Experimental results on diffraction at the Tevatron

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- Introduction
- Diffractive production (dijets, W/Z, Forward jets)
- Exclusive production (dijets, $\gamma\gamma$, ee)
- Conclusions

FCT Fundação para a Ciência e a Tecnologia
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COMPETE

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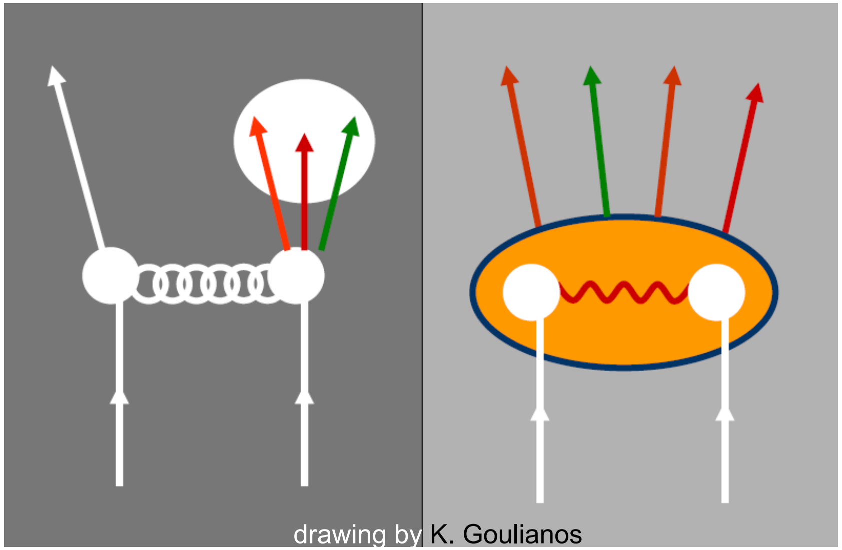
Hadronic interactions

Diffractive

vacuum exchange

Protons retain their quantum numbers



Non-Diffractive

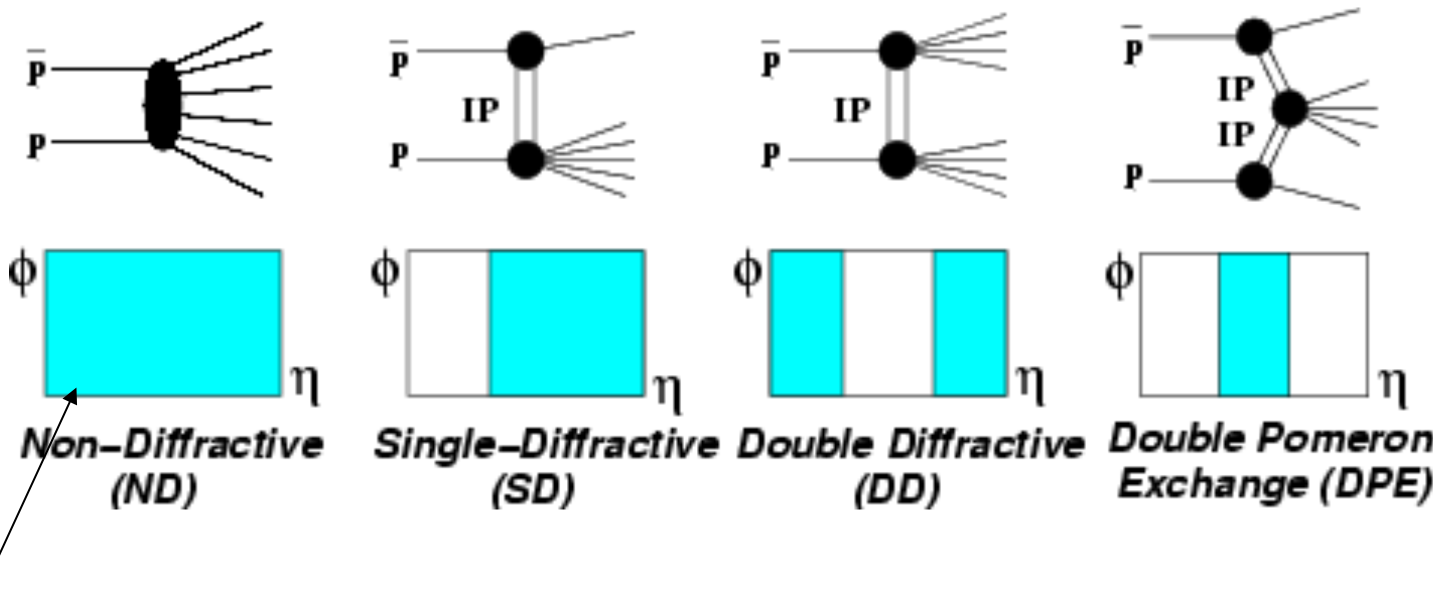
color exchange

Protons acquire color and break apart

Goal: understand the nature of the colorless exchange

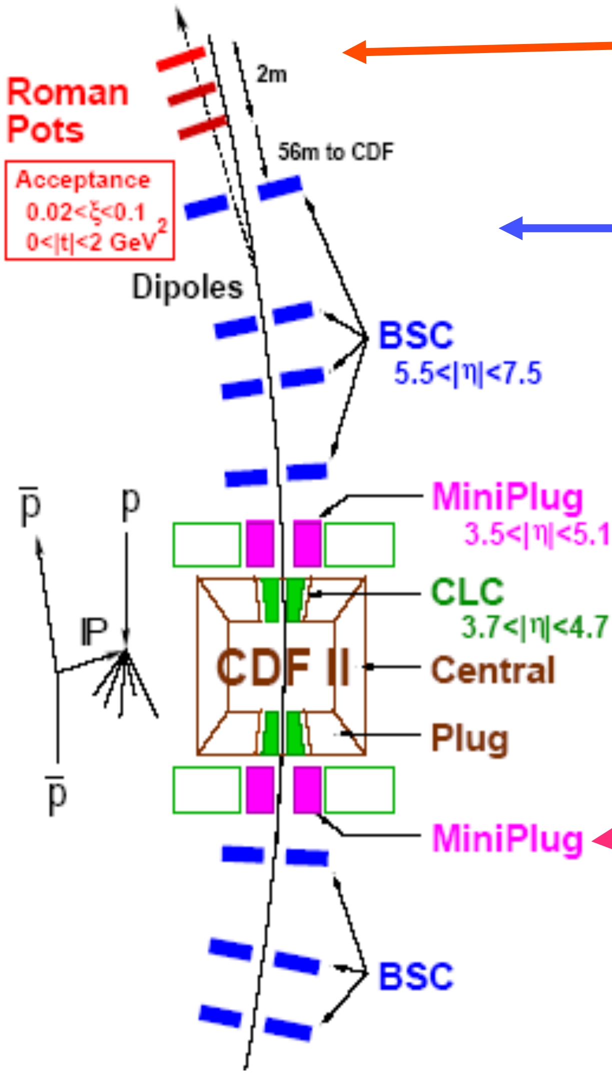
Introduction

- In diffraction no quantum numbers are exchanged



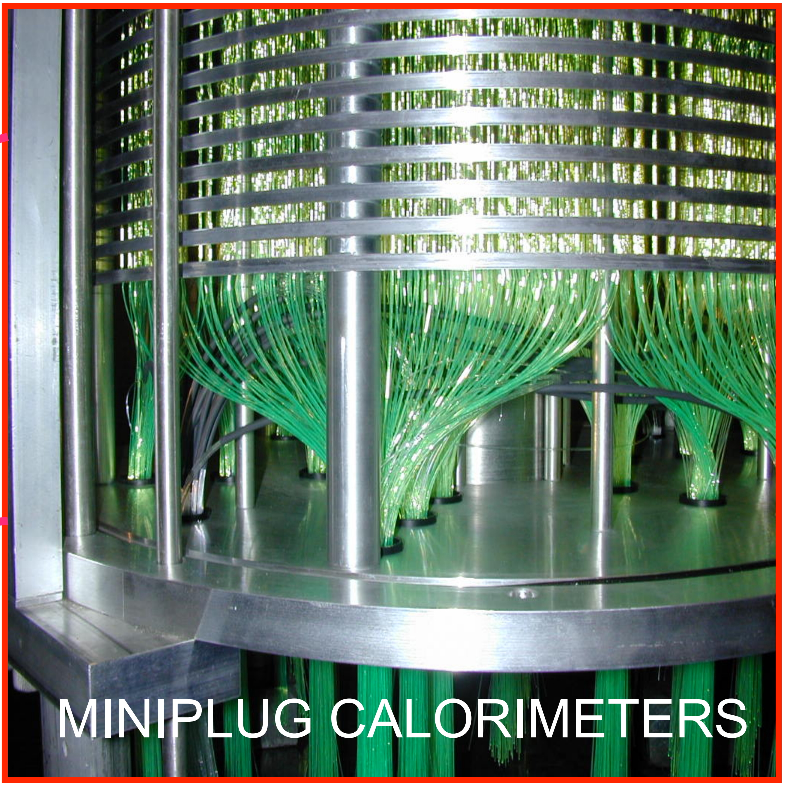
Shaded area corresponds
to particle production

CDF central and forward detectors



ROMAN POT DETECTORS

BEAM SHOWER COUNTERS: used to reject ND events

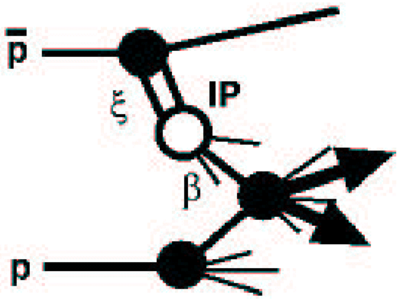


Single diffraction

- Examine partonic structure of diffractive exchange using high-p_T probes (hard diffraction)
- Confirm and extend the kinematical reach of Run I results
  - Diffractive dijet production in ranges of Q^2
  - Diffractive structure functions

Diffractive dijets

PRL 84 (2000) 5043



ξ: fraction of anti-proton momentum loss

β: fraction of Pomeron momentum carried by parton

parton $x_{Bj} \equiv \beta \cdot \xi$

$$x_{Bj} = \frac{\sum_{jet} E_T \cdot e^{-\eta}}{\sqrt{s}}$$

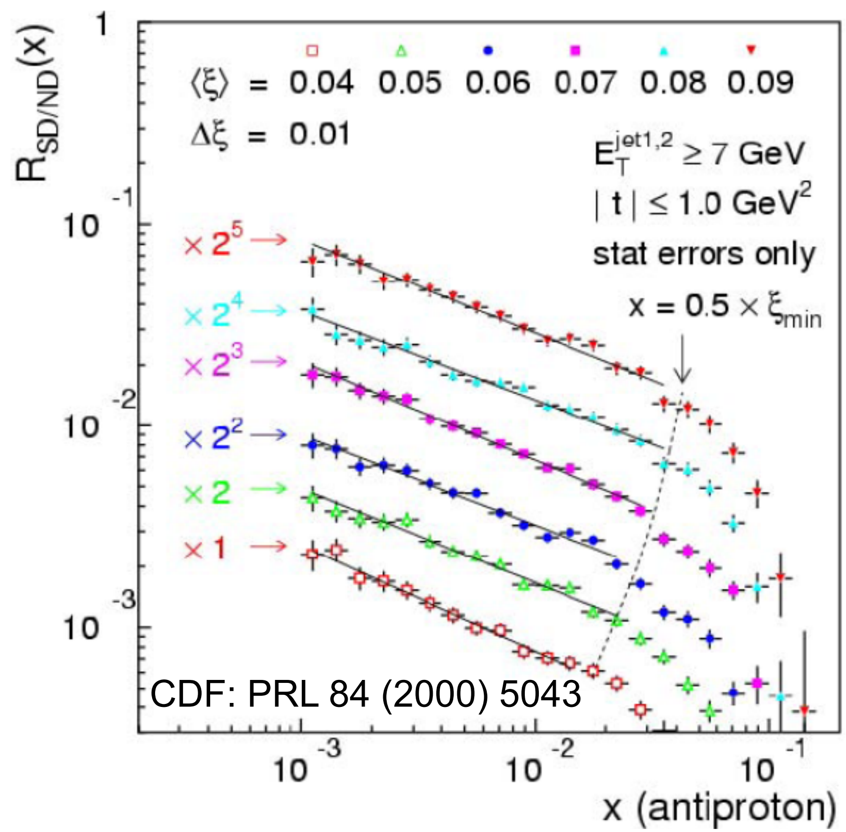
Measure SD/ND ratio of dijet rates

$$\frac{\sigma(SD_{jj})}{\sigma(ND_{jj})} = \frac{F^D_{jj}(x)}{F_{jj}(x)}$$

measure — extract — known — (LO QCD)

$$R_{SD/ND} = R_0 \cdot x^{-0.45}$$

⇨ **no significant ξ dependence**



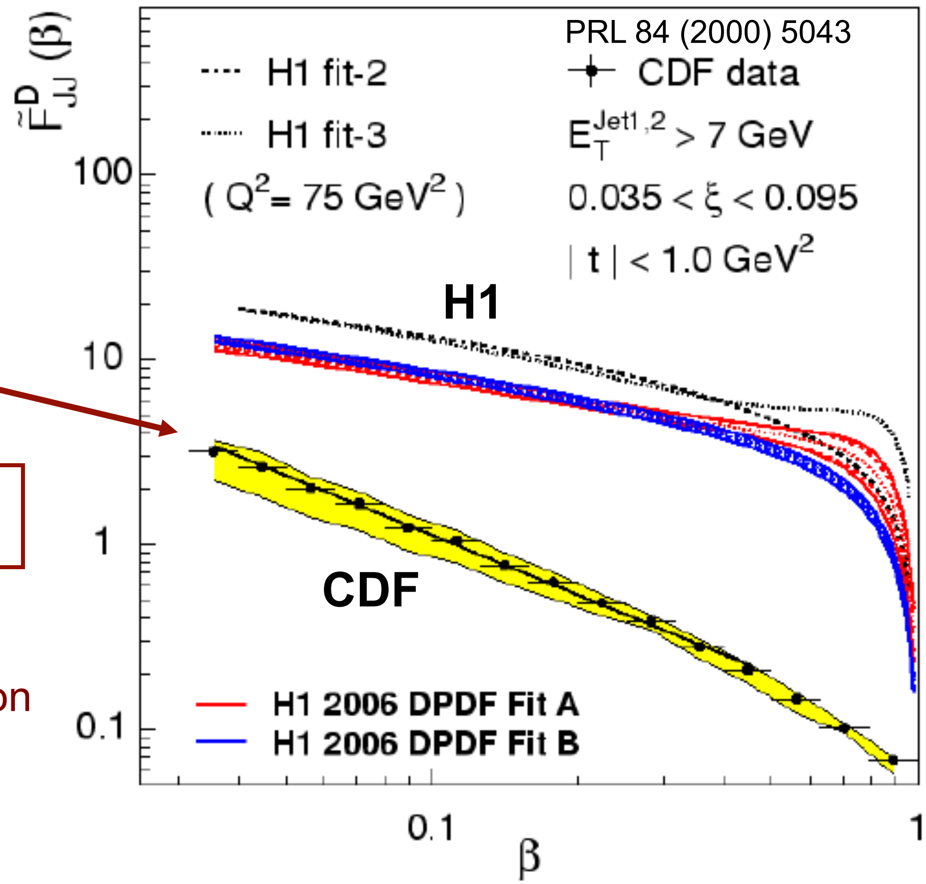
in the ratio SD/ND many systematic uncertainties cancel out

Diffractive structure function

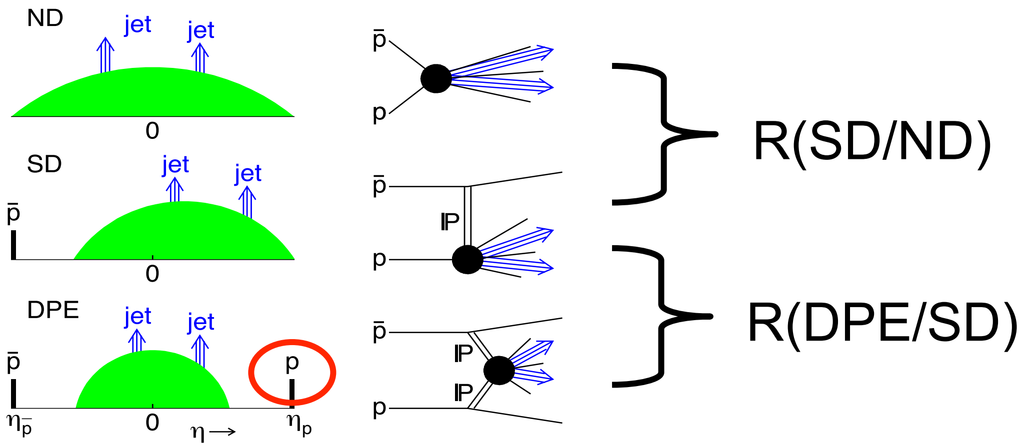
CDF Run I result suppressed
by factor of ~10 relative to HERA

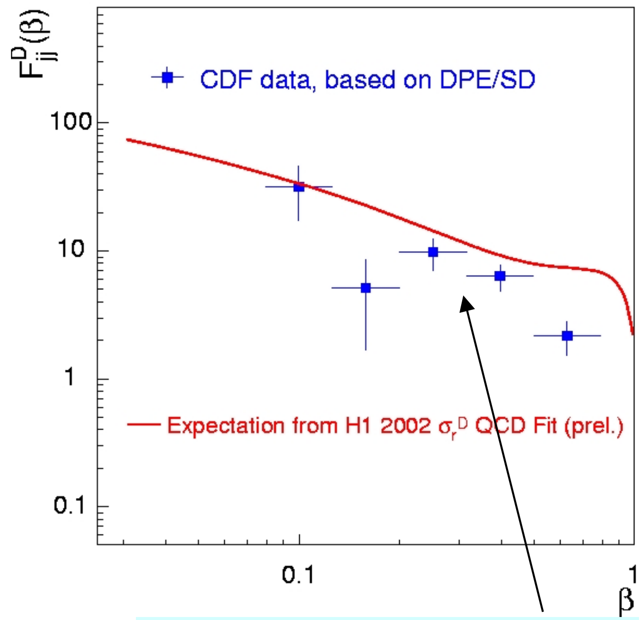
⇨breakdown of QCD factorization

discrepancy can be attributed to additional
color exchange which spoil the gap formation



Restoring factorization





factorization is restored !

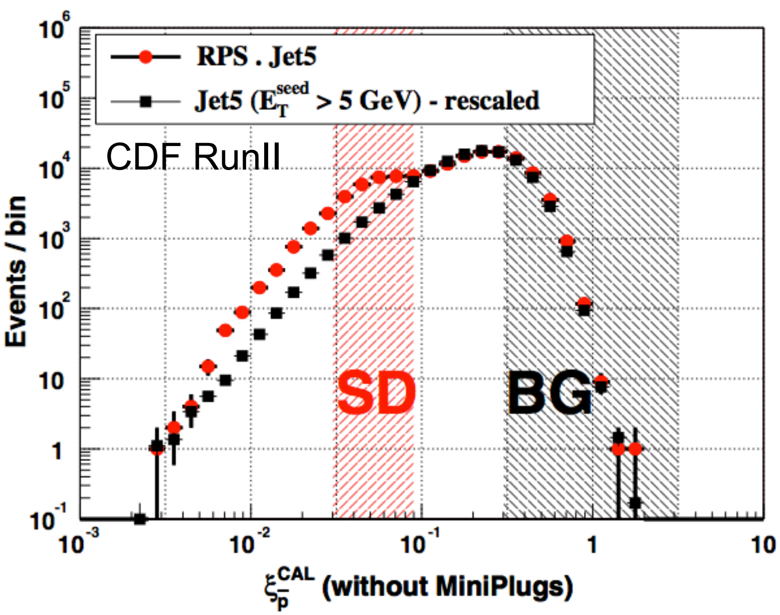
The diffractive structure function measured using DPE events is approximately the same as the one expected from HERA

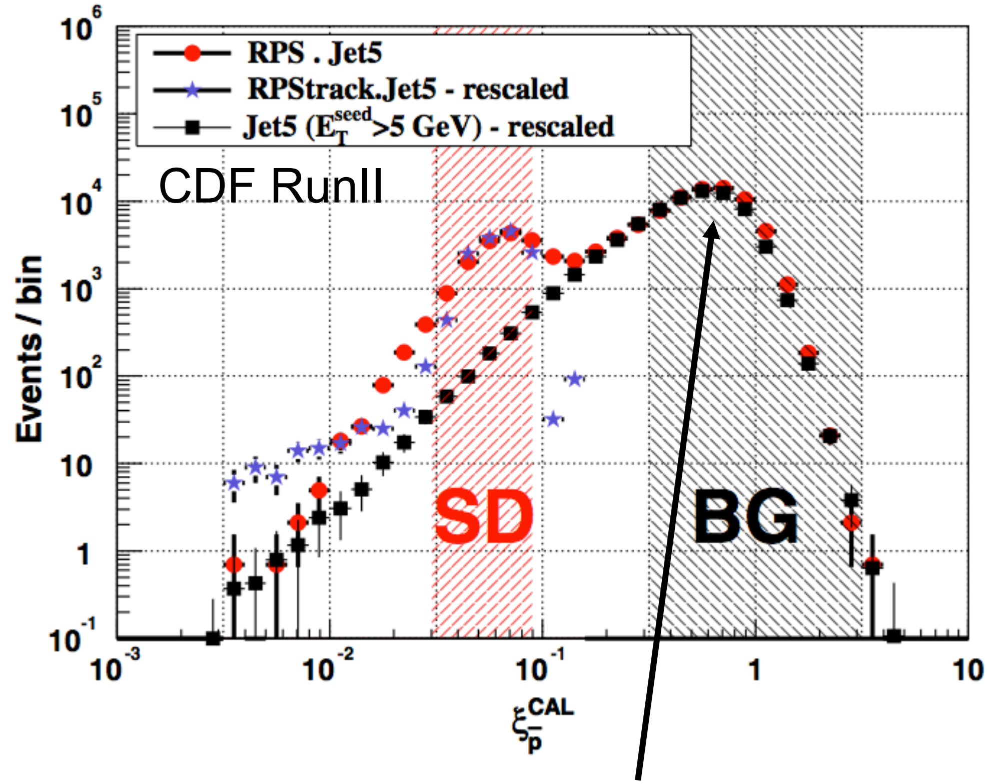
Diffractive dijets in Run II

PRD 86 (2012) 032009

ξ: momentum loss fraction of pbar

$$\xi = \frac{\Sigma_{(\text{all towers})} E_T e^{-\eta}}{\sqrt{s}}$$



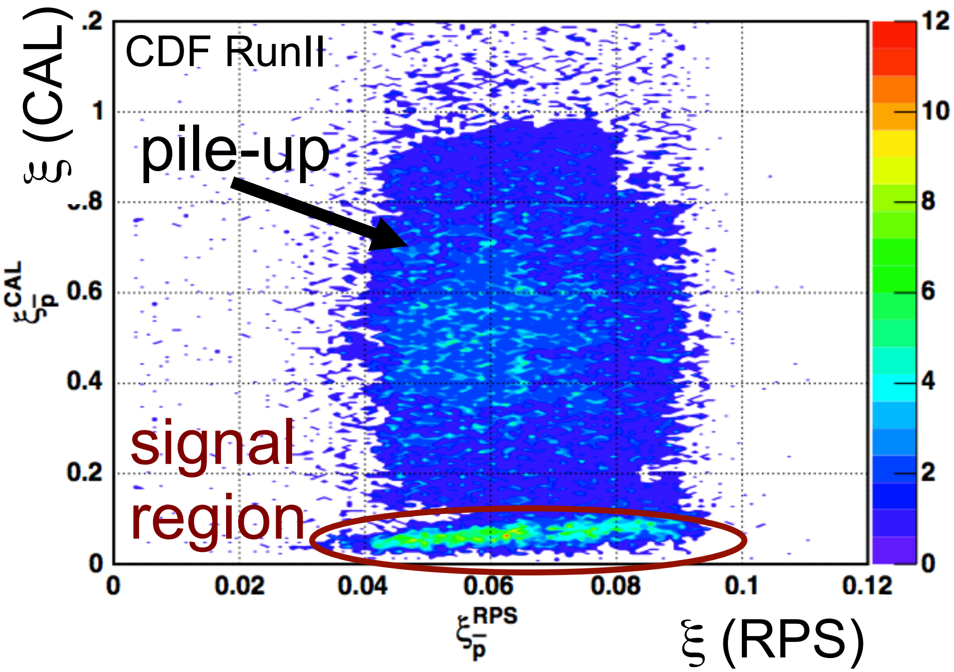


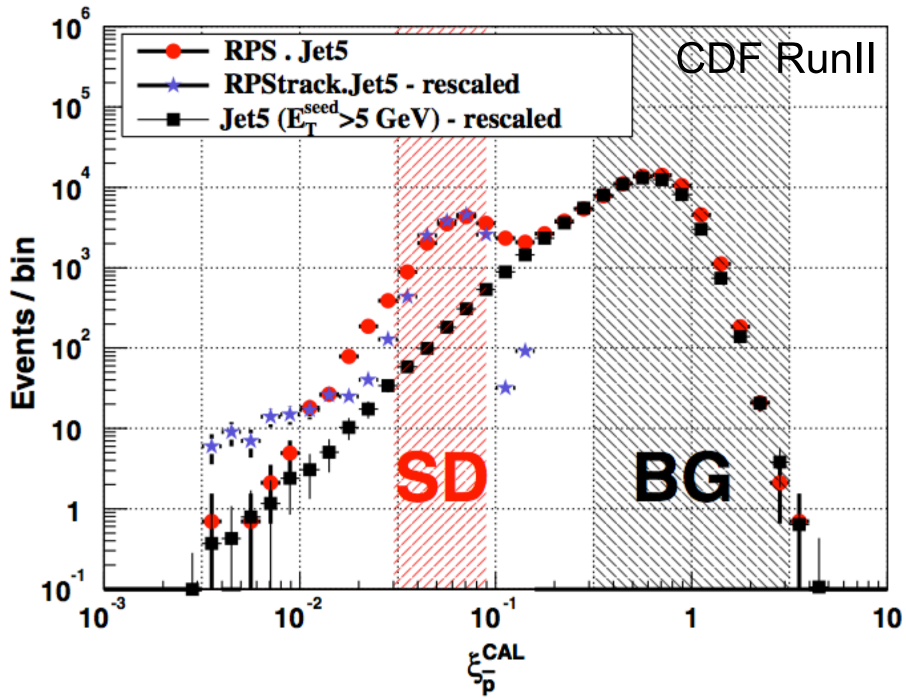
overlap events
(multiple $p\bar{p}$ interactions)

MP energy scale: ±30% →Δlogξ = ±0.1
RP acceptance (0.03<ξ< 0.09) ~ 80%

Multiple interactions in Run II

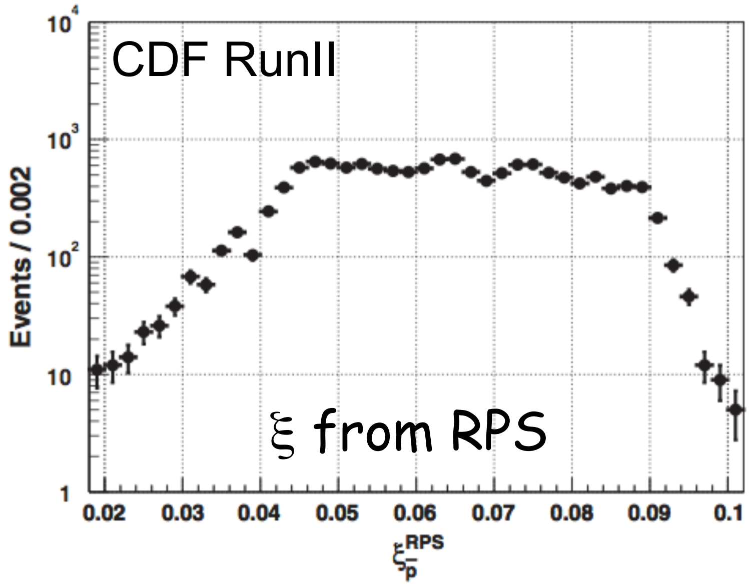
- Multiple proton-antiproton interactions spoil diffractive signature

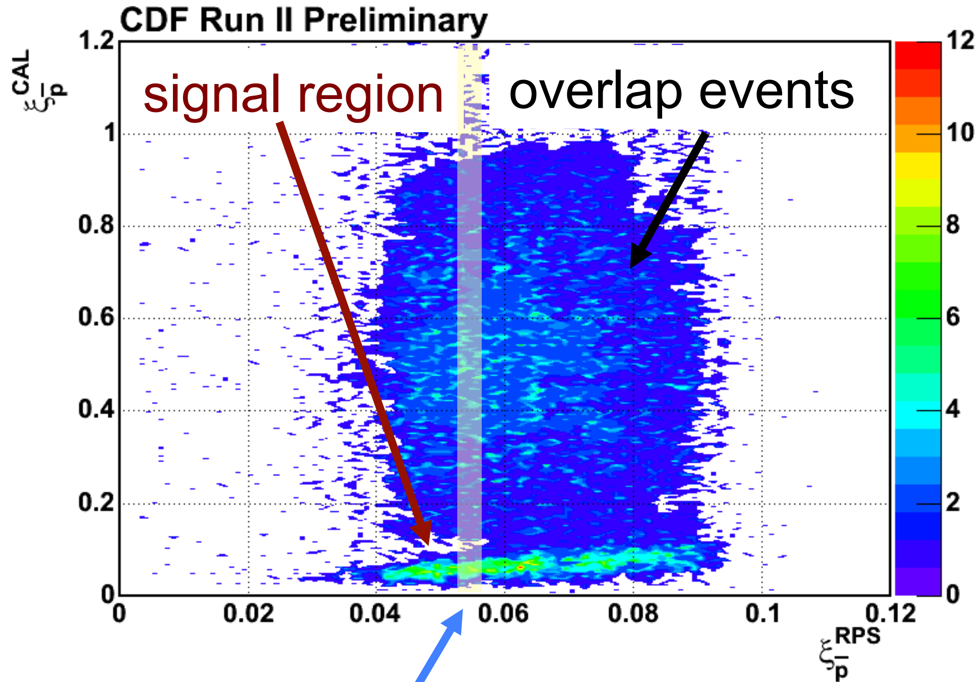


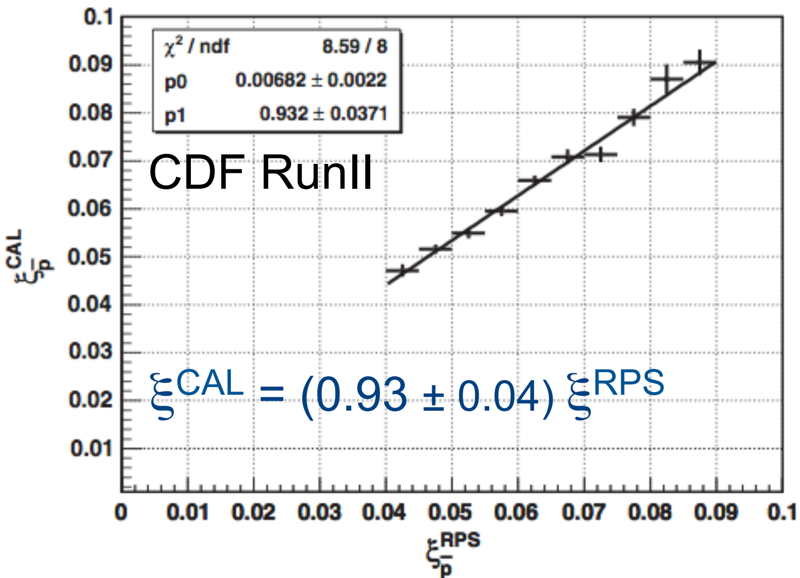


- Measure ξ from calorimeter and from RP tracking
- Reject multiple interactions
  - exclude ξ>0.1 (ND+SD interactions)

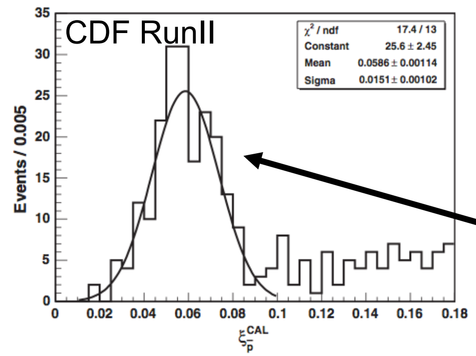
Multiple interactions in Run II







$\xi^{CAL} = (0.93 \pm 0.04)\ \xi^{RPS}$

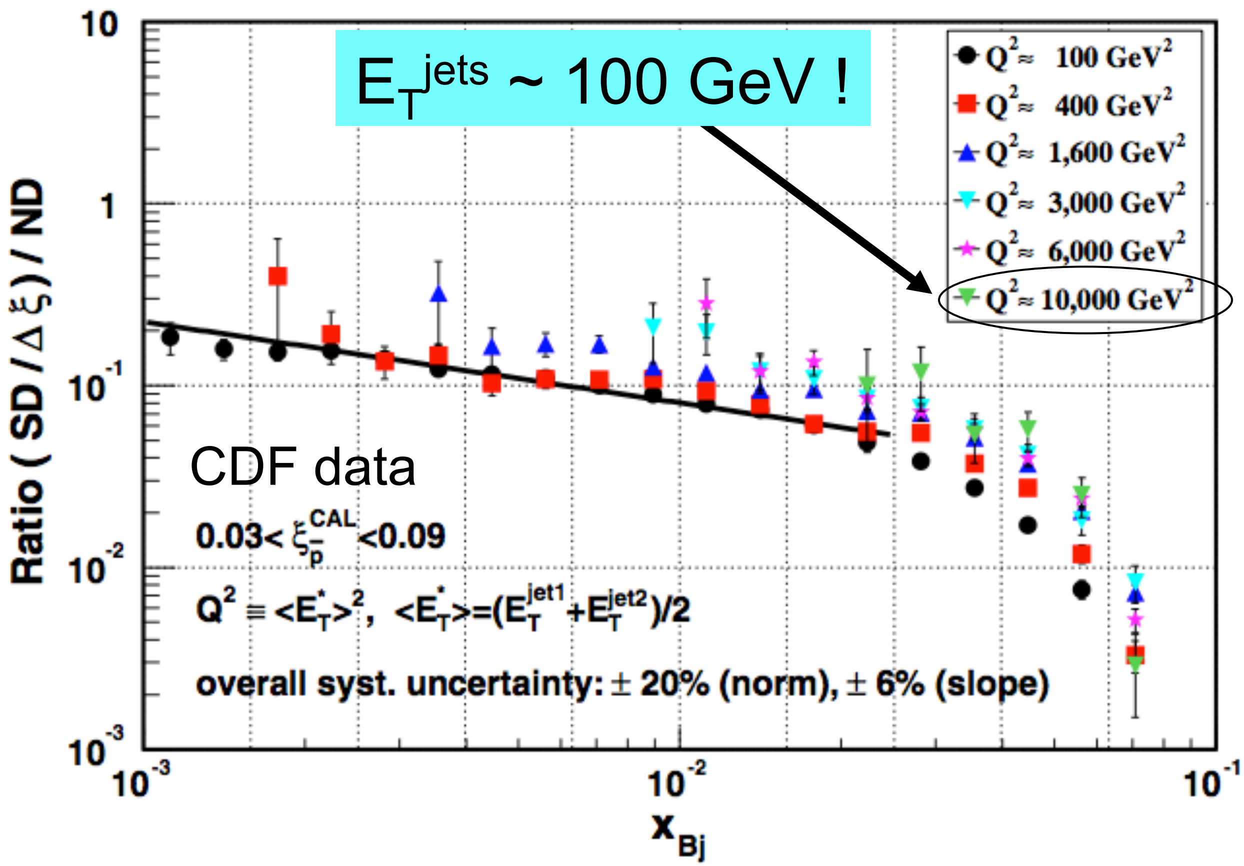


ξ^{cal} distribution for slice of ξ^{RPS}

σ / mean ~ 30%

Q^2 dependence

PRD 86 (2012) 032009



$$\mathcal{R} = \mathcal{R}_\circ \cdot x_{Bj}^r$$

$$r = -0.44 \pm 0.04$$

consistent w/Run1 result

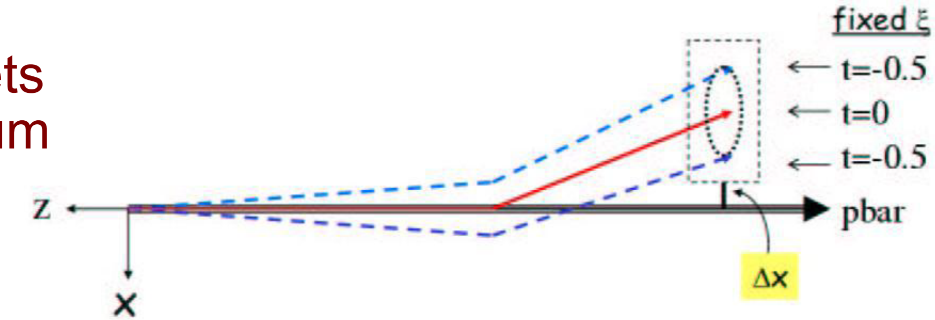
small Q^2 dependence for $100 < Q^2 < 10{,}000$ GeV^2

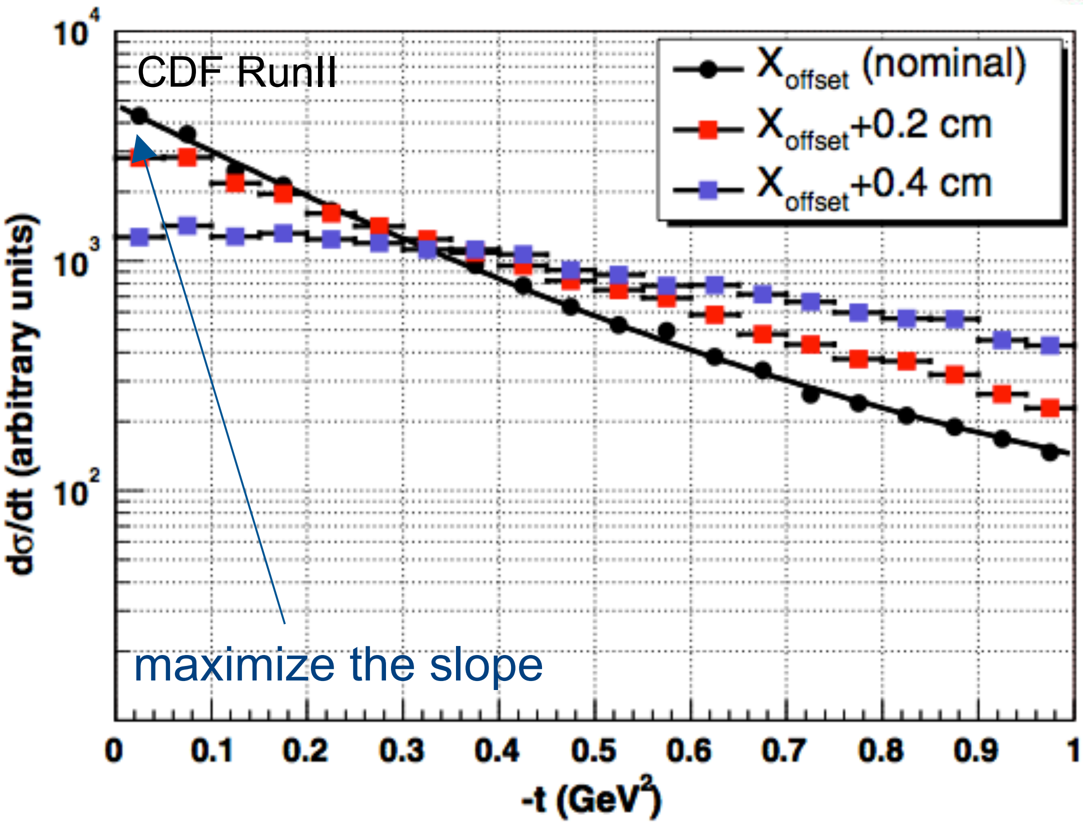
⇨ Pomeron evolves as proton

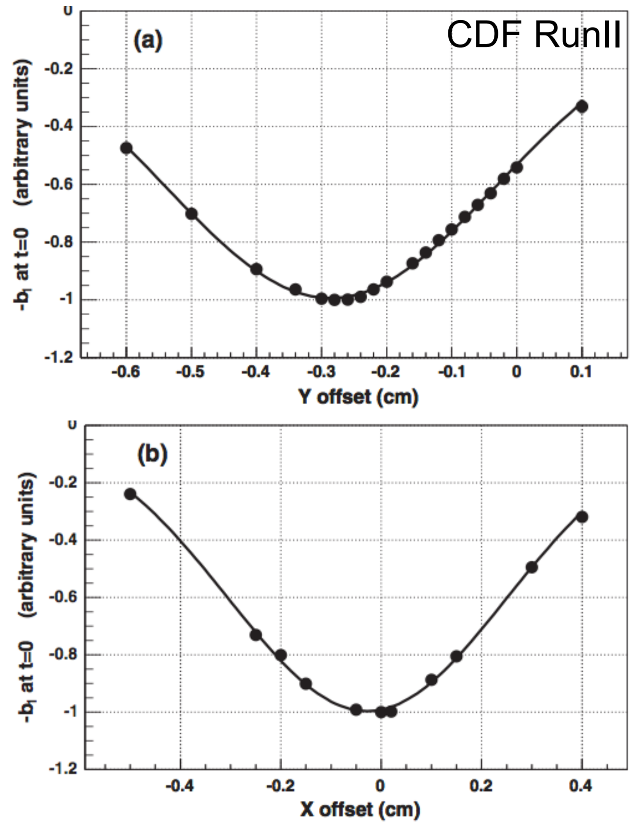
RPS dynamic alignment

arXiv:0606024, PRD 86 (2012) 032009

Method: iteratively adjust X and Y offsets from nominal beam axis until a maximum in the b-slope is obtained at t=0



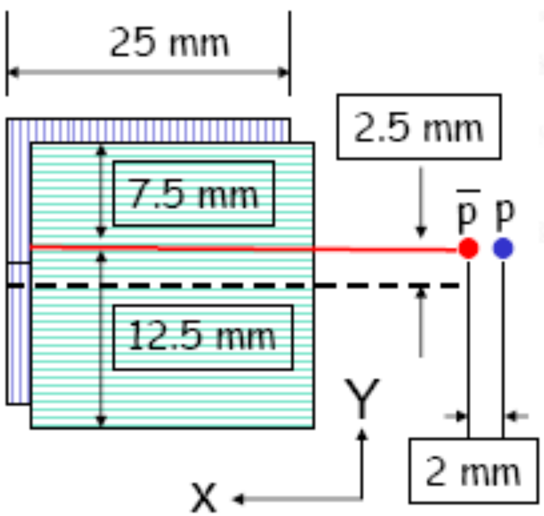


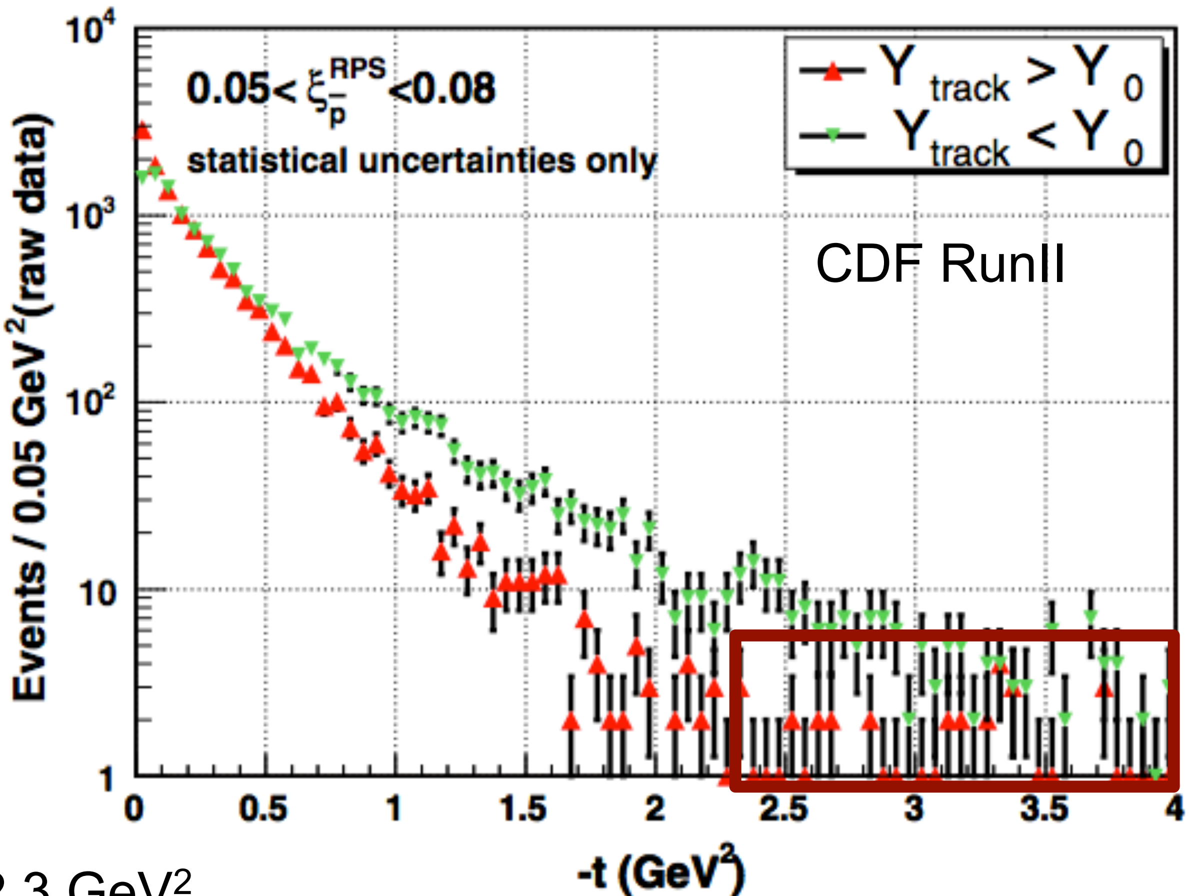


Background evaluation

PRD 86 (2012) 032009

- Schematic view of tracker

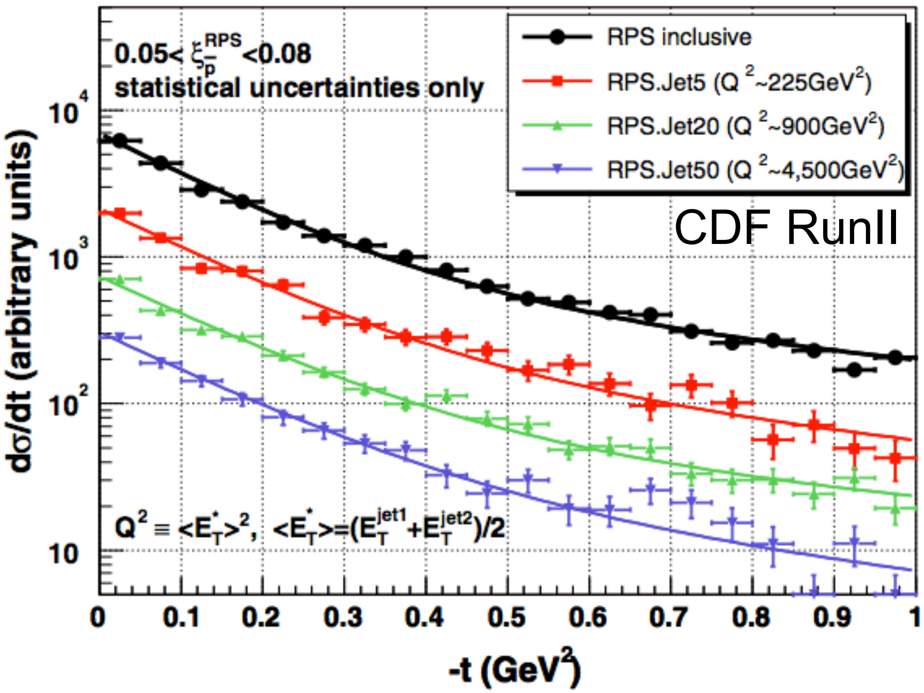


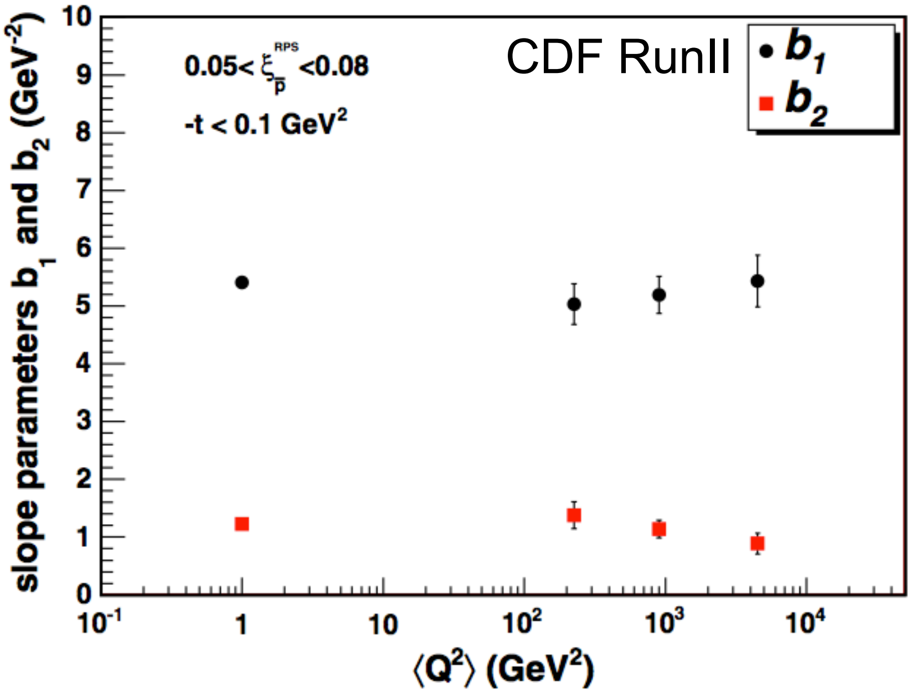


- Tracker's upper edge: $|t|=2.3$ GeV^2
- Lower edge at $|t|=6.5$ GeV^2 (not shown)
- Background level: region of $Y_{track}>Y_0$ data for $|t|>2.3$ GeV^2

|t| distribution

PRD 86 (2012) 032009





$$\frac{d\sigma}{dt} = N_{\rm norm}(A_1 e^{b_1 t} + A_2 e^{b_2 t})$$

- No diffraction `dips' observed at |t|<1
- Soft and hard diffractive events have the same slope

|t| distribution (cont.)

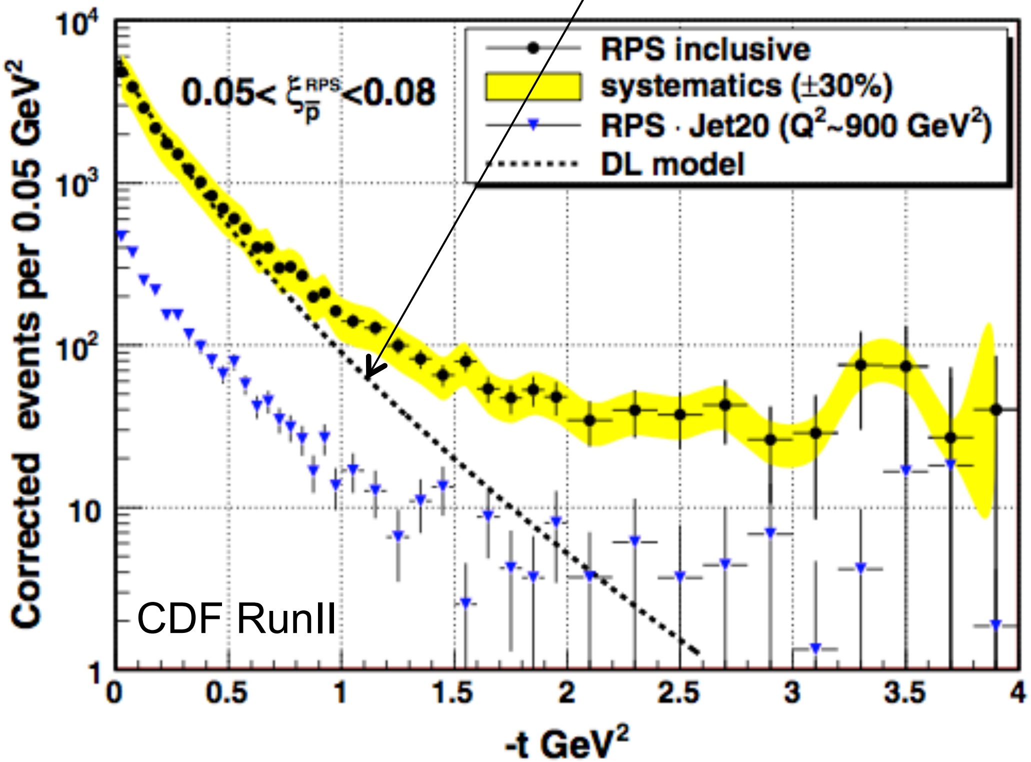
PRD 86 (2012) 032009

- Extend analysis up to |t|=4 GeV^2
- $0.05<\xi^{RPS}<0.08 \Rightarrow M_X\sim 500$ GeV

Donnachie, Landshoff, PLB518(2001)63

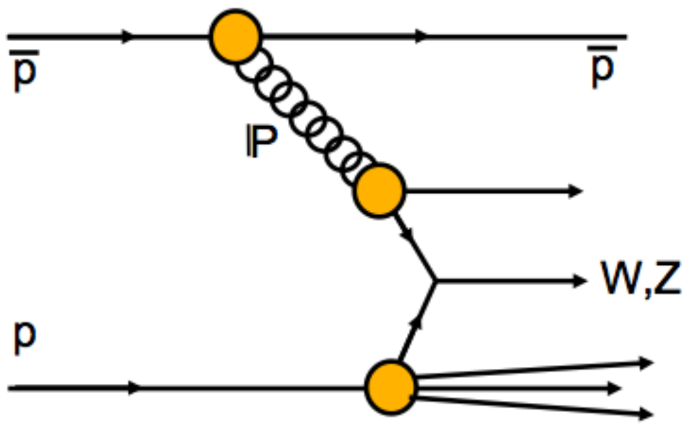
$$\frac{d\sigma^{SD}}{dt} = N_{norm} F_1(t)^2 \exp\left[2\alpha' \cdot \ln\frac{1}{\xi} \cdot t\right]$$

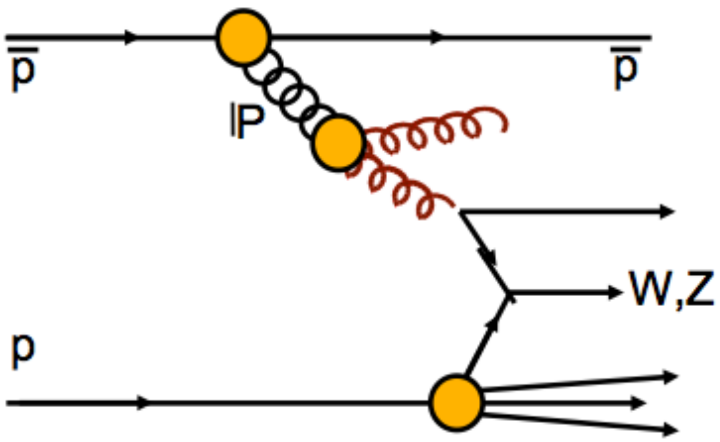
- Low-x: good agreement with DL
- High-x: data above DL model



Diffractive W/Z production

Study W/Z boson production helps to determine the **quark** content of the Pomeron





At LO, the W/Z is produced by a quark in the Pomeron

or

Production by a gluon is suppressed by α_s. Can look at additional jet.

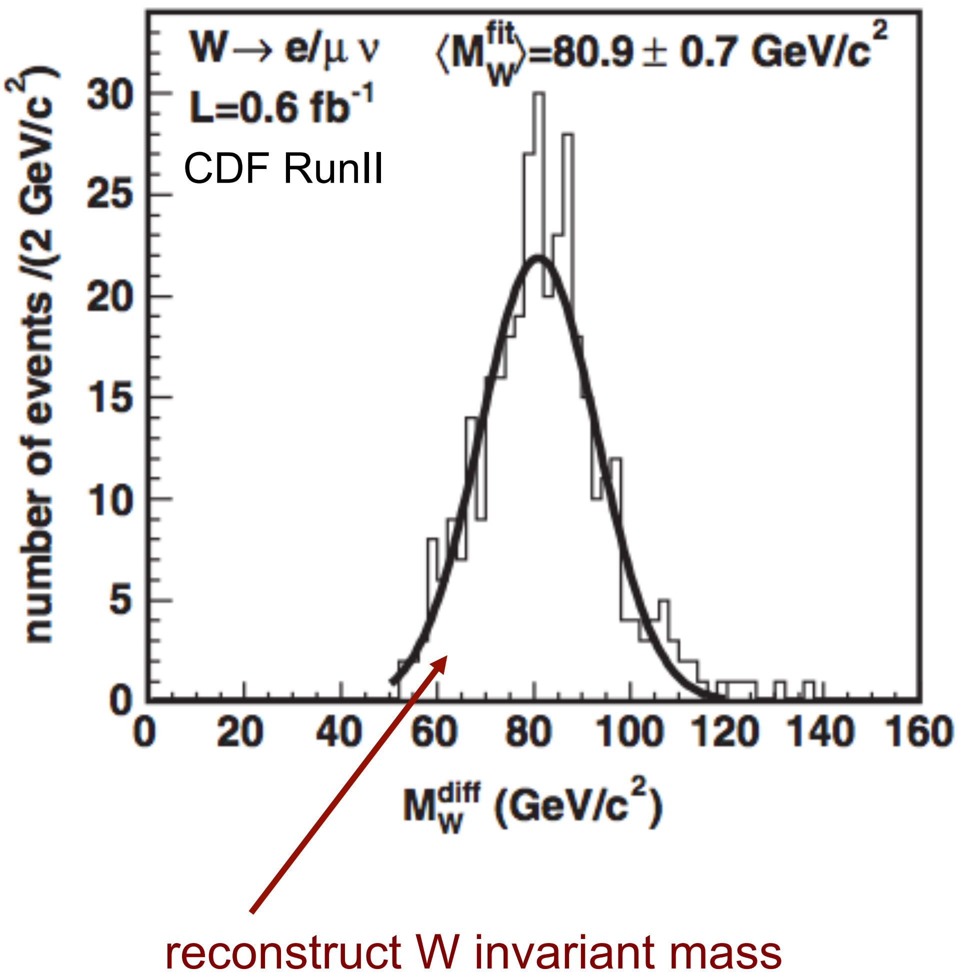
Diffractive W/Z production (cont.)

PRD 82 (2010) 112004

- Identify diffractive events using RPS
  - rapidity gaps used in RunI
- Calculate ξ from calorimeter
- In W production, difference ξ^{cal}-ξ^{RPS} is due to missing E_T, and η_ν.

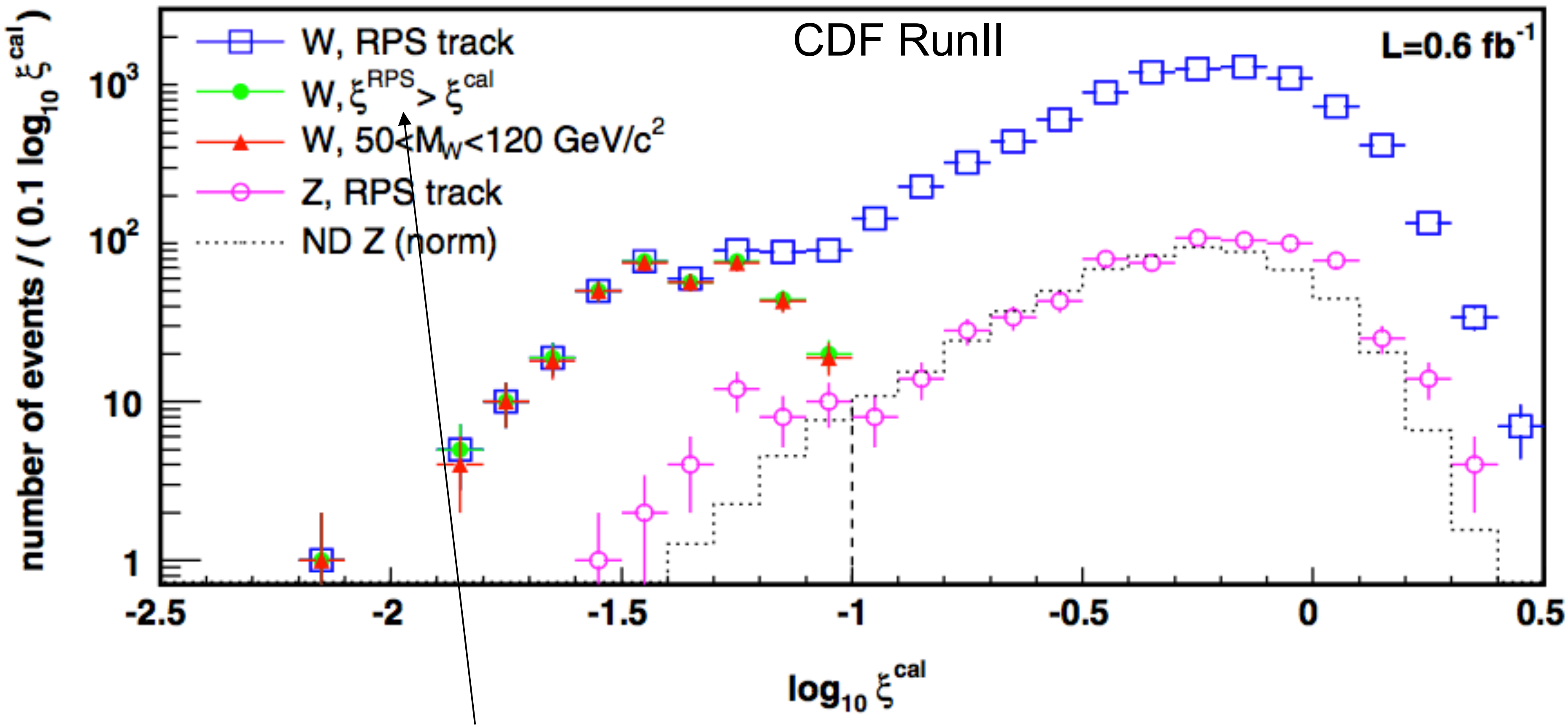
$$\xi^{RP} - \xi^{cal} = \frac{\not{E}_T}{\sqrt{s}} e^{-\eta_\nu}$$

- allows estimate neutrino and W kinematics, x_{Bj}



Diffractive W/Z production (cont.)

PRD 82 (2010) 112004



- Requiring $\xi^{cal} < \xi^{RPS}$ removes most events with multiple interactions
- $50<M_W<120$ GeV cleans up possible misreconstructed events

Diffractive W/Z measurement

PRD 82 (2010) 112004

- Measured fractions:

$$R_W = [1.00 \pm 0.05(\text{stat}) \pm 0.10(\text{syst})]\%,$$
$$R_Z = [0.88 \pm 0.21(\text{stat}) \pm 0.08(\text{syst})]\%,$$

- Run I diffractive W studies performed with rapidity gap instead of RPS
- CDF: PRL 78,2698(1997)
  - Fraction of events due to SD for $x<0.1$: **[1.15±0.51(stat)±0.20(syst)]%**
  - Combined with other SD measurements (b-quark,jet), quark-gluon content of the Pomeron is determined: $f=0.54^{+0.16}_{-0.14}$
- D0: PLB 574 (2003)169
  - Fraction of events with rapidity gap:
  - W: **$[0.89^{+0.19}_{-0.17}]\%$**
  - Z: **$[1.44^{+0.61}_{-0.52}]\%$**
  - [If correction for rapidity gap acceptance is applied…R(W): 5.1%]

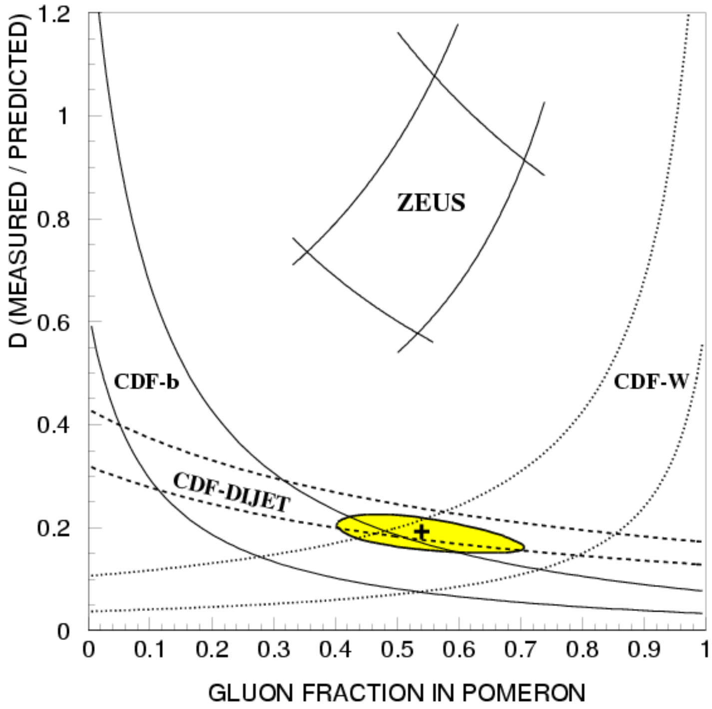
Diffractive rates

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

Measured SD/ND fractions at 1.8 TeV

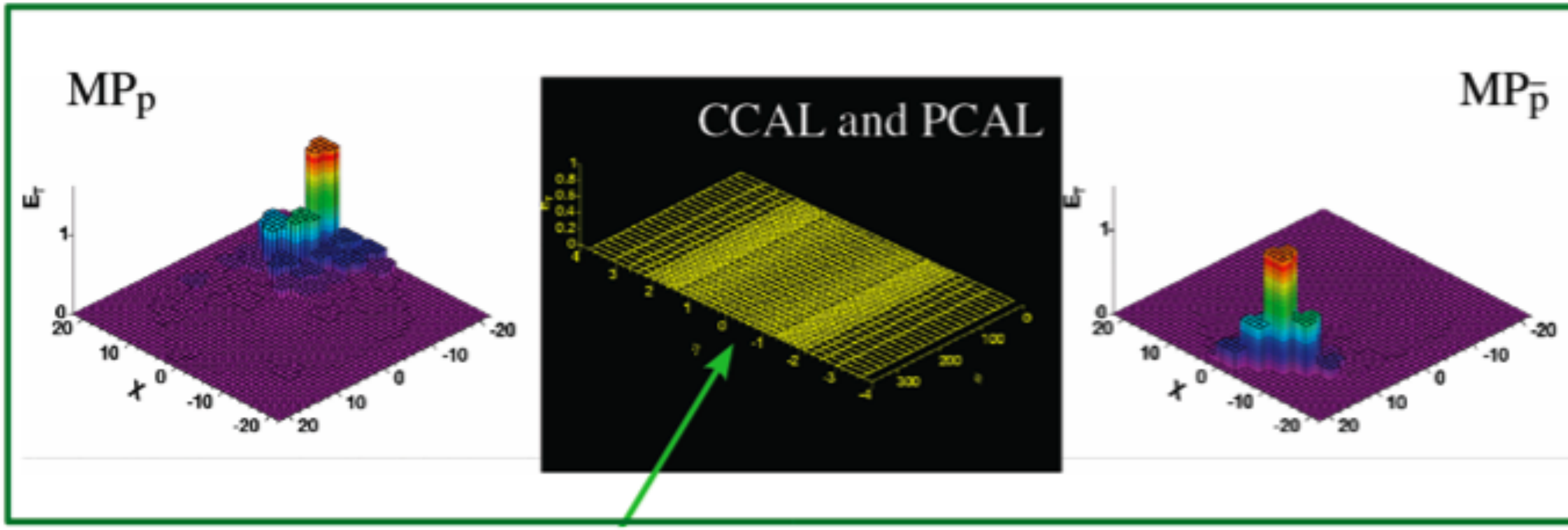
PRL	process	fraction [%]
84 (1997) 2698	W(eν)	1.15 (0.55)
PLB 574 (2003) 169	Z	1.44 (0.60)
84 (1997) 2636	jet-jet	0.75 (0.10)
84 (2000) 232	b	0.62 (0.25)
87 (2001) 241802-1	J/ψ	1.45 (0.25)

W probes quark component ($q\bar{q} \rightarrow W$)



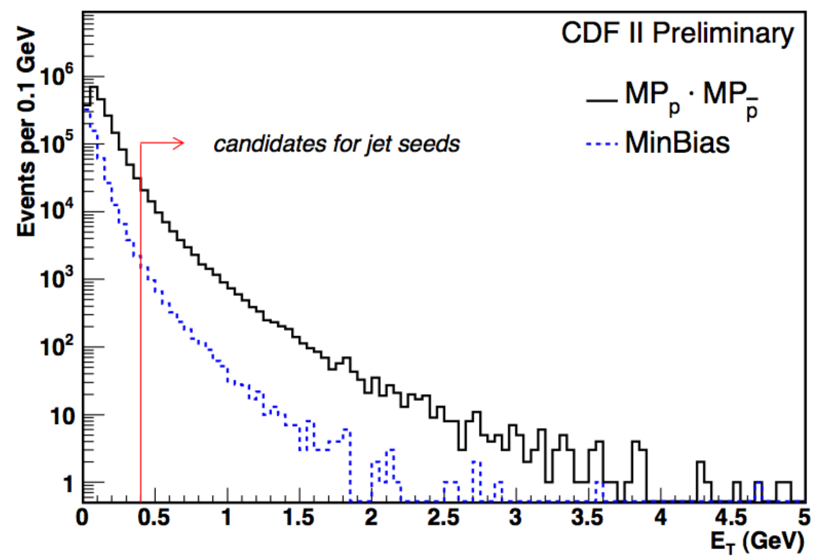
- All SD/ND fractions ~ 1% ⇨ uniform suppression
- Different sensitivities to quark/gluon ⇨ gluon fraction f_g=0.54 (0.15)

Central gap between forward jets

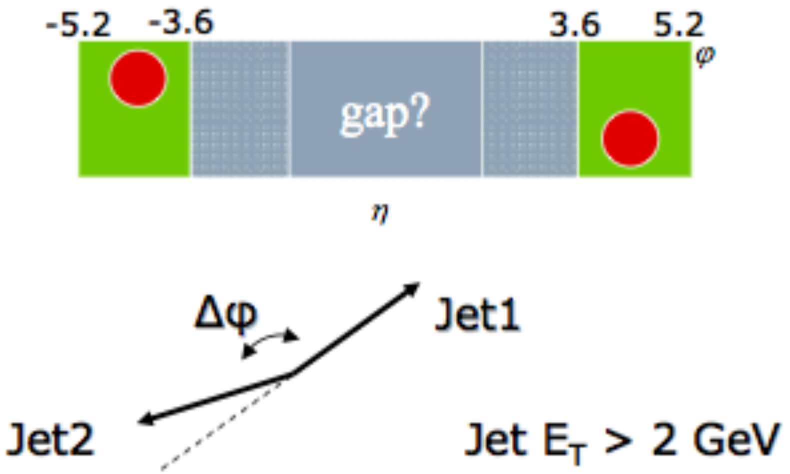


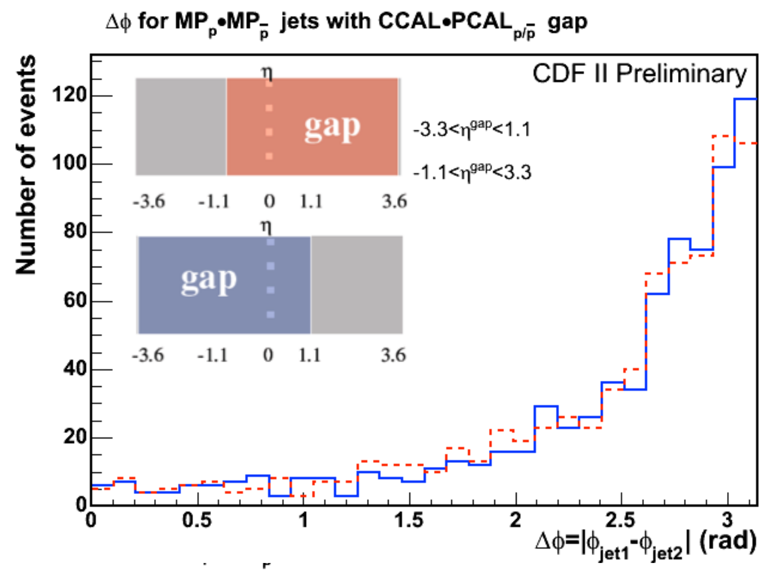
Rapidity gap in Central and Plug calorimeter

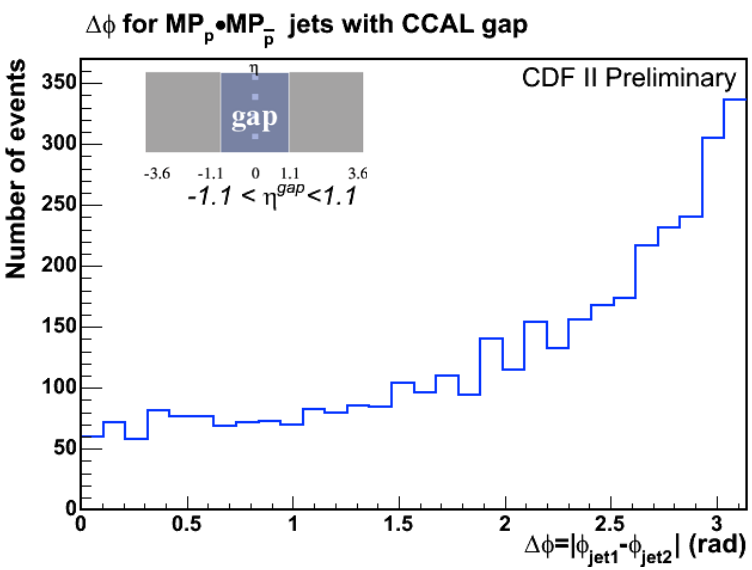
- Characterize gap formation
  - fraction of gap events (soft and hard interactions)
  - dependence on gap size
- Mueller-Navelet jets

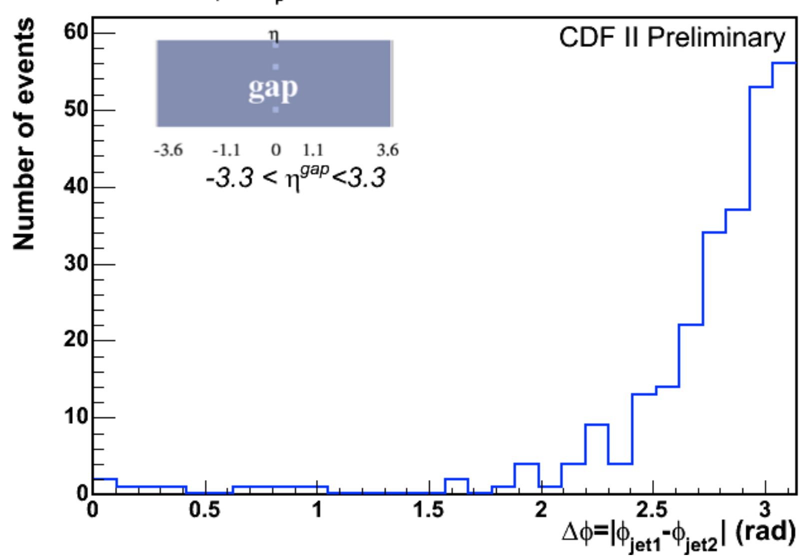


Jet Δϕ correlation

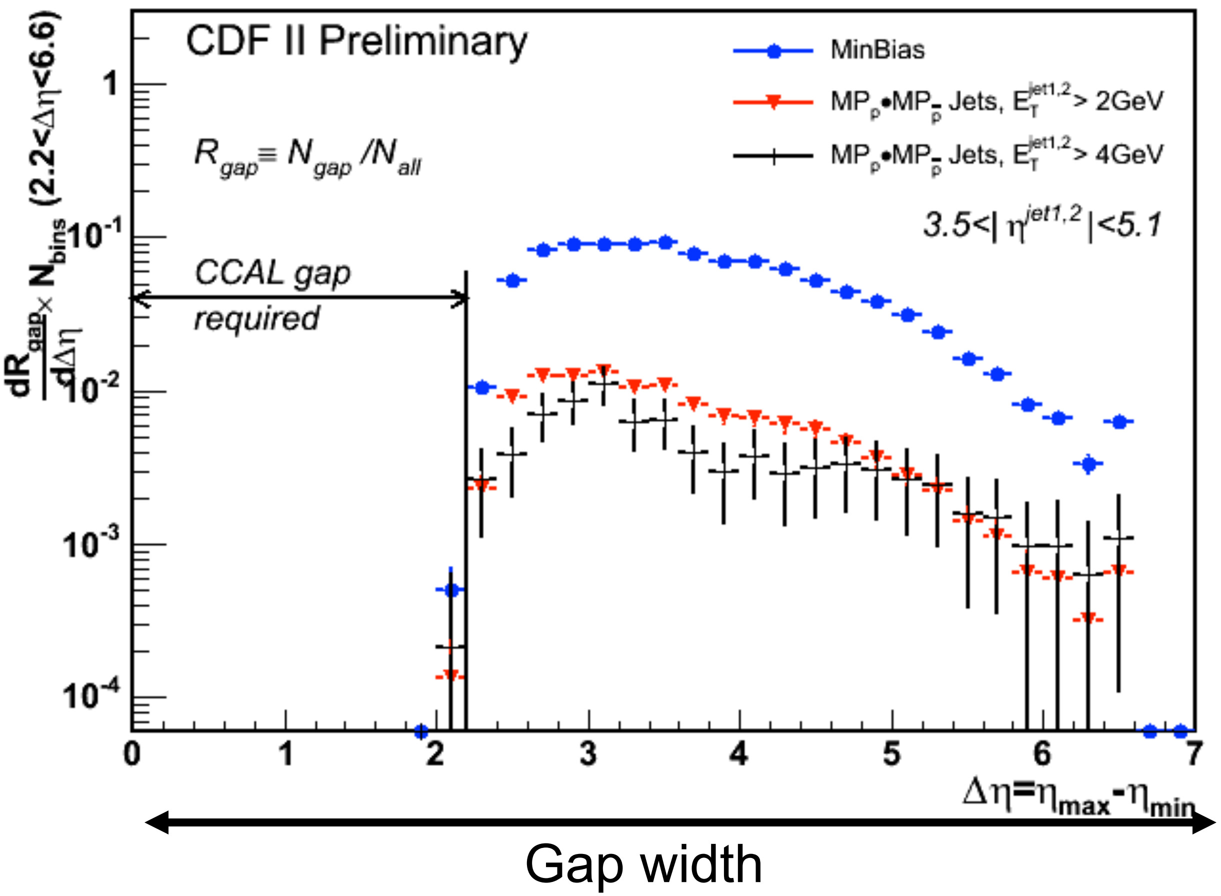


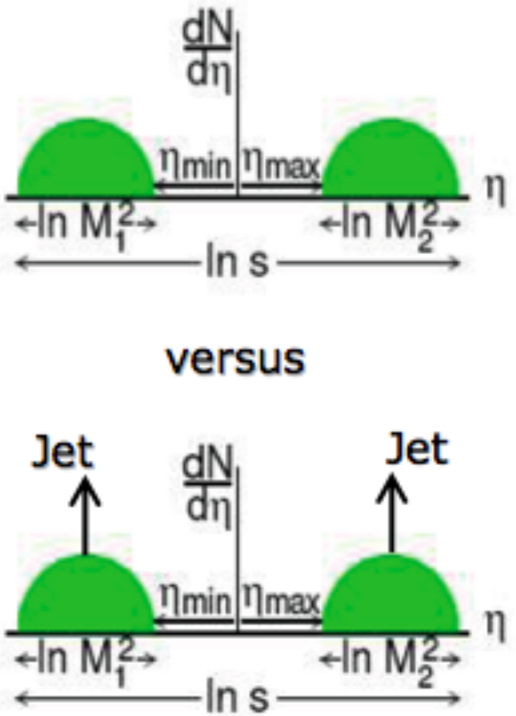






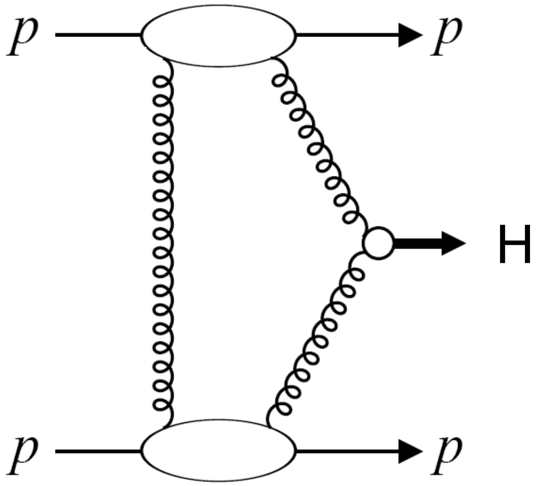
Rapidity gap event fraction





- Event fraction is ~10% in soft events, and ~1% in jet events
- Shapes are similar

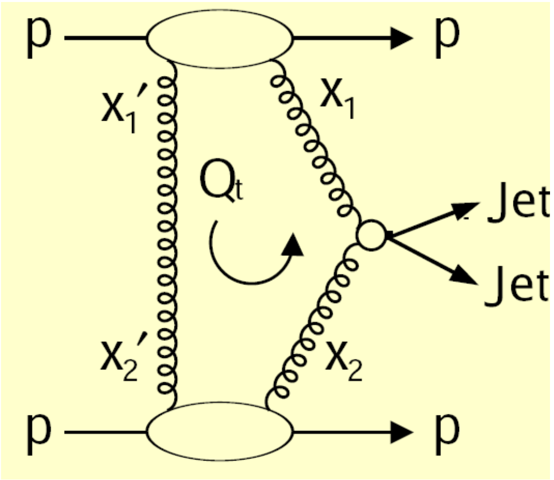
Exclusive production



✓clean process
✓exclusive $b\bar{b}$ suppressed (J_z=0 selection rule)

Khoze Martin Ryskin: σ_H(LHC)~3 fb,
signal/bkg~3 (if ΔM_{miss}=1 GeV)

Attractive Higgs production channel at the LHC

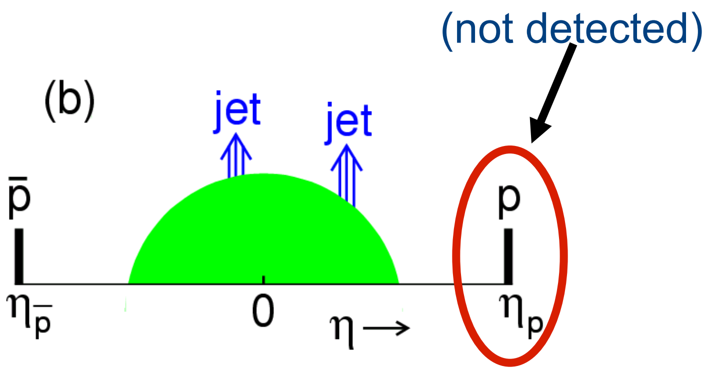


⇨much larger cross section

Goal:
➢measure exclusive dijet production
➢test/calibrate Higgs predictions at LHC

Exclusive dijets in Run I

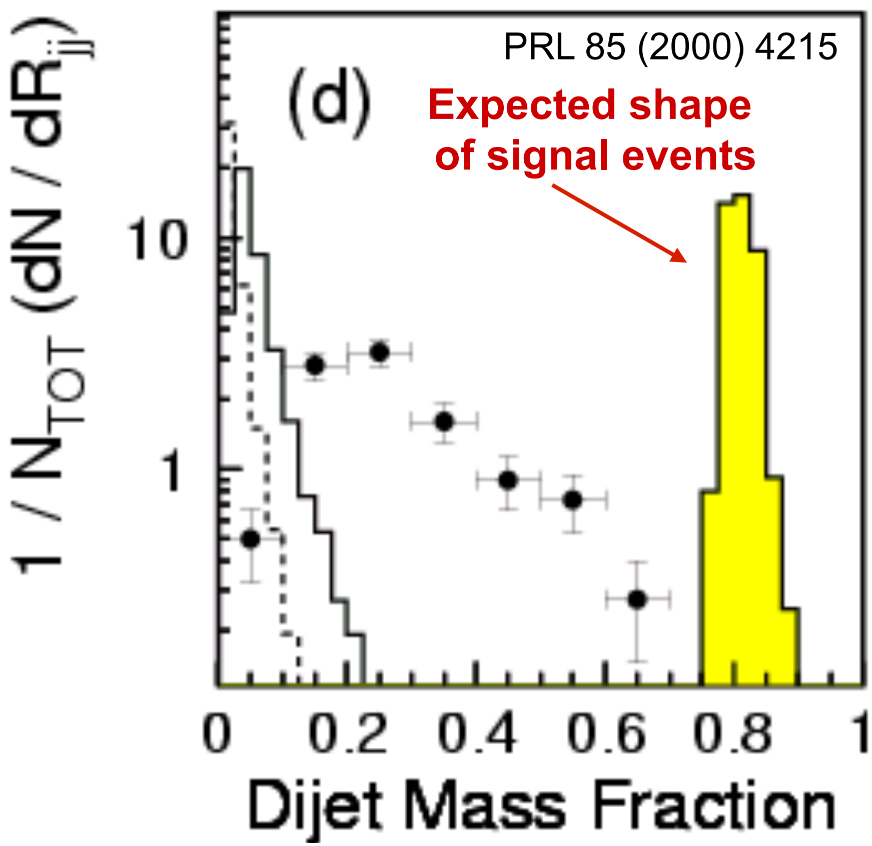
PRL 85 (2000) 4215



Mass fraction: $R_{jj} = \frac{M_{jj}}{M_X}$

Exclusive dijet limit:
Run I: PRL 85 (2000) 4215

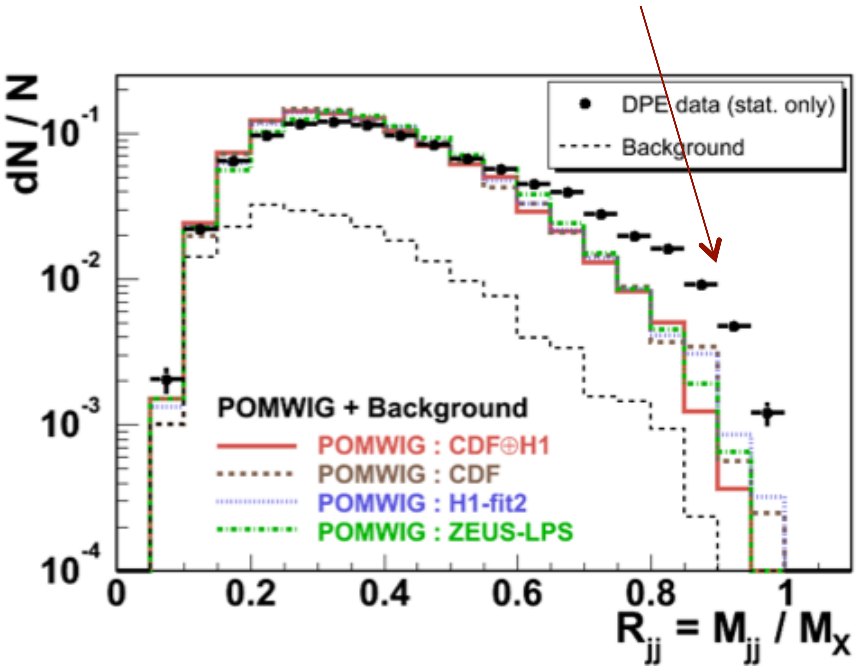
⇨ σ_{jj} (excl.) < 3.7 nb (95% CL)



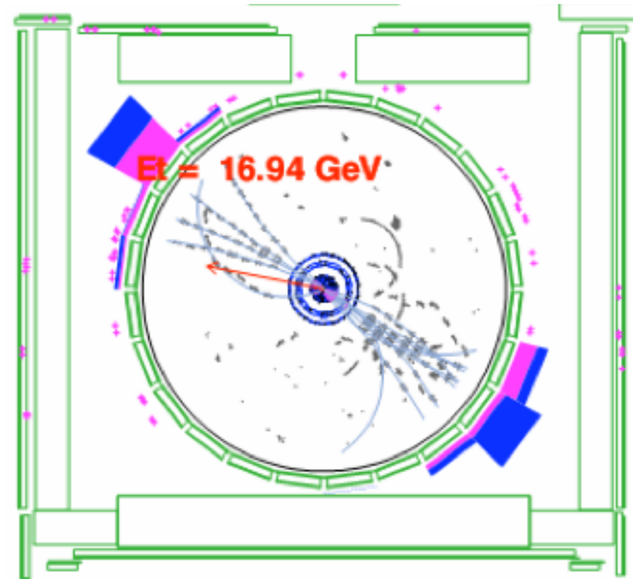
Observation of exclusive dijets

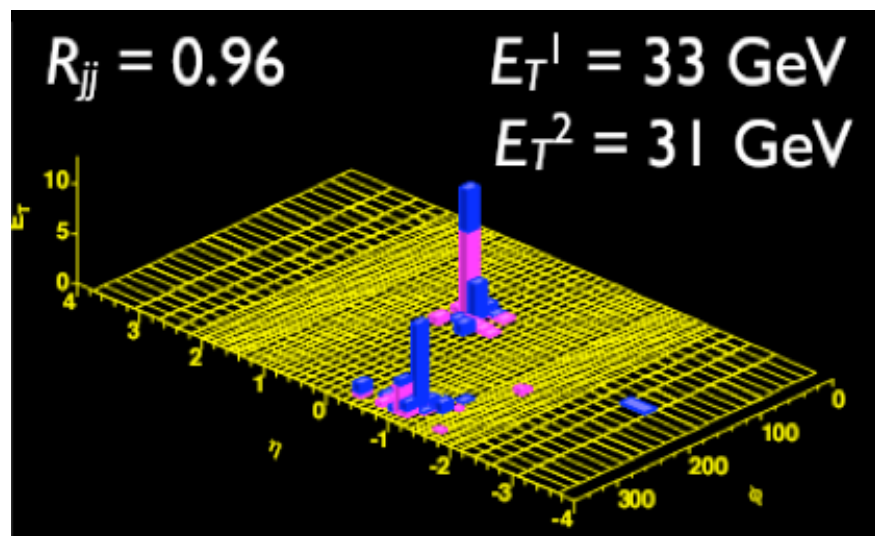
PRD 77 (2008) 052004

Observe excess over inclusive DPE at large Mjj



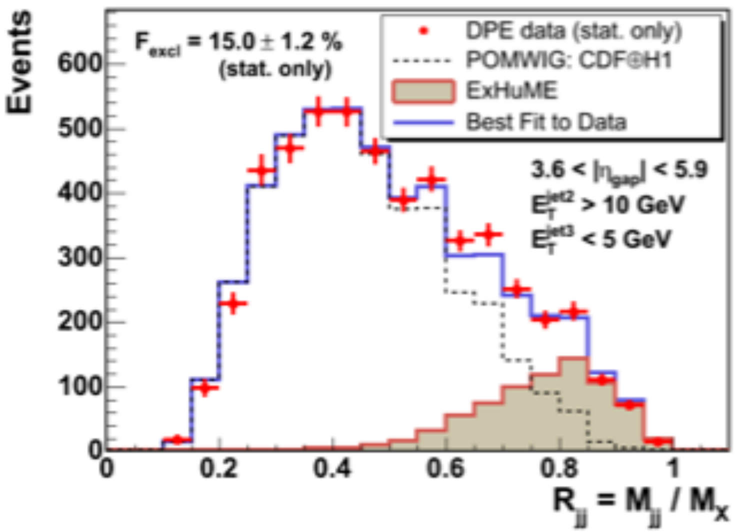
⇨ exclusive signal?

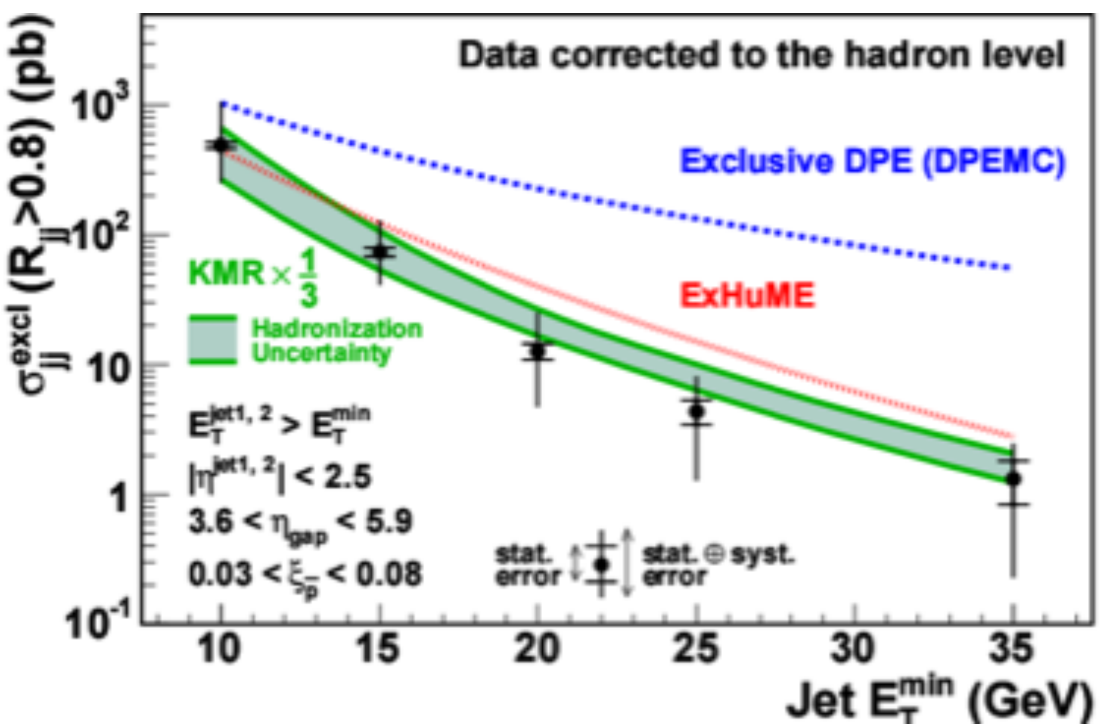




Exclusive dijet cross section

PRD 77 (2008) 052004





Calculation by KMR is consistent within it uncertainty (factor of ~3)

EPJC 14(2000)525

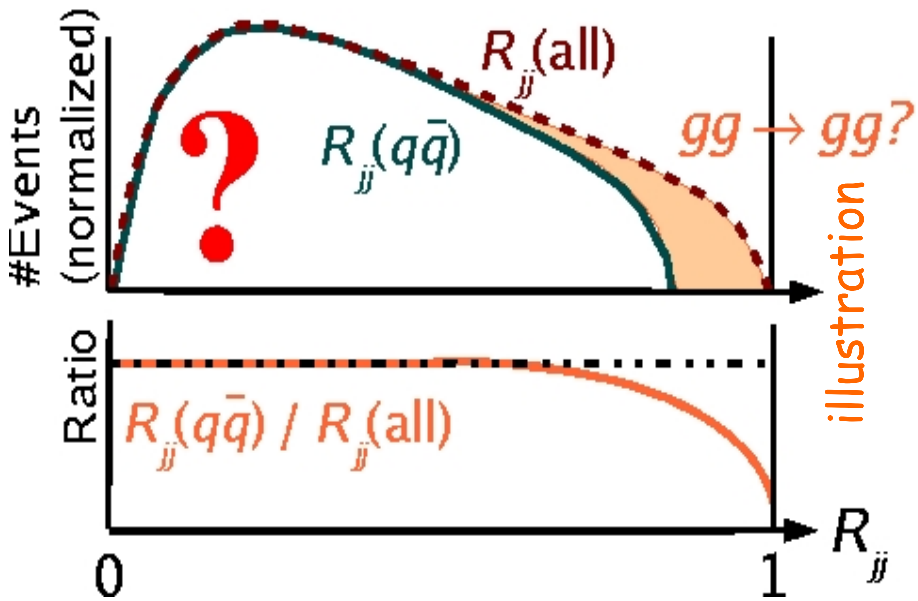
Exclusive dijets w/heavy flavor

Theory:
J_Z=0 spin selection rule
gg→gg dominant contribution at LO
gg→$q\bar{q}$ suppressed when M_{jj}>> m_q

Experimental method:
normalize R_{jj} for $q\bar{q}$ to R_{jj} for all jets
⇨look for event suppression at large R_{jj}

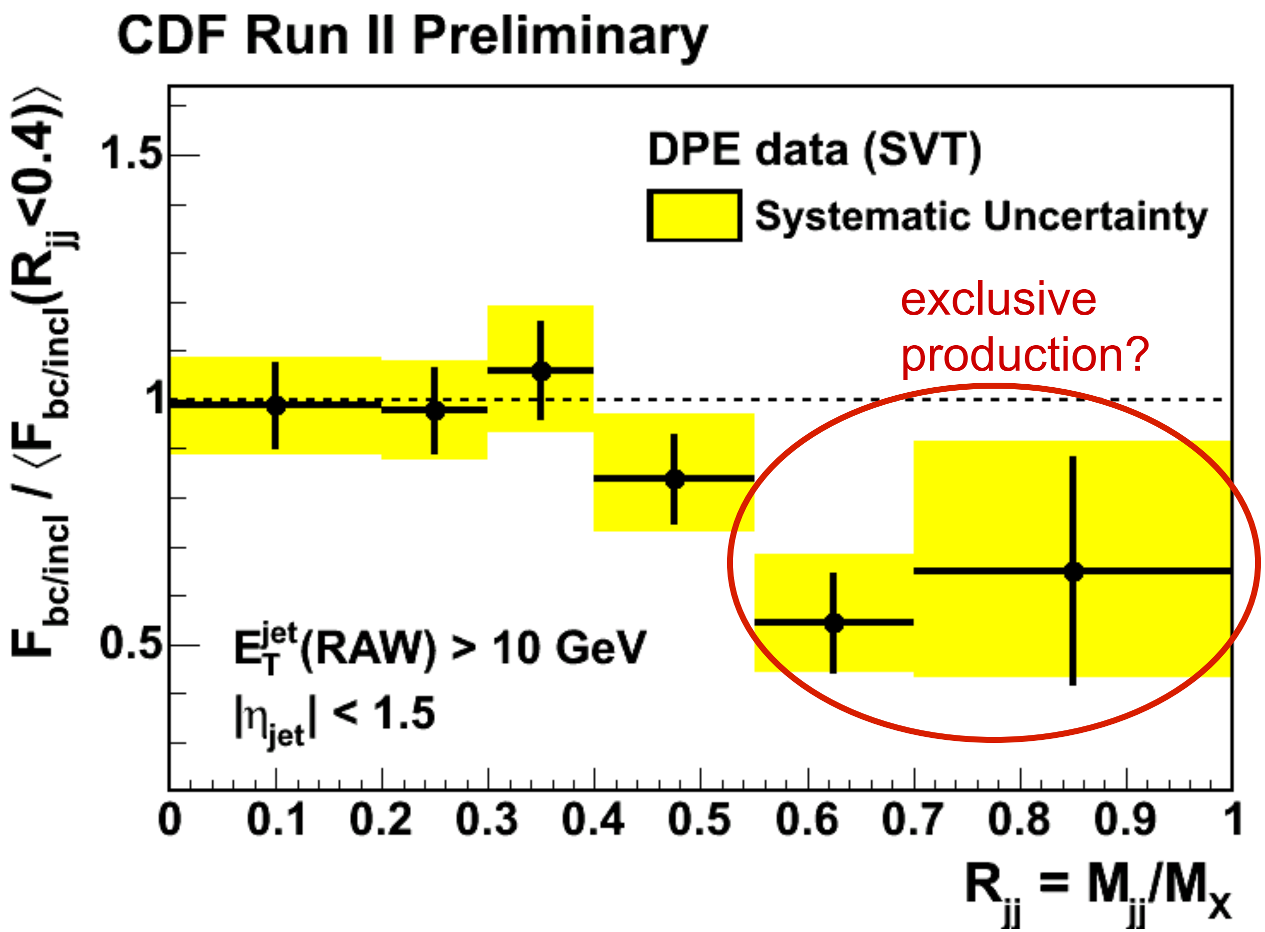
Pros: -many systematics cancel out
-good HF quarks id
-small g mistag O(1%)

Cons: -heavy quark mass:
contribution from exclusive b/c



⇨ use b-quark jets

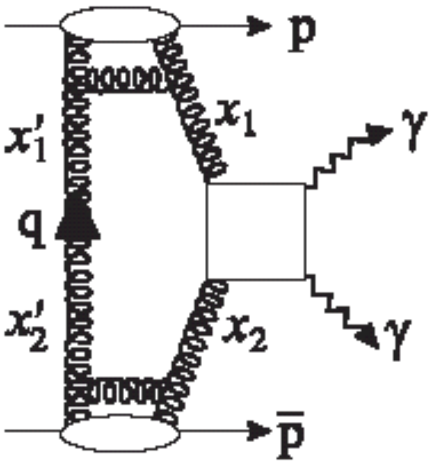
b-tagged jet fraction

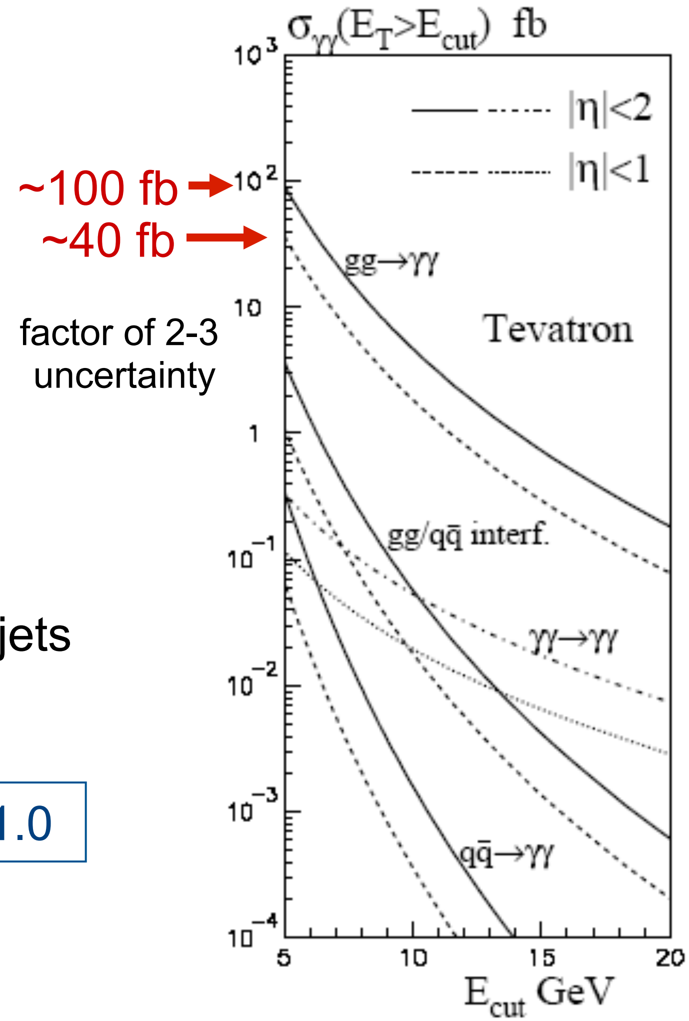


ratio of b/c jets to all jets (norm. to R_{jj}<0.4)

⇨ ratio decreases at high R_{jj}

Exclusive γγ production





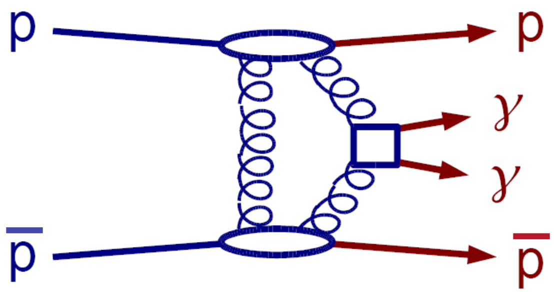
Khoze, Kaidalov, Martin, Ryskin, Stirling, hep-ph/0507040

- QCD diagram same as pHp
- smaller cross section than exclusive dijets

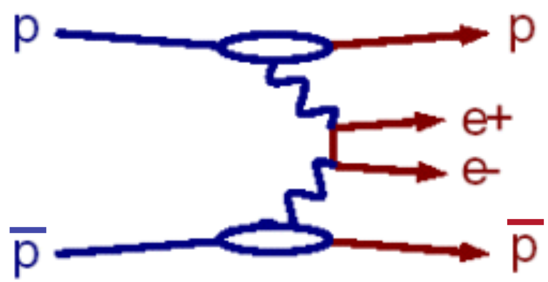
~40 events/fb^{-1} with $p_T(\gamma)$>5 GeV/c, |η|<1.0

the effective luminosity must be considered since additional interactions "populate" gaps

Exclusive ee/$\gamma\gamma$ search



$$p\bar{p} \to p + \gamma\gamma + \bar{p}$$



QED process: cross-check to exclusive $\gamma\gamma$

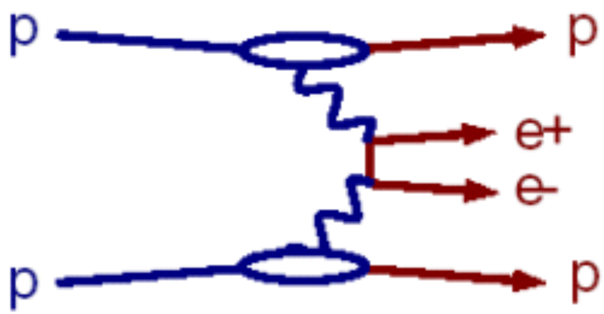
- ✓do not detect (anti)proton
- ✓require 2 EM showers (E_T>5 GeV, $|\eta|<2$)
- ✓veto all calorimetry and BSCs except 2 EM showers
- ✓L~530 pb^{-1} delivered ($L_{effective}$=46 pb^{-1})

⇨19 events have 2 EM showers +"nothing"

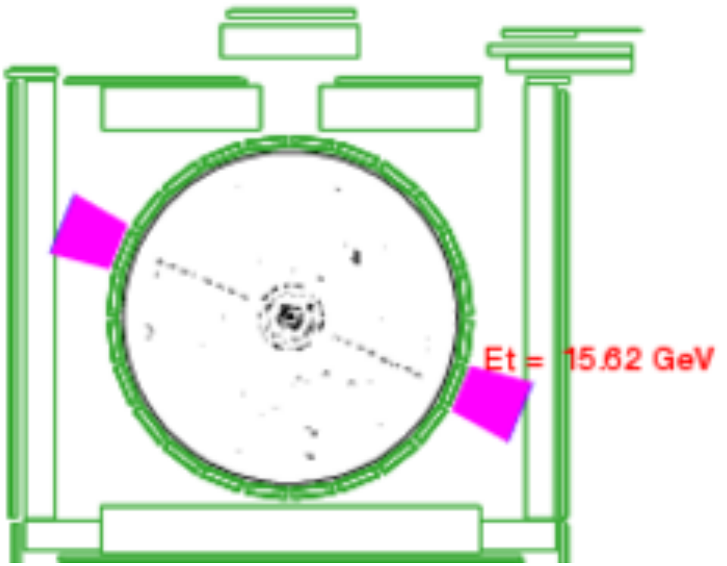
caveat: "nothing" above threshold

Exclusive ee search

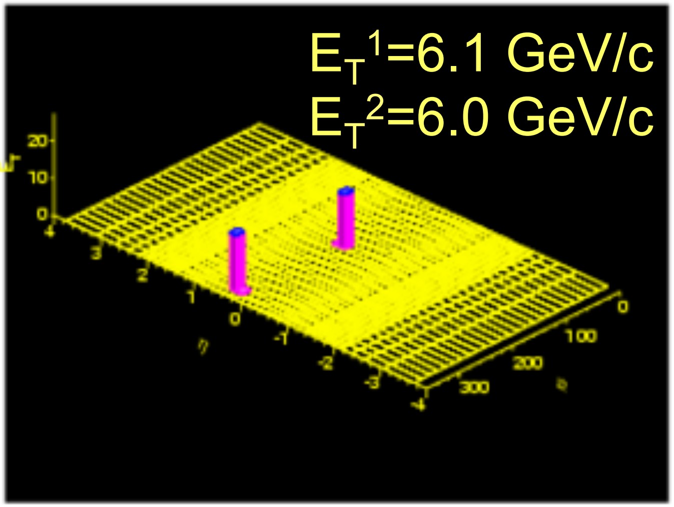
PRL 98 (2007) 112001



control sample for $\gamma\gamma$ search



⇨16 candidate events found
background: 1.9±0.3 events



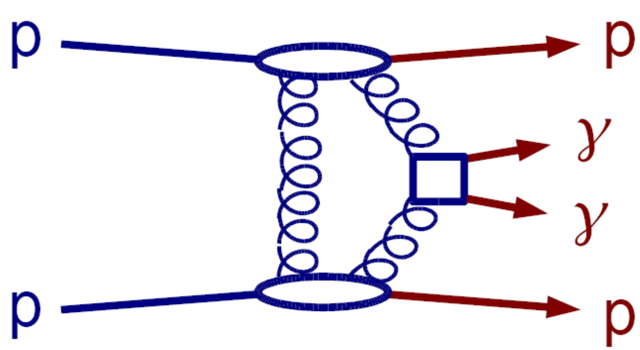
$$\sigma_{MEASURED} = 1.6\ ^{+0.5}_{-0.3}\ (stat) \pm 0.3\ (sys)\ pb$$

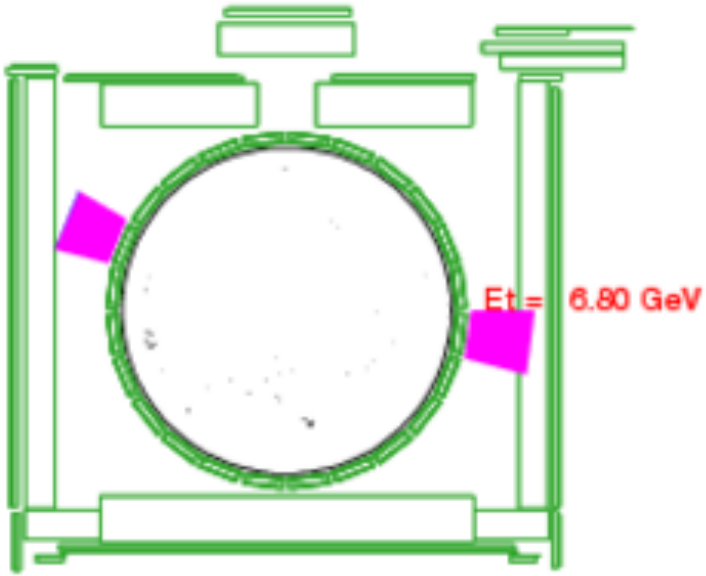
good agreement with LPAIR:

$$\sigma_{LPAIR} = 1.711 \pm 0.008\ pb$$

Exclusive γγ search

PRL 99 (2007) 242002





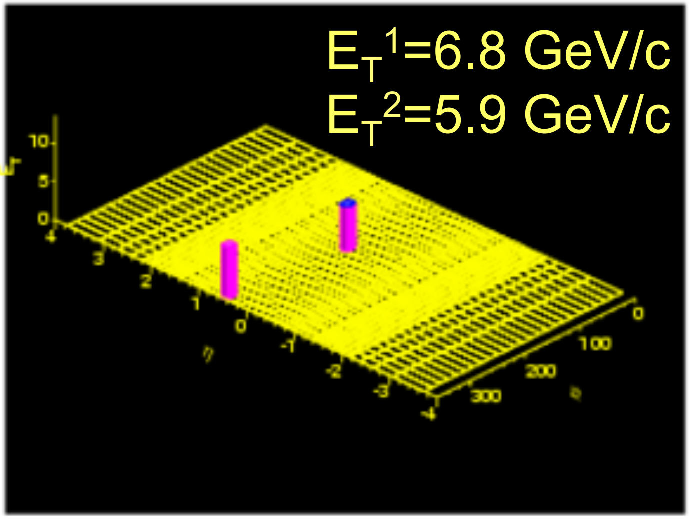
⇨ 3 candidate events found

background: $0.0^{+0.2}_{-0.0}$ events

(study noise, by looking at "zero-bias" events)

$\sigma_{measured}$ < 410 fb

limits set, more data



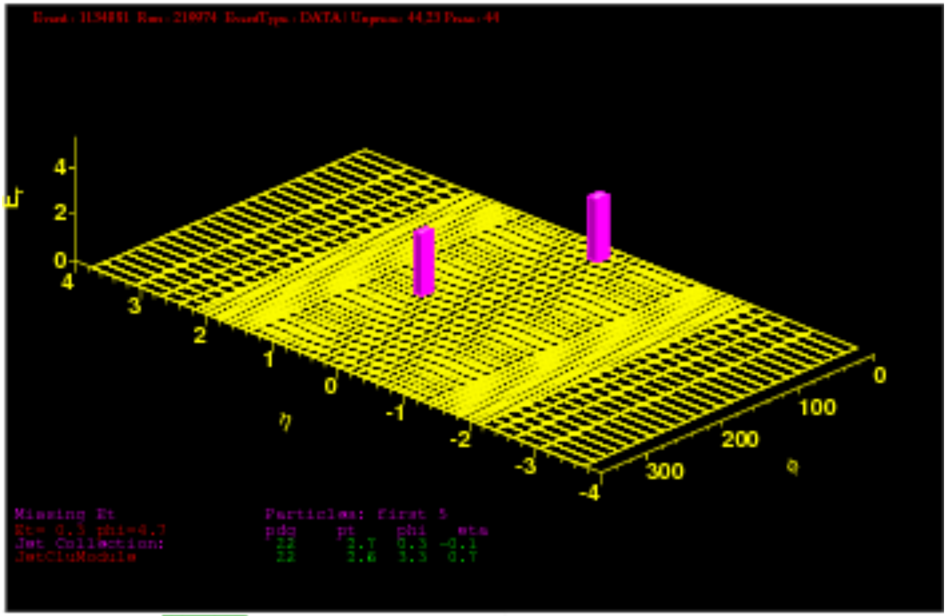
good agreement with KMR:

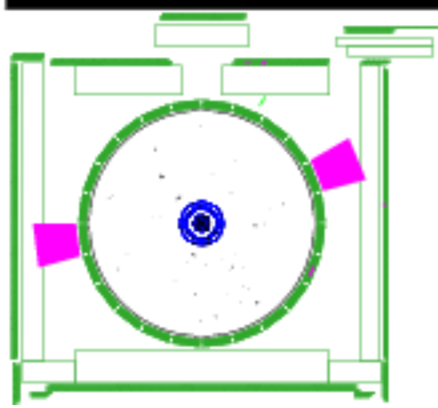
$\sigma_{KMR} = 36 \pm ^{72}_{24}$ (x2-3) fb

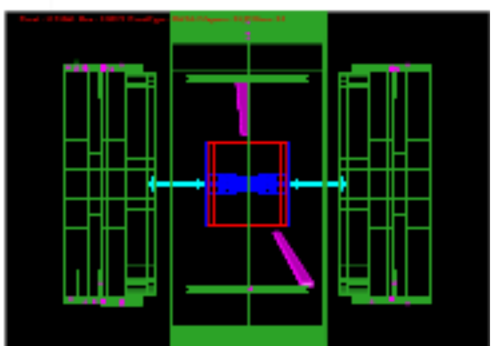
⇨ σ_H ~ 10 fb
within a factor ~ 2-3 , higher in MSSM

Exclusive γγ search

PRL 108 (2012) 081801



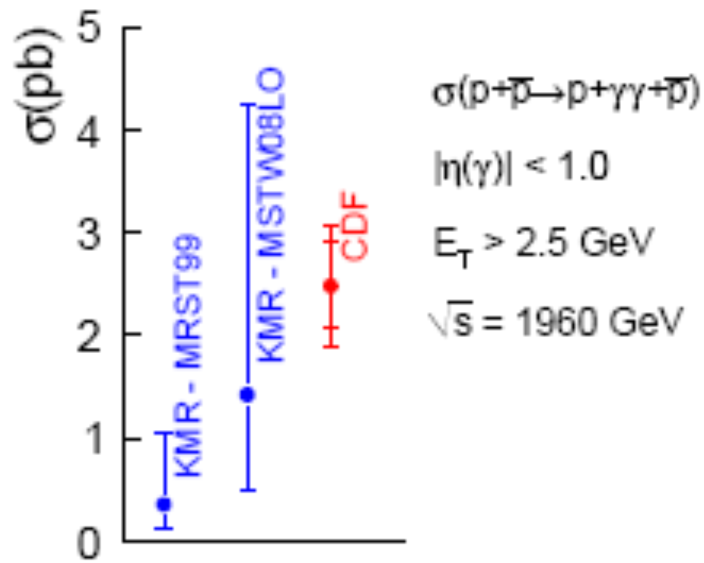




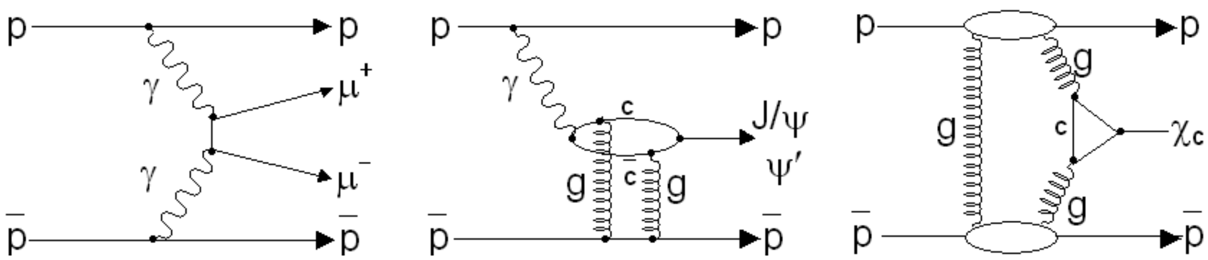
- Observed 43 events:

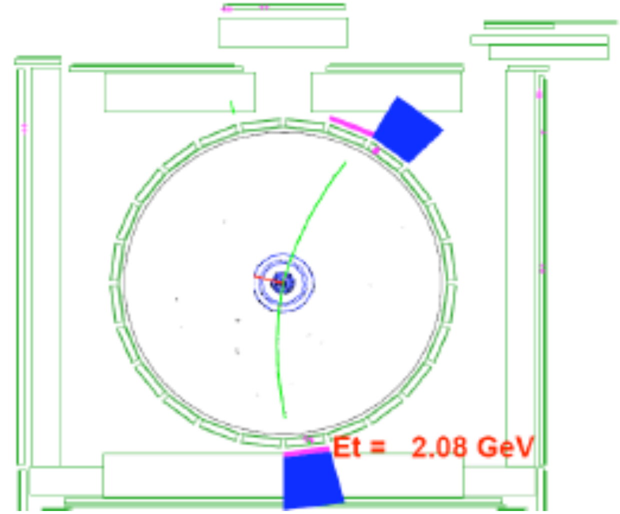
$$\sigma_{\gamma\gamma_{excl}} = 2.48^{+0.40}_{-0.35}(\text{stat})^{+0.40}_{-0.51}(\text{syst})\ \text{pb}$$

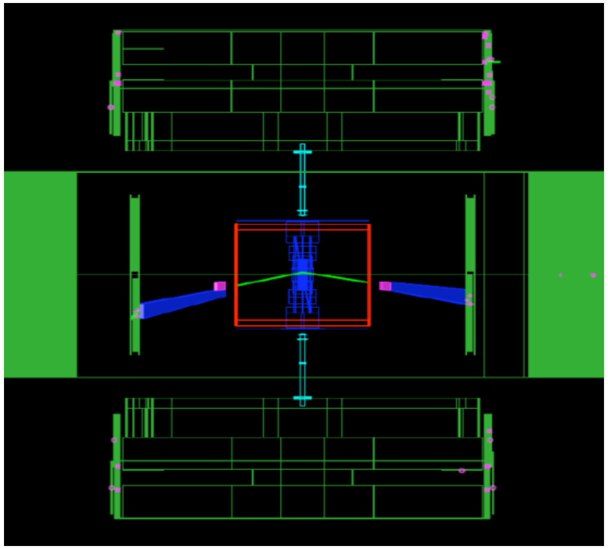
- Good agreement with theoretical predictions



Exclusive dimuons







- trigger: muon+track+forward rapidity gap (BSCs)
- two oppositely charged muon tracks with p_T>1.4 GeV
- L=1.48/fb, with L_{eff}~140/pb

Exclusive J/ψ and ψ(2S)

PRL 102 (2009) 242001

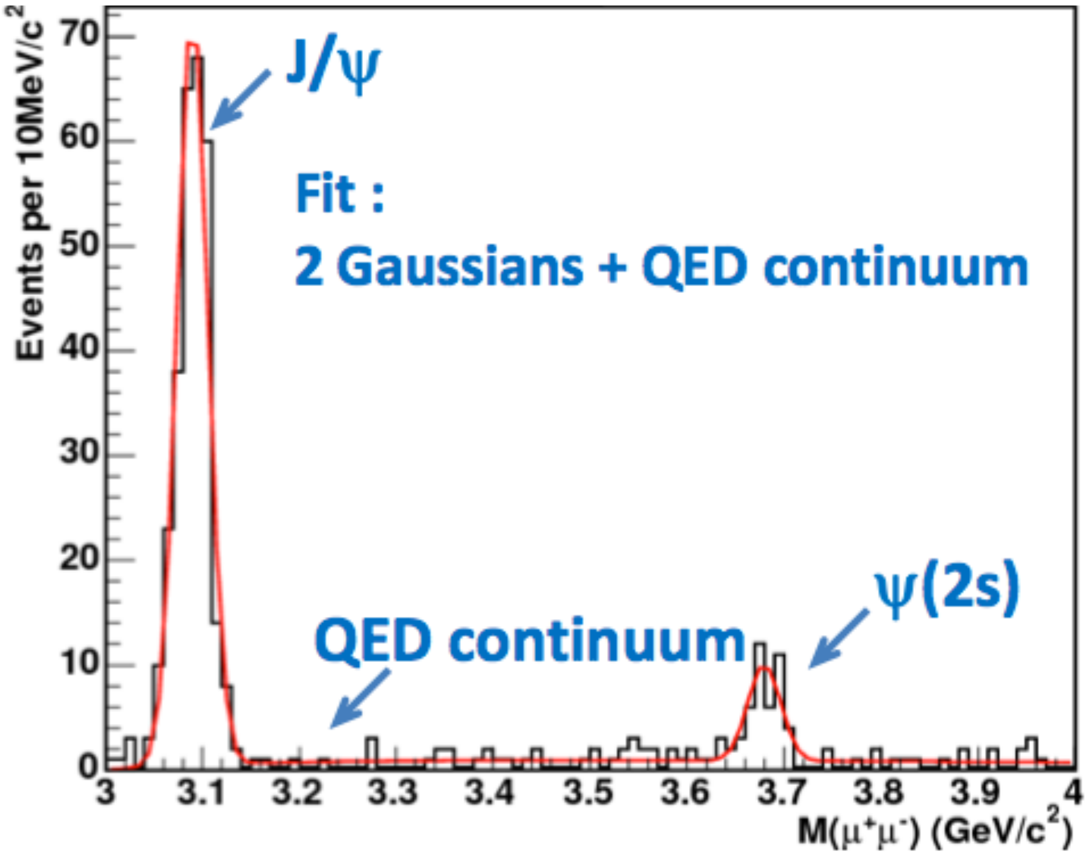
J/ψ production

243±21 events

dσ/dy=3.92±0.62 nb

Theoretical predictions

- 2.8 nb [Szczurek07]
- 2.7 nb [Klein&Nystrand04]
- 3.4 nb [Motkya&Watt08]



Y(2S) production

34±7 events

dσ/dy=0.54±0.15 nb

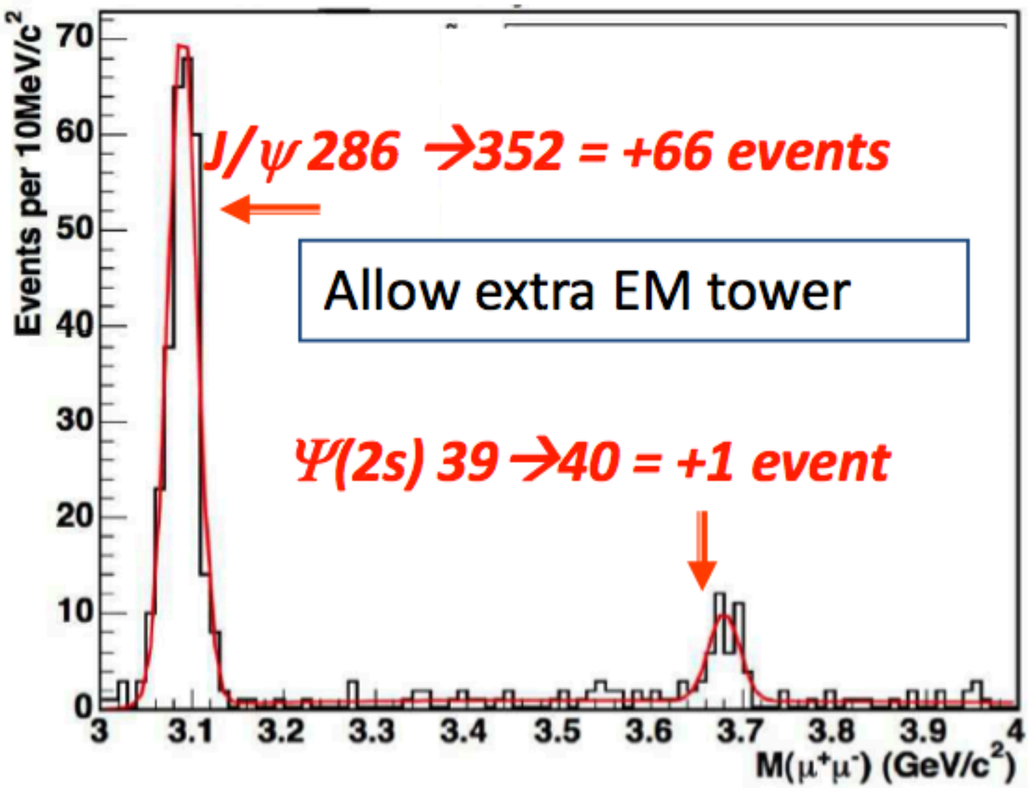
R=y(2S)/ J/y = 0.14±0.05

In agreement with HERA:

R=0.166±0.012 in similar kinematic region

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

PRL 102 (2009) 242001



- Allowing EM towers (E_T>80 MeV)
- Large increase in the J/ψ peak
- Minor change in the $\psi(2S)$ peak

⇒Evidence for $\chi_c \rightarrow J/\psi(\rightarrow \mu^+\mu^-)+\gamma$

$d\sigma/dy$=75±14 nb

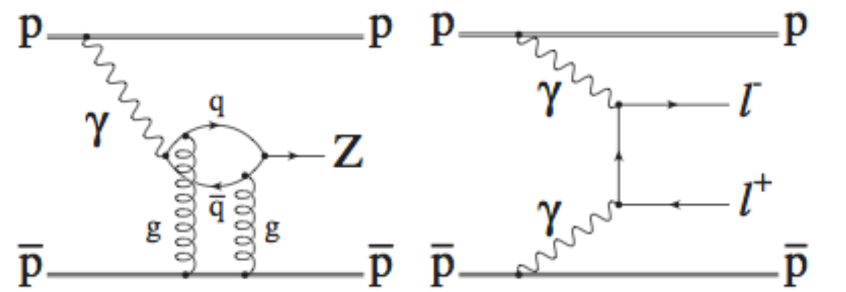
compatible with theoretical predictions

- 160 nb [Yuan01]
- 90 nb [KMR01]

Exclusive Z production

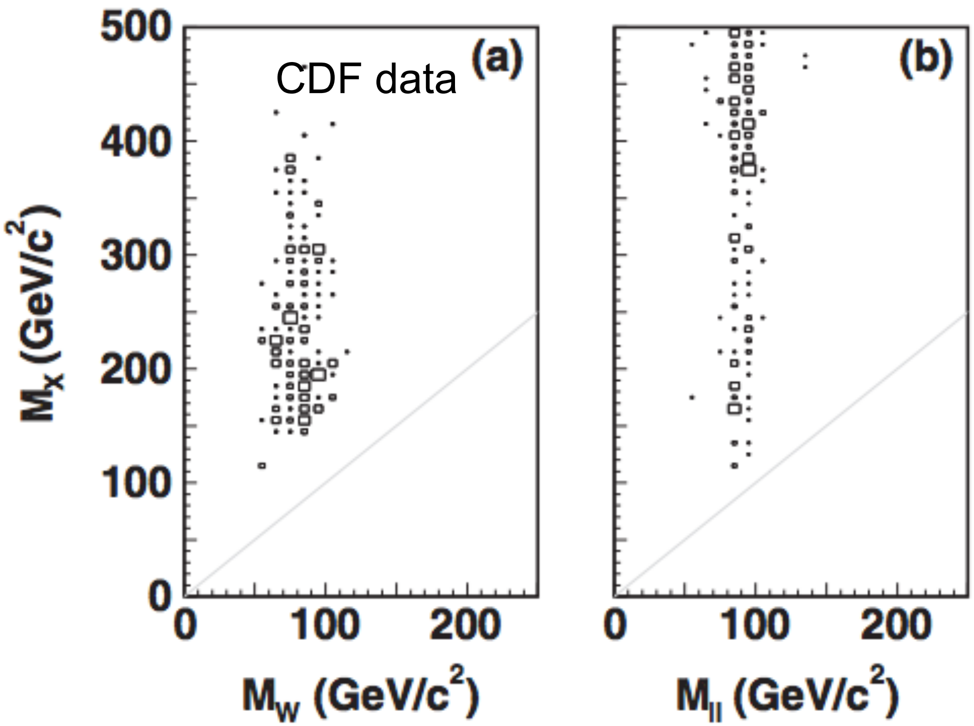
PRL 102 (2009) 222002, PRD 82 (2010) 112004

- Search for exclusive Z production with "nothing else" in the detector
- PRL 102, 222002 (2009)



Also from "diffractive Z production":

- System mass M_X vs M_{ll}
- Exclusive candidates are expected to fall on the diagonal
- Depends on thresholds
- Cross-check with W/Z production



Summary

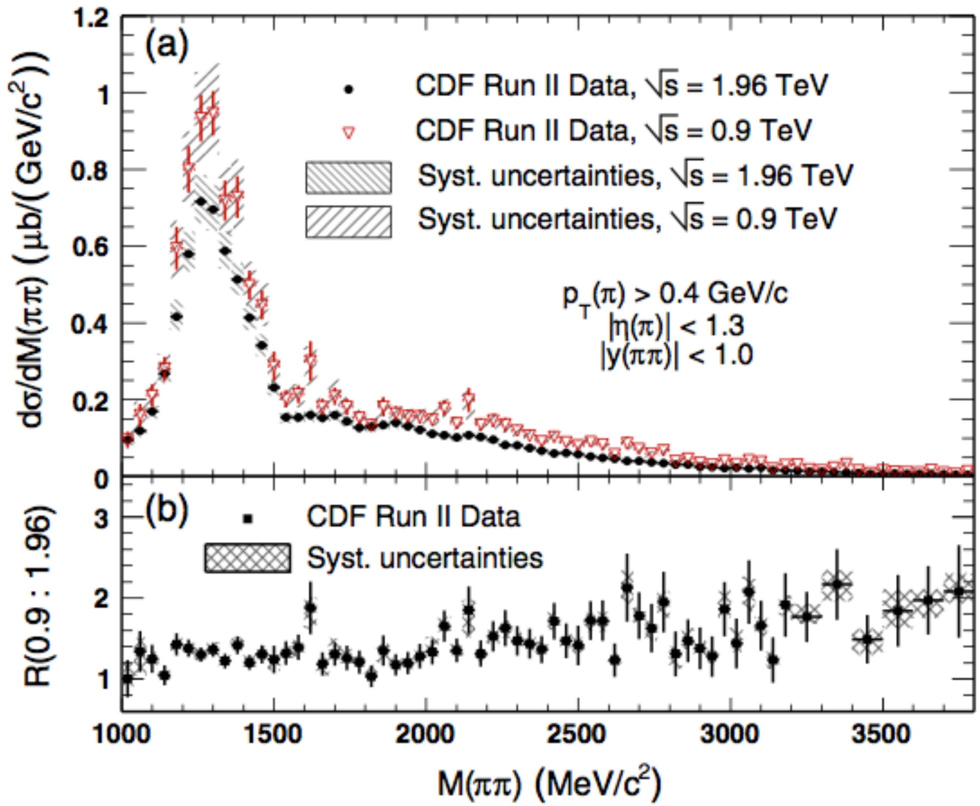
- Extensive program of diffractive studies at Tevatron
- CDF diffractive program continuing the improvement of understanding of diffractive processes
  - measured DSF at different Q^2 values
  - measured t-distribution in diffractive events
  - dijets, W/Z, forward jets, exclusive jets, etc.
- Comparison of diffractive and non-diffractive processes
- Measurements of exclusive production important to calibrate predictions for exclusive Higgs production at LHC
- General tools which can be used at LHC:
  - Roman Pot dynamic alignment

backup

Central Exclusive Production

PRD 91 (2015) 091101

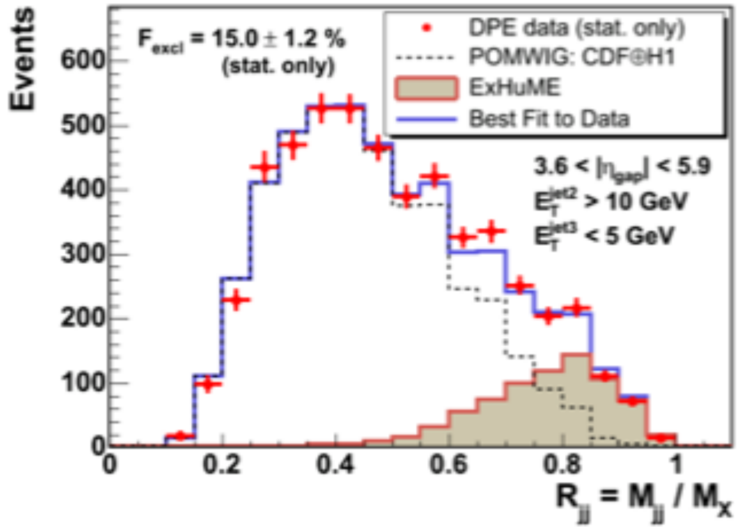
CEP studies with energy scan data at 0.9 and 1.96 TeV

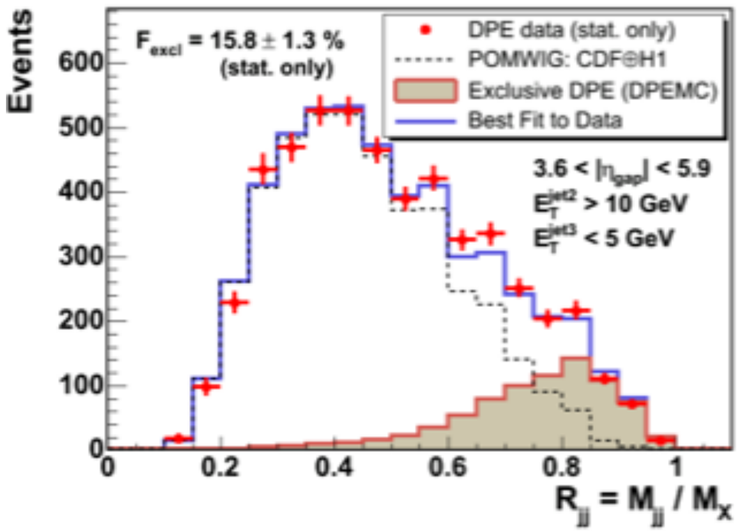


- Data extend up to dipion mass M=5 GeV and show resonance structures attributed to $f_0(1370)$ and $f_2(1270)$ mesons
- From the $\pi^+\pi^-$ and K^+K^- spectra, set upper limits on exclusive χ_c production

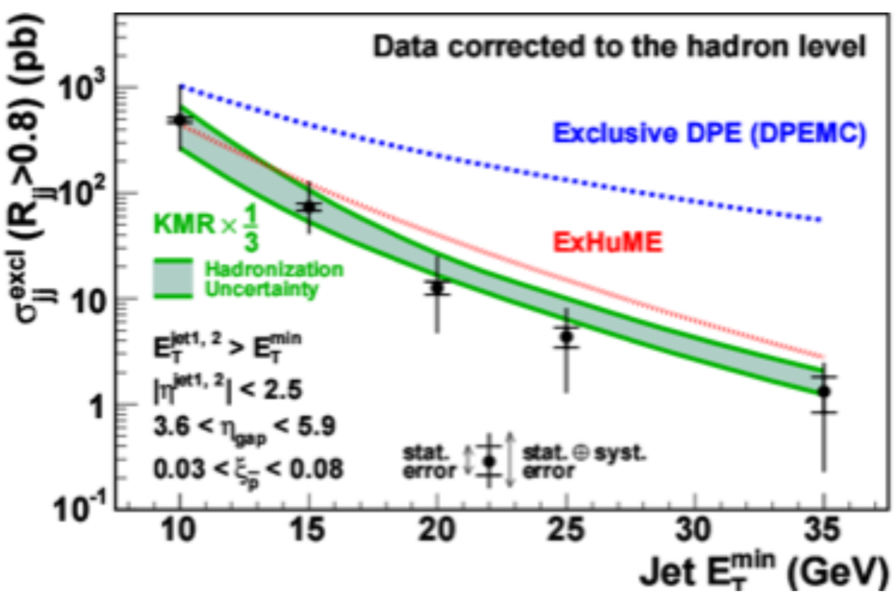
Exclusive dijet cross section

PRD 77 (2008) 052004





- R_{jj} shape described by MC based on two models (ExHuME, DPEMC)
- Cross section agrees with ExHuME
- Data favor KMR model (uncertainty ~factor of 3)

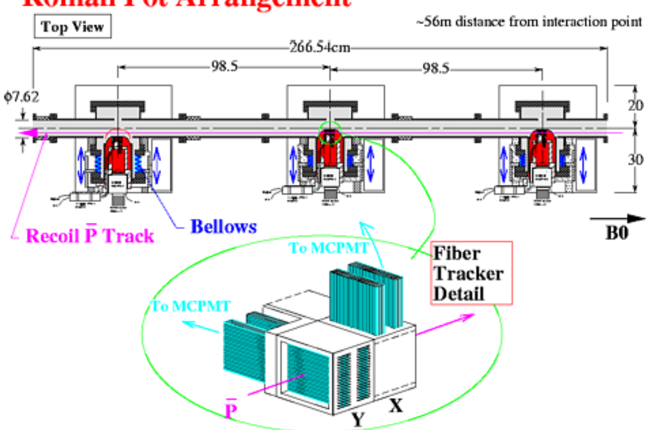


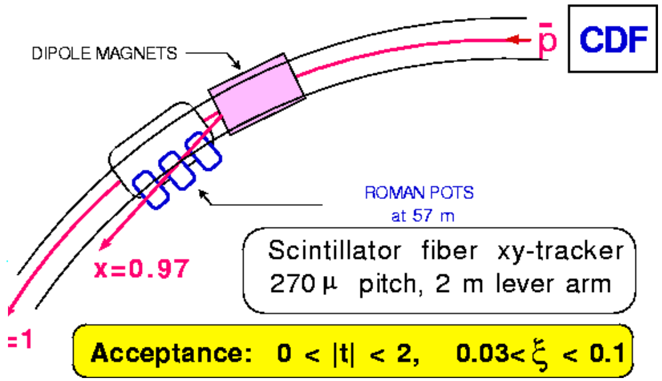
Roman Pot Spectrometer

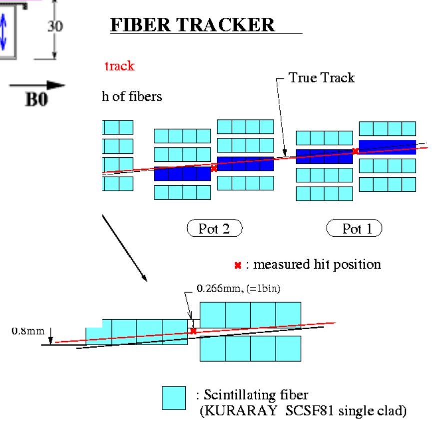
Fiber tracker

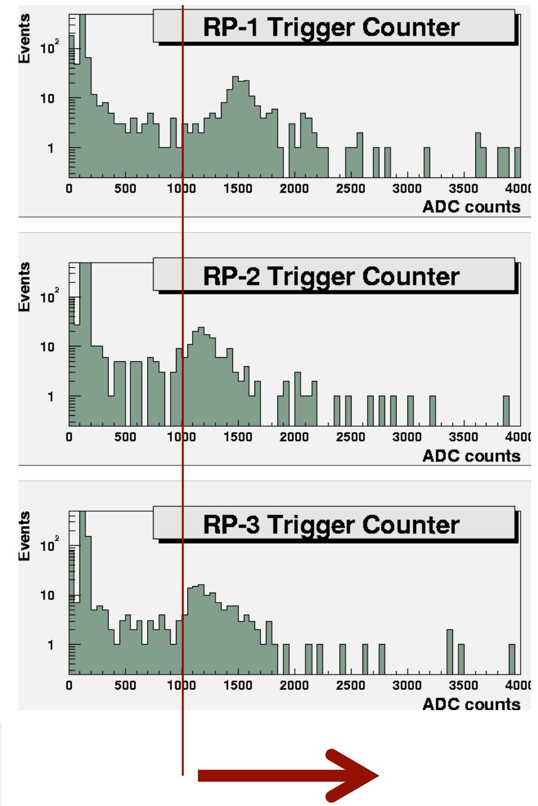
- 3 stations
- 57 meters from IP

Roman Pot Arrangement

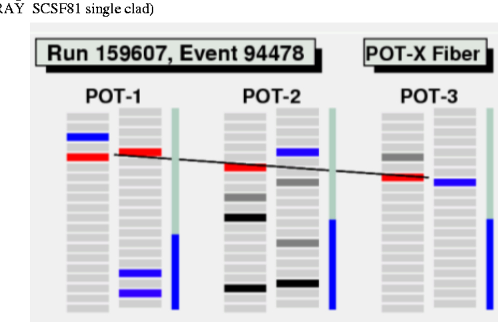








- 3 trigger counters
- 240 channels



MIP (>1000 counts)

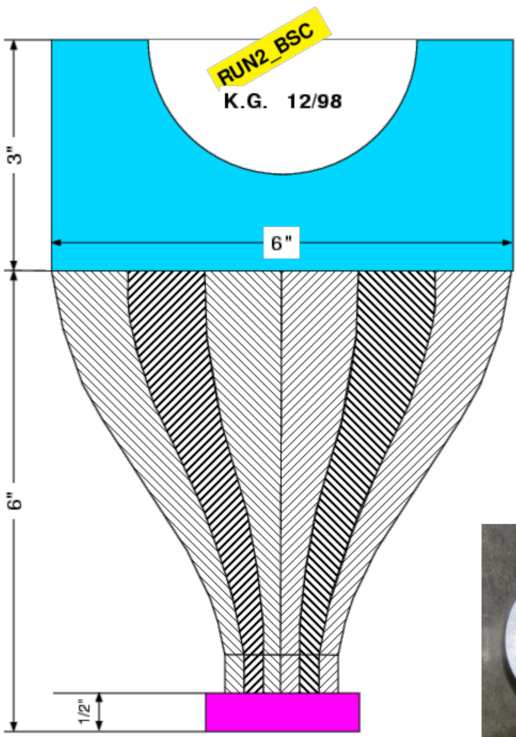
Position resolution: 80μm

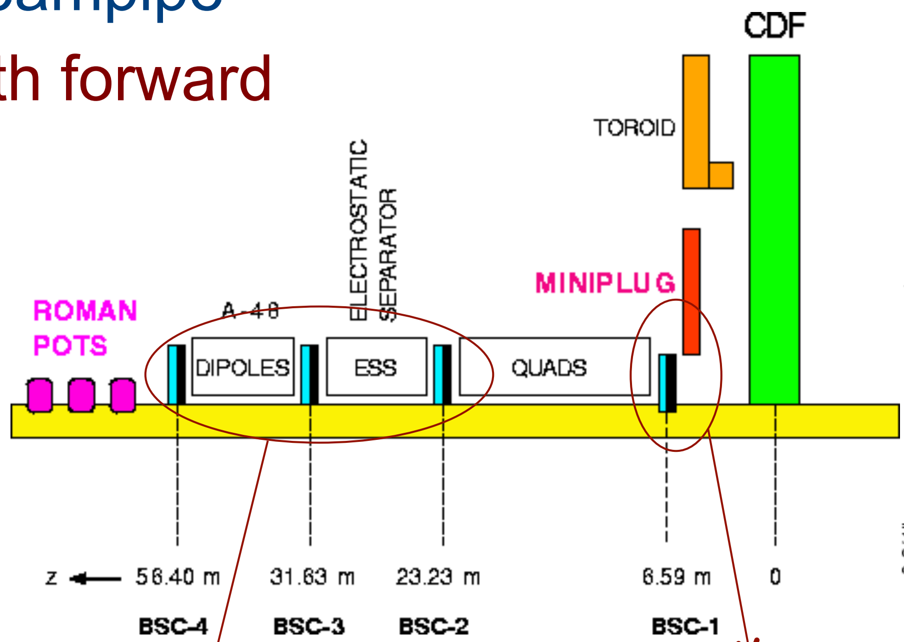
Typical resolutions

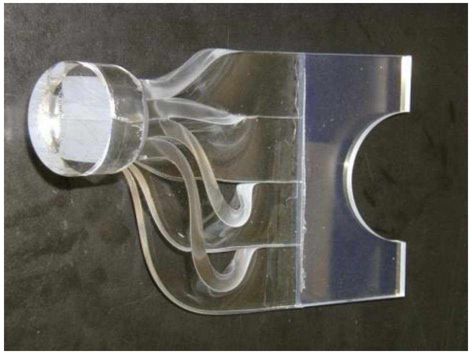
In $\Delta\xi=\pm0.001$; $\Delta t=\pm0.07 GeV^2$

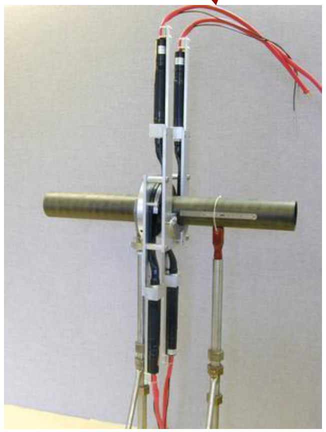
Beam Shower Counters

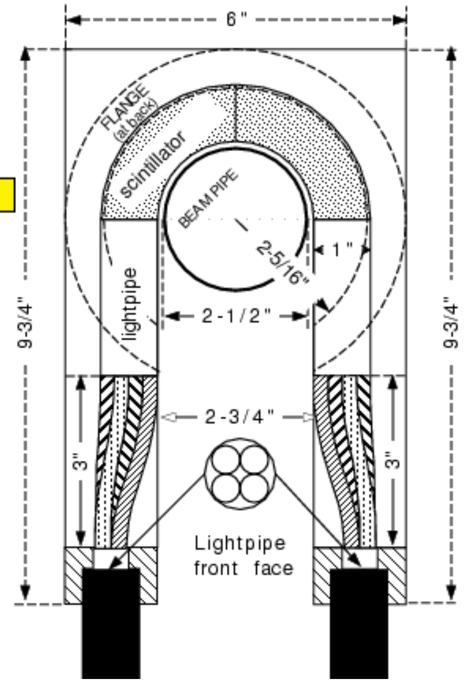
- Located along beampipe
- trigger events with forward rapidity gaps











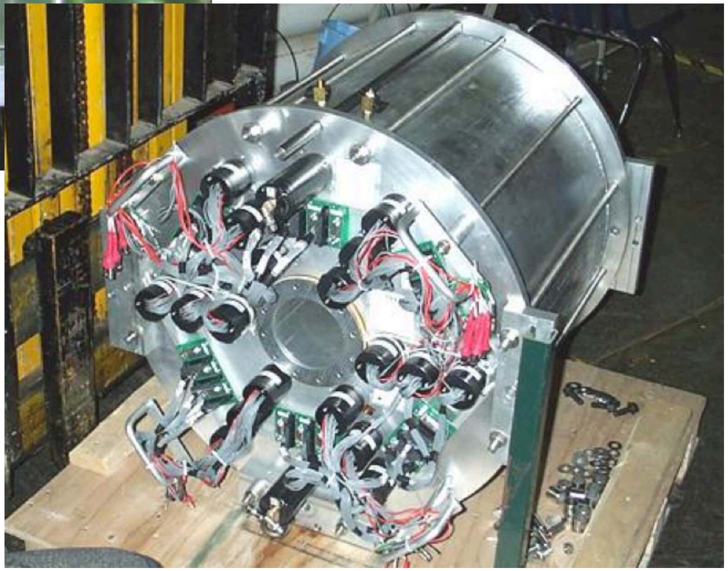
BSC-2/3/4

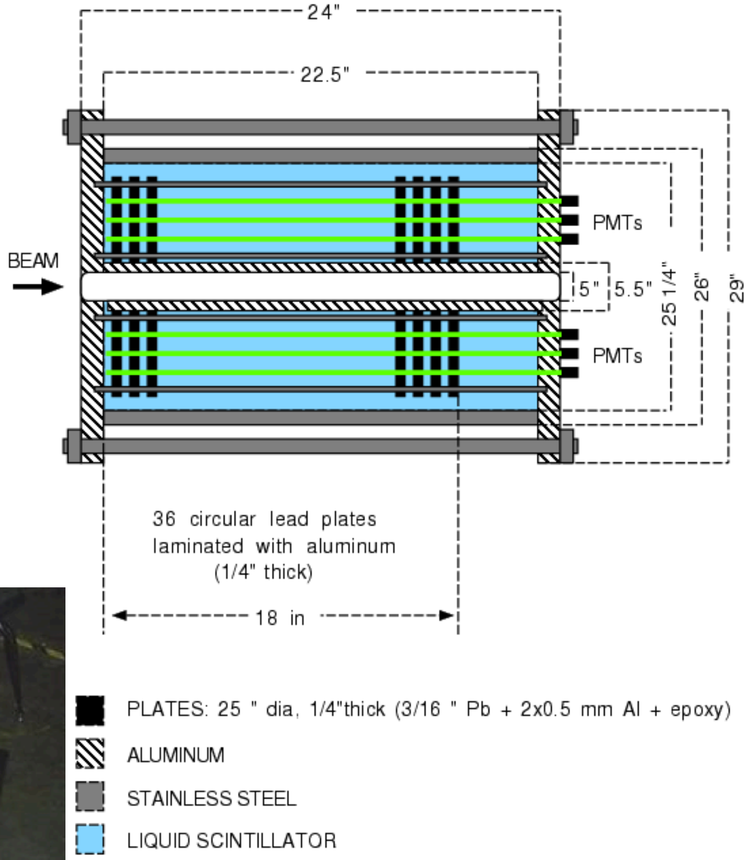
BSC-1

Miniplug Calorimeters

NIMA 518 (2004) 42, NIMA 496(2003)333, NPPS125(2003)128

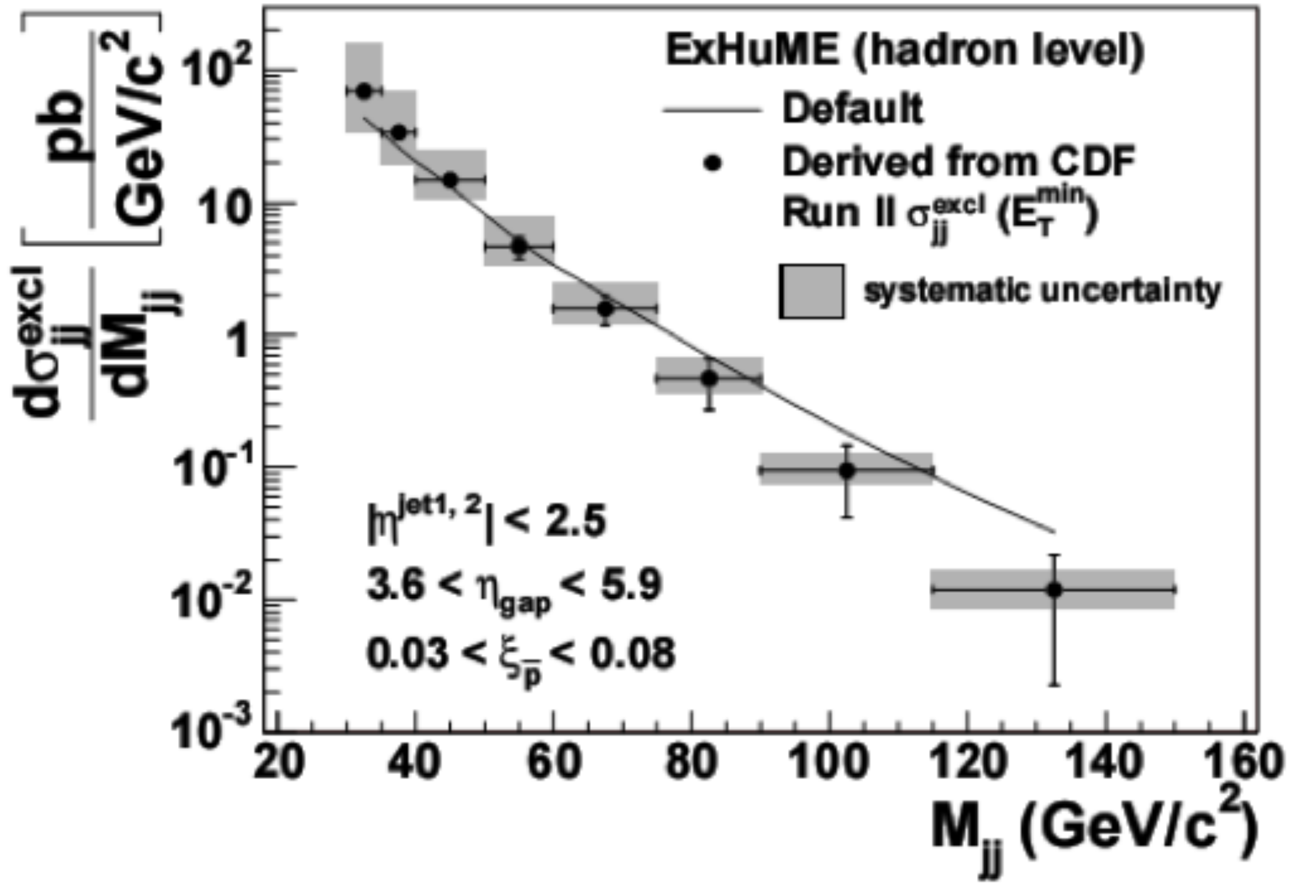
- Design to measure energy and lateral position of both EM and had showers
- “towerless” geometry (no dead region)





Exclusive cross section

derived from CDF exclusive dijet cross sections using ExHuME



Stat. and syst. errors are propagated from measured cross section uncertainties using Mjj distribution shapes of ExHuME generated data