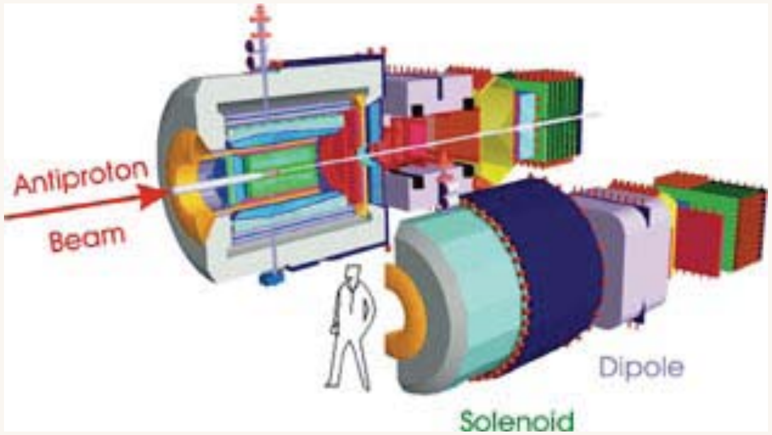
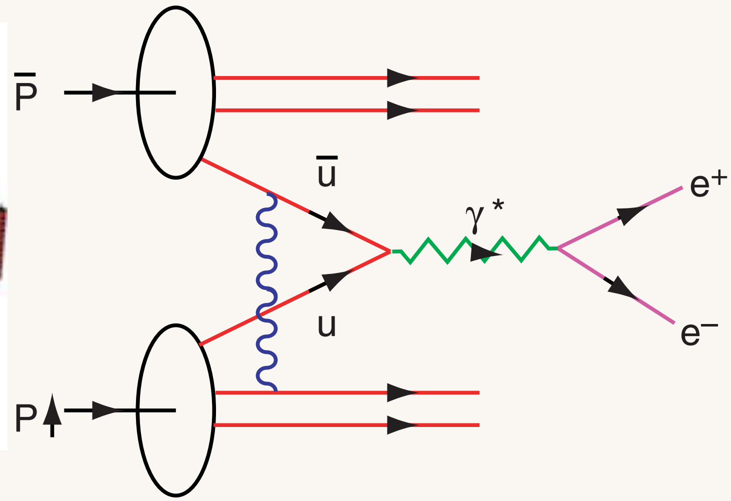
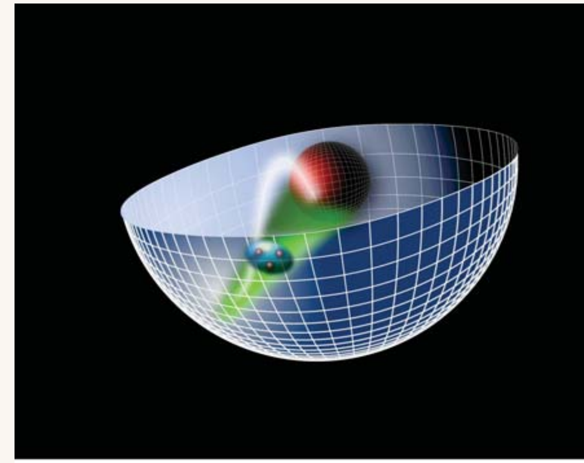
Novel Anti-Proton QCD Physics and New Insights from AdS/QCD

Stan Brodsky, SLAC

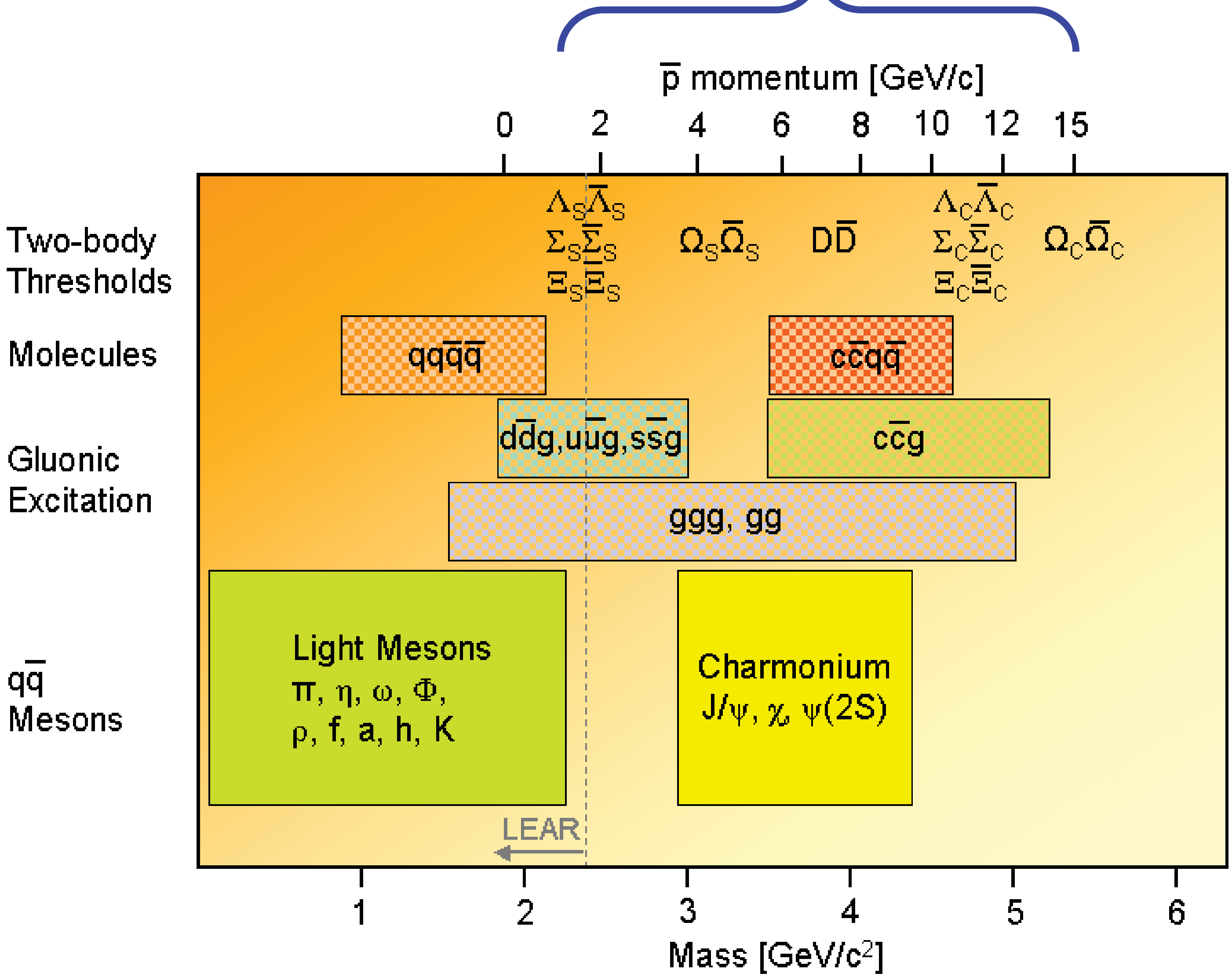






Panda Workshop, Turin, June 15-19, 2009

Mass range of PANDA



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

Michael Düren

Search for exotic states

Naive Quark Model:

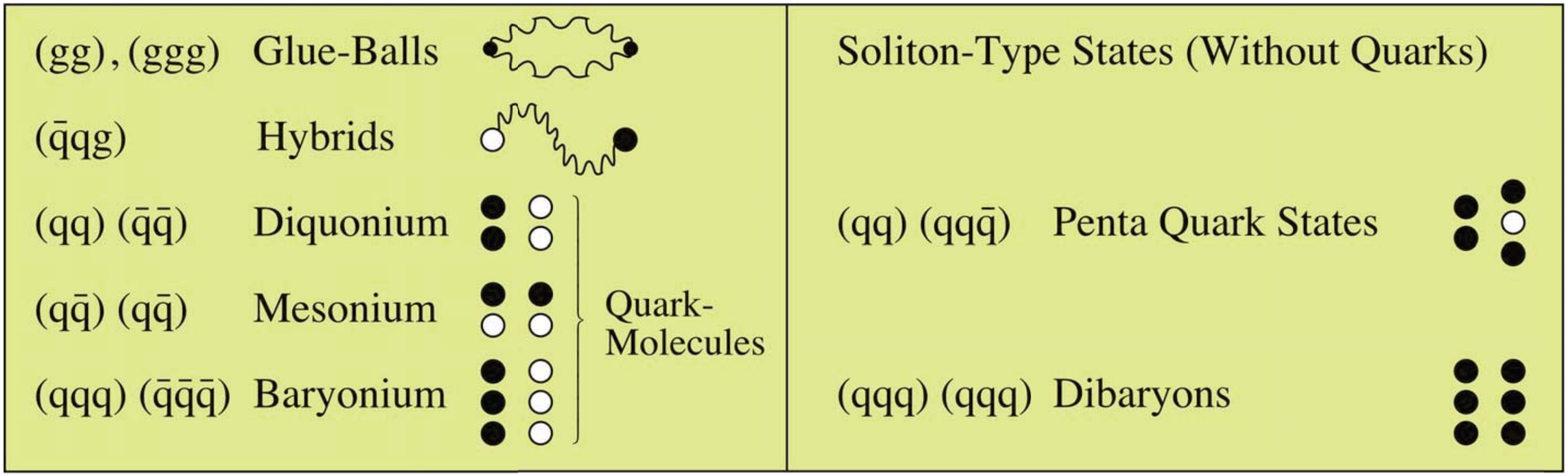
Mesons (Resonances) = $q\bar{q}$-states

Baryons (Resonances) = qqq-states

$$\bar{p}p \to \gamma + X[q\bar{q}\bar{q}q]$$

LQCD + Model calculations:

Existence of exotic states



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New feature:

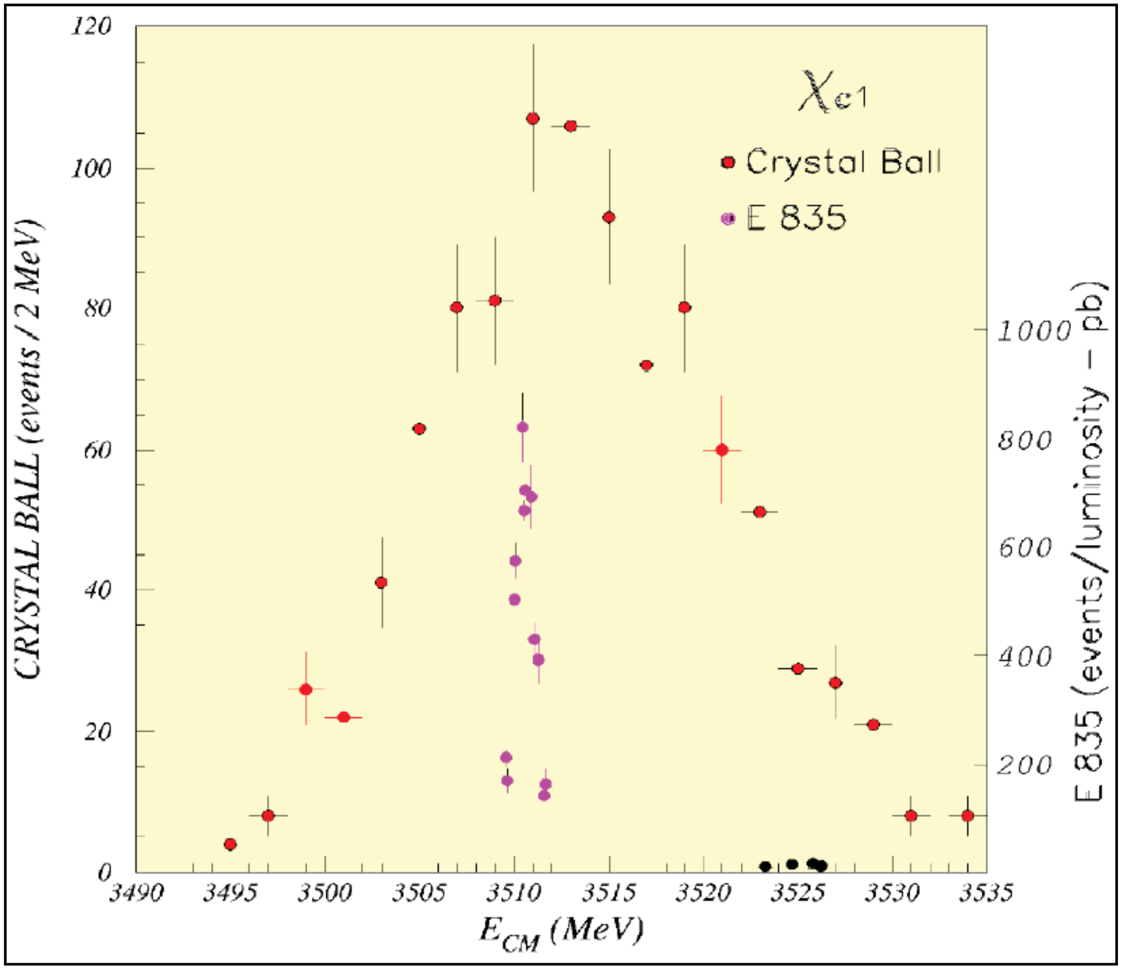
Spin-exotic quantum numbers possible, not allowed in $\bar{q}q$ ($J^{PC} = 0^{+-}, 1^{-+}, \ldots$)

New Charmonium Resonances

- **X(3872),** Belle 09’2003, 1^{++}, χ_{c1}' or D^0D^* molecule
  - decays into $J/\psi\pi^+\pi^-$, $J/\psi\pi^+\pi^-\pi^0$, $J/\psi\gamma$, D^0D^*
- **Y(3940),** Belle 09’2004, JP^+, 2^3P_1 or Hybrid??
  - decays into $J/\psi\omega$
- **Y(4260),** BaBar 06’2005, 1^{--}, 2^3D_1 (BaBar) or 4^3S_1 (CLEO) or Hybrid
  - decays into e^+e^-, $J/\psi\pi^+\pi^-$, $J/\psi\pi^0\pi^0$, $J/\psi K^+K^-$
- **X(3943),** Belle 07’2005, 0^{-+}, η_c''
  - decays into D^0D^*
- **Z(3934),** Belle 07’2005, 2^{++}, χ_{c2}'
  - decays into $\gamma\gamma$, DD
- **ψ(4320),** BaBar 06’2006, ?, Hybrid

Merits of antiprotons in hadron spectroscopy
High Resolution of M and Γ

- Crystal Ball: typical resolution ~ 10 MeV
- Fermilab: 240 keV
- PANDA: ~20 keV



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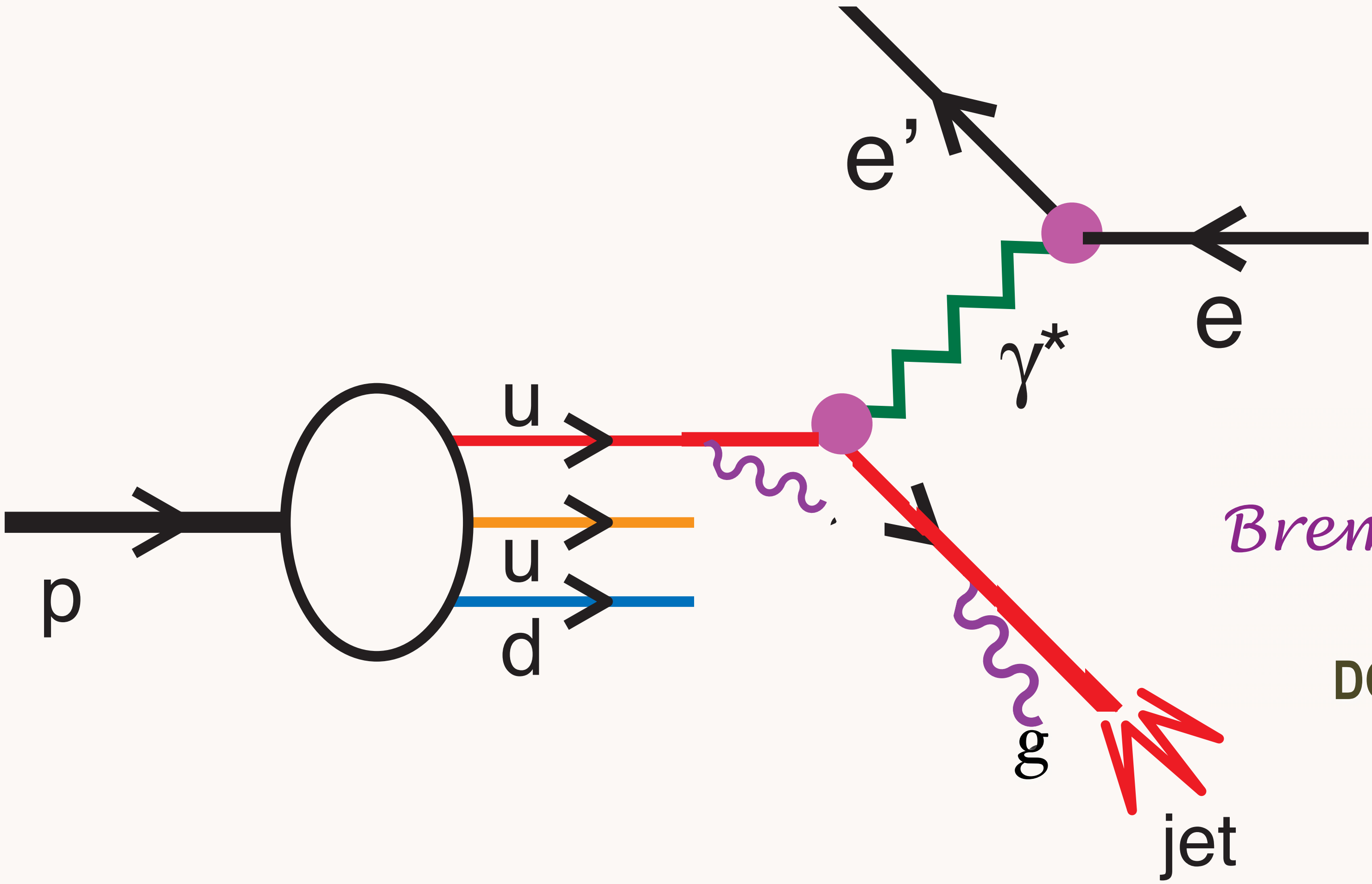
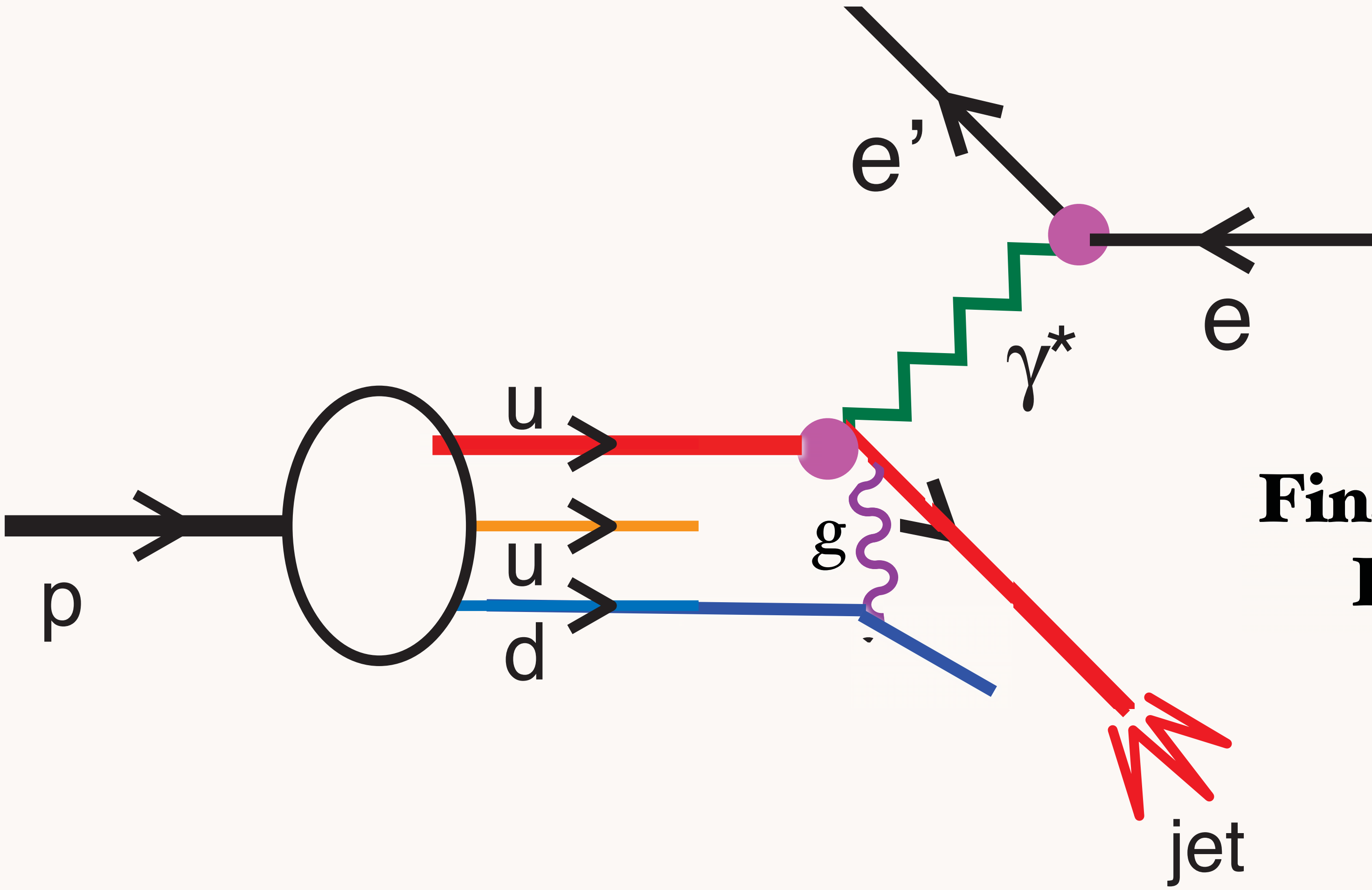
Deep Inelastic Electron-Proton Scattering



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

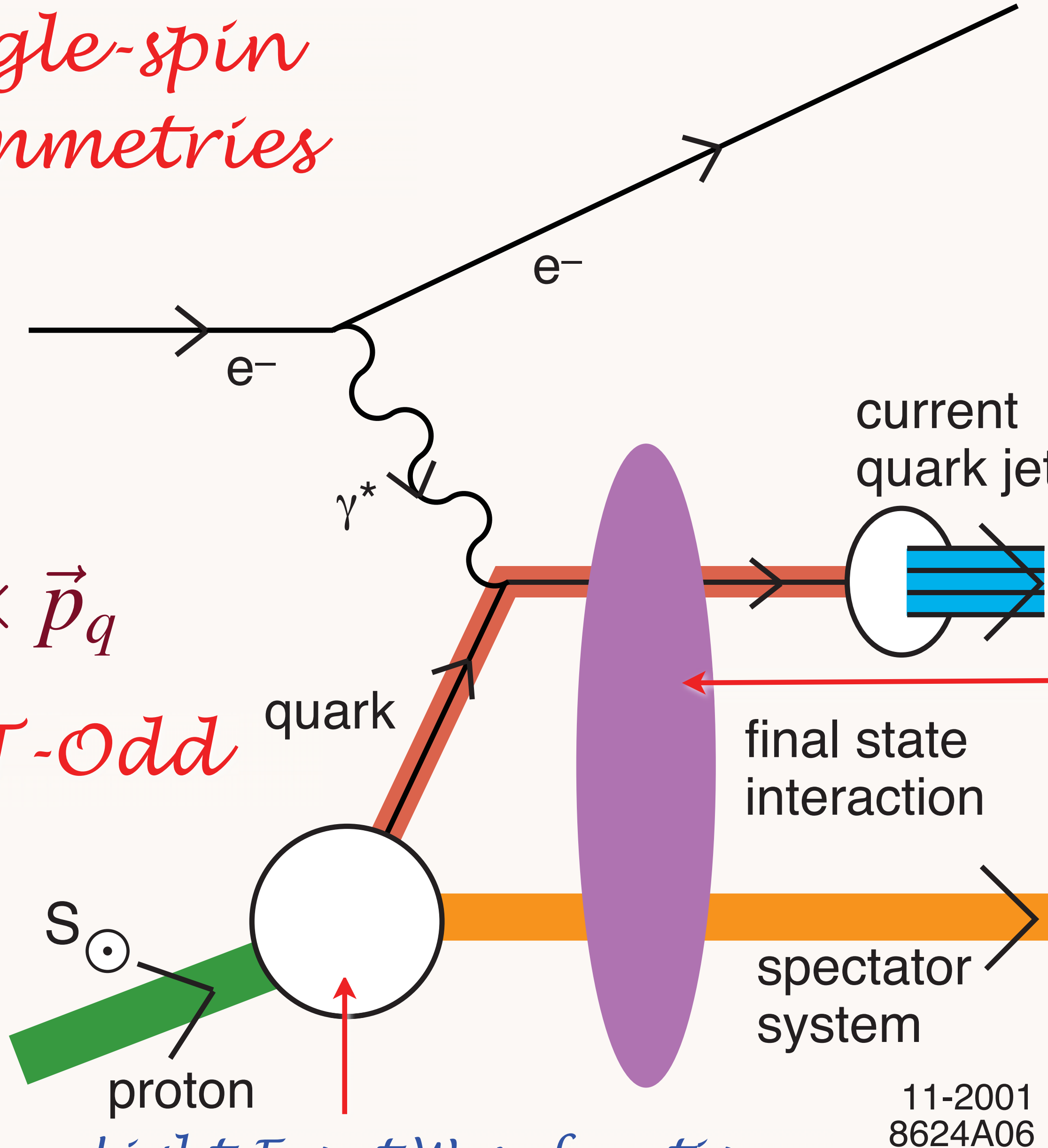
Leading Twist Sivers Effect

Hwang, Schmidt, sjb

Collins, Burkardt Ji, Yuan

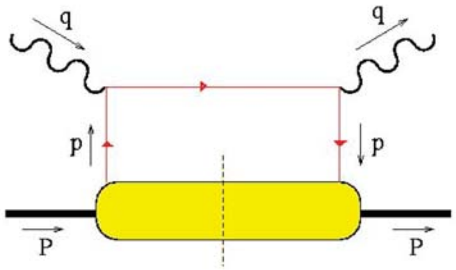
$i\,\vec{S}_p \cdot \vec{q} \times \vec{p}_q$

Pseudo-T-Odd

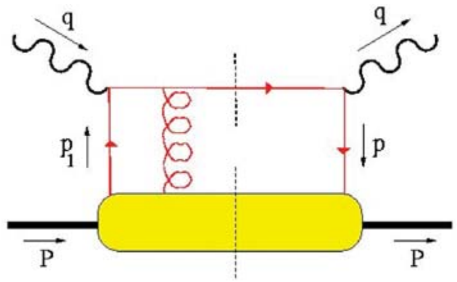


QCD S- and P-Coulomb Phases --Wilson Line

Light-Front Wavefunction S and P- Waves



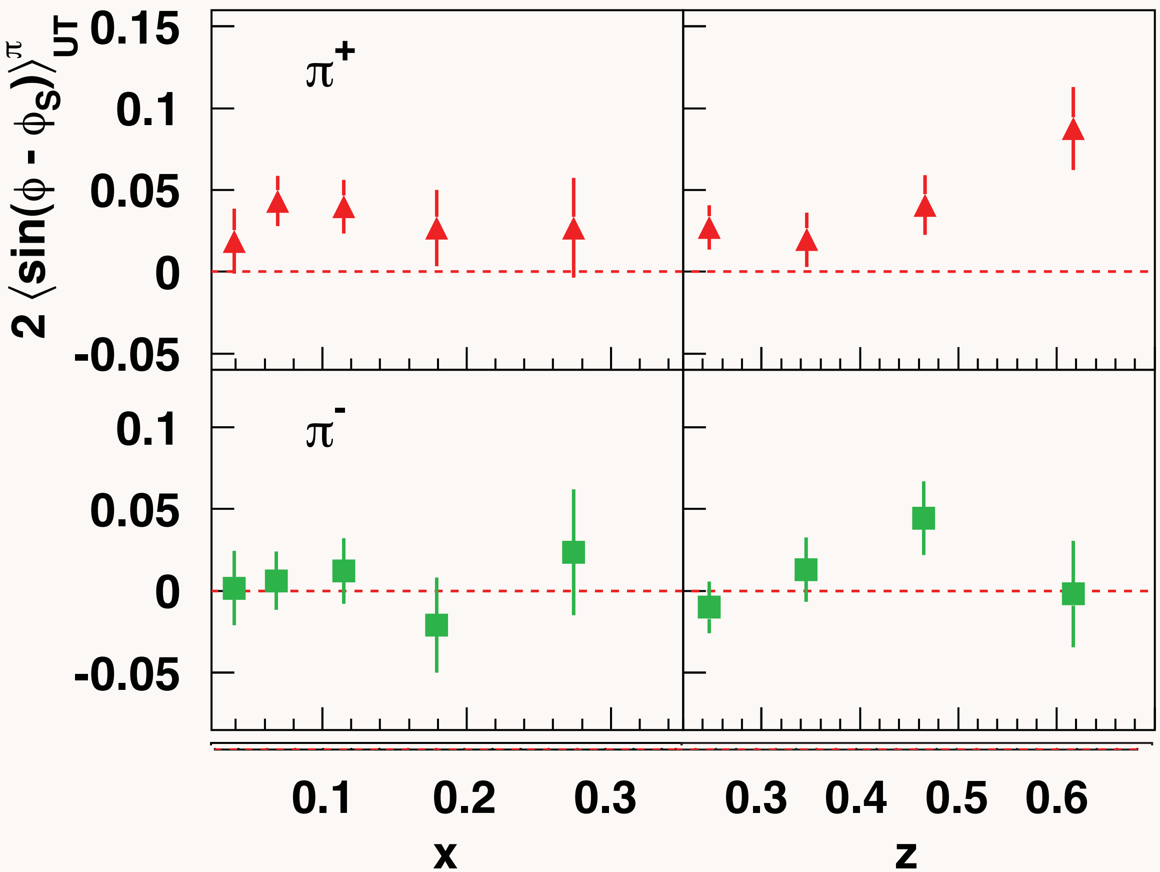
can interfere with



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



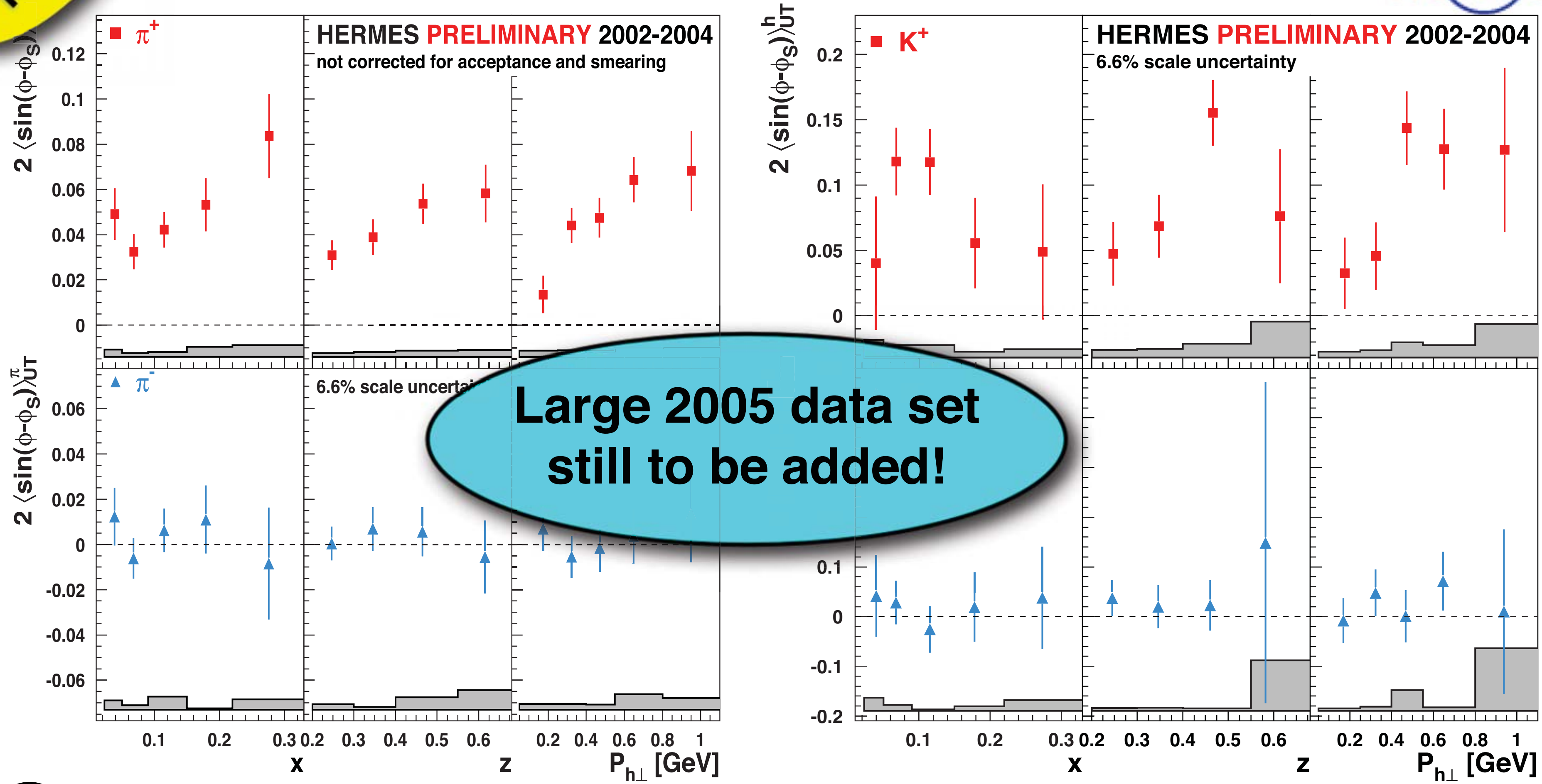
- First evidence for non-zero Sivers function!
- ⇒ presence of non-zero **quark orbital angular momentum**!
- Positive for **π^+**...
  Consistent with zero for **π^-**...

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 $x \approx 0.1$ ... !

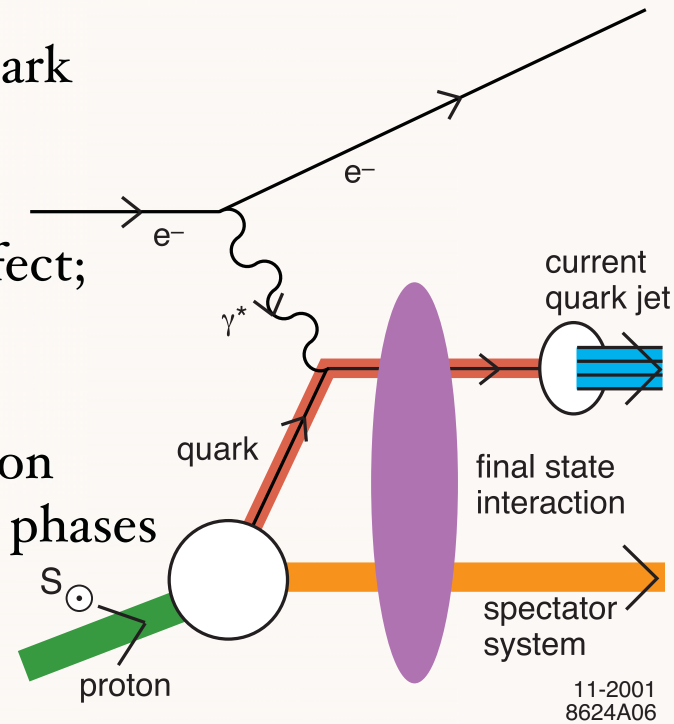
N. Makins

Schmidt, Lu:
pattern follows quark contributions to anomalous moment

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

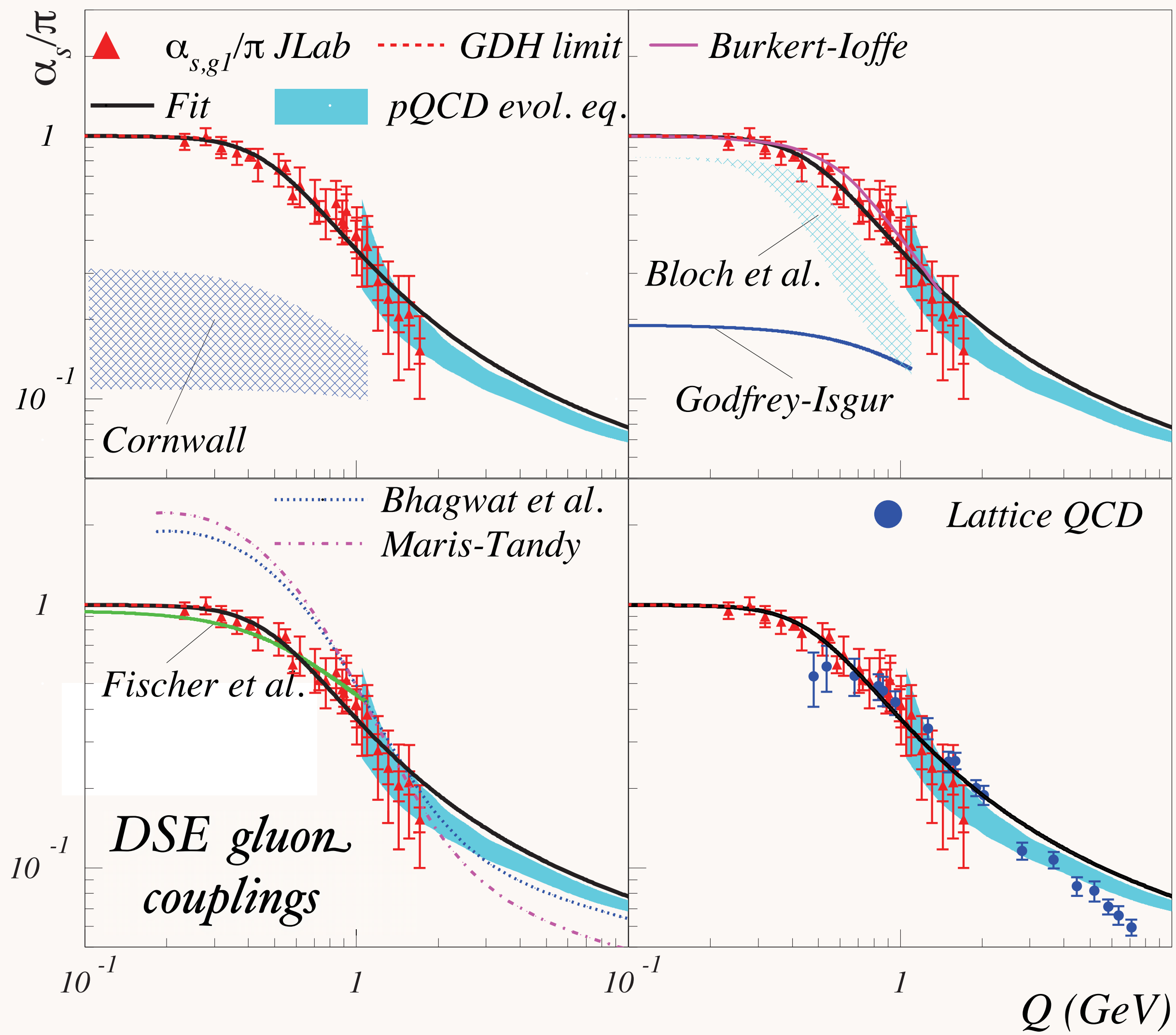
$$\mathbf{i}\ \vec{S} \cdot \vec{p}_{jet} \times \vec{q}$$

- 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



Conformal window
Infrared fixed-point

$$\beta(Q^2) = \frac{d\alpha_s(Q^2)}{d\log Q^2} \to 0$$

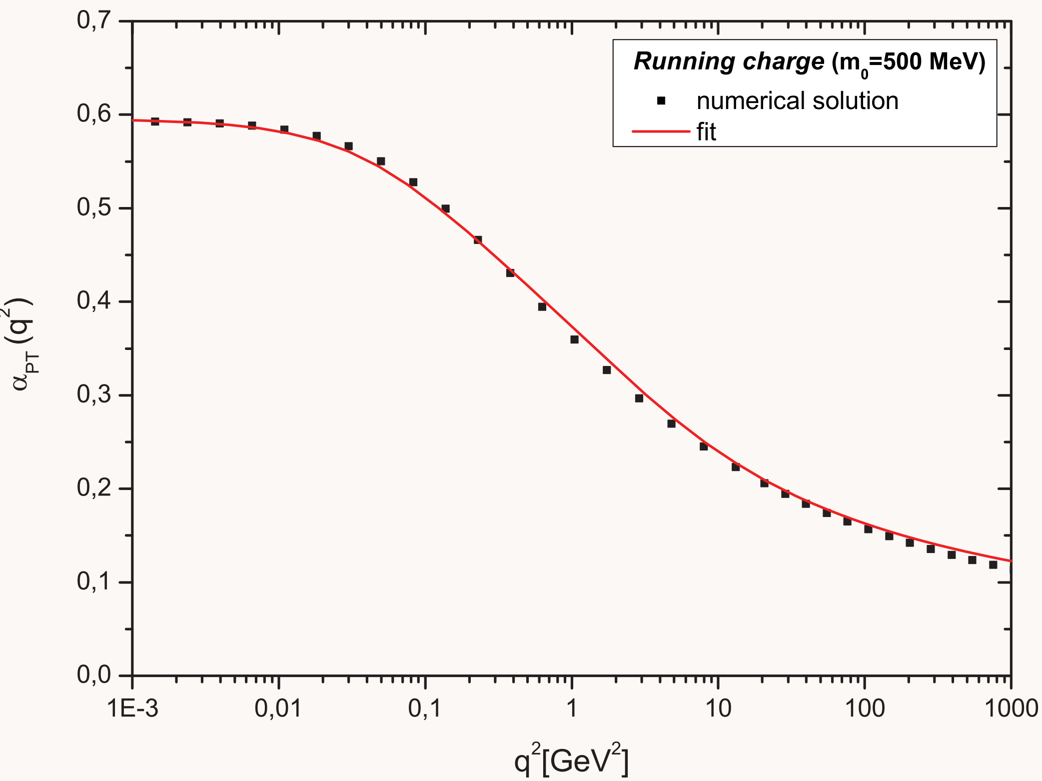


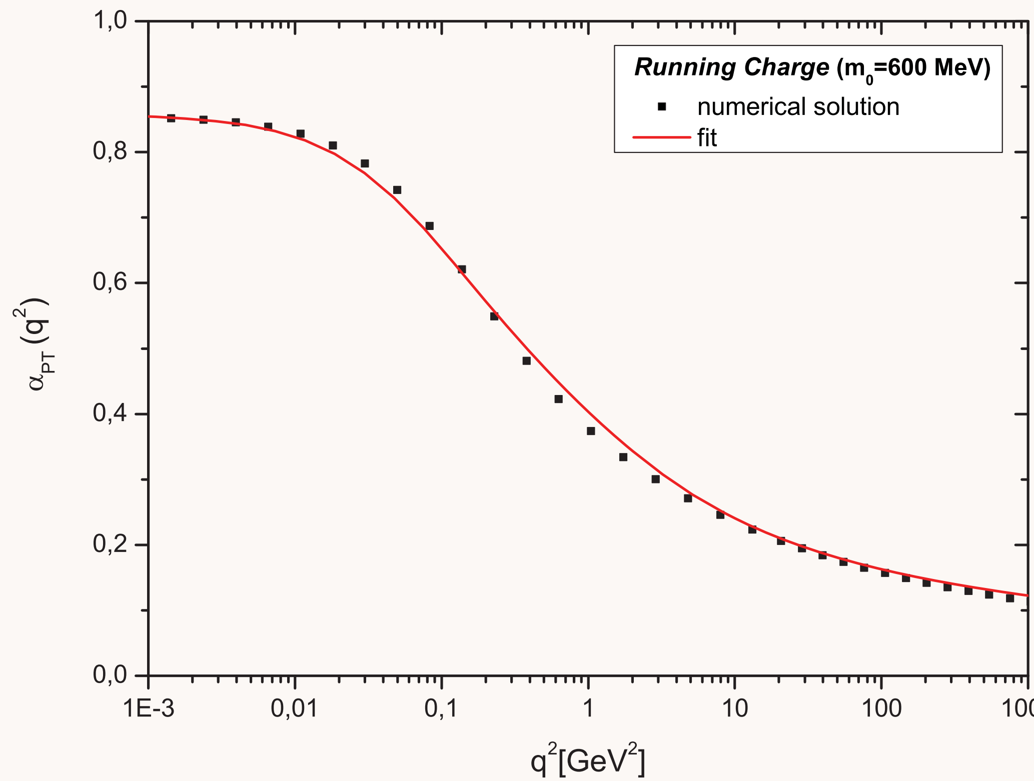
Deur, Korsch, et al.

Conformal window

Infrared fixed-point

$$\beta(Q^2) = \frac{d\alpha_s(Q^2)}{d\log Q^2} \to 0$$





Non-perturbative comparison of QCD effective charges

A. C. Aguilar,[1] D. Binosi,[2] J. Papavassiliou,[3] and J. Rodríguez-Quintero[4]

Single-spin asymmetries

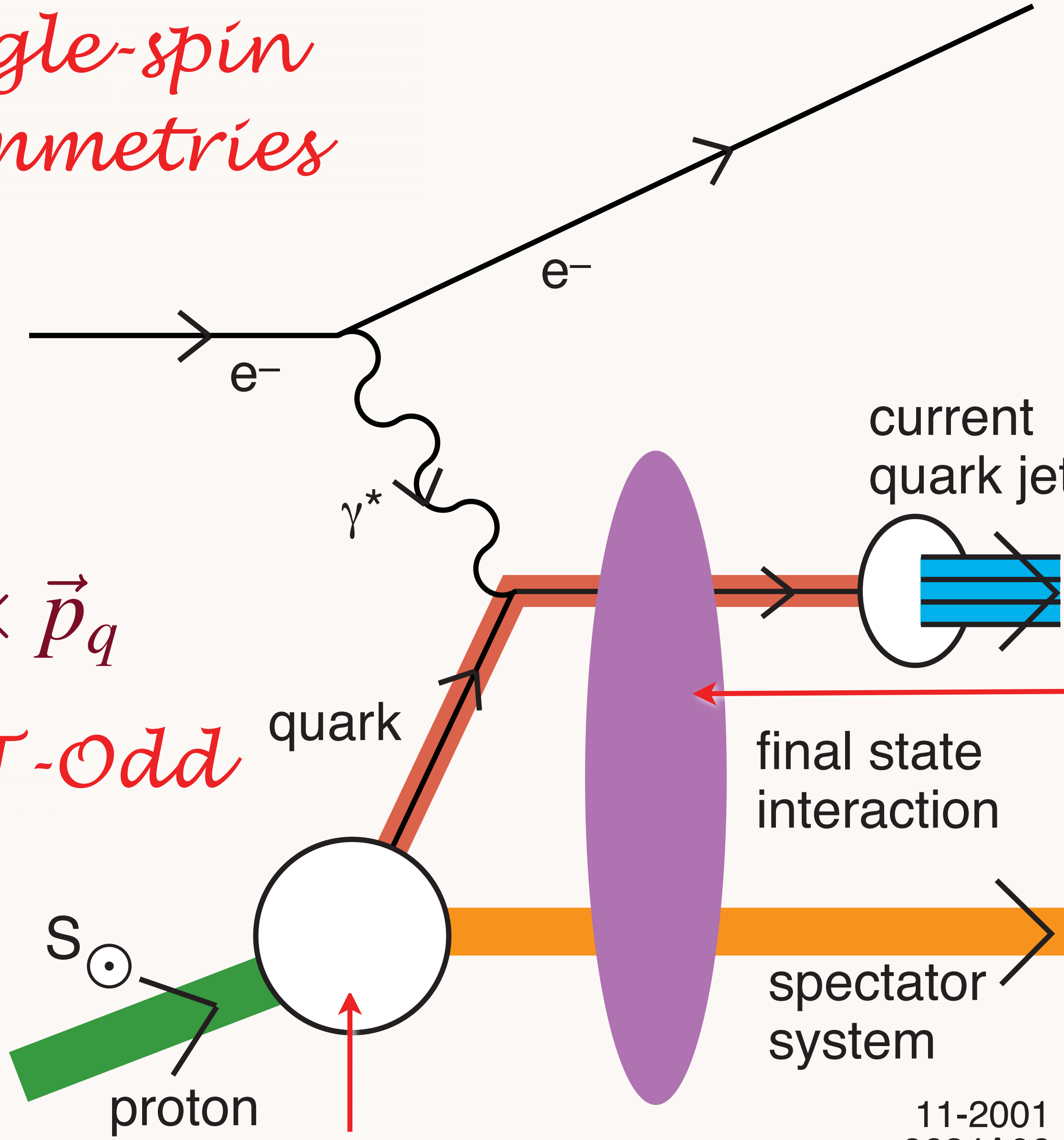
Leading Twist Sivers Effect

Hwang, Schmidt, sjb

Collins, Burkardt Ji, Yuan

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

Pseudo-T-Odd

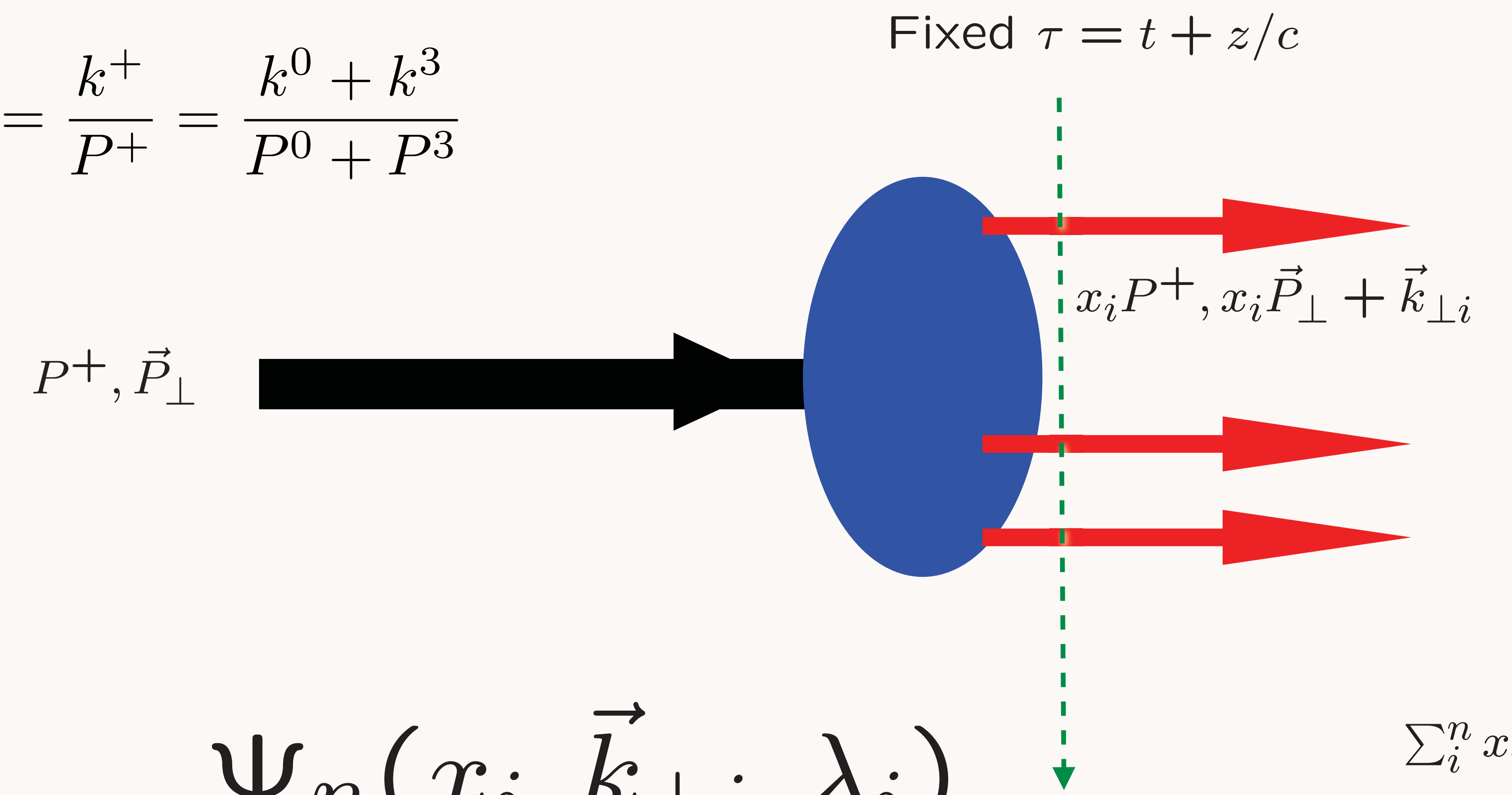


QCD S- and P-Coulomb Phases --Wilson Line

Light-Front Wavefunction S and P- Waves

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

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



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

$\sum_i^n x_i = 1$

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

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

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

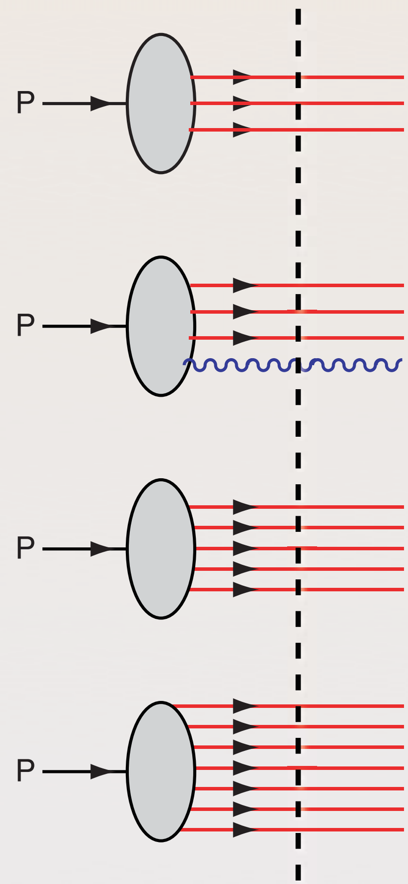
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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.

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

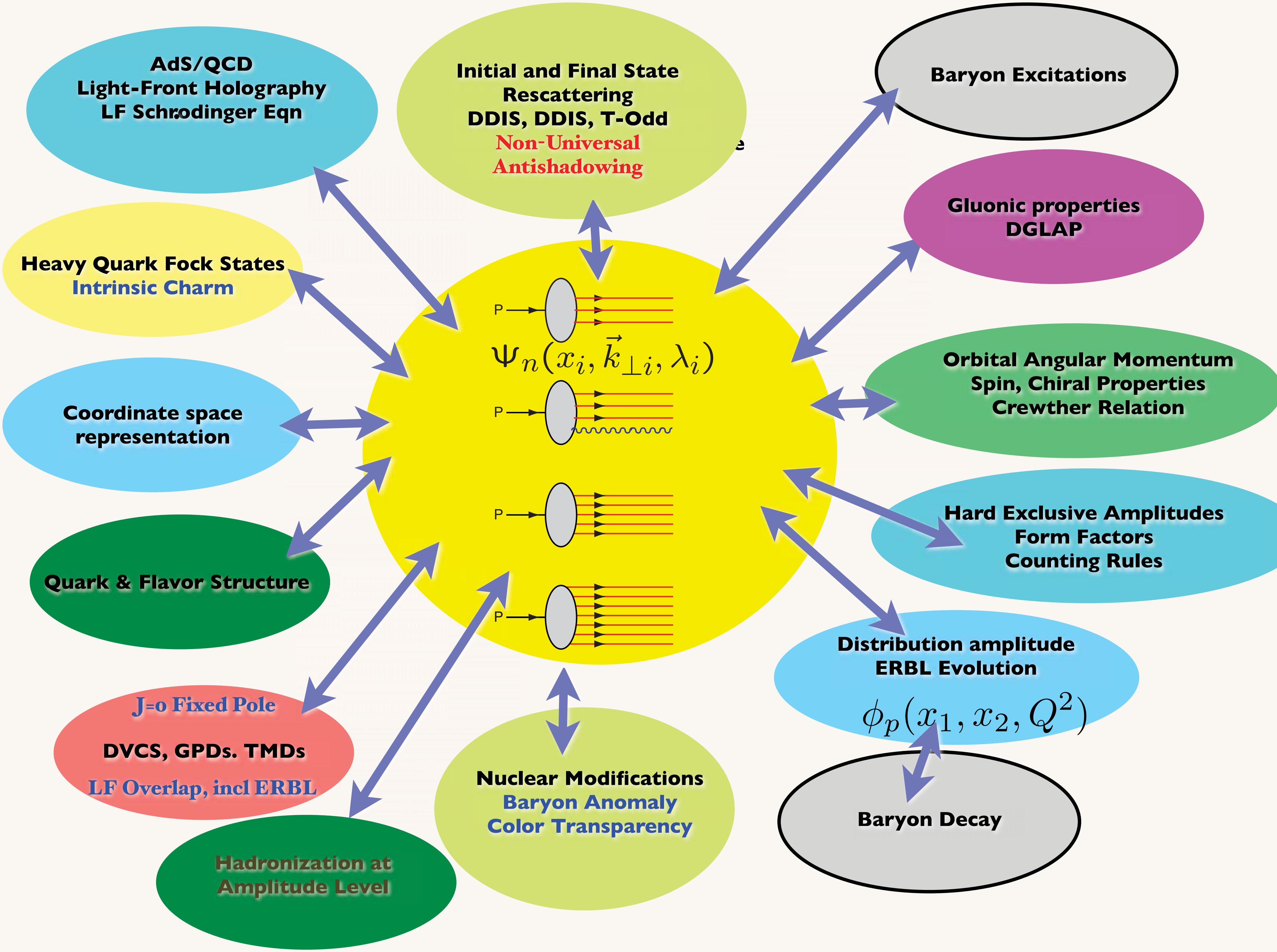


Fixed LF time

Intrinsic heavy quarks,

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

QCD and the LF Hadron Wavefunctions



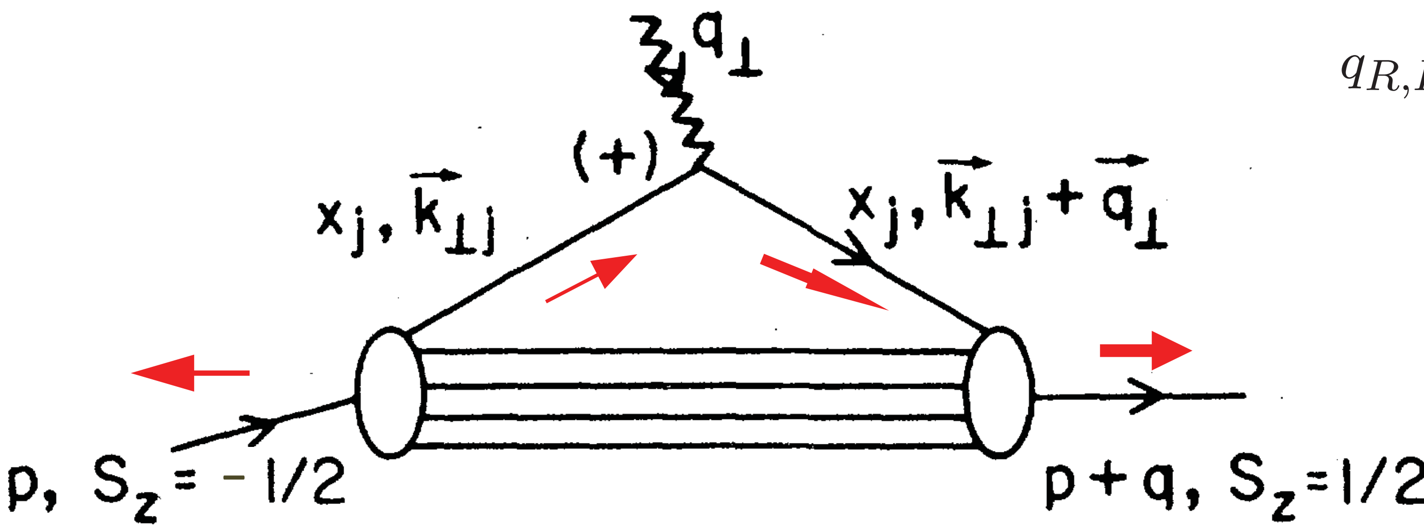
Drell, sjb

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

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

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

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



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

Final State Interactions Produce T-Odd (Sivers Effect)

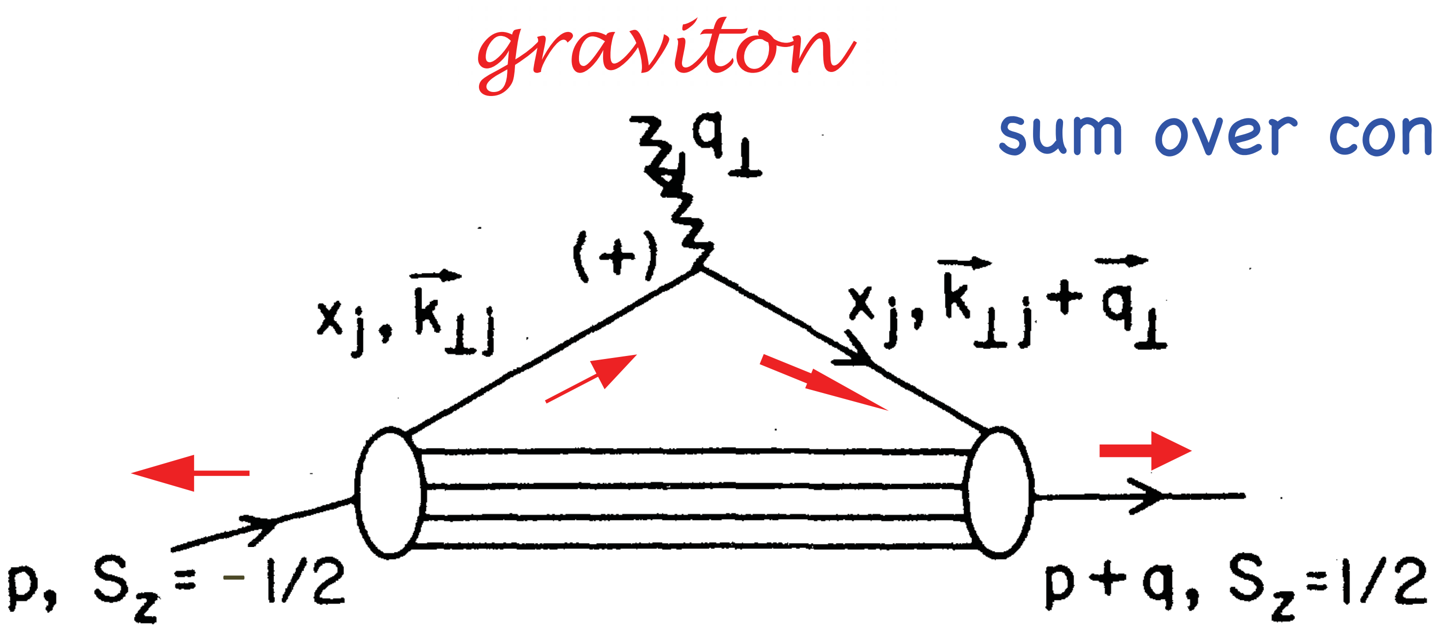
- Bjorken Scaling!
- Arises from Interference of Final-State Coulomb Phases in S and P waves
- Relate to the quark contribution to the target proton anomalous magnetic moment
- Sum of Sivers Functions for all quarks and gluons vanishes. (Zero anomalous gavitomagnetic moment)

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

Hwang, Schmidt. sjb; Burkardt

Anomalous gravitomagnetic moment B(0)

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



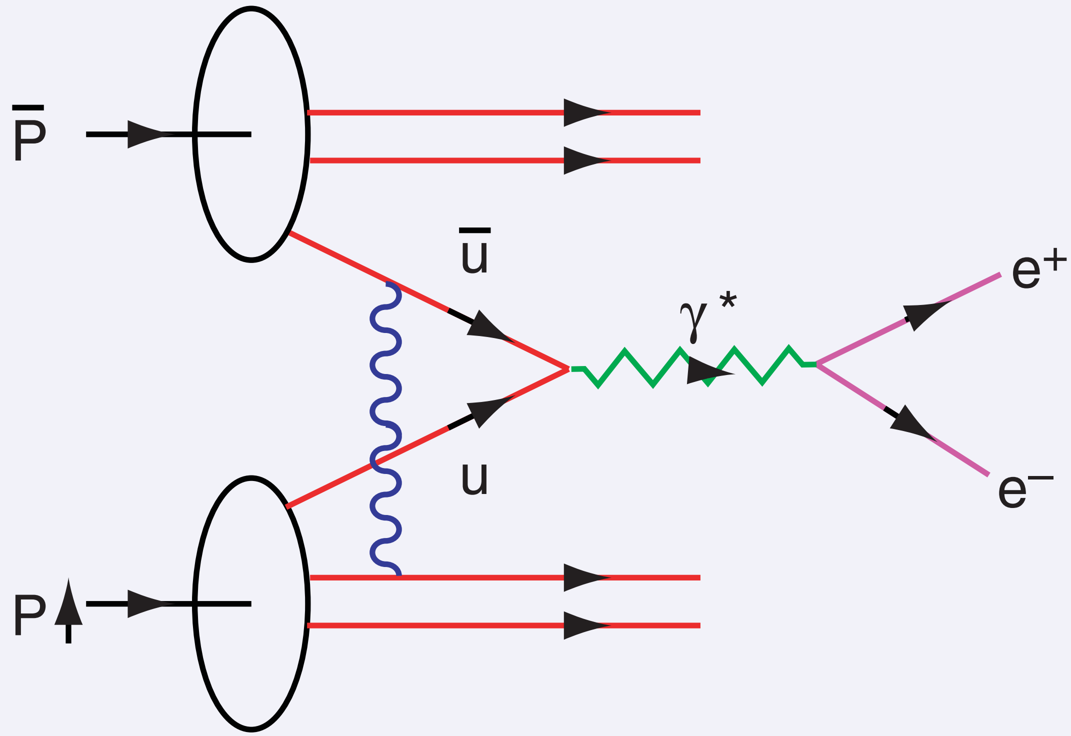
sum over constituents

Hwang, Schmidt, sjb; Holstein et al

$B(0) = 0$

Each Fock State

Predict Opposite Sign SSA in DY !



Collins;
Hwang,
Schmidt. sjb

Single Spin Asymmetry In the Drell Yan Process

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

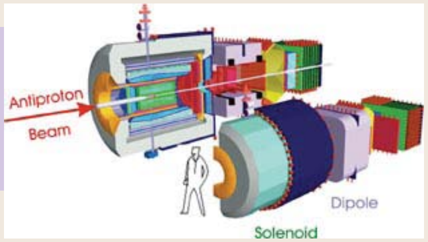
Quarks Interact in the Initial State

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

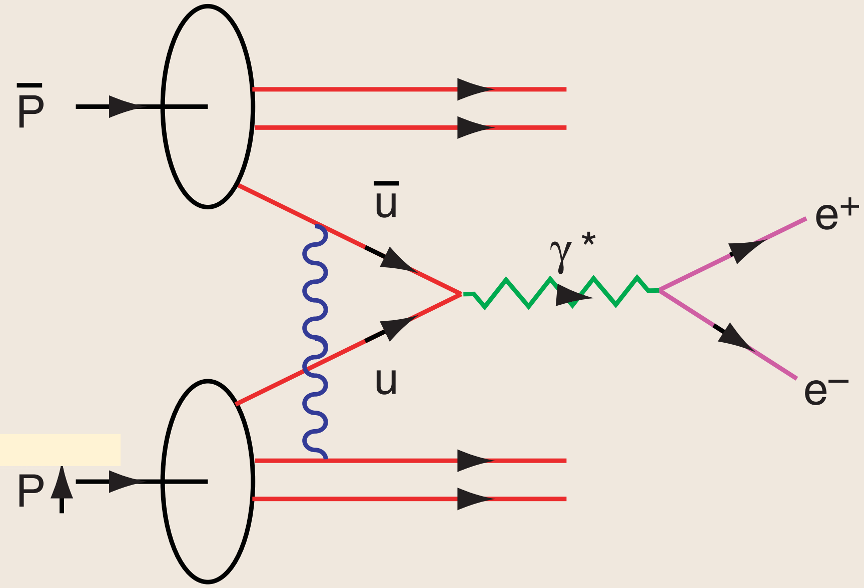
Key QCD Panda Experiment



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!



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

$$Q^2 = x_1 x_2 s$$

$$Q^2 = 4 \text{ GeV}^2, s = 80 \text{ GeV}^2$$

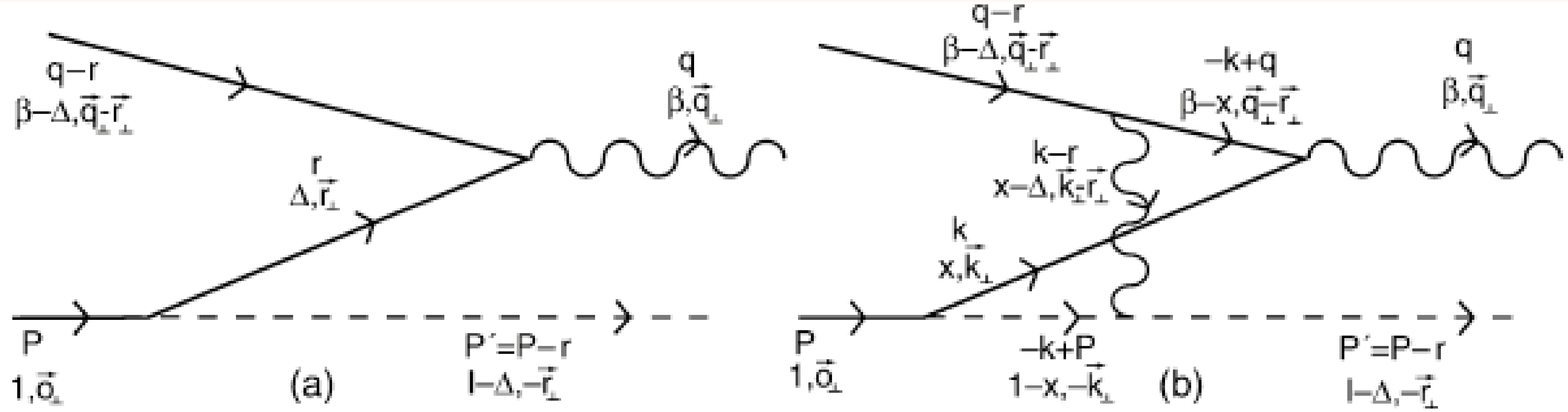
$\vec{S} \cdot \vec{q} \times \vec{p}$ correlation

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

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

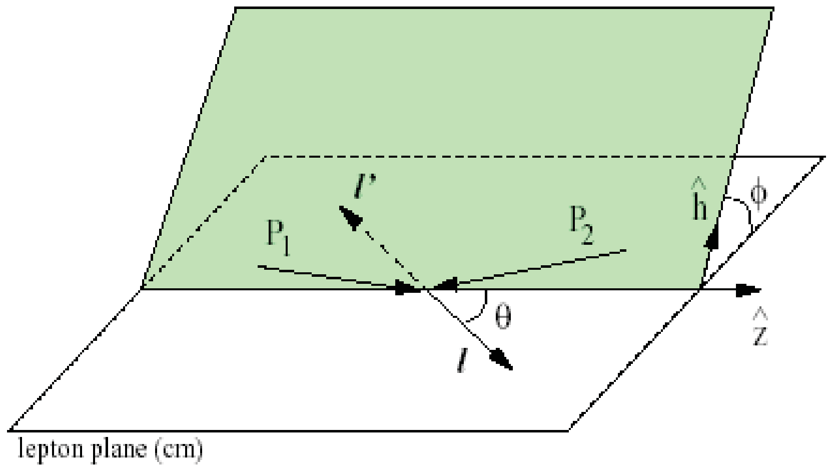


$$\mathcal{P}_y = -\frac{e_1 e_2}{8\pi}\frac{2(\Delta M + m) r^1}{[(\Delta M + m)^2 + \vec{r}_\perp^{\,2}]}\left[\vec{r}_\perp^{\,2} + \Delta(1-\Delta)\left(-M^2 + \frac{m^2}{\Delta} + \frac{\lambda^2}{1-\Delta}\right)\right]$$

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

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

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

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

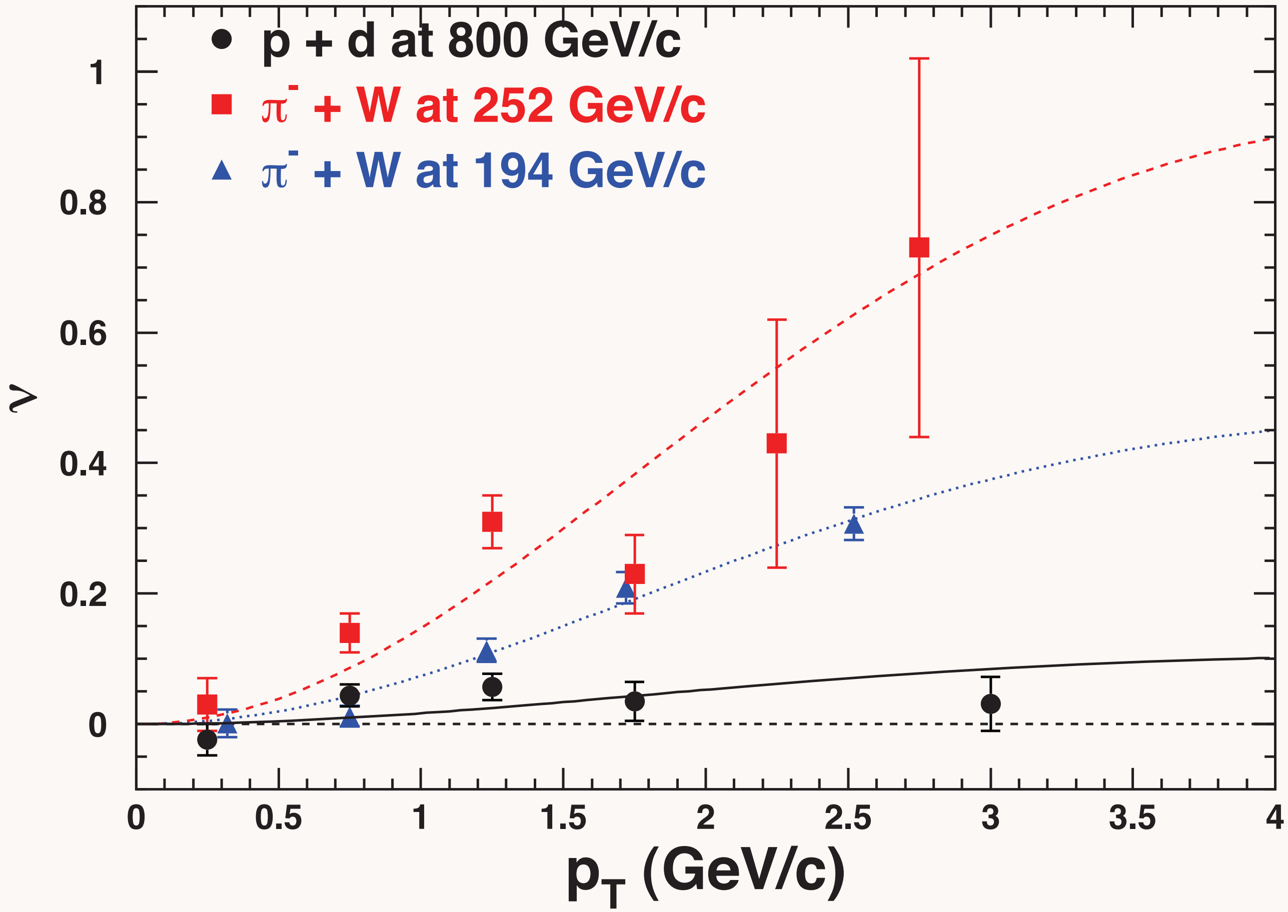
$\text{experiment}: \ \nu \approx 0.3$

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

B. Seitz

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

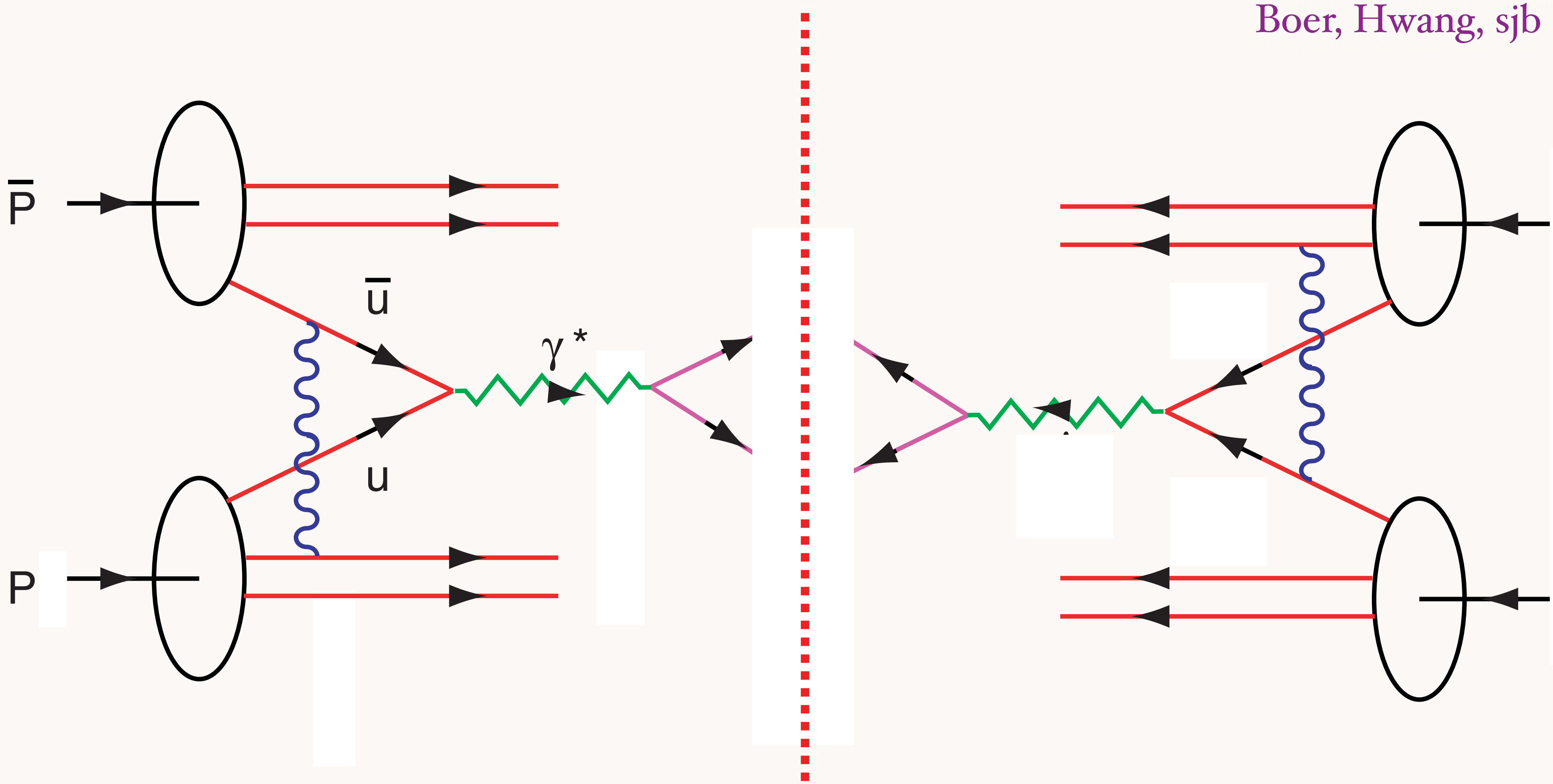
(FNAL E866/NuSea Collaboration)



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

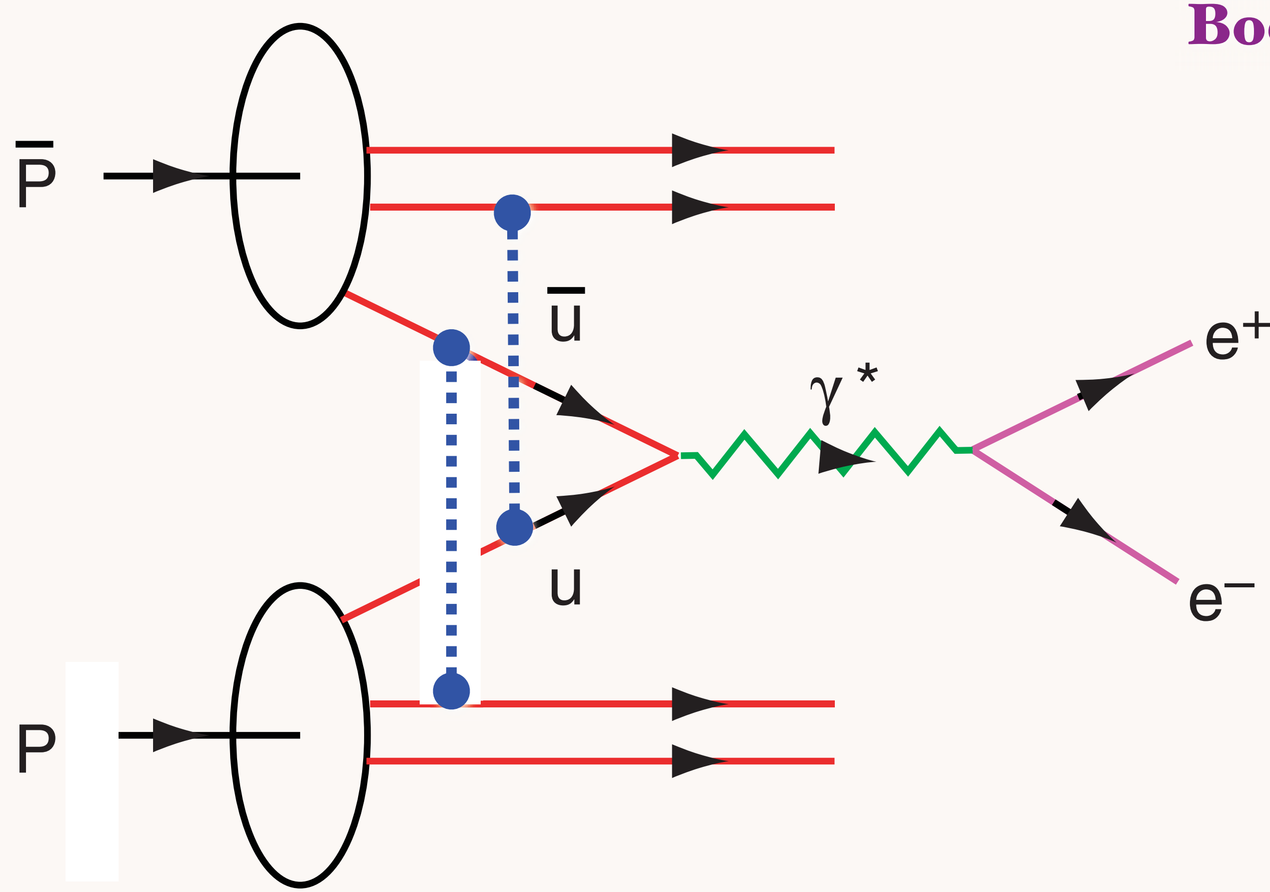
Parameter ν vs. p_T in the Collins-Soper frame for three Drell-Yan measurements. Fits to the data using Eq. 3 and $M_C = 2.4$ GeV/c^2 are also shown.

Boer, Hwang, sjb



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

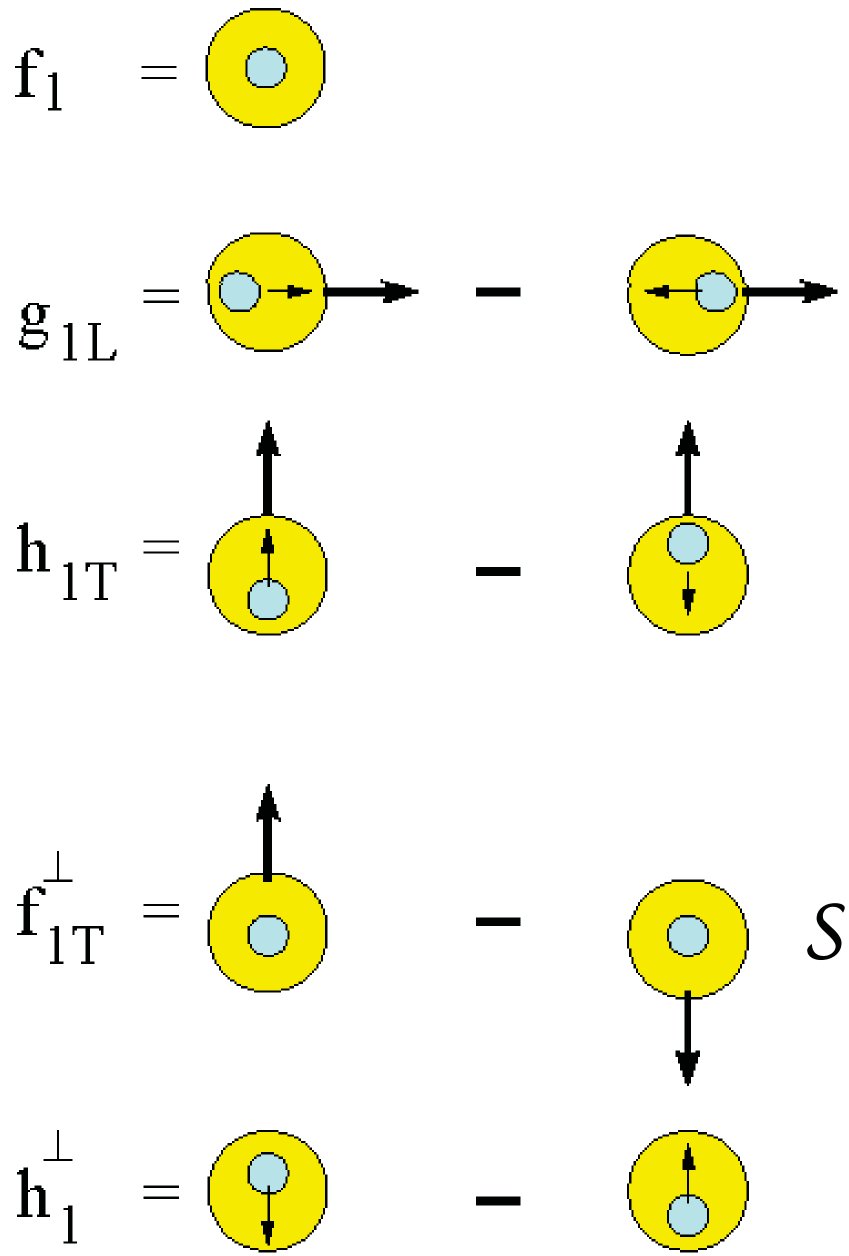
Boer, Hwang, sjb



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 $\cos 2\phi$

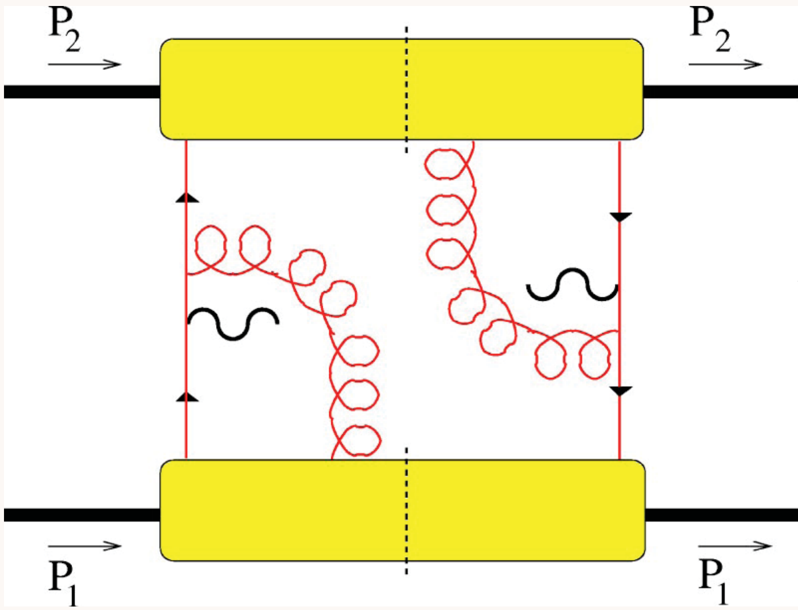
Boer, Hwang, sjb

Drell-Yan planar correlations

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

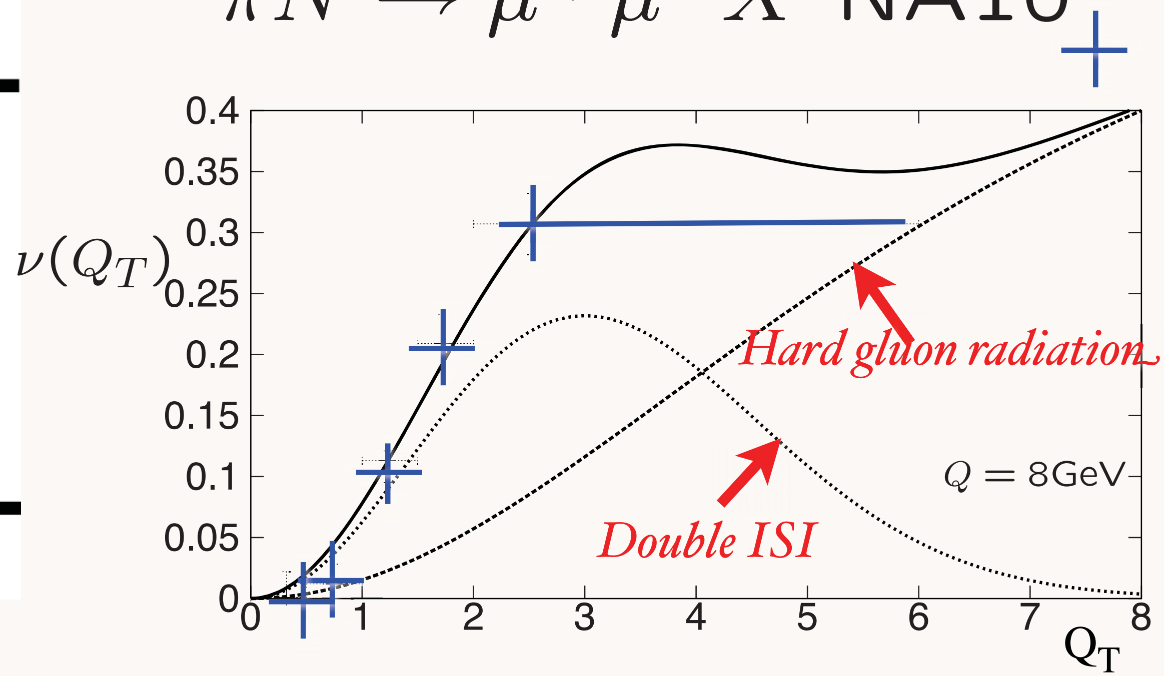
PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

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



Violates Lam-Tung relation!

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

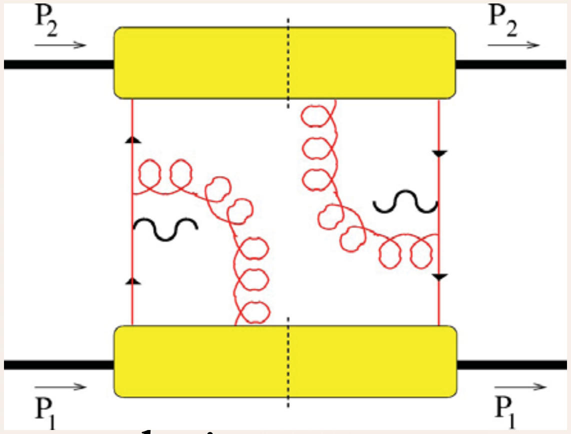


Model: Boer,

Anomalous effect from Double ISI in Massive Lepton Production

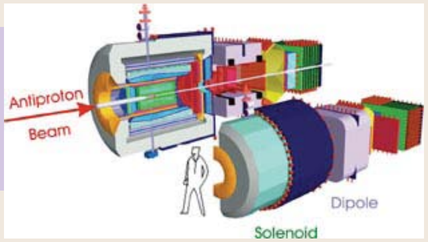
Boer, Hwang, sjb

$\cos 2\phi$ correlation

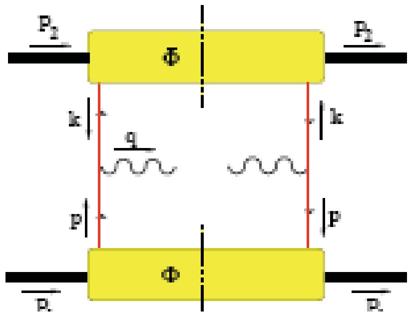


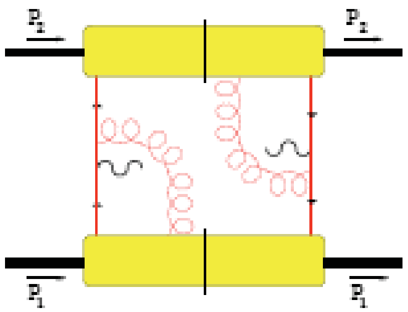
- Leading Twist, valence quark dominated
- Violates Lam-Tung Relation!
- Not obtained from standard PQCD subprocess analysis
- Normalized to the square of the single spin asymmetry in semi-inclusive DIS
- No polarization required
- Challenge to standard picture of PQCD Factorization

Key QCD Panda Experiment



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

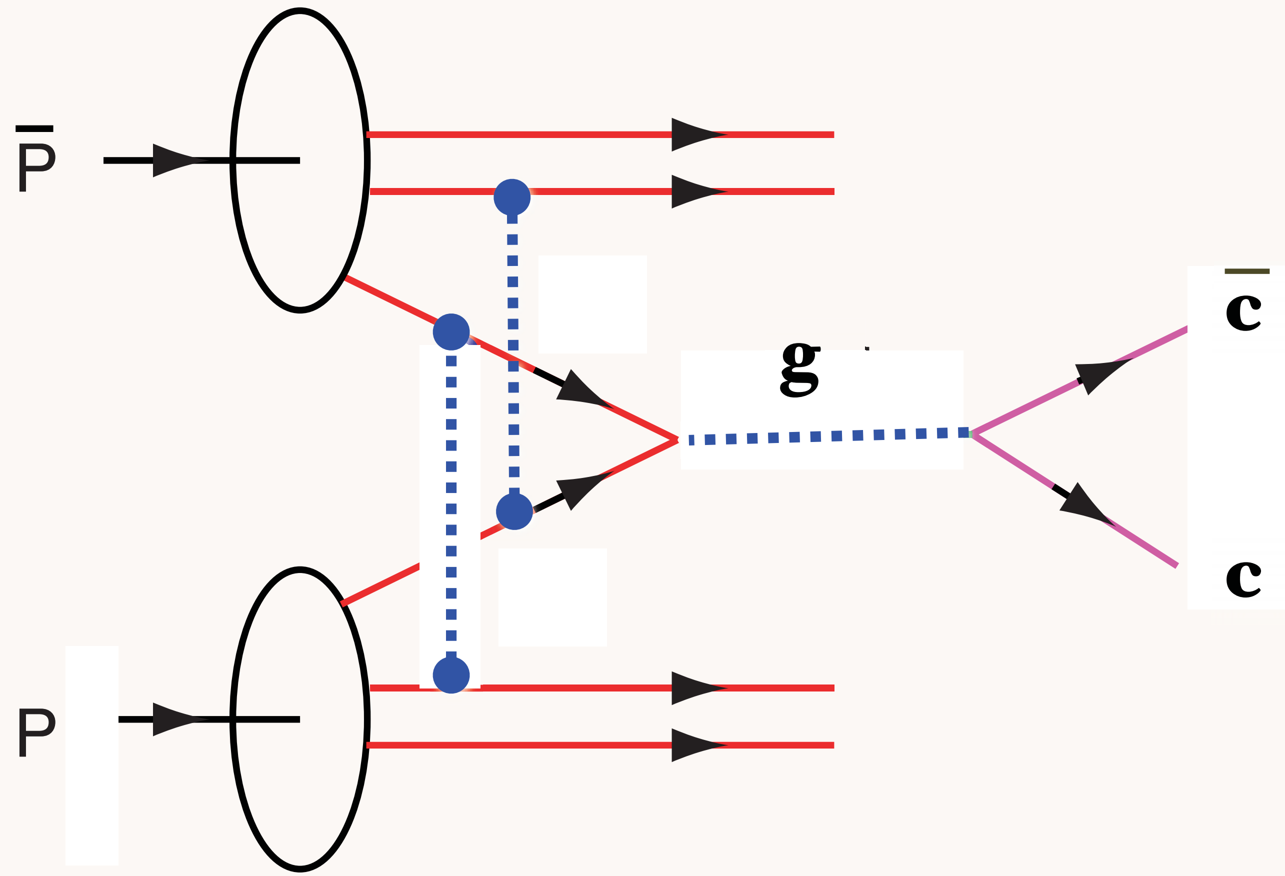




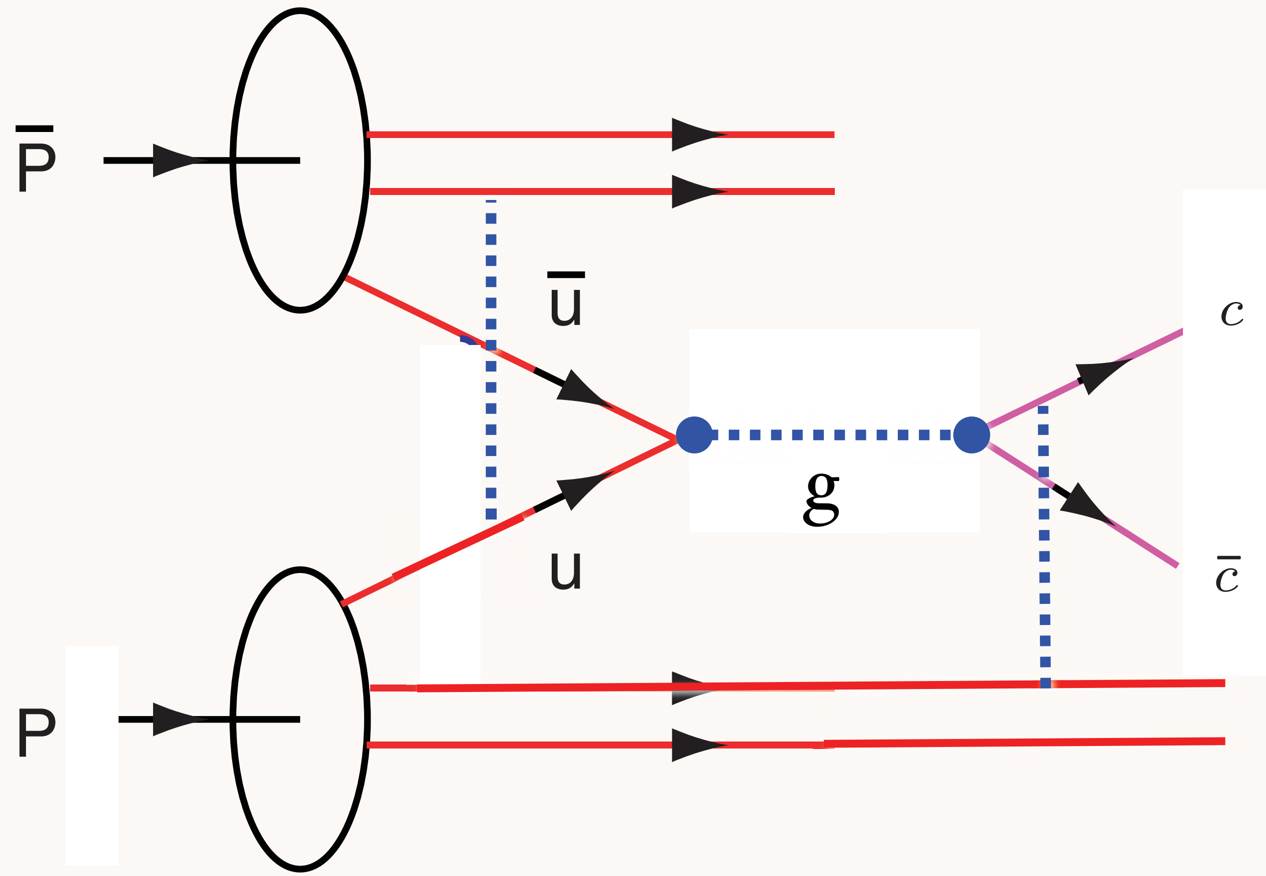
Boer, Hwang, sjb

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**

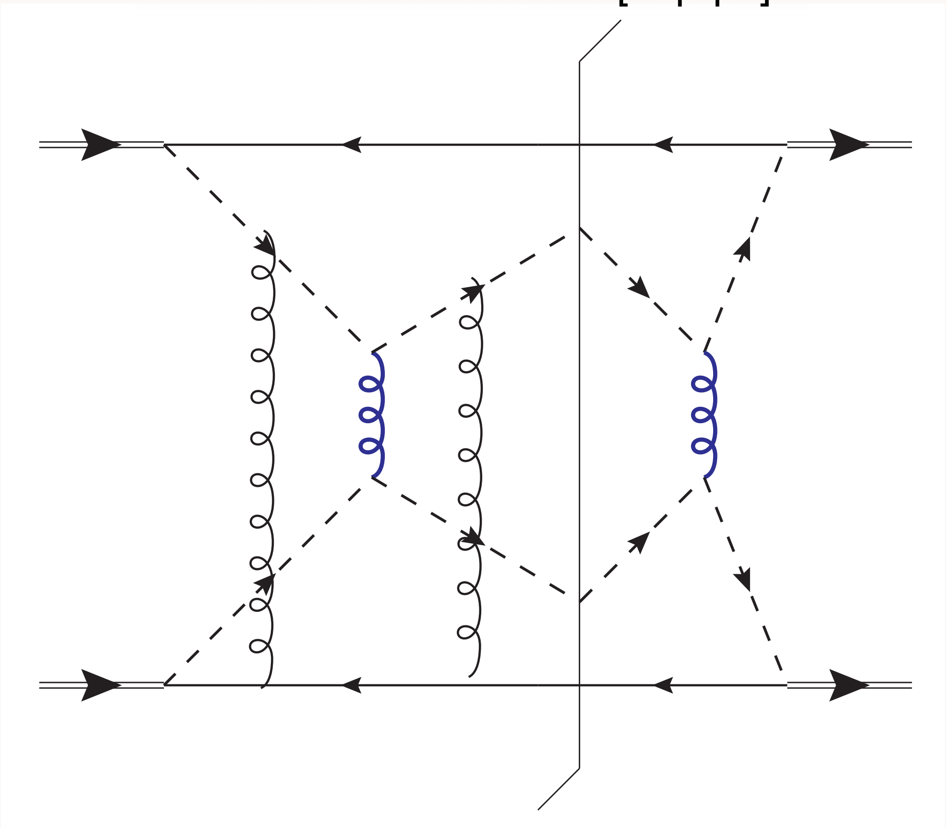


Problem for factorization when both ISI and FSI occur

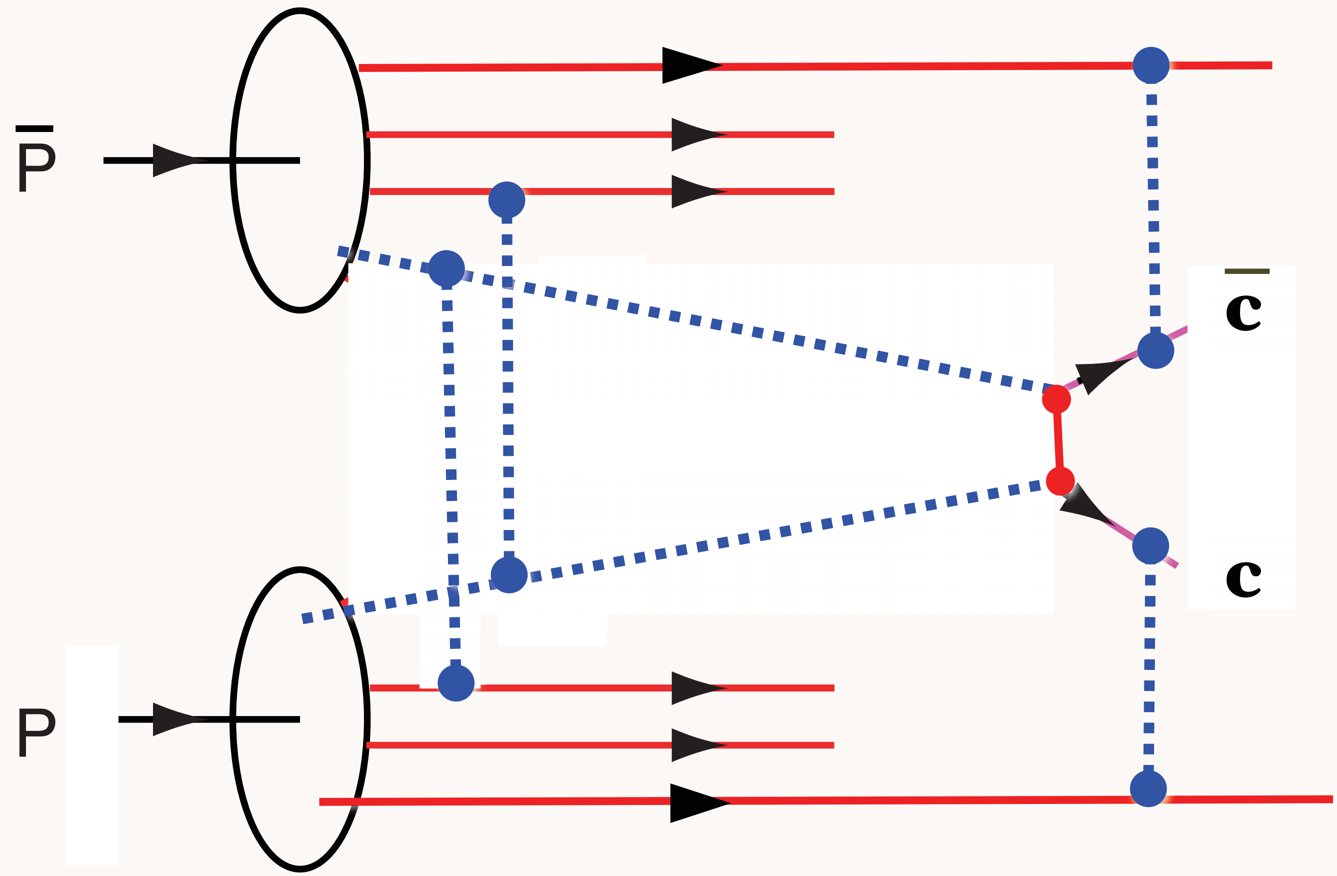
Factorization is violated in production of high-transverse-momentum particles in hadron-hadron collisions

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

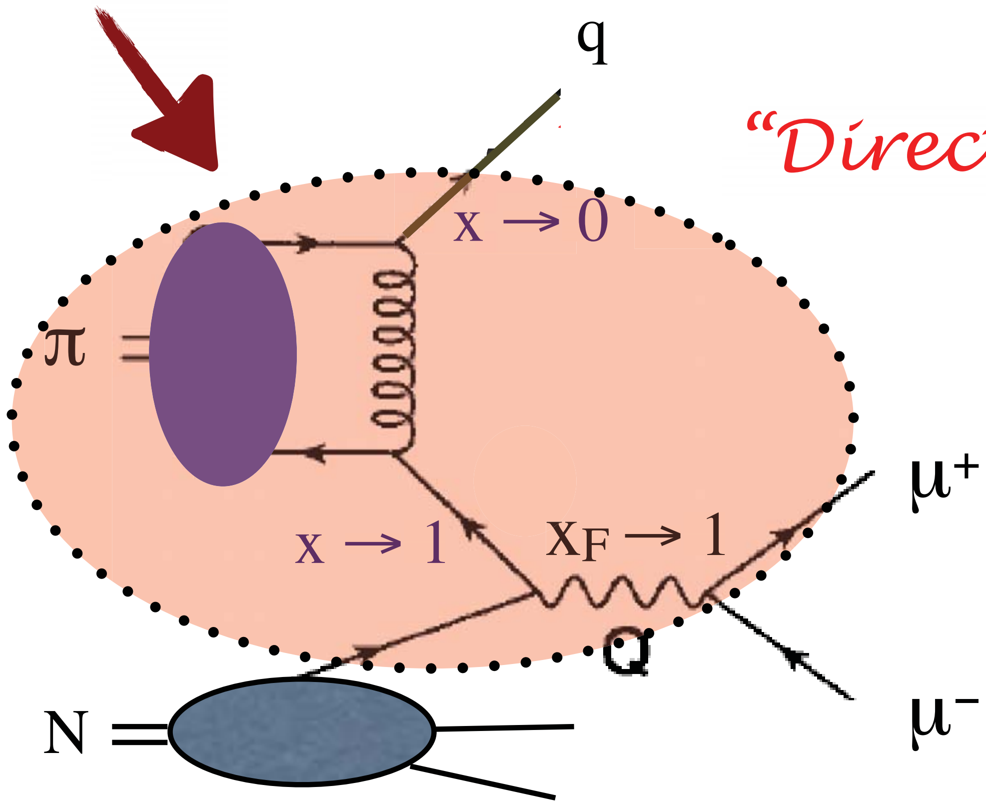
Also possible FSI

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



Virtual photon is longitudinally polarized

Berger, sjb
Khoze, Brandenburg, Muller, sjb

Hoyer Vanttinen

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

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

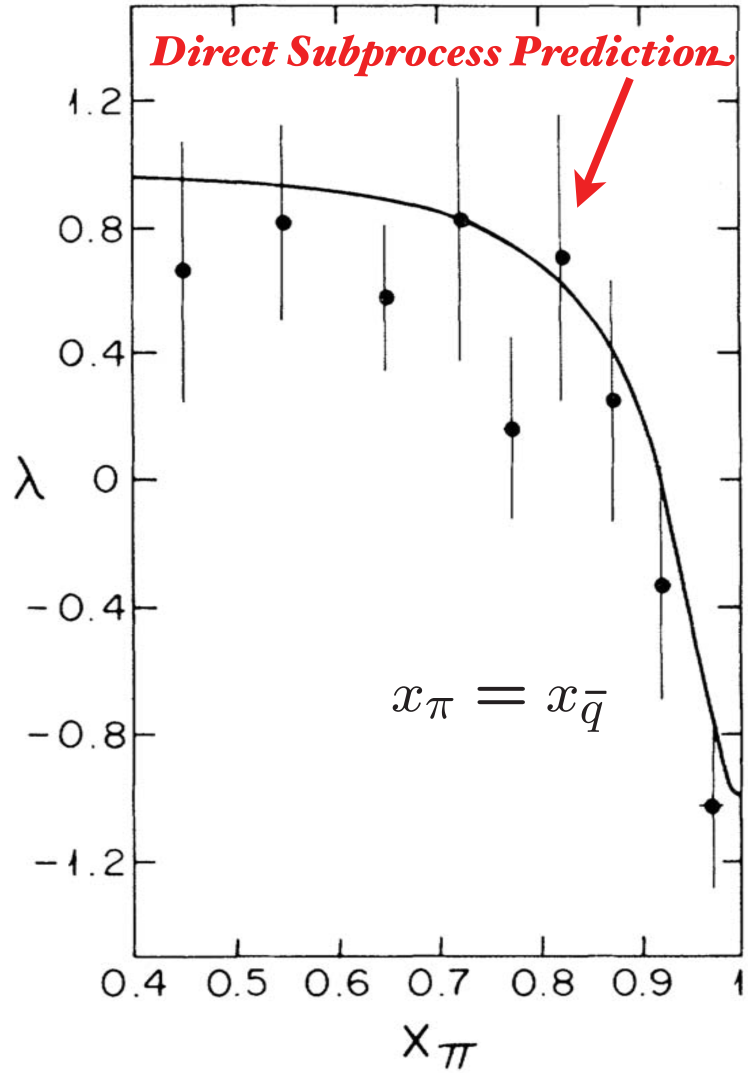
$$\frac{d^2\sigma}{dx_\pi d\cos\theta} \propto x_\pi \left[(1-x_\pi)^2 (1+\cos^2\theta) + \frac{4}{9} \frac{\langle k_T^2 \rangle}{M^2} \sin^2\theta \right]$$

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

$$Q^2 = M^2$$

Dramatic change in angular distribution at large x_F

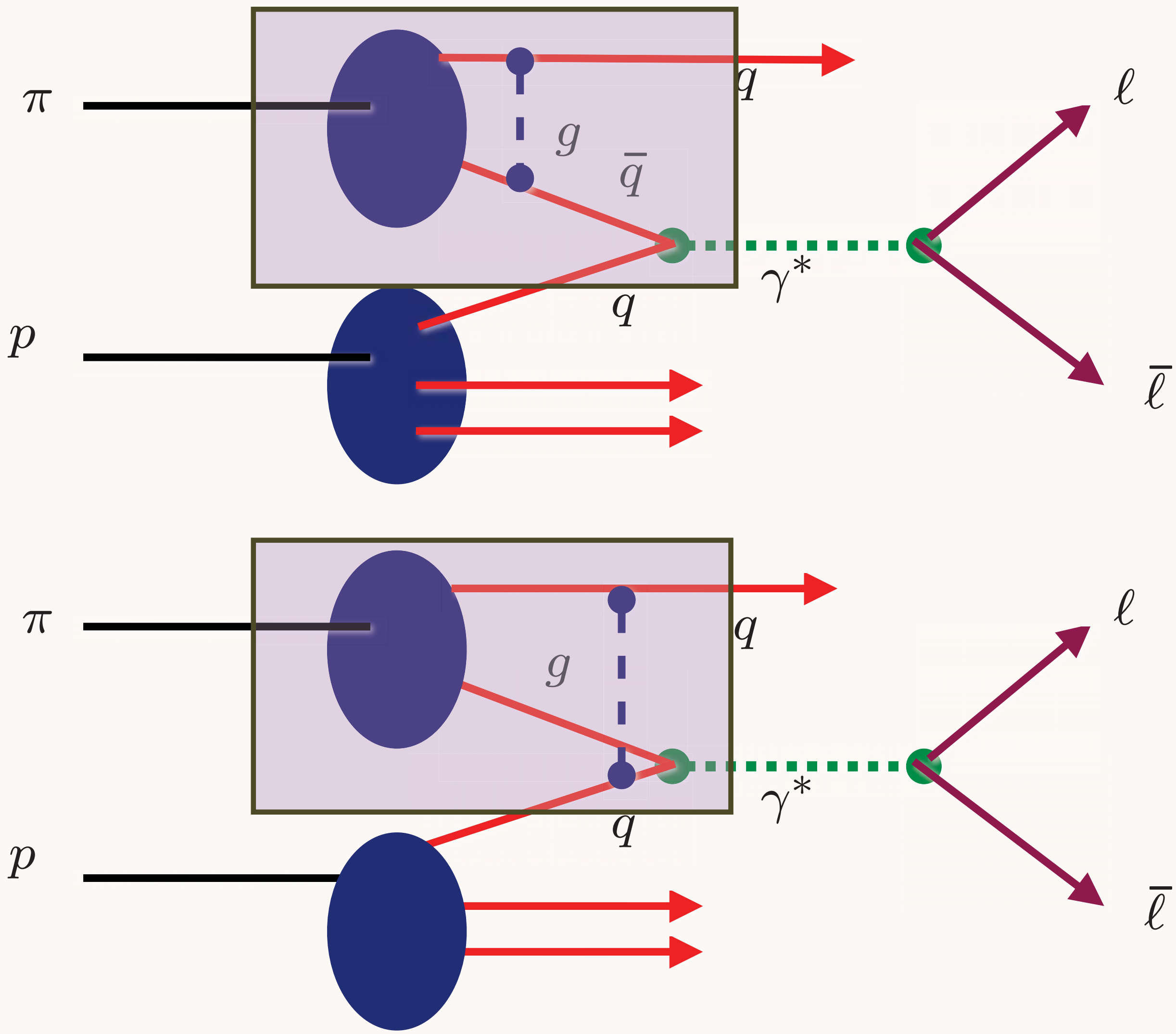
Example of a higher-twist direct subprocess



Chicago-Princeton Collaboration

Phys.Rev.Lett.55:2649,1985

Berger, Lepage, sjb



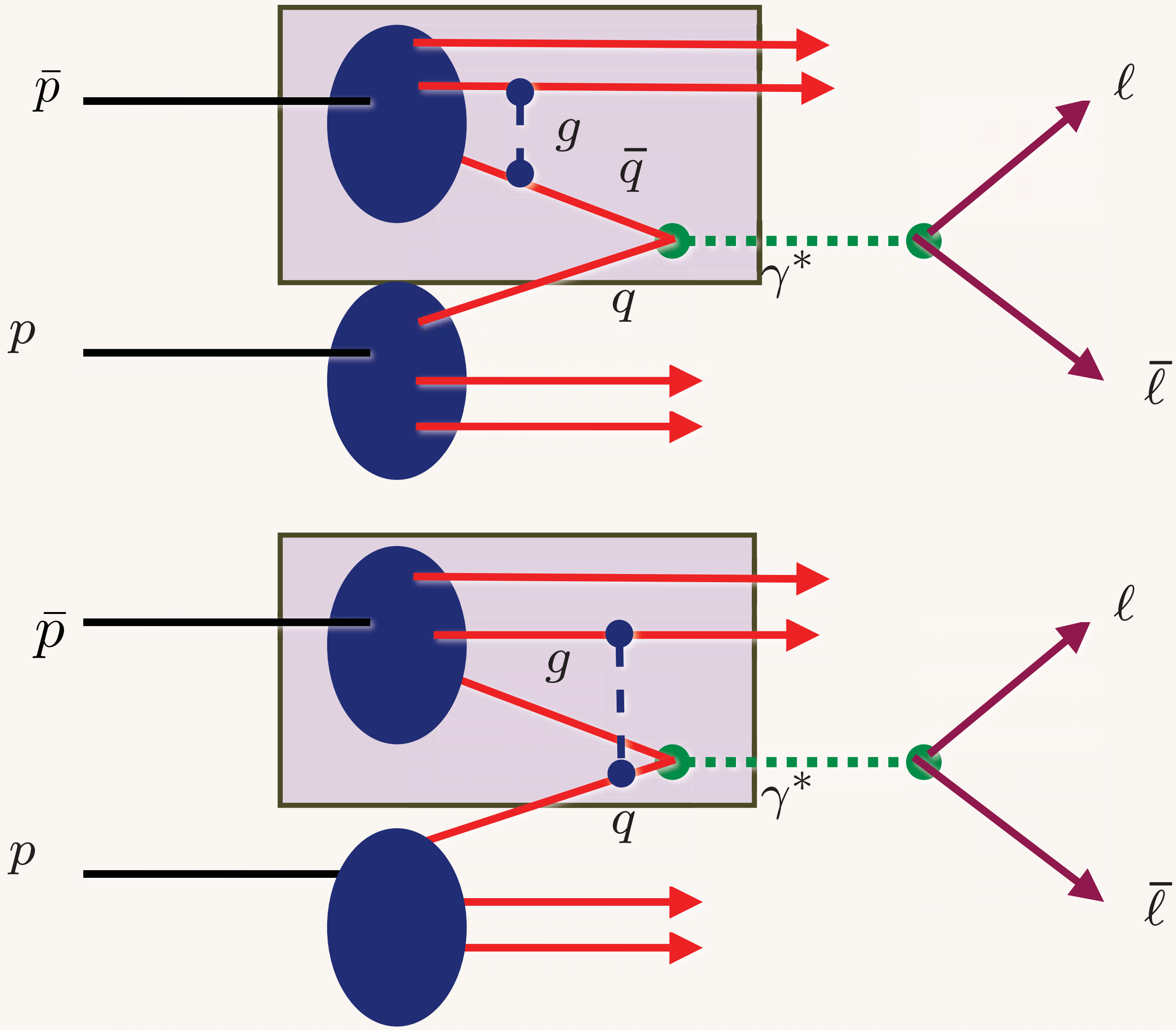
$$\pi q \to \gamma^* q$$

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 Panda Experiment

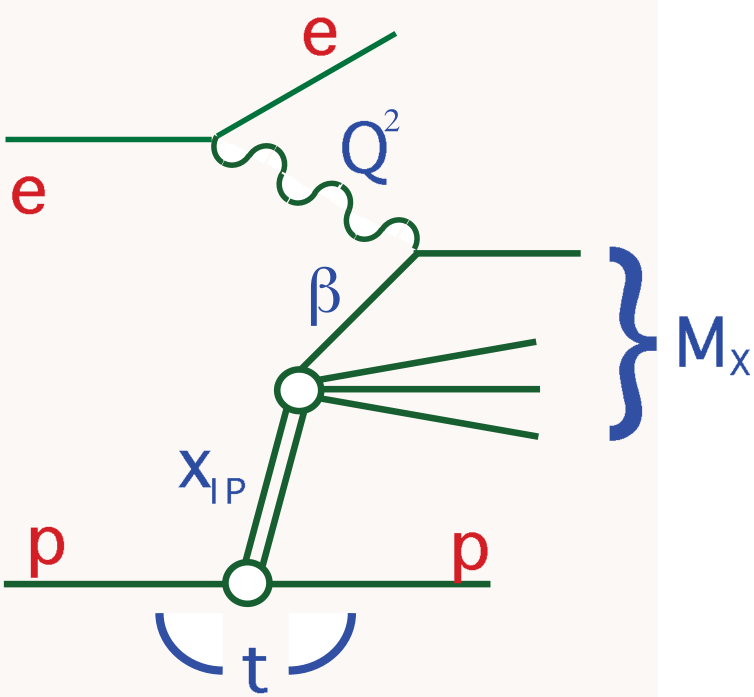
$$[\bar{q}\bar{q}]q \to \gamma^* \bar{q}$$

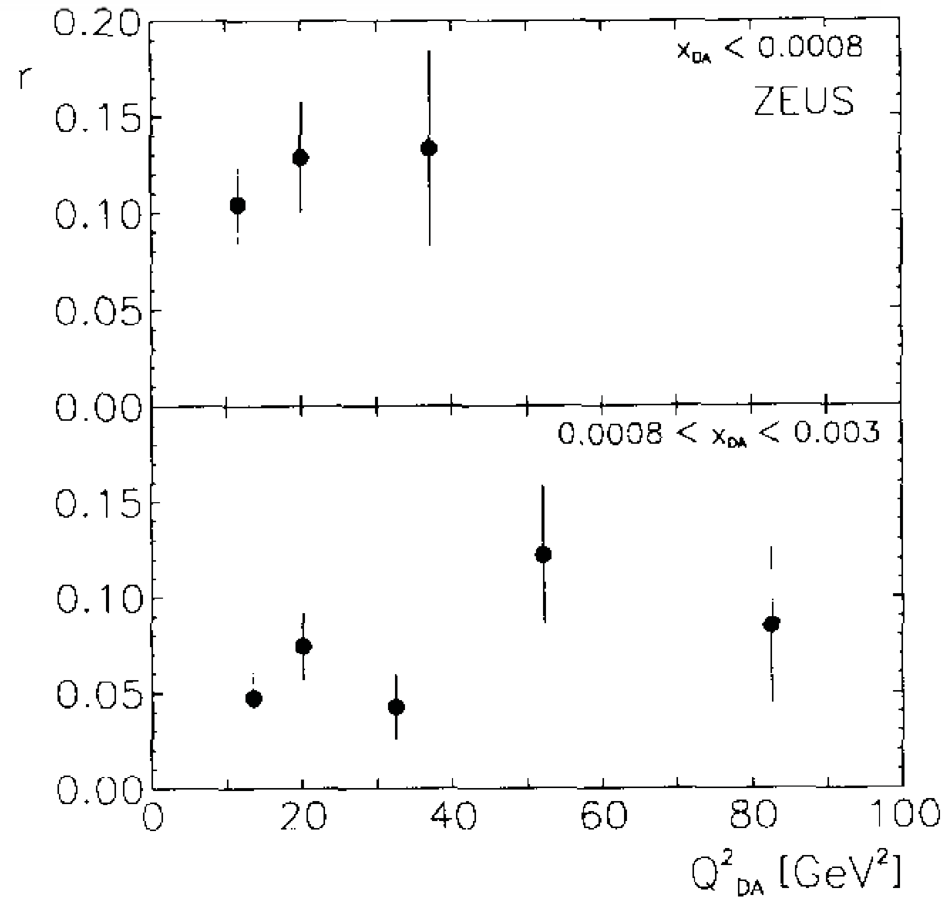
Diquark appears directly in subprocess

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

Lepton Pair is produced longitudinally polarized

Remarkable observation at HERA





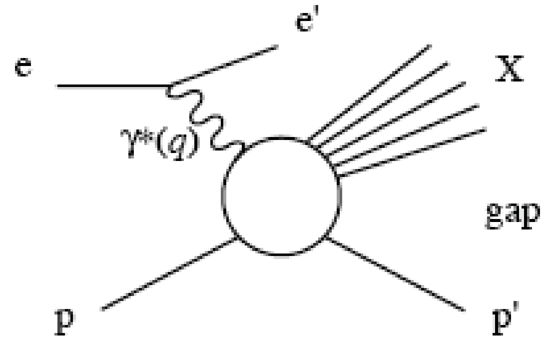
Fraction r of events with a large rapidity gap, $\eta_{max} < 1.5$, as a function of Q^2_{DA} for two ranges of x_{DA}. No acceptance corrections have been applied.

10% to 15% of DIS events are diffractive !

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

DDIS

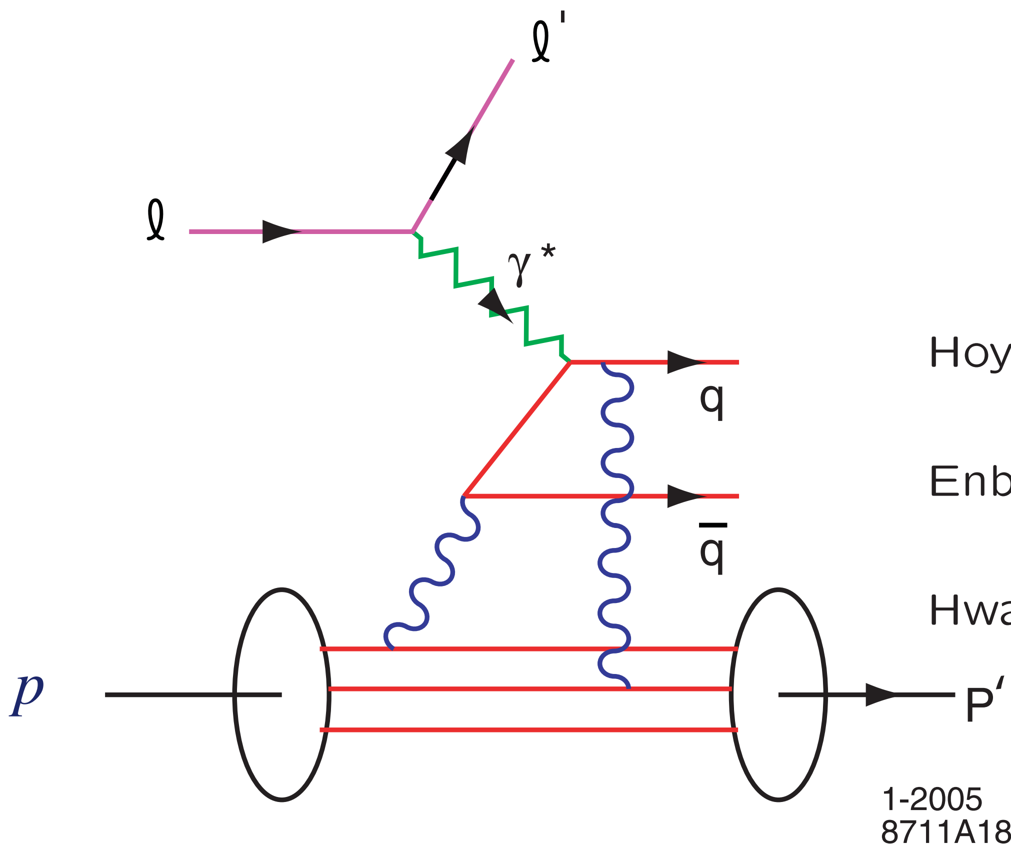
Diffractive Deep Inelastic Lepton-Proton Scattering



- 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

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

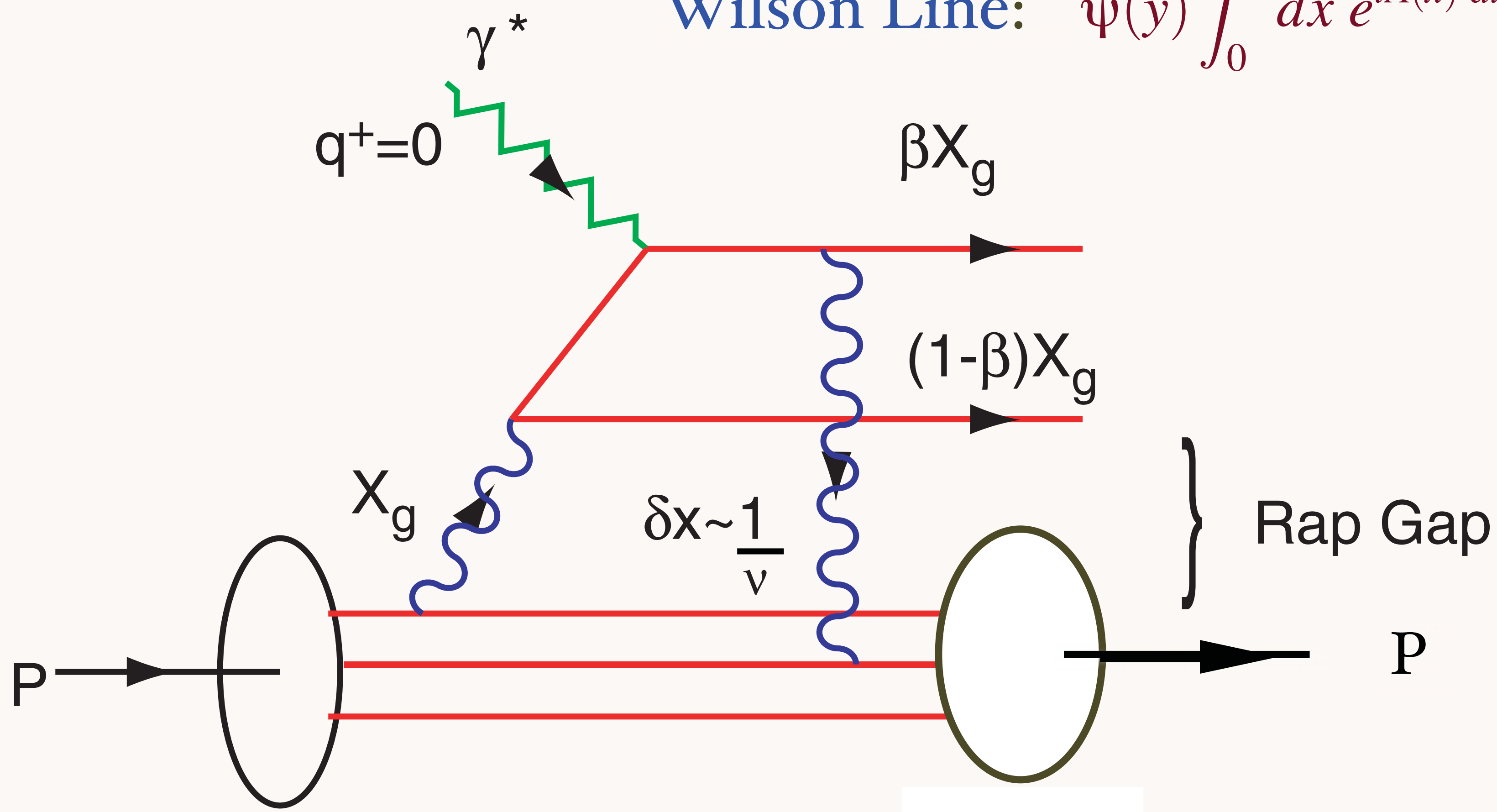
Hwang, Schmidt, SJB

Low-Nussinov model of Pomeron

Hoyer, Marchal, Peigne, Sannino, sjb

QCD Mechanism for Rapidity Gaps

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

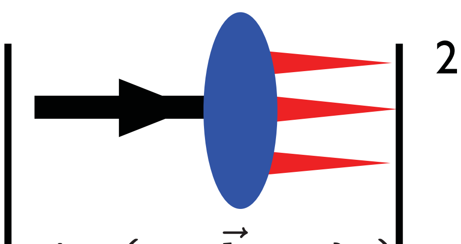


Reproduces lab-frame color dipole approach

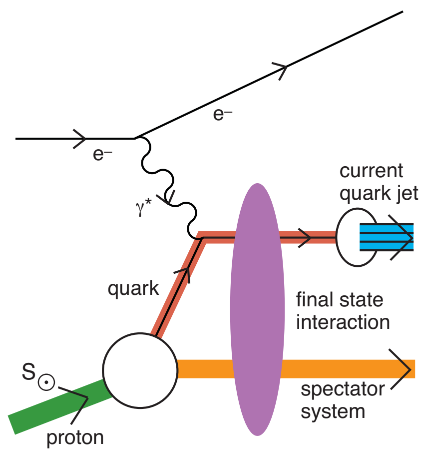
Physics of Rescattering

- 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

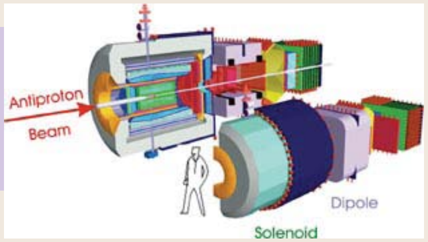
Static	Dynamic
Square of Target LFWFs	Modified by Rescattering: ISI & FSI
No Wilson Line	Contains Wilson Line, Phases
Probability Distributions	No Probabilistic Interpretation
Process-Independent	Process-Dependent - From Collision
T-even Observables	T-Odd (Sivers, Boer-Mulders, etc.)
No Shadowing, Anti-Shadowing	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



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



Key QCD Panda Experiment



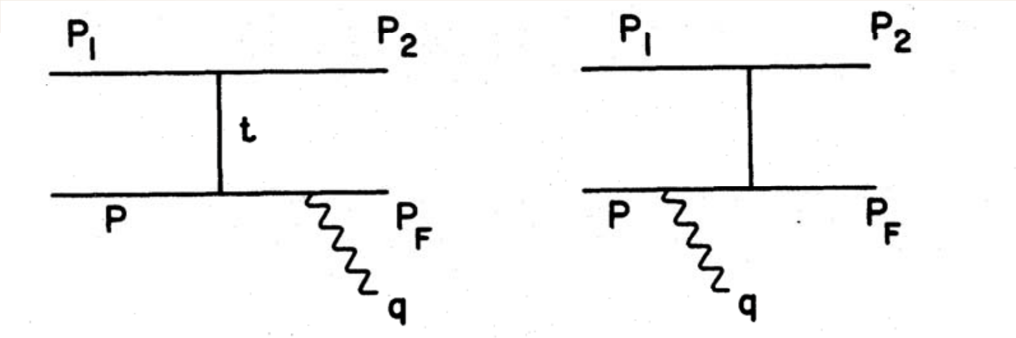
Double-Diffractive Drell-Yan

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

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

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

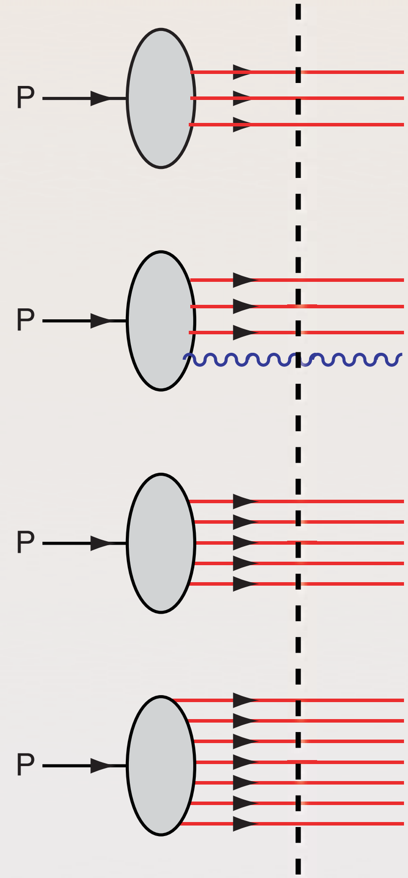
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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.

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



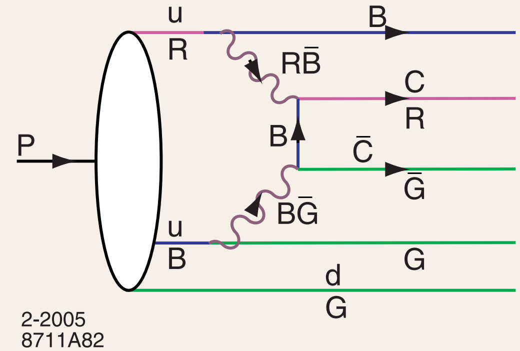
Intrinsic heavy quarks, $\bar{s}(x) \neq s(x)$

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

Fixed LF time

Hoyer, Peterson, Sakai, sjb

Intrinsic Heavy-Quark Fock States

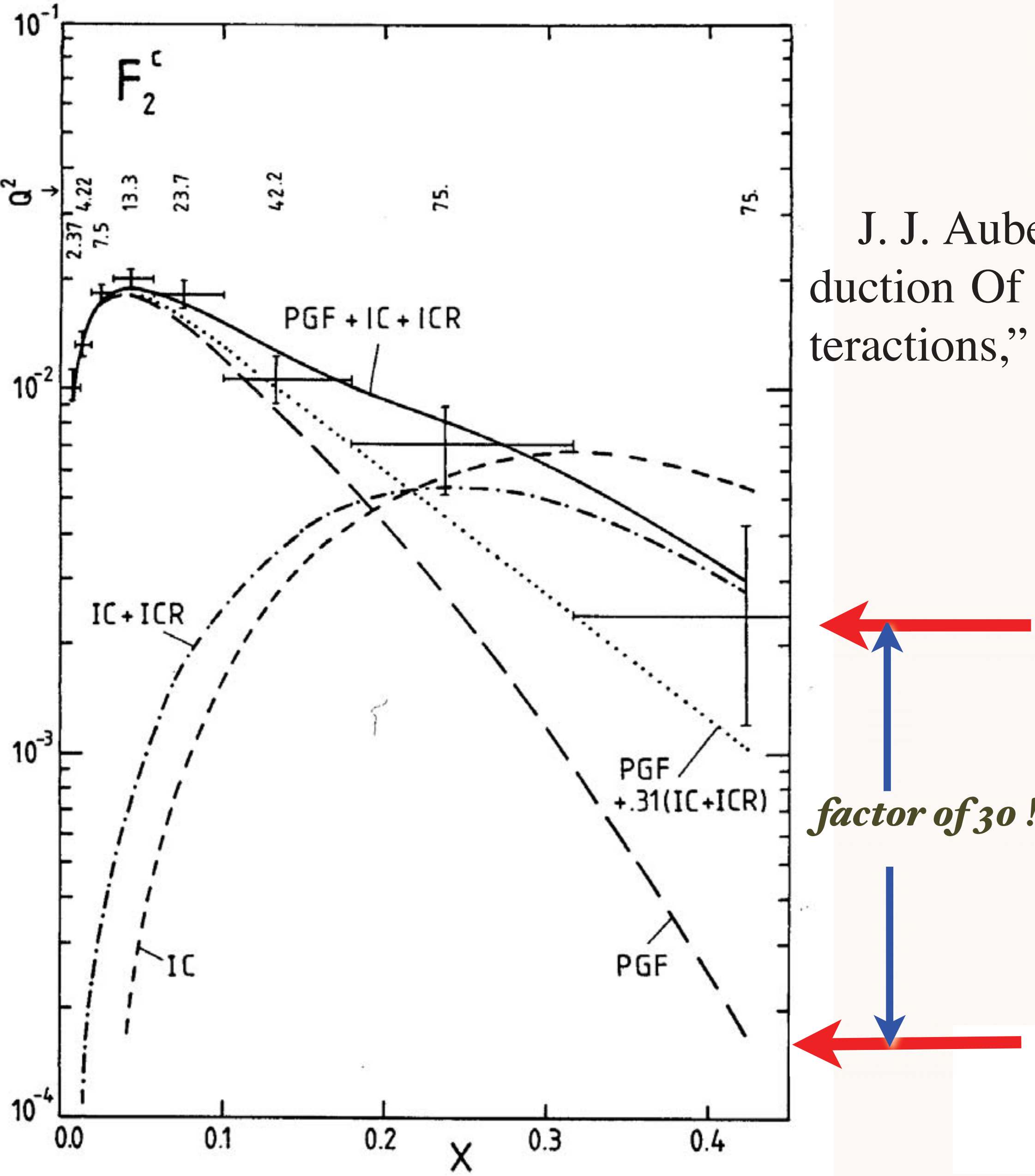


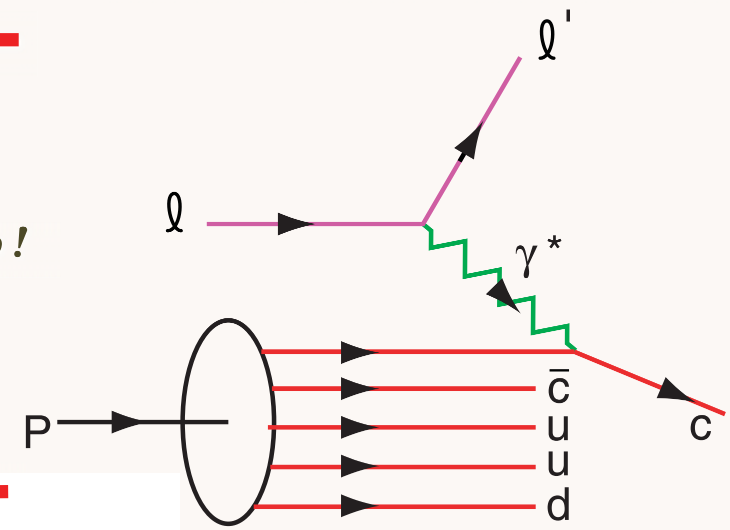
- Rigorous prediction of QCD, OPE
- Color-Octet Color-Octet Fock State!
- Probability $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- Large Effect at high x
- Greatly increases kinematics of colliders such as Higgs production (Kopeliovich, 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





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

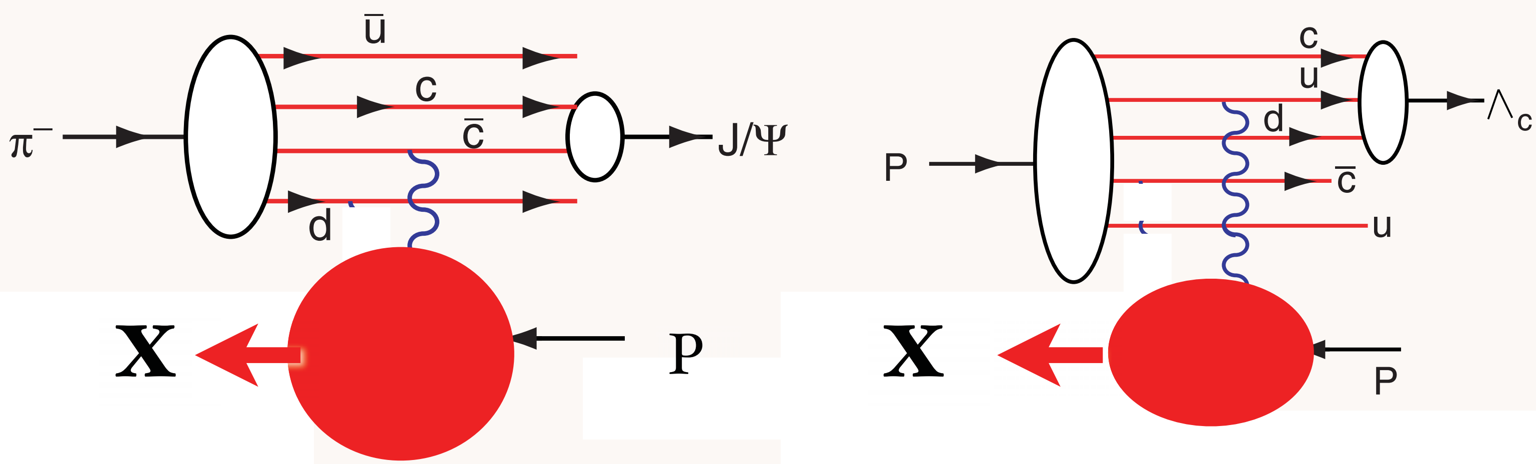
- High x_F $pp \to \Lambda_c X$

- High x_F $pp \to \Lambda_b X$

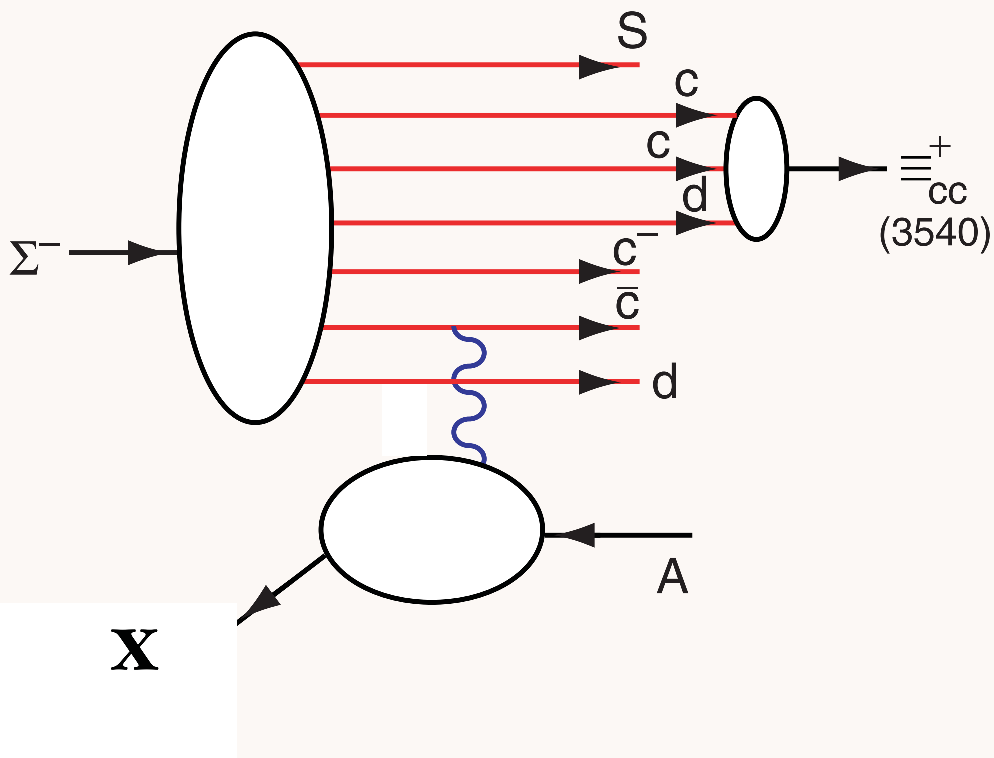
- High x_F $pp \to \Xi(ccd) X$ (SELEX)

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



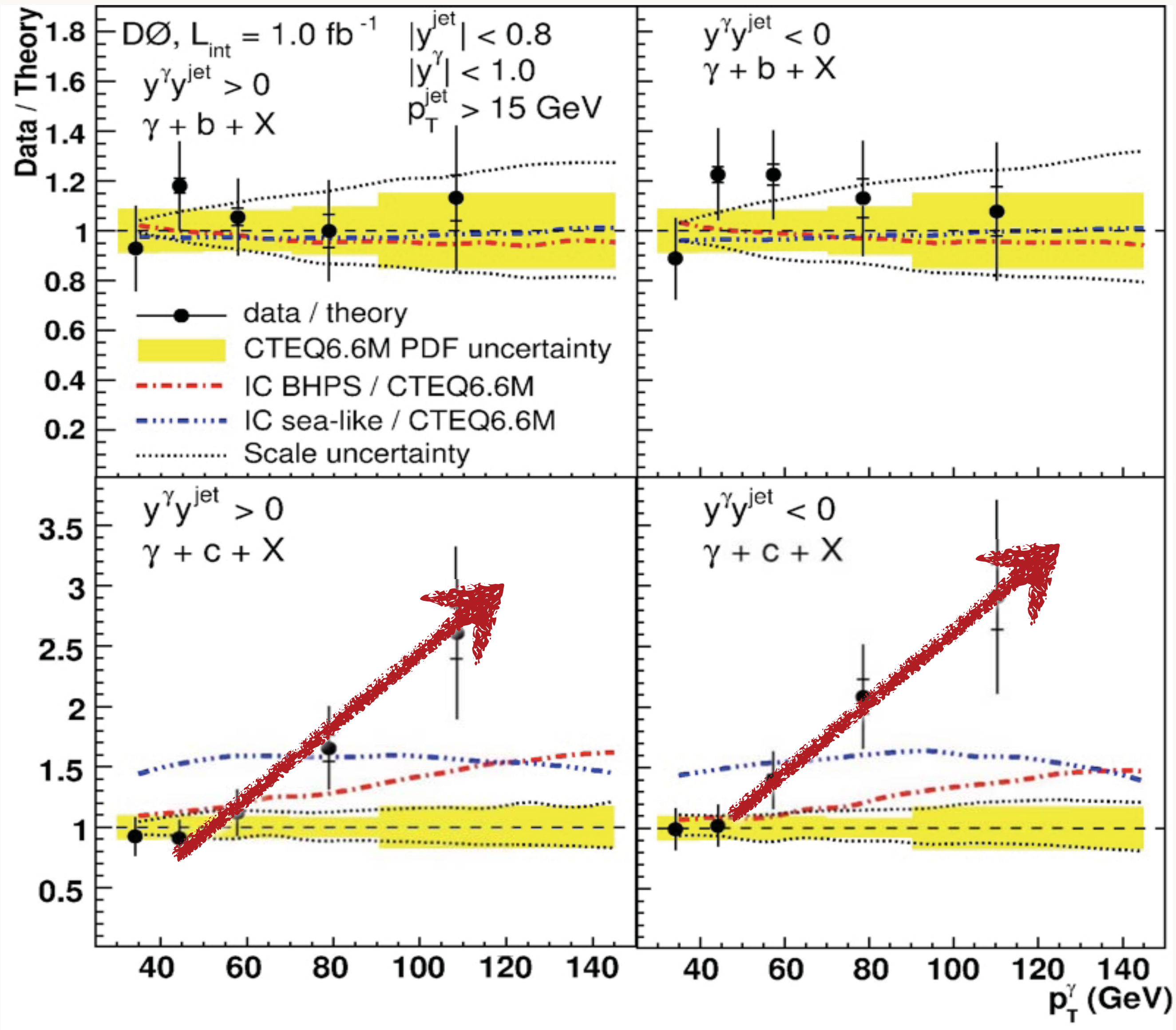
Coalescence of Comoving Charm and Valence Quarks Produce J/ψ, Λ_c and other Charm Hadrons at High x_F



Production of a Double-Charm Baryon

SELEX high x_F $< x_F >= 0.33$

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 ?

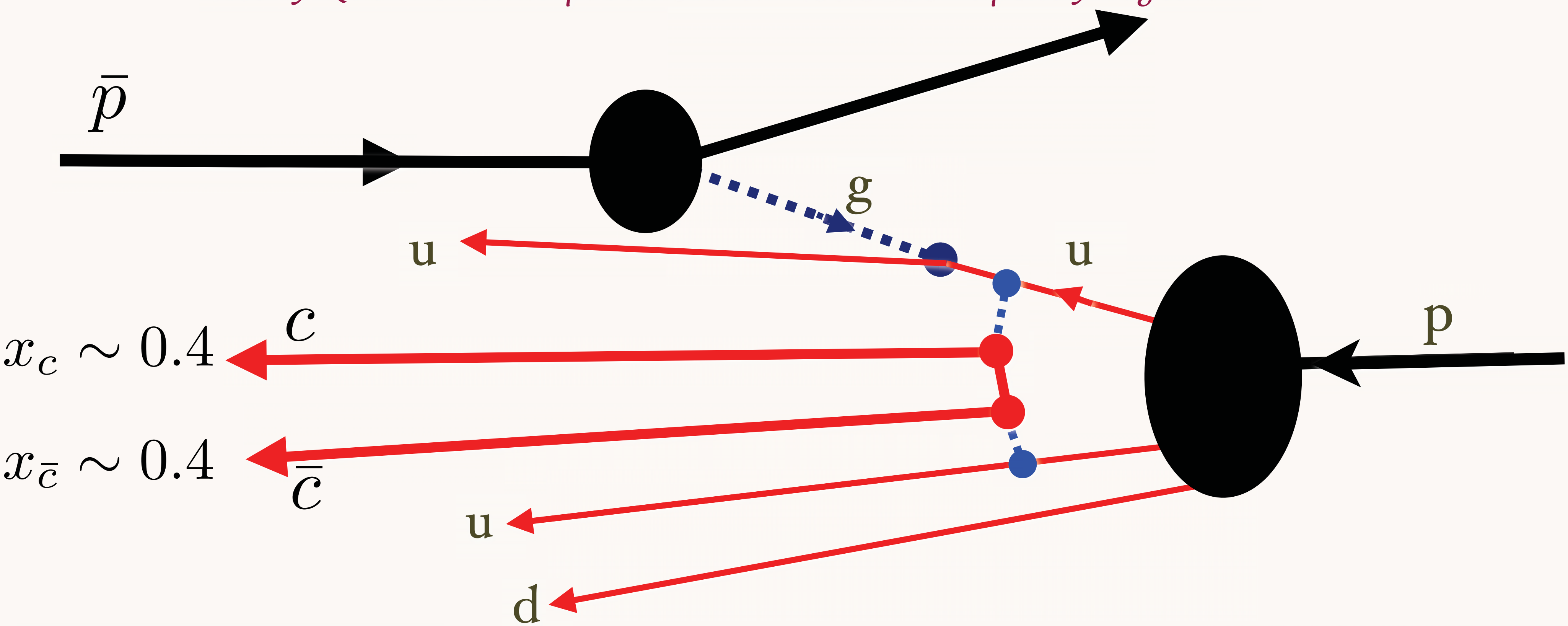
Excitation of Intrinsic Heavy Quarks in Proton

Amplitude maximal at small invariant mass, equal rapidity

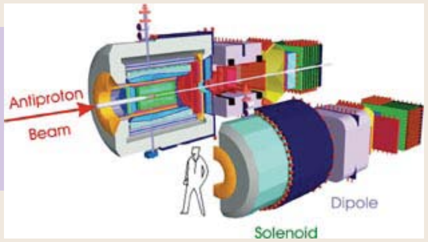
$$x_i \sim \frac{m_{\perp i}}{\sum_j^n m_{\perp j}} \qquad \frac{d\sigma}{dy_{J/\psi}}(\bar{p}p \to J/\psi X)$$

J-P Lansberg, sjb

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

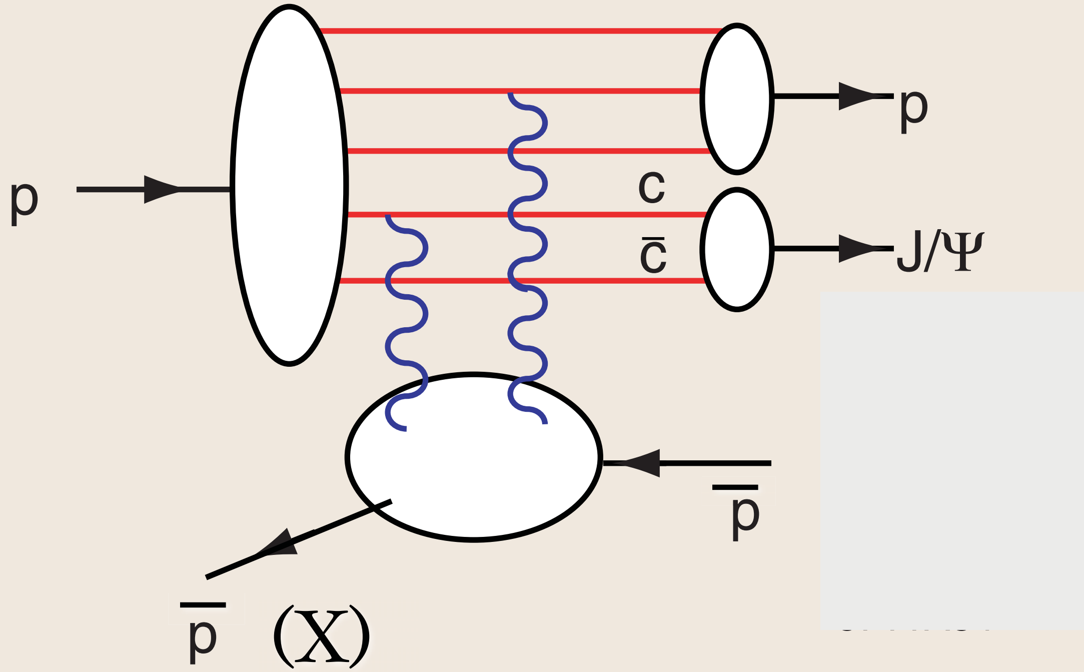


Key QCD Panda Experiment



J-P Lansberg, sjb

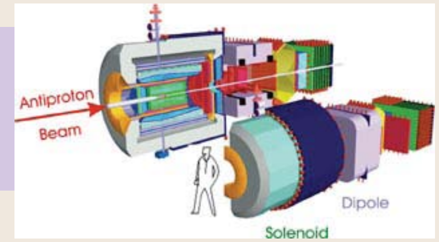
$$\frac{d\sigma}{dy_{J/\psi}}(\bar{p}p \rightarrow J/\psi X)$$



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

Important Test of Intrinsic Charm

Key QCD Panda Experiment

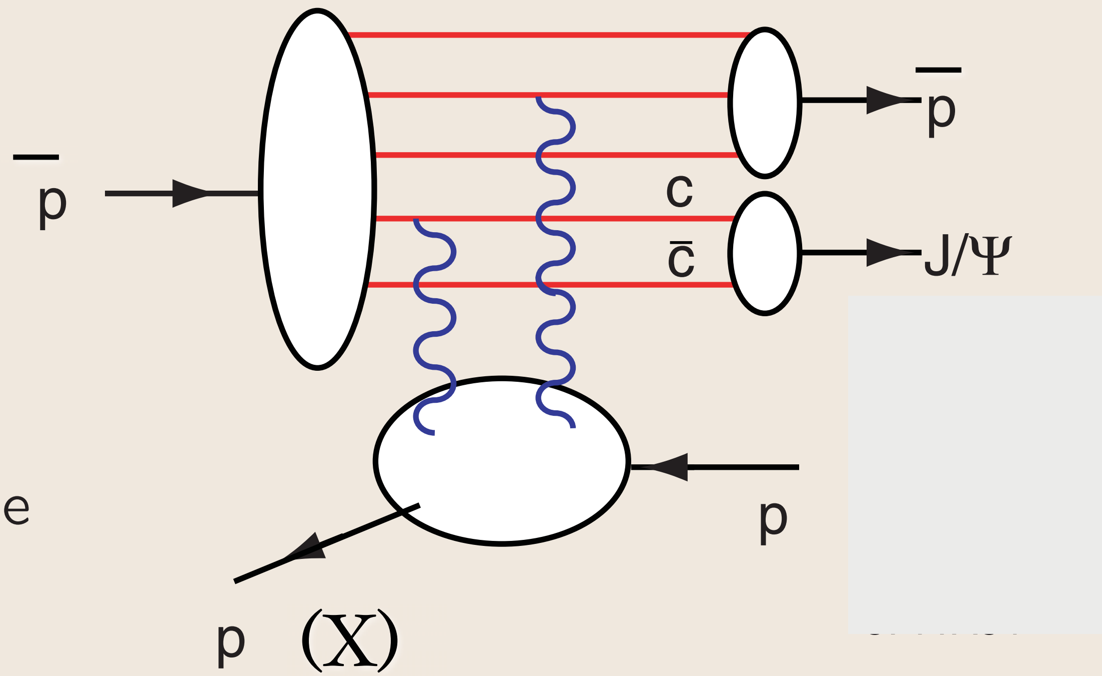


Measure diffractive hidden charm production at forward x_F

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:

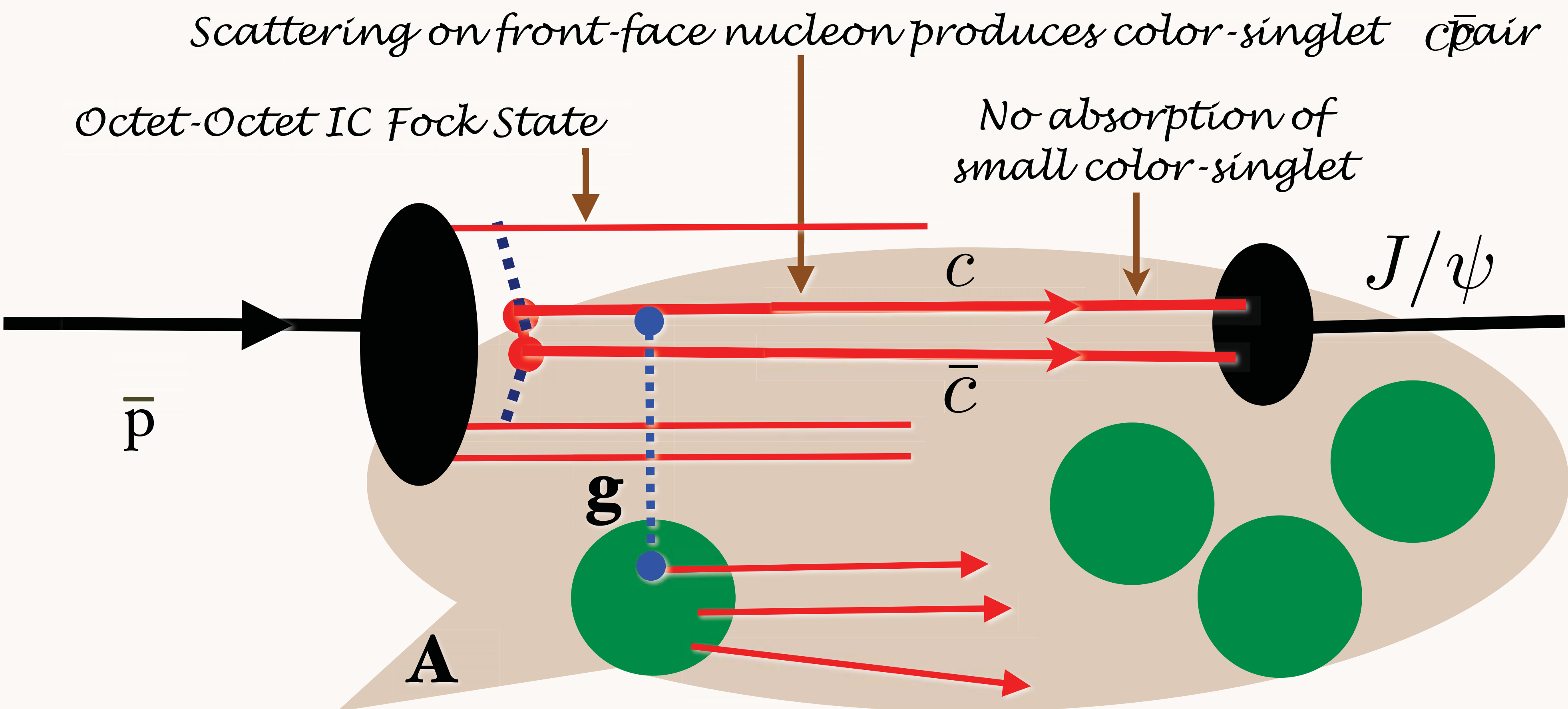
$$gg \to c\bar{c} \qquad q\bar{q} \to g \to c\bar{c}$$

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

ISI and FSI, Schwinger Sommerfeld Threshold Corrections

Kopeliovich, Schmidt, Soffer, sjb

Color-Opaque IC Fock state interacts on nuclear front surface

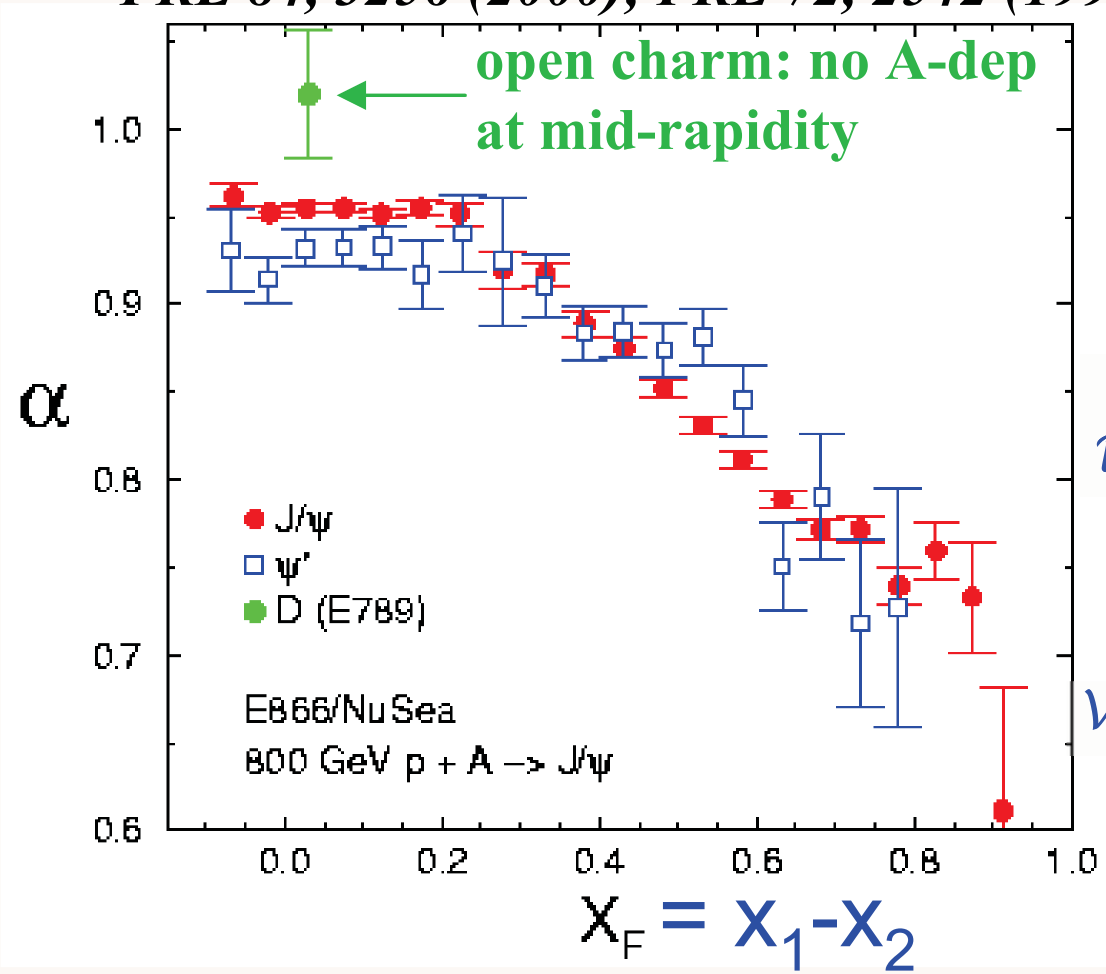


$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$

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!

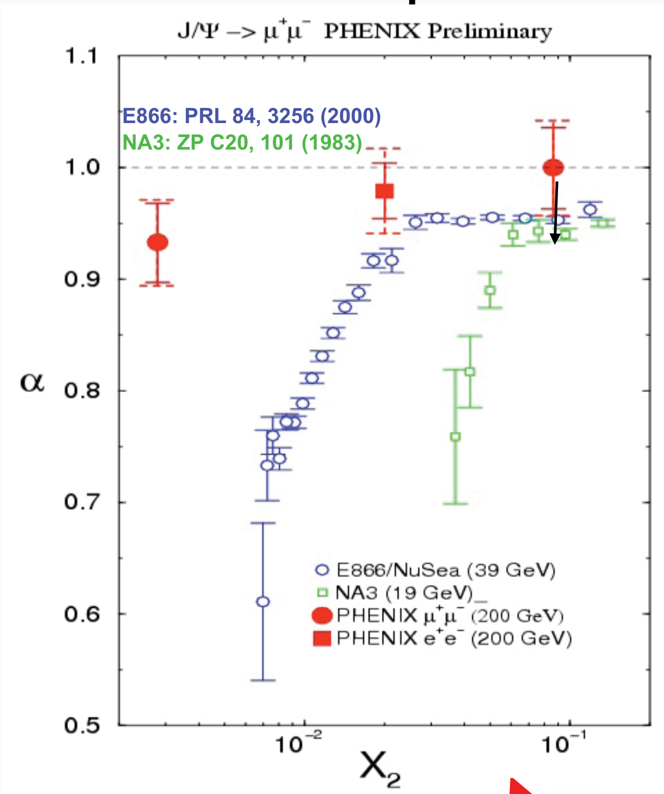
Violation of factorization in charm hadroproduction.

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

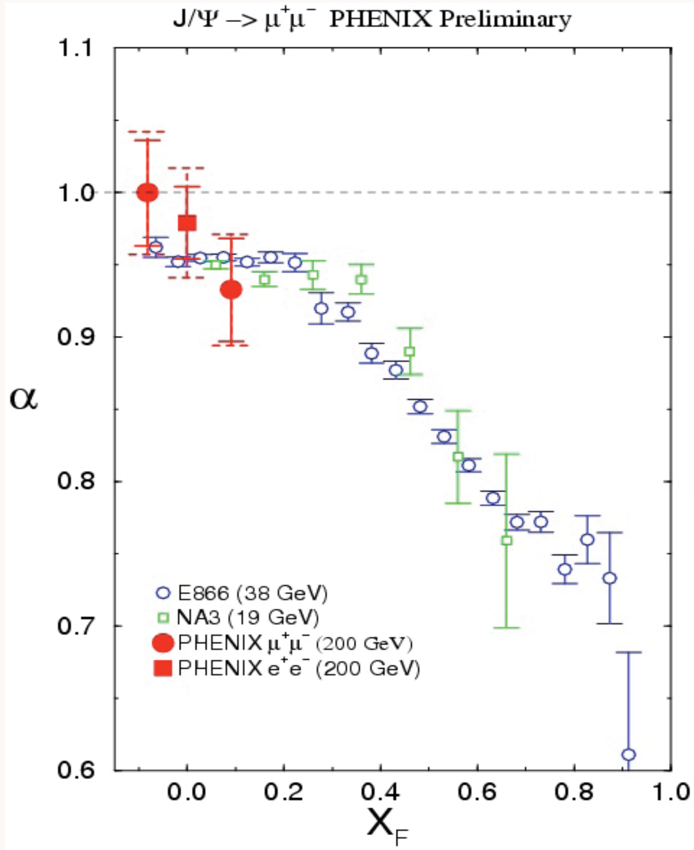
J/ψ nuclear dependence vrs rapidity, x_{Au}, x_F

M.Leitch

PHENIX compared to lower energy measurements



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

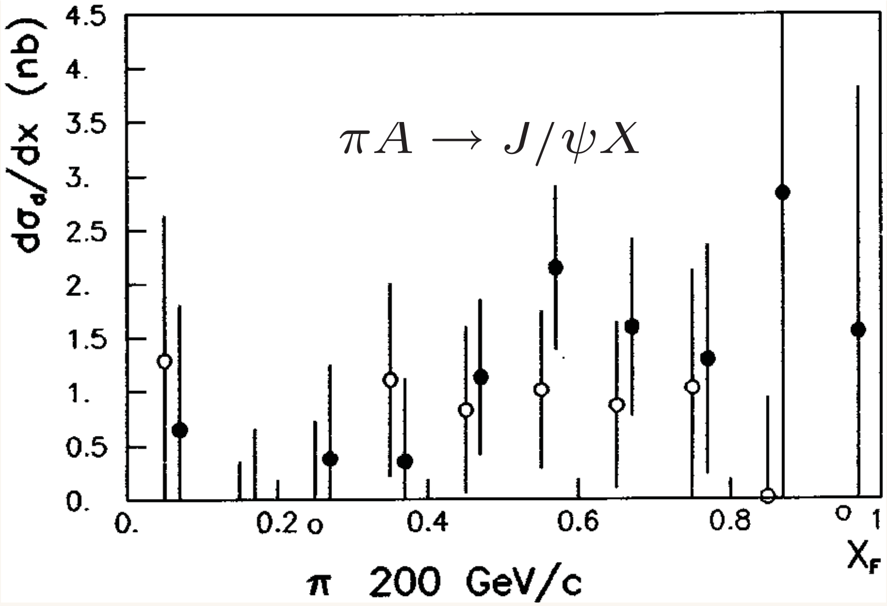


Huge "absorption" effect

Violates PQCD factorization!

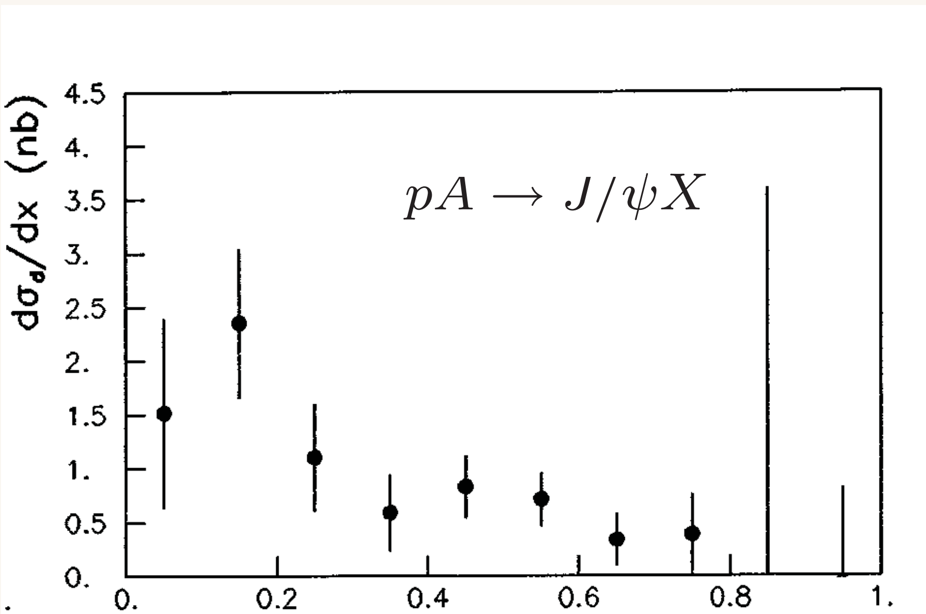
$$\frac{d\sigma}{dx_F}(pA \to J/\psi X)$$

Hoyer, Sukhatme, Vanttinen



$A^{2/3}$ component

J. Badier et al, NA3



p 200 GeV/c

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

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)

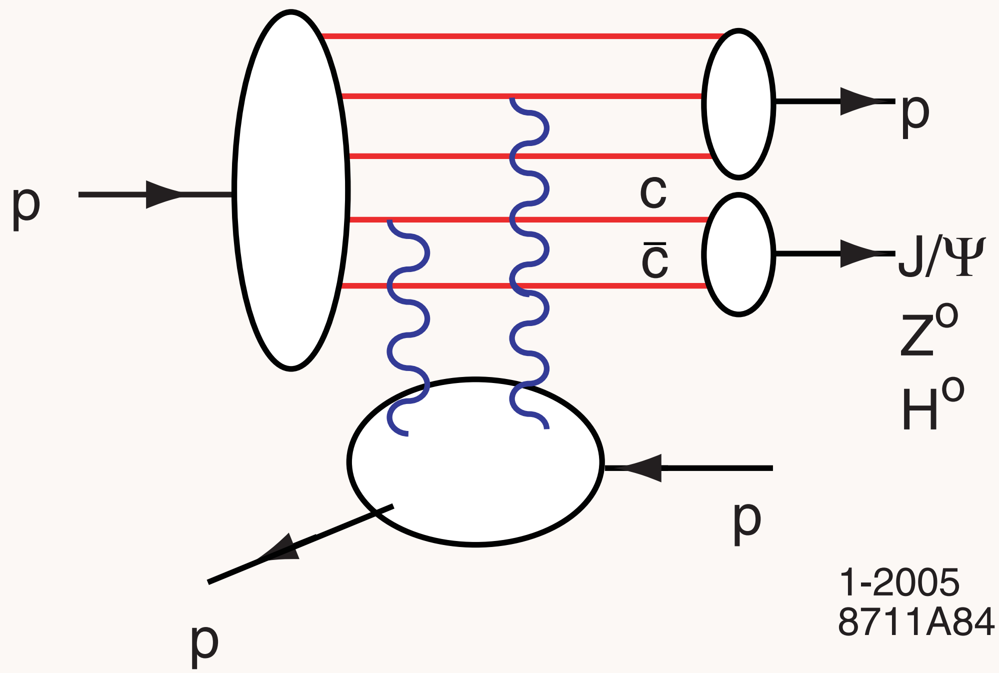
Color Opaqueness

- 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



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

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

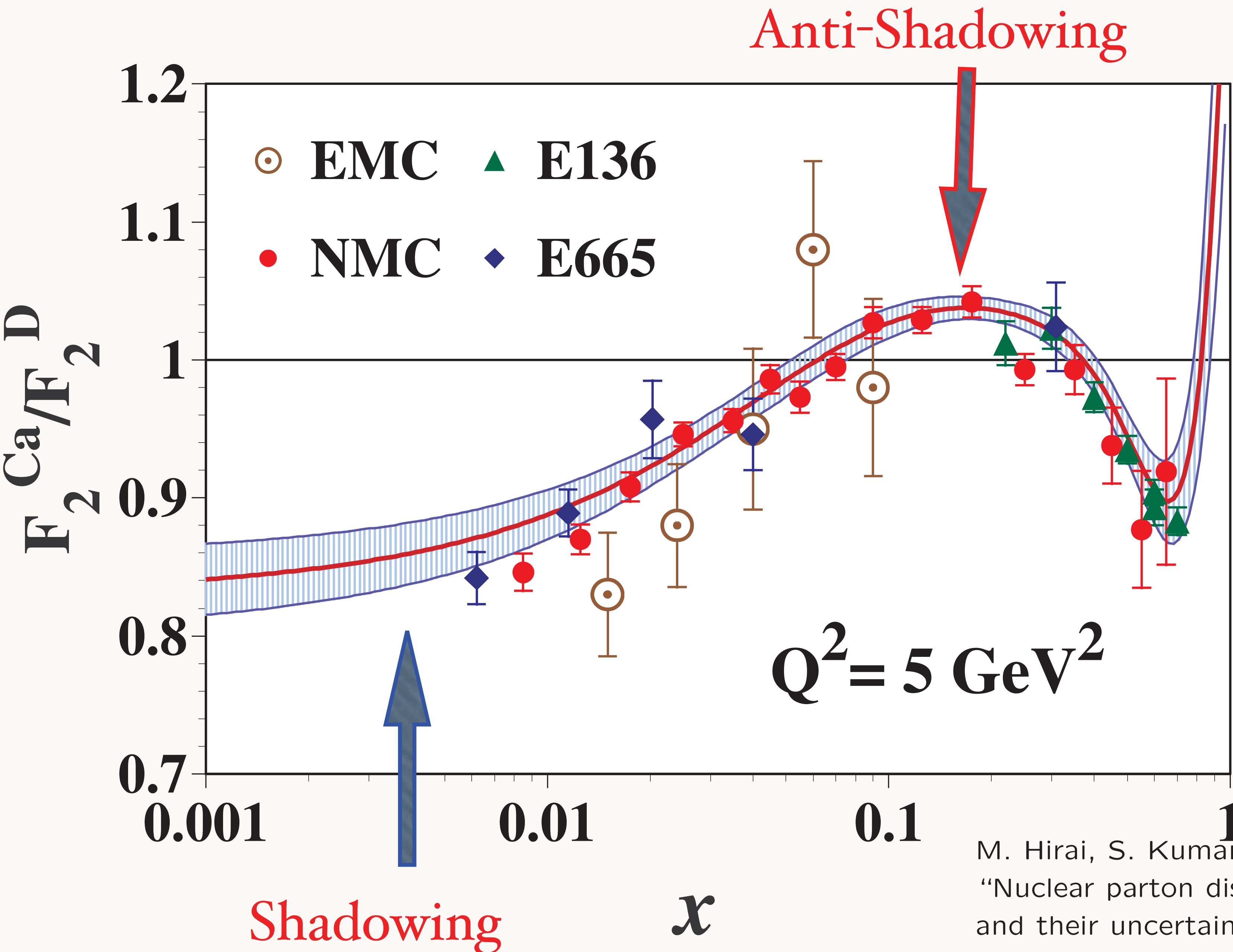
Exclusive Diffractive
High-X_F Higgs Production

Kopeliovitch, Schmidt, Soffer, sjb

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

Collision produces color-singlet J/ψ through color exchange

RHIC Experiment



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].