DIFFRACTION IN pp COLLISIONS

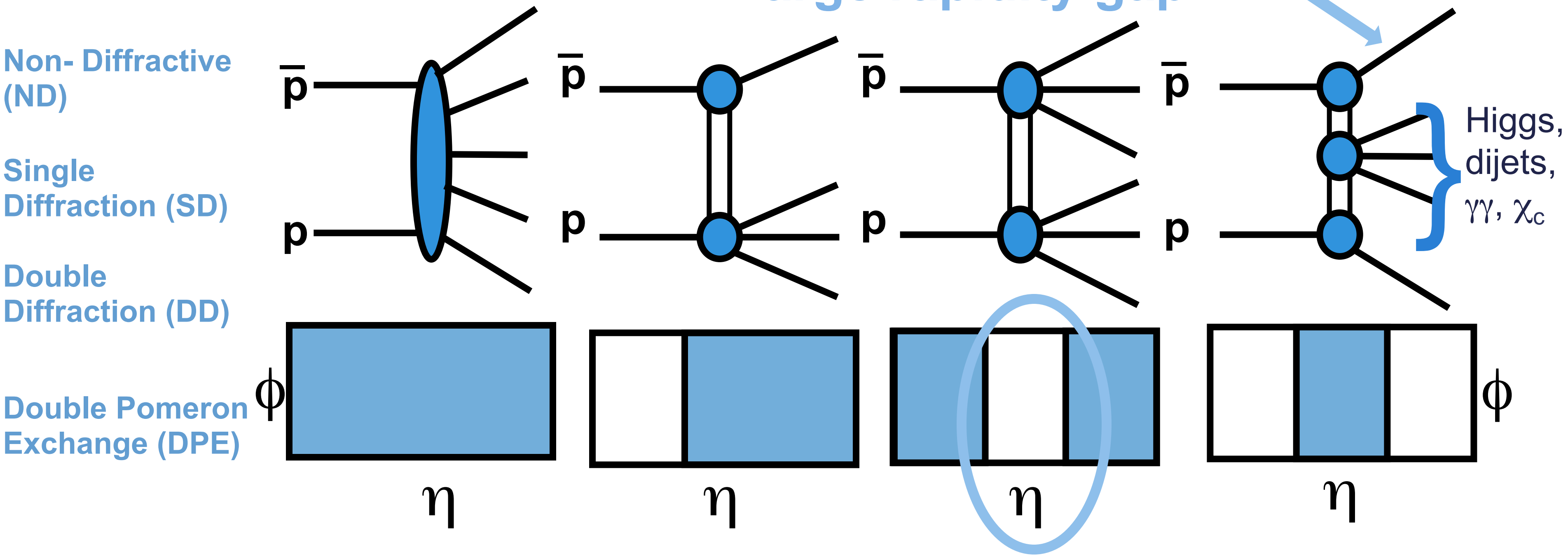
Christina Mesropian

The Rockefeller University

Definitions: Diffraction

- **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



Diffraction: definitions

y - rapidity

η - pseudorapidity

$y = 1/2 \ln((E+p_z)/E-p_z))$

$\eta \equiv y|_{m=0} = -\ln\tan(\vartheta/2)$

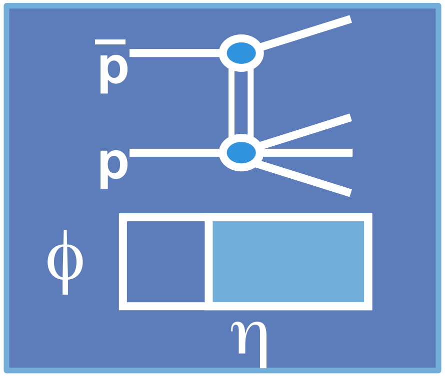
t - four-momentum transfer squared

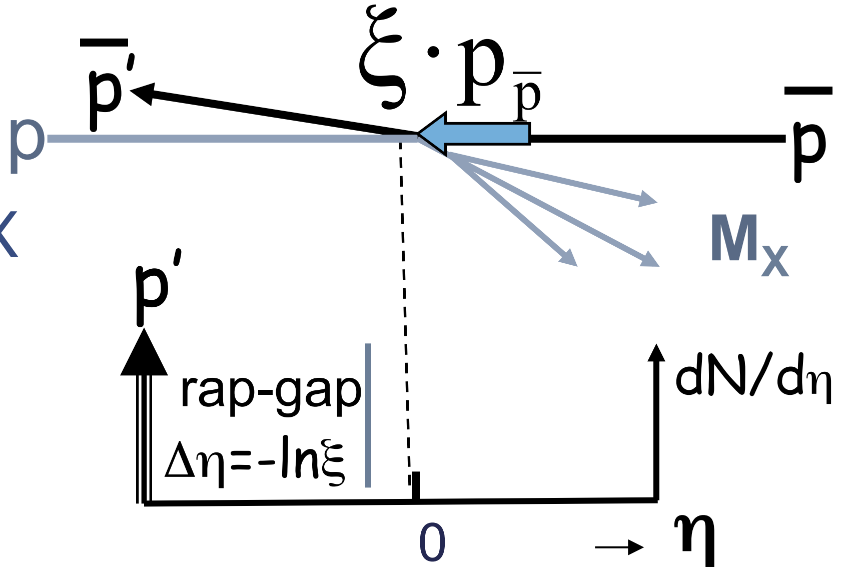
ξ - fractional momentum loss of p/pbar

M_X - mass of diffractive system X

$\xi = M_X^2/s$

$\Delta\eta \approx \ln(s/M_X^2)$





Diffractive Processes

Hadronic processes can be characterized by an energy scale:

***soft processes* -** energy scale of the order of the hadron size (~ 1 fm)
pQCD is inadequate to describe these processes

hard processes – "hard" energy scale (> 1 GeV^2)
can use pQCD,
"factorization theorems" - can separate perturbative part from non-perturbative

Discovery of ***hard diffraction*** - jet production in ppbar collisions with a leading proton in the final state (1988 UA8)

Hard diffractive processes allow to study diffraction in the pQCD framework.

At the Tevatron and LHC we study both soft and hard diffractive processes.

Experimental Techniques

Difffractive processes can be identified either

- by detecting scattered protons
- or by measuring gaps (veto on particle presence or energy flow)

Total room for particle production at LHC: $\Delta\eta \approx \ln(s/m_p^2)$

Rapidity range effectively populated by particles: $\Delta\eta \approx \ln(m_X^2/m_p^2)$

Depends on M_X, e.g. with M_X= 500 GeV: $\Delta\eta \approx 12$

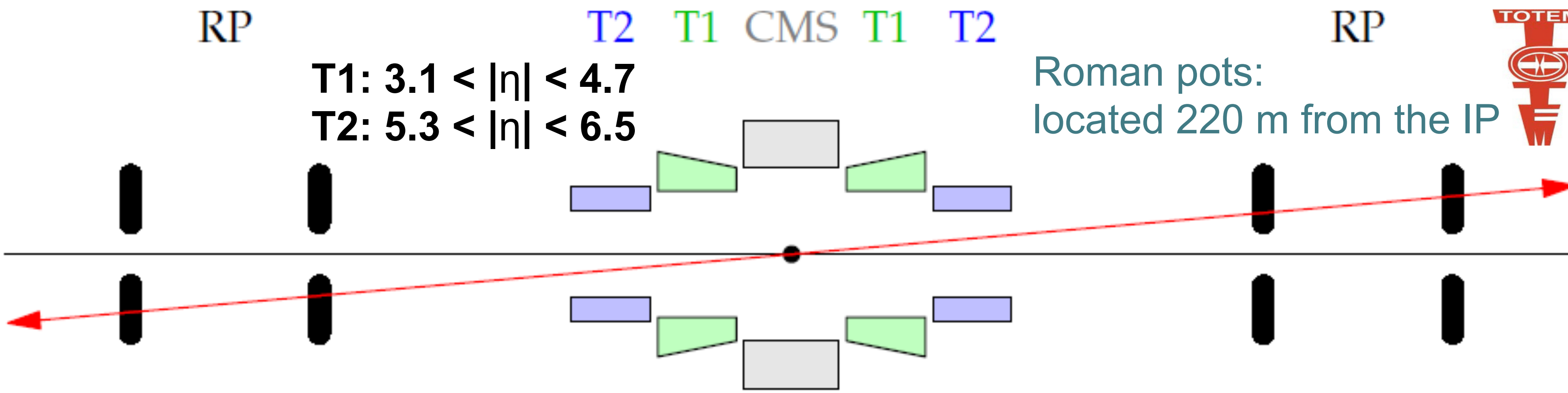
The resulting gap size depends on the process, e.g. in central diffraction, assuming two symmetric gaps, each will have a size of $\Delta\eta \approx ½ (20-12) \approx 4$ i.e. very forward, often outside CMS-ATLAS acceptance

Challenges of detecting Large Rapidity Gaps

- The rapidity gap(s) maybe very forward and outside CMS-ATLAS acceptance
- Pileup events destroy the gap(s)
- The gap(s) survival probability is low

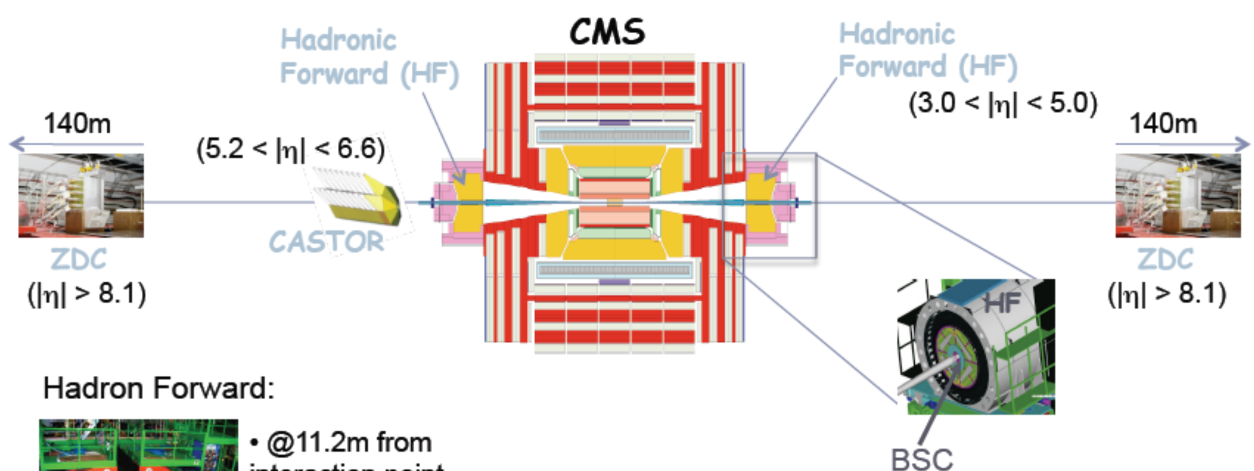
- **LRG not always/really usable => proton tracking (and timing) detectors**

Experimental Techniques



T1: 3.1 < |η| < 4.7
T2: 5.3 < |η| < 6.5

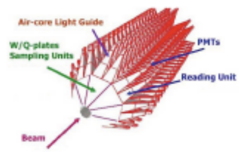
Roman pots:
located 220 m from the IP



Hadron Forward:

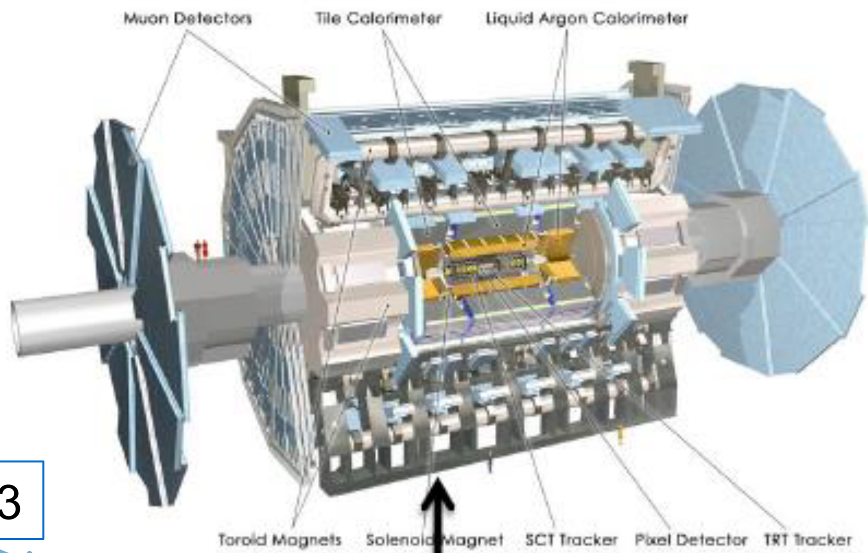
- @11.2m from interaction point ($3 < |\eta| < 5$)
- Steel absorbers/ quartz fibers (Long +short fibers)

CASTOR:



- W absorber/quartz plates ($5.2 < \eta < 6.6$)
- 16 segments in φ (EM/HAD) segments in z (no η segmentation)

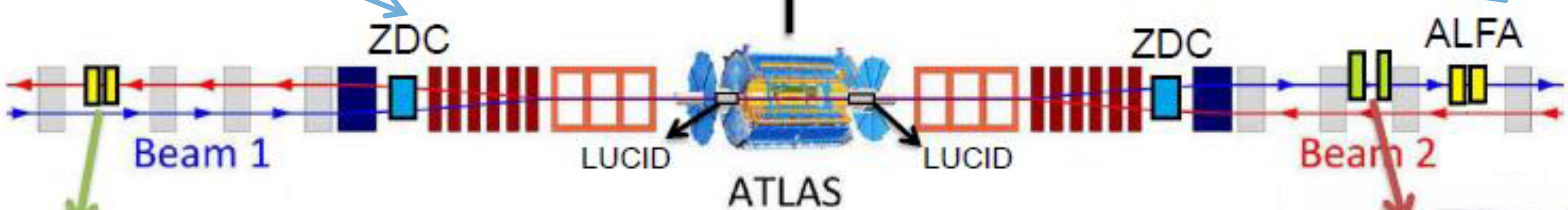
Experimental Techniques

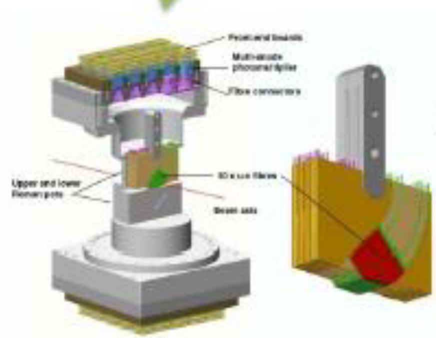


Roman pots:
located 240 m from the IP
- 4 stations, 8 detectors
Detectors:
scintillating fibers

$|\eta|>8.3$

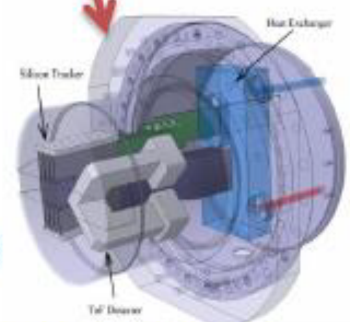
10.6-13.5



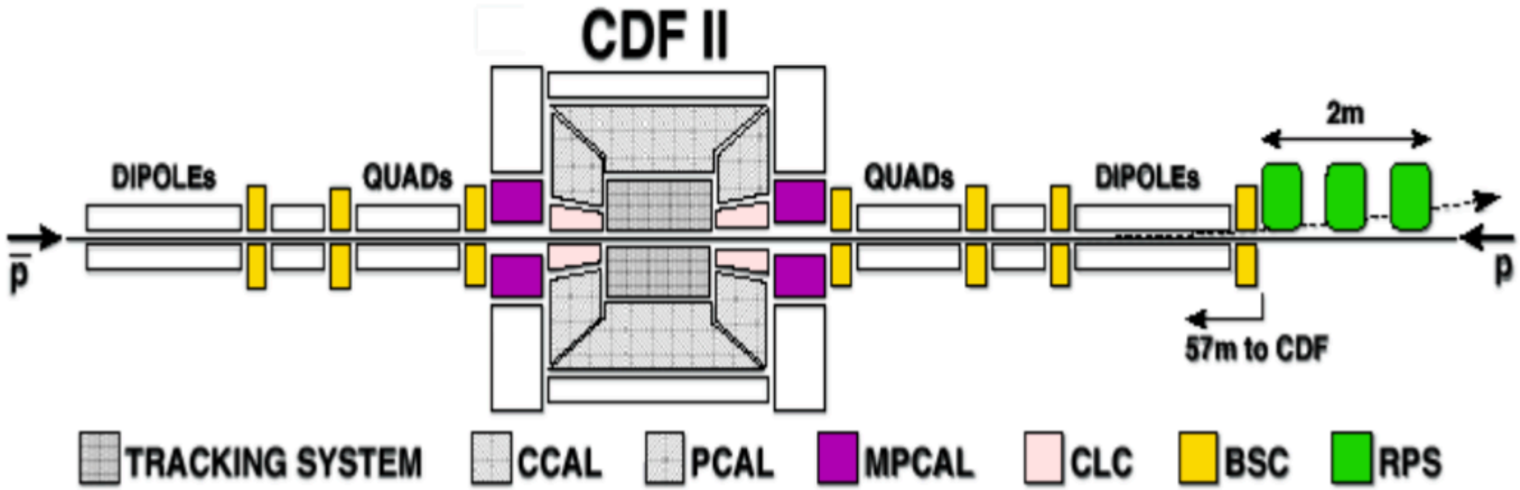


<u>ALFA</u>:
elastic protons
measurement

<u>AFP</u>:
diffractive protons
measurement.
A first-phase installation
in 2016.
CERN-LHCC-2015-009; ATLAS-TDR-024

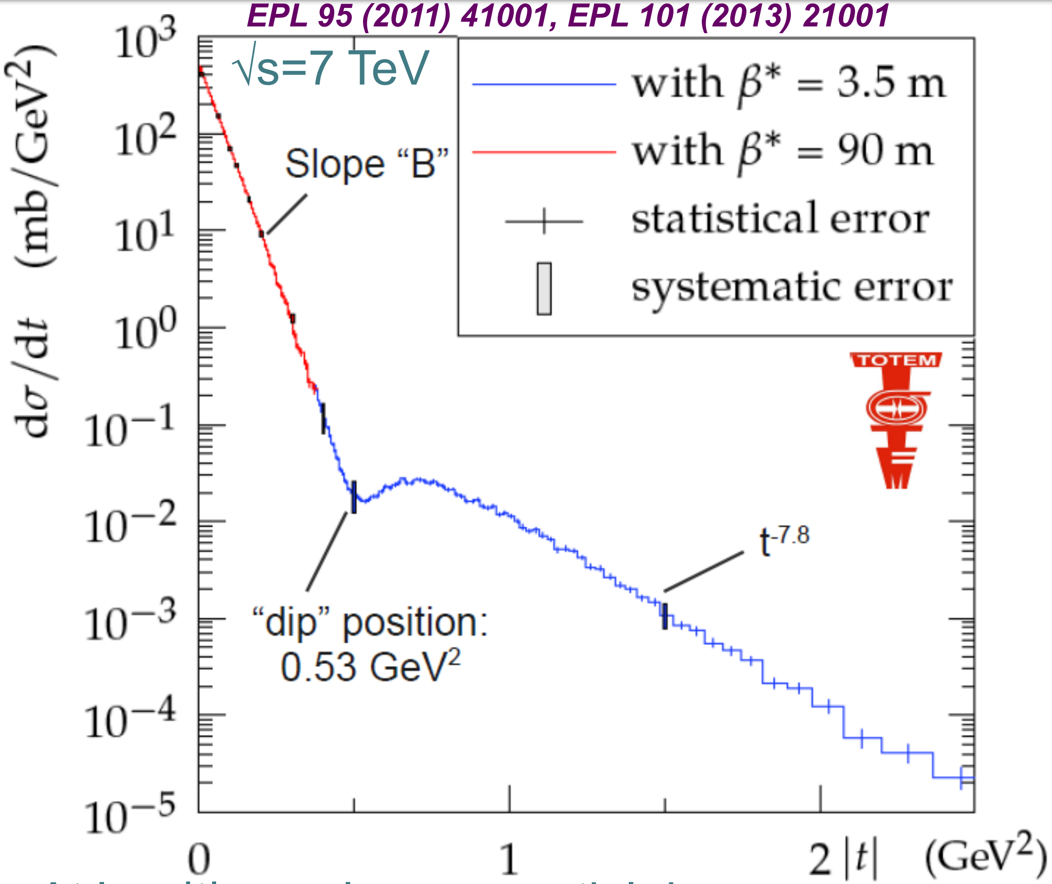


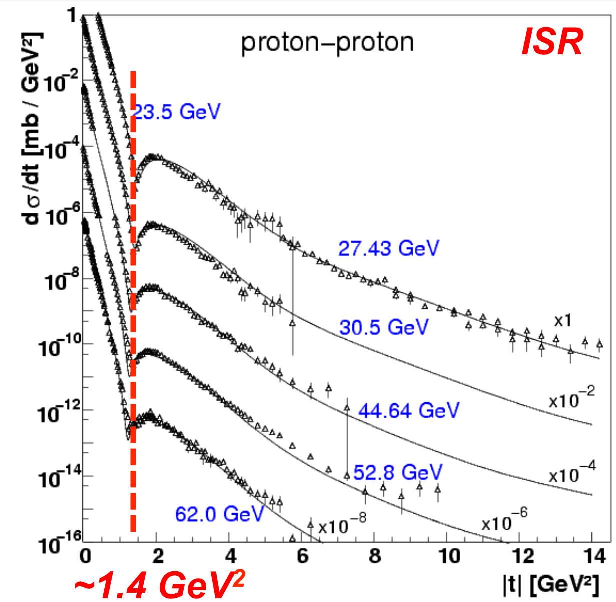
Experimental Techniques

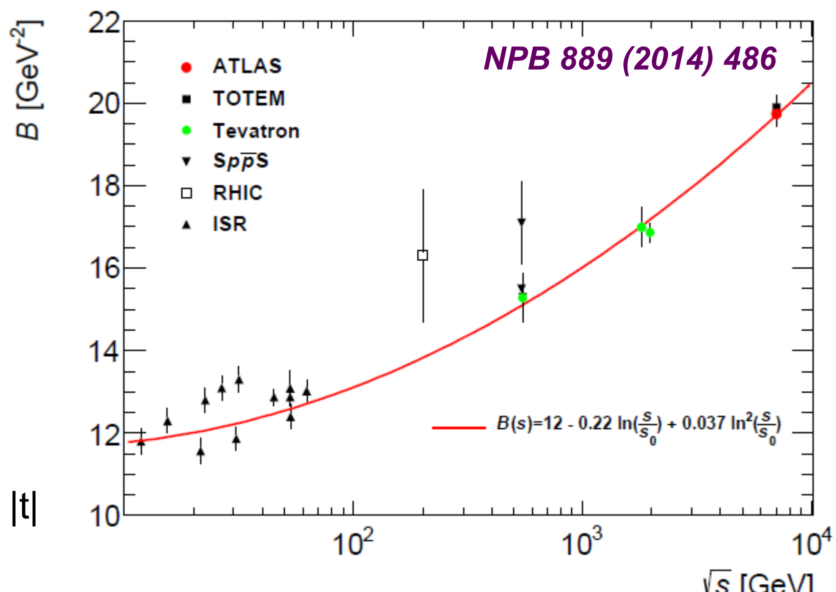


	Tracking	–	Tracking Detectors	$|\eta| < 2.0$
	CCAL, PCAL	–	Calorimeters (15°(in φ)x0.1(in η))	$|\eta| < 3.6$
	RPS	–	Roman Pot Spectrometers	$0.02 < \xi < 0.1$ $0 < |t| < 2$ GeV^2
	BSC	–	Beam Shower Counters	$5.4 < |\eta| < 7.4$
	MPCAL	–	MiniPlug Calorimeters	$3.5 < |\eta| < 5.1$

Elastic Scattering







At low |t|: nearly exponential decrease:

TOTEM B=19.9±0.3 GeV^{-2}

ATLAS B=19.7±0.3 GeV^{-2}

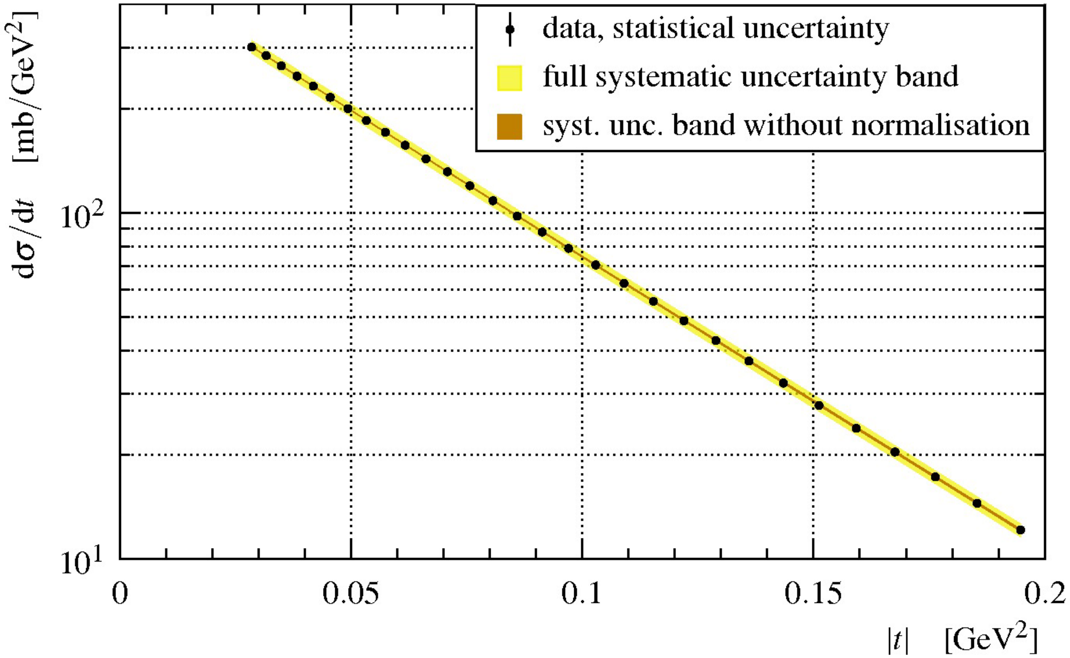
Old trends for increasing √s are confirmed:

- "shrinkage of the forward peak": minimum moves to lower |t|
- forward exponential slope B increases

Elastic Scattering - low |t|

0.027 GeV² < |t| < 0.2 GeV²
(Coulomb effect negligible)

arXiv:1503.08111
NPB 899 (2015) 527

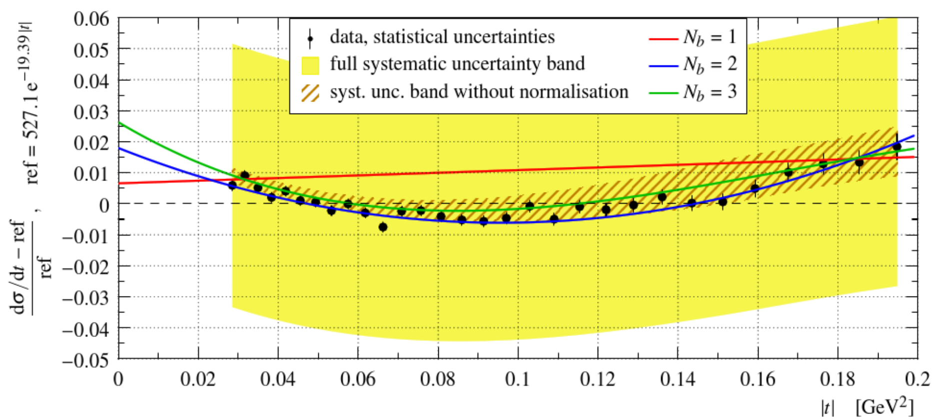


Special beam optics
with $\beta^* = 90$ m

Looks exponential but closer look reveals…

Plotting relative deviation from exponential and fitting $d\sigma/dt = Ae^{-B(t)\,|t|}$ with

$B(t) = b0$
or $B(t) = b_0 + b_1 t$
or $B(t) = b_0 + b_1 t + b_2 t^2$



Pure exponential fit excluded with 7.2 σ significance

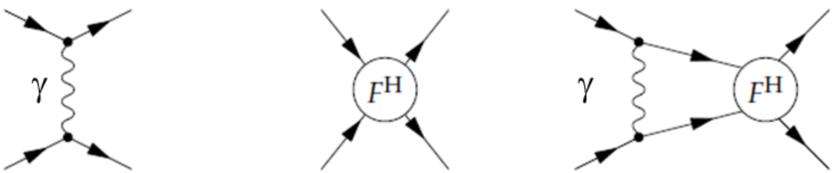
N_b	χ^2/ndf	p-value	significance
1	$117.5/28 = 4.20$	$6.1 \cdot 10^{-13}$	$7.2\,\sigma$
2	$29.3/27 = 1.09$	0.35	$0.94\,\sigma$
3	$25.5/26 = 0.98$	0.49	$0.69\,\sigma$

Elastic Scattering – very low |t| and ρ

$6 \cdot 10^{-4}$ GeV^2 < |t| < 0.2 GeV^2

CERN-PH-EP-2015-325

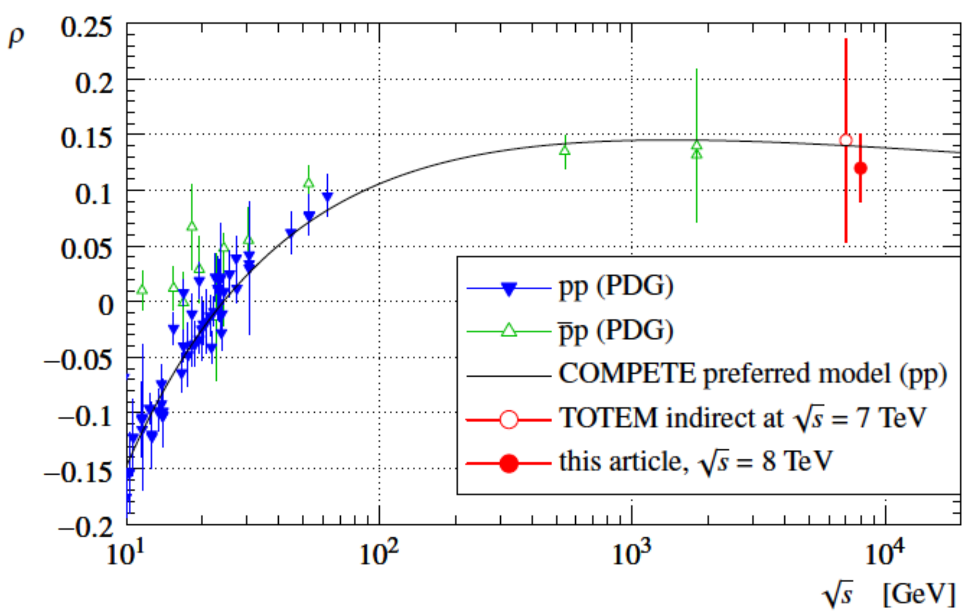
Constrain models of Coulomb-nuclear interference (nuclear phase Ψ, B(t))



$$F^{C+H} = F^{C} + F^{H} e^{i\alpha\Psi}$$

Special beam optics with $\beta^* = 90\ m$ and $\beta^* = 1000\ m$

data are compatible with hadronic phase - giving either central or peripheral behavior in the impact parameter picture of elastic scattering.



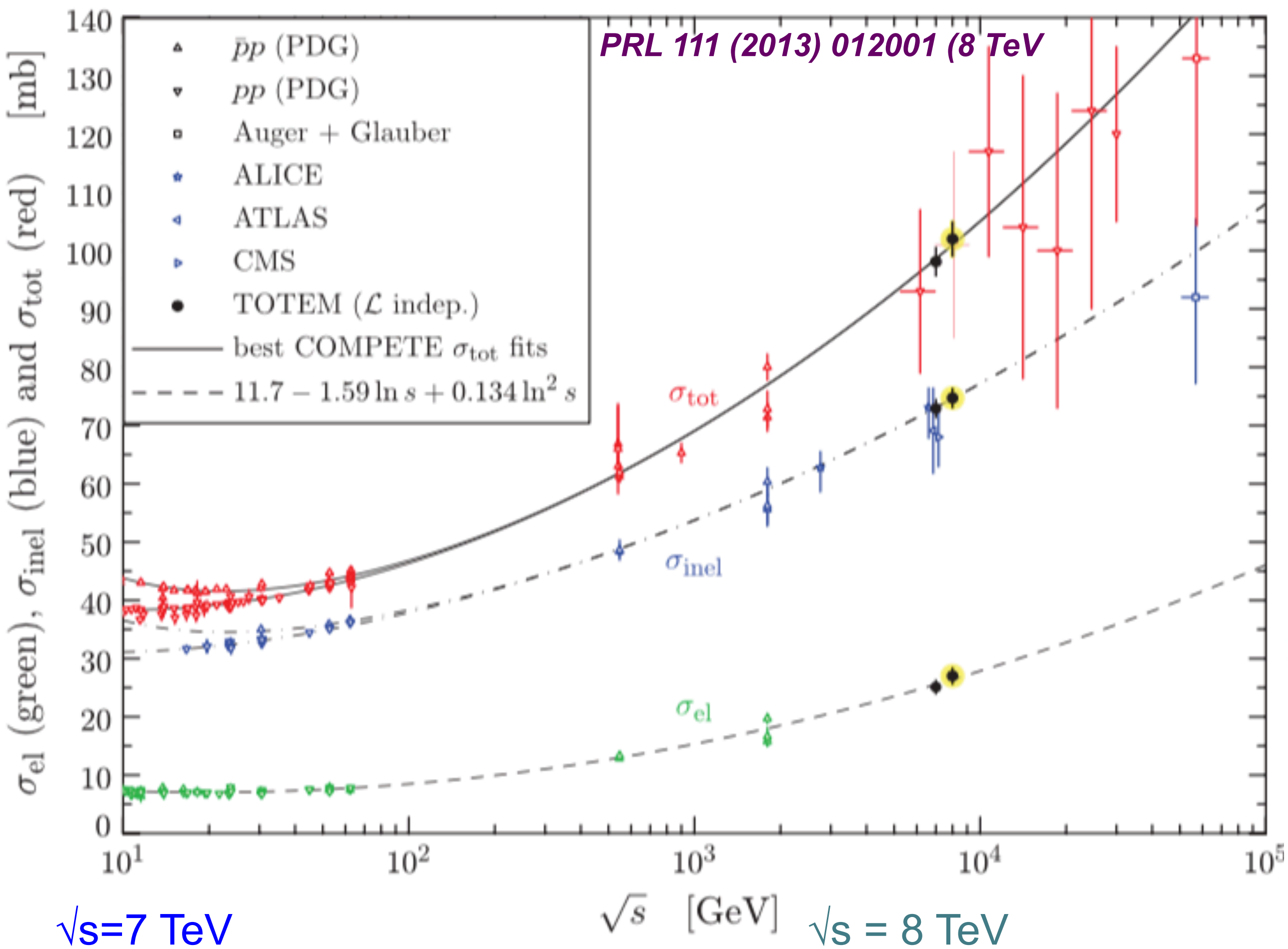
$$\rho = \frac{\mathrm{Re}(f_{el})}{\mathrm{Im}(f_{el})}\Big|_{t \to 0}$$

first time at LHC extracted via the CNI

ρ = 0.12 ± 0.03

Total Cross Section

EPL 101 (2013) 21004 (7 TeV)



From elastic observables:

$$\sigma_{tot}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2} \left.\frac{d\sigma_{el}}{dt}\right|_{t\to 0}$$

Luminosity independent:

$$\sigma_{tot} = \frac{16\pi}{1+\rho^2} \frac{dN_{el}/dt|_0}{N_{el}+N_{inel}}$$

ρ independent:

$$\sigma_{tot} = \frac{1}{\mathcal{L}}(N_{el}+N_{inel})$$

All three methods in agreement.

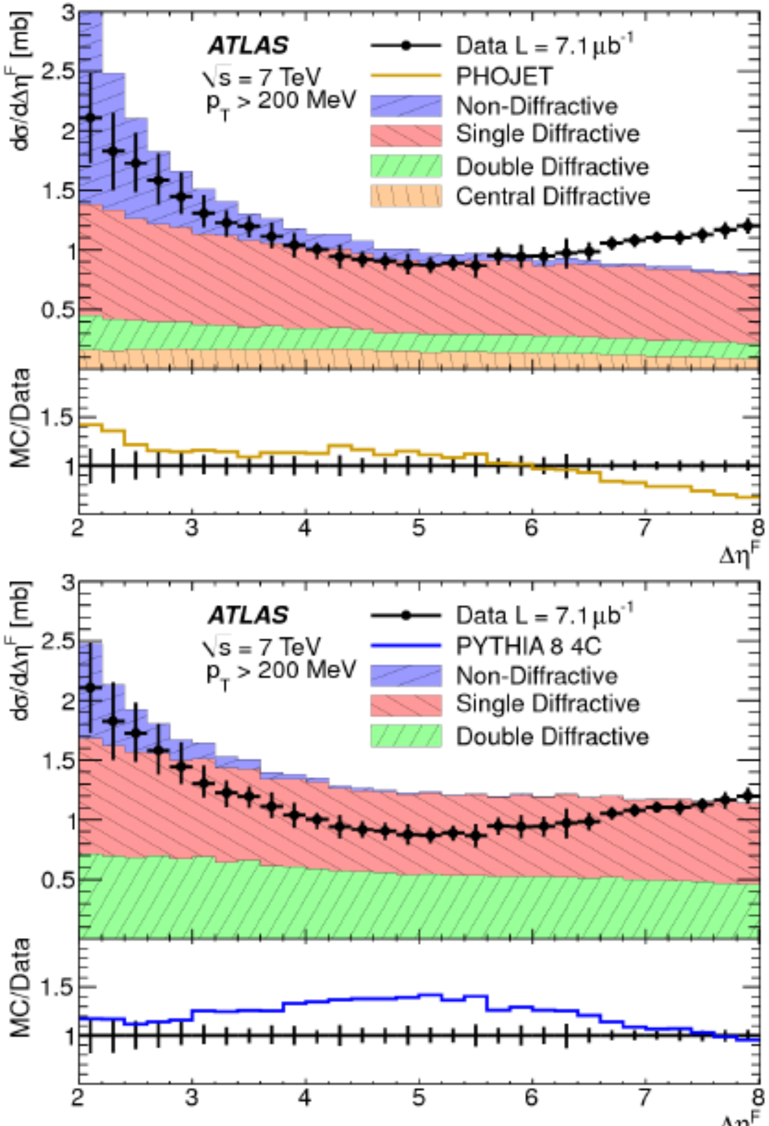
√s=7 TeV
ATLAS+ALFA σ_{tot} =95.4 ±1.4mb
TOTEM σ_{tot}=98.6 ± 2.2mb

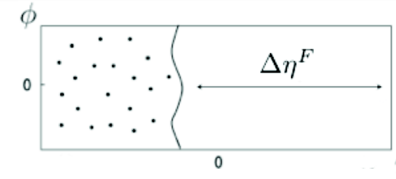
√s = 8 TeV
TOTEM σ_{tot}=101.7± 2.9mb
102.9 ±2.3mb for central
103.0 ±2.3mb for peripheral phase formulations

Soft Diffraction

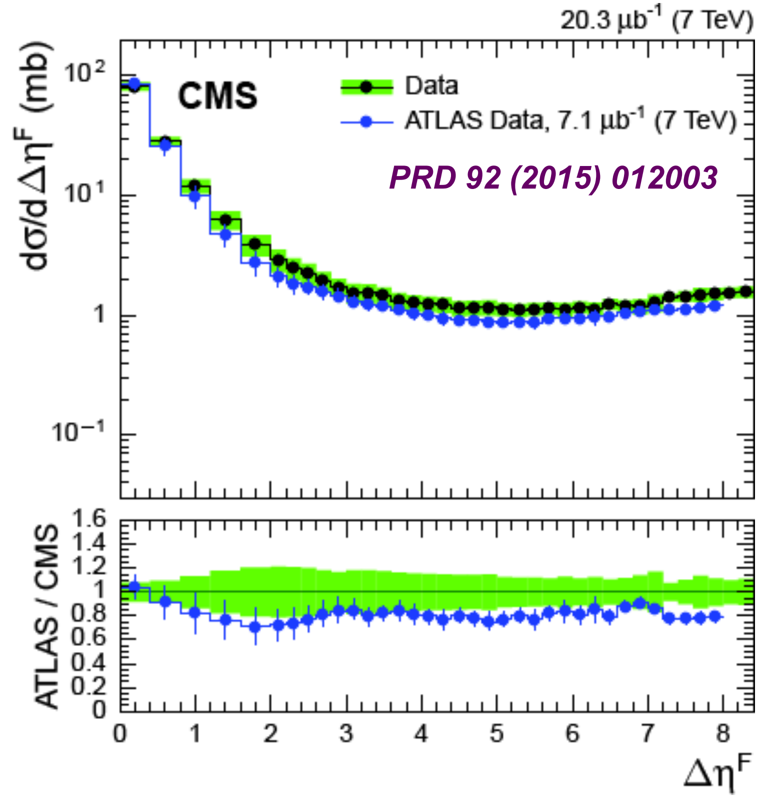
EPJC 72 (2012) 1926

Cross Section for Forward rapidity gap





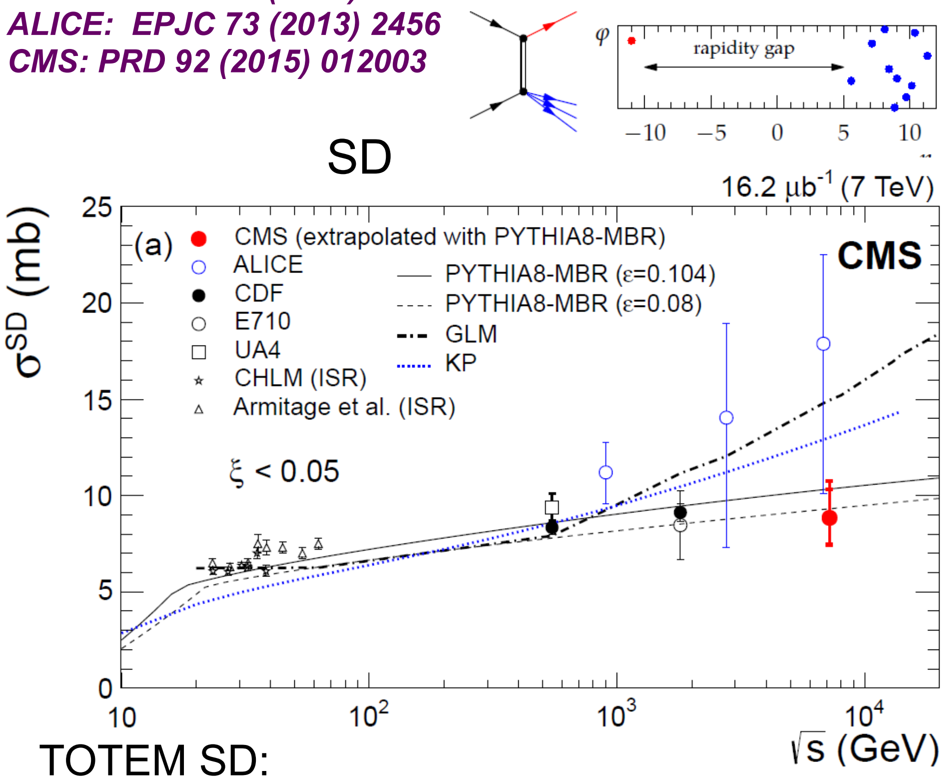
Diffractive events at high values of $\Delta\eta_F$

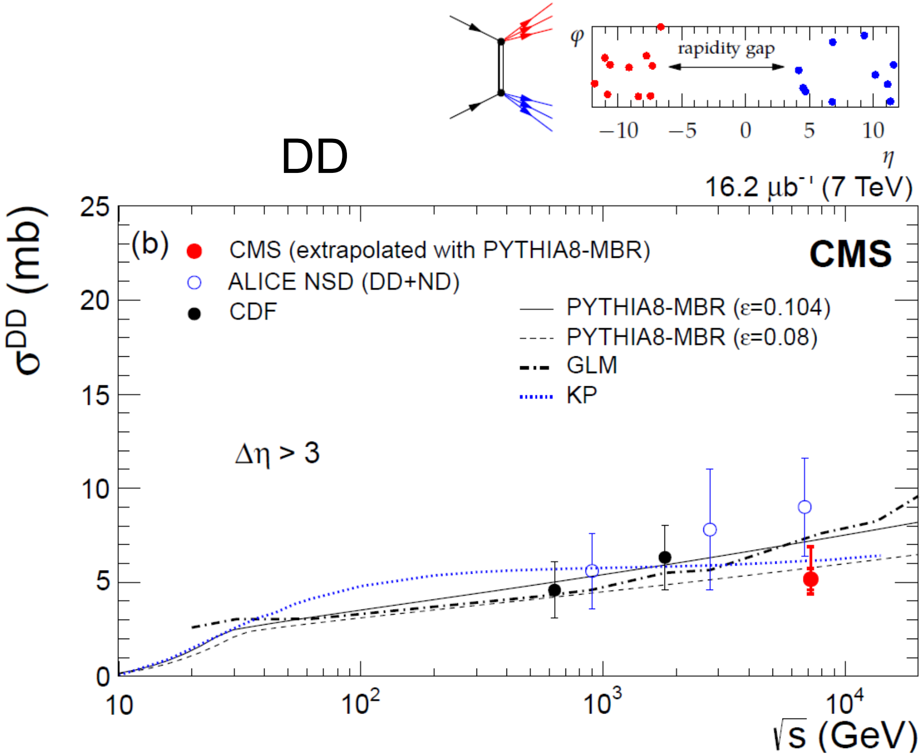


Interesting for tuning MCs and testing various diffractive models

SD and DD Cross Sections

TOTEM: PRL 111 (2013) 262001
ALICE: EPJC 73 (2013) 2456
CMS: PRD 92 (2015) 012003



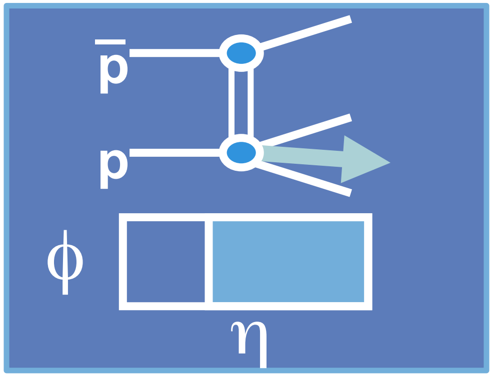


TOTEM SD:

6.5 ± 1.3 mb – SD cross section for 3.4 < MX < 1.1 GeV
2.62 ± 2.17 mb - T2-invisible cross section for MX < 3.4 GeV (SD dominated)
9.12 ± 2.53 mb - for ξ <0.025 (extrapolation to ξ <0.05 compensated by DD in T2-invisible cross section)

in agreement with extrapolated CMS SD cross section.

Hard Single Diffraction



Diffractive signature:

- ❑ large rapidity gap
- ❑ intact p/pbar detected in RomanPots

Can study diffractive production of high p_T objects:
jets, W, J/Ψ, b
different insight into the nature of Pomeron

Diffractive dijet cross section

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

at LO

Study the diffractive structure function $F_{jj}^{D} = F_{jj}^{D}(x, Q^2, t, \xi)$

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

Data

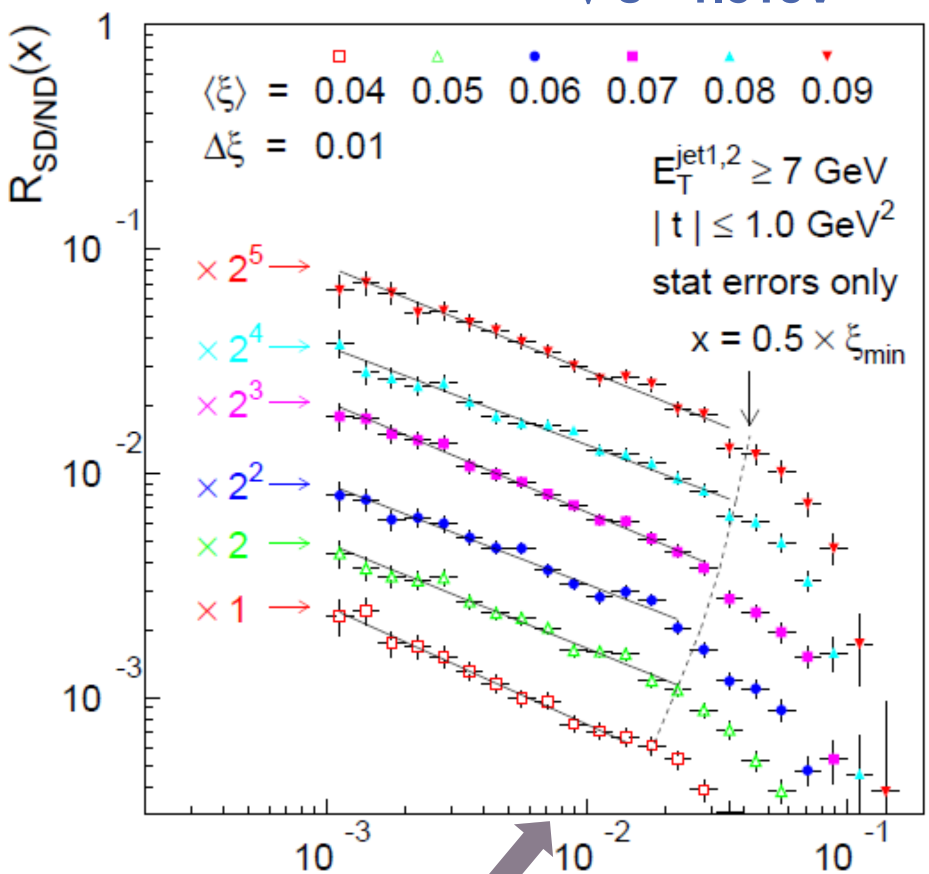
$$R_{\frac{SD}{ND}}(x,\xi) = \frac{\sigma(SD_{jj})}{\sigma(ND_{jj})} = \frac{F_{jj}^{D}(x,Q^2,\xi)}{F_{jj}(x,Q^2)}$$

known PDF

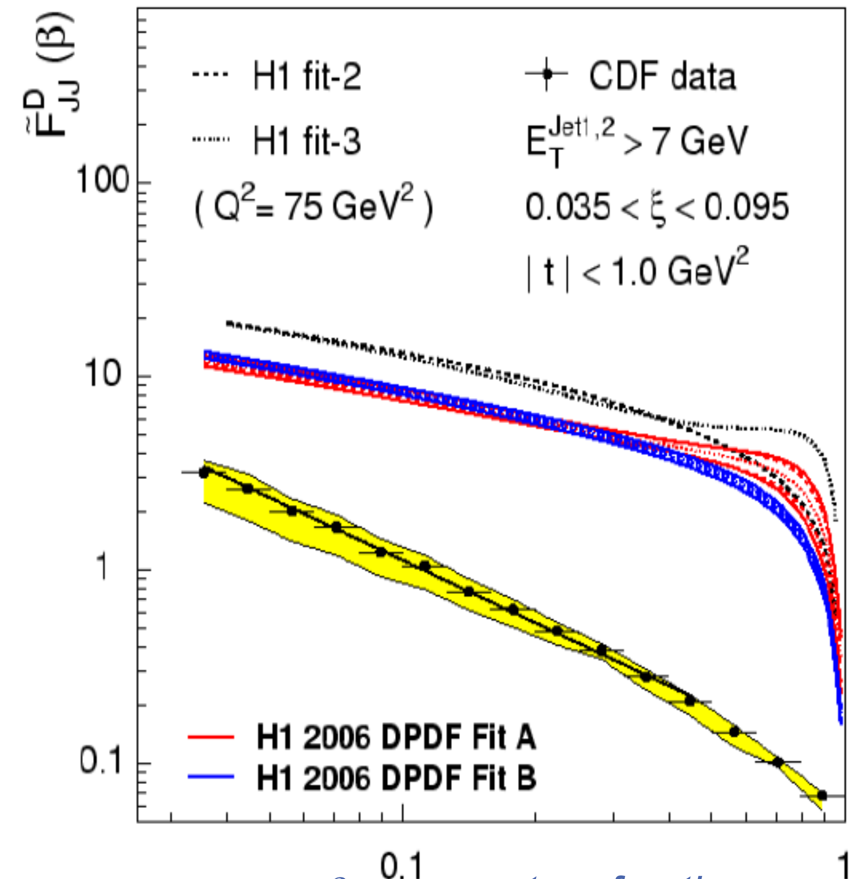
Diffractive Dijets

PRL 84, 5043 (2000)

√ s= 1.8TeV



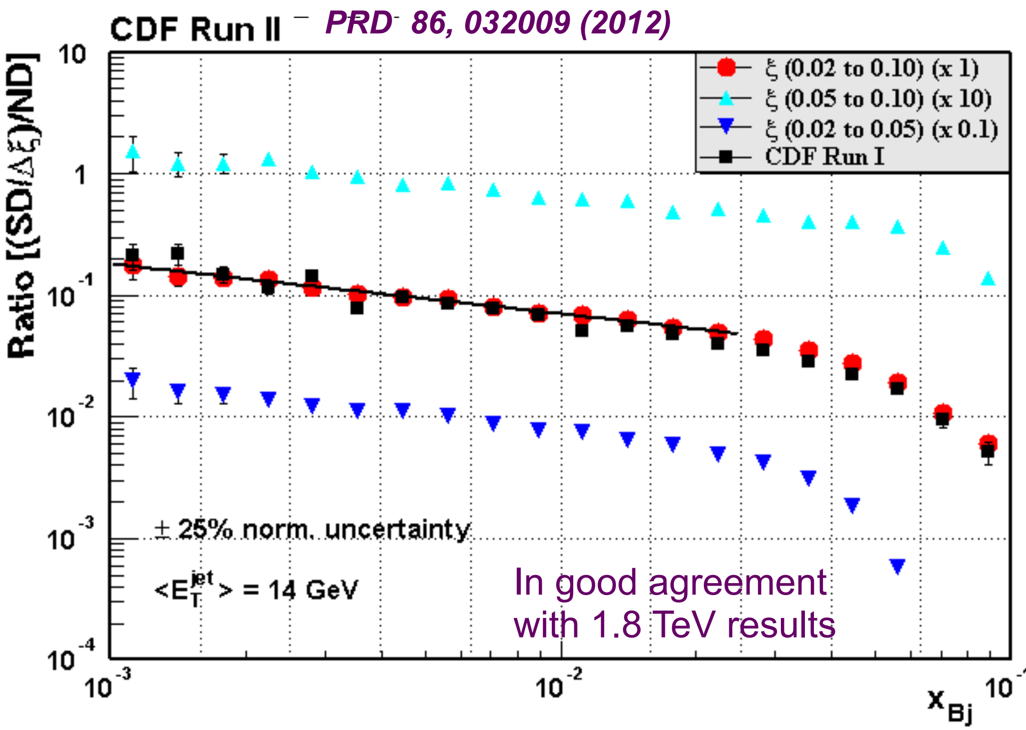
no ξ dependence



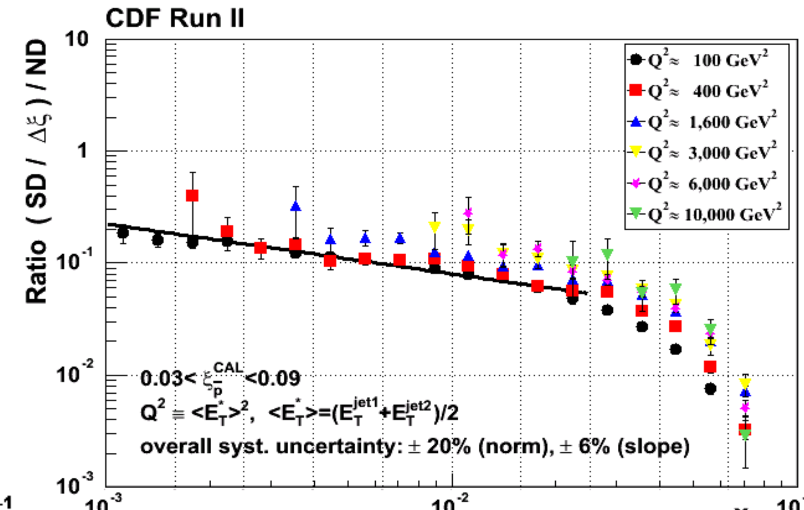
β - momentum fraction of parton in pomeron

Factorization breakdown between HERA and Tevatron

Hard Diffraction



CDF Diff. Dijets at √s= 1.96 TeV triggered by intact pbar in RPS



Q^2 varies from 100-10,000 GeV^2

Looking at Fraction for various single hard diffractive productions:

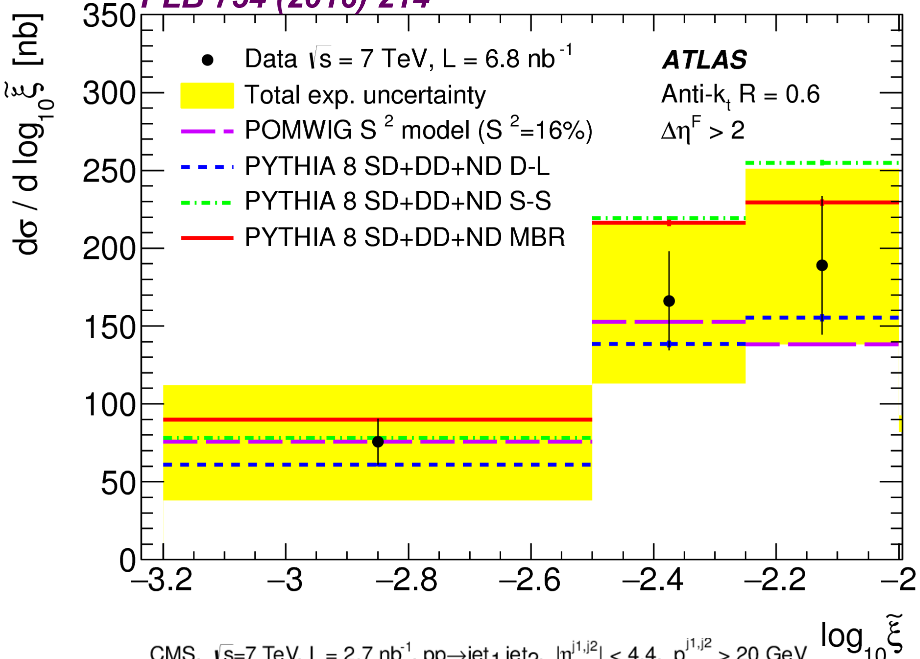
R≡SD/ND ratio
@ 1800 GeV

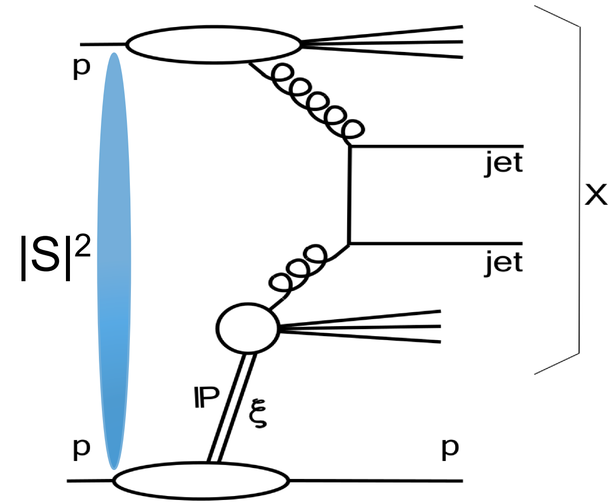
All fractions ~ 1%
(differences due to kinematics)
➢ ~ uniform **suppression**

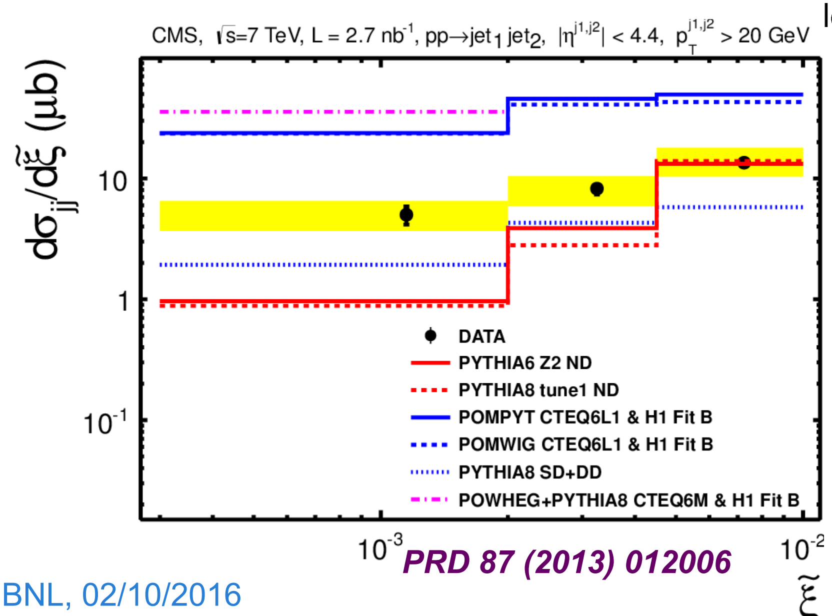
Hard component	Fraction (R) %
Dijet	0.75 ± 0.10
W	1.15 ± 0.55
b	0.62 ± 0.25
J/ψ	1.45 ± 0.25

Diffractive Dijets at LHC

PLB 754 (2016) 214







PRD 87 (2013) 012006

ATLAS ($-3.2 < \log_{10}\xi < -2.5$):
(POMWIG/PYTHIA8 extraction)

$S^2 = 0.16 \pm 0.04$ (stat.) ± 0.08 (exp. syst.)

CMS ($0.0003 < \xi < 0.002$):
After proton-dissociation correction

$S^2 = 0.12 \pm 0.05$ (LO)
$S^2 = 0.08 \pm 0.04$ (NLO)

Diffractive W Production

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

Identify diffractive events using RP:
accurate event-by-event ξ measurement
no gap acceptance correction needed
can still calculate ξ^{cal}

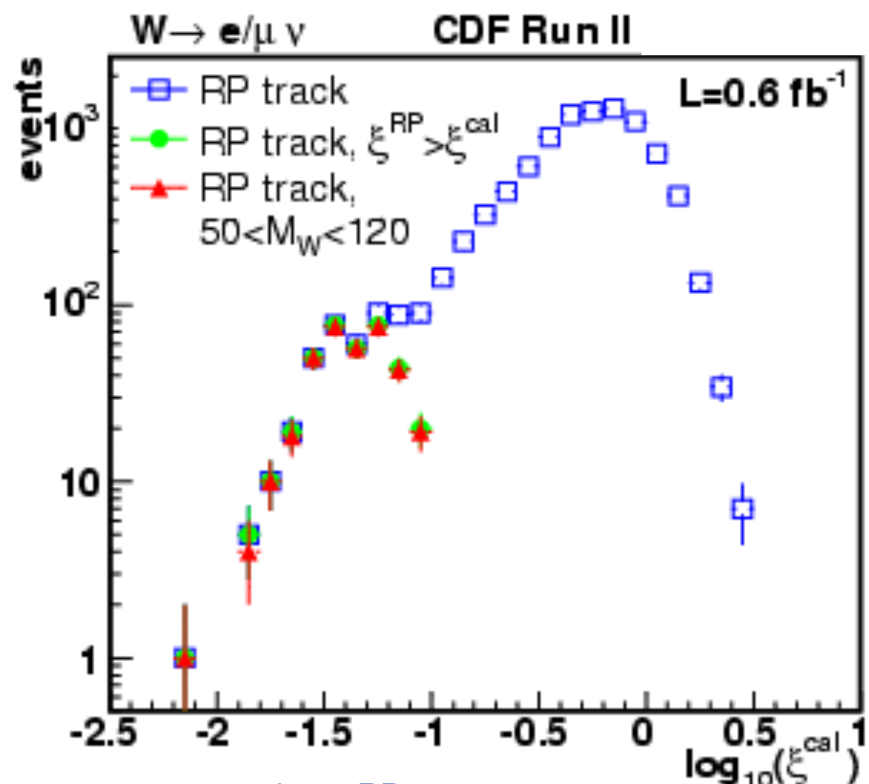
$$\xi^{cal} = \sum_{towers} \frac{E_T}{\sqrt{s}} e^{-\eta}$$

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

PRD 82,112004 (2010) √s= 1.96 TeV



- $\xi^{cal} < \xi^{RP}$ requirement removes most events with multiple pbar-p interactions

Fraction of diffractive W

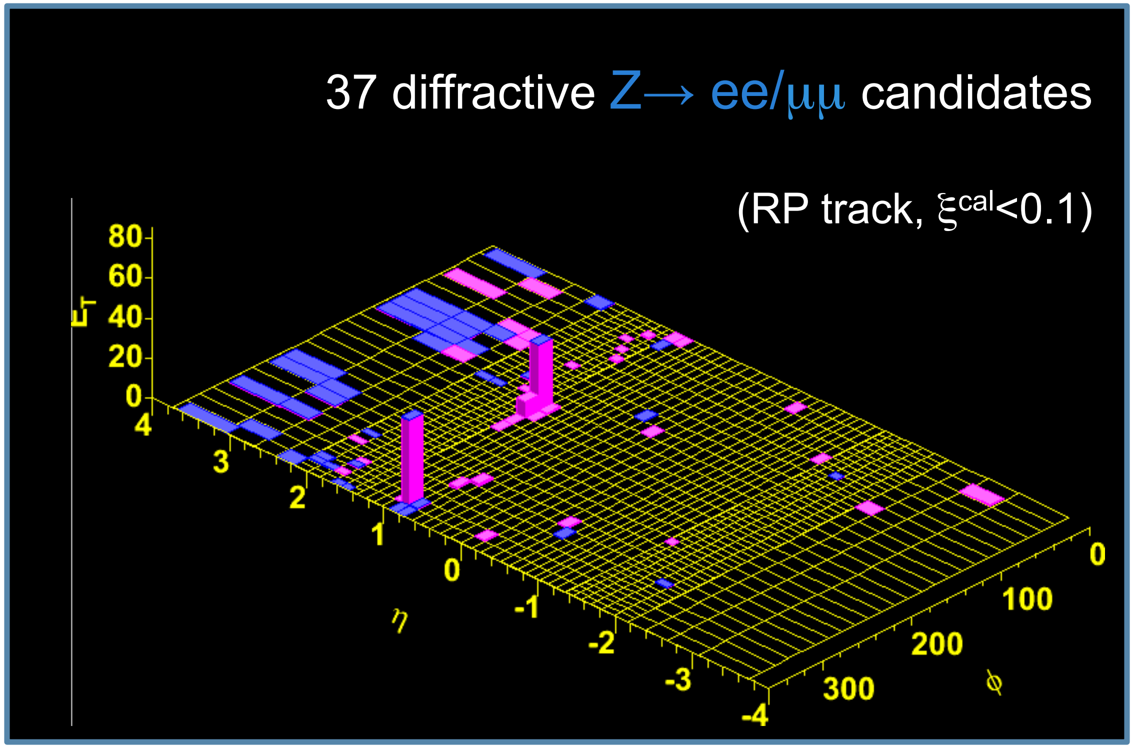
R_W (0.03<ξ<0.10, |t|<1)= [0.97 ±0.05(stat) ±0.10(syst)]%

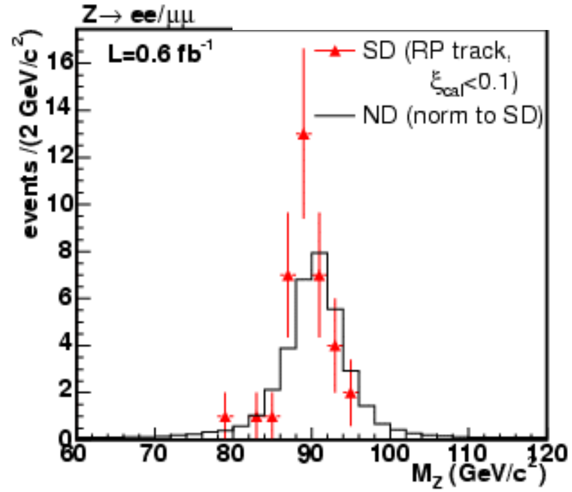
consistent with Run I result (with Large Rapidity Gap method), extrapolated to all ξ

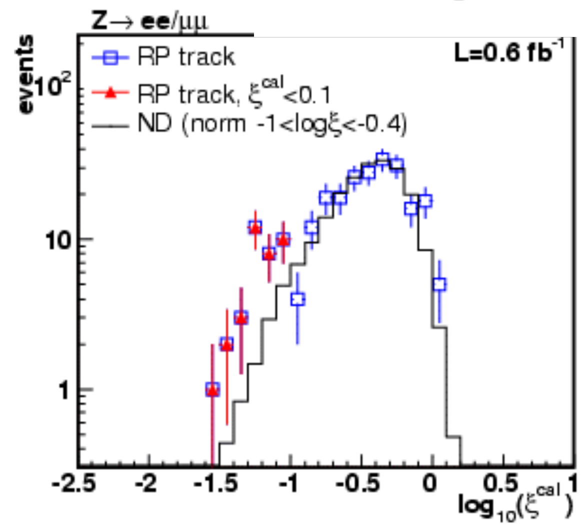
Diffractive Z Production

PRD 82, 112004, 2010

√s= 1.96 TeV
CDF Run II







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

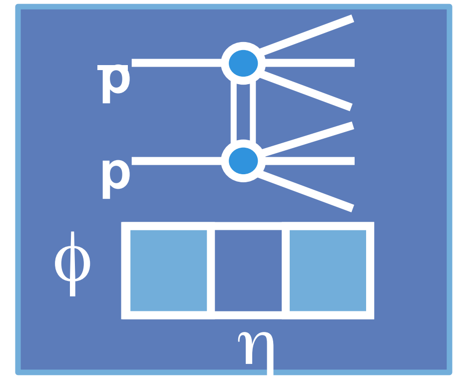
Fraction of diffractive Z

R_Z (0.03< ξ <0.10, |t|<1)= [0.85±0.20(stat)±0.08(syst)]%

Double Diffraction

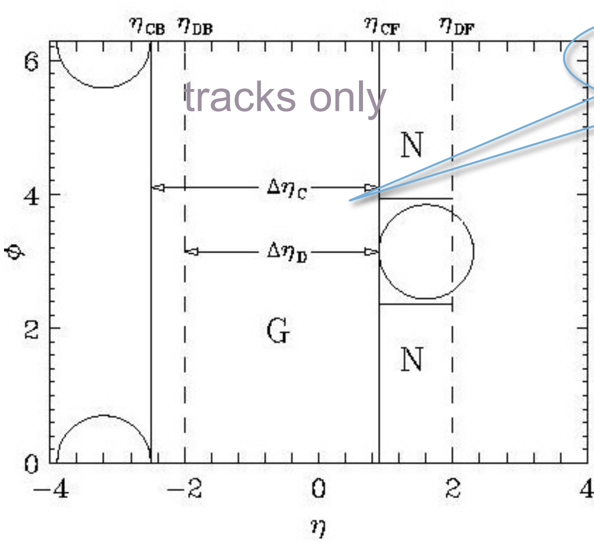
Jets separated by a large rapidity gap - Color Singlet Exchange (CSE)

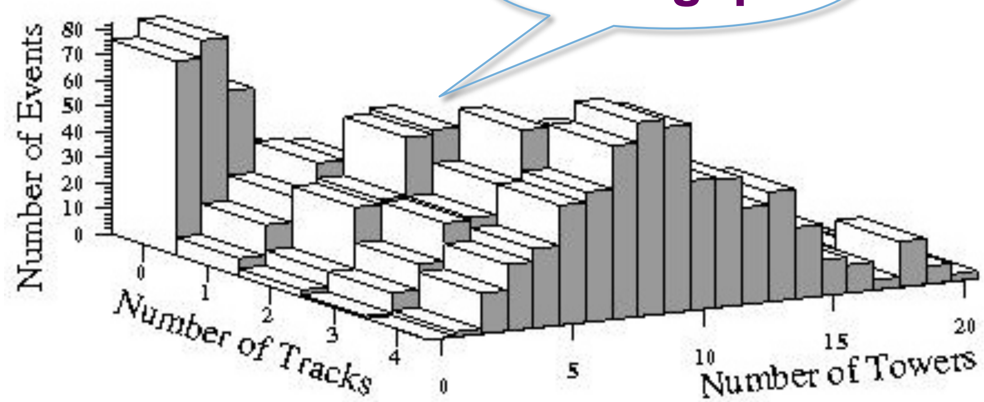
PRL 72, 2332, 1994 (D0)
PRL 74, 855, 1995 (CDF)
PRL 80, 1156, 1998 (CDF)



Diffractive signature:
large central rapidity gap – slightly different gap definitions

Bjorken's estimate of gap "survival" probability $\langle S \rangle \sim 0.1$
PRD 47, 101, 1993

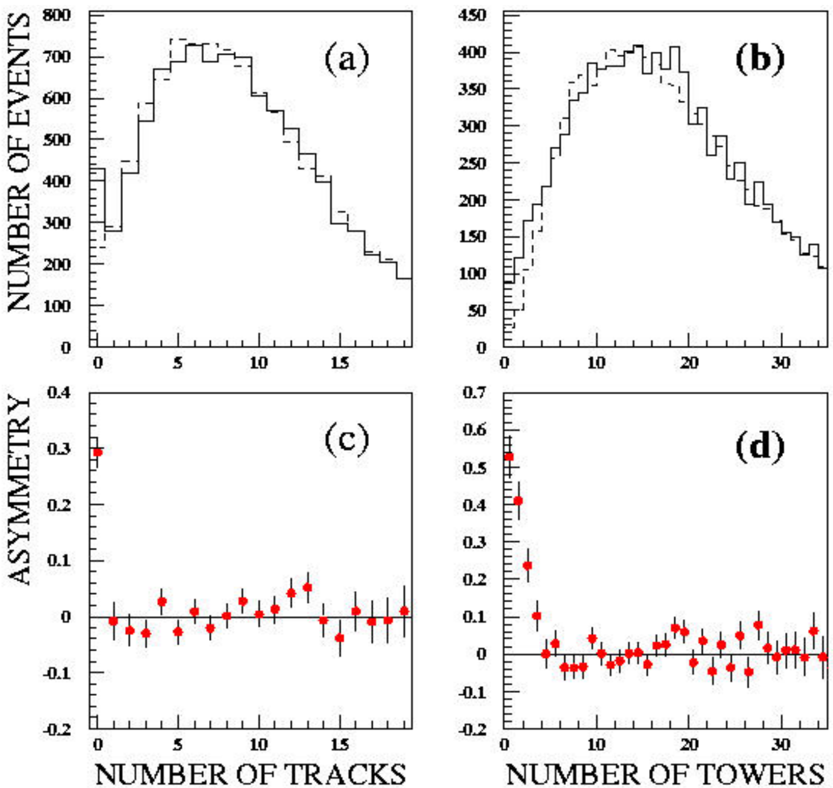




Jet-Gap-Jet at the Tevatron

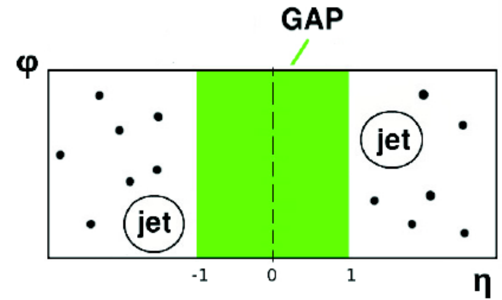
CDF
R=[1.13±0.12(stat) ±0.11(syst)]% @ 1800 GeV
R=[2.7±0.7(stat) ±0.6(syst)]% @ 630 GeV

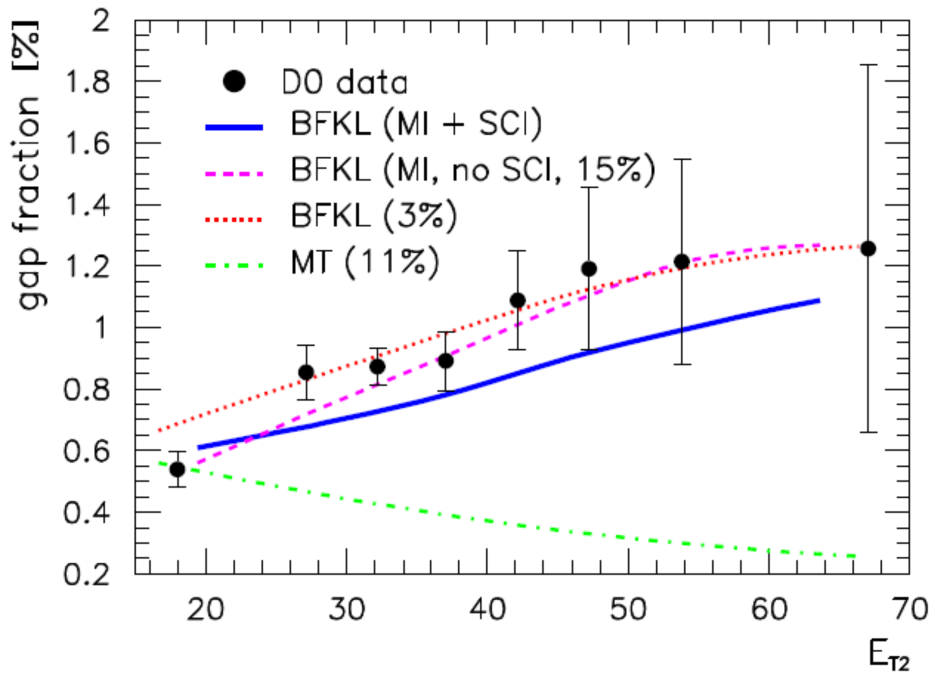
PRL 80, 1156, 1998



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

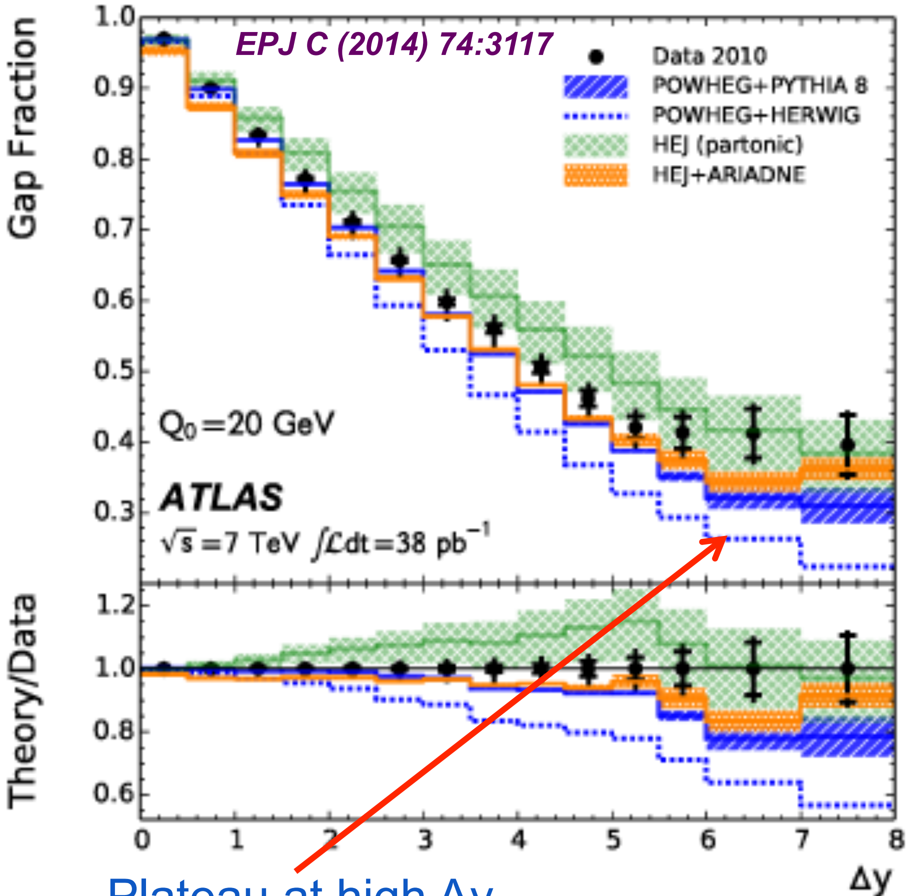
PLB 524 (2002) 273



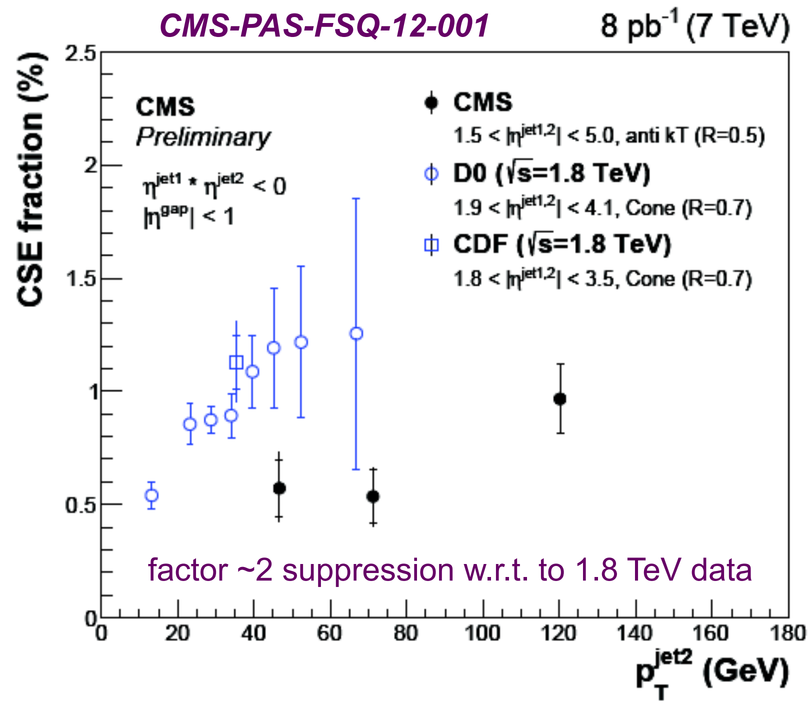


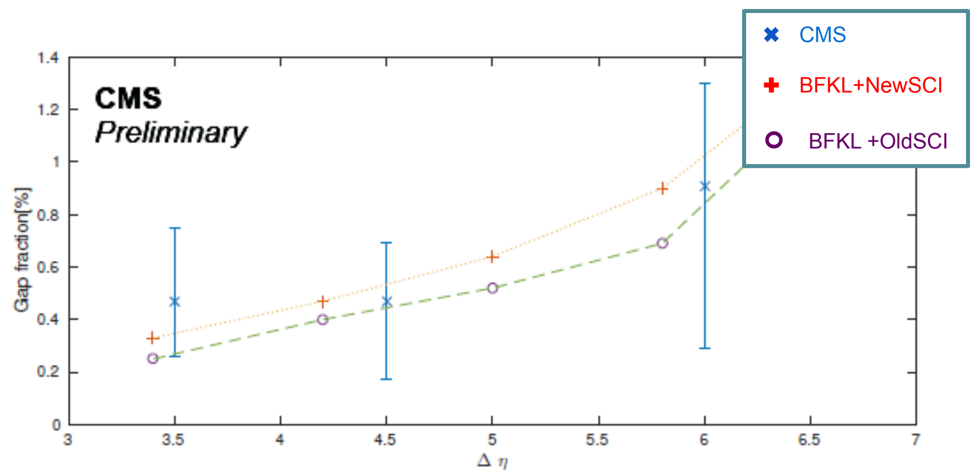
D0 data compared to Enberg, Ingelman model (NLL BFKL + MPI+SCI)

Jet-Gap-Jet Production at LHC



Plateau at high Δy





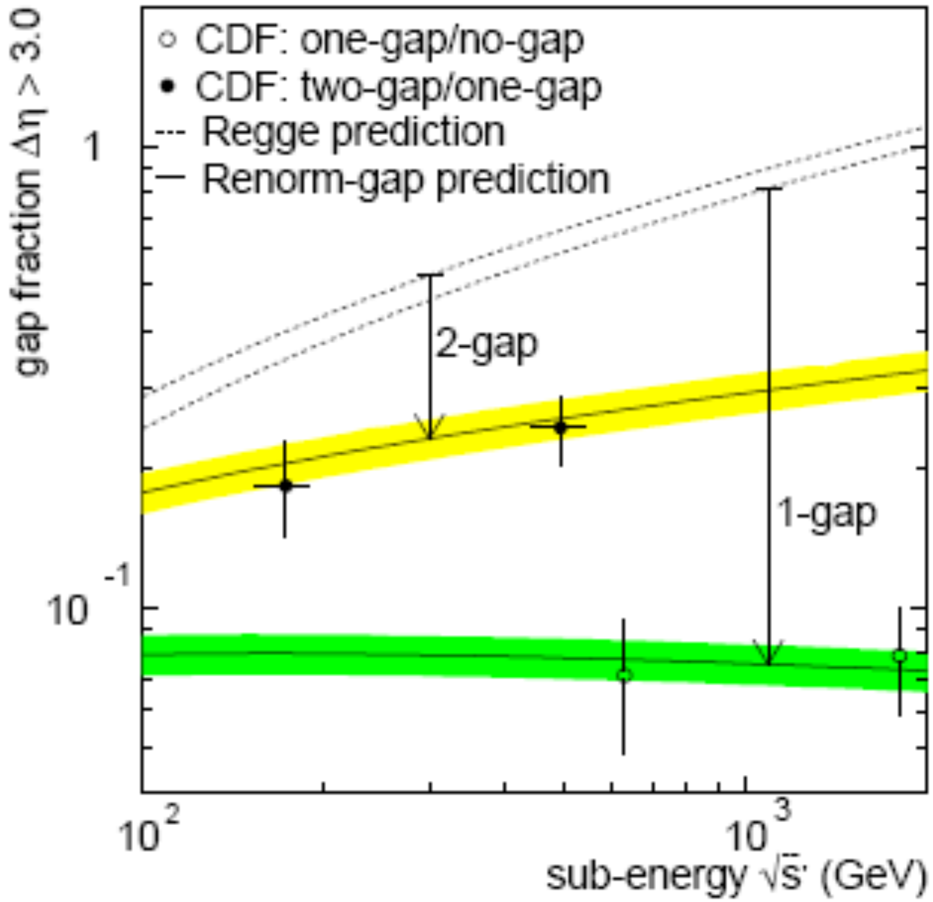
Preliminary predictions of two models for SCI - color exchange between partons (old SCI)
or strings (new SCI):
good description of gap fractions vs Δη

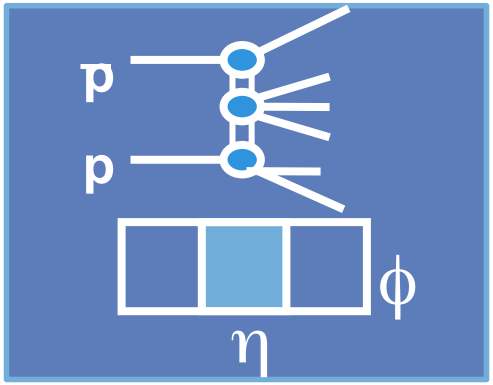
Multi Gap Events

Diffractive signature:

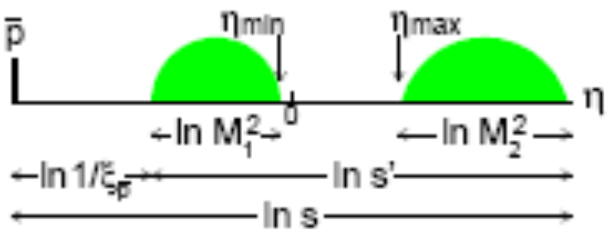
recoil pbar **AND**
large rapidity gap on proton side

PRL 91, 011802 (2003)



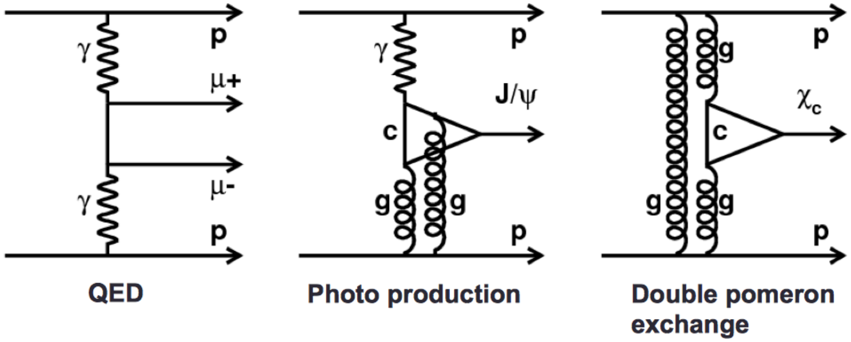


would be interesting to study at LHC



second gap production is not suppressed

Central Exclusive Production



Interactions of the form

pp ➔ p [exclusiveX] p

QED background: 2 γ exchange

QED process with small proton form-factor corrections

Pomeron exchange:

- Photoproduction: Photon-pomeron fusion

Probes gluon density at small values of proton's momentum fraction, *x*

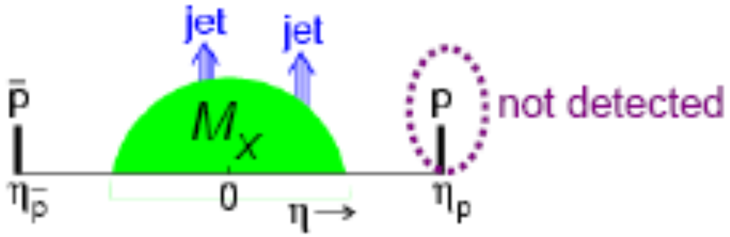
Perturbative calculations accessible for higher mass of [exclusive]

- Double pomeron exchange: Pomeron-pomeron fusion

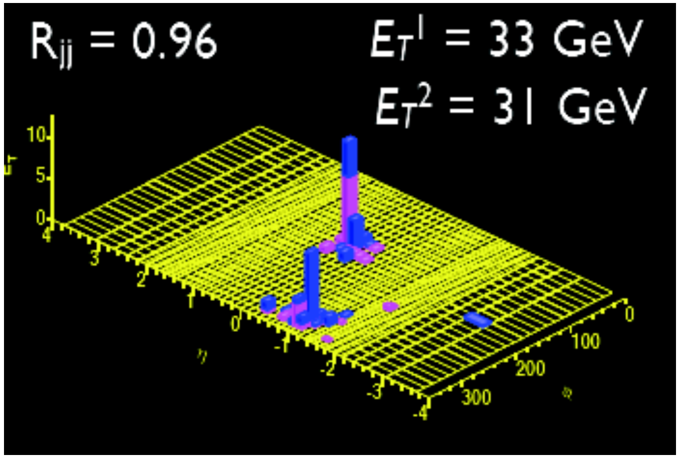
[exclusive X] must be neutral PC = ++, no net flavor: $f_{0;2}$; $\chi_{c;b}$; γγ; JJ;H

Extensive program of CEP measurements at CDF, continued by many interesting results from LHC

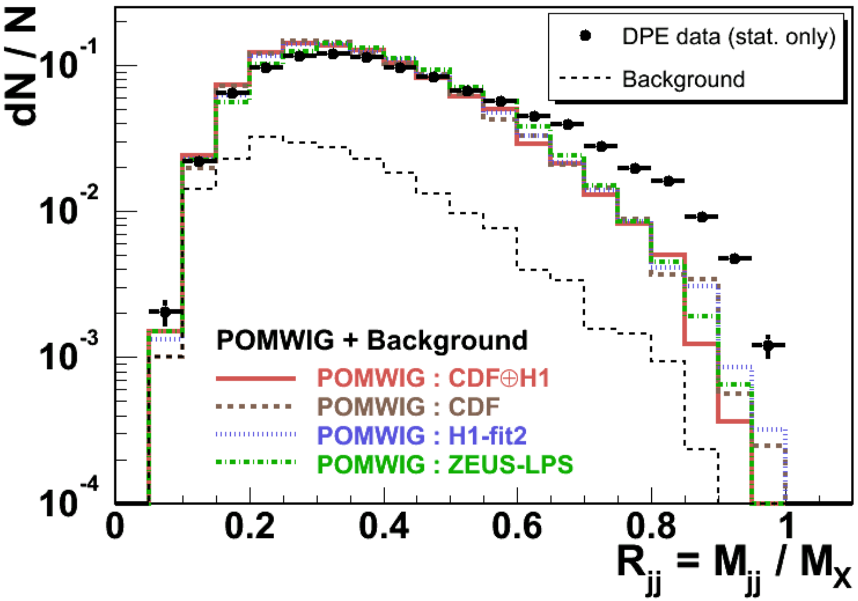
Observation of Exclusive Dijets

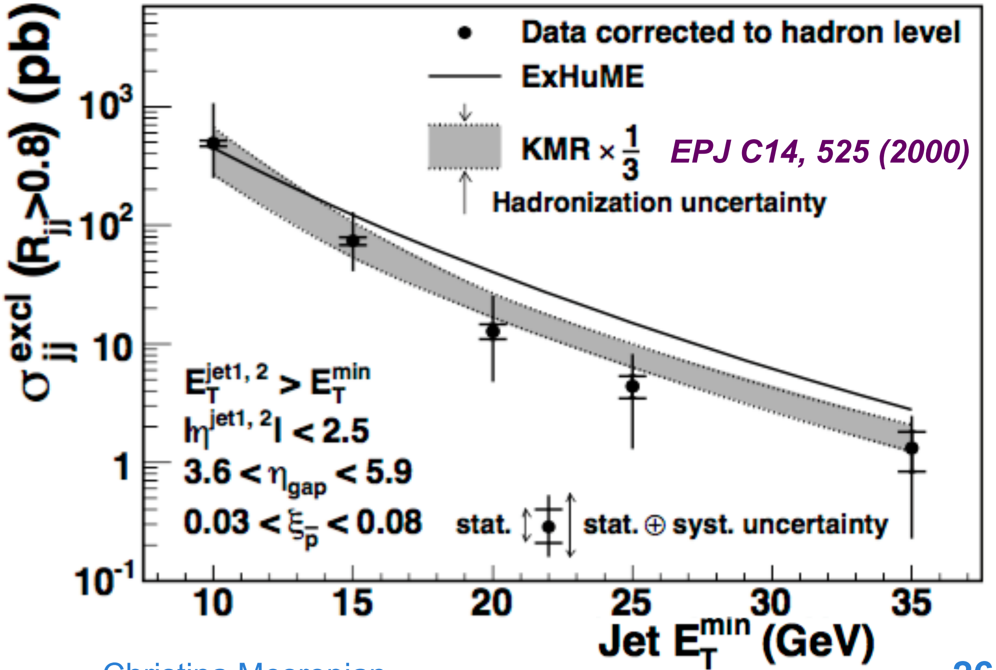


PRD 77, 052004 (2008)



Reconstruct ***$R_{jj}=M_{jj}/M_X$***, where
M_{jj} mass of dijet system, M_x – mass of system X





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

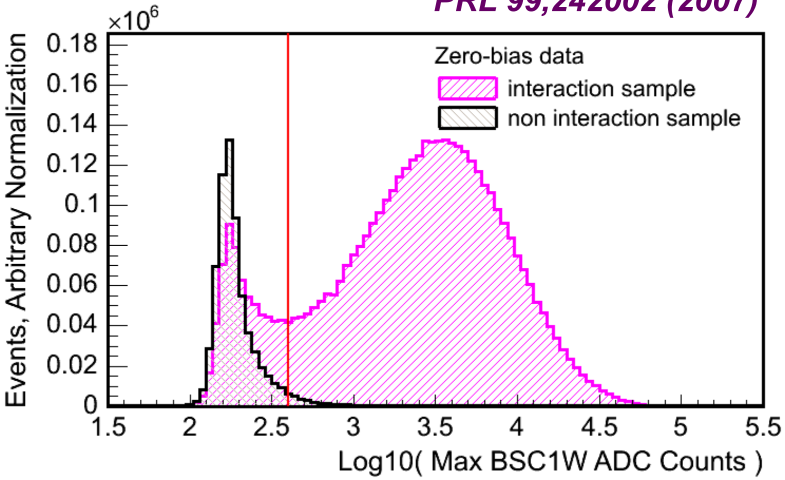
Signal at R_{jj}=1 is smeared due to shower/hadronization effects, NLO $gg \rightarrow ggg, q\bar{q}g$ contributions

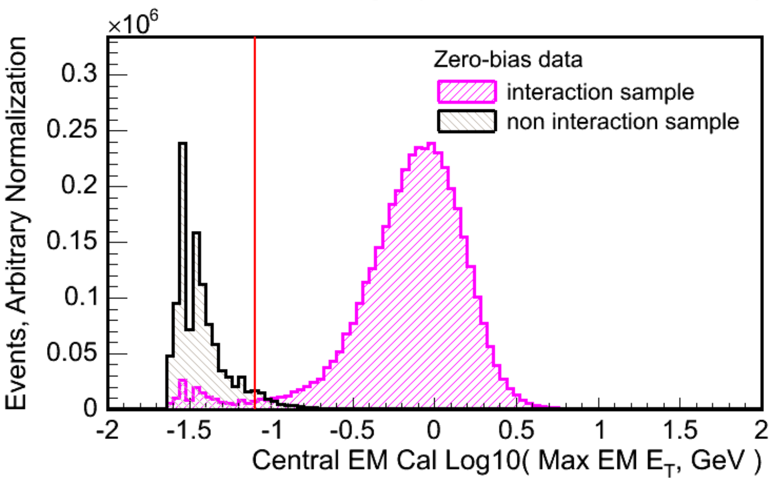
Exclusive γγ Production

Requirements : no other particles in the detectors up to $|\eta| < 7.4$

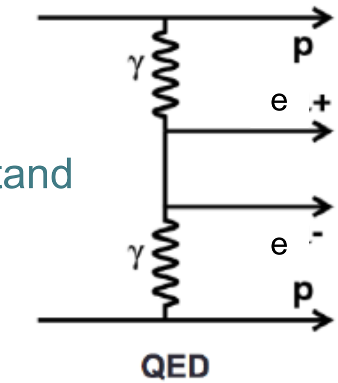
Study noise level by looking at “zero-bias” events:
“no interaction” or “interaction” class of events

PRL 99,242002 (2007)





Use control sample to understand



$$p + \overline{p} \rightarrow p + e^{+}e^{-} + \overline{p}\ via\ \gamma + \gamma\ (QED)$$

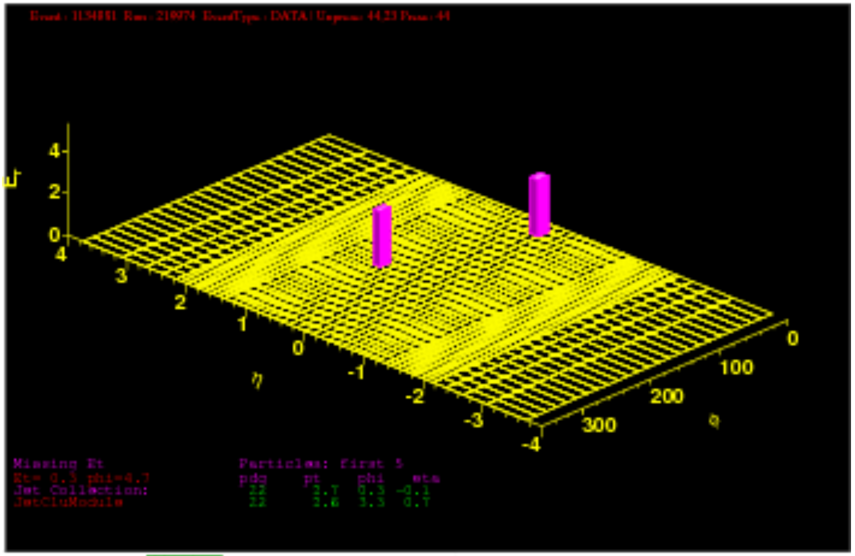
$$\sigma^{|\eta|<1, E_T>2.5GeV}_{e^+e^- excl.} = 2.88 \pm 0.59(stat) \pm 0.62(sys)\ pb$$

$$\sigma^{|\eta|<1, E_T>2.5GeV}_{LPair} = 3.25 \pm 0.07\ pb$$

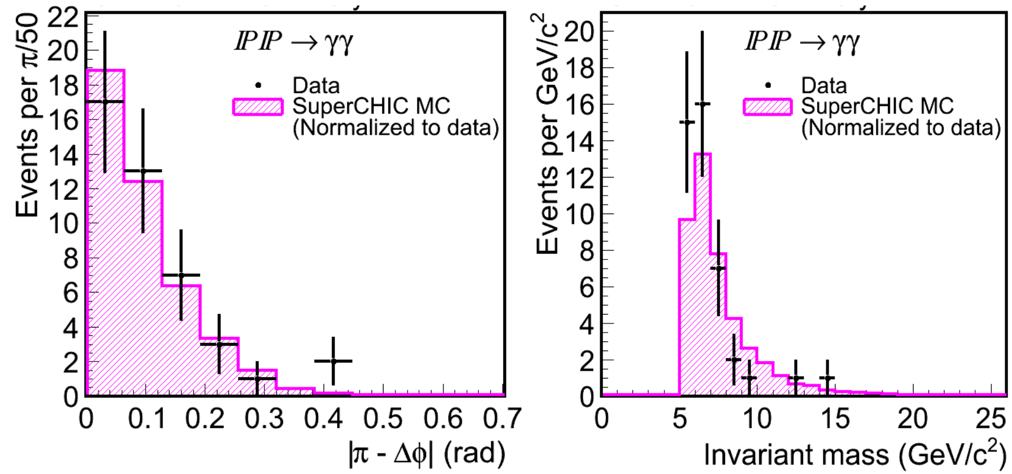
$$\sigma^{|\eta|<1, E_T>5.0GeV}_{e^+e^- excl.} = 0.60 \pm 0.28(stat) \pm 0.14(sys)\ pb$$

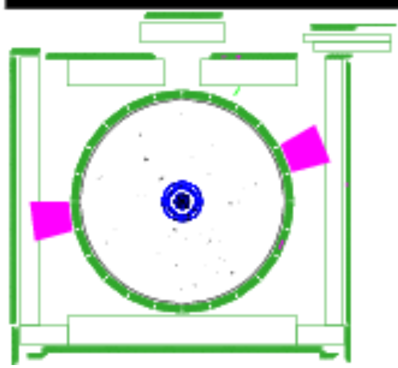
$$\sigma^{|\eta|<1, E_T>5.0GeV}_{LPair} = 0.58 \pm 0.003\ pb$$

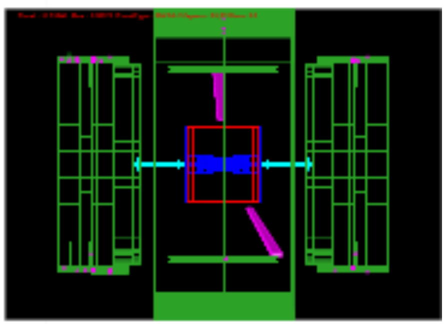
Exclusive γγ Production



PRL 108, 081801 (2012)



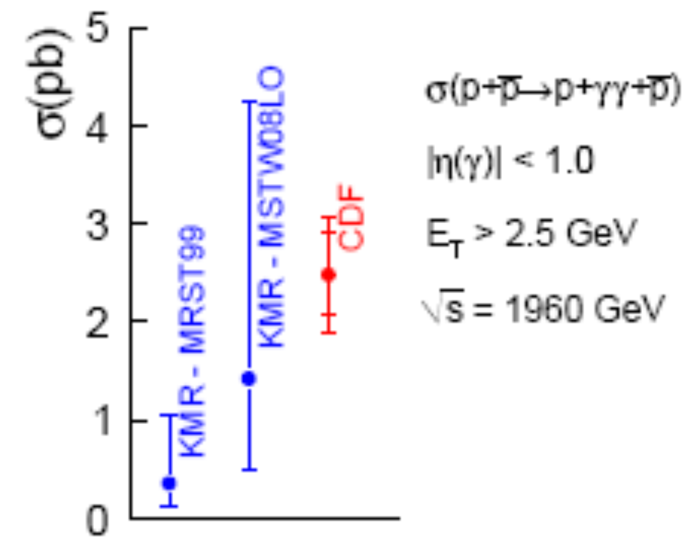




Observed 43 events >> 5 σ

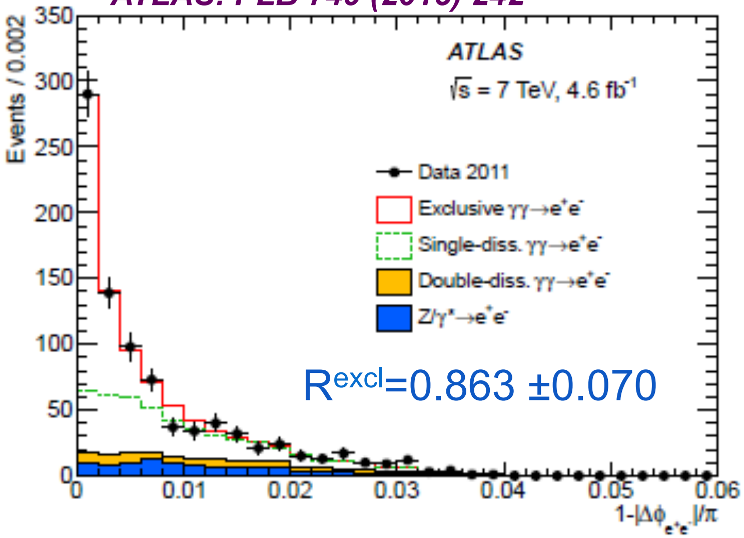
$\sigma_{\gamma\gamma_{excl}}$=2.48±0.42(stat)±0.41(sys) pb

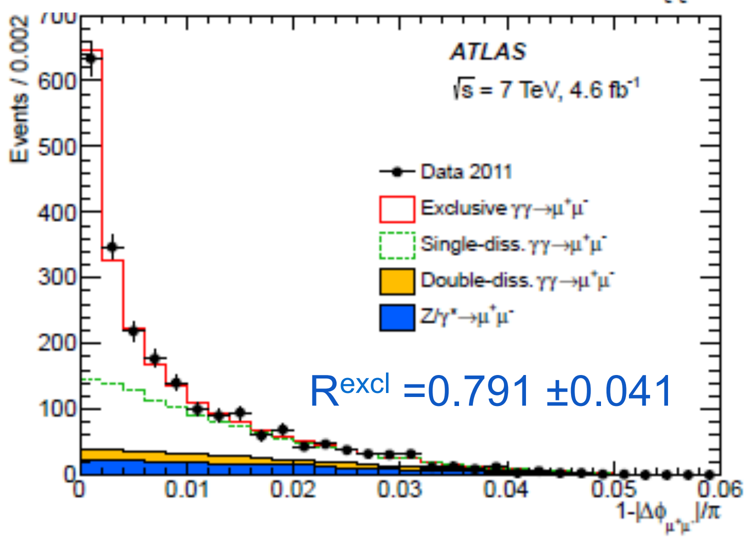
Good agreement with the theoretical predictions



Exclusive $\gamma\gamma \to e^+e^-/\mu^+\mu^-$ Production

ATLAS: PLB 749 (2015) 242



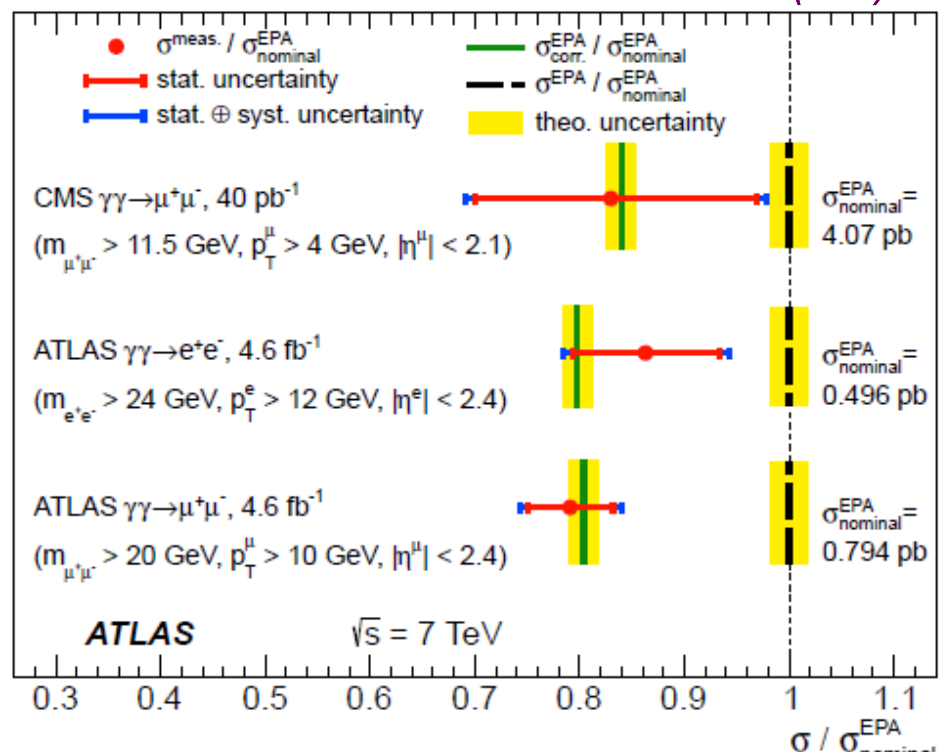


Fits to e^+e^- and $\mu^+\mu^-$ acoplanarity spectra with elastic and p-dissociation templates

QED prediction for excl. production - uncertainty of ~2%

- exclusive $\gamma\gamma \to l^+l^-$ production, requires significant corrections due to proton absorptive effects
- suppression factor is about 20%
- $R^{excl}=\sigma/\sigma^{EPA}$
  - ✧ EPA - Equivalent Photon Approximation – at this kinematic regime = full order LO QED

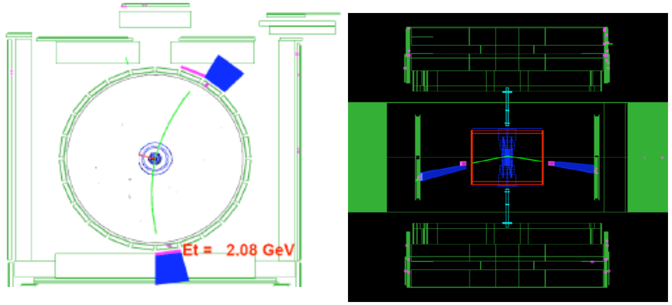
CMS: JHEP 07 (2013) 116



Exclusive J/ψ, ψ(2s) and $\chi_c \rightarrow J/\psi$

PRL 102, 242001 (2009)

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



J/ψ production

243 ±21 events

dσ/dy|$_{y=0}$ = 3.92 ± 0.62 nb

In agreement with theor. pred.

Ψ(2s) production

34±7 events

dσ/dy|$_{y=0}$ = 0.54 ± 0.15 nb

R = ψ(2s)/J/ψ = 0.14 ± 0.05

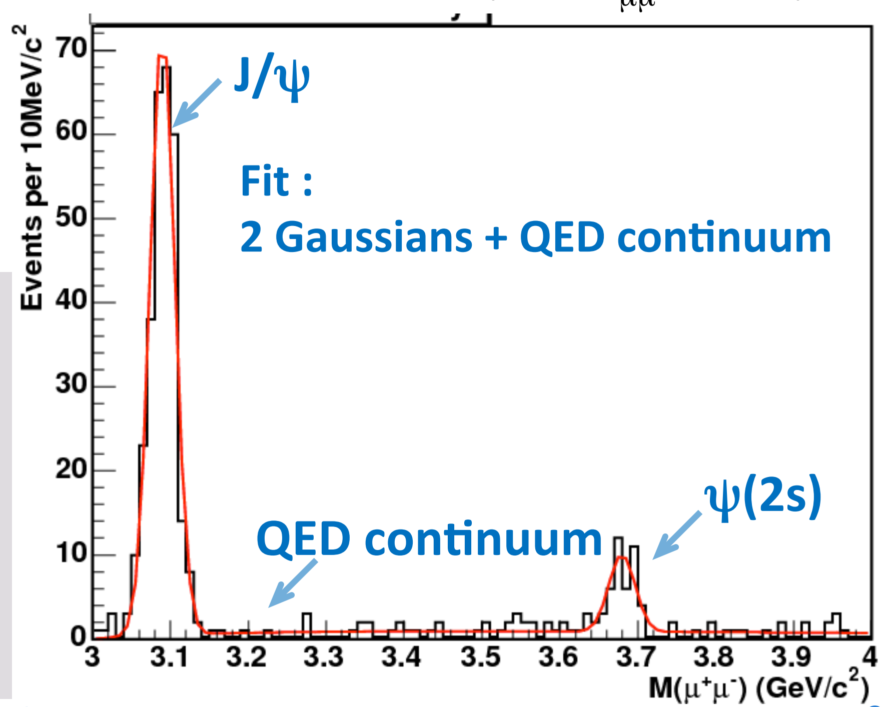
In agreement with HERA:
R = 0.166 ± 0.012 in a similar kinematic region

Trigger:

muon + track + frwd rapidity gaps in BSCs (5.1<|η|<7.1)

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

3 GeV/c² <$M_{\mu\mu}$<4 GeV/c²



Allowing EM towers (E_T>80MeV)

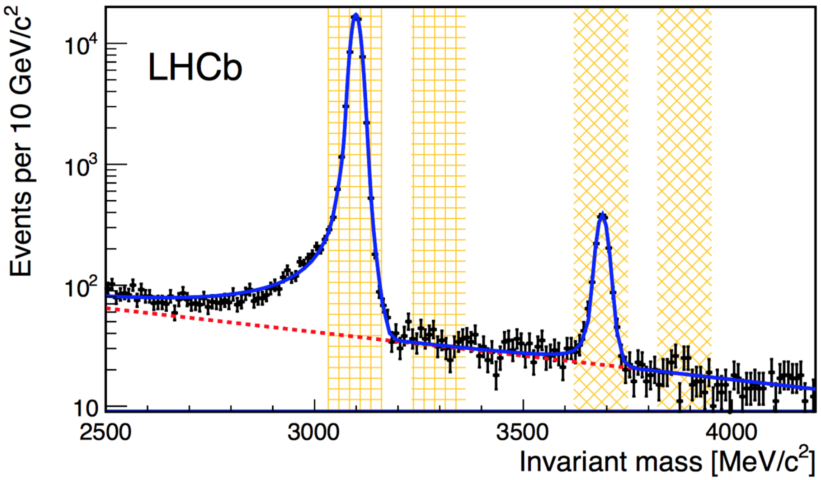
large increase in the J/ψ peak

minor change in the ψ(2s) peak ➔

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

dσ/dy|$_{y=0}$ = 75 ± 14 nb,
compatible with theoretical predictions

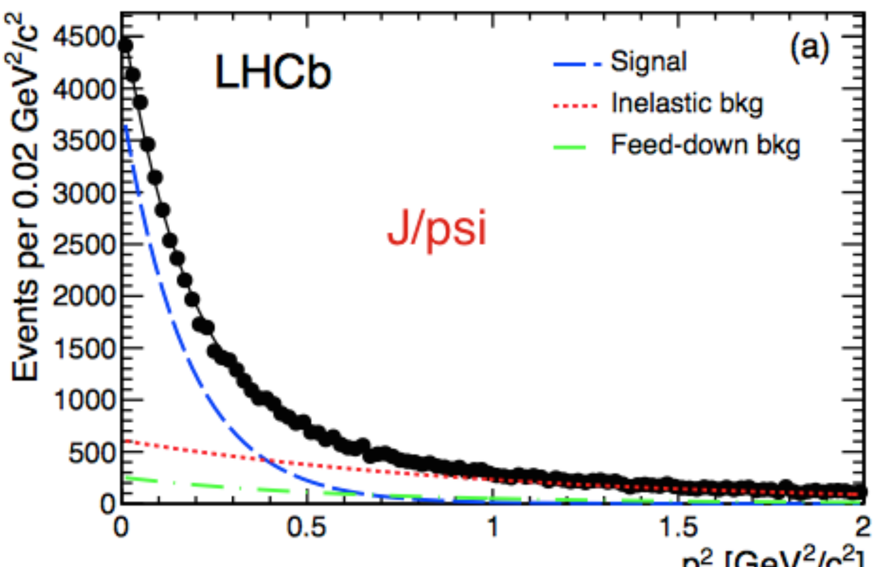
Exclusive J/ψ and ψ(2s)

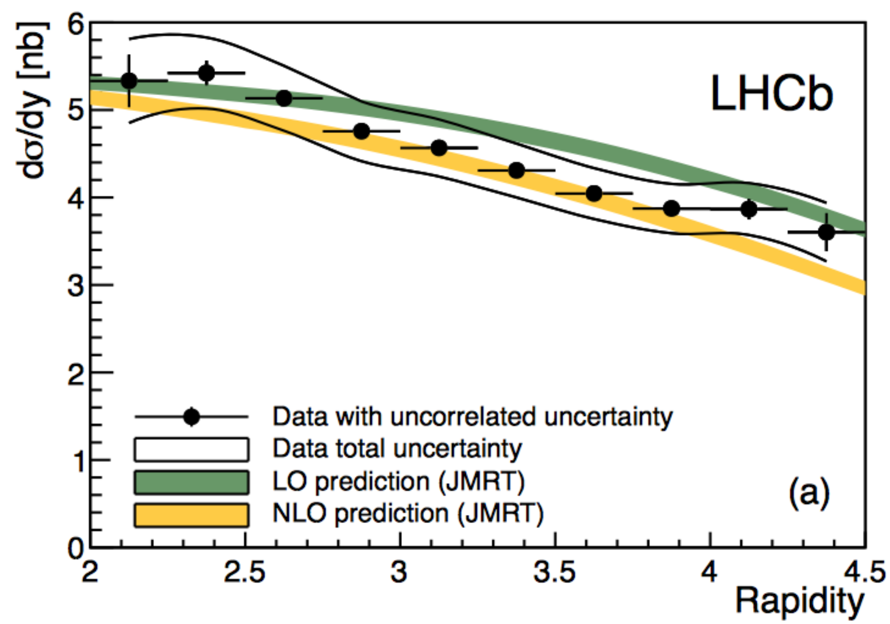


LHCb Selection:
J/ψ or $\psi(2s) \rightarrow \mu^+\mu^-$
in 930 pb^{-1} at 7 TeV data

- Two muons wth p_T>400 MeV and no other activity
- Inelastic background subtracted by fitting pT^2 spectra

- For J/Ψ: feed down from Xc and Ψ(2S) - 8% and 2.5%
- Extracted b slopes of the exponential pT^2 dependence





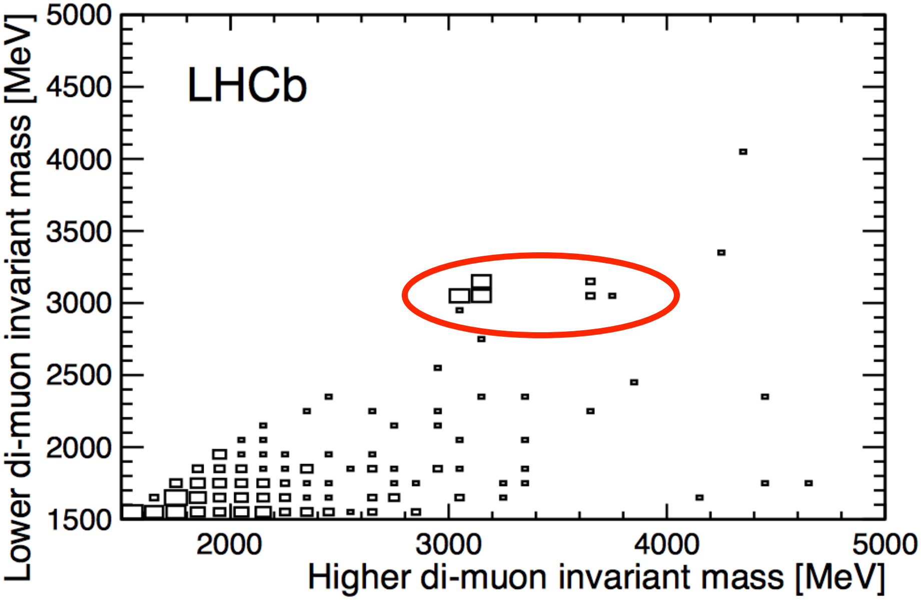
Measured cross section as a function of rapidity

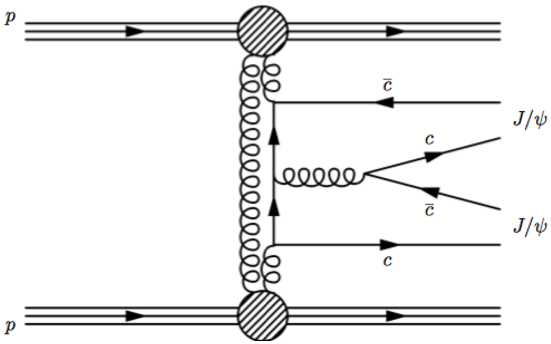
- Comparison to predictions of JMRT model
- NLO provides better agreement

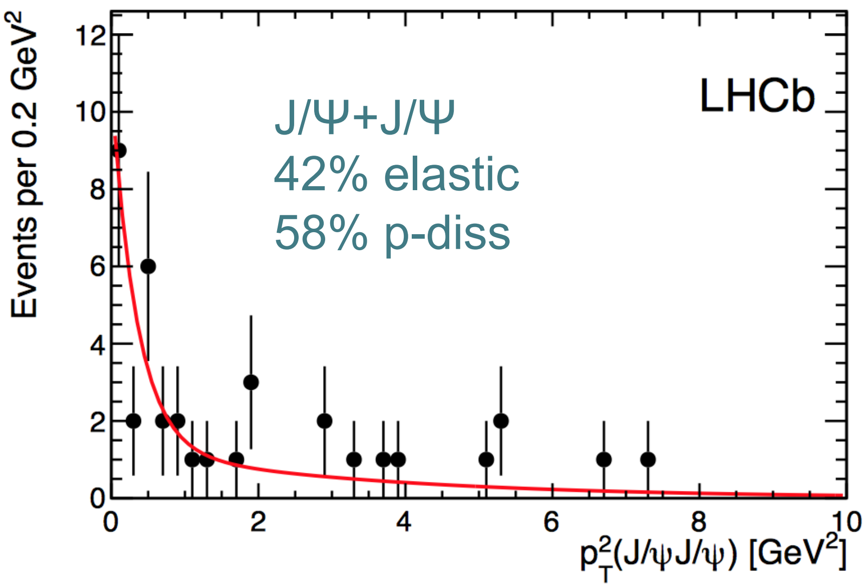
Double Charmonium Production

J. Phys. G 41 115002

First observation of CEP for pairs of charmonium mesons







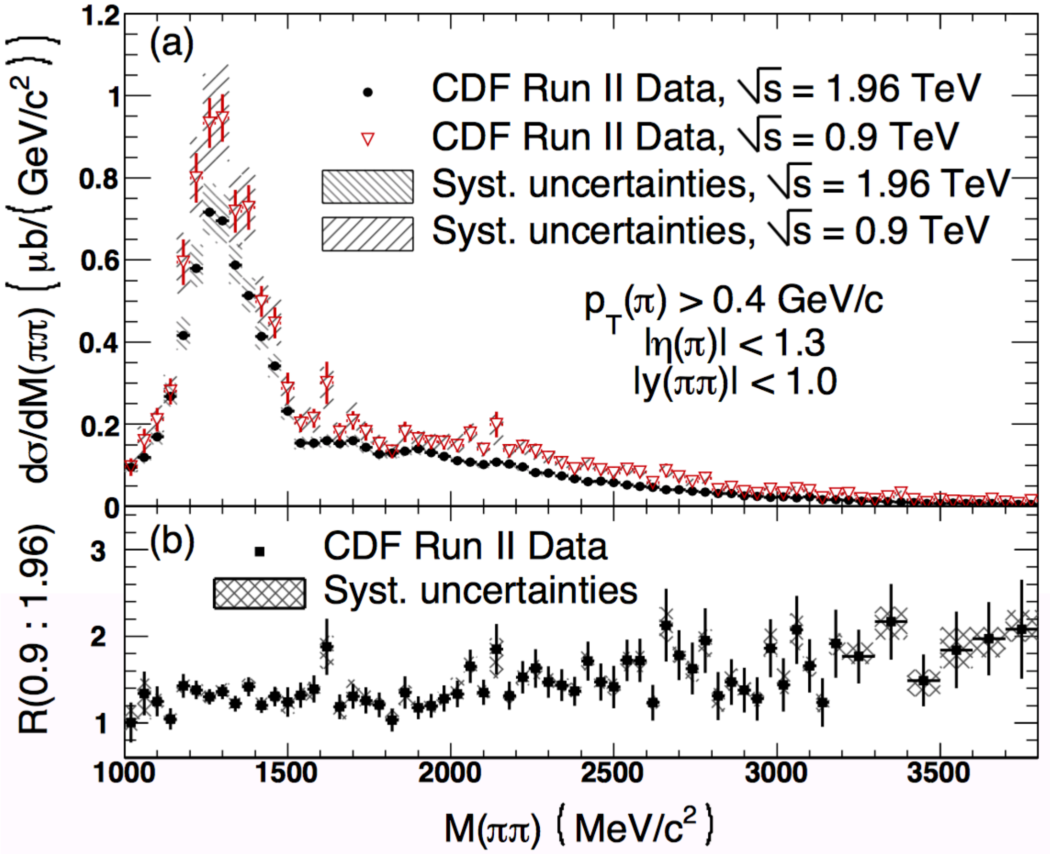
- Estimate of exclusive component in \`empty-detector' signal is 42 ± 13%
- Measurement of σ(J/ψ J/ψ) = 24 ± 9 pb in agreement with predictions of Harland-Lang, Khoze, Ryskin, Stirling: 8 pb (large theoretical uncertainties, factor of 2-3)

Exclusive $\pi^+\pi^-$ Production

PRD 91, 091101 (2015)

Central exclusive production studies with energy scan data -
300 GeV, 900 GeV and 1960 GeV

- 3x3 bunches
- Special trigger
- 1 interaction per crossing (no pile-up)



Selection:
$\pi^+\pi^-$ and no other activity in $|\eta|>5.9$

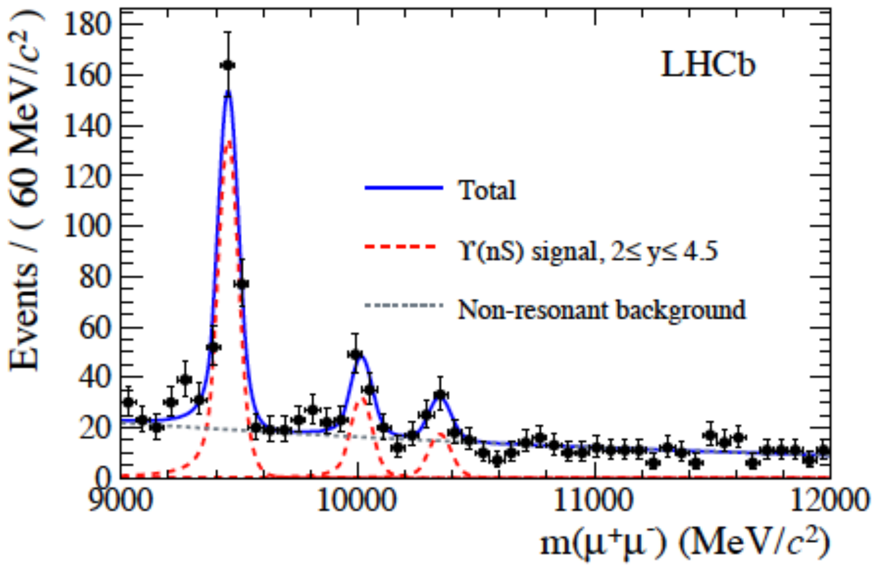
The cross section ratio
R(0.9:1.96) = 1.28
for $1<M(\pi\pi)< 2$ GeV

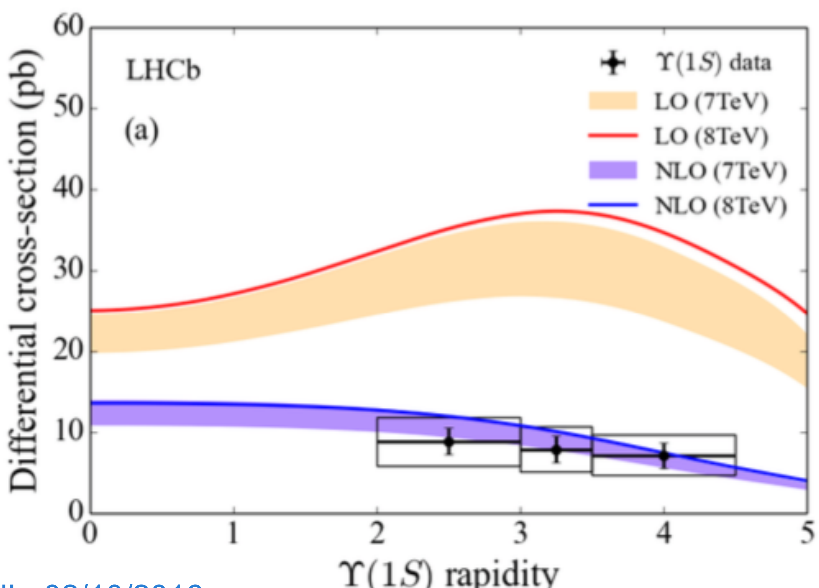
consistent with
Regge phenomenology (~1/ln(s))

- $f_2(1270)$, shoulder from $f_0(1370)$ interference
- some structure around 1.4-2.4 GeV
- data falls monotonically above 2.4 GeV

Exclusive Υ(nS) Production

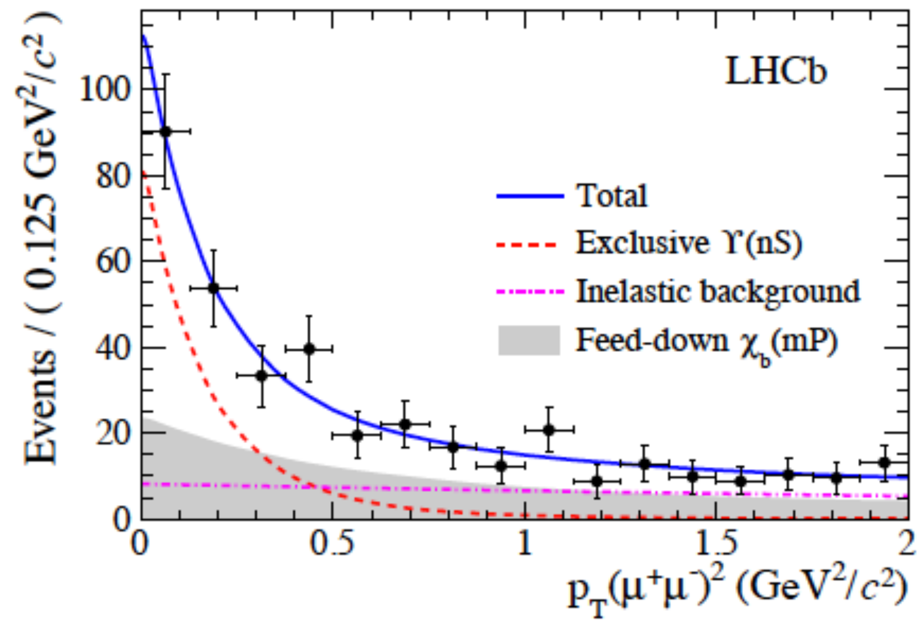
JHEP 1509 (2015) 084





Data set: 2.9 fb^{-1} pp collisions - at 7 and 8 TeV

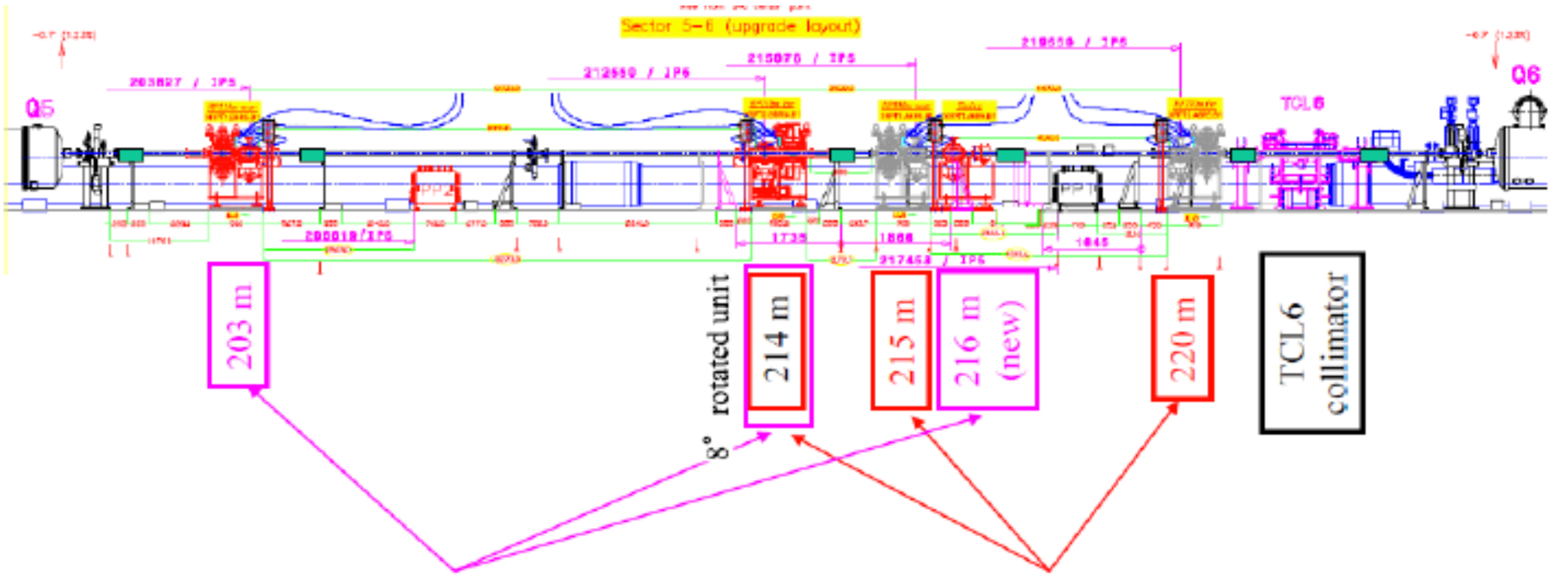
- Perturbatively calculable; sensitive to $g(x)^2$ down to $x = 1.5\times10^{-5}$
- Compare to predictions at LO and NLO (diverge in this kinematic regime)



$$\sigma(pp \to p\Upsilon(1S)p) = 9.0 \pm 2.1 \pm 1.7 \text{ pb},$$
$$\sigma(pp \to p\Upsilon(2S)p) = 1.3 \pm 0.8 \pm 0.3 \text{ pb, and}$$
$$\sigma(pp \to p\Upsilon(3S)p) < 3.4 \text{ pb at the 95\% confidence level,}$$

UPGRADES

CMS+TOTEM

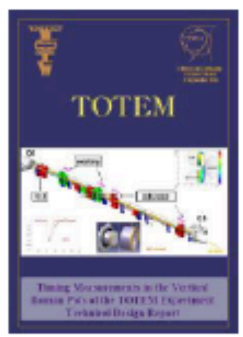


Operation at low β* (< 1 m),
high luminosity, standard runs

Operation at high β* (19 m, 90 m, > 1 km),
Low - medium luminosity, special runs

CMS-TOTEM Precision Proton Spectrometer (CT-PPS)

High statistics CEP:
DPE exclusive dijets,
photon-photon WW and
BSM EWK couplings.
2016-2017



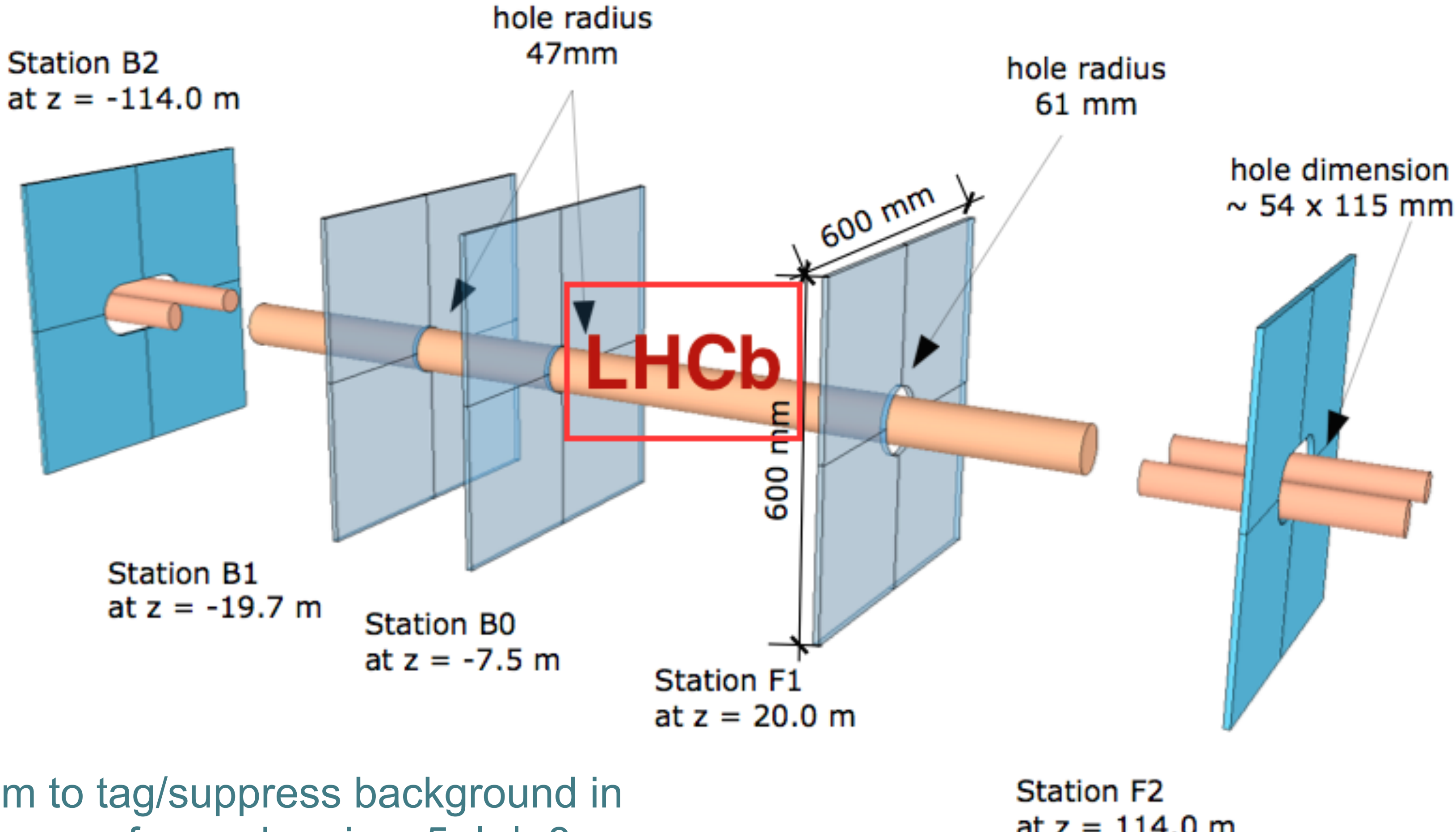
Timing Measurements in the Vertical Roman Pots of the TOTEM Experiment

Diffractive processes with TOTEM+CMS,
e.g.: SD J/Psi, Y, W, Z, dijet
DPE dijets, hadron spectroscopy (gluballs)
2015-2016

Similar physics program for ATLAS-ALFA and AFP (ATLAS Forward Physics) project

LHCb Upgrades/Future

Install scintillators either side of LHCb
Detect showers from high rapidity particles interacting with the beam-pipe elements



Aim to tag/suppress background in the very forward region: $5<|\eta|<8$

Conclusions

Very extensive program of diffractive studies at the Tevatron and now LHC– new forward detectors R&D, new methodologies developed, many pioneering measurements performed.

Total, elastic and diffractive cross sections measured - important input for phenomenological models, MC tuning, and cosmic ray physics

Hard diffraction - many interesting results from Tevatron, still little studied at the LHC, proton tagging (CMS+TOTEM, CT-PPS, AFS) is crucial for expanding number of channels e.g. diffractive dijets, W, Z, J/Ψ

Rich program for exclusive processes:

Many observations from Tevatron, new results from LHC and upgrades in progress

Ref: Papers on diffraction at CDF

Soft Diffraction

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

Single Diffraction
PRD 50, 5355 (1994)

Double Diffraction
PRL 87, 141802 (2001)

Hard Diffraction

Dijets:
1.8 TeV PRL 85, 4217 (2000)
1.96 TeV PRD 77, 052004 (2008)

Di-photons
1.96 TeV PRL 108, 081801 (2012)
1.96 TeV PRL 99, 242002 (2007)

Charmonium
1.96 TeV PRL 102, 242001 (2009)
$\pi^+\pi^-$
1.96(0.9) TeV PRD91, 091101(2015)

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:
1.96TeV PRD 86,032009 (2012)
1.8 TeV PRL 84, 5043 (2000)
630 GeV PRL 88, 151802 (2002)
W/Z:
1.96 TeV PRD 82,112004 (2010)

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