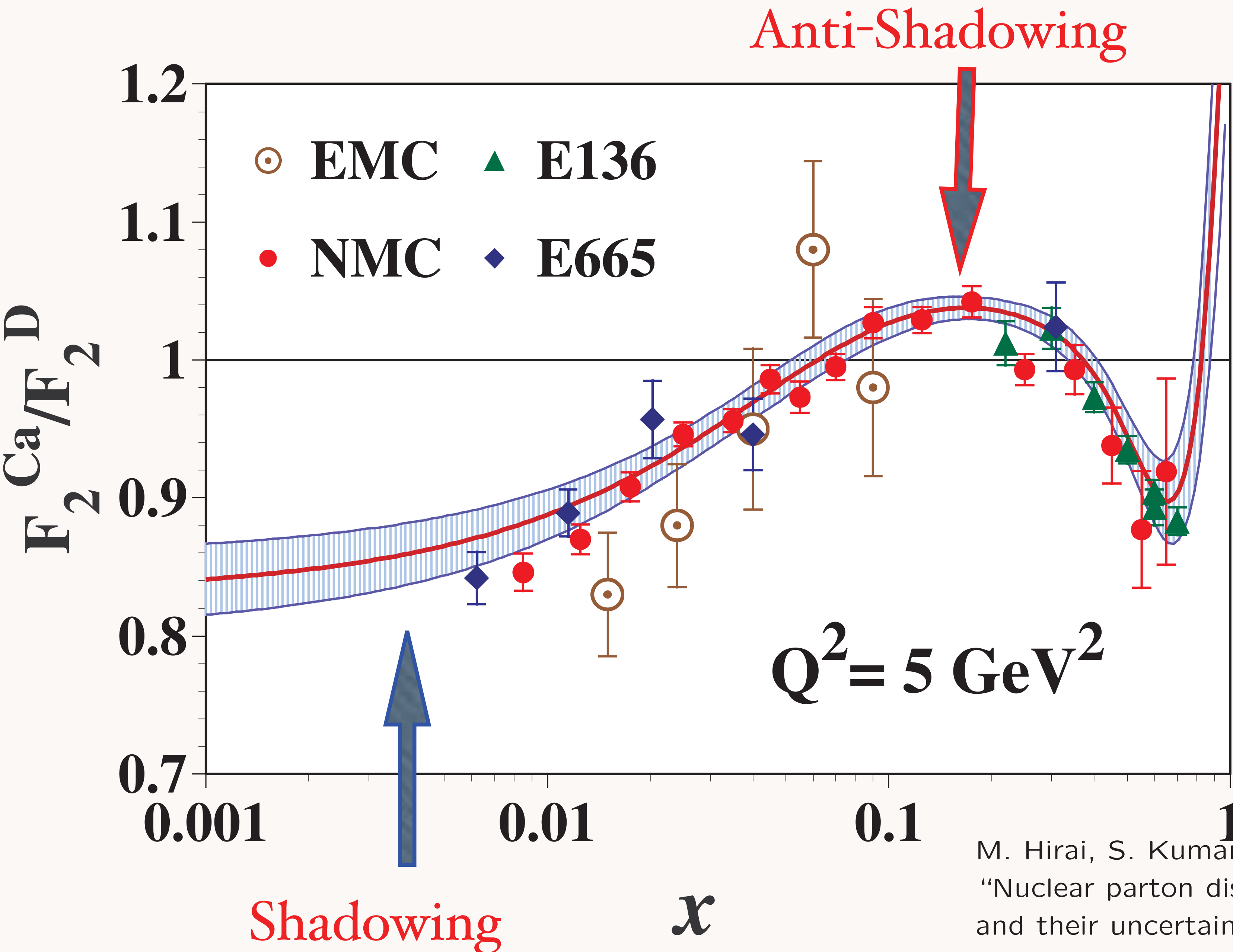


The exchange of two extra gluons, as in this graph, will tend to give non-factorization in unpolarized cross sections.



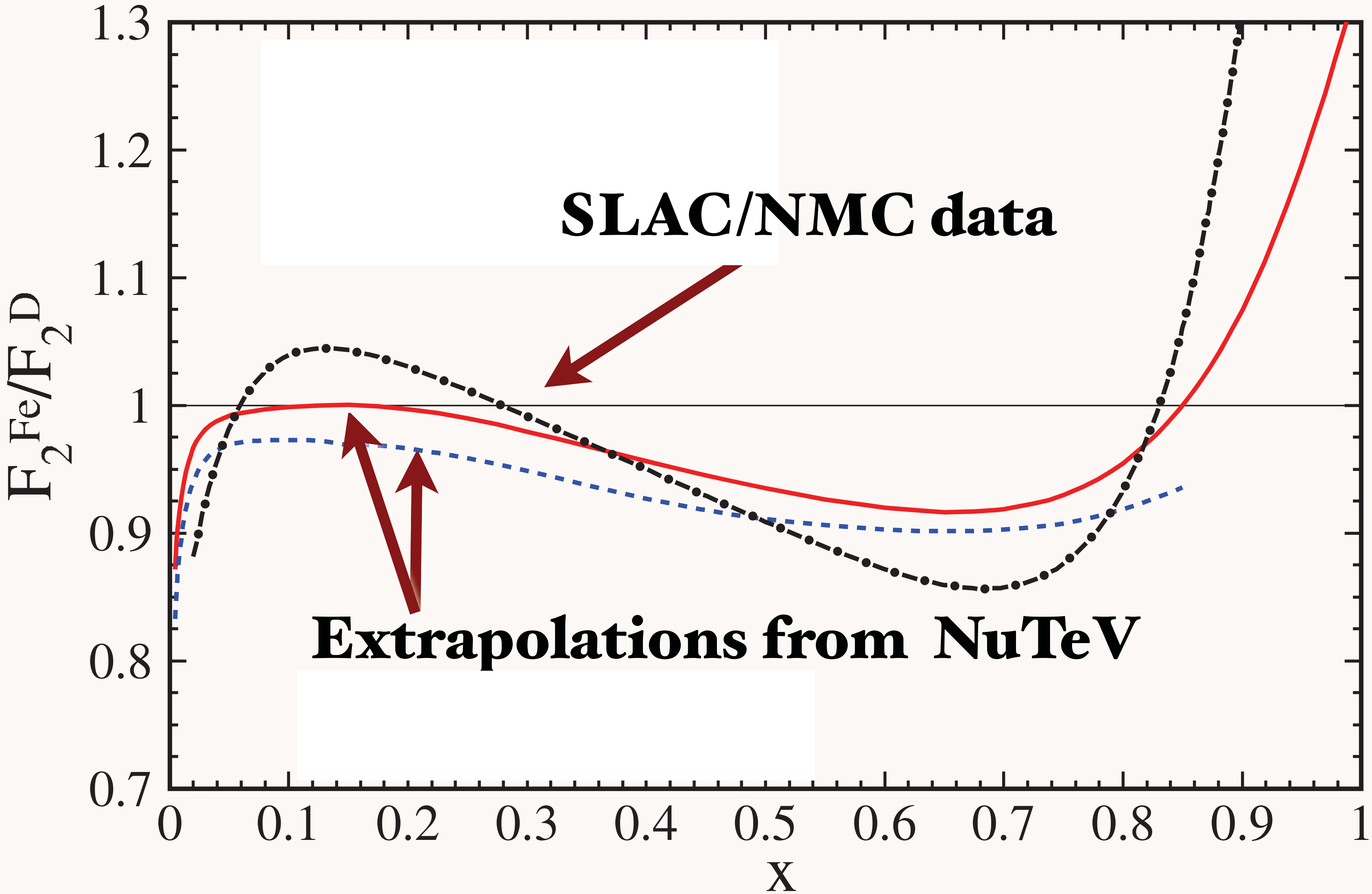
$\cos 2\phi$ **correlation for quarkonium production at leading twist from double ISI**

Enhanced by gluon color charge
Also possible FSI



M. Hirai, S. Kumano and T. H. Nagai, "Nuclear parton distribution functions and their uncertainties," Phys. Rev. C **70**, 044905 (2004) [arXiv:hep-ph/0404093].

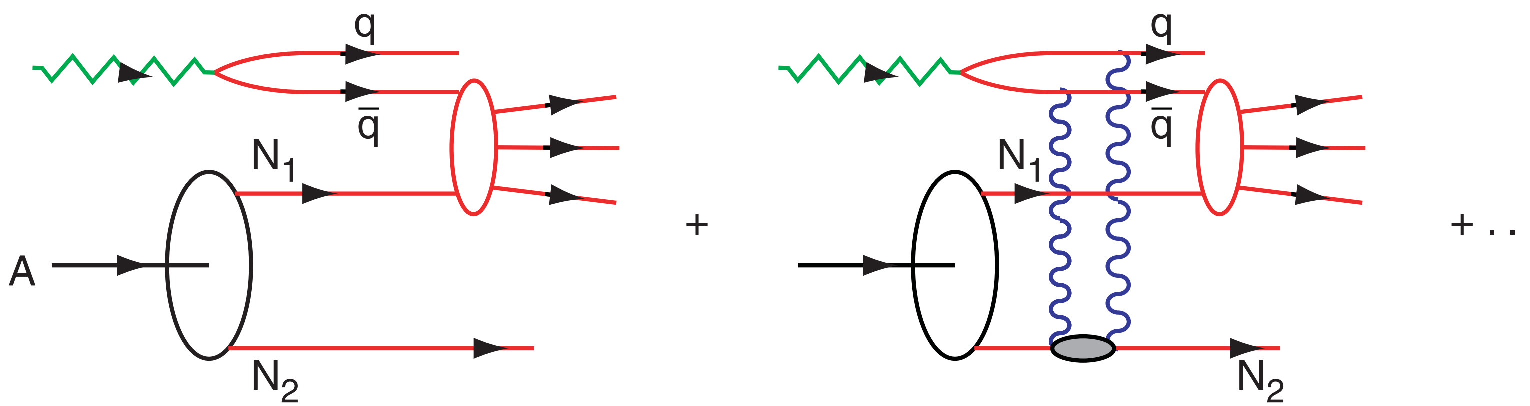
$Q^2 = 5\ \mathrm{GeV}^2$



Scheinbein, Yu, Keppel, Morfin, Olness, Owens

Stodolsky
Pumplin, sjb
Gribov

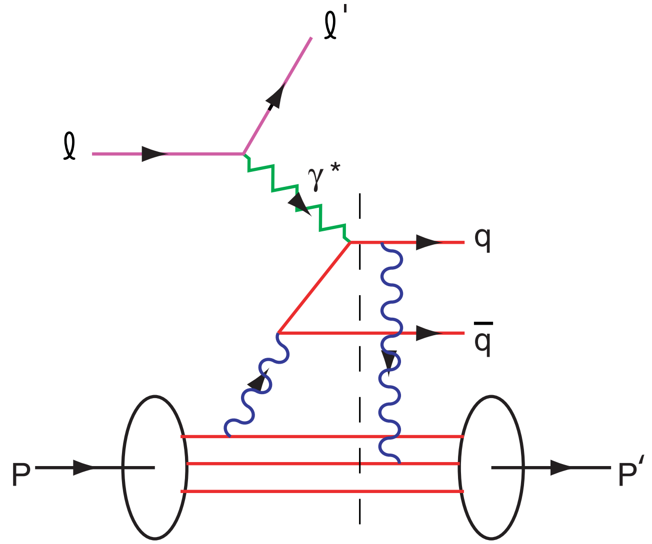
Nuclear Shadowing in QCD



Shadowing depends on understanding leading twist-diffraction in DIS

Nuclear Shadowing not included in nuclear LFWF !

Dynamical effect due to virtual photon interacting in nucleus



Shadowing depends on leading-twist DDIS

Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate Pomeron

Need Imaginary Phase to Generate T-Odd Single-Spin Asymmetry

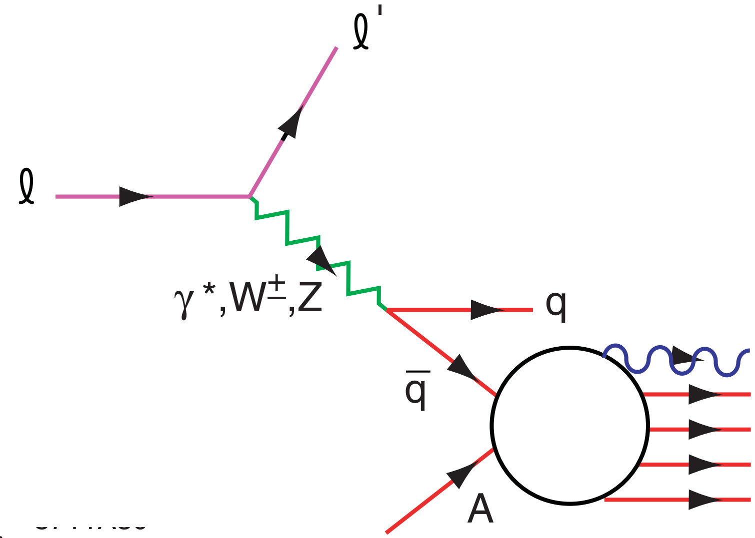
Physics of FSI not in Wavefunction of Target

Antishadowing (Reggeon exchange) is not universal!

Schmidt, Yang, sjb

Origin of Regge Behavior of Deep Inelastic Structure Functions

Antiquark interacts with target nucleus at energy $\widehat{s} \propto \frac{1}{x_{bj}}$



Regge contribution: $\sigma_{\bar{q}N} \sim \widehat{s}^{\alpha_R - 1}$

Nonsinglet Kuti-Weisskoff $F_{2p} - F_{2n} \propto \sqrt{x_{bj}}$ at small x_{bj}.

Shadowing of $\sigma_{\bar{q}M}$ produces shadowing of nuclear structure function.

Landshoff, Polkinghorne, Short

Close, Gunion, sjb

Schmidt, Yang, Lu, sjb

Reggeon Exchange

Phase of two-step amplitude relative to one step:

$$\frac{1}{\sqrt{2}}(1 - i) \times i = \frac{1}{\sqrt{2}}(i + 1)$$

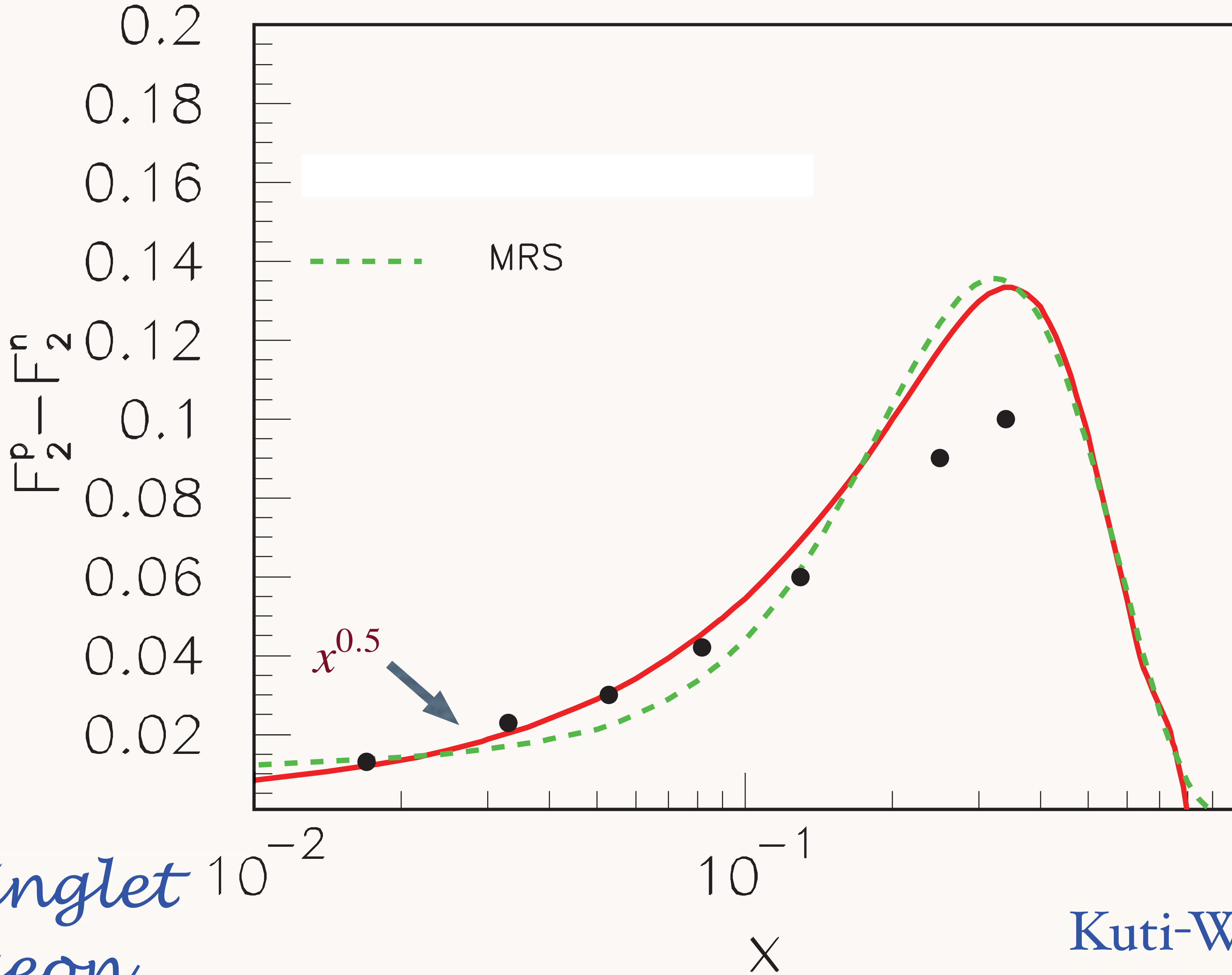
Constructive Interference

Depends on quark flavor!

Thus antishadowing is not universal

Different for couplings of $\gamma^*, Z^0, W^\pm$

Critical test: Tagged Drell-Yan



Non-singlet Reggeon Exchange

Kuti-Weisskopf behavior

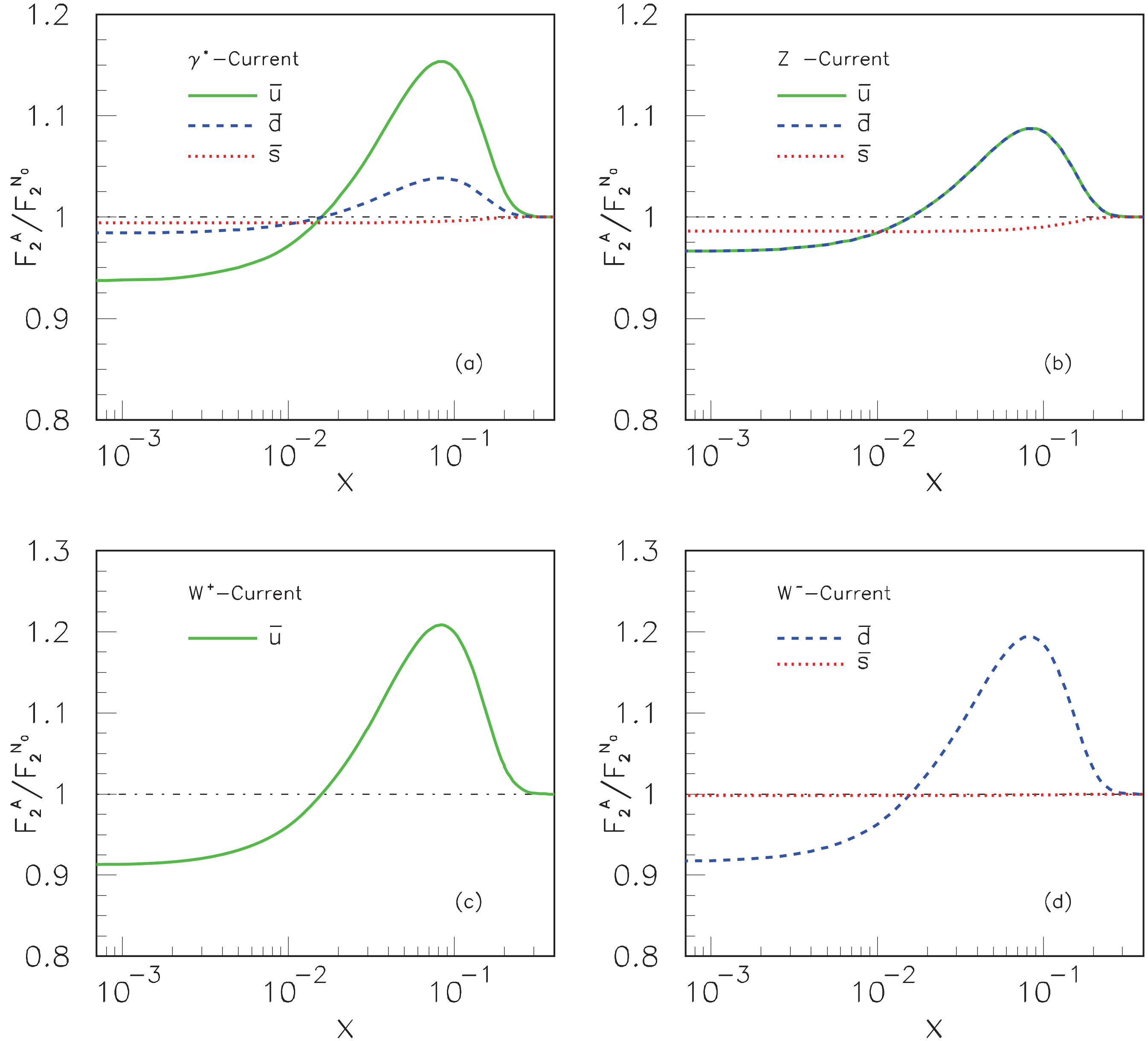
Shadowing and Antishadowing in Lepton-Nucleus Scattering

- Shadowing: Destructive Interference
of Two-Step and One-Step Processes
Pomeron Exchange

- Antishadowing: Constructive Interference
of Two-Step and One-Step Processes!
Reggeon and Odderon Exchange

- Antishadowing is Not Universal!
Electromagnetic and weak currents:
different nuclear effects !
Potentially significant for NuTeV Anomaly}

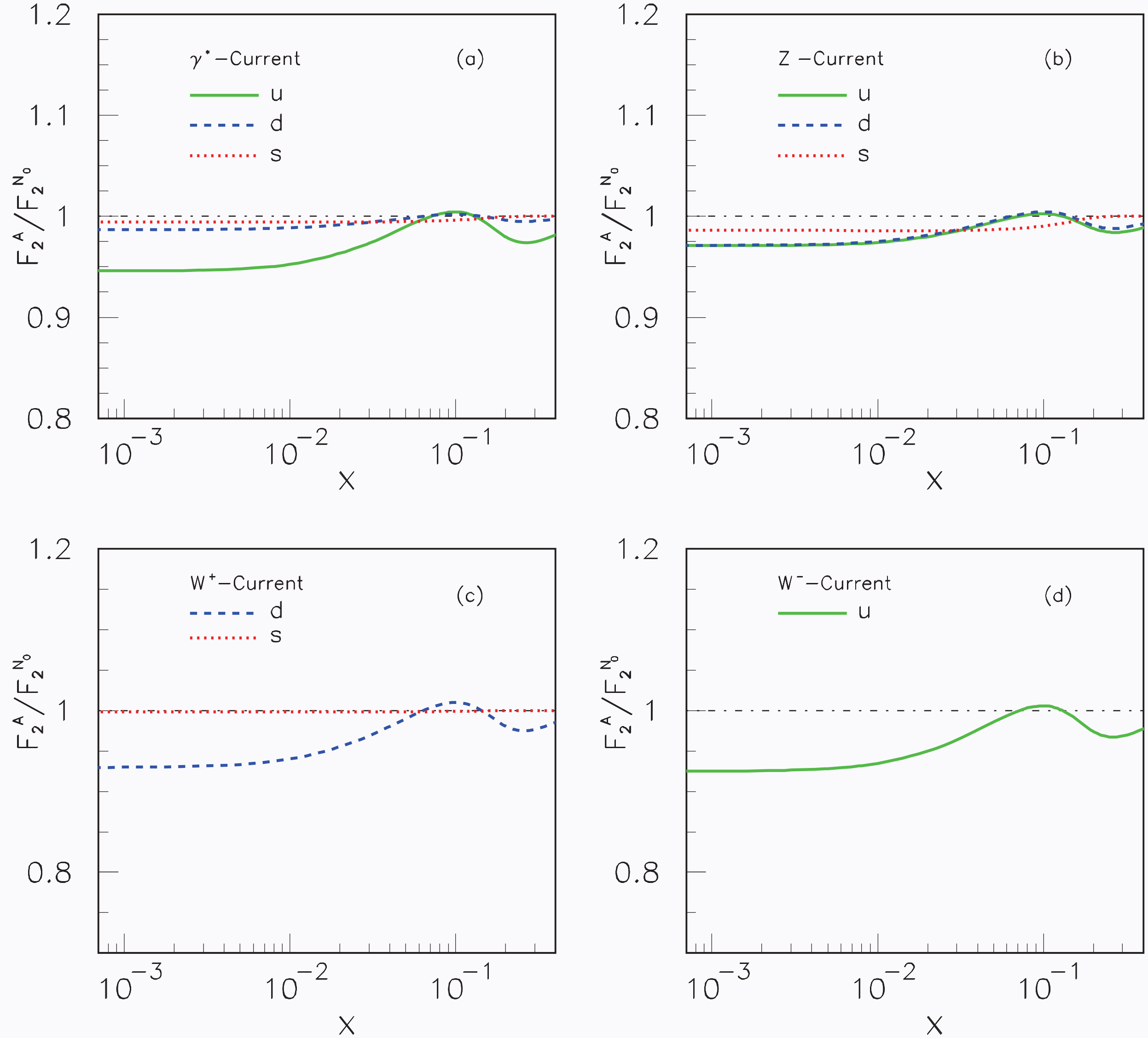
Jian-Jun Yang
Ivan Schmidt
Hung Jung Lu
sjb



Schmidt, Yang; sjb

Nuclear Antishadowing not universal !

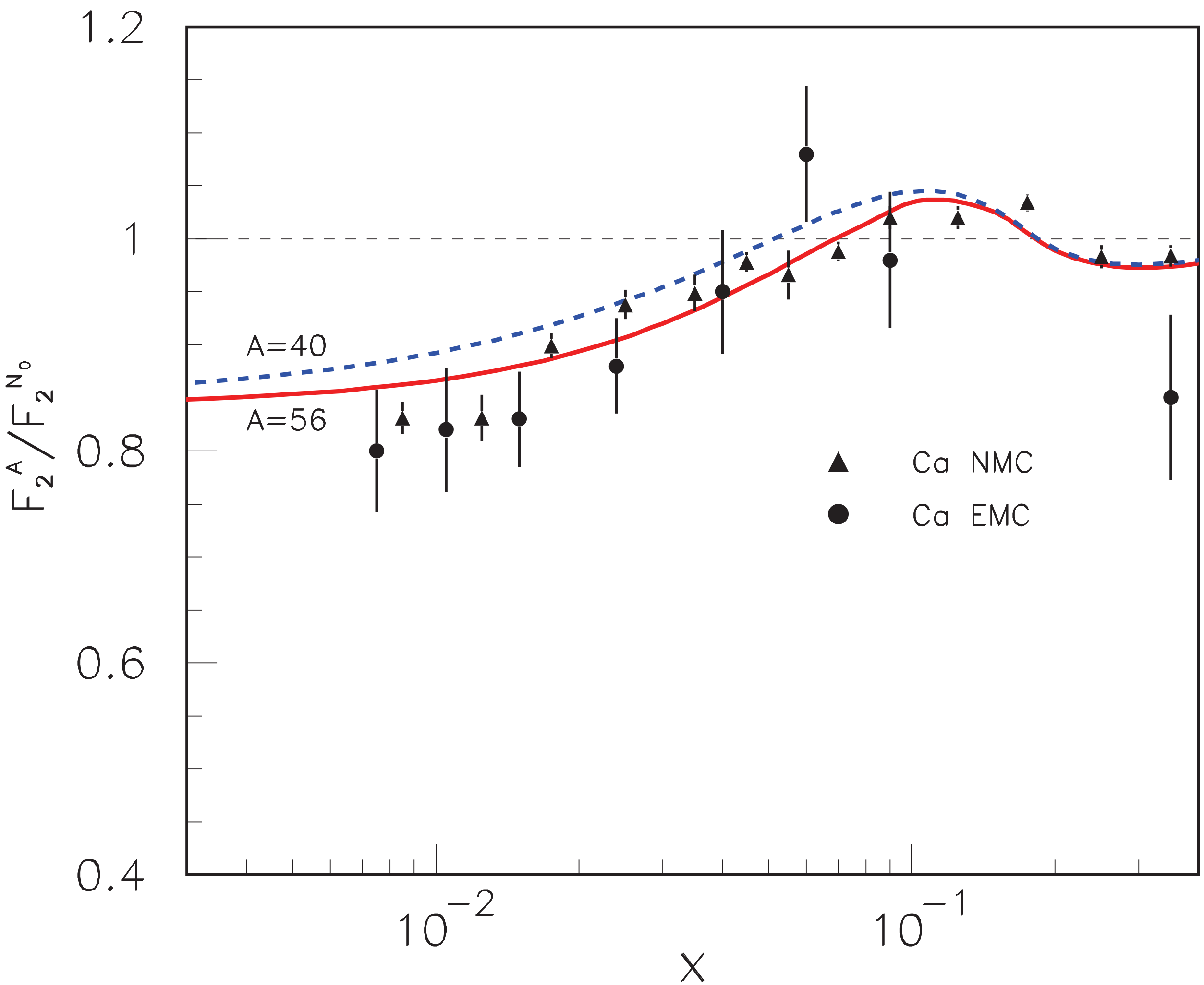
Shadowing and Antishadowing of DIS Structure Functions



S. J. Brodsky, I. Schmidt and J. J. Yang, "Nuclear Antishadowing in Neutrino Deep Inelastic Scattering," Phys. Rev. D 70, 116003 (2004) [arXiv:hep-ph/0409279].

Modifies NuTeV extraction of $\sin^2\theta_W$

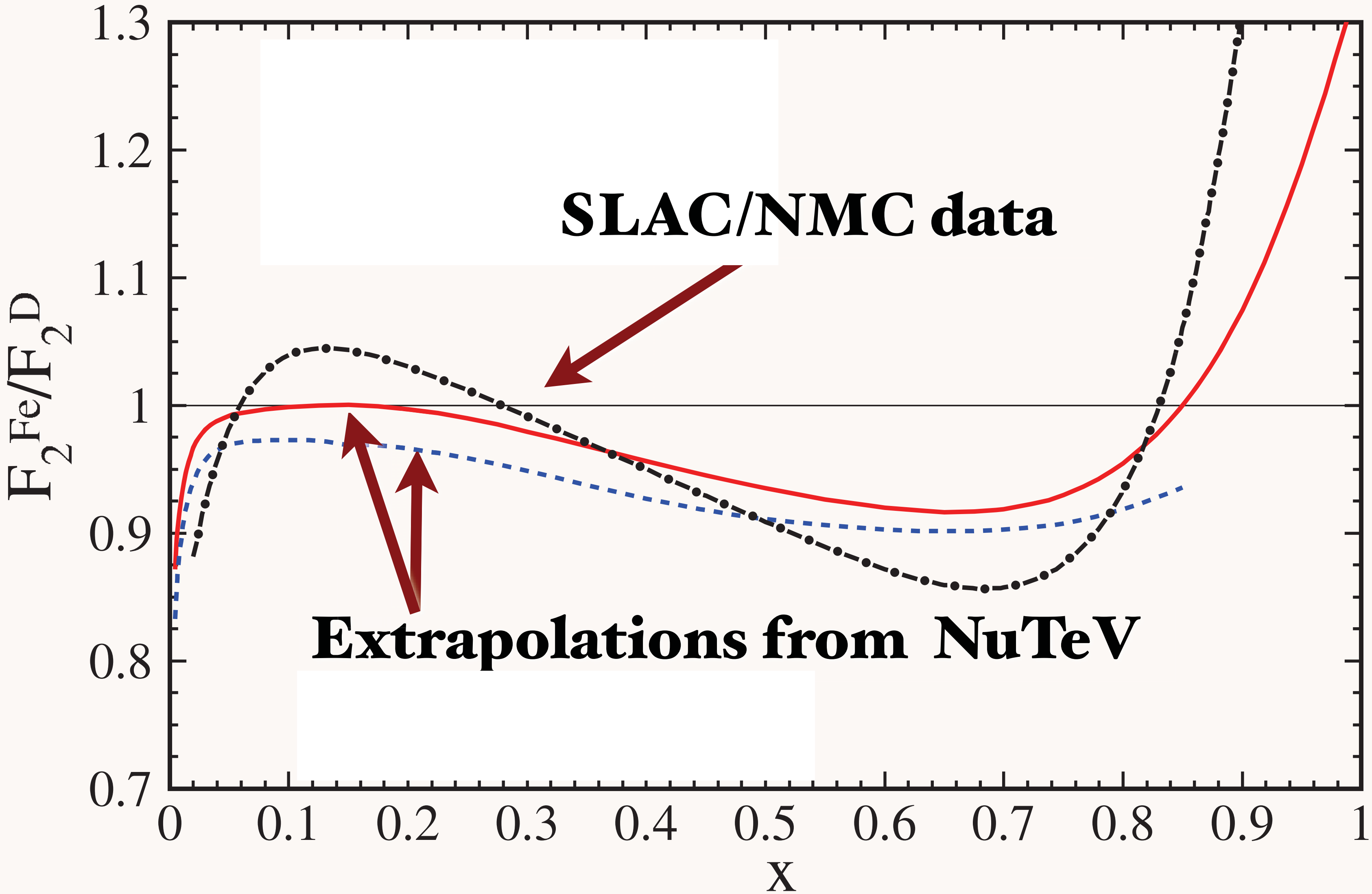
Test in flavor-tagged lepton-nucleus collisions



Predicted nuclear shadowing and and antishadowing at $Q^2 = 1 \text{ GeV}^2$

S. J. Brodsky, I. Schmidt and J. J. Yang, "Nuclear Antishadowing in Neutrino Deep Inelastic Scattering," Phys. Rev. D 70, 116003 (2004) [arXiv:hep-ph/0409279].

$$Q^2 = 5\ \mathrm{GeV}^2$$



Scheinbein, Yu, Keppel, Morfin, Olness, Owens

Key QCD FAIR Experiment

Measure Non-Universal Anti-Shadowing in Drell-Yan

$\bar{p}A \to \ell^+\ell^- X$

$Q^2 = x_1 x_2 s \qquad x_1 x_2 = .05, x_F = x_1 - x_2$

$$A^{\alpha(x_1)} = \frac{2\frac{d\sigma}{dQ^2 dx_F}(\bar{p}A \to \ell^+\ell^- X)}{A\frac{d\sigma}{dQ^2 dx_F}(\bar{p}d \to \ell^+\ell^- X)}$$

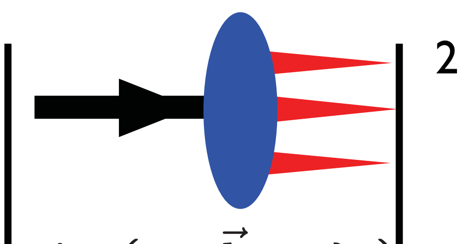
Flavor
u, d tag

Schmidt, Yang, sjb

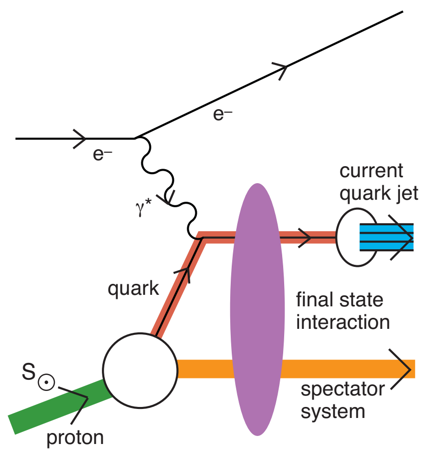
Deviations from $(1 + \cos^2\theta)$

$\cos 2\phi$ correlation.

Static	Dynamic
Square of Target LFWFs	Modified by Rescattering: ISI & FSI
No Wilson Line	Contains Wilson Line, Phases
Probability Distributions	No Probabilistic Interpretation
Process-Independent	Process-Dependent - From Collision
T-even Observables	T-Odd (Sivers, Boer-Mulders, etc.)
No Shadowing, Anti-Shadowing	Shadowing, Anti-Shadowing, Saturation
Sum Rules: Momentum and J^z	Sum Rules Not Proven
DGLAP Evolution; mod. at large x	DGLAP Evolution
No Diffractive DIS	Hard Pomeron and Odderon Diffractive DIS

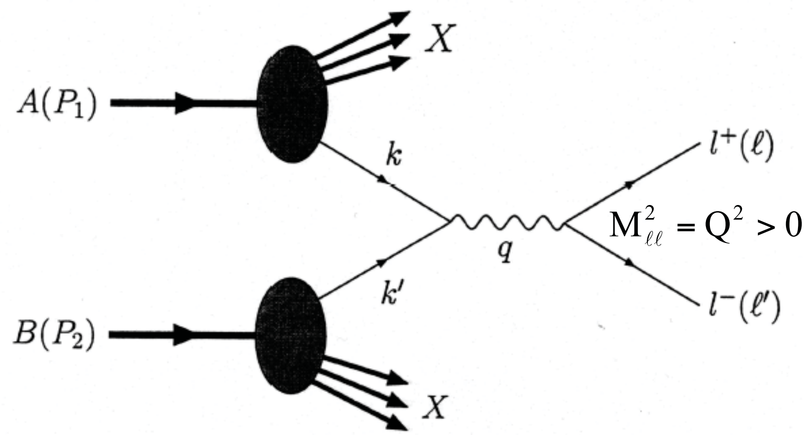


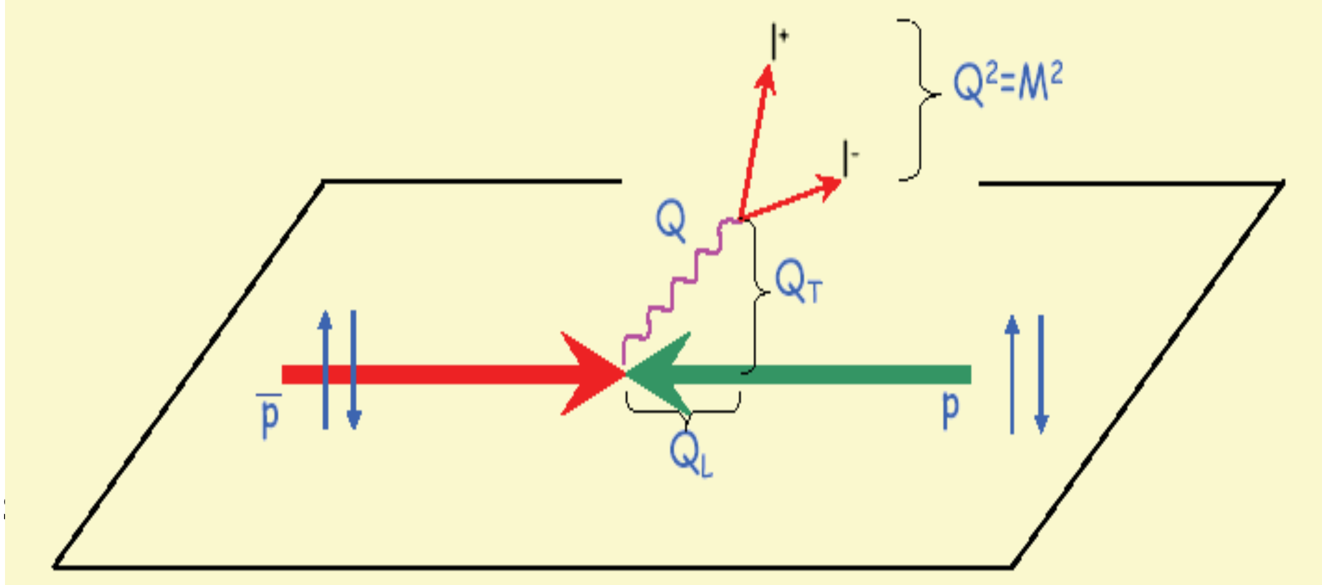
$$\left| \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) \right|^2$$



The Drell-Yan process

- process complementary to DIS
- cross section directly related to parton distribution functions
- no fragmentation functions involved
- all valence quarks will contribute in anti-proton annihilation
- wealth of (spin)-observable:





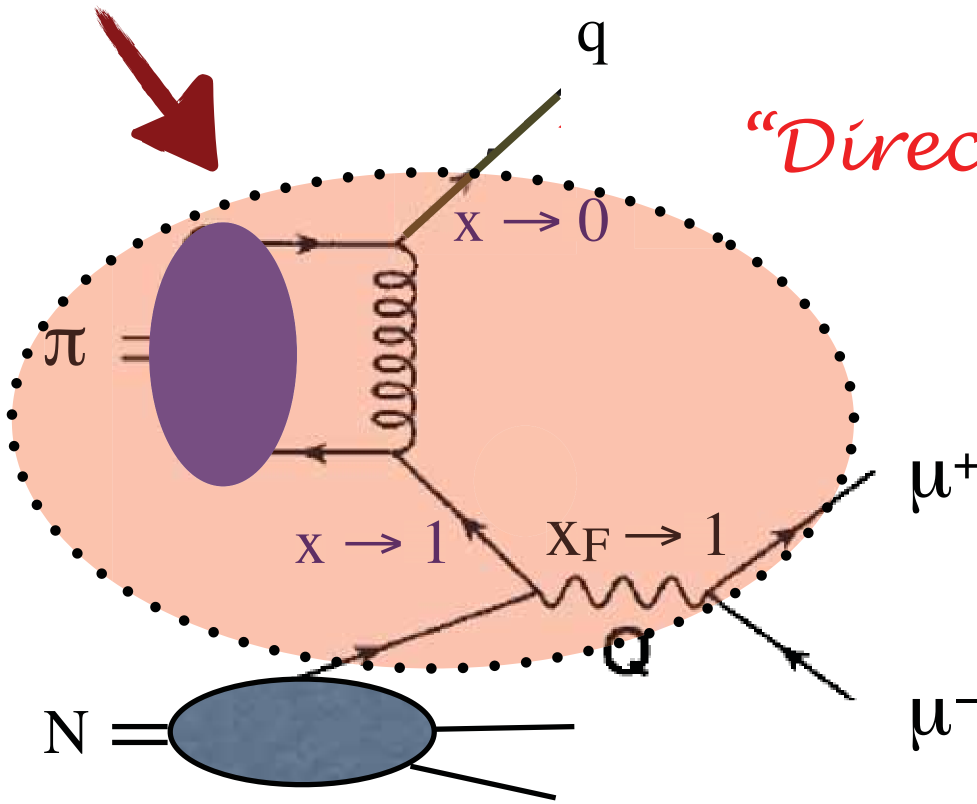
B. Seitz

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

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

Light-Front Wavefunctions from AdS/CFT

Entire pion wf contributes to hard process



"Direct" Subprocess

Virtual photon is longitudinally polarized

Berger, sjb
Khoze, Brandenburg, Muller, sjb

Hoyer Vanttinen

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

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

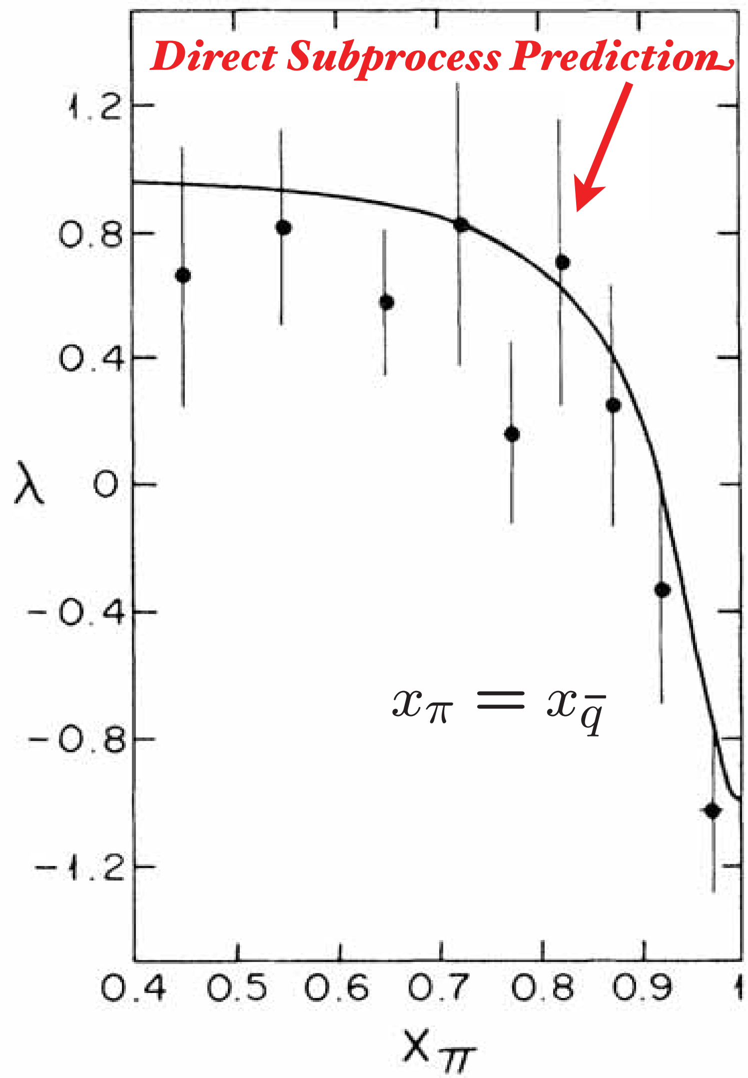
$$\frac{d^2\sigma}{dx_\pi d\cos\theta} \propto x_\pi \left[(1-x_\pi)^2 (1+\cos^2\theta) + \frac{4}{9} \frac{\langle k_T^2 \rangle}{M^2} \sin^2\theta \right]$$

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

$$Q^2 = M^2$$

Dramatic change in angular distribution at large x_F

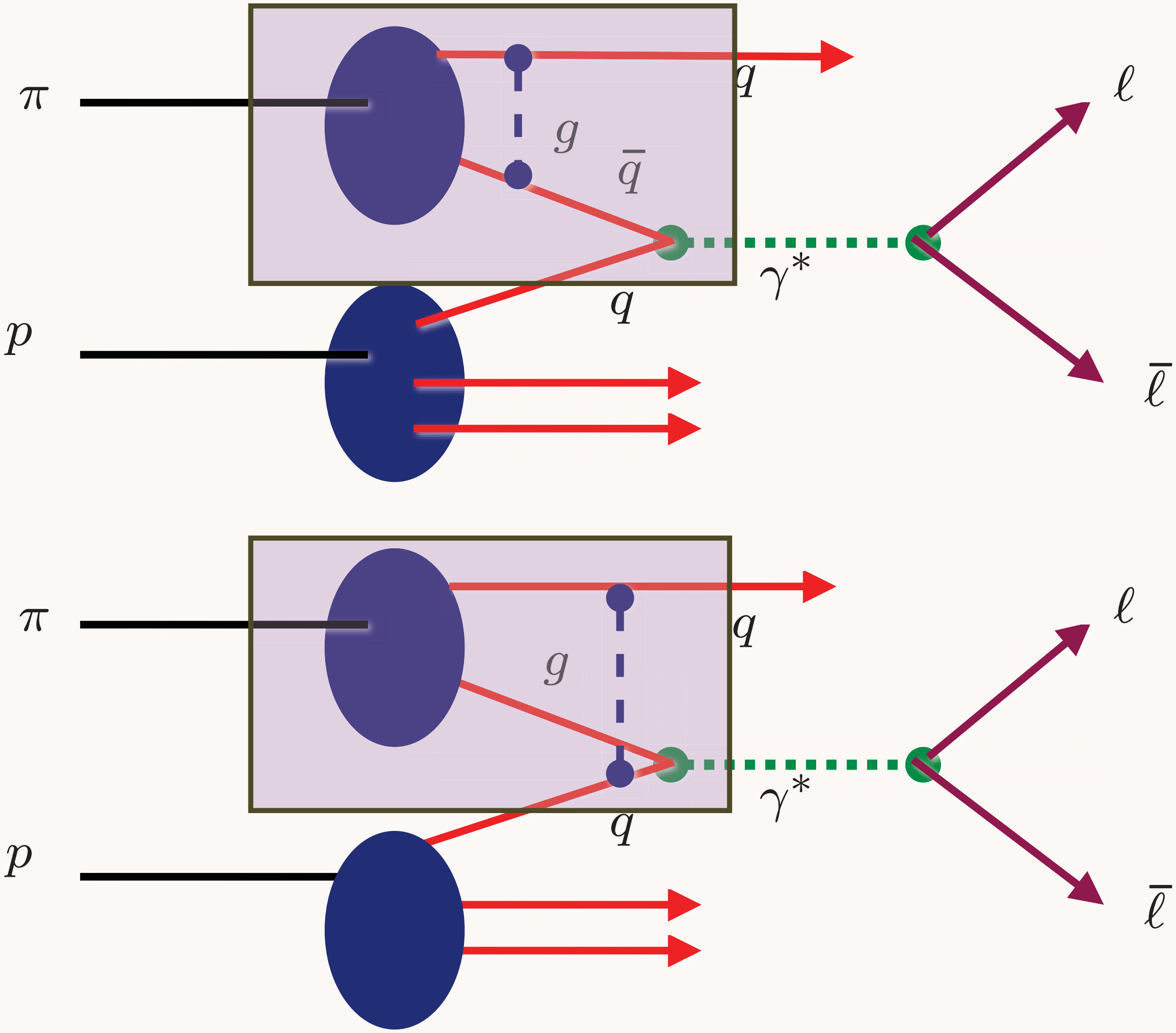
Example of a higher-twist direct subprocess



Chicago-Princeton Collaboration

Phys.Rev.Lett.55:2649,1985

Berger, Lepage, sjb



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

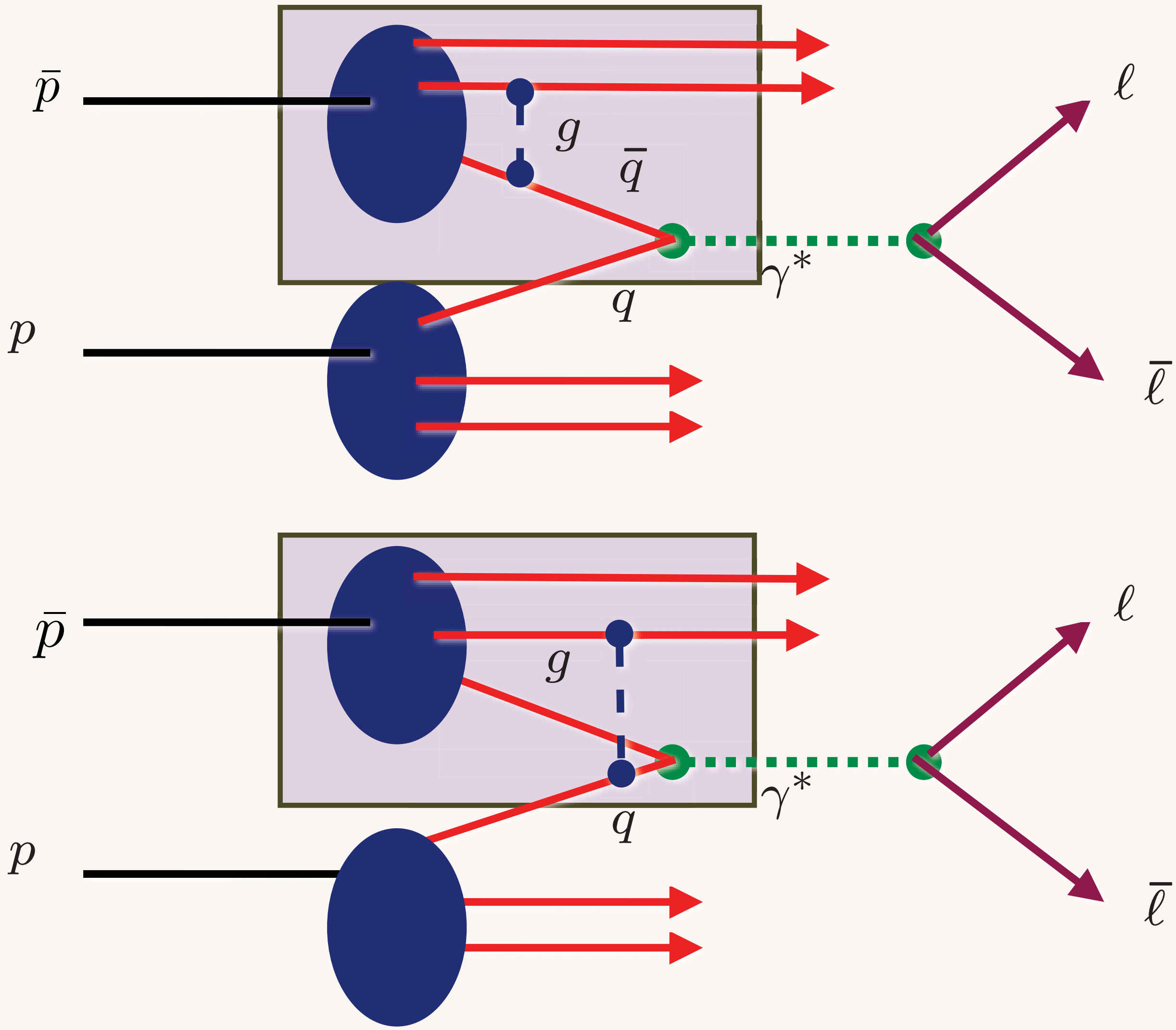
Initial State Interaction

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

$$A(1-x)^3(1+\cos^2\theta) + B\frac{(1-x)\sin^2\theta}{Q^2} + C\frac{(1+\cos^2\theta)}{(1-x)Q^4}$$



Key FAIR Experiment

$$[\bar{q}\bar{q}]q \to \gamma^* \bar{q}$$

Diquark appears directly in subprocess

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

Lepton Pair is produced longitudinally polarized

Topics for FAIR in Di-Muon Production

- Direct Higher Twist Processes
- Single-Spin Asymmetry
- Double Spin Correlation: Transversity
- Lam-Tung Violation in Continuum and J/Psi Production: Double ISI
- Role of quark-quark scattering plus bremsstrahlung: color dipole approach
- Double Drell-Yan: Glauber vs Handbag
- Associated System - Tetraquark and Gluonium States
- Non-Universal Anti-shadowing!

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

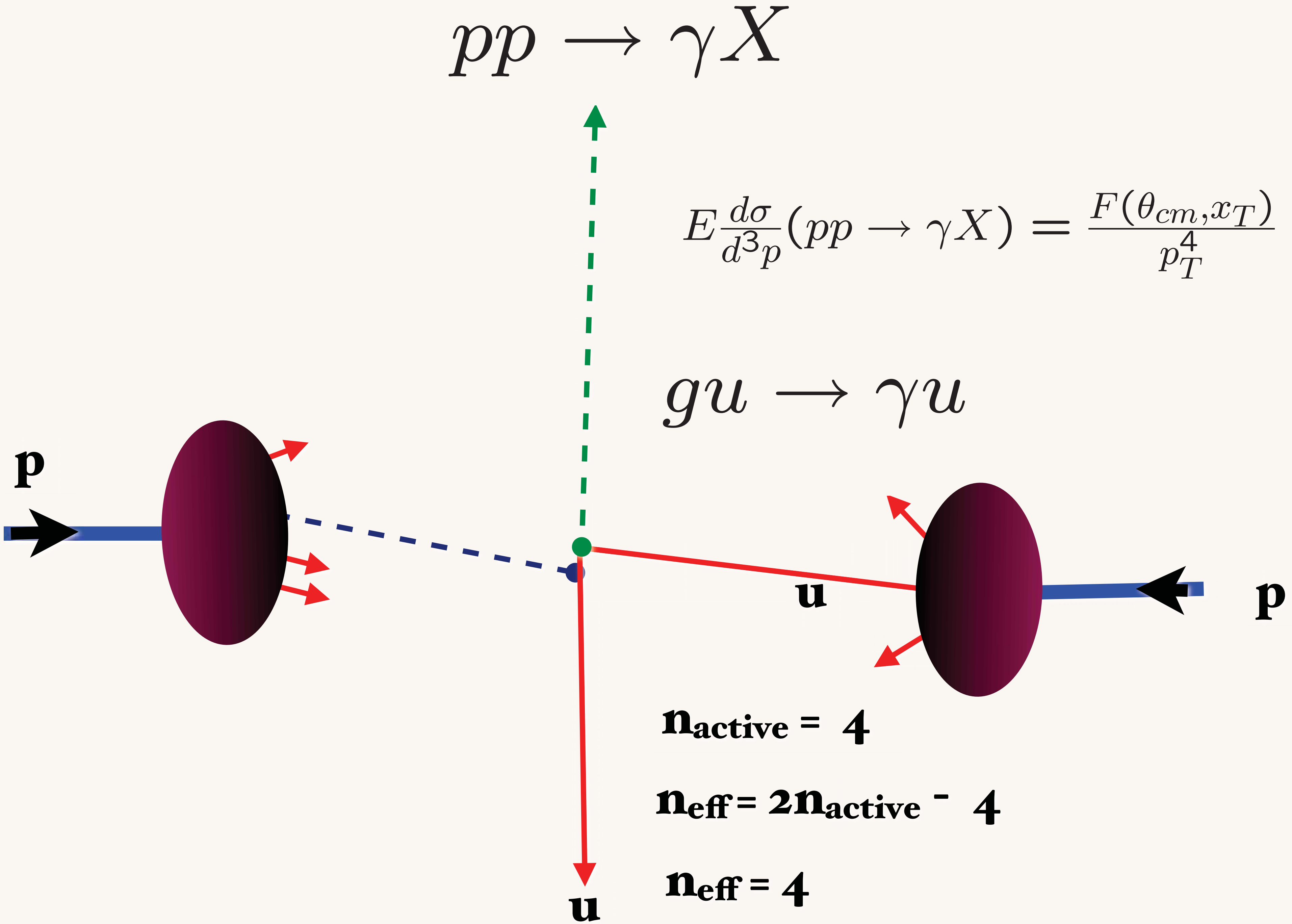
$$x_T = \frac{2p_T}{\sqrt{s}}$$

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

Parton model: $n_{eff} = 4$

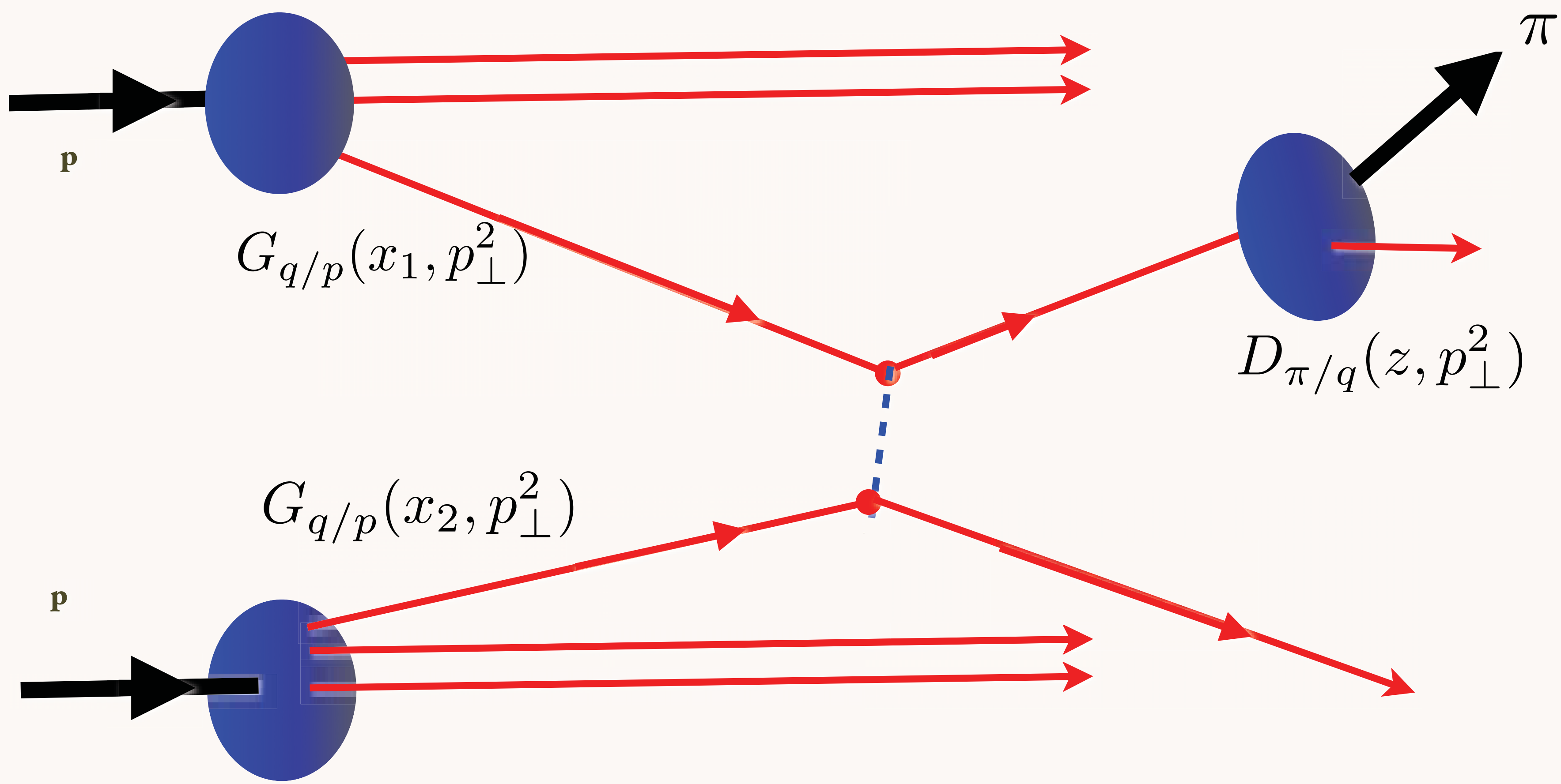
As fundamental as Bjorken scaling in DIS

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



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

Leading-Twist Contribution to Hadron Production



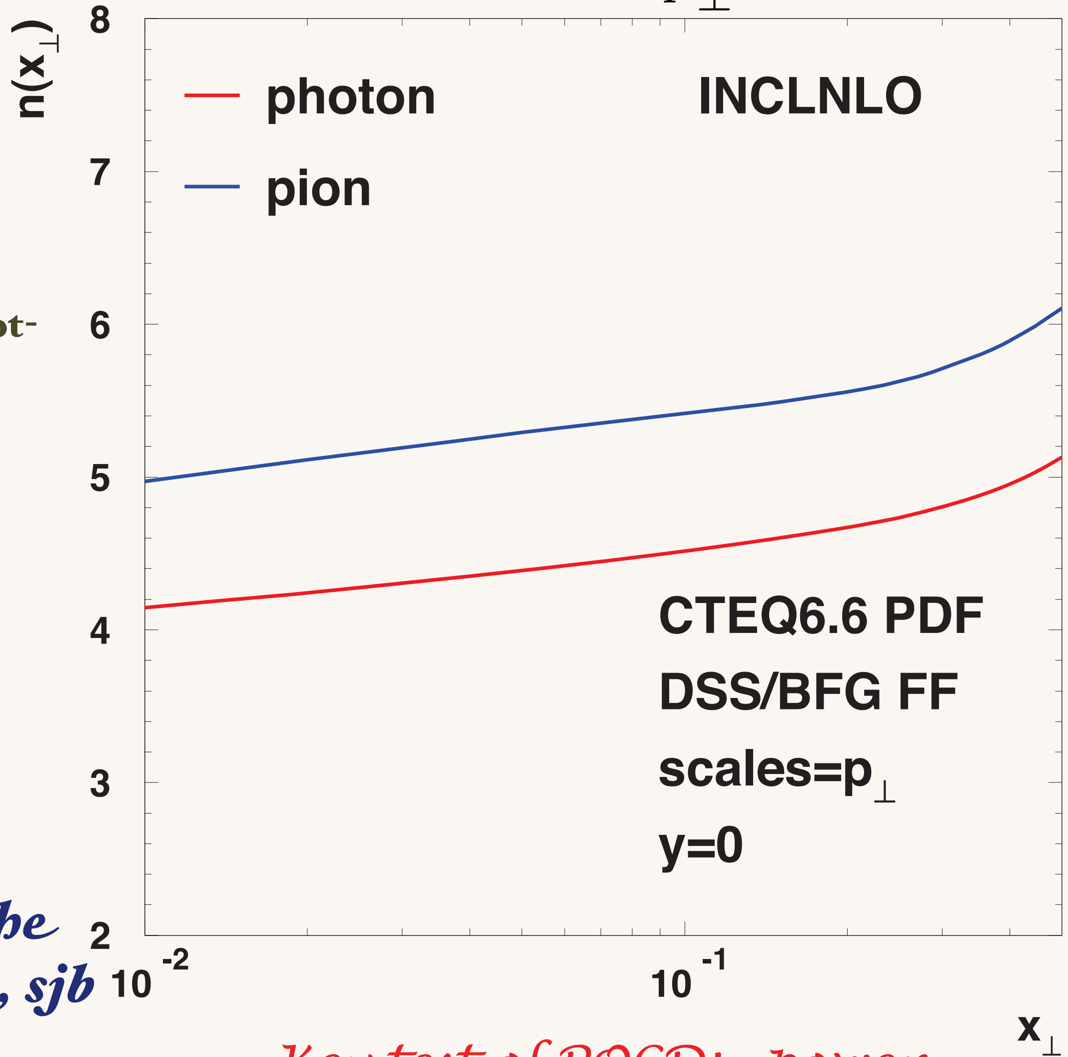
Parton model and Conformal Scaling:

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

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

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

DSS
(De Florian-Sassot-Stratmann)



$$pp \to \pi X$$

$$pp \to \gamma X$$

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

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

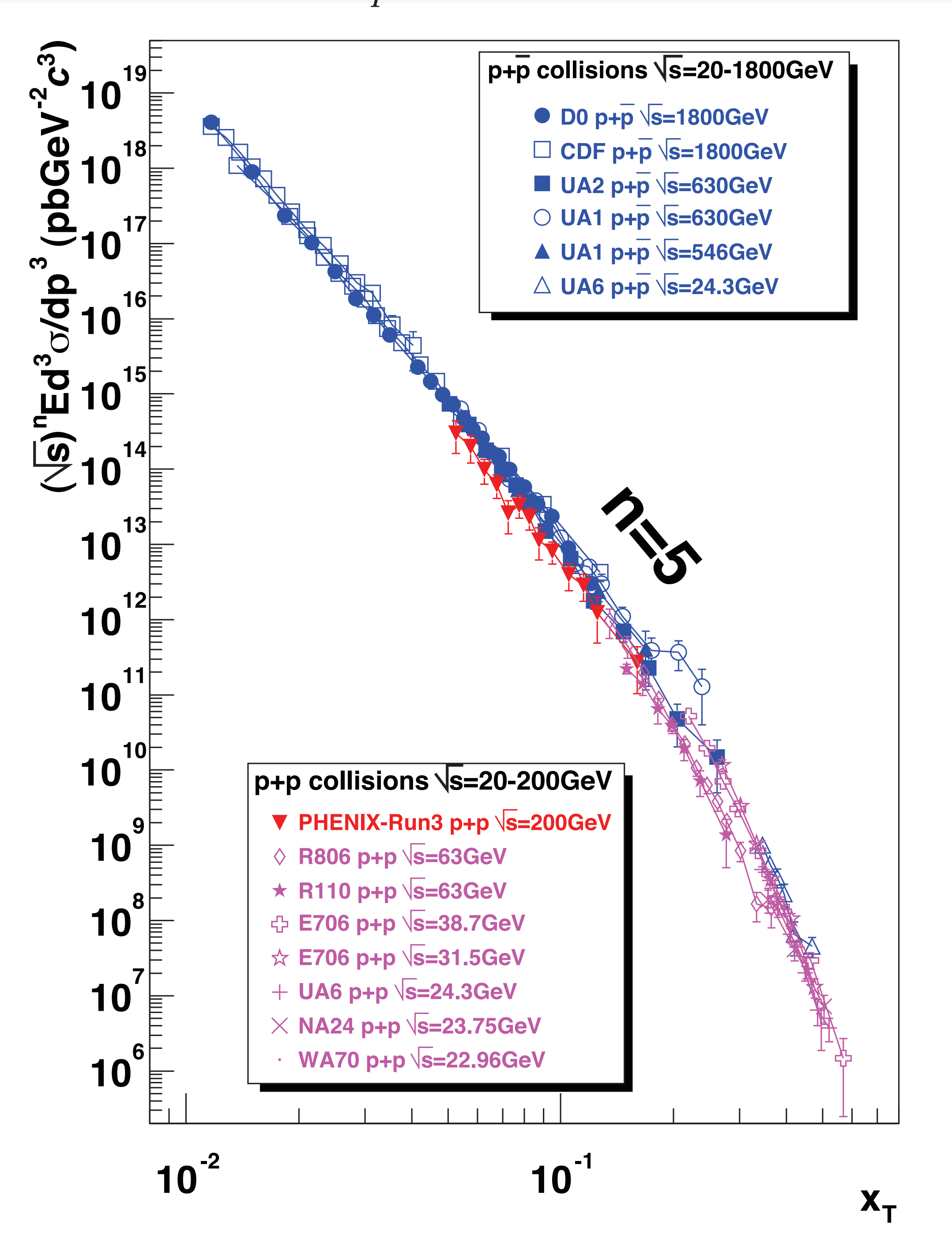
Arleo, Aurenche
Hwang, Sickles, sjb

Pirner, Raufeisen, sjb

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

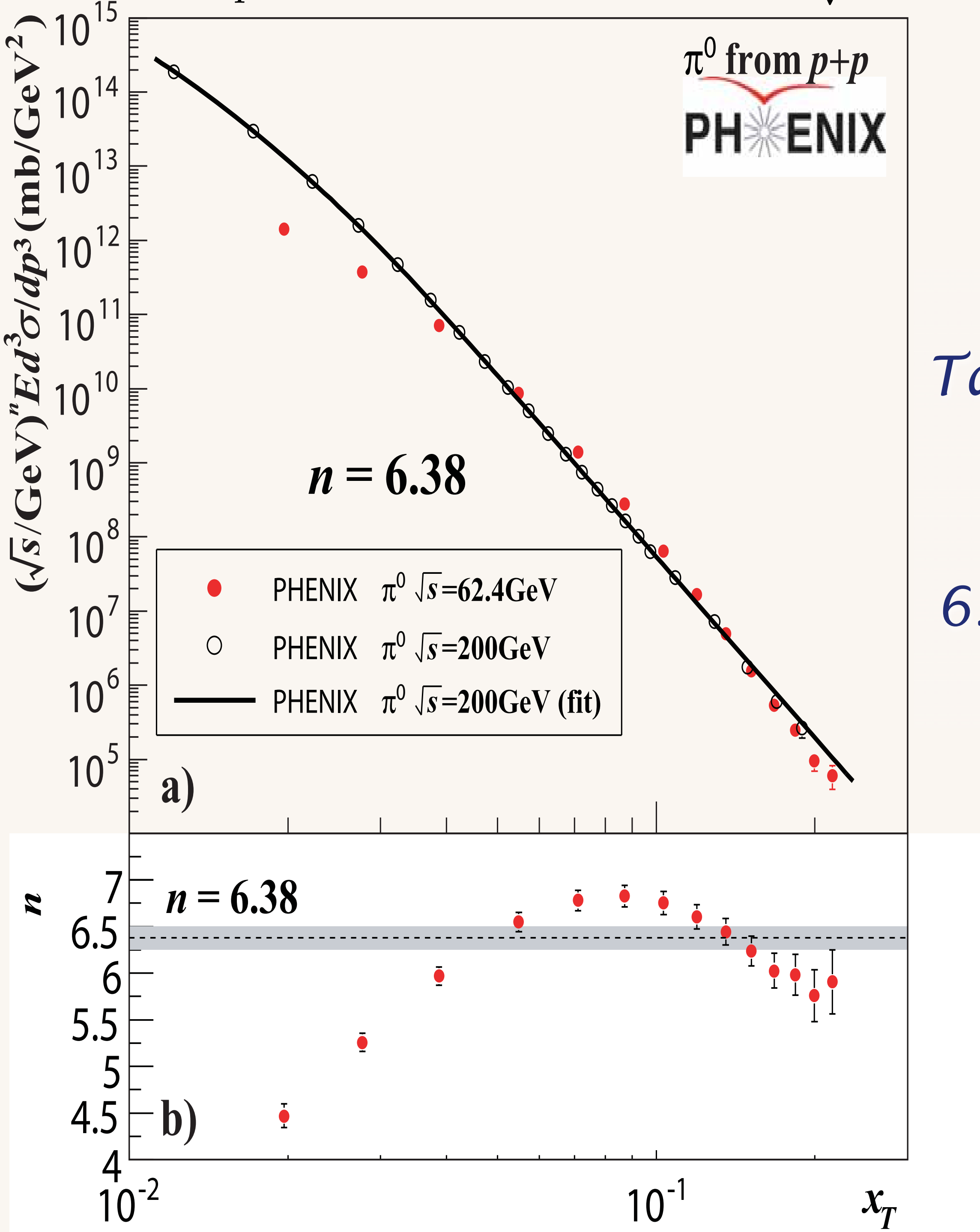
$\sqrt{s}^n E \frac{d\sigma}{d^3p}(pp \to \gamma X)$ at fixed x_T

Tannenbaum



x_T-scaling of direct photon production is consistent with PQCD

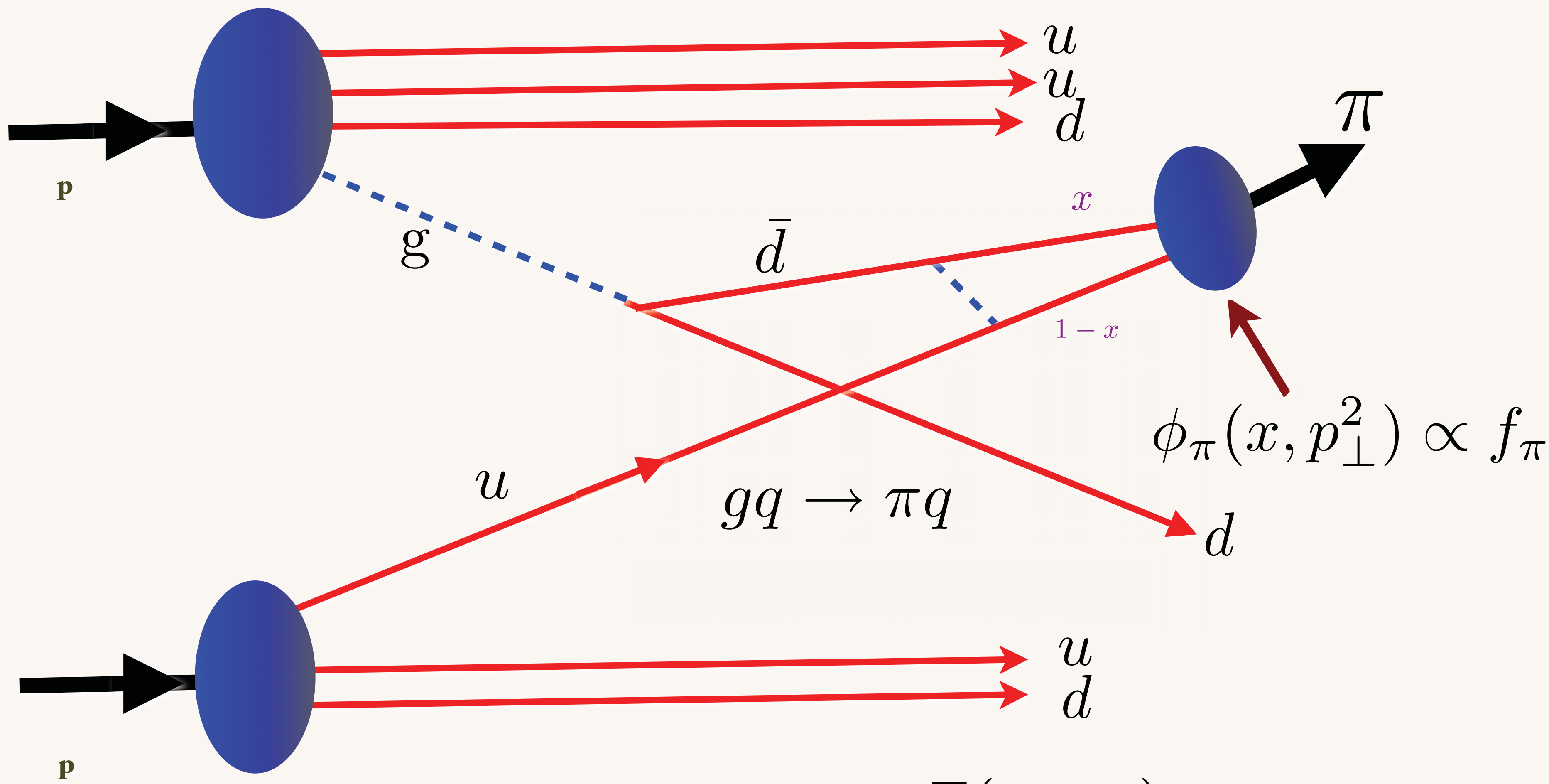
$$\sqrt{s}^n E \frac{d\sigma}{d^3p}(pp \to \pi^0 X) \text{ at fixed } x_T = \frac{2p_T}{\sqrt{s}}$$



M. J. Tannenbaum

PHENIX 62.4 and 200 GeV data

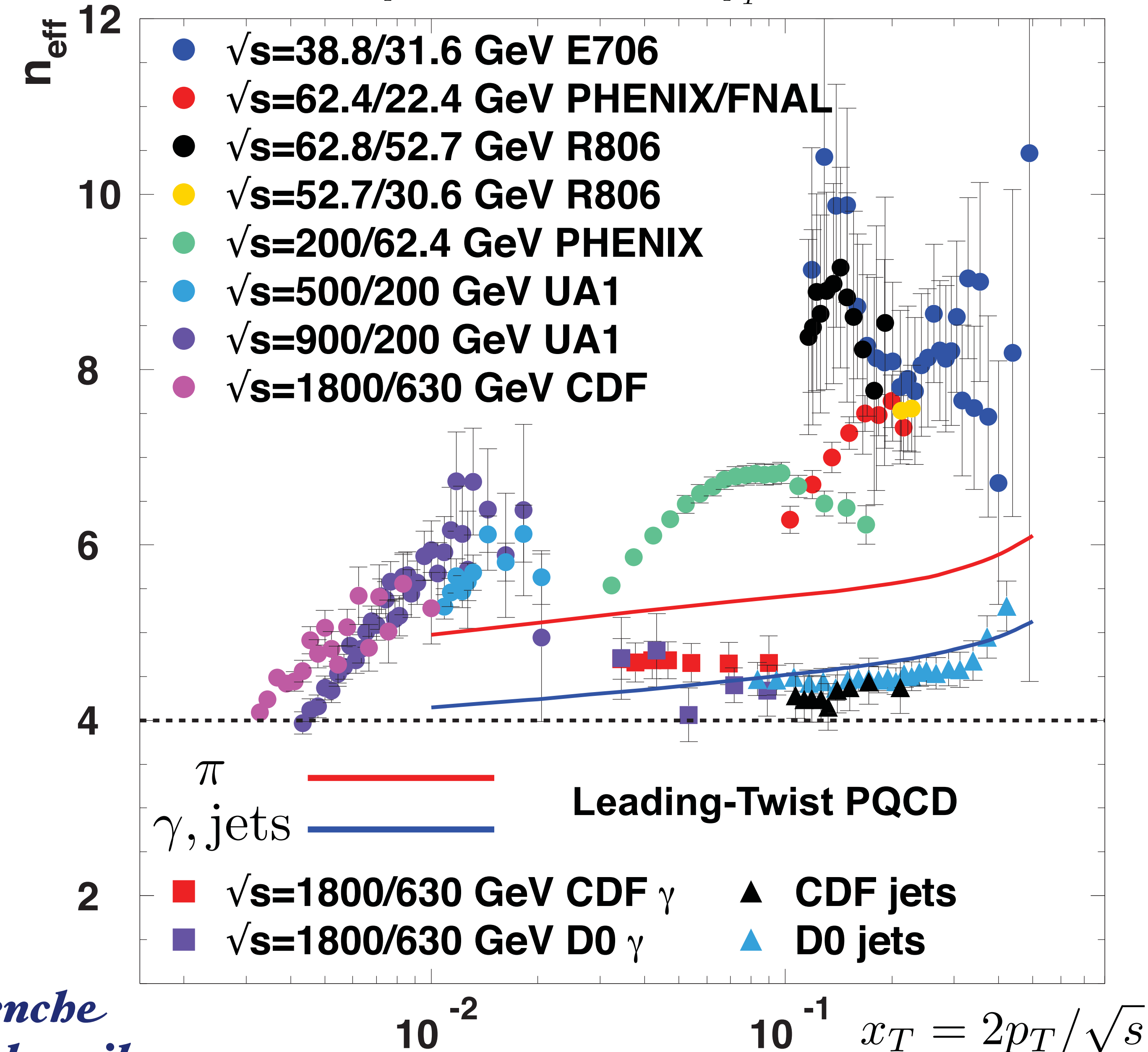
Higher-Twist Contribution to Hadron Production



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

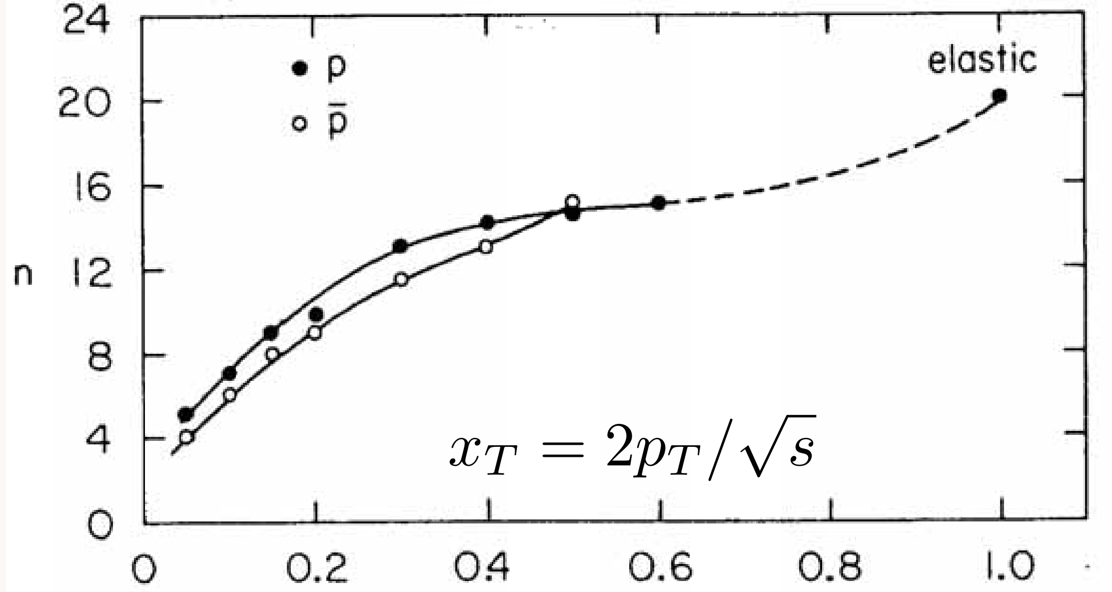
No Fragmentation Function

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



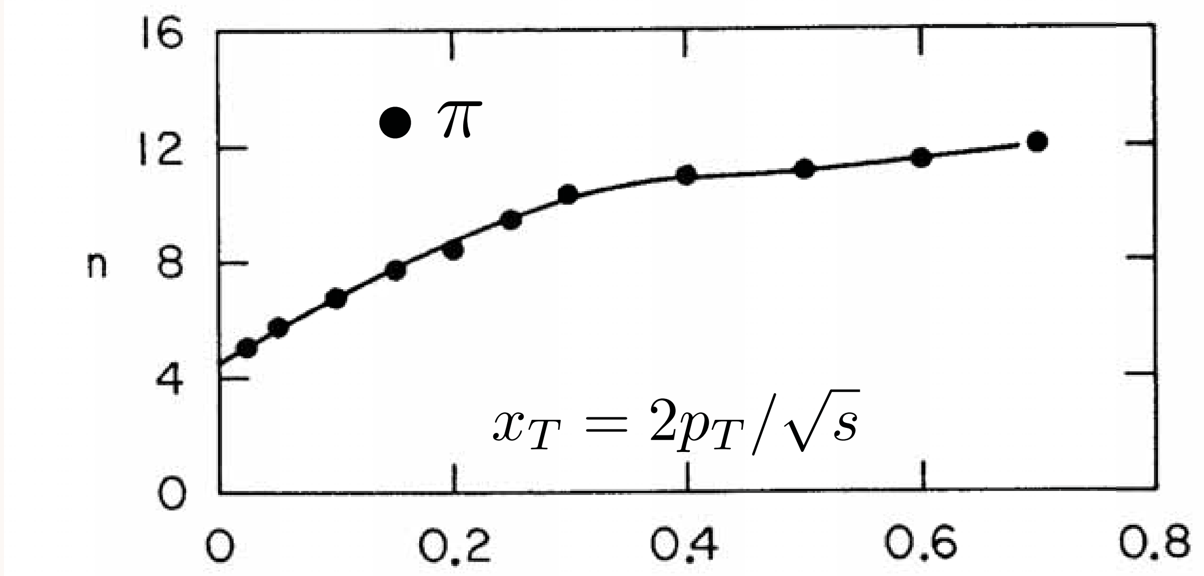
Arleo, Aurenche
Hwang, Sickles, sjb

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



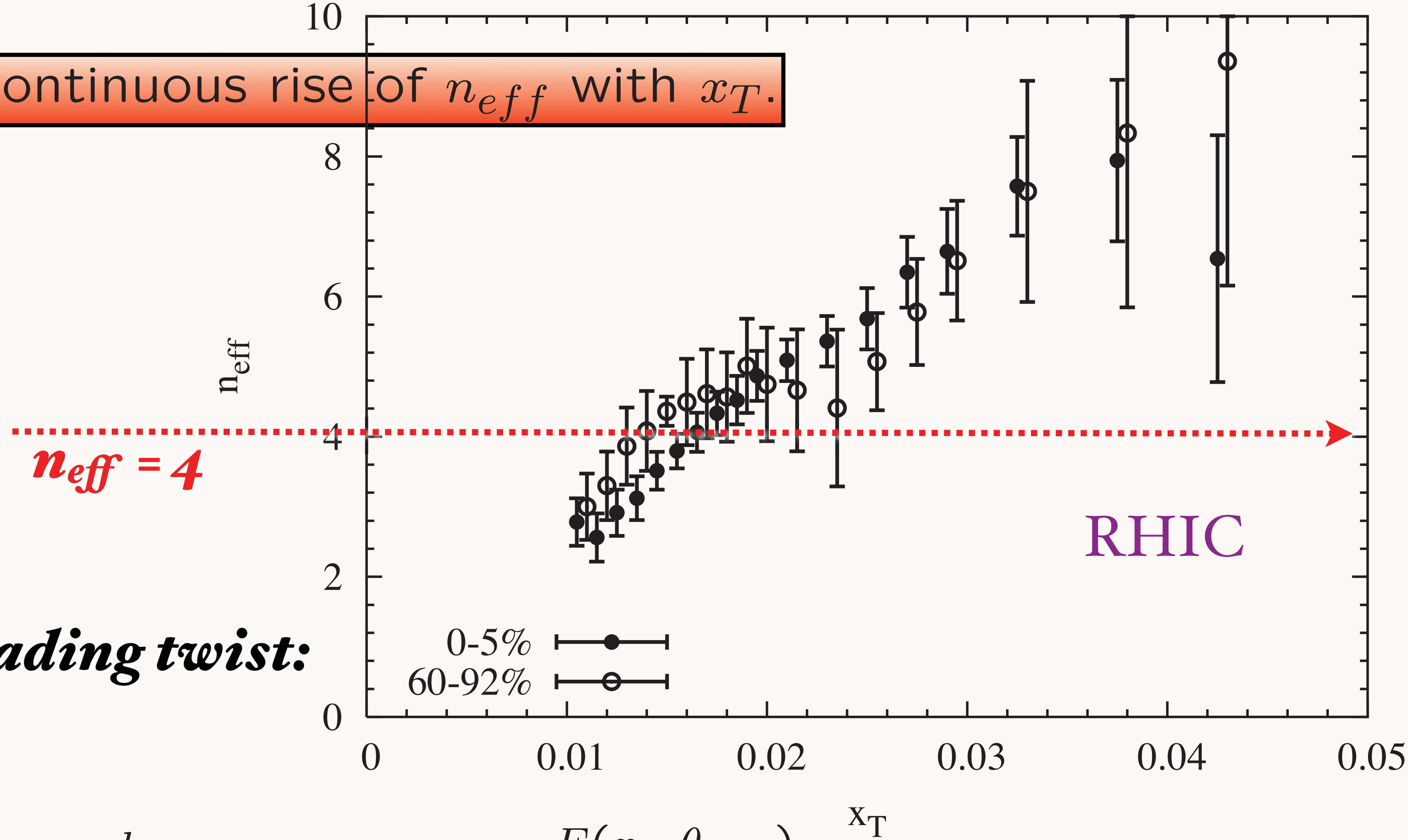
Clear evidence for higher-twist contributions

J. W. Cronin, SSI 1974



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.



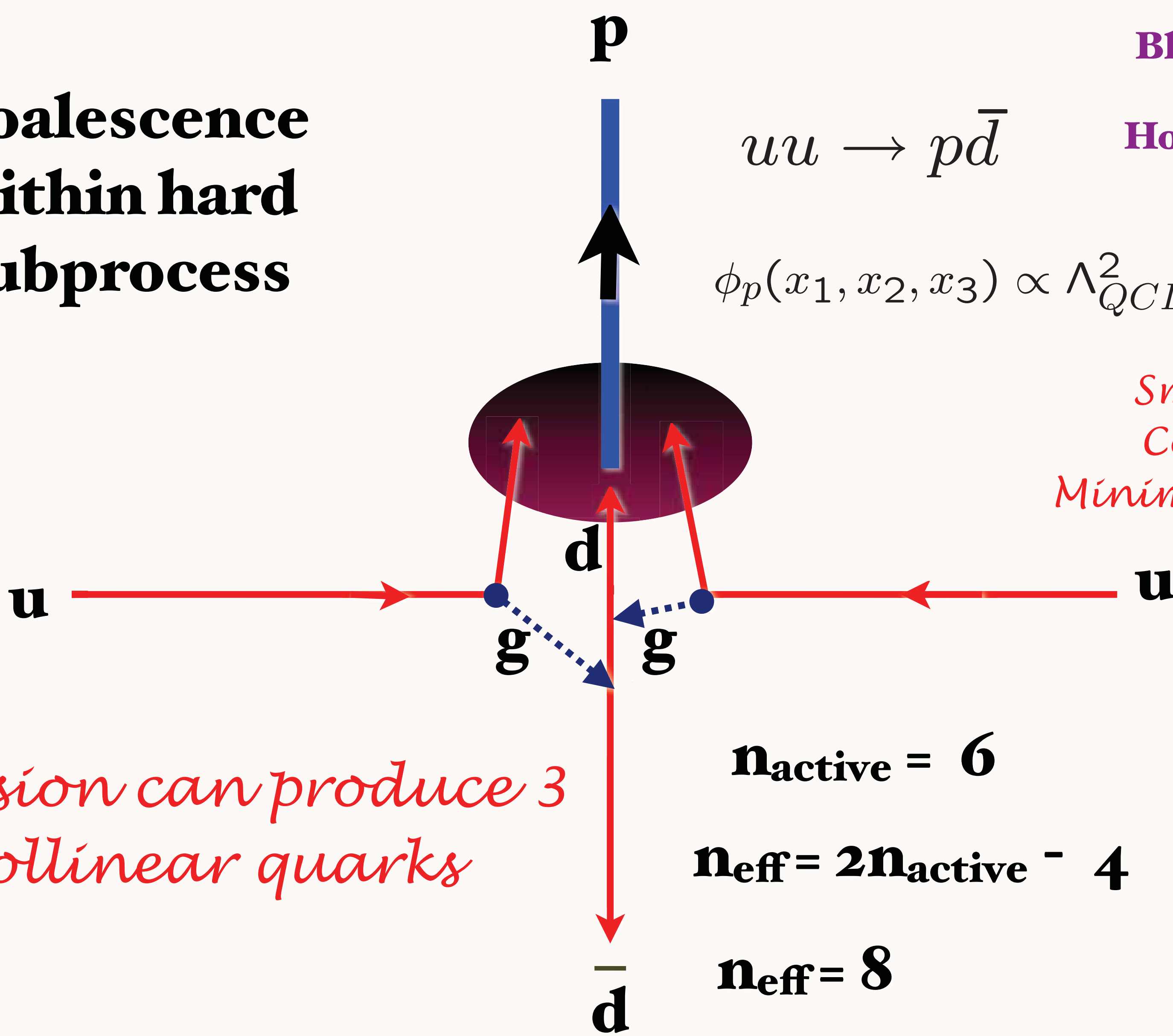
Leading twist:

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

Baryon can be made directly within hard subprocess

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

Coalescence within hard subprocess



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

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

Small color-singlet
Color Transparent
Minimal same-side energy

Collision can produce 3 collinear quarks

$n_{active} = 6$

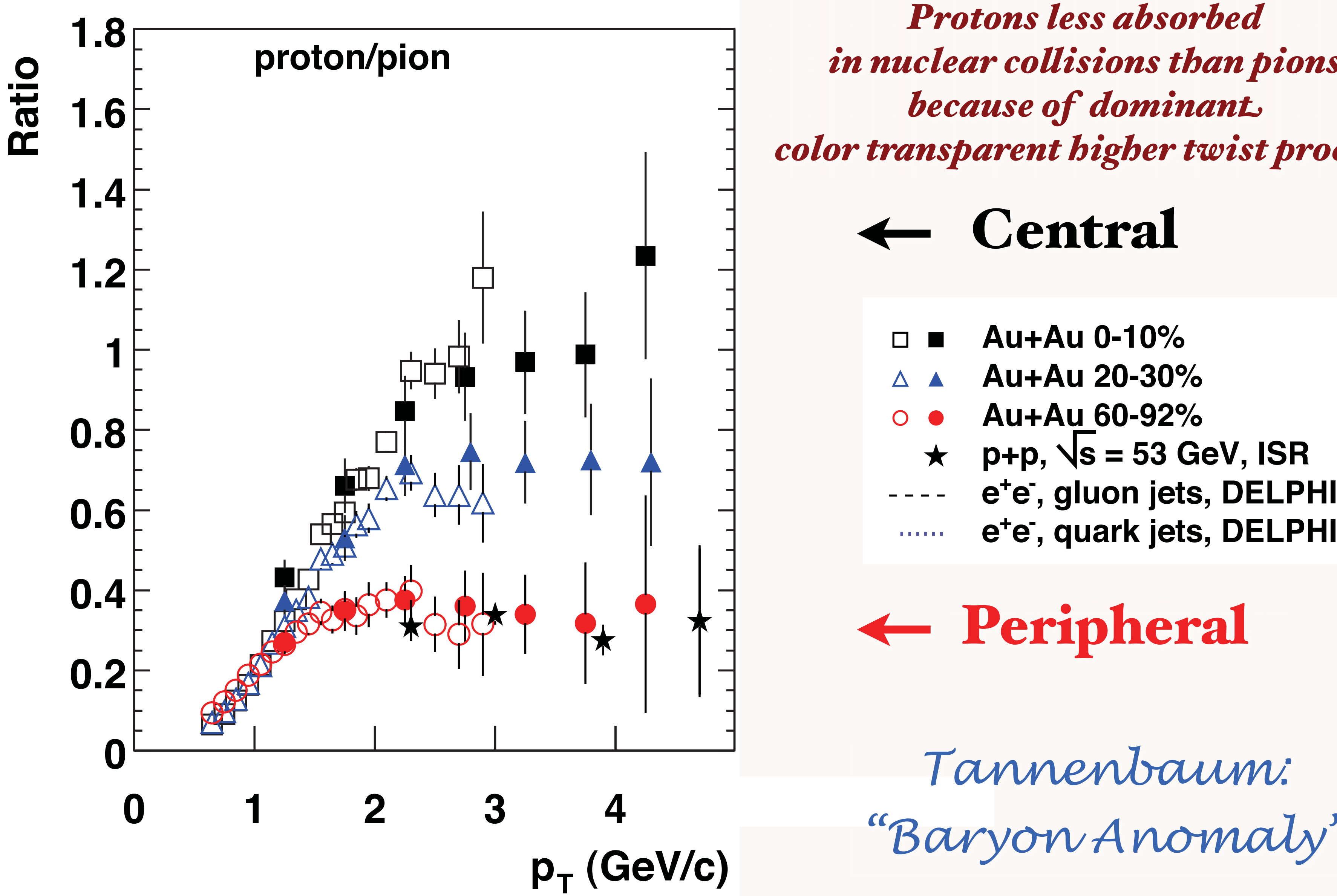
$n_{eff} = 2n_{active} - 4$

$n_{eff} = 8$

$$qq \to B\bar{q}$$

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**

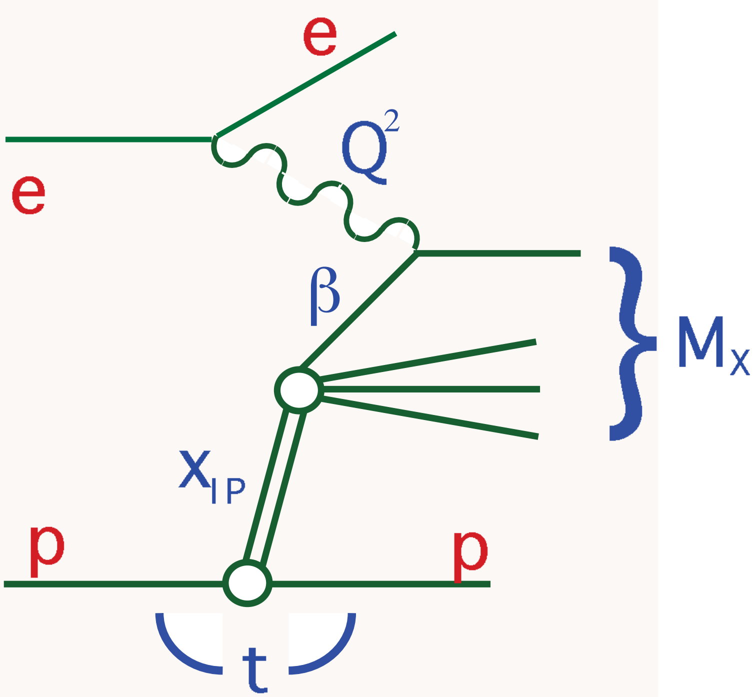
← **Peripheral**

Tannenbaum: "Baryon Anomaly"

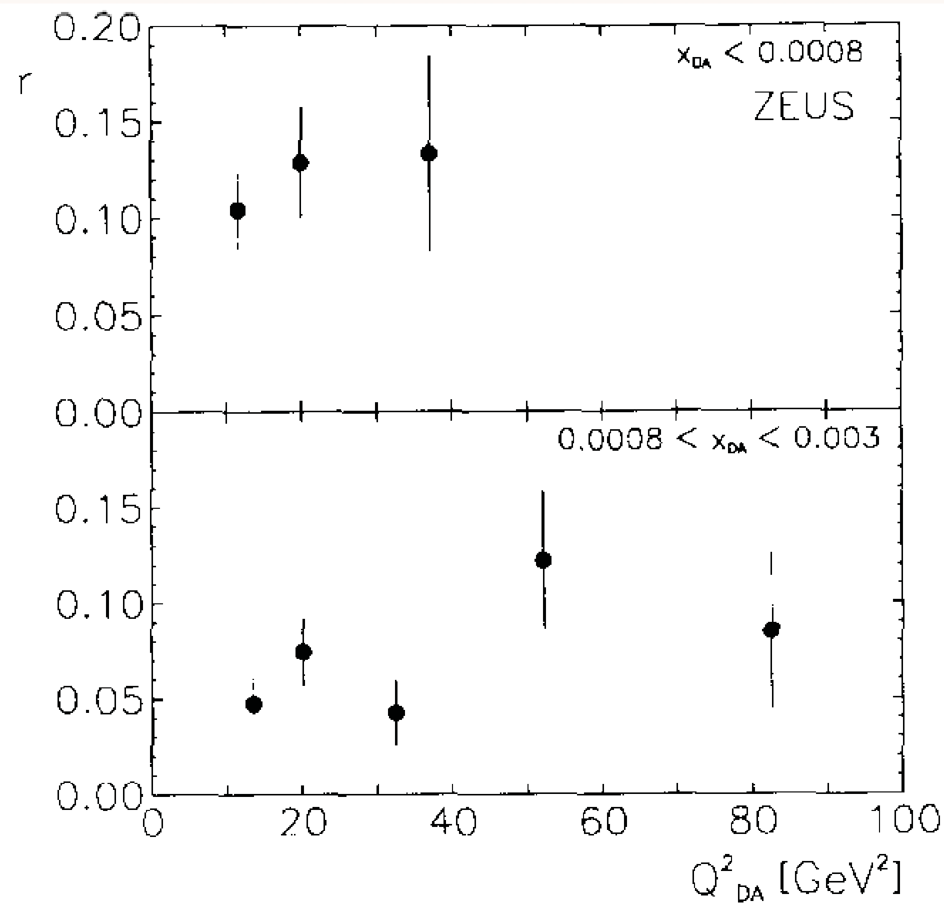
Evidence for Direct, Higher-Twist Subprocesses

- Anomalous power behavior at fixed x_T
- Protons more likely to come from direct subprocess than pions
- Protons less absorbed than pions in central nuclear collisions because of **color transparency**
- Predicts increasing proton to pion ratio in central collisions -- seen at RHIC
- Exclusive-inclusive connection at $x_T = 1$

Remarkable observation at HERA



10% to 15% of DIS events are diffractive !

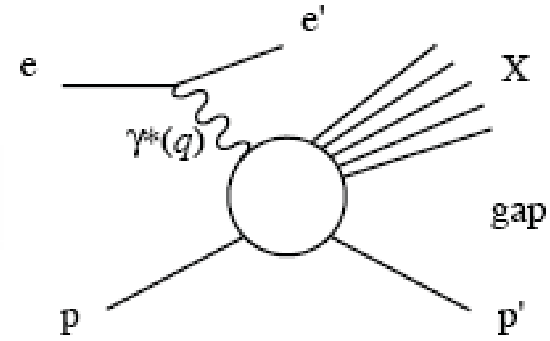


Fraction r of events with a large rapidity gap, $\eta_{max} < 1.5$, as a function of Q^2_{DA} for two ranges of x_{DA}. No acceptance corrections have been applied.

M. Derrick et al. [ZEUS Collaboration], Phys. Lett. B 315, 481 (1993).

DDIS

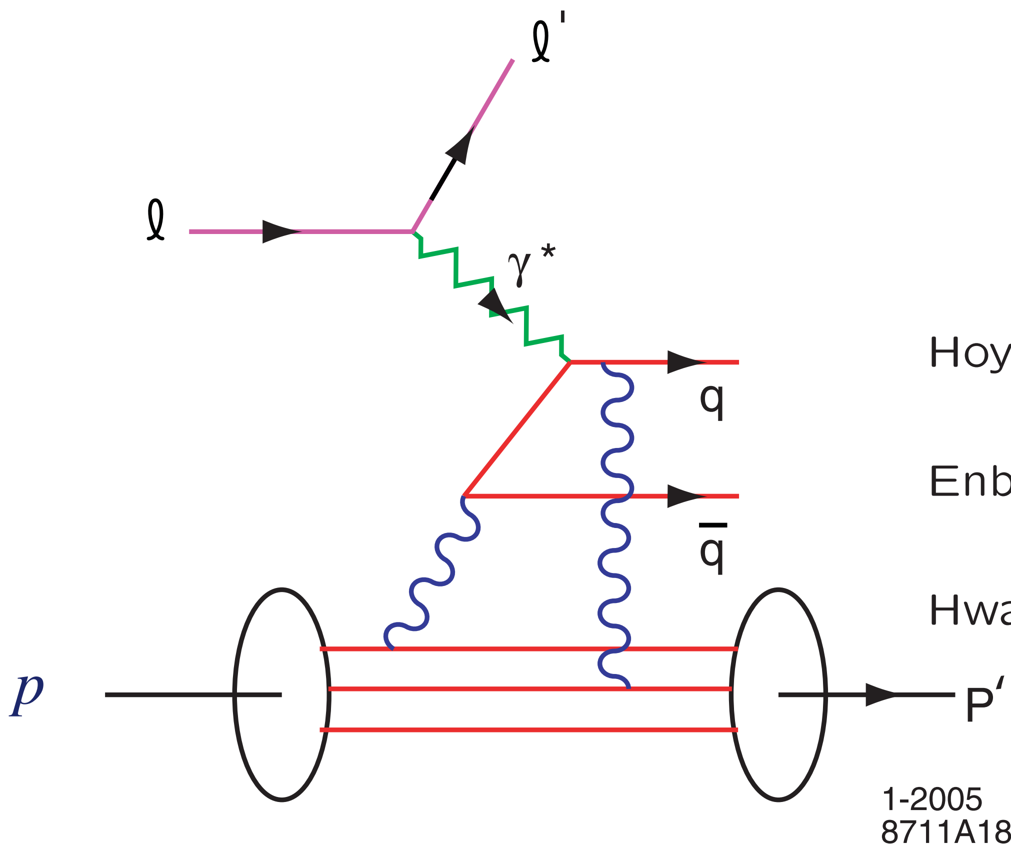
Diffractive Deep Inelastic Lepton-Proton Scattering



- In a large fraction (∼ 10–15%) of DIS events, the proton escapes intact, keeping a large fraction of its initial momentum
- This leaves a large *rapidity gap* between the proton and the produced particles
- The t-channel exchange must be *color singlet* → a pomeron

Profound effect: target stays intact despite production of a massive system X

Final-State Interaction Produces Diffractive DIS



Quark Rescattering

Hoyer, Marchal, Peigne, Sannino, SJB (BHM

Enberg, Hoyer, Ingelman, SJB

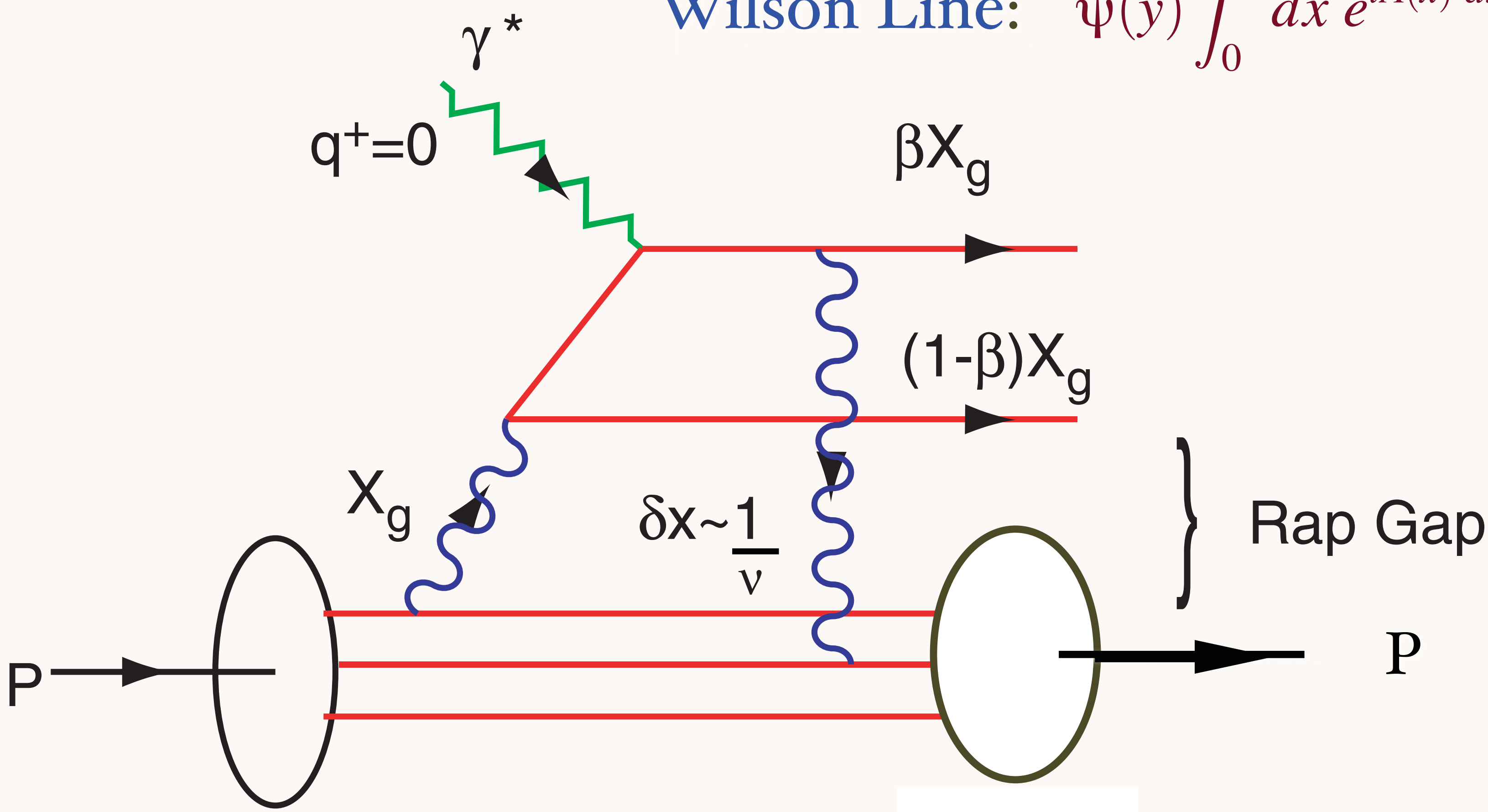
Hwang, Schmidt, SJB

Low-Nussinov model of Pomeron

Hoyer, Marchal, Peigne, Sannino, sjb

QCD Mechanism for Rapidity Gaps

Wilson Line: $\overline{\psi}(y) \int_0^y dx\, e^{iA(x)\cdot dx}\, \psi(0)$

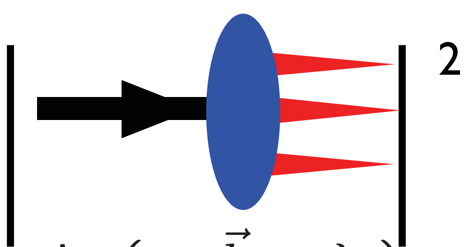


Reproduces lab-frame color dipole approach

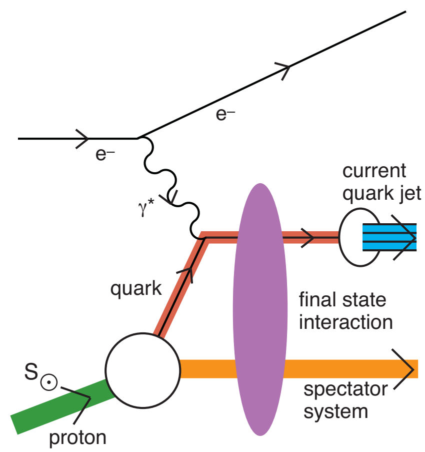
Physics of Rescattering

- Sivers Asymmetry and Diffractive DIS: New Insights into Final State Interactions in QCD
- Origin of Hard Pomeron
- Structure Functions not Probability Distributions! *Not square of LFWFs*
- T-odd SSAs, Shadowing, Antishadowing
- Diffractive dijets/ trijets, doubly diffractive Higgs
- Novel Effects: Color Transparency, Color Opaqueness, Intrinsic Charm, Odderon

Static	Dynamic
• Square of Target LFWFs	Modified by Rescattering: ISI & FSI
• No Wilson Line	Contains Wilson Line, Phases
• Probability Distributions	No Probabilistic Interpretation
• Process-Independent	Process-Dependent - From Collision
• T-even Observables	T-Odd (Sivers, Boer-Mulders, etc.)
• No Shadowing, Anti-Shadowing	Shadowing, Anti-Shadowing, Saturation
• Sum Rules: Momentum and J^z	Sum Rules Not Proven
• DGLAP Evolution; mod. at large x	DGLAP Evolution
• No Diffractive DIS	Hard Pomeron and Odderon Diffractive DIS



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



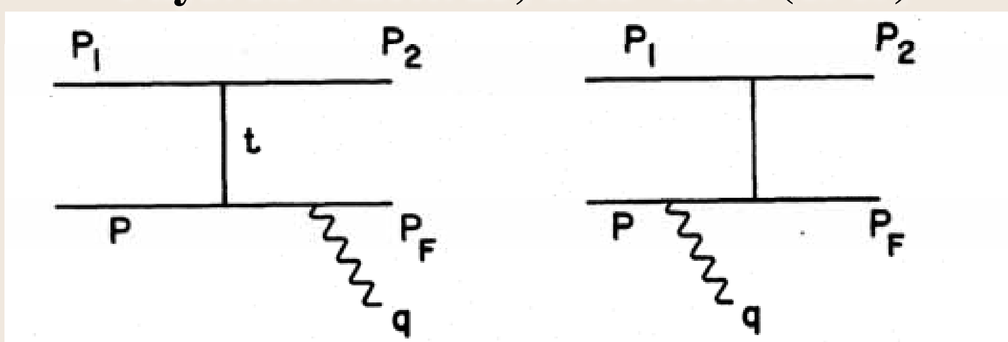
Key QCD FAIR Experiment

Double-Diffractive Drell-Yan

$$\overline{p}p \to \overline{p} + \ell^+\ell^- + p$$

Large-Mass Timelike Muon Pairs in Hadronic Interactions
S. M. Berman*, D. J. Levy, and T. L. Neff§

Phys. Rev. Lett. 23, 1363–1365 (1969)



Prototype for exclusive Higgs production

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

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

The Light Front Fock State Wavefunctions

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

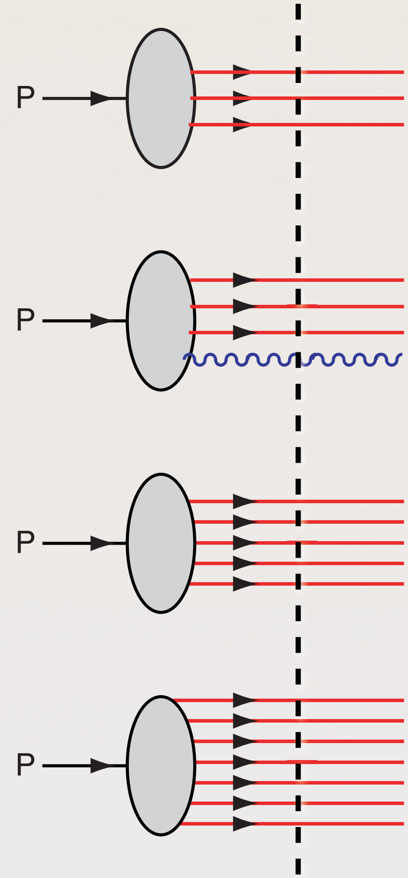
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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.

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



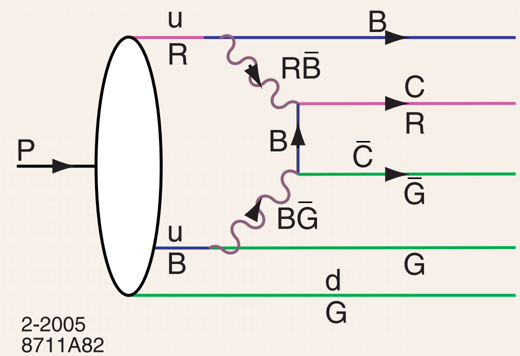
Fixed LF time

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

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

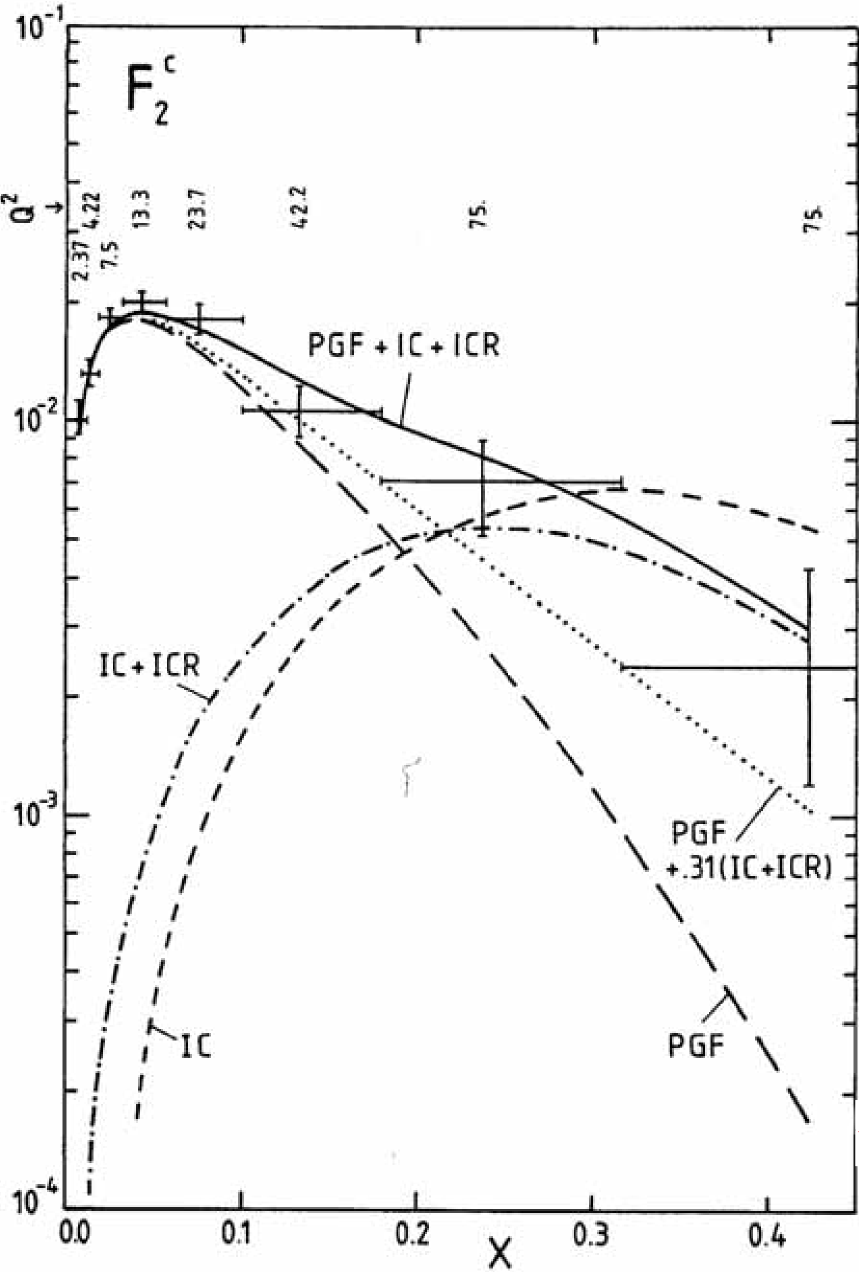
Hoyer, Peterson, Sakai, sjb

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

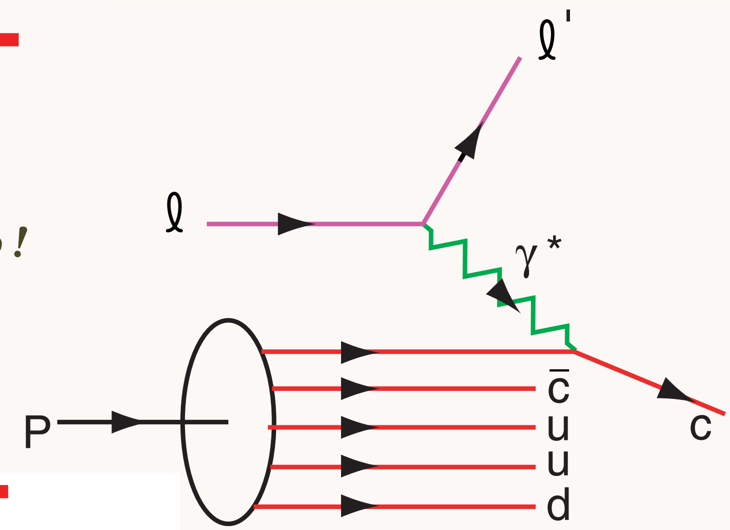
Measurement of Charm Structure Function



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

First Evidence for Intrinsic Charm

factor of 30 !



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

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

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

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

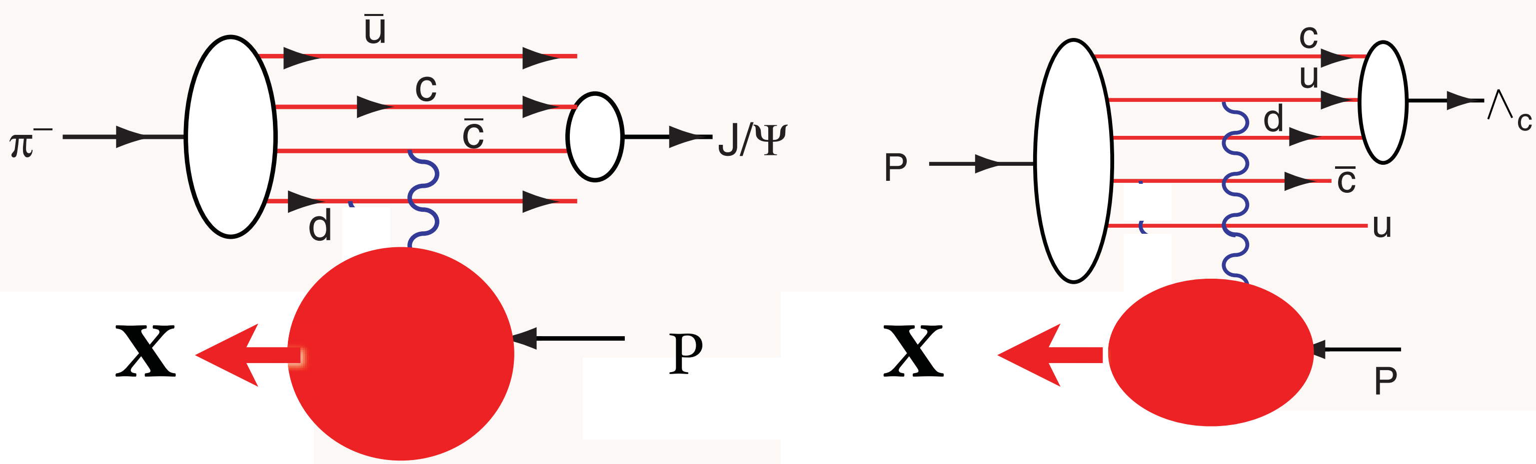
- High x_F $pp \to \Lambda_c X$

- High x_F $pp \to \Lambda_b X$

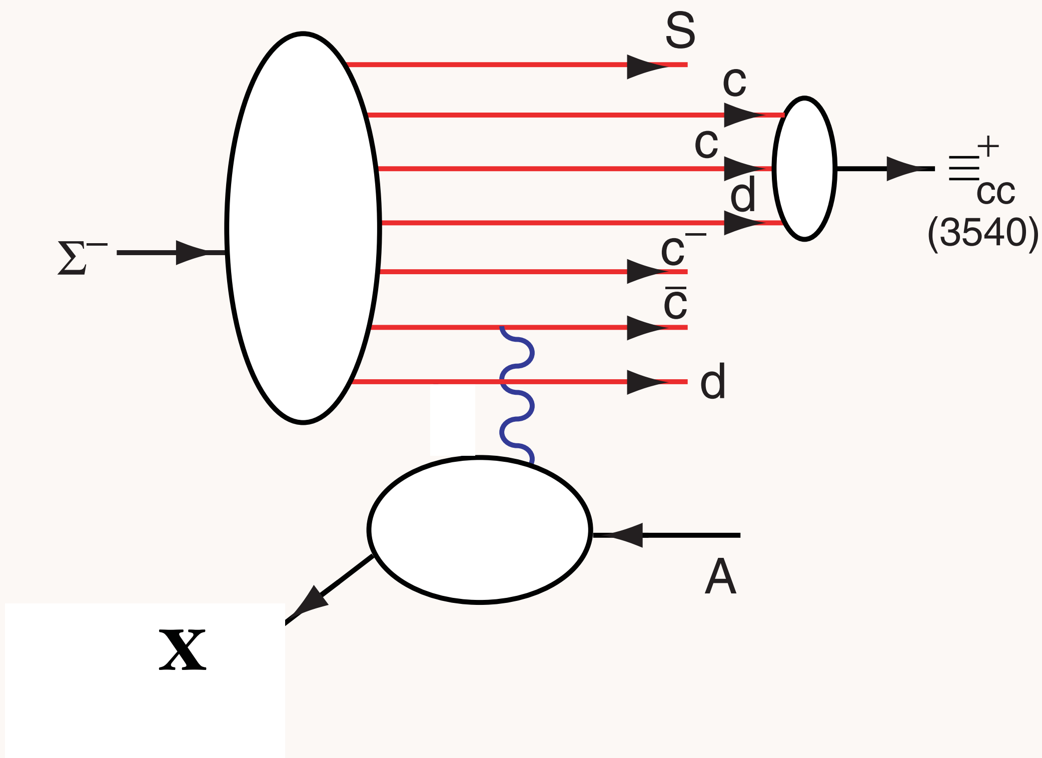
- High x_F $pp \to \Xi(ccd)X$ (SELEX)

C.H. Chang, J.P. Ma, C.F. Qiao and X.G.Wu,
Hadronic production of the doubly charmed baryon Xi/cc with intrinsic charm," arXiv:hep-ph/0610205.

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

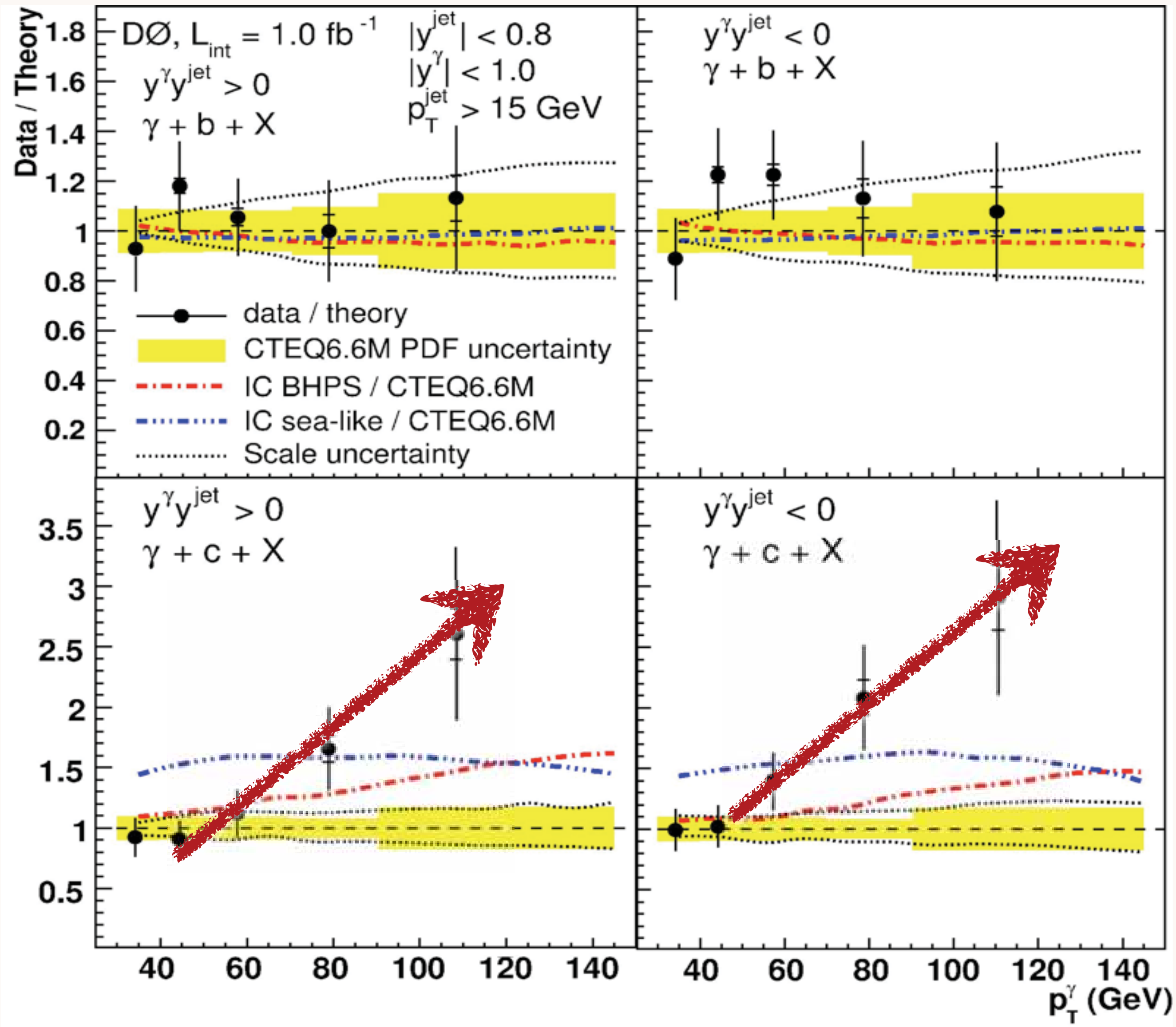


Production of a Double-Charm Baryon

SELEX high x_F $<x_F>= 0.33$

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 ?

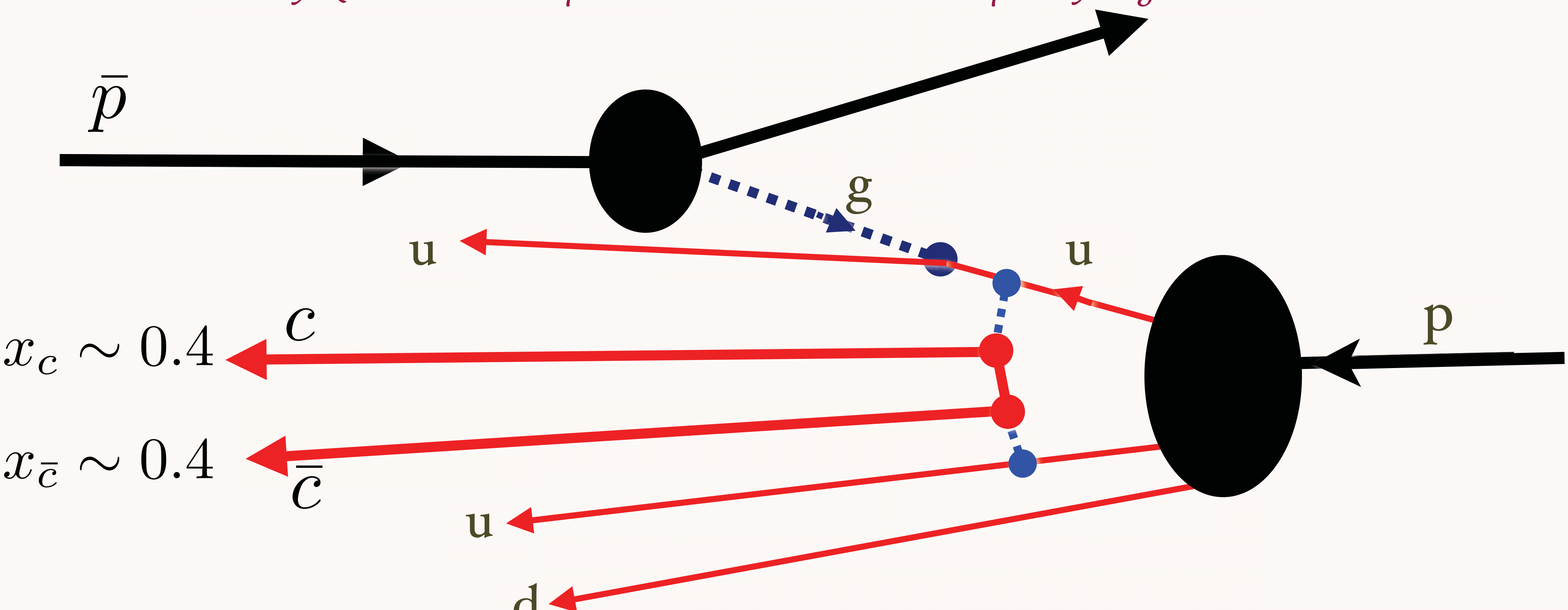
Excitation of Intrinsic Heavy Quarks in Proton

Amplitude maximal at small invariant mass, equal rapidity

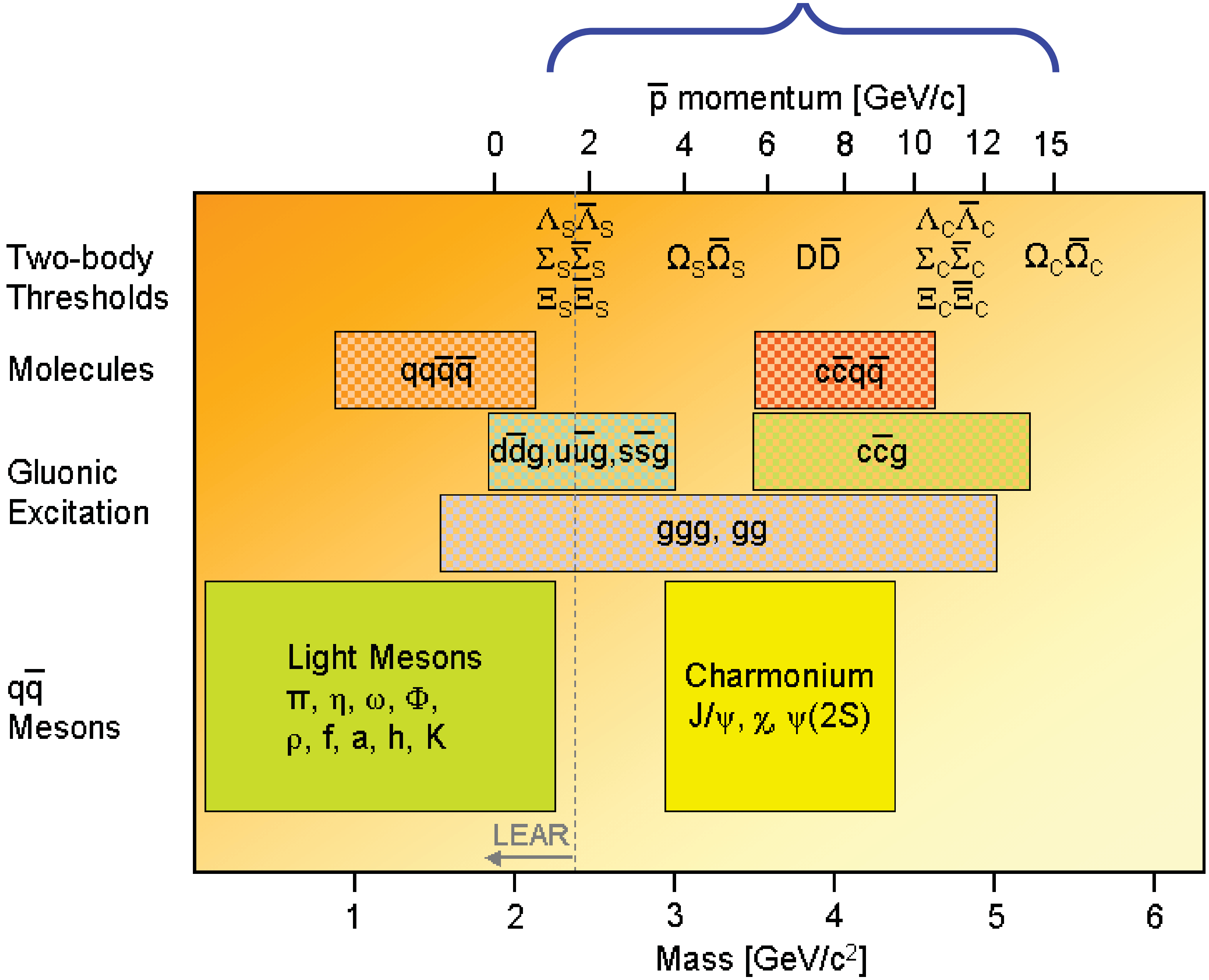
$$x_i \sim \frac{m_{\perp i}}{\sum_j^n m_{\perp j}} \qquad \frac{d\sigma}{dy_{J/\psi}}(\bar{p}p \to J/\psi X)$$

J-P Lansberg, sjb

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



Mass and Anti-Proton Momentum Range at PAX, PANDA



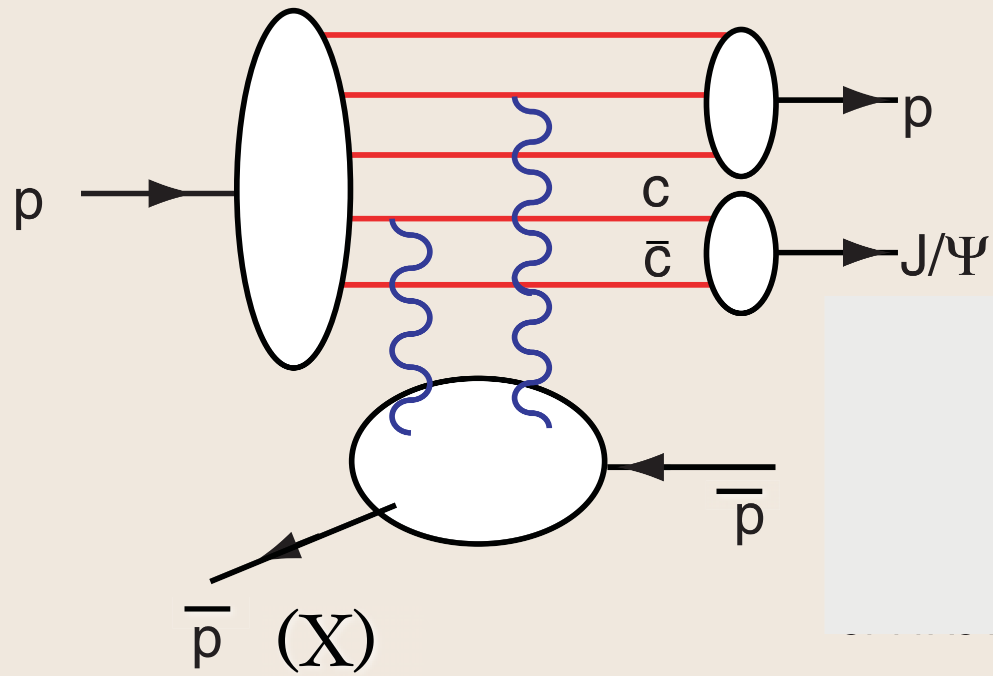
- Production of open charm
- Charmed hybrids
- Glueballs
- Charmonium

Michael Düren

Key QCD FAIR Experiment

J-P Lansberg, sjb

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



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

Important Test of Intrinsic Charm

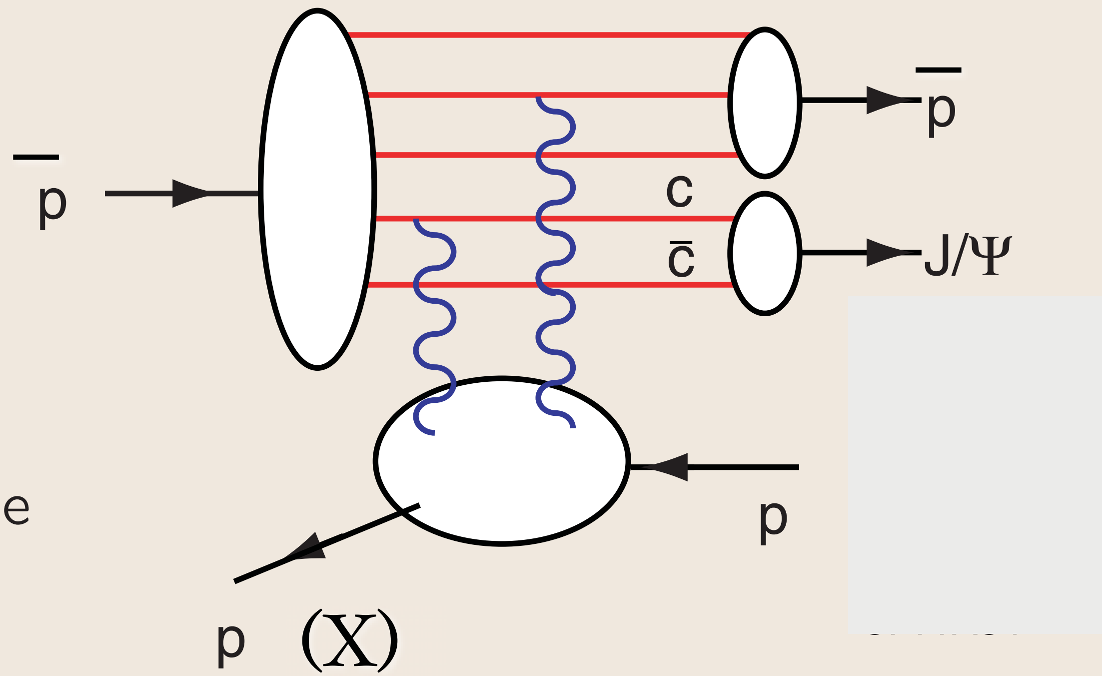
Key QCD FAIR Experiment

Measure diffractive hidden charm production at forward x_F

Even close to threshold

$$\frac{d\sigma}{dt_1 dt_2 dx_F}(\bar{p}p \to \bar{p} + J/\psi + p)$$

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



Anomalous nuclear dependence

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

$A^{\alpha(x_2)}$ versus $A^{\alpha(x_F)}$

Important Tests of Intrinsic Charm

Open and Hidden Charm Production Near Threshold

$$\bar{p}p \to J/\psi X$$
$$\bar{p}p \to D\bar{D}X$$
$$\bar{p}p \to \Lambda_c D X$$

- Several Mechanisms for Inclusive Production:

$$gg \to c\bar{c} \qquad q\bar{q} \to g \to c\bar{c}$$

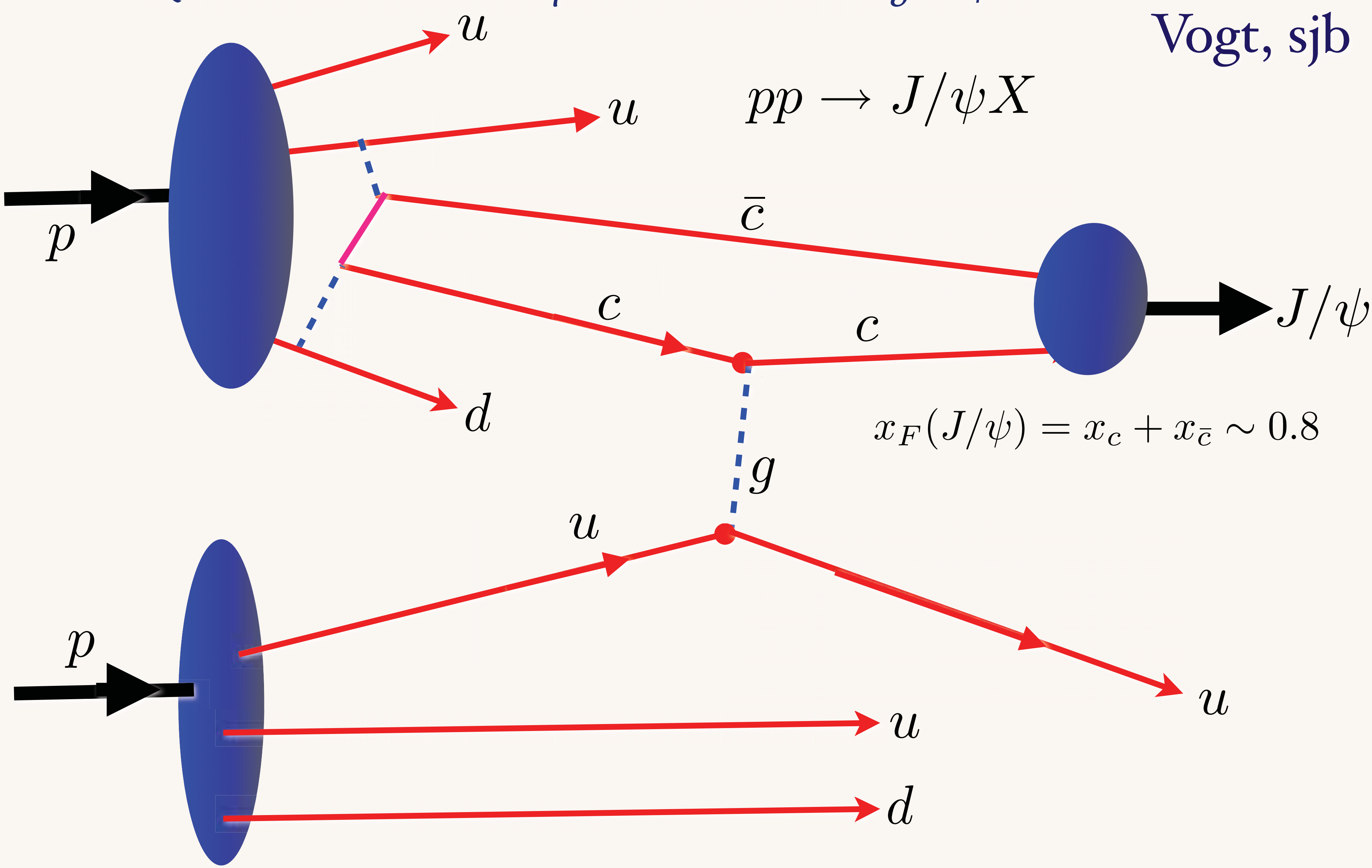
$$c_I + g \to cg \qquad [c_I + \bar{c}_I] + g \to J/\psi$$

ISI and FSI, Schwinger Sommerfeld Threshold Corrections

Intrinsic Heavy Quark Contribution to Quarkonium Hadroproduction at High x_F

Vogt, sjb

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



$$x_F(J/\psi) = x_c + x_{\bar{c}} \sim 0.8$$

Maximal Wavefunction Strength at Minimal Invariant Mass : Equal Rapidity

$$x_i \propto \frac{m_{\perp i}}{\sum_j m_{\perp j}}$$

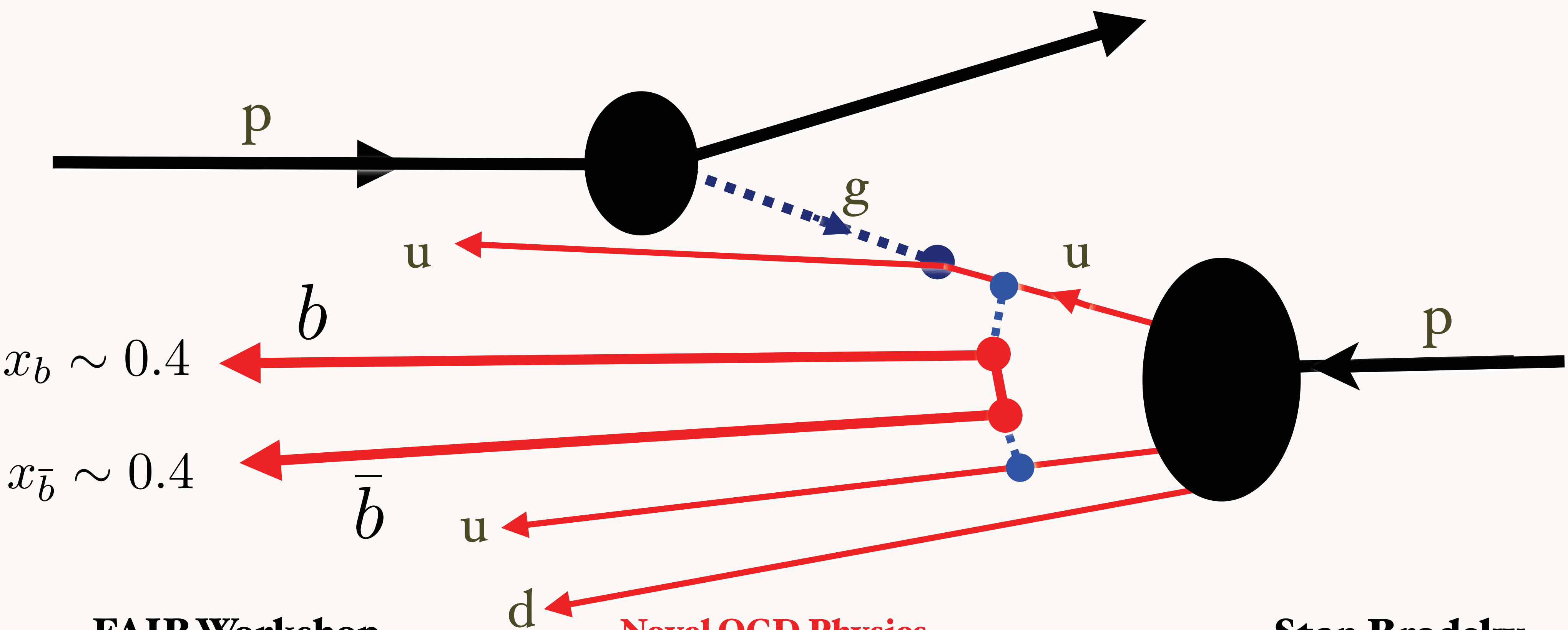
Excitation of Intrinsic Heavy Quarks in Proton

Amplitude maximal at small invariant mass, equal rapidity

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

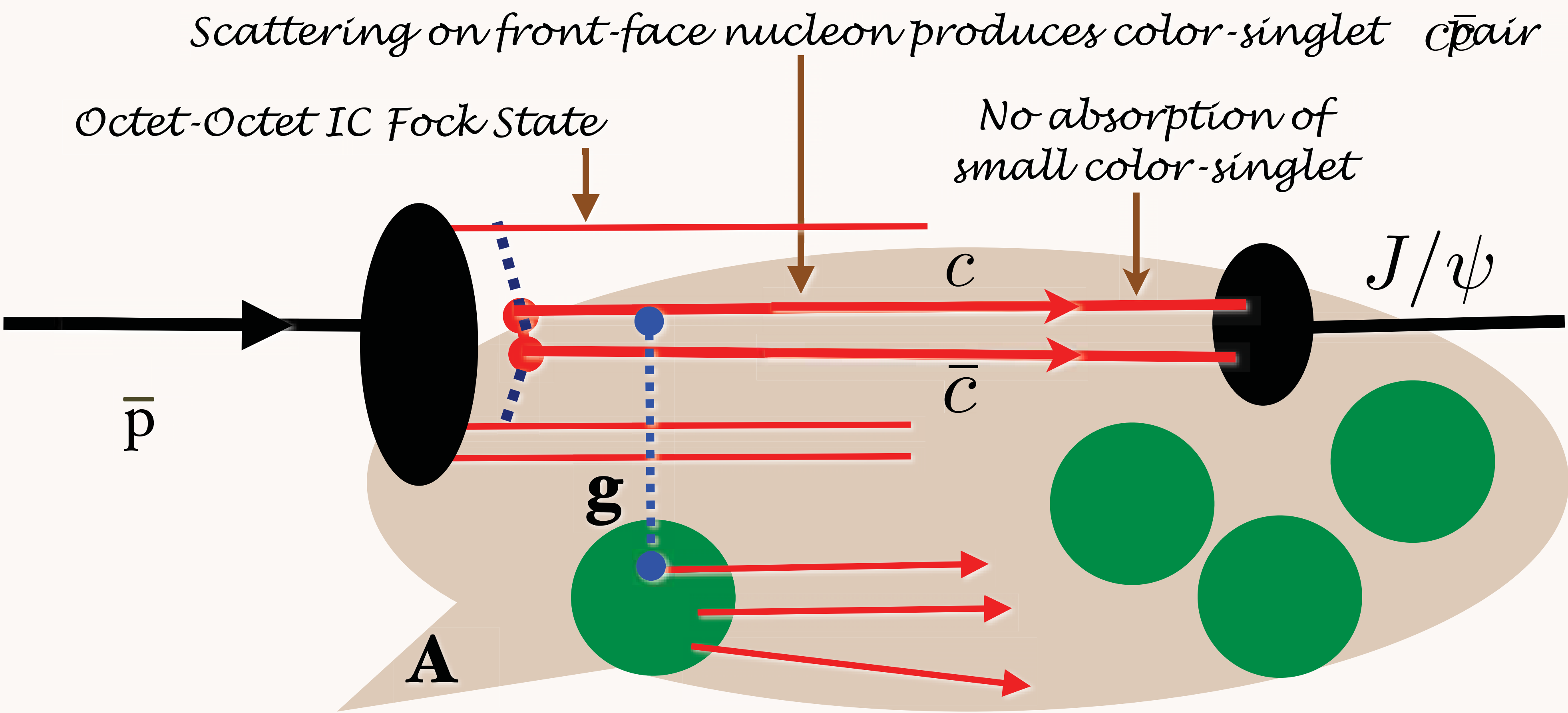
Produce forward, high x_F

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



Kopeliovich, Schmidt,
Soffer, sjb

Color-Opaque IC Fock state interacts on nuclear front surface



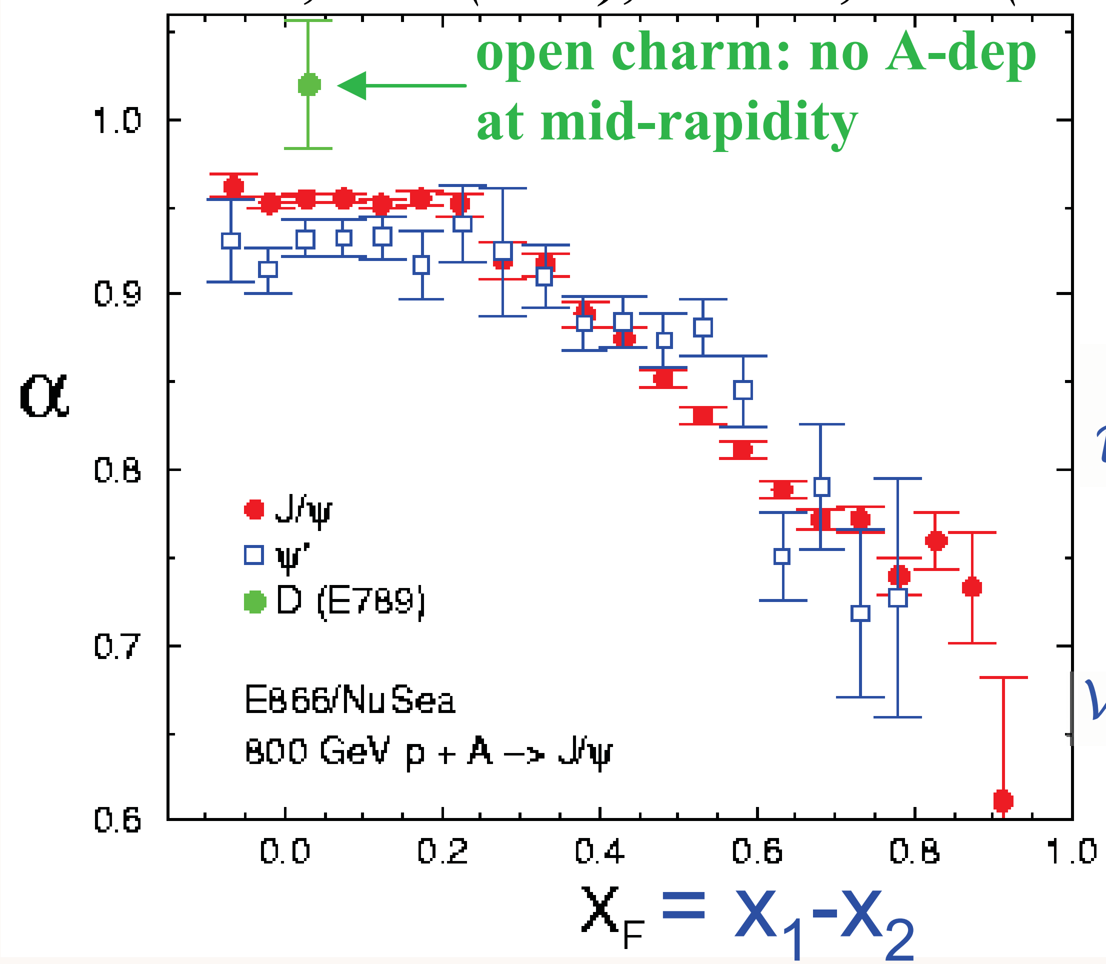
$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$

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

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

M. Leitch

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



Remarkably Strong Nuclear Dependence for Fast Charmonium

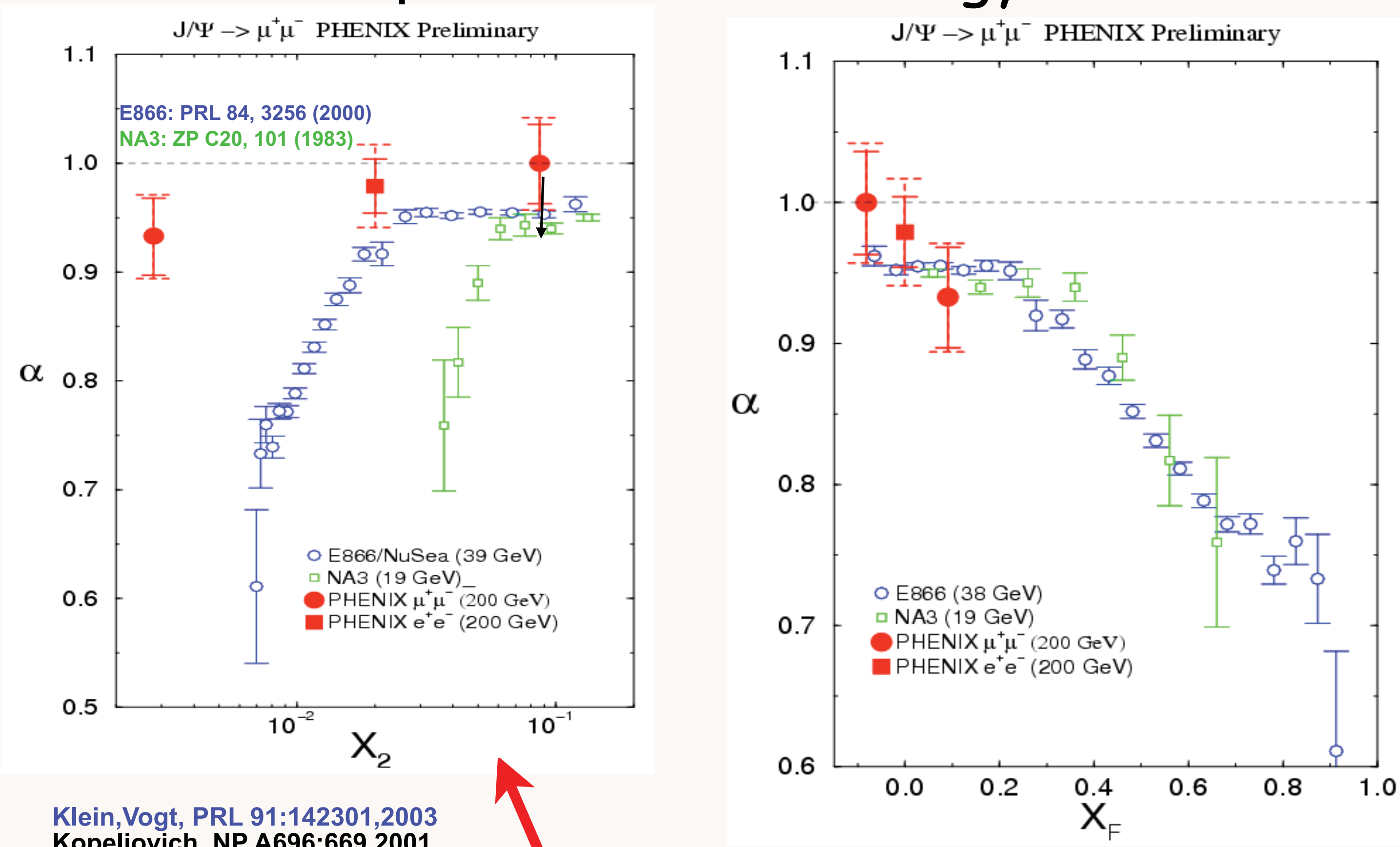
Violation of PQCD Factorization!

Violation of factorization in charm hadroproduction.
P. Hoyer, **M. Vanttinen** (**Helsinki U.**) , **U. Sukhatme** (**Illinois U., Chicago**) . **HU-TFT-90-14, May 1990. 7pp.**
Published in Phys.Lett.B246:217-220,1990

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

M.Leitch

PHENIX compared to lower energy measurements



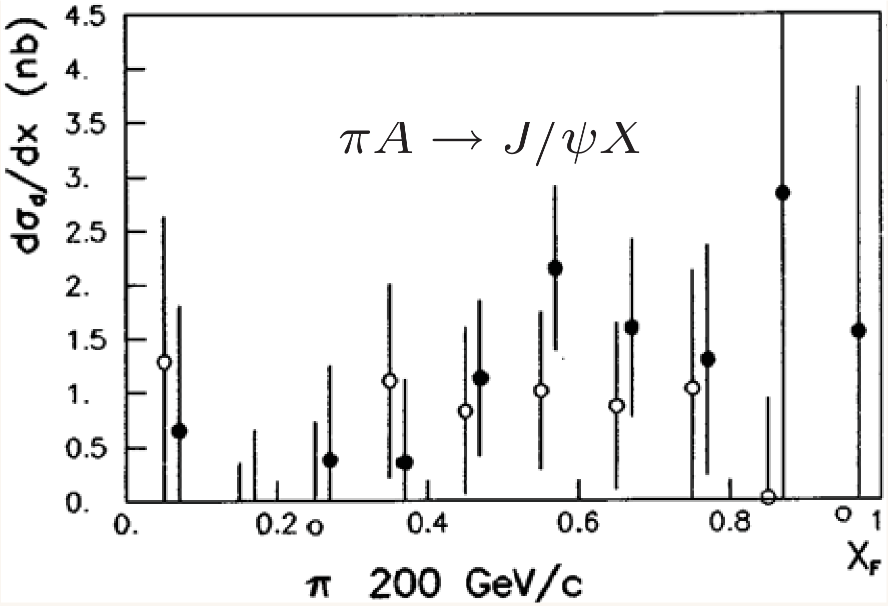
Klein,Vogt, PRL 91:142301,2003
Kopeliovich, NP A696:669,2001

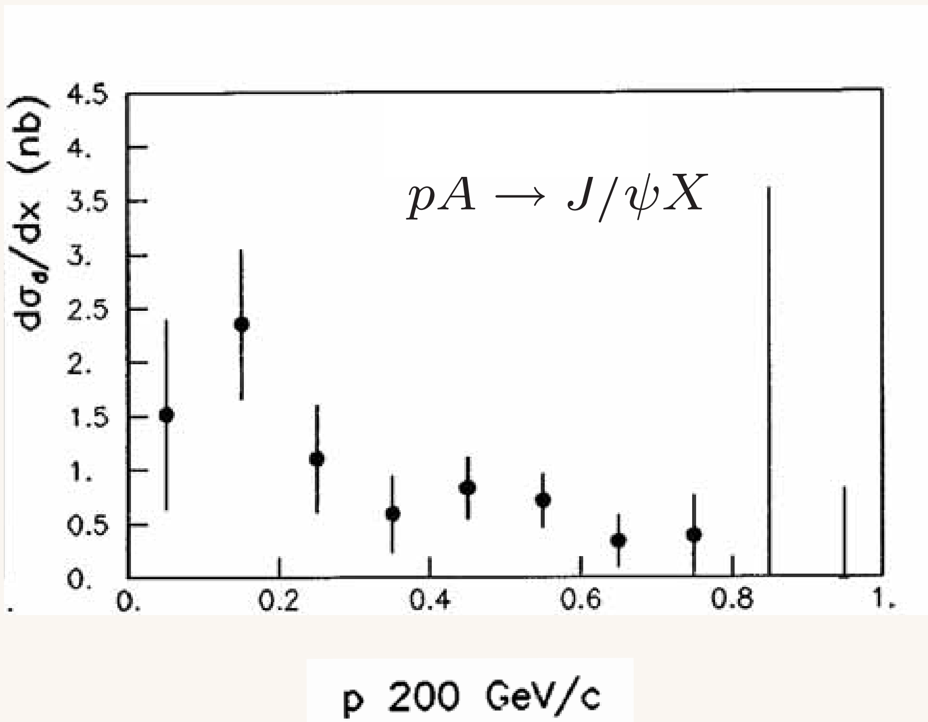
Huge "absorption" effect

Violates PQCD factorization!

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

Hoyer, Sukhatme, Vanttinen





$A^{2/3}$ 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)

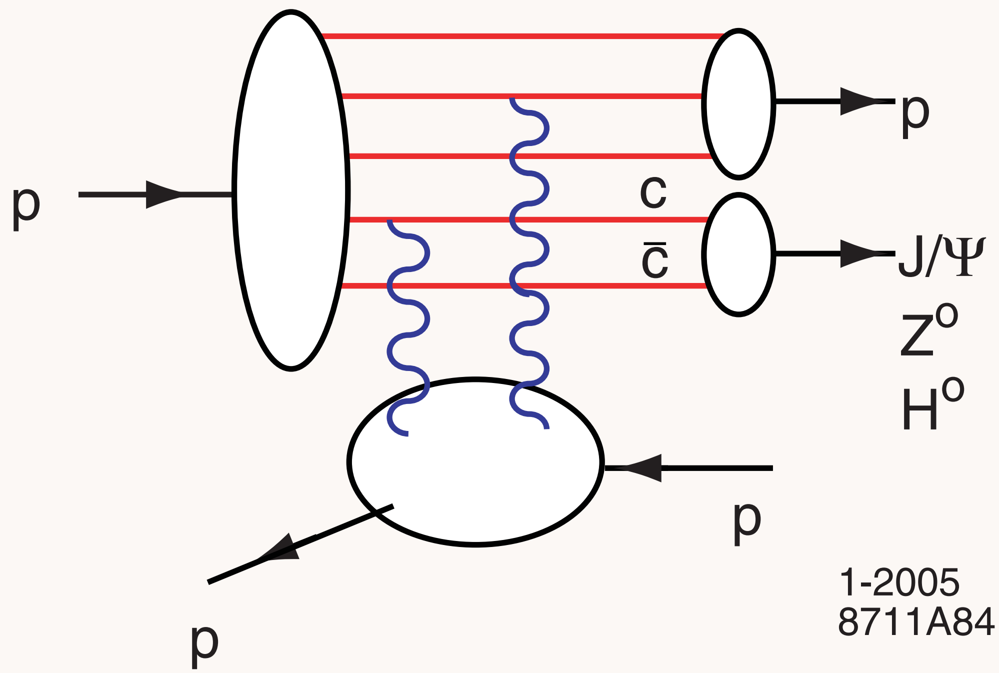
Color Opaqueness

- 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

Intrinsic Charm Mechanism for Exclusive Diffraction Production



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

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

Exclusive Diffractive High-X_F Higgs Production

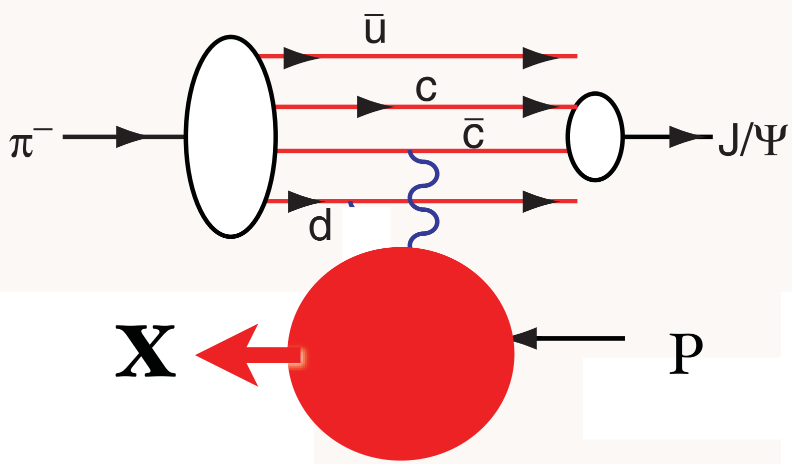
Kopeliovitch, Schmidt, Soffer, sjb

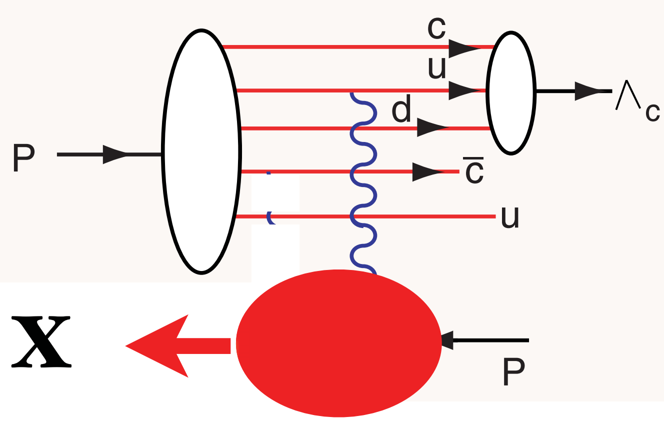
Intrinsic $c\bar{c}$ pair formed in color octet 8_C in proton wavefunction   Large Color Dipole

Collision produces color-singlet J/ψ through color exchange

RHIC Experiment

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