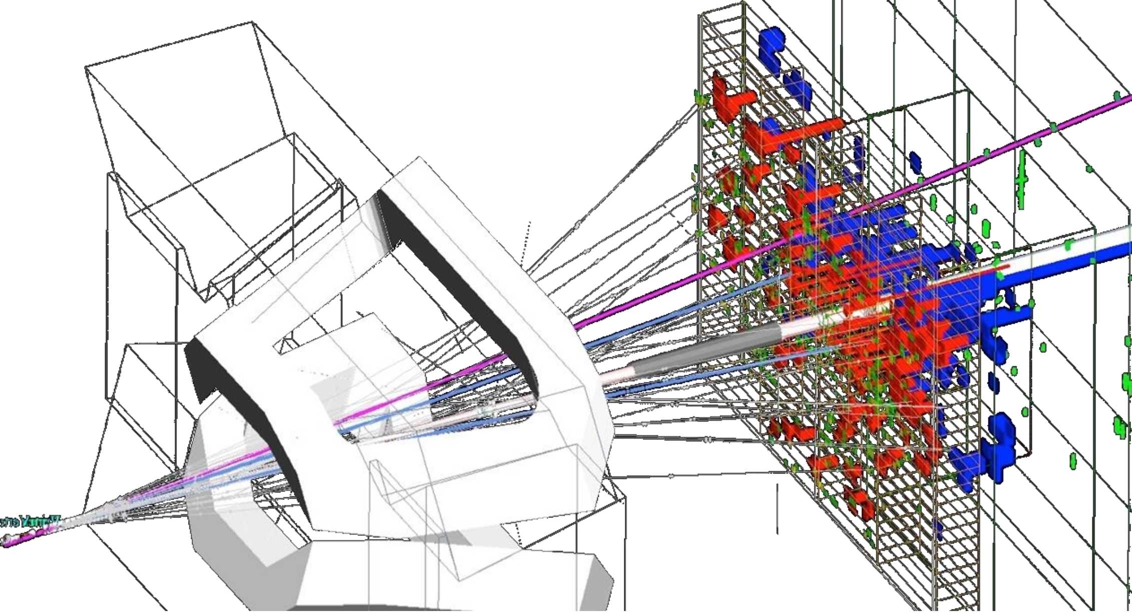
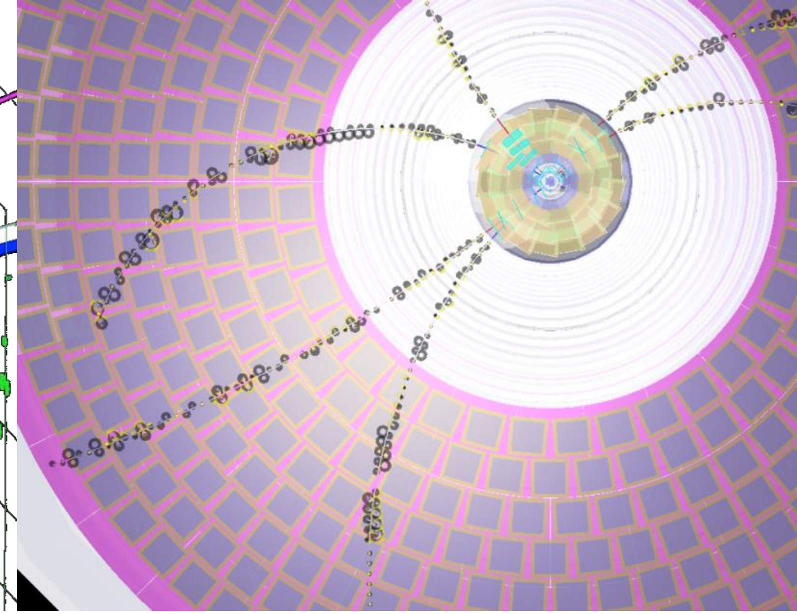



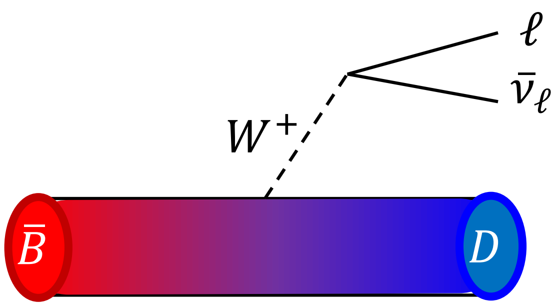
EXPERIMENTAL OVERVIEW OF LEPTON UNIVERSALITY MEASUREMENTS IN SEMILEPTONIC b-HADRON DECAYS

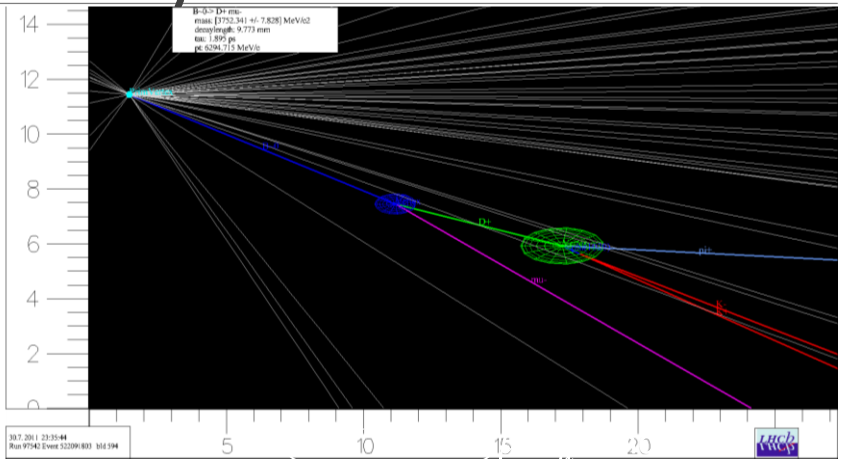
101ST ECFA PLENARY MEETING
CERN
NOVEMBER 16, 2017

BRIAN HAMILTON
(UNIVERSITY OF MARYLAND)

ON BEHALF OF THE LHCB COLLABORATION,
INCLUDING RESULTS FROM BABAR AND BELLE

Semileptonic B decays





- "Beta decay" of B hadrons – signature is lepton (μ or e (or τ!)) , recoiling hadronic system, and missing momentum
  - Tree-level transition in SM – strong V-A structure

- Theoretically under good control due to factorization of hadronic and leptonic part
  - Hadronic matrix element $\langle \bar{B} | \mathcal{O} | H_c \rangle$ decomposed in terms of Lorentz structure with nonperturbative scalar functions of momentum transfer ("*form factors*")

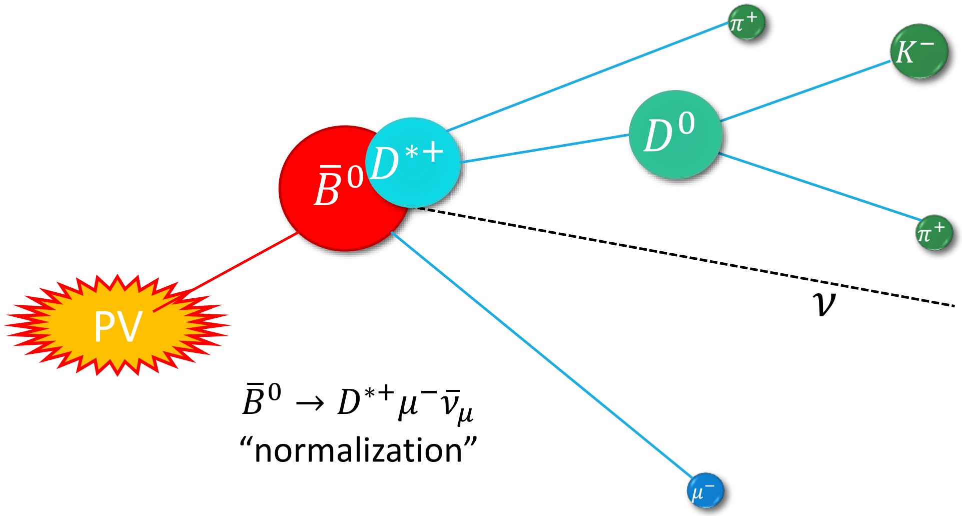
- Charged lepton universality implies branching fractions for semileptonic decays to e, μ, τ differ only by explicit mass-dependence

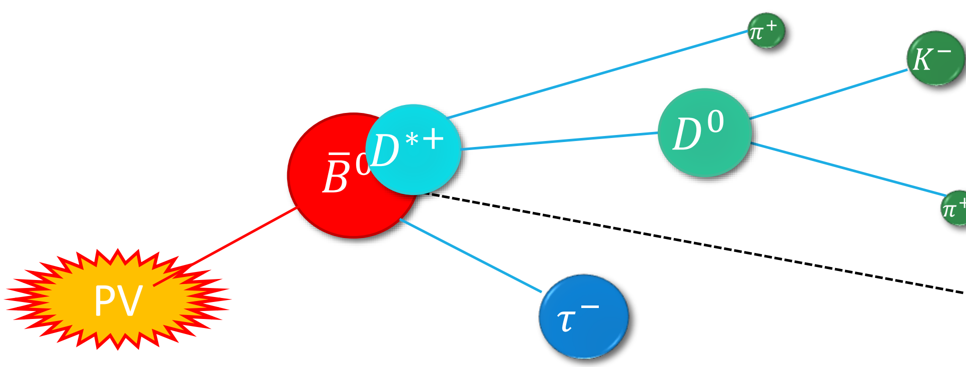
What we want to measure

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

- Theoretically clean due to cancellation of form factor uncertainties
  - Poorly-measured helicity suppressed amplitudes give dominant uncertainty
  - SM predictions are precise. HFLAV global fits currently use:
    $R(D) = 0.300(8)$
    [EPJ **C77** 112 (2017)](Lattice/FLAG)
    $R(D^*) = 0.252(3)$
    [PRD **85** 094025 (2012)] (CLN)
  - Alternate prediction with BGL z-expansion FFs plus Belle unfolded $B \to D^*\ell\nu$ differential distributions

    $R(D^*) = 0.258(5)$
    [arXiv 1707.09977]
    $R(D^*) = 0.260(8)$
    [arXiv 1707.09509]



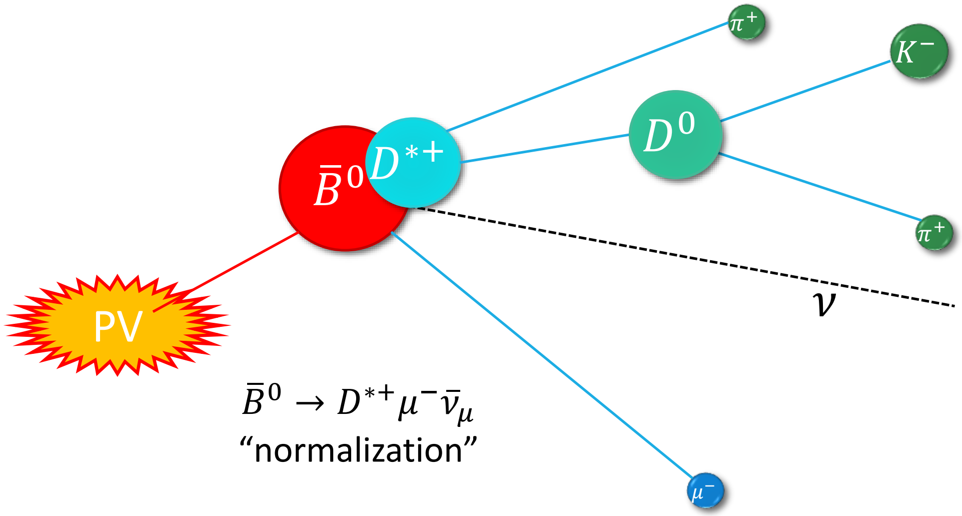


$\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$
"signal"

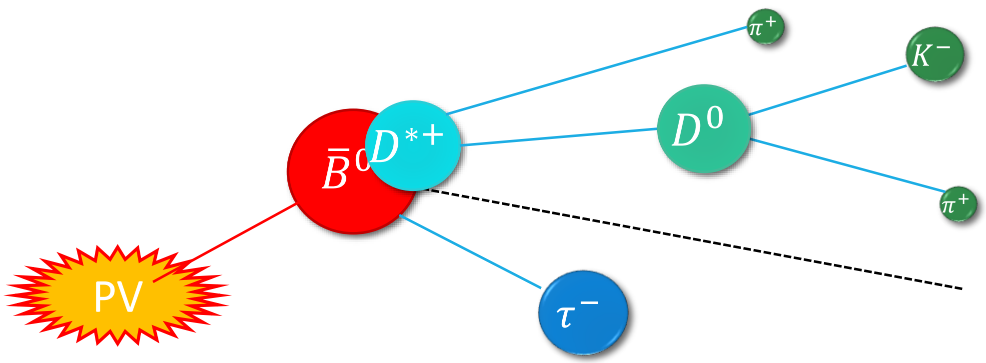
What we want to measure

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(\bar{B}^0 \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \rightarrow D^{(*)}\ell^-\bar{\nu}_\ell)}$$

- $\tau^- \rightarrow \ell^-\bar{\nu}_\ell\nu_\tau$ ("leptonic tau")
  - Identical (visible) final state is optimal for cancelling systematic uncertainties in reconstruction
  - Automatic normalization at hadron colliders
- $\tau^- \rightarrow \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$ ("3-prong")
  - Reconstructible tau vertex, but short lifetime makes this hard to exploit in B factories
  - Normalization is difficult
- $\tau^- \rightarrow \pi^-(\pi^0)\nu_\tau$ ("1-prong")
  - Allows direct measurement of tau polarization
  - Very difficult at hadron colliders (no lepton or vertex to select on)



$\bar{B}^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu$
"normalization"

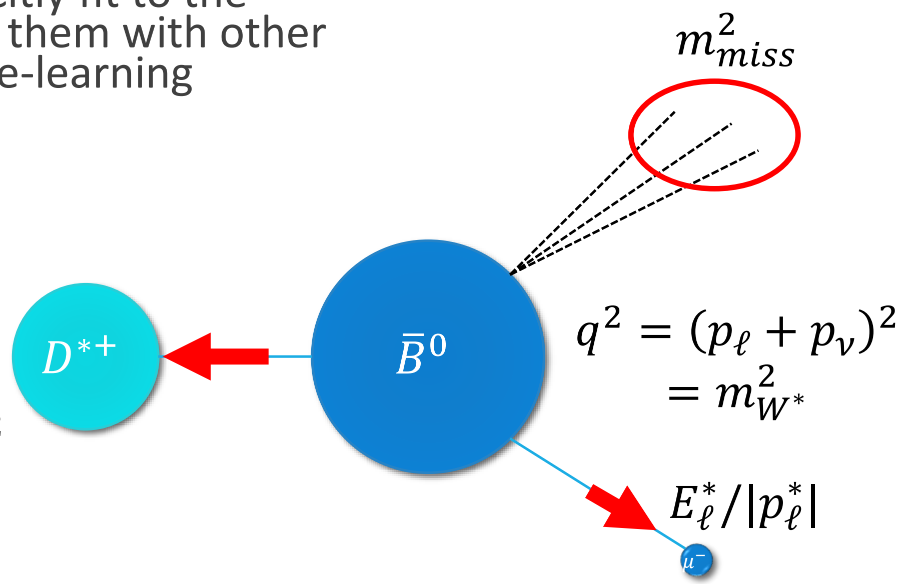


$\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\nu}_\tau$
"signal"

Kinematics of $b \to c\tau(\to \ell\nu\nu)\nu$ vs $b \to c\ell\nu$

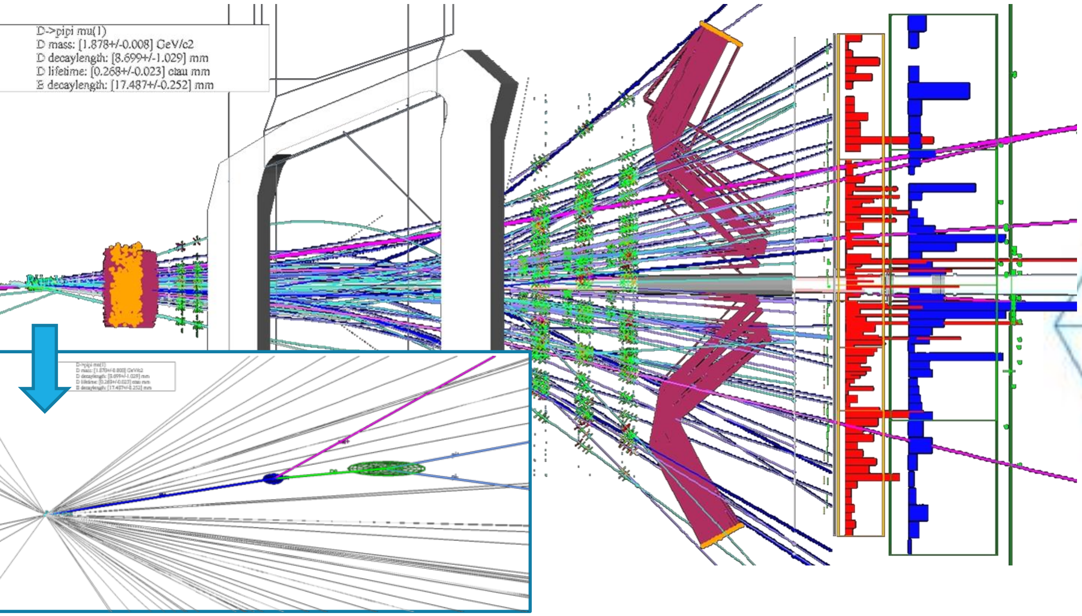
- In B rest frame, three key kinematic variables:
- Experiments can explicitly fit to the kinematics, or combine them with other detector info in machine-learning discriminants

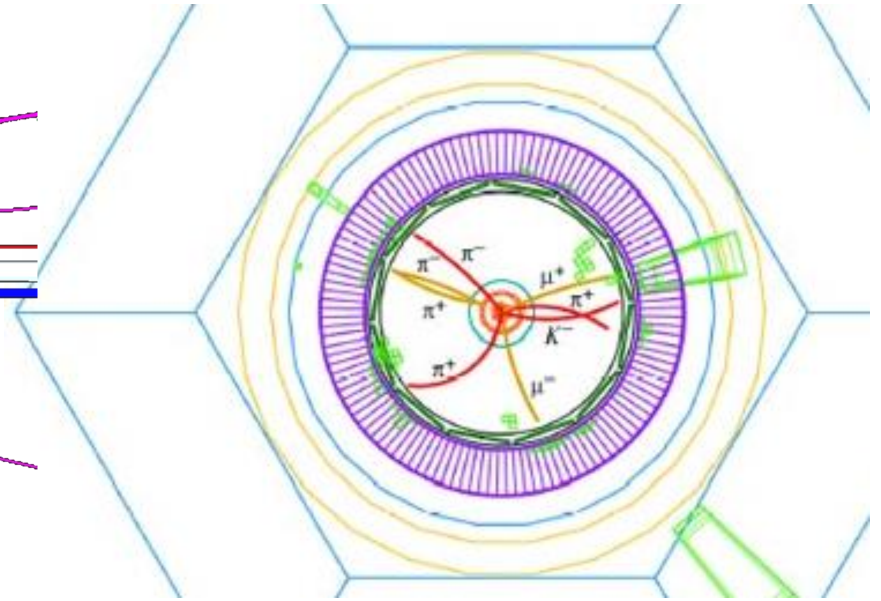
Alternately
$q^2 = (p_B - p_{D^*})^2$
$= (m_B - E^*_{D^*})^2$



$\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}$	$\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}$
$m^2_{miss} > 0$	$m^2_{miss} = 0$
E^*_l spectrum is soft	E^*_l spectrum is hard
$m^2_\tau \leq q^2 \leq 10.6\ \mathrm{GeV}^2$	$\approx 0 \leq q^2 \leq 10.6\ \mathrm{GeV}^2$

Experimental environments



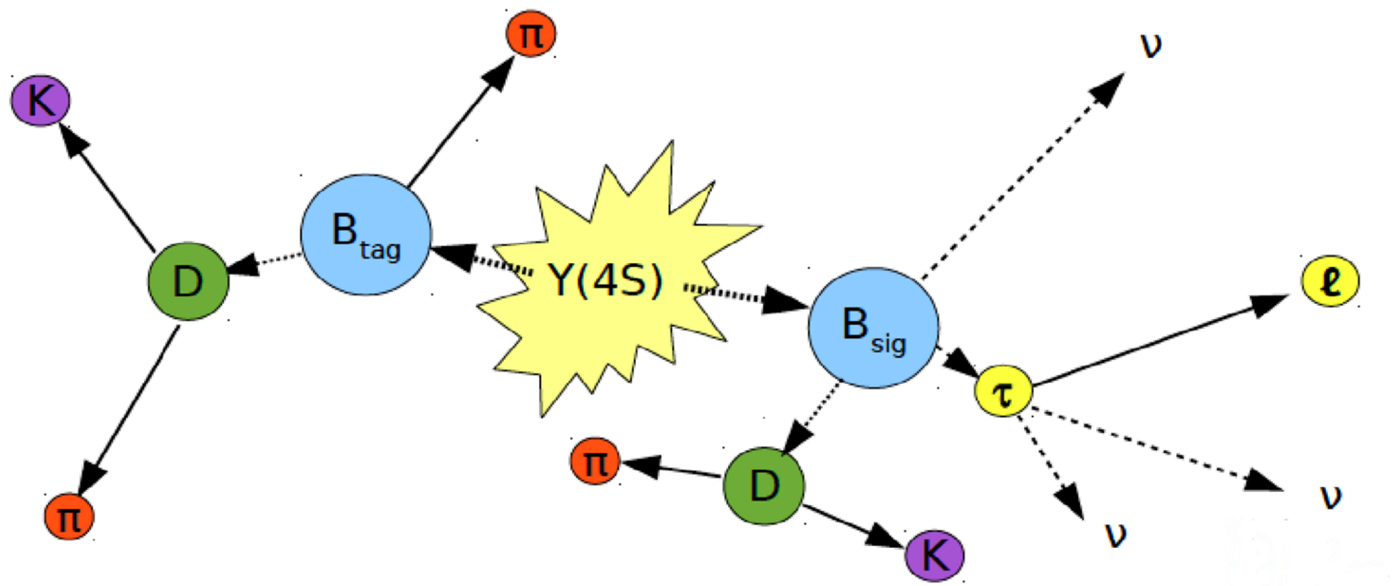


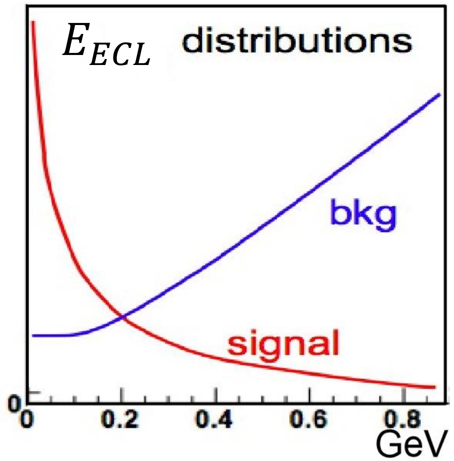
- B-factories: exploit clean BB ***production*** from $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ $(Q = 20\ \text{MeV})$
  - *A priori* knowledge of B energy and collision CM, no extra particles in signal events
  - Easy to cross-feed tracks due to low CM momentum of B mesons
    Event shape needed to separate $B\bar{B}$ vs more frequent $e^+e^- \to q\bar{q},\ q = u, d, s, c$
- LHCb: exploit clean B hadron ***decays***
  - At LHC energies, b hadrons fly macroscopic distances before decaying: use displaced vertex, large impact parameter of charged tracks, etc
  - Production is $gg \to b\bar{b} + MPI + showering + ISR + \cdots$, many extra tracks, very large background for neutrals

B-factory techniques: B_{tag}

"Hadronic tagging" algorithms semi-inclusively reconstruct a hadronically decaying B meson

(Semileptonic tag also used. Poorer separation traded for higher statistics)





Calorimeter deposits not used in from reconstruction can discriminate correctly vs wrongly reconstructed events and be used for selection or fit

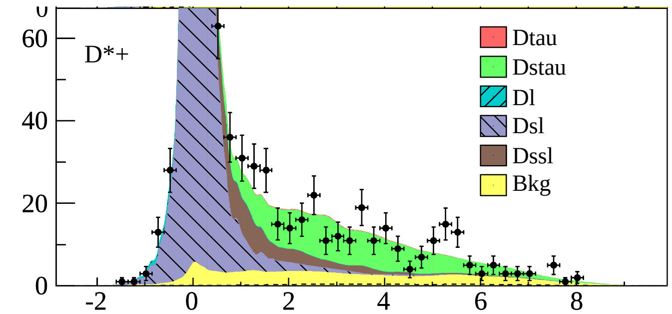
Neutrino system strongly constrained by reconstruction of the rest of event

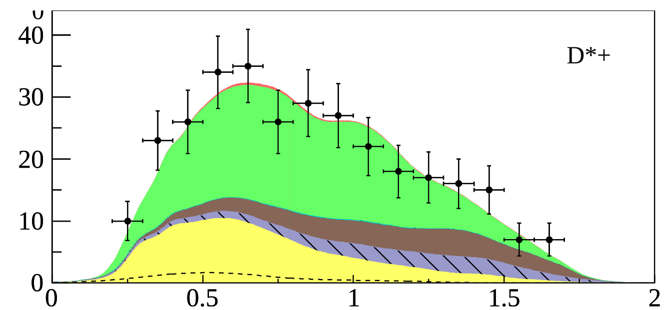
Figures from M. Rotondo, CKM2016

- Full event reconstruction capability is key to b-factory analyses

2012 *BaBar* result

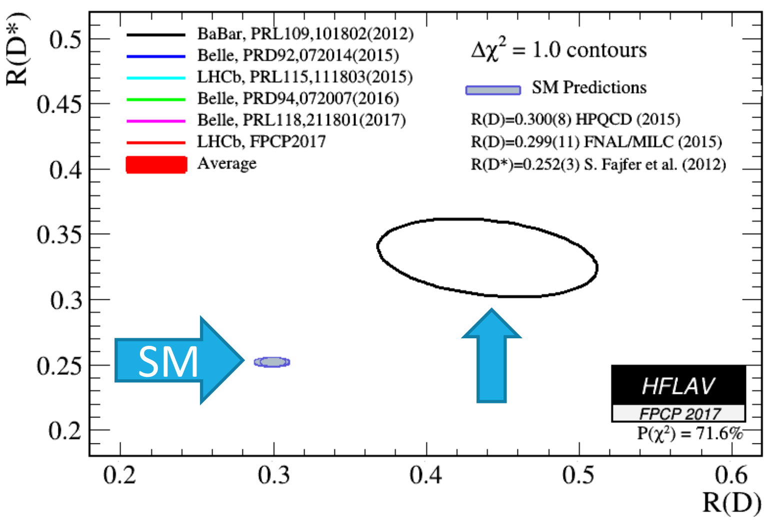
- *BaBar* fit to E_ℓ vs m_{miss}^2 in tension with the SM, but also ruled out the most obvious new physics for this mode
  - Two Higgs doublet models (2HDM-TypeII) can naturally effect $R\left(D^{(*)}\right)$, but are strongly disfavored
  - Other possibilities:
    - Non-universal leptoquark? W'? More exotic 2HDM?
- First priority for experiment: confirm or rule out the excess

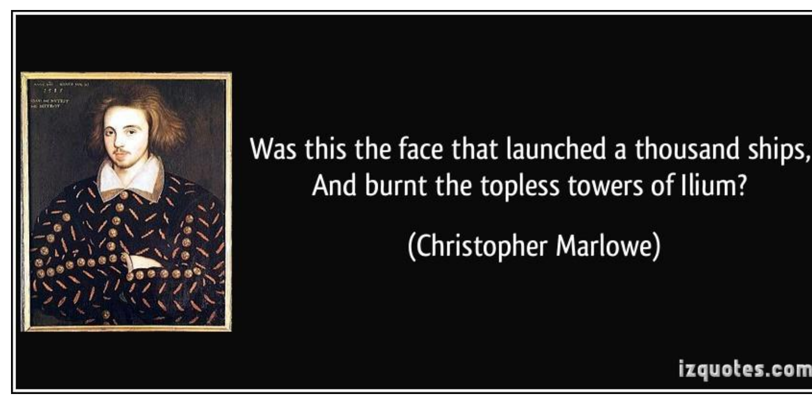




$R(D) = 0.440 \pm 0.058 \pm 0.042$

$R(D^*) = 0.332 \pm 0.024 \pm 0.018$



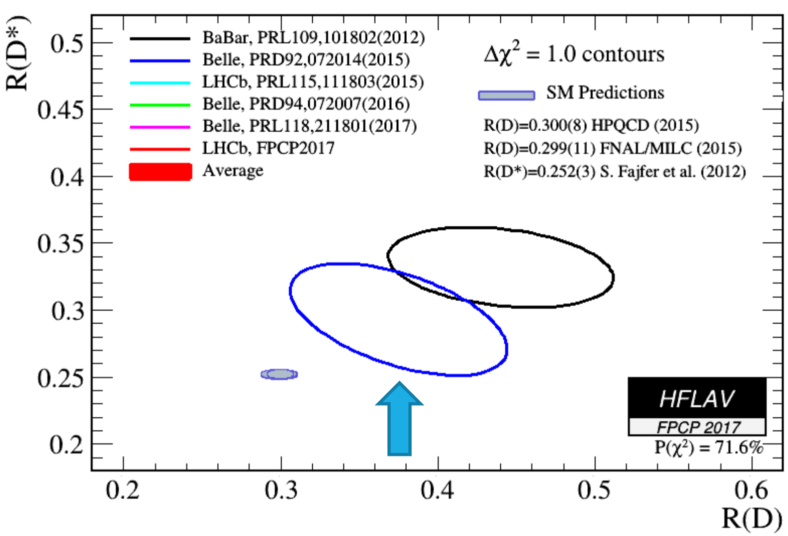


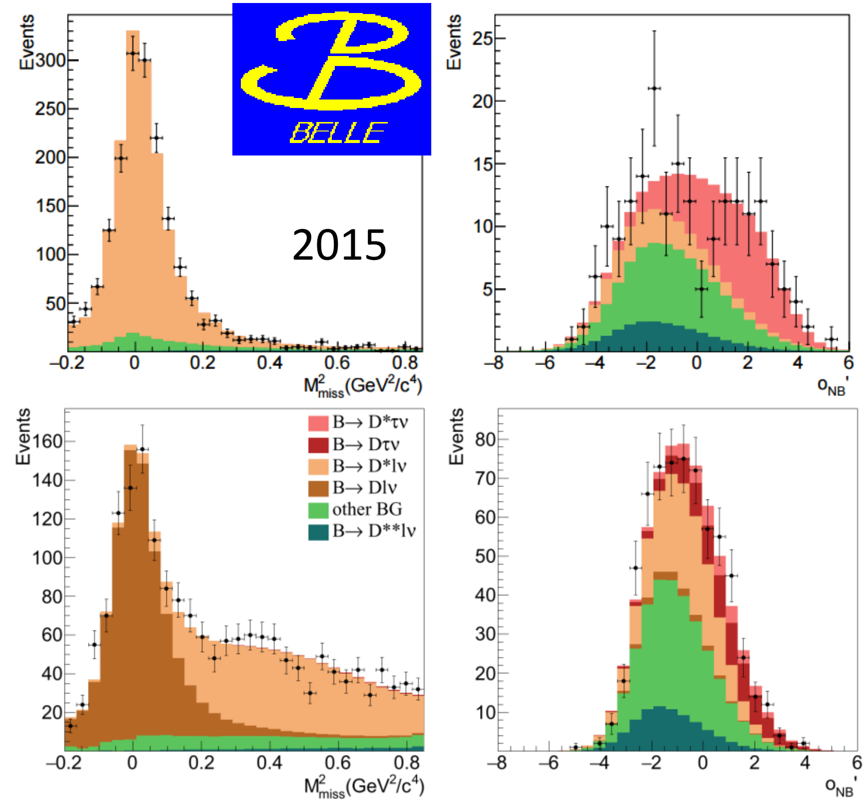
Belle Results

Belle results – hadronic tag

Hadronic B_{tag}

- At FPCP2015, Belle weighed in with their full dataset
  - Fit to neural network discriminant at high missing mass, and missing mass peak at low missing mass (for normalization)
- Results prefer slightly lower but consistent central values in R(D) and R(D*) with respect to BaBar, but still above the SM



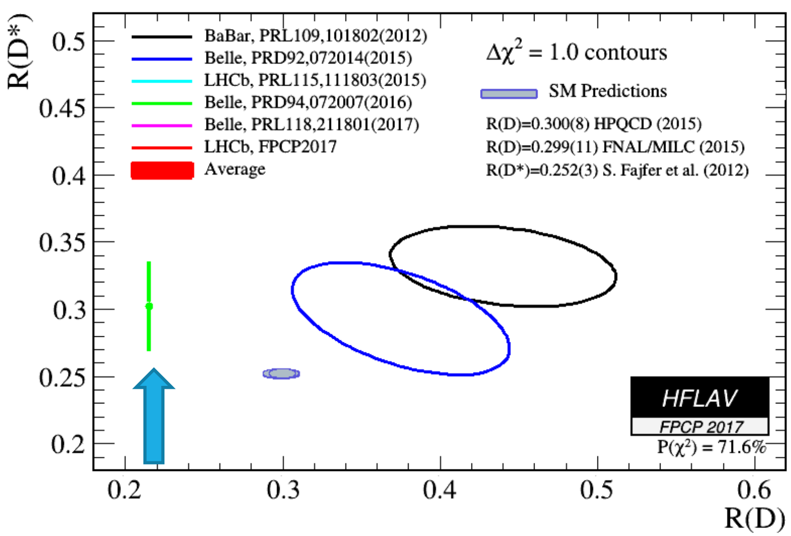


$$R(D) = 0.375 \pm 0.064 \pm 0.026$$
$$R(D^{*}) = 0.293 \pm 0.038 \pm 0.015$$

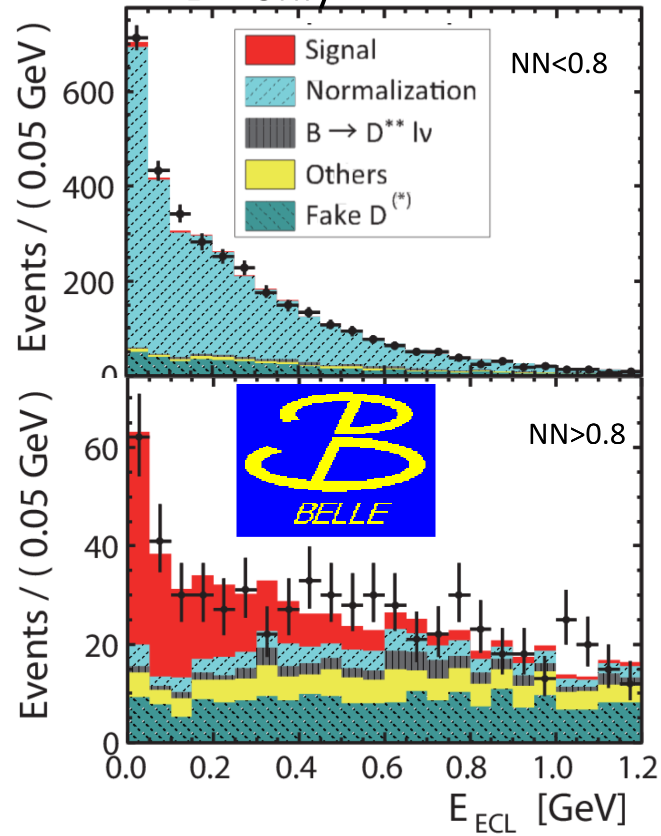
PRD 92 072014(2015)

Belle results – SL tag

- Belle has also measured $R(D^*)$ in an orthogonal sample of events tagged with a semileptonic B_{tag}
  - Technique trades away full kinematic info in favor of higher statistics
- Result:
  - $R(D^*) = 0.302 \pm 0.030 \pm 0.011$



Semileptonic B_{tag}, D^* only



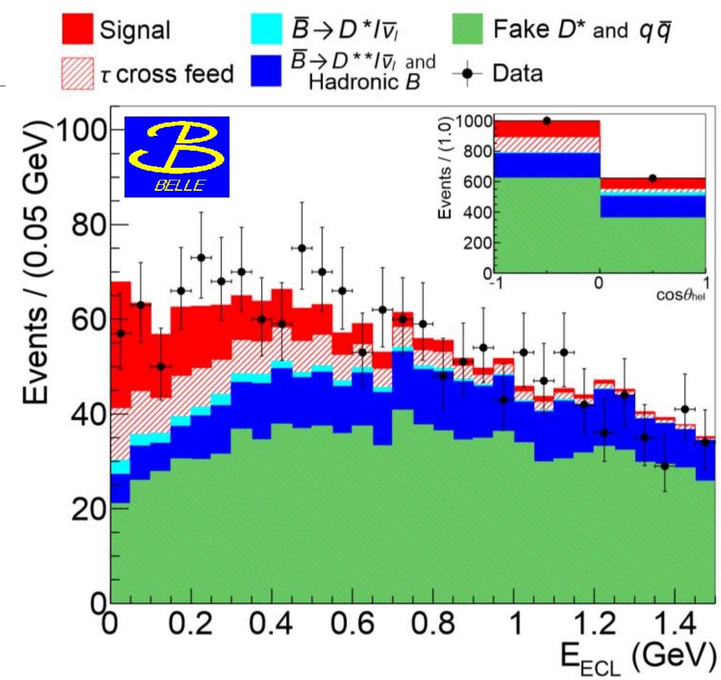
PRD 94 072007(2016)

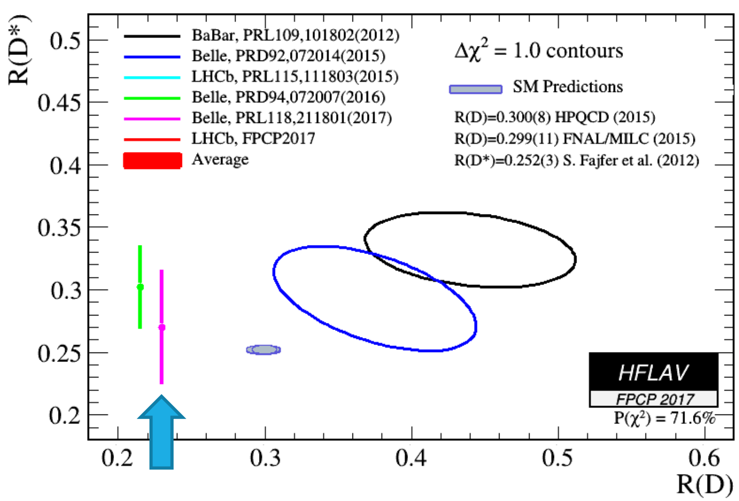
Belle hadronic tau

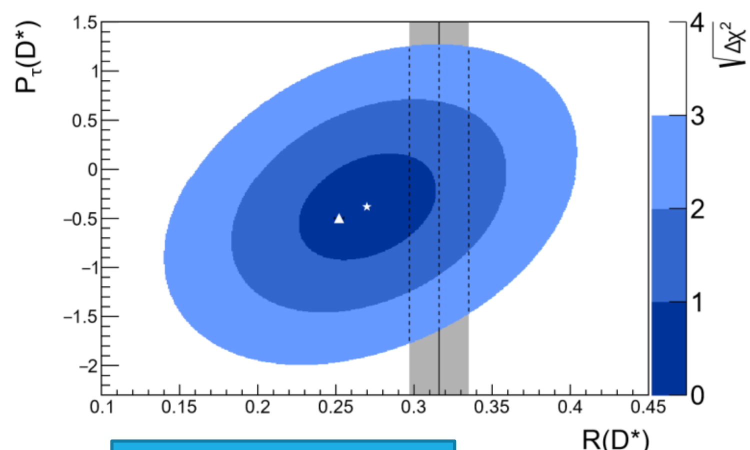
- Hadronically tagged dataset using the $\tau \rightarrow \pi^+(\pi^0)\nu$ decay mode

$$R(D^*) = 0.270 \pm 0.035^{+0.028}_{-0.025}$$

  - First BF measurement in a submode with hadronically-decaying tau
  - First study of τ polarization in semileptonic B decay
    - Important proof-of-principle towards Belle 2 polarization measurements



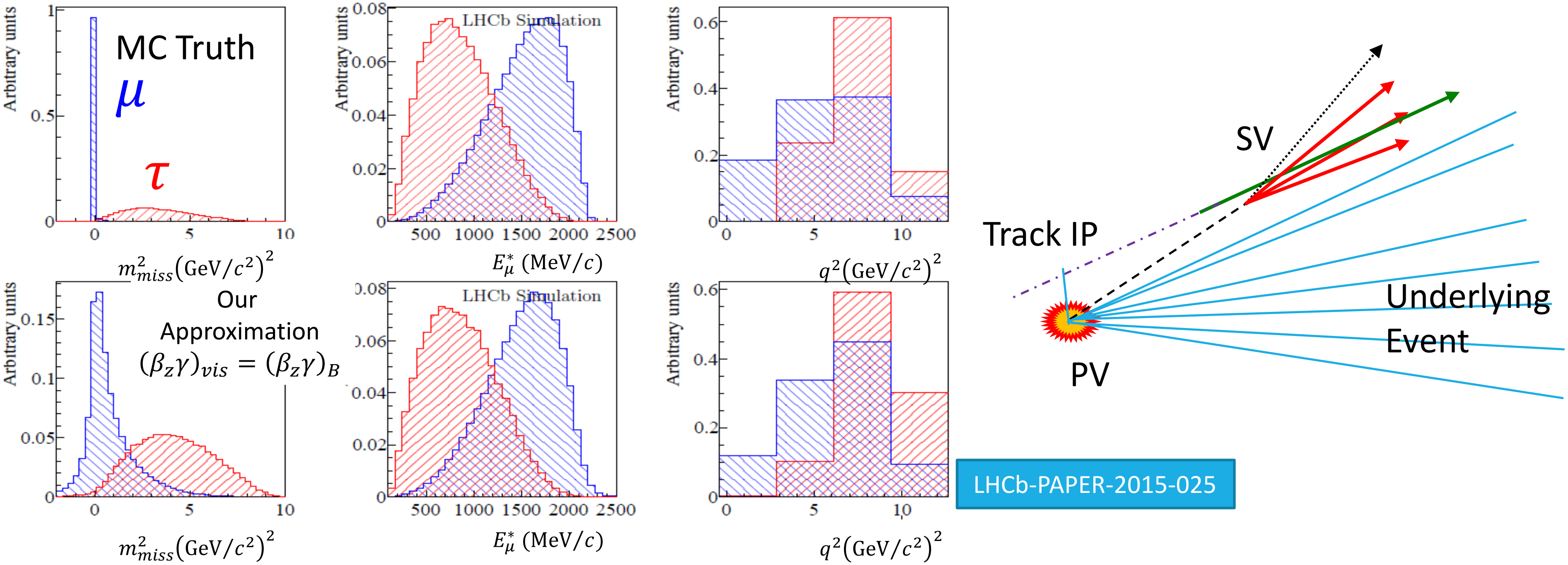




PRL 118 211801 (2017)

LHCb Results

LHCb techniques: boost approximation

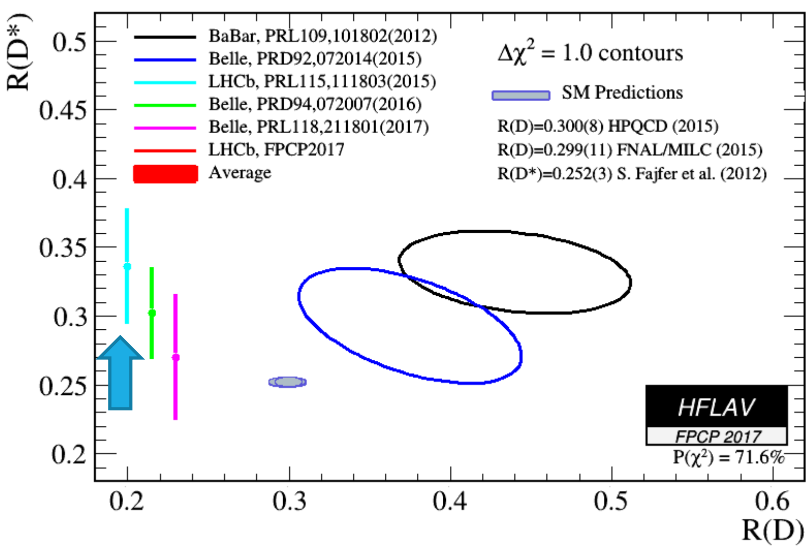


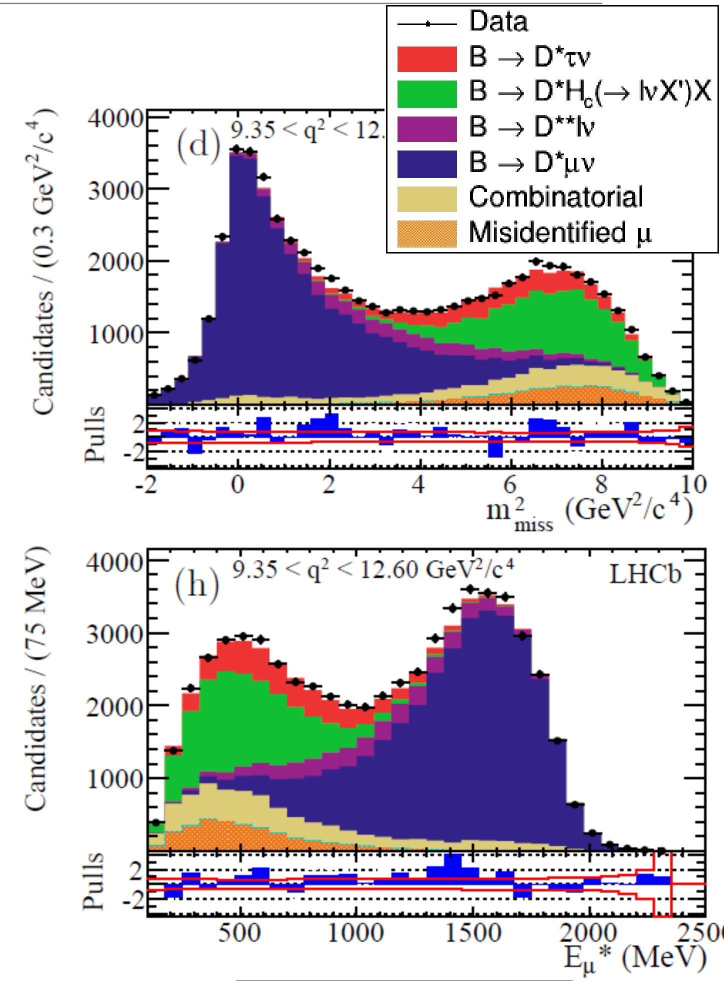
- No information on initial B momentum to reconstruct the discriminating variables
  - Key: Resolution on rest frame variables doesn't matter much because distributions are broad to begin with -- well-behaved approximation will still preserve differences for fit
  - Approximation + knowledge of direction from PV to SV = full B momentum

- Also use superb tracking system to fight huge partially-reconstructed background
  - Scan over every track and compare against $D^{*+}\mu^-$ vertex with machine-learning alg.
  - Allows for cleaner signal sample *and* data control samples enriched in key backgrounds

LHCb result

- 3D fit to m_{miss}^2, E_μ^*, q^2
- Result: $R(D^*) = 0.336 \pm 0.027 \pm 0.030$
  - (2.1 sigma from CLN prediction)
  - First measurement of a $b \to X\tau\nu$ decay at a hadron collider
- Dominant systematics from MC statistical uncertainty and background from hadrons misidentified as muons

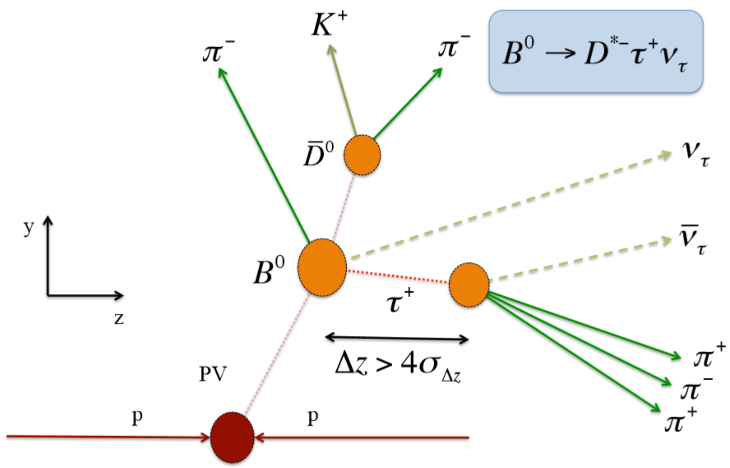


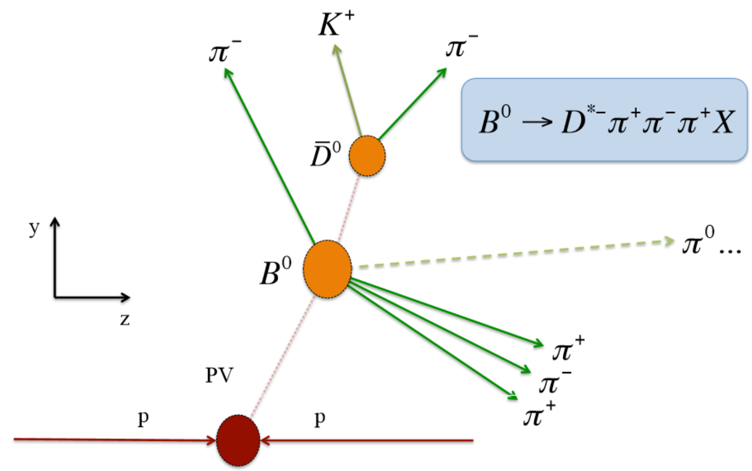


PRL 115 111803(2015)

New!

$\bar{B}^0 \to D^{*+}\tau\bar{\nu}$ with $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu$



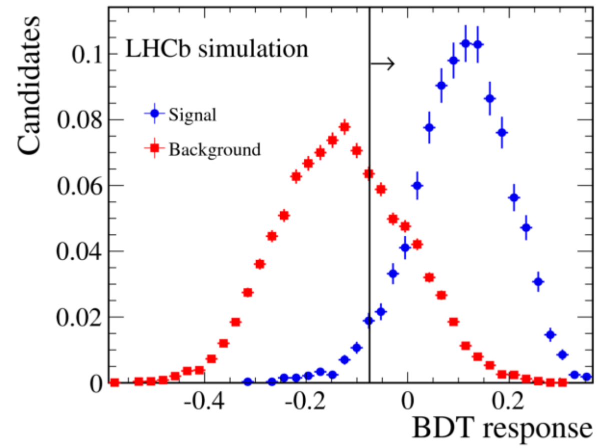


- This signal mode is historically very challenging due to the large inclusive $\bar{B} \to D^{*+}3\pi_{direct}X$ branching fraction (includes normalization mode)
  - Size is 100x expected signal
- Very large boost and excellent vertexing at LHCb comes to the rescue:
  - Requiring 4σ separation of vertices along $\hat{z}$ removes 99.9% of non-flying background
  - Signal efficiency is ~34%
    - remember, exponential distribution is largest near zero – no free lunches!
  - Result is O(11%) signal purity, compared to 4.4% in muonic mode
  - Further enhance the signal: require no tracks with $< 5\sigma$ IP significance to B vertex

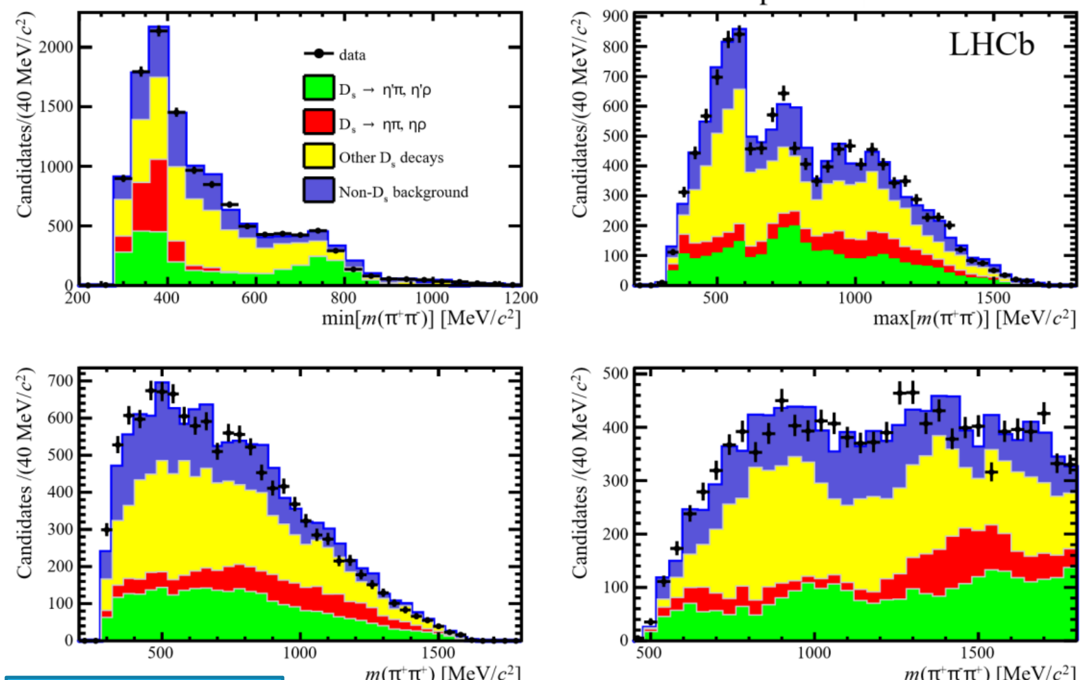
New!

Controlling Ds backgrounds

- Largest background is from $B \to D^* D_s[\to 3\pi X]$
  - Train BDT to distinguish the two decays
    - BDT uses 3π dynamics, visible mass, momenta, etc
  - BDT used both as selection and fit variable



- To use the 3π dynamics in the BDT requires improving the modeling of the D_s decay
  - Construct BDT on “vanilla” simulation → use to select pure D_s sample → correct D_s simulation modelling for fit



arXiv: 1711.02505

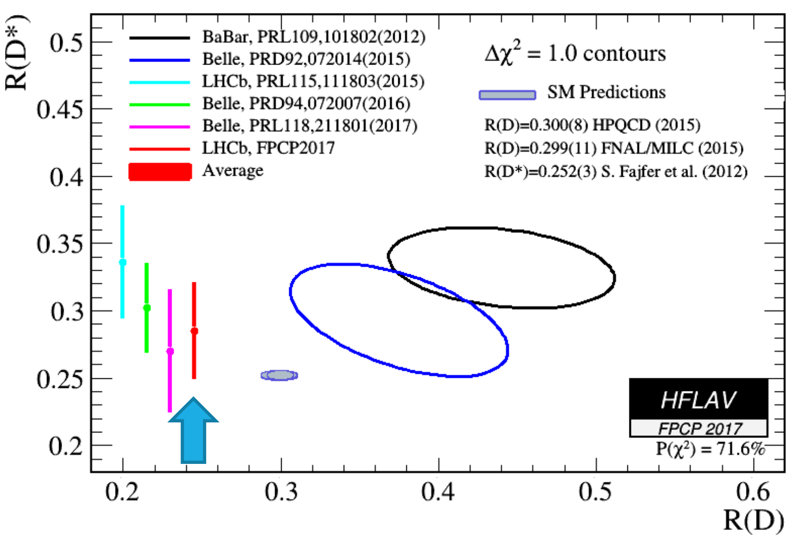
Fit

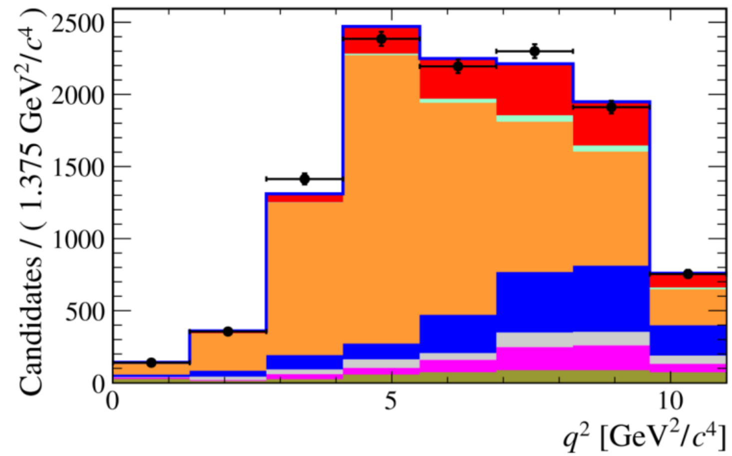
New!

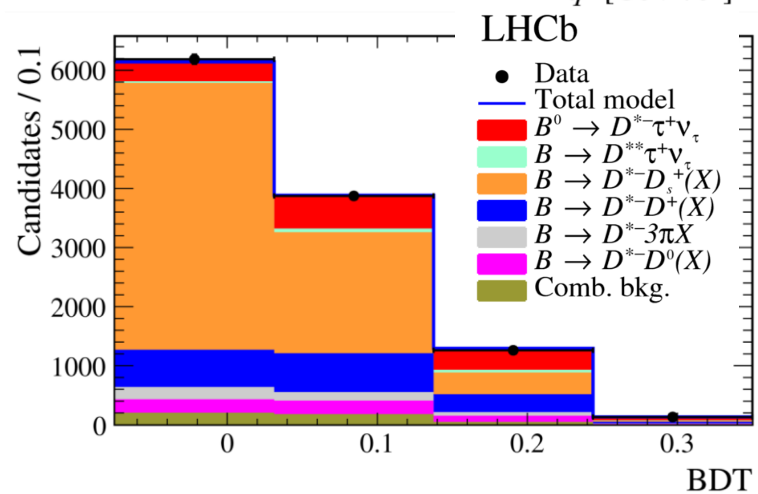
- 3D fit in q^2, τ decay time (not shown), BDT
- Exclusive $\bar{B} \to D^{*+}3\pi_{direct}$ provides normalization for measurement
  - $\mathrm{K}(D^*) \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}$

    $R(D^*) = K(D^*) \times \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\tau)}$

- **Result:** $0.286 \pm 0.019 \pm 0.025 \pm 0.021$

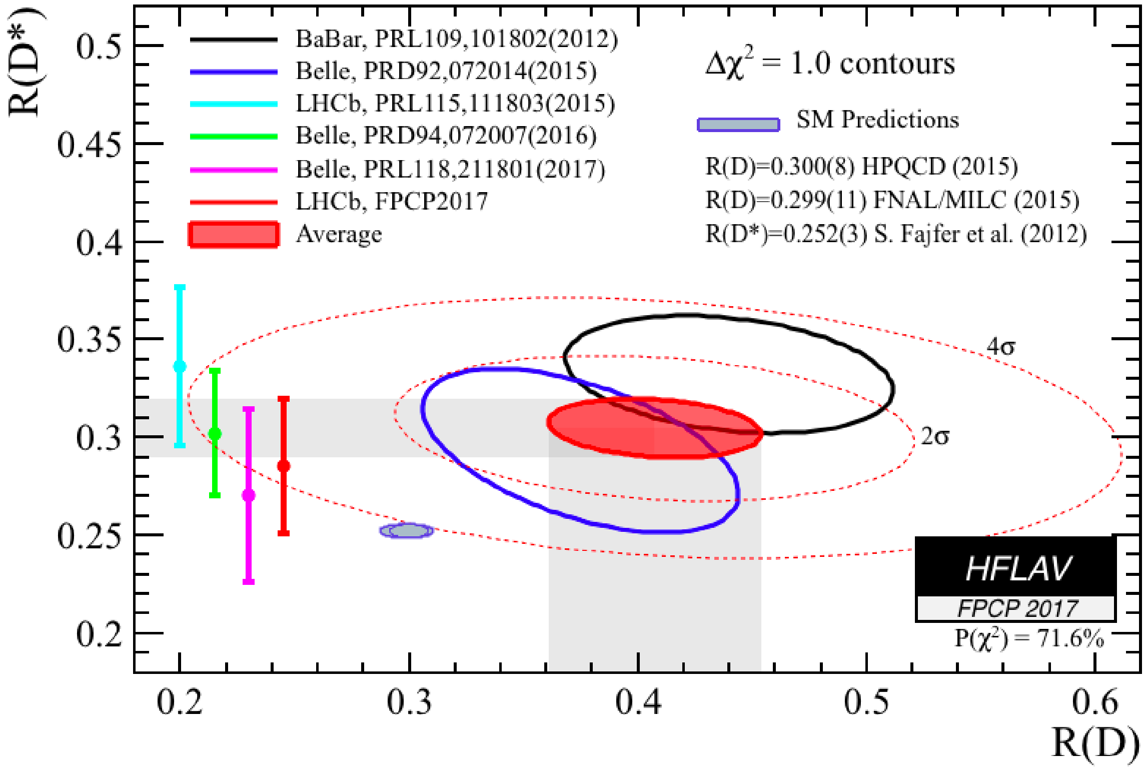






arXiv: 1711.02505

$R(D^{(*)})$ world average

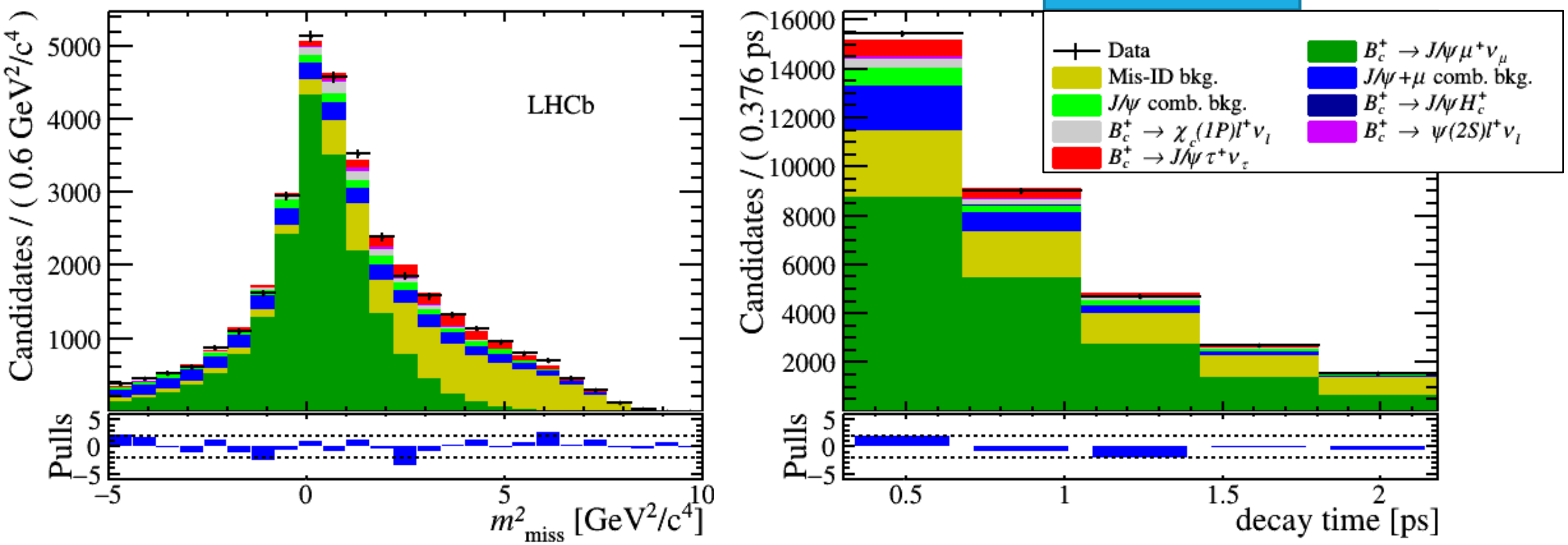


- Combination of all experimental results shows excellent agreement
- World average value vs CLN(2012)+Lattice SM predictions shows a 4.1σ tension
  - New theory predictions can change this by $\mathcal{O}(0.5\sigma)$

$R(J/\psi)$

New!

arXiv:1711.05623



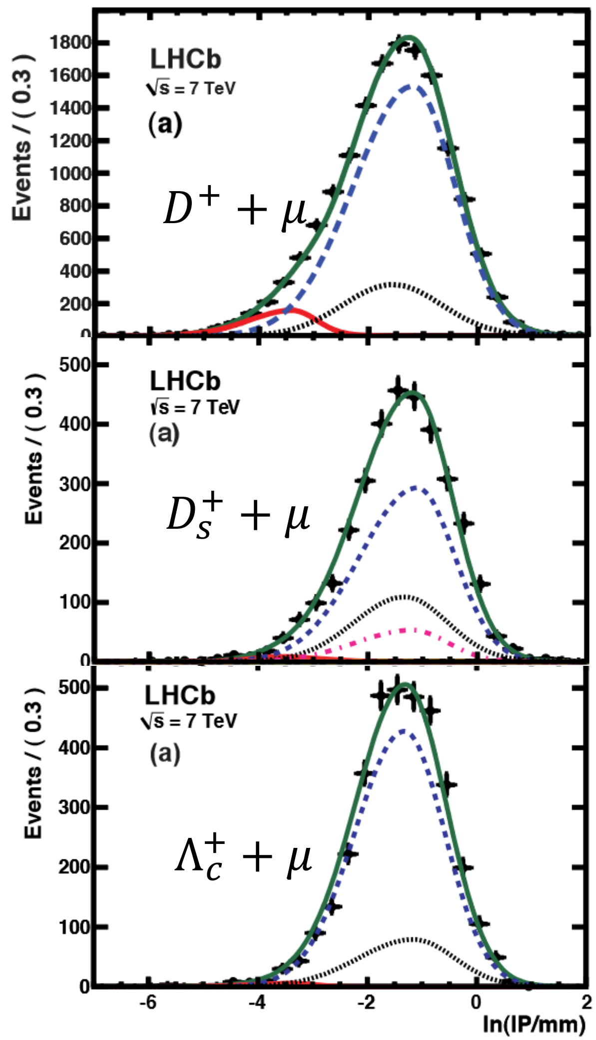
$$R(J/\psi) \equiv \frac{\mathcal{B}(B_c^+ \to J/\psi\tau\nu)}{\mathcal{B}(B_c^+ \to J/\psi\mu\nu)} = 0.71 \pm 0.17 \pm 0.18$$

- Advantage: striking tri-muon signature in $\tau \to \mu\nu\nu,\ J/\psi \to \mu\mu$ decay chain
  - Disadvantage: lighter b hadrons 100x more common – large background from inclusive J/ψ+misidentified hadron
- 3D fit in m^2_{miss}, τ_B, and q^2/E_ℓ categorical variable Z (not shown) uses only on Run1 dataset and is limited by statistics and (lack of) knowledge of form factors
  - Efficient triggering and event selection even in higher pileup (LHCb upgrade) environment – good target for any LHCb upgrade scenario
  - Analysis in the $\tau \to 3\pi\nu$ submode can also expect to benefit from high efficiency

LHCb goals

- Near term, many analyses in pipeline:
  - $R(D^0)$ vs $R(D^{*(0,+)})$ Muonic
  - $R(D^+)$ vs $R(D^{*+})$ Muonic
  - $R(D^0), R(D^+)$ 3-prong
  - $R(J/\psi), R(\Lambda_c^+)$ 3-prong

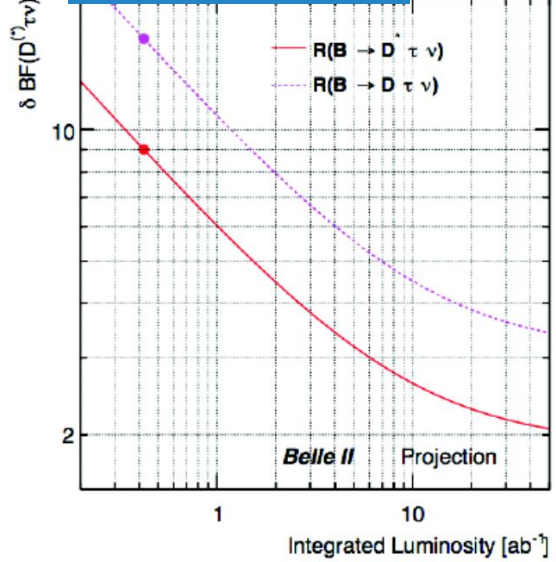
- LHCb medium-term plan is to fully exploit the capability to do these measurements in every b-hadron type
  - Each mode has different backgrounds and associated systematics – good test of robustness of current trend
    - Form factors and previously unmeasured background modes will be a challenge
  - Baryonic modes are especially powerful to distinguish various NP scenarios (e.g. by distinguishing various leptoquark spins or leptoquarks vs W', etc…)



Extrapolations

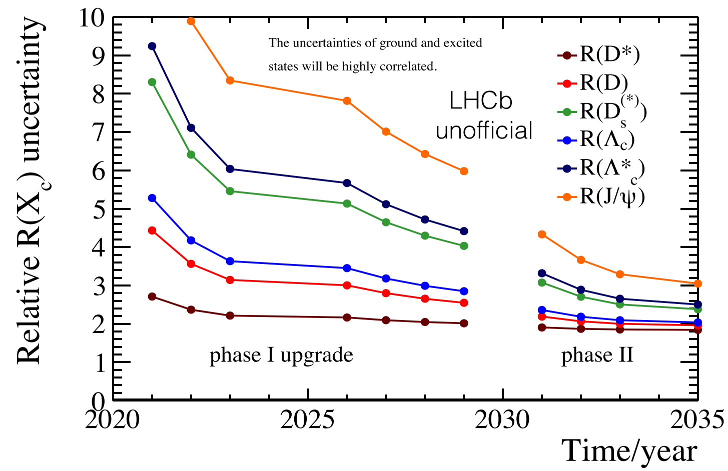
- e^+e^-
  - Belle:
    - R(D) semileptonic tag in progress
    - Revisit old inclusive-tag measurements
  - Belle-II / Super-KEKB:
    - Instantaneous Lumi increase by 50x Belle
    - Ultimate dataset goal: $50\text{ab}^{-1} \approx 6 \times 10^{10}\ B\bar{B}$ pairs
    - Could reach 2% sensitivity on R(D*) with final dataset
    - Improved vertexing resolution can open up 3-prong channel

G. De Nardo CKM 2014



- pp
  - LHCb Upgrade:
    - 40MHz synchronous readout + all-software trigger
    - $50\text{fb}^{-1} \approx 6 \times 10^{12}\ b\bar{b}$ in acceptance
    - LHCb Upgrade expects to remain competitive with final Belle-II sensitivity
      - Clear path to continuously reduce background systematics with more and better control samples
      - Challenge will be computing
    - Phase-II upgrade luminosity likely needed to get ultimate sensitivity on other b-hadrons

P. Owen LHCb Beyond Phase 1 Upgrade workshop



Summary

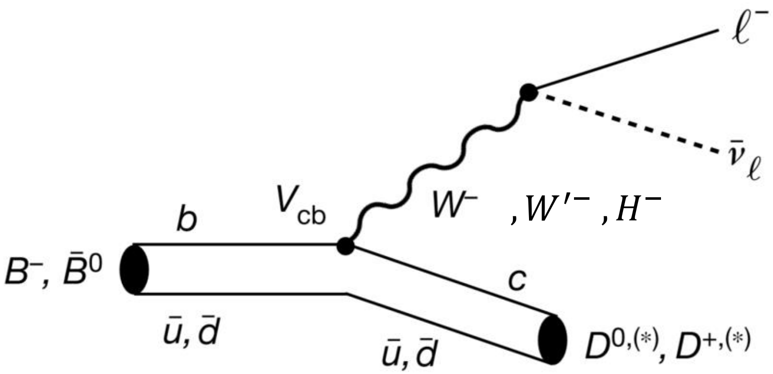
- Starting in 2015, LHCb and Belle have produced a flurry of follow-ups on the initial BaBar 3-sigma excess in semitauonic decays

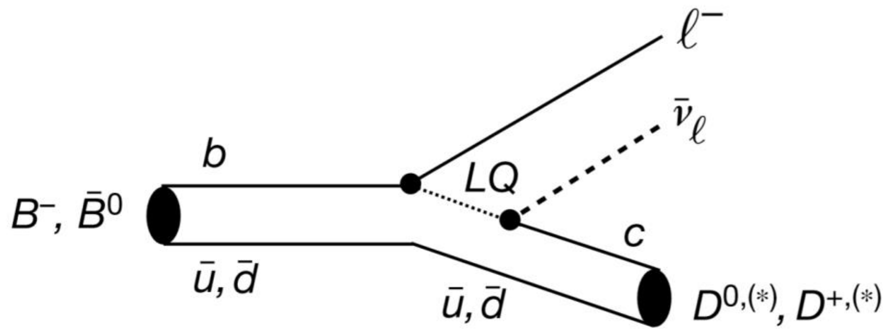
- Situation remains tantalizing but unclear
  - Reasons to be optimistic:
    - Persistent 3.5-4σ tension after 6 separate results from teams at different experiments with excellent compatibility
    - Zero downward (below SM) fluctuations!
  - Reasons to be cautious:
    - Revised SM predictions seem to be in the direction of weakened tension
    - No single-measurement result since the 2012-13 result has deviated more than 3 sigma

- More experimental and theoretical efforts needed to clarify the situation
  - More data! Currently trying to clarify a 20% excess using data with 10% error bars
  - More b hadron modes with different backgrounds (and spin, in the case of baryons)
  - Measurements of polarization and/or kinematical distributions

Backup

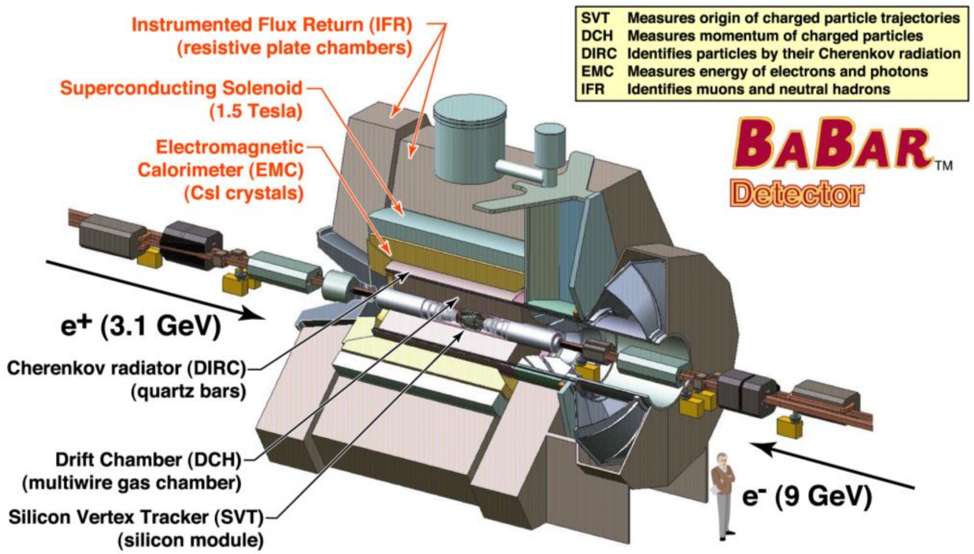
Implications of the excess

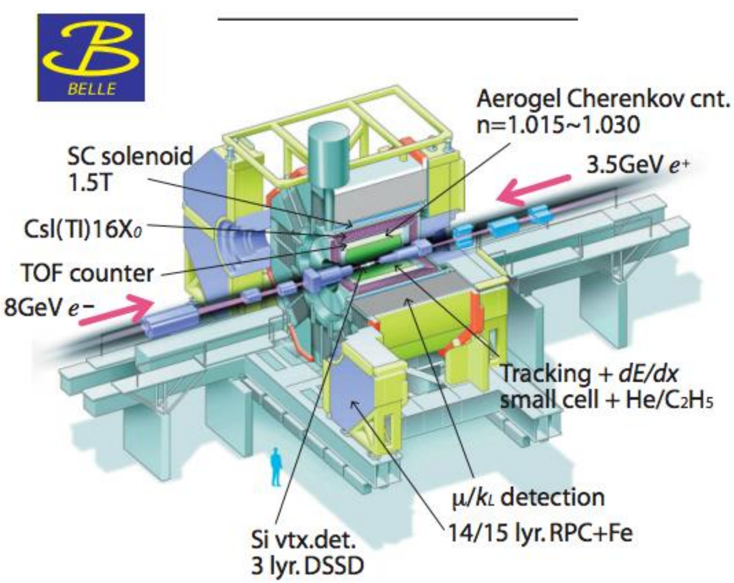




- BaBar result in tension with the SM, but also ruled out the obvious new physics
  - Two Higgs doublet models (2HDM) can naturally effect $R(D^{(*)})$, but the type favored by SUSY is strongly disfavored by BaBar central value
- Other possibilities:
  - Non-universal leptoquark?
  - W'?
  - Other types of 2HDM
- First priority for experiment: confirm or rule out the excess

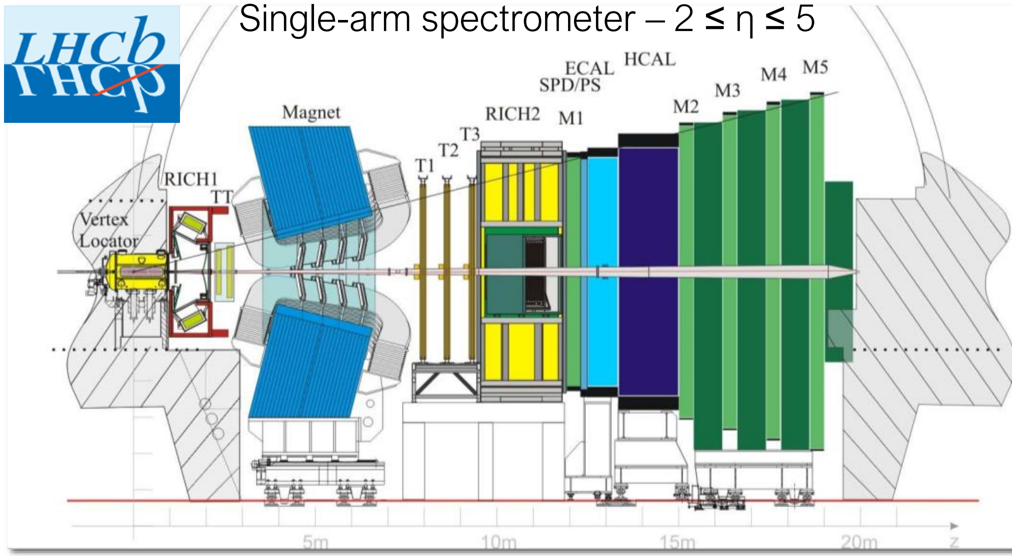
Cast pt1: B-factories

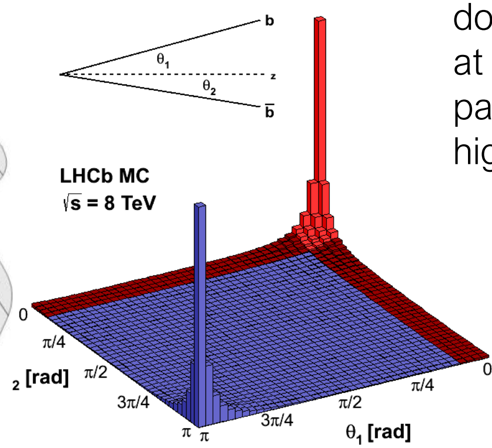




- 4π detectors for medium energy asymmetric collisions
- Two-stage tracking using drift chamber complimented by silicon strips near the interaction region
- High quality CsI(Tl) calorimeters provide excellent π^0, η, γ reconstruction and $e^\pm$ particle ID
- Excellent hadron PID at low (dEdx) and high (dedicated TOF or Cherenkov) monentum

Cast pt 2: LHCb/LHC





$b\bar{b}$ production dominately at lower p_T: parton CM frame highly boosted

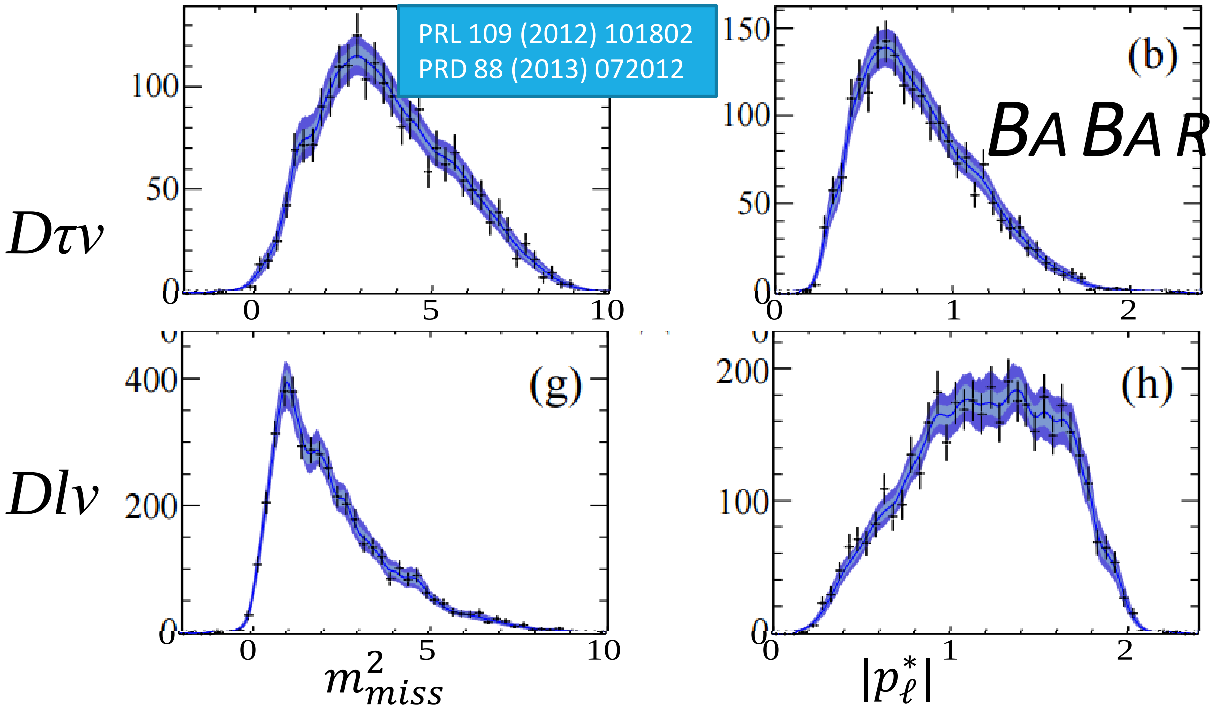
At 7 TeV:
σ_{inel} ~70 mb
$\sigma_{c\bar{c}}$ ~ 6 mb
$\sigma_{b\bar{b}}$ ~ 280 μb

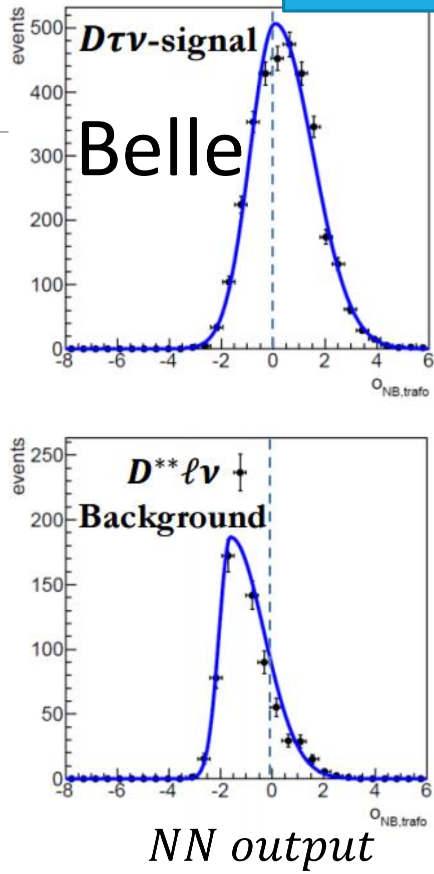
- Single arm spectrometer optimized for beauty and charm physics at large η:
  - Trigger: ~90% efficient for dimuon channels, ~30% for all-hadronic
  - Tracking: $\sigma_p/p \sim 0.4\%–0.6\%$ (p from 5 GeV to 100 GeV), $\sigma_{IP} < 20\ \mu m$
  - Vertexing: $\sigma_\tau \sim 45$ fs for $B_s \to J/\psi\phi$
  - PID: 97% μ ID for 1-3% π→μ misID
  - Dipole magnet polarity periodically flipped to change the sign of many reconstruction asymmetries
- Instruments ≲ 3% of the solid angle to cover 27% of the b-quark cross-section
- Run1 dataset: $3 fb^{-1}$, Run2 datataking has already begun with 50ns ramp

PDFs for BaBar and Belle

arXiv: 1507.03233

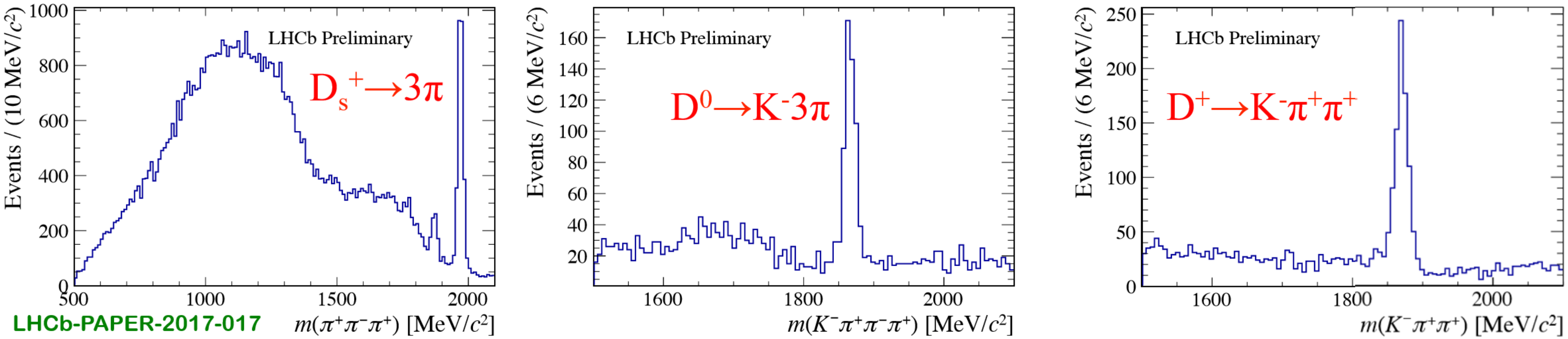
PRL 109 (2012) 101802
PRD 88 (2013) 072012





- Fit is performed in mass squared of invisible system vs lepton momentum in B frame
  - Split between D^0, D^+, D^{*0}, D^{*+} samples
- Distributions for fit taken from simulation
  - Missing mass squared best discriminator of signal from normalization ($D^{(*)}\ell\nu$)
  - Backgrounds separated in mm and pl for BaBar, special neural net for Belle
- Similar template fit technique used at LHCb

3pi - Calibrating Simulation



- q^2 distributions for each of the double charm background classes are validated and corrected in subsets of the data with fully reconstructed D mesons
  - $D_s \to m_{3\pi}$ above kinematic window for τ decay
  - $D^0 \to$ invert isolation requirements to find $D^0 \to K^- 3\pi$ decays
  - $D^+ \to$ invert PID requirements on minority-sign pion