Standard Model tests in charged-current semileptonic decays

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on behalf of the LHCb Collaboration

Towards the Ultimate Precision in Flavour Physics
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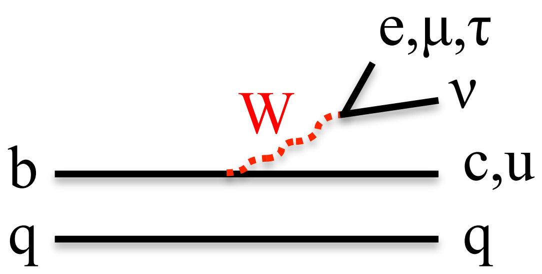
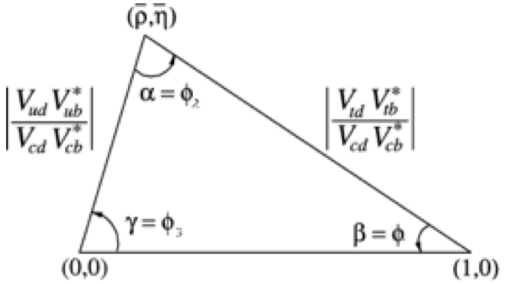
Semileptonic B-hadron decays

- 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 $|V_{cb}|$.



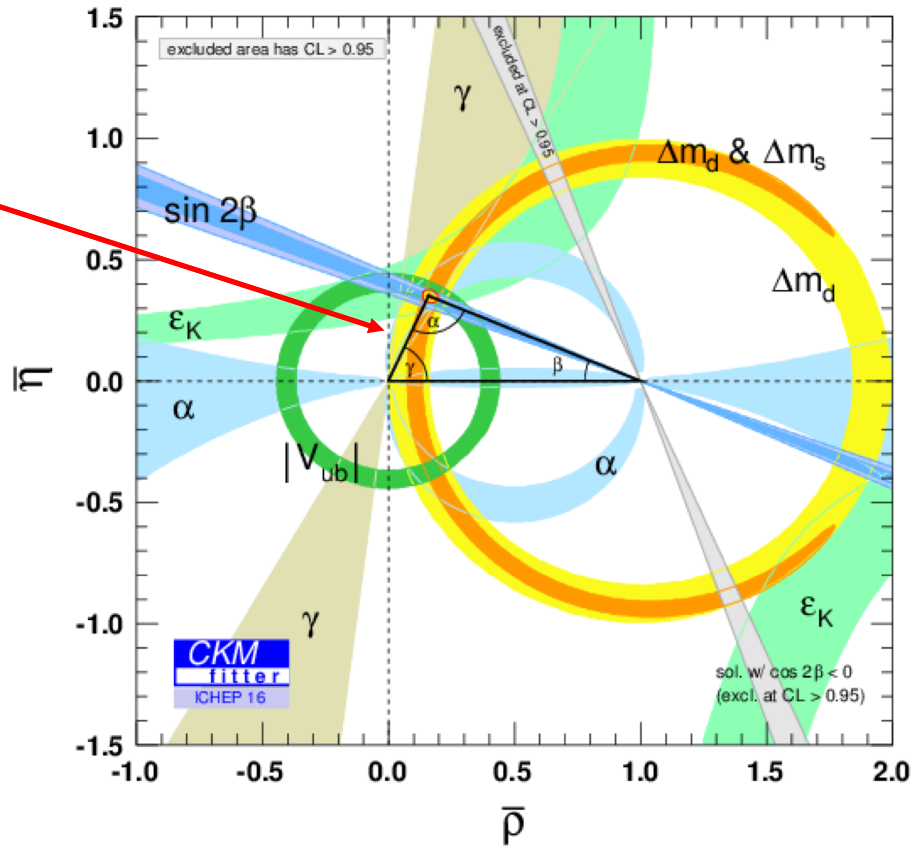
- Decays involving τ-ν (semitauonic) sensitive to contributions BSM.

CKM unitary triangle: $|V_{cb}|$ and $|V_{ub}|$

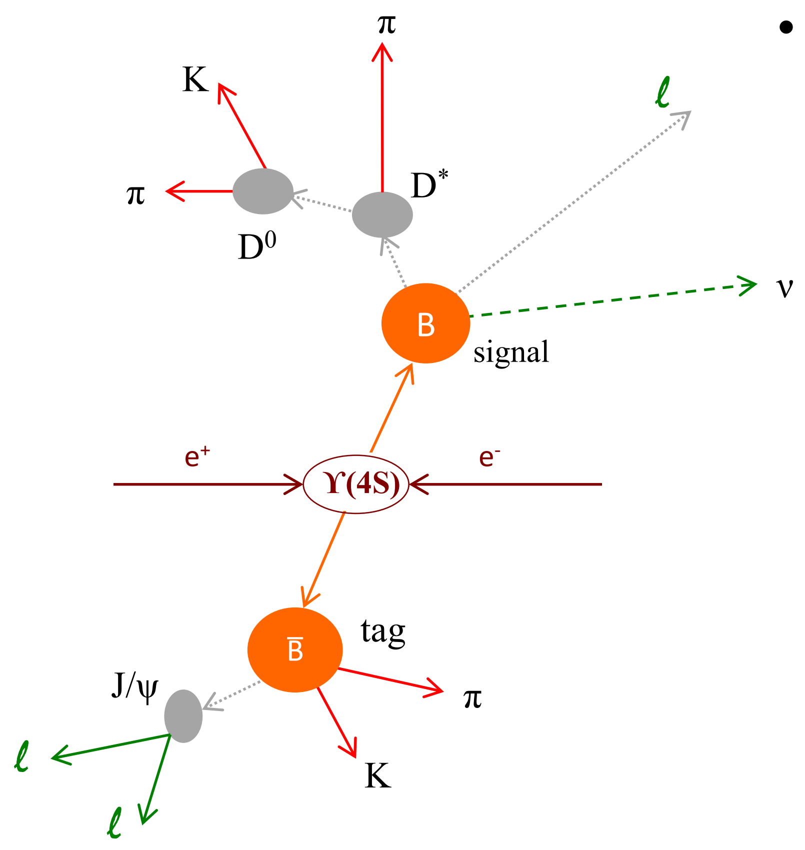
- Precision determinations of $|V_{cb}|$ and $|V_{ub}|$ allow to test the SM:

$V_{ud}V_{ub}^{*}+V_{cb}V_{cd}^{*}+V_{tb}V_{td}^{*} = 0$

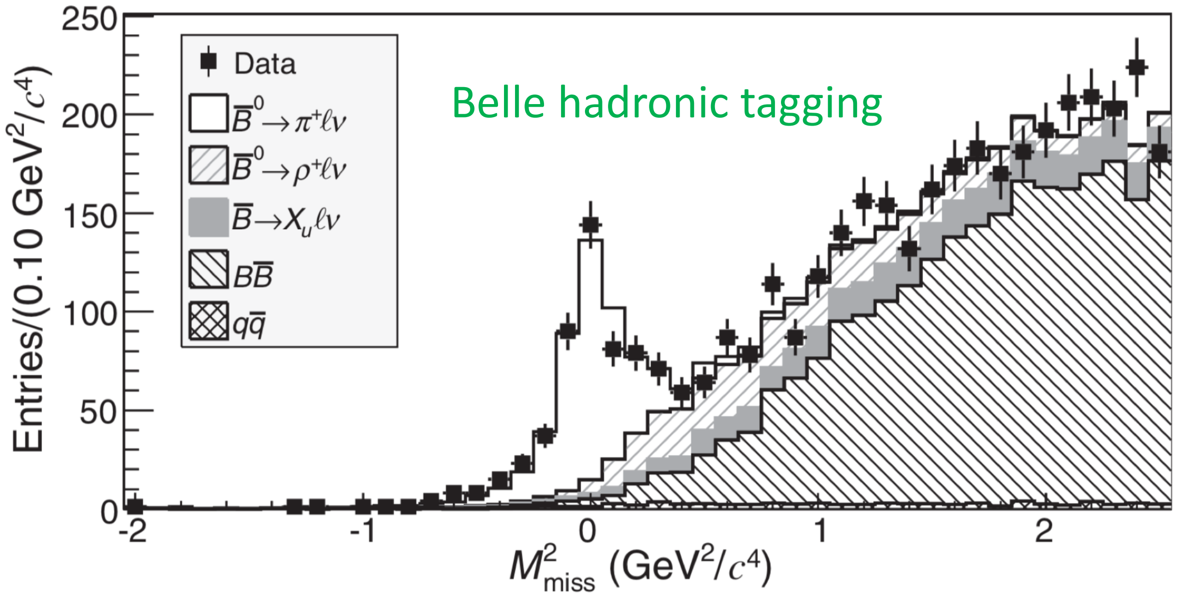
- The length of the side of the unitary triangle opposite to the phase β proportional to the ratio $|V_{ub}|/|V_{cb}|$.
- The semileptonic transitions $b\rightarrow cl\nu$ and $b\rightarrow ul\nu$ ($l=e,\mu$) used to determine $|V_{cb}|$ and $|V_{ub}|$: **inclusive and exclusive decays**.
- **B-factories** BaBar and Belle:
  - $B\rightarrow D^{*}l\nu$ (V_{cb}, exclusive)
  - $B\rightarrow Dl\nu$ (V_{cb}, exclusive)
  - $B\rightarrow X_{c}l\nu$ (V_{cb}, inclusive)
  - $B\rightarrow \pi l\nu$ (V_{ub}, exclusive)
  - $B\rightarrow X_{u}l\nu$ (V_{ub},inclusive)
- **LHCb**:
  - $\Lambda_b^0\rightarrow p\mu\nu$ vs $\Lambda_b^0\rightarrow \Lambda_c^{+}\mu\nu$ ($|V_{ub}|/|V_{cb}|$ exclusive)



Reconstruction method at B-factories



- e+/e- → Υ(4S)→B/B-bar
- B-tag allows to constrain the momentum of the B-signal.
  - Hadronic B-tag: precise measurement of p_B. Good determination of q^2 and m_{miss}^2 (eff. 0.3%)
  - SL B-tag: weaker constraint on p_B (eff. ~1%)



[PRD 88, 032005 (2013)]

Results on $|V_{cb}|$ and $|V_{ub}|$

- HFLAV averages:

$|V_{ub}|=(3.50 \pm 0.13)\times 10^{-3}$ (excl.) $|V_{cb}|=(39.13 \pm 0.59)\times 10^{-3}$ (excl.)

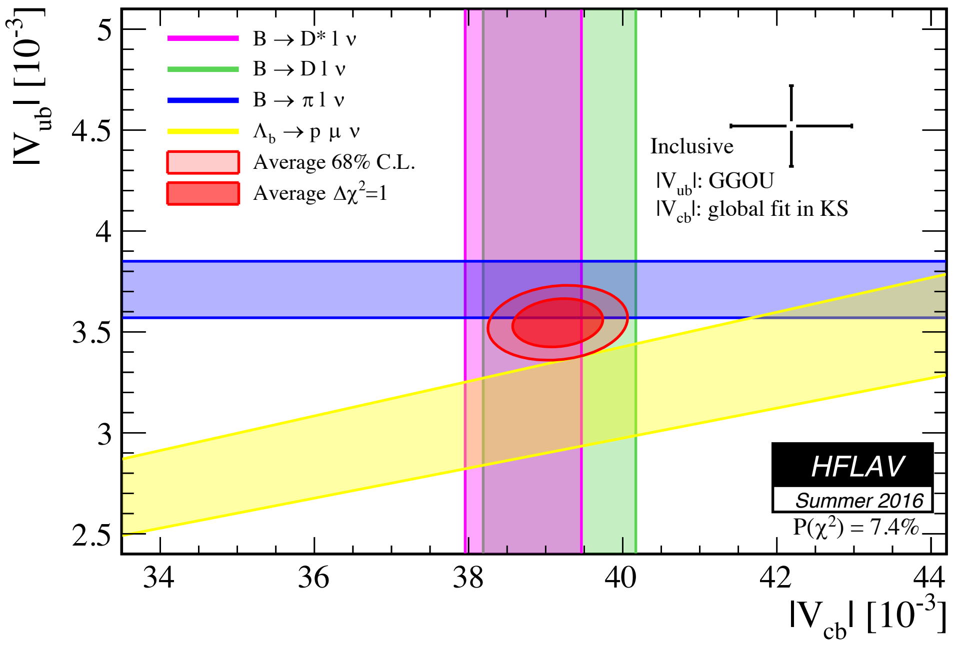
$|V_{ub}|=(4.52 \pm 0.20)\times 10^{-3}$ (incl.) $|V_{cb}|=(42.19 \pm 0.78)\times 10^{-3}$ (incl.)

- Discrepancy between inclusive and exclusive measurements.

- New $|V_{ub}|$ BaBar result on inclusive $B \rightarrow X_u e\nu$ decays tend to agree with exclusive measurements [PRD 95, 072001 (2017)].

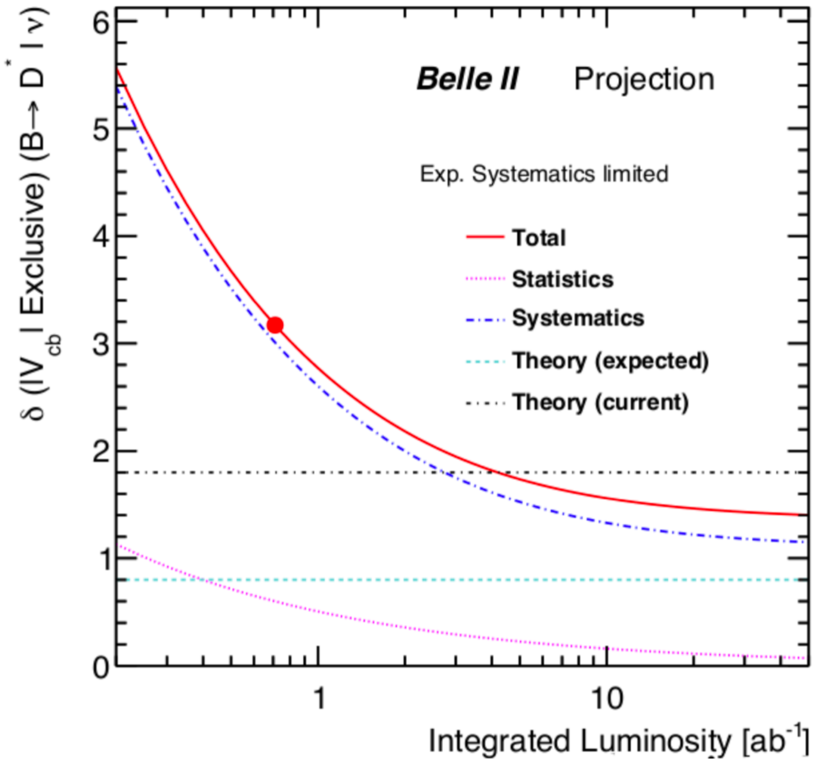
- Extraction of $|V_{ub}|$ and $|V_{cb}|$ depend on theory input (i.e.: form factors parameterisation, i.e: CLN vs BGL).

- A lot of recent theoretical work to understand this discrepancy.



Belle II prospects on $|V_{cb}|$

- Uncertainty on $|V_{cb}|$ exclusive measurements with 5 ab^{-1} and 50 ab^{-1} of Belle II data.

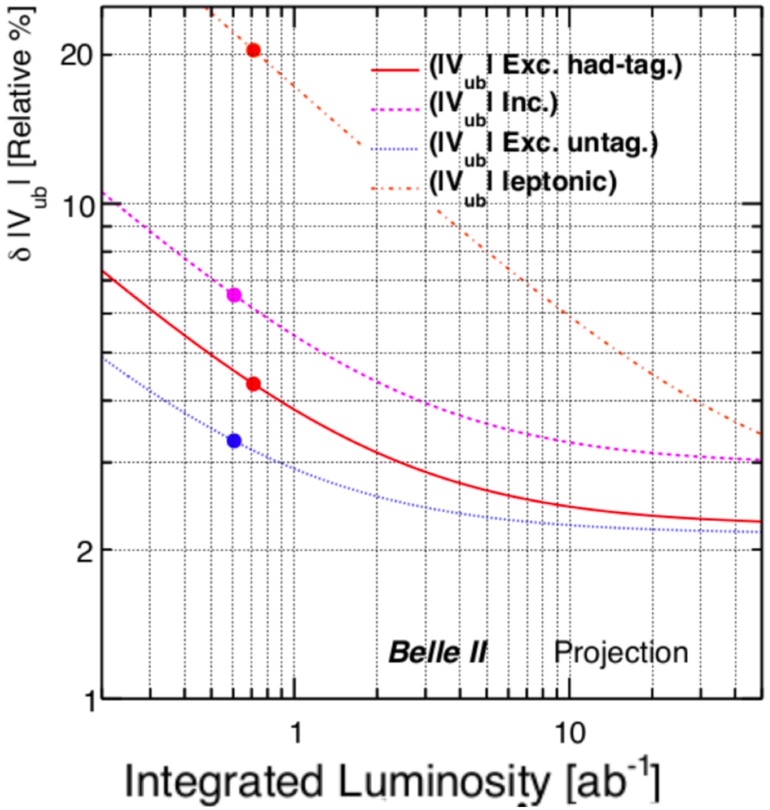


	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$\|V_{cb}\|$ exclusive : F(1)					
711 fb^{-1}	0.6	(2.8, 1.1)	3.1	1.8	3.6
5 ab^{-1}	0.2	(1.1, 1.1)	1.5	1.0	1.8
50 ab^{-1}	0.1	(0.3, 1.1)	1.2	0.8*	1.4
$\|V_{cb}\|$ exclusive : G(1)					
423 fb^{-1}	4.5	(3.1, 1.2)	5.6	2.2	3.6
5 ab^{-1}	1.3	(0.9, 1.2)	2.0	1.5*	2.7
50 ab^{-1}	0.6	(0.4, 1.2)	1.4	1.0*	1.7

- $|V_{cb}|$ measured with 1-2% uncertainty at the end of Belle II data taking (50 ab^{-1}).

Belle II prospects on $|V_{ub}|$

- Uncertainty on $|V_{ub}|$ exclusive measurements with 5 ab^{-1} and 50 ab^{-1} of Belle II data.



	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$\|V_{ub}\|$ exclusive (had. tagged)					
711 fb^{-1}	3.0	(2.3, 1.0)	3.8	8.7 (2.0)	9.5 (4.3)
5 ab^{-1}	1.1	(0.9, 1.0)	1.7	4.0 (2.0)	4.4 (2.6)
50 ab^{-1}	0.4	(0.3, 1.0)	1.1	2.0	2.3
$\|V_{ub}\|$ exclusive (untagged)					
605 fb^{-1}	1.4	(2.1, 0.8)	2.9	8.7 (2.0)	9.1 (4.0)
5 ab^{-1}	0.5	(0.8, 0.8)	1.2	4.0 (2.0)	4.2 (2.4)
50 ab^{-1}	0.2	(0.3, 0.8)	0.9	2.0	2.2
$\|V_{ub}\|$ inclusive					
605 fb^{-1} (old B tag)	4.5	(3.7, 1.6)	6.0	2.5–4.5	6.5–7.5
5 ab^{-1}	1.1	(1.3, 1.6)	2.3	2.5–4.5	3.4–5.1
50 ab^{-1}	0.4	(0.4, 1.6)	1.7	2.5–4.5	3.0–4.8

- $|V_{ub}|$ measured with 2-4% uncertainty at the end of Belle II data taking (50 ab^{-1}).

$|V_{ub}|/|V_{cb}|$ at LHCb: $\Lambda_b^0 \rightarrow p\mu\nu$

[Nature Physics 11 (2015) 743]

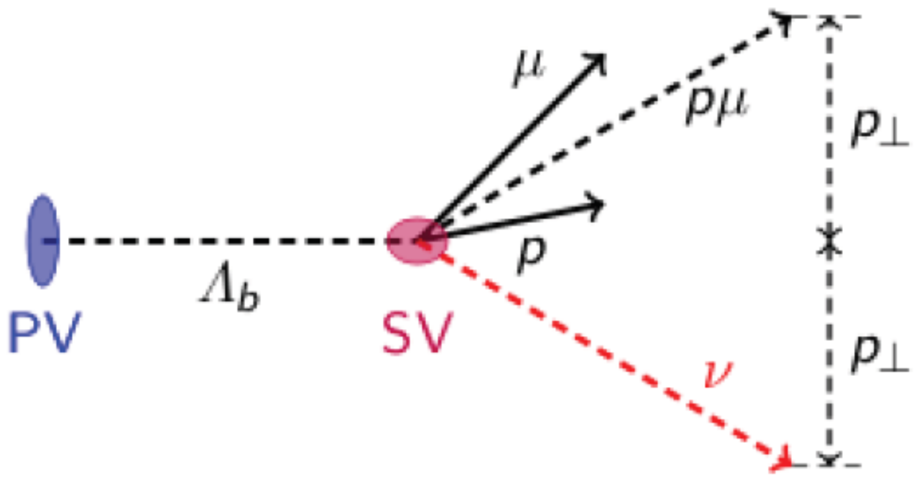
- $\Lambda_b^0 \rightarrow p\mu\nu$ decays used to measure $|V_{ub}|/|V_{cb}|$. $\Lambda_b^0 \rightarrow \Lambda_c^+\mu\nu$ decays used as normalisation channel.

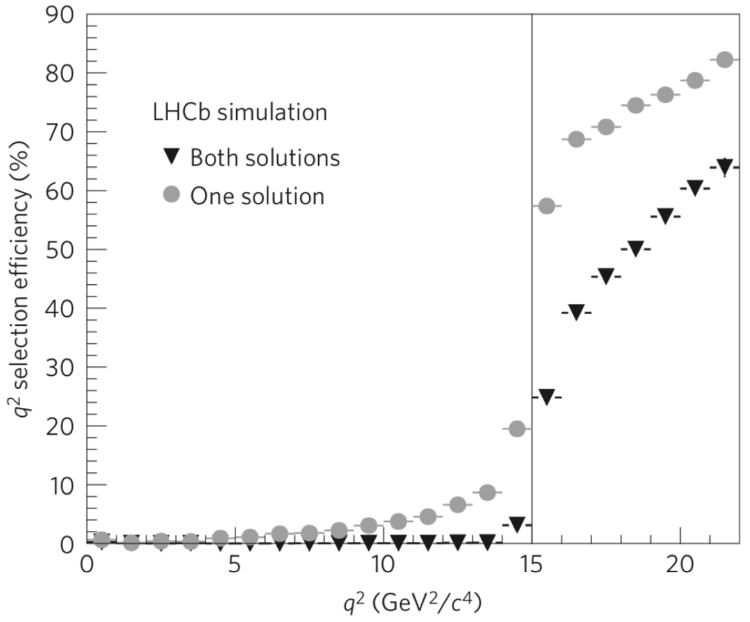
- Experimental method → reconstruct the corrected mass:

$$M_{corr} = \sqrt{M_{p\mu}^2 + p_\perp^2} + p_\perp$$

- Using the Λ_b^0 mass and direction of flight, $\mathbf{q^2} = (p_{\Lambda b} - p_p)^2$ can be estimated (up to a two-fold ambiguity).

- Events selected with $q^2 > 7$ GeV^2 ($p\mu\nu_\mu$) and >15 GeV^2 ($\Lambda_c\mu\nu_\mu$) (both q^2 solutions above cut).
  - Highest rate, best resolution (~1GeV) and most precise Lattice calculations.





$|V_{ub}|/|V_{cb}|$ at LHCb: $\Lambda_b^0 \rightarrow p\mu\nu$

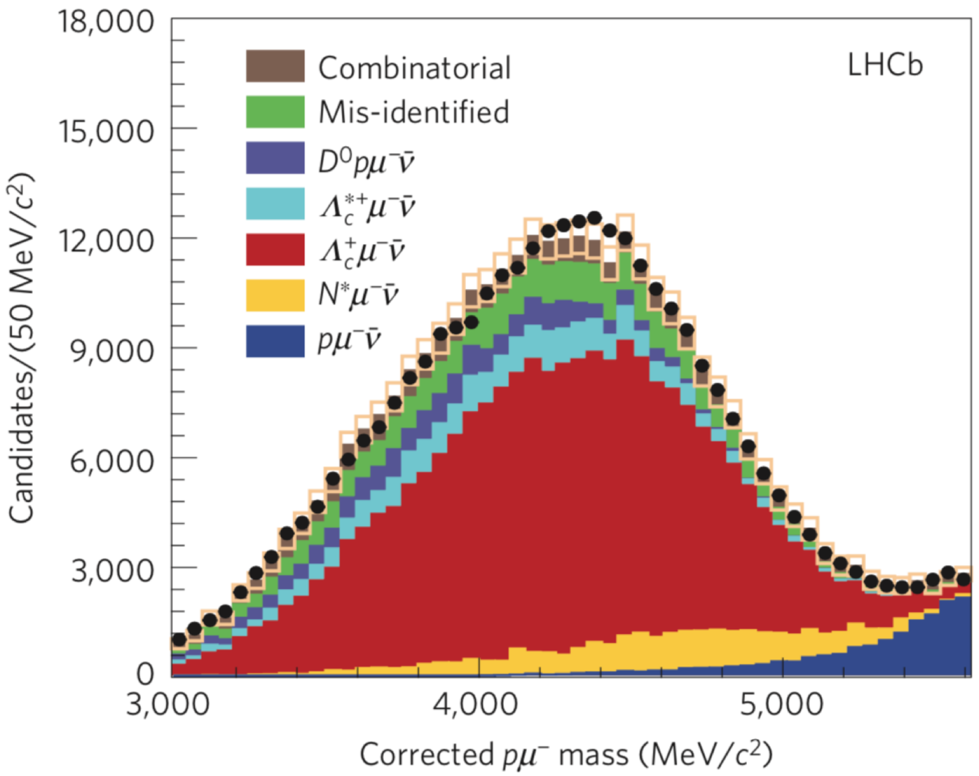
- Signal extraction from 1D fit to M_{corr}.

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)} R_{FF}$$

(R_{FF} from lattice)

$$\frac{B(\Lambda_b^0 \to p\mu\nu)_{q^2>15GeV}}{B(\Lambda_b^0 \to \Lambda_c\mu\nu)_{q^2>7GeV}} = (1.00 \pm 0.04(stat) \pm 0.08(syst)) \times 10^{-2}$$

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004(\exp) \pm 0.004(lattice)$$



- Measurement compatible with exclusive measurements from B-factories.

- Measurement dominated by $\Lambda_c^+ \rightarrow pK\pi$ branching fraction (~5%). Limiting factor for future measurements.

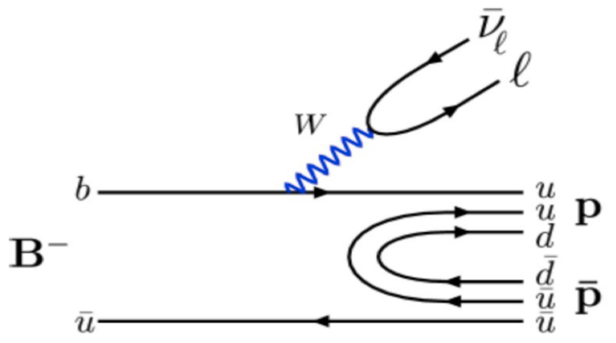
[Nature Physics 11 (2015) 743]

Next on $|V_{ub}|$ and $|V_{cb}|$ at LHCb

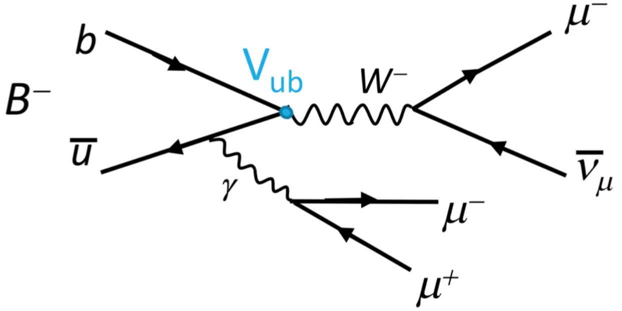
Table 2: Values used for the projections of future $|V_{ub}|$ and $|V_{cb}|$ measurements

Measurement	Current World Average ($\times 10^{-3}$) (Ref. [35])	Current Uncertainty (Ref. [35])	Projected Uncertainty: Belle II $5\,\text{ab}^{-1}$	Belle II $50\,\text{ab}^{-1}$	LHCb $8\,\text{fb}^{-1}$	LHCb $22\,\text{fb}^{-1}$	LHCb $50\,\text{fb}^{-1}$
$\lvert V_{ub}\rvert$ inclusive	4.49 ± 0.23	5.1%	3.4%	3.0%	-	-	-
$\lvert V_{ub}\rvert$ exclusive	3.72 ± 0.19	5.1%	2.5%	2.1%	-	-	-
$\lvert V_{cb}\rvert$ inclusive	42.2 ± 0.8	1.9%	1.3%	1.2%	-	-	-
$\lvert V_{cb}\rvert$ exclusive	39.2 ± 0.7	1.8%	1.6%	1.1%	-	-	-
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	83.0 ± 5.7	6.9%	-	-	3.4%	2.9%	2.1%

- $B_s^0 \to K^+\mu\nu$ will be used to measure $|V_{ub}|$.
    - Normalisation $B_s^0 \to D_s^+\mu\nu$. It can be used for $|V_{cb}|$ measurement.
    - Large $B_s^0 \to D_s^+\mu\nu$ yield but…
    - Large feed-down from excited D meson decays with neutrals: $D_s^* \to D_s\gamma$.



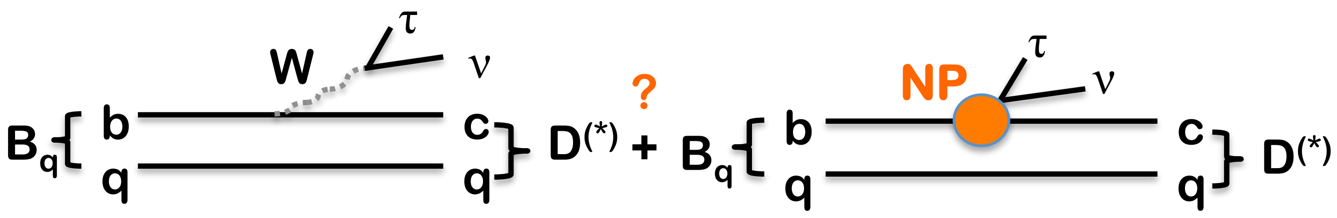
- $B^+ \to pp\mu\nu$.
    - Measured branching fraction (Belle) = $(3.1^{+3.1}_{-2.4} \pm 0.7)\times 10^{-6}$ [PRD 89, 011101 (2014)]



- $B^+ \to \mu\mu\mu\nu$ sensitive to $|V_{ub}|$.
    - No helicity suppression due to the 2 muons from the virtual photon.
    - Expected branching fraction of the order ~10^{-8}.

Tests of LFU using semitauonic B-hadron decays

- In the SM, charged lepton flavours are identical copies of one another.
- Amplitudes for processes involving e, μ, 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).



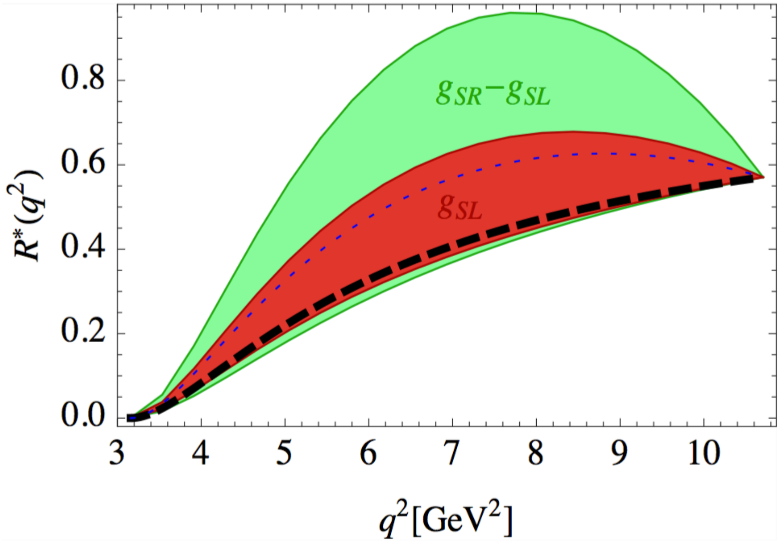
- New physics could couple most strongly to the 3th generation (τ).
- Comparison between semitauonic (τ) and semimuonic (μ) decays are sensitive to NP, which could modify branching ratios and angular distributions.

SM predictions

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

$$R(D^{(*)}) = \frac{\mathcal{B}(B^0 \to D^{(*)}\tau\nu)}{\mathcal{B}(B^0 \to D^{(*)}\mu\nu)} \quad , \quad R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\tau\nu)}{\mathcal{B}(B_c^+ \to J/\psi\mu\nu)}$$

- R(D*) very clean SM prediction due to partial cancelation of form factors uncertainties in the ratio.
- $R_{SM}(D^*) = 0.252 \pm 0.003$
- Deviation from unity due to different τ/μ masses.
- R(D*), R(J/ψ) enhanced/reduced in many BSM scenarios.



PRD 85 094025 (2012)

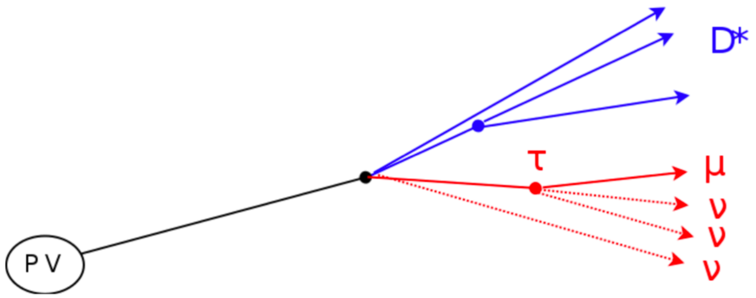
R(D*) and R(D) at Belle and BaBar

Experiment	Tag method	tau decay	Obs.	Value	Ref.
BaBar	Hadronic	$\tau \to \ell \nu \nu$	R(D)	0.440±0.058±0.042	PRL 109, 201802 (2012)
BaBar	Hadronic	$\tau \to \ell \nu \nu$	R(D*)	0.332±0.024±0.018	PRL 109, 201802 (2012)
Belle	Hadronic	$\tau \to \ell \nu \nu$	R(D)	0.335±0.064±0.026	PRD 92(7), 072014 (2015)
Belle	Hadronic	$\tau \to \ell \nu \nu$	R(D*)	0.293±0.038±0.015	PRD 92(7), 072014 (2015)
Belle	Semileptonic	$\tau \to \ell \nu \nu$	R(D*)	0.302±0.030±0.011	PRD 94(7), 072007 (2016)
Belle	Hadronic	$\tau \to h^- \nu$	R(D*)	$0.270 \pm 0.035^{+0.028}_{-0.025}$	PRL 118, 211801 (2017)
Belle	Hadronic	$\tau \to h^- \nu$	P_τ(D*)	$-0.38 \pm 0.51^{+0.21}_{-0.16}$	PRL 118, 211801 (2017)

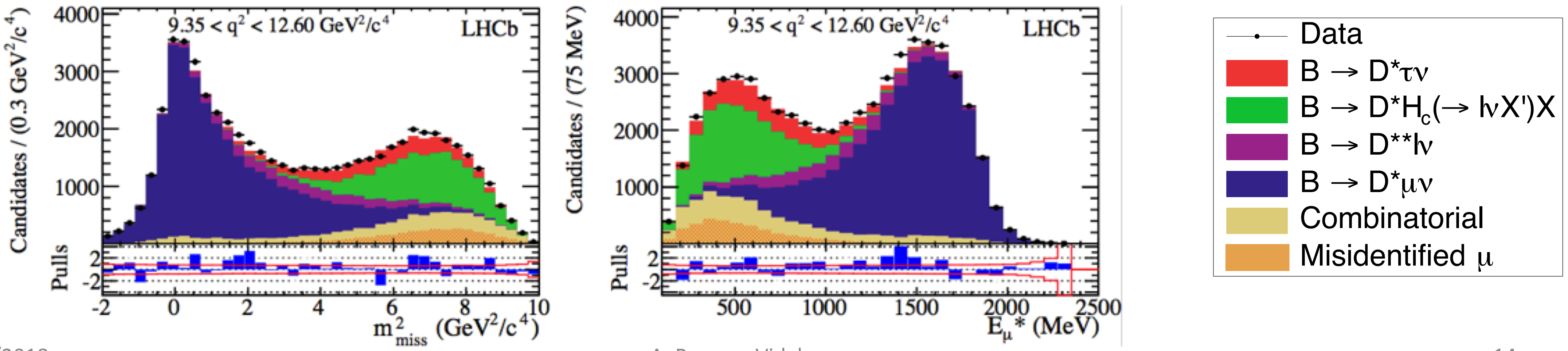
- BaBar and Belle have performed simultaneous analysis of R(D) and R(D*) using hadronic B-tagging. This introduce a correlation between the two measurements.
- Analyses assume isospin symmetry $R(D^0)=R(D^+)$ and $R(D^{*0})=R(D^{*+})$.
- All $R(D^{(*)})$ measurements consistently above the SM expectation $R_{SM}(D^*) = 0.252 \pm 0.003$.
- 1-prong tau decays used to perform a measurement of the tau polarisation.

R(D*) at LHCb using τ→μνν decays

- Difficult, due to missing kinematic constraints.
- B boost along z >> boost of decay products in B rest frame.
- The B momentum approximated by: $(\gamma\beta_z)_B = (\gamma\beta)_{D^*\mu} \Rightarrow (p_z)_B = \frac{m_B}{m(D^*\mu)}(p_z)$

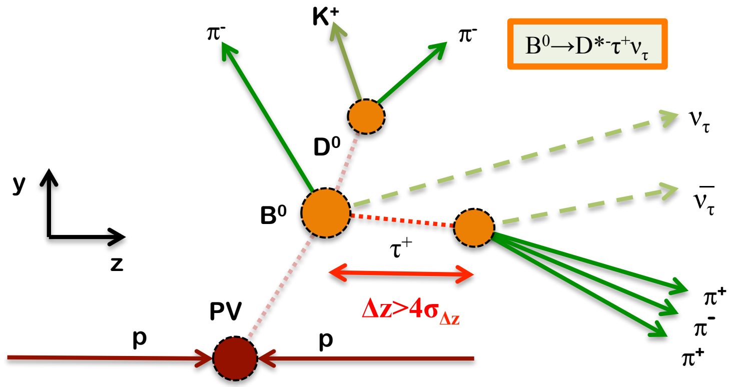


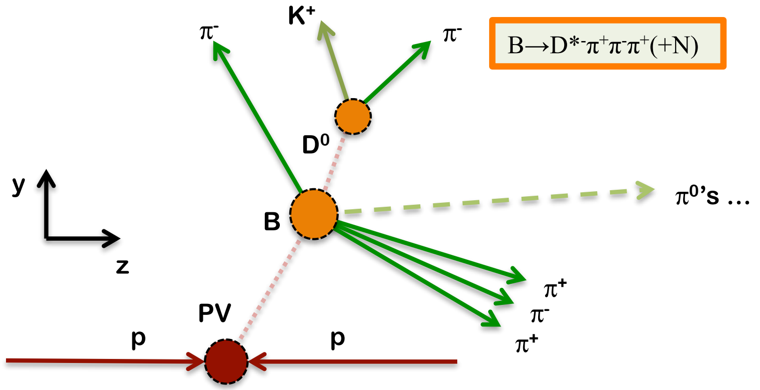
- 18% resolution on p_B still good enough to preserve signal and background discrimination.
- 3D template fit to **m^2_{miss}, E_μ* and q^2**: R(D*) = 0.336 ± 0.027 ± 0.030
- Systematics dominated by the size of simulated control samples.



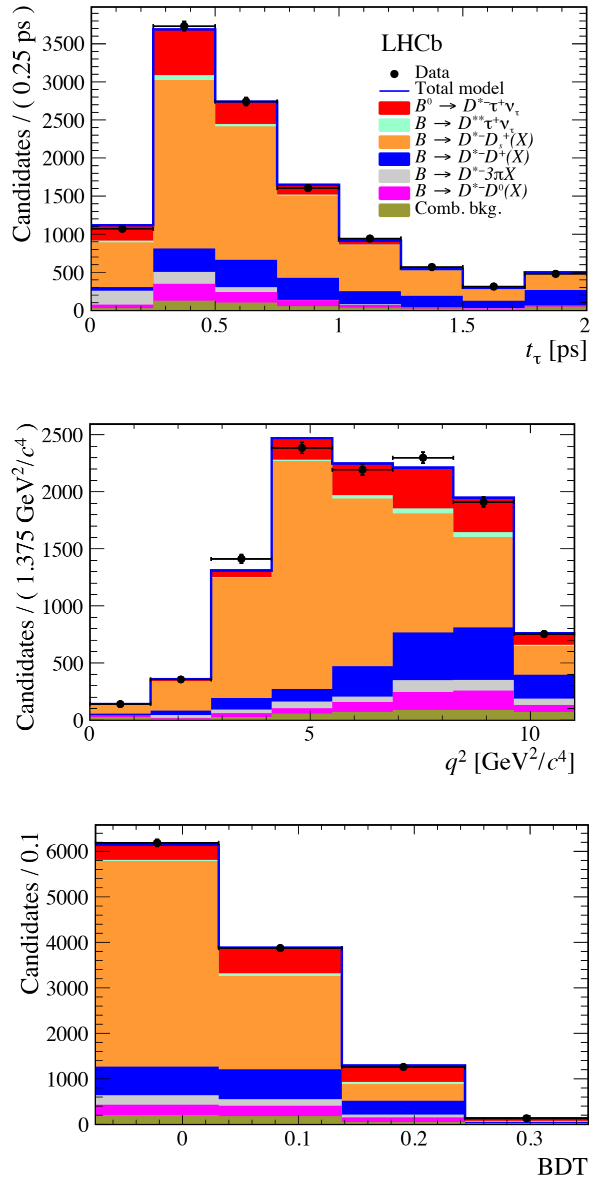
PRL 115, 111803 (2015)

Hadronic R(D*) at LHCb





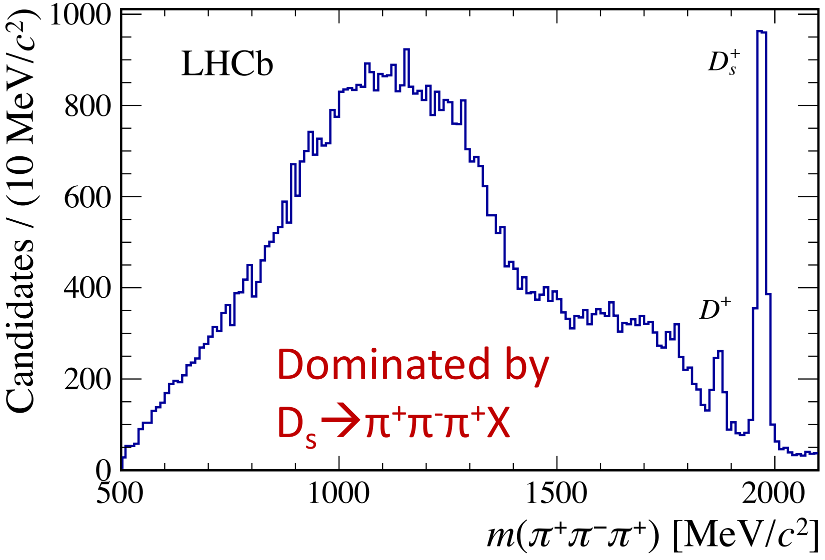
- Measurement of R(D*) using 3-prong hadronic $\tau^+ \rightarrow \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$ decays.
- Most abundant background $B \rightarrow D^{*-}\pi^+\pi^-\pi^+$(+neutrals) suppressed by requiring a significant displacement between the τ and B vertices.
- $B^0 \rightarrow D^{*-}\pi^+\pi^-\pi^+$ used as normalisation.
- Main remaining background due to $B \rightarrow D^{*-}DX$ decays, with $D \rightarrow \pi^+\pi^-\pi^+X$.
- Signal yield extracted from a 3D fit to q^2, τ decay time a BDT (includes kinematic and isolation variables).
- R(D*) = 0.285 ± 0.019(stat) ± 0.025(syst) ± 0.014(ext)

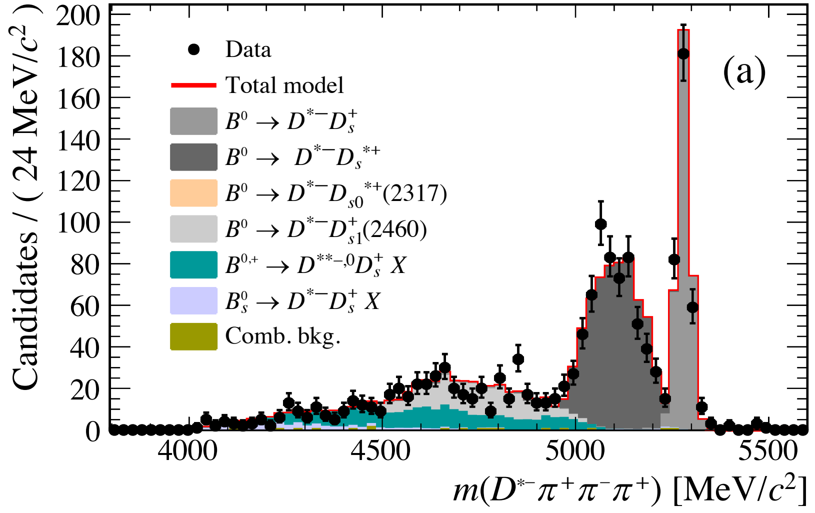


arXiv:1711.02505

Hadronic R(D*) at LHCb: systematics

- Main systematic uncertainties due to:
  - Size of simulated sample: it will be reduced by producing larger samples.
  - Shape of the $B \to D^*DX$ backgrounds: scales with statistics.
  - $D_{(s)}^+ \to \pi^+\pi^-\pi^+X$ decay model. BESIII future measurement will help to significantly reduce this uncertainty. Also, most of the inclusive $D_s^+ \to \pi^+\pi^-\pi^+X$ decays emit photons or π^0's. An upgraded ECAL would help very much in reducing this (the largest) background.
  - Branching fraction of normalisation mode $B^0 \to D^{*-}\pi^+\pi^-\pi^+$ known with ~4% precision. Belle II can measure it precisely.
  - The situation is worse in the case of, i.e.: $R(D^0)$, where the $B^+ \to D^0\pi^+\pi^-\pi^+$ branching fraction is known with ~40% precision.

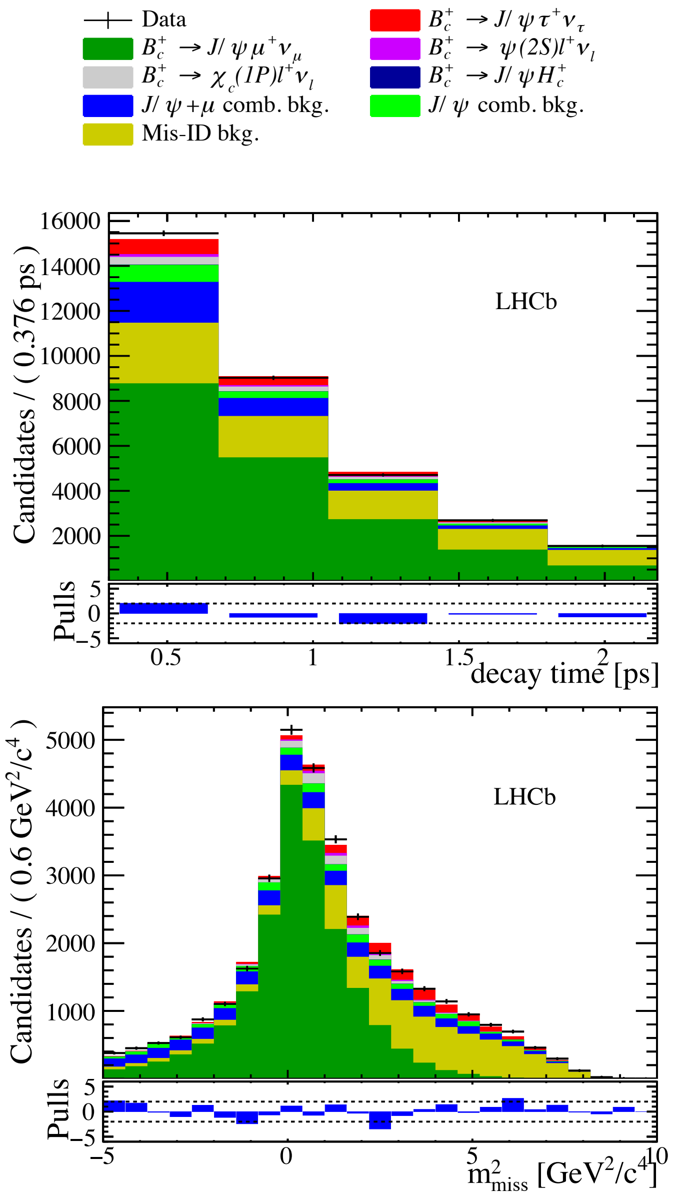




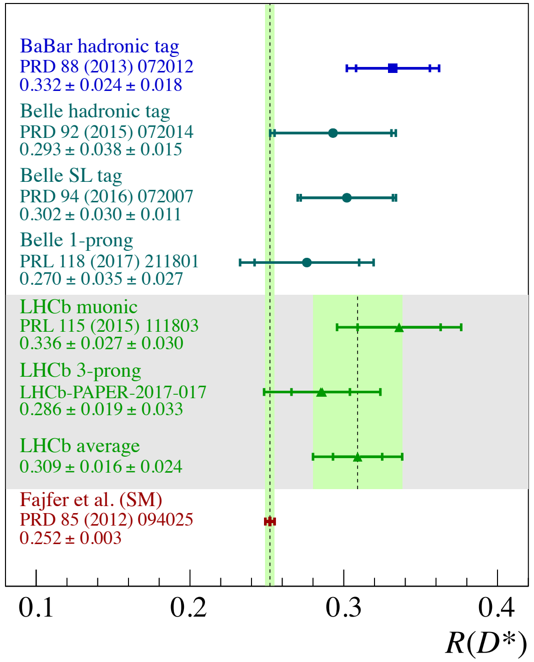
arXiv:1711.02505

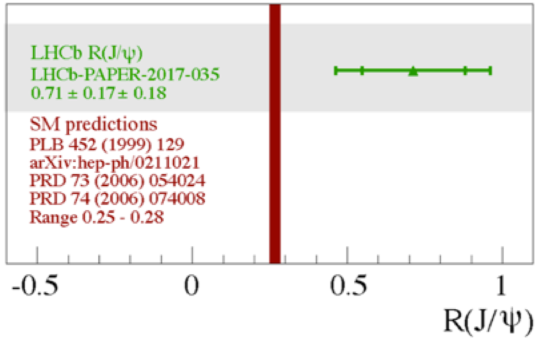
Measurement of R(J/ψ)

- Same reconstruction (p_B estimation) method as in the muonic R(D*) measurement ($\tau \rightarrow \mu\nu\nu$).
- Main backgrounds:
  - $B_c^+ \rightarrow J/\psi\mu\nu$, $B_c^+ \rightarrow \psi(2S)\mu\nu$, $B_c^+ \rightarrow J/\psi D(\rightarrow \mu\nu X)X$.
  - Hadron misidentified as a muon.
  - combinatorial background (J/ψ and μ not from same B).
- R(J/ψ) obtained from a 3D template fit, with form-factors obtained from a sample enriched in normalisation decays.
- 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).
- $R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$ ($R_{SM}(J/\psi) \sim 0.25\text{-}0.28$)

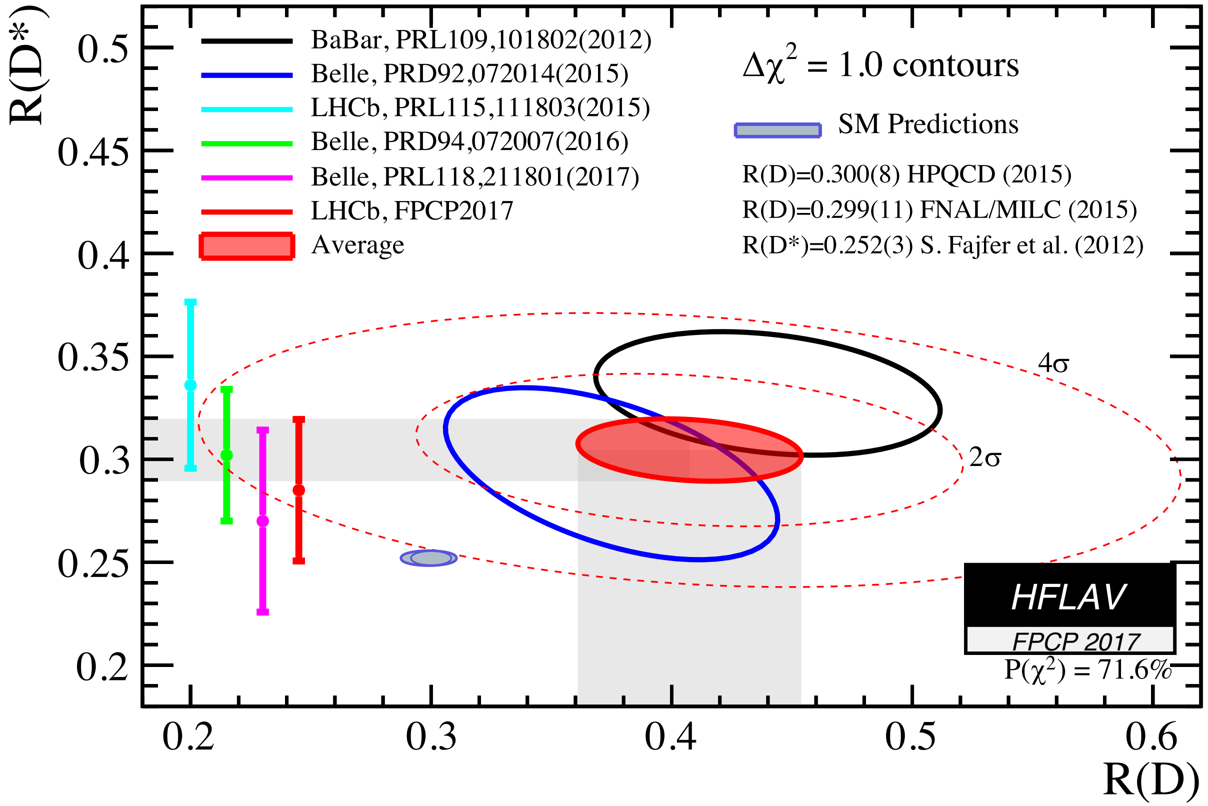


Summary on R(Xc)





- R(D)/R(D*) combination BaBar/Belle/LHCb at 4.1σ from the SM.



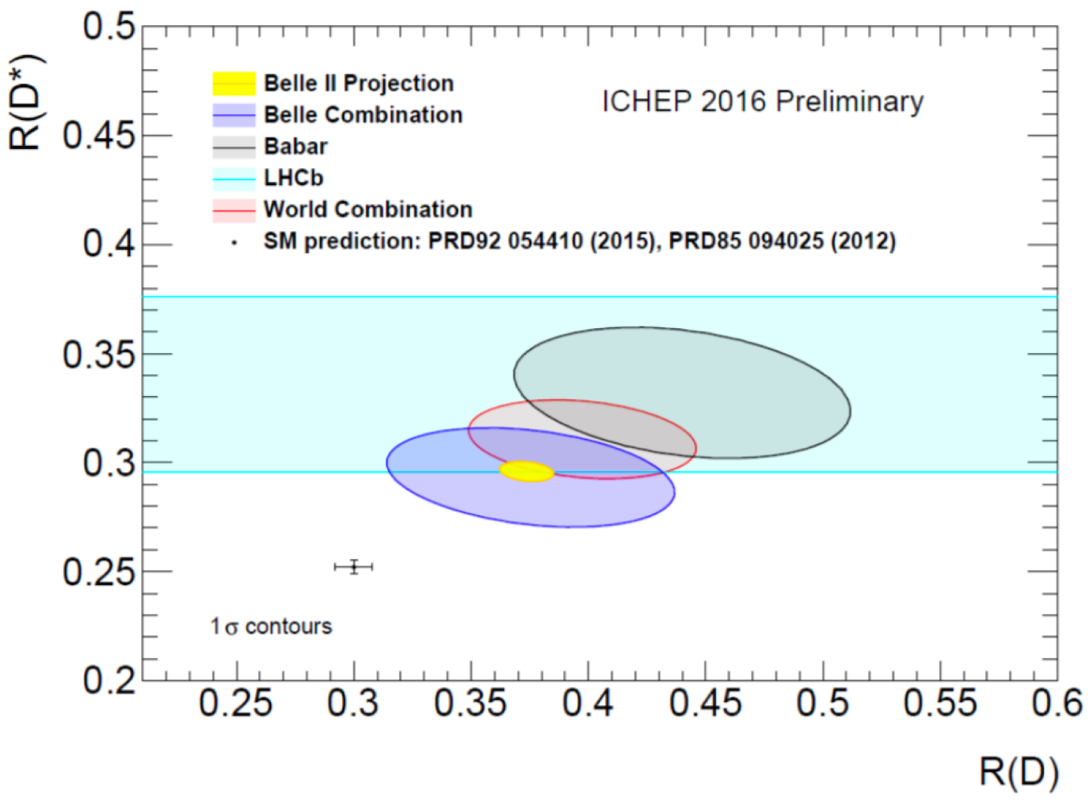
Belle II prospects on R(D) and R(D*)

- Improve the precision on R(D) and R(D*) to the 2-4% level.
- Better control on backgrounds like B→D**lν, very important for these measurements.
- Perform measurements of τ and D* polarisation.

Belle II projection:

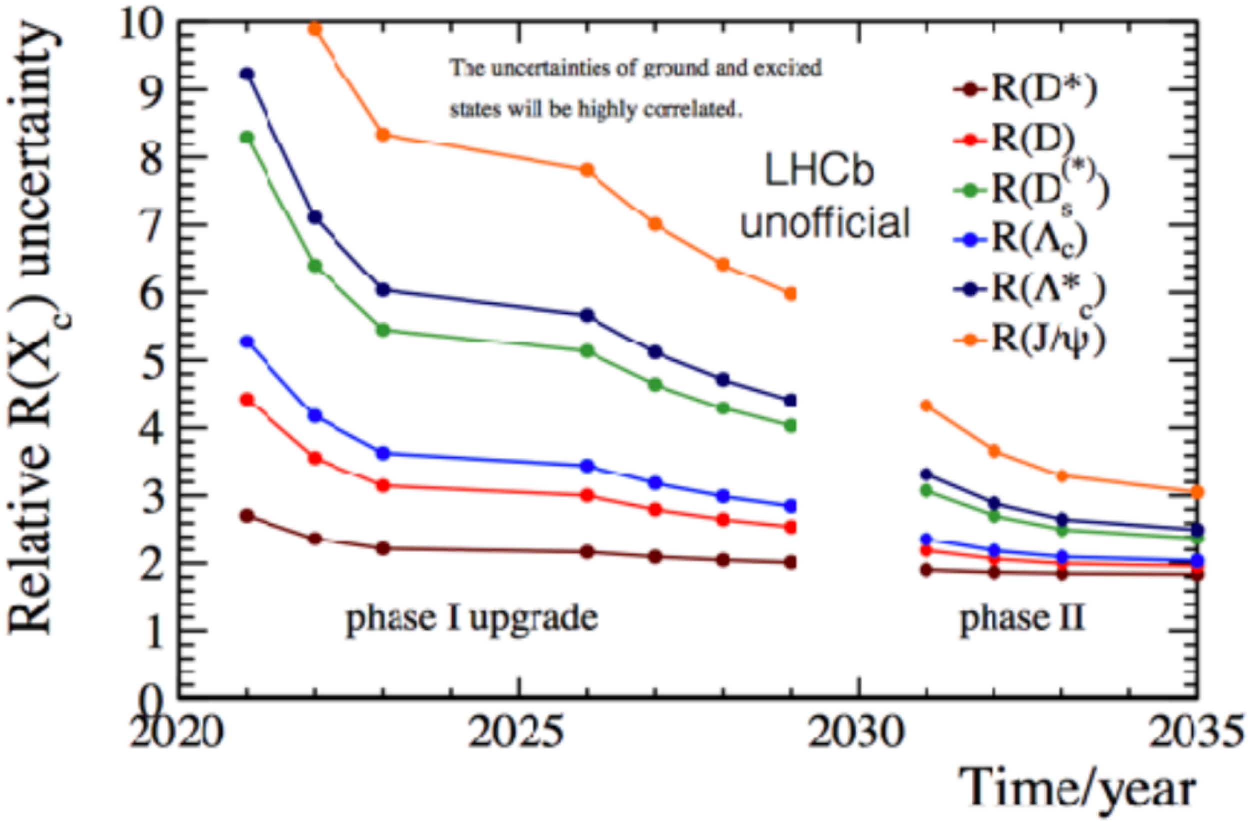
	5 ab^{-1}	50 ab^{-1}
R(D)	(6.0+-3.9)%	(2.0+-2.5)%
R(D*)	(3.0+-2.5)%	(1.0+-2.0)%
P_τ(D*)	0.18+-0.08	0.06+-0.04

First uncertainty statistical and second systematic



LHCb prospects on $R(X_c)$

- LHCb can perform measurements of LFU not accessible at Belle II:
  - $R(\Lambda_c^{(*)})$, $R(J/\psi)$ (also $R(D_s^{(*)})$).
- Production fractions and efficiencies used to extrapolate the uncertainties.
- Precision in $R(X_c)$ about 2-3% at the end of the Upgrade phase II (LHCb unofficial).
- Sensitivity to angular observables need to be studied.



Conclusions

- Study of semitauonic B decays at LHCb very challenging due to the missing neutrinos and no missing-mass constraint.
- LHCb is able to perform measurements on semitauonic B decays using $\tau \to \mu\nu\nu$ and $\tau^+ \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$ decays.
- The precision is comparable to that of Belle and BaBar.
- $R(J/\psi)$ measured for the first time (first evidence of $B_c^+ \to J/\psi\tau\nu$).
- Measurements of $R(\Lambda_c^{(*)})$, $R(J/\psi)$ and $R(D_s^{(*)})$ only possible at LHCb.
- Both Belle II and LHCb aim to measure R(D) and R(D*) with 2-3% precision.

BACKUP

Systematic uncertainties muonic R(D*)

Model uncertainties	Absolute size ($\times 10^{-2}$)
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\bar{B}^0 \to D^{*+}(\tau^-/\mu^-)\bar{\nu}$ form factors	0.6
$\bar{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^{**}\mu^-\bar{\nu}_\mu)$	0.5
$\bar{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\bar{B} \to D^{**}(\to D^{*+}\pi)\mu^-\bar{\nu}_\mu$ form factors	0.3
$\bar{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form factors	0.2
$\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

Systematic uncertainties hadronic R(D*)

Contribution	Value in %
$\mathcal{B}(\tau^+ \to 3\pi\overline{\nu}_\tau)/\mathcal{B}(\tau^+ \to 3\pi(\pi^0)\overline{\nu}_\tau)$	0.7
Form factors (template shapes)	0.7
τ polarization effects	0.4
Other τ decays	1.0
$B \to D^{**}\tau^+\nu_\tau$	2.3
$B_s^0 \to D_s^{**}\tau^+\nu_\tau$ feed-down	1.5
$D_s^+ \to 3\pi X$ decay model	2.5
D_s^+, D^0 and D^+ template shape	2.9
$B \to D^{*-}D_s^+(X)$ and $B \to D^{*-}D^0(X)$ decay model	2.6
$D^{*-}3\pi X$ from B decays	2.8
Combinatorial background (shape + normalization)	0.7
Bias due to empty bins in templates	1.3
Size of simulation samples	4.1
Trigger acceptance	1.2
Trigger efficiency	1.0
Online selection	2.0
Offline selection	2.0
Charged-isolation algorithm	1.0
Normalization channel	1.0
Particle identification	1.3
Signal efficiencies (size of simulation samples)	1.7
Normalization channel efficiency (size of simulation samples)	1.6
Normalization channel efficiency (modeling of $B^0 \to D^{*-}3\pi$)	2.0
Form factors (efficiency)	1.0
Total uncertainty	9.1

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

- The measured $q^2 = (p(\Lambda_b) - p(\Lambda_c))^2 = (p_\mu + p_\nu)^2$ distribution of $\Lambda_b^0 \to \Lambda_c^+ \mu^- \nu$ 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), $\xi_B(w)$.

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

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

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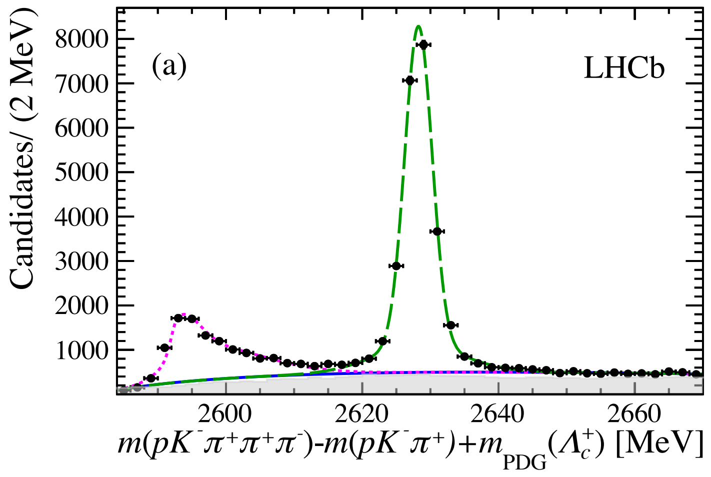
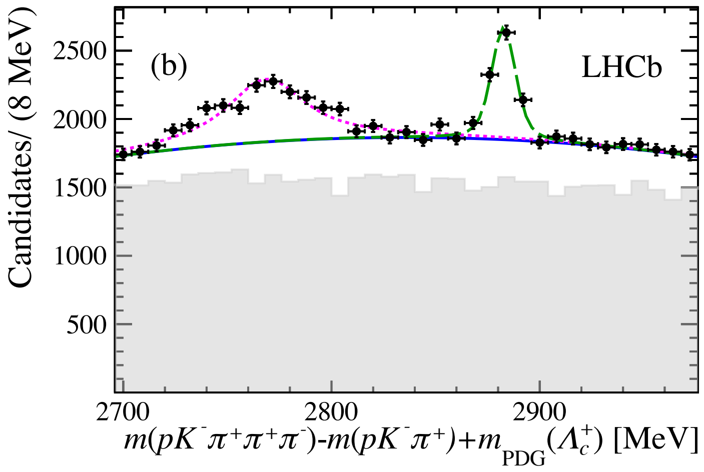
Shape of $\Lambda_b^0 \to \Lambda_c^+ \mu^- \nu$ differential decay rate

- Need to subtract feed-down from higher resonances.



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

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

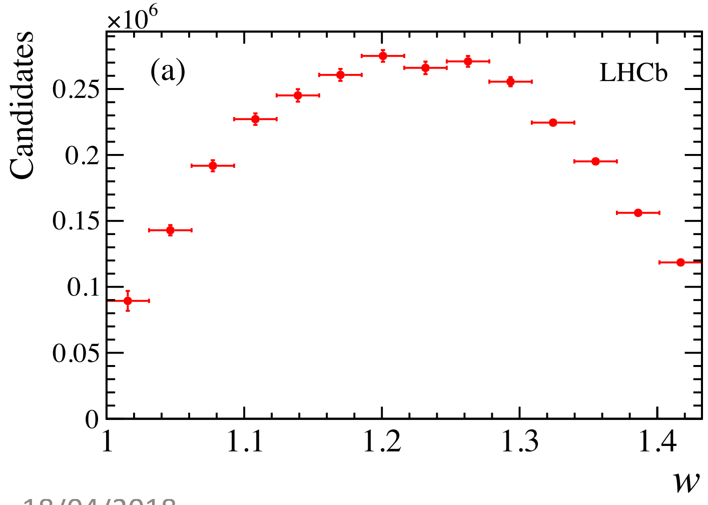


$\Lambda_c(2765)^+ \to \Lambda_c^+\pi^+\pi^-$

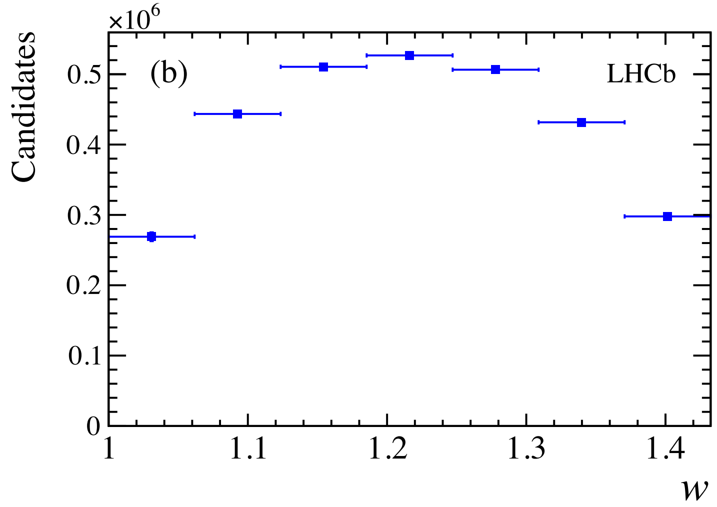
$\Lambda_c(2880)^+ \to \Lambda_c^+\pi^+\pi^-$

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

Reconstructed



Unfolded



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

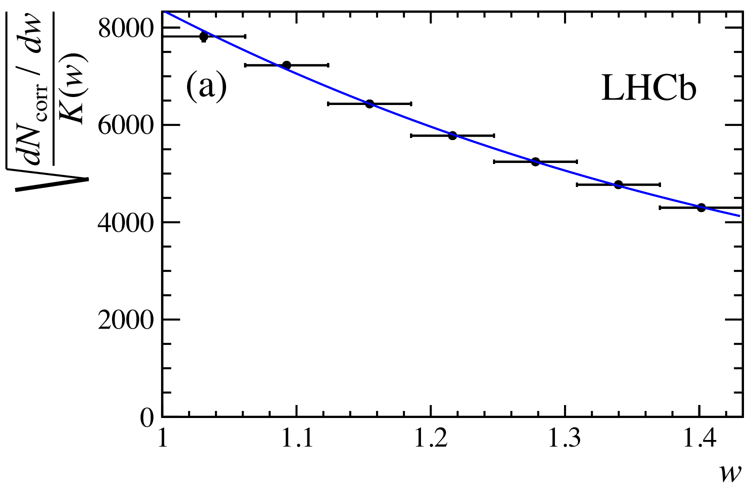
1. w distribution is then corrected by efficiency.

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.

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

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]

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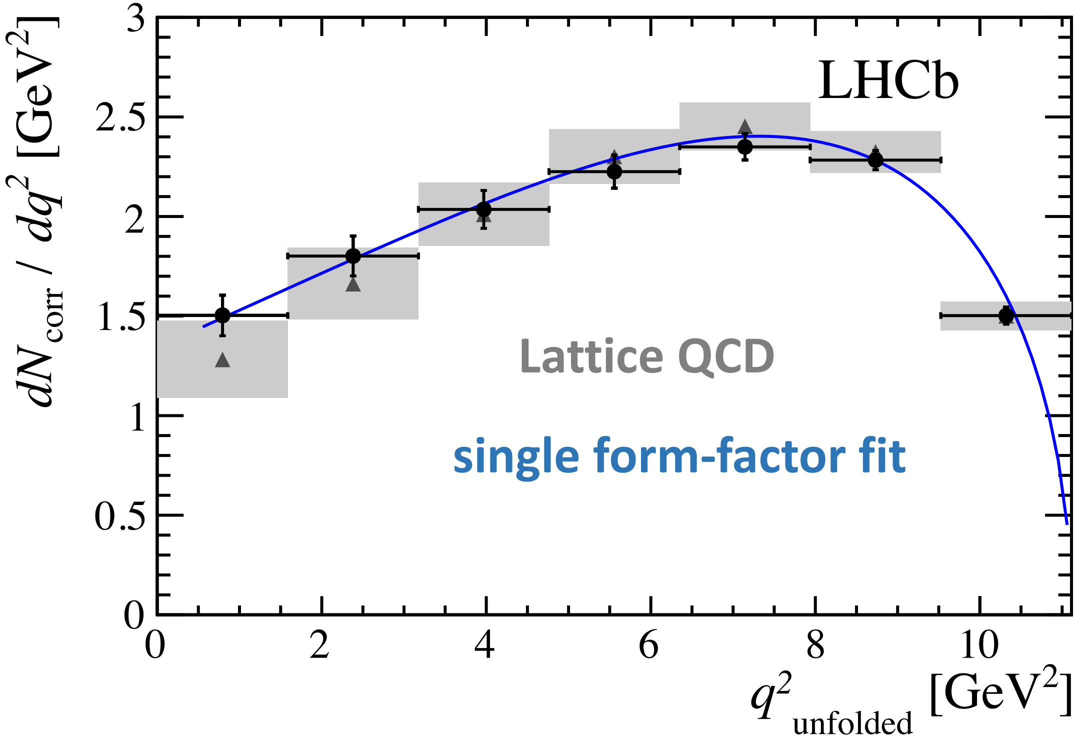
Shape of $\Lambda_b^0 \to \Lambda_c^+ \mu^- \nu$ differential decay rate

- 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 $|V_{cb}|$.



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