Tevatron
Results

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Run I
1992-1996
0.1/fb/exp
... top ...

Run II
2001-2010
8/fb/exp?
... \( B_s \) ...

Tevatron
\( p\bar{p} \)
c.m. energy 1.96 TeV
luminosity \( \sim 2 \cdot 10^{32} \text{ cm}^2 / \text{s} \)
integr. luminosity end 2007:
3/fb/exp

Phys. Inst. III A
Outline

Introduction

QCD Tests

Electroweak Results

Searches

Tevatron
Outline

Introduction

cross sections

QCD Tests

Electroweak Results

Searches
Cross Sections

**strong, soft:**
\[ \sigma \approx 10 \, \text{fm}^2 \approx 100 \, \text{mb} \]

**strong, hard:**
\[ \sigma \approx \frac{\alpha_s^2}{Q^2} \approx 10 \, \text{nb} \]

**electroweak:**
\[ \sigma \leq \frac{\alpha^2}{m^2} \approx 1 \, \text{pb} \]
„Dirty“ environment

- beam remnants
  underlying event

- multiple parton interactions
  some percent

- „pile up“ = multiple p \( \bar{p} \) int.
  minimum bias events
  2 - 10 events / bunch crossing
  every 396 ns

- „detector pile up“
  - drift time > bunch distance
  - thermalized neutrons
Outline

Introduction

QCD Tests
  - jet production
  - top
  - bound states

Electroweak Results
Searches
Standard Model – strong \text{SU}(3)

\begin{align*}
\begin{pmatrix}
  uu & uu \\
  dd & dd
\end{pmatrix}
\begin{pmatrix}
  cc & cc \\
  ss & ss
\end{pmatrix}
\begin{pmatrix}
  tt & tt \\
  bb & bb
\end{pmatrix}
\end{align*}

\[ g = \text{color octet} \]

... spin, \textit{mass} ...

\[ \alpha_s(Q^2) \]
strong some complications ...

Photon, W, Z etc.

Parton distribution

Virtual quark

Hard scattering

ISR

FSR

Renormalization scale $\mu_R \approx Q$

Factorization scale $\mu_F \approx Q$

Hadronization scale $\mu_H \approx Q$

$\frac{d \sigma_F(\sqrt{s})}{dV} = \sum_{i,j} \int dx_i dx_j f_i(x_i, \mu_F^2) f_j(x_j, \mu_F^2) \frac{d \sigma_{ij}^{ij}(x_i, x_j, \mu_R^2)}{dV}$
strong jet production

+ higher orders
+ electroweak diagrams

note:
difficult to disentangle qqq and ggg contributions

Leading Order QCD (MRS0')

$\eta_1 = \eta_2 = 0$

GG Gluon-Gluon Scattering
QQ Quark-Quark scattering
GQ Quark-Gluon scattering

theory
strong jets

K_{T} jet  Cone jet

most often use cone jets with R=0.5 or 0.7
T. Hebbeker

strong
inclusive jet production

New physics?

$\int L = 385 \text{ pb}^{-1}$

2005

CDF Run II Preliminary

$\sigma(d^2\sigma/dy dP_T) \text{ [nb/(GeV/c)]}$

$P_T \text{ (GeV/c)}$

factor $10^7$

$\pm 15\%$

absolute normalization
(luminosity, jet scale)
Determination of $\alpha_s$ from inclusive jet production

$\alpha_s(M_Z) = 0.118 \pm 0.012$ (dominated by exp. systematics, ren. scale uncertainty and pdf)
Strong top pair production and decay

\[ \sigma_{top} = 6.8 \pm 0.4 \text{ pb} \]

SM (NLO):

85% \[ q\bar{q} \rightarrow t\bar{t} \]
15% \[ gg \rightarrow t\bar{t} \]

Favorite signature:

- lepton
- missing energy
- b jets
- jets
- W constrains jet energy scale

\[ B \approx 11\% \]
\[ B \approx 100\% \]
strong  top

Jan-Henrik Andersen
strong top
strong top

$m_t = 172.7 \pm 1.2 \pm 1.8 \text{ GeV}$

$2008\ 1.9/\text{fb}$

lepton+jets

Best Independent Measurements of the Mass of the Top Quark (*=Preliminary)

- CDF-I dilepton: $167.4 \pm 11.4$
- DØ-I dilepton: $168.4 \pm 12.8$
- CDF-II dilepton*: $171.2 \pm 3.9$
- DØ-II dilepton*: $173.7 \pm 6.4$
- CDF-I lepton+jets: $176.1 \pm 7.3$
- DØ-I lepton+jets: $180.1 \pm 5.3$
- CDF-II lepton+jets*: $172.7 \pm 2.1$
- DØ-II lepton+jets*: $172.2 \pm 1.9$
- CDF-I alljets: $186.0 \pm 11.5$
- CDF-II alljets*: $177.0 \pm 4.1$
- CDF-II b decay length: $180.7 \pm 16.8$

$\chi^2/\text{dof} = 6.9/11$

Tevatron Run-I/II*: $172.6 \pm 1.4$

$m_t = 172.6 \pm 0.8 \pm 1.1 \text{ GeV}$
\[ \sigma_{\text{top}} = 7.3 \pm 0.9 \text{ pb} \]

SM: \[ \sigma_{\text{top}} = 6.8 \pm 0.4 \text{ pb} \]

(175 GeV)

QCD is flavor independent!
strong new bound state $\Xi_b$

first baryon with quarks from all three families!

$M(\Xi_b^-) = 5792.7 \pm 1.9$ MeV

quark model:

$M(\Xi_b^-) = 5805.7 \pm 8.1$ MeV

Jenkins 1997
strong new bound state $\Xi_b^-$

$\mu^+, J/\Psi, \mu^-, \pi^-$

$M(\Xi_b^-)$ (GeV/c²)

5.5σ

$\Lambda_{cm}$

$\sim 5$ cm

$\sim 0.1$ cm

1.3/fb 2007

DØ, 1.3 fb⁻¹

Data

Fit

first hints at LEP!
Outline

Introduction

QCD Tests

Electroweak Results
  masses
  boson boson couplings
  fermion boson couplings

Searches
Standard Model – electroweak SU(2)×U(1)

\[
\begin{pmatrix}
\nu_e \\
\nu_{\mu} \\
\nu_{\tau}
\end{pmatrix},
\begin{pmatrix}
u_{\mu} \\
u_{\tau}
\end{pmatrix},
\begin{pmatrix}u \\
d
\end{pmatrix},
\begin{pmatrix}c \\
s
\end{pmatrix},
\begin{pmatrix}t \\
b
\end{pmatrix},
\gamma, W, Z, H
\]

\[\gamma, Z, W, \gamma, Z, \gamma, Z, \gamma, Z\]

\[\alpha, \theta_W\]

\[\gamma, f, f, \gamma, Z, f, f\]

\[q_1, W, V_{12}(1 - \gamma^5), q_2, \text{CKM}\]

... spin, mass, width ...
Outline

Introduction

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masses

boson boson couplings

fermion boson couplings

Searches

\[ p \bar{p} \rightarrow WW, WZ, ZZ \]

FCNC \[ V_{td}, V_{ts}, V_{tb} \]
**electroweak**

**W mass measurement**

\[ m_T^2 = 2 \cdot E_T^l \cdot M E_T \cdot (1 - \cos \Delta \phi) \]

- Also: \( W \rightarrow e \nu \)
- \( M_W = 80413 \pm 34 \pm 34 \text{ MeV} = 80413 \pm 48 \text{ MeV} \)
- \( M_W = 80367 \pm 33 \text{ MeV} \)

Lepton energy scale!

use \( Z \rightarrow l l \)

for calibration
The electroweak SM Higgs mass prediction is given by the formula:

\[ M_W^2 = \frac{\pi \alpha}{\sqrt{2} G_F} \frac{1}{(1 - c_W^2)(1 - \Delta r)} \]

where \( c_W \) is the cosine of the weak mixing angle, \( \Delta r \) is a small correction, and \( G_F \) is the Fermi constant.

The plot shows the 68% CL allowed region for the Higgs mass \( M_W \) as a function of the top quark mass \( m_t \). The region is shaded, with different lines representing different experimental collaborations (LEP2 and Tevatron, LEP1 and SLD). The light Higgs is preferred if it lies within the allowed region.
electroweak  

SM:

smallest $\mu\mu$ channel 

$\sigma \cdot B$ small!

$\sigma / pb$

<table>
<thead>
<tr>
<th></th>
<th>CDF+D0</th>
<th>SM (NLO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WW$</td>
<td>$13.6 \pm 3.0$</td>
<td>$12.8 \pm 0.8$</td>
</tr>
<tr>
<td>$WZ$</td>
<td>$4.4 \pm 1.0$</td>
<td>$3.7 \pm 0.3$</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>$1.6 \pm 0.6$</td>
<td>$1.5 \pm 0.1$</td>
</tr>
</tbody>
</table>
electroweak FCNC $B_s \rightarrow \mu\mu$

$B(B_s \rightarrow \mu\mu) = 3 \cdot 10^{-9}$

Buras 2003

$B(B_s \rightarrow \mu\mu) < 5.8 \cdot 10^{-8}$ (95%)
**electroweak B oscillations**

Mixing weak, oscillation slow

\[ A(t) = \frac{N_{osc}(t) - N_{osc}^*}{N_{osc}(t) + N_{osc}^*} \]

\[ A(t) \propto \cos(\Delta m \cdot t) \]

\[ \Delta m_d \propto |V_{td}|^2 \quad \Delta m_s \propto |V_{ts}|^2 \]

Mixing strong, oscillation fast

\[ V_{tb} \sim 1 \quad |V_{td}| \sim 0.008 \]

\[ |V_{ts}| \sim 0.04 \]

\[ V_t \sim 1.5 \text{ps} \]

[Graph of Asymmetry vs. Proper Time]
electroweak B oscillations

tag initial state: \( B_s^0 \) or \( \bar{B}_s^0 \)

collision stops when B meson decays
\[ \tau \sim 1.5 \, ps \]

typical: mm vertex detectors!

\[ L = \gamma \beta t \]
**electroweak B oscillations**

\[ B_d^0 \]

\[ B_s^0 \]

Combined (0.60 < |d| ≤ 1.00)

D* sample

2006 1/ fb

\[ \text{VPDL (cm)} = \text{visible proper decay length} \]

\[ \Delta m_d = 0.506 \pm 0.020 \pm 0.016 \, \text{ps}^{-1} \]

\[ \Delta m_s = 17.77 \pm 0.10 \pm 0.07 \, \text{ps}^{-1} \]

QCD

\[ |V_{td}| = (7.4 \pm 0.8) \cdot 10^{-3} \]

\[ \left| \frac{V_{ts}}{V_{td}} \right| = 4.85 \pm 0.03 \]
electroweak  B oscillations

CKM triangle

all consistent!
**electroweak CKM single top**

SM (NLO):

\[ V_{tb} = 1 \]

\[ 0.88 \pm 0.14 \, pb \]

\[ 1.98 \pm 0.30 \, pb \]

\[ \sigma_{top} = 2.9 \pm 0.4 \, pb \sim |V_{tb}|^2 \]

\[ \sigma_{top} = 4.7 \pm 1.3 \, pb \]

\[ |V_{tb}| = 1.31^{+0.25}_{-0.21} \]

model independent
Outline

Introduction
QCD Tests
Electroweak Results

Searches
  indirect
  higgs
  susy
  exotica
searches  SUSY Models and Signatures

- 'usual' mSUGRA
  - $m_0$, $m_{1/2}$, $A_0$
  - $\tan \beta$, $\text{sign}(\mu)$

- split SUSY
  - gluino, metastable

- mSUGRA RPV
  - R-parity violated

- GMSB
  - LSP = light gravitino

- AMSB
  - mass degeneracies

- generic squarks and gluinos
- sbottom and stop
- gauginos $\rightarrow$ leptons
- stopping gluinos
- lepton-lepton couplings
- lepton-quark couplings
- photons + missing energy
- long lived heavy charged particles
indirect $B$ decays and MSSM

mSUGRA at $\tan\beta = 50$

Arnowitt, Dutta, et al., PLB 538 (2002) 121

$A_0=0, \mu>0$  
$\tan\beta=50$

$B(B_s \rightarrow \mu\mu) < 5.8 \times 10^{-8}$  
@95\% C.L.

CDF (prel.):
indirect electroweak and MSSM

![Graph showing the relationship between $M_W$ and $m_t$ with various theoretical and experimental scenarios, including SM, MSSM, and SUSY regions. The graph highlights the experimental errors at 68% CL and compares different experimental setups such as LEP2/Tevatron (today), Tevatron/LHC, and ILC/GigaZ.](image-url)
searches  SM higgs

Tevatron Run II Preliminary

95% C.L. limit $\sigma$(Higgs) / SM

- D0 Expected
- CDF Expected
- Tevatron Expected
- Tevatron Observed

$L=0.9-1.9 \text{ fb}^{-1}$

$W,Z \rightarrow \text{bb}$  $H \rightarrow WW$

$m_H (\text{GeV}/c^2)$
searches for squarks and gluinos: jets and missing energy

e.g.: $g \rightarrow q\bar{q}\tilde{\chi}_1^0$

$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$

$\sigma$ large!

CDF Run II Preliminary

3 jets

$\tan \beta = 5$

$\mu < 0$

$H_T > 280 \text{ GeV}$

Gluino Mass (GeV)

$\tilde{g} > 308 \text{ GeV}$

$\tilde{g}, \tilde{q} > 392 \text{ GeV}$ for equal masses

$A_0 = 0 \quad \mu < 0$

Tevatron Run II:

DØ observed

DØ expected

CDF observed

CDF expected

no mSUGRA solution

$2.1/fb$ 2/fb prel.
searches

split SUSY: stopping gluinos

gluino forms charged hadron stops in detector
isotr. decay → jet + χ^0, τ > 10 μs

monojet!

cosmics
beam halo

Run 164170 Evt 62966279 Sat Feb 4 15:06:30 2006

Triggers:

DO monojet event

cross section limits ~ 1 pb for gluinos 200-550 GeV

→ \tilde{g} > 270 GeV
if LSP light

m(gluino) = 400 GeV
m(LSP) = 90 GeV

L=410 pb^{-1}
Background
Signal (m_g=400 GeV, \sigma=0.71pb)
Data

2007
searches new vector bosons

$Z', W', ...$?

![Graph showing theoretical predictions and experimental limits for $m_{W'}$]
Summary/Outlook

Tevatron II: great results, already > 200 papers
many more to come!

expect 3fold increase in integr. luminosity
APPENDIX
CDF = Collider Detector Facility

\[ \eta = \frac{\eta_2}{\tan \theta} / 2 \]

\[ \eta = \frac{-\ln \tan \theta}{2} \]

Key:
- Silicon Tracker
- Fiber Tracker
- Drift Chamber
- Scintillator Counter
- Electromagnetic Calorimeter
- Hadronic Calorimeter
- Solenoid Coil
- Toroid
- Steel Shielding
D0

- mini drift tubes
- muon toroid
- scintillators
- PDT's
- tracking system: silicon, scint. fibres
- solenoid
- LAr calorimeter
- electronics, trigger, DAQ
Structure functions

Measurements:
$F_2, F_3 \ldots$ in DIS
(n,p,elm.,weak, $Q^2$-depend.)

$\rightarrow$ valence, sea, gluons...

Fits/parametrisations:
- CTEQ
- MRST
Cross section calculation in pp

Wanted: \( \frac{d \sigma_F}{d V}(\sqrt{s}, Q^2) \)

Calculable: \( \frac{d \sigma_F}{d V}^{ij}(x_i, x_j, Q^2) \)

Known: \( f_i(x_i, Q^2) \)

\[ Q^2 = (\text{"momentum transfer"})^2 \]

depends on final state

\[
\frac{d \sigma_F}{d V}(\sqrt{s}, Q^2) = \sum_{i,j} \int dx_i \, dx_j \, f_i(x_i, Q^2) \, f_j(x_j, Q^2) \frac{d \sigma_F}{d V}^{ij}(x_i, x_j, Q^2)
\]
Luminosity determination in pp

Remember: \(10^{34} \text{ / cm}^2 \text{ / s} \approx 100 / \text{fb} \) per „year“!

a) from collider parameters:

\[ L \sim \frac{f \cdot N_p \cdot N_{-p}}{\sigma_x \cdot \sigma_y} \]

...not very precise (10%)...

b) via reference process:

\[ L = \frac{N_{\text{ref}}}{\sigma_{\text{ref}}} \]

...to be measured by detector (5%)...

known, large

(in)elastic forward scattering
strong inclusive dijet production

contributions at angles $< \pi$ from multi parton final states

0.15/fb 2002
electroweak FCNC $B_s \rightarrow \mu\mu$

2/fb 2007

background: $J/\Psi K$ ...

CDF II (2fb$^{-1}$)
$0.8 < \nu_{NN} < 0.95$

$0.95 < \nu_{NN} < 0.995$

$0.995 < \nu_{NN} < 1.0$

note: in 2/fb $> 10^{10}$ B's

neural net (muon id)

high detector resolution
electroweak  CKM  single top

0.9/ fb
2008

e+μ channel
1-2 b-tags
2-4 jets
DT > 0.65
= Decision Tree

\[ m_{\text{top}} \approx M(W, \text{tag1}) \text{ [GeV]} \]

b-tag via secondary vertex
searches long lived staus

\[ \text{GMSB: decay } \tilde{\tau} \rightarrow \tau \tilde{G} \text{ suppressed} \]

heavy charged particle traversing detector slowly

\[ \sigma = \frac{1 - \text{speed}}{\sigma_{\text{speed}}} \]

measured with scintillators in muon system