Semi-tauonic physics at LHCb

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on behalf of the LHCb collaboration

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Indirect probes for New Physics

• Two ways of searching for NP:
  ◦ directly produce new particles in high energy collisions
  ◦ look for indirect effects from virtual particles in precisely predicted SM processes

• Ground state $B$ decays mediated by bosons $20 \times$ heavier than $m_B$ → sensitive to effects from heavier particles

\[
\overline{B} \left\{ b \rightarrow \nu_\tau \right\} \text{ } D^{(*)}
\]
Lepton universality

- **SM implies lepton universality**: lepton flavours are identical to one another, i.e. electroweak couplings are the same
- Amplitudes for processes involving $e$, $\mu$, $\tau$ should be the same once the effects depending on the different mass are factorised out
  - differences due to the different mass can be large! e.g:
    \[
    \mathcal{B}(Z \rightarrow \tau\tau) = \mathcal{B}(Z \rightarrow ee, \mu\mu) \\
    \mathcal{B}(\psi(2s) \rightarrow \tau\tau) = 0.39 \times \mathcal{B}(\psi(2s) \rightarrow ee, \mu\mu)
    \]
- Lepton non-universality would be a clear sign of NP
- **No definitive observation yet**
Semileptonic B hadron decays

- “β decay” of $B$ hadrons: emission of leptons and neutrinos, with recoiling hadronic system
- strong part and weak part are factorizable $\Rightarrow$ easier theoretical computation

\[
\frac{d\Gamma}{dq^2} (B \to D^* \ell \nu) \propto \frac{G_F^2 |V_{cb}|^2 f^2(q^2)}{m_{D^*}^2}
\]

- taking the ratio cancels most uncertainties in the QCD transition between $B$ and $D^*$

\[
R(D^*) \equiv \frac{\mathcal{B}(B \to D^* \tau \nu)}{\mathcal{B}(B \to D^* \mu \nu)}
\]
Semitauonic decays

- semileptonic decays to $e$ and $\mu$ extensively studied at $B$ factories
- decays to the third generation less well measured ($\sim 5\times$ larger uncertainties)

- still room for NP in tree-level decays
  - especially if NP couples preferentially to 3rd generation
  - like the Higgs does...
  - teaser: additional charged Higgs bosons, leptoquarks...
Measuring semi-tauonic decays

- long lifetime $c\tau_b \sim 400\mu m \implies$
  - important for $b$ tagging + SV reconstruction
- Take $B \to D^*\ell\nu$, with $\ell = \mu, \tau$
- with the leptonic $\tau$ decay:
  \( \tau \to \mu\nu\bar{\nu} \) ($B \approx 17\%$)
- $\mu$ and $\tau$ modes result in identical visible final states
  \( \implies \) nice normalization
- taking the ratio cancels effects due to reconstruction
What measuring $R(D^*)$ looks like

Challenges

- no sharp peaks to fit to separate $\mu$ from $\tau$ (but some handles)
- 1–3 neutrinos in the final state
- background from partially reconstructed $B$ decays
Distinguishing $\tau$ from $\mu$

Looking at the decay kinematics in the $B$ rest frame:

<table>
<thead>
<tr>
<th>$B^0 \rightarrow D^{*+} \tau^- \nu$</th>
<th>$B^0 \rightarrow D^{*+} \mu^- \nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{miss}^2 &gt; 0$</td>
<td>$m_{miss}^2 = 0$</td>
</tr>
<tr>
<td>$E_\mu^*$ spectrum is soft</td>
<td>$E_\mu^*$ spectrum is hard</td>
</tr>
<tr>
<td>$m_\tau^2 \leq q^2 \leq 10.6 \text{ GeV}^2$</td>
<td>$0 \leq q^2 \leq 10.6 \text{ GeV}^2$</td>
</tr>
</tbody>
</table>
\( R(D^*) \) at B-factories

- B factories operate at the \( \Upsilon(4s) \rightarrow B\bar{B} \) energy
- no other hadrons produced
- more kinematic information at B factories
- possibility to fully reconstruct one side of the event

\[ \Upsilon(4S) \rightarrow B\bar{B} \]

\( B \) tagging, from Lück @ ICHEP2014
$R(D^*)$ at LHC(b)

- unknown CM frame for $gg \rightarrow b\bar{b}$
- lots of additional particles
- missing neutrinos $\Rightarrow$ underconstrained kinematics
- background from partially reconstructed $B$ decays
The LHCb detector...

...is a single-arm forward spectrometer at the LHC, covering 15-300 mrad
The LHCb detector

- >96% efficient tracking system, excellent $p$ resolution
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- RICH 1, 2 + muon chambers for PID
Event selection

• online selection based on $D^0$ candidate
• combine $D^0 \rightarrow K\pi$ from the trigger with a slow $\pi$ (to form a $D^*$, which decays immediately) and a $\mu$
• $D^0$ vertex well separated from the primary vertex ($pp$)
• $\mu$, $K$ and $\pi$ not pointing to the primary vertex
• reconstructed $D^0$ not pointing to the primary vertex (suppressing prompt charm background)
B reconstruction

- ambiguities in the reconstruction of the $B$ rest frame
- $B$ boost along $z$ is much larger than the boost of its daughters in the $B$ rest frame
- well-behaved approximation, small momentum dependence on the resolution of the flight direction
Boost approximation

\[ B \rightarrow D^{* \tau \nu} \]
\[ B \rightarrow D^{* \mu \nu} \]

MC truth

Reconstructed

Fit strategy

- Obtain template histograms for all processes contributing to the $B^0 \to D^* \mu \nu$ yield
  - $\tau$ mode and $\mu$ mode, and partially reconstructed backgrounds use Monte Carlo simulation tuned on real data
    - $B \to D^{**} (\to D^* \pi, D^* \pi\pi) \ell \nu$ with missing pions
    - $B \to D^* H_c (\to \mu \nu X') X$
  - other backgrounds use control samples obtained from real data
    - combinatorial background
    - $h \to \mu$ misidentification

- Use these templates as PDF for a maximum likelihood fit to data
LHCb performed the fit in 4 bins of $q^2$.

SM: $R(D^*) = 0.252 \pm 0.003$ (Phys.Rev.D85(2012) 094025)

<table>
<thead>
<tr>
<th></th>
<th>LHCb</th>
<th>Belle</th>
<th>BaBar</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$0.293 \pm 0.038 \pm 0.015$</td>
<td>$0.302 \pm 0.030 \pm 0.011$</td>
<td>$0.332 \pm 0.024 \pm 0.018$</td>
</tr>
<tr>
<td>$0.336 \pm 0.027 \pm 0.030$</td>
<td>$0.276 \pm 0.034^{+0.029}_{-0.026}$</td>
<td></td>
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Main LHCb systematic: statistical uncertainty on simulated samples and modelling of mis-ID background. Both can be improved.
Results

- all experiments see excess of signal with respect to the SM
- $B$ factories also measured $R(D)$
- latest HFAG average reports a 3.9 $\sigma$ deviation from the SM

http://www.slac.stanford.edu/xorg/hfag
Implications

Other measured anomalies

- $R(K) = 0.745^{+0.090}_{-0.074} \pm 0.036$ \cite{PRL113,151601} (2014)
  
  $(B \to K_{ee}/B \to K\mu\mu, 2.6 \sigma$ from unity)

- $P_5'$ in $B \to K^*\mu\mu$, also at Belle
  
  \cite{JHEP02,1604.04042}

- if new particles couple more to 2$^{nd}$ and 3$^{rd}$ first generation, expect $R_K < 1$ and $R(D^*) > R(D^*)_{SM}$

- example model that fixes all anomalies: $\sim 1$ TeV leptoquarks

\begin{align*}
  b & \quad \nu \\
  \phi & \quad c \quad (s) \\
  \tau \quad (\nu) & \quad s \\
  \phi & \quad \mu \\
  \mu & \quad t \\
  b & \quad \phi \quad \mu \\
  \nu & \quad \tau \\
  \tau & \quad \phi \\
  \phi & \quad \mu
\end{align*}

\cite{M. Bauer, M. Neubert, Phys. Rev. Lett. 116, 141802 (2016)}
More semitauonic physics at LHCb

- \( R(D^*) \) with \( B \to D^*\tau (\to 3\pi)\nu \)
  - complimentary information, different systematics
  - unfortunately non-\( \tau \) \( D^*3\pi X \) is 100\( \times \) larger
  - separation of the 3\( \pi \) vertex

- \( R(D^0), R(D^+) \)
  - require careful evaluation of feed-down from \( D^* \)

- \( R(D_s) \) with \( B_s \to D_s\tau\nu \)
  - many excited states emitting neutral particles

- \( R(J/\psi) \) with \( B_c \to J/\psi\tau\nu \)
  - clean \( B(J/\psi \to \mu\mu) \) can compensate for low \( B_c \) production

- \( R(\Lambda_c), R(\Lambda^*_c) \) from \( \Lambda_b \) decays
  - different spin structure ensures different physics sensitivity, discriminating tensor contributions
Conclusions

- New physics must be out there and $B$ physics is a promising sector
- How to get rid of detector effects and of QCD uncertainty?
  - look at factorizable semileptonic decays
  - measure ratio of observables (LFU, angular analyses)

- $B \to D^* \tau \nu$ was the first measurement of a $b \to c \tau \nu$ decay at a hadron collider
- Difficult measurement, yet result is tantalizing given the history of measurements of this channel all above the SM
- Run 2 data set will reduce the uncertainty by 60%
- $R(D^*)$ marks the beginning of a vast exploration in several channels
- Not only $R$, but also angular analyses, form factors, and charmless semi-tauonic decays
Spare slides
Flavour physics

- Flavour physics is the study of different generations of fermions
- It can help in excluding/finding NP regardless of its mass scale
  - and determine its flavour structure

\[
V_{CKM} = \begin{pmatrix}
1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 
\end{pmatrix} + \mathcal{O}(\lambda^4)
\]

- \( V_{CKM} \) hierarchical and nearly diagonal
- transitions between different generations suppressed
- 3\textsuperscript{rd} generation especially isolated
  \[\implies\] tree-level \( b \) decays suppressed, long \( b \) lifetime
What measuring $R(D^*)$ looks like

**Challenges**

- 1–3 neutrinos in the final state
- no sharp peaks to fit
- difficult to separate $\mu$ from $\tau$
- at $B$ factories one can use tagging, but not at the LHC
Heavy flavour physics at LHC

- large amount of beauty hadrons produced (at 7 TeV: $\sigma_{b\bar{b}} \approx 280 \mu\text{b}$)
- $b$ hadrons produced with highly boosted CM frame
- central detector: 98% solid angle coverage provides 52% $B$ hadron acceptance
- forward detector: 3% solid angle coverage provides 27% $B$ hadron acceptance
The LHCb detector

- Tracking system (VELO+ST+OT) >96% efficient for charged particles crossing the whole detector
- VELO provides 20 μm IP resolution, 45 fs decay time resolution for $b$ hadron decays

- RICH 1, 2 + muon chambers for PID
Triggering

- avoid biasing: trigger as inclusive as possible
- L0 trigger: muons and calorimetry
- HLT: full reconstruction for tracks with $p_T > 300$ MeV

$R(D^*)$ trigger

- both $\mu$ and $\tau$ modes use charm trigger, allowing $D^0 \rightarrow K \pi$ with well separated vertex
- no triggering on the muon!
Current tests of Lepton Flavour Universality, I


$$R(K_{\ell2}) \equiv \frac{\mathcal{B}(K \to e\nu)}{\mathcal{B}(K \to \mu\nu)} = (2.488 \pm 0.010) \times 10^{-5}$$

$$R(K_{\ell2})_{SM} = (2.477 \pm 0.001) \times 10^{-5}$$

- In agreement with SM
Current tests of Lepton Flavour Universality, II

Branching fractions of $b \to s\ell\ell$ transitions are very sensitive to various NP contributions!
Current tests of Lepton Flavour Universality, III

- BaBar, Belle, LHCb:

\[
R(K) = \frac{\mathcal{B}(B \to K\mu\mu)}{\mathcal{B}(B \to K\text{ee})}
\]

\[
R(K)_{SM} = 1 \pm \mathcal{O}(10^{-3})
\]

- LHCb: PRL 113 (2014) 151601
- BaBar: PRD 86 (2012) 032012
- Belle: PRL 103 (2009) 171801
Current tests of Lepton Flavour Universality, IV

- \( B^0 \rightarrow K^* \mu \mu \)
  - BF lower than prediction (but consistent)
  - 3.4 \( \sigma \) tension in one of the variables describing the angular distributions

- CMS: PLB 753 (2016) 424
- Belle: arXiv:1604.04042
Current tests of Lepton Flavour Universality, V

- $B^0 \rightarrow K^* ee$
  - challenging due to low statistics, resolution, and triggering issues
  - in agreement with predictions
  - LHCb: JHEP 04 (2015) 064
  - SM: PRD 93 (2016) 014028

- $B_s \rightarrow \phi \mu \mu$
  - BF lower than prediction (local $3\sigma$ tension in $1 < q^2 < 6$ GeV$^2$)
  - angular observables consistent with SM
  - LHCb: JHEP 09 (2015) 179
Current tests of Lepton Flavour Universality, VI

- $B_s \rightarrow \mu \mu$ and $B^0 \rightarrow \mu \mu$
  - combined CMS and LHCb measurement + ATLAS independent measurement
  - lower BF but compatible with SM
• arXiv:1506.01705
• $SU(2)_L$ triplet of massive vector bosons
coupled predominantly to 3rd generation fermions
explains:
  ◦ $R(D^*)$
  ◦ $R(K)$
  ◦ tension between inclusive and exclusive meas. of $|V_{cb}|$ and $|V_{ub}|$

Exclusion limits:
\[
\begin{align*}
&\mathcal{B}(Z' \to \tau\tau) = 0.01 \\
&\mathcal{B}(Z' \to \tau\tau) = 0.10
\end{align*}
\]

\[
\begin{array}{cccc}
200 & 400 & 600 & 800 & 1000 & 1200 & 1400 \\
0.05 & 0.10 & 0.50 & 1 \\
\end{array}
\]

$\nu_0$ (GeV)

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