Lepton Flavour Universality tests using semitauonic decays in LHCb Status and outlook: Run 1, Run 2 and beyond

GUY WORMSER

IN BEHALF OF THE LHCB COLLABORATION

LAL, CNRS/IN2P3 , PARIS SACLAY UNIVERSITY

Talk outline

- Introduction
- The R(D*) measurement from LHCb using hadronic tau decays
  - **First public release at FPCP2017 on June 5, 2017**
  - **Published in april 2018**

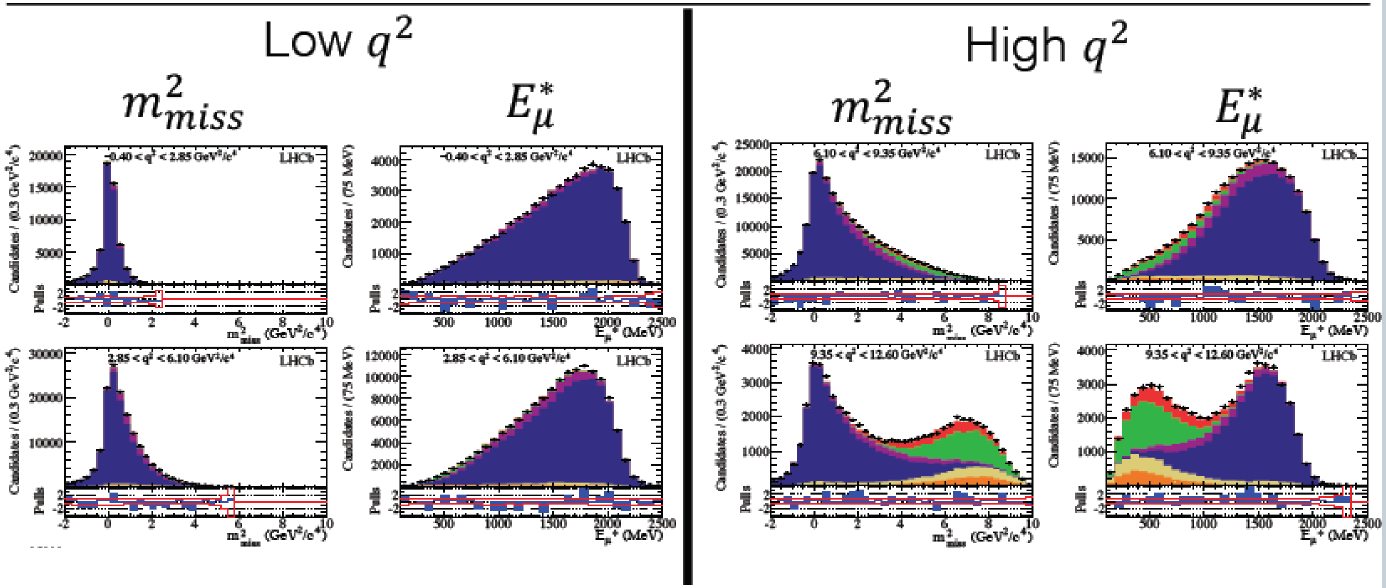
  PRL 120,171802 (2018)/PRD 97,072013(2018)

  Why hadronic tau decays is (surprisingly) the best approach towards search for New Physics
- Prospects regarding R(D*) and R(D) in LHCb
  - Run1
  - Run2
  - And beyond…
- The other R measurements in LHCb
- Conclusion

R(D*) LHCb muonic result (2015)

PRL 115 111803 (2015)

Fit Result



- Shown above: signal fit to "signal" data passing isolation selection
- Result $\frac{N_\tau}{N_\mu} = (4.32 \pm 0.37)\times 10^{-2}$, $R(D^*) = 0.336 \pm 0.027 \pm 0.030$
- $N(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu) = 363{,}000 \pm 1600$

Data
B → D*τν
B → D*H$_c$ (→ lν X')X
B → D**lν
B → D*μν
Combinatoric
Misidentified μ

The unusual features of the LHCb analysis $B^0 \to D^{*+}\tau^-\nu$; $\tau \to 3\pi(\pi^0)$
PRL 120,171802 (2018)/PRD 97,072013(2018)

- A semileptonic decay without (charged) lepton !!:
  - ZERO background from normal semileptonic decays!!!!
- In this analysis, it is the background that leads to nice mass peaks and not the signal !!!
  - This provides key handle to control the various backgrounds
- Only 1 neutrino emitted at the τ vertex
  - The complete event kinematics can be reconstructed with good precision
- No sensitivity to τ polarisation through $P_{3\pi}$ $(m_{a_1}{}^2 \approx 0.5{*}m_\tau{}^2)$
- Note : measure R(D*-) and not R(D*) as B Factories

The initial very large background

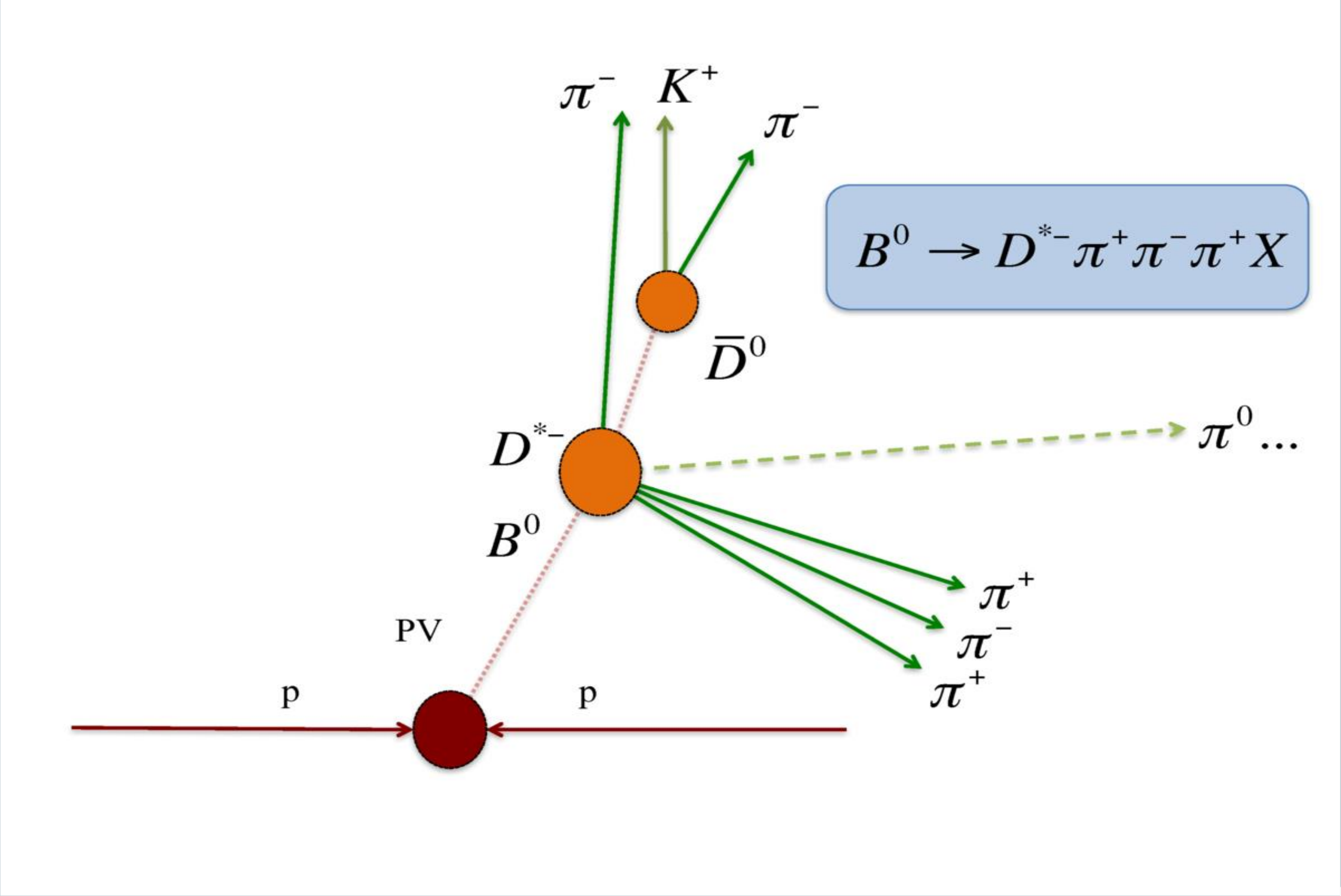
- The $D^*\tau\nu$ decay, with τ going into 3 pions (it can also be $3\pi+\pi^0$) leads to a D^* $3\pi(+X)$ final state
- Nothing is more common than a $D^*3\pi$ $(+X)$ final state in a typical B decay :

$$BR(B^o \rightarrow D^*3\pi+X)/BR(B^o \rightarrow D^*\tau\nu;\tau \rightarrow 3\pi)_{SM} \sim 100$$

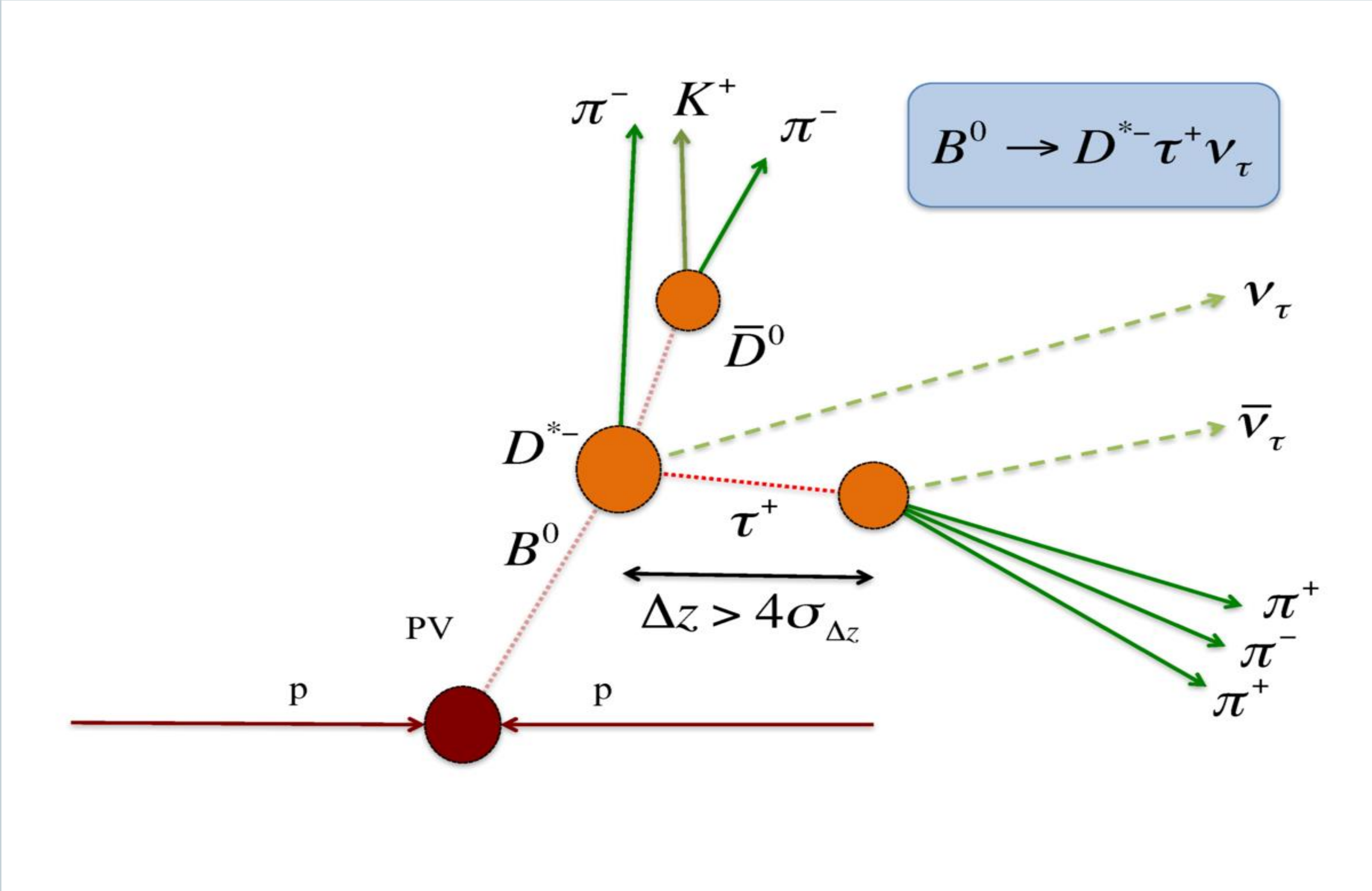
A very strong background suppression method is absolutely needed :

<u>The DETACHED VERTEX METHOD</u>

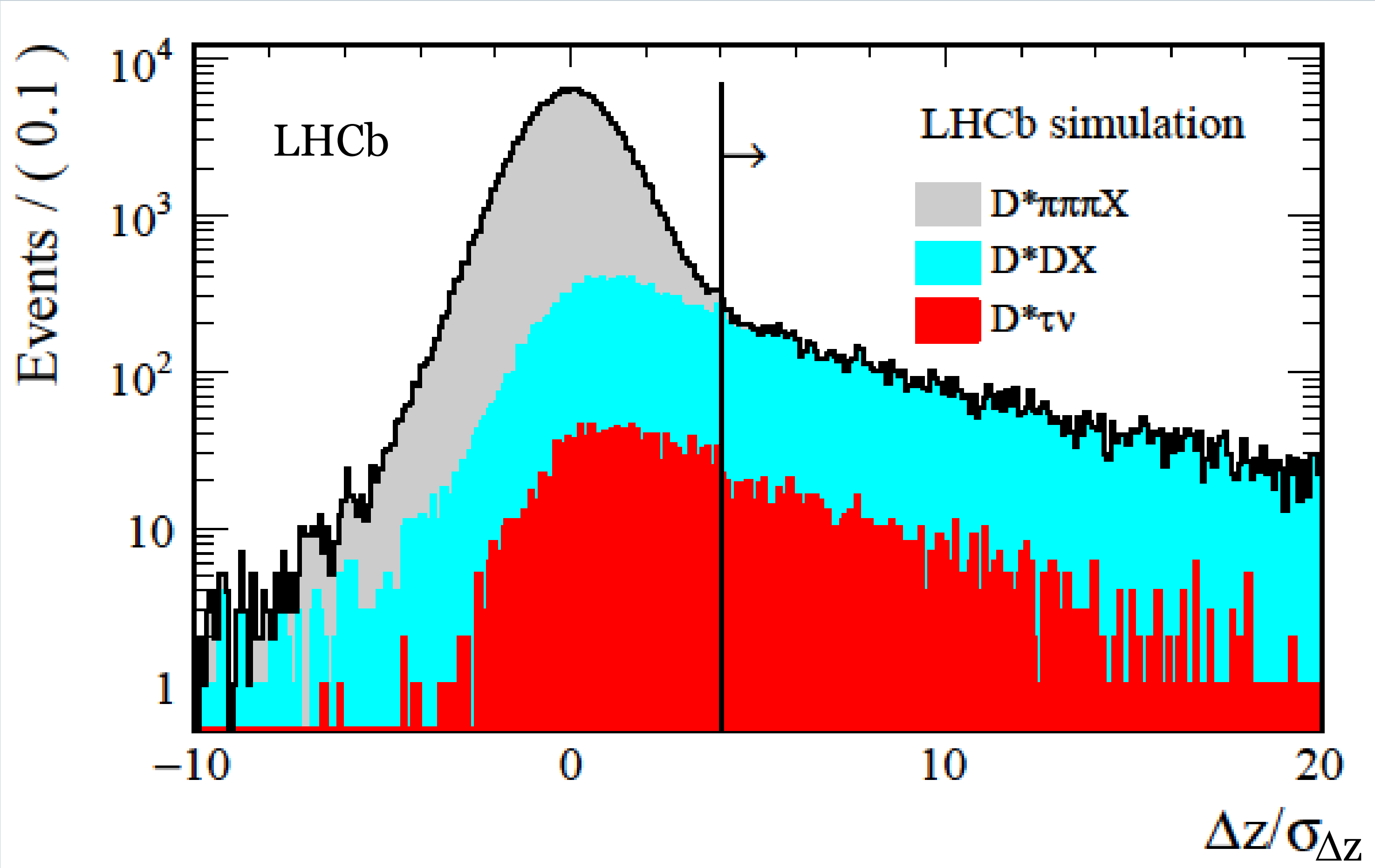
Vertex topology of the usual B decay



Selection: detached vertex



Selection: the detached vertex method
LHCb-PAPER-2017-017/2017-27
PRL 120,171802 (2018)/PRD 97,072013(2018)



The second level of background

- After the 4σ cut in $\Delta z/\sigma_{\Delta z}$, the prompt background is suppressed by ~3 orders of magnitude!!!!!
- The second level of background consists of B decays where the 3π vertex is transported away from the B^o vertex by a charm carrier: D_s, D^+ or D^o (in that order of importance)
- This background is smaller :

$BR(B^o \to D^*\ 'D';\ 'D' \to 3\pi X)/\ BR(B^o \to D^* \tau\nu; \tau \to 3\pi)_{SM} \sim 10$

- ... and we can suppress it strongly

The inclusive D_s decays in 3 pions

- The W➔c$\bar{s}$ decays can produce a single meson **D_s**, very often in an excited state D_s*, D_s** or two particles D^0K^-, D^+K^0, and their excited counterparts
- Although the exclusive D_s ➔3π is small (1% BR), the D_s is an amazingly rich source of 3π +X final states (~25%!)
- We classify hadronic D_s decays into 3 pions in 4 categories
  - ηπX (ηπ,ηρ) η'πX(η'π,η'ρ)
  - (ϕ/ω) πX (ϕ/ω π, ϕ/ω ρ) M3π, where M can be ν,K^0,η,η',ω,ϕ
- We do not have precise BR for all of these (some well measured, some poorly, some not at all)
- The inclusive BR of Ds into 3 pions that could constraint all of these is not known either

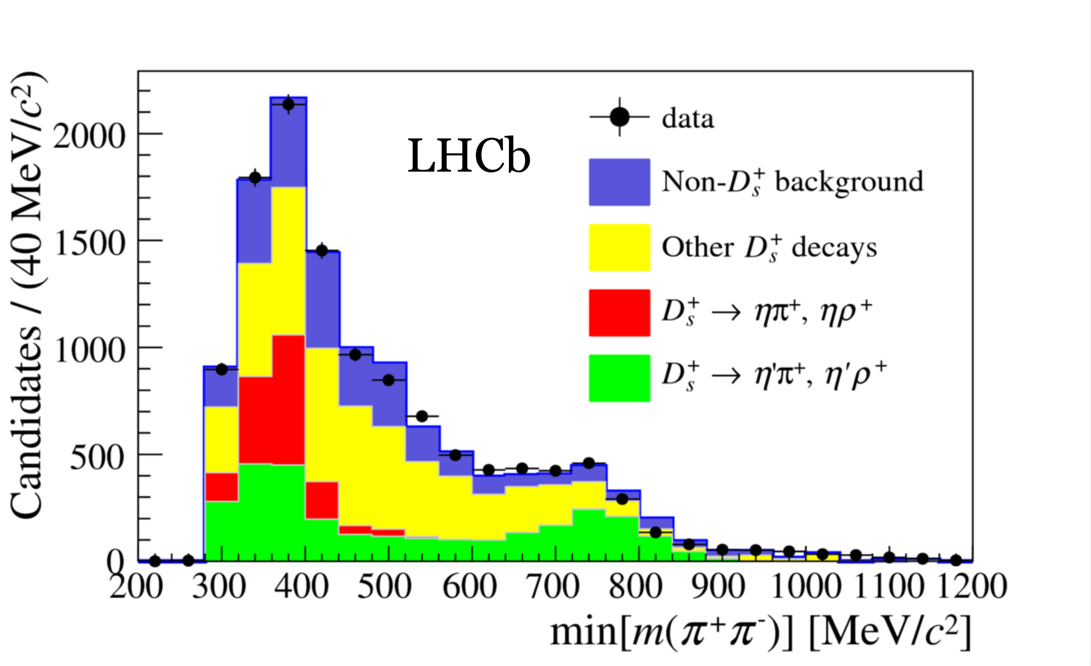
➔ **We extract these informations from LHCb data in a D_s enriched region (BDT<-0.075) (~90% D_s)**

The importance of the « D_s-o-meter »

- The minimum $\pi^+\pi^-$ mass contains critical information about the rate of η and η' decays
- At low mass, only η and η' (red,green) contributions are peaking

$\eta \rightarrow \pi^+\pi^-\ \pi^\circ$ and $\eta' \rightarrow \eta\ \pi^+\pi^-$

- At the ρ mass where the signal lives, only η' contributes ($\eta' \rightarrow \rho\gamma$)
- Using the low BDT region, one constraints the D_s decay model to be used at high BDT



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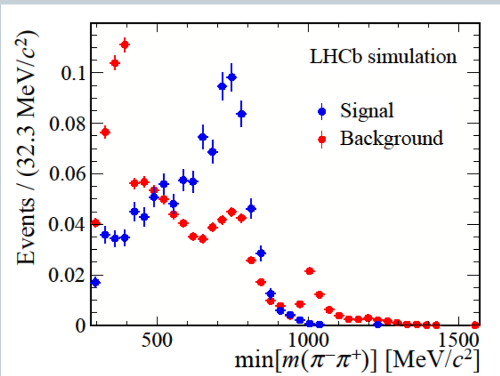
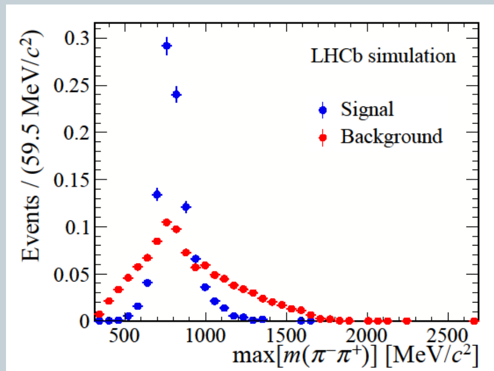
The anti-D_s BDT : 3π dynamics, partial reconstruction and isolation

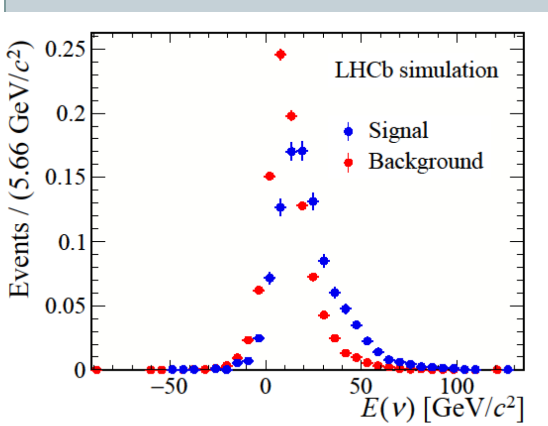
Min(mass($\pi^+\pi^-$))



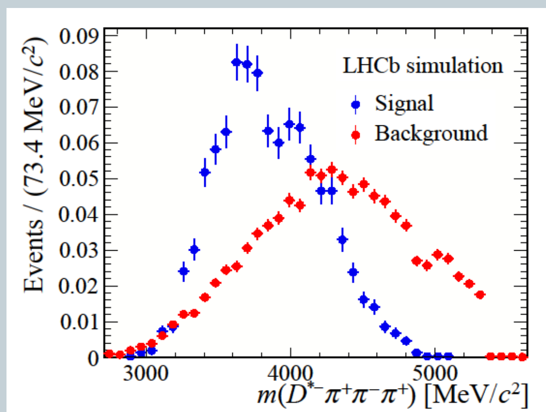
Max(mass($\pi^+\pi^-$))



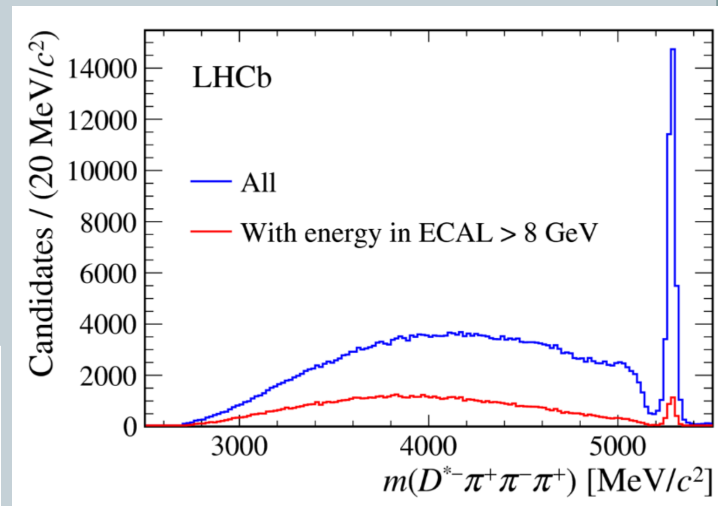
E(ν)



mass($D^{*+}\pi^-\pi^+\pi^-$)



Neutral Isolation



LHCb-PAPER-2017-027
PRL 120,171802 (2018)/
PRD 97,072013(2018)

τ partial reconstruction in 3π decay channel and sensitivity to τ polarisation

- In the hadronic decay channel, the full kinematics of the event can be reconstructed in the hadronic mode (up to 2 quadratic ambiguities)
  - 6 unknowns (3x2 neutrinos)
  - 6 constraints (2x2 flight directions, m_B, m_τ)
- The precision of the access to the B or τ center of mass is however not perfect (~15%) but known on a event per event basis (weights or selection of good events therefore possible)
- τ polarization can not be analysed thru the momentum of the 3 π system as mentioned previously but the information can in principle be still recovered in using all the techniques developped at LEP **Phys.Lett. B306 (1993) 411-417**

Factor of merit of polarization measurements at LEP for various τ decays channels

ω is the optimum variable in Ref.

t is the knowledge of τ line of flight

from Laurent Duflot Thesis (LAL 93-09)

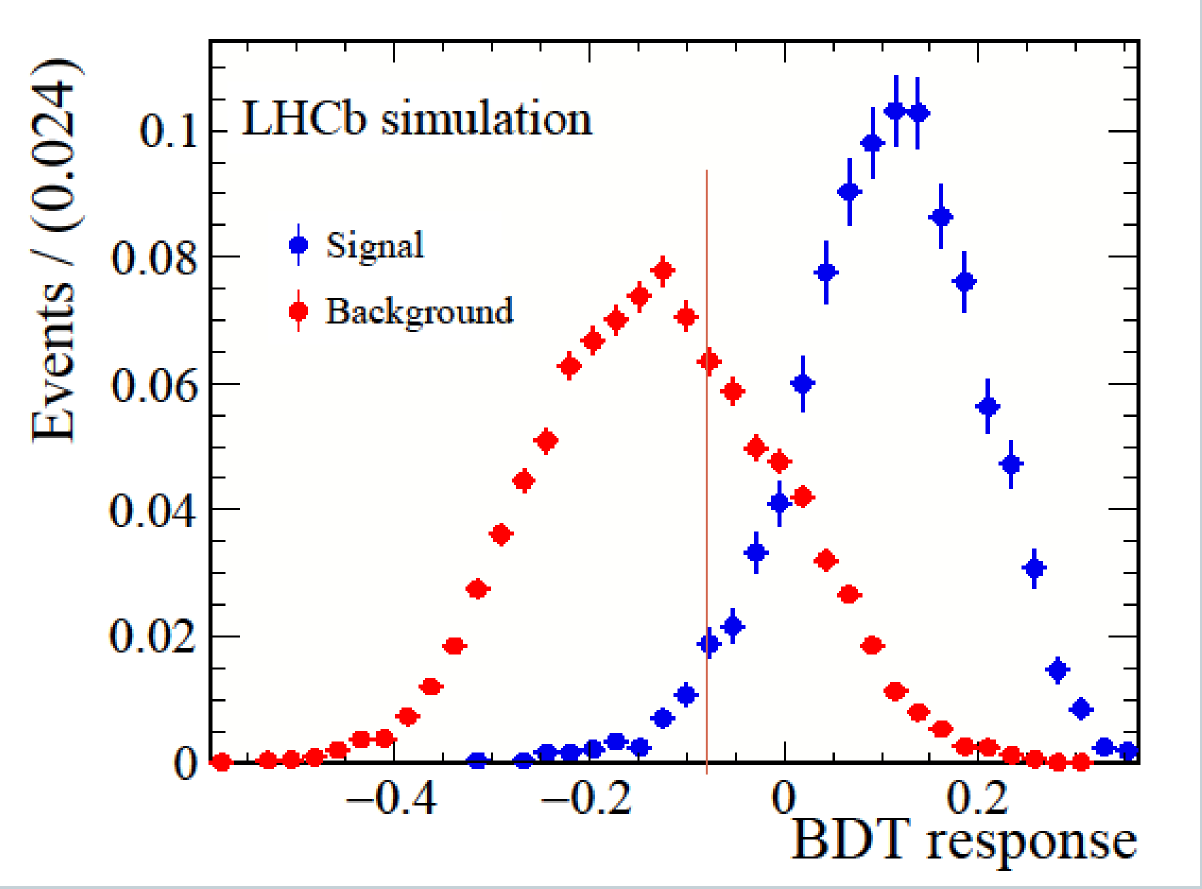
https://inspirehep.net/record/354667/files/CM-P00068750.pdf

canal	énergie [15]	deux angles [39] [40]	ω sans $\hat{\tau}$	ω avec $\hat{\tau}$
$l\nu\nu$	0.22	0.22	0.22	0.27
$\pi\nu$	0.58	0.58	0.58	0.58
$\rho\nu$	0.26	0.49	0.49	0.58
$a_1\nu$	0.03	0.23	0.44	0.58

It remains to be checked whether this method is applicable to LHCb given the precision on E_τ

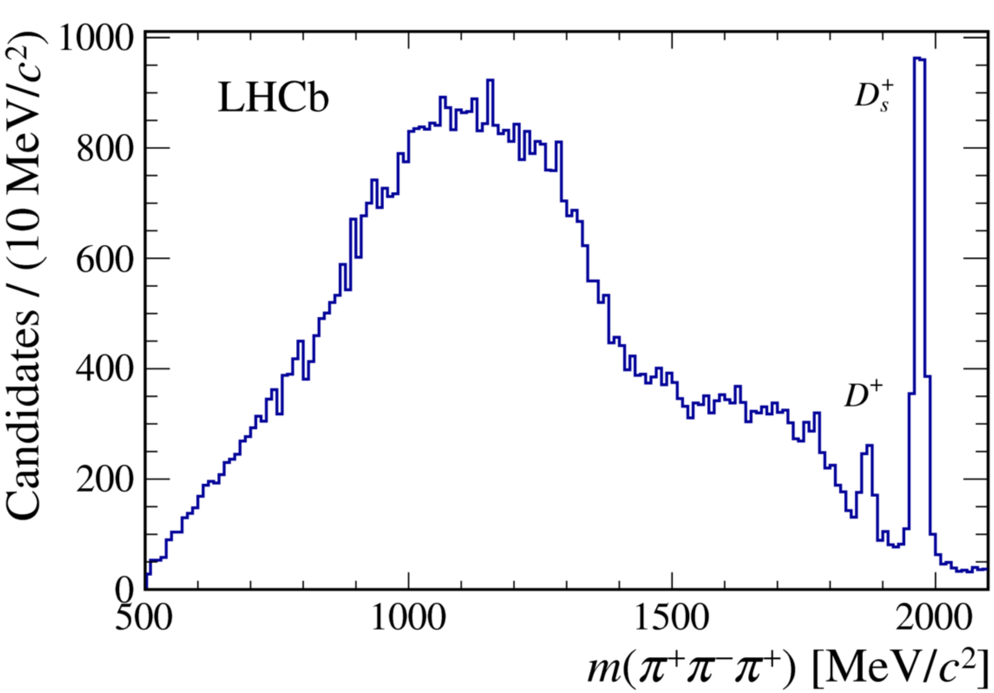
BDT results

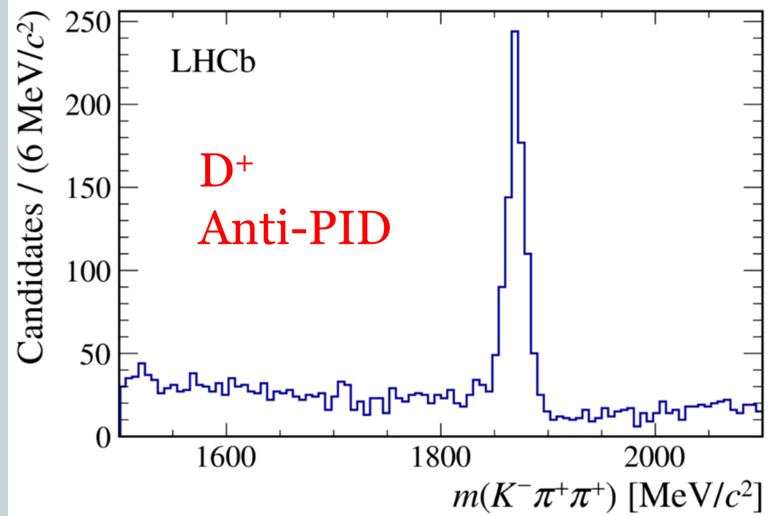
- Good separation obtained
- Allows to select an high purity sample at high efficiency
- Charged Isolation and PID cuts are also required to select candidates

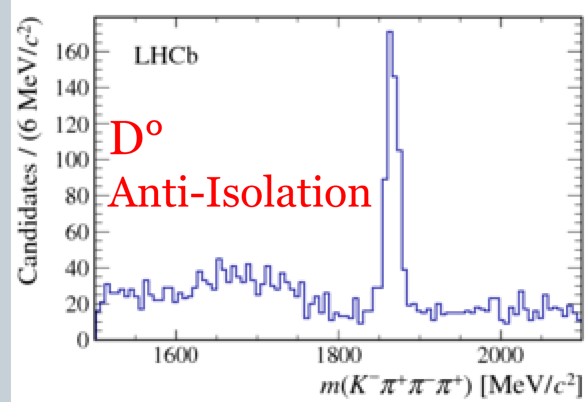


LHCb-PAPER-2017-017, PRL 120,171802 (2018)/PRD 97,072013(2018)

The control channels D_s, D°, and D^+







LHCb-PAPER-2017-017,
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Importance of the normalization channel $B^o \rightarrow D^*3\pi$

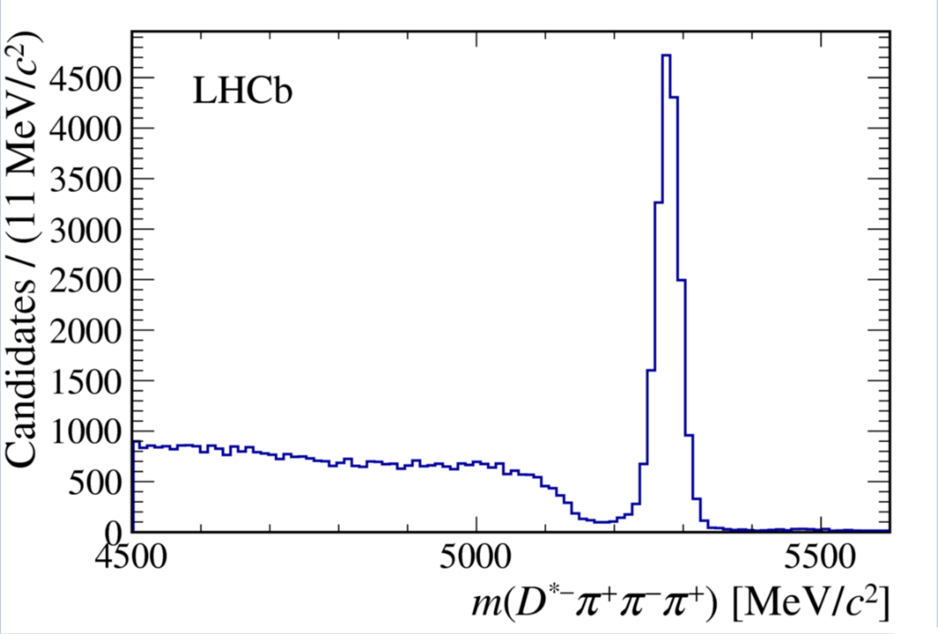
- Normalization mode as similar as possible to the signal to cancel production yield, BR uncertainties and systematics linked to trigger, PID, first selection cuts

Run 1, 3 fb^{-1}

17k events

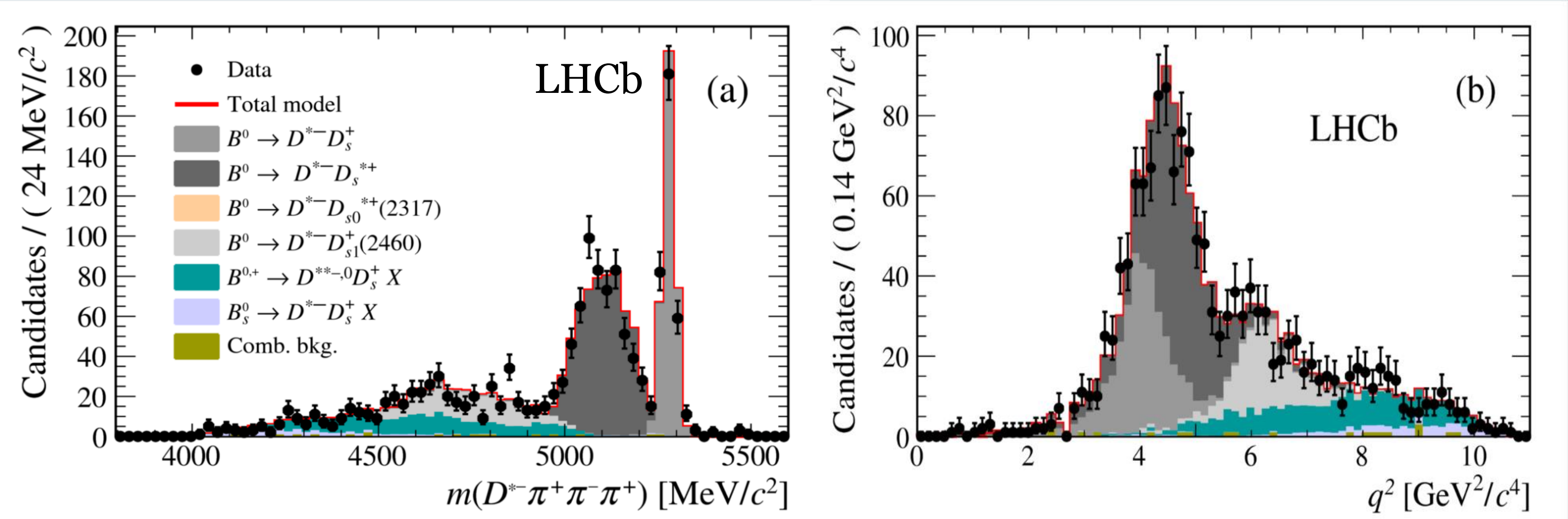
LHCb-PAPER-2017-017,

PRL 120,171802 (2018)/PRD 97,072013(2018)



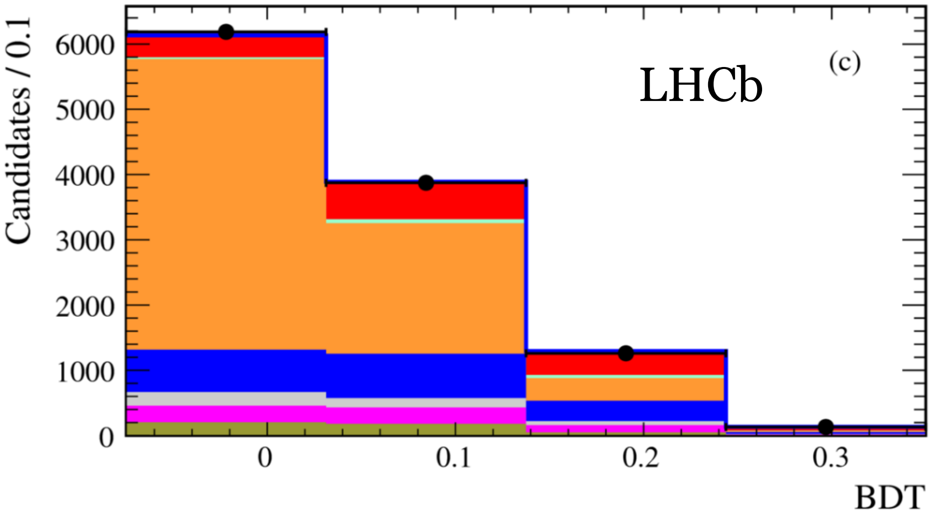
D^*D_s+X events with reconstructed D_s in 3π

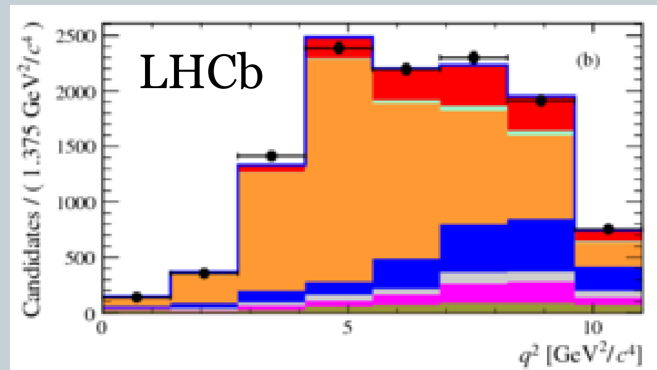
- Clear separation obtained of the D_s, D_s^* and D_s^{**} components
- Ratios ~1:2:2 (only 20% of D_s come directly from B)



LHCb-PAPER-2017-017, PRL 120,171802 (2018)/PRD 97,072013(2018)

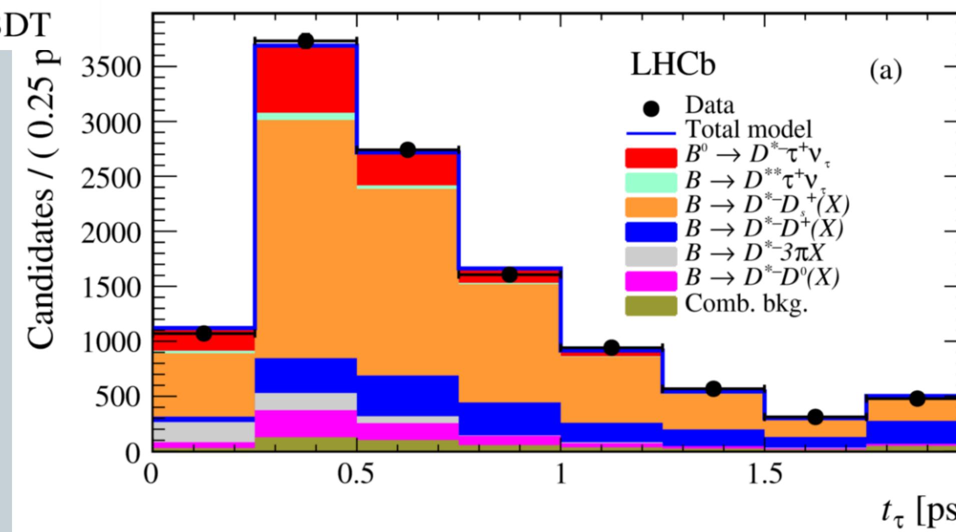
The 3 fit projections
(q^2, lifetime and BDT)





This shows the overall good quality of the fit

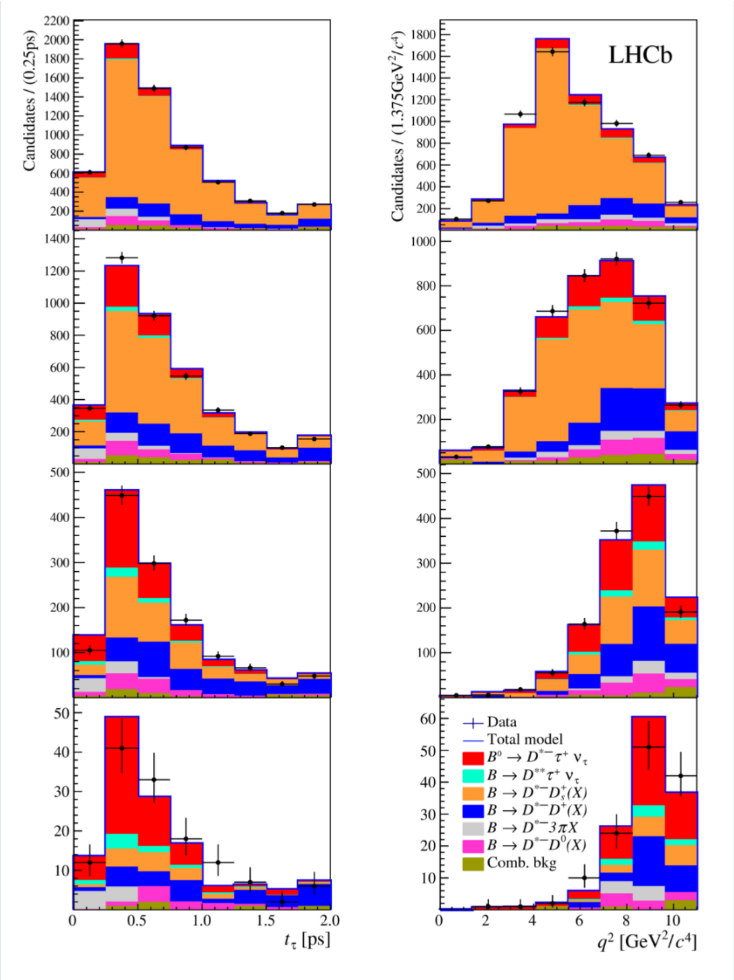
PRL 120,171802 (2018)/PRD97,072013(2018)



Fit results

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

PRL 120,171802 (2018)/PRD 97,072013(2018)



- The 3D template binned likelihood fit results are presented for the lifetime and q² in four BDT bins.
- The increase in signal (red) purity as function of BDT is very clearly seen, as well as the decrease of the D_s component (orange)
- The dominant background at high BDT becomes the D^+ component (blue) , with its distinctive long lifetime.
- The overall χ^2 per dof is 1.15

Systematic uncertainties table

PRL 120,171802 (2018)/PRD 97,072013(2018)

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
$B \to D^{*-} D_s^+ X$, $B \to D^{*-} D^+ X$, $B \to D^{*-} D^0 X$ backgrounds	3.9
Combinatorial background	0.7
$B \to D^{*-} 3\pi X$ background	2.8
Efficiency ratio	3.9
Normalization channel efficiency (modeling of $B^0 \to D^{*-} 3\pi$)	2.0
Total uncertainty	9.1

LHCb Results

LHCb-PAPER-2017-017, PRL 120,171802 (2018)/PRD 97,072013(2018)

BR($B^o \rightarrow D^*\tau\nu$)/BR($B^o \rightarrow D^*3\pi$)=1.97±0.13(stat) ±0.18(syst)

BR($B^o \rightarrow D^{*+}\tau\nu$)=(1.42±0.094(stat) ±0.129(syst)±0.054(ext))%
to be compared with the PDG(2017) (1.67±0.13) %
(Using for **BR($B^o \rightarrow D^*3\pi$)** our average of (0,721±0.028)%)
New (naive) average **BR($B^o \rightarrow D^{*+}\tau^-\nu$) =(1.58±0,10)%**

R(D*)=0.291±0.019(stat) ±0.026(syst) ±0.013(ext)
Using the HFLAV BR($B^o \rightarrow D^{*+}\mu^-\nu$)=(4,88±0,10)%

Experiment	Method	N evts $B \rightarrow D^*\tau\nu$	N evts $B^o \rightarrow D^{*+}\tau^-\nu$
BABAR	Leptonic hadronic tag	888±63	245±27
BELLE	Leptonic hadronic tag	503±65	0,4x503=200
BELLE	Single pi hadronic tag	88 ±11	88 ±11
LHCb	3π Hadronic	1296±86	1296±86

LHCb average and comparison with WA

PRL 120,171802 (2018)/PRD 97,072013(2018)

- This analysis :

R(D*)=0.291±0.019(stat)±0.029(syst)

- Reminder muonic R(D*)=

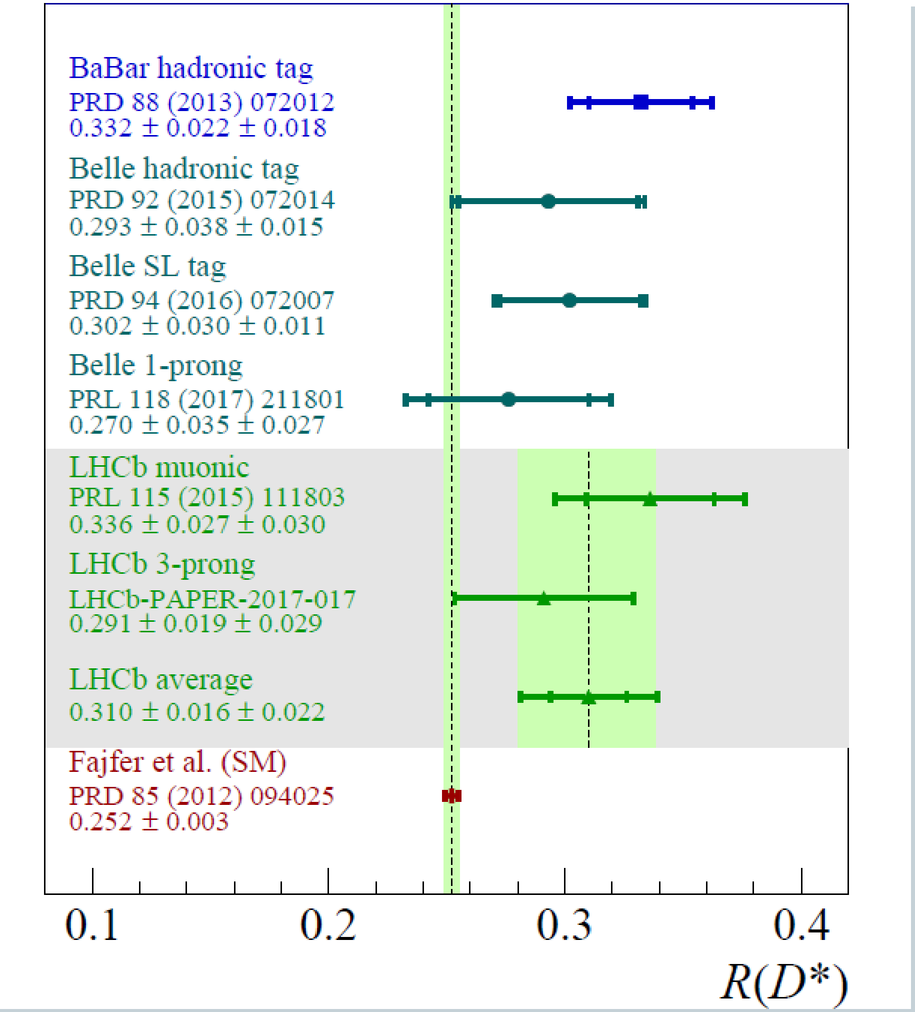
  0.336 ±0.027 ±0.030

  - 2.1 σ above SM, 0.6 σ above WA
- Final LHCb average

  0.310 ±0.016 ±0.022

  - 2.1 σ above SM, 0.1 σ above WA
  - The weight of the 3π analysis is 1.5 better than the muonic one.
- This results pulls down WA a bit but increases slightly the discrepancy wrt SM!!
- New WA

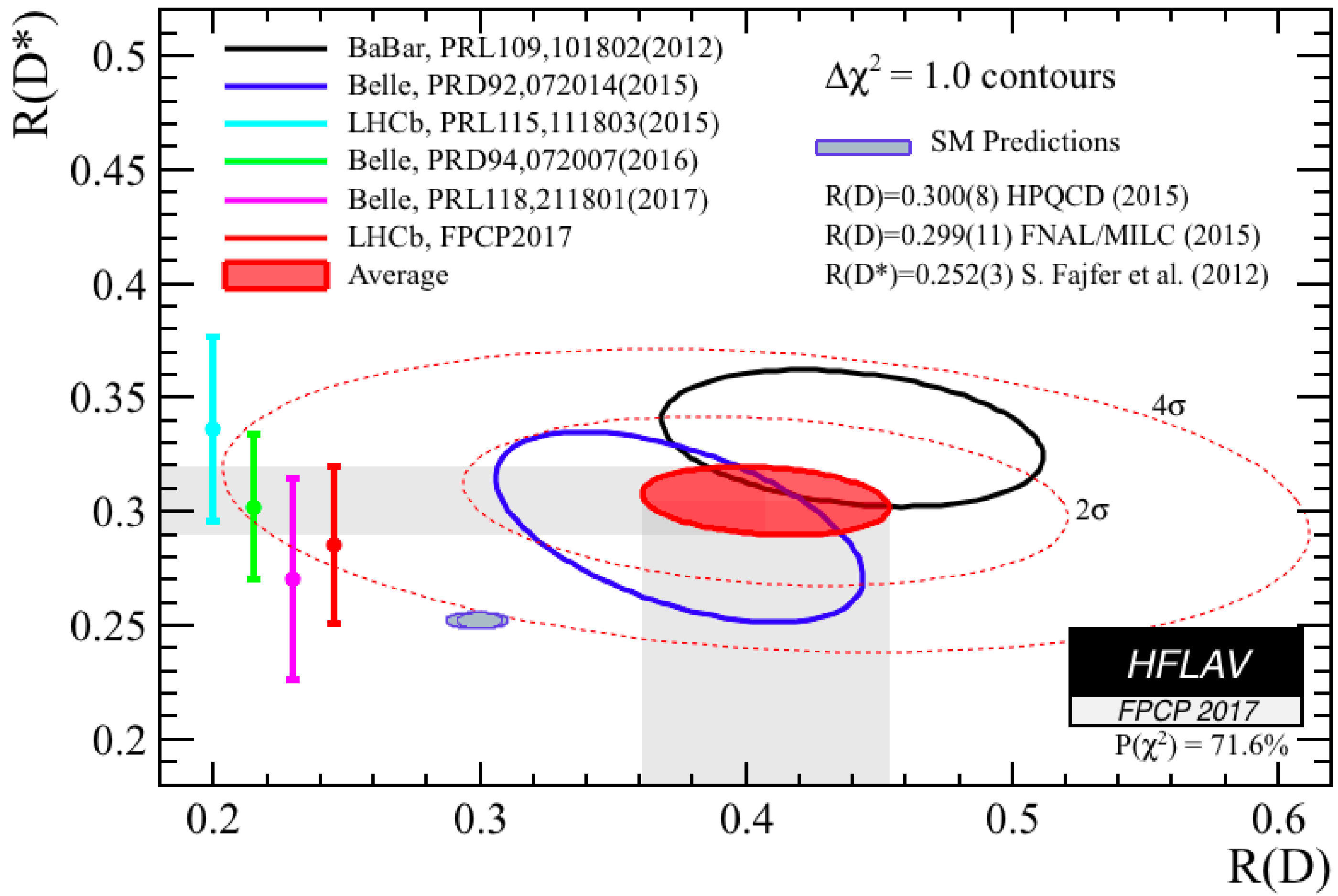
  R(D*)=0.304±0.013(stat)±0.007(syst)



The new average

PRL 120,171802 (2018)/PRD 97,072013(2018)

Combined signifance: 4.1 σ away from SM



The LHCb semitauonic program

1. Vertical extension of R(D*)

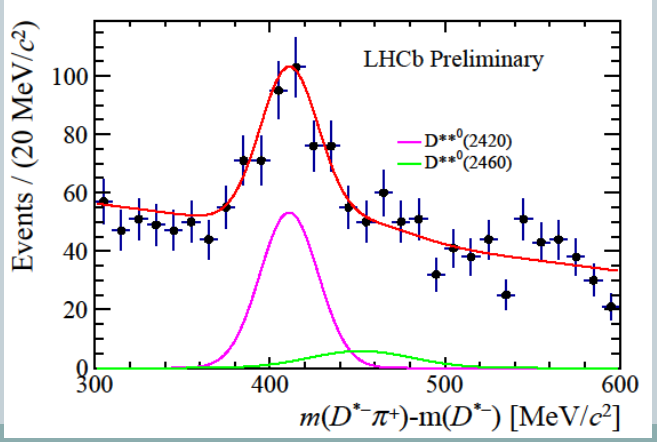
- Extraction of internal quantities , most notably q^2 , search for NP effects using our high stats high purity sample → with HAMMER or similar program
- R(D*) measurement with Run2 data
  - Hampered by slow MC production but the prospects are excellent 2015+2016=~2*Run1
  - Goal is to be competitive with the World Average
- Full Run2 paper to be expected in 2020 (statistical precision will be lower than 3% at that date)
- Measure R(D**°(2420) per se and constraint D** feed-down

D** cross check

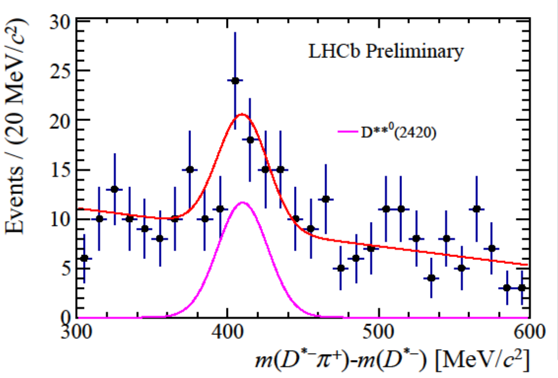
PRL 120,171802 (2018)/PRD 97,072013(2018)

- $B^0 \rightarrow D^{**} \tau\nu$ and $B^+ \rightarrow D^{**0}\tau\nu$ constitute potential feeddown to the signal
- $D^{**}(2420)^0$ is reconstructed using its decay to $D^{*+}\pi^-$ **as a cross check**
- The observation of the $D^{**}(2420)^0$ peak allows to compute the $D^{**}3\pi$ BDT distribution and to deduce a $D^{**}\tau\nu$ upper limit with the following assumption.
  - $D^{**0}\tau\nu = D^{**}(2420)^0\tau\nu$ (no sign of $D^{**}(2460)^0$
  - $D^{**+}\tau\nu = D^{**0}\tau\nu$
- This upper limit is consistent with the theoretical prediction
- Subtraction in the signal of 0.11±0.04 due to $D^{**}\tau\nu$ events leading to an error of 2.3%

All detached vertices



Detached vertice for BDT>.0.1



The future of R(D*) studies

- From 2020 onwards, it is highly likely that the systematic errors on R(D*) measurements will reach a floor that will be very difficult to beat
- Is that the end : NO ☺ The larger and larger statistics will be used to search for NP within the events !!
- We can expect in Run1+Run2 6k events with 50% purity !!!
- The same will be true after LHCb upgrade : do no expect any breakthrough in R(D*) precision but expect large improvment in NP sensitivity !!!

The « horizontal extension »

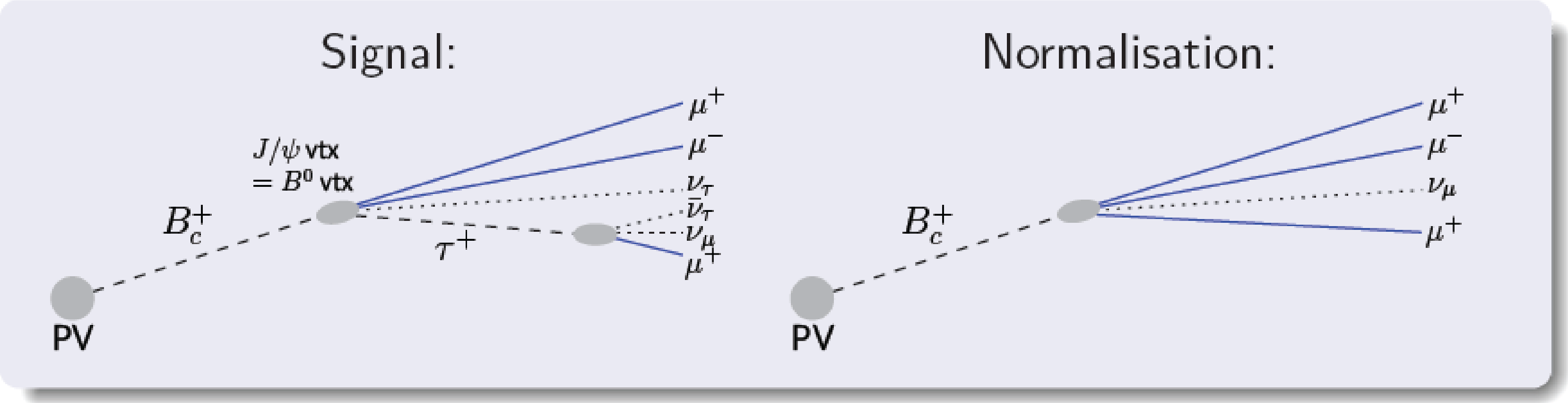
Because all b hadrons are produced at the LHC and since the measurement methods are identically valid for all of them, LHCb will measure the full collection:

- $R(\Lambda_c)$
- $R(D^+)$,$R(D^o)$
- $R(J/\psi)$
- $R(D_s)$
- V_{ub} ($R(p)$,$R(p\bar{p})$,…)
- $R(D^{**})$
- $R(\Lambda^*_c)$

$R(J/\psi)$ with leptonic tau decay

[PRL 120 (2018) 121801]

$R(J/\psi) = \frac{\mathcal{BR}(B_c \to J/\psi \tau\nu)}{\mathcal{BR}(B_c \to J/\psi \mu\nu)}$



- B_c shorter decay time:
  helps reduce background
- B_c^0 reconstructed using flight vector and $(J/\psi, \mu)$ system
- 3 muons in final state
  - Background dominated by:
    MisID, $J/\psi + \mu$ combinatorial

$R(J/\psi)$ with leptonic tau decay [PRL 120 (2018) 12180

$B_c \to J/\psi l \nu$ form factors

- Only theoretical predictions exists
  - Kiselev [arXiv:hep-ph/0211021]
  - Ebert, Faustov, and Galkin [PRD 68 (2003) 094020]
  - Hernandez, Nieves, Verde-Velasco [PRD 74 (2006) 074008]
  - Wang, Shen and Lu [PRD 79 (2009) 054012]
- $R(J/\psi)_{\mathrm{SM}} = 0.25 - 0.28$

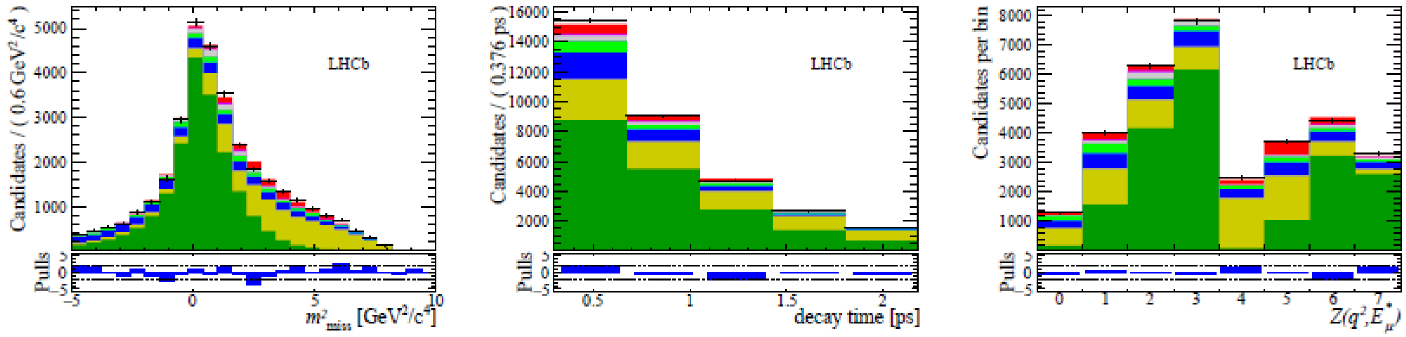
FF determination in $R(J/\psi)$

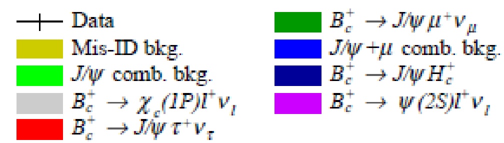
- In $B_c \to J/\psi \mu$ rich region
  - By fit estimate $A_1(q^2), A_2(q^2), V(q^2)$ (following EFG convention)
- In the nominal fit
  - $A_{1,2}, V$ fixed
  - A_0 unconstrained

$R(J/\psi)$ with leptonic tau decay

[PRL 120 (2018) 121801]

3D template fit (m^2_{miss}, $B_c$decay time, Z)[1]





Fit result

- $R(J/\psi) = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})$
- $R(J/\psi)_{\text{SM}} = 0.25 - 0.28$
- 2σ deviation
- FF largest systematic
- First measurement of $R(J/\psi)$

Source of uncertainty	Size ($\times 10^{-2}$)
Limited size of simulation samples	8.0
$B_c^+ \to J/\psi$ form factors	12.1
$B_c^+ \to \psi(2S)$ form factors	3.2
Fit bias correction	5.4
Z binning strategy	5.6
Misidentification background strategy	5.6
Combinatorial background cocktail	4.5
Combinatorial J/ψ sideband scaling	0.9
$B_c^+ \to J/\psi H_c X$ contribution	3.6
Semitauonic $\psi(2S)$ and χ_c feed-down	0.9
Weighting of simulation samples	1.6
Efficiency ratio	0.6
$\mathcal{B}(\tau^+ \to \mu^+ \nu_\mu \overline{\nu}_\tau)$	0.2
Total systematic uncertainty	**17.7**
Statistical uncertainty	**17.3**

[1] Z - categorical variable combining E_l^* and q^2

Prospects for other R using hadronic τ decays (personal guestimates)

	Present effort intensity	First result precision (stat+syst)(%)	First result date	Run1+Run2 expected stat. precision (%)	Specificity
$R(\Lambda_c)$	***	7+15	Fall 2018	3	Spin 1/2
$R(J/\psi)$	***	20+10	Winter 2018	10	Bc
$R(D^0)$,$R(D^+)$	***	3+7	2019	2	Very low SM uncertainties
$R(D_s)$	*	5+10	2020	3	Sum of Ds and Ds*
R(D**)	*	15+10	2019	7	No higher level feeddown
$R(\Lambda^*_c)$	**	10+10	2019	7	No Higher level feed-down
R(p)	-	7+10	2020	5	Vub cf annihilation

Conclusions

- The analysis to measure the ratio **$BR(B^{o} \rightarrow D^{*}\tau\nu)/BR(B^{o}\rightarrow D^{*}3\pi)$** using the 3 π hadronic decay of the τ lepton has been performed at LHCb (Preliminary)

  $R(D^{*})=0.291\pm0.019(stat)\ \pm0.026(syst)\ \pm0.013(ext)$

  New preliminary LHCb average of $R(D^{*})=0.310\pm0.026$

- This analysis was made possible due to the unique LHCb capabilities for separating secondary and tertiary vertices with unprecedented precision
- **The R(D*) result, the first one to use 3π final state, 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. However, it **slightly increases the discrepancy of the WA wrt to the SM**

Short, mid and long term LHCb Prospects

- By the end of 2018 (or early 2019) (hadronic channel)
  - First publication $R(\Lambda_c)$, $R(J/\psi)$
  - **Search for new Physics within the event**
  - Update R(D*) Run2
- In the course of 2019
  - First publication R(D*),$R(D^0)$,$R(D^+)$ (to be expected earlier in muonic version)
  - $R(\Lambda_c^*)$
  - R(D**)
- In 2020
  - First $R(D_s)$ publication
  - Complete set of Run1+Run2 papers
- The systematic floor will likely be reached for all channels by that time, except maybe for B_c
- The obvious goal is to complete this program before BELLE-II competition becomes severe ~at the end of 2021
- The post-upgrade physics program will move away from yield measurements to focus on extraction of New Physics from the event characteristics

Backup

The 2012 BABAR results statistics

Decay	N_{sig}	N_{norm}	$\varepsilon_{sig}/\varepsilon_{norm}$	$\mathcal{R}(D^{(*)})$	$\mathcal{B}(B \to D^{(*)}\tau\nu)$ (%)	Σ_{stat}	Σ_{tot}
$B^- \to D^0\tau^-\overline{\nu}_\tau$	314 ± 60	1995 ± 55	0.367 ± 0.011	$0.429 \pm 0.082 \pm 0.052$	$0.99 \pm 0.19 \pm 0.13$	5.5	4.7
$B^- \to D^{*0}\tau^-\overline{\nu}_\tau$	639 ± 62	8766 ± 104	0.227 ± 0.004	$0.322 \pm 0.032 \pm 0.022$	$1.71 \pm 0.17 \pm 0.13$	11.3	9.4
$\overline{B}^0 \to D^+\tau^-\overline{\nu}_\tau$	177 ± 31	986 ± 35	0.384 ± 0.014	$0.469 \pm 0.084 \pm 0.053$	$1.01 \pm 0.18 \pm 0.12$	6.1	5.2
$\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$	245 ± 27	3186 ± 61	0.217 ± 0.005	$0.355 \pm 0.039 \pm 0.021$	$1.74 \pm 0.19 \pm 0.12$	11.6	10.4
$\overline{B} \to D\tau^-\overline{\nu}_\tau$	489 ± 63	2981 ± 65	0.372 ± 0.010	$0.440 \pm 0.058 \pm 0.042$	$1.02 \pm 0.13 \pm 0.11$	8.4	6.8
$\overline{B} \to D^*\tau^-\overline{\nu}_\tau$	888 ± 63	11953 ± 122	0.224 ± 0.004	$0.332 \pm 0.024 \pm 0.018$	$1.76 \pm 0.13 \pm 0.12$	16.4	13.2

N($B^0 \to D^{*+}\tau\nu$)= 245±27 events
BR($B^0 \to D^{*+}\tau\nu$)= (1.76±0.19±0.12)%

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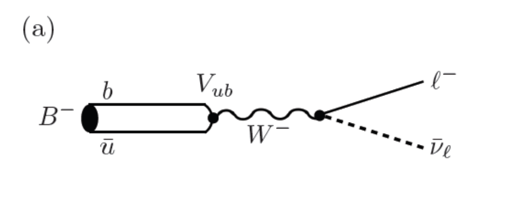
Summary of the various efficiencies

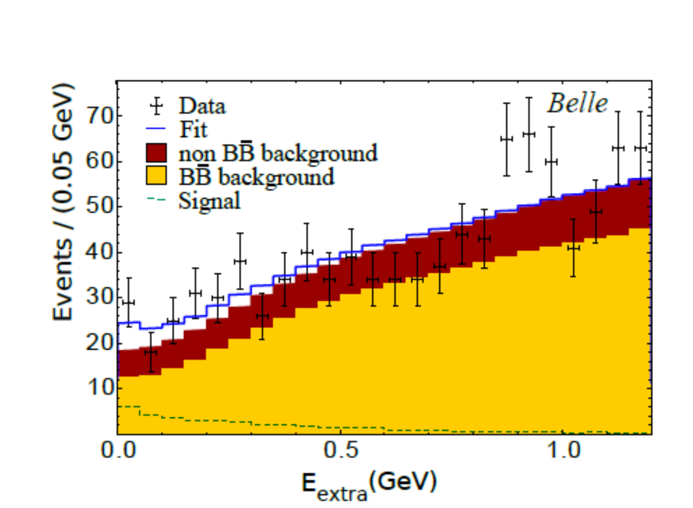
Category	$B^0 \to D^* 3\pi$	Signal		Rel. eff.	Rel. eff. signal	
		$\tau \to 3\pi$	$\tau \to 3\pi\pi^0$	$D^* 3\pi$	$\tau \to 3\pi$	$\tau \to 3\pi\pi^0$
Acceptance (%)	14.65	15.47	14.64			
After stripping	1.382	0.826	0.729			
After cleaning	0.561	0.308	0.238	40.6	37.3	32.6
After trigger requirements	0.484	0.200	0.143	86.3	65.1	59.9
After vertex selection	0.270	0.0796	0.0539	55.8	39.8	37.8
After Charged isolation	0.219	0.0613	0.0412	81.2	77.0	76.3
After D0 sideband removal	0.207	0.0583	0.0393	94.5	95.3	95.5
After MW cut	-	0.0574	0.0390	-	98.4	99.1
After BDT cut	-	0.0541	0.0292	-	94.1	74.8
After PID cut	0.136	0.0392	0.0216	65.8	72.4	74.1
Overall efficiency (%)	19.97×10^{-3}	6.08×10^{-3}	3.23×10^{-3}			
Analysis efficiency (%)	9.86	4.76	2.95			

The sources of the different efficiencies between signal and normalization have been studied in great detail. The major contribution come from the softer D*(slow pion) and 3π p and p_T spectrum for the signal induced by the presence of two extra neutrinos

Search for LFU violation in V_{ub} decays

- Note that in the long term the 'Vub' analog b->uW is also quite interesting, since its coupling to new physics can be different from the cW case
  - Rather difficult in practice B factories can search for B➔πτν
  - LHCb can look for Λ_b➔pτν or B°➔p $\bar{p}$ τν
- A similar reaction is the annihilation diagram





$$\mathcal{B}(B^- \to \tau^- \overline{\nu}_\tau) = (1.06 \pm 0.19) \times 10^{-4}.$$

$$\mathcal{B}^{SM}(B^- \to \tau^- \overline{\nu}_\tau) = (0.75^{+0.10}_{-0.05}) \times 10^{-4}.$$