Implications of LHC results for TeV-scale physics

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On behalf of the CMS and ATLAS Collaborations

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Searches for rare decays:

- $B_s \rightarrow \mu^+ \mu^-$ and $B^0 \rightarrow \mu^+ \mu^-$
- $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
- $D^0 \rightarrow \mu^+ \mu^-$
- $\tau \rightarrow 3$ leptons

CP violation in the $B_s$ system:

- $B_s \rightarrow J/\psi \phi$ and $B_s \rightarrow J/\psi f_0$

Conclusions and outlook
Searches for rare decays
Why searching for $B_{s,d} \rightarrow \mu^+ \mu^-$?

- Decays highly suppressed in SM
  - Forbidden at tree level
  - $b \rightarrow s$ FCNC transitions only through Penguin or Box diagrams
  - Helicity suppressed by factors of $(m_{\mu}/m_B)^2$

- Standard Model predictions
  - $\mathcal{B}(B_s \rightarrow \mu \mu) = (3.2 \pm 0.2) \times 10^{-9}$
  - $\mathcal{B}(B^0 \rightarrow \mu \mu) = (1.0 \pm 0.1) \times 10^{-10}$

- Sensitivity to new physics
  - MSSM Br proportional to $(\tan \beta)^6$
  - Very effective at high $\tan \beta$
Event characteristics

**Signal characteristics:**
- Two muons from a single decay vertex
- Mass compatible with $B_s$ (or $B^0$)
- Well reconstructed secondary vertex
- Momentum aligned with flight direction

**Background sources:**
- Two semi-leptonic $B$ decays (gluon splitting)
- One semi-leptonic $B$ decay + misidentified hadron
- Rare $B$ decays (e.g. $B_s \rightarrow KK$, $B_s \rightarrow K\mu^+\nu$)

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Key ingredients:
- Good di-muon vertex, correct $B$ mass assignment, momentum pointing to interaction point
Signal event selection

**All selection criteria optimized for limit sensitivity before unblinding of signal window**

- Mass window requirement:
  - Resolution: 36 (85) MeV in barrel (endcap)
  - 5.3-5.45 (5.2-5.3) GeV for $B_s$ ($B^0$)
- Selection cuts differentiated for **barrel** (both $|\eta(\mu)|<1.4$) and **endcap** region (all other $\mu$ pairs)
- Primary vertex consistent with $p(B)$ direction
- Secondary vertex fit $\chi^2$/dof<1.6
- Decay length and flight direction:
  - $l_{3D}/\sigma(l_{3D})>15$ (20), $\alpha_{3D}<50$ (25) mrad
- Single muon and $B$ candidate selection:
  - $p_T(\mu)>4.5$ or 4.0 GeV, $p_T(B)>6.5$ GeV

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Diagrams showing signal event selection criteria, including mass windows, resolution requirements, and selection cuts for primary and secondary vertices.
Signal event selection: isolation

- Relative isolation of muon pairs
  - Cone with $\Delta R=1$ around di-muon momentum
  - Include all tracks with $p_T>0.9$ GeV from same PV or $d_{CA}<500$ $\mu$m from B vertex
  - Require isolation larger than 75%

- Distance of closest approach of any track w.r.t. B vertex larger than 150 $\mu$m (endcap region only)

\[
\text{Isolation} = \frac{p_T(\mu^+ + \mu^-)}{p_T(\mu^+ + \mu^-) + \sum_{\Delta R<1} p_T} > 75\%
\]
Selection efficiency

- Validation of MC simulation performed with two exclusive decays
  - $B_s \rightarrow J/\psi (\mu^+\mu^-)\phi (KK)$
  - $B^+ \rightarrow J/\psi (\mu\mu)K^+$

- Signal and normalization efficiencies from simulation
  - **Signal efficiency**: 0.4% (0.2%) in barrel (endcap)
  - **Normalization efficiency**: 0.08% (0.03%) in barrel (endcap)

- Good agreement with simulation after sideband subtraction
  - Residual differences adopted as systematics
Branching ratio calculation

- Branching ratios calculated w.r.t. normalization channel $B^+ \rightarrow J/\psi (\mu^+ \mu^-) K^+$
  - Many systematic uncertainties cancel in ratio
  - No need for absolute luminosity and b-quark cross section
  - Large $B^+$ yield and well known branching ratio to $J/\psi K^+$ (3% uncert.)
  - Ratio of fragmentation fractions, $f_u/f_s$, from PDG (13% uncert.)

\[
\text{Br}(B_s \rightarrow \mu^+ \mu^-) = \frac{N(B_s \rightarrow \mu^+ \mu^-)}{N(B^+ \rightarrow J/\psi K^+)} \frac{f_u}{f_s} \frac{B^+}{B_s} \frac{\text{Br}(B^+ \rightarrow J/\psi K^+)}{\text{tot}}
\]

From PDG

From PDG

Candidates / 0.010 GeV

Barrel

Endcap

~13'000 candidates

~4'500 candidates
Background estimates

- **Combinatorial background:**
  - Measured in data from B mass sidebands
  - Interpolate to signal region under flat-shape assumption

- **Peaking backgrounds:**
  - $B \rightarrow hh$ backgrounds with two muons from misidentified hadrons
  - Muon mis-ID in data from $K_s \rightarrow \pi \pi$, $\phi \rightarrow KK$, $\Lambda \rightarrow p \pi$ decays
  - MC background samples with mis-ID probability from data
  - $B^0$ search more affected than $B_s$ because of lower mass
### Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fragmentation fractions from PDG</td>
<td>13%</td>
</tr>
<tr>
<td>Background estimation: <em>loosen cuts, invert isolation cut</em></td>
<td>4%</td>
</tr>
<tr>
<td>Signal acceptance: <em>vary b-quark production processes</em></td>
<td>4%</td>
</tr>
<tr>
<td>Signal selection efficiency: <em>cut-by-cut data/MC differences</em></td>
<td>8%</td>
</tr>
<tr>
<td>Track momentum scale: <em>from J/ψ resonance</em></td>
<td>3%</td>
</tr>
<tr>
<td>Normalization selection efficiency: <em>cut-by-cut data/MC differences</em></td>
<td>5%</td>
</tr>
<tr>
<td>Hadron tracking efficiency: <em>from D</em> decays*</td>
<td>4%</td>
</tr>
<tr>
<td>Normalization yield: <em>vary fit functions</em></td>
<td>5%</td>
</tr>
<tr>
<td>Muon identification efficiency ratio: <em>data/MC differences</em></td>
<td>5%</td>
</tr>
<tr>
<td>Trigger efficiency ratio: <em>data/MC differences</em></td>
<td>3%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>19%</strong></td>
</tr>
</tbody>
</table>
Consistent with expectation from background and SM signal in all four channels
CMS+LHCb combination

- LHCb analysis released at EPS 2011, based on 370 pb$^{-1}$
  - Upper limit = $1.6 \times 10^{-9}$ at 95% CL ($1.5 \times 10^{-9}$ combining with 2010 result)

- CMS and LHCb upper limits combined
  - Utilize recent LHCb $f_s/f_u$ value (8% uncert.)
    - Assumed 100% correlated between 48 LHCb bins and 2 CMS bins for signal expectation
  - p-value for background only = 8%
  - p-value for background+signal = 57%

![Graph showing CMS + LHCb combination](image-url)

**Figure 2:** The observed (solid curve) and expected (dotted curve) CLs values, for background-only (top) and background plus the Standard Model signal (bottom), as a function of $\text{BR}(B^0_s \rightarrow \mu^+ \mu^-)$. The green shaded area contains the $\pm 1\sigma$ interval of possible results compatible with the expected value; the 90w and 95w CL observed limits are illustrated by the dashed lines.

90% CL: $9 \times 10^{-9}$
95% CL: $11 \times 10^{-9}$
Implications on new physics

- Relevant impact on various SUSY scenarios at large $\tan\beta$
  - For large $\tan\beta$ (50) can extend limits from direct searches in some models

![NUHM](image1)

![CMSSM - $\mu > 0$](image2)

Current limits biting in the high $\tan\beta$ region (>50)

![Observation of SM branching would kill $\tan\beta > 45$ in CMSSM](image3)

![Many other global fitters available...](image4)
A three sigma evidence of SM branching may be at reach by early 2012

Improvement in sensitivity may be expected moving from cut&count to MV analyses

Simple scaling of current limits with no improvement in sensitivity!

5-7 times EPS11 luminosity needed for 3σ evidence of SM prediction with CMS+LHCb combination (35% already on tape!)
Prospects at Atlas

- Feasibility study based on MC:
  - Trigger:
    - L1 trigger $p_T$ threshold at 6 GeV
    - Track+muon segment combination at L2, $M(\mu^+\mu^-)<7$ GeV
  - Offline selection:
    - $l_{2D}>500\,\mu m$, $\alpha<17$ mrad, Isolation$>90\%$
    - Asymmetric search window: 4-7 GeV
    - Mass resolution: 70 (124) MeV in barrel (endcap)

First results expected in autumn 2011
Other rare decays

- $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
  - FCNC decay, $Br = (3.3 \pm 1.0) \times 10^{-6}$
  - Angular lepton asymmetries and polarization sensitive to helicity structure of new physics
  - Hints from b-factories and CDF unconfirmed by LHCb results ($A_{FB}$, $F_L$, $dI/dq^2$) at LP2011

- $D^0 \rightarrow \mu^+ \mu^-$
  - FCNC decay, $Br \sim 4 \times 10^{-13}$ [PRD 66, 014099]
  - NP could enhance $Br$ to $10^{-10}$-$10^{-8}$
  - Best published limit from Belle: $1.4 \times 10^{-7}$ (90%CL)

- $\tau \rightarrow 3$ leptons
  - SM branching $\propto (m_\tau/m_W)^4 \sim 10^{-50}$
  - NP could enhance $Br$ to as much as $10^{-7}$
  - Best limit for $3\mu$: $2.1 \times 10^{-8}$ (90%CL) [PLB 687 (2010) 139]
  - CMS simulation:
    - $3.8 \times 10^{-8}$ (95%CL) with 30 fb$^{-1}$
    - Single and di-muon triggers
    - Room for improvements at trigger level
CP violation in the $B_s$ system
CP violation in $B_s \rightarrow J/\psi \phi$

- CP violating phase induced by mixing
  - Very small SM prediction (-36±2) mrad
- Polarization amplitudes depend on CP of final state
  - Requires flavour tagged, time dependent angular analysis
  - Combined fit of 5 variables (mass, lifetime, three polarization angles)

Lepton-Photon 2011

Yield: $8276\pm96$ candidates in 337/pb

$\phi_s = 0.13\pm0.18\text{(stat)}\pm0.07\text{(syst)}$ from $J/\psi \phi$ only

$\phi_s = 0.03\pm0.18\text{(stat)}\pm0.07\text{(syst)}$ combined with $J/\psi f_0$

$\phi_s = \phi_M - 2\phi_D$

$\phi_s = -2\beta = -2 \arg \left( \frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} \right)$

Transversity angles

$\Omega = \{ \theta, \phi, \psi \}$
Studies at CMS

**Roadmap for J/ψφ studies:**

- **Cross section and average lifetime:**
  - In agreement with NLO and PDG
  - Yield: ~550 signal candidates in 40 pb⁻¹
- **(Un)tagged angular analysis with >2 fb⁻¹ ongoing**
  - Lower yields observed in 2011 due to higher trigger thresholds but overall samples larger than Tevatron

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8<p_T(B_s)<50 GeV, |y(B_s)|<2.4, σ=6.9±0.6(stat)±0.6(syst) nb
σ(MC@NLO)=4.6^{+1.9}_{-1.7}(scale)±1.4(Br) nb
Average lifetime measured with 2010 data:

- Yield: 463 signal candidates in 40/pb
- In good agreement with PDG, first step towards angular fit

### Table

<table>
<thead>
<tr>
<th>$B^0_{dJ}$</th>
<th>$B^0_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{B, ps}$</td>
<td>$1.51 \pm 0.04$</td>
</tr>
<tr>
<td>$m_B$ [MeV]</td>
<td>$5279.0 \pm 0.8$</td>
</tr>
<tr>
<td>$\sigma_{m_B}$ [MeV]</td>
<td>$34.3 \pm 0.9$</td>
</tr>
<tr>
<td>$N_{sig}$</td>
<td>$2750 \pm 90$</td>
</tr>
<tr>
<td>$\tau_{B, ps}$ - ATLAS</td>
<td>$1.51 \pm 0.04$ (stat) $\pm 0.04$ (syst)</td>
</tr>
<tr>
<td>$\tau_{B, ps}$ - PDG value</td>
<td>$1.525 \pm 0.009$</td>
</tr>
</tbody>
</table>
Conclusions and outlook

- **Competitive flavour physics program at CMS and ATLAS**

- **Search for rare decays $B_s \rightarrow \mu \mu$ and $B^0 \rightarrow \mu \mu$**
  - New results from CMS and LHCb with comparable sensitivity
  - CMS data sample ~ 3 times LHCb
  - New world best limit from LHC combination: $11 \times 10^{-9}$ (95%CL)
  - Atlas result expected in Autumn 2011
  - 5-7 times the EPS11 luminosity could lead to 3σ evidence of SM decay
  - Important constraint on SUSY models at large $\tan \beta$

- **Searches for more FCNC decays ongoing**

- **CP violation in $B_s \rightarrow J/\psi \phi$ and $J/\psi f_0$:**
  - Cross section and average lifetime already measured by CMS and ATLAS
  - Measurement of lifetime difference by end of the year
New physics is under stress...

But don’t be desperate (yet)

...AND YOU THINK YOU HAVE STRESS...
Constraints on Susy

With $B_s \rightarrow \mu \mu$

No $B_s \rightarrow \mu \mu$

Frédéric Ronga – Implications of LHC results – September 1, 2011

Preliminary

NUHM1 (with)

NUHM1 (without)

CMSSM

NUHM

O. Buchmueller et al. this workshop