Semileptonic decays in LHCb

Guy Wormser (IJCLab)
on behalf of the LHCb Collaboration

LP2021 Conference Manchester

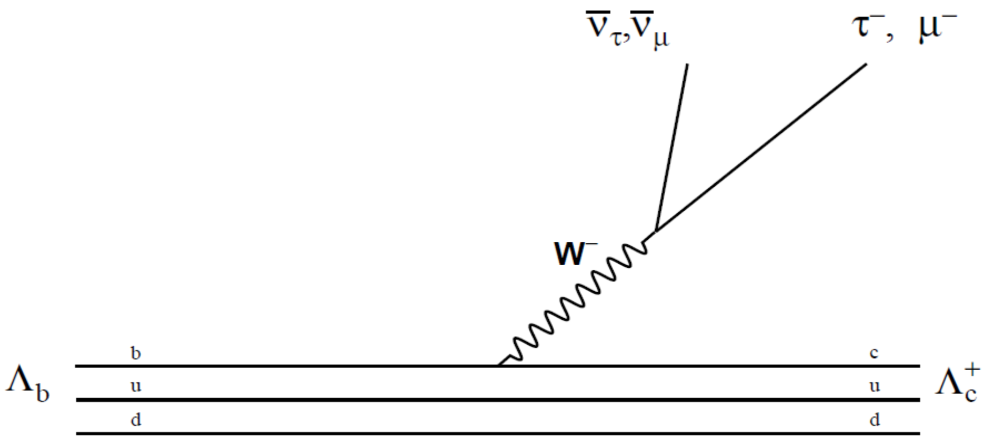
Recent semileptonic results from LHCb

- First observation of the decay $B_s^0 \to K^- \mu^+ \nu_\mu$ and a measurement of $|V_{ub}|/|V_{cb}|$
  Phys. Rev. Lett. 126, 081804 (2021)
- Measurement of $|V_{cb}|$ with $B_s^0 \to D_s^{(*)-} \mu^+ \nu_\mu$ decays Phys. Rev. D 101 (2020) 072004
- Measurement of the shape of the $B_s^0 \to D_s^{*-} \mu^+ \nu_\mu$ differential decay rate
  JHEP 2012 (2020) 144
- Observation of the semileptonic decay $B^+ \to p\bar{p}\mu^+\nu_\mu$ JHEP 2003 (2020) 146

- Observation of the decay $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$ with $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$ decay
  LHCb-PAPER-2021-044 arxiv:2201:03497

- Observation of a Λ_b-$\bar{\Lambda}_b$ production asymmetry in proton-proton collisions at $\sqrt{s}$ =7,8 TeV, JHEP 2110 (2021) 060
- Measurement of B_c^- production fraction and asymmetry at 7 and 13 TeV pp collisions, Phys. Rev. D 100 (2019) 112006

Why Lepton Flavour Universality tests with Λ_b^0 are interesting ?



$$\mathcal{R}(\Lambda_c^+) \equiv \mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)/\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)$$

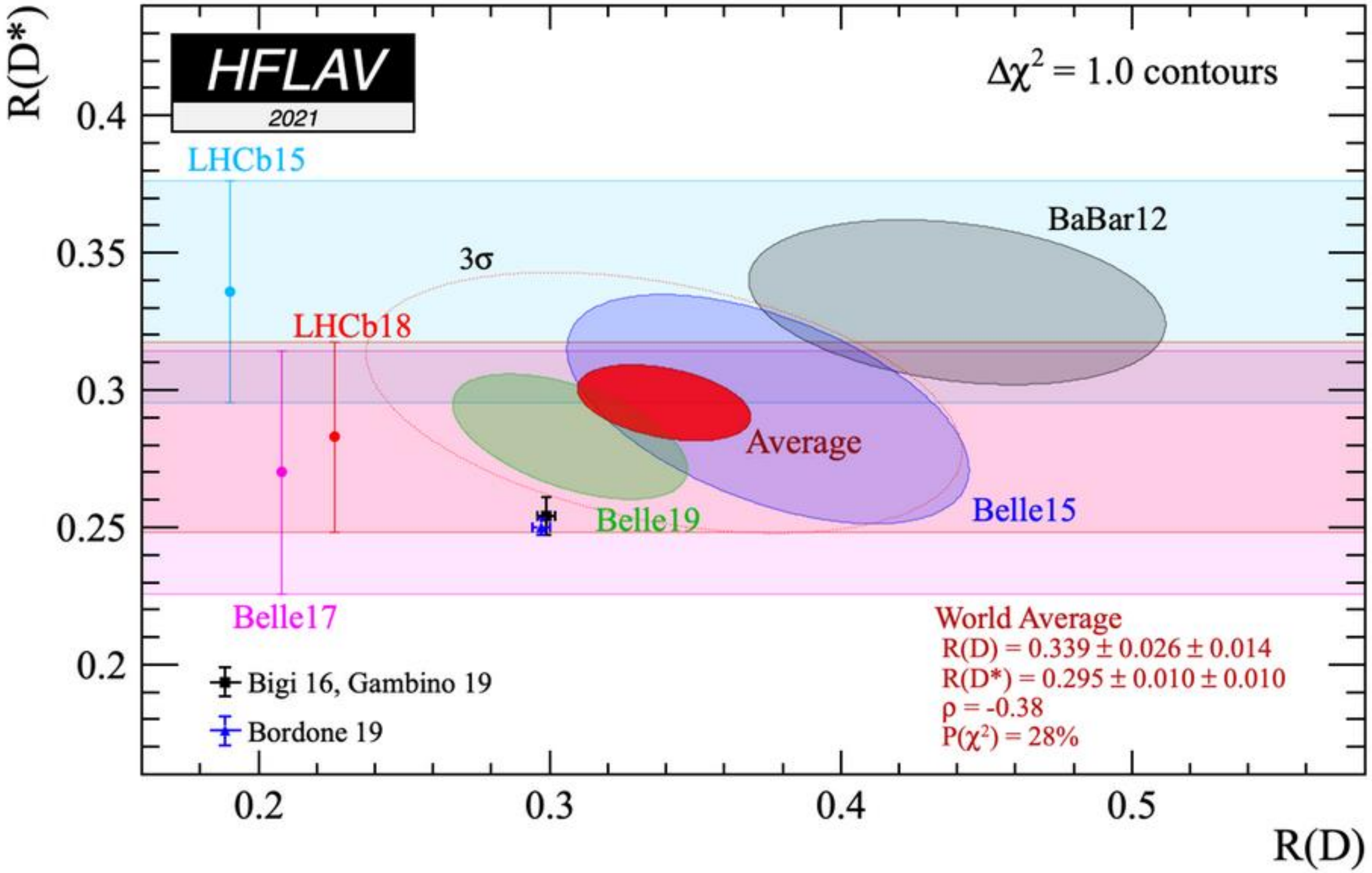
- Lepton Flavour Universality violation hints in the meson sector $\mathcal{R}(D^*)$-$\mathcal{R}(D)$: 3.4 σ away from SM in the latest 2021 HFLAV update
- With spin ½ spectator, the baryonic channel adds a very complementary test
- Similar precision on SM prediction with lattice QCD computations

$\mathcal{R}(\Lambda_c^+)_{SM}$= 0,324 ± 0,004 F. Bernlochner et al., Physical Review D 99 055008 (2019)

with input from Lattice QCD FF: W. Detmold, C. Lehner, S. Meinel, Physical Review D 92 034503 (2015)

- But different NP couplings: could help pin down NP source
- Unique to LHCb. Never searched for before!

Most recent update of $\mathcal{R}(D^*)$-$\mathcal{R}(D)$ status



NP expectations for $\mathcal{R}(\Lambda_c^+)$ in various models

A. Datta et al., Journal of High Energy Physics 1708 (2017) 131

	g_S only	g_P only	g_L only	g_R only	g_T only
	-0.4	0.3	-2.2	-0.044	0.4
$R(\Lambda_c)$	0.290 ± 0.009	0.342 ± 0.010	0.479 ± 0.014	0.344 ± 0.011	0.475 ± 0.037
$R^{Ratio}_{\Lambda_c}$	0.872 ± 0.007	1.026 ± 0.001	1.44	1.033 ± 0.003	1.426 ± 0.100
	$-1.5 - 0.3i$	$0.4 - 0.4i$	$0.15 - 0.3i$	$0.08 - 0.67i$	$0.2 - 0.2i$
$R(\Lambda_c)$	0.384 ± 0.013	0.346 ± 0.011	0.470 ± 0.014	0.465 ± 0.014	0.404 ± 0.021
$R^{Ratio}_{\Lambda_c}$	1.154 ± 0.008	1.040 ± 0.002	1.412	1.397 ± 0.005	1.213 ± 0.050

$\mathcal{R}(\Lambda_c^+)$ can be below or well above SM , when satisfying $\mathcal{R}$(D*)-$\mathcal{R}$(D) constraints

NP predictions with all present constraints from the meson sector

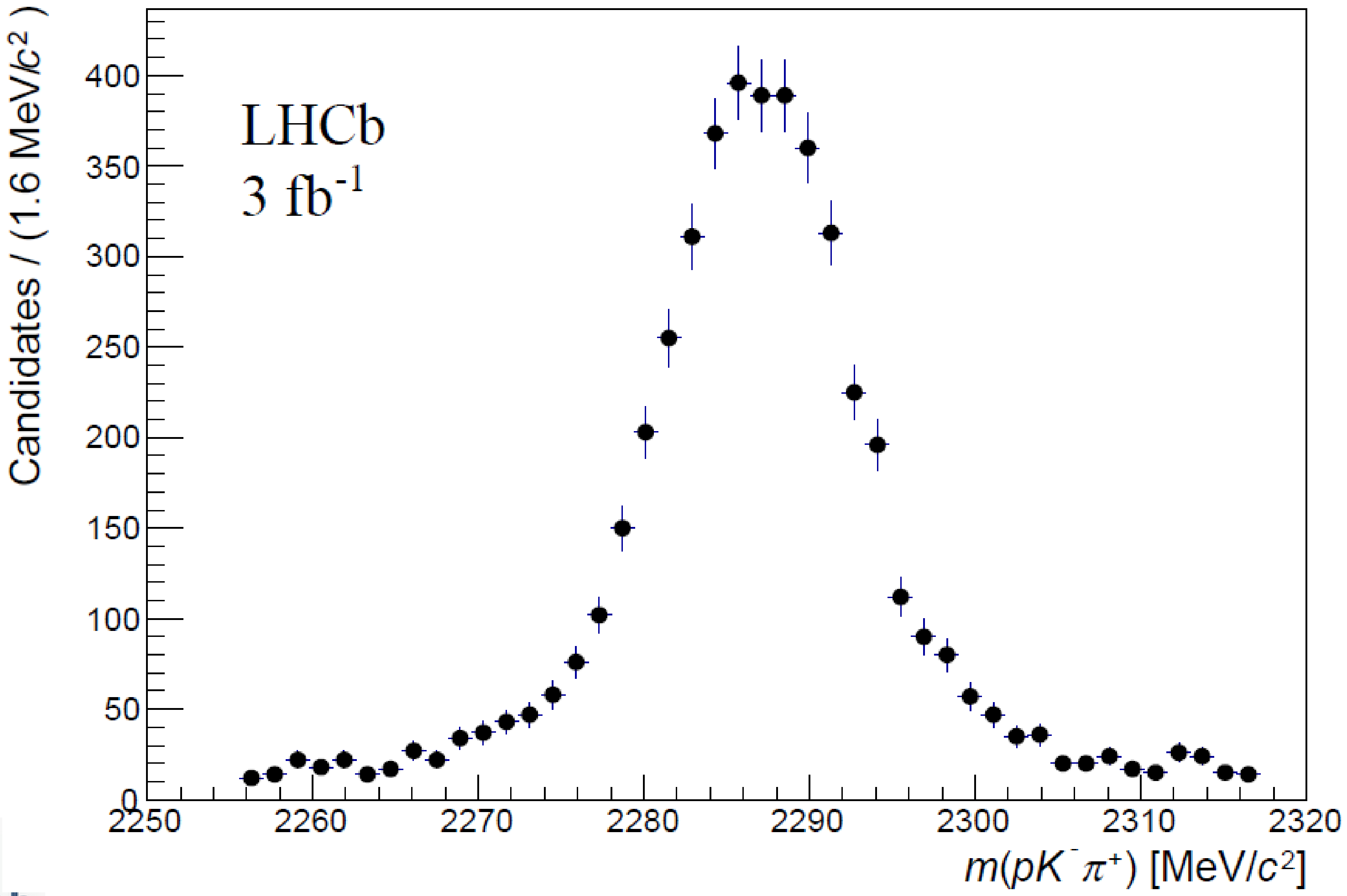
Coupling	$R(\Lambda_c)_{max}$	$R^{Ratio}_{\Lambda_c,max}$	coupling value	$R(\Lambda_c)_{min}$	$R^{Ratio}_{\Lambda_c,min}$	coupling value
g_S only	0.405	1.217	0.363	0.314	0.942	-1.14
g_P only	0.354	1.062	0.658	0.337	1.014	0.168
g_L only	0.495	1.486	$0.094 + 0.538i$	0.340	1.022	$-0.070 + 0.395i$
g_R only	0.525	1.576	$0.085 + 0.793i$	0.336	1.009	-0.012
g_T only	0.526	1.581	0.428	0.338	1.015	-0.005

$\mathcal{R}(\Lambda_c^+)$ analysis workflow with $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$

- Tight Λ_c^+ PID selection in pKπ mode. Λ_c^+ sideband template used in the signal fit to remove the background under the Λ_c^+ peak
- Combine with detached $\pi^-\pi^+\pi^-$ triplet forming τ^- candidates
- Prompt background rejection thanks to vertex topology
- Reconstruct decay kinematics
- D_s^- and D^0 exclusive peaks to control double charm background
- Anti-D_s^- to reject double charm background
- Normalisation channel : $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ (without $\Lambda_c^{*+}\pi^-$) [same final state and similar dynamics]

Tight Λ_c^+ selection

LHCb-PAPER-2021-044
arxiv:2201:03497



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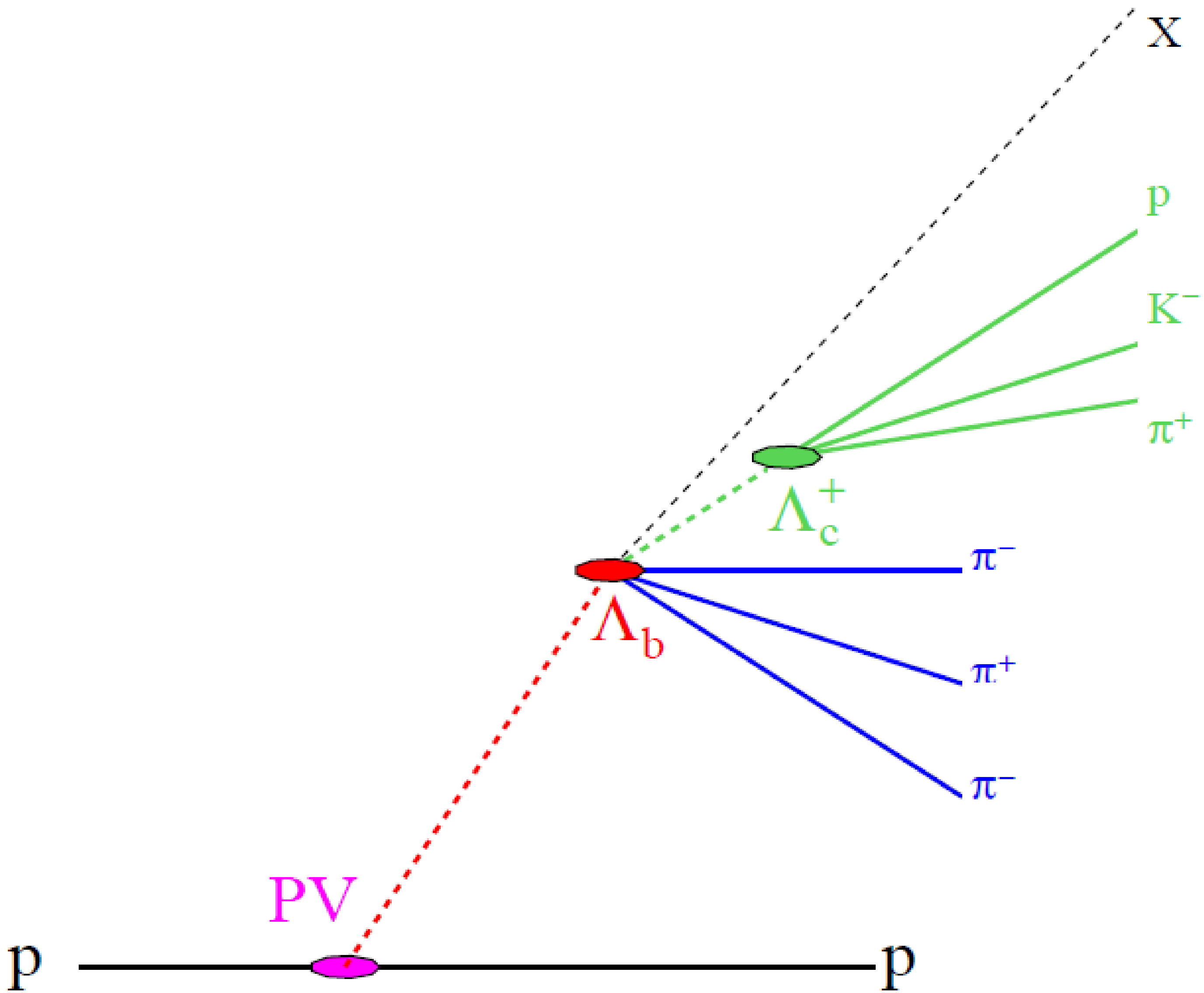
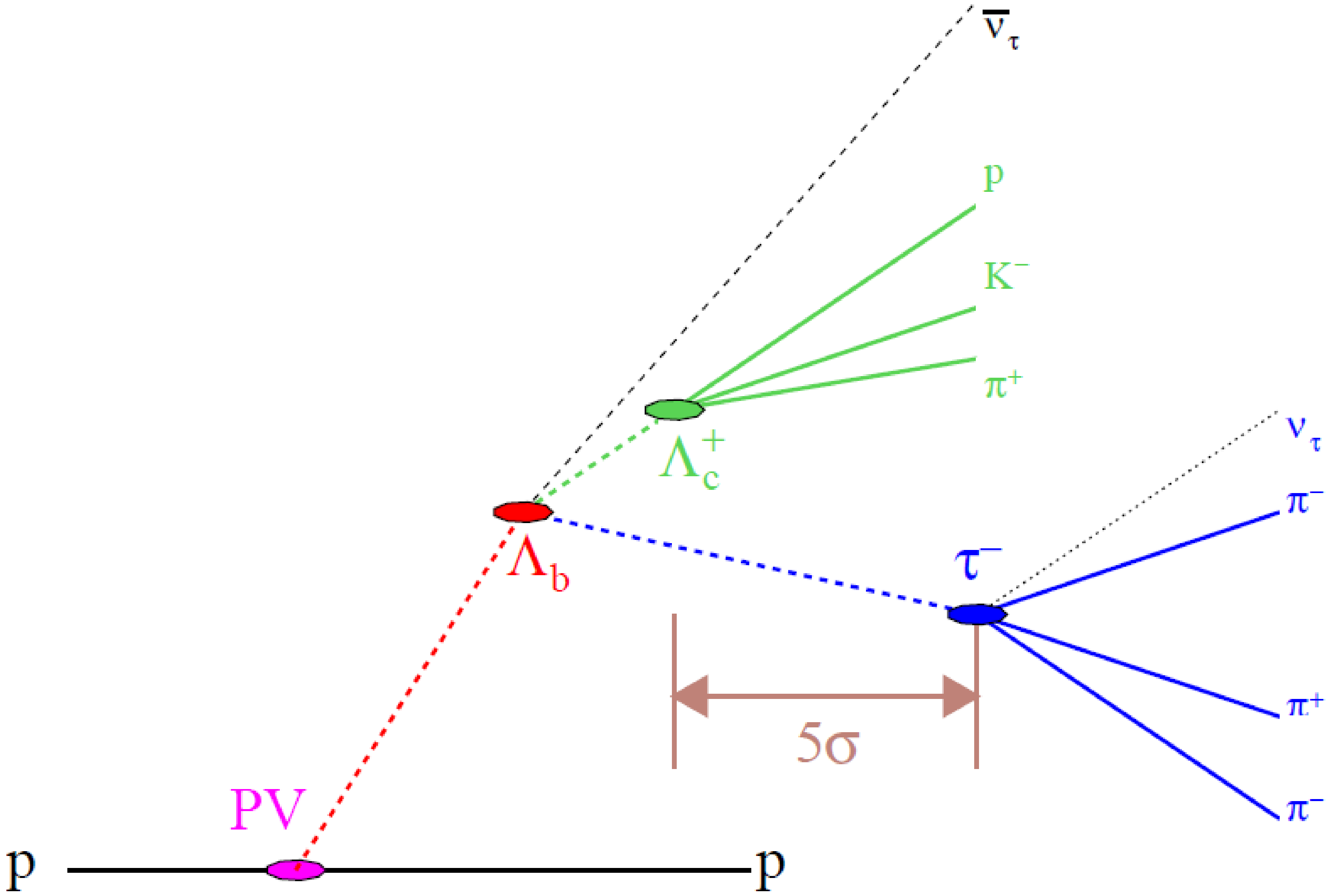
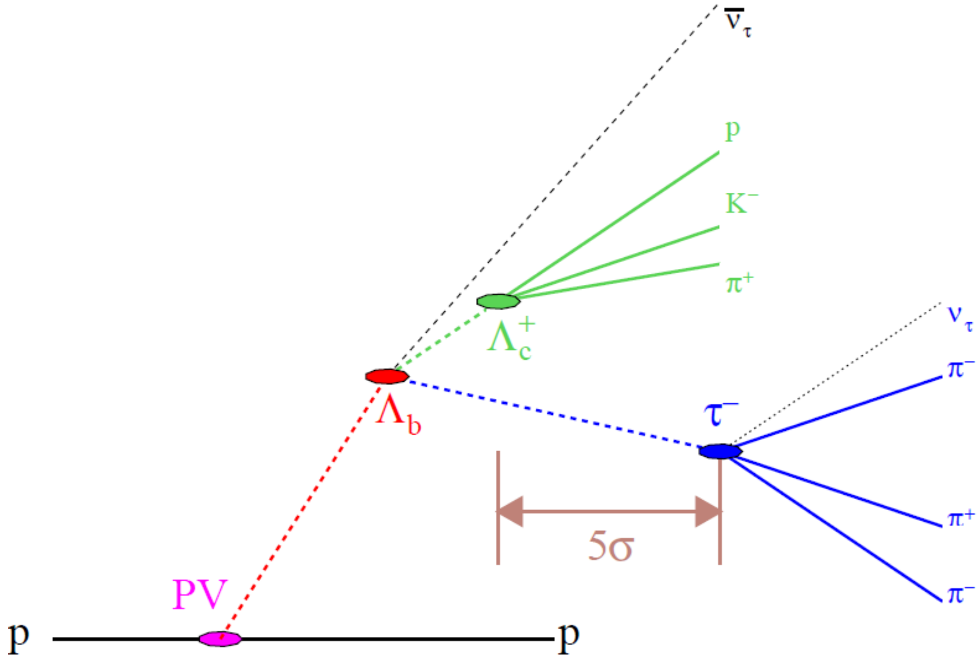

X
p
K⁻
π⁺
Λc+
π⁻
Λb
π⁺
π⁻
PV
p
p

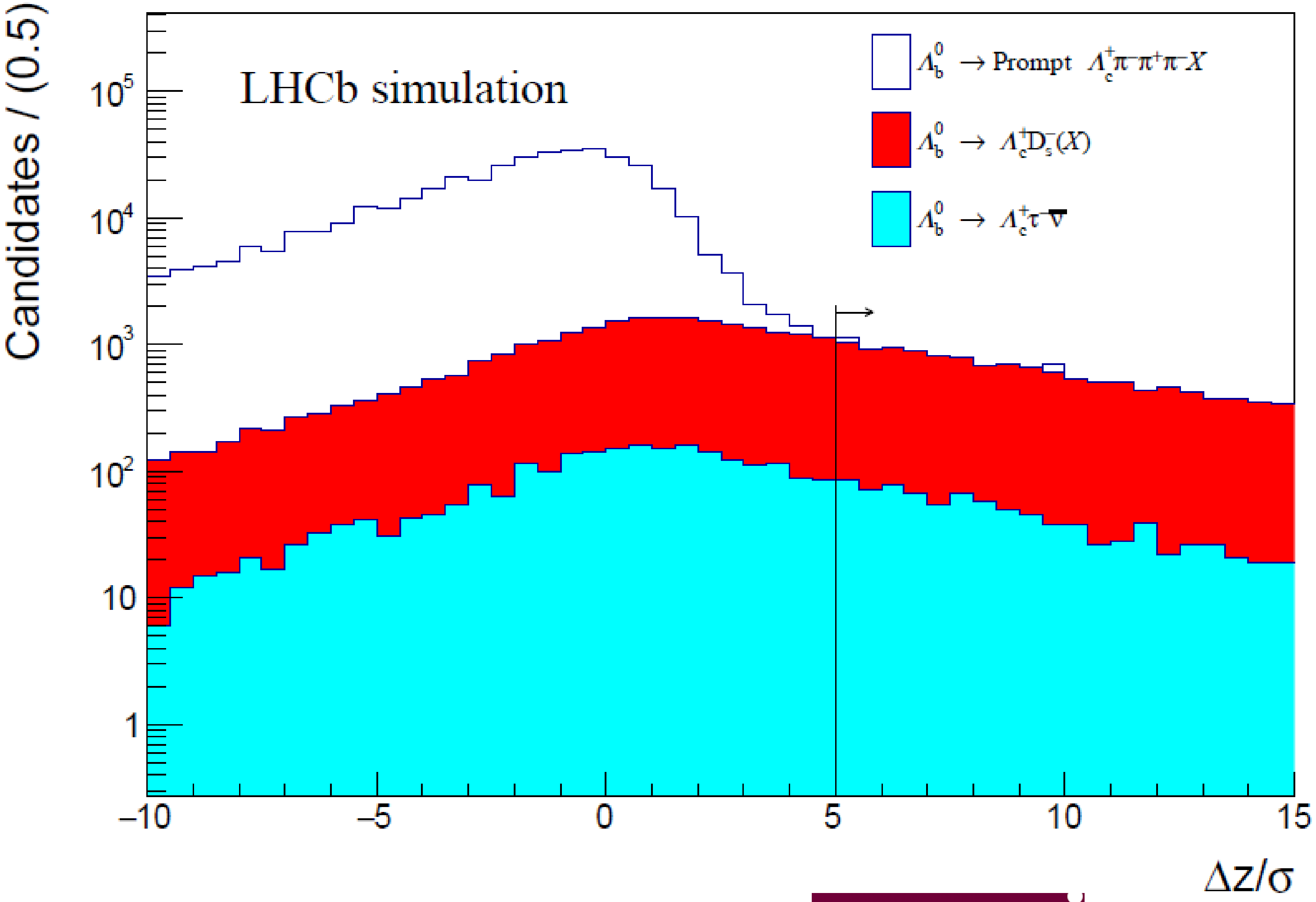


$\bar{\nu}_\tau$
p
K^-
π^+
Λ_c^+
ν_τ
π^-
Λ_b
τ^-
5σ
π^+
π^-
PV
p
p

« Prompt » background rejection



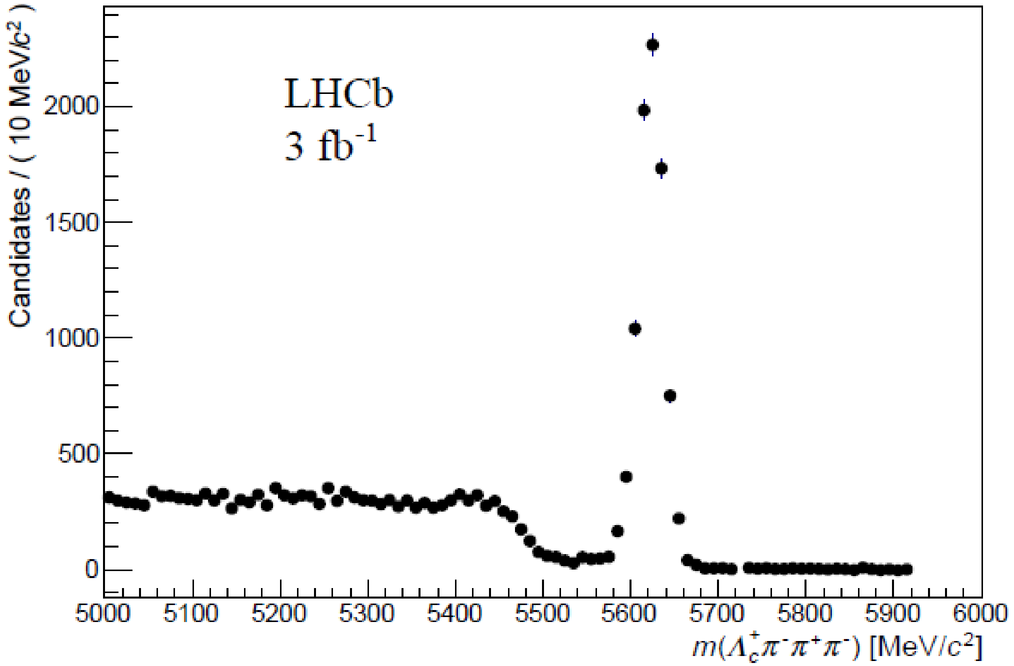
Prompt rejection ~5x10^3 level after the 5σ inversion cut



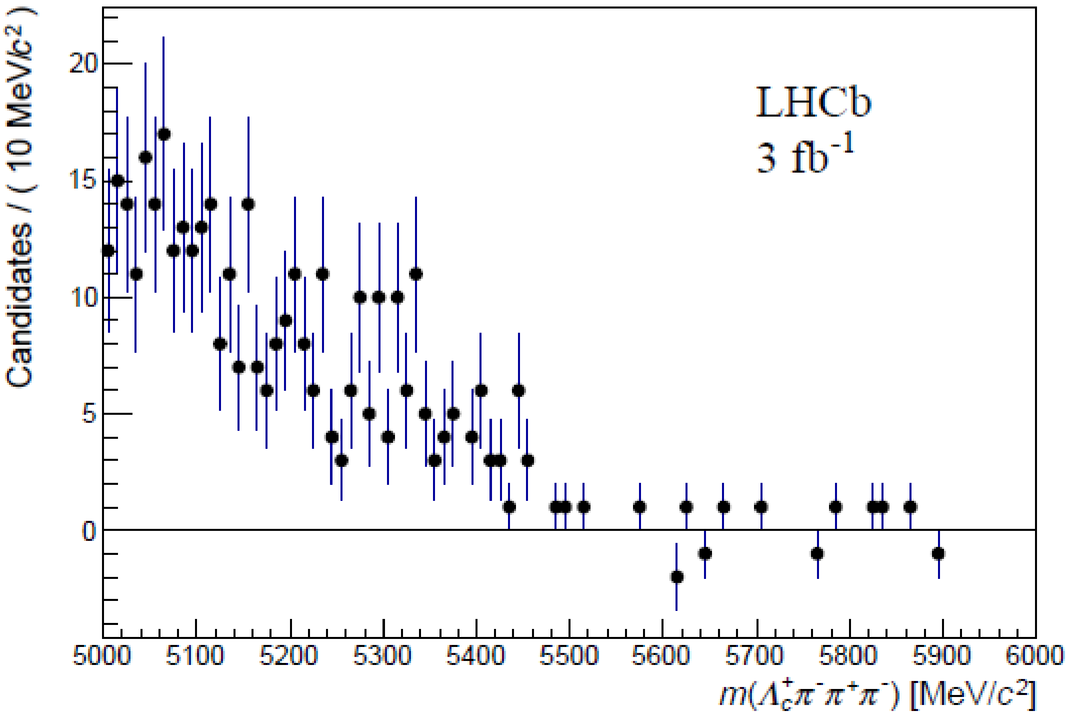
Control of the suppression factor with the normalisation channel : $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$

LHCb-PAPER-2021-044 arxiv:2201:03497

Before inverted topology cut



After inversion



$\mathcal{R}(\Lambda_c^+)$ analysis workflow

- Tight Λ_c^+ PID selection. Λ_c^+ sideband template used in the signal fit to remove the background under the Λ_c^+ peak
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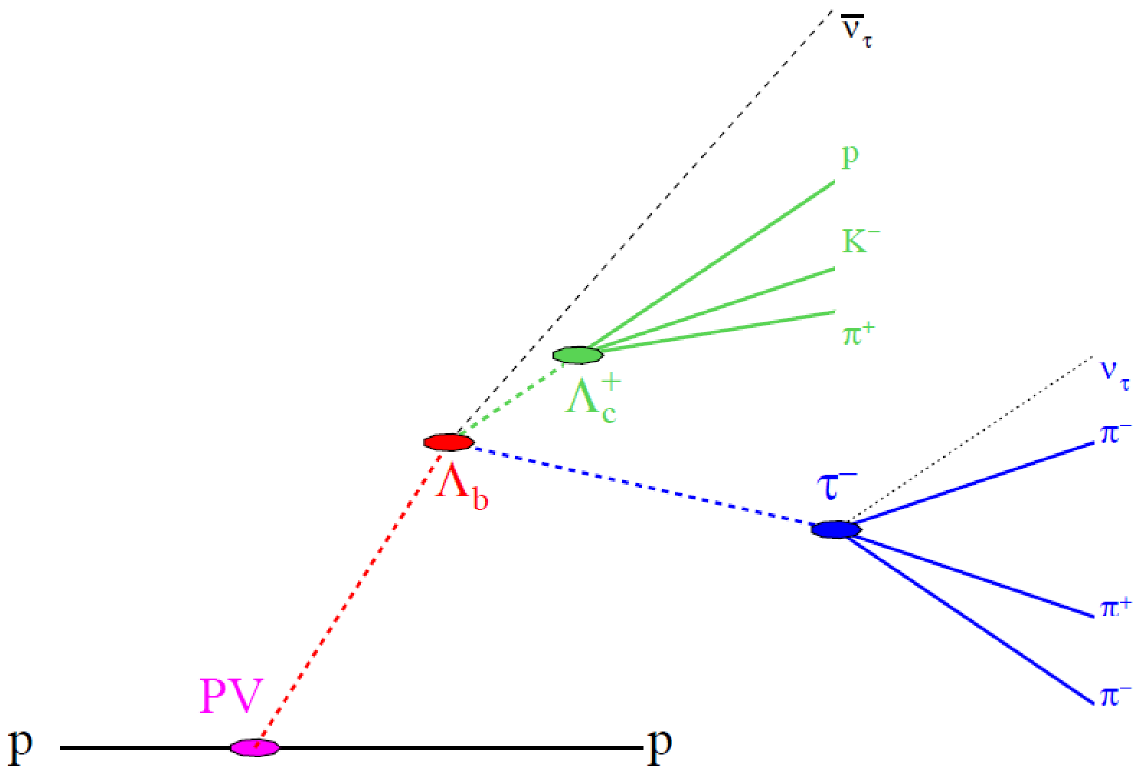
Reconstruction of the kinematics



- Using the position of the three vertices, the direction of flight of the Λ_b^0 and of the τ particles can be reconstructed.
- The momenta of these 2 particles by solving two 2nd-degree equations
- τ pseudo decay time and q^2 can be measured with a 15% resolution

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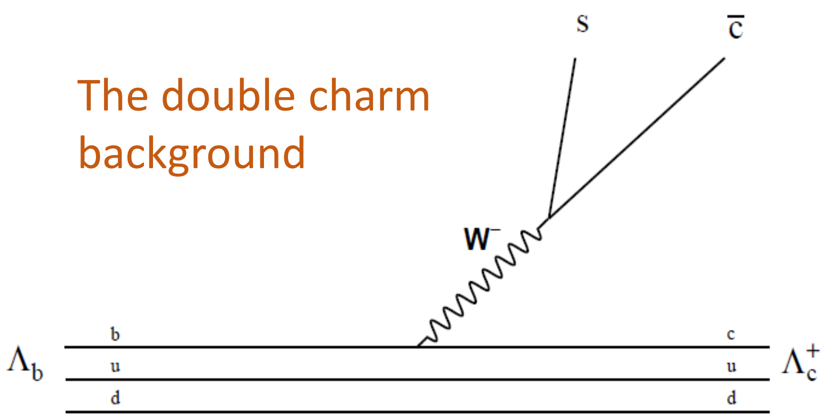
Distribution of the 3π mass after final selection

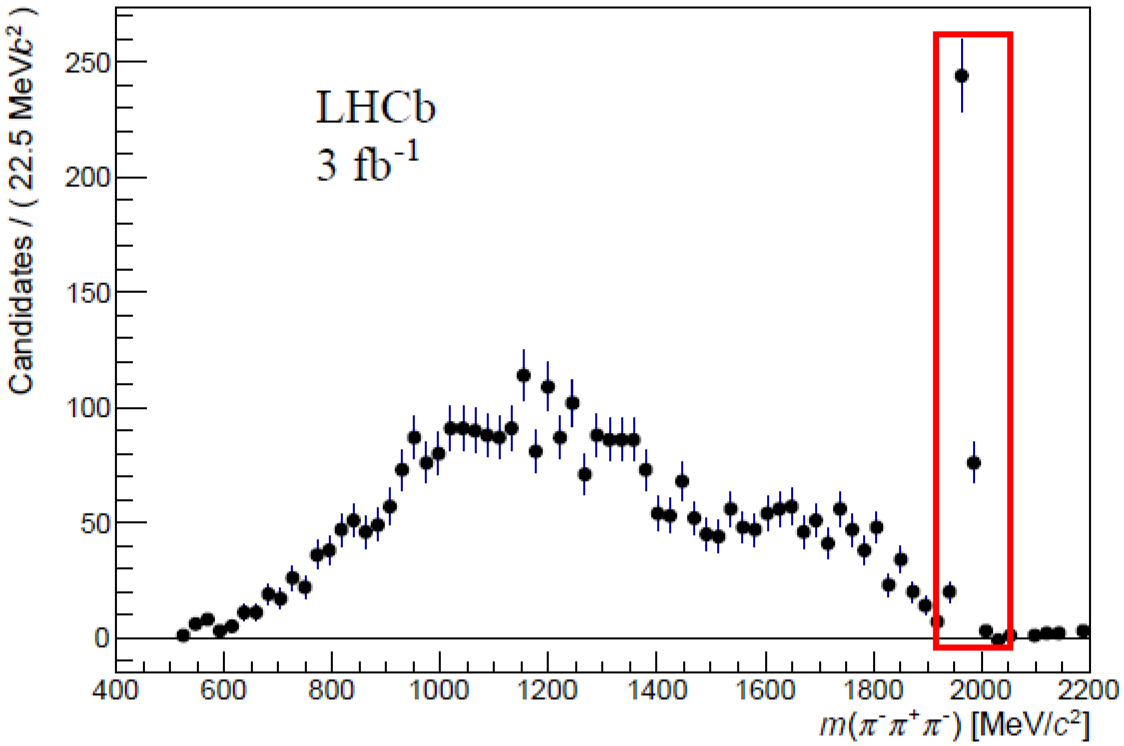
LHCb-PAPER-2021-044
arxiv:2201:03497

BR(D_s^- →3πX)~ 30xBR(D_s^- → πππ)

$D_s^{(*,**)-}$, $D^{(*)0}K^-$, $D^{(*)+}K^0$

The double charm background

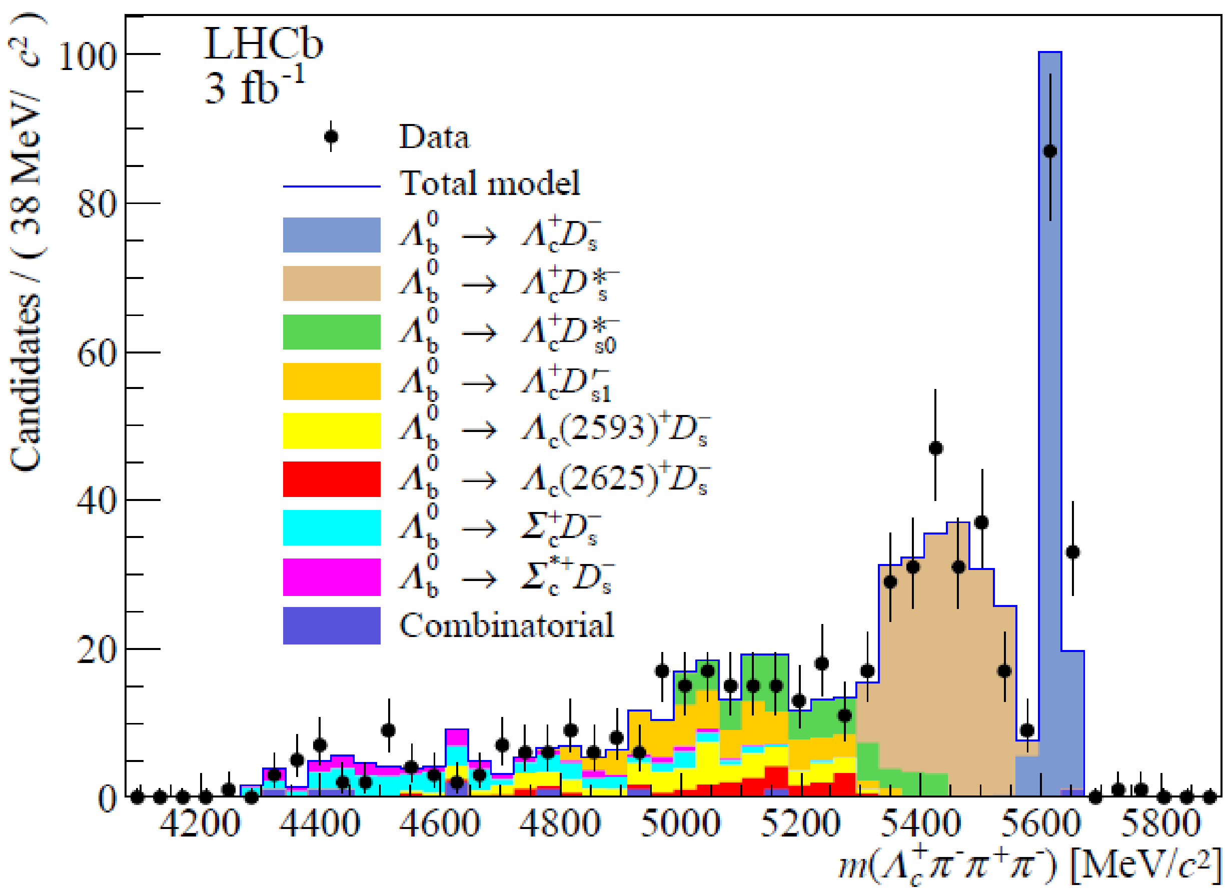




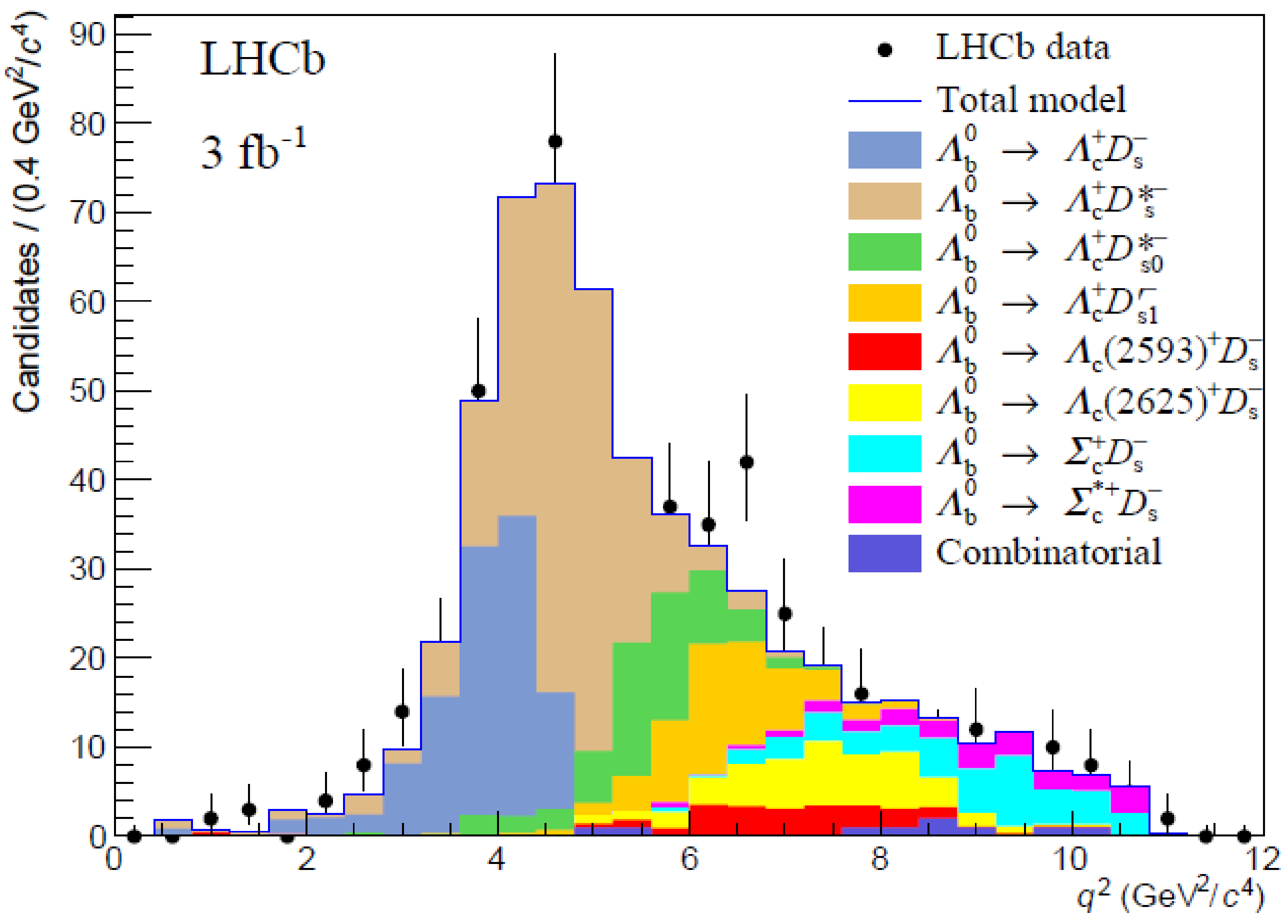
No candidates above the D_s^- mass : completely dominated by double charm background

The exclusive $\Lambda_c^+ D_s^-(X)$ control sample

LHCb-PAPER-2021-044 arxiv:2201:03497



Fit to the $\Lambda_b \rightarrow \Lambda^+_c \pi^- \pi^+ \pi^-$ mass distribution



Projection on q^2

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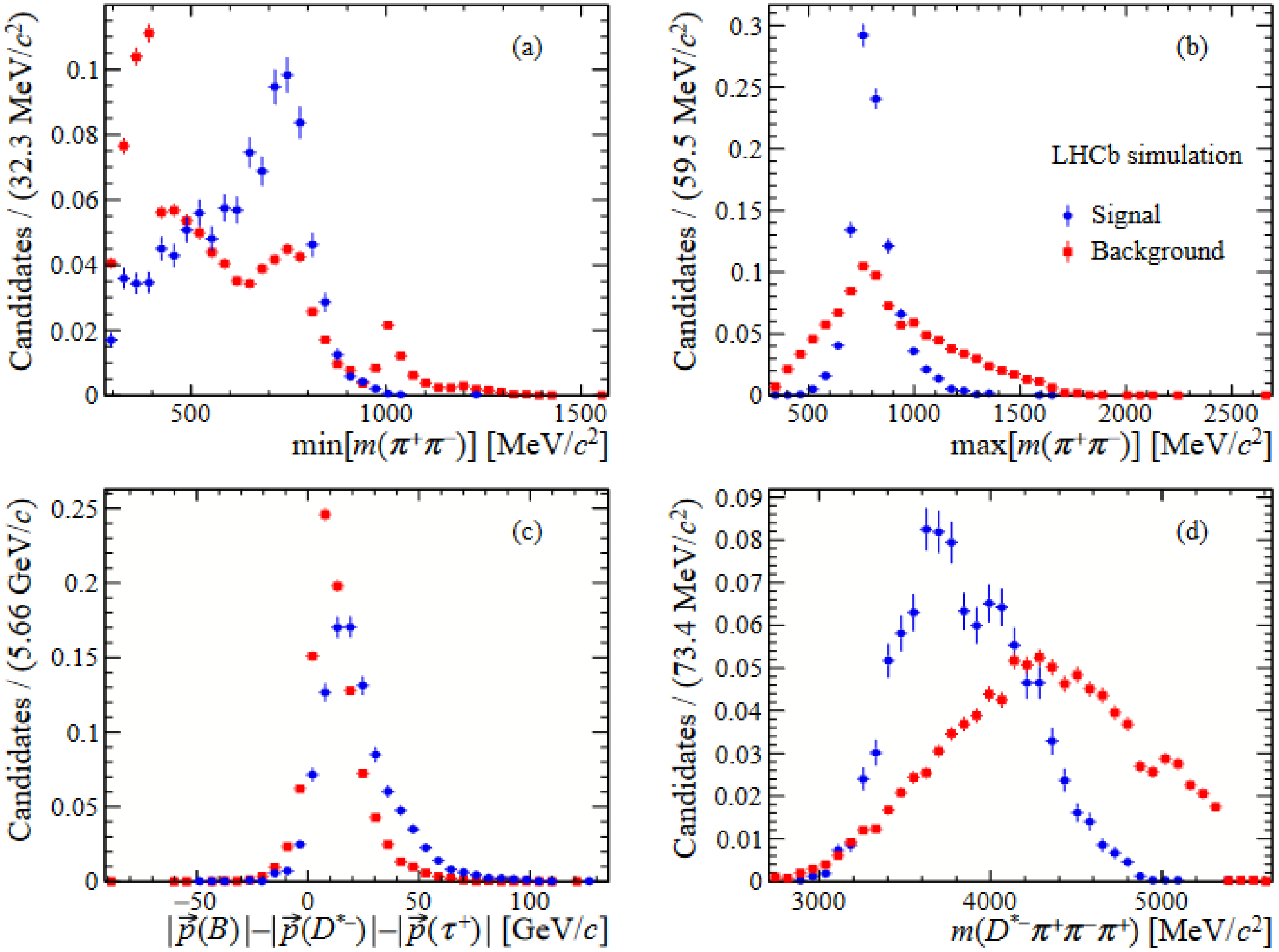
The anti- D_s^- BDT: 3π dynamics key to separate D_s^- from τ^- decays



τ^- decays thru $a_1^+ \rightarrow \rho^0\pi^+$: ρ^0 peak in both $\pi^+\pi^-$ masses

D_s^- decays thru η,η',ϕ,ω …

The three nice features of the 3-prong τ decay :

- **Suppression of the prompt background**
- **Good kinematic reconstruction**
- **Powerful τ/D_s^- distinction**

LHCb R(D*)
Phys. Rev. D97, 072013 (2018)

3D Fit results

- The fit is a 3D binned (6x6x6) maximum likelihood template fit to the data
- 3 variables :
  - τ decay time
  - q^2
  - Anti-D_s^- BDT
- Fit results :

  χ^2/dof=1.3

Signal yield = 349 ± 40

$\Lambda_c^{*}\tau\nu$ =35

N D_s^- =2757 ± 80

N D^+= 443 ± 55

N D^0 = 186 ± 7

Combinatorial 679

Fit projections : τ decay time and BDT

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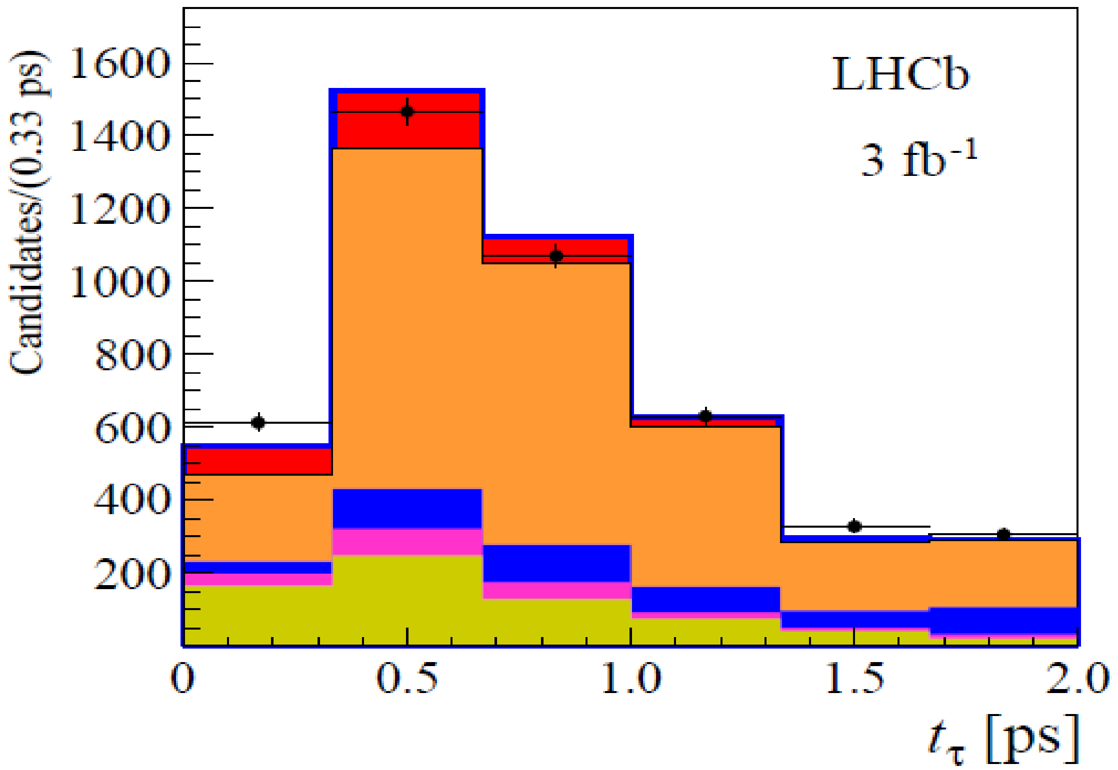
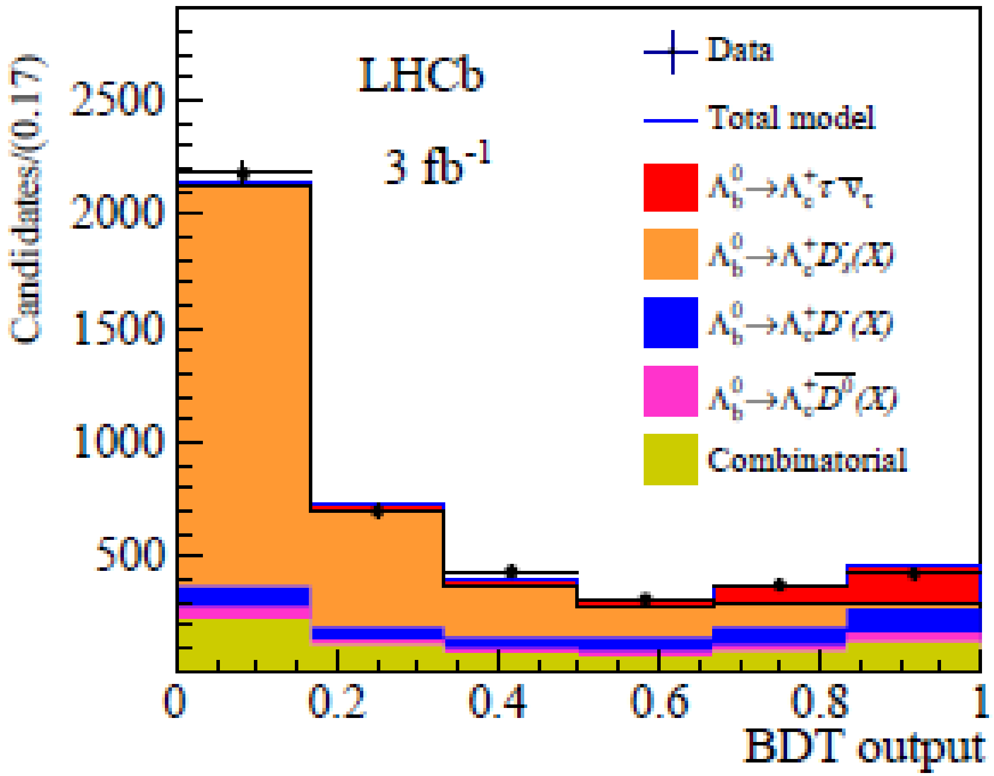
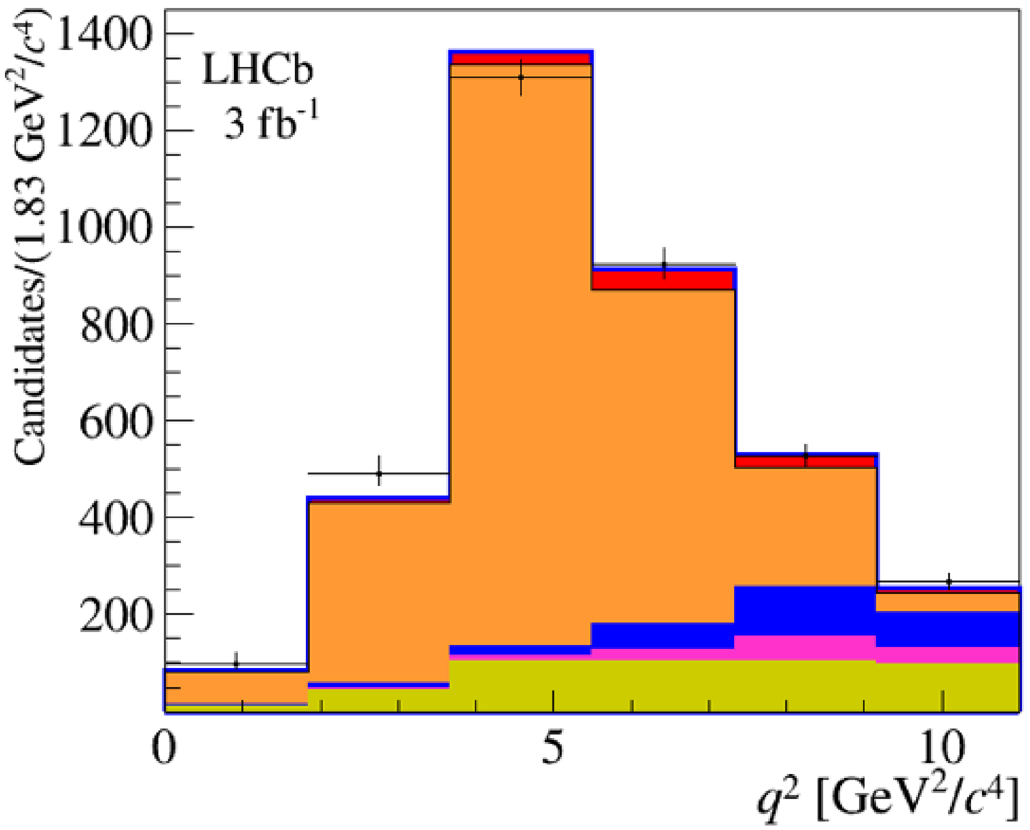




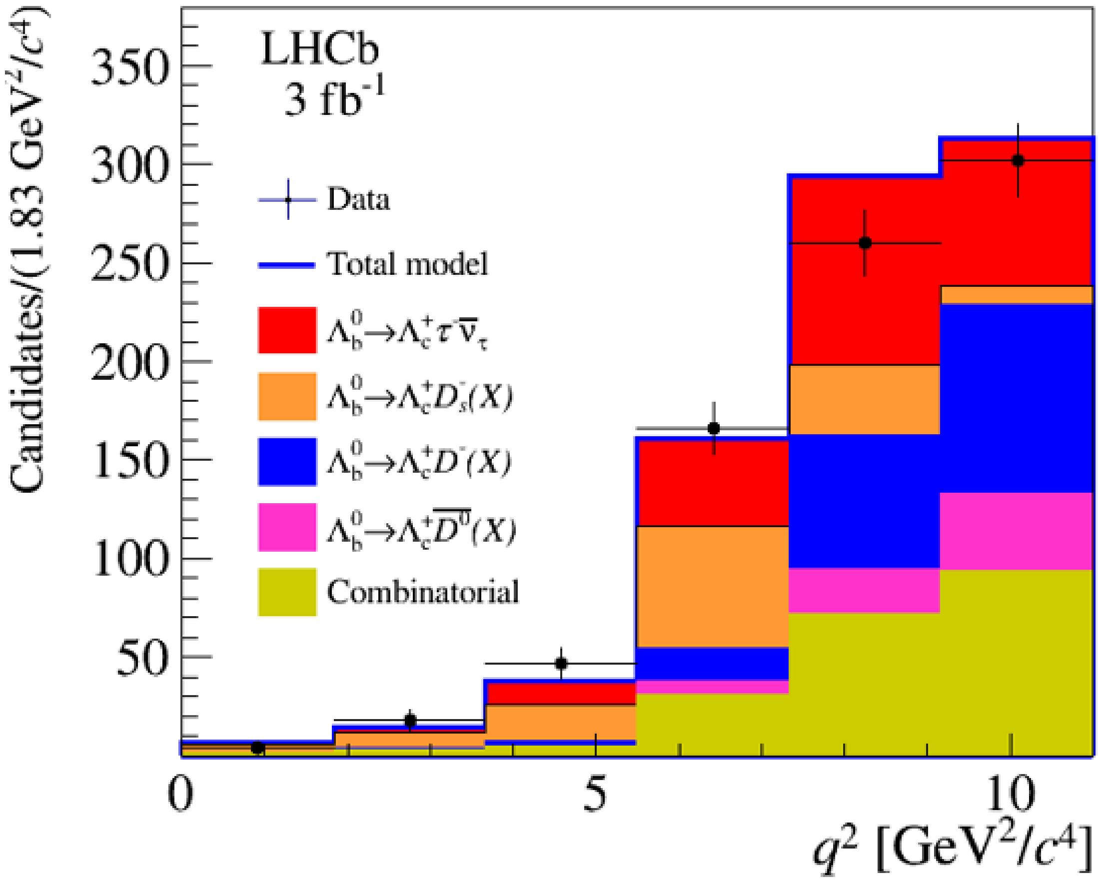
Fit projection : q^2

LHCb-PAPER-2021-044 arxiv:2201:03497

Low BDT



High BDT(>0.66)



Observation of the decay $\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau$

- Increase of fit χ^2 with signal forced to 0 : 7.3 σ statistical only
- Increase of fit χ^2 with signal forced to 0 after inclusion of systematic uncertainty (dominated by template shapes): 6.1 σ

- We can claim observation of the decay $\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau$!

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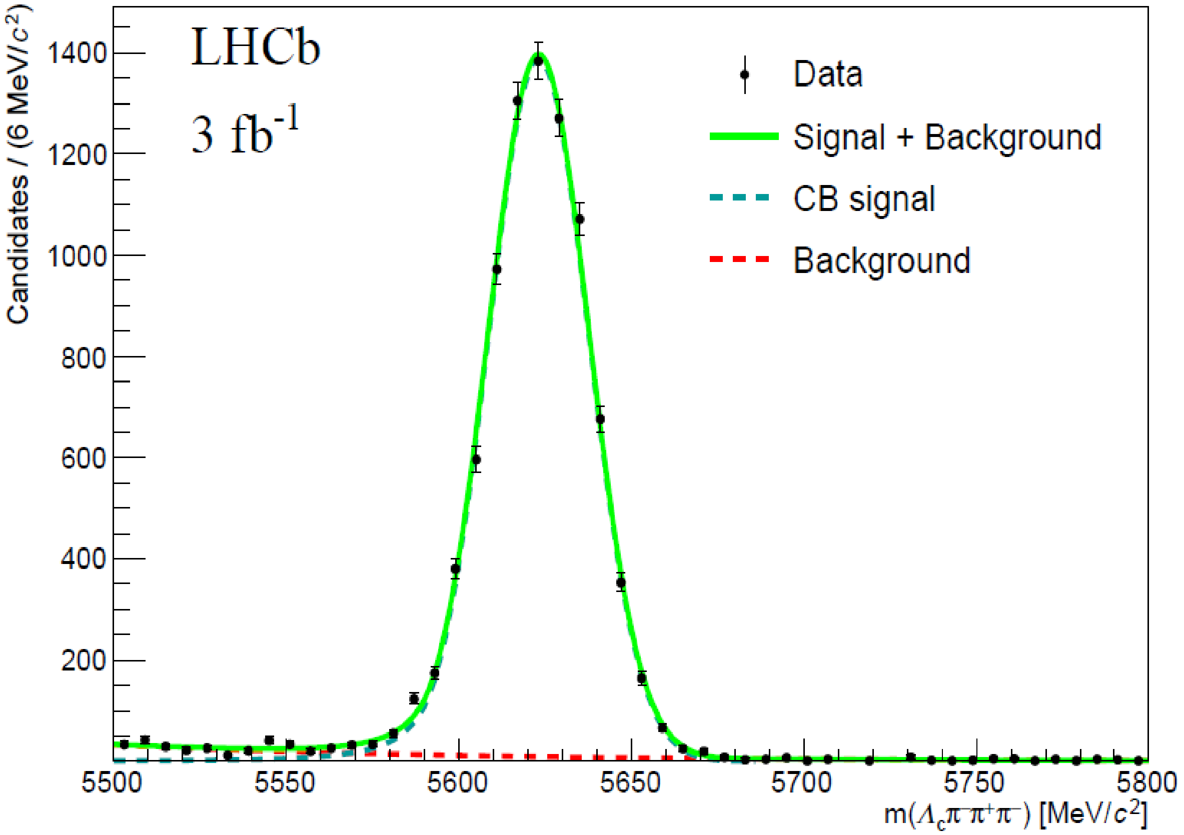
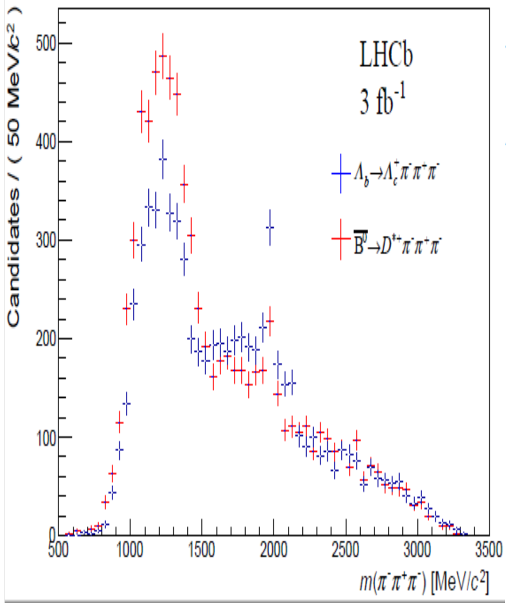
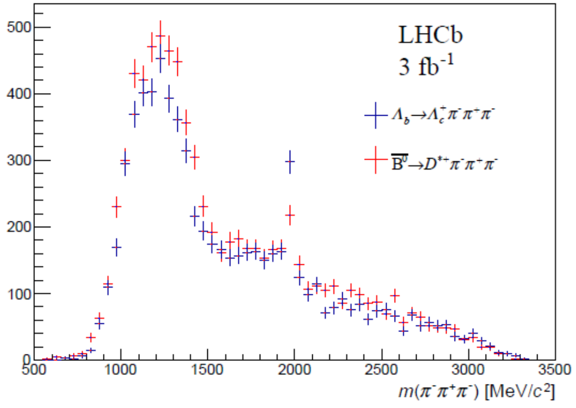
$\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ normalisation peak



Comparison of the 3π mass distribution for $\Lambda_c^+ 3\pi$ and D*3π events before and after $\Lambda_c^{*+}\pi$ events removal





Normalisation yield after Λ_c^{*+} subtraction: 8584 ± 102

LHCb-PAPER-2021-044
arxiv:2201:03497

Largest systematic : template shapes

Source	$\delta\mathcal{K}(\Lambda_c^+)/\mathcal{K}(\Lambda_c^+)[\%]$
Simulated sample size	3.8
Fit bias	3.9
Signal modeling	2.0
$\Lambda_c^{*+}\tau^-\overline{\nu}_\tau$	2.5
$D_s^- \to 3\pi X$ decay model	2.5
$\Lambda_b^0 \to \Lambda_c^+ D_s^- X$, $\Lambda_b^0 \to \Lambda_c^+ D^- X$, $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 X$ background	4.7
Combinatorial background	0.5
Particle identification and trigger corrections	1.5
Data/simulation agreement for isolation and vertex	4.5
D_s^+, D^-, $\overline{D}^0$ templates shapes	13.0
Efficiency ratio	2.8
Normalization channel efficiency (modeling of $\Lambda_b^0 \to \Lambda_c^+ 3\pi$)	3.0
Total uncertainty	16.5

LHCb-PAPER-2021-044 arxiv:2201:03497

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Physics results

$$\mathcal{K}(\Lambda_c^+) \equiv \mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)/\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-)$$

$$\mathcal{K}(\Lambda_c^+) = 2.46 \pm 0{,}27\ (\text{stat}) \pm 0{,}40\ (\text{syst})$$

- Using $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-)_{\text{no}\ \Lambda_c^{*+}}$ =(0. 614 ± 0.094)% [PDG2020],

$$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)=(1{,}50 \pm 0{,}16\ (\text{stat}) \pm 0{,}25\ (\text{sys}) \pm 0{,}23\ (\text{ext}))\ \%$$

(SM expectation=(1.8± 0.1)%

- Using $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu) = (6.2 \pm 1.4)\%$ [PDG2020],

$$\mathcal{R}(\Lambda_c^+)=0.242 \pm 0.026\ (\text{stat}) \pm 0.040\ (\text{syst}) \pm 0.059\ (\text{ext})$$

(SM expectation=0.324 ± 0.004)

F. Bernlochner et al., Physical Review D 99 055008 (2019)
with input from W. Detmold, C. Lehner, S. Meinel, Physical Review D 92 034503 (2015)

Constraints on New Physics models (including all meson-based results)

Coupling	$R(\Lambda_c)_{max}$	$R^{Ratio}_{\Lambda_c,max}$	coupling value	$R(\Lambda_c)_{min}$	$R^{Ratio}_{\Lambda_c,min}$	coupling value
g_S only	0.405	1.217	0.363	0.314	0.942	-1.14
g_P only	0.354	1.062	0.658	0.337	1.014	0.168
g_L only	0.495	1.486	$0.094 + 0.538i$	0.340	1.022	$-0.070 + 0.395i$
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A. Datta et al., Journal of High Energy Physics 1708 (2017) 131

Our result excludes regions of the parameter space of effective theories with only one vector, axial-vector or tensor coupling

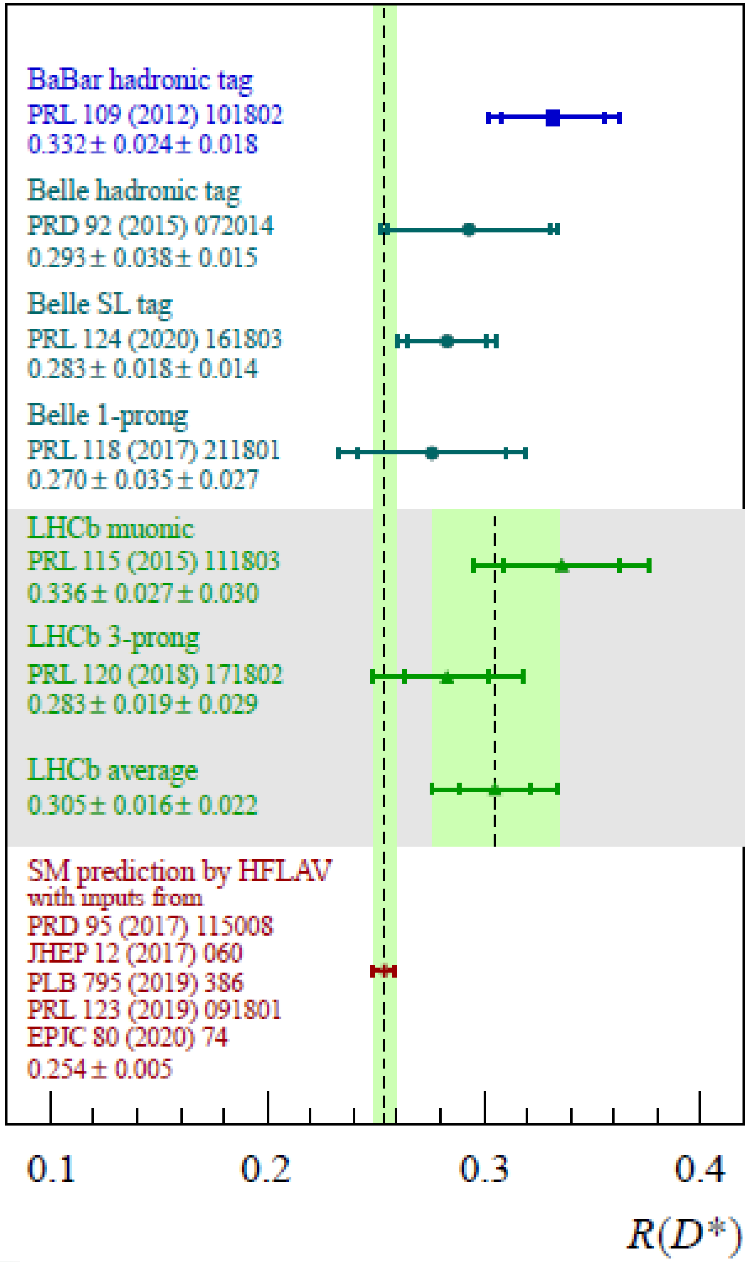
Semitauonic prospects in LHCb

- Many more semitauonic results expected soon using the muonic and hadronic τ decay channel :
  - $\mathcal{R}(D^*)$ using 2015-2016 data
  - D^* polarization measurement
  - $\mathcal{R}(D^\circ)$-$\mathcal{R}(D^{*+})$
  - $\mathcal{R}(\Lambda_c^+)$ using the full Run2 data
  - $\mathcal{R}(D^+)$
- Work is also ongoing on $\mathcal{R}(D_s)$, $\mathcal{R}(J/\psi)$, full angular analysis

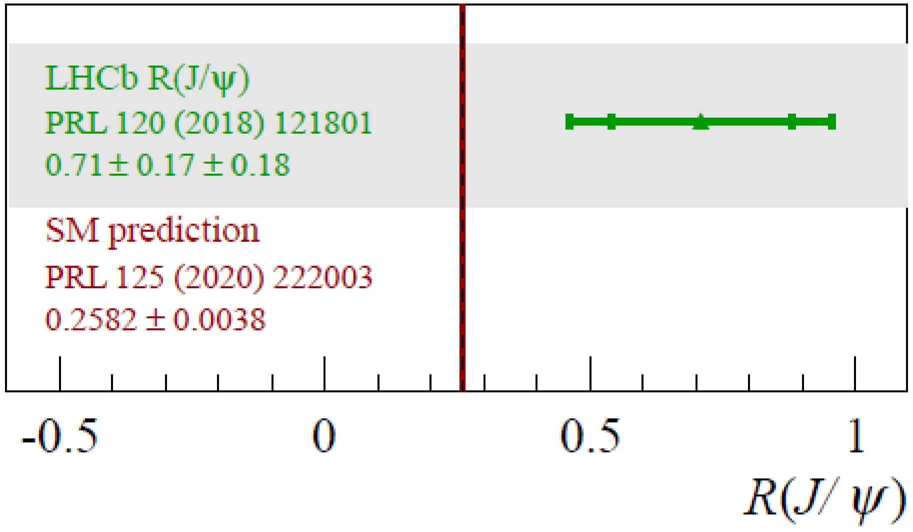
Conclusions

LHCb-PAPER-2021-044
arxiv:2201:03497

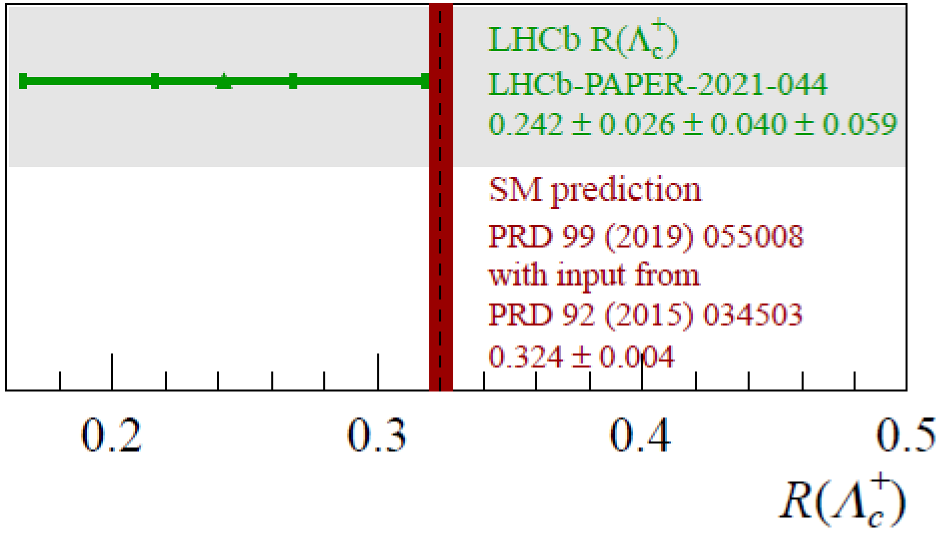
- The decay $\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau$ has been observed for the first time with a significance of 6.1 σ
  - $\mathcal{K}(\Lambda_c^+)$ = 2.46 ± 0.27 (stat) ± 0.40 (syst)
  - $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)$= (1,50 ± 0,16 (stat) ± 0,25 (sys) ± 0,23 (ext)) %
  - $\mathcal{R}(\Lambda_c^+)$=0.242 ± 0.026 (stat) ± 0.040 (syst) ± 0.059 (ext)
- Everything compatible with SM (~1 σ below)
- A fraction of the parameter space of effective theories with only one vector, axial-vector or tensor couplings can be excluded



BaBar hadronic tag
PRL 109 (2012) 101802
0.332 ± 0.024 ± 0.018
Belle hadronic tag
PRD 92 (2015) 072014
0.293 ± 0.038 ± 0.015
Belle SL tag
PRL 124 (2020) 161803
0.283 ± 0.018 ± 0.014
Belle 1-prong
PRL 118 (2017) 211801
0.270 ± 0.035 ± 0.027
LHCb muonic
PRL 115 (2015) 111803
0.336 ± 0.027 ± 0.030
LHCb 3-prong
PRL 120 (2018) 171802
0.283 ± 0.019 ± 0.029
LHCb average
0.305 ± 0.016 ± 0.022
SM prediction by HFLAV
with inputs from
PRD 95 (2017) 115008
JHEP 12 (2017) 060
PLB 795 (2019) 386
PRL 123 (2019) 091801
EPJC 80 (2020) 74
0.254 ± 0.005
0.1
0.2
0.3
0.4
R(D*)



LHCb R(J/ψ)
PRL 120 (2018) 121801
0.71 ± 0.17 ± 0.18
SM prediction
PRL 125 (2020) 222003
0.2582 ± 0.0038
-0.5
0
0.5
1
R(J/ψ)



LHCb R(Λc+)
LHCb-PAPER-2021-044
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SM prediction
PRD 99 (2019) 055008
with input from
PRD 92 (2015) 034503
0.324 ± 0.004
0.2
0.3
0.4
0.5
R(Λc+)

Backup slides

Regarding $\Lambda_c^+\pi^+\pi^-\pi^+$ mode: PDG2020

$\Gamma(\Lambda_c^+\pi^+\pi^-\pi^-)/\Gamma_{total}$ — **Γ_{29}/Γ**

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
7.7±1.1 OUR FIT	Error includes scale factor of 1.1.				
$14.9^{+3.8}_{-3.2}\pm1.2$		[1] AALTONEN	12A	CDF	$p\bar{p}$ at 1.96 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	90	BARI	91	SFM	$\Lambda_c^+ \to pK^-\pi^+$

[1] AALTONEN 12A reports $[\Gamma(\Lambda_b^0 \to \Lambda_c^+\pi^+\pi^-\pi^-)/\Gamma_{total}]$ / $[B(\Lambda_b^0 \to \Lambda_c^+\pi^-)]$ = $3.04 \pm 0.33^{+0.70}_{-0.55}$ which we multiply by our best value $B(\Lambda_b^0 \to \Lambda_c^+\pi^-) = (4.9 \pm 0.4) \times 10^{-3}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(\Lambda_c^+\pi^+\pi^-\pi^-)/\Gamma(\Lambda_c^+\pi^-)$ — **Γ_{29}/Γ_{24}**

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
1.56±0.21 OUR FIT				
1.43±0.16±0.13	AAIJ	11E	LHCB	pp at 7 TeV

For $\Lambda_c^+\pi^+\pi^-\pi^+$ data, the PDG error is 14%. (a bit better for some reason than the combination of the 8% of the absolute BR(Λ_b^0 ➔ $\Lambda_c^+\pi^-$) and the 13.5% ratio coming from the ratio.)

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Subtracting $\Lambda_c^{*+}\pi^-$

$\Gamma(\Lambda_c(2595)^+\pi^-, \Lambda_c(2595)^+ \to \Lambda_c^+\pi^+\pi^-)/\Gamma(\Lambda_c^+\pi^+\pi^-\pi^-)$ **Γ_{30}/Γ_{29}**

VALUE (units 10^{-2})	*DOCUMENT ID*		*TECN*	*COMMENT*
$4.4\pm1.7^{+0.6}_{-0.4}$	AAIJ	11E	LHCB	pp at 7 TeV

HTTP://PDG.LBL.GOV Page 11 Created: 6/1/2020 08:33

Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

$\Gamma(\Lambda_c(2625)^+\pi^-, \Lambda_c(2625)^+ \to \Lambda_c^+\pi^+\pi^-)/\Gamma(\Lambda_c^+\pi^+\pi^-\pi^-)$ **Γ_{31}/Γ_{29}**

VALUE (units 10^{-2})	*DOCUMENT ID*		*TECN*	*COMMENT*
$4.3\pm1.5\pm0.4$	AAIJ	11E	LHCB	pp at 7 TeV

$\Gamma(\Sigma_c(2455)^0\pi^+\pi^-, \Sigma_c^0 \to \Lambda_c^+\pi^-)/\Gamma(\Lambda_c^+\pi^+\pi^-\pi^-)$ **Γ_{32}/Γ_{29}**

VALUE (units 10^{-2})	*DOCUMENT ID*		*TECN*	*COMMENT*
$7.4\pm2.4\pm1.2$	AAIJ	11E	LHCB	pp at 7 TeV

$\Gamma(\Sigma_c(2455)^{++}\pi^-\pi^-, \Sigma_c^{++} \to \Lambda_c^+\pi^+)/\Gamma(\Lambda_c^+\pi^+\pi^-\pi^-)$ **Γ_{33}/Γ_{29}**

VALUE (units 10^{-2})	*DOCUMENT ID*		*TECN*	*COMMENT*
$4.2\pm1.8\pm0.7$	AAIJ	11E	LHCB	pp at 7 TeV

for a total of (20.3±4) % of the full $\Lambda_c^+\pi^-\pi^+\pi^-$ yield. This corresponds to a total error of 14.8% .

Regarding $\Lambda_c^+ \mu^- \bar{\nu}_\mu$

$\Gamma(\Lambda_c^+ \ell^- \bar{\nu}_\ell)/\Gamma_{total}$ **Γ_{39}/Γ**

VALUE	DOCUMENT ID		TECN	COMMENT
$0.062^{+0.014}_{-0.013}$ OUR FIT				
$0.050^{+0.011}_{-0.008}{}^{+0.016}_{-0.012}$	[1] ABDALLAH	04A	DLPH	$e^+e^- \to Z^0$

[1] Derived from a combined likelihood and event rate fit to the distribution of the Isgur-Wise variable and using HQET. The slope of the form factor is measured to be $\rho^2 = 2.03 \pm 0.46^{+0.72}_{-1.00}$.

$\Gamma(\Lambda_c^+ \ell^- \bar{\nu}_\ell)/\Gamma(\Lambda_c^+ \pi^-)$ **Γ_{39}/Γ_{24}**

VALUE	DOCUMENT ID		TECN	COMMENT
$12.7^{+3.1}_{-2.7}$ OUR FIT				
$16.6 \pm 3.0^{+2.8}_{-3.6}$	AALTONEN	09E	CDF	$p\bar{p}$ at 1.96 TeV

- 22.6% for the semileptonic channel
- Combining with the $\Lambda_c^+ \pi^- \pi^+ \pi^-$ the crude number is 27%.
- It reduces to 24% by removing the 13% relative error mentioned in the PDG for their $f_{\Lambda b}$ fraction (8.4+1.1)%

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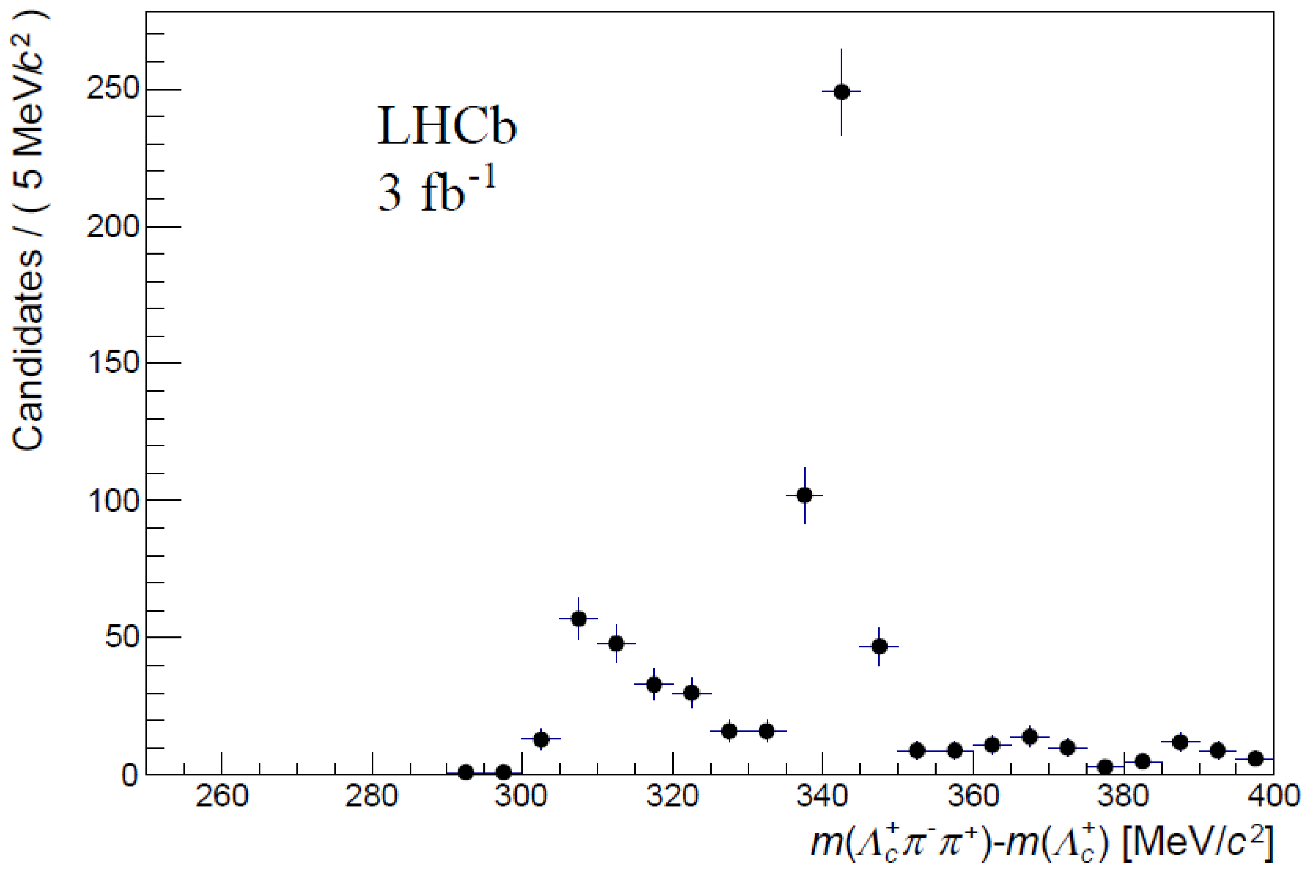
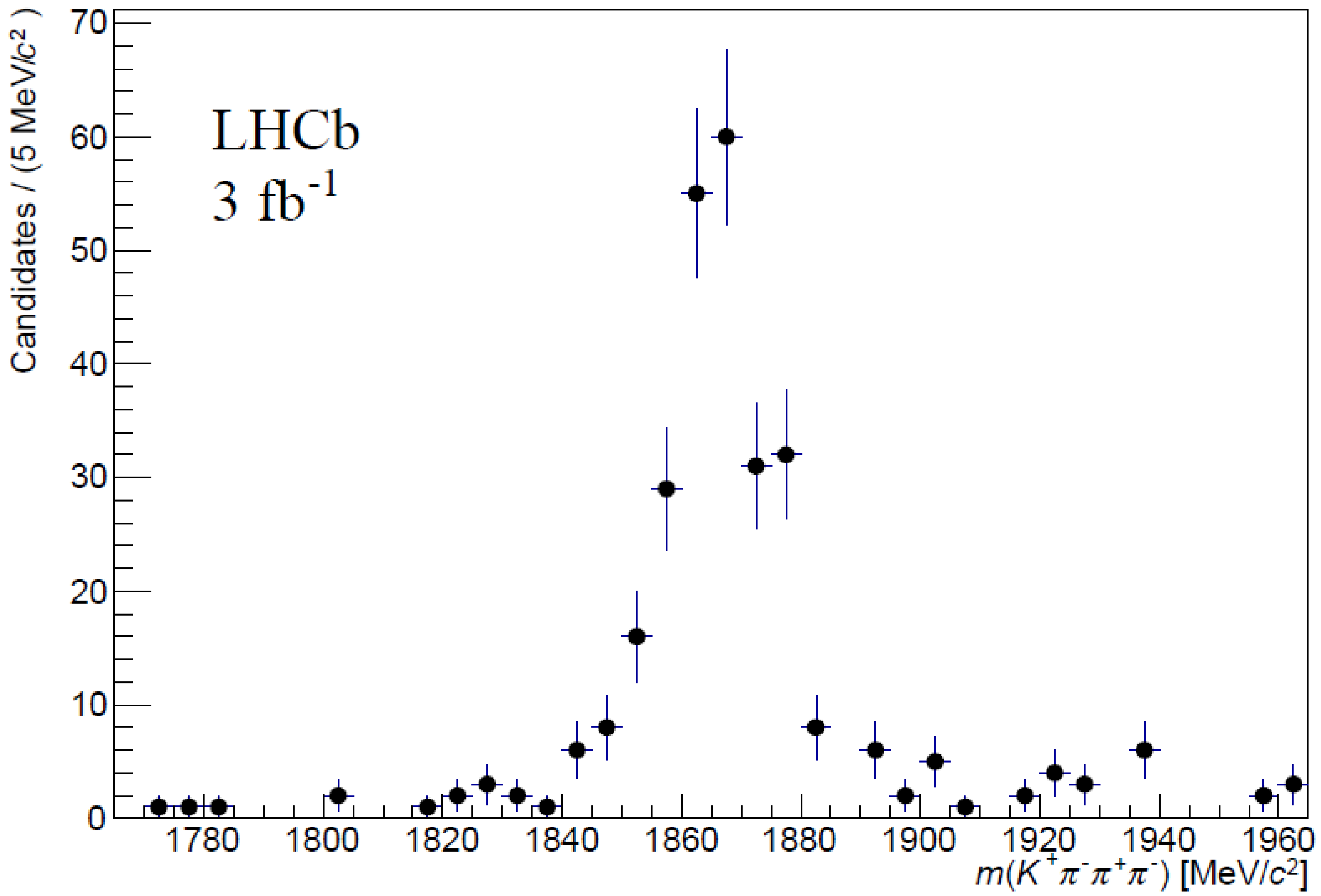
Distribution of the difference m($\Lambda_c^+\pi^+\pi^-$)-m(Λ_c^+) in the $\Lambda_b^0 \to \Lambda_c^+ \pi^-\pi^+\pi^-$ mass peak



Distribution of the $K^{+}\pi^{-}\pi^{+}\pi^{-}$ mass for events with one extra kaon track at the 3π vertex



Results of the nominal fit

Parameter	Fit result	Constraint value
N_{sig}	349 ± 40 (11.8%)	
$f_{\tau\to 3\pi\nu}$		0.78
$f_{\Lambda_c^{*}\tau\overline{\nu}_\tau}$		0.1
$N_{D^0}^{same}$	80.2 ± 8.3	81.4 ± 7.4
$f_{D^0}^{v_1-v_2}$	1.3 ± 0.7	
N_{D_s}	2755.9 ± 81	
f_{D_s}	0.49 ± 0.09	0.65 ± 0.08
$f_{D_{s0}^*}$	0.0 ± 0.012	0.28 ± 0.12
$f_{D'_{s1}}$	0.41 ± 0.07	0.29 ± 0.12
$f_{\Lambda_c(2625)D_s^{(*)}}$	0.19 ± 0.06	0.22 ± 0.09
$f_{\Sigma_c\pi D_s^{(*)}}$	0.0 ± 0.02	0.22 ± 0.05
N_{D+}	443 ± 54	
N_{combi}		40.3
$N_{\Lambda_c^+}^{bkg}$		639
χ^2	256	
reduced χ^2 $(ndof = 216)$	1.30	

Baryon production from B mesons

- The only way to get $\Lambda_c 3\pi$ with the inverted vertex topology is the production of two charmed baryons
- Two such decays exist
  - Two-body mode $B° \rightarrow \Lambda_c \Xi c$ BR =(0,12+_ 0.08)% similar to signal mode
  - Three-body mode $B° \rightarrow \Lambda_c \Lambda_c K°$ (can come partially from $\Lambda_c \Xi_c (2930)$
    BR= (0.04+_0.009)%

The decay $\Xi_c \rightarrow \Xi 3\pi$ (BR=1.7%) or $\Lambda_c \rightarrow \Lambda 3\pi$ (BR=5%) is then needed

(The 3 pions have to come from the same vertex)

- Small but $f_d=4*f_\Lambda$

  Important to note that mass(3π) <1.1 GeV

- B^+ contribution suppressed by isolation requirements