# Diffractive Structure Function and Exclusive Final States at CDF

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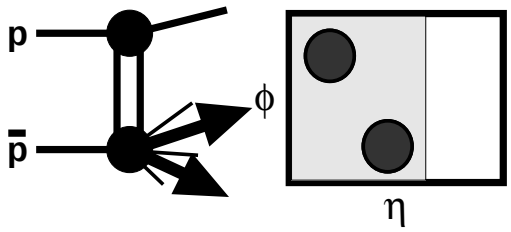
## Diffractive Structure Function

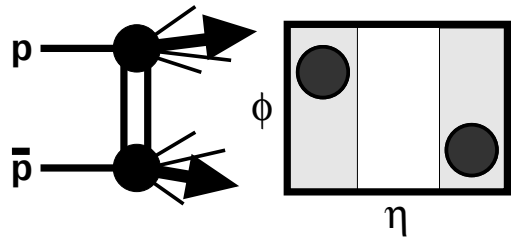
- Results
- Prospects

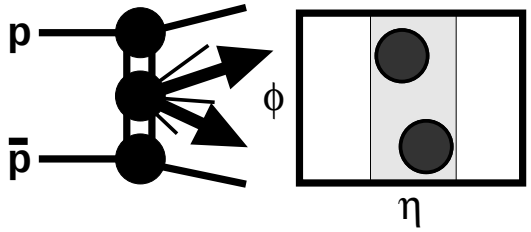
## Exclusive Final States

- Results
- Prospects

# Diffractive Measurements in Run I



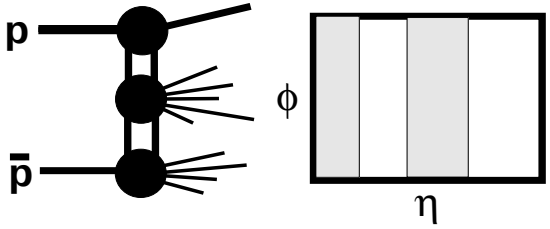

## Soft Diffraction

Single Diffraction
PRD 50, 5535 (1994)

Double Diffraction
87, 141802 (2001)

Double Pomeron Exchange PRL submitted

Multi-Gap Diffraction
91, 011802 (2003)




## Hard Diffraction

### Rapidity Gap Tag

- *W* 78, 2698 (1997)
- Dijets 79, 2636 (1997)
- *b*-quark 84, 232 (2000)
- *J/Ψ* 87, 241802 (2001)

- Jet-Gap-Jet :
  1.8TeV 74, 855 (1995)
  1.8TeV 80, 1156 (1998)
  630GeV 81, 5278 (1998)

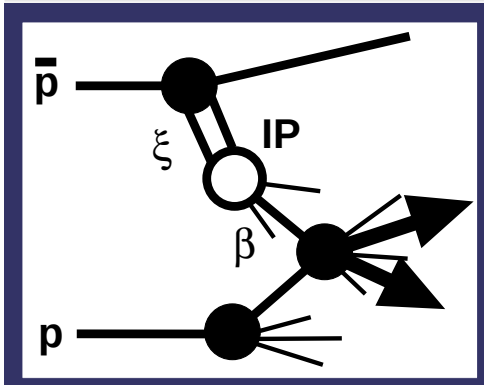
### Roman Pot Tag

- Dijets :
  1.8TeV 84, 5043 (2000)
  630GeV 88, 151802 (2002)

- Dijets 1.8TeV
  85, 4217 (2000)

* PRL references

# Diffractive Structure Function in Dijets




ND : $$\frac{d\sigma^3(ND_{jj})}{dx_p\,dx_{\bar{p}}\,d\hat{t}} = F_{jj}(x_p, Q^2)\,F_{jj}(x_{\bar{p}}, Q^2)\,\frac{d\hat{\sigma}(ab \to jj)}{d\hat{t}}$$

SD : $$\frac{d\sigma^4(SD_{jj})}{dx_p\,dx_{\bar{p}}\,d\xi\,d\hat{t}} = F_{jj}(x_p, Q^2)\,F^D_{jj}(x_{\bar{p}}, \xi, Q^2)\,\frac{d\hat{\sigma}(ab \to jj)}{d\hat{t}}$$

$$F_{jj}^{\,D} = g^D(x, \xi, Q^2) + \frac{4}{9}\,q^D(x, \xi, Q^2)$$

Experimental Measurement of $F_{jj}^{\,D}$

$$\mathrm{R}(x) \text{ of } \frac{\sigma(SD_{jj})}{\sigma(ND_{jj})} = \frac{F^D_{jj}(x)}{F_{jj}(x)} \text{ (LO QCD)}$$

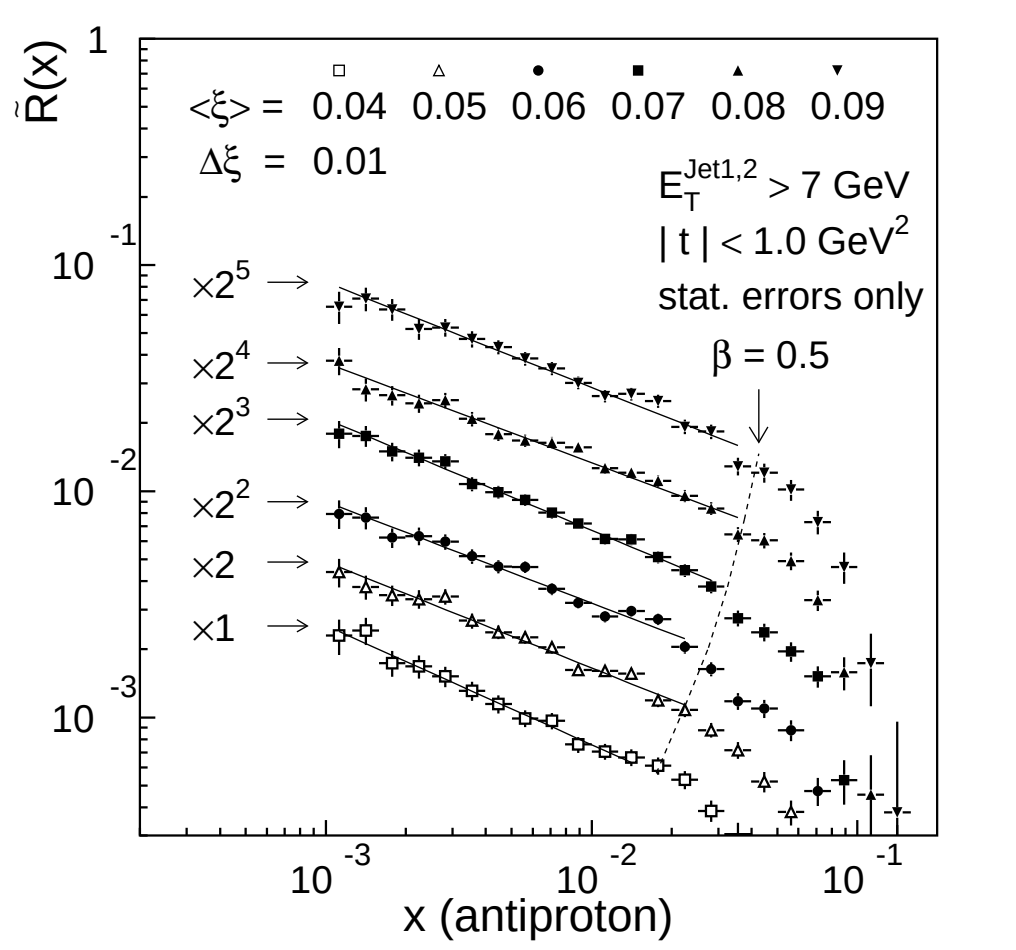
Measure — Known LO PDF

parton $x = \beta\xi$

$\beta$ = mom. fraction of parton in Pomeron

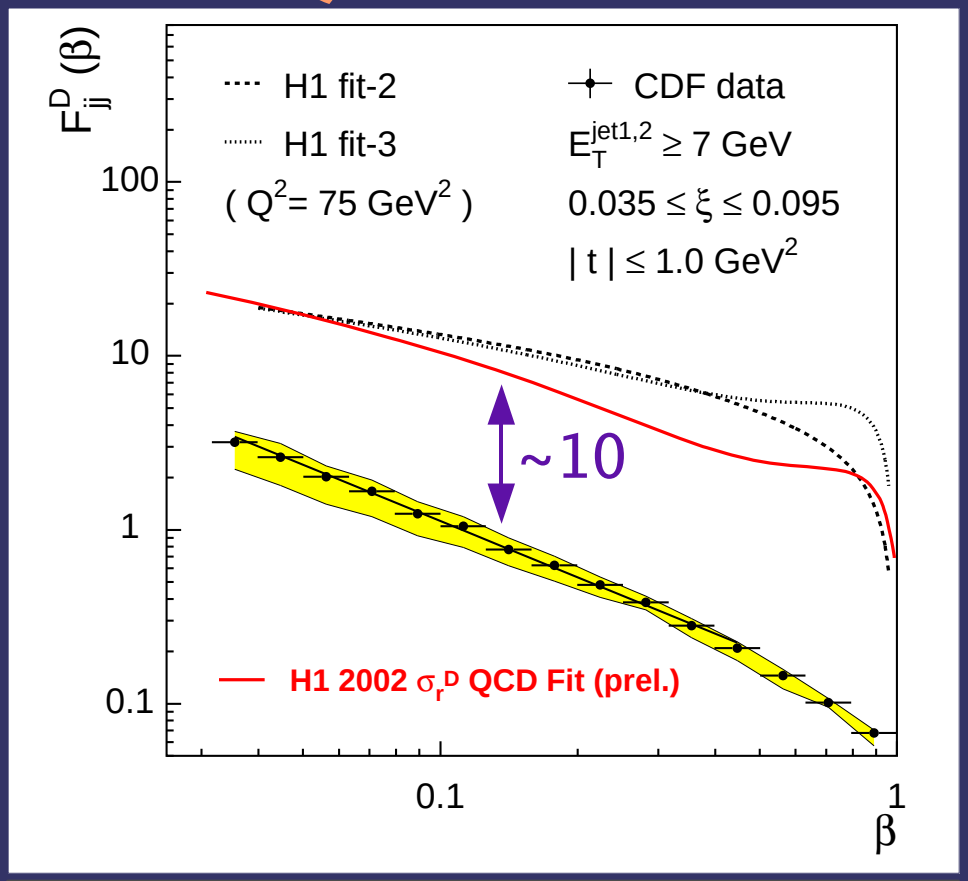
$\xi$ = mom. fraction of Pomeron in proton

$$F_{jj}^{\,D}(x, \xi, Q^2) \;\Rightarrow\Rightarrow\Rightarrow\; F_{jj}^{\,D}(\beta, \xi, Q^2)$$



# Diffractive Structure Function measured using SD Dijets

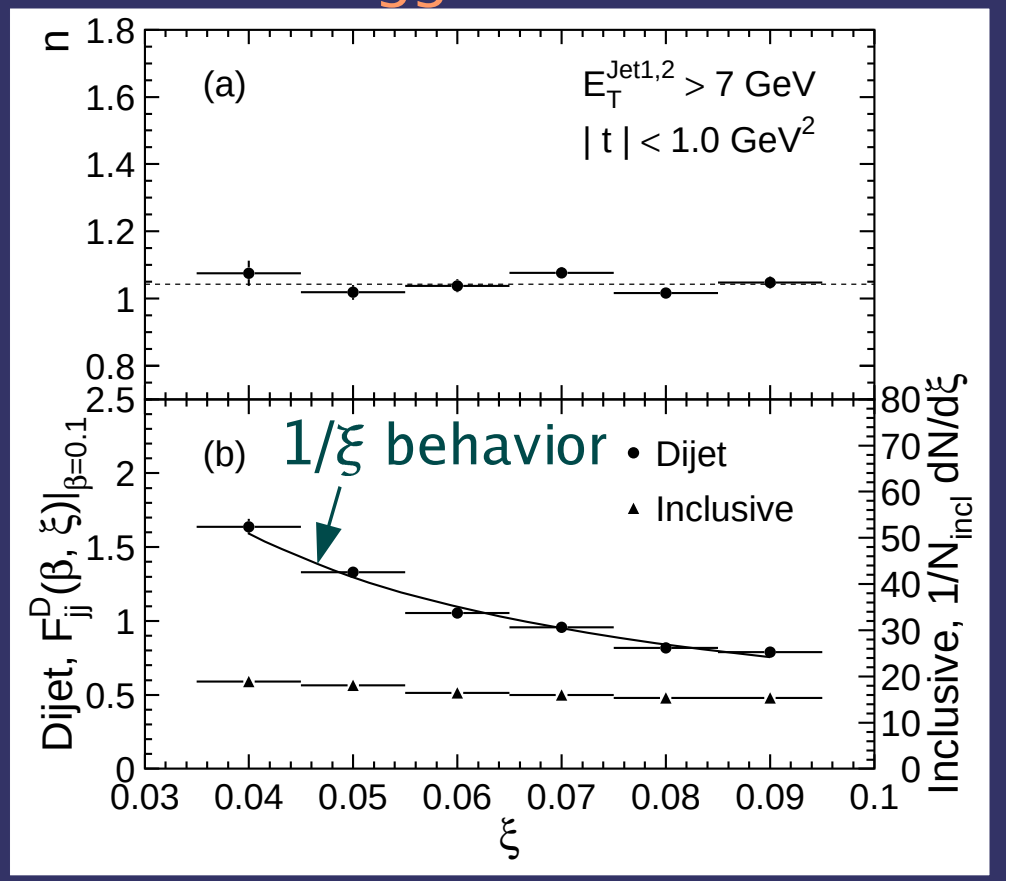
## Test QCD Factorization




$F_{jj}^D(\beta)$ measured using SD dijets suppressed relative to expectations from diffractive DIS at HERA

➔ QCD factorization breakdown

## Test Regge Factorization

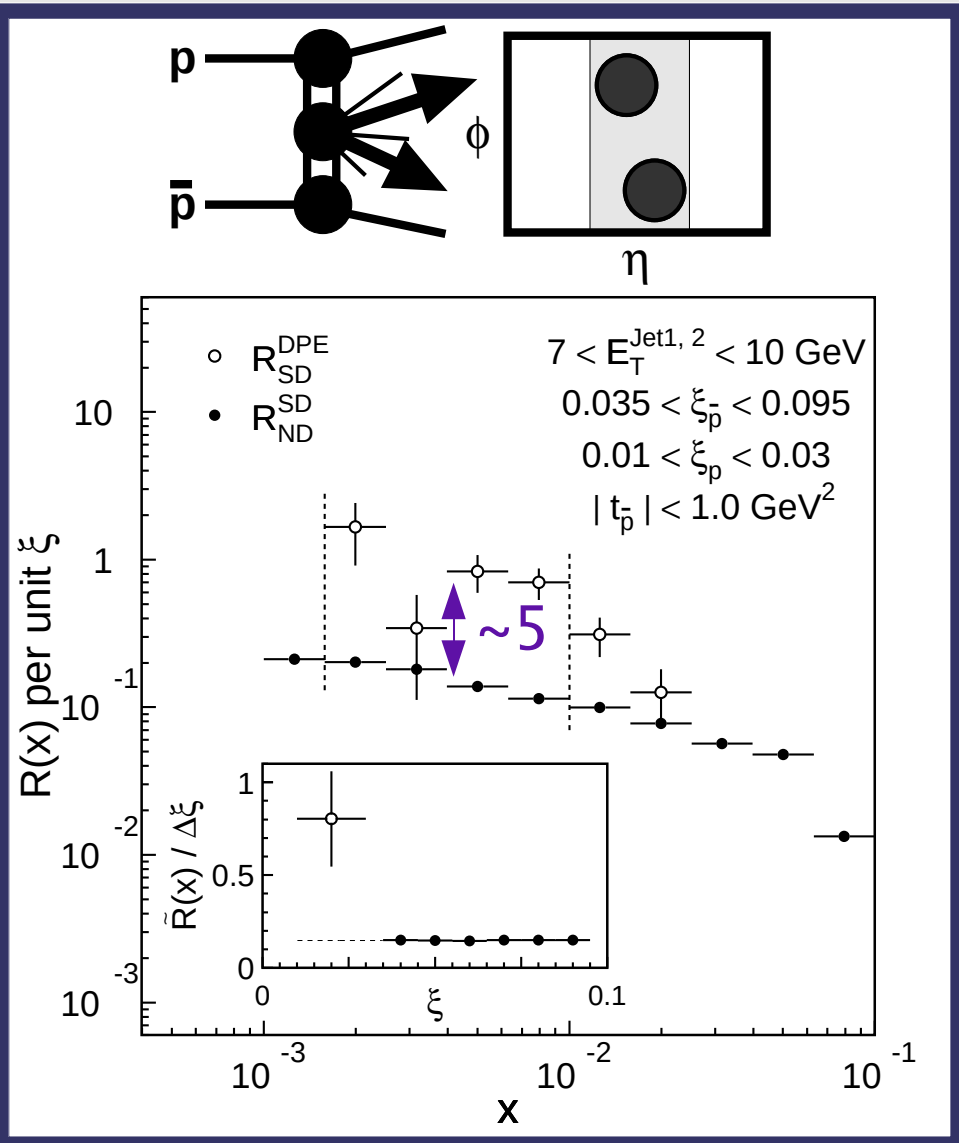


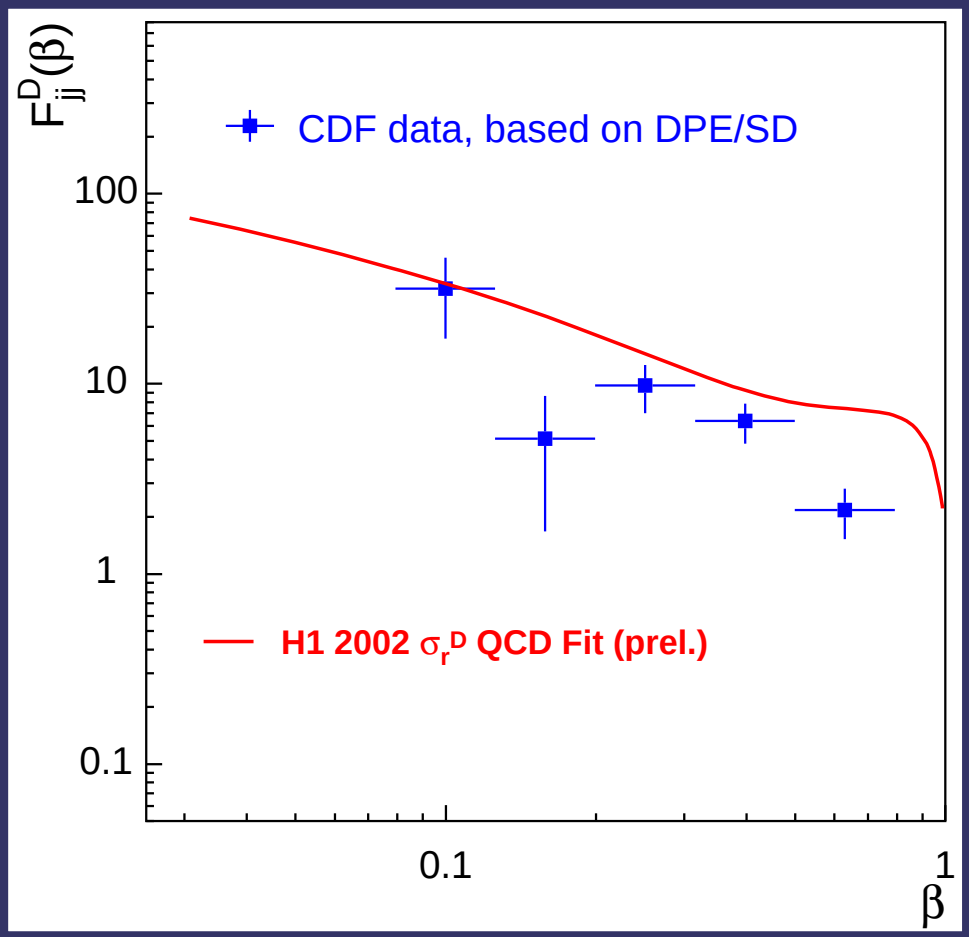

$$F_{jj}^D(\beta, \xi) = C\, \beta^{-n}\, \xi^{-m}$$

Regge factorization holds

$m$=0.9±0.1 → Pomeron exchange

# Diffractive Structure Function measured using DPE Dijets




$R_{ND}^{SD} / R_{SD}^{DPE} = 0.19 \pm 0.07$

Factorization breakdown, but!

$F_{jj}^{D}(\beta)$ measured using DPE dijets is approximately equal to expectations from HERA!

➔ **Factorization holds?**

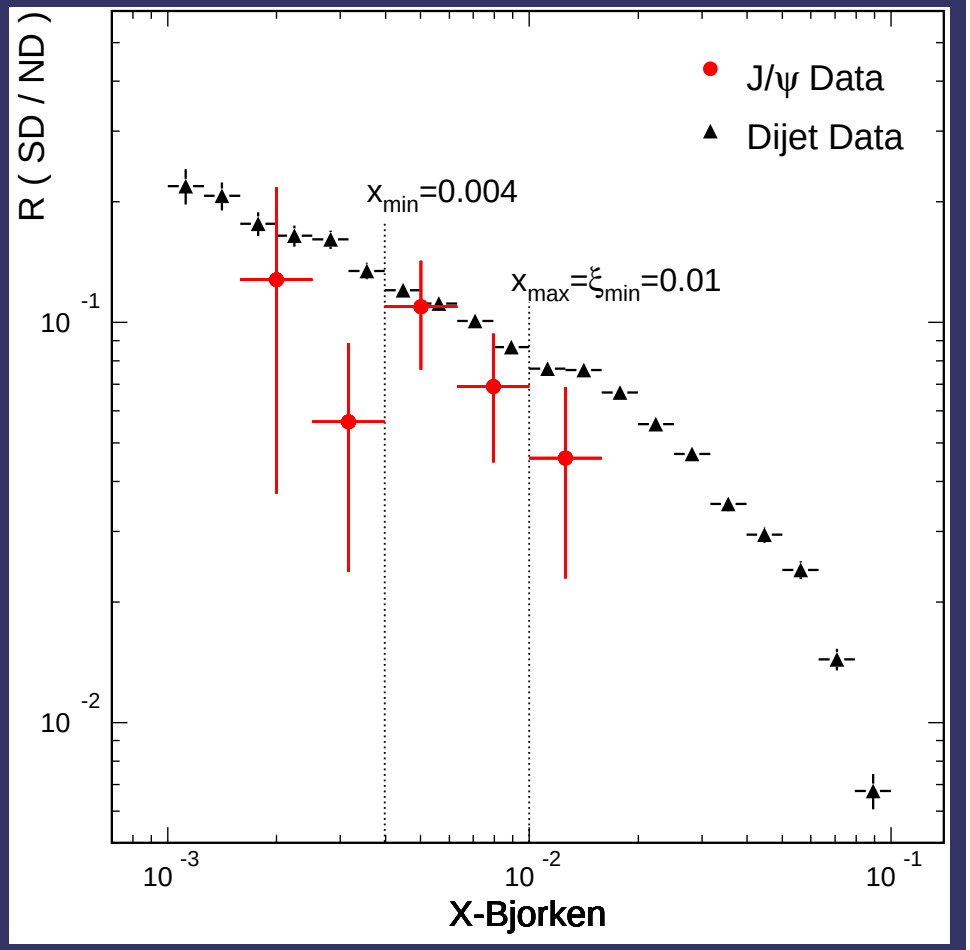
# Diffractive Structure Function measured using SD $J/\Psi$ Events

Ratio of SD to ND $J/\Psi$ event rates as a function of $x_{Bj}$ at $\sqrt{s}$ = 1.8 TeV

$$x_{Bj}^{\pm} = \frac{p_T^{J/\psi}\left(e^{\pm\eta^{J/\psi}} + e^{\pm\eta^{jet}}\right)}{\sqrt{s}}$$

$$\left[\frac{R_{jj}}{R_{J/\psi}}\right]_{\exp} = \frac{\left(g^D + \frac{4}{9}q^D\right) / \left(g^{ND} + \frac{4}{9}q^{ND}\right)}{\left(g^D / g^{ND}\right)}$$

= 1.17 ± 0.27 (stat.)




→ Gluon fraction : $f_g^D$ = 0.59 ± 0.15

Cf. *W*, dijets, *b*-quark : $f_g^D$ = 0.54 ± 0.15

➔ Factorization seems to hold between different processes at same c.m. energy at Tevatron

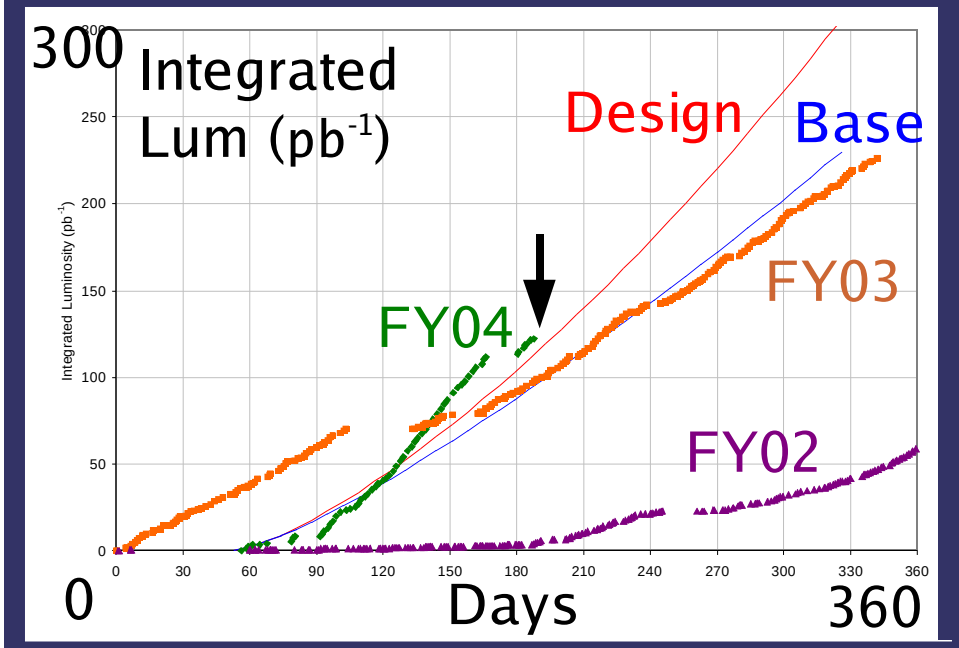
# Run II

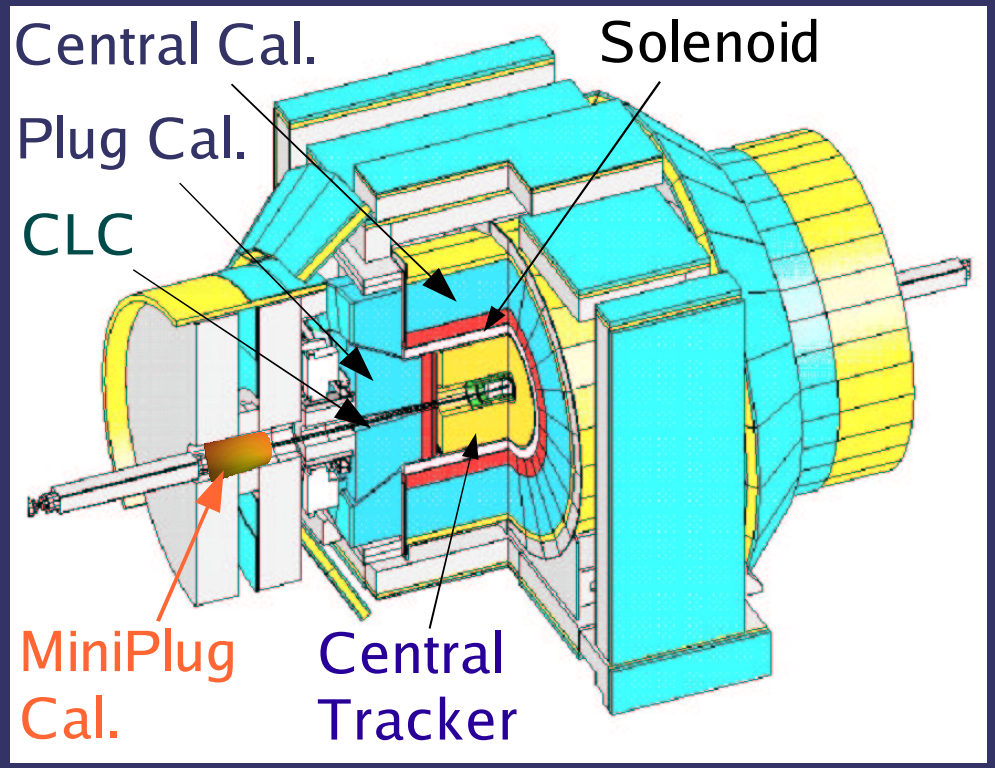
## Tevatron

- ✔ 1.96 TeV center-of-mass energy
- ✔ 396 nsec bunch spacing (36x36)
- ✔ 370 $pb^{-1}$ of luminosity delivered as of end Jan. 2004

current performance :

- ➢ peak luminosity ~ 5-6$\times 10^{31}$ $cm^{-2}s^{-1}$
- ➢ luminosity per week ~ 10-12 $pb^{-1}$

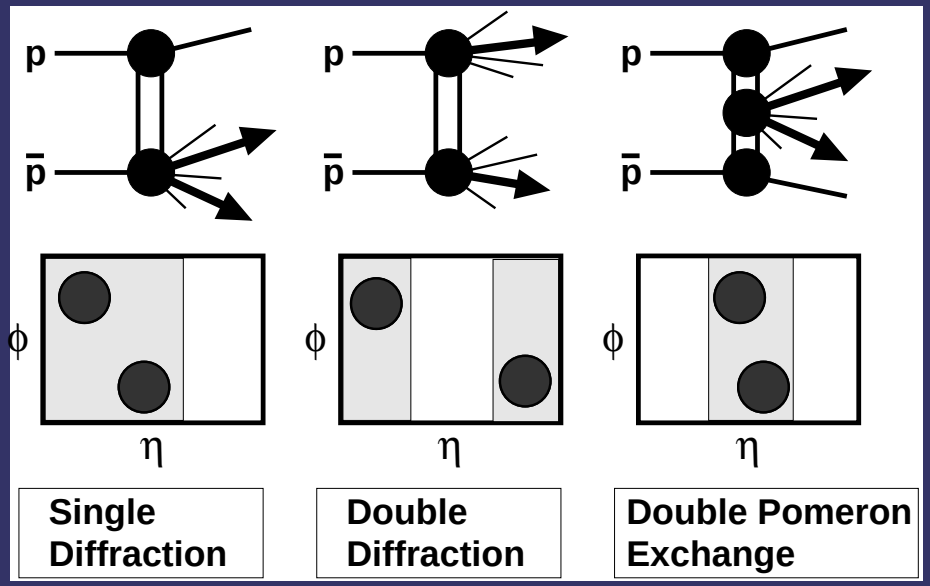



Data Taking Efficiency : ~80-90 %
As of end Jan. 2004, 290 $pb^{-1}$ on tape

Forward Detectors fully integrated in CDF (DAQ, trigger)

# Run II Diffractive Program




## Single Diffraction

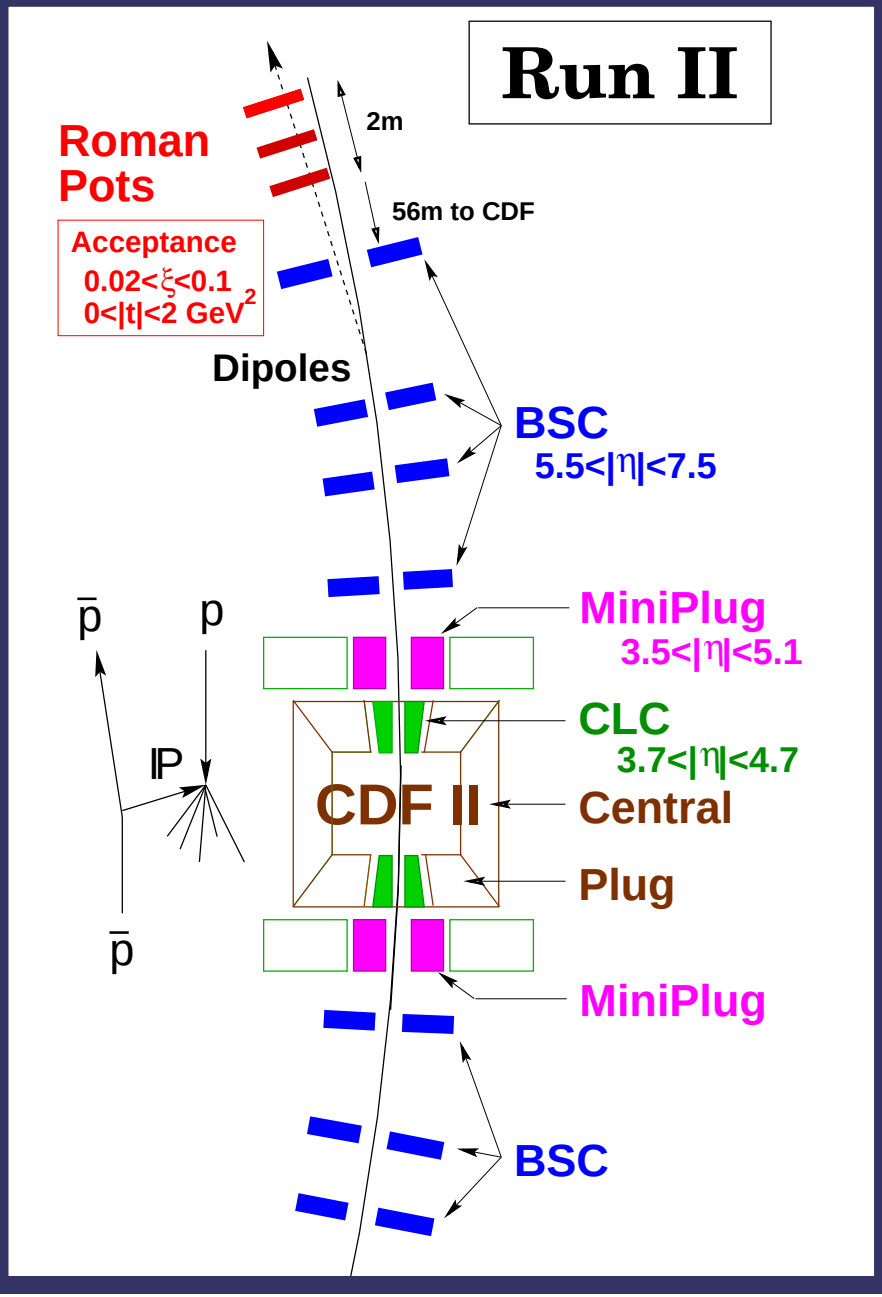
- $Q^2$ and $\xi$ dependence of $F_{jj}^{D}$
- process dependence of $F^{D}$

## Double Diffraction

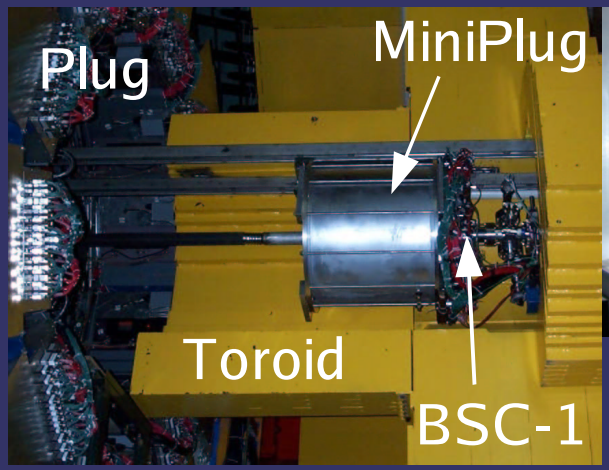
- jet-gap-jet at large $\Delta\eta$ (with MiniPlugs)

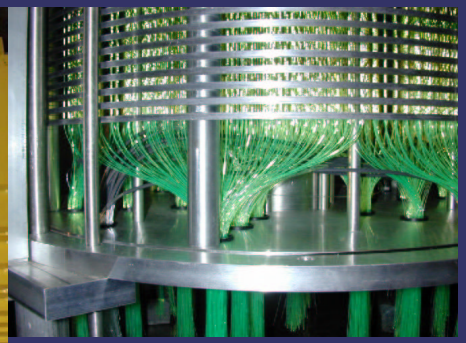
## Double Pomeron Exchange

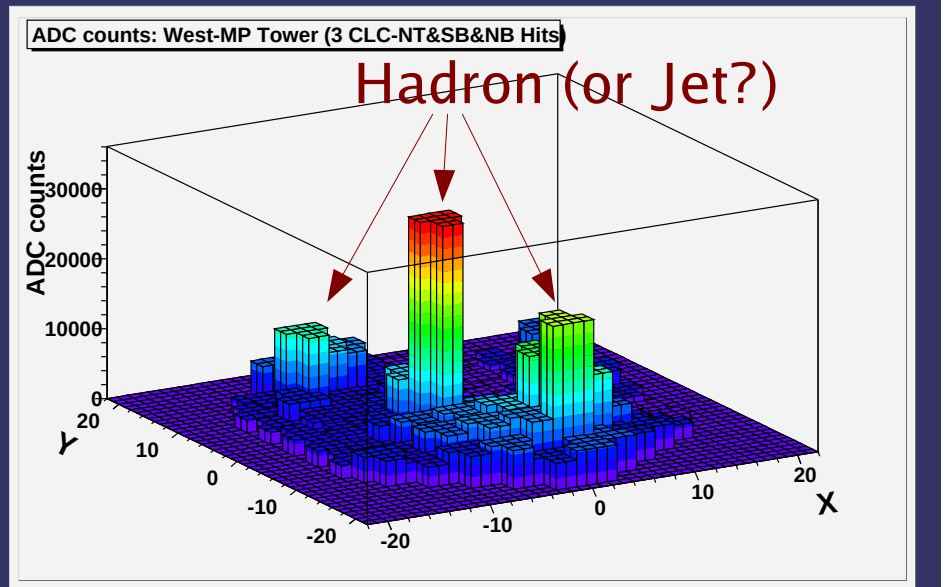
- $F_{jj}^{D}$ vs gap width on the other side
- exclusive dijet/$b\bar{b}$ production
- low mass exclusive states

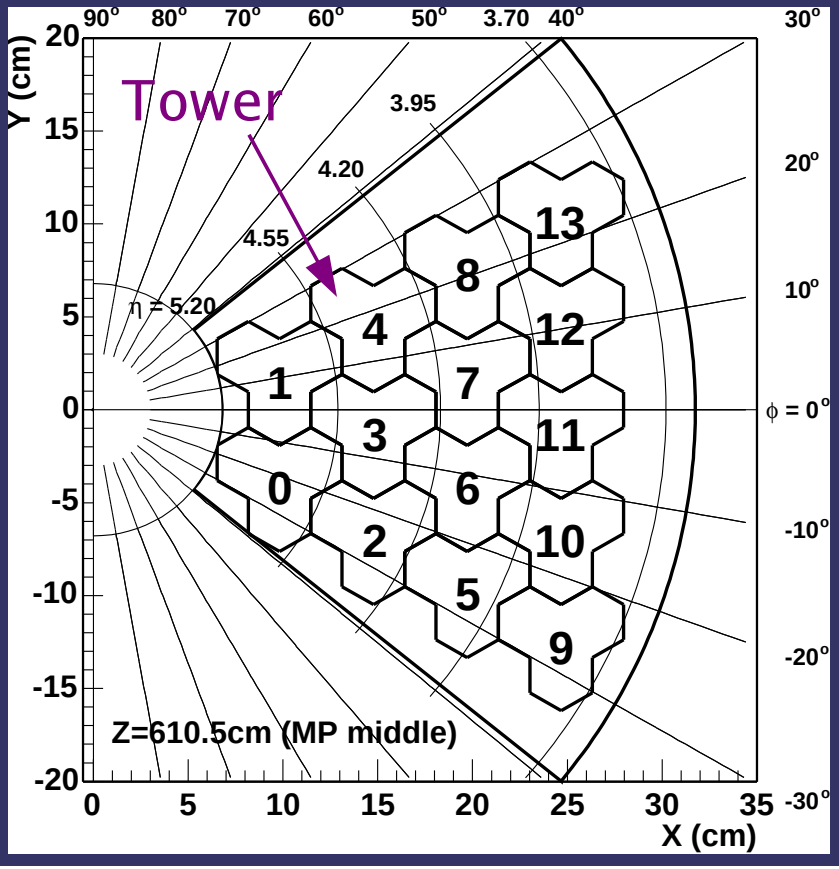


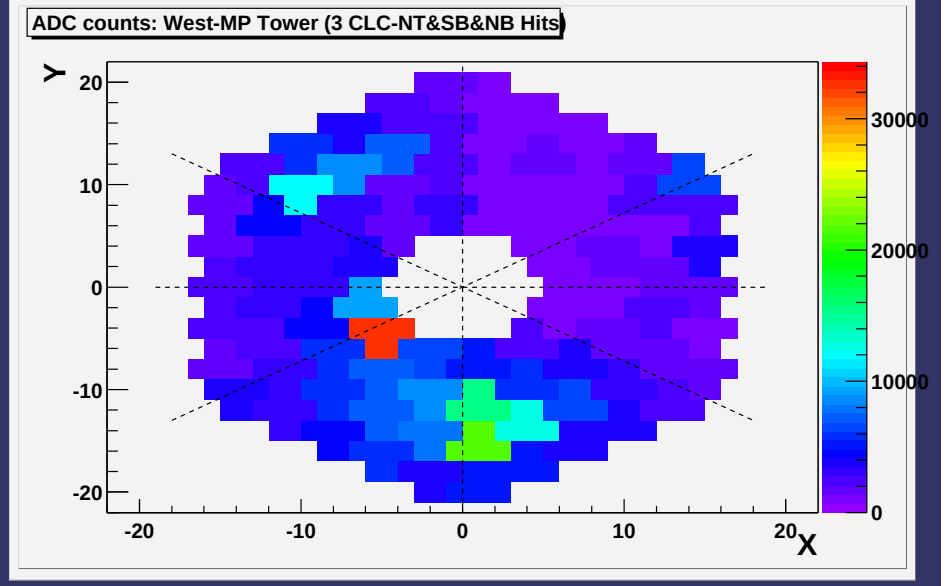
# MiniPlug Calorimeters






ADC counts in MiniPlug towers :
Approximately 1000 counts = 1 GeV

# Run II Diffractive Dijet Sample

J5 : ≥1 Cal. Tower with $E_T$> 5 GeV

RP+J5 : Leading Antiproton in RP + ≥1 Cal. Tower with $E_T$> 5 GeV

- RP acceptance ($0.03 < \xi_{\bar{p}} < 0.1$) ≈ 80% (Run I)

$$\xi_{\bar{p}}^{X} = \frac{M_X^2}{s} \approx \frac{\Sigma_i E_T^i e^{-\eta_i}}{\sqrt{s}}$$

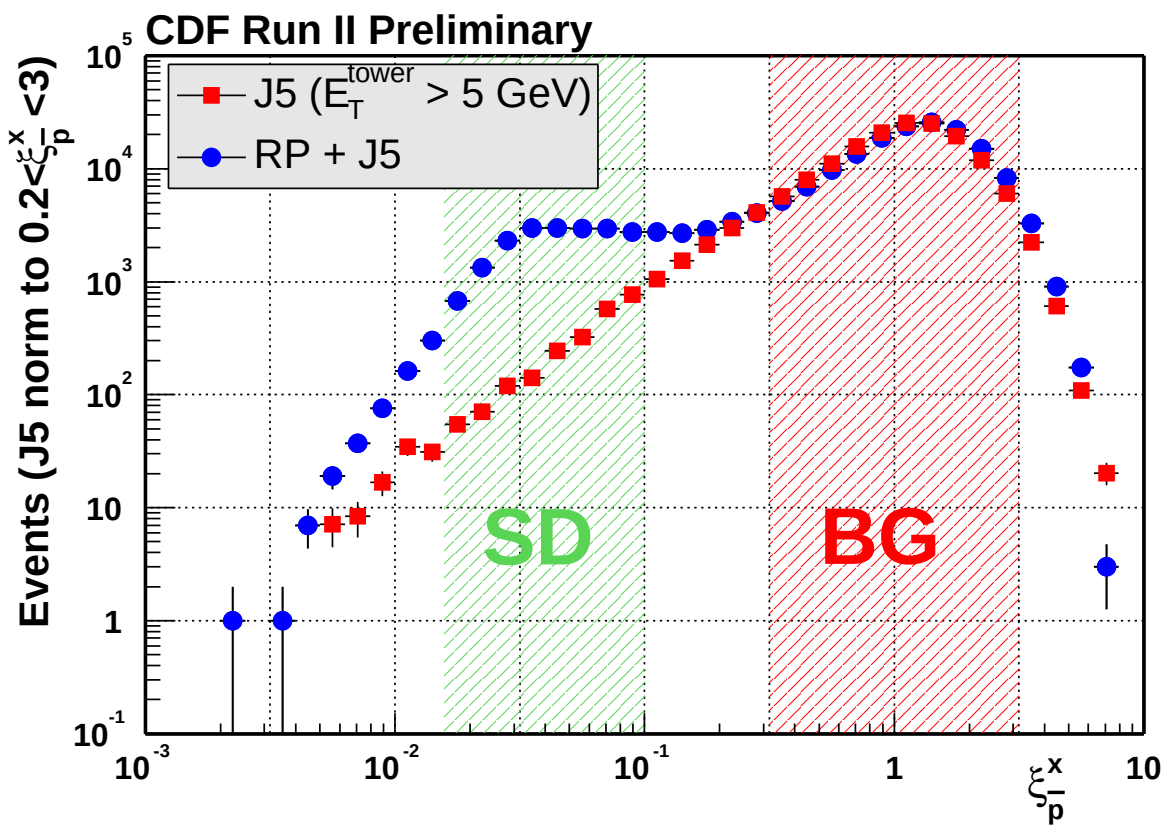
- sum over all particles except antiproton
- use calorimeter towers of $E_T$ >100 MeV
- MiniPlug energy scale: ±25% → $\Delta \log \xi = \pm 0.1$

Flat part at $\xi < 0.1$:

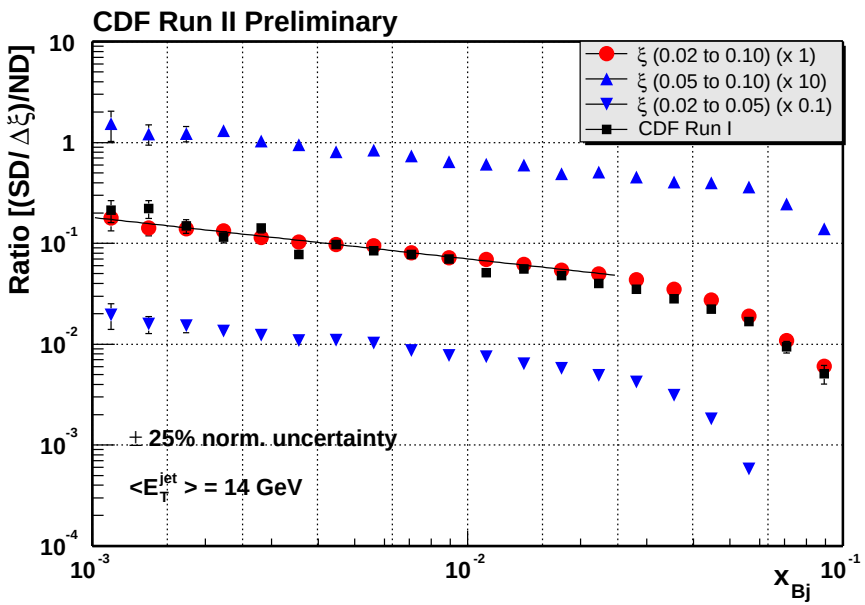
$$\frac{d\sigma}{d\xi} \propto \frac{1}{\xi} \rightarrow \frac{d\sigma}{d(\log \xi)} = Constant$$

Peak at $\xi \sim 1$:

→ overlap of ≥1 ND events



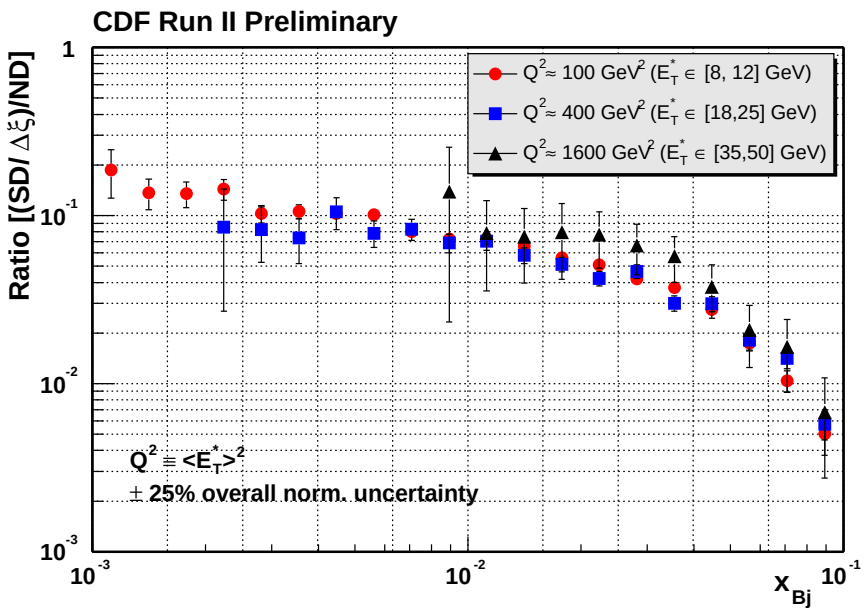
# Diffractive Structure Function in Run II




Ratio of SD to ND dijet event rates as a function of $x_{Bj}$ compared with Run I data

No $\xi$ dependence observed within $0.03 < \xi_{\bar{p}} < 0.1$

**Confirms Run I Result**




Ratio of SD to ND dijet event rates as a function of $x_{Bj}$ for different values of $Q^2 \equiv E_T^2$

No appreciable $Q^2$ dependence observed within $100 < Q^2 < 1600$ GeV$^2$

**Pomeron evolves like proton?**

# Diffractive Structure Function : Run II Prospects

## Goal :

- Measure $Q^2$ and $\xi$ (at low $\xi < 0.03$) dependence of $F_{jj}^D$
- Study process dependence of $F^D$

## $Q^2$ Dependence : analysis in progress!!

- Explored the range $100 < Q^2 < 1600$ GeV$^2$ using RP+J5 data
- Use RP + Higher $E_T$ Jet ($E_T$>20 and 50 GeV) data

  → possible to explore even higher $Q^2$ range with more statistics

## $\xi$ Dependence : analysis in progress!!

- Use BSC-Gap + Jet data to go below $\xi = 0.03$
- Measure $\xi$ using calorimeter Information

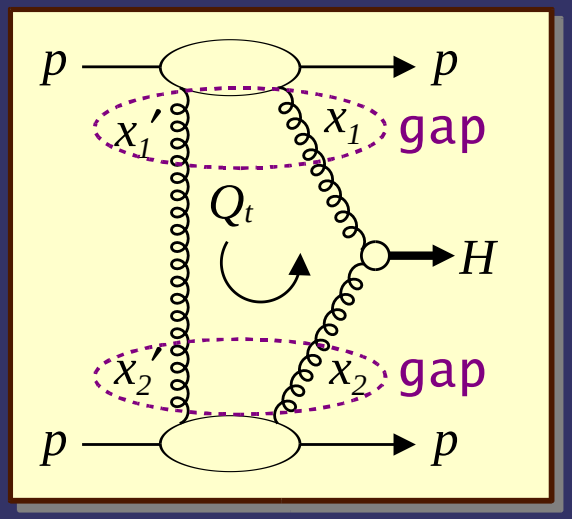
  → possible to extend $\xi$ range down to 0.001 for $Q^2 > 100$ GeV$^2$

## Process Dependence :

- Measure $F^D$ from SD $W$ (probing quark) and $J/\Psi$ (probing gluon) events?
- Measure $F_{jj}^D$ from DPE dijets : $F_{jj}^D$ vs gap width on other side

# Diffractive Higgs Production in DPE(?)

Exclusive

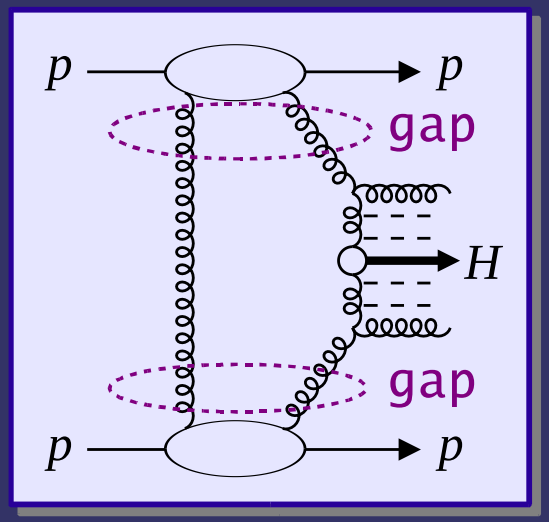



$gg^{PP} \rightarrow H$

Khoze, Martin, Ryskin

Eur. Phys. J.
C23, 311 (2002),
C25, 391 (2002),
C26, 229 (2002)

Inclusive




$gg^{PP} \rightarrow H + X$

## Standard Model light Higgs ($M_H$~120GeV) :

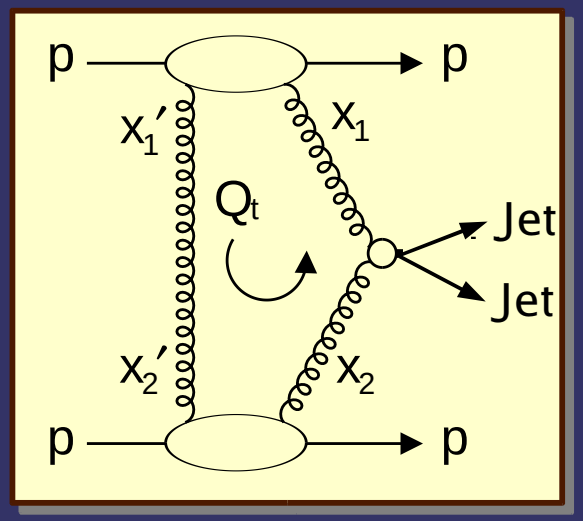
- $gg \rightarrow H$ via $t$-quark loop + soft $g$ exchange → color neutral
- $p + p \rightarrow p + H(\rightarrow b\bar{b}) + p$ : "exclusive" channel → clean signal
- $M_H = M_{miss} = (s \cdot \xi_p \cdot \xi_{\bar{p}})^{1/2}$
- $\sigma_H^{excl}$ ~ 3 fb, signal/background ~ 3 @ LHC (if $\Delta M_{miss}$ = 1 GeV)

→ Attractive Higgs discovery channel at LHC !

# Calibrating Diffractive Higgs Predictions using Exclusive Dijet/$\chi_c^0/\gamma\gamma$ Production

Exclusive Dijets : $gg^{PP} \to gg$

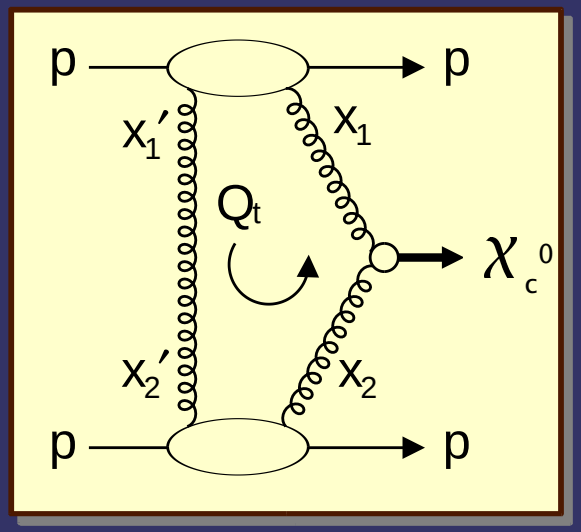
- large cross section
- exclusive $gg^{PP} \to q\bar{q}$ suppressed




Exclusive $\chi_c^0$ : $gg^{PP} \to \chi_c^0$ ($c$-loop)

Exclusive $\gamma\gamma$ : $gg^{PP} \to \gamma\gamma$ ($u$-loop)

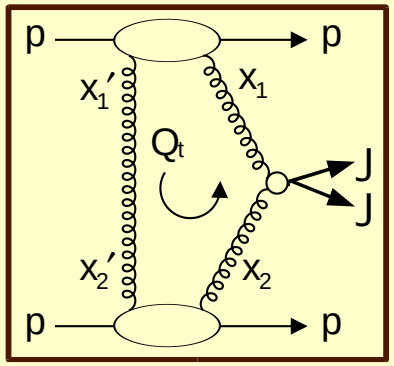
- small cross section but clean signal




Cross sections or limits for exclusive processes can be used to calibrate Higgs sensitivity at Tevatron/LHC

# Predictions for Exclusive Dijets in DPE

Exclusive

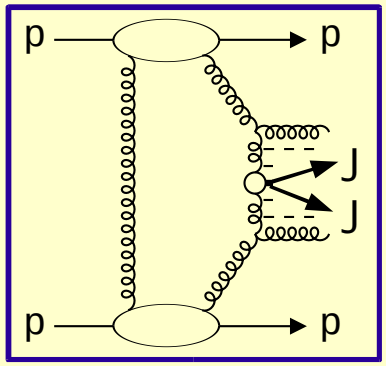



$gg^{PP} \rightarrow gg$

Khoze, Martin, Ryskin

Eur. Phys. J. C23, 311 (2002), C25, 391 (2002), C26, 229 (2002)

Inclusive




$gg^{PP} \rightarrow gg + X$

Run I : PRL 85, 4215 (2000)

Dijet Mass Fraction:

$$R_{jj} = \frac{M_{jj}^{cone}}{M_X}$$

<u>Exclusive Dijet</u> : $gg^{PP} \rightarrow gg$

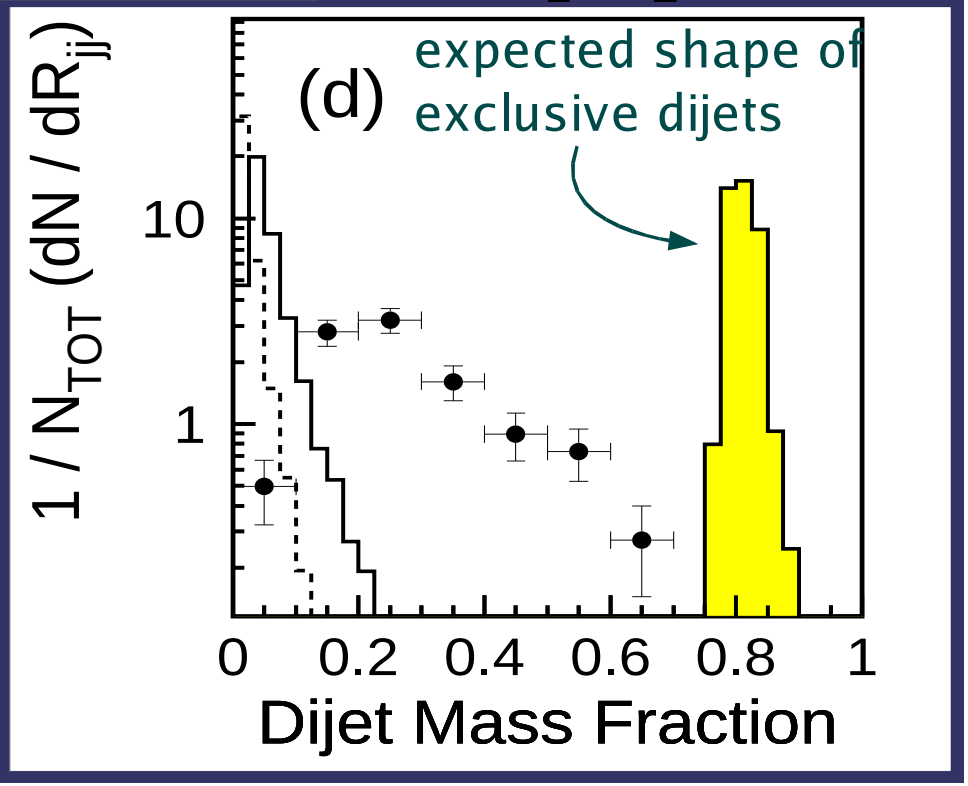
Run I : ~130 inclusive DPE dijets

→ $\sigma_{excl}$ < 3.7 nb (95% C.L.)

KMR Prediction :

~1 nb (factor 2 uncertainty)

@ Run I Kinematic Region

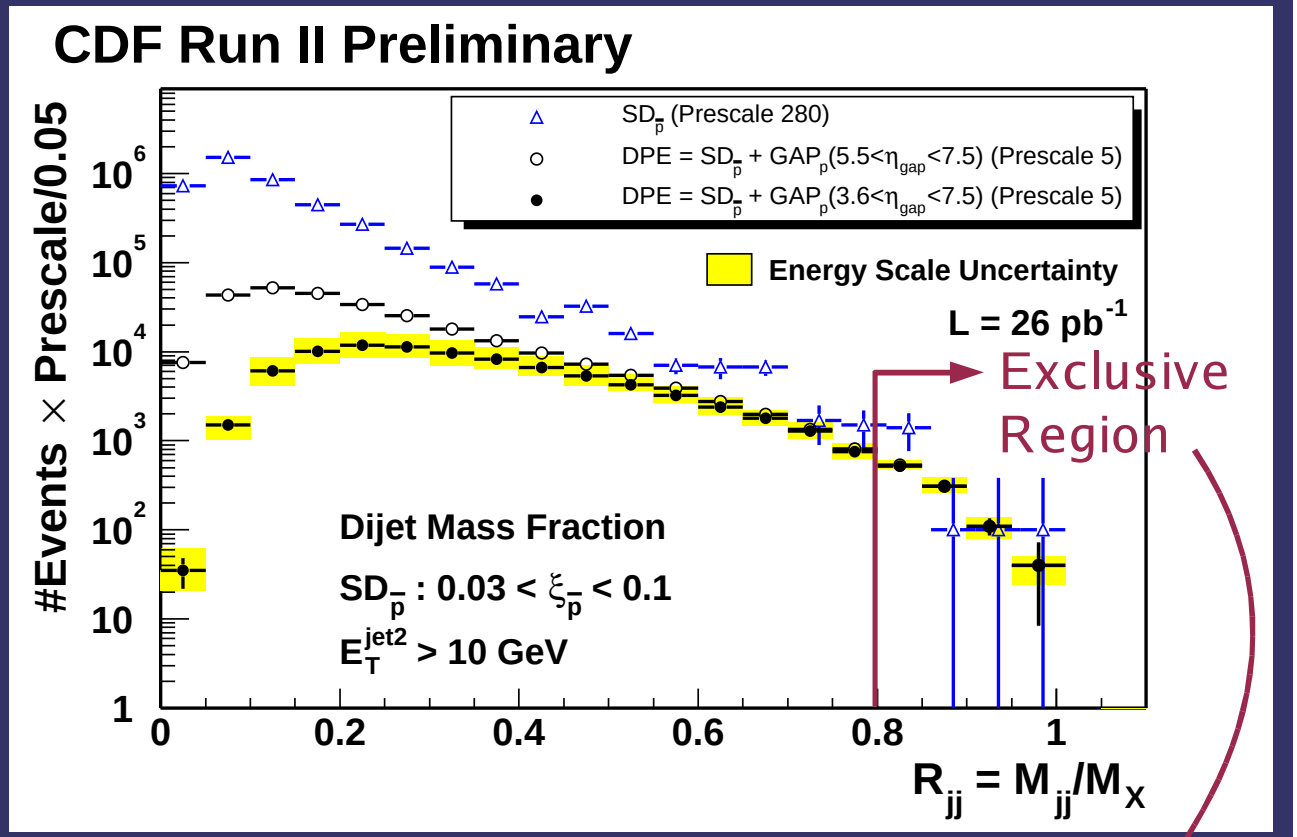


# Exclusive Dijet Cross Section Limit

Dedicated DPE Trigger : RP + J5 + $GAP_p^{BSC}$

26 $pb^{-1}$ data (Sep-Dec 2002)

- $R_{jj}$ falls smoothly as $R_{jj} \rightarrow 1$
- No significant excess at high $R_{jj}$




$|\eta^{jet1,2}|<2.5$, $0.03<\xi_{\bar{p}}<0.1$, $3.6<\eta_{gap}<7.5$, $R_{cone}=0.7$

$\sigma_{DPE}(R_{jj}>0.8)$ = 970 ± 65(stat) ± 272(syst) pb ($E_T^{jet1}$ > 10 GeV)

34 ± 5(stat) ± 10(syst) pb ($E_T^{jet1}$ > 25 GeV)

KMR prediction → 60 pb (factor 2 uncertainty)

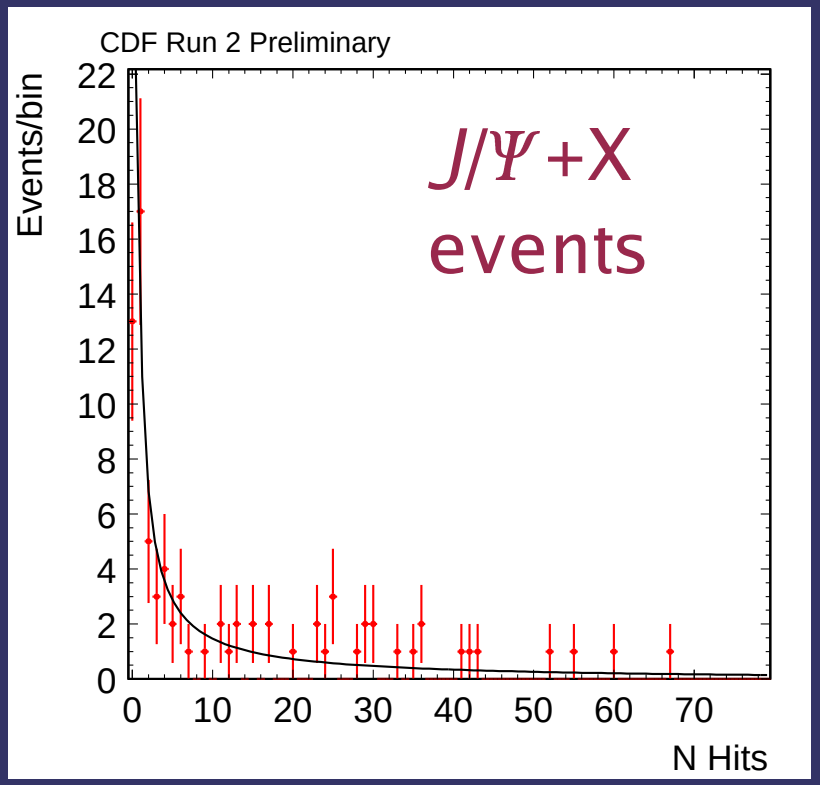
Eur. Phys. J. C23, 311 (2002)

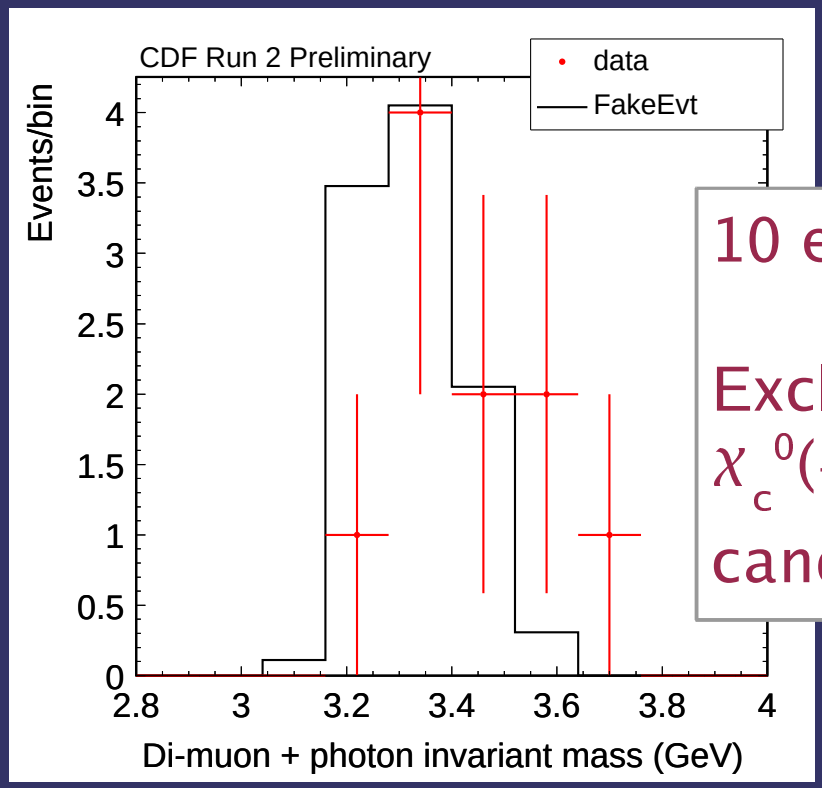
@ $25<E_T^{jet}<35$ GeV, $|\eta^{jet1}-\eta^{jet2}|<2$

# Exclusive $\chi_c^0$ Production in DPE

$$\bar{p} + p \rightarrow \bar{p} + \chi_c^0 (\rightarrow J/\Psi + \gamma) + p$$

- Di-muon trigger data (muons with $p_T$>1.5 GeV, $|\eta|$<0.6)
- Reject cosmic rays with time of flight information
- Select events in $J/\Psi$ mass window
- Require large gaps on both $p$ and $\bar{p}$ sides



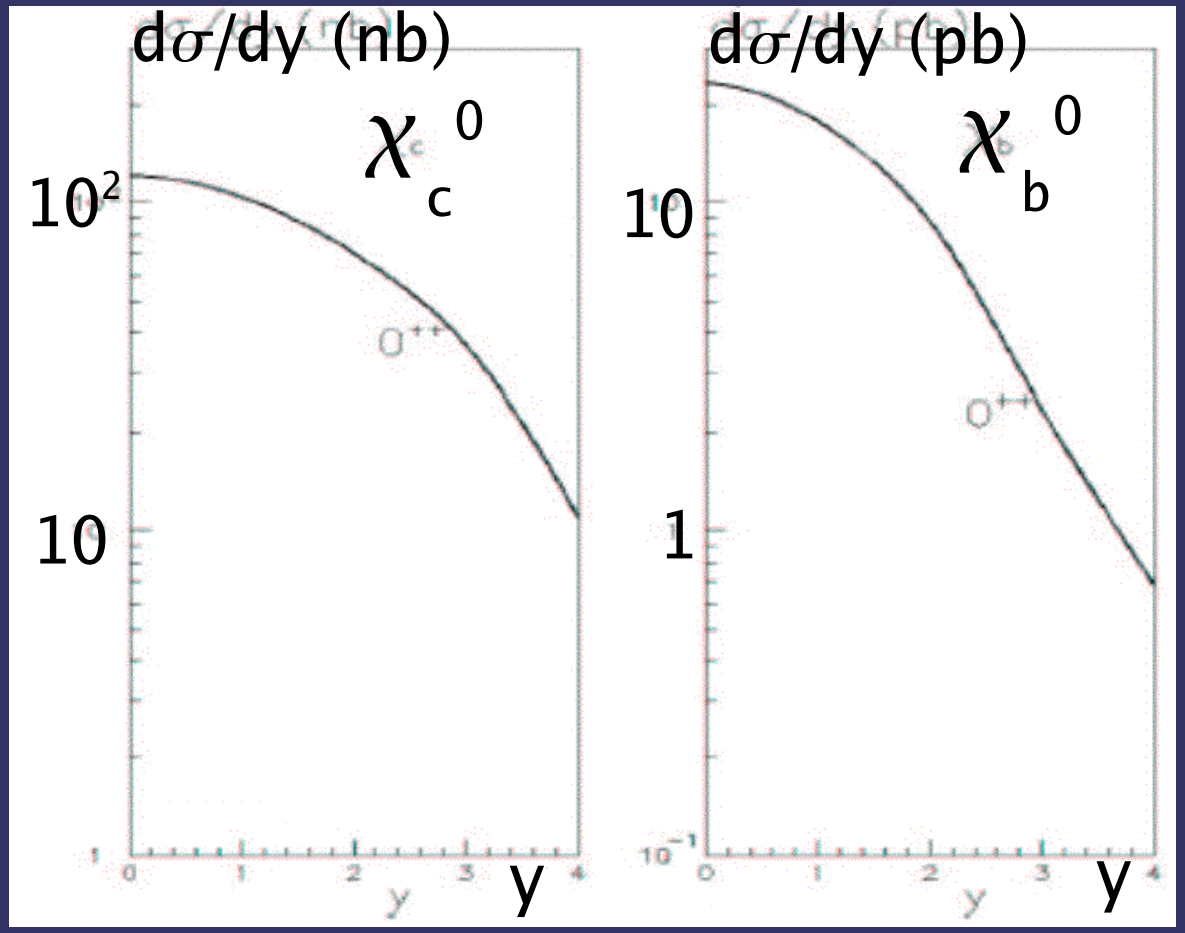

10 events:

Exclusive $\chi_c^0(\rightarrow J/\Psi+\gamma)$ candidates

# Exclusive $\chi_c^0$ Cross Section Limit

KMR Prediction
Eur. Phys. J. C19, 477 (2001)

- $\sigma(\bar{p}p \to \bar{p}+\chi_c^0+p) \approx 600$ nb (factor 2-5 uncertainty)
- $\sigma(\bar{p}p \to \bar{p}+\chi_c^0(\to J/\Psi+\gamma)+p) \approx 70$ pb at $|y^{J/\Psi}|<0.6$




Assume 10 events are all $J/\Psi+\gamma$

$|y^{J/\Psi}|<0.6$, $p_T^{J/\Psi}>2$ GeV

$\sigma(\bar{p}p \to \bar{p}+J/\Psi+\gamma+p) = 49 \pm 18(\text{stat}) \pm 39(\text{syst})$ pb

→ "Upper Limit" on exclusive $\chi_c^0$ production cross section

# Extracting Exclusive Dijets in DPE

## Theory

Khoze, Martin, Ryskin
Eur. Phys. J. C23, 311 (2002)

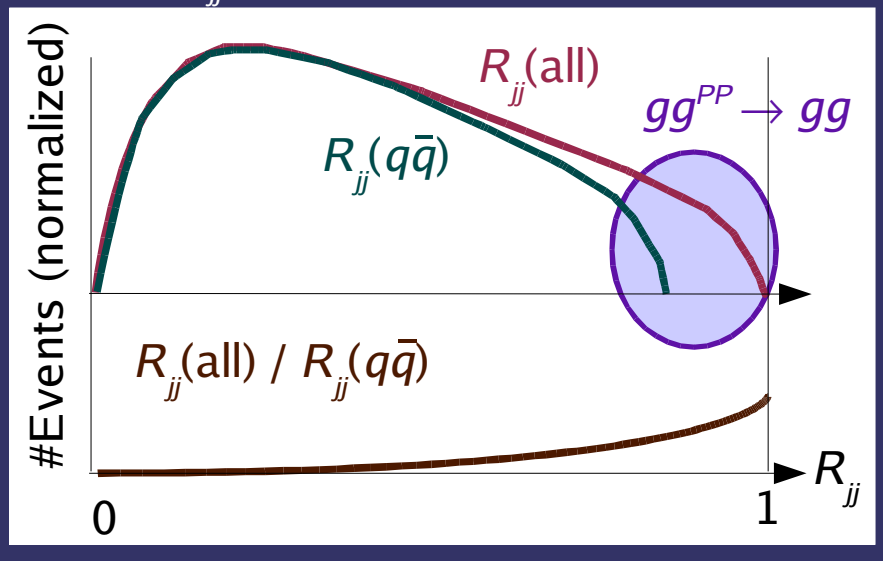
$\sigma^{excl}(gg^{PP} \to q\bar{q}) \to 0$ at $M_{JJ} \gg m_q$

→ exclusive dijet : $gg^{PP} \to gg$ only

⇩

**Use exclusive $q\bar{q}$ suppression:**

Exclusive $gg^{PP} \to gg$ might manifest itself as an excess over inclusive $qq$ at high $R_{jj}$




## Experiment

### Heavy Flavor Quark Jets

- normalize $R_{jj}$ for all jets to $R_{jj}$ for $Q\bar{Q}$ jets
- look for excess as $R_{jj} \to 1$

☺ many exp. systematics canceled out
☺ HF quarks identified well : $g$ mistag @ $O(1\%)$
☹ heavy quark mass
→ exclusive $b/c$ not suppressed as $uds$

### Difference of Quark and Gluon Jets

charged particle multiplicity in jet : $N_{jet}$

$N_{g\text{-jet}} \cong 1.6\ N_{q\text{-jet}}$ (CDF Run I)

- look into how $N_{jet}$ behaves as $R_{jj} \to 1$
- if $q\bar{q}$ suppressed as $R_{jj}$=0.5 → 1, then

$N_{jet}^{Rjj=0.5} < N_{jet}^{Rjj=1} \cong N_{g\text{-jet}}$?

☺ light quark mass → exclusive $uds$ suppressed
☹ light $q/g$ jets not well separated

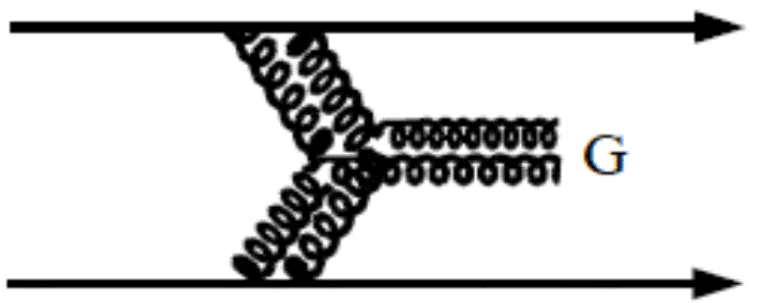
→ analysis in progress!!

# Exclusive Low Mass States in DPE

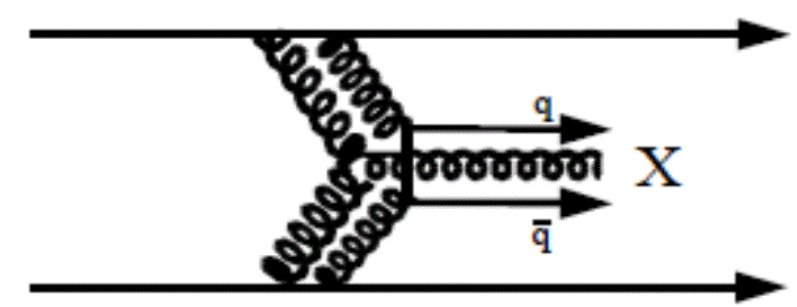
Rapidity Gaps

$$\bar{p} + p \rightarrow \bar{p} + X + p$$

Central system with
- low mass (< 4 GeV)
- low multiplicity (2-6 charged particles)




GlueBall States




Hybrid States

Look for Hyperons, Glueballs, Hybrids and other interesting states

Status: trigger under development

# Exclusive Final States : Run II Prospects

## Goal :

- Investigate existence/properties of exclusive final states (dijets, $\chi_{c(b)}^{0}$, $\gamma\gamma$ and other exotic states)
- Derive the cross sections or limits of exclusive processes

## Exclusive Dijets : analysis in progress!!

- $R_{jj}$(all) / $R_{jj}$(*b*-quark) for $R_{jj} > 0.75$ → extract exclusive dijets
- quark/gluon composition as a function of $R_{jj}$ → complementary analysis
- DPE *b*-jet trigger under development

## Exclusive Low Mass States :

- $\chi_c^0$ : DPE-$J/\Psi$ trigger in DAQ soon, $\chi_c^0 \rightarrow h^+h^-$ trigger being investigated
- $\gamma\gamma$ : DPE-$\gamma\gamma$ trigger in DAQ soon
- Hadronic states : trigger under study

# Summary

Studies of Run II diffractive physics in good progress

Diffractive Structure Function $F^D$ :

- Re-established Run I results using single diffractive dijets
- $Q^2$ dependence of $F_{jj}^D$ → Pomeron evolves like proton?
- Study of $\xi$ and process dependence of $F^D$ in progress

Exclusive Final States :

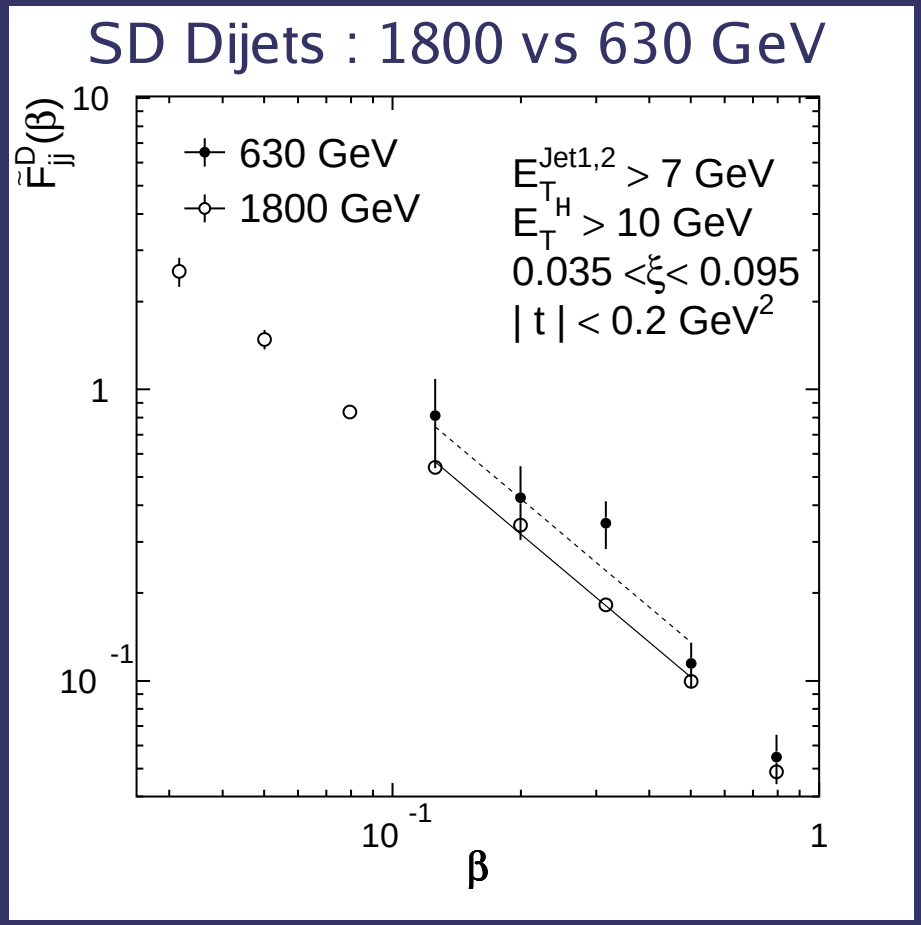
- Improved upper limit on exclusive dijet production
- Obtained upper limit on exclusive $\chi_c^0$ production
- DPE $b$-jet analysis in progress
- New DPE triggers ($b\bar{b}$, $\chi_c^0$, $\gamma\gamma$, hadronic states)

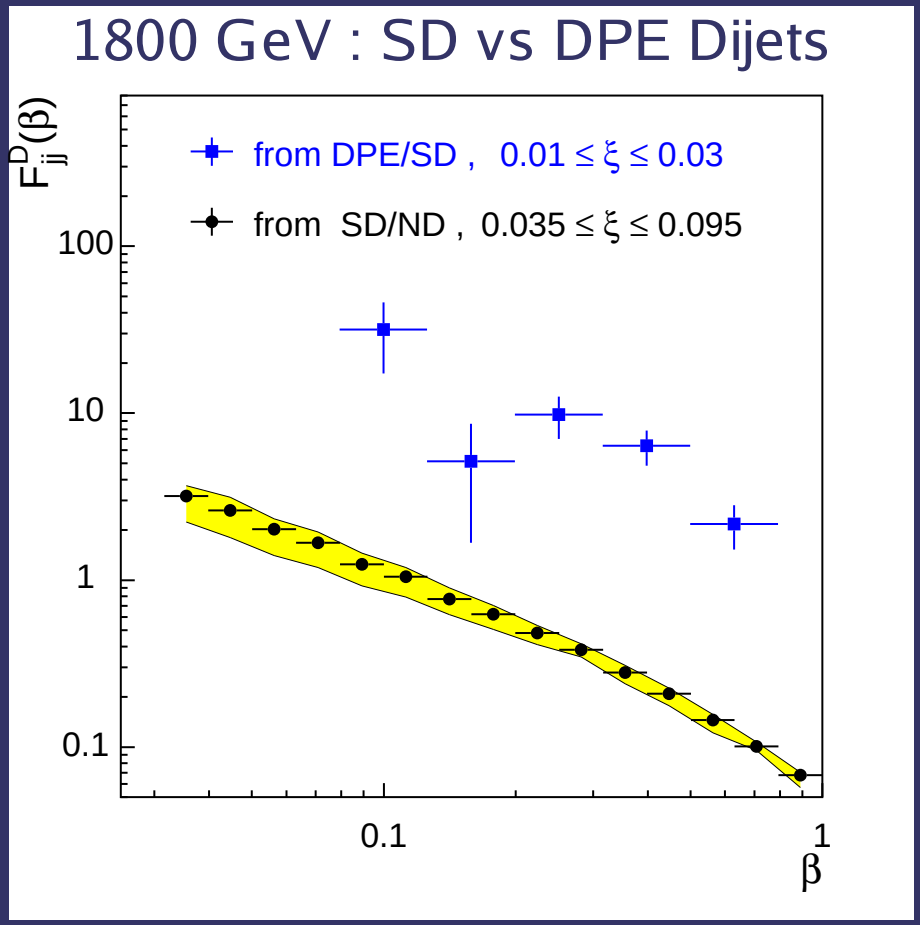
New (exciting) results will be coming soon!!

# Backup

# Diffractive Structure Function measured using Single Diffractive Dijets at 630 GeV

## Test QCD Factorization at Tevatron



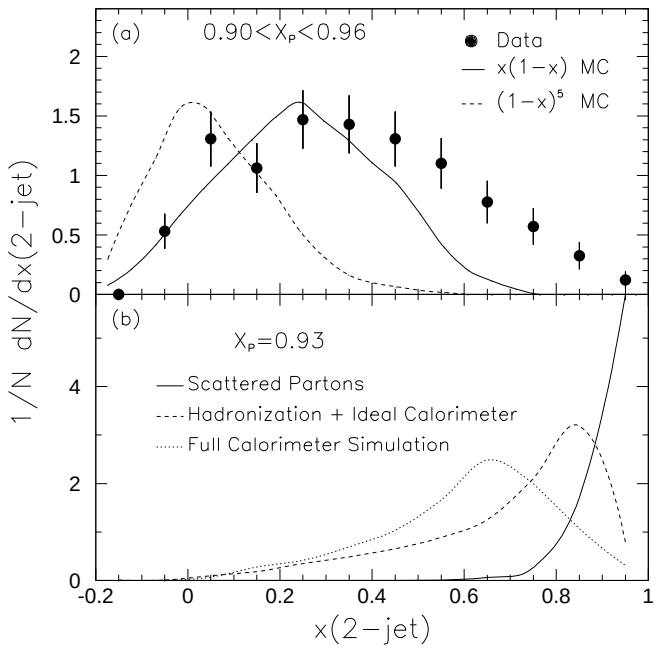




$R_{ND}^{SD}(630) / R_{ND}^{SD}(1800) = 1.3 \,^{+0.5}_{-0.4}$

$R_{SD}^{DPE}(1800) / R_{ND}^{SD}(1800) = 5.3 \pm 1.9$

# Pomeron Structure : Comparison with UA8

Phys. Lett. B 297, 417 (1992)



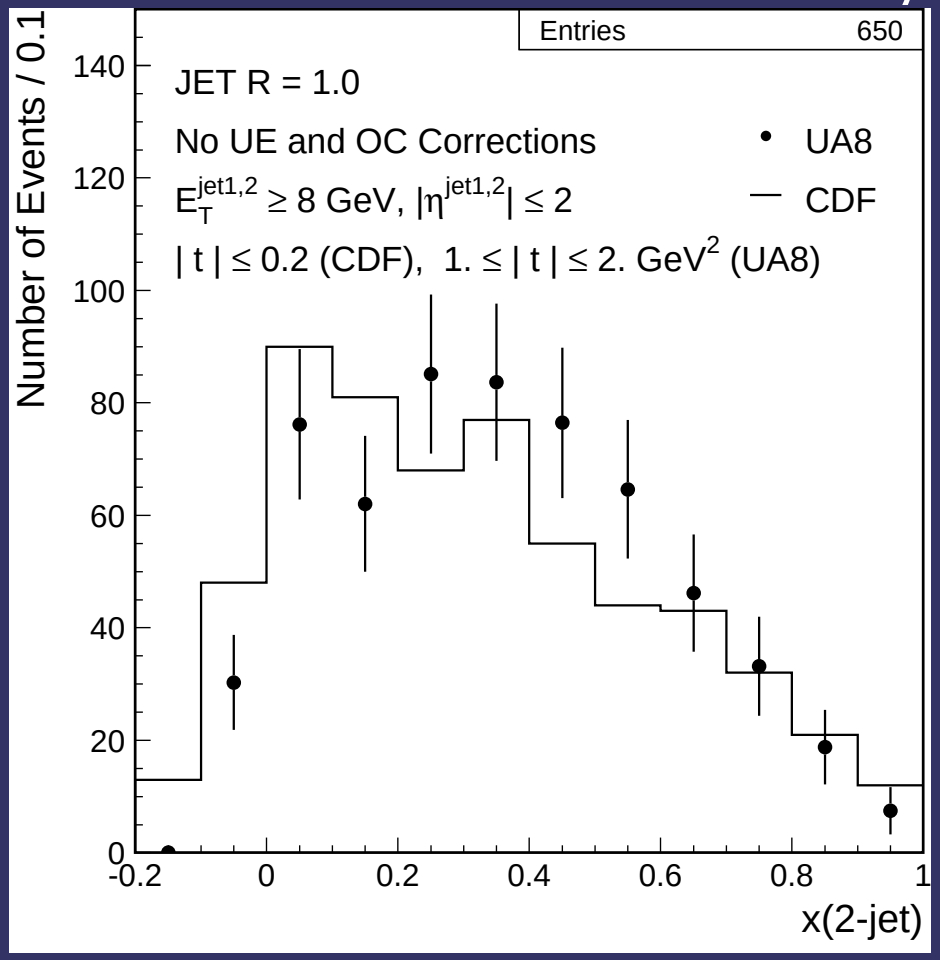

x(2-jet) = $\beta$ - x(proton)

UA8 pioneered diffractive dijets in $p\bar{p}$ collisions at $\sqrt{s}$=630 GeV ($Sp\bar{p}S$)

Pomeron structure from UA8 data :

- $\delta(1 - \beta)$ : super-hard 30 %
- $6\beta(1 - \beta)$ : hard 57 %
- $6(1 - \beta)^5$ : soft 13 %

CDF Preliminary




630 GeV data re-analyzed à la UA8

x(2-jet) distributions are not in-consistent between UA8 and CDF

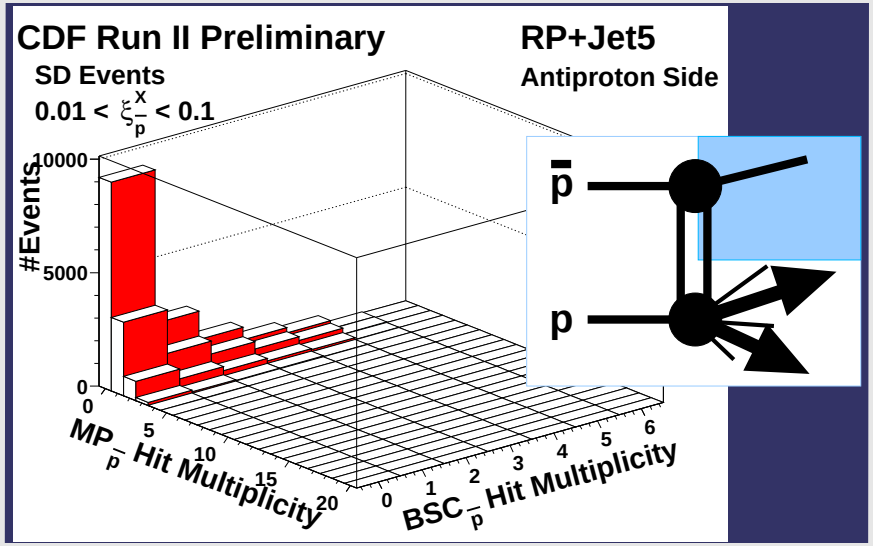
# Data Selection : DPE Dijet Analysis

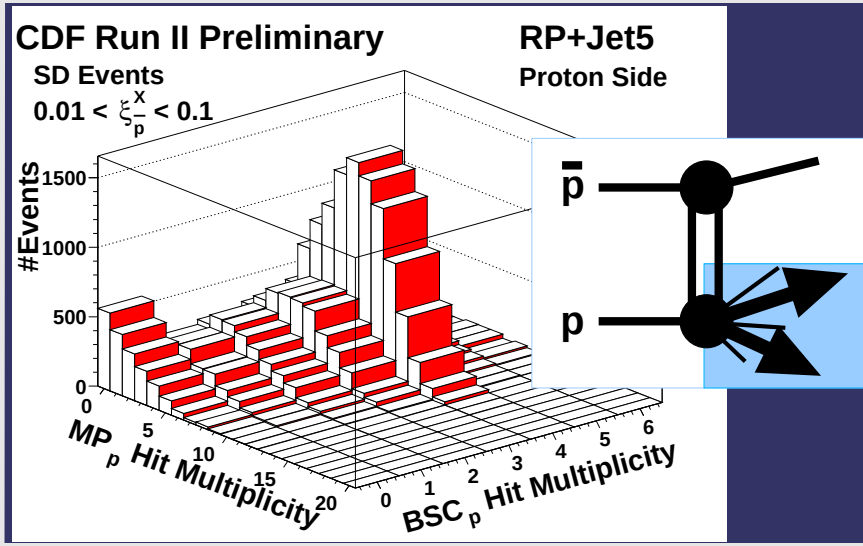
| Cuts | DPE PS5/26 $pb^{-1}$ | SD PS*[1]280/26 $pb^{-1}$ | ND PS6K/6 $pb^{-1}$ |
|---|---|---|---|
| Triggered Events | 397K | 356K | 278K |
| Single Vertex | 365K | 205K | 196K |
| $\lvert Z_{vertex}\rvert < 60$ cm | 347K | 195K | 186K |
| # Jets (R=0.7) $\geq 2$ | 204K | 158K | 160K |
| $\lvert$detector $\eta^{jet1,2}\rvert < 2.5$ | 163K | 122K | 123K |
| $E_T^{jet1,2} > 10$ GeV[*2] | 116,473 | 93,567 | 85,038 |
| $0.01 < \xi_p^X < 0.1$ | 54,552 | 14,956 | N/A |
| $GAP_p$ (MiniPlug) | 17,101 | N/A | N/A |

[*1] Effective prescale factors in total sample
[*2] Jet energy corrected to the parton level, Run I UE energy subtracted

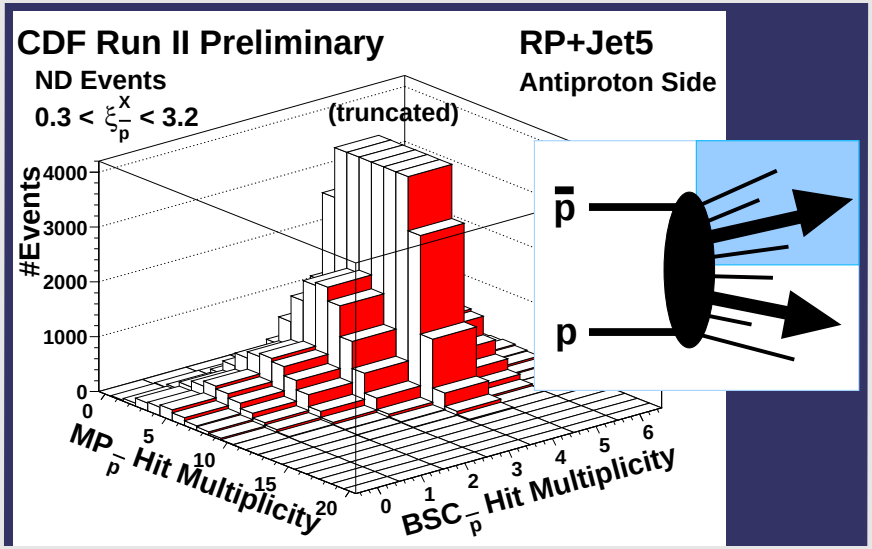
# DPE Signal in SD Trigger Data

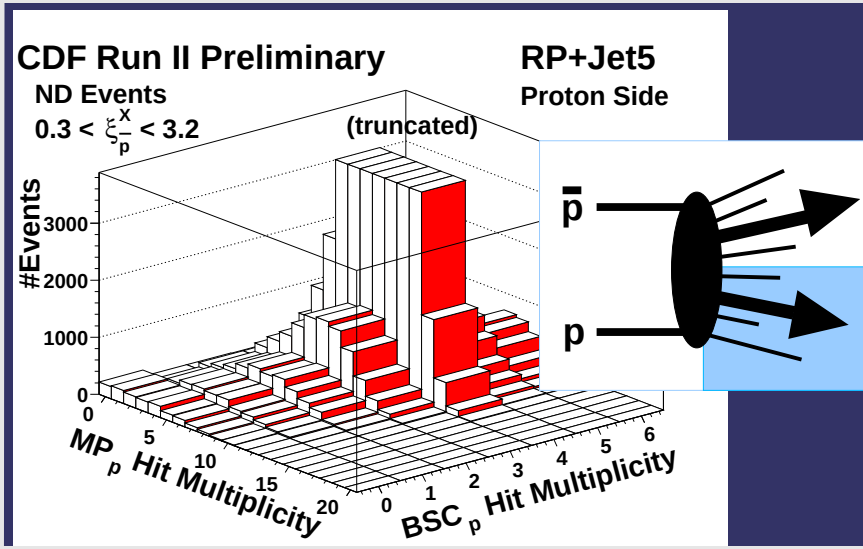
SD



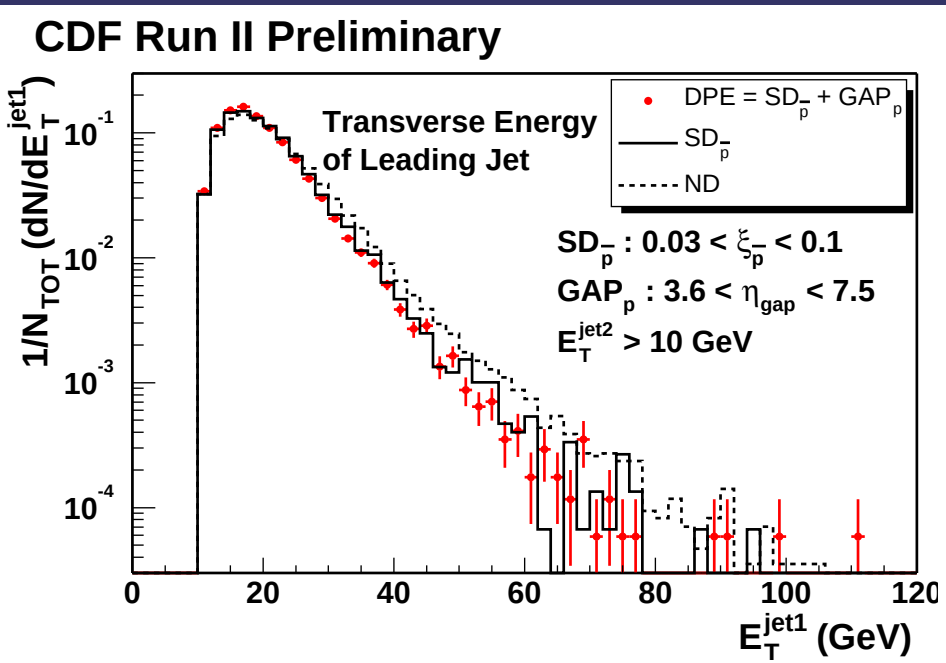

ND

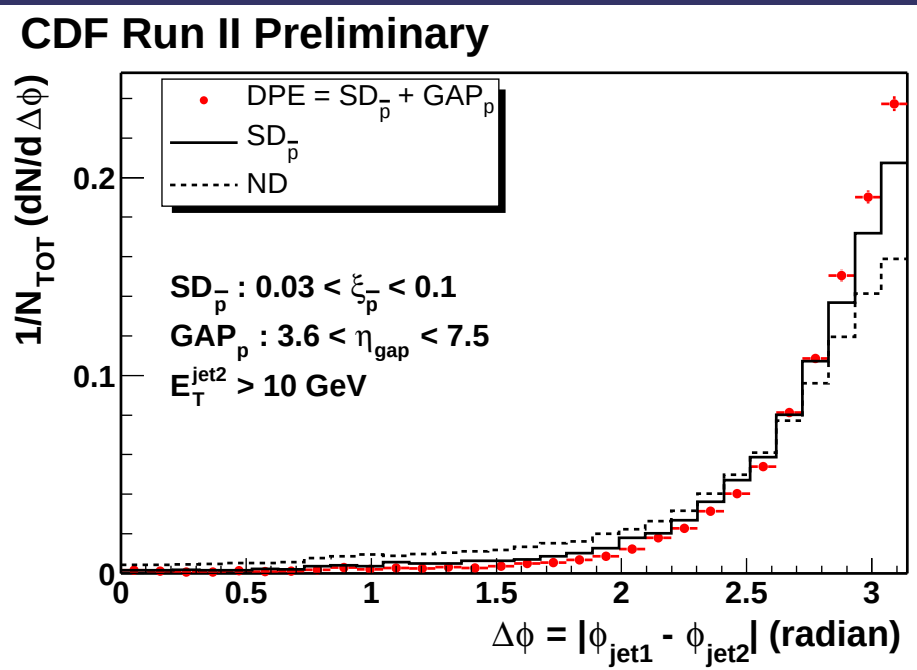


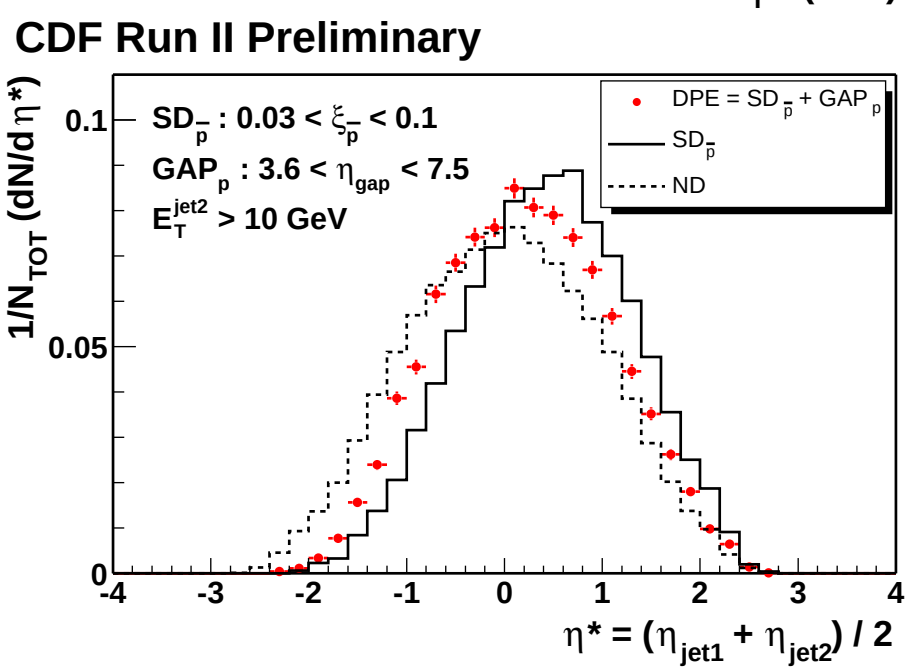




Antiproton Side | Proton Side

# Kinematic Distributions

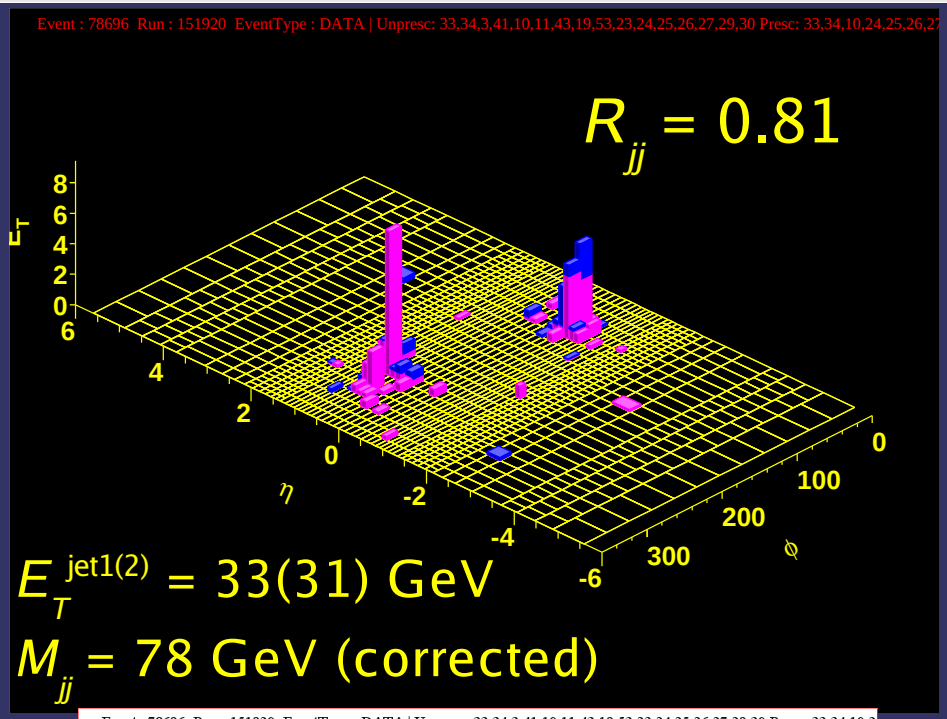


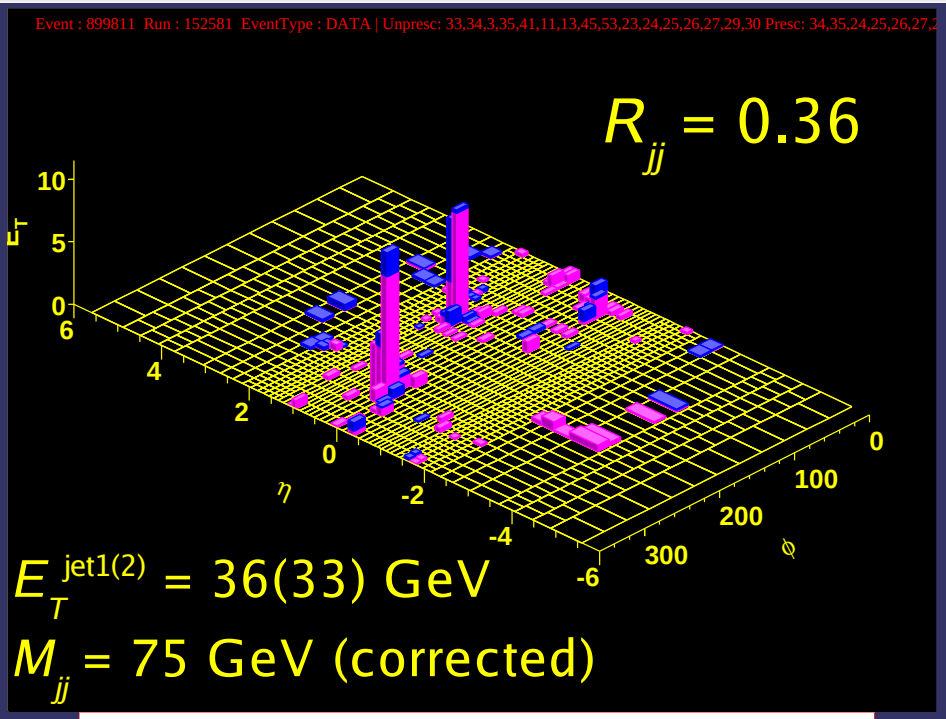



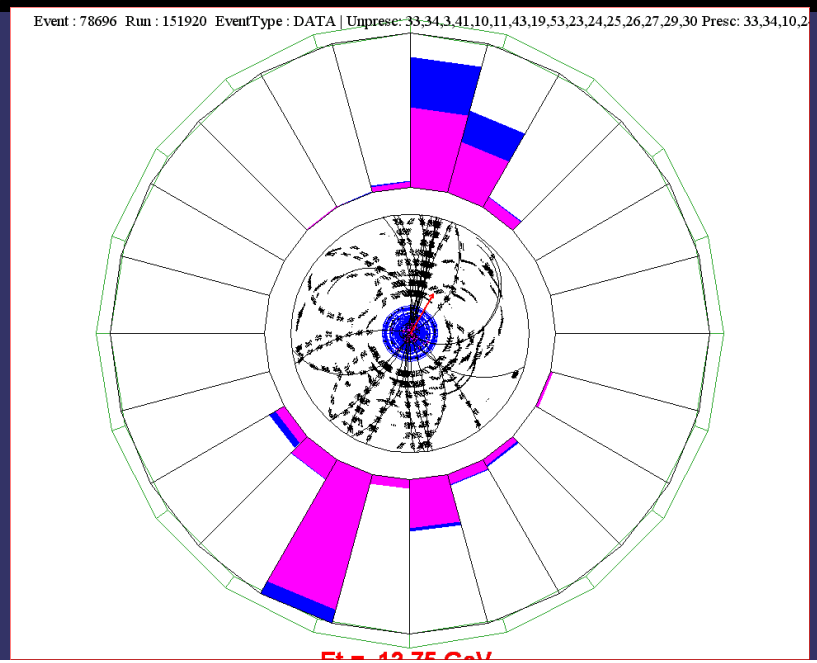



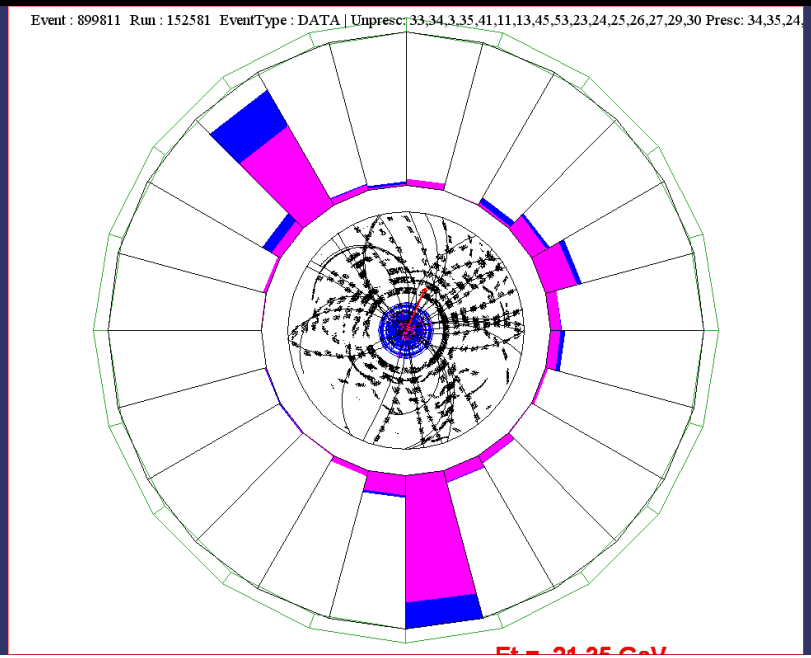

- DPE\SD jet $E_T$ steeper than ND
- SD jets boosted away from $\bar{p}$
- $\overline{\Delta\Phi}_{DPE} > \overline{\Delta\Phi}_{SD} > \overline{\Delta\Phi}_{ND}$

# DPE Dijet Event Displays

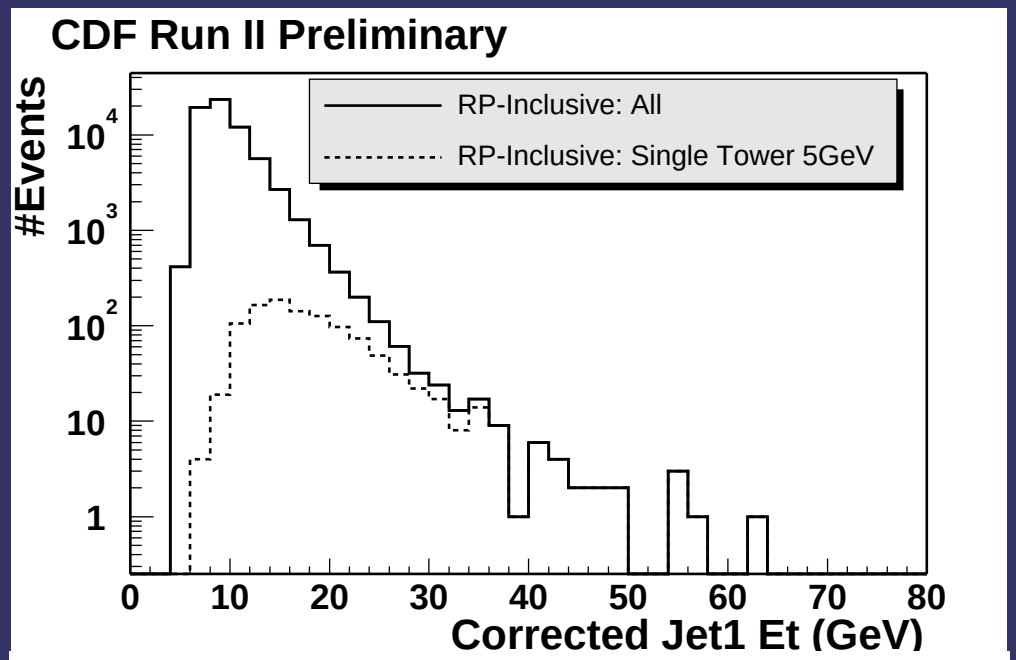


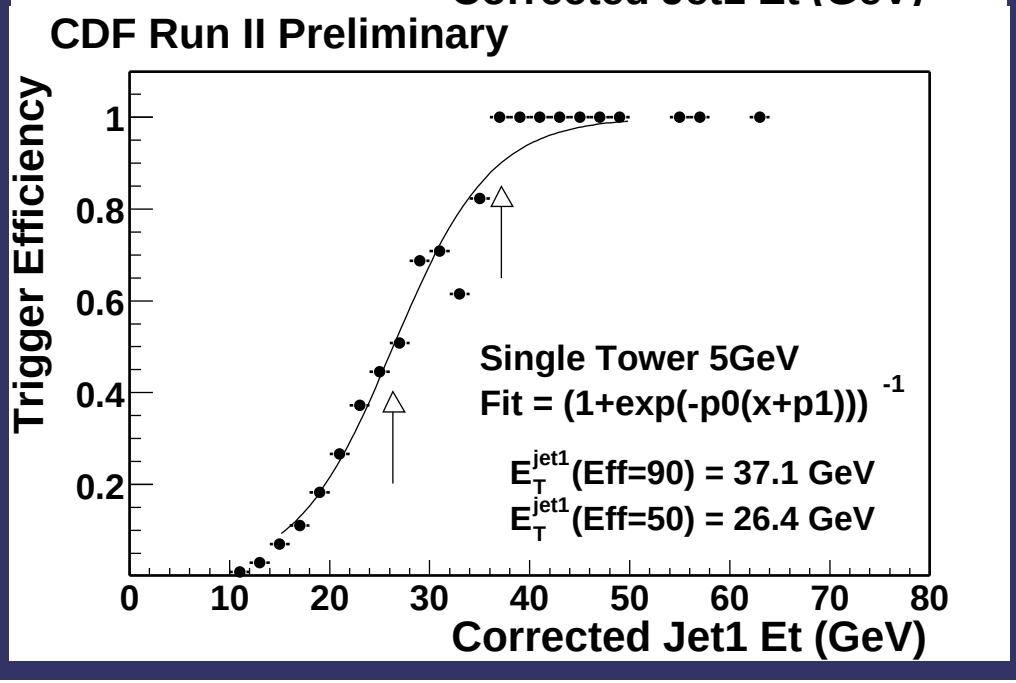



# Jet Trigger Efficiency




Trigger Efficiency vs Leading Jet $E_T$ intervals

| $E_{T1}^{min}$ | $E_{T1}^{max}$ | $\epsilon(\Delta E_{T1})$ |
|---|---|---|
| 10 | 15 | 5.77 ± 0.29 % |
| 15 | 20 | 14.4 ± 0.7 % |
| 20 | 25 | 31.6 ± 1.6 % |
| 25 | 35 | 66.6 ± 3.3 % |
| 35 | 50 | 95.1 ± 4.8 % |
| 50 | 110 | $100^{+0}_{-5}$ % |

±5% error assigned