Measurements of $R(D^{(*)})$ and similar ratios

from Belle, BaBar and an outlook for Belle II

XXIV Cracow EPIPHANY Conference on Advances in Heavy Flavour Physics
\[ R = \frac{b \rightarrow q \tau \bar{\nu}_\tau}{b \rightarrow q \ell \bar{\nu}_\ell} \]

\[ R(D^{(*)}, \pi, J/\psi) \]

1. How do we measure?

2. How do we predict?

3. Is it really 4σ?

4. The future
1. How do we measure?

and why do we think we got it (mostly) right!

Florian Bernlochner
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contours hold 68% CL

$R(D^*)$

$R(D)$
Overview

1. Leptonic or Hadronic $\tau$ decays?

Some properties (e.g. $\tau$ polarisation) only accessible in hadronic decays.

2. Albeit not necessarily a rare decay of $O(\%)$ in BF, TRICKY to separate from normalisation and backgrounds

LHCb: Isolation criteria, displacement of $\tau$, kinematics

B-Factories: Full reconstruction of event (Tagging), matching topology, kinematics
Overview

3. **Semileptonic decays at B-Factories**

- $e^{+}/e^{-}$ collision produces $Y(4S) \rightarrow BB^-$

- Fully reconstruct one of the two $B$-mesons (‘tag’) → **possible** to measure **momentum** of signal $B$

- **Missing four-momentum** (neutrinos) can be reconstructed with high precision

\[
p_{\text{miss}} = (p_{\text{beam}} - p_{B\text{tag}} - p_{D(*)} - p_{\ell})
\]

✓ **Small efficiency (~0.2-0.4%)** compensated by large integrated luminosity

![Diagram of B meson decay](image)
BaBar Measurement of $R(D^{(*)})$

- Use of $\tau \to e\nu\nu$ and $\tau \to \mu\nu\nu$ to reconstruct $\tau$-lepton
- Simultaneous analysis of $R(D)$ vs. $R(D^*)$ using $B^0 \to D^{*-}\tau\nu$, $B^- \to D^{*0}\tau\nu$, $B^0 \to D^-\tau\nu$, $B^- \to D^0\tau\nu$
- Unbinned maximum likelihood fit in 2D to $m_{\text{miss}}^2$ and $|p_t^*|$

$$ (p_{\text{beam}} - p_{B\text{tag}} - p_{D^{(*)}} - p_\ell)^2 = m_{\text{miss}}^2 $$
BaBar Measurement of $R(D^{(*)})$

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- Unbinned maximum likelihood fit in 2D to $m_{\text{miss}}^2$ and $|p_t^*|$
BaBar Measurement of \( R(D^{(*)}) \)

- Use of \( \tau \rightarrow e \nu \nu \) and \( \tau \rightarrow \mu \nu \nu \) to reconstruct \( \tau \)-lepton
- Simultaneous analysis of \( R(D) \) vs. \( R(D^*) \) using \( B^0 \rightarrow D^{*-} \tau \nu \), \( B^- \rightarrow D^{*0} \tau \nu \), \( B^0 \rightarrow D^- \tau \nu \), \( B^- \rightarrow D^0 \tau \nu \)
- Unbinned maximum likelihood fit in 2D to \( m_{\text{miss}}^2 \) and \( |p_\tau^*| \)

\[
R(D) = 0.440 \pm 0.058 \text{ (stat)} \pm 0.042 \text{ (syst)} \quad (2\sigma \text{ from SM})
\]

\[
R(D^*) = 0.332 \pm 0.024 \text{ (stat)} \pm 0.018 \text{ (syst)} \quad (2.7\sigma \text{ from SM})
\]

✓ Combination is 3.4\( \sigma \) from SM
Belle Measurements of $R(D^{(*)})$

Several results using different techniques:

- $\tau \rightarrow e\nu\nu$ and $\tau \rightarrow \mu\nu\nu$, hadronic tag
  
  $$R(D) = 0.375 \pm 0.064 \text{ (stat)} \pm 0.026 \text{ (syst)}$$
  $$R(D^*) = 0.293 \pm 0.038 \text{ (stat)} \pm 0.015 \text{ (syst)}$$

  Analysis very similar to BaBar

- $\tau \rightarrow e\nu\nu$ and $\tau \rightarrow \mu\nu\nu$, semileptonic tag
  
  $$R(D^*) = 0.302 \pm 0.030 \text{ (stat)} \pm 0.011 \text{ (syst)}$$

- $\tau \rightarrow \pi\nu$ and $\tau \rightarrow \rho\nu$, hadronic tag
  
  $$R(D^*) = 0.270 \pm 0.035 \text{ (stat)} \pm 0.027 \text{ (syst)}$$
  $$P\tau(D^*) = -0.38 \pm 0.51 \text{ (stat)} \pm 0.18 \text{ (syst)}$$

First measurement of polarisation

✓ All $R(D^{(*)})$ measurements consistent but above SM

$R(D)_{SM} = 0.299 \pm 0.003$
$R(D^*)_{SM} = 0.257 \pm 0.003$
Belle Measurements of $R(D^{(*)})$

- Use of $\tau \to e\nu\nu$ and $\tau \to \mu\nu\nu$ to reconstruct $\tau$-lepton
- Simultaneous analysis of $R(D)$ vs. $R(D^*)$ using $B^0 \to D^{*-}\tau\nu$, $B^- \to D^{*0}\tau\nu$, $B^0 \to D^-\tau\nu$, $B^- \to D^0\tau\nu$
- Multivariate hadronic tagging algorithm with Neural Network
- Use binned likelihood fit in 2D to $m_{\text{miss}}^2$ and signal Neural Network

- $E_{\text{ECL}}$ (unassigned energy in the calorimeter)
- $q^2$ (four-momentum transfer)
  \[ q^2 = (p_X^b - p_X^q)^2 \]
- $|p_l^*|$ + more variables

Most discriminating variable: $E_{\text{ECL}}$
Belle Measurements of $R(D(\ast))$

- Use of $\tau \to e\nu\nu$ and $\tau \to \mu\nu\nu$ to reconstruct $\tau$-lepton
- Simultaneous analysis of $R(D)$ vs. $R(D^\ast)$ using $B^0 \to D^\ast - \tau\nu$, $B^- \to D^\ast 0 \tau\nu$, $B^0 \to D^- \tau\nu$, $B^- \to D^0 \tau\nu$
- Multivariate hadronic tagging algorithm with Neural Network
- Use binned likelihood fit in 2D to $m_{\text{miss}}^2$ and signal Neural Network

Classifier Distributions after $m_{\text{miss}}^2$ cut to enhance signal

$$R(D(\ast)) = \frac{N_{\text{sig}}\varepsilon_{\text{norm}}}{N_{\text{norm}}\varepsilon_{\text{sig}}}.$$
Belle Measurements of $R(D^{(*)})$

- Use of $\tau \rightarrow \nu \nu \nu$ and $\tau \rightarrow \mu \nu \nu$ to reconstruct $\tau$-lepton
- Simultaneous analysis of $R(D)$ vs. $R(D^*)$ using $B^0 \rightarrow D^{*-} \tau \nu$, $B^- \rightarrow D^{*0} \tau \nu$, $B^0 \rightarrow D^- \tau \nu$, $B^- \rightarrow D^0 \tau \nu$
- Multivariate hadronic tagging algorithm with Neural Network
- Use binned likelihood fit in 2D to $m_{\text{miss}}^2$ cut to enhance signal

Classifier Distributions after $m_{\text{miss}}^2$ cut to enhance signal

$R(D) = 0.375 \pm 0.064$ (stat) $\pm 0.026$ (syst) (1.1$\sigma$ from SM)

$R(D^*) = 0.293 \pm 0.038$ (stat) $\pm 0.015$ (syst) (0.9$\sigma$ from SM)

✓ Combination is 1.8$\sigma$ from SM
Belle Measurements of $R(D^*)$

- Use of $\tau \rightarrow \nu\nu\nu$ and $\tau \rightarrow \mu\nu\nu$ to reconstruct $\tau$-lepton
- Instead of hadronic use prompt semileptonic for tag-side reconstruction; only measures $R(D^*)$ due to large backgrounds
  - Larger BF, but less information due to tag-side neutrino

Discriminating variable $m_{\text{miss}}^2$ less powerful due to second neutrino, but can use angle between $B$ and $D^*$

$$\cos \theta_{B-D^*\ell} \equiv \frac{2E_{\text{beam}}E_{D^*\ell} - m_B^2c^4 - M_{D^*\ell}^2c^4}{2|\vec{p}_B| \cdot |\vec{p}_{D^*\ell}|c^2},$$

Diagram:
- $B \rightarrow D^{(*)}\tau[\tau \rightarrow \nu\nu\nu]\nu$
- $B \rightarrow D^{(*)}\nu$
- Other Background

Belle Measurements of $R(D^*)$

- Use of $\tau \to e\nu\nu$ and $\tau \to \mu\nu\nu$ to reconstruct $\tau$-lepton
- Instead of hadronic use prompt semileptonic for tag-side reconstruction; only measures $R(D^*)$ due to large backgrounds
  - Neural Network with $\cos \Theta_{B-D^*l}$, $m_{\text{miss}}^2$, visible energy
- Use binned likelihood fit in 2D to $E_{\text{ECL}}$ and Neural Network
  - Post-fit projections:
Belle Measurements of $R(D^*)$

- Use of $\tau \rightarrow e \nu \nu$ and $\tau \rightarrow \mu \nu \nu$ to reconstruct $\tau$-lepton

- Instead of hadronic use prompt semileptonic for tag-side reconstruction; only measures $R(D^*)$ due to large backgrounds
  - Neural Network with $\cos \Theta_{B-D^*,\nu}$, $m_{\text{miss}}^2$, visible energy

- Use binned likelihood fit in 2D to $E_{\text{ECL}}$ and Neural Network

- Post-fit projections:

\[ R(D^*) = 0.302 \pm 0.030 \text{ (stat)} \pm 0.011 \text{ (syst)} \text{ (1.4}\sigma \text{ from SM) } \]
Belle Measurements of $R(D^*)$

- Decay angles of $\tau \rightarrow \pi \nu$ and $\tau \rightarrow \rho \nu$ encode $\tau$-polarisation, sensitive to NP!
  - Need to reconstruct helicity angle, but a-priorio $\tau$-restframe not accessible
  - Luckily there is a relation between $<(\tau h)$ in $\tau \nu$-frame and this angle
  - **Hadronic** tagging essential to reconstruct this frame
Belle Measurements of $R(D^*)$

- Decay angles of $\tau \to \pi \nu$ and $\tau \to \rho \nu$ encode $\tau$-polarisation, sensitive to NP!

  ✓ Need to reconstruct helicity angle, but a-priorio $\tau$-restframe not accessible

  ✓ Luckily there is a relation between $<(\tau h)$ in $\tau \nu$-frame and this angle

- Signal extraction via $E_{ECL}$ (unassigned energy in the calorimeter) and in two bins of helicity angle $\cos \Theta_{hel}$ with binned likelihood fit

$$R(D^*) = \frac{\epsilon_{ECL} \, N_{\text{sig}}^{ij}}{B_i \, \epsilon_{\text{sig}} \, N_{\text{norm}}^{ij}},$$

$$P_{\tau}(D^*) = \frac{2 \, N_{\text{sig}}^{F ij}}{\alpha_i \, N_{\text{sig}}^{F ij} + N_{\text{sig}}^{B ij}},$$

Normalisation: $B \to D^* \ell \nu$
Belle Measurements of $R(D^*)$

- Decay angles of $\tau \rightarrow \pi \nu$ and $\tau \rightarrow \rho \nu$ sensitive to $\tau$-polarisation
  - Need to reconstruct helicity angle, but a-priorio $\tau$-restframe not accessible
  - Luckily there is a relation between $<\chi_h>$ in $\tau\nu$-frame and this angle

![Graph showing $E_{ECL}$ vs. Events (0.05 GeV)]

$\nu^2$ $\tau$ [W] $\rho$ [W] $\rho$ [$\tau$]
\vdots

--- W $\rightarrow$ tau $\rightarrow$
\vdots

W rest frame $\tau$ rest frame

Nice Illustration

Florian Bernlochner
One more interesting ratio from Belle

\[ R(\pi) = \frac{\mathcal{B}(B \to \pi \tau \bar{\nu}_\tau)}{\mathcal{B}(B \to \pi \ell \bar{\nu}_\ell)} \]

- Use **Hadronic** tagging and reconstruct
  \[ \tau \to \ell \nu \nu, \tau \to \pi \nu \nu, \tau \to \rho \nu \nu, \tau \to a_1 \nu \nu \]

1D Likelihood fit in \( E_{ECL} \)

\[ R(\pi) = 1.05 \pm 0.51 \]

\[ R(\pi)_{SM} = 0.641 \pm 0.016 \]
2. How do we predict?

with a focus on $R(D/D^*/\pi)$, similar things do apply though to $R(J/\psi)$
Form Factor Bootcamp with $B \to D\ell\nu$ as an example

\[ f_+ (q^2) \quad \text{and} \quad f_- (q^2) \]

Four-momentum transfer squared encodes QCD dynamics

\[ H^\mu L_\mu = \langle B(p) | V^\mu - A^\mu | D(p') \rangle L_\mu = \left[ f_+(q^2) (p + p')^\mu + f_-(q^2) (p - p')^\mu \right] L_\mu \]

1. Leptonic & Hadronic current
2. Leptonic & Hadronic current

\[ V_{cb} \]

$\tau^-$ \quad $\bar{\nu}_\tau$
Form Factor Bootcamp with $B \rightarrow D \ell \nu$ as an example

Can be studied with light lepton modes, but also in lattice (high $q^2$) or sum rules.

$\frac{d\Gamma}{dw} [\text{GeV}]$

$\bar{B} \rightarrow D \ell \bar{\nu}_\ell$

\[
f_+(q^2) = \frac{1}{m_\ell + m_\nu} \bar{u}(p_\nu) \nu(p_\ell) \approx \frac{v(p_\ell) (m_\ell + m_\nu) \bar{u}(p_\nu)}{m_\ell + m_\nu}
\]

\[
f_-(q^2)
\]
Form Factor Bootcamp with $B \rightarrow D\ell\bar{\nu}$ as an example

\[ f_+ (q^2) \]

Can be studied with light lepton modes, but also in lattice (high $q^2$) or sum rules

\[ f_- (q^2) \sim v(p_\ell) (m_\ell + m_\nu) \bar{u}(p_\nu) \]

Proportional to basically $\sim 0$ in light lepton modes, cannot be constrained experimentally in this way

But important for heavy leptons, need input from lattice or HQET relations
Form Factor Bootcamp with $B \rightarrow D\ell\nu$ as an example

$$f_+(q^2)$$

$$f_-(q^2) \sim v(p_\ell) (m_\ell + m_\nu) \bar{u}(p_\nu)$$

State of the art predictions combine light lepton measurements and lattice + QCD sum rules for

Different inputs leave a fairly consistent picture

arXiv: 1606.08030
arXiv: 1703.05330
arXiv: 1707.09509

...
3. Is it really $4\sigma$?

well, depends what you want to conclude!
Let me explain what I mean:

Let’s say you want to use the **measured ratios** to learn something about the anomaly and **your favourite model** that could explain it!
Let me explain what I mean:

- Let’s say you want to use the measured ratios to learn something about the anomaly and your favourite model that could explain it!
Let me explain what I mean:

- As it turns out, **not that easy** — the measured points themselves are extracted assuming the SM.
Let me explain what I mean:

- Why is this happening exactly?
  - Change in kinematics of final state particles ($q^2$)
  - Dominant effect here: \( \tau \)-polarisation

(full explanation in backup)
You can **test models** against the measured ratios, but keep in mind that these **results** should be **taken with a grain of salt**.

- Fully **consistent tests** right now only possible within experiments

**Examples:**

- BaBar disfavours 2HDM type II
- Belle more compatible

Belle studied two types of leptoquark models. Results allow additional contributions from scalar and vector operators.
Thus..

- You can **test models** against the measured ratios, but **keep in mind** that these **results** should be **taken with a grain of salt**

- Fully **consistent tests** right now **only possible within experiments**

**Better:** Experiments should extract limits on **Wilson coefficients** directly, that **allow meaningful reinterpretation**

- Need help from theorists

180x.xxxxx FB, S. Duell, M. Papucci, Z. Ligeti, D. Robinson
4. Looking ahead

\[
\begin{align*}
\text{BaBar data set} & \sim \text{Belle II data set} \\
\text{CLEO data set} & \sim \text{Belle data set} \\
& \sim 50:1 \sim \text{LHCb Upgrade} \\
& \sim \text{LHCb 1/fb}
\end{align*}
\]
**Belle II: a next generation B-Factory experiment**

**Electromagnetic Calorimeter:**
Thallium activated Caesium Iodide scintillation crystals

**Vertex detectors (PXD+SVD):**
2 layers of Pixel (DEPFET) + 4 layers of strips (DSSD)

**Central drift chamber:**
Gas mixture of Helium and Ethan (C$_2$H$_6$)

**KL and Muon detection system:**
RPC based

**Particle identification:**
Time-of-propagation counter, Aerogel Cherenkov ring detector

**LER / HER**

<table>
<thead>
<tr>
<th>KEKB</th>
<th>SuperKEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5 / 8</td>
<td>4.0 / 7.0</td>
</tr>
<tr>
<td>2.1</td>
<td>80</td>
</tr>
</tbody>
</table>

**Energy [GeV]**

<table>
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<tr>
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<th>SuperKEKB</th>
</tr>
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<td>3.5 / 8</td>
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</tr>
</tbody>
</table>

**Luminosity [10$^{34}$ cm$^{-2}$ s$^{-1}$]**

<table>
<thead>
<tr>
<th>KEKB</th>
<th>SuperKEKB</th>
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<tr>
<td>2.1</td>
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</tr>
</tbody>
</table>
Belle II ramp up Phases

- Ramp up in **three** phases
  - **Phase I 2016**: No detector over interaction region, study of beam properties
  - **Phase II 2018**: First collisions, but no PXD. Instead BEAST II (radiation monitoring system)
  - **Phase III 2019**: First Physics with full detector
Phase 2 Set Up

Motivation for BEAST II:
- Machine commissioning
- Radiation safe environment for the VXD:
  - Two (four) PXD (SVD) ladders
  - Dedicated radiation monitors
    FANGS, CLAWS, PLUME

Many thanks to Carlos Marinas, Patrick Ahlburg and Botho Paschen
For the nice illustrations and pictures!
Belle II Control Room
Phase 2

Tsukuba Hall (End of 2017)

Belle II parked over the Interaction region

Super conducting focusing magnet
- 2 PXD and 4 SVD layers in +X where the highest backgrounds are expected
- At 90°, 180° and 270° in $\phi$ are the three FANGS staves
- FANGS uses the ATLAS IBL modules for background measurements at BEAST II
The trip of the BEAST II PXD modules to KEK
Airplane business class with extra pillows – 4000 Eur
Bus to Tsukuba station 1.5 hr - 10 Eur
BEAST PXD in the Belle clean room - priceless
VXD Clean Room

Granite table with Phase 2 beam pipe + rotation stage
Warm-up phase..
First recorded collisions:
April 2018 (10 weeks)
to record about ~ 20/fb
Looking ahead…

\[
\begin{align*}
R(D) & \\ 0.3 & 0.35 & 0.4 & 0.45 \\
0.24 & 0.26 & 0.28 & 0.3 & 0.32 \end{align*}
\]

- **LHCb**
  - 10/fb & 22/fb
  - 4\% & 2\%

- **Belle II**
  - 5/ab & 50/ab
  - R(D): 5.6\% & 3.2\%
  - R(D\*): 3.9\% & 2.2\%

\[
LHCb
\]

\[
Belle II
\]
More slides
Table 1: The luminosity scenarios considered along with the estimated number of $b\bar{b}$-pairs produced inside the acceptance of the experiments are given. The LHCb cross sections are taken from Ref. [25] assuming an increase in $b\bar{b}$-production cross section with LHC beam energy. For Belle II only $\epsilon^+\epsilon^-$ $(4S)B\bar{B}$ data sets are estimated.

<table>
<thead>
<tr>
<th>Year</th>
<th>Milestone I</th>
<th>Milestone II</th>
<th>Milestone III</th>
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<tbody>
<tr>
<td>2017</td>
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<td>2018</td>
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<td>2021</td>
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Belle II

- Start of Data taking period

LHCb

- Run 2
- $\sim 8$ fb$^{-1}$
- LHC Shutdown

Belle II

- $\sim 5$ ab$^{-1}$

LHCb

- Run 3
- $\sim 22$ fb$^{-1}$
- LHC Shutdown

Belle II

- $\sim 50$ ab$^{-1}$

LHCb

- Run 4
- $\sim 50$ fb$^{-1}$
- LHC Shutdown

Fig. 1: An overview of the expected Belle II and LHCb timelines along with their estimated integrated luminosities at each milestone. The scenarios compared in this manuscript are shown in bold. For more details of the expected luminosities and number of produced $b\bar{b}$-pairs at each milestone see Table 1. The LHCb Phase-I-Upgrade is currently scheduled for the duration of the LHC shutdown between 2019 – 2020. The LHCb experiment has recently expressed its interest to continue running past the Phase-I-Upgrade until the end of the funded LHC Run in 2035.

The study of quarkonia, can still easily allow for tree-level new physics effects of order 10% [31]. Effects of this size can cause shifts in the tree-level determination of $\delta_{ub}$ of up to $4\sigma$. Thus, comparison between the point in $(\delta_{ub}, \delta_{cb})$ space determined using $|V_{ub}|/|V_{cb}|$ with that found using $\sin(2\beta)$ and $|m_d/m_s|$ is a cornerstone of the flavour physics program at both LHCb and Belle II, where any discrepancies will be of huge importance.
All the stuff we don’t want

- From the beams:
  - **Touschek scattering (1):** Coulomb scattering between two particles in the same bunch
  - **Beam-gas (2):** scattering off residual gas atoms in the beam pipe
  - **Synchrotron radiation (3):** photons emitted when electrons are bent by magnetic fields

- From collisions:
  - **Radiative Bhabha (4)**
Table V. Systematic uncertainties and correlations on $R(D^{(*)})$.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\mathcal{R}(D^0)$</th>
<th>$\mathcal{R}(D^{*0})$</th>
<th>$\mathcal{R}(D^+)$</th>
<th>$\mathcal{R}(D^{*+})$</th>
<th>$\mathcal{R}(D)$</th>
<th>$\mathcal{R}(D^*)$</th>
<th>Correlation $D^0/D^{*0}$</th>
<th>$D^+/D^{*+}$</th>
<th>$D/D^*$</th>
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<td><strong>Additive uncertainties</strong></td>
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<tr>
<td>$B \to D^{(*)}(\tau^-/\ell^-)\bar{\nu}$ FFs</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
<td>-0.52</td>
<td>-0.13</td>
<td>-0.35</td>
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<tr>
<td>$D^{<em>+} \to D^{(</em>)}(\pi^0/\pi^\pm)$</td>
<td>0.7</td>
<td>0.5</td>
<td>0.7</td>
<td>0.5</td>
<td>0.7</td>
<td>0.5</td>
<td>0.22</td>
<td>0.40</td>
<td>0.53</td>
</tr>
<tr>
<td>$B(\bar{B} \to D^{**}\ell^-\bar{\nu}_l)$</td>
<td>1.0</td>
<td>0.4</td>
<td>1.0</td>
<td>0.4</td>
<td>0.8</td>
<td>0.3</td>
<td>-0.63</td>
<td>-0.68</td>
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<td>$B(\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau)$</td>
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<td>2.0</td>
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<td>$D^{<em>+} \to D^{(</em>)}\pi\pi$</td>
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<td><strong>Cross-feed constraints</strong></td>
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<td>MC statistics</td>
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<td>$f_{D^{**}}$</td>
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<td>2.6</td>
<td>5.3</td>
<td>1.8</td>
<td>5.0</td>
<td>2.0</td>
<td>0.22</td>
<td>0.40</td>
<td>0.53</td>
</tr>
<tr>
<td>Feed-up/feed-down</td>
<td>1.9</td>
<td>0.5</td>
<td>1.6</td>
<td>0.2</td>
<td>1.3</td>
<td>0.4</td>
<td>0.29</td>
<td>0.51</td>
<td>0.47</td>
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<tr>
<td>Isospin constraints</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.2</td>
<td>0.3</td>
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<tr>
<td><strong>Fixed backgrounds</strong></td>
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<tr>
<td>MC statistics</td>
<td>4.3</td>
<td>2.3</td>
<td>4.3</td>
<td>1.8</td>
<td>3.1</td>
<td>1.5</td>
<td>-0.48</td>
<td>-0.05</td>
<td>-0.30</td>
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<tr>
<td>Efficiency corrections</td>
<td>4.8</td>
<td>3.0</td>
<td>4.5</td>
<td>2.3</td>
<td>3.9</td>
<td>2.3</td>
<td>-0.53</td>
<td>0.20</td>
<td>-0.28</td>
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<tr>
<td><strong>Multiplicative uncertainties</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC statistics</td>
<td>2.3</td>
<td>1.4</td>
<td>3.0</td>
<td>2.2</td>
<td>1.8</td>
<td>1.2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>$B \to D^{(*)}(\tau^-/\ell^-)\bar{\nu}$ FFs</td>
<td>1.6</td>
<td>0.4</td>
<td>1.6</td>
<td>0.3</td>
<td>1.6</td>
<td>0.4</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>Lepton PID</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.5</td>
<td>0.6</td>
<td>0.6</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
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<tr>
<td>$\pi^0/\pi^\pm$ from $D^* \to D\pi$</td>
<td>0.1</td>
<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>0.1</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Detection/Reconstruction</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>$B(\tau^- \to \ell^-\nu\nu_\tau)$</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td><strong>Total syst. uncertainty</strong></td>
<td>12.2</td>
<td>6.7</td>
<td>11.4</td>
<td>6.0</td>
<td>9.6</td>
<td>5.5</td>
<td>-0.21</td>
<td>0.10</td>
<td>0.05</td>
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<tr>
<td><strong>Total stat. uncertainty</strong></td>
<td>19.2</td>
<td>9.8</td>
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<td>11.0</td>
<td>13.1</td>
<td>7.1</td>
<td>-0.59</td>
<td>-0.23</td>
<td>-0.45</td>
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<tr>
<td><strong>Total uncertainty</strong></td>
<td>22.7</td>
<td>11.9</td>
<td>21.3</td>
<td>12.5</td>
<td>16.2</td>
<td>9.0</td>
<td>-0.48</td>
<td>-0.15</td>
<td>-0.27</td>
</tr>
</tbody>
</table>
**Bellev Measurement of $R(D^{(*)})$**

<table>
<thead>
<tr>
<th>Source</th>
<th>$R(D^*)$</th>
<th>$P_\tau(D^*)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronic $B$ composition</td>
<td>$+7.7%$</td>
<td>$0.134$</td>
</tr>
<tr>
<td>$\pm 6.9%$</td>
<td>$-0.103$</td>
<td></td>
</tr>
<tr>
<td>$\pm 4.0%$</td>
<td>$+0.146$</td>
<td></td>
</tr>
<tr>
<td>$\pm 2.8%$</td>
<td>$-0.108$</td>
<td></td>
</tr>
<tr>
<td>MC statistics for PDF shape</td>
<td>$+3.4%$</td>
<td>$0.018$</td>
</tr>
<tr>
<td>$\pm 3.4%$</td>
<td>$0.018$</td>
<td></td>
</tr>
<tr>
<td>Fake $D^*$</td>
<td>$2.4%$</td>
<td>$0.048$</td>
</tr>
<tr>
<td>$\pm 2.4%$</td>
<td>$0.048$</td>
<td></td>
</tr>
<tr>
<td>$\bar{B} \to D^{**} \ell^- \bar{\nu}_\ell$</td>
<td>$1.1%$</td>
<td>$0.001$</td>
</tr>
<tr>
<td>$\pm 1.1%$</td>
<td>$0.001$</td>
<td></td>
</tr>
<tr>
<td>$\bar{B} \to D^{**} \tau^- \bar{\nu}_\tau$</td>
<td>$2.3%$</td>
<td>$0.007$</td>
</tr>
<tr>
<td>$\pm 2.3%$</td>
<td>$0.007$</td>
<td></td>
</tr>
<tr>
<td>$\tau$ daughter and $\ell^-$ efficiency</td>
<td>$1.9%$</td>
<td>$0.019$</td>
</tr>
<tr>
<td>$\pm 1.9%$</td>
<td>$0.019$</td>
<td></td>
</tr>
<tr>
<td>MC statistics for efficiency estimation</td>
<td>$1.0%$</td>
<td>$0.019$</td>
</tr>
<tr>
<td>$\pm 1.0%$</td>
<td>$0.019$</td>
<td></td>
</tr>
<tr>
<td>$B(\tau^- \to \pi^- \nu_\tau, \rho^- \nu_\tau)$</td>
<td>$0.3%$</td>
<td>$0.002$</td>
</tr>
<tr>
<td>$\pm 0.3%$</td>
<td>$0.002$</td>
<td></td>
</tr>
<tr>
<td>$P_\tau(D^*)$ correction function</td>
<td>$0.0%$</td>
<td>$0.010$</td>
</tr>
<tr>
<td>$\pm 0.0%$</td>
<td>$0.010$</td>
<td></td>
</tr>
</tbody>
</table>

**Common sources**

<table>
<thead>
<tr>
<th>Source</th>
<th>$R(D^*)$</th>
<th>$P_\tau(D^*)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tagging efficiency correction</td>
<td>$1.6%$</td>
<td>$0.018$</td>
</tr>
<tr>
<td>$\pm 1.6%$</td>
<td>$0.018$</td>
<td></td>
</tr>
<tr>
<td>$D^*$ reconstruction</td>
<td>$1.4%$</td>
<td>$0.006$</td>
</tr>
<tr>
<td>$\pm 1.4%$</td>
<td>$0.006$</td>
<td></td>
</tr>
<tr>
<td>Branching fractions of the $D$ meson</td>
<td>$0.8%$</td>
<td>$0.007$</td>
</tr>
<tr>
<td>$\pm 0.8%$</td>
<td>$0.007$</td>
<td></td>
</tr>
<tr>
<td>Number of $B\bar{B}$ and $B(\Upsilon(4S) \to B^+ B^- \text{ or } B^0 \bar{B}^0)$</td>
<td>$0.5%$</td>
<td>$0.006$</td>
</tr>
<tr>
<td>$\pm 0.5%$</td>
<td>$0.006$</td>
<td></td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>$+10.4%$</td>
<td>$+0.21$</td>
</tr>
<tr>
<td>$\pm 9.4%$</td>
<td>$-0.16$</td>
<td></td>
</tr>
</tbody>
</table>
The results of the fit to the signal sample are shown in Fig. 1. Values of the $B_0 \to D^{(*)+} \mu \bar{\nu}$ form factor parameters determined by the fit agree with the current world average values. The fit finds 363 000 $\pm$ 1600 $B_0 \to D^{(*)+} \mu \bar{\nu}$ decays in the signal sample and an uncorrected ratio of yields $N(B_0 \to D^{(*)+} \nu) / N(B_0 \to D^{(*)+} \mu \bar{\nu}) = (4.54 \pm 0.46) \times 10^{-2}$. Accounting for the $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$ branching fraction [25] and the ratio of efficiencies results in $R(D^*) = 0.336 \pm 0.034$, where the uncertainty includes the statistical uncertainty, the uncertainty due to form factors, and the statistical uncertainty in the kinematic distributions used in the fit. As the signal yield is large, this uncertainty is dominated by the determination of various background yields in the fit and their correlations, which are as large as 0.68 in the case of $B \to D^{(*)+} H_c (\to \mu \bar{\nu} X^0) X$.

Systematic uncertainties on $R(D^*)$ are summarized in Table 1. The uncertainty in extracting $R(D^*)$ from the fit (model uncertainty) is dominated by the statistical uncertainty of the simulated samples; this contribution is estimated via the reduction in the fit uncertainty when the sample statistical uncertainty is not considered in the likelihood. The systematic uncertainty from the kinematic shapes of the background from hadrons misidentified as muons is taken to be half the difference in $R(D^*)$ using the two unfolding methods. Form factor parameters are included in the likelihood as nuisance parameters, and represent a source of systematic uncertainty. The total uncertainty on $R(D^*)$ estimated Table 1: Systematic uncertainties in the extraction of $R(D^*)$.

<table>
<thead>
<tr>
<th>Model uncertainties</th>
<th>Absolute size ($\times 10^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated sample size</td>
<td>2.0</td>
</tr>
<tr>
<td>Misidentified $\mu$ template shape</td>
<td>1.6</td>
</tr>
<tr>
<td>$B^0 \to D^{*+}(\tau^-/\mu^-)\bar{\nu}$ form factors</td>
<td>0.6</td>
</tr>
<tr>
<td>$B \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections</td>
<td>0.5</td>
</tr>
<tr>
<td>$\mathcal{B}(B \to D^{<em>+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(B \to D^{</em>+}\mu^-\bar{\nu}_\mu)$</td>
<td>0.5</td>
</tr>
<tr>
<td>$B \to D^{*+}(\to D^\star\pi\pi)\mu\nu$ shape corrections</td>
<td>0.4</td>
</tr>
<tr>
<td>Corrections to simulation</td>
<td>0.4</td>
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<tr>
<td>Combinatorial background shape</td>
<td>0.3</td>
</tr>
<tr>
<td>$B \to D^{*+}(\to D^\star+\pi)\mu^-\bar{\nu}_\mu$ form factors</td>
<td>0.3</td>
</tr>
<tr>
<td>$B \to D^{*+}(D_s \to \tau\nu)X$ fraction</td>
<td>0.1</td>
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<tr>
<td><strong>Total model uncertainty</strong></td>
<td><strong>2.8</strong></td>
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</table>

<table>
<thead>
<tr>
<th>Normalization uncertainties</th>
<th>Absolute size ($\times 10^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated sample size</td>
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</tr>
<tr>
<td>Hardware trigger efficiency</td>
<td>0.6</td>
</tr>
<tr>
<td>Particle identification efficiencies</td>
<td>0.3</td>
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<tr>
<td>Form-factors</td>
<td>0.2</td>
</tr>
<tr>
<td>$\mathcal{B}(\tau^- \to \mu^- \bar{\nu}<em>\mu \nu</em>\tau)$</td>
<td>$&lt; 0.1$</td>
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<tr>
<td><strong>Total normalization uncertainty</strong></td>
<td><strong>0.9</strong></td>
</tr>
<tr>
<td><strong>Total systematic uncertainty</strong></td>
<td><strong>3.0</strong></td>
</tr>
</tbody>
</table>
4. Semileptonic decays at LHCb

- No constraint from beam energy at a hadron machine, **but..**

- **Large Lorentz boost** with decay lengths in the range of **mm**

  ✓ Well separated decay vertices

  ✓ Momentum direction of decaying particle is well known

- With known masses and other decay products can even **reconstruct four-momentum transfer squared** $q^2$ up to a two-fold ambiguity

$$q^2 = (p X_b - p X_q)^2$$

Nice Illustration from C. Bozzi
LHCb Measurements of $R(D^*)$

Two measurements using different final states:

- $\tau \rightarrow \mu \nu \nu$ using $B^0 \rightarrow D^{*-} \tau \nu$

- $\tau \rightarrow \pi \pi \pi (\pi^0) \nu$ using $B^0 \rightarrow D^{*-} \tau \nu$ **New!**

✓ All $R(D^*)$ measurements consistent but above SM
LHCb Measurements of $R(D^*)$

- First measurement at a hadron collider!
- Tau reconstructed with $\tau \rightarrow \mu \nu \nu$
- The B momentum is approximated by:

\[
(\gamma \beta_Z)_B = (\gamma \beta_Z)_{D^* \mu} \quad \Rightarrow \quad (p_Z)_B = \frac{m_B}{m(D^* \mu)} (p_Z)_{D^* \mu}
\]

B boost along z axis much larger than boost of decay products in B rest frame, results in a resolution of about 18% on $p_B$

- Can be used to calculate $m_{\text{miss}}^2$ and $q^2 = (p_B - p_{D^*})^2$ and boost muon in B-rest frame
LHCb Measurements of $R(D^*)$

- First measurement at a hadron collider!
- Tau reconstructed with $\tau \rightarrow \mu \nu \nu$
- The B momentum is approximated by:

\[
B \text{ boost along } z \gg B \text{ boost of decay products in } B \text{ rest frame}
\]

18% resolution on $p_B$ gives excellent shapes to use for fit.

\[
m_{\text{miss}}^2, \ E^*_\mu, \ q^2
\]

**Signal**

**Normalization**
LHCb Measurements of $R(D^*)$

- No additional particles via MVA isolation
- Extract signal in binned 3D fit to $m_{\text{miss}}^2$, $E^*\mu$ and 4 bins of $q^2$
  Simultaneously fit 3 control regions defined by isolation criteria
- Signal yield: $\sim 16500$ Events
  B-Factories: $O(1000 \text{ Events})$

$R(D^*) = 0.336 \pm 0.027 \text{ (stat)} \pm 0.030 \text{ (syst)}$

Compatible with BaBar and Belle, but 2.1$\sigma$ from SM
Tau reconstructed via $\tau \rightarrow \pi^+ \pi^+ \pi^- (\pi^0) \nu$, only two neutrinos missing

Although a semileptonic decay is studied, nearly no background from $B \rightarrow D^* X \mu \nu$

- Main background: prompt $X_b \rightarrow D^* \pi \pi \pi + \text{neutrals}$

  BF $\sim$ 100 times larger than signal, all pions are promptly produced

- Suppressed by requiring minimum distance between $X_b$ & $\tau$ vertices ($>4 \sigma_{\Delta z}$)

  $\sigma_{\Delta z}$: resolution of vertices separation

- Reduces this background by three orders of magnitudes
New LHCb Measurement of $R(D^*)$

- Tau reconstructed via $\tau \to \pi^+\pi^+\pi^-(\pi^0)\nu$, only two neutrinos missing

  Although a semileptonic decay is studied, nearly no background from $B \to D^*\tau\bar{\nu}$

- Main background: prompt $X_b \to D^*\pi\pi\pi + $ neutrals

  BF $\sim$ 100 times larger than signal, all pions are promptly produced

- Suppressed by requiring minimum distance between $X_b$ & $\tau$ vertices ($> 4 \sigma_{\Delta z}$)

  $\sigma_{\Delta z} :$ resolution of vertices separation

- Remaining double charm bkgds:

  $X_b \to D^*-D_s+X \sim 10 \times \text{Signal}$
  $X_b \to D^*-D^+X \sim 1 \times \text{Signal}$
  $X_b \to D^*-D_{s0}^+X \sim 0.2 \times \text{Signal}$

- Reduces this background by three orders of magnitudes
New LHCb Measurement of $R(D^*)$

- Remaining backgrounds reduced via isolation & MVA

Require signal candidates to be well isolated

i.e. reject events with extra charged particles pointing to the B and/or $\tau$

Events with additional neutral energy are suppressed with a MVA

More information about that in backup
New LHCb Measurement of $R(D^*)$

- Extraction in **3D fit** to
  
  MVA : $q^2 : \tau$ decay time

  Invariant masses of $3\pi$ system
  Invariant mass of $D^*3\pi$ system
  Neutral isolation variables

  Both reconstructed with some tricks (more in backup)

  4 Bins  8 Bins  8 Bins

- Components:

  1 Signal component for $\tau \rightarrow \pi^+ \pi^+ \pi^- (\pi^0) \nu$

  11 Background components

- ~ 1273 ± 85 Signal events

- Using normalisation mode and light lepton BFs:

  More information about normalisation in backup

  $R(D^*) = 0.286 \pm 0.019$ (stat) ± 0.025 (syst)
  
  ± 0.021 (norm)

  0.9σ higher than SM

---

\[ R(D^*) = 0.286 \pm 0.019 \text{ (stat)} \pm 0.025 \text{ (syst)} \pm 0.021 \text{ (norm)} \]

\[ 0.9\sigma \text{ higher than SM} \]
More interesting ratios from LHCb and Belle!

\[ R(J/\psi) = \frac{B(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau)}{B(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)}, \]

\[ R(\pi) = \frac{B(B \rightarrow \pi \tau \nu_\tau)}{B(B \rightarrow \pi \ell \bar{\nu}_\ell)}. \]

**3D fit \( (q^2, m_{\text{miss}}^2, Z) \) determines**

\[ R(J/\psi) = 0.71 \pm 0.17 \pm 0.18 \quad R(J/\psi_{\text{SM}}) \sim 0.28 \]

**1D fit in \( E_{\text{ECL}} \) determines**

\[ R(\pi) = 1.05 \pm 0.51 \quad R(\pi_{\text{SM}}) = 0.641 \pm 0.016 \]
New LHCb Measurement of $R(D^*)$

- Actually measure BF relative to $B^0 \to D^{*}\pi^+\pi^+\pi^-$

\[
K_{had}(D^*) = \frac{BR(B^0 \to D^{*-}\pi^+\nu_\tau)}{BR(B^0 \to D^{*-}\pi^+\pi^+\pi^-)} = \frac{N(B^0 \to D^{*-}\pi^+\nu_\tau)}{N(B^0 \to D^{*-}\pi^-\pi^+\pi^-)} \times \frac{1}{BR(\tau^+ \to \pi^+\pi^-\pi^0(\pi^0)\nu_\tau)} \times \frac{\epsilon(B^0 \to D^{*-}\pi^+\pi^+\pi^-)}{\epsilon(B^0 \to D^{*-}\pi^+\nu_\tau)}
\]

- Measured to about 4% precision
  most precise measurement from BaBar: Phys. Rev. D94 (2016) 091101

- Dedicated control samples for remaining backgrounds
  \[X_b \to D^{*-}D_s^+X\]  Use $D_s^+ \to 3\pi$ and fit $m(D^*D_s)$ to constrain individual contributions
  \[X_b \to D^{*-}D^+X\]  Use $D^+ \to K3\pi$ to correct $q^2$, but float in fit

- Extraction in 3D maximum likelihood fit
  to MVA : $q^2 : \tau$ decay time
  Invariant masses of $3\pi$ system
  Invariant mass of $D^*3\pi$ system
  Neutral isolation variables

Both reconstructed with some tricks (more in backup)
4-fold ambiguity:

\[
|\vec{p}_\tau| = \frac{(m_{3\pi}^2 + m_\tau^2) |\vec{p}_{3\pi}| \cos \theta \pm E_{3\pi} \sqrt{(m_\tau^2 - m_{3\pi}^2)^2 - 4m_\tau^2 |\vec{p}_{3\pi}|^2 \sin^2 \theta}}{2(E_{3\pi}^2 - |\vec{p}_{3\pi}|^2 \cos^2 \theta)}
\]

\[
|\vec{p}_{B^0}| = \frac{(m_{D^{*}\tau}^2 + m_{B^0}^2) |\vec{p}_{D^{*}\tau}| \cos \theta \pm E_{D^{*}\tau} \sqrt{(m_{B^0}^2 - m_{D^{*}\tau}^2)^2 - 4m_{B^0}^2 |\vec{p}_{D^{*}\tau}|^2 \sin^2 \theta'}}{2(E_{D^{*}\tau}^2 - |\vec{p}_{D^{*}\tau}|^2 \cos^2 \theta')}
\]

Can be approximated by doing:

\[
\theta_{max} = \arcsin \left( \frac{m_\tau^2 - m_{3\pi}^2}{2m_\tau |\vec{p}_{3\pi}|} \right)
\]

\[
\theta'_{max} = \arcsin \left( \frac{m_{B^0}^2 - m_{D^{*}\tau}^2}{2m_{B^0} |\vec{p}_{D^{*}\tau}|} \right)
\]

**Possible to reconstruct rest frame variables such as tau decay time and q^2.**

These variables have **negligible biases**, and **sufficient resolution** to preserve good discrimination between signal and background.
New LHCb Measurement of $R(D^*)$: Control samples

Use **exclusive** $D_s \rightarrow 3\pi$ decays to select a $X_b \rightarrow D^* D_s^+ X$ control sample

Determine the different $X_b \rightarrow D^* D_s^+ X$ contributions from a fit to $m(D^*D_s)$:

- $B^0 \rightarrow D^* D_s$, $B^0 \rightarrow D^* D_s^*$, $B^0 \rightarrow D^* D_{s0}^*$, $B^0 \rightarrow D^* D_{s1}^*$, $B_s \rightarrow D^* D_s X$, $B \rightarrow D^{**} D_s X$

only 20% of $D_s$ originates directly from $B$, 40% originates from $D_s^*$, 40% from $D_s^{**}$

- Uncertainties in the fit parameters propagated to final analysis.

Slide from C. Bozzi
\( X_b \rightarrow D^*-D^0 X \) decays can be isolated by selecting exclusive \( D^0 \rightarrow K^-3\pi \) decays (kaon recovered using isolation tools).

A correction to the \( q^2 \) distributions is applied to the Monte Carlo to match data.

In contrast to the \( D_s^+ \) case, most 3\( \pi \) final states in \( D^+ \) and \( D^0 \) decays originate from \( D^{+,0} \rightarrow K^{0,+} 3\pi \)

For the \( D^0 \), the inclusive 4 prongs BR constrains strongly the rate of 3\( \pi \) events

Unfortunately, this constraint does not exist for the \( D^+ \) mesons, \( K3\pi\pi^0 \) is poorly known, the inclusive BR is not measured.

We let the \( D^+ \) component float in the fit

Slide from C. Bozzi
**New LHCb Measurement of \( R(D^*) \): Systematics**

<table>
<thead>
<tr>
<th>Source</th>
<th>( \delta R(D^{<em>-}) / R(D^{</em>-}) )[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated sample size</td>
<td>4.7</td>
</tr>
<tr>
<td>Empty bins in templates</td>
<td>1.3</td>
</tr>
<tr>
<td>Signal decay model</td>
<td>1.8</td>
</tr>
<tr>
<td>( D^{<strong>}\tau\nu ) and ( D_s^{</strong>}\tau\nu ) feeddowns</td>
<td>2.7</td>
</tr>
<tr>
<td>( D_s^+ \rightarrow 3\pi X ) decay model</td>
<td>2.5</td>
</tr>
<tr>
<td>( B \rightarrow D^{<em>-}D_s^+X, B \rightarrow D^{</em>-}D^+X, B \rightarrow D^{*-}D^0X ) backgrounds</td>
<td>3.9</td>
</tr>
<tr>
<td>Combinatorial background</td>
<td>0.7</td>
</tr>
<tr>
<td>( B \rightarrow D^{*-}3\pi X ) background</td>
<td>2.8</td>
</tr>
<tr>
<td>Efficiency ratio</td>
<td>3.9</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>8.9</td>
</tr>
</tbody>
</table>
Impact of $\tau$-polarisation in $\tau^- \rightarrow \ell^- \bar{\nu}_\ell \nu_\tau$ decays:

- **secondary lepton** emitted preferentially in the direction of the $\tau$
  - Carries more momentum of the $\tau$-lepton
- **secondary lepton** emitted preferentially against the direction of the $\tau$
  - Carries less momentum of the $\tau$-lepton

**Benchmark point**

- 2HDM Type II

**SM**

- $m^2_{\text{miss}}$ (GeV$^2$)
  - $\text{Probability/GeV}^2$
  - $\text{Probability/GeV}$

- $|p_\ell^*|$ (GeV)

- $\tan\beta/m_{H^+}$
  - $0.3 \text{ GeV}^{-1}$
  - $0.5 \text{ GeV}^{-1}$
  - $1 \text{ GeV}^{-1}$

**Figure 18**

- The type II 2HDM, we study the dependence of the fit distribution in the plane. The white crosses correspond to the benchmark points.