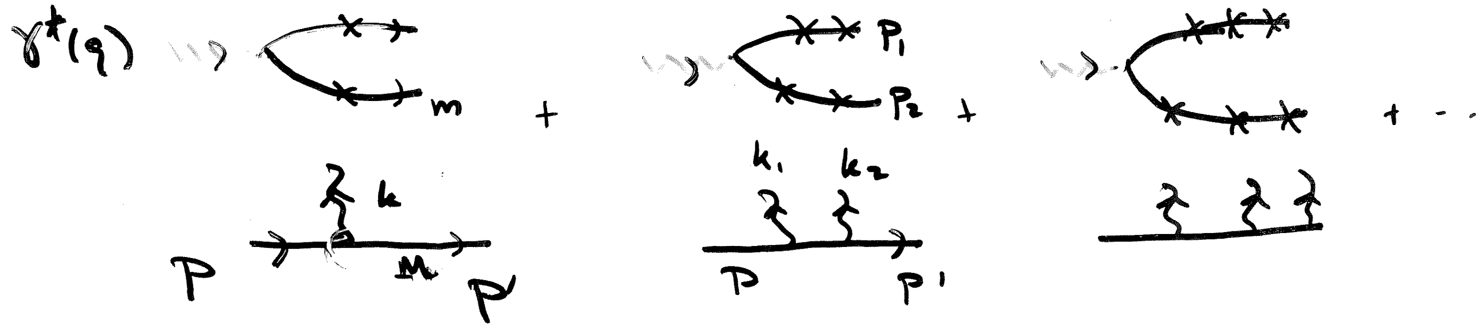
Model Calculation



Scalar quarks, crossed + uncrossed graphs, large M
+ seagulls

Eikonal factorization in $\vec{r}_\perp$, $\vec{R}_\perp$

Verified to 3-loops in Feynman, l.c.g.

$$* \quad \mathcal{M} = \mathcal{M}_{Born}\left[1 - e^{-ig^2 W}\right]$$

$$\mathcal{M}_{Born} = -2ieMQ\,p_2^-\,V(m_{\parallel}, r_\perp)$$

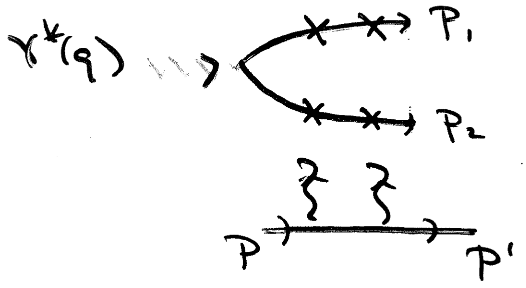
$$V(m_{\parallel}, r_\perp) = \int \frac{d^2p_\perp}{(2\pi)^2} \frac{e^{i\vec{r}_\perp\cdot\vec{p}_\perp}}{p_\perp^2 + m_{\parallel}^2} = \frac{1}{2\pi} K_0(m_{\parallel} r_\perp)$$

$$m_{\parallel}^2 = p_2^- M x_B + m^2$$

$$W(\vec{r}_\perp, \vec{R}_\perp) = \int \frac{d^2k_\perp}{(2\pi)^2} \frac{1 - e^{i\vec{r}_\perp\cdot\vec{k}_\perp}}{k_\perp^2} e^{i\vec{R}_\perp\cdot\vec{k}_\perp} = \frac{1}{2\pi} \ln \frac{|\vec{R}_\perp + \vec{r}_\perp|}{R_\perp}$$

$$Q^4 \frac{d\sigma}{dQ^2\,dx_B} = \frac{\alpha}{16\pi^2} \frac{1-y}{y^2} \frac{1}{2M\nu} \int \frac{dp_2^-}{p_2^-} d^2r_\perp\, d^2R_\perp\, |\mathcal{M}|^2$$

Effect of Rescatterings on the DIS Cross Section



$+ \cdots$

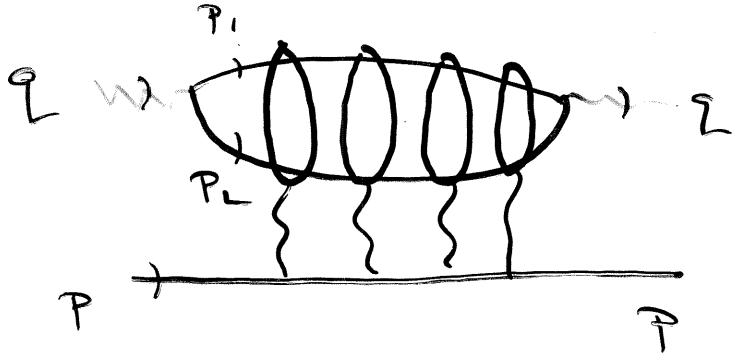
P_1: aligned jet
P_2: spectator jet

$$Q^4 \frac{d\sigma}{dQ^2\, dx_B} = \frac{\alpha}{16\pi^2}\,\frac{1-y}{y^2}\,\frac{1}{2M\nu}\int \frac{dp_2^-}{p_2^-}\, d^2r_\perp\, d^2R_\perp\, |M|^2$$

$$|M| = \left| \frac{\sin[g^2 W(\vec{r}_\perp,\vec{R}_\perp)/2]}{g^2 W(\vec{r}_\perp,\vec{R}_\perp)/2}\, M_{Born}(p_2^-,\vec{r}_\perp,\vec{R}_\perp) \right|$$

< 1 for all $\vec{r}_\perp, \vec{R}_\perp$

Equiv. to sum of cuts of forward virt. Compt. ampl.



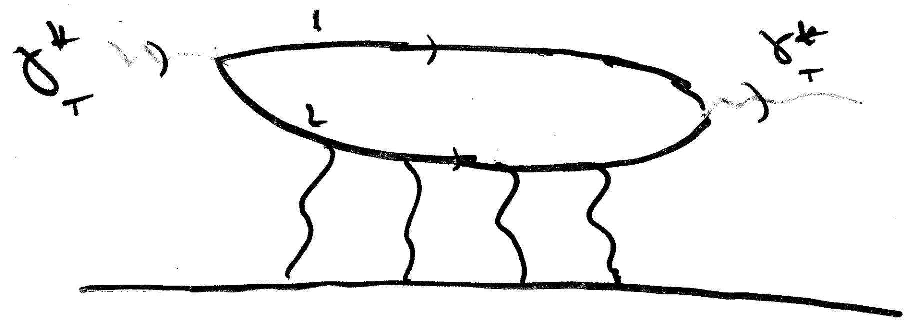
Find shadowing only arises from diagrams involving attachments to p_1 !

cuts give Glauber-Gribov shadowing

Same result in Feynman, l.c.g. (ML)

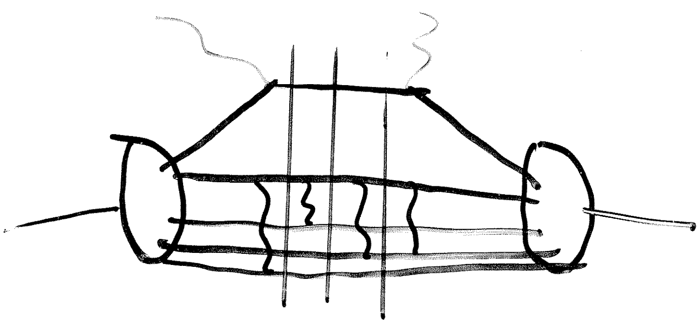
↑ from $\frac{2\vec{p}_{\perp 1}-\vec{k}_\perp}{k^+}$ term

In lab frame, l.c. gauge calc. looks like:



aligned jet config

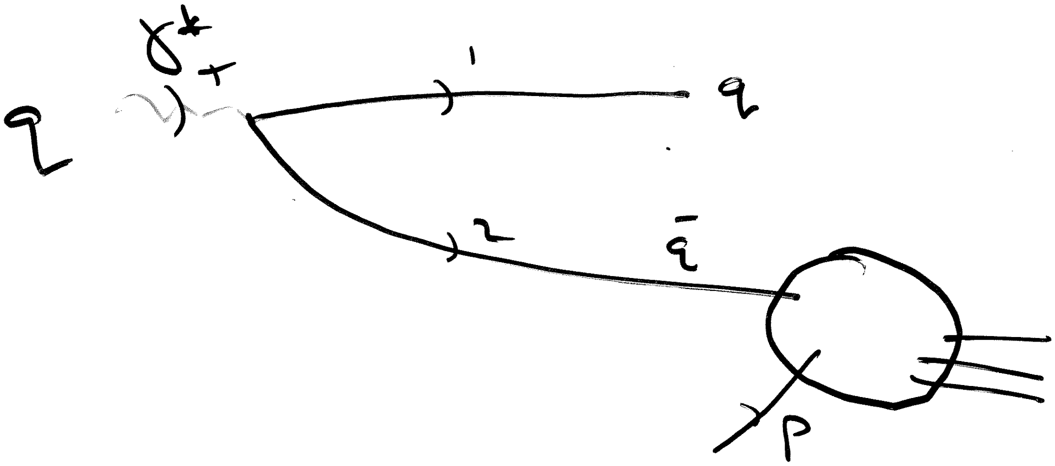
* On-shell rescattering of line p_2
* Shadowing of structure functions
- leading twist
* large color dipole moment $r_\perp \sim O(\frac{1}{M})$
* leading twist diffractive dissociation
* Not part of l.c. wavefunctions



leading twist not in $\psi_n(x, k_\perp)$

Compare with covariant parton model

Landshoff, Polkinghorne, Short



aligned jet configuration

$$\hat{s} = (p_2 + p)^2 = O\left(\frac{M^2}{x_{Bj}}\right)$$

- Regge behavior of $\sigma_{\bar{q}p}(\hat{s}) \sim \hat{s}^{\alpha_R - 1}$

$\Rightarrow F_2(x_{Bj}) \sim x_{Bj}^{1-\alpha_R}$

Ioffe
Kuti - Weisskopf

- Shadowing of $\sigma_{\bar{q}A} \Rightarrow$ shadowing of $\sigma_{\gamma^* A}$

- Also antishadowing from $\alpha_{Reggeon}$

H. Lu
SJB

H. Lu
+ SJB

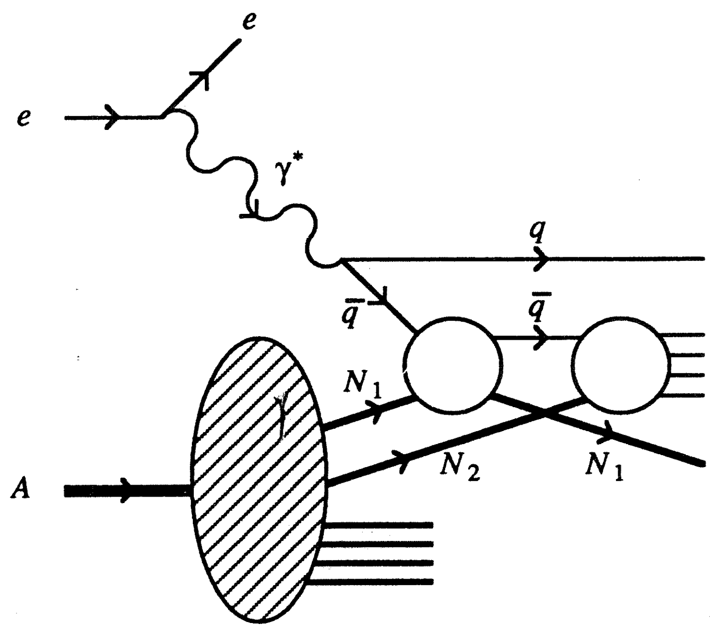


Fig. 1-a

Lab Picture

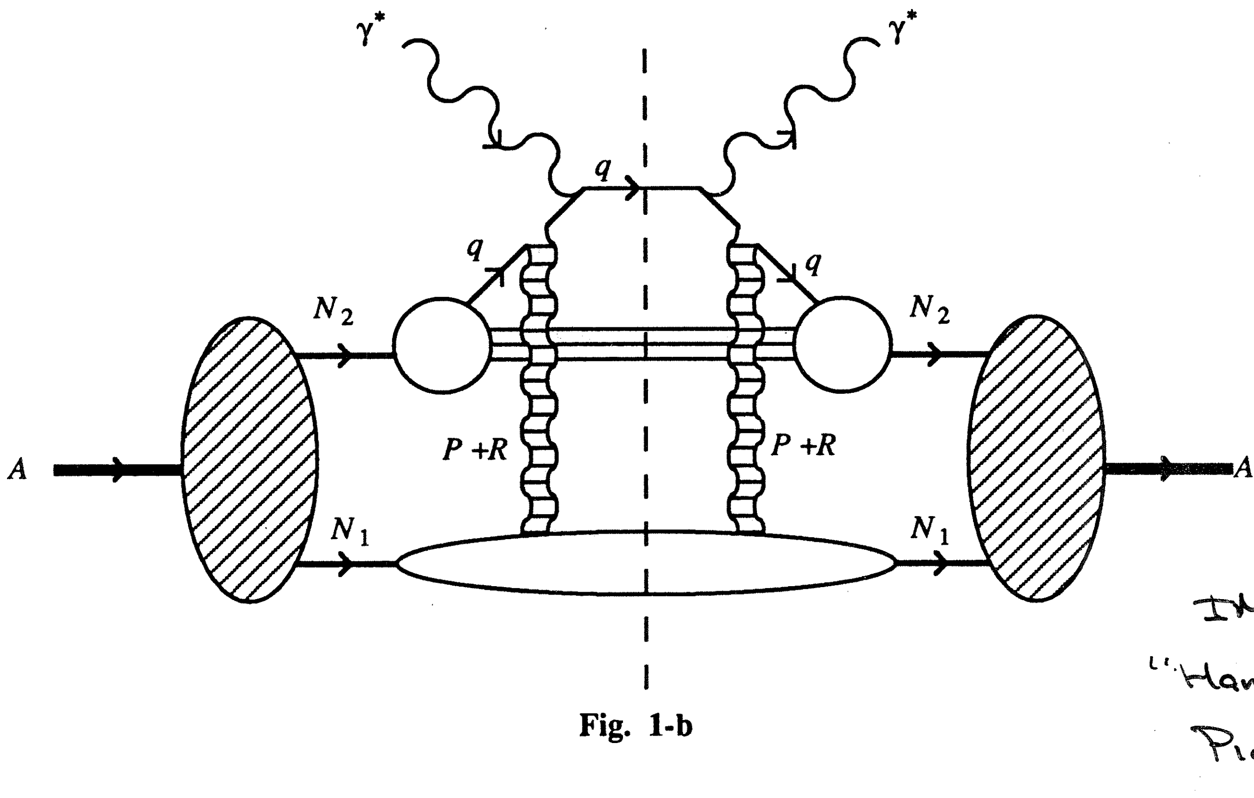


Fig. 1-b

IMF/LC
"Handbag"
Picture

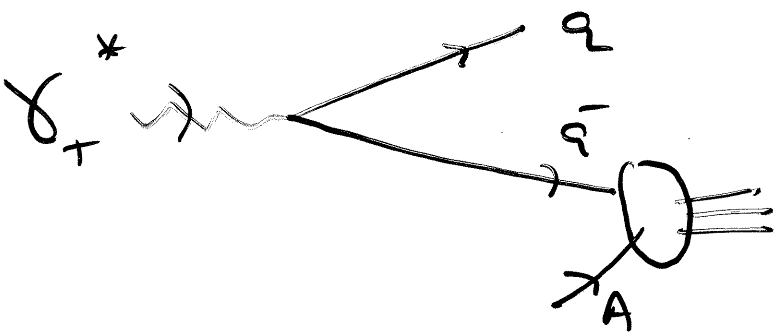
Leading Twist Mechanism
for shadowing and anti-shadowing

Shadowing and Antishadowing of Structure Functions

Collins, Soper
Sterman
Bodwin

Leading Twist Factorization :

<u>Universal</u> $q_A(x, Q^2)$, $\bar{q}_A(x, Q^2)$, $g_A(x, Q^2)$

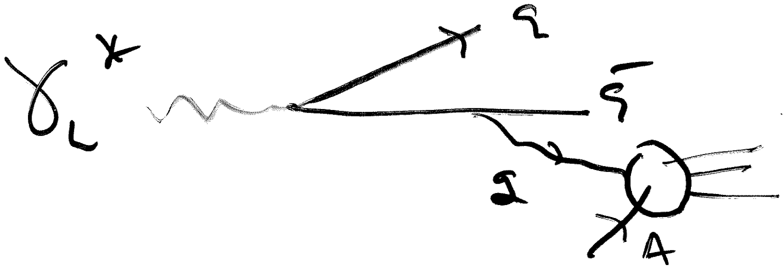


Measures

$\sigma_{\bar{q}A}\left(s \sim \frac{\mu^2}{x}\right)$

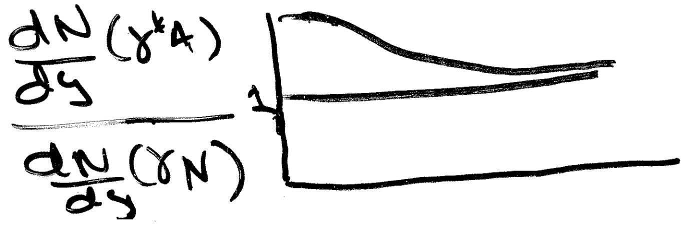
at low x

$$\tau_F = \frac{2\nu}{Q^2 + M^2_{q\bar{q}}} \sim \frac{1}{2xM}$$ Ioffe



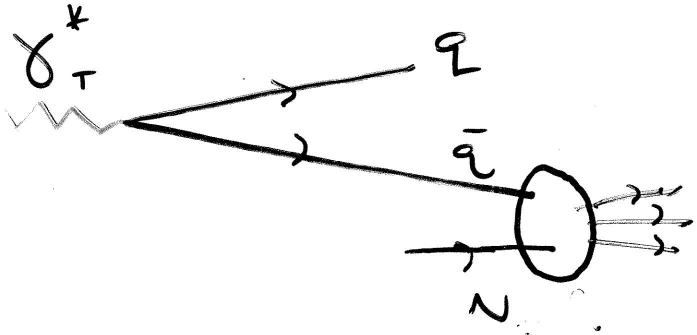
Measures

$\sigma_{gA}\left(s \sim \frac{M^2}{x}\right)$



measures
"wounded" nucleons

H. Lu + SJB



aligned jet model

Bjorken

$$q_N(x) = C \, \frac{x}{1-x} \int ds \, d^2k_\perp \, \mathrm{Im}\, T_{\bar{q}N}(s, \mu^2)$$

$$\mu^2 = -x \, \frac{(s + k_\perp^2)}{1-x} + x M^2 - k_\perp^2$$

Landshoff
Polkinghorne
Short

Connects $q_N(x)$, $q_A(x)$ to $\sigma_{\bar{q}N,\, \bar{q}A}$

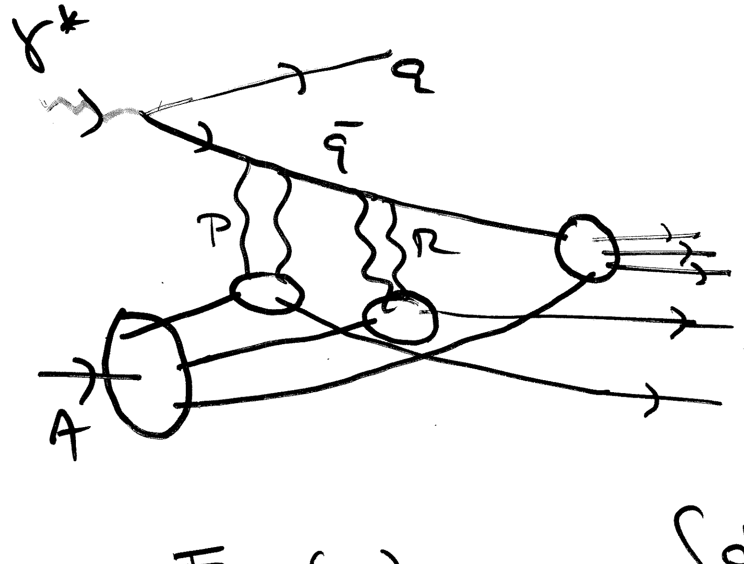
$$T_{\bar{q}N}(s, \mu^2) = i s \, \beta_1(\mu^2) + (1-i) s^{1/2} \beta_{1/2}(\mu^2) + i s^{-1} \beta_{-1}(\mu^2)$$

Reproduces $F_{2N}(x)$, Pomeron, Reggeon, Val.

$q(x) \sim \sum \beta x^{-\alpha}$

Now apply Glauber theory to $T_{\bar{q}A}$

$$T_{\bar{q}A}(s,\mu^2) = T_{\bar{q}N}(s,\mu^2) \cdot \sum_{J=1}^{A} \frac{1}{J} \begin{bmatrix} A \\ J \end{bmatrix} \left[\frac{i\, T_{\bar{q}N}(s,\mu^2)}{4\pi\, p_{cm}\, s^{1/2} (R^2 + 2b)} \right]^{J-1}$$

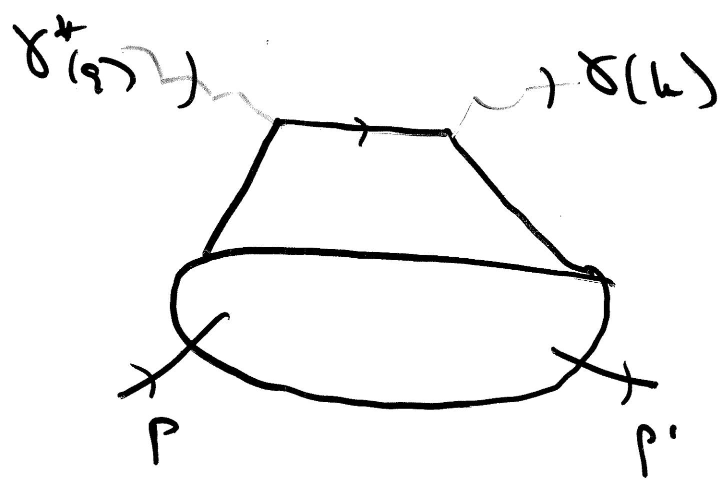


$$\frac{F_{2A}(x)}{A\, F_{2N}(x)} = \frac{\int ds\, d^2k_\perp\, \mathrm{Im}\, T_{\bar{q}A}}{A \int ds\, d^2k_\perp\, \mathrm{Im}\, T_{\bar{q}N}}$$

produces shadowing from Pomeron $x \ll 0.1$
<u>anti shadowing</u> from Reggeon !
$x \sim 0.15$

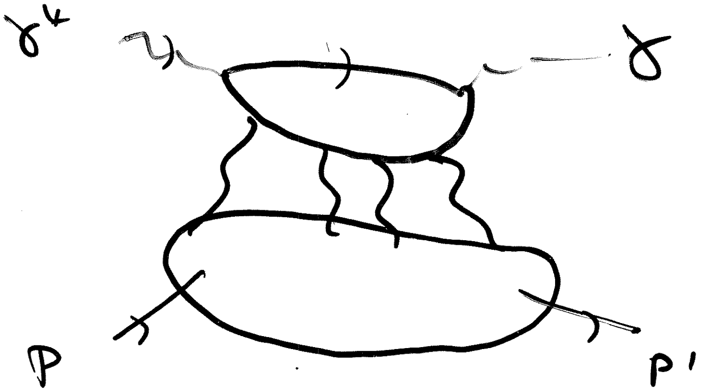
Also effects DVCS

D-S Hwang
P. Hoyer
S.J.B.



handbag approx.

$\Rightarrow$



l.c.g. (k)

Not included in l.c. wavefunctions.

$\Rightarrow$ Shadowing, P_T broadening in nuclei (quasi elastic)

$\Rightarrow$ phase acquired at leading twist: $1 + e^{i\alpha_R(t)}$

$\Rightarrow$ new types of single spin asymmetries remain at leading twist

Modeling L.C. Wavefunctions

D.-S. Hwang + SJB

$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) = \frac{\Gamma_n(x_i, \vec{k}_{\perp i}, \lambda_i)}{M^2 - \sum_i \left(\frac{k_\perp^2 + m^2}{x}\right)_i}$$

$\leftarrow \beta$

* Numerator polynomial dictated by J_z, l_z:

$$J_z = \sum_{i=1}^{n} S_z^i + \sum_{i=1}^{n-1} l_z^i$$

$x_i \frac{\partial}{\partial k_{\perp i}}$

* Perturbation w.f. are templates $\Gamma = \Gamma_{pert} * F(\beta)$

* Denominator:

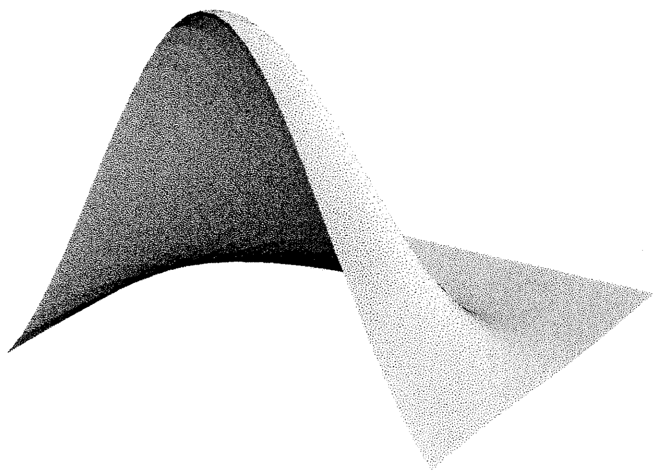
$$\frac{1}{M^2 - \sum_{i=1}^{n}\left(\frac{k_\perp^2 + m^2}{x}\right)_i} \Rightarrow \frac{1}{\delta^2 + \sum_{i=1}^{n} \frac{(x_i - \hat{x}_i)^2}{\hat{x}_i}}$$

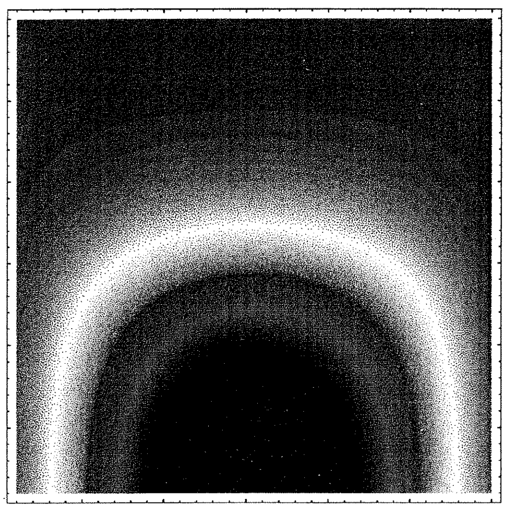
$\therefore$ quadratic peaking at $x_i \Rightarrow \hat{x}_i = \frac{m_{\perp i}(k_\perp)}{\sum m_{\perp j}(k_\perp)}$

* Ladder relations: $\Psi_n \to \Psi_{n+1}$ Antonuccio Dalley, SJB

* Variational ansatz Listerink

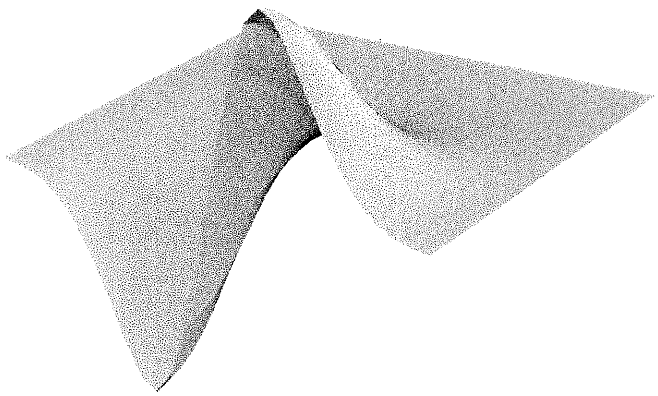
Ground state: Mass = 0.793414

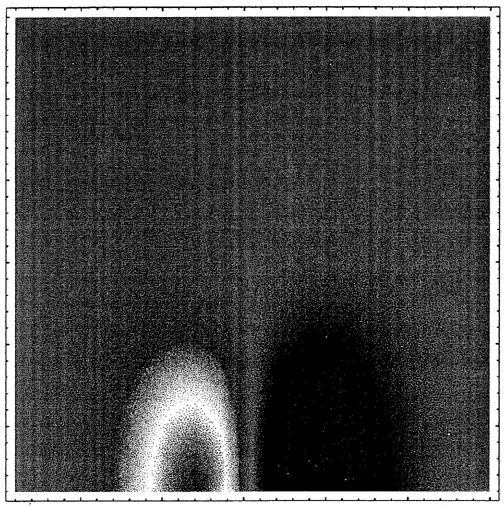




M. van Iersel
B. Bakker
F. Pijlman

First excited state: Mass $= 1.64681$





M. van Iersel
B. Bakker
F. Pijlman

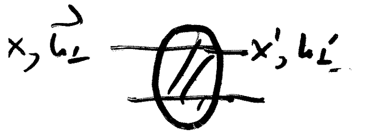
New Proposal (Trento Method)

$$\boxed{\text{Combine DLCQ with } V_{eff}}$$

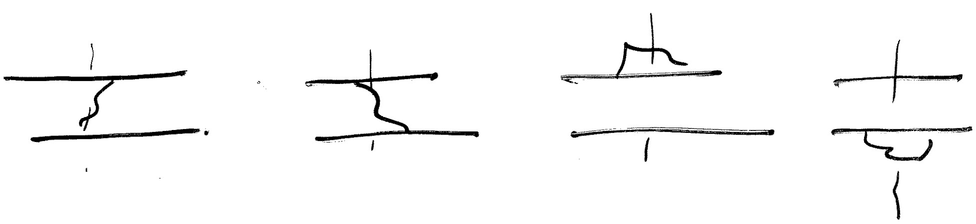
Construct $V_{valence}(M^2, g)$ Lepage SDB

from resolvent with DLCQ grid

$$V_{valence} = \sum_{DLCQ} \frac{\langle val \,|\, H_I \,|\, n\rangle\langle n \,|\, H_I \,|\, val\rangle}{M^2 - \sum_i^n \left(\frac{k_\perp^2+m^2}{x}\right)_i + i\epsilon}$$



$+ \cdots$ (up to $|n_{max}\rangle$)

$=$  $+ \cdots$

$$\left[M^2 - \sum^{val}\left(\frac{k_\perp^2+m^2}{x}\right)_i\right]\psi_{val}(x_i, k_{\perp i}, \lambda_i)$$

$$= \sum_{DLCQ} V_{valence} \otimes \psi_{val}(x_i, k_{\perp i}, \lambda_i)$$

eival problem in g or M^2.

— DLCQ: $P^+ = \frac{2\pi}{L} K$, $k_i^+ = \frac{2\pi}{L} n_i$

$$\sum_{i=1}^{n} n_i = K$$

HCP
SDB

*** Foch space limited!

$V_{valence}$: automatically truncated
maximal Foch state
maximal $g^{P(K)}$!

— Compute $V_{valence} = \sum_{\alpha=2}^{P(K)} g^\alpha V_\alpha$ (matrix mult!)

only once!! e.val. in g

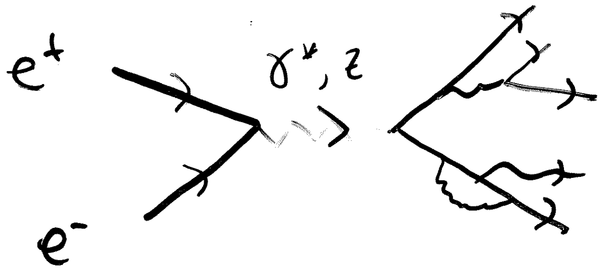
— Use methods of Bakker et al.

— Retain all advantages of DLCQ
Lorentz Symmetries. (add zero modes?)

— Test against Heavy $Q\bar{Q}$ first
Hiller, McCartor SJB
Paston et al

— P.V. regularization

Event Amplitude Generator



High accuracy needed for QCD bckgrds to Higgs, Susy, ..

Conventional method:

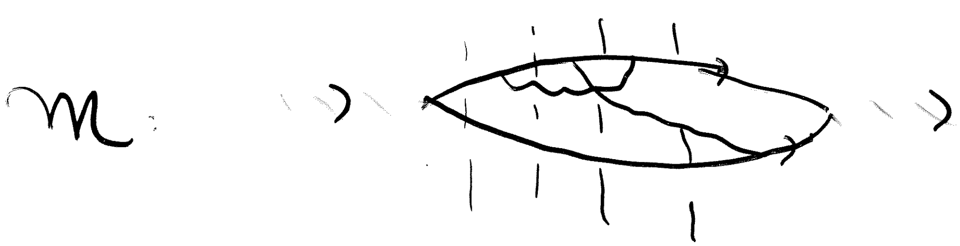
- generate probabilities
- physical phase space — physical polarization

but — virtual contributions — Feynman gauge
d^4k dimensional regulariz.

Light-cone method:

disc. with
J. Hiller
G. McCartor
D.S. Hwang

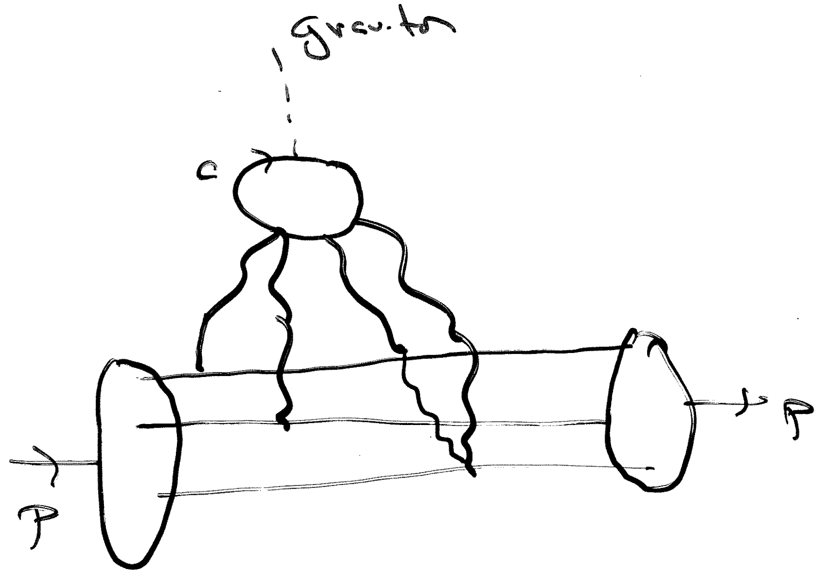
see also
Soper, Sterman



* generate amplitudes, specific l.c. spins
* Physical phase-space, pol: real + virtual
* Mren from alternating denom. method.

Intrinsic Charm Matrix Elements

M. Polyakov
A. Schäfer
O.V. Teryaev



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

"Intrinsic Chevrolets"

$$\mathcal{M}^{c\bar{c}}_{2(\mathrm{int})} = \frac{i}{2(p^+)^2}\,\frac{g_s^3}{m_c^2}\langle p|\,\mathrm{Tr}_c\, G^{\alpha +} G^{\beta +} G_{\alpha\beta}\,|p\rangle$$

$\uparrow$

$\langle x_{c\bar{c}}\rangle_p$

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

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

use instanton gas to model Λ

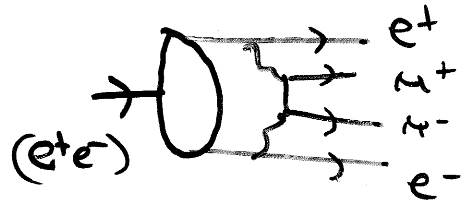
Use $\langle p|\, G^{+\alpha} G^{+}_{\alpha}\,|p\rangle$ to normalize to $\langle x_g\rangle_p$

Consistent with Harris, Smith, Vogt IC norm.

S. Gardner + SJB

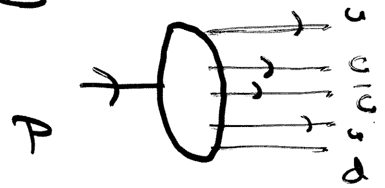
Color - Octet Intrinsic Charm

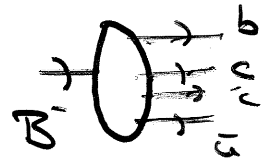
QED:



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

QCD

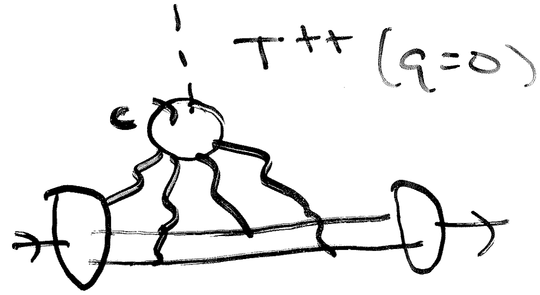




Only suppressed by $\frac{1}{m_{c\bar{c}}^2}$ if color octet

Franz et al:

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



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

$\therefore$ $P_{rob} \sim \alpha_s^4 \frac{\mu_{Bohr}^2}{m_{Q\bar{Q}}^2}$ for color octet

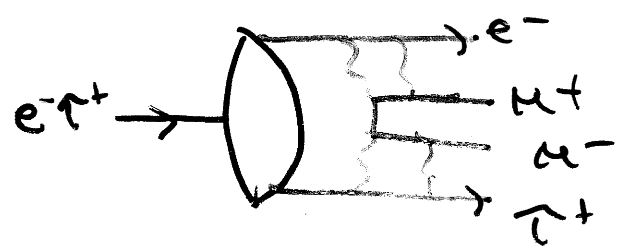
$\frac{1}{m_r} = \frac{1}{m_1} + \frac{1}{m_2}$: $\mu^{B}_{Bohr} \sim 2\,\mu^{\pi}_{Bohr}$

More IC in B !

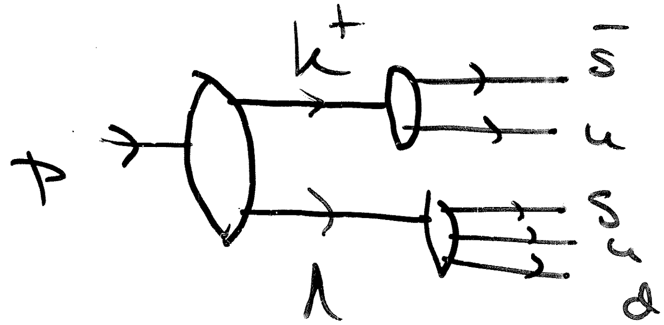
Properties of Intrinsic sea

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

QED analog



Coulomb
interactions
break $\mu^\pm$ symmetry



$$\langle x_{\bar{s}} \rangle < \langle x_s \rangle$$

$$\lambda_s \sim -\lambda_p$$

Leading particle effects

triple Regge

New approach: Pillar, Rothman, SJB

Thomas, et al

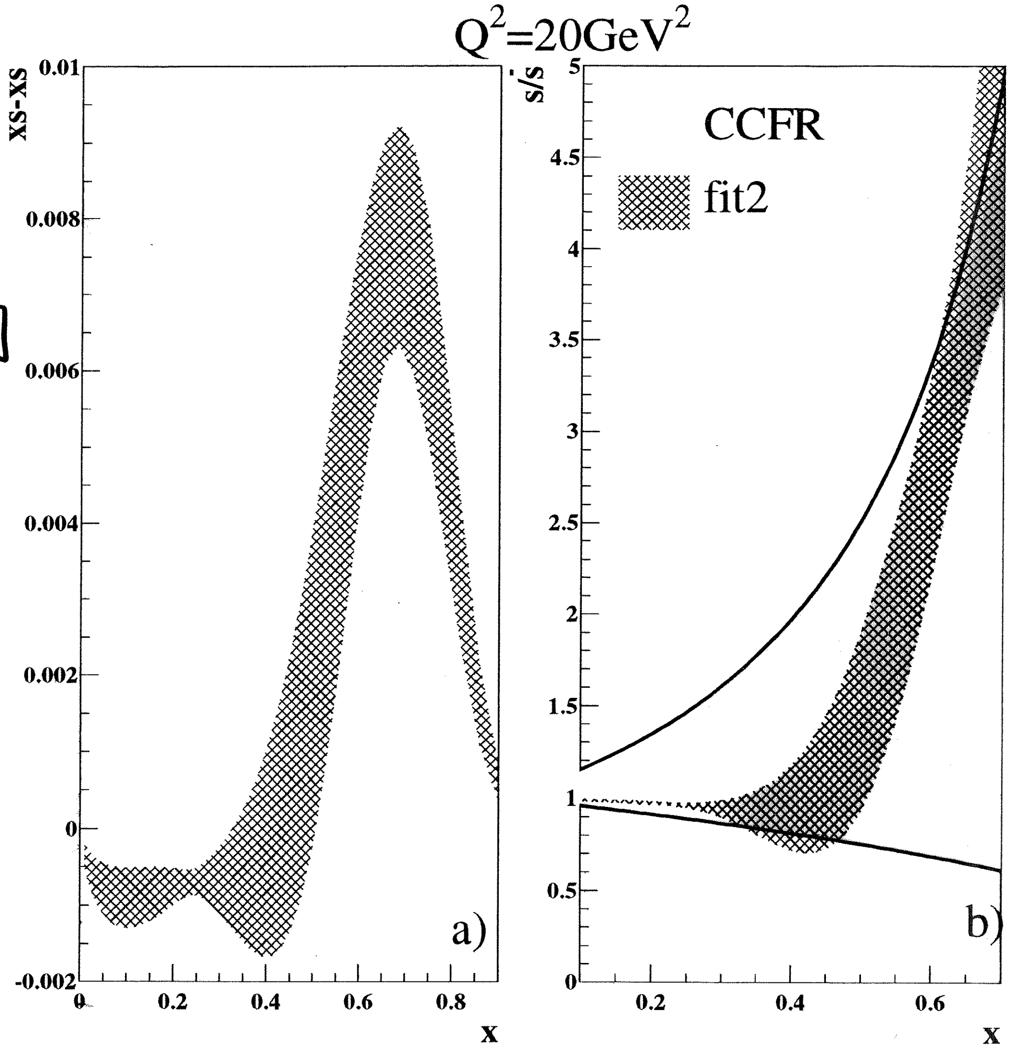
SJB + Ma

Burkardt, Warr

Nielsen, et al

Barone, Pascaud, Zomer
hep-ph/9907512

$x[s(x) - \bar{s}(x)]$

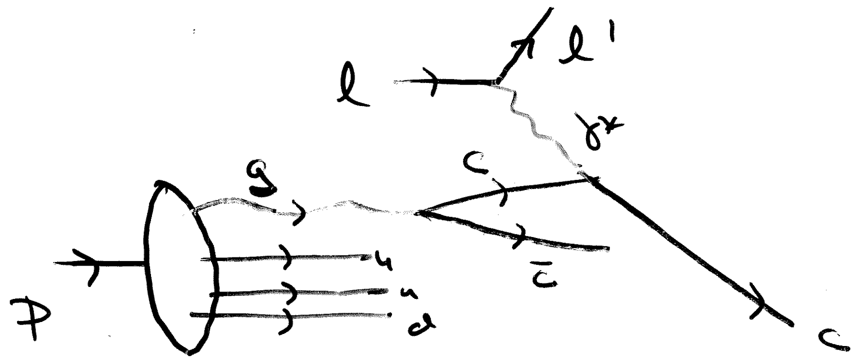


$\frac{s(x)}{\bar{s}(x)}$

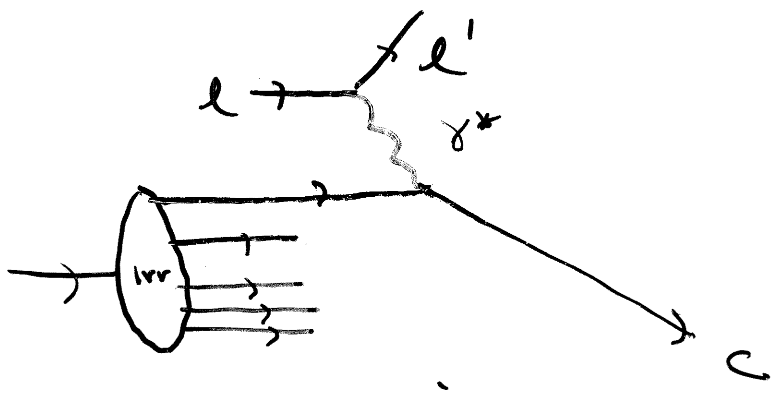
Figure 17: Results of `fit2` for: a) the difference $x(s - \bar{s})$ and b) the ratio $s/\bar{s}$ at $Q^2 = 20\text{GeV}^2$. In the box b) the result of CCFR is also shown.

Fit 2: $\begin{cases} \text{BEBC} \\ \text{CDHS} \\ \text{CDHSW} \end{cases}$ data

Two Contributions to Sea Quark Distributions



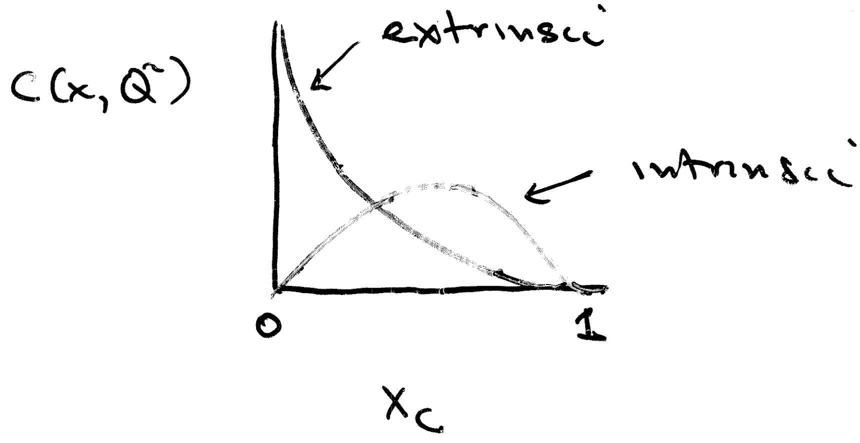
extrinsic = photon-gluon fusion $g\gamma^* \to c\bar{c}$



1 gluon irreducible

intrinsic

initial state for DGLAP evolution.



$Q^2 \gg 4m_c^2$

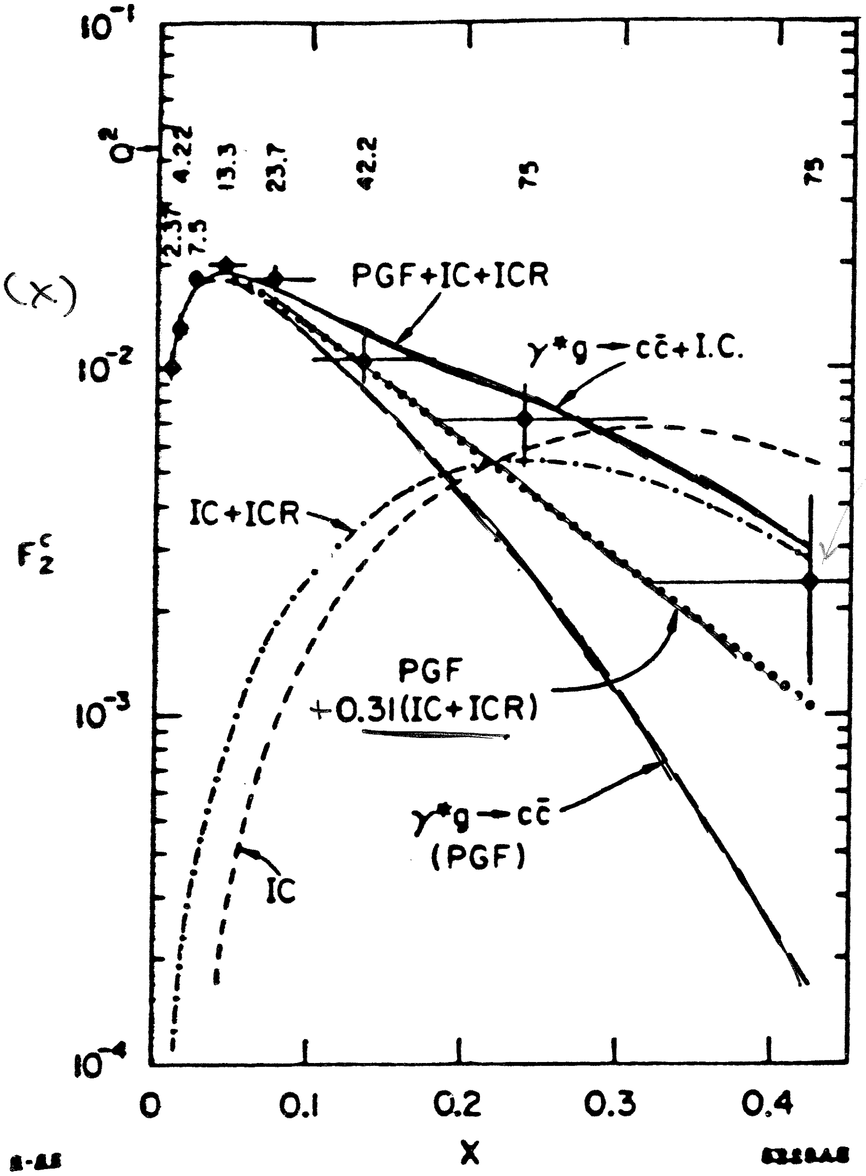
$c_I \propto \frac{1}{m_c^2 R^2}$

SJB, Hoyer, Sakai.
Peterson

Thomas
Sons

Ingelman & Thunberg

$F_{2c}(x)$



Hoffman + Moore

* Smith, Vogt, Harr

EMC data

Prob (IC)

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

Steffens,

Melnitchouk

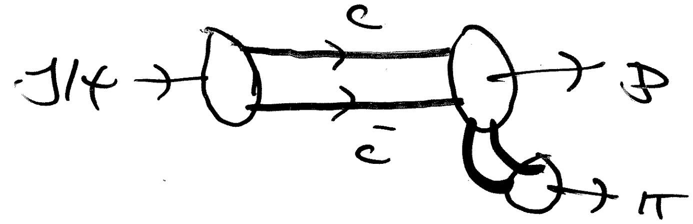
Thomas

(variable quark mass scheme)

CBM for IC

Consequences of Intrinsic Charm

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



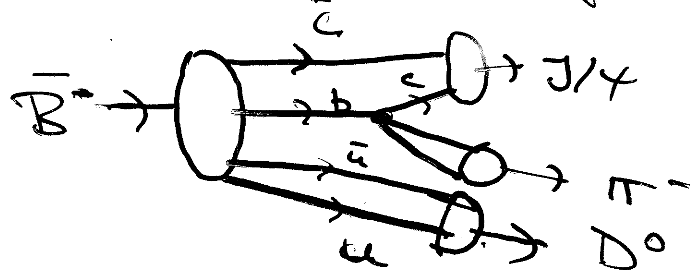
Karliner
SJB

* $\Upsilon \to J/\psi\, X$ spectrum   Hou

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

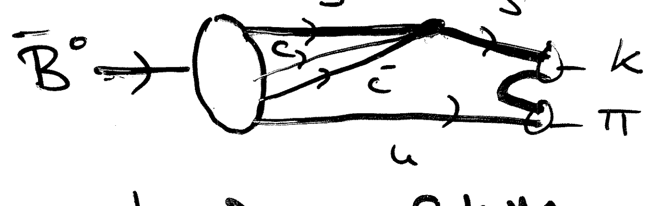
Hoyer et al

Consequences for B-decays



Hou

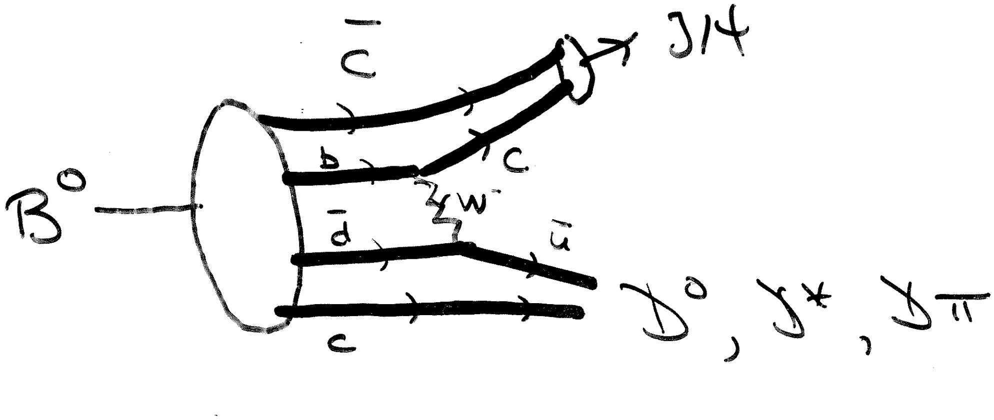
CESR, Belle
bump at low $P_{J/\psi}$



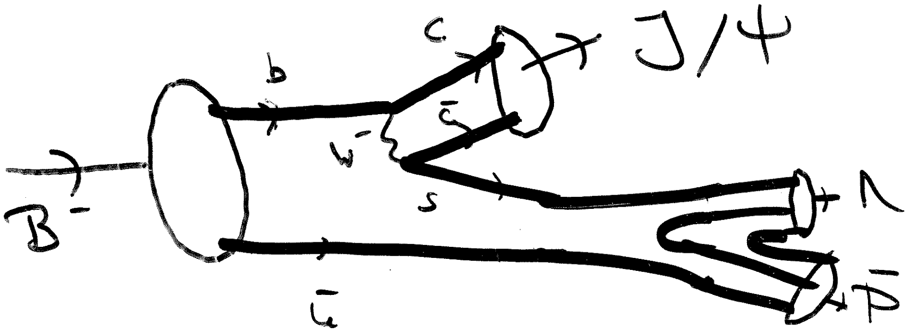
Leading CKM

Evasion of CKM!

Gardner
SJB



Great
Hou



Nouvus
SJB

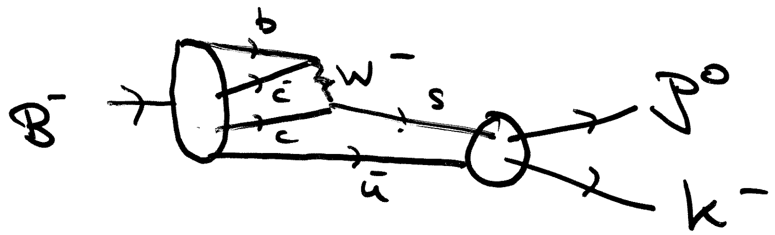
* Both produce bump in M_X spectrum
~ 2 GeV

* $B \to \eta' k$

$$|\eta'\rangle = (\ )|gg\rangle + (\ )|gc\bar{c}\rangle + \ldots ?$$

Use color-octet intrinsic charm to evade the CKM Hierarchy

S. Gardner + SJB

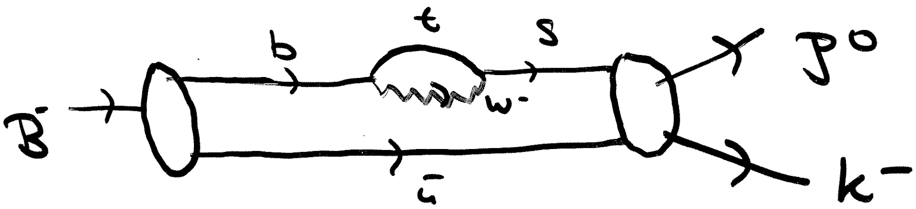


(s very fast)

New pattern of exclusive decays

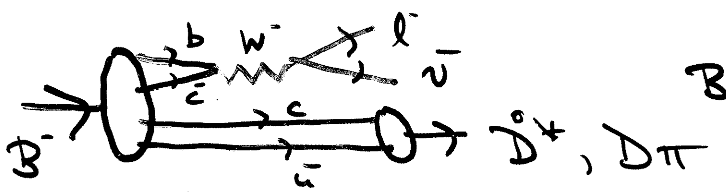
Enhances rate

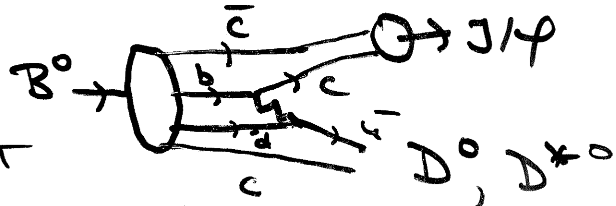
Interferes with standard contributions



Other examples of IC in B decays

Chang + Hou





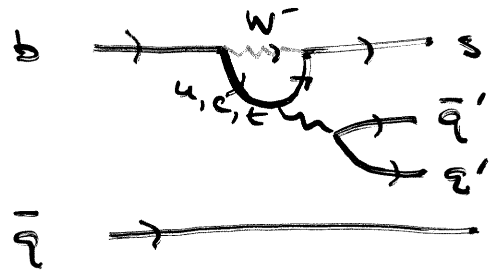
Measure lepton pairs

Seen at CLEO? bump at low $p_{J/\psi}$

$\bar{B}^0 \to \rho^+ K^-$: $B^- \to \rho^0 K^-$: $B^- \to \rho^- \bar{K}^0$: $\bar{B}^0 \to \rho^0 \bar{K}^0$

$B^0 \to \pi^+ K^-$: $B^- \to \pi^0 K^-$: $B^- \to \pi^- \bar{K}^0$: $\bar{B}^0 \to \pi^0 \bar{K}^0$

Suppose only penguin contribution



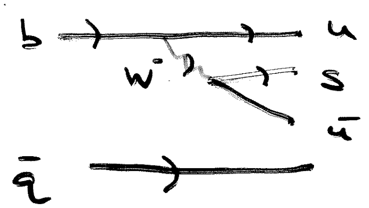
$q, q' \in u, d$

Then isospin predicts BR : $2 : 1 : 2 : 1$

(includes 6% corr. from $\tau_{B^-} / \tau_{\bar{B}^0}$)

Agrees with experiment!

But

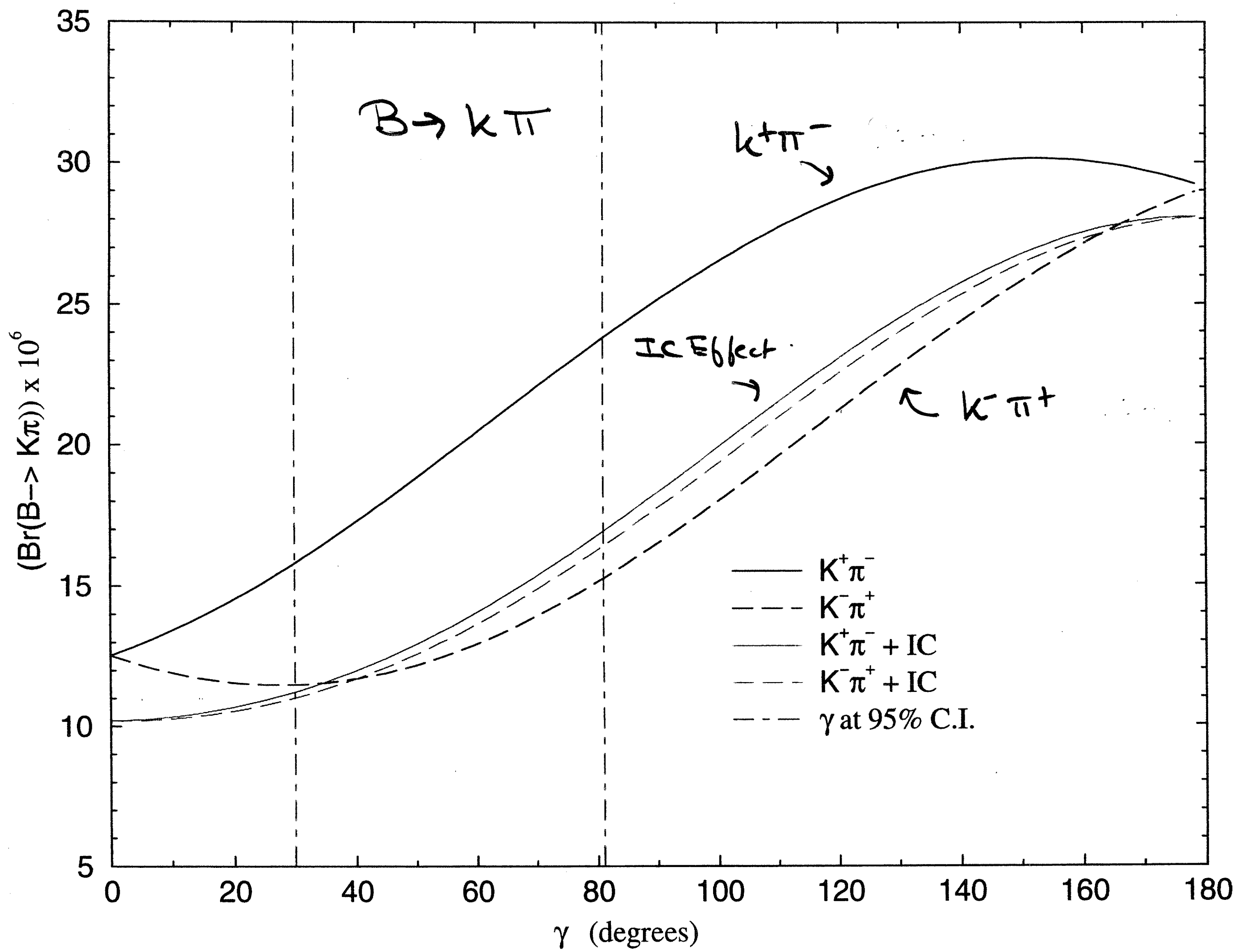


CKM suppressed
but large Wilson coef.
Destroys agreement

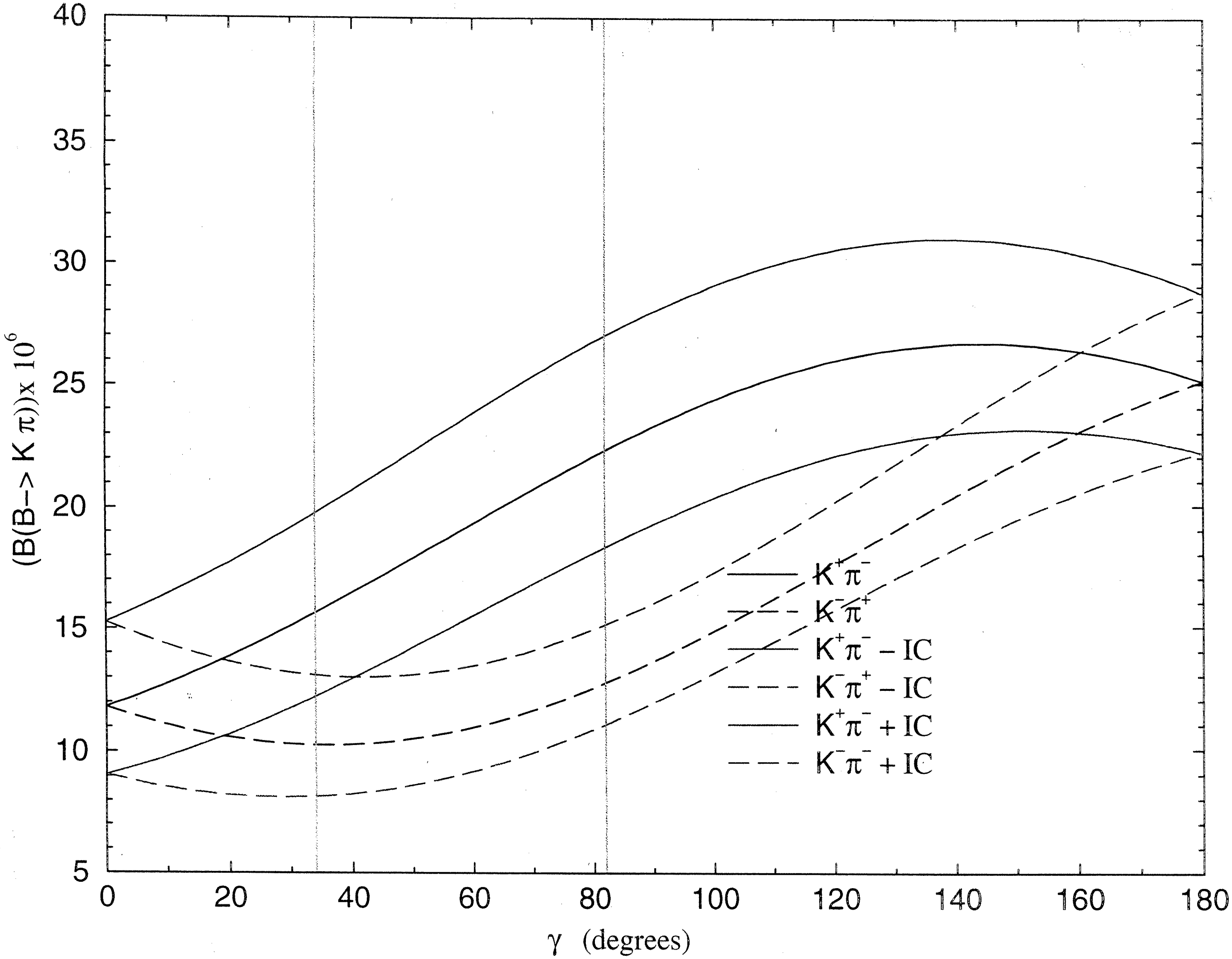
Add new contributions

Ciuchini et al : [illegible] Fit ⇒ "Charming penguins"
intrinsic charm
$\Big\} \to$ Identical phenomenology $2 : 1 : 2 : 1$

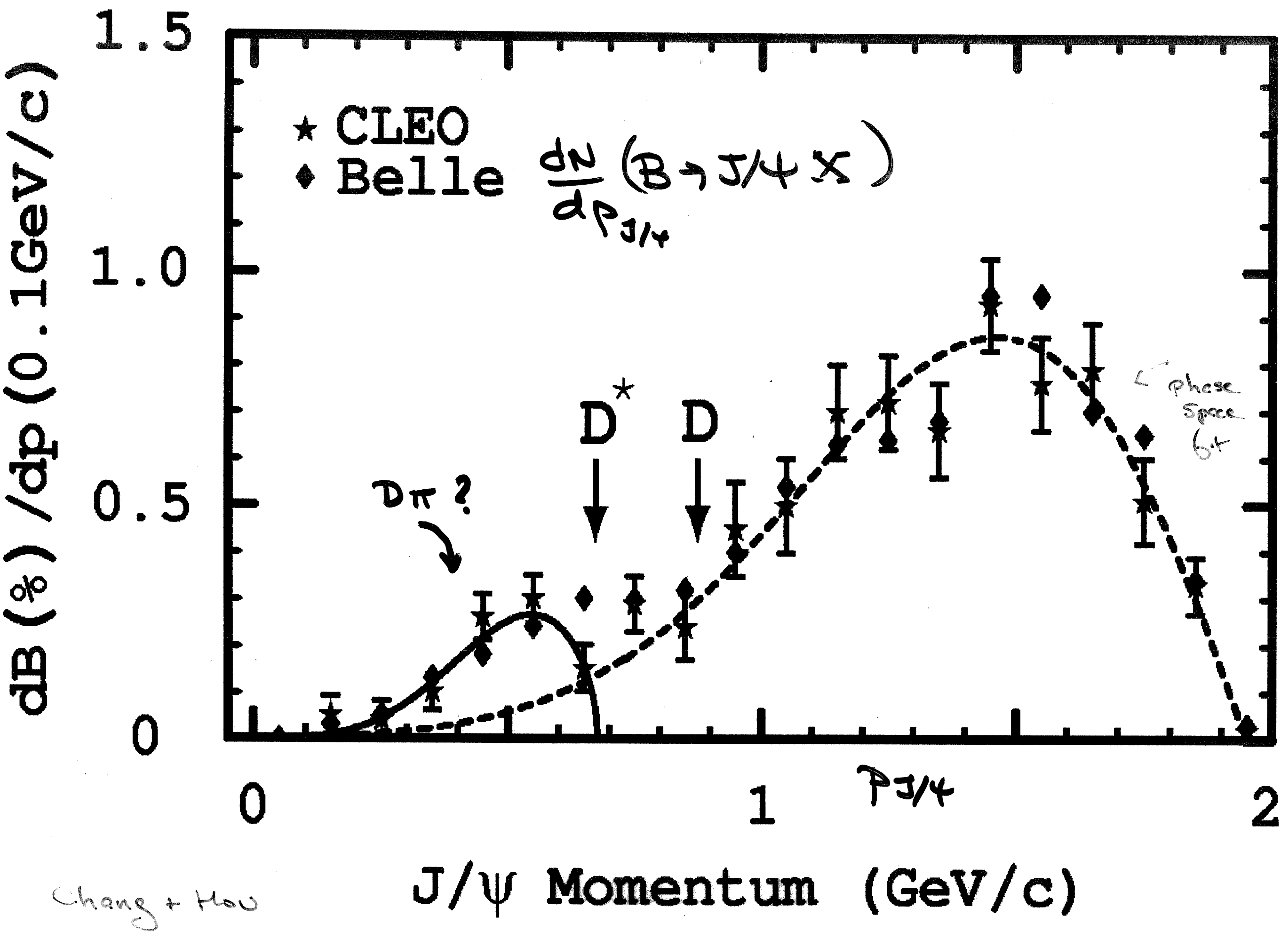
annihilation contribs. → similar



S. Gardner
&JB (prelim)

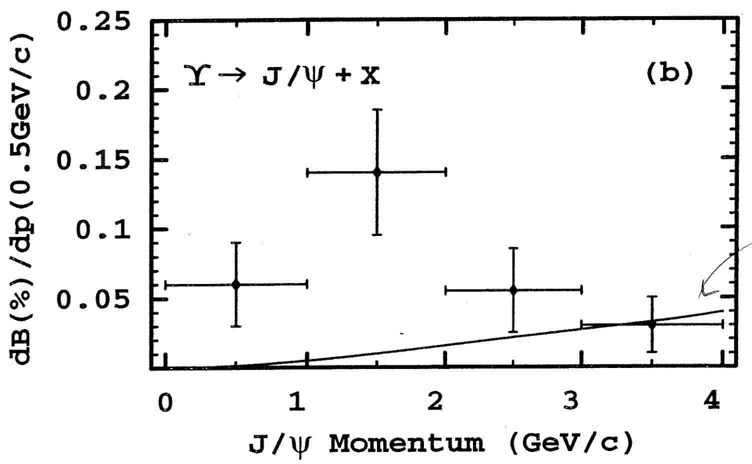


(B(B–> K π))x 10^6
40
35
30
25
20
15
10
5
0
20
40
60
80
100
120
140
160
180
γ (degrees)
K⁺π⁻
K⁻π⁺
K⁺π⁻ – IC
K⁻π⁺ – IC
K⁺π⁻ + IC
K⁻π⁻ + IC



dB (%) /dp (0.1GeV/c)
1.5
1.0
0.5
0
CLEO
Belle
$\frac{dN}{dp_{J/\psi}}(B \to J/\psi X)$
Dπ ?
D*
D
$p_{J/\psi}$
phase space fit
0
1
2
J/ψ Momentum (GeV/c)

Chang + Hou



color octet model

Intrinsic charm in Υ ?

Chang + Hou

$\{ \psi^{LC}_{n/H} (x_i, \vec{k}_{\perp i}, \lambda_i) \}$

repn. of hadron in terms of q, g

* Frame-independent
* $P^+, \vec{P}_\perp, J_z$ conserved for each ψ_n
* Trivial vacuum  $= 0$
* Exact repn. $F(t)$, OPE, $B(0) \equiv 0$

  vanishing gravitomagnetic moment
* $\bar{q}(x) \neq q(x)$, $\bar{u}(x) \neq \bar{d}(x)$
* $\langle x_Q \rangle_H \sim \frac{\Lambda^2}{M_Q^2}$ from $\langle H | G^3(0) | H \rangle$

* ψ_n predictable from PQCD at large M_n^2

  $x \to 1$, $k_\perp^2 \to \infty$, heavy sea

  $x \to 0$ Ladder relns.
* Helicity retention, counting rules
* Hidden color
* Color transparency at small $b_\perp$

QCD in Space and Time

* Large longitudinal distances in DIS

$$L_{Ioffe} = \frac{2\nu}{Q^2} = \frac{1}{Mx_{Bj}} > R_{Target}$$

* Coherence of gauge couplings

<u>Diffractive Dissociation</u>

- leading twist in $\sigma_T(\gamma^* N)$
- Shadowing ; anti-shadowing from Reggeons?
- Odderon Effects in $\gamma p \to c\bar{c}\, p'$ asymmetry
- $\sigma_T(\gamma^* p \to M_x p')$, $\sigma_L(\gamma^* p \to M p')$

$\left\{ \begin{array}{l} \text{distinction } Q^2, \nu \text{ dep.} \\ \text{color dipole effects} \end{array} \right.$

- $HA \to$ Jets A' : resolves H l.c.w.f. color transparency

* Structure Functions , DVCS
  - not given by $q(x,Q^2) = \sum |\Psi_n|^2$
  - Intrinsic Charm at large x_{Bj}, x_F

Major questions for LCQ:

* Chiral Symmetry Breaking
* Gluon Condensate
* Higgs Mechanism
* Θ - vacuum , Gribov Ambiguity
* Instantons
* Regularization , LC gauge prescription dep

$\boxed{\text{Zero Modes ?.}}$

*** Confinement

Haller
Van Baal
Heinzl

Connections to Lattice, String Theory

Conclusions

QCD Phenomena and Light-Cone Wavefunctions

* Universal, frame-independent $\{\psi_n(x, k_\perp, \lambda)\}$

* Distribution amplitudes $\begin{cases} \phi_M(x, Q) \\ \phi_B(x_1, x_2, Q \end{cases}$

  - key hadronic input to factorizable exclusive amplitudes

  - Unify B-physics, Form Factors, high momentum transfer amplitudes

* New experimental tool: diffractive jet prod.

* Novel Phenomena

  - Color Transparency
  - Intrinsic Charm
  - Hidden Color
  - Extremum physics : $x \to 1$
    high $k_\perp$
    heavy quark threshold

* New theory methods

Effective V, DLCQ, Transverse Lattice, BS
SDLCQ, LFQM ...

Thanks to

Antonio Bassetto

and his Padua colleagues

and

ECT ****

for a great

Light-Cone Physics

meeting