CMS B Physics

Results and prospects for the future

Franco Ligabue
SNS and INFN, PISA
On behalf of
The CMS Collaboration
**B physics at LHC**

- **b quark in pp collisions:**
  - high cross section
  - efficient tagging possibilities
  - provide a test of QCD higher order corrections (production mechanism)
  - weak (production and) decay:
    - tool for testing also the weak sector
B physics at LHC

- Early B physics at CMS (low luminosity):
  - Quarkonia production
  - inclusive b-jet production

- Later, with higher statistics:
  - exclusive b-hadron decays
    - test SM and BSM physics (CP, rare decays)

- Main tools:
  - muons (semileptonic b, quarkonia ID)
  - secondary vertexing (b-jet tagging)
LHC and CMS performance

Very good LHC performance and rapid improvement

LHC instantaneous pp luminosity
\[ 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \]

end of 2010 pp run:

43 pb\(^{-1}\) collected by CMS

Low \(p_T\) dimuon triggers initially optimized for J/\(\psi\) and Upsilon

Only a fraction of the collected data is used for the results presented here

\[ L \approx 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \]
relevant detectors for B physics (b-tagging and quarkonium detection):

- **Silicon Tracker**
- **Muon Chambers**
tracker performance

**Impact Parameter Resolution**
- Very good data/MC agreement

**Impact Parameter Significance**
- Secondary vertex displacement significance

---

Franco Ligabue  CMS B Physics  Discrete2010
Di-lepton invariant mass

Stricter triggers now in place to limit storage rates.

Level-1 and HLT trigger: high capability and flexibility
down to low masses and $p_T$, (especially low $p_T$ muon triggers)
(lower instantaneous luminosities at LHC start-up)
Muon Trigger

- **Two trigger levels**
  - **Level 1** (hardware)
    - (fast) based on calorimeters & muon system (not combined)
  - **High Level Trigger** (software)
    - matches different subdetectors
    - based on fast local tracking for muons

- **trigger requirements changing with increasing luminosity** (due to total rate issues)
  - **Single muon**:
    - $p_T > 3$ GeV at start-up
    - increasing to $p_T > 7$ GeV at $L \approx 10^{31}$ cm$^{-2}$s$^{-1}$
  - **Double muon**:
    - No $p_T$ threshold at start-up!
    - at $L \approx 10^{31}$ cm$^{-2}$s$^{-1}$ ad-hoc strategies for quarkonia (combination of different single muon triggers)
CMS muon detectors
pseudorapidity reach
Global muon (outside-in):

Muon reconstructed in Muon detectors

matched to

reconstructed track

High purity
Low efficiency for low momentum muon

Tracker muon (inside-out):

Track reconstructed in Silicon detectors

matched to

Track element in Muon detectors

lower purity (high fake rate)
Higher efficiency for low momentum muon
muon identification performance

Muons from minimum bias events

detectors commissioned with cosmic runs in 2008 in 2009

Franco Ligabue       CMS B Physics       Discrete2010
muon identification performance

Tracker Muons

Global Muons

pion misidentification probability from $K_S$ decays

kaon misidentification probability from $\phi$ decays

CMS-PAS-MUO-10-002
muon efficiencies:
Tag & Probe method

CMS-PAS-MUO-10-002

exploit $J/\Psi \rightarrow \mu\mu$ mass peak

tag muon: strictly identified

probe muon: used to measure efficiency

can be used to measure on data different efficiencies:

muon-ID trigger
track quality cuts
prompt and non-prompt J/ψ production

- motivations:
  - prompt production:
    - test theoretical models (e.g. color singlet vs octet)
    - historical discrepancies with Tevatron data
  - non prompt: from b hadron decays
    - test B production and decay models at high energies
    - test QCD and PDFs
prompt and non-prompt J/ψ production

CMS Analysis:
(first 314 nb⁻¹)

- Acceptance window for muons
- Track quality:
  - number of hits in full tracker
  - number of hits in pixel layers
  - track fit $\chi^2$
- Muon quality:
  - fit $\chi^2$
  - track-muon matching
- Di-muon vertex quality

vertexing and tracking allow separation between prompt and non-prompt production

~27000 events selected
prompt J/ψ cross section

invariant mass fit in pre-defined $p_T$ and $y$ regions

measured yield is corrected for

acceptance and efficiency

linked to detector performance from data (T&P)

depends on the polarization of the J/ψ: computed for 5 «extreme» cases

in the MC:

- **prompt J/ψ**: unpolarized (isotropic decay)
- **non-prompt**: polarized as predicted by EvtGen

$$\sigma(pp \rightarrow J/\psi + X) \cdot BR(J/\psi \rightarrow \mu^+ \mu^-) = 97.5 \pm 1.5(\text{stat}) \pm 3.4(\text{syst}) \pm 10.7(\text{luminosity}) \text{ nb}$$
**J/ψ: acceptance**

Figure 2: Left: Acceptance as a function of the $J/\psi$ $p_T$ and rapidity. Right: Number of muon pairs within ±100 MeV/$c^2$ of the nominal $J/\psi$ mass, in bins of $p_T$ and $|y|$. 
non-prompt $J/\psi$ cross section

\[ u = \frac{p_T}{|p_T|} \quad x = SV_{xy} - PV_{xy} \]

**Pseudo proper decay length**

\[ \ell_{J/\psi} = L_{xy} \cdot m_{J/\psi} / p_T \]

projection of measured vertex distance onto momentum direction

Decay length $l_{xy}$ resolutions depend on the $p_T$ and mildly on the rapidity

- $p_T$ (J/Psi) 0-2 GeV/c $\sim$ 250 µm
- $p_T$ (J/Psi) 10-30 GeV/c $\sim$ 35 µm

**Decay length parametrization**:

- **Prompt**: $\delta$-function
- **Non-prompt**: MC templates all convoluted with a 3-Gaussian resolution
non-prompt J/$\psi$ cross section

CMS $\sqrt{s} = 7$ TeV
L = 314 nb$^{-1}$

### Fraction of J/$\psi$ from b hadrons

- $1.6 < |y| < 2.4$
- $1.2 < |y| < 1.6$
- $|y| < 1.2$

### Relative error (in %)

| Source | $|y| < 1.2$ | $1.2 < |y| < 1.6$ | $1.6 < |y| < 2.4$ |
|--------|------------|------------------|------------------|
| Tracker misalignment | 0.5 – 0.7 | 0.9 – 4.6 | 0.7 – 9.1 |
| b-lifetime model | 0.0 – 0.1 | 0.5 – 4.8 | 0.5 – 11.2 |
| Vertex estimation | 0.3 | 1.0 – 12.3 | 0.9 – 65.8 |
| Background fit | 0.1 – 4.7 | 0.5 – 9.5 | 0.2 – 14.8 |
| Resolution model | 0.8 – 2.8 | 1.3 – 13.0 | 0.4 – 30.2 |
| Efficiency | 0.1 – 1.1 | 0.3 – 1.3 | 0.2 – 2.4 |

---

**Notes:**
- CMS $\sqrt{s} = 7$ TeV
- CDF $\sqrt{s} = 1.96$ TeV
- PRD 71 (2005) 032001

---

**Graphs:**
- 2D distribution of events with fit
- Reduced $\chi^2 = 0.36$
prompt and non-prompt $J/\psi$: comparison with theory

$\sigma(pp \rightarrow J/\psi + X) \cdot BR(J/\psi \rightarrow \mu^+\mu^-) = 70.9 \pm 2.1\text{(stat)} \pm 3.0\text{(syst)} \pm 7.8\text{(luminosity)}$ nb

$\sigma(pp \rightarrow bX \rightarrow J/\psi X) \cdot BR(J/\psi \rightarrow \mu^+\mu^-) = 26.0 \pm 1.4\text{(stat)} \pm 1.6\text{(syst)} \pm 2.9\text{(luminosity)}$ nb
Y(nS) production

- Similar selection as J/ψ:
  - acceptance from MC
  - efficiencies from data (T&P)
- fit to 3 Crystal Ball functions + linear background
- main systematics from efficiency

X-section result depends on assumed polarization (~20% variation between 5 extreme scenarios)

Important systematic uncertainties cancel out in the ratio.
Y(nS) production: comparison with theory and Tevatron
exclusive B channels

\[ \text{B}^{\pm} \rightarrow \text{J/\(\psi\)} \text{ K}^{\pm} \]

- Analysis ongoing, based on larger statistics (measuring differential cross section)
- fit: 3 gaussians + exponential bkg

Also:

\[ \text{B}^{0} \rightarrow \text{J/\(\psi\)} \text{ K}^{0} \]

\[ \text{B}^{0} \rightarrow \text{J/\(\psi\)} \text{ K}^{*0} \]
$B_s \rightarrow J/\psi \phi$

**Fit results:**

$\mu_{\text{gauss}} = 5.3670 \pm 1.2e-03$ GeV/c$^2$

$\sigma_{\text{gauss}} = 16.4 \pm 1.2$ MeV/c$^2$

$N_{\text{signal}} = 377 \pm 26$

$N_{\text{BG}} = 978 \pm 36$

$\chi^2/\text{ndof} = 0.91$

$S/\sqrt{(S+B)} \approx 10$

$S/B \approx 0.4$

$\sqrt{s} = 7$ TeV

CMS Preliminary

$\int L dt = 39$ pb$^{-1}$
larger transverse momentum relative to jet axis than with lighter flavour

use $p_T^{rel}$ template shapes to fit for the $b$ fraction in the selected events

**signal** template: MC validated on data with $b$-enriched sample

**light flavour** templates: from hadron spectra in data combined with muon faking probability from MC

**charm** template: from MC
b semileptonic decays

charm and light-flavours merged into a single template (shapes too similar)

binned log-likelihood fit (bins of muon $p_T$ and $\eta$)

non-lumi systematics 11-16% dominated by
• underlying event simulation
• light flavour template shape
b semileptonic decays

MC@NLO consistently underestimates the cross section
larger discrepancies in the central region and at low transverse momentum

\[ \sigma = (1.48 \pm 0.04_{\text{stat}} \pm 0.22_{\text{syst}} \pm 0.16_{\text{lumi}}) \mu b \]

\[ \sigma_{\text{PYTHIA}} = 1.8 \mu b \]

\[ \sigma_{\text{MC@NLO}} = [0.84^{+0.36}_{-0.19}(\text{scale}) \pm 0.08(m_b) \pm 0.04(\text{pdf})] \mu b \ (m_F=m_R=p_T) \]

Franco Ligabue
CMS B Physics
Discrete2010
Inclusive b-jet production

b-jet tagging exploiting secondary vertices (pixel detector)

b-tagging efficiency validated on data using semi-leptonic decays:

\[ \frac{\text{data}}{\text{MC}} = 0.98 \pm 0.08 \text{(stat)} \pm 0.08 \text{(syst)} \]
Inclusive b-jet production

Sample purity validated on data using:
- vertex mass fit
- MC fake rates and measured signal efficiency

\[
\frac{d^2 \sigma_{b\text{-jets}}}{dp_T dy} = \frac{N_{\text{tagged}} f_b C_{\text{smear}}}{\epsilon_{\text{jet}} \epsilon_b \Delta p_T \Delta y \mathcal{L}}
\]
Inclusive b-jet production

Experimental uncertainties (~20%) dominated by b-tagging efficiency and jet energy scale (~5%)

MC@NLO uncertainties dominated by scale variations (+40%, -25%) and b-quark mass (+17%, -14%)

good agreement with Pythia at high Pt

discrepancy with MC@NLO at high pt and rapidity
Inclusive b-jet production

Jet energy corrections and luminosity systematic uncertainties cancel out

Pythia in perfect agreement in measured range

Indicates shape discrepancies with NLOJet++ (used to generate inclusive jets) to MC@NLO ratio

Ratio of b-jet to all jets.
Prospects

- Analysis of the entire 2010 data set going on
- Many results expected:
  - b-jet angular correlations to study production mechanism
  - quarkonia production updates and polarization measurements (smaller systematics, also from increased statistics and finer binning)
  - integrated B meson mixing parameter
  - $\chi_c$ observation
  - b hadron exclusive decays: ($B^+ \rightarrow J/\psi \ K^+$, $B^0 \rightarrow J/\psi \ K_S$, $B_s \rightarrow J/\psi \ \phi$, $\Lambda_b \rightarrow J/\psi \Lambda$)
    - ($\Delta\Gamma/\Gamma$, CP violation)
Conclusions

- CMS has recorded more than $40\text{pb}^{-1}$ of data at $\sqrt{s} = 7 \text{ TeV}$
- only a fraction used for the results shown here (basically data collected before the summer)
- **Quarkonia** production measurements already allow the comparison with theoretical models and with other experiments
  - systematics will go down with increasing statistics
- **b quark inclusive production** measured with complementary techniques: semileptonic decays and secondary vertexing
  - hints of discrepancies with theoretical models (errors comparable)
- some **exclusive decays** reconstructed
- more results to come with full 2010 statistics!
Backup
CMS detector

**Technical Specifications**

- **Total Weight**: 14,500 t.
- **Overall Diameter**: 14.60 m
- **Overall Length**: 21.60 m
- **Magnetic Field**: 4 Tesla
**J/ψ: acceptance**

Figure 2: Left: Acceptance as a function of the J/ψ $p_T$ and rapidity. Right: Number of muon pairs within ±100 MeV/$c^2$ of the nominal J/ψ mass, in bins of $p_T$ and $|y|$. 

Franco Ligabue  
CMS B Physics  
Discrete2010
J/ψ from b hadrons

CMS, $\sqrt{s} = 7\text{ TeV}$
$L = 314\text{ nb}^{-1}$

$|y_{J/ψ}| < 1.2$

$1.2 < |y_{J/ψ}| < 1.6$

$1.6 < |y_{J/ψ}| < 2.4$
J/ψ from b-hadrons: comparison with other LHC experiments and with Tevatron

![Graph showing the fraction of J/ψ from B-hadrons as a function of p_T for different experiments at LHC and Tevatron.]

- CMS 100 nb⁻¹, 1.4 < |y| < 2.4
- CMS 100 nb⁻¹, |y| < 1.4
- LHCb 14.2 nb⁻¹, 2.5 < y < 4.0
- ATLAS 17.5 nb⁻¹, |y| < 2.25

LHC √s = 7 TeV
Preliminary

- CDF √s = 1.96 TeV, |y| < 0.6

PRD 71 (2005) 032001
quarkonia to electrons
b quark production mechanisms

- **LO:**
  - Flavour creation

- **Large NLO contributions:**
  - Flavour Excitation
  - Gluon splitting

- **Test benchmark for perturbative QCD, MC tools and detector performance**
  - Long standing problems with lower energy data resolved
  - Measurements could have smaller errors than NLO QCD predictions currently available
b-jet ansatz fit

assumed jet production shape:

\[ f(p_T) = N_0 \left( \frac{p_T}{\text{GeV}} \right)^{-\alpha} \left( 1 - \frac{2p_T \cosh(y_{\text{min}})}{\sqrt{s}} \right)^\beta \exp(-\gamma/p_T). \]

smeared with a gaussian resolution function

\[ F(p_T^{\text{meas}}) = \int_0^\infty f(p_T^{\text{gen}}, y; p_i) g(p_T^{\text{meas}} - p_T^{\text{gen}}, y; \sigma) dp_T^{\text{gen}}. \]

unfolding correction

\[ C_{\text{smear}}(p_T) = \frac{f(p_T)}{F(p_T)}. \]
CMS muon system

3 Super Layer (2φ and 1θ) for the first 3 stations
2 Super Layer (2φ) for the last station
4 Layer for each Super Layer $\sigma_x \approx 200\ \mu m$

RPC

$\sigma_t \approx 2\ \text{ns}$

2 RPC chamber for the first 2 DT stations
1 RPC chamber for the last 2 DT stations and for the CSC chamber till $|\eta|<1.6$

CSC

6 gaps (Layers) for each camber
1 wire plane and 1 cathode plane with strips $\sigma_x \approx 100-240\ \mu m$
### J/$\psi$ B fraction absolute systematics

<table>
<thead>
<tr>
<th>$p_T^{J/\psi}$ (GeV/c)</th>
<th>Misalignment</th>
<th>B-lifetime model</th>
<th>Vertex estimation</th>
<th>Background fit</th>
<th>Resolution model</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>y</td>
<td>&lt; 1.2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.5 – 6.5</td>
<td>0.0045</td>
<td>0.0041</td>
<td>0.0038</td>
<td>0.0007</td>
<td>0.0129</td>
<td>0.0020</td>
</tr>
<tr>
<td>6.5 – 10.0</td>
<td>0.0017</td>
<td>0.0000</td>
<td>0.0008</td>
<td>0.0120</td>
<td>0.0073</td>
<td>0.0010</td>
</tr>
<tr>
<td>10.0 – 30.0</td>
<td>0.0021</td>
<td>0.0004</td>
<td>0.0012</td>
<td>0.0004</td>
<td>0.0032</td>
<td>0.0036</td>
</tr>
<tr>
<td>$1.2 &lt;</td>
<td>y</td>
<td>&lt; 1.6$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0 – 4.5</td>
<td>0.0067</td>
<td>0.0040</td>
<td>0.0181</td>
<td>0.0032</td>
<td>0.0191</td>
<td>0.0019</td>
</tr>
<tr>
<td>4.5 – 6.5</td>
<td>0.0020</td>
<td>0.0086</td>
<td>0.0002</td>
<td>0.0169</td>
<td>0.0024</td>
<td>0.0007</td>
</tr>
<tr>
<td>6.5 – 10.0</td>
<td>0.0019</td>
<td>0.0006</td>
<td>0.0027</td>
<td>0.0000</td>
<td>0.0002</td>
<td>0.0010</td>
</tr>
<tr>
<td>10.0 – 30.0</td>
<td>0.0056</td>
<td>0.0004</td>
<td>0.0101</td>
<td>0.0051</td>
<td>0.0098</td>
<td>0.0011</td>
</tr>
<tr>
<td>$1.6 &lt;</td>
<td>y</td>
<td>&lt; 2.4$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00 – 1.25</td>
<td>0.0052</td>
<td>0.0064</td>
<td>0.0375</td>
<td>0.0022</td>
<td>0.0172</td>
<td>0.0001</td>
</tr>
<tr>
<td>1.25 – 2.00</td>
<td>0.0051</td>
<td>0.0041</td>
<td>0.0206</td>
<td>0.0011</td>
<td>0.0049</td>
<td>0.0002</td>
</tr>
<tr>
<td>2.00 – 2.75</td>
<td>0.0044</td>
<td>0.0047</td>
<td>0.0085</td>
<td>0.0168</td>
<td>0.0027</td>
<td>0.0001</td>
</tr>
<tr>
<td>2.75 – 3.50</td>
<td>0.0019</td>
<td>0.0061</td>
<td>0.0004</td>
<td>0.0001</td>
<td>0.0068</td>
<td>0.0011</td>
</tr>
<tr>
<td>3.50 – 4.50</td>
<td>0.0017</td>
<td>0.0024</td>
<td>0.0043</td>
<td>0.0027</td>
<td>0.0109</td>
<td>0.0018</td>
</tr>
<tr>
<td>4.50 – 6.50</td>
<td>0.0067</td>
<td>0.0003</td>
<td>0.0016</td>
<td>0.0021</td>
<td>0.0083</td>
<td>0.0041</td>
</tr>
<tr>
<td>6.50 – 10.00</td>
<td>0.0017</td>
<td>0.0035</td>
<td>0.0033</td>
<td>0.0004</td>
<td>0.0105</td>
<td>0.0040</td>
</tr>
<tr>
<td>10.00 – 30.00</td>
<td>0.0057</td>
<td>0.0008</td>
<td>0.0045</td>
<td>0.0008</td>
<td>0.0015</td>
<td>0.0019</td>
</tr>
</tbody>
</table>
LHC in 2011

2011: “reasonable” numbers

- 4 TeV (to be discussed at Chamonix)
- 936 bunches (75 ns)
- 3 micron emittance
- $1.2 \times 10^{11}$ protons/bunch
- $\beta^* = 2.5$ m, nominal crossing angle
- Hubner factor 0.2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak luminosity</td>
<td>$6.4 \times 10^{32}$</td>
</tr>
<tr>
<td>Integrated per day</td>
<td>11 pb$^{-1}$</td>
</tr>
<tr>
<td>200 days</td>
<td>2.2 fb$^{-1}$</td>
</tr>
<tr>
<td>Stored energy</td>
<td>72 MJ</td>
</tr>
</tbody>
</table>

Usual warnings apply – see problems, problems above
primary vertex resolution: 25, 20 μm
$B^\pm \rightarrow J/\psi K^\pm$

- Select opposite sign di-muon combinations,
- Select combination/event with mass closest to the J/psi mass
- Select events with a di-muon vertex Probability >0.1%
- Muons satisfying quality criteria (require a muon chamber segment matching in position and direction with the prediction of the associated track extrapolation)
- At least one muon required to fire the trigger
- Both muons required to have $p_T^{\mu}(\mu)>3$ GeV/c, $|\eta(\mu)|<2.4$
- Combine J/psi candidate with tracks ($p_T>0.9$ GeV/c)
- Kinematic fit with J/psi mass constraint
- Require vertex probability > 0.1%
- If multiple candidates/event, choose highest $p_T$ $B^-$ candidate

Single Muon trigger ($p_T>3$ GeV/c cut at HLT level)

$ct/sigma_{ct}>1$

$ct$: transverse decay length of J/psiK$^-$ vertex relative to primary vertex

$sigma_{ct}$: error on transverse decay length

1-d fit to J/psiK$^-$ invariant mass:
- Signal: sum of three Gaussians (means and widths fixed to MC)
  - Mean: 5.280 GeV/c$^2$
  - Resolution = 32 MeV/c$^2$ (weighted sum of gaussian resolutions)
- Background is fitted with exponential function (slope floated in the fit)
  - $N_{\text{sig}} = 48 \pm 8$
Bs → J/Ψφ mass peak

Only certified BPAG good runs [140042 - 149442]. Scraping and GoodVertex filters on each event applied;

**Triggers:** HLT\_doubleMu0 OR HLT\_DoubleMu0\_Quarkonium\_v1;

**Muons:** used Global or Tracker, if Tracker muon arbitration/selection TMLastStationOptimizedBarrelLowPtTight is applied, $p(\mu)>3$ GeV/c and $|\eta|<2.4$;

Selected a pair of opposite-sign muons, both muons required to fire the trigger. Track/muon and muon/muon overlaps removed;

**J/ψ:** candidate mass within 150 MeV/c² around the J/ψ mass PDG value, $p_t(J/ψ)>0.5$ GeV/c;

**Kaons:** transverse momentum $p_t(K)>0.6$ GeV/c and $|\eta|<2.5$;

**φ:** candidate mass within 10 MeV/c² around the mass PDG value;

Kinematic fit of the four tracks with the J/ψ PDG mass constraint, cut on vertex probability > 2%; Significance cut $c\tau_{2D}/\sigma_{2D}>3$, where $c\tau_{2D}$ is transverse decay length of J/ψφ vertex relative to primary vertex and $\sigma_{2D}$ is the error on transverse decay length;