Flavor physics with CMS: Status and Perspectives

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Flavor Physics and CP Violation 2010
2010/05/25

• Introduction
• Data results at $\sqrt{s} = 7$ TeV
  ▶ tracks and muons
• Example Perspectives
  ▶ $B_s^0 \rightarrow \mu^+ \mu^-$
  ▶ top
Heavy Flavor Physics in CMS

- **Beauty and top quark physics**
  - production: QCD (and EW)
  - decays: $FP$($CP$)
  - Search for ‘New Physics’
    - indirectly: $b$, $t$ decays
    - directly: $t$ production

- **Motivations**
  - interesting physics:
    - SM rediscovery and measurements
    - BSM searches
  - abundant signals from the start
  - commissioning
    - detector
    - trigger
    - data management
  - essential background determination for many other searches
Continuous Evolving Program

- Reminder:
  - 2010: roughly $100 \text{ pb}^{-1}$ of delivered integrated luminosity at $\sqrt{s} = 7 \text{ TeV}$
  - 2011: roughly $1 \text{ fb}^{-1}$ at $\sqrt{s} = 7 \text{ TeV}$
  - $10^{34} \text{ cm}^{-2}\text{s}^{-1}$: roughly $30 \text{ fb}^{-1}$ per year (at $\sqrt{s} = 14 \text{ TeV}$)

- $\text{Excl } D \text{ signals}$
- $J/\psi$: prod./polarization
- Incl $b$ and $\Upsilon(nS)$
- $\text{Excl } b\bar{b}$
- $\text{correlations} \rightarrow \mu^+\mu^-$
- $\text{decays} \rightarrow \mu^+\mu^-$
- $\text{UL}(B^0_s \rightarrow \mu^+\mu^-), \text{etc}$
- $\Lambda_b \rightarrow \mu^+\mu^-, \text{etc}$
- $B(B^0_s \rightarrow \mu^+\mu^-)$
- $B(B^0 \rightarrow \mu^+\mu^-)$

$c/b \text{ physics}$

$tt$ production

$R = \frac{\Gamma(tbW)}{\Gamma(tb\gamma)}$

$\text{UL}(X \rightarrow tt)$

$\text{UL}(t \rightarrow q\gamma)$

$\text{UL}(t \rightarrow qZ)$

with many intermediate and/or improved results
The CMS Detector

- **Requirements**
  - lepton ID
  - $b/\tau$ tagging
  - jets and $E_T$ (and affordable)

<table>
<thead>
<tr>
<th>Component</th>
<th>Characteristics</th>
<th>resolutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel</td>
<td>3/2 Si layers</td>
<td>$\delta z \approx 20 \mu m$, $\delta \phi \approx 10 \mu m$</td>
</tr>
<tr>
<td>Tracker</td>
<td>10/12 Si strips</td>
<td>$\delta (p_\perp)/p_\perp \approx 1%$</td>
</tr>
<tr>
<td>ECAL</td>
<td>PbWO$_4$</td>
<td>$\delta E/E \approx 3%/\sqrt{E} \pm 0.5%$</td>
</tr>
<tr>
<td>HCAL (B)</td>
<td>Brass/Sc, $&gt;7.2\lambda$</td>
<td>$\delta E/E \approx 100\sqrt{E}%$</td>
</tr>
<tr>
<td>HCAL (F)</td>
<td>Fe/Quartz</td>
<td>$\delta (E_T) \approx 0.98\sqrt{\sum E_T}$</td>
</tr>
<tr>
<td>Magnet</td>
<td>4T solenoid</td>
<td>$\delta (p_\perp)/p_\perp \approx 10%$ (STA)</td>
</tr>
<tr>
<td>Muons</td>
<td>DT/CSC + RPC</td>
<td></td>
</tr>
</tbody>
</table>

**Component Characteristics**

- **Weight**: 12'500 t
- **Length**: 21.6 m
- **Diameter**: 15 m
- **Magnetic field**: 4 T
- **Cost**: ‘500’ MCHF
Muon Reconstruction

- Redundant precise muon trajectory measurement
  - barrel: drift tubes (tracking) plus RPC (timing)
  - endcap: cathode strip chambers (tracking) plus RPC (timing)
  - inner tracker: silicon pixel and strip detectors

- Muons
  - standalone muon: reconstructed in muon system only
  - global muon (‘GM’): outside-in standalone muon → to inner track
  - tracker muon (‘TM’): inside-out inner track → muon detector
Muon Trigger (at ‘high’ luminosity)

- Muon trigger
  - L1 trigger: DT/CSC/RPC
  - High-level trigger:
    - L2: improve L1 measurement
    - L3: combine with inner tracker (in r.o.i.)
- L3 efficiency measured in 2008 cosmic muon data taking
  - OIHit: outside-in with tracker seeds
  - OIState: outside-in with L2 seeds
  - IOHit: inside-out (low efficiency b/c pixel r/o only 1bc; cosmics asynchronous)

- HLT thresholds:
  - double muon: 3 GeV
Low-luminosity triggering

- Beam monitoring detectors used for triggering at low luminosity
  - beam scintillator counters
    - BSC1: located at $\pm 10.9$ m inner radius 20 cm
    - BSC2: located at $\pm 14.4$ m inner radius 4 cm
    - NIM electronics
  - beam pickup timing detectors
    - measure mirror charges of passing beam (bunches)

- Other applications:
  - beam halo triggers
  - beam gas triggers
  - zero-bias triggers
  - minimum-bias triggers

- BSC to be replaced after run 1
  - radiation damage
  - essential for HI MB triggering
Data Taking

- Early April:
  - delay scans for many subdetectors

- Except for detector studies: data taking efficiency > 90%
Detector Performance Impressions

Track multiplicity and $p_T$ spectrum

Pixel cluster charge

- **MC simulation**
  - detector well described
  - need for some physics tuning

CMS Preliminary $\sqrt{s}=900\text{GeV}$

PV resolution

CMS-PAS-TRK-10-001

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V0 reconstruction

- Long-lived particles ($cT > 1$ cm)
  - oppositely-charged tracks
  - detached from primary vertex
  - forming a good secondary vertex
  - $\Lambda$: high-momentum track = $p$

- Track requirements
  - $N_{\text{hits}} > 5$
  - $\chi^2$/dof < 5
  - $d_{xy}/\sigma(d_{xy}) > 0.5$

- Vertex requirements
  - $\chi^2$/dof < 7 and $d_{xy}/\sigma(d_{xy}) > 15$

- Both lifetimes consistent with PDG

<table>
<thead>
<tr>
<th>V0</th>
<th>Data [MeV]</th>
<th>MC [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_S$ peak</td>
<td>497.68 ± 0.06</td>
<td>498.11 ± 0.01</td>
</tr>
<tr>
<td>$K_S$ width</td>
<td>7.99 ± 0.14</td>
<td>7.63 ± 0.03</td>
</tr>
<tr>
<td>$\Lambda$ peak</td>
<td>1115.97 ± 0.06</td>
<td>1115.93 ± 0.02</td>
</tr>
<tr>
<td>$\Lambda$ width</td>
<td>3.01 ± 0.08</td>
<td>2.99 ± 0.03</td>
</tr>
</tbody>
</table>
More Baryons: $\Xi^- \rightarrow \Lambda\pi^-$, $\Omega^- \rightarrow \Lambda K^-$

- Reconstruction of $\Lambda(\pi, K)$
  - loose $\Lambda$ selection
    - vertex $d_{xy} > 10\sigma$
    - track $d_0 > 0.5\sigma$
    - $|m_\Lambda - m_\Lambda^{\text{PDG}}| < 8\text{ MeV}$
  - track selection
    - $d_0^{3d} > 3\sigma$ wrt PV (w/o signal tracks)
    - kaon $p_\perp > 600\text{ MeV}$
    - charge correlation of meson tracks
  - vertexing
    - $P(\chi^2) > 1\%$
    - $d_{Vtx} > 4\sigma$

- events with single candidates only

- Masses and widths
  - consistent with PDG and MC
Candidate decay $\Xi^+ \rightarrow \bar{\Lambda} (\rightarrow \bar{p}\pi^+) \pi^+$
Particle identification: tracker $dE/dx$

- **Measure specific ionization energy loss**
  - analog readout of silicon strip detector
  - high purity tracks, $N_{\text{hits}} > 9$
  - robust $dE/dx$ estimator
  \[ I_h = \left( \frac{1}{N} \sum_i c_i^k \right)^{1/k}, \quad k = -2 \]

- **Inclusive reconstruction of $\phi \rightarrow K^+ K^-$**
  - Tracks: $p > 1 \text{ GeV}$ or $|m - m_K| < 200 \text{ MeV}$

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**CMS-PAS-TRK-10-001**

**CMS preliminary**

$\sqrt{s} = 900 \text{ GeV}$

- $1728 \pm 102$ $\phi$ candidates
- $\text{Mass} = (1.019.58 \pm 0.22) \text{ MeV/c}^2$
- $\Sigma = (1.29 \pm 0.32) \text{ MeV/c}^2$
- Width fixed to PDG value

**CMS preliminary**

$\sqrt{s} = 900 \text{ GeV}$

- $dE/dx = K \frac{m^2}{p^2} + C$
- with $K = 2.468 \pm 0.009$
- with $C = 2.679 \pm 0.011$

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**CMS-PAS-TRK-10-001**

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- Width fixed to PDG value
Inclusive Reconstruction of $D^0$

- Dataset: 27 million minimum bias events
- Decay mode reconstruction
  \[ D^0 \rightarrow K^- \pi^+ \]
- Selection criteria
  - transverse momentum cuts
    \[ p_\perp(K) > 1.25 \text{ GeV} \]
    \[ p_\perp(\pi) > 1.0 \text{ GeV} \]
    \[ p_\perp(D^0) > 3.0 \text{ GeV} \]
  - Vertexing cuts
    \[ d(K, \pi) < 0.025 \text{ cm} \]
    \[ \chi^2 < 4.5 \]
    \[ 3 < l_{xy}/\sigma(l_{xy}) < 20 \]
    \[ \sigma(l_{xy}) < 0.03 \text{ cm} \]
  - $D^0$ momentum vs. PV-SV direction
    \[ \angle(\vec{p}_{D^0}, \overrightarrow{PV} : SV) < 0.1 \]
  - allow for multiple candidates
- MC expectations
  - Peak: $1.863 \pm 0.002 \text{ GeV}$
  - Width: $0.014 \pm 0.002 \text{ GeV}$
More Open Charm: $D^{*+}$

- Data set: 37 million minimum bias events
- Decay mode reconstruction

$$D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+_s$$

- Kinematic selection

$$p_{\perp}^{\text{track}} > 0.6 \text{ GeV}$$
$$p_{\perp}^{\pi_s} > 0.25 \text{ GeV}$$
$$p_{\perp}^{D^{*+}} > 5 \text{ GeV}$$

choose single $D^{*+}$ candidate
(with highest transverse momentum)

- Mass windows (for other projections)

$$|m_{K\pi} - m^{D^0}_{\text{PDG}}| < 25 \text{ MeV}$$
$$|m_{K\pi\pi_s} - m_{K\pi} - \delta m_{\text{PDG}}| < 1.2 \text{ MeV}$$
and $D^+$

- Data set: $\approx 11$ million minimum bias events
- Decay mode:
  $$D^+ \rightarrow K^- \pi^+ \pi^+$$
- Kinematic selection
  - $p_\perp > 0.1$ GeV
  - $p > 1$ GeV
- Vertexing selection
  - $\vec{p}_{D^+}$ should point to PV ($5\sigma$)
  - PV: $P(\chi^2) > 0.01$
  - SV: $P(\chi^2) > 0.02$
  - $L/\delta(L) > 7$
- Note: $D^0$ vs. $D^{*+}$ vs. $D^+$
  - three independent analyses
  - unified selection was not a goal
Charmonium

- This is not really flavor physics
  - but important ingredient and milestone

- Dataset: ≈ 1 nb$^{-1}$, single muon trigger
  - $p_\perp > 3$ GeV (rate limited at some point)

- Reconstruction of $J/\psi \rightarrow \mu^+\mu^-$
  - track selection
    - $N_{\text{hit}} > 10$
    - $d_0 < 5$ cm, $d_z < 20$ cm
  - vertex selection
    - $P(\chi^2) > 0.1\%$

- Yields

<table>
<thead>
<tr>
<th>Category</th>
<th>Yield</th>
<th>Mass [MeV]</th>
<th>Width [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GM+GM</td>
<td>$24 \pm 5$</td>
<td>$3094 \pm 9$</td>
<td>$35.5 \pm 6.8$</td>
</tr>
<tr>
<td>GM+TM</td>
<td>$76 \pm 12$</td>
<td>$3095 \pm 7$</td>
<td>$42.5 \pm 6.3$</td>
</tr>
</tbody>
</table>

- Mass resolution
  - strongly pseudorapidity dependent
  - average $\approx 30$ MeV with ‘100 pb$^{-1}$ alignment’
$B^0_{s} \rightarrow \mu^+ \mu^-$: Search for New Physics

- **Decays highly suppressed** in Standard Model (Artuso et al, 2008)
  - effective FCNC, helicity suppression
  - SM expectation:
    \[
    \mathcal{B}(B^0_{s} \rightarrow \mu^+ \mu^-) = (3.86 \pm 0.15) \times 10^{-9} \\
    \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.04) \times 10^{-10}
    \]
  - Cabibbo-enhancement ($|V_{ts}| > |V_{td}|$) of $B^0_{s} \rightarrow \mu^+ \mu^-$ over $B^0 \rightarrow \mu^+ \mu^-$ only in MFV models

- **Sensitivity to new physics**
  - 2HDM: $\mathcal{B} \propto (\tan \beta)^4, m_{H^+}$; MSSM: $\mathcal{B} \propto (\tan \beta)^6$
  - Constraints on parameter regions
  - ‘Measurement’ of $\tan \beta$ (Kane, et al. ph/0310042)

- **Plus: ‘time-dependent’ physics program**
  - very early data: $\pi, K$ muon misid rates with $b \rightarrow \mu D^0(K^-\pi^+)X$
  - early data: $B^+ \rightarrow J/\psi K^+$, $B^0_{s} \rightarrow J/\psi \phi$ normalization/control sample
  - some more data: $\mathcal{B}(B^0_{s} \rightarrow \mu^+ \mu^-)$ upper limit
  - even more data: $\mathcal{B}(B^0_{s} \rightarrow \mu^+ \mu^-)$ measurement
$B_s^0 \rightarrow \mu^+ \mu^-$: Analysis Overview

- $b$-hadrons produced in
  - gluon splitting (close together)
  - flavor excitation
  - gluon-gluon fusion (back-to-back)

- Signal signature
  - two muons from one decay vertex and not much else in vicinity
  - dimuon mass around $m_{B_s^0}$

- Background composition
  - two independent semileptonic $B$ decays (mostly from gluon splitting)
  - one semileptonic ($B$) decay and one misidentified hadron
  - rare single $B$ decays (peaking and non-peaking)
    → roughly similarly important
  - no prompt+cascade muons from one single $B$ decay (within current BG MC statistics)

⇒ High signal efficiency and high background reduction
  - one decay vertex and large/significant flight length
  - isolation of dimuon system
  - mass window, sidebands for non-peaking background estimation
MC simulations: $B^0_s \rightarrow \mu^+ \mu^-$

- **Muon selection**
  - 2 global muons (GM)
  - $p_\perp > 4 \text{ GeV}$, $|\eta| < 2.4$

- **$B^0_s$ candidate**
  - $p_\perp > 5 \text{ GeV}$, $|\eta| < 2.4$
  - $4.8 < m_{\mu^+ \mu^-} < 6.0 \text{ GeV}$
  - Secondary vertex fit
    - $\cos(\alpha) > 0.9985$ (i.e. $3.1^\circ$)
    - $l_{3D}/\sigma_{3D} > 17.0$
    - $\chi^2 < 5.0$
  - Isolation
    - $I = \frac{p_\perp(B^0_s)}{p_\perp(B^0_s) + \sum_{trk} |p_\perp|} > 0.850$
    - using tracks with $p_\perp > 0.9 \text{ GeV}$ and $\Delta R(t, B^0_s) < 1$
\[ \mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) \leq 1.6 \times 10^{-8} \]

- With 1.0 fb\(^{-1}\) at \(\sqrt{s} = 14\) TeV, expect to obtain at 90\% C.L.

Signal yield \(n_S = 2.36^{+0.076}_{-0.074}\) (stat)

Signal efficiency \(\varepsilon_S = 0.023 \pm 0.001\) (stat)

BG rejection \(\varepsilon_B = (7.82 \pm 0.369) \times 10^{-9}\) (stat)

BG: dimuons \(n_{B}^{\mu\mu} = 2.54^{+0.719}_{-0.560}\) (stat)

BG: muon+fake \(n_{B}^{\mu h} = 2.54^{+0.719}_{-0.560}\) (stat)

\[ n_{B}^{\text{non-rare}} = n_{B}^{\mu\mu} + n_{B}^{\mu h} = 5.07^{+1.44}_{-1.12}\] (stat)

BG: rare \(n_{B}^{\text{rare}} = 1.45^{+0.276}_{-0.276}\) (total)

\[ n_{B} = n_{B}^{\text{non-rare}} + n_{B}^{\text{rare}} = 6.53^{+2.43}_{-2.43}\] (total)

- Substantial improvement with respect to 2006
  - no pile-up, \(\sqrt{s} = 14\) TeV
  - high-luminosity trigger, no tracker muons, cut-n-count analysis
**b-tagging of a different kind**

- **Not** $B$-flavor tagging, but determination of $b$ vs. $udsg$ jet-origin
  - impact parameter (wrt primary vertex)
  - secondary vertex reconstruction
  - leptons

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**CMS Preliminary**

**Number of Tracks in Jet**

**Number of Secondary Vertices**

**Signed 3D IP Significance**

**CMS Preliminary, $\sqrt{s} = 900$ GeV**

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**CMS-PAS-TRK-10-001**

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Top Flavor Physics: $R$

- Top decays to $b$ vs all quarks

$$R = \frac{\Gamma(t \rightarrow bW)}{\Gamma(t \rightarrow qW)}$$

$$= \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} \quad \text{(in SM)}$$

- $|V_{tb}|$ measurement (in SM with 3 generations)
- Constraints on $|V_{tb}|$ (in BSM)

- $P_i$: Probability to find $i$ $b$-tagged jets

$$A_i(R; \varepsilon_b, \varepsilon_q) = R^2 P_i(t\bar{t} \rightarrow WWb\bar{b})$$
$$+ 2R(1 - R)P_i(t\bar{t} \rightarrow WWbq)$$
$$+ (1 - R)^2 P_i(t\bar{t} \rightarrow WWqq)$$

- In $250 \text{ pb}^{-1}$ with dilepton $e\mu + 2$ jets sample

$$\delta R = 0.02_{\text{stat}} \oplus 0.09\varepsilon_b \oplus 0.03_{\text{syst}}$$

$$\delta \varepsilon_b = 0.02_{\text{stat}} \oplus 0.04_{\text{syst}}$$
LHC as a Top Factory

- The LHC at $\sqrt{s} = 14$ TeV is a top ‘factory’
  \[
  \sigma_{\text{tot}}(pp \rightarrow t\bar{t}) \approx 830 \text{ pb}
  \]
  - 100-fold increase of cross section wrt Tevatron
    (LHC at 10/7 TeV $\approx 50/20 \times$ Tevatron)
  - 100-fold increase of (design) luminosity

- Decays
  - $2/3$: $t \rightarrow q\bar{q}'$
  - $11\%$: $t \rightarrow \ell^+\nu$, $\ell = e, \mu$

- Example analysis at $\sqrt{s} = 14$ TeV
  - isolated muon $p_{\perp} > 30$ GeV
  - jets with $E_T > 65, 40, 40, 40$ GeV
  - observable: hadronic top 3-jet mass
    - In 10 pb$^{-1}$
      - 128 signal events
      - 90 background events
  \[\Rightarrow\] or: ‘recoil’ physics . . .
Top Flavor Physics: Rare Decays

- FCNC top decays are an excellent area for BSM searches

<table>
<thead>
<tr>
<th>Decay</th>
<th>SM</th>
<th>two-Higgs</th>
<th>SUSY with $R$</th>
<th>Exotic Quarks</th>
<th>Exper. Limits (95% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t \to gg$</td>
<td>$5 \times 10^{-11}$</td>
<td>$\sim 10^{-5}$</td>
<td>$\sim 10^{-3}$</td>
<td>$\sim 5 \times 10^{-4}$</td>
<td>&lt; 0.29 (CDF+TH)</td>
</tr>
<tr>
<td>$t \to \gamma q$</td>
<td>$5 \times 10^{-13}$</td>
<td>$\sim 10^{-7}$</td>
<td>$\sim 10^{-5}$</td>
<td>$\sim 10^{-5}$</td>
<td>&lt; 0.0059 (HERA)</td>
</tr>
<tr>
<td>$t \to Zq$</td>
<td>$\sim 10^{-13}$</td>
<td>$\sim 10^{-6}$</td>
<td>$\sim 10^{-4}$</td>
<td>$\sim 10^{-2}$</td>
<td>&lt; 0.14 (LEP-2)</td>
</tr>
</tbody>
</table>

- Event selection
  - 1 isolated high-$p_{\perp}$ lepton ($p_{\perp} > 20$ GeV) + 1 high-$E_T$ photon ($E_T > 50$ GeV)
  - exactly 1 $b$ jet ($E_T > 40$ GeV) + 1 non-$b$ jet ($E_T > 50$ GeV)
  - $150 < m_{\gamma q} < 200$ GeV, $\cos(t_{\gamma q}, t_{SM}) < -0.95$
  - efficiency $\varepsilon \approx 2\%$

Branching fraction measurements at $5\sigma$
Conclusions and Outlook

- CMS has started successfully with data taking at 7 TeV
  - multitude of light and heavy particles reconstructed as expected
  - muon triggers running wide open (compared to ‘high-lumi’ trigger scenarios)

- Heavy flavor physics expectations
  - for this summer: production (QCD)
    - quarkonia ($c\bar{c}$ and $b\bar{b}$)
    - inclusive $b$ production cross section
    - exclusive $b$ production cross section
    - $b\bar{b}$ correlations
    - $t\bar{t}$ production cross section
  - for next year: flavor physics in $B$ (and top) sector
    - $B_s^0 \rightarrow \mu^+\mu^-$
    - $B_s^0 \rightarrow J/\psi\phi$

- Ultimately:
  - measurement of very rare (leptonic) $B_s^0$ and $B_d^0$ decays
  - top flavor ‘recoil’ physics