Semitauonic B decays, a window on new Physics

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Why semitauonic decays are interesting?

- As tree level decays, they combine the advantages:
  - Very precise prediction from SM: \( R(D^*) \) known to 2% precision, using
    \[
    R(D^*) = \frac{\text{BR}(B^0 \rightarrow D^*\tau\nu)}{\text{BR}(B^0 \rightarrow D^*\mu\nu)}
    \]
  - Abundant channel \( \text{BR}(B^0 \rightarrow D^*\tau\nu) = 1.24\% \), one of the largest individual BR
  - Sensitivity to new physics: (simplest realization) A charged Higgs will automatically couple more to the \( \tau \). LFU violation can also occur through other mechanisms (leptoquarks,..)

- They offer several hadronisation implementations:
  - \( D^*, D^0, D^+, D_s, \Lambda_c, J/\psi \)
  - Differing not only by various properties of the spectator particle but also its spin: 0 (\( D^0, D^+, D_s \)), 1 (\( D^* \) and \( J/\psi \)) and \( \frac{1}{2} \) (\( \Lambda_c \)))
R(D*) with $\tau \rightarrow \mu \nu \nu$

Using the known B flight direction, approximate the B momentum using $\gamma \beta_{z,\text{vis}} = \gamma \beta_{z,B}$:

- Estimate gives $\sim 18\%$ resolution on B momentum, but preserves shapes of already-broad distributions of $m_{\text{miss}}^2$, $E_\mu^*$ and $q^2$
- 3d MC-template based binned fit to $m_{\text{miss}}^2$ vs $E_\mu^*$ in coarse $q^2$ bins
Fit Result

- Shown above: signal fit to “signal” data passing isolation selection
- Result $\frac{N_T}{N_\mu} = (4.32 \pm 0.37) \times 10^{-2}$, \(R(D^*) = 0.336 \pm 0.027 \pm 0.030\)
- \(N(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu) = 363,000 \pm 1600\)
If WA is correct, 22% of the D*τν events are mediated by new physics!

New ! $R(D^*)$ using $\tau$ hadronic decays in $3\pi$

Unusual features of this analysis

- A semileptonic decay without (charged) lepton !!:
  - Amusing but more importantly ZERO background from normal semileptonic decays!!!!

- The background leads to nice mass peaks and not the signal !!!
  - Amusing but more importantly provides key handles to control the various backgrounds

- Only 1 neutrino emitted at the $\tau$ vertex
  - The complete event kinematics can be reconstructed with reasonable precision

- But very large potential background from « bread and butter » $D^*3\pi X$ decays; 100 times larger than the signal : A trick must be found!!
The normal topology of a $D^{*3}\pi X$ event

THIS topology for $D^{*}\tau\nu$ events

The $4\sigma$ requirement kills the $D^{*3}\pi X$ background by $\sim10^3$: the road to the treasure is open 😊!!!
The second gate: the double charm background

The second gate consists of $B^0$ decays where the $3\pi$ vertex is transported away from the $B^0$ vertex by a charm carrier: $D_s$, $D^+$ or $D^0$ (in that order of importance)

- This gate is thinner:
  - Double Charm $\rightarrow 3\pi X \sim 10 \times$ signal

LHCb has three very good weapons to blow this gate away:
- $3\pi$ dynamics
- Neutral isolation
- Background partial reconstruction
Importance of the normalization channel \( B^0 \rightarrow D^* 3\pi \)

- Normalization as similar as possible to the signal to cancel production yield, BR uncertainties and systematics linked to trigger, PID, first selection cuts

- Absolute BR recently measured by BABAR with a precision of 4.3%
  
  \( \text{(Phys.Rev. D94 (2016) no.9, 091101)} \)
The importance of the « D_s-o-meter »

- The D_s meson is the highest background since the W decays dominantly in D_s and the D_s is a very rich source of 3π +X final states.
- At low mass, only η and η' (red,green) contributions are peaking
  \[ η \rightarrow π^+π^-π^0 \text{ and } η' \rightarrow η π^+π^- \quad \Rightarrow \quad M_{π^+π^-} < 415 \text{ MeV} \]
- At the ρ mass where the signal lives (τ→a_1,a_1→ρπ), only η’ contributes (η’→ ργ)
- Using the low BDT region, one constraints the D_s decay model to be used at high BDT
The anti-$D_s$ BDT

- A BDT is constructed to get rid of the $D_s$ background. It contains the following variables:
  - $3\pi$ dynamics: $\min(m_{\pi\pi})$, $\max(m_{\pi\pi})$,
  - B dynamics: $D^*3\pi$ mass
  - Partial reconstruction: the 4 constraints from the 2 lines of flight allows to reconstruct fully the event in the background hypothesis (no neutrinos)
  - Neutral isolation: energy in a cone around the $3\pi$ direction
  - Very $D_s$ enriched at low BDT, good purity for signal at high BDT

- Opens the gate for search for BSM inside the events in addition to yields measurements
The control channels $D_s$, $D^0$, and $D^+$

**$\pi\pi\pi$ mass in detached topology**

**$D_s$**

**Run 1, 3 fb$^{-1}$**

**$D^0$ to $K\,3\pi$ peak : Antisolation cut**

**$D^+$ peak : Anti-PID cut**

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The $D_s \to 3\pi$ control channel is used to measure the ratio of $D^*D_s/D^*D^*_s/D^*D_s^{**}$ and to correct for their $q^2$ distribution.

A full fit is then performed at high BDT, as a 3D template binned fit of BDT,$q^2$ and $\tau$ lifetime.

$D^*3\pi$, $D^0$ background constrained by their signal in the control channels.

[Graph showing data from BaBar, Belle, LHCb, and an average, with a note that the results are from Run-1 and include only the central value and statistical errors.]
Systematic uncertainties

- **External**
  - 4.3% from $\text{BR}(B^o \rightarrow D^*3\pi)$ PDG 2016
  - 2% from $\text{BR}(B^o \rightarrow D^*\mu\nu)$

- **Internal**
  - MC statistics
  - $D_s, D^+, D^o$ backgrounds
  - Prompt $B^o$ backgrounds
  - Stripping, Trigger
  - FF and $\tau$ decay model

**In red**: can be reduced with help from other experiments (BELLE, BES,..)
- Expected overall to be larger than statistical error for the first publication (soon to come)
- Room for progress exists on a longer timescale on both internal and external sources!
Conclusion and Perspectives

- Semitauonic B decays are a great tool to discover new physics: high SM precision, high rate and high sensitivity.
- The exceptional LHCb capability to separate secondary and tertiary vertices open up the best road to study the semitauonic decays of all B particles, thanks to a new method based on 3 prongs $\tau$ decays.
- The statistical precision on Run1 should be around 6.5%, the best achieved so far for a single measurement.
- The very successful RunII data taking in 2015-2016 leads to a quadrupling of the data set.
- High statistics and high purity samples to search for BSM effects in the event observables.