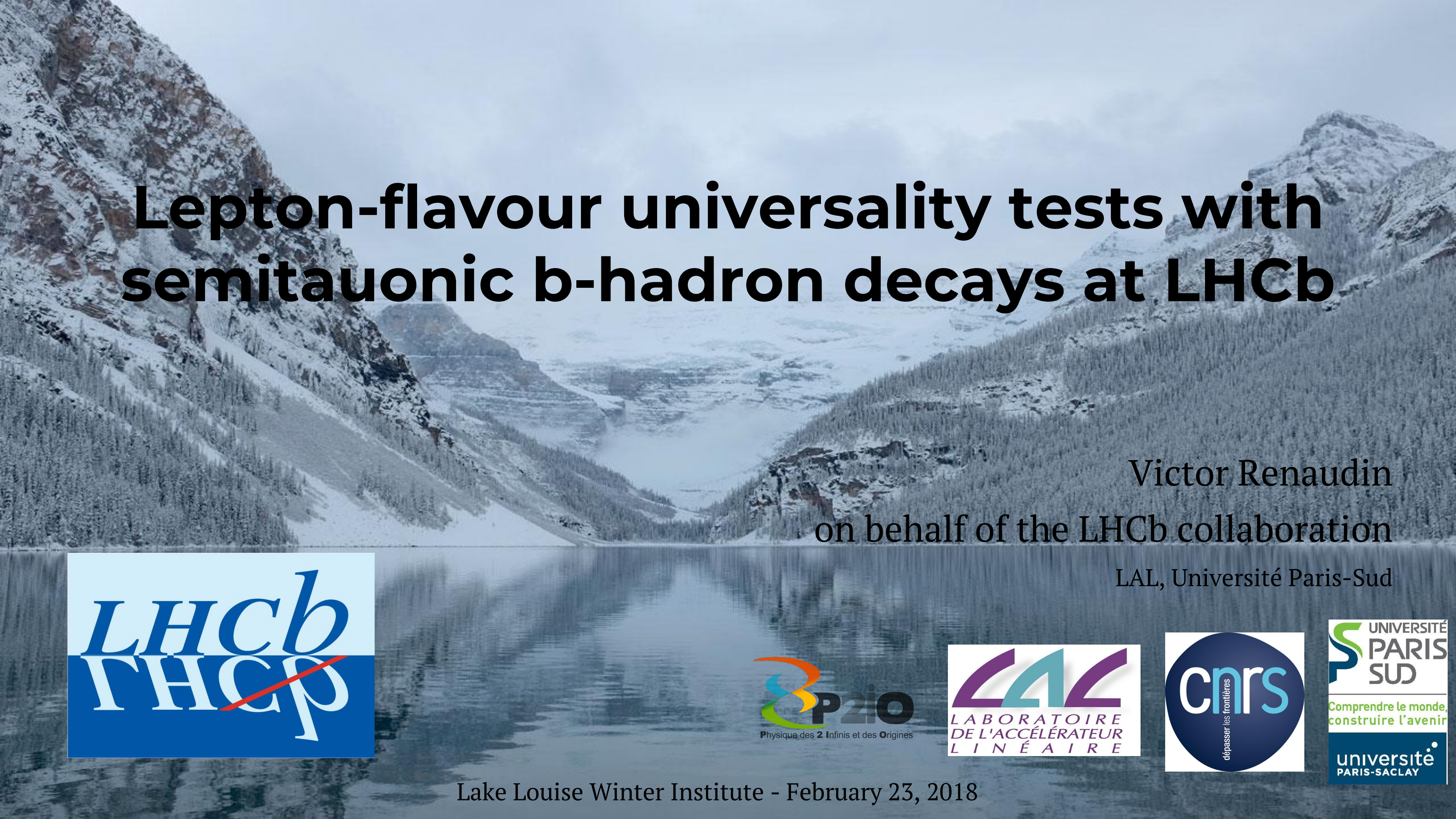

Lepton-flavour universality tests with semitauonic b-hadron decays at LHCb

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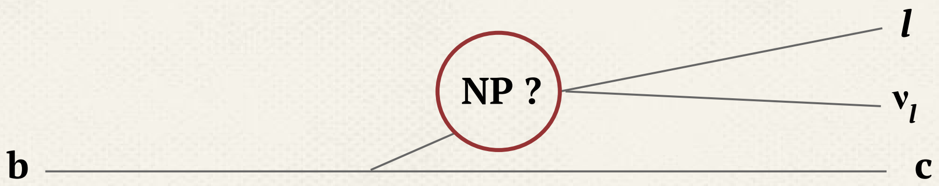
Lake Louise Winter Institute - February 23, 2018

LFU: a hot topic

- The Standard Model predicts ***Lepton Flavour Universality*** *(LFU)*: equal couplings between gauge bosons and the three lepton families

$$\mathcal{R}(H_c) = \frac{\mathcal{B}(H_b \to H_c\tau\nu)}{\mathcal{B}(H_b \to H_c\mu\nu)}$$ **should only account for phase space effects**

- Yet, tensions between SM expectations and experimental results are found in:
  - semitauonic B decays →this talk
  - b→*sll* transitions →Violaine's presentation
- Several models (charged Higgs, leptoquarks, W') add new interactions with a stronger coupling with the τ
- Some models (leptoquarks & W'/Z' models) try to explain both discrepancies.



arXiv:1604.03088,
arXiv:1206.4977

Why using semitauonic B decays ?

As tree level decays, they combine some nice features:

- **Precise prediction from SM** using ratios with shared systematics cancelling
- **Abundant channel**: BR($B \to D^* \tau \nu$) ~ 1.2% (in SM)
- **Sensitivity to NP** contributions

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

Different hadron species:

- D^*, D^0, D^+, D_s, $\Lambda_c^{(*)}$, J/Ψ
- Not only spectator quarks differ but also the **spin**:
  - 0: D^0, D^+, D_s
  - 1: D^*, J/Ψ
  - ½: $\Lambda_c^{(*)}$

Only at LHCb

Two reconstruction channels for τ at LHCb:

$\tau \to \mu \nu \nu$

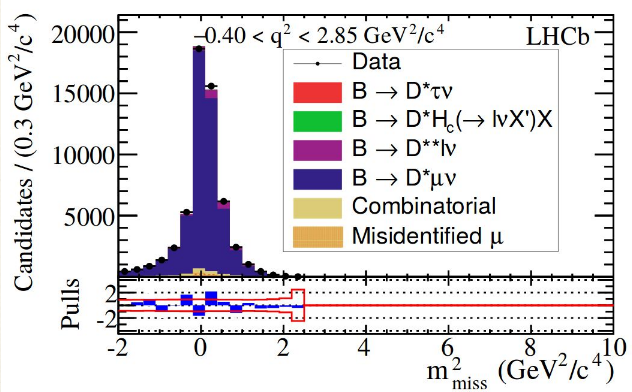
- longitudinal component of B momentum missing:
  - Assuming $\beta\gamma_{z,tot} = \beta\gamma_{z,visible}$
- Can then calculate rest frame quantities: $\mathbf{m^2_{missing}}$, $\mathbf{E_\mu}$, $\mathbf{q^2}$

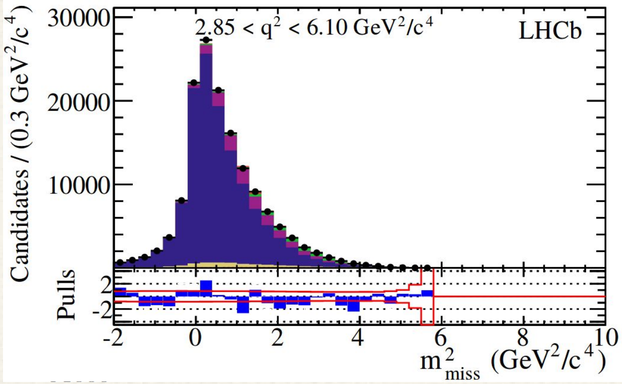
$\tau \to \pi^- \pi^+ \pi^- (\pi^0) \nu$ → later in the talk

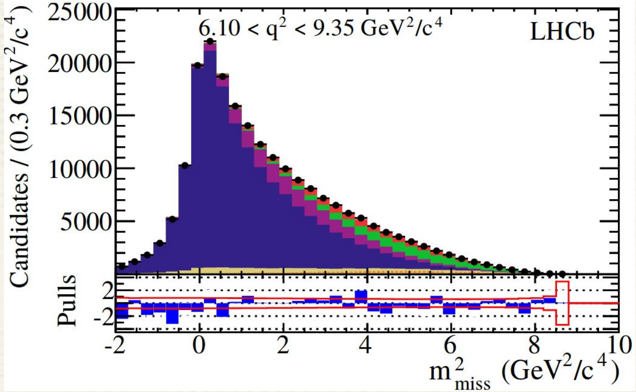
Phys. Rev. Lett. 115, 111803

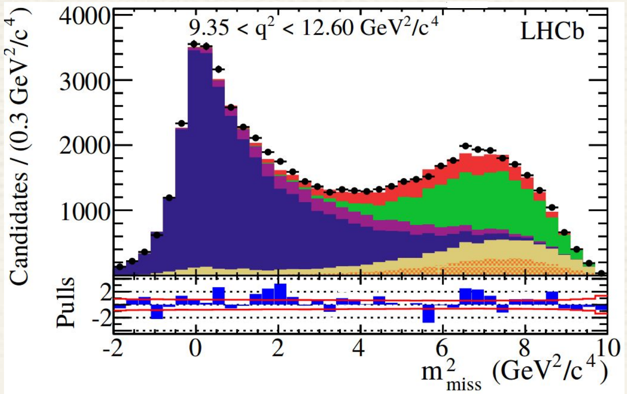
R(D*) with τ→μνν

- 3D MC-template based binned fit to $m^2_{missing}$ vs E_μ in coarse q^2 bins
- Fit to isolated data, used to determine ratio of $B \to D^* \tau\nu$ and $B \to D^* \mu\nu$
- Templates are a good description of the data









R(D*) = 0.336 ± 0.027 ± 0.030 → consistent with SM at **2.1σ** level

arXiv:1711.05623

R(J/ψ)

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)}$$

LFU probed with a new hadronisation:

- SM expectation: 0.25 – 0.28
- Lower statistics due to B_c^+ production fraction

Same strategy as R(D*) analysis:

- Use of m^2_{miss}, q^2, E_μ.
  - q^2 and E_μ combined into Z

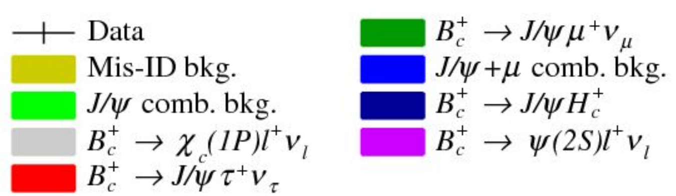
B_c^+ specificities:

- **B_c^+ decay-time shorter** than other B → helps reducing background
- $B_c^+ \to J/\psi$ form-factors unknown
  - estimated from fit to enriched sample of the normalisation mode.

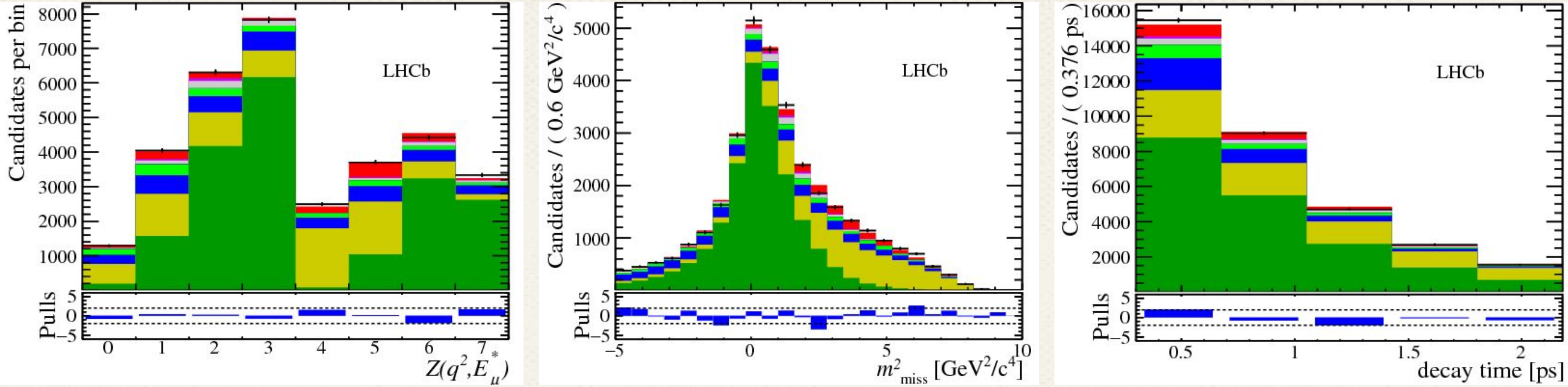
arXiv:1711.05623

R(J/ψ)

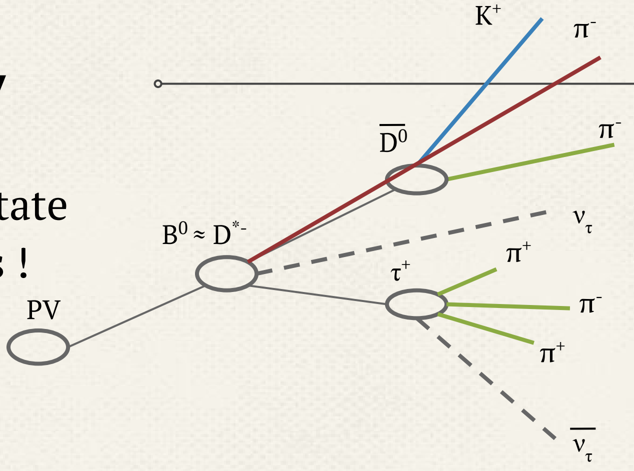
- 3D template fit using $\tau(B_c^+)$, m^2_{miss}, Z
- Largest systematics
  - □ $B_c^+ \rightarrow J/\psi$ form-factor
  - □ simulation sample size
- First evidence of $B_c^+ \rightarrow J/\psi \tau \nu$



R(J/ψ) = 0.71 ± 0.17 ± 0.18 → compatible with SM at **2σ.**



R(D*) with $\tau \to \pi^- \pi^+ \pi^- (\pi^0) \nu$



- Semileptonic decay **without charged lepton** in the final state
  - → **Zero** background from normal semileptonic decays !

- **No signal mass peak due to neutrinos**
- **but several hadronic ones** ($D^0 \to K3\pi$, $D^+ \to K\pi\pi$, ...)
  - It provides control on the various background channels
- Only one ν at the τ vertex
  - **Partial reconstruction can be applied** with good precision
- $B^0 \to D^* \pi^+ \pi^- \pi^+$ is used as normalisation

$$R_{had}(D^*) = \boxed{\frac{\mathcal{B}(\bar{B}^0 \to D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+} \pi^+ \pi^- \pi^+)}}$$

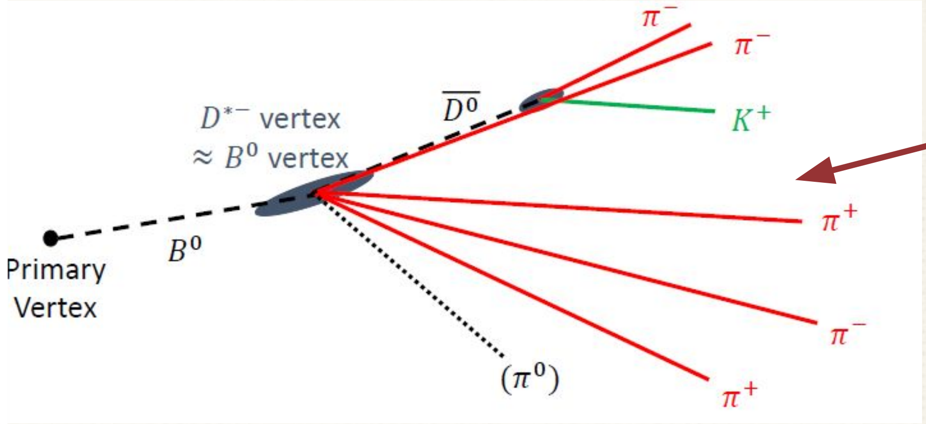
$$R(D^*) = R_{had} \times \boxed{\frac{\mathcal{B}(\bar{B}^0 \to D^{*+} \pi^+ \pi^- \pi^+)}{\mathcal{B}(\bar{B}^0 \to D^{*+} \mu^- \bar{\nu}_\mu)}}$$

Same final state: shared systematics uncertainties cancel

External inputs

arXiv:1708.08856, arXiv:1711.02505

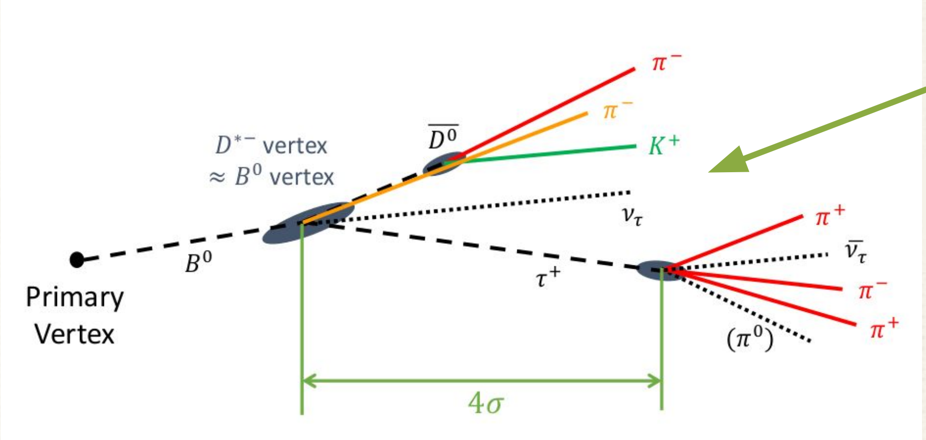
Vertex topology



Most abundant background: hadronic B decays into **D*3πX:**

yield is **100x bigger** than SM expectation for signal yield !

Good precision on τ decay vertex position



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

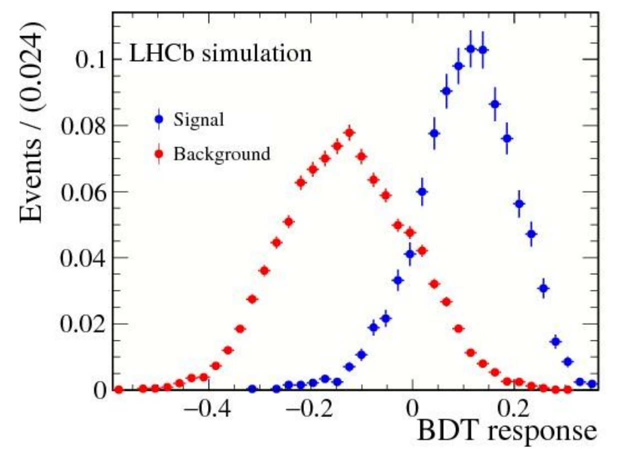
D*3π background reduced by 3 orders of magnitude

arXiv:1708.08856, arXiv:1711.02505

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_s, D^+ or D^0, e.g. $B \to D^* \mathbf{D} X$, $D \to 3\pi X$
- Total yield is ~10x higher than SM expectation for signal

- LHCb has three very good tools to limit this background:
  - **3π dynamics**
  - **Isolation criteria** against charged tracks and neutral energy deposits
  - **Partial reconstruction** in both signal and background hypotheses
- **A Boosted Decision Tree** (BDT) is trained using these tools to discriminate double charm decays from signal



arXiv:1708.08856, arXiv:1711.02505

Signal extraction and fit

Signal reconstruction:

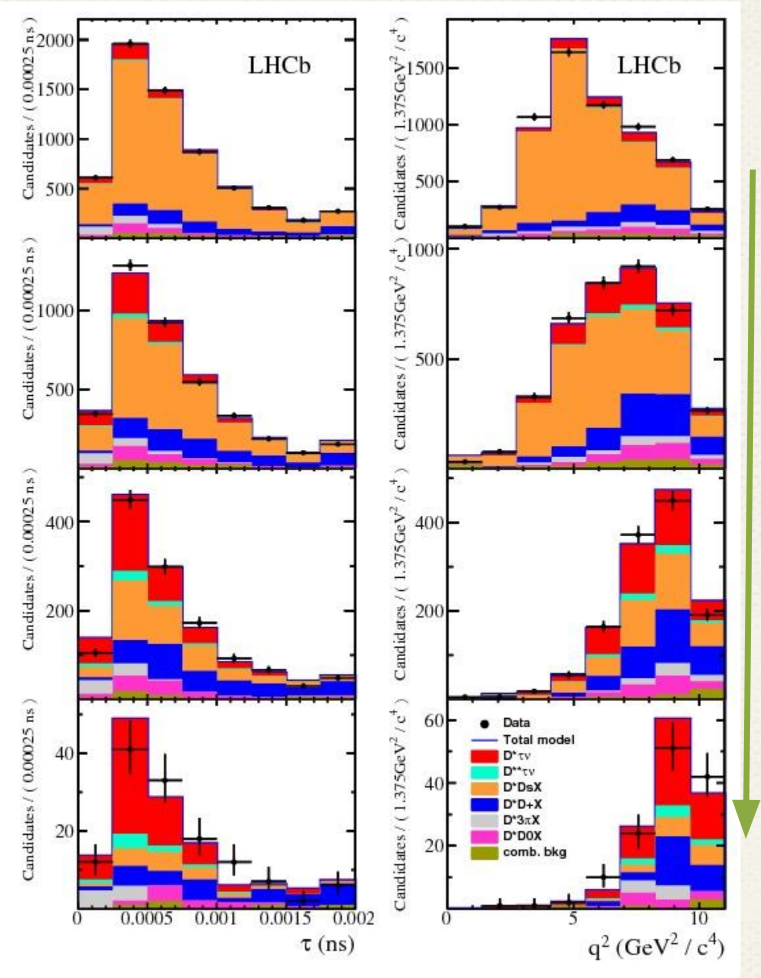
- Assume 2 neutrinos in the event → can be used to access full kinematics
  - Reconstruction of τ and B^0 momentum and τ decay time
  - Kinematics solution found ~95% of the time

Fit strategy:

- A high BDT cut is applied
- A 3D template fit is performed in
  - $\mathbf{q^2}$ (squared-momentum transferred to the τ-ν system)
  - **τ lifetime**
  - The output of the **BDT**

arXiv:1708.08856, arXiv:1711.02505

q^2 distribution



Bins of increasing BDT output

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

arXiv:1708.08856, arXiv:1711.02505

Main systematics

Room for progress exists on a longer timescale on both internal and external sources !

Contribution	Value %
Simulated sample size	4.7
Signal modeling	1.8
$D^{**}\tau\nu$ and $D_s^{**}\tau\nu$ feed-downs	2.7
$Ds \to 3\pi X$ decay model	2.5
$B \to D^{*-}D_s^{+}X$, $B \to D^{*-}D^{+}X$, $B \to D^{*-}D^{0}X$ backgrounds	3.9
Combinatorial background	0.7
$B \to D^{*}3\pi X$ background	2.8
Empty bins in templates	1.3
Efficiency ratio	3.9
Normalisation channel efficiency	2.0
Total internal uncertainty	**9.1**
$\mathcal{B}(B^0 \to D^{*}3\pi)$ and $\mathcal{B}(B^0 \to D^{*}\mu\nu_\mu)$	**4.8**

In red: can be reduced with help from other experiments (BELLE, BES, ...)

In green: can be reduced internally by LHCb

arXiv:1708.08856, arXiv:1711.02505

R(D*) results

- The fit results give a branching fraction which is:

$BR(B^0 \to D^{*+} \tau \nu) = (1.40 \pm 0.09(stat) \pm 0.13(syst) \pm 0.18(ext))$ %

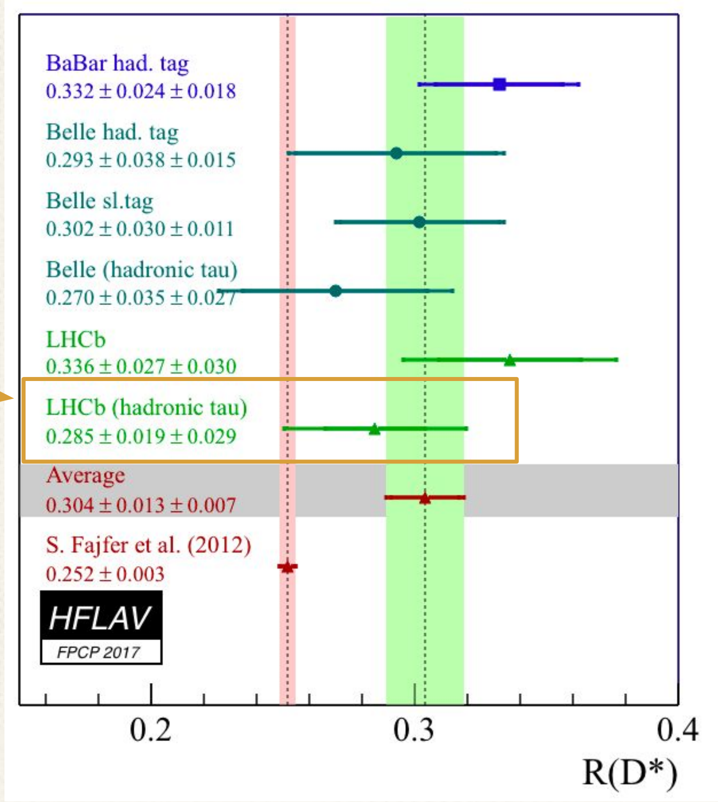
To be compared to PDG 2017: $BR(B^0 \to D^{*+} \tau \nu) = (1.67 \pm 0.13)$ %

- Using the HFLAV $BR(B^0 \to D^* \mu \nu) = (4.88 \pm 0.1)$ %, we get:

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

- Impact on World Average:
  - R(D*): **3.3σ → 3.4σ** from SM prediction
  - Adding R(D): **4.0σ→ 4.1σ**

- It is also possible to compute an LHCb average of $R(D^*)$:
  - **$R_{LHCB}(D^*) = 0.309 \pm 0.016(stat) \pm 0.024(syst)$**

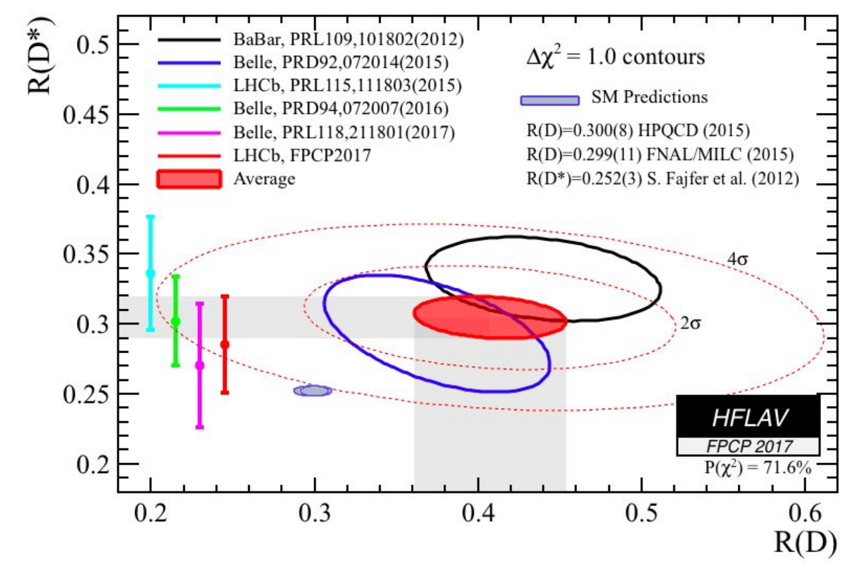


Conclusion

- Latests results of Run1 dataset:
  - **R(J/ψ) using muonic τ**
  - **$R(D^*)$ using hadronic τ**

- **both statistical and systematic uncertainties will be reduced** using large statistics collected during Run2

- LFU can be tested using
  - Precise measurements of $R(D^{(*)})$
  - several hadrons (J/ψ but also $D^{0,+}$, D_s, $\Lambda_c^{(*)}$) → probing different dynamics and spin structures



WA combination of R(D) and $R(D^*)$ is in tension with SM at the **4.1σ* level!**

*: this is reduced with latest theory input

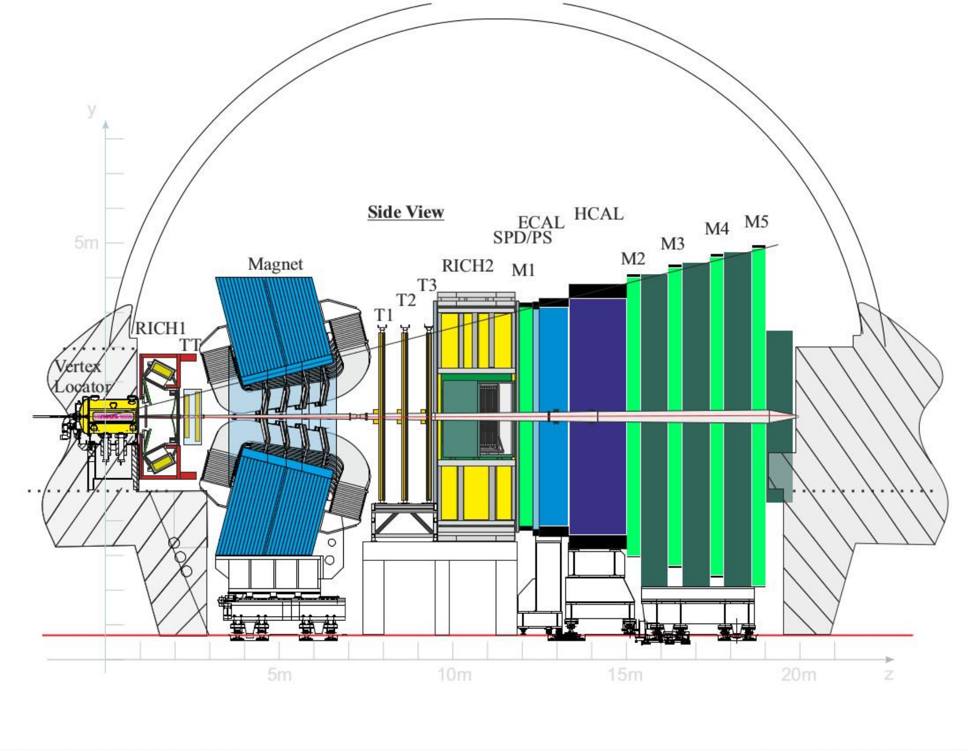
arXiv:1707.0950

Thank you for your attention !

Any question ?

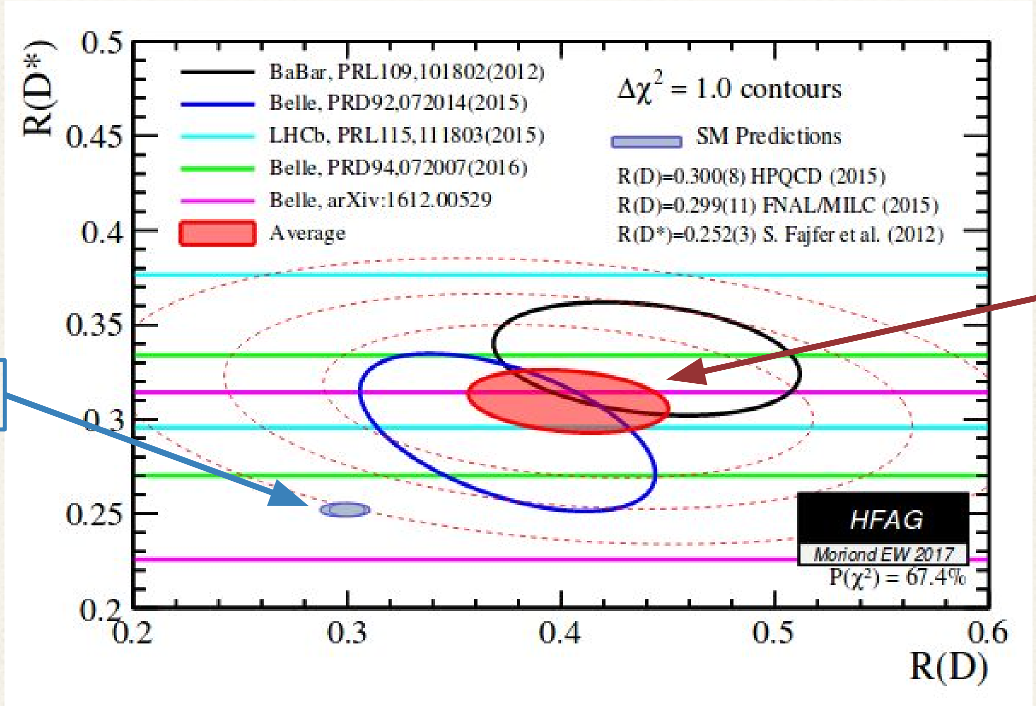
Backup

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)

R(D*) status before hadronic result



SM: 1.19% uncertainty

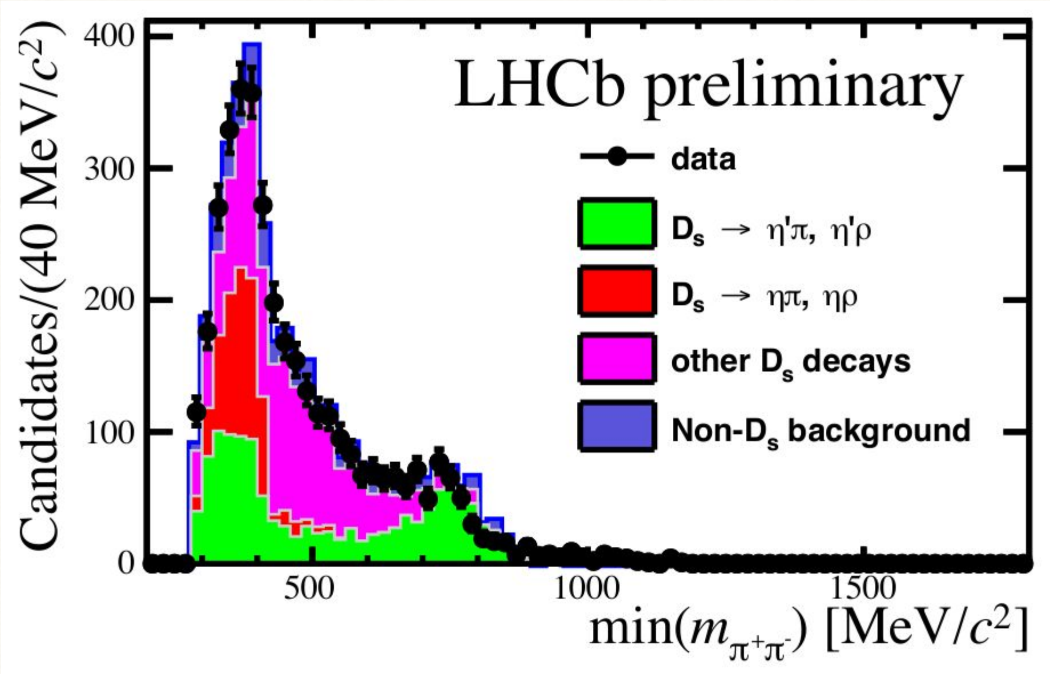
WA: 5% uncertainty

The world average of the combination of R(D) and R(D*) is in tension with the SM expectation at the **4σ level !**

Double charm background

- To determine the D_s decay model:
  - The BDT output is used to select an enriched sample of D_s events directly from data
  - Several variables related to the 3π dynamics are simultaneously fitted

The weights obtained are used to construct the D_s templates

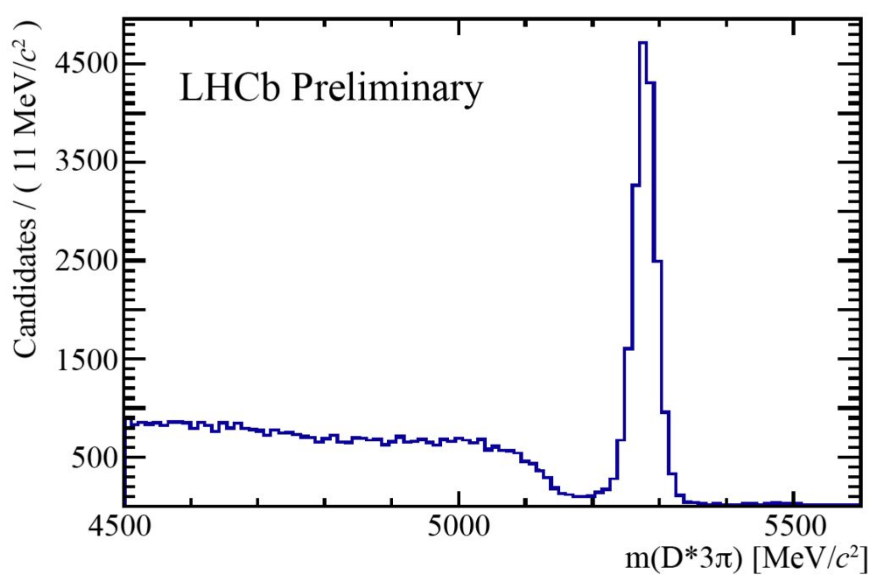


Normalisation channel

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

Absolute BR recently measured by BABAR with a precision of 4.3%

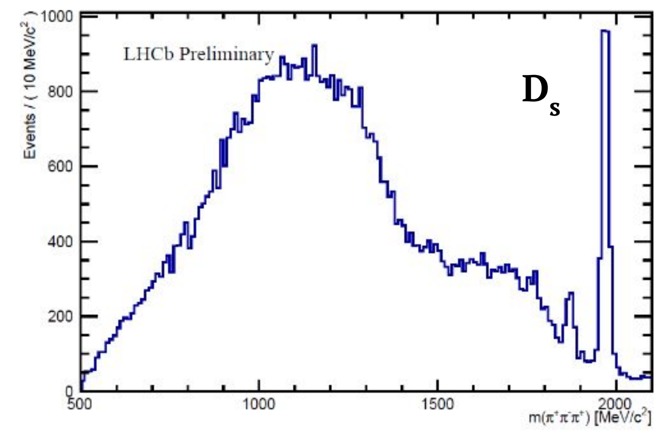
Run 1, 3 fb^{-1}

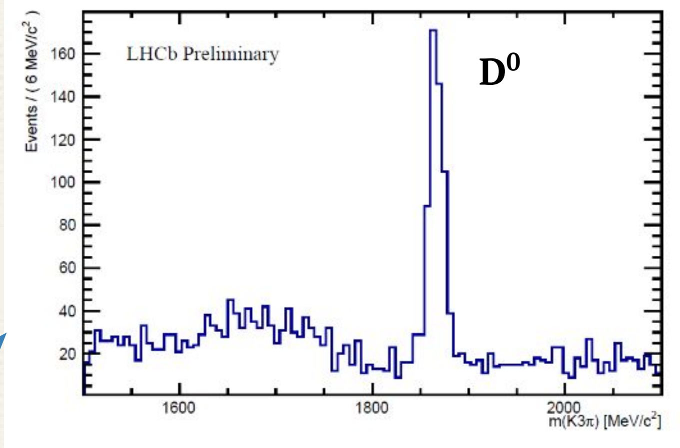


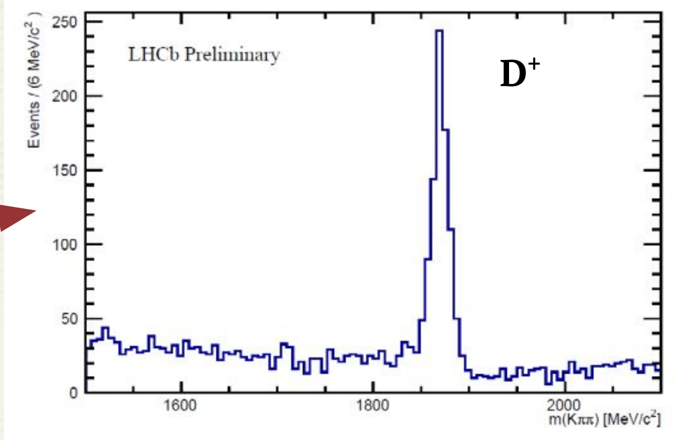
Phys.Rev. D94 (2016) no.9, 091101

Control channels

Run 1, 3 fb^{-1}







3π mass after vertex topology cut

$D^0 \to K3\pi$ peak: anti-isolation cut

$D^+ \to K\pi\pi$ peak: anti-PID cut

“Standard candles” used to check Data and MC agreement