Krisch Anomaly and Strong $(c\bar{c})N$ interactions

Krisch et al: Sudden jump at $\sqrt{s} \cong 5$ GeV

$$R_{NN} = \frac{\frac{d\sigma}{dt}(p_\uparrow p_\uparrow \to pp)}{\frac{d\sigma}{dt}(p_\downarrow p_\uparrow \to pp)} \cong 4$$

Heppelmann et al Sudden drop at $\sqrt{s} \cong 5$ GeV

$$T = \frac{\frac{d\sigma}{dt}(pA \to pp X)}{Z \frac{d\sigma}{dt}(pp \to pp X)}$$

Simple Explanation:

Alternate: Pire/Ralston [illegible] scale

$$p_\uparrow p_\uparrow \to \underbrace{pp(c\bar{c})} \to pp$$

strong resonance at threshold

$J = L = S = 1$ $\quad$ $p_\uparrow p_\uparrow$ only

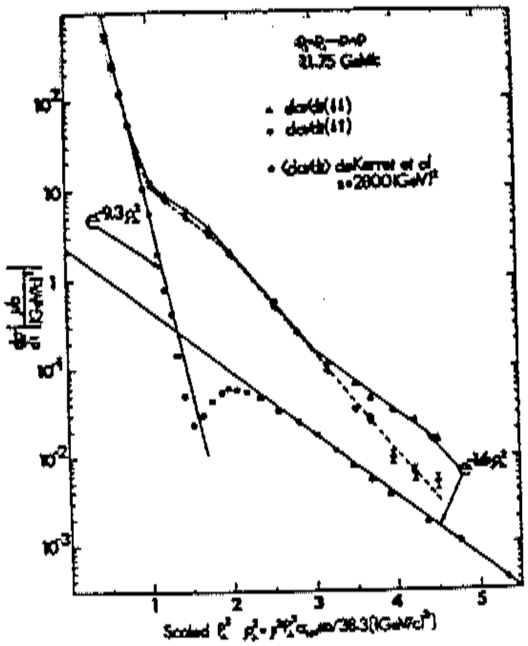


Fig. 1: Proton-proton elastic scattering cross-sections in parallel and anti-parallel initial spin states plotted against the scaled $P_\perp^2$ variable.[3]

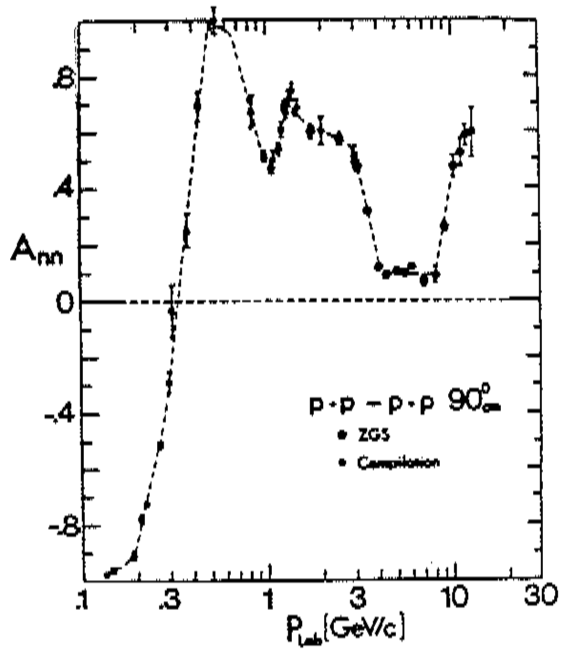


Fig. 2: Compilation of the proton-proton elastic spin-spin parameter at 90°_{cm}.[4]

CT breakdown and sharp rise in A_{nn}

⇒ charm threshold effect?

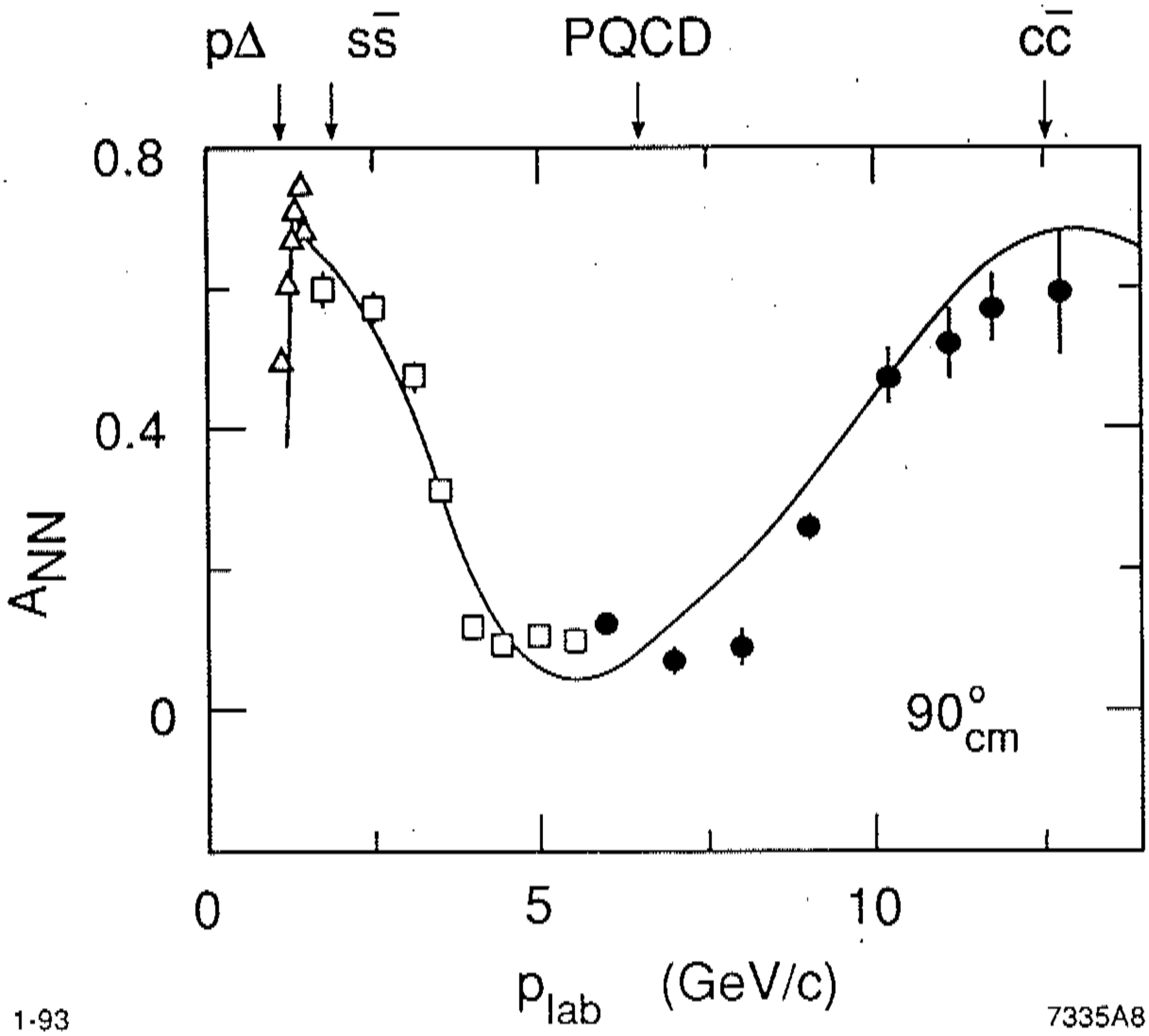
J = L = S = 1

uud uud $c\bar{c}$ resonance

at $\sqrt{s}$ = 5 GeV

G. de Teramond
SJB

Ralston + Pire



1-93 7335A8

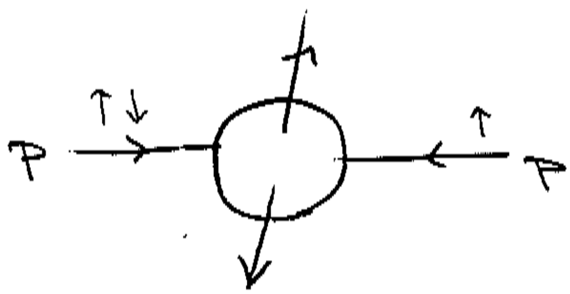
Model:

PQCD (quark interchange)

plus J = L = S = 1
resonances
at strange, charm th.

Spin-Spin Correlations in $pp \to pp$

$$A_{NN} = \frac{\frac{d\sigma}{dt}(\uparrow\uparrow) - \frac{d\sigma}{dt}(\uparrow\downarrow)}{\frac{d\sigma}{dt}(\uparrow\uparrow) + \frac{d\sigma}{dt}(\uparrow\downarrow)}$$



incident spins
normal to scatt. plan

A. Krisch: "We observe unexpected and often startling behavior that challenges the current theory of the proton's structure and forces, QCD".

BNL expt $\quad pp \to pp \quad \theta_{cm} = 90°$

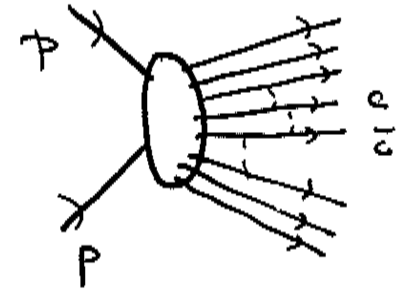
A_{NN} rises to 0.6 at $p_{Lab} = 11.75$ GeV/c
$\sqrt{s} \cong 5$ GeV

$$\frac{d\sigma}{d\Omega}(\uparrow\uparrow) \cong 4 \frac{d\sigma}{d\Omega}(\uparrow\downarrow)$$

Crabb, Krisch, Ratner ... $\quad$ ANL / ...

Spin, Coherence at heavy quark thresholds

$p\vec{\vec{p}} \to Q\bar{Q}X$



Strong distortion at threshold $\vec{p}_{rel} \sim 0$

$\sqrt{s}_{Th} = 3+2 \cong 5$ GeV $\quad pp \to c\bar{c}X$

8 quarks in S-wave odd parity!

$\therefore \quad J = L = S = 1$ for pp

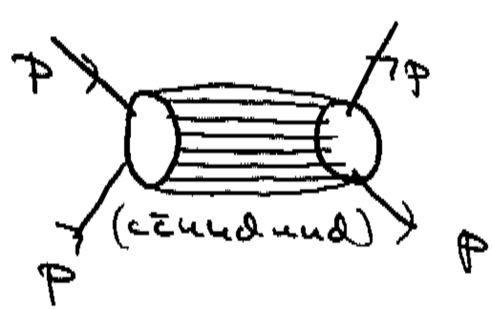
$B = 2$

resonance near threshold?

S&B + determined

$\frac{d\sigma}{dt}(pp \to pp)$

$\sqrt{s} \sim 5$ GeV



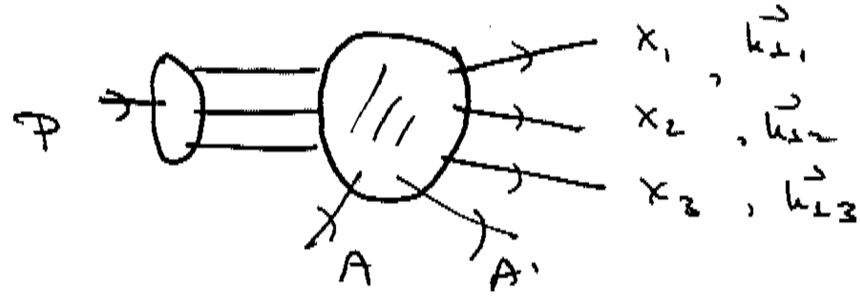
$A_{NN} = 1$ for $J=L=S=1$ $\quad p\uparrow p\uparrow$ only!

expect increase of A_{NN} at $\sqrt{s} = 3, 5, 12$ GeV

$\theta_{cm} = 90°$

Nuclear Diffraction

Test at HERA-B
FNAL, RHIC ?



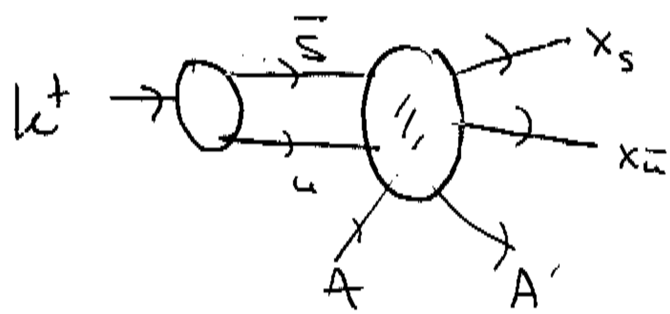
$\sum x_i \cong 1$

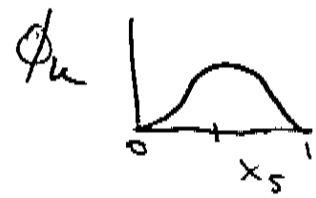
$\sum \vec{k}_{\perp i} \cong \vec{0}_\perp$

Frankfurt
Strikman
Miller

measure nucleon $\psi_{3q}(x_i, \vec{k}_{\perp i})$

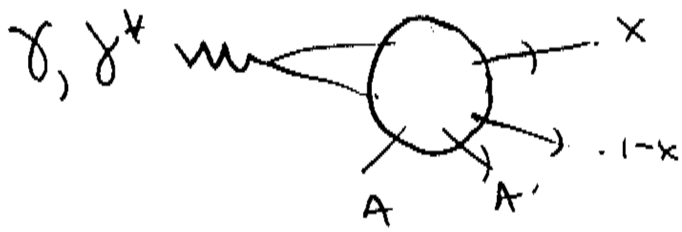
Factorization





$\langle x_s \rangle > 1/2$?

M. Diehl
A. Martin et



$\sigma_T : \; x^2 + (1-x)^2$

$\sigma_L : \; x(1-x)$

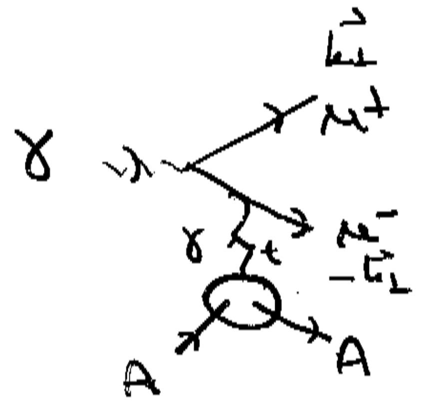
measure $\psi_{q\bar{q}/\gamma^*}(x, k_\perp)$ charm component

$eA \to e' A' J J$ rapidity gap

Hoyer, Magnea, SJB

Coulomb Dissociation

P. Hoyer, S. Peigné, SJB

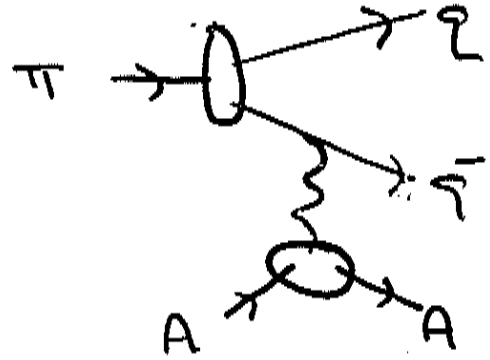


Bethe-Heitler

$$\frac{d\sigma}{dt\,dk_\perp^2} \cong \frac{\alpha(Z\alpha)^2}{k_\perp^4}\frac{F_Z^2(t)}{t}$$

measure $\phi_\gamma^i(x)$

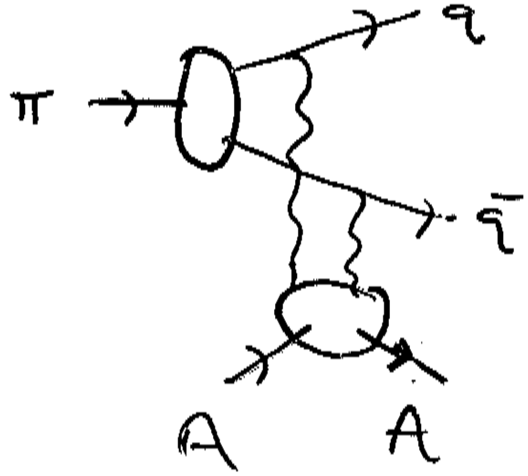
pion dissociation to jets also has Coulomb component



$$\frac{d\sigma}{dt\,dk_\perp^2} \cong \frac{f_\pi^2(Z\alpha)^2}{k_\perp^6}\frac{F_Z^2(t)}{t}$$

↑ gives log

Miller, Strikman, Frankfurt

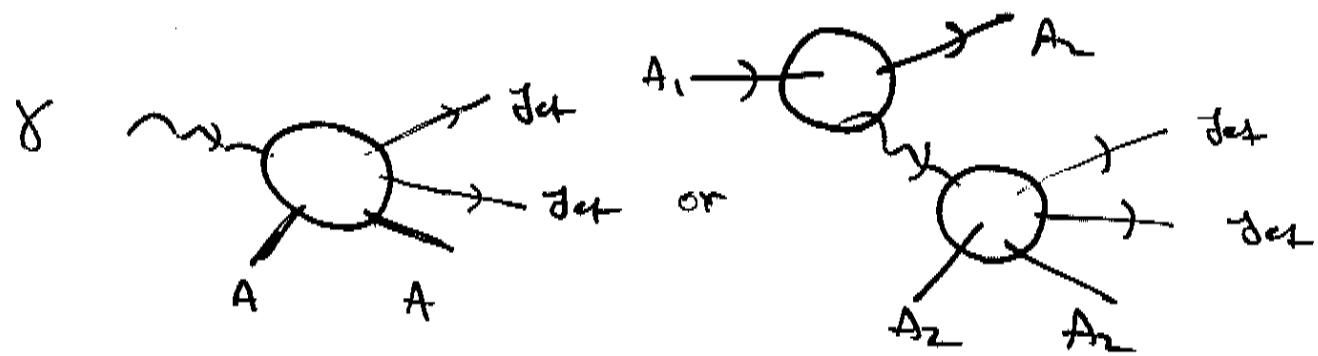


$$\frac{d\sigma}{dt\,dk_\perp^2} \cong \frac{f_\pi^2\,\alpha_s^2\,g^2(\bar{x})\,A^2 F_A^2(t)}{k_\perp^8}$$

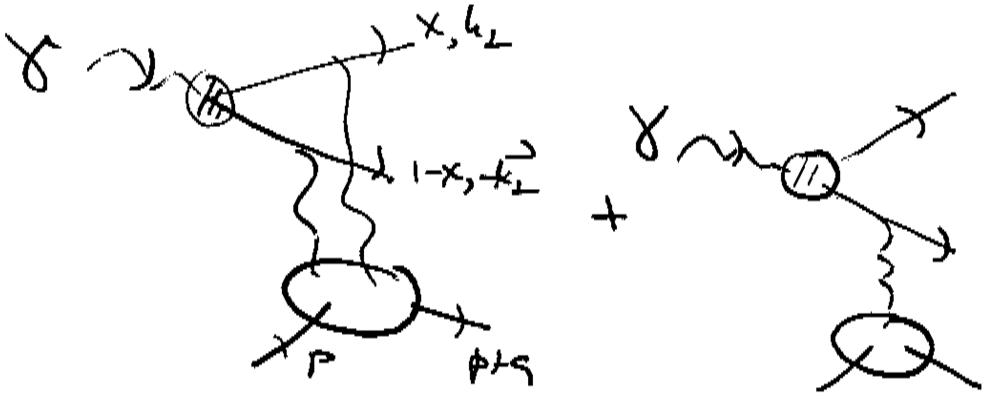
γ exchange may be comparable at large $k_\perp$

both measure $\phi_\pi(x)$

Resolve Photon Wavefunction



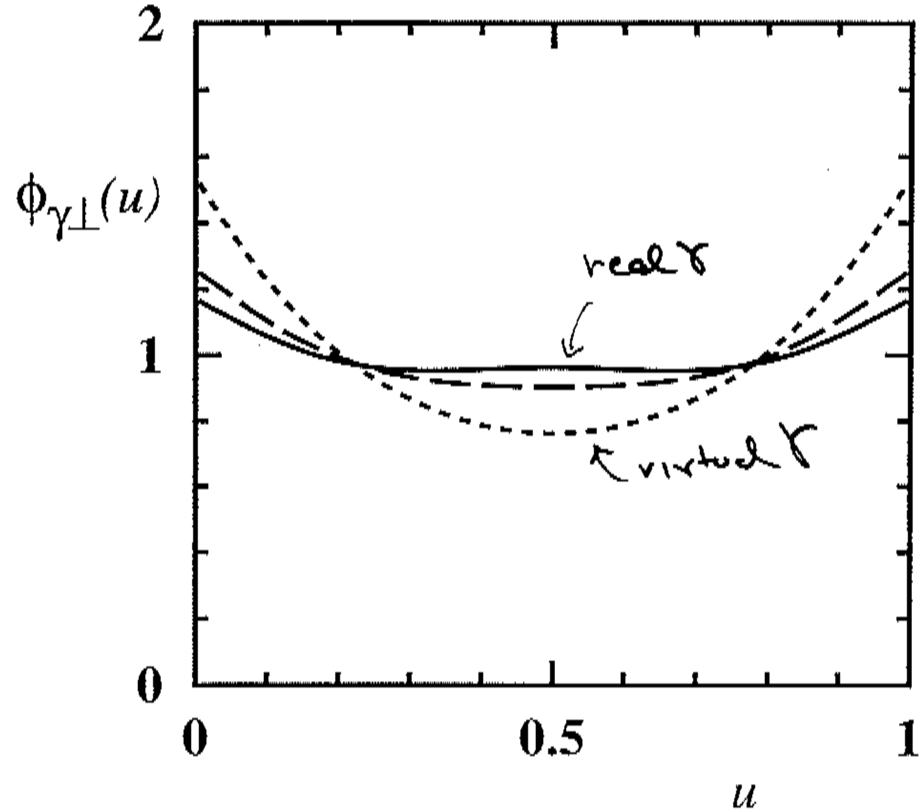
HERA RHIC, LHC, UPC



$$\mathcal{M} \sim \frac{\partial^2}{\partial k_\perp^2}\psi_{q\bar{q}/\gamma}(x,\vec{k}_\perp) \qquad \frac{\partial}{\partial k_\perp}\psi_{q\bar{q}}(x,\vec{k}_\perp)$$

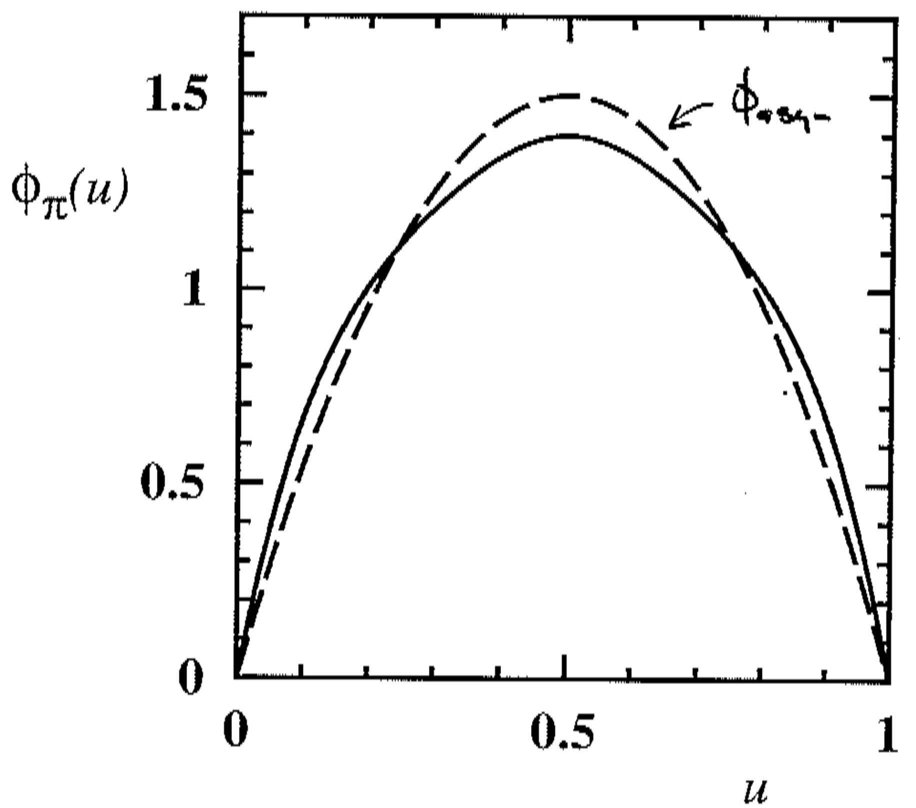
$$\mathcal{M}_+ \sim A\,F(q_\perp^2) \qquad \mathcal{M}_A \sim Z\alpha F(q_\perp^2)$$

$$\frac{d\sigma}{dk_\perp^2} \sim \frac{1}{k_\perp^6} \qquad \frac{d\sigma}{dk_\perp^2} \sim \frac{1}{k_\perp^4}$$



V.Y. Petrov, et al
hep-ph/9807229

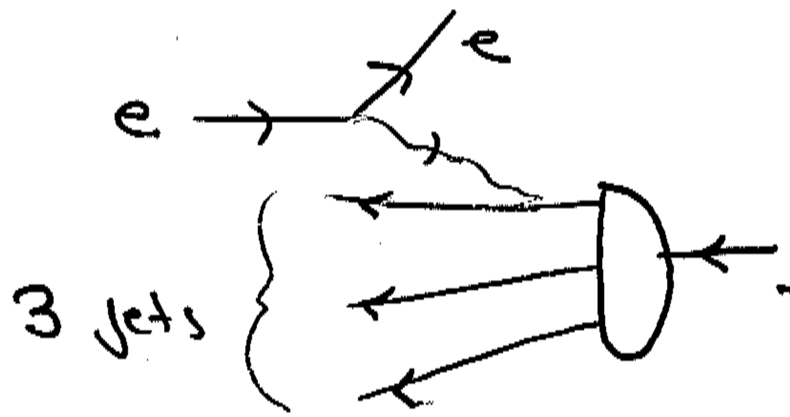
Models for $\int \psi_\gamma(x, k_\perp) d^2k_\perp$



Model for $\phi_\pi(x)$

V.M. Petrov et al
hep-ph/9807229

Diffractive Dissociation of the Proton



$q^2 \sim 0$

Frankfurt Miller Strikman

Bergin, Hoyer, SJB
Coulomb Dissoc.

$$\sum \vec{k}_\perp = \vec{q}_\perp \cong 0$$

$$\sum x_i = 1$$

e-p Collider
app.

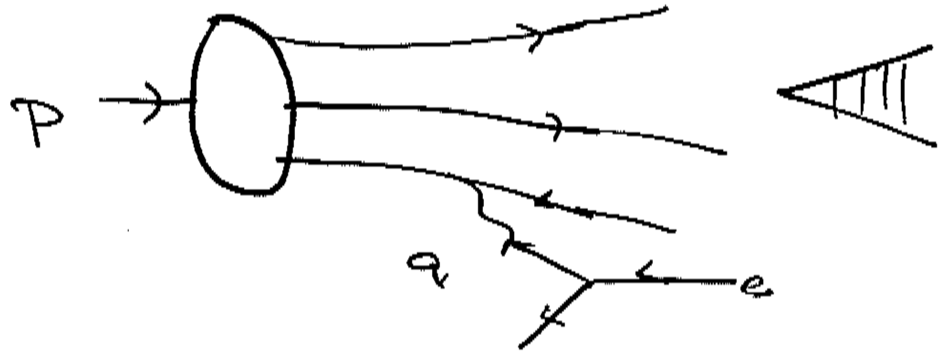
Use E791 techniques — Ashery et al

measure $\psi^p_{3q}(x_i, \vec{k}_{\perp i})$

non-symmetric $\phi_p(x_i, Q)$?

$$\psi \sim \frac{\alpha_s(k_\perp^2)}{k_\perp^2}$$

Estimate of cross section:



$m^2 > m_0^2 = p^{+2}\theta_0^2$

$$\text{Ampl} \sim \sum e_i \, \vec{q}_\perp \cdot \frac{\partial}{\partial \vec{k}_{\perp i}} \psi_{LC}(x_i, \vec{k}_{\perp i}, \lambda_i)$$

$$P(x_i, m_0^2) = \int \left| \frac{\partial}{\partial k_{\perp i}} \psi_{LC}(x_i, k_{\perp i}) \right|^2 \prod_{i=1}^{2} d^2k_{\perp i} \; \Theta\left(\sum \frac{k_\perp^2 + m^2}{x} > m_0^2\right)$$

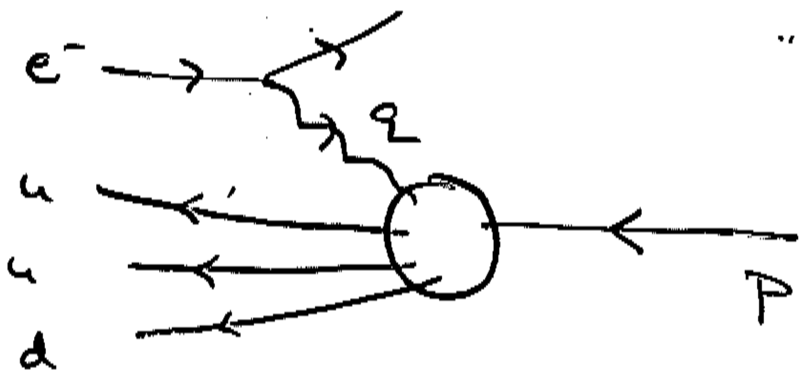
$$\frac{d\sigma}{d\ln q_\perp^2 \, dx_1 dx_2}(m^2 > m_0^2) \sim \alpha^2 P(x_i, m_0^2)$$

$$\sim \frac{\alpha^2 f_N^2}{(m_0^2)^3} |\phi(x_i)|^2$$

$[f_N] \sim m^2$

"Self-Resolving" e-p Interactions

HERA, ERHIC



"Coulomb" dissociation of proton

Diehl
Hoyer
Peigne
SJB

Observe 3 jets $\langle q_\perp^2 \rangle \ll \langle k_\perp^2 \rangle$

at large $\vec{k}_{\perp i}$ low $q_\perp^2$

$$\frac{dN}{d\ln q_\perp^2 \, dx_1 dx_2 \, d^2k_{\perp 1} \, d^2k_{\perp 2}} \sim \left| \sum_i e_i \frac{\partial}{\partial \vec{k}_{\perp i}} \psi(\vec{k}_\perp, x)_{3q/p} \right|^2$$

$$\frac{d\sigma}{d\ln q_\perp^2 \, dx_1 dx_2}(\vec{k}_{\perp i}^2 > \vec{k}_{\perp min}^2) \sim \frac{\alpha f_N^2 g(x_i)}{(k_{\perp min}^2)^4}$$

$$[f_N] = [M^2]$$

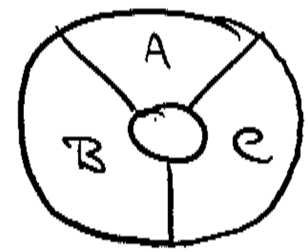
Measure proton distribution ampl.

$\phi(x_i)$

Experimental Measures

ep * $\frac{d\sigma}{dm^2} \sim \left(\frac{1}{m^2}\right)^4$ $\left(\frac{1}{m^2}\right)^6$ for pA

* Jet structure



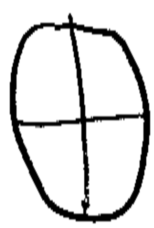
* x_i - distribution

$x_A > x_B > x_C$

* measure $\frac{x_B}{x_A}$, $\frac{x_C}{x_A}$

$e p\uparrow \to e'$ Jet Jet Jet

* proton polarized normal $\uparrow$



look for oblate dist

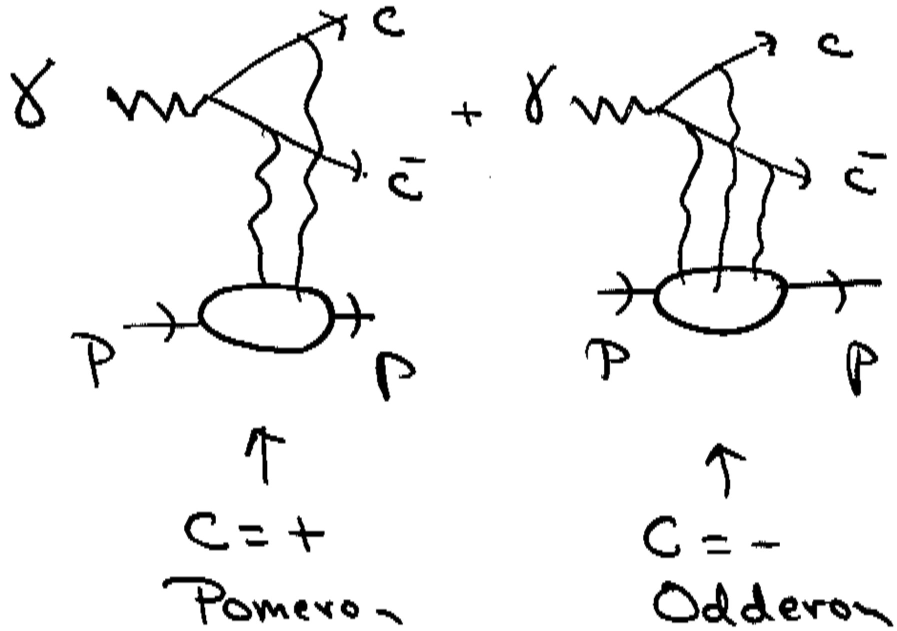
Sphericity variables

* Connection to proton distribution ampl

Same tools for $pA \to A'$ Jet Jet Jet at RHIC (pA)

Measure Odderon - Pomeron Interference

J. Rathsman
C. Merino, SJB



$\gamma p \to c\bar{c} p$
diffractive
(rap-gap)

HERA
FNAL
SLAC
Compass
MUSES

Interference give $c \leftrightarrow \bar{c}$ asymmetry:

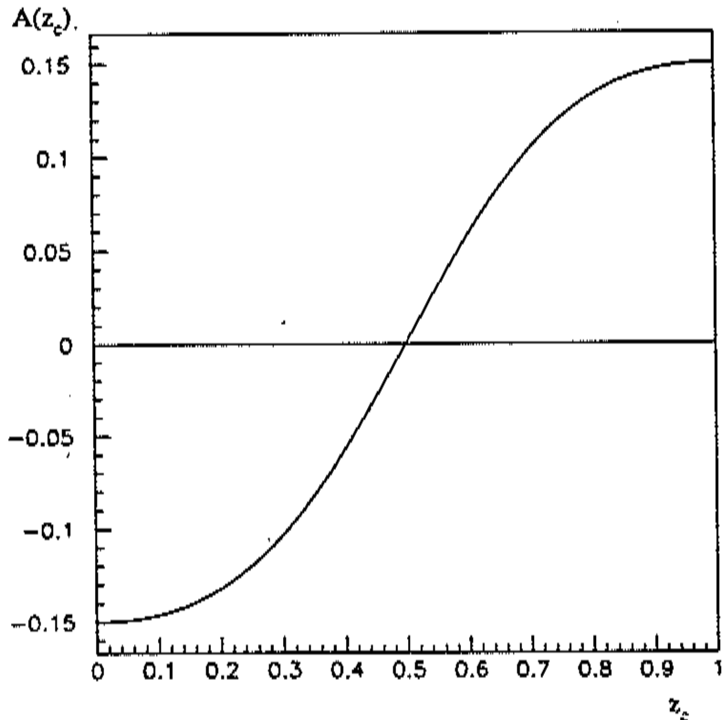
$$A = \frac{\frac{d\sigma}{dt\,dm^2\,dz_c} - \frac{d\sigma}{dt\,dm^2\,dz_{\bar{c}}}}{\frac{d\sigma}{dt\,dm^2\,dz_c} + \frac{d\sigma}{dt\,dm^2\,dz_{\bar{c}}}}$$

$$\propto \sin\left[\pi\frac{(\alpha_O - \alpha_P)}{2}\right] s^{\alpha_O - \alpha_P}$$

$$\cdot \frac{2z_c - 1}{z_c^2 + (1-z_c)^2}$$

$$A(t, M_x^2, z_c) = \frac{\dfrac{d\sigma}{dt\,dM_x^2\,dz_c} - \dfrac{d\sigma}{dt\,dM_x^2\,d\bar{z}_c}}{+}$$

$$\gamma p \to c\bar{c}\, p'$$



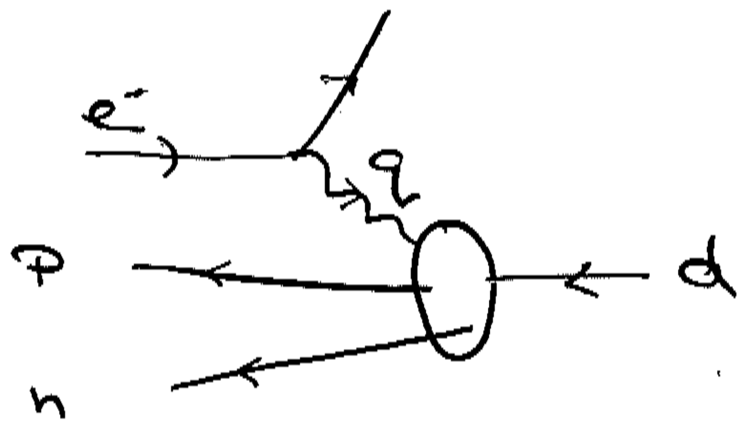
estimate $$A(t=0, M_x^2, z_c) \simeq 0.3 \left(\frac{S_{\gamma p}}{M_x^2}\right)^{-0.18} \frac{2z_c - 1}{z_c^2 + (1-z_c)^2}$$

magnitude saturates

pp vs $\bar{p}p$

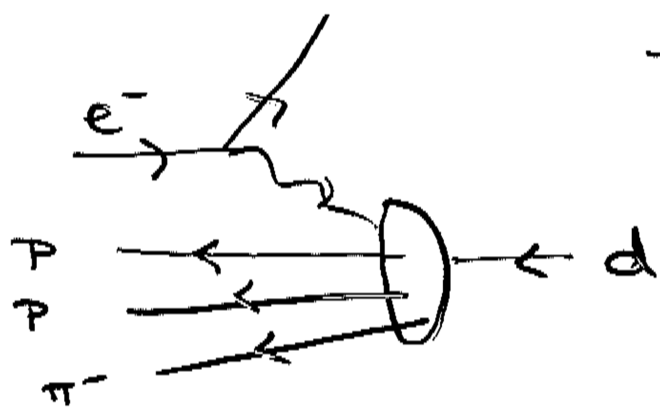
Self-Resolving Nuclear Interactions

Hoyer
Peigne
SJB

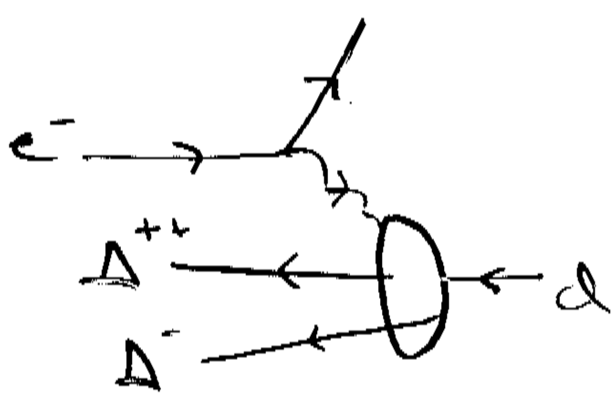


$q_\perp^2 << \langle k_\perp^2 \rangle$

— photon acts last



measure all
Fock components
of nuclei!

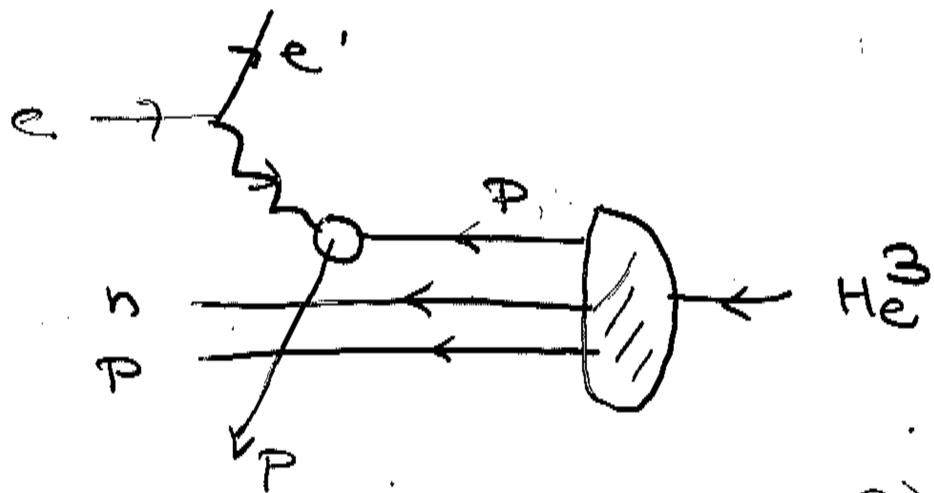


$$x = \frac{k^+}{P^+} = \frac{k^0 + k^z}{P^0 + P^z}$$

* measures $\sum_i e_i \frac{\partial}{\partial k_{\perp i}} \psi_d(x_i, k_{\perp i}, \lambda_i)$

Check Hermes effect
Miller, Karliner, SJB

Nuclear Physics and Fragmentation



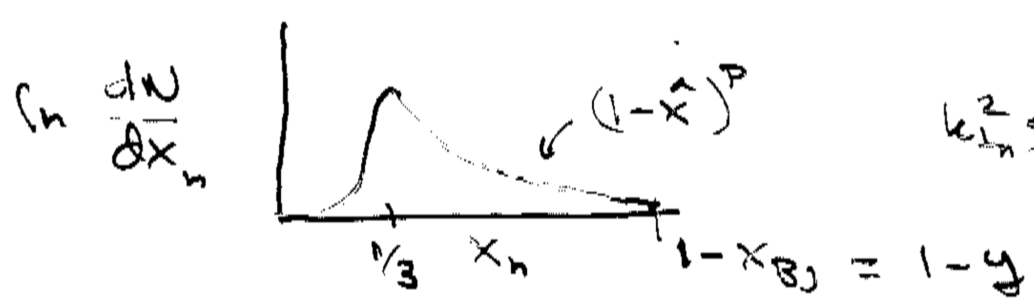
also: neutron form factors and structure funct.

— Measure $x_n = \frac{k_n^+}{P^+_{He^3}} = \frac{(k^0 + k^3)_n}{(P^0 + P^3)_{He^3}}$

$\vec{x}_n, \vec{k}_{\perp n}$: reflect $\psi^{LC}_{ppn/He^3}(x_i, \vec{k}_{\perp i}, \lambda_i)$

Relativistic nuclear physics !

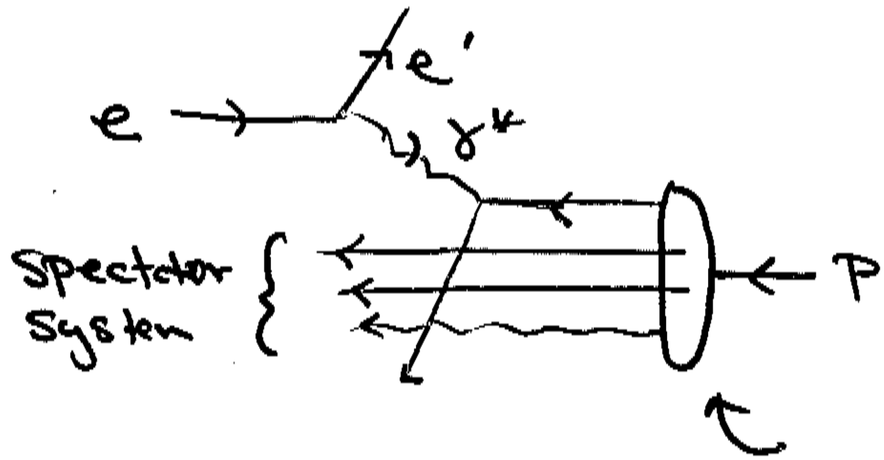
$\psi^{LC} \Rightarrow \psi^{\text{Schroedinger}}$ in non-rel domain



$k^2_{\perp n} \lesssim \frac{1}{R_A^2}$

Proton Fragmentation

- Physics intrinsic to nucleon structure!



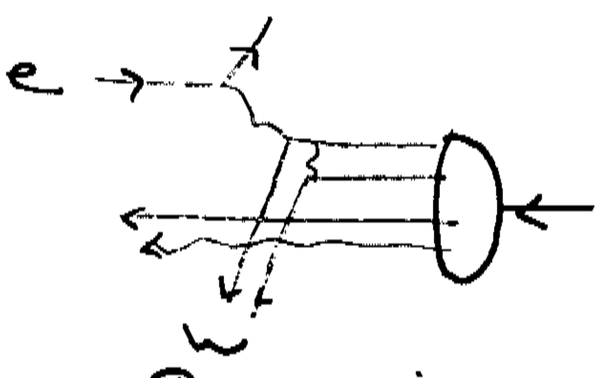
$\psi^P_{gqqq}(x_i, \vec{k}_{\perp i}, \lambda_i)$

$\Sigma x_i = 1, \ \Sigma \vec{k}_{\perp i} = \vec{0}_\perp$

* "Fracture" Function: forward radiation of struck quark evolves

* Non-evolved spectator "diquark" system

* Distinguish higher twist subprocesses



$(1-x)^3\left[1 + \frac{C}{Q^4(1-x)^2}\right]$

Baryon-rich diquark jet

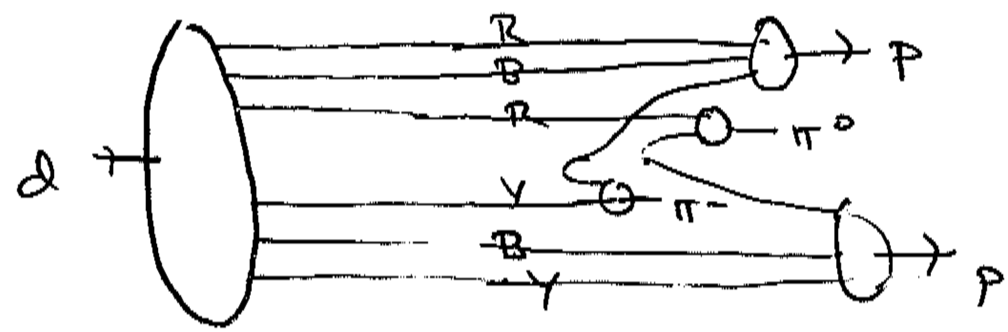
Hidden Color in Deuteron

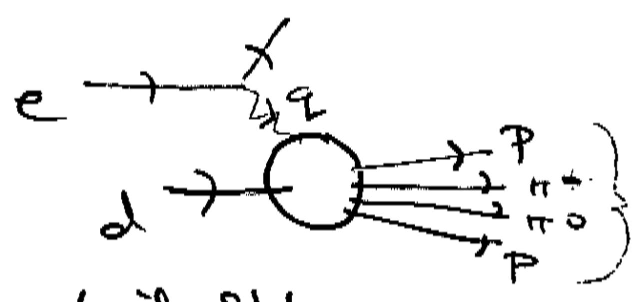
① Dominates at $Q \to \infty$, $b_\perp^i \to 0$ — Lepage Ji SJB

② Probably changes normalization of TH by large factor — Farrar Bhang

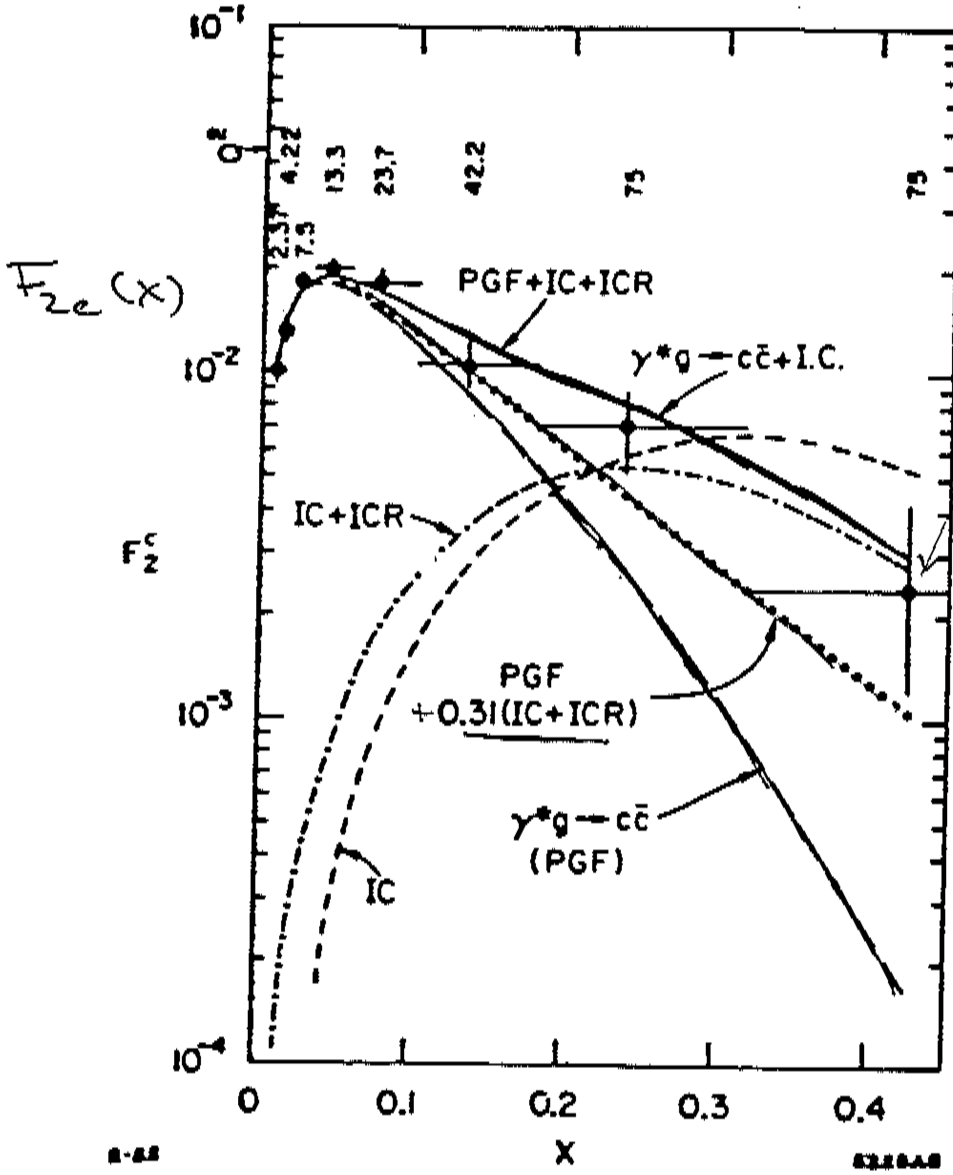
③ $\psi_{HC} \Rightarrow$ multihadron state?

Diffraction dissociate $d \to pp\pi\pi$ — Holzer Dick! SJB





look for dominant final state



$Q^2 = 75\ \text{GeV}^2$

$x_{Bj} = 0.42$

Hoffman & Moore

* Smith, Vogt, [illegible]

EMC data

Prob (IC)

$\cong \begin{cases} 0.3\% & \text{HM} \\ 1.0\% & \text{S..H} \end{cases}$

Steffens,

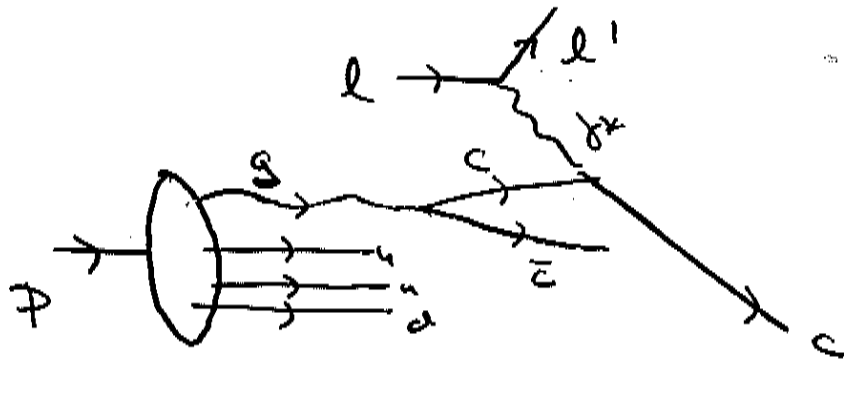
Melnitchouk

Thomas

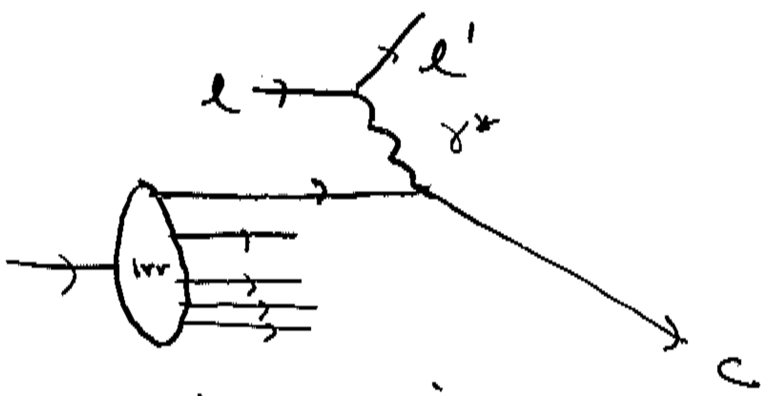
(variable quark mass scheme)

CBM for IC

Two Contributions to Sea Quark Distributions



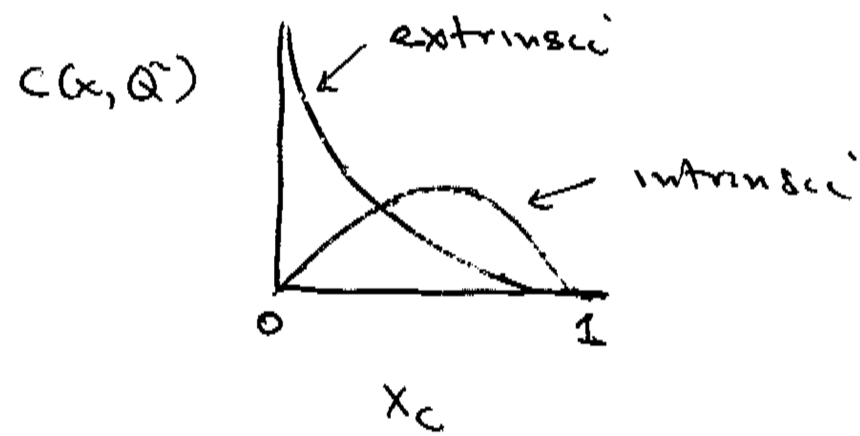
extrinsic = photon-gluon fusion $g\gamma^* \to c\bar{c}$



1 gluon irreducible

intrinsic

initial state for DGLAP evolution



$Q^2 \gg 4m_c^2$

$c_I \propto \frac{1}{m_c^2 R^2}$

SJB, Hoyer, Sakai, Peterson

Vogt

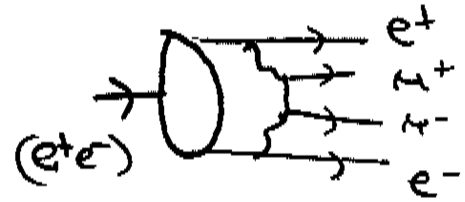
Thomas Soas

Ingelman + Thunman

S. Gardner
+
SJB

Color - Octet Intrinsic Charm

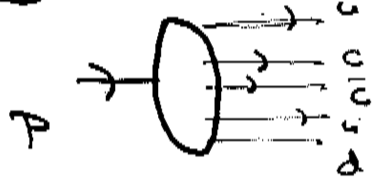
QED:

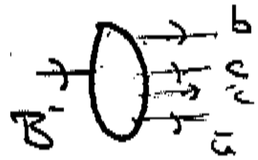


$P_{rob} \sim \left(\frac{\mu_{Bohr}}{m_{\mu^+\mu^-}}\right)^4$

$\times\ \alpha^4$

QCD





Only suppressed by $\frac{1}{m^2_{c\bar{c}}}$ if color octet

Franz et al:

$\langle x_{c\bar{c}} \rangle_H \Rightarrow$

$T^{++} \Rightarrow \frac{G^{+\nu}\, G^{+\mu}\, G_{\mu\nu}}{m_c^2} \leftarrow [A_\mu, A_\nu]$

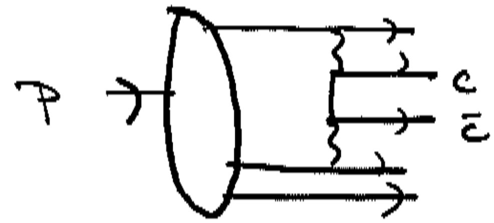
∴ Prob $\sim \alpha_s^4 \, \frac{\mu^2_{Bohr}}{m_{Q\bar{Q}}^2}$ for color octet

$\frac{1}{m_r} = \frac{1}{m_1} + \frac{1}{m_2}$: $\mu^B_{Bohr} \sim 2\, \mu^\pi_{Bohr}$

More IC in B!

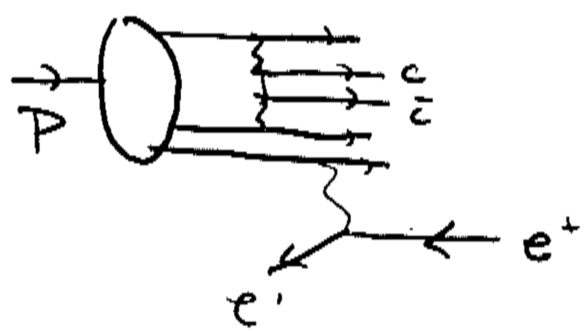
Resolve Intrinsic Charm

Hoyer, Sakai, Peterson, SJB



$x_c \sim \frac{m_{\perp c}}{\sum_i m_{\perp i}}$ large x_c

* Observe at $x_{Bj} \sim 0.4$ in DIS — Harris, Vogt, Smith
* Diffractively dissociate (Coulomb, Pomeron)



Observe Λ_c at large x_F
Observe J/ψ " "
proton frag region

$c(x) \neq \bar{c}(x)$?

* why important:
  - $P_{Q\bar{Q}} \sim \frac{1}{m_Q^2}$ non-Abelian only — Franz et al
  - $B(J/\psi \to \rho\pi, \psi' \to \rho\pi)$ puzzle — Karliner, SJB
  - Evade CKM Heirarchy in B-decays — Gardner, SJ

Intrinsic Charm Matrix Elements

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A. Schäfer
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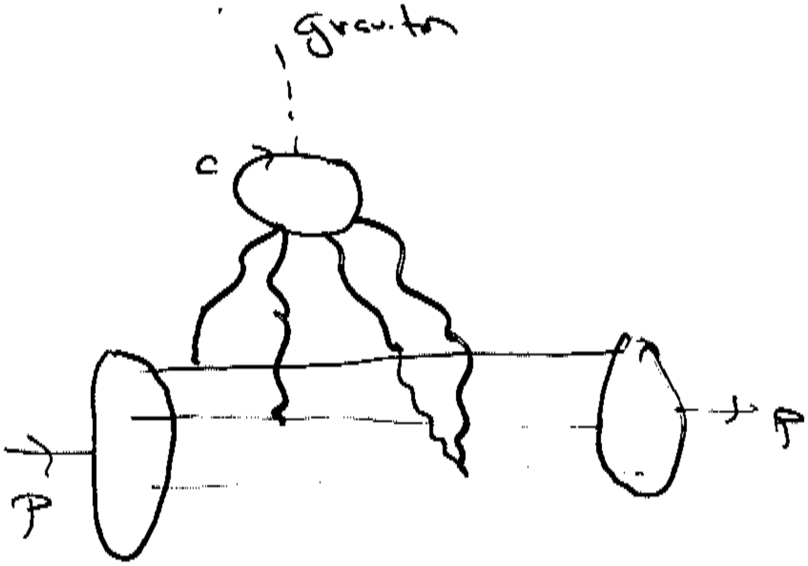


J. Collins
J. Gunion
A Mueller
J. Ellis
SJB

"Intrinsic Chevrolets"

Color Octet IC!
K-T. Chao

$$M_{2(IC)}^{c\bar{c}} = \frac{i}{2(p^+)^2} \frac{g_s^3}{m_c^2} \langle p | Tr_c \, G^{\alpha +} G^{\beta +} G_{\alpha\beta} | p \rangle$$

↑
$\langle x_{c\bar{c}} \rangle_p$

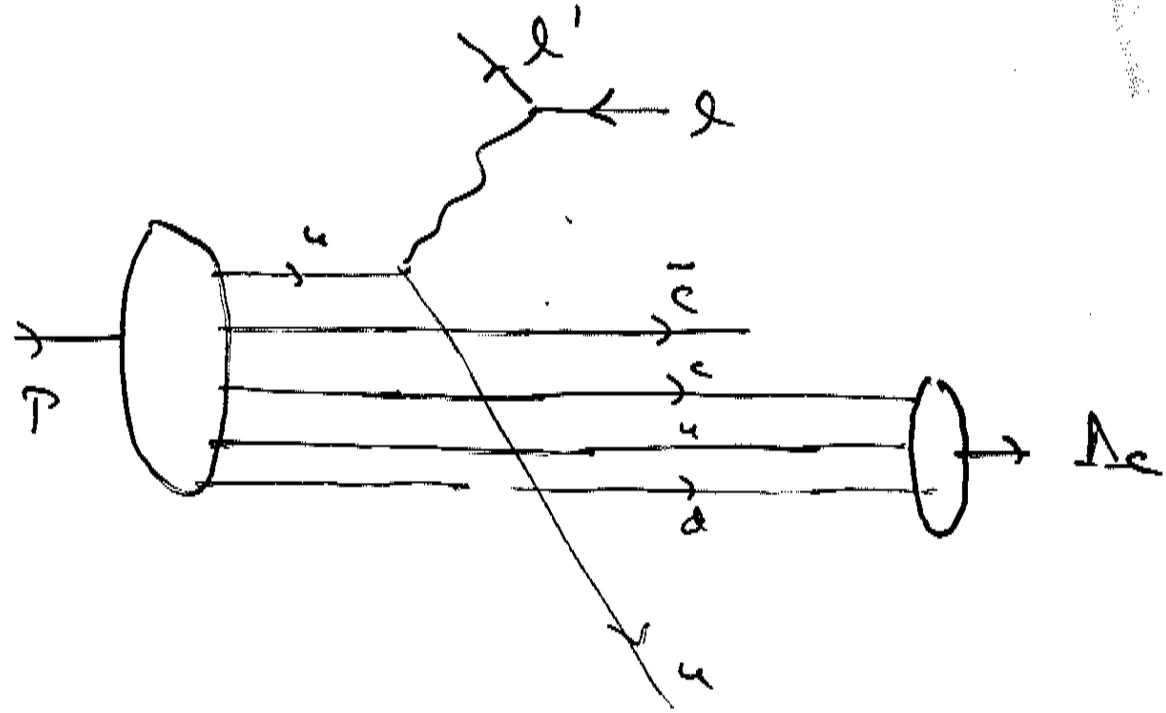
$$= \frac{1}{120\pi^2} \frac{i}{2(p^+)^2} \frac{g_s^4}{m_c^2} \langle p | Tr_c \, \partial^+ A^\alpha \partial^+ A^\beta [A_\alpha, A_\beta] | p \rangle$$

$$= O\left(\frac{\Lambda^2}{m_c^2}\right) \frac{1}{120\pi^2}$$

use instanton gas to model Λ

Use $\langle p | G^{+\alpha} G^+_\alpha | p \rangle$ to normalize to $\langle x_g \rangle_p$

Consistent with Harris, Smith, Vogt IC norm.



Λ_c at large x_F in electroproduction

$$x_{\Lambda_c} = x_c + x_u + x_d < 1 - x_\gamma$$

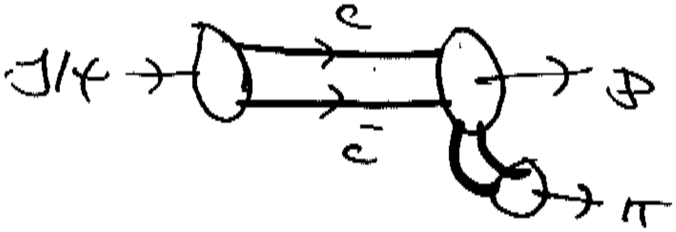
Convolution at amplitude level

Vogt
Rathsman
& SJB

Gutierrez
+
Vogt

Consequences of Intrinsic Charm

* $J/\psi \to \rho\pi$, $\psi' \not\to \rho\pi$



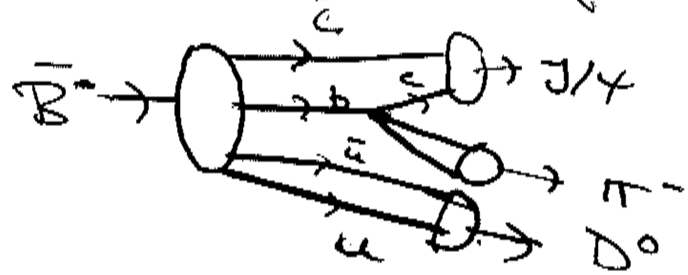
Karliner
SJB

* $\Upsilon \to J/\psi\ X$ Spectrum Hoo

* $\pi p \to D^\pm X$, $\Sigma p \to \Lambda_c X$

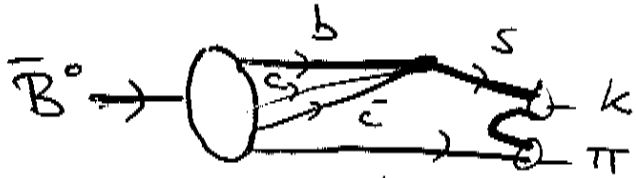
Hoyer et al

Consequences for B-decays



How

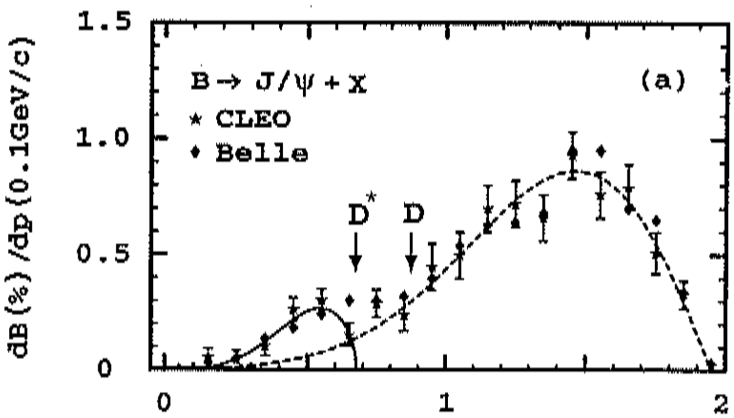
CSR, Belle
bump at low $p_{J/\psi}$



Leading CKM

Evasion of CKM!

Gardner
SJB


1.5
1.0
0.5
0
dB(%)/dp(0.1GeV/c)
B→ J/ψ + X
(a)
* CLEO
♦ Belle
D*
D
0
1
2

Conclusions:

Solving and Testing QCD — one of the greatest scientific challenges

- * Lattice Gauge Theory
- * DLCQ
- * Bethe - Salpeter

} Rigorous approach to non-perturbative QCD

- New novel, extraordinary effects [Spin]
- Saturation, shadowing, antishadowing
- Color Transparency
- Charm Threshold = Ann, ..
- Intrinsic Charm
- Nuclear - Bound Quarkonium
- Diffraction ⟹ $\Psi(x, k_\perp)$
- Single - Spin Asymmetries : W_1', W_2', W_4

(EIC)

Transverse not Leading SF!

Conclusions:

⇒ Unexpected Role of FSI, ISI

* Leading Twist Diffraction, Color Dipole Physics
* Single-Spin Asymmetries – Bjorken Scaling!
* Nuclear Shadowing – Fundamental Understanding in QCD!
* Many new tests, effects

New Questions:

* How is mom. sum rule maintained in the face of shadowing
* What is the mechanism for antishadowing Reggeons?
* How does DHG account for shadowing?

$$\int_{\nu_{th}}^{\infty} \frac{d\nu}{\nu} \left[\sigma_{\gamma A}^{P} - \sigma_{\gamma A}^{A} \right] = \alpha \kappa_A^2$$

Back face not seen for large A?