



Particle Experiments Tools - Accelerators





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From Fixed Target to Colliders







Fermions		Bosons
Dup Up Up down	charm	photon Z boson
Ve electron electron electron	Vμ muon mutrina μ muon	no gluon

- In late 1970's the hunt for heavier and heavier elementary particles continued
 - Fixed target E_{cms} ~ √2mE : for 100 GeV particle
 ~ 5 TeV accelerator is required
- Brilliant idea: use existing proton accelerators and circulate antiprotons in the same beam pipe to collide
- Main challenge was to make enough antiprotons to have dense particle beams
 - SppS and Tevatron were born



Tevatron: Proton-antiproton Collider





- Chain of six accelerators to get to 1 TeV per beam energy
- Single magnet ring protons and antiprotons circulate in the opposite directions
- Elaborate source of antiprotons main driver of the Tevatron luminosity
 - Use of electron cooling of antiproton beam



Peak Luminosity vs Time





- Improvements to antiproton production and cooling increased Tevatron peak luminosity
- Very high reliability: ~80% of ~24 hours stores were ended by planned termination
- Average number of interactions per crossing is ~12 peak and ~6 average in 2011



Tevatron Data Set





- Total data set is ~5 times above original Tevatron Run II goal
- Detectors and accelerator components operated well till last store on September 30, 2011

Tevatron Physics Program

Precision tests of the Standard Model

- Weak bosons, top quark, QCD, B-physics...

Search for particles and forces beyond those known

– Higgs, supersymmetry, extra dimensions...

Fundamental Questions

- ✓ Quark sub-structure?
- ✓ Origin of mass? Higgs?
- ✓ Matter-antimatter asymmetry?

✓ What is cosmic dark matter? SUSY?

✓ What is space-time structure? Extra dimensions?...

The CDF and DZero Collaborations

Tevatron collaborations are ~1000 scientists from 26 countries

CDF and DØ Detectors

Driven by physics goals detectors are rather "similar": silicon, central magnetic field, hermetic calorimetry and muon systems

Layout of the hadron collider detectors have been finalized at the Tevatron

Tevatron Results

- Over 1000 publications in referenced journals from CDF and DØ
- From discoveries of the top quark, new mesons and baryons to extremely
 precise measurements and searches for new phenomena
- ~ 100 new results over last year alone visit CDF and DZero Web pages
 - Only few highlights in this talk

Tevatron Cross Sections

Studies of Quantum Chromo Dynamics – QCD

- PDFs, higher order corrections, α_s measurements, production of vector bosons and jets, direct photons, double parton interactions and many others
- Understand how strong force works and to be able to predict backgrounds for processes with much lower cross sections

Various QCD Measurements

b-quark Studies

High b quark cross section at Tevatron

- ~10⁻³ σ_{tot}
- ~10⁴ b's per second produced!

Large data samples of particles with b-quarks provide

- B mesons lifetime studies
- Mass spectroscopy (B_c, etc.)
- Studies of B_s oscillations
- CP violation studies
- Search for new b hadrons
- Search for rear decays

Discoveries of b-Baryons

DØ di-muon Charge Asymmetry

Di-muon Asymmetry Anomaly

Electroweak: W Boson Mass Measurement

Single and pair W/Z production, asymmetries, weak mixing angle...

- W boson mass is measured using decay products: electron and neutrino
- DØ : calibration of energy scale is performed using Z boson mass

World Average W boson Mass

Top Quark Studies

Discovery of the Top Quark

Due to relatively low backgrounds (high top quark mass, pair production) "a few" candidates only required for the discovery

Top Quark Mass Measurement

- Top quark mass is measured using decay products in many different channels
- Lepton+jets channel with two jets coming from W boson is the most precise

Anomaly in Top Quark Studies

- In Standard Model, there is no asymmetry in leading order, but next to leading order predicts asymmetry
 - Positive asymmetry from box diagrams
 - Negative asymmetry from ISR and FSR
- Forward backward asymmetry
 - Enhanced in some beyond standard models scenarious

Top Quark Forward-Backward Asymmetry

- Options
 - Statistics?
 - Not accurate enough QCD predictions?
 - New Physics?

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- Top quark mass: $m_t = 173.2\pm0.9 \text{ GeV}$ (0.5% accuracy)
- Are top and antitop masses the same? Test of CPT
 △m=0.8± 1.9 GeV (equal to 1%)
- Top quark lifetime

 Γ_t =1.99(+0.69/-0.55) GeV agrees with SM

- Top charge |q|=2/3e to 95% C.L.
- W helicity in top decay expect 70% longitudinal, 30% left-handed SM looks good
- Asymmetry of top quark in p vs pbar direction expected to be a few % Anomalous asymmetry of ~15% - requires theory improvements?
- Correlations of spins of top and anti-top are consistent with SM
- No flavor changing neutral currents $<2x10^{-4}$ (t \rightarrow gu); $<4x10^{-3}$ (t \rightarrow gc)
- No evidence for SUSY H[±] in top decays
- Anomalous top vector/tensor couplings?
 Combination of W helicity & single top is in good agreement with SM V-A
- 4th generation t'? None below ~450 GeV
- tt resonances? None below ~800 GeV
- Is W in t decay color singlet? Singlet preferred
- Electroweak single top quark production observed: $|V_{tb}| > 0.77 @ 95\%$ C.L.

Very well know quark by now!

Higgs Searches – Indirect Limits

Higgs Searches Status: ~1.5 Years Ago

- Higgs masses 158-173 GeV are excluded by the Tevatron
- Precision measurements point to Higgs masses below ~150 GeV
- LEP results indicate Higgs mass is above ~114 GeV

• Most probable value was... 125 GeV

Higgs Production and Decays at the Tevatron

Search strategy:

 $M_H < 135$ GeV associated production and bb decay W(Z)H \rightarrow Iv(II/vv) bb Main backgrounds: top, Wbb, Zbb

M_H >135 GeV gg → H production with decay to WW Main background: electroweak WW production

Experimental Challenges

Number of Higgs Events

- Number of Higgs events available to CDF+DØ with the full Tevatron Run II data set of 10 fb⁻¹ at 125 GeV is ~10³
- Reconstruction/selection efficiencies
 - ~10% in H→bb channels and ~25% in H→WW channels

Higgs Search: $H \rightarrow WW \rightarrow I_V I_V (M_H > 130 \text{ GeV})$

Multivariate Analyses (neural networks, boosted decision trees, etc.) are used to provide a gain sensitivity beyond that obtained from optimized, cut-based analysis

Even for a single channel reach S/B ~1 in high discriminant region!

CDF/D0 H→WW→lvlv Limits

Limits are presented as ration to Standard Model predictions Both experiments exclude Standard Model Higgs boson around 165 GeV

$H \rightarrow W^+W^-$ Tevatron Combination

Exclude 147 < M_H < 180 GeV at 95% CL

165 GeV Mass - Number of Events

Events in all channels are sorted based on signal/background ratio No excess observed

Low Mass Higgs Channels

- Main discriminant is di-jet mass from b-quarks pair
- Elaborate b-tagging of jets
- Multivariate analyses help to extract full information about event kinematic

Results from DØ

All channels are consistent and demonstrate sensitivity to the Higgs

Results from CDF

Pattern of an excess is starting to appear...

Cross Check on Di-boson Processes

Benchmark for $H \rightarrow bb$ searches using well known process

WZ, ZZ with W or Z decaying to leptons and Z decaying to heavy flavor jets

Apply exactly the same selections and multivariate analysis as for WH/ZH searches

CDF+DØ combination cross-section: 3.9 +/- 0.9 pb Standard Model prediction: 4.4 +/- 0.3 pb 4.5 σ significance

CDF and DØ Higgs Search Results

CDF and DØ combinations of all Higgs search channels: $H \rightarrow WW, H \rightarrow bb, H \rightarrow \gamma\gamma + other modes$

Remarkably similar shapes:no excess below~110 GeVbroad excess around~120-140 GeVexclusion around~165 GeV

June 2012 Tevatron Combination

Real Data Analysis

Signal Injection Study

Injection of Standard Model Higgs signal at 125 GeV provides very similar to the observed behavior "background like" shape above ~140 GeV "signal like" shape in 115-140 GeV region

Probability of Background to Mimic Signal

3.0σ local excess at 120 GeV

2.5σ global excess taking into account "look elsewhere effect" as we perform studies at many data points

Tevatron H→bb Combination

$\mathbf{M} \to \mathbf{B}$ H \rightarrow bb, Probability of Background to Mimic Signal

Significance of observed excess	Channels	Local	Global
	H→bb	3.3 σ	3.1 σ Evidence!

Events Count for 125 GeV Higgs Search

Clear excess in the high Signal/Background region

Best Fit Cross Sections

- Using data we extract σ x Br for H \rightarrow bb, H \rightarrow WW and H $\rightarrow \gamma\gamma$ values normalized by the Standard Model predictions
- All data are compatible with predictions for the Standard Model Higgs boson

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Evidence for the Higgs Boson with Full Tevatron Data Set

• Tevatron Higgs search data are incompatible with background only hypothesis

• For Higgs to bb channel p-value is 3.1σ

 Tevatron data are compatible with Standard Model Higgs boson production in the mass range

- 115 GeV < M_H < 135 GeV in all studied channels including H \rightarrow bb, H \rightarrow WW and H $\rightarrow \gamma\gamma$
- $(\sigma_{WH} + \sigma_{ZH}) \times \mathcal{B}(H \to b\bar{b}) = 0.23^{+0.09}_{-0.08} \text{ (stat + syst) pb}$
- Based on Tevatron results, including precision W boson and top quark mass measurements, new particle has properties predicted for the Higgs in the Standard Model and couples to fermions

All of the above is interpreted as

Evidence for the Higgs boson production at the Tevatron

Current Status of Higgs "Searches"

- LHC provides large samples of Higgs bosons (x100 Tevatron cross section)
 - Rare and clean decay modes, like $\gamma\gamma$ can be used for searches discovery this summer!
- Tevatron, due to proton-antiproton collisions, provides unique opportunity to study most probable at 125 GeV decay mode: pair of b quarks and indicate coupling to fermions

Careful analysis of all available data, including cross sections at vastly different collision energies, demonstrates good agreement between properties of the observed particle and predicted in the Standard Model Higgs boson

Self-consistency of the Standard Model

of ~125 GeV are in perfect agreement

Tevatron

- Improved analysis will gain another ~10% in sensitivity
 - HCP, Kyoto next week
- Using mass constrain of 125 GeV will improve measurements of branching fraction to a pair of b-quarks
- Measurement of Higgs couplings

• LHC

- More data coming: ~30 fb⁻¹ by later this year before ~2 years shutdown
- Sensitivity over 3 σ for majority decay modes, including fermions
- Measurement of Higgs spin using large data sets
- Measurement of Higgs couplings
- Higgs factory
 - As Higgs mass is relatively low
 - Medium energy lepton collider will suffice
 - High luminosity is required for reasonable number of Higgs bosons
 - Exciting option widely discussed

Chicago Tevatron Highlights Summary

- Tevatron experiments published over 1000 fundamental results
 - From the discovery of the top quark to the evidence of the Higgs boson production and decay to fermions

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- Many extremely precise measurements of the Standard Model parameters
- 100's of searches for physics beyond Standard Model with two "clouds" remaining
 - Top quark forward-backward asymmetry
 - Anomalous di-muon asymmetry
- 10 fb⁻¹ unique proton-antiproton collisions 1.96 TeV data set is accumulated
- Tevatron collaborations will publish ~150 papers in 2012 and 2013
- Large number of analyses in all physics areas continue including
 - Unique for proton-antiproton collider measurements
 - Top quark mass to ~0.6 GeV accuracy and W boson mass to ~10 MeV accuracy

& Recycler

Thank you for the invitation to visit KEK and present an exciting summary of recent Tevatron results! ありがとうございます。

Backup Slides

Cross Section * BR Measurement

Higgs to yy

Best Fit Cross Sections

Full Combination Events Count

H to bb Combination Events Count

