Diffraction and Exclusive Production at CDF

~ Towards Exclusive Higgs at LHC ~

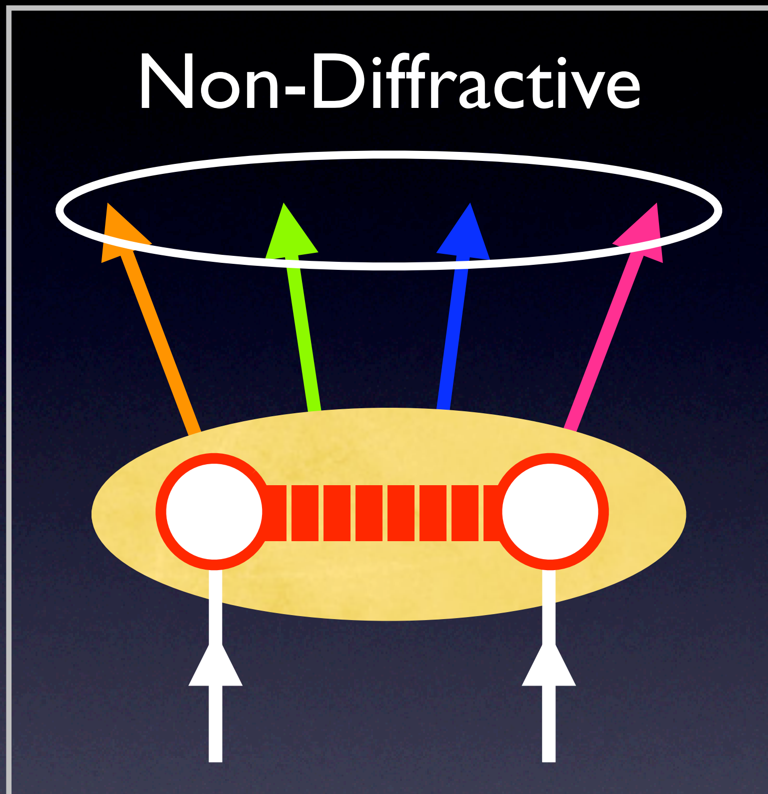
Koji Terashi
The Rockefeller University
for the CDF Collaboration

Wine & Cheese Seminar, March 30th, 2007

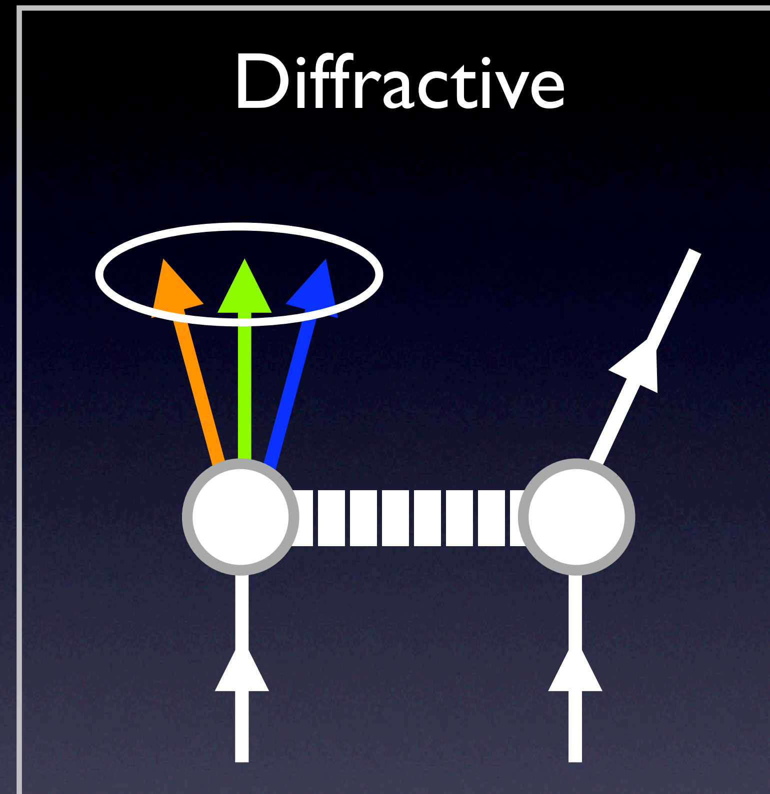
Outline

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

Diffractive Physics



Color exchange

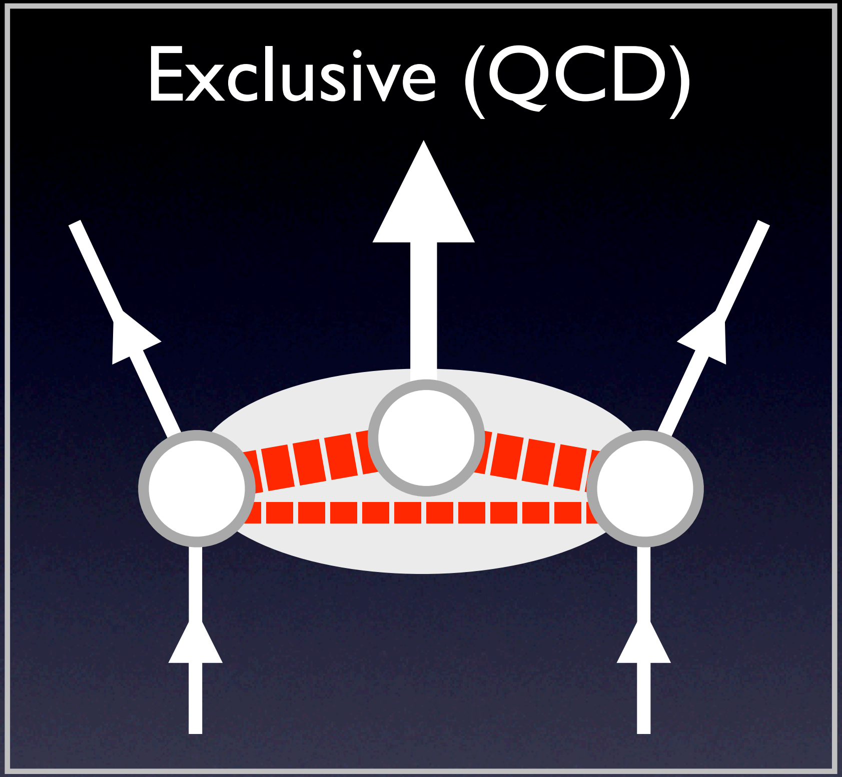


Colorless exchange with vacuum quantum numbers

GOAL :

Understand the QCD nature of diffractive exchange

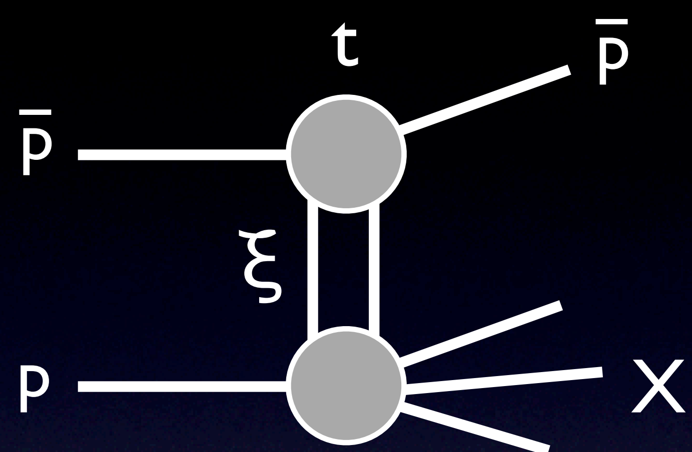
Exclusive Production

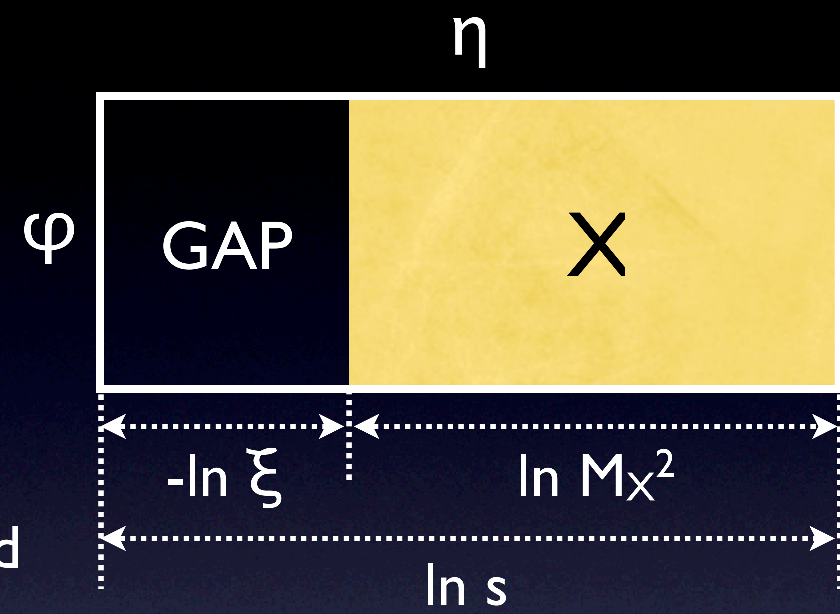


Gluon exchange with extra soft gluon
→neutralize color-flow

<u>GOAL</u> :
Test and calibrate theoretical calculations of exclusive production

Diffractive $\bar{p}p$ Interactions





ξ : momentum fraction of $\bar{p}$ carried by diffractive exchange

t : 4-momentum transfer squared

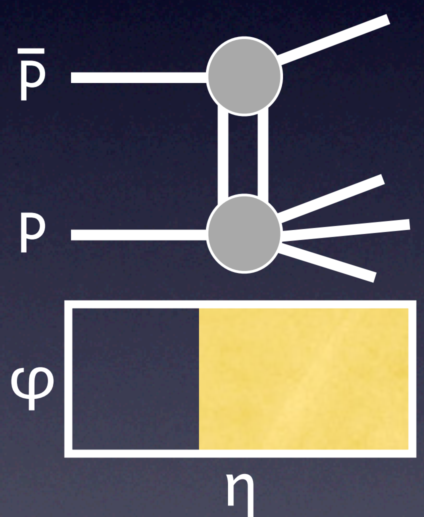
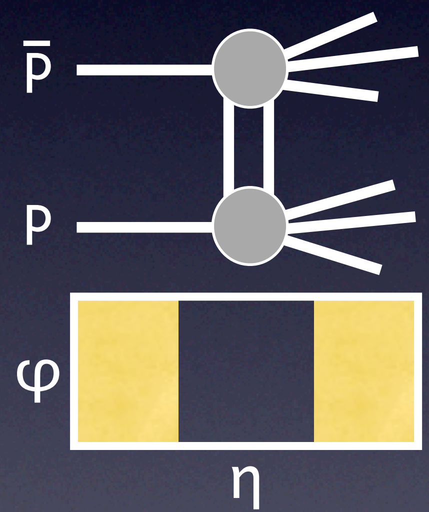
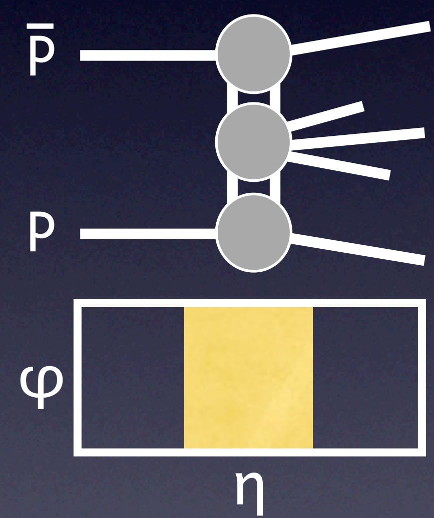
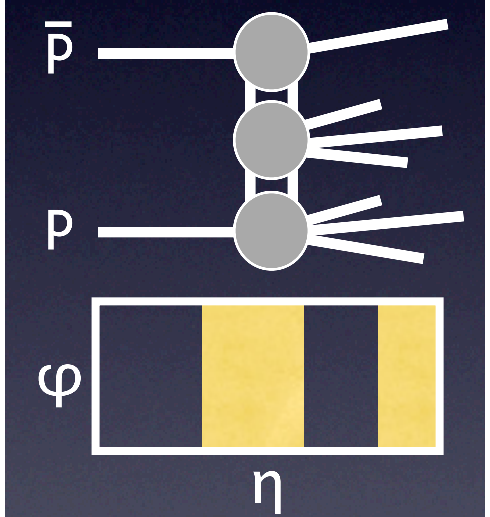
M_X : mass of system X

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

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

Single Diffraction	Double Diffraction	Double Pomeron Exchange	Single + Double Diffraction
			

14 published papers : 13 PRL and 1 PRD

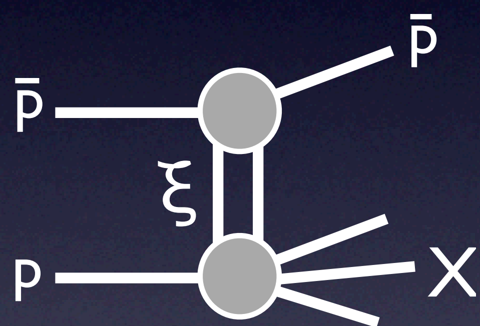
σ_{total} and $\sigma_{elastic}$ (not discussed today)

Diffraction in Regge Theory

Single Diffraction Cross Section

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

Flux $f_{IP/\bar{p}}(\xi, t)$ $\qquad$ $\sigma_{IPp}{}^{total}$



- Pomeron trajectory : $\alpha_{IP}(t) = 1 + \epsilon + \alpha' t$
- $\epsilon \simeq 0.1$
- $s' = M_X{}^2 = s\xi$

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

$\xi_{min} = M_0{}^2/s$ $\qquad$ cf. $\sigma_{total} = \beta_{IPp}(0)^2\left(\frac{s}{s_0}\right)^{\epsilon} \sim s^{\epsilon}$

Soft Single Diffraction

K. Goulianos, PLB 358,379(1995)

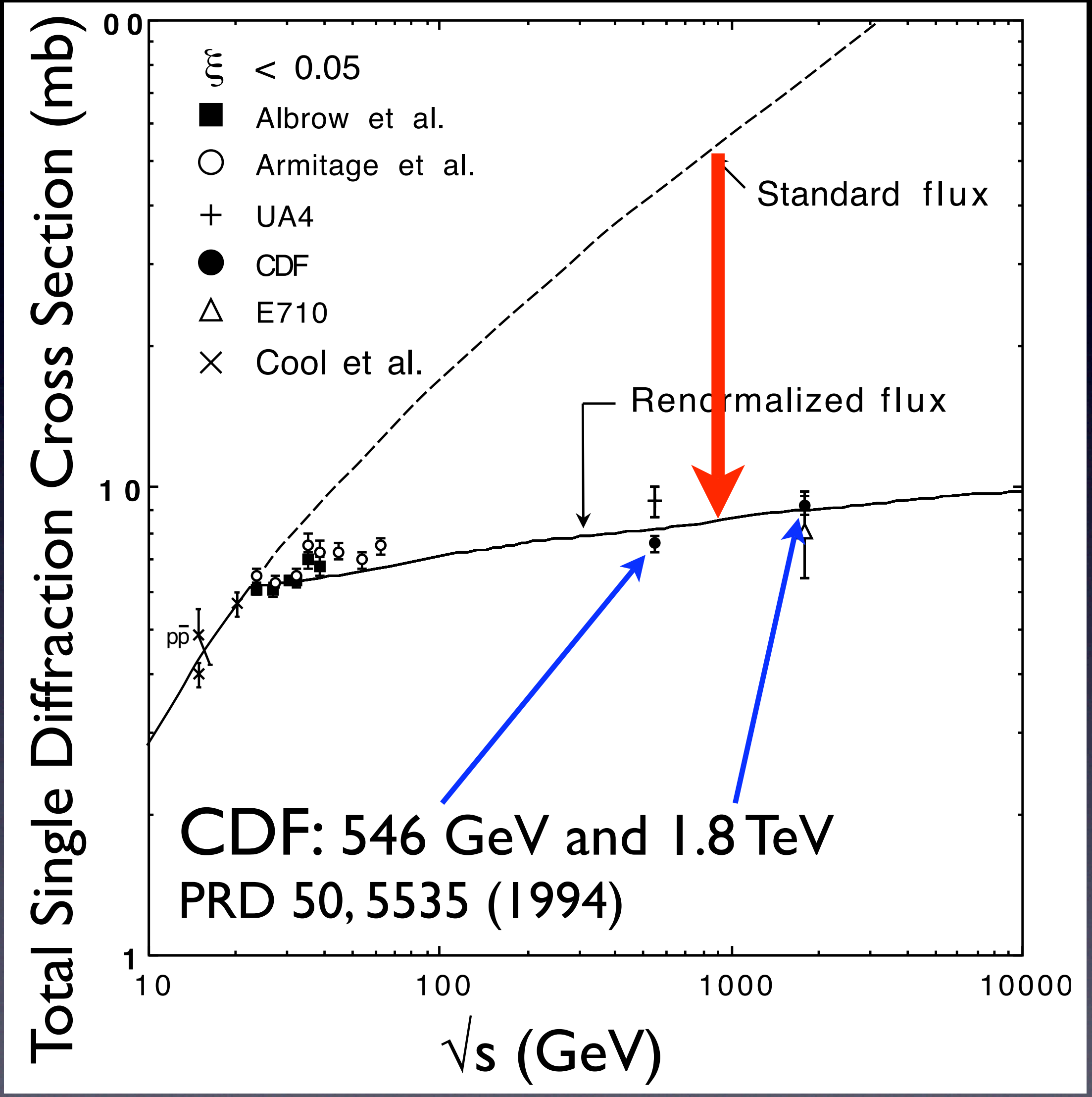
<u>Regge Theory</u>

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

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

<u>Measurement</u>

- $\sigma_{SD} \sim s^{2(0.015\pm0.008)}$
  $\Rightarrow$ much weaker s-dependence
  ➡ A factor of ~10 suppressed in normalization
- $d\sigma/d\xi \sim \xi^{-(1+\epsilon)}$ dependence
  ➡ Same as Regge theory



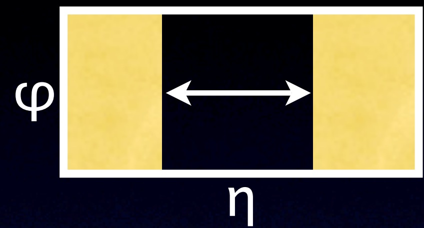
<u>Renormalization</u>

Pomeron flux integral (re)normalized to unity

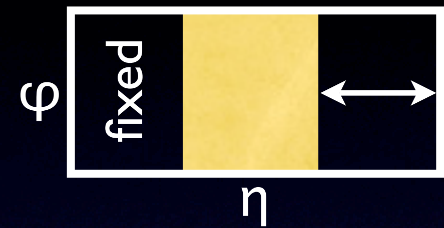
$$\int_{\xi_{min}}^{0.1} d\xi \int_{-\infty}^{0} dt \; f_{IP/p}(\xi,t) = 1$$

Soft Diffraction

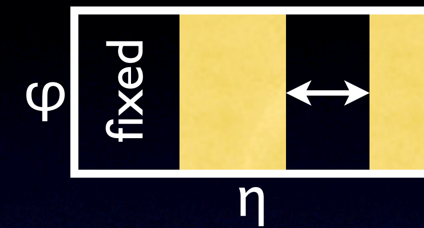
DD
PRL 87,141802(2001)



DPE
PRL 93,141601(2004)

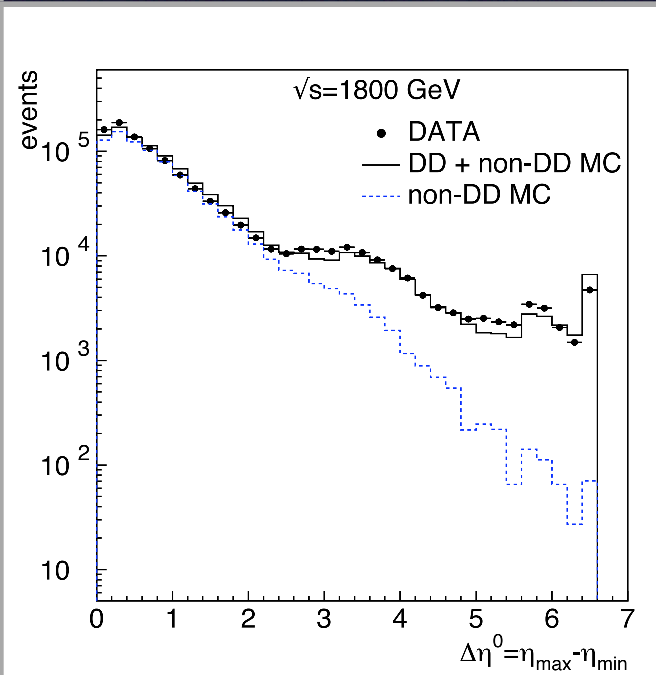


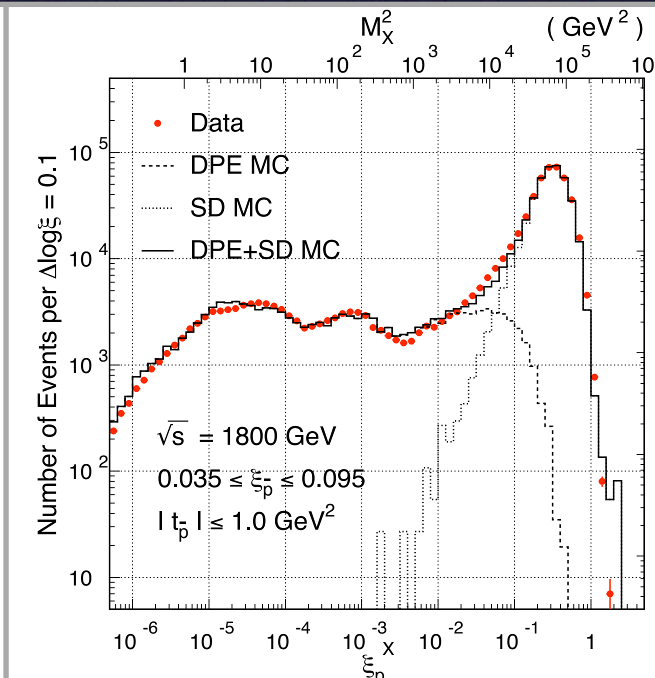
SDD
PRL 91,011802(2003)

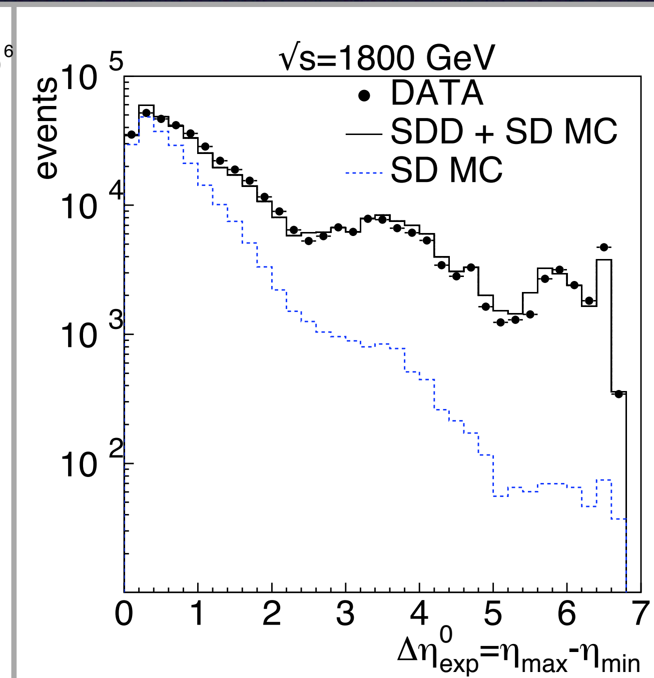


Event yield as a function of $\Delta\eta_{gap}$ or ξ

Regge-based MC simulations normalized to data



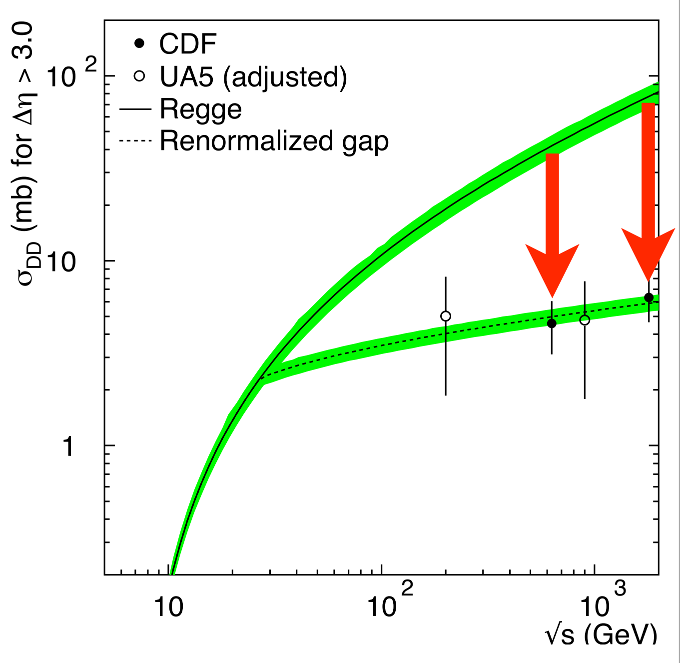


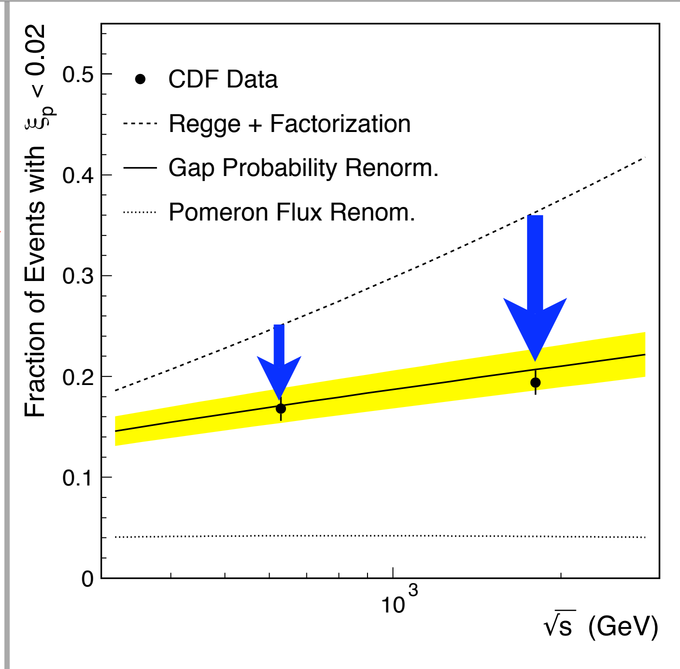


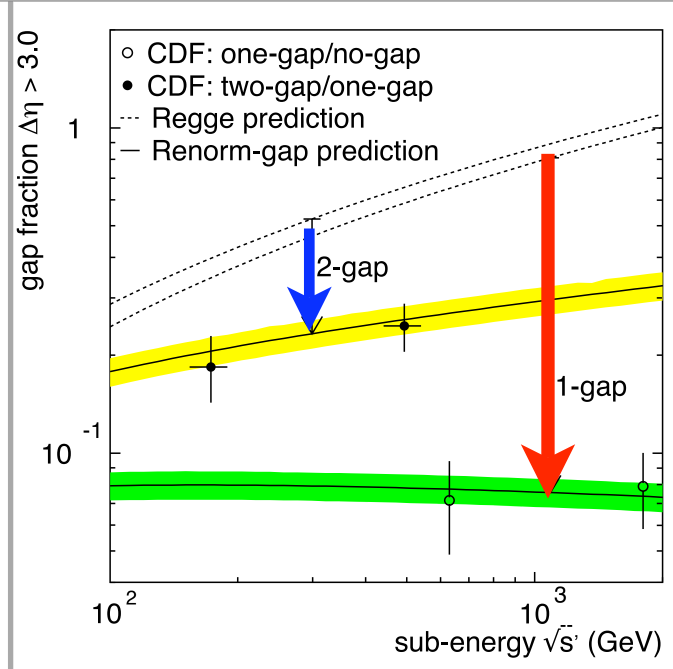
➡ Data agree with Regge predictions in ξ-dependence

Soft Diffraction

DD	DPE	SDD
Fraction (or cross section) of gap events as a function of √s		





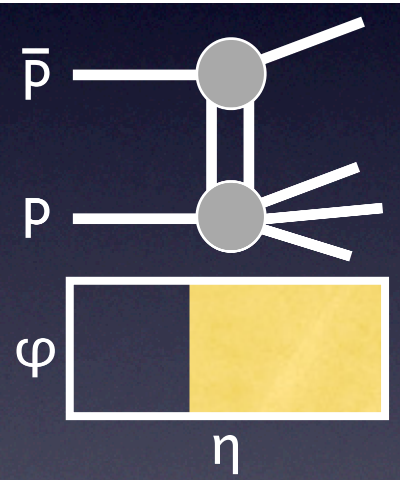
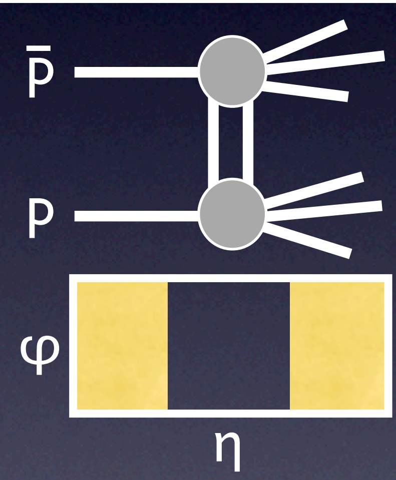
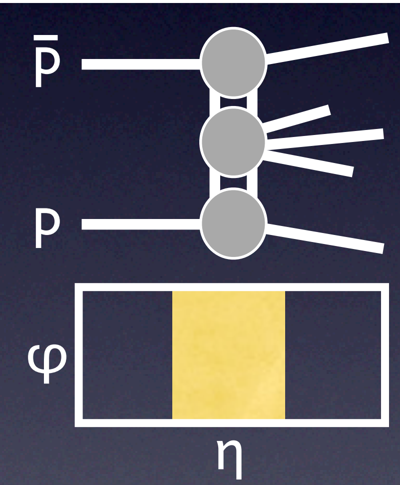


- Single gap rates are suppressed by O(10)
- Double gap rates are less suppressed relative to Regge predictions

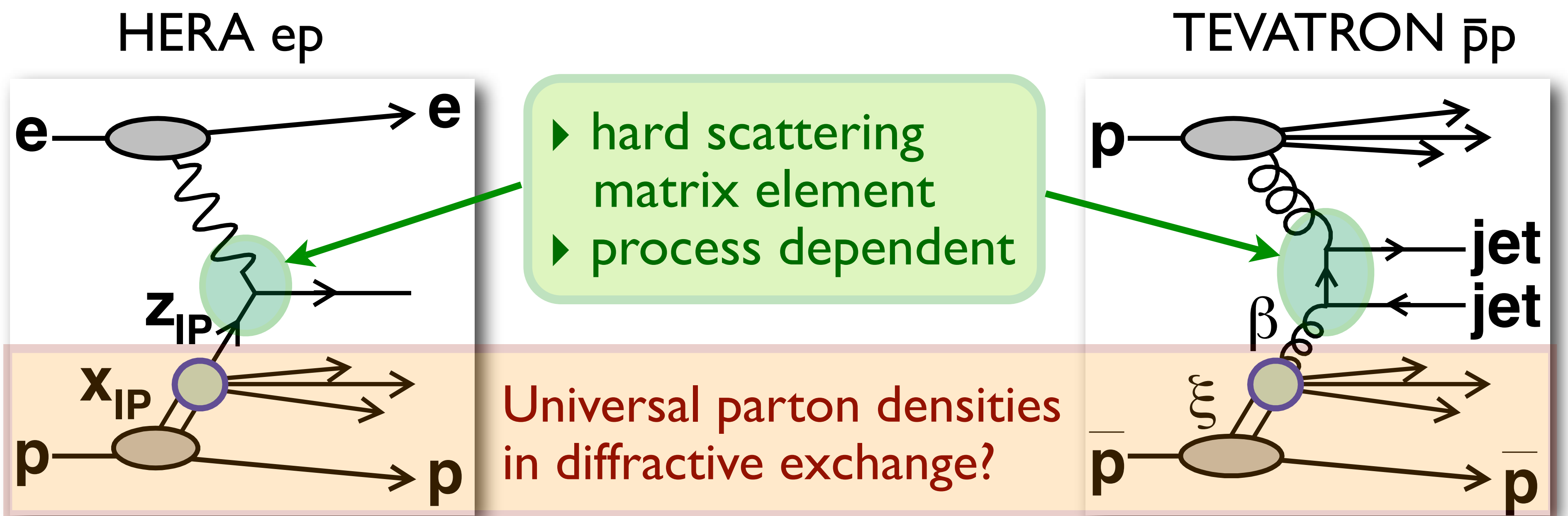
Hard Diffraction

- Proposed by Ingelman and Schlein in 1985 — PLB 152, 256(1985)
- Discovery of diffractive di-jets by UA8 — PLB 211,239(1988), 297,417(1992)

Probing partonic structure of the diffractive exchange

SD	DD	DPE
		
▸ W boson ▸ Di-jet ▸ b-quark ▸ J/ψ meson	▸ jet-gap-jet (not shown today)	▸ Di-jet

QCD Factorization



Proved by J. Collins
PRD 57,3051(1998)

Factorization Test

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

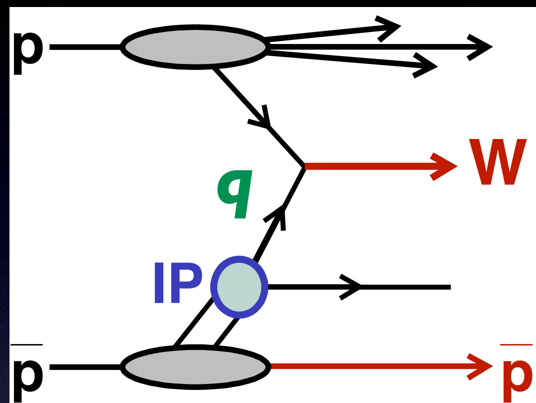
?

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

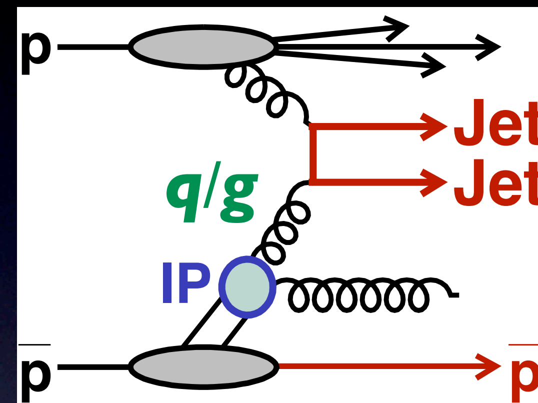
W

PRL 78,2698(1997)



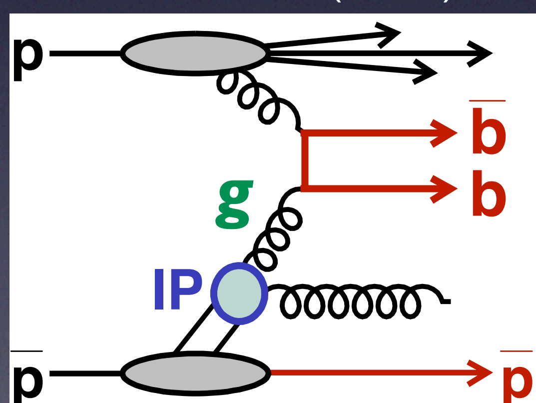
Di-jet

PRL 79,2636(1997)



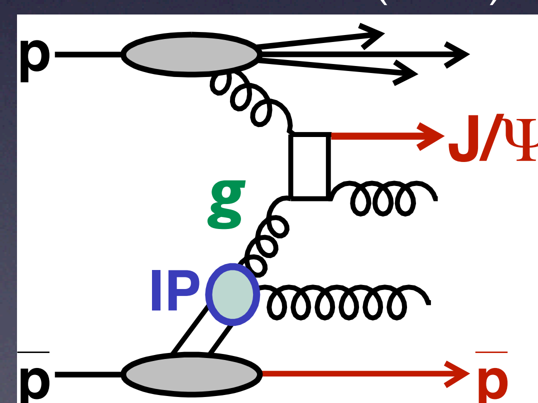
b-quarks

PRL 84,232(2000)



J/ψ

PRL 87,241802(2001)



Probing quark and gluon contents in diffractive exchange

Diffractive to Inclusive Ratio

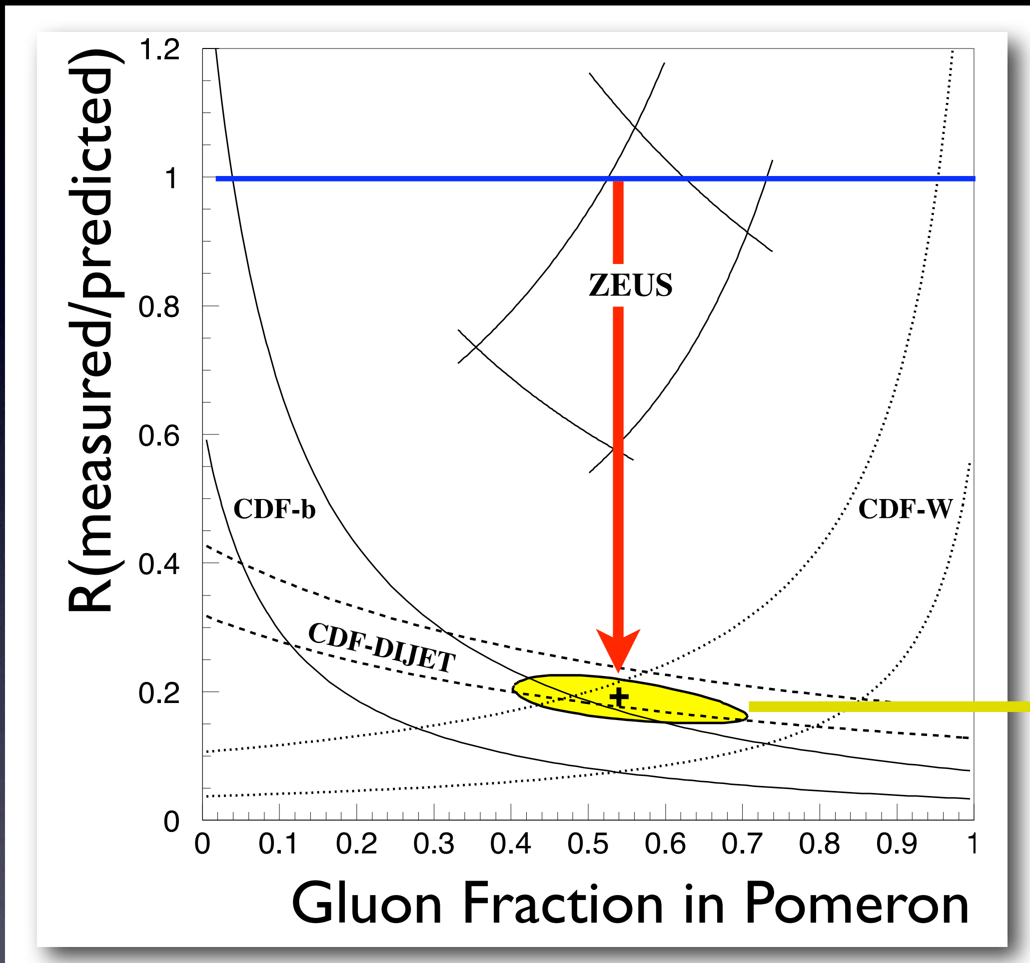
$\sqrt{s}$=1.8 TeV	W	Di-jet	b-quark	J/ψ
$R\left[\frac{\text{diff}}{\text{incl}}\right]$ (%)	1.15±0.55	0.75±0.10	0.62±0.25	1.45±0.25

➡ Diffractive production rates are all similar at ~1% relative to inclusive rates

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

Factorization Breaking

PRL 84, 232(2000)



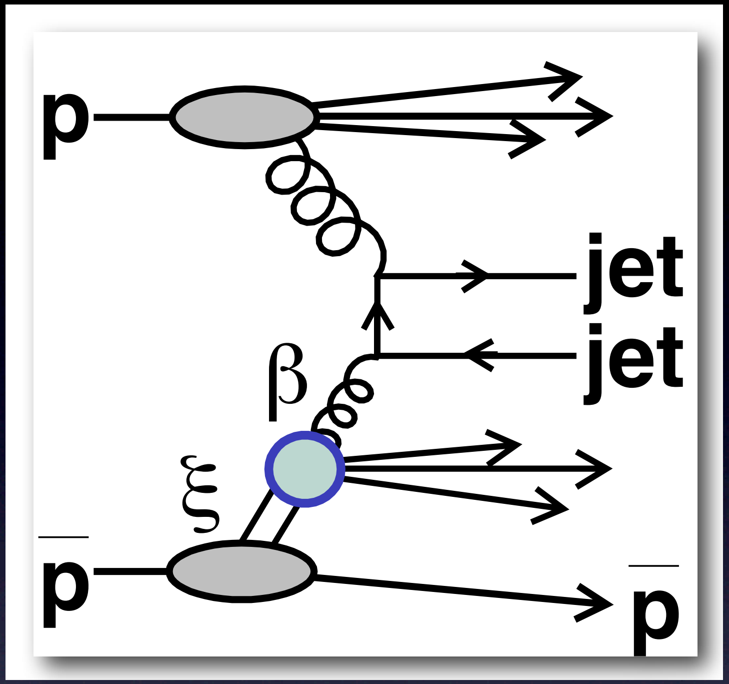
R = 1 : factorization valid

R = 0.19 ± 0.04

SD production rates are severely suppressed relative to HERA

➡ Factorization breakdown between Tevatron and HERA

Diffractive Structure Function



Diffractive Di-jet Production

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

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

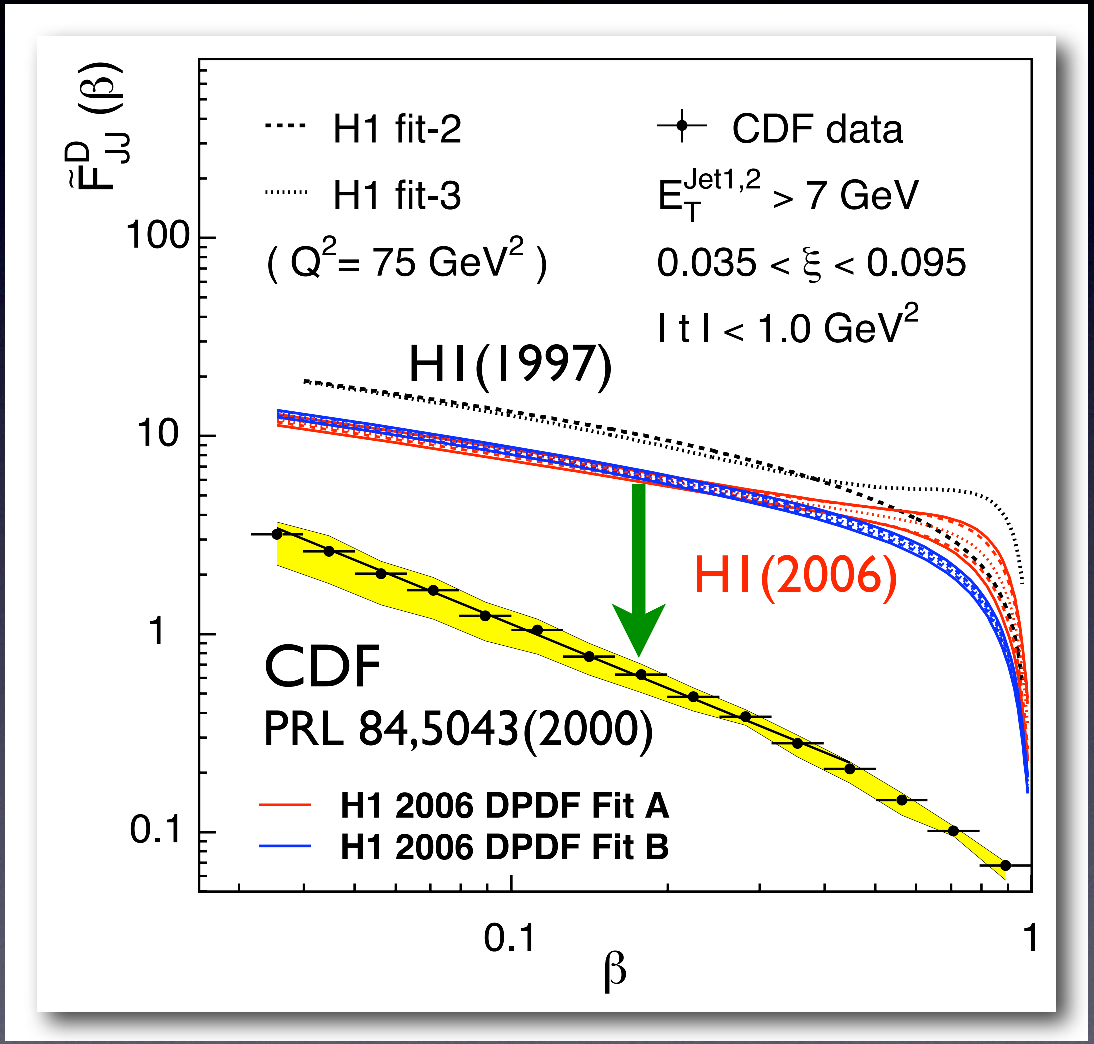
$$F_{jj}^D\,(x_{Bj}, Q^2) = R(x_{Bj}) \text{ of } \frac{\sigma_{jj}(\text{Diff})}{\sigma_{jj}(\text{Non-Diff})} \times F_{jj}\,(x_{Bj}, Q^2)$$

Data

Proton PDF

Diffractive Structure Function

P. Newman : Hera-LHC workshop, March 2007
(Also, see M. Ruspa's talk in Small-x workshop)

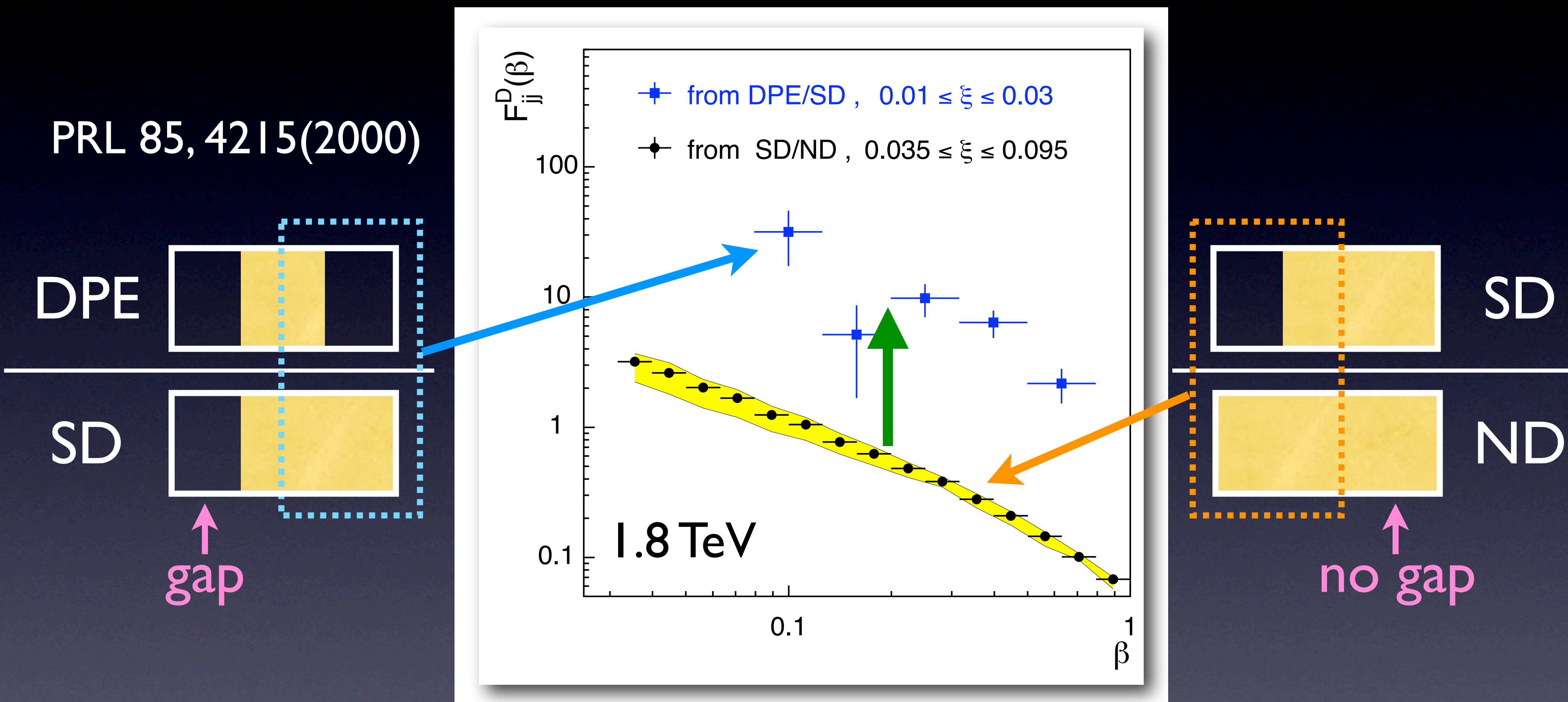


F_{jj}^{D} at the Tevatron is suppressed relative to expectations from dPDFs measured by H1 at HERA

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

Diffractive Structure Functions from DPE and SD Data

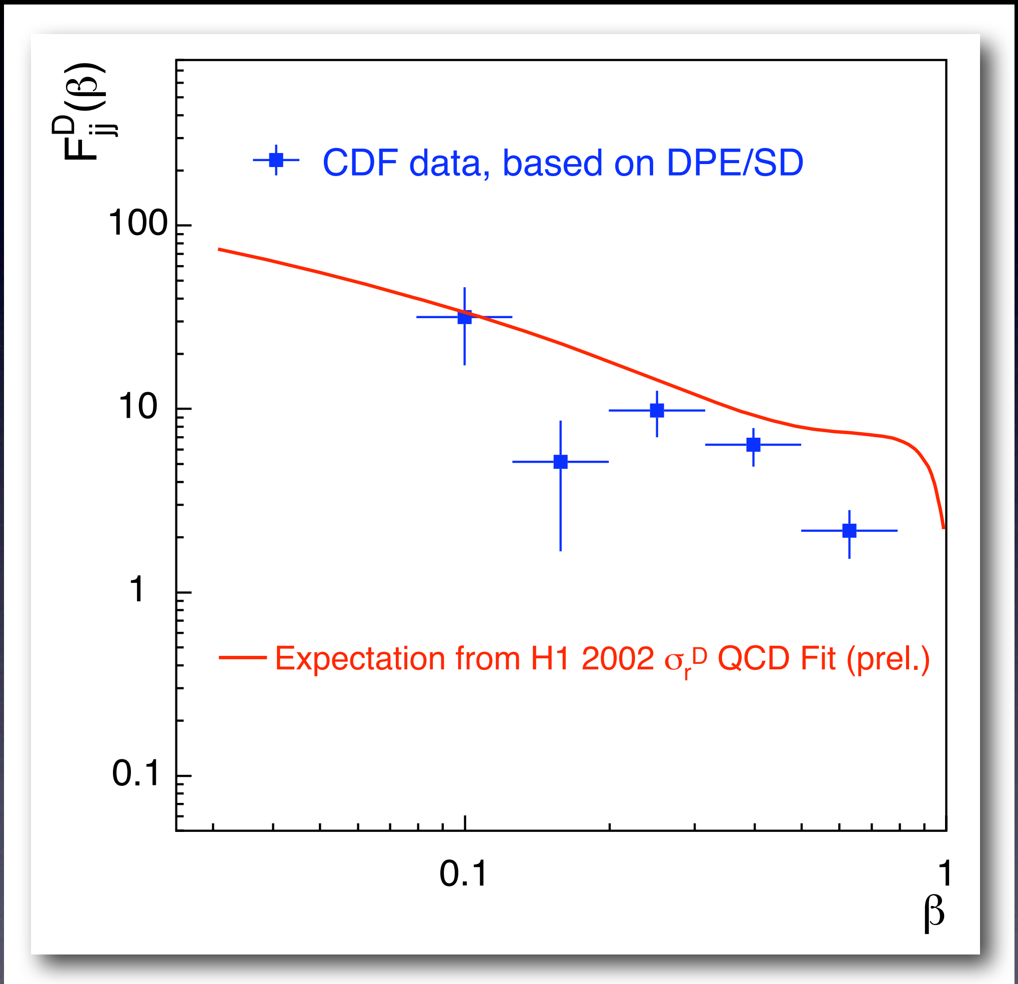
PRL 85, 4215(2000)



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 from DPE is approximately equal to expectations from dPDFs measured at HERA

➡ QCD factorization between HERA and Tevatron restored?

➡ 2nd gap less suppressed if a gap is already present in the events

Run II Diffractive Program

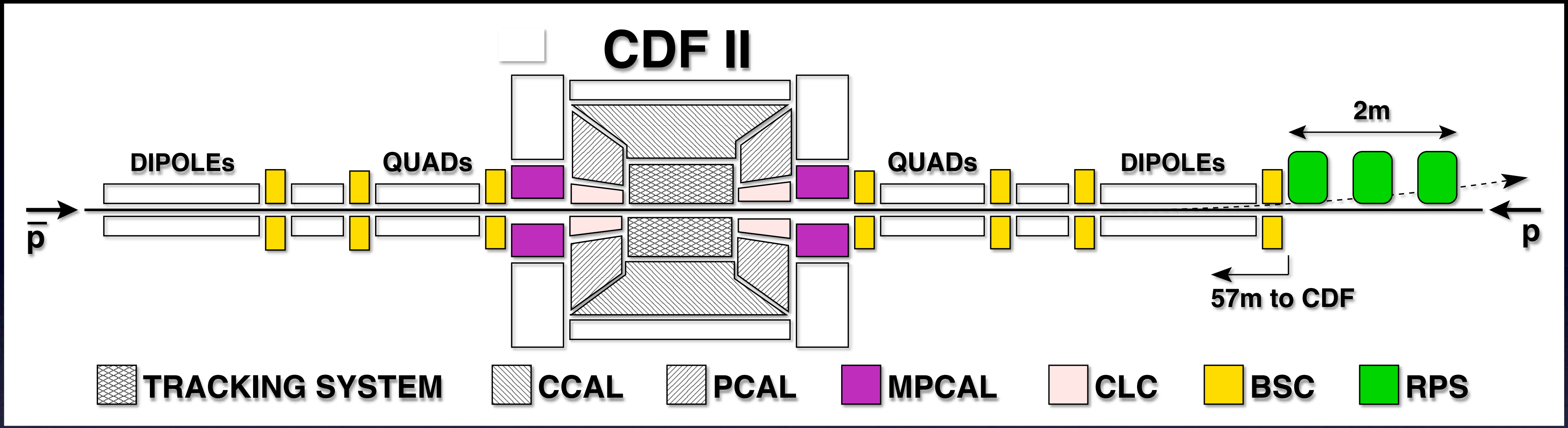
GOAL

- Further characterize diffractive structure function and diffractive exchange
- Measure exclusive production and calibrate theoretical calculations

SD	▸ ξ, t, and Q^2 dependence of F_{jj}^D ▸ Process dependence of $F^D(W, Z)$ →M. Convery's talk
DPE	▸ $\xi_{\bar{p}}$ dependence on F_{jj}^D measured on p-side
DD	▸ $\Delta\eta_{gap}$ dependence for fixed large $\Delta\eta_{jj}$ →C. Mesropian's talk
Exclusive	▸ di-jet, di-photon, χ_c ▸ e^+e^-, $\mu^+\mu^-$ →L. Zhang's talk

Results presented in this talk

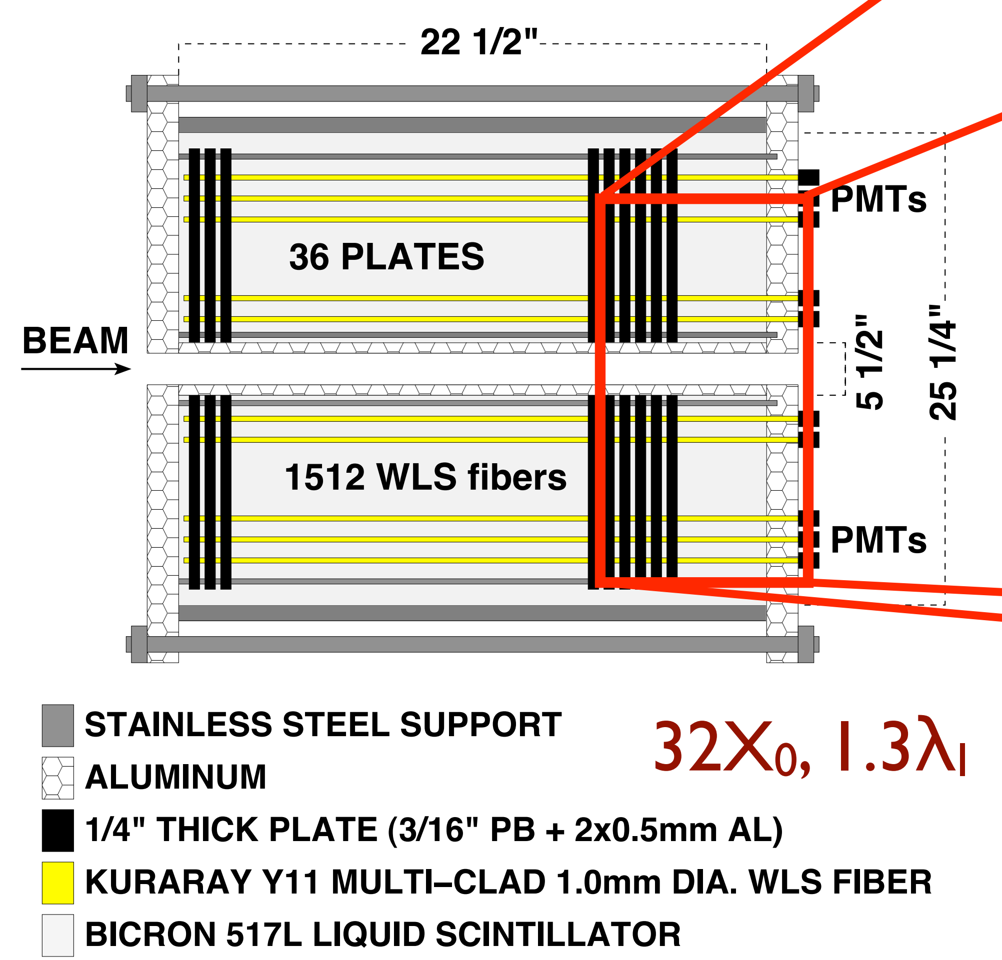
CDF II Detector



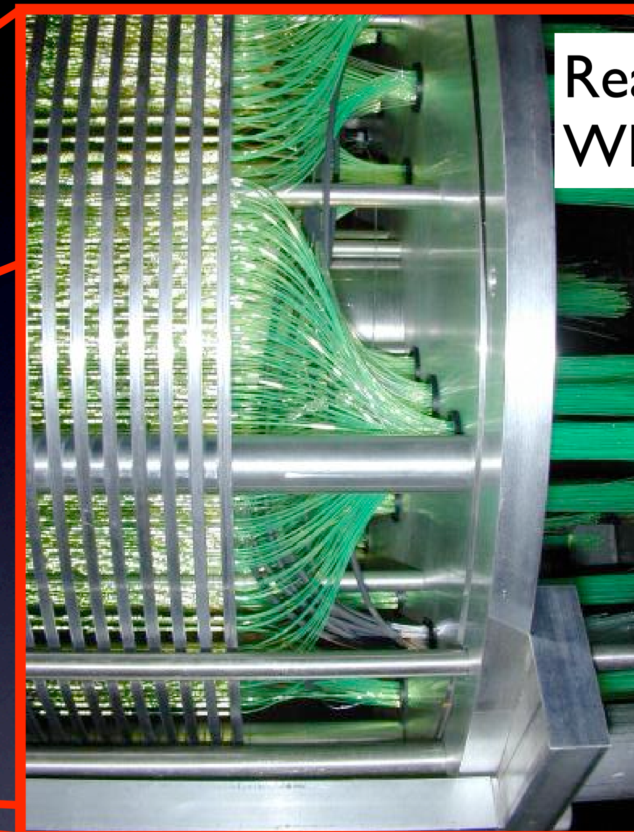
- Tracking Detectors : $|\eta| < 2.0$
- Calorimeters : $|\eta| < 5.2$
- Beam Shower Counters (BSC) : $5.4 < |\eta| < 7.4$
- Roman Pot Spectrometers (RPS) : $0.02 < \xi < 0.1$
  $0 < |t| < 2\ \mathrm{GeV}^2$

MiniPlug Calorimeters

Electromagnetic calorimeter with hadron detection capability



$32X_0$, $1.3\lambda_I$



- ➡ Good position resolution retained

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

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

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

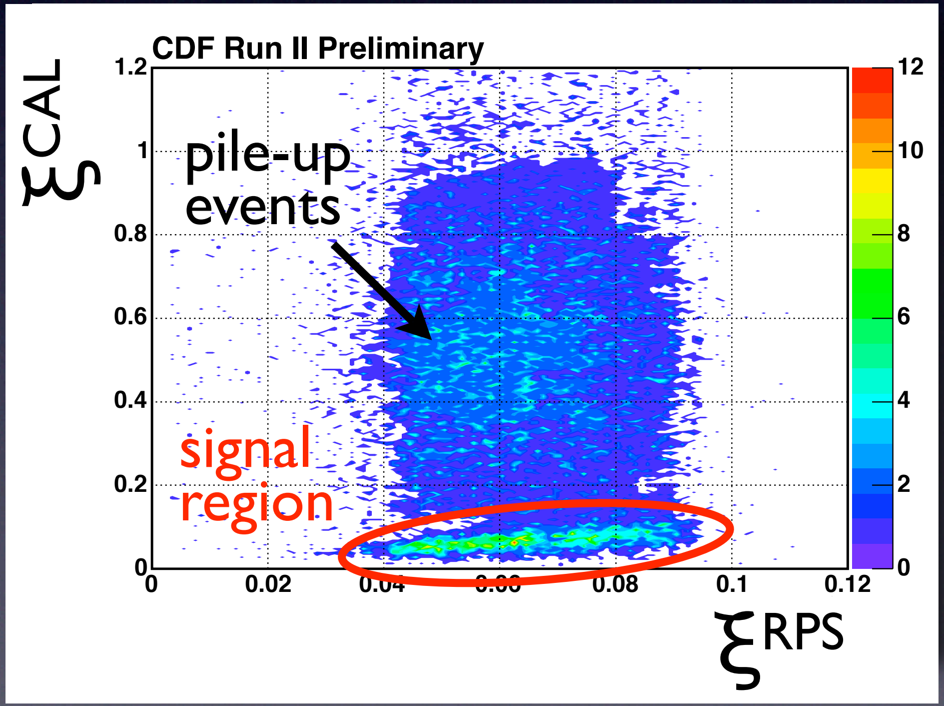
Built by Rockefeller Group

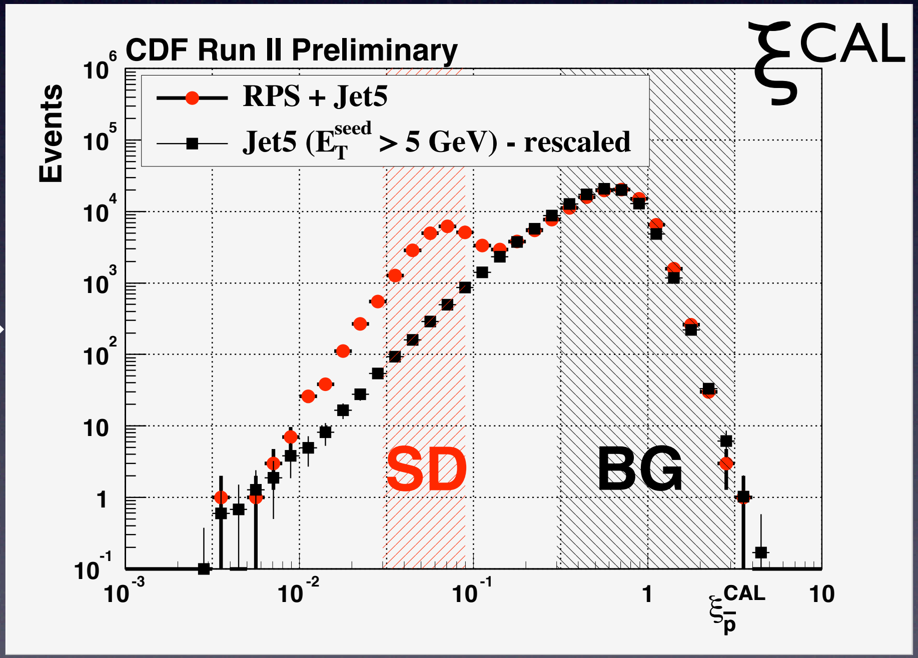
Run II Challenge

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

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

$L_{inst} \sim 2\times10^{31} cm^{-2}s^{-1}$ (not "high" lum!)

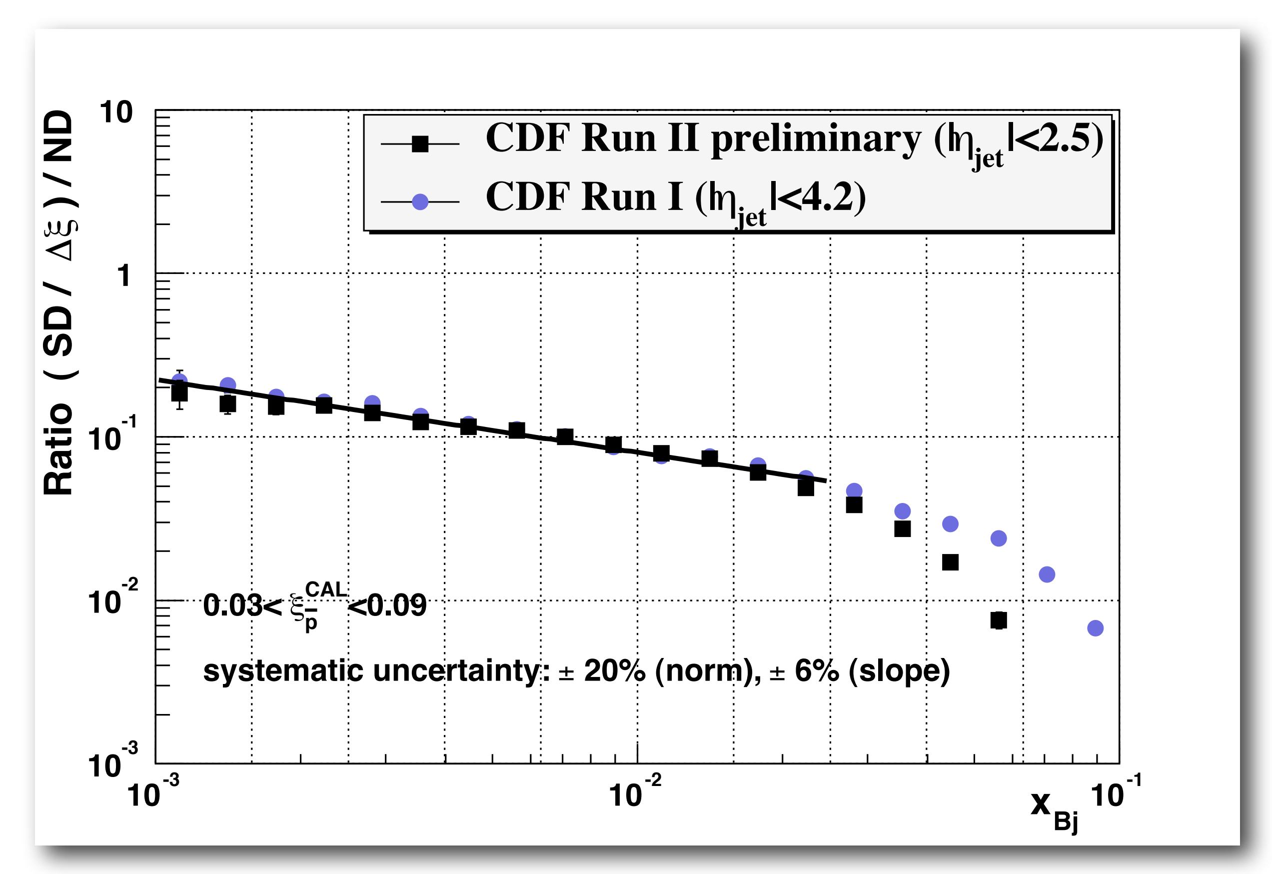




Used to reject pile-up events by selecting $\xi^{CAL} < 0.1$

$x_{Bjorken}$-dependence of F_{jj}^D

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

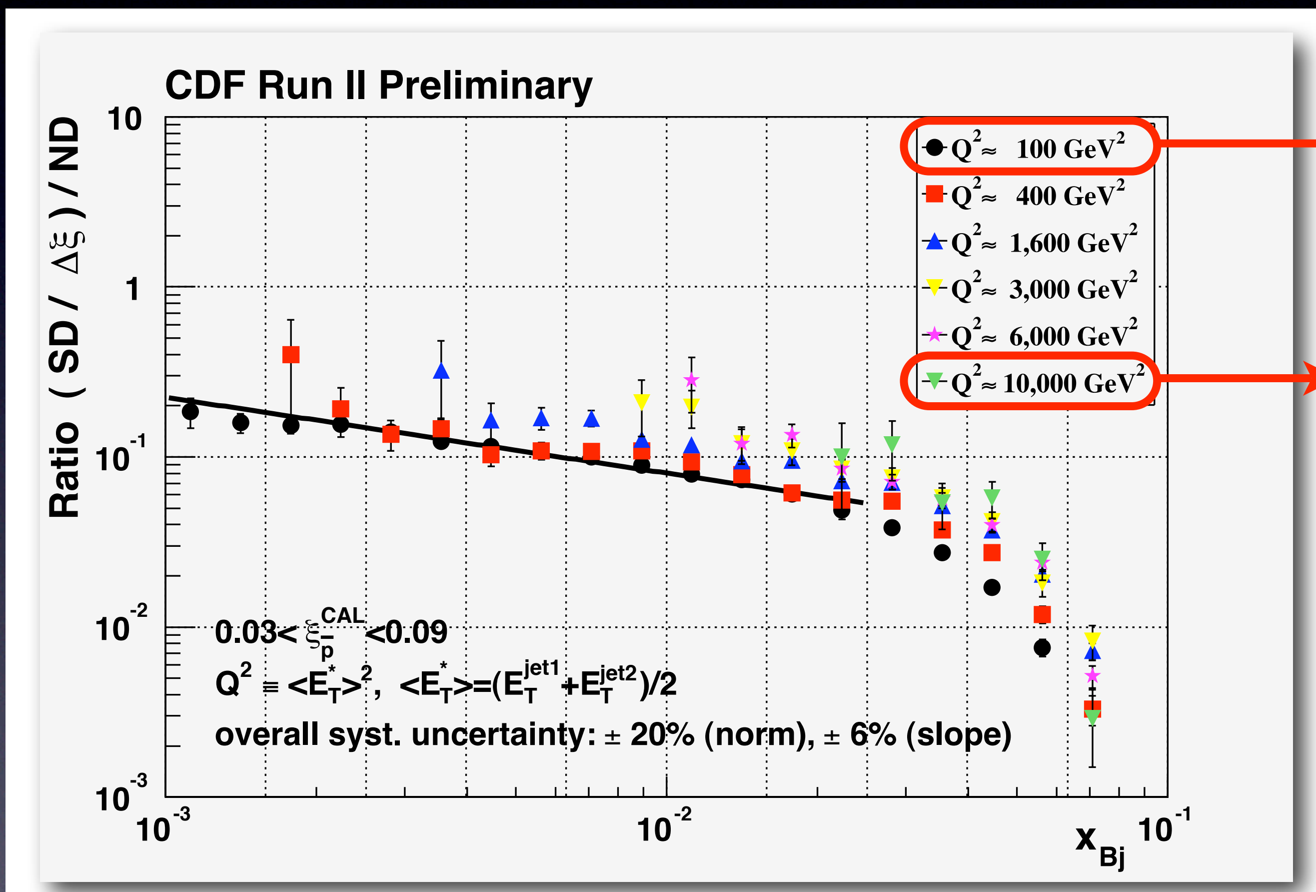


➡ Run I result is confirmed

(difference at high x_{Bj} caused from different jet acceptance)

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

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

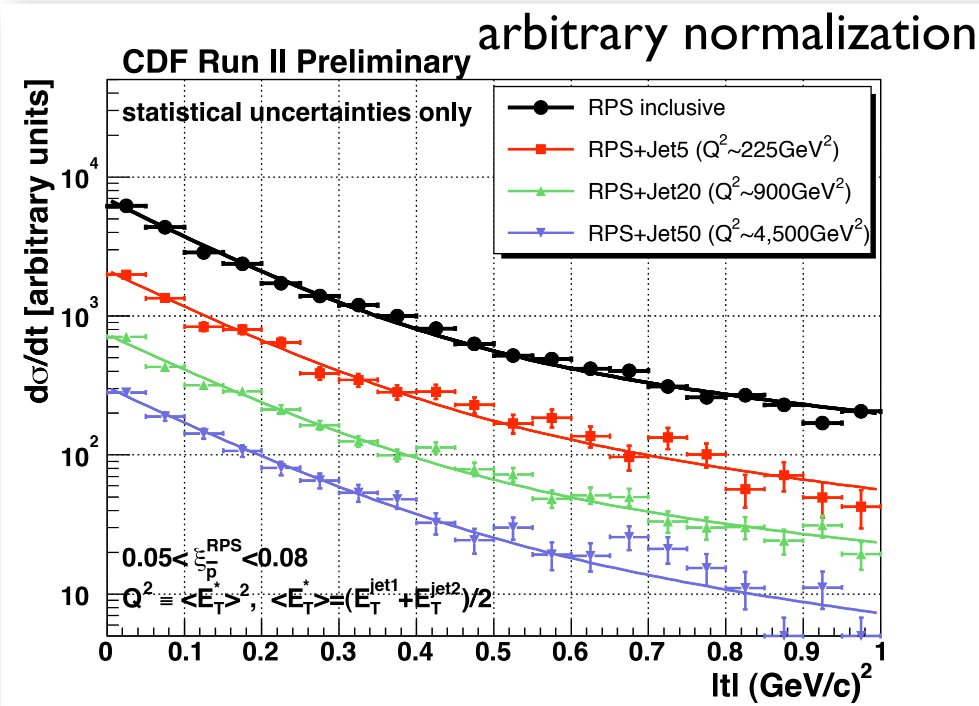


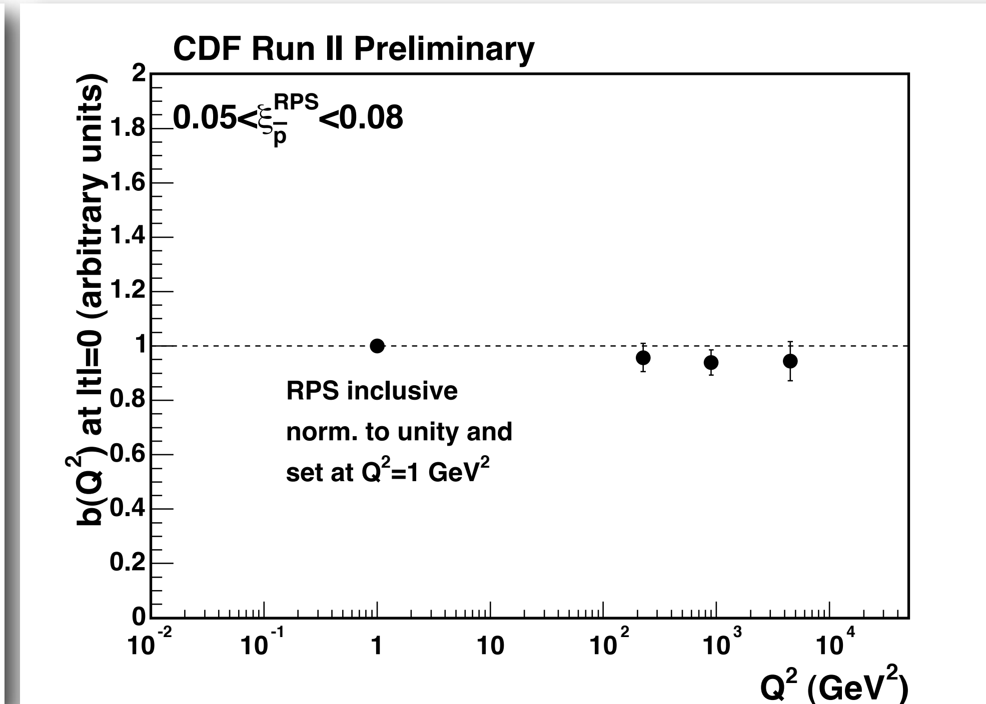
$\langle E_T^* \rangle$	Normalization
~10 GeV	N
↓	↓
~100 GeV	~10^{-4}N

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

➡ Pomeron evolves similarly to proton

t-dependence of F_{jj}^D





Fit t-distributions to a double exponential function :

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

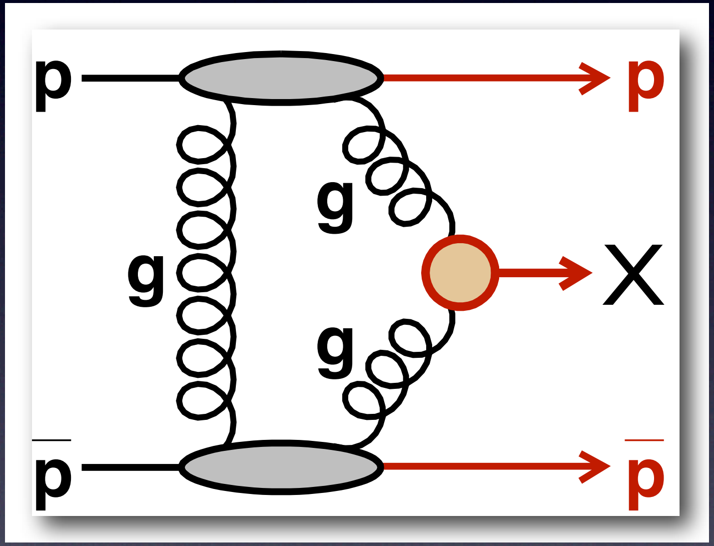
→M. Gallinaro's talk

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

Work in progress for
➡ absolute t-slope values
➡ larger |t| range up to ~4 GeV^2

Exclusive Production

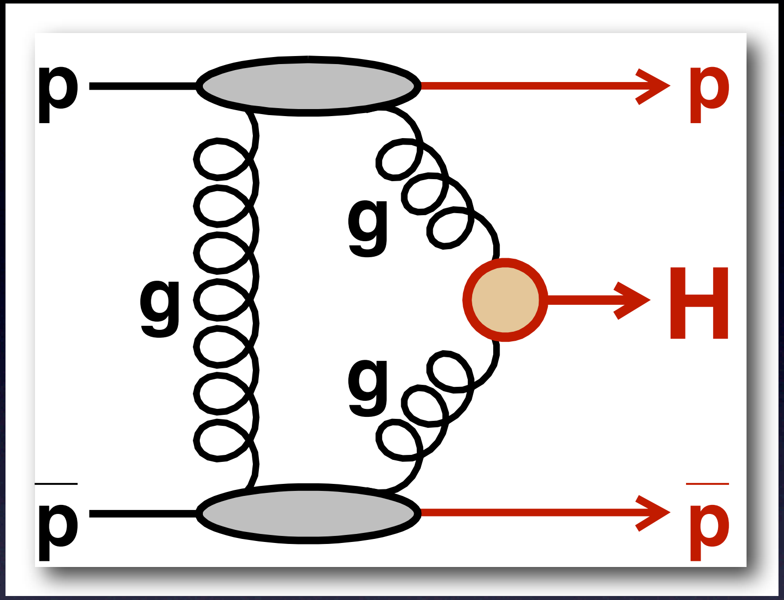
Motivated by unique potential to measure particle state produced in exclusive reaction $\bar{p}p \rightarrow \bar{p}Xp$



- $J^{PC} = 0^{++}$ state due to Jz = 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 < 2~3 GeV using missing mass method: $M_H = (p_{in} + \bar{p}_{in} - p_{out} - \bar{p}_{out})^{1/2}$

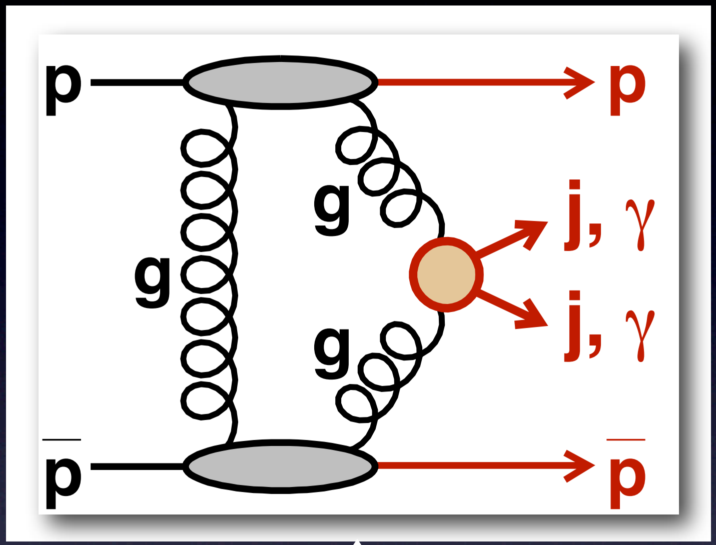
SM Higgs boson (M_H=120 GeV):

$\sigma(pp \rightarrow pHp)$ < 0.1 fb at Tevatron, = 1~10 fb at LHC

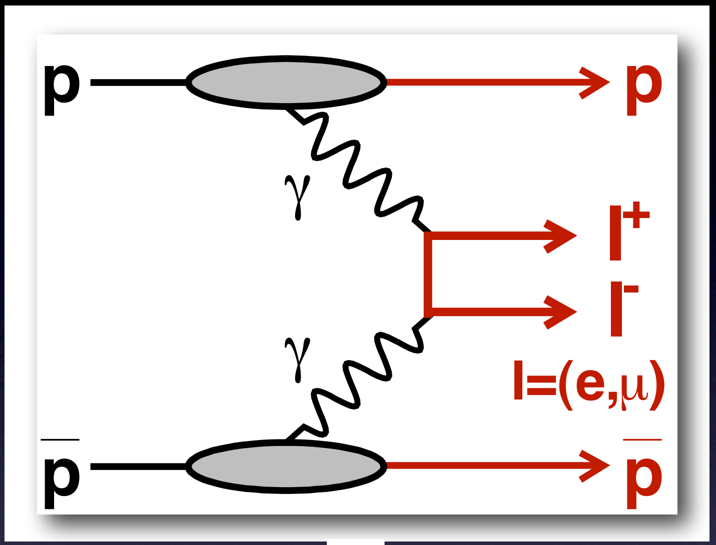
➡ Calibrate theoretical calculations using exclusive processes with higher cross sections

Exclusive Production at CDF

Exclusive Di-jet/Di-photon



Exclusive Di-lepton



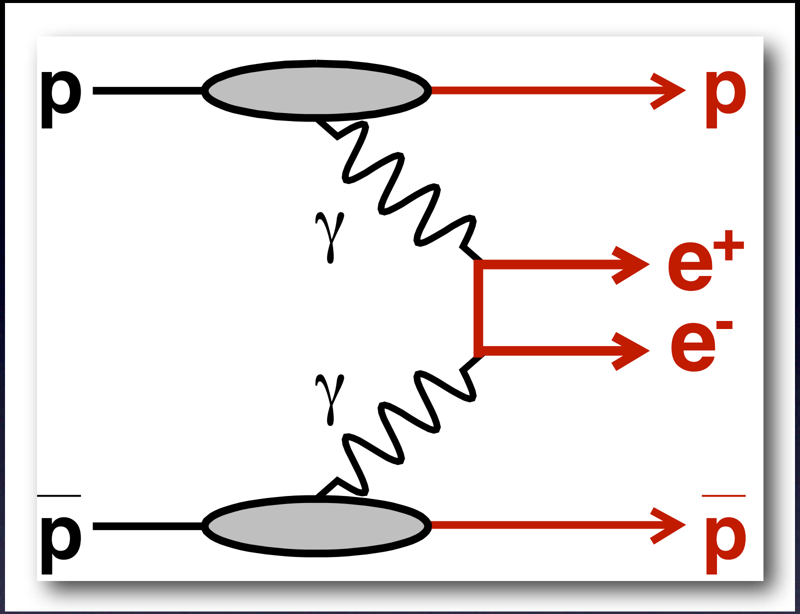
- QED-mediated process
- Cross section well known (< 1%)

Validate analysis method

Potential to improve LHC luminosity measurements

Exclusive e^+e^- Production

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

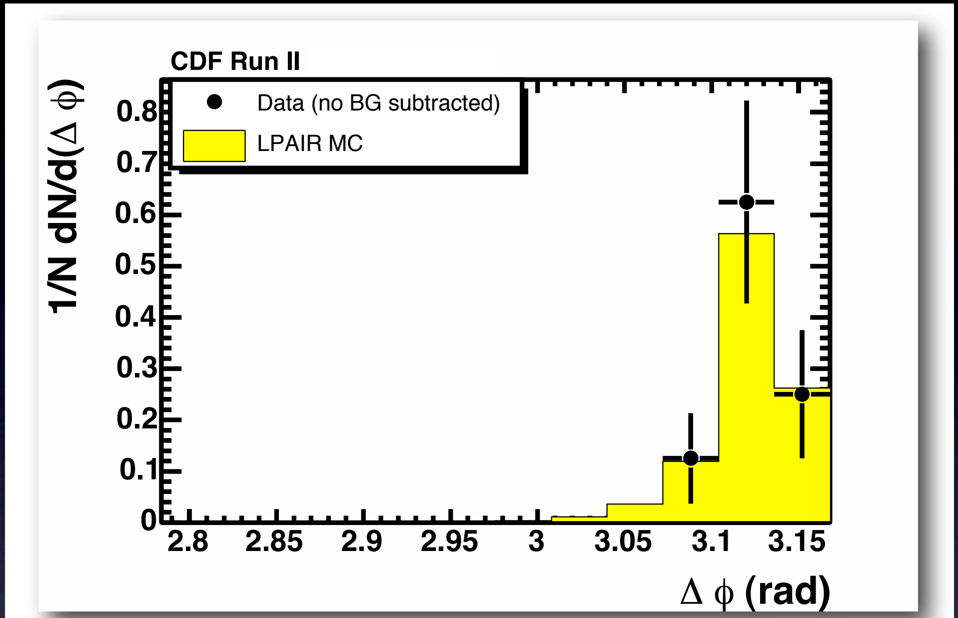


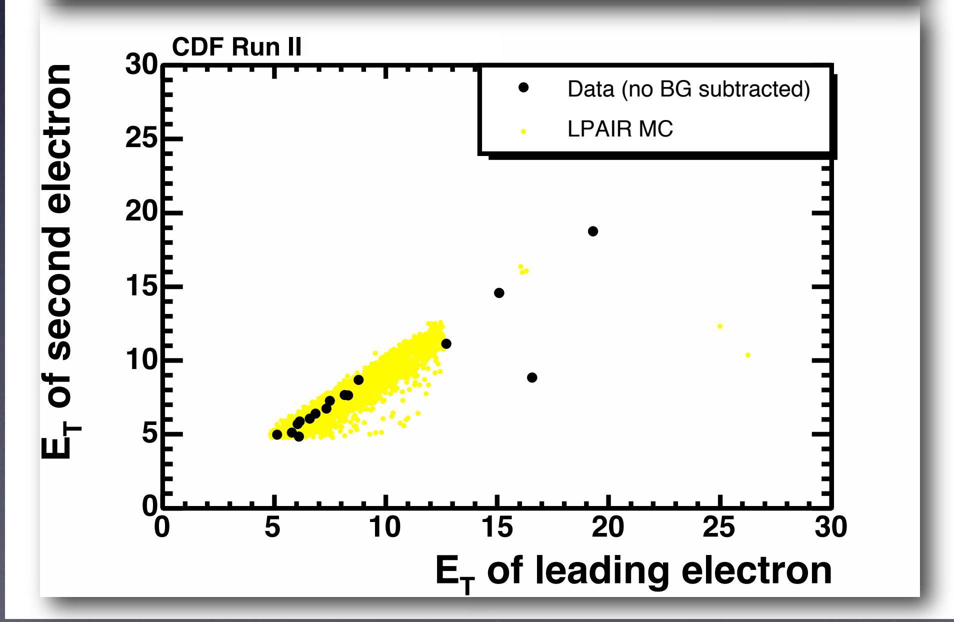
Analysis requires
- protons do not dissociate
- only e^+e^- produced (E_T>5GeV, $|\eta|$<2) and nothing else

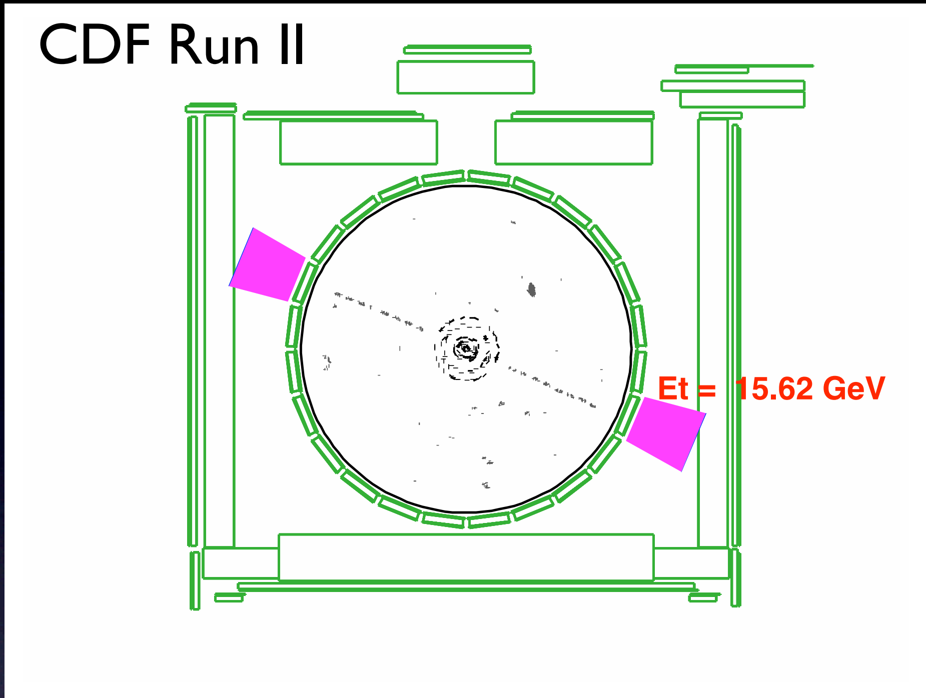
Detailed analysis performed to set thresholds for each detector
Effective Luminosity : 46±3 pb^{-1} (out of 532 pb^{-1})

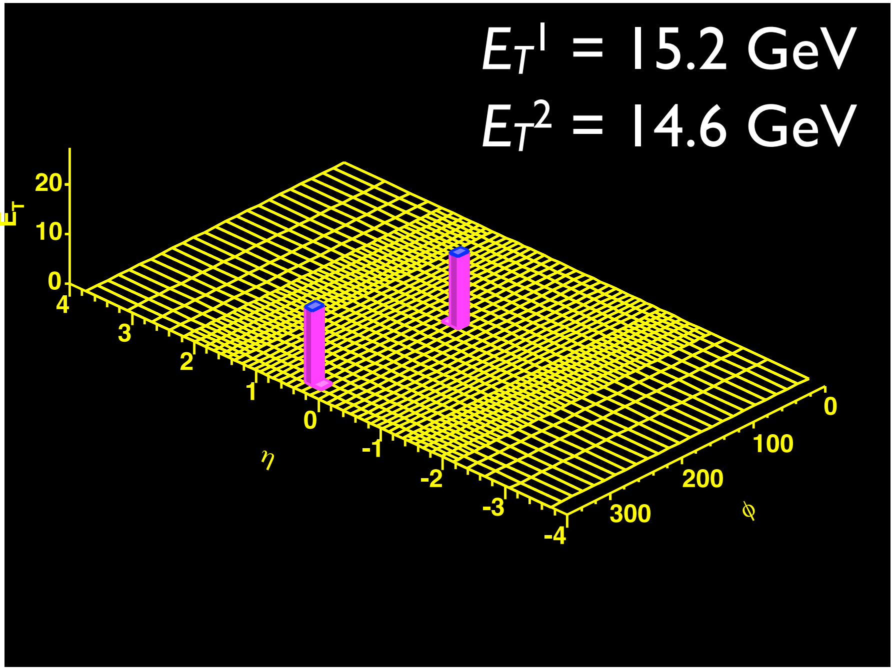
Exclusive e^+e^- Production

16 candidate events observed

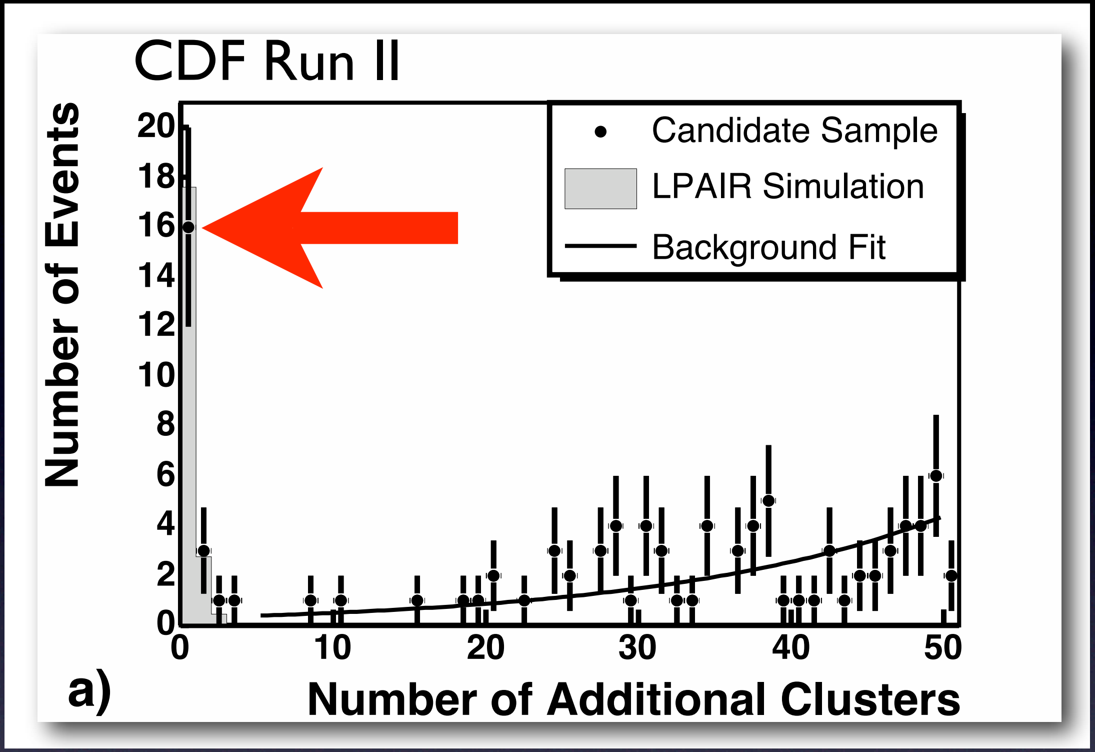








Exclusive e^+e^- Production



PRL 98, 112001 (2007)

16 candidate events

Background: 1.9±0.3 events

➡ 5.5σ observation

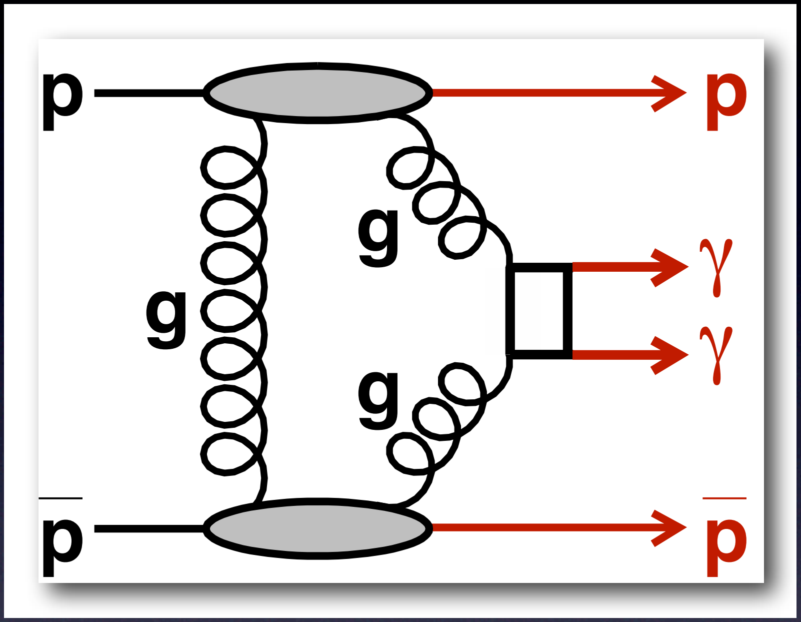
$\sigma_{MEAS.} = 1.6\ ^{+0.5}_{-0.3}(\text{stat}) \pm 0.3(\text{syst})$ pb

agrees with LPAIR Monte Carlo (QED) prediction

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

➡ Good agreement serves to validate analysis method

Exclusive Di-photon Production



Gluon exchange process

➡ factor 3~4 uncertainty in σ

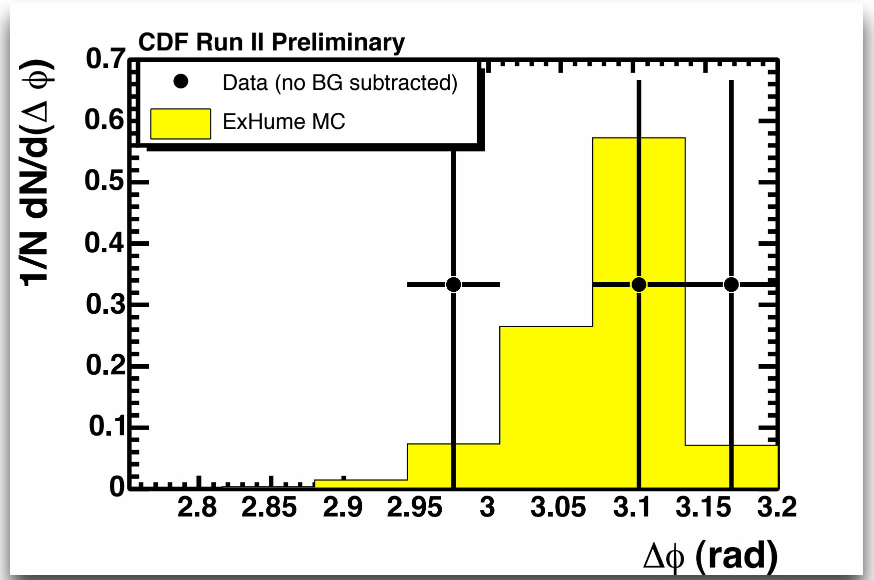
- Can be used to calibrate exclusive Higgs cross section

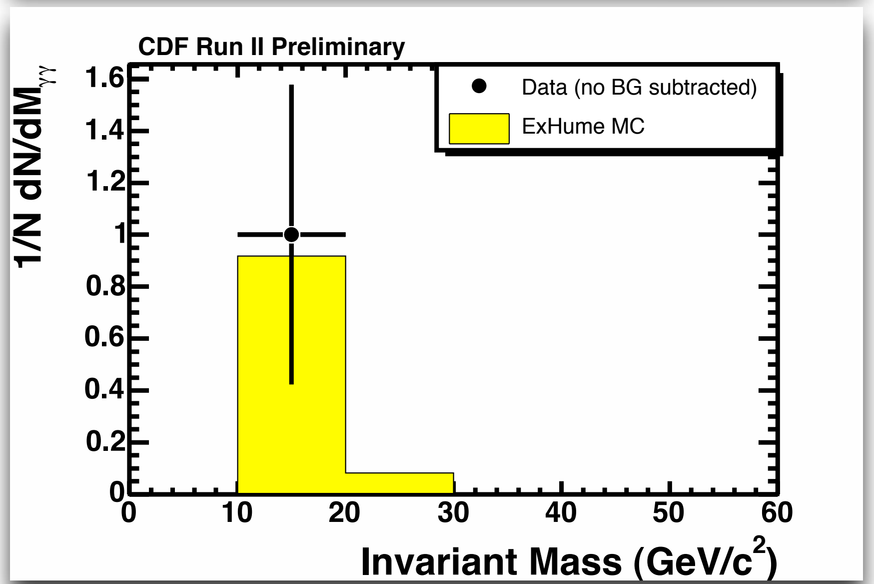
Analysis requires

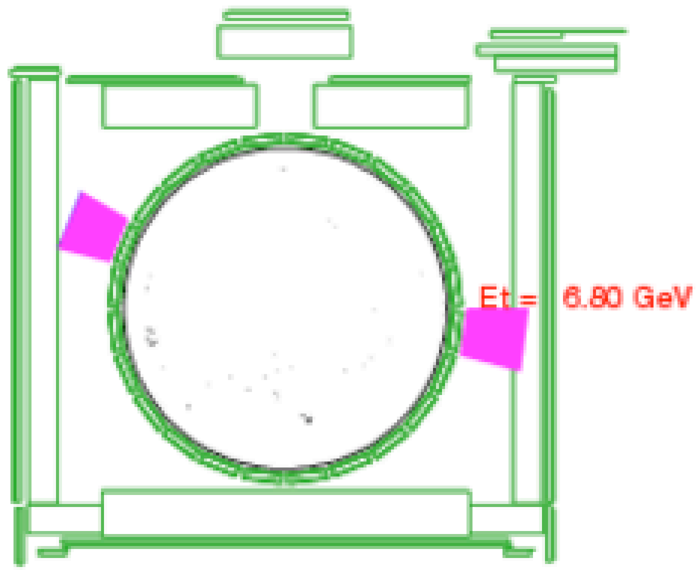
- same event selections as $\bar{p}p \rightarrow \bar{p}eep$ (except e_{track} veto)
- only γγ produced (E_T>5GeV, |η|<1) and nothing else

Exclusive Di-photon Production

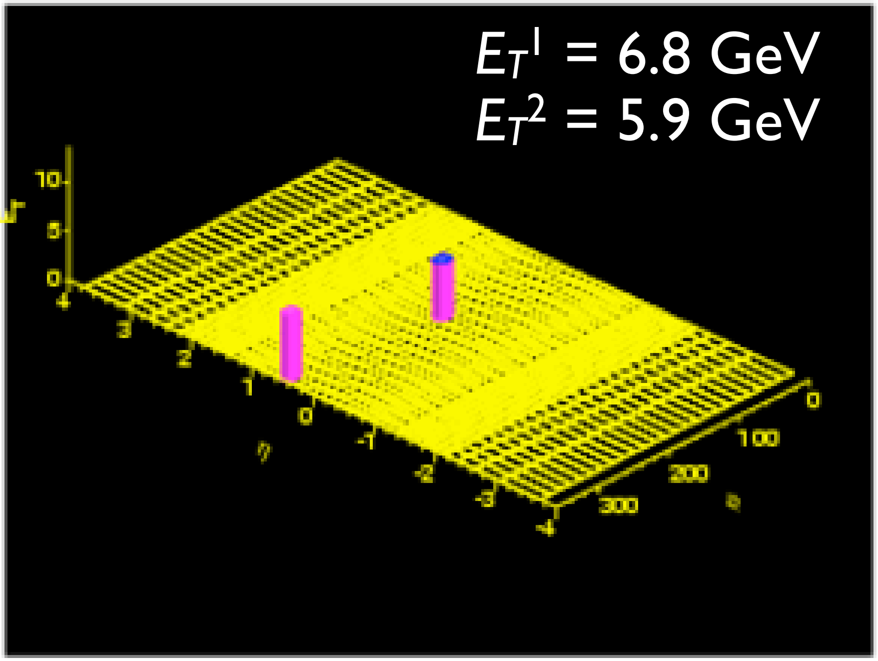
3 candidate events observed







CDF Run II Preliminary



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±0.04 events

➡ 3.7σ 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 fb (95% C.L.)

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

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

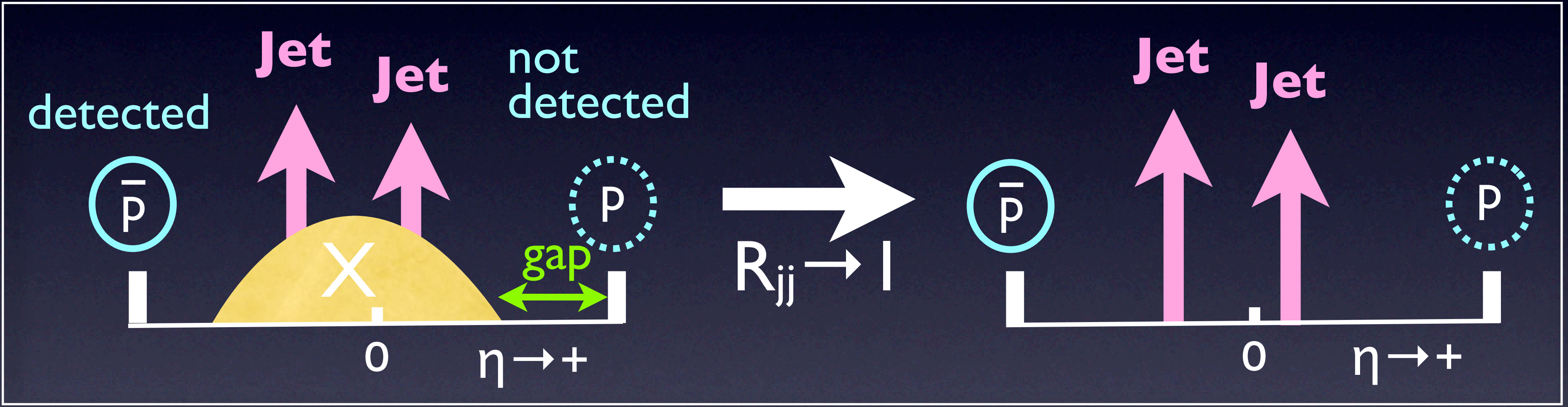
$\sigma(\bar{p}p\rightarrow\bar{p}\gamma\gamma p) = 90\ ^{+120}_{-30}(\text{stat}) \pm 16(\text{syst})$ fb

→M. Albrow's talk

Exclusive Di-jet Production

Strategy

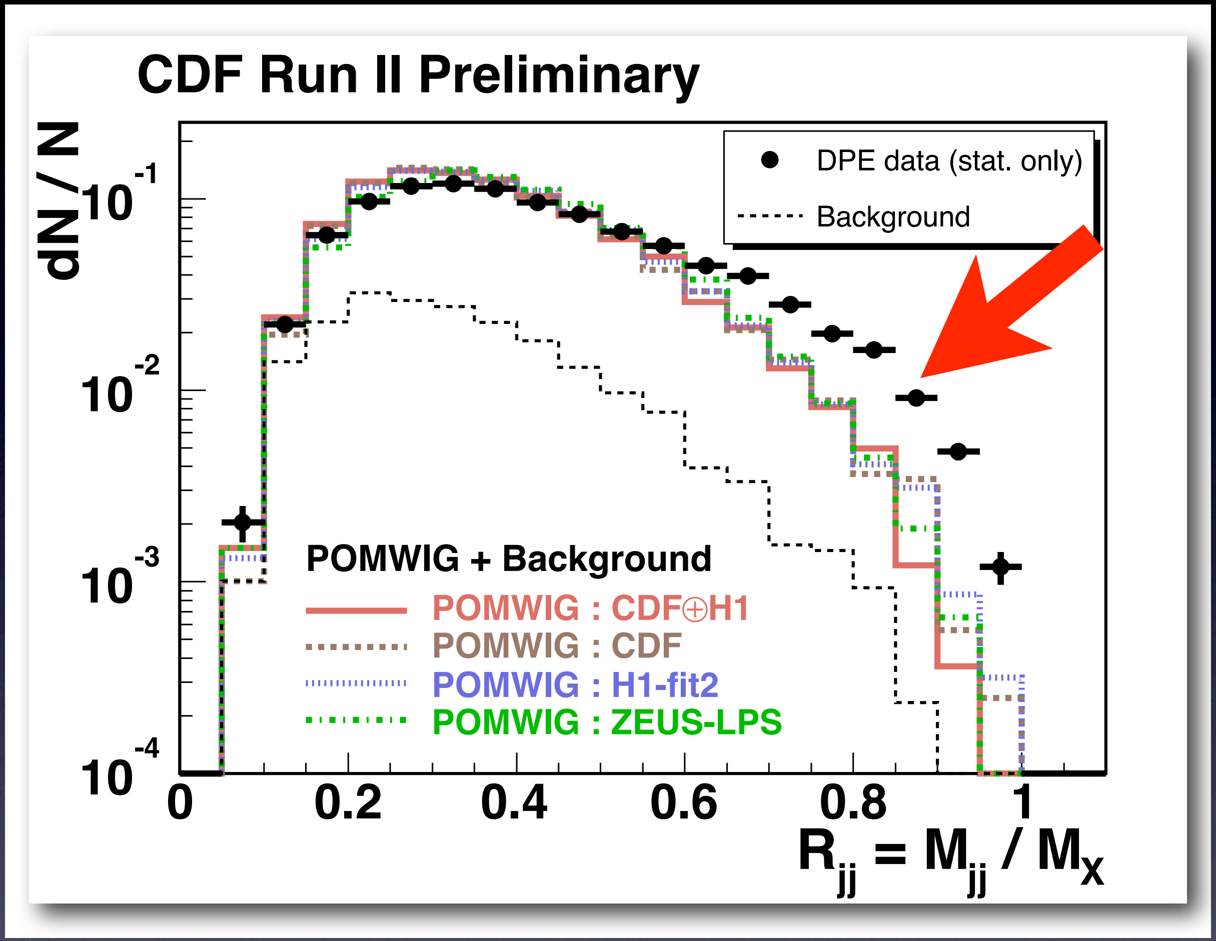
- Select inclusive DPE di-jets : $\bar{p}+p \rightarrow \bar{p}+X(\ni 2\text{jets})+\text{gap}$
- Reconstruct di-jet mass fraction : $R_{jj} = M_{jj}/M_X$
- Look for data excess over DPE di-jet background as $R_{jj} \rightarrow 1$

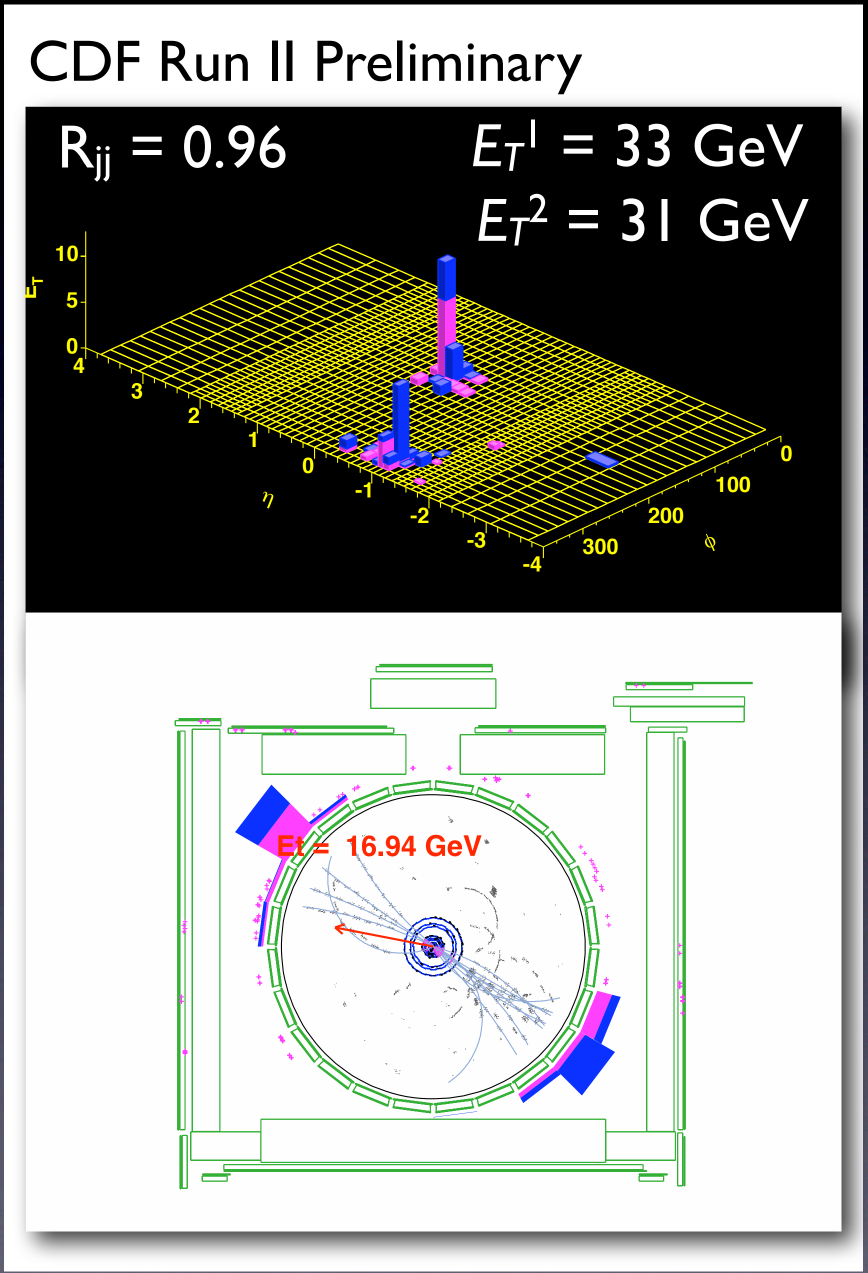


➡ Signal (R_{jj}=1) smeared due to shower/hadronization effects, NLO $gg \rightarrow ggg$, $q\bar{q}g$ contributions, etc.

➡ DPE di-jet background shape from POMWIG MC simulation (⇒ Uncertainty from Pomeron PDF)

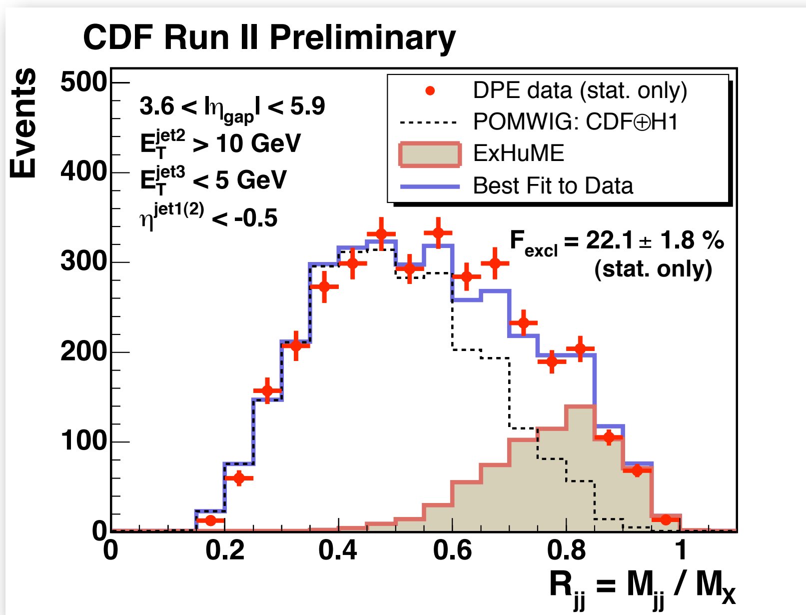
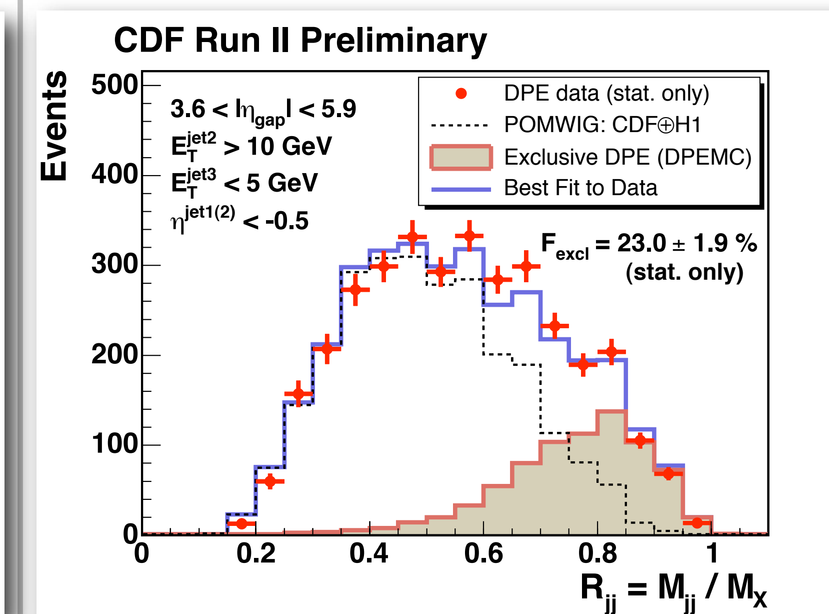
Di-jet Mass Fraction





Excess observed over MC simulations with varied PDFs

MC Fit to R_{jj} Shape

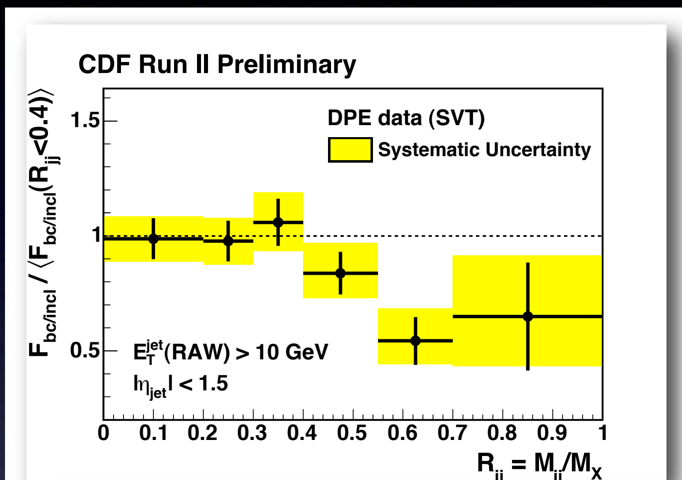
Binned likelihood fits (MC normalizations as free parameters)		
Signal MC	ExHuME CPC 175,232(2006)	Exclusive DPE (DPEMC) CPC 167,217(2005)
data bkgd signal fit		
CDF⊕H1	22.1±1.8 %	23.0±1.9 %
CDF	21.7±1.8 %	22.6±1.9 %
H1-fit2	24.7±2.0 %	26.0±2.1 %
ZEUS-LPS	24.3±2.0 %	25.4±2.1 %

stat. error only

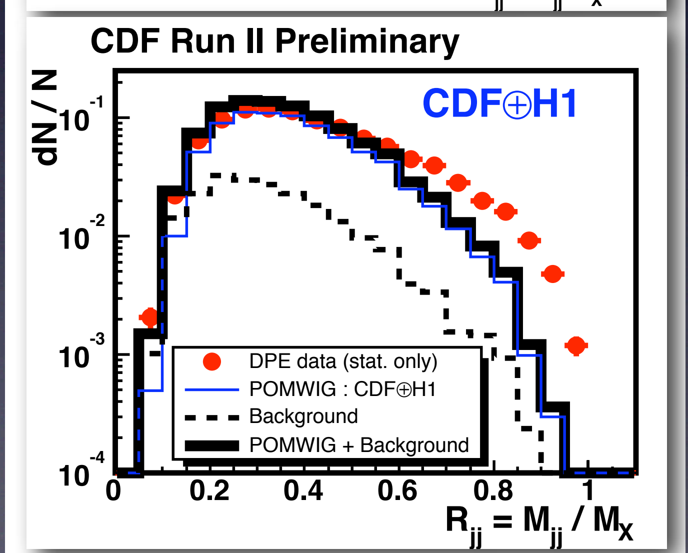
Exclusive Di-jet Signal

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

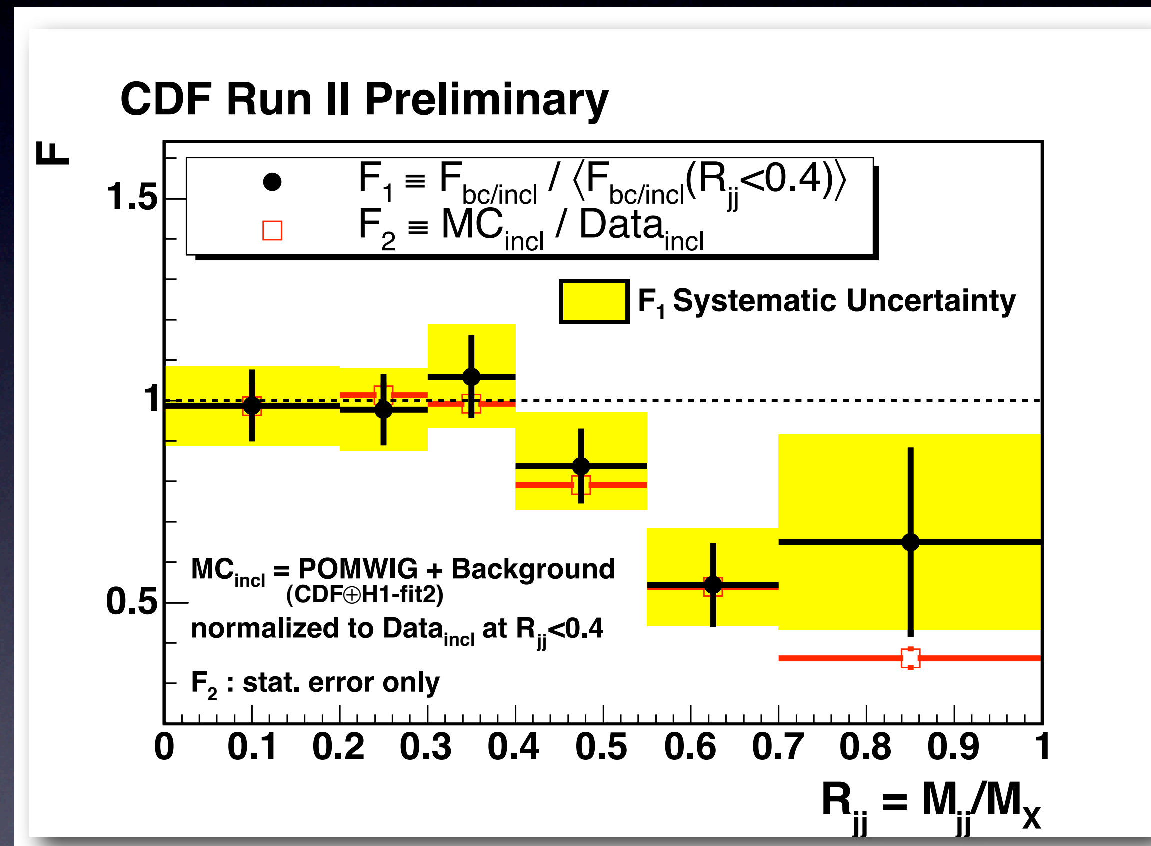
➡ Look for the suppression in heavy flavor jet fraction vs R_{jj}



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

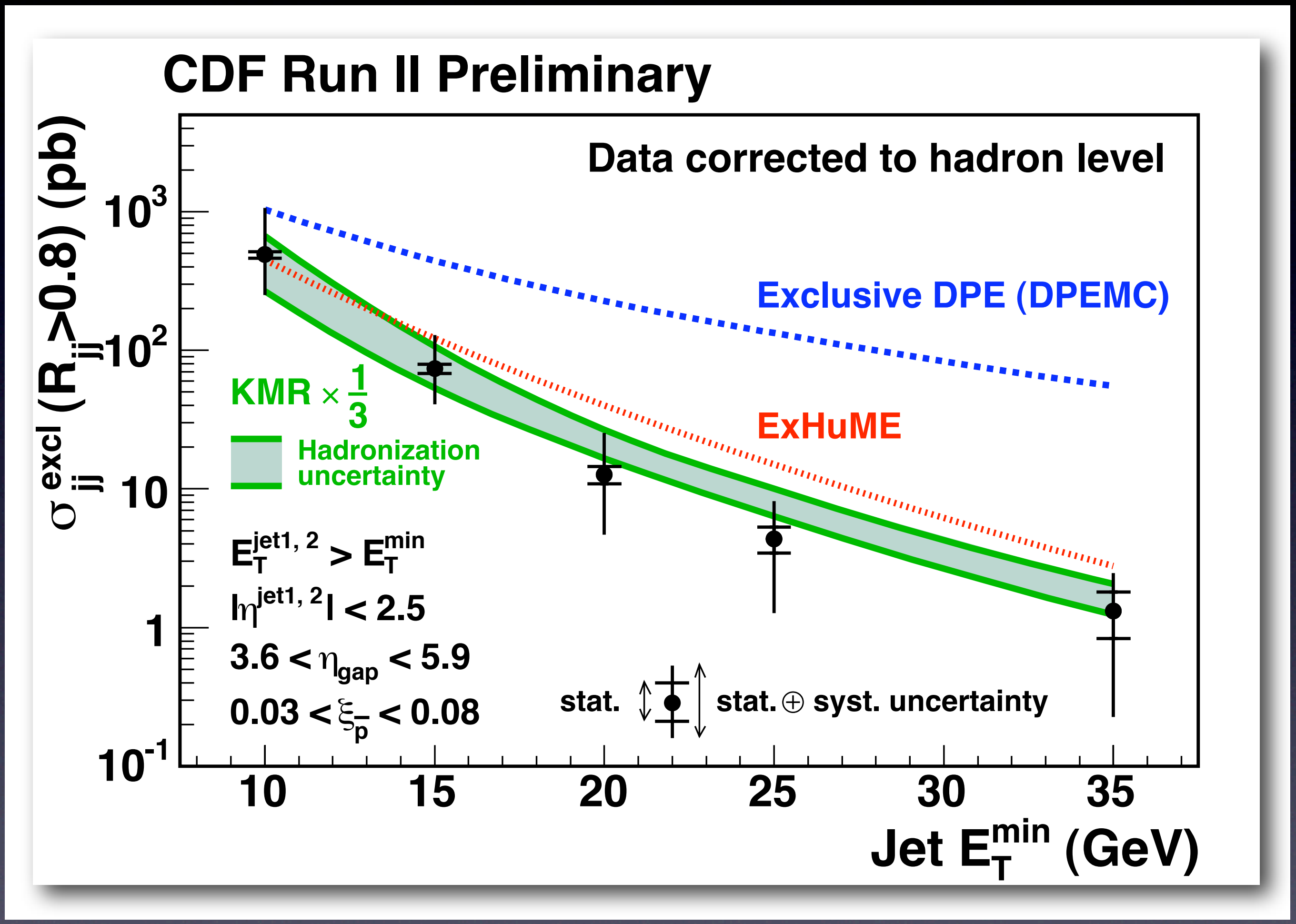


$\frac{incl_{MC}}{incl_{data}}$



The two results are consistent with each other

Exclusive Di-jet Cross Section



Exclusive DPE (DPEMC)

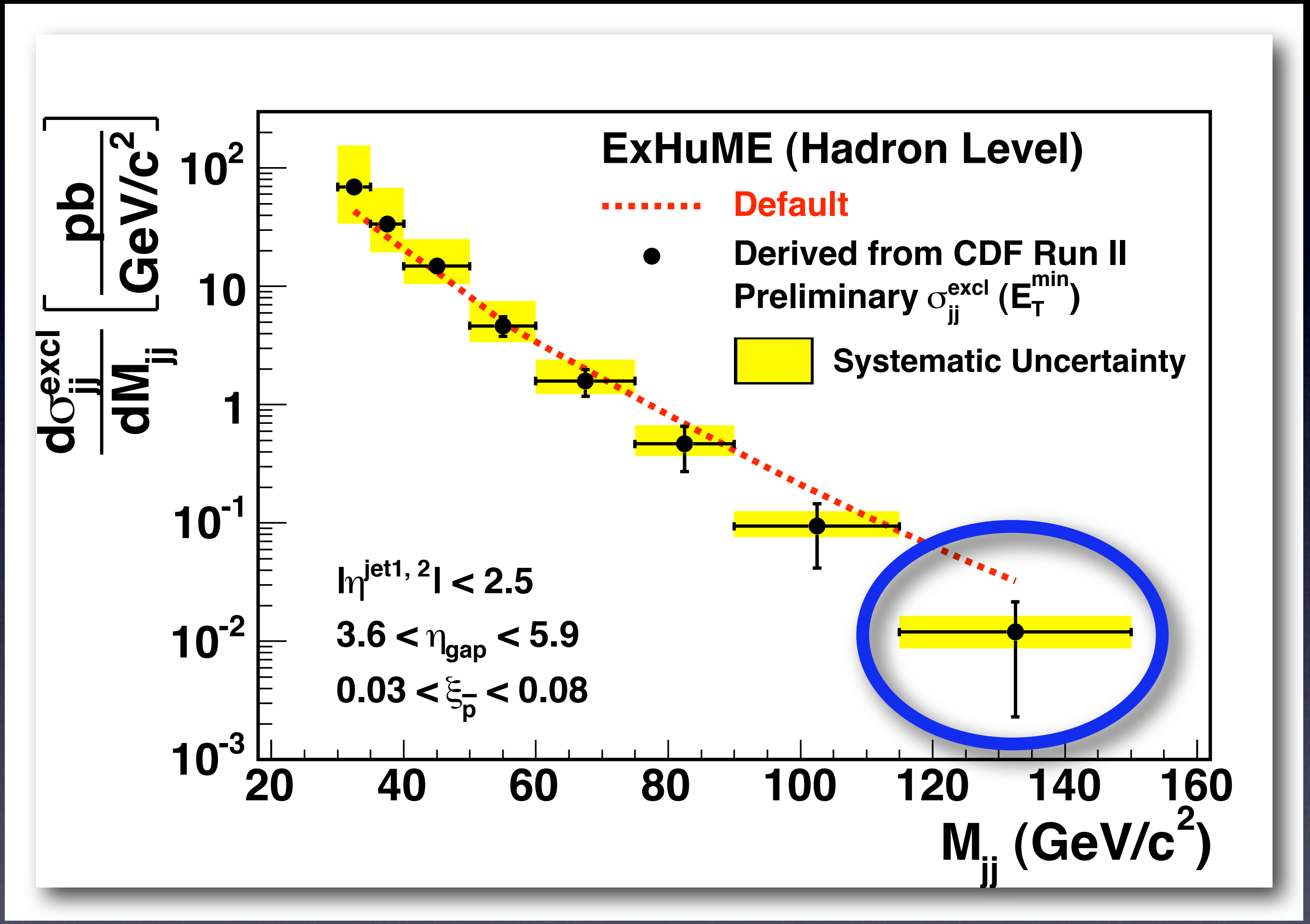
ExHuME

Khoze, Martin, Ryskin
at LO parton-level
(factor 3 uncertainty)
hep-ph/0507040

Measured σ_{jj}^{excl} prefers ExHuME and KMR calculations

Exclusive Di-jet Mass Reach

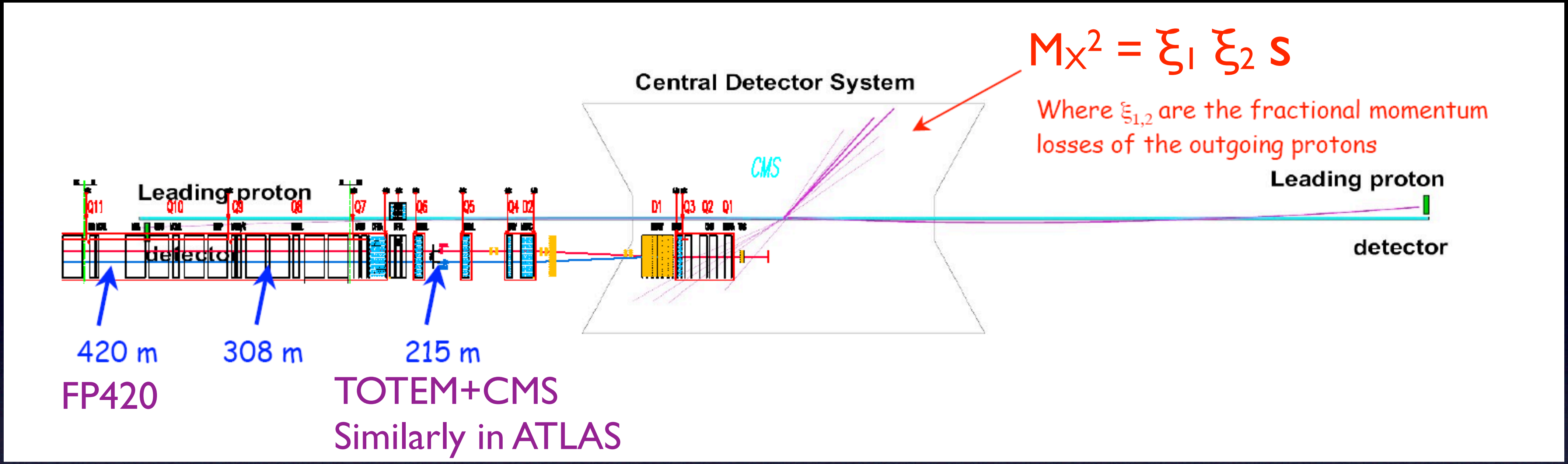
Unfold measured σ_{jj}^{excl} to $d\sigma_{jj}^{excl}/dM_{jj}$ using ExHuME

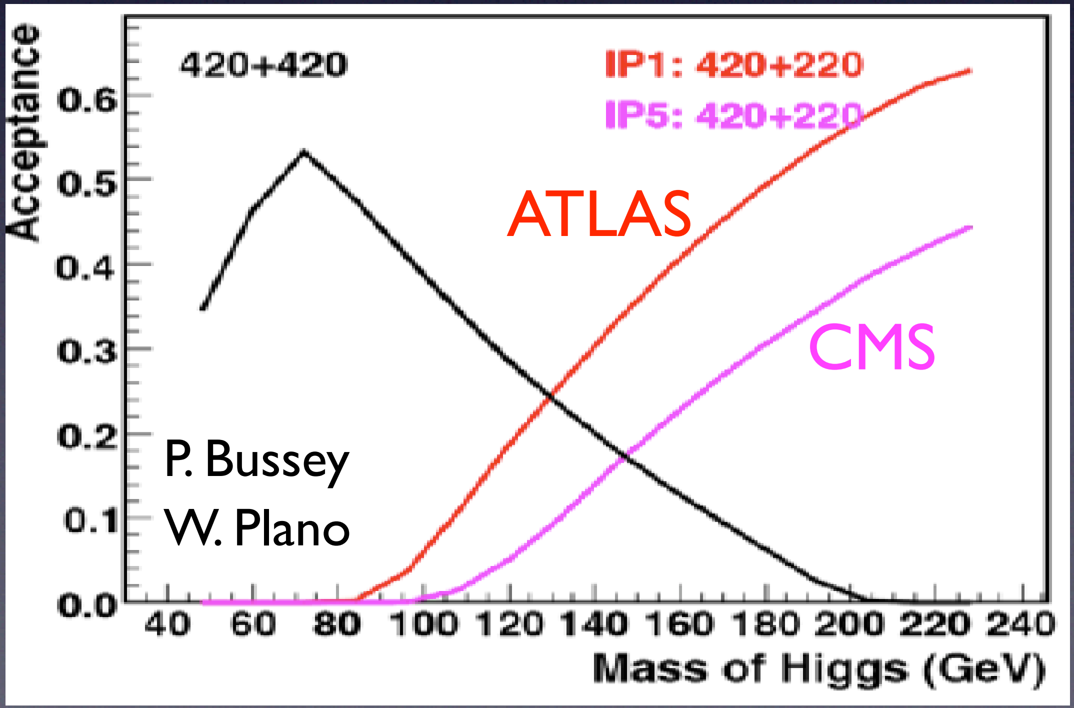


CDF $\bar{p}p \to \bar{p}jjp$ reaches Higgs mass range!!

➡ $pp \to pHp$ at LHC

pp→pHp Acceptance at LHC



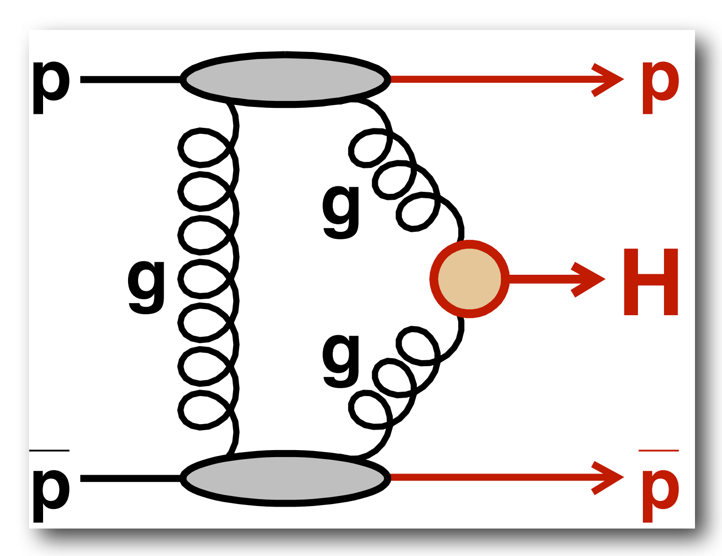


Lum = $10^{33\text{-}34}$ cm^2 (Low β^*)

Acceptance	ξ	M_X (GeV)
220m+220m	0.02-0.2	200-2000
420m+420m	0.002-0.02	30-200

⇒ FP420 project

Exclusive Higgs→WW$^{(*)}$ at LHC



- H→WW$^{(*)}$ for M_H=135-200 GeV
- M_H resolution ~ 2 GeV (any W decay) by tagging forward protons

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

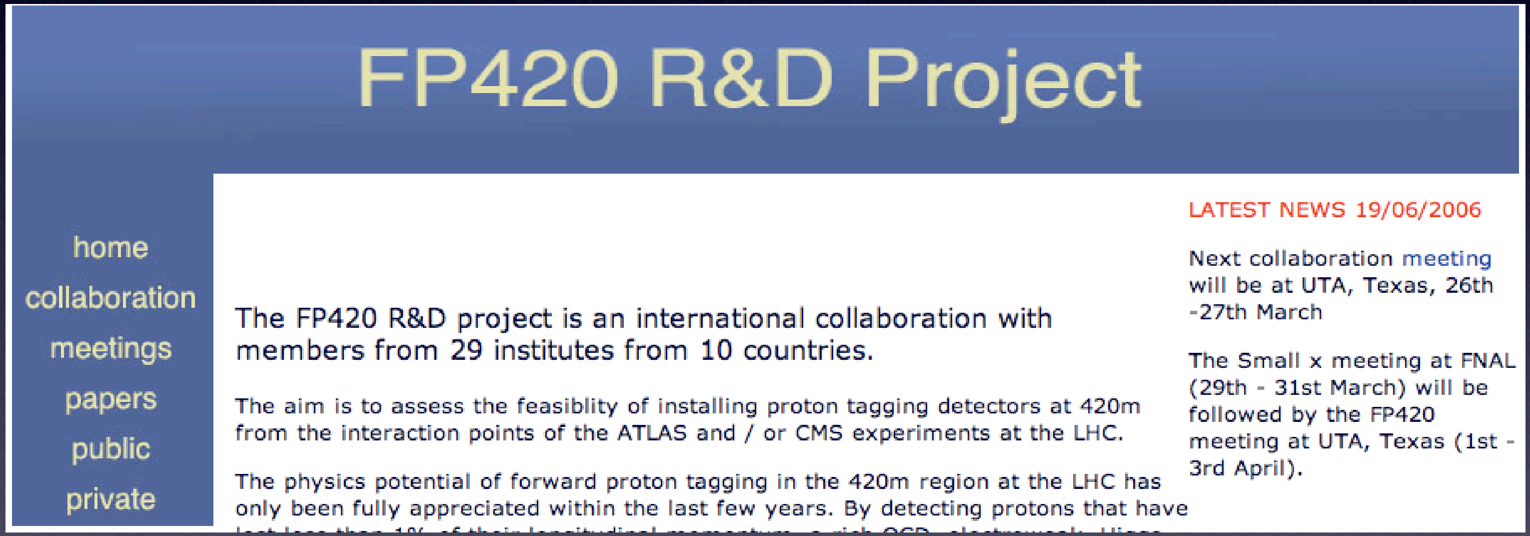
M_H (GeV)	120	140	160
H→WW$^{(*)}$→lνjj (fb) proton tagger acceptance	0.25	0.63	0.83
#Events at 30 fb^{-1} ATLAS lepton trigger	1.1	3.6	5.8

"Very small backgrounds" (continuum within ΔM_H)

FP420 Project

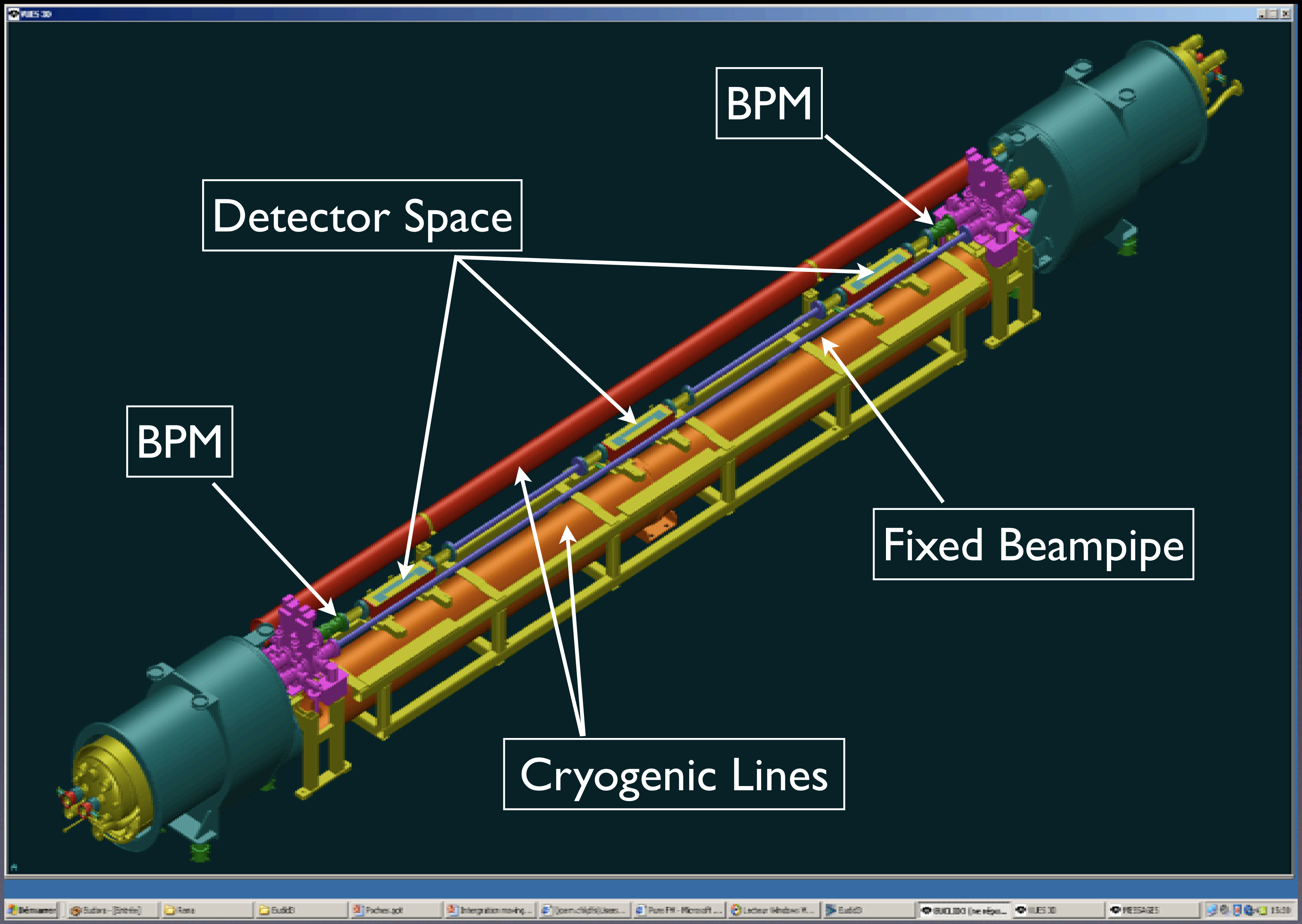
Feasibility study and R&D for the proton detector at 420m from the IP in normal high luminosity running

www.fp420.com



- R&D fully funded
- Aim is to install detectors in Fall 2008

Mechanics at 420m



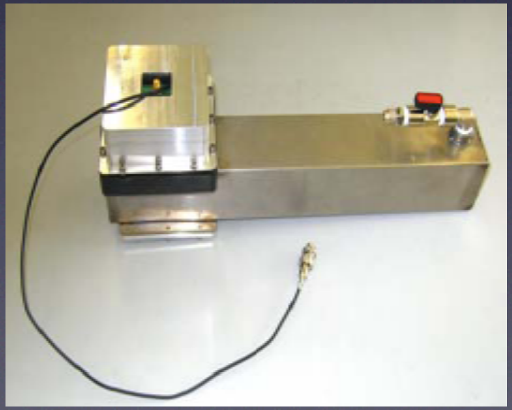
Silicon Detectors

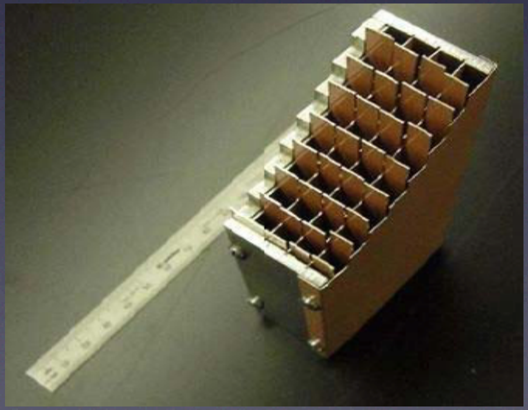
Test beam at CERN in Sep 2007

Fast Timing Detectors

Reject pile-up backgrounds by measuring Z_{vertex} using time-of-flight information

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