HEAVY-FLAVOR RESULTS AT CMS

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PHYSICS AT THE LHC
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Muon reconstruction from combined information of silicon tracker and external detectors (DT, CSC, RPC)

**Di-muon triggers:**
- Level 1: segments in muon detectors
- High-Level Trigger:
  - fast regional track reconstruction
  - “Special” requirements for B-physics (invariant mass, vertex displacement, etc.)
MUON EFFICIENCIES

- Use data-driven measurements of the muon efficiency ("tag-and-probe" method) on dedicated trigger streams
  - In events with a $J/\psi$ candidate, ask for one well-identified muon ("tag")
  - The other muon ("probe") can pass or not pass the selection $S$ under investigation
  - The fitted $N_{\text{pass-}S}/N_{\text{all}}$ yield gives an unbiased estimate of the efficiency $\varepsilon_S$

- Limitation of the method: assumes efficiency factorization, does not take into account correlations due e.g. to trigger requirements

(Small) MC corrections required
1. QUARKONIA
PHYSICS MOTIVATIONS (I)

- **Quarkonium prompt production:**
  - Includes feed-down for J/ψ
    \( (\chi_{cJ}, \psi(2S) \rightarrow J/\psi) \) and Y \( (\chi_{bJ} \rightarrow Y) \)
  - **Direct only** in the \( \psi(2S) \) case: theoretically cleaner

- Recent calculations at **NLO in NRQCD** \( (O(\alpha_s^4 v^4)) \), including both color-singlet and color-octet contributions, are available for charmonium
  - Good agreement with TeVatron and first (low-\( p_T \)) LHC measured cross-sections
  - Interesting to investigate:
    - \( 1/p_T^n \) dependence at high \( p_T \)
    - \( \psi(2S) \) vs. \( J/\psi \) with same LDMEs
    - **Ratios** to reduce experimental uncertainties
PHYSICS MOTIVATIONS (II)

- J/ψ non-prompt production:
  - Test FONLL approach at 7 TeV
  - Test improved b- fragmentation function (fitted from data of several experiments)

- $\chi_c$ studies
  - Measurement of $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ and the fraction of J/ψ coming from $\chi_c$ decays ($\chi_c \rightarrow J/\psi \gamma$) provide additional important “handles” for comparison to NRQCD predictions

M. Cacciari et al., JHEP 0407, 033 (2004)

M. Cacciari et al., JHEP 0604, 006 (2006)
J/ψ AND Ψ(2S) CROSS-SECTIONS

\[
\frac{d^2\sigma}{dp_T dy}(Q\bar{Q})BR(Q\bar{Q} \rightarrow \mu^+\mu^-) = \frac{N_{fit}(Q\bar{Q})}{\int L dt \cdot A \cdot \epsilon \cdot \Delta p_T \Delta y}
\]

\[
N_{fit}(J/\psi, \psi(2S)) = \begin{cases} 
(1 - f_B)N_{tot} & \text{(prompt)} \\
 f_B N_{tot} & \text{(non prompt)}
\end{cases}
\]

- \( A \) = acceptance \( \rightarrow \) determined from simulation using unpolarized production as a default. Maximum variations are given based on “extreme” polarization scenarios
- \( \epsilon \) = efficiency \( \rightarrow \) tag-and-probe
- \( L \) = luminosity
- \( \Delta p_T, \Delta y \) = sizes of \( p_T, y \) bins

(acceptance x efficiency)
unpolarized J/ψ

JHEP 1202, 011 (2012)
MASS AND DECAY LENGTH FITS

• Use unbinned maximum likelihood fits to mass distributions extract yields ($N_{tot}$)
  • Typical mass resolution: 20-60 MeV/c² depending on rapidity
• To determine non-prompt fraction ($f_B$):
  • Fit simultaneously invariant mass and

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

$L_{xy} = \frac{u^T \sigma^{-1} x}{u^T \sigma^{-1} u}$

\[\chi^2/n_{\text{Dof}} = 94.4/99\]
CROSS-SECTION RESULTS

Shown here: $J/\psi$ inclusive cross-section by merging CMS results with 0.3 pb$^{-1}$ (low $p_T$) and 37 pb$^{-1}$ (high $p_T$)

Main systematic uncertainties:
- Total cross sections
- Efficiency correlations
- Acceptance edge effects
- Luminosity uncertainty
- Non-prompt fractions
- Tracker alignment
- B-lifetime model
- Resolution model
PROMPT/NON-PROMPT $J/\psi, \psi(2S)$

- Excellent agreement with NRQCD predictions
- Good agreement with FONLL predictions
  - Overall shift in the $\psi(2S)$ case (uncertainty on $B \to \psi(2S)$ rate) → improved determination of $B \to \psi(2S)$ BR from non-prompt ratio:

$$B(B \to \psi(2S)X) = (3.08 \pm 0.12\text{ (stat.+syst.)} \pm 0.13\text{ (theor.)} \pm 0.42\text{ (}$B_{PDG}$)) \times 10^{-3}$$
\( \chi_{c2} / \chi_{c1} \) CROSS-SECTION RATIO (I)

- Full 2011 sample (4.6 \text{ fb}^{-1})
- Combine a prompt J/\( \psi \) candidate with a photon converted to e\(^+\)e\(^-\) in the silicon tracker (\( \sigma \approx 6 \text{ MeV/c}^2 \))
- Conversion selection:
  - Vertex compatibilities
  - Conversion radius
  - \( p_T \)
  - \( \pi^0 \) veto combining candidates with photons in the EM calorimeter
- UML simultaneous fits to the two states give yield ratios

**CMS-PAS-BPH-11-010 (2012)**

**Conversion reconstruction efficiency**

**CMS Preliminary**
- \( pp, \sqrt{s} = 7 \text{ TeV} \)
- \( L = 4.62 \text{ fb}^{-1} \)
- \( 11 \text{ GeV} < p_T (J/\psi) < 13 \text{ GeV} \)
\( \chi_{c2} / \chi_{c1} \) CROSS-SECTION RATIO (II)

- Yield ratio corrected with MC-derived efficiency ratio
  - Departures from 1 mostly due to slightly different \( p_T(\gamma) \) spectra in the laboratory frame
- Main systematic uncertainties:
  - Signal-MC statistics
  - Signal and background mass-difference parameterization
  - Unknown production \( p_T \) spectrum and polarization (not shown) of the \( \chi_c \) states
- NLO NRQCD: \( \sigma \cdot BR(\chi_{c2}) / \sigma \cdot BR(\chi_{c1}) \sim 0.3 - 0.5 \)
  - Waiting for exact calculation in CMS acceptance

Statistical
Systematic

CMS Preliminary
\( pp, \sqrt{s} = 7 \text{ TeV} \)
\( L = 4.62 \text{ fb}^{-1} \)

\[ \frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} \]

\[ \frac{\sigma(\chi_{c2}) B(\chi_{c2} \rightarrow J/\psi \gamma)}{\sigma(\chi_{c1}) B(\chi_{c1} \rightarrow J/\psi \gamma)} \]

Y.-Q. Ma et al.
2. B-BARYONS
INTEREST IN B-BARYONS

- Properties of the lightest B-baryon ($\Lambda_b^0$) still unknown or not precisely measured:
  - Production cross-section in hadron collisions ($f_{\Lambda_b}$)
  - Polarization in hadron collisions
  - Lifetime (known with ~5-6% uncertainty)

- Vast “zoology” of B-baryon multiplets expected by the quark model
  - Detectable even in high-multiplicity pp collisions thanks to cascade weak decays $\rightarrow$ detached vertices
Λ_b, Λ_bbar CROSS-SECTIONS (I)

- Differential cross-sections in p_T > 10 GeV/c, |y| < 2
  - analysis performed on 1.9 fb-1
- Select Λ_b^0 → J/ψ Λ^0 → μ^+μ^- pπ^-
  - Track and muon quality
  - Pointing angle of J/ψ
  - Significance of J/ψ and Λ^0 transverse vertex displacement
- UML fit to Λ_b candidates from mass-constrained vertex fit
- Efficiencies from tag-and-probe (muons, trigger) and MC simulation (selection criteria)

$\Lambda_B, \bar{\Lambda}_B$ CROSS-SECTIONS (II)

- Slight excess in total cross-section
  - also observed in other $B$ species production

- Spectrum shape falling more steeply than NLO QCD predictions (and $B$-meson spectra)
  - attributed to hadronization effects

$\sigma(\Lambda_b)/\sigma(\bar{\Lambda}_b)$

Particle/anti-particle cross-section ratio compatible with 1
OBSERVATION OF $\Xi_B^{*0}$ (I)

• “Cascade” B-baryons (valence quark content = usb or dsb) so far only observed in the $J^P = 1/2^+$ state

• Color hyperfine-splitting models predict the mass of the $J^P = 3/2^+$ state $\Xi_b^*$ to be large enough for a $\Xi_b^* \rightarrow \Xi_b \pi$ transition

• Reconstruct $\Xi_b^{*0}$ in the decay chain:
  • $\Xi_b^{*0} \rightarrow \Xi_b^- \pi^+ \rightarrow \Xi^- J/\psi \pi^+ \rightarrow \Lambda^0 \pi^- \mu^+ \mu^- \pi^+ \rightarrow p \pi^- \pi^- \mu^+ \mu^- \pi^+$
  • Three weakly-decaying particles: $\Xi_b^-, \Xi^-, \Lambda^0 \rightarrow$ reconstruction of one primary and three secondary vertices allow to separate signal from huge prompt background
OBSERVATION OF $\Xi_B^{*0}$ (II)

$M(\Xi_B^{*0}) = (5945.0 \pm 0.7\text{(stat)} \pm 0.3\text{(syst)} \pm 2.7(\Xi_B^-)) \text{ MeV/c}^2$

- Theory: $5.94 \text{ GeV/c}^2$
- $6.9\sigma$ significance

Wrong-sign data used to check absence of excess

Systematics:
- Track/muon momentum scale
- Fitting model

3. RARE DECAYS
Decays highly suppressed in SM
- Effective FCNC decay
- Helicity suppression
- Overall Cabibbo suppression

Enhancements in several BSM physics scenarios:
- **CMSSM**
  \[
  \frac{B_{MSSM}}{B_{SM}} = \frac{(\tan \beta)^6}{M_A^4}
  \]
- **NUHM1**

\[B(B_s^0 \rightarrow \mu^+ \mu^-) = (3.2 \pm 0.2) \times 10^{-9}\]
\[B(B^0 \rightarrow \mu^+ \mu^-) = (1.0 \pm 0.1) \times 10^{-10}\]

Buras, Isidori & Paradisi

Isidori & Paradisi
ANALYSIS TECHNIQUE

- Blind analysis
- Use of “normalization channel” $B^+ \rightarrow J/\psi \ K^+$ to
  - remove large uncertainties on luminosity and $\sigma_{\text{bb}}$
  - reduce efficiency systematic uncertainties in the ratio

\[
B(B_q^0 \rightarrow \mu^+\mu^-) = B_{\text{norm}} \times \frac{f_{\text{norm}}}{f_{B_q^0}} \times \frac{N_{B_q^0 \rightarrow \mu^+\mu^-}}{N_{\text{norm}}} = \alpha_{B_q^0 \rightarrow \mu^+\mu^-} \times N_{B_q^0 \rightarrow \mu^+\mu^-}
\]

- Separated analysis in barrel/endcap: signal resolution: 36/77 MeV/c^2
- Main backgrounds:
  - Collimated muons from two semileptonic B decays ($\rightarrow$ gluon splitting)
  - One muon from semileptonic B decay plus one misidentified hadron
  - Rare decays
    - Peaking (e.g. $B_s \rightarrow K^+ K^-$)
    - Non-peaking (e.g. $B_s \rightarrow K^+ \mu^- \nu$)

arXiv:1203.3976 [hep-ex]
to appear in JHEP
SIGNAL SELECTION

• Selection variables:
  1) Muon and dimuon $p_T$
  2) vertex $\chi^2$ probability
  3) Pointing angle
  4) Impact parameter and flight length significance
  5) Di-muon isolation in a cone around the B direction
     - $\sum p_T + \#$ of close tracks + DCA of the closest track
• Cut optimization and count in $B^0$ and $B_s$ mass windows
  • check robustness against large pile-up variations
  • mass sidebands for expected background estimation
• Efficiency ratios from MC and checked in data
  • Muon efficiencies: using the “tag-and-probe” method
  • Selection efficiency: using the $B_s \rightarrow J/\psi \phi$ control sample
NORMALIZATION AND BACKGROUND

- $N_{\text{norm}}$ from invariant mass fit to the $B^+ \rightarrow J/\psi K^+$ sample
  - Uncertainties include statistics and systematics (mainly from background shape)

- Combinatorial background from dimuon mass sideband interpolation assuming flat distribution
- Peaking background shapes from MC → sum of many exclusive decays
  - Contribution in the signal region estimated by weighting with measured $K$, $\pi$ and $p$ muon mistag probabilities in data (from $K_s \rightarrow \pi^+ \pi^-$, $\phi \rightarrow K^+ K^-$ and $\Lambda \rightarrow p \pi^-$)
RESULTS

<table>
<thead>
<tr>
<th>Variable</th>
<th>$B^0 \rightarrow \mu^+\mu^-$ Barrel</th>
<th>$B^0_s \rightarrow \mu^+\mu^-$ Barrel</th>
<th>$B^0 \rightarrow \mu^+\mu^-$ Endcap</th>
<th>$B^0_s \rightarrow \mu^+\mu^-$ Endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{\text{tot}}$</td>
<td>$0.0029 \pm 0.0002$</td>
<td>$0.0029 \pm 0.0002$</td>
<td>$0.0016 \pm 0.0002$</td>
<td>$0.0016 \pm 0.0002$</td>
</tr>
<tr>
<td>$N_{\text{signal}}^{\text{exp}}$</td>
<td>$0.24 \pm 0.02$</td>
<td>$2.70 \pm 0.41$</td>
<td>$0.10 \pm 0.01$</td>
<td>$1.23 \pm 0.18$</td>
</tr>
<tr>
<td>$N_{\text{total}}^{\text{exp}}$</td>
<td>$0.97 \pm 0.35$</td>
<td>$3.47 \pm 0.65$</td>
<td>$1.01 \pm 0.35$</td>
<td>$2.45 \pm 0.56$</td>
</tr>
<tr>
<td>$N_{\text{obs}}$</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>4</td>
</tr>
</tbody>
</table>

- **Expected ULs:**
  \[ \text{BR}(B_s \rightarrow \mu\mu) < 8.4 \times 10^{-9} \text{ @ 95\% CL} \]
  \[ \text{BR}(B_d \rightarrow \mu\mu) < 1.6 \times 10^{-9} \text{ @ 95\% CL} \]

- **Observed ULs:**
  \[ \text{BR}(B_s \rightarrow \mu\mu) < 7.7 \times 10^{-9} \text{ @ 95\% CL} \]
  \[ (~2.5\times \text{SM value}) \]
  \[ \text{BR}(B_d \rightarrow \mu\mu) < 1.8 \times 10^{-9} \text{ @ 95\% CL} \]
D⁰ → μ⁺μ⁻ : STRATEGY

• (Not so) similar to B_{s,d} → μ⁺μ⁻ → long-distance processes play an important role in the decay
  - SM branching ratio ~ 10⁻¹³, analogous enhancements from NP models
• Consider BF ratio of
  \[
  \frac{D^{*+} \rightarrow D^0(μ^−μ^+)π^+}{D^{*+} \rightarrow D^0(K−μ^+ν)π^+}
  \]
• D⁰ → Kμν used as a normalization mode, not triggered throughout the full CMS dataset → use 90 pb⁻¹ total statistics
• D* → D⁰π decay used to:
  • produce a clean signal sample (use of Δm variable)
  • estimate approximately the z-component of the neutrino momentum (use of decay kinematics) in the normalization mode
**D⁰ → μ⁺μ⁻**: RESULTS

- Acceptance/efficiency ratio from MC
  - Main systematics on single-muon trigger and kaon tracking efficiencies
- Observed limit:

\[ \text{BR}(D⁰ → \mu\mu) < 5.4 \times 10^{-7} \text{ @ 90\% CL} \]

<table>
<thead>
<tr>
<th>Trigger</th>
<th>(Y(D⁰ → K^-\mu^+\nu))</th>
<th>(N_{obs})</th>
<th>(N_{bkg})</th>
</tr>
</thead>
<tbody>
<tr>
<td>HLT_Mu3</td>
<td>2361 ± 131</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HLT_Mu5</td>
<td>2259 ± 180</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>HLT_Mu7</td>
<td>11690 ± 209</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>HLT_Mu9</td>
<td>9912 ± 170</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>
CONCLUSIONS

• CMS is pursuing a wide program of heavy flavor physics of which I have selected a few topics:
  • Heavy-flavor production
    • S- and P-wave quarkonium production in good agreement with (Tevatron-tuned) NLO NRQCD \( \rightarrow \) test universality of long-distance matrix elements
    • Inclusive and exclusive \( B \rightarrow J/\psi \) production measurements show excellent shape agreement with NLO QCD, normalization overshooting predictions
  • Baryon spectroscopy \( \rightarrow \) new \( \Xi_b \) excited state observed
  • Rare decays:
    • BR limits on \( B_s, B_d, (D^0) \rightarrow \mu^+\mu^- \) competitive with those of HF-dedicated experiments
    • Stringent constraints on new physics models (CMSSM, NUHM...)

6/4/2012  CMS - R. Covarelli
BACKUP SLIDES
Polarization uncertainties not shown in the plots: quoted as typical variations using the 4 extreme acceptance scenarios.

- fully longitudinal polarization (Collins-Soper frame): $\pm 15\%, \pm 15\%$
- fully transverse polarization (Collins-Soper frame): $-6\%, -6\%$
- fully longitudinal polarization (helicity frame): $-20\%, -28\%$
- fully transverse polarization (helicity frame): $+18\%, +25\%$. 