B physics in ATLAS and CMS

- Can take advantage of the huge cross section at the LHC:
  - $\sim 500 \mu b \Rightarrow O(10^{12}-10^{13})$ pairs/yr/experiment

- Detectors and triggers flexible enough to accommodate B-physics needs.

- Most studies thought for first period of low luminosity running ($L=10^{33} \text{ cm}^{-2} \text{ s}^{-1}$):
  - not so “low”: many precise measurements already available after 1 yr ($10^4 \text{ pb}^{-1}$).
  - pile-up: $\sim 2.3$ events on average
B physics in ATLAS and CMS

- Low luminosity run time will depend on LHC schedule and performance.
- Full study of what can be done at higher luminosity (up to $L = 10^{34}$ cm$^{-2}$ s$^{-1}$) still needs to be done:
  - possibility to continue for some studies at high luminosity (with different trigger/cuts if needed) already demonstrated
- Need also to look at the impact of staged detectors on this strategy.
B-physics triggers

- Triggering is a major issue:
  - enormous \( pp \) interaction rate
  - select decays with complex signatures
- Rate reduction from 40 MHz to \( \sim 100 \) Hz with multi-level trigger system
- LVL1 trigger based on leptonic signatures from \( b \) decay:
  - ATLAS: 1 \( \mu \) with \( p_T > 6 \) GeV (dimuon trigger with lower threshold is under study)
B-physics triggers

- CMS: 1 or 2 leptons, $\eta/p_T$ dependent cuts:

<table>
<thead>
<tr>
<th></th>
<th>$1\mu$</th>
<th>$2\mu$</th>
<th>$1e$</th>
<th>$2e$</th>
<th>$e+\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_T$ (GeV)</td>
<td>7</td>
<td>2-4</td>
<td>12</td>
<td>5</td>
<td>5+4</td>
</tr>
</tbody>
</table>

- Still $\sim 2.3 \, \mu b \Rightarrow \sim 2 \times 10^{10} \, b\bar{b}$ pairs/yr (ATLAS)

- Selections of specific channels done at next trigger levels:
  - feasibility demonstrated for some exclusive and inclusive channels
B-physics triggers

- List of triggers can/will evolve as physics needs change
- **No purely hadronic triggers**
- Reduced statistics in hadronic B decays:
  - but when flavour tagging needed, additional lepton in the event can be used as lepton tag from decay of the other $b$ in the event
Flavour tagging

- LEP/CDF taggers appear feasible.
- Opposite Side Tagging:

<table>
<thead>
<tr>
<th></th>
<th>$\varepsilon$ (%)</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>lepton</td>
<td>2-3</td>
<td>0.4-0.5</td>
</tr>
<tr>
<td>jet charge</td>
<td>65</td>
<td>0.18</td>
</tr>
</tbody>
</table>

- Same Side Tagging:

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$B-\pi$</td>
<td>82</td>
<td>0.16</td>
</tr>
<tr>
<td>$B^{**}$</td>
<td>21</td>
<td>0.32</td>
</tr>
<tr>
<td>jet charge</td>
<td>50</td>
<td>0.23</td>
</tr>
</tbody>
</table>
Particle Identification

- No dedicated detectors for hadron identification available in ATLAS /CMS:
- Limited but useful $\pi/K$ separation achieved indirectly:
  - ATLAS: $\sim 1 \sigma$ separation using $dE/dx$ in straw tracker
    - Can be used on a statistical basis.
Characteristics for B physics

- **ATLAS:**
  - LVL1 trigger on 1µ with $p_T>6$ GeV (2µ under study)
  - good secondary vertex reconstruction
  - low $p_T$ µ ID (µ spectrometer+calorimeters)
  - electron ID down to $\approx 0.5$ GeV (TRT+calorimeters)
  - limited hadron ID ($\pi/K$) using dE/dx in TRT

- **CMS:**
  - LVL1 triggers also on low $p_T$ dileptons
  - good secondary vertex reconstruction
  - low $p_T$ µ ID (µ spectrometer)
  - low $p_T$ electron ID (tracking+calorimeters)
  - stronger B field (4 T) ⇒ better mass resolution
B physics performance

- Precision measurements possible in several channels:
  - better than Tevatron and B-factories
  - competitive with LHCb

- Higher luminosity than LHCb:
  - Precision measurements available just after few months/1 year of running
  - Ultimate precision might be better for other experiments (LHCb, BTeV) but first precise measurements might be done by ATLAS/CMS
B-physics performance

Moreover, can enhance overall precision of LHC:
- combine ATLAS/CMS and LHCb
- provide cross-check of LHCb results
  - different systematics
B-physics programme

- Not all B-physics possibilities of ATLAS and CMS assessed yet.
- Some “benchmark” channels looked at in great detail:
  - full simulation, sophisticated analysis method
- Programme will evolve with time:
  - follow theoretical developments
  - look at B-factories and Tevatron results
J/ψ samples

- Both $J/\psi \rightarrow \mu^+ \mu^-$ and $J/\psi \rightarrow e^+ e^-$ samples available:
  - low background

- mass resolutions:
  - $\sim 40$ MeV ($\mu\mu$) (ATLAS)
  - $\sim 20$ MeV ($\mu\mu$) (CMS)

- Good performance also in $b \rightarrow J/\psi$ inclusive samples at high $p_T$ (>50 GeV):
  - useful for production studies
J/ψ samples

Examples of channels studied so far:

- $B_{d,s}^0 \rightarrow J/ψ K_s^0$
- $B_s^0 \rightarrow J/ψ φ$
- $B_d^0 \rightarrow J/ψ K^{*0}$ and $B^+ \rightarrow J/ψ K^+$
- $B_c^+ \rightarrow J/ψ π^+$
- $B_{d,s}^0 \rightarrow J/ψ η$
- $b \rightarrow J/ψ X$
- $Λ_b \rightarrow J/ψ Λ^0$
Large and clean samples of $B_{d,s}^0 \rightarrow J/\psi K_{s}^0$
- ~165k (ATLAS), ~450k (CMS) events in 1 year

Excellent sensitivity to $A_{CP}^{mix} = -\sin 2\beta$ (1 yr):
- $\sigma(\sin2\beta) \approx 0.017$ (ATLAS), $\sigma(\sin2\beta) \approx 0.015$ (CMS)
  - LHCb: 90k evs/yr $\Rightarrow \sigma(\sin2\beta) \approx 0.021$ (LHC SM workshop)

Sensitivity to $A_{CP}^{dir}$:
- 5\sigma discovery limit: $A_{CP}^{dir} \approx 0.10$(ATLAS)

$B_{s}^0 \rightarrow J/\psi K_{s}^0$ studied to extract $\gamma$ (CMS):
- smaller $\sigma$.BR, smaller S/B, need good mass resolution
- $\gamma \approx 76^0 \Rightarrow \sigma(\gamma) \sim 9^0$ (3 yrs)
$B^0_{d,s} \rightarrow J/\psi K^0_s$

ATLAS: $B^0_d \rightarrow J/\psi(ee)K^0_s$

B-CMS

$J/\psi K_s$

with $10^4$ evts/Pb

Pt($\pi$) > 1.5 GeV
Large and clean samples also available:
- 100k (ATLAS), 200k (CMS) evs/yr (untagged)
  - compare with LHCb: 74k evs/yr (LHC SM workshop)
- More complex study: angular analysis
  - tagged and untagged samples needed
- Can be used to fit $\Delta \Gamma_s$, $\Gamma_s$ and $\phi_s = -2 \delta \gamma$

<table>
<thead>
<tr>
<th></th>
<th>$\Delta \Gamma_s$</th>
<th>$\Gamma_s$</th>
<th>$\phi_s(x_s=20)$</th>
<th>$\phi_s(x_s=40)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>12%</td>
<td>0.7%</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>CMS</td>
<td>8%</td>
<td>0.5%</td>
<td>0.014</td>
<td>0.03</td>
</tr>
<tr>
<td>LHCb</td>
<td>9%</td>
<td>0.6%</td>
<td>0.02</td>
<td>0.03</td>
</tr>
</tbody>
</table>

$\phi_s = \mathcal{O}(0.03)$: good place to look for NP
Final state is CP eigenstate

Preliminary results show that only the $B_s$ mode appear feasible:

- 10k events (ATLAS/3 yrs), $S/B \sim 1$

again $A_{CP}^{mix} = \sin \phi_s$, small asymmetry

- But NP can enhance the asymmetry

First estimates (ATLAS, 3 yrs):

- $\sigma(\sin \phi_s) = 0.17$ for $x_s=19$
- $\sigma(\sin \phi_s) = 0.33$ for $x_s=30$
$B^0_{d,s} \rightarrow J/\psi \eta$

$\eta \rightarrow \gamma \gamma$

$B_s$ mass peak + bkg
b-production

- Large samples of exclusive and inclusive b-hadron decay will be available for b-production studies:
  - total/differential cross sections
  - $b\bar{b}$ correlations
- $J/\psi$ samples candidates for these studies:
  - at $p_T$ up to $\sim 400$ GeV: inclusive b-jet tagging
  - $b \rightarrow J/\psi X$ events look promising for $b\bar{b}$ correlation studies
Select 3 $\mu$ events and study $\mu$-J/ψ angular separation:
- lower background than dimuon events especially at low $p_T$ ($\pi/K$, cascade decays, …)
- Can access low $\Delta\phi_{bb}$ region with higher efficiency
Dimuon samples

- Outside the J/ψ and ψ′ resonances
- Examples of channels studied so far:

\[ B_s^0 \rightarrow \mu^+ \mu^- \]
\[ B_d^0 \rightarrow \mu^+ \mu^- \]
\[ B_d^0 \rightarrow K^{*0} \mu^+ \mu^- \]
\[ B_d^0 \rightarrow \rho^0 \mu^+ \mu^- \]
\[ B_s^0 \rightarrow \phi \mu^+ \mu^- \]
Rare decays

- Rare decays with low SM BR ($<10^{-5}$):
  - FCNC loops, sensitive to NP effects
  - BR may be substantially higher if new physics appears

- Self-triggering modes at LVL1

- Studies can be continued also at high luminosity:
  - dimuon trigger rate sustainable at LVL1
Rare decays

- Estimates for 3 yr at low $L + 1$ yr at high $L$
- If SM BR$\sim3.5\times10^{-9}$ for $B_s^0 \rightarrow \mu^+\mu^-$:
  - clear $5\sigma$ observation should be possible
- For $B_d^0 \rightarrow \mu^+\mu^-$ (SM BR$\sim1.5\times10^{-10}$):
  - handful of events, more difficult
- For $B_d^0 \rightarrow K^{*0} \mu^+\mu^-$ (SM BR$\sim1.5\times10^{-6}$):
  - events/year: $\sim700$ (ATLAS), $\sim4.2k$ (CMS)
    - compare with LHCb: 4.5k events/year (LHC SM workshop)
  - will allow detailed studies of this decay
\[ B_d^{0} \rightarrow K^{*0} \mu^+ \mu^- \]

- \( A_{FB} \) asymmetry in this decay sensible to NP
- 5\% precision on \( A_{FB} \) after 3 years (ATLAS)
  - compare with LHCb:
    - 2.4\% after 1 year (LHC SM workshop)
- can distinguish SM from some SUSY models
Hadronic channels

- Examples of channels studied so far:

  $B_s^0 \rightarrow D_s^+ \pi^-$

  $B_s^0 \rightarrow D_s^+ a_1^-$

  $B^0 \rightarrow h^+ h^-$

  $B^+ \rightarrow K^+ K^+ \pi^-$
\[ B_d^0 \rightarrow \pi^+ \pi^- \]

- \( B_d^0 \rightarrow \pi^+ \pi^- \) yields:
  - 2.3k events/yr, S/B~0.2 (2-body bkg) (ATLAS)
  - compare with LHC: 4.9k, S/B~15 (LHC SM workshop)

- Hadron identification important

- Allow extraction of sensitivities on and correlation coefficient (1 yr): \( A_{CP}^{\text{dir}} \quad A_{CP}^{\text{mix}} \)

<table>
<thead>
<tr>
<th></th>
<th>( \sigma(A_{CP}^{\text{dir}}) )</th>
<th>( \sigma(A_{CP}^{\text{mix}}) )</th>
<th>( \sigma^{\text{corr}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>0.16</td>
<td>0.21</td>
<td>-0.25</td>
</tr>
<tr>
<td>LHCb</td>
<td>0.09</td>
<td>0.07</td>
<td>-0.49</td>
</tr>
</tbody>
</table>

- Extraction of \( \alpha \) not straightforward:
\( \alpha \) extraction

- 2 linearized relations relating \( \alpha, |P/T|, \delta \)
  - \( P \) (penguin) and \( T \) (tree) amplitudes and \( \delta \) their strong phase difference
  - \( \delta \) cannot be calculated, need to be measured
- Present estimate of \( |P/T| > \sim 0.36 \pm 0.05 \) implies an exact parameterization in terms of \( \alpha, \alpha_{\text{eff}}, |P/T| \) is preferable
- Sensitivity on \( \alpha \) highly dependent on \( \alpha, \alpha_{\text{eff}}, |P/T| \) and \( \sigma(|P/T|) \)
- It will be difficult to measure \( \alpha \) but can test the SM predictions (\( \alpha + \beta + \gamma = \pi \)).
Sensitivity on $\alpha$

\[ A_{CP}^{\text{mix}} = -\sqrt{1 - A_{CP}^{\text{dir}}^2} \sin 2\alpha_{\text{eff}} \]

\[ \cos(2\alpha - 2\alpha_{\text{eff}}) = \frac{1}{\sqrt{1 - A_{CP}^{\text{dir}}^2}} \left[ 1 - \left( 1 - A_{CP}^{\text{dir}}^2 \cos 2\alpha_{\text{eff}} \right) \left| \frac{P}{T} \right|^2 \right] \]

- Example of dependende of $\sigma(\alpha)$ on various parameters (LHC combined).
CP asymmetries in $B_d^0 \rightarrow \pi^+\pi^-$ and $B_s^0 \rightarrow K^+K^-$ can be related to $\beta$, $\gamma$ and to hadronic amplitude $d$ and phase $\theta$:

- can be determined simultaneously
- $B_s^0 \rightarrow K^+K^-$ yields: 1.4k events/yr (ATLAS)
  - compare with LHCb: 4.6k evs, S/B~6 (LHC SM workshop)
  - but ATLAS fits all together using a MLE

Sensitivity depends on parameter choice:

- $\gamma \approx 60^0 \Rightarrow \sigma(\gamma) \sim 8^0$ (3 yrs)
Sensitivity on $\gamma$

$\sigma(\gamma) = 8, 10, 15, 20$
Large samples (ATLAS uses also $B_s^0 \rightarrow D_s^+ a_1$):
- ~3.5k (ATLAS), ~4.5k (CMS) events/yr
- Automatically tagged by LVL1 muon

Exclusive channels, good proper time resolutions:
- $\sigma(\tau) = 71$ fs (ATLAS), $\sigma(\tau) = 65$ fs (CMS)

Measurement of mixing parameter $\Delta m_s$:
- 95% CL sensibility up to $\Delta m_s \sim 40$ ps$^{-1}$ (after 1 yr)
  - LHCb: 34.5k evs/yr, $\sigma(\tau) = 43$ fs, $\Delta m_s \sim 58$ ps$^{-1}$
  - $\sigma(\Delta m_s) = 0.11$ ps$^{-1}$ at about $\Delta m_s = 23$ ps$^{-1}$
Conclusions

- Rich, competitive B-physics programmes appear feasible by ATLAS and CMS
  - “Physics performance TDR” (ATLAS)
  - ‘99 SM physics at LHC workshop (ATLAS, CMS)
- Many studies on-going
- Need also to look at:
  - recent changes in the detector design
  - perspectives with staged detectors