Diffractive Structure Function and Exclusive Final States at CDF

Results and Prospects

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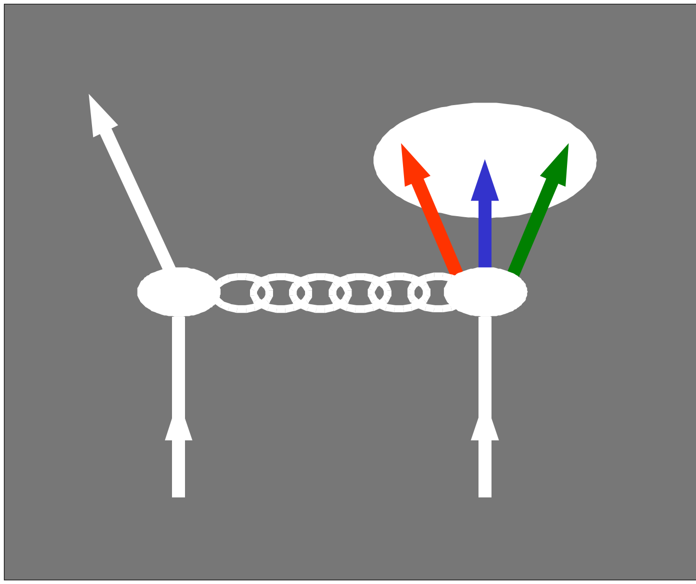
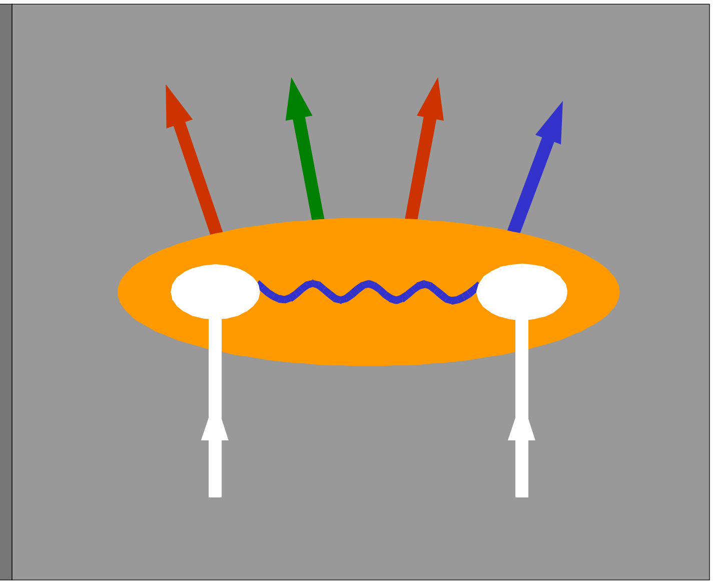
$\bar{p}$-p Interactions

Diffractive: vacuum exchange	Non-diffractive: color exchange





Protons retain their quantum numbers

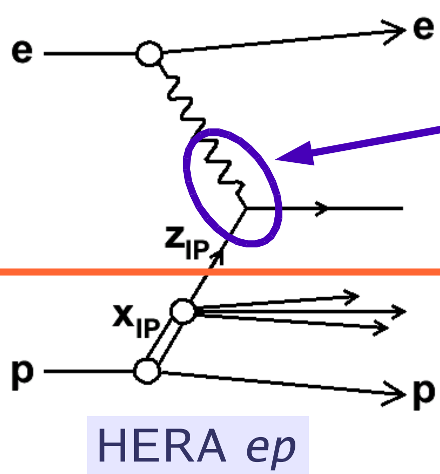
Protons acquire color and break apart

GOAL :

understand the nature of the colorless exchange

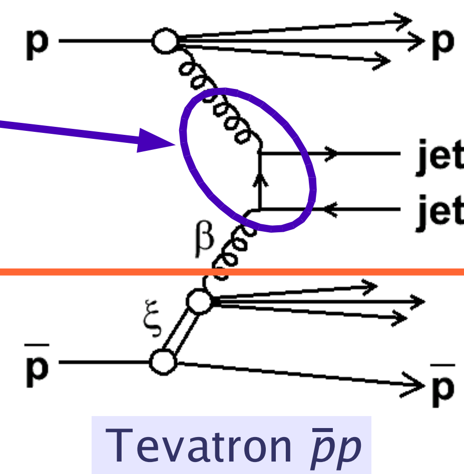
Factorization and Diffraction

QCD factorization : $\sigma(\bar{p}p \to \bar{p}X) \approx F^{D}_{a/\bar{p}}(\xi, t; \beta, Q^2) \otimes \hat{\sigma}(ab \to jj)$

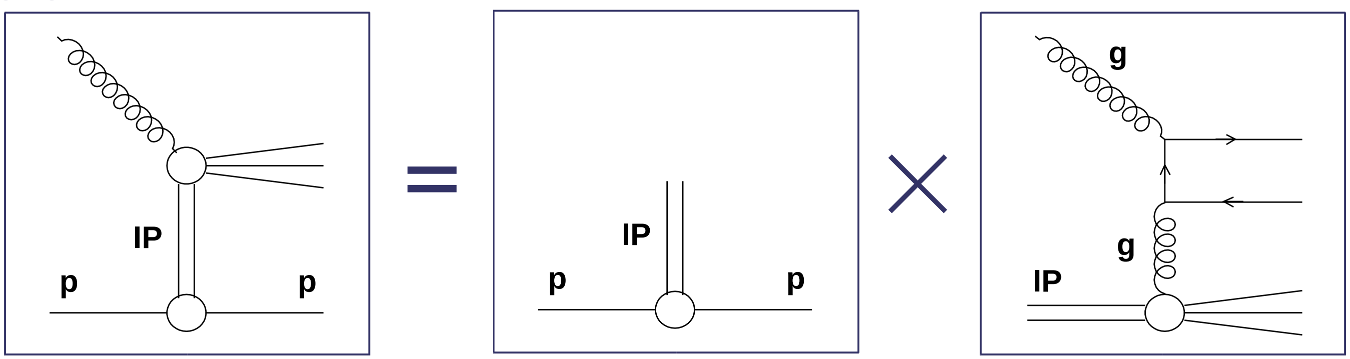


- Hard scattering
  QCD matrix element
- Process dependent

Universal parton densities in diffractive exchange ?



Regge factorization :

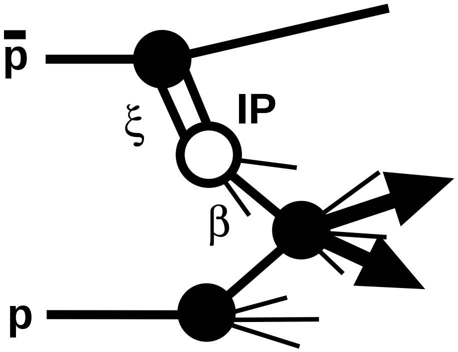


$\beta = P_{parton} / P_{Pomeron}$

$\xi = P_{Pomeron} / P_{proton}$

$$F^{D}_{a/\bar{p}}(\xi, t; \beta, Q^2) \approx \underbrace{f_{IP/\bar{p}}(\xi, t)}_{\text{Regge-based Pomeron Flux}} \otimes \underbrace{F_{a/IP}(\beta, Q^2)}_{\beta\text{-dependence of Pomeron structure}}$$

Diffractive Structure Function in Dijets



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

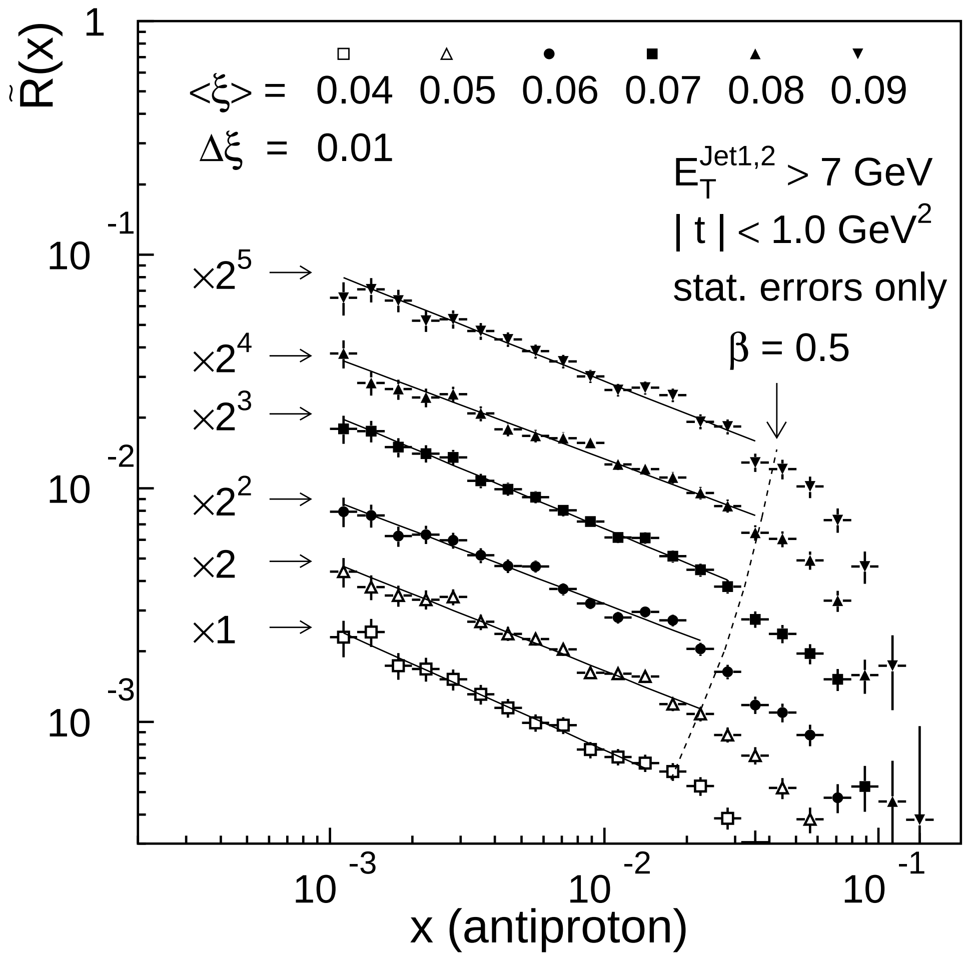
$$\mathrm{SD}: \quad \frac{d\sigma^4(SD_{jj})}{dx_p\,dx_{\bar p}\,d\xi\,d\hat t} = F_{jj}(x_p, Q^2)\,F^D_{jj}(x_{\bar p}, \xi, Q^2)\,\frac{d\hat\sigma(ab\to jj)}{d\hat t}$$

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

Experimental Measurement of F^D_{jj}

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

Measure — Known LO PDF

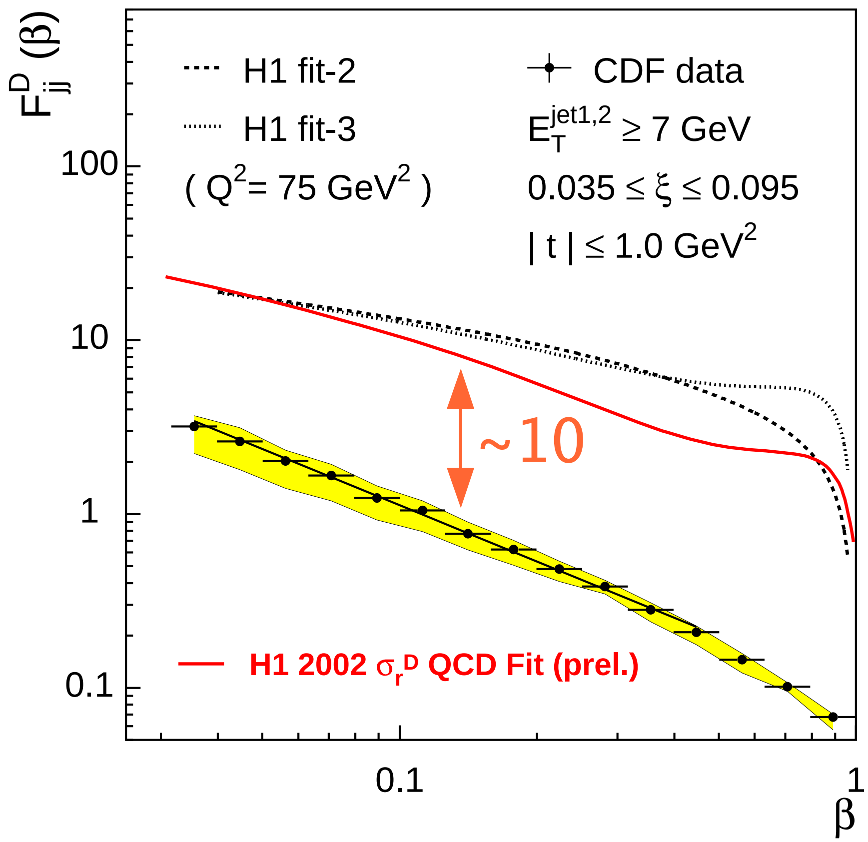


parton $x = \beta\xi$

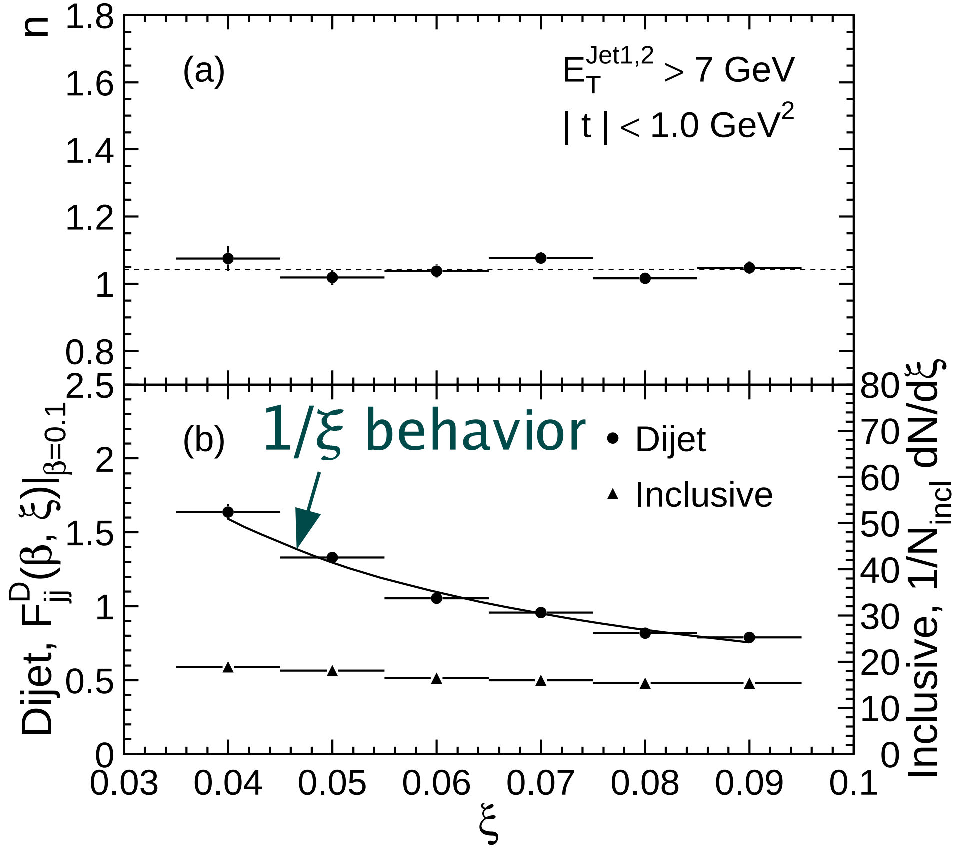
$$F^D_{jj}(x,\xi,Q^2) \;\Rightarrow\Rightarrow\Rightarrow\; F^D_{jj}(\beta,\xi,Q^2)$$

F_{jj}^{D} measured using SD Dijets

Test QCD Factorization



Test Regge Factorization



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

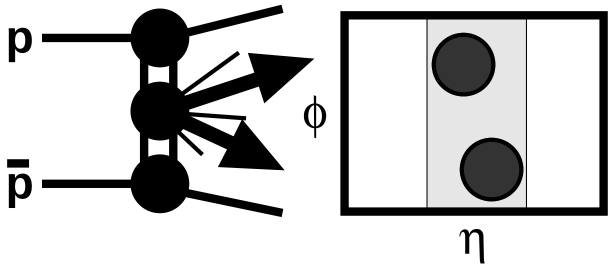
➔ QCD factorization breakdown

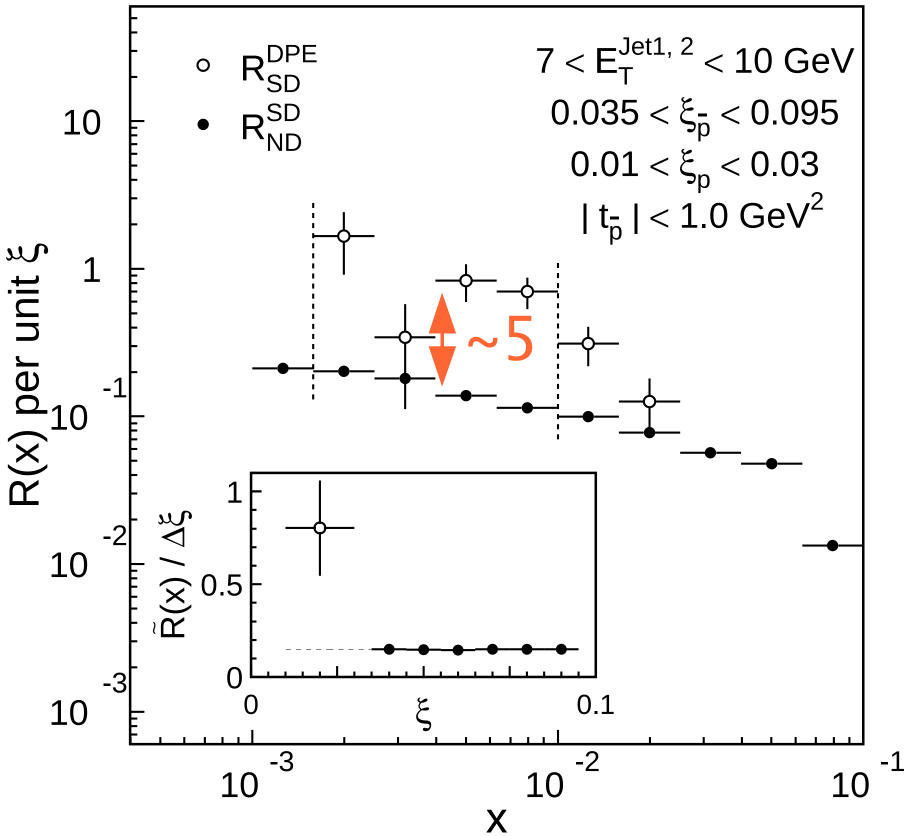
$$F_{jj}^{D}(\beta,\xi) = C\,\beta^{-n}\,\xi^{-m}$$

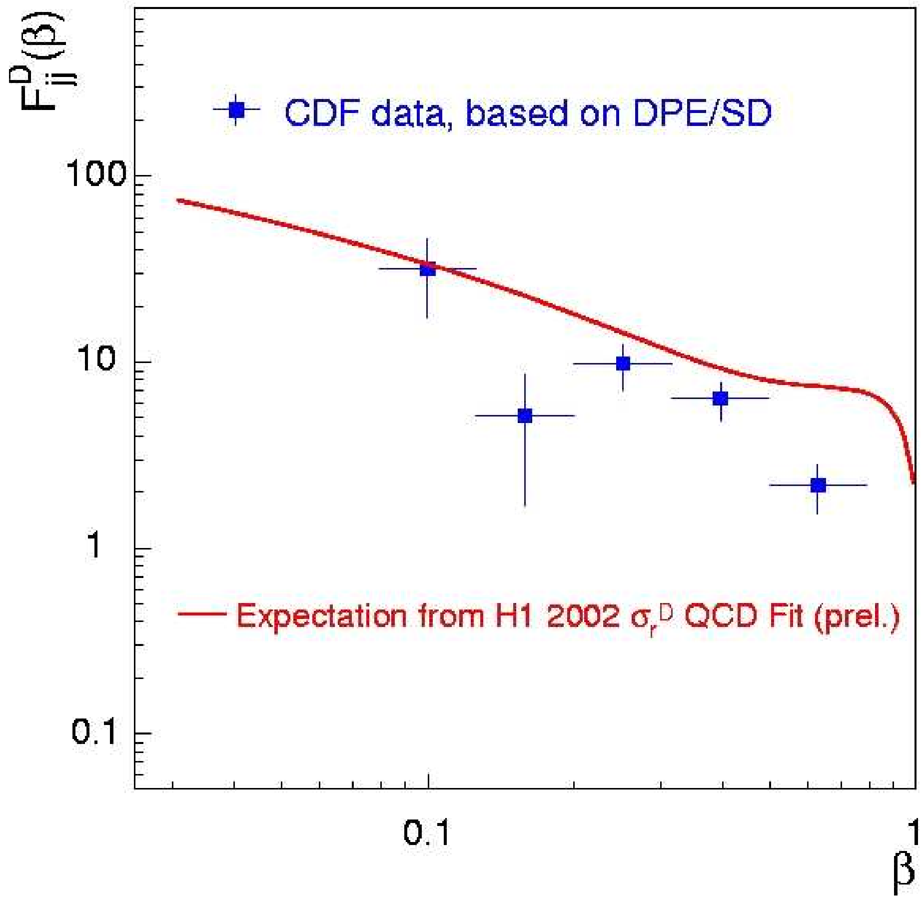
Regge factorization holds

$m=0.9\pm0.1$ → Pomeron exchange

F_{jj}^{D} measured using DPE Dijets







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

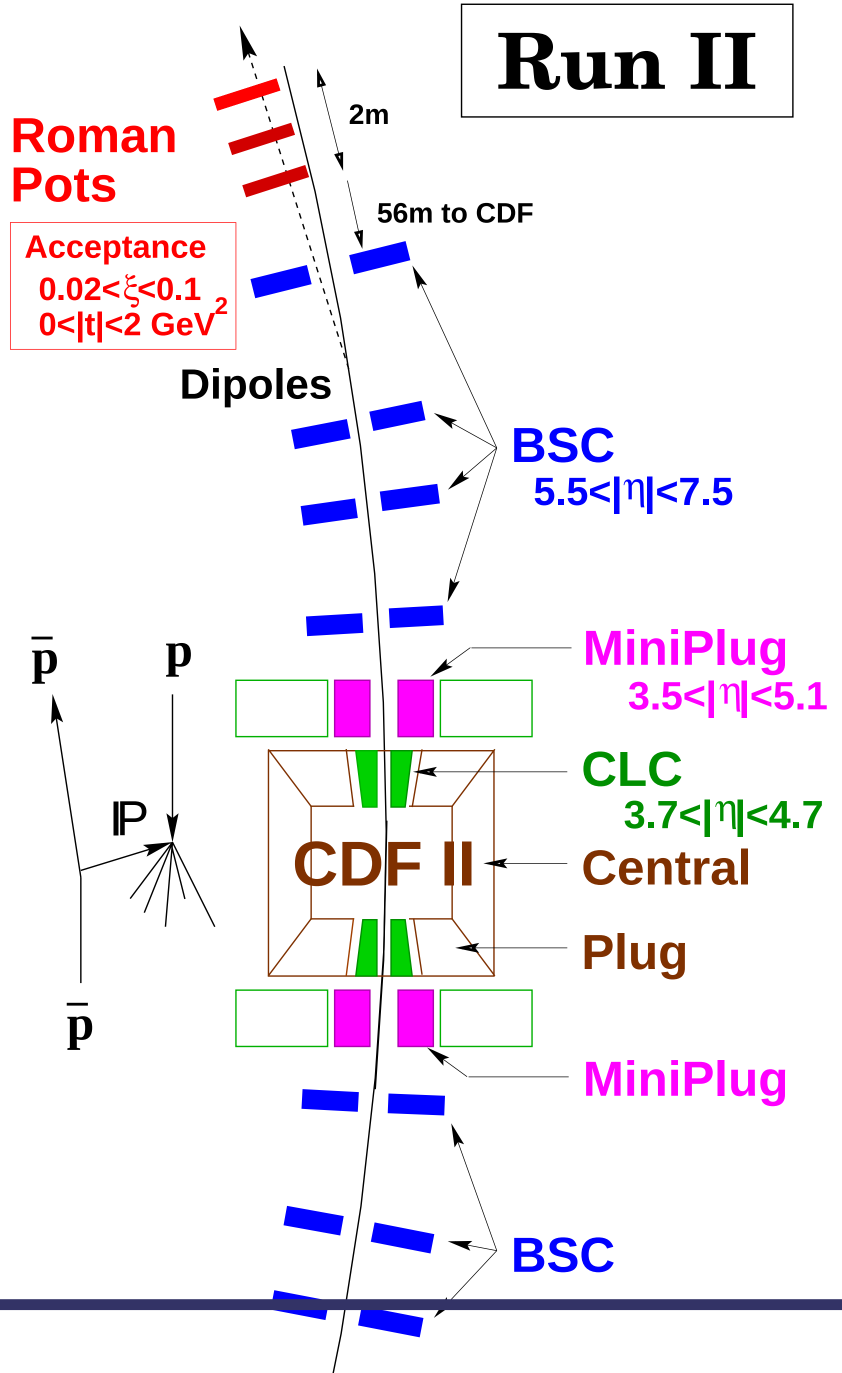
Factorization breakdown, but!

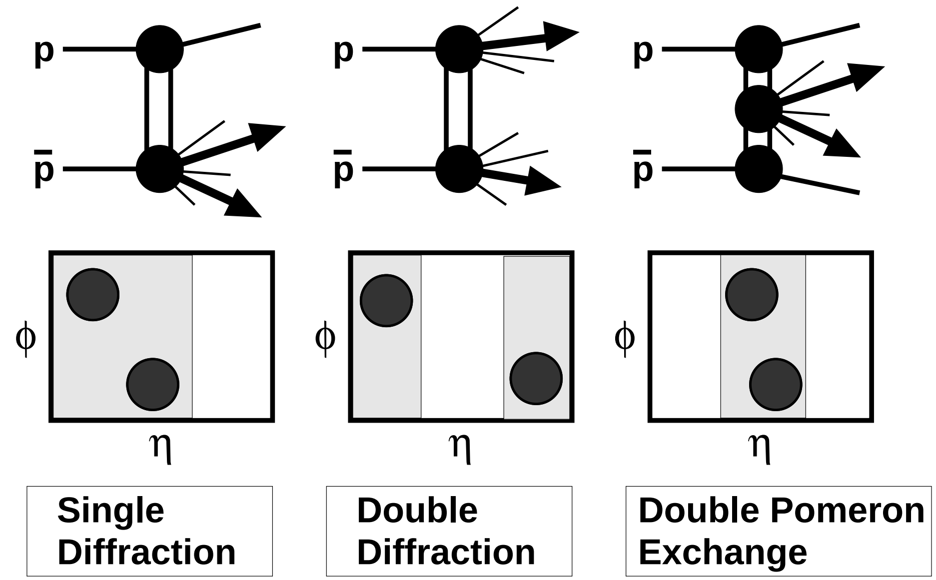
$F_{jj}^{D}(\beta)$ measured using DPE dijets is approximately equal to expectations from HERA!

➔ **Factorization restored?**

CDF II Forward Detectors

Run II





Single Diffraction

- Q^2 and ξ dependence of F_{jj}^D
- F^D in diffractive W and J/Ψ

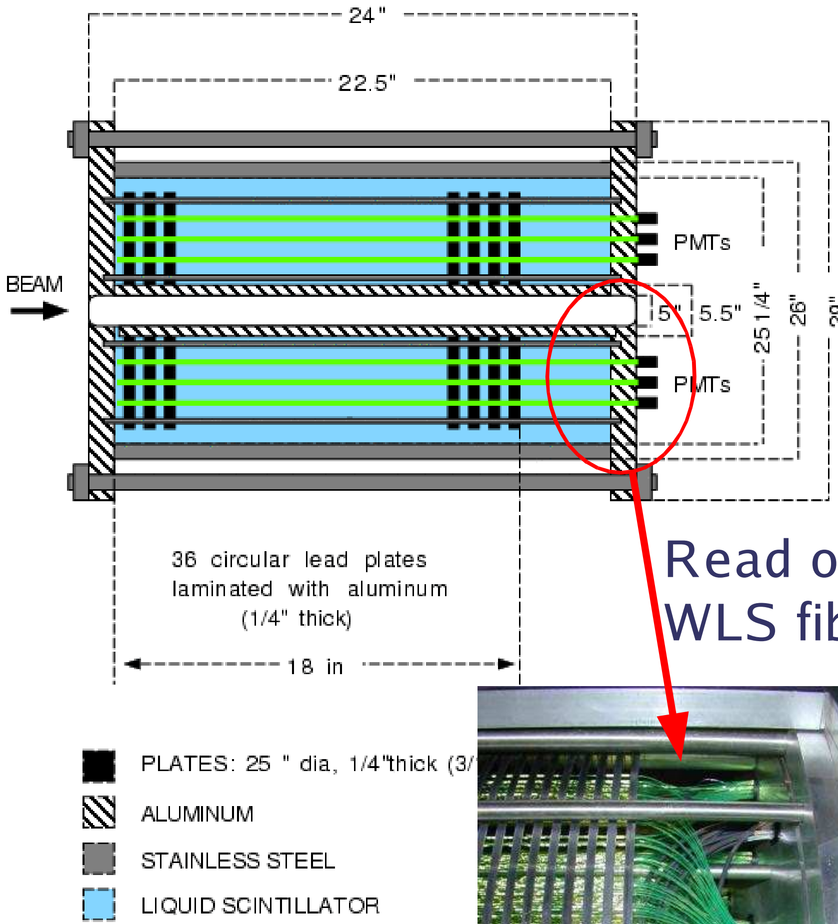
Double Diffraction

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

Double Pomeron Exchange

- F_{jj}^D vs gap width on the other side
- exclusive dijets and $b\bar{b}$
- exclusive χ_c, diphoton, etc.

MiniPlug Calorimeters



$32X_0, 1.3\lambda_I$

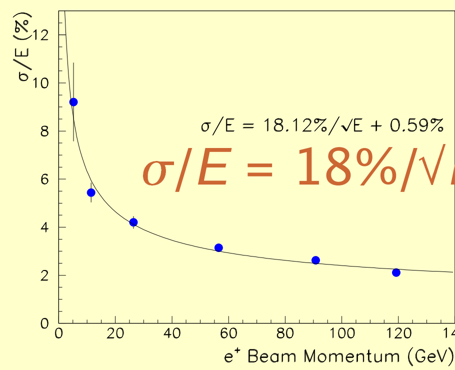
$3.6 < |\eta| < 5.1$

Read out by
WLS fibers

Electromagnetic calorimeter with hadron detection capability

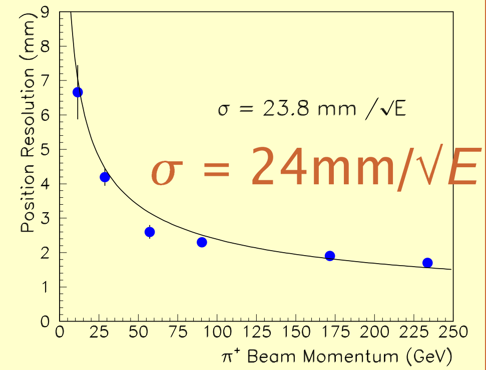
MiniPlug prototype ($28X_0$, $1\lambda_I$)

e^+ energy resolution



$\sigma/E = 18\%/\sqrt{E}$

π position resolution



$\sigma = 24\text{mm}/\sqrt{E}$

Hadronic Showers:

- energy resolution ~ 40%
  (due to large energy fluctuations)
- good position resolution retained by detecting hadrons before they make (big) showers

Run II Diffractive Dijet Sample

J5 : $\geq$1 Cal. Tower with E_T> 5 GeV

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

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

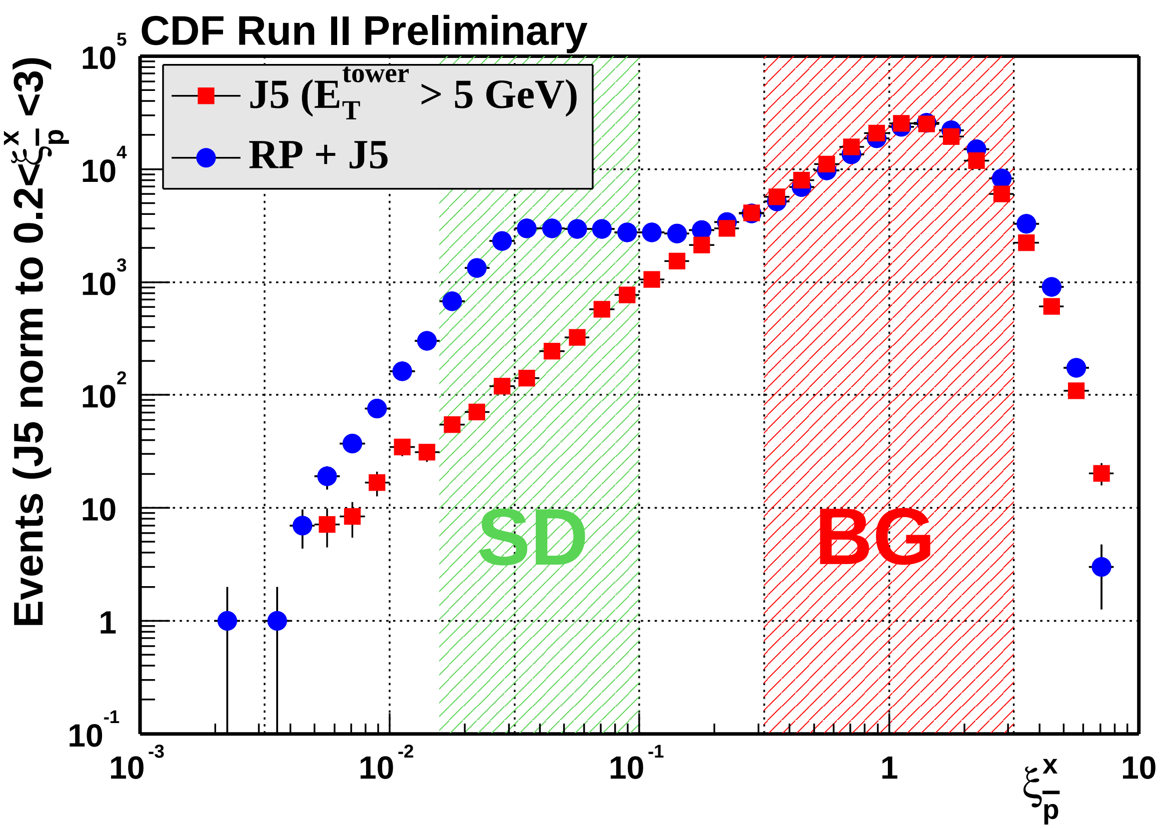
- sum over all particles except antiproton
- use calorimeter towers of E_T >100 MeV
- MiniPlug energy scale: ±25% → $\Delta \log \xi$ = ±0.1

Flat part at ξ < 0.1:

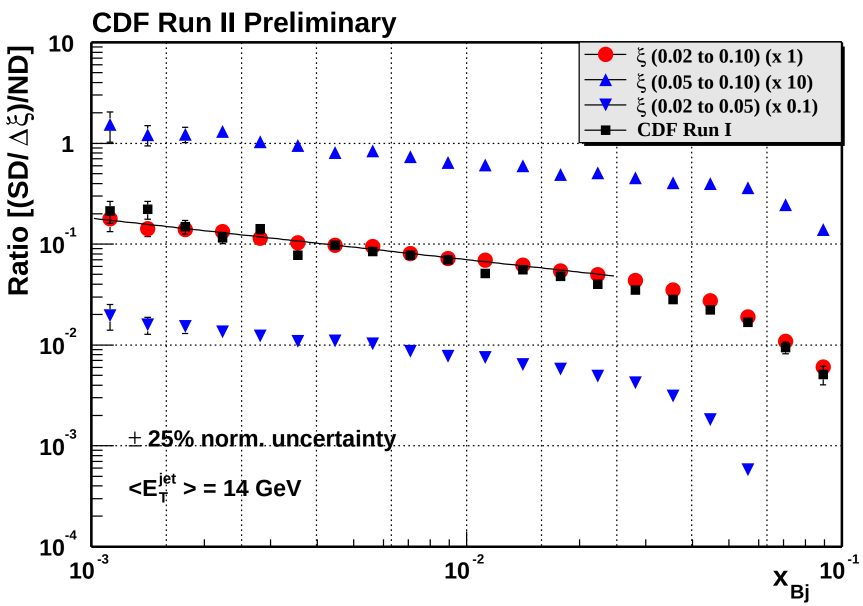
$$\frac{d\sigma}{d\xi} \propto \frac{1}{\xi} \rightarrow \frac{d\sigma}{d(\log \xi)} = Constant$$

Peak at ξ ~ 1:

→ overlap of ≥1 ND events



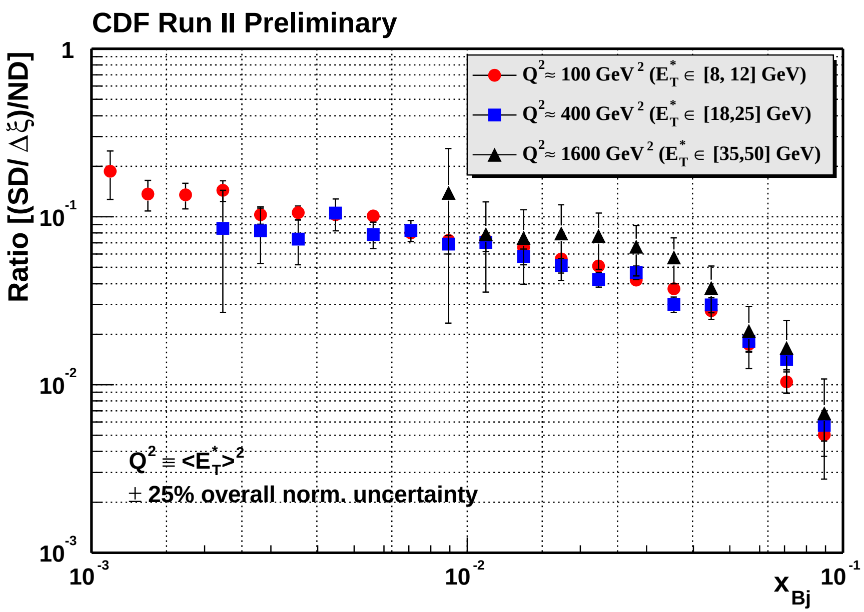
Diffractive Structure Function in Run II



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

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

Confirms Run I Result



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

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

Pomeron evolves like proton?

Diffractive Structure Function : Run II Prospects

GOAL :

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

Q^2 Dependence :

- Use RP + Higher E_T Jet (E_T>20 and 50 GeV) data

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

ξ Dependence :

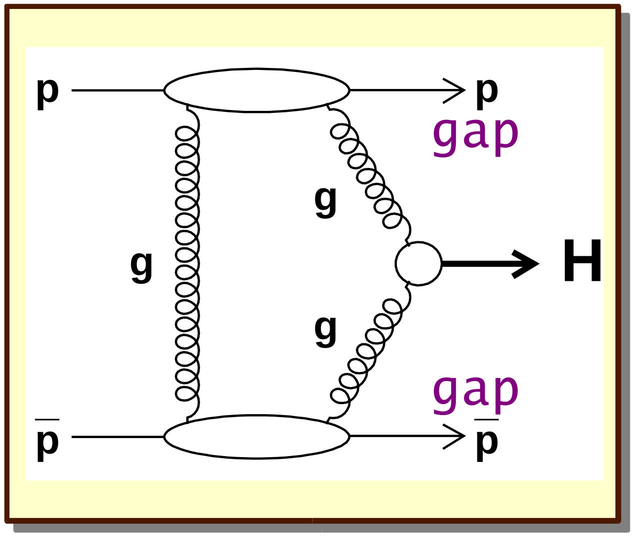
- Use BSC-Gap + Jet data to go below ξ = 0.03

  → possible to extend ξ range down to 0.001 for Q^2 > 100 GeV^2

Process Dependence :

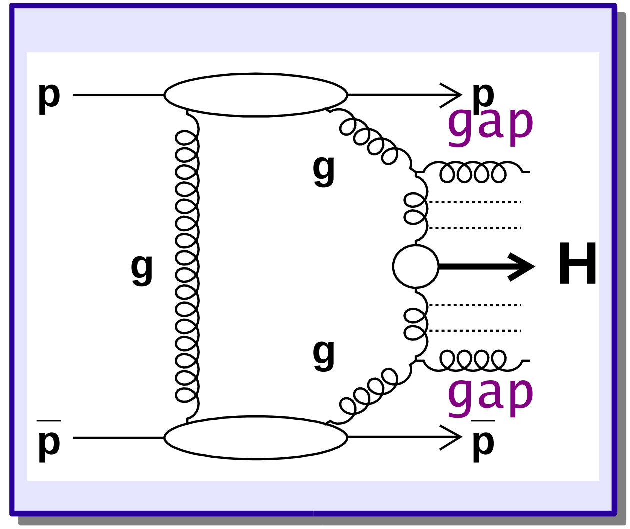
- Measure F^{D} from SD W (probing quark) and J/Ψ (probing gluon) events

Exclusive Higgs at LHC



$gg \rightarrow H$

- ➔ Bialas, Landshoff
- ➔ Khoze, Martin, Ryskin
- ➔ Boonekamp, Peschanski, Royon



$gg \rightarrow H + X$

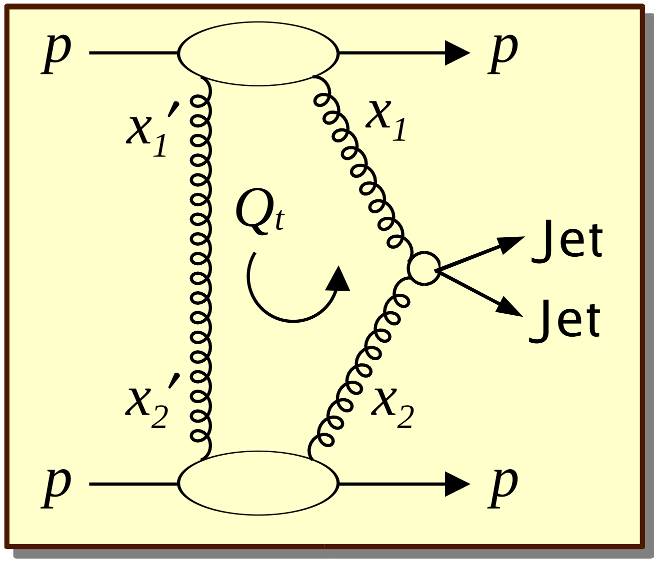
Standard Model light Higgs (M_H~120 GeV) :

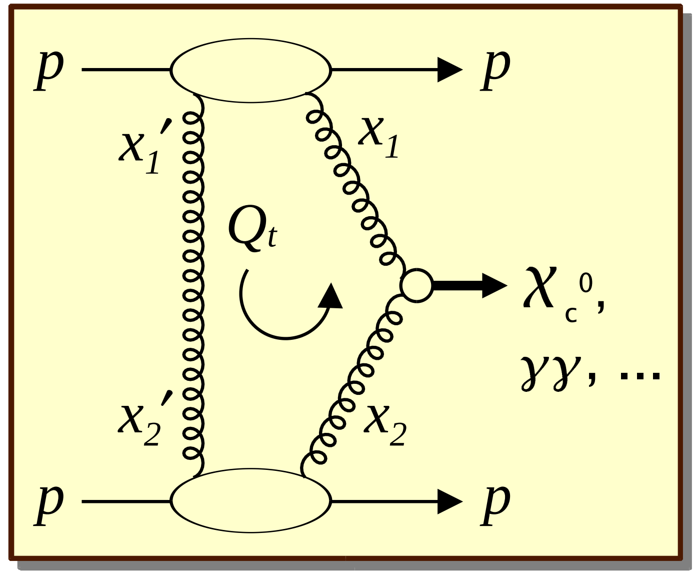
- hard $gg \rightarrow H$ process + soft g exchange → color neutral
- $p + p \rightarrow p + H(\rightarrow b\bar{b}) + p$: "exclusive" channel → clean signal
- $p + p \rightarrow p + b\bar{b} + p$: exclusive $b\bar{b}$ suppressed
- M_H = "Missing Mass" = $(s \cdot \xi_{\bar{p}} \cdot \xi_p)^{1/2}$

Khoze, Martin, Ryskin : σ_H^{excl} ~ 3 fb, S/B ~ 3 @ LHC (if $\Delta M_{miss} \approx 1$ GeV)

➔ **A potential discovery place at LHC**

Exclusive Processes at Tevatron





Exclusive Dijets : $gg \rightarrow gg$

- large cross section (less clean)
- high p_T events accessible
- exclusive $gg \rightarrow qq$ suppressed

Exclusive χ_c^0 : $gg \rightarrow \chi_c^0$

Exclusive $\gamma\gamma$: $gg \rightarrow \gamma\gamma$

- clean signal
- low p_T process dominates

GOAL

- Establish exclusive processes experimentally (if exist)
- Measure cross sections or limits

➔ ***Calibrate Higgs predictions at LHC***

Search for Exclusive Dijets

Strategy

- Obtain inclusive DPE dijets : $\bar{p} + p \rightarrow \bar{p}$ + dijet + X + gap (+ p)
- Look for exclusive signature using dijet mass fraction :

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

M_{jj}^{cone} = dijet mass

M_X = (dijet + X) mass

Exclusive Dijet Limit

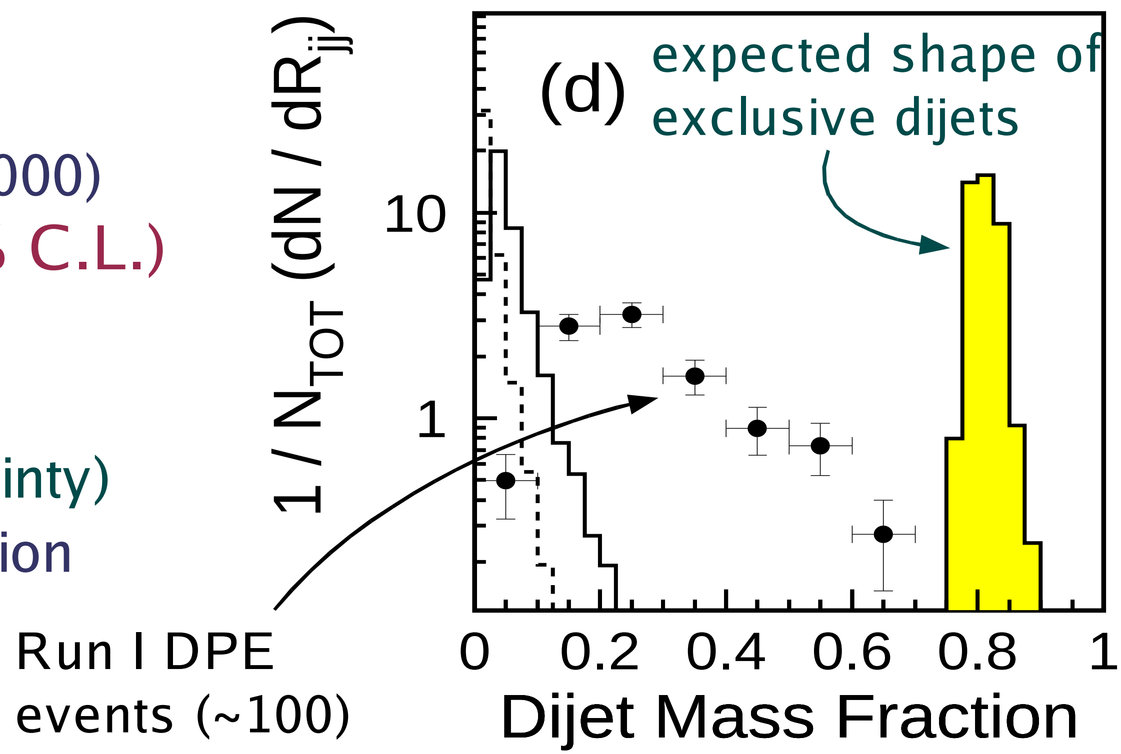
Run I : PRL 85, 4215 (2000)

→ $\sigma_{excl} < 3.7$ nb (95% C.L.)

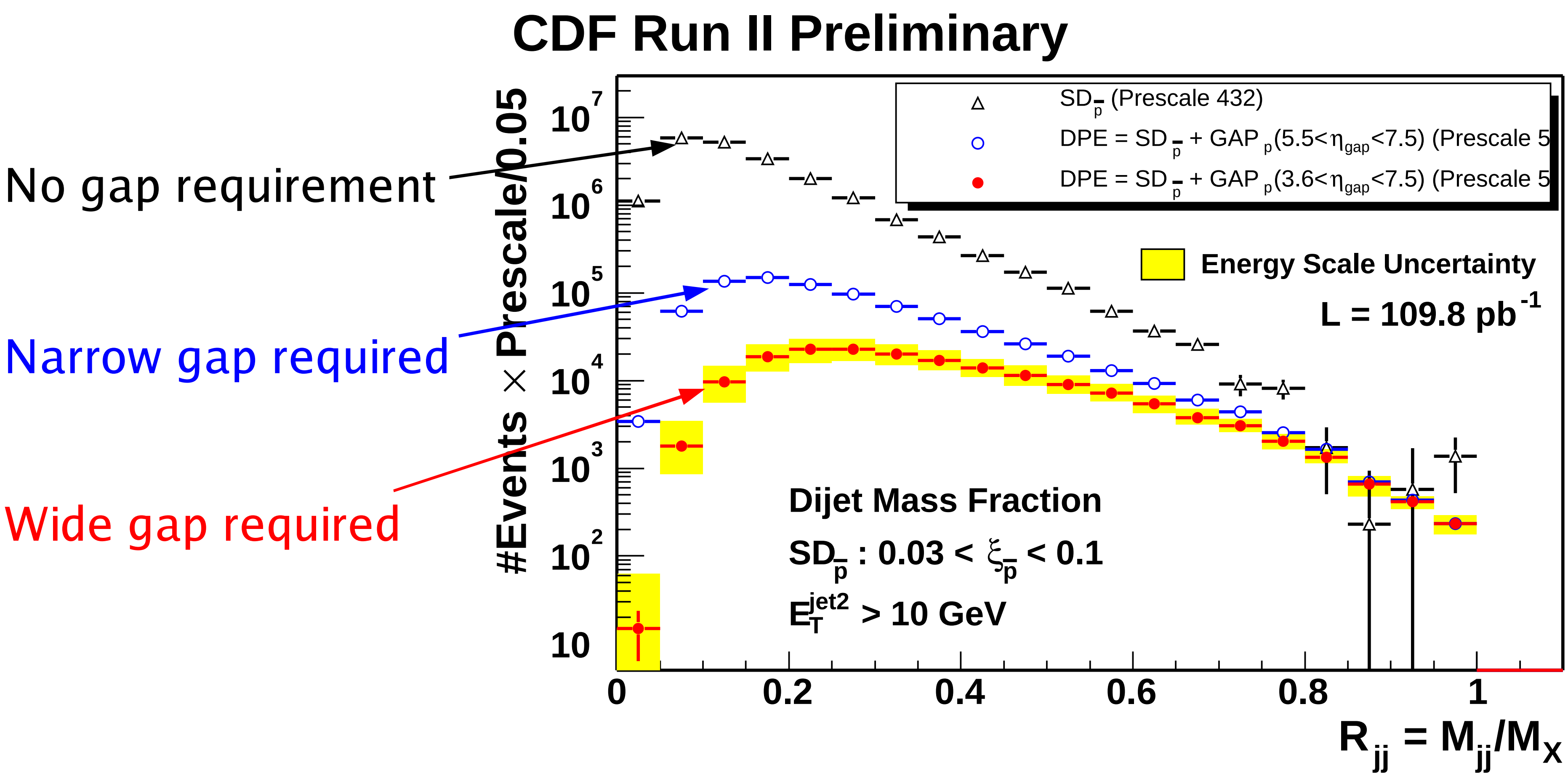
KMR Prediction :

~1 nb (factor 2 uncertainty)

@ Run I Kinematic Region



Dijet Mass Fraction in Run II



- >100-fold increase in observed DPE dijets
- Similar event yield at R_{jj}>0.8 regardless of gap requirements
- **Smoothly falling spectra all the way to R_{jj}=1**

Limits on Exclusive Dijets

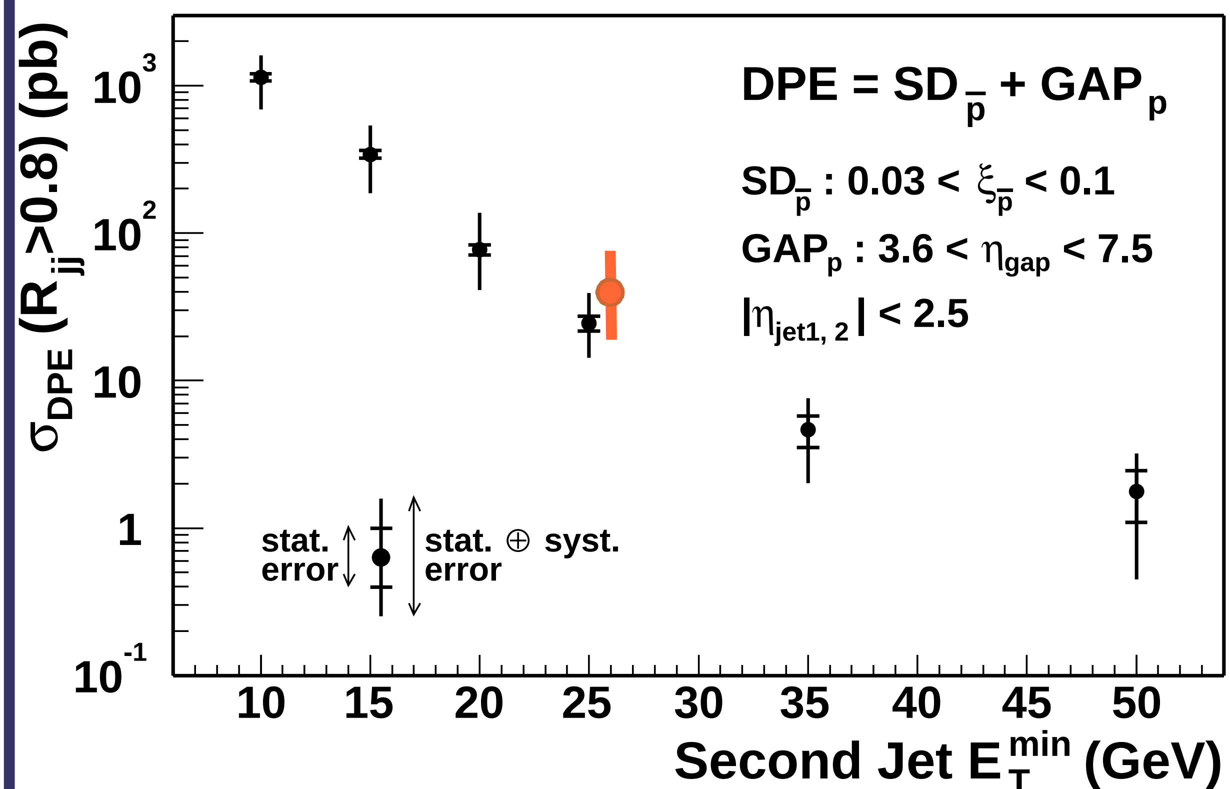
Cross Sections of DPE Dijets with R_{jj}>0.8

E_T^{min} = 10 GeV : $1.14 \pm 0.06(stat)\ ^{+0.47}_{-0.45}(syst)$ nb

E_T^{min} = 25 GeV : $25 \pm 3(stat)\ ^{+15}_{-10}(syst)$ pb

$E_T^{jet1,2} > E_T^{min}$ GeV,
$|\eta_{jet1,2}| < 2.5$,
$0.03 < \xi_{\bar{p}} < 0.1$,
$3.6 < \eta_{gap} < 7.5$

CDF Run II Preliminary



Martin, Kaidalov, Khoze, Ryskin and Stirling (hep-ph/0409258):

~40 pb for E_T>25 GeV (and CDF cuts)

Extracting Exclusive Dijets

Theory

Bialas, Landshoff
Berera, Collins
Khoze, Martin, Ryskin

Exclusive $q\bar{q}$ suppression :

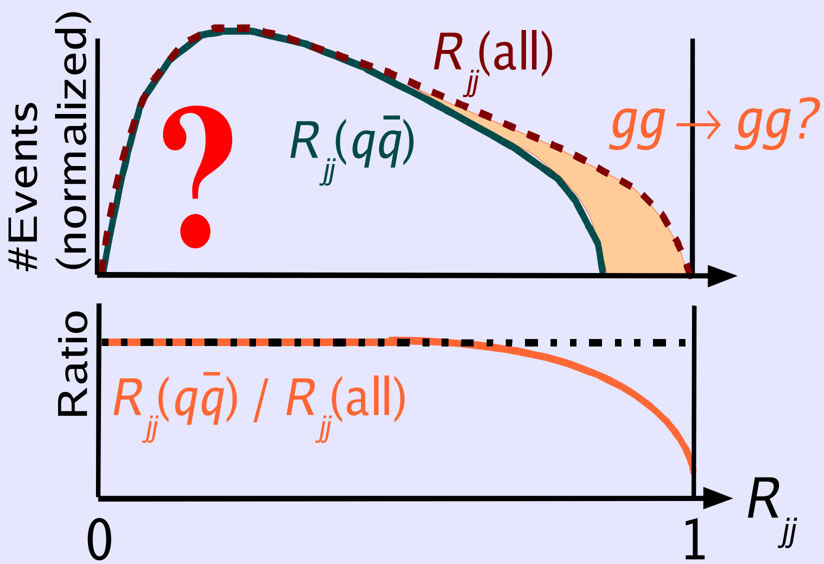
$\sigma^{excl}(gg \to q\bar{q}) \sim (m_q^{\,2}/E_T^{\,2})\ \sigma^{excl}(gg \to gg)$
$\to 0$ as $m_q \to 0$ or $E_T \gg m_q$

➔ "$J_z = 0$ spin selection rule"

⇨ ***Exclusive "gg" Jets:***

gluon jets enriched
at high $R_{jj} \sim 1$?

Experiment

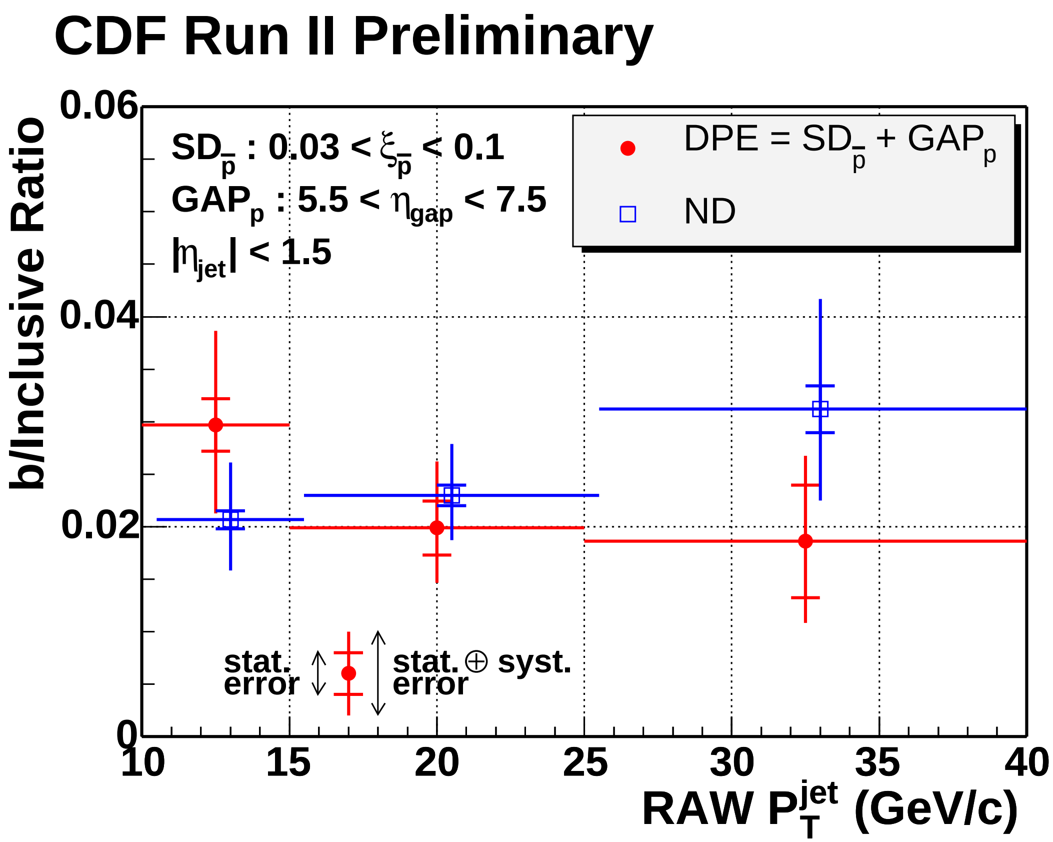


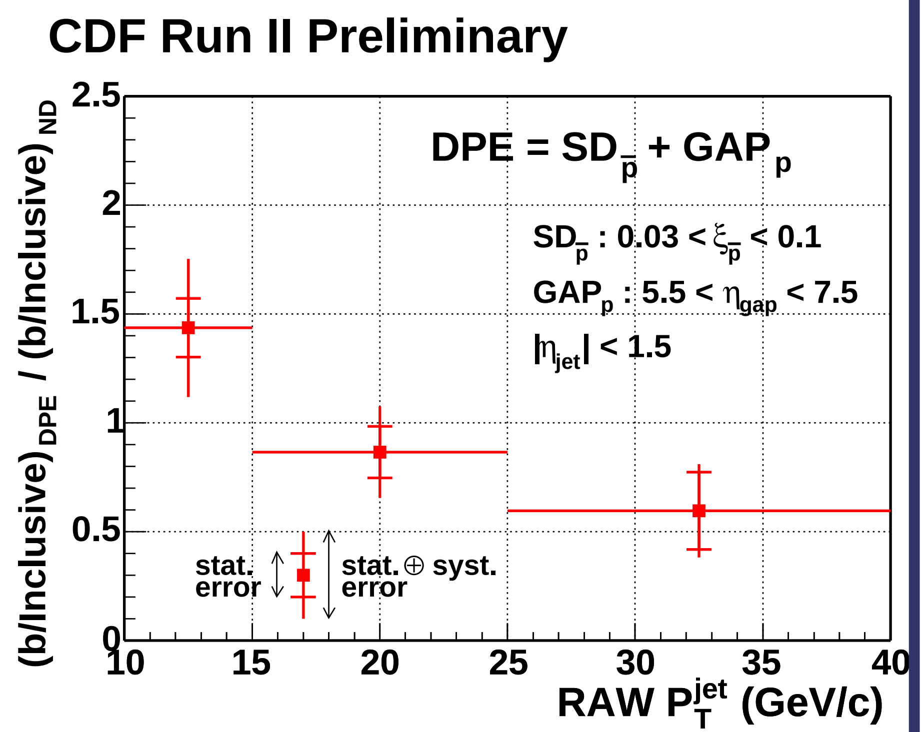
Using b-Quark Jets

Look for the suppression of b-quark jets in the exclusive region

- ☺ many exp. systematics canceled out
- ☺ b-quarks identified well: g mistag @ O(1%)
- ☹ large m_b ➔ non-zero exclusive $b\bar{b}$
- ☹ NLO background: $g \to bb$, $gg \to b\bar{b}g$, etc

b-Quark Jet Yield : DPE vs ND





Ratio of b-jet to inclusive jet :

DPE: ***2.43 ± 0.17(stat) $^{+0.58}_{-0.49}$(syst) %***

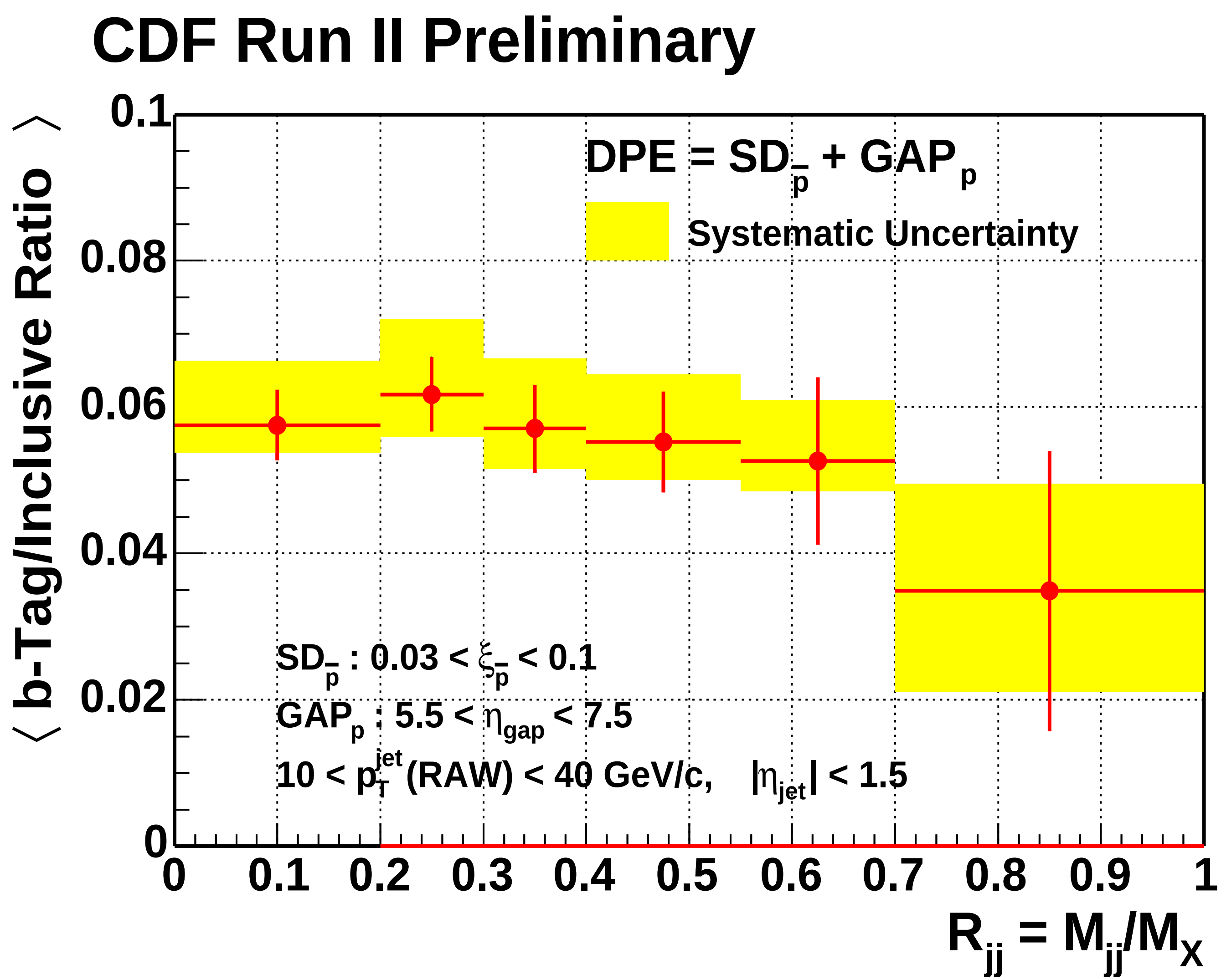
ND: ***2.24 ± 0.06(stat) $^{+0.43}_{-0.34}$(syst) %***

Ratio of R_b^{DPE} to R_b^{ND} :

1.08 ± 0.08(stat) $\pm$ 0.22(syst)

$10 < p_T < 40$ GeV/c, $|\eta_{jet}| < 1.5$

SecVtx Tag Fraction vs R_{jj}

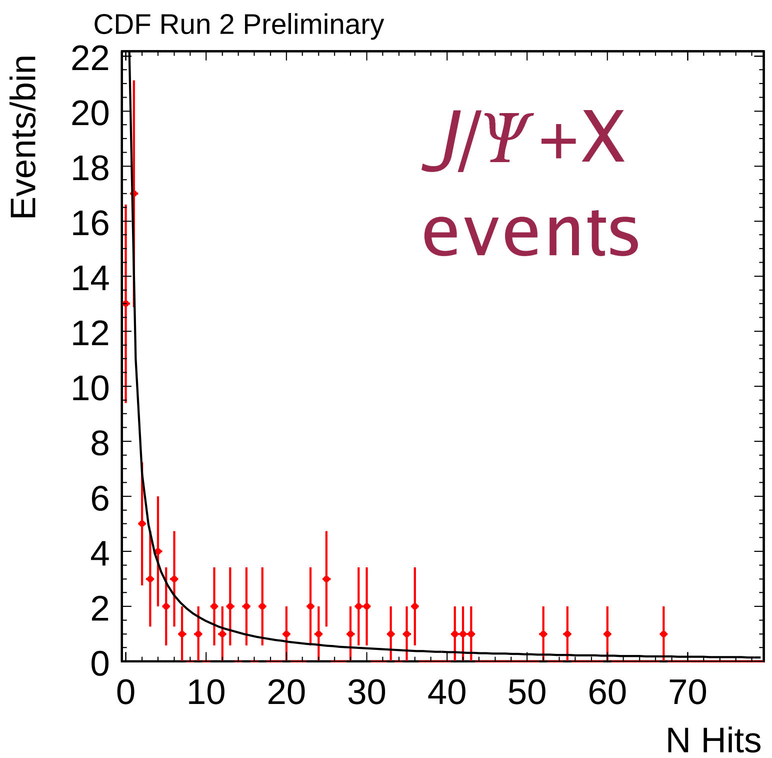


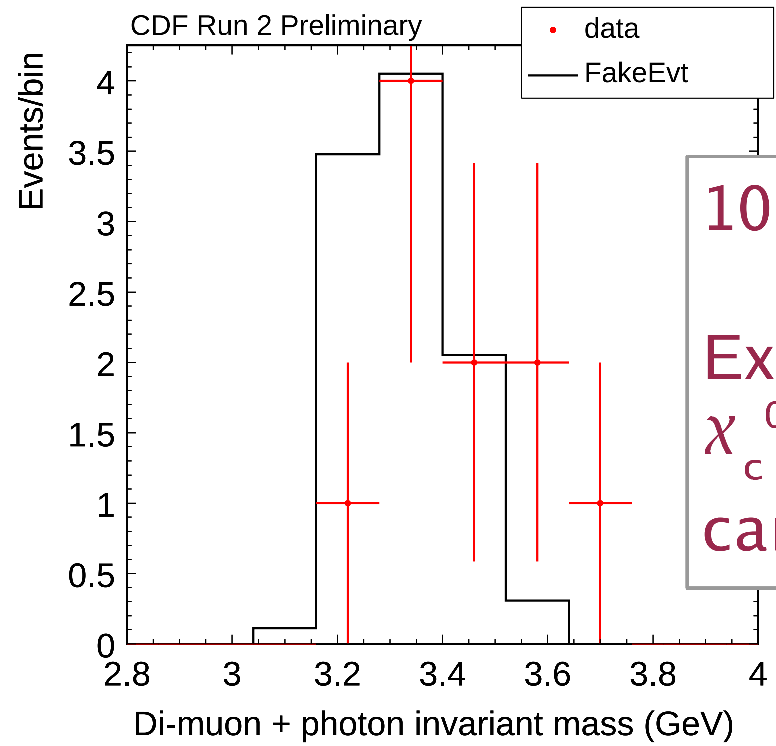
$R_{btag}(R_{jj}>0.7)\,/\,R_{btag}(R_{jj}<0.4) = 0.59 \pm 0.33(stat) \pm 0.23(syst)$

Exclusive χ_c^0 Production

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

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





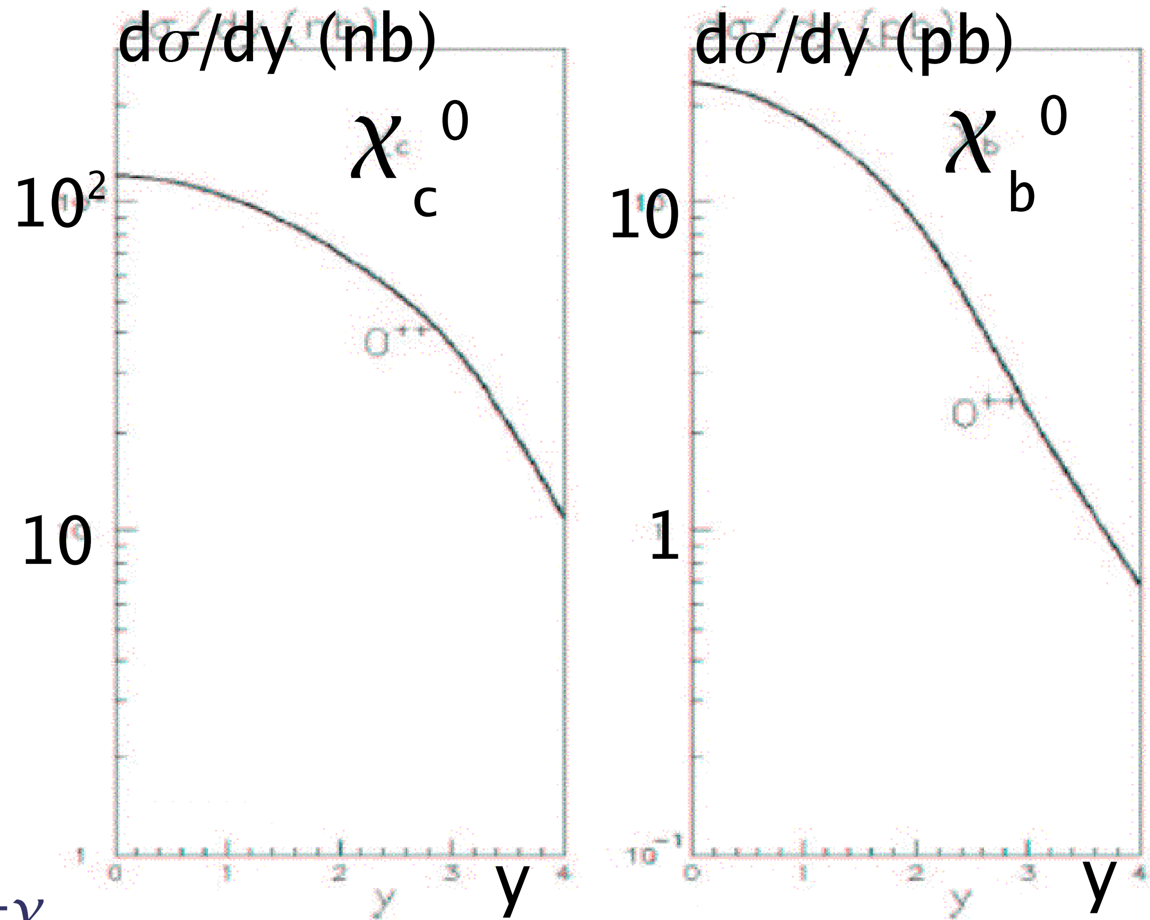
10 events:

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

Exclusive χ_c^0 Cross Section Limit

Khoze, Martin, Ryskin
Eur. Phys. J. C19, 477 (2001)

$\sigma(\bar{p}p \rightarrow \bar{p}+\chi_c^0+p)$ ∗
BR$(\chi_c^0 \rightarrow J/\Psi+\gamma)$
≈ 70 pb at $|y^{J/\Psi}|<0.6$
(factor 2-5 uncertainty)



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

$|y^{J/\Psi}|<0.6$, $p_T^{J/\Psi}>2$ GeV
$\sigma(\bar{p}p \rightarrow \bar{p}+J/\Psi+\gamma+p)$ = 49 ± 18(stat) ± 39(syst) pb

→ "Upper Limit" on exclusive χ_c^0 production cross section

Exclusive Final States : Run II Prospects

GOAL :

- Investigate existence/properties of exclusive final states
- Derive their cross sections or limits

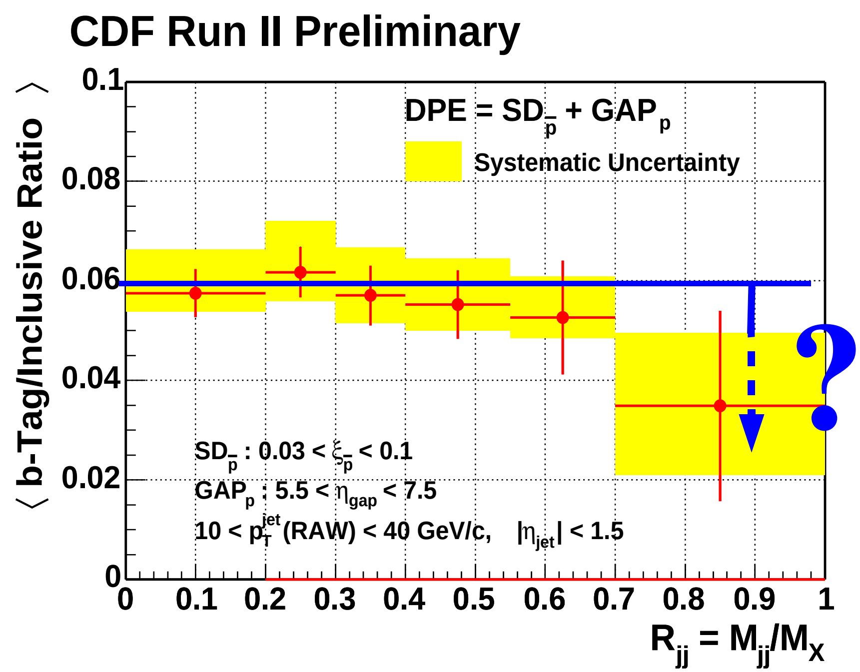
Exclusive Dijets :

- Ratio (b-jet / all) vs R_{jj}
- More DPE b-jet data with new trigger

Exclusive Low Mass States :

- χ_c^0 : new data with DPE-J/Ψ trigger
- $\gamma\gamma$: new data with DPE-$\gamma\gamma$ trigger

Analysis of exclusive physics in good progress



Summary

<u>Diffractive Structure Function F^D</u> :

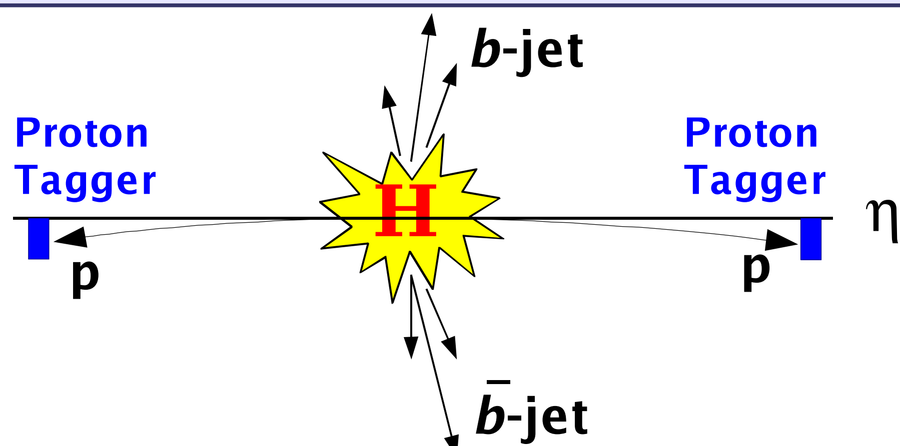
- Re-established Run I results using single diffractive dijets
- Q^2 dependence of F_{jj}^D → Pomeron evolves like proton?
- Studies of ξ and process dependence of F^D in progress

<u>Exclusive Final States</u> :

- Improved upper limit on exclusive dijet production
- Obtained upper limit on exclusive χ_c^0 production
- New DPE triggers ($b\bar{b}$, χ_c^0 and $\gamma\gamma$) taking more data

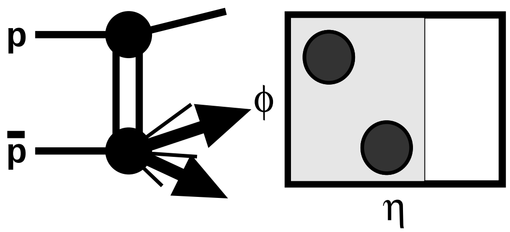
Important inputs to exclusive Higgs at LHC:

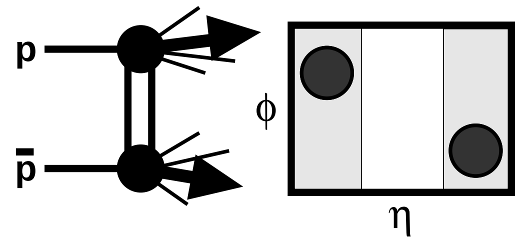
$pp \rightarrow pHp$

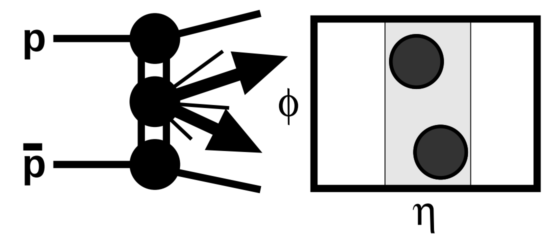


Backup

Diffractive Measurements in Run I







Soft Diffraction

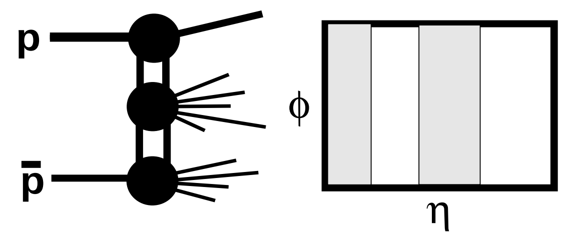
Single Diffraction
PRD 50, 5535 (1994)

Double Diffraction
87, 141802 (2001)

Double Pomeron Exchange
93, 141601 (2004)

Hard Diffraction

Multi-Gap Diffraction
91, 011802 (2003)



Rapidity Gap Tag

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

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

Roman Pot Tag

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

* PRL references

- Dijets 1.8TeV
  85, 4217 (2000)

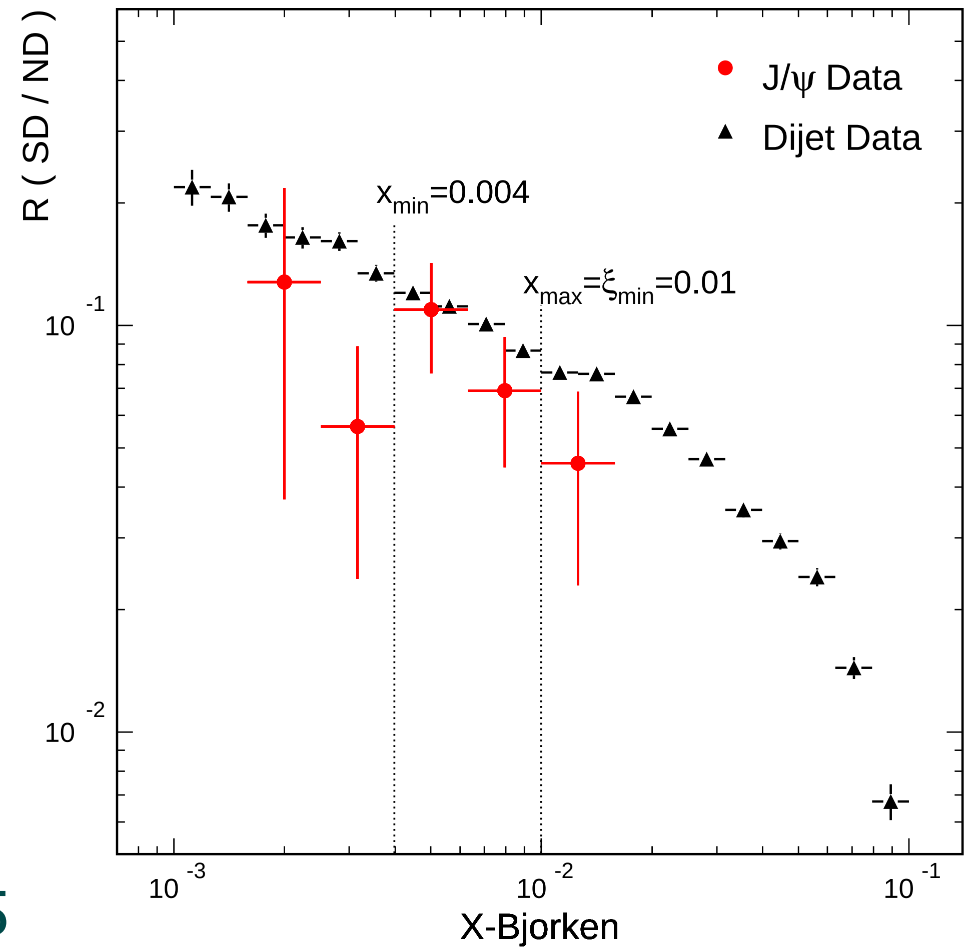
F_{jj}^{D} measured using SD J/Ψ Events

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

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

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

= 1.17 ± 0.27 (stat.)



→ Gluon fraction : f_g^{D} = 0.59 ± 0.15

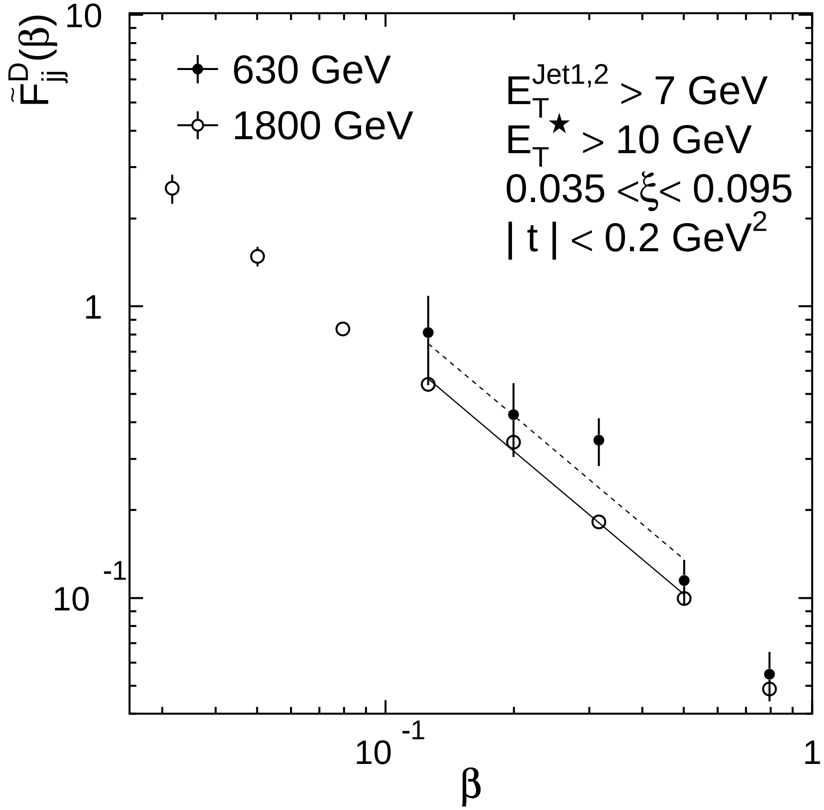
cf. *W*, dijets, *b*-quark : f_g^{D} = 0.54 ± 0.15

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

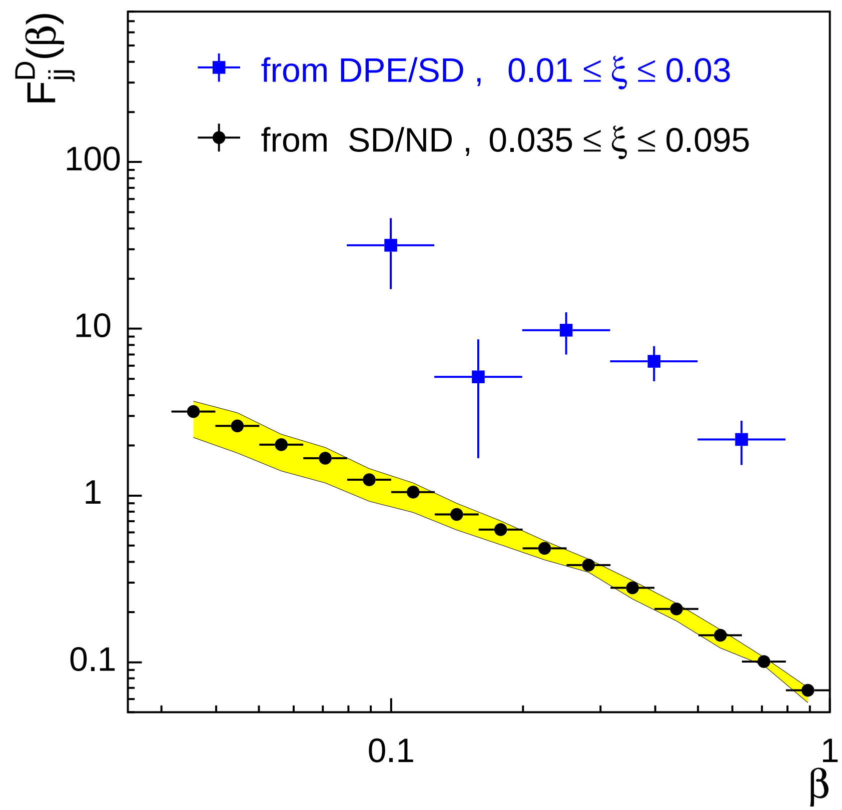
Diffractive Structure Function measured using Single Diffractive Dijets at 630 GeV

Test QCD Factorization at Tevatron

SD Dijets : 1800 vs 630 GeV



1800 GeV : SD vs DPE Dijets

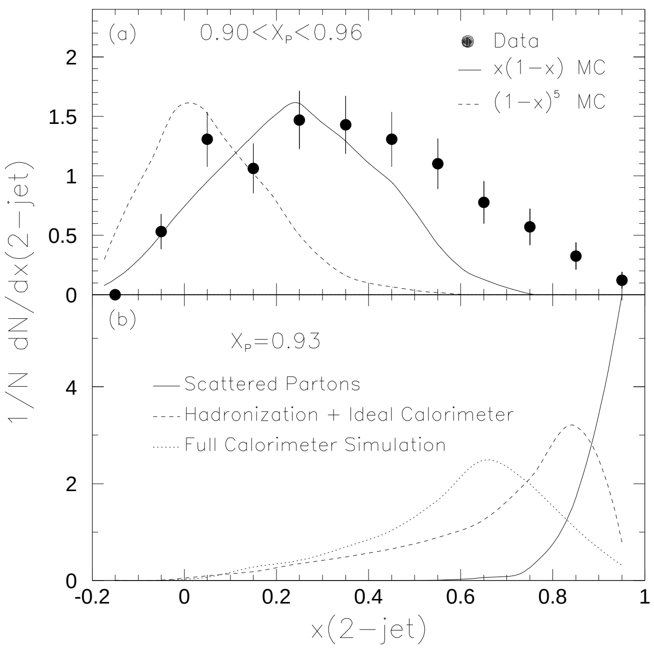


$R^{SD}_{ND}(630) / R^{SD}_{ND}(1800) = 1.3 \, ^{+0.5}_{-0.4}$

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

Pomeron Structure : Comparison with UA8

Phys. Lett. B 297, 417 (1992)



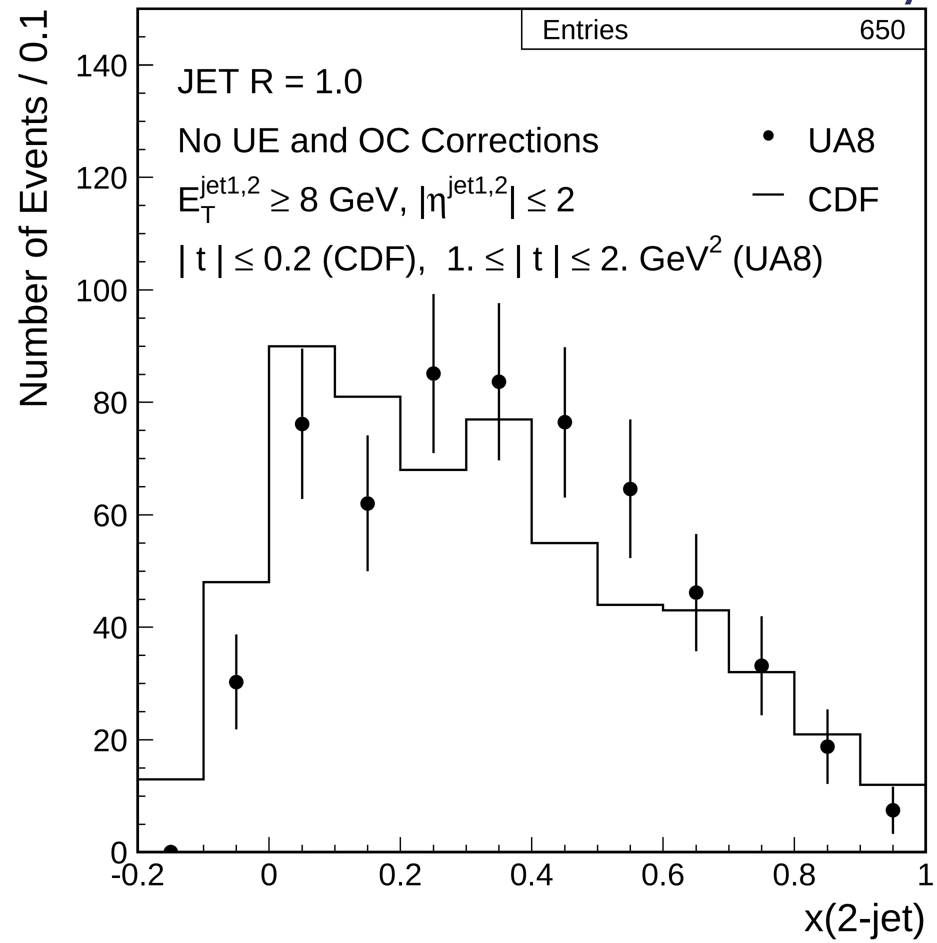
x(2-jet) = β - x(proton)

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

Pomeron structure from UA8 data :

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

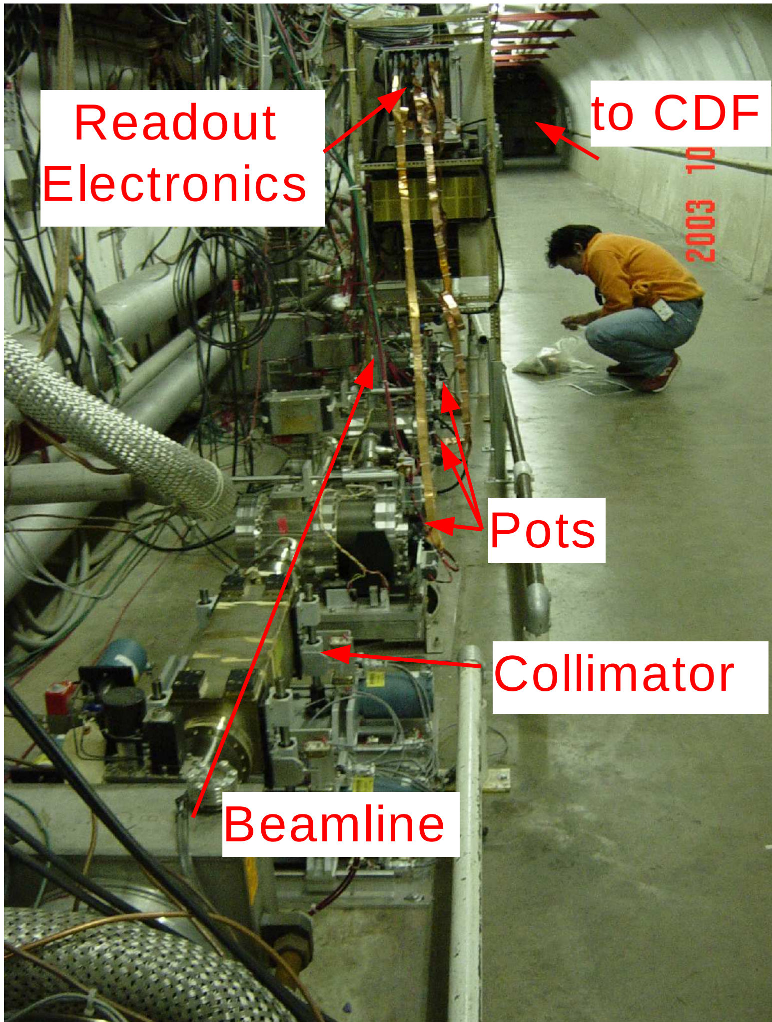
CDF Preliminary

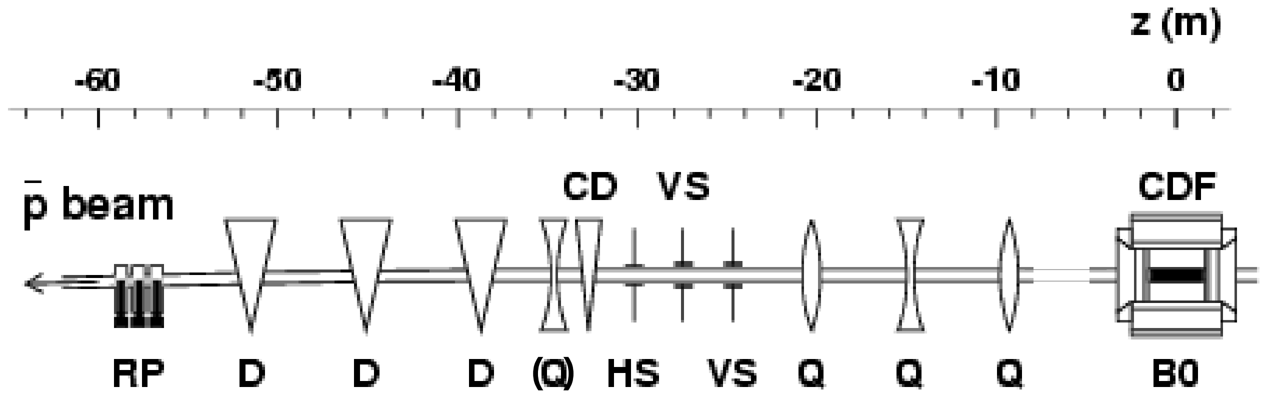


630 GeV data re-analyzed à la UA8

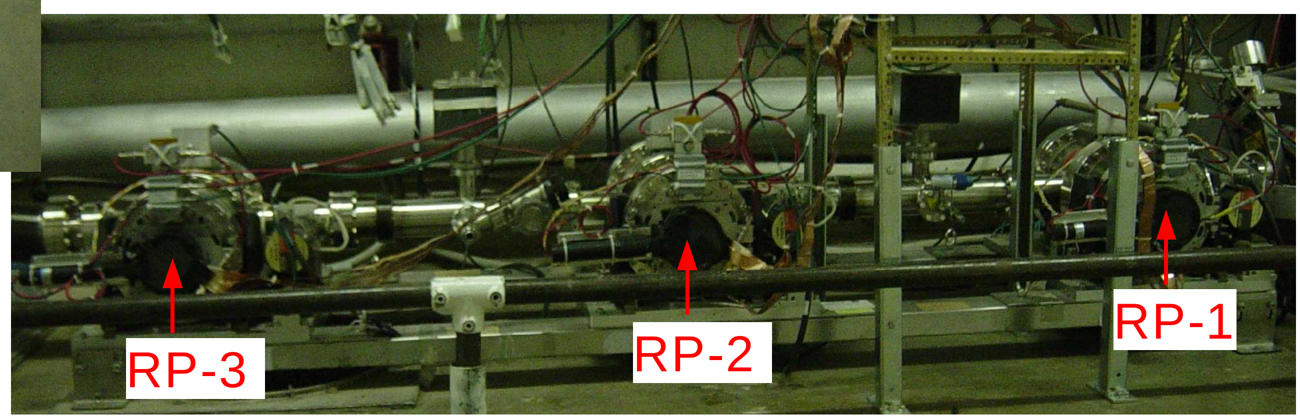
x(2-jet) distributions are not in-consistent between UA8 and CDF

CDF Roman Pots

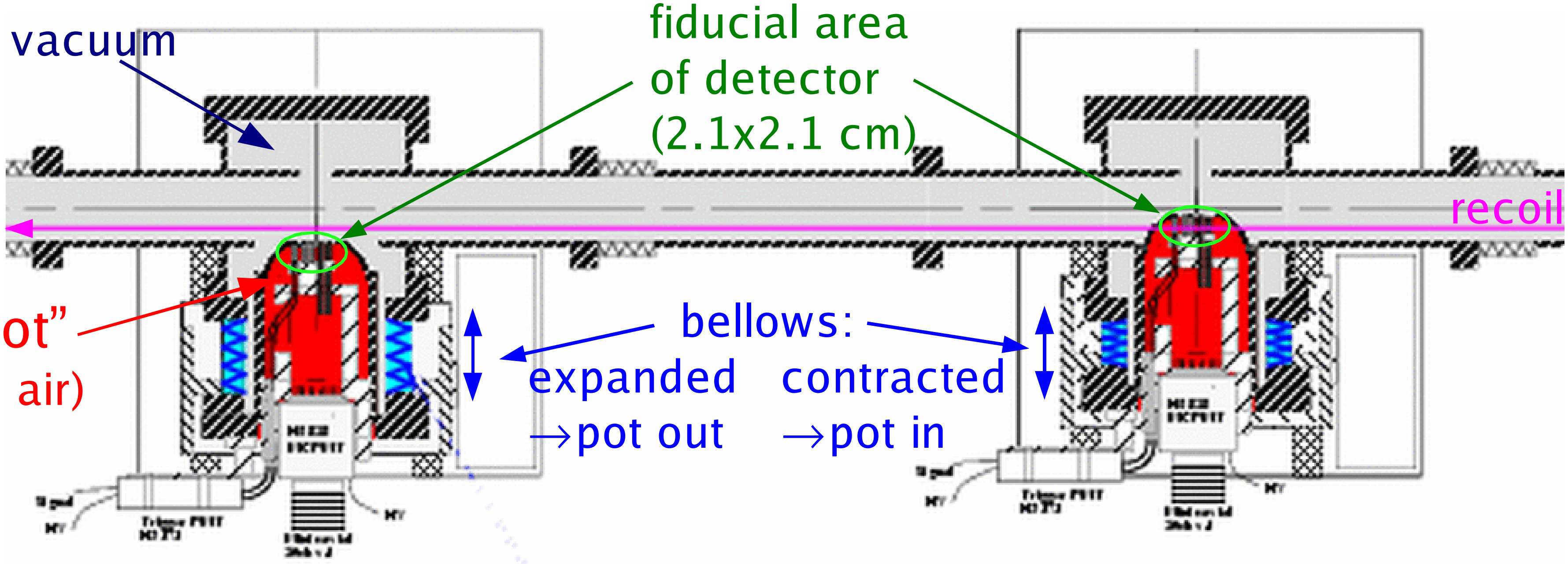




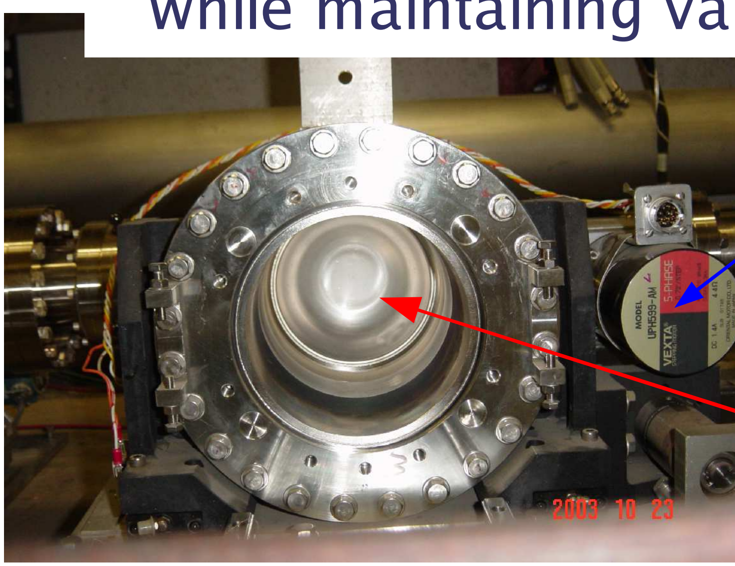
- Dipole Spectrometers (0.03<ξ<0.1)
- Knowledge of the beam optics, collision vertex position, and a single RP hit allows us to reconstruct the kinematics of diffractive $\bar{p}$

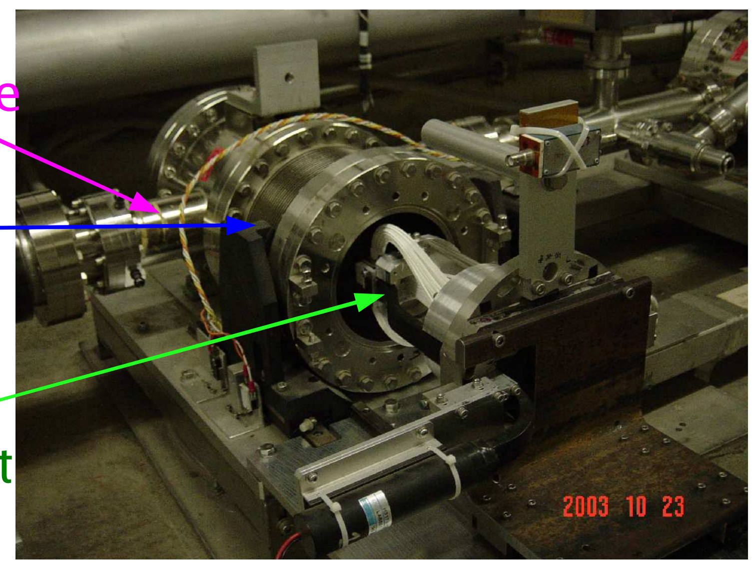


Concepts of CDF Roman Pot



Bellows allow detectors to be moved in/out of the beamline while maintaining vacuum

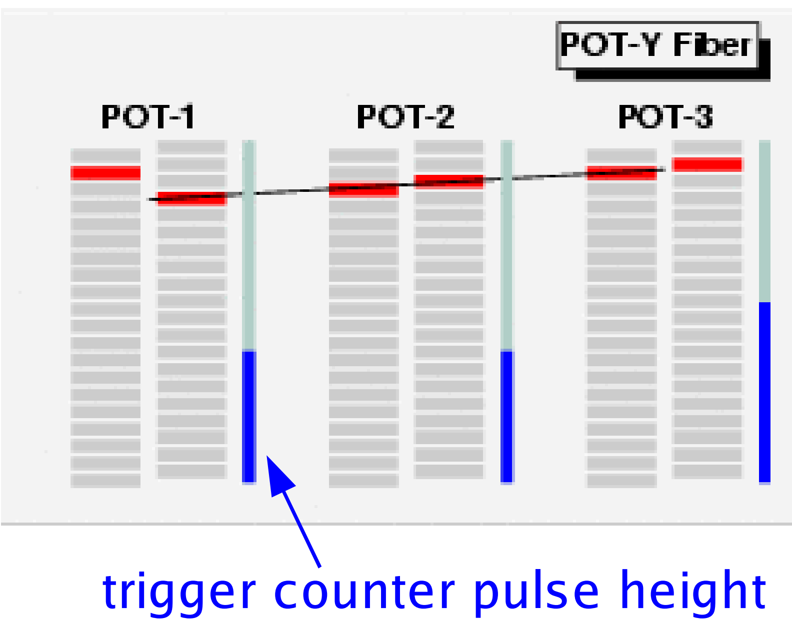


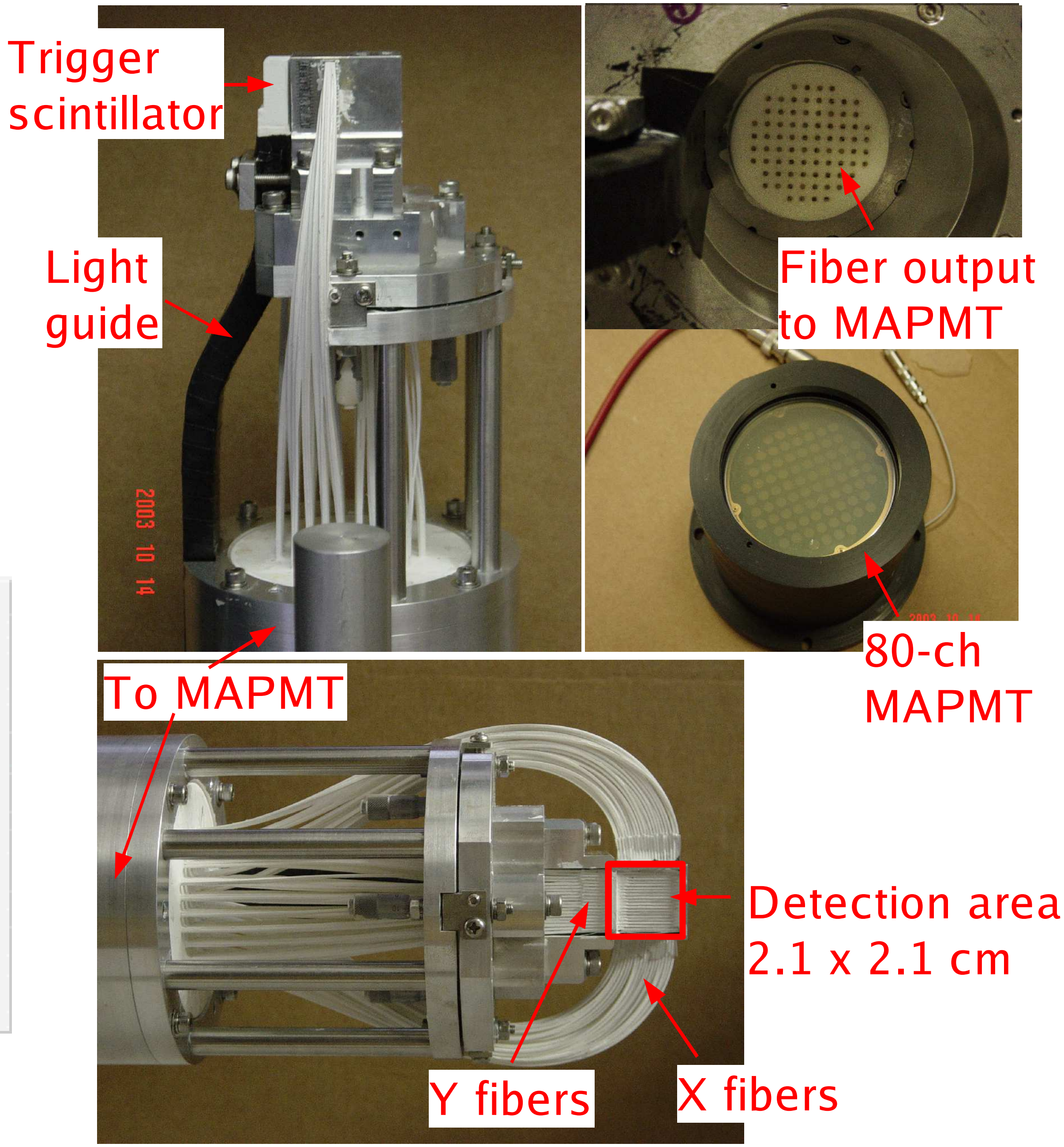


Roman Pot Detectors

3 pots each with

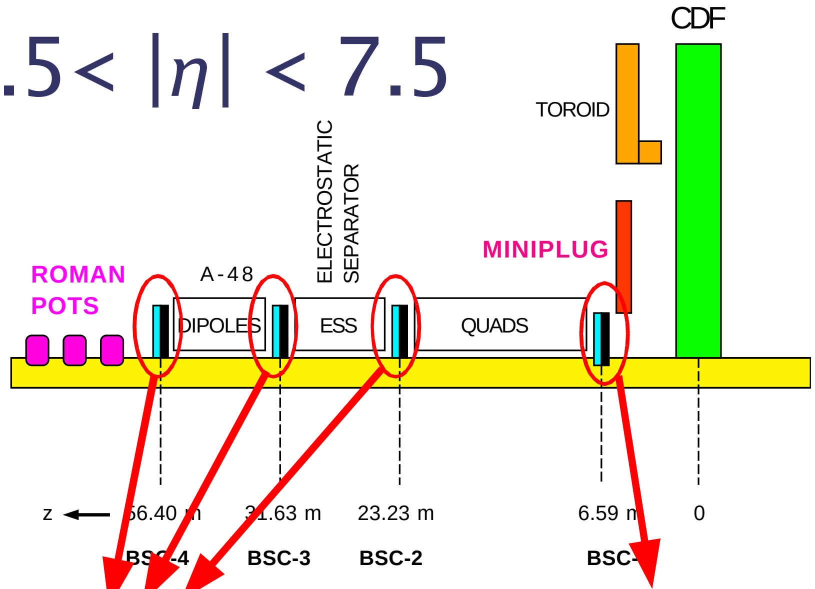
- Trigger counter 2.1x2.1x0.8 cm^3 scintillator
- 40X + 40Y fiber arrays, 1 array consists of 4 single clad 0.8x0.8 mm^2 fibers (KURARAY SCSF81)



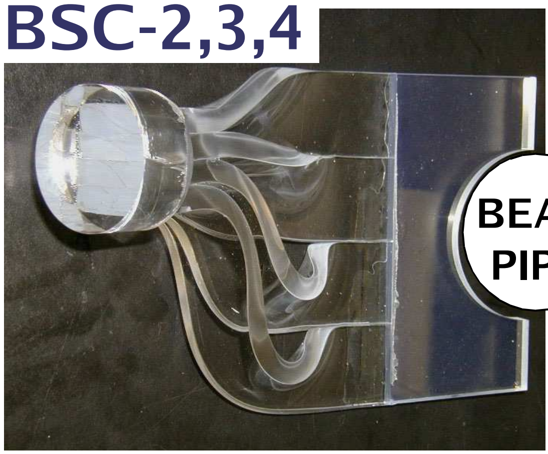


Beam Shower Counters

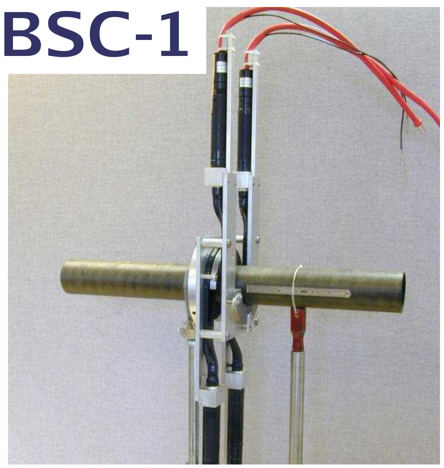
$5.5 < |\eta| < 7.5$



BSC-2,3,4



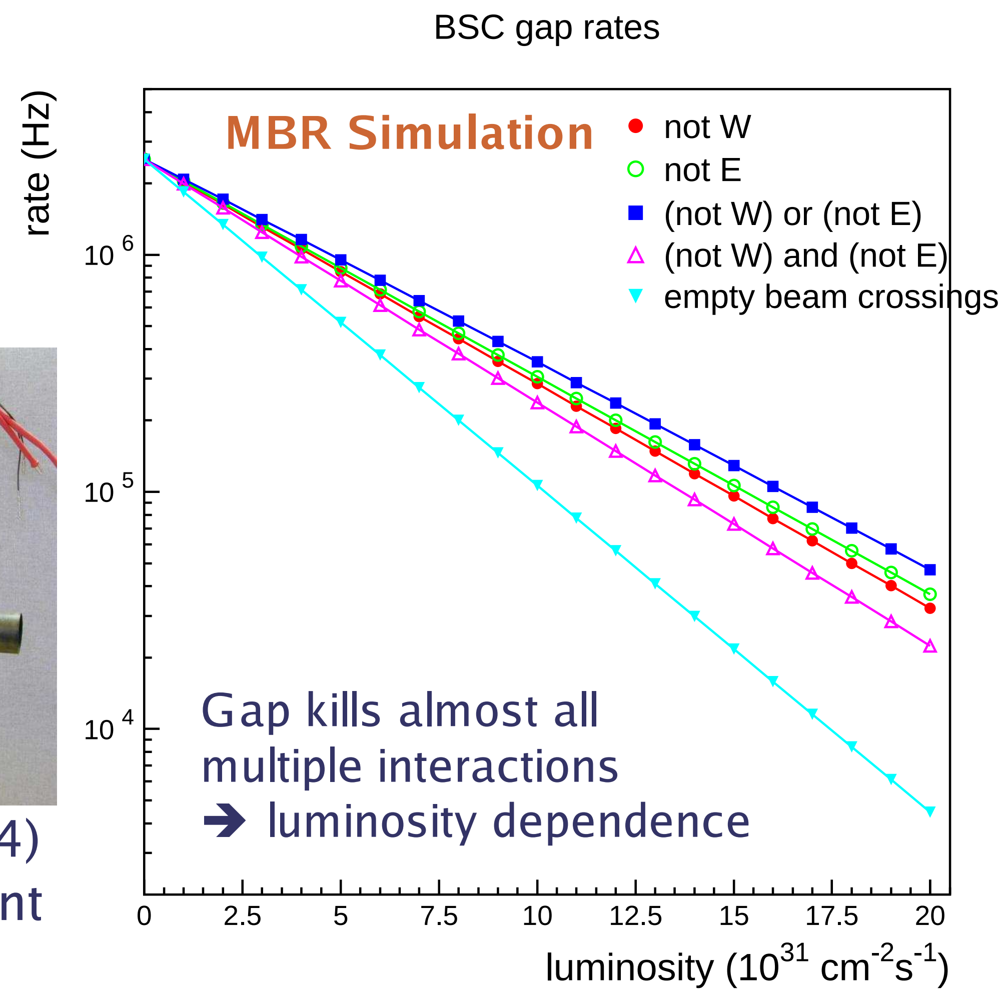
BSC-1



- 6.4(9.0)mm SCSN-81 for BSC-1 (2,3,4)
- BSC-1 has lead plates attached in front to convert γ's

Require BSC veto (gap)

- reject ≥95% of non-diffractive events
- retain ≥95% of diffractive events with ξ<0.1



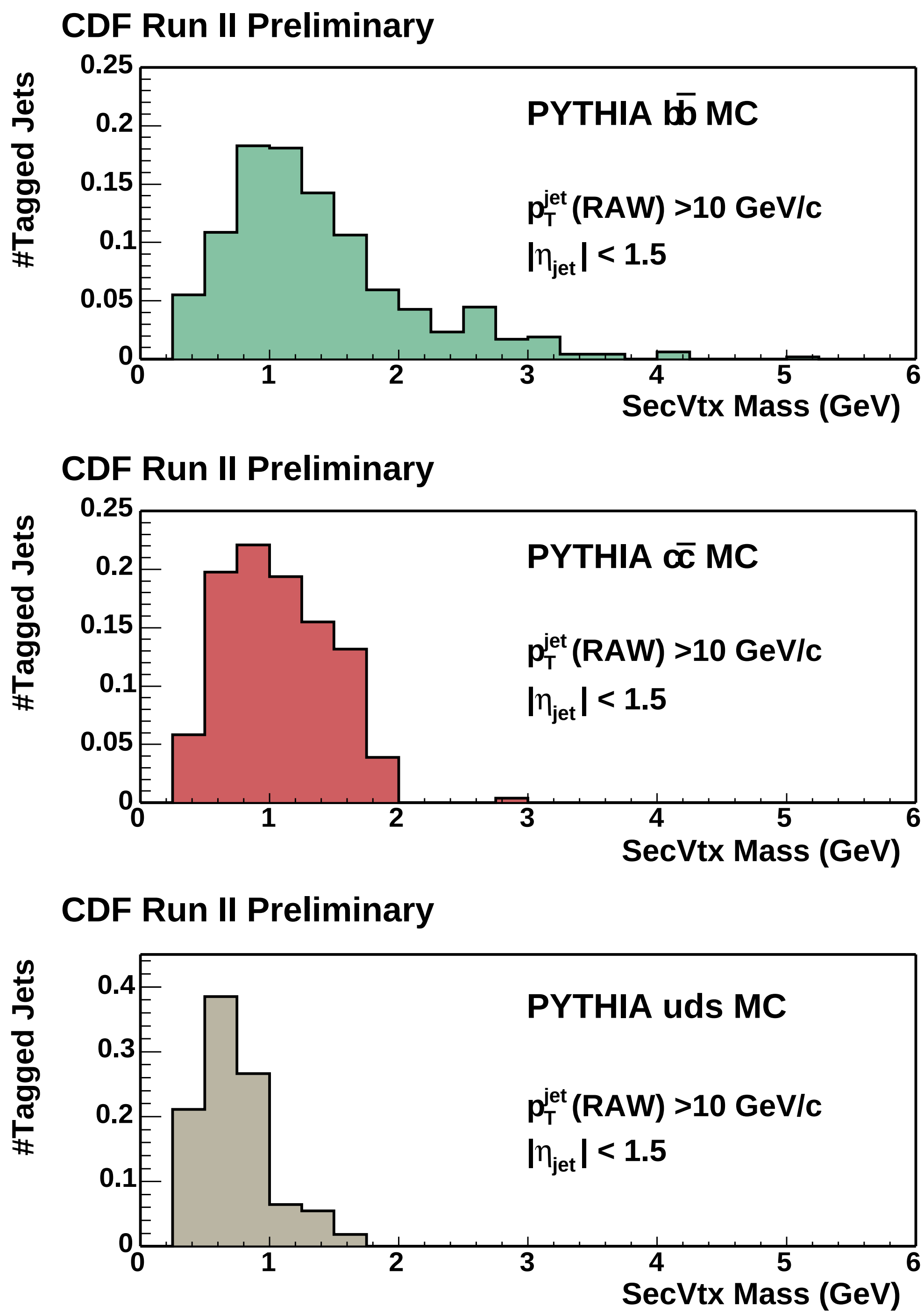
SecVtx Mass

Strategy

- Tag *b*-quark jets in DPE using secondary vertex (SecVtx)
- Obtain *b*-quark fraction using SecVtx mass

SecVtx mass is a good discriminator for *b*-, *c*-, and *uds*-quark jets

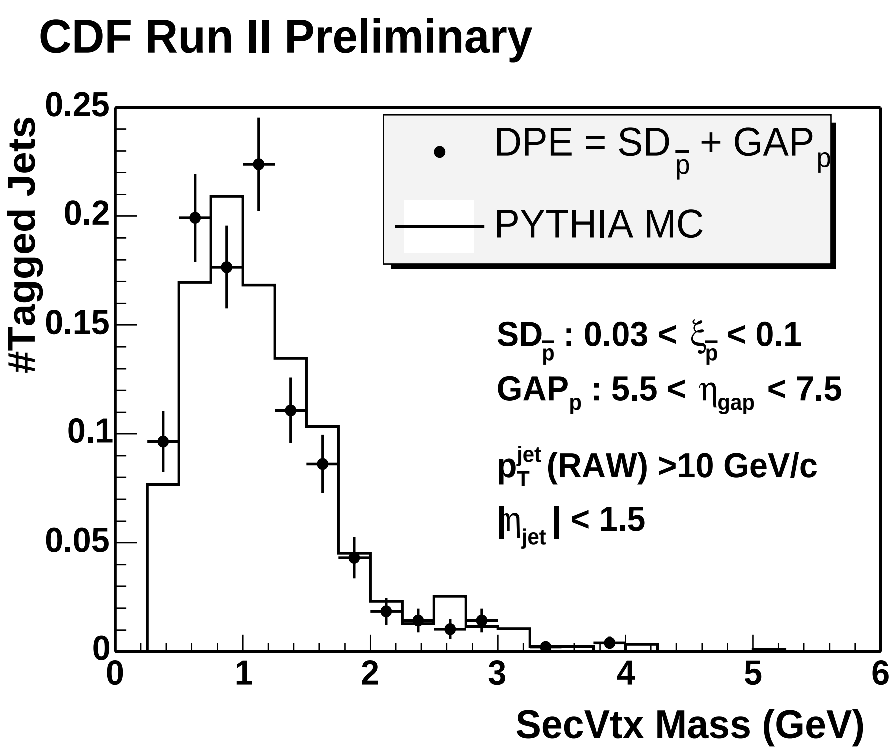
PYTHIA :
M_{SecVtx} >2 GeV are all b-jets



SecVtx Mass of Tagged Jets

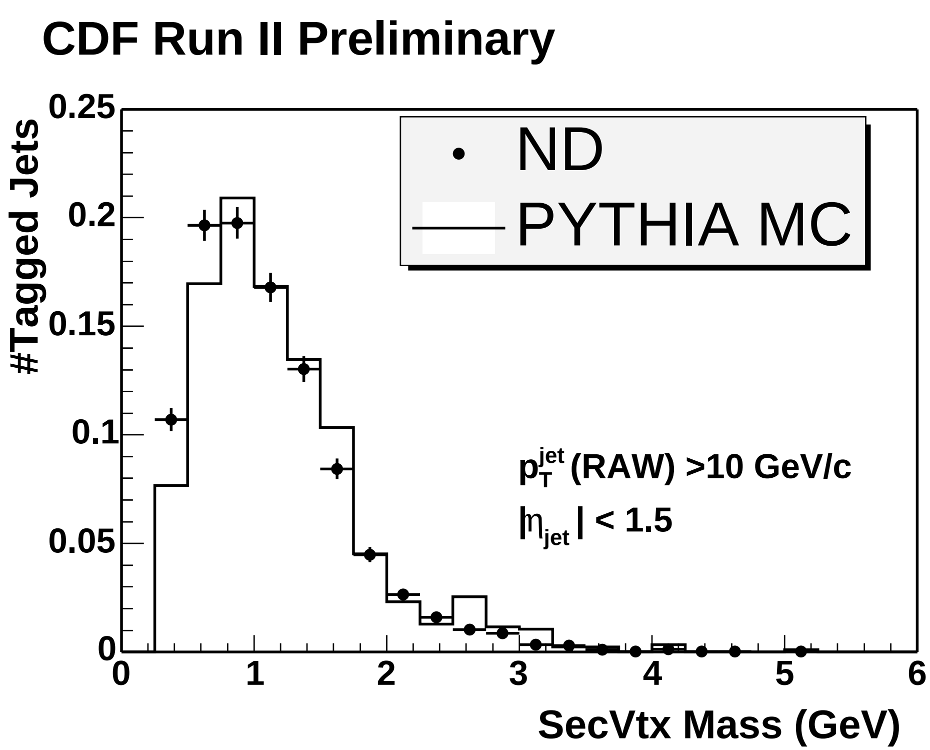
DPE

F_b = 39 ± 7 %



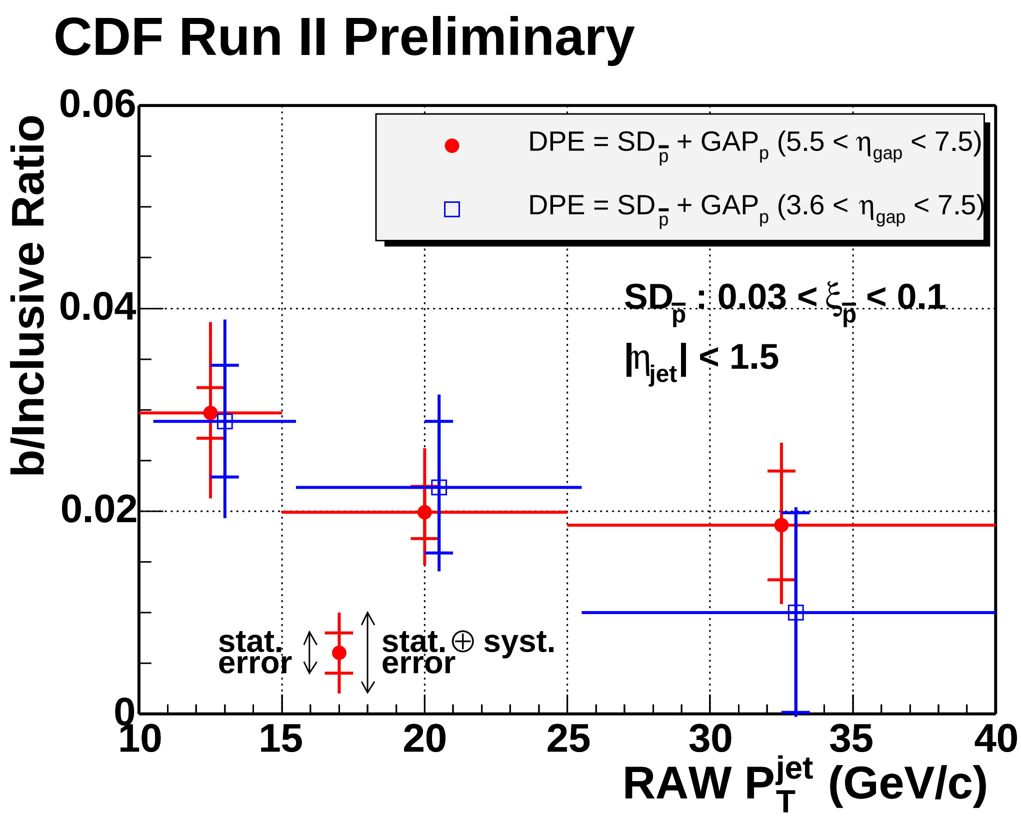
ND

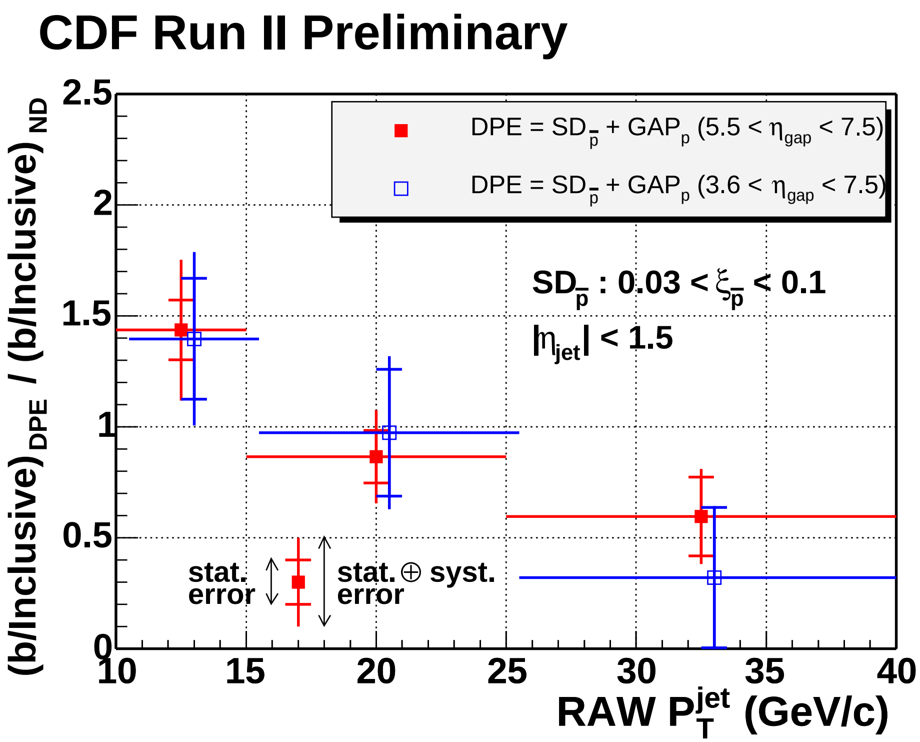
F_b = 44 ± 3 %



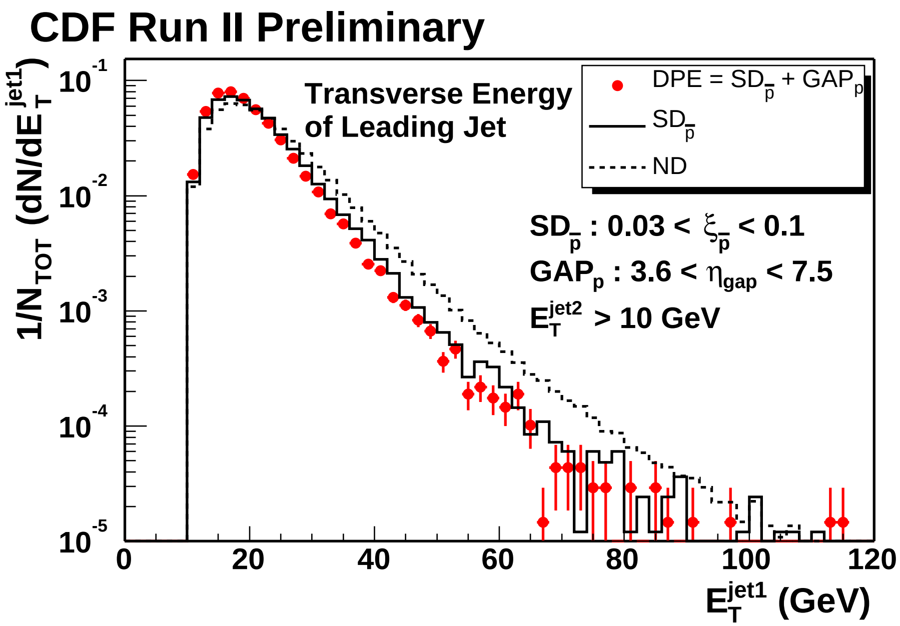
Assume M_{SecVtx} >2 GeV are all *b*-jets

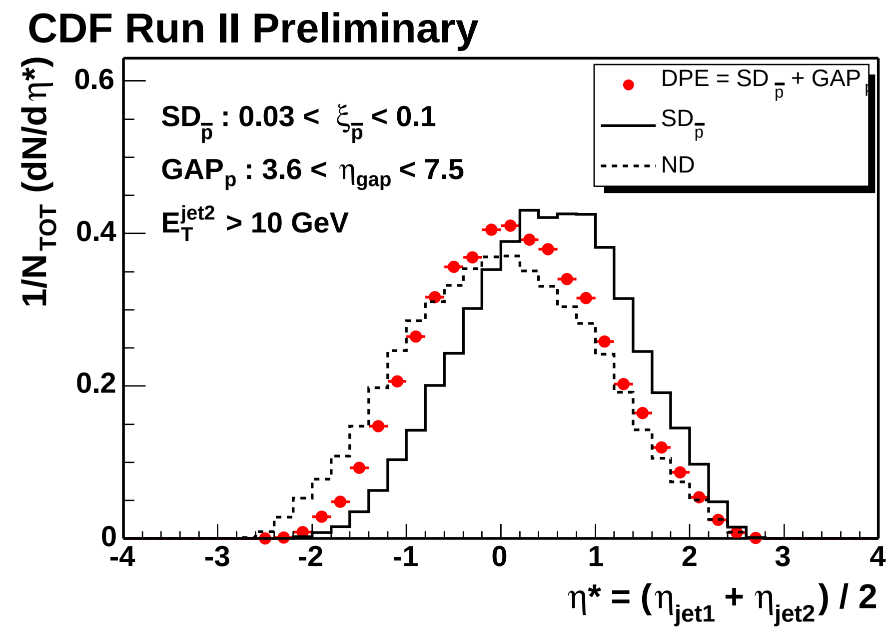
b-Quark Jet Yield :
DPE Narrow vs Wide Gap

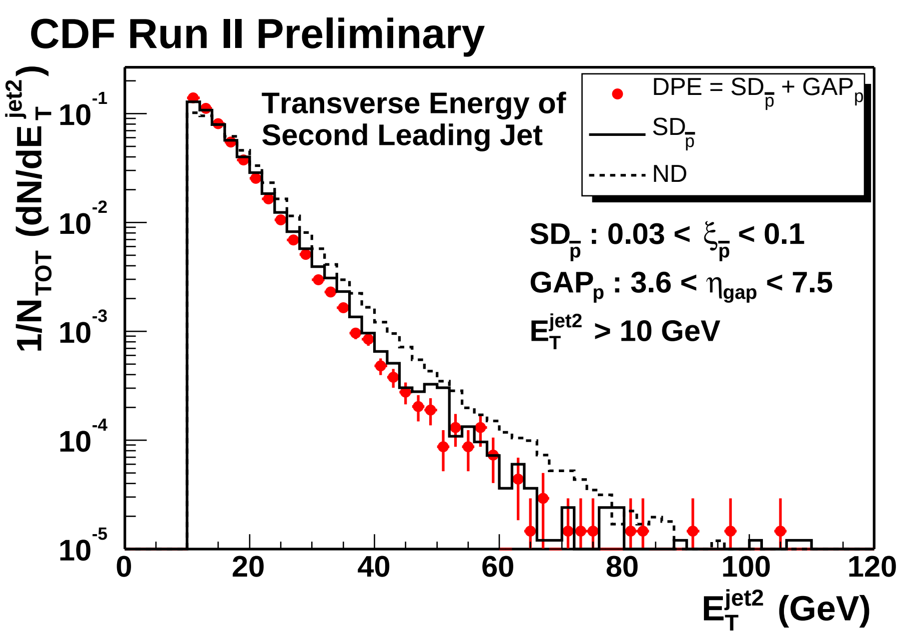


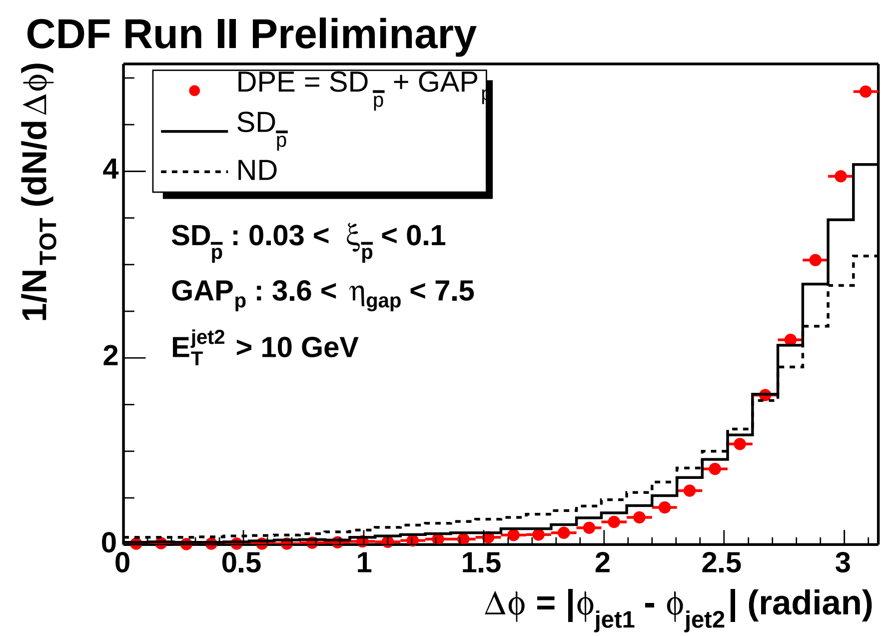


Kinematic Distributions of Jets









Cross Section and Systematics

$$\sigma_{DPE}^{jj}(R_{jj}>0.8)=\frac{N_{DPE}^{PS}(1-F_{BG})}{L\cdot\epsilon\cdot A}$$

N_{DPE}^{PS} : # of observed DPE events with R_{jj}>0.8 corrected for
- prescale factors,
- live time acceptance,
- multiple interactions

F_{BG} : Non-DPE background fraction

L : integrated luminosity

ϵ : trigger and vertex cut efficiencies

A : RP acceptance ≈ 80% $(0.03 < \xi_{\bar{p}} < 0.1)$

Systematic uncertainties on the cross sections

- ***Energy Scale*** — ***TOTAL***

E_T^{min}	Calorimeter: *Central/Plug*	Calorimeter: *MiniPlug*	Jet	TOTAL
10	±28 %	+17 % -7 %	+24 % -26 %	***+41 % -39 %***
25	±15 %	+19 % -10 %	+54 % -36 %	***+59 % -40 %***

- RP acceptance ±10 %
- Luminosity ±6 %

Systematic Uncertainties

Summary

p_T^{jet} range (GeV/c)		10-15	15-25	25-40	10-40
R_b^{DPE}	F_b	±26%	±21%	±30%	±19%
	ϵ^b_{tag}	±7.4%	±8.9%	±4.9%	±6.0%
	SecVtx acc.	+10%	+18%	+13%	+14%
	Total	***+29% -27%***	***+29% -23%***	***+33% -30%***	***+24% -20%***
R_b^{ND}	F_b	±22%	±16%	±27%	±14%
	ϵ^b_{tag}	±7.4%	±8.9%	±4.9%	±6.0%
	SecVtx acc.	+12%	+11%	+19%	+12%
	Total	***+26% -23%***	***+21% -18%***	***+33% -27%***	***+19% -15%***
D_{ND}^{DPE}	F_b	±16% (DPE) / ±10% (ND)			
	SecVtx acc.	±3%			
	Cal. Energy Scale	±4%			
	Total	***±20%***			