Perspectives on QCD and EW physics from the Tevatron

The Evolution of a Logo

Bob Hirosky for the CDF and D0 Collaborations

DIS2015

SMU

Tevatron

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DIS 27Apr, 2015
Outline of Tevatron Results

The Tevatron experiments, CDF and D0, continue a rich physics program analyzing ~$10\text{fb}^{-1}$ of recorded data from ~2001-2011

- World's highest energy $p\bar{p}$ data set (2 TeV C.O.M.)
- Unique physics studies
- Complementary/competitive in LHC era

>1100 Tevatron papers and counting
Outline of Tevatron Results

The Tevatron experiments, CDF and D0, continue a rich physics program analyzing $\sim10\text{fb}^{-1}$ of recorded data from $\sim2001-2011$

**Focus today on recent results**

**Outline of topics**

- Heavy flavor states and production/final state asymmetries (incl. CPV)
- Top
- EW production and decay kinematics
- $(V)V+\text{jets/HF}$
- QCD, low-$x$
- Exotics and non-SM Higgs
**Heavy flavor states**

**B^0's lifetime in the flavor-specific decay channel** \( B^0 \rightarrow D_s \mu^+ \nu + C.C. \) with the D0 detector

- Flavor oscillations yield lifetime as linear combo of light+heavy mass eigenstates
- Superposition of states => lifetime distribution:

\[
\tau_{fs}(B^0_s) = \frac{1}{\Gamma_s} \cdot \frac{1 + (\Delta \Gamma_s/2\Gamma_s)^2}{1 - (\Delta \Gamma_s/2\Gamma_s)^2}
\]

Flavor-specific final state

\[ B^0_s \rightarrow D_s \mu^+ \nu + C.C. \]

Determines \( B^0, \bar{B}^0 \) state at decay

Lifetime from (pseudo) proper decay length. K-factor for kinematic effects of \( \nu \), soft particles from excited states


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Heavy flavor states

$B^0$s lifetime in the flavor-specific decay channel $B^0s \rightarrow Ds \mu X$ with the D0 detector

- All contributions in signal region enter in the fit
- $\tau(B^0)$ from $B^0 \rightarrow D\mu+\nu X$ decays is also obtained and the ratio $\tau(B_s^0)/\tau(B^0)$ calculated

$\tau_{fs}(B_s^0) = 1.479 \pm 0.010\text{(stat)} \pm 0.021\text{(syst)} \text{ps}$
$\tau_{fs}(B_s^0)/\tau(B^0) = 0.964 \pm 0.013\text{(stat)} \pm 0.007\text{(syst)}$

- Reduce $\Delta\Gamma$s and $\Gamma$s => Constraint on CPV
- Precise ratio to $\tau(B^0)$ => Constrain NP operators

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D0+LHCb

Contours of $\Delta(\log L) = 0.5$

10.4 fb$^{-1}$
Heavy flavor states

Measurement of indirect CP-violating asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

Measure CPV asymmetries $A_\Gamma$ in charm mesons

- Identify $D_0$ flavor at production from strong decay $D_0^* \to D_0\pi^+$ (+ CC)
- Measure decay time-rate asymmetries, for slow mixing:

$$A_{CP}(t) \approx A_{CP}^{dir}(h^+h^-) - \frac{t}{\tau} A_\Gamma(h^+h^-)$$

(asymmetry in lifetimes of $D$, $\bar{D}$)

Sensitive to exchange of virtual non-SM particles, non-SM loops. SM(<1%)

$$A_\Gamma = (-0.12 \pm 0.12)\%$$ (combined)

Consistent with best determinations, improve global constraints on indirect CPV in charm-meson dynamics.
Heavy flavor states

Measurement of the direct CP-violating parameter

\[ A_{CP}(D^+ \to K^-\pi^+\pi^+) \]

High precision measurement of CPV parameters in Cabibbo favored decays crucial to establish experimental basis for charge symmetric process

\[
A_{CP}(D^+ \to K^-\pi^+\pi^+) = \frac{\Gamma(D^+ \to K^-\pi^+\pi^+) - \Gamma(D^- \to K^+\pi^-\pi^-)}{\Gamma(D^+ \to K^-\pi^+\pi^+) + \Gamma(D^- \to K^+\pi^-\pi^-)}
\]

- Simultaneous fit
- Consistent with zero (SM)
- 2.5x improvement on measure

\[ A_{CP}(D^+ \to K^-\pi^+\pi^+) = [-0.16 \pm 0.15 \text{ (stat.)} \pm 0.09 \text{ (syst.)}] \%
\]

Phys. Rev. D 90, 111102(R) (2014)
arXiv:1408.6848

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10.4 fb⁻¹

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Production mechanism dominated by gluon-gluon fusion $\rightarrow$ no $A_{FB}$

$A_{FB}$ receives contribution in $q\bar{q}$ and $qg$ interactions from interference:

- initial and final-state radiative gluon diagrams
- box diagram + Born
- different amplitudes in flavor excitation
- electro-weak process ($qq \rightarrow Z/\gamma \rightarrow b\bar{b}$)

In $pp$ collisions $b(\bar{b})$ quark follows $p(\bar{p})$ direction

$A_{FB}$ depends on $m(b\bar{b})$

**D0:**

$A_{FB}$ using fully reconstructed B meson and $\Lambda_b$

**CDF:**

$A_{FB}$ with $b\bar{b}$ jets in low and high mass

\[
A_{FB} \simeq \frac{N_F - N_B}{N_F + N_B}
\]

$\eta < 0$ \hspace{1cm} $\eta > 0$

$\Lambda_b$ (also $\Lambda$)
Forward-backward asymmetries

Production asymmetries of $B^\pm$

\[ A_{FB}(B^\pm) = \frac{N(-q_B \eta_B > 0) - N(-q_B \eta_B < 0)}{N(-q_B \eta_B > 0) + N(-q_B \eta_B < 0)} \]

Fully reconstructed $B$ meson

\[ A_{FB}(B^\pm) = (-0.24 \pm 0.41 \pm 0.19)\% \]

Systematically lower than calculated in MC@NLO

More rigorous determination of the SM predtn. needed to interpret results

Less room for new physics causing anomalous F-B asymmetries (top and bottom)

arXiv:1411.3021

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Two b-quark jets using displaced secondary vertices, muon tag

b-quark flavour: charged muon in the jet (muon Jet)
at particle level unfold M and Δy distributions

AFB at particle level → unfold Mbb and Δy_b distributions

Integrated asymmetry: (1.2 ± 0.7)%

AFB:
- agreement with SM, including feature around Z pole mass
Forward-backward asymmetries

$A_{FB}$ in $b\bar{b}$ pairs at high mass

Sample with at least two $b$-quark jets, $m(b\bar{b})>150$ GeV/$c^2$

- $b$-quark identified requiring displaced secondary vertex
- vertex mass used to determine sample composition ($b,c,LF$)
- $b$-quark charge via jet charge

Poisson Likelihood defined for: background, systematics, purity, smearing and signal asymmetry

Use Bayesian technique to extract the hadron-jet level $A_{FB}$ posterior probability distribution in each bin

Results consistent with zero & SM

Exclude wide axigluon model $m\sim 200$ GeV

Reduction of parameter space for $t\bar{t}$ asymmetry
Forward-backward asymmetries

$\Lambda^0_b$ and $\bar{\Lambda}^0_b$ baryon production

Production through $q\bar{q}$, $gg$ has small asymmetry ($\sim$1%) from NLO corrections

$\Rightarrow$ Study hadronization effects, eg “string drag” model (Rosner) favor production of $(\bar{\Lambda}_b)\Lambda_b$ in (anti)proton beam direction

Clean signals
Forward/backward events shown

General agreement with heavy quark drag model $\Rightarrow$

(More details and “rapidity loss” analysis in parallel talk)
Forward-backward asymmetries

$\Lambda^0$ and $\bar{\Lambda}^0$ baryon production

$A_{FB}$ measured in 3 separate samples:

- $\Lambda(\bar{\Lambda}) X$
- $\mu^\pm \Lambda(\bar{\Lambda}) X$
- $J/\Psi \Lambda(\bar{\Lambda}) X$

$A_{FB}$ consistent with strong connection to quark flavor of incoming hadron

$\bar{\Lambda}/\Lambda$ production ratio is approximately a universal function of the proton “rapidity loss” $y_p - y$

Little dependence on $\sqrt{s}$, target, or kinematic factors
**Top**

Single top (s+t)-channel Tevatron XS combo and Vtb extraction

Tevatron: **strong advantage of pp initial state for s-channel production**

- **Tevatron**: $\sigma_{\text{tot}} = 3$ pb
- **LHC**: $\sigma_{\text{tot}} = 114$ pb @ 8 TeV

Complex background environment, small signal component

- Extensive studies: event selection, discriminating variables
- Exploit MVA and analytic methods: NN, BNN, BDT, ME

Combination:

- **CDF**:
  - arXiv:1503.05027
  - arXiv:1410.4909
  - arXiv:1407.4031
Single top (s+t)-channel Tevatron XS combo and Vtb extraction

CDF: lepton+jets
s+t discriminant

D0: s-channel, t-channel

Combined discriminant

X-axis units:
t-channel s/b  s-channel s/b
**Top**

Single top (s+t)-channel Tevatron XS combo and V_{tb} extraction

\[ \sigma_{s+t} \propto |V_{tb}|^2 \]
Precision measurement of the top-quark mass in lepton+jets final states

**Matrix element method**

- Innovations in ME calculation via arXiv:/1410.6319

- **Single-most precise measurement!**

- Detailed PRD, e.g. cross-check of b-quark jet energy scale:
  \[ R_{bl} = 1.008 \pm 0.0195 \text{ (stat.)} \pm 0.037 \text{ (syst.)} \]

**l+jets channel**
- \( \frac{\delta m_t}{m_t} = 0.43\% \) (D0)
- \( \frac{\delta m_t}{m_t} = 0.45\% \) (CMS)
- \( \frac{\delta m_t}{m_t} = 0.65\% \) (CDF)

\[ DØ 9.7 \text{ fb}^{-1} \]

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Precision Measurement of the Top Quark Mass in Dilepton Events

Measure of top quark mass in dilepton channel with full D0 data set

(see talk by Huanzhao Liu for 1st public result)

Neutrino weighting method:
- Kinematic reconstruction with weights for multiple solutions based on calculated and observed MET (ω)
- Integrate solutions, η(ν) range + jet-lepton assignments, over m(top) hypotheses
- Characterize events by moments of the distribution: μ(ω) and σ(ω)

Correction factor derived from l+jets analysis (kJES) reduces JES uncertainty ~4x

Multiply likelihoods from all events to get a combined \( L(m_{\text{top}}^{\text{MC}}) \)
W charge asymmetry is sensitive to Parton Distribution Functions (PDFs)
- Tevatron measurements => stringent constraints on valence $u,d$ distributions
- Straightforward observable. Convolution of the $W$ production asymmetry and V-A decay (important to measure both)

CP-folded electron asymmetry compared to MC@NLO(NNPDF2.3), RESBOS(CTEQ6.6)
Most precise measurements of electron charge (+previous W production) asymmetry in electron channel.

- Extended $\eta$ coverage to 3.2
- Improvement of PDF models in the $x - Q^2$ region of interest for W production at the Tevatron (Estimated to reduce the PDF uncertainty in the DØ $M_W$ measurement by approximately 30% (2-3 MeV))

Various comparisons vs kinematic range:

- $e/\mu$ channel, experiments, generators

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arXiv:1412.2862

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Measurement of the $\phi^*\eta$ distribution of muon pairs with masses between 30 and 500 GeV

$\phi^* = \tan(\phi_{acop}/2) \sin \theta^*$

$\phi_{acop} = \pi - \Delta \phi_\ell$

$\cos \theta^* = \tanh[(\eta_- - \eta_+)/2]$

Collins-Soper angle

Probes same physics as $p_{T\ell\ell}$, $\phi^* \sim a_T/M_{\ell\ell}$

Less sensitive to detector resolution and efficiency (Uses angles only)

Collins-Soper angle

First measured in Z peak region by D0 (7.3 fb-1) PRL 106, 122001 (2011)

Data used to improve ResBos and make predictions for LHC

ATLAS: PLB 720, 32(2013)

LHCb: JHEP 1302, 106(2013)

Z peak region


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Measurement of the $\phi^*\eta$ distribution of muon pairs with masses between 30 and 500 GeV

- Ratio $1/\sigma \frac{d\sigma}{d\phi^*}$ in the central to forward rapidity regions can reduce the uncertainty band from QCD scales => suggests the possibility of a new variable that is less sensitive to theoretical uncertainty

- First low mass measurement
  - More sensitive to small-$x$ effects

- Also first ever high mass measurement
  - For constraining QCD ISR in high mass final states

**EW production and decay**

10.4 fb$^{-1}$

Phys. Rev. D 91, 072002
arXiv:1410.8052
Measurement of the effective weak mixing angle in pp → Z/γ* → e+e- events

Drell-Yan pairs produced via $q\bar{q}$ annihilation at Tevatron

Weak mixing angle measured from forward-backward asymmetry of lepton polar angle distribution:

$$A_{FB} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

Sensitive to $\sin^2\theta_W$ through interference of vector and axial vector couplings of Z boson

- Measure $A_{FB}$ vs dilepton pair invariant mass
- Compare to MC $A_{FB}(M_{ee}, \sin^2\theta_W)$ templates
- Analysis for CC-CC, CC-EC, EC-EC cases and running periods

arXiv:1408.5016
Measurement of the effective weak mixing angle in $pp \rightarrow Z/\gamma^* \rightarrow e^+e^-$ events

**EW production and decay**

<table>
<thead>
<tr>
<th>$\sin^2 \theta_W$</th>
<th>CC-CC</th>
<th>CC-EC</th>
<th>EC-EC</th>
<th>Combined</th>
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<td>Total</td>
<td>0.00116</td>
<td>0.00048</td>
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</tr>
</tbody>
</table>

$\sin^2 \theta_{eff} = 0.23147 \pm 0.00047$

World’s best from hadron collider

Relates to observed tension involving most precise quark and lepton couplings

arXiv:1408.5016
**Diboson cross sections**

WW and WZ production in the lepton+Heavy Flavor jets channel

Diboson WW and WZ production in final state consistent with semileptonic W decay plus heavy flavor quarks

\[ W \rightarrow cs, \; Z \rightarrow b \bar{b}, \; c \bar{c} \]

Analysis of the di-jet invariant mass spectrum

3.69 s.d. evidence of WW+WZ w/ HF final states

Cross section measurement

\[ \sigma_{WW+WZ} = 13.7 \pm 3.9 \text{ pb} \]

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CDF Note 11157

25Apr, 2015
Diboson WW and WZ production in final state consistent with semileptonic W decay plus heavy flavor quarks

\[ W \rightarrow cs, \quad Z \rightarrow bb, \quad cc \]

- Use different HF decay pattern of the W and Z and the analysis of the secondary-decay vertex properties

- Independently measure the WW and WZ production cross section in a hadronic final state, for the first time at hadron colliders

Measured cross sections:

\[ \sigma_{WW} = 9.4 \pm 4.2 \text{ pb} \]
\[ \sigma_{WZ} = 3.7 + 2.5 - 2.2 \text{ pb} \]

Consistent with the SM predictions, correspond to signal significance of 2.87 s.d. and 2.12 s.d. for WW and WZ respectively
**Diboson cross sections**

**W+W− Production Cross Section and Differential Cross Sections**

Production via quark radiation, multi-gauge-boson coupling

- Background for H→WW
- XS measure similar to H→WW search
  - Extend to 1, 2-or-more jets regions
  - 1-jet measure differential in jet pT

<= combined NN for inclusive measurement

Good modeling of input variables for Signal and Background regions
Diboson cross sections

W+W− Production Cross Section and Differential Cross Sections

Production via quark radiation, multi-gauge-boson coupling

- Results unfolded for bin migration and acceptance differences
- Uniformly higher than, but consistent with predictions

First differential $\sigma$ in a massive diboson state

Very challenging at LHC due to $t\bar{t}$ background
9.4 fb^{-1}

**Search for production of an Upsilon(1S) meson in association with a W or Z boson**

**Probe of QCD, NRQCD, and long distance matrix elements (LDME)**

Search for excursions from SM production
- Charged Higgs may decay into YW with high BR
- SM Higgs can decay into YZ, as can other light scalars

**Observe**
- 1 Y(→μ+μ-) + W(→lν) candidate
  - Expected bkg: 1.2±0.5 events
- 1 Y(→μ+μ-) + Z(→l+l-) events
  - Expected bkg: 0.1±0.1 events

**95% CL limits**

\[ \sigma(YW) < 5.6 \text{ pb} \]
\[ \sigma(YZ) < 21 \text{ pb} \]

Event selection:

Y(1S) candidate + W or Z selections

4-muon event
**V+Jets**

Measurement of the W+b-jet and W+c-jet differential production

W+c is a probe of s-quark PDF
Tevatron W+c 85% s-quark initial state, $Q^2 < 10^4 \text{ GeV}^2$

W+c and W+b are backgrounds to WH($\rightarrow bb$), ttH or beyond the SM

New selections => Enhance contribution from $qq \rightarrow W+g(g \rightarrow cc)$
(almost half gluon splitting at high $p_T$)

First measures differential in $p_T$ and
Sensitive to gluon splitting process

Missing higher order corrections, enhanced cc splitting, strange sea?

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**V+jets**

Ratio of inclusive cross sections

\[ \sigma(pp^- \rightarrow Z+2b \text{ jets}) / \sigma(pp^- \rightarrow Z+2 \text{ jets}) \]

\[ 8.7 \text{ fb}^{-1} \]

(See talk by A. Kumar)

- Z+2b is significant background to ZH(H → bb) and searches for sbottom
- Important test of pQCD and non-pQCD (gluon splitting)
- At Tevatron
  - qq → Zbb 76%
  - gg → Zbb 24%
- Discriminate between Z+2b, Z+2c after SM bkg subtraction
- Fit 2D templates of b-jet discriminant using both jets

Measure in ee and mumu channels

\[ R = 0.0236 \pm 0.0032 \pm 0.0035 \]

In agreement w/ NLO pred w/in exp & theory uncertainties

QCD low-x
Exclusive pi-pi production
(double pomeron exchange)

- 2 charged particles (π+π-)
in |η|<1.3
- No particles in 1.3<|η|<5.9

Expect dominance of DPE production

σ(p+(π+π-)+p)~1/ln(s) consistent with Regge theory

Measured at √s=0.9, 1.96 TeV
(see talk by M. Albrow)

- f_0(1500), f_0(1710) glueball candidates, no significance

Possible information for:
- isoscalar meson spectroscopy
- pomeron in transition to pQCD

f_2(1270)
F_0(980), KK

M(ππ) distribution

data, √s=1960 GeV
Syst. uncertainties

P_t(X)>1.0 GeV/c
P_t(π)>0.4 GeV/c
|η(π)|<1.3
|y(X)|<1.0

arXiv:1502.01391
Search for $W'$ decaying to a $t+b$ quark pair

Tevatron is sensitive to observed single top production through a time-like virtual $W$ boson

- Same topology can be used to search for heavier $W$-boson
- Use MET-based trigger, optimize for channels w/ and w/o charged lepton
- Examine a benchmark left-right symmetric NLO model. Assume SM couplings of $W'$, allowed or forbidden leptonic decay modes

$W'$ excluded up to $860(880)$ GeV/$c^2$, assuming allowed(forbidden) leptonic decay modes

Best exclusion limit below $700$ GeV/$c^2$
Search for Dirac monopoles

Unique signature => low background + high efficiency
Dedicated trigger
  • Heavy ionization (LIGHT!) in TOF scint
  • Track: heavy ionization, no $\phi$ curvature
    (parabolic arc along B)
Correcting for acceptance, trigger effs, & pileup inefficiency
  • 30-40% overall acceptance
  • Expected fake rate $\sim 3.4 \times 10^{-9}$!

Exclude monopole up to mass of 476 GeV/c$^2$ at 95% CL
Best limit up to 300 GeV/c$^2$
**Exotics**

Constraints on Models of the H Boson with Exotic $J^P$
Using Decays to Bottom-Antibottom Quark Pairs

Exploit sensitivities of $V_{bb}$ mass distributions to spin-parity of exotic H boson in decay: $VX, X \rightarrow b\bar{b}$

0− excluded at $4.9\sigma$ and 2+ at $5\sigma$, in the absence of 0+, assuming SM production and decay rates

95% CL limits of production rates at 36% of SM rate set for both 0− and 2+, in the absence of 0+

![Plot of $VX \rightarrow V_{bb}$ with Tevatron Run II data](image)

Unique study in $bb$ final states, compliments outstanding LHC work in $VV$


27Apr, 2015

[35]
Summary
Tevatron experiments continue a rich physics legacy

Exploiting advantages: better S/B, $q\bar{q}$ initial states, triggering capabilities, … for competitive and complimentary physics program

- Precision EW results including fundamental parameters of standard model ($W_{\text{mass}}, \sin^2\theta_W$) and $W,Z$ production and PDF inputs
- World leading top mass, unique and complimentary measures ($A_{FB}$, cross sections, properties, single top, …)
- Rich b-physics program (CPV studies, hadron properties, new work in production and hadronization asymmetries)
- Closing the gaps between earlier results and LHC for moderately high mass new physics. Limit exotic higgs to fermions
- Unique and complimentary work in QCD (V(V)+jets/HF, low-x, extensive DPI studies, …)

Visit the parallels for more details and watch for significant updates to come!