QCD results from the Tevatron

on behalf of CDF and D0 Collaborations

Christina Mesropian

The Rockefeller University
New York
Introduction -
Tevatron pp̅ collider at Fermilab
Tevatron

- Superconducting storage ring
  1 km radius, 1 beam-pipe
  Collisions from 1985 to 2011

  Runs 0 and I - $\sqrt{s}=546, 630$ GeV, 1800 GeV

- Run II: Mar 2001-Sept 2011
- Produced ppbar 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)
- ~10 fb\(^{-1}\) per experiment
Central Exclusive Production (CEP)

Interactions of the form

$$pp(\bar{p}p) \rightarrow p + \text{exclusive } X + p(\bar{p}p)$$

QED background: $2\gamma$ 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
Central Exclusive Production (CEP)

$\sqrt{s} = 1.96$ TeV  
*Practical Application of CEP* (2008)

CDF Run II

- Data corrected to hadron level
- ExHuME

**Observation of Exclusive Dijets, $\gamma\gamma$, $J/\psi$, $\chi_c$**

Fit:

- 2 Gaussians + QED continuum
- $PRL 102, 242001 (2009)$
- $\sqrt{s} = 1.96$ TeV  
  CDF Run II

QED continuum

$J/\psi$  
$PRL 102, 242001 (2009)$  
$\sqrt{s} = 1.96$ TeV  
CDF Run II

**Observed 43 events >> 5 $\sigma$**

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

Good agreement with the theoretical predictions
Central Exclusive Production (CEP)

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

Similar distributions are observed in all sub-detectors.
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:
π⁺π⁻ and no other activity in |η|<5.9

The cross section ratio
R(0.9:1.96) = 1.28
for 1<M_{ππ} < 2 GeV

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

- f₂(1270), shoulder from f₀(1370) interference
- some structure around 1.4-2.4 GeV
- data falls monotonically above 2.4 GeV
Soft QCD - MPI

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

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 \( A \neq B \).

\[
\sigma_{\text{eff}} = \left[ \int d^2 b T^2(b) \right]^{-1}
\]

where \( T(b) \) is the overlap function that characterizes the transverse area occupied by the interacting partons in the impact parameter space \( b \).

Pocket formula is derived under assumption of independent parton scattering where:
- longitudinal, transverse components factorize
- longitudinal components are 2 independent single-PDFs

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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 $\sigma_{\text{eff}}$ 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: $\gamma$+jet+2jets

Key discriminant:
azimuthal angle between $\gamma$+jet and dijet

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

- templates based on Sherpa (and Pythia)
- estimated via mix of events with $\gamma$+jet and $\geq 1$ jet for 1(2 )vtx samples

$\sigma_{\text{eff}}=12.7\pm 0.2(\text{stat}) \pm 1.3(\text{syst})$ mb
Soft QCD - MPI: $\gamma$+b/c-jet+2jets

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

Consistent with the result for $\gamma$+jet+dijet sample $\rightarrow$
no evidence of $\sigma_{\text{eff}}$ dependence on the initial parton flavor
Soft QCD - MPI: $2\gamma + 2\text{jets}$

PRD 93, 052008 (2016)

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.

Key discriminant:
azimuthal angle between $\gamma\gamma$+jet and dijet

$\Delta S \equiv \Delta \phi(q_T^1, q_T^2)$

$\sigma_{\text{eff}} = 19.3 \pm 1.4(\text{stat}) \pm 7.8(\text{syst}) \text{ mb}$
Background:
non-prompt J/ψ (B decays)

Signal:
prompt J/ψ + J/ψ

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

DØ, L = 8.1 fb⁻¹

PRD 90, 111101(R) (2014)

Usual techniques (Δφ_{ψψ}) don’t work for separation of SP and DP events

Much better variable is Δη_{ψψ} -
SP J/ψ highly correlated in Δη

Baranov et al, PRD 87 (2013)

σ_{DPS}(J/ψ+J/ψ) = 59±6±22 fb
σ_{SPS}(J/ψ+J/ψ) = 70±6±22 fb
σ_{eff} = 4.8 ± 0.5 ± 2.5 mb
The production of $J/\psi$ and $\Upsilon$ mesons is expected to be dominated by DP interactions.

The simultaneous production through SP interactions is suppressed by add. powers of $\alpha_s$ 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

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<th>Fiducial Acceptance ($\mu$):</th>
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<td>$p_T &gt; 4$ GeV/c</td>
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$\sigma(J/\psi) = 28 \pm 7$ nb

$\sigma(\Psi) = 2.1 \pm 0.3$ nb

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

$\sigma_{\text{eff}} = 2.2 \pm 0.7 \pm 0.9$ mb
For most final states: $\sigma_{\text{eff}}$ is in the range of 15 to 20mb indicating a universal value.

The exception: final states consisting of heavy vector mesons, $J/\psi$ and/or $\Upsilon$, for which $\sigma_{\text{eff}}$ is smaller.

The origin of this effect is not yet understood.

Another interesting observation: it has been pointed out that the value of $\sigma_{\text{eff}}$ 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.
What if we missed something at low mass?

Di-jet searches at the LHC are pushing the limits for New Physics to really high masses. At low mass (100-300 GeV/c²) they are limited by ability to trigger low energy b-jets.

CDF II data can help to fill this gap.

**b-jet identification at CDF:**
- displaced vertex
- $L_{xy}$ cut
- vertex mass separation

**Performance:**
- 40% efficiency on b-jets
- 1% fake rate (light jets)

**Triggering on 2 b-jets with 15 GeV/c²**
- Fast $\mathcal{O}(10\mu s)$ and efficient (40%) on-line b-tagging on one jet
  - 5% efficiency for $Z \rightarrow b\bar{b}$
  - 10% efficiency for $H \rightarrow b\bar{b}$

- The b-jet enriched data sample
- Inclusive $Z \rightarrow b\bar{b}$ measurement
- Inclusive $H \rightarrow b\bar{b}$ limit
- $b\phi \rightarrow b\bar{b}b$ limit, $\phi$ Higgs-like particle
Measurement of $Z \rightarrow b \overline{b}$ jets: search for SM $Z$ and $H$ resonances

**Signal** searched in a sample with two $b$-tagged jets
- Fit to the invariant mass of the two leading jets using:
  - QCD multijet background templates from data driven technique
  - $Z \rightarrow b \overline{b}$ signal template from Monte Carlo simulation

**Background Templates:**
- Sample with a single $b$-tagged jet and another untagged jet (Bx)
- Non-$b$ component removed from the single $b$-tagged sample with a cut on the SecVtx mass
- $b$-tagging parametrization from simulations for the different jet flavors
- $b$-tagging parameterizations to simulate the bias on the untagged jet
  - Templates for $Bb$, $Bc$ and $Bq$ backgrounds

More than $5\sigma$ significance including systematics

**Measurement:**
$$\sigma(pp^\rightarrow Z) \mathcal{B}(Z \rightarrow b \overline{b}) = 1.11 \pm 0.08{\text{(stat)}} \pm 0.13{\text{(sys)}} \text{ pb}$$

**Theoretical NLO prediction:**
$$\sigma(pp^\rightarrow Z) \mathcal{B}(Z \rightarrow b \overline{b}) = 1.13 \pm 0.02 \text{ pb}$$
Limit on the inclusive SM $H \rightarrow b\bar{b}$

Test of a different production mechanism than the one that led to the Tevatron $H \rightarrow b\bar{b}$ evidence

Search validated by the $Z \rightarrow b\bar{b}$ measurement:
- Same event selection
- Same background modeling
Very low $S/\sqrt{B} \sim 0.04$

Upper limit set using CL$_S$ method

Test statistic:
$\chi^2$ difference between fits in the $B$ or $S+B$ hypothesis

Result:
Observed(expected) limit at 95% C.L. 33 (46) times the Standard Model cross section
Signal Signature:
Narrow neutral scalar $\phi$ into a $b$ quark pair 
Additional 3rd $b$ quark to reduce bkg 
- Bump in $m_{b\bar{b}}$, taken as 2 lead. jets inv.mass

Analysis Strategy:
- Signal search in a sample with three $b$-tagged jets 
- Signal and background modeling based on 2D templates: $x_{tag}$ vs invariant mass $m_{12}$ 
- $x_{tag}$ variable sensitive to the flavor of the jet, carries the information of the SV mass

No excess in the “hot” region 100 – 150 GeV/c² found
7 years after shutdown of the Tevatron: many interesting results are coming from both experiments!
**Signal:** prompt $J/\psi + J/\psi$

Fiducial Acceptance ($J/\psi$):
- $p_T > 4$ GeV/c
- $|\eta| < 2$

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

\[
\sigma_{\text{DPS}}(J/\psi+J/\psi) = 59 \pm 6 \pm 22 \text{ fb} \\
\sigma_{\text{SPS}}(J/\psi+J/\psi) = 70 \pm 6 \pm 22 \text{ fb} \\
\sigma_{\text{eff}} = 4.8 \pm 0.5 \pm 2.5 \text{ mb}
\]

The $|\Delta \eta(J/\psi, J/\psi)|$ distribution of bckg subtr. double $J/\psi$ events after all selection. 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.