B Physics @ CMS

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On behalf of the CMS Collaboration

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- Simulation/reconstruction software
- Trigger issues
- Some issues about Tracking
- Exclusive B decay channels
- Results
- Conclusions
Introduction

b production at LHC

- Peak luminosity: \(2 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}\) → \(10^{34} \text{ cm}^{-2} \text{s}^{-1}\)
- \(\sigma = 500 \mu \text{b} \quad \text{O(10^5-10^6) b pairs/sec}\)
- Only 100 ev/sec on tape for ALL interesting physics channels

B-physics program

- Rare decays
- CP violation
- \(B^0_s - \overline{B^0_s}\) mixing

Trigger highly challenging

- \(B_S \rightarrow \mu\mu\)
- \(B_S \rightarrow J/\psi \phi \rightarrow \mu\mu \ K K\)
- \(B_S \rightarrow D_S \pi \rightarrow K K \ \pi \pi\)

Results from DAQ-TDR (CERN/LHCC 2002-26)
**Simulation & Reconstruction Software**

- **Event Generation:** PYTHIA 6.158
  - Interface to the user: CMKIN
  - Minimum bias event pile-up
  - Gluon splitting, heavy quark fusion, flavour excitation taken into account for b\(\bar{b}\) events production

- **Detector description and simulation:** CMSIM based on Geant3
  - Geometry and material budget as in 2002

- **Detector response:**
  - Digitization, noise, effects due to pile-up, ...
  - Level 1 trigger simulation

- **Reconstruction:**
  - Deposits in the calorimeters
  - Muons
  - Tracks
  - Primary and secondary vertices

Fortran based. Their equivalent C++ version is on the way …..

C++ Object Oriented
Same software for online and offline reconstruction and selection
### L1 Trigger

#### Low Luminosity L1 Trigger Table (Prototype)

<table>
<thead>
<tr>
<th>Trigger type</th>
<th>Threshold ($\varepsilon=95%$) (GeV)</th>
<th>Indiv. Rate (kHz)</th>
<th>Cumul rate (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1e/\gamma, 2e/\gamma</td>
<td>29, 17</td>
<td>4.6</td>
<td>4.3</td>
</tr>
<tr>
<td>1\mu, 2\mu</td>
<td>14, 3</td>
<td>3.6</td>
<td>7.9</td>
</tr>
<tr>
<td>1\tau, 2\tau</td>
<td>86, 59</td>
<td>3.2</td>
<td>10.9</td>
</tr>
<tr>
<td>1-jet, 3-jets, 4-jets</td>
<td>177, 86, 70</td>
<td>3.0</td>
<td>12.5</td>
</tr>
<tr>
<td>Jet * MissE_T</td>
<td>88 * 46</td>
<td>2.3</td>
<td>14.3</td>
</tr>
<tr>
<td>e * jet</td>
<td>21 * 45</td>
<td>0.8</td>
<td>15.1</td>
</tr>
<tr>
<td>Min-bias</td>
<td></td>
<td>0.9</td>
<td>16.0</td>
</tr>
</tbody>
</table>

- Designed to cover the widest possible range of physics for discovery
- Total L1 allocated rate - 50 KHz x 1/3 safety factor

- B Physics selection triggered @ L1 by single or di-muon triggers
- Particles from B decays have relatively soft spectrum
- Important keeping the L1 threshold as low as possible
- Muons are preferred to electron because of the lower trigger threshold
Muons in the High Level Trigger

- After HLT only 100Hz can be stored on tape
- 30Hz allocated to 1µ, 2µ (25Hz+5Hz) (P_T > 19GeV, P_T > 7GeV)
- The content in b is too little (~5Hz for b/c)
- Need to push and select exclusive b events

Exploit the online tracking

1Hz \rightarrow 10^7 \text{ evts/year} @ low luminosity
Insufficient for processes with BR < 10^{-4}
High-Level Trigger Tracking

Limited amount of CPU time available for trigger decision:
500 ms on a 1GHz machine
possibly 50 ms in 2007

Regional seed generation
Limited to some region identified by Lvl1 objects
(e.g. cone around $\mu$ direction)

Partial/Conditional Tracking
Stopped when:
- $N$ hits are reconstructed
- $P_T$ resolution $>$ given threshold
- $P_T$ value $<$ given threshold

Reduce
- # of track seeds
- # of operations per seed

HLT Tracking does not need to be as accurate as in the offline
Primary vertex reconstruction

- Pixel hit pairing in R-z and R-ϕ
  - $d_0 \leq 1 \text{ mm } , P_T > 1 \text{ GeV}$
- Matching with 3rd layer $\rightarrow$ track candidate
- PV candidate if $\geq 3$ track cross z-axis
- PV list $\rightarrow$ Signal vertex from $\Sigma P_T$ and $N_{\text{tracks}}$
- Cleaning of tracks not pointing to PV

Average time: 50msec @1 GHz

Only Pixel Detector

$\sigma = 26 \mu m$
Partial Tracking

Transverse Momentum Resolution

Impact parameter Resolution

Tracking time proportional to the number of hits
Good efficiency/ghost rate & resolution with just 5 hits

Full Tracker

0 < |η| < 0.9
2.5 < pt [GeV/c] < 5

σ(p_{re}-p_{sim}) [GeV/c]

σ(d_0_{re}-d_0_{sim}) [μm]
Exclusive B decay channels

Three decay channels chosen as benchmark

1. $B_S \rightarrow \mu^- \mu^+$
   - FCNC $b \rightarrow s$, loop-level process in SM
   - Indicator of possible new physics
   - Observable before LHC only if drastically enhanced
   - Unique signature....but BR $\sim O(10^{-9})$

2. $B_S \rightarrow J/\psi \, \phi \rightarrow \mu^- \mu^+ K-K^+$
   - Gold-plated decay mode for CP-violation
   - Sensitive to new physics
   - Won't be studied with big accuracy before LHC

3. $B_S \rightarrow D_S \pi^+ \rightarrow \phi \pi^- \pi^+ K^- K^+$
   - $B^0 - \bar{B}^0$ Mixing
   - $B_S$ flavour @ decay time unambiguously tagged by $D_S$ sign

Triggered @ L1 by the presence of 2$\mu$

Triggered @ L1 by the presence of 1$\mu$ (from the semileptonic decay of the other $b$ hadron in the event)
@ L1: 
- 2μ trigger, \( p_T > 3 \) GeV, \( |\eta| < 2.1 \)

@ High Level Trigger:
- **Regional tracking**: Look for pixel seeds only in a cone around the 2μ, with \( p_T > 4 \) GeV and \( d_0 < 1 \) mm, and compatible with PV

- **Conditional tracking**: Reconstruct tracks from good seeds
  - Stop reconstruction if \( p_T < 4 \) GeV @ 5σ
  - Keep only tracks with \( \sigma(p_T)/p_T > 2\% \), \( N_{hit} = 6 \)

IF 2 Opposite Signs tracks found
- Calculate the invariant mass
- Retain pairs with
  a) \( |M_{\mu\mu} - M_{B_s}| < 150 \) MeV
  b) Vertex \( \chi^2 < 20 \) & \( d_0 > 150 \) μm

<table>
<thead>
<tr>
<th>Lvl-1 ε</th>
<th>HLT ε</th>
<th>Global ε</th>
<th>Events/ 10fb^{-1}</th>
<th>Trigger Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.2%</td>
<td>33.5%</td>
<td>5.1%</td>
<td>47</td>
<td>&lt;1.7Hz</td>
</tr>
</tbody>
</table>

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$B_S \rightarrow \mu^-\mu^+$

**Old offline analysis (hep-ph/9907256 Jul 1999) predicts:**

- 14 events ± 2 bkg @ 90 C.L. with 20 fb$^{-1}$ (1 year @ 2x10$^{33}$ cm$^{-2}$s$^{-1}$)
- 5$\sigma$ observation with 40 fb$^{-1}$ and feasibility @ high lumi too

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……… But L1 is in $|\eta| < 2.4$ + slightly different kinematics cut
Update foreseen for the CMS Physics TDR
```
$B_S \rightarrow J/\psi \phi \rightarrow \mu \mu$ KK

**CP violation weak phase**

$\phi_s = 2 \delta \gamma = 2 \lambda^2 \eta$

SM predicts tiny CP asymmetry $\phi_s \sim O(0.03)$

$\text{BR}(B_S \rightarrow J/\psi \phi) = (9.3 \pm 3.3) \times 10^{-4}$

$\text{BR}(J/\psi \rightarrow \ell^+ \ell^-) \approx 6\%$

$\text{BR}(\phi \rightarrow K^+ K^-) \approx 49\%$

1st step: J/$\psi$ reconstruction → Retain muon pairs with

$|M_{\mu\mu} - M_{J/\psi}| < 100$ MeV & Vertex $\chi^2 < 10$ & $d_0 > 200$ $\mu$m

Rate = 15 Hz

2nd step: $\phi$ and $B_S$ reconstruction

Regional/conditional tracking around the J/$\psi$ direction + $|M_{KK} - M_{\phi}| < 10$ MeV

Then invariant mass $|M_{J/\psi\phi} - M_{B_S}| < 60$ MeV + $B_S$ vertexing

$t>\sim 800$ ms

<table>
<thead>
<tr>
<th>Lvl-1 $\epsilon$</th>
<th>HLT step 1 $\epsilon$</th>
<th>HLT step 1 Rate</th>
<th>HLT step 2 $\epsilon$</th>
<th>HLT step 2 Rate</th>
<th>Events/ 10fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.5%</td>
<td>13.7%</td>
<td>14.5 Hz</td>
<td>8.7%</td>
<td>&lt;1.7Hz</td>
<td>83800</td>
</tr>
</tbody>
</table>
The strong solenoid magnetic field $\rightarrow$ Good $B_s$ mass resolution and lower background
\[ \mathcal{B}_S \rightarrow J/\psi \phi \rightarrow \mu \mu KK \]

Old CMS analysis (CERN-2000-004) not updated yet

Angular distribution analysis
Expected number of signal evts \( \sim 600K \)
(yield with \( 30 \text{fb}^{-1} \))

Trigger was NOT optimized

<table>
<thead>
<tr>
<th>( \Delta \Gamma_s )</th>
<th>( \phi_s(x_s=20) )</th>
<th>( \phi_s(x_s=40) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>0.15 x ( \Gamma_s )</td>
<td>0.04</td>
</tr>
<tr>
<td>Error</td>
<td>8.0%</td>
<td>0.014</td>
</tr>
</tbody>
</table>

Expected yields from HLT: \( \sim 300K \) with \( 40 \text{fb}^{-1} \)

\[ \sigma(\Delta \Gamma_s)/\Delta \Gamma_s \sim 12\% \]
\[ \delta \phi_s(x_s=20) \sim 0.02 \text{ rad} \]
\[ \delta \phi_s(x_s=40) \sim 0.04 \text{ rad} \]
Secondary vertex reconstruction

$B_s \rightarrow \mu \mu$

$B_s \rightarrow J/\psi \phi$

<table>
<thead>
<tr>
<th></th>
<th>$B_s \rightarrow \mu \mu$</th>
<th>$B_s \rightarrow J/\psi \phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(x)$ $\mu$m</td>
<td>$47.5 \pm 3.63$</td>
<td>$55.3 \pm 0.95$</td>
</tr>
<tr>
<td>$\sigma(z)$ $\mu$m</td>
<td>$71.5 \pm 1.3$</td>
<td>$72.7 \pm 1.4$</td>
</tr>
<tr>
<td>CPU time msec</td>
<td>1.9</td>
<td>3</td>
</tr>
</tbody>
</table>

CPU time in msec.
\[ B_S \rightarrow D_S \pi \rightarrow \phi \pi \pi \rightarrow K K \pi \pi \]

**Current W.A.:** \( B_S^0 - \bar{B}_S^0 \) mixing: \( \Delta M_S \geq 14.4 \text{ ps}^{-1} \) @95%CL

**SM prediction:** \( 14.8 \leq \Delta M_S \leq 25.9 \text{ ps}^{-1} \) @ 99%CL

@ L1:

- single \( \mu (P_T > 14 \text{ GeV}) \) or low-\( P_T \mu + \) low-\( E_T \) jet (various threshold scenarios possible). The \( \mu \) also serves for tagging the \( B_S \) flavour @ production time.

@ HLT:

**Pixel Primary vertex** reconstruction

**Partial Tracking:** Seeds with \( P_T > 0.7 \text{ GeV} \), 3 Hits (2 pixels + 1 SST) & \( z \pm 1 \text{ mm} \) from PV

**Topological cuts:** \( \Delta R(KK) < 0.3, \Delta R(\phi \pi) < 1.2, \Delta R(D_S \pi) < 2.0, \Delta \phi(B_S, \mu) > 0.6 \)

**Kinematical cuts:** \( P_T(\phi) > 2 \text{ GeV}, P_T(D_S) > 4 \text{ GeV}, P_T(B_S) > 5 \text{ GeV} \)

**Mass reconstruction:** \( \Delta M_\phi < 15 \text{ MeV}, \Delta M_{D_S} < 75 \text{ MeV}, \Delta M_{B_S} < 270 \text{ MeV} \)

**HLT efficiency ~ 9%, \( \langle t \rangle = 640 \text{ msec} \)**
\[ B_s \rightarrow D_s \pi \rightarrow \phi \pi \pi \rightarrow KK \pi \pi \]

- \( \sigma = 5 \text{ MeV} \)
- \( \sigma = 25 \text{ MeV} \)
- \( \sigma = 95 \text{ MeV} \)

**HLT Mass resolutions (only 3 hits used for Tracking)**

- \( \phi \)
- \( D_s \)
- \( B_s \)

**# of signal evts depends on the L1 B.W. allocated to the channel**

Assuming 1KHz allocated @ L1 (5Hz @ HLT)

- 300-400 signal events/year
- sensitivity to \( \Delta m_s \) up to 20 ps\(^{-1}\)
- 1000 evts needed to cover the whole SM allowed range \( \Delta m_s \leq 26 \text{ ps}^{-1} \)

*(CMS NOTE 2000/038, CMS NOTE 2002/045)*
$B_s \rightarrow D_s \pi \rightarrow \phi \pi \pi \rightarrow K K \pi \pi$

Machine conditions/instantaneous luminosity might allow lowering the L1 thresholds below the nominal value.

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**Table: Trigger rates (KHz) vs cuts on the muon $p_T$ and jet $E_T$**

<table>
<thead>
<tr>
<th>$p_T^{\mu}$</th>
<th>$E_T^{\text{jet}}$</th>
<th>0 GeV</th>
<th>20 GeV</th>
<th>30 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 GeV</td>
<td>0.27 (50)</td>
<td>0.15 (15)</td>
<td>0.08 (5.7)</td>
<td></td>
</tr>
<tr>
<td>5 GeV</td>
<td>0.19 (33)</td>
<td>0.10 (11)</td>
<td>0.06 (4.2)</td>
<td></td>
</tr>
<tr>
<td>6 GeV</td>
<td>0.16 (26)</td>
<td>0.082 (8.5)</td>
<td>0.055 (3.6)</td>
<td></td>
</tr>
<tr>
<td>7 GeV</td>
<td>0.11 (18)</td>
<td>0.062 (6.2)</td>
<td>0.045 (2.7)</td>
<td></td>
</tr>
<tr>
<td>10 GeV</td>
<td>0.037 (6.4)</td>
<td>0.021 (2.5)</td>
<td>0.014 (1.3)</td>
<td></td>
</tr>
<tr>
<td>14 GeV</td>
<td>0.017 (3.2)</td>
<td>0.010 (1.3)</td>
<td>0.008 (0.7)</td>
<td></td>
</tr>
</tbody>
</table>

**HLT (Lvl-1)**
### High Level Trigger Table @ Low Luminosity

<table>
<thead>
<tr>
<th>Trigger type</th>
<th>Threshold (e=90-95%) (GeV)</th>
<th>Indiv. Rate (Hz)</th>
<th>Cumul. rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1e, 2e</td>
<td>29, 17</td>
<td>34</td>
<td>34</td>
</tr>
<tr>
<td>$1\gamma, 2\gamma$</td>
<td>80, (40*25)</td>
<td>9</td>
<td>43</td>
</tr>
<tr>
<td>$1\mu, 2\mu$</td>
<td>19, 7</td>
<td>29</td>
<td>72</td>
</tr>
<tr>
<td>$1\tau, 2\tau$</td>
<td>86, 59</td>
<td>4</td>
<td>76</td>
</tr>
<tr>
<td>Jet * Miss$E_T$</td>
<td>180 * 123</td>
<td>5</td>
<td>81</td>
</tr>
<tr>
<td>1-jet, 3-jet, 4-jet</td>
<td>657, 247, 113</td>
<td>9</td>
<td>89</td>
</tr>
<tr>
<td>e * jet</td>
<td>19 * 52</td>
<td>1</td>
<td>90</td>
</tr>
<tr>
<td>Inclusive b-jets</td>
<td>237</td>
<td>5</td>
<td>95</td>
</tr>
<tr>
<td>Calibration/other</td>
<td>237</td>
<td>5</td>
<td>105</td>
</tr>
</tbody>
</table>

**B-Physics is missing ……...**

- **Bandwith for B-physics @ LHC start-up will depend on:**
  - **Luminosity**
    - Lower luminosity → larger bandwith
  - **Background conditions**
    - The safety factor of 3 might be pessimistic → lower thresholds, add trigger types, exploit the full B.W.

- In addition a possible strategy is to introduce B-triggers as the luminosity drops during the fill (2 drops expected)
Conclusions

- LHC huge bb statistics will allow first observations (e.g. $B_s \rightarrow \mu^-\mu^+$) and very accurate studies (e.g. determination of $\Delta \Gamma_s$ from $B_s \rightarrow J/\psi \phi$).

- Although CMS design is not B-physics specific, it can support a competitive B-physics program.

- Fast Tracking is a key point in B-decay selection at High Level Triggers as demonstrated for few benchmark channels in the DAQ TDR.

- LHC operating conditions, especially at start-up are critical: Low luminosity for a while $\rightarrow$ lots of B physics.

- The Physics TDR, due in the next few years, will address in more details the CMS B-physics potential, turning the attention from the HLT selection to detailed offline analysis.
Backup material
Trigger & DAQ architecture

Two level trigger: Lvl-1 and High Level Triggers

Several staging scenarios possible. Each slice allows 12.5 KHz

4 DAQ slices at start-up => 50 KHZ
Lvl-1 Trigger: Muon Stream

Low Luminosity

16 kHz DAQ
3.6 kHz for $\mu$, $\mu\mu$

$\eta < 2.1$

Symmetric di-muon $p_T^{cut}$ / GeV/c

Single muon $p_T^{cut}$ / GeV/c

14 ; 3.3
2.7 + 0.9 = 3.6 kHz
$\varepsilon_W = 90\%$
$\varepsilon_Z = 99\%$
$\varepsilon_{Bs \rightarrow \mu\mu} = 15\%$