Lepton Flavour Universality tests at LHCb

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HFCPV MEETING
WUHAN, OCT 27 2017

Where to look for LFU

- In rare K decays
  - πee, $\pi\mu\mu$ (known το 6%) hadronic effects
- In rare D decays
  - K(*)ee, K(*)μμ (only limits) hadronic effects
- In B decays

  The only place where to look for e/mu/tau comparison
  - **At tree level in Charged current interactions**
  - **in supressed neutral current reactions**
  - Can also to be searched for, in annihilation reactions

    $B \to \tau\nu$ vs $B \to \mu\nu$ (BELLE-II)
- $D_s, D^+ \to \tau\nu$ $D_s, D^+ \to \mu\nu$, (hadronic corrections)

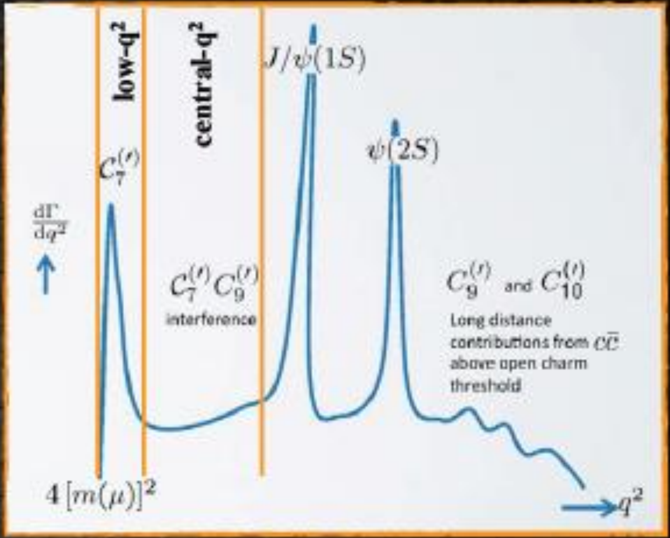
Semileptonic Vub decays $b \to u\tau\nu$ probe the same vertex as the annihilation (LHCb) $B^+ \to pp\tau\nu$, $\Lambda_b \to p\tau\nu$)

The criterium for a good LFU

- Very robust theoretical prediction
- Experimental precision in the same ball park
- High sensitivity to new physics (involving third family of quarks and/or leptons)
- Two channels meet these criteria :
  - $B \rightarrow K(*) l^{+} l^{-}$ $R(K^*)=K^*\mu\mu/K^*ee$
  - $B \rightarrow D(*)\ \tau\nu$ $R(D*)=D*\tau\nu/D*\mu\nu$

Today ...

- Test of LFU with **$B^0 \to K^{*0}\mu\mu$** and **$B^0 \to K^{*0}ee$, $R_{K^{*0}}$**

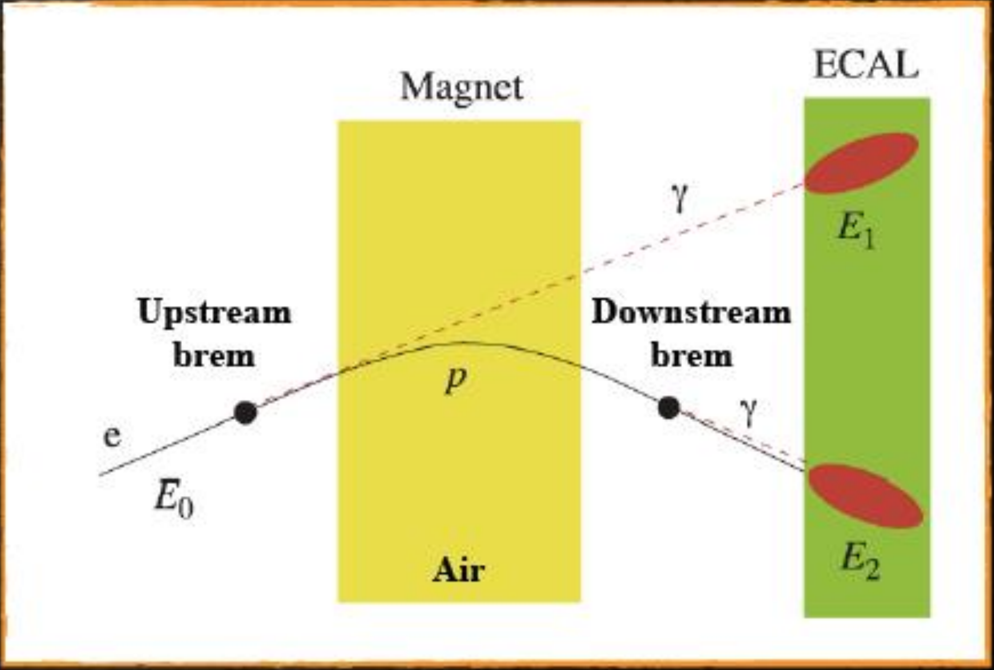


- **Two regions of q^2**
  - Low [0.045-1.1] GeV²/c⁴
  - Central [1.1-6.0] GeV²/c⁴
- Measured relative to **$B^0 \to K^{*0} J/\psi(ll)$** in order to reduce systematics
- K^{*0} reconstructed as **$K^+\pi^-$** within 100MeV from the $K^*(892)^0$
- **Blind analysis** to avoid experimental biases
- Extremely challenging due to significant differences in the way μ and e "interact" with the detector
  - Bremsstrahlung
  - Trigger

Bremsstrahlung – I

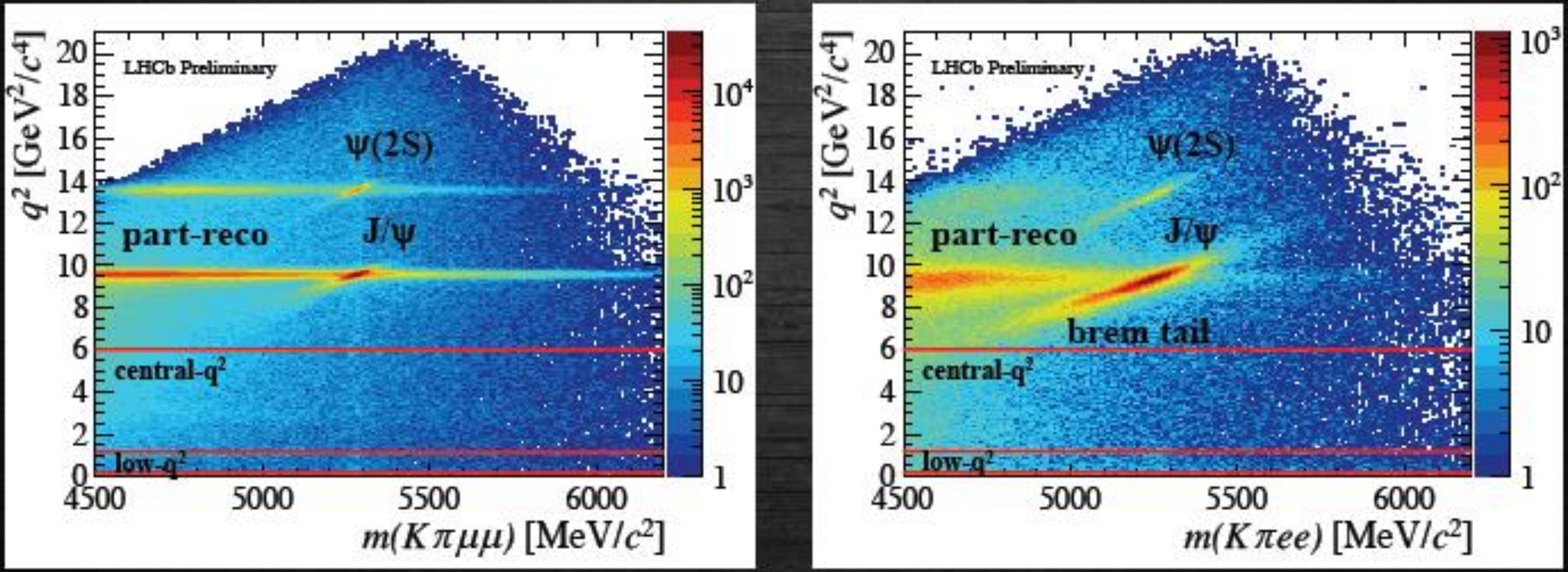
- Electrons emit a large amount of bremsstrahlung that results in degraded momentum and mass resolutions

- Two types of bremsstrahlung
  - Downstream of the magnet
    - photon energy in the same calorimeter cell as the electron
    - momentum correctly measured
  - Upstream of the magnet
    - photon energy in different calorimeter cells than electron
    - momentum evaluated after bremsstrahlung



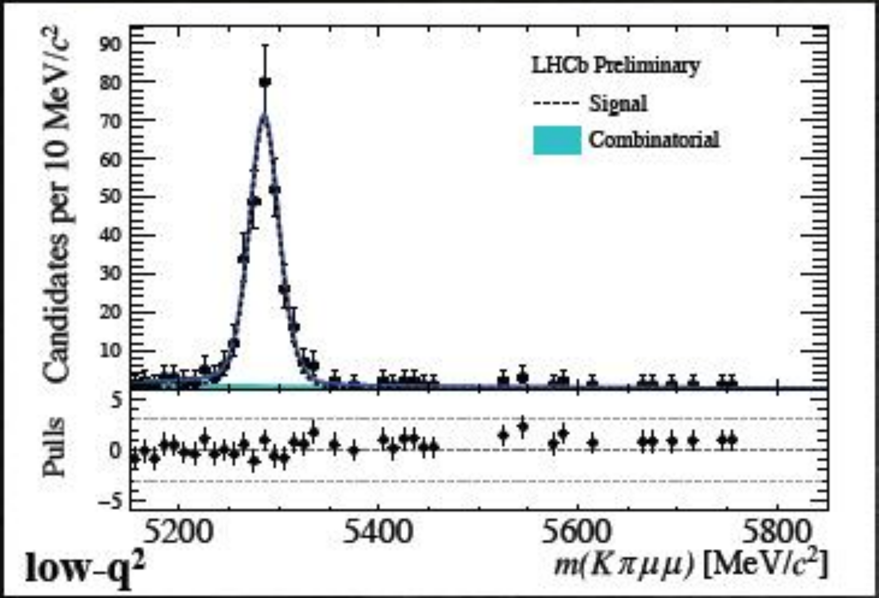
Bremsstrahlung – II

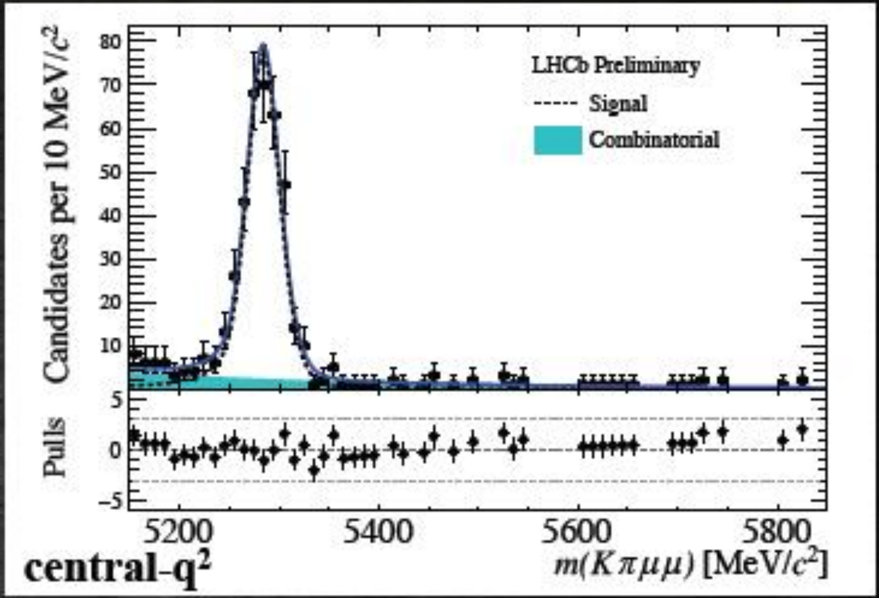
- A **recovery procedure** is in place to improve the momentum reconstruction
- Events are categorised depending on the number of recovered photon clusters
- Incomplete recovery due to
  - Energy threshold of the bremsstrahlung photon ($E_T > 75$ MeV)
  - Calorimeter acceptance
  - Presence of energy deposits mistaken as bremsstrahlung photons

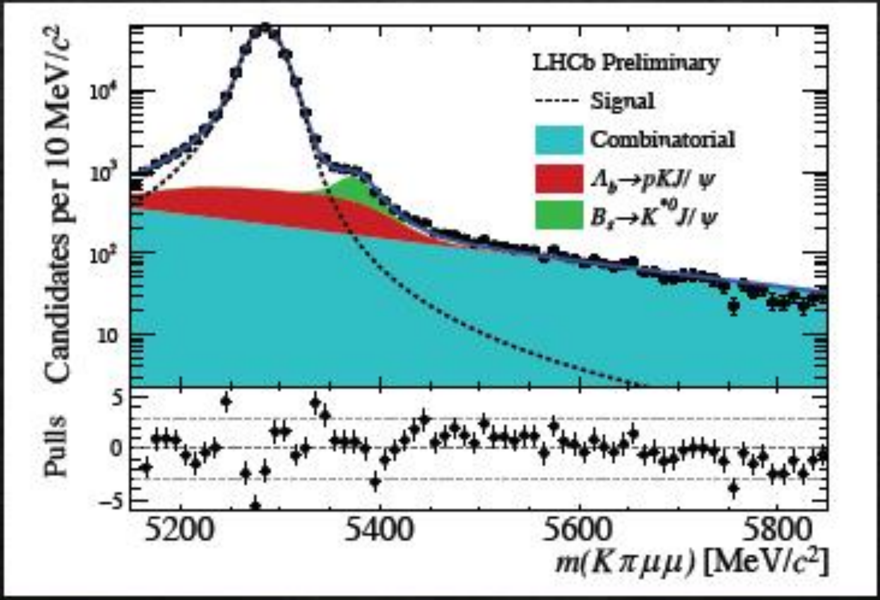


- Incomplete recovery causes the reconstructed B mass to shift towards lower values and events to migrate in and out of the q² bins

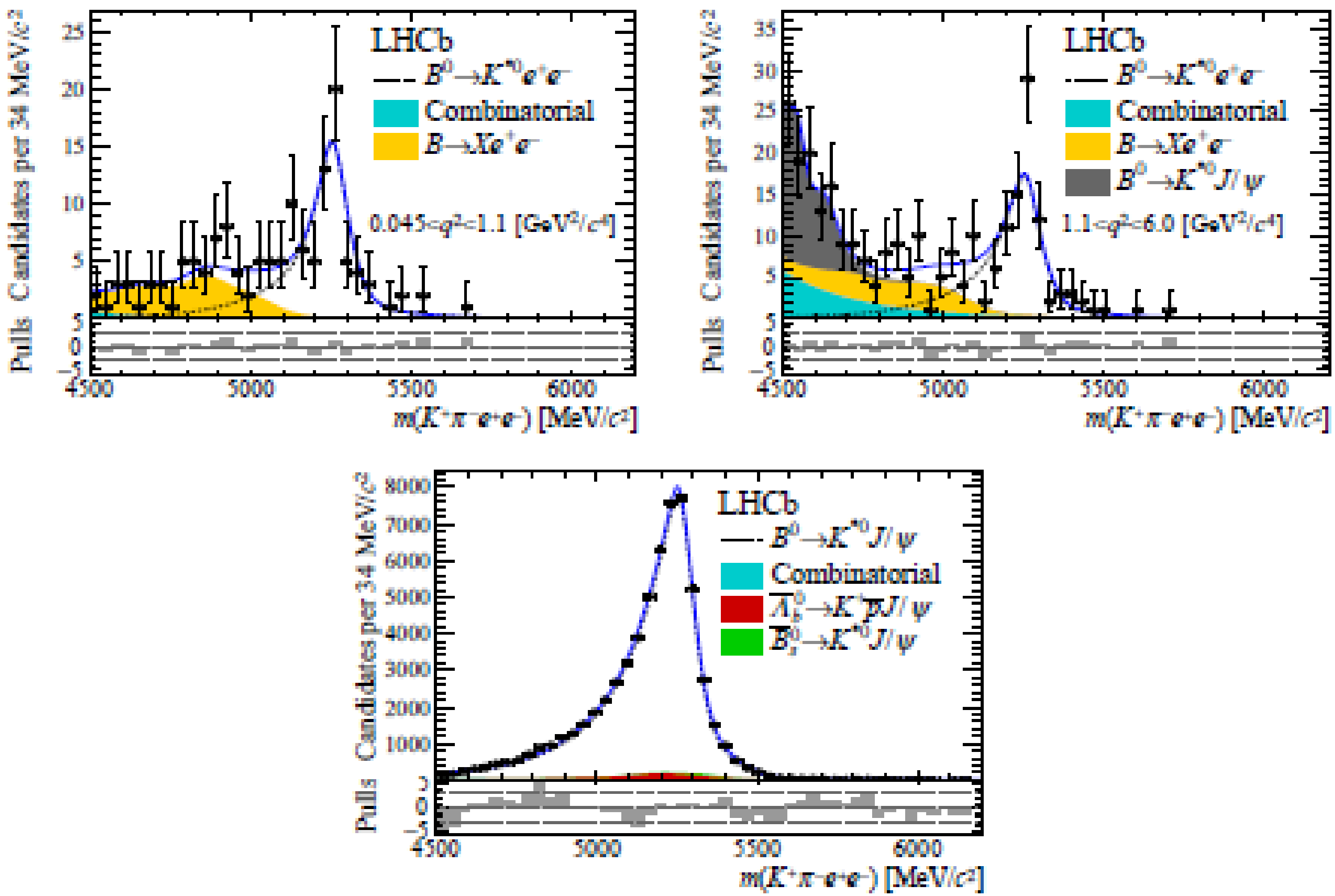
Fit Results – μμ





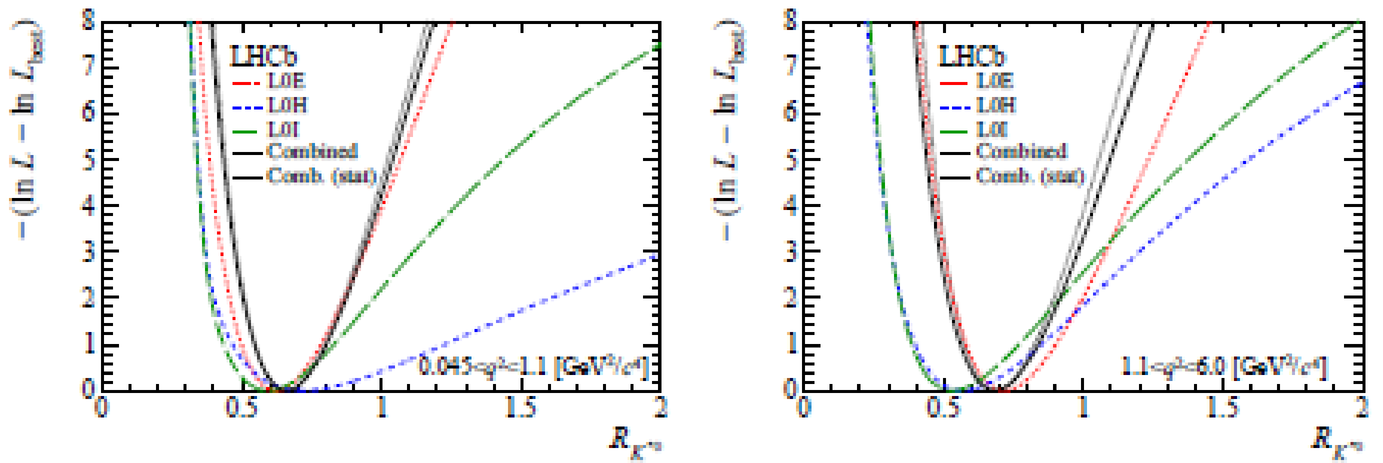


LHCb JHEP 08 (2017) 055



Results on R(K*)   LHCb JHEP 08 (2017) 055

	low-q^2	central-q^2
$R_{K^{*0}}$	$0.66\ ^{+\ 0.11}_{-\ 0.07} \pm 0.03$	$0.69\ ^{+\ 0.11}_{-\ 0.07} \pm 0.05$
95.4% CL	$[0.52, 0.89]$	$[0.53, 0.94]$
99.7% CL	$[0.45, 1.04]$	$[0.46, 1.10]$



Cross-Checks – I

› **Control of the absolute scale of the efficiencies** via the ratio

$$r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$$

which is expected to be unity and measured to be

LHCb JHEP 08 (2017) 055

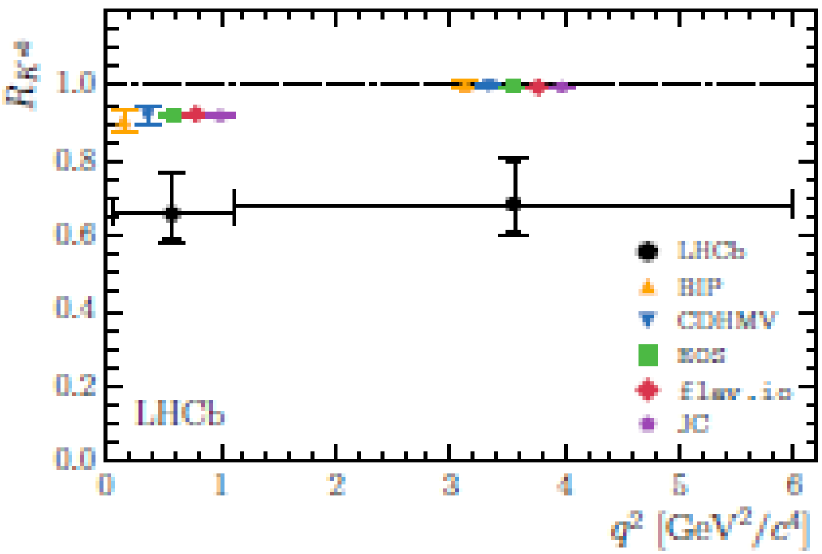
$$1.043 \pm 0.006\,(\mathrm{stat}) \pm 0.045\,(\mathrm{syst})$$

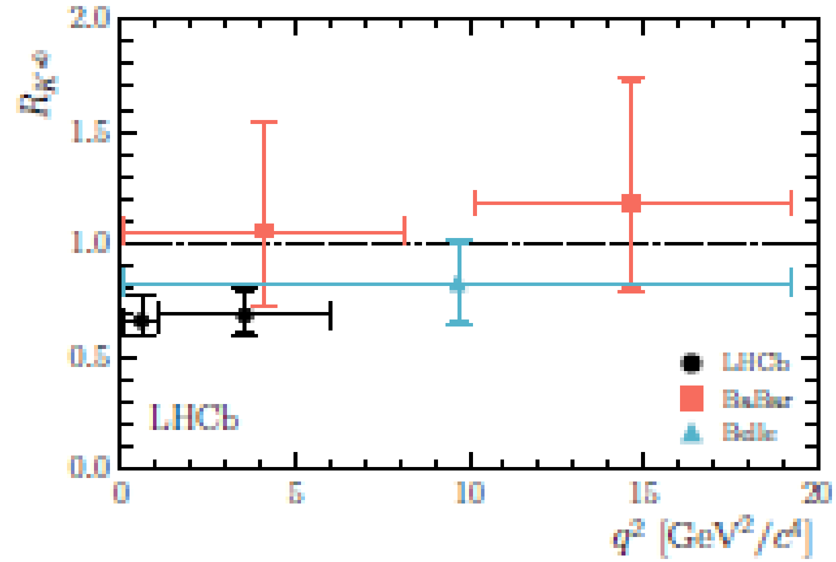
› Result observed to be reasonably flat as a function of the decay kinematics and event multiplicity

› Extremely stringent test, which does not benefit from the cancellation of the experimental systematics provided by the double ratio

Results – II

LHCb JHEP 08 (2017) 055



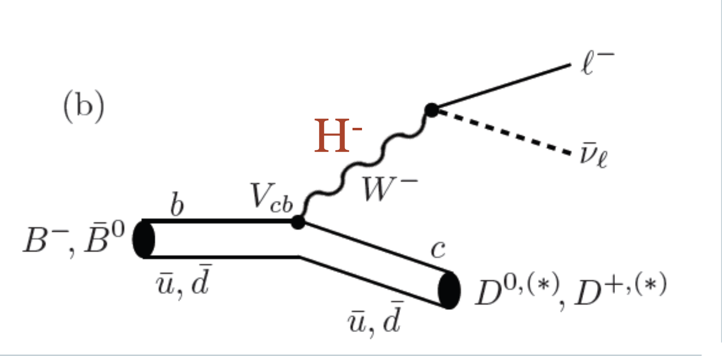


- The compatibility of the result in the **low-q^2** with respect to the SM prediction(s) is of **2.2-2.4** standard deviations
- The compatibility of the result in the **central-q^2** with respect to the SM prediction(s) is of **2.4-2.5** standard deviations

Why semitauonic decays are interesting? Very simple b->c W system

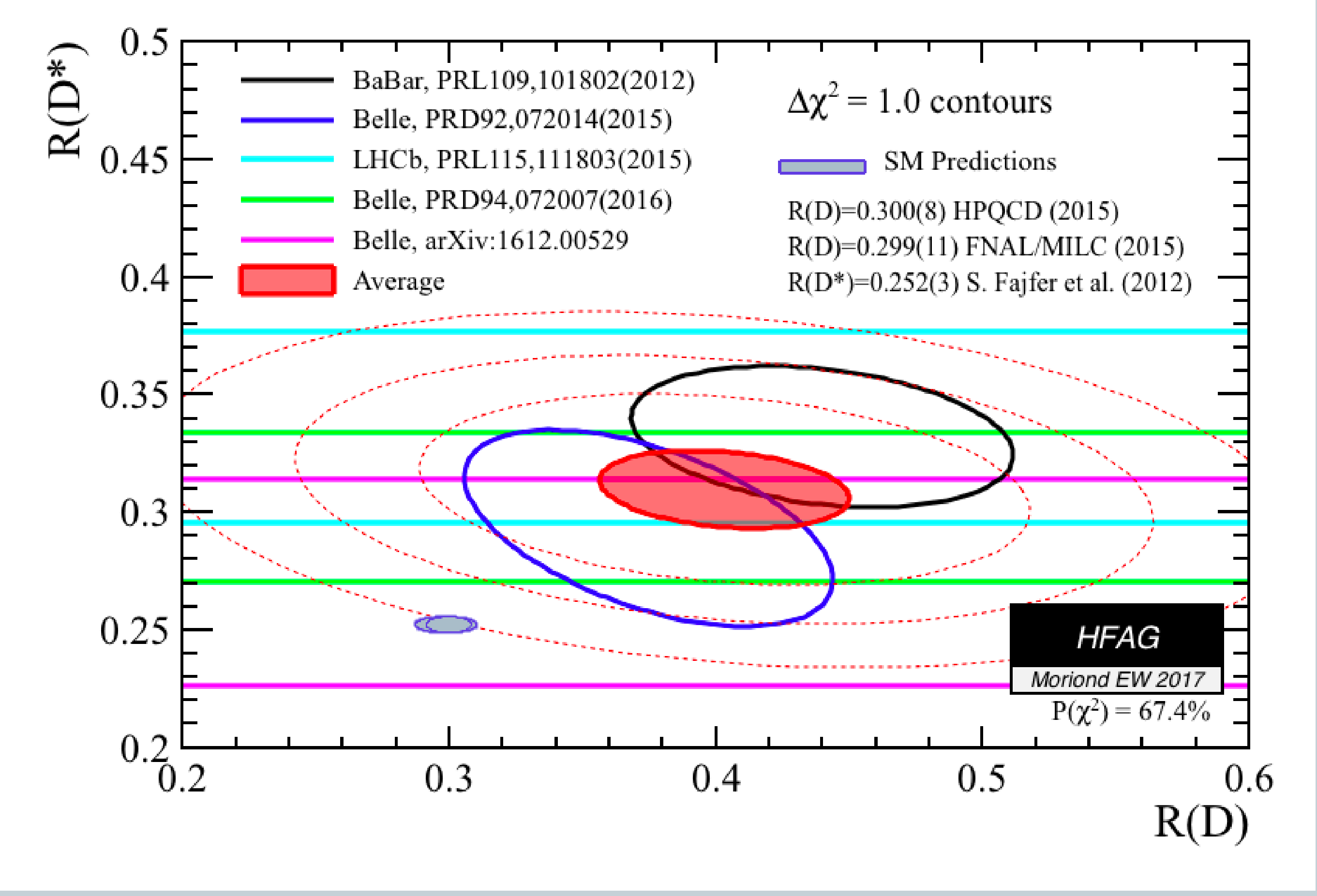
- Tree Level decays combine the advantages :
  - Very precise prediction from SM :R(D*) known better than to 2% precision, using
    R(D*) =(B➔D*τν/B➔D*μν)
  - Abundant channel BR(B°➔D*τν)=1,24%, one of the largest individual BR
  - Sensitivity to new physics : (simplest realization) A charged Higgs will automatically couple more to the τ . LFU violation can also occur through other mechanisms (leptoquarks,..)
- They offer several hadronisation implementations:
  - D*,D°,D+,Ds,Λ_c,J/ψ
  - Differing not only by various properties of the spectator particle but also its spin 0,1(D* and J/ψ) and ½ (Λ_c!!)

$$\frac{d\Gamma^{SM}(\bar{B}\to D^{(*)}\ell^-\bar{\nu}_\ell)}{dq^2} = \underbrace{\frac{G_F^2\,|V_{cb}|^2\,|p^*_{D^{(*)}}|\,q^2}{96\pi^3 m_B^2}\left(1-\frac{m_\ell^2}{q^2}\right)^2}_{\text{universal and phase space factors}} \tag{3}$$
$$\times \underbrace{\left[\left(|H_+|^2+|H_-|^2+|H_0|^2\right)\left(1+\frac{m_\ell^2}{2q^2}\right)+\frac{3m_\ell^2}{2q^2}|H_s|^2\right]}_{\text{hadronic effects}}.$$



ArXiv: HEP-1703-01766

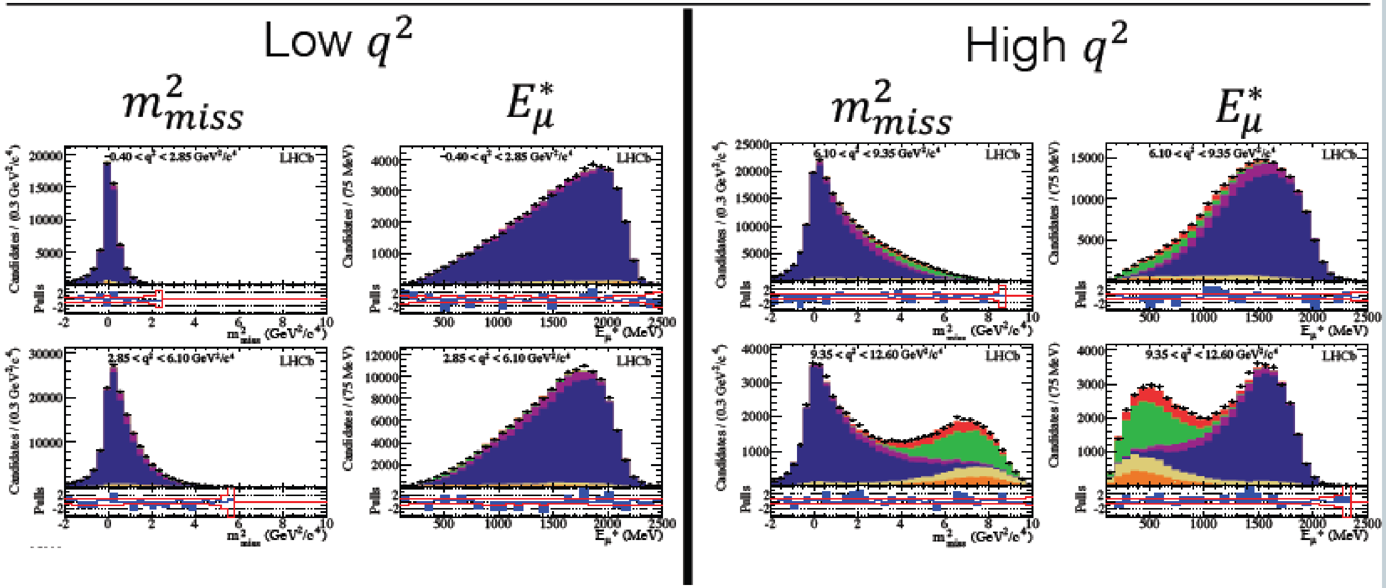
R(D) and R(D*) as of March 2017



LHCb muonic result (2015)

PRL 115 111803 (2015)

Fit Result



- Shown above: signal fit to "signal" data passing isolation selection
- Result $\frac{N_\tau}{N_\mu} = (4.32 \pm 0.37)\times10^{-2}$, $R(D^*) = 0.336 \pm 0.027 \pm 0.030$
- $N(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu) = 363{,}000 \pm 1600$

Data
$B \to D^*\tau\nu$
$B \to D^*H_c(\to l\nu X')X$
$B \to D^{**}l\nu$
$B \to D^*\mu\nu$
Combinatoric
Misidentified μ

The unusual features of the LHCb analysis $D^*\tau\nu$; $\tau \to 3\pi(\pi^\circ)$

- 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

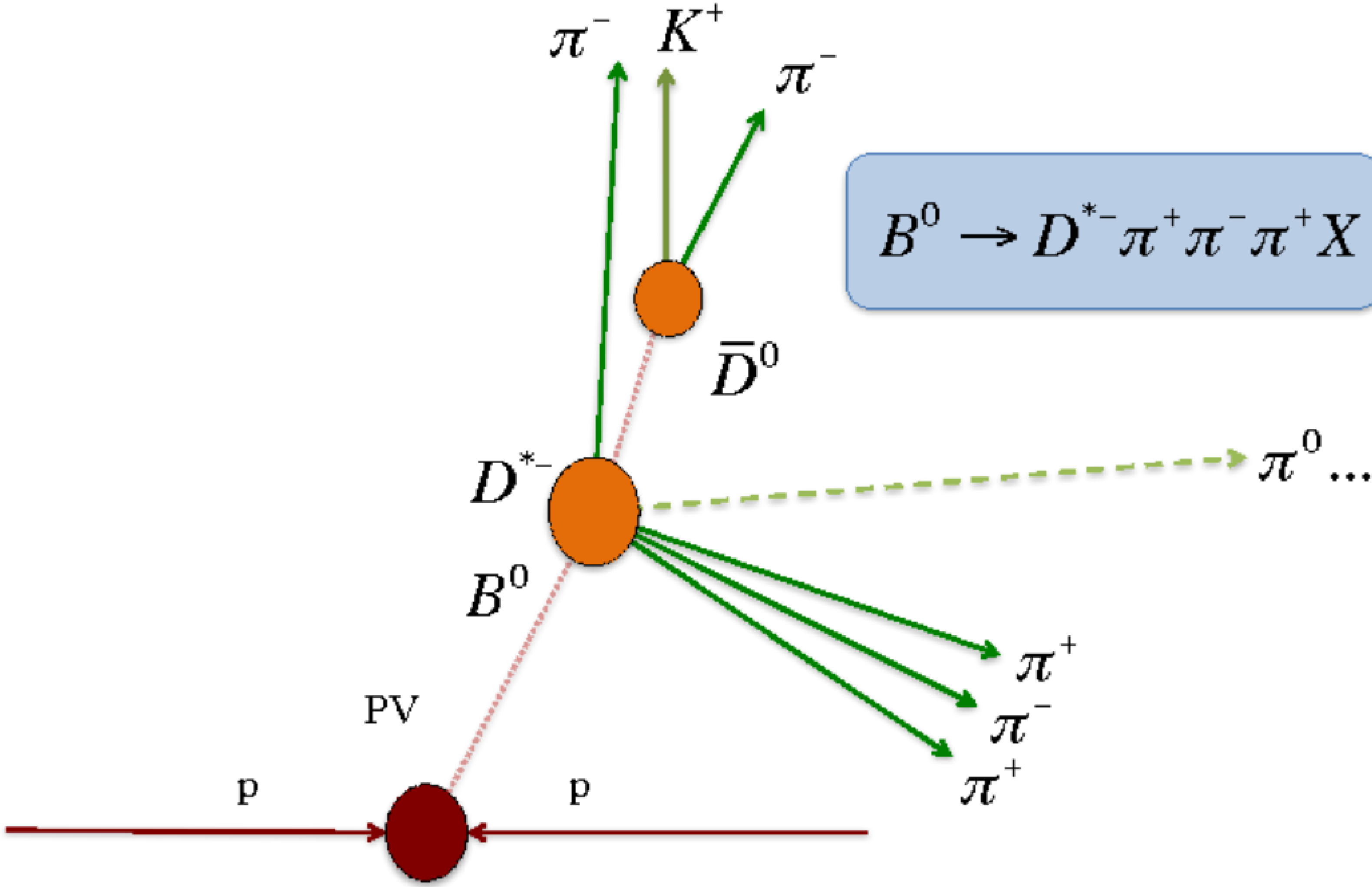
- The $D^*\tau\nu$ decay, with τ going into 3 pions (it can also be $3\pi+\pi^0$) leads to a $D^*\ 3\pi(+X)$ final state
- Nothing is more common than a $D^*3\pi\ (+X)$ final state in a typical B decay :

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

A very strong background suppression method is absolutely needed :

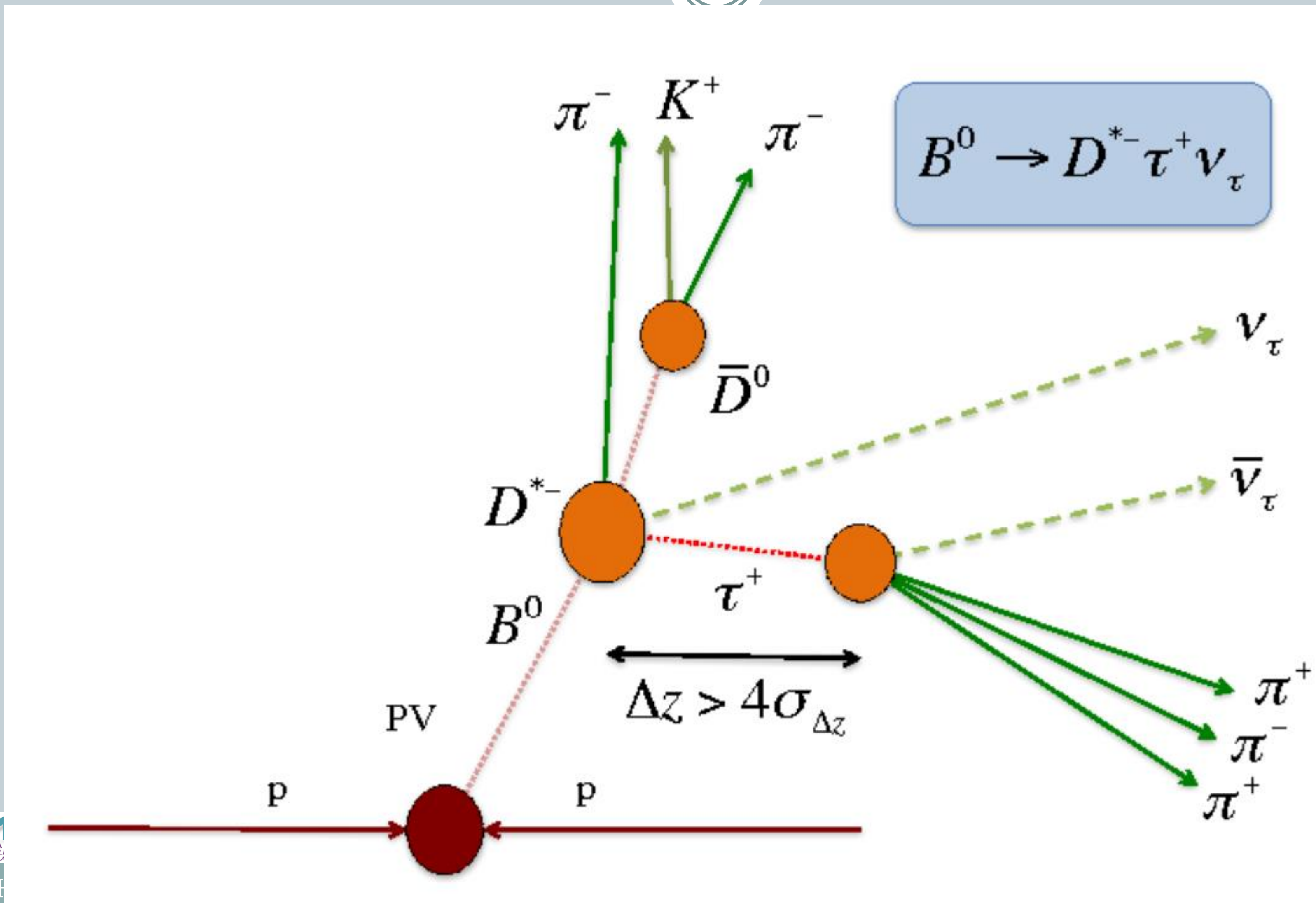
The DETACHED VERTEX METHOD

Vertex topology of the usual B decay



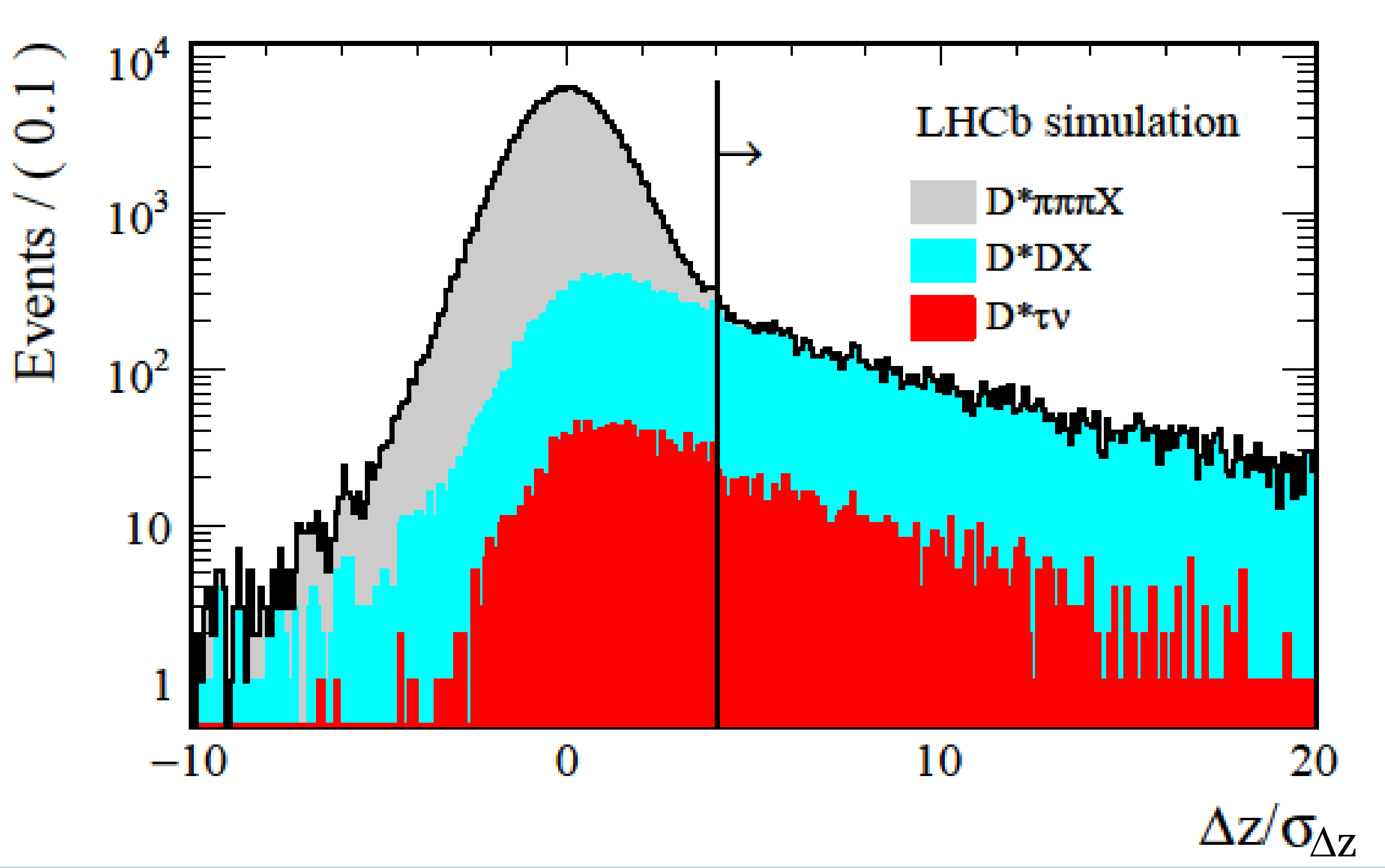
$$B^0 \rightarrow D^{*-}\pi^+\pi^-\pi^+X$$

Selection: detached vertex



Selection: the detached vertex method

LHCb-PAPER-2017-017 arxiv 1708.08856



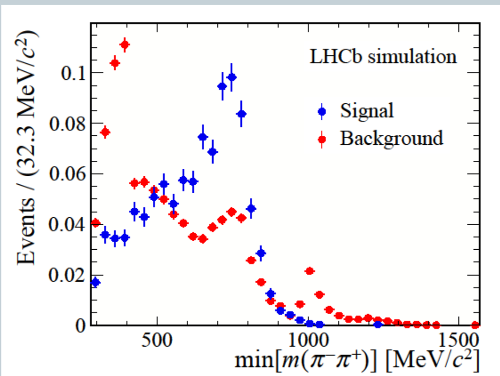
The inclusive D_s decays in 3 pions

- The $W \rightarrow c\bar{s}$ decays can produce a single meson $\mathbf{D_s}$, 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 $D_s \rightarrow 3\pi$ 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
  - $\eta\pi X$ ($\eta\pi$, $\eta\rho$)
  - $\eta'\pi X$($\eta'\pi$, $\eta'\rho$)
  - $(\phi/\omega)\ \pi X$ ($\phi/\omega\ \pi$, $\phi/\omega\ \rho$)
  - $M3\pi$, 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

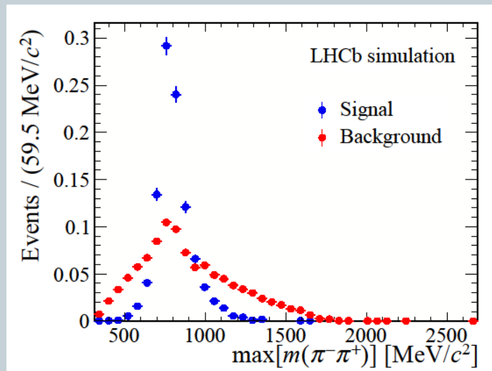
→ **We extract these informations from LHCb data in a D_s enriched region (BDT<-0.075) (~90% D_s)**

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

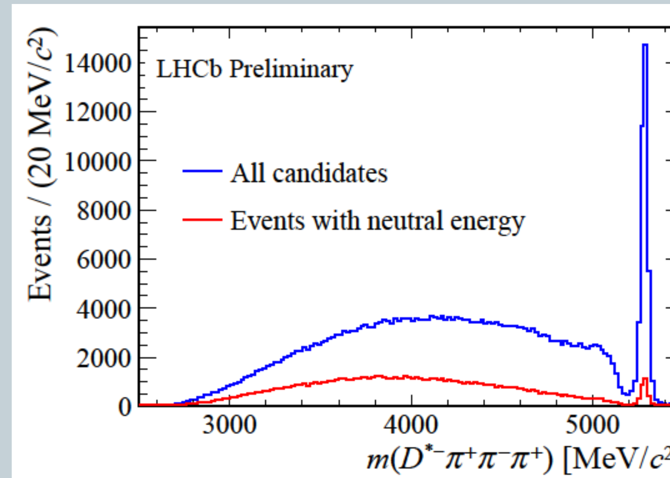
Min(mass($\pi^+\pi^-$))



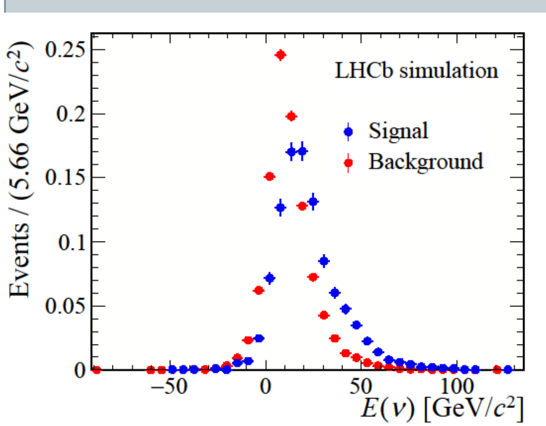
Max(mass($\pi^+\pi^-$))



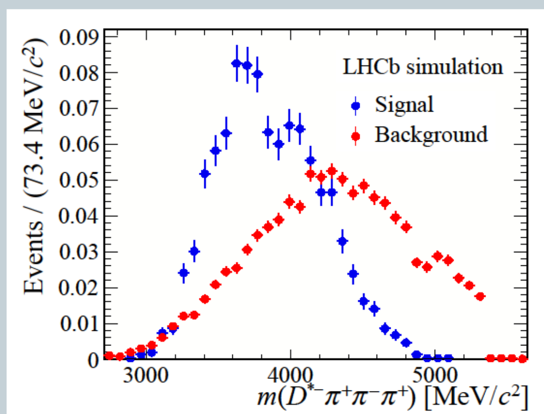
Neutral Isolation



E(ν)



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



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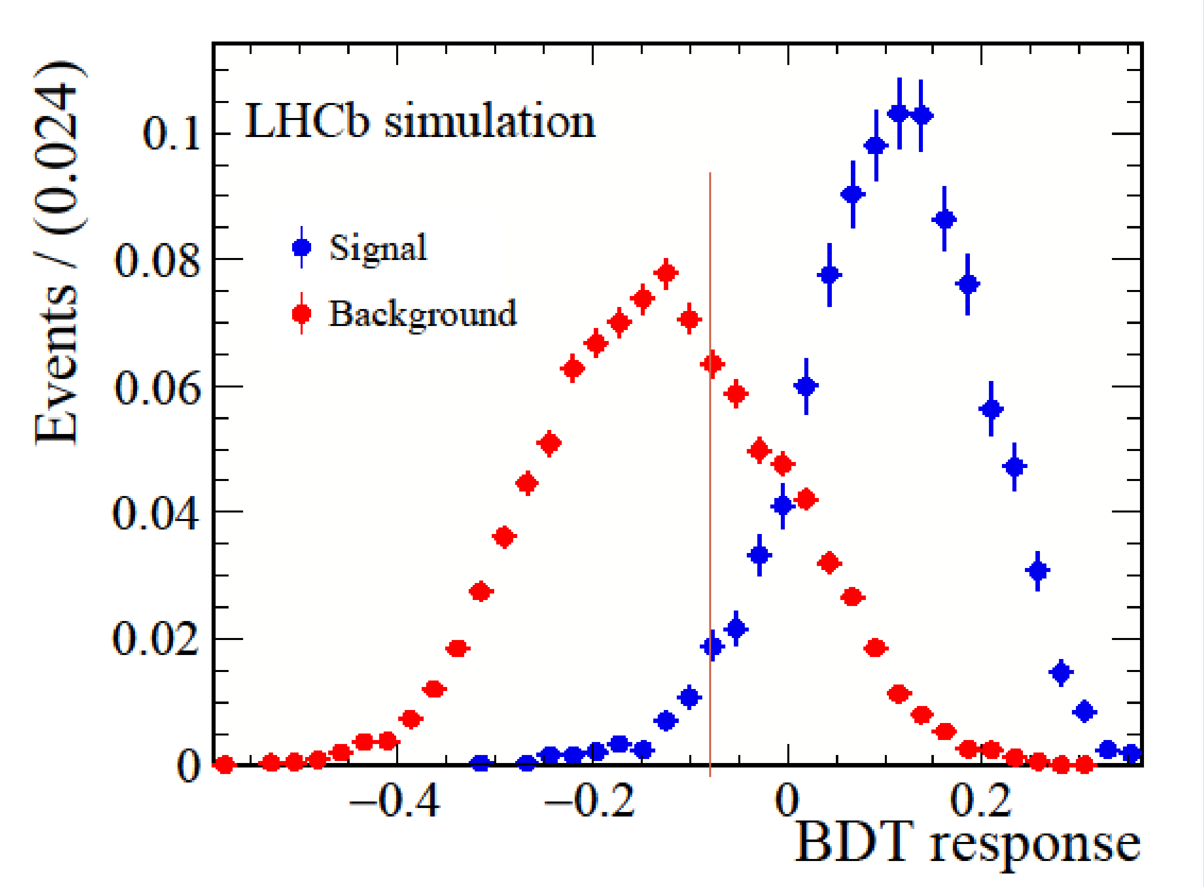
BDT results

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



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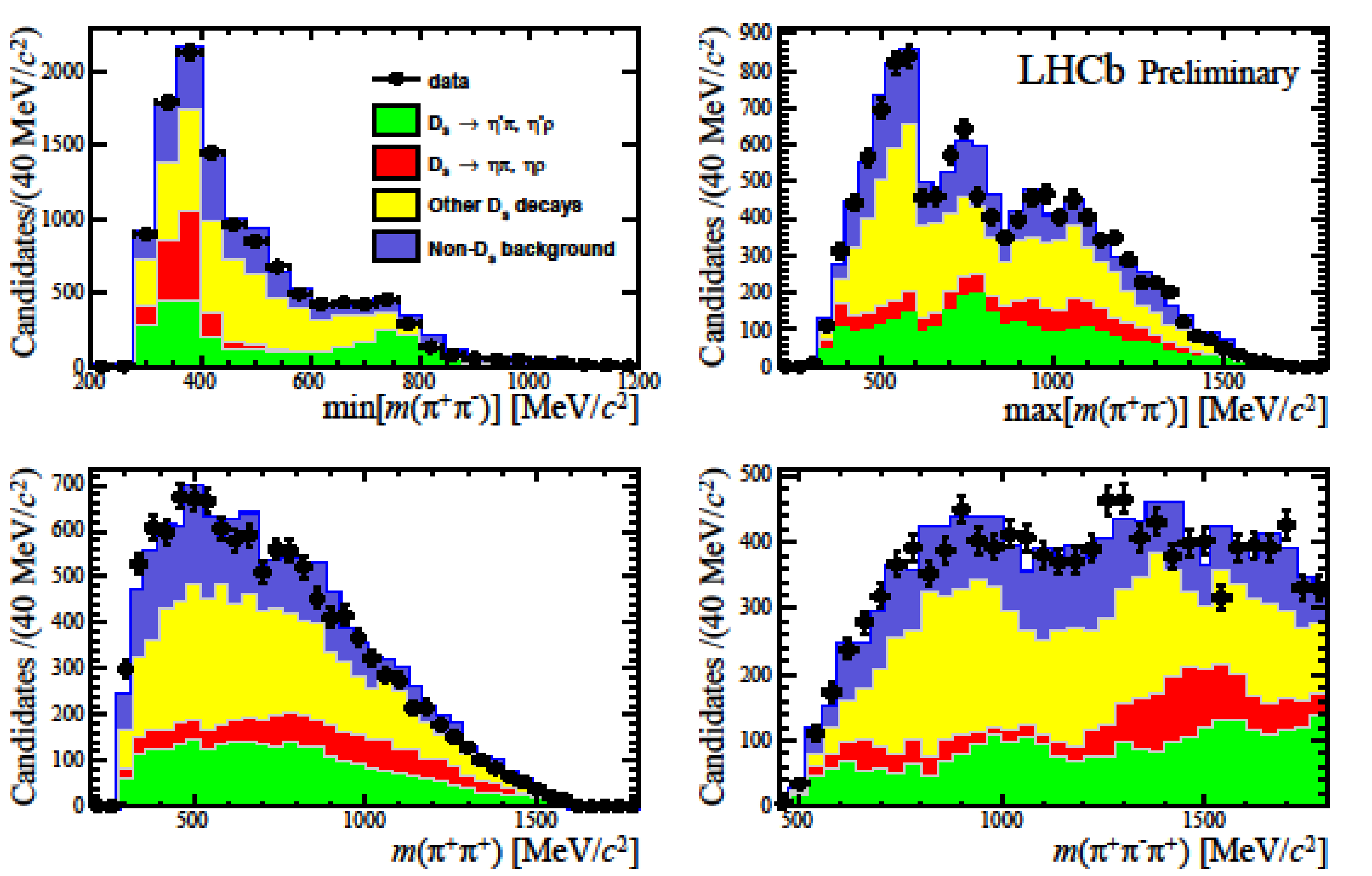
The D_s decay model fit at low BDT



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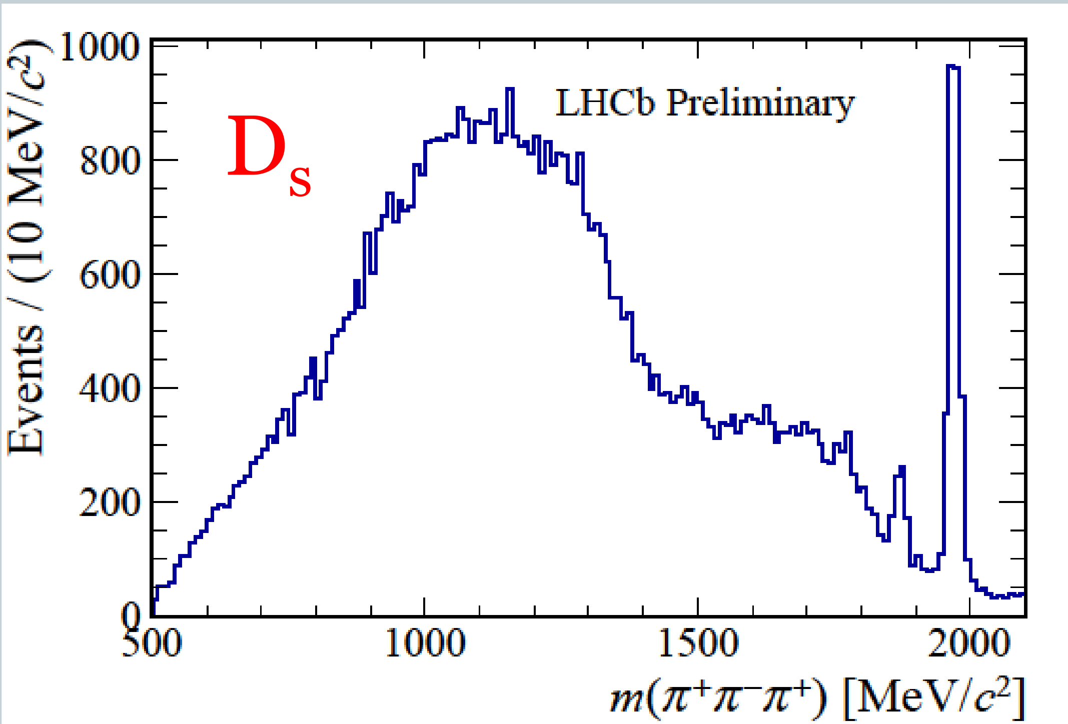
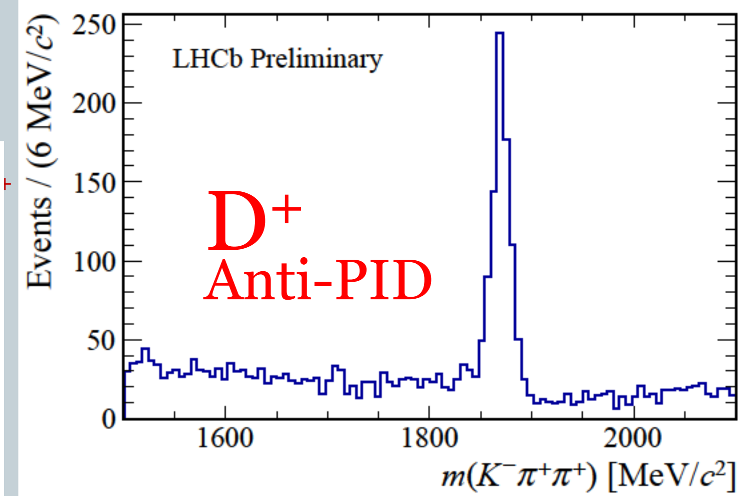
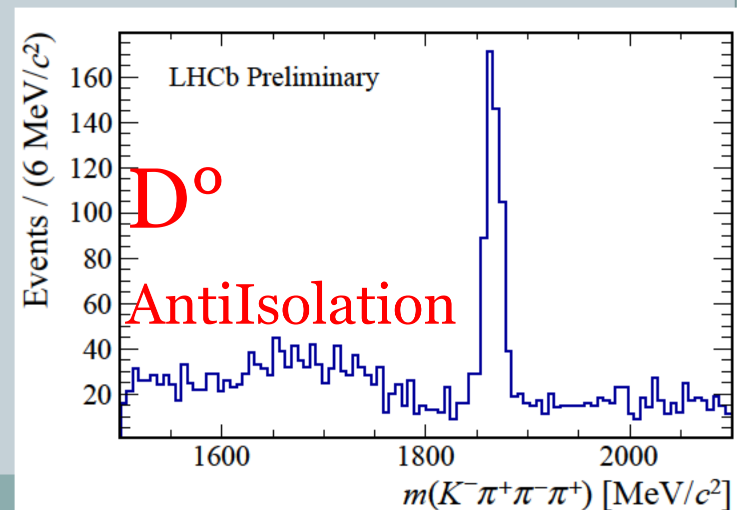
The control channels D_s, D°, and D^+





peak : Anti-Isolation



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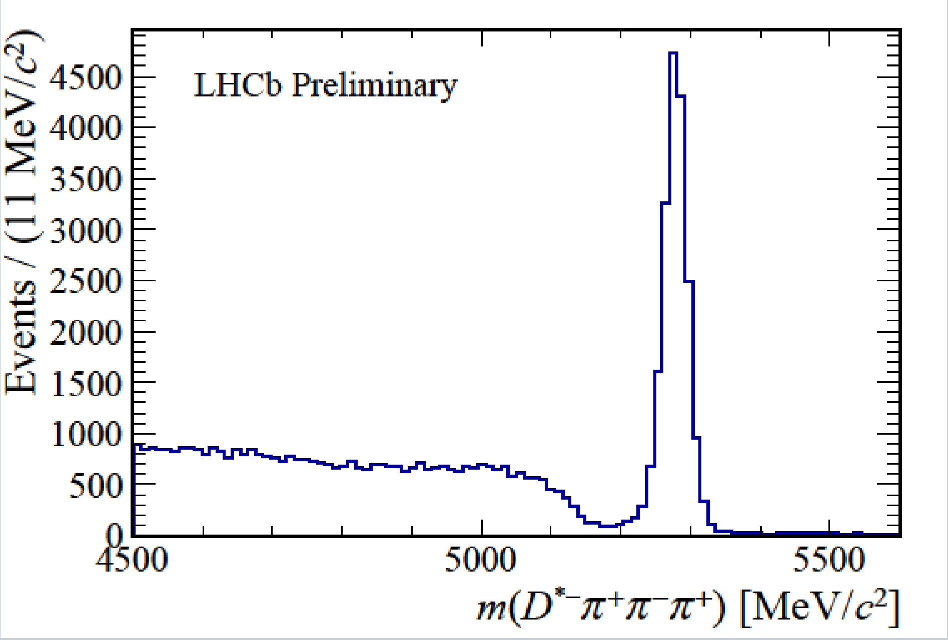
Run 1, 3 fb^{-1}

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



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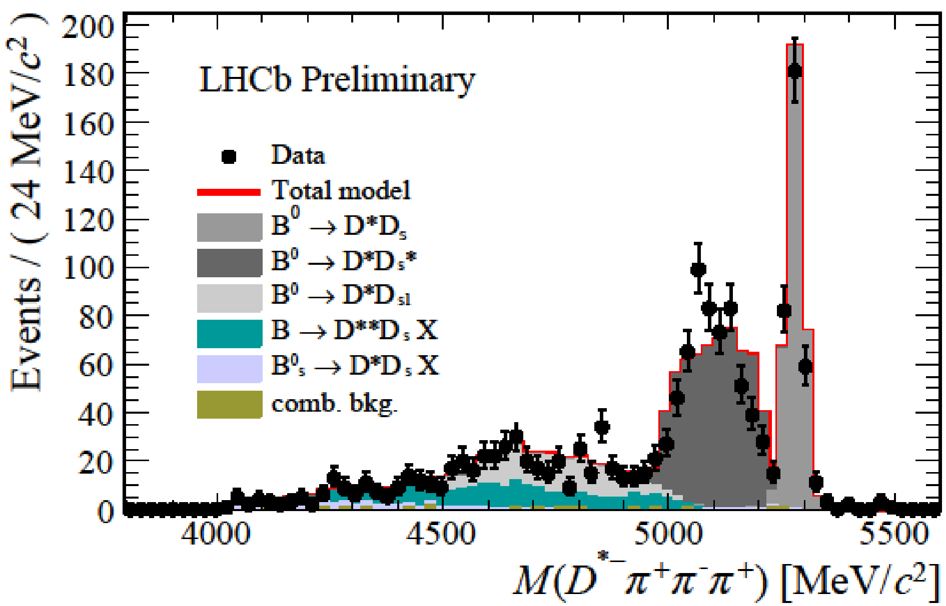
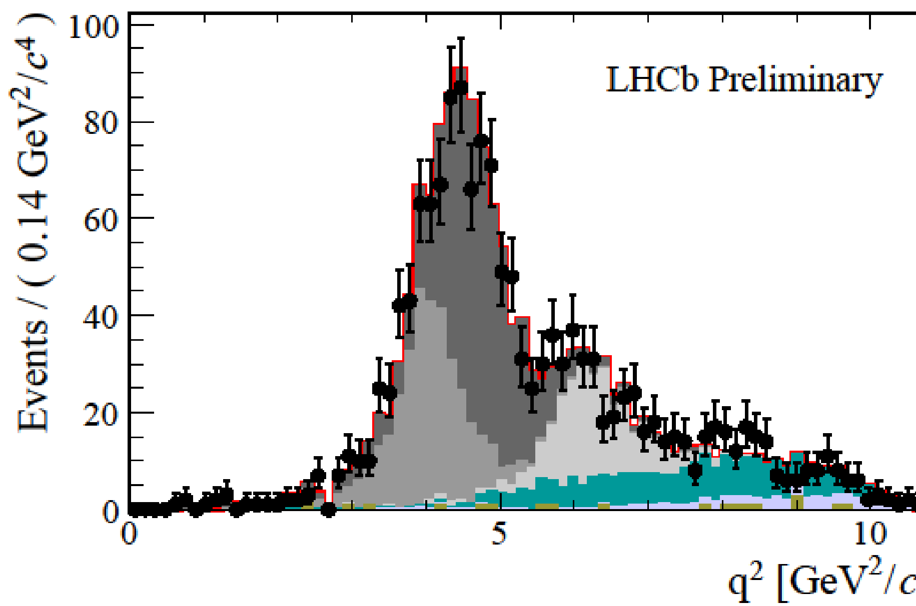
D^*D_s+X events with reconstructed D_s in 3π

- 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)





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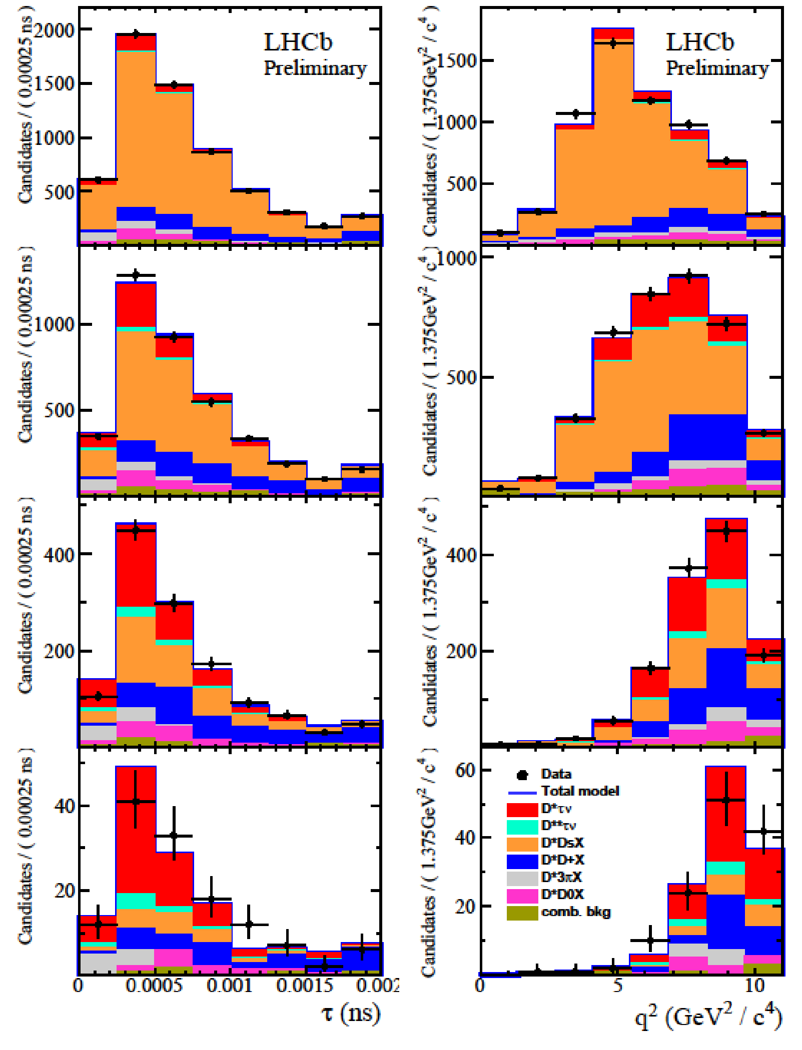
Fit results
LHCb-PAPER-2017-017, arxiv 1708.08856



- 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

Contribution	Value %
Simulated sample size	4.7
Signal modeling	1.8
$D^{**}\tau\nu$ and $D_s^{**}\tau\nu$ feed-downs	2.7
$D_s^+ \to 3\pi X$ decay model	2.5
$B \to D^{*-}D_s^+X$, $B \to D^{*-}D^+X$, $B \to D^{*-}D^0X$ backgrounds	3.9
Combinatorial background	0.7
$B \to D^* 3\pi X$ background	2.8
Empty bins in templates	1.3
Efficiency ratio	3.9
Total internal uncertainty	8.9
$\mathcal{B}(B^0 \to D^* 3\pi)$ and $\mathcal{B}(B^0 \to D^* \mu\nu_\mu)$	4.5

LHCb Results

LHCb-PAPER-2017-017, arxiv 1708.08856

$BR(B^{\circ} \rightarrow D^{*}\tau\nu)/BR(B^{\circ} \rightarrow D^{*}3\pi)=1.93\pm0.13(stat)\pm0.17(syst)$

$BR(B^{\circ} \rightarrow D^{*+}\tau\nu)=(1.39\pm0.09(stat)\pm0.12(syst)\pm0.06(ext))\%$

Using for **$BR(B^{\circ} \rightarrow D^{*}3\pi)$** the new PDG 2017 WA of 0,721±0.029

to be compared with the PDG(2017) (1.67±0.13) %

New (naive) average **$BR(B^{\circ} \rightarrow D^{*}\tau\nu)=(1.56\pm0,10)\%$**

$R(D^{*})=0.285\pm0.019(stat)\pm0.025(syst)\pm0.013(ext)$

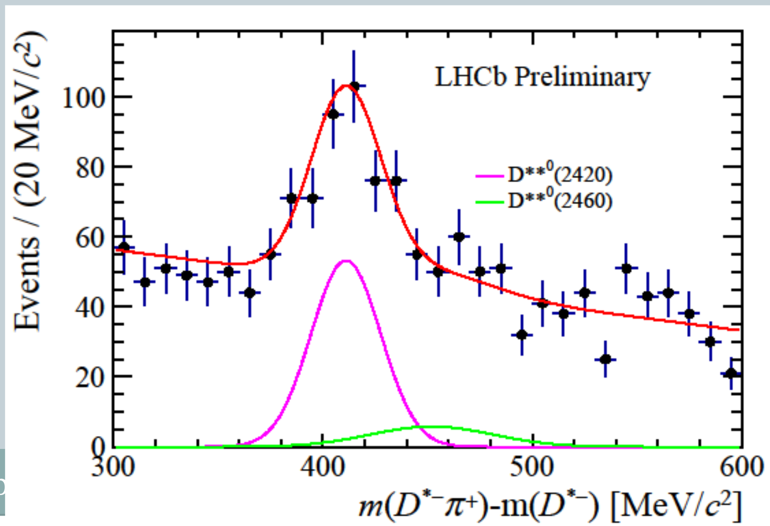
Using the HFLAV $BR(B^{\circ} \rightarrow D^{*}\mu\nu)=(4,88\pm0,10)\%$

Experiment	Method	N evts $B \rightarrow D^{*}\tau\nu$	N evts $B^{\circ} \rightarrow D^{*+}\tau^{-}\nu$
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	1273±95	1273±95

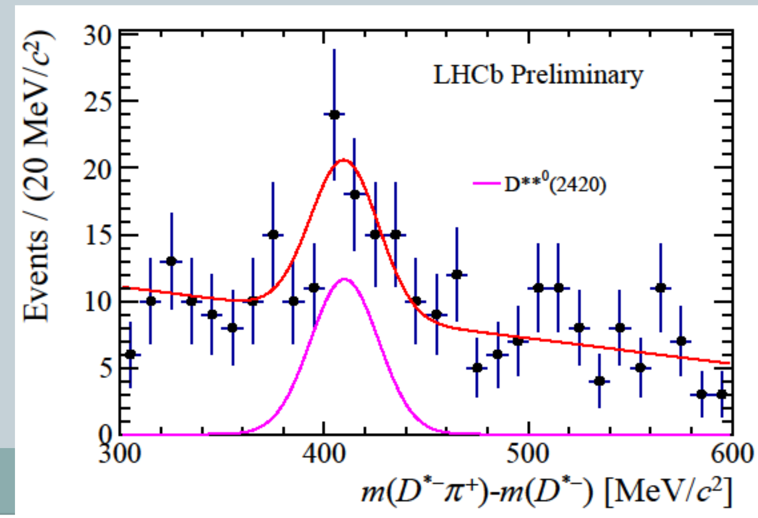
D** cross check

- $B^o \rightarrow D^{**}\,\tau\nu$ and $B^+ \rightarrow D^{**o}\tau\nu$ constitute potential feeddown to the signal
- $D^{**}(2420)^{o}$ is reconstructed using its decay to $D^{*+}\pi^-$ **as a cross check**
- The observation of the $D^{**}(2420)^o$ peak allows to compute the $D^{**}3\pi$ BDT distribution and to deduce a $D^{**}\tau\nu$ upper limit with the following assumption.
  - $D^{**o}\tau\nu = D^{**}(2420)^o\tau\nu$ (no sign of $D^{**}(2460)^o$
  - $D^{**+}\tau\nu = D^{**o}\tau\nu$
- 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

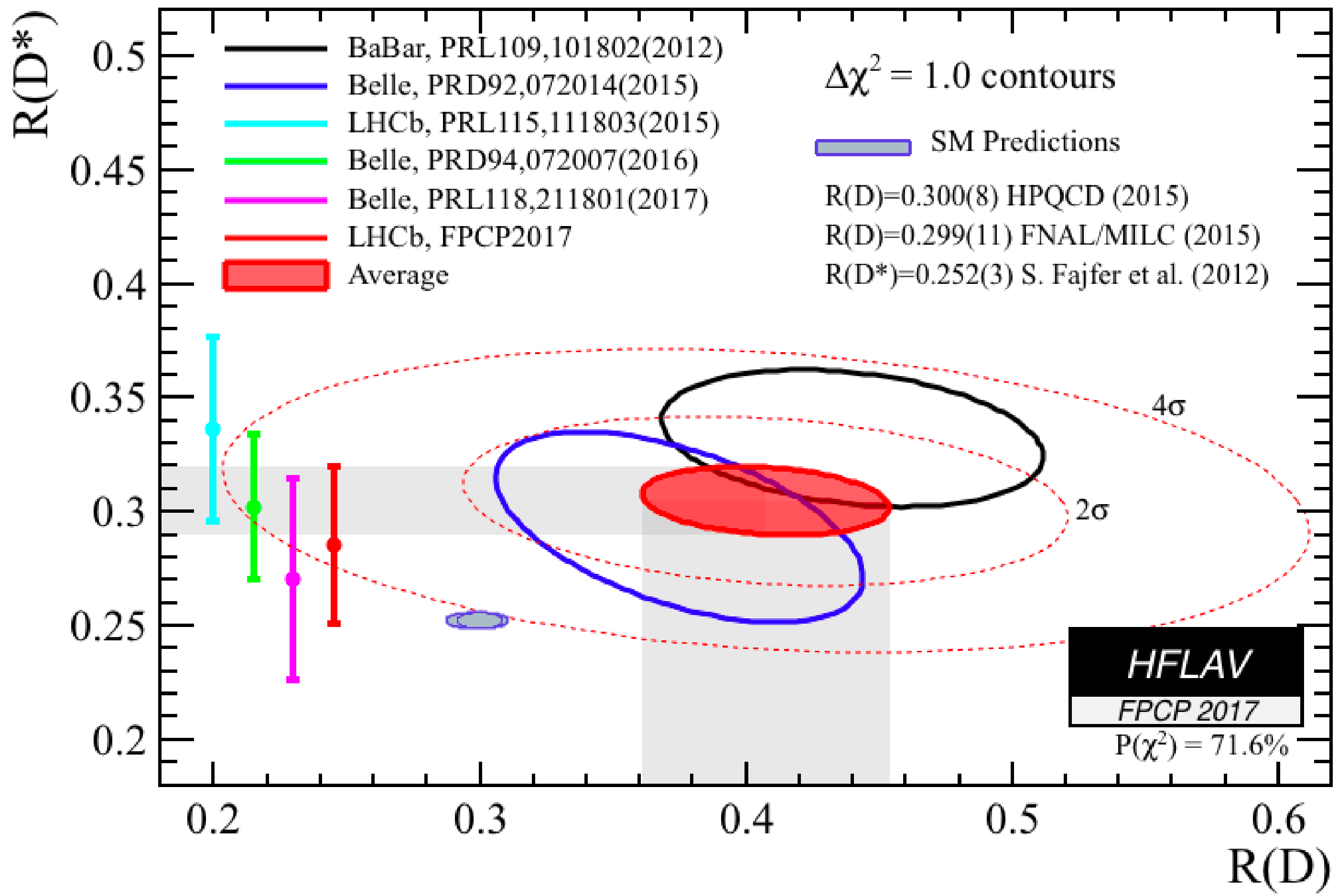


Detached vertice for BDT>.0.1



The new FPCP average

Combined signifance: 4.1 σ away from SM



Precision Goals for Run1+Run2 data

- Run2 =2015+2016 (already available) + 2017
- Statistical precision ~4%-3%
- Internal systematic precision ~5% (if we can get new results from BES)
- External systematic precision ~3% (if we can get new results from BELLE-1)
- The emphasis will also shift towards search for NP in the various angular distributions !

The semitauonic program

1. Vertical extension of R(D*)
   - R(D*) measurement with Run2 data
   - Extraction of internal quantities , most notably q^2 , search for NP effects using our high stats high purity sample
   - Measure R(D**°(2420) per se and to constraint D** feed-down
2. Horizontal extension of R(D*)
   - $R(\Lambda_c)$
- **R(J/ψ) under Chinese responsability Prof. Jibo He (UCAS)**
   - $R(D^+)$,$R(D^o)$
   - $R(D_s)$
   - V_{ub}

The semitauonic workshop

- To be held in Orsay Nov 13-15 2017

Open sessions : Monday Nov 13 (afternoon)- Tuesday Nov 14 (all day)

LHCb-BES synergy

- There is an official document endorsed by both collaborations :
- Two main items :
  - γ-related measurements (e.g. phases in D⁰->K⁰ππ decays)
  - Branching fractions

LHCb-PUB-2016-025
March 29, 2017
v2.0

Synergy of BESIII and LHCb physics programmes

5.2 Inputs required for the study of hadronic tau decays at LHCb

Decay mode	Priority
$D_s^+ \to \pi^+\pi^-\pi^+ X$ inclusive	very high
$D_s^+ \to N3\pi$	high
$D_s^+ \to \eta\pi^+ X$	medium
$D_s^+ \to \eta'\pi^+ X$	medium
$D_s^+ \to \phi\pi^+ X$	medium
$D_s^+ \to \omega\pi^+ X$	medium
$D_s^+ \to \pi^+\pi^-\pi^+\pi^-\pi^+ X$ inclusive	medium

Decay mode	Priority
$D^+ \to \pi^+\pi^-\pi^+ X$ inclusive	high
$D^+ \to K^0\pi^+\pi^-\pi^+\pi^0$	high
$\frac{D^+ \to K^0\pi^+\pi^-\pi^+ X}{D^+ \to \pi^+\pi^-\pi^+ X}$	medium
$D^+ \to \pi^+\pi^-\pi^+\pi^0$	low

D_s and D^+ inclusive decays to 3π : a nice recoil analysis !!

- Many mesons will be present in the missing mass spectrum of D_s / D^+ to 3π (for 3-prongs events):

  π^o, K^o, η, η', ω, ϕ, ($\nu\nu$) + non resonant if any
- A nice plot for a PhD thesis ☺
- Another way to measure to $D_s \rightarrow \tau\nu$!!
- The ratio 5-prongs/3-prongs is not small for the D_s and should be measured precisely

- Please come and see me if you or one person around you could be interested!!

BES-LHCb first formal workshop

- Will take place in IHEP, Beijing, on Feb 8-9 2018
- http://indico.ihep.ac.cn/event/7249/
- Registration open up to Jan 2018

- I hope that regarding the measurements I mentioned we can come to this workshop with some initial status reports !!!!

How BELLE-1 data could help !!

- BR($B^o \rightarrow D^*3\pi$)
  - Not as simple as it appears:
    - $a_1(1260)$, $\rho\pi$, f_2 (1270), 3π nr, D** states
    - An effective $a_1(1260)$ region could be the best thing to use
- Study of $B \rightarrow D^{*}(^{*})D_s(^{*})(^{*})$
  - « Straightforward » recoil study (performed by BABAR in 2006) BR($B \rightarrow D^*D_s$), high q^2 templates
- R(D**) as new measurement of its own and as a control of D** feeddown
- And of course all improvments in $D^*l\nu$ decays are very useful for theorist to further improve R(D) and R(D**) predictions

Conclusions

- Intriguing hints of LFU in sll channels: Run2 data will soon tell us more !
- The analysis to measure the ratio **$BR(B^{\circ} \rightarrow D^{*}\tau\nu)/BR(B^{\circ} \rightarrow D^{*}3\pi)$** using the 3π hadronic decay of the τ lepton has been performed at LHCb (Preliminary)

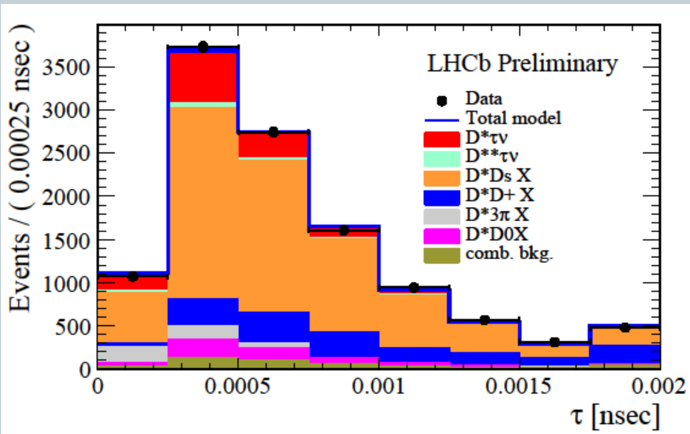
$R(D^{*})=0.285\pm0.019(stat)\pm0.025(syst)\pm0.013(ext)$

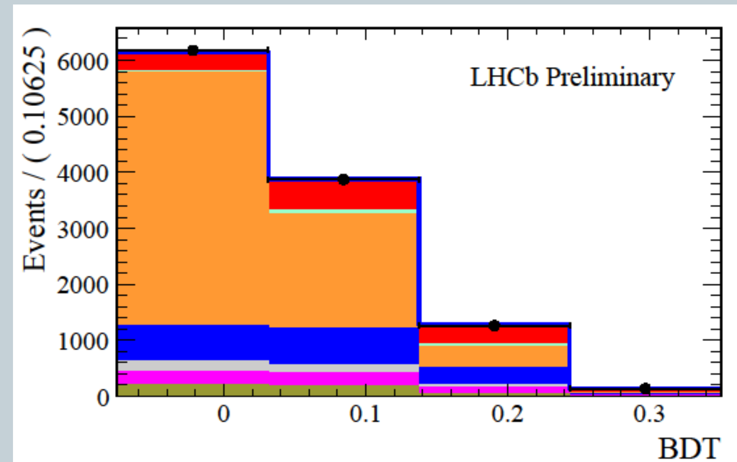
New preliminary LHCb average of $R(D^{*})=0.306\pm0.026$

- This analysis was made possible due to the unique LHCb capabilities for separating secondary and tertiary vertices with unprecedented precisio
- **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**
- This method **paves the way** for many new measurements of the other Rs and will allow the study of **high statistics high purity samples**

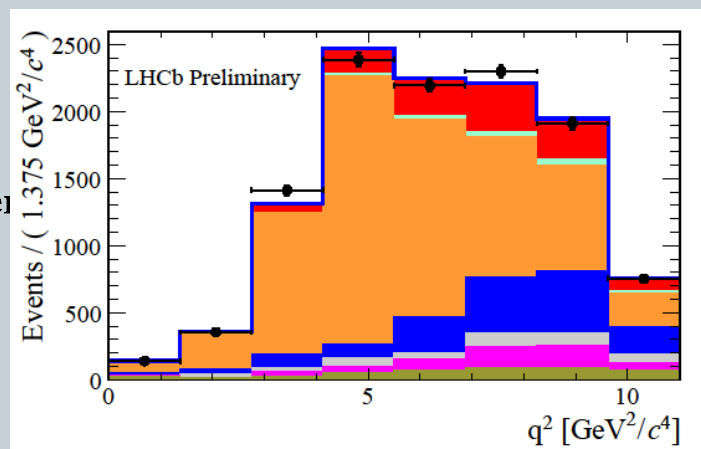
- **Key inputs from BES are needed to reduce the systematic uncertainties.**

The 3 fit projections (q², lifetime and BDT)





This shows the over
quality of the fit



Recent trends(1): R(D) better than R(D*)

- Regarding R(D) P. Gambino and D. Bigi, Phys. Rev. D 94, 094008 (2016)
  - "First, two calculations of the form factors of $B \rightarrow Dl\nu$ beyond zero-recoil have appeared in 2015 . They represent the first unquenched calculations of these form factors performed at different q2 values, which significantly reduces the uncertainty of the extrapolation from the q2 region where most data are taken.
  - Second, a new, more precise Belle measurement has been published , which for the first time provides the q2 differential distribution with complete statistical and systematic uncertainties and correlations. The combination of these steps forward allows for a competitive extraction of |Vcb| and for a very precise determination of the $B \rightarrow D$ form factors."
- R(D)=0.299 (3)

Recent trends(2): R(D) better than R(D*)

- Regarding R(D*) P. Gambino, D. Bigi, S.Schacht arxiv 1707.09509 (July 29,2917)
  - Change of CLN to BGL parametrization leads to Vcb exclusive of 0.42(2) 10^{-3} in agreement with inclusive results
  - and to R(D*)=0.260(10)

- F. Bernlocher et al.
  - **R(D*)=0.257 (3) Phys.Rev. D95 (2017) no.11, 115008 (June 8, 2017)**
  - Tensions and correlations in $|V_{cb}|$ determinations **arXiv:1708.07134**
    - "The tensions concerning the exclusive and inclusive determinations of $|V_{cb}|$ cannot be considered resolved."