Plan

- Kaon physics and SM construction (bit of history)
- Establishing SM experimentally
- Looking for breakdown of SM

Hard to cover everything in details in three lectures, some details are offloaded to exercises
Outline – lecture 3

- Why we need new physics
- Where to look for new physics
  - CPV in $B_s \rightarrow J/\psi \phi$
  - $b \rightarrow s l^+ l^-$
  - $B_s \rightarrow \mu \mu$
  - $B^+ \rightarrow \tau \nu$
  - Charm mixing and CPV
Why new physics?

- What we saw up to now is extreme success of SM
- So why we are so excited about new physics if we can describe all measurements without it?
- SM does not tell why we have three generations (do we?)
- SM does not tell anything about masses of fermions
- Way SM works needs quite some fine tuning (final result is often difference between two huge numbers)
- Higgs mass in SM is not really stable
- Cosmology argument:
  - No candidate for Dark matter
  - Not possible to generate current matter-antimatter asymmetry in Universe
Sakharov

- In 1967 Andrei Sakharov formulated three necessary conditions to produce baryon-antibaryon asymmetry
  - Baryon number violation
  - CP violation
  - Interactions out of equilibrium

- Surprisingly SM can best cope with baryon number violation – but non-perturbative QCD effect

- CP violation exists in SM, but definitely not large enough

- In SM there is nothing which could drive system out of equilibrium

- Those are in my view strongest needs for new physics
Typical NP scenarios

- SUSY – most popular
  - Each SM particle gets its SUSY partner
  - Squarks can also mix (similar to quarks) and provide additional phases

- Fourth generation
  - Puts in additional fermion generation
  - Not as appealing as SUSY and cannot answer all questions, but can make huge difference on CPV

- Technicolor
  - Gets more popular again as it can dynamically create Higgs like effect without need of Higgs
### NP DNA

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<tr>
<th>Observation</th>
<th>AC</th>
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Table 2: “DNA” of flavour physics effects [55] for the most interesting observables in a selection of SUSY and non-SUSY models. ⭐⭐⭐⭐ signals large effects, ⭐⭐ visible but small effects and ⭐ implies that the given model does not predict sizable effects in that observable.

Buras, arXiv:0910.1032v1
$B_s \rightarrow \mu^+ \mu^-$

- SM prediction $\text{Br} = (3.2 \pm 0.2) \times 10^{-9}$
- Extremely sensitive to new physics
- Already with limits 10 times above SM one could severely restrict NP models

Background plot is from Buchmuller et al arXiv:0907.5568

Blue regions are allowed regions for given measurement.

Experiments
Experiments
LHCb is not small one
Main experimental issues

- As decay is rare, main issue is to control background
- Special care is needed for $B \rightarrow h h'$ decays which peak in same place as signal
- Selection ranges from cut based (CMS) to BDT (LHCb) to NN (CDF, D0)
$B_S \rightarrow \mu^+ \mu^-$

CMS 2011, 1.14 fb$^{-1}$, Preliminary

$\sqrt{s} = 7$ TeV

Combinatorial background

$B \rightarrow hh$ misid background

$0.1 \pm 0.1$ events in each of 4 BDT bins

Data

Signal with SM BR
$B_s \rightarrow \mu^+ \mu^-$

CMS 2011, 1.14 fb$^{-1}$, Preliminary

$\sqrt{s} = 7$ TeV

Candidates / 0.025 GeV

- $B_0^0$ signal window
- $B^0$ signal window

Barrel

Endcap

$B \rightarrow hh$ misid background

0.1 $\pm$ 0.1 events in each of 4 BDT bins

Combinatorial background

Data

Signal with SM BR

LHCb preliminary

300 pb$^{-1}$
$B_s \rightarrow \mu^+ \mu^-$

(a) DØ, 6.1 fb$^{-1}$

$0.98 \leq \beta \leq 1$

(b) DØ, 6.1 fb$^{-1}$

$5.2 \text{ GeV} \leq m_{\mu\mu} \leq 5.5 \text{ GeV}$

Candidates per 24 MeV/c$^2$

$0.70 < \nu_N < 0.76$

$0.76 < \nu_N < 0.85$

$0.85 < \nu_N < 0.90$

$0.90 < \nu_N < 0.94$

$0.94 < \nu_N < 0.97$

$0.97 < \nu_N < 0.987$

$0.987 < \nu_N < 0.995$

$\nu_N > 0.995$

Background

+Signal (SM x 5.6)
$B_s \rightarrow \mu^+ \mu^-$

- D0, LHCb and CMS compatible with pure background (plus tiny SM signal)
- CDF sees excess of events above background
- Results:
  - $B(B_s^0 \rightarrow \mu^+ \mu^-) < 5.1 \times 10^8$ @ 95% C.L. (D0)
  - $B(B_s^0 \rightarrow \mu^+ \mu^-) < 1.9 \times 10^8$ @ 95% C.L. (CMS)
  - $B(B_s^0 \rightarrow \mu^+ \mu^-) < 1.5 \times 10^8$ @ 95% C.L. (LHCb)
  - $B(B_s^0 \rightarrow \mu^+ \mu^-) < 3.9 \times 10^8$ @ 95% C.L. (CDF)
  - $B = (1.8^{+1.1}_{-0.9}) \times 10^{-8}$ (CDF interpreting excess as signal)
- About factor 5 above SM
- Expect to come close to SM at latest end of next year
CPV induced by $B_s$ mixing

- CPV stems from interference of decays with and w/o mixing
- In SM it is expected to be tiny – Effect of almost real $V_{ts}$
- Needs some care in interpretation of what is really measured
- Up to now measured with $B_s \to J/\psi \phi$ and $B_S \to J/\psi f_0(980)$
- Difficult due to large $\Delta m_s \sim 17.8$ ps$^{-1}$
- Needs very good time resolution
Master formulas of time evolution

\[
\Gamma(M(t) \rightarrow f) = N_f |A_f|^2 e^{-\Gamma t} \left\{ \frac{1 + |\lambda_f|^2}{2} \cosh \frac{\Delta \Gamma t}{2} + \frac{1 - |\lambda_f|^2}{2} \cos(\Delta M t) \\
-\text{Re} \lambda_f \sinh \frac{\Delta \Gamma t}{2} - \text{Im} \lambda_f \sin(\Delta M t) \right\}, \tag{50}
\]

\[
\Gamma(M(t) \rightarrow \bar{f}) = N_f |A_f|^2 \frac{1}{1-a} e^{-\Gamma t} \left\{ \frac{1 + |\lambda_f|^2}{2} \cosh \frac{\Delta \Gamma t}{2} - \frac{1 - |\lambda_f|^2}{2} \cos(\Delta M t) \\
-\text{Re} \lambda_f \sinh \frac{\Delta \Gamma t}{2} + \text{Im} \lambda_f \sin(\Delta M t) \right\}. \tag{51}
\]

\[
\Gamma(M(t) \rightarrow \bar{f}) = N_f |\bar{A}_f|^2 e^{-\Gamma t} (1-a) \left\{ \frac{1 + |\lambda_f|^2}{2} \cosh \frac{\Delta \Gamma t}{2} - \frac{1 - |\lambda_f|^2}{2} \cos(\Delta M t) \\
-\text{Re} \frac{1}{\lambda_f} \sinh \frac{\Delta \Gamma t}{2} + \text{Im} \frac{1}{\lambda_f} \sin(\Delta M t) \right\}, \tag{53}
\]

\[
\Gamma(M(t) \rightarrow \bar{f}) = N_f |\bar{A}_f|^2 e^{-\Gamma t} \left\{ \frac{1 + |\lambda_{\bar{f}}|^2}{2} \cosh \frac{\Delta \Gamma t}{2} + \frac{1 - |\lambda_{\bar{f}}|^2}{2} \cos(\Delta M t) \\
-\text{Re} \frac{1}{\lambda_{\bar{f}}} \sinh \frac{\Delta \Gamma t}{2} - \text{Im} \frac{1}{\lambda_{\bar{f}}} \sin(\Delta M t) \right\}. \tag{54}
\]
Decay $B_s \to J/\psi f_0$

- This final state is CP-eigenstate
- In master formula this (with some additional assumptions) means $|\lambda_f|=1$
- For $B_s$ the $a$ is at most ~ 1% and $\Delta \Gamma$ is in principle non-zero

\[
\frac{1 + \cos(\phi)}{2} e^{-\Gamma_H t} + \frac{1 - \cos(\phi)}{2} e^{-\Gamma_L t} - e^{-\Gamma t} \sin(\phi) \sin(\Delta m t)
\]

\[
\frac{1 + \cos(\phi)}{2} e^{-\Gamma_H t} + \frac{1 - \cos(\phi)}{2} e^{-\Gamma_L t}
\]
Decay $B_s \rightarrow J/\psi f_0$ - CDF

CDF Run 2 \quad L = 3.8 \text{ fb}^{-1}

- Data
- Fit projection
- Signal
- Long lived background
- Short lived background

**Results:**

- Lenz, Nierste
  \[ 1.63 \pm 0.03 \text{ ps} \]

- HFAG
  \[ 1.544 \pm 0.041 \text{ ps} \]

- CDF $5.2 \text{ fb}^{-1}$ $\beta_s$
  \[ 1.622 \pm 0.068 \text{ ps} \]

- CDF $B_s \rightarrow J/\psi f_0(980)$
  \[ 1.70^{+0.12}_{-0.11} \pm 0.03 \text{ ps} \]
Decay $B_s \rightarrow J/\psi f_0$ - LHCb

- Takes input of $\Gamma$ and $\Delta \Gamma$ from LHCb $B_s \rightarrow J/\psi \phi$ result
- Consistent with SM

$\phi_s = -0.44 \pm 0.44 \pm 0.02$
Decay $B_s \rightarrow J/\psi \phi$

- This decay was first to study as it has higher signal yield.
- Complication arises from the fact that both $J/\psi$ and $\phi$ are have spin 1 => mixture of CP-even and CP-odd.
- Need additional work (angular analysis) to statistically distinguish two.
- On the other hand it also helps to gain additional sensitivity from interference.
- There are many details to care about, much beyond scope of this lecture.
- If there is interest, in some free time I can walk you through CDF analysis to full depth.
Decay $B_S \to J/\psi \phi$

CDF Run II Preliminary: $2.8 \text{ fb}^{-1}$ + DØ $2.8 \text{ fb}^{-1}$

DØ Run II, $8 \text{ fb}^{-1}$ Preliminary

$\Delta M_s \int 17.77 \pm 0.12 \text{ ps}^{-1}$

$\Delta \Gamma_s$ ($\text{ps}^{-1}$)

$\phi_s^{J/\psi\phi}$ (rad)

$\beta_s$ (rad)

$\Delta \Gamma$ ($\text{ps}^{-1}$)

68% CL
95% CL
99% CL

SM $p$-value = 30%

SM prediction

95% CL
88% CL

8/Sept/2011
**B_s → J/ψφ: ΔΓ_s vs. φ_s**

Most precise measurement of φ_s
- φ_s = 0.13 ± 0.18 (stat) ± 0.07 (syst) rad
- Consistent with SM

4 σ Evidence for ΔΓ_s ≠ 0:
- ΔΓ_s = 0.123 ± 0.029 (stat) ± 0.008 (syst) ps⁻¹
- Γ_s = 0.656 ± 0.009 (stat) ± 0.008 (syst) ps⁻¹

(Lenz, Nierste arXiv:1102.4274)
$b\rightarrow s l^+ l^-$
$b \rightarrow s l^+ l^-$

CDF Run II Preliminary $L = 6.8\, fb^{-1}$

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$
- Data
- SM

$\frac{dB}{dq^2} \left( 10^{-7} / \text{GeV}^2 c^2 \right)$

$q^2$ (GeV$^2$/c$^2$)

$\frac{d\Gamma/dq^2} {10^{-7} \cdot c^4 / \text{GeV}^3}$

$q^2$ [GeV$^2$/c$^4$]
$b \rightarrow s l^+ l^-$

CDF Run II Preliminary $L=6.8 \text{fb}^{-1}$
$b \rightarrow s l^+ l^-$

CDF Run II Preliminary $L=6.8\text{fb}^{-1}$

- $B \rightarrow K^* \mu^+ \mu^-$
  - Data
  - SM
  - $C_\gamma = -C_{SM}$

$LHCb$ Preliminary

- Theory
- $LHCb$

$q^2 (\text{GeV}^2/c^2)$

$A_{FB}$

$J/\psi$ and $(2S)$

(a)
\[ \text{CDF Run II Preliminary } L = 6.8 \text{ fb}^{-1} \]

**Yield:** 24 ± 5  
**Mass:** 5621 ± 6 MeV/c\(^2\)

\[ \Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^- \]

+ Data  
- Total Fit  
   - Signal  
   - Background

\[ \text{B(}\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-) = [1.73 \pm 0.42 \text{(stat)} \pm 0.55 \text{(syst)}] \times 10^{-6} \]

\[ \text{B(B_s^0 \rightarrow } \phi \mu^+ \mu^-) = [1.47 \pm 0.24 \text{(stat)} \pm 0.46 \text{(syst)}] \times 10^{-6} \]
Charm mixing and CPV

- Basic physics is same as in B mixing
- Important because it tests down type quarks in loops
- Complementary to B mixing
- CP violation in SM is very small
  - Mixing in first two generations is real
  - Bottom quark contribution strongly CKM suppressed
- Theory predictions difficult as long distance contributions play important role
- Experiments resolving mixing difficult because of very slow mixing
Mixing in Standard Model is Very Small

- Off-diagonal mass matrix element – two leading terms:
  \[ \Delta C = 2 \text{ (short-range)} \]
  \( \Delta C \) contributes mostly to \( x \)

\[ \Delta m / \Gamma \]

Hadronic intermediate states (long-range)

\[ \Delta C = 1 \]

Difficult to compute (need to know all the magnitudes and phases, ...)

Most computations predict \( x \) and \( y \) in the range \( 10^{-3} \text{--} 10^{-2} \) and \( |x| < |y| \)

Recent predictions: \( |x| \leq 1\% \), \( |y| \leq 1\% \)

(consistent with current observation)

\( x = \Delta m / \Gamma \)
\( y = \Delta \Gamma / 2 \Gamma \)

Down-type quarks in loop:

- \( b \): CKM-suppressed (\( |V_{ub}V_{cb}|^2 \))
- \( d, s \): GIM-suppressed

\[ x \propto \left( m_s^2 - m_d^2 \right) / m_c^2 \sim 10^{-5} \]

(almost 2 orders of magnitude less than current sensitivity)

\( x_D, y_D \) at 1\% consistent with SM, BUT

\( CPV \) at \( 10^{-3} \) levels would be signal for NP

Brian Meadows

Charm mixing - technique

CDF II Preliminary (1.5 fb⁻¹)

Events / 5 μm

0 100 200 300 400 500

$d_0 (\mu m)$

BaBar
3-D flight path
$L \sim 200 \, \mu m$
$\sigma_L \sim 100 \, \mu m$

beam spot interaction
Wrong Sign (WS) Decays \( D^0 \rightarrow K^+ \pi^- \)

- The WS decay rate \( R_{WS} \) is:
  \[
  R_{WS} = e^{-\Gamma t} |A_f|^2 \left[ 1 + \lambda_f y'_D (\Gamma t) + \frac{|\lambda_f|^2}{4} (x'^2_D + y'^2_D) (\Gamma t)^2 \right]
  \]
  - Direct decay
  - Interference
  - Decay through Mixing

- Since \(|\lambda_f| >> 1\), all three terms are comparable

- For “right-sign” (RS) decays \( D^0 \rightarrow K^- \pi^+ \) though, \(|\lambda_f| << 1\), so 2nd two terms are negligible and \( R_{RS} \) is approximately exponential.
  \[
  R_{RS} \approx e^{-\Gamma t} |A_f|^2
  \]


Brian Meadows
Charm mixing in DCS decays
Evidence for Mixing in $D^0 \rightarrow K^+\pi^-$

Mixing seen by Babar and CDF in time-dependence of the $R_{WS}/R_{RS}$ ratio

Belle result was the most sensitive, BUT evidence for mixing not significant!
Charm mixing - global status

\[ x = \frac{\Delta m}{\Gamma} \]
\[ y = \frac{\Delta \Gamma}{2 \Gamma} \]
Charm CPV

- Concentrate on $D^0$ here
- What is usually done is time integrated measurement in common final state
  - Tagged by $D^*$
- Time integrated measurements sensitive also to time-dependent CPV as oscillation is very slow

\[
A_{\text{CP}}(h^+h^-) = \frac{\Gamma(D^0 \rightarrow h^+h^-) - \Gamma(D^0 \rightarrow h^+h^-)}{\Gamma(D^0 \rightarrow h^+h^-) + \Gamma(D^0 \rightarrow h^+h^-)}.
\]

\[
A_{\text{CP}}(h^+h^-) = a_{\text{CP}}^{\text{dir}}(h^+h^-) + \int_0^\infty A_{\text{CP}}(t)D(t)dt \approx a_{\text{CP}}^{\text{dir}}(h^+h^-) + \frac{(t)}{\tau} a_{\text{CP}}^{\text{ind}}(h^+h^-).
\]

- Method uses also $K\pi$ decays to measure detector asymmetry
- LHCb has additional complication of production asymmetry
CDF result

CDF Run ll Preliminary $\int L \, dt = 5.94 \text{ fb}^{-1}$

\begin{align*}
\frac{a_{\text{CP}}^{\text{dir}}(D^0 \rightarrow \pi^+\pi^-)}{\%} & \quad \frac{a_{\text{CP}}^{\text{dir}}(D^0 \rightarrow K^+K^-)}{\%} \\
\text{CDF 2011} & \quad \text{CDF 2011} \\
\text{BaBar 2008} & \quad \text{BaBar 2008} \\
\text{Belle 2008} & \quad \text{Belle 2008} \\
\mathbf{\bullet} \text{ No CPV point} & \quad \mathbf{\bullet} \text{ No CPV point} \\
& \quad \text{68\%-95\% C.L.} \\
\end{align*}
LHCb charm CPV

- Measure difference $A(KK) - A(\pi\pi)$
- Detector and production asymmetry cancels in first order
- Mainly sensitive to direct CP violation as indirect is independent of final state

\[ A_{CP}(KK) - A_{CP}(\pi\pi) = (-0.275 \pm 0.701 \pm 0.25)\% \]
$B \rightarrow \tau \nu$

- SM branching fraction given by
  \[ BF = \frac{g_F^2 m_B}{8\pi} m^2 \left(1 - \frac{m^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B \]

- One can extract $f_B$ or $|V_{ub}|$

- SM $BF = 1.20 \pm 0.25 \times 10^{-4}$

- Practically only B-factories thanks to clean environment

- After reconstructing tag $B$ and all charged particles from signal $B$, only neutrinos missing
$B \rightarrow \tau \nu$

**Semileptonic**

- $3.8\sigma$

**Hadronic**

- $3.5\sigma$
- $S: 1.65^{+0.38}_{-0.37} \pm 0.35 \times 10^{-4}$
- $H: 1.79^{+0.56}_{-0.49} \pm 0.46 \times 10^{-4}$

hep-ex/0809.3834,
PRL 97, 251802 (2006)

- $S: 1.7 \pm 0.8 \pm 0.2 \times 10^{-4}$
- $H: 1.8^{+0.9}_{-0.8} \pm 0.4 \pm 0.2 \times 10^{-4}$

PRD 81, 051101 (2010)
PRD 77, 011107 (2008)

**$B^+ \rightarrow \tau^+ \nu$**

- $2.3\sigma$
- $2.2\sigma$
$B \rightarrow \tau \nu$

- Naive average of exp. results
  $BF_{\text{exp}} = 1.73 \pm 0.35 \times 10^{-4}$

- SM prediction
  $BF_{\text{SM}} = 1.20 \pm 0.25 \times 10^{-4}$

- Effect of charged Higgs
  $BF_{\text{exp}} = BF_{\text{SM}} \times r_H$
  
  \[ r_H = \left( 1 - \frac{m_B^2 \tan^2 \beta}{m_H^2} \frac{1}{1 + \epsilon_0 \tan \beta} \right)^2 \]

- For Type-II 2HDM $\epsilon_0 = 0$
Global status of the triangle

Globally no large discrepancy, but few tensions exist
Final remarks

- Lot of work was done in last few years to discover new physics
- Many places where some tension with SM was observed with small statistics
- Latest results from this summer now agree quite well with SM
- Despite the agreement with SM, there is still quite some room for new physics