Diffraction: the Tevatron experience

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- Definition of diffractive processes
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Introduction

Diffractive reactions at hadron colliders are defined as reactions in *which no quantum numbers* are exchanged between colliding particles

Identified by presence of:

intact leading particle or

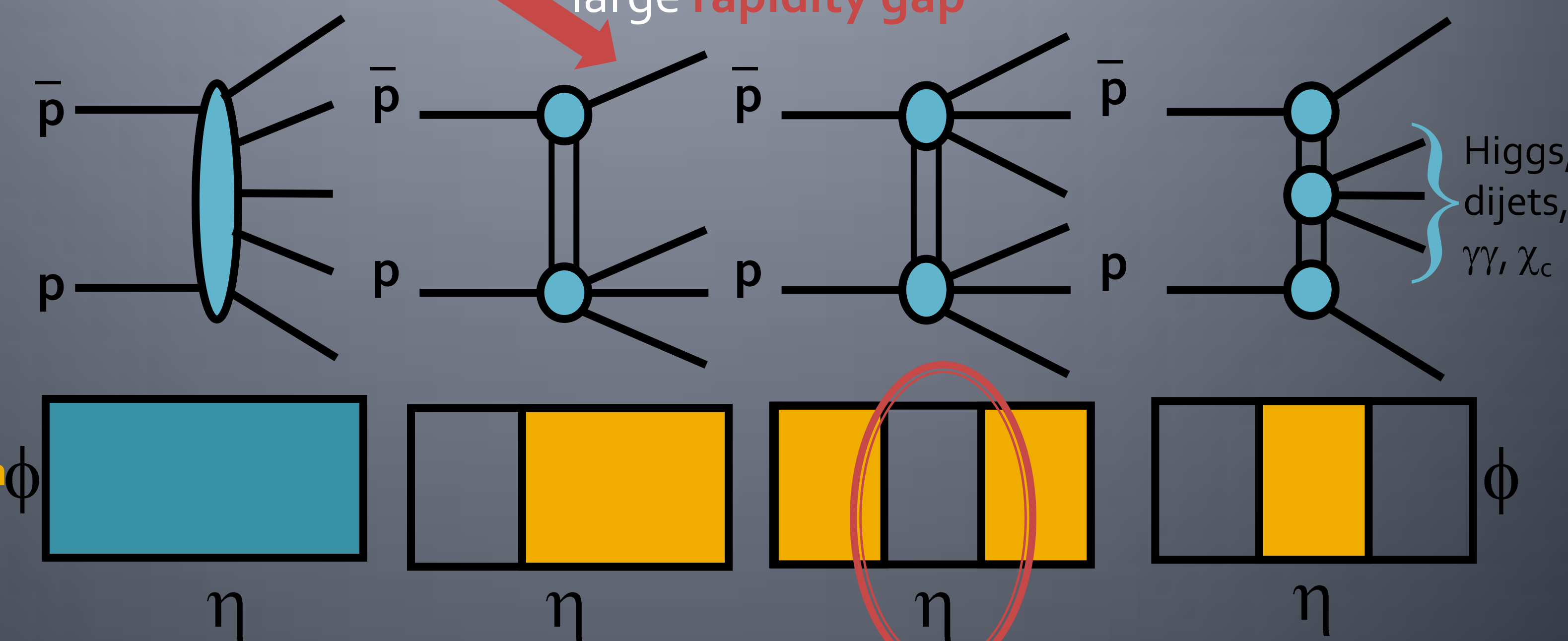
large rapidity gap

Non- Diffractive (ND)

Single Diffraction (SD)

Double Diffraction (DD)

Double Pomeron Exchange (DPE)



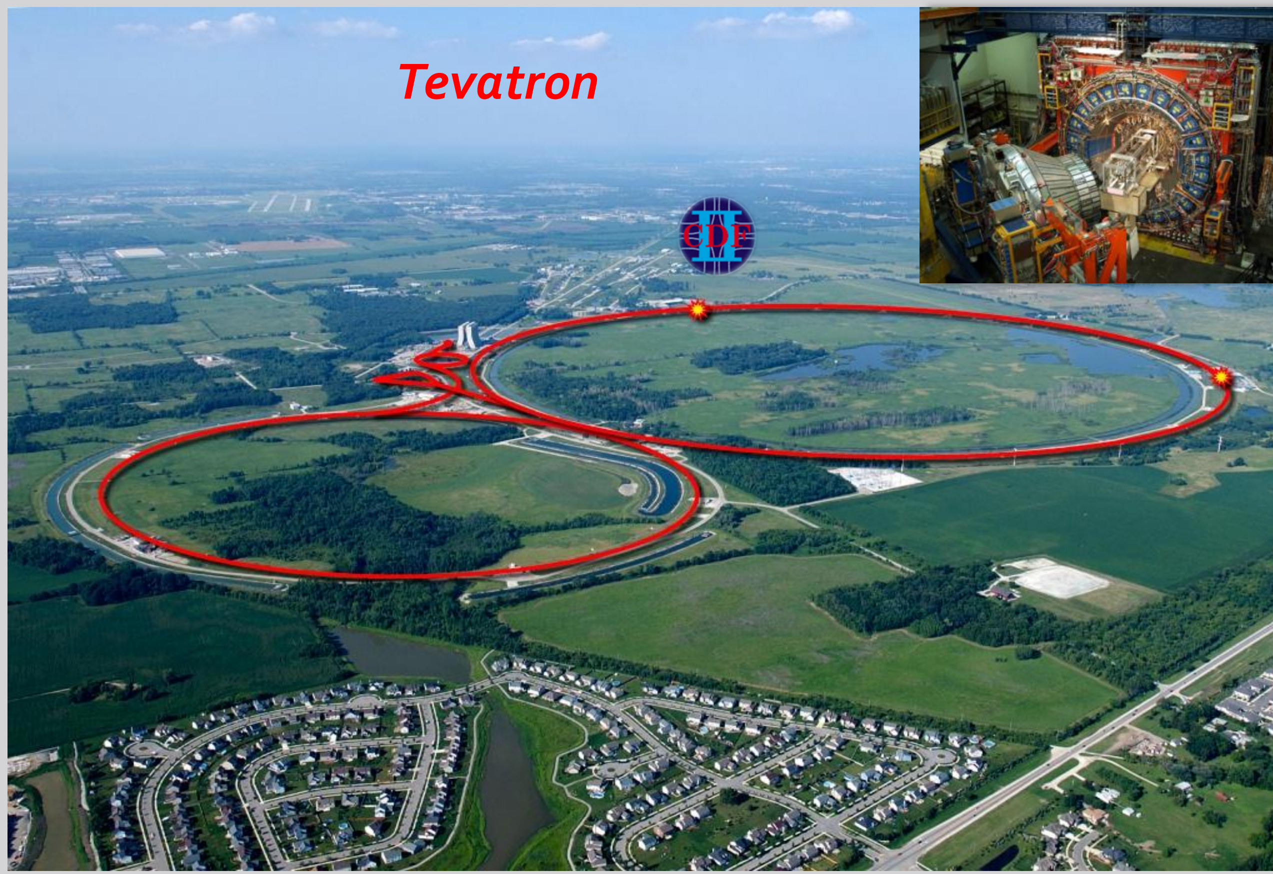
Tevatron $p\bar{p}$ Collider

3 center-of-mass energies

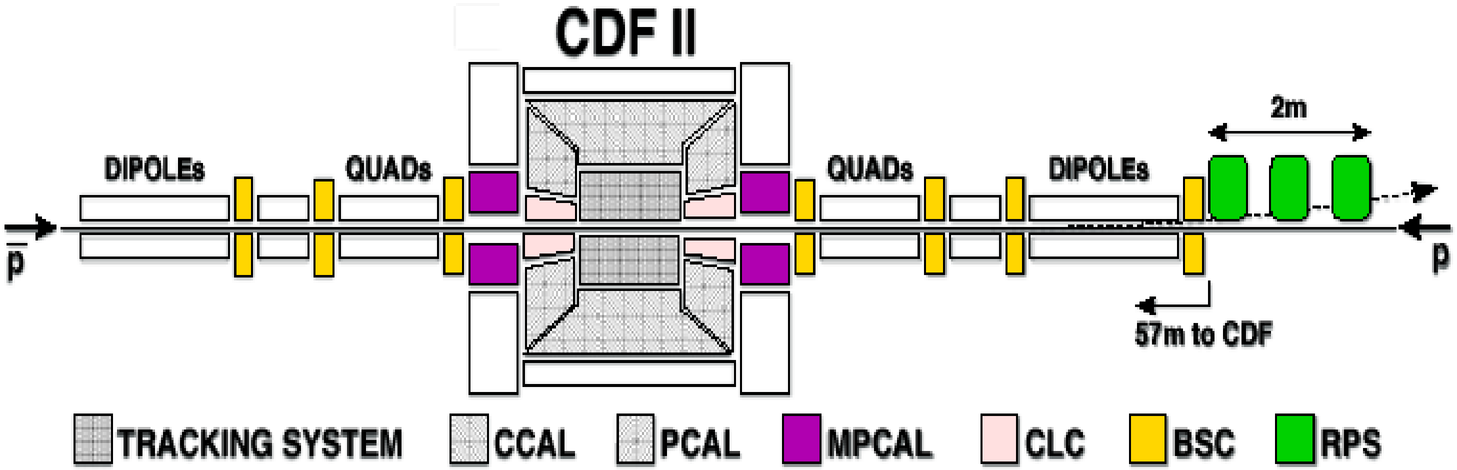
Run I (1992-1996)
$\sqrt{s}$=1.8 TeV (~120 pb^{-1})

Run IC (1994 -1995)
$\sqrt{s}$=630 GeV

Run II (2001- current)
$\sqrt{s}$= 1.96 TeV



CDF II Detectors

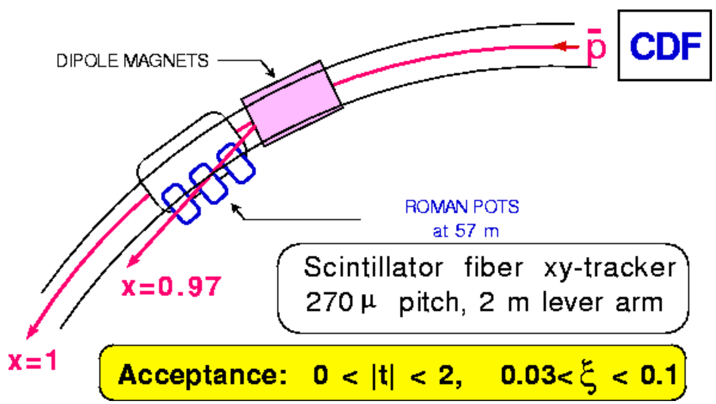


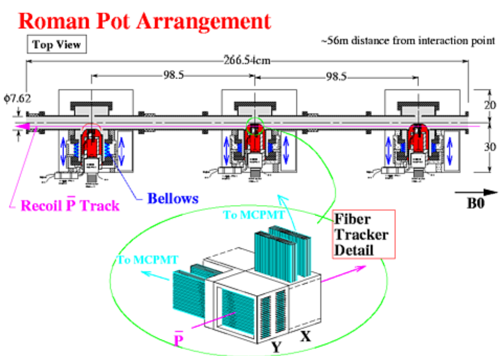
- Tracking – Tracking Detectors $|\eta| < 2.0$
- CCAL, PCAL – Calorimeters $|\eta| < 3.6$
- RPS – Roman Pot Spectrometers $0.02 < \xi < 0.1$
  $0 < |t| < 2\ GeV^2$
- BSC – Beam Shower Counters $5.4 < |\eta| < 7.4$
- MPCAL – MiniPlug Calorimeters $3.5 < |\eta| < 5.1$

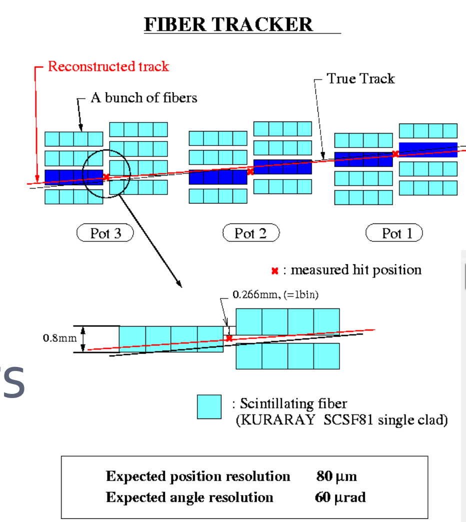
Forward Detectors:
Roman Pot Spectrometers (RPS)

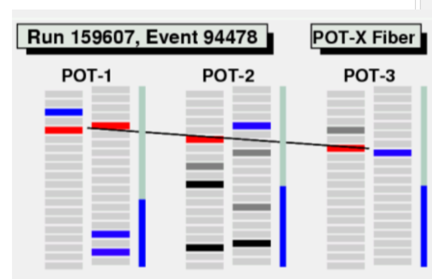
Fiber Tracker

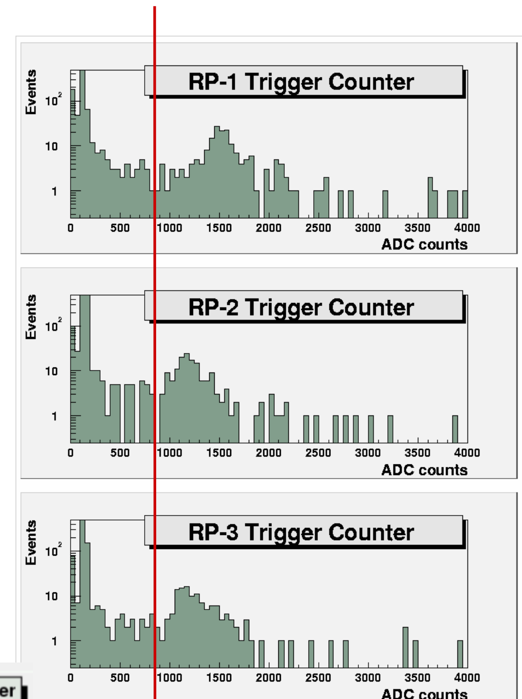
- 3 stations
- 57 meters from IP









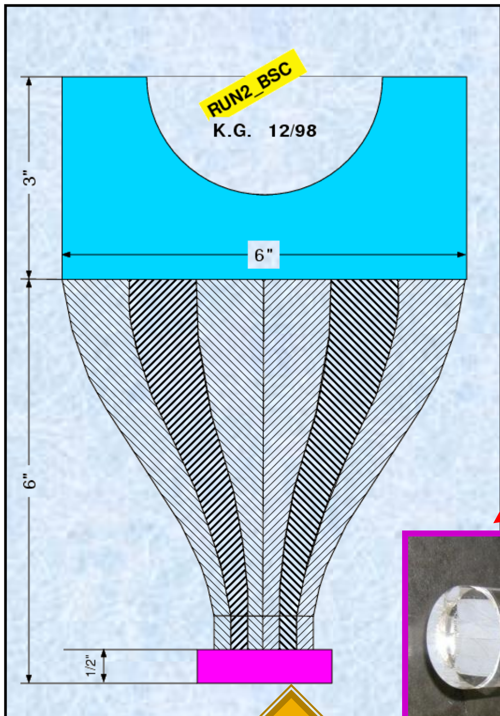


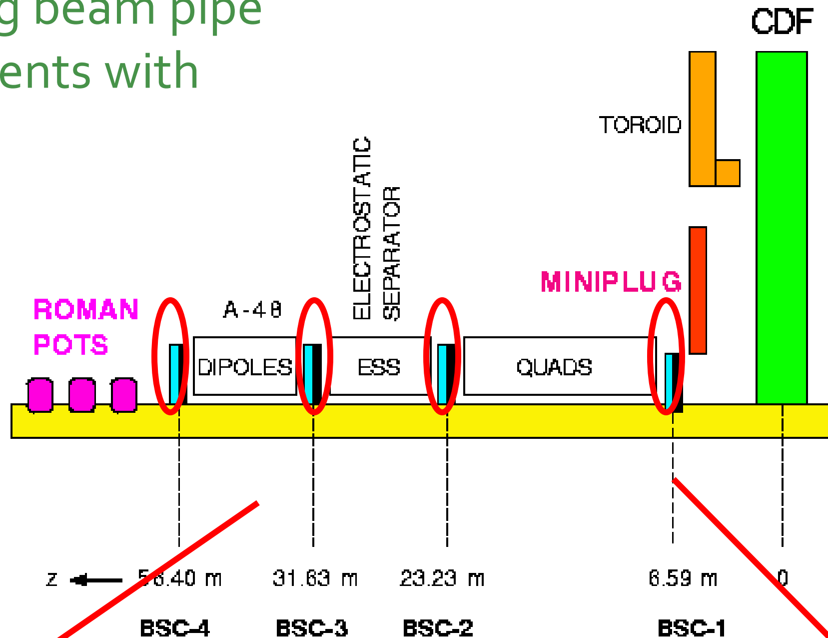
MIPs (>1000 counts)

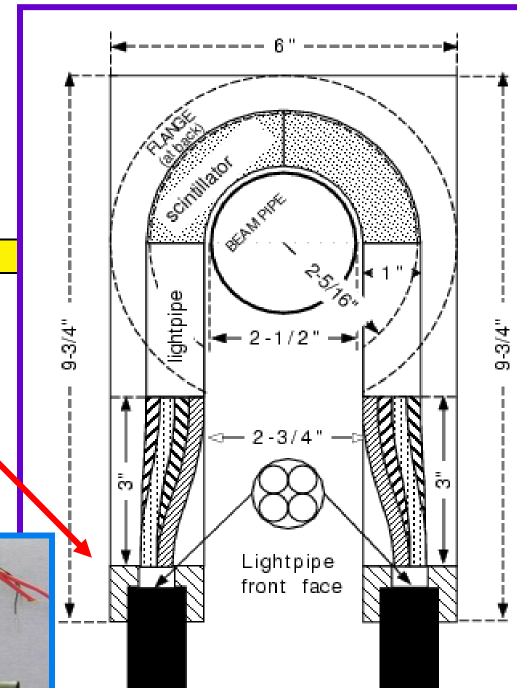
- 3 trigger counters
- 240 channels

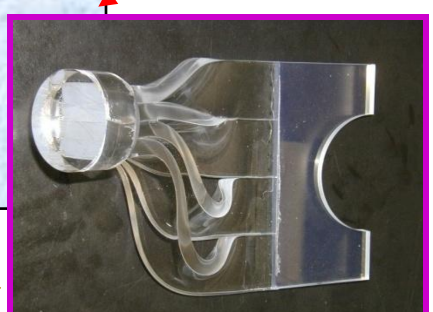
Forward Detectors:
Beam Shower Counters (BSCs)

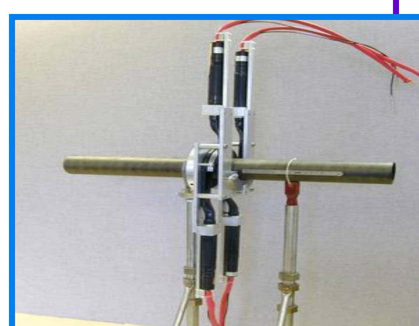
BSCs are located along beam pipe used for triggering events with forward rapidity gaps











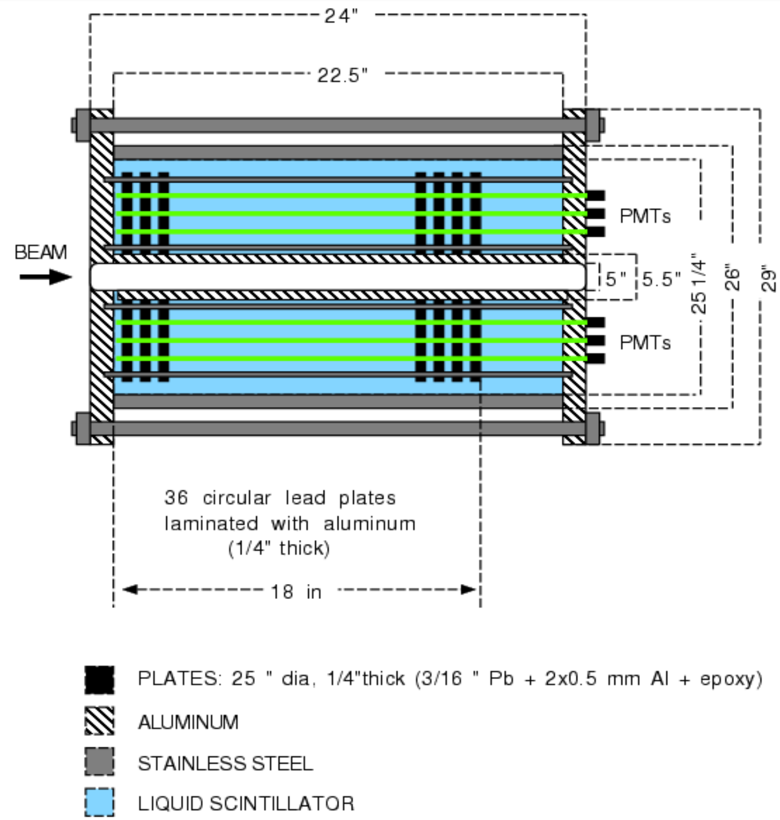
BSC-2,3,4

BSC-1

Forward Detectors: MiniPlug Calorimeters (MPs)

Nucl. Instrum. Meth. ***A****518 (2004) 42.*

Nucl. Instrum. Meth. ***A****496 (2003) 333.*



designed to measure the energy and lateral position of both electromagnetic and hadronic showers

“towerless” geometry – no dead regions

Single Diffraction

Diffractive signature:

recoil pbar or
large rapidity gap

Soft Diffraction

Single Diffraction
PRD 50, 5355 (1994)

Hard Diffraction

Rapidity Gap Tag

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

Roman Pot Tag

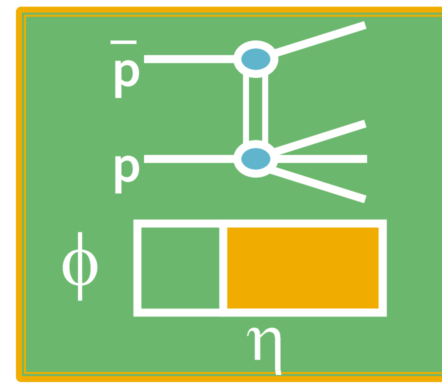
Dijets:

1.8 TeV	PRL 84, 5043 (2000)
630 GeV	PRL 88, 151802 (2002)

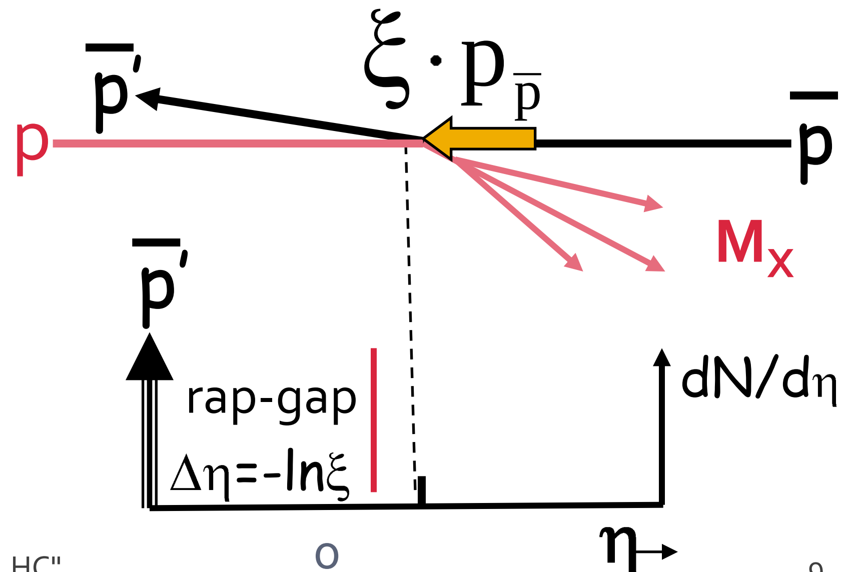
t - four-momentum transfer squared

ξ - fractional momentum loss of pbar

M_X - mass of system X



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



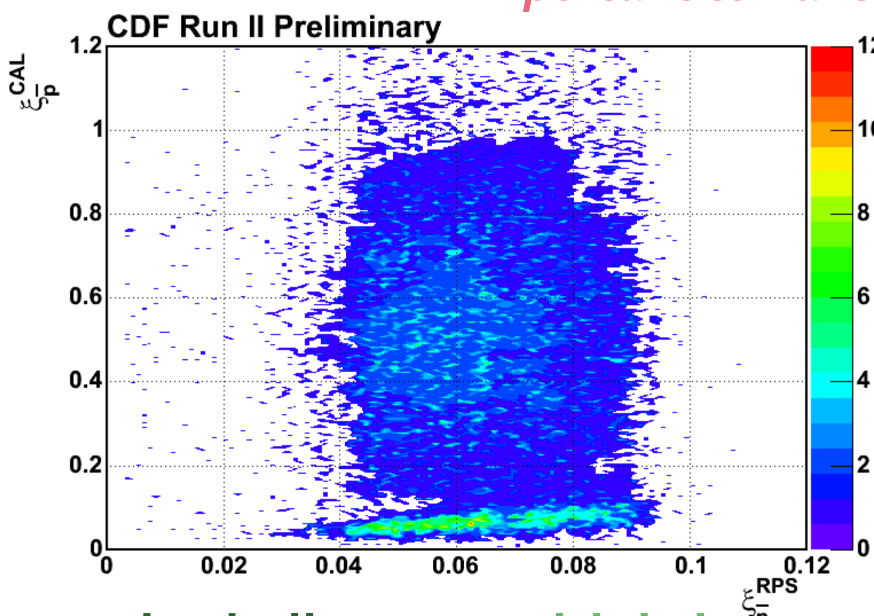
Methods and Challenges

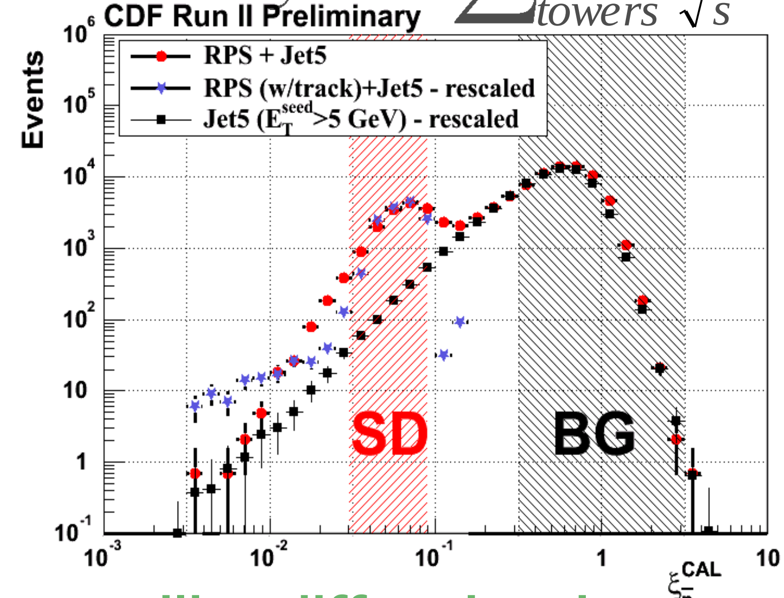
Results are mostly MC free

- Determine ξ using Roman Pots tracking
- Also can determine ξ from E_T in calorimeters

important to have MiniPlugs ↗

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





Main challenge: multiple interactions spoiling diffractive signatures

use ξ^{cal} < 0.1 to reject overlap events → non-diffractive contributions

Diffractive Structure Function

Diffractive dijet cross section

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

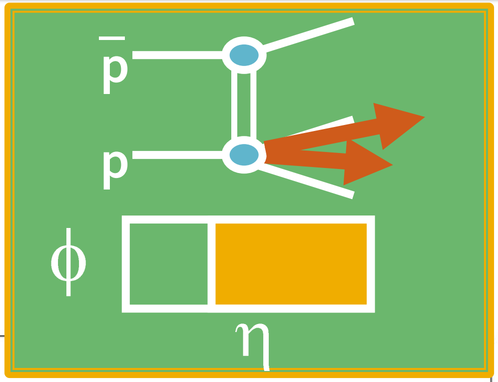
Study the diffractive structure function

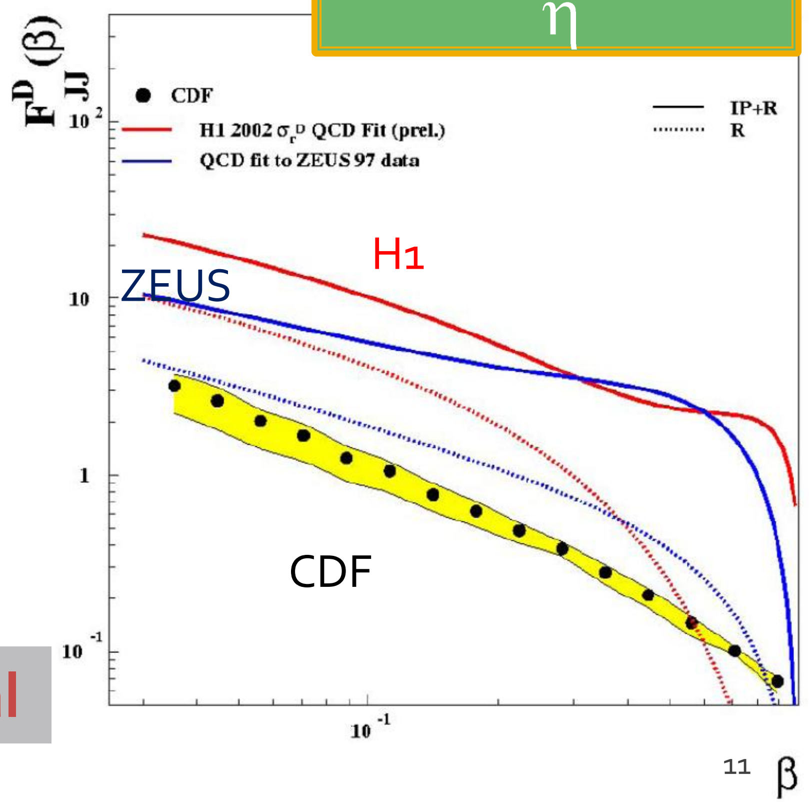
$$F_{jj}^{D} = F_{jj}^{D}(x, Q^2, t, \xi)$$

Experimentally determine diffractive structure function F_{jj}^{D}

$$\text{at LO} \quad R_{\frac{SD}{ND}}(x,\xi) = \frac{\sigma(SD_{jj})}{\sigma(ND_{jj})} = \frac{F_{jj}^{D}(x,Q^2,\xi)}{F_{jj}(x,Q^2)}$$

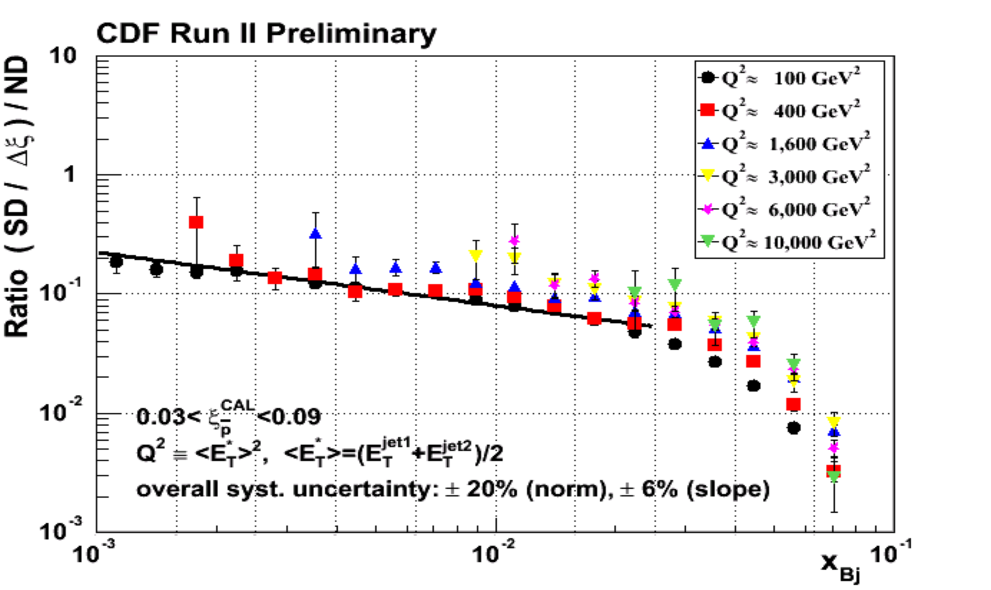
Data — known PDF

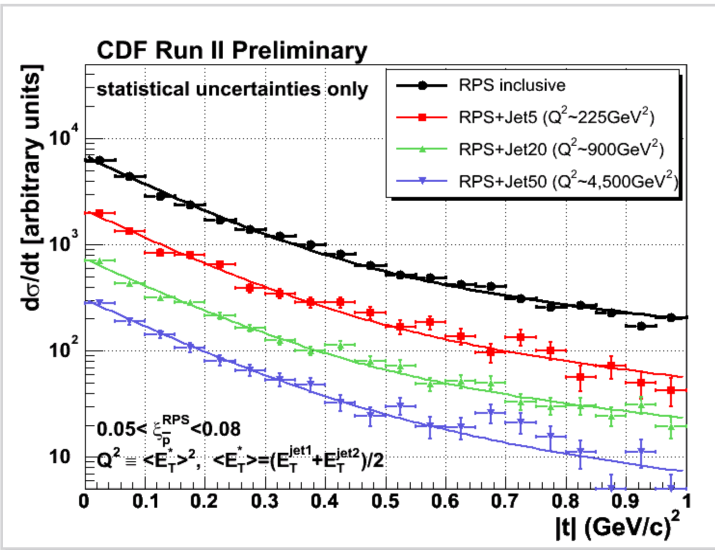




Factorization breakdown – gap survival

Diffractive Structue Function and *t* Distribution





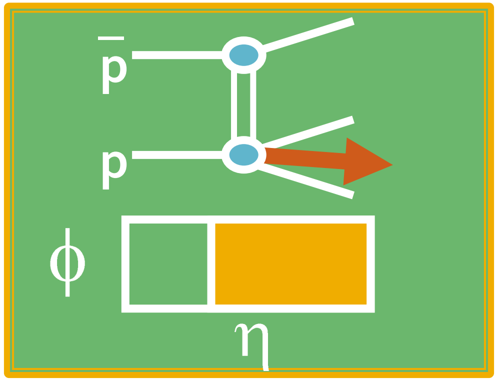
Good agreement with Run I results

Fit to double exponential function:

$d\sigma/dt \propto 0.9\, e^{b_1 t} + 0.1\, e^{b_2 t}$

- no diffractive dips
- no Q^2 dependence in slope from inclusive to $Q^2 \sim 10^4$ GeV^2

Hard Single Diffraction



Diffractive signature:

large rapidity gap –
slightly different
gap definitions

method used as a model for LHC analyses

Fraction:
R≡SD/ND ratio
@ 1800 GeV

Hard component	Fraction (R) %
Dijet	0.75 ± 0.10
W	1.15 ± 0.55
b	0.62 ± 0.25
J/ψ	1.45 v 0.25

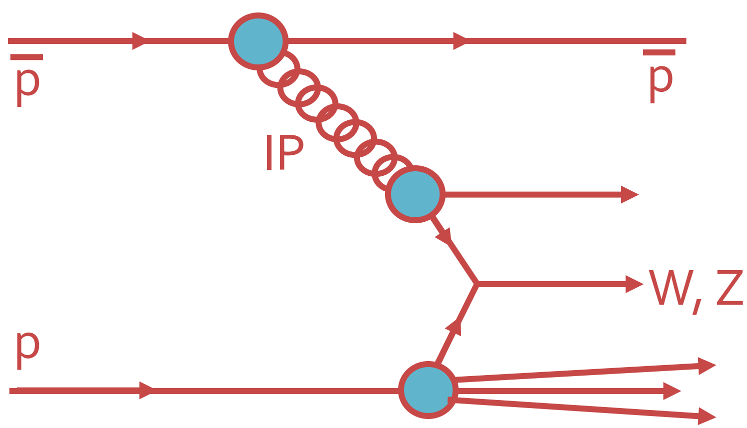
All fractions ~ 1%
(differences due to kinematics)

➢ ~ uniform suppression

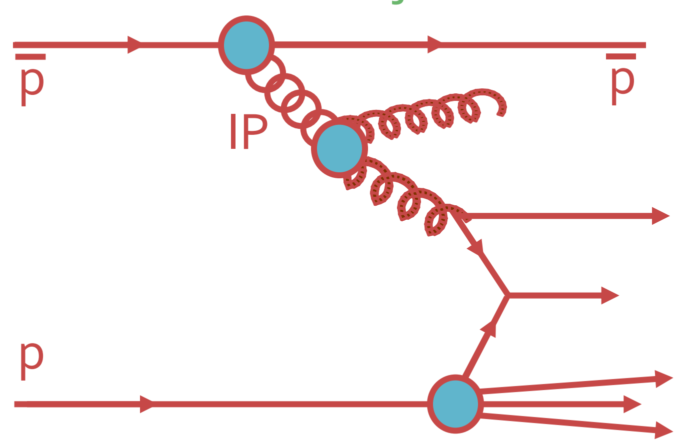
Example: Diffractive W/Z Production

Diffractive W/Z production probes the quark content of the Pomeron

- to Leading Order the W/Z are produced by a **quark** in the Pomeron



- production by gluons is suppressed by a factor of α_S and can be distinguished by an associated jet



Example: Diffractive W production – Run I

Rapidity gaps method

- CDF Phys Rev Lett **78, 2698 (1997)**
  - Fraction of W events due to SD [1.15±0.51(stat) ± 0.20(syst)]%
- DØ Phys Lett B **574, 169 (2003)**
  - Fraction of events with rapidity gap (uncorrected for gap survival)
  - W: [0.89+0.19-0.17]%
  - Z: [1.44+0.61-0.52]%

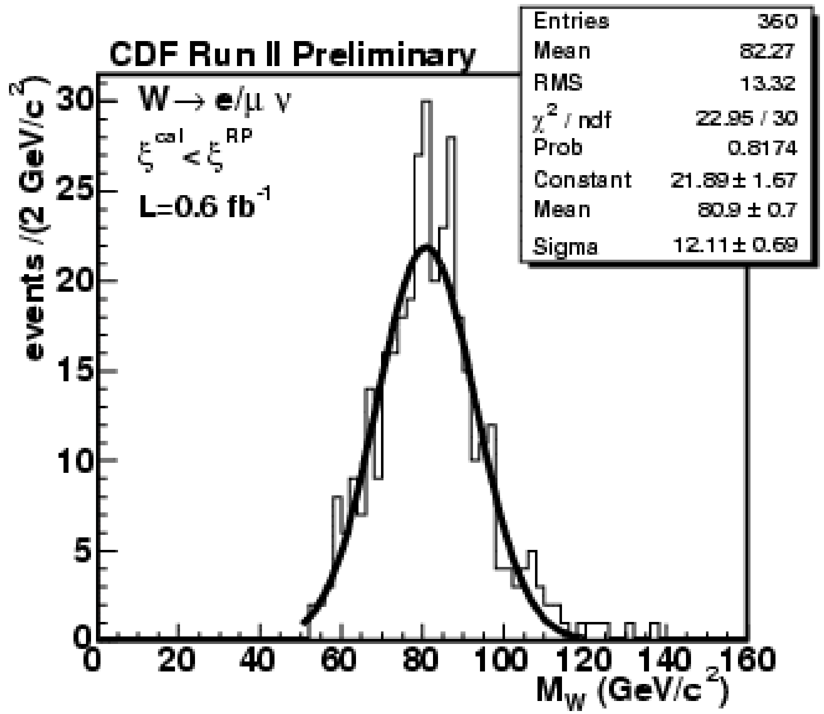
Diffractive W Production – Run II

Identify diffractive events using Roman Pots:

accurate event-by-event ξ measurement

no gap acceptance correction needed

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



In W production, the difference between ξ^{cal} and ξ^{RP} is related to missing E_T and η_ν

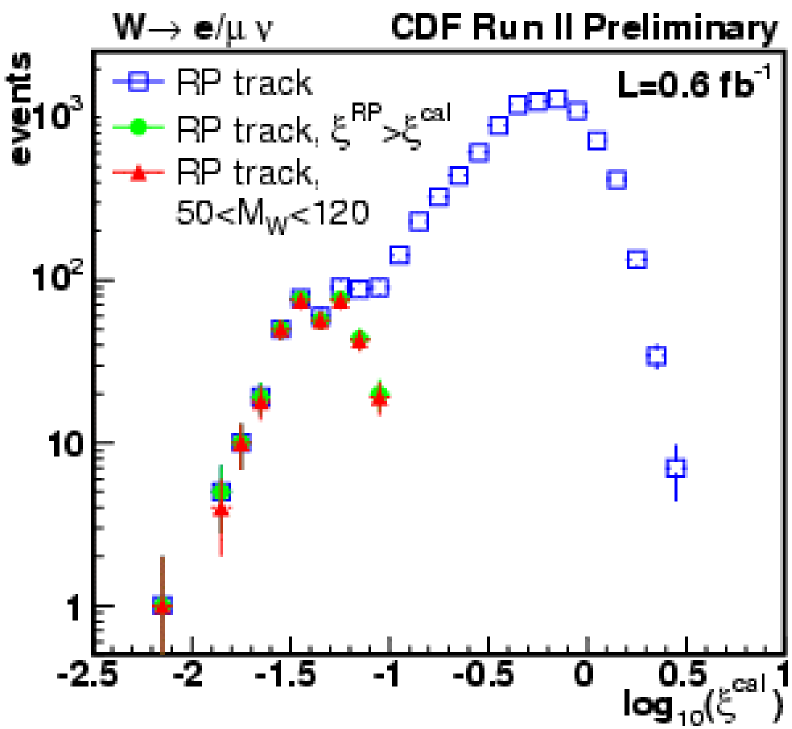
$$\xi^{RP} - \xi^{cal} = \frac{E_T}{\sqrt{s}} e^{-\eta_\nu}$$

allows to determine:

neutrino and W kinematics

reconstructed diffractive W mass

Diffractive W Production: measurement



- $\xi^{cal} < \xi^{RP}$ requirement removes most events with multiple pbar-p interactions
- $50 < M_W < 120$ GeV/c^2 requirement on the reconstructed W mass cleans up possible mis-reconstructed events

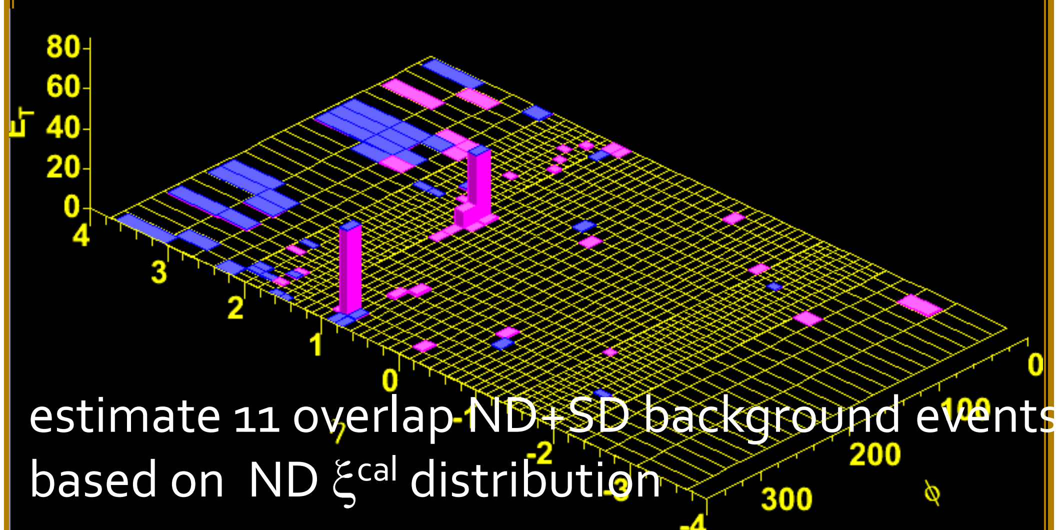
Fraction of diffractive W

R_W (0.03<ξ<0.10, |t|<1)= [0.97 ±0.05(stat) ±0.10(syst)]%

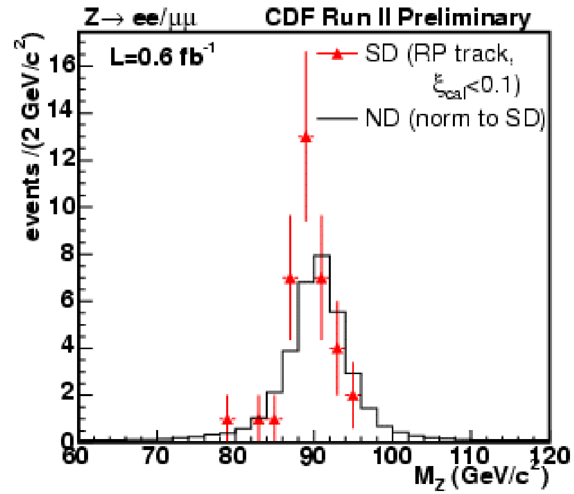
consistent with Run I result, extrapolated to all ξ

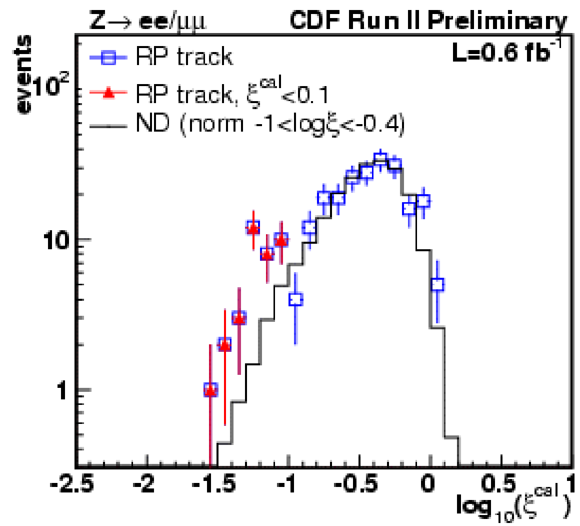
Diffractive Z Production

37 diffractive $Z \rightarrow ee/\mu\mu$ candidates
(RP track, $\xi^{cal}<0.1$)



estimate 11 overlap ND+SD background events based on ND ξ^{cal} distribution





Fraction of diffractive Z

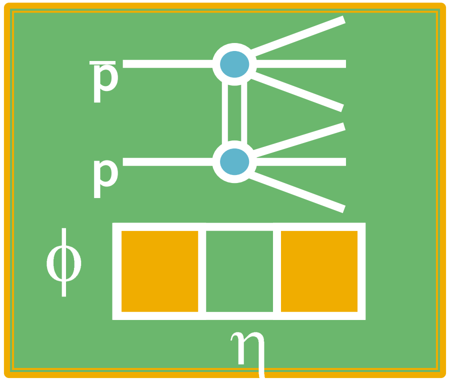
$R_Z(0.03<\xi<0.10, |t|<1)=$

$[0.85\pm0.20(stat)\pm0.08(syst)]\%$

Double Diffraction

Diffractive signature:

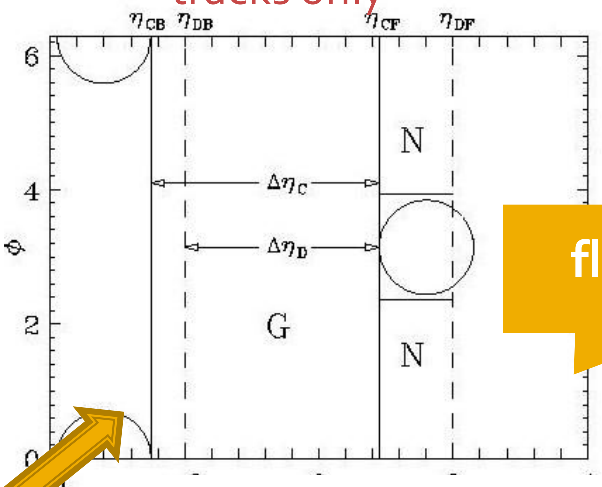
large central rapidity gap –
slightly different
gap definitions



Soft Diffraction

Double Diffraction
PRL 87, 141802 (2001)

tracks only

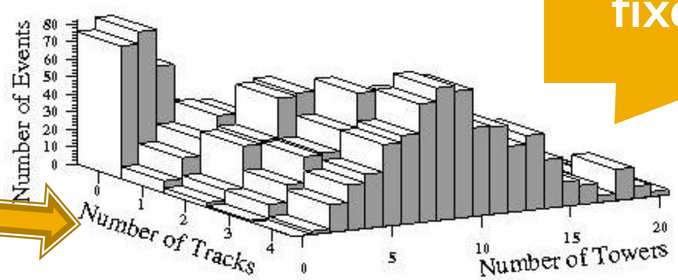


floating gap

Hard Diffraction

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

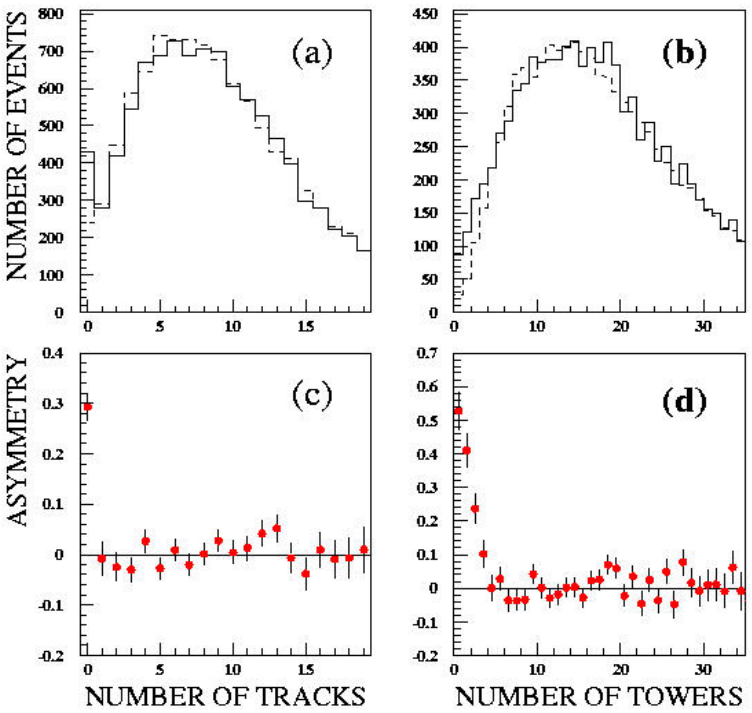
fixed gap

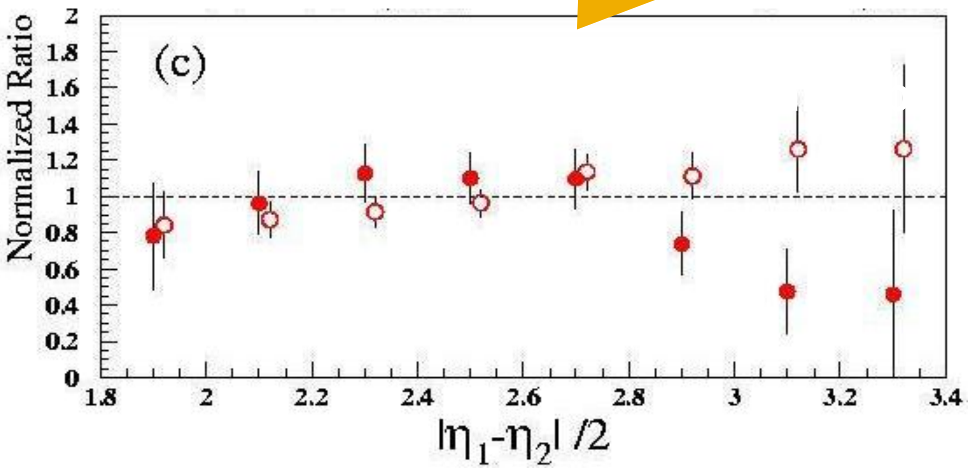


Central Gaps in Run I

R=[1.13±0.12(stat) ±0.11(syst)]% @ 1800 GeV
R=[2.7±0.7(stat) ±0.6(syst)]% @ 630 GeV

floating jets
fixed central gap





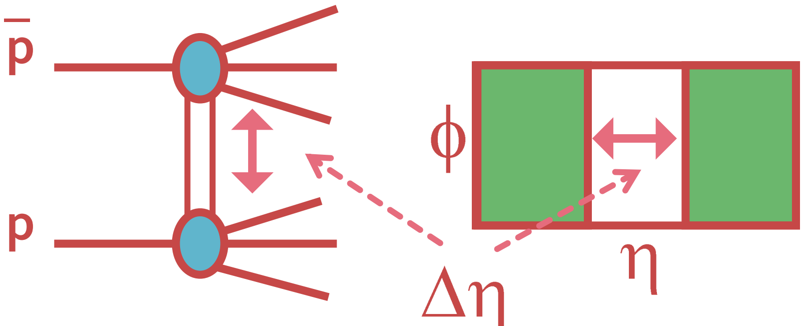
R is estimated using OS jets as signal and SS jets as a control sample

- look for events with rapidity gap in |η|<1 when jets are at 1 .8<|η|<3.5

- both track and tower multiplicities produce similar results

Rapidity Gaps in Minbias Events

Soft Double-Diffraction (DD)



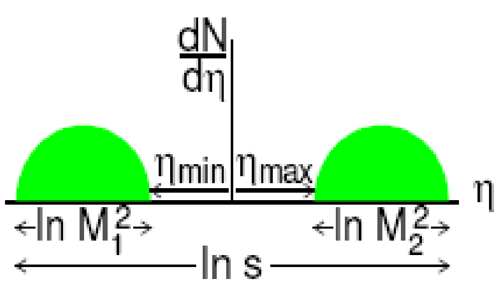
Strategy of analysis:

look for "experimental gaps" defined as

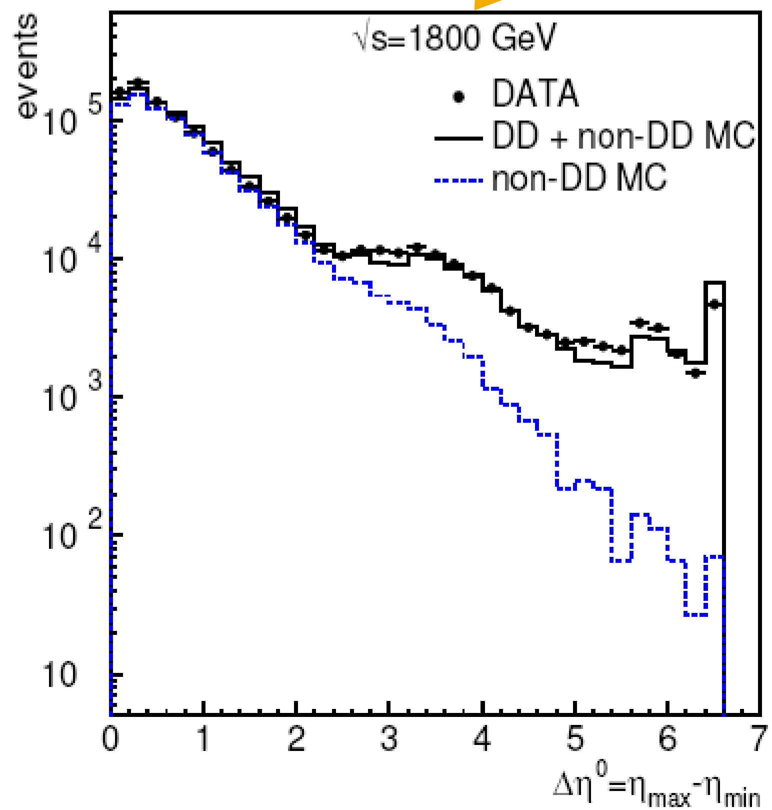
$\Delta\eta \equiv \eta_{max} - \eta_{min}$

$\eta_{max}(\eta_{min})$- "particle" closest to η=0

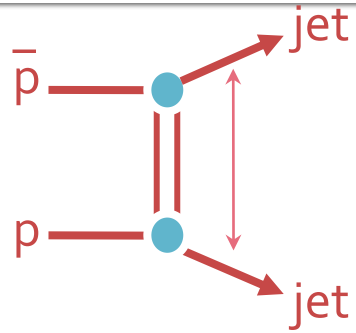
in the p(p) direction

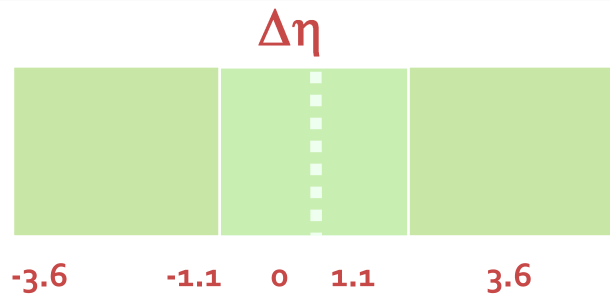


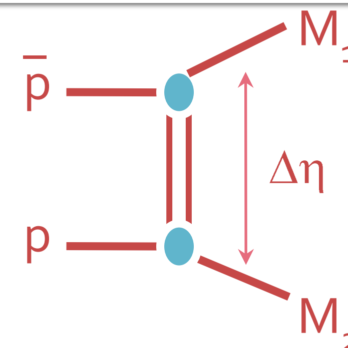
floating gap



Central Gaps in Soft and Hard DD







To **compare gap probability** in soft and hard DD dissociation:

reconstruct $\Delta\eta$ in both cases

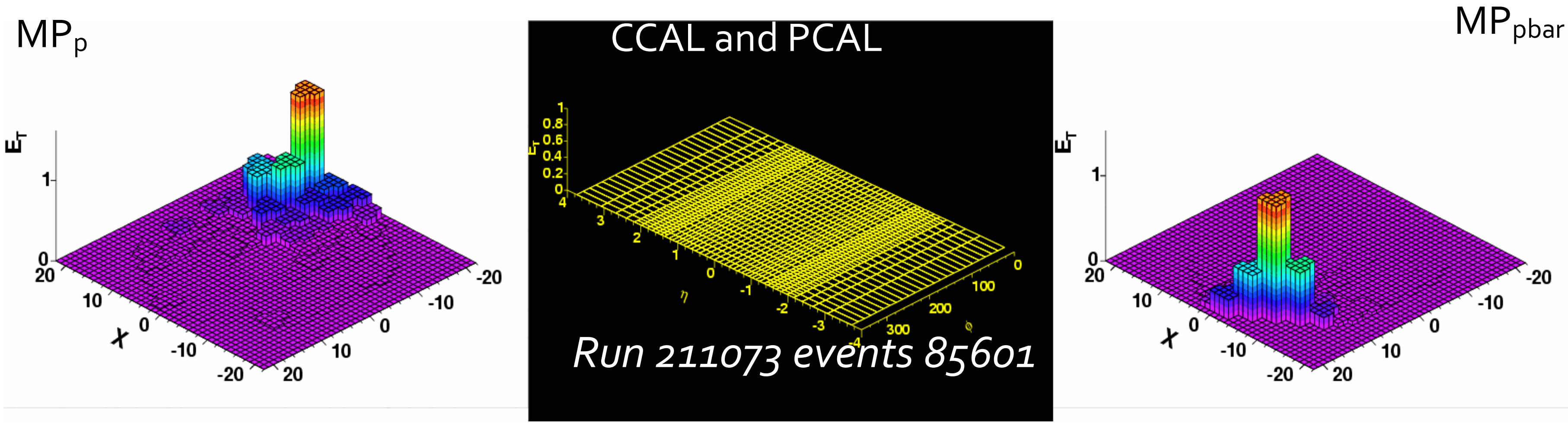
require events to have gap in CCAL $|\eta|<1.1 \Rightarrow \Delta\eta>2$ => significant DD contribution

require opposite side MP jets for hard DD, with $E_T>2$ GeV

For this analysis we use "floating" – not-necessarily central gap

Direct comparison of the results is relatively free of systematic uncertainties.

Forward Jets and Rapidity Gaps

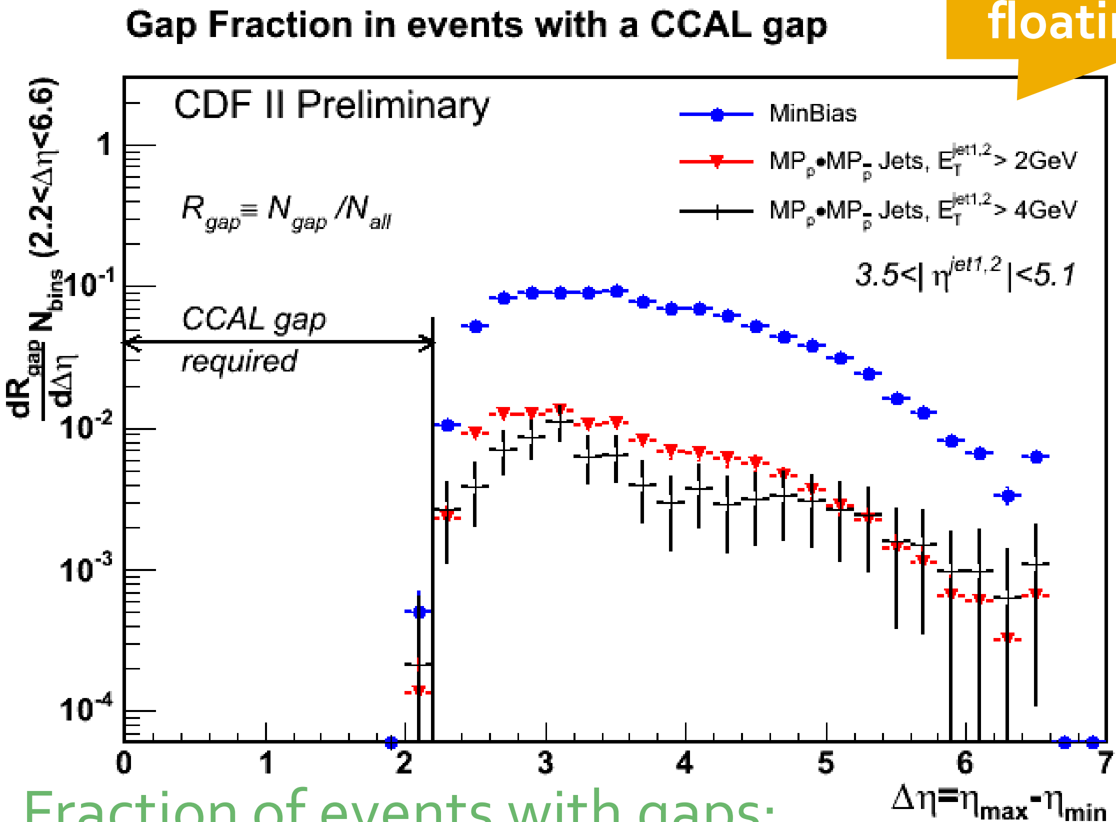


Gaps:

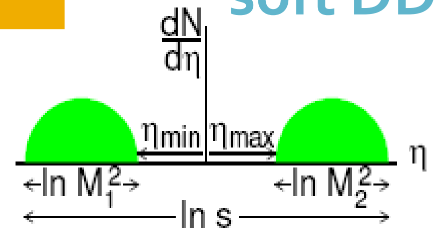
- what is under the “carpet”? - detector noise etc…

Central Gaps in Soft and Hard DD

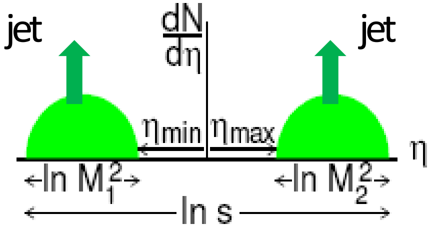
fixed jets
floating gap



soft DD



compare with



hard DD

Fraction of events with gaps:

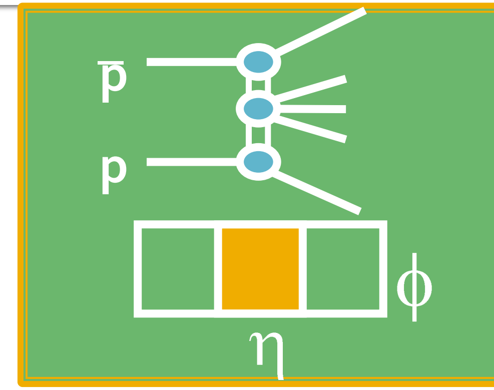
~10% in soft DD events and ~1% in jet events

The distributions are similar in shape within the uncertainties

Double Pomeron Exchange Exclusive Studies

Diffractive signature:

recoil pbar /large rapidity gap **AND**
large rapidity gap on proton side



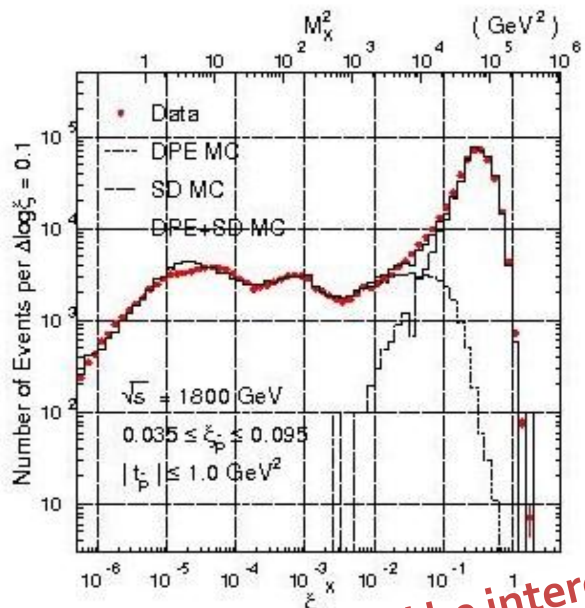
Soft Diffraction

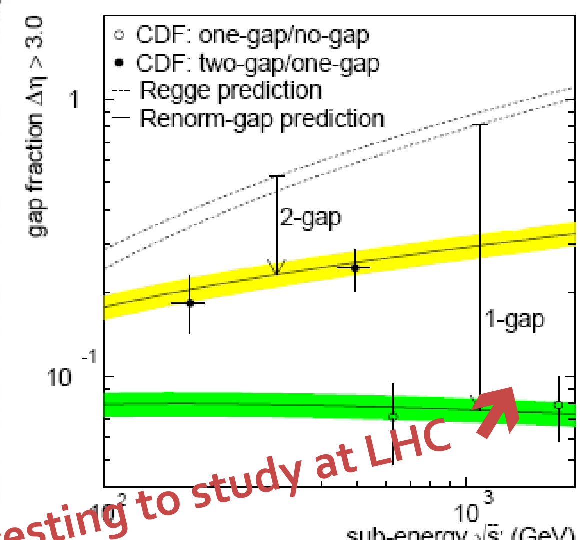
Double Pomeron Exc.
PRL 93,141603 (2004)
Multi-Gap Diffraction
PRL 91, 011802 (2003)

Hard Diffraction

Dijets:
1.8 TeV PRL 85, 4217 (2000)
1.96 TeV PRD 77, 052004 (2008)
Di-photons
1.96 TeV PRL 99, 242002 (2007)
Charmonium
1.96 TeV PRL 102, 242001 (2009)

Inclusive DPE ξ distribution



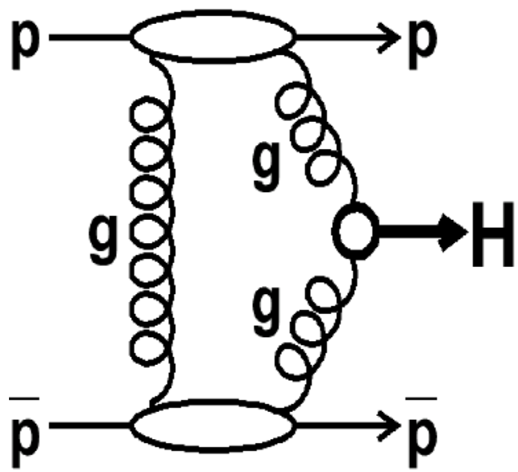


would be interesting to study at LHC

second gap production is not suppressed

Exclusive Production

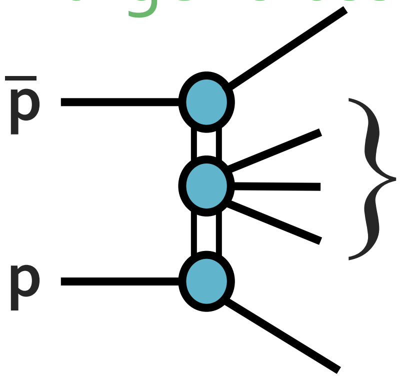
LHC



- suppression at LO of the background sub-processes (J_z=0 selection rule)
- "exclusive channel" → clean signal (no underlying event)

- At the Tevatron we use similar processes with larger cross sections to test and calibrate theor. predictions

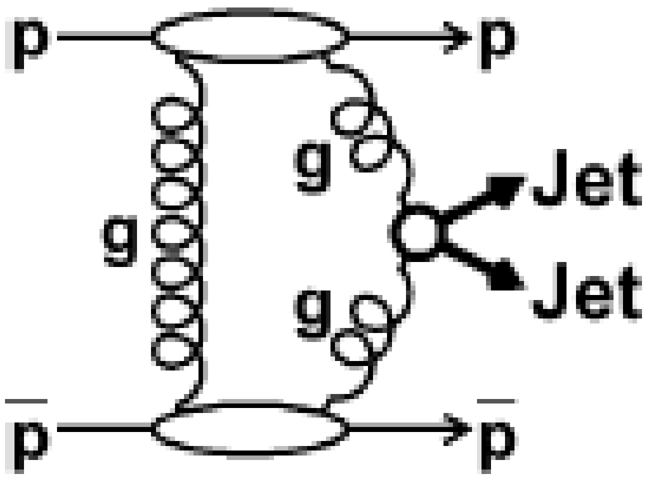
CDF



Dijets,
$\gamma\gamma$,
χ_c

Exclusive Dijet Production

RUN I



CDF limit of

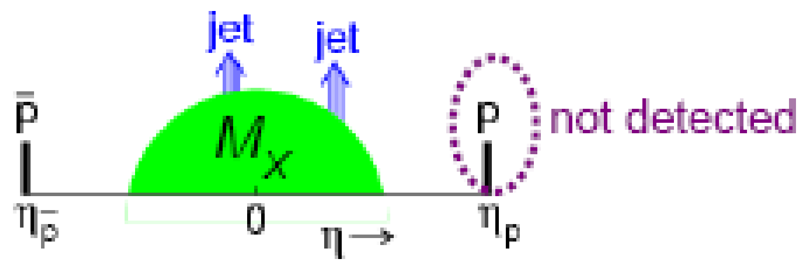
σ_{excl}<3.7 nb(95% CL)

RUN II

Method:

Select inclusive diffractive dijet events produced by DPE

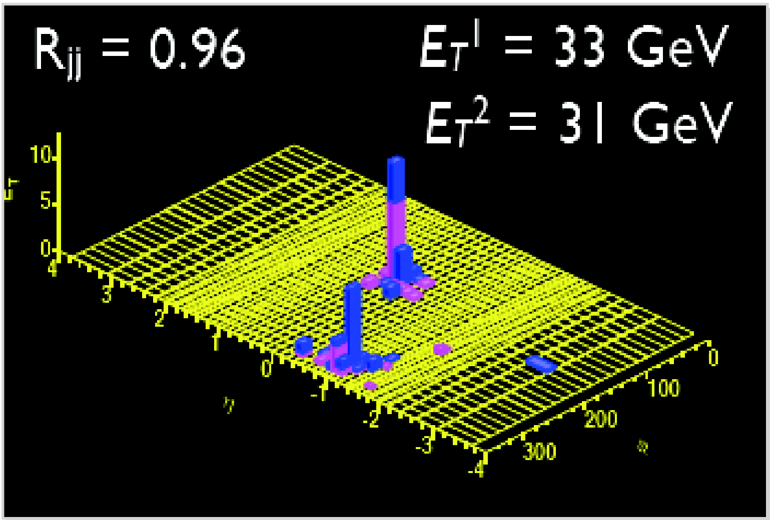
$$p+\bar{p} \rightarrow I\!P + I\!P \rightarrow \bar{p} + X(\geq 2 \text{ jets}) + \text{gap}$$

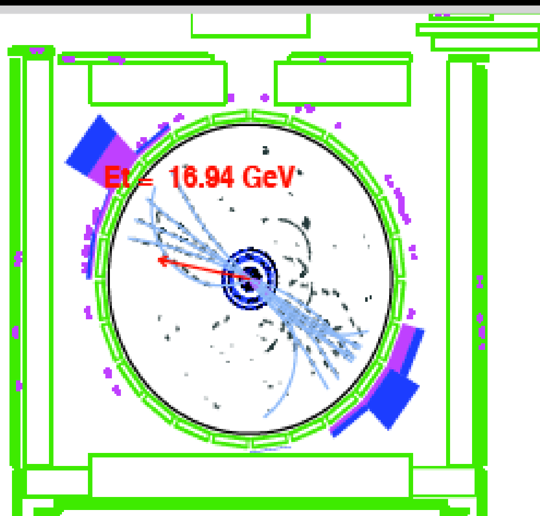


Reconstruct $R_{jj} = \frac{M_{jj}}{M_X}$, where

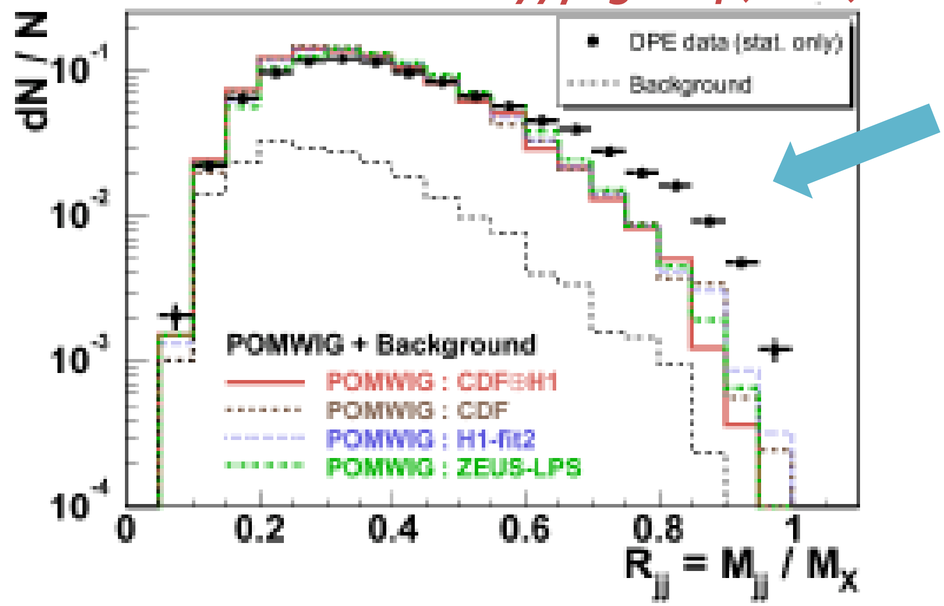
M_{jj} - dijet mass, M_X - mass of system X

Observation of Exclusive Dijet Production





PRD 77, 052004 (2008)



Observe excess over inclusive DPE dijet MC's at high dijet mass fraction

Signal at R_{jj}=1 is smeared due to shower/hadronization effects, NLO $gg \rightarrow ggg, qqg$ contributions

Exclusive Dijets

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

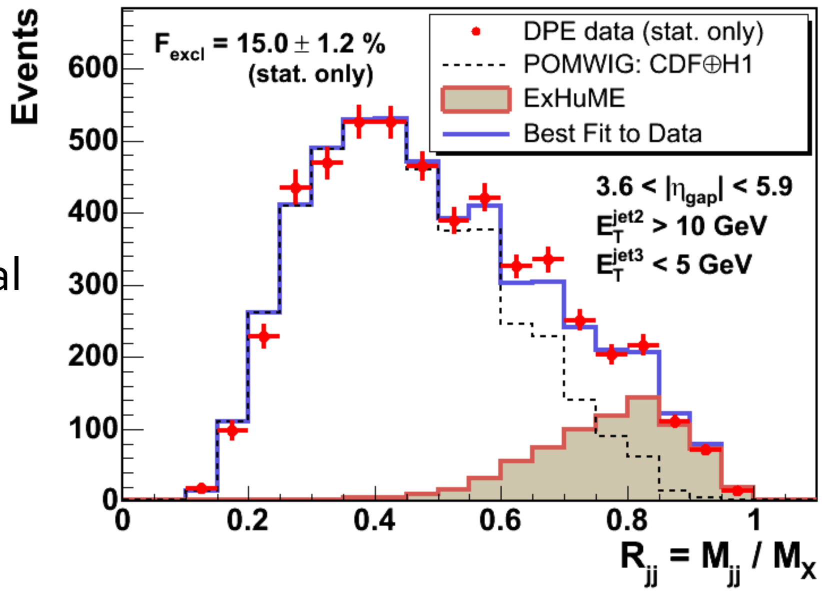
Exclusive DPE as input to DPEMC *CPC 167,217 (2005)*

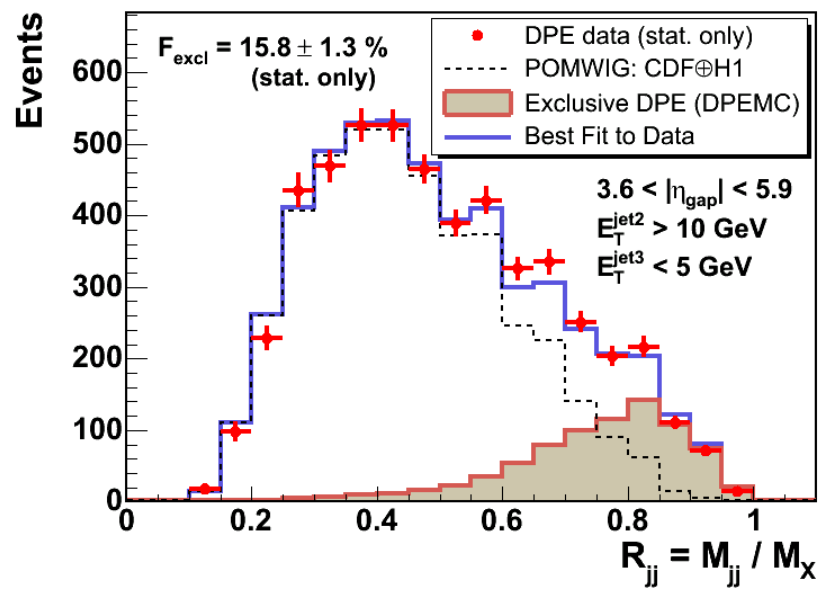
● data

···· bkgd

signal

fit

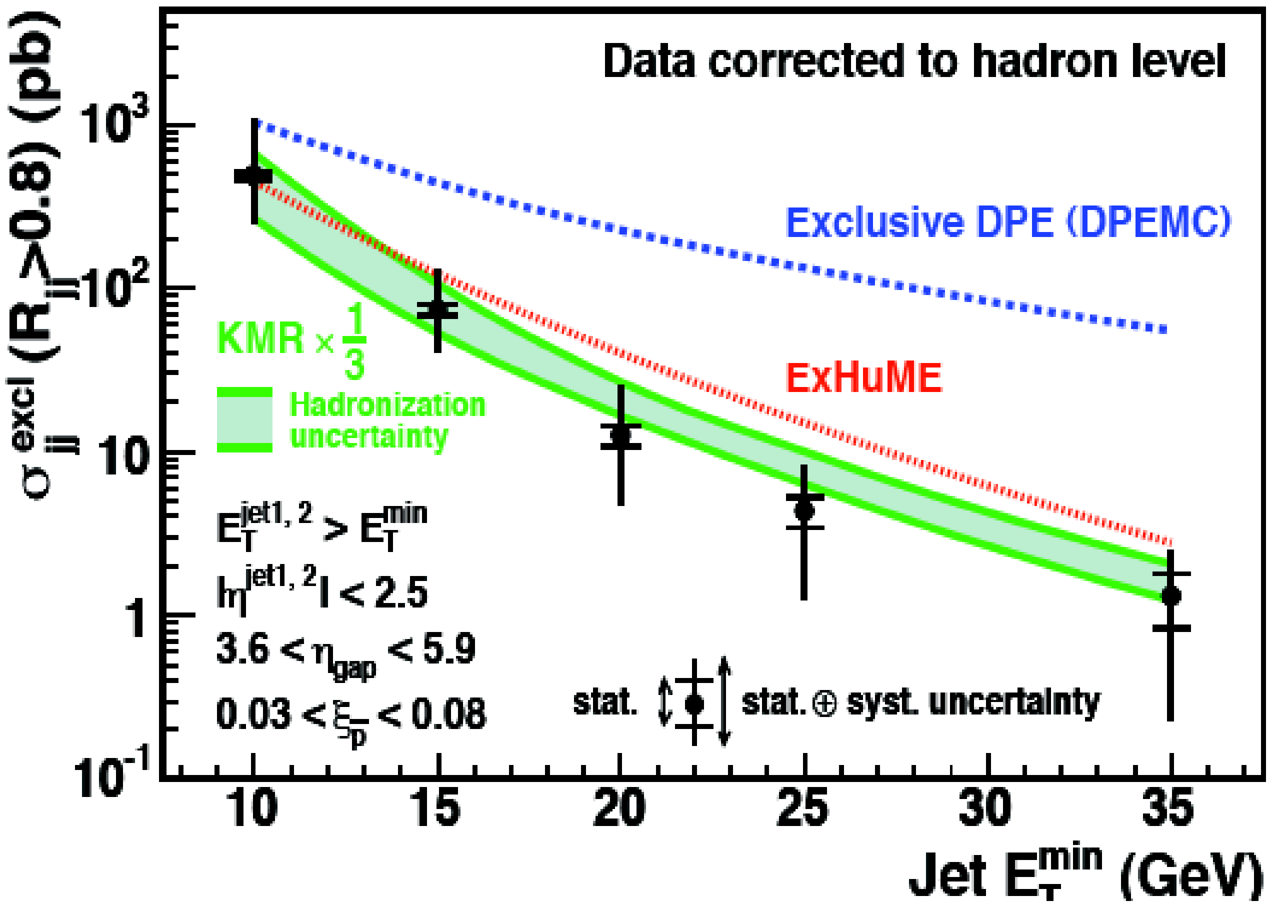




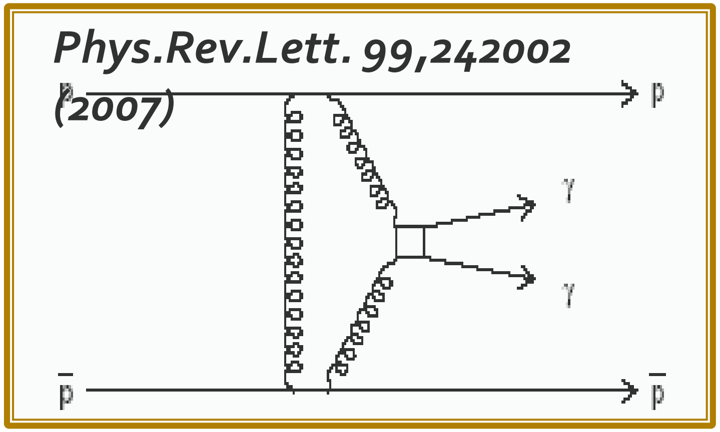
➔ Shape of excess described by exclusive dijet MC based on two models (ExHuME, DPEMC), shows good agreement

Exclusive Dijet Cross Section

- ➔ Exclusive dijet cross section compared with MC based on two models : ExHuME, and excl. DPE DPEMC.
- ➔ Cross section disfavors exclusive DPE model.
- ➔ Calculation by Khoze, Martin, and Ryskin consistent within its factor of 3 uncertainty. *Eur. Phys J C**14**, **525** (**2000**).*



Exclusive $\gamma\gamma$ Production



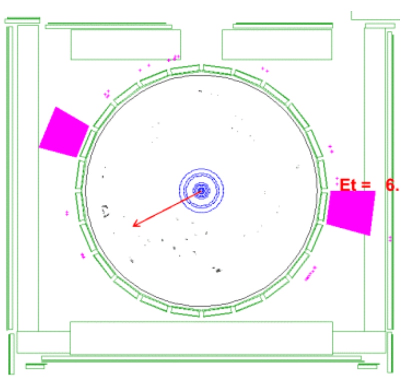
Phys.Rev.Lett. 99,242002 (2007)

Method for excl. $\gamma\gamma$ search is calibrated vs excl e+e- analysis:

3 candidates observed:

2 events are good $\gamma\gamma$ candidates

1 event is good $\pi^0\pi^0$ candidate



$E_T(\gamma) > 5$ GeV

$|\eta(\gamma)| < 1.0$

Theoretical Prediction:

V.A.Khoze et al. Eur. Phys. J C38, 475 (2005)

σ (with our cuts) = (36 +72 – 24) fb

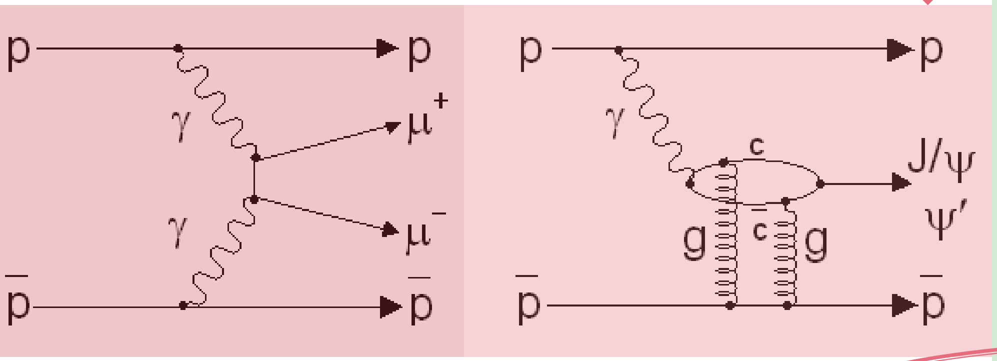
= 0.8 +1.6 –0.5 events.

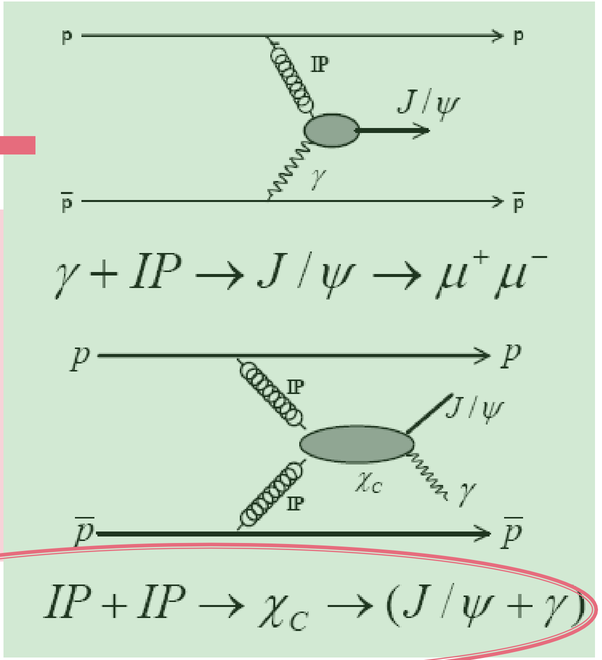
Cannot yet claim "discovery" as b/g study *a posteriori*,

2 events correspond to σ ~ 90 fb, agreeing with Khoze *et al.*

Exclusive Dimuon Production

Many Physics Processes in this data:





exclusive χ_c in DPE

- Observation of exclusive χ_c PRL 102 242001 (2009)

Exclusive J/ψ and ψ(2s)

J/ψ production

243 ±21 events

dσ/dy|$_{y=0}$* = *3.92 ± 0.62 nb

Theoretical Predictions

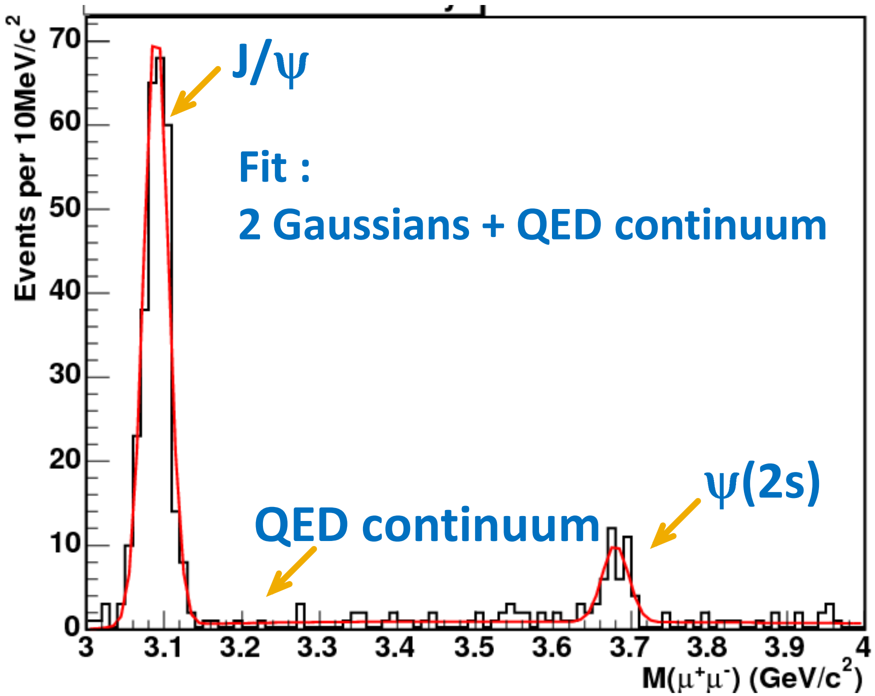
2.8 nb [Szczurek07,],

2.7 nb [Klein&Nystrand04],

3.0 nb [Conclaves&Machado05], and

3.4 nb [Motkya&Watt08].

PRL 242001 (2009)



Ψ(2s) production

34±7 events

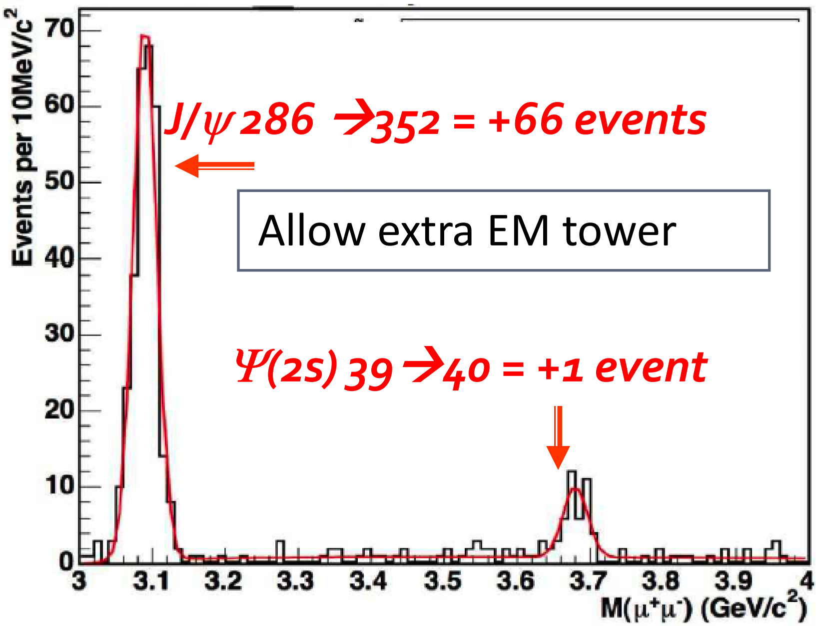
dσ/dy|$_{y=0}$* = *0.54 ± 0.15 nb

R = ψ(2s)/J/ψ = 0.14 ± 0.05

In agreement with HERA: R = 0.166 ± 0.012 in a similar kinematic region

Exclusive $\chi_c \rightarrow J/\psi(\rightarrow \mu^+\mu^-)+\gamma$

PRL 242001 (2009)



➔ Allowing EM towers (E_T>80MeV)

large increase in the J/ψ peak

minor change in the ψ(2s) peak

↓

Evidence for

$\chi_c \rightarrow J/\psi + \gamma$ production

$d\sigma/dy|_{y=0}$ = 75 ± 14 nb,

compatible with theoretical predictions

160 nb (Yuan 01)

90 nb (KMR01)

Conclusions

Very diverse diffractive program at CDF:

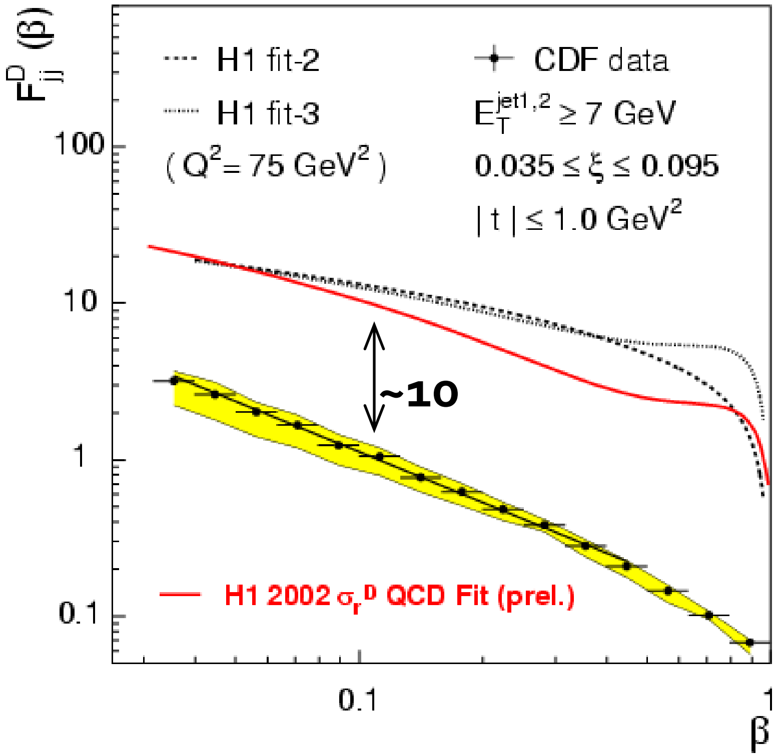
- measurements at 3 different c.o.m. energies
- introduced new methods for diffractive studies at hadron-hadron colliders
- designed and constructed new detectors for forward regions

✓Majority of measurements are MC free

✓Different identifications of diffractive event signatures:
Results between RPS and large rapidity gap are consistent.

Back up

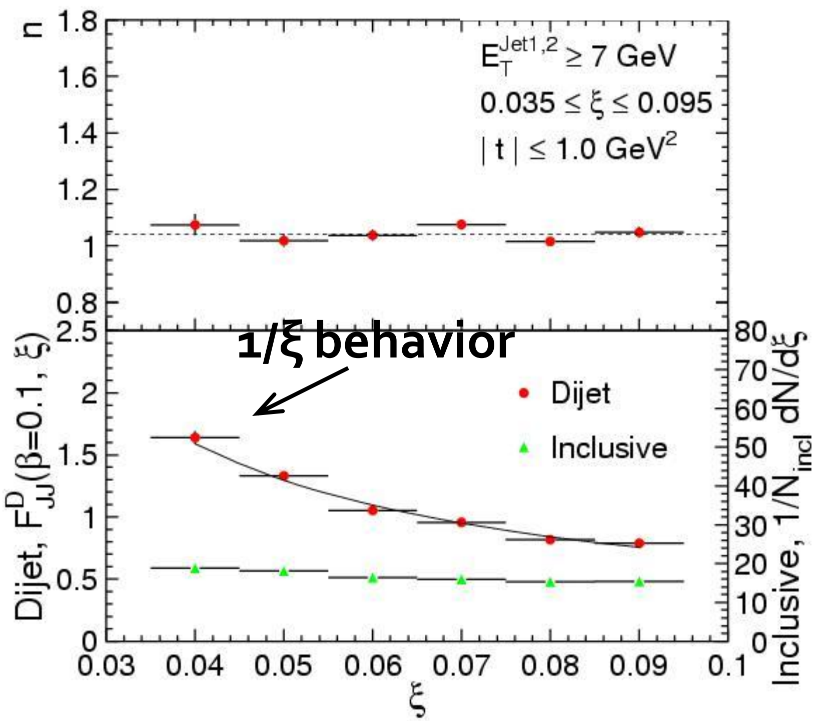
The Diffractive Structure Function



discrepancy in normalization

↓

QCD factorization breakdown



$$F^D_{jj} = C\beta^{-n}\xi^{-m}$$

for $\beta < 0.5$

$n = 1.0 \pm 0.1$

$m = 0.9 \pm 0.1$

Regge factorization holds

pomeron exchange

W/Z Selection

$$E_T^{e}(p_T^{\mu}) > 25\,\text{GeV}$$
$$\not{E}_T > 25\,\text{GeV}$$
$$40 < M_T^{W} < 120\,\text{GeV}$$
$$|Z_{vtx}| < 60\,\text{cm}$$

$$E_T^{e1}(p_T^{\mu 1}) > 25\,\text{GeV}$$
$$E_T^{e2}(p_T^{\mu 2}) > 25\,\text{GeV}$$
$$66 < M^{Z} < 116\,\text{GeV}$$
$$|Z_{vtx}| < 60\,\text{cm}$$

- RPS trigger counters – require MIP
- RPS track - $0.03 < \xi < 0.10$, $|t| < 1\,\text{GeV}^2$
- W ➔ $\xi^{cal} < \xi^{RP}$, $50 < M_W(\xi^{RPS}, \xi^{cal}) < 120\,\text{GeV}^2$
- Z ➔ $\xi^{cal} < 0.1$

W/Z Results

R^W (0.03 < ξ < 0.10, |t|<1)= [0.97 ± 0.05(stat) ± 0.11(syst)]%

Run I: R^W (ξ<0.1)=[1.15±0.55] % ➔ **0.97±0.47 %** in **0.03 < ξ < 0.10 & |t|<1**

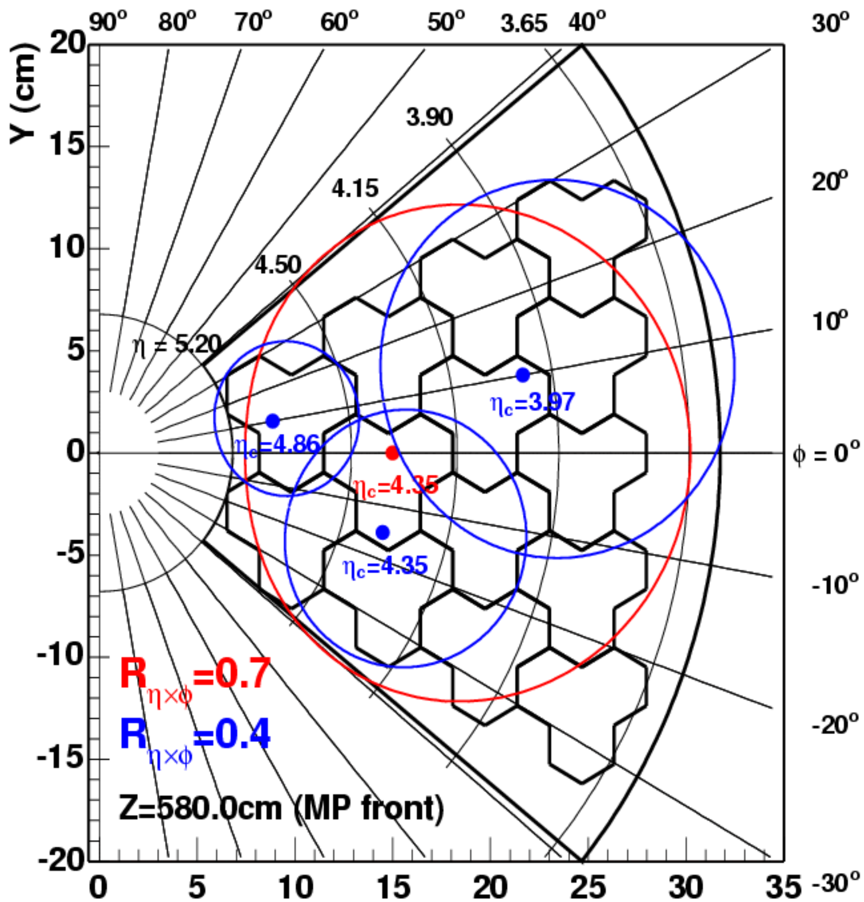
R^Z (0.03 < x < 0.10, |t|<1)= [0.85 ± 0.20(stat) ± 0.11(syst)]%

CDF/DØ Comparison – Run I (ξ < 0.1)

CDF PRL 78, 2698 (1997)
R^w=[1.15±0.51(stat)±0.20(syst)]%
gap acceptance A^{gap}=0.81
Uncorrected for A^{gap}
R^W=(0.93±0.44)%

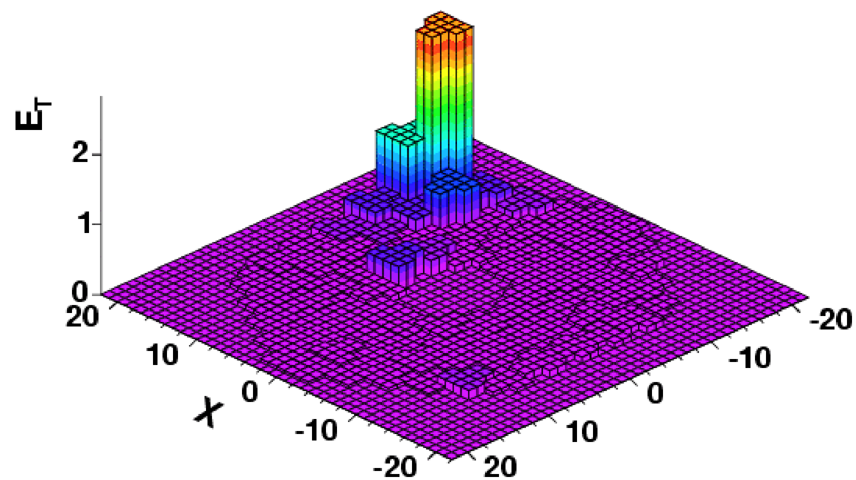
DØ Phys Lett B **574**, 169 (2003)
R^w=[5.1±0.51(stat)±0.20(syst)]%
gap acceptance A^{gap}=(0.21±4)%
Uncorrected for A^{gap}
R^W=[0.89+0.19-0.17]%
R^Z=[1.44+0.61-0.52]%

MiniPlug Jets



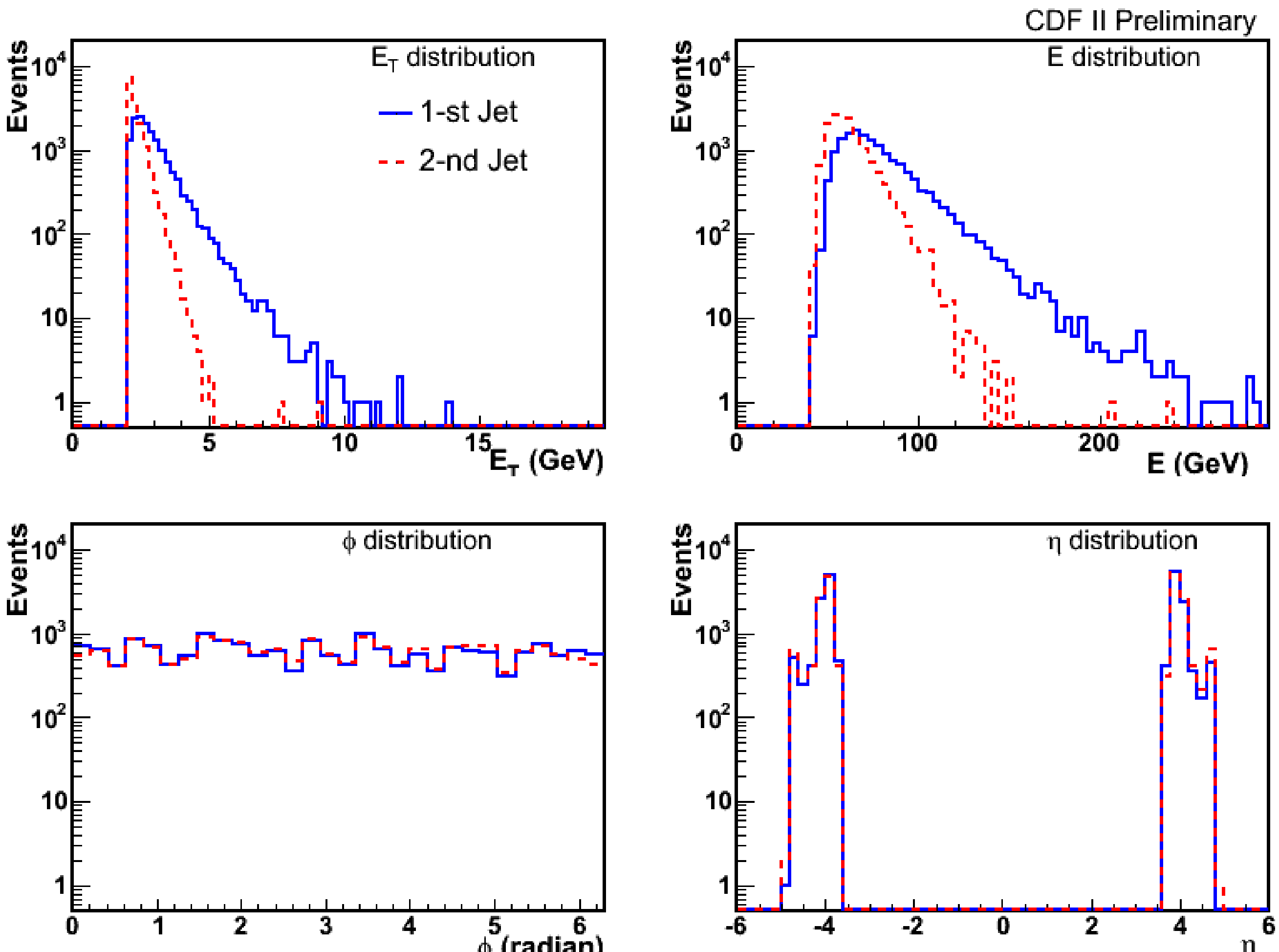
MP jet is defined as a vector pointing to a cluster with seed tower (E_T > 400 MeV) and 1 layer of surrounding towers

MP Jet energy = energy of the seed tower
+
energy of the towers in
the layer surrounding the seed



jet cone radius
R = 0.4 (0.7)

Kinematic Distributions for MP Jets



$E^{Jet1,2}_T > 2$ GeV

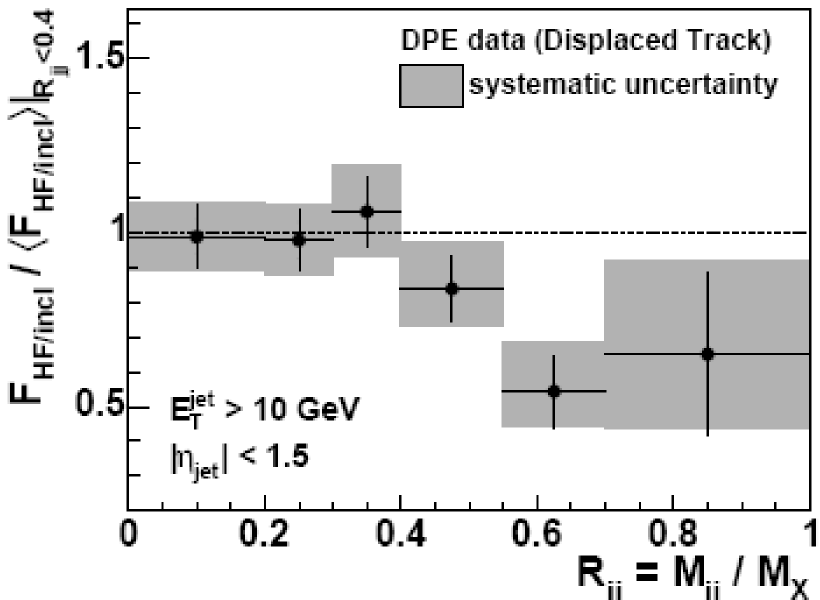
$3.5 < |\eta^{Jet1,2}| < 5.$

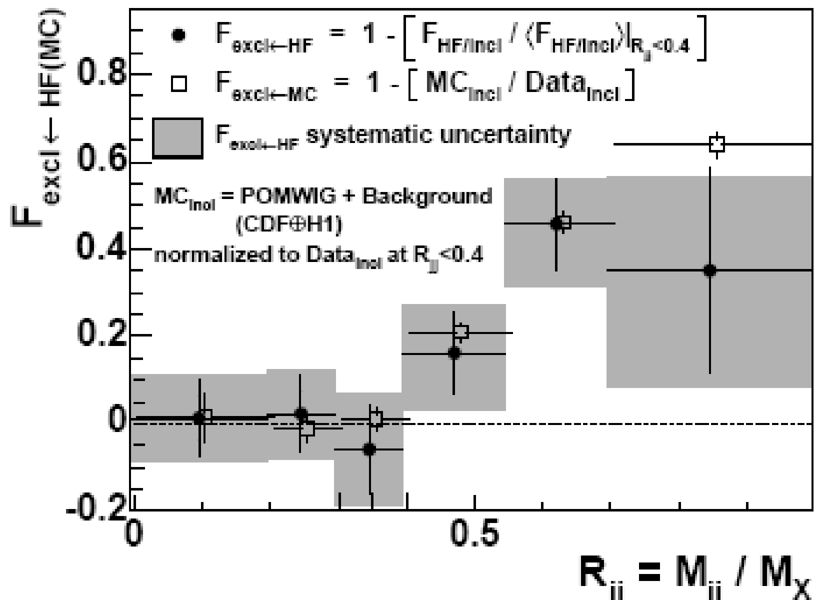
$\eta^{Jet1} \cdot \eta^{Jet2} < 0$

Kinematic distributions for the two leading jets in the $MP_p \cdot MP_{pbar}$ sample

Heavy Flavor Suppression

- ➔ LO exclusive gg →qq suppressed (J_Z =0 rule)
- ➔ Look for **heavy flavor jet suppressio**n relative to inclusive dijets at high Rjj

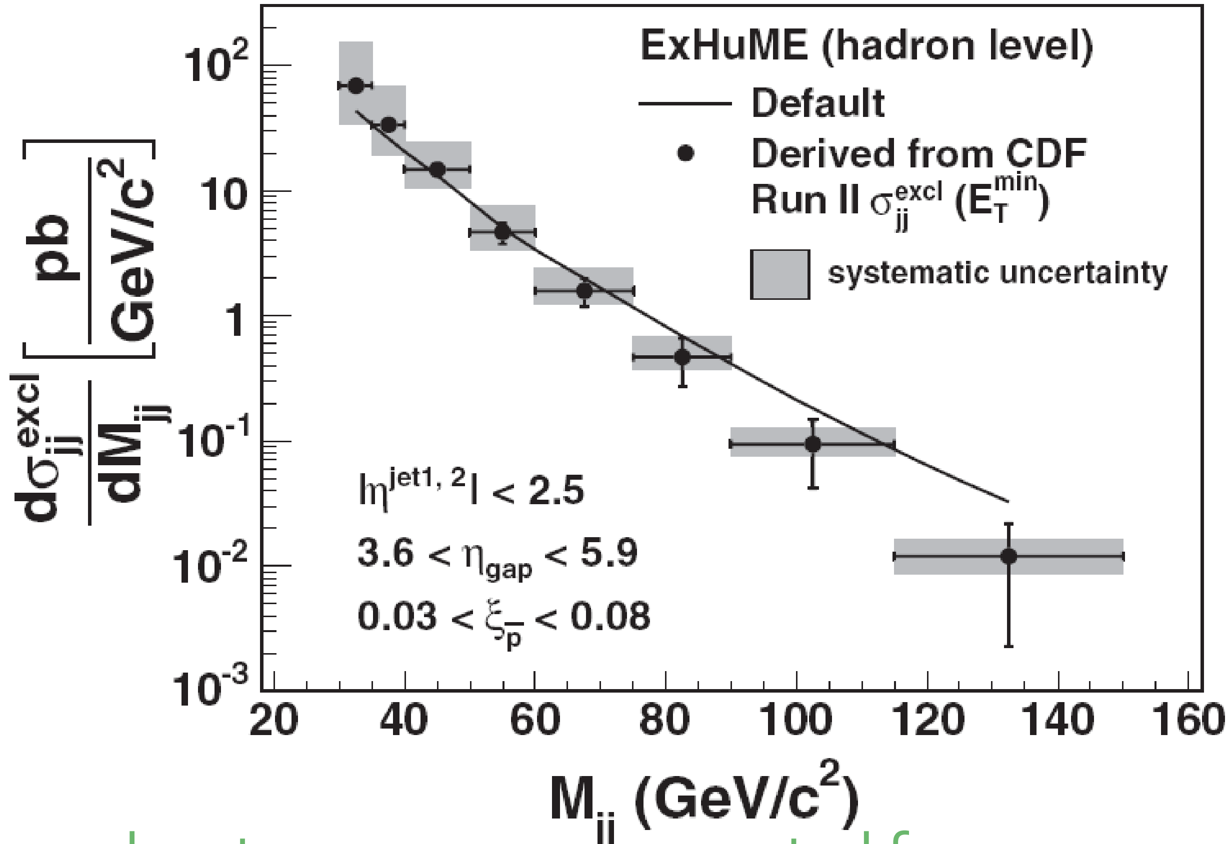




Suppression of heavy flavor for R_{jj}> 0.4 is consistent in shape and magnitude with the results based on MC based extraction of exclusive dijet signal.

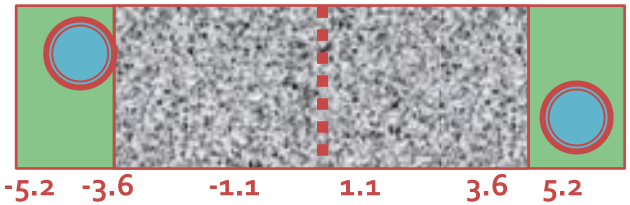
Excl. Cross Section vs Dijet Mass

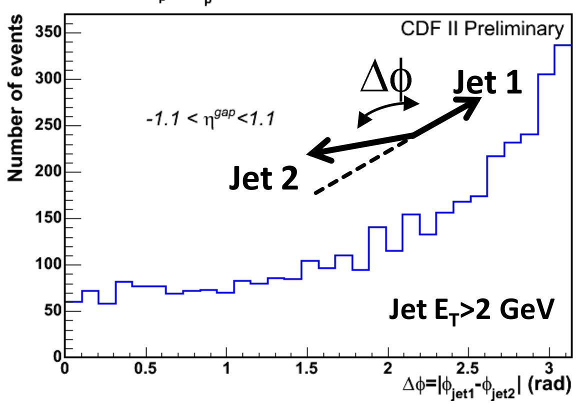
derived from CDF excl. dijet x-sections using ExHuME

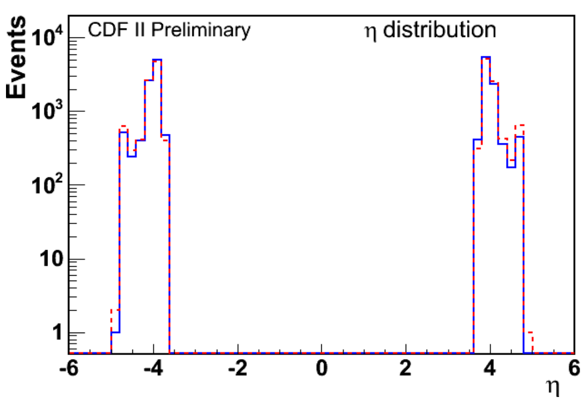


- Stat. and syst. errors are propagated from measured cross section uncertainties using M_{jj} distribution shapes of ExHuME generated data.

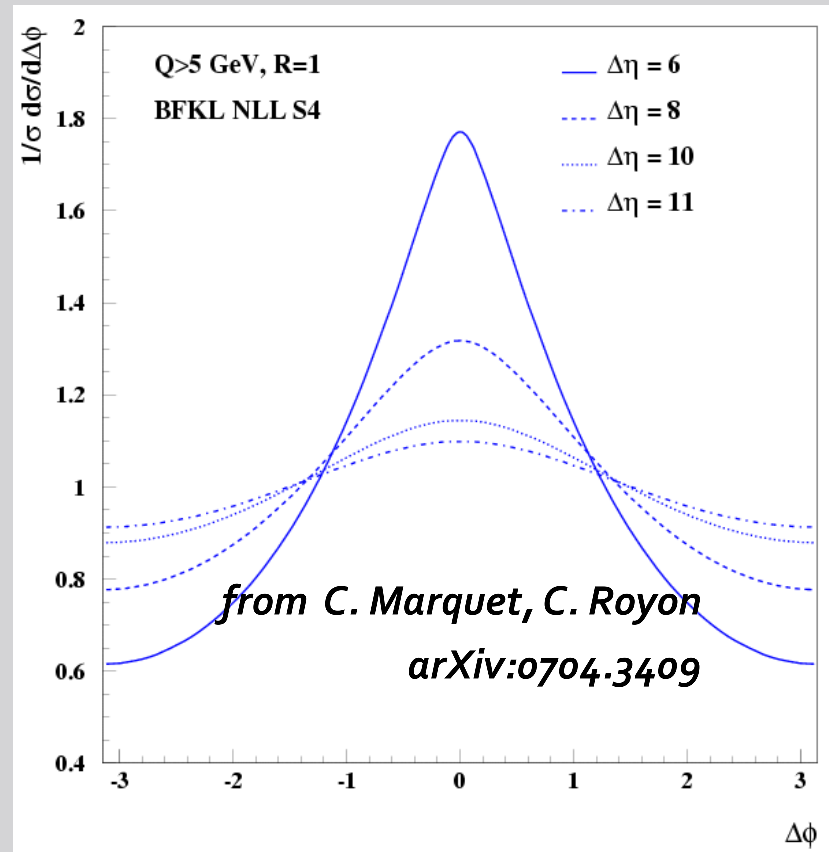
Jet Azimuthal Angle (De)correlation





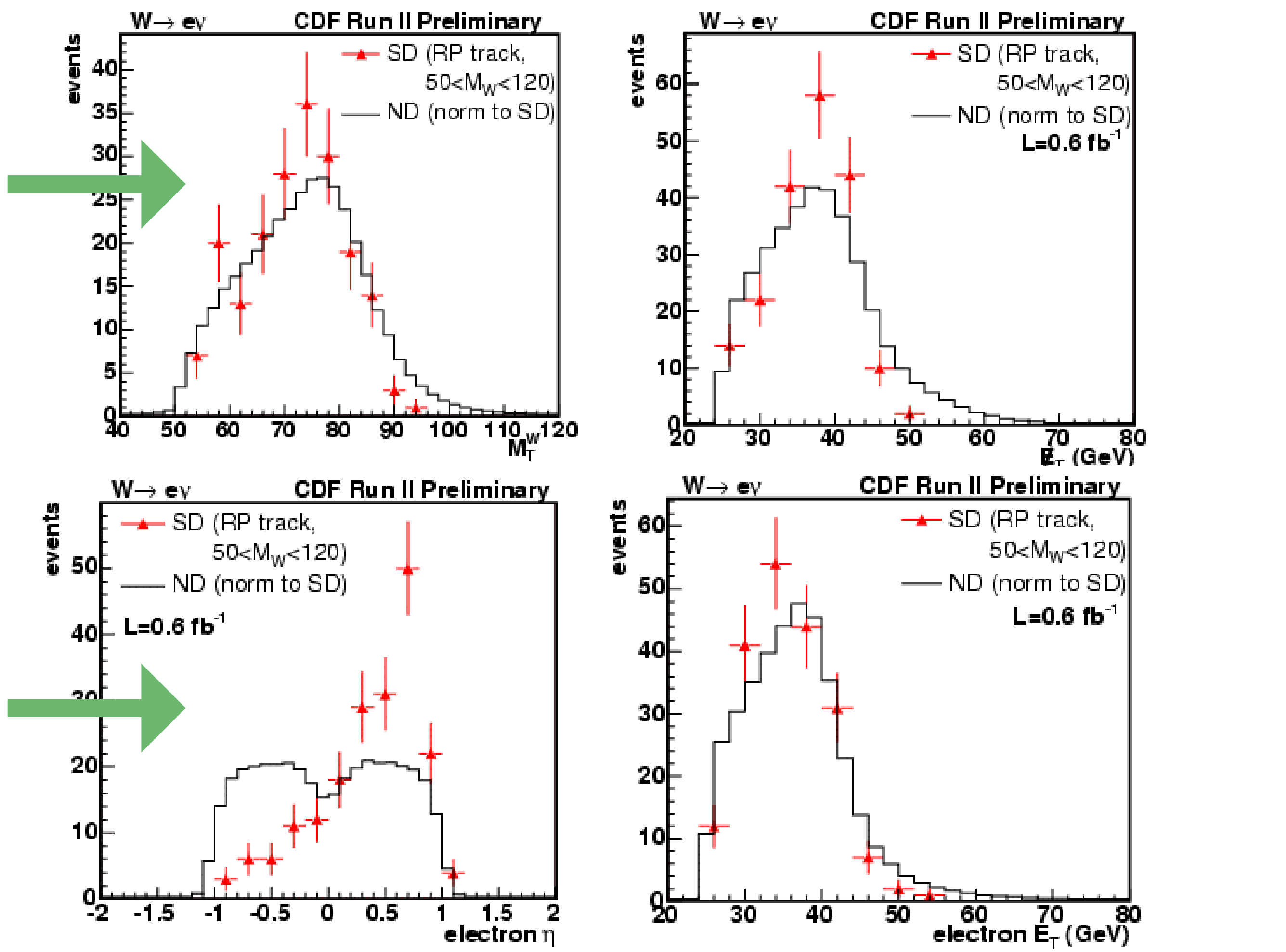


azimuthal decorrelation for CDF kinematics



work in progress…

$W \to e\,\nu$ Kinematics

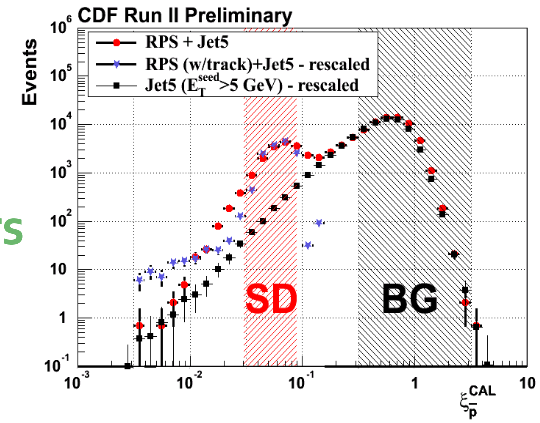


Forward Jets and Central Gaps

Nucl. Instrum. Meth. ***A****518 (2004) 42.*

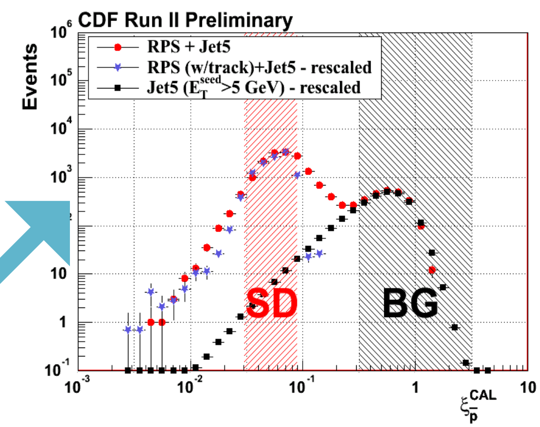
Nucl. Instrum. Meth. ***A****496 (2003) 333.*

to detect forward jets $3.6 < |\eta| < 5.2$ we use **MiniPlug Calorimeters**

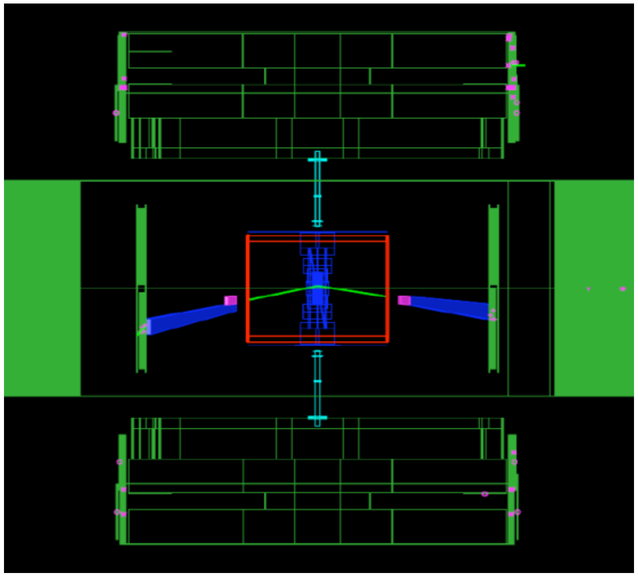


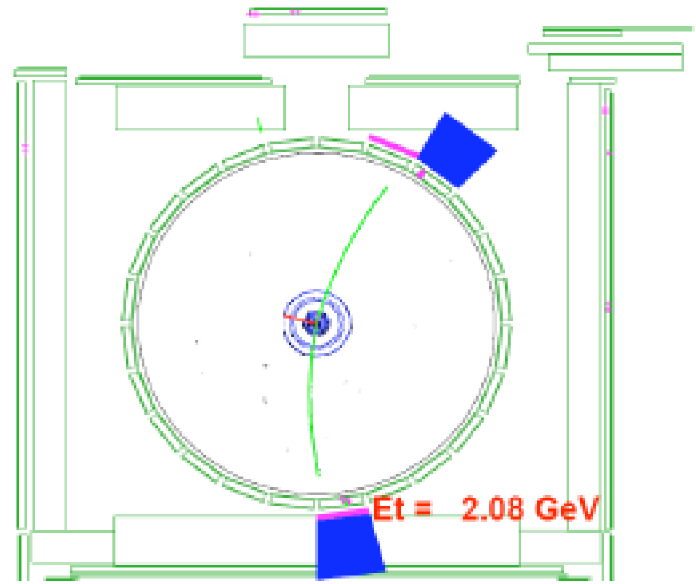
for gap studies need **low luminosity** run

average luminosity
$\mathcal{L} \sim 1 \times 10^{30} cm^{-2}s^{-1}$



Exclusive dimuon production





$$p + \bar{p} \rightarrow p + \mu^+ \mu^- + \bar{p}$$

$3\ GeV/c^2 < M_{\mu\mu} < 4\ GeV/c^2$

Trigger:

muon + track + forward rapidity gaps in BSCs

2 oppositely charged muon tracks with $p_T > 1.4$ GeV/c, $|\eta| < 0.6$

$\varepsilon_{excl} \sim 0.093$ => $L = 1.48\ fb^{-1}$ but $L_{eff} \sim 140 pb^{-1}$

Double Diffraction

Diffractive signature:

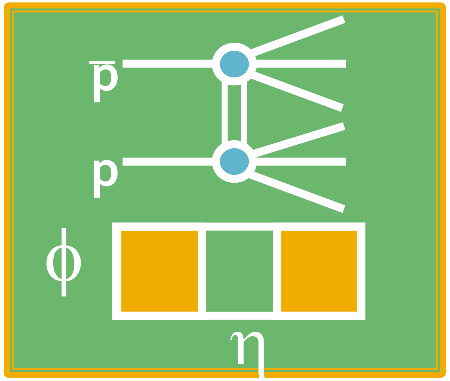
large central rapidity gap

Soft Diffraction

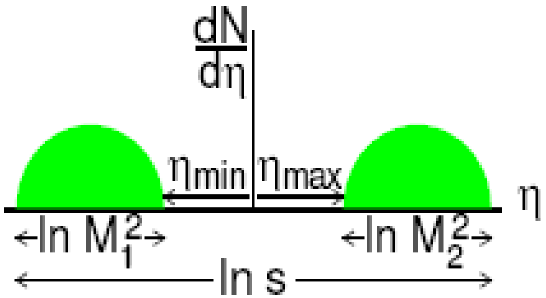
Double Diffraction
PRL 87, 141802 (2001)

Hard Diffraction

Jet-Gap_Jet
1.8 TeV PRL 74, 855 (1995)
1.8 TeV PRL 80, 1156 (1998)
J630 GeV PRL 81, 5278 (1998)



Strategy of analysis:
to look for "experimental gaps" defined as
$\Delta\eta \equiv \eta_{max} - \eta_{min}$
$\eta_{max}(\eta_{min})$- "particle" closest to $\eta=0$
in the p(p̄) direction



Double Diffraction