Latest soft QCD results from Tevatron

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on behalf of the CDF and DØ Collaborations

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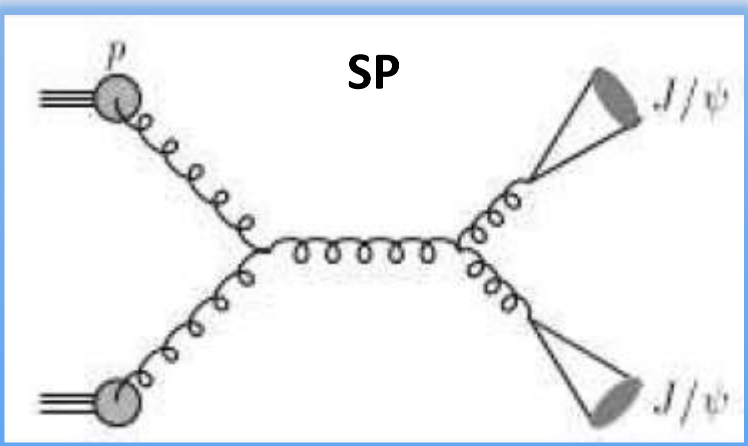
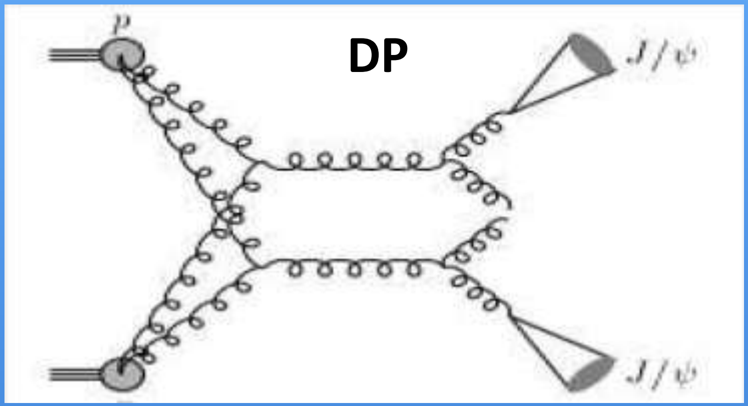
Double J/ψ production: Motivation

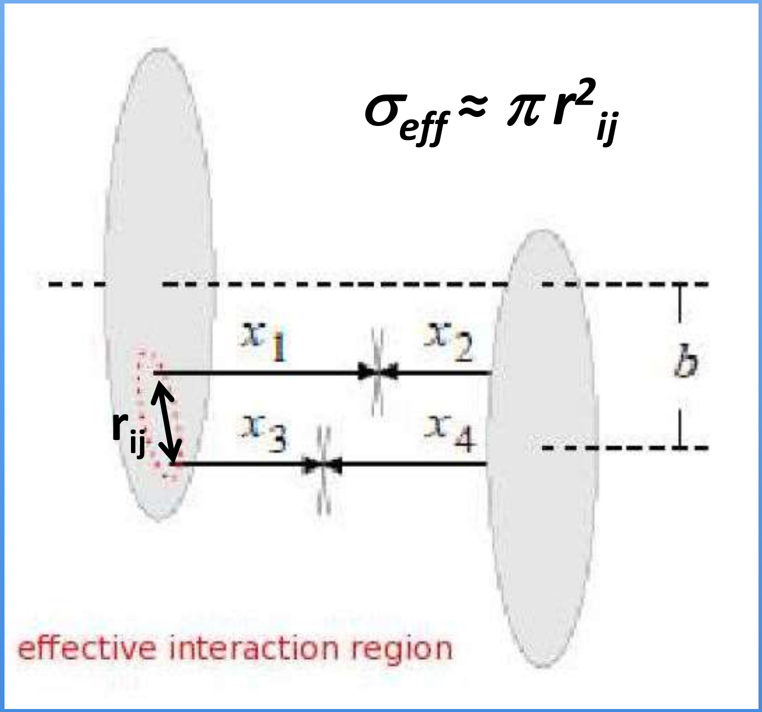
Single Parton (SP) and Double Parton (DP) interactions in J/ψ pair production





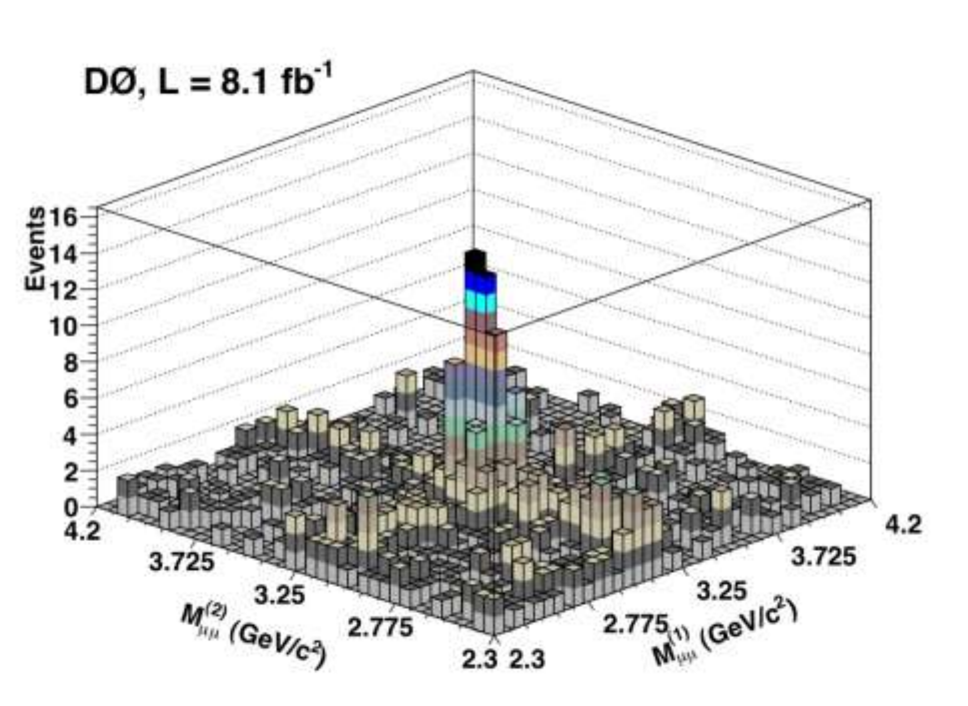
DP effective cross section (σ_{eff}): a parameter characterizing an effective spatial area of parton-parton interaction and related to parton spatial density inside the nucleon

$$\sigma_{ab} = \frac{m}{2} \cdot \frac{\sigma_a \cdot \sigma_b}{\sigma_{eff}} \Rightarrow \sigma_{eff} = \frac{\sigma^2 (J/\psi)}{2 \cdot \sigma_{DP}(J/\psi J/\psi)}$$



$J/\psi + J/\psi$: Analysis

- 1-2 muon pairs (Single J/ψ or Double J/ψ analysis)
- $p_T^\mu > 2.0$ GeV, $|\eta^\mu| < 1.35$
  $p^\mu > 4.0$ GeV, $1.35<|\eta^\mu|<2.0$
- Good muon tracks
- Opposite electric charge of muons in a pair
- $2.85 < m(J/\psi) < 3.35$ GeV, $p_T(J/\psi) > 4$ GeV, $|\eta(J/\psi)| < 2.0$

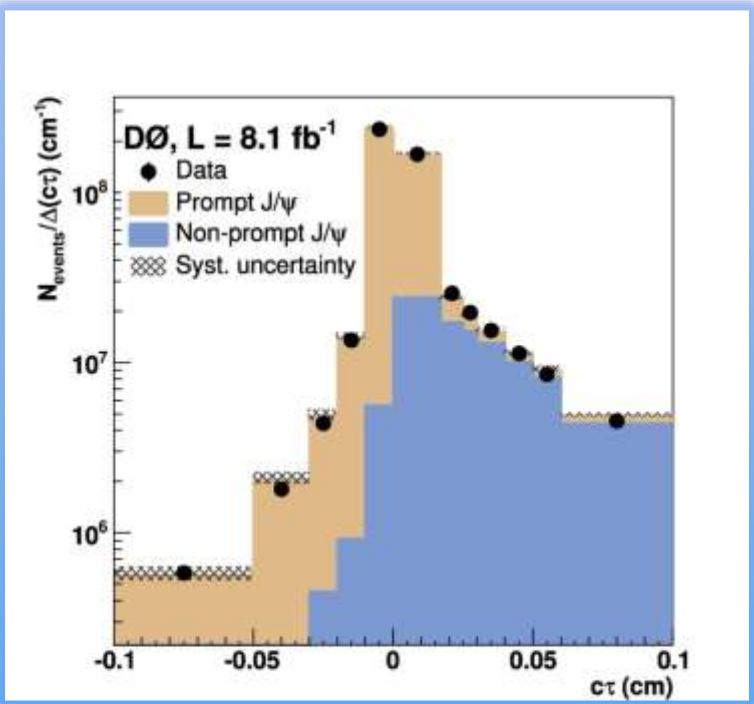


Total statistics: 8.1 fb^{-1}

242 Double J/ψ events selected

$7.4 \cdot 10^6$ Single J/ψ events selected

J/ψ + J/ψ: Analysis



Non-prompt background

$$c\tau = L_{xy} \cdot M_{J/\psi}/p^T_{J/\psi}$$

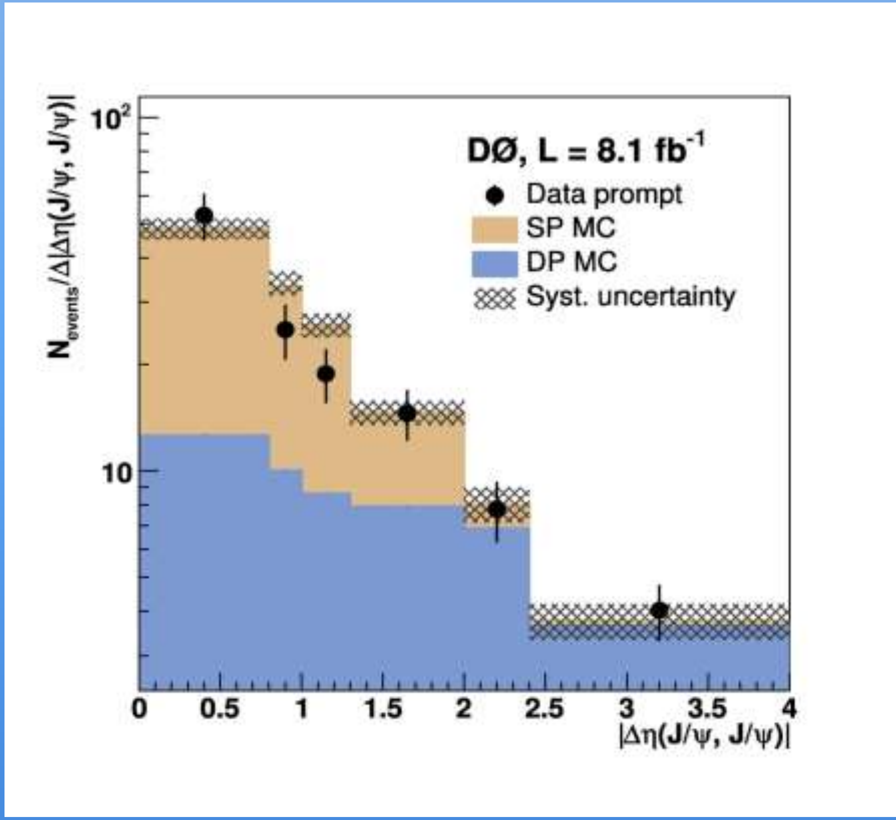
Prompt fractions:

Single J/ψ:	0.814 ± 0.009
Double J/ψ:	0.592 ± 0.101

SP and DP fractions

|Δη(J/ψ J/ψ)| distribution is used to discriminate between SP and DP (DP distribution will be broader)

Fraction of SP:	0.58 ± 0.12
Fraction of DP:	0.42 ± 0.12



J/ψ + J/ψ: Results

Single J/ψ

$\sigma(J/\psi)\times Br(J/\psi\rightarrow\mu^+ \mu^-) = 23.9 \pm 4.6$ (stat.) ± 3.7 (syst.) nb

Double J/ψ

$\sigma_{SP}(J/\psi\ J/\psi)\times Br(J/\psi\rightarrow\mu^+ \mu^-)^2 = 70 \pm 6$ (stat.) ± 22 (syst.) fb
$\sigma_{DP}(J/\psi\ J/\psi)\times Br(J/\psi\rightarrow\mu^+ \mu^-)^2 = 59 \pm 6$ (stat.) ± 22 (syst.) fb
$\sigma(J/\psi\ J/\psi)\times Br(J/\psi\rightarrow\mu^+ \mu^-)^2 = 129 \pm 11$ (stat.) ± 37 (syst.) fb

DP effective cross section

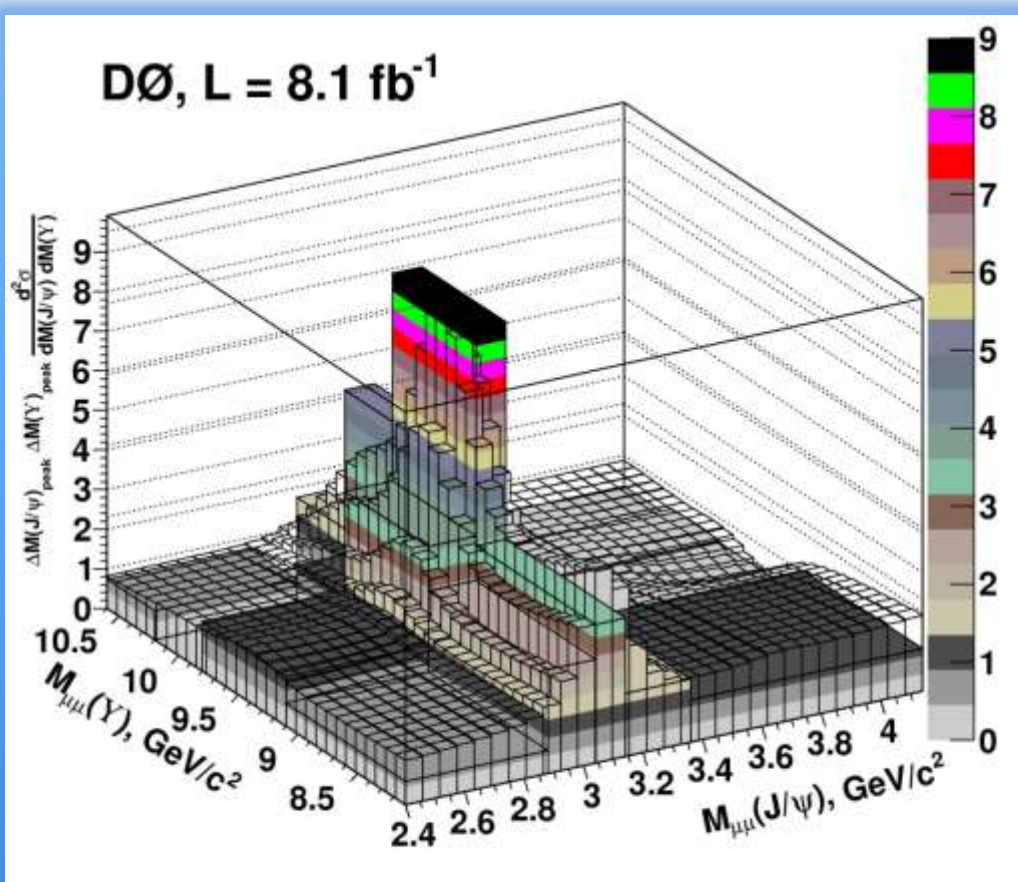
$\sigma_{eff} = 4.8 \pm 0.5$(stat.) ± 2.5(syst.) mb

The measured σ_{eff} agrees with results, obtained in 4jets final states. However, it is lower than the results obtained in γ+jets and W+jets final states.
This difference may indicates a smaller average distance in the transverse space between gluons than between quarks or between a quark and a gluon.

V. M. Abazov et al., Physical Review D 90, 111101(R) (2014)

Evidence of the simultaneous production of J/ψ + Υ

J/ψ + Υ production is expected to be dominated by DP interactions, initial state is mostly gg – spatial distribution of gluons inside the nucleon (characterizing by DP σ_{eff}) can be directly probed.



Total statistics: 8.1 fb^{-1}

Two $\mu^+\mu^-$ pairs

$p_T^\mu > 2.0$ GeV, $|\eta^\mu| < 2$

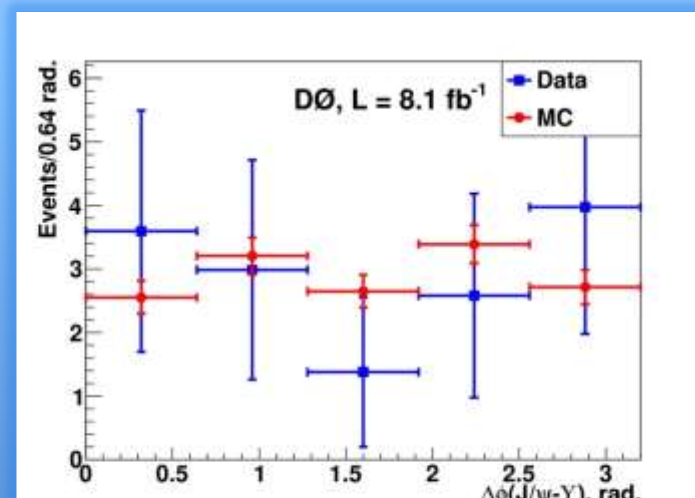
$2.88 < m(J/\psi) < 3.36$ GeV

$9.1 < m(\Upsilon) < 10.2$ GeV

21 selected events,

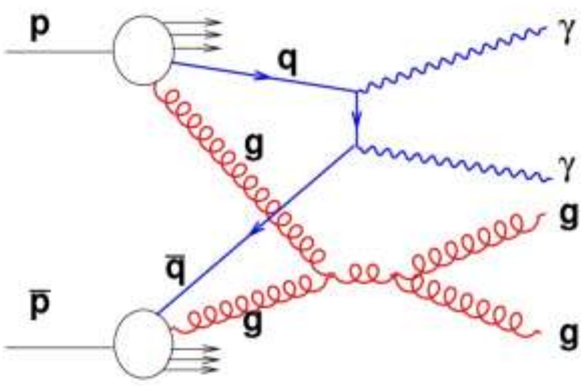
$N_{sig} = 14.5 \pm 4.6(stat) \pm 3.4(syst)$

(Stat. significance 3.5σ)

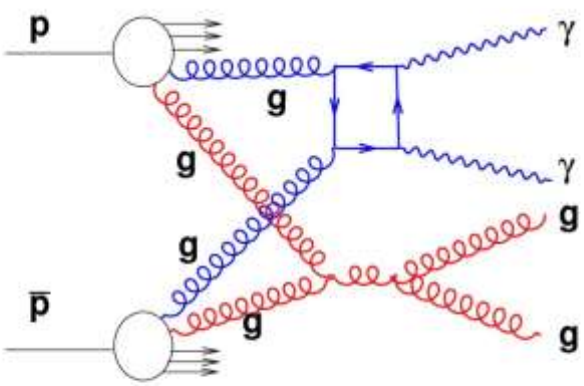


Study of Double Parton interactions in γγ + jj events

Born mechanizm



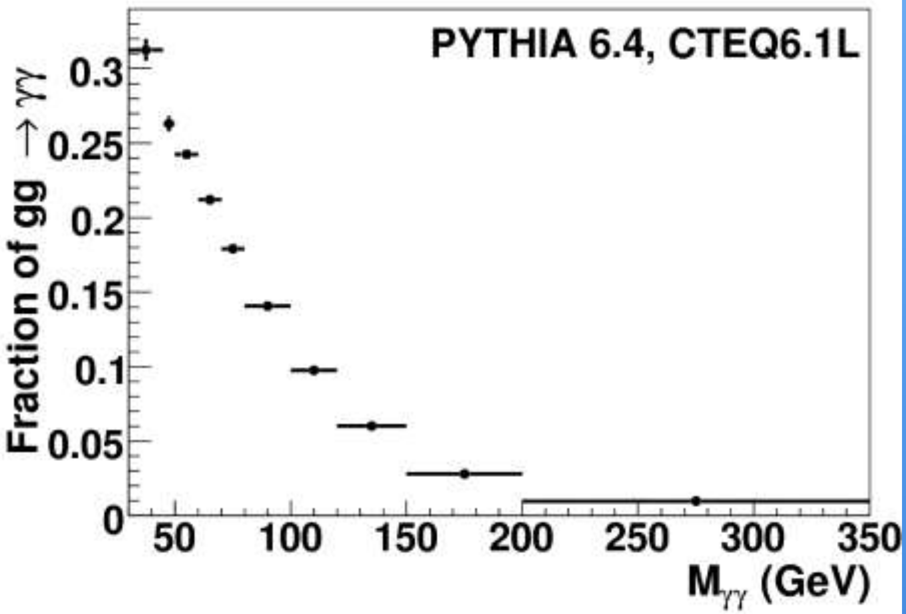
Box mechanizm



Substitution of one of the two dijet parton processes by a diphoton process leads to about an order of magnitude increase in the DP/SP ratio.

Main contribution to the diphoton production are from $q\bar{q}$ -> γγ (Born) and gg -> γγ (Box) subprocesses.

For this analysis Born is dominant with its fraction of about 70-80%.



Study of Double Parton interactions in $\gamma\gamma$ + jj events

The technique for extracting σ_{eff} is based on a comparison of the number of $\gamma\gamma$+jj events produced in DP interactions in single $p\bar{p}$ collision (DP events) to the number of such events produced in two separate $p\bar{p}$ collisions within the same beam crossing (DI events).

$$\sigma_{eff} = \frac{N_{DI}}{N_{DP}} \frac{A_{DP}}{A_{DI}} \frac{\epsilon_{DP}}{\epsilon_{DI}} \frac{\epsilon_{1vtx}}{\epsilon_{2vtx}} R_c \sigma_{hard}$$

N_{DI}, N_{DP} - number of DI (DP) events;
A_{DI}, A_{DP} - geometric and kinematic acceptance;
$\epsilon_{DI}, \epsilon_{DP}$ - selection efficiencies for DI(DP) events;
$\epsilon_{1vtx}, \epsilon_{2vtx}$ - one and two-vertex selection efficiency;
$R_c = \frac{1}{2}\frac{N_c(1)}{N_c(2)}$, where $N_c(1), N_c(2)$ – number of beam crossings with exactly 1 (2) collisions;
σ_{hard} - cross section of the hard $p\bar{p}$ interactions.

a) $\sigma_{\gamma\gamma}, \sigma_{jj}$ cancel in the ratio; b) remaining efficiencies and acceptances enter only as ratios (all common uncertainties are reduced).

Total statistics 8.7 fb^{-1}

Kinematic cuts

$p_T^{\gamma_1} > 16\text{GeV}, p_T^{\gamma_2} > 15\text{GeV}$,
$|\eta| < 1.0$;

$15 < p_T^{jet_{1,2}} \leq 40$ GeV,
$|\eta| < 3.5$;

Upper requirement for jet p_T increases the fraction of DP events in the sample.

Study of Double Parton interactions in $\gamma\gamma$ + jj events

Fraction of DP events f_{DP}

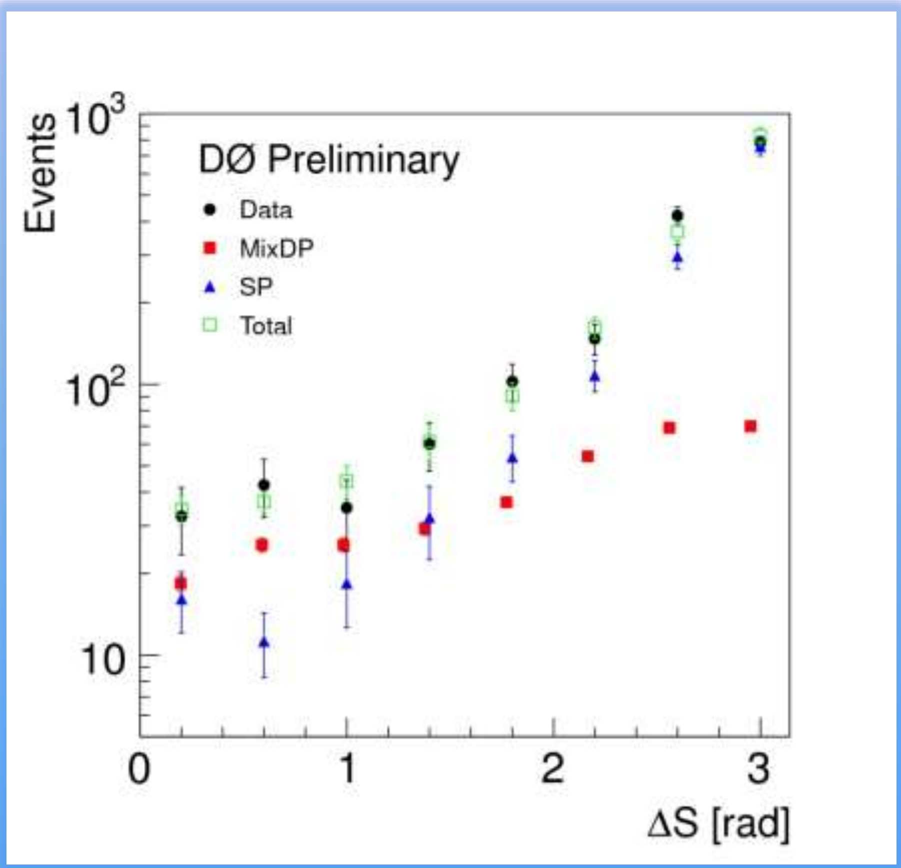
Discriminating variable $\Delta S \equiv \Delta\phi(\vec{q}_T^{\,1}, \vec{q}_T^{\,2})$,
$\vec{q}_T^{\,1} = \vec{p}_T^{\,\gamma 1} + \vec{p}_T^{\,\gamma 2}$, $\vec{q}_T^{\,2} = \vec{p}_T^{\,jet1} + \vec{p}_T^{\,jet2}$.

f_{DP} from template fit: **0.191 ± 0.067**.

$$f_{DP} = \frac{\varepsilon_{data} - \varepsilon_{SP}}{\varepsilon_{DP} - \varepsilon_{SP}},$$

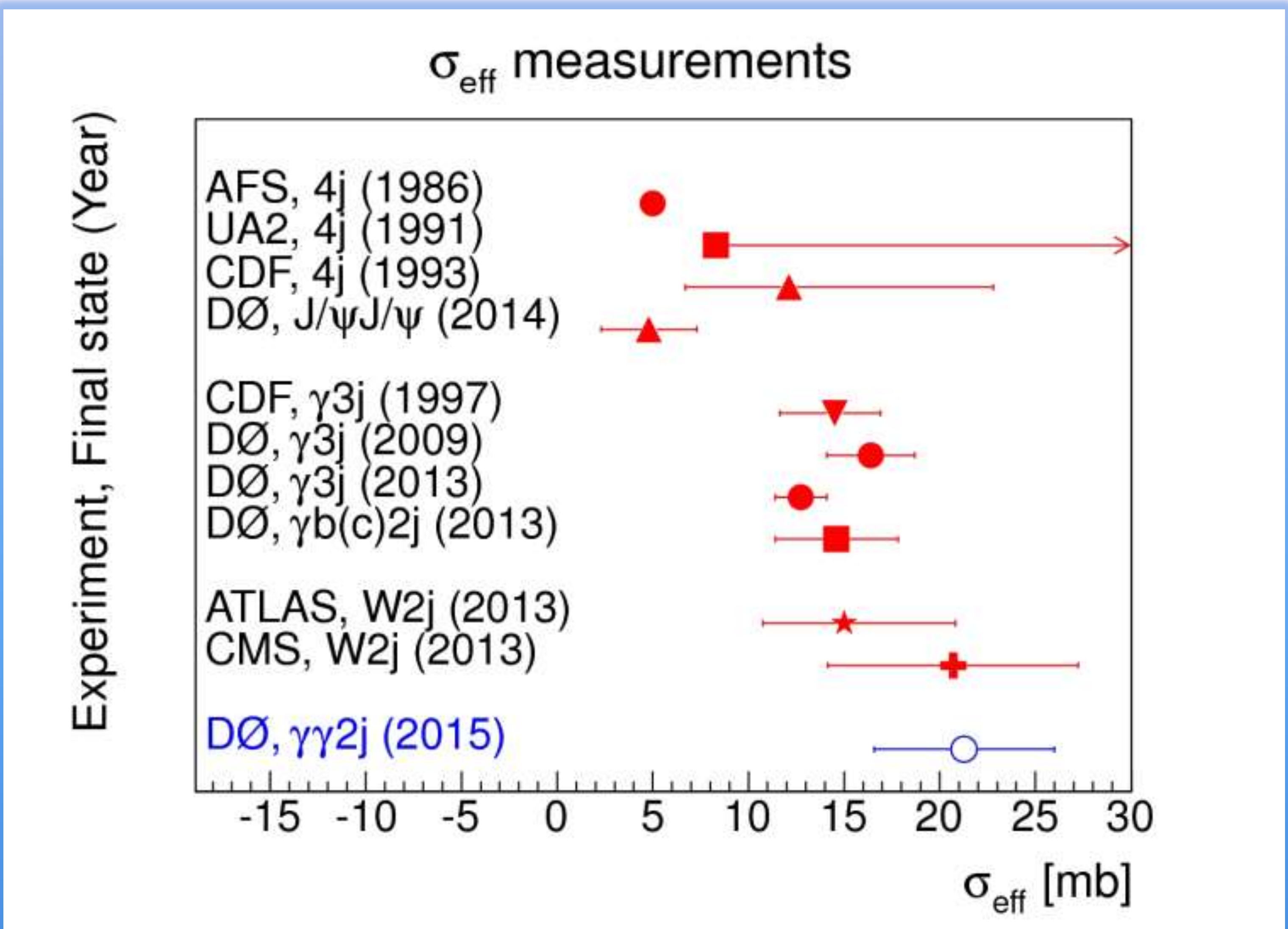
ε_{data}, ε_{DP}, ε_{SP} - numbers of equally normalized data, DP and SP events (in DP and SP templates).

Average f_{DP}: **0.193 ± 0.037**.

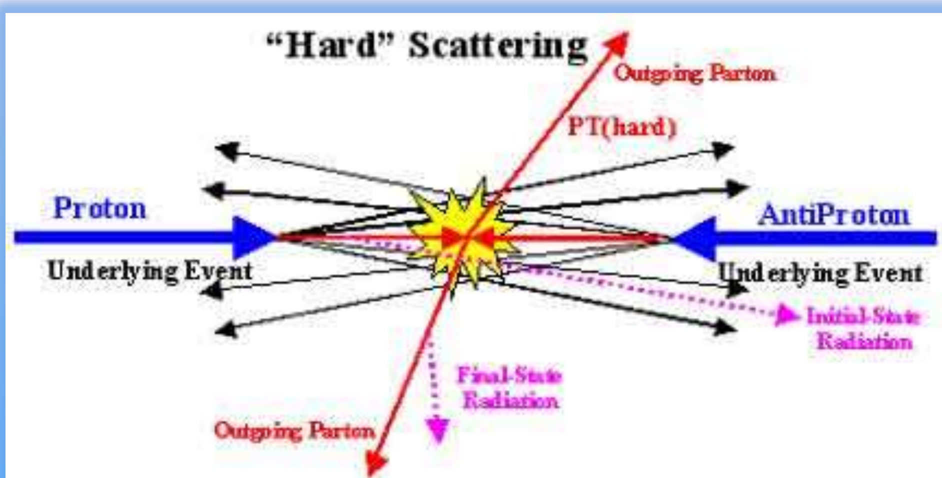


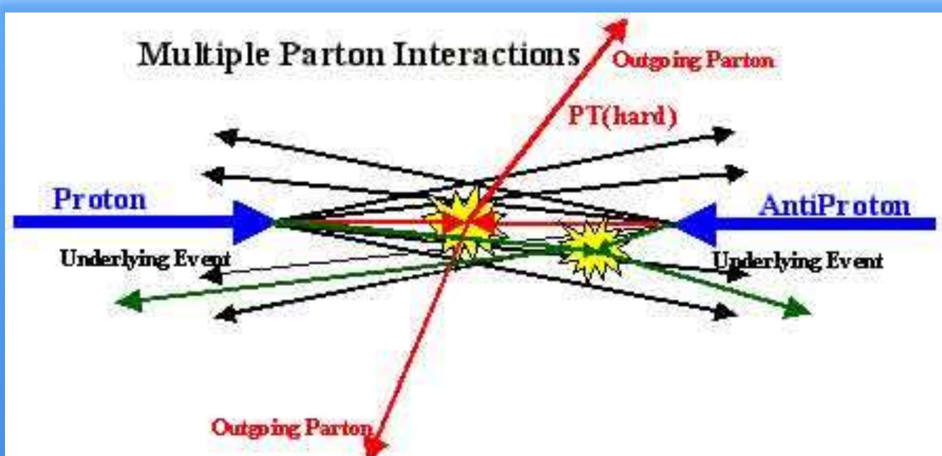
σ_{eff} = 21.3 ± 1.5(stat.) ±4.5(syst.) mb

DP σ_{eff} : All the measurements



The Energy Dependence of the Underlying Event at CDF ($\sqrt{S} = 300$, 900 and 1960 GeV)



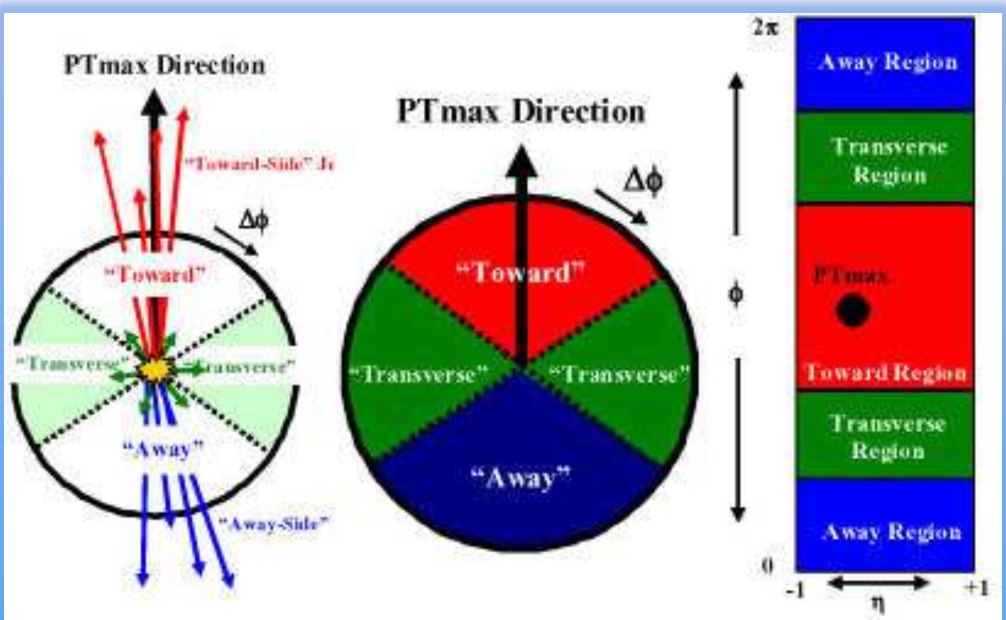


Hard scattering collider events have a distinct topology and usually consist of two collections of high p_T hadrons (i.e. jets) which are roughly back to back in azimuthal angle and a collection of low p_T hadrons traveling roughly in the direction of initial beam particles.

The second collection is usually called an "Underlying Event": beam-beam remnants that accompany a hard scattering, unavoidable background to hard scattering collider events.

CDF Min-Bias trigger: at least one charged particle in the forward region ($3.2<\eta<5.9$) and simultaneously at least one charged particle in the backward region ($-5.9<\eta<-3.2$)

The Energy Dependence of the Underlying Event at CDF ($\sqrt{S}$ = 300, 900 and 1960 GeV)



Examined observables

Average number of charged particle per unit η ($\frac{dN}{d\eta}$).

Transverse charged particle density ($\frac{d^2N}{d\eta d\phi}$).

Transverse charged PTsum density ($\frac{d^2\sum_{scalar} p_T}{d\eta d\phi}$).

Transverse charged particle average p_T

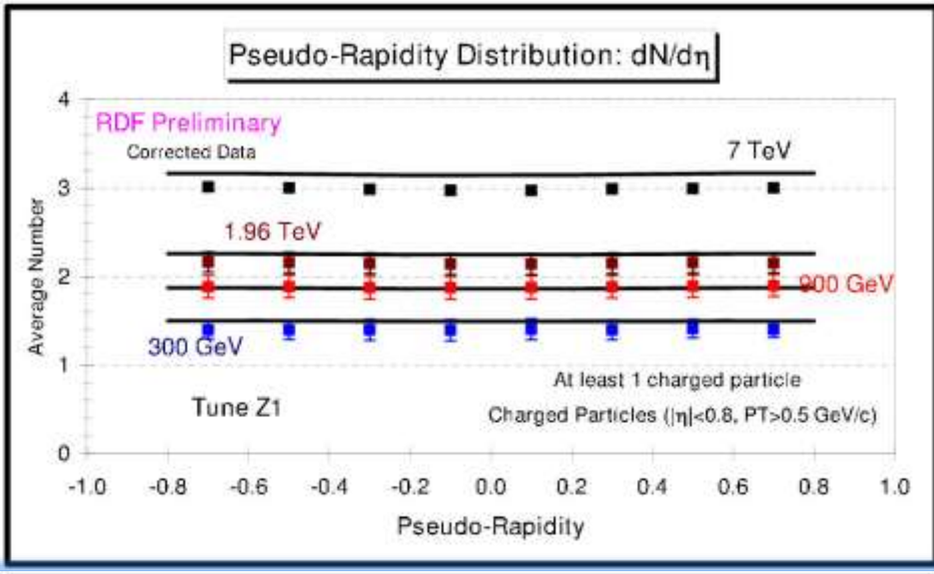
Latter three are plotted vs. PTmax and all of them are compared with predictions from PYTHIA 6.4 Tune Z1

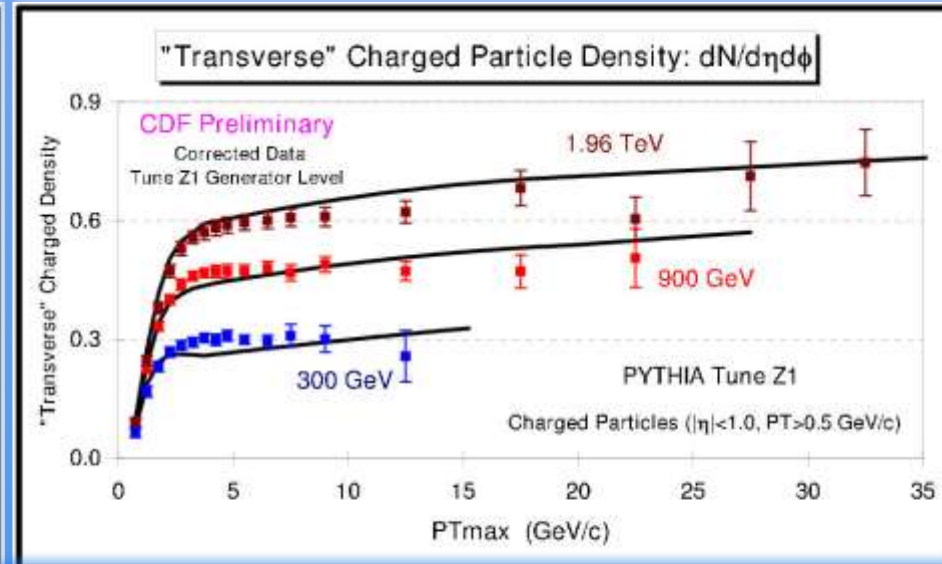
"Toward region" contains the leading jet, "away region" contains the away-side jet.

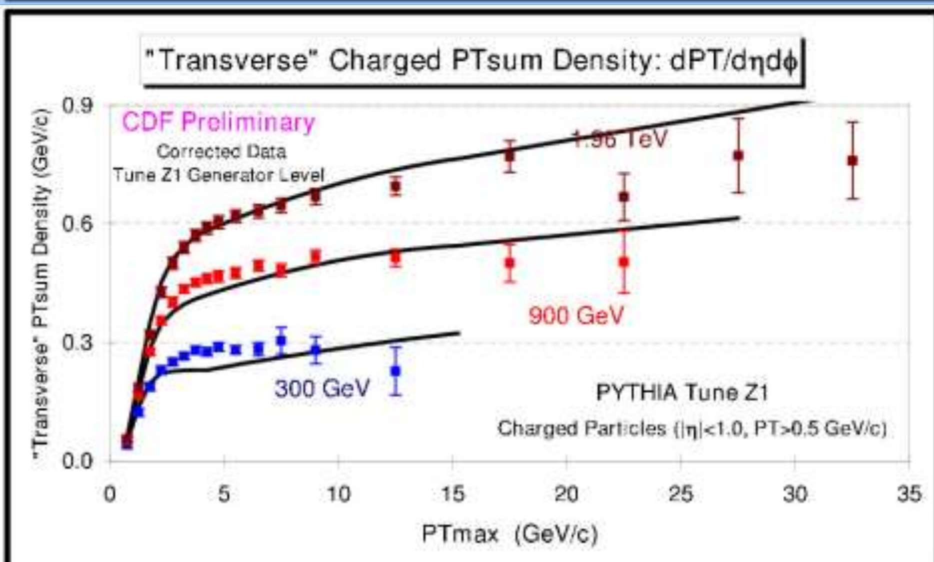
"Transverse region": |η|<1.0, 60°<Δϕ<120°, where Δϕ is measured relative to the direction of the leading charged particle in the event with transverse momentum PTmax. Sensitive to the underlying event.

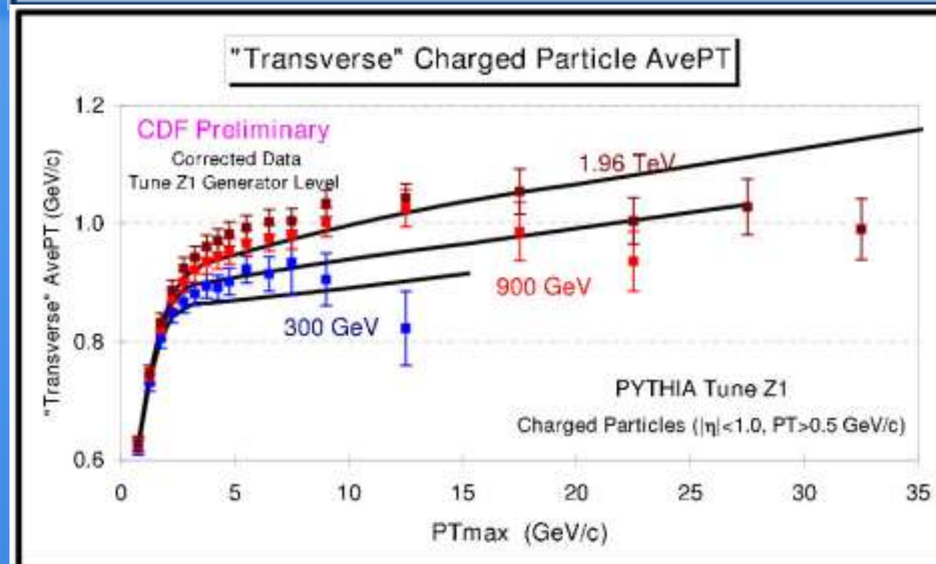
300 GeV and 900 GeV data are a result of the "Tevatron energy scan" which was performed just before the Tevatron was shut down.

The Energy Dependence of the Underlying Event at CDF









Tune Z1 does a good job to describe a CDF data, but none of the QCD MC models fit all the data perfectly yet. The new and improved tunes are definitely needed.

Measurement of central exclusive $\pi^+\pi^-$ production in $p\bar{p}$ collisions at CDF ($\sqrt{S} = 900$ and 1960 GeV)

Central exclusive production:

$$p\bar{p} \to p^{(*)} \oplus X \oplus p^{(*)},$$

where X is a specific central ($|y| < 1$) state and $\oplus$ represents a "rapidity gap" – large region of rapidity ($1.3 < |\eta| < 5.9$) where no particles are detected.

With two large rapidity gaps and central hadrons, the process is expected to be dominated by double pomeron exchange (DPE). In this case central state X must have $I^G J^{PC}$ = $0^+(\mathit{even})^{++}$ - quantum number filter favoring states having high glue content (such as glueballs).

Total statistics:

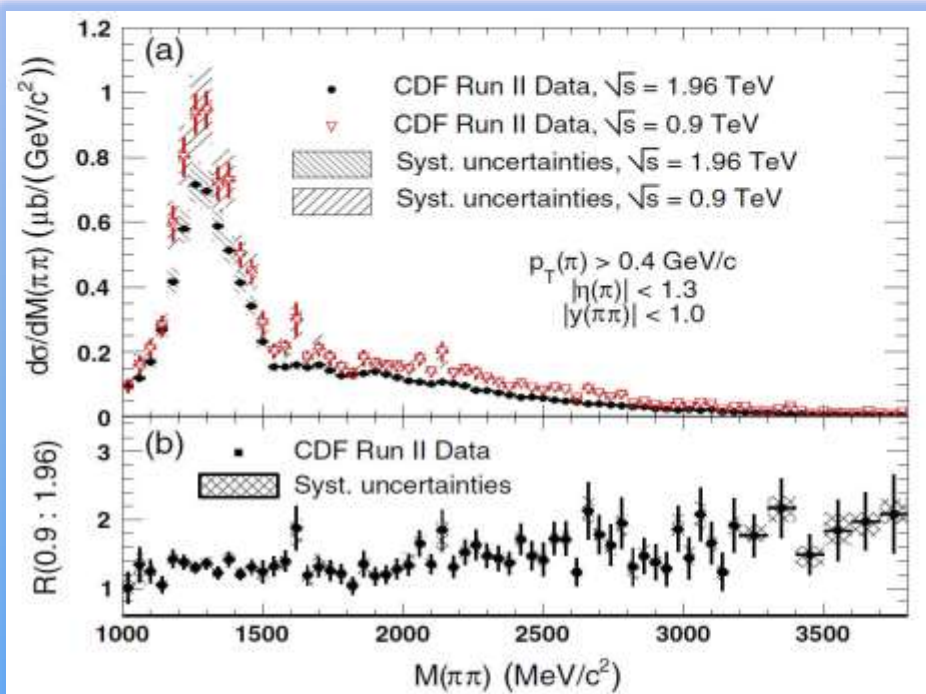
7.23 pb^{-1} for 1960 GeV, 0.075 pb^{-1} for 900 GeV.

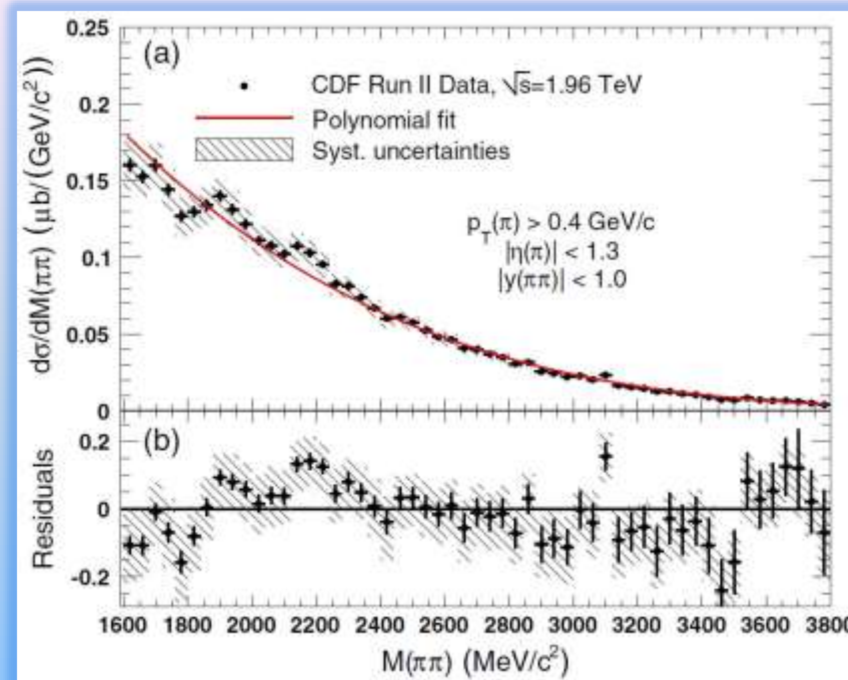
Kinematic cuts:

Two charged particles (assuming $X \to \pi^+\pi^-$) with $|\eta| < 1.3$ and $p_T > 0.4$ GeV with no other activity above the noise level in the full detector.

Selected samples 127340 (6240) events for $\sqrt{S} = 1960\ (900)$ GeV.

Measurement of central exclusive $\pi^+\pi^-$ production in $p\bar{p}$ collisions





Cross sections ratio (900/1600 GeV)

R(0.9:1.96) = 1.28 ± 0.04,
1000<M(ππ)<2000 MeV (1.3 expected from Regge phenomenology,
R ~ 1/ln(S)).

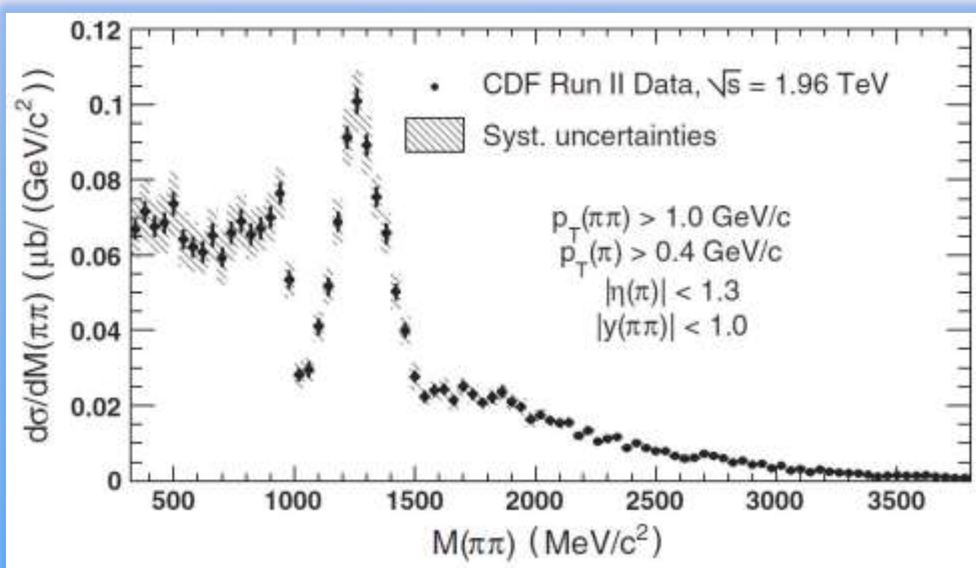
R(0.9:1.96) = 1.56 ± 0.06,
2000<M(ππ)<3000 MeV

Cross section for M(ππ) > 1000 MeV

Peak at ~1300 GeV consistent with $f_2(1270)$ and $f_0(1370)$.
An abrupt change of slope at 1500 MeV.
Structures in the higher mass region up to 2400 MeV, suggesting production of higher mass resonances.

J/ψ photoproduction at 3100 MeV.

Measurement of central exclusive $\pi^+\pi^-$ production in $p\bar{p}$ collisions



With additional $p_T(\pi\pi)$>1 GeV cut the acceptance extends down to $M(\pi\pi)$ = 300 MeV.

Cross section for $M(\pi\pi)$ < 1000 MeV, $p_T(\pi\pi)$>1 GeV:

Sharp drop at $M(\pi\pi)$ 1000 Mev ($f_0(980)$ and K^+K^- threshold).

This analysis is a continuation of very special program in central exclusive production studies, that resulted in "observation" papers for exclusive dijets, dimuons, χ_c, diphotons.

Limit to exclusive $\chi_{c0}(3415)$ production:
$^{d\sigma}/_{dy}|_{y=0} < 3.35\ (23.4)\mathbf{nb}$ at 90% CL
in the $\pi\pi$ (KK) decay channels.

T. Aaltonen et al., Physical Review D 91, 091101(R) (2015)

Conclusion

- DP effective cross section measurements in different final states.
- Evidence of $J/\psi + \Upsilon$ simultaneous production.
- Precise study of the energy dependence of the underlying event.
- Measurement of the mass spectra for the central exclusive $\pi^+\pi^-$ events.

Although was shut down 4 years ago, the Tevatron is still producing a large amount of unique and important results, many of them are complementary to the LHC results.

Stay tuned for more!