News from the flavour frontier - heavy quark physics at the LHC

• Introduction
• Production (in brief)
• Decays
• Conclusions

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Flavour Physics is Important

Many of open questions in Standard Model (SM) found in flavour sector:

- Why are there 3 generations? (and is it only 3?)
- What determines the extreme hierarchy of fermion masses?
- What determines the elements of the CKM matrix?
- What is the origin of CP violation (CPV)?

Progress in flavour physics may help understand open questions in cosmology - SM CPV insufficient to explain matter/antimatter asymmetry

Flavour physics is a proven tool of discovery:

- Kaon mixing, $\text{BR}(K^0_L\rightarrow\mu\mu)$ & GIM $\rightarrow$ prediction of charm
- CP violation $\rightarrow$ need for a third generation
- B mixing $\rightarrow$ mass of top is very heavy
- SUSY parameter space already severely constrained by e.g. $b\rightarrow s\gamma$

Precise studies of flavour observables are an excellent way to look for New Physics!
Reign of the $\Upsilon(4S)$ machines

For most of the last decade flavour physics = BABAR + Belle, and $e^+e^-$ was king

BABAR and Belle performed many beautiful and sophisticated analyses, making use of their pristine environment. But BABAR and Belle are no more. Instead…
Barbarians at the gate

Many flavour physicists have been wary about the onset of the LHC.

A ‘dark ages’ in which will be forgotten the sophistications of the previous era?

I scorn your effete ways!
I lay waste to your inclusive, low background reconstructions!
I bring desolation to all that is not high-$p_T$ with leptons in the final state!

But there is no need to worry:

• Tevatron has already demonstrated flavour physics possible in hadronic environment
• Large cross-sections, high statistics...
• ...but also clean measurements possible...
• and also $B_s$, $B_c$ and baryon studies!
LHCb Essentials

LHCb optimised for flavour physics. Various attributes distinguish it from Tevatron detectors + ATLAS/CMS:

- **Dedicated heavy flavour trigger**
  - L0: hardware trigger firing on high $p_t$ hadrons and muons (~few GeV/c)
  - HLT: software trigger exploiting, in particular, tracking and vertexing. Outputs at 3 kHz
    → Efficient for hadronic B and D decays, as well as leptonic channels

- **Very precise vertexing**
  - VELO (planes of forward silicon) approach to within 8mm of beam

- **Hadron identification**
  - Two RICHes provide good $\pi/K$ separation over $2 < p < 100$ GeV/c

- **LHCb design luminosity << maximum design luminosity of machine**
  - LHCb already operating at (even above!) design luminosity ($2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$)
LHCb data taking

LHCb collected 37 pb\(^{-1}\) in 2010, and so far 460 pb\(^{-1}\) in 2011

2011 analyses presented today use up to \(-330\) pb\(^{-1}\)

Luminosity levelling delivers \(-constant\) operation at \(-3 - 3.5 \times 10^{32}\) cm\(^{-2}\) s\(^{-1}\)
Heavy Flavour Production

- Onia
- Exotics
- Open heavy flavour
Onia production

Big challenge to understand mechanism of onia production: colour single model, octet model, evaporation model...? Measurements from all 4 LHC experiments*:

* also see ALICE, arXiv:1105.0380

More precise than theory (modulo polarisation assumption)! Need new observables:

- more studies of higher states, e.g. $\Psi(2S)$, $\chi_c$ – some available already
- polarisation measurements – a powerful discriminant. Coming soon!
Radiative decays of $\chi_c$ states

First studies of radiative decays $\chi_c \rightarrow J/\Psi \gamma$! Challenge is to resolve $\chi_{c1}$ vs $\chi_{c2}$

Using tracks from $\gamma$ conversions

ECAL based approach

First results for relative production of $\chi_{c2}$ vs $\chi_{c1}$ are not in good agreement with NLO NRQCD predictions
Learning about exotics: X(3872)

LHC experiments are starting to study the X(3872) - observation, xsection & mass:

Ratio of inclusive X(3872) to Ψ(2S) production times branching ratio for J/Ψπ+π− decay mode

\[ R = 0.087 \pm 0.017 \text{(stat.)} \pm 0.009 \text{(syst.)} \]

for \( p_T(X) > 8 \text{ GeV/c} \) and \(|y(X)| < 2.2 \) (2010 data).

With 2011 data it will be possible to perform very precise mass measurements as well as angular studies* in B→X(3872)K to learn about the J^{PC} of the X(3872)

LHCb inclusive 2010 measurements:

\[ M_{X(3872)} = 3871.96 \pm 0.46 \text{(stat)} \pm 0.10 \text{(syst.) MeV/c}^2 \]

\[ \sigma_{X(3872)} \times BR(X(3872) \rightarrow J/\Psi\pi^+\pi^-) = 4.74 \pm 1.10 \text{(stat)} \pm 1.01 \text{(syst.) nb} \]

* see LHCb-PUB-2010-003
Search for the X(4140)

Studies of other possible exotics are underway.

CDF reported observation of narrow structure, X(4140), in the m(J/ΨK+K−)-m(J/Ψ) spectrum in $B^+\rightarrow J/Ψ\phi K^+$ events [arXiv:1101.6058]. LHCb now has a large sample of these decays.

$LHCb$ preliminary $376\text{ pb}^{-1}$

$B^+\rightarrow J/Ψ\phi K^+$

$\sim 360$ decays

(c.f. 115 for CDF in $6\text{ fb}^{-1}$)

Background model is 3-body phase space convolved with resolution

$LHCb$ does not confirm presence of X(4140).

2.4σ tension with CDF (using this bckgd model)
b-hadron production

B production studied with displaced J/ψ tag (ATLAS, CMS, LHCb), D+μ tag (LHCb), fully reconstructed J/ψX states (LHCb, CMS) and lepton and dilepton tags (CMS)

New CMS dimuon study
μ’s with $p_T > 4$ GeV, $|\eta| < 2.1$.
Fit to IP distributions.

\[ \sigma(pp \rightarrow b\bar{b}X \rightarrow \mu\mu Y) = 26.18 \pm 0.14 \text{ (stat.)} \]
\[ \pm 2.82 \text{ (syst.)} \pm 1.05 \text{ (lumi.)} \text{ nb} \]

All measurements reasonably well described by theory (FONLL, MC@NLO) – an achievement!
b-production: going deeper

Other observables under study (e.g. $B\bar{B}$ correlations [CMS, JHEP 1103 (2011) 136])

LHCb has measured the fragmentation fractions: the relative rates of $B^+, B^0, B_s, \Lambda_b, \ldots$

Two complementary approaches:

1. ratio of related hadronic decays, e.g. $B^0 \rightarrow D^- K^+$ and $B_s \rightarrow D_s \pi^+$ [arXiv:1106.4436, sub. to PRL]

2. semi-leptonic analysis with $D^0 \mu X$, $D^+ \mu X$, $D_s \mu X$ & $\Lambda_c \mu X$ events and accounting for cross-feeds [LHCb-CONF-2011-028]

Consistent results for $B_s/B^0$ fragmentation ratio, $f_s/f_d$, which thus can be combined:

$$\langle f_s / f_d \rangle_{LHCb} = 0.267^{+0.021}_{-0.020}$$

$f_s/f_d$ not a priori a ‘universal’ number, but agreement nonetheless seen with other measurements:

$$\langle f_s / f_d \rangle_{LEP} = 0.271^{+0.027}_{-0.027}$$

Necessary input for e.g. BR($B_s \rightarrow \mu \mu$)!
Charm and beauty hadron decays

• Charm physics – Cinderella goes to the ball
• Precise CKM metrology – the gateway to $\gamma$
• $A_{FB}$ in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
• Two-body charmless B decays
• New observations in b-baryon decays (for examples of new $B_s$ and $B_c$ decays see backups)
• Hot topics in the $B_s$ sector
  - CPV in $B_s$-$B_s$ oscillations
  - $B_s \rightarrow \mu^+ \mu^-$

B-factory domain

Beyond the $\Upsilon(4S)$
Cinderella goes to the ball: the search for CPV in charm

Charm physics was regarded as poor relation of flavour studies – this has been changed by discovery of mixing

• Mixing parameters x,y are small (~1%) but still larger than anticipated. Any CP violating effects in mixing (SM or NP) are driven by these parameters.

Real incentive to look for CPV in D mixing, which in SM is negligible, but can be enhanced in many models

• Direct CPV best looked for in Singly Cabibbo suppressed decays, where gluonic Penguins are significant. Here it is possible even SM could generate a signal!

The 6.5 mb cross-section means that charm is abundant at LHC, but can measurements be performed with these low $p_T$ decays in this environment?
Measurement of $A_Γ$ at LHCb

Search for non-zero value of $A_Γ$ is one of most important ways to search of CP-violation in charm mixing

Preliminary $A_Γ$ measurement now available from LHCb using 28 pb$^{-1}$ of 2010 data, using $D^*\rightarrow D^0\pi$, $D^0\rightarrow K^+K^-$ decays

Two main challenges in time-dependent charm studies at LHC:

- Understand ‘pollution’ to prompt charm sample coming from $B\rightarrow DX$
- Understand lifetime trigger acceptance

Preliminary result:

$A_Γ = (-0.59 \pm 0.59 \pm 0.21) \times 10^{-2}$

c.f. world average: $0.12 \pm 0.25$

Recall this with only fraction of 2010 data...

Obtained event-by-event in data!
Direct CPV search at LHCb

Perform model independent binned CPV search in singly Cabibbo suppressed $D^+ \rightarrow K^- K^+ \pi^-$ events

- Normalise $D^+$ vs $D^-$ to remove production asymmetries
- Use a resonance motivated binning & a uniform binning
- Look for statistically significant difference in $D^+$ vs $D^-$ bin contents (method based on PRD 80 (2009) 096006)
- Look for fake CPV in sidebands and control modes

No evidence of CPV for signal in any binning

Cabibbo favoured control modes (no CPV expected)

Same topology $D_s^+ \rightarrow K^+ K^- \pi^+$

No fake CPV seen – data & method very robust against biases!

Paper in preparation

Compare with 43k events in BABAR 80 fb$^{-1}$ study [PRD 71 (2005) 091101 (R)]

$37 \text{ pb}^{-1}$

$370k$ decays

$37 \text{ pb}^{-1}$

$10x$ more abundant $D^+ \rightarrow K^- \pi^- \pi^+$

LHC Heavy Flavour Physics
EPS 2011, Grenoble
Good prospects for 2011 charm studies

\[ D^+ \rightarrow K^+ K^- \pi^+ \]
\[ D_s^+ \rightarrow K^+ K^- \pi^+ \]
\[ D^{*+} \rightarrow D^0(K^+K^-)\pi^+ \]
\[ \Delta m (\text{MeV/c}^2) \]

LHCb Preliminary
\[ \sqrt{s} = 7 \text{ TeV Data} \]
220 pb\(^{-1}\)

LHCb Preliminary
195 pb\(^{-1}\)

LHC Heavy Flavour Physics
EPS 2011, Grenoble
Precision CKM-metrology: the next challenge

B-factories (& others) have done a great job in mapping out unitarity triangle. But progress needs improved knowledge of angle $\gamma$ (a.k.a. $\phi_3$).

Look in $B^\pm \rightarrow DK^\pm$ decays using common mode for $D^0$ & $\bar{D}^0$

$\rightarrow \gamma$ sensitive interference

$\rightarrow$ different rates for $B^+$ & $B^-$ (CPV!)

To *maximise* interference look for mode *suppressed* for $D^0$ & *favoured* for $\bar{D}^0$

e.g. $D^0 \rightarrow K^+\pi^-$ (DCS) , $\bar{D}^0 \rightarrow K^+\pi^-$ (CF)  

the ‘ADS’ method

[Atwood, Dunietz, Soni]

Total visible BR very small ($\sim 10^{-7}$), and not yet observed (4.1$\sigma$ signal from Belle).

The suppressed ‘ADS’ mode $B^\pm \rightarrow (K^\mp\pi^\pm)K^\pm$ is the gateway to $\gamma$!
Evidence for suppressed ADS mode

Signal seen with 4.0σ significance, & hint of asymmetry, consistent with previous results

\[ B^\pm \rightarrow (K^\mp \pi^\pm)K^\pm \]

World Average (without LHCb)\n
\[ R_{ADS}^{DK} = (1.66 \pm 0.39 \pm 0.24) \times 10^{-2} \]

\[ A_{ADS}^{DK} = -0.39 \pm 0.17 \pm 0.02 \]

World Average (without LHCb)\n
-0.58 ± 0.21
$B^0 \rightarrow K^{*+} l^{-} l^{-}$

Many observables exist in $B^0 \rightarrow K^{*+} l^{-} l^{-}$ to probe helicity structure of any New Physics...

...in particular, forward-backward asymmetry ($A_{FB}$) of lepton system as a function of lepton invariant mass ($q^2$).

Early results from CDF & B-factories show intriguing behaviour at low $q^2$, But precision too low yet to speak of an ‘anomaly’

CDF: ~100 $K^{*+} l^{-} l^{-}$ events

BaBar: ~65 $K^{*+} l^{-} l^{-}$ events

Belle: ~250 $K^{*+} l^{-} l^{-}$ events
$B^0 \rightarrow K^* \mu^+ \mu^-$ at LHCb

Select events using Boosted Decision Tree from sample of 309 pb$^{-1}$
Veto decays in $J/\Psi$ and $\Psi(2S)$ resonance regions

Measure in 6 $q^2$ bins:
- differential branching fraction, $d\Gamma/dq^2$
- longitudinal polarisation, $F_L$
- $A_{FB}$

Simultaneous fit of 1D projections of helicity angles of kaon & lepton
Performance of fit validated on MC and $B^0 \rightarrow J/\Psi K^*$ decays

303 signal events after mass cut
$A_{FB}$ in $B^0 \rightarrow K^* \mu^+ \mu^-$ in LHCb with 309 pb$^{-1}$

Systematic uncertainties are small, and generally themselves statistics limited.

Data are consistent with predictions at present sensitivity. Next tasks:

- determine crossing point: sensitive to NP; cleanly predicted in SM
- study other observables, e.g. $A_T^{(2)}$, sensitive to RH currents
The RICHness of ‘$B \rightarrow hh’$ (h=π,K,p)

Two-body charmless B decays are central goal of LHCb physics. Significant contribution of Penguin diagrams provides entry point for New Physics

Rely on good performance of trigger and RICH
**A closer look at B_{d,s} → K\pi: direct CPV**

The ultimate goal is to perform time dependent study, particularly of B_s → K\pi: this will enable New Physics sensitive measurement of $\gamma$ [e.g. Fleischer, PLB 459 (1999) 306]

First step: look for direct CPV in flavour specific final states [LHCb-CONF-2011-042]:

- Focus on B^0 → K\pi - here, significant CPV well established

Existing world average:

$$A_{CP}(B^0 \rightarrow K^+\pi^-) = -0.088 \pm 0.011\text{ (stat)} \pm 0.008\text{ (syst)}$$

Most precise single measurement and first 5\sigma observation of CPV at a hadron machine!

- Now look at B_s → K\pi

CDF result:

$$A_{CP}(B^0_s \rightarrow \pi^+K^-) = 0.39 \pm 0.17$$

First evidence of CPV in B_s decays!
New measurements with b-baryons

Interesting to look for the decay $\Lambda_b \to D^0 pK$, as it is a potentially powerful mode for measuring CKM angle $\gamma$. First step is to reconstruct normalisation mode $\Lambda_b \to D^0 p\pi$.

$\Lambda_b \to D^0 pK$ observed for first time with significance of $6.3\sigma$.

$$\frac{\mathcal{B}(\Lambda_b \to D^0 pK^-)}{\mathcal{B}(\Lambda_b \to D^0 p\pi^-)} = 0.112 \pm 0.019^{+0.011}_{-0.014}$$
New measurements with b-baryons

Looking closer at the $D^0pK^-$ there is a signal $\sim 5.8 \text{ GeV}/c^2$ with statistical + systematic significance of $2.6 \sigma$. Consistent with $\Xi^0_b \rightarrow D^0pK^-$ decay.

$\Xi^0_b \rightarrow D^0pK$

Measure relative production rate $\times$ BR:

$$\frac{f_{b \rightarrow \Xi^0_b} \times B(\Xi^0_b \rightarrow D^0pK^-)}{f_{b \rightarrow \Lambda^0_b} \times B(\Lambda^0_b \rightarrow D^0pK^-)} = 0.29 \pm 0.12 \pm 0.08$$

Measure mass relative to $\Lambda_b$:

$$m(\Xi^0_b) - m(\Lambda^0_b) = (181.8 \pm 5.5 \pm 0.5) \text{ MeV}/c^2$$

$\Xi^0_b [\rightarrow \Xi^+_c\pi^-, \Xi^+_c \rightarrow \Xi^-\pi^+\pi^-, \Xi^- \rightarrow \Lambda\pi^-, \Lambda \rightarrow p\pi^-]$ recently observed by CDF [arXiv:1107.4015]. Consistent masses from two experiments: $m_{\text{LHCb}} - m_{\text{CDF}} (\Xi^0_b) = -14.6 \pm 8.5 \text{ MeV}/c^2$
CPV in $B_s$ mixing

CPV phase in $B_s$ mixing-decay interference, $\phi_s$, measured in $B_s \rightarrow J/\Psi \phi$ a golden observable for NP

- a priori: unprobed box diagram, phase small in SM
- a posteriori: tension with SM in Tevatron measurements, and synergy with D0 dilepton asymmetry study

LHCb 37 pb$^{-1}$ result: less precise than Tevatron, but shows the same trend. ~350 pb$^{-1}$ currently under analysis – exciting possibilities await!

Sensitivity can be improved through inclusion of CP-eigenstate modes such as $B_s \rightarrow J/\Psi f_0(980)$

ππ spectrum in $B_s \rightarrow J/\Psi \pi \pi$

$B_s \rightarrow J/\Psi \phi$

Assuming identical analysis performance + central values
ATLAS lifetime results

Preliminary measurements of B-lifetimes indicate that ATLAS is well prepared to play important role in LHC $\phi_s$ campaign & other b-decay studies with di-muons.

Simultaneous mass & lifetime fit:

$\tau_{B_d} = 1.51 \pm 0.04 \text{ (stat)} \pm 0.04 \text{ (syst) ps}$

(PDG: $1.525 \pm 0.009 \text{ ps}$)

$\tau_{B_s\text{ single}} = 1.41 \pm 0.08 \text{ (stat)} \pm 0.05 \text{ (syst) ps}$

(fit with single exponential)

(PDG: $1.472 \pm 0.026 \text{ ps}$)
The golden mode: $B_s \to \mu \mu$

B physics rare decay par excellence:

$$\text{BR}(B_s \to \mu \mu)_{\text{SM}} = (3.2 \pm 0.2) \times 10^{-9}$$


Precise prediction (which will improve)!

Very high sensitivity to NP, eg. MSSM:

One example [O. Buchmuller et al, arXiv:0907.5568]: NUHM (= generalised version of CMSSM)

$$\text{BR}(B_s \to \mu \mu)$$ - highly discriminatory

$BR_{MSSM}^{MSSM}(Bq \to l^+ l^-) \propto \frac{m_b m_l^2 \tan^6 \beta}{M_{A0}^4}$

BR UL 95% CL as of Spring 2011:

CDF (3.7 fb$^{-1}$): < $4.3 \times 10^{-8}$

D0 (6.1 fb$^{-1}$): < $5.1 \times 10^{-8}$

LHCb (37 pb$^{-1}$): < $5.6 \times 10^{-8}$

Recent exciting hint from CDF (7 fb$^{-1}$):

$$\text{BR} = 1.8^{+1.1}_{-0.9} \times 10^{-8}$$

[arXiv:1107.2304]
CMS search for $B_{s,d} \rightarrow \mu^+\mu^-$ with 1.14 fb$^{-1}$

Dimuon trigger at L1, with track information added at HLT. Then, offline:

- Cut based analysis, optimised on MC and data sidebands prior to unblinding
- Analysis divided into two geometrical regions
  - ‘Barrel’
    - Both $\mu \mid \eta \mid < 1.4$
  - ‘Endcap’
    - At least one $\mu \mid \eta \mid > 1.4$
- Selection variables: $\mu$ id, ‘pointing angle’, flight length significance, fit quality, isolation criteria, $p_T(\mu\text{-max}) > 4.5$ GeV, $p_T(\mu\text{-min}) > 4.0$ GeV, $p_T(B) > 4$ GeV...

- Normalisation & calibration modes:
  - $B^+ \rightarrow J/\Psi K^+$
  - $B_s \rightarrow J/\Psi \phi$ used to check MC description of $B_s$ fragmentation dependent quantities
Good agreement found between data and MC for all selection variables.

Efficiency of variables potentially sensitive to pileup (e.g. isolation, flight length) checked on data.

Excellent stability observed – good news for higher luminosity!
2011 $B_s \rightarrow \mu^+\mu^-$ search at LHCb with 300 pb$^{-1}$

Strategy very similar to 2010 analysis
[PLB 699 (2011) 330] After di-$\mu$ preselection:

• Build Boosted Decision Tree out of 9 kinematical and topological variables
  Train BDT on MC, but calibrate on data:
  - signal response: use $B \rightarrow hh$ decays triggered on ‘other B’ (avoid biases!)
  - background response: use sidebands

• Invariant mass of expected signal parameterised as crystal ball, with scale & resolution (~25 MeV) calibrated from data (dimuon resonances & $B \rightarrow hh$)

• Now look in a 6 x 4 grid of $\mu^+\mu^-$ invariant mass vs BDT output

• To obtain relative BR for signal use three normalisation channels:
  $B^+ \rightarrow J/\Psi K^+$, $B_s \rightarrow J/\Psi \phi$ and $B^0 \rightarrow K\pi$ – all give consistent results
Do we see a peak?

Doigt de Dieu, or Pic Central de la Meije (3973m). Not far from Grenoble...
Not exactly...
CMS results for $B_s \rightarrow \mu^+ \mu^-$ search with 1.14 fb$^{-1}$

No significant excess seen

<table>
<thead>
<tr>
<th></th>
<th>Barrel</th>
<th>Endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{signal}^{exp}$</td>
<td>0.80 ± 0.16</td>
<td>0.36 ± 0.07</td>
</tr>
<tr>
<td>$N_{bg}^{exp}$</td>
<td>0.60 ± 0.35</td>
<td>0.80 ± 0.40</td>
</tr>
<tr>
<td>$N_{peak}^{exp}$</td>
<td>0.07 ± 0.02</td>
<td>0.04 ± 0.01</td>
</tr>
<tr>
<td>$N_{obs}$</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Calculate upper limits using frequentist CLs approach and taking $f_s/f_u = 0.282 \pm 0.037$ [PDG]

Expected limit at 95% C.L. (including presence of SM signal)

Observed limit at 95% (90%) C.L.

p-value of bckgd only hypothesis

1.8 x 10$^{-8}$

1.9 (1.6) x 10$^{-8}$

11%
LHCb $B_s \rightarrow \mu^+\mu^-$ results in $B_s$ mass region with 300 pb$^{-1}$

<table>
<thead>
<tr>
<th>BDT Region</th>
<th>Exp. combinatorial</th>
<th>Exp. SM signal</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>BDT&lt;0.25</td>
<td>2968 ± 69</td>
<td>1.26 ± 0.13</td>
<td>2872</td>
</tr>
<tr>
<td>0.25&lt;BDT&lt;0.5</td>
<td>25 ± 2.5</td>
<td>0.61 ± 0.06</td>
<td>26</td>
</tr>
<tr>
<td>0.5&lt;BDT&lt;0.75</td>
<td>2.99 ± 0.89</td>
<td>0.67 ± 0.07</td>
<td>3</td>
</tr>
<tr>
<td>0.75&lt;BDT</td>
<td>0.66 ± 0.40</td>
<td>0.72 ± 0.07</td>
<td>2</td>
</tr>
</tbody>
</table>

Combinatorial background
B→hh misid background
0.1 ± 0.1 events in each of 4 BDT bins

Data
Signal with SM BR
$m_{\mu\mu} = 5.357$ GeV
BDT = 0.90
Decay length = 11.5 mm
Tracks shown for $p_T > 0.5$ GeV
LHCb preliminary limit (stat + syst) on $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$

Compute limits using frequentist CLs method and LHCb combined result for $f_s/f_d$

Expected limit at 95% (90%) C.L.

- Background only: $1.0 (0.8) \times 10^{-8}$
- Background + SM signal: $1.5 (1.2) \times 10^{-8}$

p-value of bckgd only hypothesis:

- Observed limit at 95% (90%) C.L.: $1.6 (1.3) \times 10^{-8}$
- 14%

Observed limit at 95% (90%) C.L. when combined with 2010 result:

- $1.5 (1.2) \times 10^{-8}$
Preliminary BR($B_s \rightarrow \mu^+ \mu^-$) combination

A preliminary CMS-LHCb combination on BR($B_s \rightarrow \mu^+ \mu^-$) has been performed, again using the CLs approach, & taking LHCb value of $f_s/f_d$ as common input.

Observed limit at 95% (90%): $1.1 (0.9) \times 10^{-8}$

This is 3.4 times the expected SM value

A BR of $1.8 \times 10^{-8}$ has a CLs value of $\sim 0.3%$
Conclusions

LHC flavour physics has come very far, very quickly:

- comprehensive series of clean measurements performed over a wide range of topics
- B-factory & Tevatron sensitivity overtaken or matched in many benchmark analyses
- broad flavour programme of LHCb now augmented by CMS in $B_s \to \mu^+\mu^-$ search

No sign of discrepancies with the SM yet:

- but flavour observables do have excellent sensitivity to New Physics contributions!
- much higher precision expected over next ~5 years...
- ...and beyond: LHCb upgrade

LHC has become the flavour frontier, and will remain so for a long time to come
Come to where the flavor is. The LHC

Many thanks to all who contributed material and advice for this presentation!
Backups
$\chi_b$ at LHCb

LHCb Preliminary
$\sqrt{s} = 7$ TeV Data 2010

- $\chi^2 / \text{ndf} = 30.43 / 34$
- $N = 349.9 \pm 58.6$
- $\Delta M = 0.4433 \pm 0.0034$
- $\sigma = 0.0276 \pm 0.0043$
- $A = 5.253 \times 10^7 \pm 34381126$
- $\alpha = 18.69 \pm 3.76$
- $a_0 = -26.75 \pm 8.82$
- $a_1 = 71.8 \pm 21.7$
- $a_2 = -42.17 \pm 19.71$
- $a_3 = 10.72 \pm 7.57$

Entries / 20 MeV

$m(\mu \mu \gamma) - m(\mu \mu)$ (GeV)
Open charm production

Preliminary results on open charm cross-section exist from ALICE, ATLAS & LHCb

Open charm cross-section at $\sqrt{s} = 7$ TeV $\sim$6.5 mb - good news for flavour physics!
Dependence on $p_T$?

In semileptonic analysis study whether fragmentation fractions vary with $\eta$ and $p_T$. No dependence is seen in $f_s/f_d$ (here plotted as $f_s/ [f_d+f_u]$):

However, there is an indication of significant $p_T$ dependence in $\Lambda_b$ fraction:

Upcoming results to watch out for: measurement of production asymmetries!
LHCb ADS analysis results in context

\[ R_{ADS} \text{ Averages} \quad \text{HFAG EPS 2011 PRELIMINARY} \]

\[ A_{ADS} \text{ Averages} \quad \text{HFAG EPS 2011 PRELIMINARY} \]

LHC Heavy Flavour Physics
EPS 2011, Grenoble
dΓ/dq^2 and F_L in B^0 → K^*μ^+μ^- 

These observables have good consistency with the SM expectations!
Search for $B_s \rightarrow \pi^+ \pi^-$

Possible contribution of suppressed diagrams, e.g. penguin annihilation, complicates extraction of weak phase info from $B \rightarrow hh$ decays.

To learn more, look for decays where only suppressed amplitudes contribute, for example $B_s \rightarrow \pi^+ \pi^-$. Deploy tight selection:

Signal observed with $5.2 \sigma$ significance – this is a first observation

$$\mathcal{B}\mathcal{R}(B_s^0 \rightarrow \pi^+ \pi^-) = (0.98^{+0.23}_{-0.19}(\text{stat}) \pm 0.11(\text{syst})) \times 10^{-6}$$

Consistent with CDF preliminary result: $0.57 \pm 0.15 \pm 0.10 \times 10^{-6}$ [CDF-note-10498]
Observation of $B_c \rightarrow J/\Psi \pi\pi\pi$

Until now, only observed $B_c$ decay modes were $J/\Psi \mu\nu$ and $J/\Psi \pi$.

Measure relative BR w.r.t. $J/\Psi \pi^+$:

$$\frac{\text{BR}(B_c \rightarrow J/\Psi \pi^+\pi^-\pi^+)}{\text{BR}(B_c \rightarrow J/\Psi \pi^+)} = 3.0 \pm 0.6 \pm 0.4$$

Compare background subtracted data mass projections with MC with $B_c \rightarrow J/\Psi a_1(1260)$, $a_1(1260) \rightarrow \rho^0\pi$, $\rho^0 \rightarrow \pi\pi$

First observation!
**CMS $B_{d,s} \rightarrow \mu\mu$ results**

<table>
<thead>
<tr>
<th></th>
<th>Barrel</th>
<th>Endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acceptance</strong></td>
<td>$B^0 \rightarrow \mu^+\mu^-$</td>
<td>$B^0 \rightarrow \mu^+\mu^-$</td>
</tr>
<tr>
<td>$\varepsilon_{\text{analysis}}$</td>
<td>$(24.62 \pm 0.99) \times 10^{-2}$</td>
<td>$(24.72 \pm 0.99) \times 10^{-2}$</td>
</tr>
<tr>
<td>$\varepsilon_{\text{tot.}}$</td>
<td>$(2.23 \pm 0.19) \times 10^{-2}$</td>
<td>$(2.22 \pm 0.19) \times 10^{-2}$</td>
</tr>
<tr>
<td>$N_{\text{signal}}^{\text{exp}}$</td>
<td>$0.065 \pm 0.011$</td>
<td>$0.80 \pm 0.16$</td>
</tr>
<tr>
<td>$N_{\text{sig}}^{\text{Bkg}}$</td>
<td>$0.40 \pm 0.23$</td>
<td>$0.60 \pm 0.35$</td>
</tr>
<tr>
<td>$N_{\text{exp}}^{\text{peak}}$</td>
<td>$0.25 \pm 0.06$</td>
<td>$0.07 \pm 0.02$</td>
</tr>
<tr>
<td>$N_{\text{obs}}$</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

- **As expected**
  - based on sidebands
  - studied with $I < 0.7$
  - no evidence for anomalous signal

- **Expected UL (median)**
  - $B^0_s \rightarrow \mu^+\mu^- : 1.8 \times 10^{-9}$

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*Urs Langenegger*

Search for $B^0_{s(d)} \rightarrow \mu^+\mu^-$ with the CMS experiment (2011/07/22)

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LHC Heavy Flavour Physics
EPS 2011, Grenoble
LHCb $B^0_d \rightarrow \mu\mu$ results (2011, 300 pb$^{-1}$)

<table>
<thead>
<tr>
<th>BDT Interval</th>
<th>Exp. combinatorial</th>
<th>Exp. MisID</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>BDT &lt; 0.25</td>
<td>3175 ± 72</td>
<td>0.6 ± 0.1</td>
<td>3025</td>
</tr>
<tr>
<td>0.25 &lt; BDT &lt; 0.5</td>
<td>26.6 ± 2.5</td>
<td>0.6 ± 0.1</td>
<td>31</td>
</tr>
<tr>
<td>0.5 &lt; BDT &lt; 0.75</td>
<td>3.1 ± 0.8</td>
<td>0.6 ± 0.1</td>
<td>5</td>
</tr>
<tr>
<td>0.75 &lt; BDT</td>
<td>0.7 ± 0.4</td>
<td>0.6 ± 0.1</td>
<td>4</td>
</tr>
</tbody>
</table>
LHCb $B^0_d \rightarrow \mu\mu$ results (2011, 300 pb$^{-1}$)

<table>
<thead>
<tr>
<th></th>
<th>Bkg only 90(95) %CL</th>
<th>CLb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected stat+syst</td>
<td>2.4 (3.1) x10$^{-9}$</td>
<td></td>
</tr>
<tr>
<td>Observed stat+syst</td>
<td>4.2 (5.2) x10$^{-9}$</td>
<td>0.90</td>
</tr>
</tbody>
</table>
Background description vs $M_{\mu\mu}$ in LHCb

Different parameterisations performed for background shape → systematics
**Limits on \( \text{BR}(B_d \rightarrow \mu^+\mu^-) \)**

No significant excess seen in \( B_d \rightarrow \mu^+\mu^- \) search

<table>
<thead>
<tr>
<th></th>
<th>95% (90%) C.L. limits</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CMS observed</strong></td>
<td>4.6 (3.7) ( \times 10^{-9} )</td>
</tr>
<tr>
<td><strong>CMS expected</strong></td>
<td>4.8 ( \times 10^{-9} )</td>
</tr>
<tr>
<td><strong>LHCb expected</strong></td>
<td>3.1 (2.4) ( \times 10^{-9} )</td>
</tr>
<tr>
<td><strong>LHCb observed</strong></td>
<td>5.2 (4.2) ( \times 10^{-9} )</td>
</tr>
</tbody>
</table>

(NB here LHCb results are 2011 data only)
\( B_s \to \mu^+\mu^- \) — extrapolations performed from 2010 LHCb analysis