Requirements on BR measurements from LHCb, esp. B→D*τν

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Talk outline

- Motivation for absolute branching fractions measurements
- Motivation for a complete set of new measurements for inclusive decays of charm mesons into $3\pi(X)$
  - Presentation of LHCb results on $R(D^*)$
  - Run2 projections and beyond
  - Details about what are needed
- This program has already started ☺
  - Next steps
- Conclusion

Motivation for absolute Branching Fractions

- LHCb has often the need to measure an absolute franching fraction for particular decay of a B hadron species:
  - Λ_b to $\Lambda_c\mu\nu$ is a typical example
  - For this one needs to know the production rate of B baryons at LHC times the branching fraction of Λ_c to $pK\pi$, whic is sued to reconstruct the Λ_c
- This branching fraction « irrigates » all the B baryon sector since all decay modes are normalized to this one.
- The best precision is required for the main decay mode of the Λ_c ($pK\pi$) and D_s ($KK\pi$)
  - **Total BR**
  - **And also internal dynamics**

Extract of the 2017 PDG

Λ_c^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	(MeV/c)
Hadronic modes with a p: $S = -1$ final states				
$p K_S^0$		(1.58 ± 0.08) %	S=1.2	873
$p K^- \pi^+$		(6.35 ± 0.33) %	S=1.4	823
$p \overline{K}^*(892)^0$	[r]	(1.98 ± 0.28) %		685
$\Delta(1232)^{++} K^-$		(1.09 ± 0.25) %		710
$\Lambda(1520)\pi^+$	[r]	(2.2 ± 0.5) %		627
$p K^- \pi^+$ nonresonant		(3.5 ± 0.4) %		823
$p K_S^0 \pi^0$		(1.99 ± 0.13) %	S=1.1	823

HTTP://PDG.LBL.GOV Page 32 Created: 5/30/2017 17:12

Total BR is now know with 5% precision, internal dynamics to only 10%. This BR uncertainty has significantly improved but is still a dominant factor in several LHCb analysis.

Lepton Universality is the hottest game in town

- Lepton Universality is one the the pillars of the SM
- It predicts equal properties of e,m and t , except for obvious phase space effects.
- However, the largest hints of a potential SM breaking lie precisely in this area:
  - 4 σ deviation in R(D*) -R(D) measurements
  - 2.5 σ from Kll and K*ll decays
- Some NP physics scenarios can explain both effects at the same time (cf LHCb Semitauonic workshop recently organised in Orsay)
  - https://indico.cern.ch/event/648989/

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 ➔ BES_III (today only limits) (beware :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➔τν vs B ➔μν (BELLE-II)
- D_s,D^+➔τν D_s,D^+ ➔ μν , ➔ BES_III (beware :hadronic effects)

  Semileptonic Vub decays b->uτν probe the same vertex as the annihilation (LHCb) B^+➔ppτν, Λ_b➔ pτν)

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 :
  - $B \rightarrow K(^*)l^+l^-$ $R(K^*)=K^*\mu\mu/K^*ee$
  - $B \rightarrow D(^*)\tau\nu$ $R(D^*)=D^*\tau\nu/D^*\mu\nu$

BES-III input is required!!!

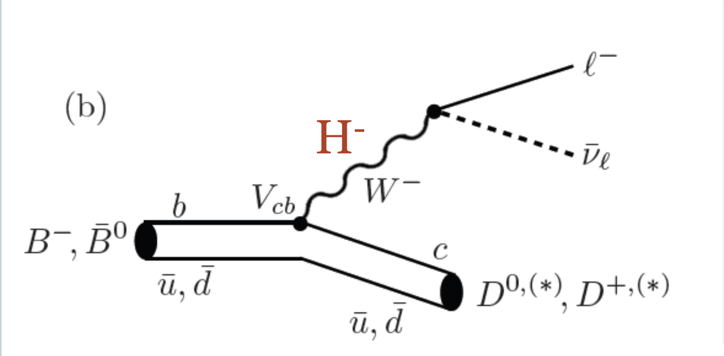
- In 2018-2020, LHCb will publish its semitauonic RunII-based results. The statistical precision for the favoured modes (R(D*),R(D), R(Λ_c)) will be significantly below 5%
- … To be followed by BELLE-II ……
- We must try to launch now an HEP-wide effort to measure all the important « bread-and-butter » measurements that play a significant role in the systematic uncertainty budget
- Some impact all R(D) measurements, some are quite specific..
- Some can be performed in several experiments, some only in a single one….
  - BABAR/BELLE for normalization B decays
  - **BES-III for charm meson decay model**

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!!)

$$\frac{d\Gamma^{SM}(\bar{B}\to D^{(*)}\ell^-\bar{\nu}_\ell)}{dq^2} = \underbrace{\frac{G_F^2\,|V_{cb}|^2\,|p^*_{D^{(*)}}|\,q^2}{96\pi^3 m_B^2}\left(1-\frac{m_\ell^2}{q^2}\right)^2}_{\text{universal and phase space factors}} \quad (3)$$

$$\times \underbrace{\left[(|H_+|^2+|H_-|^2+|H_0|^2)\left(1+\frac{m_\ell^2}{2q^2}\right)+\frac{3m_\ell^2}{2q^2}|H_s|^2\right]}_{\text{hadronic effects}}.$$

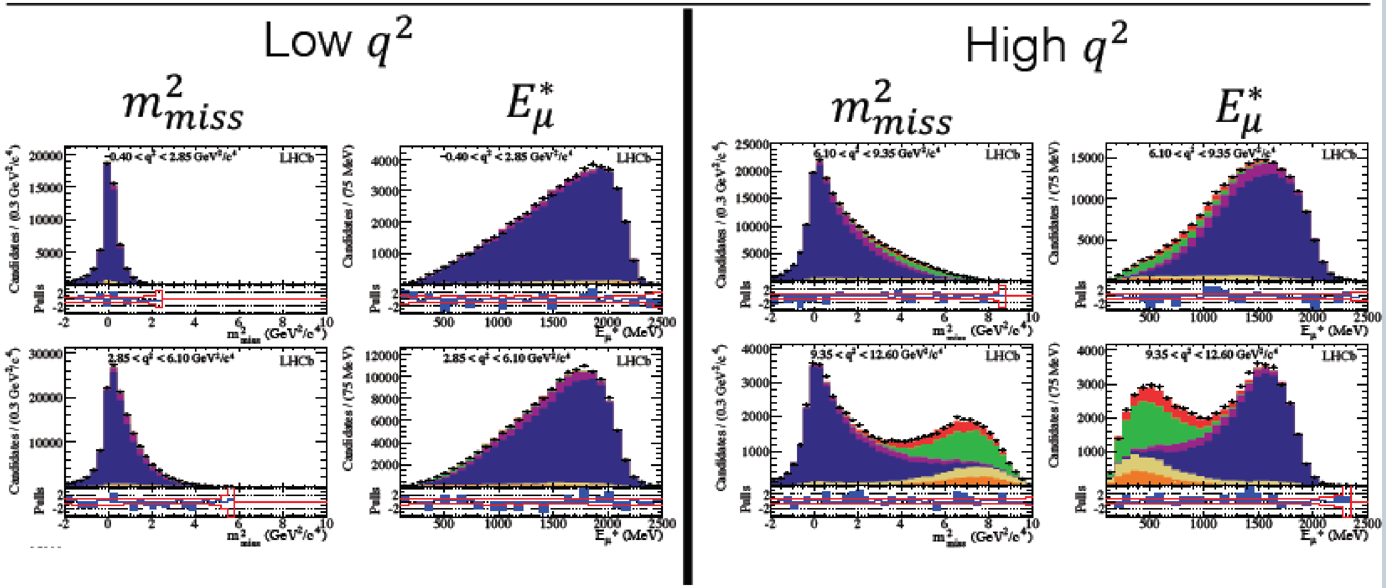


ArXiv: HEP-1703-01766

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 $D^{*}\tau\nu$; $\tau \rightarrow 3\pi(\pi^{\circ})$

- 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

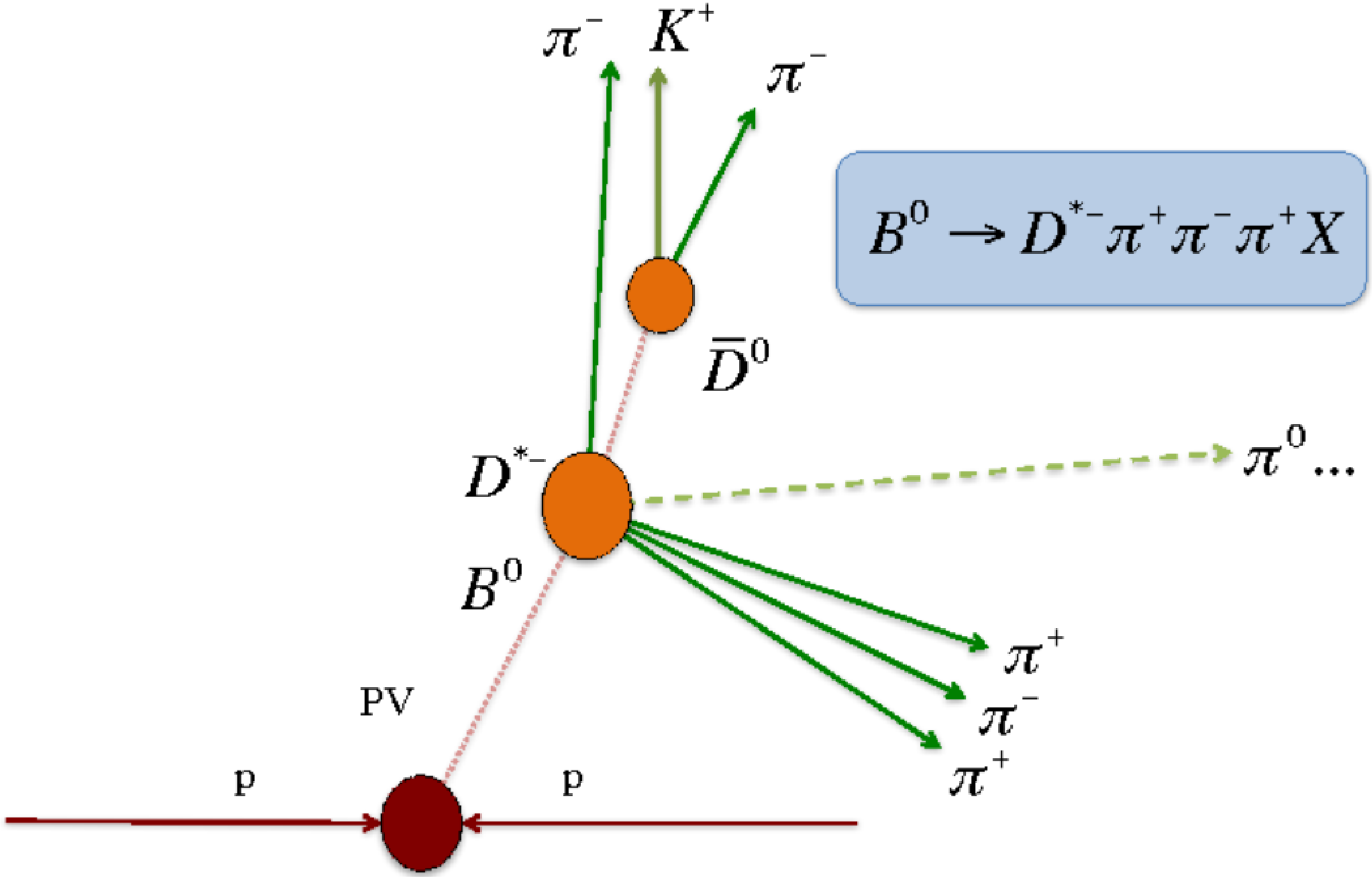
- The $D^*\tau\nu$ decay, with τ going into 3 pions (it can also be $3\pi+\pi^0$) leads to a D^* 3π(+X) final state
- Nothing is more common than a $D^*3\pi$ (+X) final state in a typical B decay :

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

A very strong background suppression method is absolutely needed :

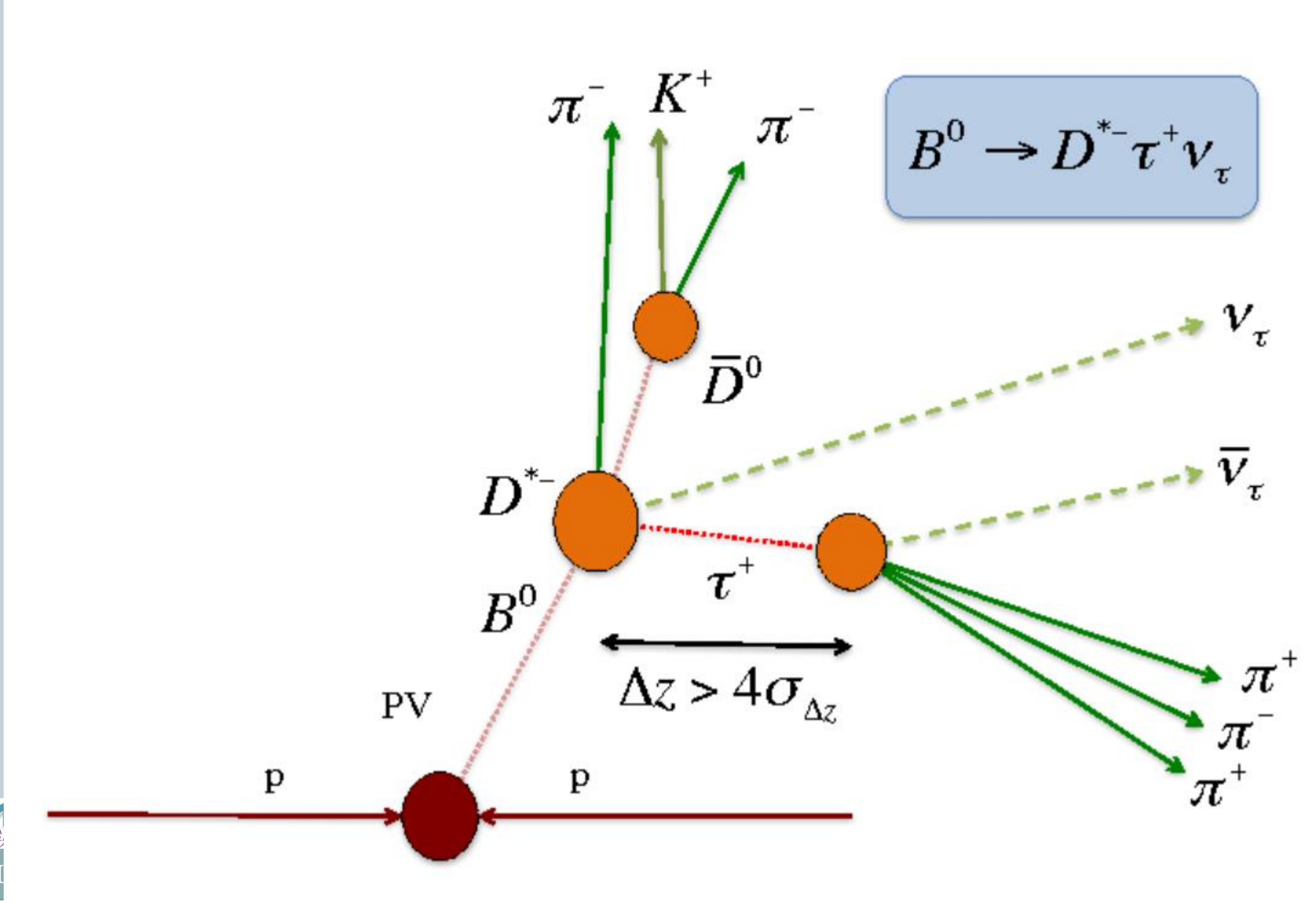
The DETACHED VERTEX METHOD

Vertex topology of the usual B decay



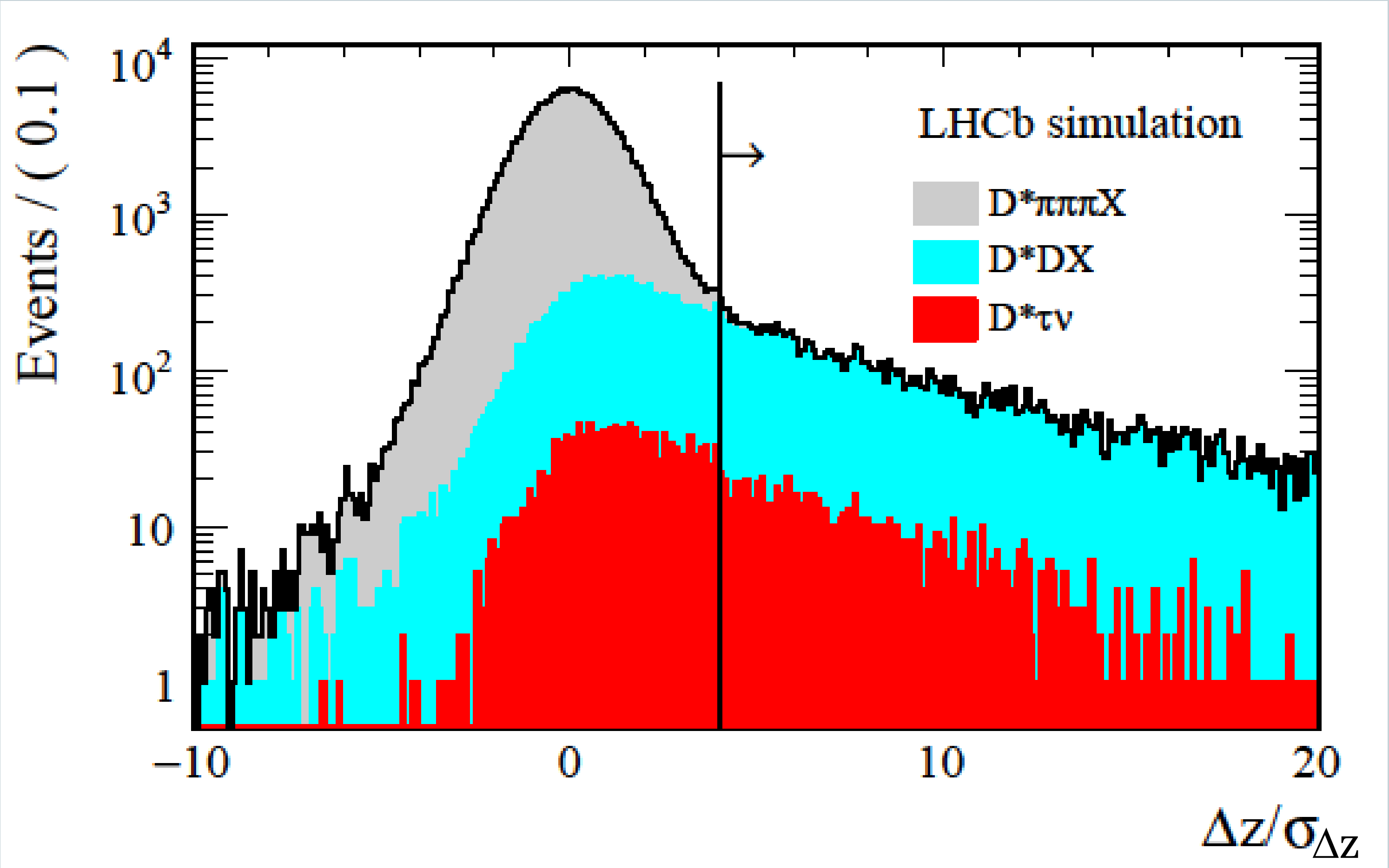
$$B^0 \rightarrow D^{*-}\pi^+\pi^-\pi^+X$$

Selection: detached vertex



Selection: the detached vertex method

LHCb-PAPER-2017-017 arxiv 1708.08856



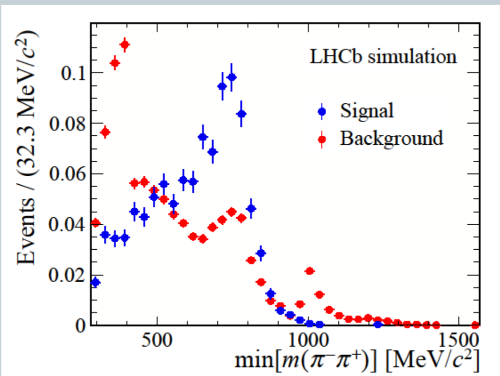
The inclusive D_s decays in 3 pions

- The W➔$c\bar{s}$ 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 ➔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

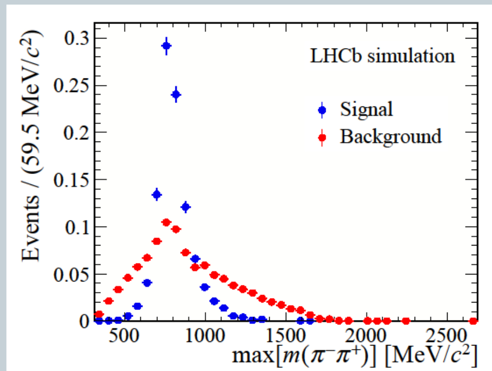
➔ **We extract these informations from LHCb data in a D_s enriched region (BDT<-0.075) (~90% D_s)**

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

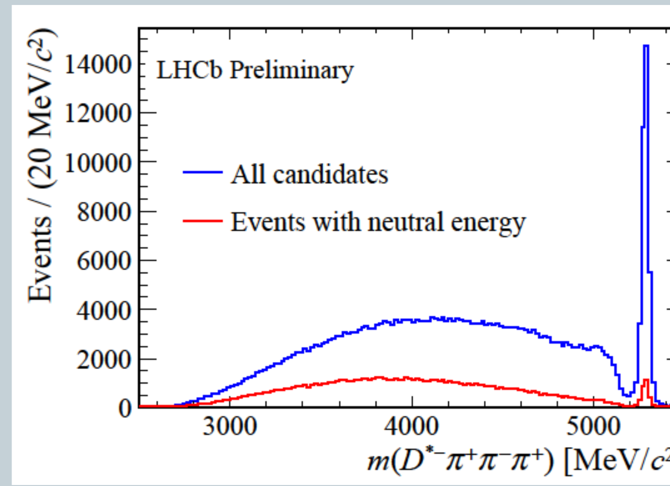
Min(mass($\pi^+\pi^-$))



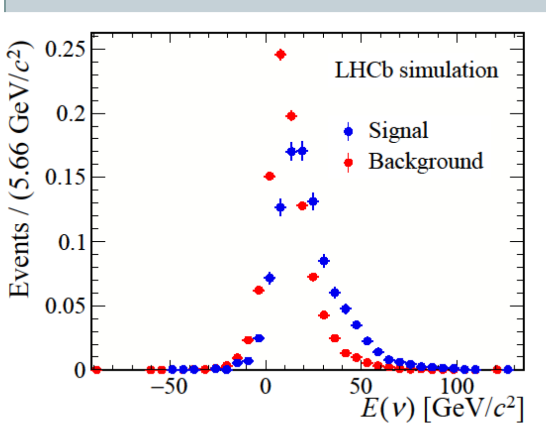
Max(mass($\pi^+\pi^-$))



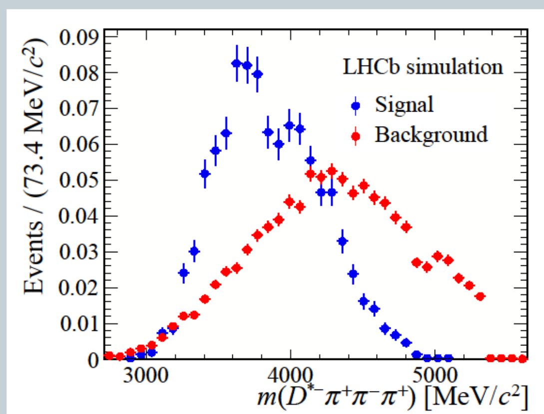
Neutral Isolation



E(ν)



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



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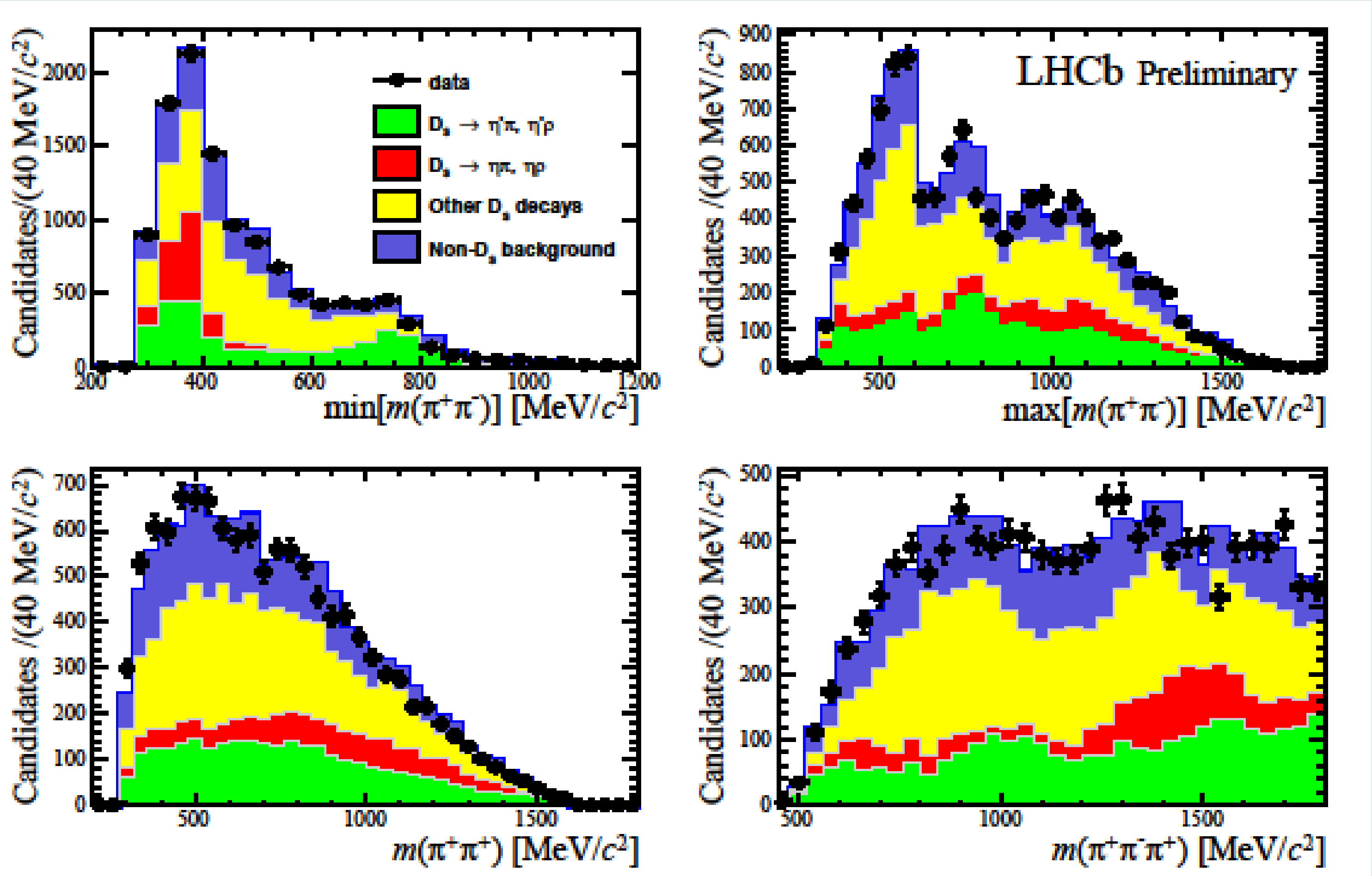
The D_s decay model fit at low BDT



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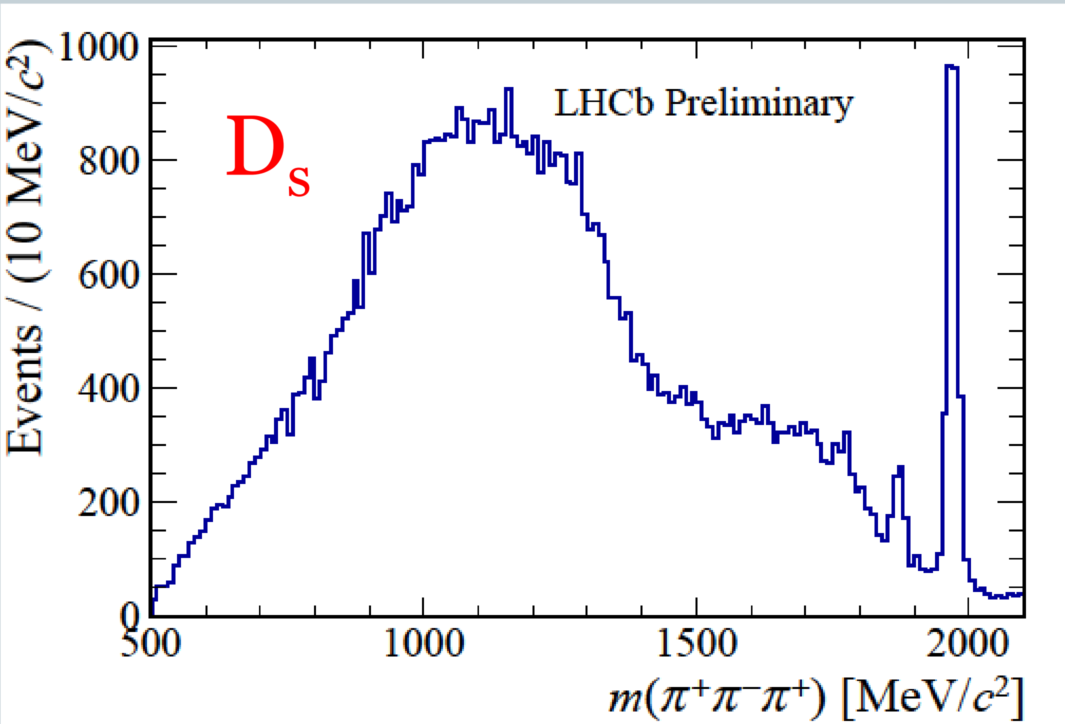
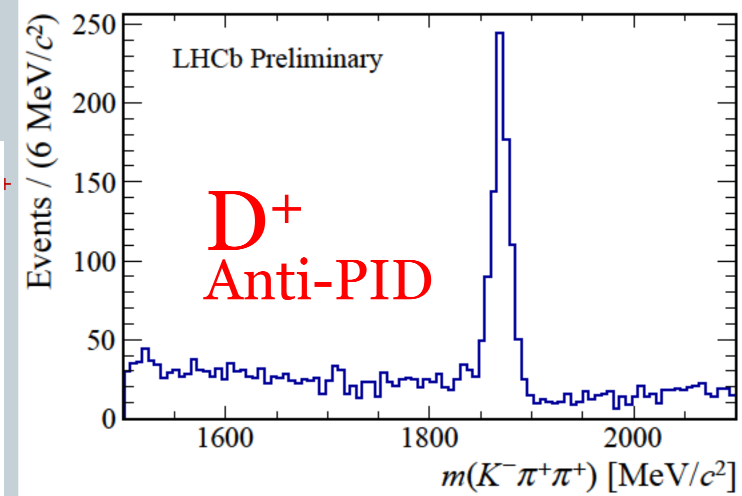
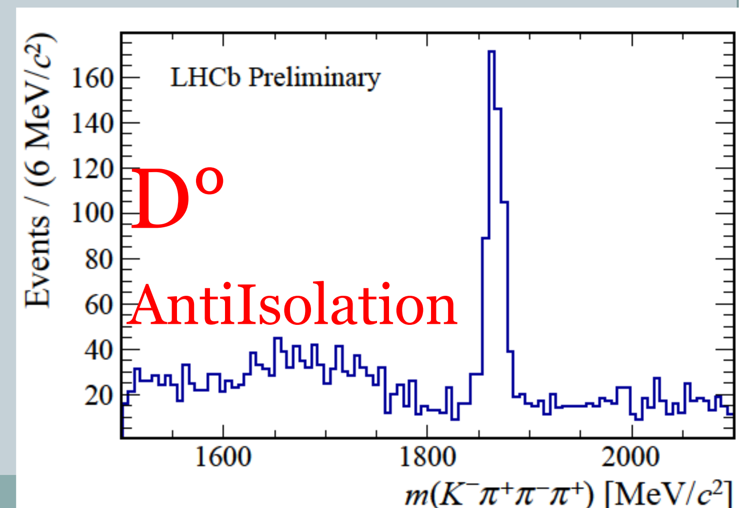
The control channels D_s, D°, and D^+





peak : Anti-Isolation



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Run 1, 3 fb^{-1}

Fit results
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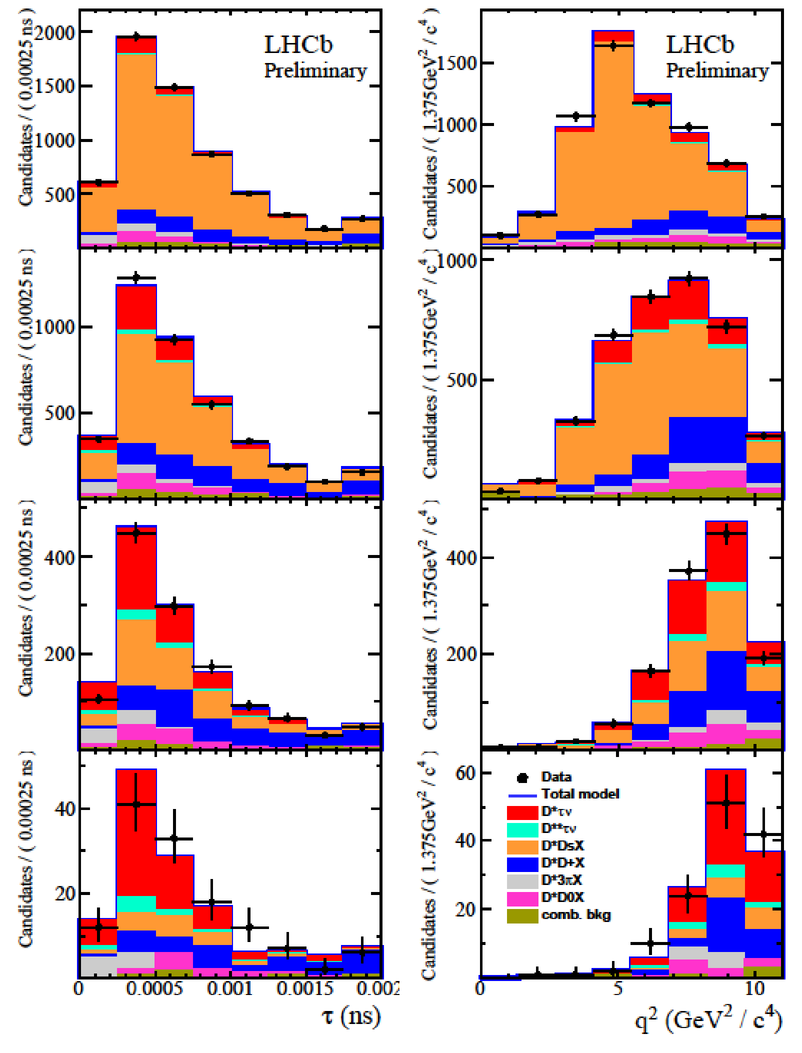


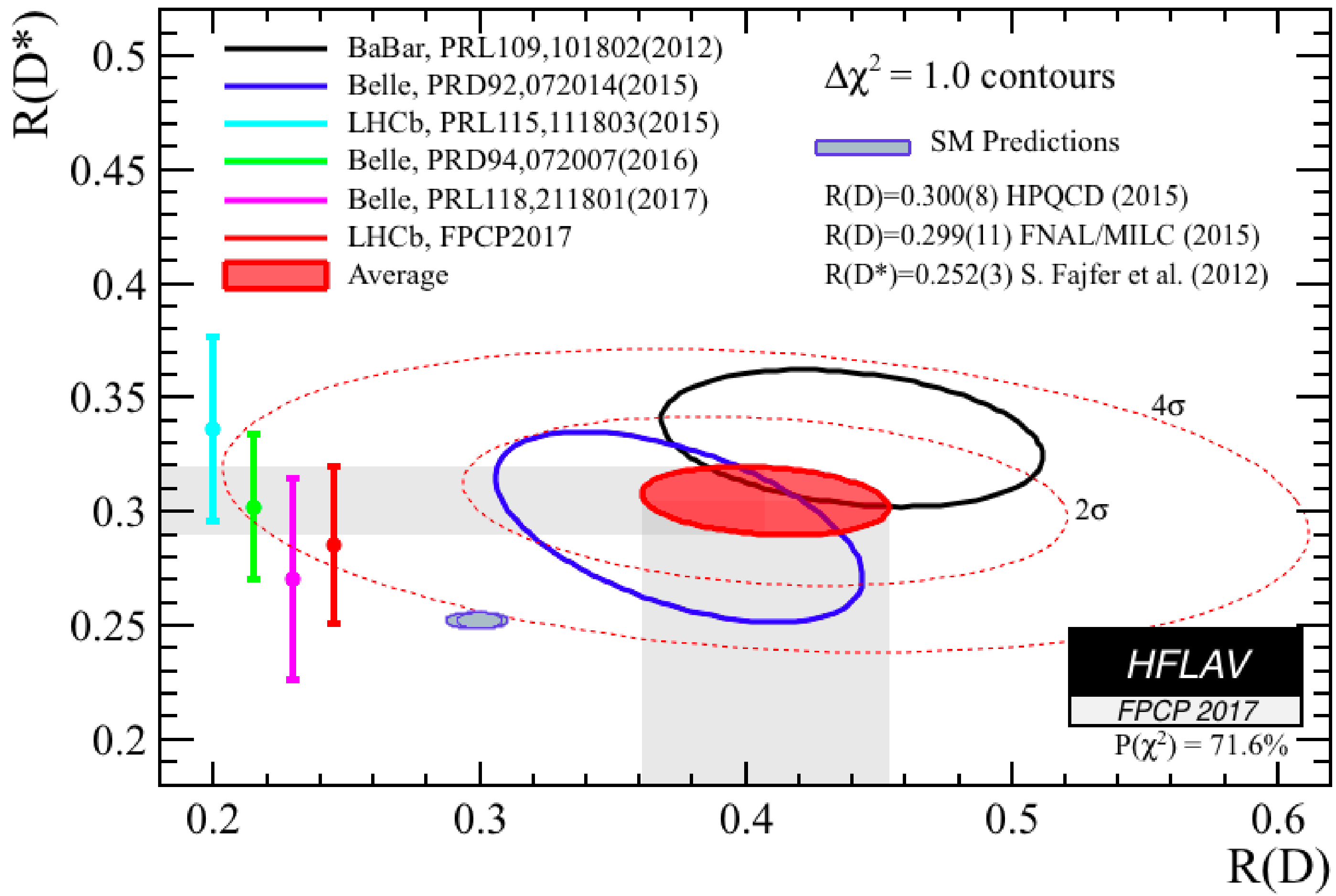
- The 3D template binned likelihood fit results are presented for the lifetime and q^2 in four BDT bins.
- The increase in signal (red) purity as function of BDT is very clearly seen, as well as the decrease of the D_s component (orange)
- The dominant background at high BDT becomes the D^+ component (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

The new FPCP average

Combined signifance: 4.1 σ away from SM



LHCb Results

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

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

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

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

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

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

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

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	1273±95	1273±95

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}

A whole new look to the charm decays into inclusive 3π

- LHCb physics program has now **a major focus of tau decays to 3 pions,** selecting detached 3π tertiary vertices . Background is almost entitrely **charmed hadrons inclusively decaying into 3 pions.**
- Hence, it is now critical to measure the inclusive decays of charmed hadrons into 3 pions
- Largest source is D_s meson
  - Larger branching fraction for B to D^*D_s (W hadronization)
  - The D_s is an incredibly large source of inclusive 3p final states, although the exclusive decay mode D_s to 3π is only 1%
  - Ds decays through light resonances (η, η',ω,ϕ,..) $\pi^{+/}\rho^{+}$
  - But also with $M3\pi$ modes where M is π°,K°,η,η',ω,ϕ,$\nu\nu(\tau)$
- D+ decays : dominant modes $K^\circ3\pi(X)$
- D° decays : dominant modes $K^-3\pi$ (X) –well constrained by inclusive 4-prong measurements

What is precisely needed

- Both for Ds and D+, we need a good « Decay model » fit that gives
  - The **total inclusive rate of Ds to 3 pions** (excluding K° parents). This will allow to constraint the total Ds background since we measure the Ds control peak in 3π. Can be given either as an absolute BR or a ratio wrt the exclusive measurement
  - The detailed sharing of the 3π channels between the 15 potential decay channels
    - ηπ,ηρ,η'π,η'ρ,ωπ,ωπ,φπ,φρ ➔**BES-III tagged direct reco.**
    - M3π where M is (π°,η,η',K°,ω,φ) ➔ BESIII recoil analysis
    - τν; τ➔3π
  - This input is **critical** for the complete R(X) program of LHCb
  - The same analysis is **also needed for the D$^+$ meson**

Very Good news : this program is ongoing !!!

- My first visit to China in March 2017 , thanks to a very effective Chinese Academy of Sciences grant, allowed several initial contacts on that theme
- Second visit to China in October 2017, thanks to a kind invitation to the Chine Heavy Favour workshop in Wuhan : very productive discussion and contacts there
  ➔ See next talk ☺
- Some discussion also took place with the Ferrara BES-III group : agreement in principle to study one of the two channels , starting Spring 2018 (to be confirmed)
- Third visit to China today : the work is already well advanced ....

Conclusion

- It will not be possible to benefit from the tantalizing statistical precision of upcoming round of semitauonic measurements (LHCb, BELLE-II) **without dedicated efforts on complementary measurements**
- I like to view this as a HEP-wide common effort to come to a final answer on the semitauonic NP hints
- Hottest topics on the list :
  - **Inclusive D_s and D^+ decays to 3 pions (BES data)**
  - Two- and Three-body Double charm events (BABAR and BELLE data)
- Such a collaborative effort can work !!!