Topics in Heavy Quark Physics at CMS

B Physics
Top Physics

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Introduction

- pp collisions at \( \sqrt{s} = 14 \text{ TeV} \) at LHC
- access to new regions in phase space and rates
- Large Beauty and Top quark production cross section
- First goal of LHC physics: Rediscover Standard Model
- Search for New Physics:
  - Investigation of heavy flavor decays as signal
  - \( b\bar{b} \) and \( t\bar{t} \) events as background
The CMS Detector

- **Magnet**
  - 4T, superconducting

- **Tracking**
  - 200 m$^2$ silicon
  - Pixels+Strips

- **Calorimeter**
  - ECAL: 76000 PbWO$_4$ crystals
  - HCAL: brass absorber and scintillator

- **Muon System**
  - Drift Tubes
  - Cathode Strip Chambers
  - Resistive Plate Chambers

- **Trigger System**
  - 40 MHz bunch crossing rate
  - L1: hardware, 100 kHz output rate
  - 3$\mu$s latency time
  - HLT: software, full detector information
  - permanent storage at 100 Hz

HLT muon $p_T$- thresholds [GeV]

<table>
<thead>
<tr>
<th>Luminosity</th>
<th>Single muon</th>
<th>Di-muon</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2 \cdot 10^{30}$ cm$^{-2}$s$^{-1}$</td>
<td>5</td>
<td>3/3</td>
</tr>
<tr>
<td>$2 \cdot 10^{31}$ cm$^{-2}$s$^{-1}$</td>
<td>11</td>
<td>3/3</td>
</tr>
<tr>
<td>$10^{32}$ cm$^{-2}$s$^{-1}$</td>
<td>16</td>
<td>3/3</td>
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B Physics at CMS

- **Large $b\bar{b}$ cross section at LHC**
  \[ \sigma_{b\bar{b}}(\sqrt{s} = 14 \text{ TeV}) \approx 500 \mu \text{b} \]

- **CMS very well suited for B Physics even at high luminosity**
  - excellent tracking and muon detectors
  - low $p_T$ muon trigger

- **Rich B Physics program at CMS**
  - **Heavy Quark Production**
    - $b$ production (inclusive, $B^{\pm} \rightarrow J/\psi K^{\pm}$)
    - Quarkonia studies
    - $b\bar{b}$ correlations (inclusive, $J/\psi + \mu$)

- **B Decays**
  - Lifetime measurements ($B \rightarrow \mu + X$)
  - Measurement of $\Delta \Gamma$ (inclusive, $B_s \rightarrow J/\psi \phi$)
  - Mass and lifetime of $B_c$ meson ($B_c^{\pm} \rightarrow J/\psi \pi^{\pm}$)

- **Rare Decays and New Physics**
  - $B^0_s \rightarrow \mu^+ \mu^-$
  - $D^0 \rightarrow \mu^+ \mu^-$
  - $\tau \rightarrow \mu^+ \mu^+ \mu^-$
Inclusive $b$ production cross section ($\mathcal{L} = 10$ fb$^{-1}$)

- Semileptonic $b$-decays into muons ($b \rightarrow \mu + jet$)
- Methodology: Fit to $p_T^{rel}$ distribution
- Trigger: muon+jet
  - $p_T^{\mu} > 19$ GeV, $E_T^{jet} > 50$ GeV
- Event selection:
  - most energetic $b$ tagged jet
  - muon inside the jet
- 16M selected events
- $b$ purity: 70% – 55% depending on $p_T$
- Systematics dominated (jet energy scale, fragmentation)
**J/ψ** cross section measurement ($\mathcal{L} = 3$ pb$^{-1}$)

- Inclusive and prompt $J/ψ$ production
- Disentangle prompt and non-prompt component
  - Use B-hadron lifetime
  - Measure B production

- Event selection:
  - 2 muons with $p_T > 3$ GeV
  - $2.8$ GeV < $m_{\mu\mu}$ < $3.4$ GeV
  - common vertex

\[ \frac{d\sigma}{dp_T} \cdot BR(J/ψ \rightarrow \mu\mu) = \frac{N_{fit}}{\mathcal{L} \cdot \epsilon \cdot \Delta p_T} \]

- Unbinned maximum-likelihood fit to flight length
  - $l_{xy} = L_{xy} \cdot m_{J/ψ} / \rho_{J/ψ}$
  - Extract prompt fraction

- Limited by systematic uncertainty
  - at 15% level
  - statistic uncertainty negligible
$B^0_s \rightarrow \mu^+ \mu^- (\mathcal{L} = 10 \text{ fb}^{-1})$

- Highly suppressed in SM $BR_{SM} = (3.42 \pm 0.54) \cdot 10^{-9}$
- Sensitive to New Physics $BR_{MSSM} \propto \tan^6 \beta$
- Current limit from CDF $BR^{95\%} \leq 5.8 \cdot 10^{-8}$
- Trigger:
  - 2 muons with $p_T > 3$ GeV
  - displaced vertex
- Event selection:
  - 2 isolated muons: $I = \frac{p_T(B_s)}{p_T(B_s) + \Sigma_{trk} |p_T|}$
  - flight length significance and secondary vertex fit
  - $m_{B_s} \pm 100$ MeV
- $n_S = 6.1 \pm 0.6_{\text{stat}} \pm 1.5_{\text{sys}}$, $n_B = 13.8^{+22.0}_{-13.8}$
- $BR^{90\%} \leq \frac{N(n_{obs}, n_B, n_S)}{\epsilon_{gen} \epsilon_{total}} \leq 1.4 \cdot 10^{-8}$

Top Quark Physics at CMS

- $\sigma_{NLO+NLL}(\sqrt{s} = 14 \text{ TeV}) = 833 \text{ pb, } m_{\text{top}} = 175 \text{ GeV}$
- LHC will produce 8M $t\bar{t}$ events per year ($\mathcal{L} = 10 \text{ fb}^{-1}$)
- Top Quark Physics Program at CMS:
  - Rediscovery of $t\bar{t}$ events
  - Cross section and differential cross sections
  - Top quark events as calibration tool
  - Validate MC predictions
  - Top quark resonances and properties
  - Single top
- At the beginning: focus on leptonic $W$ decays
  - Clean signal
  - Easy to trigger
  - $BR(t\bar{t} \rightarrow l_1 \nu_{l_1} l_2 \nu_{l_2}) \approx 10\% \ (l_1, l_2 = e, \mu, \tau)$
  - $BR(t\bar{t} \rightarrow l\nu_l + \text{jet}) \approx 45\% \ (l = e, \mu, \tau)$
Observability of $t\bar{t}$ events ($\mathcal{L} = 10 \text{ pb}^{-1}$)

- Rediscovery of top quark events
- Semileptonic muon channel
  - $pp \rightarrow t\bar{t} + X \rightarrow b\bar{q}q\nu\nu_\mu \bar{b} + X$
- Trigger: non-isolated single muon
  - $p_T > 16 \text{ GeV}$
- Event selection:
  - 1 isolated muon with $p_T > 30 \text{ GeV}$
  - 4 jets with $E_T > 65(40) \text{ GeV}$
  - $dR_{\mu,jet} > 0.3$
  - no b tagging used
  - no cut on missing energy
- Result:
  - 128 signal events
  - 25 other $t\bar{t}$ events
  - 45(7) $W(Z)+\text{jet}$ events
  - 11 QCD events
\( \bar{t}t \) cross section in the dilepton channel \((\mathcal{L} = 100 \text{ pb}^{-1})\)

- \( ee, \mu\mu \) and \( e\mu \) (incl. \( \tau \rightarrow l\nu_l\nu_\tau \))
- Trigger: single/double \( e/\mu, e\mu \)
  - \( p_T^{\text{min}}(e/\mu) > 10/3 \text{ GeV} \)
- Event selection:
  - 2 isolated leptons with \( p_T > 20 \text{ GeV} \) (os, \( Z \)-mass veto)
  - 2 b-jets with \( E_T > 30 \text{ GeV} \) (13\% mistag)
  - transverse missing energy > 50 GeV

\[ \sigma \times BR = \frac{N_{\text{sel}} - N_{\text{bkg}}}{\epsilon_{t\bar{t}} \times \mathcal{L}} \]

\( N_{\text{sig}} = 160 \) events, \( N_{\text{bkg}} \approx 3 \)

\[ S/B = 26/90/90 \ (ee/\mu\mu/e\mu) \]
$t\bar{t}$ events as calibration tool ($\mathcal{L} = 100 \text{ pb}^{-1}$)

- Measurement of the Jet Energy Scale corrections
- $t\bar{t} \rightarrow WbW\bar{b} \rightarrow bq\bar{q}\mu\nu\mu\bar{b}$
- Event selection:
  - High $p_T$ muon, 4 jets with $E_T > 40 \text{ GeV}$
  - Select correct jet combination by maximum likelihood
  - 130 signal events, 27 background events
- $\chi^2$-fit to constrain W and t mass to nominal value
- Adjust energy scale to maximize fit probability
- $\Delta E_b = -7.0 \pm 0.9\%$, $\Delta E_{q,\bar{q}} = -12.9 \pm 0.9\%$
Conclusions

- Rich Beauty and Top Quark Physics program at CMS
- CMS detector well suited due to excellent tracking and muon detectors
- $b$ quark and quarkonium cross section measurement feasible with $\mathcal{L} < 3 \text{ pb}^{-1}$
- Promising prospect for searches of rare B-decays
- $t\bar{t}$ signal observable with $\mathcal{L} \approx 10 \text{ pb}^{-1}$
- Measurement of $t\bar{t}$ production cross section at $\mathcal{L} \approx 10 - 100 \text{ pb}^{-1}$
- $t\bar{t}$ events qualify as calibration tool