Rare B decays (at the LHC) as a probe of $b \rightarrow s$ transitions

Gerhard Raven
NIKHEF & Vrije Universiteit, Amsterdam

• Framework
• LHC & experiments
• $b \rightarrow s \gamma$
• $b \rightarrow s l^+l^-$
• $B_s \rightarrow \mu^+\mu^-$
• LHC Schedule
• Summary

ITEP Meeting on The Future of Heavy Flavour Physics
Disclaimers

• This talk heavily borrows from:
  – Patrick Koppenburg: Beach, Physics at LHC
  – Pavel Reznicek: Beach
  – Olivier Schneider: Flavour at the LHC
  – Thomas Speer: Beach, Capri workshop
  – Nikolay Nikitine: Capri workshop
  – And others…

• Little new news, a lot of the attention right now is on installation, commissioning, calibrations, alignment, preparations for data-taking…
Describe $b \rightarrow s$ transitions by an effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu) O_i(\mu)$$

- **Long Distance:**
  - Operators $O_i$
- **Short Distance:**
  - Wilson coef. $C_i$

New physics shows up as modified $C_i$, (or as new operators)

From G. Hiller [hep-ph/0308180]
### Operators & Observables

<table>
<thead>
<tr>
<th>$O_{\tau\gamma}$</th>
<th>magnitude</th>
<th>phase</th>
<th>helicity flip $O_{i}^{'}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b \rightarrow s\gamma$</td>
<td>$a_{CP}(b \rightarrow s\gamma)$</td>
<td>$\Lambda_b \rightarrow \bar{\Lambda}_\gamma$</td>
<td>$B \rightarrow (K^* \rightarrow K\pi)\ell^+\ell^-$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B \rightarrow (K^{**} \rightarrow K\pi\pi)\gamma$</td>
</tr>
<tr>
<td>$O_{8g}$</td>
<td></td>
<td></td>
<td>$\Lambda_b \rightarrow \bar{\Lambda}_\phi$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B \rightarrow K^{*}\phi$</td>
</tr>
<tr>
<td>$O_{9\ell,10\ell}$</td>
<td></td>
<td></td>
<td>$b \rightarrow s\ell^+\ell^-$</td>
</tr>
<tr>
<td>$O_{S,P}$</td>
<td></td>
<td></td>
<td>$B_{d,s} \rightarrow \mu^+\mu^-$</td>
</tr>
</tbody>
</table>

For Rare Decay analysis, having access to large samples produced is an obvious starting requirement...

<table>
<thead>
<tr>
<th></th>
<th>$e^+e^- \rightarrow \Upsilon(4S) \rightarrow BB$ PEPII, KEKB</th>
<th>$pp \rightarrow bbX (\sqrt{s} = 14 \text{ TeV}, \Delta t_{\text{bunch}}=25 \text{ ns})$ LHC (LHCb–ATLAS/CMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Production $\sigma_{bb}$</strong></td>
<td>1 nb</td>
<td>$\sim 500 \mu b$</td>
</tr>
<tr>
<td><strong>Typical bb rate</strong></td>
<td>10 Hz ($L=10^{34} \text{cm}^{-2}\text{s}^{-1}$)</td>
<td>100–1000 kHz</td>
</tr>
<tr>
<td><strong>bb purity</strong></td>
<td>$\sim 1/4$</td>
<td>$\sigma_{bb}/\sigma_{\text{inel}} = 0.6%$ Trigger is a major issue!</td>
</tr>
<tr>
<td><strong>Pileup</strong></td>
<td>0</td>
<td>0.5–5</td>
</tr>
<tr>
<td><strong>b-hadron types</strong></td>
<td>$B^+B^- (50%)$</td>
<td>$B^+ (40%), B^0 (40%), B_s (10%)$</td>
</tr>
<tr>
<td></td>
<td>$B^0B^0 (50%)$</td>
<td>$B_c (&lt; 0.1%), b$-baryons (10%)</td>
</tr>
<tr>
<td><strong>b-hadron boost</strong></td>
<td>Small</td>
<td>Large (well separated vertices)</td>
</tr>
<tr>
<td><strong>Production vertex</strong></td>
<td>Not reconstructed (Not needed)</td>
<td>Reconstructed (many tracks)</td>
</tr>
<tr>
<td><strong>Neutral B mixing</strong></td>
<td>Coherent $B^0B^0$ mixing</td>
<td>Incoherent $B^0$ and $B_s$ mixing (extra flavour-tagging dilution)</td>
</tr>
<tr>
<td><strong>Event structure</strong></td>
<td>BB pair alone</td>
<td>Many particles not associated with the two b hadrons</td>
</tr>
</tbody>
</table>

Next step is collecting the data…
The LHC Experiments (that have a B physics program)

- **LHCb:**
  - dedicated B physics experiment

- **ATLAS/CMS:**
  - general purpose experiments, optimized for high-$p_T$ discovery physics at $10^{34}$ cm$^{-2}$s$^{-1}$
Detector Acceptance

- **ATLAS/CMS:**
  - central detectors, $|\eta|<2.5$
  - will do B physics using high-$p_T$ muon triggers, mostly with modes involving dimuons
    - purely hadronic modes triggered by tagging muon

- **LHCb:**
  - designed to maximize B acceptance (within cost and space constraints)
  - forward spectrometer, $1.9 < \eta < 4.9$
    - more b hadrons produced at low angles
    - single arm OK since $b \bar{b}$ pairs produced correlated in space
  - rely on much softer, lower $p_T$ triggers, efficient also for purely hadronic B decays
Luminosity & Pile-up

Pileup:
- number of inelastic pp interactions in a bunch crossing is Poisson-distributed with mean $n = L \sigma_{inel}/f$

ATLAS/CMS ($f = 32$ MHz)
- Will run at highest luminosity available
- Expect $L < 2 \times 10^{33}$ cm$^{-2}$s$^{-1}$ ($n < 5$) for first 3 years
- At $L = 10^{34}$ cm$^{-2}$s$^{-1}$ ($n = 25$), expect only $B_s \rightarrow \mu\mu$ still possible

LHCb ($f = 30$ MHz)
- $L$ tuneable by defocusing the beams
- Choose to run at $\langle L \rangle \sim 2 \times 10^{32}$ cm$^{-2}$s$^{-1}$ (max. $5 \times 10^{32}$ cm$^{-2}$s$^{-1}$)
  - Clean environment ($n = 0.5$)
  - Less radiation damage
    - LHCb 8mm from beam, ATLAS 5 cm, CMS 4 cm
  - Will be available from 1st physics run

$2 \text{ fb}^{-1}$ / year $\rightarrow 10^{12}$ bb events
10 fb$^{-1}$ in first 5 years

$\sigma_{inel} = 80 \text{ mb}$
$f = \text{non-empty crossing rate}$
Atlas (di)muon Trigger

Collisions rate 40 MHz

LVL1 rate 200 Hz

LVL2 rate 100 Hz

Event Filter 10 Hz

LVL1:
- $P_T(1)>6$ GeV/c, $P_T(2)>4$ GeV/c
- $L<10^{33}$: single mu
- $L\sim 10^{33}$: dimuon

LVL2
- Confirm LVL1, refine pt

LVL2&EF
- vertex constraints + mass

Pipeline memories

Derandomizers

Readout drivers

Readout buffers

Event Builder

Data recording
Triggers for B-physics

– Level1:
  • Single muon, pt>14 GeV/c
  • Dimuon, pt>3 GeV/c

– HLT:
  • Inclusive b,c trigger
    – L1: high ET jet,
      → 5 Hz
  • Exclusive B decays
    – Partial reconstruction of detector in the region around the muons
      → O(1 Hz) per decay

From T. Speer [Capri workshop on Theory, Phenomenology and Experiment in Heavy Flavour Physics]
LHCb Trigger

10 MHz (visible bunch crossings)

Hardware trigger
- Fully synchronized (40 MHz), 4 µs fixed latency
- “High p_T” μ, μμ, e, γ and hadron + pileup info (e.g. p_T(μ) > 1.3 GeV/c)

1 MHz (full detector readout)

Software trigger
- Full detector info available, only limit is CPU time
- 1st stage: ~1 ms → 40 kHz (could change)
  - Tracks with min. impact param. and p_T
  - (di)muon
- High-Level trigger: ~ 10 ms
  - Full event reconstr.: excl. and incl. streams

≤ 2 kHz (storage)

Main changes since original design:
2003: track p_T at 1 MHz
2005: increased output rate
2005: full readout at 1 MHz
### Trigger Summary

<table>
<thead>
<tr>
<th>Trigger level</th>
<th>Total output rate (at startup)</th>
<th>Output rate B physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>LVL1</td>
<td>75 kHz</td>
<td>10–15 kHz</td>
</tr>
<tr>
<td>LVL2</td>
<td>2 kHz</td>
<td>1–1.5 kHz</td>
</tr>
<tr>
<td>EF</td>
<td>200 Hz</td>
<td>10–15 Hz</td>
</tr>
</tbody>
</table>

- **CMS**

<table>
<thead>
<tr>
<th>Trigger level</th>
<th>Total output rate (at startup)</th>
<th>Output rate B physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV 1</td>
<td>50 kHz</td>
<td>14 kHz (1µ) 0.9 kHz (2µ)</td>
</tr>
<tr>
<td>HLT</td>
<td>100 Hz</td>
<td>~ 5 Hz of incl. b,c→µ+jet + O(1 Hz) for each excl. B mode</td>
</tr>
</tbody>
</table>

- **LHCb**

<table>
<thead>
<tr>
<th>Trigger level</th>
<th>Total output rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0</td>
<td>1000 kHz</td>
</tr>
<tr>
<td>HLT</td>
<td>2000 Hz</td>
</tr>
</tbody>
</table>
Expected Performance

Mass resolutions in MeV/c²

<table>
<thead>
<tr>
<th>Decay</th>
<th>ATLAS</th>
<th>CMS</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_s \to \mu\mu )</td>
<td>80</td>
<td>46</td>
<td>18</td>
</tr>
<tr>
<td>( B_s \to D_s \pi )</td>
<td>46</td>
<td>?</td>
<td>14</td>
</tr>
<tr>
<td>( B_s \to J/\psi \phi )</td>
<td>38</td>
<td>32</td>
<td>16</td>
</tr>
<tr>
<td>( B_s \to J/\psi \phi )</td>
<td>17</td>
<td>13</td>
<td>8</td>
</tr>
</tbody>
</table>

Good proper time resolution essential for time-dependent \( B_s \) measurements!

Proper time resolution:
- CDF: \( \sigma_t \sim 100 \) fs
- ATLAS: \( \sigma_t \sim 100 \) fs (was 70 fs)
- CMS: \( \sigma_t \sim 100 \) fs
- LHCb: \( \sigma_t \sim 40 \) fs

Good proper time resolution important for background rejection!

\( B_s \to D_s \pi \)

Proper time resolution

\( \sigma_t = 33 \pm 1 \) fs (69%)
\( \sigma_2 = 67 \pm 3 \) fs

\( \sigma_t \sim 40 \) fs
Back to the physics…
\begin{array}{|c|c|c|c|}
\hline
\text{O}_{\tau\gamma} & b \rightarrow s\gamma & a_{CP}(b \rightarrow s\gamma) & \begin{array}{l}
\Lambda_b \rightarrow \Lambda\gamma \\
B \rightarrow (K^* \rightarrow K\pi)\ell^+\ell^- \\
B \rightarrow (K^{**} \rightarrow K\pi\pi)\gamma
\end{array} \\
\hline
\text{O}_{8g} & b \rightarrow s\gamma & a_{CP}(b \rightarrow s\gamma) & \begin{array}{l}
\Lambda_b \rightarrow \Lambda\phi \\
B \rightarrow K\phi \\
B \rightarrow K^*\phi
\end{array} \\
\hline
\text{O}_{9\ell,10\ell} & b \rightarrow s\ell^+\ell^- & A_{FB}(b \rightarrow s\ell^+\ell^-) & B \rightarrow (K^* \rightarrow K\pi)\ell^+\ell^- \\
\hline
\text{O}_{s,P} & B_{d,s} \rightarrow \mu^+\mu^- & B_{d,s} \rightarrow \tau^+\tau^- & b \rightarrow s\tau^+\tau^- \\
\hline
\end{array}

From G. Hiller [hep-ph/0308180]
\[ b \rightarrow s \gamma \]

- Amplitude \( \propto V_{ts}|C_7| \)
- First evidence for penguins ('93)
- WA: \( Br = (3.55 \ 0.26) \ 10^{-4} \)
- SM: \( Br = (3.7 \ 0.3) \ 10^{-4} \)
- Sets strong constraints on charged Higgs, New Physics…
LHCb: $B \rightarrow K^{*}\gamma$, $B_s \rightarrow \phi\gamma$

Charged Tracks:
- Consistent with req. PID
- Inconsistent with primary vertex
- Good secondary vertex
- Consistent $K^*$, $\phi$ mass

Photons:
- $E_t > 2.8$ GeV
- Remove $B \rightarrow K^*\pi^0$, $B_s \rightarrow \phi\pi^0$ using $K^*$, $\phi$ polarisation

From I. Belyaev, G. Pakhlova [LHCb-2003-090]
LHCb: $B \rightarrow K^*\gamma$, $B_s \rightarrow \phi\gamma$

- Require $B$ to point back to the Primary Vertex
- Mass resolution: 65 MeV
- Lifetime resolution: 62 fs

<table>
<thead>
<tr>
<th></th>
<th>Yield</th>
<th>$B/S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow K^*\gamma$</td>
<td>35 000</td>
<td>$&lt; 0.7$</td>
</tr>
<tr>
<td>$B_s \rightarrow \phi\gamma$</td>
<td>9 000</td>
<td>$&lt; 2.4$</td>
</tr>
<tr>
<td>$B^0 \rightarrow \omega\gamma$</td>
<td>40</td>
<td>$&lt; 3.5$</td>
</tr>
</tbody>
</table>


\[ b \rightarrow s \gamma : \text{photon polarization} \]

\[ b \rightarrow s \gamma \]

How to measure?

- Virtual photons (eg. \( b \rightarrow s e^+e^- \))
  Melinkov et al., [PLB442 381-389, 1998]

- Converted photons
  Grossman et al., [JHEP06 29, 2000]

- \( B \rightarrow \gamma K^{**} (K_{\pi\pi}) \)
  Gronau & Pirjol, [PRD66 054008, 2002],
  Gronau et al., [PRL88 051802, 2002]

- Time Dependent \( A_{CP}(K^{*}\gamma) \)

- \( \Lambda_b \) baryons
  Hiller & Kagan, [PRD65 074038, 2002]

Photon Polarization is not well known

- (New) Right-handed operators could increase this!
- But gluons could also contribute \( O(10\%) \)

Grinstein et al., [PRD71:011504, 2005]
Expect $\Lambda_b$ to be polarized
- Can be measured with $\Lambda_b \rightarrow \Lambda J/\psi$ at 1% level
- Assume 20% for now…
  [E. Leader] [Hrivnac et al, hep-ph/9405231]

But
- $\Lambda\gamma$ does not have a distinctive secondary vertex
- Most $\Lambda$ decay after escaping the vertex detector

$\Lambda_B \rightarrow \Lambda\gamma$ polarisation

\[
\begin{align*}
  r &= \frac{C'_{\gamma\Lambda}}{C_{\gamma\Lambda}} \\
  \alpha_\gamma &= \frac{1 - |r|^2}{1 + |r|^2} \\
  \frac{d\Gamma}{d \cos \theta_{\gamma}} &\propto 1 - \alpha_\gamma P_{\Lambda_b} \cos \theta_{\gamma} \\
  \frac{d\Gamma}{d \cos \theta_p} &\propto 1 - \alpha_\gamma \alpha_{p^{1/2}} \cos \theta_{\gamma} \\
  \alpha_{p^{1/2}} &= 0.642 \pm 0.013
\end{align*}
\]

[Hiller, Kagan, PRD 65, 074038 (2002)]

\[ \Lambda_B \rightarrow \Lambda \gamma \]

Annual yields (2fb-1) @ LHCb:

<table>
<thead>
<tr>
<th></th>
<th>Yield</th>
<th>( B/S )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Lambda_b \rightarrow \Lambda \gamma )</td>
<td>750</td>
<td>&lt; 42</td>
</tr>
<tr>
<td>( \Lambda_b \rightarrow \Lambda(1520)\gamma )</td>
<td>4200</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>( \Lambda_b \rightarrow \Lambda(1670)\gamma )</td>
<td>2500</td>
<td>&lt; 18</td>
</tr>
<tr>
<td>( \Lambda_b \rightarrow \Lambda(1690)\gamma )</td>
<td>2200</td>
<td>&lt; 18</td>
</tr>
</tbody>
</table>

Approx 20% resolution on \( r = C_7'/C_7 \) after one year

- Far from SM, but already interesting for some NP models
\[
\begin{align*}
\mathcal{O}_{7\gamma} \quad & b \rightarrow s\gamma \\
\mathcal{O}_{8g} \quad & b \rightarrow s\gamma, \quad B \rightarrow X_c \quad a_{CP}(b \rightarrow s\gamma) \\
\mathcal{O}_{9\ell,10\ell} \quad & b \rightarrow se^{+}e^{-} \quad A_{FB}(b \rightarrow s\ell^{+}\ell^{-}) \\
\mathcal{O}_{S,P} \quad & B_{d,s} \rightarrow \mu^{+}\mu^{-} \quad B_{d,s} \rightarrow \tau^{+}\tau^{-} \\
\end{align*}
\]

From G. Hiller [hep-ph/0308180]
Radiative decays & $b \rightarrow s \ell^+\ell^-$

Suppressed by $\alpha_{EM}$

- $\text{Br}(b \rightarrow s \ell^+\ell^-) = (4.5 \ 1.0) \times 10^{-6}$
- $\text{Br}(B^+ \rightarrow K^+\ell^+\ell^-) = (0.5 \ 0.1) \times 10^{-6}$

Currently rarest *observed* B decay
$b \rightarrow s \ell^+\ell^-$

Suppressed by $\alpha_{EM}$

- $\text{Br}(b \rightarrow s \ell^+\ell^-) = (4.5 \ 1.0) \ 10^{-6}$
- $\text{Br}(B^+ \rightarrow K^+\ell^+\ell^-) = (0.5 \ 0.1) \ 10^{-6}$

Currently rarest observed B decay

Sensitive to

- Susy
- Graviton exchange
- …
Inclusive decays well described by theory
• Shape of dilepton mass distribution sensitive to NP
• SM branching ratio \((1.36 \pm 0.08) \times 10^{-6}\) (NNLL) for \(s = q^2/m_b^2 < 0.25\)

… but hard to analyze experimentally (impossible at hadron colliders?)

Exclusive decays much easier for experiment

… but what about hadronic uncertainties?

From Goto et al. [PRD55 4273 (1997)]
Use ratios to cancel hadronic uncertainties

- Forward-Backward asymmetry ($A_{FB}$)
- Zero of $A_{FB}$: $s_0 = 2C_7/C_9(s_0)$
- CP asymmetry
- CP asymmetry in $A_{FB}$
- Ratio of $e^+e^-$ to $\mu^+\mu^-$

From Goto et al. [PRD55 4273 (1997)]
Reminder: current B-factory results

\[ b \rightarrow s \ell^+\ell^- : C_9 \text{ and } C_{10} \]

\[ b \rightarrow s\gamma : C_{7\gamma} \]

Again: any deviation likely to be small…

Likely need \textit{high precision} measurement to recognize deviations from SM…

Belle [PRL93 061803 (2004)]

BaBar [hep-ex/0507001]

Belle [hep-ex/060318]
Exclusive $B^0 \rightarrow \mu^+\mu^-K^{*0}$

- Expected signal and background for 2 fb$^{-1}$ (one nominal year)
  - Assuming $Br = 12 \cdot 10^{-7}$

<table>
<thead>
<tr>
<th>Sample</th>
<th>Stats.</th>
<th>Yield</th>
<th>B/S</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow \mu\mu K^*$</td>
<td>50k</td>
<td>$4400 \pm 100$</td>
<td></td>
</tr>
<tr>
<td>$B\bar{B}$</td>
<td>11M</td>
<td>$1000\text{–}11700$</td>
<td></td>
</tr>
<tr>
<td>$b \rightarrow \mu c(\mu q)$</td>
<td>200k</td>
<td>$500\text{–}1900$</td>
<td>$0.2\text{–}2.6$</td>
</tr>
<tr>
<td>$2 (b \rightarrow \mu)$</td>
<td>1.8M</td>
<td>$750 \pm 130$</td>
<td>$0.17 \pm 0.03$</td>
</tr>
<tr>
<td>$J/\psi$</td>
<td>200k</td>
<td>$20\text{–}80$</td>
<td>$0.02\text{–}0.1$</td>
</tr>
</tbody>
</table>

New: updated analysis expects 7.7K/year, at similar background levels...
$A_{FB}(B^0 \rightarrow \mu^+ \mu^- K^{*0})$

- Toy MC, based on full simulation results
- Generate several experiments

<table>
<thead>
<tr>
<th>Entries</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>4.007</td>
</tr>
<tr>
<td>RMS</td>
<td>0.526</td>
</tr>
</tbody>
</table>

Typical $A_{FB}(s)$ measurement

2 fb$^{-1}$: $s_0 = 4.0 \pm 1.2$ GeV$^2$

10 fb$^{-1}$: $s_0 = 4.0 \pm 0.5$ GeV$^2$ $\Rightarrow$ 13\% error on $C_7/C_9$
Atlas: \(A_{FB}(B^0 \rightarrow \mu^+\mu^-K^{*0})\)

**\(A_{FB}\) for \(B^0_d \rightarrow K^*(892)\mu^+\mu^-\) decay**

From N. Nikitine [Capri workshop on Theory, Phenomenology and Experiment in Heavy Flavour Physics]

ATLAS statistics corresponding to 1 fb\(^{-1}\)

ATLAS statistics corresponding to 30 fb\(^{-1}\)

A. Ishikawa et al., hep-ex/0603018
**Atlas: $\Lambda_b \rightarrow \mu^+\mu^-\Lambda$**

- Very similar to $B^0 \rightarrow \mu^+\mu^-K^*$
- Select $\Lambda$ with
  - $t > 0.5$ ps
  - $1 < R_\Lambda < 45$ cm
- $M(\Lambda_b)$: 75 MeV resolution
- After 3 years: ~1500 events

---

**Forward-Backward Asymmetry**

From P. Reznicek [Flavour at the LHC]
\[ R_X = \frac{\int ds \frac{d\Gamma(B \rightarrow X \mu^+ \mu^-)}{ds}}{\int ds \frac{d\Gamma(B \rightarrow X e^+ e^-)}{ds}} \]

\[ R_X \text{ is related to } Br(B_s \rightarrow \mu\mu) \]

\[ \text{SM} \begin{cases} 
1.000 \pm 0.001 & X = K \\
0.991 \pm 0.002 & X = K^* 
\end{cases} \]

\[ \text{Can get } O(10\%) \text{ corrections due to Higgs boson exchanges...} \]

Hiller & Krueger [PRD69 (2004) 074020]
**RK in B⁺ → ℓ⁺ℓ⁻K⁺**

### Current Status:

<table>
<thead>
<tr>
<th></th>
<th><strong>RX</strong></th>
<th><strong>RK</strong></th>
<th><strong>RK</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BaBar (208 fb⁻¹)</td>
<td>1.06 ± 0.48 ± 0.05</td>
<td>0.93 ± 0.46 ± 0.12</td>
</tr>
<tr>
<td></td>
<td>[hep-ex/0507005]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Belle (250 fb⁻¹)</td>
<td>1.38 +0.39 +0.06 -0.41 -0.07</td>
<td>0.98 +0.30 -0.31 ± 0.08</td>
</tr>
<tr>
<td></td>
<td>[hep-ex/0410006]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ B_s \rightarrow \mu\mu: \text{ The present CDF limit is } 1.0 \cdot 10^{-7} \text{ at } 90\% \text{ CL} \]

[CDF Note 8176]
RK at LHCb…

- 2 fb\(^{-1}\): signal yield from fit:

<table>
<thead>
<tr>
<th></th>
<th>Signal</th>
<th>Mean</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>eeK</td>
<td>349 ± 34</td>
<td>5245 MeV</td>
<td>74 MeV</td>
</tr>
<tr>
<td>(\mu\mu K)</td>
<td>1550 ± 50</td>
<td>5279 MeV</td>
<td>15 MeV</td>
</tr>
</tbody>
</table>

- Addition of dedicated inclusive di-electron trigger should gain O(40%) in eeK (*not* included here)
- Note: llK* background not yet considered…
  - Could complicate eeK, so maybe just do \(R_K^*\) instead ;-)
- 10% error on \(R_K\)

[ Patrick Koppenburg Beach, Physics at LHC ]
$R_K \& \text{Br}(B_s \rightarrow \mu^+\mu^-)$ with $10 \text{ fb}^{-1}$

Broken lepton universality...

Minimal Flavour Violation

SM, or MSSM with small $\tan\beta$

$10^6 \times \text{BR}(B_s \rightarrow \mu\mu)$

[ Patrick Koppenburg  Beach, Physics at LHC ]
\( B_{d,s} \rightarrow \mu^+\mu^- \)

<table>
<thead>
<tr>
<th>( O_{\gamma\gamma} )</th>
<th>magnitude</th>
<th>phase</th>
<th>helicity flip ( \mathcal{O}_i' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b \rightarrow s\gamma )</td>
<td>( a_{CP}(b \rightarrow s\gamma) )</td>
<td>( \Lambda_b \rightarrow \Lambda\gamma )</td>
<td></td>
</tr>
<tr>
<td>( B \rightarrow (K^* \rightarrow K\pi)\ell^+\ell^- )</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>( B \rightarrow (K^{**} \rightarrow K\pi\pi)\gamma )</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>( O_{8g} )</th>
<th>magnitude</th>
<th>phase</th>
<th>helicity flip ( \mathcal{O}_i' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b \rightarrow s\gamma )</td>
<td>( a_{CP}(b \rightarrow s\gamma) )</td>
<td>( \Lambda_b \rightarrow \Lambda\phi )</td>
<td></td>
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<tr>
<td>( B \rightarrow X_c )</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>( B \rightarrow K\phi )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( B \rightarrow K^*\phi )</td>
<td></td>
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<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>( O_{9\ell,10\ell} )</th>
<th>magnitude</th>
<th>phase</th>
<th>helicity flip ( \mathcal{O}_i' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b \rightarrow s\ell^+\ell^- )</td>
<td>( A_{FB}(b \rightarrow s\ell^+\ell^-) )</td>
<td>( B \rightarrow (K^* \rightarrow K\pi)\ell^+\ell^- )</td>
<td></td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>( O_{S,P} )</th>
<th>magnitude</th>
<th>phase</th>
<th>helicity flip ( \mathcal{O}_i' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_{d,s} \rightarrow \mu^+\mu^- )</td>
<td>( B_{d,s} \rightarrow \tau^+\tau^- )</td>
<td>( b \rightarrow s\tau^+\tau^- )</td>
<td></td>
</tr>
</tbody>
</table>

From G. Hiller [hep-ph/0308180]
Very rare decay, sensitive to new physics:

- \( \text{BR} \sim 3.5 \times 10^{-9} \) in SM, can be strongly enhanced in SUSY: \( \text{Br} \propto \tan^6 \beta / M_H^2 \)
- Current limit from Tevatron (CDF+D0): \( 1.5 \times 10^{-7} \) at 95% CL

- CDF+D0 could exclude up to few times \( 10^{-8} \) with 10 fb\(^{-1} \)
$B_s \rightarrow \mu^+\mu^-$

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Expect CMS and Atlas to do very well
- Higher luminosity, sufficiently easy to trigger on
  ➔ more signal

But LHCb has also some advantages
- Better invariant mass resolution, better propertime resolution
  ➔ easier background rejection!

<table>
<thead>
<tr>
<th>Mass Resolution (MeV/c^2)</th>
<th>ATLAS</th>
<th>CMS</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s \rightarrow \mu\mu$</td>
<td>80</td>
<td>46</td>
<td>18</td>
</tr>
</tbody>
</table>
$B_{s,d} \rightarrow \mu^+\mu^- : \pi \ & K \text{ misidentification}$

- Two body modes:
  - Eg. $Br(B^0 \rightarrow K\pi) = 2 \times 10^{-5}$
  - Misid rate: need better than $O(1\%)$
  - Fake rate: $2 \times 10^{-5} \times (1\%)^2 = 2 \times 10^{-9}$

$LHCb$:
- $1$ event/fb$^{-1}$ in a $2\sigma$ mass window
  - Does not seem to be a major problem...
  - (but: eg. Atlas has a $\sim 4x$ worse mass resolution than LHCb)

$LHCb$ background at $B^0_s \rightarrow hh$, Kirill Voronchev
$B_{s,d} \rightarrow \mu^+\mu^-$: LHCb selection

Tracks with
- $P_t > 1$ GeV
- $IP/\sigma > 3$

B candidate
- Vertex $\chi^2 < 9$
- $\angle$(momentum, decay direction) $< 5$ mrad

<p>| | |</p>
<table>
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</thead>
<tbody>
<tr>
<td>yields</td>
<td>2 fb$^{-1}$</td>
</tr>
<tr>
<td>$B_s \rightarrow \mu^+\mu^-$ signal (SM)</td>
<td>17</td>
</tr>
<tr>
<td>$b \rightarrow \mu^+$, $b \rightarrow \mu^-$ background</td>
<td>$&lt; 100$</td>
</tr>
<tr>
<td>Inclusive $bb$ background</td>
<td>$&lt; 7500$</td>
</tr>
<tr>
<td>All backgrounds</td>
<td>???</td>
</tr>
</tbody>
</table>
LHC should have prospect for significant measurement, but difficult to get reliable estimate of expected background:

- **LHCb:** Full simulation: 10M inclusive bb events + 10M $b \rightarrow \mu$, $b \rightarrow \mu$ events (all rejected for $M(\mu^+\mu^-)>4$ GeV/c$^2$)

- **ATLAS:** 80k $bb \rightarrow \mu^+\mu^-$ events with generator cuts, efficiency assuming cut factorization

- **CMS:** 10k $b \rightarrow \mu$, $b \rightarrow \mu$ events with generator cuts, trigger simulated at generator level, efficiency assuming cut factorization

<table>
<thead>
<tr>
<th></th>
<th>1 year</th>
<th>$B_s \rightarrow \mu^+\mu^-$ signal (SM)</th>
<th>$b \rightarrow \mu$, $b \rightarrow \mu$ background</th>
<th>Inclusive bb background</th>
<th>All backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LHCb</strong></td>
<td>2 fb$^{-1}$</td>
<td>17</td>
<td>&lt; 100</td>
<td>&lt; 7500</td>
<td></td>
</tr>
<tr>
<td><strong>ATLAS</strong></td>
<td>10 fb$^{-1}$</td>
<td>7</td>
<td>&lt; 20</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CMS (1999)</strong></td>
<td>10 fb$^{-1}$</td>
<td>7</td>
<td>&lt; 1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
(current) LHC Startup Schedule

• End of Summer 2007
  – Closure of beam vacuum in August
  – Closure of interaction regions
• “November-December” 2007
  – Pilot run at injection energy (450 GeV)
• Jan—April 2008
  – Shutdown
• Summer 2008
  – Run at Full Energy…
LHCb Installation Status

Muon system

Calorimeter
HCAL, ECAL

RI CH2
Tracking Stations

Magnet

RI CH1
Trigger Tracker

Vertex Locator
Summary & Conclusions

- The hadronic flavour sector will surely contribute significantly to the overall LHC effort to find and study physics beyond the SM:
  - New physics will be chased at LHC in $b\to s$ transitions
    - A few superb (highly-sensitive) $b\to s$ observables are accessible: $B_s$ mixing magnitude and phase, exclusive $b\to s\mu\mu$, $B(\bar{s})\to \mu\mu$
    - Large phase space can already be covered with the first good year of data
  - LHCb will improve precision on CKM angles
    - Several $\gamma$ measurements from tree decays only: $\sigma_{\text{stat}}(\gamma) \sim 2.5^\circ$ in 5 years
    - May reveal inconsistencies with other/indirect measurements after several years
  - Looking forward to end of LHC machine installation and first collisions in 2007
    - LHCb aiming for complete detector at end of 2006, ready to exploit nominal luminosity from day 1
$B_s \rightarrow \mu^+\mu^-$: Atlas & CMS...

<table>
<thead>
<tr>
<th>Integral LHC Luminosity</th>
<th>BG ev. $p_T(\mu) &gt; 6$ GeV, $\Delta R_{\mu\mu} &lt; 0.9$</th>
<th>Expected Signal ev. after cuts</th>
<th>Expected BG ev. after cuts</th>
<th>ATLAS upper limit at 90% CL</th>
<th>CDF&amp;D0 best upper limit at 90% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 pb$^{-1}$</td>
<td>$6.0 \times 10^4$</td>
<td>$\sim 0$</td>
<td>$\sim 0.2$</td>
<td>$6.4 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>10 fb$^{-1}$</td>
<td>$6.0 \times 10^6$</td>
<td>$\sim 7$</td>
<td>$\sim 20$</td>
<td>$7.0 \times 10^{-9}$</td>
<td>$1.2 \times 10^{-7}$</td>
</tr>
<tr>
<td>30 fb$^{-1}$</td>
<td>$1.8 \times 10^7$</td>
<td>$\sim 21$</td>
<td>$\sim 60$</td>
<td>$6.6 \times 10^{-9}$</td>
<td></td>
</tr>
</tbody>
</table>

From N. Nikitine [Capri workshop on Theory, Phenomenology and Experiment in Heavy Flavour Physics]

- **Low luminosity** 10 fb$^{-1}$ \(\sim 1\) year at $10^{33}$ cm$^{-2}$s$^{-1}$
  - Signal: 7.0
  - Background: < 1.0

- **High luminosity** 100 fb$^{-1}$ \(\sim 1\) year at $10^{34}$ cm$^{-2}$s$^{-1}$
  - Signal: 26.0
  - Background: < 6.4

From T. Speer [Capri workshop on Theory, Phenomenology and Experiment in Heavy Flavour Physics]

4σ observation with 30 fb$^{-1}$ (3 year low-lumi)
Trigger output rates and physics

- **Output rates:**
  - Rough guess at present (split between streams still to be determined)
  - Large inclusive streams to be used to control calibration and systematics tracking, PID, tagging

<table>
<thead>
<tr>
<th>Output rate</th>
<th>Event type</th>
<th>Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 Hz</td>
<td>Exclusive B candidates</td>
<td>B (core program)</td>
</tr>
<tr>
<td>600 Hz</td>
<td>High mass di-muons</td>
<td>J/ψ, b→J/ψX (unbiased)</td>
</tr>
<tr>
<td>300 Hz</td>
<td>D* candidates</td>
<td>Charm</td>
</tr>
<tr>
<td>900 Hz</td>
<td>Inclusive b (e.g. b→μ)</td>
<td>B (data mining)</td>
</tr>
</tbody>
</table>

- **Charm physics possibilities (to be explored):**
  - Could trigger on 500M signal D*→D⁰(h⁺h⁻)π per year, 50M D⁰→K⁺K⁻
  - D⁰ mixing (x and yₜₚ) and CP violation in D⁰→K⁺K⁻
    - could reach SM levels or close
    - systematics ?
Particle ID: $K/\pi$ separation

- Fully simulated pattern recognition in two LHCb RICHes:
  - Reconstruct rings around reconstructed tracks
  - Good $K-\pi$ separation achievable in 2–100 GeV/c range

Kaon ID: ~88%
Pion mis-ID: 3%
Flavour tagging

LHCb:
- Most powerful tag is opposite kaon (from $b \rightarrow c \rightarrow s$)
- Combined $\epsilon D^2 \sim 7\% \ (B_s)$ or $\sim 4\% \ (B^0)$
- Recent neural network approach leads to $\sim 9\%$ for $B_s$

### Tag

<table>
<thead>
<tr>
<th>Tag</th>
<th>$\epsilon D^2 = \epsilon (1-2w)^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opposite $\mu$</td>
<td>0.7%–1.8%</td>
</tr>
<tr>
<td>Opposite $e$</td>
<td>0.4%–0.6%</td>
</tr>
<tr>
<td>Opposite $K$</td>
<td>1.6%–2.4%</td>
</tr>
<tr>
<td>Opposite $Q_{vtx}$</td>
<td>0.9%–1.3%</td>
</tr>
<tr>
<td>Same side $\pi$ ($B^0$)</td>
<td>0.8%–1.0%</td>
</tr>
<tr>
<td>Same side $K$ ($B_s$)</td>
<td>2.7%–3.3%</td>
</tr>
<tr>
<td>Combined ($B^0$)</td>
<td>4%–5%</td>
</tr>
<tr>
<td>Combined ($B_s$)</td>
<td>7%–9%</td>
</tr>
</tbody>
</table>

Compare with:
- CDF achieved 4\% (SS) +1.5\% (OS)
- B factories achieved $\sim 30\%$ (Coherent Production!)
**Di-muon Trigger**

- **B-physics mostly during initial stage of low luminosity \( \sim 10^{33} \text{ cm}^{-2}\text{s}^{-1} \)**
  - vary by factor \( \sim 2 \) during beam-coast
  - 2-3 interactions/collision
- **bb pairs production \( \sim 500 \text{ kHz} \)**
  - 1% of collisions
  - \( 5 \times 10^{12} \) bb pairs / year = \( 10^{7} \) sec.
- **LVL1 trigger is based on detection of two muons \( p_{T_{\mu 1}} > 6 \text{ GeV}, p_{T_{\mu 2}} \geq 4 \text{ GeV} \)** by muon trigger chambers
- **LVL2 trigger + Event Filter confirms LVL1 measurement by precise MDT, calorimeters and tracks extrapolation to Inner Detector**
  - refits tracks in LVL2 ROIs
  - decay vertices search, mass cuts, decay length, opening angles, etc.

**Collisions rate**
- 40 MHz

**LVL1 rate**
- 200 Hz

**LVL2 rate**
- 100 Hz

**Event Filter**
- 10 Hz

*Flavour in the era of the LHC - 3rd meeting, Pavel Reznicek, reznicek@fmp.cas.cz, IFHE Charles University, Prague*
Expected LHCb tracking performance

- High multiplicity environment:
  - In a bb event, ~30 charged particles traverse the whole spectrometer

- Full pattern recognition implemented:
  - Track finding efficiency > 95%
    for long tracks from B decays
    (only 4% ghosts for \( p_T > 0.5 \) GeV/c)
  - \( K_S \to \pi^+\pi^- \) reconstruction 75% efficient for decay in the VELO, lower otherwise