



WE-Heraeus Physics School

QCD – Old Challenges and New Opportunities

Bad Honnef, Sept 24–30, 2017



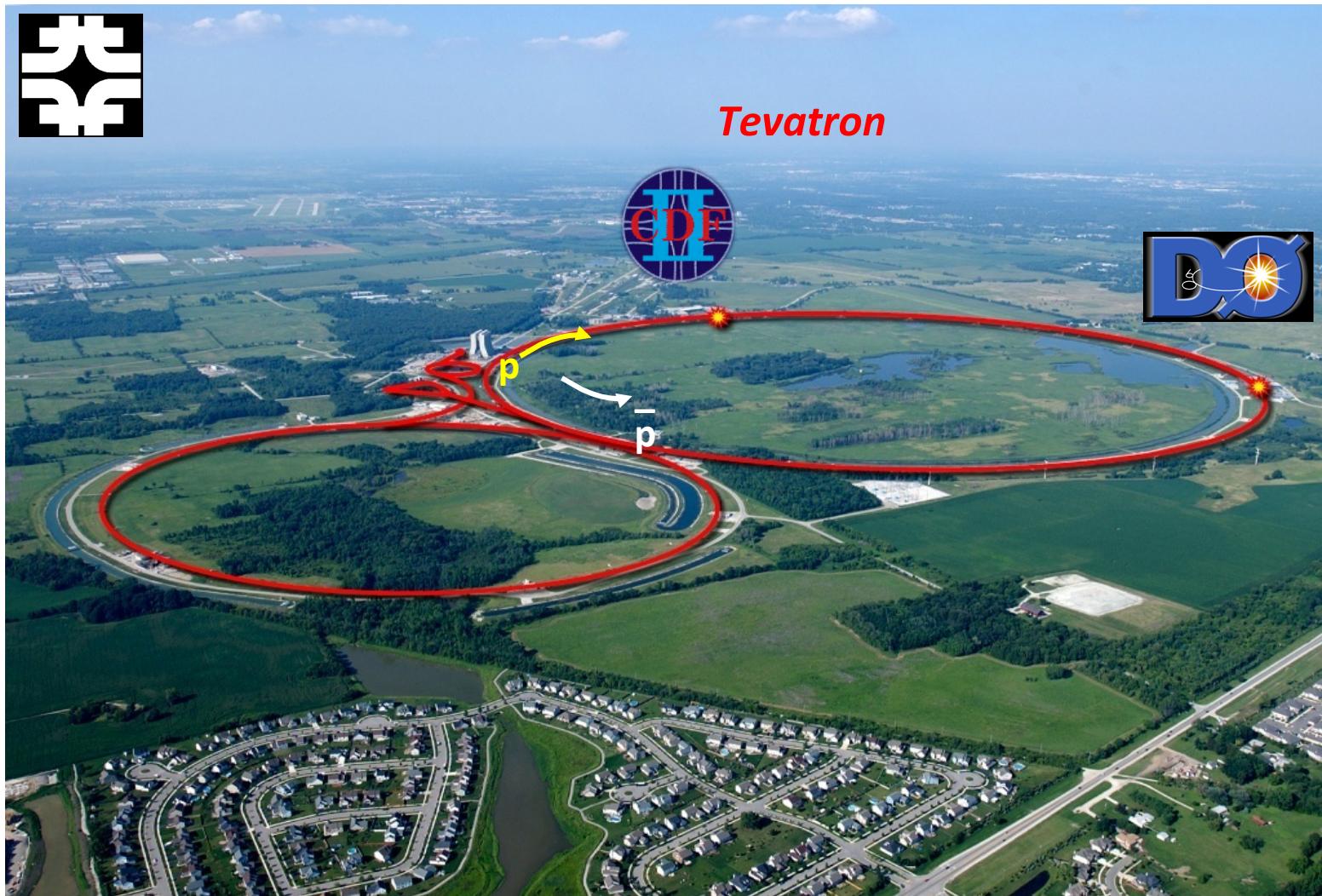
Soft and Hard QCD processes at the Tevatron

Christina Mesropian

The Rockefeller University

New York

Introduction – Tevatron p \bar{p} collider at Fermilab



Tevatron



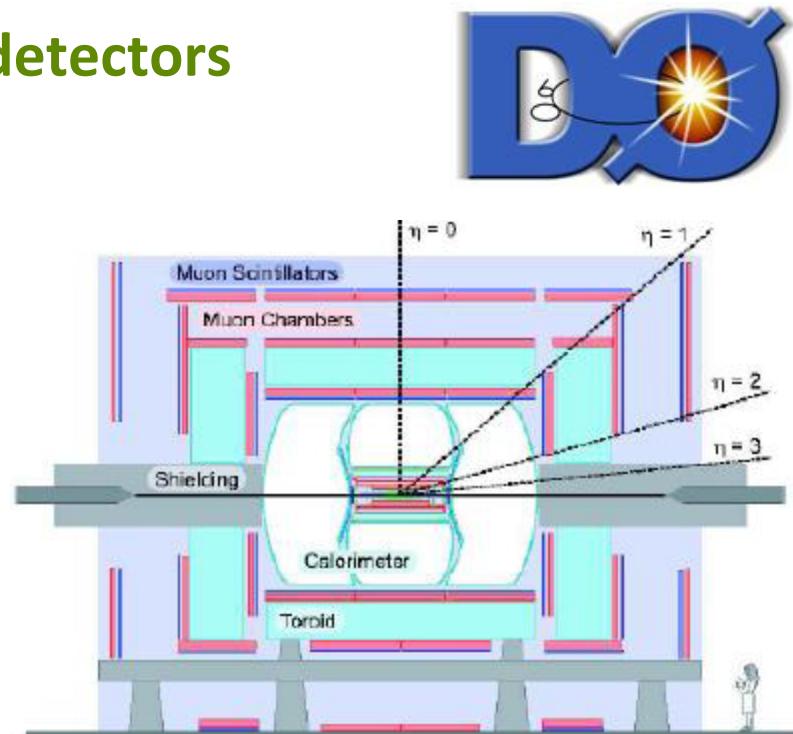
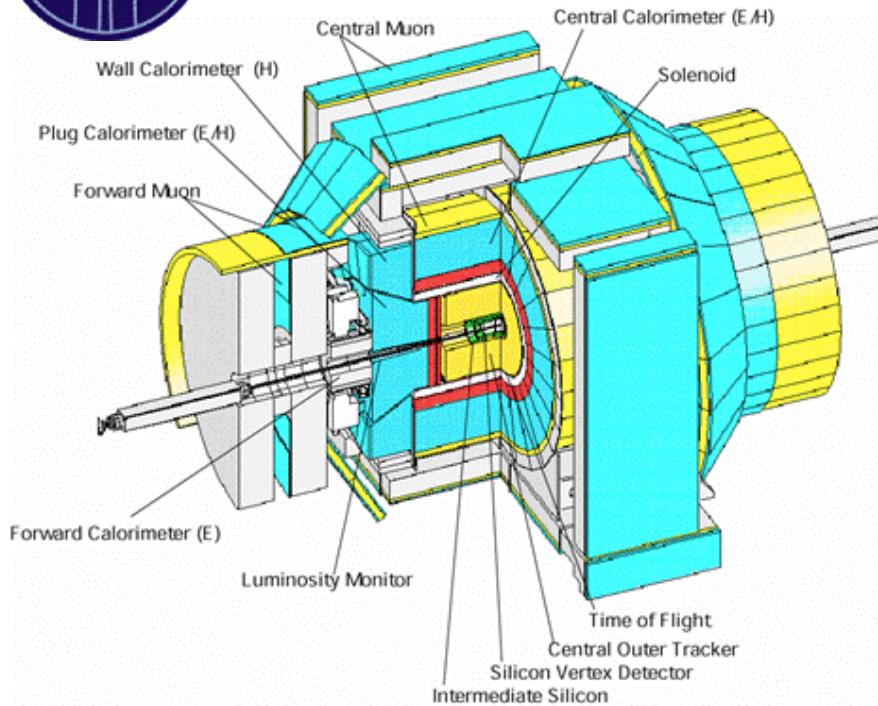
- Superconducting storage ring
1 km radius, 1 beam-pipe
- Collisions from 1985 to 2011
- Runs 0 and I - $\sqrt{s}=546, 630 \text{ GeV}, 1800 \text{ GeV}$
- Run II: Mar 2001-Sept 2011
- Produced $p\bar{p}$ collisions at 1.96 TeV
 - 36x36 bunches
 - $\sim E10-E11$ particles per bunch



CDF and D0 Experiments



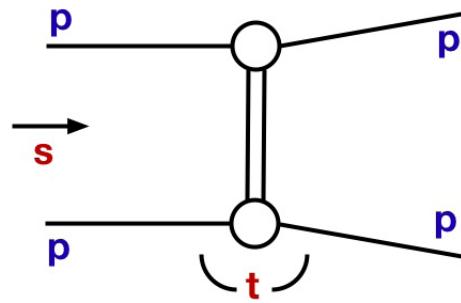
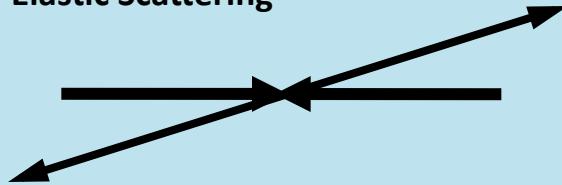
General purpose detectors



- Top performance (>85% data taking efficiency)
- $\sim 10 \text{ fb}^{-1}$ per experiment

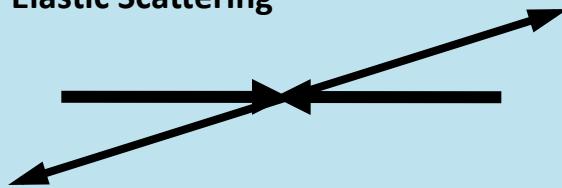
Proton-(anti)Proton Collisions

Elastic Scattering

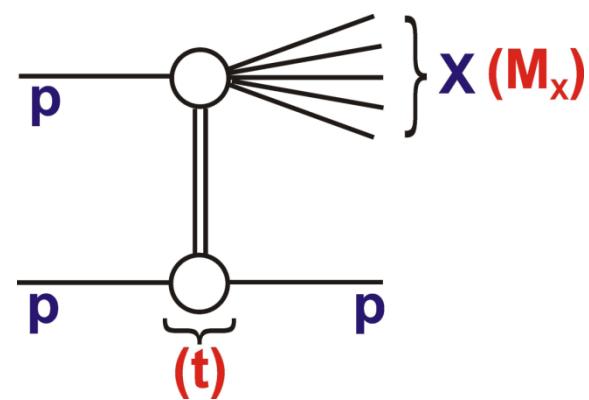
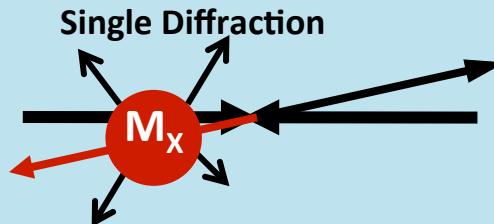


Proton-(anti)Proton Collisions

Elastic Scattering

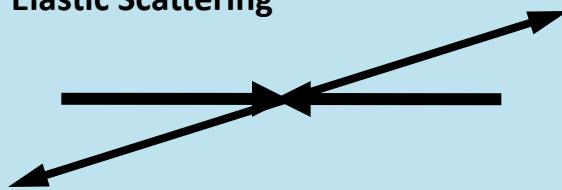


Single Diffraction

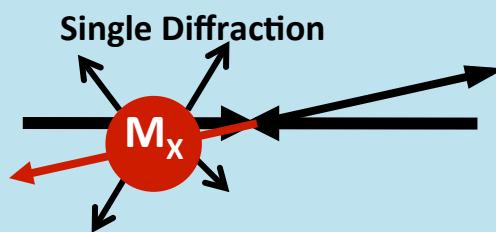


Proton-(anti)Proton Collisions

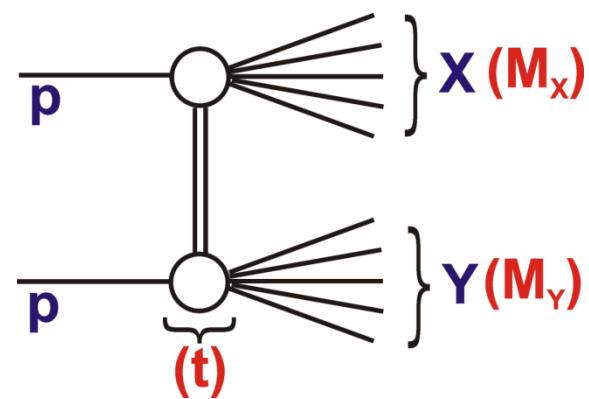
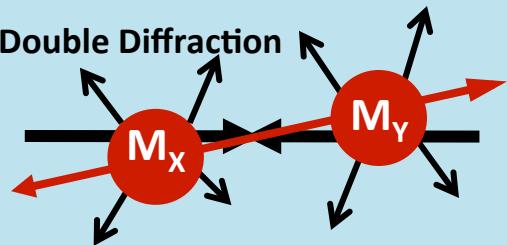
Elastic Scattering



Single Diffraction

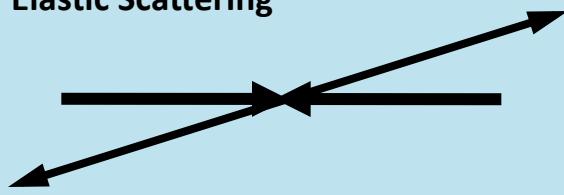


Double Diffraction

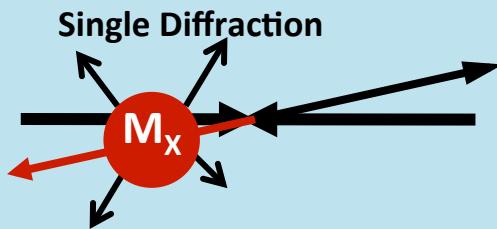


Proton-(anti)Proton Collisions

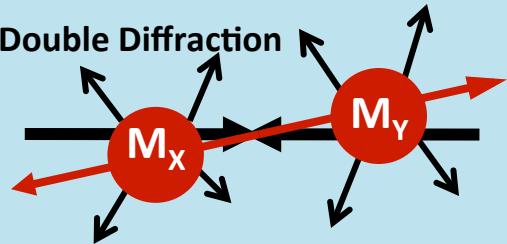
Elastic Scattering



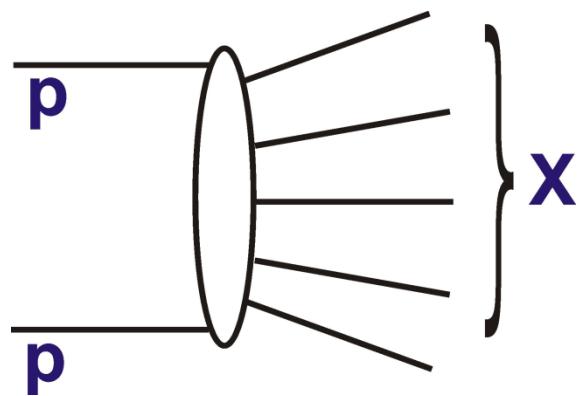
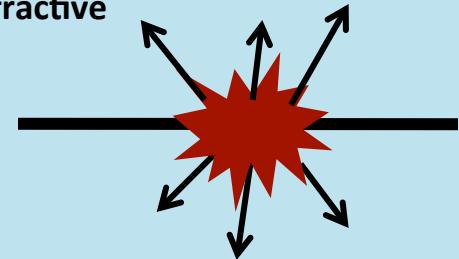
Single Diffraction



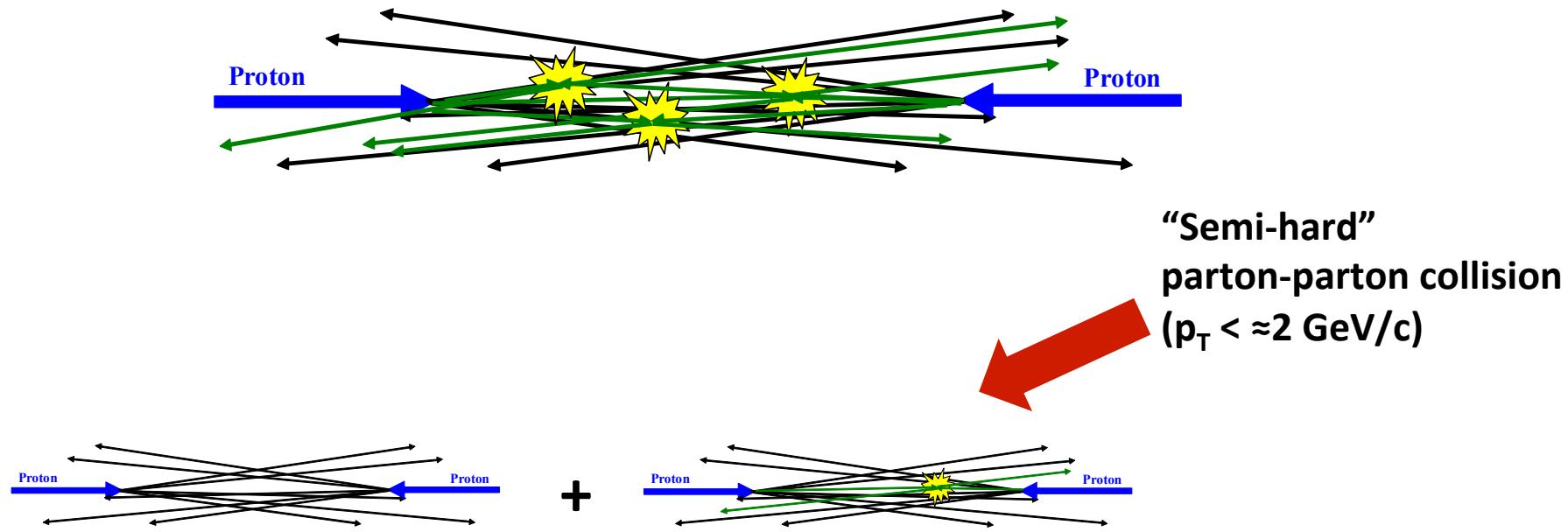
Double Diffraction



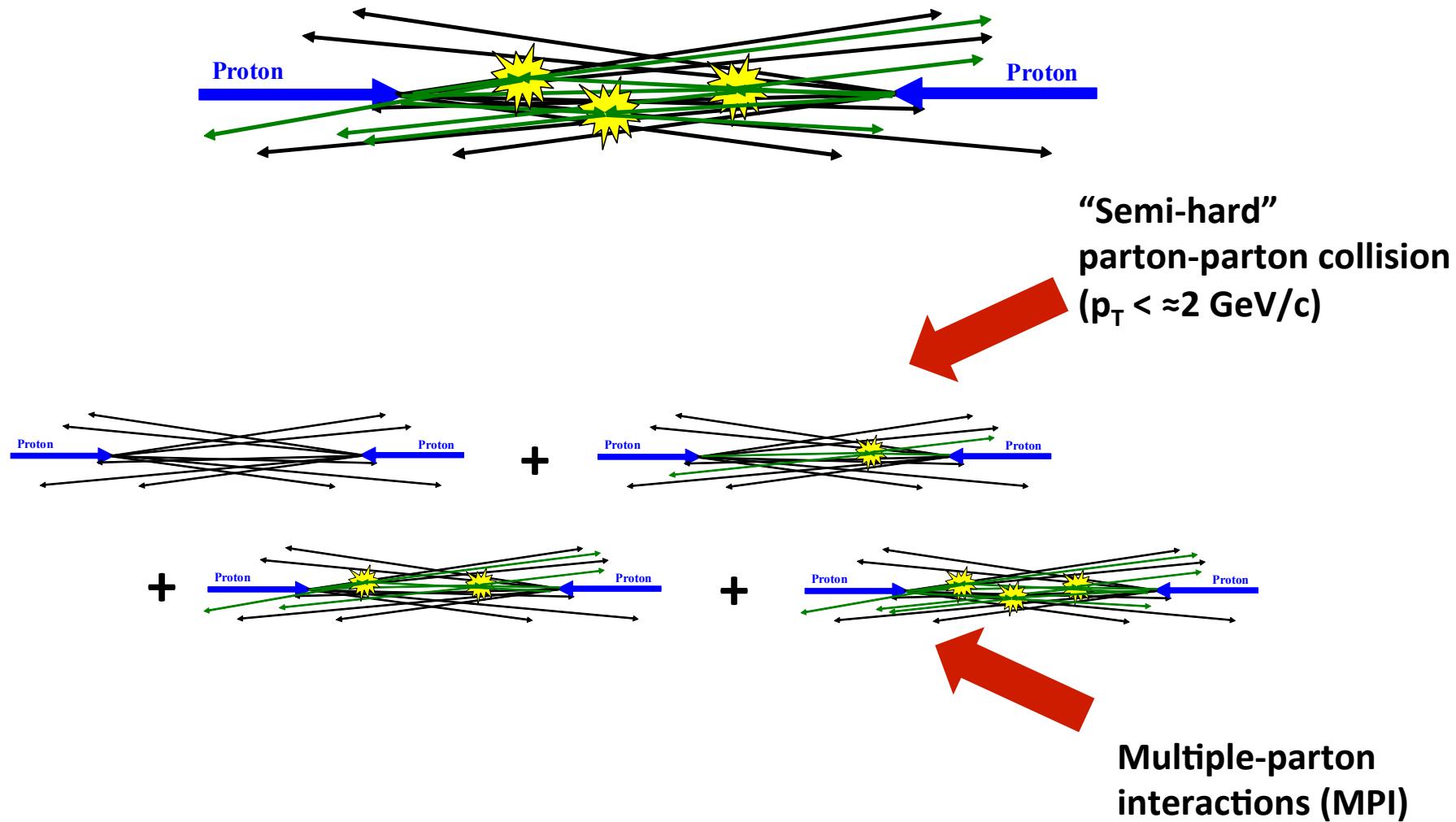
“Inelastic Non-Diffractive Component”



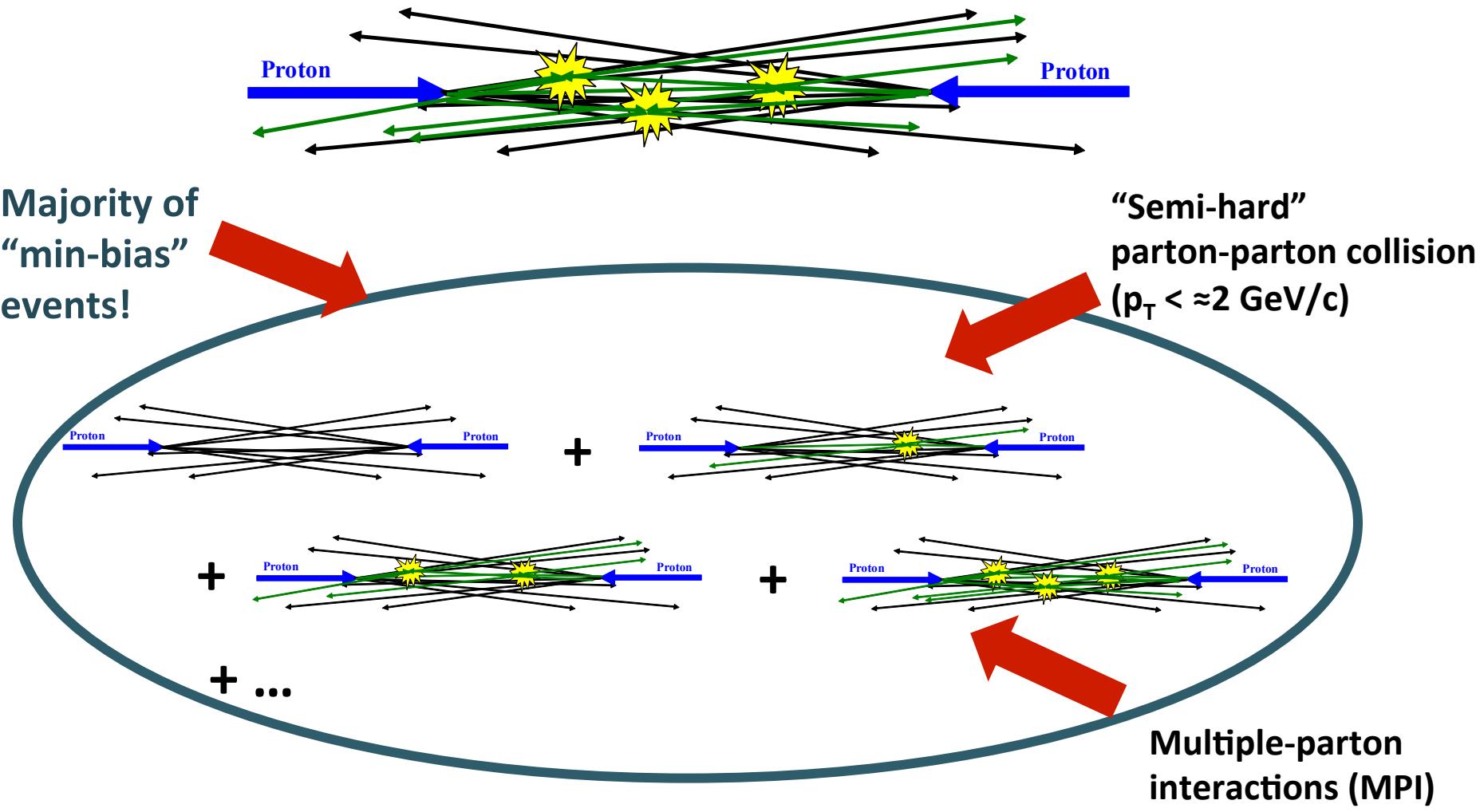
The Inelastic Non-Diffractive Cross-Section



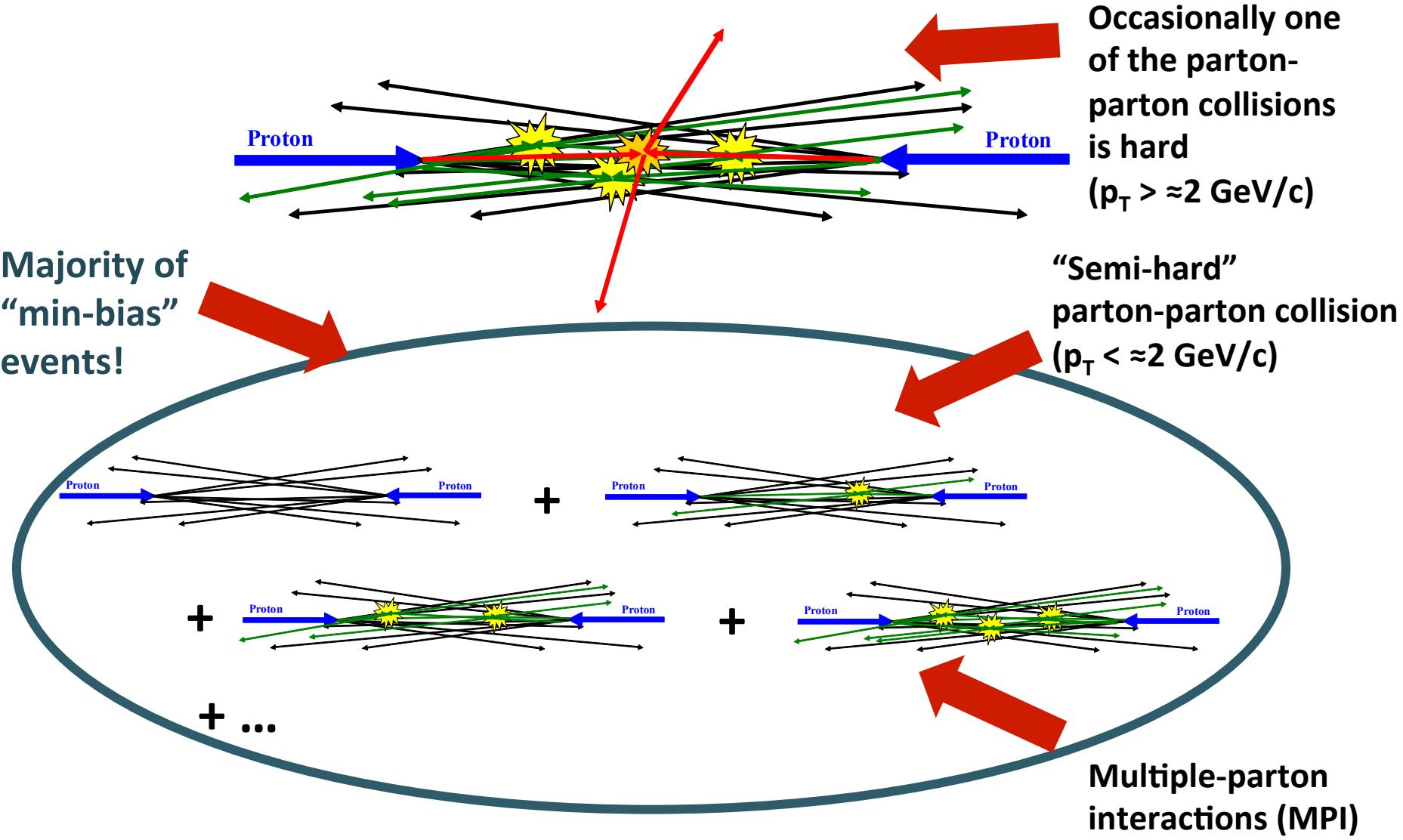
The Inelastic Non-Diffractive Cross-Section



The Inelastic Non-Diffractive Cross-Section

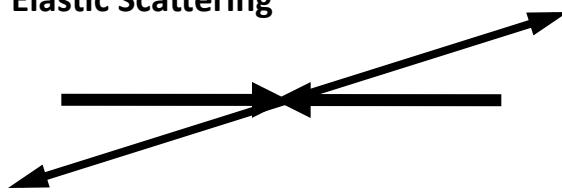


The Inelastic Non-Diffractive Cross-Section

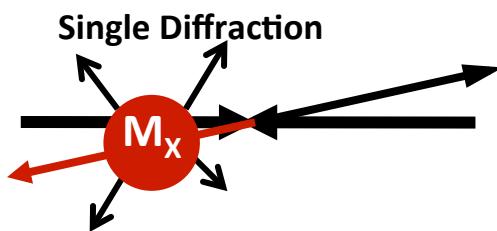


Proton-(anti)Proton Collisions

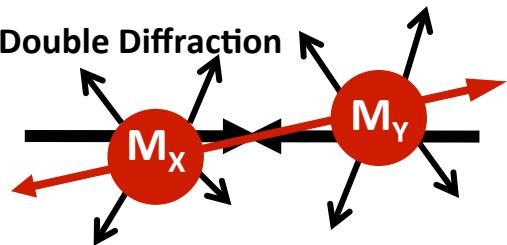
Elastic Scattering



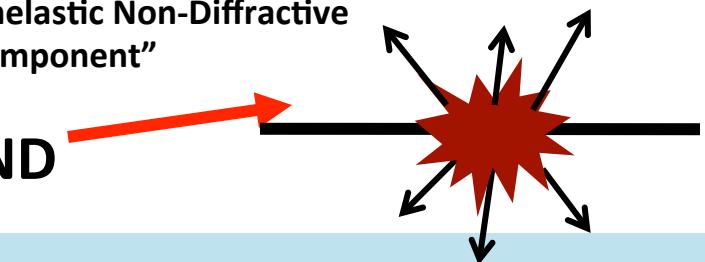
Single Diffraction



Double Diffraction



"Inelastic Non-Diffractive Component"



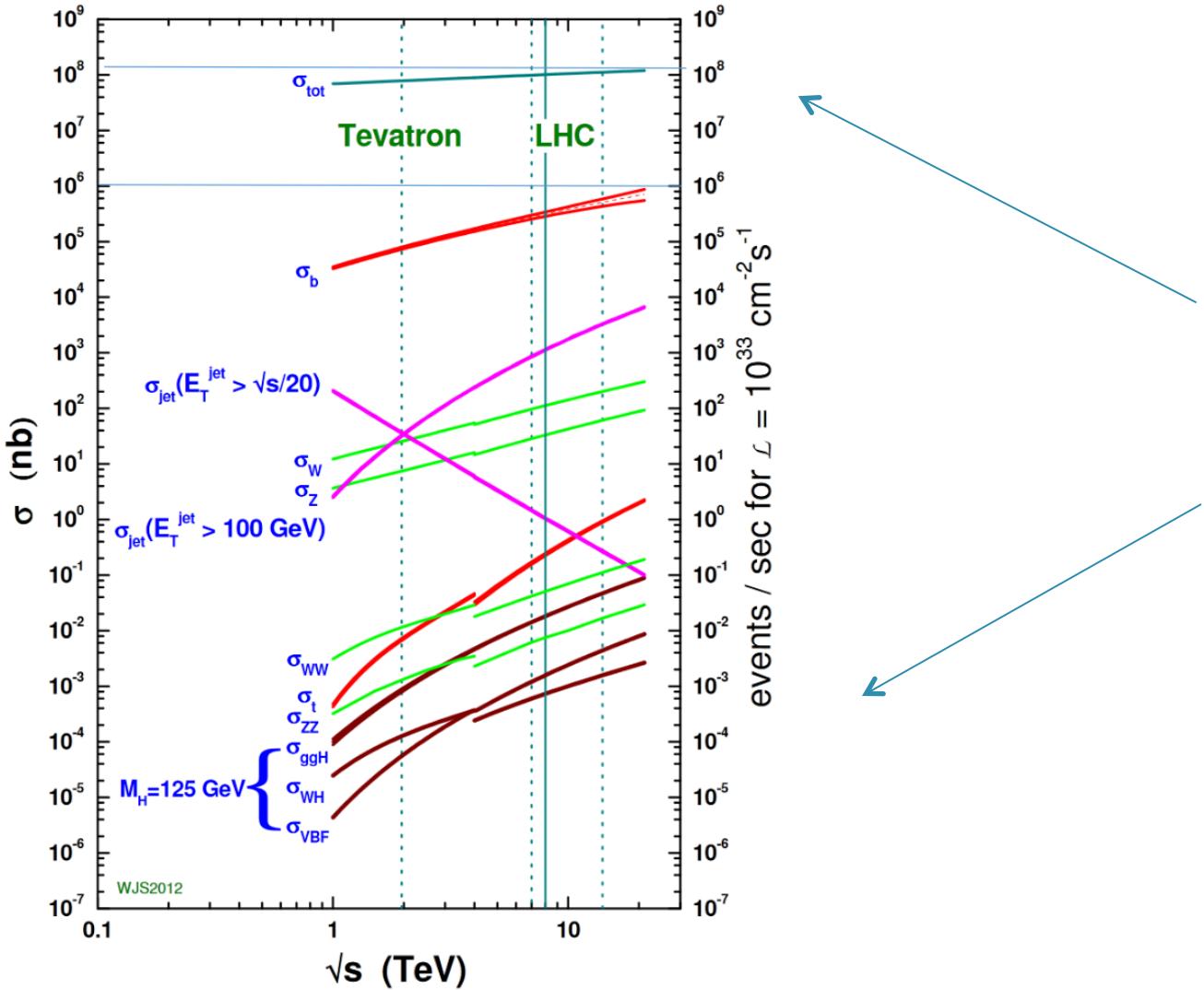
$$\sigma_{\text{Total}} = \sigma_{\text{EL}} + \sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{ND}}$$

- Non-Diffractive
- Single Diffractive
- Double Diffractive
- Elastic Scattering



Proton-(anti)Proton Collisions

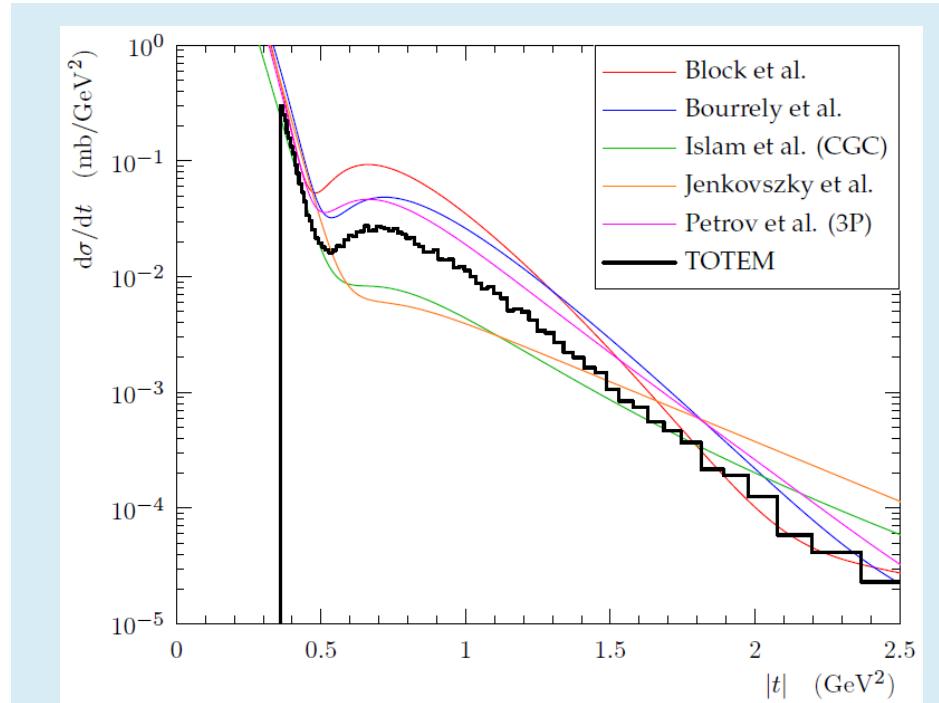
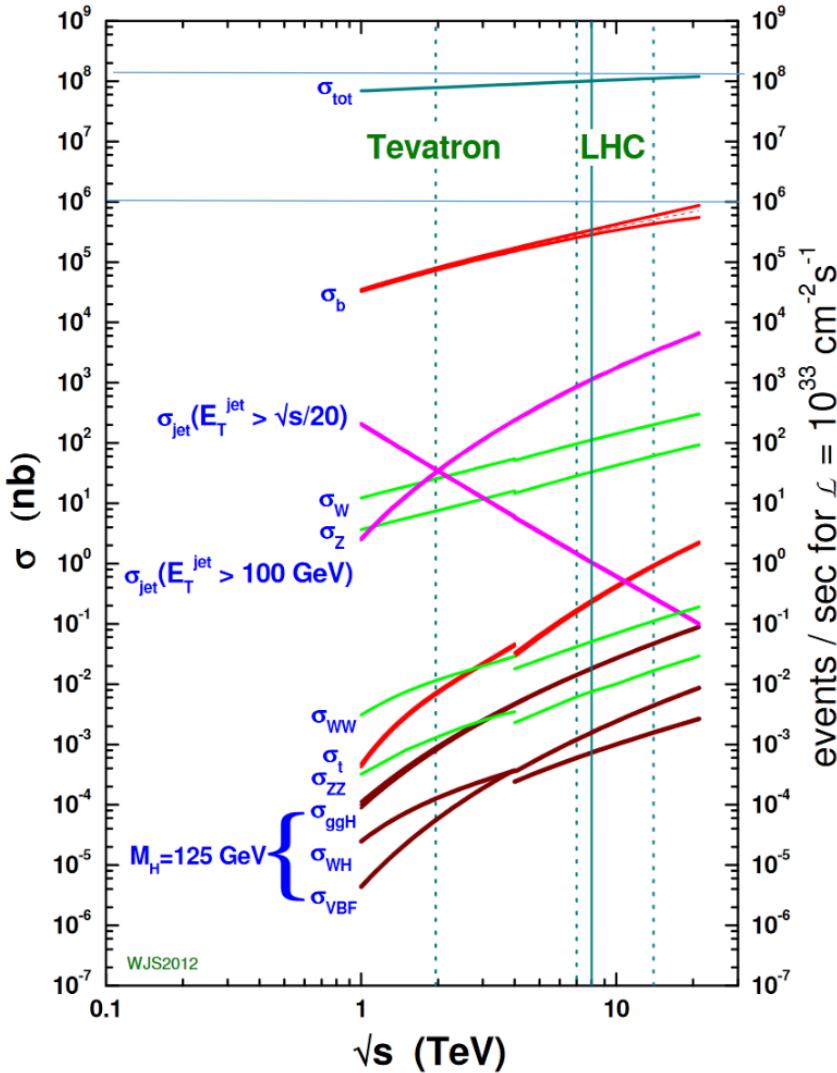
proton - (anti)proton cross sections



much harder
to calculate
this
than
this

Proton-(anti)Proton Collisions

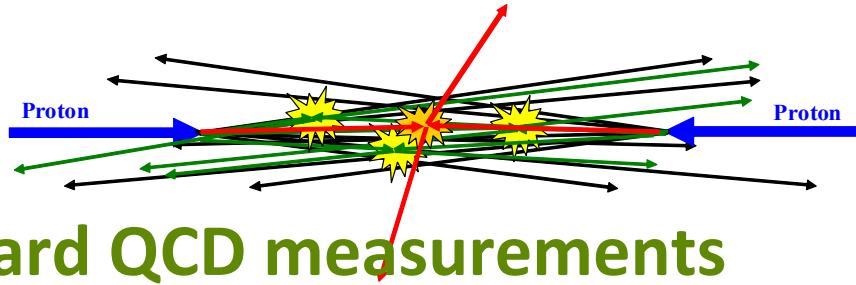
proton - (anti)proton cross sections



Comparison of recent TOTEM results
of the total cross section
(t -distribution) with
several theoretical models

Hard QCD

Full variety of “standard” hard QCD measurements



Jet Final States

- ❖ Inclusive jet cross-sections at 630, 1800 and 1960 GeV
 - ✓ Various jet algorithms
- ❖ Multijet cross sections
 - ✓ including large rapidity dijet cross sections
 - ✓ 3-jet + Ratios of 3- to 2-jet cross sections
 - ✓ New phenomena searches (dijet mass spectrum)
- ❖ α_s measurements
- ❖ Jet substructure
- ❖ Jet shapes

❖ Photon Final States

- ❖ Inclusive photon cross sections at 630, 1800, 1960 GeV
- ❖ Photon+jet
- ❖ Photon +HF
- ❖ Diphoton production

❖ W/Z Final States

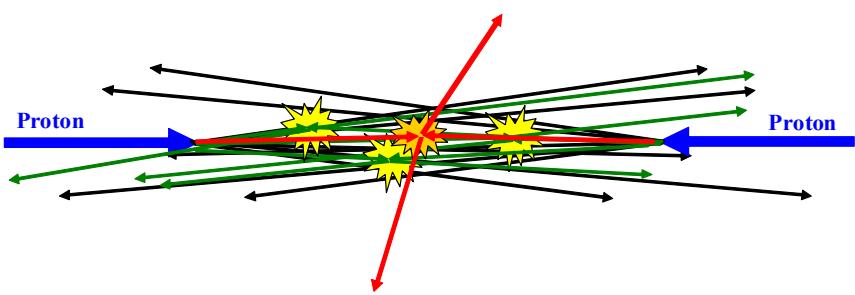
- ❖ W/Z +jet production
- ❖ W/Z+heavy flavor jet production

see Review of Tevatron QCD Results:

CM, D. Bandurin

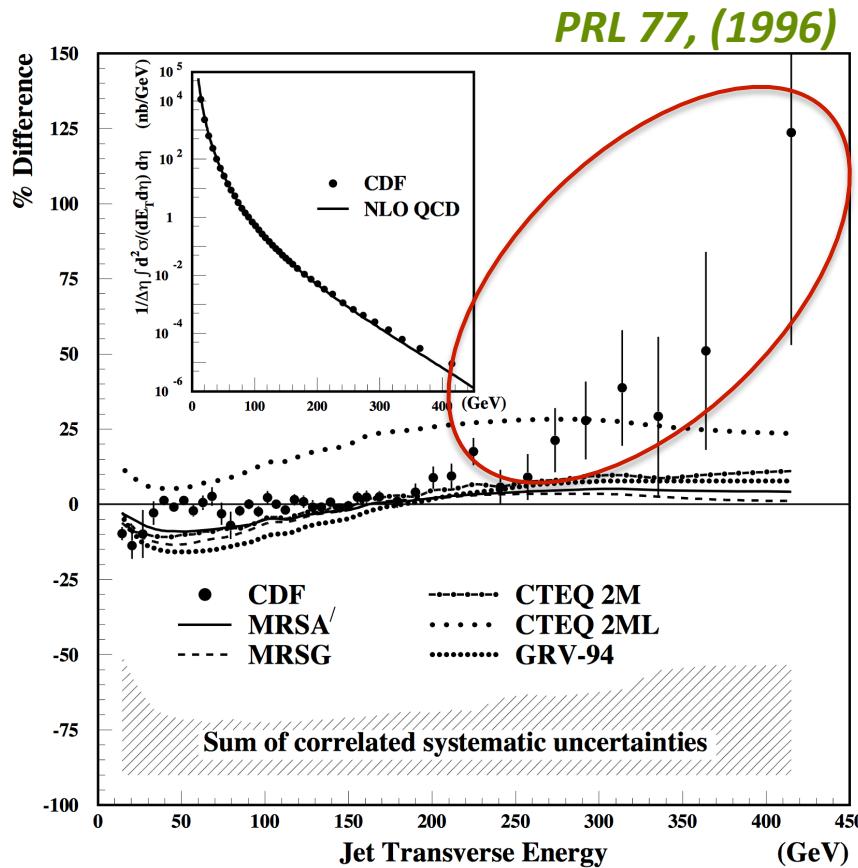
Int. J. of Modern Physics A, Vol. 30, 06 (2015)

Hard QCD - Jets



A bit of history –

Inclusive Jet Cross Section measurement – no longer limited by stat. uncertainties → systematic uncertainties comparable to theoretical uncertainties

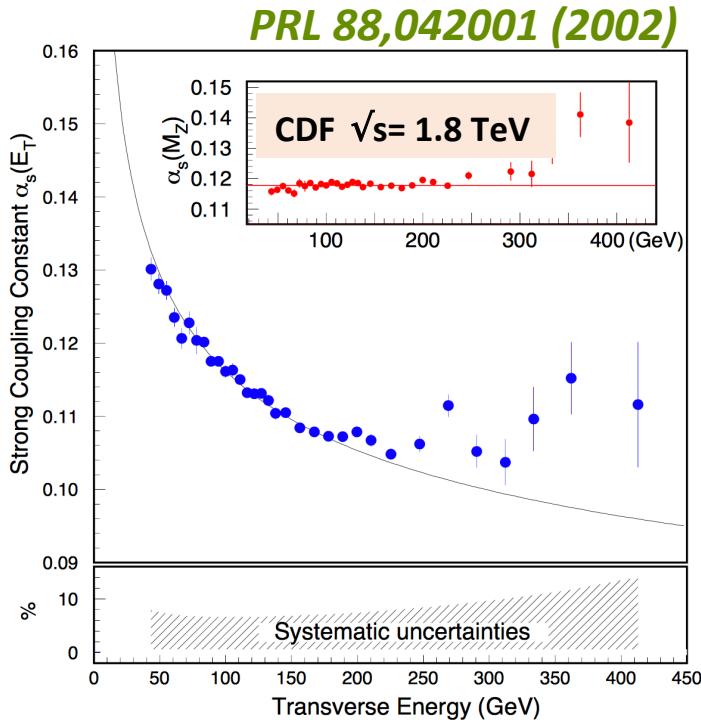


Quite a discrepancy!

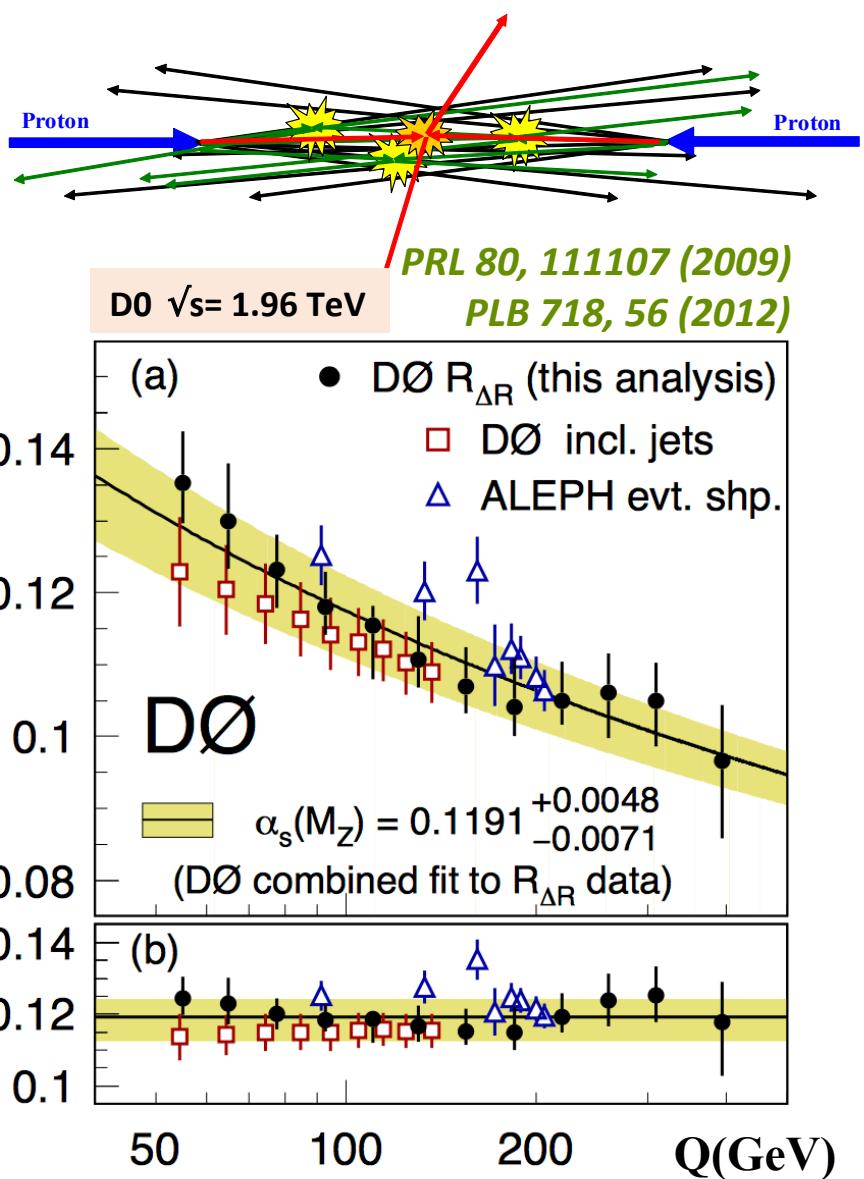
- ❖ Revealed significant flexibility in PDFs - particularly large x gluons
- ❖ Motivated inclusion of the Tevatron jet data in the global PDF analyses to constrain gluon distributions

Hard QCD - α_s

More history -

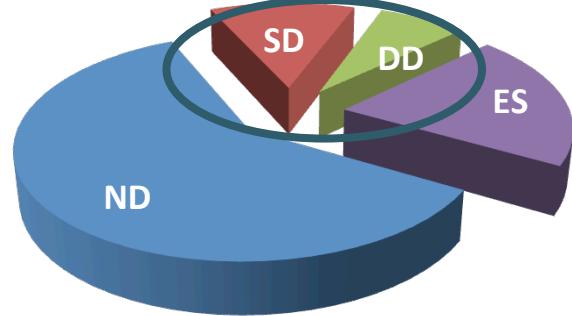


First measurement of α_s from the incl. jet cross section – showing running of α_s in a single measurement over wide E_T range



Fast forward 10 years- nice and sophisticated measurements of α_s from various jet observables

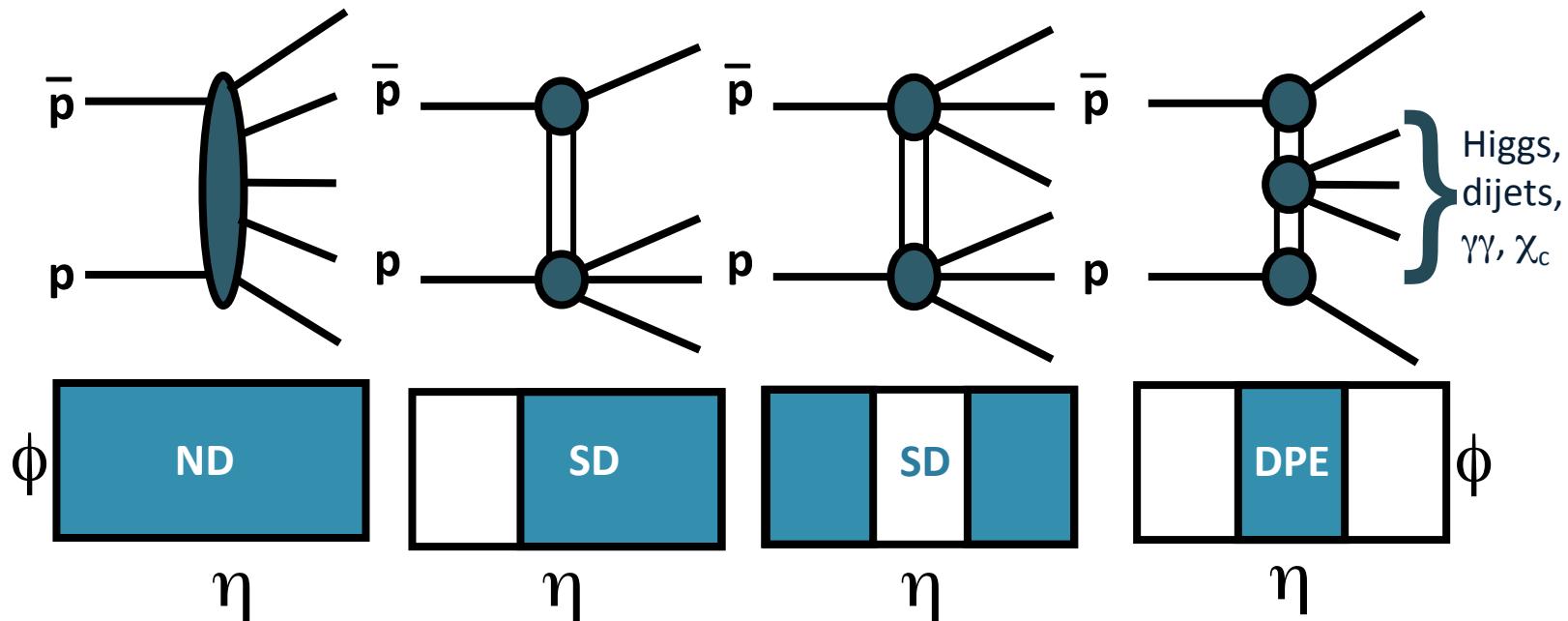
Definitions: Diffraction



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

$$y = \frac{1}{2} \ln \left(\frac{(E + p_z)}{E - p_z} \right)$$

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

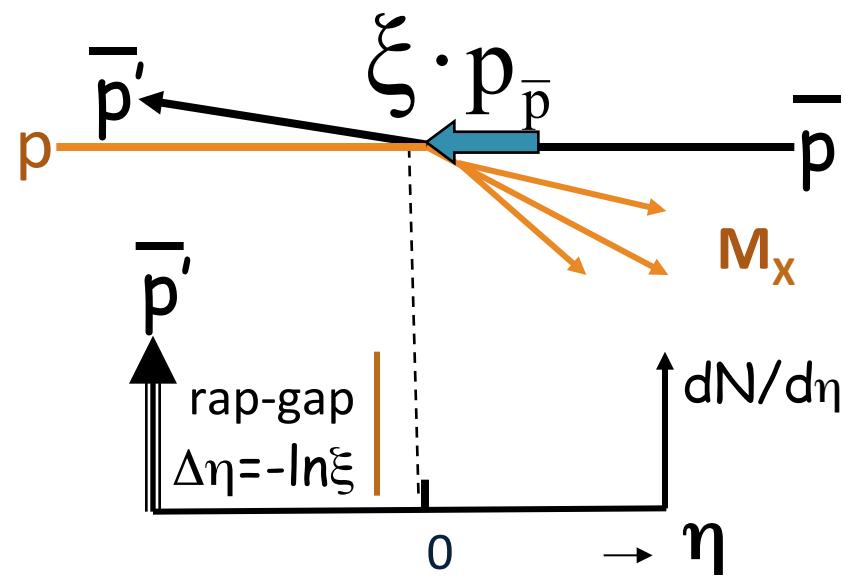
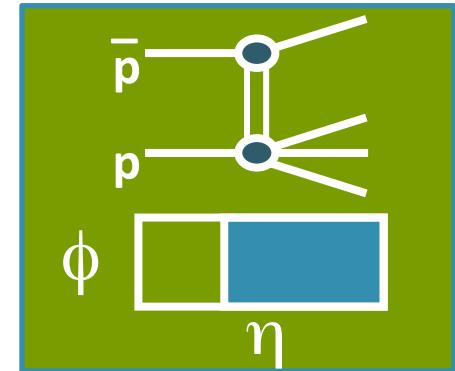
t - four-momentum transfer squared

ξ - fractional momentum loss of $p\bar{p}$

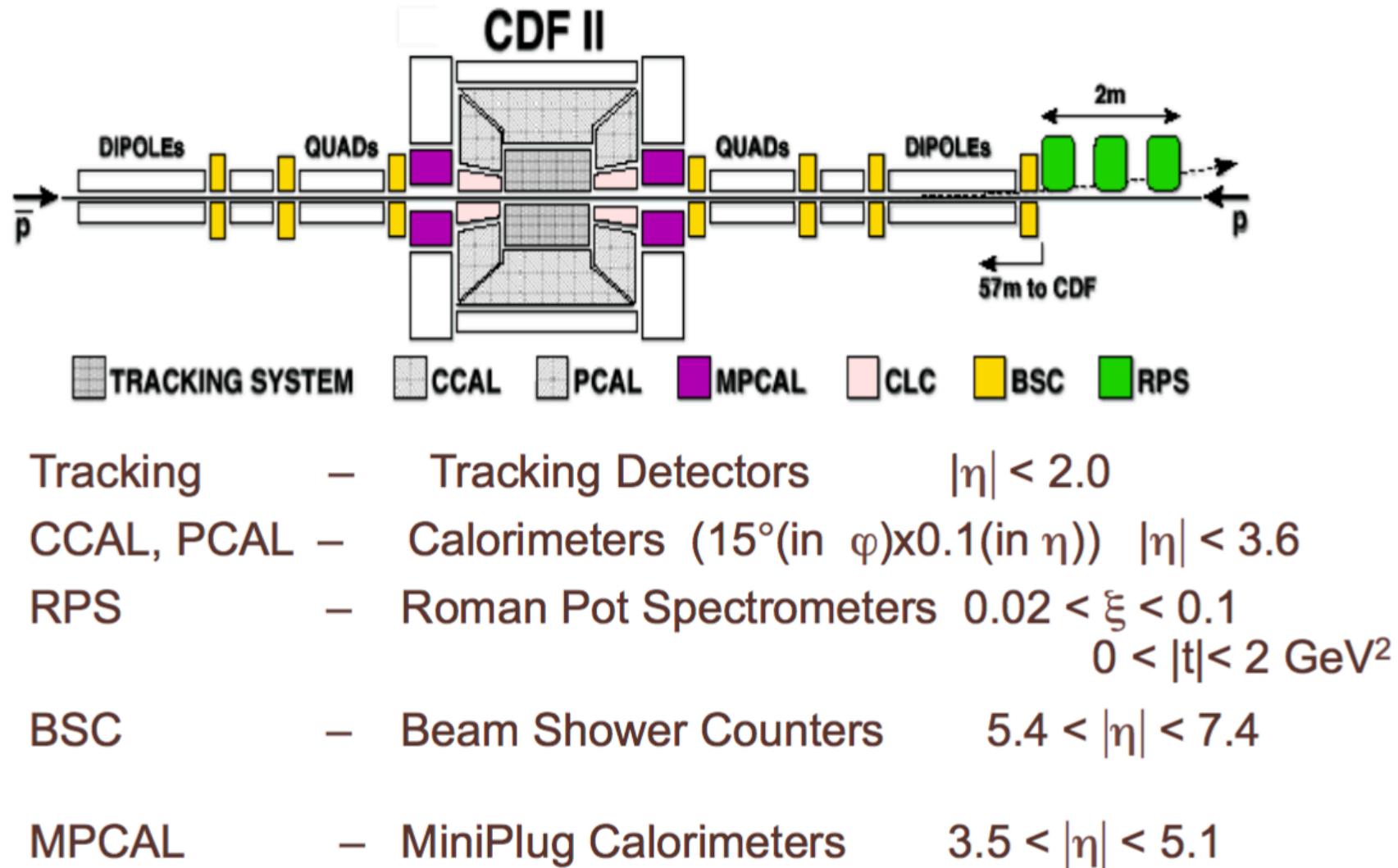
M_x - mass of diffractive system X

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

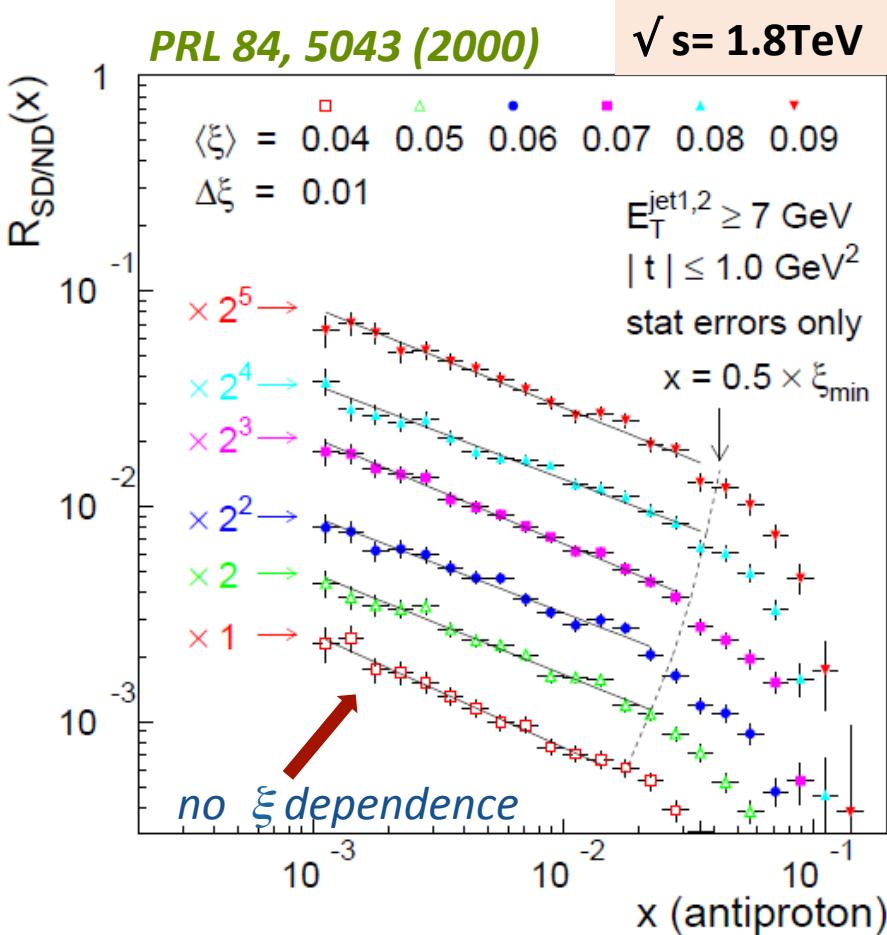
$$\Delta\eta \approx \ln(s/M_x^2)$$



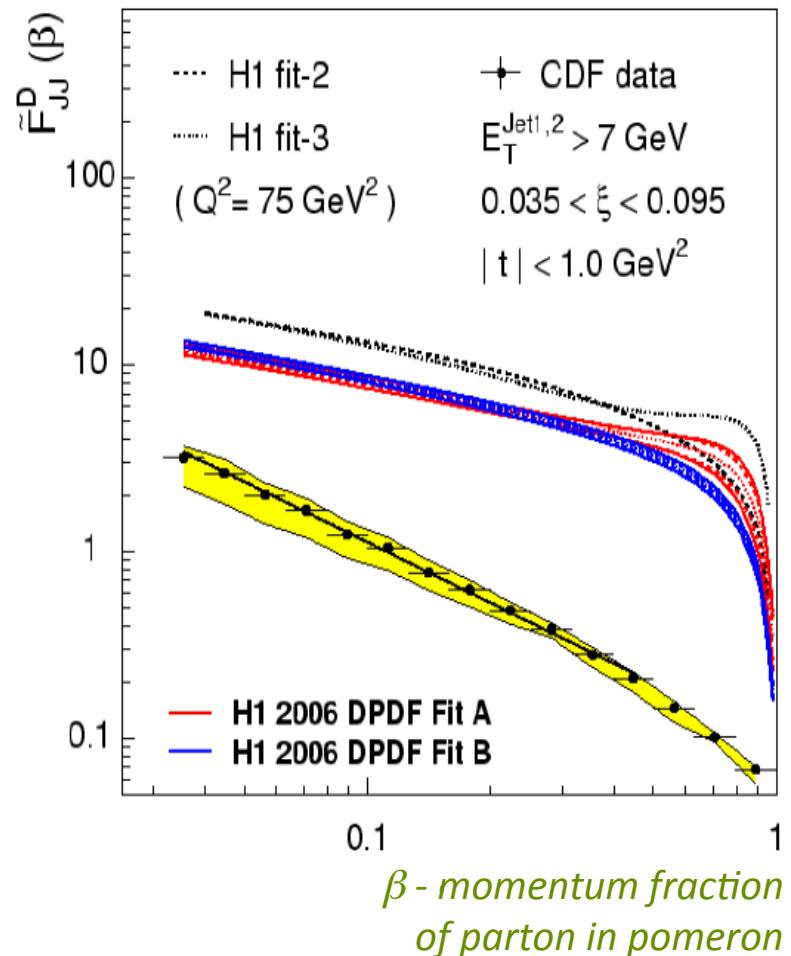
Experimental Techniques



Hard Diffraction: Diffractive Dijets

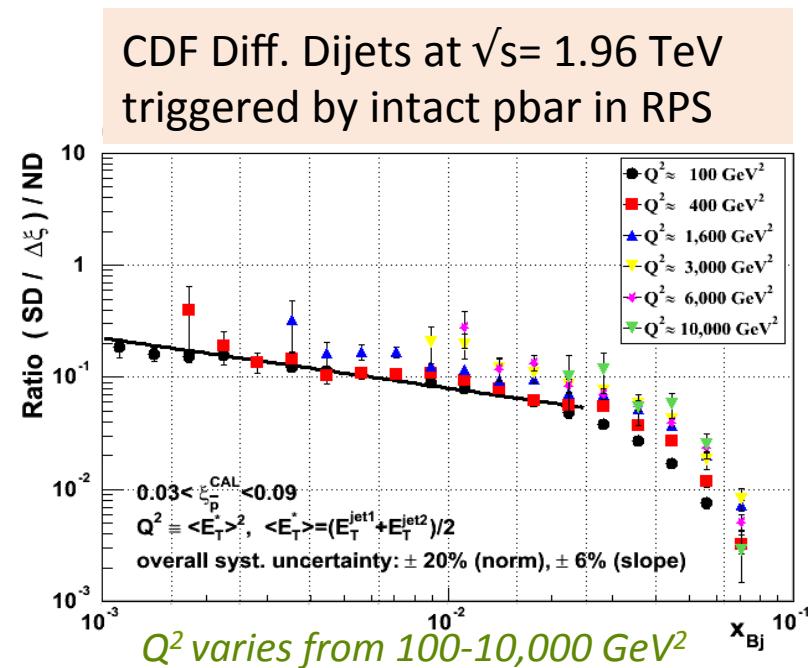
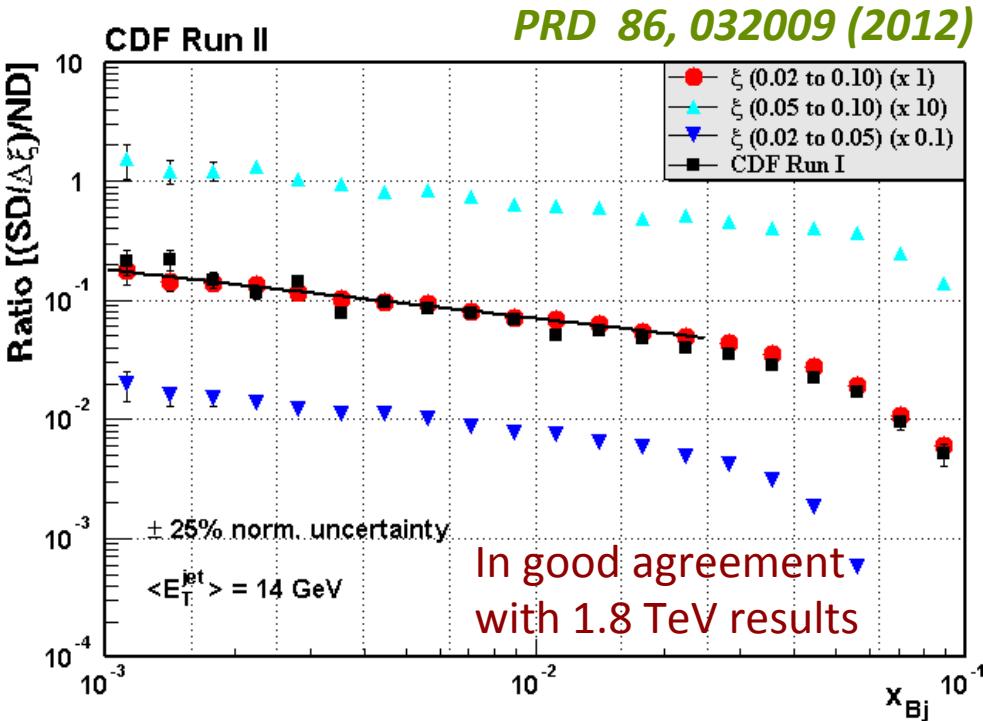


R – ratio of Single Diffractive (SD) dijets to Non-Diffractive (ND) dijets



Factorization breakdown between HERA and Tevatron

Hard Diffraction: Diffractive Dijets



Looking at Fraction for various single hard diffractive productions:

$R \equiv SD/ND$ ratio @ 1800 GeV

All fractions $\sim 1\%$ (diff. 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

Hard Diffraction: Diffractive W

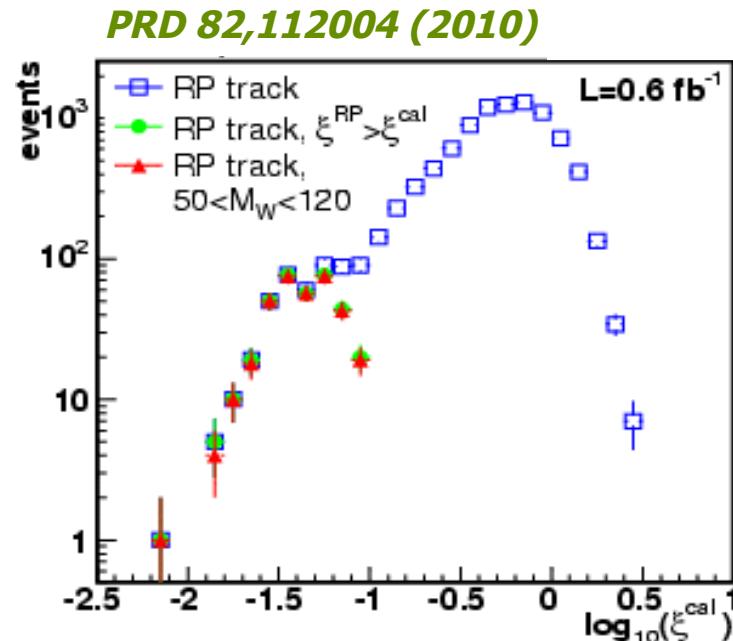
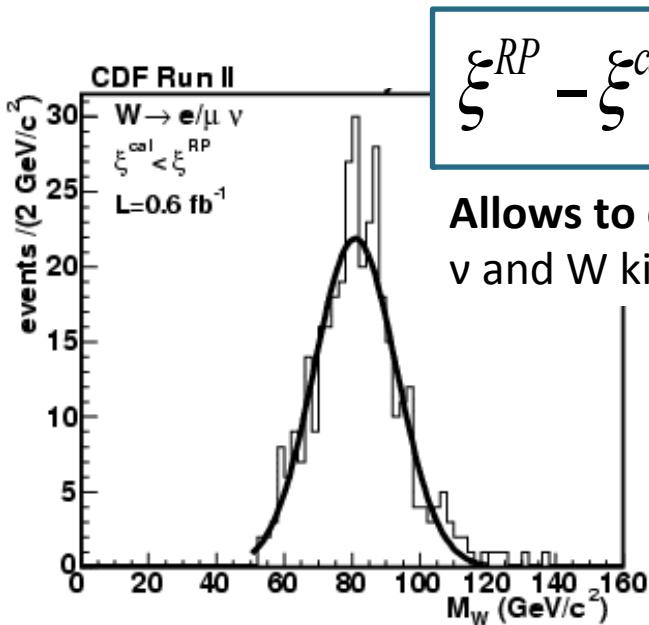
Diffractive W/Z production probes the quark content of the Pomeron

$\sqrt{s} = 1.96 \text{ TeV}$
CDF Run II

Identify diffractive events using RP:

- ◊ accurate event-by-event ξ measurement
- ◊ no gap acceptance correction needed
- ◊ can still calculate ξ^{cal}

The diff. btwn ξ^{cal} and ξ^{RP} is related to miss. E_T and η_ν

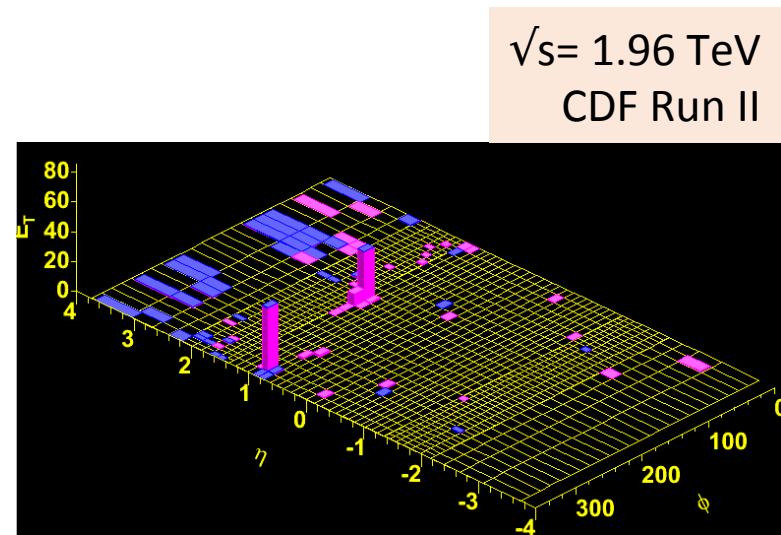
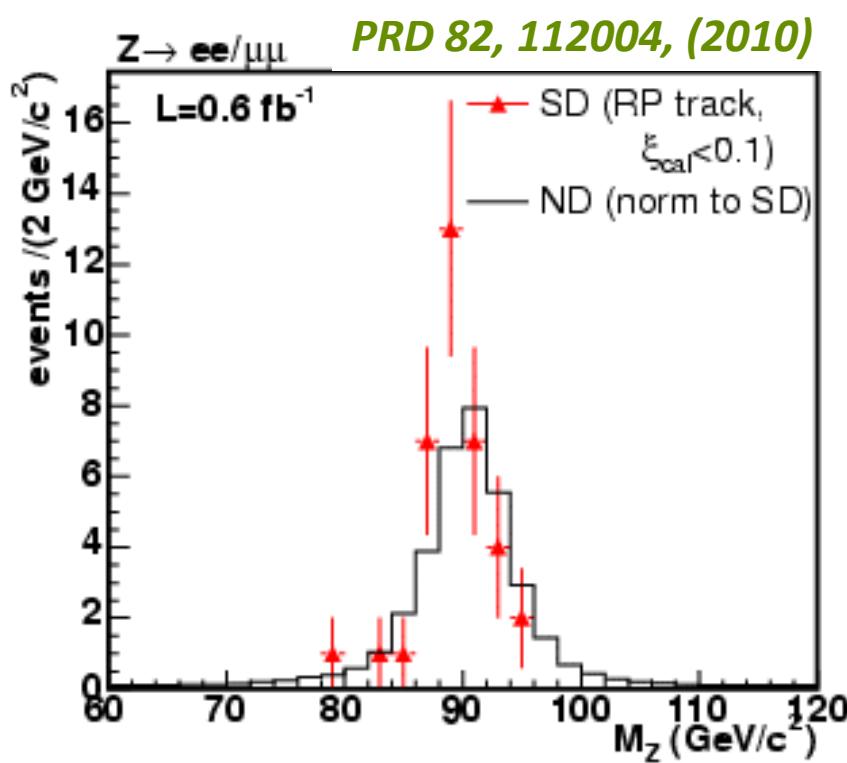


■ $\xi^{\text{cal}} < \xi^{\text{RP}}$ requirement
removes most events with
multiple pbar-p interactions

Fraction of diffractive W

$$R_W (0.03 < \xi < 0.10, |t| < 1) = [0.97 \pm 0.05(\text{stat}) \pm 0.10(\text{syst})]\%$$

Hard Diffraction: Diffractive Z



- ✧ 37 diffractive $Z \rightarrow ee/\mu\mu$ candidates
- ✧ (RP track, $\xi^{\text{cal}} < 0.1$)
- ✧ estimate 11 overlap ND+SD bckg. events based on ND ξ^{cal} distribution

Fraction of diffractive Z

$$R_Z(0.03 < \xi < 0.10, |t| < 1) = [0.85 \pm 0.20(\text{stat}) \pm 0.08(\text{syst})]\%$$

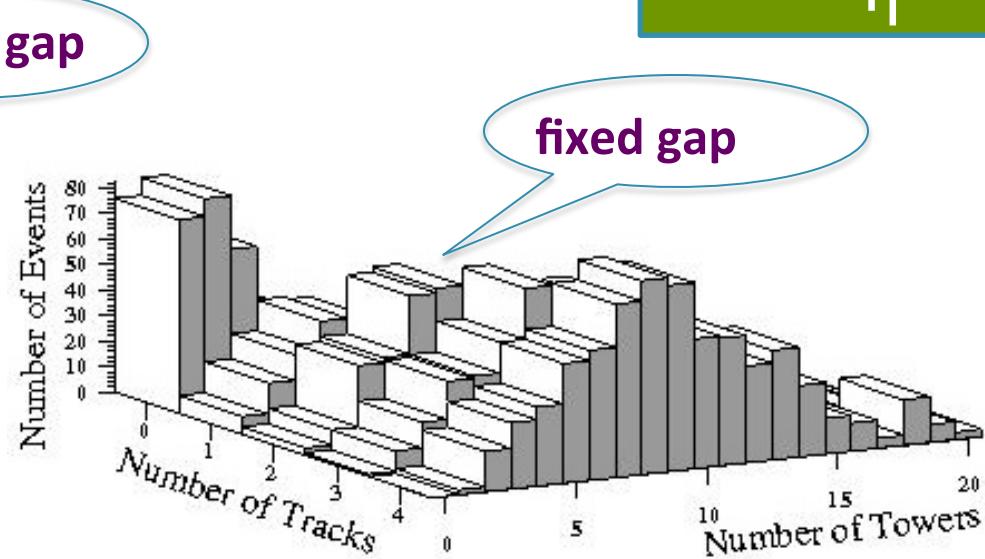
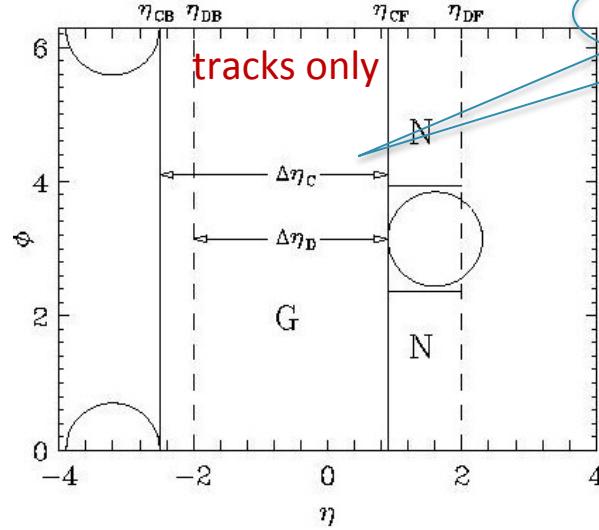
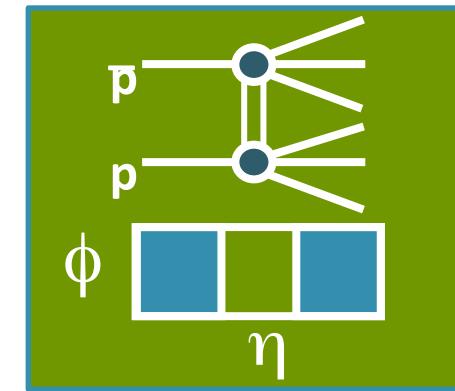
Hard Diffraction: Jet-Gap-Jet

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

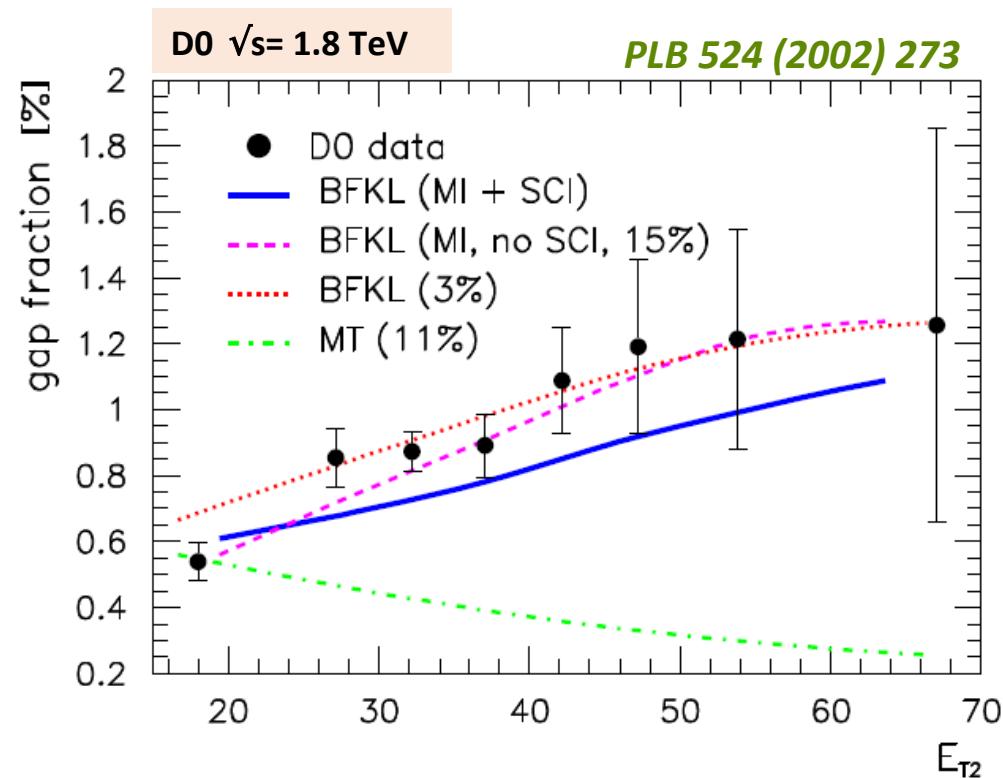
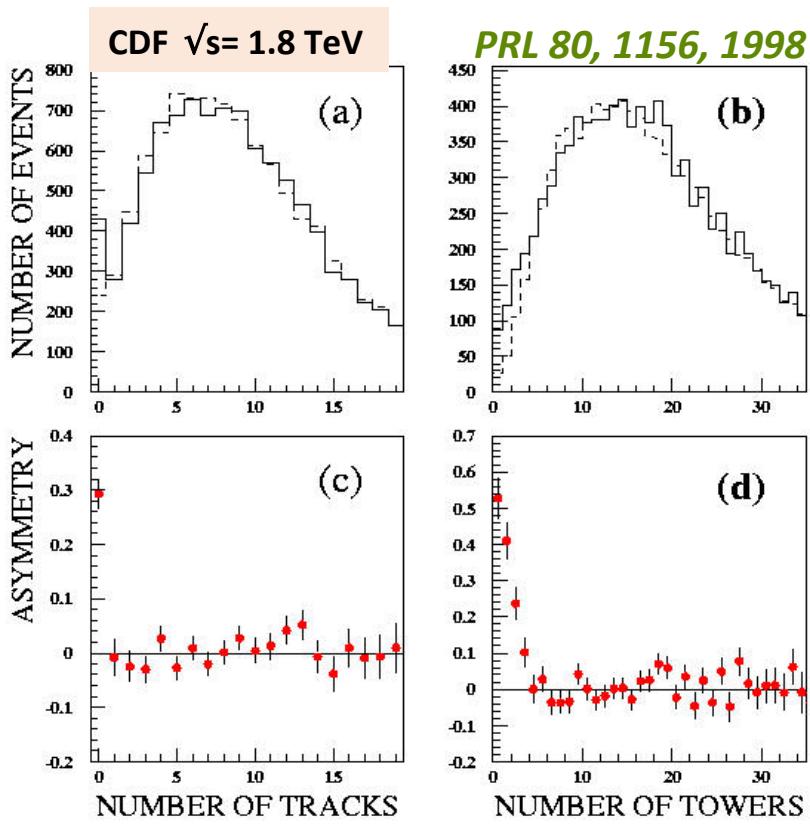
PRL 72, 2332, 1994 (D0)
PRL 74, 855, 1995 (CDF)
PRL 80, 1156, 1998 (CDF)

Diffractive signature:

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



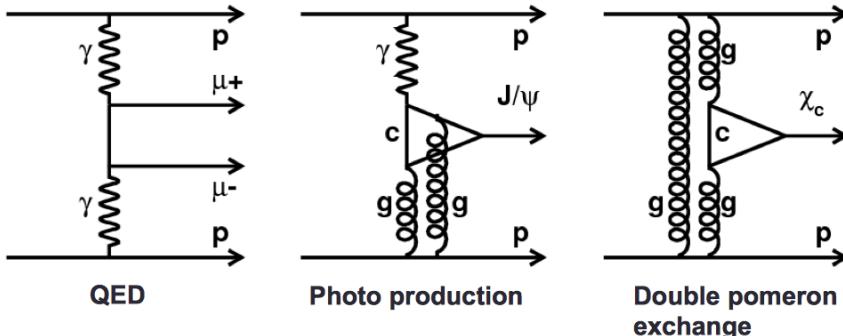
Hard Diffraction: Jet-Gap-Jet



$R = [1.13 \pm 0.12(\text{stat}) \pm 0.11(\text{syst})]\% @ 1800 \text{ GeV}$
 $R = [2.7 \pm 0.7(\text{stat}) \pm 0.6(\text{syst})]\% @ 630 \text{ GeV}$

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

Central Exclusive Production (CEP)



Interactions of the form

$pp(p\bar{p}) \rightarrow p \text{ [exclusiveX]} p(p\bar{p})$

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

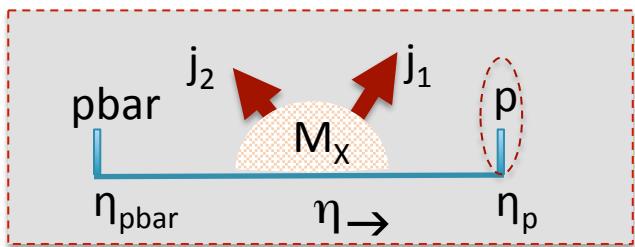
[exclusive X] must be neutral PC = ++, no net flavor: $f_{0;2}; \chi_{c;b}; \gamma\gamma; JJ; H$

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

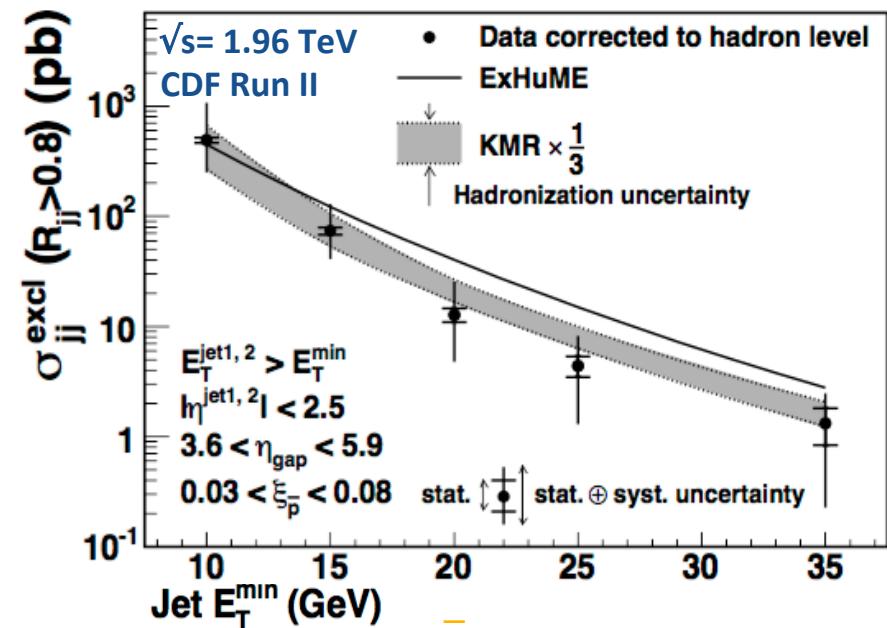
CEP: Observation of Excl. Dijets

PRD 77, 052004 (2008)

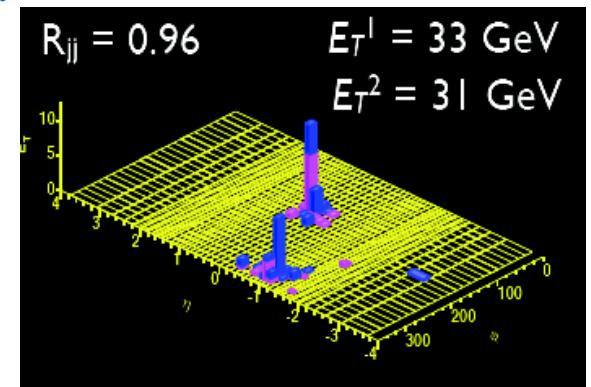
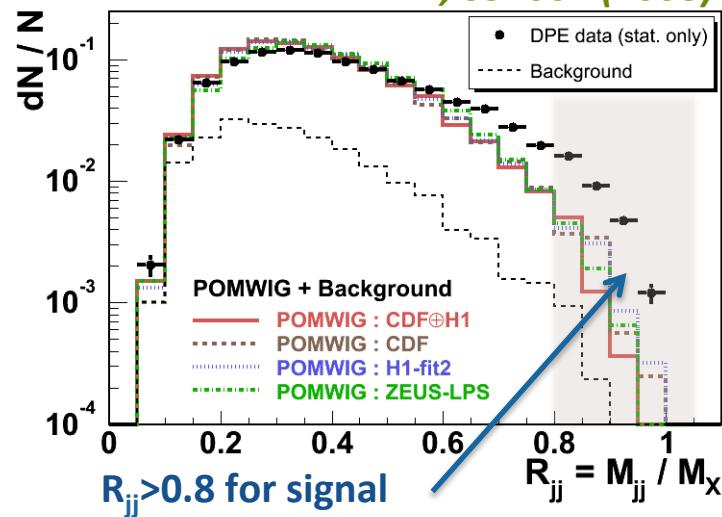
Reconstruct $R_{jj} = M_{jj}/M_X$



- ❖ M_{jj} – mass of dijet system
- ❖ M_X – mass of system X



September 24, 2017

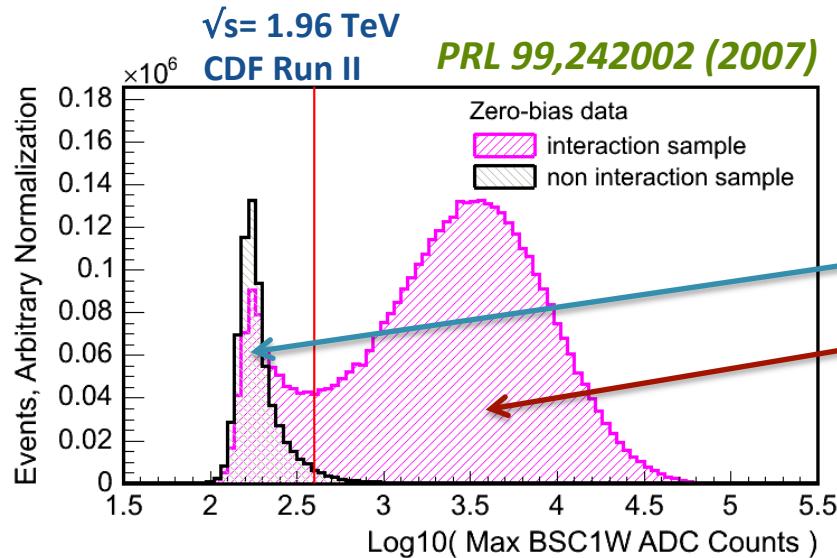


- ❖ Observation of Exclusive Dijet production
- ❖ Measured cross-section consistent with KMR predictions

Christina Mesropian

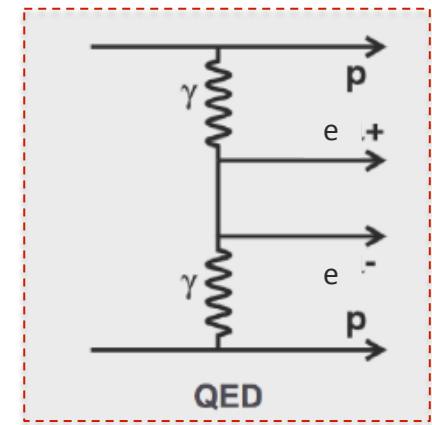
29

CEP: Exclusive $\gamma\gamma$ Production

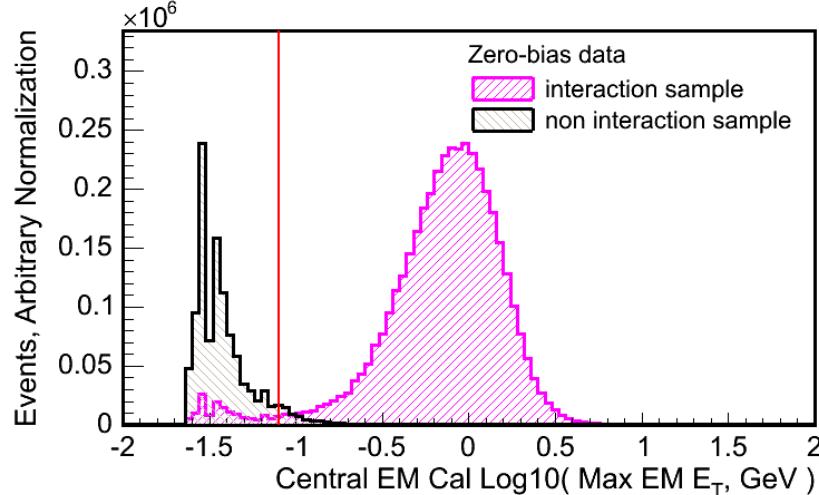


Requirements :
no other particles in the detectors up to $|\eta| < 7.4$

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



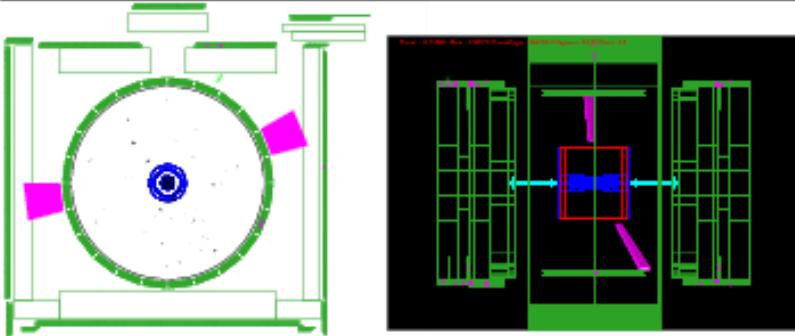
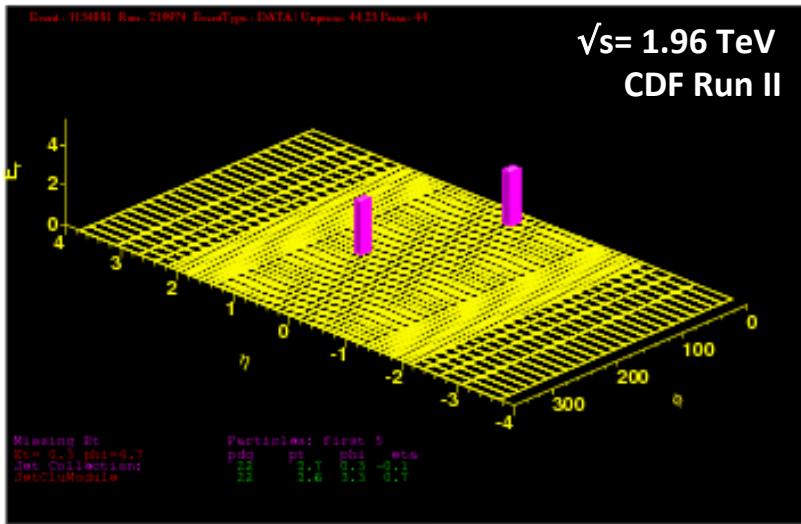
Use control sample
to understand



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

$$\begin{aligned} \sigma_{e^+e^- \text{ excl.}}^{|\eta| < 1, E_T > 2.5 \text{ GeV}} &= 2.88 \pm 0.59(\text{stat}) \pm 0.62(\text{sys}) \text{ pb} \\ \sigma_{\text{LPair}}^{|\eta| < 1, E_T > 2.5 \text{ GeV}} &= 3.25 \pm 0.07 \text{ pb} \\ \sigma_{e^+e^- \text{ excl.}}^{|\eta| < 1, E_T > 5.0 \text{ GeV}} &= 0.60 \pm 0.28(\text{stat}) \pm 0.14(\text{sys}) \text{ pb} \\ \sigma_{\text{LPair}}^{|\eta| < 1, E_T > 5.0 \text{ GeV}} &= 0.58 \pm 0.003 \text{ pb} \end{aligned}$$

CEP: Exclusive $\gamma\gamma$ Production

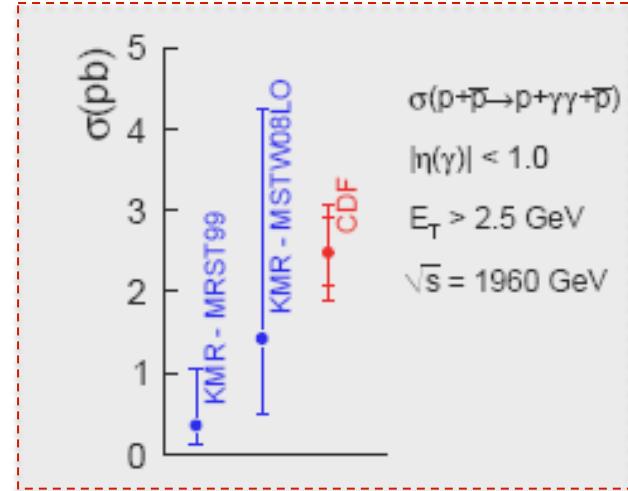
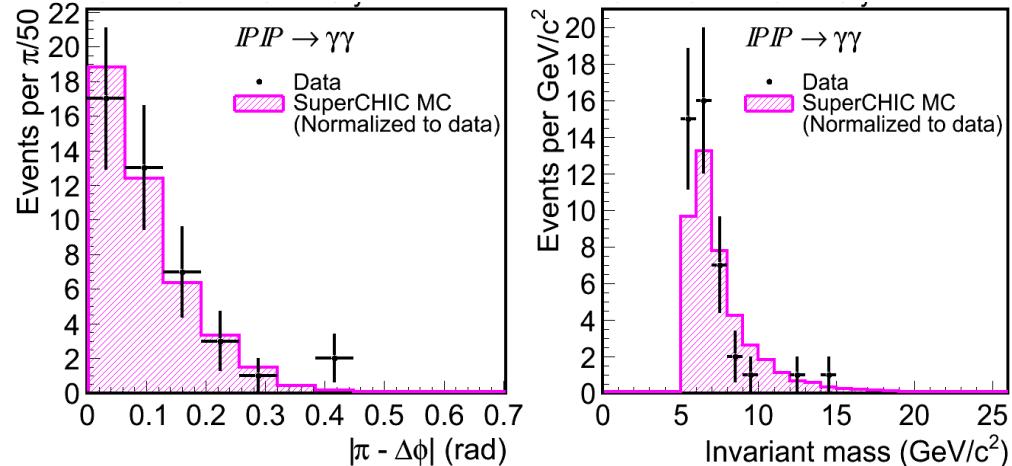


Observed 43 events $>> 5\sigma$

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

Good agreement with the theoretical predictions

PRL 108, 081801 (2012)



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



J/ψ production

243 ± 21 events

$$d\sigma/dy|_{y=0} = 3.92 \pm 0.62 \text{ nb}$$

In agreement with theor. pred.

$\Psi(2s)$ production

34 ± 7 events

$$d\sigma/dy|_{y=0} = 0.54 \pm 0.15 \text{ nb}$$

$$R = \psi(2s)/J/\psi = 0.14 \pm 0.05$$

In agreement with HERA:

$R = 0.166 \pm 0.012$ in a similar kinem. region

Allowing EM towers ($E_T > 80 \text{ MeV}$)

large increase in the J/ψ peak

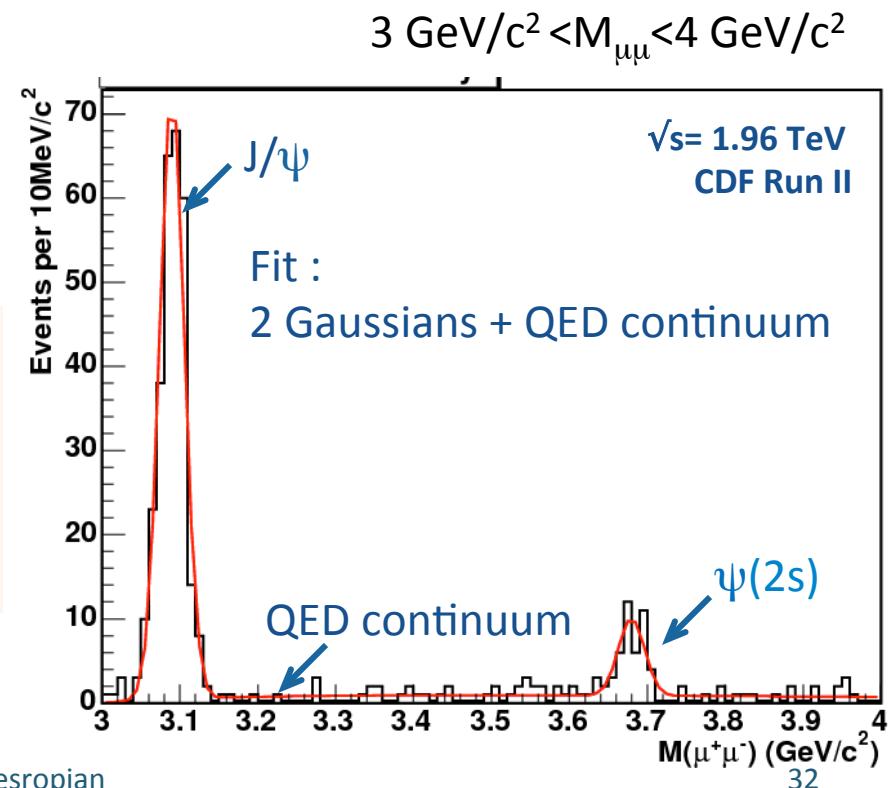
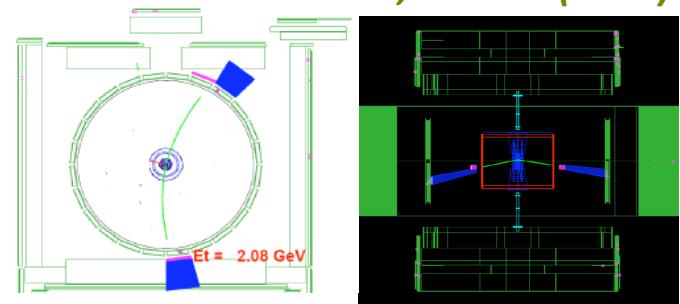
minor change in the $\psi(2s)$ peak →

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

$$d\sigma/dy|_{y=0} = 75 \pm 14 \text{ nb},$$

compatible with theoretical predictions

PRL 102, 242001 (2009)



CEP: Exclusive $\pi^+\pi^-$

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 PU)

Selection:

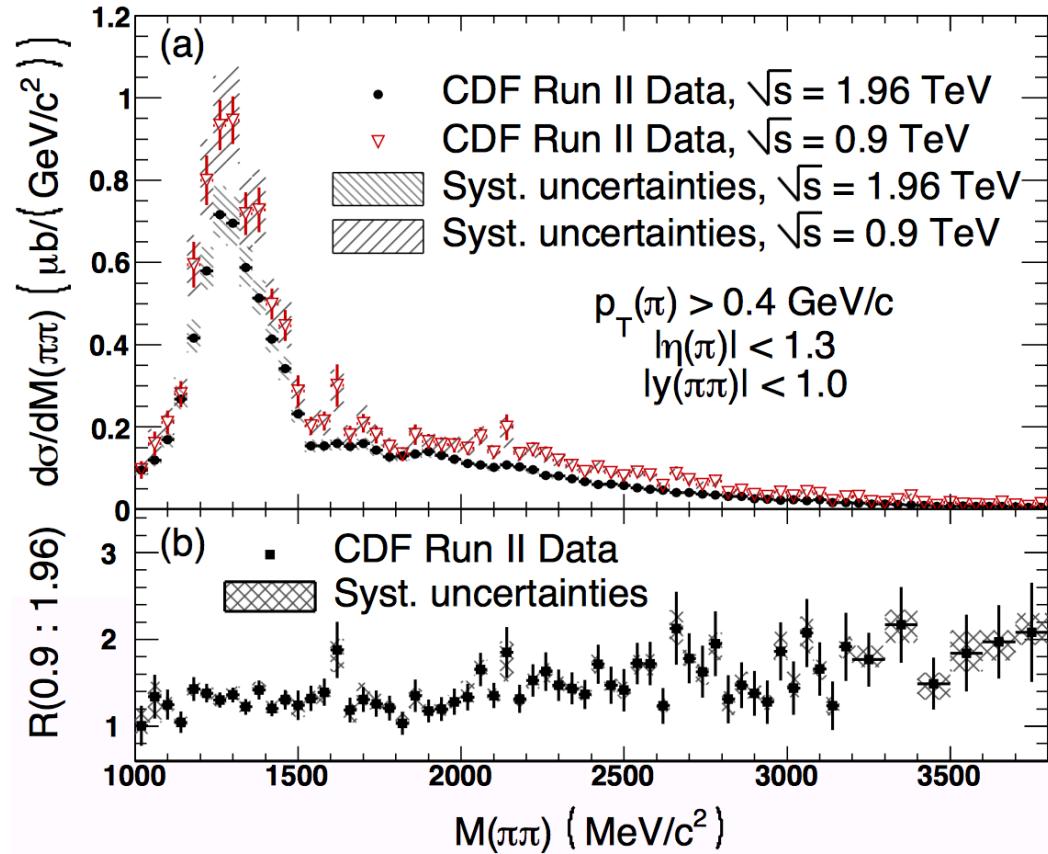
$\pi^+\pi^-$ and no other activity in $|\eta| > 5.9$

The cross section ratio

$$R(0.9:1.96) = 1.28$$

for $1 < M_{\pi\pi} < 2 \text{ GeV}$

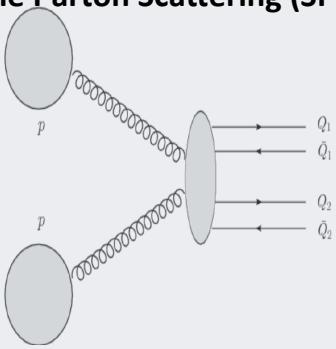
Consistent with
Regge phenomenology ($\sim 1/\ln(s)$)



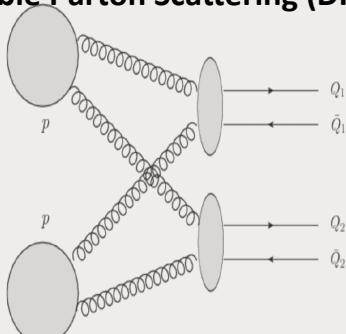
- ❖ $f_2(1270)$, shoulder from $f_0(1370)$ interference
- ❖ some structure around 1.4-2.4 GeV
- ❖ data falls monotonically above 2.4 GeV

Soft QCD – MPI

Single Parton Scattering (SPS)



Double Parton Scattering (DPS)



DPS results are usually interpreted in terms of a “pocket formula”

$$\sigma_{\text{DPS}}^{AB} = \frac{m}{2} \frac{\sigma_{\text{SPS}}^A \sigma_{\text{SPS}}^B}{\sigma_{\text{eff}}},$$

where m is the combinatorial factor:

- $m = 1$ for identical final states A and B
- $m = 2$ for $A \neq B$.

σ_{eff}

- ❖ effective transverse overlap area
- ❖ transverse distance btwn partons
- ❖ partonic density
- ❖ tells about conditional probability to have a 2-nd hard scatter
- ❖ theory estimates $\sim 30\text{mb}$
- ❖ data says $\sim 5\text{-}25\text{mb}$
- ❖ calculations typically use 15mb

Pocket formula is derived under assumption of independent parton scattering where:

- longitudinal, transverse components factorize
- long'tl comps are 2 independent single-PDFs

If the assumption of factorization is correct, the value of σ_{eff} should be universal, independent of final states or phase space.

Soft QCD – MPI

Why study MPI (DPS)?

Increasingly important at higher center of mass energies

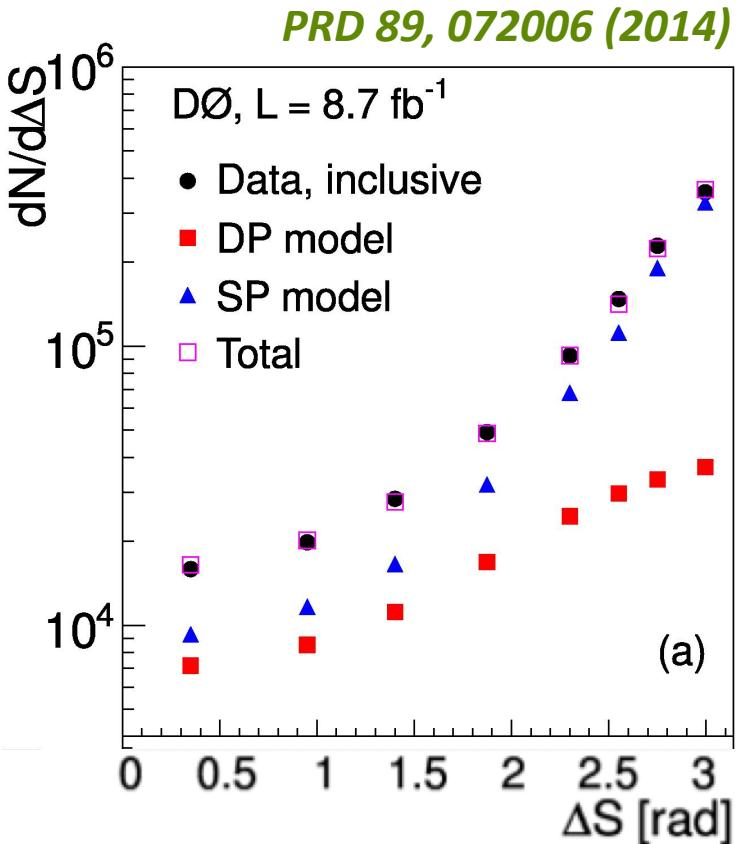
- ❖ Probe transverse profile of proton PDF
- ❖ Partonic correlations
 - color, flavor interference, spin effects

Background to many rare processes, especially with multi-jet final states

Experimentally, the determination of σ_{eff} is based on the % of identified DPS events. The latter is extracted based on topological considerations which involves a proper understanding of topologies expected in SPS.

The CDF and D0 collaborations comprehensively studied the phenomenon of MPI events in a series of Run I and Run II measurements.

Soft QCD – MPI: γ +jet+2jets

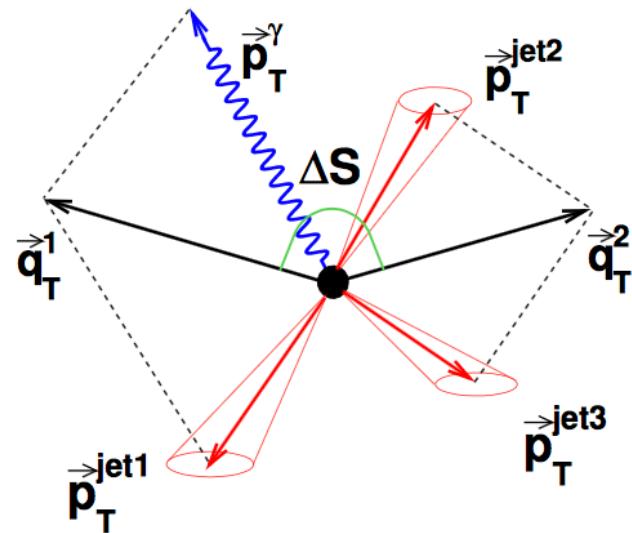


- ◊ templates based on Sherpa (& Pythia)
- ◊ estimated via mix of evts with γ +jet and ≥ 1 jet for 1(2)vtx samples

Key discriminant:

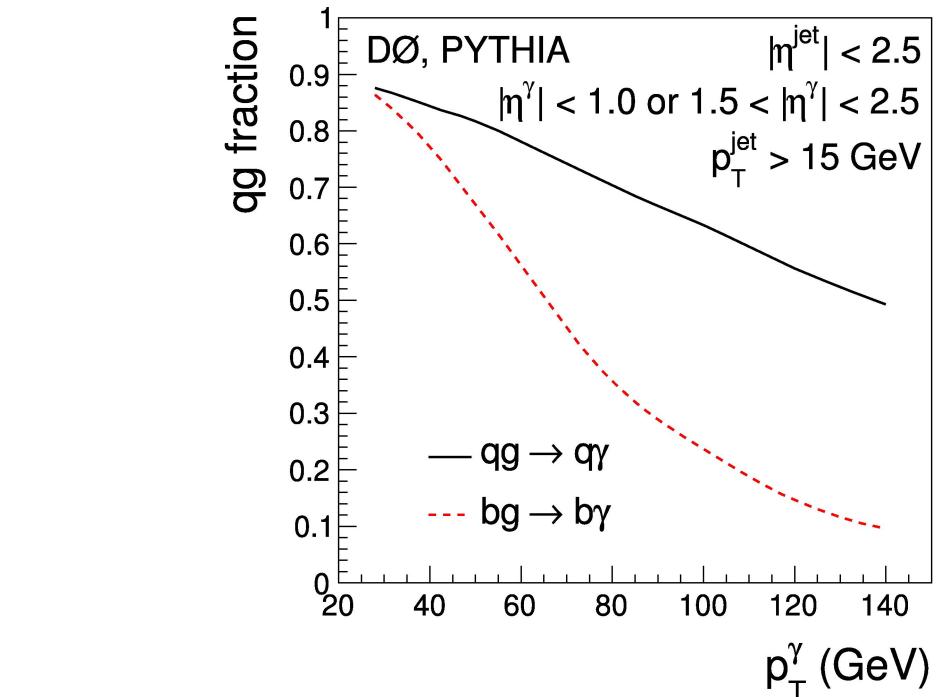
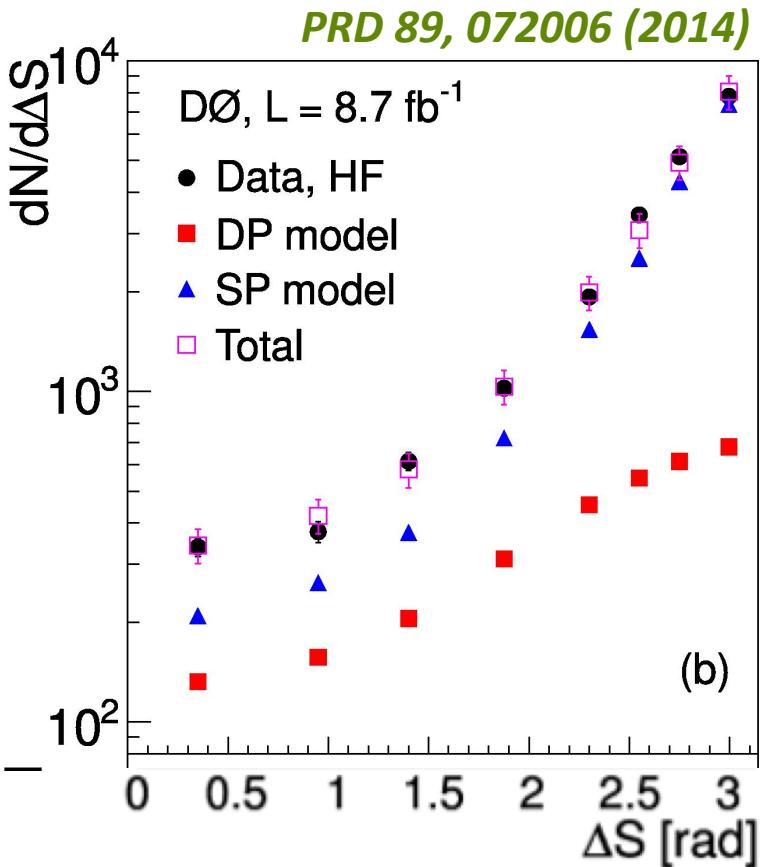
azimuthal angle between γ +jet & dijet

$$\Delta S \equiv \Delta\phi(\vec{q}_T^1, \vec{q}_T^2),$$



$$\sigma_{\text{eff}} = 12.7 \pm 0.2(\text{stat}) \pm 1.3(\text{syst}) \text{ mb}$$

Soft QCD – MPI: $\gamma+b/c\text{-jet}+2\text{jets}$

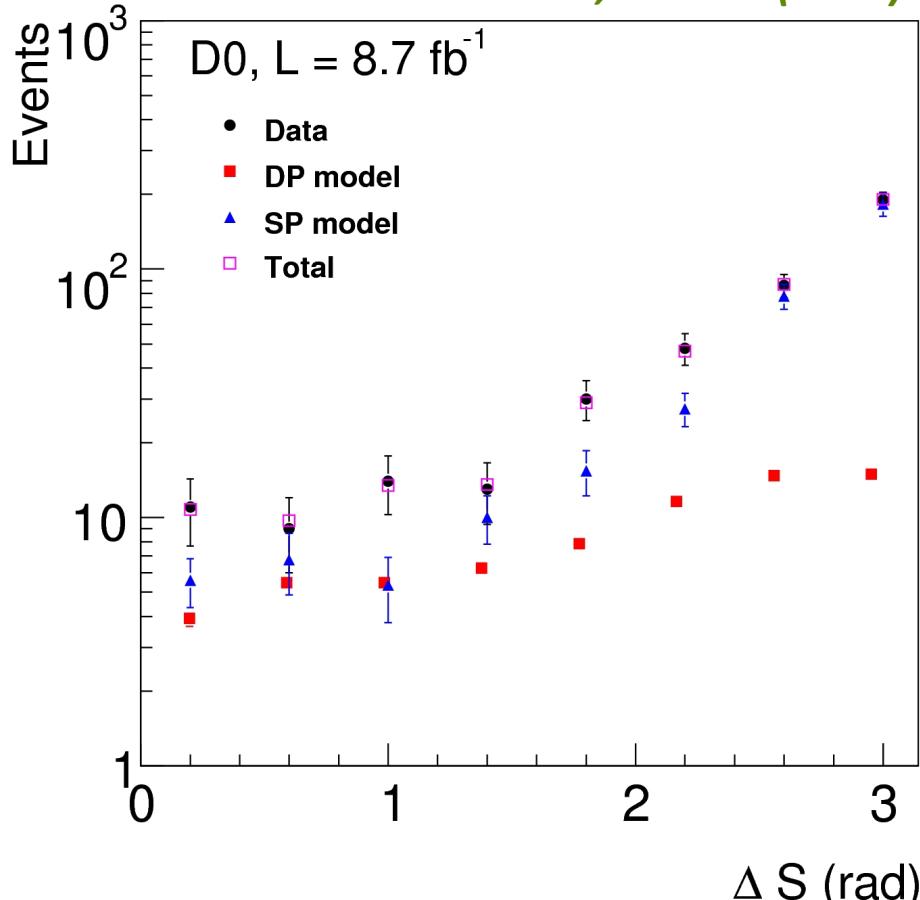


$$\sigma_{\text{eff}} = 14.6 \pm 0.6(\text{stat}) \pm 3.2(\text{syst}) \text{ mb}$$

Consistent with the result for $\gamma+\text{jet+dijet}$ sample →
no evidence of σ_{eff} dependence on the initial parton flavor

Soft QCD – MPI: $2\gamma+2\text{jets}$

PRD 93, 052008 (2016)

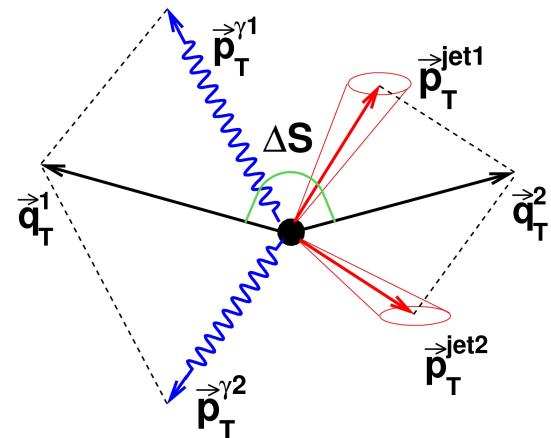


$$\sigma_{\text{eff}} = 19.3 \pm 1.4(\text{stat}) \pm 7.8(\text{syst}) \text{ mb}$$

Key discriminant:

azimuthal angle between $\gamma+\text{jet}$ & dijet

$$\Delta S \equiv \Delta\phi(\vec{q}_T^1, \vec{q}_T^2),$$



The technique is based on a comparison of the $N_{\gamma\gamma + \text{dijet}}$ events produced in DP interactions in single pp^- collisions to $N_{\gamma\gamma + \text{dijet}}$ events produced in 2 separate pp^- collisions.

Soft QCD – MPI: Double J/ ψ

PRD 90, 111101(R) (2014)

Signal:

prompt J/ ψ + J/ ψ

Observables in this measurement:

$\Delta\eta_{\psi\psi}, \Delta\varphi_{\psi\psi}, M_{\psi\psi}, p_T^{\psi\psi}$

Cuts for
signal:
mass cut (x2)

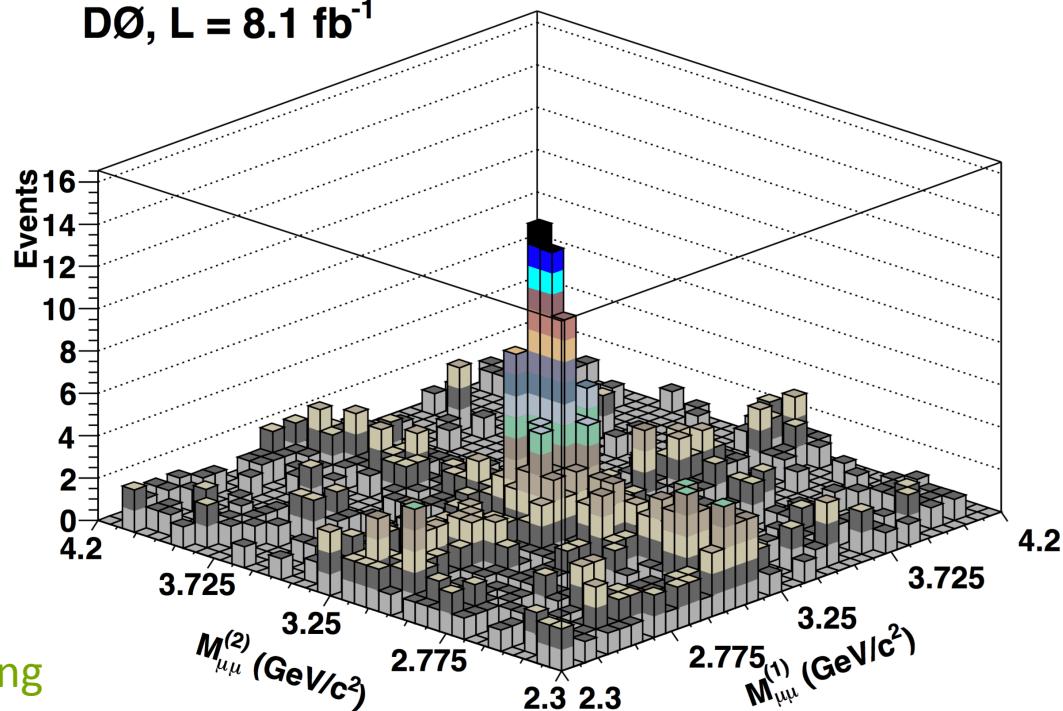
backgrd:
di-muon decay vertex cuts
J/ ψ – J/ ψ separation distance
fit combinatorial/bkg

The initial state is dominated by gg scattering →
the fraction of DP scatterings representing simultaneous, independent parton interactions, should significantly depend on the spatial distribution of gluons in a proton

Background:

- ◊ non-prompt J/ ψ (B decays)
- ◊ prompt J/ ψ + unassociated $\mu\mu$
- ◊ unassociated $\mu\mu$ + unassociated $\mu\mu$

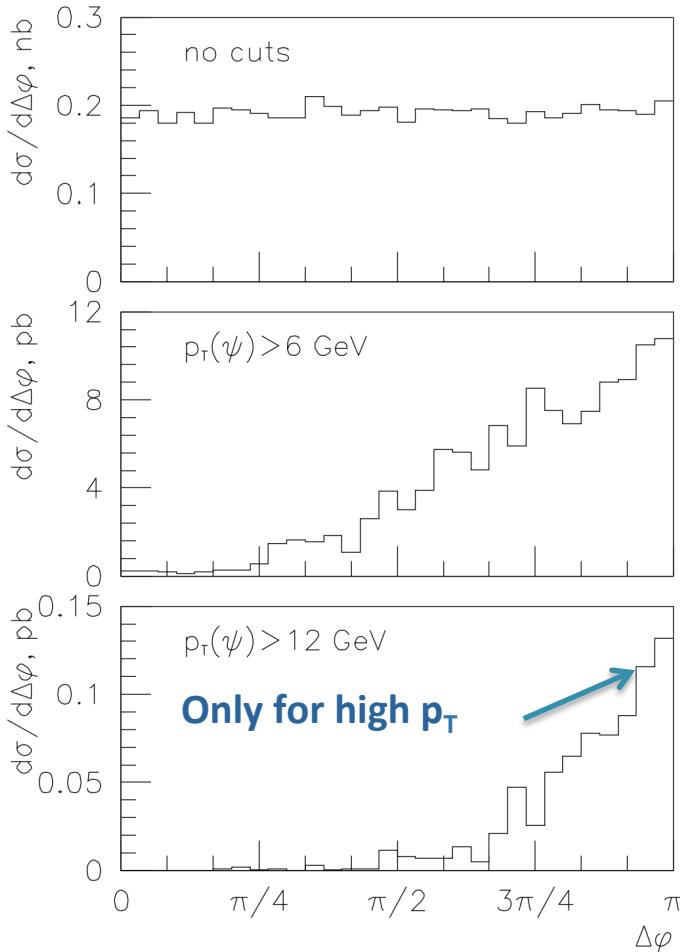
DØ, L = 8.1 fb $^{-1}$



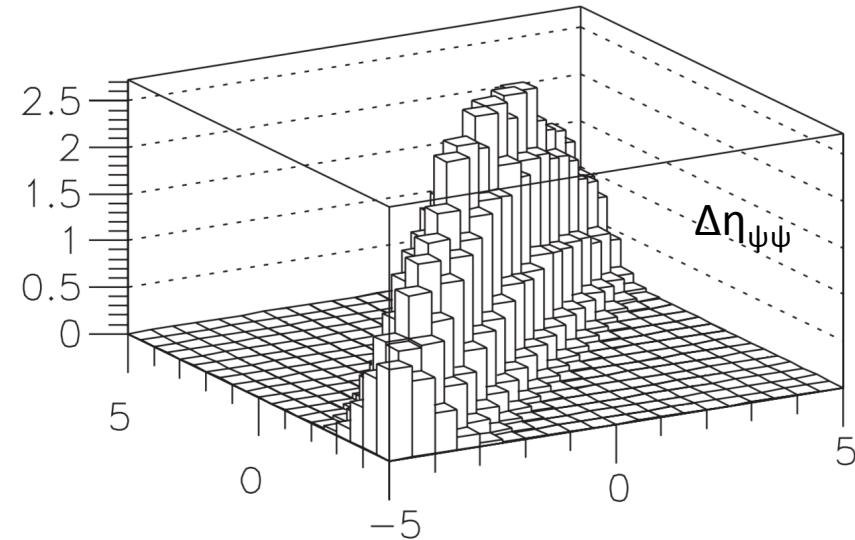
Soft QCD – MPI: Double J/ ψ

Baranov et al, PRD 87 (2013)

Usual techniques ($\Delta\varphi_{\psi\psi}$) don't work for **separation of SP and DP events**:

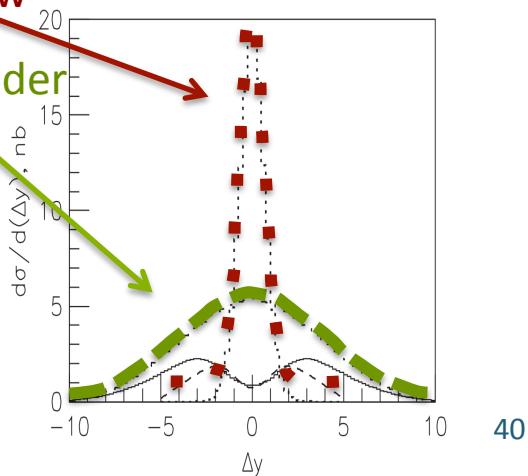


Much better variable is $\Delta\eta_{\psi\psi}$ -
SP J/ ψ highly correlated in $\Delta\eta$



SP – $\Delta\eta_{\psi\psi}$ very narrow

DP – $\Delta\eta_{\psi\psi}$ much broader



Soft QCD – MPI: Double J/ ψ

PRD 90, 111101(R) (2014)

Signal:

prompt J/ ψ + J/ ψ

Fiducial Acceptance (J/ ψ):

$p_T > 4 \text{ GeV}/c$

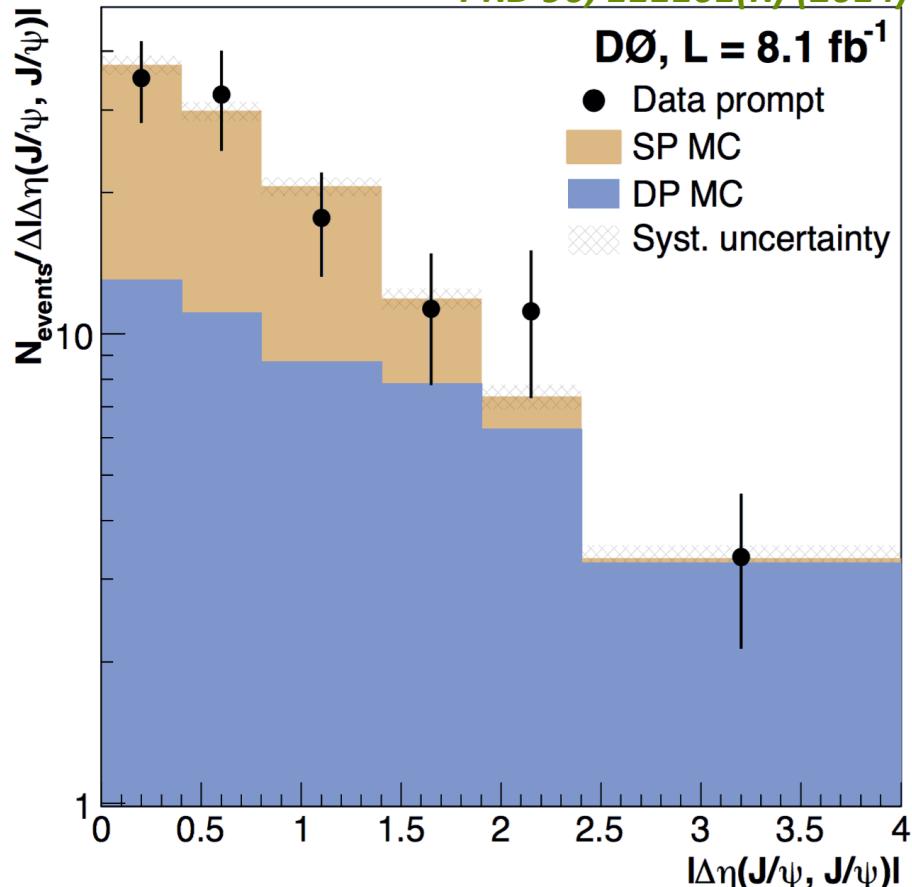
$|\eta| < 2$

- ◊ Use template fit to $\Delta\eta_{\psi\psi}$ (and decay vertex)
- ◊ Subtract background

$$\sigma_{DPS}(\text{J}/\psi + \text{J}/\psi) = 59 \pm 6 \pm 22 \text{ fb}$$

$$\sigma_{SPS}(\text{J}/\psi + \text{J}/\psi) = 70 \pm 6 \pm 22 \text{ fb}$$

$$\sigma_{\text{eff}} = 4.8 \pm 0.5 \pm 2.5 \text{ mb}$$



The $|\Delta\eta(\text{J}/\psi, \text{J}/\psi)|$ distribution of bckg subtr. double J/ ψ events after all selections. The distributions for the SP and DP templates are shown normalized to their fitted fractions. The unct. band corresponds to the total syst.uncertainty on the sum of SP and DP events.

Soft QCD – MPI: J/ ψ + γ

PRL 116, 082002 (2016)

- ❖ The production of J/ ψ and γ mesons is expected to be dominated by DP interactions.
- ❖ The simultaneous production through SP interactions is suppressed by add. powers of α_s and by the small size of the allowed color octet ME
Baranov et al PLB 705, 116 (2011)

This analysis assumes that there is
no SP contribution

Fiducial Acceptance (μ):
 $p_T > 4 \text{ GeV}/c$
 $|\eta| < 2$

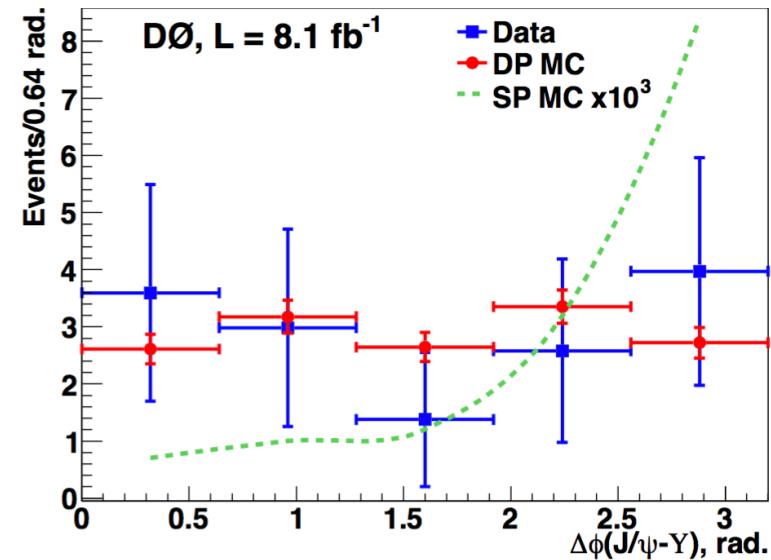
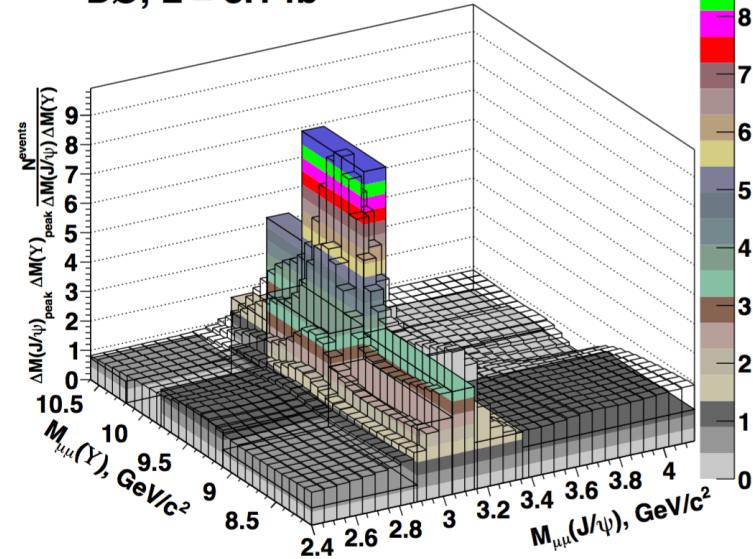
$$\sigma(J/\psi) = 28 \pm 7 \text{ nb}$$

$$\sigma(\Psi) = 2.1 \pm 0.3 \text{ nb}$$

$$\sigma_{\text{DPS}}(J/\psi + \Psi) = 27 \pm 9 \pm 7 \text{ fb}$$

$$\sigma_{\text{eff}} = 2.2 \pm 0.7 \pm 0.9 \text{ mb}$$

DØ, L = 8.1 fb⁻¹



Soft QCD – MPI

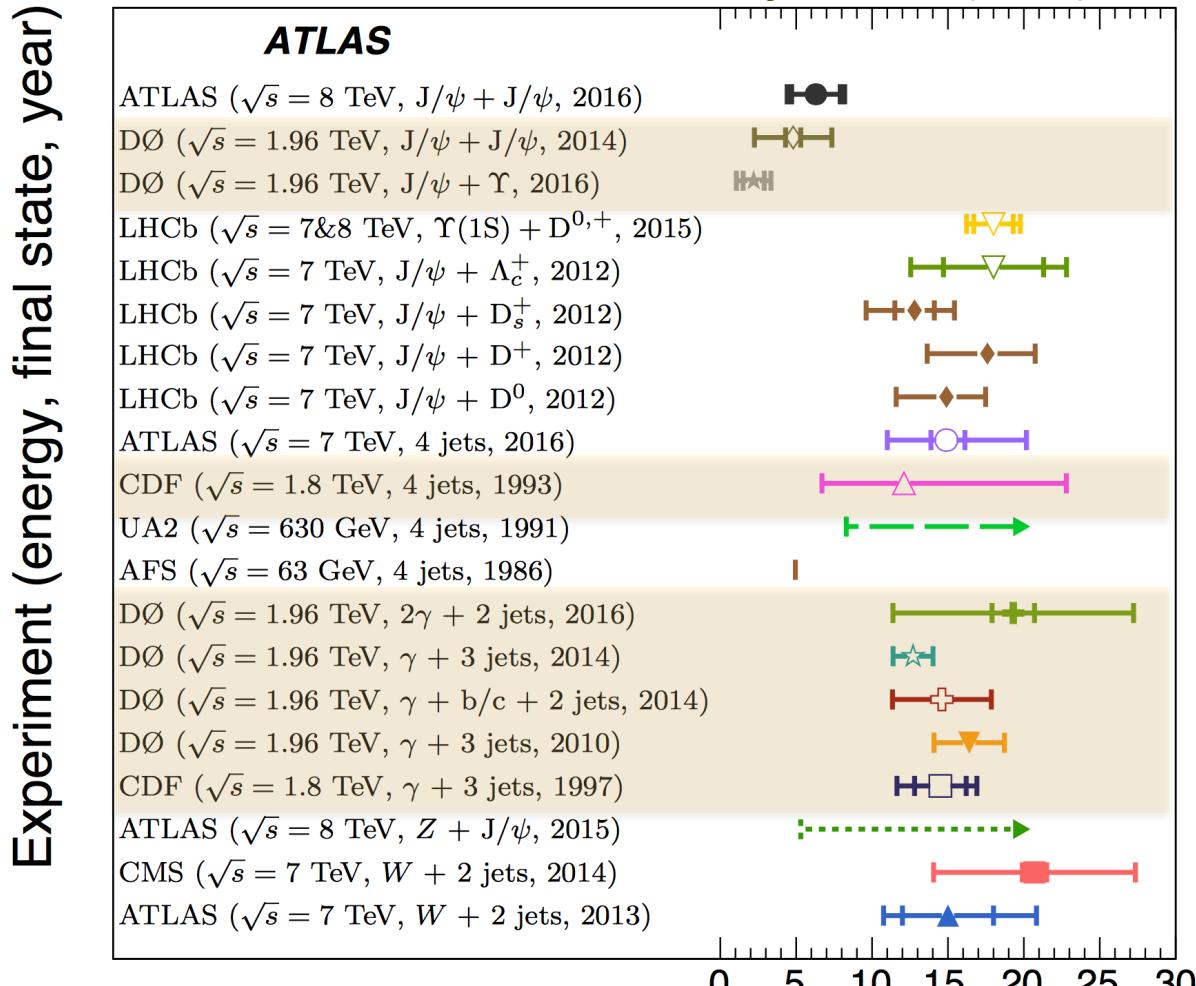
Eur. Phys. J. C 77 (2017) 76

For most final states:
 σ_{eff} is in the range of
15 to 20mb
 indicating a universal value.

The exception:
 final states consisting of
 heavy vector mesons,
J/ψ and/or Υ,
 for which σ_{eff} is smaller.

**The origin of this effect is
 not yet understood.**

*Another interesting observation:
 it has been pointed out that the
 value of σ_{eff} derived from
 the gluon formfactor of the proton > than the one observed in DP
 indicating the presence of parton-parton correlations not included in the pocket formula*



$\sigma_{\text{eff}} [\text{mb}]$

Conclusions

Quantitatively different stage of QCD studies now

- ✧ before: testing perturbative QCD
- ✧ now: very sophisticated measurements.

However, the **old challenges** are still there –

- ✧ Diffraction
- ✧ MPI
- ✧ Despite significant tuning efforts – still no perfect description of UE and MB

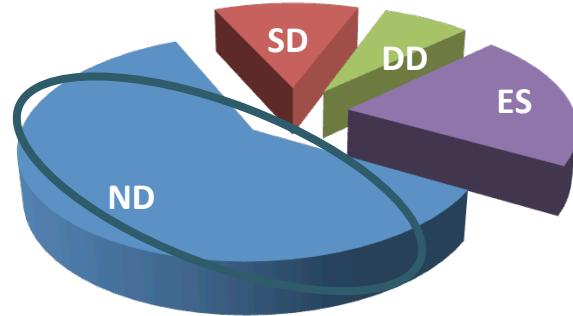
New opportunities –

- ✧ Increased interest in pursuing these types of studies
- ✧ New theoretical developments
- ✧ Improved MC models
- ✧ Very interesting measurements from all experiments

Additional material

(if time allows)

Definitions: MB and UE

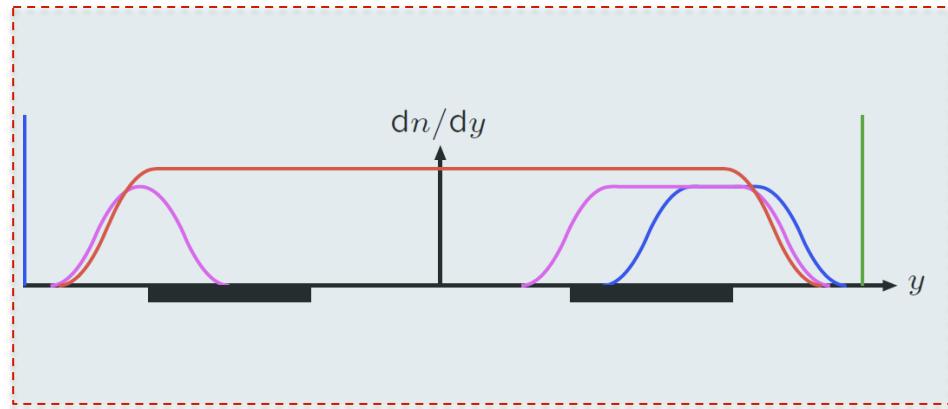


Minimum Bias (MB) – is the name of trigger

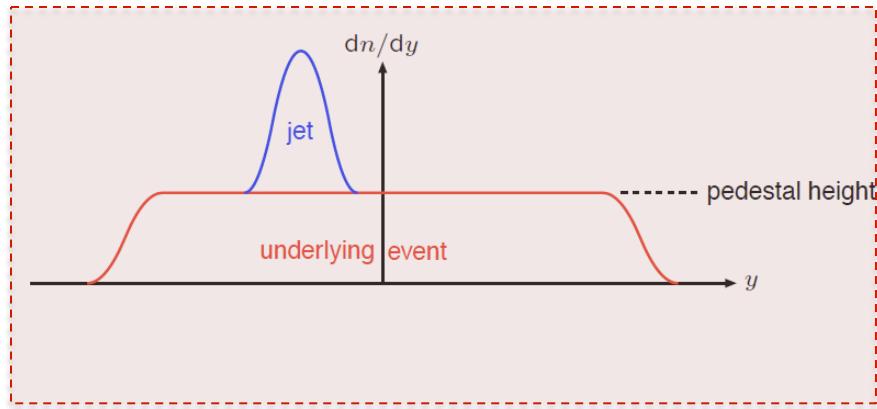
data sample is defined by trigger implementation

Underlying Event (UE) – is defined on event by event basis

everything else except 2->2 hard scatter



MB is background to high luminosity pile-up events



UE is background to high p_T observables (jets etc...)

The Underlying Event

PRD 65, 092002 (2002)

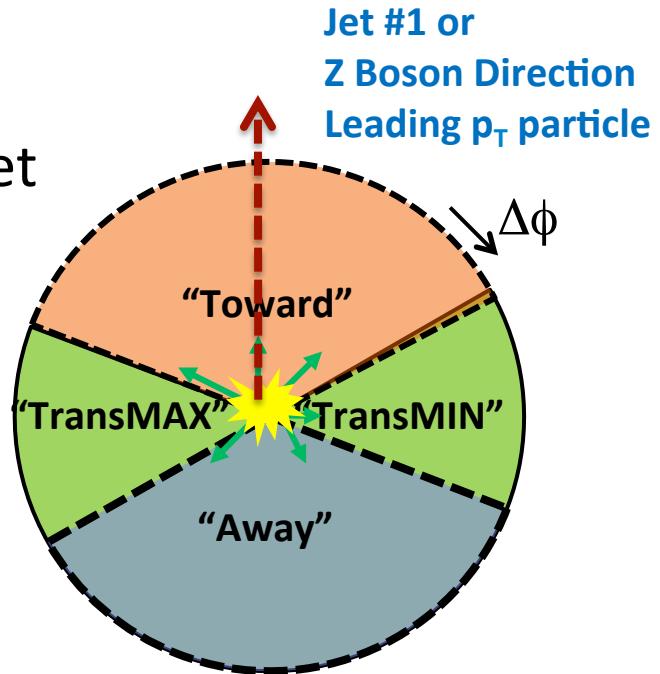
PRD 70, 072002 (2004)

PRD 82, 034001 (2010)

$\Delta\phi$ relative to the leading calorimeter jet
(or the Z-boson, or leading p_T particle)

- $|\Delta\phi| < 60^\circ$ as **Toward**
- $60^\circ < |\Delta\phi| < 120^\circ$ as **Transverse**
- $|\Delta\phi| > 120^\circ$ as **Away**
- TransMAX (MIN) - “Transverse” region with largest (smallest) number of charged particles

Underlying Event is
Beam Beam Remnants (BBR)
Final State Radiation (FSR)
Initial State Radiation (ISR)
Multi-Parton Interactions (MPI)



Data corrected to the particle level:
Tracks $p_T > 0.5$ GeV/s; $|\eta| < 1$
Jets with $|\eta| < 2$
Drell-Yan : $ll = ee, \mu\mu$
 $p_T > 20$ GeV/c; $|\eta| < 1$
 $70 \text{ GeV}/c^2 < M_{\text{pair}} < 110 \text{ GeV}/c^2$

The Underlying Event

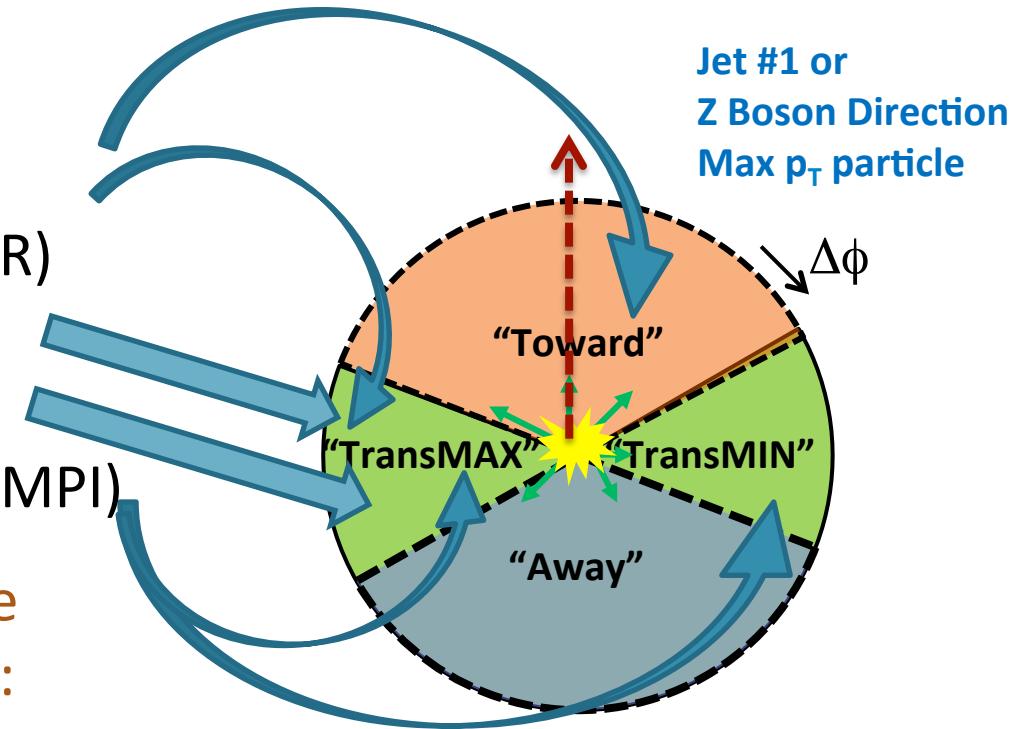
Underlying Event is

Beam Beam Remnants (BBR)

Final State Radiation (FSR)

Initial State Radiation (ISR)

Multi-Parton Interactions (MPI)



Different regions sensitive
to different contributions:

TransMIN – BBR+MPI

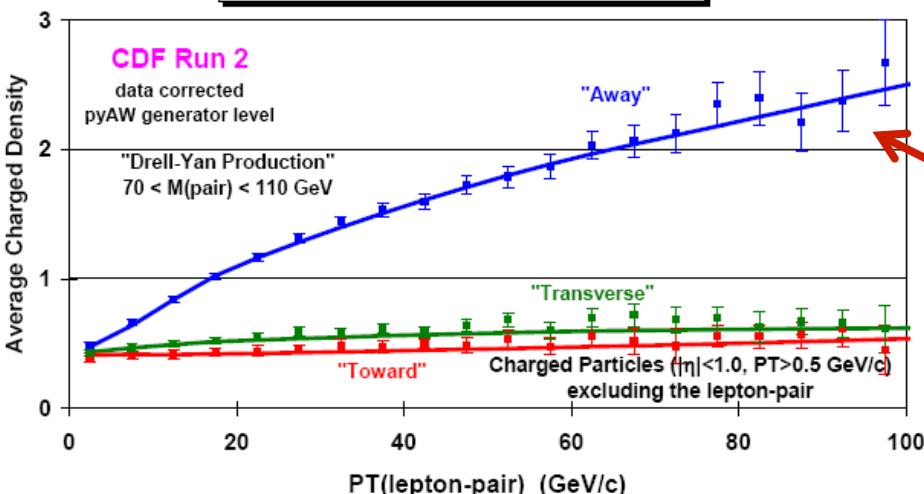
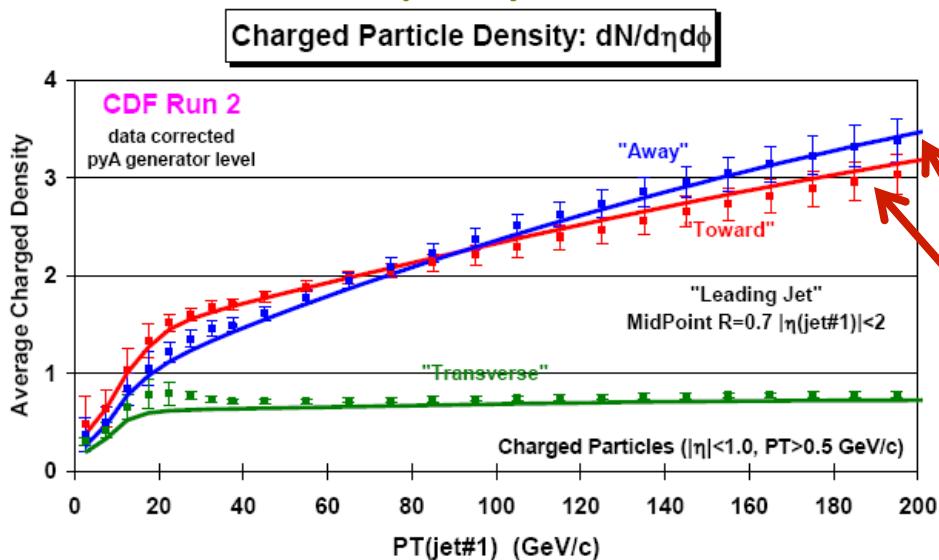
TransMAX – BBR+MPI+
ISR+FSR

TransDif = TransMAX-TransMIN

Data corrected to the particle level:
Tracks $p_T > 0.5 \text{ GeV}/c$; $|\eta| < 1$
Jets with $|\eta| < 2$
Drell-Yan : $\ell\ell = ee, \mu\mu$
 $p_T > 20 \text{ GeV}/c$; $|\eta| < 1$
 $70 \text{ GeV}/c^2 < M_{\text{pair}} < 110 \text{ GeV}/c^2$

UE in Drell-Yan and incl. jet events

PRD 82, 034001 (2010)



Event topologies:

- ◊ Leading Jet
- ◊ Drell-Yan

at high leading jet p_T –
“toward”-side and “away”-side
jets

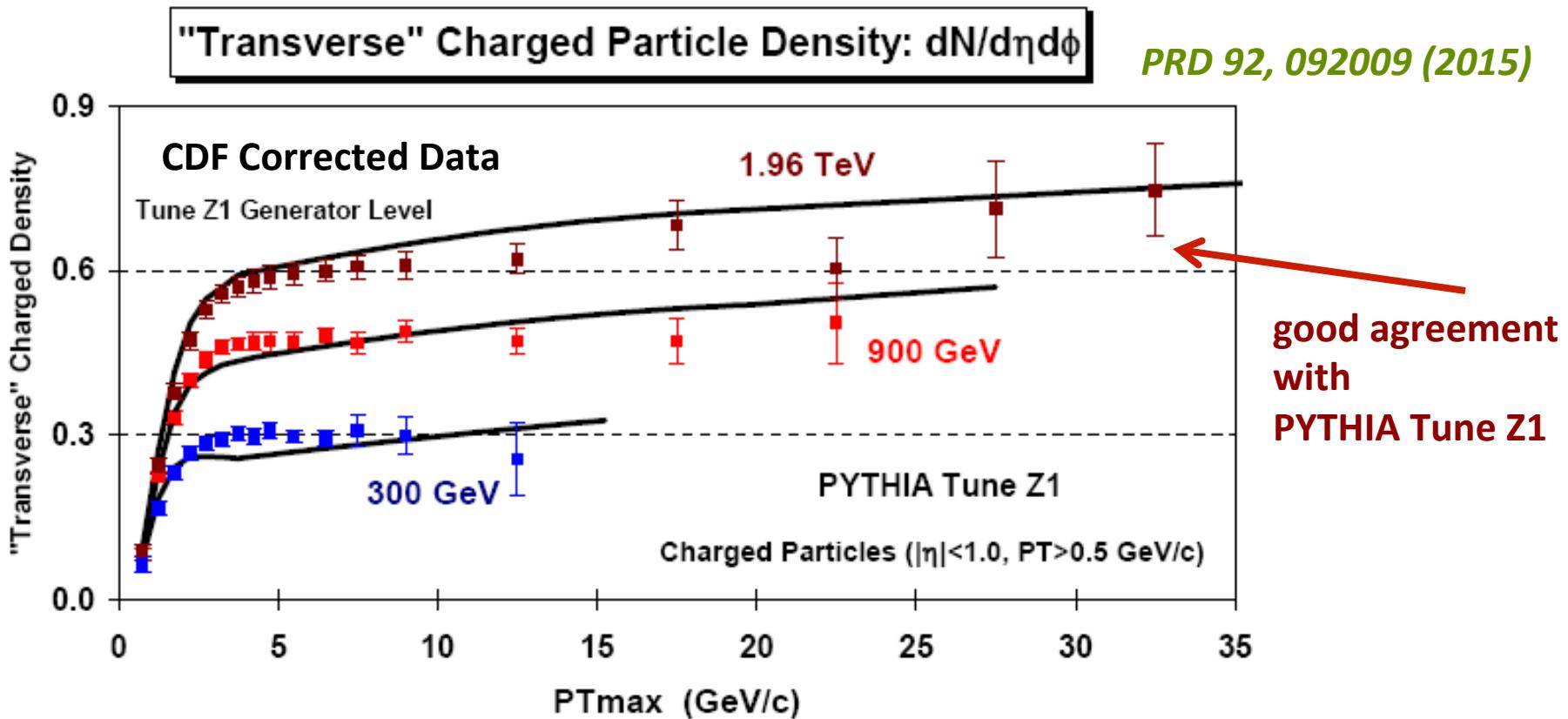
away side jet

no FSR!
exclude leptons
“towards” = “Trans”

Energy Dependence of UE

use “Tevatron energy scan” data at 300 GeV, 900 GeV, 1960 GeV

studying charged particles ($p_T > 0.5$ GeV, $|\eta| < 0.8(1.0)$) produced in association with the leading charged particle $P_{T\max}$



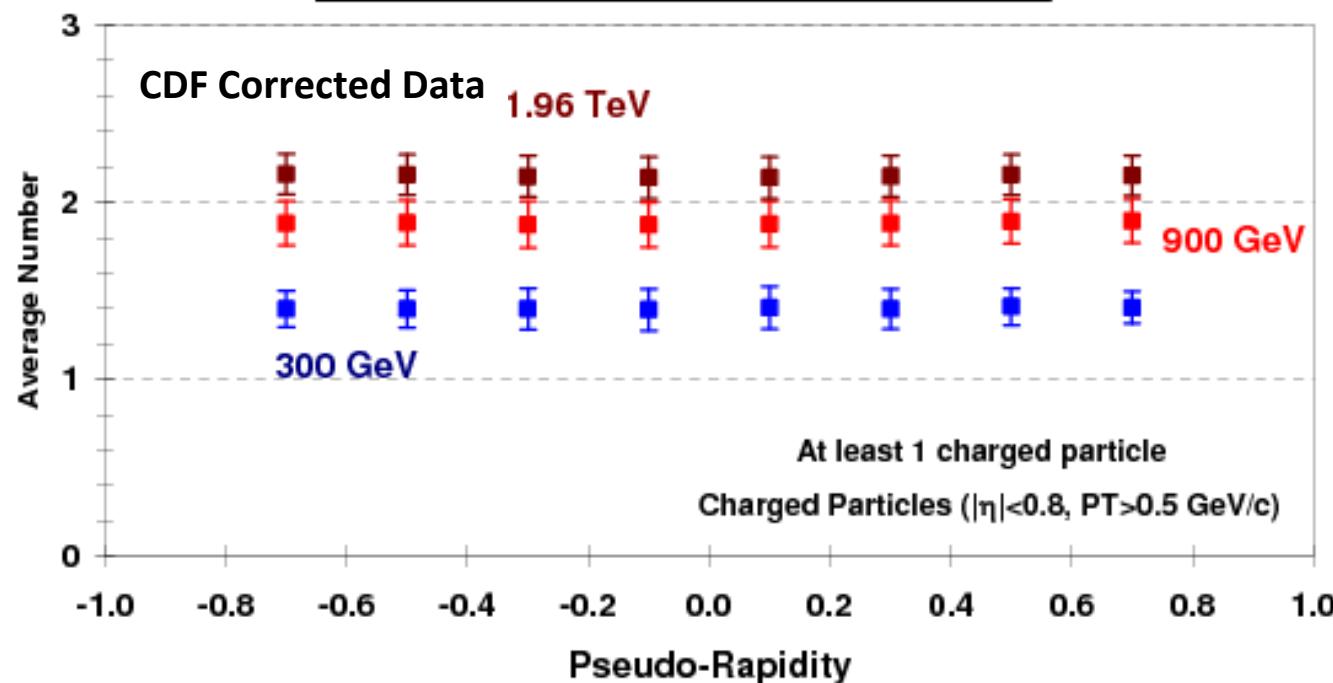
Energy Dependence of MB

use “Tevatron energy scan” data at 300 GeV, 900 GeV, 1960 GeV

studying pseudo-rapidity distribution, $dN/d\eta$, for charged particles ($p_T > 0.5$ GeV, $|\eta| < 0.8(1.0)$)

$$N_{chg} = \int_{-0.8}^{0.8} \frac{dN}{d\eta} d\eta$$

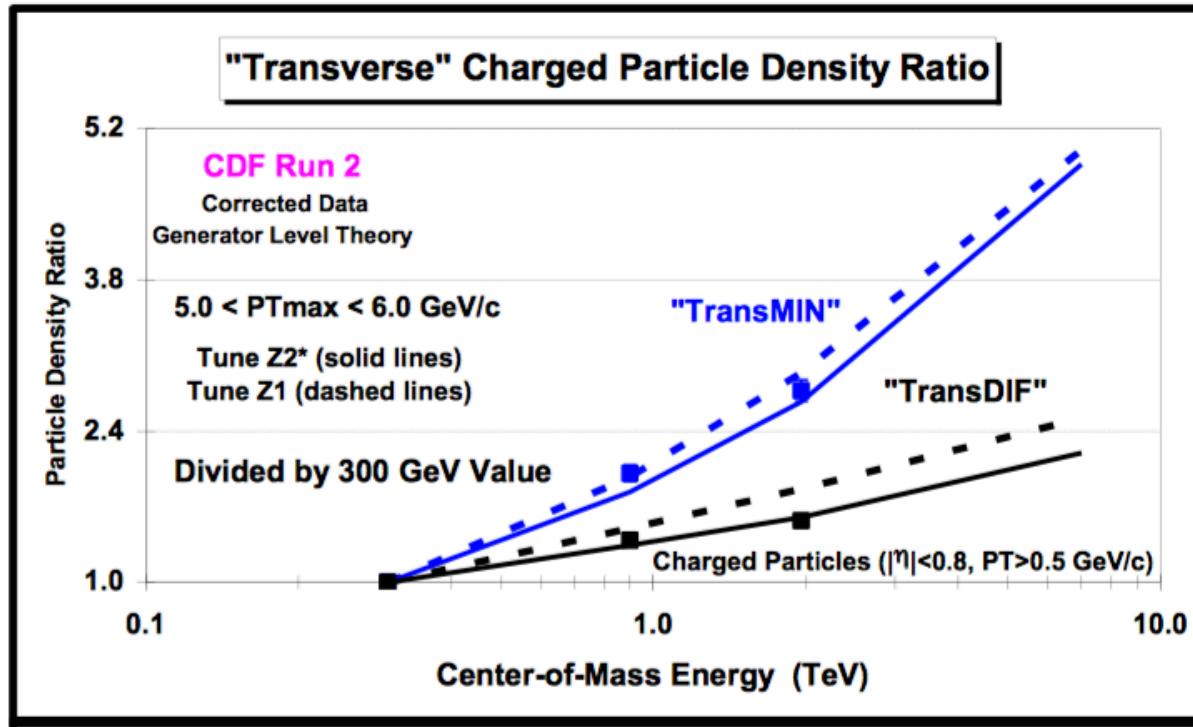
Pseudo-Rapidity Distribution: $dN/d\eta$



Energy Dependence of UE

use “Tevatron energy scan” data at 300 GeV, 900 GeV, 1960 GeV

studying charged particle density ratio, for charged particles ($p_T > 0.5 \text{ GeV}$, $|\eta| < 0.8(1.0)$)



TransMIN (more sensitive to MPI & BBR –
increases much faster as \sqrt{s} in comparison to
TransDIF (sensitive to ISR, FSR)