Semitauonic B decays, a window on new Physics
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
    $$R(D^*) = \frac{BR(B^0 \rightarrow D^* \tau \nu)}{BR(B^0 \rightarrow D^* \mu \nu)}$$
  - Abundant channel $BR(B^0 \rightarrow D^* \tau \nu) = 1.24\%$, 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 $1/2$ ($\Lambda_c!!$)
R(D*) with $\tau \to \mu \nu \nu$

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

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

Low $q^2$

$m_{miss}^2$

$E_\mu$

High $q^2$

$m_{miss}^2$

$E_\mu$

- Shown above: signal fit to “signal” data passing isolation selection
- Result $\frac{N_\tau}{N_\mu} = (4.32 \pm 0.37) \times 10^{-2}$, $R(D^*) = 0.336 \pm 0.027 \pm 0.030$
- $N(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu) = 363,000 \pm 1600$
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

The detached vertex method

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

The 4\sigma requirement kills the $D^{*3}\pi X$ background by $\sim 10^3$; the road to the treasure is open 😊!!!
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% (Phys.Rev. D94 (2016) no.9, 091101)
A promenade through charm physics

- As mentioned already, the background is formed of the various charm mesons $D_s, D^0, D^+$ produced in the decay of the $W$ into a $c\bar{s}$ pair. These charm mesons have to decay into 3 pions.

- This analysis is therefore a promenade to the various inclusive $3\pi$ decays of the charm mesons!
  - A lot of data is already available but not enough!!
  - BES data could play a key role in reducing many systematics in the future (hopefully relatively quickly!)

- These $W \rightarrow c\bar{s}$ decays can produce a single meson, very often in an excited state $D_s, D_s^*, D_s^{**}$ or two particles $D^0K^-, D^+K^0$, and their excited counterparts.
The inclusive $D_s$ decays in 3 pions

- Although the exclusive $D_s \rightarrow 3\pi$ is small (1% BR), the $D_s$ is a amazingly rich source of $3\pi + X$ final states
- We classify hadronic $D_s$ decays into 3 pions in 4 categories
  - $\eta\pi X (\eta\pi, \eta\rho)$
  - $\eta'\pi X (\eta'\pi, \eta'\rho)$
  - $(\phi/\omega)\pi X (\phi/\omega \pi, \phi/\omega \rho)$
  - $M3\pi$, where $M$ can be $K^0, \eta, \eta', \omega, \phi$
- We would need precise BR for all of these (some well measured, some poorly, some not at all)
- And the inclusive BR of $D_s$ into 3 pions to constraint all of these !!!!
D\(^+\) and D\(^0\) decays into 3 \(\pi\)

- The situation is simpler to D\(^+\) and D\(^0\) decays whose main 3\(\pi\) decay mode is thru the K3\(\pi\) decay
- For the D\(^0\), the inclusive 4 prongs BR constrains strongly the rate of 3\(\pi\) events
- Unfortunately, nothing exists for the D\(^+\) mesons, K3\(\pi\)\(\pi^0\) is poorly known, the inclusive BR is critical
- Existence of 1.4 GeV edge in the 3\(\pi\) mass distribution is useful to see their presence
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
  \[ \eta \rightarrow \pi^+\pi^-\pi^0 \quad \text{and} \quad \eta' \rightarrow \eta \, \pi^+\pi^- \quad \Rightarrow \quad M_{\pi^+\pi^-} < 415 \, \text{MeV} \]
- At the ρ mass where the signal lives (τ→a₁;a₁→ρπ), only η’ contributes (η’→ ργ)
- Using the low BDT region, one constraints the D_s decay model to be used at high BDT

![Signal region](image)
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 antiDs BDT: $3\pi$ dynamics, partial reconstruction and isolation

Current trends in Flavor Physics, March 30 2017
Charged Isolation

- LHCb software can attach a track passing nearby a vertex: very useful to tag $D^0$ decays in $K_3\pi$
- Necessity to reject also 5 prong $D_s$ decays which are frequent when there is the combined presence of an $\eta$ and $\eta'$ presence in the decay chain.
- Very efficient for $D^0$ decays which is often accompanied by 2 charged kaons, less for the $D^+$
- To keep the background low, we request only events with 1 combination
Background Partial reconstruction

Partial reconstruction

For $B^0 \rightarrow D^{*-}D_s^+$: $|\vec{p}_B| \hat{u}_B = |\vec{p}_{D_s^+}| \hat{u}_{D_s^+} + |\vec{p}_{D_s^+}| \hat{u}_{D_s^+} \Rightarrow 0$

After some vectorial algebra \rightarrow get magnitude of $B^0$ and $D_s^+$ momenta

First approximation \rightarrow $\hat{u}_{D_s^+}$ is the 3π direction

Apply a correction to $B^0$ vertex due to the presence of neutral particles in $D_s^+$ decay \rightarrow parametrization of this correction as function of 3π mass on $D^{*-}D_s^+$ MC \rightarrow get $B^0$ and $D_s^+$ momenta at a next-level of approximation

Reconstruction of $D_s^+$ mass, with nominal $B^0$ and $D^{*-}$ masses values
The control channels $D_s$, $D^0$, and $D^+$

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

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

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

$D^+$ peak: Anti-PID cut
Signal extraction

- The $D_s \rightarrow 3\pi$ 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.
Systematic uncertainties

- **External**
  - 4.3% from BR(B° → D*3π) PDG 2016
  - 2% from BR(B° → D*μν)

- **Internal**
  - MC statistics
  - D_s, D^+, D° backgrounds
  - Prompt B° backgrounds
  - Stripping, Trigger
  - FF and τ 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!
LHCb prospects using muonic channel

- $R(D)$ underway
- $R(J/\psi)$ very advanced
- $R(D_s), R(\Lambda_c^*)$ started
LHCb prospects using hadronic channel

- $R(D)$ nothing really problematic
- $R(J/\psi)$ just starting
- $R(\Lambda_c)$ well advanced
- $R(D_s)$ under consideration

Expected precision in the ~10% range due to
  - Statistics
  - Normalization strategy
  - Systematics

- for $R(J/\psi)$, the dimuon trigger will allow a direct comparison with $B_c \rightarrow J/\psi \mu \nu$
Search for LFU violation in leptonic decays

- The annihilation diagram $B^+ \rightarrow \tau \nu$ is not yet doable in LHCb. Note: same final state for $B^+$ and $B_c$.

- Note that however this can be replaced by the ‘$V_{ub}$’ analog $b \rightarrow u W$ which probes the same diagram. Rather difficult in practice for lack of specificity but LHCb can look for:
  - $\Lambda_b \rightarrow p \tau \nu$ (very challenging but statistical power similar as $R(Lc)$)
  - $B^+ \rightarrow p \bar{p} \tau \nu$ (underway)
Agreement within LHCb to hold a second semitauonic workshop in Orsay

Preliminary schedule April 10-12. Did not work because preemption by a similar workshop taking place in Nagoya organised by BELLE-II

Delayed in the Spring (or Fall?) : idea is to open it not only to theoreticians but also to others experiments

Quite a large attendance expected even from LHCb alone since now basically all the Rs are being covered, and for a good number of them both hadronic and muon channels.
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 τ 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.