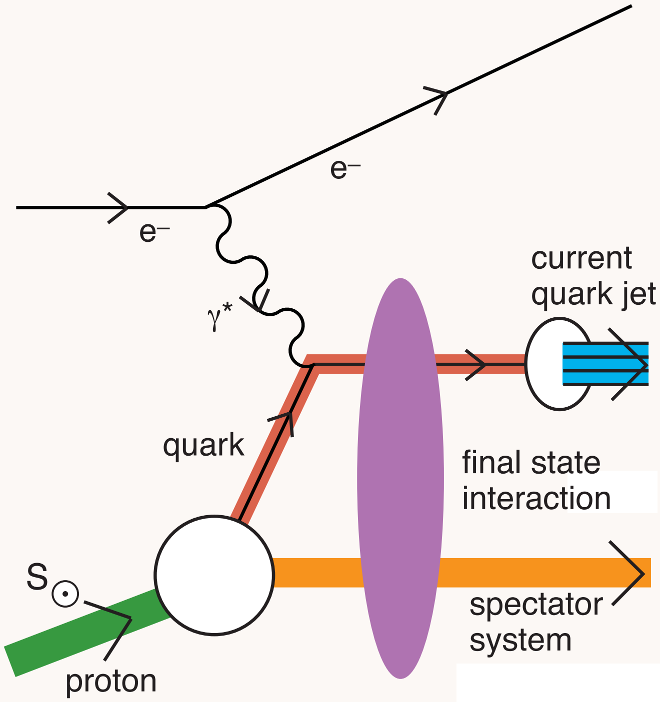
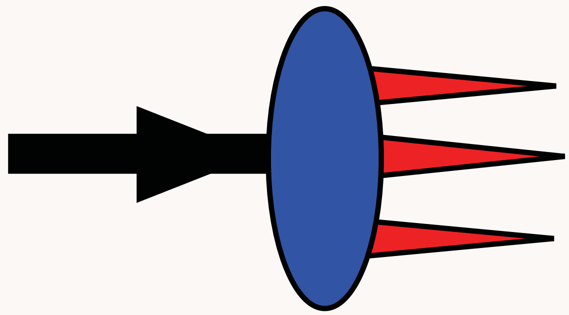
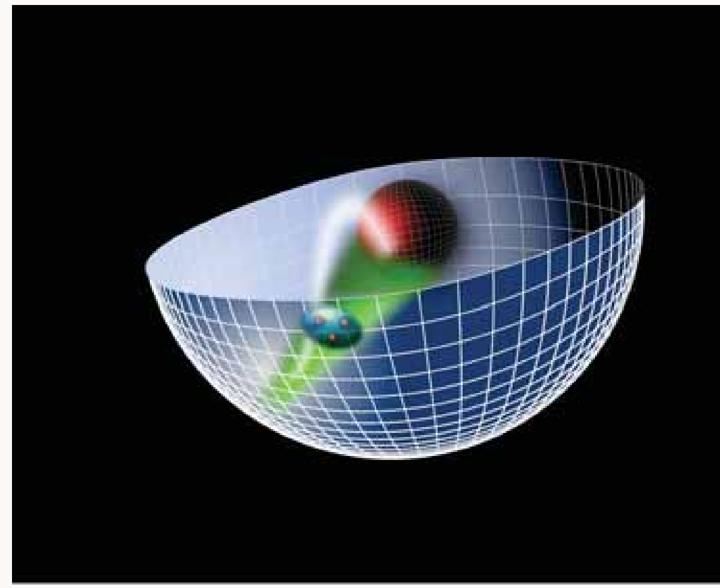
Novel QCD Phenomena

Stan Brodsky
SLAC Stanford University





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

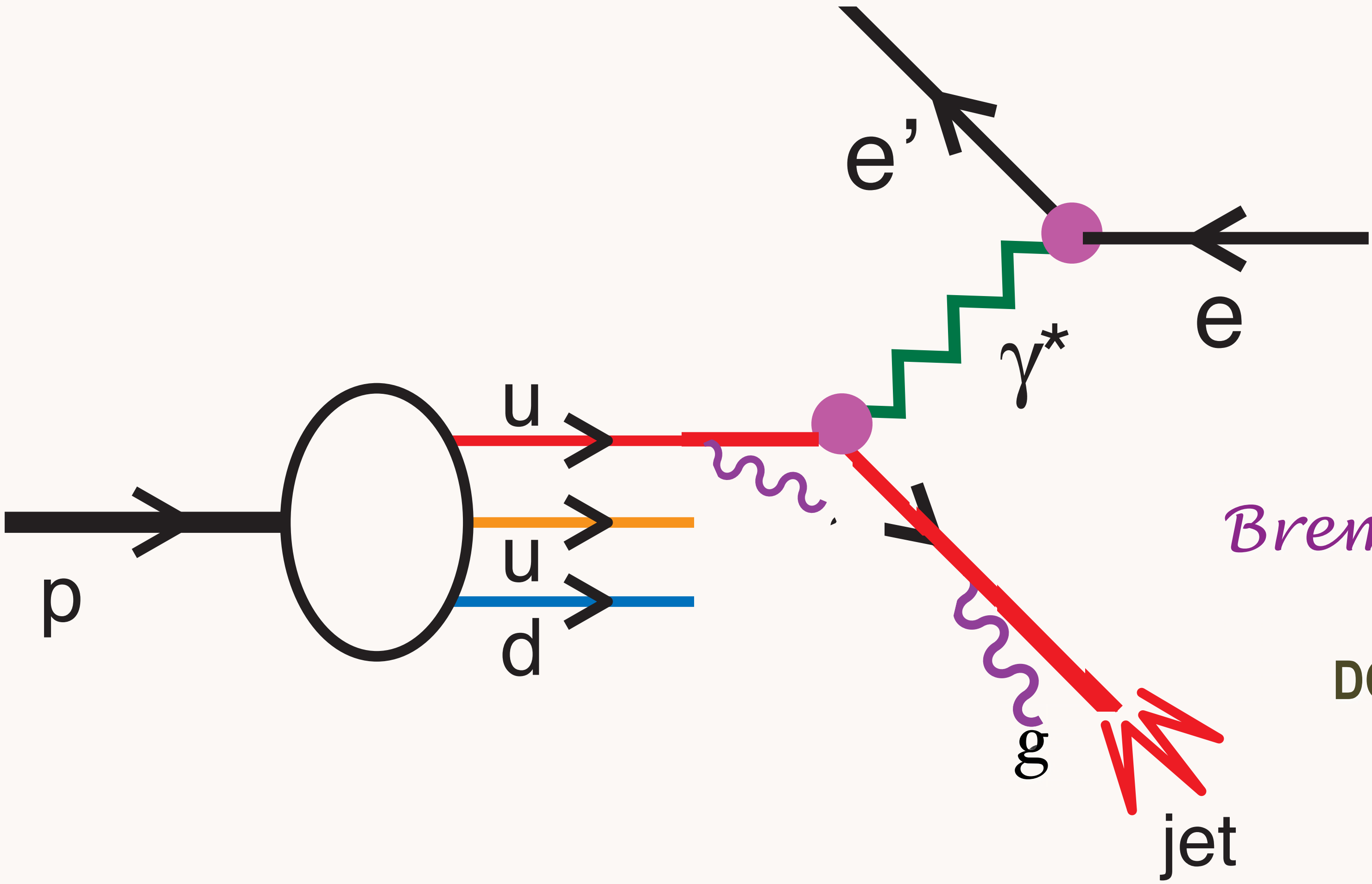


LBNL
November 18, 2010

QCD Myths

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

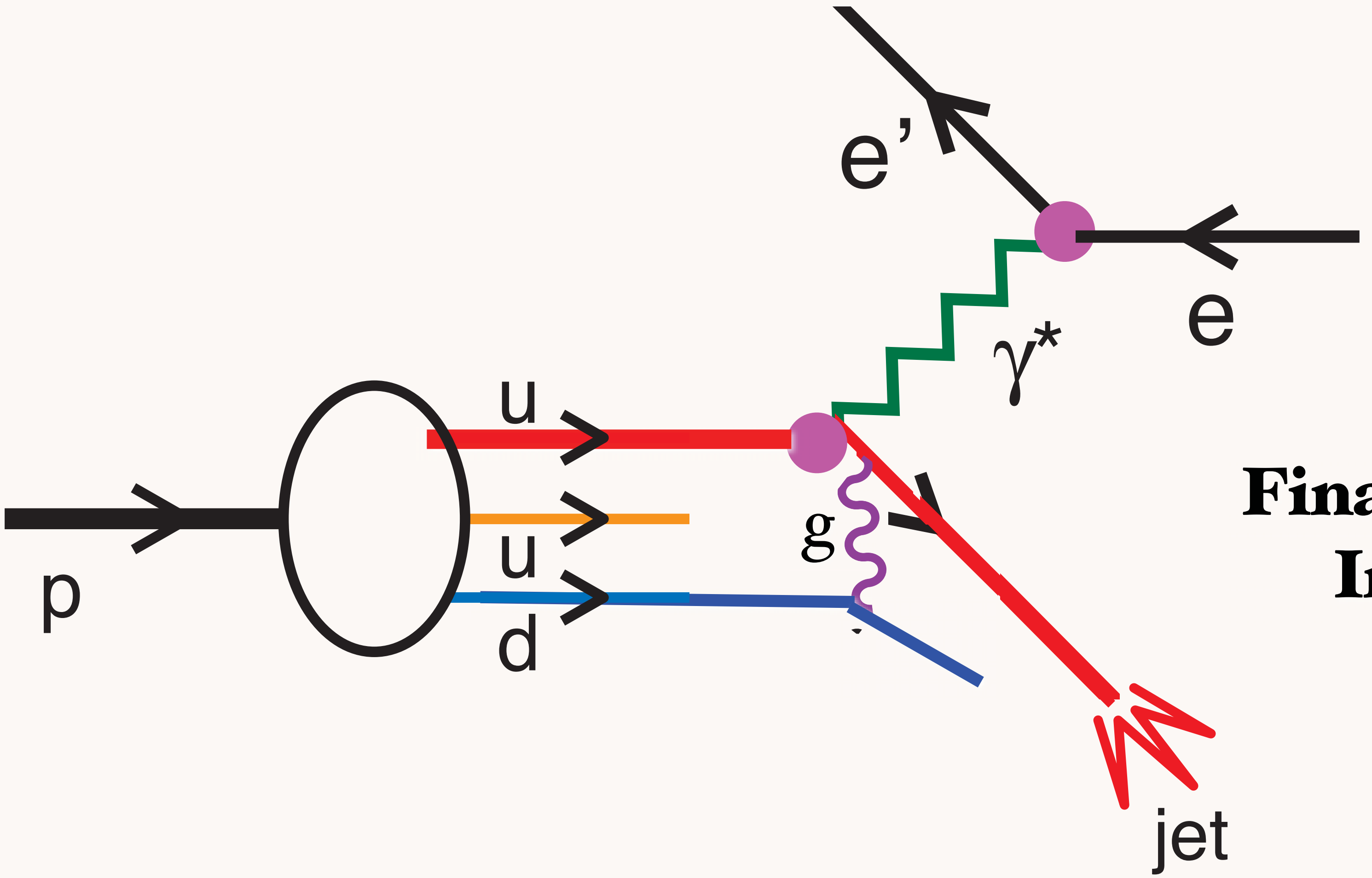
Deep Inelastic Electron-Proton Scattering



Gluonic Bremmstrahlung

DGLAP Evolution

Deep Inelastic Electron-Proton Scattering



Final-State QCD Interaction

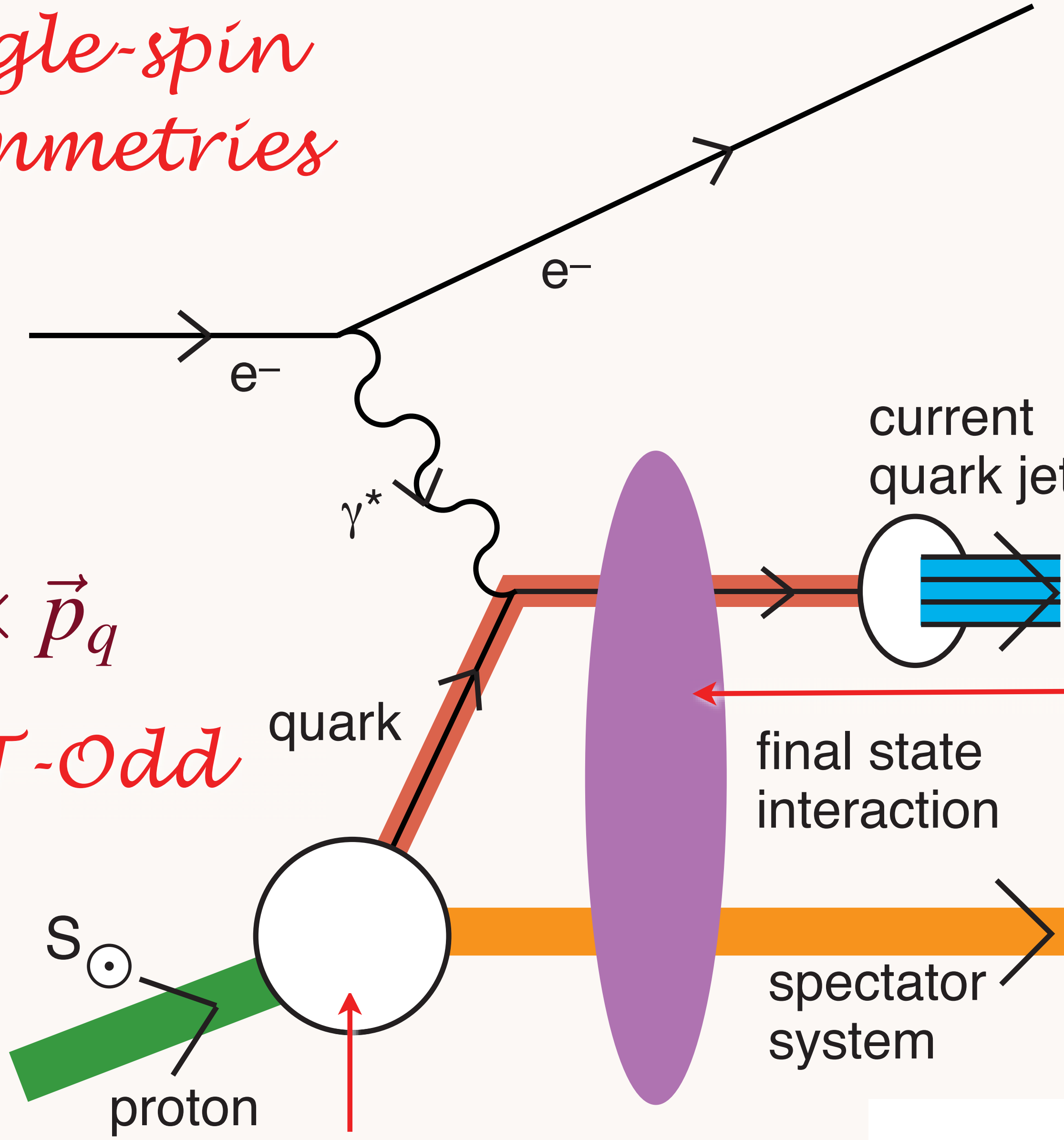
Conventional wisdom:
Final-state interactions of struck quark can be neglected

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

Light-Front Wavefunction S and P- Waves

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

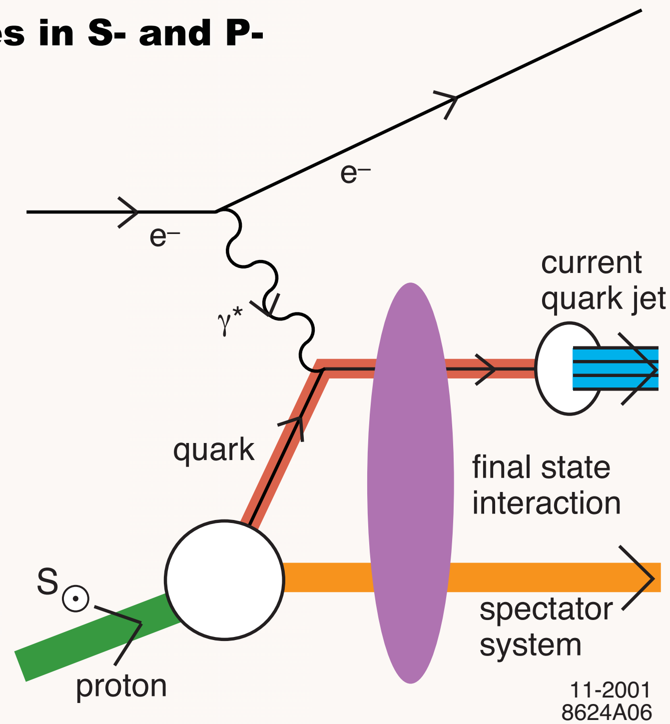
Leading-Twist Rescattering Violates pQCD Factorization!

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

Hwang, Schmidt, sjb
Collins

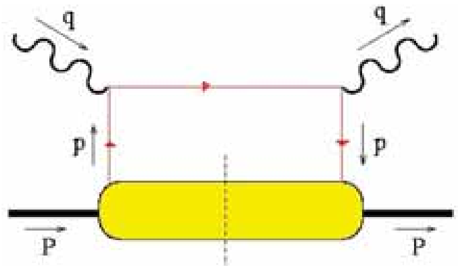
- **Leading-Twist Bjorken Scaling!**
- **Requires nonzero orbital angular momentum of quark**
- **Arises from the interference of Final-State QCD Coulomb phases in S- and P-waves;**
- **Wilson line effect -- gauge independent**
- **Relate to the quark contribution to the target proton anomalous magnetic moment and final-state QCD phases**
- **QCD phase at soft scale!**
- **New window to QCD coupling and running gluon mass in the IR**
- **QED S and P Coulomb phases infinite -- difference of phases finite!**
- **Alternate: Retarded and Advanced Gauge: Augmented LFWFs**

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

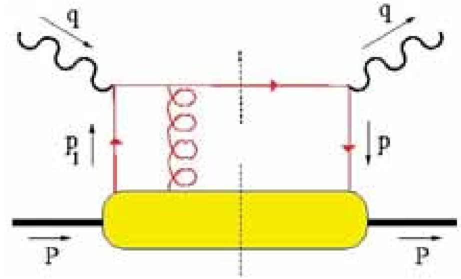


Pasquini, Xiao, Yuan, sjb

Mulders, Boer   Qiu, Sterman



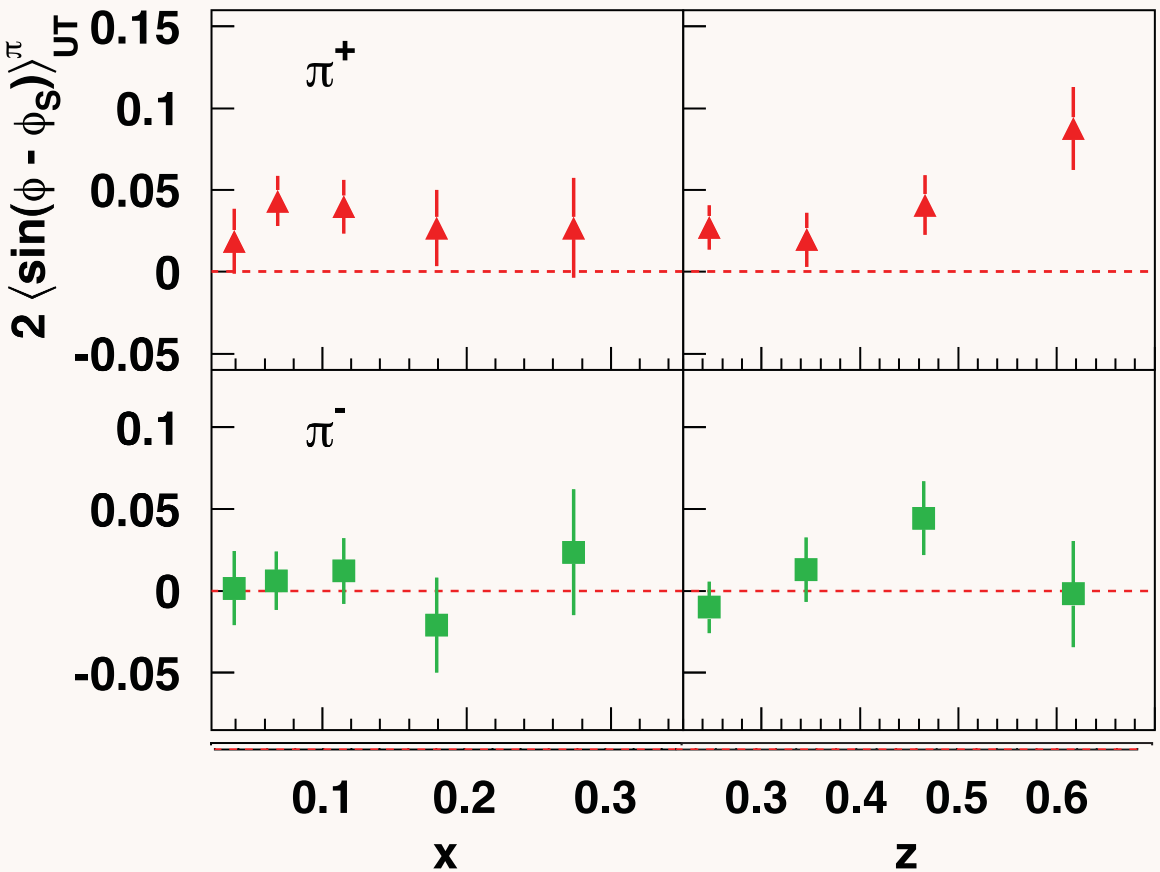
can interfere with



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⁻**...

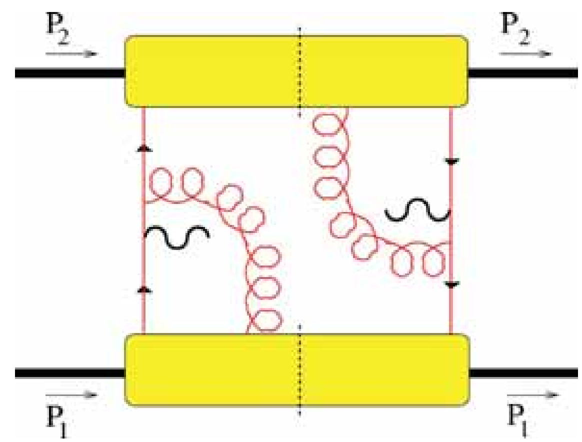
Gamberg: Hermes data compatible with BHS model

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

Anomalous effect from Double ISI in Massive Lepton Production

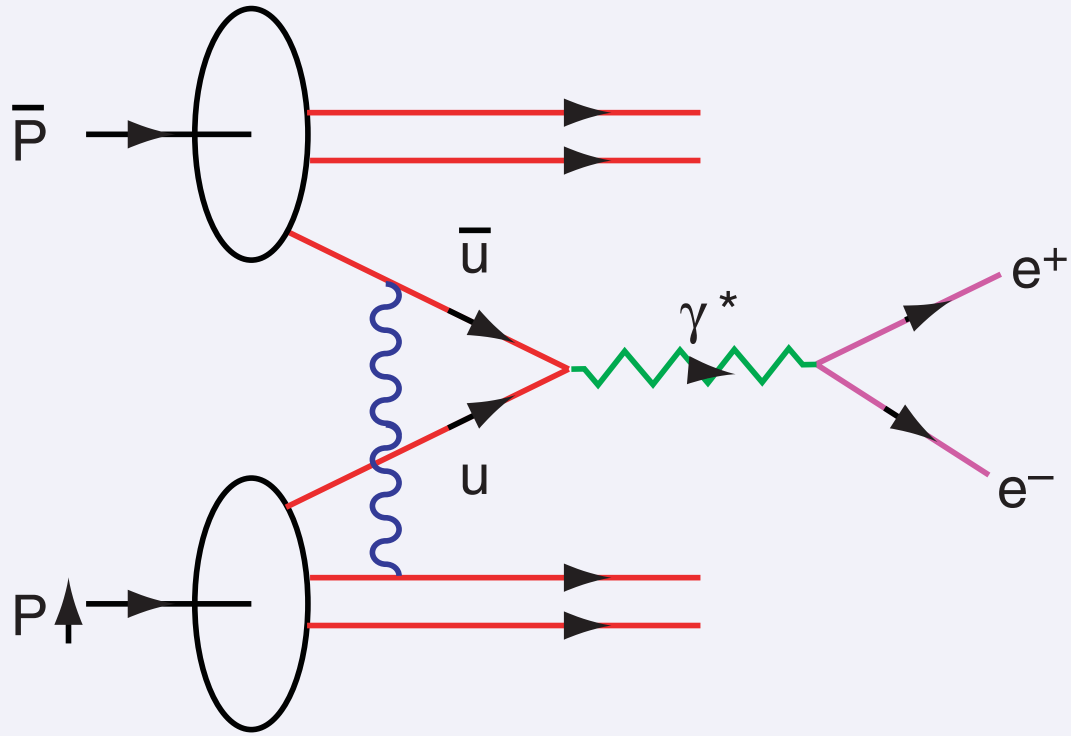
Boer, Hwang, sjb

$\cos 2\phi$ 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

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

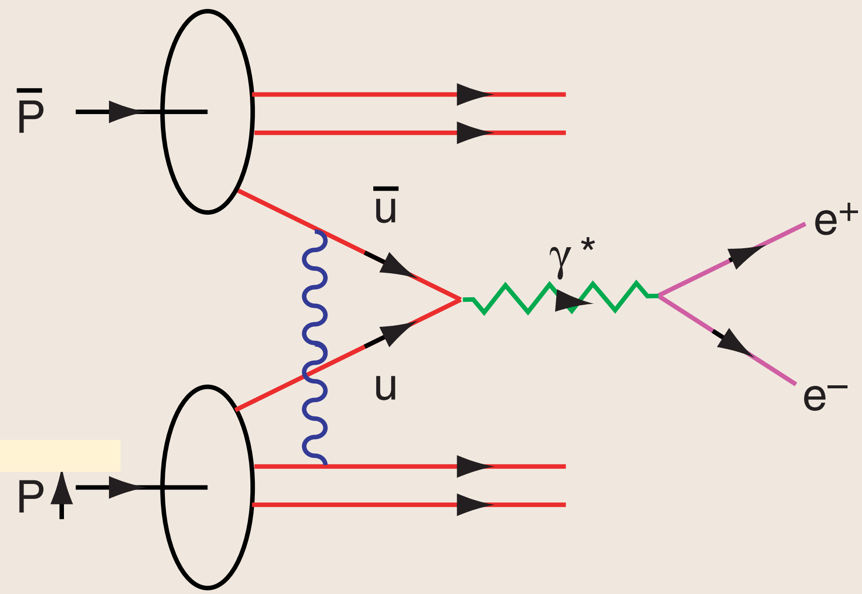
Key QCD Experiment

Collins; Hwang, Schmidt. sjb

Measure single-spin asymmetry A_N in Drell-Yan reactions

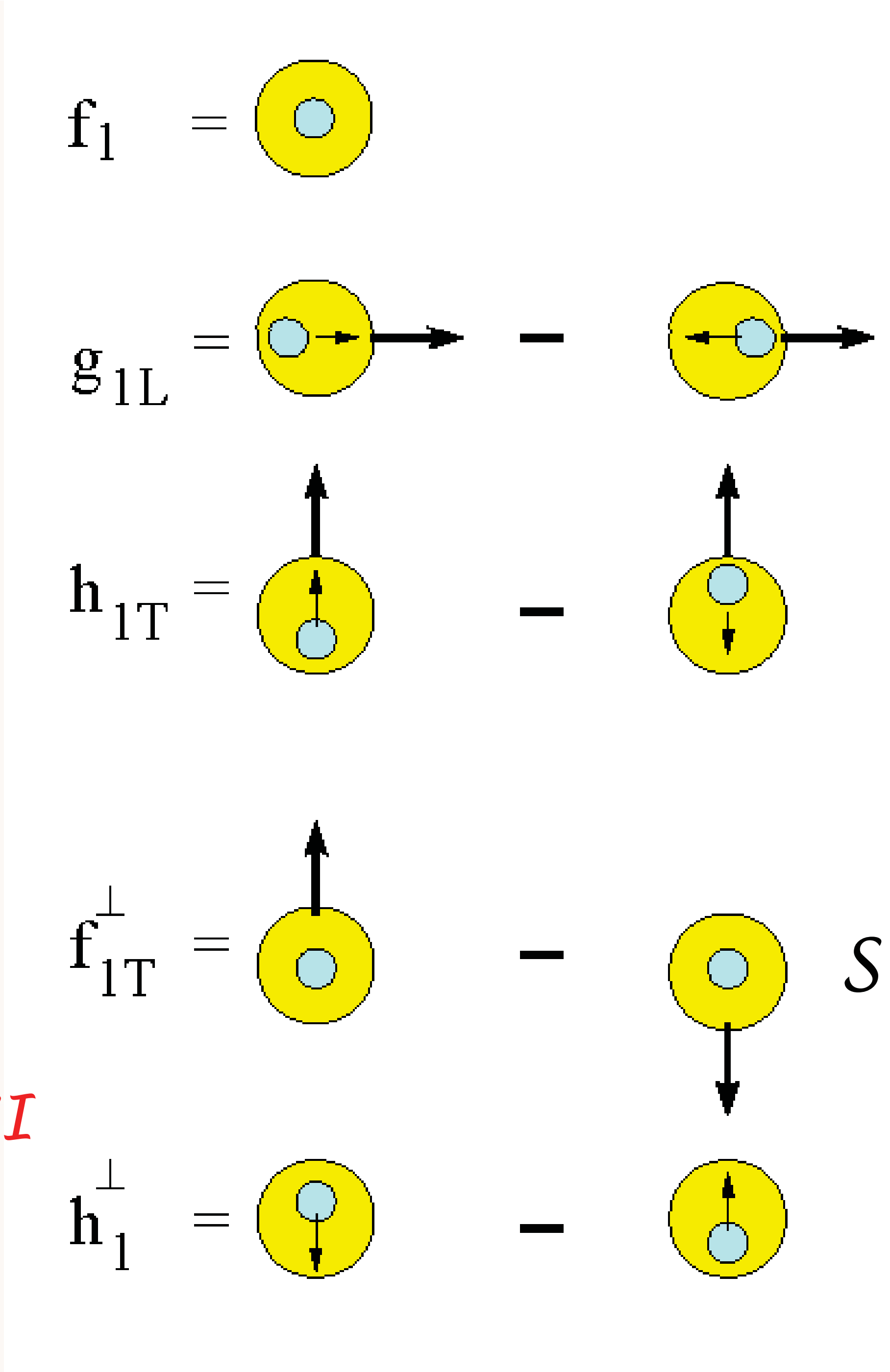
Leading-twist Bjorken-scaling A_N from S, P-wave initial-state gluonic interactions

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



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

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



Unpolarized Distribution

Bj Sum Rule

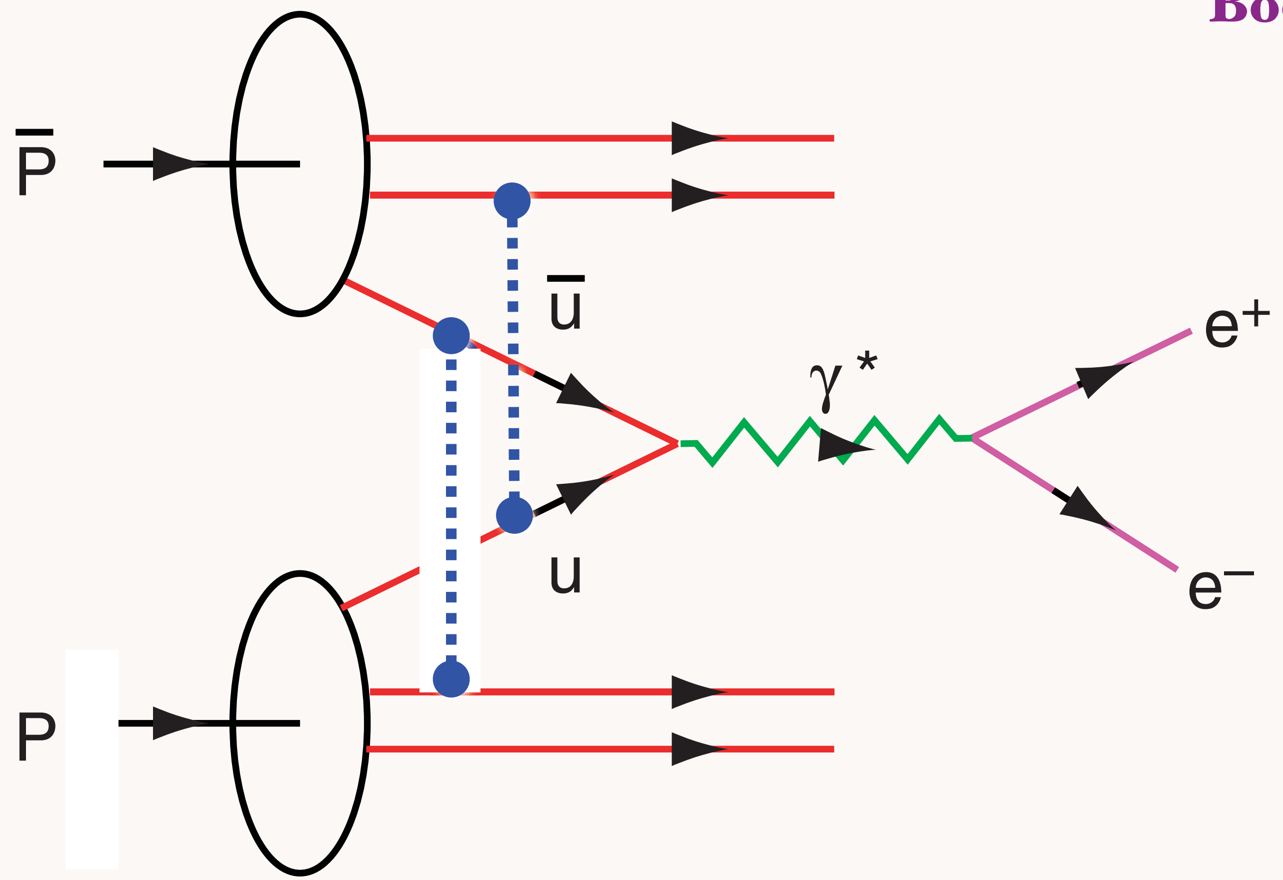
Transversity

Sivers Function

Boer-Mulders Function

T-Odd: Require ISI or FSI

Boer, Hwang, sjb



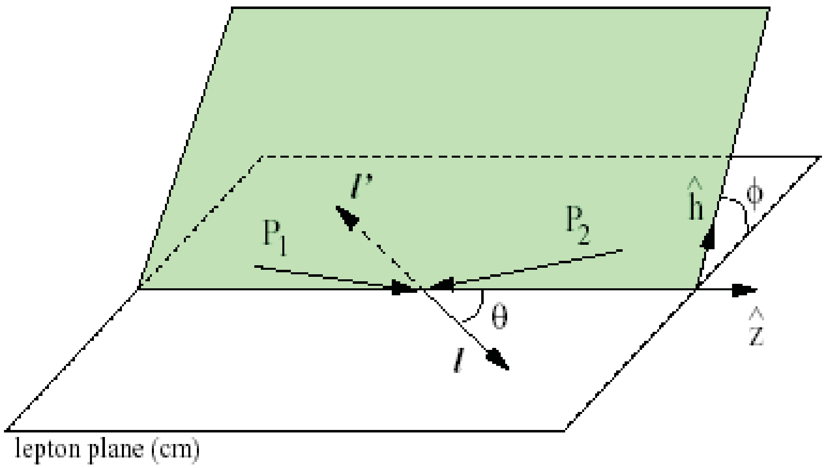
DY $\cos 2\phi$ **correlation at leading twist from double ISI**

Product of Boer - Mulders Functions

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

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

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

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

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1 + \lambda\cos^2\theta + \mu\sin2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos2\phi\right)$$

$\text{Experiment:} \ \nu \simeq 0.6$

B. Seitz

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

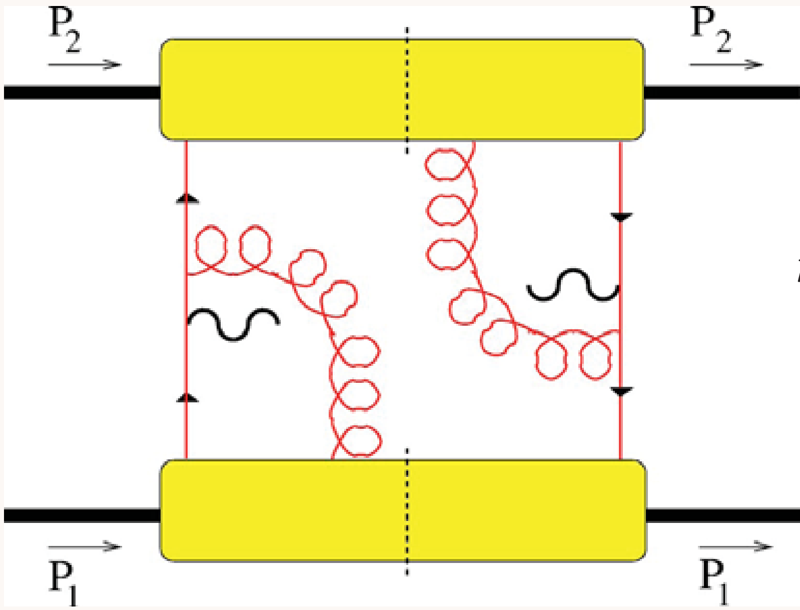
Boer, Hwang, sjb

Drell-Yan planar correlations

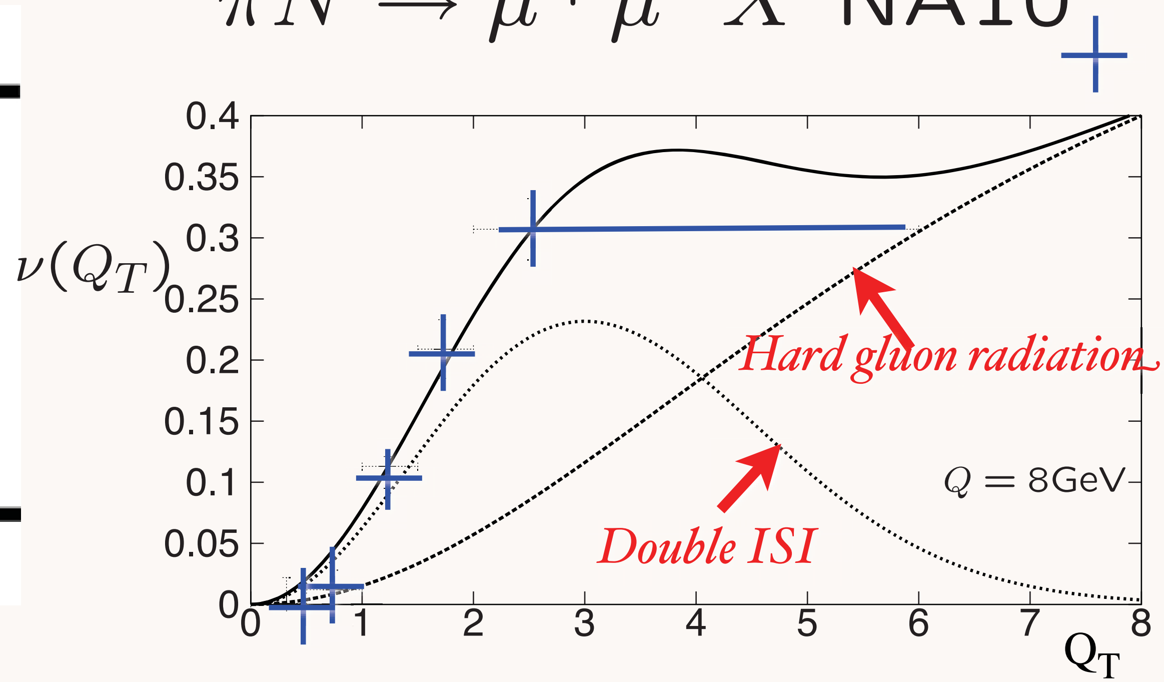
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \left(1 + \lambda\cos^2\theta + \mu\sin 2\theta\,\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right)$$

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

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



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

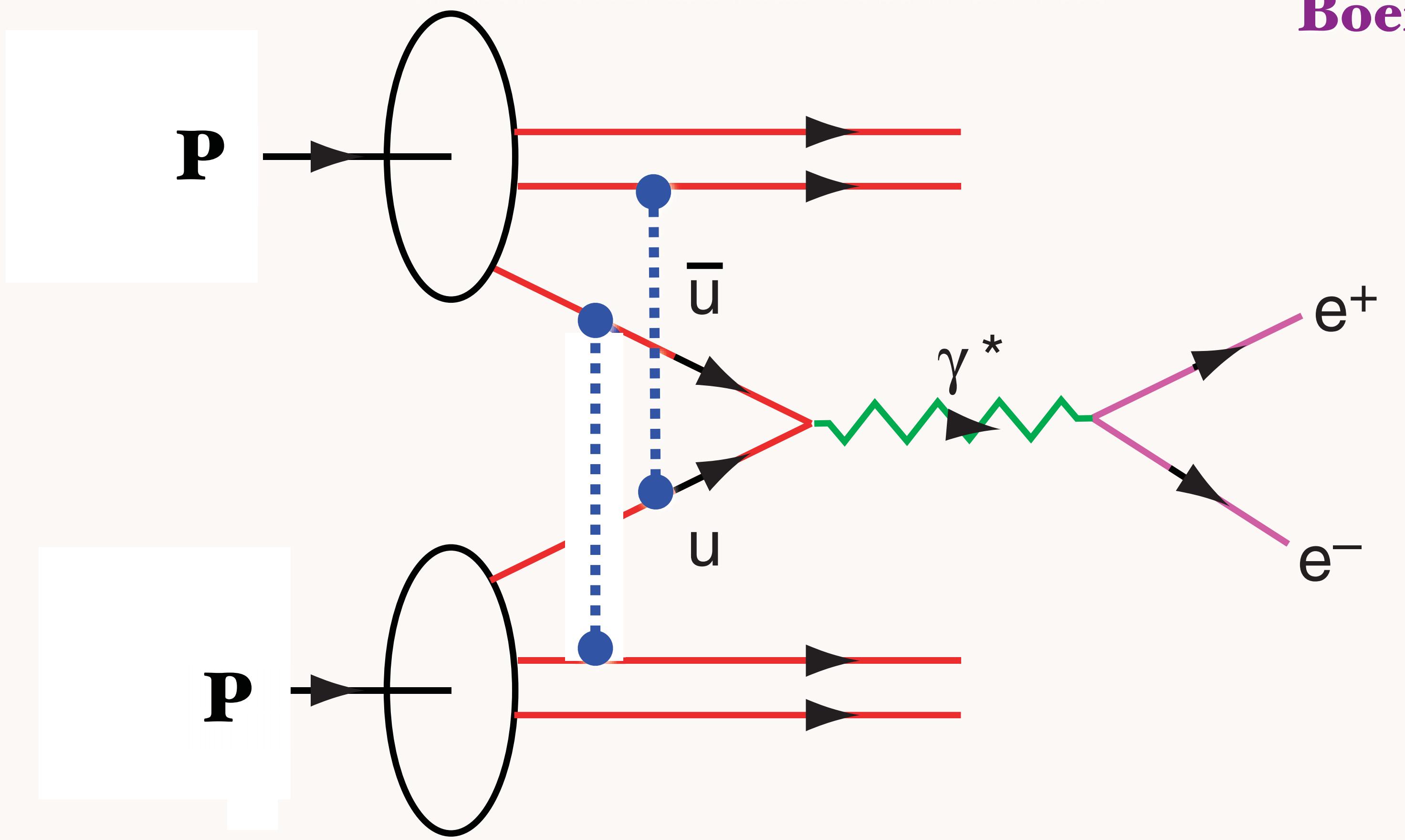


Violates Lam-Tung relation!

Model: Boer,

LHC Experiment

Boer, Hwang, sjb



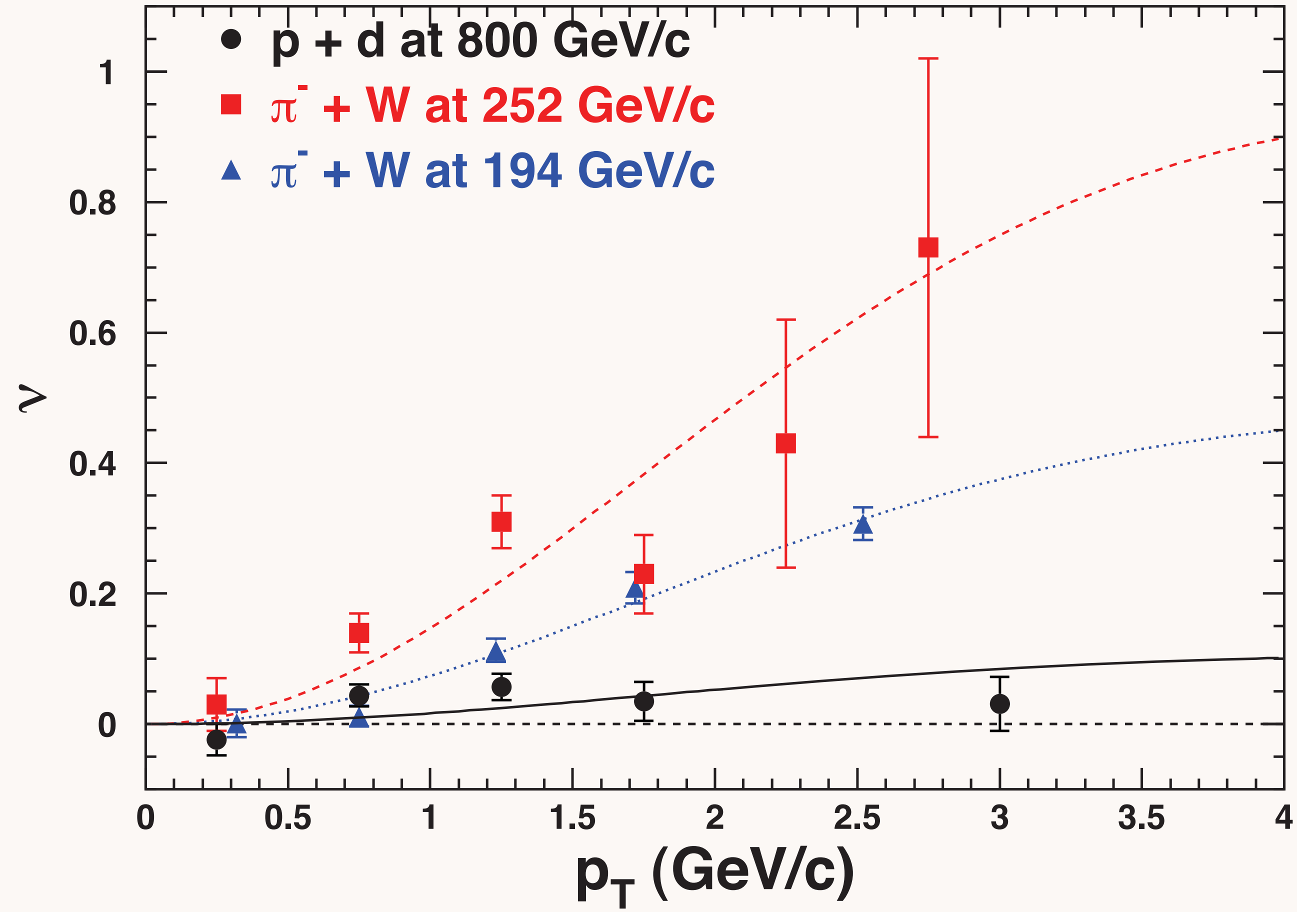
DY $\cos 2\phi$ correlation at leading twist from double ISI

Product of Boer - Mulders Functions

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

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

(FNAL E866/NuSea Collaboration)

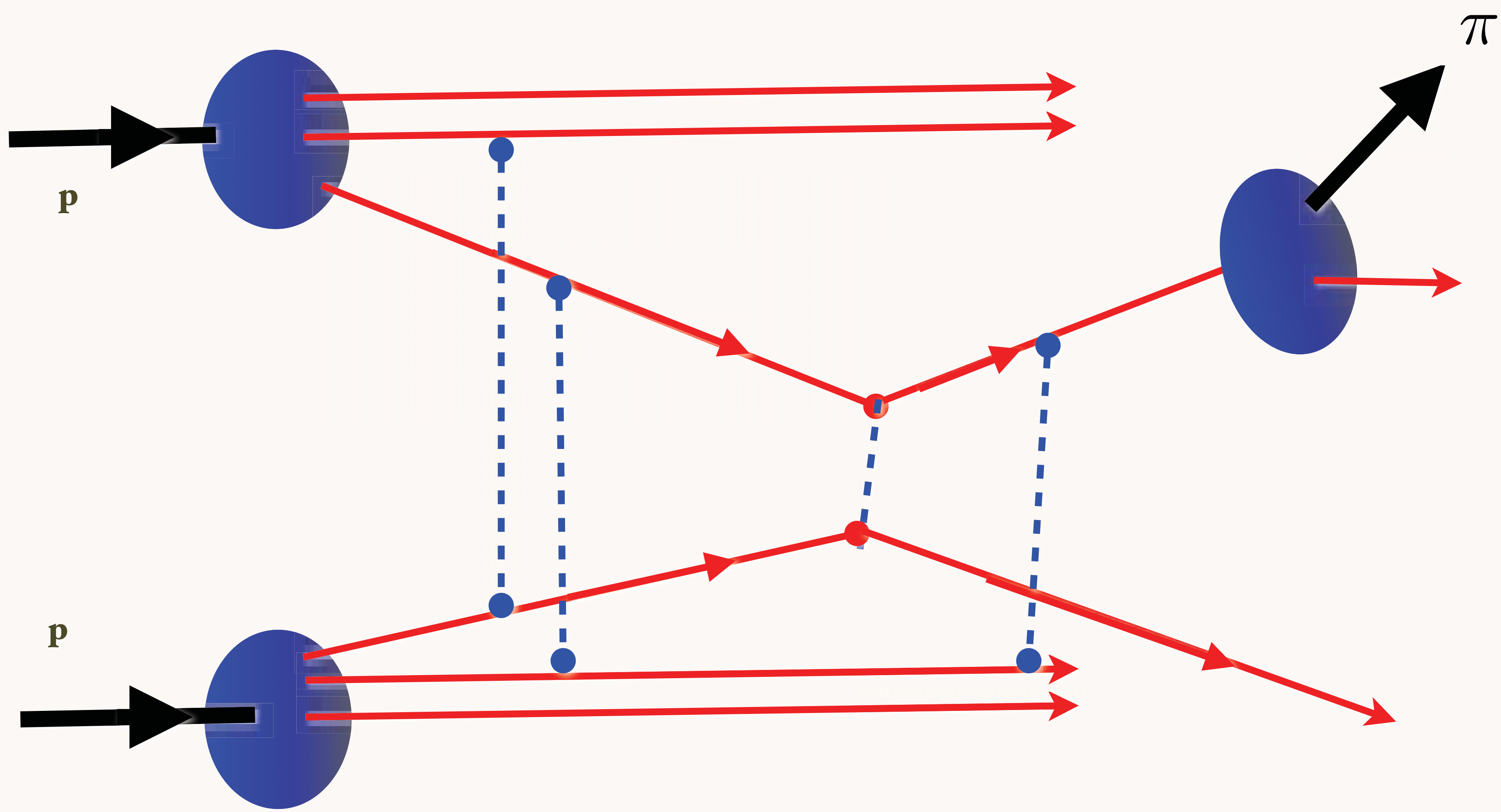


Huge Effect in $\pi W \to \mu^+ \mu^- X$

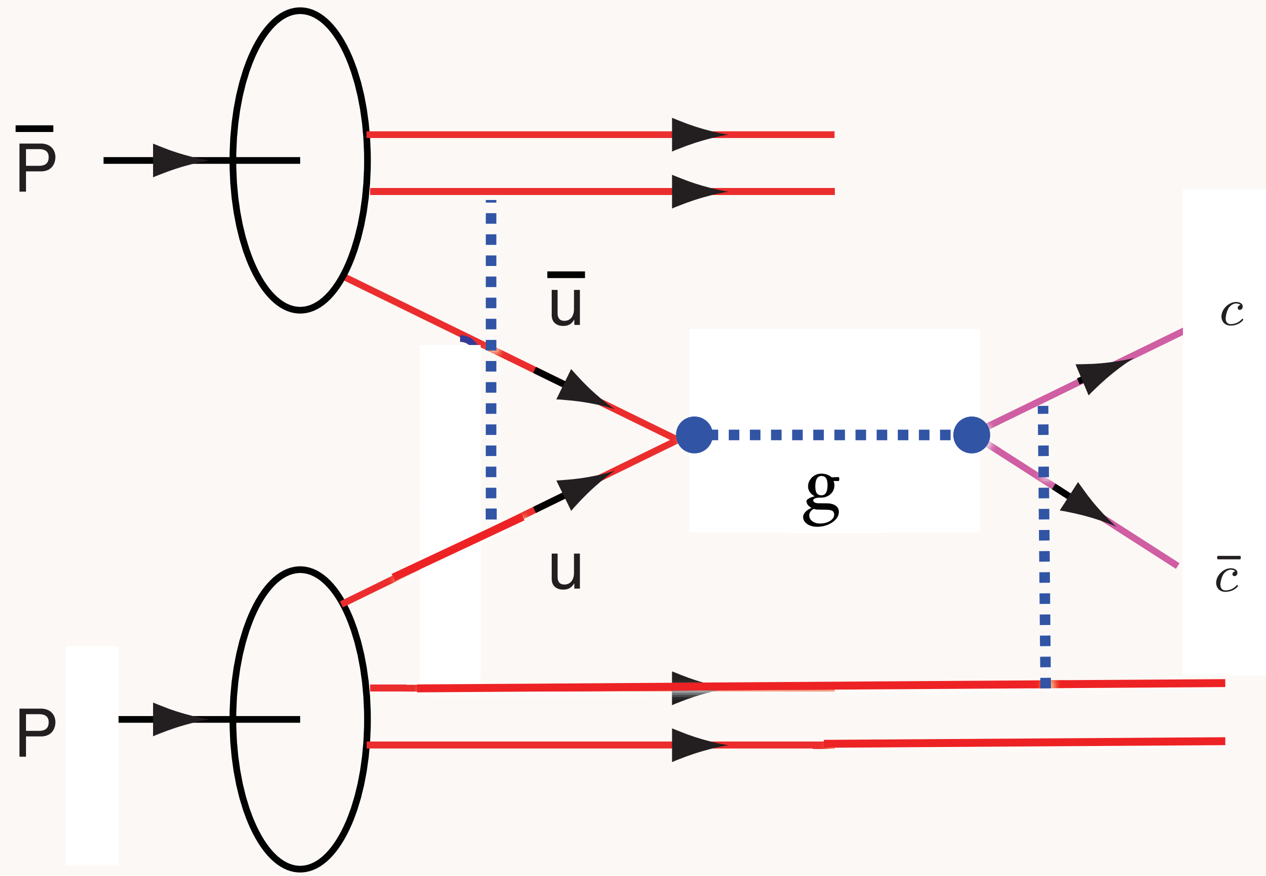
Negligible Effect $pd \to \mu^+ \mu^- X$

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.

Important Corrections from Initial and Final State Corrections



Sivers & Collins Odd-T Spin Effects, Co-planarity Correlations

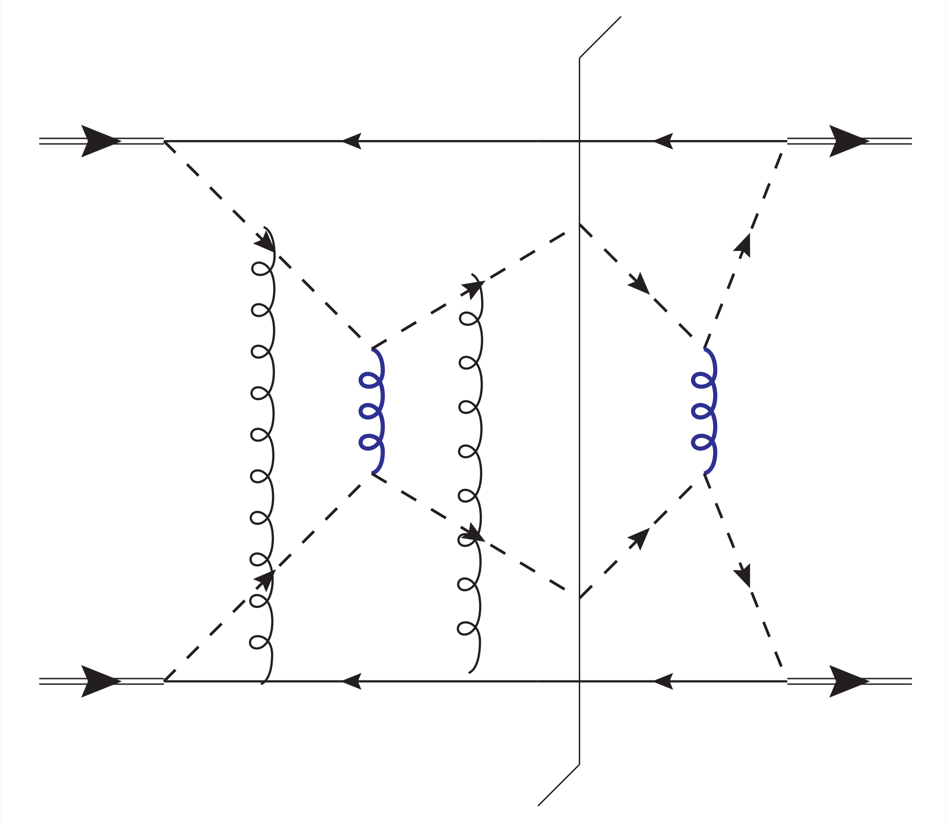


Problem for factorization when both ISI and FSI occur

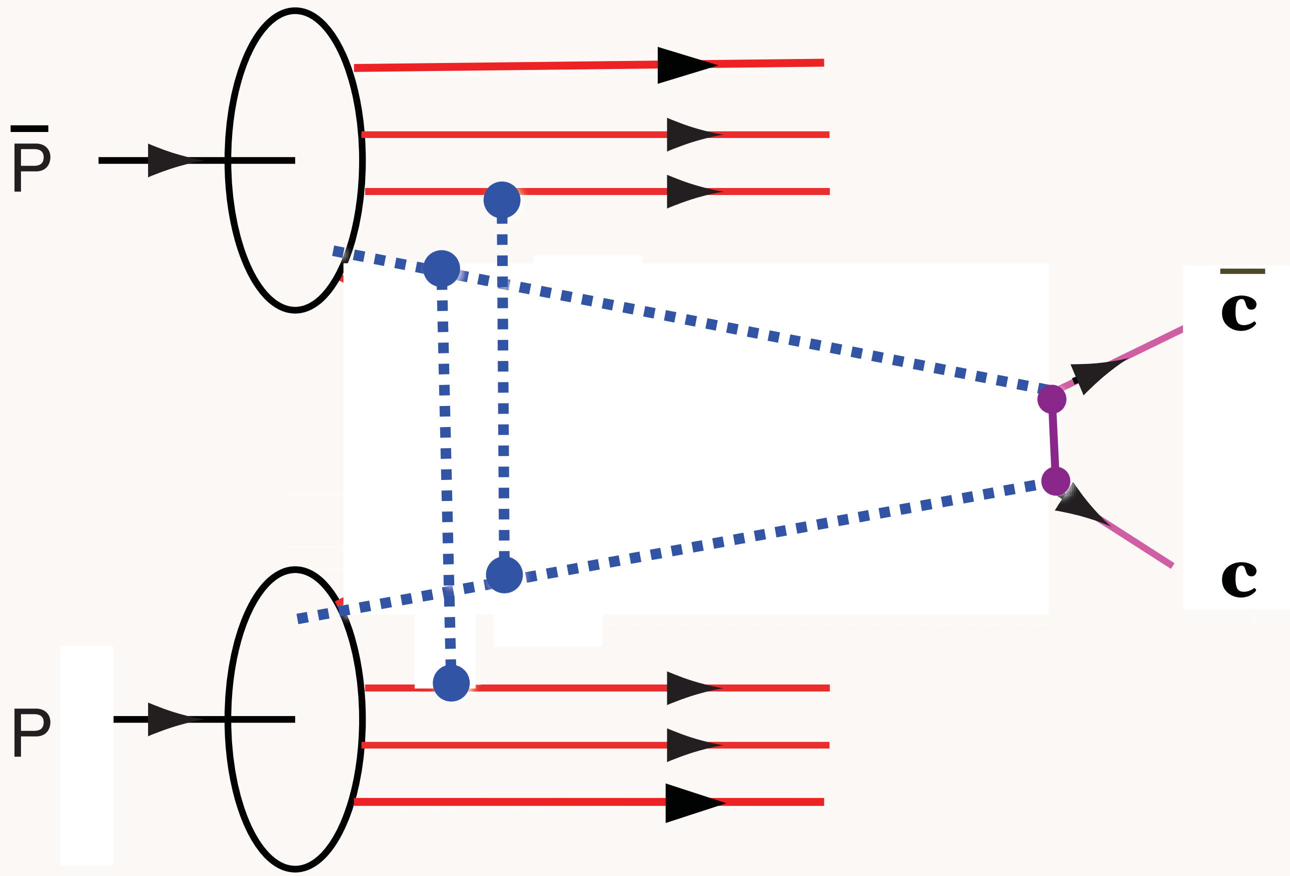
Factorization is violated in production of high-transverse-momentum particles in hadron-hadron collisions

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

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



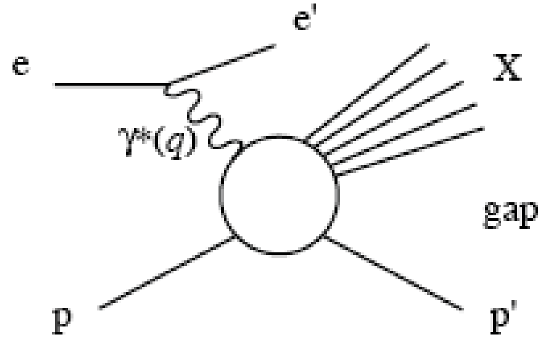
The exchange of two extra gluons, as in this graph, will tend to give non-factorization in unpolarized cross sections.



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

Enhanced by gluon color charge

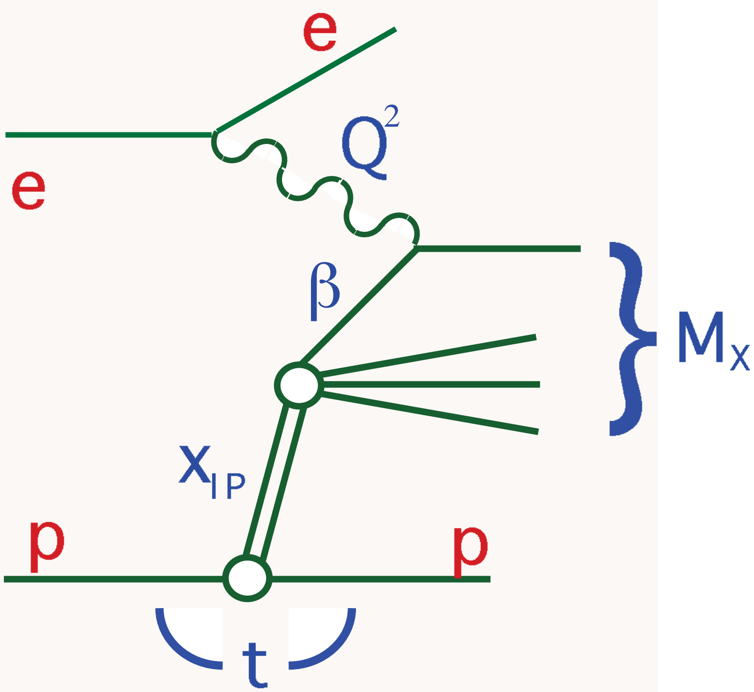
DDIS

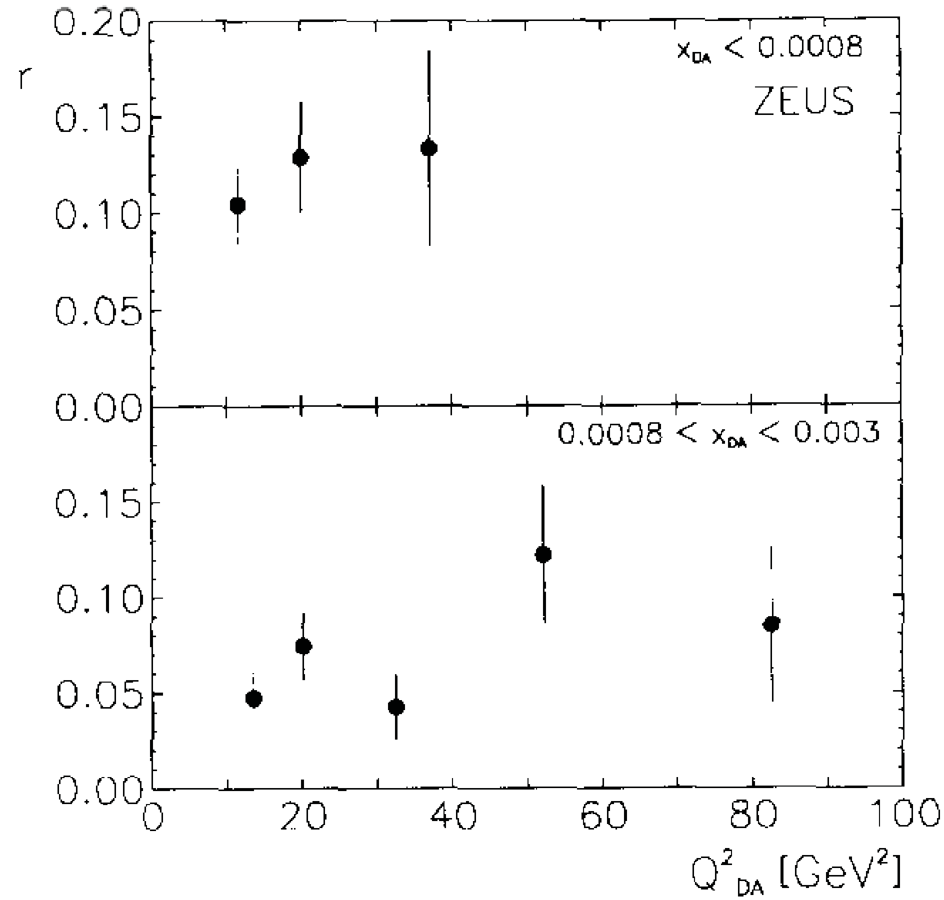


- In a large fraction ($\sim$ 10–15%) of DIS events, the proton escapes intact, keeping a large fraction of its initial momentum
- This leaves a large *rapidity gap* between the proton and the produced particles
- The t-channel exchange must be *color singlet* $\rightarrow$ a pomeron??

Diffractive Deep Inelastic Lepton-Proton Scattering

Remarkable observation at HERA



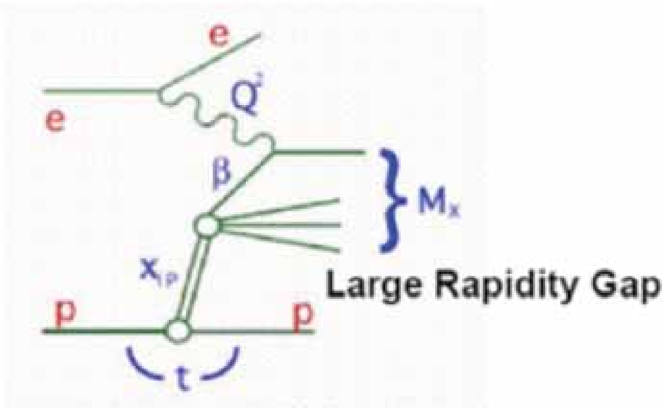


Fraction r of events with a large rapidity gap, $\eta_{max} < 1.5$, as a function of Q^2_{DA} for two ranges of x_{DA}. No acceptance corrections have been applied.

10% to 15% of DIS events are diffractive !

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

Diffractive Structure Function F_2^D



Diffractive inclusive cross section

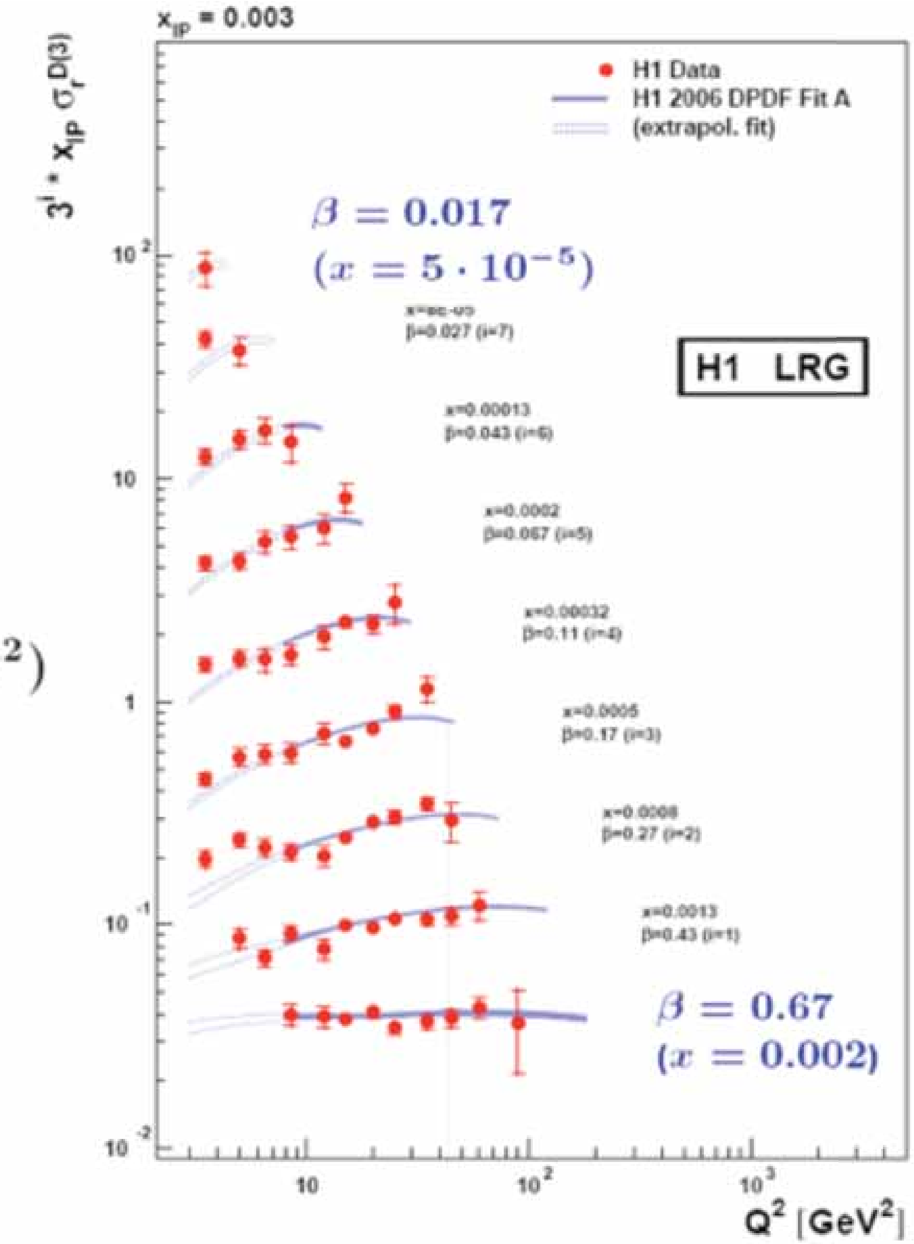
$$\frac{d^3\sigma_{NC}^{diff}}{dx_{I\!P}\,d\beta\,dQ^2} \propto \frac{2\pi\alpha^2}{xQ^4} F_2^{D(3)}(x_{I\!P},\beta,Q^2)$$

$$F_2^D(x_{I\!P},\beta,Q^2) = f(x_{I\!P}) \cdot F_2^{I\!P}(\beta,Q^2)$$

extract DPDF and $xg(x)$ from scaling violation

Large kinematic domain $3 < Q^2 < 1600\,\mathrm{GeV}^2$

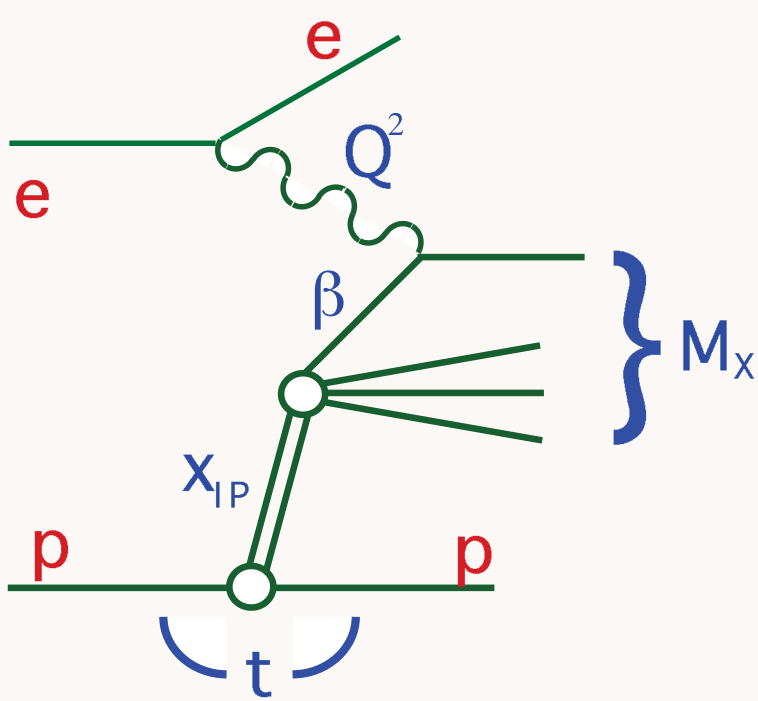
Precise measurements *sys 5%, stat 5–20 %*

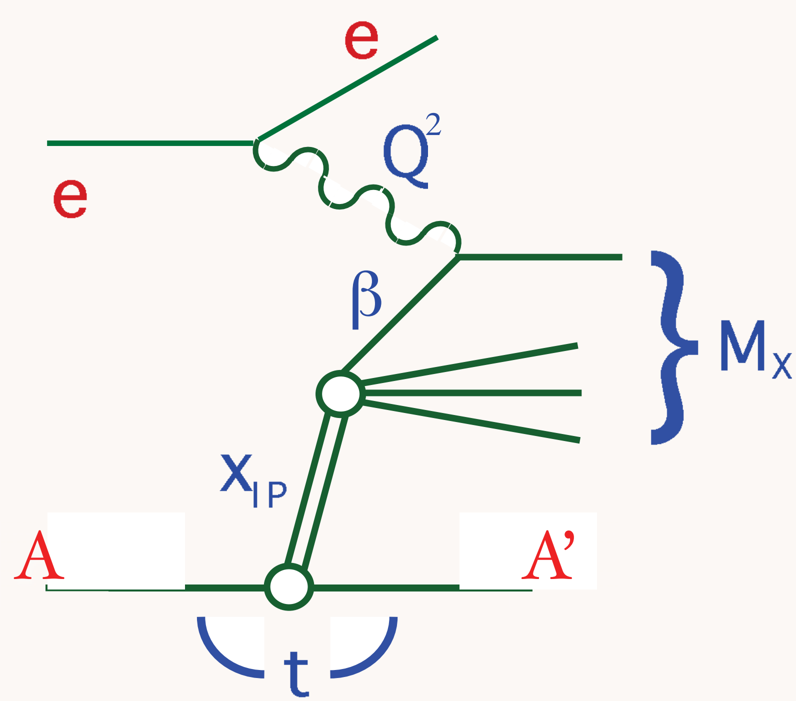


Diffractive Deep Inelastic Scattering

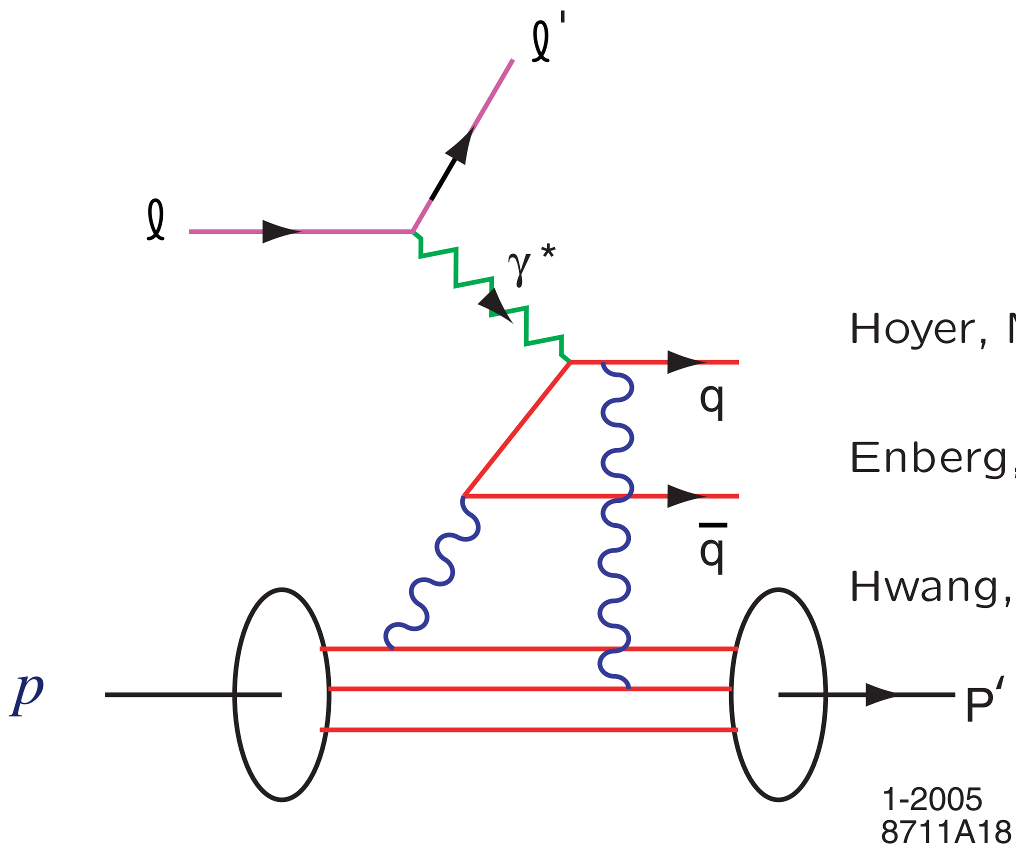
Diffractive DIS $ep \to epX$ where there is a large rapidity gap and the target nucleon remains intact probes the final state interaction of the scattered quark with the spectator system via gluon exchange.

Diffractive DIS on nuclei $eA \to e'AX$ and hard diffractive reactions such as $\gamma^* A \to VA$ can occur coherently leaving the nucleus intact.





Final-State Interaction Produces Diffractive DIS



Quark Rescattering

Hoyer, Marchal, Peigne, Sannino, SJB (BHMPS)

Enberg, Hoyer, Ingelman, SJB

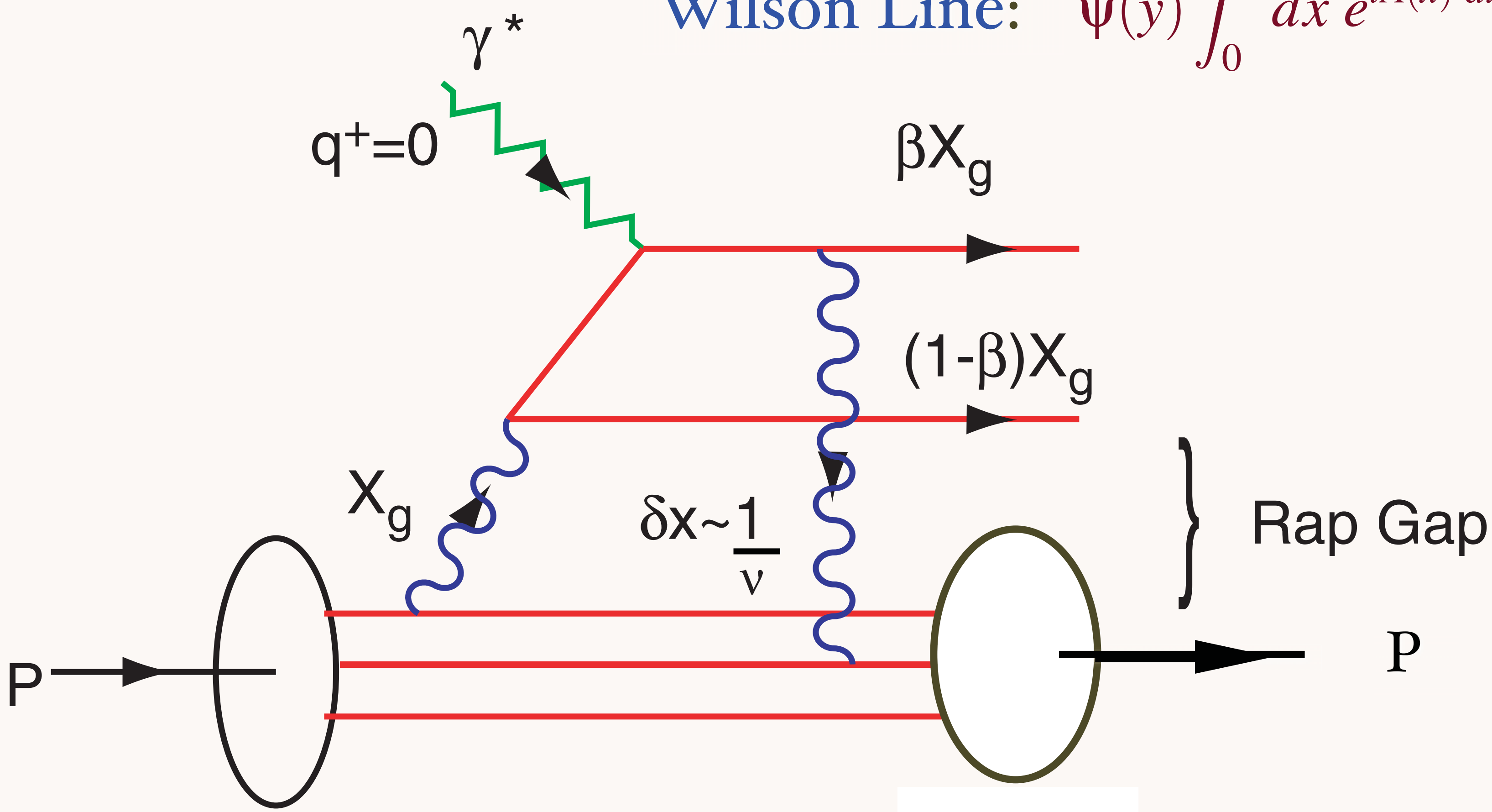
Hwang, Schmidt, SJB

Low-Nussinov model of Pomeron

Hoyer, Marchal, Peigne, Sannino, sjb

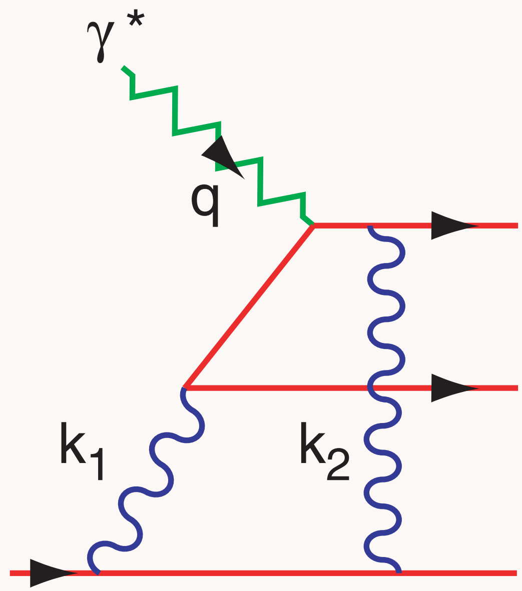
QCD Mechanism for Rapidity Gaps

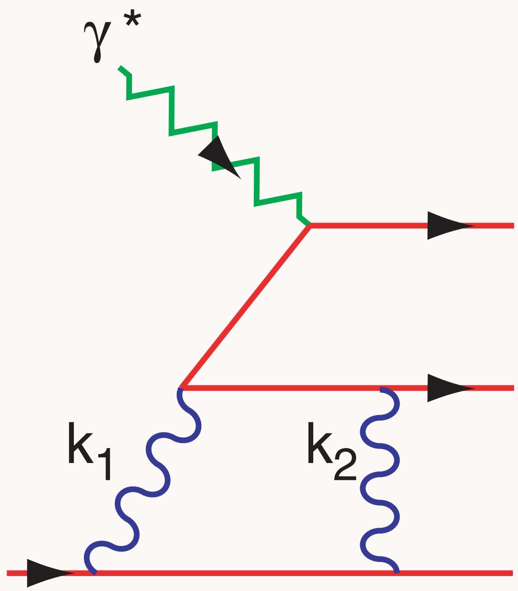
Wilson Line: $\overline{\psi}(y)\int_0^y dx\, e^{iA(x)\cdot dx}\,\psi(0)$



Reproduces lab-frame color dipole approach

Final State Interactions in QCD

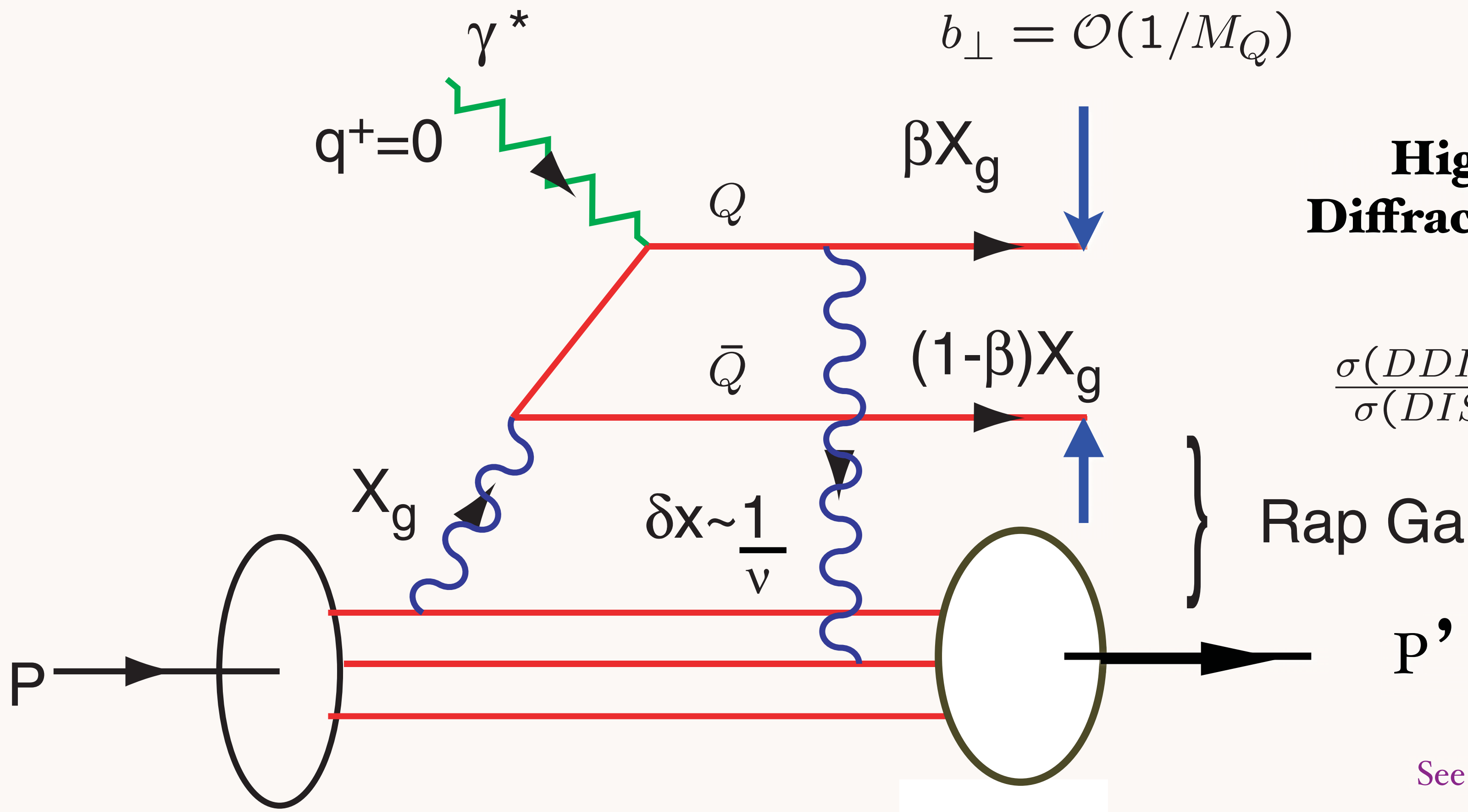




Feynman Gauge   Light-Cone Gauge

Result is Gauge Independent

Predict: Reduced DDIS/DIS for Heavy Quarks



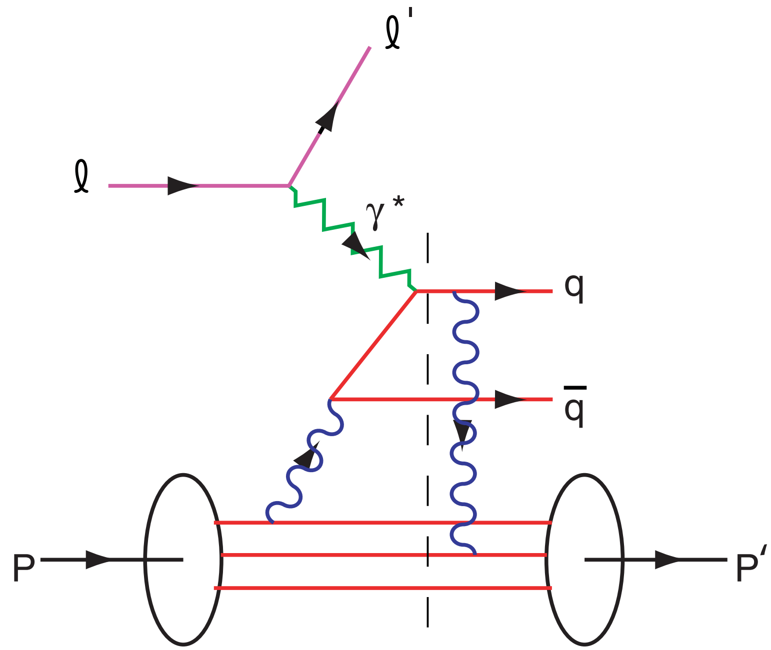
Higher Twist Diffraction Fraction

$$\frac{\sigma(DDIS)}{\sigma(DIS)} \simeq \frac{\Lambda^2_{QCD}}{M^2_Q}$$

See also: Bartels et al

Kopeliovitch, Schmidt, sjb

Reproduces lab-frame color dipole approach



Integration over on-shell domain produces phase i

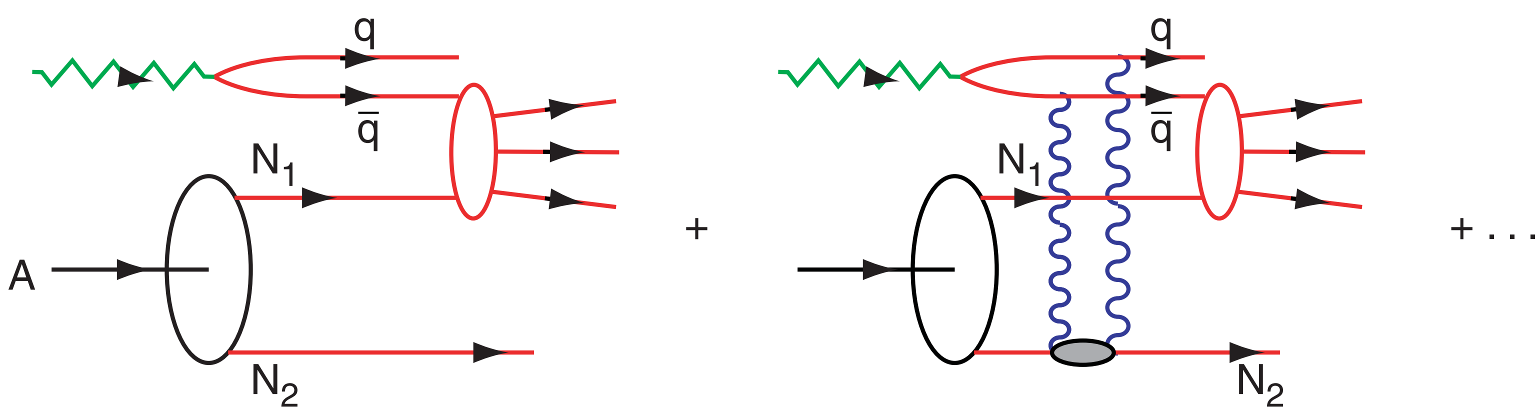
Need Imaginary Phase to Generate Pomeron and DDIS

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

Physics of FSI not in Wavefunction of Target

Stodolsky
Pumplin, sjb
Gribov

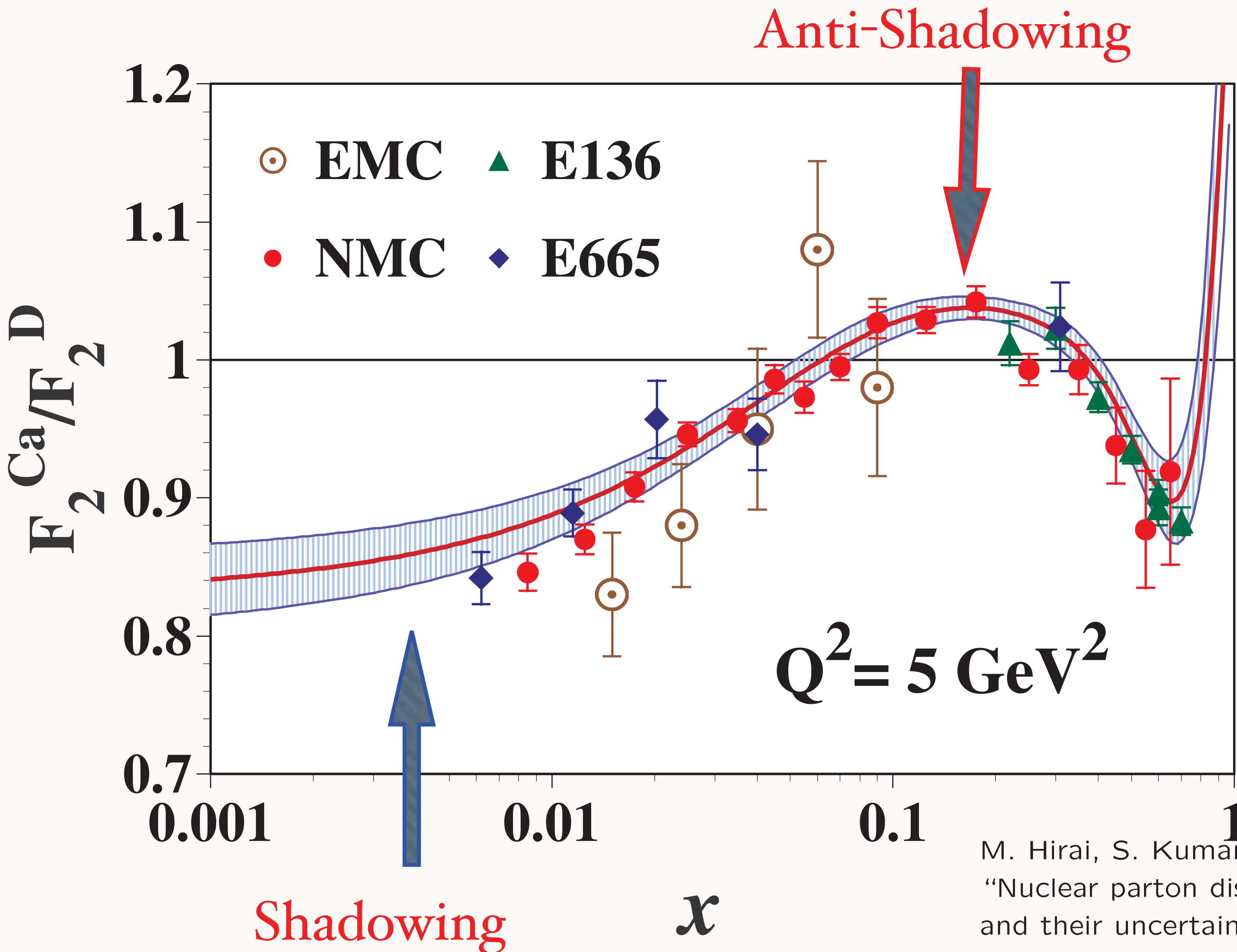
Nuclear Shadowing in QCD



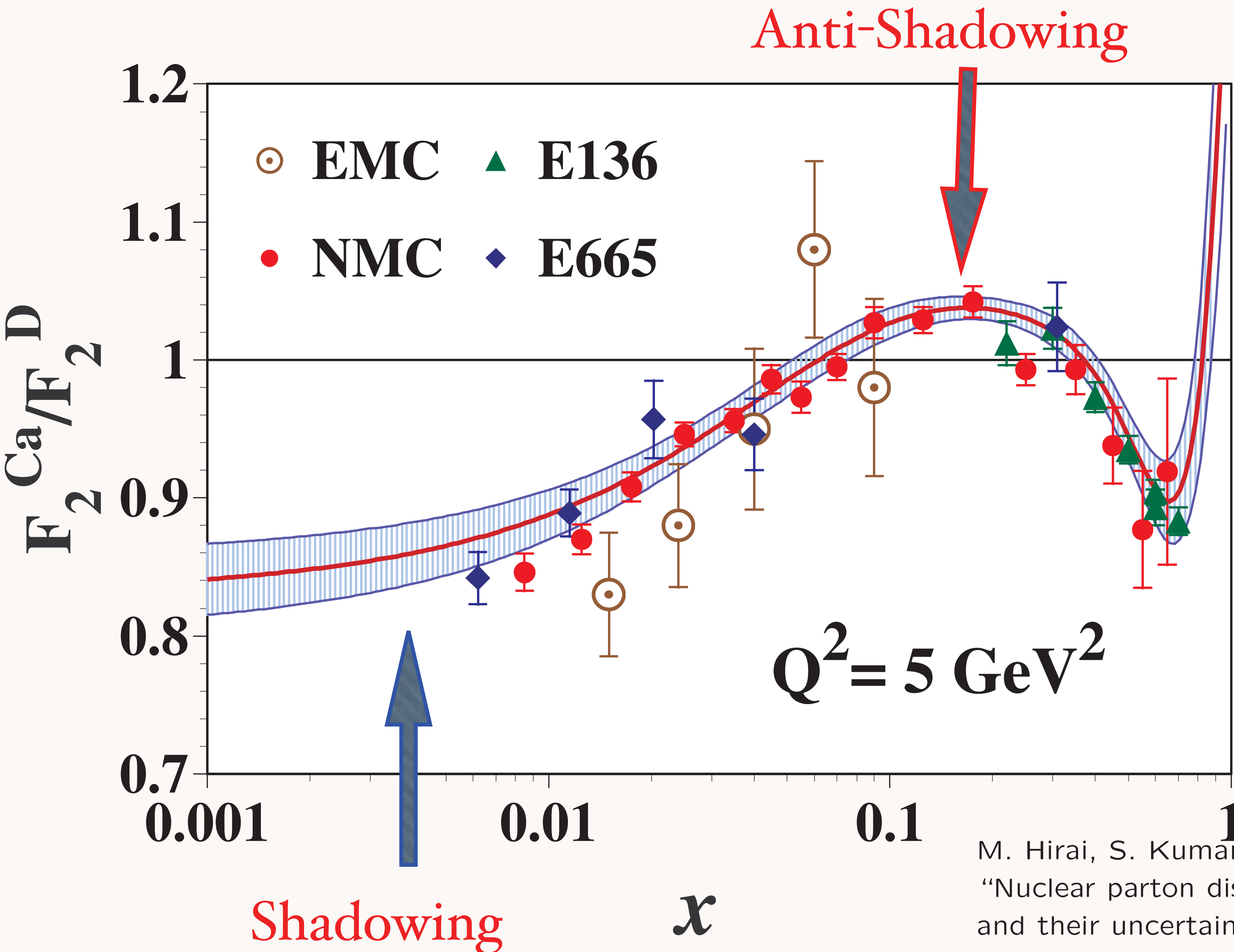
Shadowing depends on understanding leading twist-diffraction in DIS

Nuclear Shadowing not included in nuclear LFWF !

Dynamical effect due to virtual photon interacting in nucleus



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].



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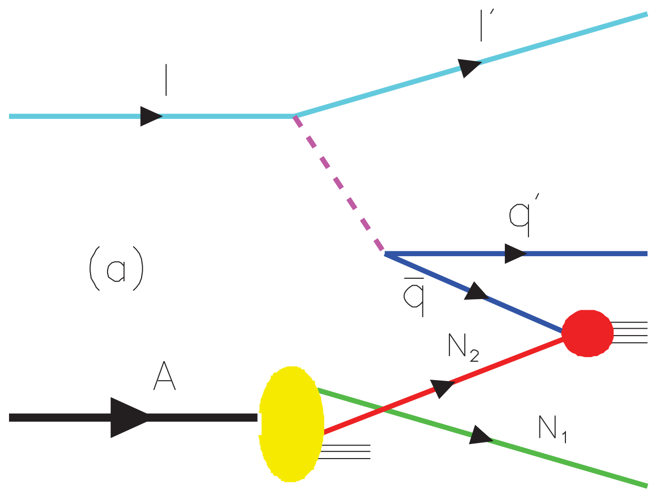
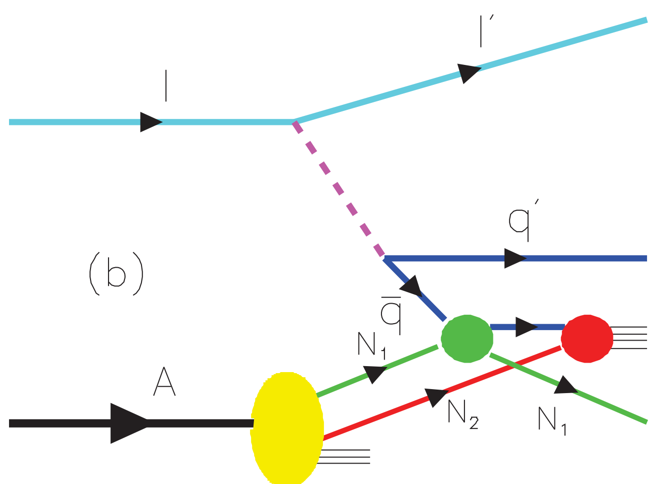


The one-step and two-step processes in DIS on a nucleus.

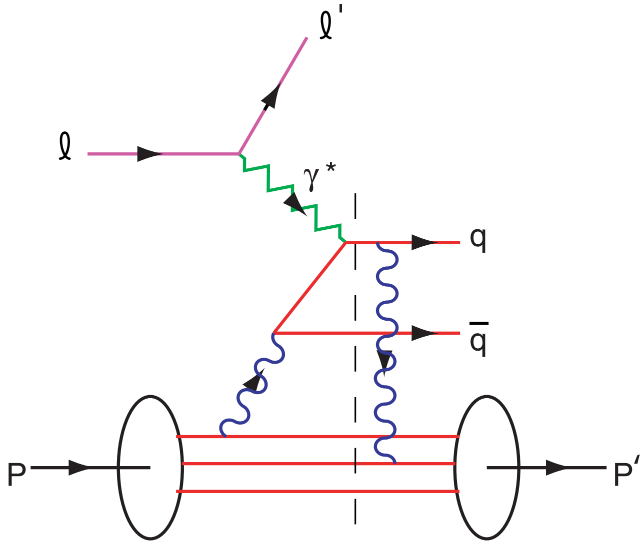
Coherence at small Bjorken x_B : $1/Mx_B = 2\nu/Q^2 \geq L_A$.



If the scattering on nucleon N_1 is via pomeron exchange, the one-step and two-step amplitudes are opposite in phase, thus diminishing the $\overline{q}$ flux reaching N_2.

$\rightarrow$ Shadowing of the DIS nuclear structure functions.

Observed HERA DDIS produces nuclear shadowing



Shadowing depends on leading-twist DDIS

Integration over on-shell domain produces phase i

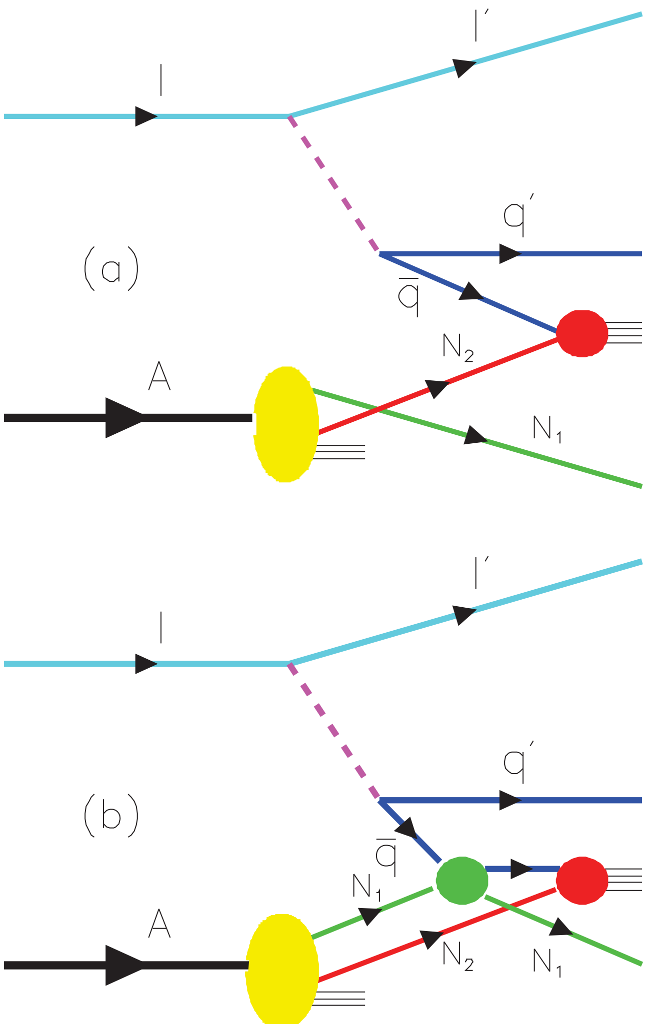
Need Imaginary Phase to Generate Pomeron

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



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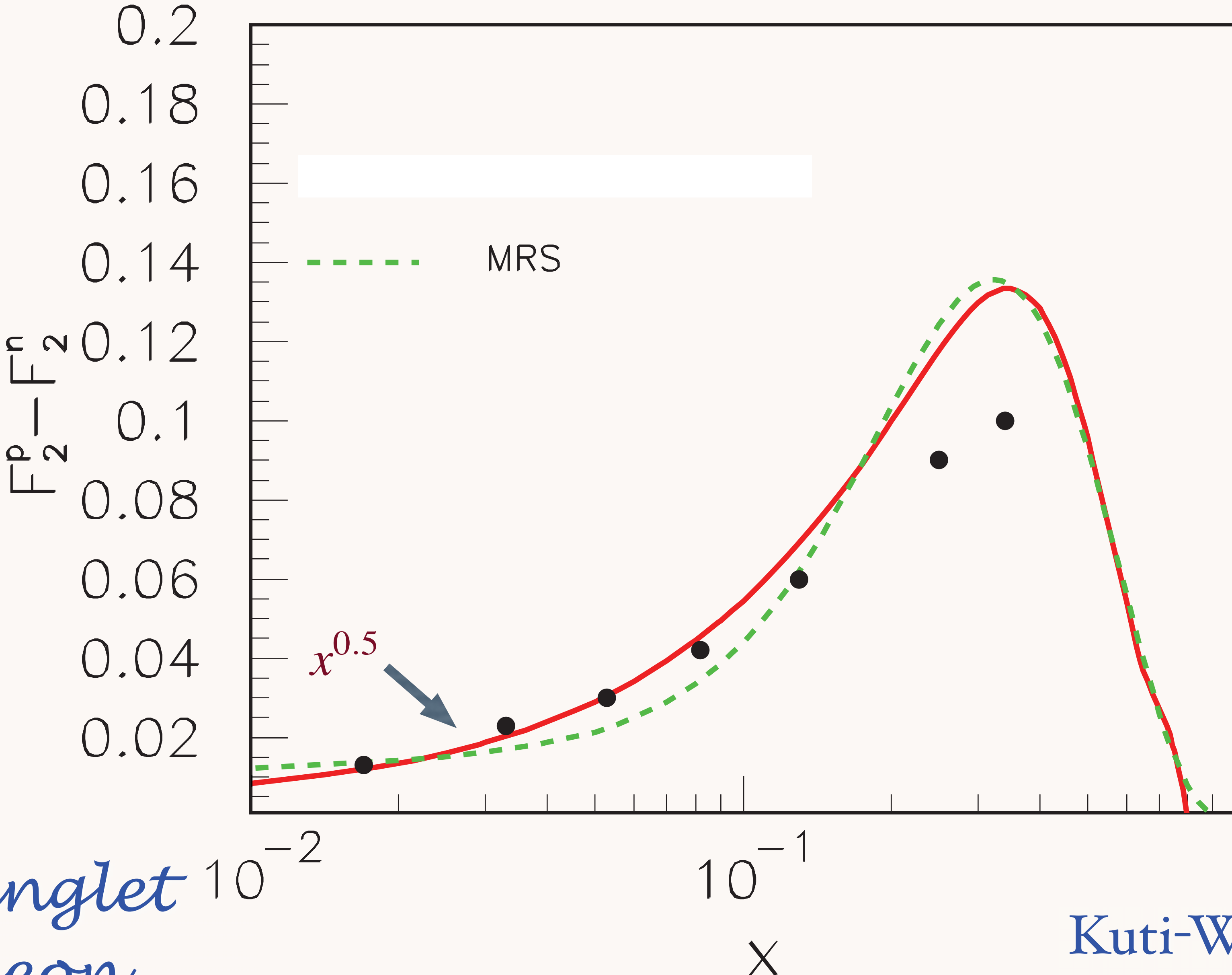
If the scattering on nucleon N_1 is via ~~pomeron~~ *Reggeon* exchange, the one-step and two-step amplitudes are ~~opposite~~ in phase, thus ~~diminishing~~ *increasing* the $\bar{q}$ flux reaching N_2.

→ ***Anti-*** Shadowing of the DIS nuclear structure functions.



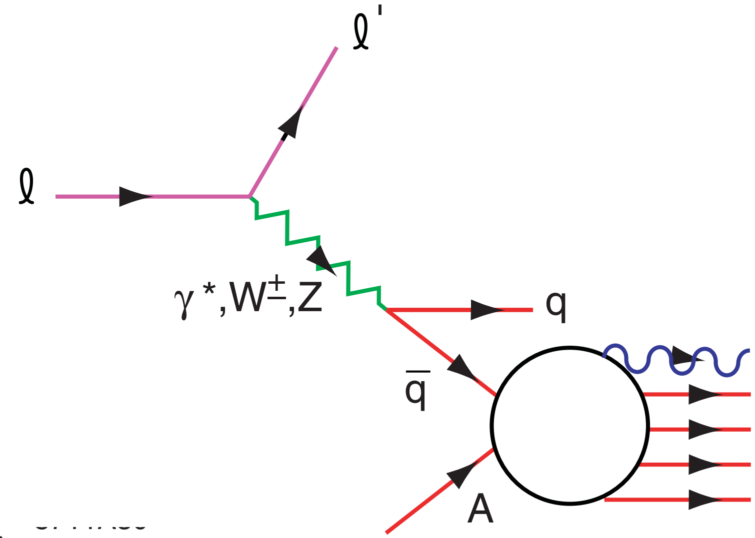
Non-singlet Reggeon Exchange

Kuti-Weisskopf behavior

Origin of Regge Behavior of Deep Inelastic Structure Functions

$$F_{2p}(x) - F_{2n}(x) \propto x^{1/2}$$

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:

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

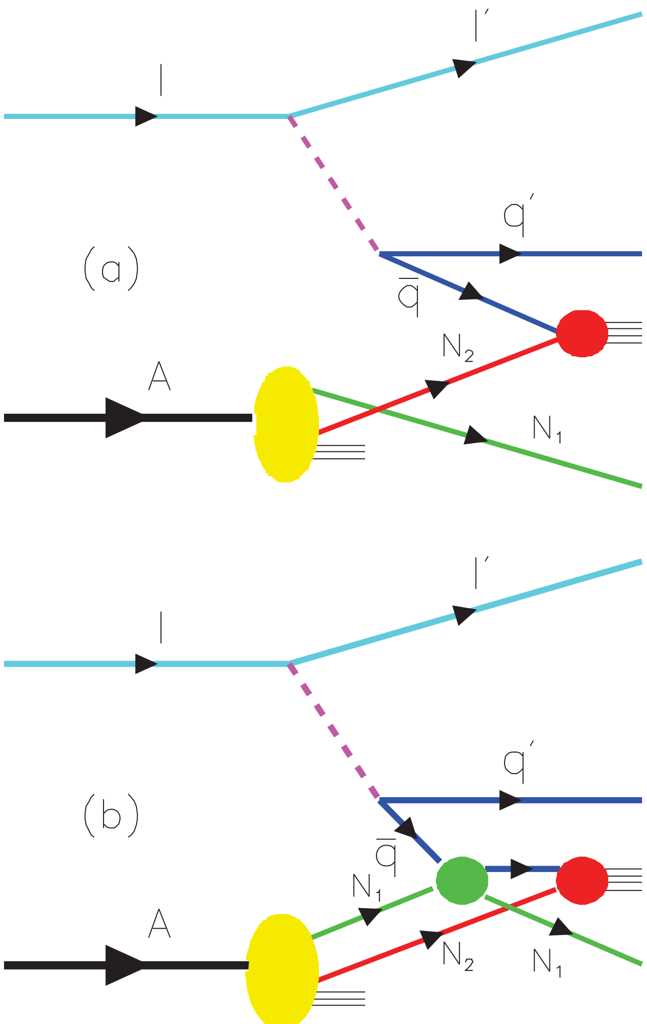
Constructive Interference

Depends on quark flavor!

Thus antishadowing is not universal

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

Critical test: Tagged Drell-Yan



The one-step and two-step processes in DIS on a nucleus.

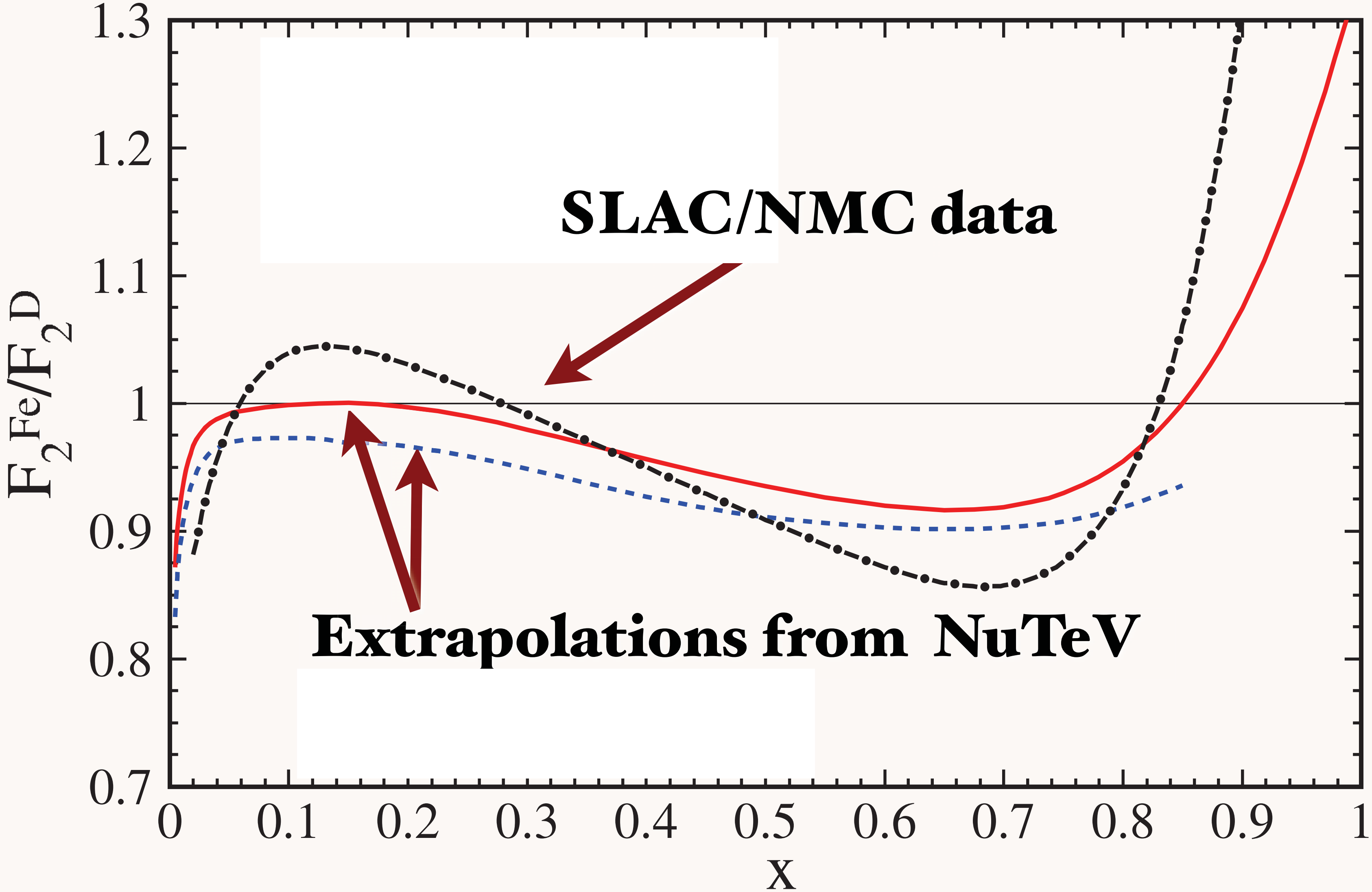
Coherence at small Bjorken x_B :
$1/Mx_B = 2\nu/Q^2 \geq L_A$.

Reggeon

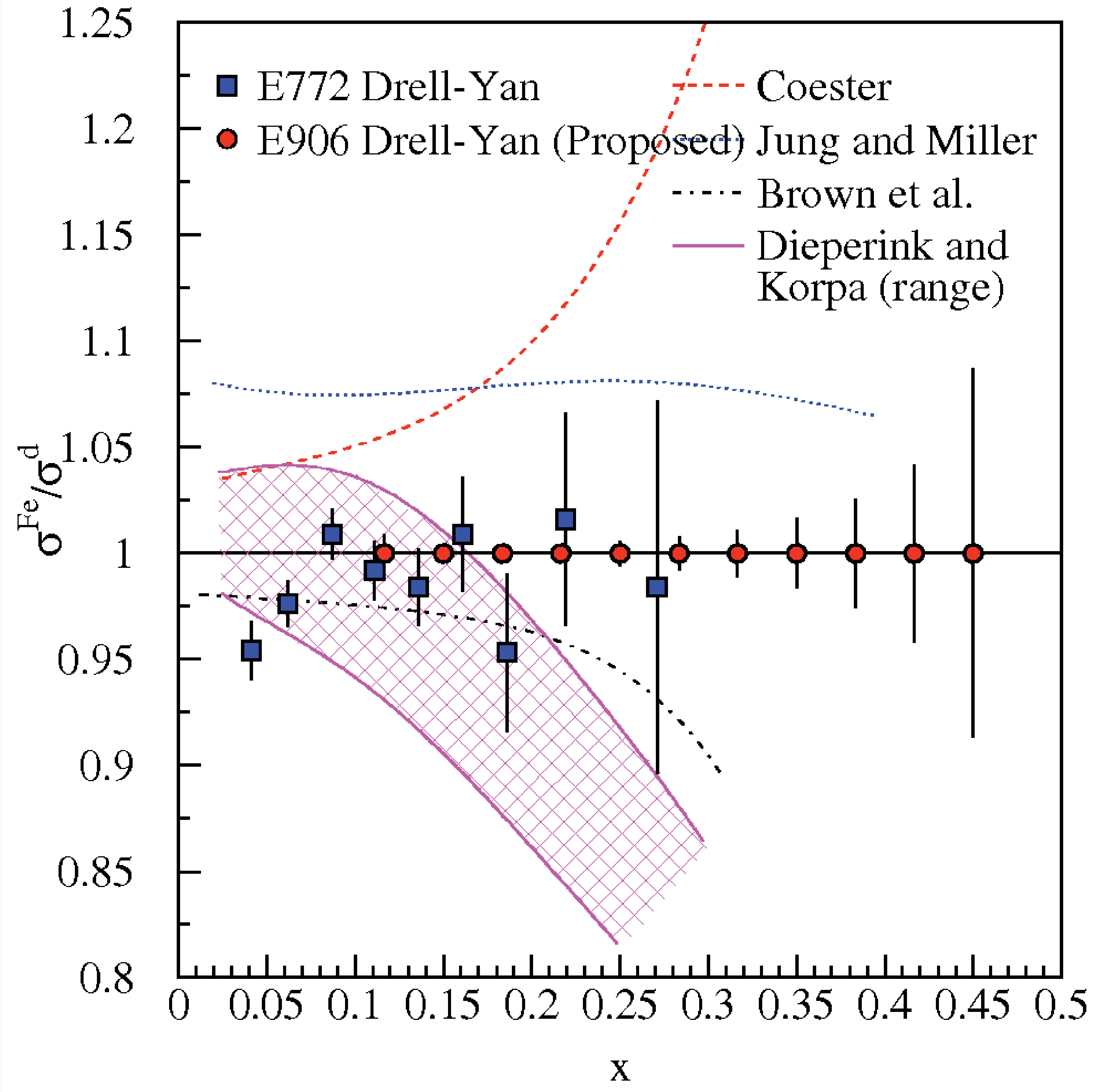
If the scattering on nucleon N_1 is via ~~pomeron~~ exchange, the one-step and two-step amplitudes are ~~opposite~~ in phase, thus ~~diminishing~~ the $\bar{q}$ flux reaching N_2. *increasing*

→ *Anti-* Shadowing of the DIS nuclear structure functions.

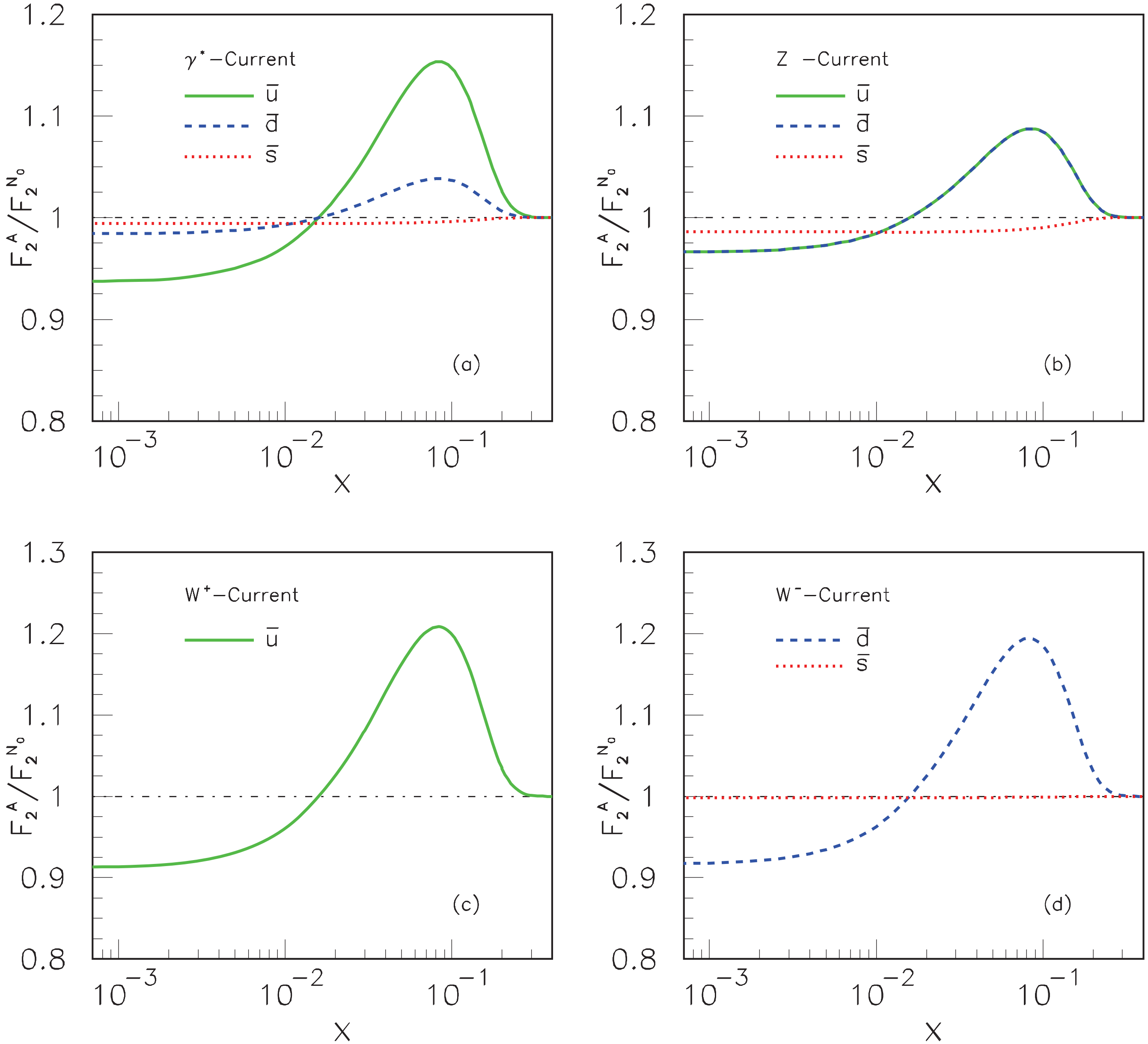
$$Q^2 = 5\ \mathrm{GeV}^2$$



Scheinbein, Yu, Keppel, Morfin, Olness, Owens



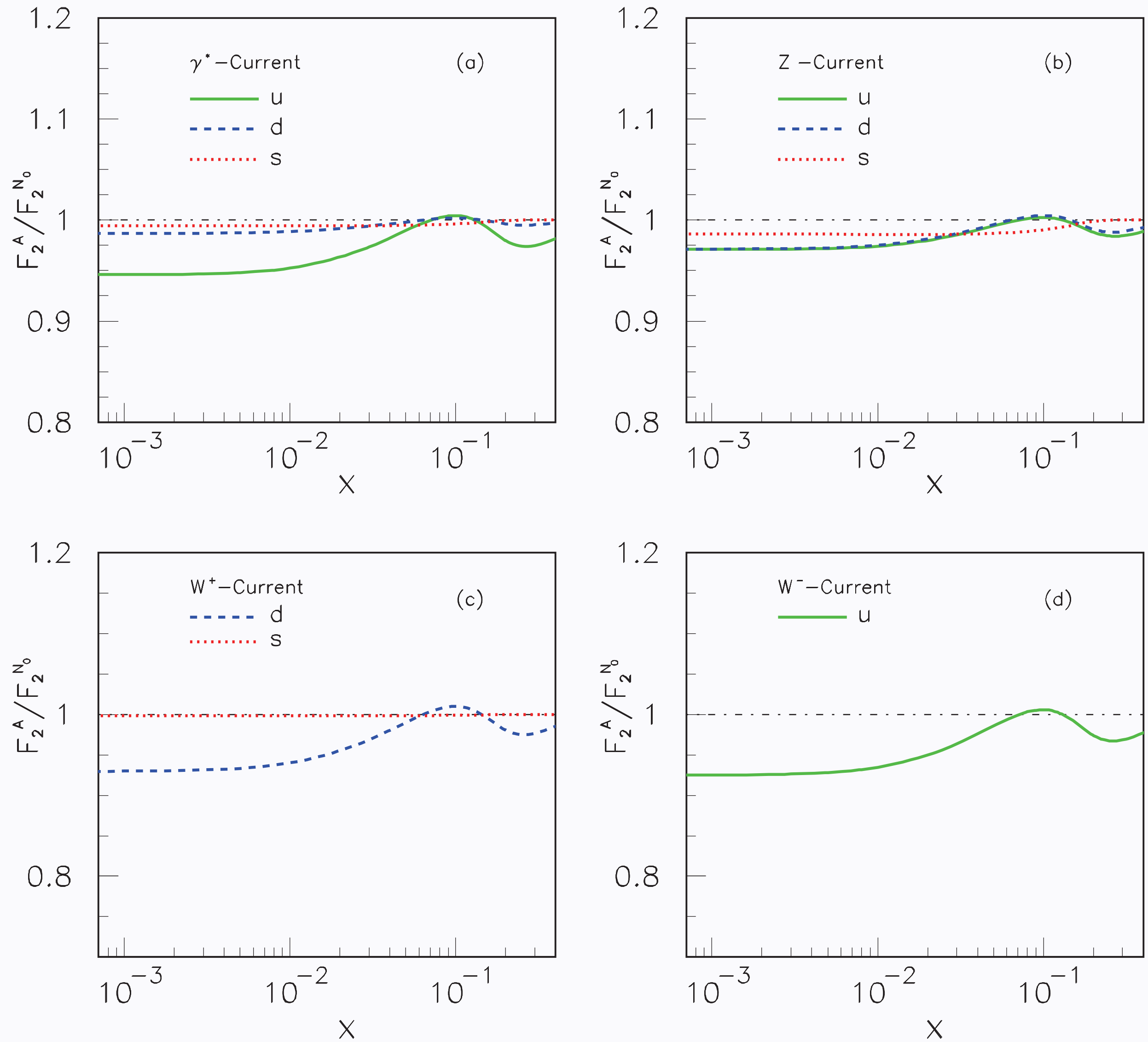
E772 Drell-Yan
E906 Drell-Yan (Proposed)
Coester
Jung and Miller
Brown et al.
Dieperink and Korpa (range)
σ^{Fe}/σ^{d}
x
1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5



Schmidt, Yang; sjb

Nuclear Antishadowing not universal !

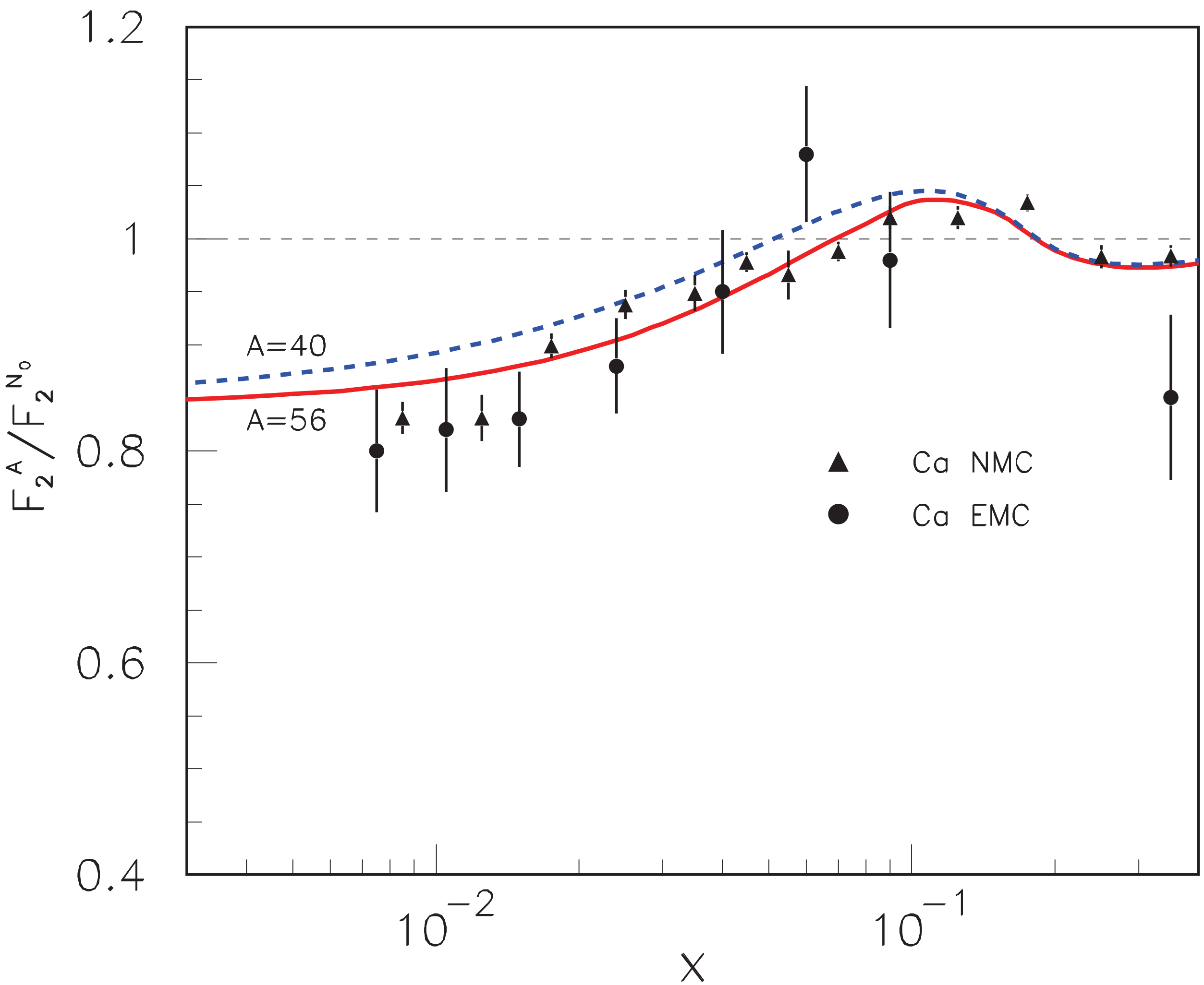
Shadowing and Antishadowing of DIS Structure Functions



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 $Q^2 = 1\ \mathrm{GeV}^2$

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].

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 !

Jian-Jun Yang
Ivan Schmidt
Hung Jung Lu
sjb

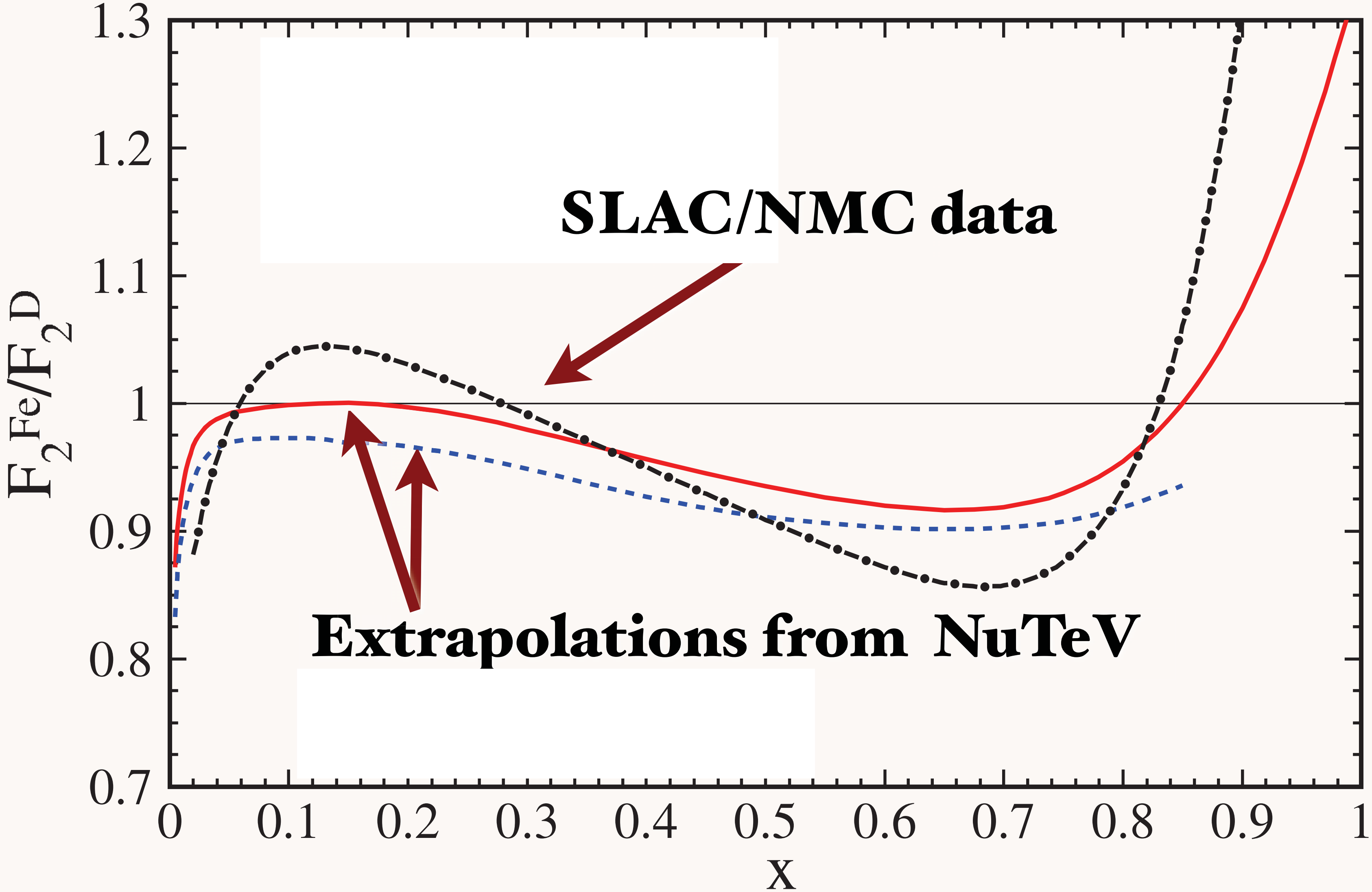
Can explain NuTeV result

We emphasize that the nuclear antishadowing of the different currents is not universal since it depends on the different quark species.

Nuclear antishadowing in neutrino deep inelastic scattering.
Stanley J. Brodsky (SLAC), Ivan Schmidt (Santa Maria U., Valparaiso), Jian-Jun Yang (Santa Maria U., Valparaiso & Regensburg U. & Nanjing Normal U.). SLAC-PUB-9677, USM-TH-136. Aug 2004. 36 pp.
Published in **Phys.Rev. D70 (2004) 116003**
e-Print: **hep-ph/0409279**

Many phenomenological tests

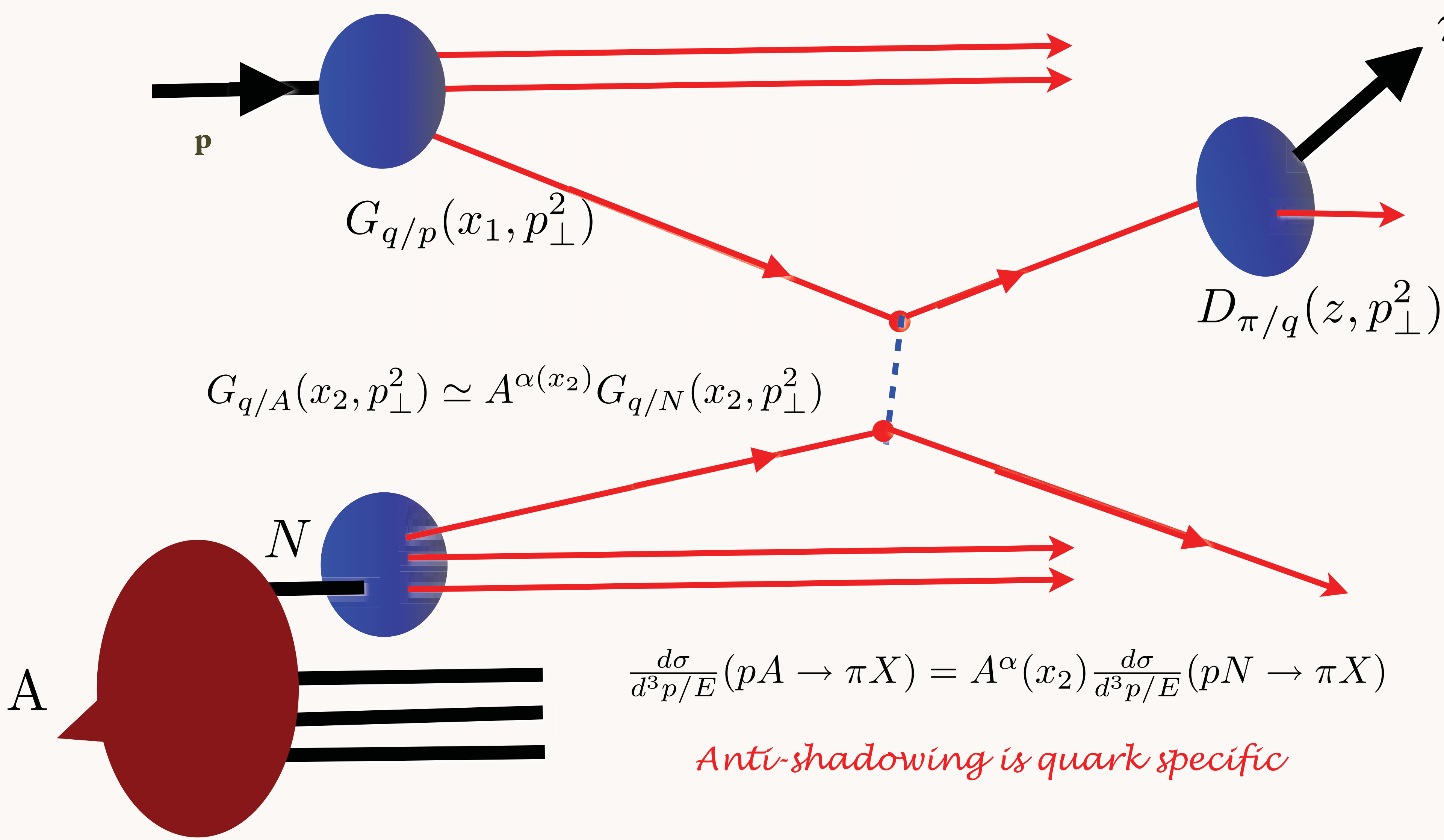
$$Q^2 = 5\ \text{GeV}^2$$



Scheinbein, Yu, Keppel, Morfin, Olness, Owens

LHC p-A Collisions

Leading-Twist Contribution to Hadron Production on Nuclei



$$\frac{d\sigma}{d^3p/E}(pA \to \pi X) = A^{\alpha}(x_2) \frac{d\sigma}{d^3p/E}(pN \to \pi X)$$

Anti-shadowing is quark specific

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

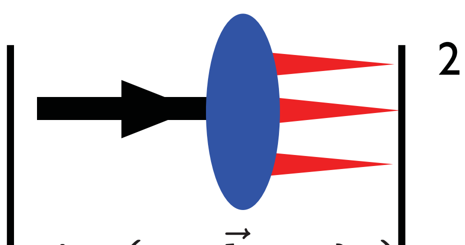
Hwang, Schmidt, sjb,

Mulders, Boer

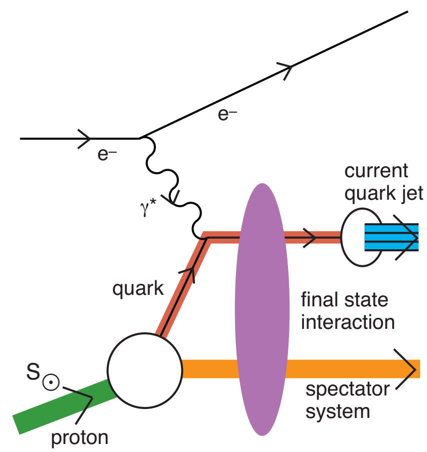
Qiu, Sterman

Collins, Qiu

Pasquini, Xiao, Yuan, sjb



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



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

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

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

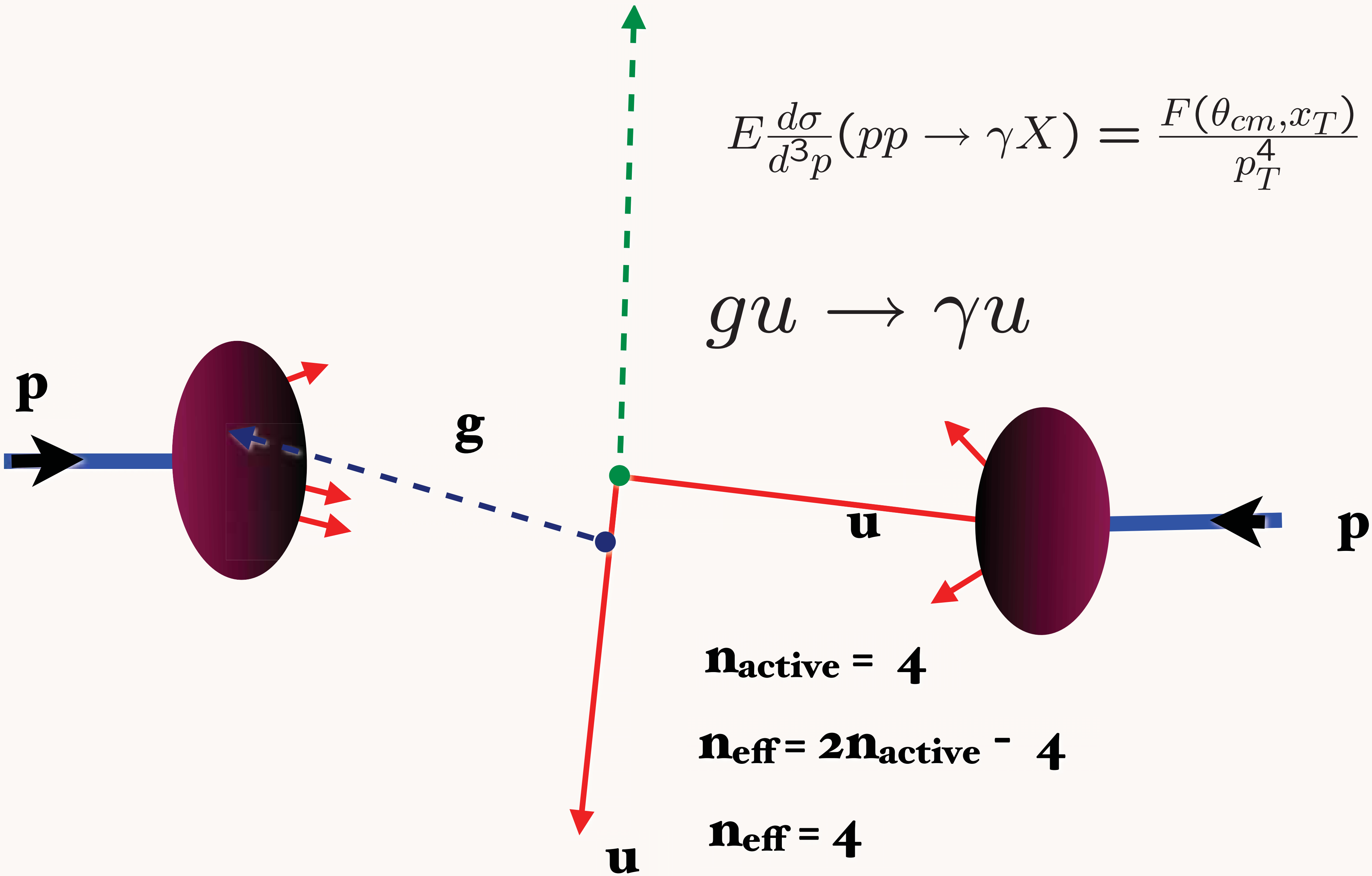
Parton model: $n_{eff} = 4$

As fundamental as Bjorken scaling in DIS

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

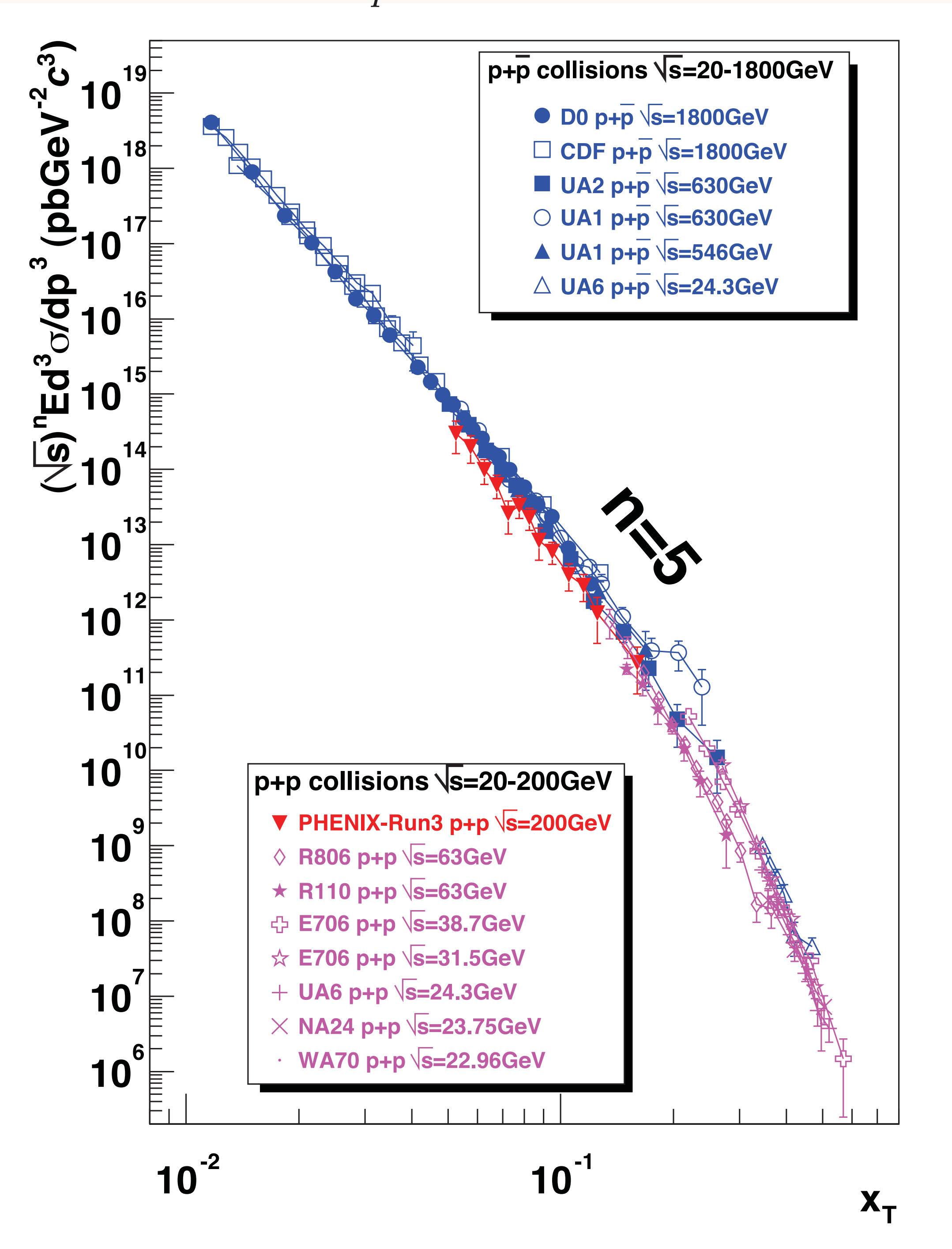
$$pp \longrightarrow \gamma X$$

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



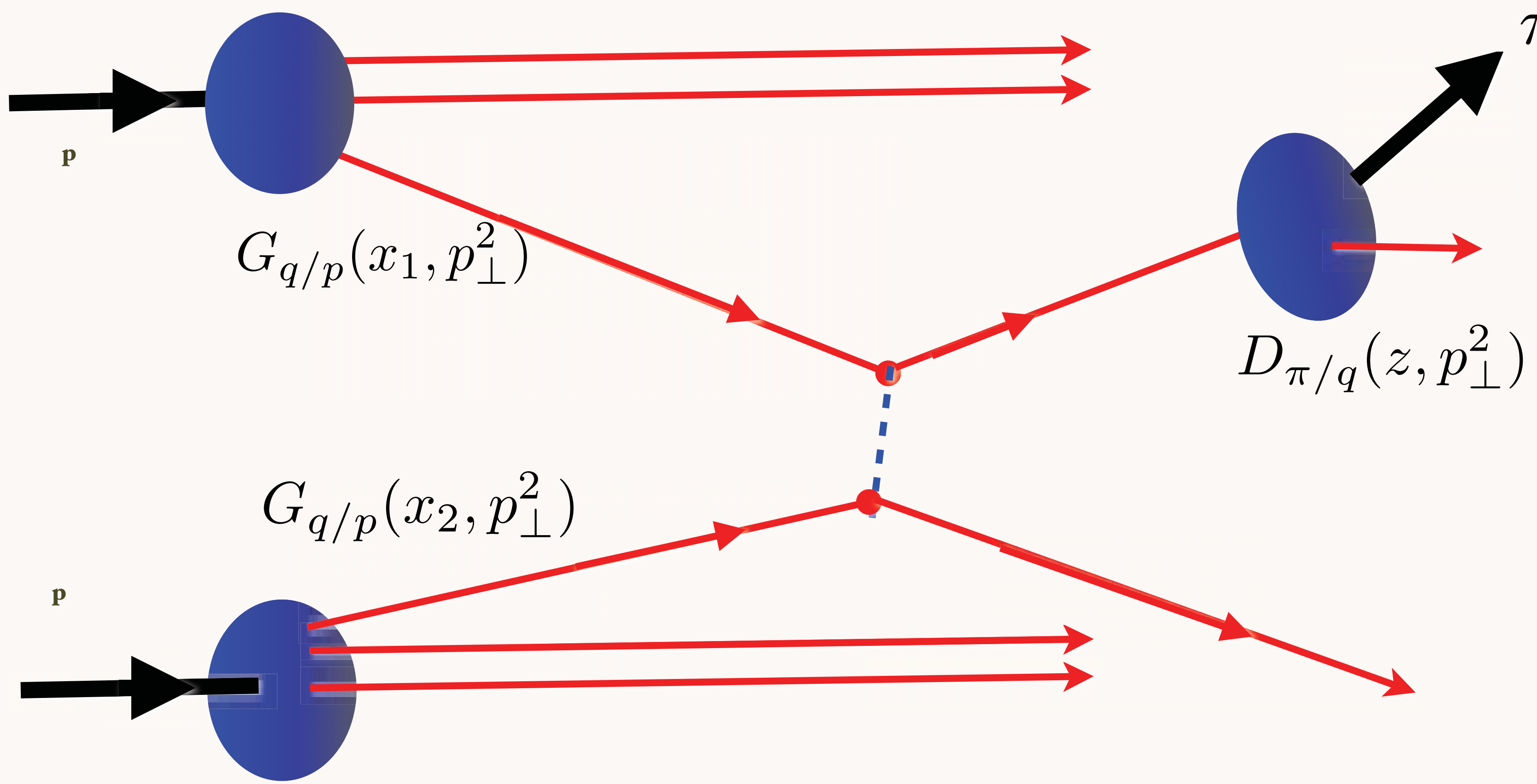
$\sqrt{s}^n E \frac{d\sigma}{d^3p}(pp \to \gamma X)$ at fixed x_T

Tannenbaum



x_T-scaling of direct photon production: consistent with PQCD

Leading-Twist Contribution to Hadron Production

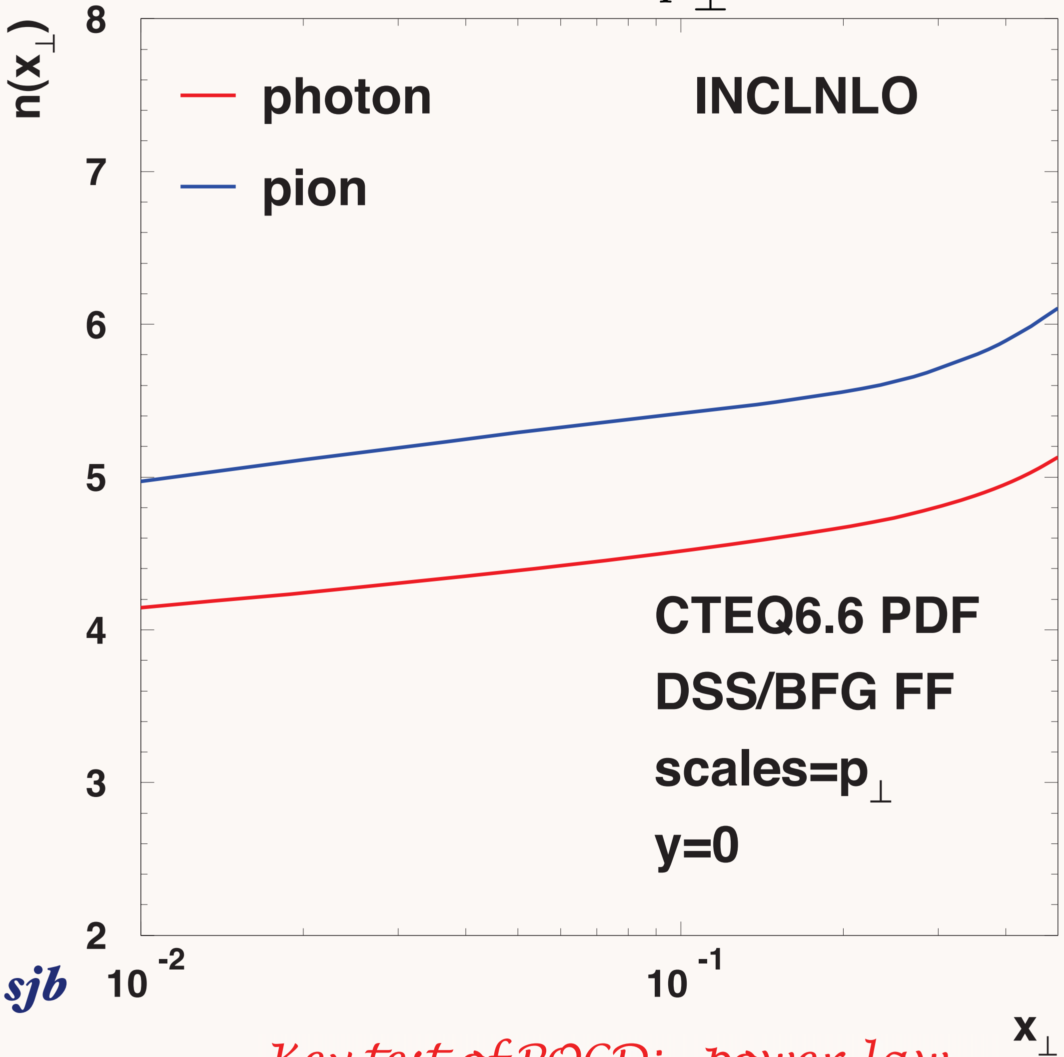


Parton model and Conformal Scaling:

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

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

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



$pp \to \pi X$

$pp \to \gamma X$

$5 < p_\perp < 20\ GeV$

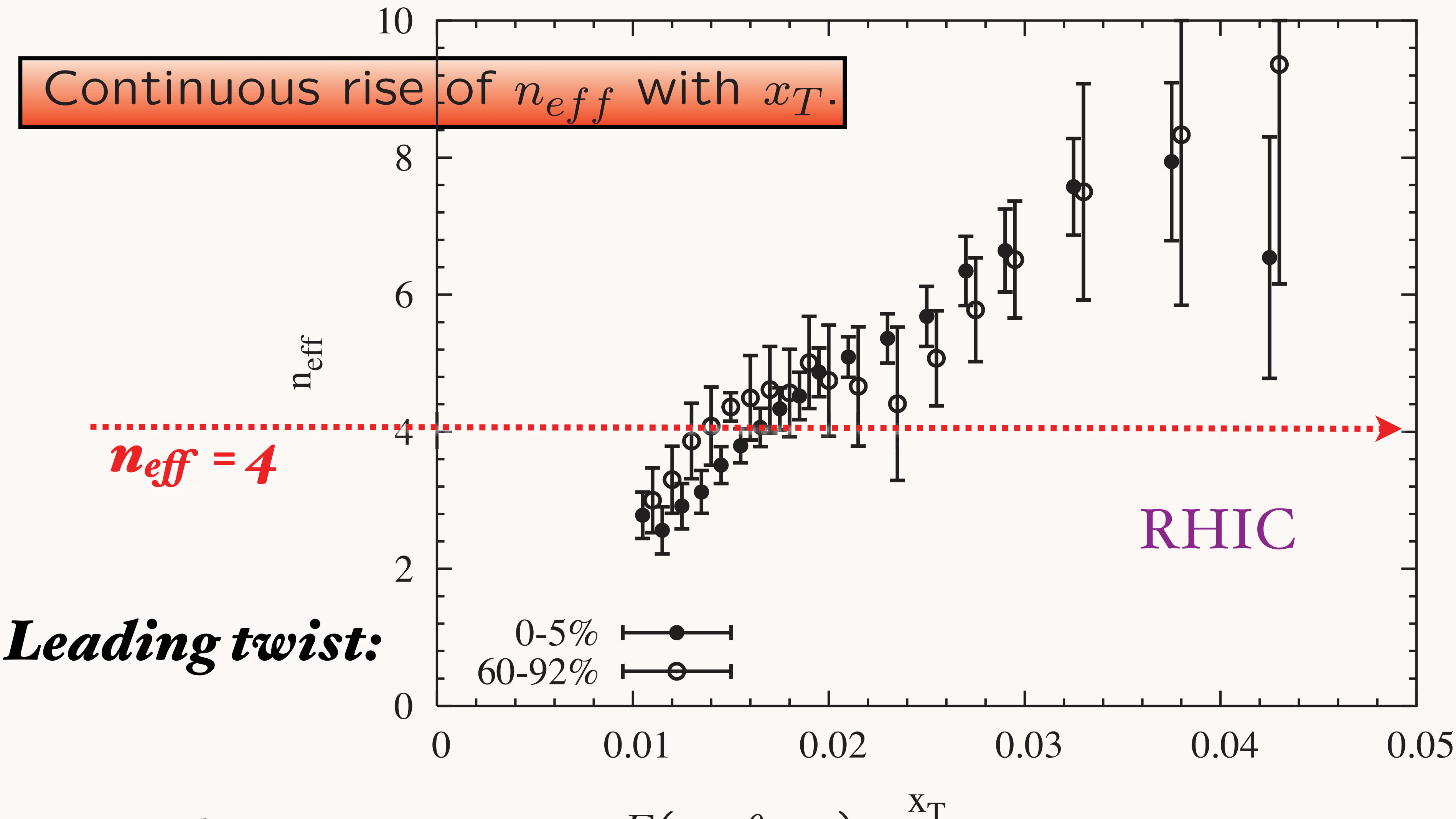
$70\ GeV < \sqrt{s} < 4\ TeV$

Arleo, Hwang, Sickles, sjb

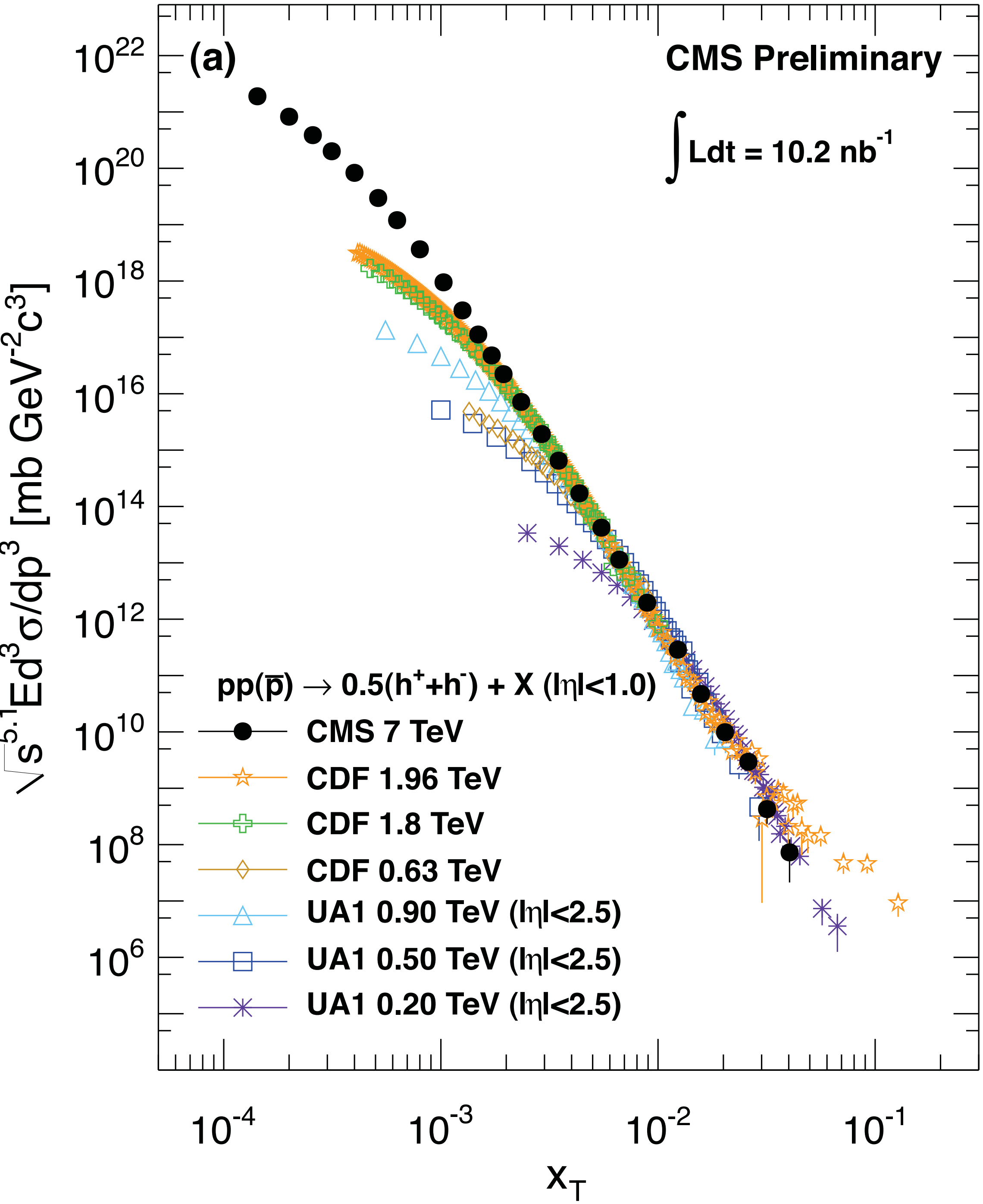
Pirner, Raufeisen, sjb

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

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.



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



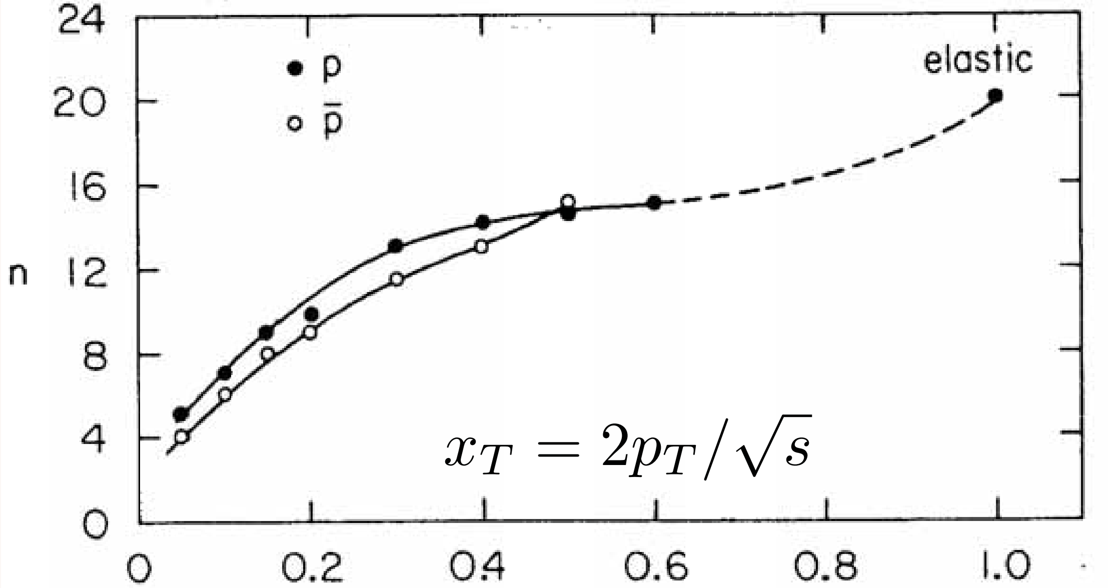
Jet-triggered charged particle transverse momentum spectra in pp collisions at 7 TeV

The CMS Collaboration

x_T scaling fails

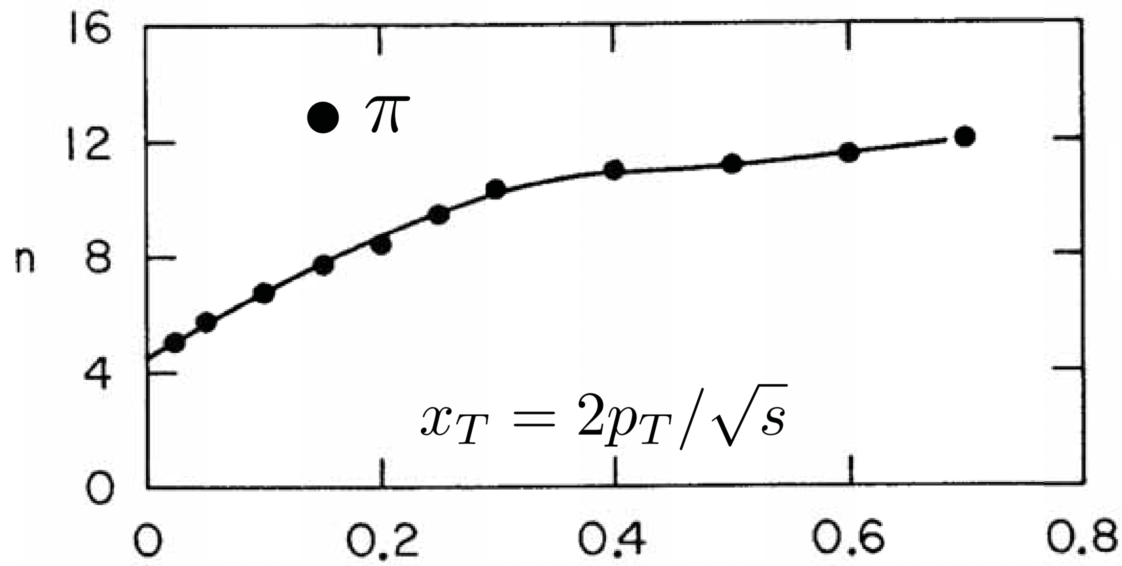
Inclusive invariant cross sections, scaled by $\sqrt{s}^{5.1}$

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



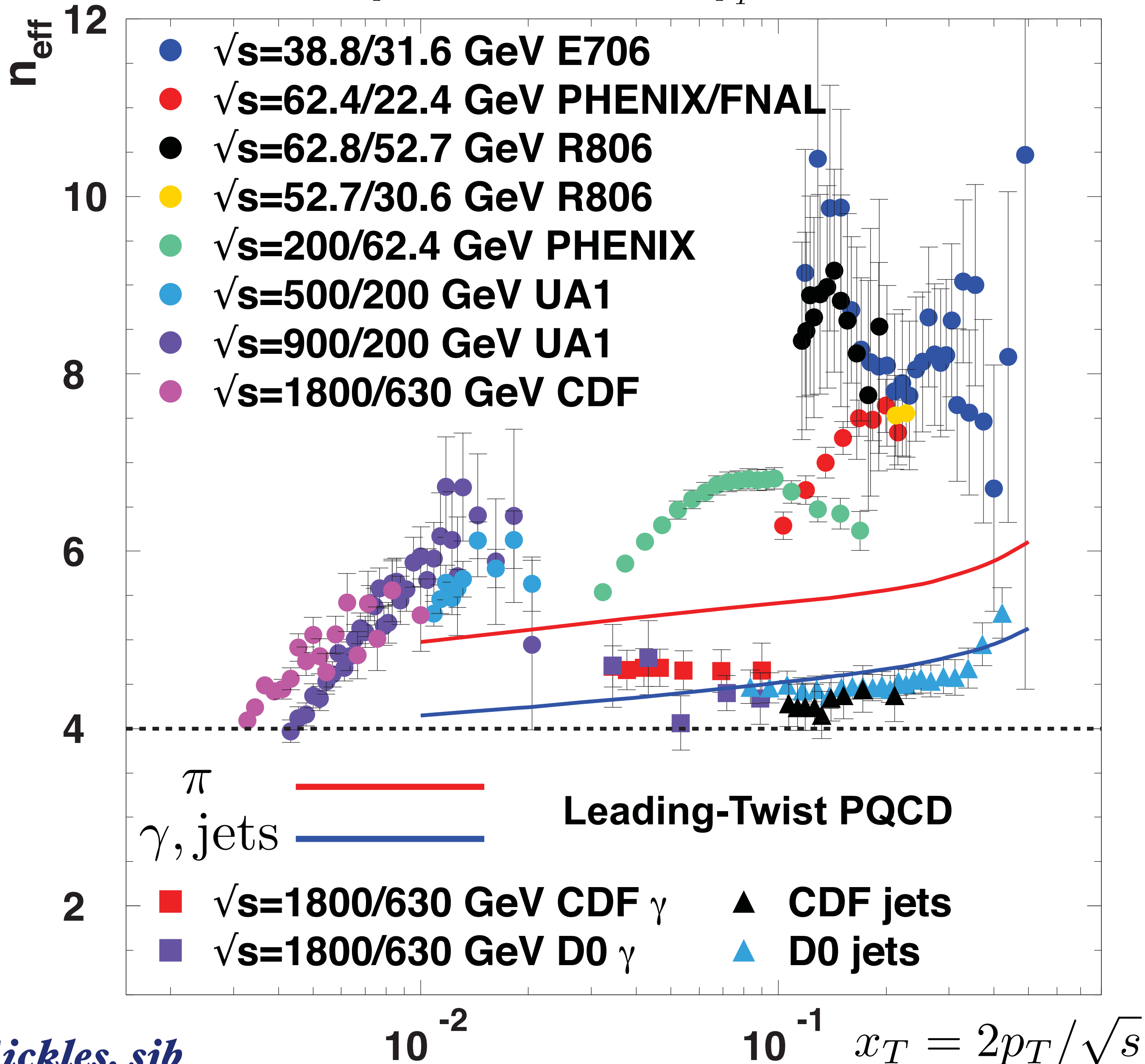
Clear evidence for higher-twist contributions

J. W. Cronin, SSI 1974

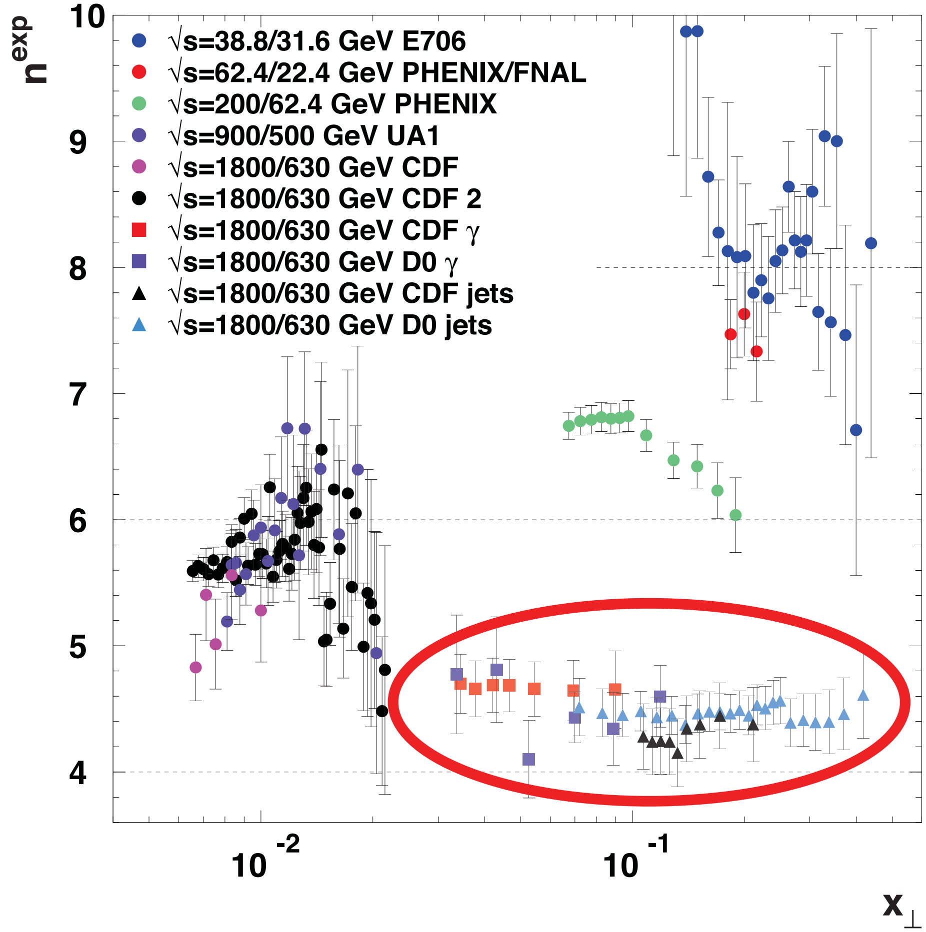


Chicago-Princeton FNAL

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



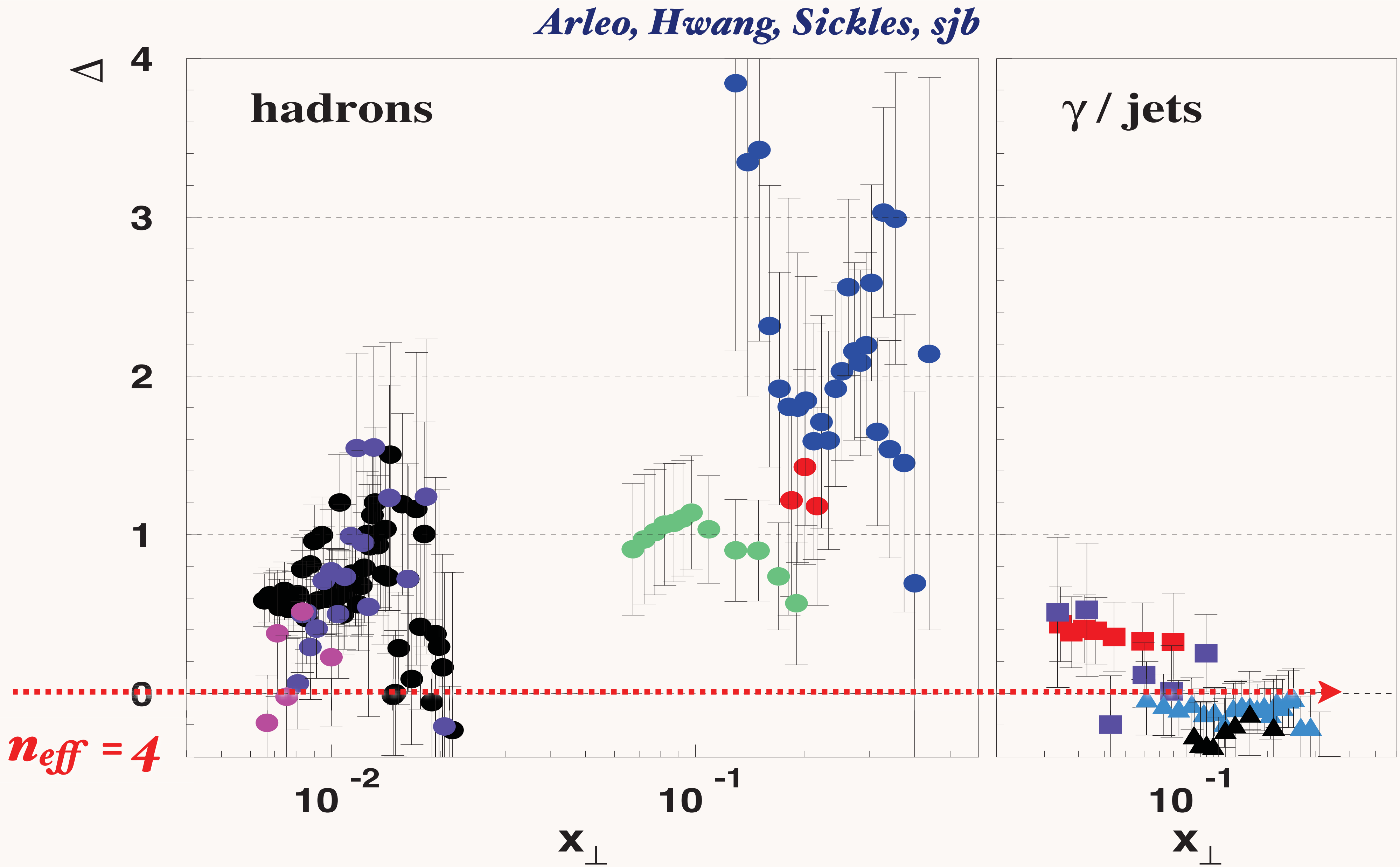
Arleo, Hwang, Sickles, sjb



Photons and Jets agree with PQCD x_T scaling

Hadrons do not!

- Significant increase of the hadron $n^{\rm exp}$ 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 $x_\perp$



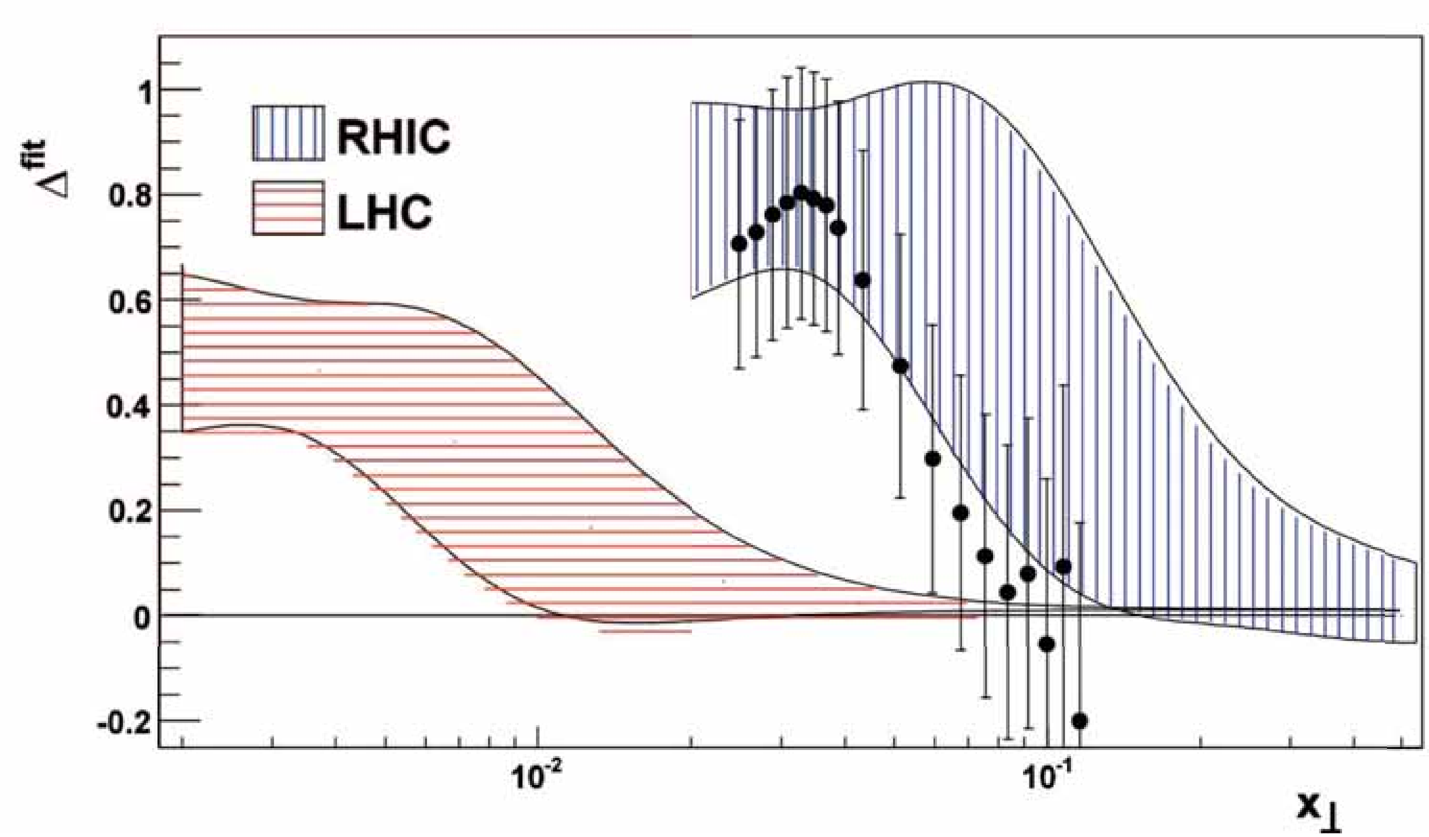
$$\Delta(x_\perp) = n^{\rm exp}(x_\perp) - n^{\rm NLO}(x_\perp)$$

RHIC/LHC predictions

PHENIX results

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

[A. Bezilevsky, APS Meeting]



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

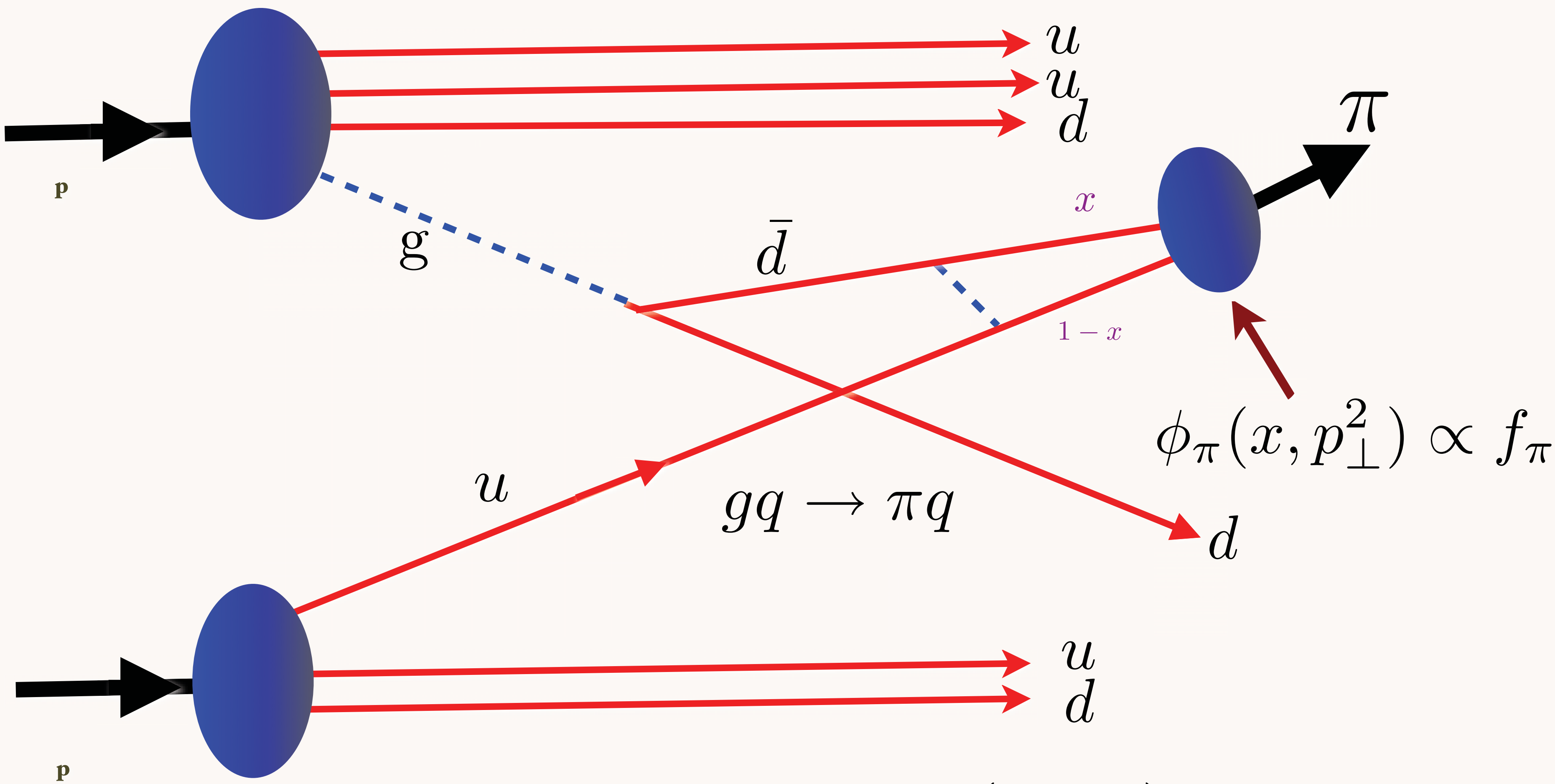
Direct Higher Twist Processes

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

$$\phi_H(x_i, Q)$$

- Satisfies ERBL evolution

Direct Contribution to Hadron Production

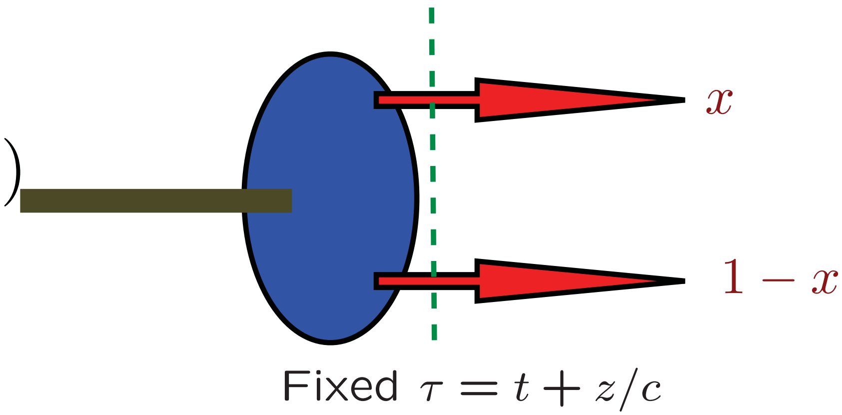


$$\frac{d\sigma}{d^3p/E} = \alpha_s^3 f_\pi^2 \frac{F(x_\perp, y)}{p_\perp^6}$$

No Fragmentation Function

Hadron Distribution Amplitudes

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



$$\sum_i x_i = 1$$

$k_\perp^2 < Q^2$

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

Lepage, Huang, sjb

Efremov, Radyushkin

- Evolution Equations from PQCD, OPE,

Sachrajda, Frishman Lepage, sjb
Braun, Gardi

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

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

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

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

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

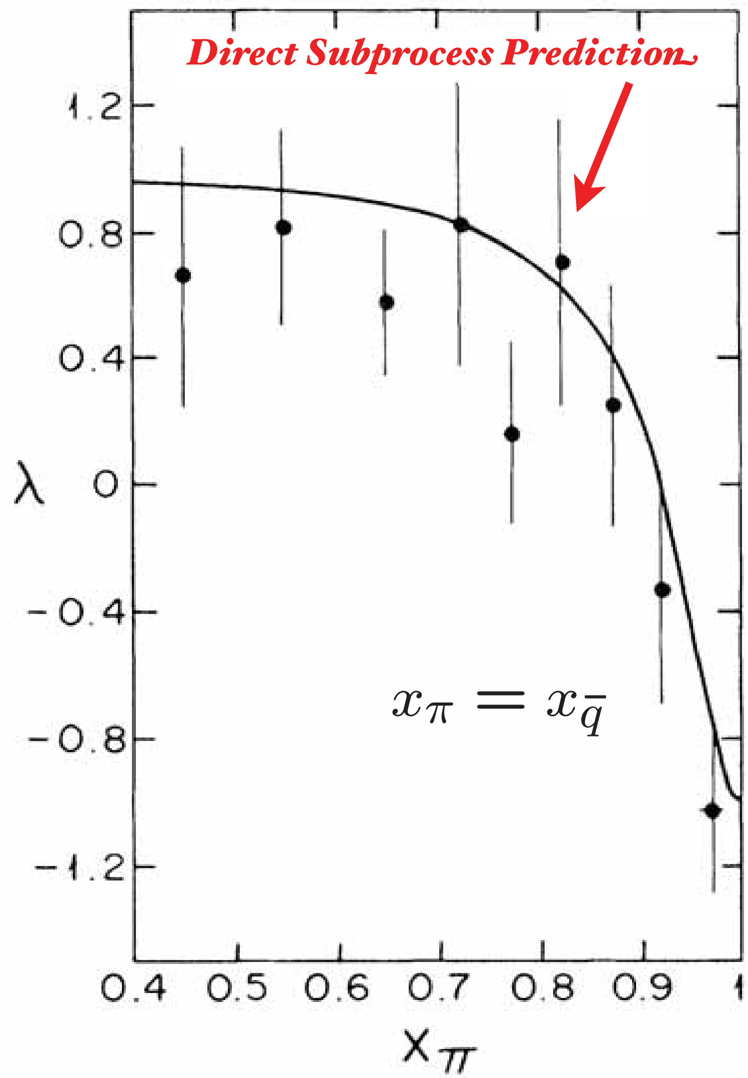
$$Q^2 = M^2$$

Text

Dramatic change in angular distribution at large x

$$x_\pi = x_{\bar{q}}$$

Example of a higher-twist direct subprocess



Chicago-Princeton Collaboration

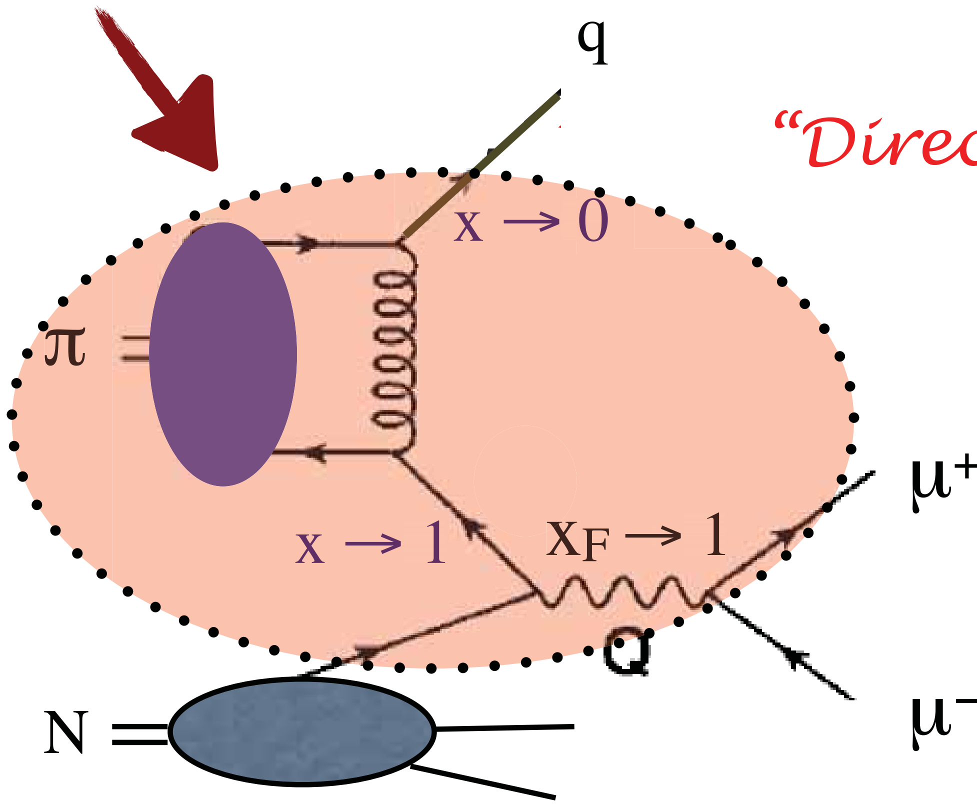
Phys.Rev.Lett.55:2649,1985

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

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

Distribution amplitude from AdS/CFT

Entire pion wf contributes to hard process



"Direct" Subprocess

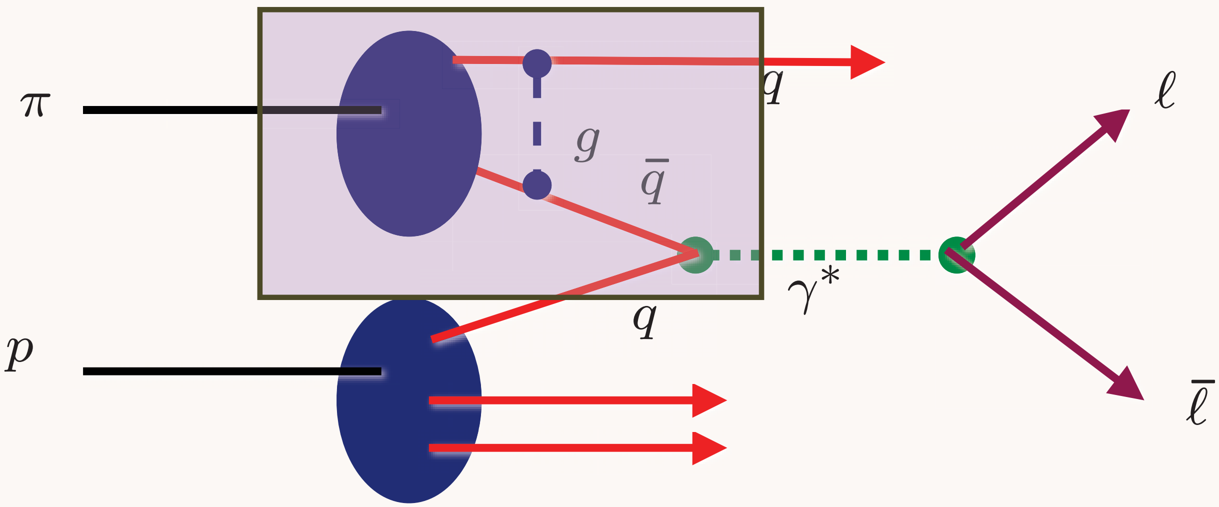
Virtual photon is longitudinally polarized

Similar higher twist terms in jet hadronization at large z

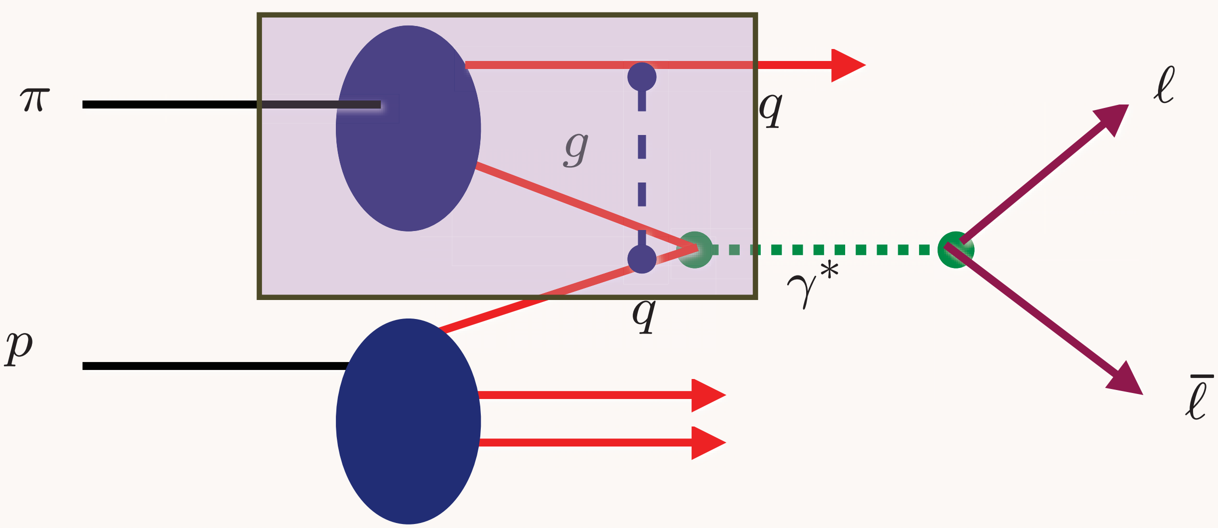
Berger, sjb
Khoze, Brandenburg, Muller, sjb

Hoyer Vanttinen

Berger, Lepage, sjb



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



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

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

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

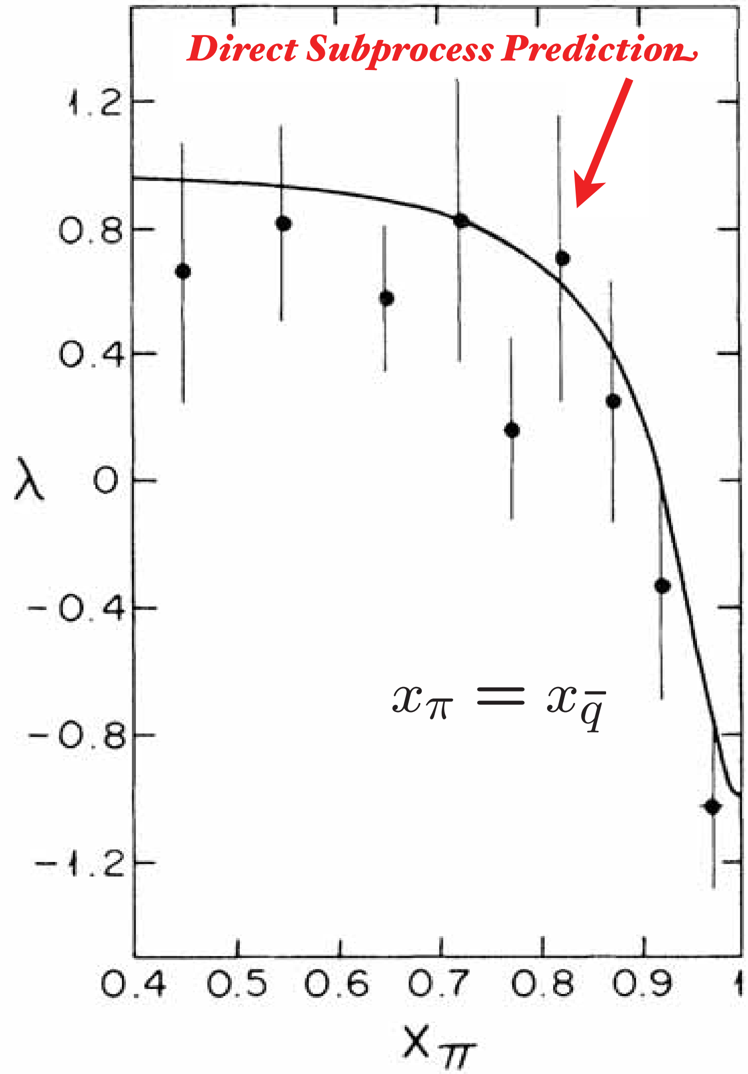
$$\frac{d^2\sigma}{dx_\pi d\cos\theta} \propto x_\pi \left[(1-x_\pi)^2 (1+\cos^2\theta) + \frac{4}{9} \frac{\langle k_T^2 \rangle}{M^2} \sin^2\theta \right]$$

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

$$Q^2 = M^2$$

Dramatic change in angular distribution at large x_F

Example of a higher-twist direct subprocess

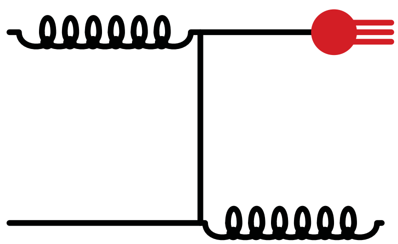


Chicago-Princeton Collaboration

Phys.Rev.Lett.55:2649,1985

Scaling laws in inclusive pion production

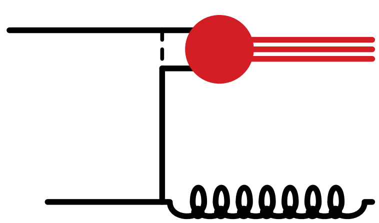
- Conventional pQCD picture (leading twist): $2 \to 2$ process followed by fragmentation into a pion on long time scales



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

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

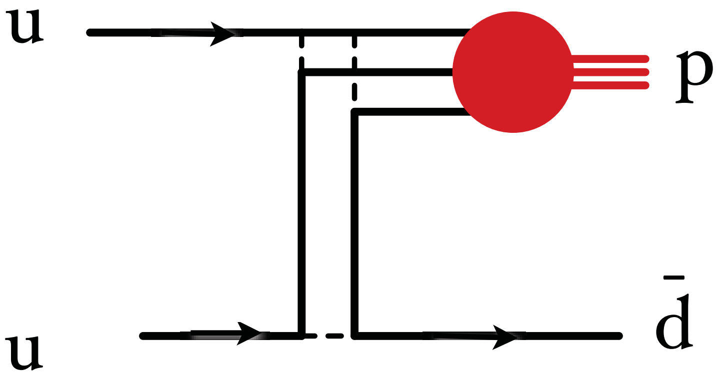
- Direct higher-twist picture: pion produced directly in the hard process



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

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

Direct Proton Production



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

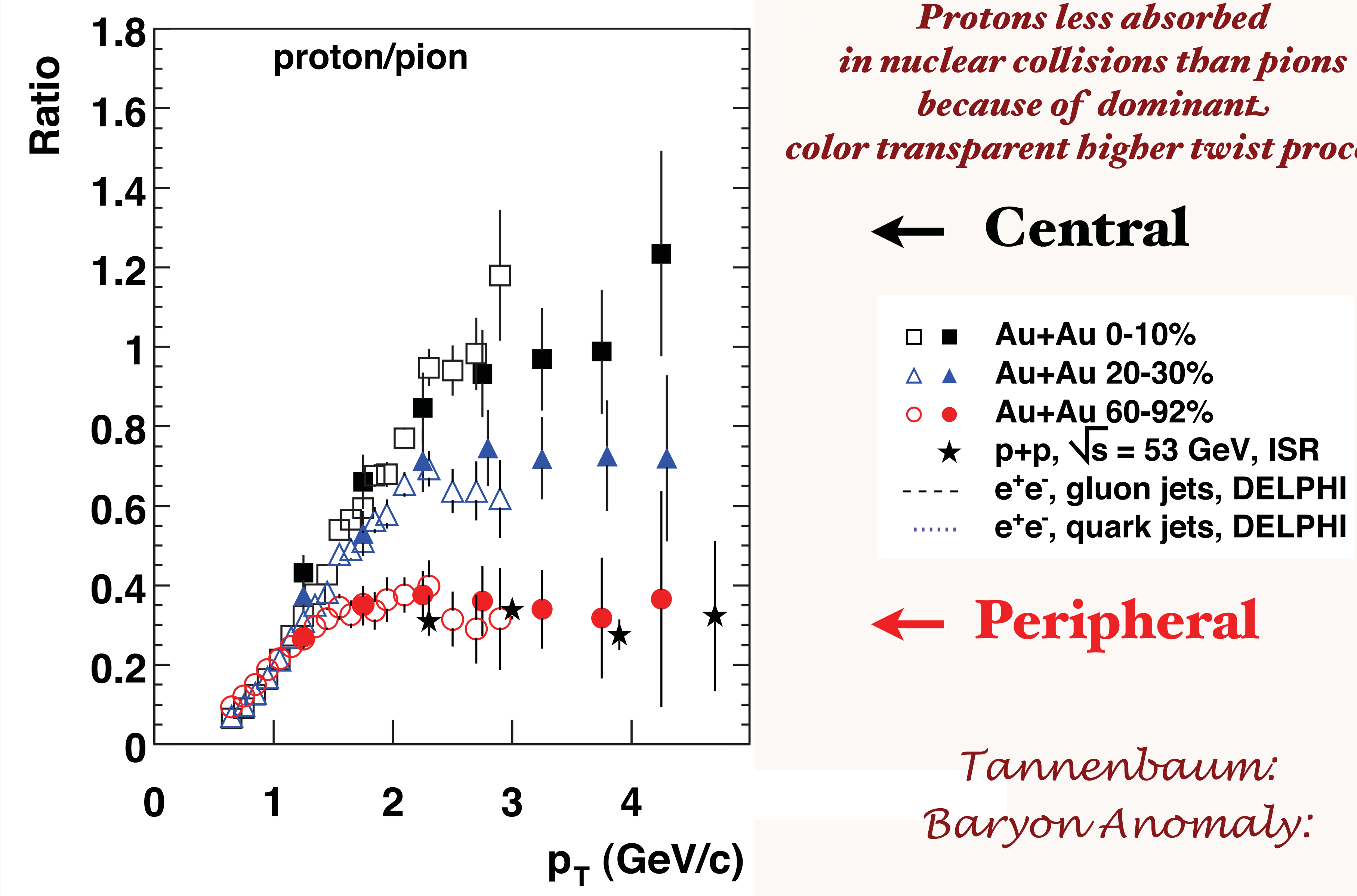
$$E \frac{d\sigma}{d^3p}(p\ p \to p\ X) \sim \frac{F(x_\perp, \vartheta^{\rm cm})}{p_\perp^8}$$

Explains "Baryon anomaly" at RHIC!

Sickles, sjb

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

Particle ratio changes with centrality!



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

← **Central**

← **Peripheral**

Tannenbaum: Baryon Anomaly:

Baryon can be made directly within hard subprocess!

Coalescence within hard subprocess

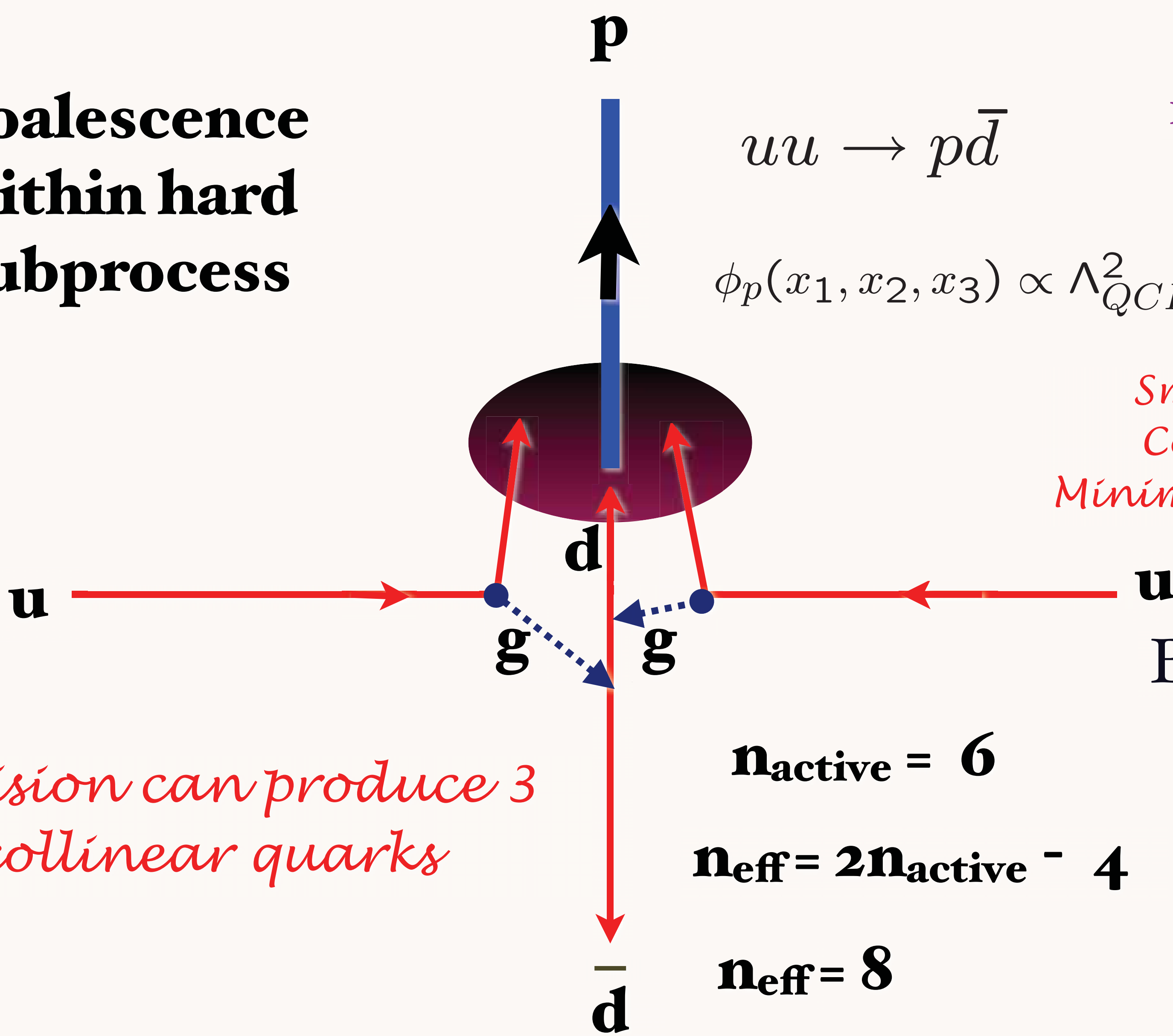
Bjorken
Blankenbecler, Gunion, sjb
Berger, sjb
Hoyer, et al: Semi-Exclusive

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

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

Sickles; sjb

Small color-singlet
Color Transparent
Minimal same-side energy



Baryon anomaly

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

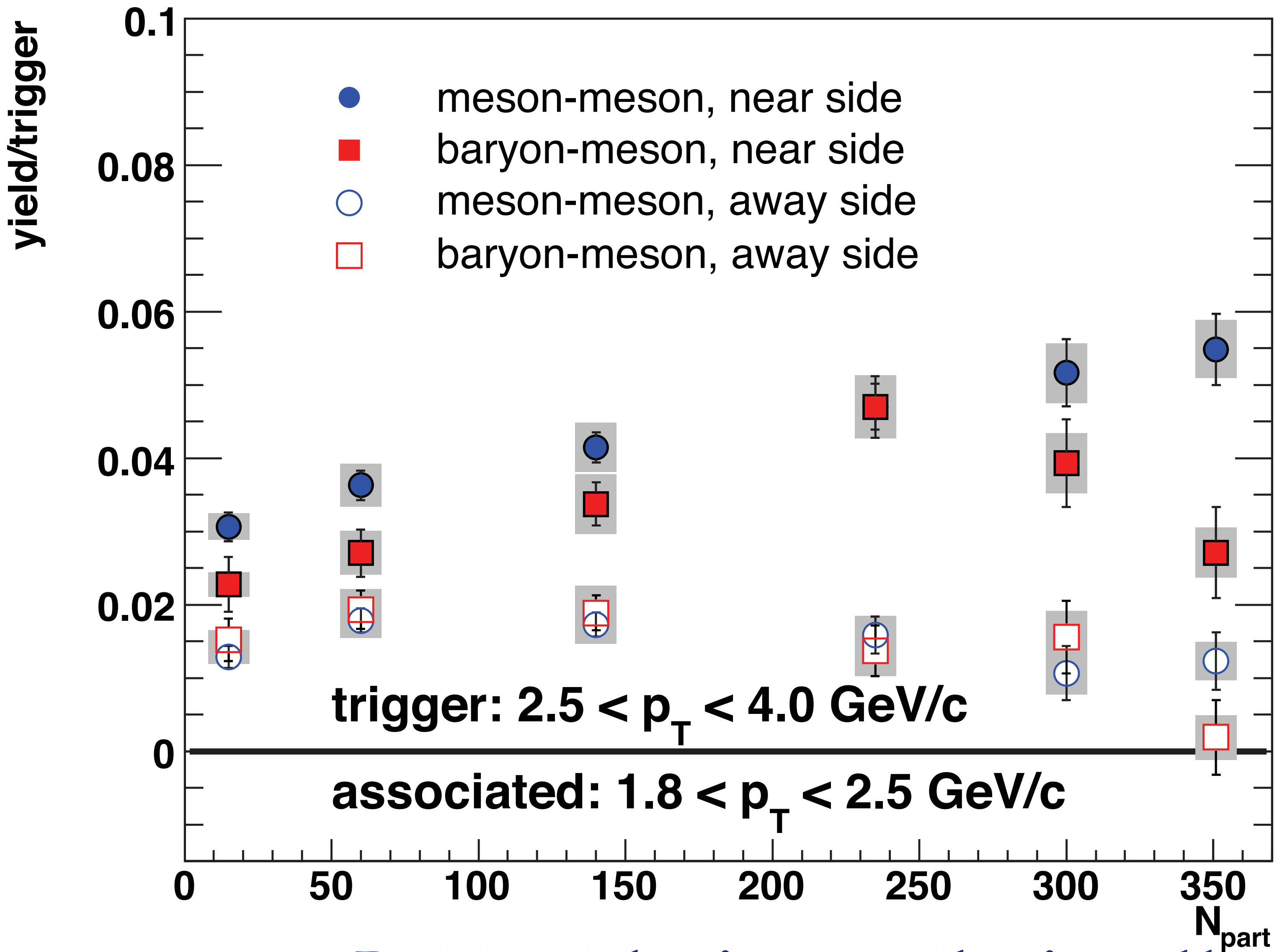
n_{active} = 6

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

$n_{eff} = 8$

Collision can produce 3 collinear quarks

Anne Sickles



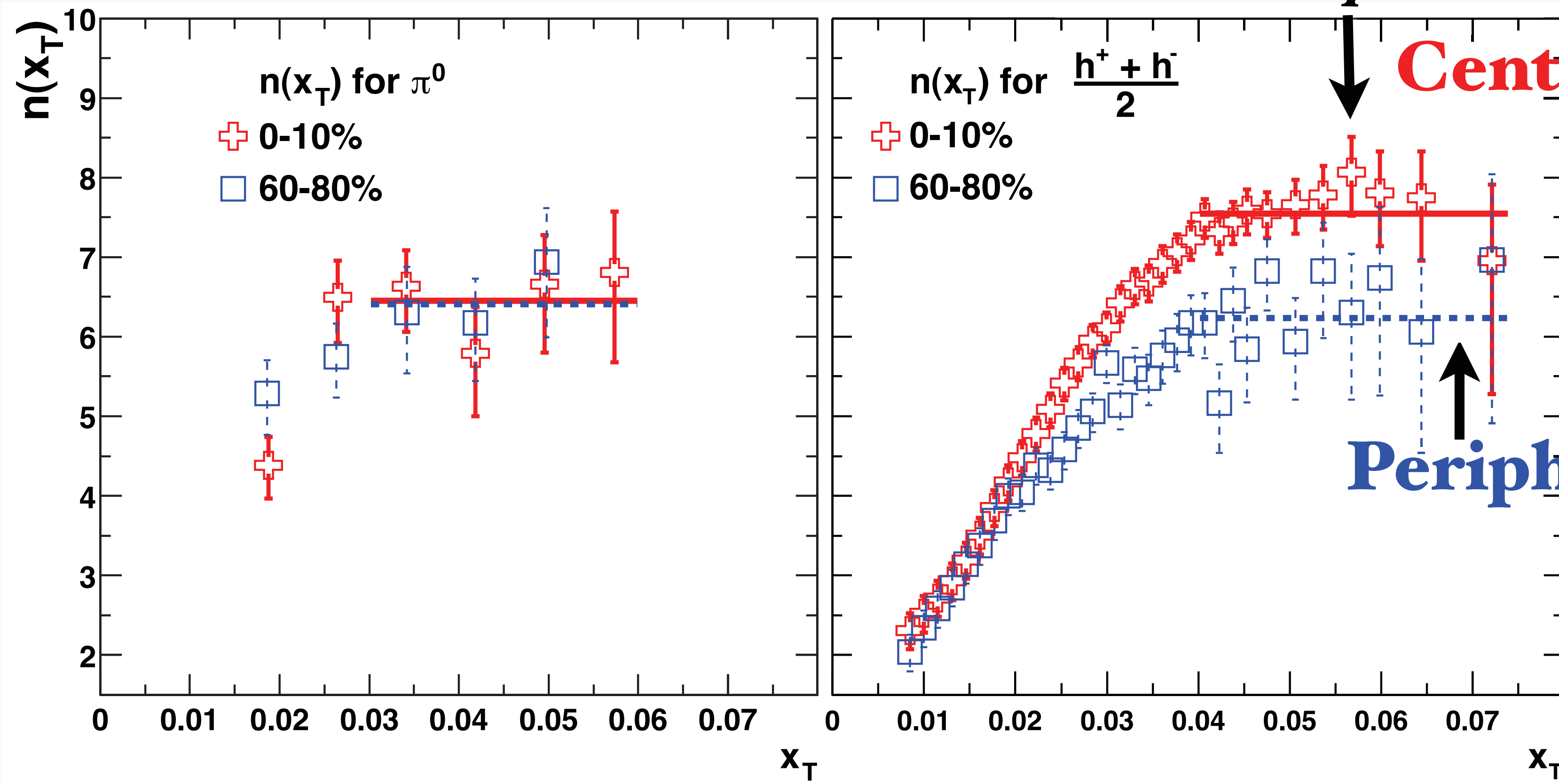
proton trigger: # same-side particles decreases with centrality

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

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

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

h+ includes protons

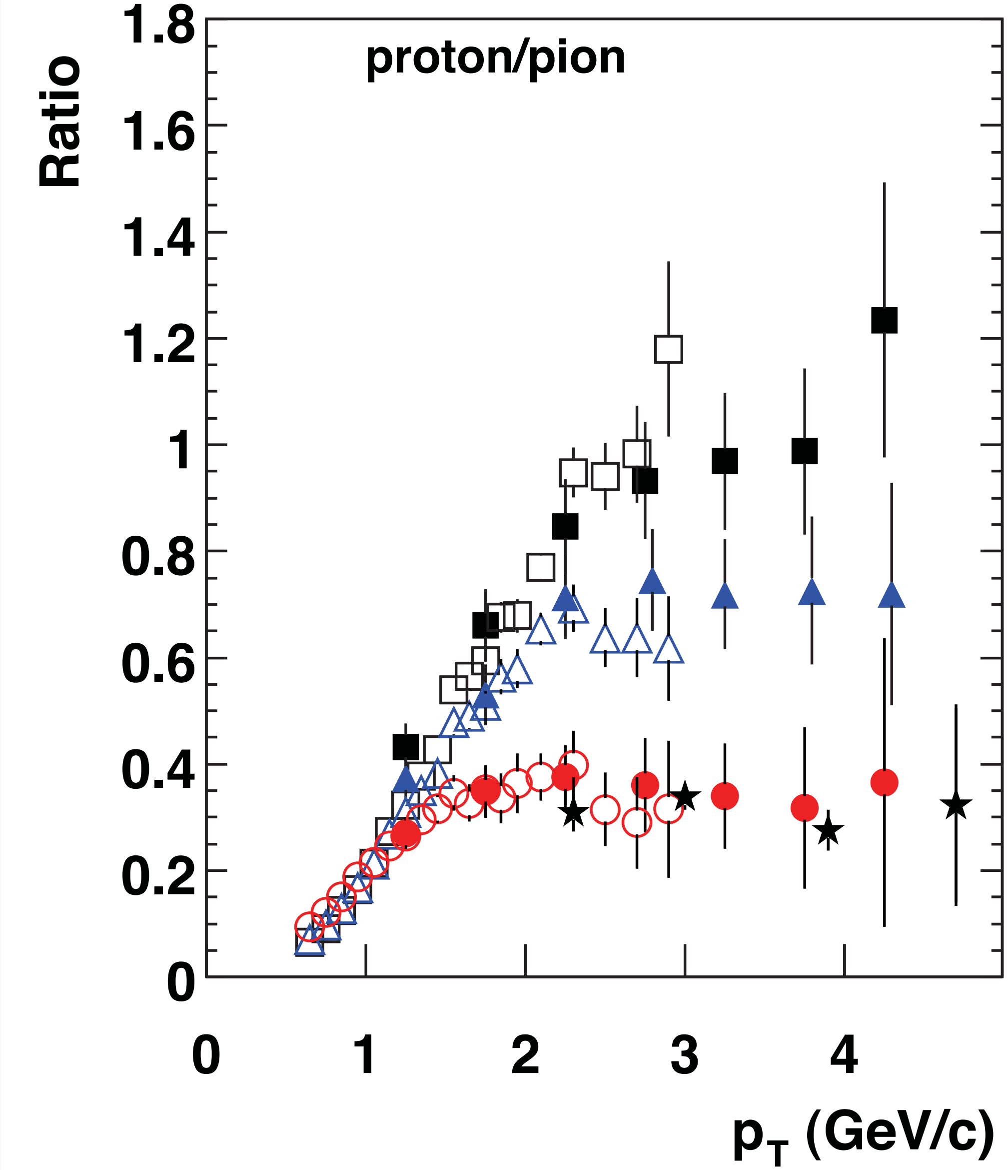


Proton power changes with centrality !

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

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

Particle ratio changes with centrality!



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

← **Central**

← **Peripheral**

Tannenbaum: Baryon Anomaly:

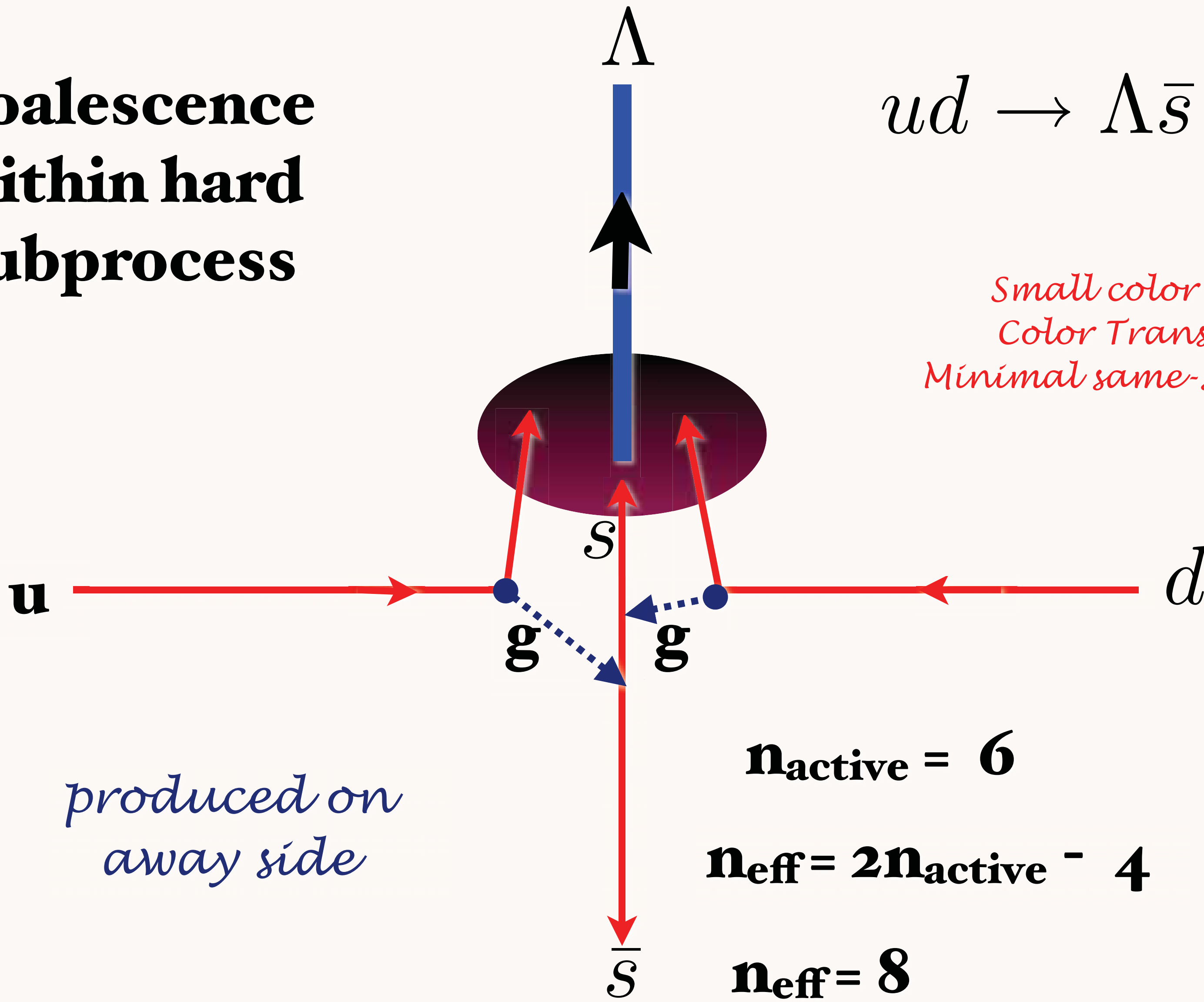
Lambda can be made directly within hard subprocess

Anne Sickles, sjb

Coalescence within hard subprocess

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

Small color-singlet
Color Transparent
Minimal same-side energy



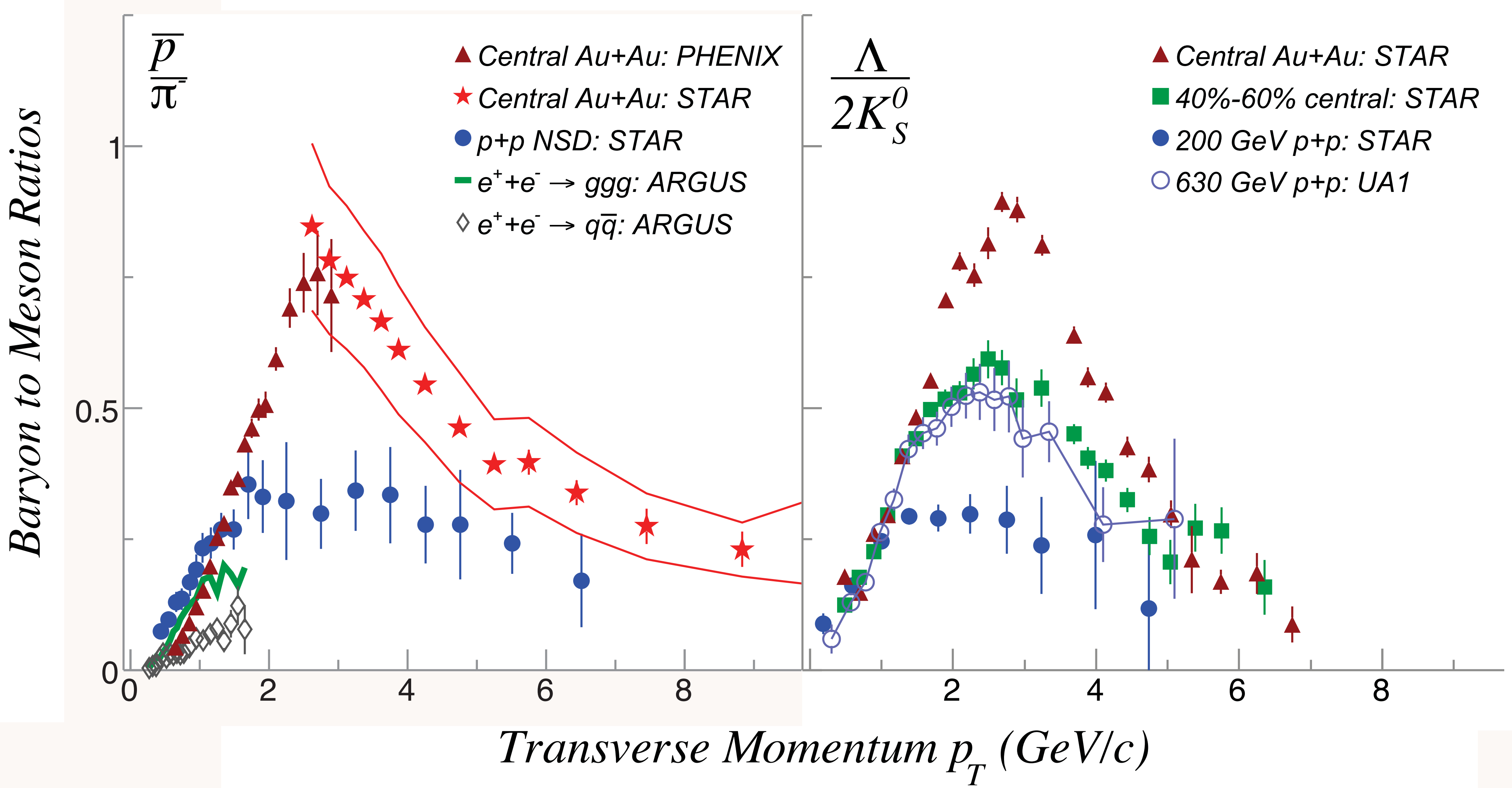
$\bar{s}$ produced on away side

$n_{active} = 6$

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

$n_{eff} = 8$

Paul Sorensen



Baryon Anomaly: Evidence for Direct, Higher-Twist Subprocesses

- **Explains anomalous power behavior at fixed x_T**
- **Protons more likely to come from direct higher-twist subprocess than pions**
- **Protons less absorbed than pions in central nuclear collisions because of color transparency**
- **Predicts increasing proton to pion ratio in central collisions**
- **Proton power n_{eff} increases with centrality since leading twist contribution absorbed**
- **Fewer same-side hadrons for proton trigger at high centrality**
- **Exclusive-inclusive connection at $x_T = 1$**

Anne Sickles, sjb

Higher Twist at the LHC

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

Isolated hadrons

Leading twist

Hadrons accompanied by a significant hadronic activity ⇒ inside jets

Higher twist

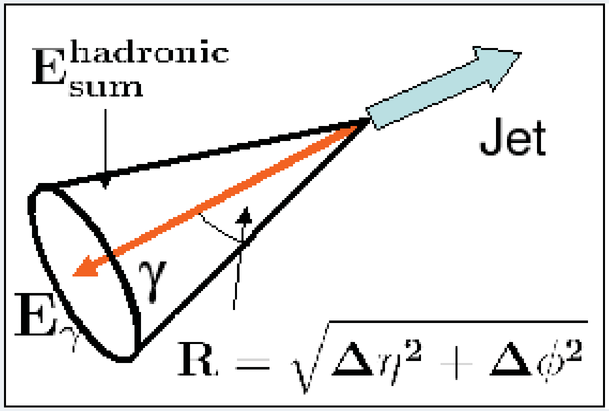
Color-singlet produced in the hard process ⇒ "isolated" hadrons

Idea: use isolation criteria to filter the leading twist component

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

for particles inside a cone

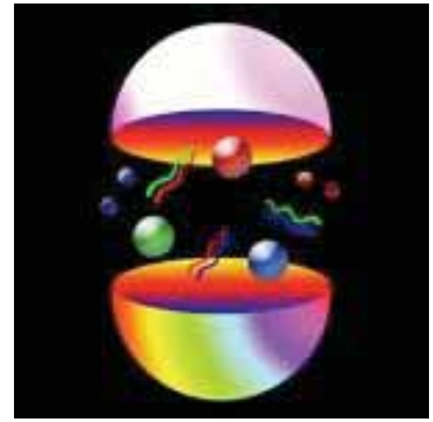
$$(\eta - \eta_\gamma)^2 + (\phi - \phi_\gamma)^2 \leq R^2$$



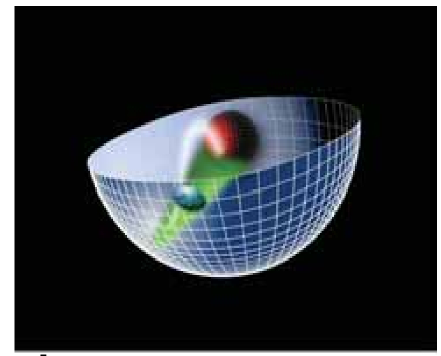
Consequence

Enhanced scaling exponent for isolated hadrons

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

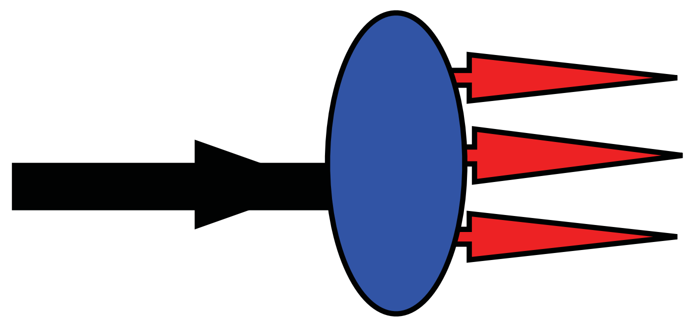


- Quarks and Gluons:
  Fundamental constituents of hadrons and nuclei
- *Quantum Chromodynamics (QCD)*
- New Insights from higher space-time dimensions: *AdS/QCD*



- *Light-Front Holography*
- *Hadronization at the Amplitude Level*
- *Light Front Wavefunctions:* analogous to the Schrodinger wavefunctions of atomic physics

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



Each element of flash photograph illuminated at same LF time

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

Evolve in LF time

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

Eigenstate -- independent of τ

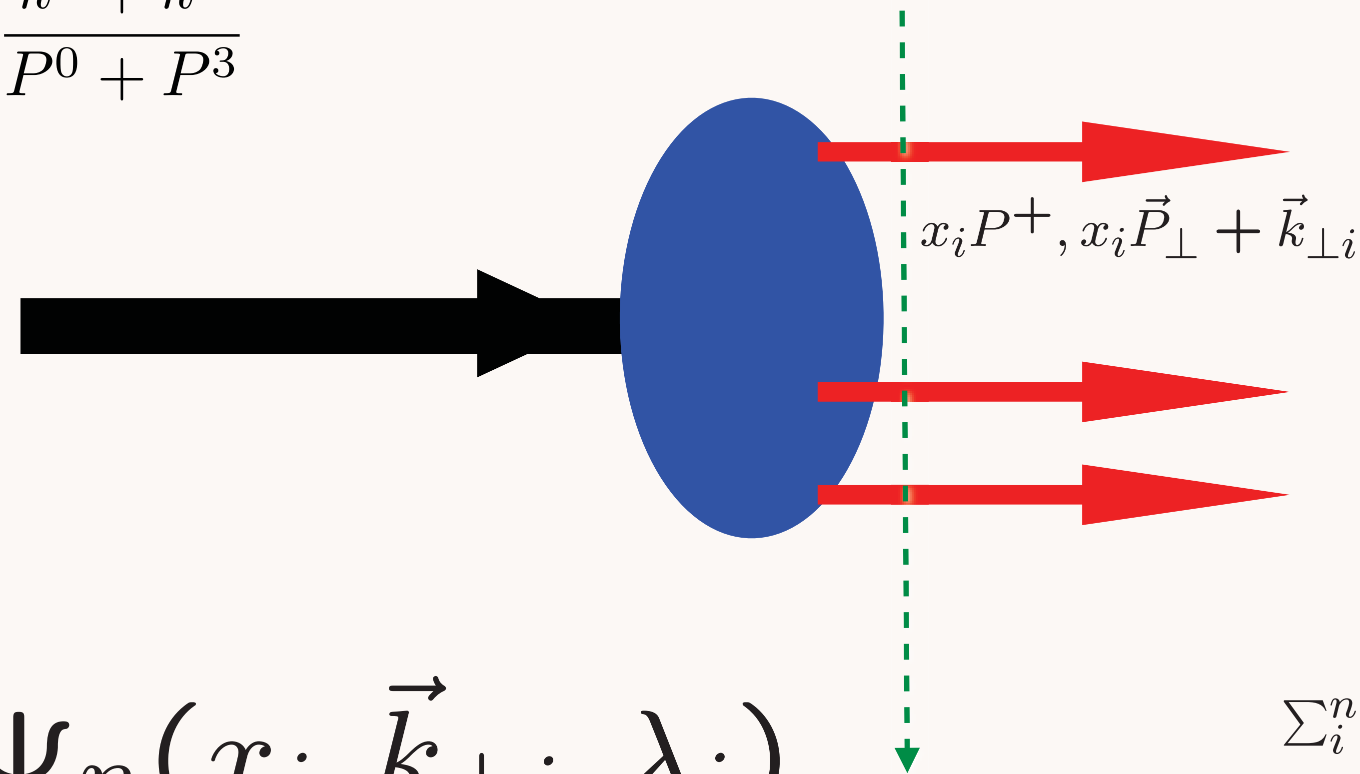
HELEN BRADLEY - PHOTOGRAPHY

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

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

Fixed $\tau = t + z/c$

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



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

$\sum_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

Angular Momentum on the Light-Front

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

Conserved
LF Fock state by Fock State

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

n-1 orbital angular momenta

Nonzero Anomalous Moment -->Nonzero orbital angular momentum

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

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

The Light Front Fock State Wavefunctions

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

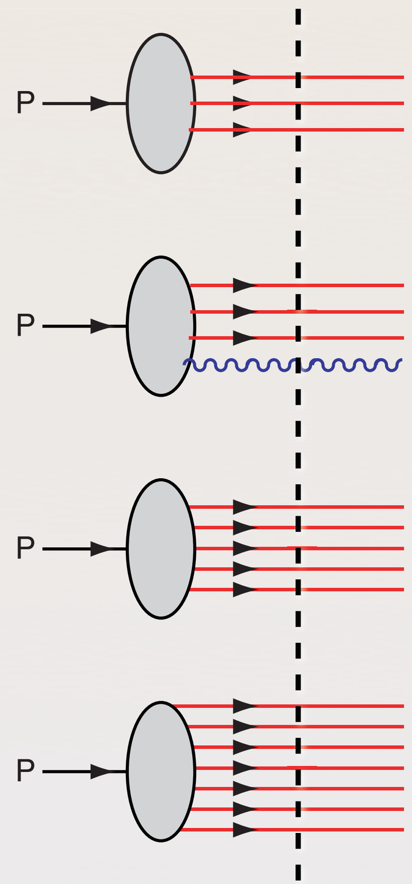
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

The light-cone momentum fraction

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

are boost invariant.

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



Fixed LF time

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

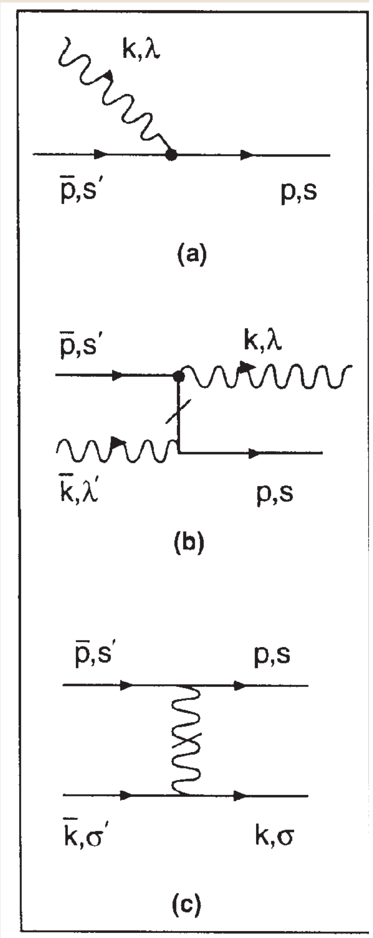
$\bar{s}(x) \neq s(x)$
$\bar{u}(x) \neq \bar{d}(x)$

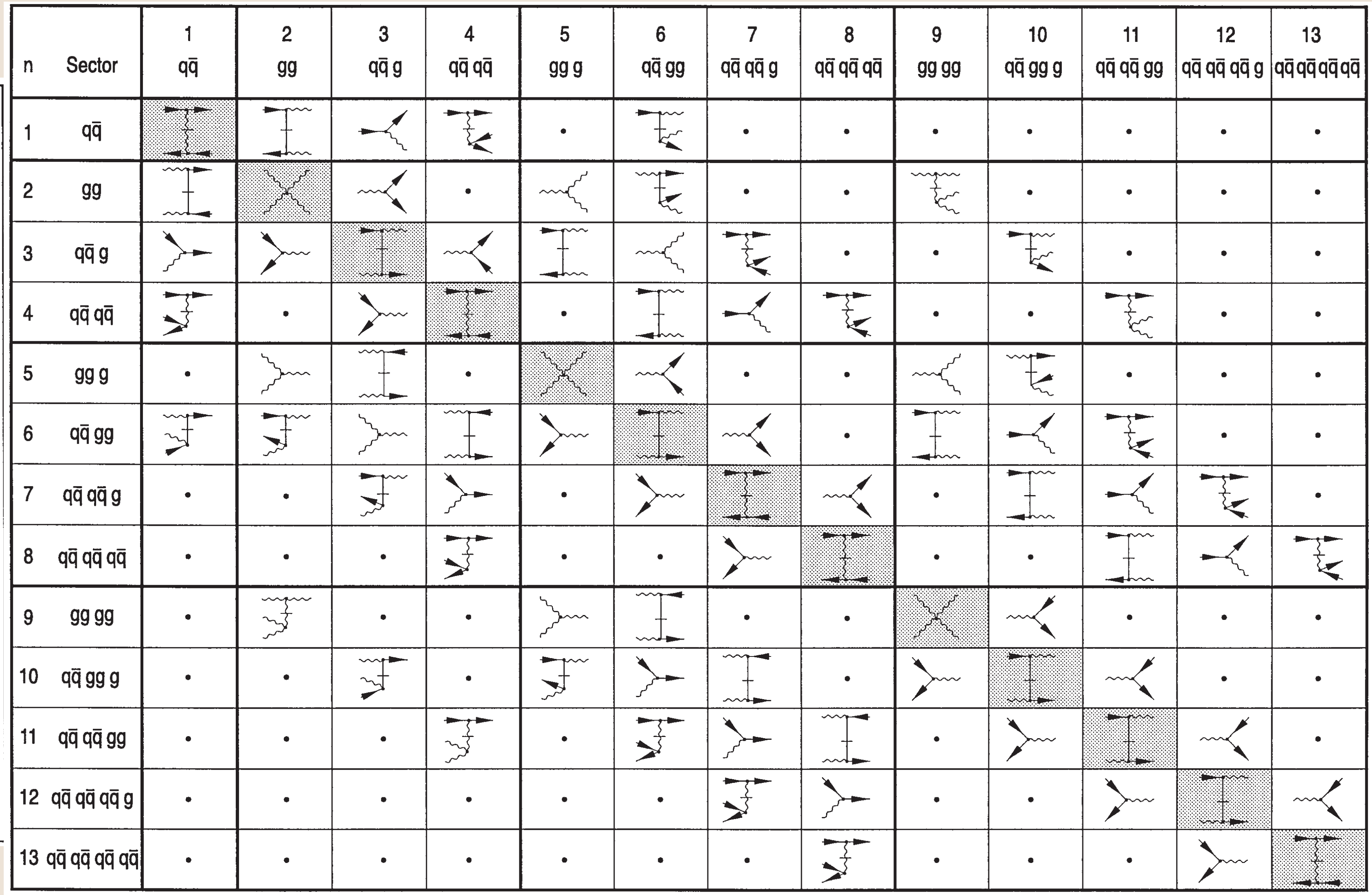
Deuteron: Hidden Color

Mueller: gluon Fock states → BFKL

Light-Front QCD Heisenberg Equation

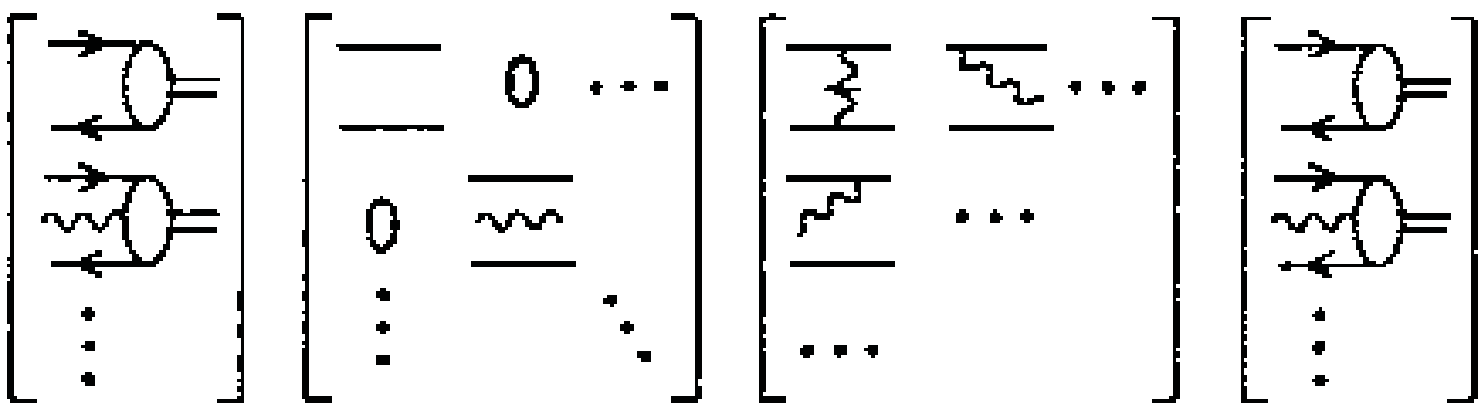
$$H_{LC}^{QCD}|\Psi_h\rangle = \mathcal{M}_h^2\,|\Psi_h\rangle$$





LIGHT-FRONT SCHRODINGER EQUATION

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



$A^+ = 0$

G.P. Lepage, sjb

Remarkable Features of Hadron Structure

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

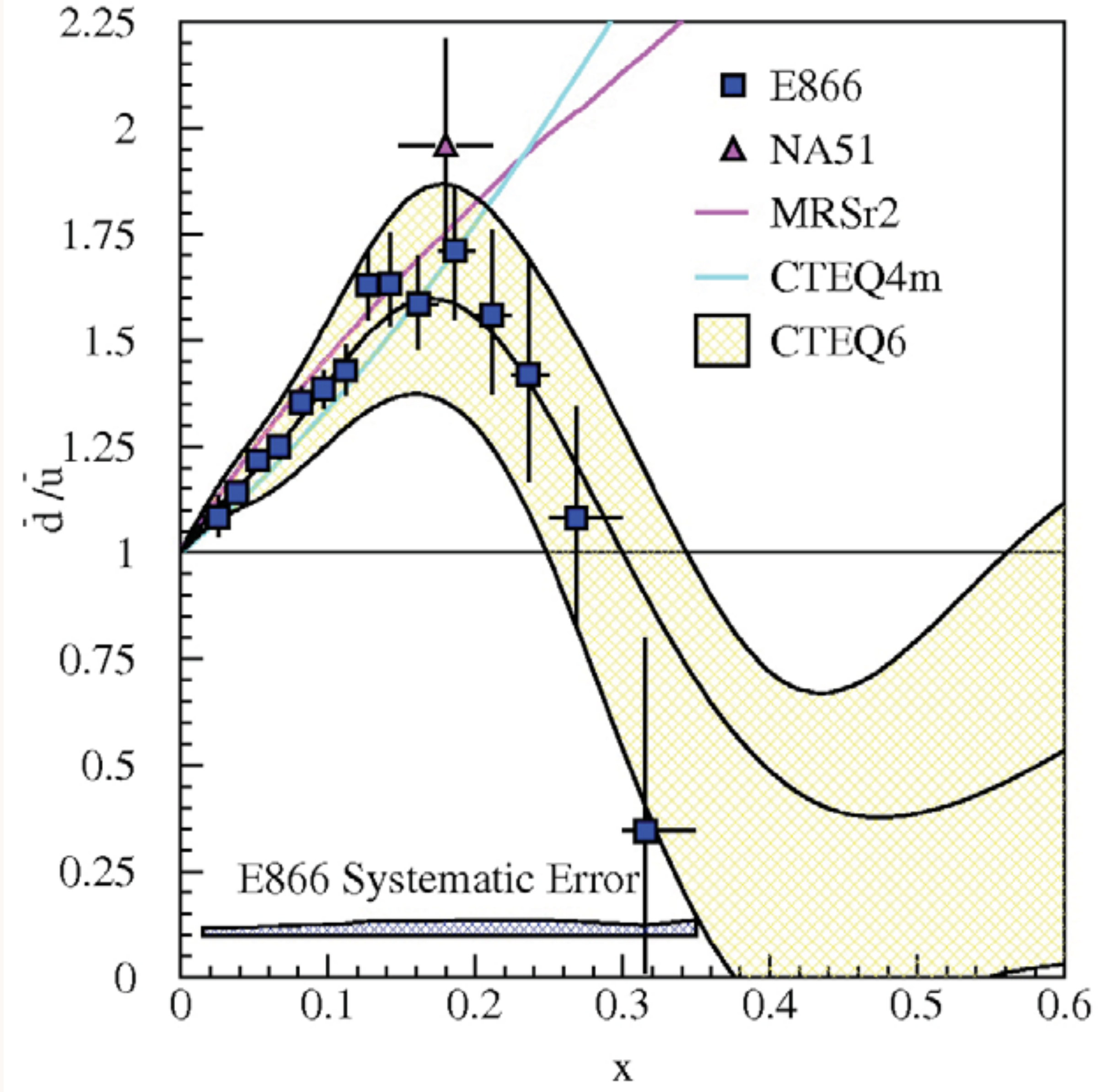
$\bar{d}(x)/\bar{u}(x)$ for $0.015 \leq x \leq 0.35$

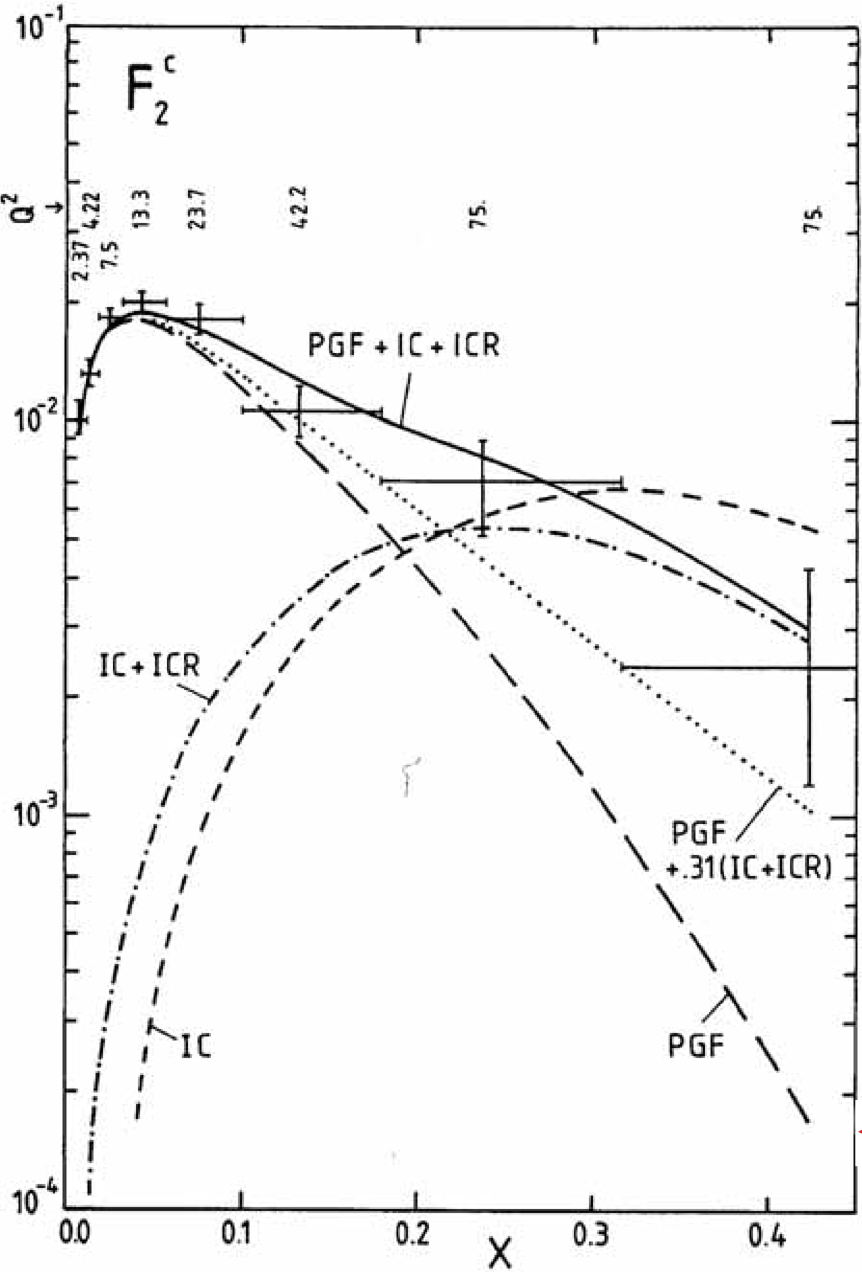
- E866/NuSea (Drell-Yan)

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

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

Intrinsic glue, sea, heavy quarks

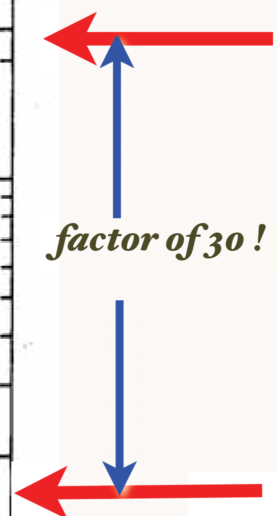


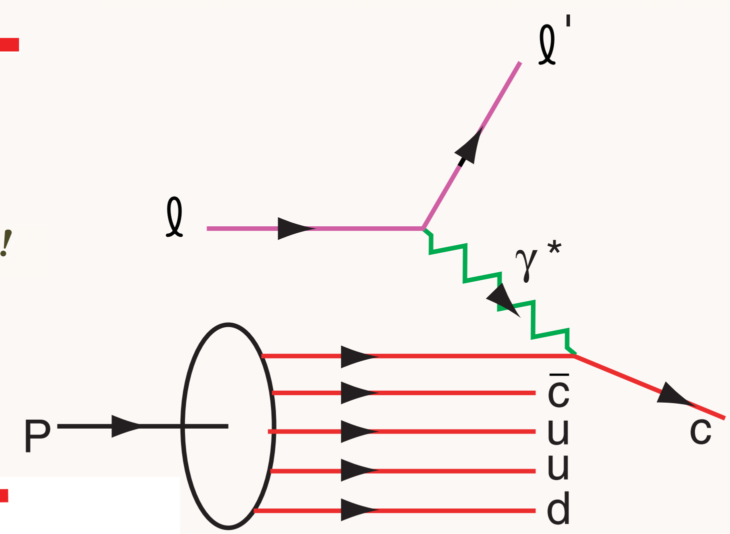


Measurement of Charm Structure Function

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

First Evidence for Intrinsic Charm

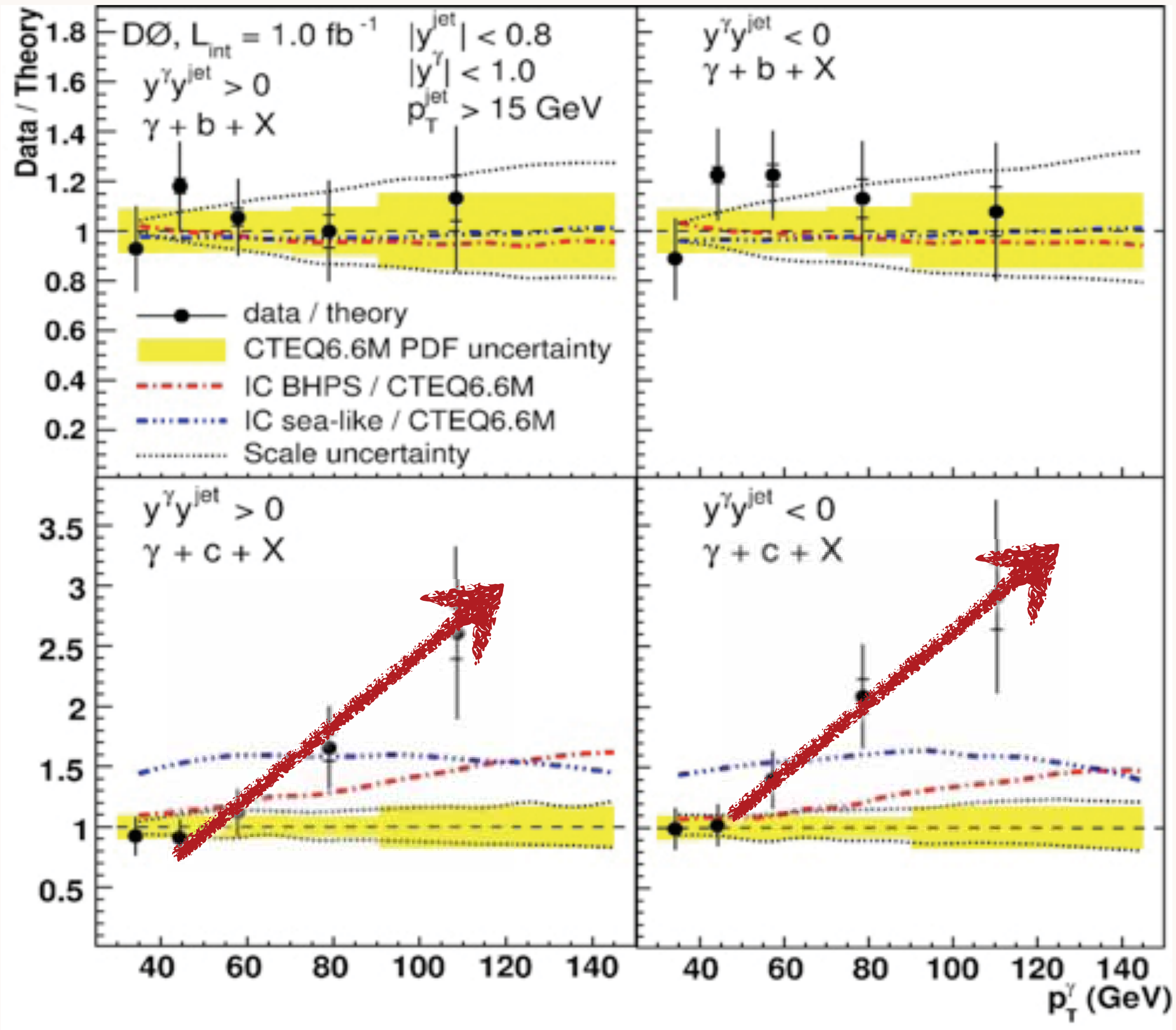




DGLAP / Photon-Gluon Fusion: factor of 30 too small

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



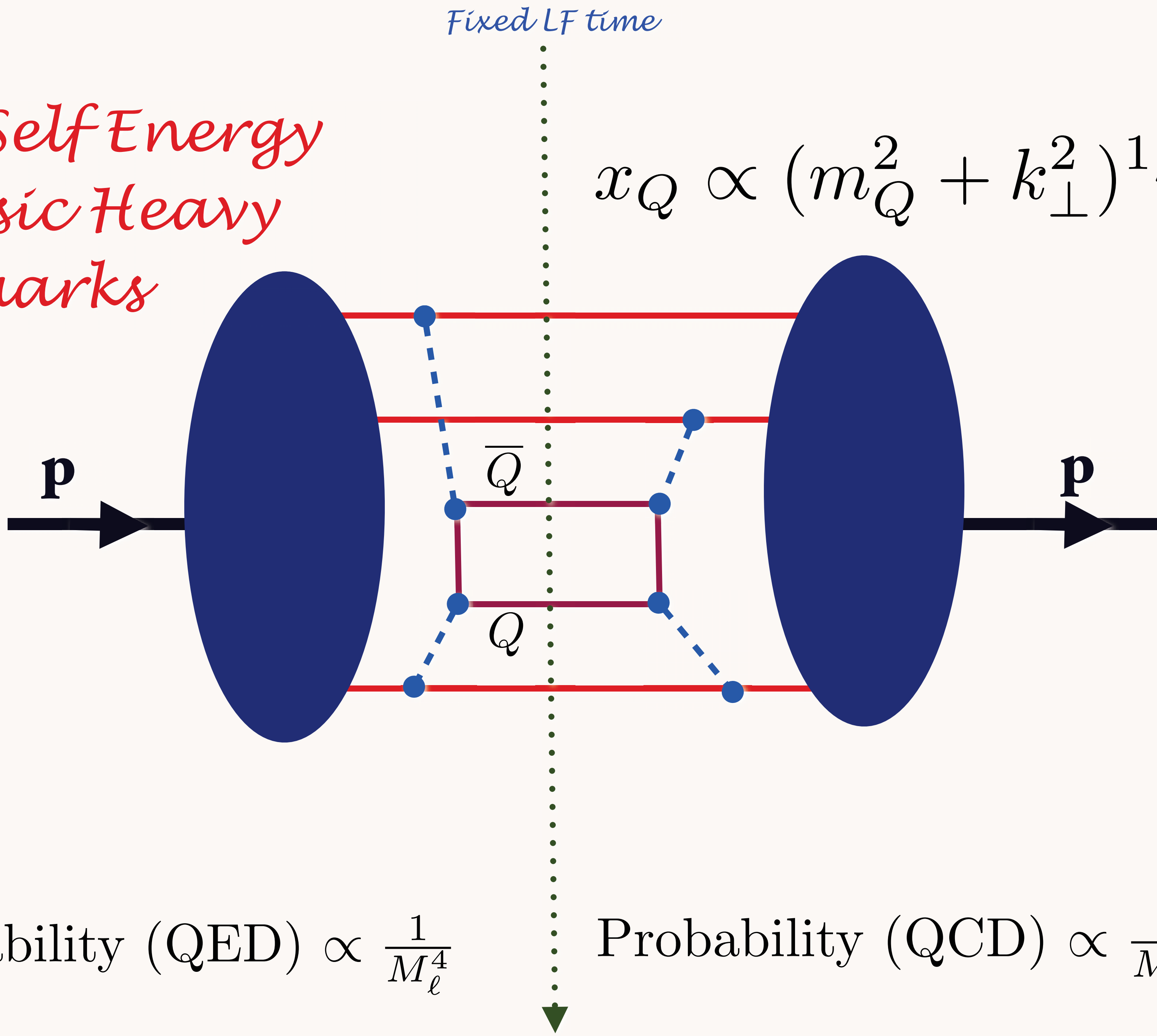
$$\frac{\Delta\sigma(\bar{p}p \to \gamma c X)}{\Delta\sigma(\bar{p}p \to \gamma b X)}$$

Ratio insensitive to gluon PDF, scales

Signal for significant IC at x > 0.1 ?

Proton Self Energy Intrinsic Heavy Quarks

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

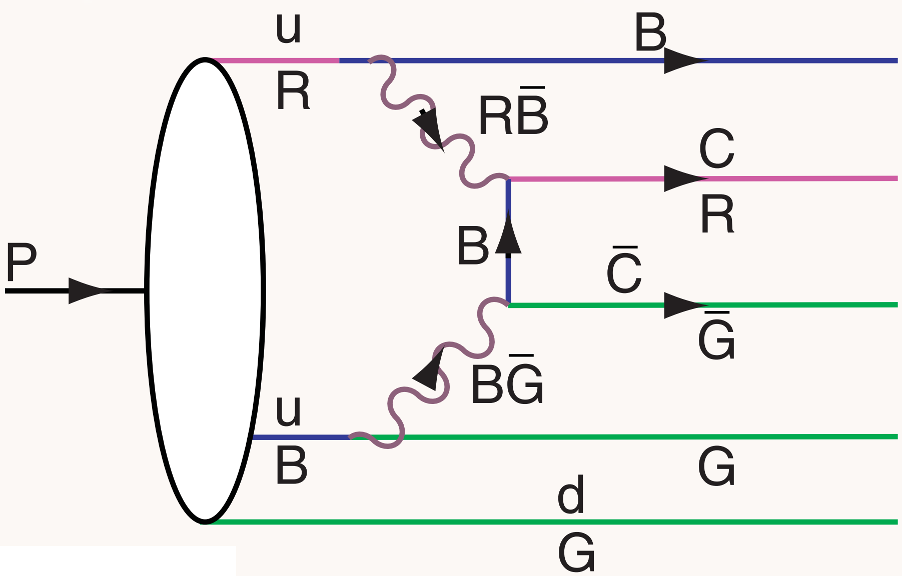


Probability (QED) $\propto \frac{1}{M_\ell^4}$

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

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

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

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

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

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

- High x_F $pp \to \Lambda_c X$

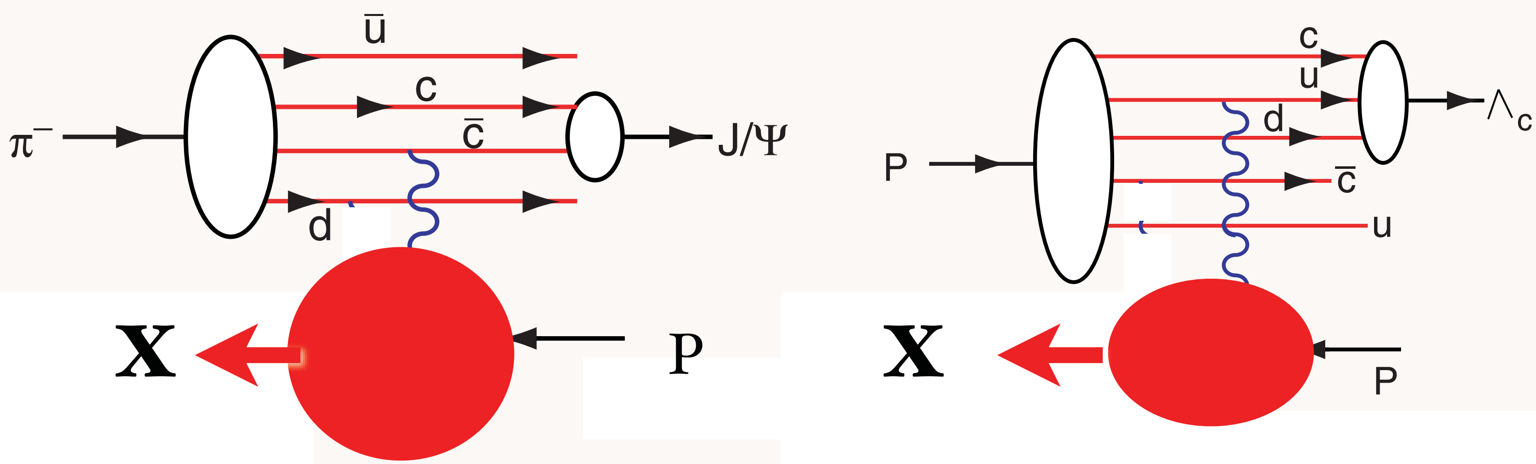
- High x_F $pp \to \Lambda_b X$

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

IC Structure Function: Critical Measurement for EIC

Many interesting spin, charge asymmetry, spectator effects

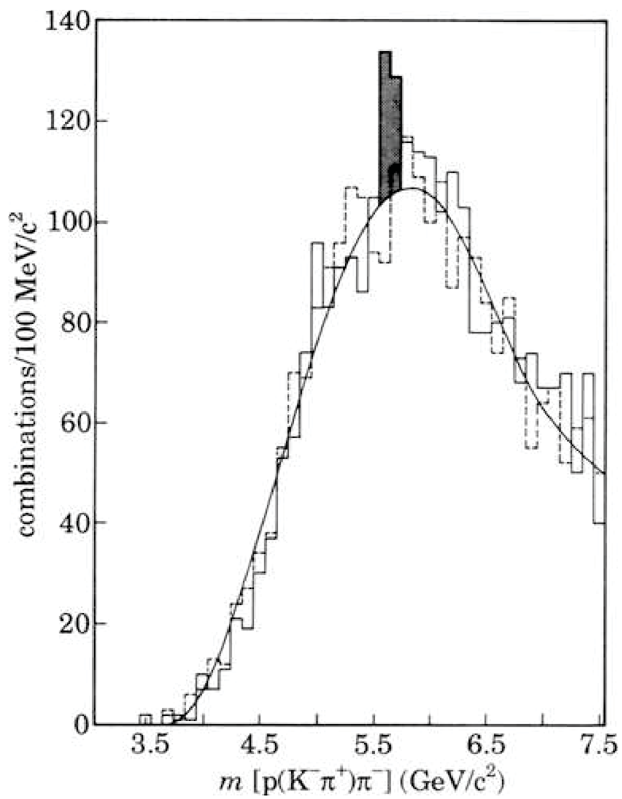
Leading Hadron Production from Intrinsic Charm

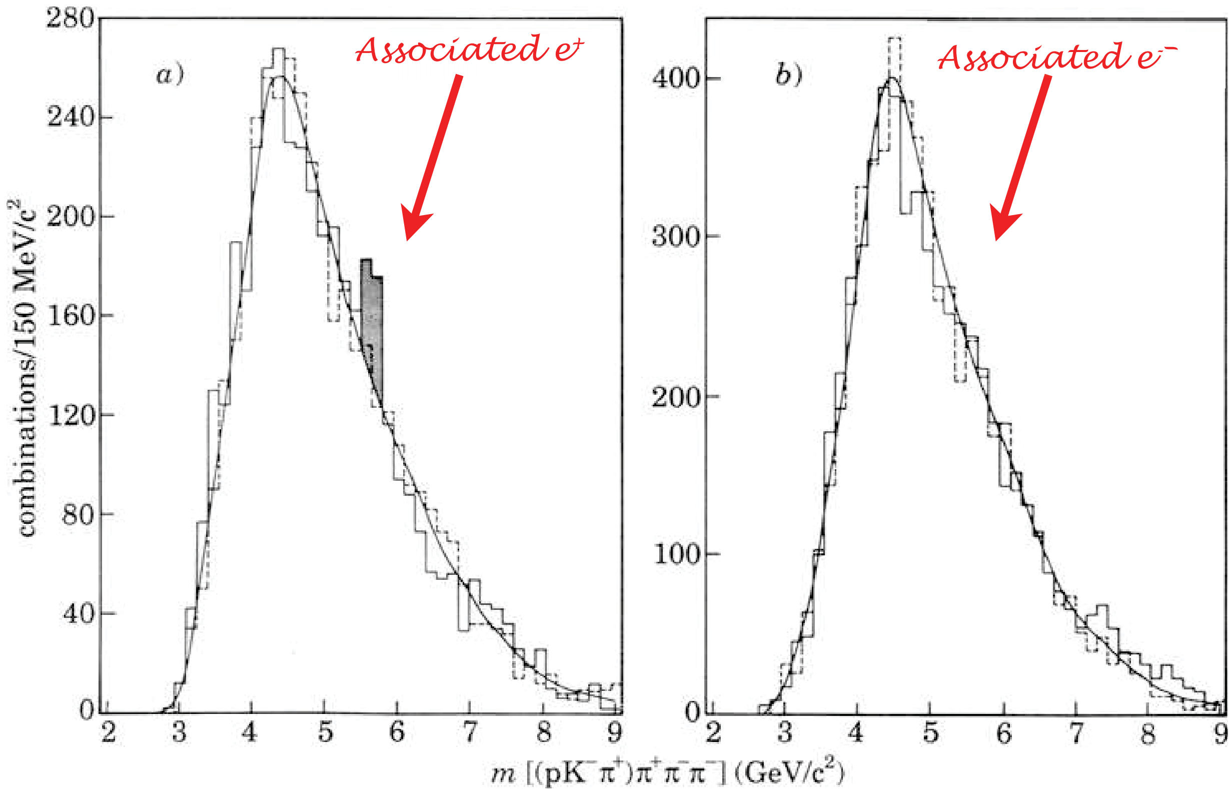


Coalescence of Comoving Charm and Valence Quarks Produce J/ψ, Λ_c and other Charm Hadrons at High x_F

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

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



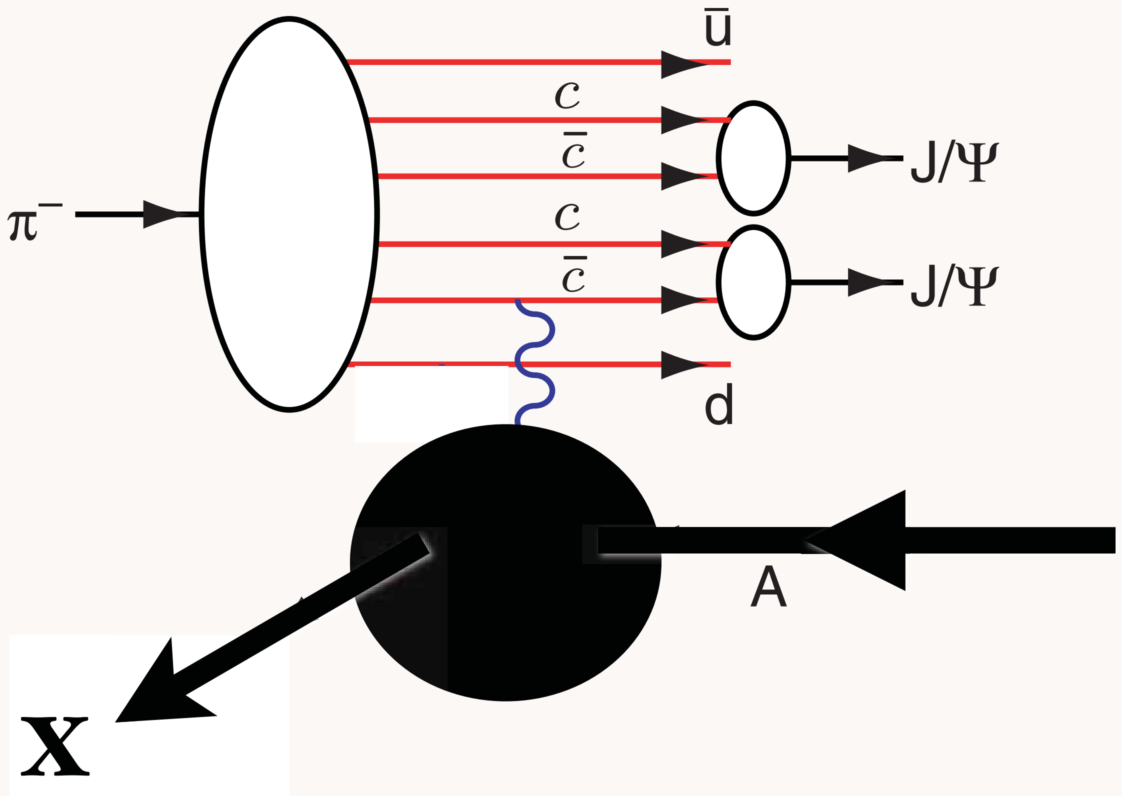


$\Lambda_b^0 \to pD^0\pi^-$

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

Il Nuovo Cimento 104, 1787

Production of Two Charmonia at High x_F



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

Excludes `color drag' model

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

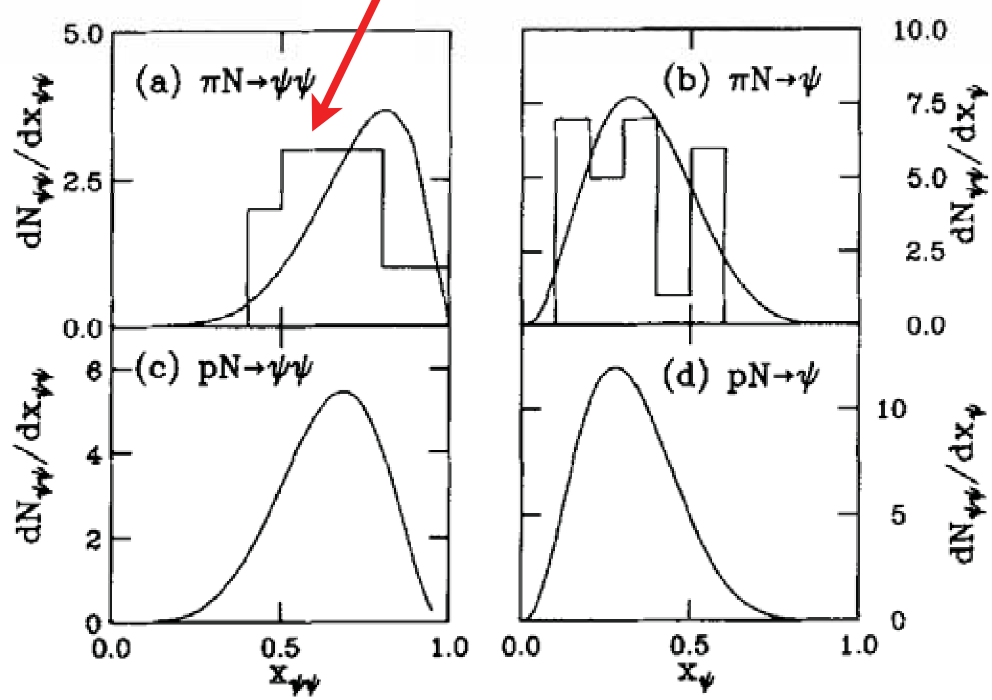


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized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

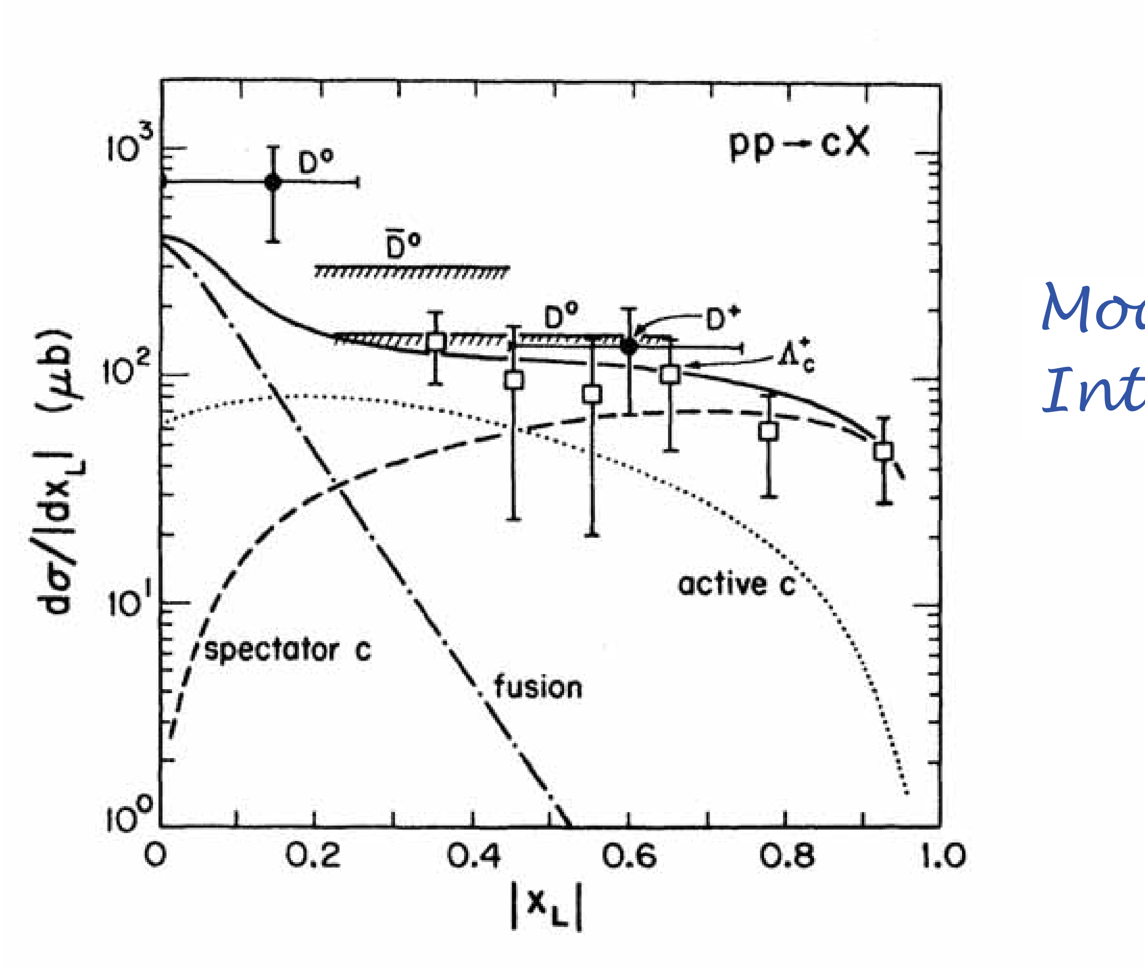
NA3 Data

Intrinsic charm contribution to double quarkonium hadroproduction ★

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

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

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



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).