The Large Hadron Collider beauty Experiment

Precision measurements of loop-dominated B decays as possible probe for New Physics
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Slides of this lecture:
http://www.physi.uni-heidelberg.de/~menzemer/LHC08.html
Literature

General Particle Physics:

Jonathan Allday: “Quarks, Leptons and the Big Bang”
(entertaining, almost no formula, however informative)

David Griffiths: Introduction to elementary particle physics
(very good introduction, “a bit old” no modern developments)

B Physics:

(good intro to CKM physics (1st chapter), however status of 2001)


LHCb specific:

LHCb Technical Design Report (TDR), especially TDR 9
http://lhcb.web.cern.ch/lhcb/TDR/TDR.htm
Till 1977:

2 lepton families \((e, \nu_e, \mu, \nu_{\mu})\) & 2 quark families \((u, d), (c, s)\)

(+ antiparticles)

All sofar observed particles could be composed out of them.

Observation of \(Y(4S) = |b\bar{b}>\) at Fermilab: proton beam on fixed target experiment.
Top quark ($\sim 171$ GeV) too heavy to form bounded states. Decays immediately dominantly in: $t \rightarrow bW$

$b$ heaviest quark which forms mesons ($|q\bar{q}>$) & baryons ($|qqq>$)

Due to energy conversation, particle decay in lighter particles.

$\rightarrow$ B hadrons have large phase space for decay (many modes).
$b\bar{b}$ pair production (> 99.9%) (only exception: top decays)

- EM interaction @ $e^+e^-$ collider
e.g. LEP, SLAC, KEK

- strong interaction @ $p\bar{p}$ or $pp$ collider
e.g. Tevatron (Fermilab), LHC

$q\bar{q} \rightarrow b\bar{b}$ dominant at Tevatron
($\sqrt{s} = 1.98$ TeV)

$gg \rightarrow b\bar{b}$ dominant at LHC
($\sqrt{s} = 14$ TeV)
B Production

One low and one very high momentum parton produce heavy particles, however very high momentum partons are very rare.

→ heavy particle production via two partons of \( \sim \) same energy
→ heavy particles have little boost → central region

For light particles a low and a medium momentum parton work.
→ it is very unlikely that the two partons have same energy
→ light particles are produced in forward direction.

\[
2 \times m(b) \approx 10 \text{ GeV}
\]

\[
m(Higgs) > 114 \text{ GeV}
\]

\[
2 \times m(t) \approx 350 \text{ GeV},
\]

\[
m(\text{"New Physics"}) \approx 100 \text{ GeV} - 1 \text{ TeV}
\]

In \( pp/p\bar{p} \) collisions optimal B detectors are forward spectrometers!
$b\bar{b}$ Production x-Section

$\sim 10^{11}$ $b\bar{b}$ pairs per year at LHC running a nominal luminosity!

$B$ physics is high statistics physics!
B Hadronisation and Decay

Hadronisation:

B mesons: $B^+ = |\bar{b}u>$, $B^0_d = |\bar{b}d>$, $B^0_s = |\bar{b}s>$, $B_c = |\bar{b}c>$

B baryons: sofar discovered: $\Lambda_b = |udb>$, $\Xi_b = |dsb>$, $\Sigma^+_b = |usb>$

heavier ones should exist not yet discovered.

Hadronisation ratio (if enough center of mass energy available):

$B^+ : B^0 : B_s : \lambda_b = 0.4 : 0.4 : 0.1 : 0.09$

Other baryons have very small x-section

Decay:

Average lifetime of B hadrons $\sim 1.5$ ps

Decay into lighter quarks $\rightarrow$ transition to quarks of other families
$\rightarrow$ only possible via weak interaction
Decay of $\phi = |s\bar{s}\rangle$

**strong IA**

- $\phi$ transitions to $s\bar{u}\bar{s}$ and $K^-$
- $\bar{s}\bar{u}\bar{s}$ transitions to $s\bar{u}$ and $K^+$

**weak IA**

- $\phi$ transitions to $s\bar{u}\bar{s}$ and $K^-$
- $\bar{s}\bar{u}\bar{s}$ transitions to $s\bar{u}$ and $K^+$
- Weak decay by far dominant!

**EM IA**

- $\phi$ transitions to $s\bar{u}\gamma\bar{u}$ and $K^-$
- $\bar{s}\bar{u}\gamma\bar{u}$ transitions to $s\bar{u}$ and $K^+$

Quark sum identical in initial and final state!
Decay of $B^0 = |\bar{b}d>$

1 $b$ quark in initial state, 0 $b$ quarks in final state

→ only possible via weak interaction!

All $B$ decays are weak decays, however large phase space
→ long lifetime of 1.5 ps
Tons of Decay Modes ...

300 known $B^+$ decay modes (all listed in PDG)

decays for analysis of lifetime, CP violation, ...: $\text{BR} \sim 10^{-4} - 10^{-6}$

rare decays: $\text{BR} \sim 10^{-8}$, e.g. $B_s \rightarrow \mu^+\mu^-$

very rare decays: $\text{BR} \sim 10^{-10}$

(additional have to BR of B daughters into account)
Flavour Mixing

mass eigenstates ≠ eigenstates of weak interaction

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix}
= \begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

weak CKM matrix mass

CKM-Matrix fully determined via: 3 angles & 1 complex phase

⇒ 4 fundamental Standard Model parameters
B Physics: Test of the CKM Mechanism

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix}
= \begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

\((V_{tb} \sim 1)\)
Standard Model Quark sector extremely well understood:

- Very precise theoretical predictions for weak IA
- High statistic B decays give experimentally high precision measurements.

→ B physics: unique place to perform precision tests of the Standard Model (measurement of branching ratios, CP violation ...)

Any deviation from Standard Model expectation:
Unambiguous sign of “New Physics”
Precision $B$ physics as probe for New Physics in loop processes:

Many New Physics models predict deviations from SM predictions. Complementary to direct searches by ATLAS and CMS. Direct searches sensitive to particles up to 1 TeV. Indirect searches are sensitive to particles up to 10 TeV. (new particles in the loop are virtual)
Reminder: Quantum Mechanics

Interference Experiments

QM gives probability for arrival point at screen:

\[ P = |A_1 + A_2|^2 = |A_1|^2 + |A_2|^2 + 2\text{Re}(A_1^*A_2) \]

Interference!!

Take into account all possible paths, sum up amplitudes!
Examples from the Past

GIM Mechanism

Observed branching ratio $K^0 \rightarrow \mu^+ \mu^-$

$$\frac{BR(K_L \rightarrow \mu^+ \mu^-)}{BR(K_L \rightarrow all)} = (7.2 \pm 0.5) \times 10^{-9}$$

In contradiction with theoretical expectations in the 3 quark model

⇒ Glashow, Iliopolus, Maiani (1970):

Prediction of a $2^{nd}$ up type quark, additional Feynman graph cancels the “u box graph”
Examples from the Past

Indirect measurement of the Top quark mass at LEP

\[ P_{tot} = \sigma_{kad} = |A_1 + A_2 + A_3 + \ldots|^2 = \]
\[ = |A_1|^2 + |A_2|^2 + |A_3|^2 + 2 \text{Re} A_1^* A_2 + \ldots \]
\[ |A_1|^2 \gg |A_2|^2 \gg |A_3|^2 \gg \ldots \quad |A_1|^2 > 2 \text{Re} A_1^* A_2 \]

\[ A_2 = f(\sqrt{m_{top}}) \propto m_{top}^2 \quad A_3 = f(\sqrt{m_{Higgs}}) \propto \log m_{Higgs} \]
1994 at LEP ($\sqrt{s} = 91$ GeV): measurement of partial decay width of Z: $m(t) = 179 \pm 12/-9$ GeV/c$^2$

Top quark discovery 1995 at the Tevatron ($\sqrt{s} = 1.8$ TeV)
$m(t) = 178 \pm 4.3$ GeV/c$^2$;
Examples from the Past

Precision electro-weak physics @ LEP and the Tevatron:
e⁺e⁻ B-Fabriken

B Produktion in p¯p (pp) Kollisionen
Advantage at $pp$ collider

$e^+ e^-$

Babar/Belle

$\sqrt{s}=Y(4S)=10.6$ GeV

(limit energy due to synchrotron radiation!)

$B^0$, $B^+$

decay length: $\sim 200$ $\mu$m

(produced almost at rest)

$\sqrt{s}=14$ TeV

heavy & excited B states

$B_c$, $B_s$, $\Lambda_b$, $\Xi_b$, $B^*$, ...

decay length: $\sim 2$ cm

$\rightarrow$ good proper time resolution

center-of-mass energy

production rate

$10^9 \ b\bar{b}$ pairs/y

$10^{11} \ b\bar{b}$ pairs/y
Challenge at Hadron-Collider

Babar/Belle

only $B \bar{B}$ daughter tracks

simple selection criteria

isotrop $b \bar{b}$ events

e.g. LHCb

about 400 additional tracks

$\sigma(pp \rightarrow X) = 1000 \sigma(pp \rightarrow b\bar{b}X)$

Trigger $\equiv$ key to B-Physics
B Physics at LHC

Dedicated B Experiment

B Production at LHC:

- $pp @ 14 \text{ TeV} \rightarrow \sigma_{bb} \approx 500 \mu b$
- 40% $B^0/B^+$, 10% $B_s$, 10% $b$-baryons
- but 40 MHz IA rate $\sigma_{\text{inel}} \approx 80 \text{ mb}$
The LHCb Cavern

- Shielding wall (against radiation)
- Offset interaction point (to make best use of existing cavern)
- Electronics + CPU farm
- Detectors can be moved away from beam-line for access
Typical $B$ Event

- decay length $L$ typically $\sim 7$ mm
- momentum of decay products: 1-60 GeV
- signal event very background like ...

⇒ high vertex resolution to identify PV & SV
⇒ good momentum resolution to measure proper time ($c\tau = \frac{L}{mp}$)
⇒ particle ID to select decay products
  (background mixture: 80% pions, 10% kaons, 5% protons)
Berilium Beam Pipe

Particles in forward direction traverse beam pipe under large angle.

→ Multiple scattering, imprecise vertex resolution.

Replace “standard” beam pipe by ultra fine foil in IA region.

Vertex detector (directly at beam pipe) as well in vacuum.
10 mrad cone to guide particles out of LHCb detector w/o IA.
25 mrad cone for particles which are reconstructed but not in Velo
Extremely thin foil between both cones, where particles leave
beam pipe. → vertex detector is as well in vacuum.
2 halves, each 21 silicon discs; track resolution $\approx 30 \mu m$.

Detector halves will be moved before each run (fill of proton bunches in LHC) in open position (10 cm from beam) and be closed (8 mm) once beam is stable. Change of position $< 1 \mu m$. 
Angle of tracks before and after magnet $\rightarrow$ momentum.
Plan half of the runs with positive and half with negative polarity.
Important for asymmetry measurements!
T stations important to guide to calorimeters & muon chambers.
RICH Detectors

Kaon, pion & proton ID for low momentum tracks (10-100 GeV);
unique to LHCb.
RICH detectors are the specialized detectors to allow charged hadron (π, K, p) identification.

Important for B physics, as there are many hadronic decay modes e.g.: $B_s \rightarrow D_s^- K^+ \rightarrow (K^+ K^- \pi) K^+$

Since $\sim 7\times$ more π than K are produced in pp events, making the mass combinations would give rise to large **combinatorial background** unless K and π tracks can be separated

Rich 1:
Aerogel: $n = 1.03$ (p: 1-10 GeV)
$C_4F_{10}$: $n = 1.0014$ (p: < 60 GeV)

Rich 2:
$CF_4$: $n = 1.0005$ (p: < 100 GeV)
RICH Detectors

No RICH

\[ \text{purity 13\%} \]

With RICH

\[ \text{purity 84\% efficiency 79\%} \]

\[ \text{purity 67\% efficiency 89\%} \]

\[ \text{BS} \rightarrow \text{KK} \]

\[ \text{BS} \rightarrow \text{DSK} \]
Trigger System

Calorimeter
Muon system
Pile-up system

Level-0 Hardware: (4μs)
High p_T μ, e, h, γ signatures
1.1, 2.8, 3.6, 2.6 GeV

PC Farm:
Higher Level Trigger (full event info)
High Level Trigger

Write out at 2 kHz:
less read out channels and events less busy $\rightarrow$ less data/event
(50 kB) compared to CMS and ATLAS

Select $B$ daughter tracks by requiring large impact parameter (or secondary vertex)

For rare $B$ decays, largest background comes from other $B$ decays
$\rightarrow$ full $B$ reconstruction on trigger level for some decay modes.
The LHCb Experiment
**B Physics & LHC Detectors**

**ATLAS/CMS:**
- optimized for high-$p_T$ discovery
- central detectors, $|\eta| < 2.5$
- $B$ physics using muon triggers
- aim for highest possible luminosity:
  - run at $L \rightarrow 2 \times 10^{33} \text{cm}^{-2}\text{s}^{-1} \ n=5$, later $L \rightarrow 10^{34} \text{cm}^{-2}\text{s}^{-1} \ n=25$

**LHCb:**
- designed to maximize $B$ acceptance
  - excellent vertexing and particle ID
- forward spectrometer, $1.9 < \eta < 4.9$
- “low” $p_T$ & impact parameter triggers
- Luminosity tuneable by adjusting beam focus:
  - run at $L \rightarrow 2 \times 10^{32} \text{cm}^{-2}\text{s}^{-1} \ n=0.5$