

# Diffraction and Exclusive Production at CDF

~ Towards Exclusive Higgs at LHC ~

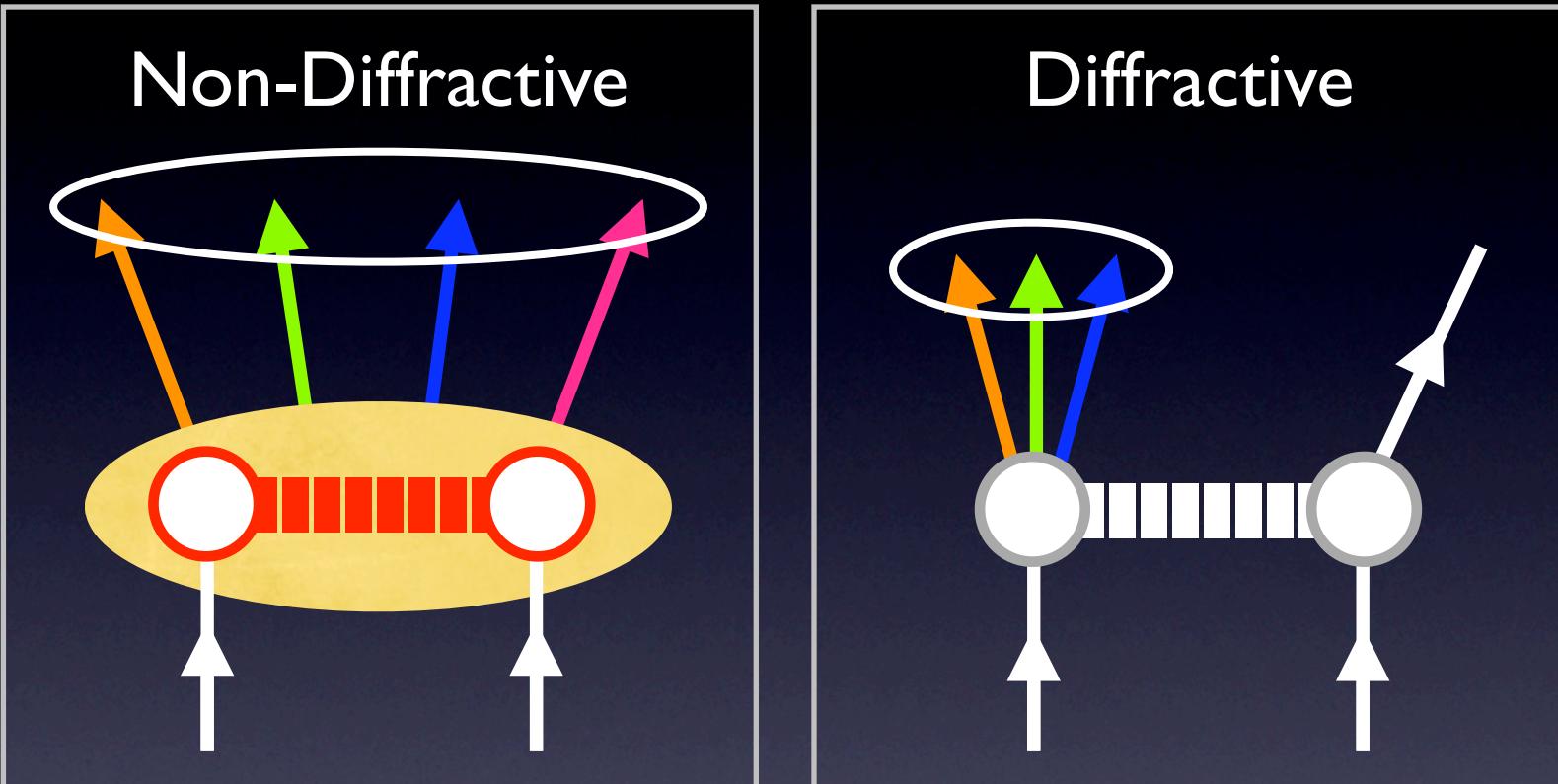
Koji Terashi  
The Rockefeller University  
for the CDF Collaboration

Wine & Cheese Seminar, March 30th, 2007

# Outline

- Motivation
- Run I Results
- Run II Results and Prospects
- Road towards LHC
- Summary

# Diffractive Physics in CDF



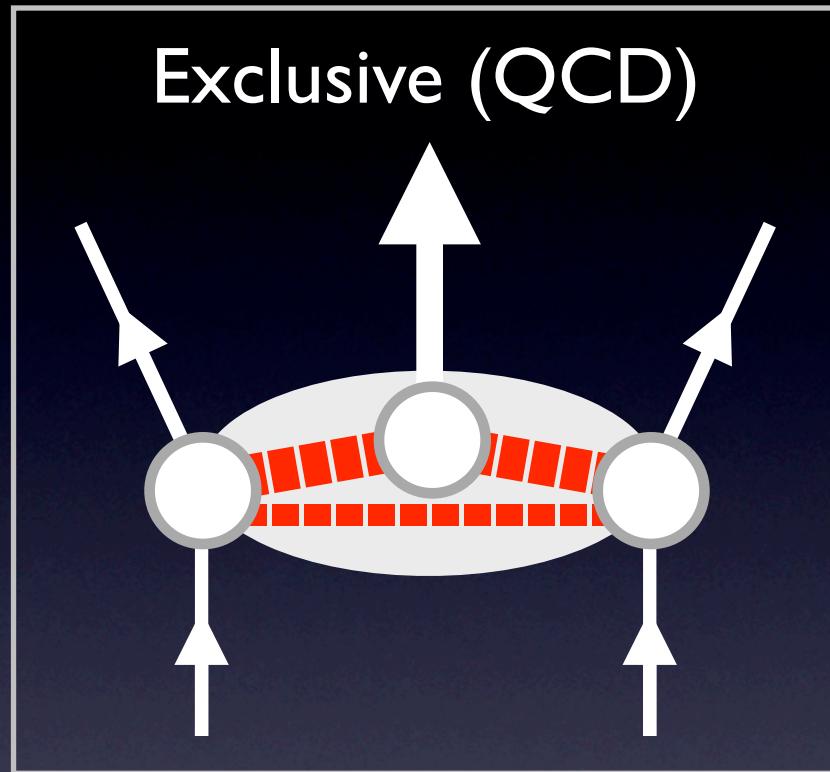
Color exchange

Colorless exchange with  
vacuum quantum numbers

GOAL :

Understand the QCD nature of diffractive exchange

# Exclusive Production

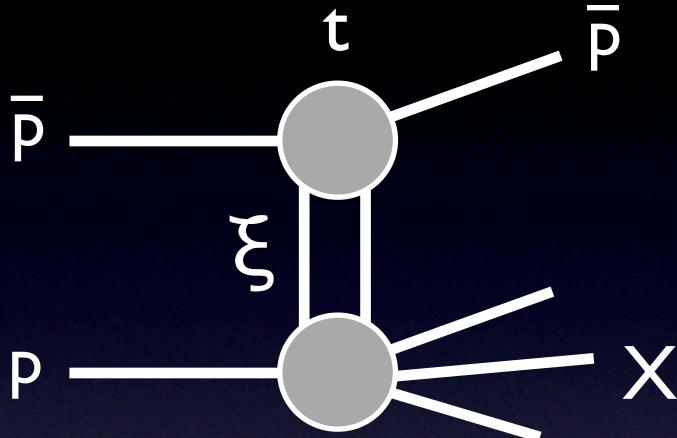


Gluon exchange with extra soft gluon  
→ neutralize color-flow

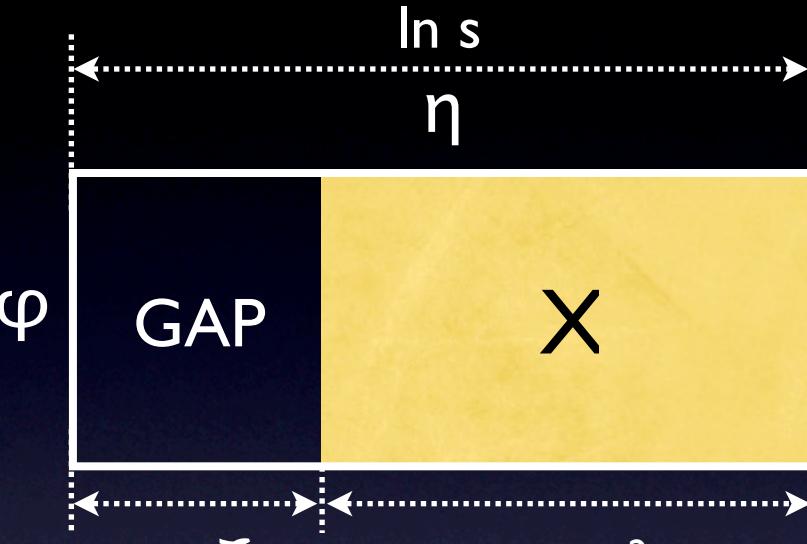
GOAL :

Test and calibrate theoretical calculations  
of exclusive production

# Diffractive $\bar{p}p$ Interactions



$\xi$  : momentum fraction of  $\bar{p}$  carried  
by diffractive exchange  
 $t$  : 4-momentum transfer squared

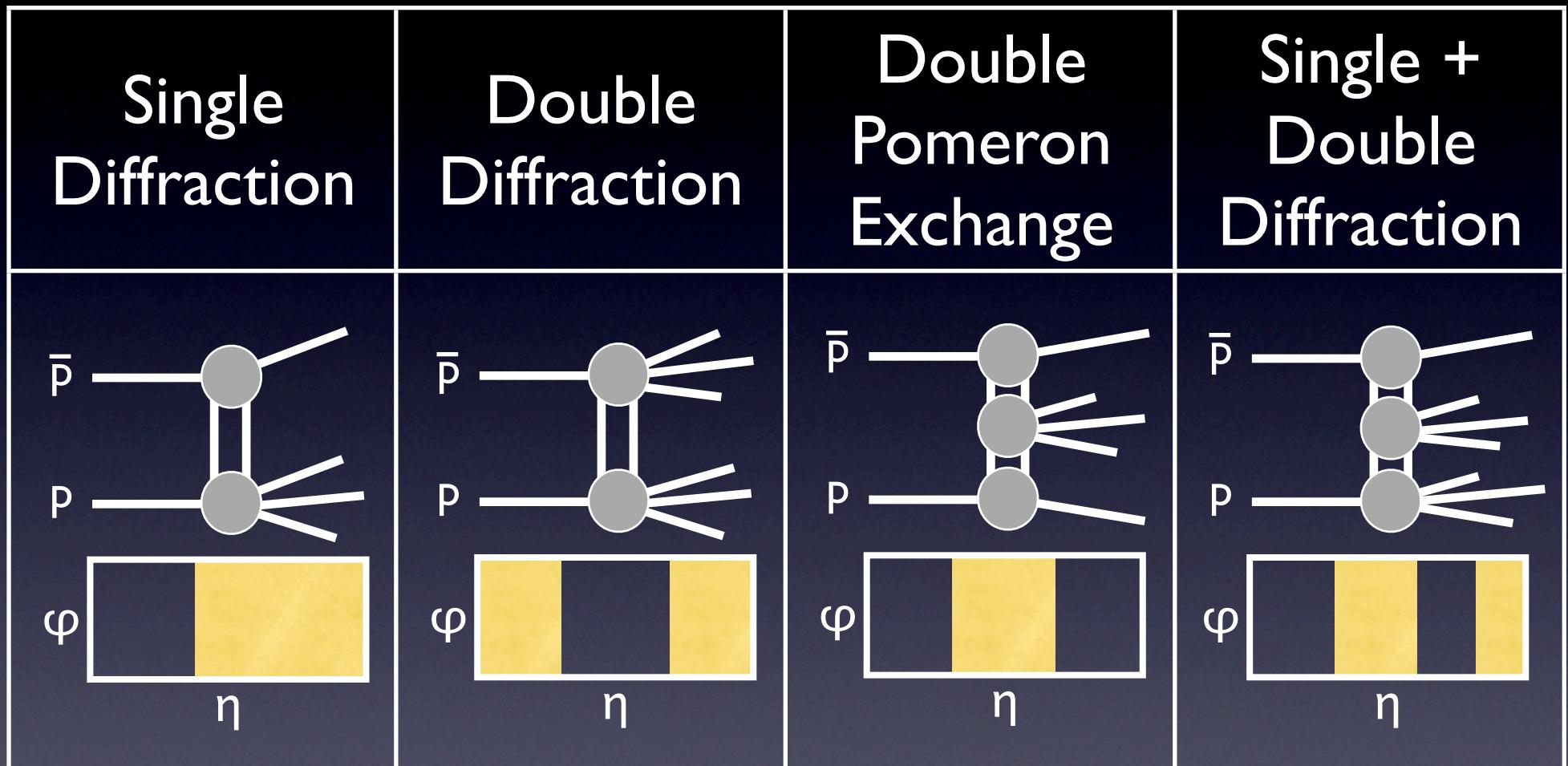


$$\xi = Mx^2 / s$$

## Strategy

- Characterize formation of rapidity gap(s) in events with different gap topology
- Examine partonic structure using high  $p_T$  probes

# CDF Diffraction in Run I



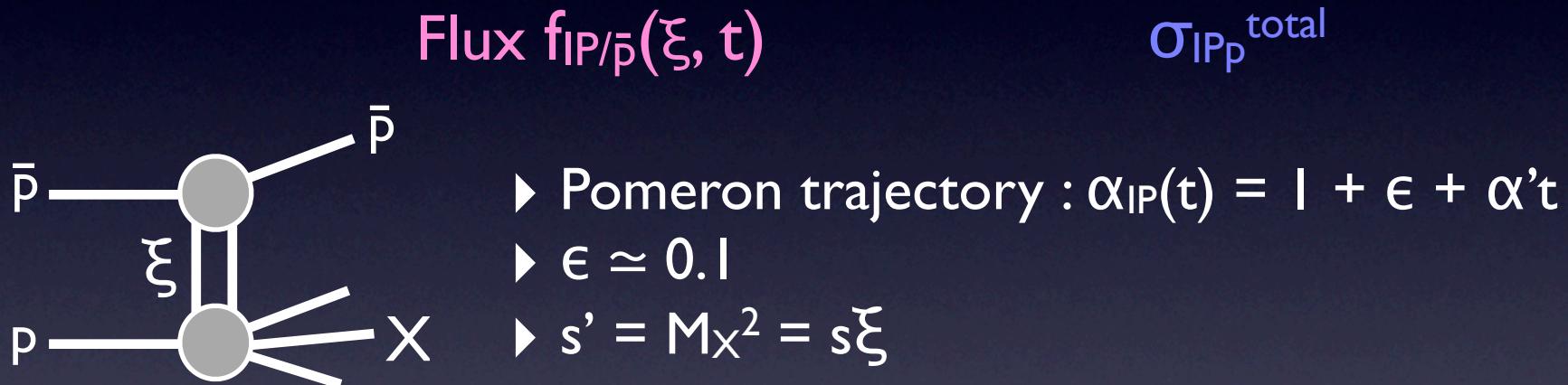
14 published papers : 13 PRL and 1 PRD

$\sigma_{\text{total}}$  and  $\sigma_{\text{elastic}}$  (not discussed today)

# Diffraction in Regge Theory

## Single Diffraction Cross Section

$$\frac{d^2\sigma_{SD}}{d\xi dt} = \frac{1}{16\pi} \beta_{IPP}(t)^2 \xi^{1-2\alpha_{IP}(t)} \left[ \beta_{IPP}(0)g(t)\left(\frac{s'}{s_0}\right)^{\alpha_{IP}(0)-1} \right]$$



$$\rightarrow \sigma_{SD} = \int_{\xi_{\min}}^{0.1} d\xi \int_{-\infty}^0 dt f_{IP/\bar{p}}(\xi, t) \sigma_{IPP}^{\text{total}} \sim s^\epsilon \int_{\xi_{\min}}^{0.1} \xi^{-(1+\epsilon)} d\xi \sim s^{2\epsilon}$$

$$\sigma_{\text{total}} = \beta_{IPP}(0)^2 \left(\frac{s}{s_0}\right)^\epsilon \sim s^\epsilon$$

# Soft Single Diffraction

K. Goulian, Phys. Lett. B 358,379(1995)

## Regge Theory

$$\sigma_{SD} \sim s^{2\epsilon} \quad (\epsilon \approx 0.1)$$

$\Rightarrow$  exceeds  $\sigma_{total}$  at  $\sqrt{s} \approx 2 \text{ TeV}$

## Measurement

►  $\sigma_{SD} \sim s^{2(0.015 \pm 0.008)}$

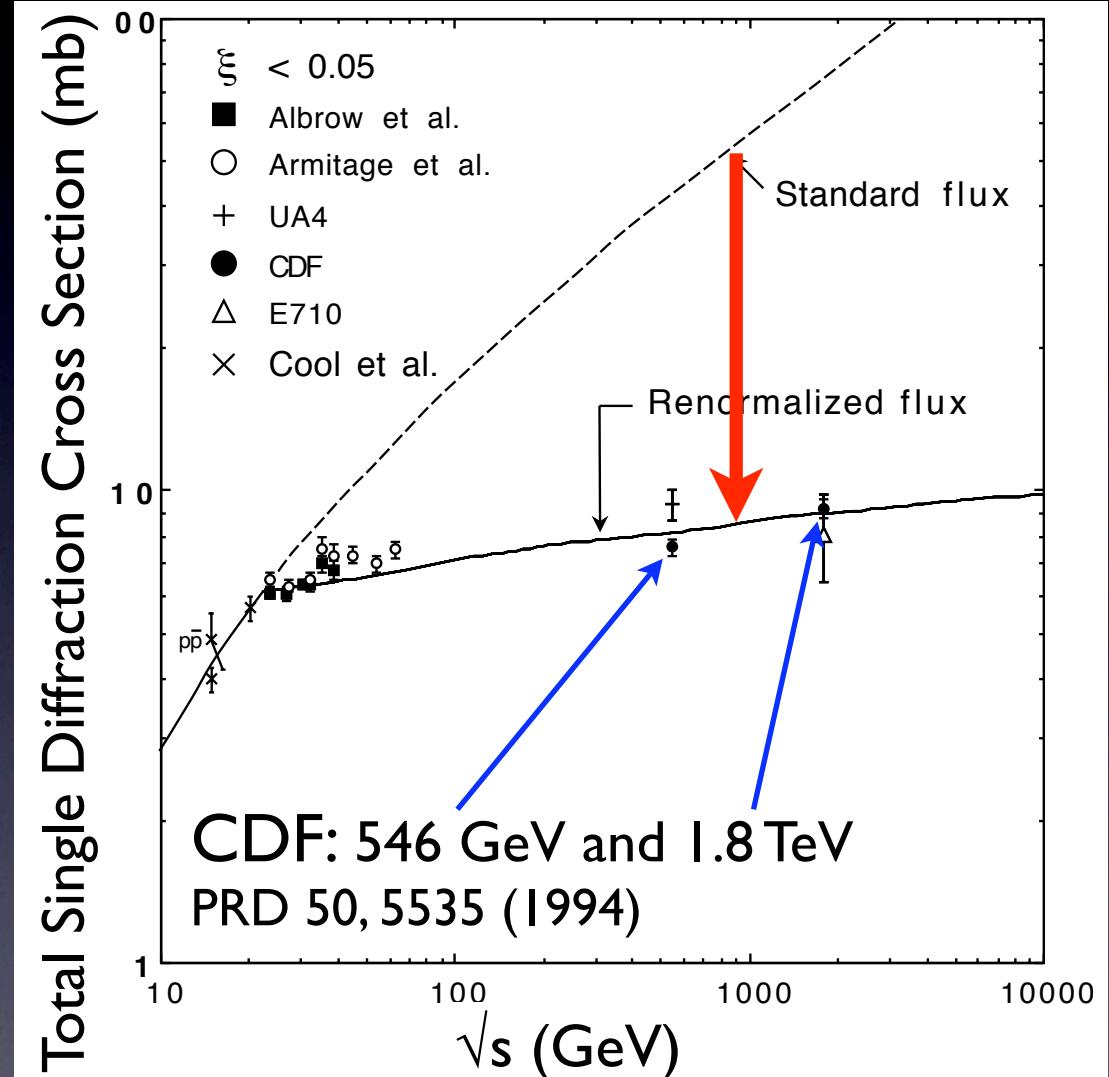
$\Rightarrow$  much weaker  $s$ -dependence

► A factor of  $\sim 10$  suppressed  
in normalization

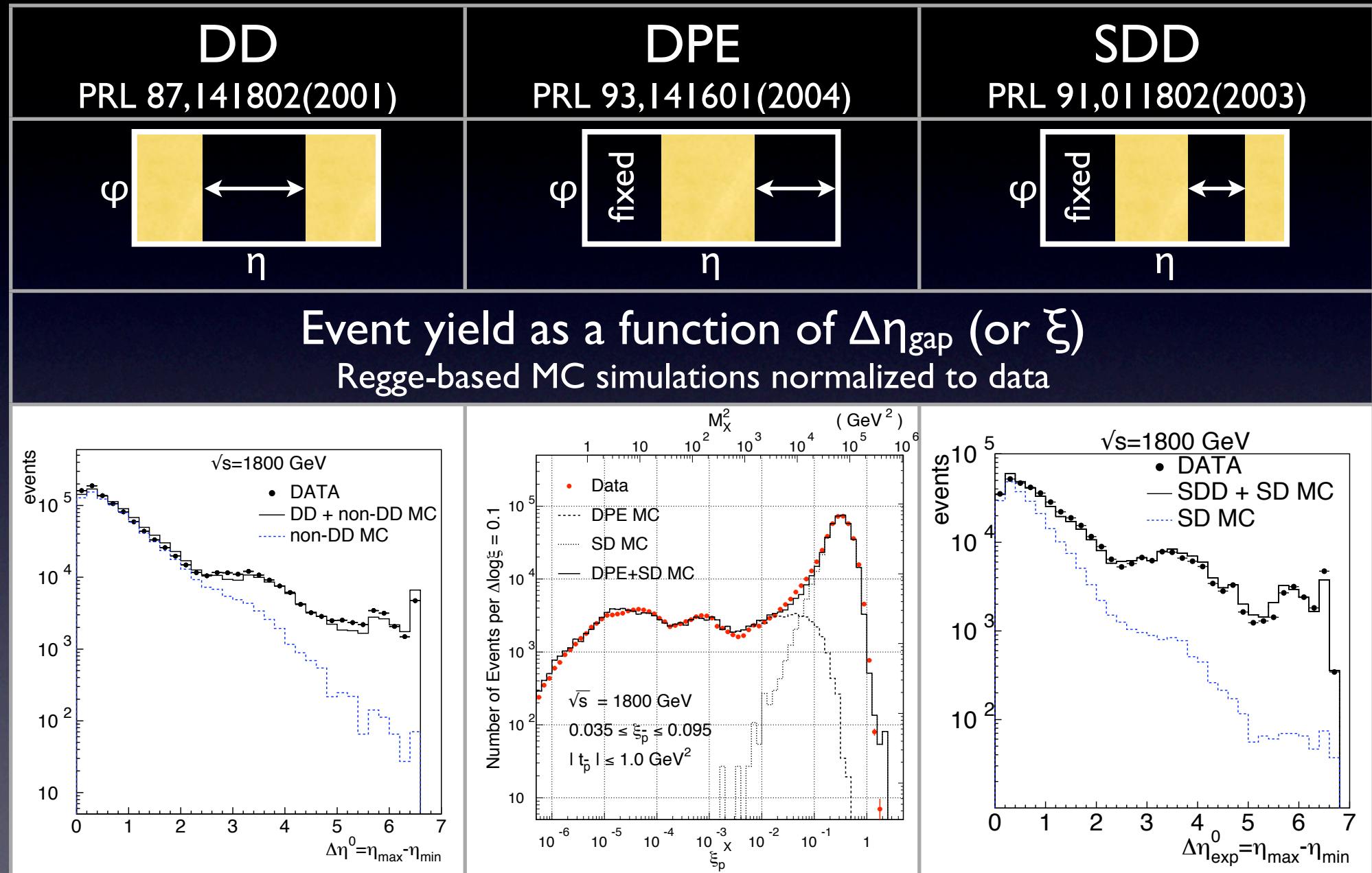
►  $d\sigma/d\xi \sim \xi^{-(1+\epsilon)}$  dependence  
► Same as Regge theory

## Renormalization

Pomeron flux integral  
(re)normalized to unity  $\int_{\xi_{min}}^{0.1} d\xi \int_{-\infty}^0 dt f_{IP/p}(\xi, t) = 1$



# Soft Diffraction



→ Data agree with Regge predictions in  $\xi$ -dependence

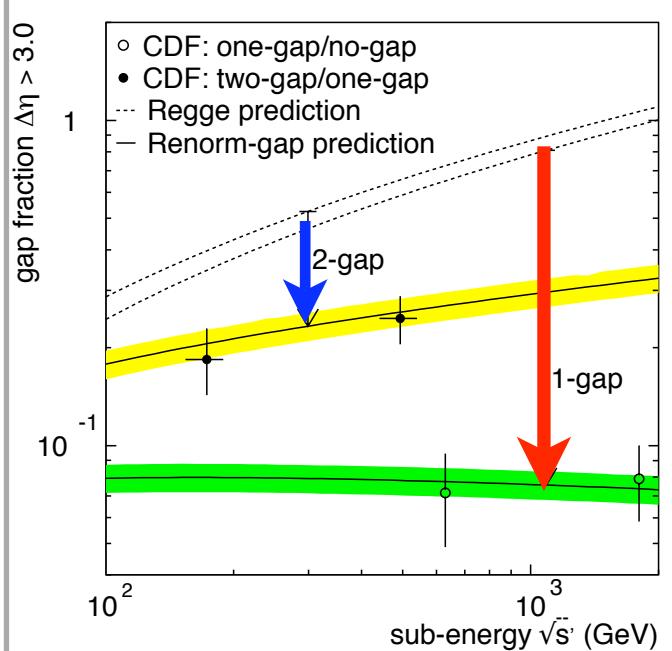
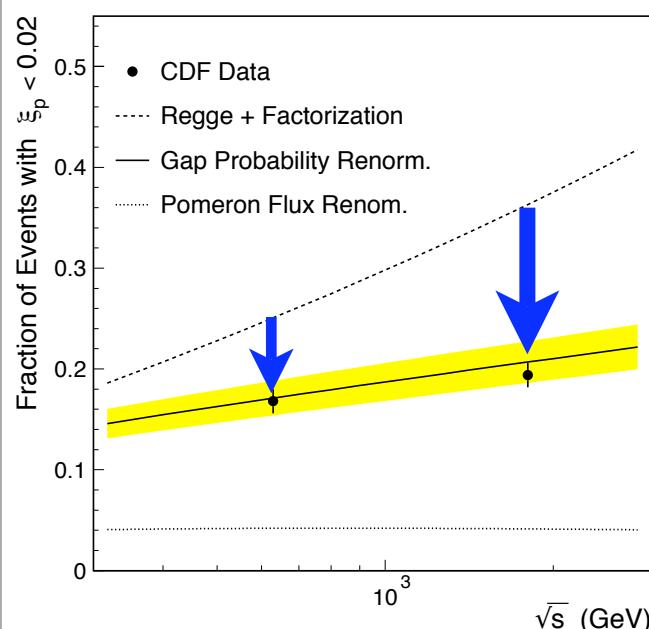
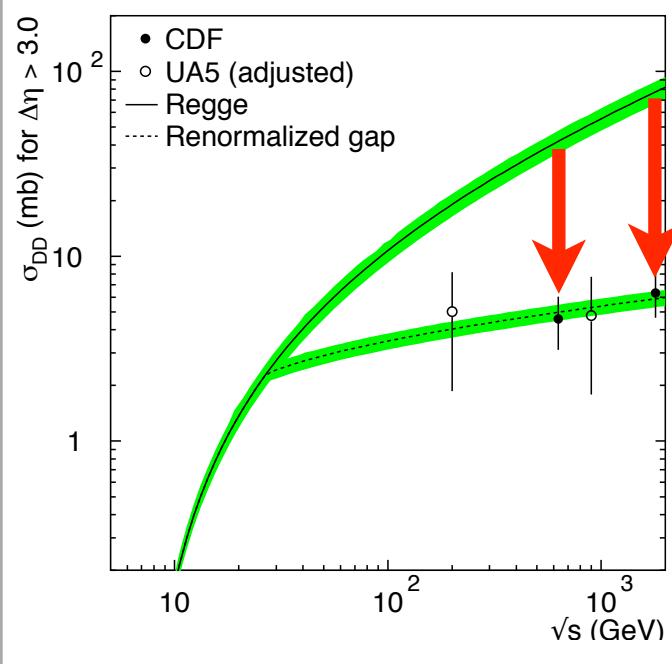
# Soft Diffraction

DD

DPE

SDD

Fraction (or cross section) of gap events as a function of  $\sqrt{s}$

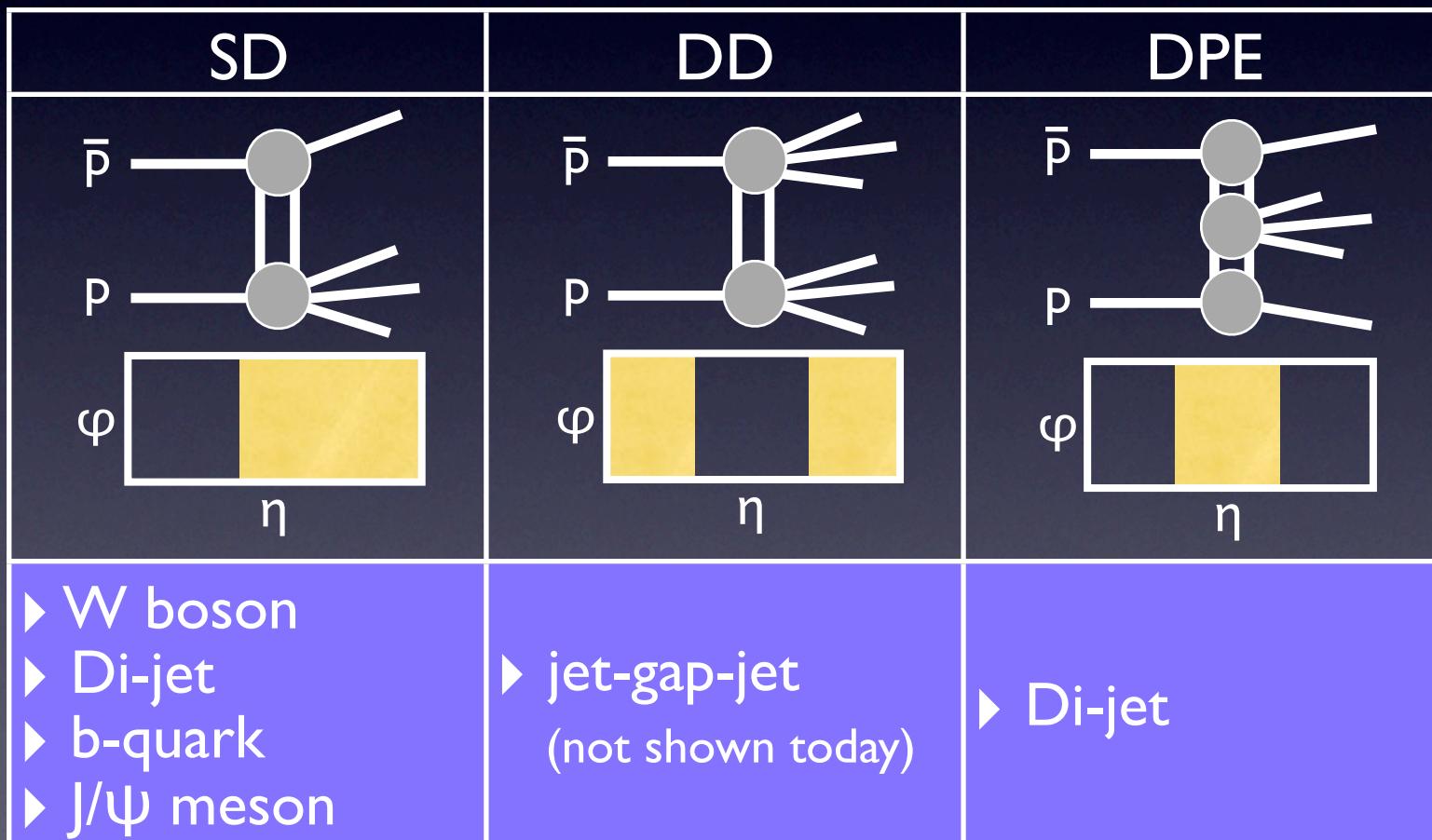


- • Single gap rates are suppressed by  $O(10)$
  - Double gap rates are less suppressed ↓
- relative to Regge predictions

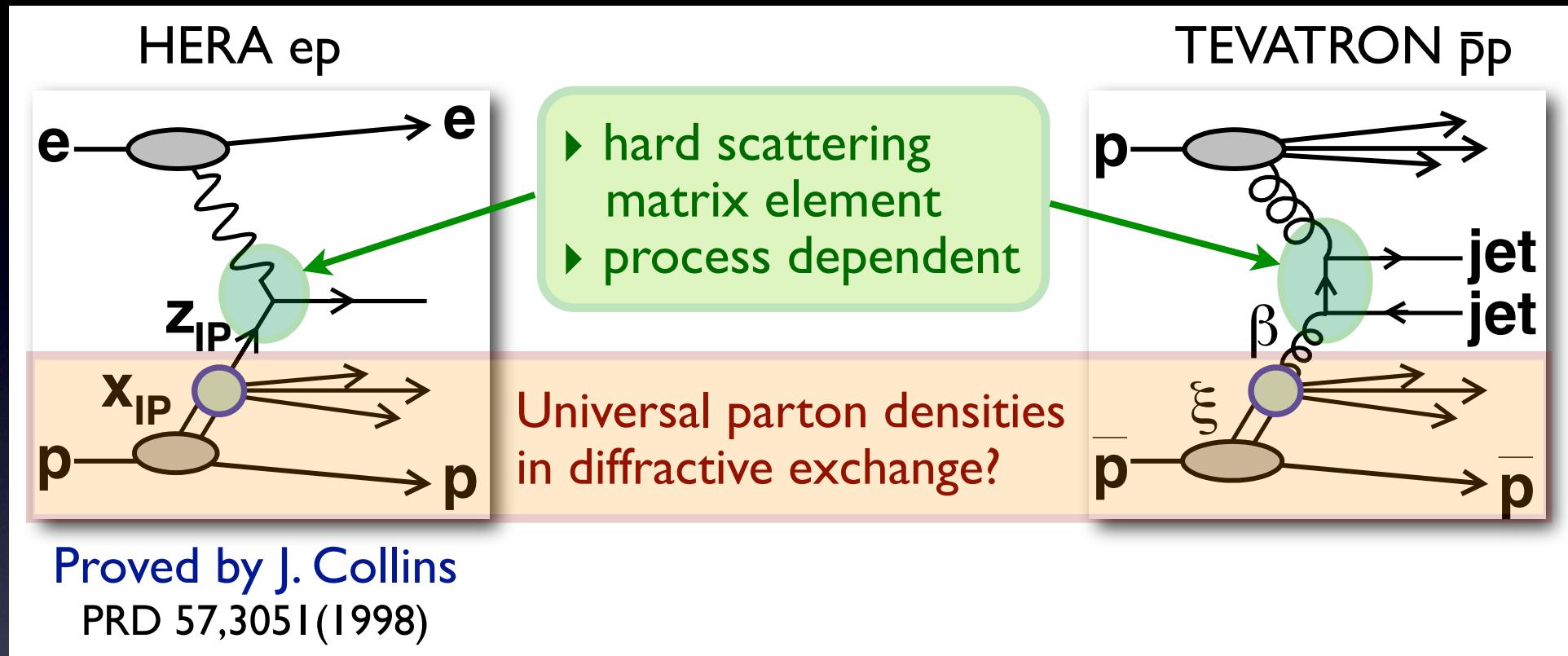
# Hard Diffraction

- Proposed by Ingelman and Schlein in 1985 Phys. Lett. B 152, 256(1985)
- Discovery of diffractive dijets by UA8 Collaboration Phys. Lett. B 211, 239(1988), 297, 417(1992)

Probing partonic structure of the diffractive exchange



# QCD Factorization



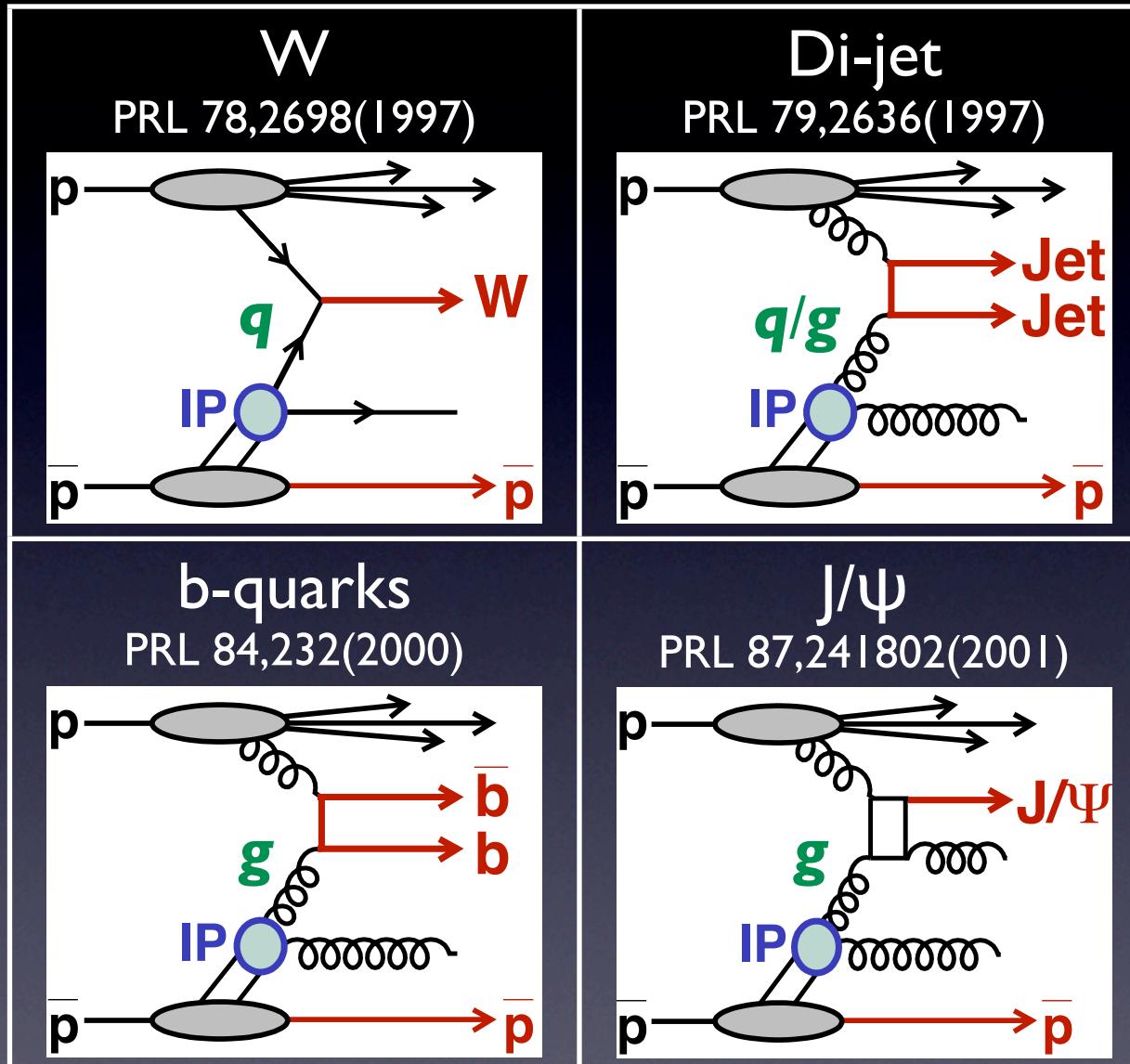
## Factorization Test

$$\text{HERA : } \sigma(ep \rightarrow eX_p) = \boxed{F_{jj}^D} \otimes \sigma(ab \rightarrow jj)$$

?

$$\text{Tevatron : } \sigma(\bar{p}p \rightarrow \bar{p}X) \approx \boxed{F_{jj}^D} \otimes F_{jj} \otimes \sigma(ab \rightarrow jj)$$

# Hard Single Diffraction in CDF



Probing quark and gluon contents in diffractive exchange

# Diffractive to Inclusive Ratio

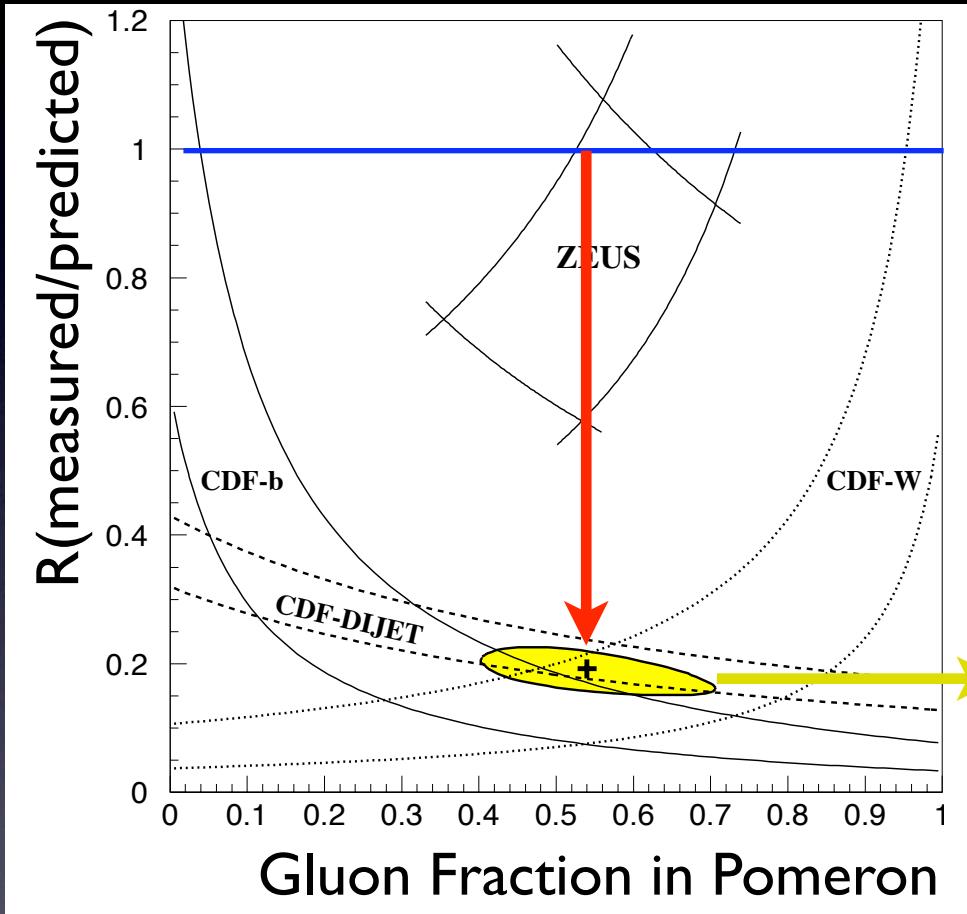
$\sqrt{s} = 1.8 \text{ TeV}$	W	Di-jet	b-quark	J/ $\psi$
$R \left[ \frac{\text{diff}}{\text{incl}} \right] (\%)$	$1.15 \pm 0.55$	$0.75 \pm 0.10$	$0.62 \pm 0.25$	$1.45 \pm 0.25$

→ Diffractive production rates are all similar  
at  $\sim 1\%$  relative to inclusive rates

Factorization approximately holds within Tevatron  
(at fixed  $\sqrt{s}$ )

# Factorization Breaking

PRL 84, 232 (2000)



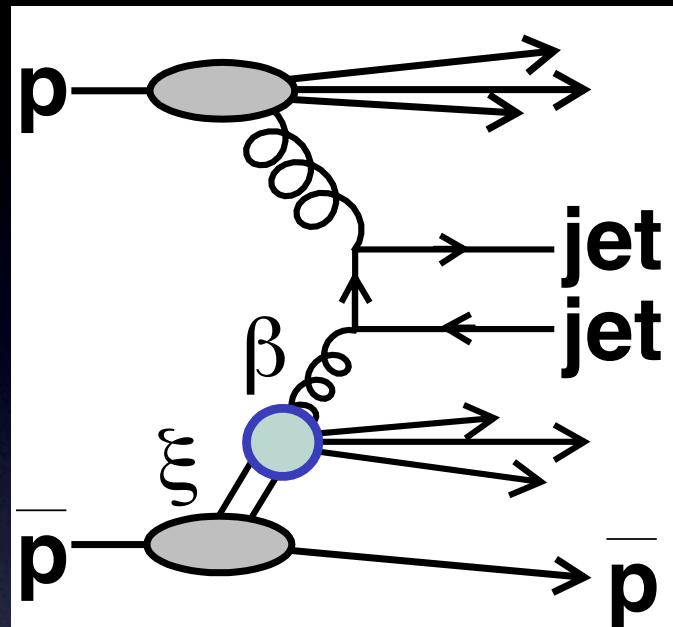
$R = 1$  : factorization valid

$$R = 0.19 \pm 0.04$$

SD production rates are severely suppressed relative to HERA

→ Factorization breakdown between Tevatron and HERA

# Diffractive Structure Function



Diffractive Di-jet Production

$$\sigma(\bar{p}p \rightarrow \bar{p}X) \approx F_{jj} \otimes F_{jj}^D \otimes \sigma(ab \rightarrow jj)$$

$$F_{jj}^D = F_{jj}^D (\xi, t, x_{Bj}, Q^2)$$

Diffractive Structure Function

$\beta = x_{Bj}/\xi$  : Momentum fraction of diffractive exchange carried by the scattering parton

Determine  $F_{jj}^D$  in LO QCD using

$$F_{jj}^D (x_{Bj}, Q^2) =$$

$$R(x_{Bj}) \text{ of } \frac{\sigma_{jj}(\text{Diff})}{\sigma_{jj}(\text{Non-Diff})}$$

↑  
Data

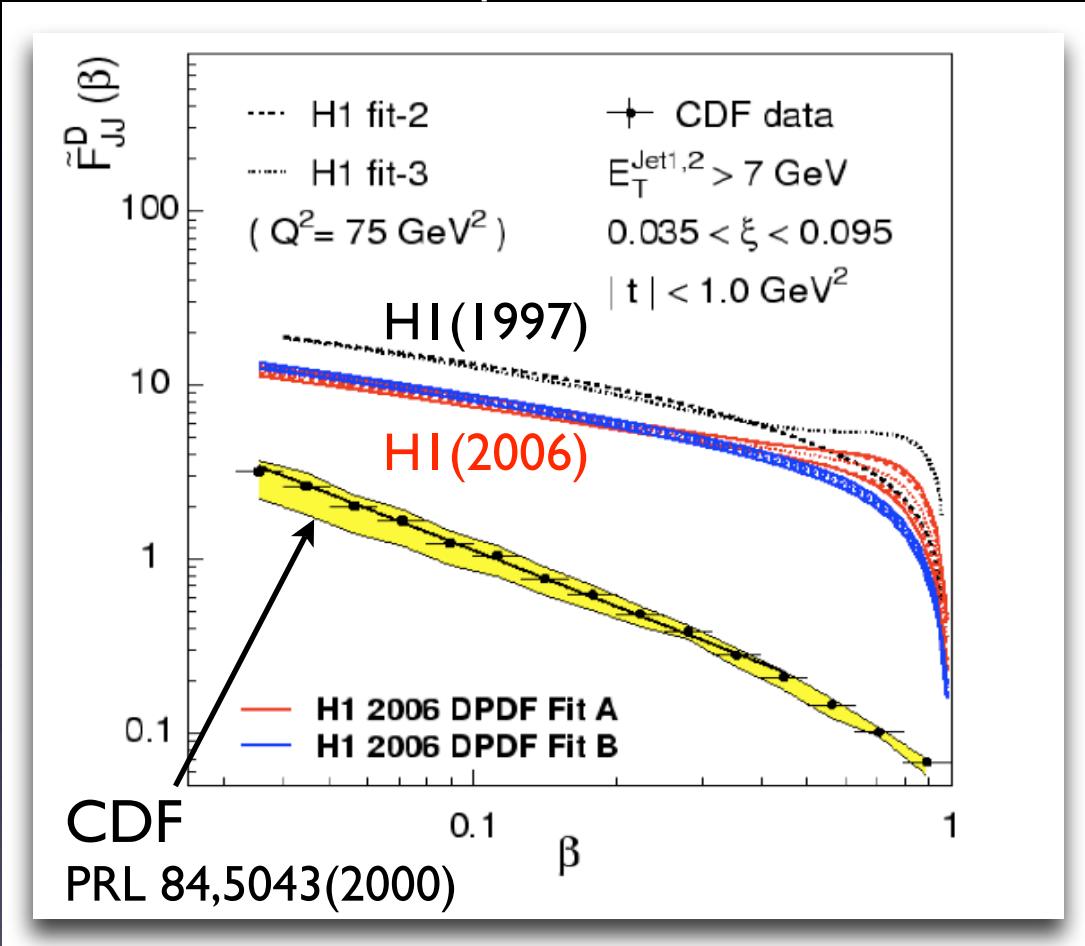
$$\times F_{jj} (x_{Bj}, Q^2)$$

↑  
Proton PDF

# Diffractive Structure Function

P. Newman

Hera-LHC workshop, March 12-16, 2007



$F_{jj}^D$  at the Tevatron is suppressed relative to expectations from PDFs measured by H1 at HERA

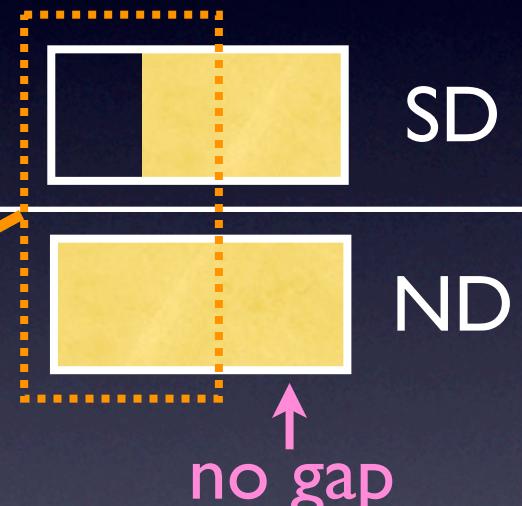
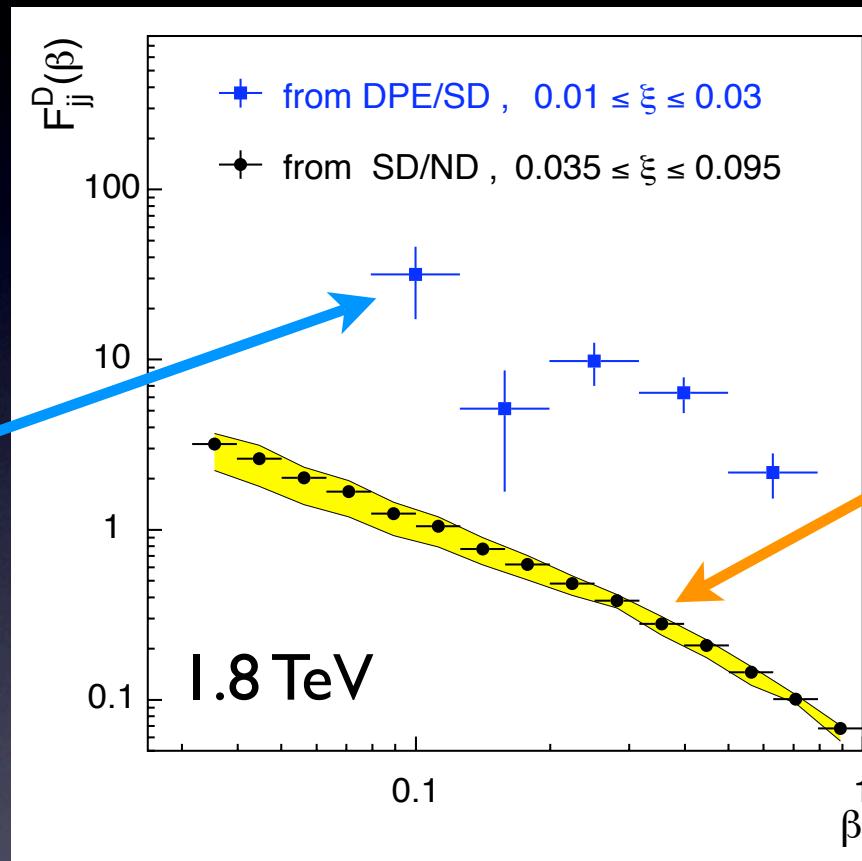
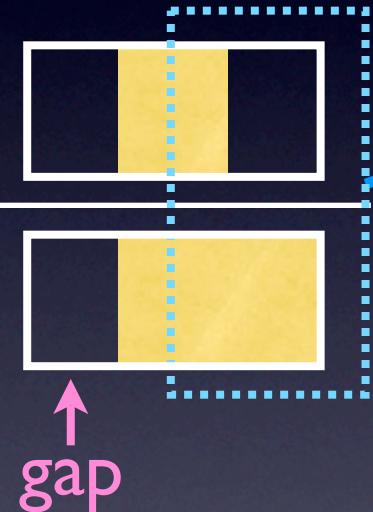
- ➡ Breakdown of QCD Factorization confirmed
- ➡ Similar suppression as in soft SD relative to Regge expectations

# Diffractive Structure Functions from DPE and SD Data

PRL 85, 4215 (2000)

DPE

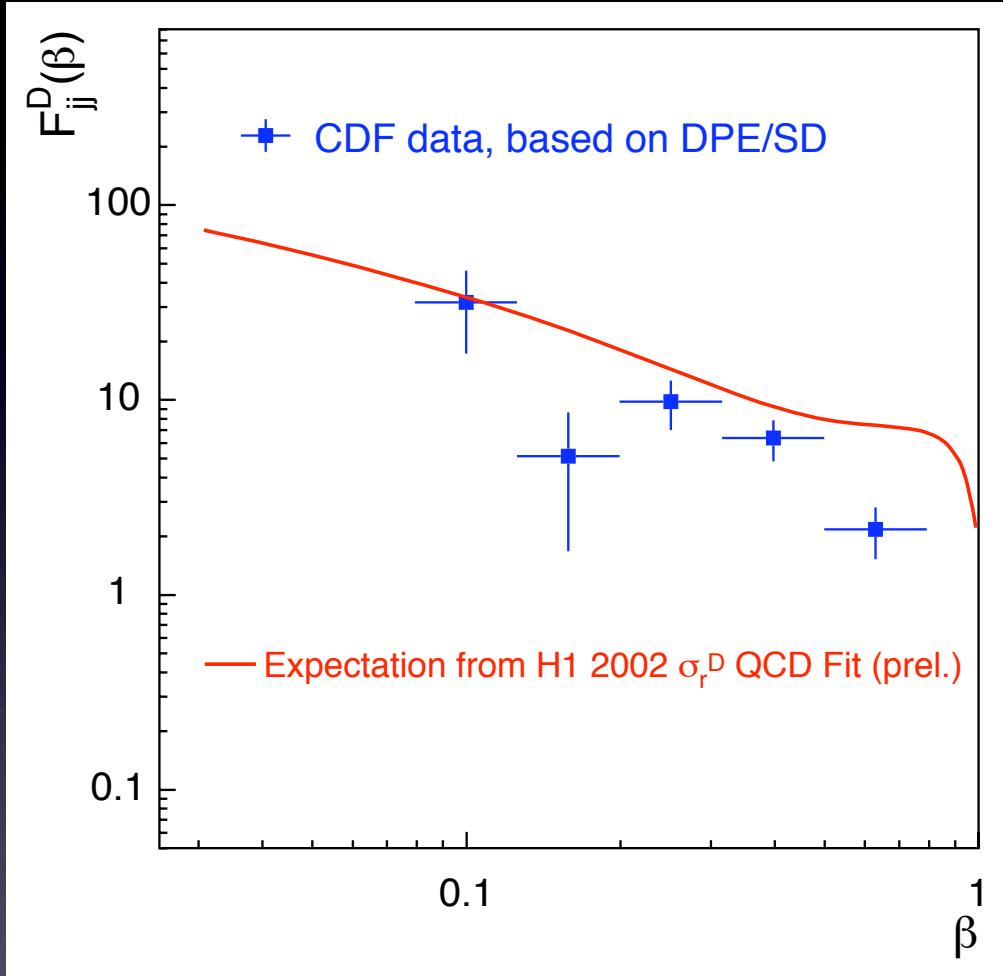
SD



$F_{jj}^D$  from DPE/SD is larger than  $F_{jj}^D$  from SD/ND

Factorization breakdown within the Tevatron

# Restoring QCD Factorization?



$F_{jj}^D$  measured in DPE events is approximately equal to expectations from PDFs measured at HERA

- ➡ 2nd gap less suppressed if a gap is already present in the events
- ➡ QCD factorization between HERA and Tevatron restored?

# Run II Diffraction Program

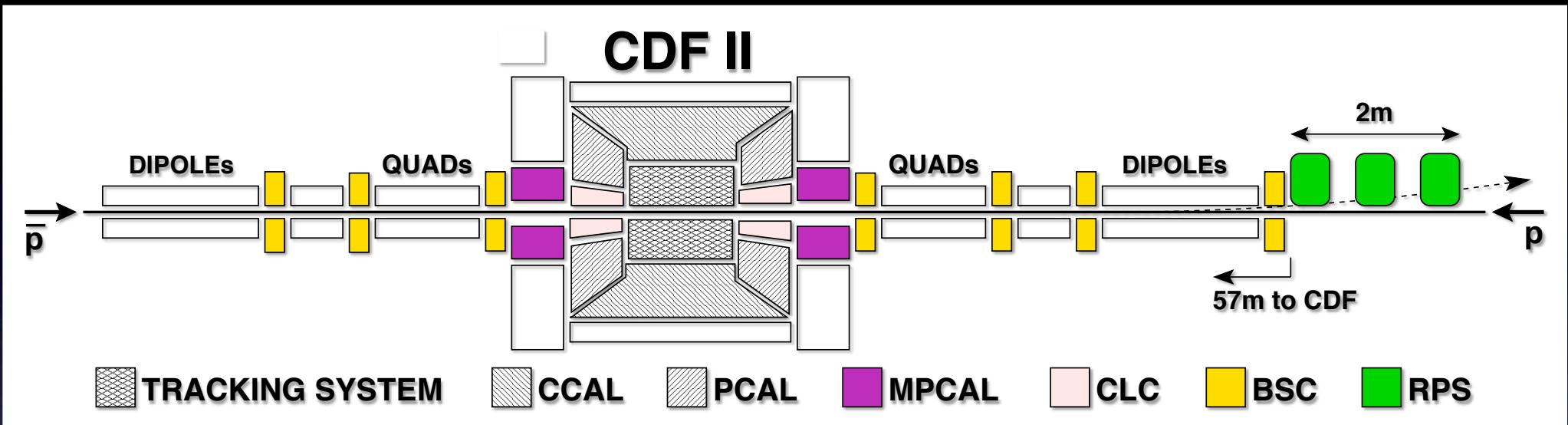
## GOAL

- To further characterize diffractive structure function and diffractive exchange
- To measure exclusive production and calibrate theoretical calculations

SD	▶ $\xi$ , $t$ , and $Q^2$ dependence of $F_{jj}^D$ ▶ Process dependence of $F^D$ ( $W, Z$ )
DPE	▶ $\xi_{\bar{p}}$ dependence on $F_{jj}^D$ measured on p-side
DD	▶ $\Delta n_{gap}$ dependence for fixed large $\Delta \eta_{jj}$
Exclusive	▶ di-jet, di-photon, $X_c$ ▶ $e^+e^-$ , $\mu^+\mu^-$

Results presented in this talk

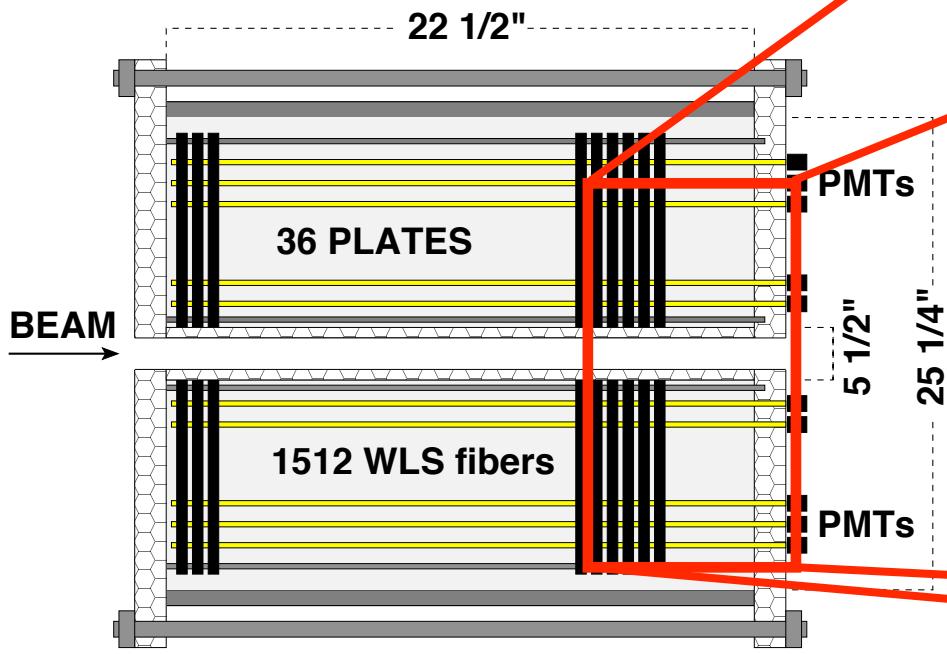
# CDF II Detector



- Tracking Detectors :  $|\eta| < 2.0$
- Calorimeters :  $|\eta| < 5.2$
- Beam Shower Counters (BSC) :  $5.4 < |\eta| < 7.4$
- Roman Pot Spectrometers (RPS) :  $0.02 < \xi < 0.1$   
 $0 < |t| < 2 \text{ GeV}^2$

# MiniPlug Calorimeters

Electromagnetic calorimeter with hadron detection capability



■ STAINLESS STEEL SUPPORT

□ ALUMINUM

■ 1/4" THICK PLATE (3/16" PB + 2x0.5mm AL)

■ KURARAY Y11 MULTI-CLAD 1.0mm DIA. WLS FIBER

□ BICRON 517L LIQUID SCINTILLATOR

$32X_0, 1.3\lambda_l$



Read out by WLS fibers

→ Good position resolution retained

$$e^+ : \sigma_{\text{position}}/E = 9.2\text{mm}/\sqrt{E}$$

$$\sigma_{\text{energy}}/E = 18\%/\sqrt{E} + 0.6\%$$

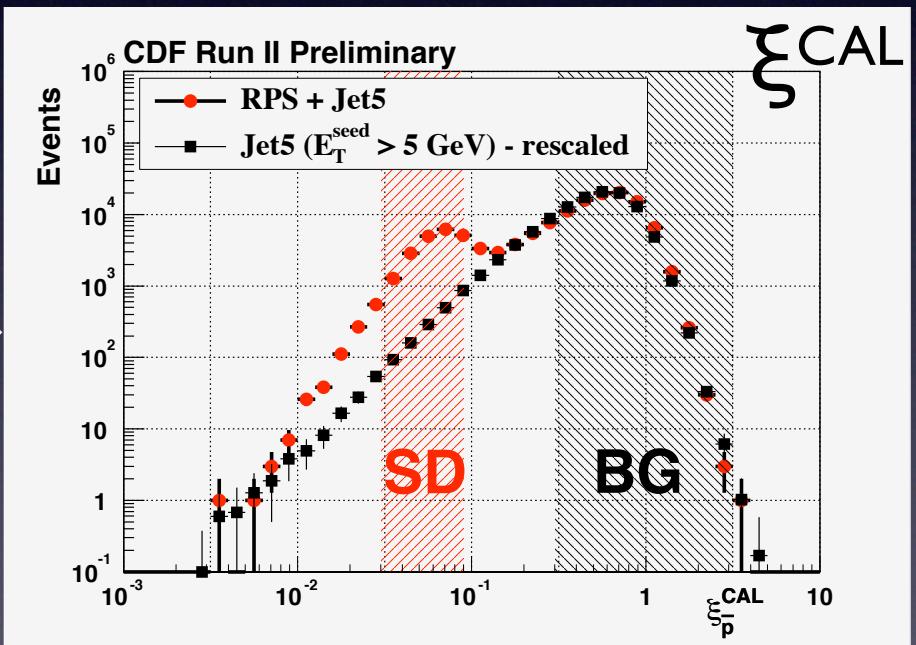
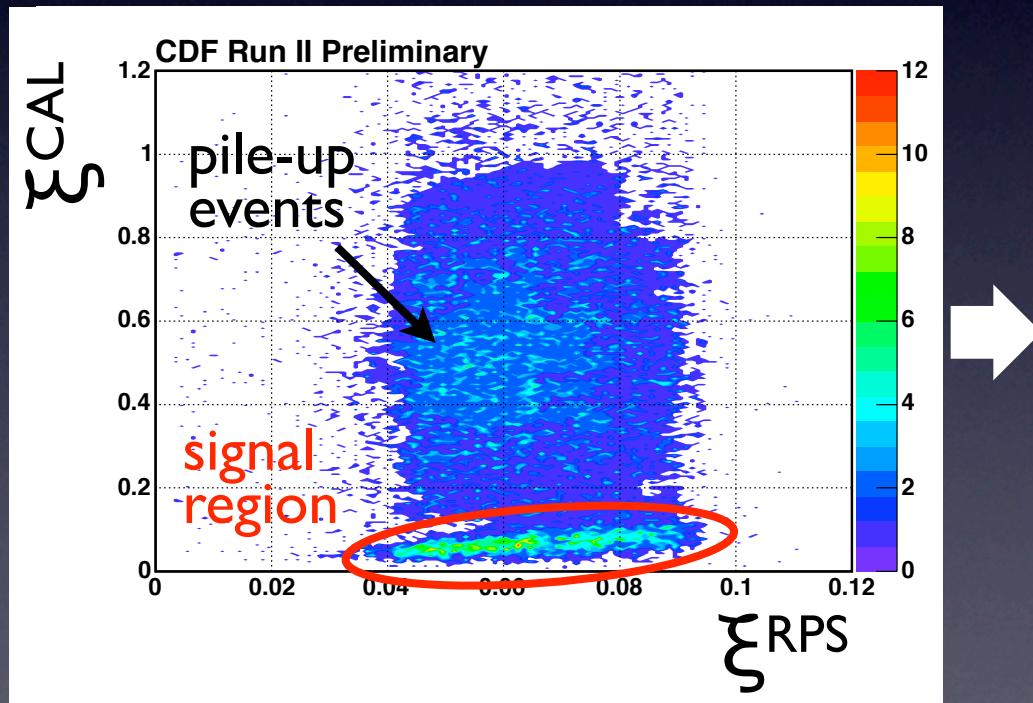
→ Used to measure particle energy and multiplicity in  $3.6 < |\eta| < 5.2$

# Run II Challenge

Among problems we had to overcome, the most challenging one is multiple  $\bar{p}p$  interactions (pile-up) that spoil diffractive signatures

$$\xi^{\text{CAL}} = \frac{\sum_{\text{towers}} E_T e^{-\eta}}{\sqrt{s}}$$

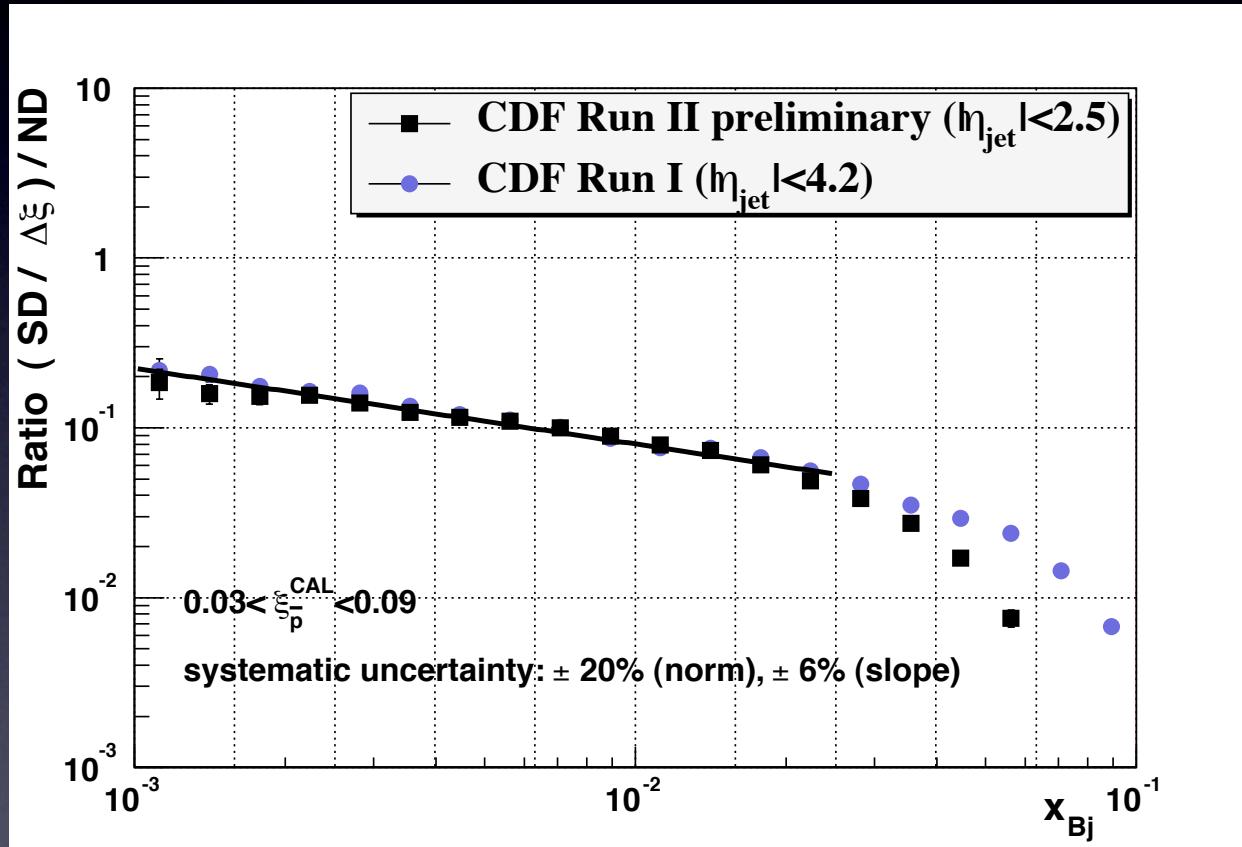
$L_{\text{inst}} \sim 2 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$  (not “high” lum!)



Used to reject pile-up events by selecting  $\xi^{\text{CAL}} < 0.1$

# $x_{\text{Bj}}\text{-dependence of } F_{jj}^D$

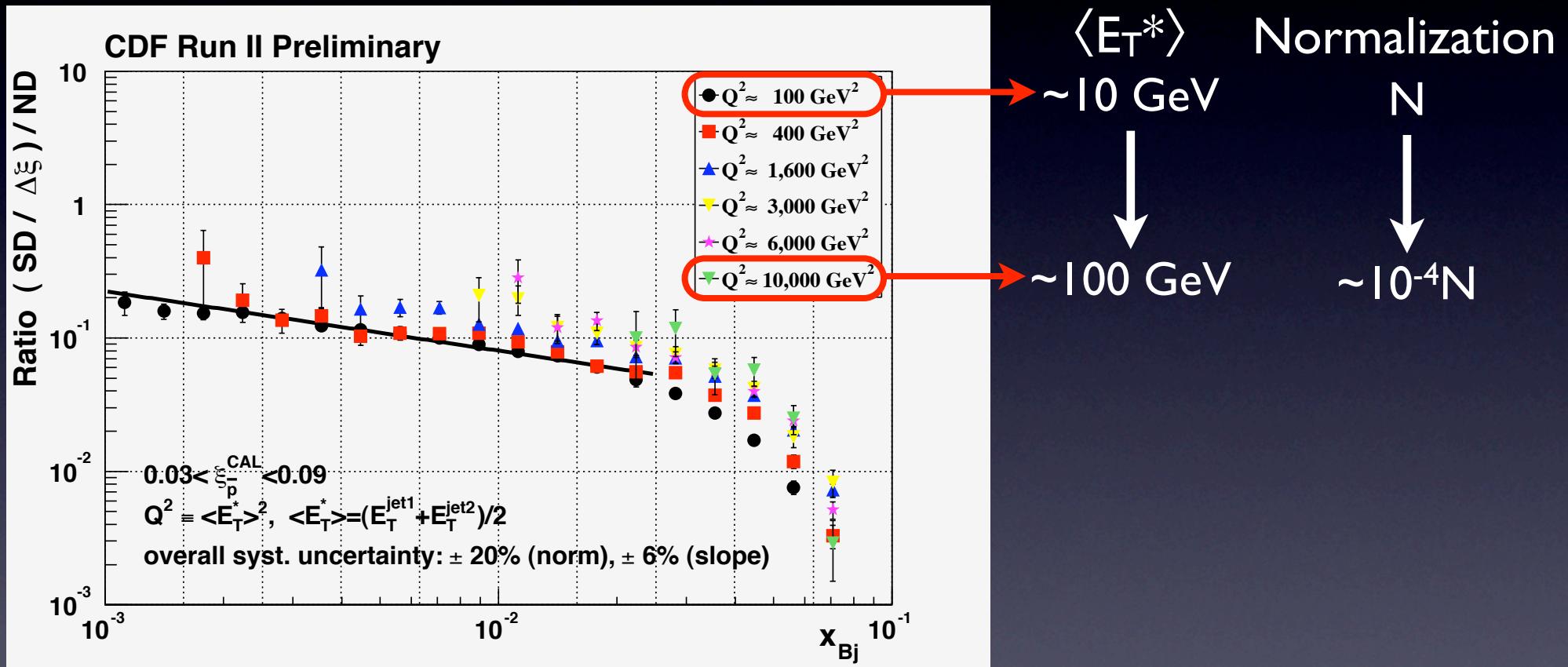
$$R^{\text{SD}}_{\text{ND}}(x_{\text{Bj}}) \approx \frac{F_{jj}^D(x_{\text{Bj}}, Q^2)}{F_{jj}(x_{\text{Bj}}, Q^2)}$$



→ Run I result is confirmed  
(difference at high  $x_{\text{Bj}}$  caused from different jet acceptance)

# $Q^2$ -dependence of $F_{jj}^D$

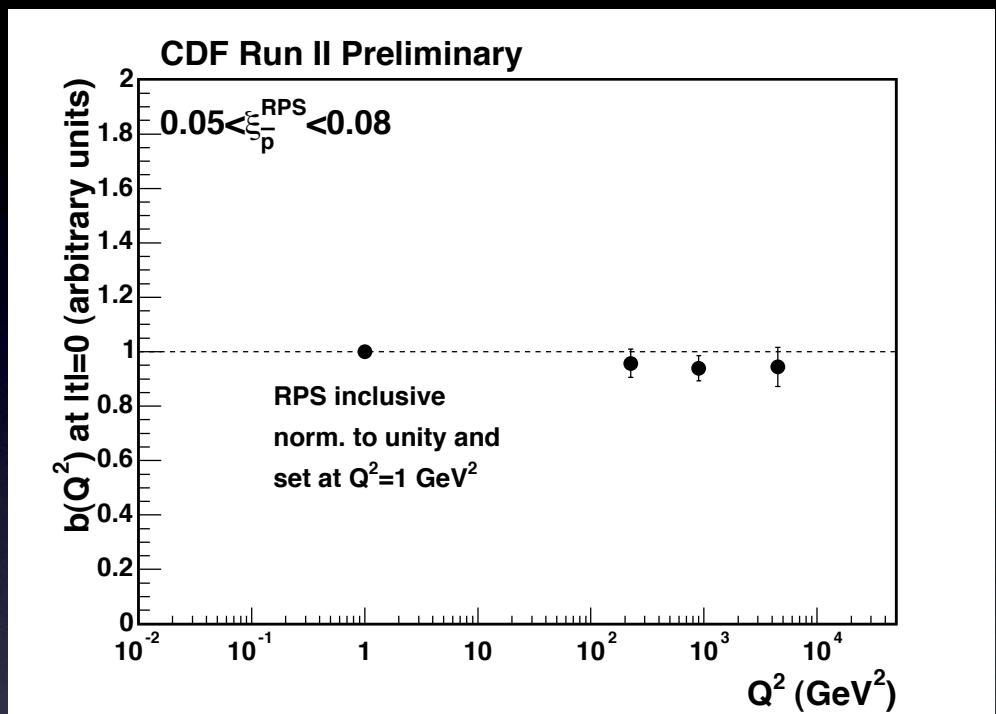
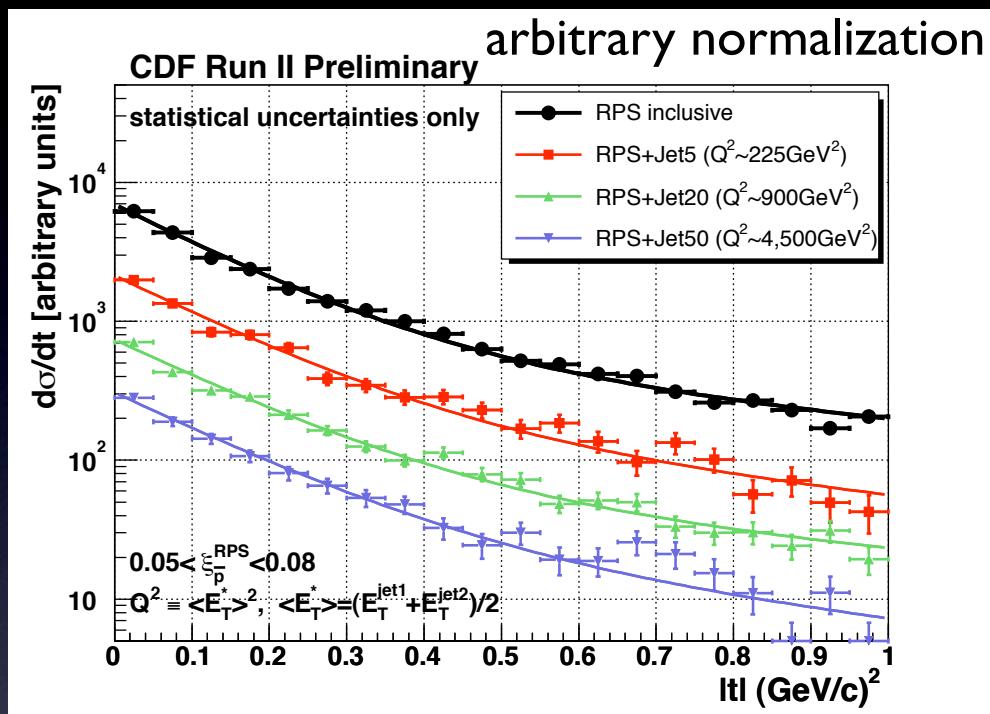
$$R^{SD}_{ND}(x_{Bj}) \approx \frac{F_{jj}^D(x_{Bj}, Q^2)}{F_{jj}(x_{Bj}, Q^2)}$$



No appreciable  $Q^2$  dependence relative to  $F_{jj}$  in  $100 < Q^2 < 10000 \text{ GeV}^2$

→ Pomeron evolves similarly to proton

# t-dependence of $F_{jj}^D$



Fit t-distributions to a double exponential function :

$$F = 0.9e^{b_1 t} + 0.1e^{b_2 t}$$

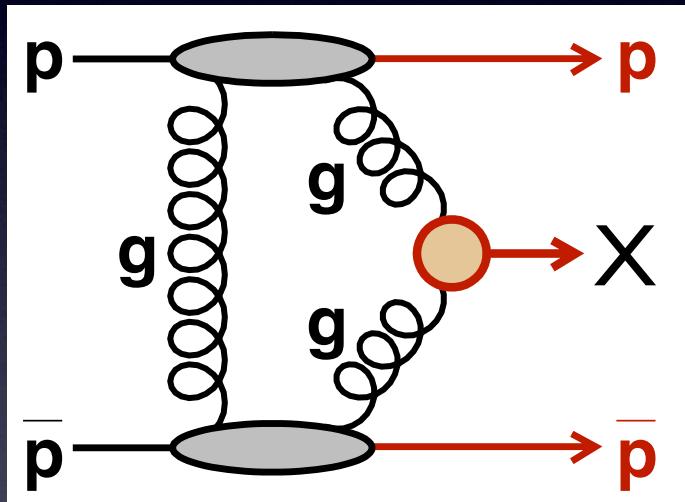
Slope at  $t=0$  is independent of  $Q^2$  in the range  $0 < Q^2 < 4500 \text{ GeV}^2$

Work in progress for

- absolute t-slope values
- larger  $|t|$  range up to  $\sim 4 \text{ GeV}^2$

# Exclusive Production

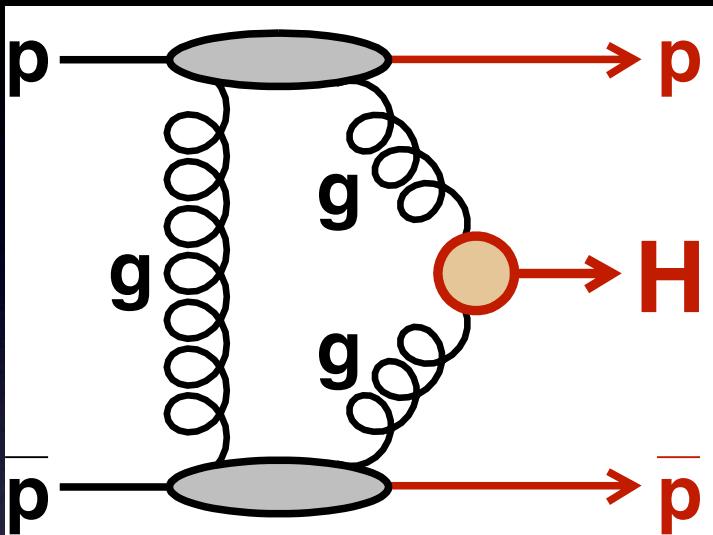
Motivated by unique potential to measure particle state produced in **exclusive reaction**  $\bar{p}p \rightarrow \bar{p}Xp$



- $J^{PC}=0^{++}$  state due to  $J_z=0$  rule
- clean signal (no underlying event)

Primary aim is Higgs boson (and new physics)

# Standard Model Higgs Boson



Tagging forward nucleons  
→ Higgs quantum numbers  
→ mass resolution  $< 2\sim 3$  GeV  
using missing mass method:  
 $M_H = (\vec{p}_{in} + \vec{p}_{in} - \vec{p}_{out} - \vec{p}_{out})^{1/2}$

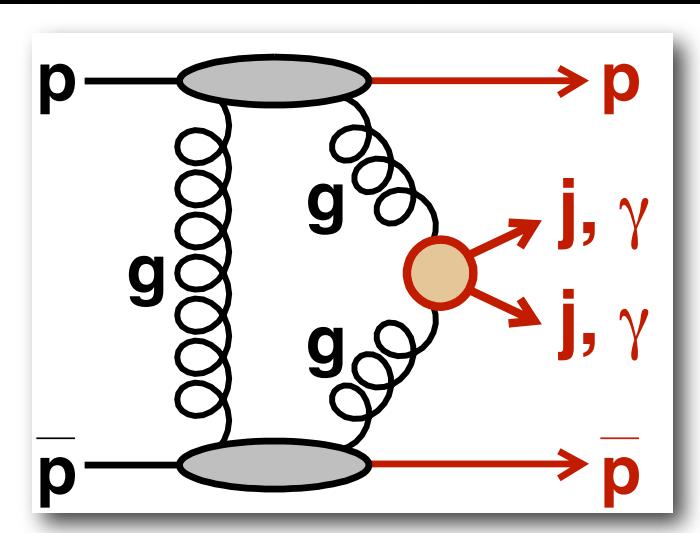
SM Higgs boson ( $M_H=120$  GeV):

$\sigma(pp \rightarrow pH\bar{p}) < 0.1$  fb at Tevatron, =  $\sim 10$  fb at LHC

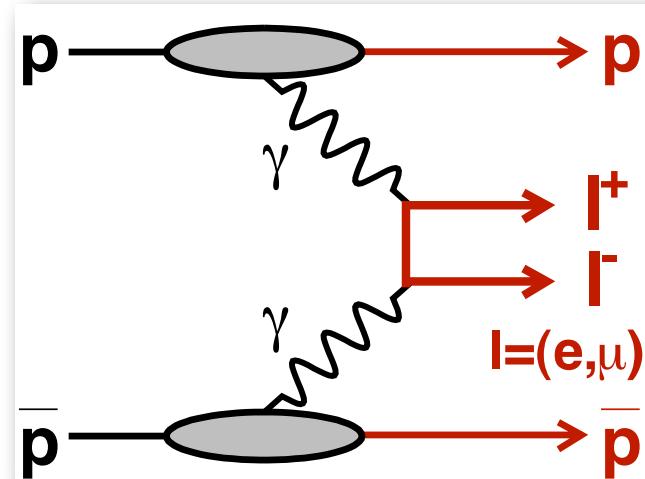
➡ Calibrate theoretical calculations using exclusive processes with higher cross sections

# Exclusive Production at CDF

Exclusive Di-jet/Di-photon



Exclusive Di-lepton



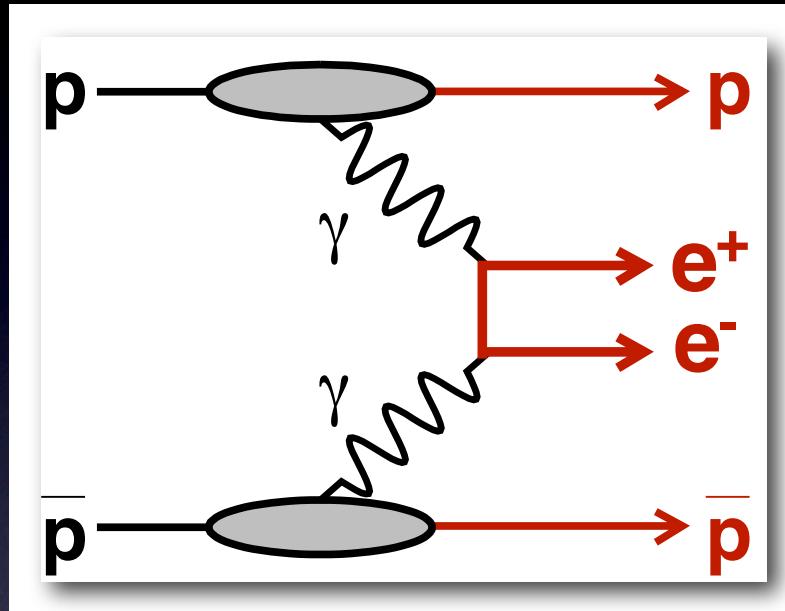
Validate analysis method

- QED-mediated process
- Cross section well known (< 1%)

Potential to improve LHC luminosity measurements

# Exclusive $e^+e^-$ Production

Good control sample for  $\bar{p}p \rightarrow \bar{p}\gamma\gamma p$  search



Analysis requires

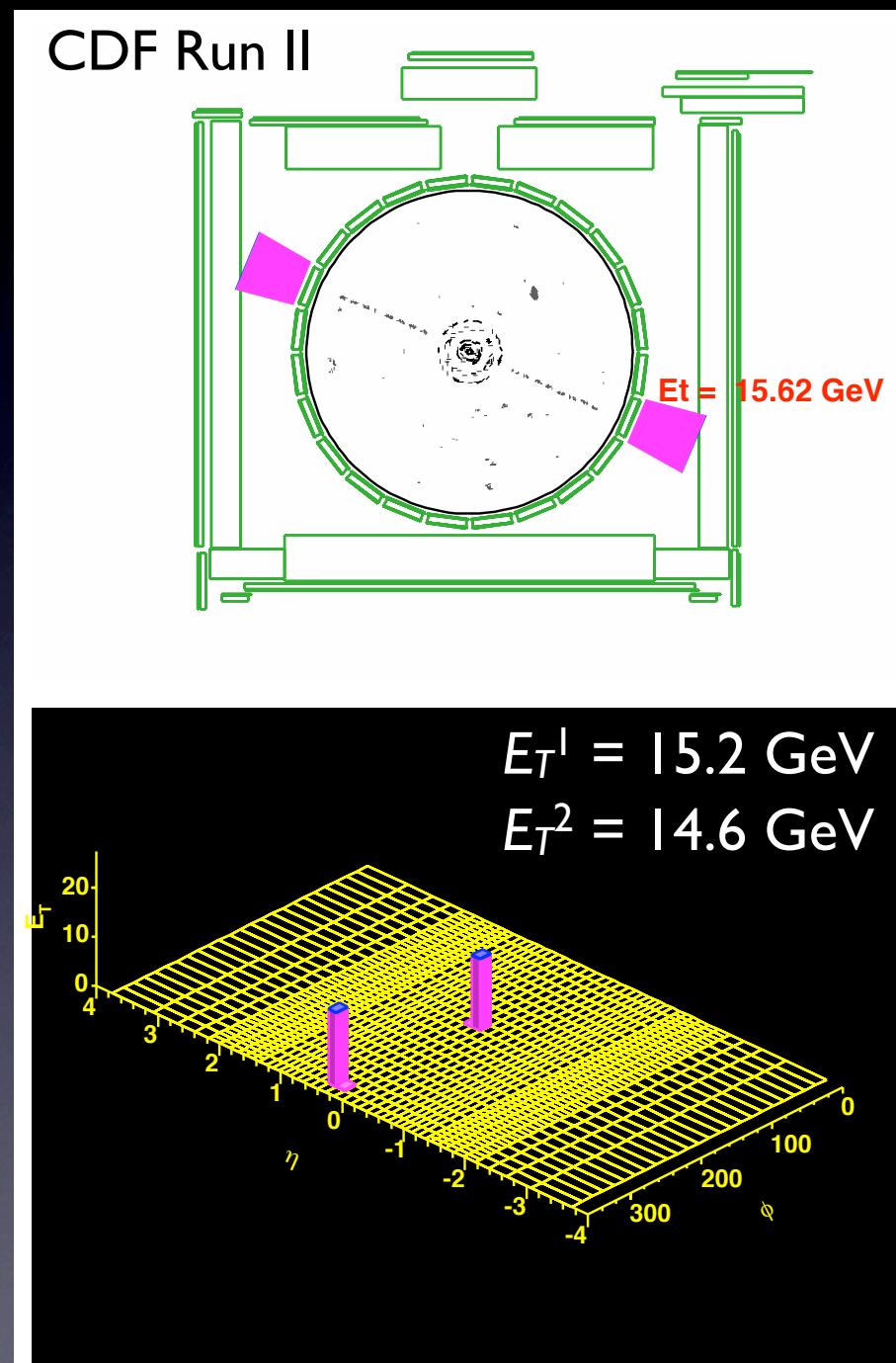
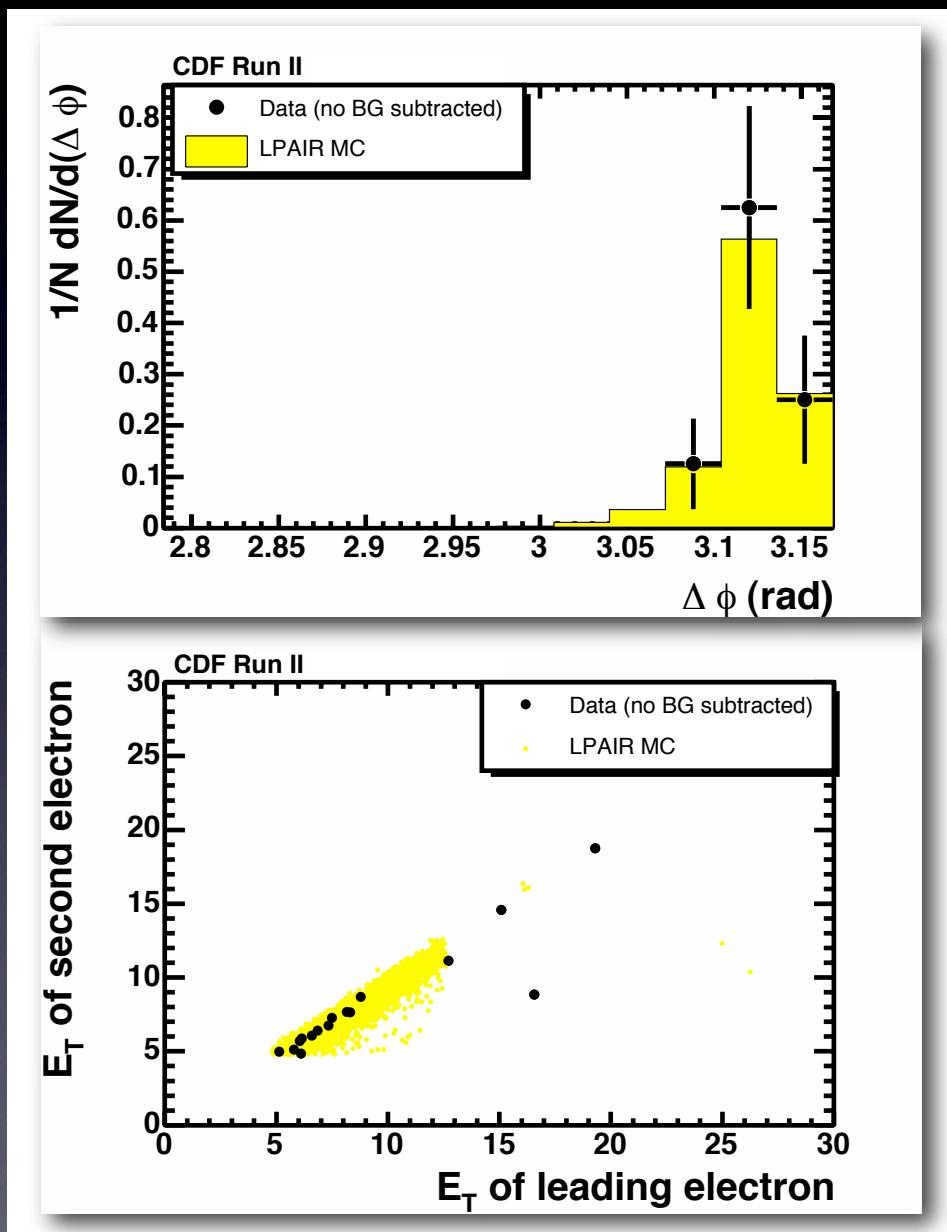
- protons do not dissociate
- only  $e^+e^-$  produced ( $E_T > 5\text{GeV}$ ,  $|\eta| < 2$ ) and nothing else

Detailed analysis performed to set thresholds for each detector

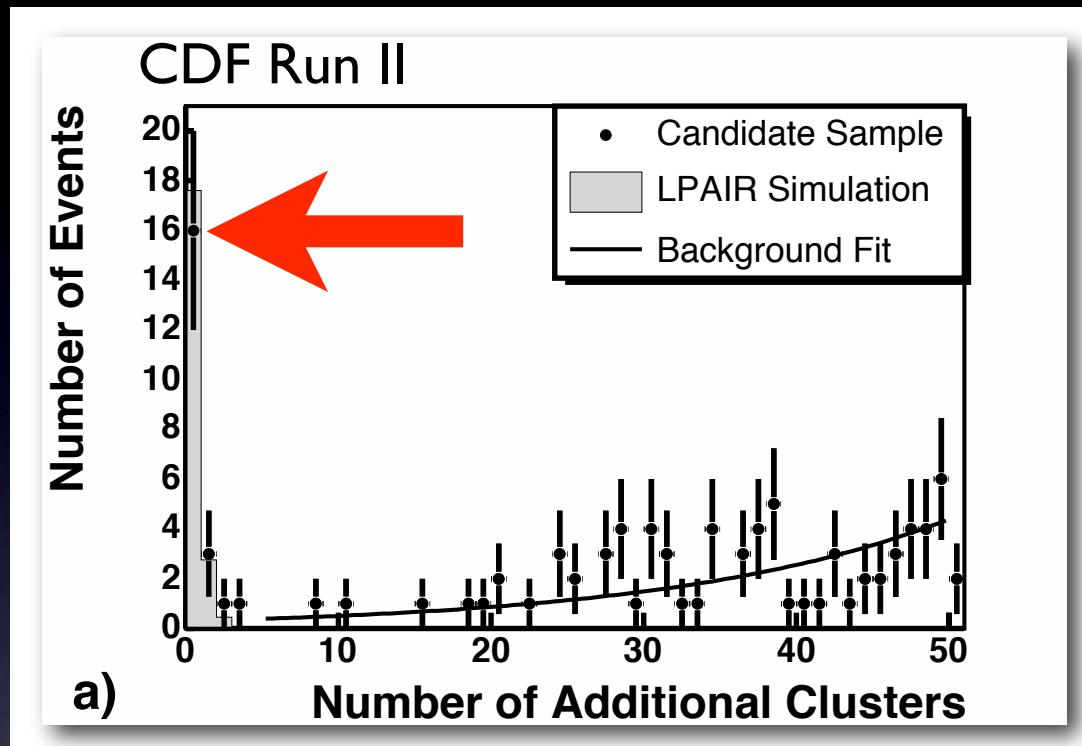
Effective Luminosity :  $46 \pm 3 \text{ pb}^{-1}$  (out of  $532 \text{ pb}^{-1}$ )

# Exclusive $e^+e^-$ Production

16 candidate events observed



# Exclusive $e^+e^-$ Production



PRL 98, 112001 (2007)

16 candidate events  
Background:  $1.9 \pm 0.3$  events  
→  $5.5\sigma$  observation

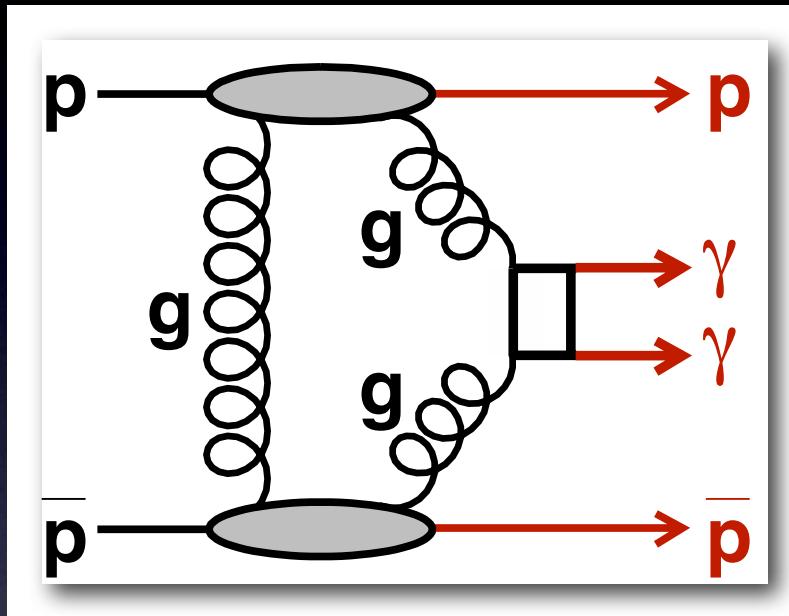
$$\sigma_{\text{MEAS.}} = 1.6^{+0.5}_{-0.3}(\text{stat}) \pm 0.3(\text{syst}) \text{ pb}$$

agrees with LPAIR Monte Carlo (QED) prediction

$$\sigma_{\text{LPAIR}} = 1.71 \pm 0.01 \text{ pb}$$

→ Good agreement serves to validate analysis method

# Exclusive Di-photon Production



QCD gluon exchange process  
→ factor 3~4 uncertainty in  $\sigma$

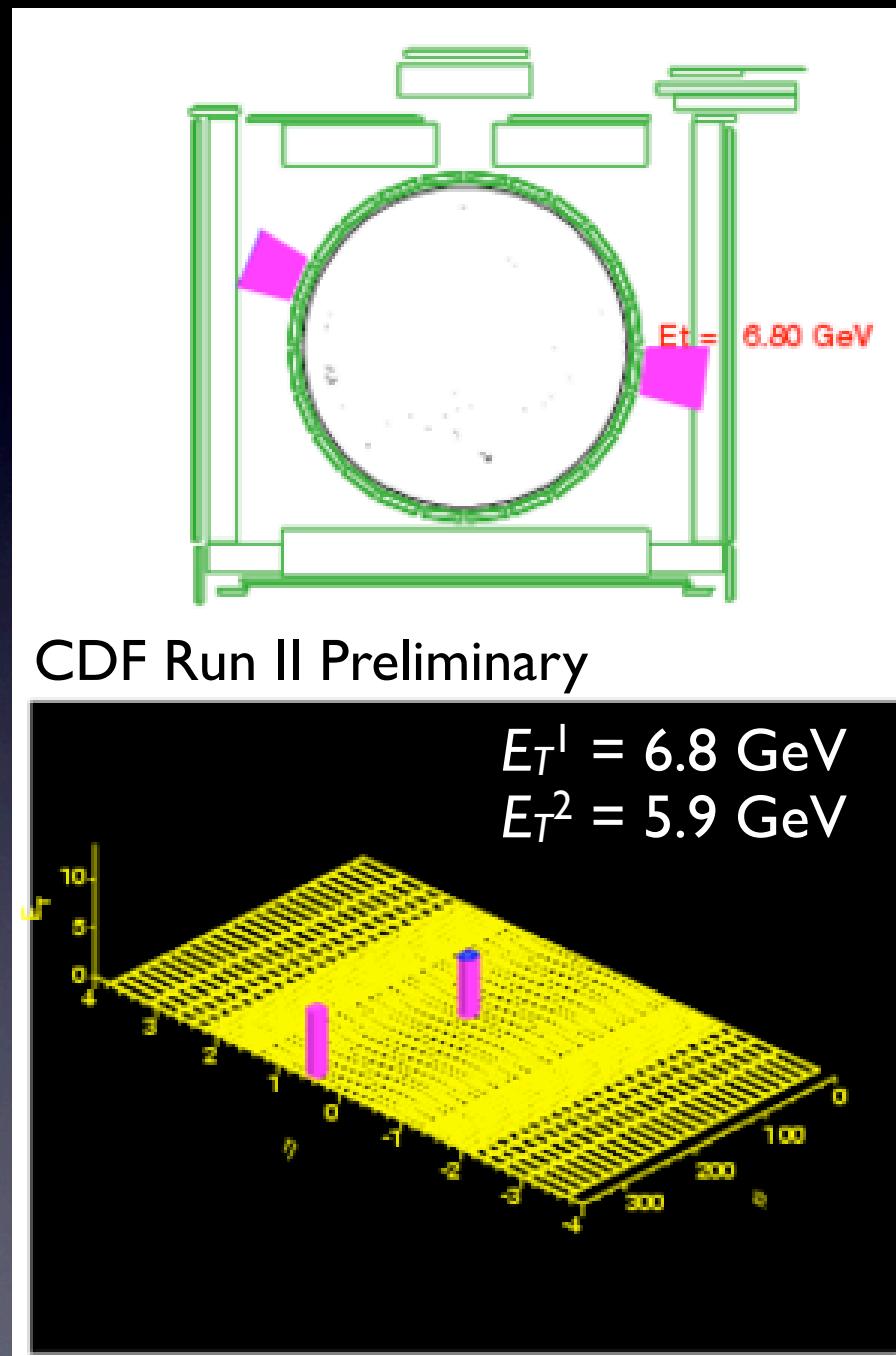
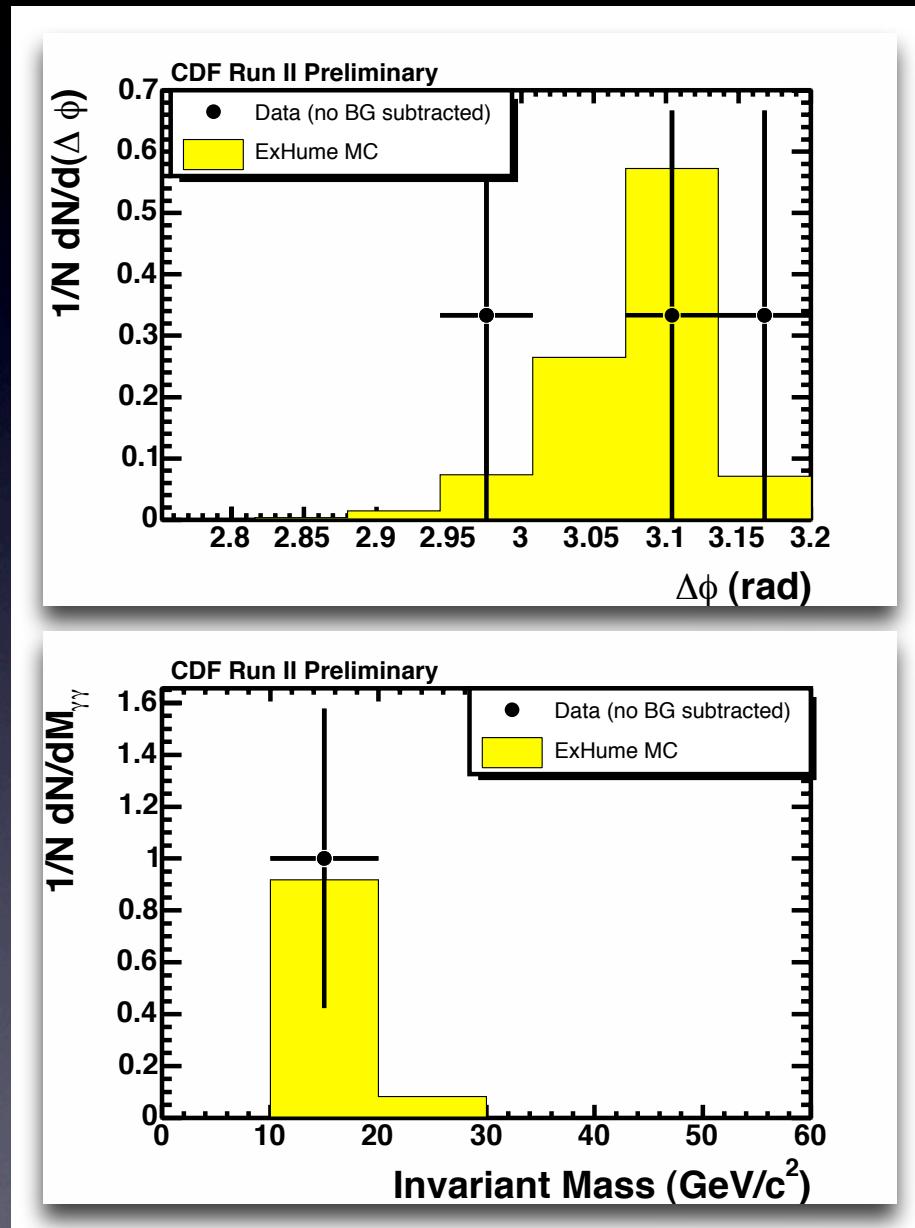
- Can be used to calibrate exclusive Higgs cross section

Analysis requires

- same event selections as  $\bar{p}p \rightarrow \bar{p}p e^+e^-$  (except  $e_{\text{track}}$  veto)
- only  $\gamma\gamma$  produced ( $E_T > 5\text{GeV}$ ,  $|\eta| < 1$ ) and nothing else

# Exclusive Di-photon Production

3 candidate events observed



# Exclusive Di-photon Production

3 candidate events including exclusive  $\pi^0\pi^0$  or  $\eta\eta$  ( $\pi^0, \eta \rightarrow \gamma\gamma$ )

Background :  $0.09 \pm 0.04$  events

→  $3.7\sigma$  evidence for combined exclusive ( $\gamma\gamma, \pi^0\pi^0, \eta\eta$ ) signal

EM shower analysis indicates 2 of 3 events are likely  $\gamma\gamma$

$$\sigma(\bar{p}p \rightarrow \bar{p}\gamma\gamma p) < 410 \text{ fb (95% C.L.)}$$

Khoze, Martin, Ryskin :  $\sigma_{\gamma\gamma} \sim 40 \text{ fb}$  (factor 3 uncertainty)

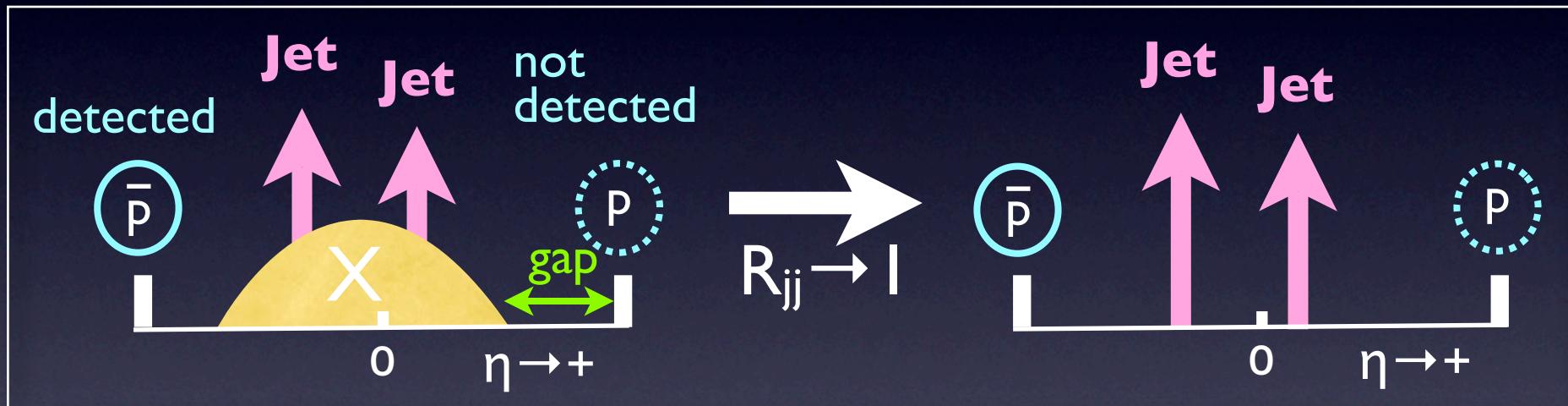
Assuming 2 events are exclusive  $\gamma\gamma$ ,

$$\sigma(\bar{p}p \rightarrow \bar{p}\gamma\gamma p) = 90^{+120}_{-30}(\text{stat}) \pm 16(\text{syst}) \text{ fb}$$

# Exclusive Di-jet Production

## Strategy

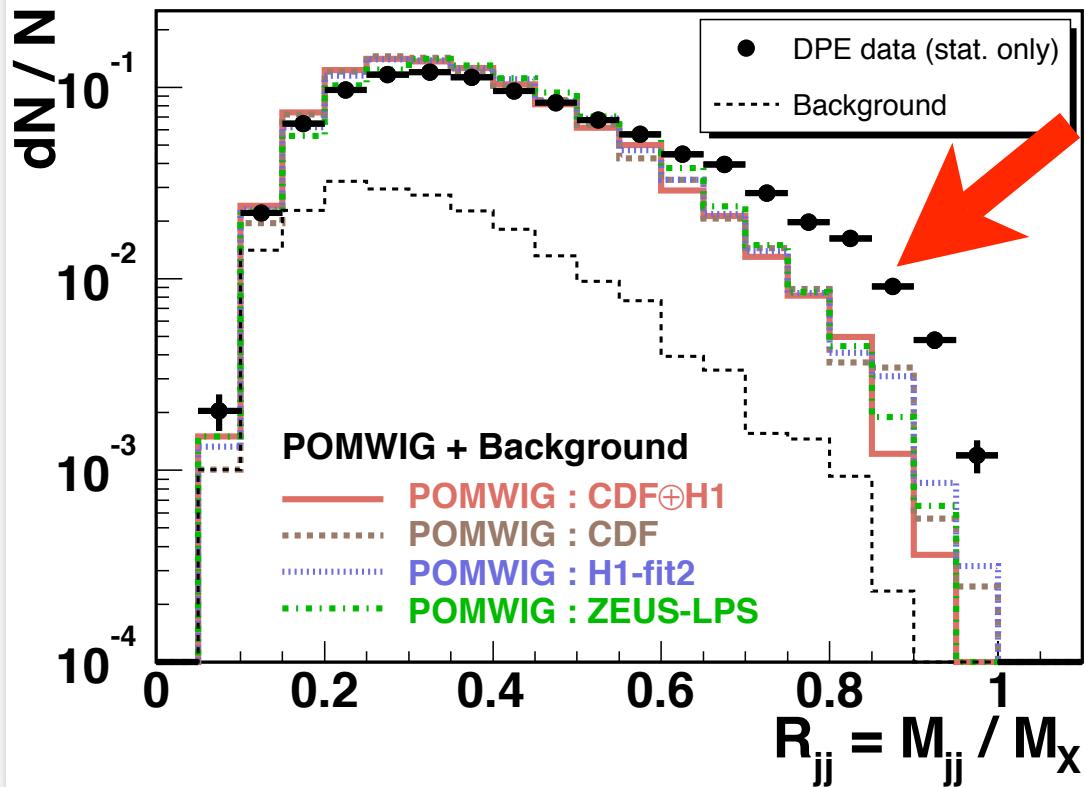
- Select inclusive DPE di-jets :  $\bar{p}+p \rightarrow \bar{p}+X(\exists 2\text{jets})+\text{gap}$
- Reconstruct di-jet mass fraction :  $R_{jj} = M_{jj}/M_X$
- Look for data excess over DPE di-jet background as  $R_{jj} \rightarrow 1$



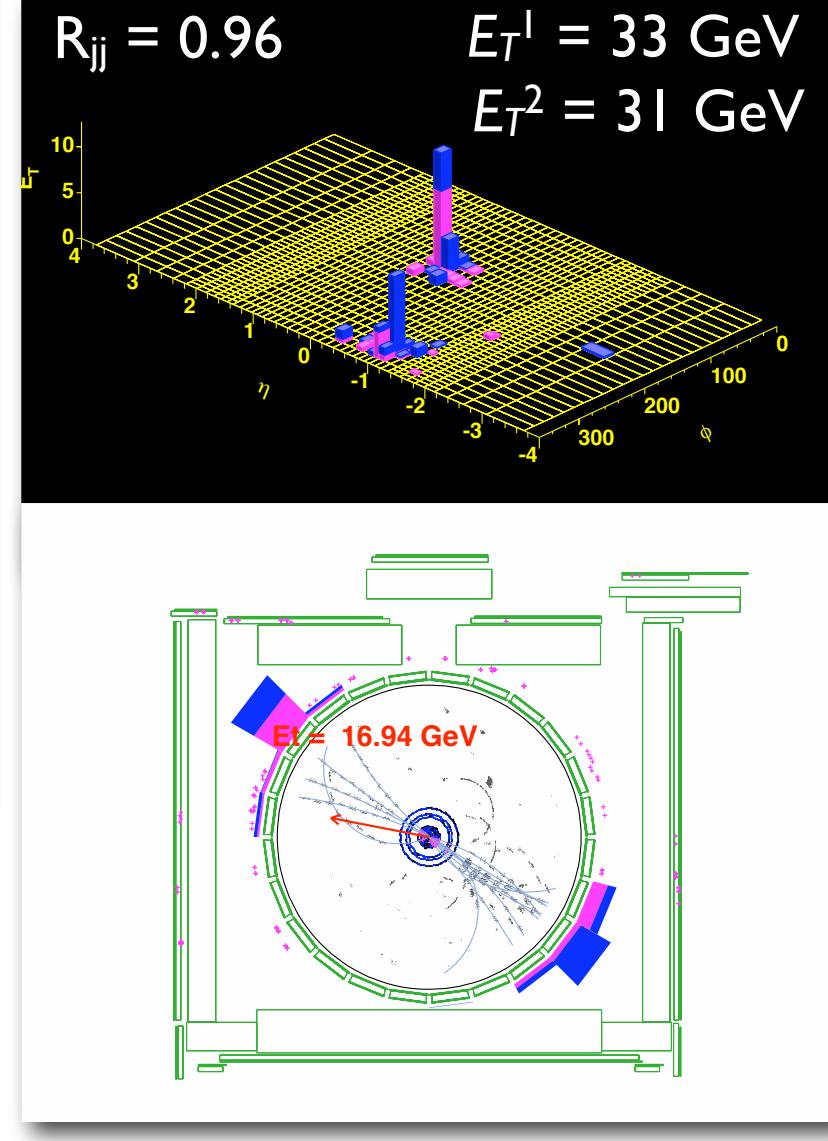
- Signal ( $R_{jj}=1$ ) smeared due to shower/hadronization effects, NLO  $gg \rightarrow ggg, q\bar{q}g$  contributions, etc.
- DPE di-jet background shape from POMWIG MC simulation ( $\Rightarrow$  Uncertainty from Pomeron PDF)

# Di-jet Mass Fraction

CDF Run II Preliminary



CDF Run II Preliminary



Excess observed over MC simulations with varied PDFs

# MC Fit to $R_{jj}$ Shape

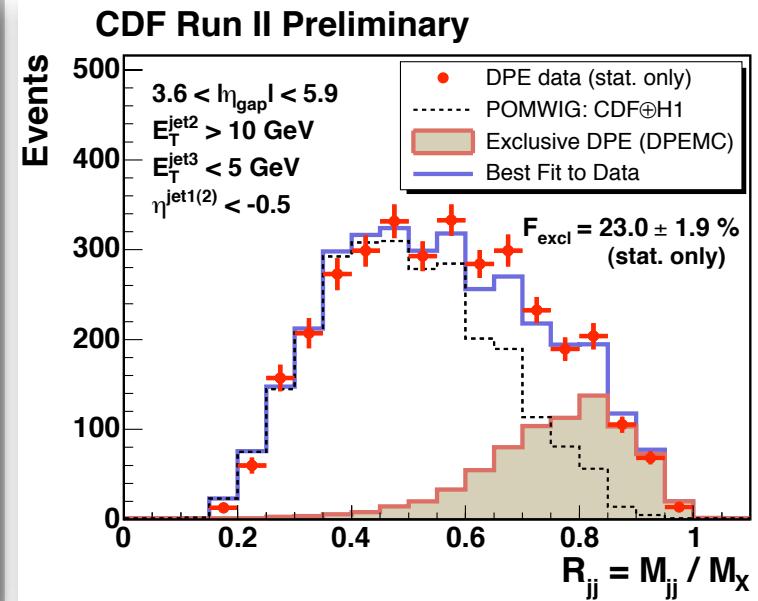
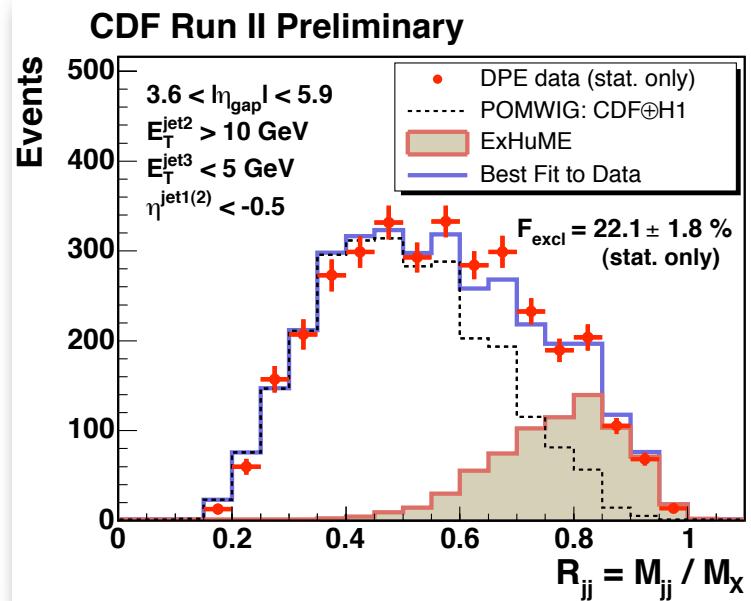
Binned likelihood fits (MC normalizations as free parameters)

Signal MC

**ExHuME**  
CPC 175,232(2006)

**DPEMC Exclusive DPE**  
CPC 167,217(2005)

- data
- bkgd
- signal
- fit



CDF⊕HI  
CDF  
HI-fit2  
ZEUS-LPS

$22.1 \pm 1.8 \%$   
 $21.7 \pm 1.8 \%$   
 $24.7 \pm 2.0 \%$   
 $24.3 \pm 2.0 \%$

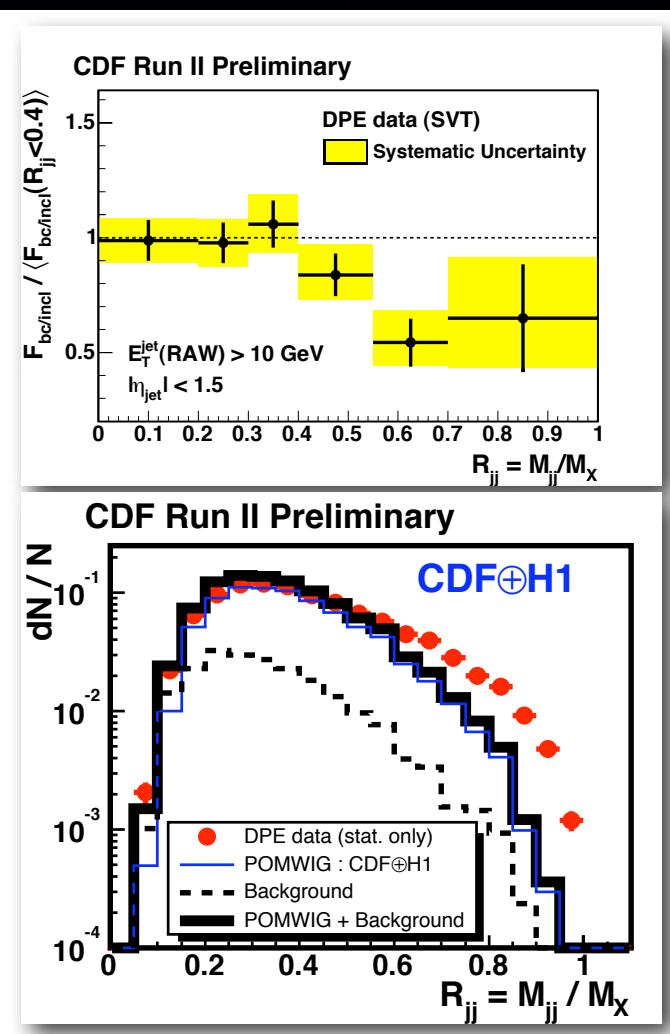
$23.0 \pm 1.9 \%$   
 $22.6 \pm 1.9 \%$   
 $26.0 \pm 2.1 \%$   
 $25.4 \pm 2.1 \%$

stat. error only

# Exclusive Di-jet Signal

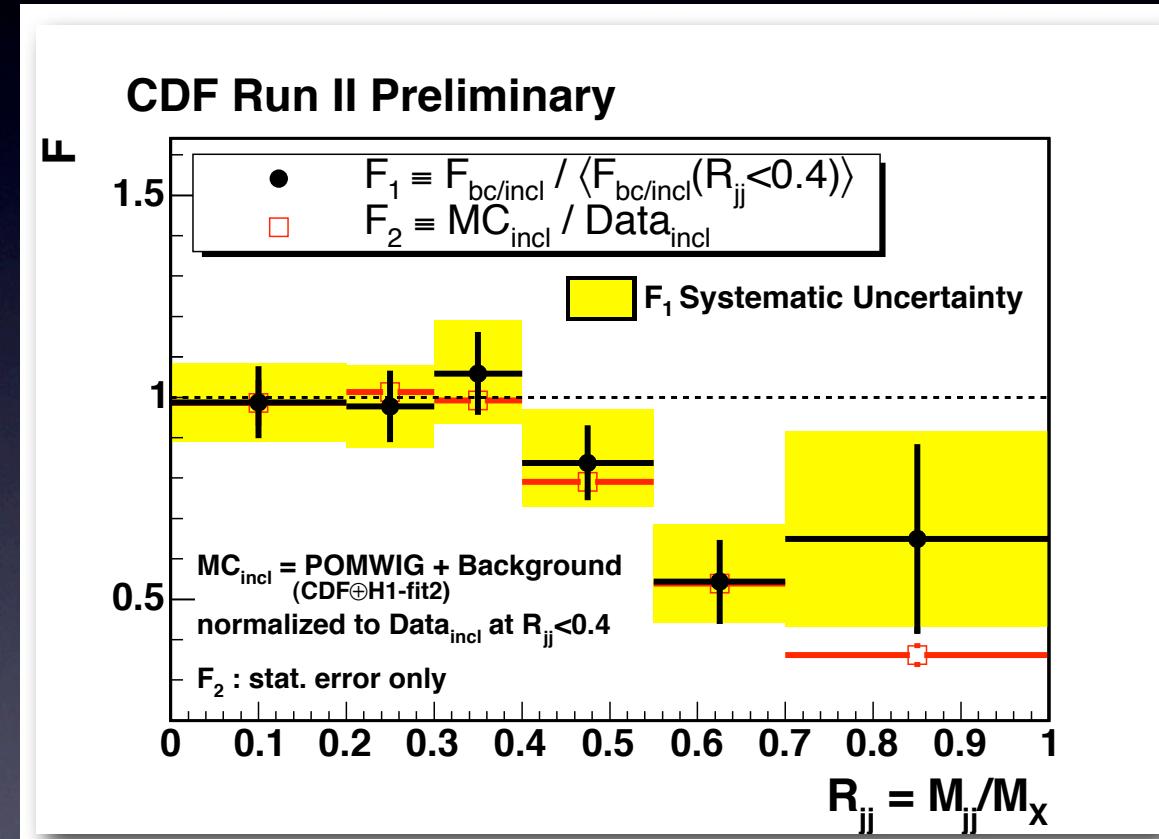
LO exclusive  $gg \rightarrow q\bar{q}$  suppressed due to  $J_z=0$  rule

→ Look for the suppression in heavy flavor jet fraction vs  $R_{jj}$



$\frac{HF_{\text{data}}}{incl_{\text{data}}}$

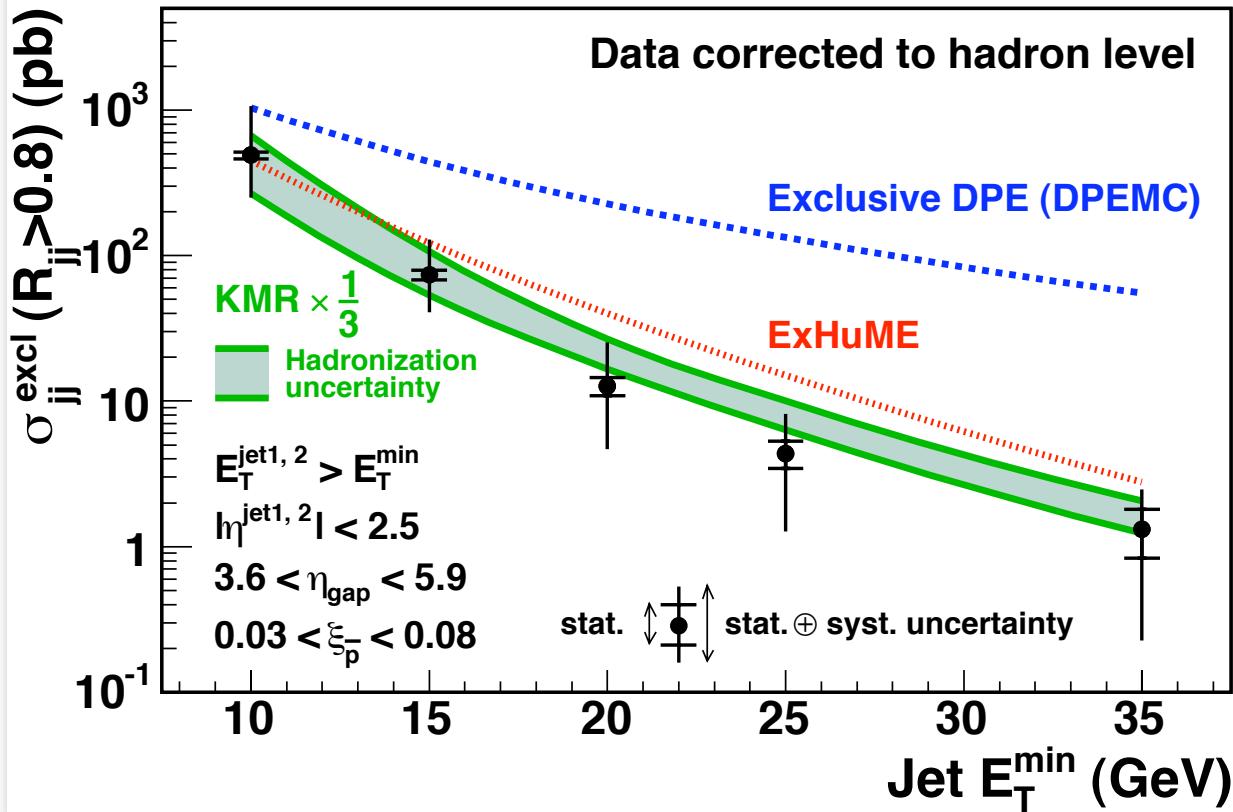
$\frac{incl_{\text{MC}}}{incl_{\text{data}}}$



The two results are consistent with each other

# Exclusive Di-jet Cross Section

CDF Run II Preliminary



DPEMC Exclusive DPE

ExHuME

Khoze, Martin, Ryskin

at LO parton-level

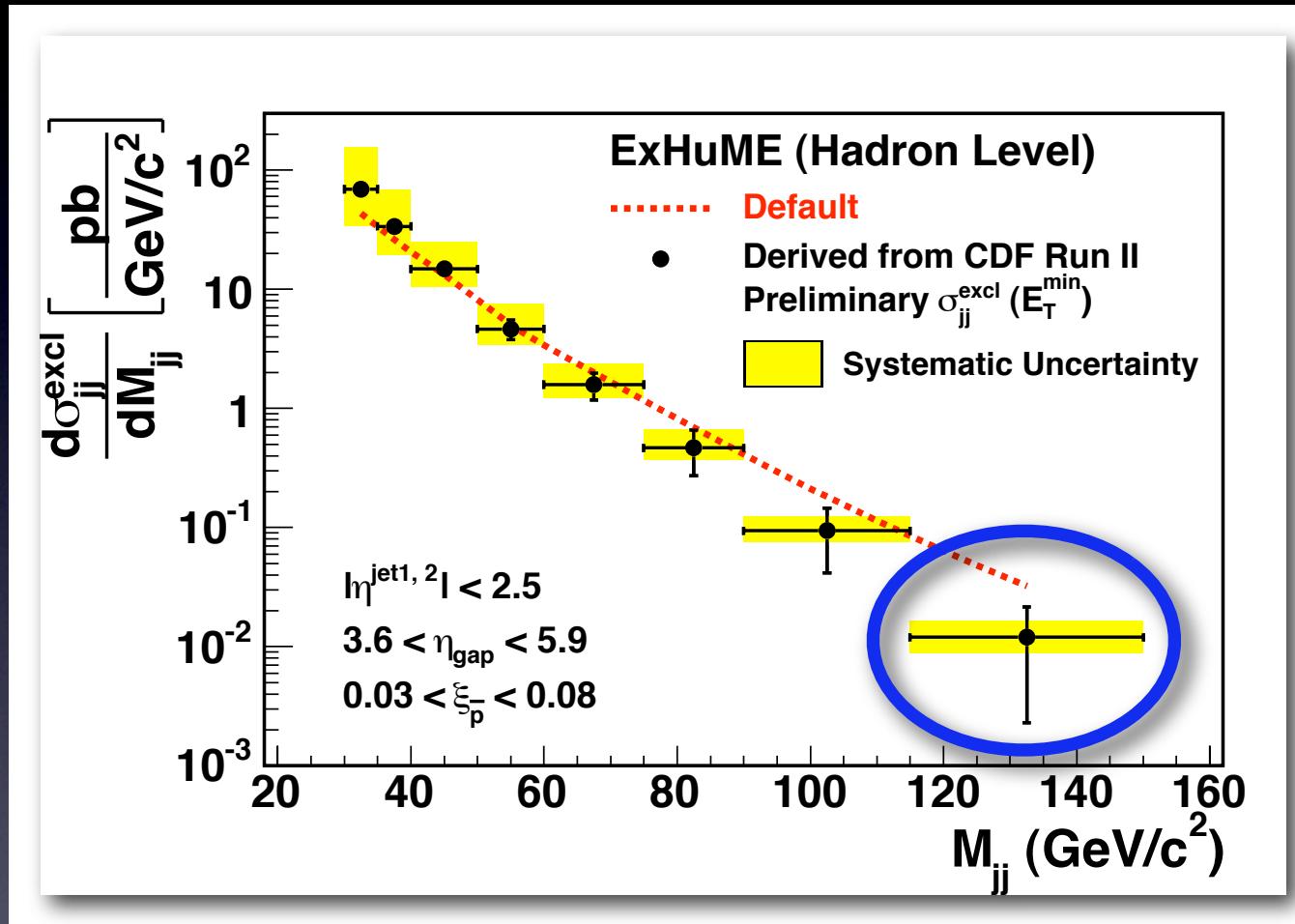
(factor 3 uncertainty)

hep-ph/0507040

Measured  $\sigma_{jj}^{excl}$  prefers ExHuME and KMR calculations

# Exclusive Di-jet Mass Reach

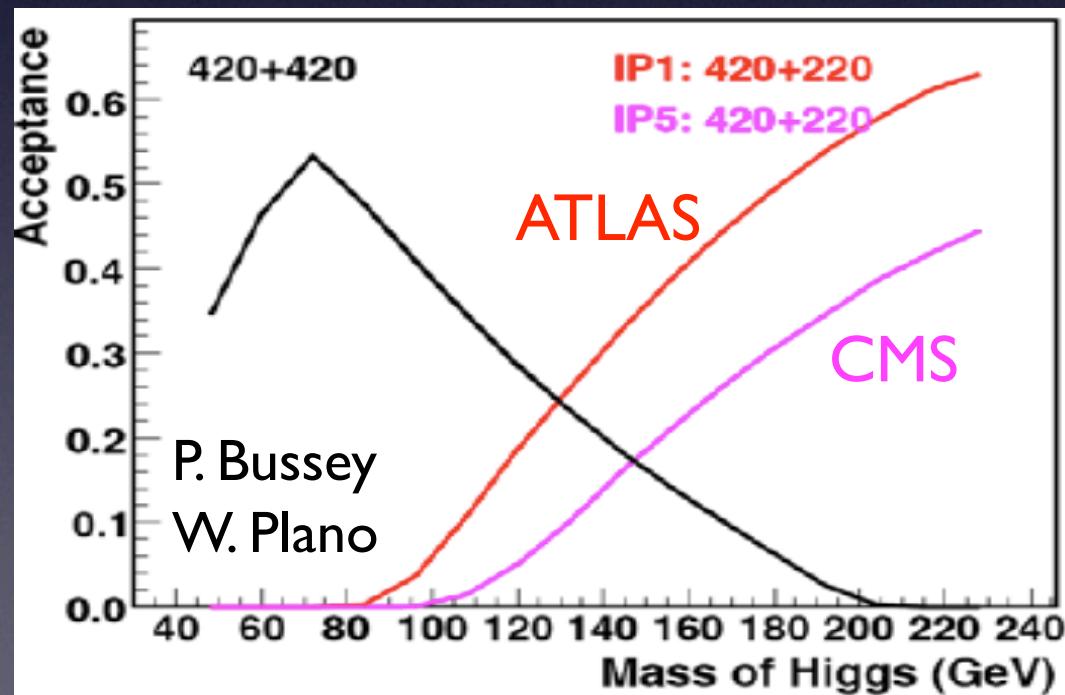
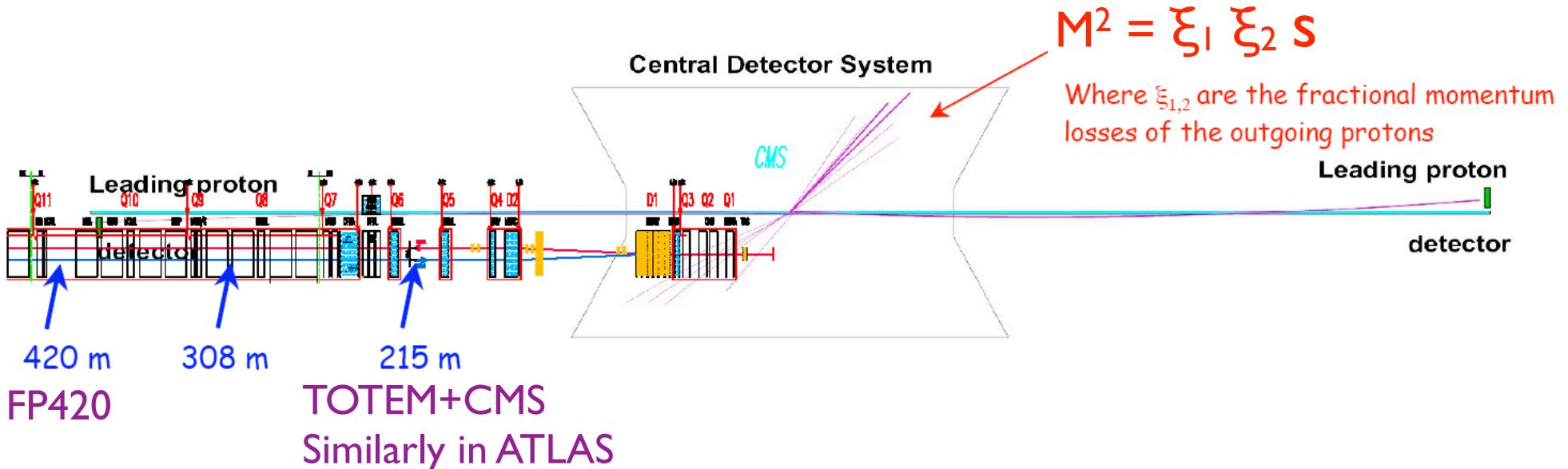
Derive  $d\sigma_{jj}^{\text{excl}}/dM_{jj}$  from measured  $\sigma_{jj}^{\text{excl}}$  using ExHuME



CDF  $\bar{p}p \rightarrow \bar{p}jjp$  reaches Higgs mass range!!

→  $p\bar{p} \rightarrow pH\bar{p}$  at LHC

# PP → pHp Acceptance at LHC

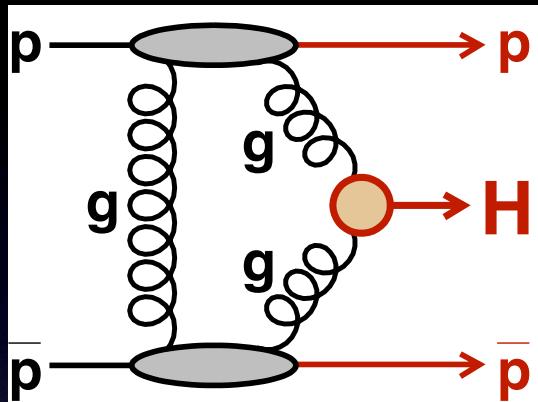


Lumi=10<sup>33-34</sup>cm<sup>2</sup> (Low  $\beta^*$ )

Acceptance	$\xi$	$M$
220m+220m	0.02-0.2	200-2000
420m+420m	0.002-0.02	30-200

⇒ FP420 project

# Exclusive Higgs at LHC



Will work more  
on this slide (Koji)

$M_H$ (GeV)	120	140	160
$H \rightarrow WW^{(*)} \rightarrow l\nu jj$ (fb) proton tagger acceptance	0.25	0.63	0.83
#Events ( $30\text{fb}^{-1}$ ) ATLAS lepton trigger	1.1	3.6	5.8
#Background	xx	xx	xx

B .Cox et al., Eur. Phys. J. C45, 401 (2006)

# FP420 Project

Feasibility study and R&D for the proton detector at 420m from the IP in normal high luminosity running

[www.fp420.com](http://www.fp420.com)

## FP420 R&D Project

home  
collaboration  
meetings  
papers  
public  
private

The FP420 R&D project is an international collaboration with members from 29 institutes from 10 countries.

The aim is to assess the feasibility of installing proton tagging detectors at 420m from the interaction points of the ATLAS and / or CMS experiments at the LHC.

The physics potential of forward proton tagging in the 420m region at the LHC has only been fully appreciated within the last few years. By detecting protons that have lost less than 1% of their longitudinal momentum in rich QCD interactions in the

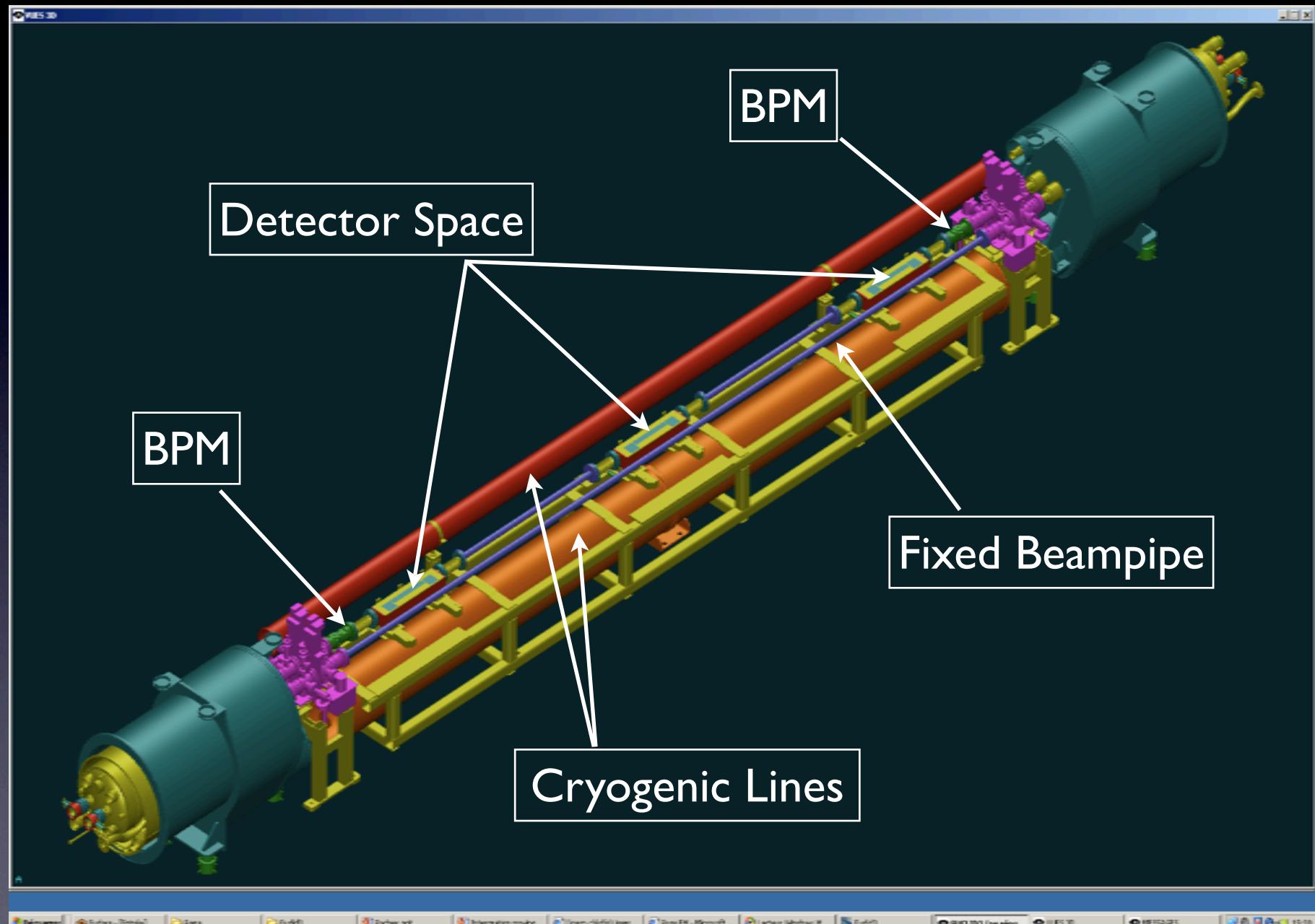
LATEST NEWS 19/06/2006

Next collaboration meeting will be at UTA, Texas, 26th -27th March

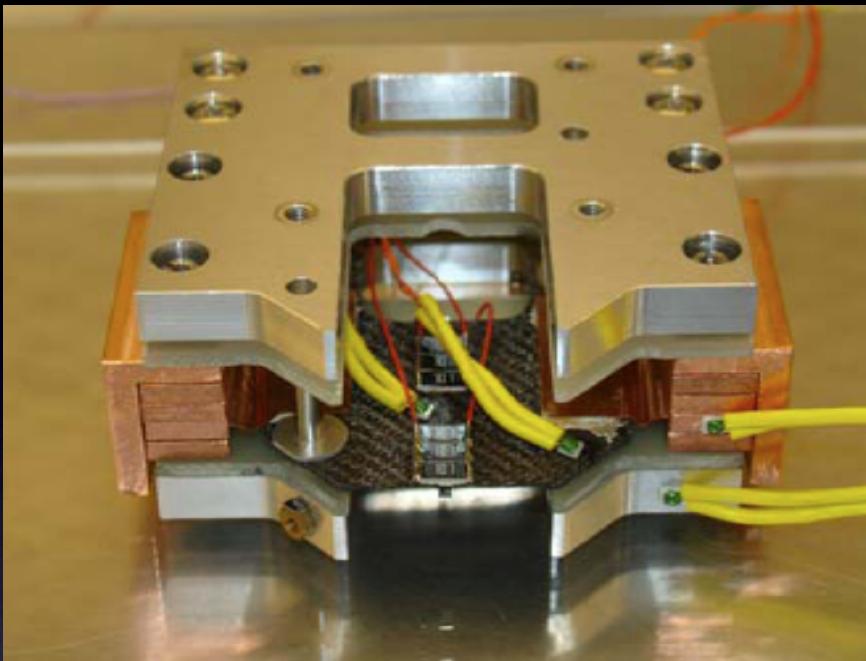
The Small x meeting at FNAL (29th - 31st March) will be followed by the FP420 meeting at UTA, Texas (1st - 3rd April).

- ▶ Project fully funded
- ▶ Aim is to install detectors in Fall 2008

# Mechanics at 420m



# Silicon Detectors

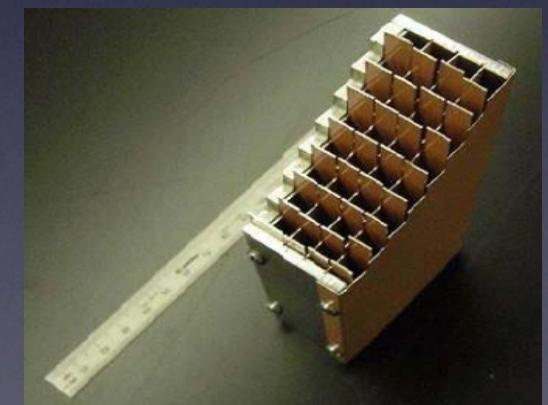


Test beam at CERN in Sep 2007

## Fast Timing Detectors

Reject pile-up backgrounds by measuring  
 $Z_{\text{vertex}}$  from time-of-flight

UTA, Albert, FNAL, Louvain



# Summary

Both soft and hard diffraction results appear to point to a picture of diffractive exchange;

- Universality of rapidity gap formation (soft↔hard)
- Composite ‘proton-like’ structure
- Factorization breakdown and restoration

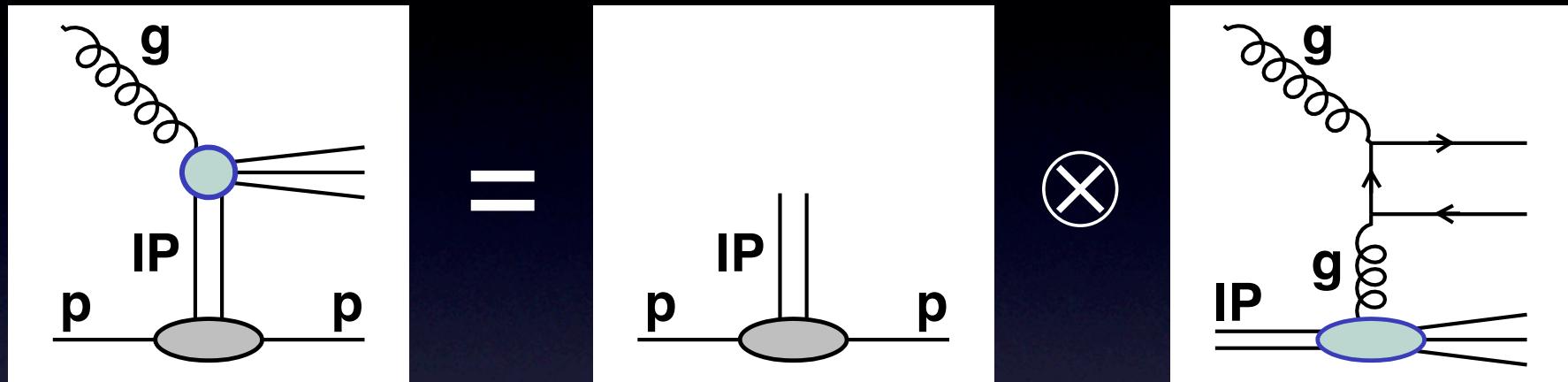
→ Run II studies will help understand the QCD aspects

Exploring physics with exclusive production

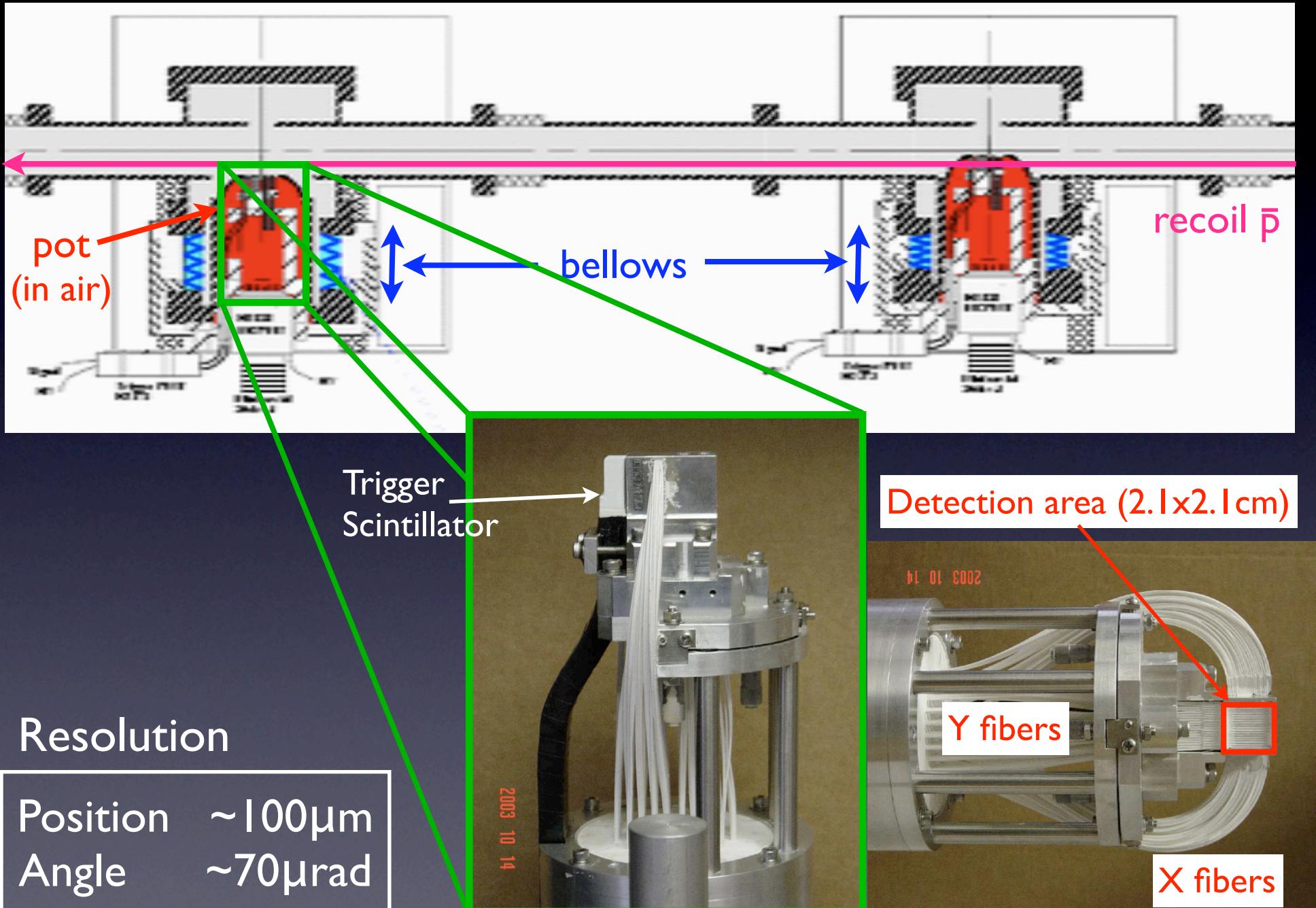
- Perturbative QCD appears to work well
- CDF results encouraging for future prospects at LHC
- Ongoing efforts to install proton taggers at LHC  
→ FP420 project

# Backup

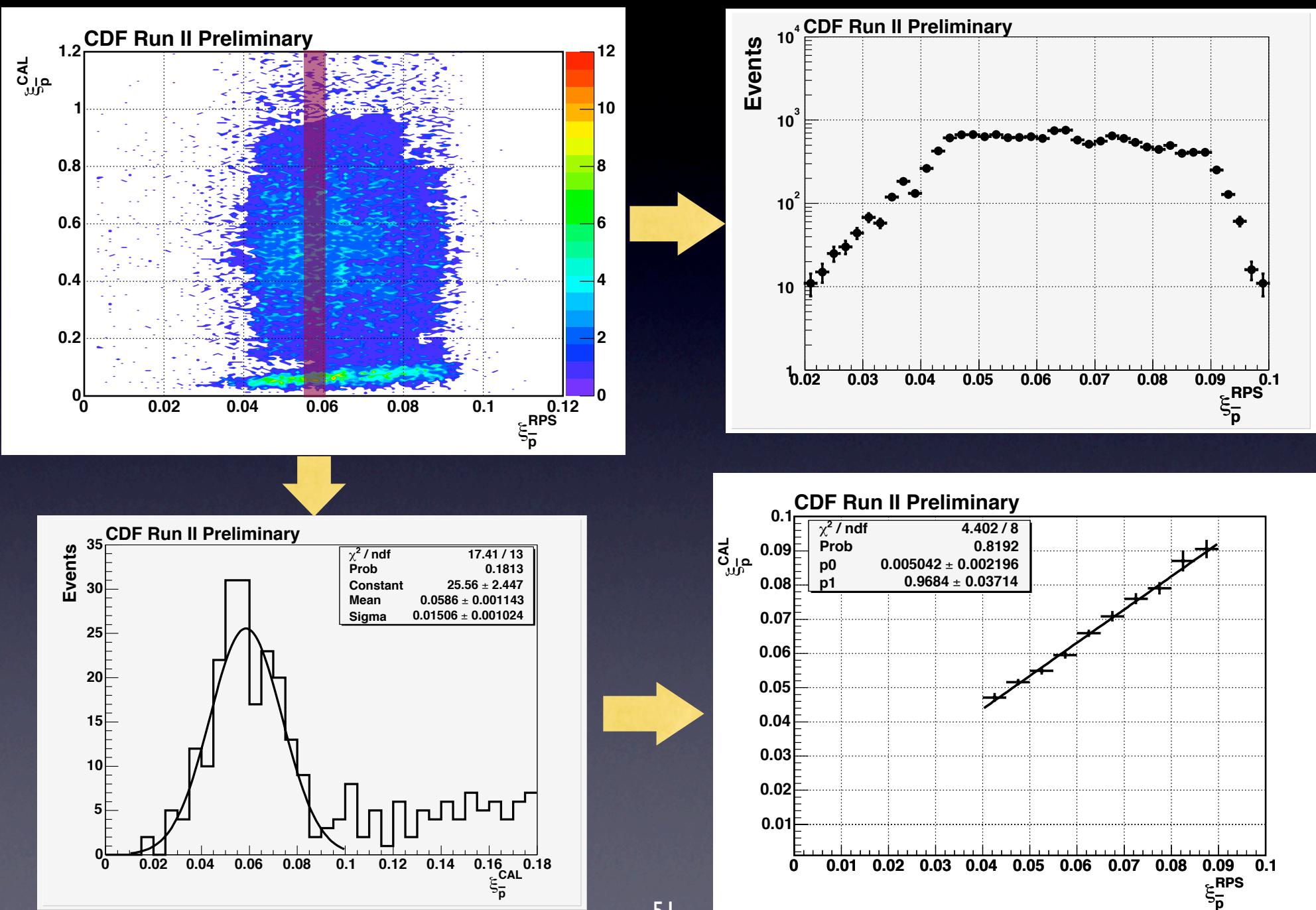
# Regge Factorization



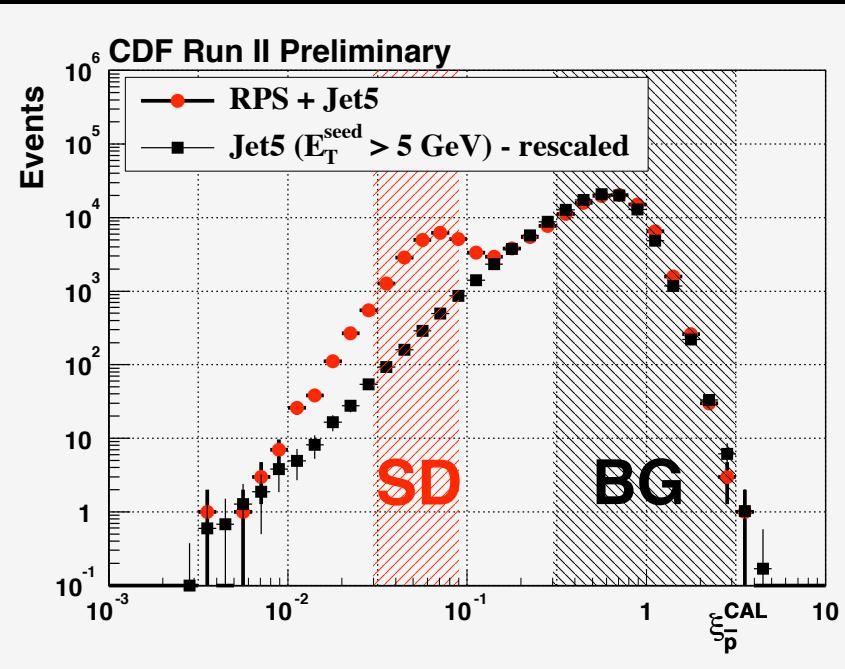
# Roman Pot Spectrometers



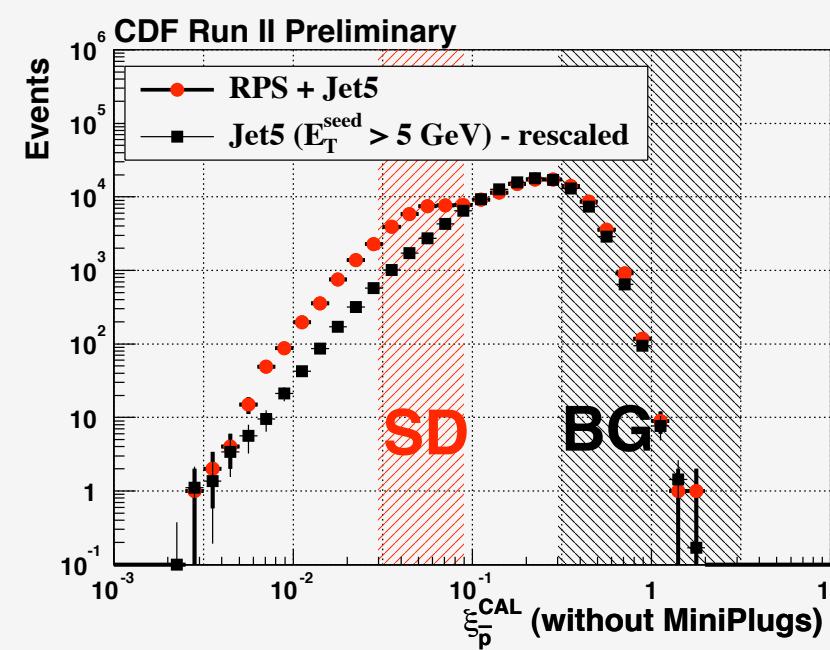
# $\xi$ Calibration



# Run II Challenge



With MiniPlugs

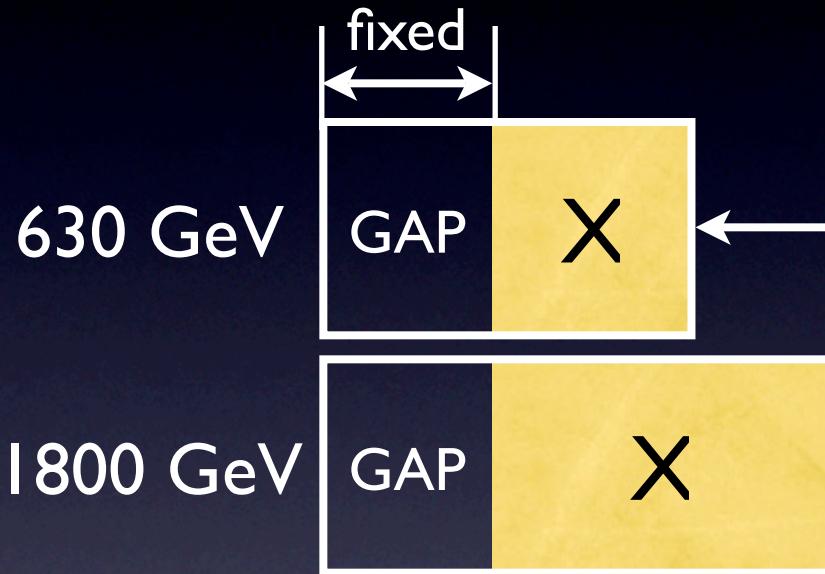


Without MiniPlugs

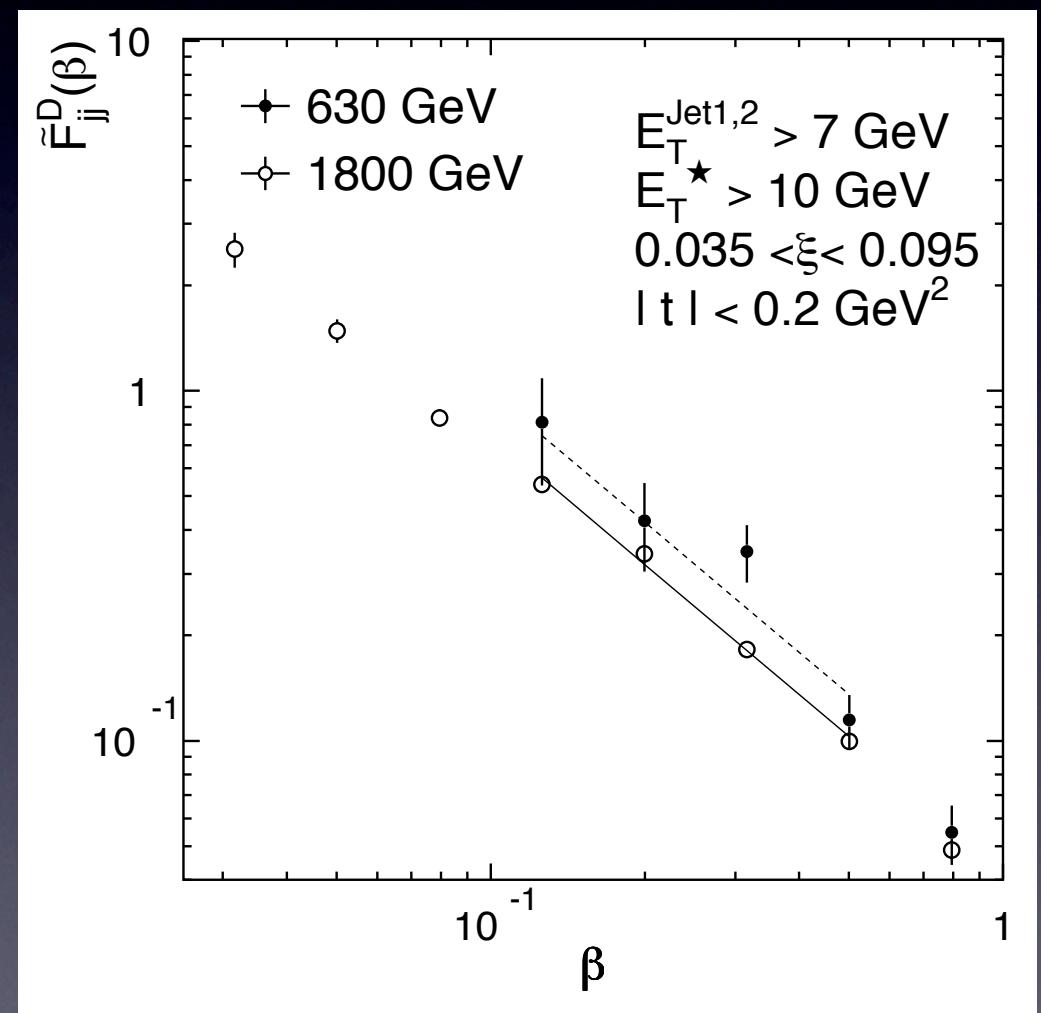
→ Important to have MiniPlugs to have this method work

# Diffractive Structure Functions at 630 and 1800 GeV

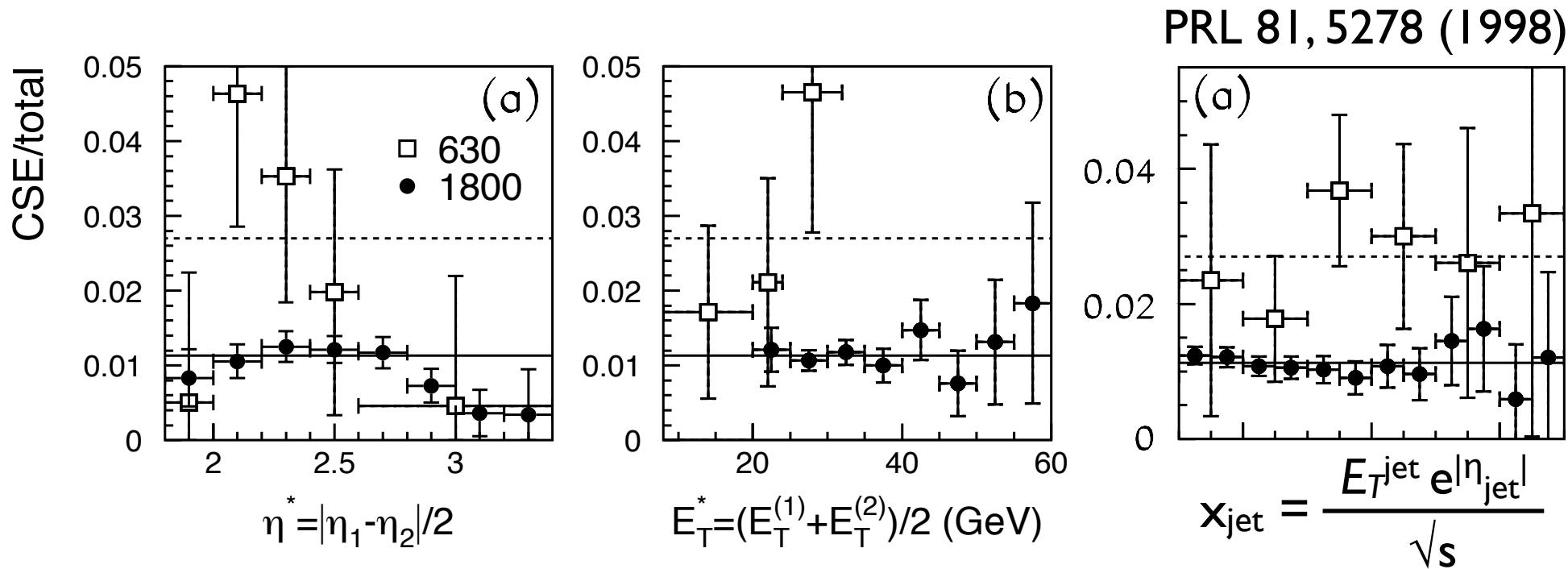
PRL 88, 151802 (2002)



Similar shape  
 $R_{630/1800} = 1.3 +/- **$



# Double Diffraction : Jet-Gap-Jet



$$R_{1800\text{GeV}} = 1.13 \pm 0.16\%, R_{630\text{GeV}} = 2.7 \pm 0.9\% \Rightarrow R[\frac{630}{1800}] = 2.4 \pm 0.9$$

$R_{1800\text{GeV}}$  is approximately flat vs  $\eta^*$ ,  $E_T^*$ , and  $x_{jet}$

Flat  $x_{jet}$  dependence ( $0.1 < x_{jet} < 0.7$ )

→ color singlet (diffractive) exchange couples to quarks and gluons with same strength as color exchange

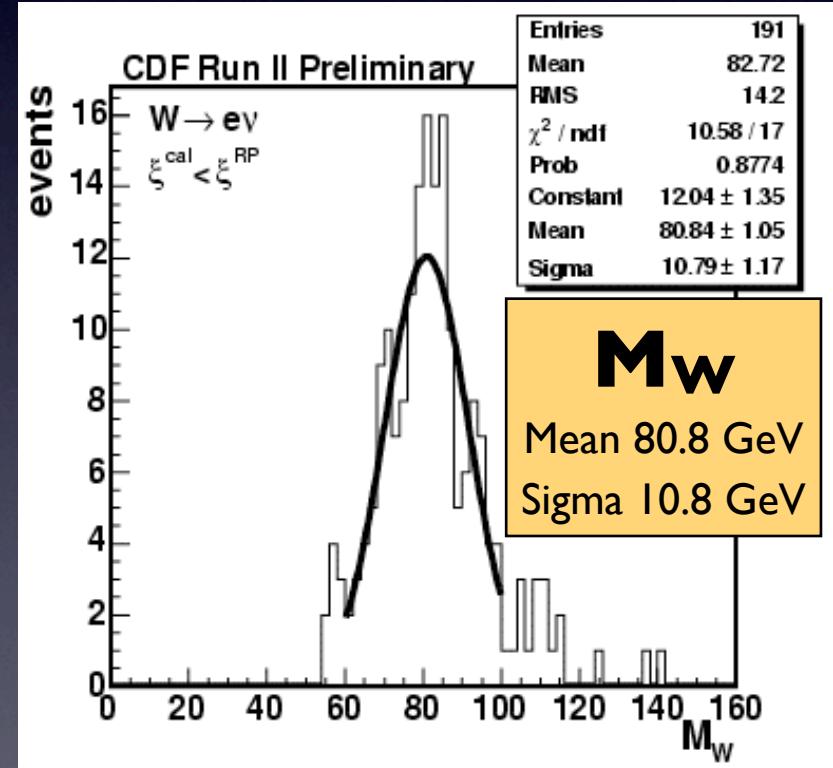
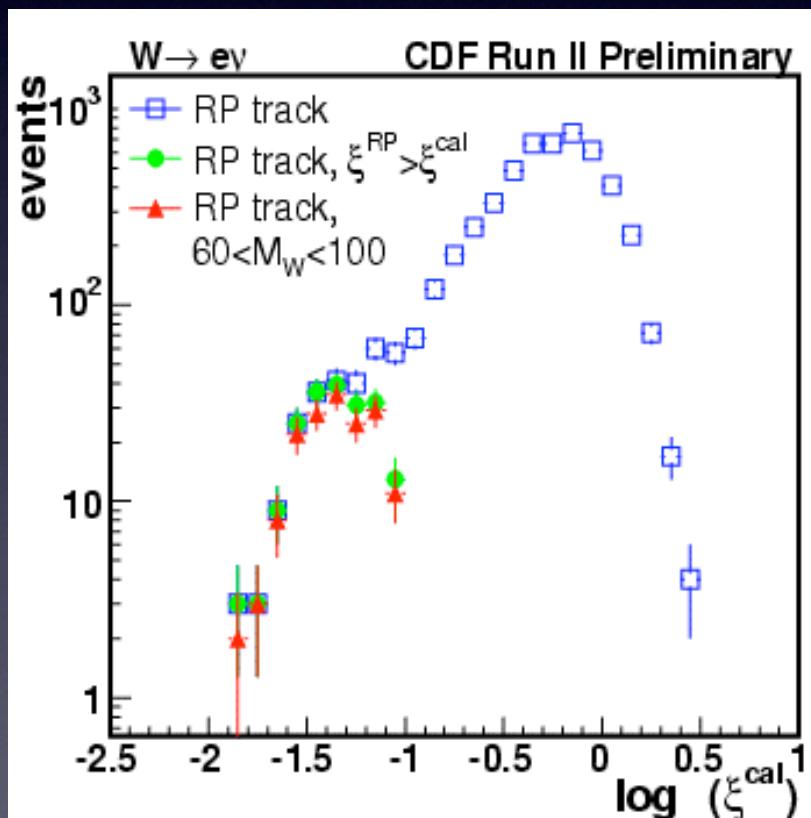
# Diffractive W/Z Production

- Resolve difference between Run I CDF and D0 results (W)
- Use RPS to measure neutrino  $\eta$  (W)
- Measure  $F_W^D$  ( $\rightarrow$  HERA  $F_2^D$ )
- Candidate Z events found

$$\xi^{\text{RPS}} - \xi^{\text{CAL}} = \frac{E_T^V e^{-\eta_V}}{\sqrt{s}}$$

$E_T^V = \text{Missing } E_T$

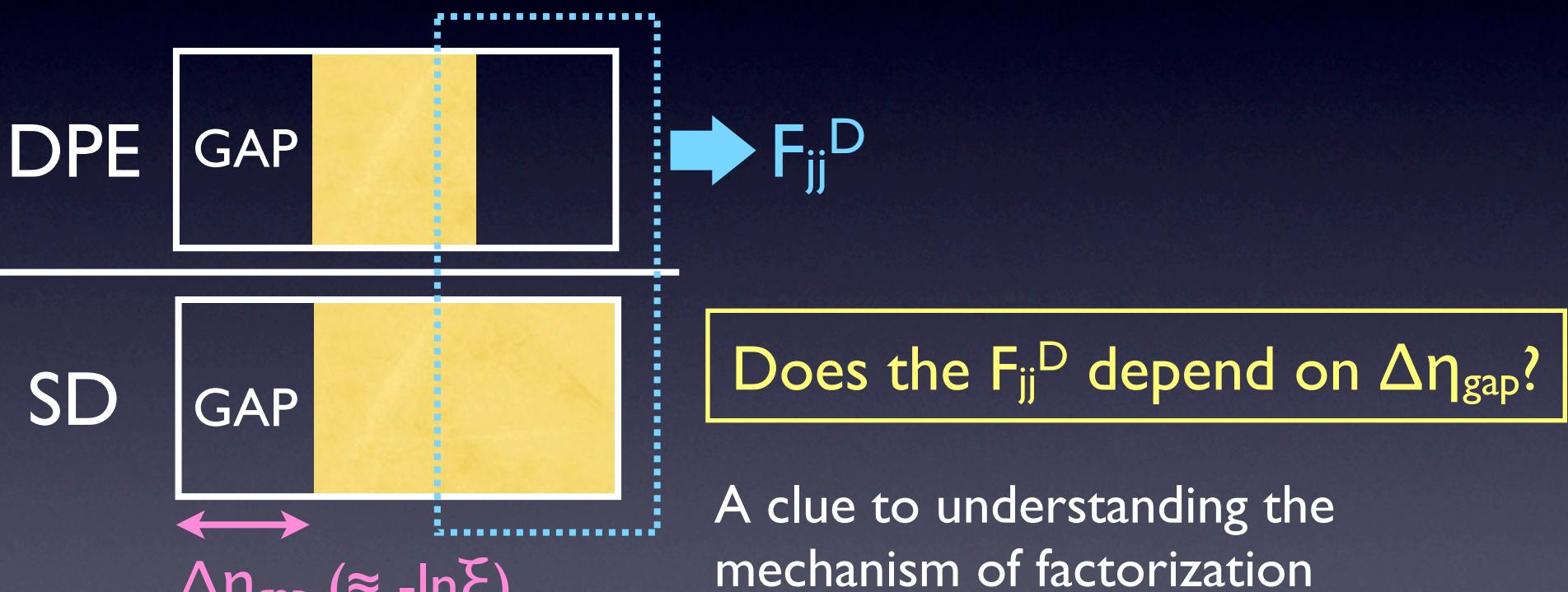
→  $M_W$  and Parton-X ( $x_{Bj}$ )



⇒ Analysis in progress!

# $F_{jj}^D$ versus $\xi_{\bar{P}}$ in DPE

Factorization appears to hold for the formation of the 2nd gap in events that already have a gap

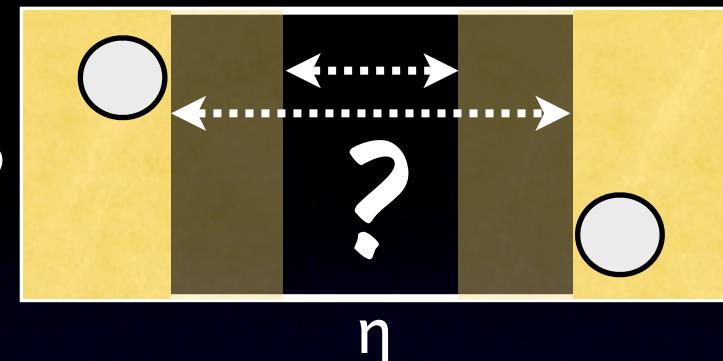


A clue to understanding the mechanism of factorization breaking and restoration(?)

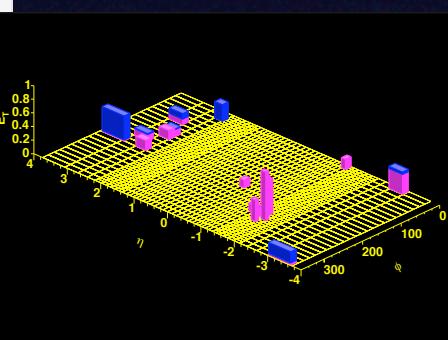
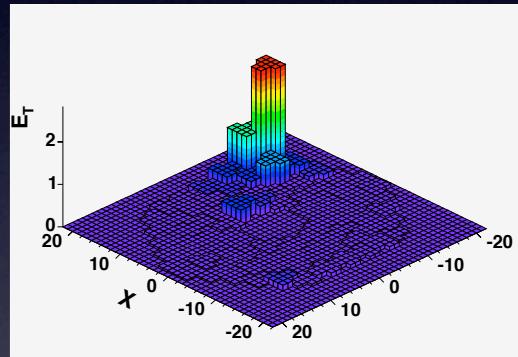
⇒ Analysis in progress!

# Jet-Gap-Jet with Large $\Delta\eta_{jj}$

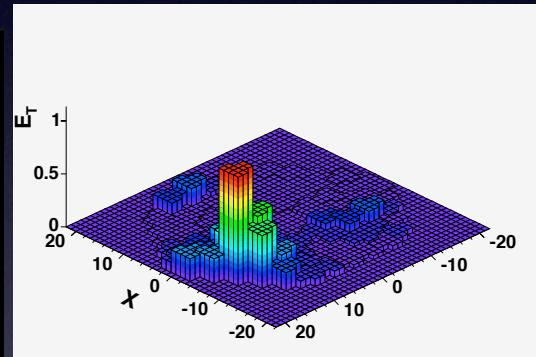
Is the diffractive exchange  
BFKL-like or a color  
rearrangement?



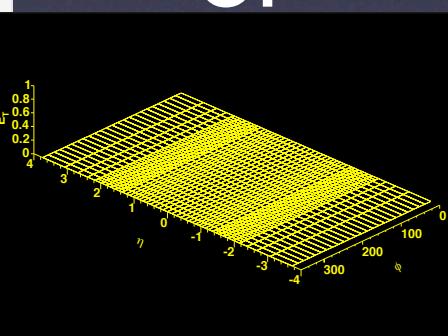
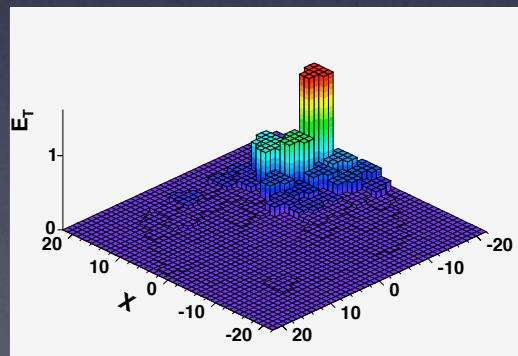
MiniPlug ( $3.6 < \eta < 5.2$ )



MiniPlug ( $-5.2 < \eta < -3.6$ )

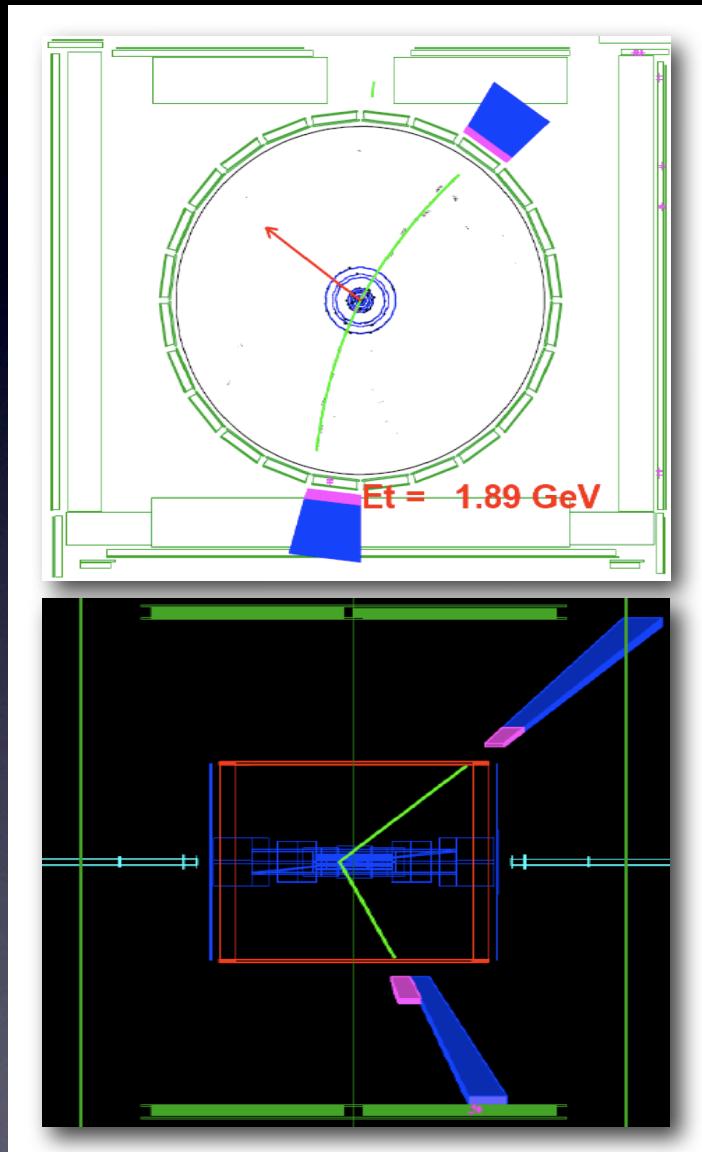


or

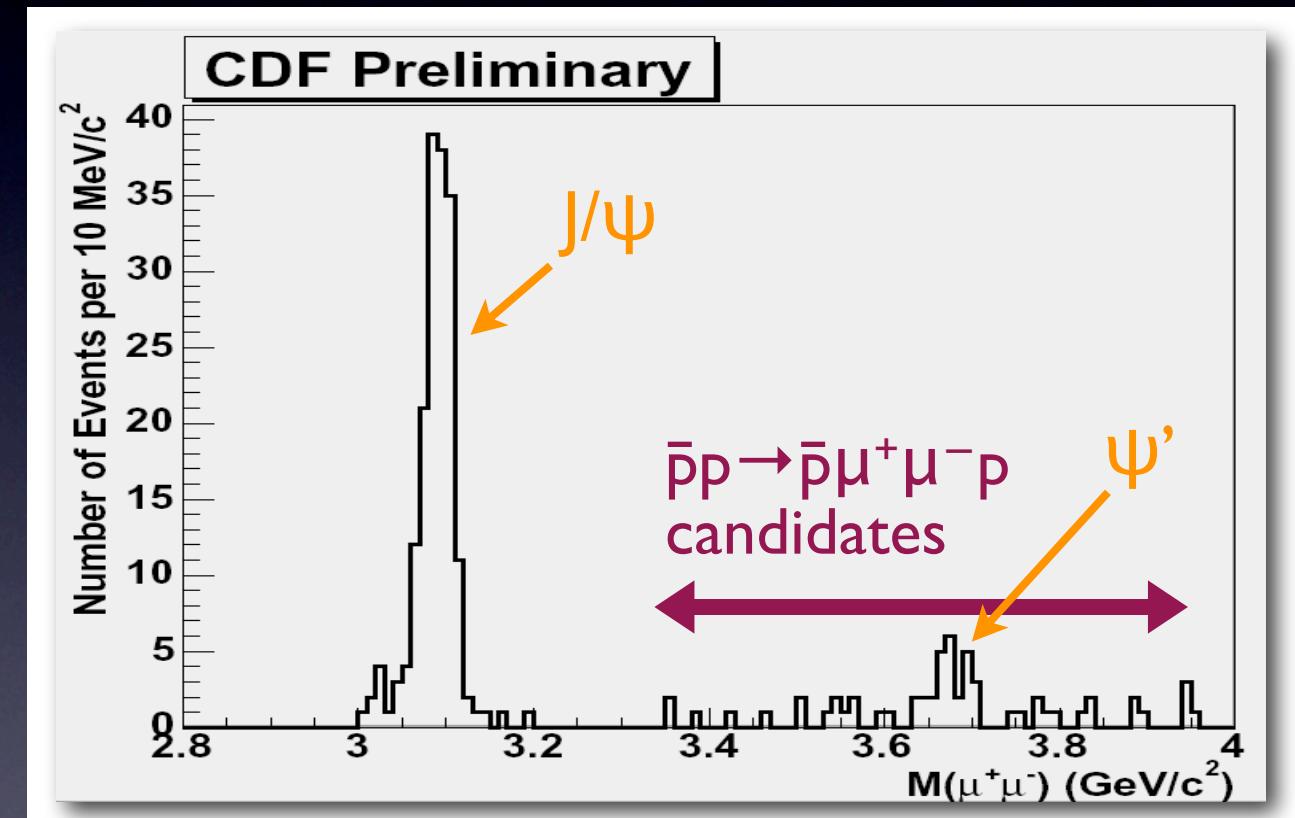


⇒ Analysis in progress!

# Exclusive $\mu^+\mu^-$ Production



- Di-muon trigger :  $p_T(\mu) > 1.5 \text{ GeV}/c$
- 2 muons + exclusive selections applied



Diffractive photo-production  
 $\bar{p}p \rightarrow \bar{p} + \gamma lP (\rightarrow J/\psi \text{ or } \psi') + p$  ?

# MSSM Higgs Boson

A. Kaidalov et al., Eur. Phys. J. C33, 261 (2004)

Exclusive  $gg \rightarrow b\bar{b}$  background suppressed (LO)

MSSM Higgs yield enhanced by an order of magnitude in central exclusive production

$\tan\beta=50$

Higgs	$h(0+)$	$H(0+)$	$A(0-)$
Mass (GeV)	124	134	130
#Events ( $30\text{fb}^{-1}$ )	71	124	1

