Charm Production from Fixed Target Experiments

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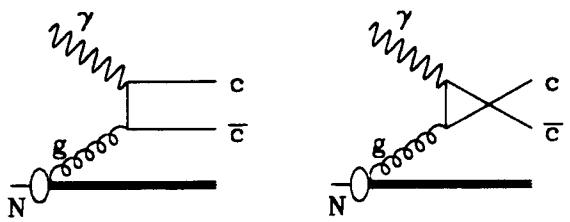
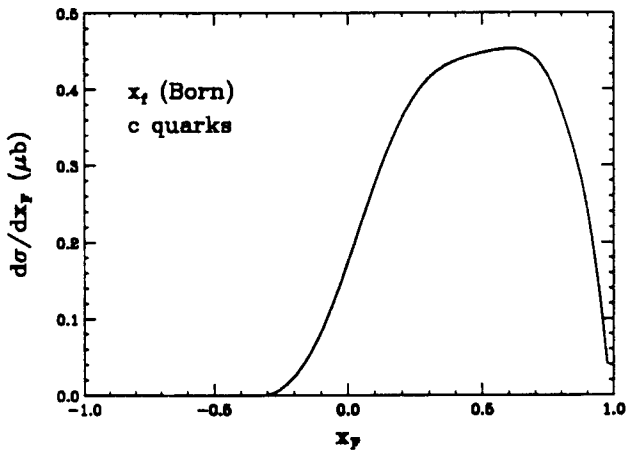
Charm Photoproduction

(Fermilab E687: 220 GeV $\gamma\mathcal{N} \to c\bar{c}$)

- PGF & ideal hadronization $\gamma\, g \to c\bar{c}$ $\mathcal{O}(\alpha_{em}\alpha_s)$



- QCD analogy of $\gamma\mathcal{N} \to e^+e^-\,\mathcal{N}$
- $\sigma(\gamma p \to c\bar{c}) = \int_{4m_c^2/s}^{1} dx_g\; g(x_g, \mu^2)\;\; \hat{\sigma}(s\; x_g)\;\;,\;\; \hat{s} = s\; x_g$



$$X_F = 2P_{\|}^*/\sqrt{s}$$

$$< X_F >= 1/2$$

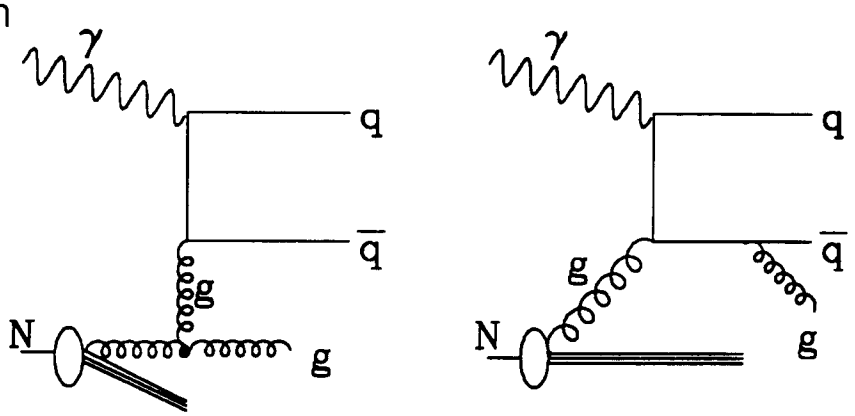
$$E_{\text{lab}} \approx X_F\; E_\gamma$$

- Higher order and nonperturbative effects will modify this simple picture

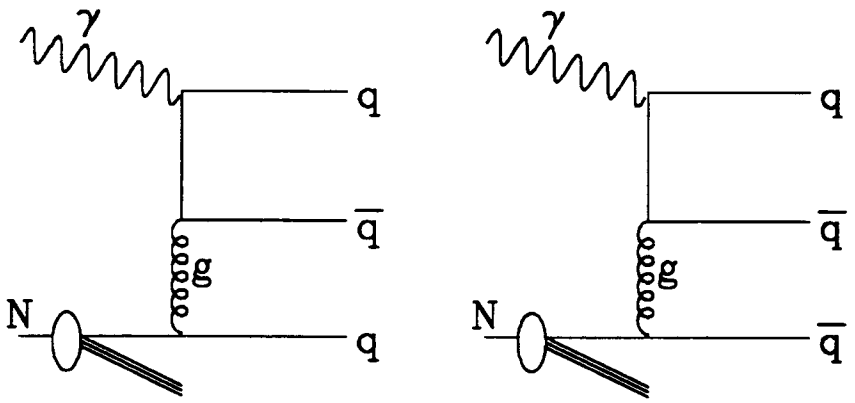
NLO QCD for γN Collisions

Contributions from $\mathcal{O}(\alpha_{em}\alpha_s^2)$ graphs, for example:

- gluon brem

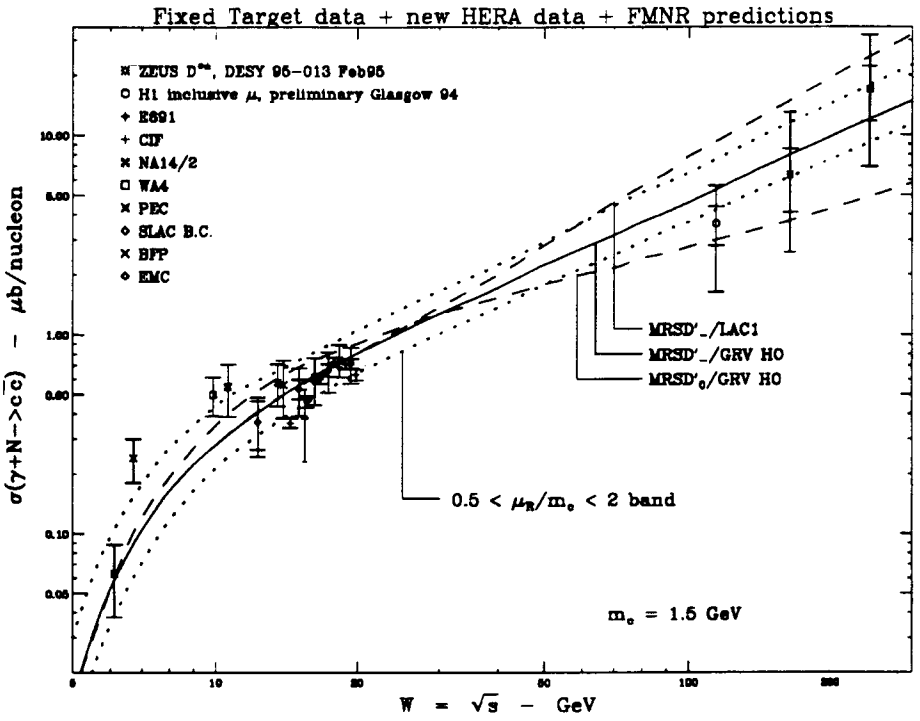


- γ + quark



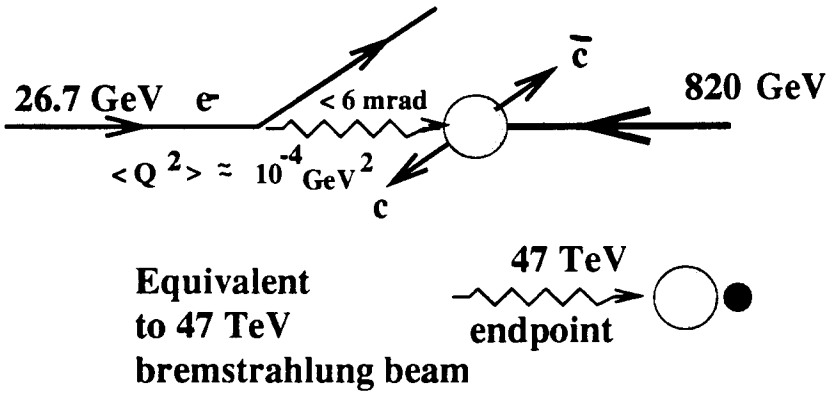
- Calculations from Frixione, Mangano, Nason & Ridolfi (aka FMNR)

$\gamma N \to c\bar{c}$ total cross section



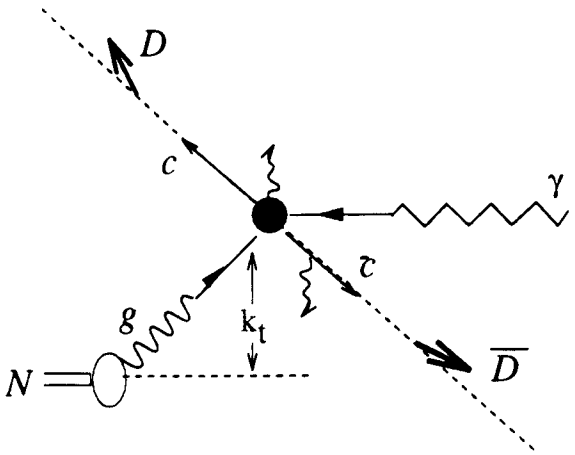
ZEUS reconstructs 48 $D^* \to (K\pi)\pi$ but with a long lever arm!

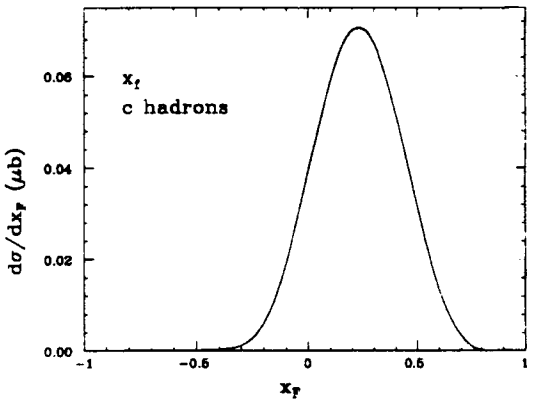
- FMNR NLO calcs fit data over vast energy range



$$s\, x_g > 4\, m_c^2 \Rightarrow \begin{array}{l} x_g > 0.04 \quad \text{FixedTarget} \\ x_g > 1.6 \times 10^{-4} \quad \text{HERA} \end{array}$$

Nonperturbative effects



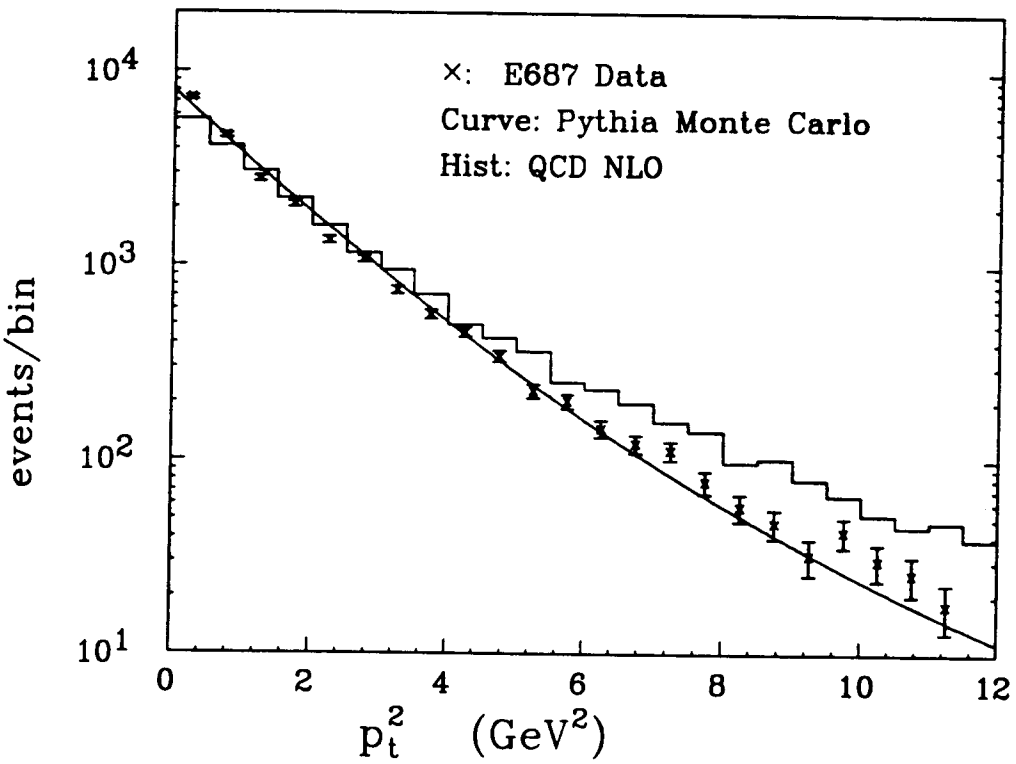


- Softens charm spectrum: $< X_F > \approx 0.25$

(from $\langle x_F \rangle \approx .5$ c-quarks)

1. Intrinsic k_t (average $p_\perp$ carried by the gluon)
2. fragmentation (c-quark into c-hadron)
3. Compare w/ parton shower Monte Carlo (Pythia)
   - LO $\gamma N \to c\bar{c}$ matrix element
   - Lund string fragmentation model

Test calculation with inclusive $p_t^2(D^+)$

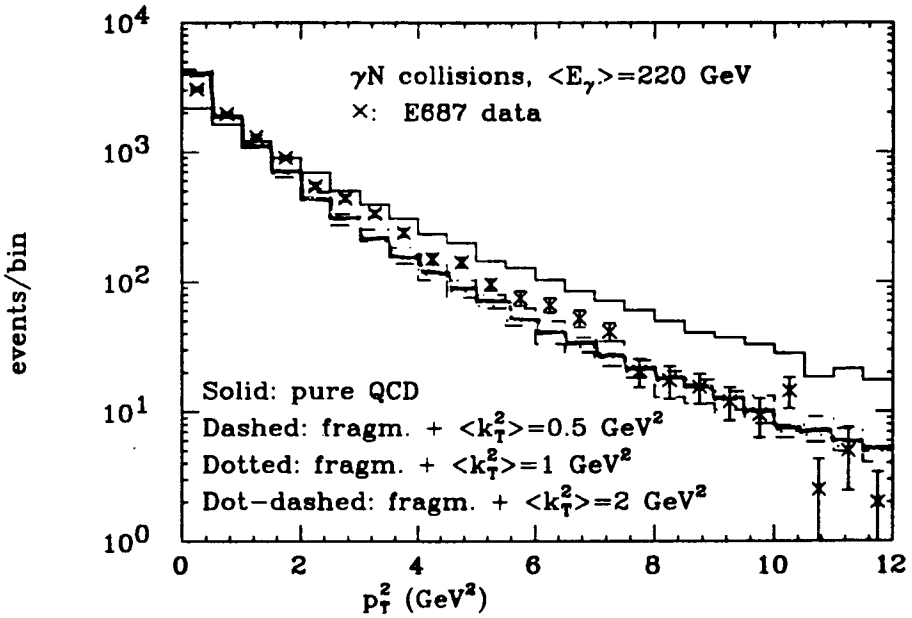


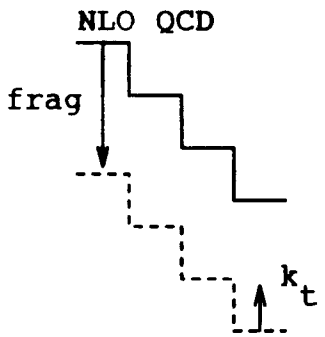
$$dN/dp_t^2 = A\ exp(ap_t^2 + bp_t^4)$$

	a	b
E687 data	-0.84 ± 0.02	0.030 ± 0.002
"bare" QCD NLO	-0.656	0.021
Pythia Monte Carlo	-0.79 ± 0.02	0.023 ± 0.002

- 9σ data $\leftrightarrow$ NLO !

- Supplement w/ nonperturbative descriptions
  - Intrinsic k_t added "by hand"
  - Peterson fragmentation





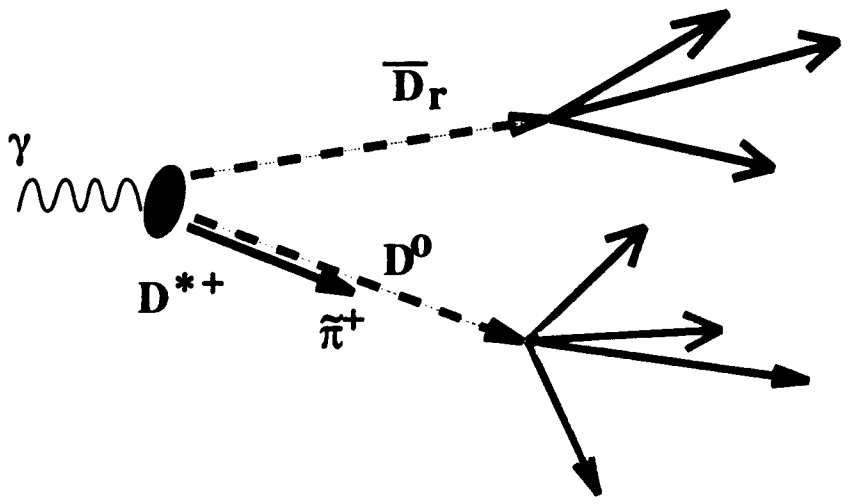
$$dN/dp_t^2 = A\ exp(ap_t^2 + bp_t^4)$$

	a	b
E687 data	-0.84 ± 0.02	0.030 ± 0.002
"bare" QCD NLO	-0.656	0.021
NLO + frag + $< k_t^2 >= 1$ GeV^2	-0.947	0.035

- tradeoff: fragmentation softens / k_t hardens
- NLO + frag + $< k_t^2 >= 1$ GeV^2 nearly sufficient

Reconstructing $D\overline{D}$ pairs

- fully reconstruct both D and $\overline{D}$
- partially reconstruct a D^{*+}
  - event type: $\gamma + N \rightarrow D^{*+}\overline{D_r}$
  - low Q for $D^{*+} \rightarrow D^o\tilde{\pi}$ implies $\vec{P}^* \approx 13.8\ \vec{P}_{\tilde{\pi}}$

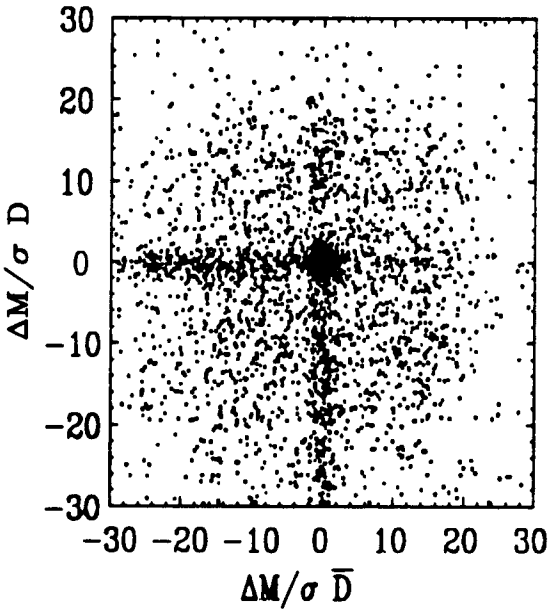


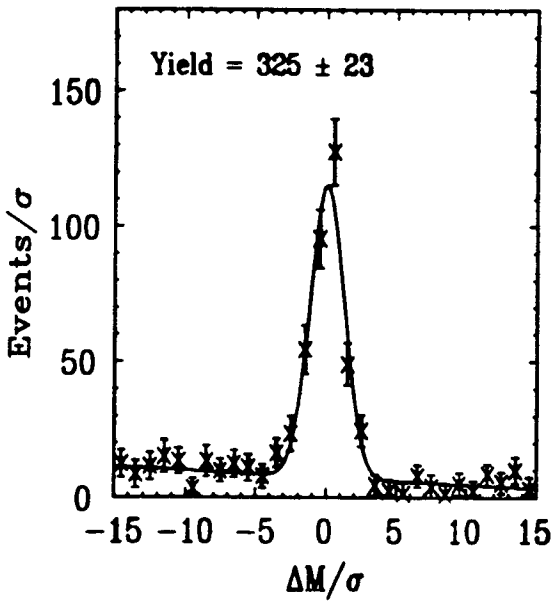
  - Expect P_t balance between recoil $\vec{P}^{(r)}$ and 13.8 $\vec{\tilde{P}}$
    $\Delta_x = 13.8P_x^{(\pi)} + P_x^{(r)} \qquad \Delta_y = 13.8P_y^{(\pi)} + P_y^{(r)}$
  - $\Delta_x \approx \Delta_y \approx 0$
  - Exploit $\tilde{Q} + Q(\overline{D}_r) = 0, \quad \Delta_t^2$ excess

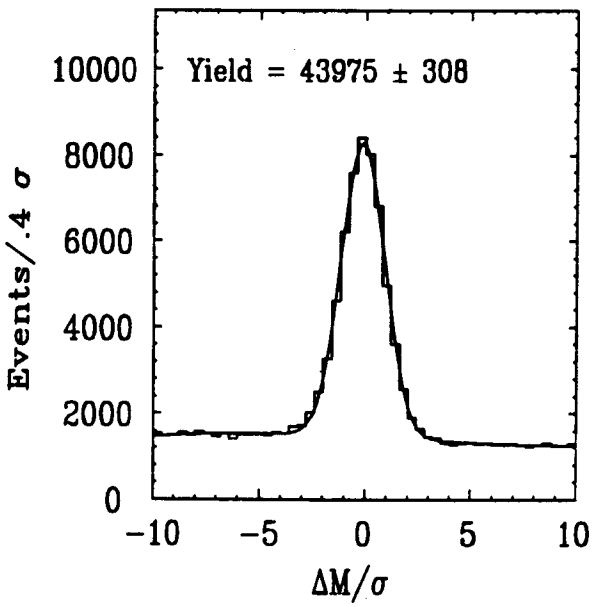
Signals for $D\overline{D}$ pairs

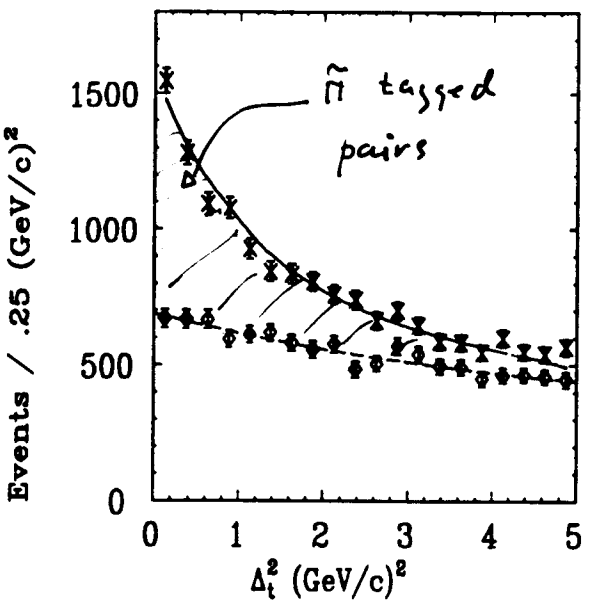
[E687] + [E791]

- Fully reconstructed & D^*-tagged





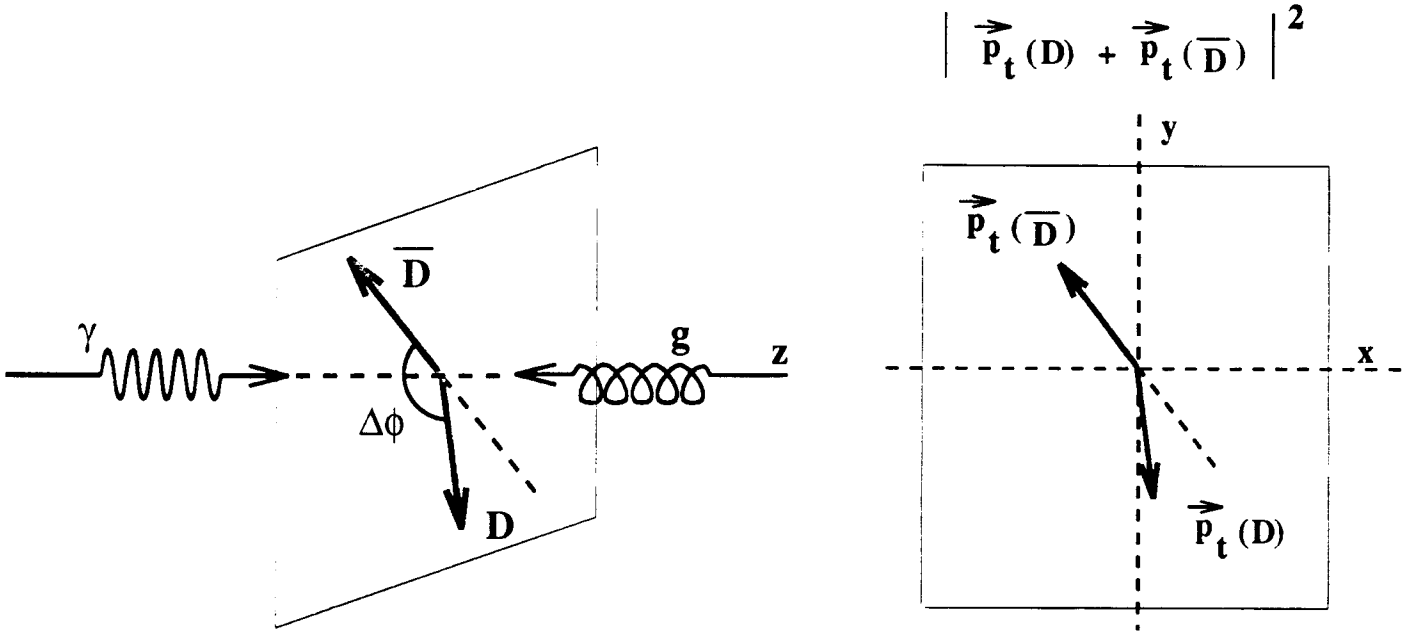




correlation variables

1. acoplanarity $\Delta\phi$ and $p_t^2(D\overline{D})$

   - $\Delta\phi$ measures transverse correlation



2. rapidity difference ($\Delta Y = Y_D - Y_{\overline{D}}$)

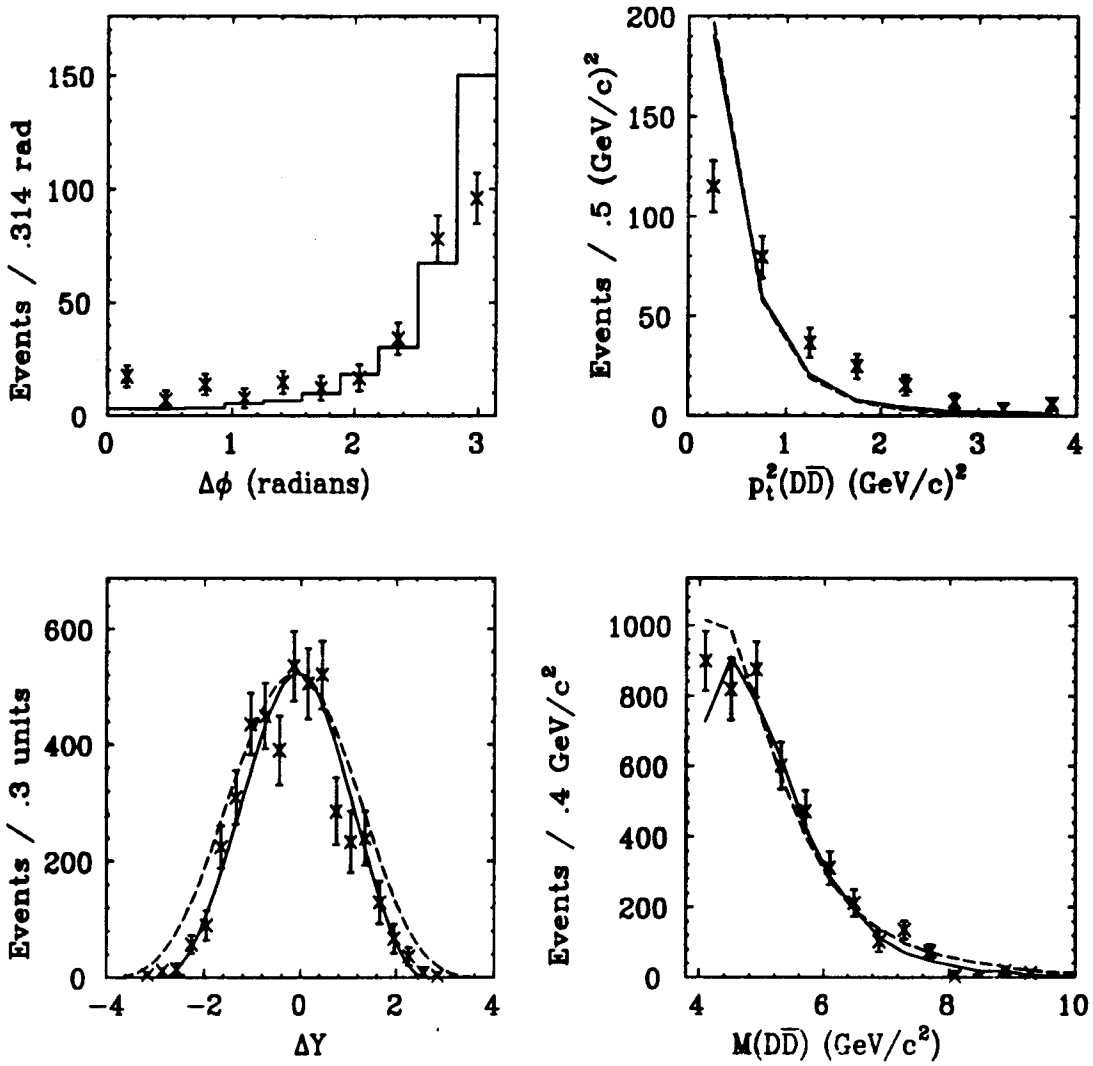
   - $Y_D = \frac{1}{2} log(\frac{E+P_z}{E-P_z})$

   - frame independent $D - \overline{D}$ longitudinal "velocity"

3. $M(D\overline{D})$

   - measures transverse and longitudinal correlation

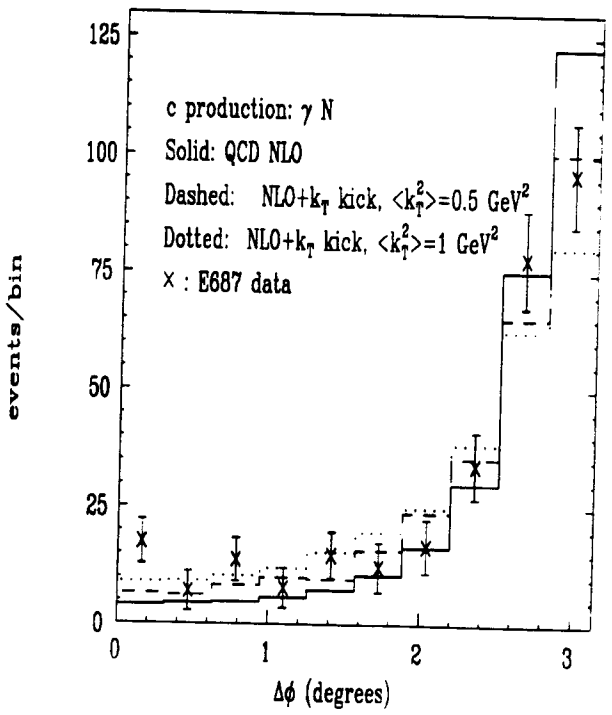
Investigate $D\overline{D}$ correlations (E687 Data vs Pythia MC)

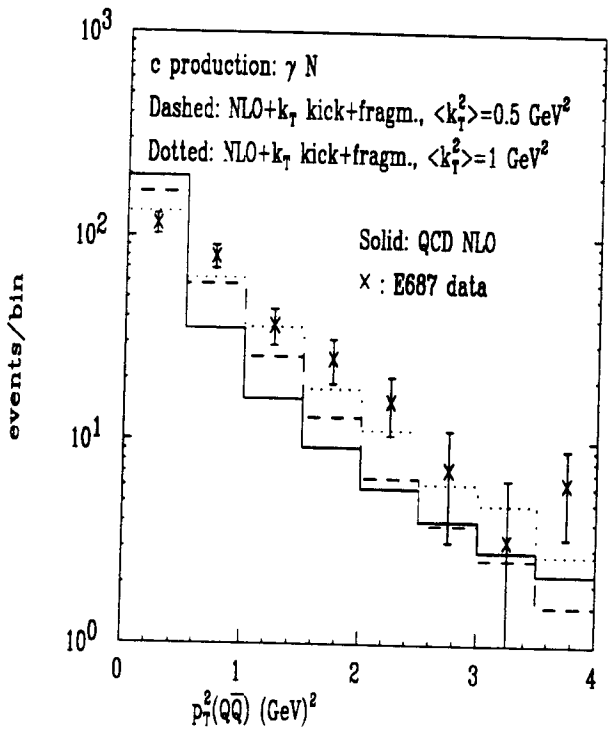


- Data vs Model:
  - Fair agreement in ΔY, $M(D\overline{D})$
  - Data much less peaked in $\Delta\phi$, $p_t^2(D\overline{D})$
  - Can NLO corrections make up the difference?

- NLO QCD predictions for correlations

(predictions from FMNR) data from E687





- Intrinsic k_t broadens both $\Delta\phi$ and $p_t^2(D\overline{D})$
- NLO + $< k_t^2 > \approx$ .5 GeV^2 OK for $\Delta\phi$
- But $p_t^2(D\overline{D})$ needs $< k_t^2 > \approx$ 1.0 GeV^2

$< k_t^2 > \approx$ 1.0 gives slightly too smeared $\Delta\phi$

Particle/anti-particle production asymmetries

E687 [γN] and E791 [π-N]

- In LO QCD, charm and anticharm are produced "symmetrically"
- NLO QCD may introduce small ($<< 1\%$) asymmetry in quark momenta
- $\alpha = \frac{N_c - N_{\bar{c}}}{N_c + N_{\bar{c}}}$ a probe of the nonperturbative effects

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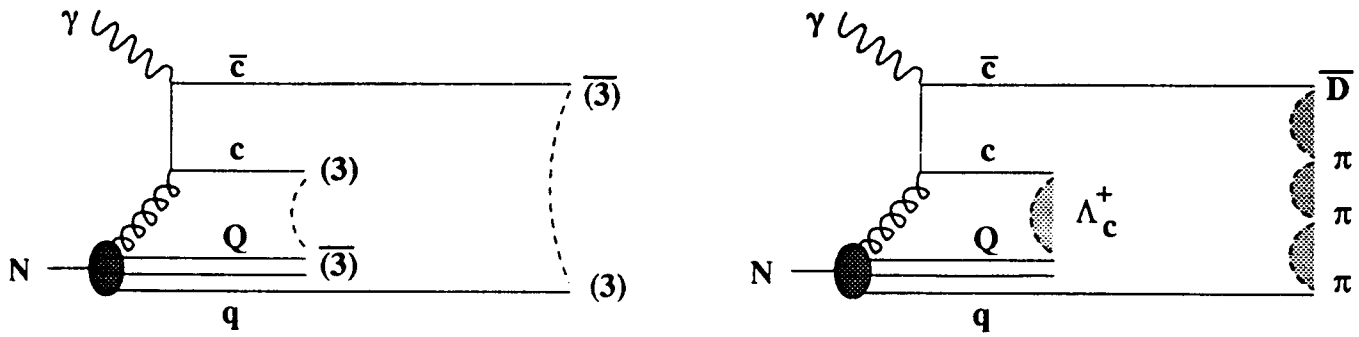
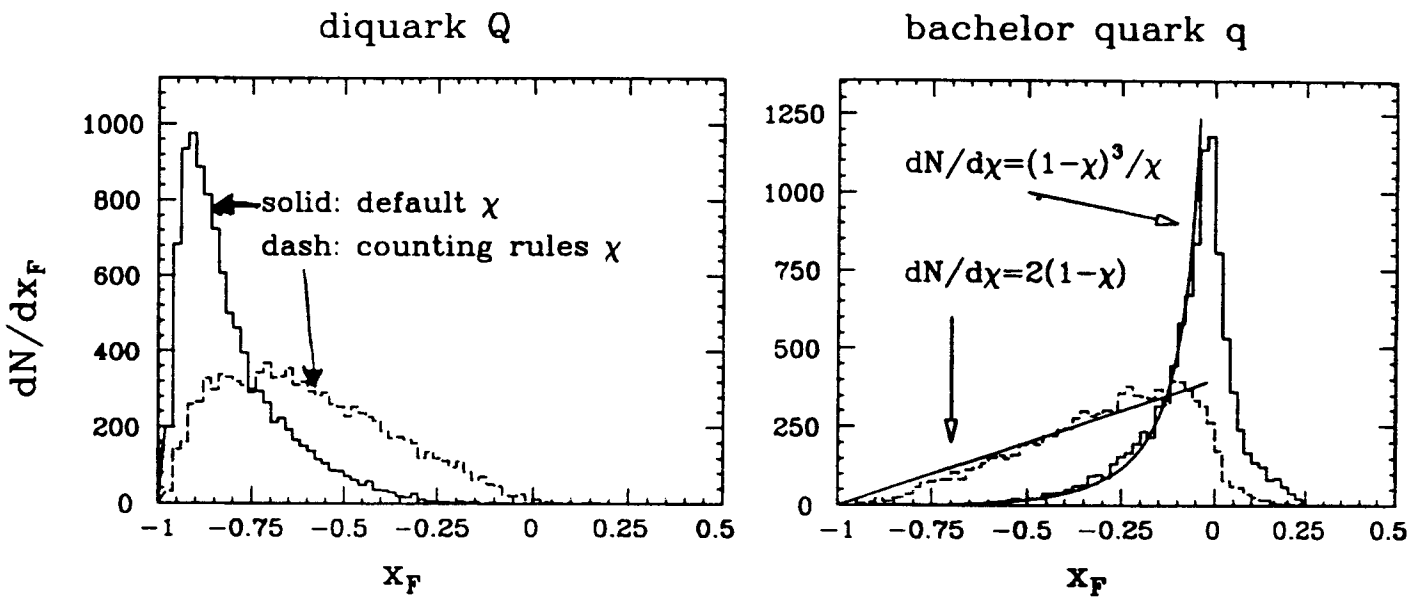
Lund string fragmentation picture (photoproduction)



- Solves color match problem for PGF
- $c - \bar{c}$ asymmetry due to q -Q asymmetry

Two bachelor quark χ hypotheses



$$P_q = \chi \, P_{\mathcal{N}}$$

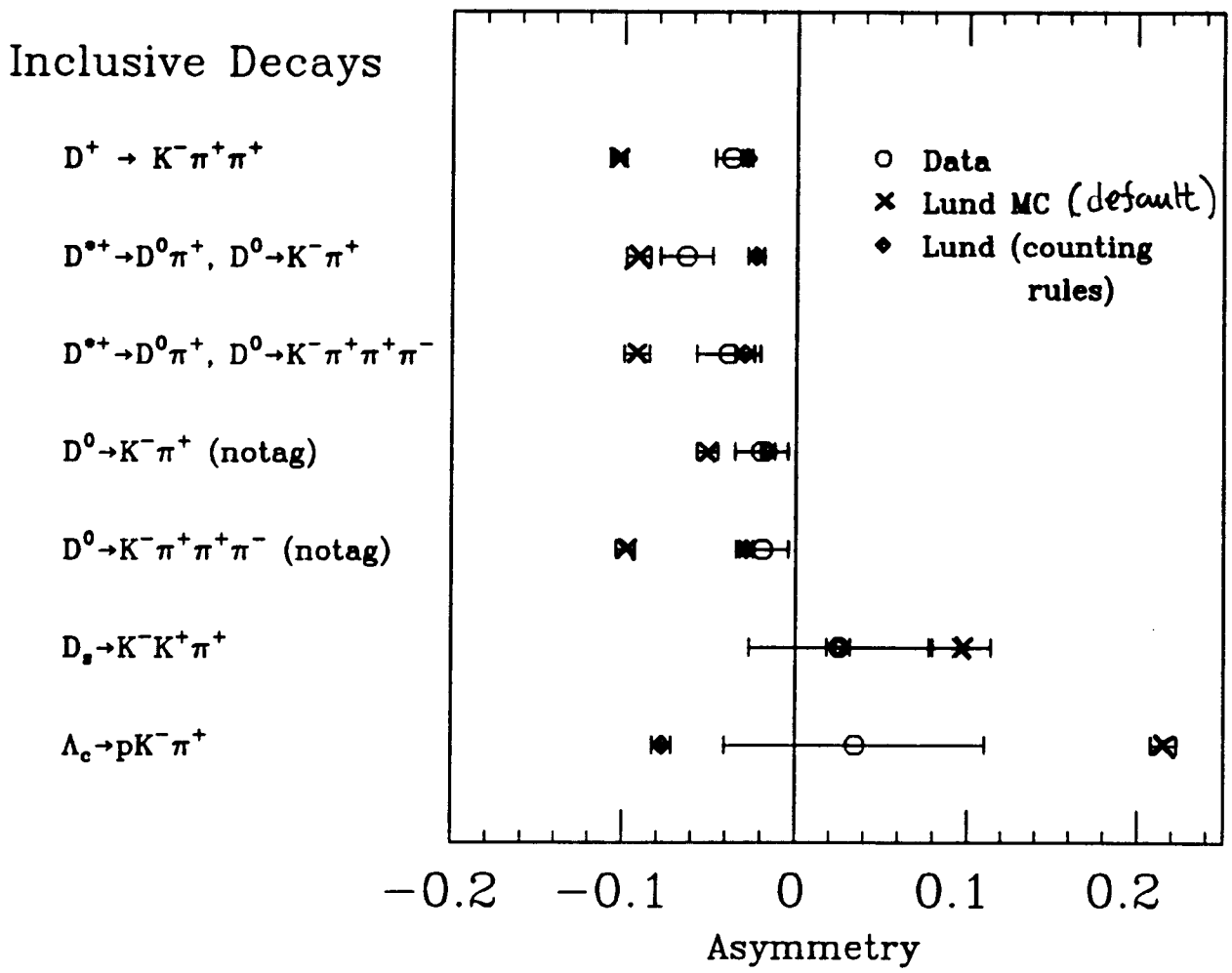
$$dN/d\chi = \frac{(1-\chi)^3}{\chi} \quad \text{sea quark like}$$

$$= 2(1-\chi) \quad \text{counting rules}$$

- Counting rules assign $< \chi >_q = \frac{1}{3}$ and $< \chi >_Q = \frac{2}{3}$
- χ_Q, χ_q more evenly distributed w/ counting rules
- If $\chi_Q = \chi_q = 0.5$ then $\alpha \approx 0$

Asymmetry summary for D, D_s, Λ_c

(photoproduction)

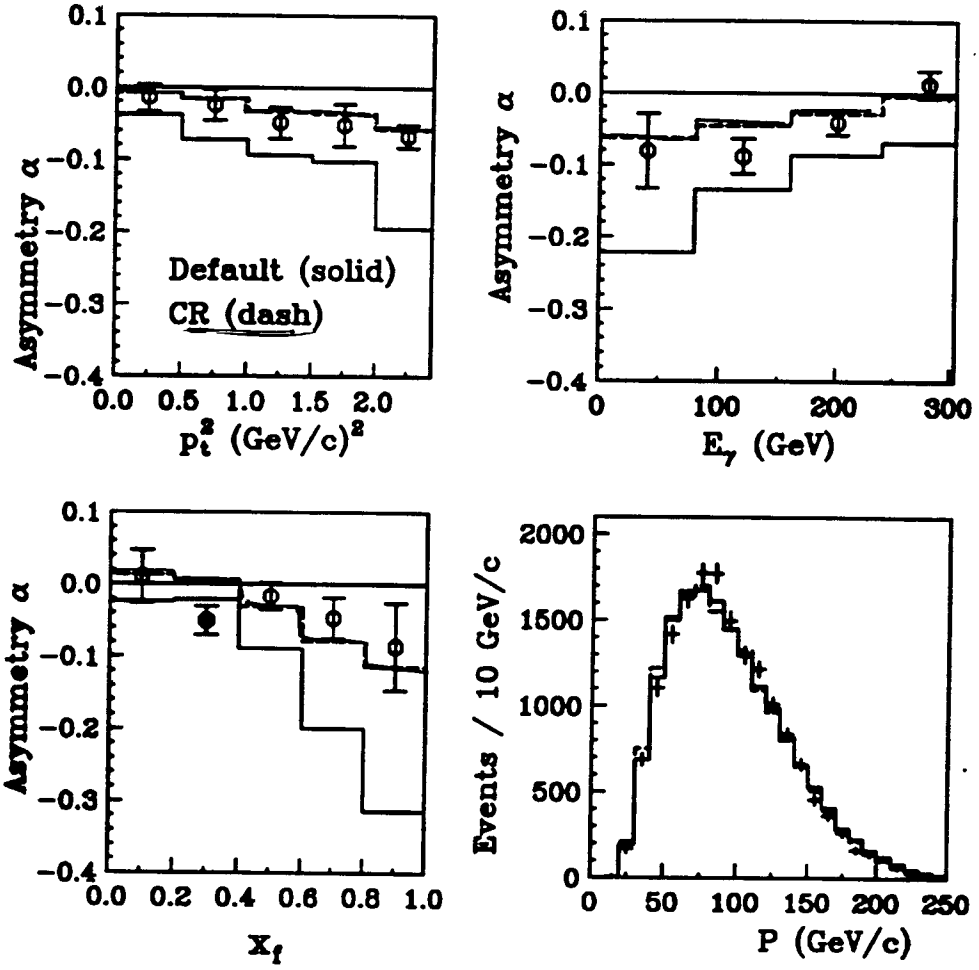


- CL(consis w/ no asymmetry) $= 8 \times 10^{-8}$ (D mesons)

- Counting rules favored by D's

α Kinematic variations

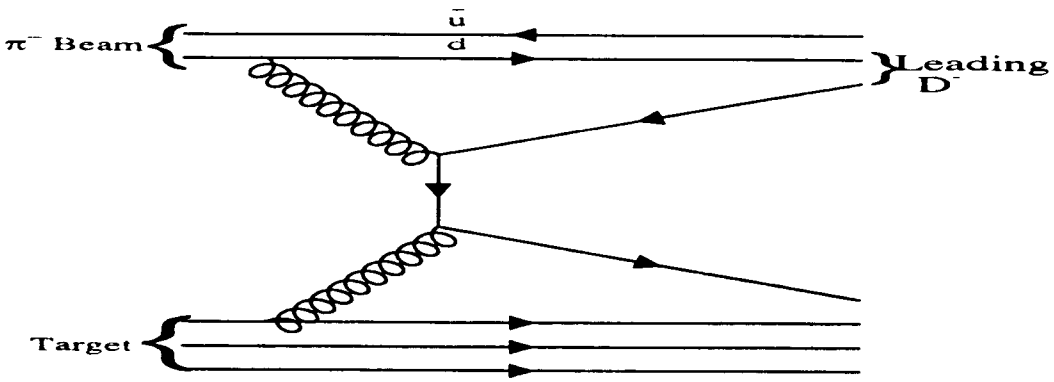
- Divide charm samples into E_γ, x_F bins



- The more symmetric CR q-Q model matches kinematic asymmetry found in data
- Either q-Q distribution does an excellent job in conjunction with Pythia at matching lab momenta of accepted $D^+ \to K^-\pi^+\pi^+$

α [(E791)] (T. CARTER et. al.)

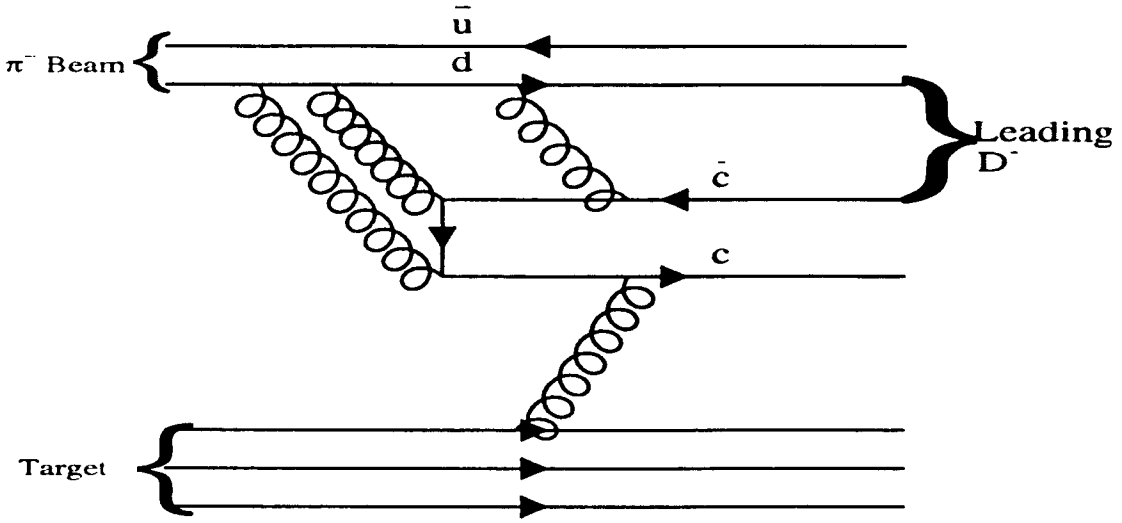
String Model with π^- Beam[1]



- Model used by PYTHIA for fragmentation ("beam dragging")
- Color Field is modeled as 1-dimensional string. When attached to beam remnant, string will tend to drag c or $\bar{c}$ forward.
- Results compared to default PYTHIA model and to modified PYTHIA.
- Modifications included:
  - Increasing primordial $\boxed{\langle k_t^2 \rangle}$ from 0.44 $(\mathrm{GeV}/c)^2$ to 1.0 $(\mathrm{GeV}/c)^2$
  - Increasing c quark mass from 1.35 GeV/c^2 to 1.7 GeV/c^2.
- Modifications suggested by another analysis within E791 and by other publications (e.g. S. Frixone *et al.*, Nucl. Phys. B 431 (1994) 453)

[1] Sjostrand, T., International Journal of Modern Physics A, Vol 3, pp 751-823

Intrinsic Charm[2]



- Virtual $c\bar{c}$ pair is in quark sea of the pion
- Knocked onto mass shell during interaction with target
- $c\bar{c}$ will tend to be co-moving with pion quarks. Easier to recombine with pion quarks. Cause asymmetry at high x_f.
- Final charm mesons will tend to have low P_t
- Key prediction is an increase in asymmetry in high x_F - low p_t^2 region.

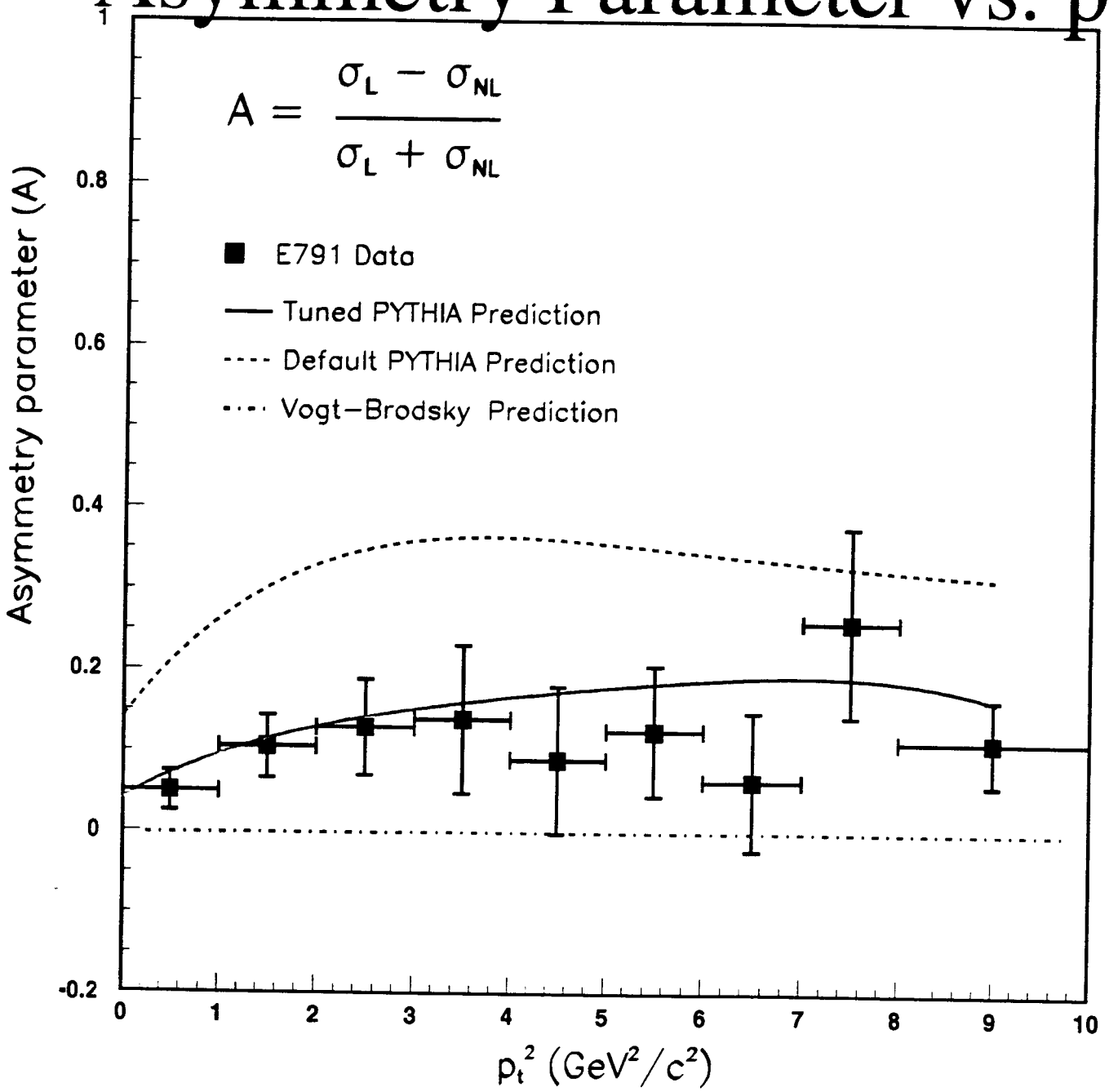
[2] Brodsky, S.J. *et al*, Phys Lett 93B, June 20, 1980, pp 451-455

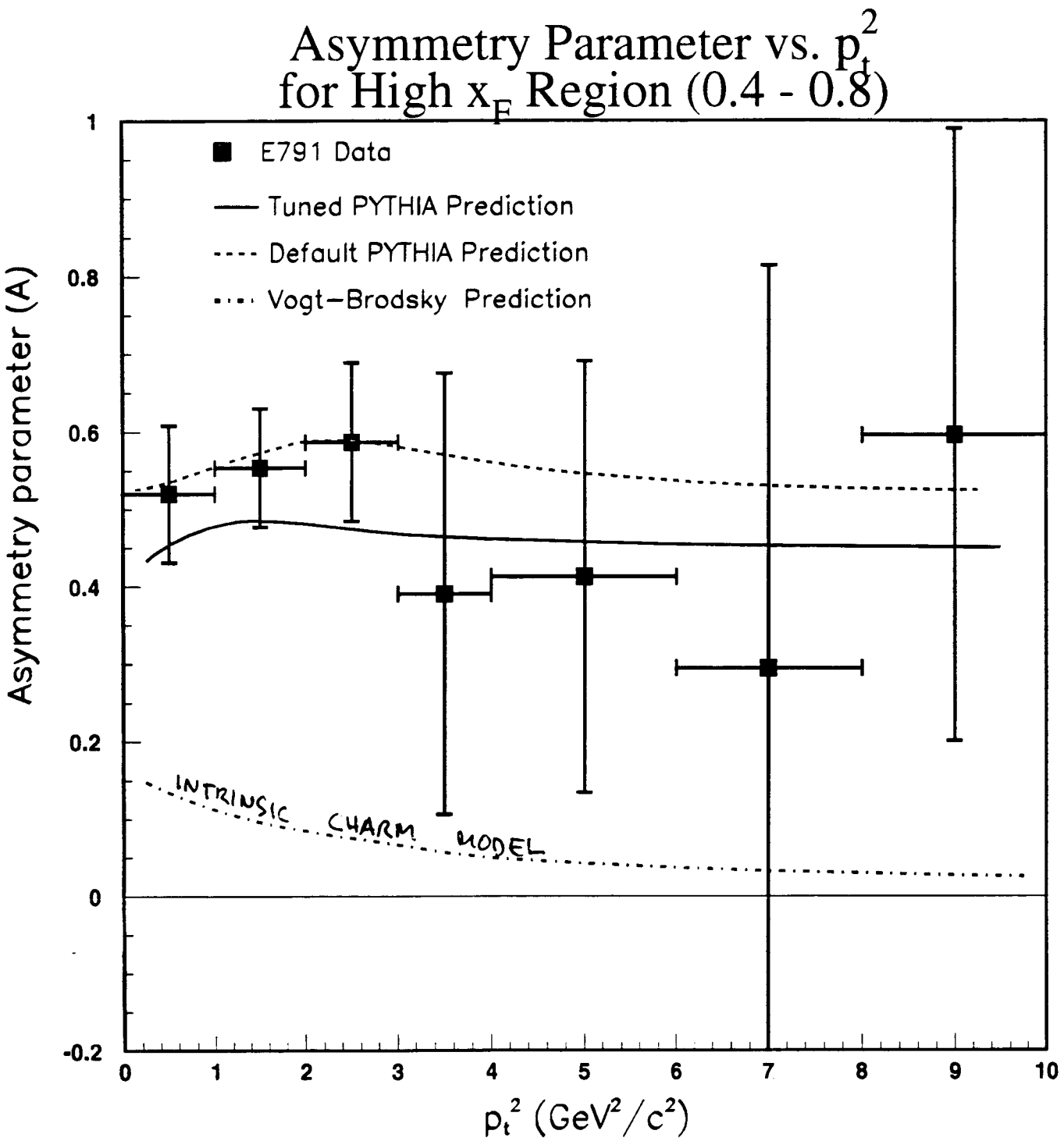
- Examine asymmetries by plotting:

$$A \equiv \frac{N_L - N_{NL}}{N_L + N_{NL}}$$

- "Leading Particle" has quark in common with beam.
- In case of E791 $\pi^-(\bar{u}d)$ beam, $D^-(\bar{c}d)$ is leading
- $A \to 1$: large difference in production
- $A \to 0$: no difference in production

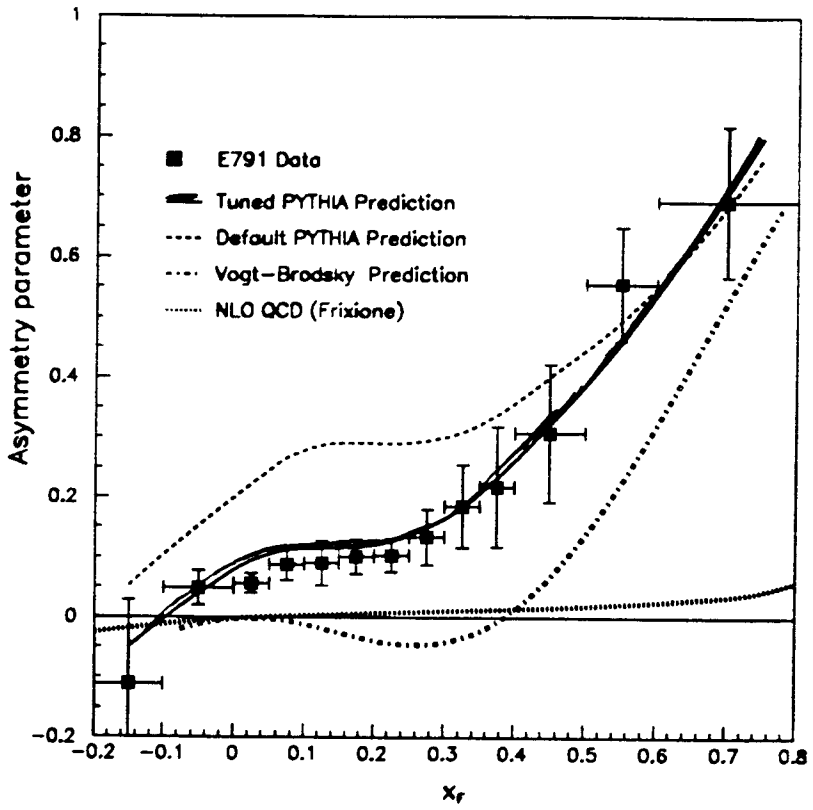
Asymmetry Parameter vs. p_t^2




Asymmetry Parameter vs. p_t^2
for High x_F Region (0.4 - 0.8)
E791 Data
Tuned PYTHIA Prediction
Default PYTHIA Prediction
Vogt–Brodsky Prediction
INTRINSIC CHARM MODEL
Asymmetry parameter (A)
p_t^2 (GeV^2/c^2)
1
0.8
0.6
0.4
0.2
0
-0.2
0
1
2
3
4
5
6
7
8
9
10

Conclusions of E791 in hadroproduction :

- A 74,000 event charmed meson sample from $\pi^- \mathcal{N}$ collisions at 500 GeV



- FMNR NLC predicts α very small for quarks
- Intrinsic charm pattern not quite right
- Default PYTHIA predicts a too large α
- Increasing $< k_t^2 > \rightarrow 1\ GeV^2$ and $m_c \rightarrow 1.7$ GeV reproduces data.

Some Remaining Puzzles & Challenges for the Not-so-heavy Charm Quark

- Is there a practical way to augment NLO calcs with a realistic fragmentation model?
  - How does one join up the perturbative and soft physics?
  - Both seem to be important in describing charm production
- When "tuning" model parameters such as

  m_c k_t dressing NLO

  care should be taken to consistently predict:

  $\sigma(c\bar{c})$ p_t^2 $\Delta\phi$ $\alpha(c\bar{c})$ x_F ...
  - My experience with photoproduction data indicates that such a fit may not be possible with current models and calculations
- Are these really puzzles or are we just intellectually challenged?