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Lepton-flavour universality tests with semi-leptonic B decays at LHCb

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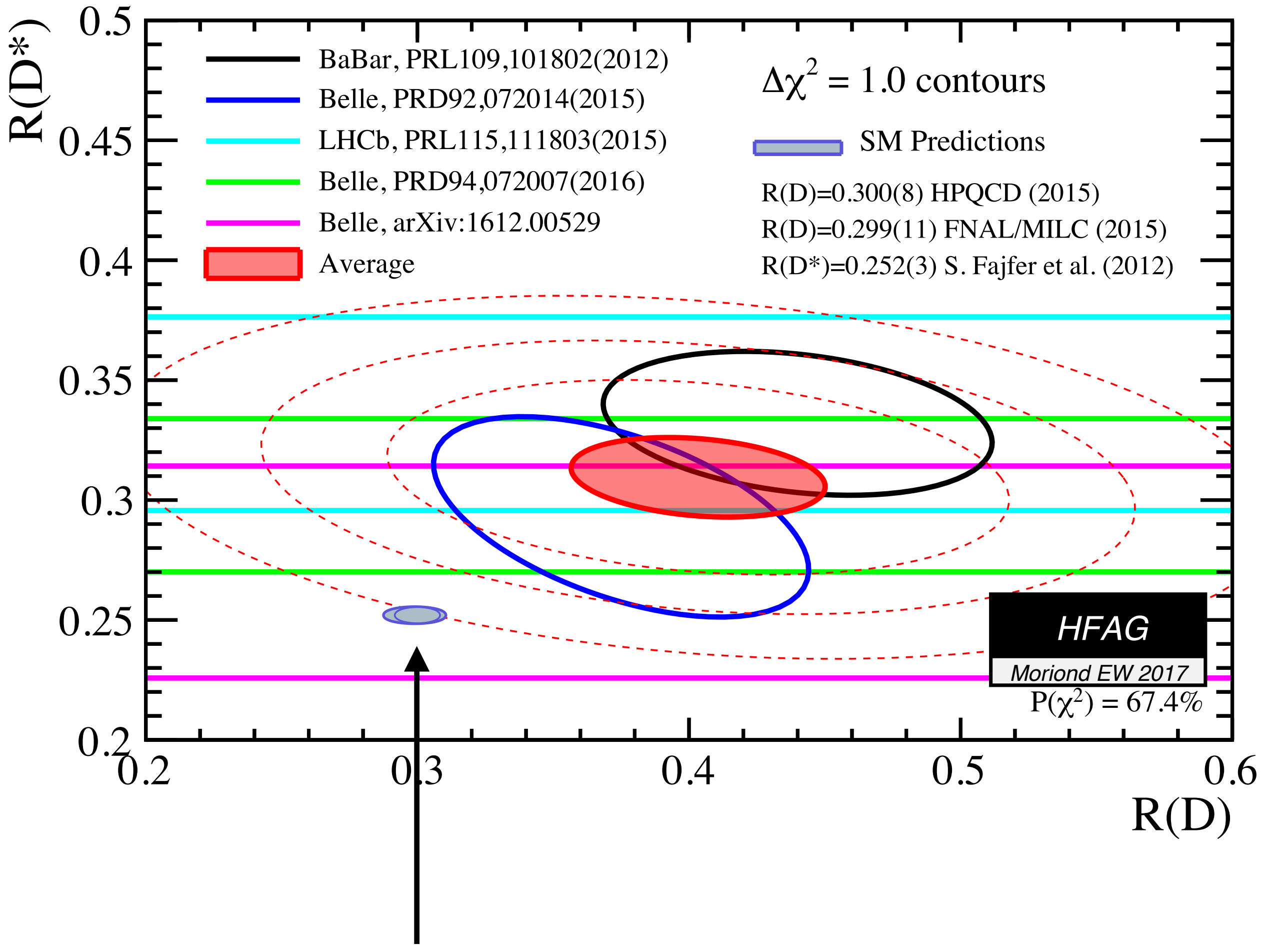
B hadron semileptonic decays in tau leptons final states



SM precision = 1.19%

- Challenging in LHCb
- Nevertheless unexpected contributions
- Today: an (unexpected) contribution
  - Measurement of $R(D^*)$ with hadronic 3-prong τ decays using Run1 data (3 fb^{-1})
  - Two papers in preparation (LHCb-PAPER-2017-017 and LHCb-PAPER-2017-027)
  - Shown for the first time at FPCP on June 5th and in CERN seminar on June 6th

Up to now:

- The τ has been reconstructed in the muonic mode $\tau \to \mu\nu\nu$
- The normalization channel $B^0 \to D^*\mu\nu$ share the same visible final state

Tau leptons with hadronic final state

- Semileptonic decay without charged leptons in the final state
- In our analysis the τ is reconstructed in the hadronic $\tau\to\pi\pi\pi\nu$ decay mode
- The normalization channel used is $B^0\to D^*\pi\pi\pi$ decay

$$K(D^*) = \boxed{\frac{Br(B^0 \to D^{*-}\tau^+\nu_\tau)}{Br(B^0 \to D^{*-}3\pi)}} \longrightarrow R(D^*) = K(D^*) \times \frac{Br(B^0 \to D^{*-}3\pi)}{Br(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

Same final state

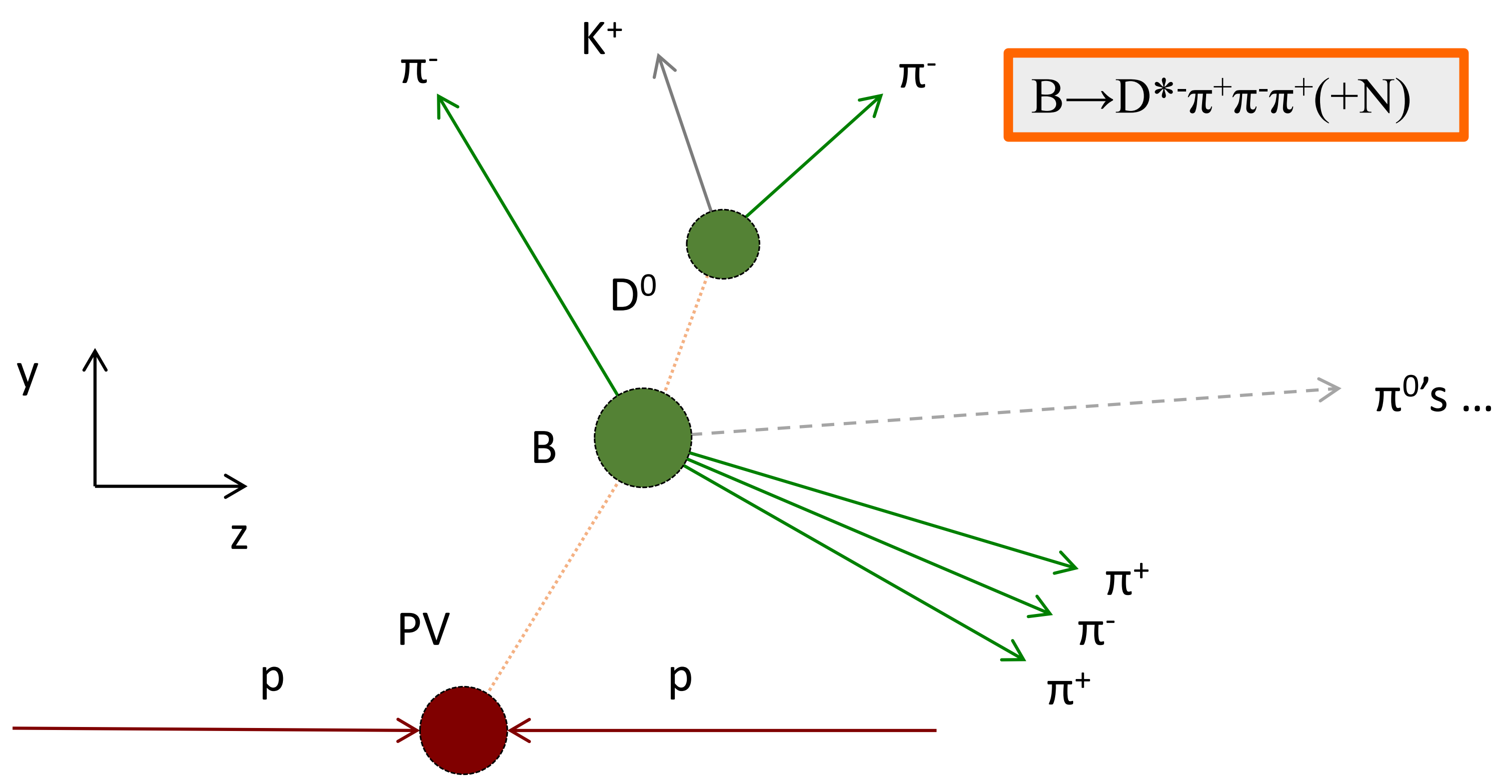
Most of the systematic uncertainties cancel

We will take the last two as external input

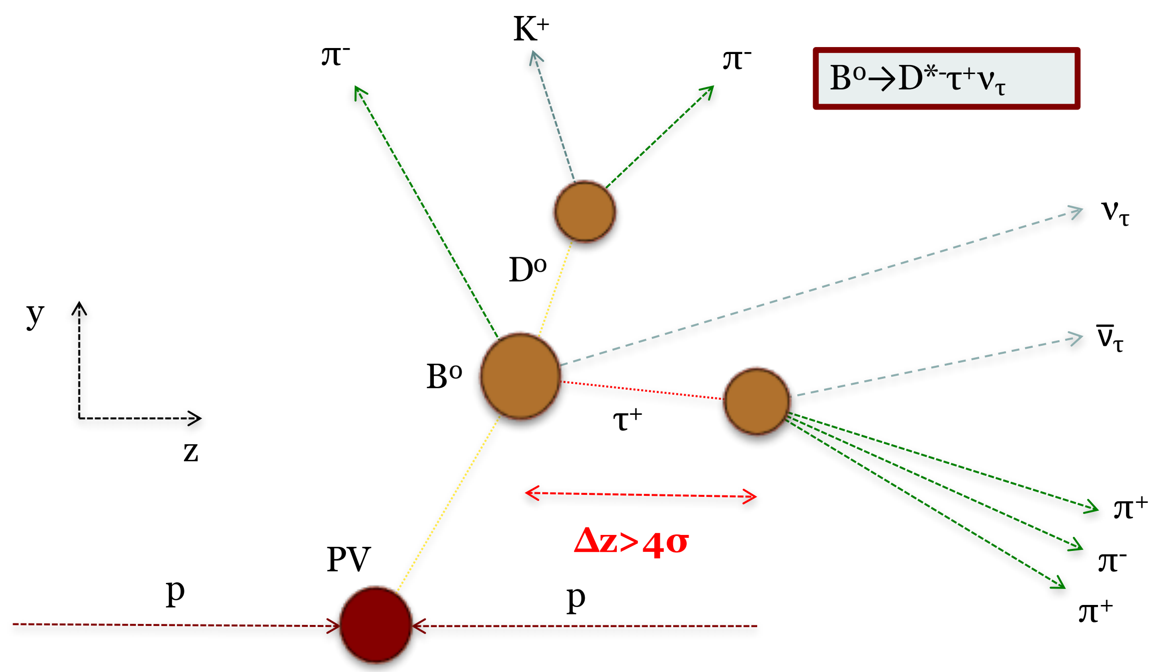
Detached Vertex method

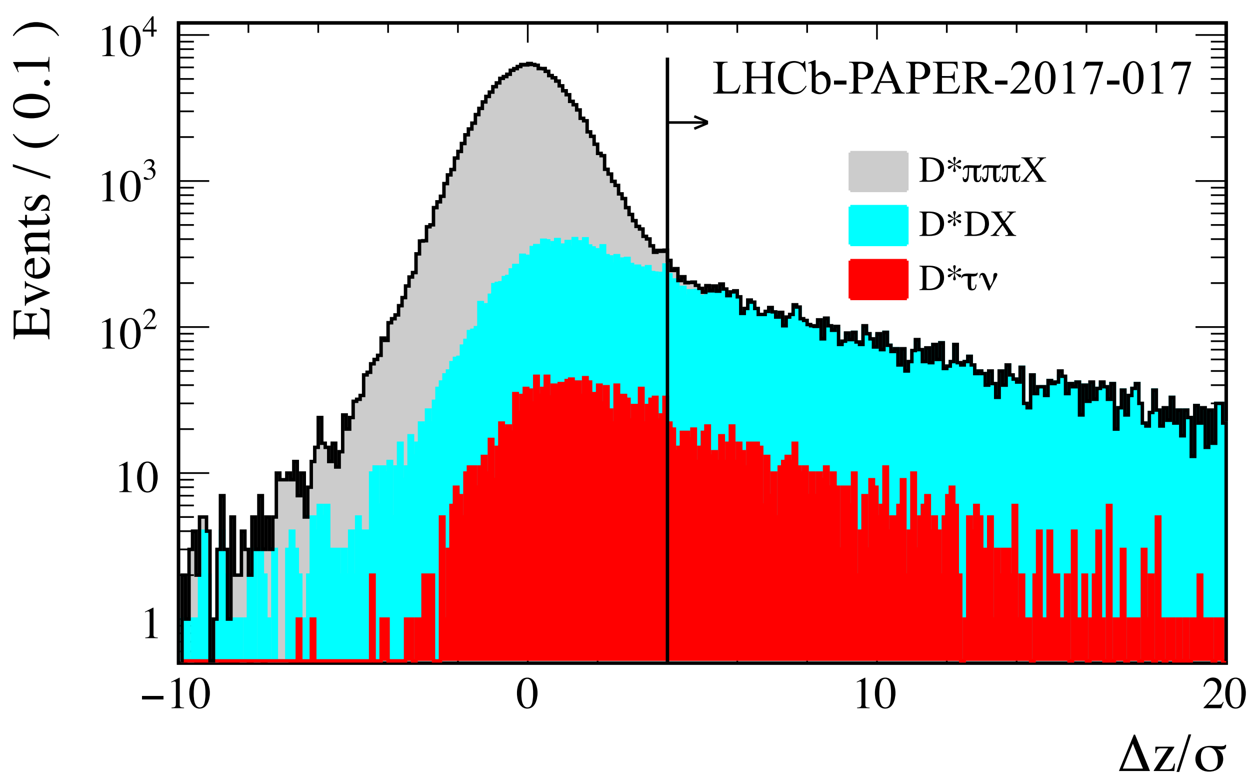
The most abundant **background** source due to hadronic B decays into $D^{*}3\pi X$.

$$\frac{\mathcal{B}(B^0 \to D^* 3\pi + N)}{\mathcal{B}(B^0 \to D^* \tau\nu)_{SM}} \sim 100$$



Detached Vertex method





Good precision in **τ decay vertex** reconstruction

τ vertex is downstream with respect to the B^0 vertex with a significance of at least at 4σ.

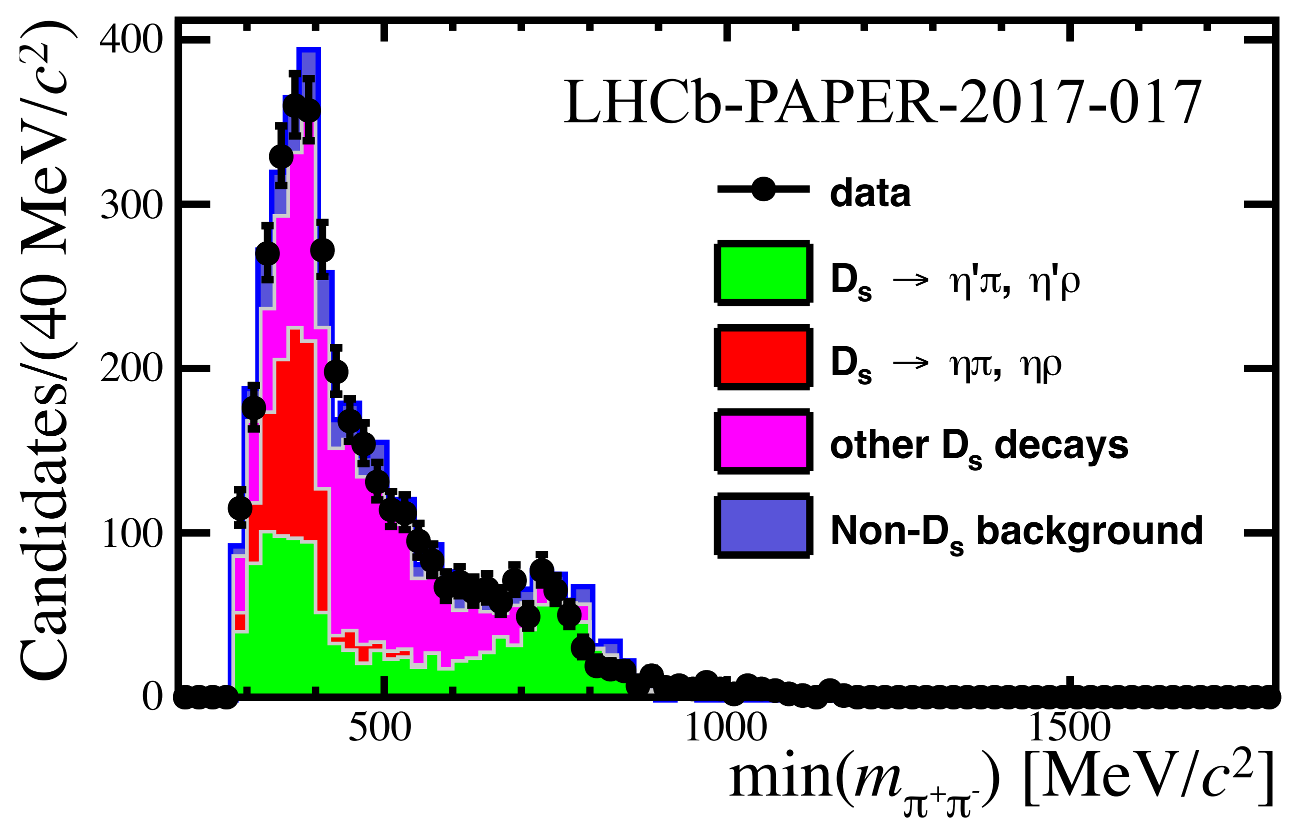
- Background coming from $B \to D^* 3\pi X$ is suppressed by 3 orders of magnitude
- 35% signal efficiency

Double charm background

- The remaining background consists of B^0 decays where the 3π vertex is transported away from the B^0 vertex by a charm carrier (D^0, D^+, D_s)

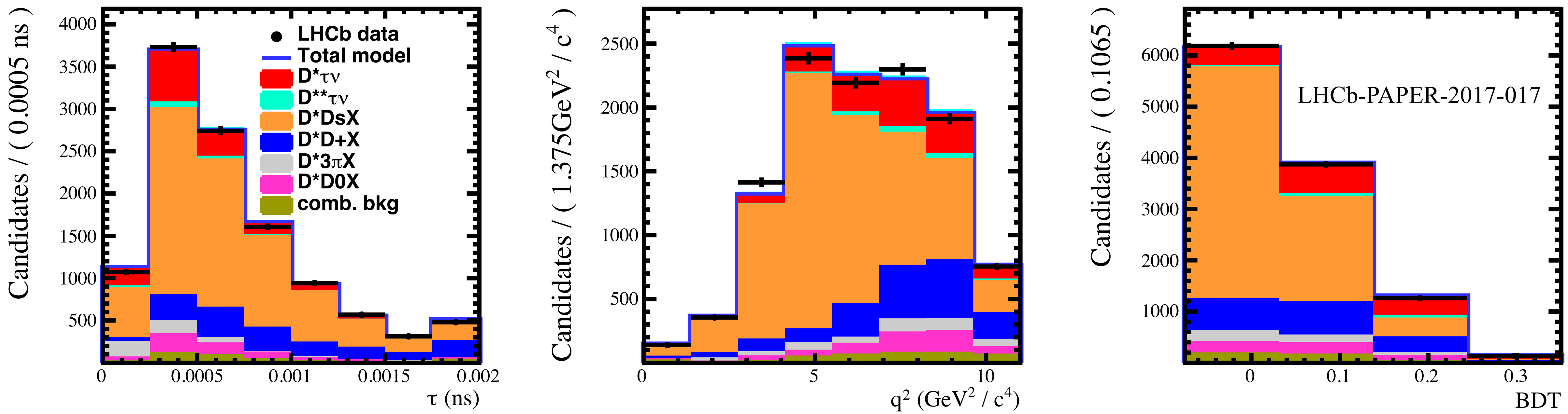
$$\frac{BR(B^0 \to D^* D_{(s)}^{(*)}; D_{(s)}^{(*)} \to 3\pi + X)}{BR(B^0 \to D^* \tau \nu)_{SM}} \sim 10$$

- LHCb has three very good tools to limit this background:
  - 3π dynamics
  - Isolation criteria against charged tracks and neutral energy deposits
  - Partial reconstruction in the signal and background hypotheses
- A Boosted Decision Tree is trained using variables computed with partial reconstruction and isolation criteria to discriminate double charm decays from signal



Fit results

- An extended maximum likelihood 3-dimensional fit using templates in:
  - q^2 (the squared momentum transferred to the τ-ν system),
  - 3π decay time,
  - The output of the BDT extracted from simulated and Data-Driven control samples



Signal Yield:
$N_{D*\tau\nu} = 1300 \pm 85$ candidates

$$K(D^*) \equiv \frac{Br(B^0 \to D^{*-}\tau^+\nu_\tau)}{Br(B^0 \to D^{*-}3\pi)} = (1.93 \pm 0.13_{stat} \pm 0.17_{syst})$$

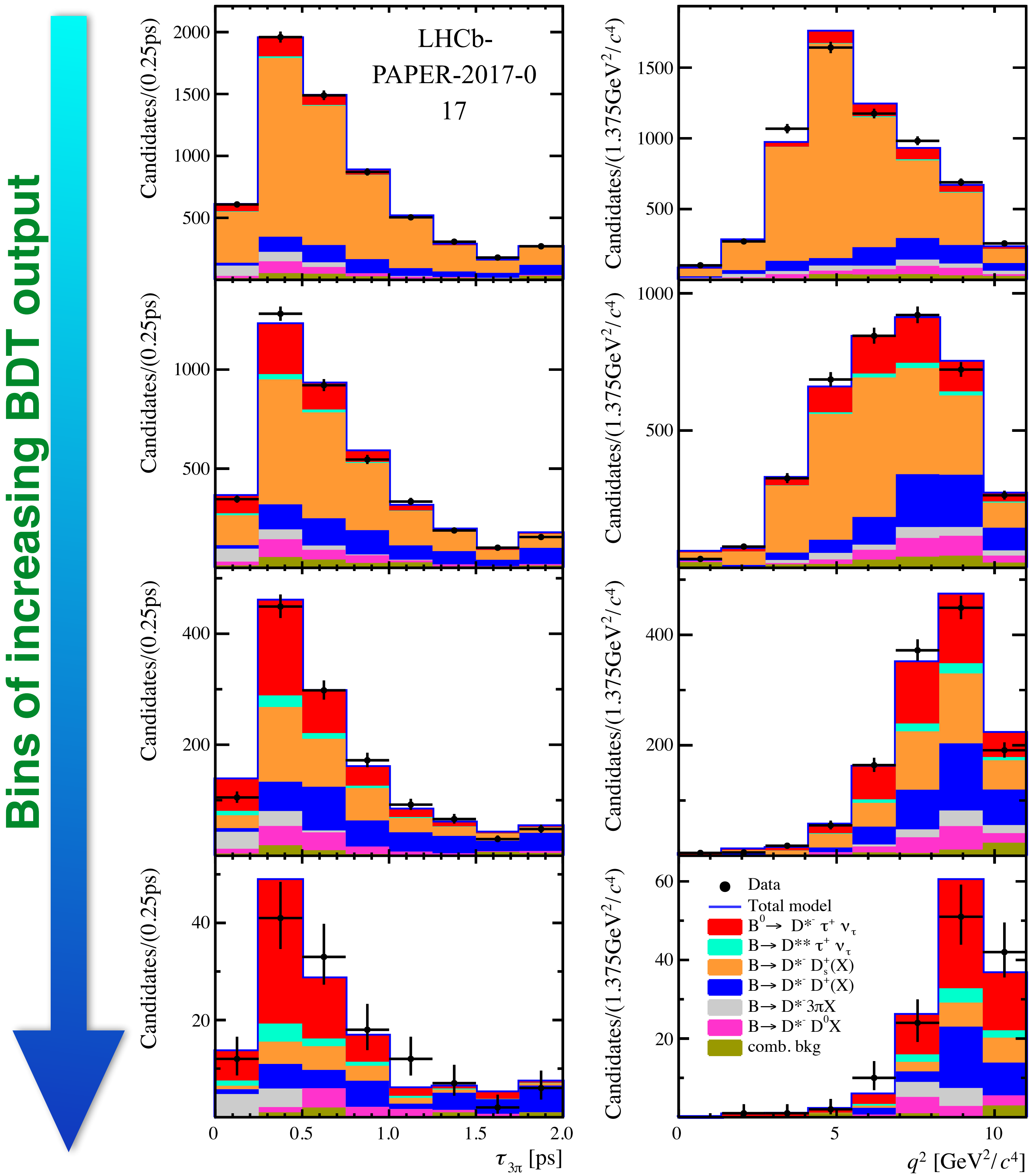
$$Br(B^0 \to D^{*-}\tau^+\nu_\tau) = (1.39 \pm 0.09_{stat} \pm 0.12_{syst} \pm 0.06_{ext})\%$$

PDG2017 = (1.67 ± 0.13)%

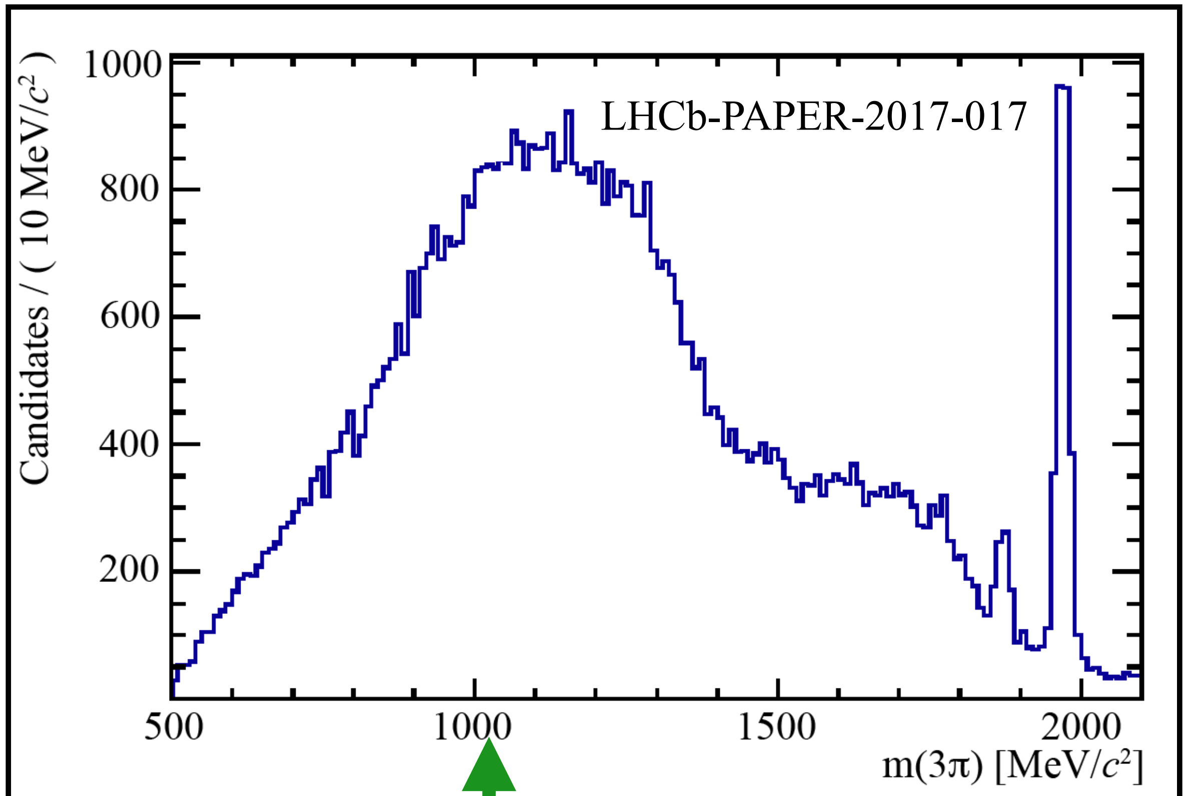
New naive average = (1.56 ± 0.10)%

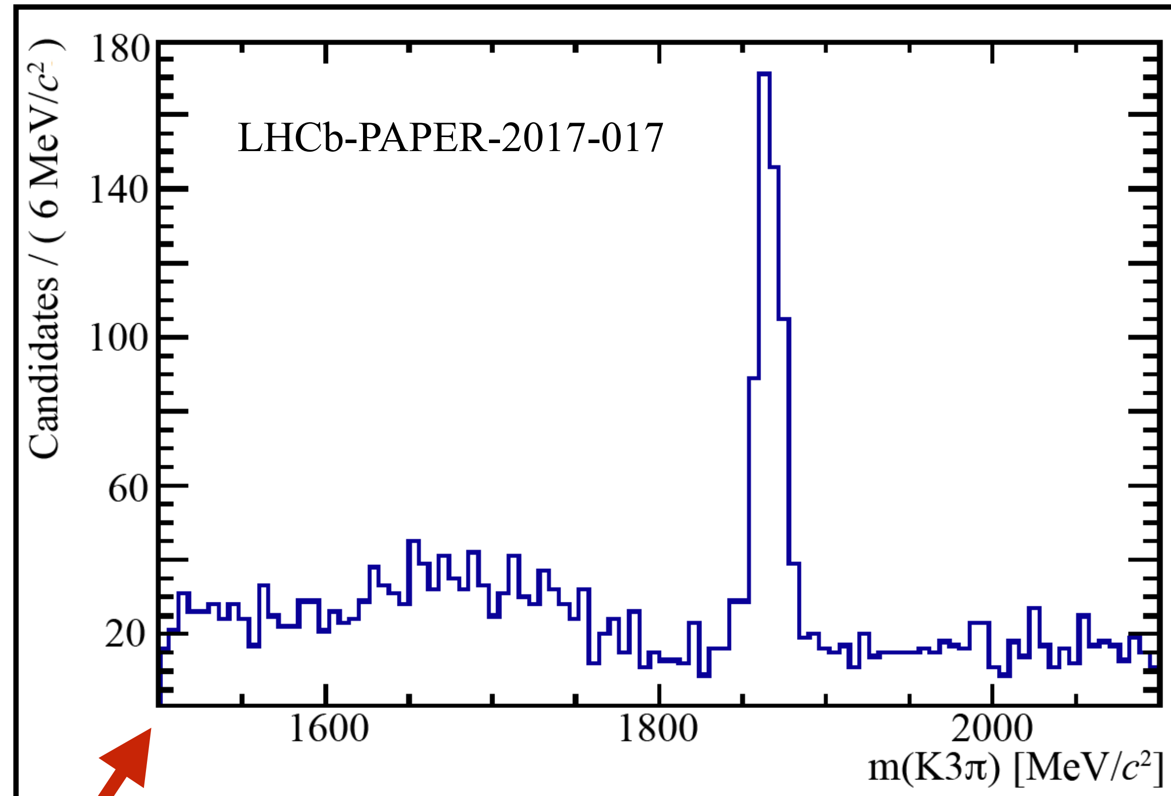
Fit projections

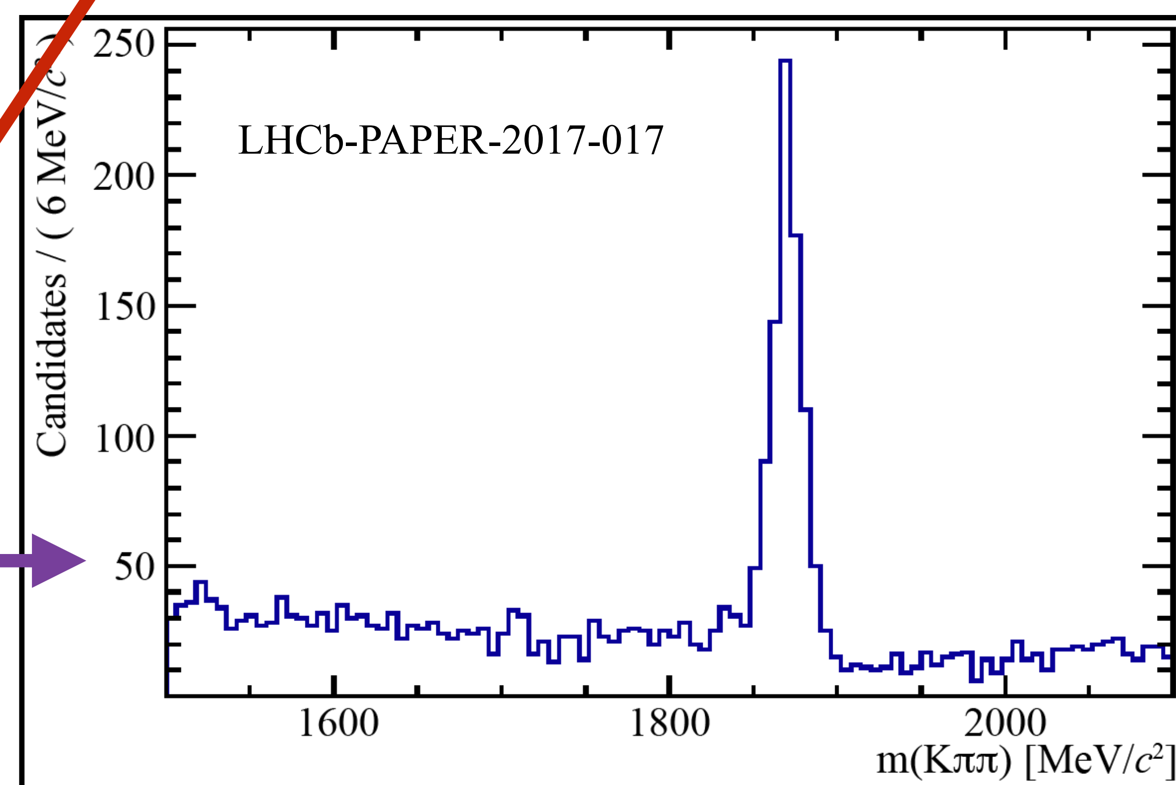
- The 3D template binned likelihood fit results are presented for the lifetime and q^2 in four BDT output bins
- The increase in signal (red) purity as function of BDT output is very clearly seen, as well as the decrease of the D_s component (orange)
- The dominant background at high BDT output becomes the D^+ component (blue), with its distinctive long lifetime.
- The overall χ^2 per dof is 1.15



Control channels D_s, D^0 and D^+



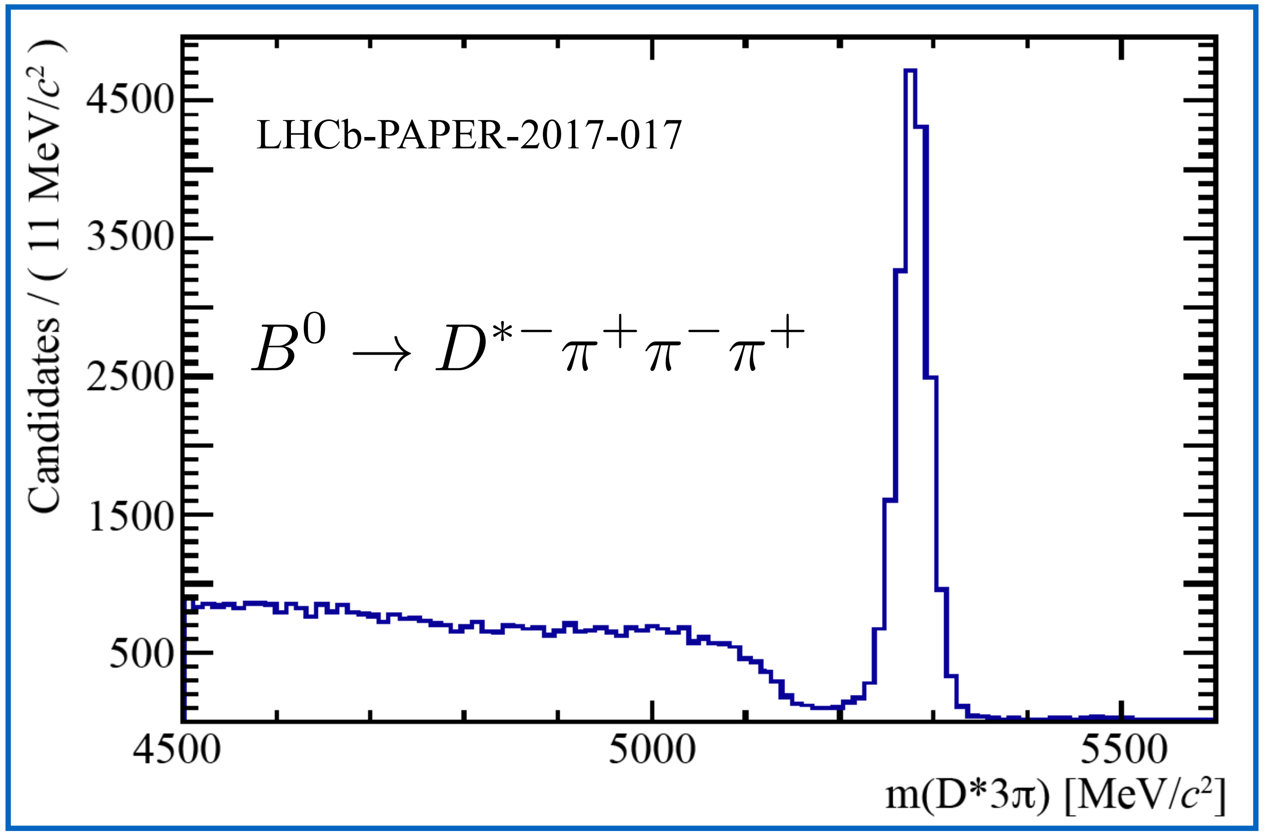




- 3π invariant mass, at early stage of the data selection
- $D^0 \to K3\pi$ peak: anti-isolation cut
- $D^+ \to K\pi\pi$ peak: anti-PID cut
- "Standard candles" used to check Data and MC agreement

Normalization channel

- The normalization channel has to be as similar as possible to the signal channel
- This cancel all systematics linked to trigger, particle ID, selection cuts
- They differ by: softer pions and D^* due to the presence of two neutrinos, kinematics of the 3π system is not exactly the same:
  - This gives a residual effect on the efficiency ratio.



$N_{D^*3\pi}$ ~17000 candidates (1% precision)

Main systematics

- MC statistics: difficult to produce very large samples
- $B \to D^{*}$ (D_s, D^0, D^+)X and $B^0 \to D^{*}3\pi X$ backgrounds

The total is above the statistical precision

Improvements with more data, more MC.

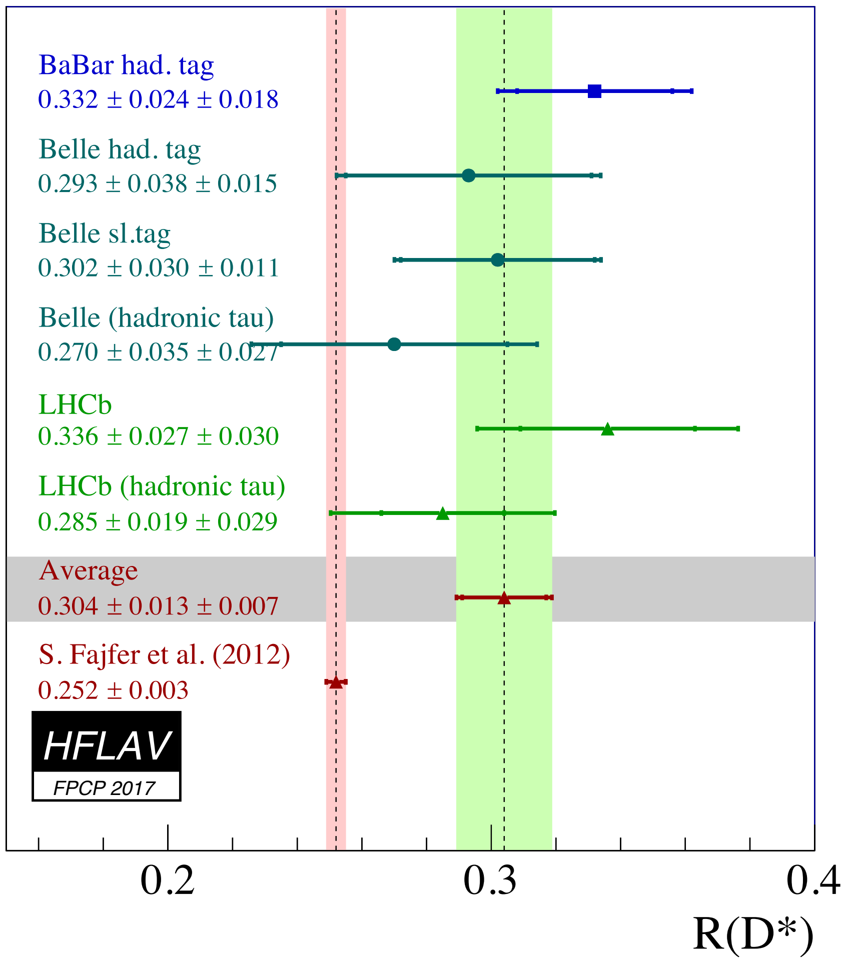
Uncertainties due to the knowledge of external BRs can be reduced with the help of other experiments

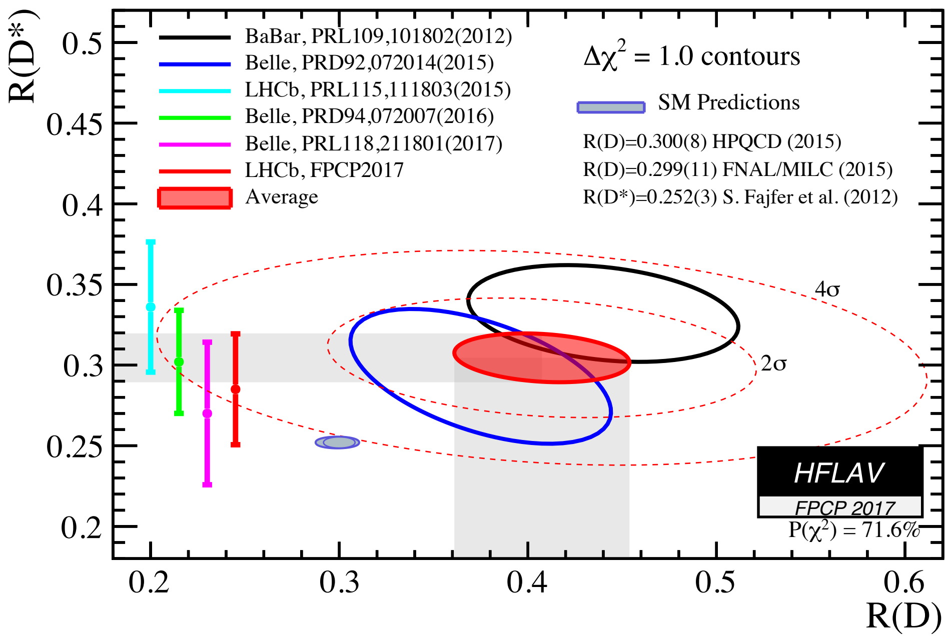
Source	$\delta R(D^{*-})/R(D^{*-})[\%]$
Simulated sample size	4.7
Empty bins in templates	1.3
Signal decay model	1.8
$D^{**}\tau\nu$ and $D_s^{**}\tau\nu$ feeddowns	2.7
$D_s^+ \to 3\pi X$ decay model	2.5
$B \to D^{*-}D_s^+X$, $B \to D^{*-}D^+X$, $B \to D^{*-}D^0X$ backgrounds	3.9
Combinatorial background	0.7
$B \to D^{*-}3\pi X$ background	2.8
Efficiency ratio	3.9
Total uncertainty	8.9

A systematic uncertainty of 4.5% needs to be added, due to the limit of knowledge of external branching fractions.

Conclusions

- Semitauonic B decays are great tool to discover new physics
- Thanks to the LHCb excellent performance, it is possible to reconstruct hadronic tau decays with good precision separating secondary and tertiary vertices.
- ☑ New measurement of the ratio $K_{had}(D^*) = BR(B^0 \to D^{*-}\tau^+\nu)/BR(B^0 \to D^{*-}3\pi)$ using the $3\pi(\pi^0)$ hadronic decay of the τ lepton for the first time.
- ☑ The resulting $R(D^*)$ is one of the best single measurements, having the smallest statistical error. It is compatible both with the SM prediction and with the present WA. It slightly increases the discrepancy of the WA wrt the SM.
- Systematic uncertainty expected to decrease





Backup

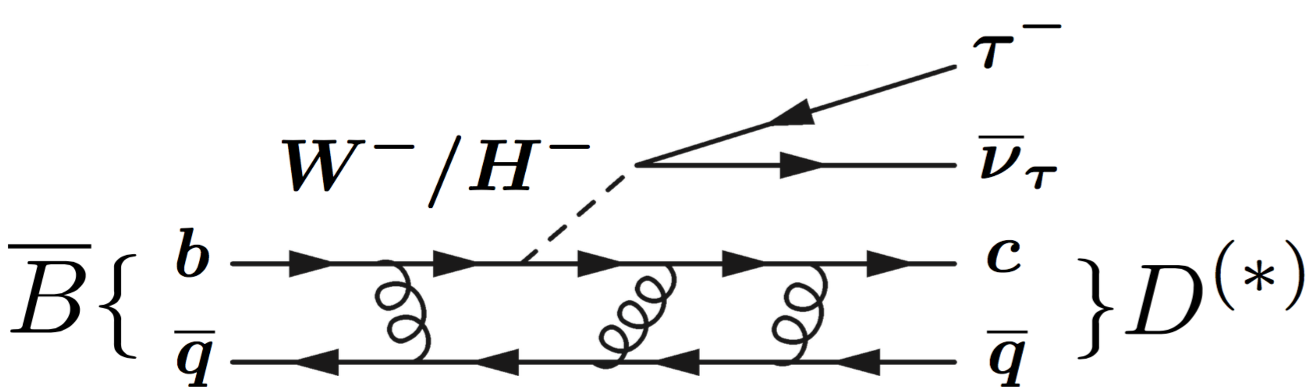
B hadron semileptonic decays in tau lepton final states

Lepton universality, described in the Standard Model, predicts equal coupling between gauge bosons and the three lepton families.

SM extensions bring in additional interactions, implying in some cases a stronger coupling with the third generation of leptons.

Semileptonic decays of b hadrons provide a *sensitive probe to such New Physics effects*.

Presence of additional charged Higgs bosons, required by such SM extensions, can have significant effect on the semi-tauonic decay rate for example in $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$



$$R(D^*) = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\tau)} \qquad R(D) = \frac{\mathcal{B}(\bar{B}^0 \to D^{+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{+}\mu^-\bar{\nu}_\tau)}$$

B hadron semileptonic decays in tau leptons final states

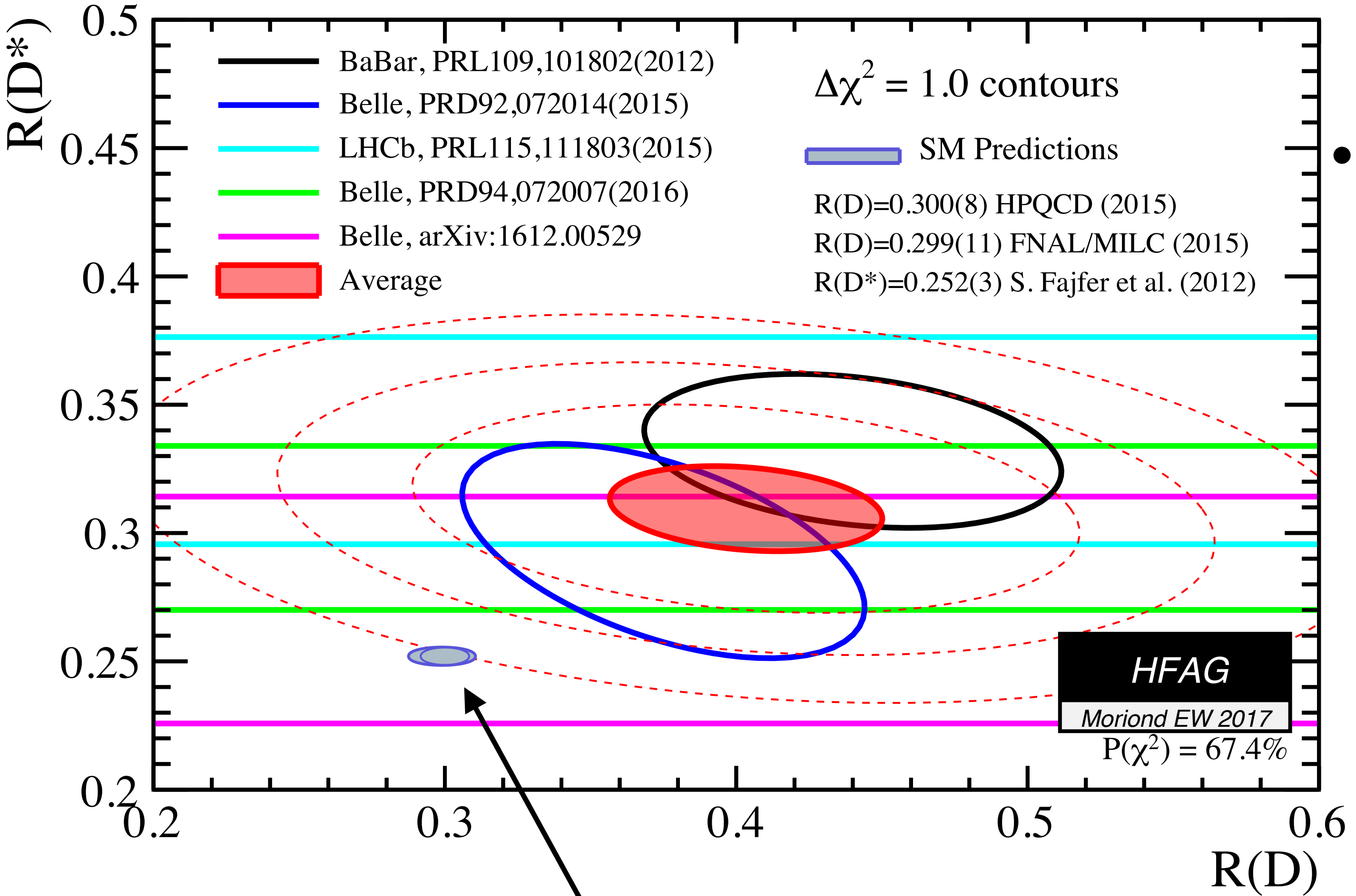
- These decays are successfully studied in B factories with high purity and high statistics $D^{(*)}\tau\nu$ samples
- Despite the hadronic environment LHCb is also able to study such kind of decays and extend to other b hadrons thanks to the high boost of the b hadrons and excellent vertexing

Analysis Challenges

- Finding kinematic variables that distinguish signal from background
- Suppressing background with additional charged/neutral particles
- Normalization channel

- These challenges have different levels of importance and difficulty, and different solutions between analyses
  - Especially between analyses of muonic and hadronic τ decays

B hadron semileptonic decays in tau leptons final states

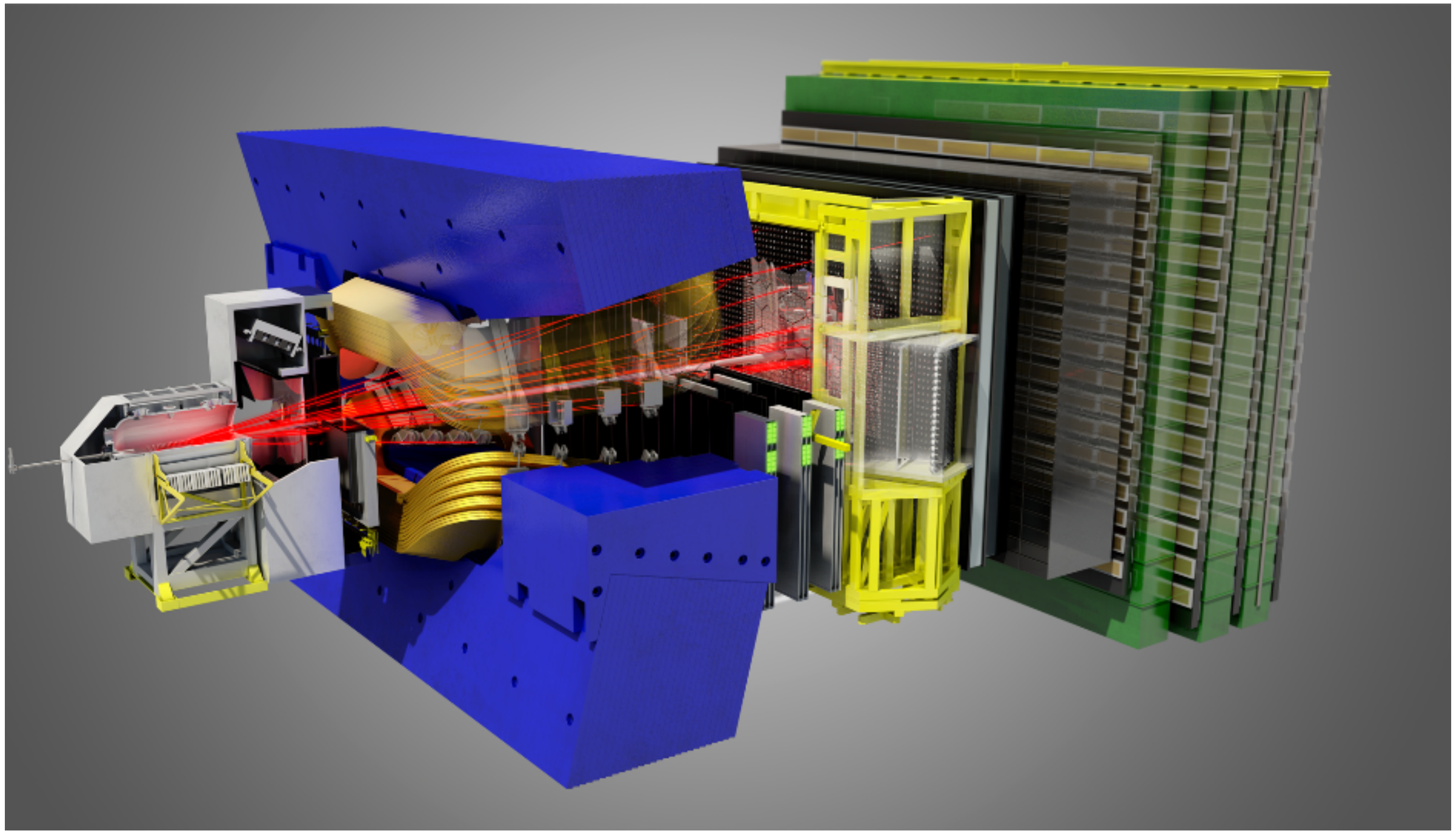


SM precision = 1.19%

- Previous measurements of the combination of R(D) and R(D^*) performed by Belle, BaBar and LHCb are in tensions with the Standard Model expectation (~4σ standard deviations)

- The τ has been reconstructed in the muonic mode $\tau \rightarrow \mu\nu\nu$
- The normalization channel $B^0 \rightarrow D^* \tau\nu$ share the same visible final state

The LHCb Detector



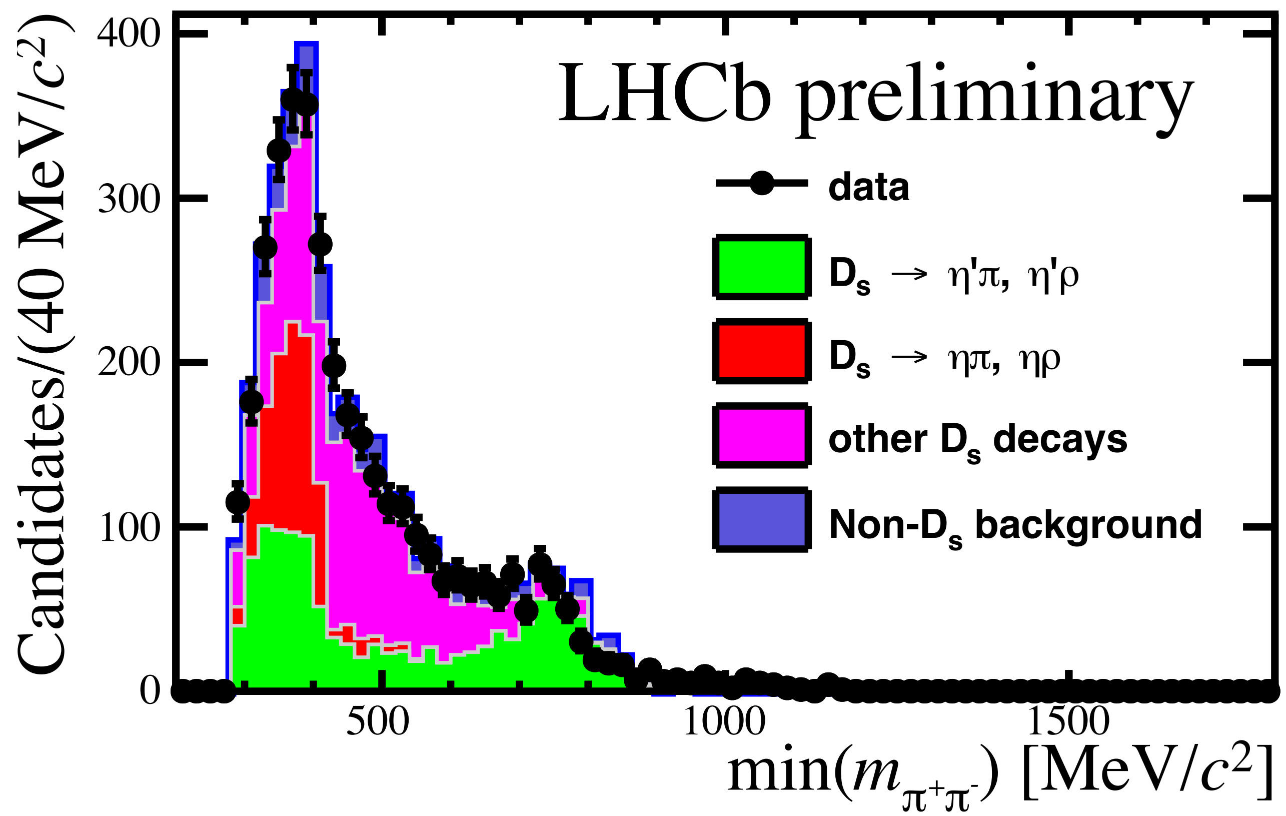
- **Single arm spectrometer** at LHC in the pseudorapidity range $2<\eta<5$;
- Optimized to study hadron decays containing **b** and **c** quarks:
  - CP violation, rare decays, heavy flavor production;
- **Excellent vertex resolution** and separation of B vertices;
- Good **momentum and mass resolution**;
- Excellent **PID** capabilities (good separation **K-π** and muon identification);

- Run 1: collected about 1 fb^{-1} @ $\sqrt{s}$ = 7 TeV in 2011 and about 2 fb^{-1} @ $\sqrt{s}$ = 8 TeV in 2012
- Run 2: collected about 2.0 fb^{-1} @ $\sqrt{s}$ = 13 TeV

Double charm background

- The D_s decay model has been determined directly from data, using a enriched sample obtained using a BDT output region that is enriched in such decays (high purity)
- The min $M(2\pi)$, max $M(2\pi)$, $M(\pi^+\pi^+)$ and $M(3\pi)$ mass are fitted simultaneously

- PDF contains:
  - D_s decays where at least 1 pion is from η or η': $\eta\pi$, $\eta\rho$, $\eta'\pi$, $\eta'\rho$
  - D_s decays where at least 1 pion is from an IS other η, η': $IS\pi$, $IS\rho$ (IS could be ω, ϕ)
  - D_s decays where none of the 3 pions comes from an IS, subdivided in: $K^0 3\pi$, $\eta 3\pi$, $\eta' 3\pi$, $\omega 3\pi$, $\phi 3\pi$, 3π non resonant final state.



- The weights obtained by this fit are then used to construct the D_s templates

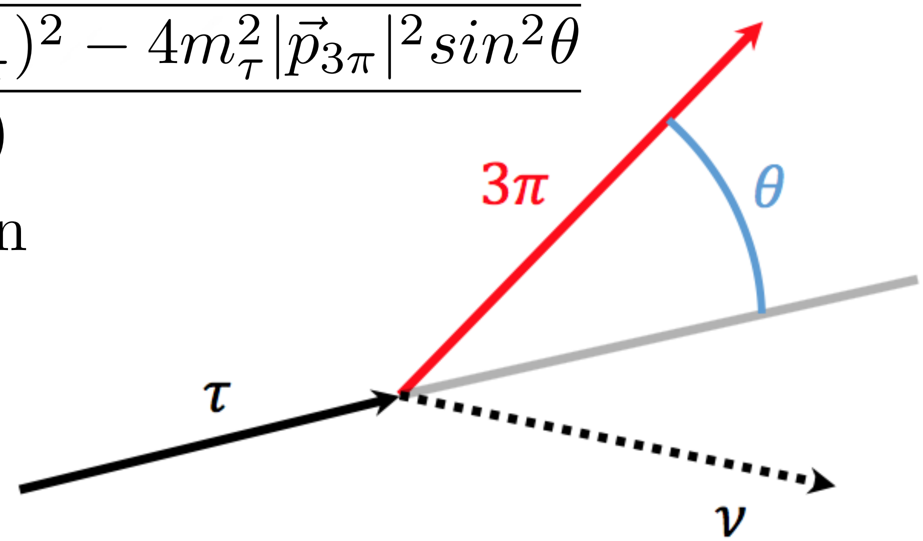
Signal extraction

Signal Reconstruction:

- The presence of the neutrino in the final state of the signal decay can be inferred, up two a two-fold ambiguity, by exploiting the flight direction of the tau lepton.

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

where θ is the angle between τ and 3π direction



This ambiguity can be resolved by choosing the maximum value for the opening angle between the three charged pion system and the direction of the tau lepton

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

Fit Model

- An extended maximum likelihood 3-dimensional fit using templates in:
  - q^2 (the squared momentum transferred to the τ-ν system),
  - 3π decay time,
  - The output of the BDT extracted from simulated and Data-Driven control samples

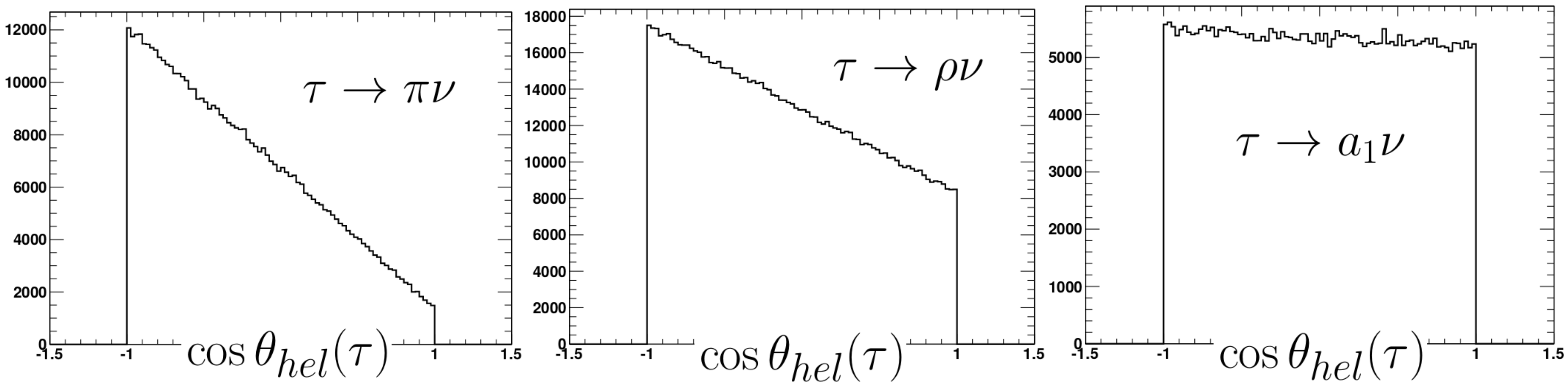
- The Fit Model consists of 5 categories:
  - Signal described by the sum of $\tau\to\pi\pi\pi\nu$ and $\tau\to\pi\pi\pi\pi^0\nu$
  - $B^0\to D^{**}\tau\nu$
  - Double Charm components
  - $B^0\to D^*3\pi X$
  - Combinatorial background

τ polarization study

Belle:(arXiv:1612.00529)
from Karol ADAMCZYK talk at CKM 2016

- D$*$ and τ polarizations in semitauonic B decays are sensitive probes of various NP scenarios
- $\cos\theta_{hel}$ (τ) can be measured if there is a single ν in τ decay $\tau \to h\nu_\tau$, h = π, ρ, a1

Spin analysers: $$\frac{d\Gamma}{dcos(\theta_{hel}(\tau))} = \frac{1}{2}(1+\alpha P_\tau cos(\theta_{hel}(\tau)))$$ With $$P_\tau = \frac{2}{\alpha}\frac{\Gamma_{cos\theta_{hel}>0} - \Gamma_{cos\theta_{hel}<0}}{\Gamma_{cos\theta_{hel}>0} + \Gamma_{cos\theta_{hel}<0}}$$



$\alpha = 1$ for $\tau \to \pi\nu$

$$\alpha = \frac{m_\tau^2 - 2m_V^2}{m_\tau^2 + 2m_V^2},\ \alpha = 0.45 \text{ for } \tau \to \rho\nu$$

- In the case of hadronic R(D*)
  - Pros: The systematics due to the knowledge of τ polarization is small ($\alpha \approx 0.02$)
  - Cons: Difficult to perform polarization studies