Results from Lepton Flavor Universality Tests at LHCb

2019 Meeting of the Division of Particles & Fields of the American Physical Society

Tuesday 30 July 2019

Phoebe Hamilton
University of Maryland/LHCb

Lepton universality

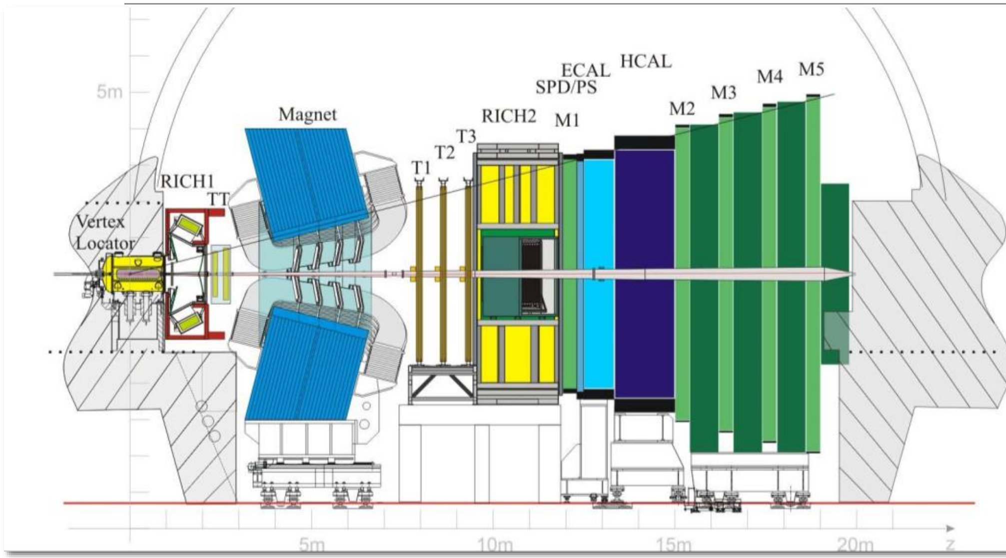
- In Standard Model (SM), charged lepton flavors are ***identical copies*** of one another
  - Electroweak couplings are trivially equal for all three flavors by construction, only Higgs Yukawa couplings differentiate them
  - Amplitudes for processes involving e, μ, τ must all be identical up to explicit mass dependence (phase space, fermion helicity)
    - Examples:
      - $\mathcal{B}(Z \to e^+e^-) = \mathcal{B}(Z \to \mu^+\mu^-) = \mathcal{B}(Z \to \tau^+\tau^-)$
      - $\mathcal{B}(\psi(2S) \to e^+e^-) = \mathcal{B}(\psi(2S) \to \mu^+\mu^-) = 2.574 \times \mathcal{B}(\psi(2S) \to \tau^+\tau^-)$ (P = 1840 MeV for e^+e^- vs 489 MeV for $\tau^+\tau^-$)
  - Tests of SM LFU have been performed in a number of different systems over the years
    - $Z \to \ell\ell, W \to \ell\nu, \tau \to \ell\nu\bar{\nu}, \pi \to \ell\nu, K \to \pi\ell\nu$, etc...

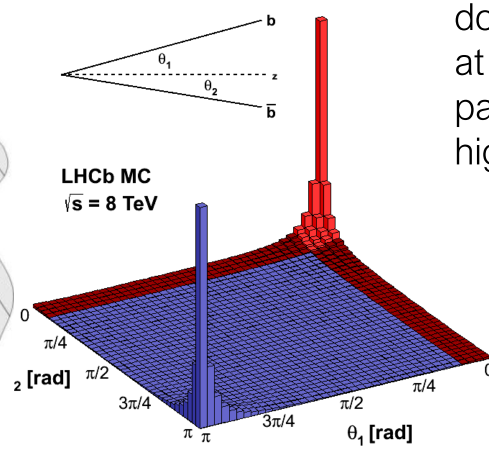
- Universality of the EW interactions does not necessarily imply universality of physics beyond the SM

- New physics preferentially coupling to the 3rd generation is usually less well-constrained, and can modify SM charged and neutral currents
  - Examples: $A^0, H^\pm$, new vectors coupled to SM Higgs doublet, leptoquarks

- Many LFU violating NP models are strongly constrained by direct searches, but can be tuned to evade these bounds while preserving their effect on heavy flavor observables

The LHCb Detector





$b\bar{b}$ production dominantly 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

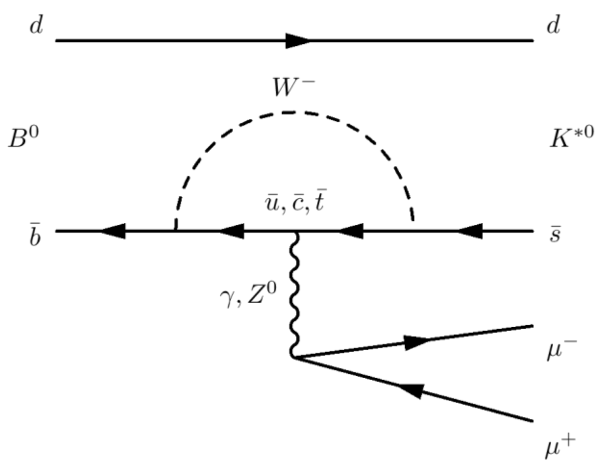
- Focus on forward direction to exploit highly-boosted b quark production at LHC: cover 27% (25%) of (pair) production while instrumenting < 3% of the solid angle (value!)
- Single arm spectrometer optimized for beauty and charm physics at large η:
  - Trigger: ~90% efficient for dimuon channels, ~30% for all-hadronic
  - Tracking: σ_p/p ~ 0.4%–0.6% (p from 5 GeV to 100 GeV), $\sigma_{IP} < 20\ \mu m$
  - Vertexing: σ_τ ~ 45 fs for $B_s \rightarrow J/\psi\phi$
  - PID: 97% μ ID for 1-3% $\pi \rightarrow \mu$ misID
  - Dipole magnet polarity periodically flipped to change the sign of many reconstruction asymmetries

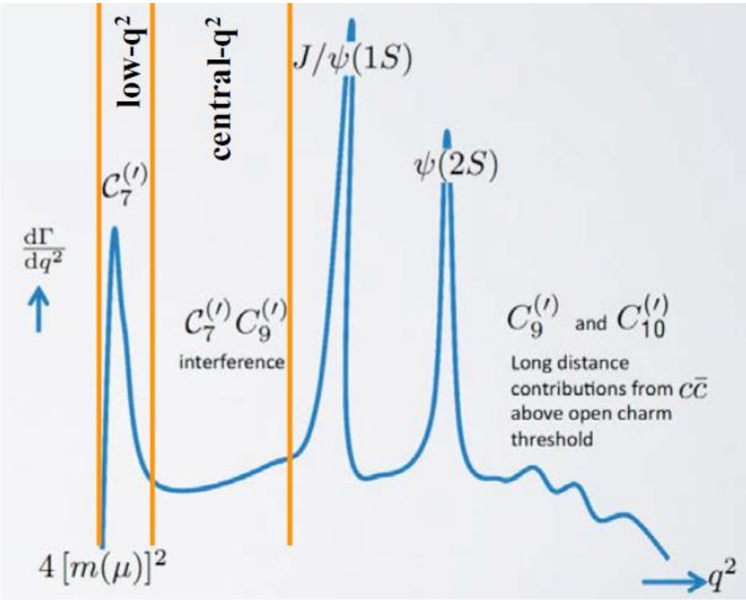
Electroweak Penguin Decays

- Penguin transitions stringently test the structure of the electroweak interaction
  - In SM: loop structure with almost all major SM EWSB players at once: W, Z, γ, t
  - New particles connected to EWSB can appear and introduce q^2- or angular-dependent interference
    - $q^2 \equiv (p_{\ell^+} + p_{\ell^-})^2$
- Excellent targets for LHCb
  - Dilepton in final state allows for clean event selection
  - Rich phenomenology with scalar and vector hadronic daughters
  - SM calculations become unreliable at higher q^2: tree-level $b \to c\bar{c}s$ amplitudes, $c\bar{c}$ vacuum polarization, long distance effects…
    - Focus on $q^2 < 6\ \mathrm{GeV}^2$ to avoid these issues
- Lepton universality test: general consensus in literature that if only SM fields participate

$$R_{K^{(*)}} \equiv \frac{\mathcal{B}\left(B \to K^{(*)}\mu^+\mu^-\right)}{\mathcal{B}\left(B \to K^{(*)}e^+e^-\right)} = 1 \pm \mathcal{O}\left(10^{-3}\right)$$

- *Today: focus on new measurement with 5/fb (all data up to 2016) in "central q^2"*





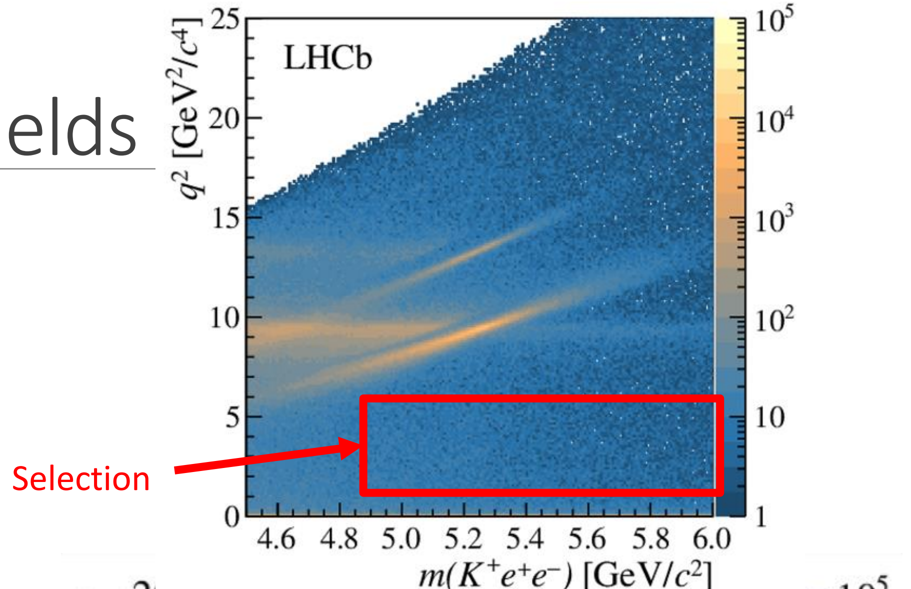
RK event selection and raw yields

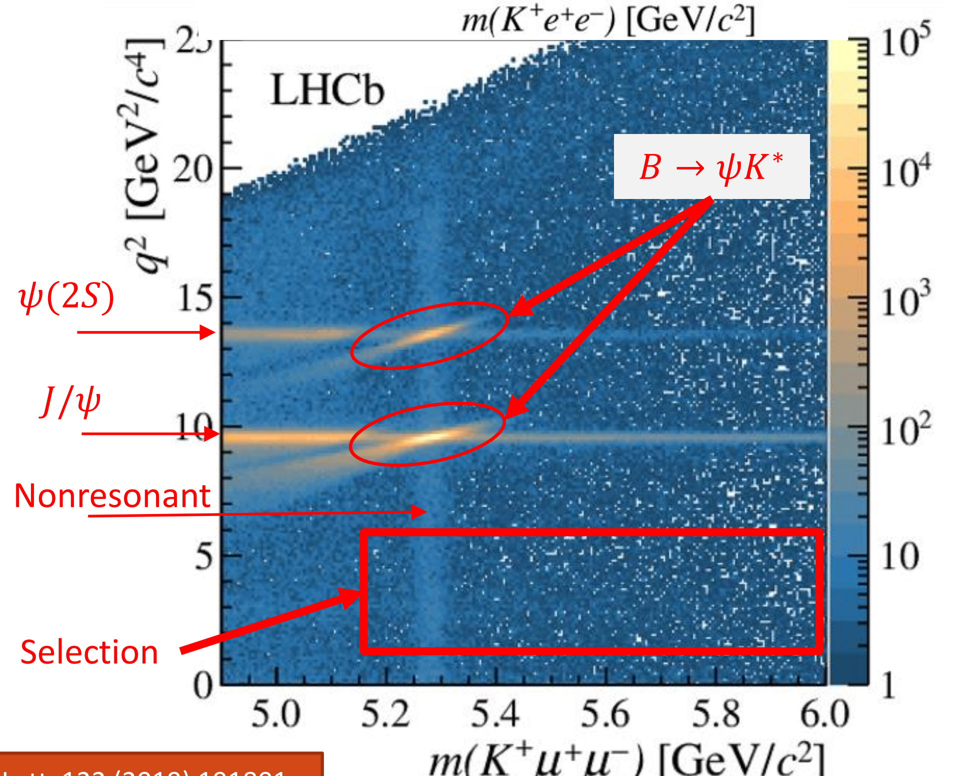
- Main challenge experimentally at LHCb: **electron reconstruction**
  - Electron momentum resolution is considerably worsened by bremsstrahlung
    - $X/X_0 \approx 30\%$ before magnet)
    - Recovery algorithms find the hardest pre-magnet emissions ($E_T > 75$ MeV)
  - Dielectron mass resolution also dependent on trigger path
- Minimize impact of reconstruction systematics with double ratio

$$\frac{\mathcal{B}(B\to K^*\mu\mu)}{\mathcal{B}(B\to J/\psi[\to\mu\mu]K^*)} \Big/ \frac{\mathcal{B}(B\to K^*ee)}{\mathcal{B}(B\to J/\psi[\to ee]K^*)}$$

$$= \frac{\mathcal{B}(B\to K^*\mu\mu)}{\mathcal{B}(B\to K^*ee)} \Big/ r_{J/\psi}$$

- Extensively cross-checked
  - double-ratio of $\psi(2S)K$ vs $J/\psi K$
  - Single ratio $r_{J/\psi}$ average and stability vs lab-frame kinematics affecting reconstruction





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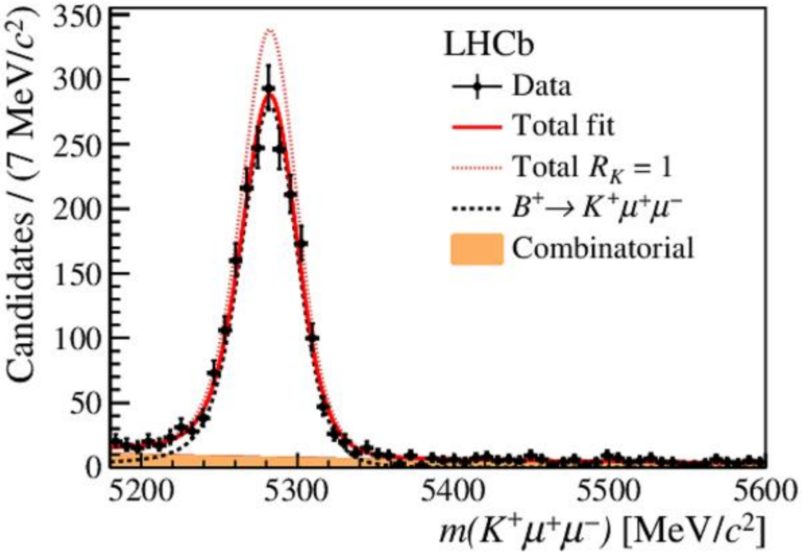
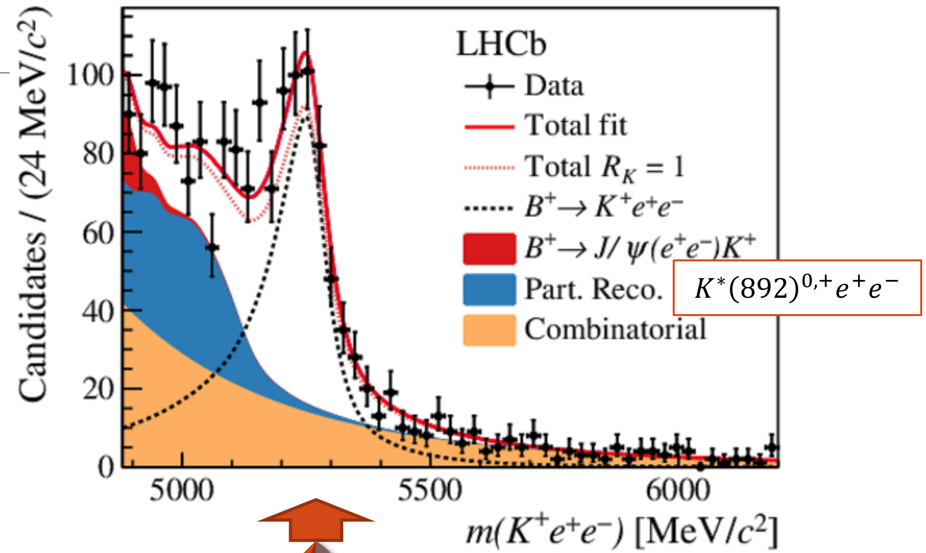
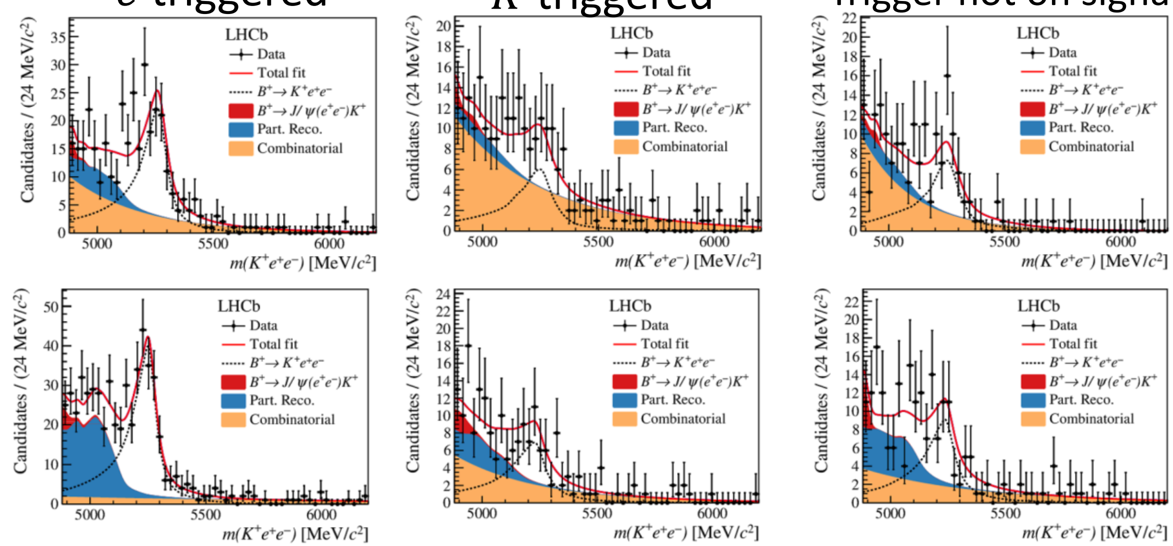
R_K fit





- Mass shape in electron mode is sum of shapes corresponding to brem reco for 0, 1, both electrons
  - Relative fractions from simulation
  - Mass shape parameters fixed from fits to (corrected) simulation
    - Corrections from subsample of resonant mode

	e triggered	K triggered	Trigger not on signal
Run1			
Run2			



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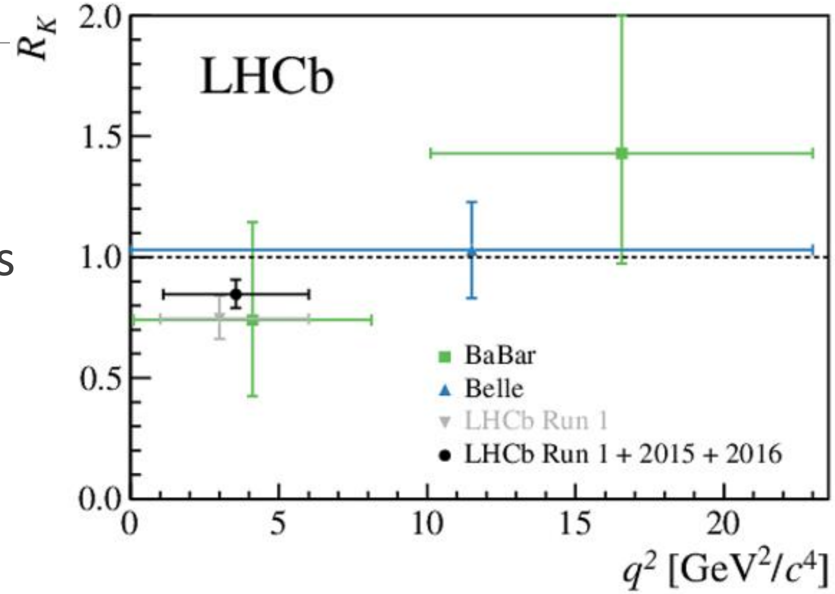
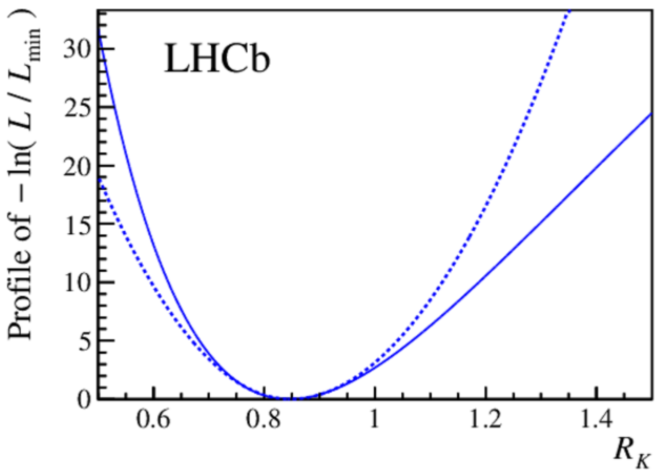
RK results

- $R_K(1.1 - 6.0\ \mathrm{GeV}^2) = 0.846^{+0.060}_{-0.054}{}^{+0.016}_{-0.014}$
  - 2.5σ from SM
  - Run1 consistent with previous, Run2 pulls slightly higher
- Other LHCb results:
  - $R_{K^*}(low\ q^2) = 0.66\ ^{+0.11}_{-0.07} \pm 0.03$
    - predictions (~0.92)
  - $R_{K^*}(central\ q^2) = 0.69\ ^{+0.11}_{-0.07} \pm 0.05$
    - predictions (~1.0)
- Low RK consistent with $C_9/C_9 - C_{10}$-type new physics picture preferred by global fits to $b \to s\ell\ell$ data
- *Still the "poster child" of statistics-limited measurements. Fast improvements as more data are incorporated*

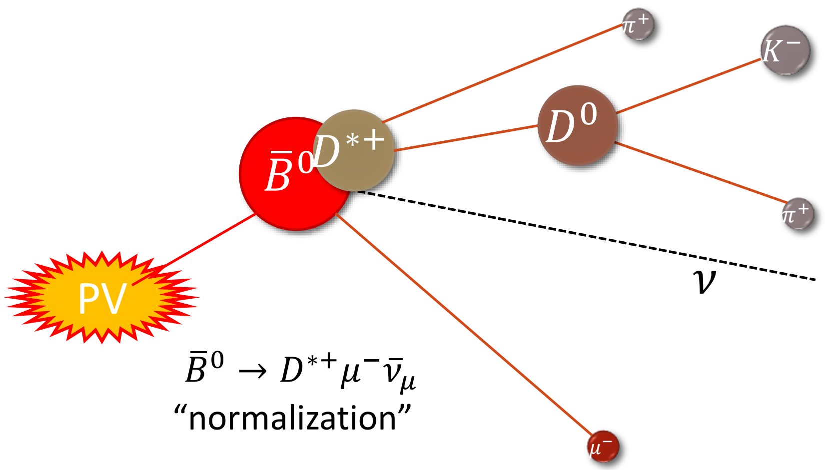




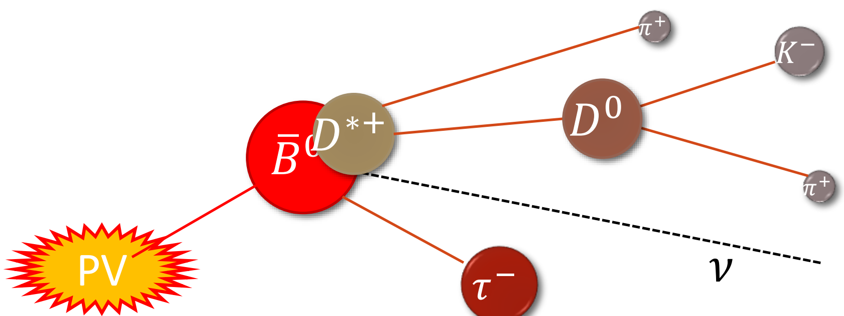
LFU in Semileptonic B Decays

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

- Theoretically clean due to cancellation of most of the form factor uncertainty
  - Helicity-suppressed amplitudes as well as the FFs in the low q^2 normalization region don't cancel
  - SM (BGL, HQET): $R(D^*) = 0.258(5)$ [HFLAV]
    [JHEP **1711** 061 (2017), JHEP **1712** 060 (2017), PRD 95 115008 (2017)]
- $\tau^- \to \mu^-\bar{\nu}_\ell\nu_\tau$
  - Direct normalization from identical (visible) final state
  - Must disentangle from $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$ in fit
- $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$
  - Clear signature at LHCb: higher signal purity
  - Reliant on external measurements to get back R(D*)
- Common Challenges: missing neutrinos with poorly constrained momentum
  - Don't know full momentum -> unknown rest frame
  - Large partially-reconstructed B backgrounds

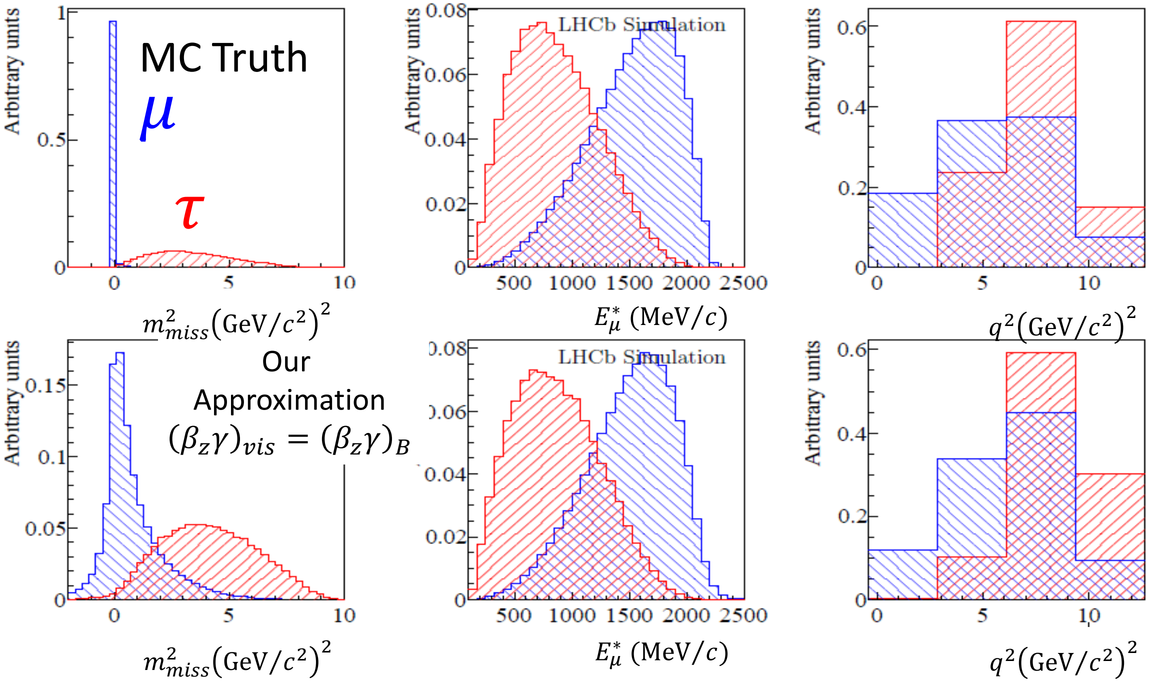


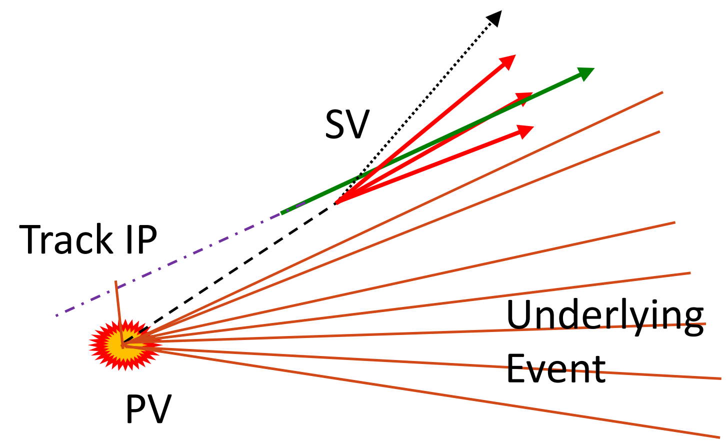
$\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$
"normalization"



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

LHCb techniques: boost approximation





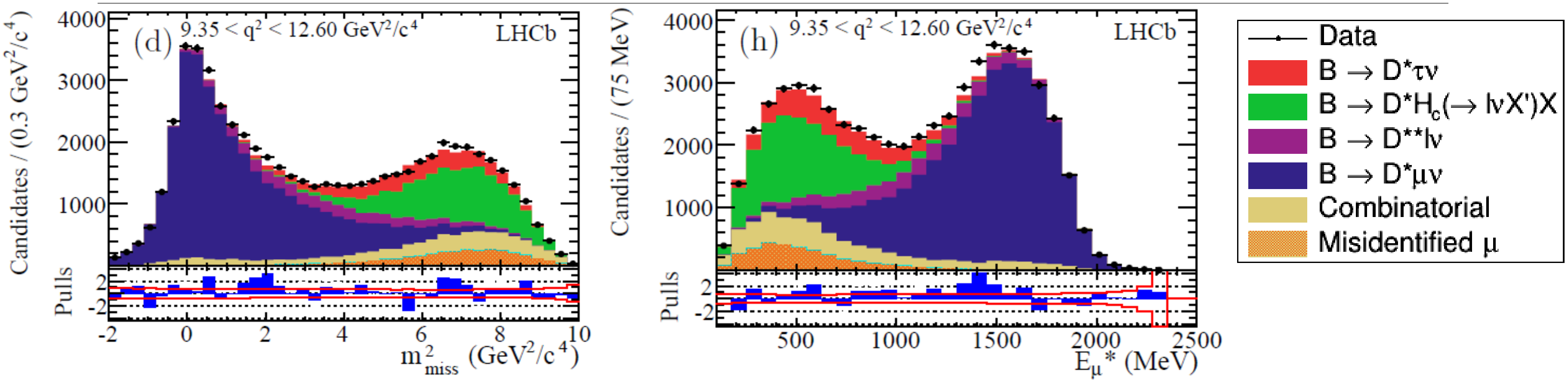
LHCb-PAPER-2015-025 supplemental

- 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 => solve for full B momentum

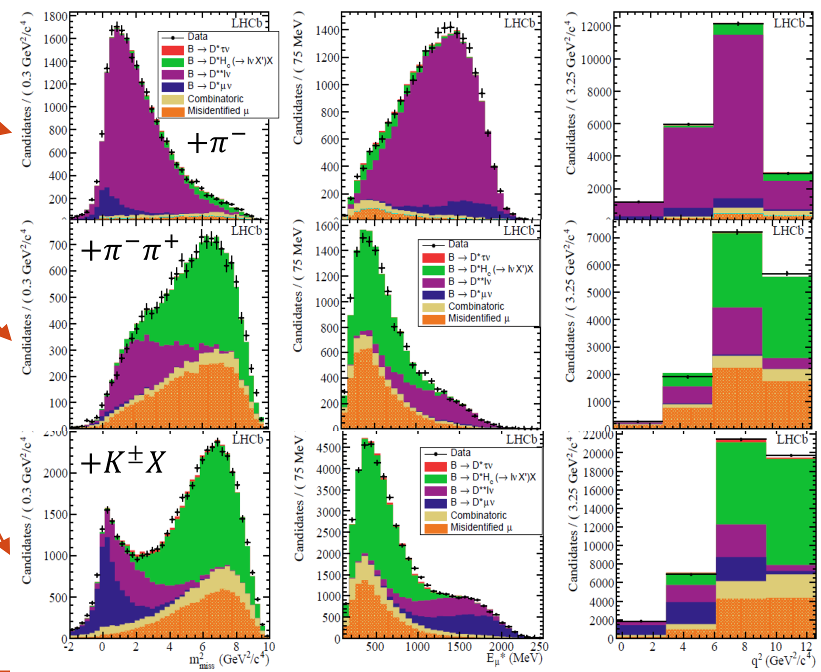
- Use superb tracking system to fight huge partially-reconstructed background
  - Scan over every track and compare against $D^{*+}\mu^-$ vertex with machine-learning alg.
  - Allows for cleaner signal sample *and* data control samples enriched in key backgrounds

PRL **115** 111803(2015)

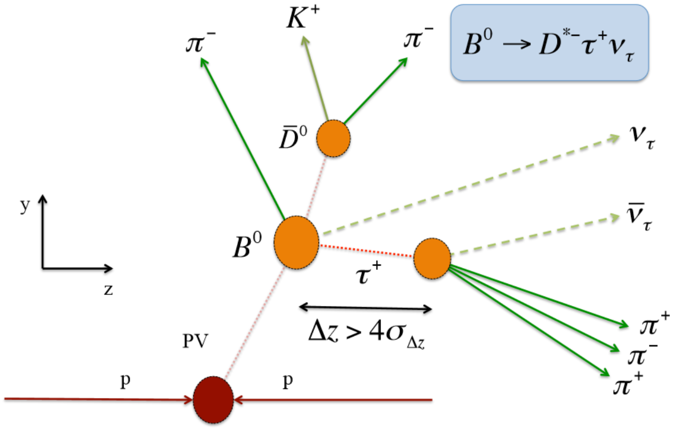
Result

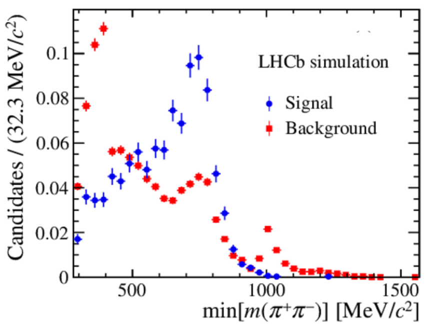


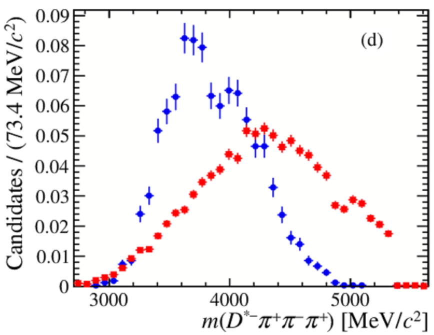
- 3D fit to m_{miss}^2, E_μ^*, q^2
  - Multiple control samples to validate and constrain shapes of backgrounds in fit
- Result: $R(D^*) = 0.336 \pm 0.027 \pm 0.030$
  - First measurement of a $b \to X\tau\nu$ decay at a hadron collider
  - Excellent agreement with BaBar 2012
- Dominant systematics from MC statistical uncertainty and background from hadrons misidentified as muons
  - Latter can be greatly improved with new techniques



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

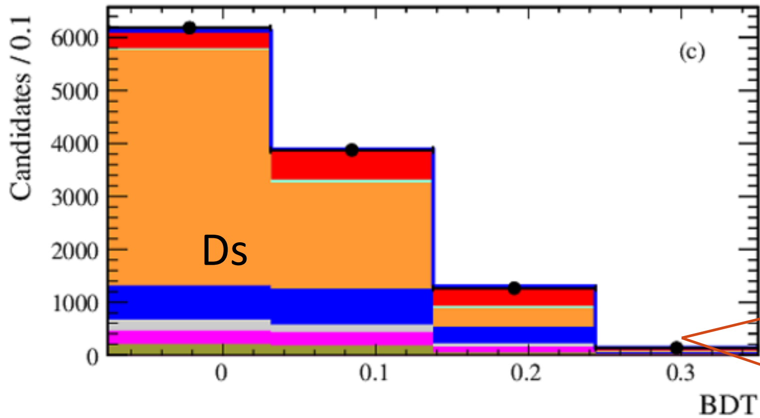


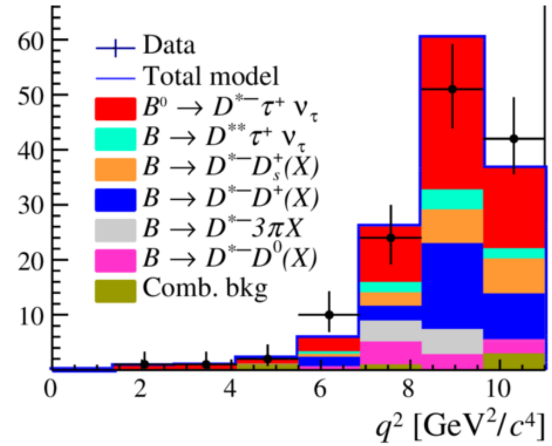


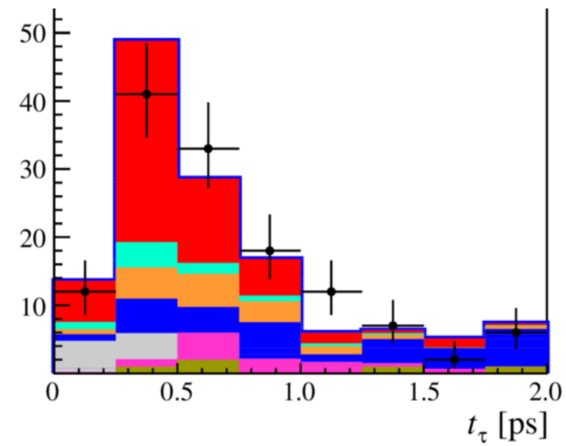


- This mode is historically very challenging due to the large inclusive $\bar{B} \to D^{*+}3\pi_{direct}X$ branching fraction (100x expected signal)
- Very large boost and excellent vertexing at LHCb comes to the rescue:
  - 4σ separation of vertices along $\hat{z}$ removes 99.9% of non-flying background, retains ~34% of signal
  - Result is O(11%) signal purity, compared to 3.5% signal in muonic mode
  - Further enhance the signal: require no tracks with $< 5\sigma$ IP significance to B vertex
- Different approximation for B-frame used (see backups)
- Use BDT to distinguish signal vs $B \to D^* D_s[\to 3\pi X]$ backgrounds as selection and fit variable
  - calibrate simulation decay model in anti-selected region

$\bar{B}^0 \to D^{*+}\tau^-[\to 3\pi(\pi^0)\nu]\bar{\nu}$ result







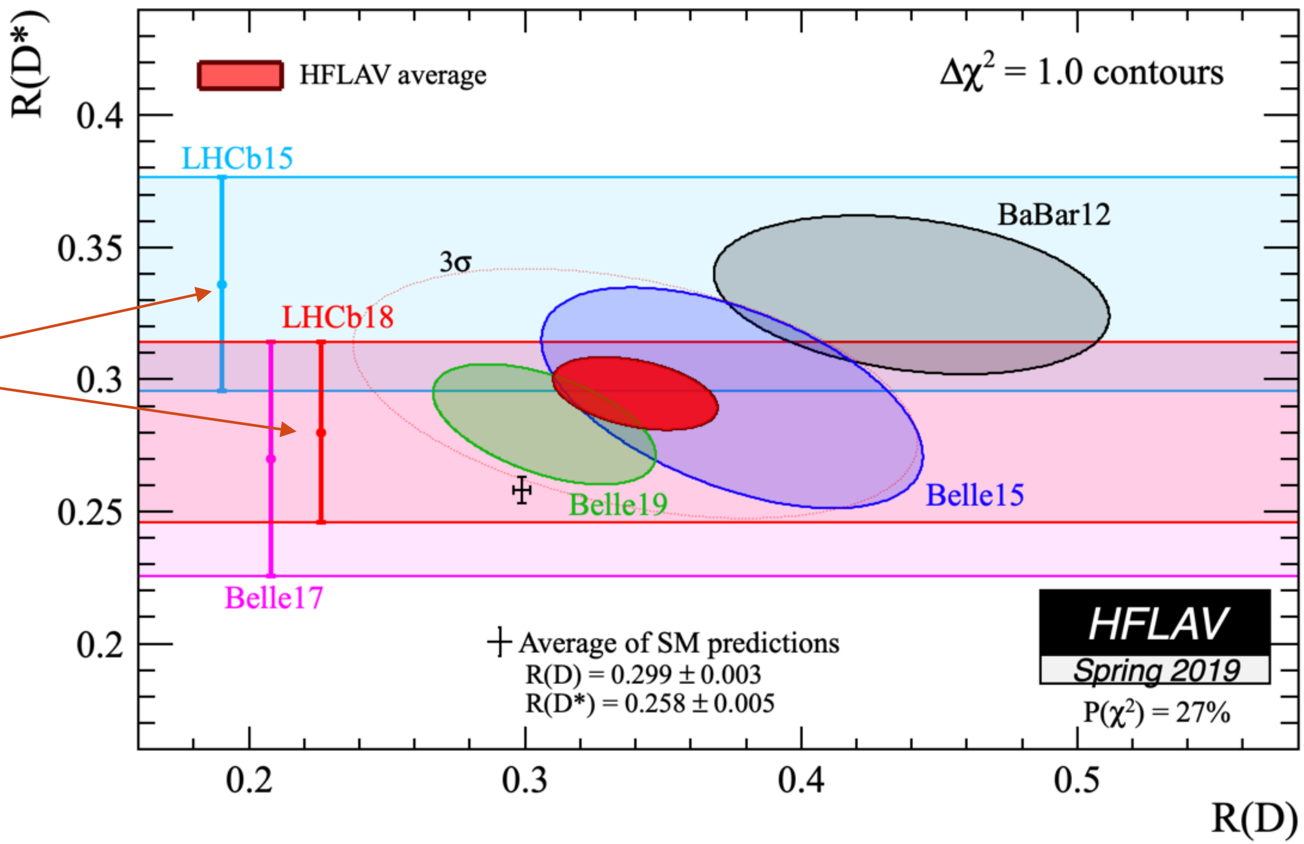
- 3D fit in q^2, τ decay time, BDT
  - Control data improves q^2 description for 3π from D^0, $D^\pm$
- Exclusive $\bar{B} \to D^{*+}3\pi_{direct}$ provides normalization
  - $\mathrm{K}(D^*) \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}$

    $R(D^*) = K(D^*) \times \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\tau)}$
- **Result:** $0.291 \pm 0.019 \pm 0.026 \pm 0.013$
  - HFLAV2019 inputs: $0.280 \pm 0.018 \pm 0.026 \pm 0.012$

PRD **97**, 072018 (2018)

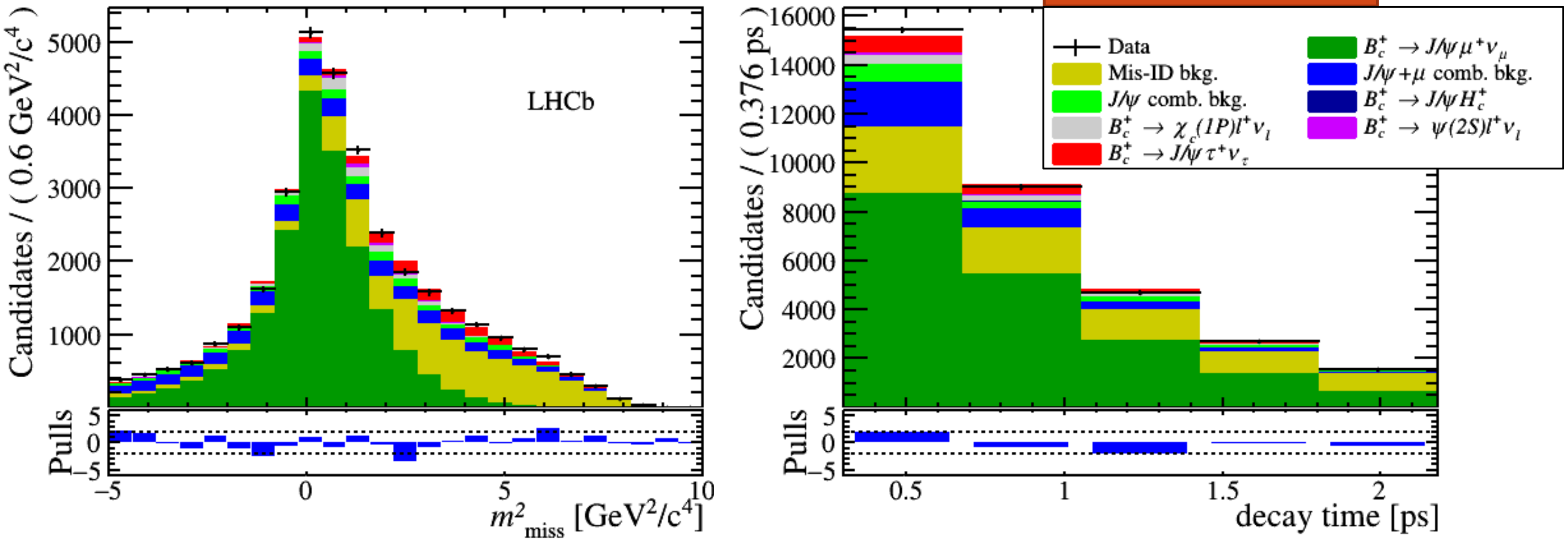
LHCb R(D*) summary

This talk



$R(J/\psi)$

PRL **120**, 121801 (2018)

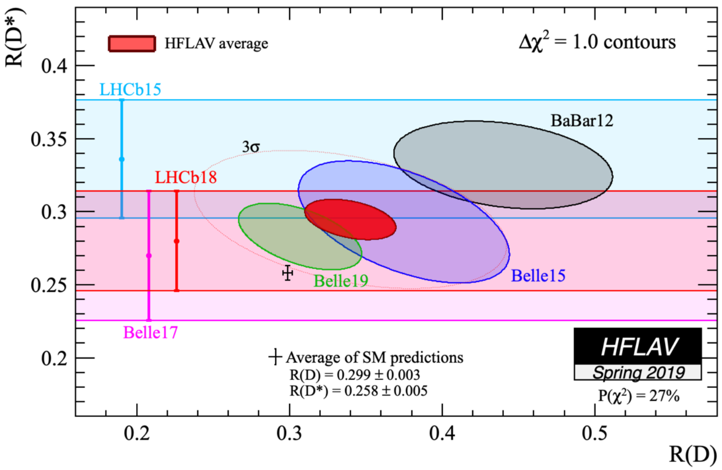


$$R(J/\psi) \equiv \frac{\mathcal{B}(B_c^+ \to J/\psi\tau\nu)}{\mathcal{B}(B_c^+ \to J/\psi\mu\nu)} = 0.71 \pm 0.17 \pm 0.18$$

- 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 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

$R(D^0)$ vs $R(D^*)$ with $\tau \to \mu\bar{\nu}\nu$



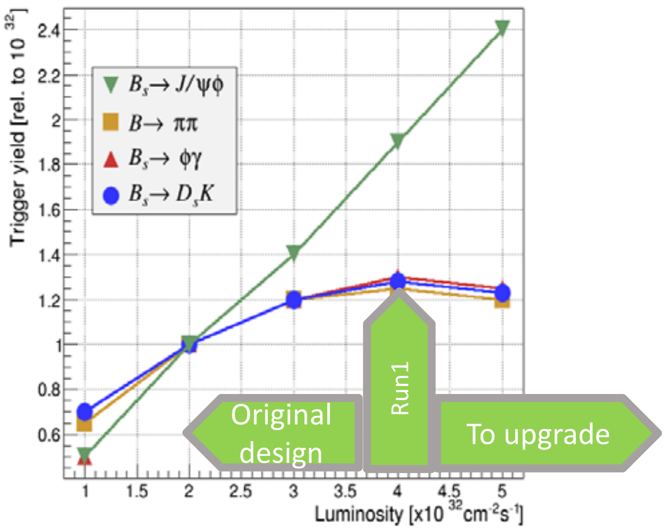
$$\frac{B^- \to D^{*0}[\to D^0(\pi^0/\gamma)]\mu\bar{\nu}}{B^- \to D^0\mu\bar{\nu}} \approx 2.5$$

$$\frac{B^0 \to D^{*+}[\to D^0\pi^+_{missing}]\mu\bar{\nu}}{B^- \to D^0\mu\bar{\nu}} \approx 0.75$$

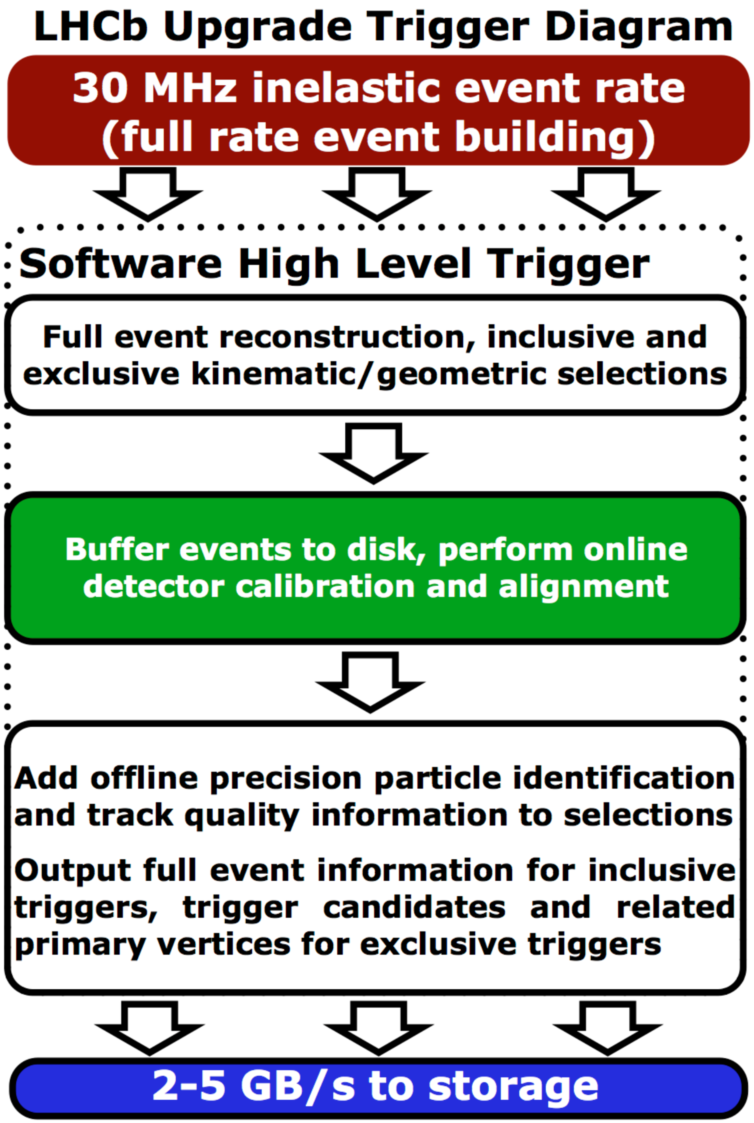
$$\frac{B^0_s \to D^{**+}_s[\to D^0K^+_{missing}]\mu\bar{\nu}}{B^- \to D^0\mu\bar{\nu}} \approx 0.06$$

- Muonic $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}$ served as a prototype due to simpler structure of and better handles on backgrounds
  - Goal: Turn our band into an ellipse
- $B^- \to D^0\tau^-\bar{\nu}$ appears very possible at LHCb (with *lots* of effort!)
  - Simultaneous fit to disjoint $D^0\mu^-$ and $D^{*+}\mu^-$ samples
    - Feed-down from D* always present in $D^0\mu^-$ sample
      - Refitting $D^{*+}\mu^-$ sample helps control & constrain
    - Low slow pion efficiency $\to$ $D^0\mu^-$ sample is 5x larger
      - 75% is D* feed down → big improvement in R(D*)
      - Challenge: simulation mismodeling in templates must be controlled to high precision
- $R(D^+)$ not feasible with Run1 dataset (no suitable trigger)
  - Run 2 added dedicated triggers for $D^0\mu X$ these final states as well as $D^+\mu X$, $\Lambda_c^+\mu X$, $D_s^+\mu X$

To the LHCb Upgrade



- Goal: increase dataset by an order of magnitude over next phase of running
- Upgrade: 26 kHz of beauty in acceptance (10 MHz of charm!) with 5-7 interactions per crossing
  - Hardware must be able to be read out much faster than 1 MHz
    - Readout of all subdetectors must be replaced
    - Occupancy demands all-new tracking system
  - Cannot rely on hardware E_T thresholds and expect to make intelligent trigger decisions
- All-software trigger needed to react to this data rate



Summary

- B physics experiments are pushing lepton universality tests beyond validating the electroweak interaction, with LHCb playing a key role

- Measurements of LFU in electroweak penguin decays are continuing to push to higher precision
  - Consistent but inconclusive results favoring lower muon (higher electron) branching fractions fit in with consistently low $b \to s\mu\mu$ branching fractions from other analyses
  - Improvements already observed with early Run2 data ✓
    - More lumi is on disk already, stay tuned!

- LHCb has launched a program of studying semileptonic $b \to X\tau\nu$ decays (initially dismissed as too hard to do in pp collisions)
  - “Prototype” measurements completed in both $\tau \to \mu\nu\nu$ and $\tau \to \pi\pi\pi\nu$ sub-modes ✓
  - Lots of “to-do”s to extend the program, limited by manpower and long lead times required for these systematics-sensitive analyses (precision template fits are **hard**!)

- Run2 LHCb data-taking very smooth and successful, with 5.7/fb of 13 TeV data

- LHCb upgrade will allow continued progress on flavor observables at the current pace post-2020
  - Ideas already in the pipeline beyond first upgrade

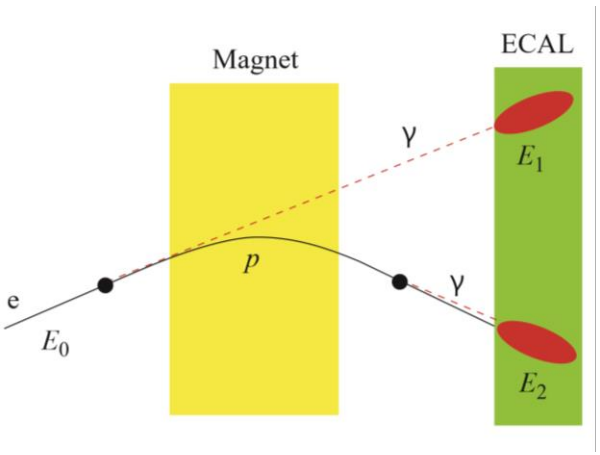
Backup

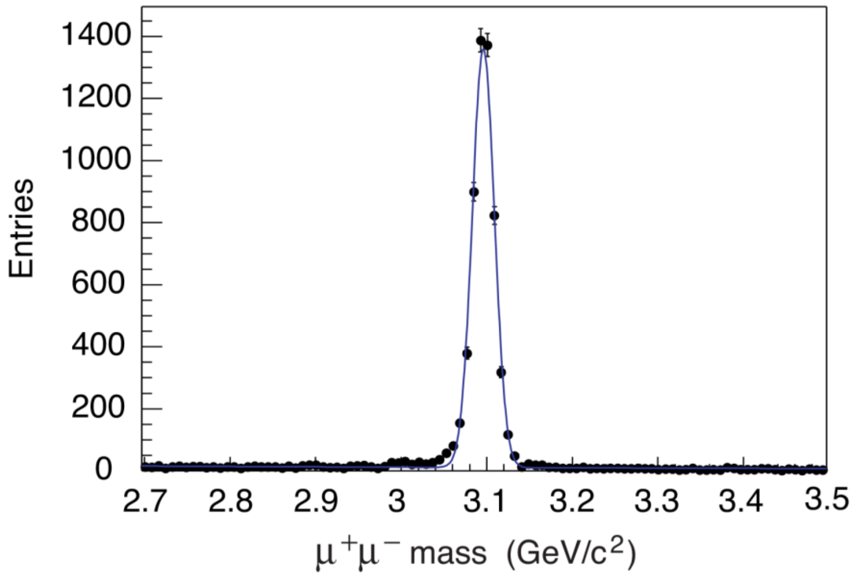
[JINST 3 S08005 (2008)]

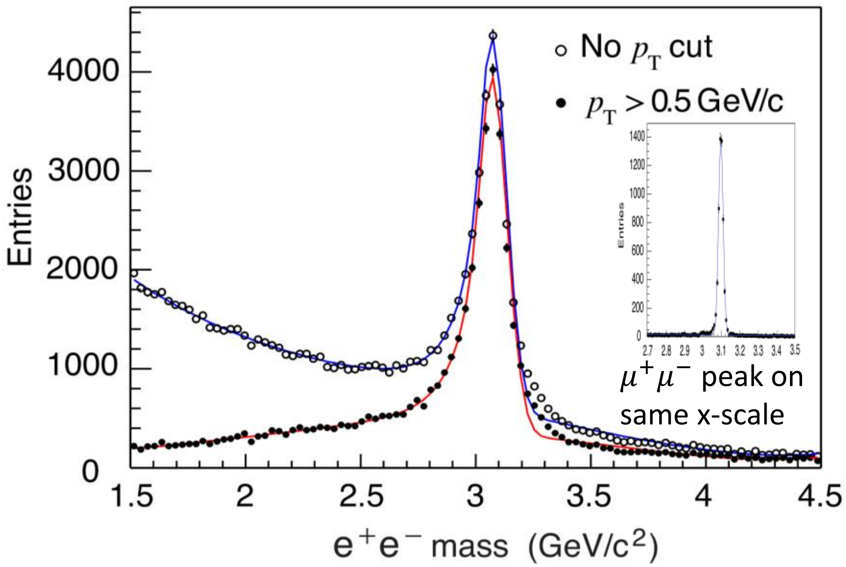
[arXiv:1705.05802]

Electron mode tools

- Hard bremsstrahlung (top) can be corrected by explicitly searching for the calorimeter deposits from the emitted γ (E1 in left figure)
  - LHCb reconstruction searches for such deposits isolated from tracks with ET above threshold
  - Late emissions (E2) are typically merged with the electron shower and are used for e/hadron separation (E/p)
    - Remember, p measured by curvature, so p~p_final+E2



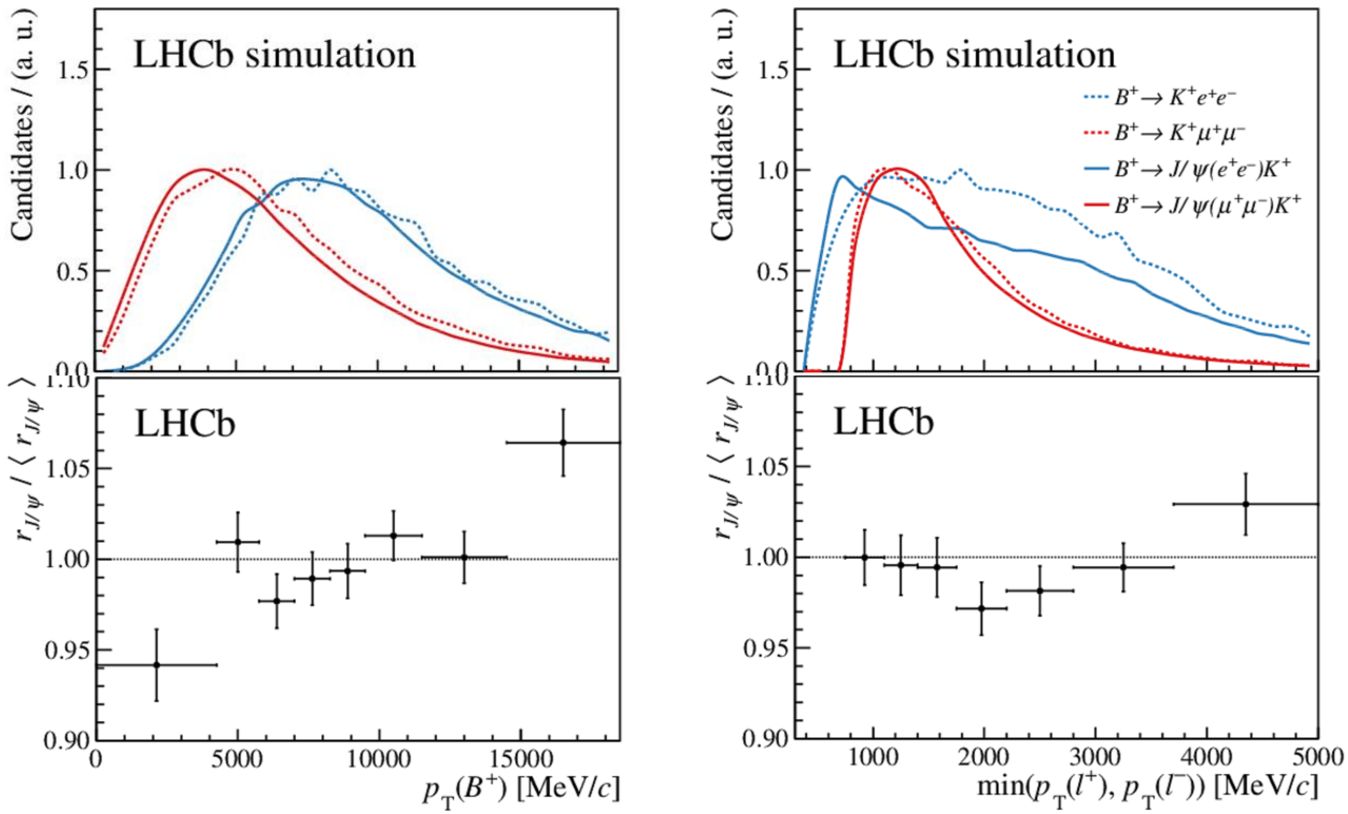




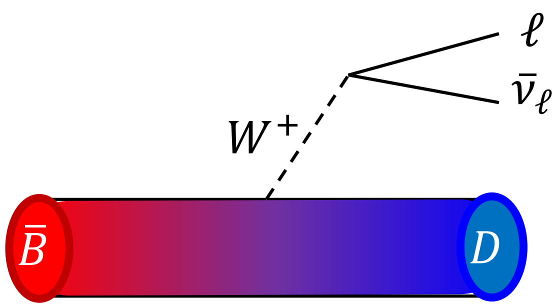
Phys. Rev. Lett. 122 (2019) 191801

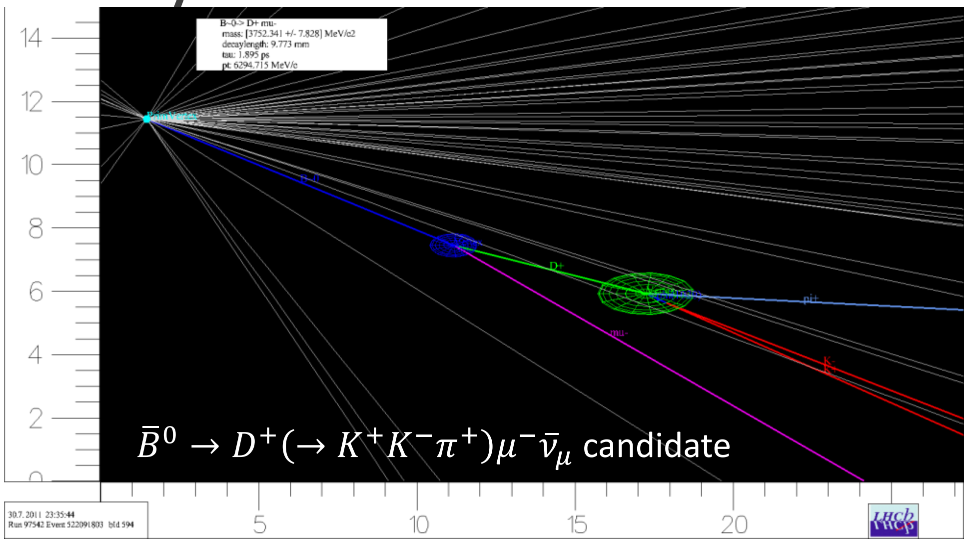
Validation of Double Ratio

- To check calibration and efficiency estimates, use single ratio (more sensitive to reconstruction issues)
  - Find $\langle r_{J/\psi} \rangle = 1.014 \pm 0.035$ (error only includes systematics for double ratio)
    - Check variation as function of e and μ kinematics
      - Quantities with worst overlap below. Variation seen gives only 0.002 variation in R_K



Semileptonic B decays





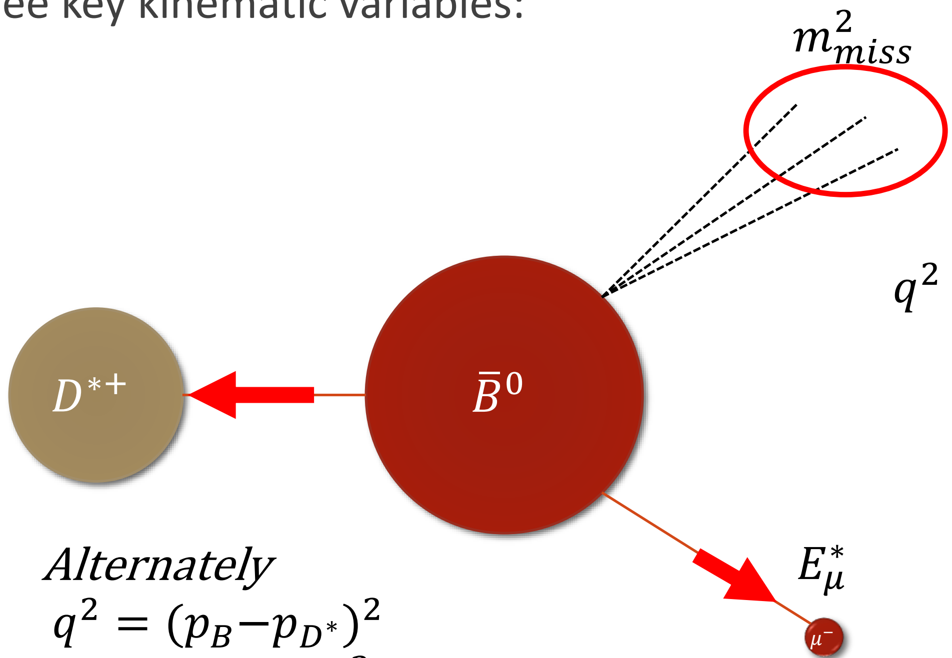
- "Beta decay" of B hadrons – signature is lepton (μ or e (or τ!)) , recoiling hadronic system, and missing momentum

- Theoretically well-understood in the SM
  - Tree level virtual W emission – strong V-A structure
  - No QCD interaction between the lepton-neutrino system and the recoiling hadron(s)
    - $\bar{B} \to W^{*\pm}D^{(*)}$ half of the decay still needs non-perturbative input

- Charged lepton universality implies branching fractions for semileptonic decays to e, μ, τ differ only phase space and helicity-suppressed contributions

Distinguishing $b \to c\tau(\to \mu\nu\nu)\nu$ from $b \to c\mu\nu$

- In B rest frame, three key kinematic variables:



$$q^2 = (p_\ell + p_\nu)^2 = m_{W^*}^2$$

Alternately

$$q^2 = (p_B - p_{D^*})^2 = \left(m_B - E_{D^*}^*\right)^2$$

$\boldsymbol{\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}}$	$\boldsymbol{\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}}$
$m_{miss}^2 > 0$	$m_{miss}^2 = 0$
E_l^* spectrum is soft	E_l^* spectrum is hard
$\mathrm{m}_\tau^2 \le q^2 \le 10.6\ \mathrm{GeV}^2$	$0 \le q^2 \le 10.6\ \mathrm{GeV}^2$

Semileptonic Backgrounds

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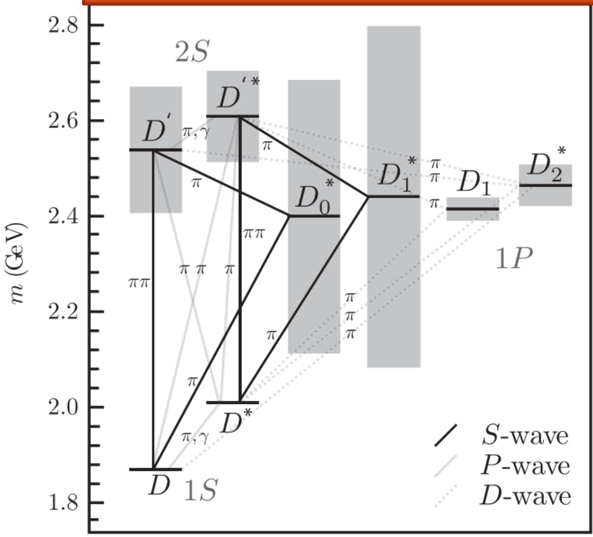
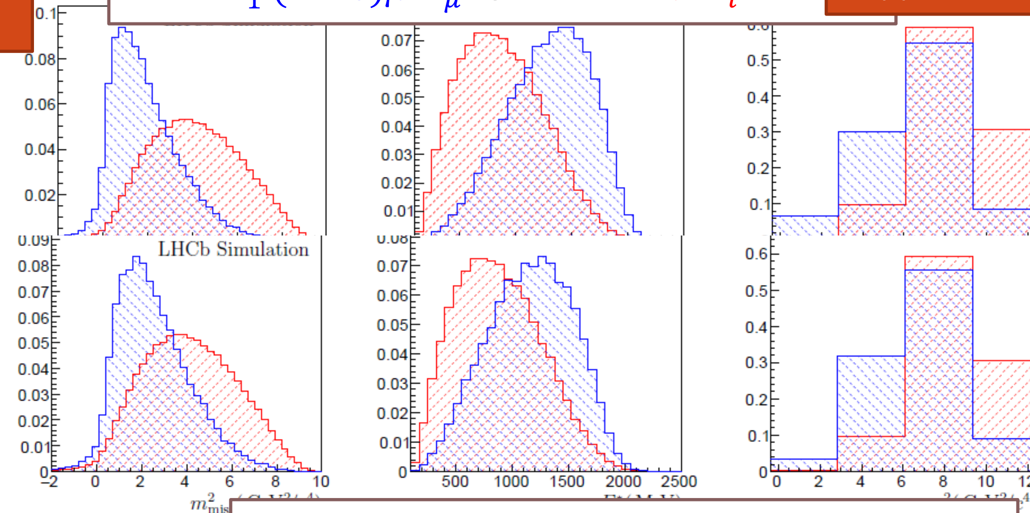
Bernlochner et al, PRD 85 094033 (2012)



$\bar{B}^0 \rightarrow D_1^+(2420)\mu^-\bar{\nu}_\mu$ vs $\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\nu}_\tau$



$\bar{B}^0 \rightarrow D^{**+}(\rightarrow D^{*+}\pi\pi)\mu^-\bar{\nu}_\mu$ vs $\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\nu}_\tau$

- Contributions of excited charm states in the $B^{\pm,0} \rightarrow (c\bar{q})\mu\nu$ transition are large
  - **We directly fit for contributions of 1P states constrained and unconstrained**
    - Excellent consistency of resulting R(D*) with and without external measurements as input
    - $D^{*+}\mu^-\pi^-$ control sample sets nonperturbative shape parameters for input to signal fit ~ 1.8% relative systematic
  - States decaying as $D^*\pi\pi$ less well-understood, fit insensitive to exact composition.
    - $D^{*+}\mu^-\pi^+\pi^-$ control sample used to correct q^2 spectrum to match data ~ 1.2% relative systematic

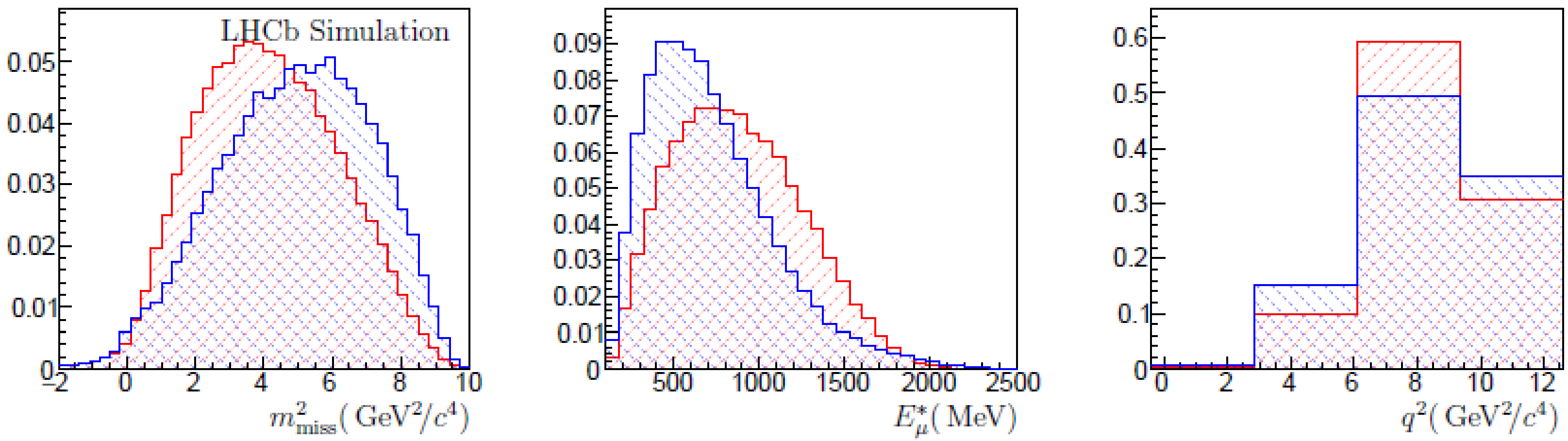
- Distinguishable by “edge” at missing mass $\approx (2)m_\pi$

- Use mu component plus reasonable guess (with large error bars) on R(D**) to constraint tau component (only adds 1.5% relative systematic)

$B \to D^{*+} H_c(\to \mu\nu X')X$ background

- $b \to c\bar{c}q$ decays can lead to very similar shapes to the semitauonic decay (e.g. $\bar{B}^0 \to D^{*+}D_s^-(\to \phi\mu\nu)$ +many others)
- Branching fractions well-cataloged, but detailed descriptions of the $D^*DK(n \geq 0\ \pi)$ final states are not simulated using full Dalitz plot description
  - Dedicated $D^{*+}\mu^- K^{\pm}$ control sample used to improve the template to match data
  - (1.5% relative systematic)
- Nastiest background – unconstrained in fit (major contributor to statistical uncertainty)

$\bar{B}^0 \to D^{*+} H_c(\to \mu\nu X')X$ vs $\bar{B}^0 \to D^{*+}\tau^-\nu_\tau$



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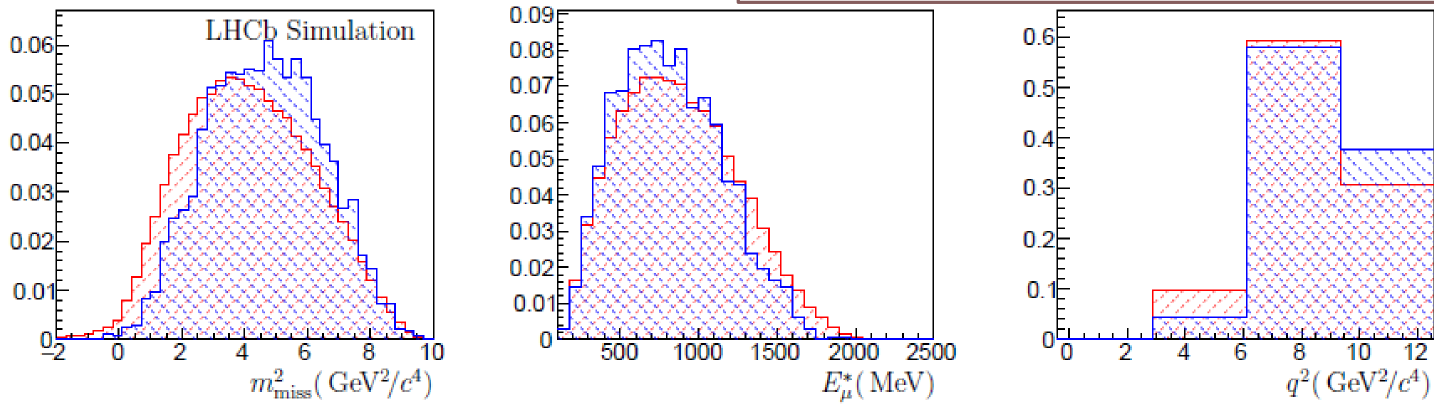
Tau backgrounds

$\bar{B}^0 \to D_2^{*+}(2460)\tau^-\bar{\nu}_\tau$ vs $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$



- All backgrounds with real $\tau \to \mu\bar{\nu}\nu$ decays are an order of magnitude (at least) smaller than the signal
  - Background contributions from $\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau$ are considered to be fixed relative to the corresponding decay modes to muons
    - Very small component, varying this contribution by 50% only moves R(D*) by 0.005
  - Similarly, $\bar{B} \to D^{*+}D_s^-(\to \tau^-\nu)X$ are fixed to a known fraction of the $\bar{B} \to D^{*+}H_c(\to \mu\nu X')X$ background
    - Again, these have a negligible effect on R(D*)

Fit structure and control samples

$\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$ (normalization)

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

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

$D^{*+}\mu^-\pi^-$

$\bar{B}_s^0 \to D_s^{**+}\mu^-\bar{\nu}_\mu$
$D_s^{**+} \to D^{*+}K_S^0$

$B^{+,0} \to \bar{D}^{**}\mu^+\nu_\mu$
$\bar{D}^{**} \to D^{*-}\pi\pi$

$D^{*+}\mu^-\pi^-\pi^+$

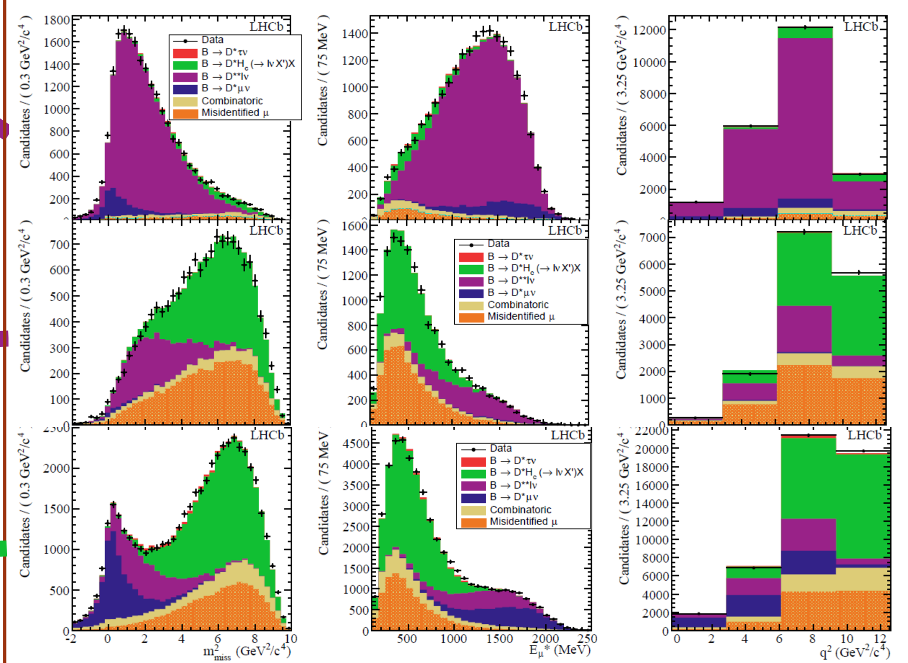
$\bar{B} \to D^{*+}H_c(\to \mu\nu X')X$
$+\bar{B} \to D^{*+}D_s^-(\to \tau^-\bar{\nu}_\tau)X$

$D^{*+}\mu^-K^\pm$

combinatorial D^{*+}
combinatorial $D^{*+}\mu^-$

$h \to \mu$ misidentification

Control sample fits to constrain shapes



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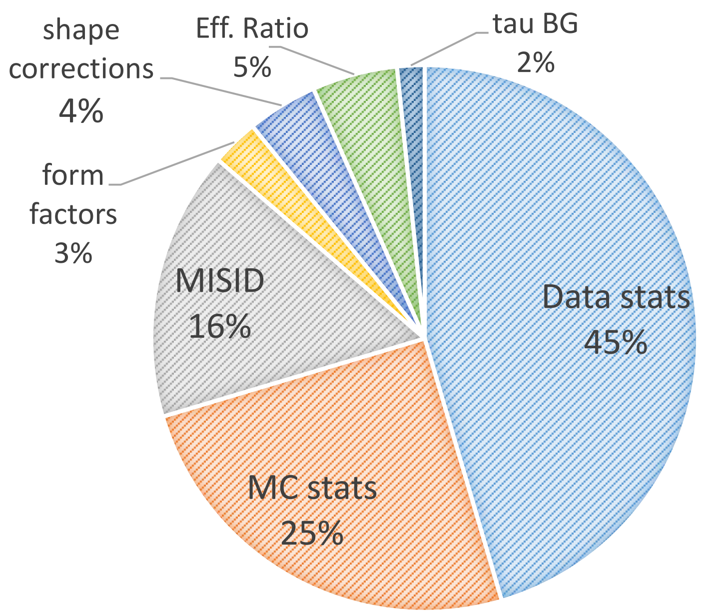
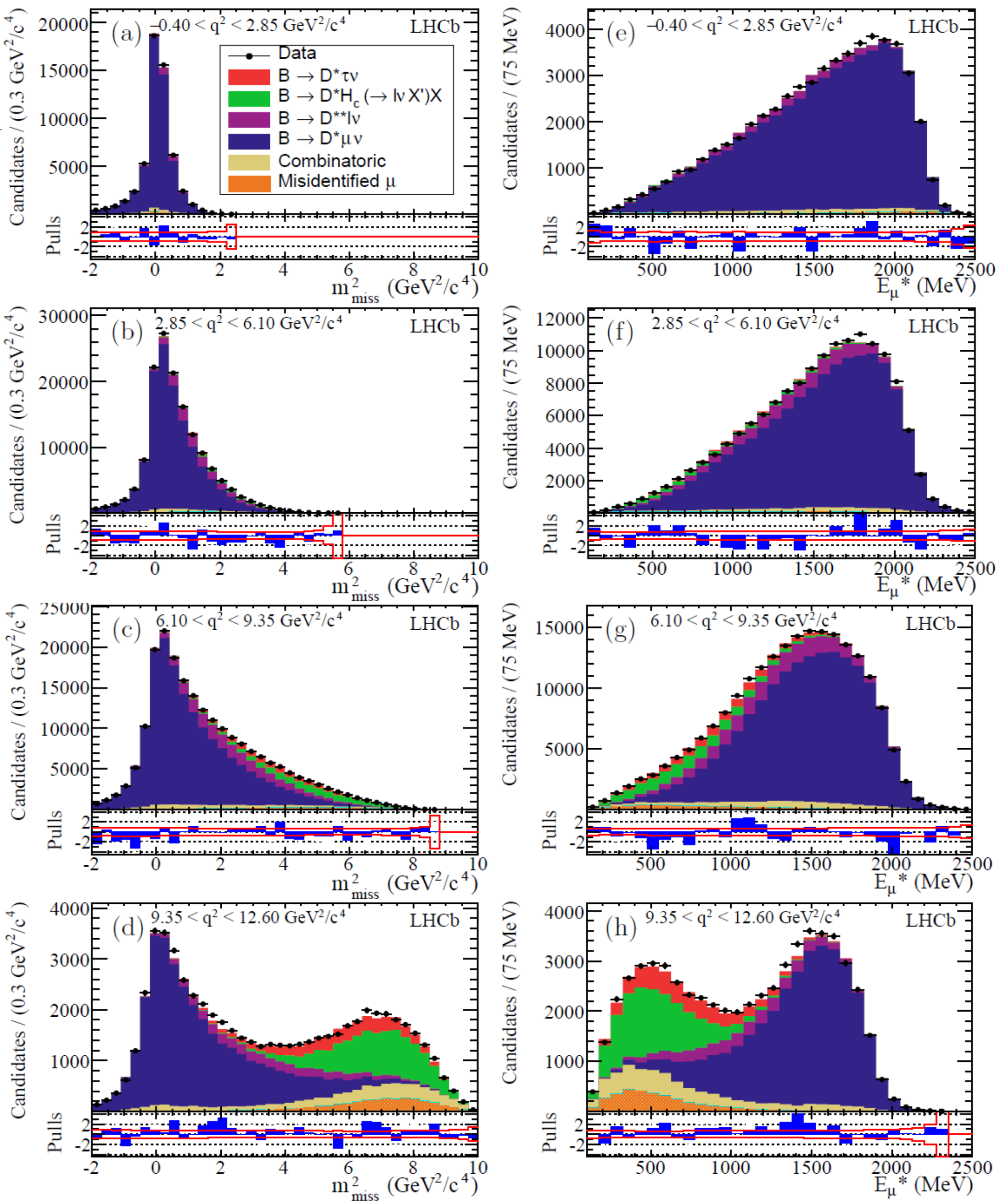
R(D*) fit result and systematics



Contribution of each source to the squared total measurement uncertainty



Reconstruction of Fit Variables

- Reconstructed variables used for 3-dimensional fit to q^2, τ decay time, BDT

- This measurement again hits the difficulty of underconstrained kinematics with missing neutrinos
  - Know: $p_{3\pi}, p_{D^*}$, B flight vector from PV, 3π flight vector from D^*
  - Using known B and τ mass to solve results in 2×2-fold quadratic ambiguities – better than previous situation, but still not complete!

$$|\vec{p}_{B^0}| = \frac{(m^2_{D^*\tau} + m^2_{B^0})|\vec{p}_{D^*\tau}|\cos\theta_{B^0,D^*\tau} \pm E_{D*\tau}\sqrt{(m^2_{B^0} - m^2_{D^*\tau})^2 - 4m^2_{B^0}|\vec{p}_{D^*\tau}|^2\sin^2\theta_{B^0}}}{2(E^2_{D^*\tau} - |\vec{p}_{D^*\tau}|^2\cos^2\theta_{B^0,D^*\tau})}$$

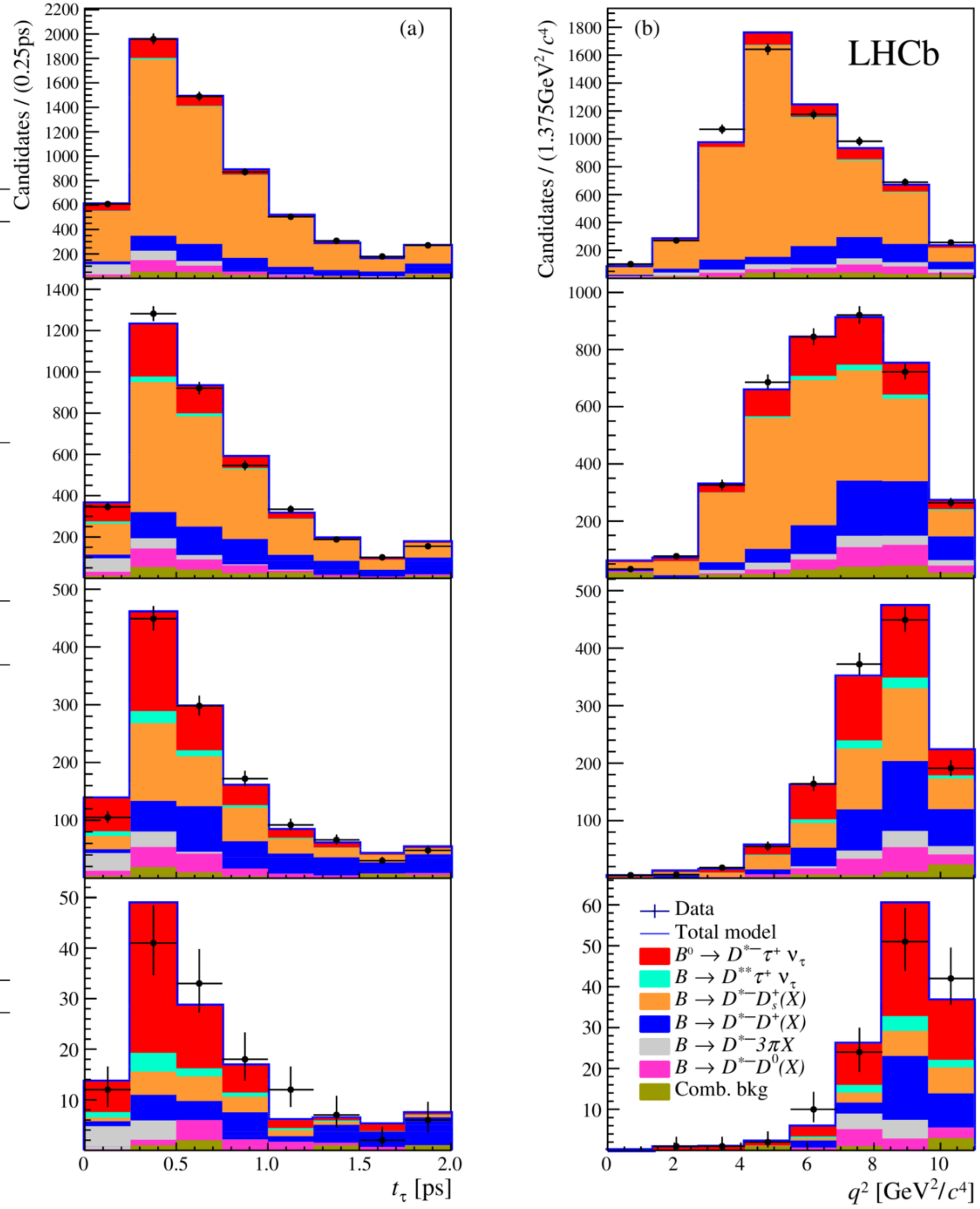
$$|\vec{p}_\tau| = \frac{(m^2_{3\pi} + m^2_\tau)|\vec{p}_{3\pi}|\cos\theta_{\tau,3\pi} \pm E_{3\pi}\sqrt{(m^2_\tau - m^2_{3\pi})^2 - 4m^2_\tau|\vec{p}_{3\pi}|^2\sin^2\theta_{\tau,3\pi}}}{2(E^2_{3\pi} - |\vec{p}_{3\pi}|^2\cos^2\theta_{\tau,3\pi})}$$

- Choose θ, θ' such that the ambiguity vanishes
  - Provides $\approx 10\%$ resolution on q^2

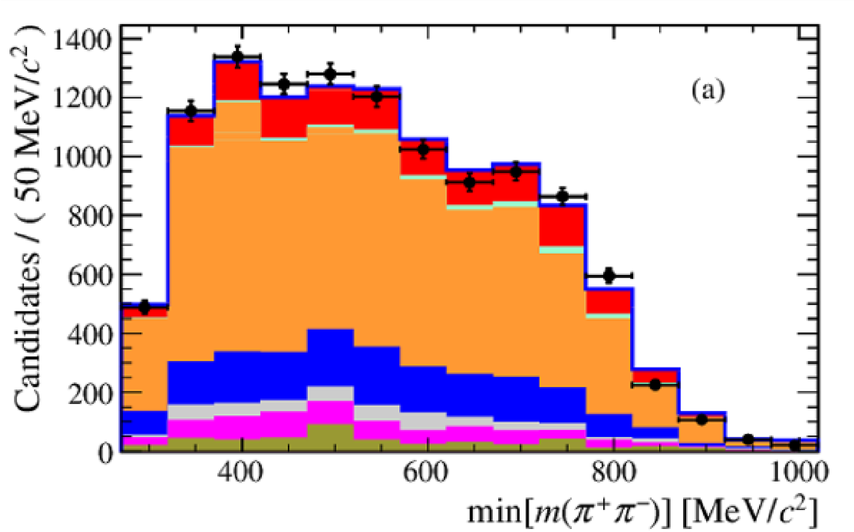
- 2nd reconstruction hypothesis: assume no neutrinos at B vertex, unknown mass neutral system at 3pi vertex – obtain estimate for mass m(3pi+N) which peaks for Ds bkgnd

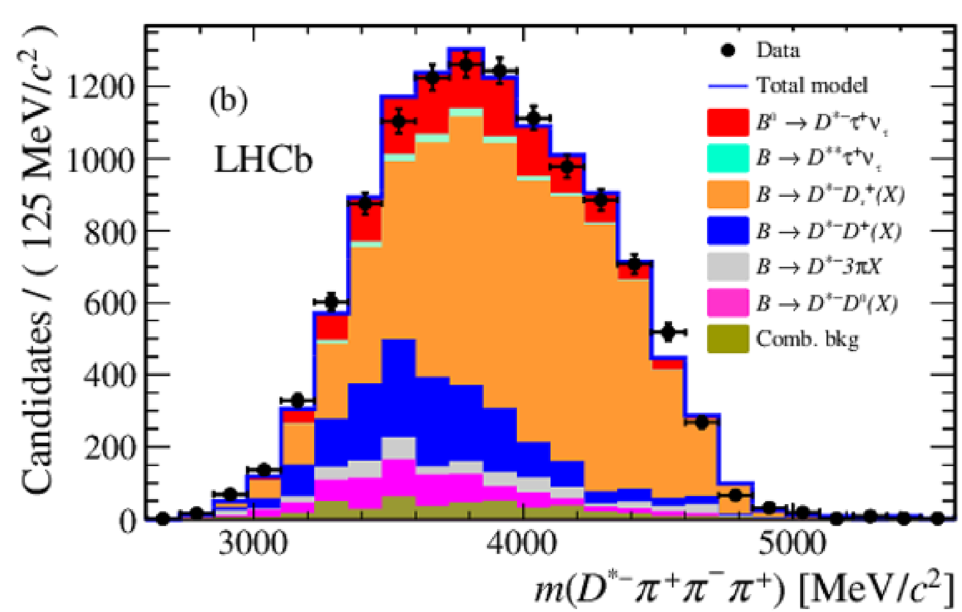
R(D*) 3pi fit detail

Contribution	Value in %
$\mathcal{B}(\tau^+ \to 3\pi\overline{\nu}_\tau)/\mathcal{B}(\tau^+ \to 3\pi(\pi^0)\overline{\nu}_\tau)$	0.7
Form factors (template shapes)	0.7
Form factors (efficiency)	1.0
τ polarization effects	0.4
Other τ decays	1.0
$B \to D^{**}\tau^+\nu_\tau$	2.3
$B_s^0 \to D_s^{**}\tau^+\nu_\tau$ feed-down	1.5
$D_s^+ \to 3\pi X$ decay model	2.5
D_s^+, D^0 and D^+ template shape	2.9
$B \to D^{*-}D_s^+(X)$ and $B \to D^{*-}D^0(X)$ decay model	2.6
$D^{*-}3\pi X$ from B decays	2.8
Combinatorial background (shape + normalization)	0.7
Bias due to empty bins in templates	1.3
Size of simulation samples	4.1
Trigger acceptance	1.2
Trigger efficiency	1.0
Online selection	2.0
Offline selection	2.0
Charged-isolation algorithm	1.0
Particle identification	1.3
Normalization channel	1.0
Signal efficiencies (size of simulation samples)	1.7
Normalization channel efficiency (size of simulation samples)	1.6
Normalization channel efficiency (modeling of $B^0 \to D^{*-}3\pi$)	2.0
Total uncertainty	9.1



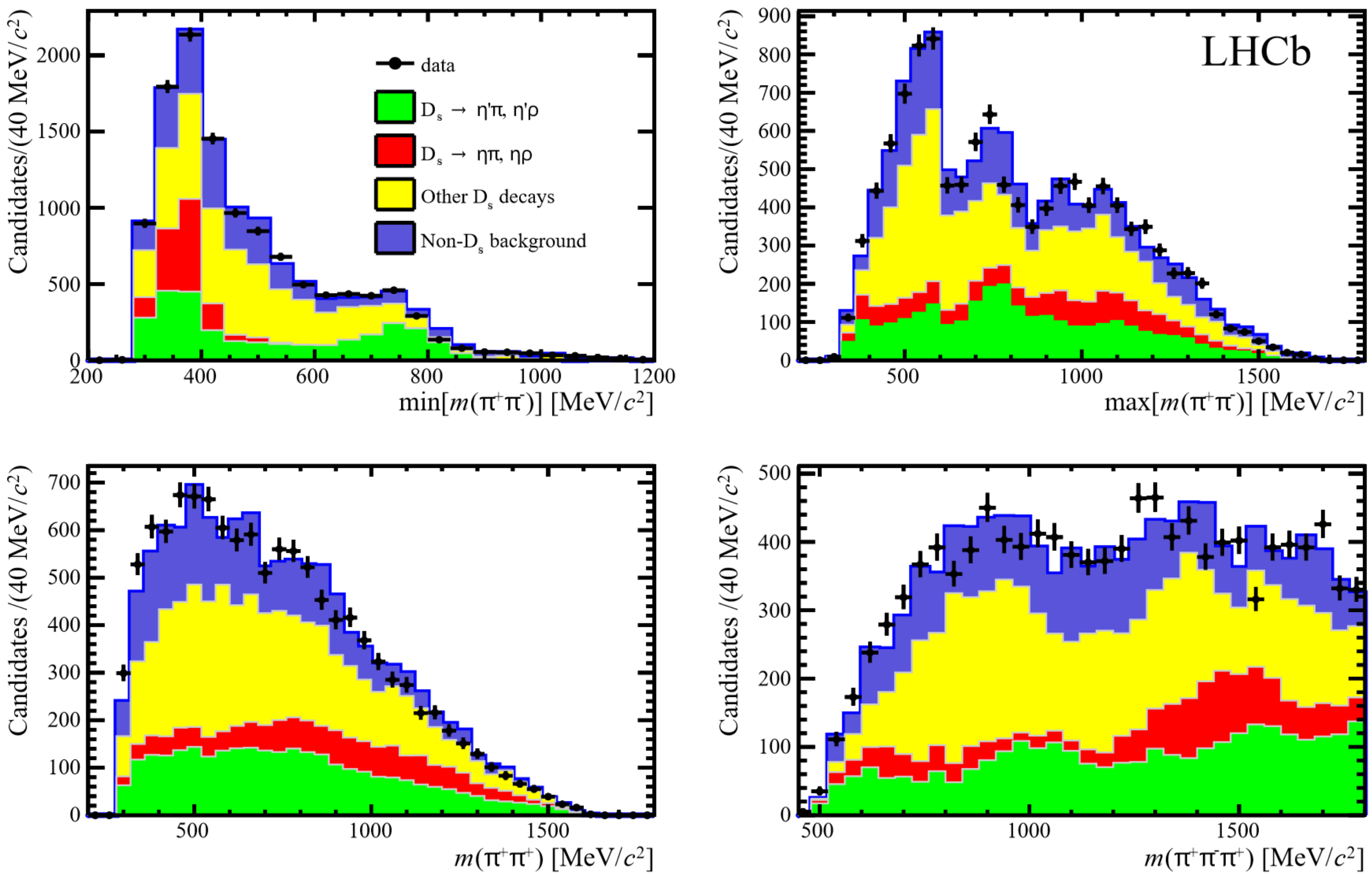
Post-fit agreement



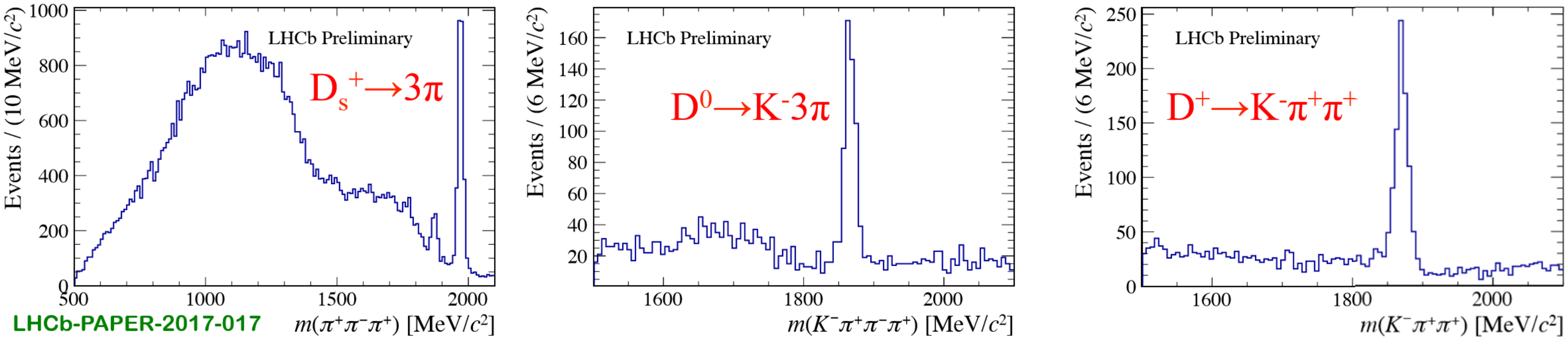


PRD **97**, 072018 (2018)

Ds Background calibration



Calibrating Simulation



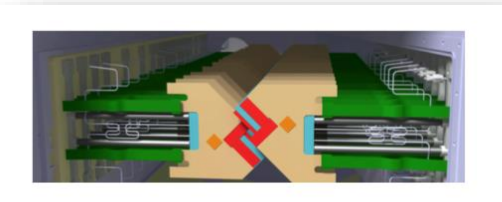
- q^2 distributions for each of the double charm background classes are validated and corrected in subsets of the data with fully reconstructed D mesons
  - $D_s \to m_{3\pi}$ above kinematic window for τ decay
  - $D^0 \to$ invert isolation requirements to find $D^0 \to K^- 3\pi$ decays
  - $D^+ \to$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

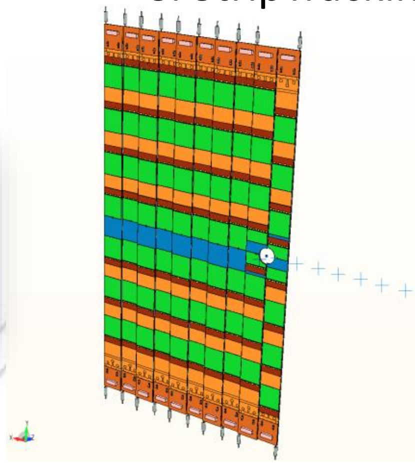
LHCb Upgrade Hardware

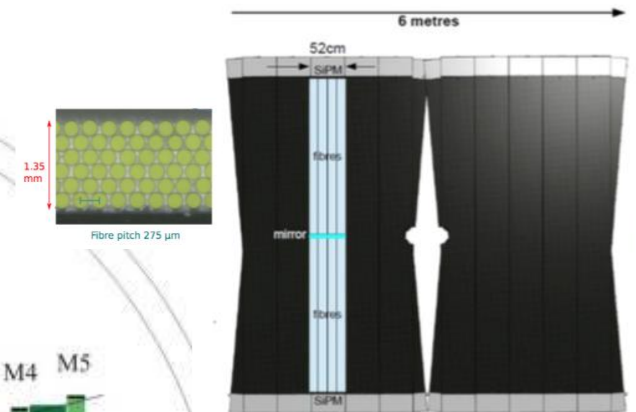
Improved Upstream Si StripTracking

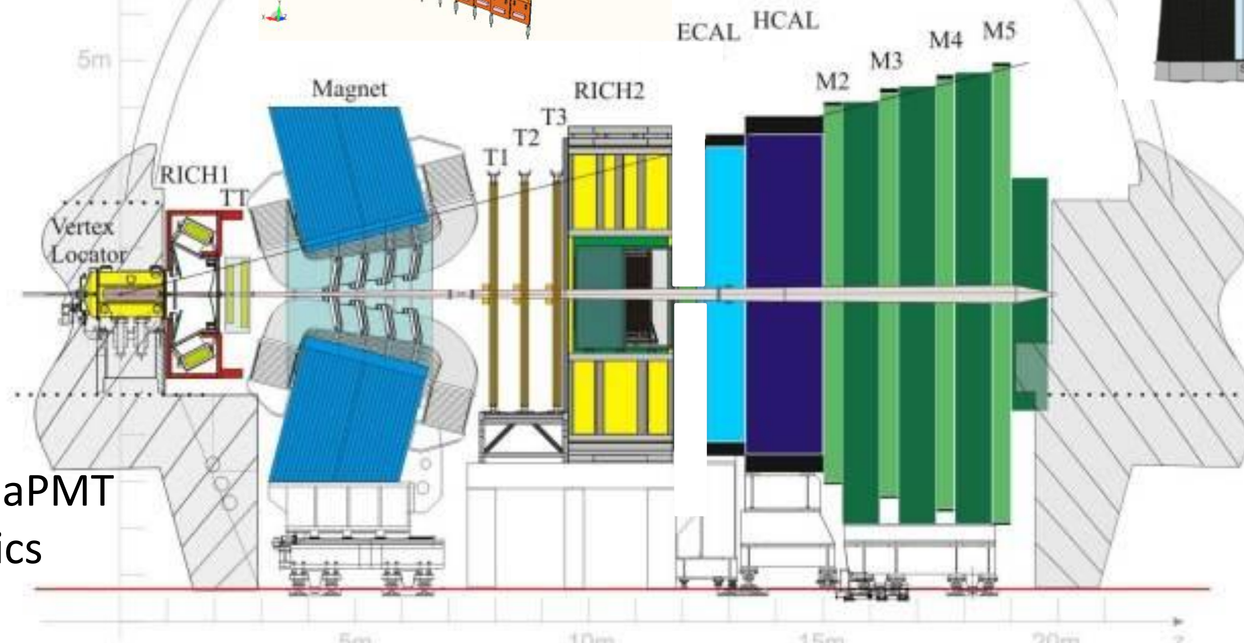
Scintillating Fibre Downstream Tracking

Pixel Velo









40MHz Muon Readout

New RICH MaPMT sensors+optics