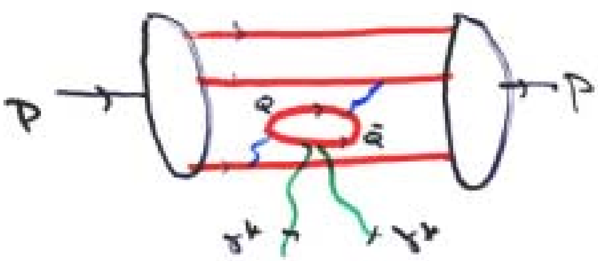
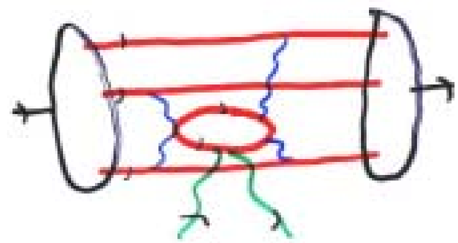
Intrinsic Heavy Quark Fock States
⇒ Implications for RHIC

Hoyer
Peterson
Sakai
SJB





Extrinsic (~DGLAP) — Intrinsic (LO, L)

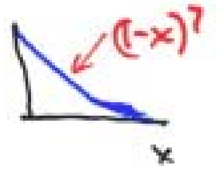
$Q_E(x, Q^2) \sim (1-x)^7 \ln \frac{Q^2}{m_Q^2}$ — $Q_I(x) \sim \frac{F_I(x)\,\Lambda^2_{QCD}}{M_Q^2}$

$\langle p | GG | p \rangle$ — $\langle p | GGG | p \rangle$

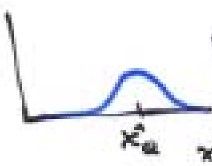
$\langle p | FFFF | p \rangle$ QED

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

$\ln Q_E$



Q_I



equal rapidity

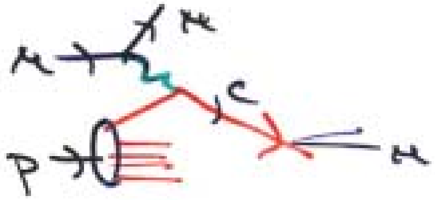
Seen at EMC $\mu p \to \mu' c X$ ~1% IC Hoffman Moore Vogt Smith

ENAL 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 ($\times 30$) 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

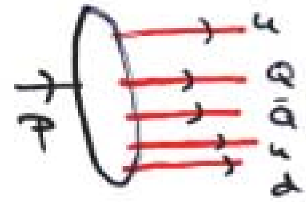
* 4. $\pi^- N \to D^{\pm} X$: strong "leading particle" effect

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

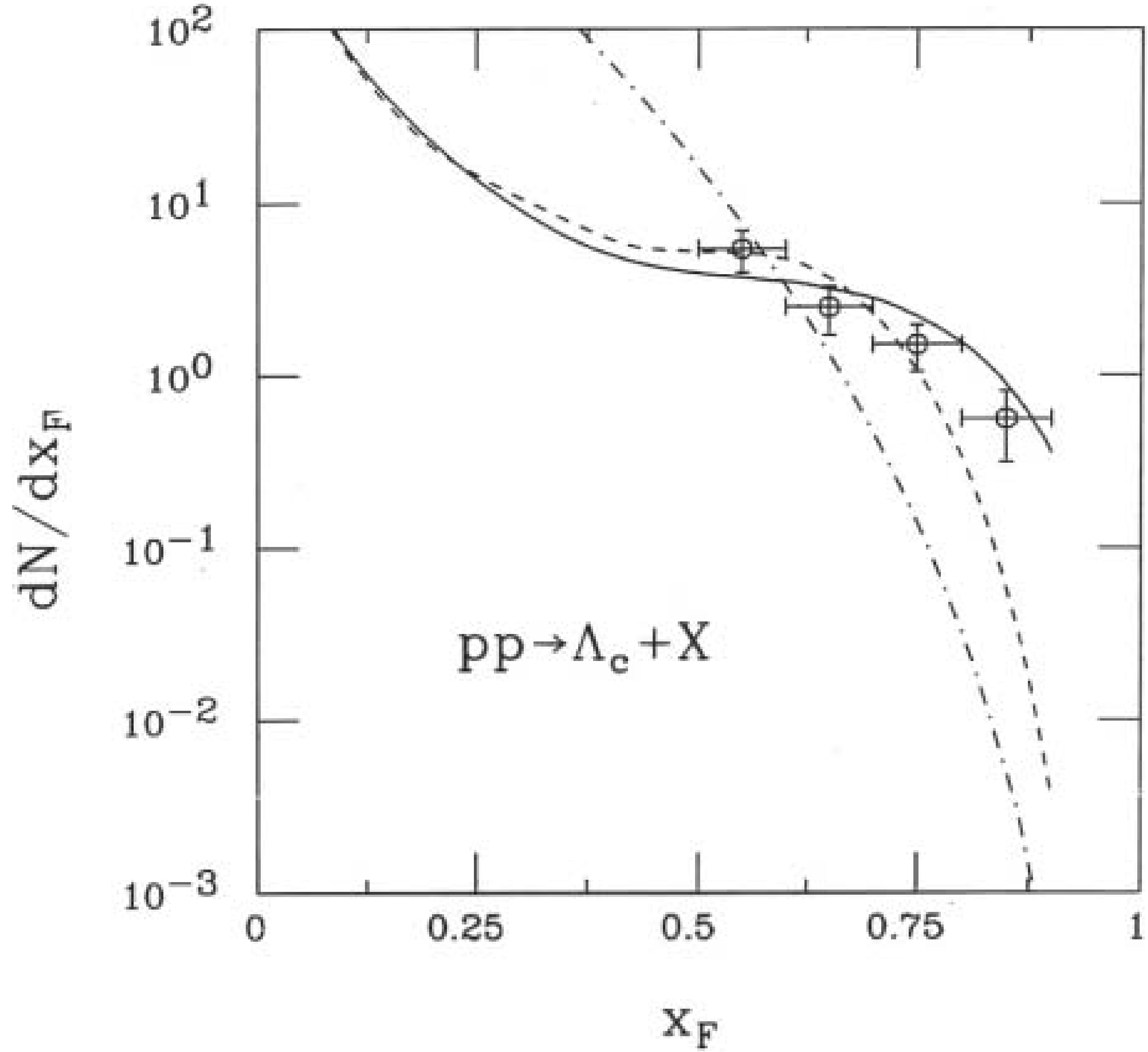
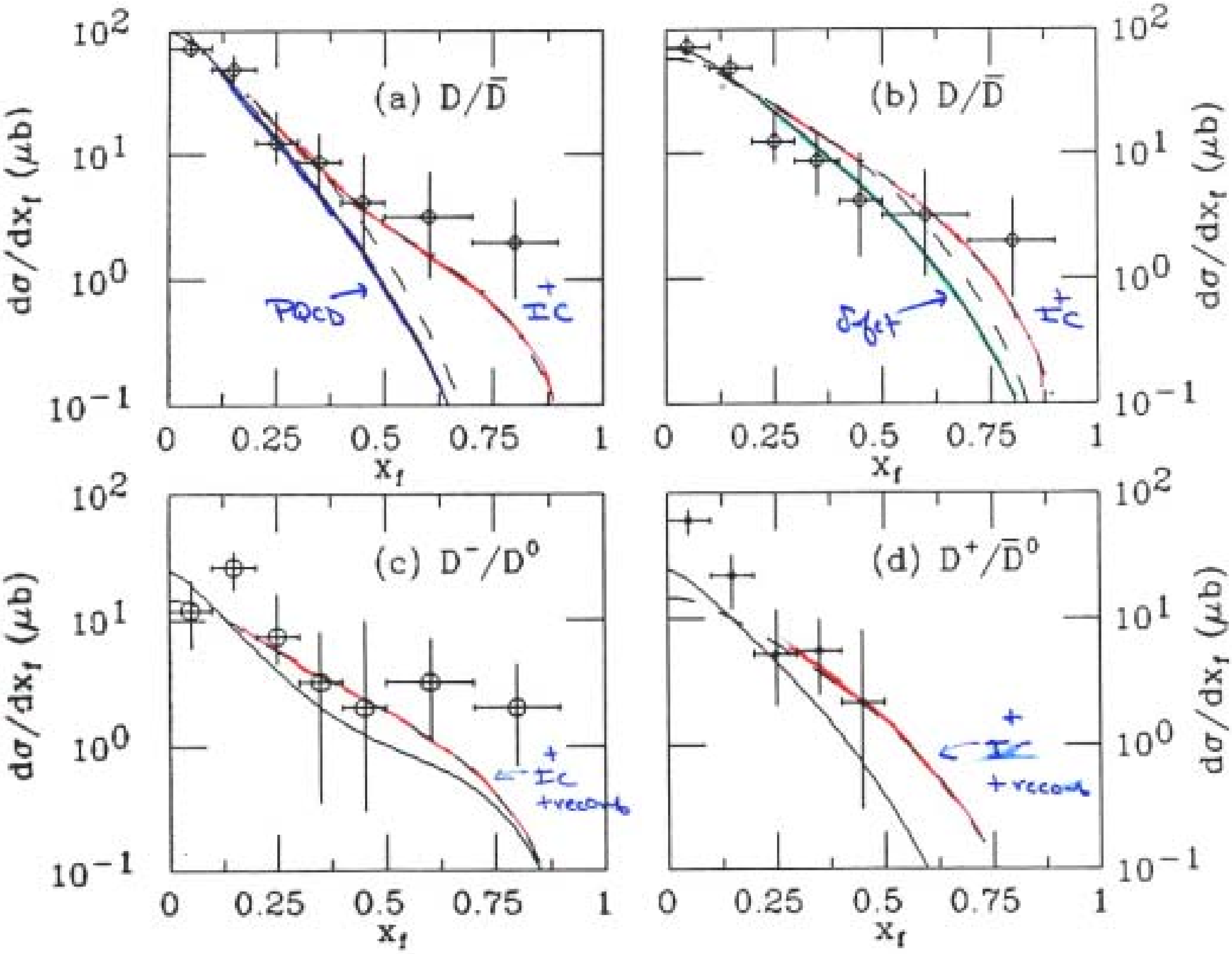


Figure 3: The x_F distribution for $pp \to \Lambda_c + X$. Data from Ref. [10] is compared to: (i) dotdash — $gg + q\overline{q} \to c\overline{c}$ fusion followed by $c \to \Lambda_c$; (ii) solid — fusion plus $n = 2$ intrinsic charm contributions; (iii) dashes — fusion plus $n = 8$ IC contributions. 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_π = 360 GeV

LEBC



Leading

Non-Leading

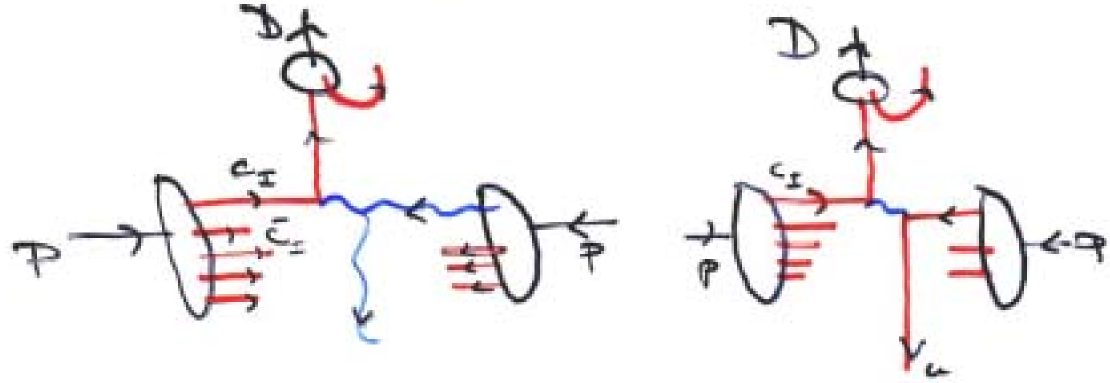
Vogt
Hoyer, 80

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

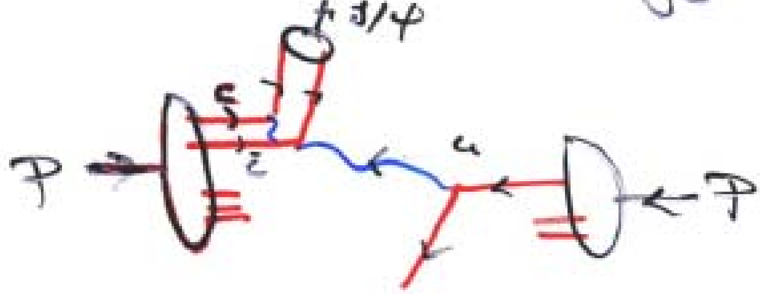
⇒ production at large $x_T^2 = \frac{m^2 + p_T^2}{s}$

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

more sensitivity at lower s

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

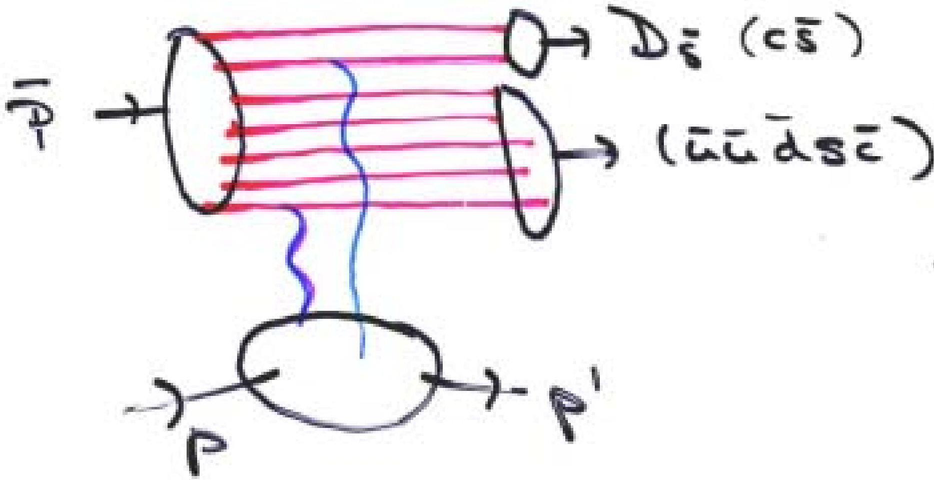
J/ψ:



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

Lipkin, Jaffe

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

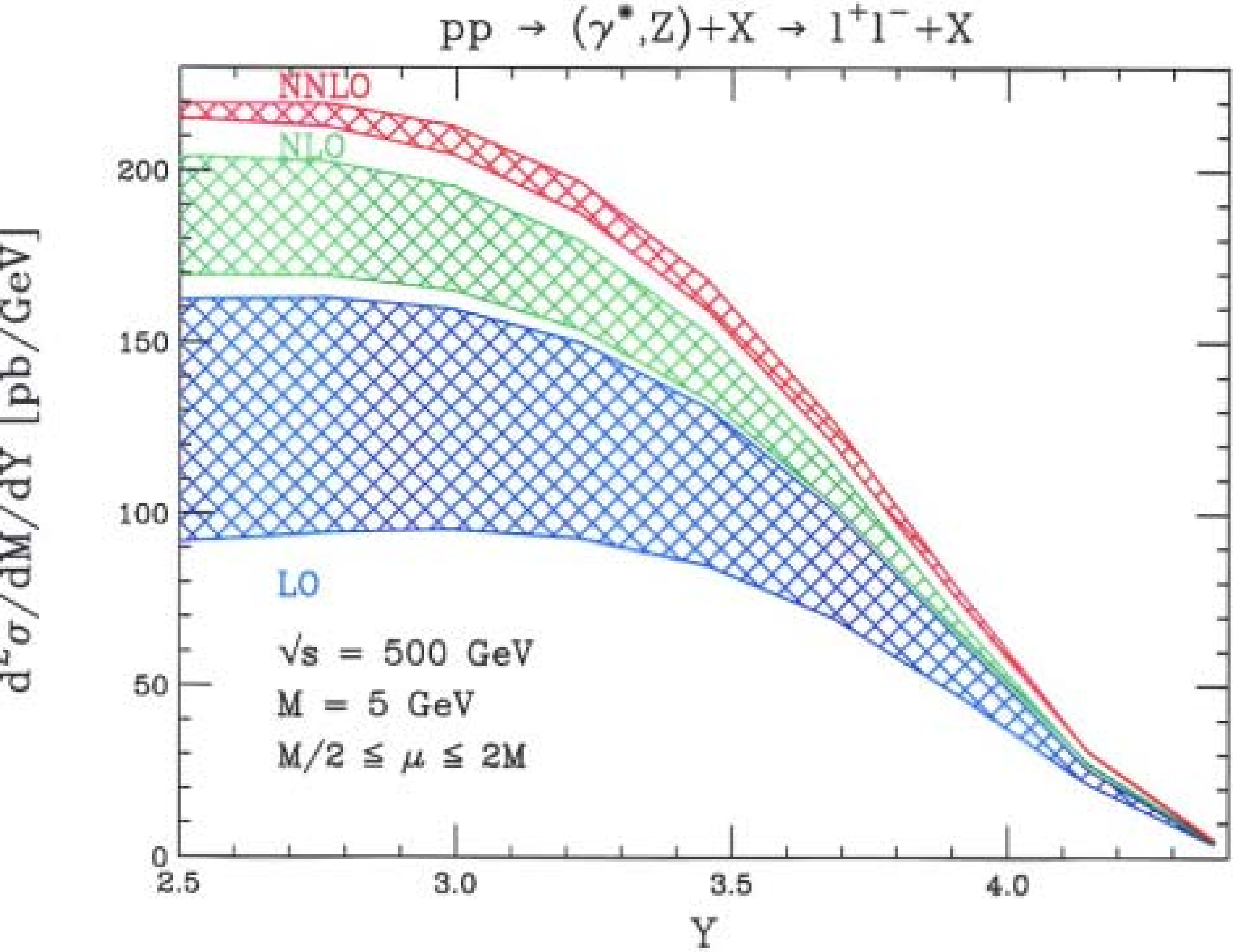


Example of Diffraction Prod.

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

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

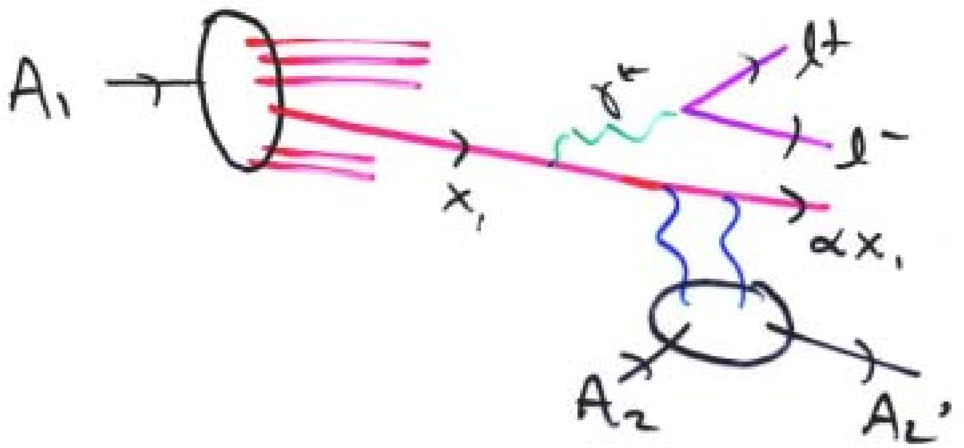
for $E_{\bar{p}} = 15$ GeV



Anastasiou, Dixon, Melnikov, Petriello

Measure shadowing and anti-shadowing

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



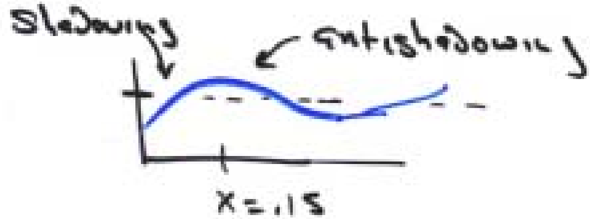
$x_F \sim x_1$

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

rap gap

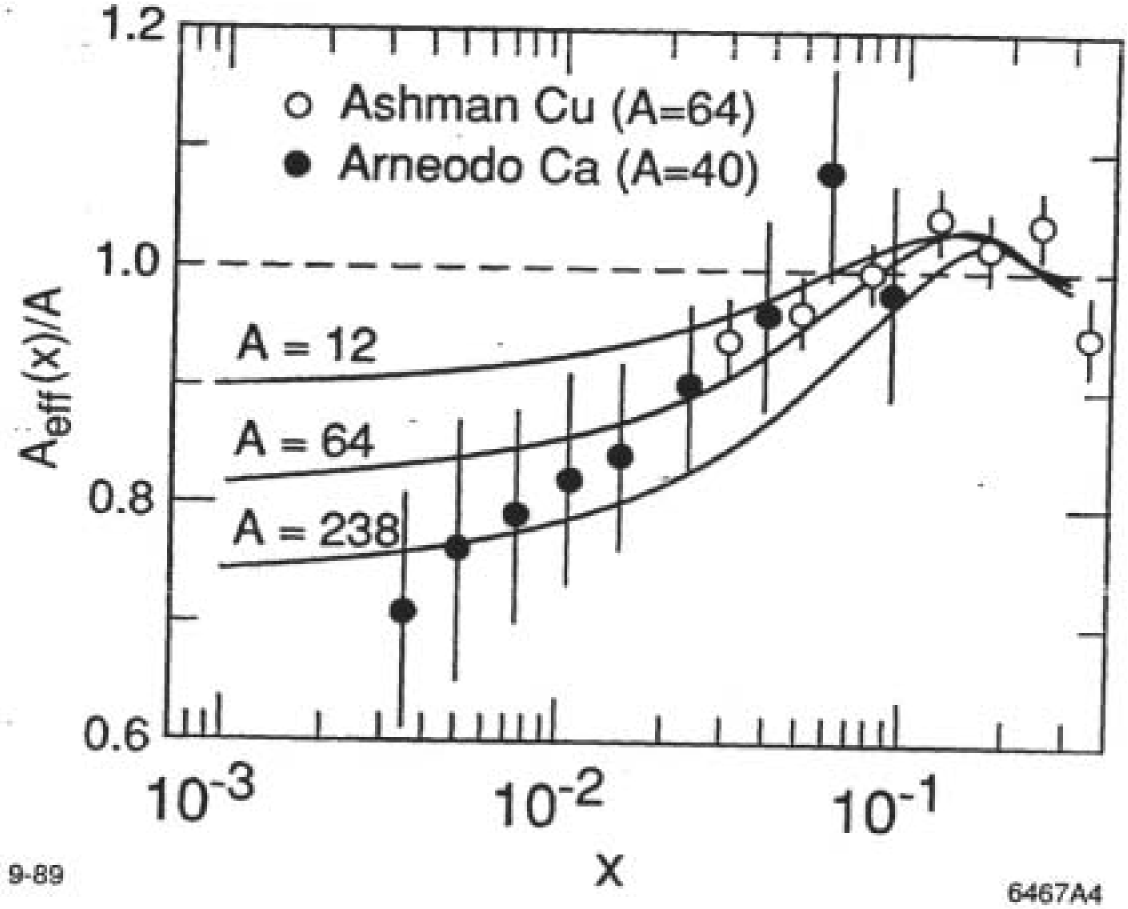
Measure

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



* Isospin dep of antishadowing? $\quad$ NuTeV anomaly!

- Compare different A_1 projectile
- Theory of antishadowing – $\quad$ H. J. Lu, SJB

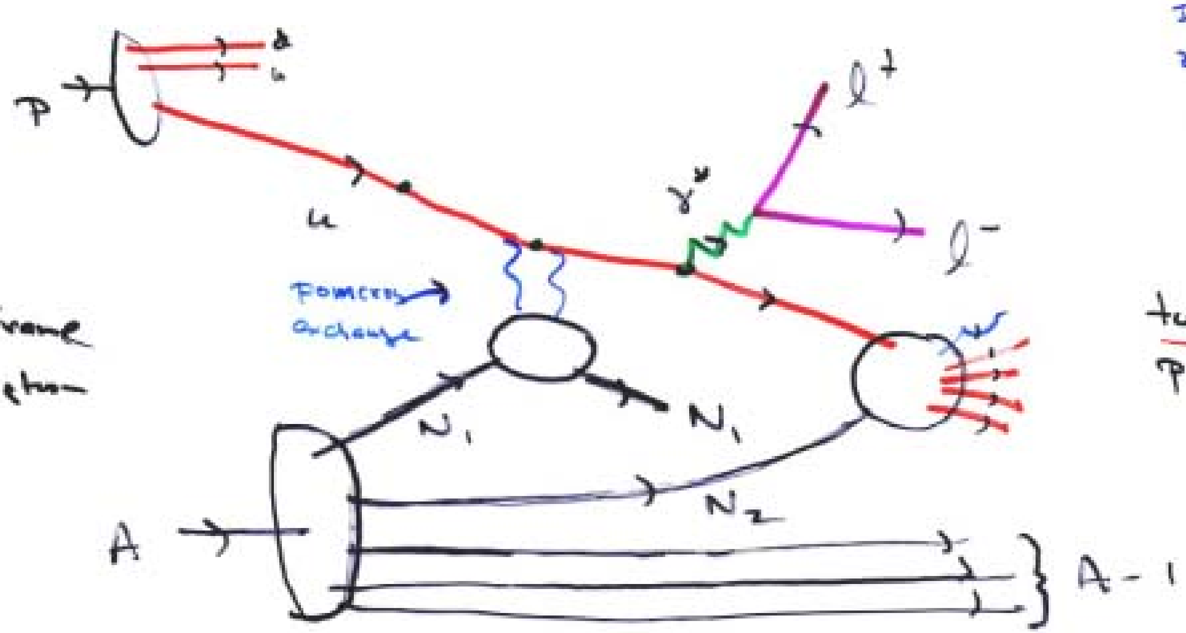


1.2
1.0
0.8
0.6
Ashman Cu (A=64)
Arneodo Ca (A=40)
A = 12
A = 64
A = 238
$A_{eff}(x)/A$
10^{-3}
10^{-2}
10^{-1}
X
9-89
6467A4

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

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

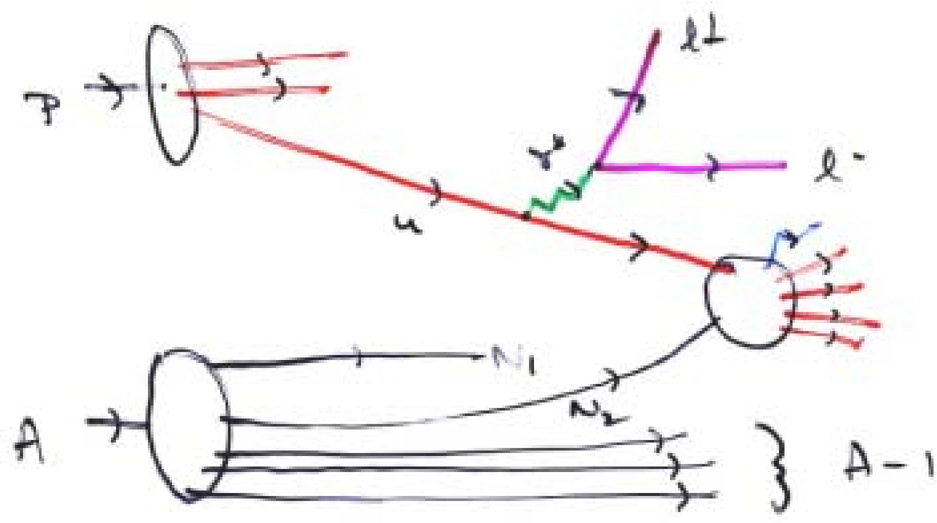
Lab Frame Description



two-step process

→ Interferes with

color-dipole effect
Kopeliovich et al



one-step process

$i \; i \; T_{uN_2} = - T_{uN_2}$

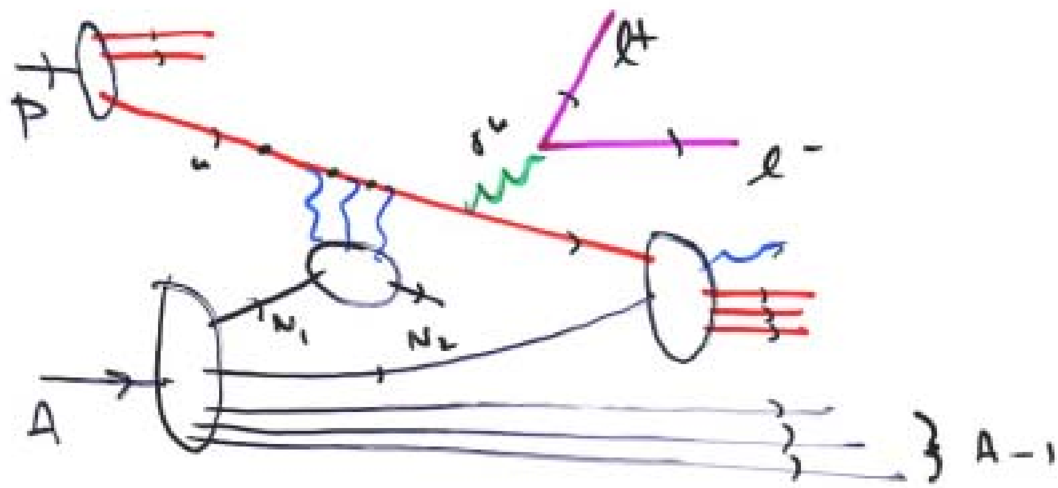
↑ Pom ↑ cut

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

$\text{Im}\,[T_{uN_1}\ i\ T^*_{uN_2}]$ (from two-step / one-step interference)

$\Rightarrow \text{Im}\,[1\ \ i\ \ (1 \pm i)] \to \text{Im}\ i$ constructive interference with one-step Reggeon.

↑ Odderon Real   ↑ Reggeon

Antishadowing 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

  Diffraction , Shadowing , Anti-Shadowing
  Saturation , CGC

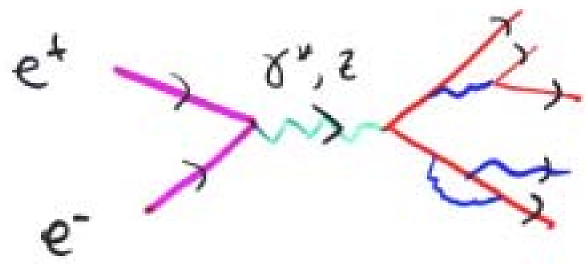
  Convolute q, g amplitudes with $\psi_n^{LF}(x_i, k_{\perp i}, \lambda)$:

  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:

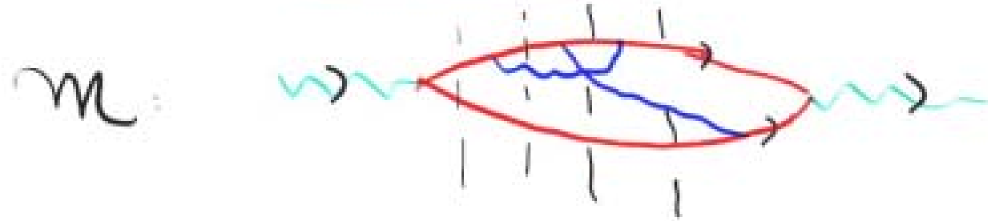
- generate probabilities
- physical phase space – physical polarization

but – virtual contributions – Feynman gauge
d^4k dimensional regularization.

Light-cone method:

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

see also
Soper, Sterman



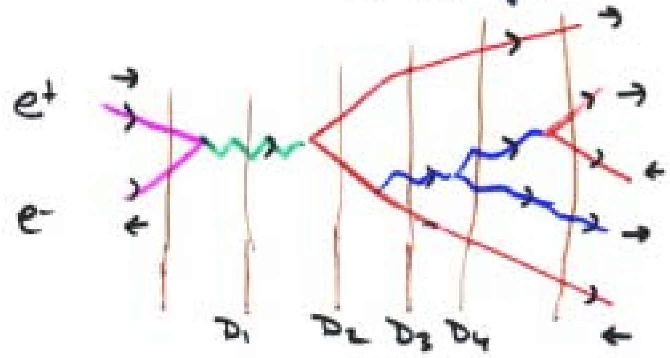
* generate amplitudes, specific l.c. spin
* Physical phase-space, pol: real + virtual
* Mren from alternating denom- method.

Roskies, Suaya, SB

"Event Amplitude Generator"

Generate amplitude from LF TO PTh { Tree + Virtual

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



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

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

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

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

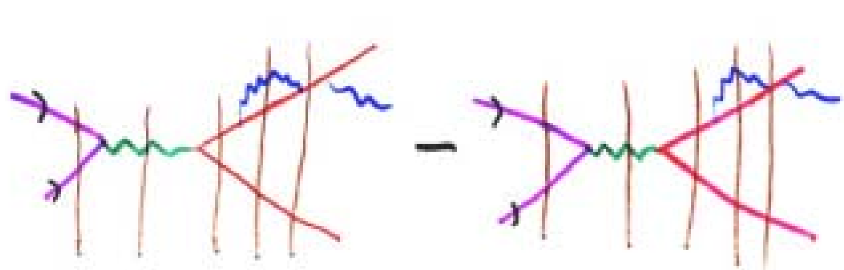
$(i) = 1, 2, 3$ ← Standard Model W

Compute renormalized amplitude

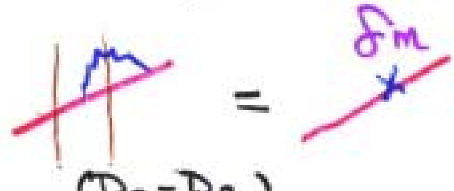
– "alternating denominator" method

Roskies
Suaya
SJB

Example:



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 Renormalization Scale Ambiguity!

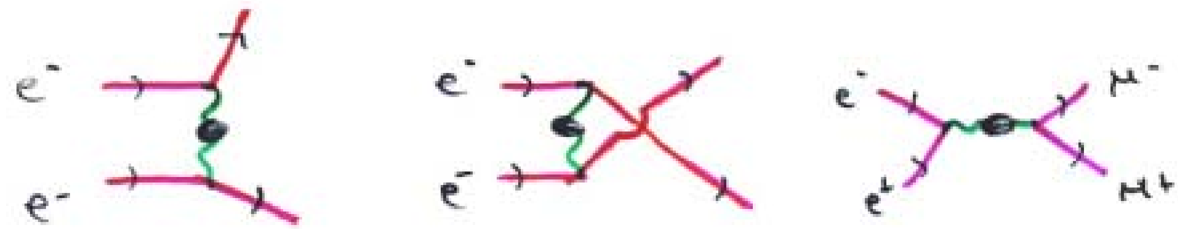
Why choose range

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

* Scale variation only sensitive to β_0 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: $\alpha(t)$, $\alpha(u)$.
* Problematic for $pp \to HX$ at RHIC

No renormalization scale ambiguity in QED

Lamb shift, g-2, hfs precision tests



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

$\alpha(t) = \frac{\alpha(0)}{1-\Pi(t)}$ $\quad$ Gell-Mann-Low effective charge $\quad$ 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

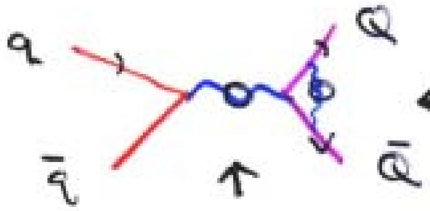
to correct error

Implications of BLM Scale-Setting for RHIC High p_T

high p_T jet production

$\alpha_s(t)$ pinch ∩ V scheme

heavy quark pair production



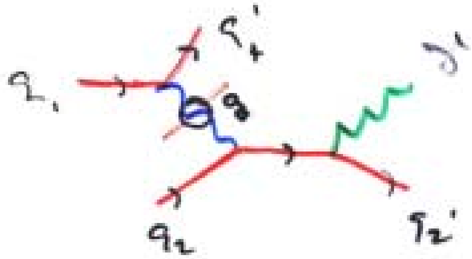
$\alpha_s(s)$

$\left\{ \begin{array}{ll} \alpha_s(\beta_0^2 s) & \text{Coulomb} \\ \alpha_s(s\, e^{3/4}/4) & \text{transverse} \end{array} \right.$

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

  QCD ⇒ C QCD for $\beta \to 0$
  $m_q \to 0$

  Parisi

* violates abelian limit

  Huet
  SJB

  QCD (N_C) ⇒ 'QED' for $N_C \to 0$
  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

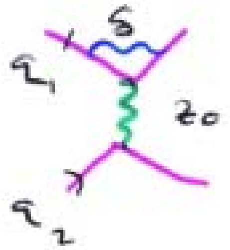
Necessary for precision tests

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

$\mu_R \Rightarrow Q_n^*$

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

↑ 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. Rinyer / SJB
- Grand unification

Future RHIC Physics

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

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!