# Signals for Double Parton Scattering

**Presented by**
**Brenna Flaugher**
**Fermilab**

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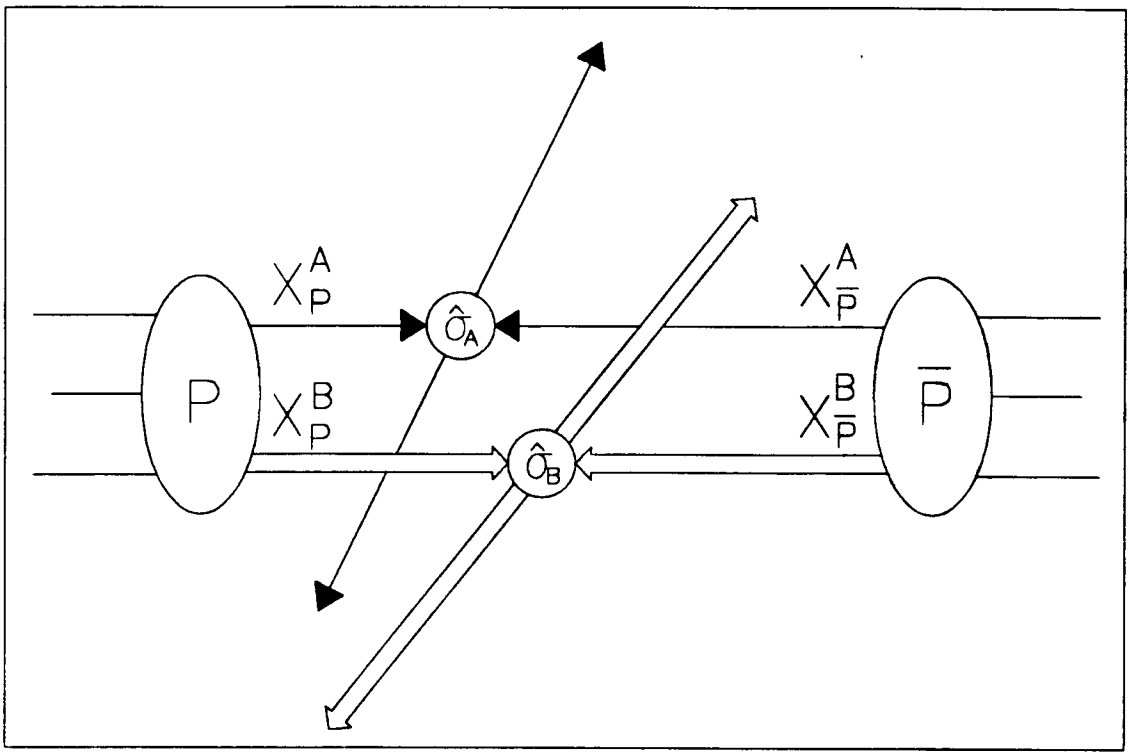
# Double Parton Scattering (DPS)

**Two parton-parton hard scatters in one $p\bar{p}$ collision.**

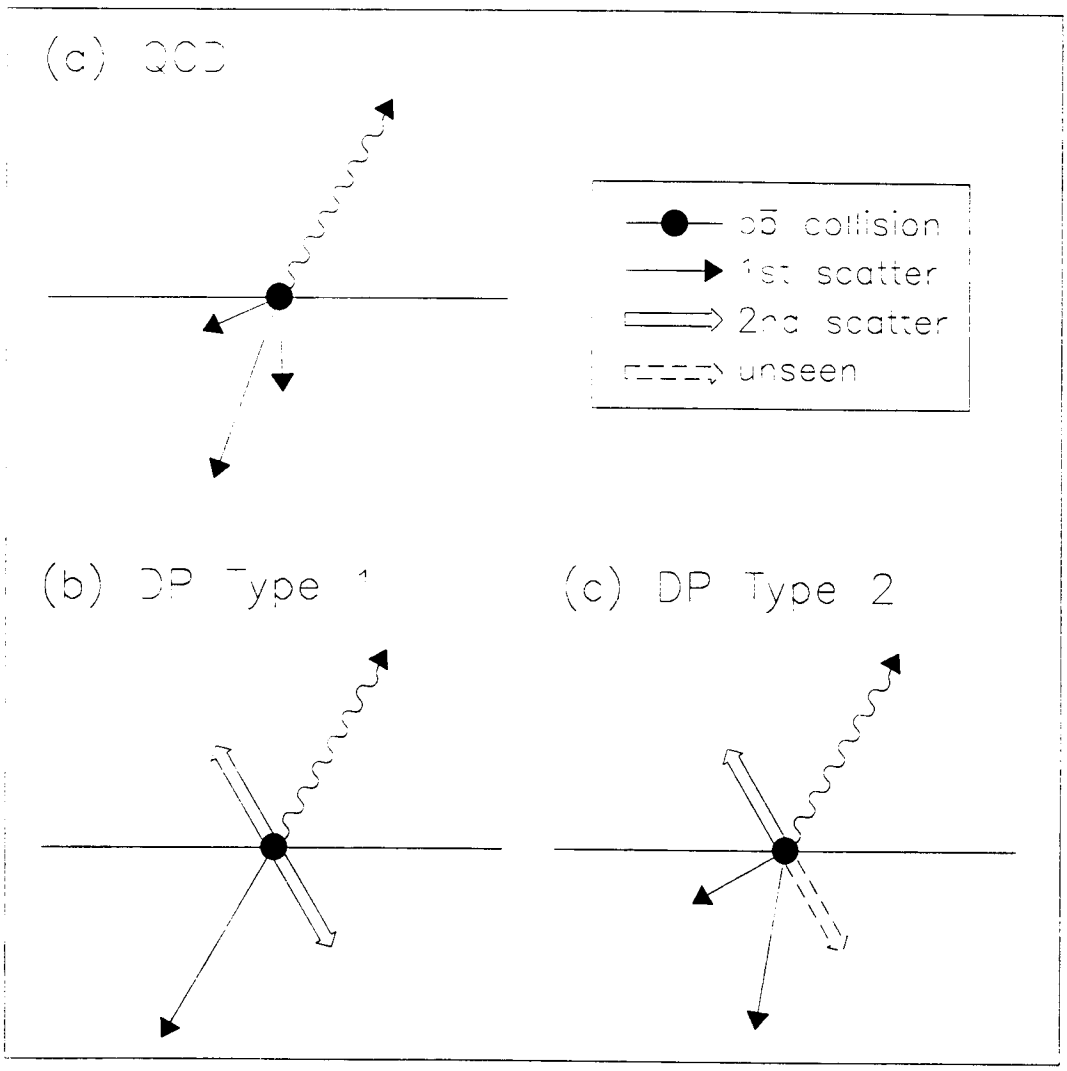



**Extend knowledge of proton structure**

- **spatial distribution of partons inside proton**
- **parton-parton correlations**

**$\rightarrow$ impact on PDFs?**

# QCD and Double Parton Scattering (DPS) in $\gamma + 3$ jet events



# Double Parton Scattering Cross Section

**DPS cross section: the product of two hard scatters modulated by a scale factor ($\sigma_{eff}$):**

↳ A, B

$$\sigma_{\mathrm{DP}} = \mathrm{m}\,\sigma_{\mathrm{A}}\,\frac{\sigma_{\mathrm{B}}}{2\sigma_{\mathrm{eff}}}$$

**factor of 2 is convention (Poisson statistics)**
**m is a combinatorial factor:**
**m=2 when A and B are distinguishable**
**m=1 when A and B are NOT distinguishable**

Uniform parton distribution
$\rightarrow \sigma_{eff}$ **is large and** $\sigma_{DP}$ **is small**

**Clumpy parton distribution**
$\rightarrow \sigma_{eff}$ **is small and** $\sigma_{DP}$ **is large**

**If assume protons are spheres with constant parton density:**

$$2\sigma_{eff} \approx \frac{\sigma_{NSD}}{2.3} \Rightarrow \sigma_{eff} \approx 11mb$$

No reason to assume DPS does not take place. In fact it must occur at some level.

Theoretical discussion of DPS has been going on many years, at least since the early 1980's.

Problem is experimentally extracting a signal from double brem background

Typically experiments choose 4-jet samples $\rightarrow$ high cross section.

Measuring $\sigma_{eff}$ in 4-jet samples:

$$\sigma_{\mathrm{DP}} = \frac{\sigma_{\mathrm{JJ}}^2}{2\sigma_{\mathrm{eff}}}$$

m = 1: two 2-jet events are indistinguishable

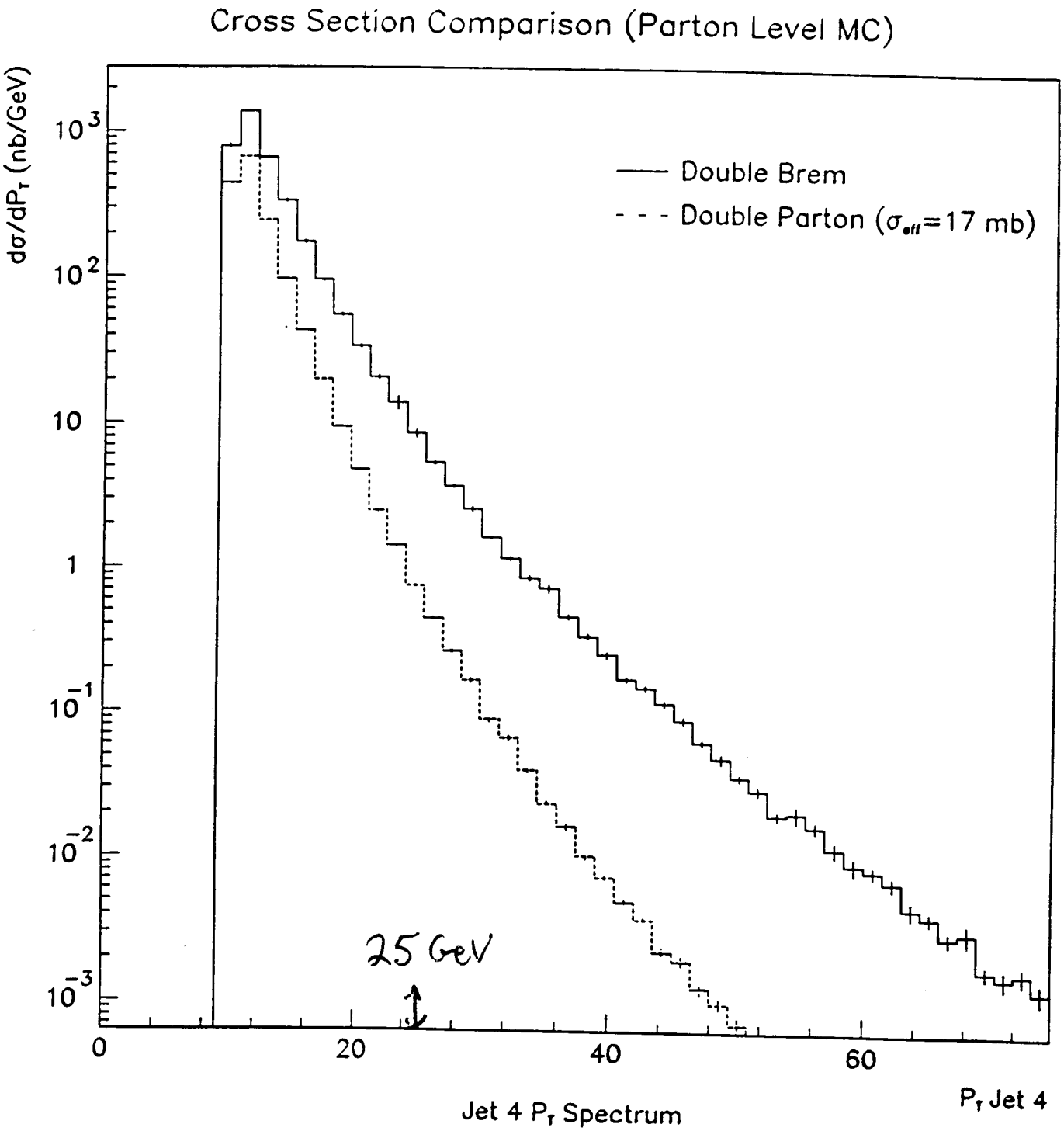
Measure $\sigma_{DP}$ but need QCD calculations of $\sigma_{JJ}$ to get $\sigma_{eff}$.

Another problem:

$$\frac{\sigma(DP)}{\sigma(QCD)}$$

decreases as $P_T$ increases.

Effect of $P_T$ cut on Double Parton content



# Measuring $\sigma_{DP}$

**use topological variables sensitive to pairwise $P_T$ balance:**

$$S(A,B) = \frac{1}{\sqrt{2}}\sqrt{\frac{|\mathbf{P_t(A)}|^2}{\delta_\mathbf{A}^2} + \frac{|\mathbf{P_t(B)}|^2}{\delta_\mathbf{B}^2}}$$

**A and B are the best two-body pairs**
$P_t(A)$, $P_t(B)$ = **pair transverse momentum**
$\delta_A$, $\delta_B$ = **momentum resolution for** $P_t(A)$, $P_t(B)$.
**QCD: S is broad distribution**
**DPS: S is peaked toward low values**

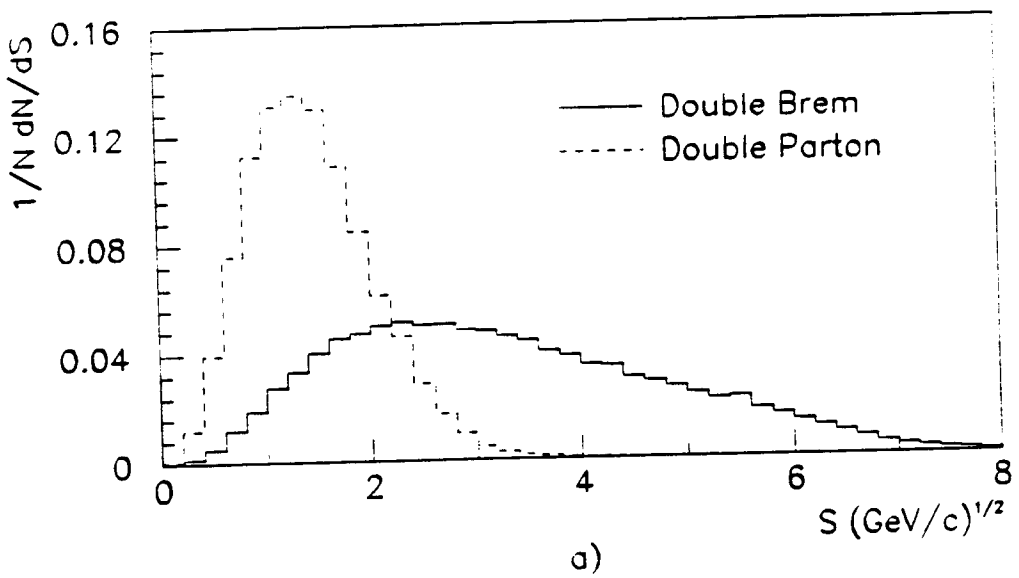
$\Delta$**S** $\equiv$ **angle between** $P_t(A)$ **and** $P_t(B)$
**QCD:** $\Delta$**S** $\approx \pi$
**DPS:** $\Delta$**S** $\approx$ **flat , random**

QCD Monte Carlo $\rightarrow$ Double Brem shapes
**DPS: combine two 2-jet events from data.**

Double parton fraction: **fit data distributions to a linear combination of Double Brem and Double Parton shapes.**

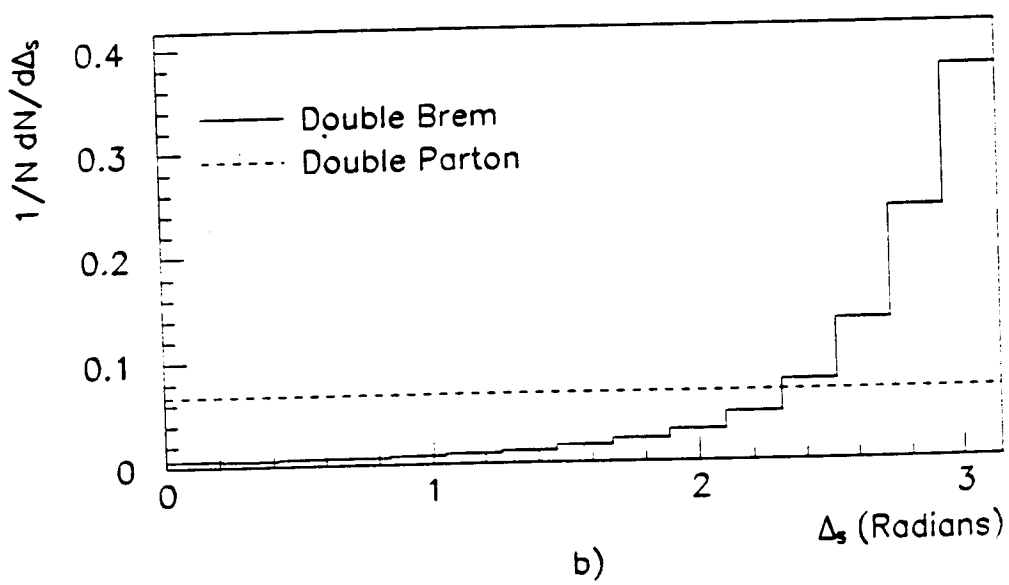
Shape of topological Variables

S and $\Delta_s$ for QCD Double Brem and for Double Parton Model.




a)

S




b)

$\Delta_s$

Previous 4-jet measurements:

- **AFS:** $\sqrt{s} = 63$ **GeV,** $E_T > 4$ **GeV** Z. Phys. C 34, 163 (1987)
  $\Rightarrow \sigma_{eff} \approx 5$ **mb**
- **UA2:** $\sqrt{s} = 630$ **GeV** $E_T > 15$ **GeV** Phys. Lett. B 268, 145 (1991)
  $\Rightarrow \sigma_{eff} > 8.3$ **mb**
- **CDF-1989:** $\sqrt{s} = 1800$ **GeV,** $E_T > 25$ **GeV** PRD 47, 4857 (1993)
  $\Rightarrow \sigma_{eff} = 12.1^{+10.7}_{-5.4}$ **mb,**
  $\Rightarrow$ **DP fraction** $= 5.4^{+1.6}_{-2.0}\%$

New analyses by CDF and D0:

**D0: 4-jets** $E_T > 25$ **GeV, Neural Net compare data and QCD (Pythia 4-jets).**

**CDF:** $\gamma + 3$ **jet** $\rightarrow$ **low** $E_T$**:**
$E_T^{photon} > 16$ **GeV,** $E_T^{jet} > 5$ **GeV**

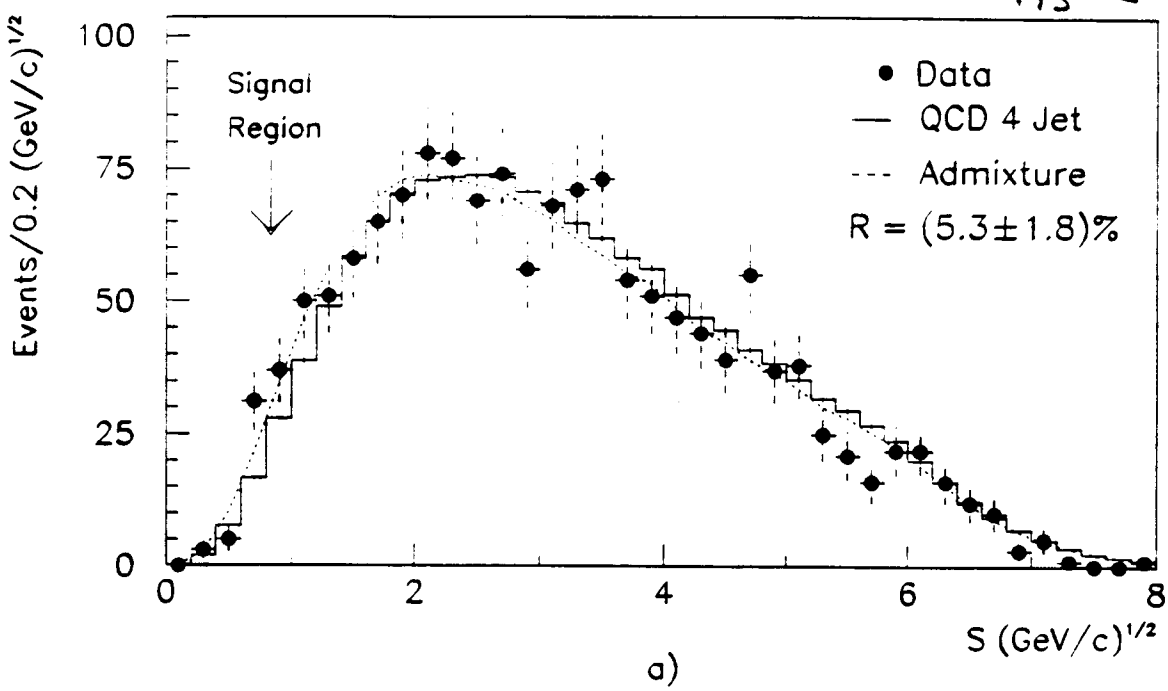
New idea

**Use ratio of Double Interaction (two separate** $p\bar{p}$ **collisions) and DPS rates to extract** $\sigma_{eff}$
$\rightarrow$ **reduce dependence on Monte Carlo.**

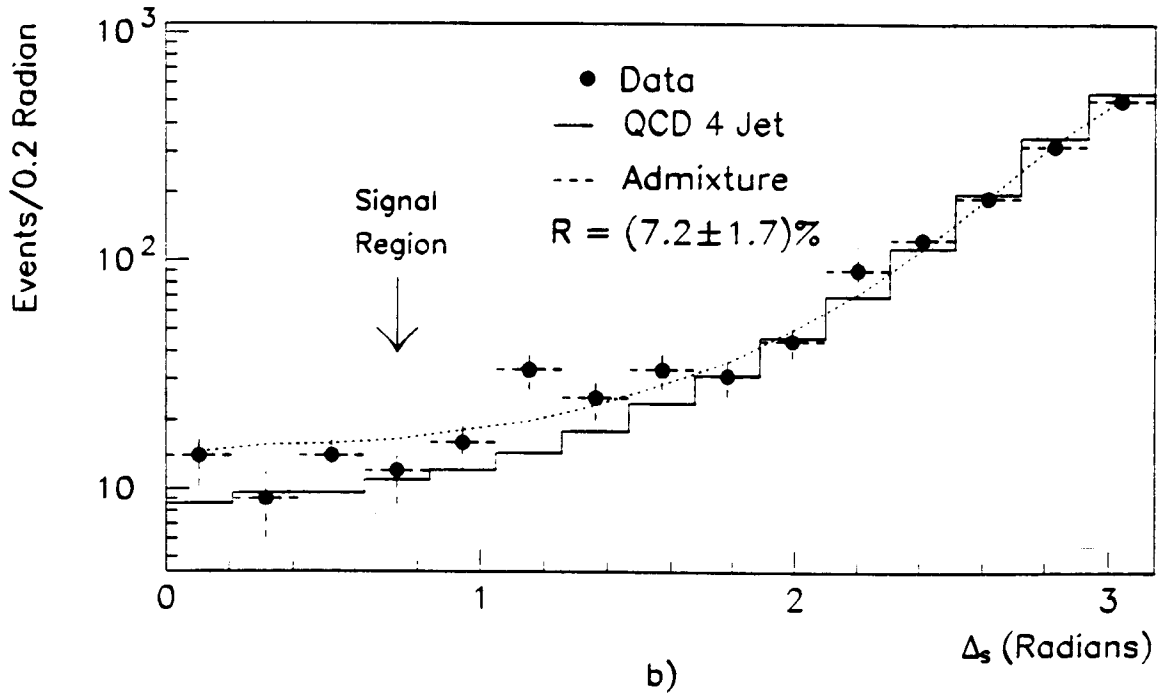
# CDF 1989 Result

CDF 4-Jet Data compared to 4 Jet M.C. and to best fit admixture of QCD double brem. + Double Parton Scattering

$P_{T5} < 15$ GeV




a)

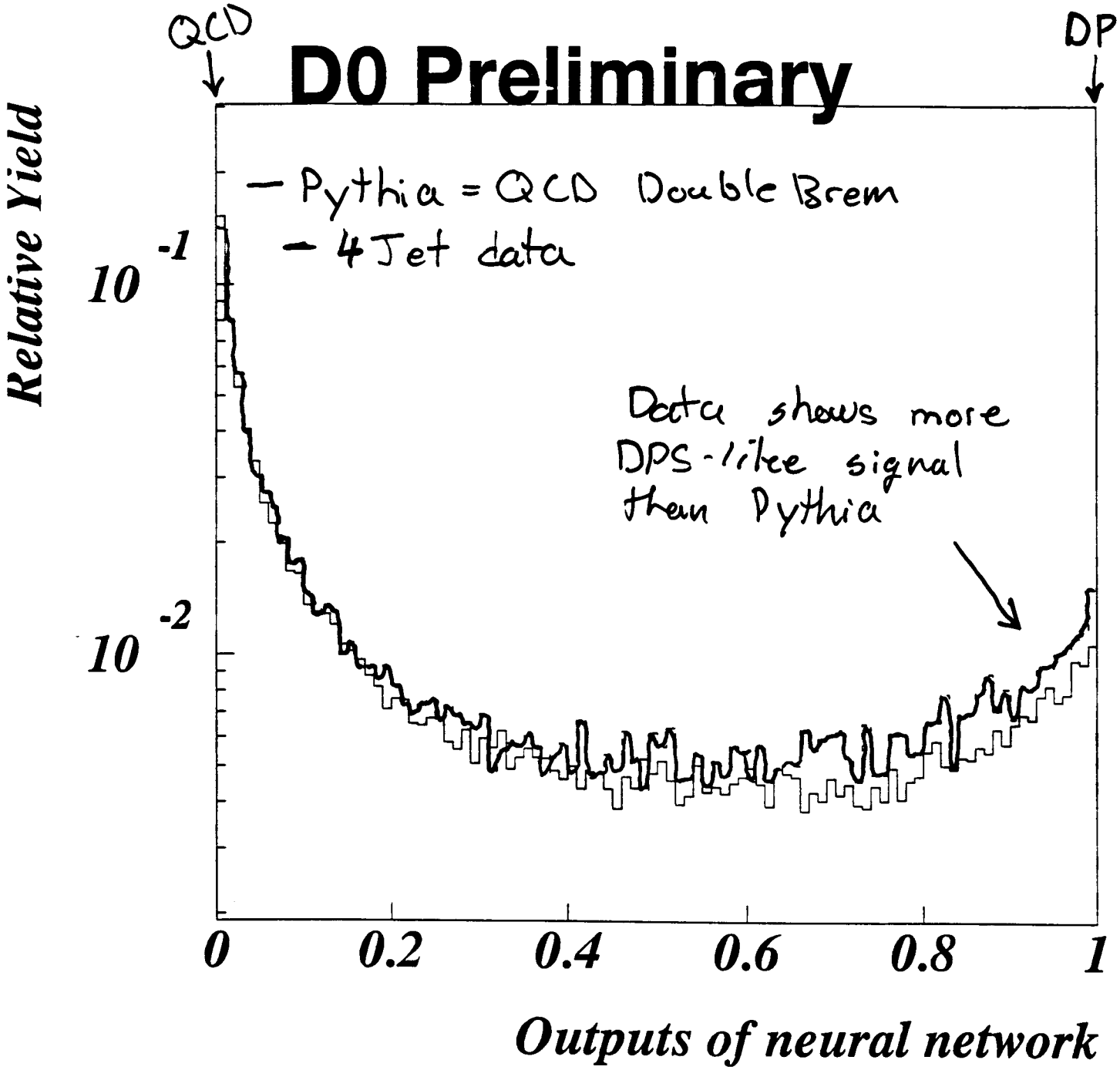



b)

# DØ DPS analysis

4 Jet $E_T > 25$ GeV

Train Neural Net to separate
DP model from 2-Jet + 2Jet data = 1
Independent 4 Jet data sample ~ Double Brem QCD = 0

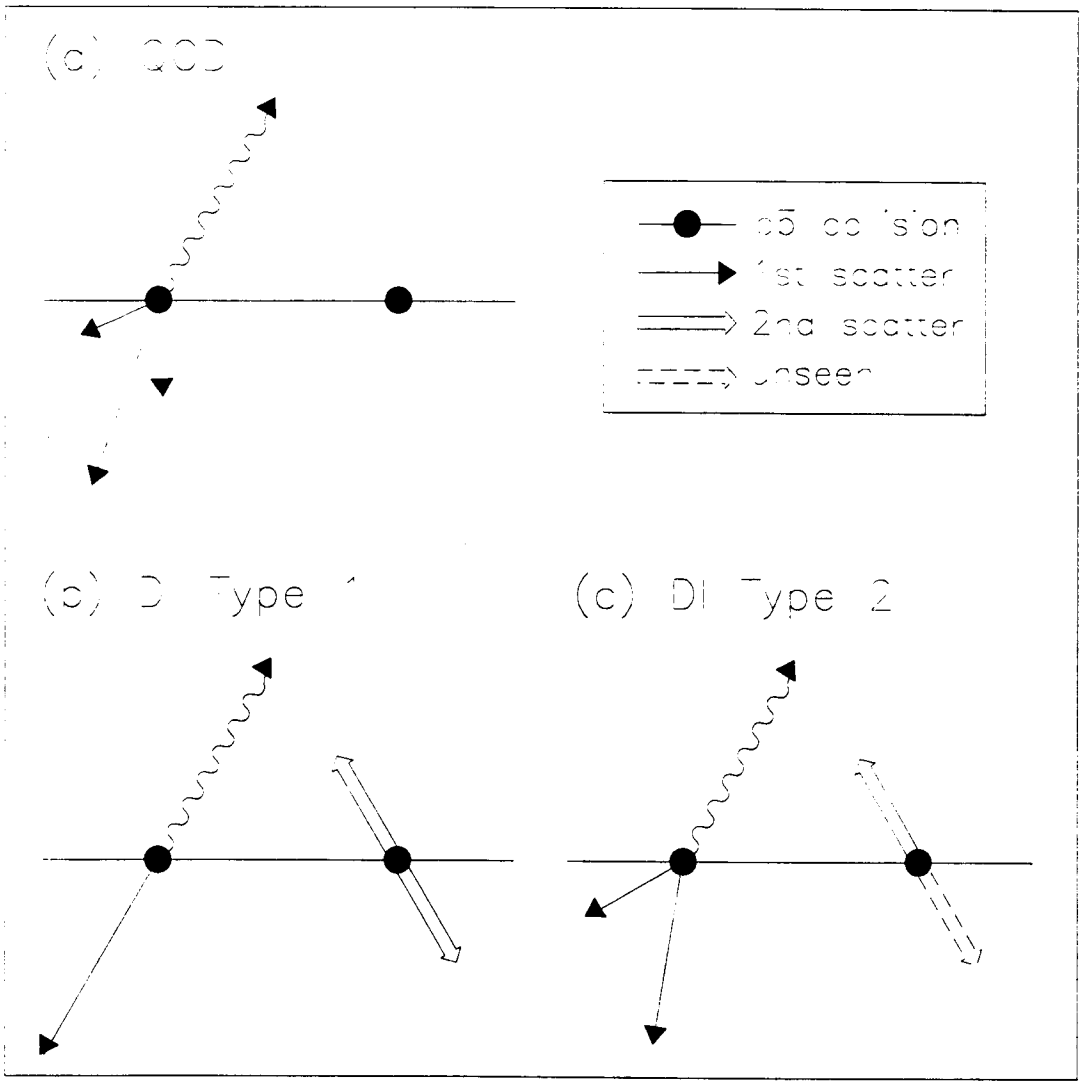


# Data Sample: CDF $\gamma$ + 3 jet analysis

- **Trigger:** $E_T^\gamma$ **>16 GeV**
- **Run 1A: 16 pb$^{-1}$**
- $|\eta^\gamma|$ **<0.9**
- **Isolation <4 GeV in cone R=0.7 around** $\gamma$
- $|\eta^{jet}|$ **<4**
- **# jets = 3**
- $E_T^{jet1}$ **>5 GeV**
- **5 GeV<** $E_T^{jet2}, E_T^{jet3}$ **<7 GeV**

$\Rightarrow \approx$ **16,000** $N_{VTX} =$ **1 DP candidates**
$\Rightarrow \approx$ **5,500** $N_{VTX} =$ **2 DI candidates**

# QCD and Double Interactions (DI)




**To separate types a, b, and c, associate tracks in jets to a vertex.**

**DI $\equiv \geq 1$ jet from second vertex**

Goals of $\gamma$ + 3 jet analysis

**Determine $f_{DP} = \frac{\#DPS}{Total}$ events**

**Determine $\sigma_{eff}$**

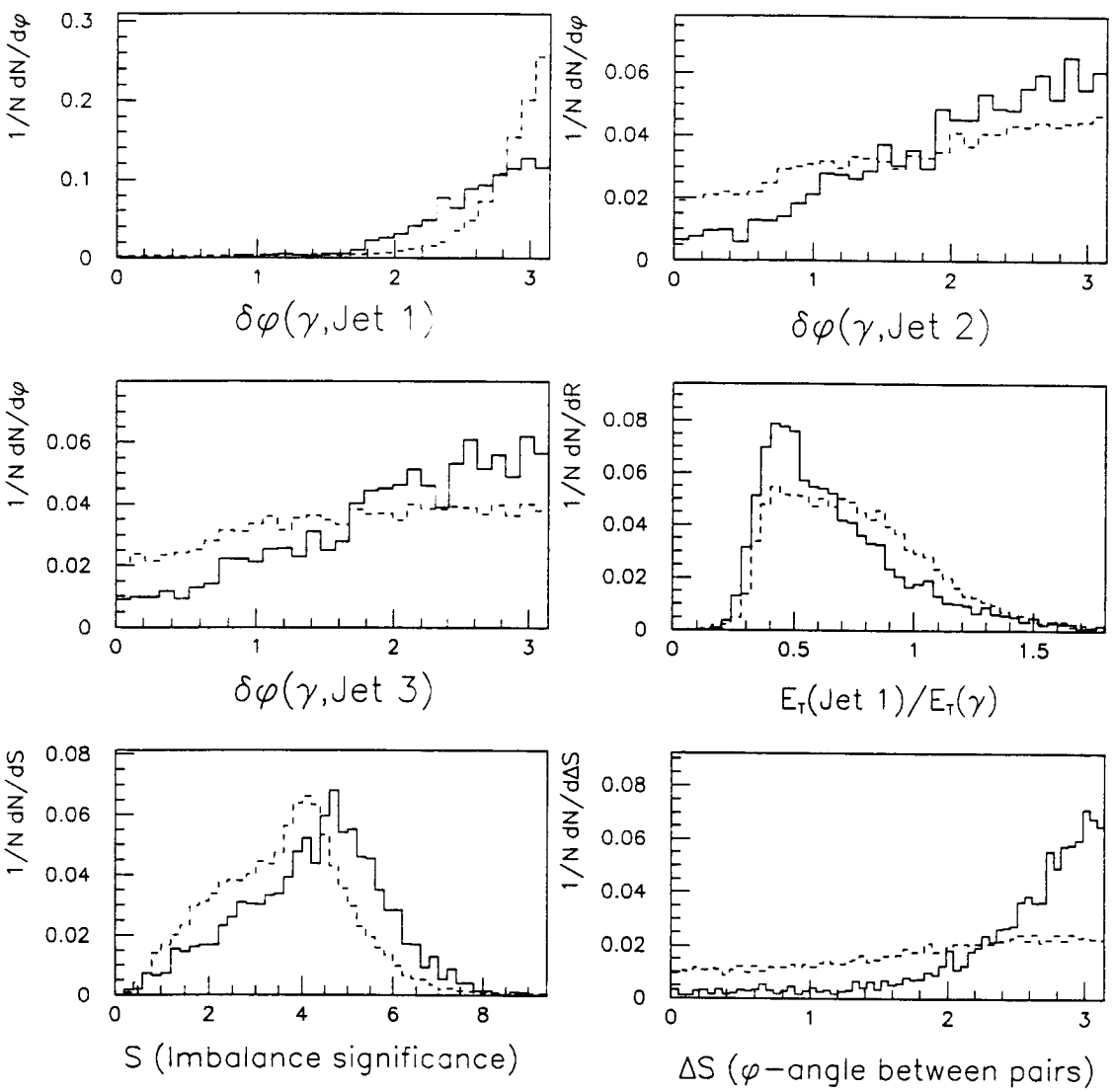
**Look for parton correlations**

**Two approaches to measuring $f_{DP}$:**

- **Like 4-jet analysis:**
  **use Pythia to model QCD double brem, combine events to model DPS**
  **$\rightarrow$ fit distributions for $f_{DP}$ $f_{QCD}$.**
- **Use data: contrast two separate data samples which have different $f_{DP}$ to determine $f_{DP}$ and $f_{QCD}$**

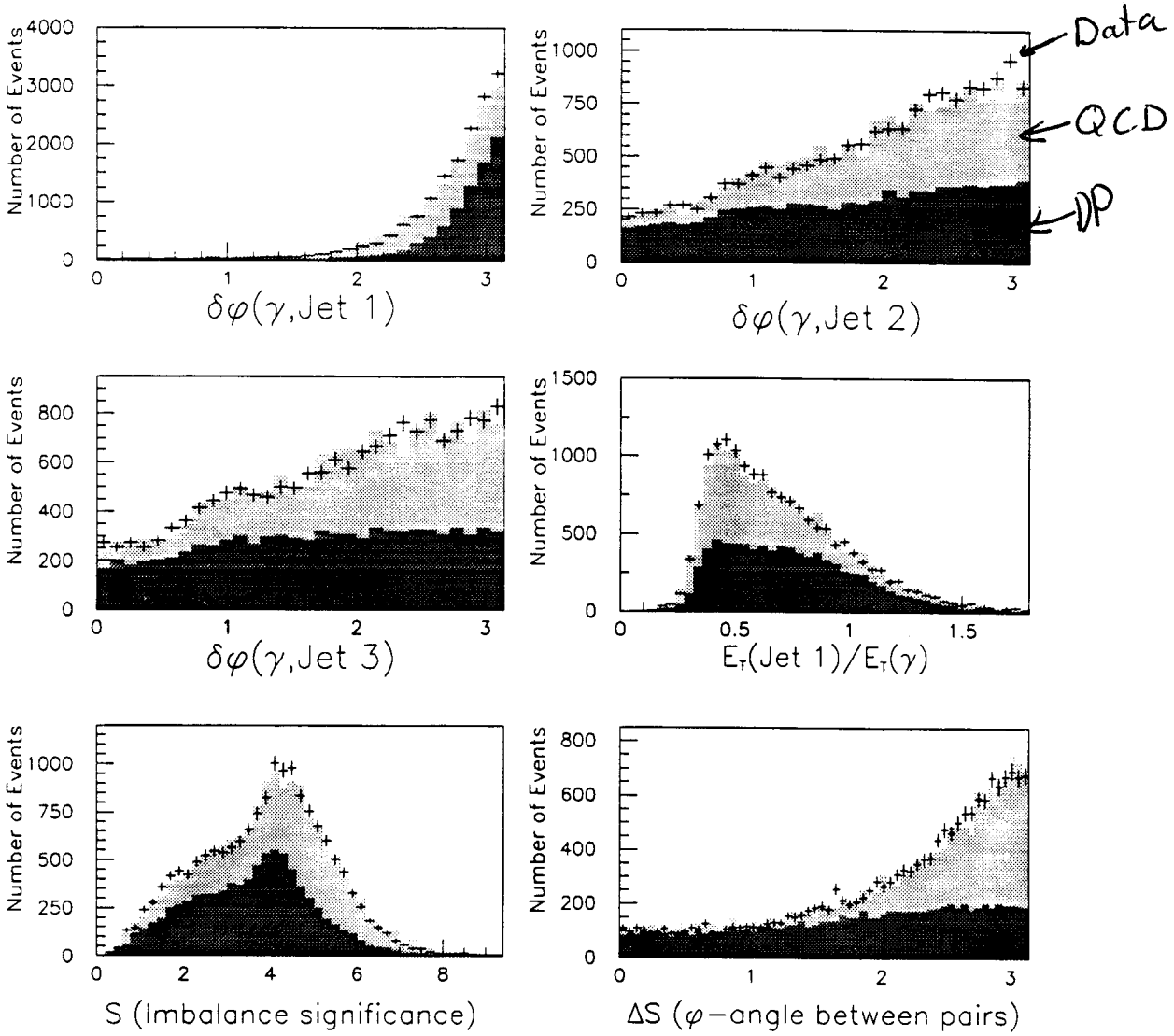
**$\Rightarrow$ both give similar results:**
**$f_{DP} = 52 \pm 1$ % stat.**

## To measure $f_{DP}$ and $f_{QCD}$ use 6 variables:



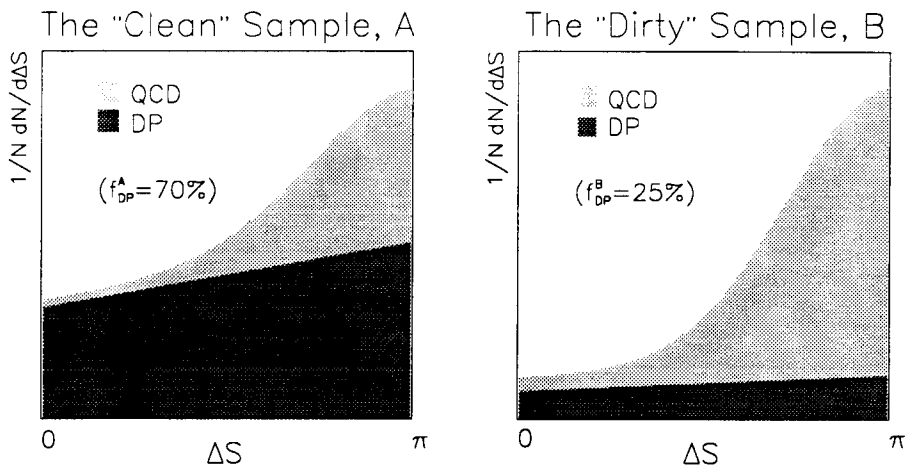

**solid = Pythia, dashed = Double Parton Model**

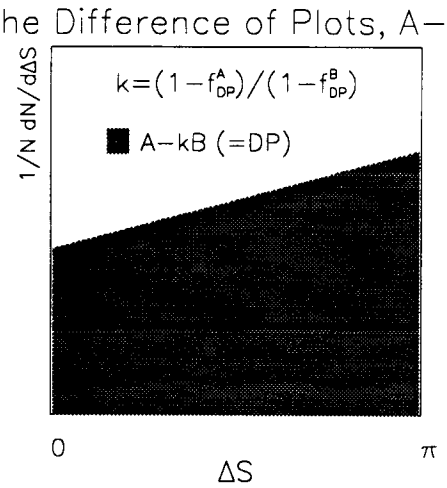
**Admixture of 52% DP + 48% QCD provides best fit to the data.**



# Two Dataset Method

**Know signal (DP) properties from Mixed event sample, but not BKG (QCD).**
**Separate data into 2 samples:**




**Assume QCD component has same shape in A and B. Vary $k$ until A-$k$B distribution = the DP distribution. Extract $f_{DP}$ from $k$: Result $\rightarrow$ $f_{DP} = 52\%$**

# Determination of $\sigma_{eff}$

**Previous 4-jet analysis:**

$$\sigma_{\mathbf{eff}} = \mathbf{m}\,\sigma_{\mathbf{A}}\,\frac{\sigma_{\mathbf{B}}}{\mathbf{2}\sigma_{\mathbf{DP}}}$$

**Processes A and B were dijets, $\sigma_A = \sigma_B = \sigma_{JJ}$, calculated by Monte Carlo, and m=1**

**CDF has developed new way to extract $\sigma_{eff}$:**
**Number of DPS events in 1-VTX $\equiv N_{DP}$**
**Number of DI events in 2-VTX $\equiv N_{DI}$**
**(associate tracks in jets to a vertex,**
**DI $\equiv \geq$ 1 jet came from 2nd vertex.)**

$$\sigma_{eff} = (\frac{N_{DI}}{N_{DP}})(\frac{\sigma_{NDS}}{2})(\frac{m}{2})(\frac{N_C(1)}{N_C(2)})$$

**$N_C(1)$ and $N_C(2)$ are the # beam crossings with 1 or 2 collisions**

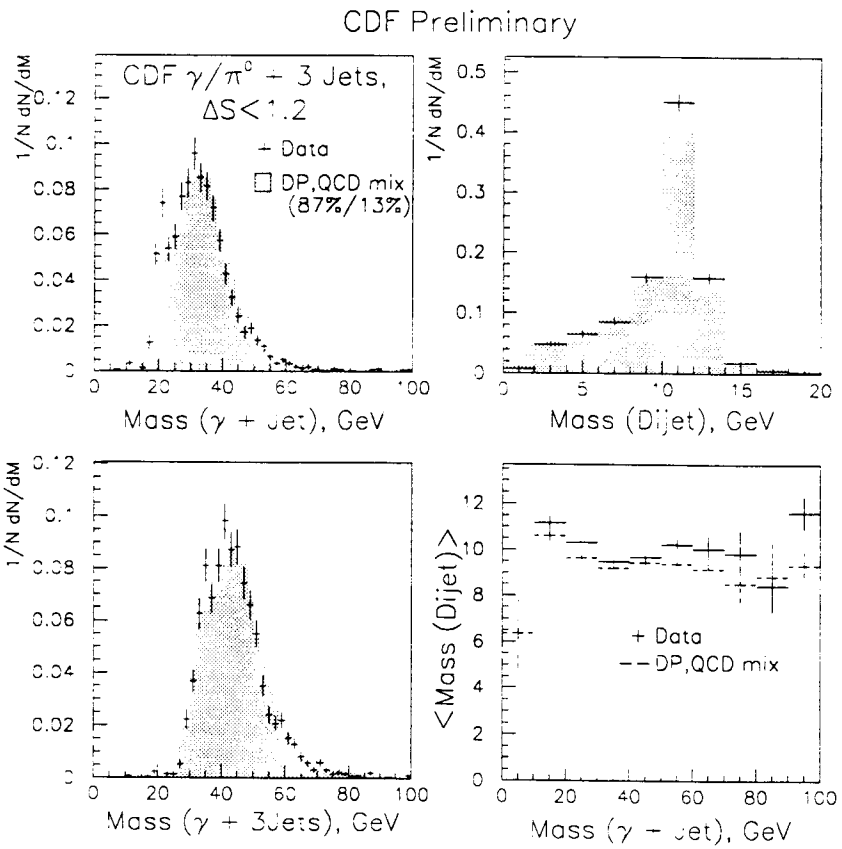
**Preprint from Drees and Han: if A and B are distinguishable, then m=2 $\rightarrow$ under discussion**

**If m=2 $\Rightarrow$ $\sigma_{eff}$ = 10 $\pm 1^{+1}_{-2}$ mb**

# Parton Correlations

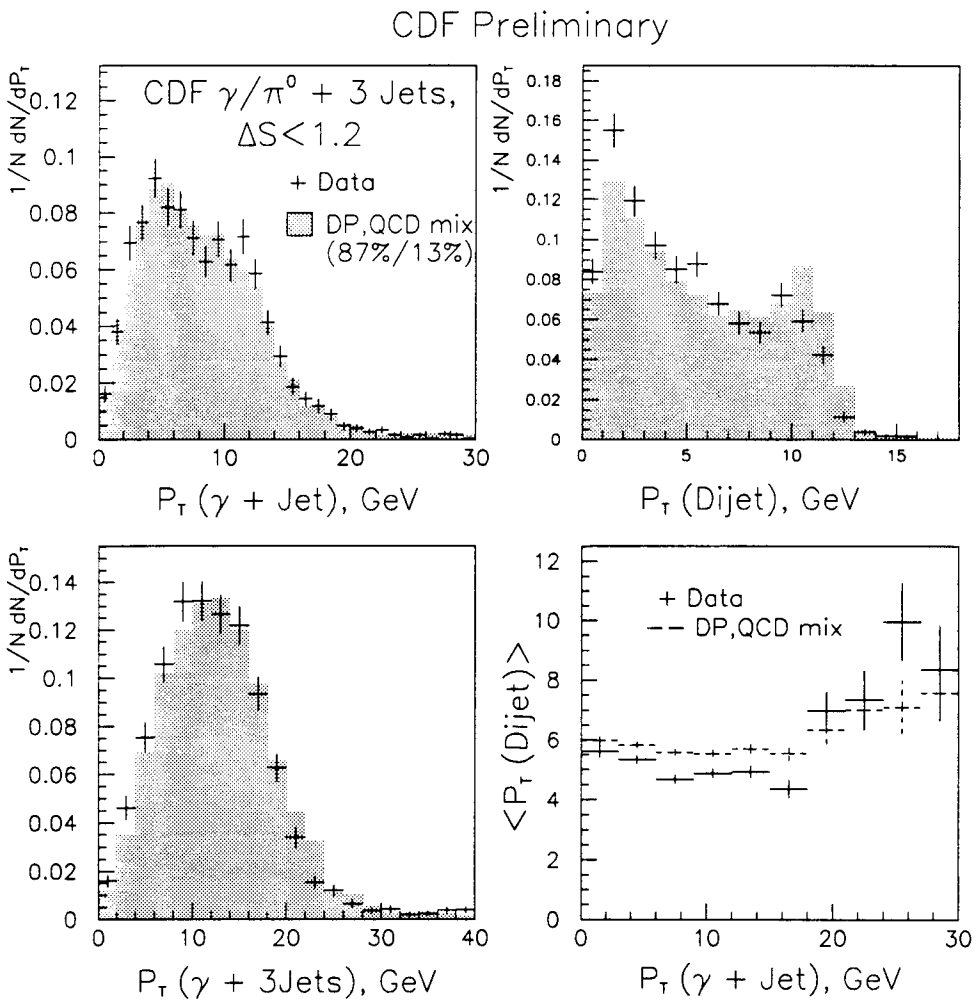
Clumpy parton distribution: If one collision is at high x other one will be too.

**Look for x dependence to $\sigma_{eff}$ in enriched DPS sample: $\Delta$ S $< 1.2 \Rightarrow f_{DP} = 87\%$**
**Compare data (Correlations?) to DP model (NO Correlations)**



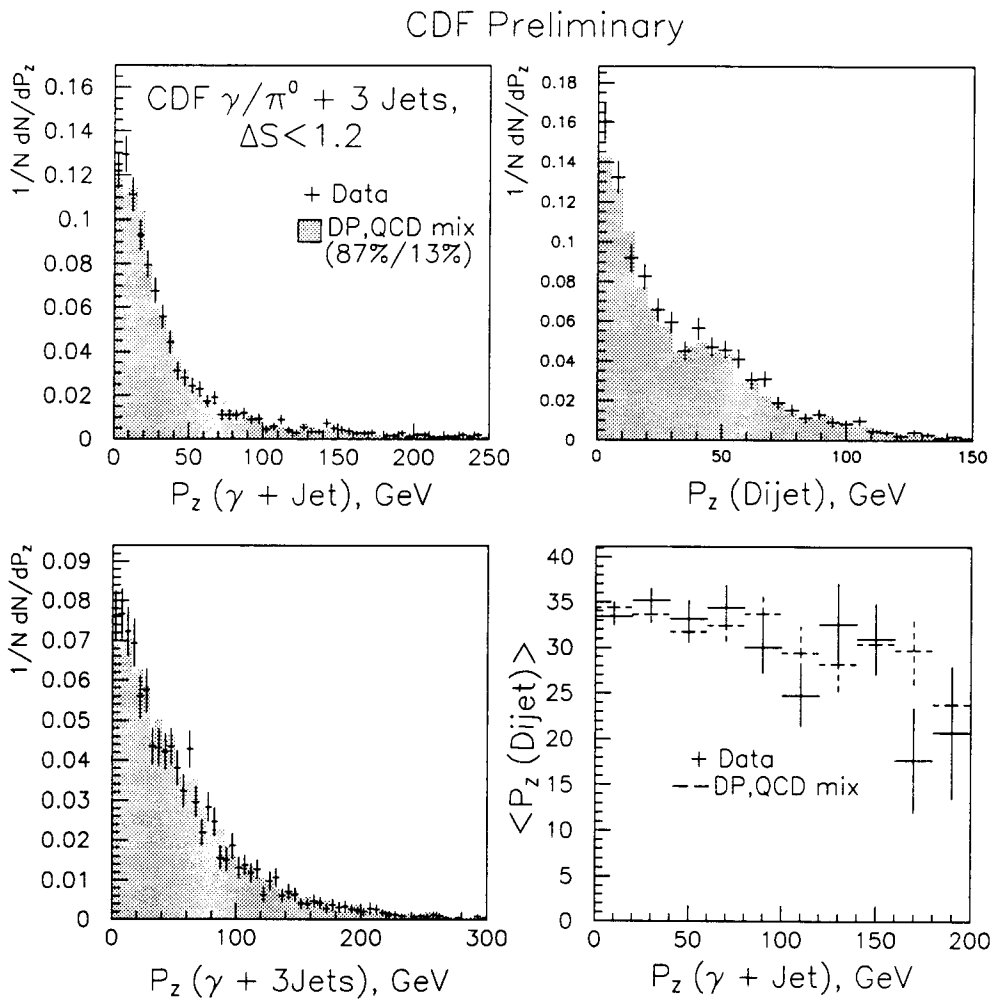
# Parton Correlations

## Also look at $P_t$:



# Parton Correlations

## Also look at $P_z$:




**Data and uncorrelated DPS model show good agreement**

**$\Rightarrow$ No correlations in Mass, $P_t$ or $P_z$**

# Conclusions

CDF has observed a strong signal for Double Parton Scattering:

- factor of ≈10 increase in signal strength
- factor of ≈8 increase in statistics
- developed new technique which is ≈ independent of QCD Modeling

CDF PRELIMINARY:

$f_{DP} = 52 \pm 1\%$ stat.

$\sigma_{eff} = 10 \pm 1^{+4}_{-2}$ mb (if m=2)

No kinematic correlations observed

## Future:

- determine m
- study possible correlations
- Quantify D0 Neural Net observation
- extend to other processes:
  $\gamma, \gamma$ jet, jet
  e, e, jet, jet ....