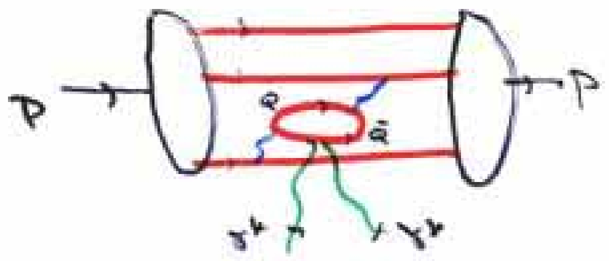
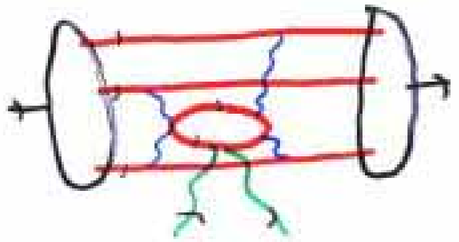
Intrinsic Heavy Quark Fock States
⇒ Implications for RHIC

Hoyer
Peterson
Sakai
STB





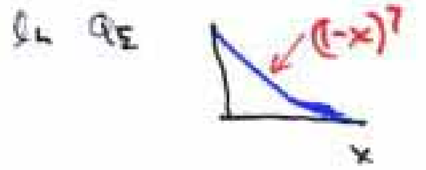
Extrinsic (~DGLAP) Intrinsic (L by L)

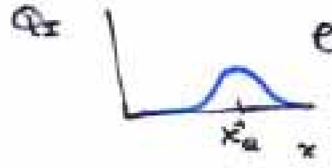
$Q_E(x,Q^2) \sim (1-x)^7 \ln\frac{Q^2}{m_Q^2}$ $Q_I(x) \sim \frac{F_I(x)\Lambda_{QCD}^2}{M_Q^2}$

$\langle p | GG | p \rangle$ $\langle p | GGG | p \rangle$ [illegible]

$\langle p | FFFF | p \rangle$ QE

peaked at $x \sim 0$ peaked at $\hat{x}_Q = \frac{m_{\perp Q}}{\sum_i m_{\perp i}}$





equal rapidity

~ 1% IC
Hoffman Moore
Vogt Smith

Seen at EMC $\mu p \to \mu' c X$

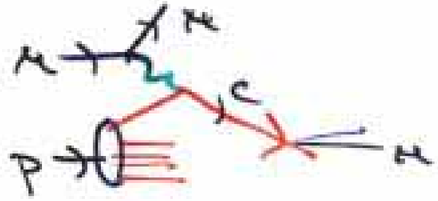
FNAL ISR High x_F Λ_c, D in $pp \to \Lambda_c X$, $pp \to \Lambda_b X$?

FNAL CP High x_F J/ψ $pp \to J/\psi X$, $J/\psi J/\psi X$

Intrinsic Charm: Heavy Quark has large fraction of hadron momentum

* 1. EMC measurement of $c(x)$

Hoffman Moore



large excess (×30) at $x_{Bj} = 0.42$ $Q^2 = 75\ \mathrm{GeV}^2$

$\mu p \to \mu \mu X$

* 2. NA3 measurement of $\pi N \to \psi \psi X$

$x_F(\psi\psi)$ maximal!

SJB Vogt

* 3. NA3, .. measurement of $\pi N \to \psi X$

anomalous large x_F production

anomalous A-dep.

Mueller, Hoyer Tang SJB

* 4. $\pi^- N \to D^{\pm} X$ Strong "leading particle" effect

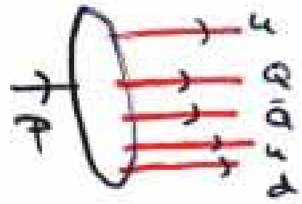
FNAL

coalescence of valence quark with high x c

SJB Gunion Soper

SJB Vogt

Intrinsic Heavy Quarks



- Rigorous consequences of quantum fluctuations in QCD

  M. Polyakov

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

  Thomas, Melnitchouk, Ma, SJB

- Implications for B-decays, extraction of CKM

  Gardner, SJB

- Solution to $J/\psi \to \rho\pi$ puzzle?

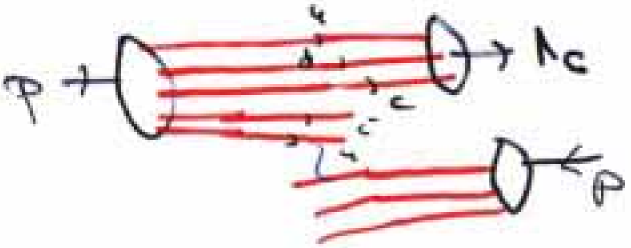
  Karliner, SJB

- Leading charm hadrons

  Coalescence with comovers

$pp \to \Lambda_c X$:

large x_F



- Large range of phenomenology

  R. Vogt, Gunion, SJB

- Ignored in CTEQ, MRST, .. parameterizations

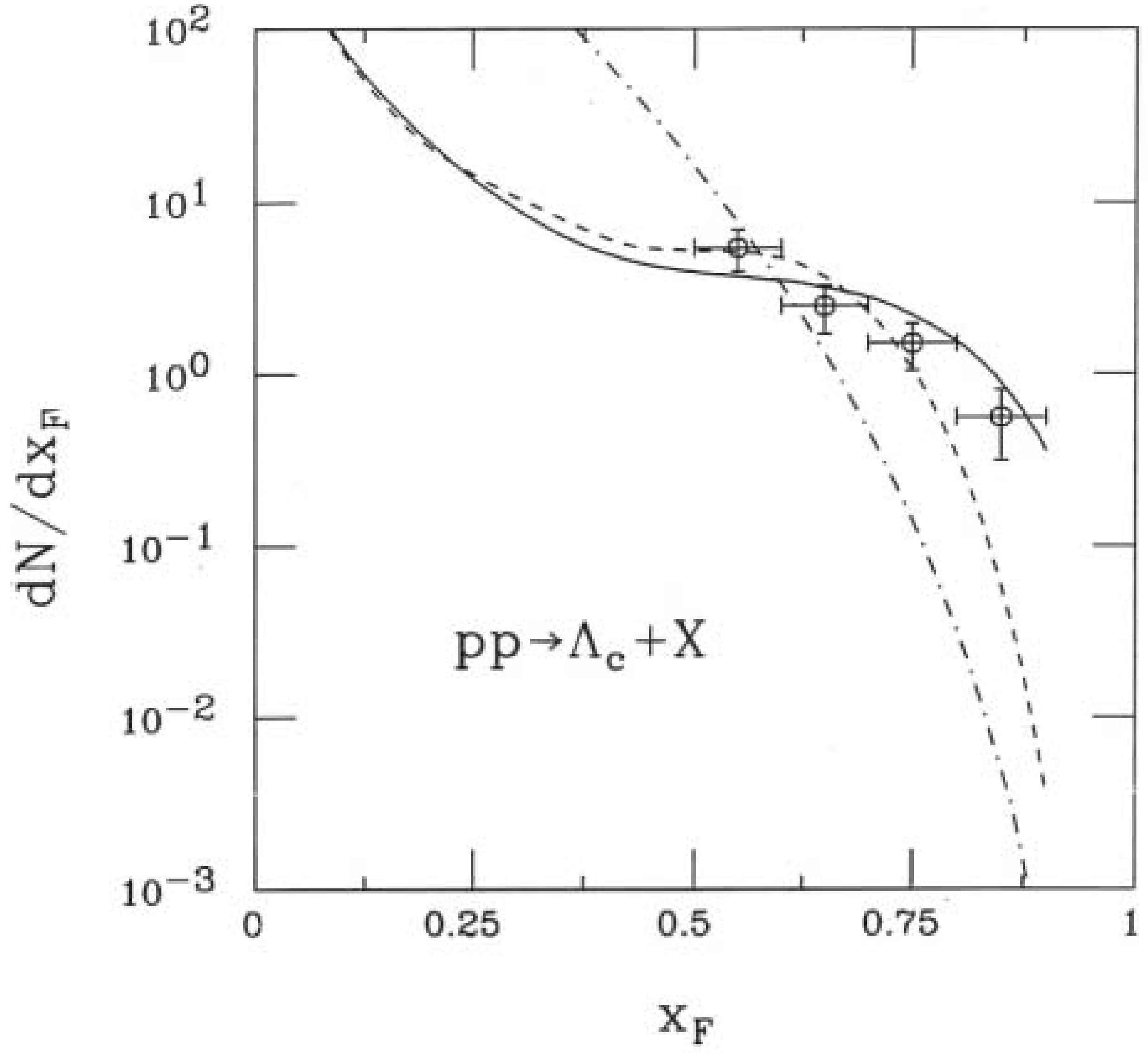
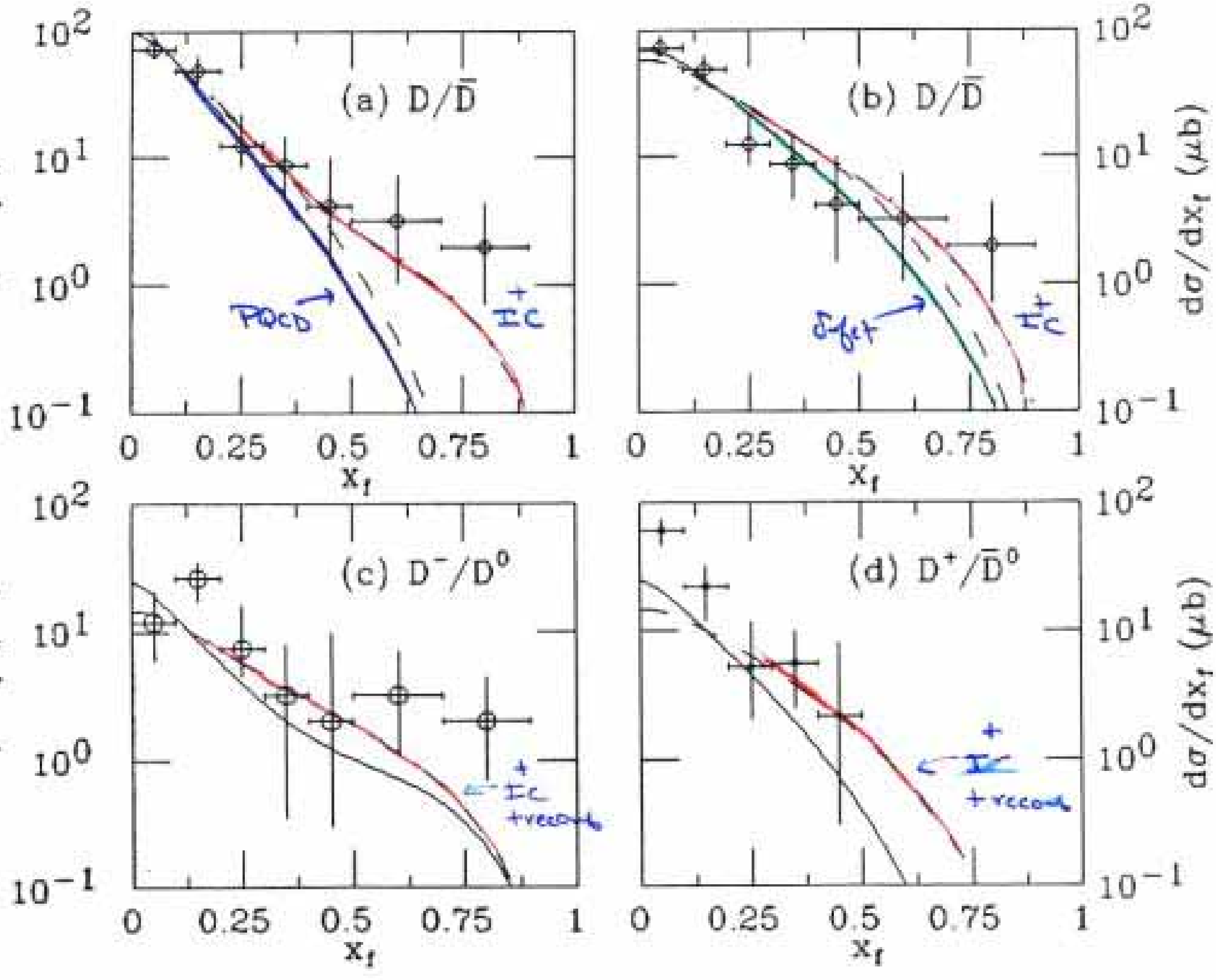


Figure 3: The x_F distribution for $pp \to \Lambda_c + X$. Data from Ref. [10] is compared to: (i) dotdash — $gg + q\overline{q} \to c\overline{c}$ fusion followed by $c \to \Lambda_c$; (ii) solid — fusion plus $n = 2$ intrinsic charm contributions; (iii) dashes — fusion plus $n = 8$ IC contributions. A 1% probability for the IC component of the proton wave function is used to fix the IC cross section. In all three cases, the overall normalization is fixed by $\sigma(x_F \geq 0.5)$.

$$\frac{d\sigma}{dx_F}\ (\pi^- p \to D/\bar{D}\ X)$$

$E_\pi = 360$ GeV LEBC



Leading

Non-leading

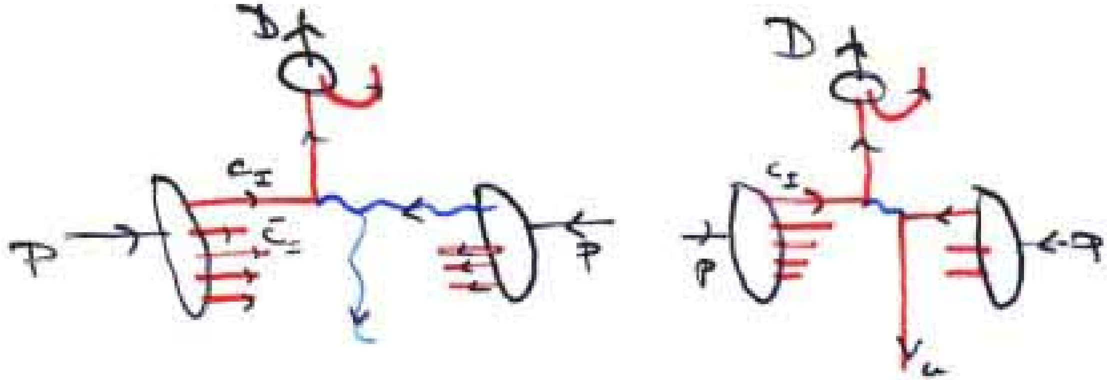
Vogt
Hoyer, 80

Intrinsic Heavy Quarks

⇒ Consequences for RHIC

New mechanisms for Open, Hidden Charm Production

D:



$g c_I \to g c_I$ $\qquad$ $u c_I \to u c_I$

hard $u(x)$, $c_I(x)$ distributions

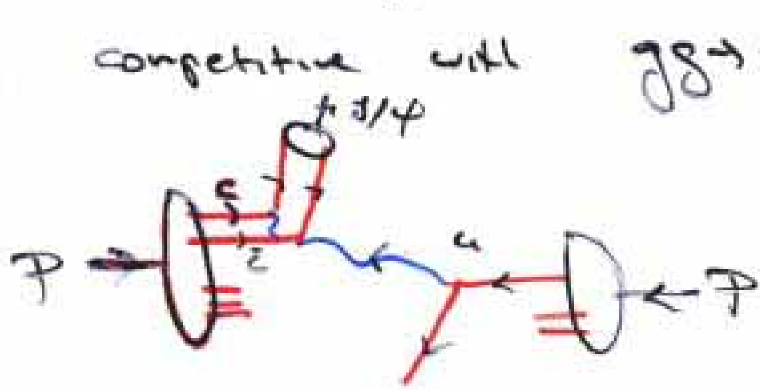
⇒ production at large $x_T^2 = \frac{M^2 + p_T^2}{s}$

⇒ broad distributions in $x_F = |x_1 - x_2|$

more sensitivity at lower s

Vogt: competitive with $gg \to c\bar{c}$, $q\bar{q} \to c\bar{c}$

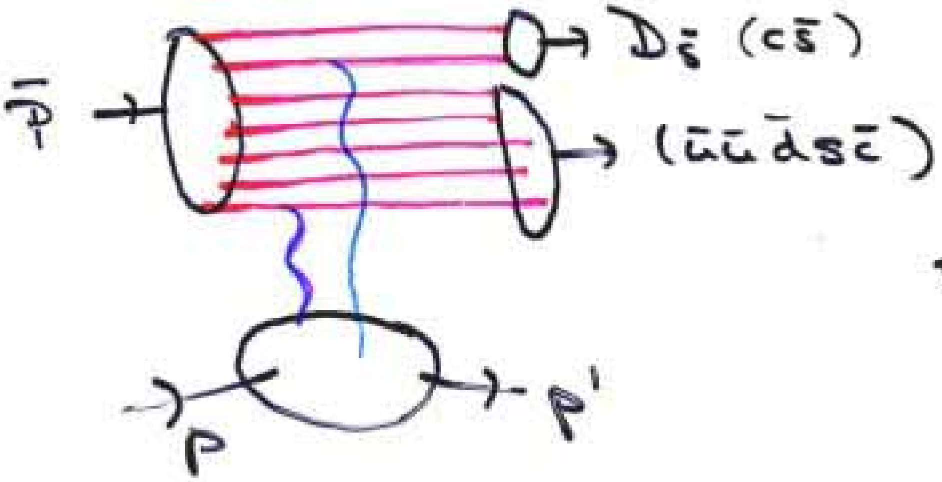
J/ψ:



"Direct" production of J/ψ at high x_T, x_F

Lipkin, Jaffe

Produce Pentequarks $|\bar{q}\bar{q}\bar{q}Q\bar{Q}\rangle$?

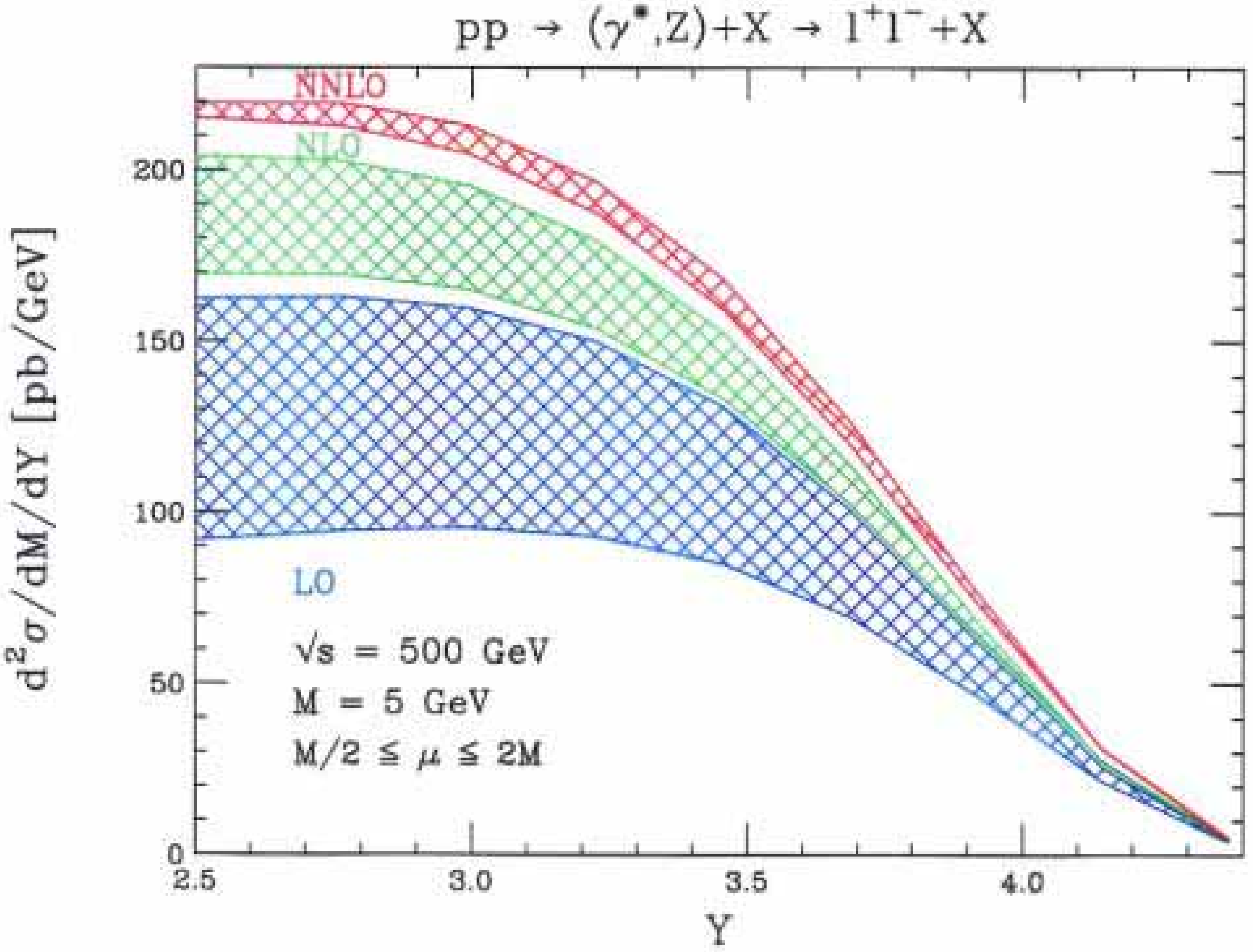


Example
of Diffractive Prod.

$$\bar{p}p \to D_{\bar{s}}\, P_{\bar{u}\bar{u}\bar{d}s\bar{c}}\, p'$$

$$\Delta P_\ell \simeq \frac{85\ \mathrm{GeV}^2}{2E_{\bar{p}\,\mathrm{lab}}} \sim 1\ \mathrm{GeV}/c$$

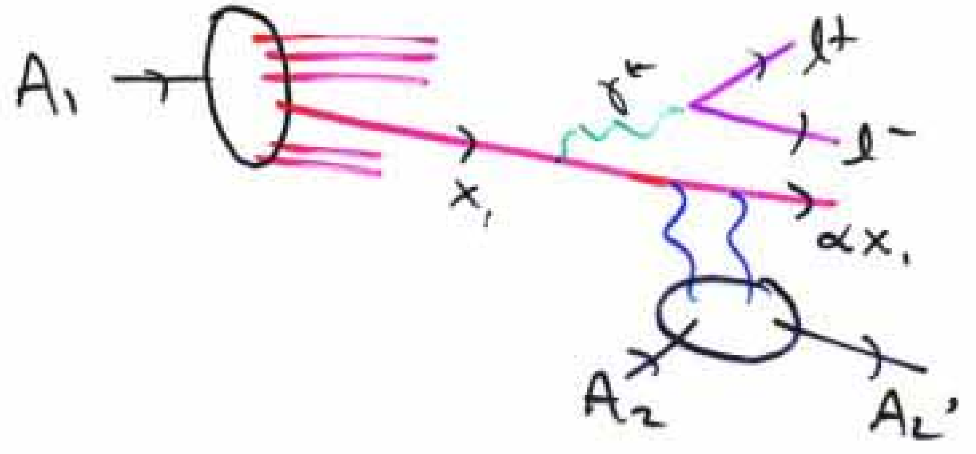
for $E_{\bar{p}} = 15\,\mathrm{GeV}$



Anastasiou, Dixon, Melnikov, Petriello

Measure shadowing and anti-shadowing

at RHIC $A_1 A_2 \to \ell^+ \ell^- A_2' X$



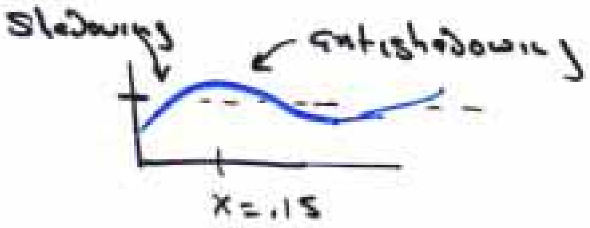
$x_F \sim x_1$

$\alpha \sim \mathcal{O}\left(\frac{\Lambda^2}{Q^2}\right)$

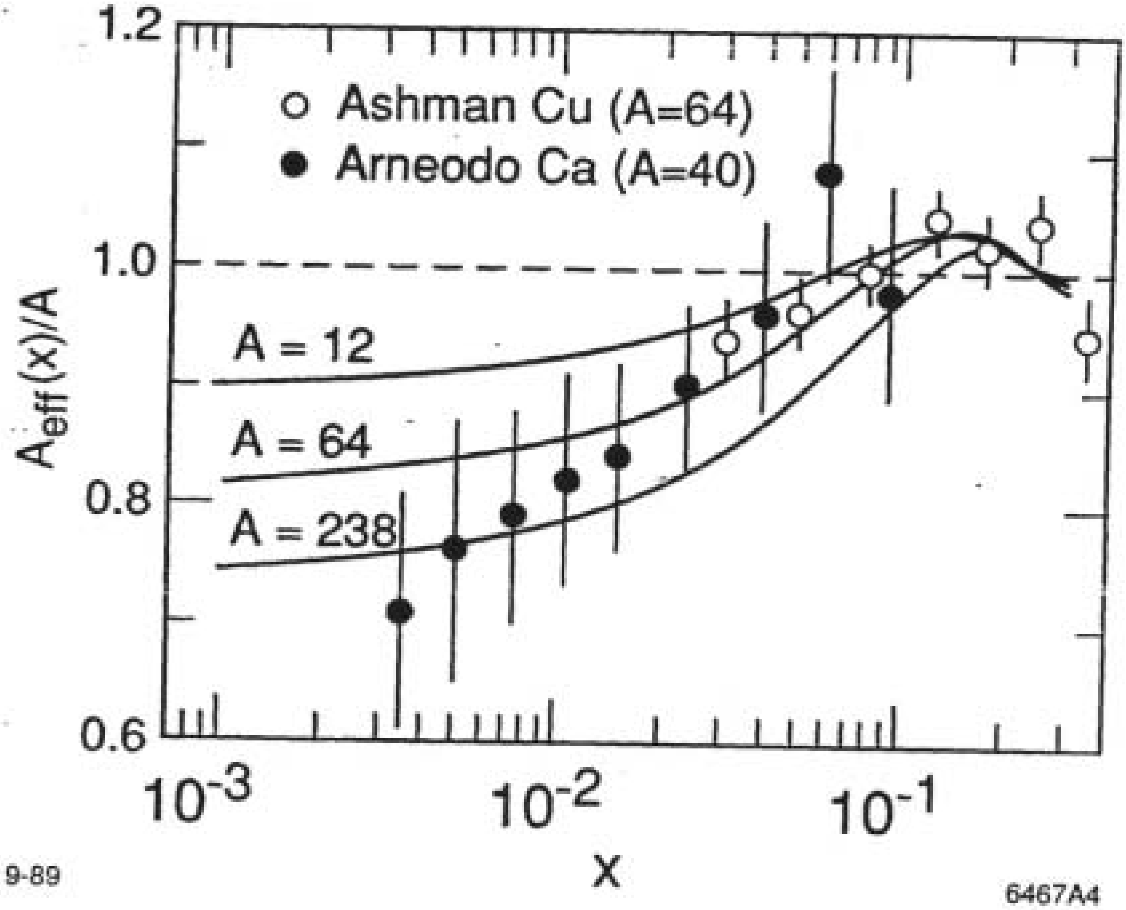
rap gap

Measure

$$\frac{dN}{dx_1} \sim q_{A_1}(x_1)$$



- * Isospin dep of antishadowing ? NuTeV anomaly!
  - Compare different A_1 projectile
  - Theory of antishadowing — H. J. Lu SJB

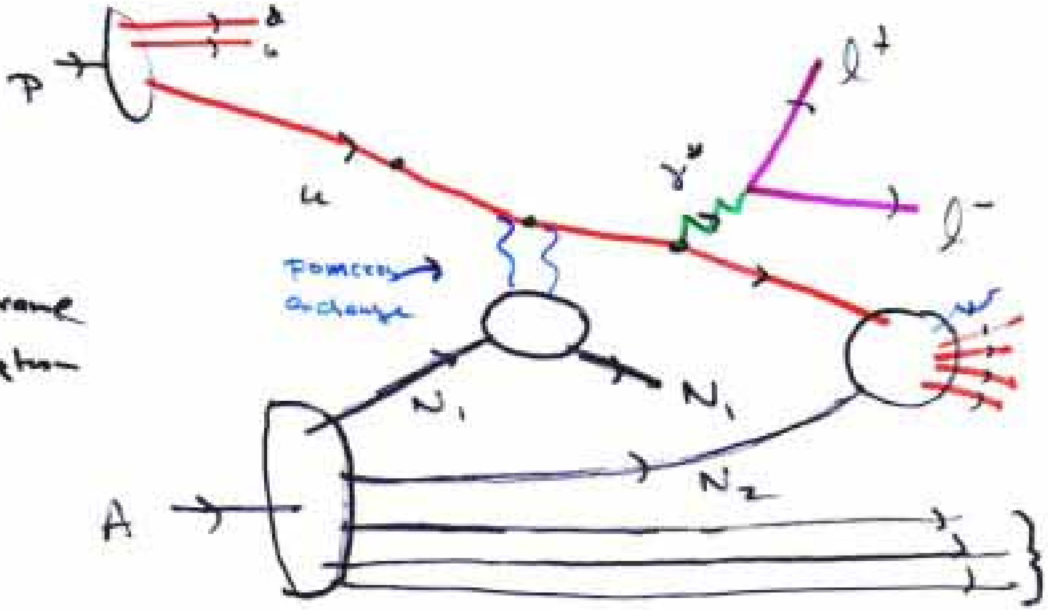


○ Ashman Cu (A=64)
● Arneodo Ca (A=40)
A = 12
A = 64
A = 238
$A_{eff}(x)/A$
1.2
1.0
0.8
0.6
10^{-3}
10^{-2}
10^{-1}
X
9-89
6467A4

Theory of Shadowing and Anti-Shadowing in Drell-Yan $pA \to \ell^+\ell^- X$

H. Lu
I. Schmidt
J.-J. Yang
SJB

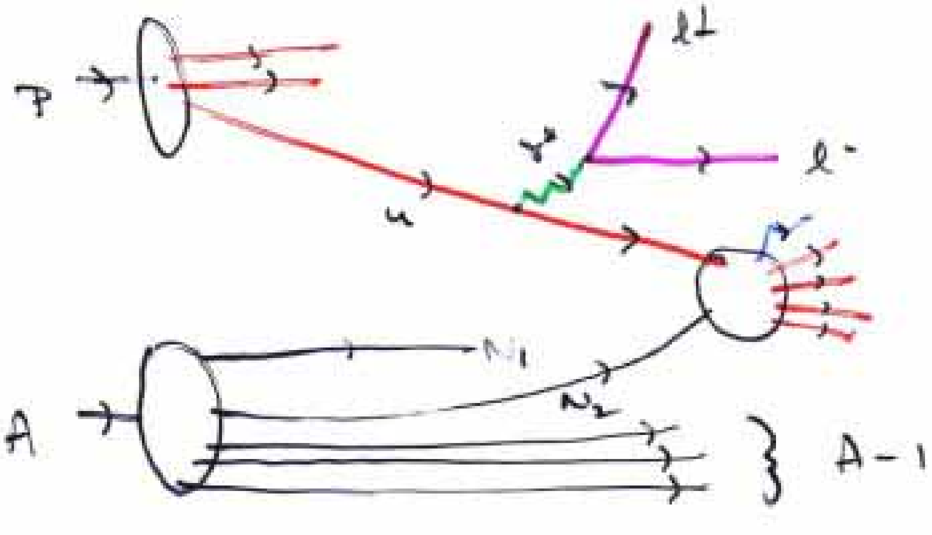
Lab Frame Description



two-step process

→ Interferes with

color-dipole effect
Kopeliovich et al



one-step process

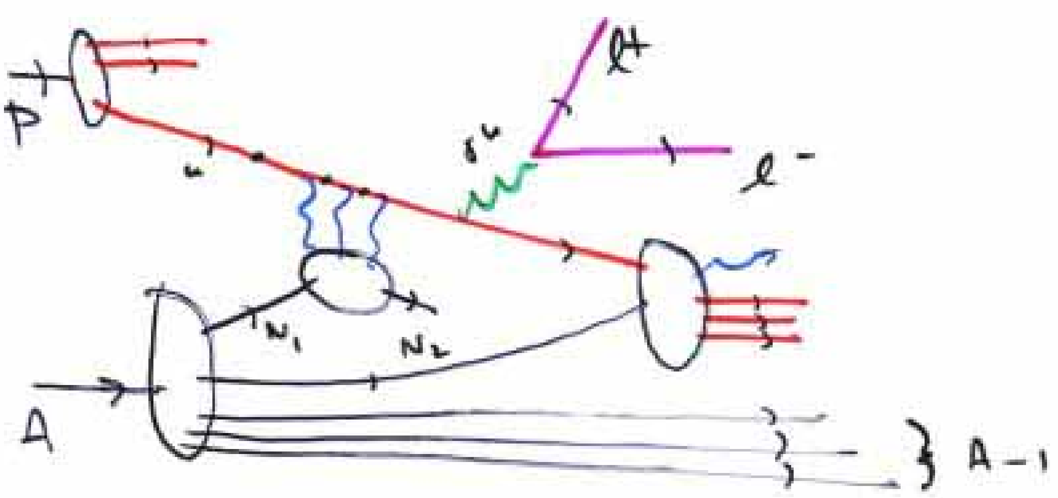
$$\underset{\text{pom}}{\overset{\uparrow}{i}}\ \underset{\text{cut}}{\overset{\uparrow}{i}}\ T_{uN_2} = -T_{uN_2}$$

Shadowing (Glauber)

Odderon $i T^R_{uN_2}$ gives constructive interference for Reggeon

antishadowing

Anti-Shadowing in $pA \to \ell^+\ell^- X$



T_{uN_2} : Reggeon + Pom contrib.

Odderon : two-step process

$$\mathrm{Im}\left[T_{uN_1}\quad i\quad T^{R}_{uN_2}\right]$$ (from two-step/one-step interference)

$$\Rightarrow \mathrm{Im}\left[\underset{\substack{\uparrow\\ \text{Odderon}\\ \text{Real}}}{1}\quad i\quad \underset{\substack{\uparrow\\ \text{Reggeon}}}{(1\pm i)}\right]$$ → Im i constructive interference with one-step Reggeon.

<u>Antishadowing</u> from constructive interference at $x_2 \sim 0.1 \to 0.2$

Since Reggeon contribution is flavor-specific antishadowing depends on quark flavor.

Implications for NuTeV.

RHIC High p_T Physics
- Challenge to Theory

* Dynamics of q, g plasma

gluon cascading - new approach

* Need Event Amplitude Generator ! QCD

Incorporate coherent phenomena :

LPM, Color Coherence, Color Transparency

Single-Spin Asymmetries - final + initial phases

Saturation, CGC

Diffraction, Shadowing, Anti-Shadowing

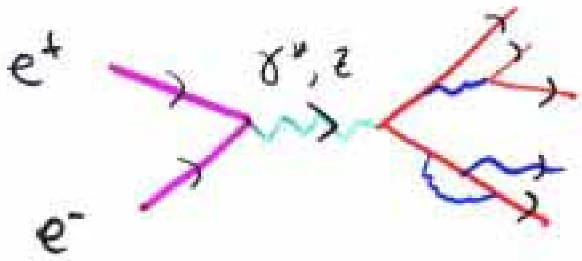
Convolute q, g amplitudes with $\psi_n^{LF}(x_i, k_{\perp i}, \lambda)$:

Coalescence with comovers

higher twist, direct subprocesses, semi-exclusive amplitudes

intrinsic heavy quark Fock States - Quantum Fluctuations

Event Amplitude Generator



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

Conventional method:

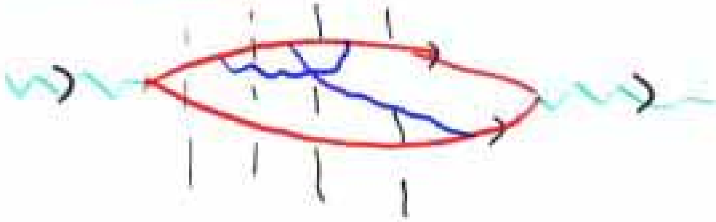
- generate probabilities
- physical phase space — physical polarization

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

Light-cone method:

disc. w.th
J. Hiller
G. McCartor
D.S. Hwang

see also
Soper, Sterman

$\mathcal{M}$:


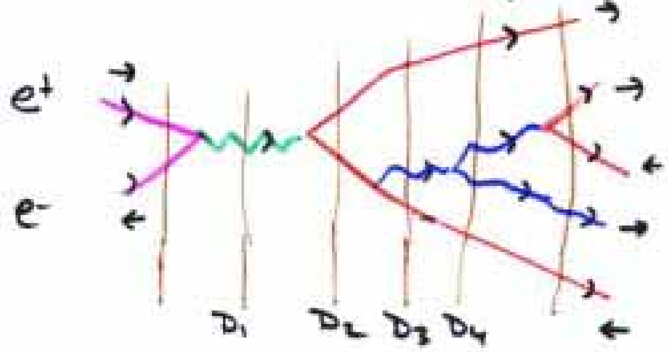
* generate amplitudes, specific l.c. spin
* Physical phase-space, pol: real + virtual
* Renorm from alternating denom- method.

Roskies, Suaya, SB

"Event Amplitude Generator"

Generate amplitude from LF TO PTh $\left\{ \begin{array}{l} \text{Tree} + \\ \text{Virtual} \end{array} \right.$

$$\mathcal{M} = \sum_{\substack{\text{time-}\\\text{orderings}}} \mathcal{M}_\alpha \quad (\text{Specific spins } S_z)$$



$$\mathcal{M}_\alpha = H_I \frac{1}{D_1} H_I \frac{1}{D_2} \cdots$$

$\sum k^+, \sum_i k_\perp, \sum_i J_z$ conserved

$k^+ > 0$: Few surviving LF time-orderings

Physical polarization sums: $\sum_{(i)} \epsilon_\mu^{(i)} \epsilon_\nu^{(i)}$

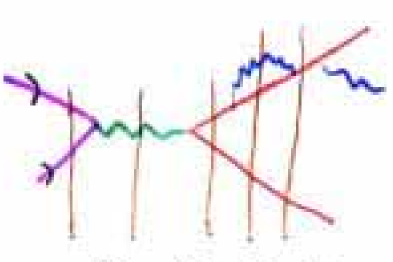
$(i) = 1, 2, 3$
↑
Standard Model W

Compute renormalized amplitude

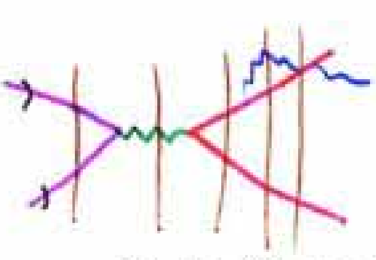
- "alternating denominator" method

Roskies
Suaya
SJB

Example:

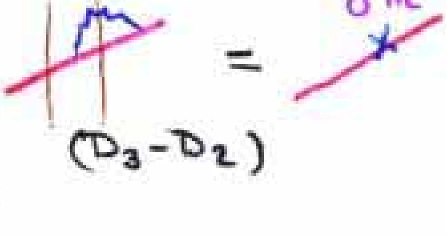


—



$D_1 \; D_2 \; D_3 \; D_4$ $\qquad$ $D_1 \; D_2 (D_3 - D_2) \; D_4$

equivalent to subtracting mass counterterm!



$\pi \, d^2k_\perp dx$, unitary, no ghosts.

Light-Front Thermodynamics

Covariant approach!

Set B.C. at Equal $\tau = t + z/c$

on light-front, not $t=0$

Raya, Das

Raufeisen, SJB

No Renormalisation Scale Ambiguity!

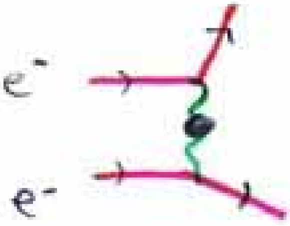
Why choose range

$$\boxed{-\frac{Q}{2} < \mu_R < \frac{Q}{2}} \quad ?$$

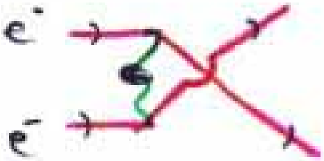
- Scale variation only sensitive to β terms
  not accurate for higher order terms.
- Range is scheme-dependent
- Wrong thresholds
- violates conformal limit
- violates Abelian limit
- Renormalon growth
- Wrong for QED, EW
- multiscales : $\alpha(t)$, $\alpha(s)$.
- Problematic for $pp \to HX$ at RHIC

No renormalization scale ambiguity in QED

Lamb shift, g-2, hfs precision tests



$\frac{s-u}{t}\,\alpha(t)$



$\frac{s-t}{u}\,\alpha(u)$

$\alpha(s)$

$\alpha(t) = \frac{\alpha(0)}{1-\Pi(t)}$ Gell-Mann - Low effective charge defined from $D^{\mu\nu}(t)$

$\alpha(s)$: correct heavy lepton threshold

correct analytic structure, cuts

$\alpha(t)$, $\alpha(u)$ multi-scales

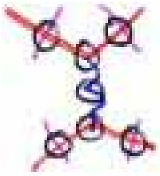
Cannot use any other scale: $\mu_R^2 \neq p_T^2 = \frac{tu}{s}$

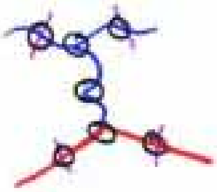
$\Rightarrow$ infinite # diagrams generated

to correct error

Implications of BLM Scale-Setting for RHIC High p_T

high p_T
jet
production

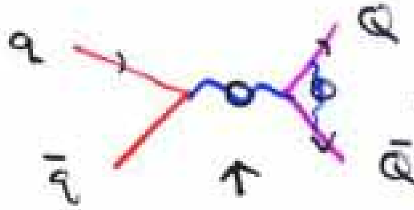




$\alpha_s(t)$

pinch
in
V
scheme

heavy
quark pair
production



$\uparrow$

$\alpha_s(s)$

$\leftarrow$ $\begin{cases} \alpha_s(\beta_0^2 s) & \text{Coulomb} \\ \alpha_s(s\, e^{3/4}/4) & \text{transverse} \end{cases}$

two scales!

Hoang, Kuhn, Teubner
SJB

Direct γ
production

$g\, q_2 \to \gamma'\, q_2'$

$\alpha_s(k_g^2)$

$\int^{M_F^2} \frac{d\ell^2}{\ell^2}\alpha_s(\ell^2)$ from $q_1(x, M_F^2)$

$k_g^2 \sim (M_F^2\, k_\perp^2)^{1/2}$

QCD Scale-Setting Methods

FAC : choose μ_R to eliminate H.O. terms

Grunberg

- violates conformal limit

$$\text{QCD} \Rightarrow \text{CQCD} \quad \text{for} \quad \beta \to 0, \; m_q \to 0$$

Parisi

- violates abelian limit

Huet
SJB

$$\text{QCD}(N_c) \Rightarrow \text{`QED'} \quad \text{for} \quad N_c \to 0$$

fixed $C_F \alpha_s$
n_f / C_F

- wrong analytic structure

- wrong physical results for jet observ.

No renormalization scale ambiguity
in electro-weak theory

Non-abelian complications: "pinch" scheme

Cornwall, Papavassiliou

Kennedy, Lynn

Peskin, Takeuchi

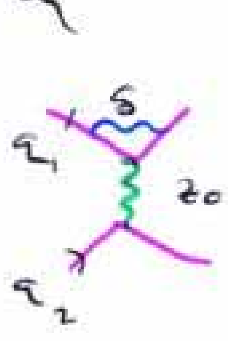
Necessary for precision tests

Correct analytic, cut structure

Generalization of QED Gell Mann-Low

Why do we have a scale-ambiguity in QCD ?

Why $-\frac{Q}{2} < \mu < \frac{Q}{2}$?



QCD scale ambiguity?
in mixed QCD-EW
Process,

Lepage
Mackenzie
SJB

BLM Scale Fixing

$$\mu_R \Rightarrow Q_n^*$$

$$\mathcal{O} = \sum_{n=0} \underset{\uparrow}{C_n} \, \alpha_s^n (Q_n^*)$$

conformal coefficients

non-conformal
β-terms
eliminated by
$\mu_R \to Q_n^*$

- Q_n^* - physical - MVT
- Multiscales
- scheme indep prediction, transitivity
- Conformal limit: $\mathcal{O} \to \sum_{n=0} C_n \alpha_s^n$ for $\beta = 0$
- Abelian limit: same method in QED, EW
- C_n: no n! renormalon growth
- Physical effective charges: $\alpha_R, \alpha_\tau, \ldots$
- Relate observable to observable
- Commensurate Scale Relations
- No scheme ambiguities
- correct heavy particle thresholds
- correct analytic behavior
- hidden conformal relations — Generalized Crewther Rel.
- Grand unification — Binger / SJB

Future RHIC Physics

Spin program , $\vec{P}\vec{P} \to W X$, $\vec{P}P \to \text{jet } X$

Heavy Quark Phenomena

Large x_F : ISR Anomalies

Improved Detectors, RHIC II

eRHIC

Measure Properties of

New Form of Hadronic Matter

q , g plasma

Thanks to

RIKEN

BNL

BNL Theorists

Tammy Heinz

and participants!