Semitauonic B decays, a window on new Physics

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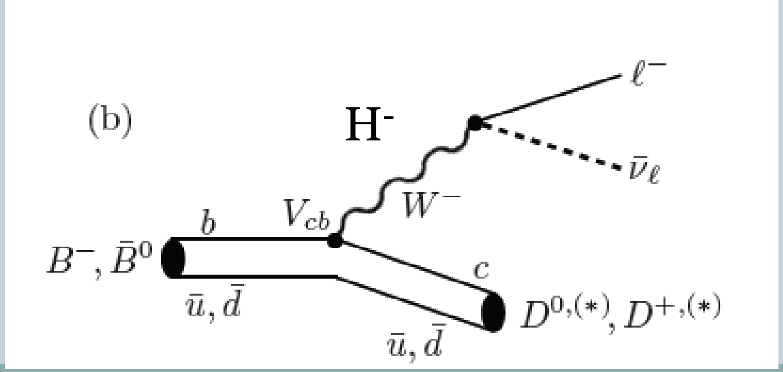
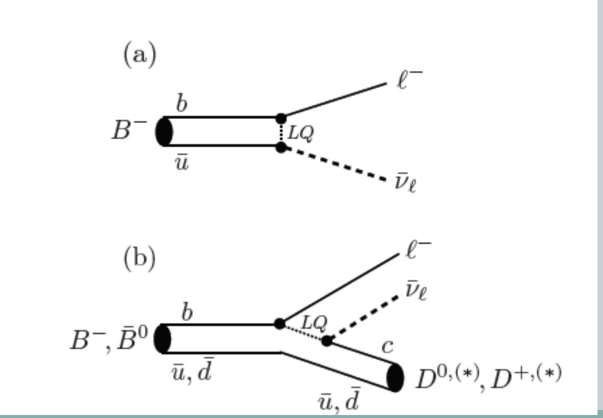
Why semitauonic decays are interesting?

- As tree level decays, they combine the advantages :
  - Very precise prediction from SM :R(D*) known to 2% precision, using

    $R(D^*) = BR(B^o \rightarrow D^* \tau \nu)/BR(B^o \rightarrow D^* \mu \nu)$
  - Abundant channel $BR(B^o \rightarrow D^* \tau \nu)$=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^o, D^+, D_s, Λ_c, J/ψ
  - Differing not only by various properties of the spectator particle but also

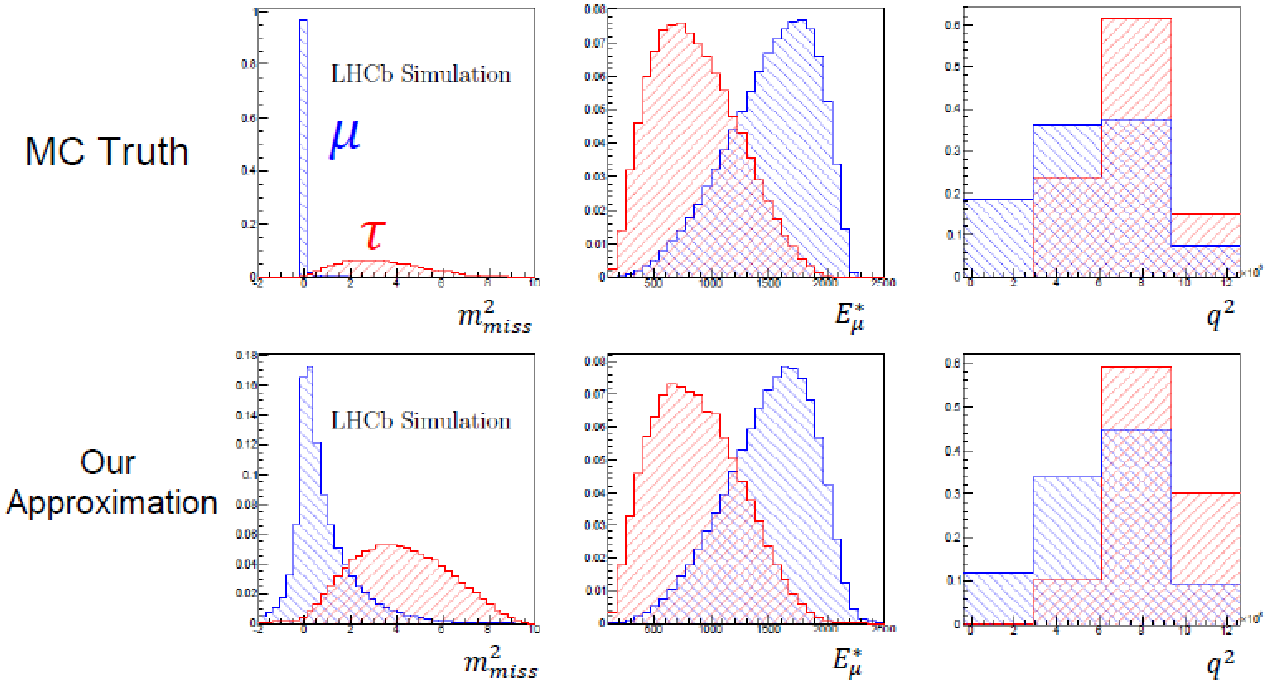
  its spin 0 (D^o,D^+,D_s), 1 (D^* and J/ψ) and ½ (Λ_c!!)





R(D*) with τ →μνν

PRL 115 111803 (2015)

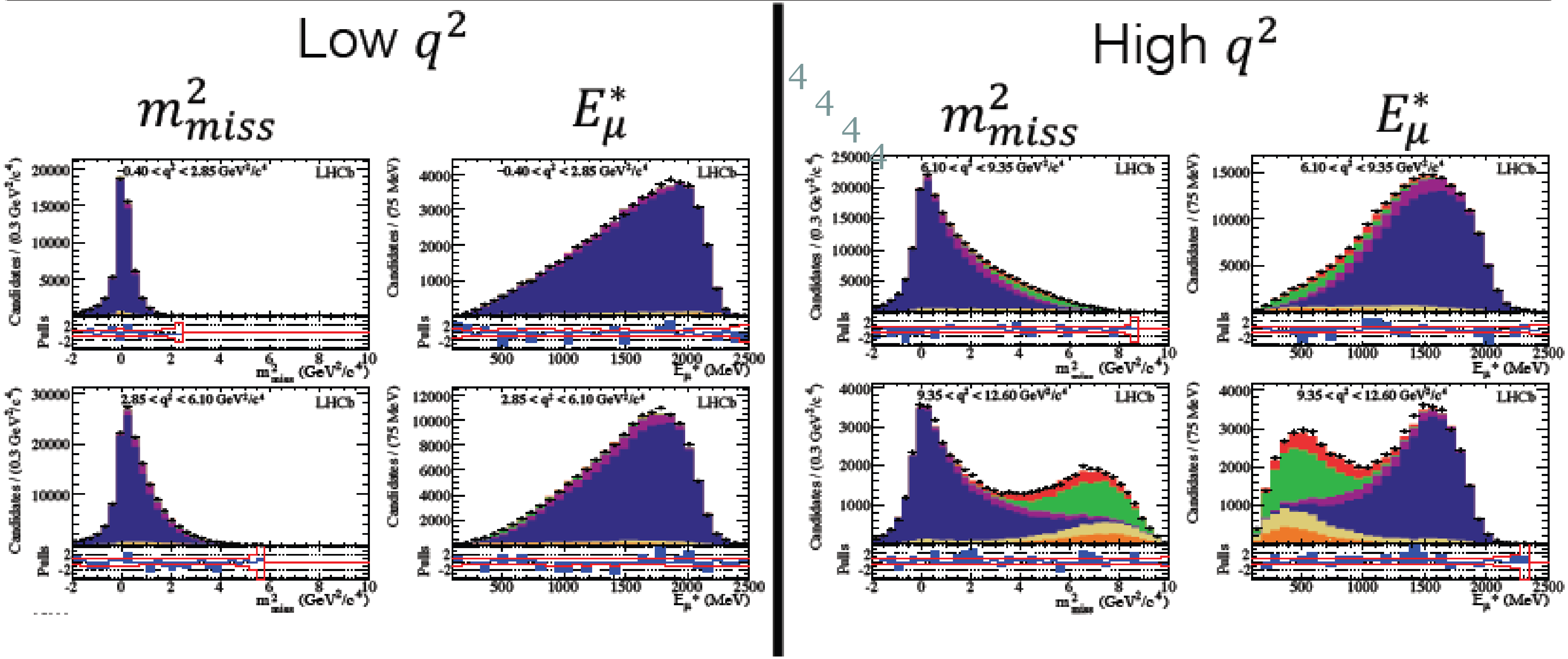


Using the known B flight direction, approximate the B momentum using $\gamma\beta_{z,vis}=\gamma\beta_{z,B}$:

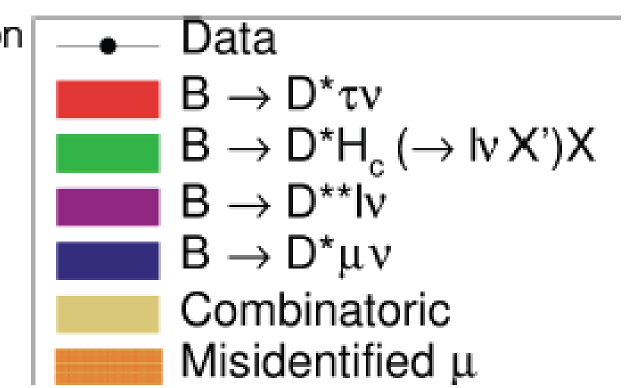
- Estimate gives ~ 18% resolution on B momentum, but preserves shapes of already-broad distributions of to m^2_{miss}, E^*_μ and q^2
- 3d MC-template based binned fit to m^2_{miss} *vs* E^*_μ in coarse q^2 bins

PRL 115 111803 (2015)

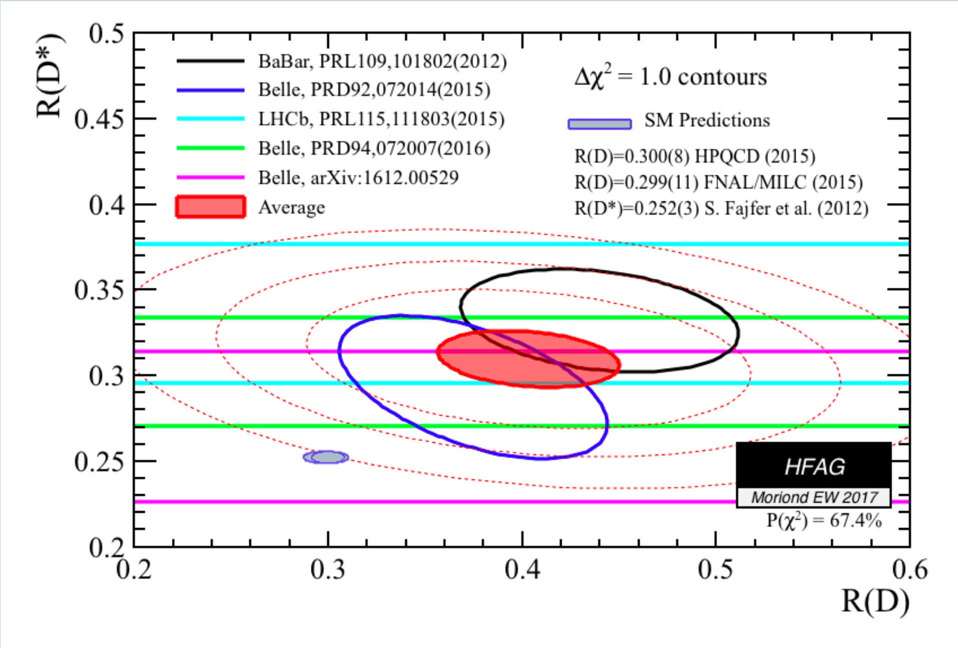
Fit Result



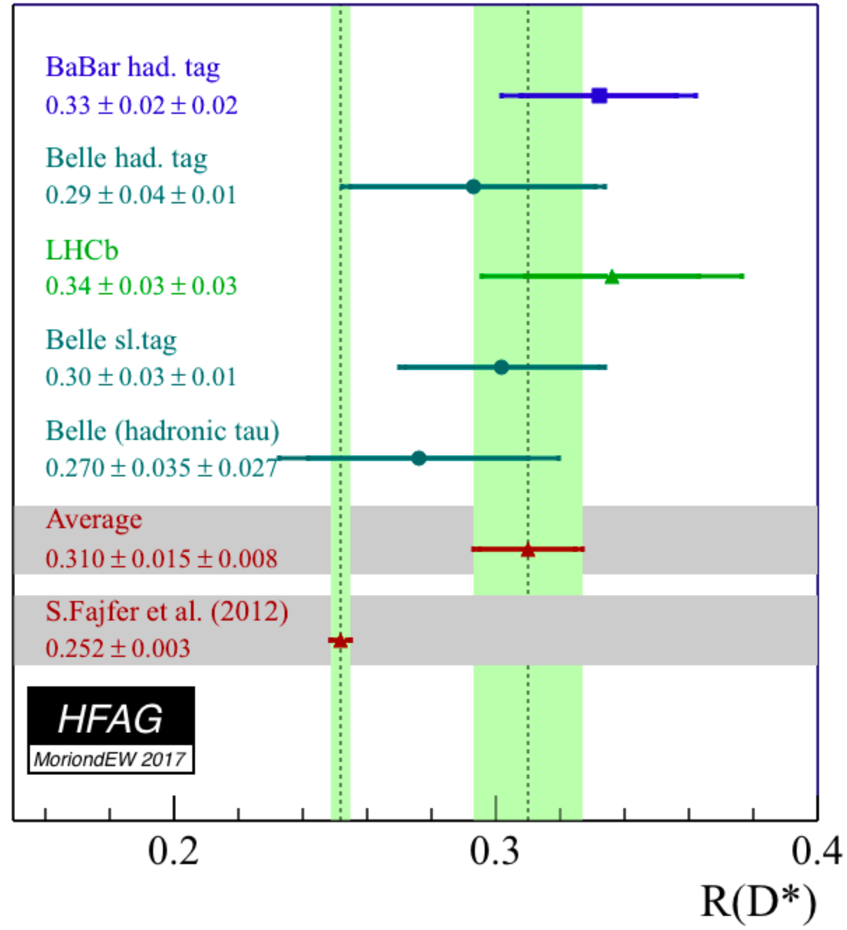
- Shown above: signal fit to "signal" data passing isolation selection
- Result $\frac{N_\tau}{N_\mu} = (4.32 \pm 0.37)\times 10^{-2}$, $R(D^*) = 0.336 \pm 0.027 \pm 0.030$
- $N(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu) = 363{,}000 \pm 1600$



R(D*) status today



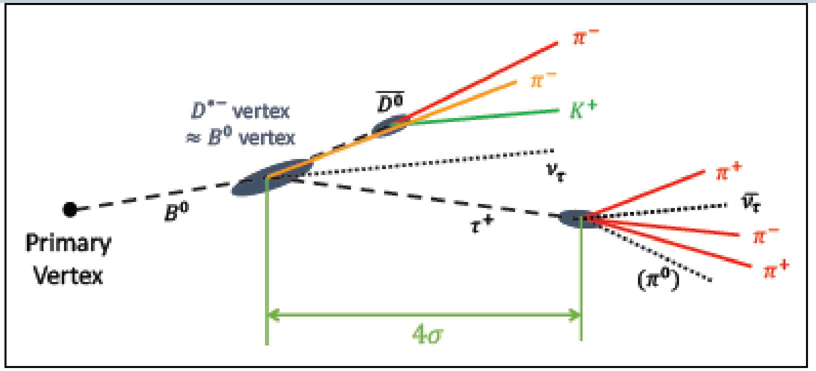
http://www.slac.stanford.edu/xorg/hfag/semi/index.html



If WA is correct, 22% of the D*τν events are mediated by new physics!

New ! R(D*) using τ hadronic decays in 3π
Unusual features of this analysis

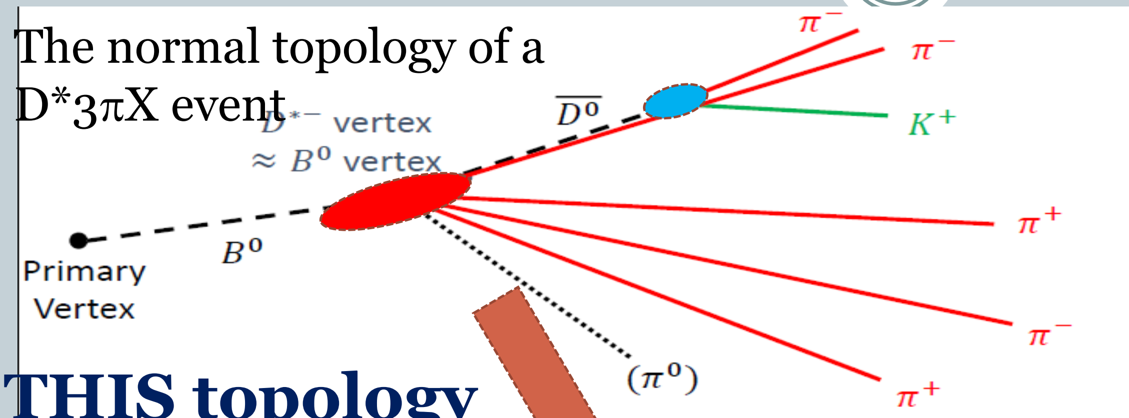
- A semileptonic decay without (charged) lepton !!:
  - Amusing but more importantly ZERO background from normal semileptonic decays!!!!



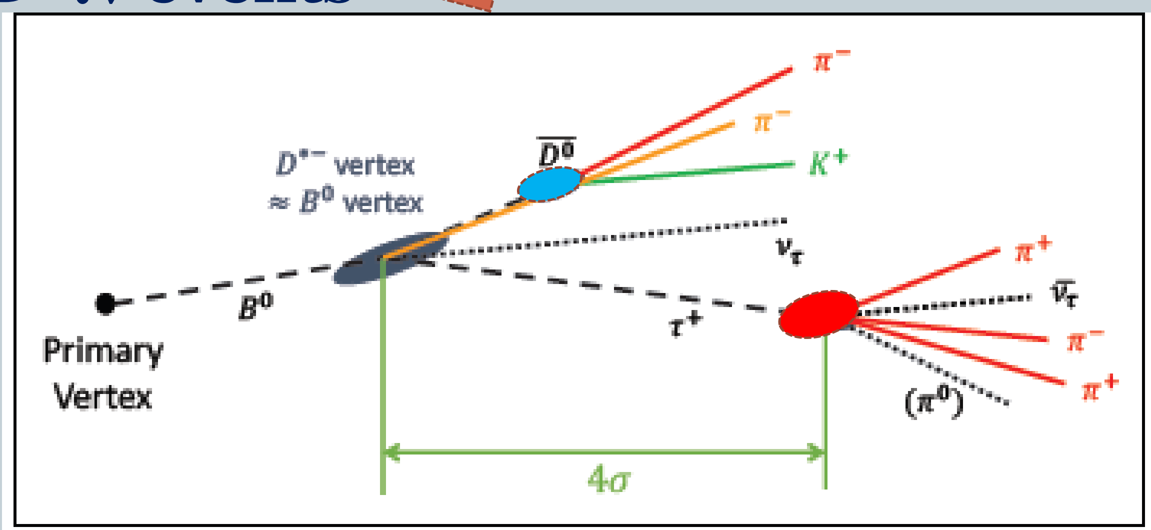
- The background leads to nice mass peaks and not the signal !!!
  - Amusing but more importantly provides key handles to control the various backgrounds
- Only 1 neutrino emitted at the τ vertex
  - The complete event kinematics can be reconstructed with reasonable precision
- But very large potential background from « bread and butter » D*3π X decays; 100 times larger than the signal : A trick must be found!!

The detached vertex method

The normal topology of a D*3πX event



THIS topology for D*τν events



The 4σ requirement kills the D*3πX background by ~10^3: **the road to the treasure is open ☺!!!**

The second gate : the double charm background

The second gate consists of B^o 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)

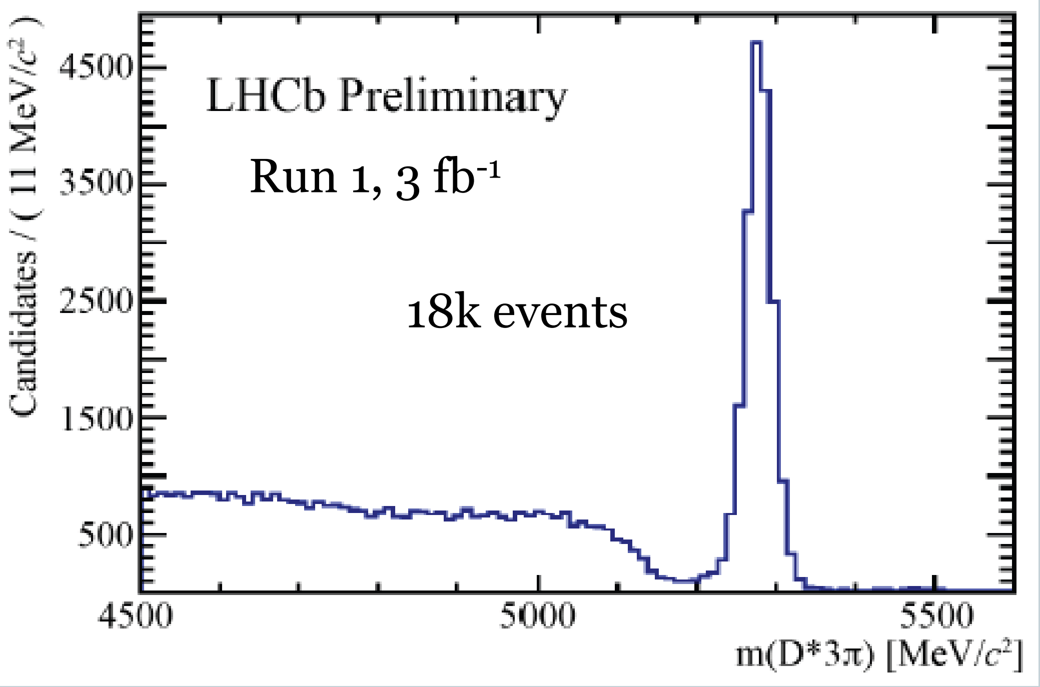
- This gate is thinner :
  - Double Charm→$3\pi X$ ~10 x signal

LHCb has three very good weapons to blow this gate away:

- 3π dynamics
- Neutral isolation
- Background partial reconstruction

Importance of the normalization channel $B^0 \to D^*3\pi$

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



- Absolute BR recently measured by BABAR with a precision of 4.3% (**Phys.Rev. D94 (2016) no.9, 091101**)

A promenade through charm physics

- As mentioned already, the background is formed of the various charm mesons D_s,D^o, D^+ produced in the decay of the W into a $c\bar{s}$ pair. These charm mesons have to decay into 3 pions
- This analysis is therefore a promenade to the various **inclusive 3π** decays of the charm mesons!
  - A lot of data is already available but not enough!!
  - BES data could play a key role in reducing many systematics in the future (hopefully relatively quickly!)
- These $W \rightarrow c\bar{s}$ decays can produce a single meson, very often in an excited state D_s, D_s*, D_s** or two particles D^oK^-, D^+K^o, and their excited counterparts

The inclusive D_s decays in 3 pions

- Although the exclusive $D_s \rightarrow 3\pi$ is small (1% BR), the D_s is a amazingly rich source of 3π +X final states
- We classify hadronic D_s decays into 3 pions in 4 categories
  - $\eta\pi X$ ($\eta\pi$,$\eta\rho$)
  - $\eta'\pi X$($\eta'\pi$,$\eta'\rho$)
  - (ϕ/ω) πX ($\phi/\omega\ \pi$, $\phi/\omega\ \rho$)
  - $M3\pi$, where M can be K^0,η,η',ω,ϕ
- We would need precise BR for all of these (some well measured, some poorly, some not at all)
- And the inclusive BR of Ds into 3 pions to constraint all of these !!!!

D^+ and D° decays into 3 π

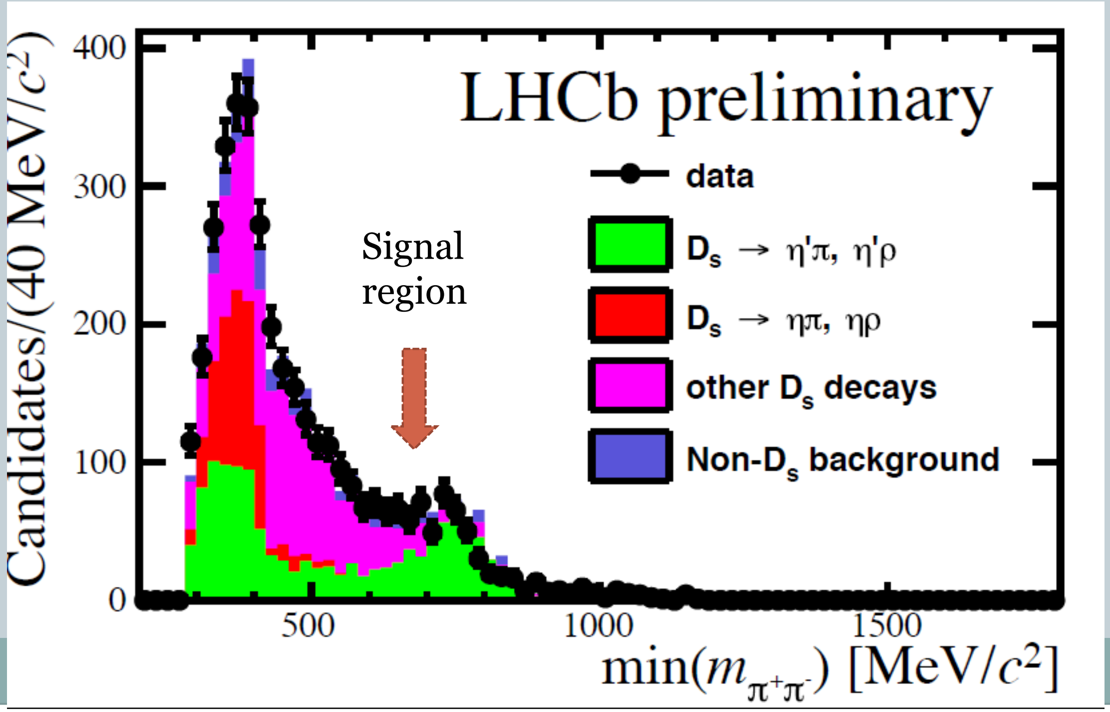
- The situation is simpler to D^+ and D° decays whose main 3π decay mode is thru the K3π decay
- For the D°, the inclusive 4 prongs BR constrains strongly the rate of 3π events
- Unfortunately, nothing exists for the D^+ mesons, K3ππ° is poorly known, the inclusive BR is critical
- Existence of 1.4 GeV edge in the 3π mass distribution is useful to see their presence

The importance of the « D_s-o-meter »

- The D_s meson is the highest background since the W decays dominantly in D_s and the D_s is a very rich source of 3π +X final states.
- At low mass, only η and η' (red,green) contributions are peaking

  $\eta \rightarrow \pi^+\pi^- \pi^\circ$ and $\eta' \rightarrow \eta\, \pi^+\pi^-$ ⟹ $M_{\pi+\pi-} < 415$ MeV

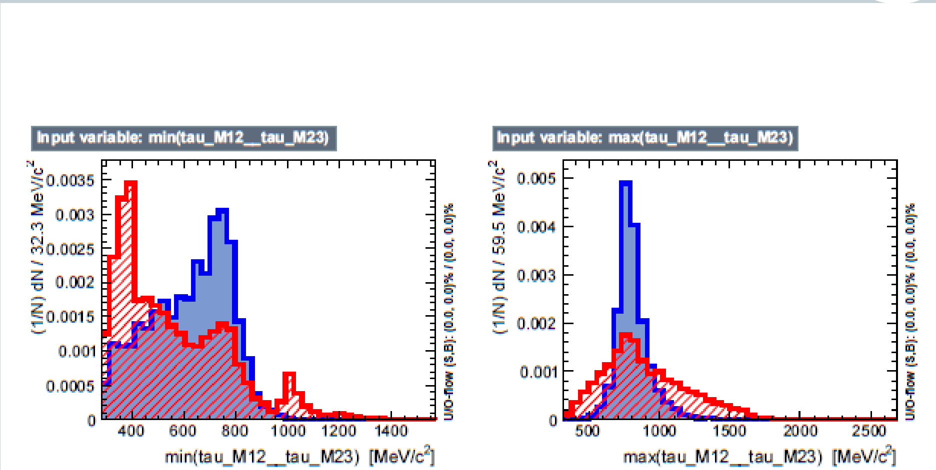
- At the ρ mass where the signal lives ($\tau \rightarrow a_1; a_1 \rightarrow \rho\pi$), only η' contributes ($\eta' \rightarrow \rho\gamma$)
- Using the low BDT region, one constraints the D_s decay model to be used at high BDT

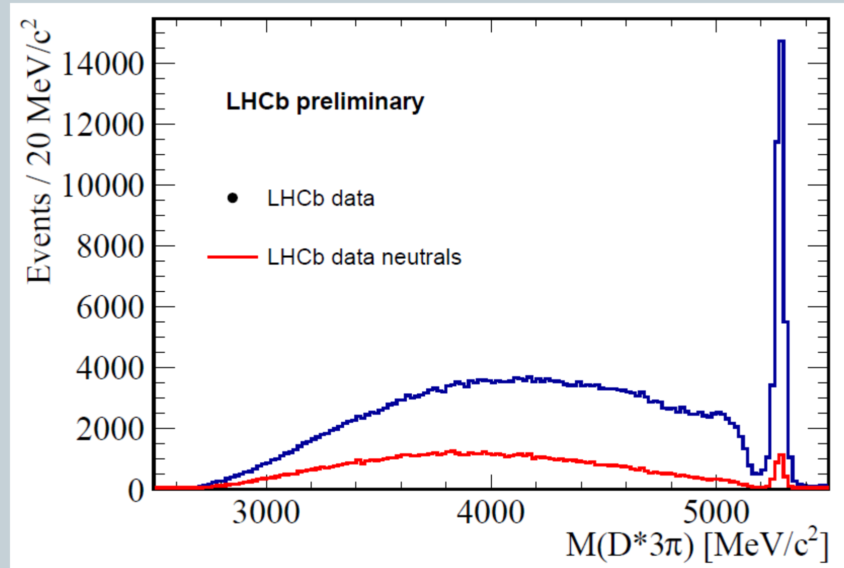


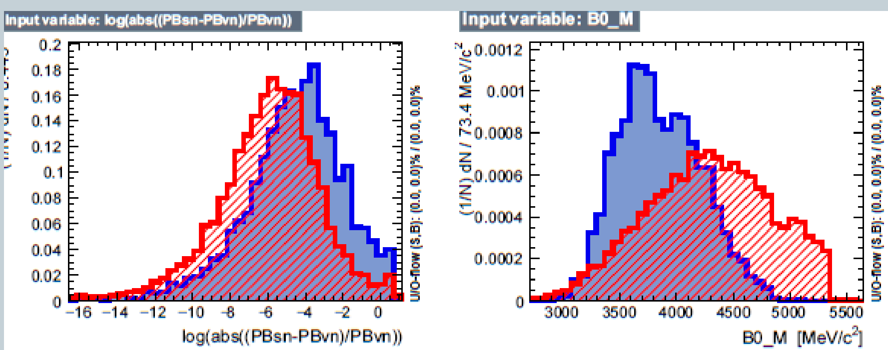
The anti-D_s BDT

- A BDT is constructed to get rid of the D_s background. It contains the following variables:
  - 3π dynamics : $\min(m_{\pi\pi})$, $\max(m_{\pi\pi})$,
  - B dynamics: $D^*3\pi$ mass
  - Partial reconstruction: the 4 constraints from the 2 lines of flight allows to reconstruct fully the event in the background hypothesis (no neutrinos)
  - Neutral isolation : energy in a cone around the 3π direction
  - Very D_s enriched at low BDT, good purity for signal at high BDT
- **Opens the gate for search for BSM inside the events in addition to yields measurements**

The antiDs BDT : 3π dynamics, partial reconstruction and isolation







Charged Isolation

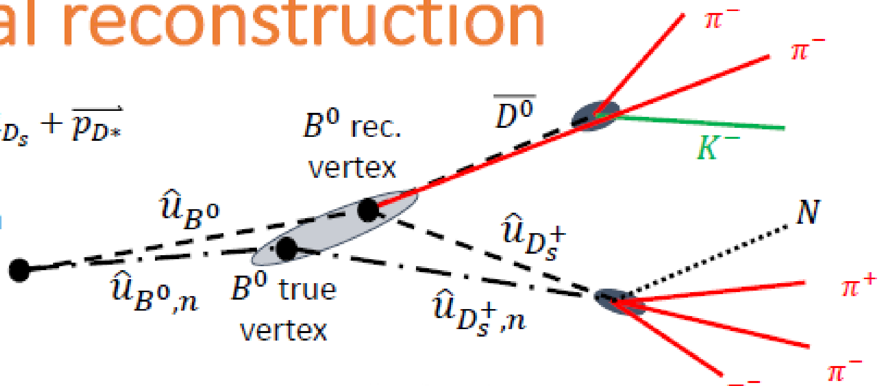
- LHCb software can attach a track passing nearby a vertex: very useful to tag D^0 decays in $K3\pi$
- Necessity to reject also 5 prong D_s decays which are frequent when there is the combined presence of an η and η' presence in the decay chain.
- Very efficient for D^0 decays which is often accompanied by 2 charged kaons, less for the D^+
- To keep the background low, we request only events with 1 combination

Background Partial reconstruction

Partial reconstruction

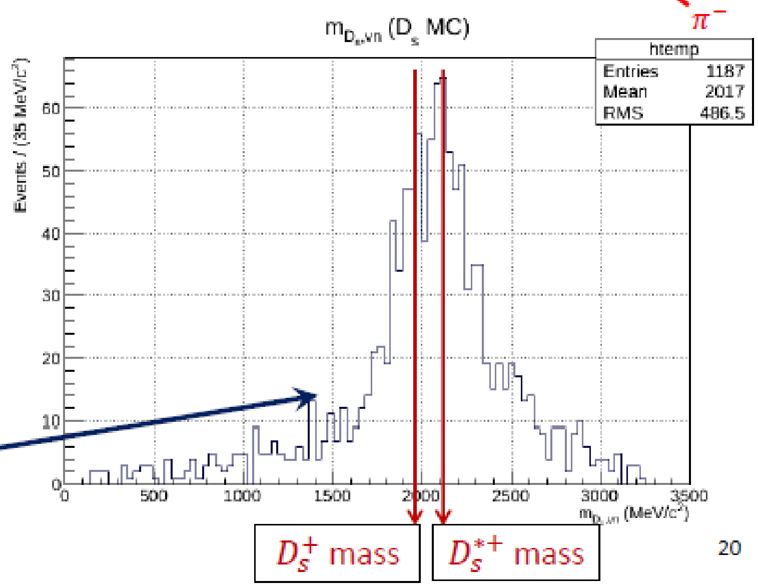
For $B^0 \to D^{*-} D_s^+$: $|\overrightarrow{p_B}|\hat{u}_B = |\overrightarrow{p_{D_s}}|\hat{u}_{D_s} + \overrightarrow{p_{D^*}}$

After some vectorial algebra → get magnitude of B^0 and D_s^+ momenta



First approximation → $\hat{u}_{D_s}$ is the 3π direction

Apply a **correction** to B⁰ vertex due to the presence of neutral particles in D_s^+ decay → **parametrization** of this correction as function of 3π mass on $D^{*-}D_s^+$ MC → get B^0 and D_s^+ momenta at a **next-level of approximation**



Reconstruction of $\boldsymbol{D_s^+}$ **mass**, with nominal B^0 and D^{*-} masses values

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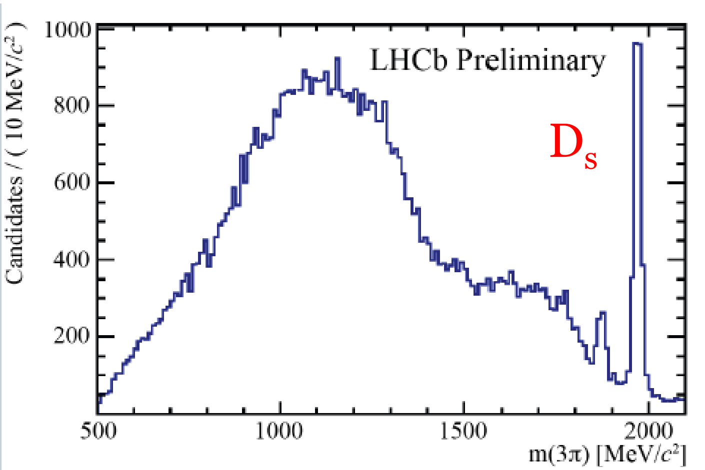
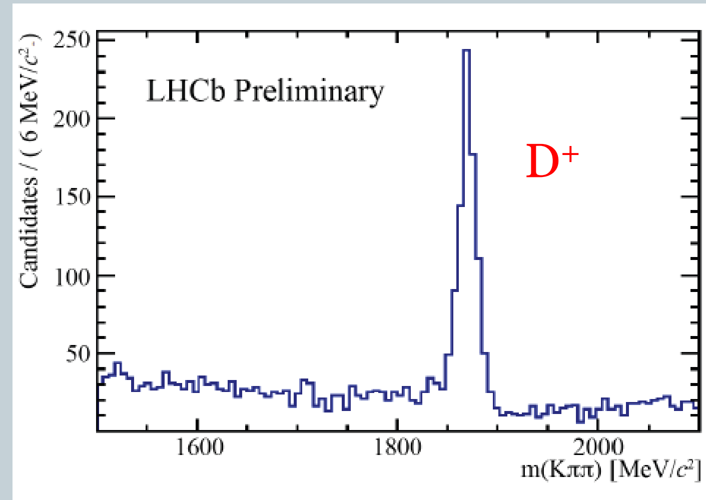
The control channels D_s, D°, and D^+



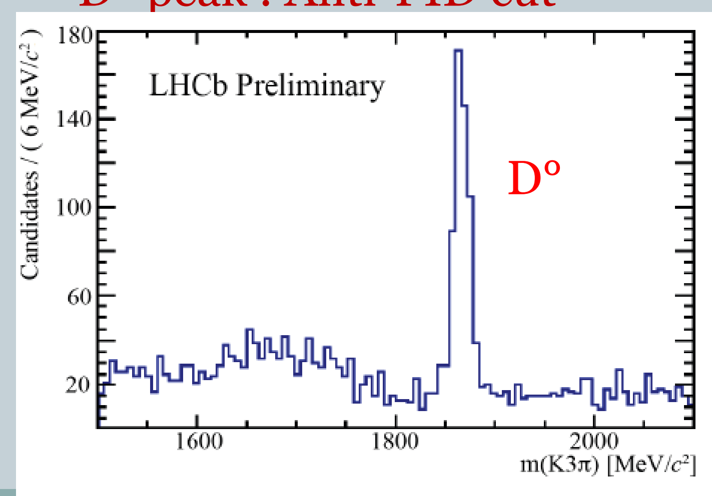
πππ mass in detached topology



D^+ peak : Anti-PID cut

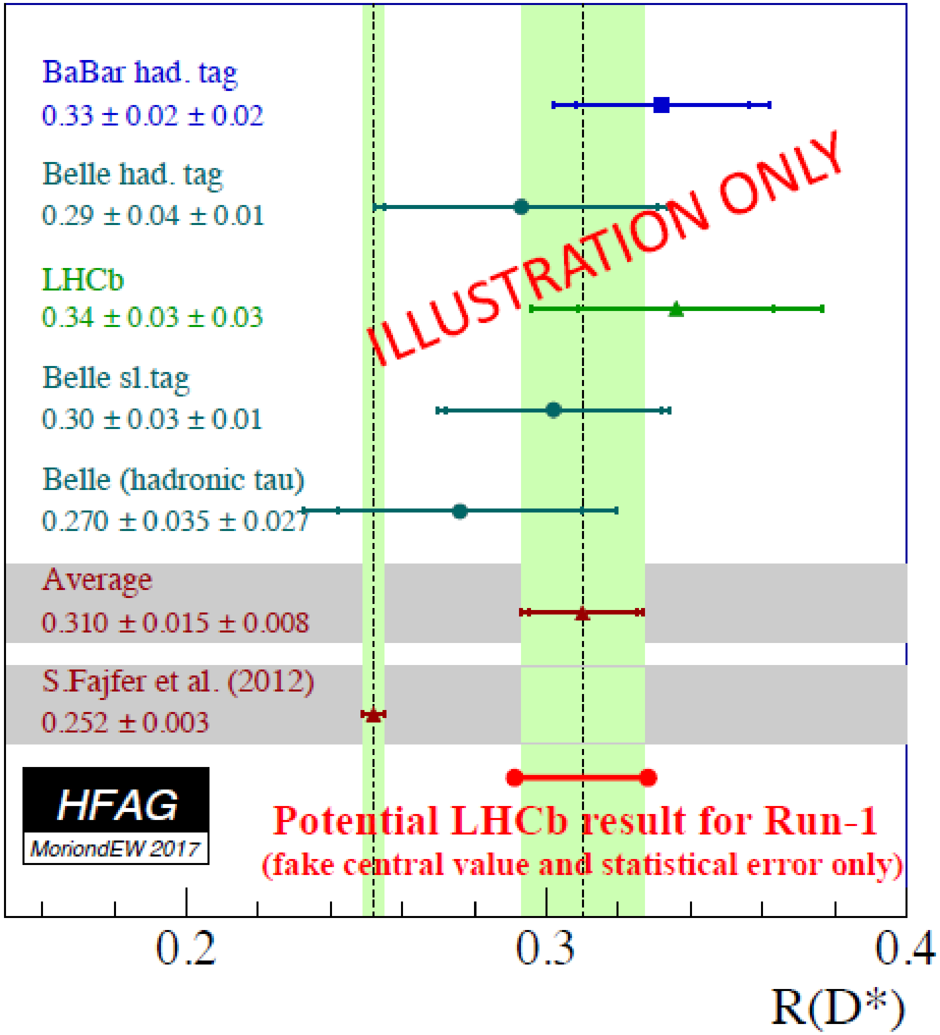
Run 1, 3 fb^{-1}

D° to K 3π peak : Antisolation cut



Signal extraction

- The $D_s \rightarrow 3\pi$ control channel is used to measure the ratio of $D^*D_s/D^*D_s^*/D^*D_s^{**}$ and to correct for their q^2 distribution
- A full fit is then performed at high BDT, as a 3D template binned fit of BDT,q^2 and τ lifetime.
- $D^*3\pi$, D^0 background constrained by their signal in the control channels



Systematic uncertainties

- External
  - 4,3 % from BR($B^0 \rightarrow D^* 3\pi$) PDG 2016
  - 2% from BR($B^0 \rightarrow D^* \mu\nu$)
- Internal
  - MC statistics
  - D_s,D^+,D^0 backgrounds
  - Prompt B^0 backgrounds
  - Stripping, Trigger
  - FF and τ decay model

In red : can be reduced with help from other experiments (BELLE, BES,..)

- Expected overall to be larger than statistical error for the first publication (soon to come)
- Room for progress exists on a longer timescale on both internal and external sources!

LHCb prospects using muonic channel

- R(D) underway
- $R(J/\psi)$ very advanced
- $R(D_s)$, $R(\Lambda_c^*)$ started

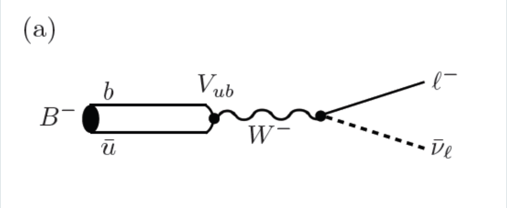
LHCb prospects using hadronic channel

- R(D) nothing really problematic
- R(J/ψ) just starting
- R(Λ_c) well advanced
- R(D_s) under consideration

Expected precision in the ~10% range due to
  - Statistics
  - Normalization strategy
  - Systematics
- for R(J/ψ), the dimuon trigger will allow a direct comparison with B_c->J/ψ μν

Search for LFU violation in leptonic decays

- The annihilation diagram $B^+ \rightarrow \tau\nu$ is not yet doable in LHCb. Note : same final state for B^+ and B_c
- Note that however this can be replaced by the 'V_{ub}' analog b->uW which probes the same diagram. Rather difficult in practice for lack of specifity but LHCb can look for:
  - $\Lambda_b \rightarrow p\tau\nu$ (very challenging but statistical power similar as R(Lc))
  - $B^+ \rightarrow p\bar{p}\,\tau\nu$ (underway)



Semitauonic workshop

- Agreement within LHCb to hold a second semitauonic workshop in Orsay
- Preliminary schedule April 10-12 . Did not work because preemption by a similar workshop taking place in Nagoya organised by BELLE-II
- Delayed in the Spring (or Fall ?) : idea is to open it not only to theoreticians but also to others experiments
- Quite a large attendance expected even from LHCb alone since now basically all the Rs are being covered, and for a good number of them both hadronic and muon channels.

Conclusion and Perspectives

- Semitauonic B decays are a great tool to discover new physics : high SM precision, high rate and high sensitivity
- The exceptional LHCb capability to separate secondary and tertiary vertices open up the best road to study **the semi-tauonic decays of all B particles** , thanks to a new method based on **3 prongs τ decays**.
- The **statistical precision on Run1 should be around 6.5%**, the best achieved so far for a single measurement.
- The very successfull RunII data taking in 2015-2016 leads to **a quadrupling of the data set**
- High statistics and high purity samples to search for BSM effects in the event observables