EXPERIMENTAL OVERVIEW ON SEMILEPTONIC DECAYS

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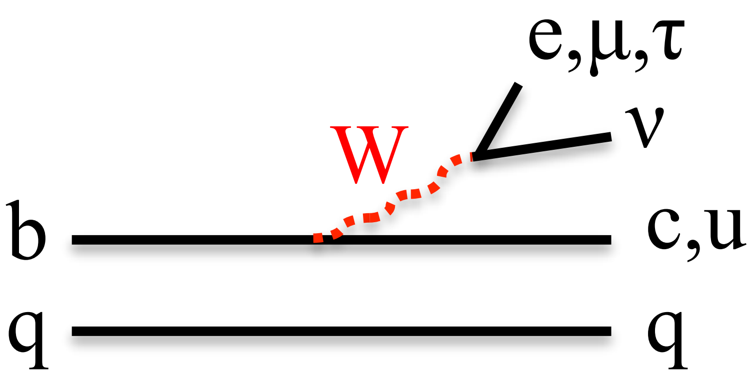
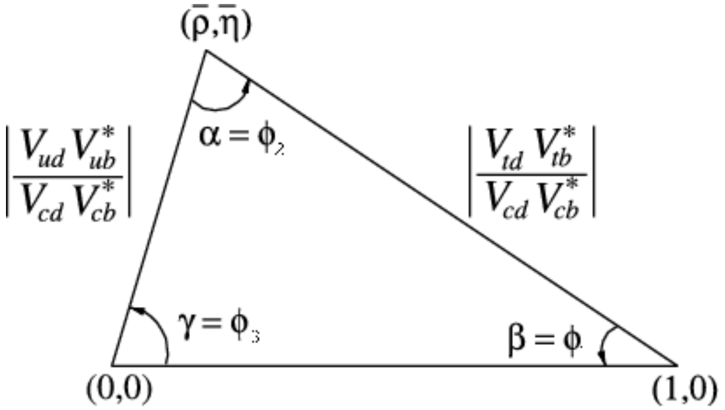
SEMILEPTONIC B-HADRON DECAYS

- Semileptonic (SL) b-hadron decays provide powerful probes for **testing the SM** and for **searching for physics beyond the SM** (BSM).



- In the **SM**, mediated by a **W boson**. They involve only one hadronic current, parametrised in terms of scalar functions (**form-factors**).

- SL b-hadron decays involving **electrons** and **muons** expected to be free of BSM contributions. They are used to **test the SM** by measuring the CKM parameters **$|V_{ub}|$** and **$|V_{cb}|$**.



- Decays involving **τ-ν** (semitauonic) sensitive to contributions **BSM**.

OUTLINE

- Measurement of the **shape of the $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \nu$** differential decay rate (**LHCb-PAPER-2017-016**).

- **Lepton universality** tests using **semitauonic** B-hadron decays:
  - Measurement of **R(D*)** using $B^0 \rightarrow D^{*-} \tau \nu$ decays (**LHCb-PAPER-2017-017, LHCb-PAPER-2017-027**).
  - Measurement of **R(J/Ψ)** using $B_c^+ \rightarrow J/\Psi \tau \nu$ decays (**LHCb-PAPER-2017-035**).

MEASUREMENT OF THE $\Lambda_b \rightarrow \Lambda_c^+ \mu\nu$ DECAY RATE SHAPE

LHCb-PAPER-2017-016

`arXiv:1709.01920, submitted to PRD`

Shape of $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \nu$ differential decay rate

- The **measured** ***q*²** = $(p(\Lambda_b) - p(\Lambda_c))^2 = (p_\mu + p_\nu)^2$ distribution of $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \nu$ decays is **compared with expectations** from heavy-quark effective theory (**HQET**) and from unquenched **lattice QCD** predictions.

- Due to the spin of the Λ_b and Λ_c^+ baryons, **6 form-factors** needed to describe the decay. A full angular analysis needed to measure them.

- In the **limit of infinite heavy quark** (HQ) mass, all form factors reduced to a universal function, known as **Isgur-Wise** (IW), $\boldsymbol{\xi_B(w)}$.

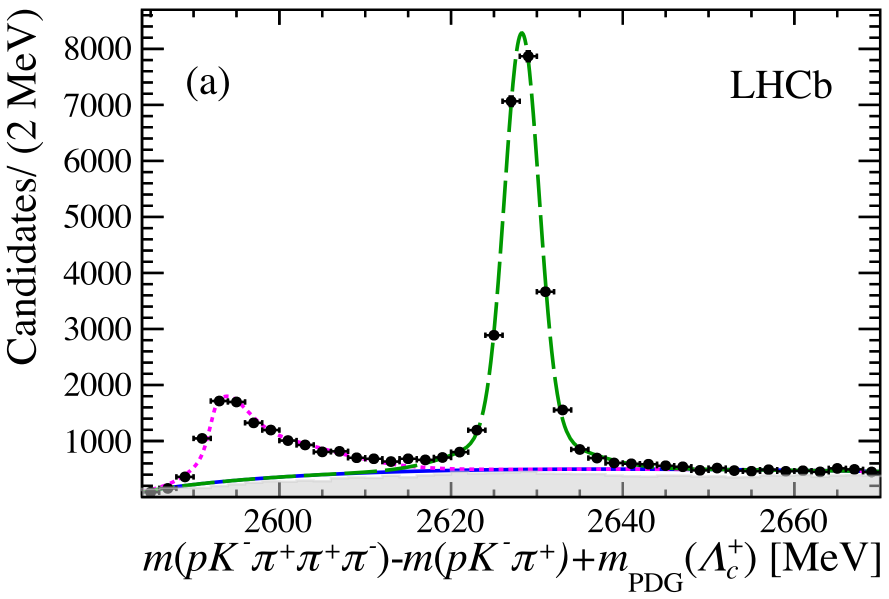
$$\frac{d\Gamma(\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \overline{\nu}_\mu)}{dw} = \frac{G_F^2 m_{\Lambda_b}^5 |V_{cb}|^2}{24\pi^3} K(w) \xi_{\Lambda_b}^2(w) \qquad w = \frac{m_{\Lambda_b}^2 + m_{\Lambda_c}^2 - q^2}{2 m_{\Lambda_b} m_{\Lambda_c}}$$

- Different functional forms for the Isgur-Wise function are tested.

LHCb-PAPER-2017-016

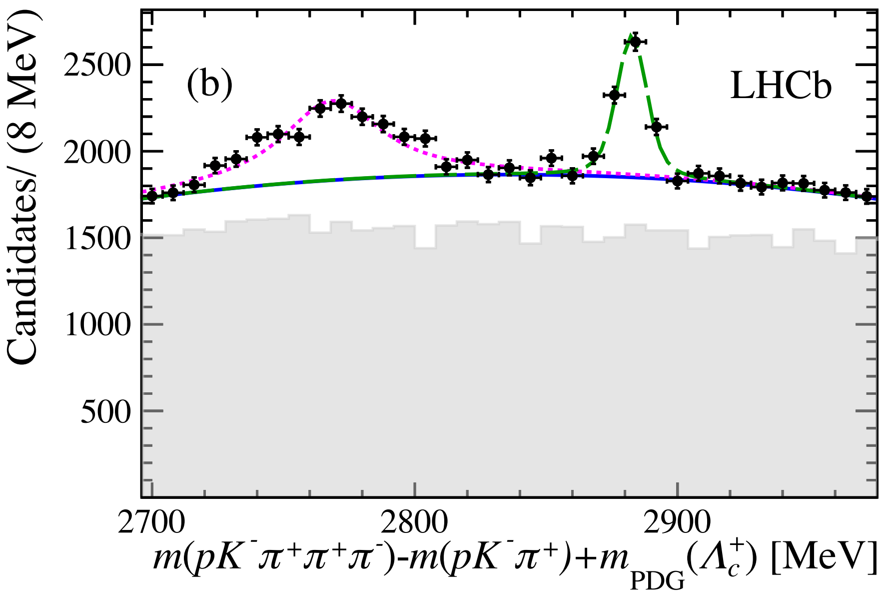
Shape of $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \nu$ differential decay rate

- Need to subtract **feed-down** from higher resonances.



$\Lambda_c(2595)^+ \rightarrow \Lambda_c^+\pi^+\pi^-$

$\Lambda_c(2625)^+ \rightarrow \Lambda_c^+\pi^+\pi^-$

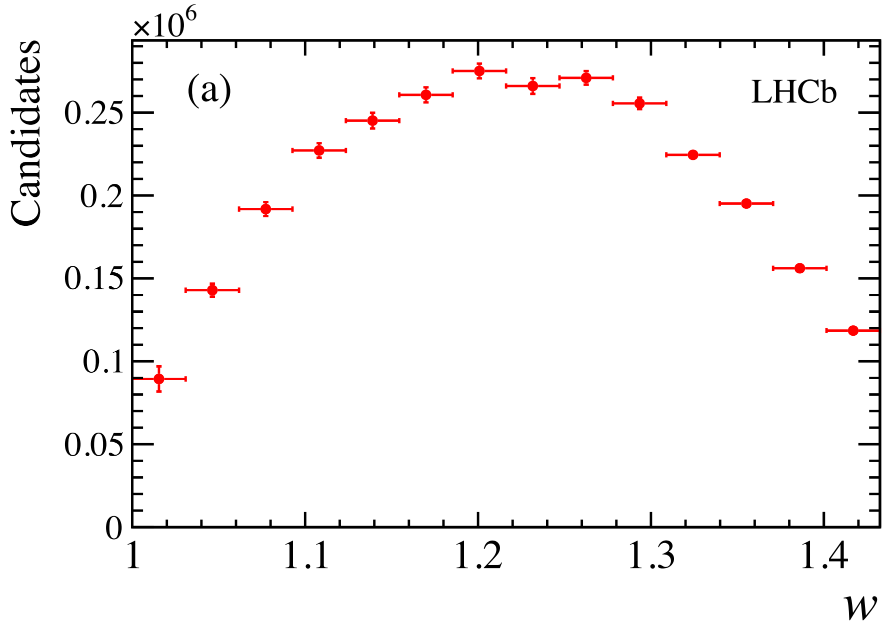


$\Lambda_c(2765)^+ \rightarrow \Lambda_c^+\pi^+\pi^-$

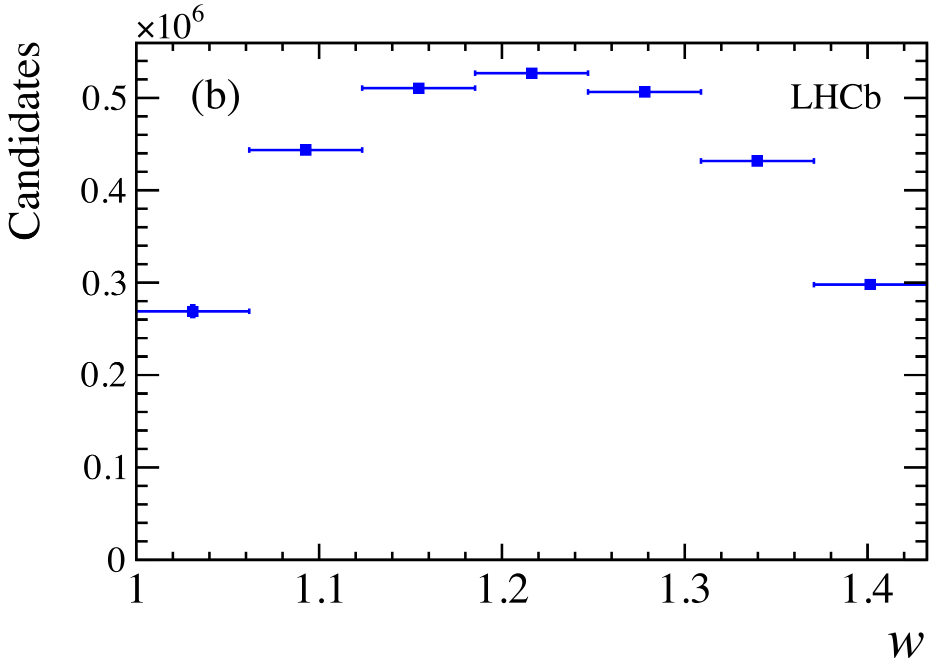
$\Lambda_c(2880)^+ \rightarrow \Lambda_c^+\pi^+\pi^-$

- Next step is to unfold the w and q^2 distributions.

Reconstructed



Unfolded



LHCb-PAPER-2017-016

Shape of $\Lambda_b^0\to\Lambda_c^+\mu^-\nu$ differential decay rate

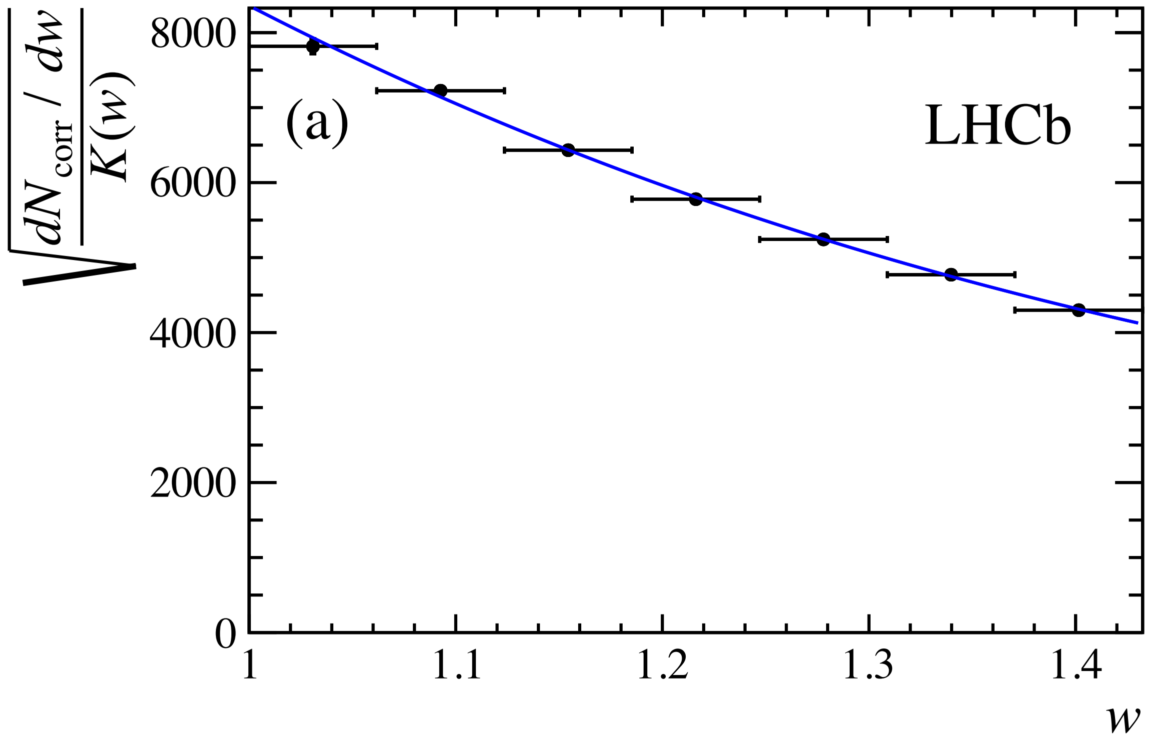
1. w distribution is then corrected by efficiency.

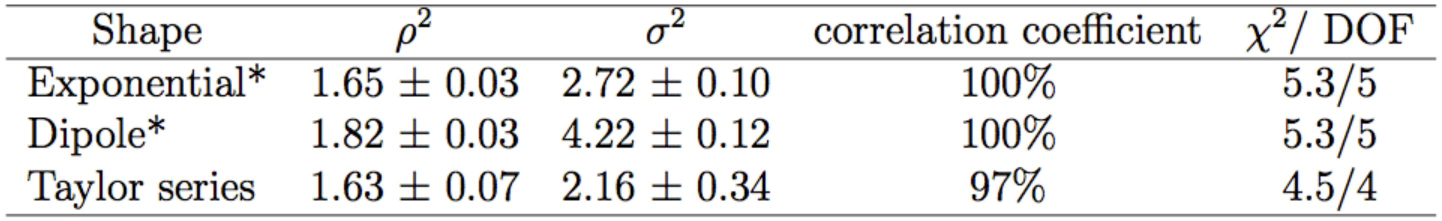
2. Isgur-Wise function expressed as a Taylor series expansion used to fit the w distribution (other functions are used). Two other functions used as well.

$$\xi_B(w) = 1 - \rho^2(w-1) + \frac{1}{2}\sigma^2(w-1)^2 \qquad \xi_B(w) = \left(\frac{2}{w+1}\right)^{2\rho^2} \qquad \xi_B(w) = \exp[-\rho^2(w-1)]$$

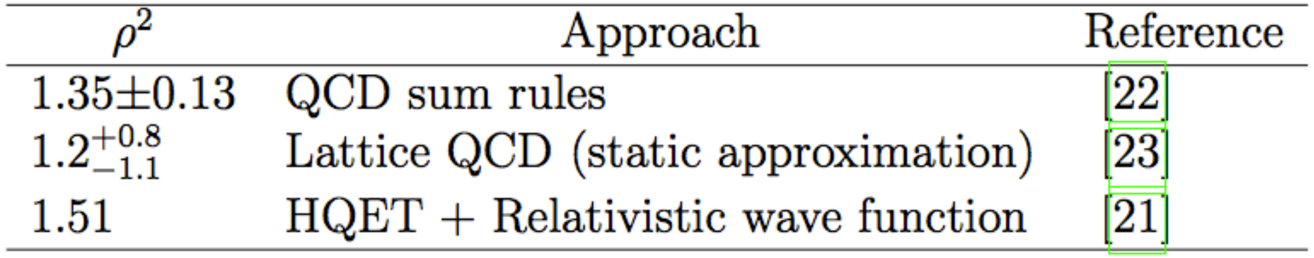
3. The measured ρ^2 parameter is consistent with Lattice, QCD sum rules and relativistic quark models.

ξ(w) distribution





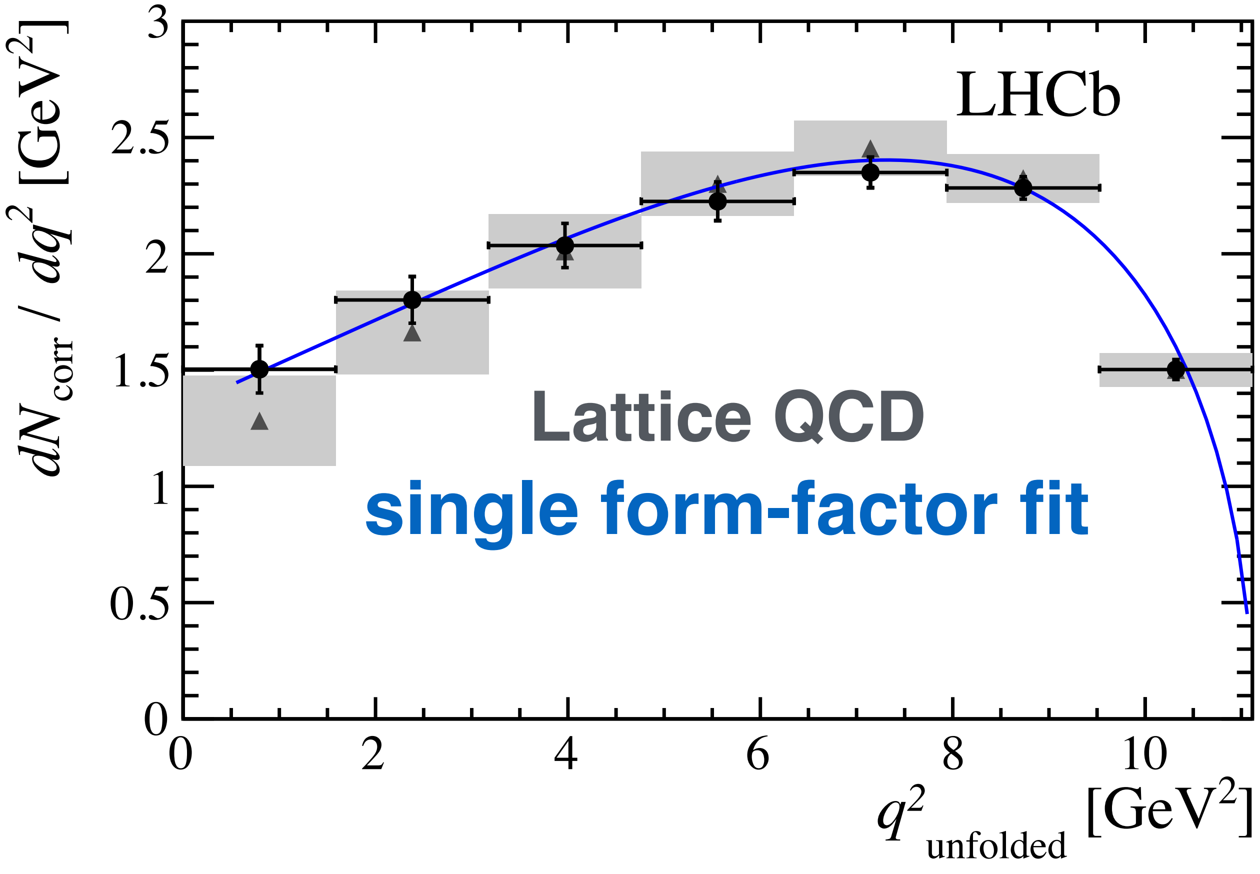
Shape	ρ^2	σ^2	correlation coefficient	χ^2/ DOF
Exponential*	1.65 ± 0.03	2.72 ± 0.10	100%	5.3/5
Dipole*	1.82 ± 0.03	4.22 ± 0.12	100%	5.3/5
Taylor series	1.63 ± 0.07	2.16 ± 0.34	97%	4.5/4



ρ^2	Approach	Reference
1.35 ± 0.13	QCD sum rules	[22]
$1.2^{+0.8}_{-1.1}$	Lattice QCD (static approximation)	[23]
1.51	HQET + Relativistic wave function	[21]

Shape of $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \nu$ differential decay rate

- The unfolded q^2 distribution can be compared with theoretical predictions.
- A comparison of the $d\Gamma/dq^2$ distribution with **lattice QCD expectation** shows an excellent agreement.
- A single form-factor fit in the z-expansion ([PRD92 (2015) 034503]) reproduces well the data, consisting with the static limit (infinite heavy quark masses).
- Further studies with a suitable normalisation channel will lead to a precise independent determination of **$|V_{cb}|$**.

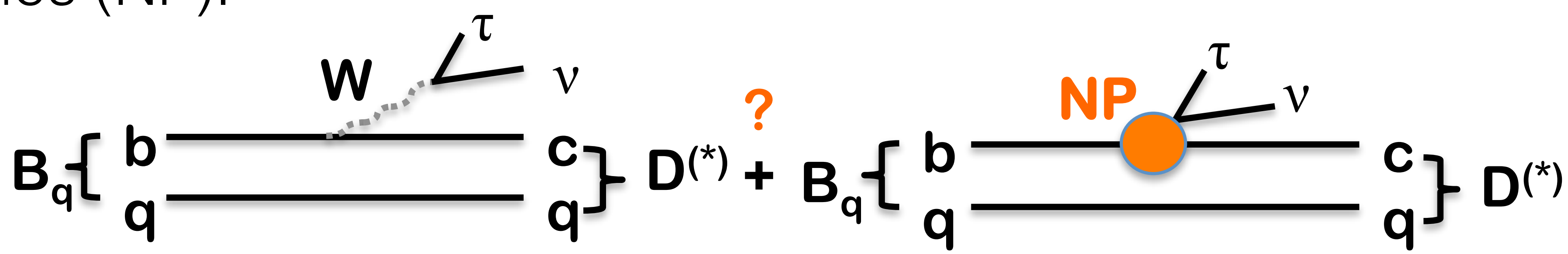


LHCb-PAPER-2017-016

SEMILEPTONIC B DECAYS AS A TEST OF LEPTON UNIVERSALITY

SEMILEPTONIC DECAYS AS A TEST OF LU

- In the **SM**, charged **lepton flavours** are **identical copies** of one another.
  - Amplitudes for processes involving **e, μ, and τ** must be identical up to effects depending on lepton mass (**lepton universality**).
- Observation of violations of lepton flavour universality would be a clear sign for new physics (NP).



- 3th generation (τ) sensitive to NP.
- Comparison between **semitauonic** (τ) and **semimuonic** (μ) decays sensitive to NP, which could modify branching fractions and angular distributions.

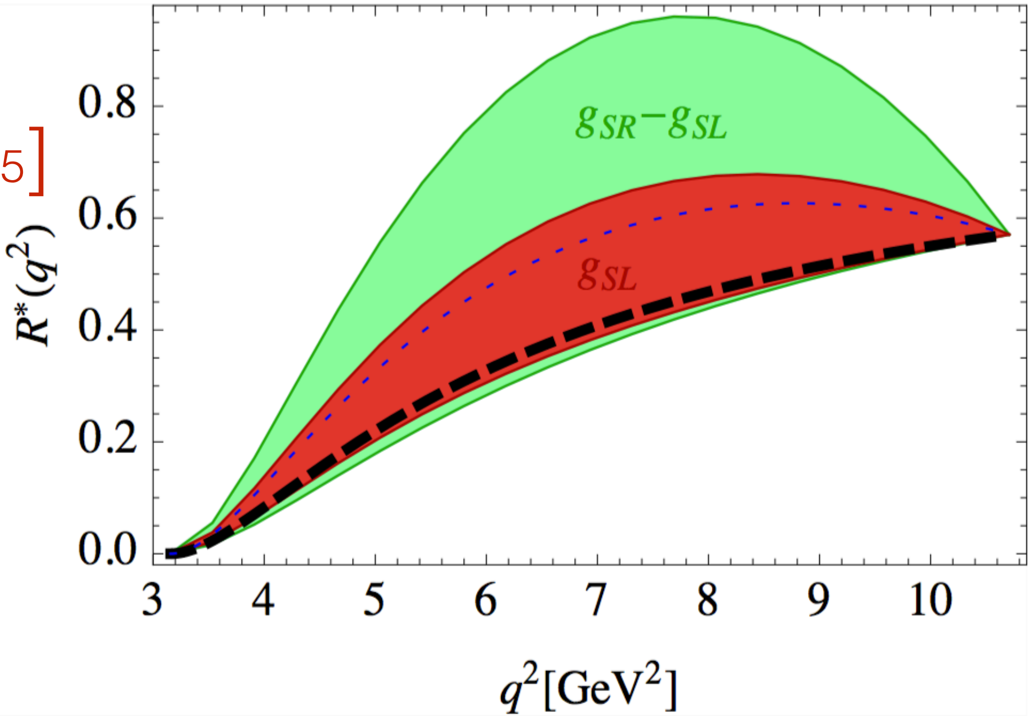
R(D$^{(*)}$) AS A TEST OF LU

- Ratios of branching fractions of semitauonic vs semimuonic B decays are sensitive to contributions from physics BSM.

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

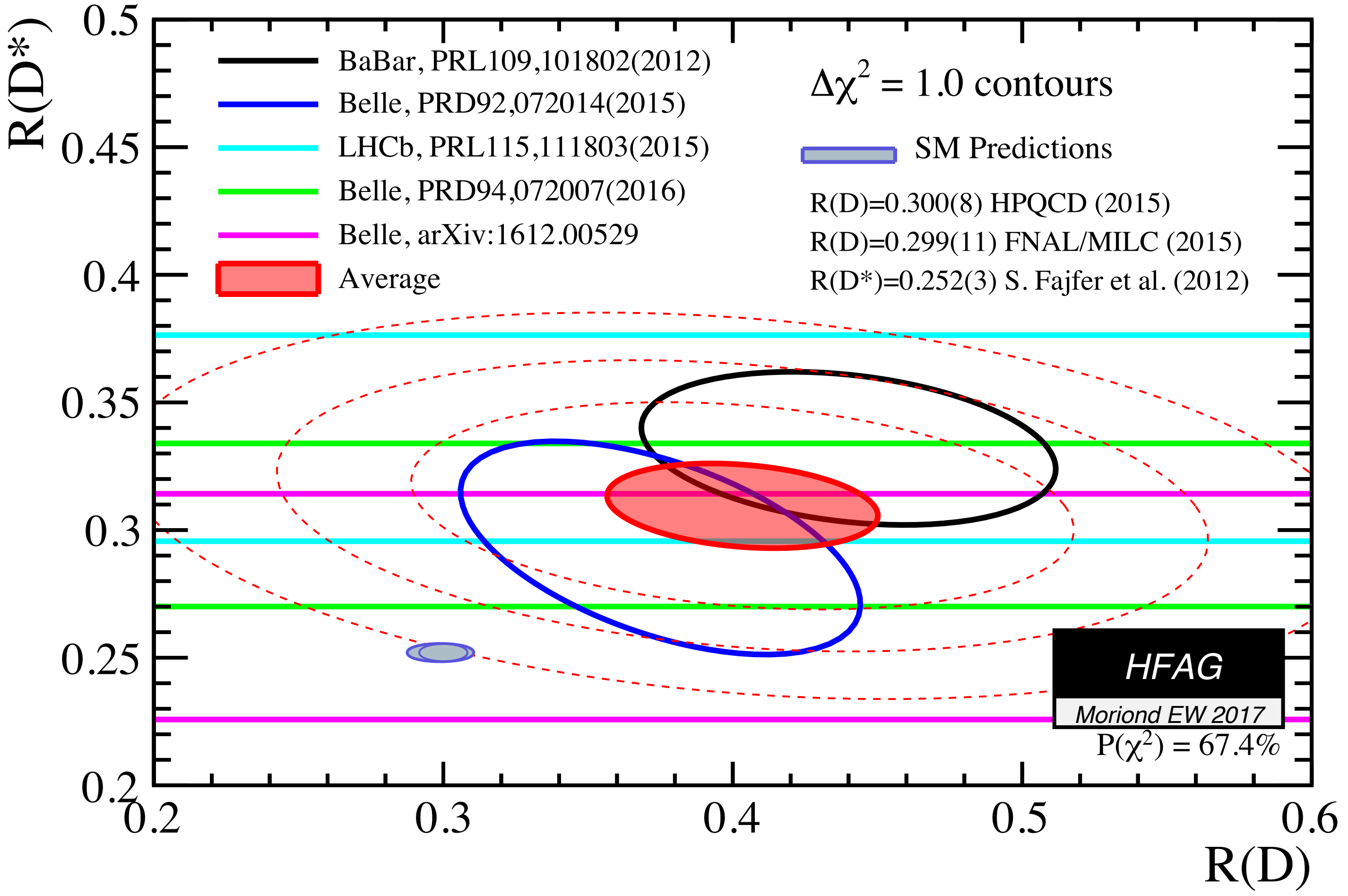
- R(D*) very clean SM prediction due to cancelation of form factors in the ratio.
  - R(D*) = 0.252 ± 0.003 [S. Fajfer et al. PRD85 (2012) 094025]
  - For recent calculations see S. Schacht talk.
- Deviation from unity due to different τ/μ masses.
- R(D*) enhanced/reduced in many BSM scenarios.

PRD 85 094025 (2012)



STATUS AT THE LAST IMPLICATIONS WORKSHOP

- R(D) and R(D*) average exceed the SM predictions by 2.2 and 3.4σ, respectively.
- Their combination is 3.9σ above the SM expectation.
- New measurements from LHCb:
  - R(D*) using 3-prong hadronic $\tau \to 3\pi\nu$ decays.
  - R(J/ψ) using $B_c^+ \to J/\psi\tau\nu$ decays and $\tau \to \mu\nu\nu$.



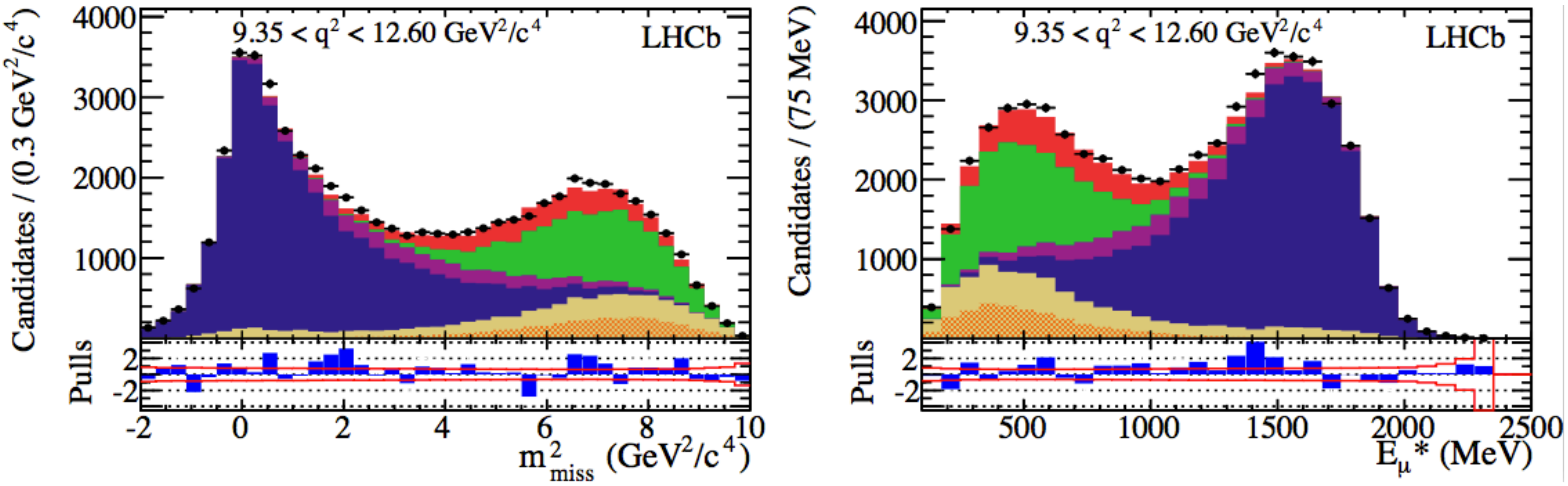
REMINDER: first measurement of R(D*) at LHCb

- R(D*) obtained, with $\tau \rightarrow \mu\nu\nu$ decays, from a 3D fit to q^2, m^2_{miss} and E_μ^* using templates from simulation (validated using control samples).

- R(D*) = 0.336 ± 0.027(stat) ± 0.030(syst), consistent with SM at 2.1σ level.

- Systematic uncertainties dominated by MC statistics and particle misID.

—•— Data
🟥 $B \rightarrow D^*\tau\nu$
🟩 $B \rightarrow D^*H_c(\rightarrow l\nu X')X$
🟪 $B \rightarrow D^{**}l\nu$
🟦 $B \rightarrow D^*\mu\nu$
🟨 Combinatorial
🟧 Misidentified μ



LHCb-PAPER-2015-025

R(D*) using hadronic $\tau \to 3\pi\nu$ decays

LHCb-PAPER-2017-017, LHCb-PAPER-2017-027

`arXiv:1708.08856, submitted to PRL`
`arXiv:1711.02505, submitted to PRD`

R(D*) USING HADRONIC TAU DECAYS

- Hadronic τ→3πν and τ→3ππ^{0}ν decays used to reconstruct the τ lepton.

- What we measure is:

$$K(D^*) = \frac{\mathcal{B}(B^0 \to D^* \tau \nu)}{\mathcal{B}(B^0 \to D^* \pi^+ \pi^- \pi^+)}$$

- Signal and normalisation decays share the same visible final state.

- Most of the systematic uncertainties cancel in the ratio.

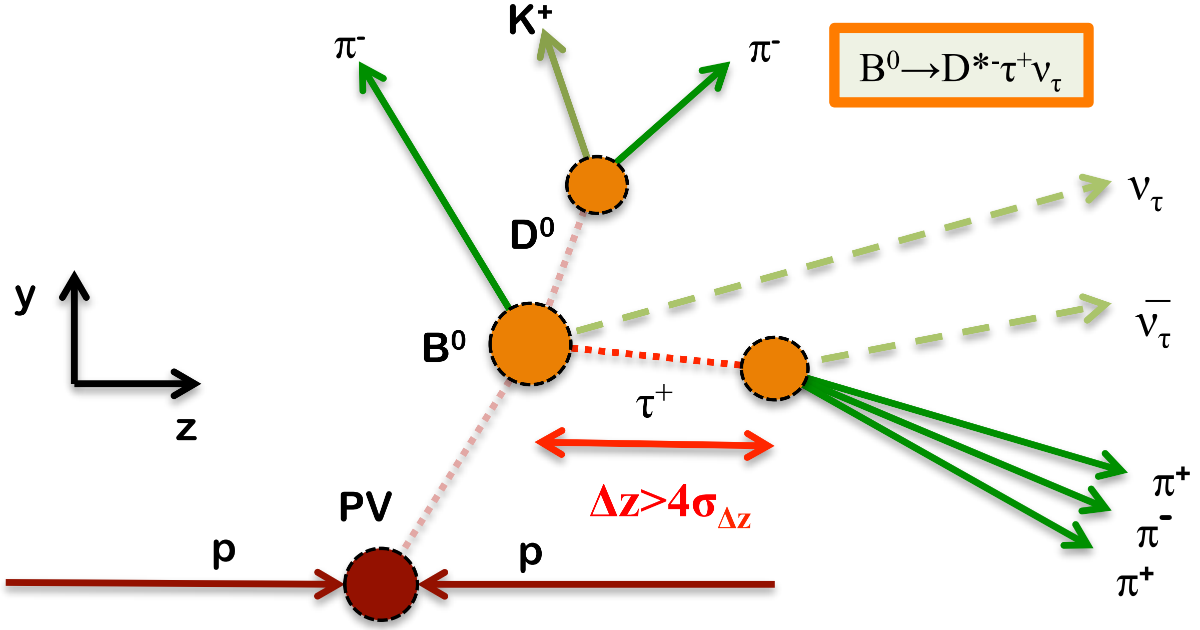
- R(D*) is then obtained using external inputs:

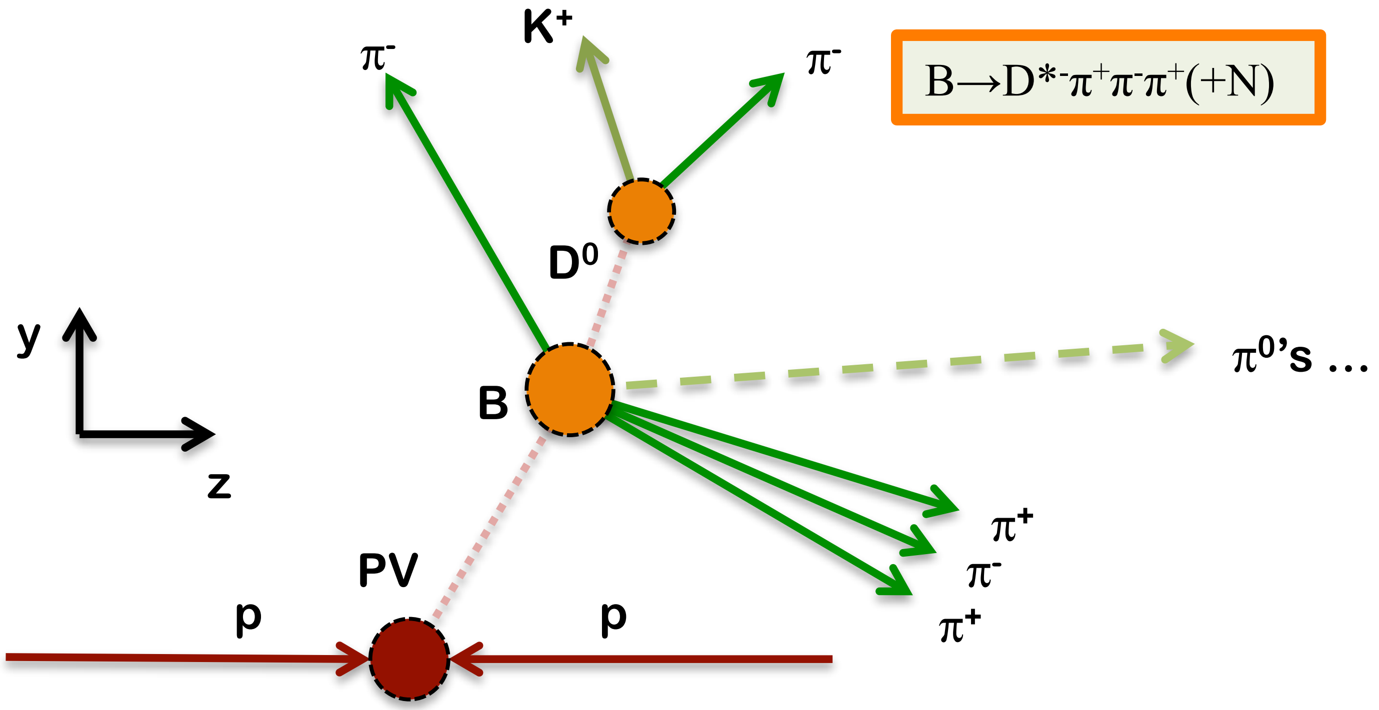
$$R(D^*) = K(D^*) \times \frac{\mathcal{B}(B^0 \to D^* \pi^+ \pi^- \pi^+)}{\mathcal{B}(B^0 \to D^* \mu \nu)}$$

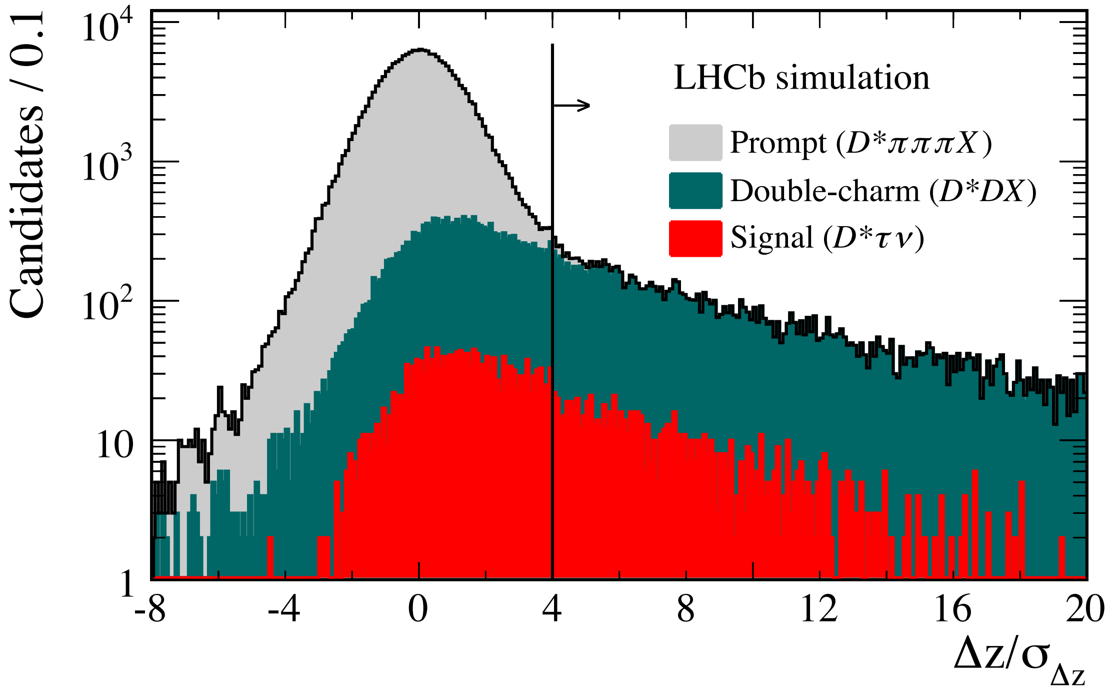
- Signal yield obtained from a 3D template fit.

- Normalisation yield obtained from a likelihood fit to m(D*3π) distribution.

DETACHED-VERTEX METHOD







- **Most abundant background** (~100 times signal) due to ("prompt") **B→D*3πX**, where the 3π comes from the B vertex.
- Suppressed (3 orders of magnitude) by requiring minimum **distance between B and τ vertices** ($>4\sigma_{\Delta z}$), thanks to the excellent vertex resolution (VELO).
- **Remaining background** due to double-charm **B→D*DX** decays (due to D lifetime).

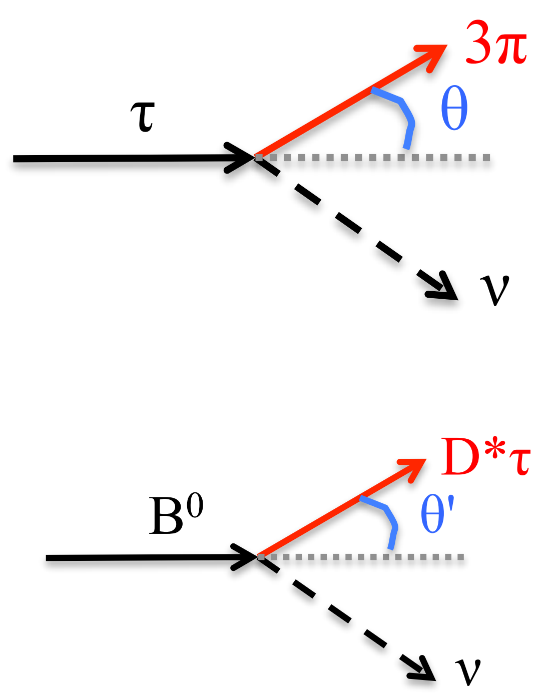
R(D*) hadronic: signal reconstruction

- Due to the 2 neutrinos, p$_\tau$ and p$_B$ reconstructed with **2-fold ambiguities**:

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

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

Lab. frame:



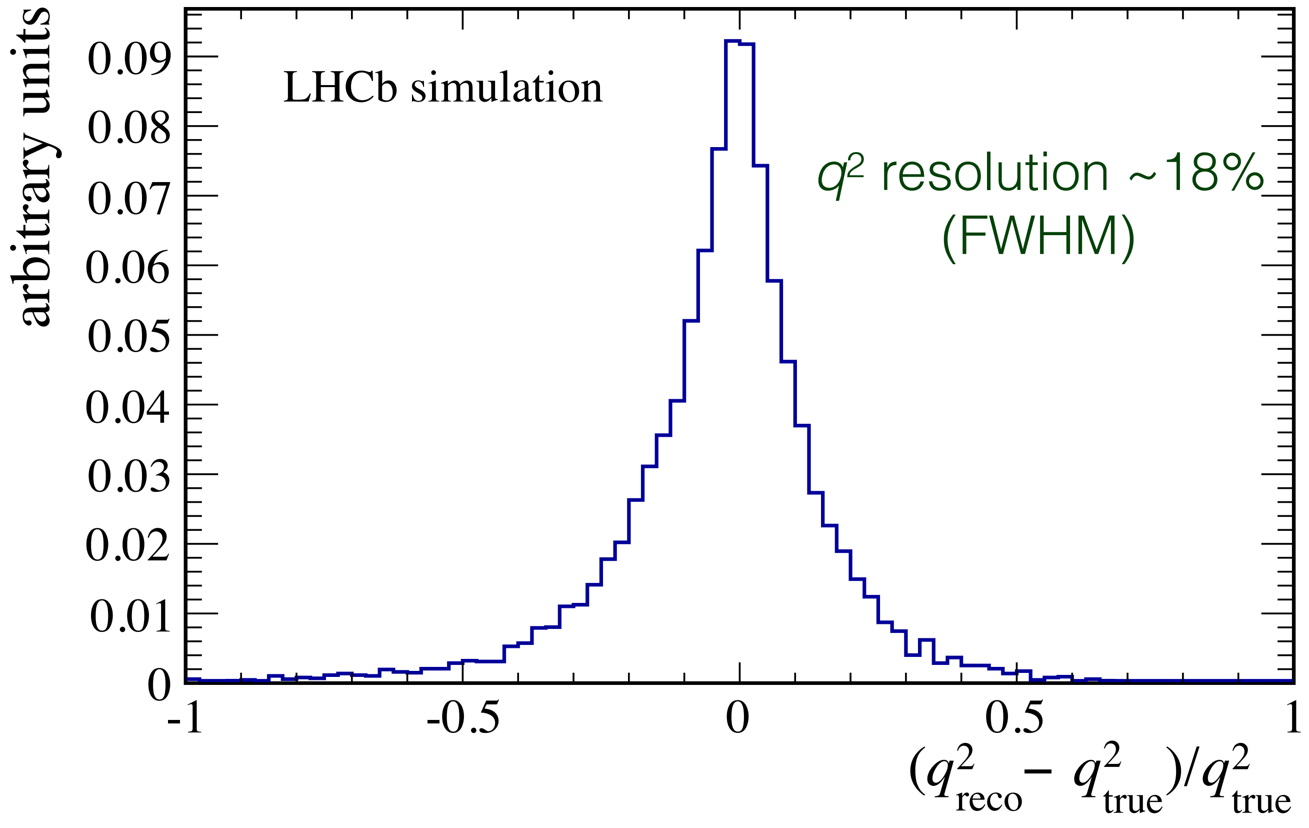
- Our approach is set to zero the square roots:

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

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

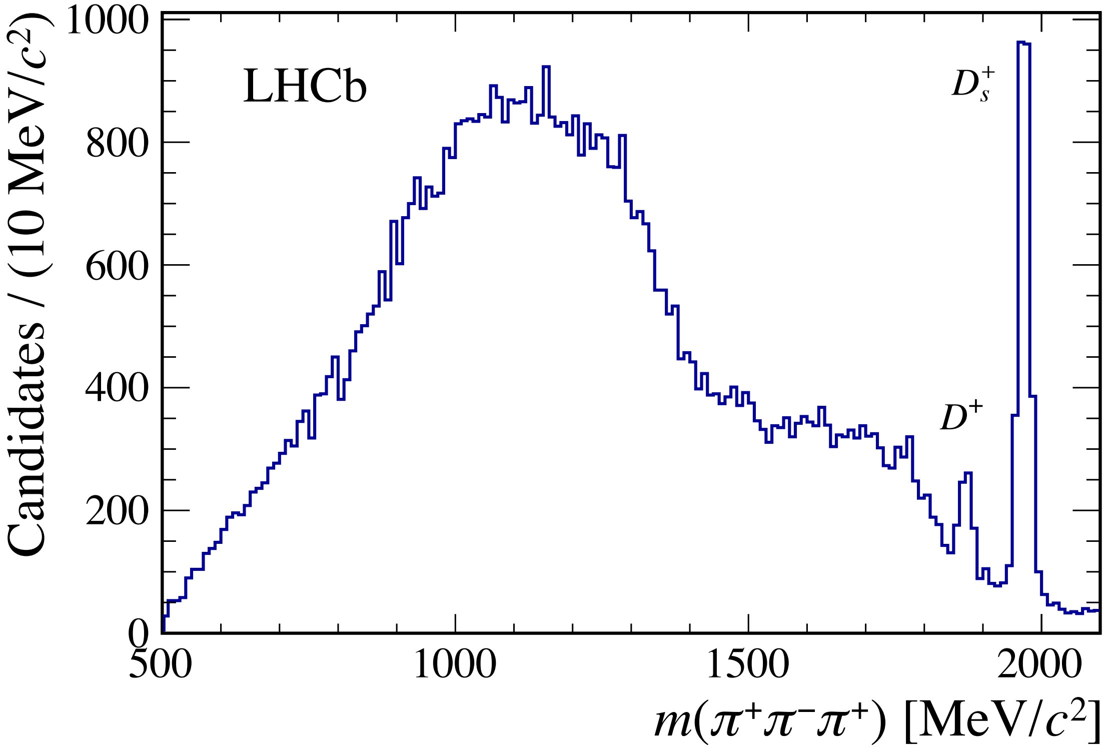
- Possible to reconstruct rest frame variables: ***q*²** and **τ decay time, t$_\tau$**.

- Reconstruction can be tested using control samples.



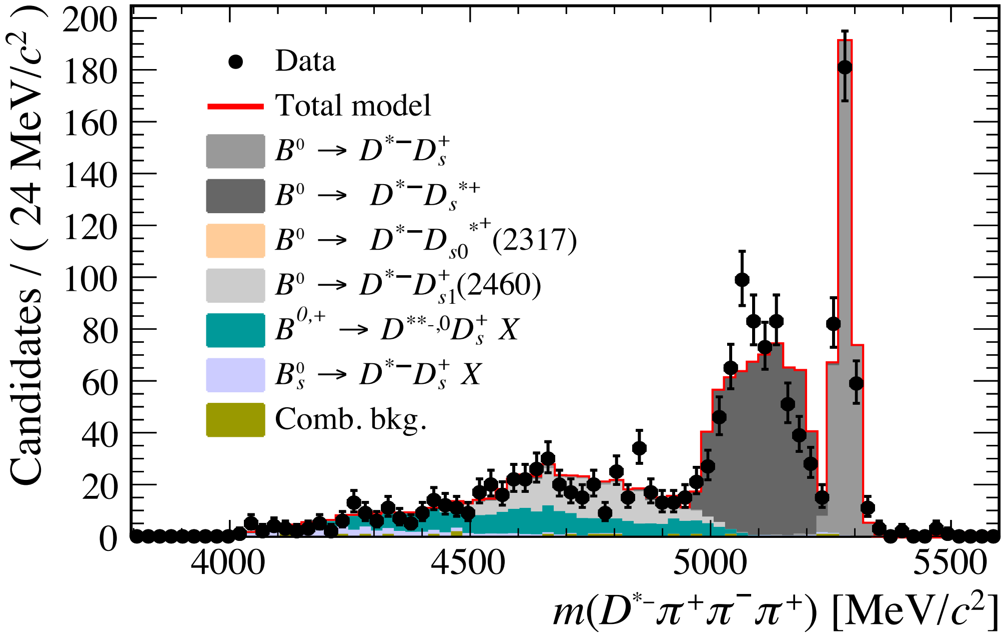
Control samples: $B\rightarrow D^{*}D_{s}X$ background

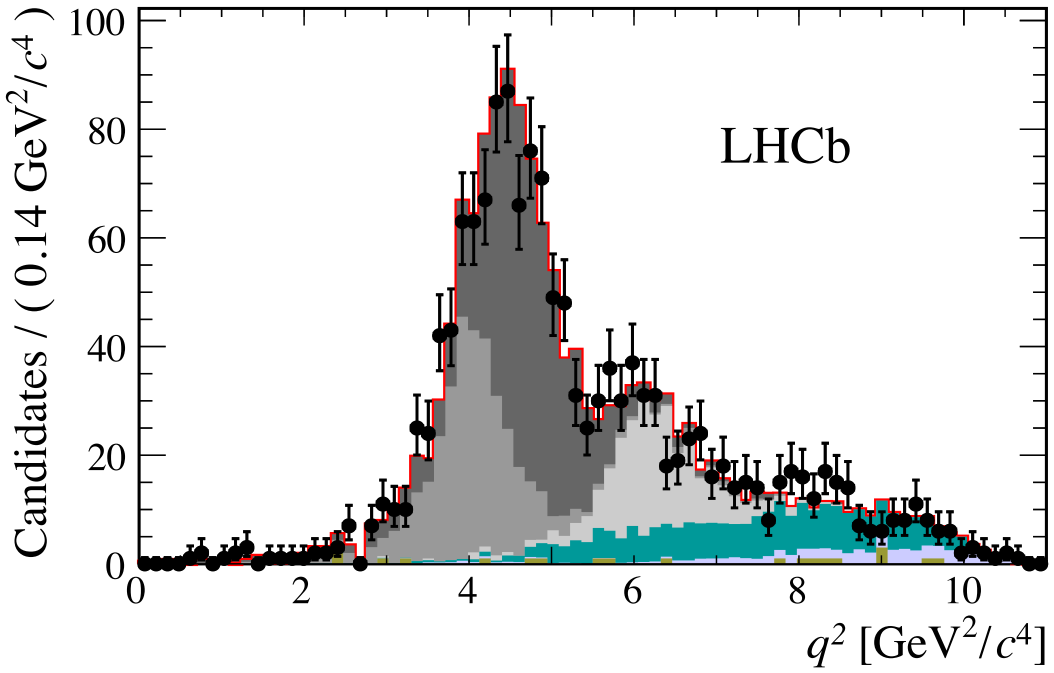
- Control samples of $B\rightarrow D^{*}D_{s}^{+}X$, $B\rightarrow D^{*}D^{+}X$ and $B\rightarrow D^{*}D^{0}X$ obtained by using events at the $D_{s}^{+}\rightarrow 3\pi$, $D^{+}\rightarrow K\pi\pi$ and $D^{0}\rightarrow K3\pi$ exclusive peaks.



- Contributions from $B\rightarrow D^{*}D_{s}^{*}$, $D^{*}D_{s1}$ … obtained from a fit to $M(D^{*}D_{s}^{+})$.

- $B\rightarrow D^{*}D^{+}X$ and $B\rightarrow D^{*}D^{0}X$ shapes corrected from the corresponding samples.





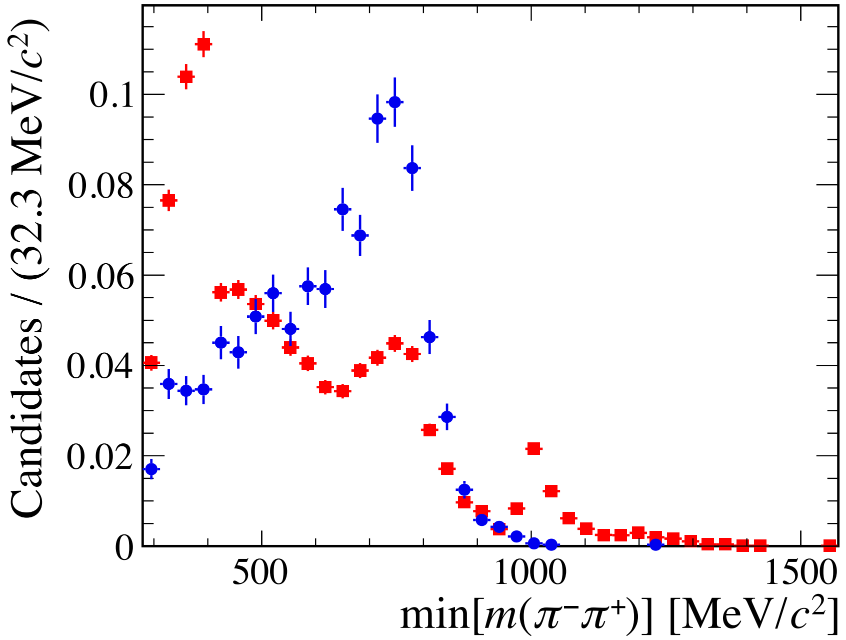
Suppressing the B→D*D_sX background

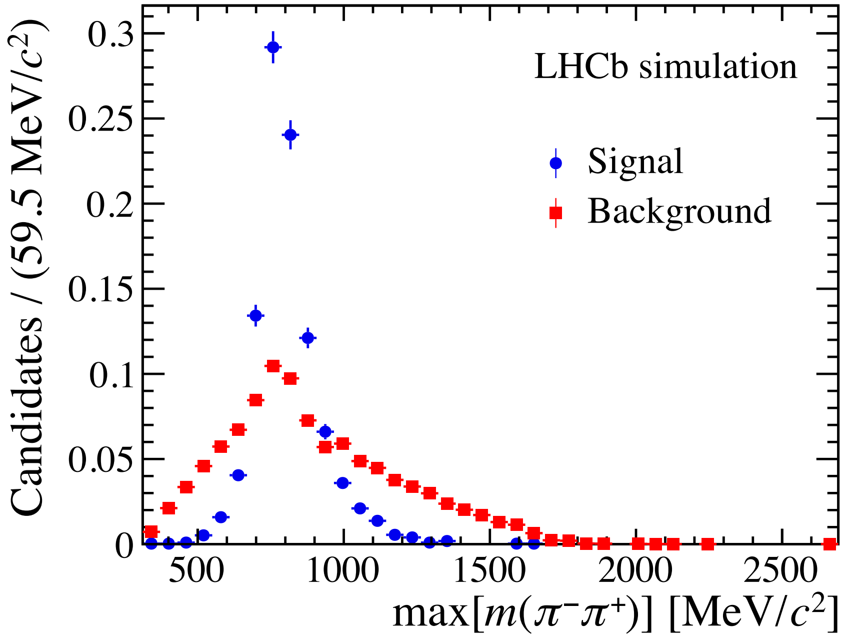
- **BDT** trained to suppress main background due to **B→D*D_sX** decays: background MC vs signal MC.

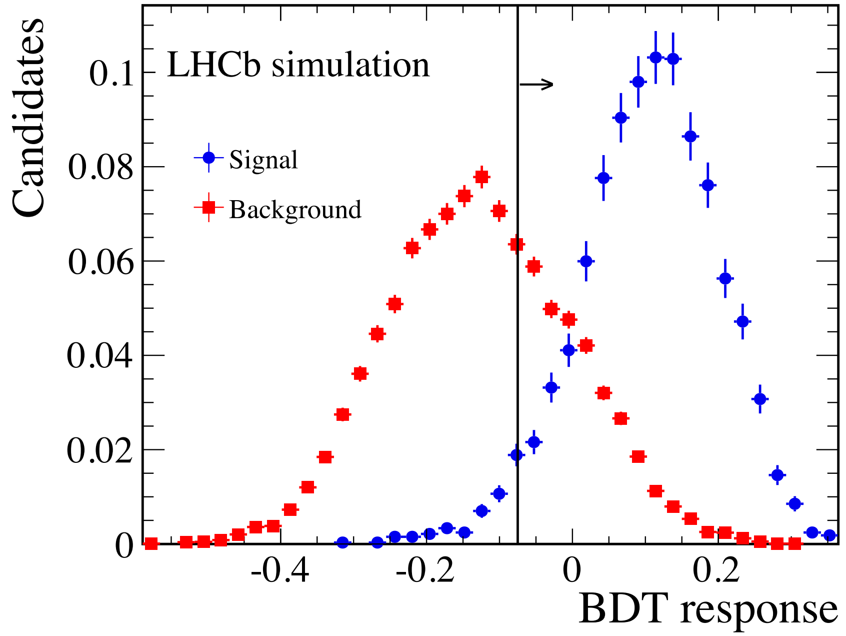
- Input variables:
  - **3π** dynamics.
  - **D*3π** dynamics.
  - **Neutrals** (π^0, γ) isolation variables (calorimeters).

- BDT used as a **variable in the fit** to obtain the signal yield.

- A soft BDT cut applied to suppress main D_s^+ background.







FIT RESULTS

- **3D fit** to **q^2, t_τ and BDT** output.

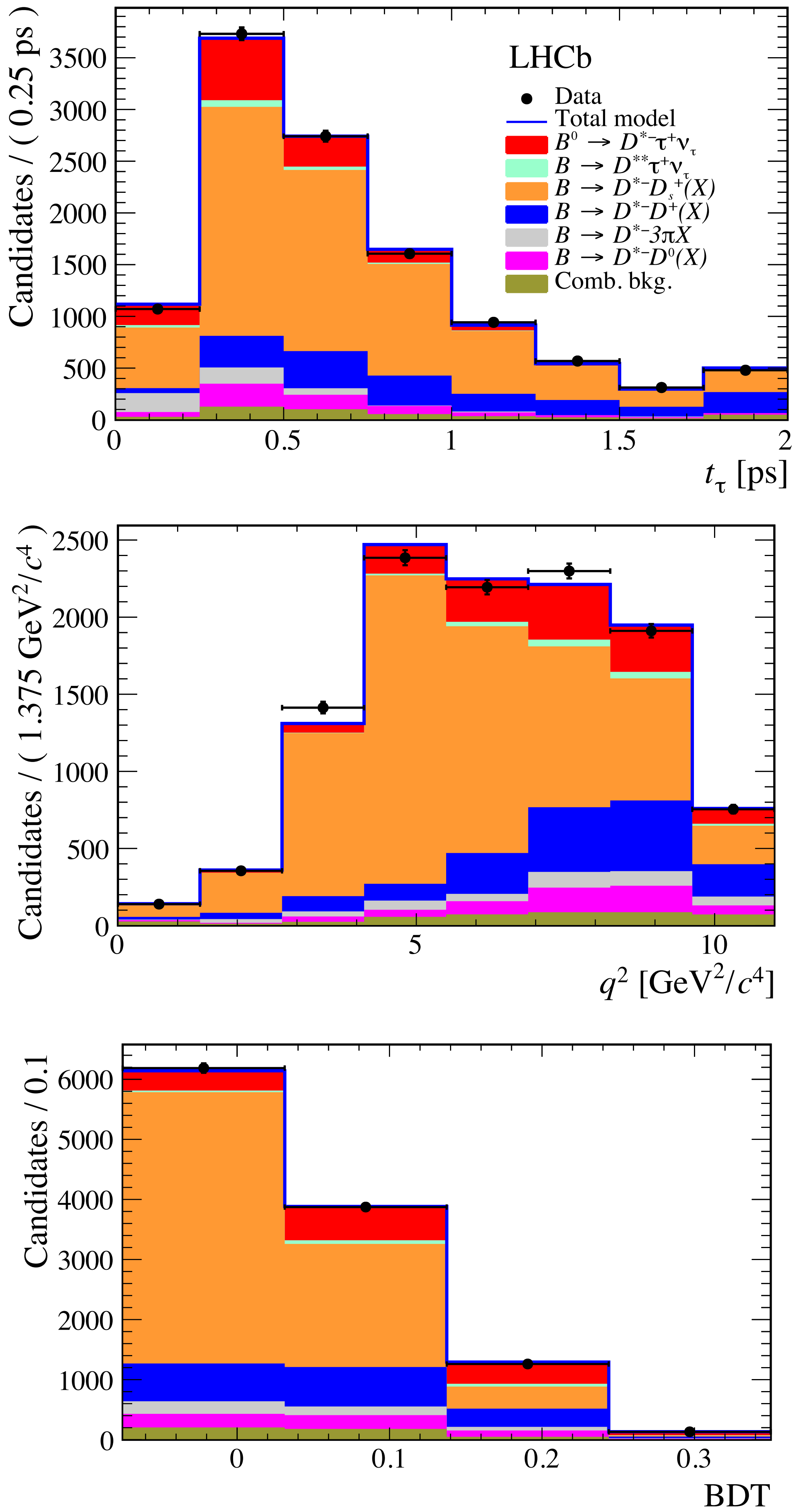
- Fit components described by templates obtained from simulation (validated in control samples):

  - q^2 (8 bins).
  - t_τ (8 bins): important to separate D^+ component (large lifetime).
  - BDT output (4 bins).

- N_{sig} = 1273 ± 85 (6.5% stat. uncertainty)

- K(D*) = 1.93 ± 0.12(stat) ± 0.17 (syst)

- R(D*) = 0.286 ± 0.019 ± 0.033 (1σ compatible with SM)



R(J/ψ) AT LHCb USING $\tau \to \mu\nu\nu$ DECAYS

LHCb-PAPER-2017-035

R(J/ψ) AT LHCb USING $\tau\rightarrow\mu\nu\nu$ DECAYS

- Same reconstruction method as in R(D*) measurement: $\tau\rightarrow\mu\nu\nu$

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

- B_c^+ **form factors not known** precisely → Theoretical prediction not precise: R(J/ψ) predicted to be in range [0.25,0.28] ([Phys. Lett. B452 (1999) 129] [arXiv:hep-ph/0211021] [Phys. Rev. D73 (2006) 054024] [Phys. Rev. D74 (2006) 074008])

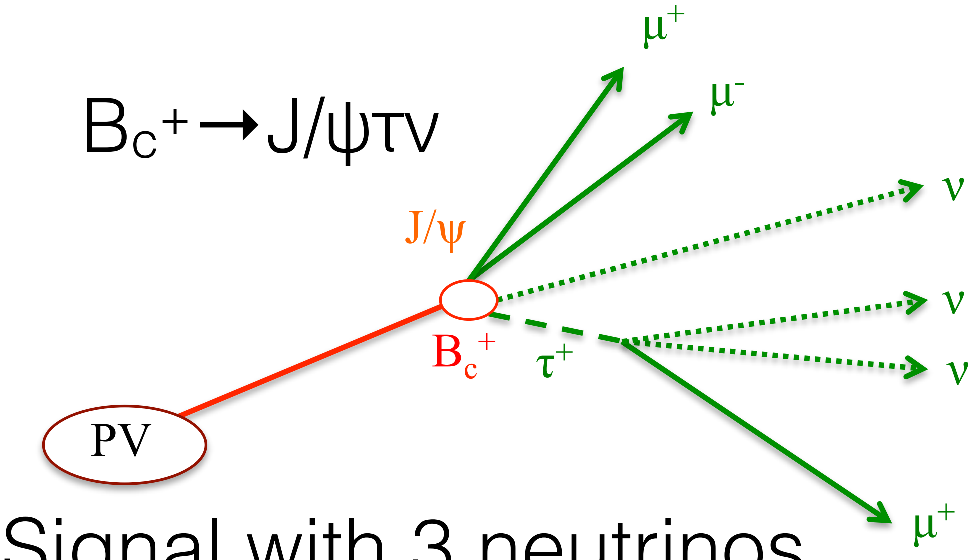
- Improvements in form-factor calculation needed. (see Jonna Koponen's talk).

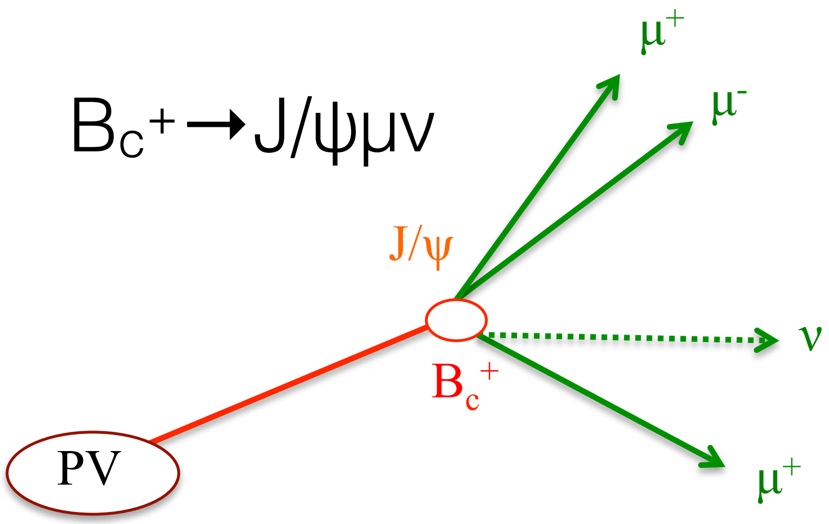
- This measurement only possible at LHCb (B_c^+ not produced in B-factories).

- B_c^+ decay time used in addition to q^2, m^2_{miss} and E_μ^* in fit model. q^2 and E_μ^* combined in a single variable (Z).

R(J/ψ) AT LHCb USING $\tau\to\mu\nu\nu$ DECAYS

LHCb-PAPER-2017-035





- Signal with 3 neutrinos.

- Main backgrounds:
  - $B_c^+\to J/\psi\mu\nu$, $B_c^+\to\psi(2S)\mu\nu$, $B_c^+\to J/\psi D(\to\mu\nu X)X$.
  - Hadron misidentified as a muon.
  - combinatorial background (J/ψ and μ not from same B).

- Reconstruction:
  - Using B flight direction we can measure transverse momentum.
  - To measure longitudinal component we use the approximation:

$$(p_{B_c})_z = \frac{m_{B_c}}{m(J/\psi\mu)} \times (p_{J/\psi\mu})_z$$

- This method allows to estimate p_B and the rest frame variables q^2, m^2_{miss} and E_μ^*.

R(J/Ψ) RESULTS

LHCb-PAPER-2017-035

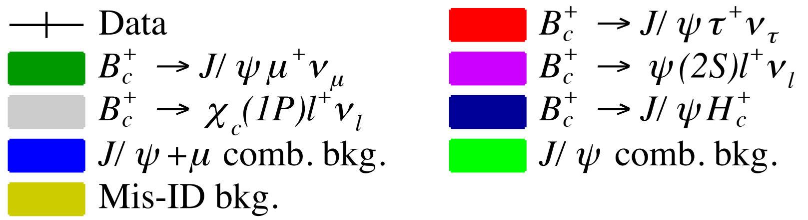
- R(J/ψ) obtained from a 3D template fit, with form-factors obtained from a sample enriched in normalisation decays.

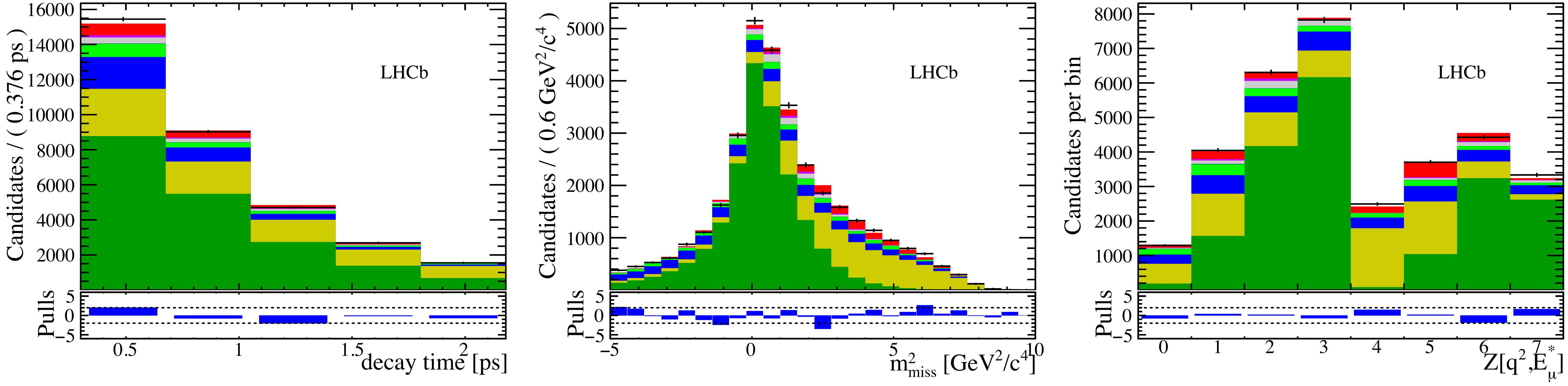
- Templates obtained from control samples or from simulation validated with control samples.

- Systematic uncertainties dominated by knowledge of form-factors and the size of the simulation samples.

- First evidence of the $B_c^+ \rightarrow J/\psi\tau\nu$ decay (3σ).

- R(J/ψ) = 0.71 ± 0.17 ± 0.18 (compatible with the SM at 2σ level).





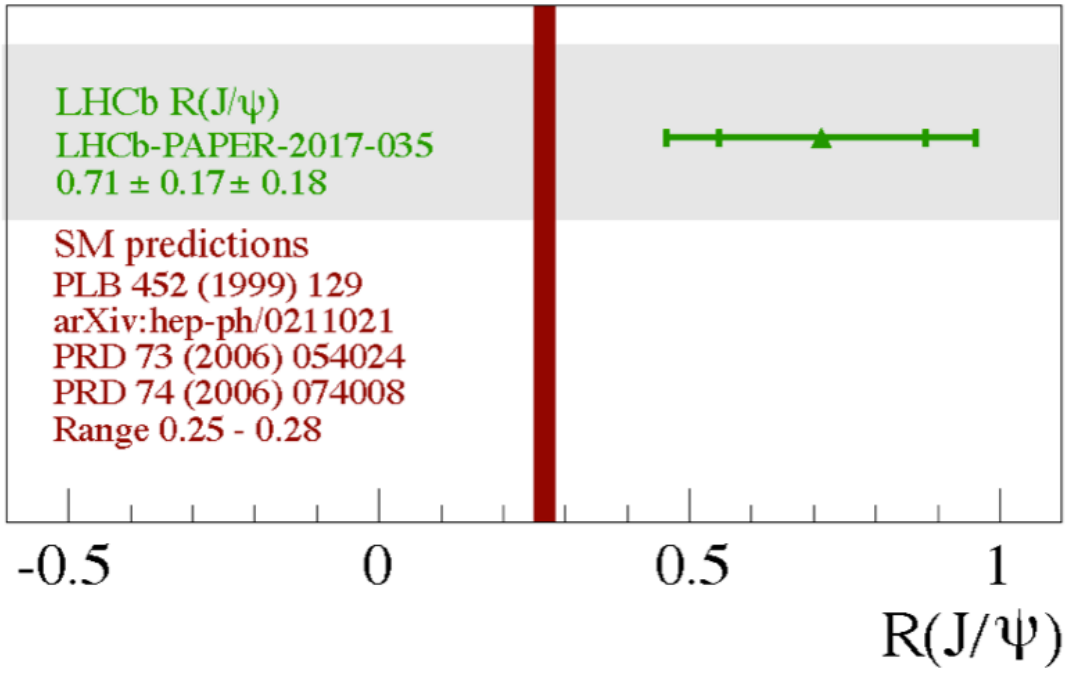
R(D*) AND R(J/Ψ) SUMMARY

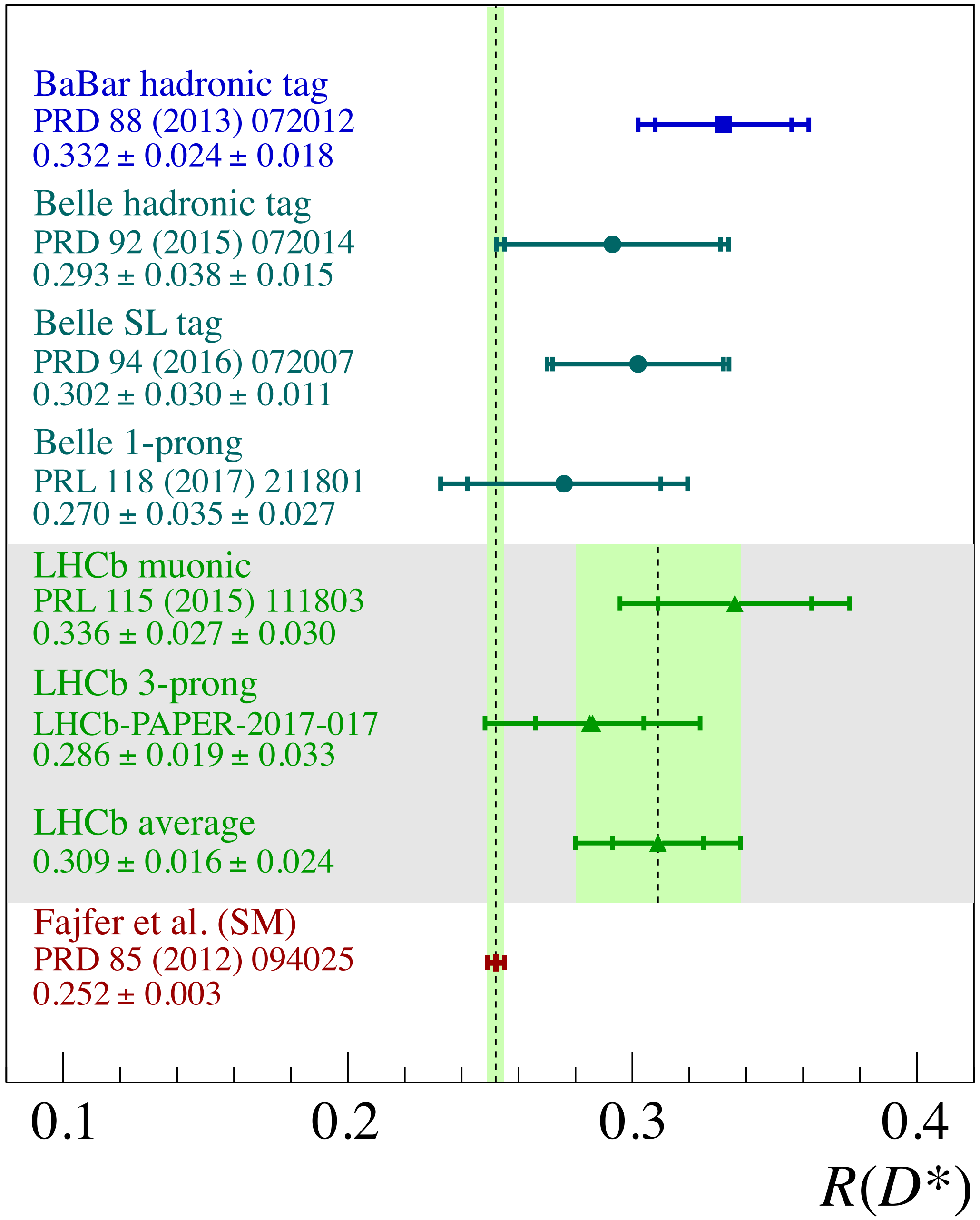
- R(D*) has been measured using two different approaches: muonic and hadronic τ decays.

- R(J/ψ) measured for the first time.

- Results are based on run-1 data. Run-2 data will improve precision (statistical and systematic).

- We will have soon new results.



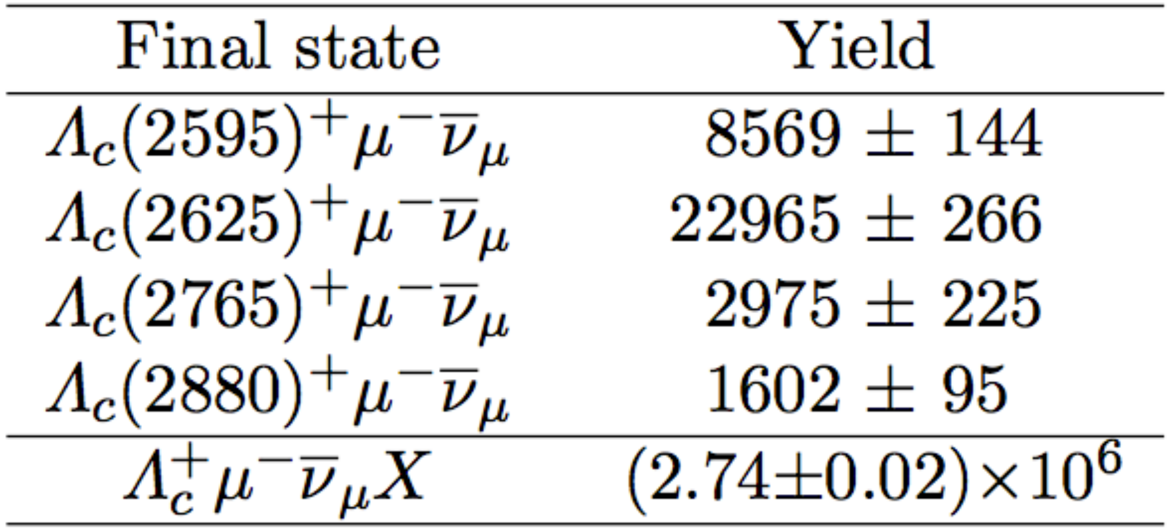


SUMMARY AND CONCLUSIONS

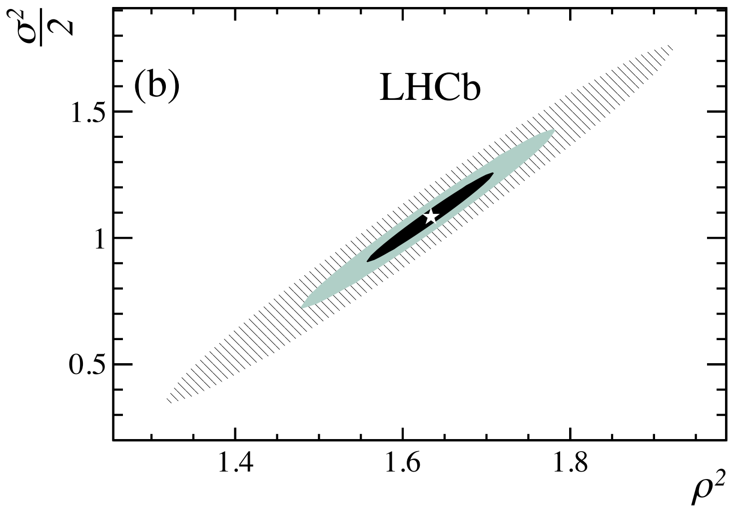
- Recent LHCb results on semileptonic B decays have been presented.
- Precision in measurements of LU using semitauonic B-hadron decays will improve after including Run-2 data.
- If the world-average in $R(D^{(*)})$ is correct, LHCb and Belle-2 (data taking starting end of 2018) could confirm the existing tension with the SM in the next years.
- Other analyses ongoing:
  - $R(p\bar{p})$, $R(\Lambda_c)$, $R(\Lambda_c^*)$, $R(D^*)$ vs $R(D^0)$, $R(D_s^{(*)})$, $R(D^-)$, $R(J/\psi)$.
- Some of them only possible at LHCb (Λ_b, B_c^+).

BACKUP

$\Lambda_b^0 \to \Lambda_c^- \mu^+ \nu_\tau$

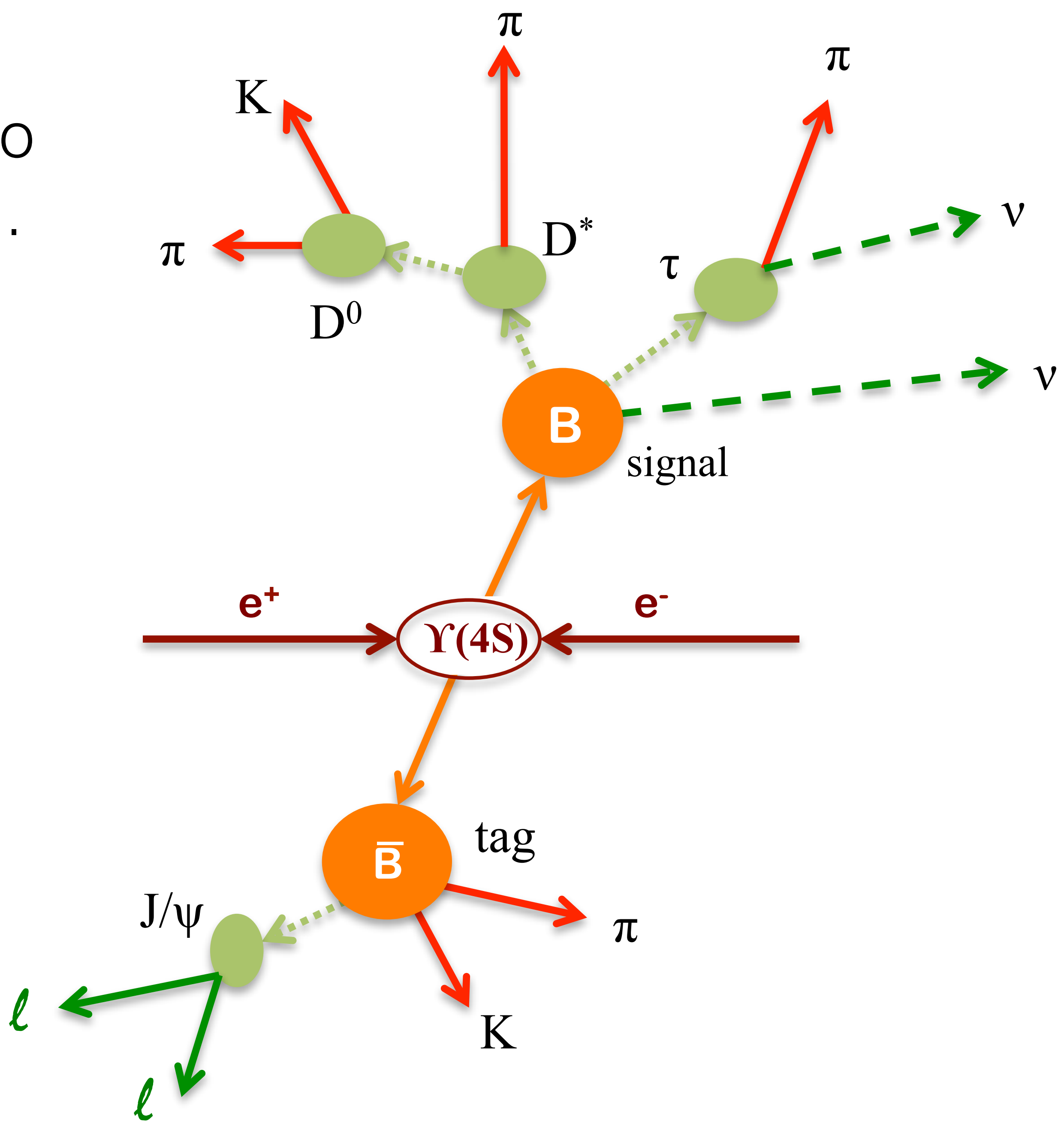


Final state	Yield
$\Lambda_c(2595)^+\mu^-\overline{\nu}_\mu$	8569 ± 144
$\Lambda_c(2625)^+\mu^-\overline{\nu}_\mu$	22965 ± 266
$\Lambda_c(2765)^+\mu^-\overline{\nu}_\mu$	2975 ± 225
$\Lambda_c(2880)^+\mu^-\overline{\nu}_\mu$	1602 ± 95
$\Lambda_c^+\mu^-\overline{\nu}_\mu X$	$(2.74\pm0.02)\times10^6$



R(D) AND R(D*) AT THE B-FACTORIES

- e^+/e^- collisions producing $\Upsilon(4S) \to B\bar{B}$.
- Using fully reconstructed B-tag and a constraint to the Υ(4S) mass, possible to measure the momentum of the B-signal.
- Missing mass (neutrinos) can be measured with high precision.
- At the B-factories, semitauonic B decays studied using:
  - Leptonic: $\tau \to \mu\nu\nu$ and $\tau \to e\nu\nu$. R(D) and R(D*) measured with respect to $[BR(B \to D^{(*)}\mu\nu) + BR(B \to D^{(*)}e\nu)]/2$.
  - Hadronic: $\tau \to \pi\nu$ and $\tau \to \rho\nu$.
  - Hadronic and semileptonic B-tag are used.



SEMITAUONIC B DECAYS AT LHCB

- At LHCb, *B* hadrons produced in p-p collisions → No possible to apply mass constraint on the $\Upsilon(4S)$. Two approaches are followed:

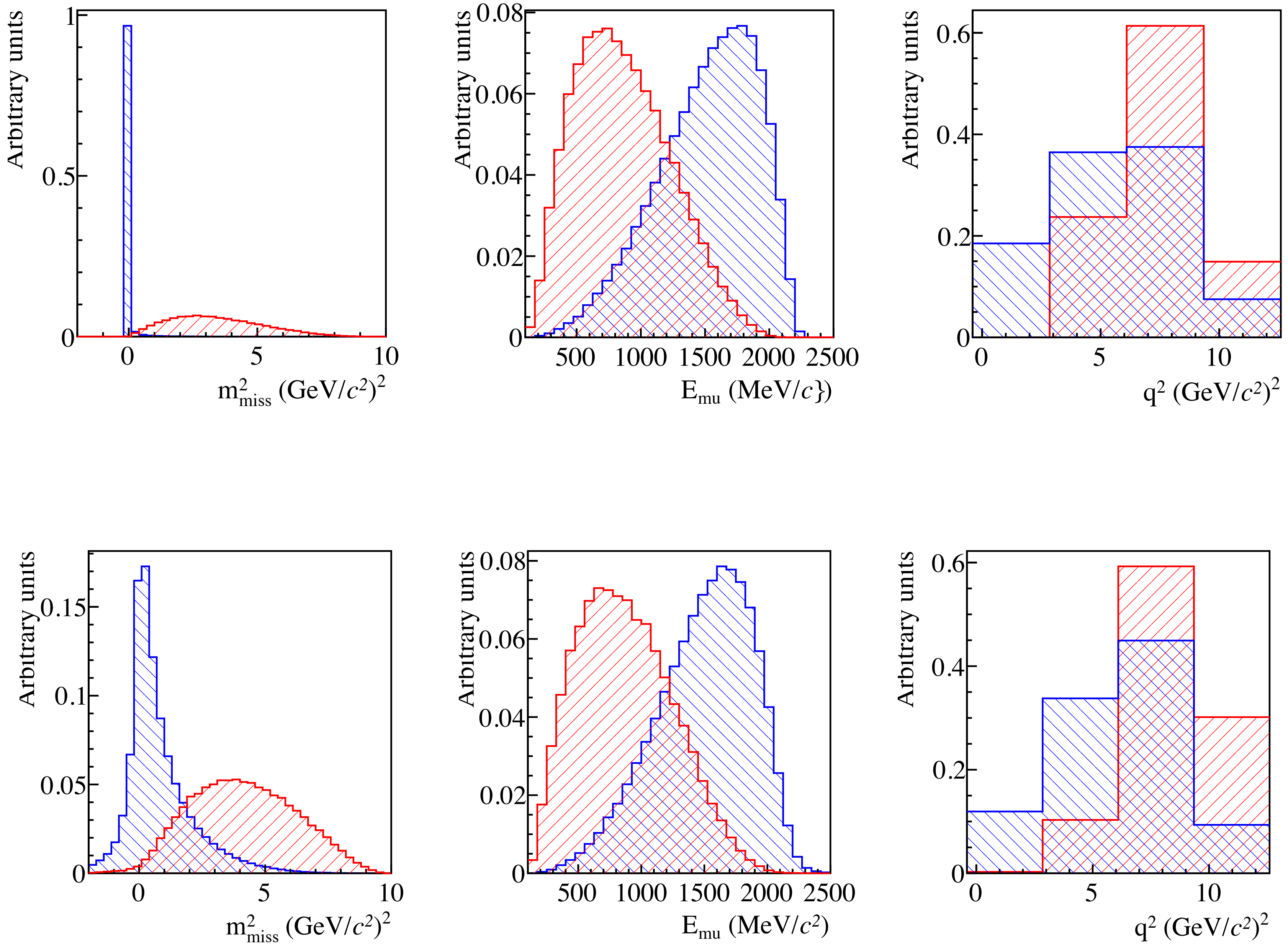
Muonic ($\tau \to \mu\nu\nu$)

- τ branching fraction (~17%)
- High trigger efficiency for muons.
- 3 unreconstructed neutrinos.
- Measured *B*-hadron direction is used to approximate the B momentum.
- Sample composed by $B \to X_c^{(*)}\mu\nu$, $B \to X_c\tau\nu$ and $B \to D^*D(\to\mu\nu X)X'$ decays.
- $R(X_c)$ directly obtained from a fit using this method.

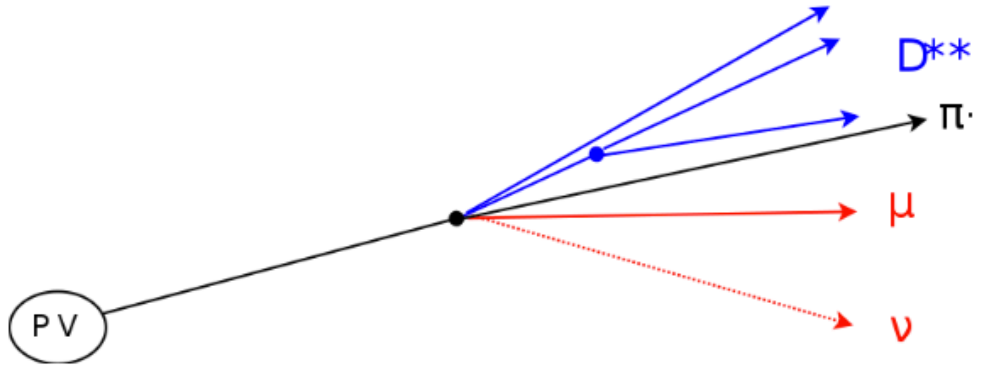
Hadronic ($\tau \to 3\pi(\pi^0)\nu$)

- BF's: 9% ($3\pi\nu$) and 4% ($3\pi\pi^0\nu$).
- 2 unreconstructed neutrinos.
- The 3 pions allows to measure τ decay vertex → Reconstruct τ direction.
- Sample include signal and double-charm background (non-negligible lifetime) $B \to D^*DX$.
- The $B \to D^*\tau\nu$ BF can be measured related to a normalisation channel ($B^0 \to D^*3\pi$).

R(D*) MUONIC: RECONSTRUCTION



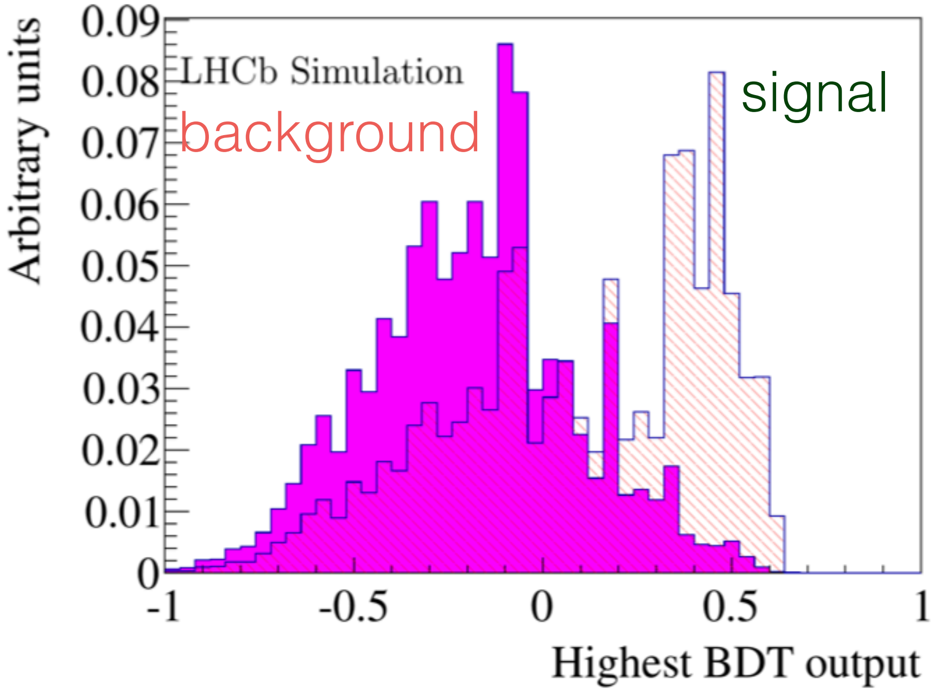
SIGNAL ISOLATION

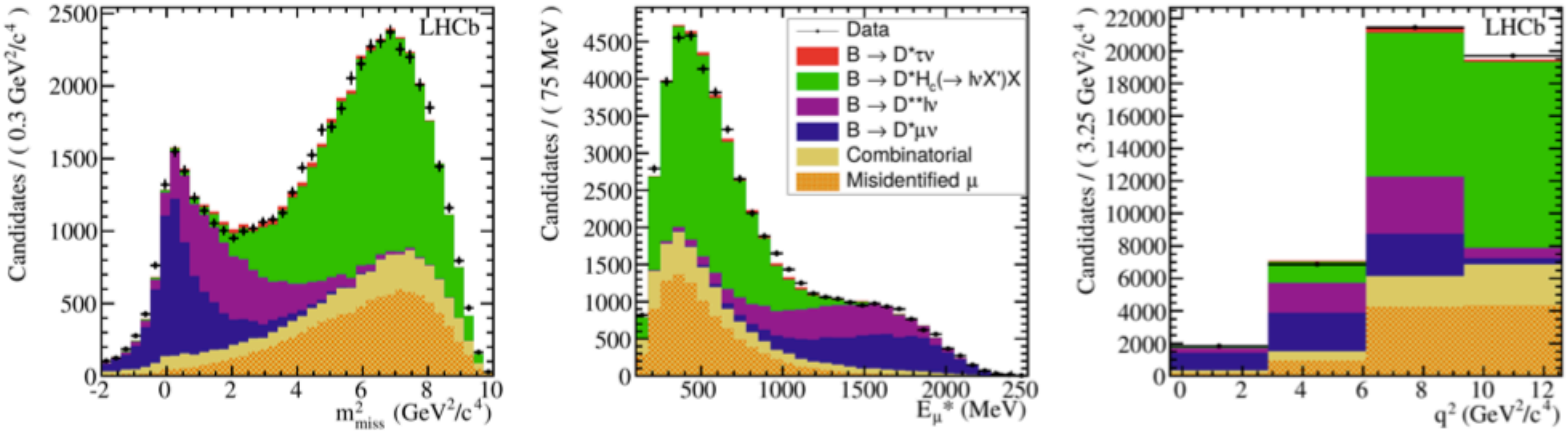


- Multi-variate (MV) algorithm with information from charged tracks close to the signal candidate used to reject physics background.

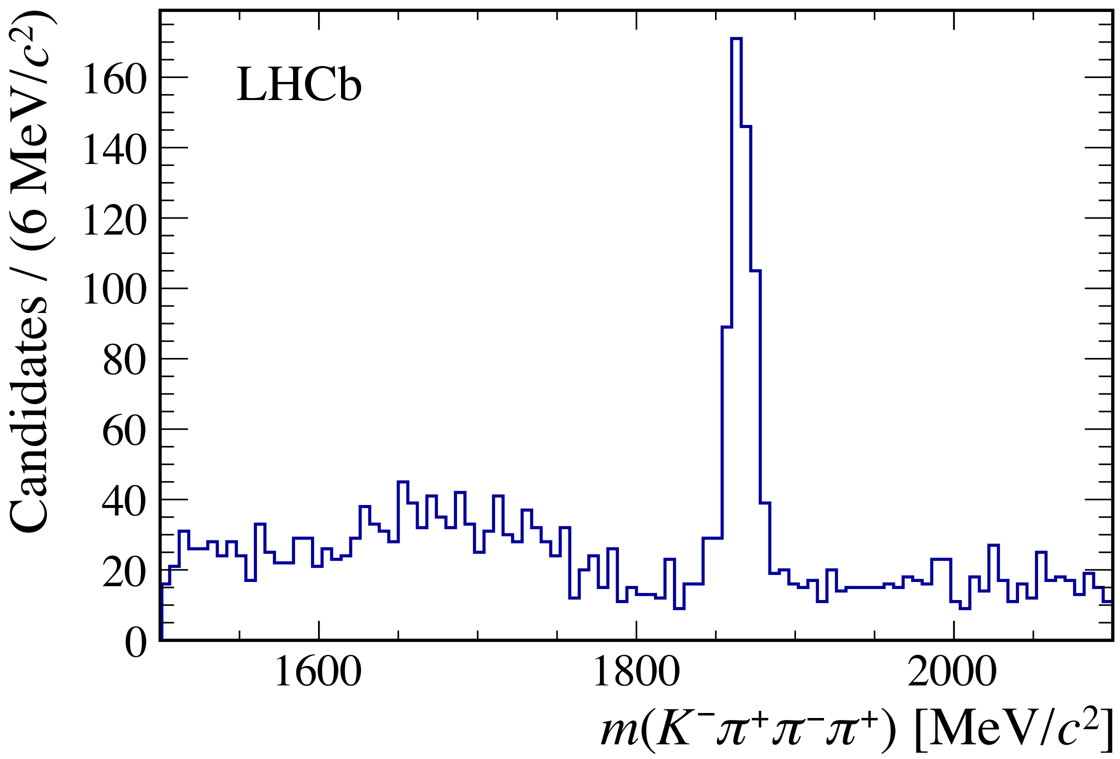
- **Control samples** enriched in $B \to D^{**}\mu\nu$ and $B \to D^{*}D(\to \mu X)X$ decays can be obtained by inverting the MV cut.

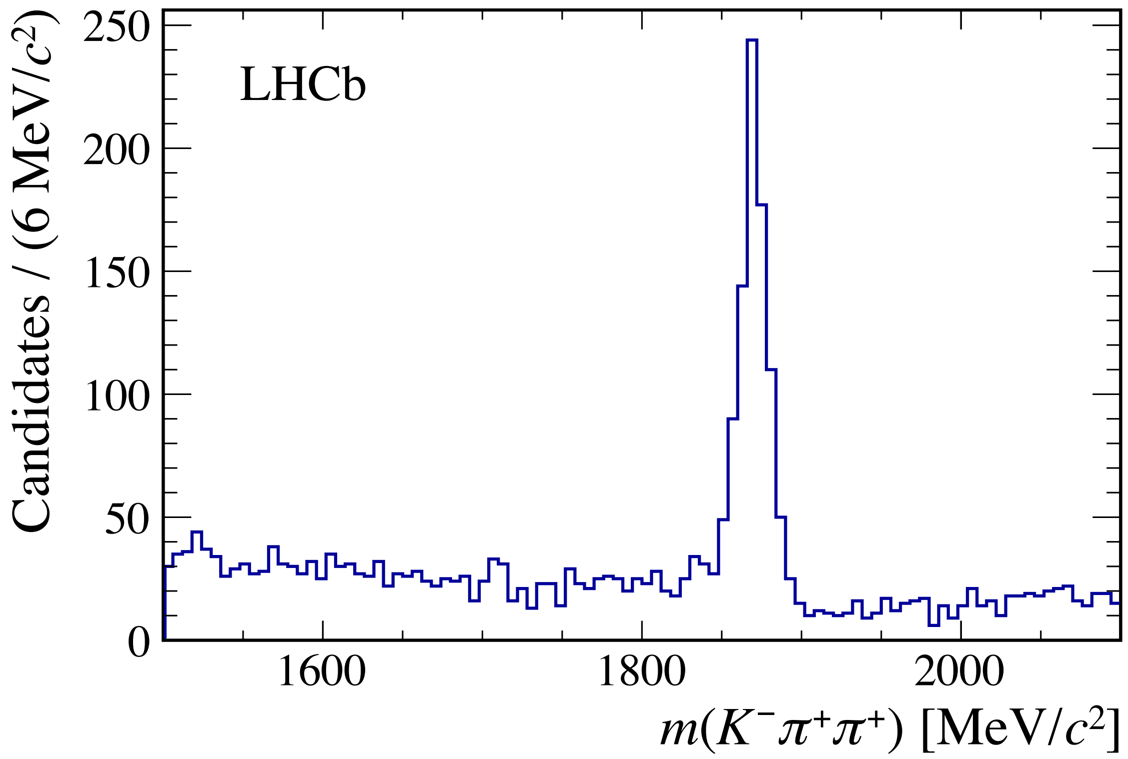
- Our model reproduced well the data.

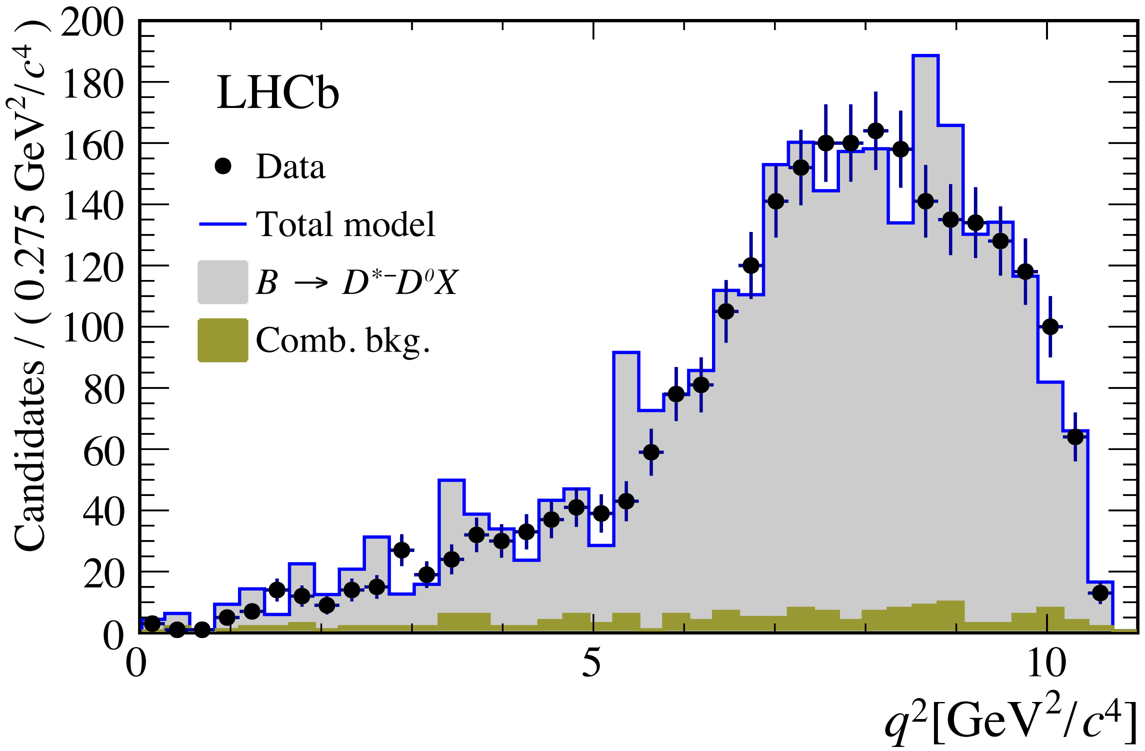


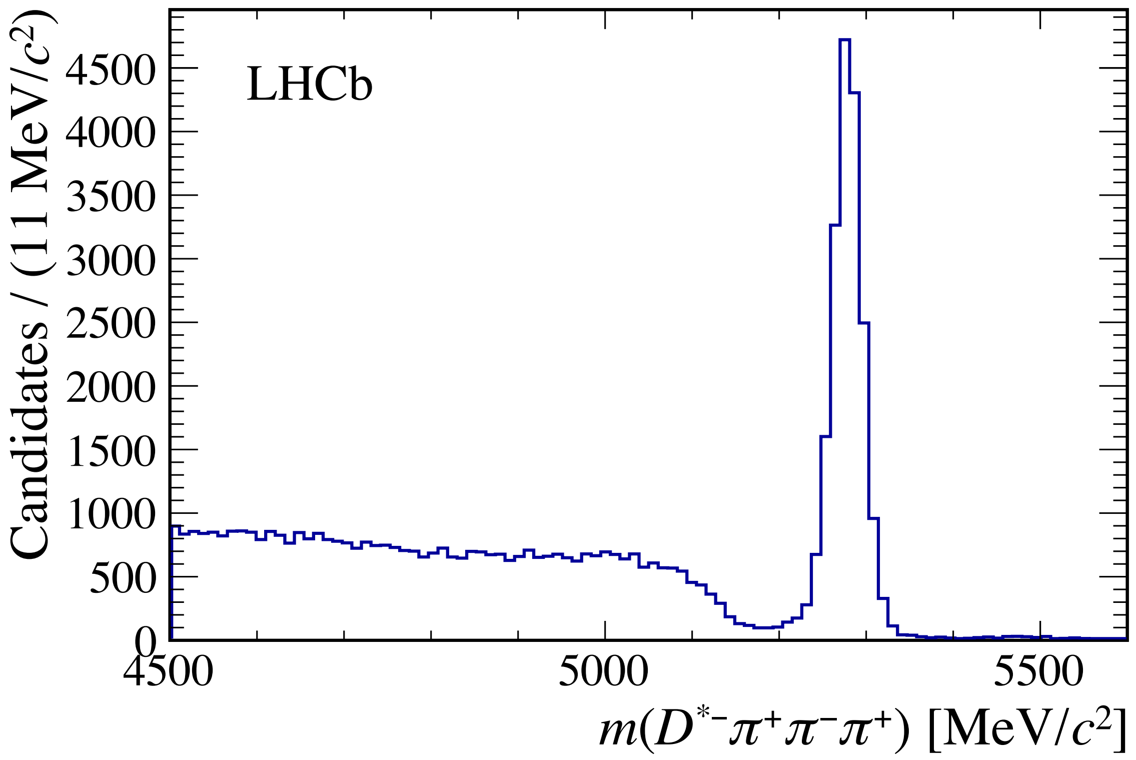


R(D*) HADRONIC: CONTROL SAMPLES

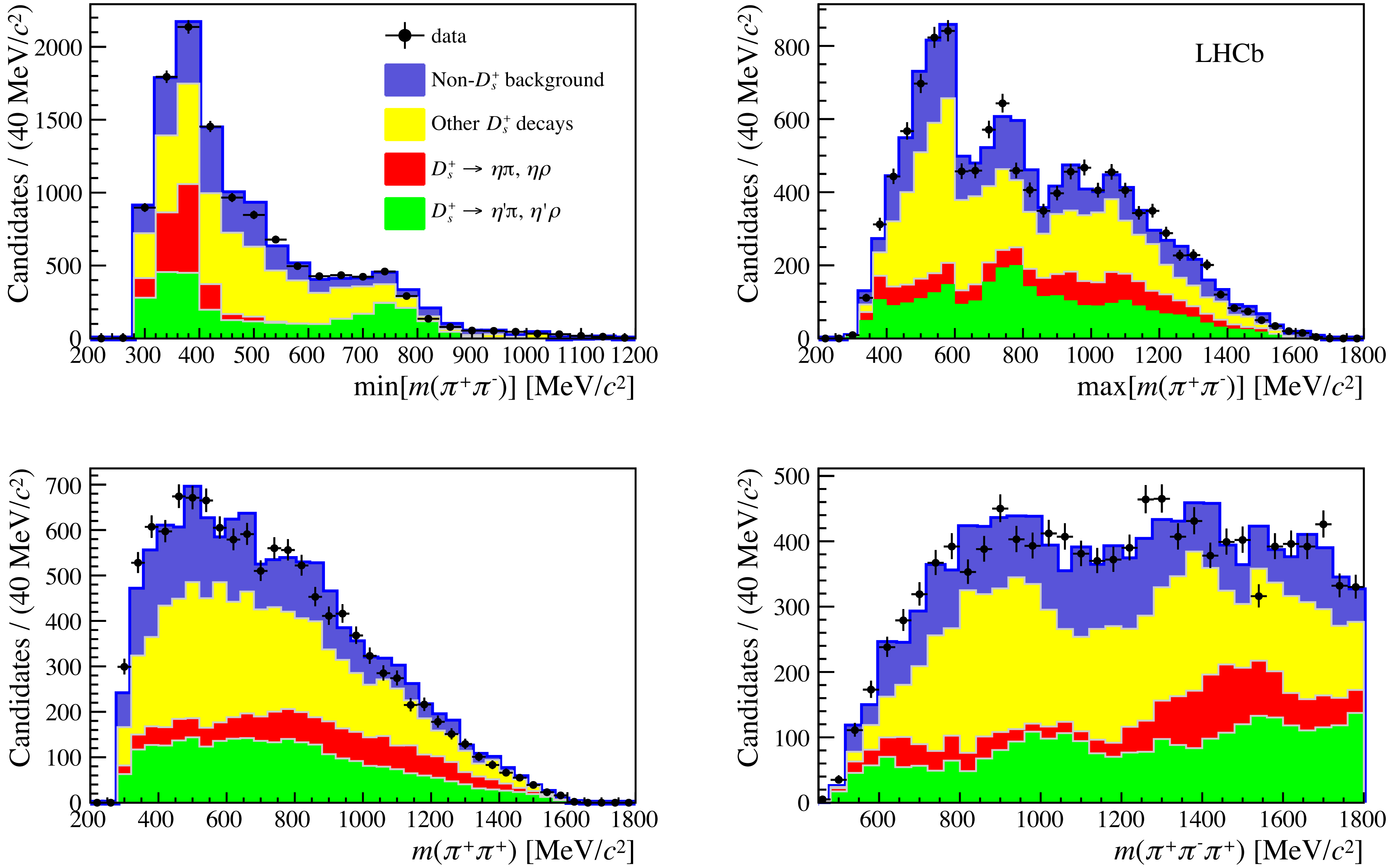








R(D*) HADRONIC: D_S→3ΠX CONTROL SAMPLE



2nd LHCb open semitauonic workshop

November 13-15, 2017

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