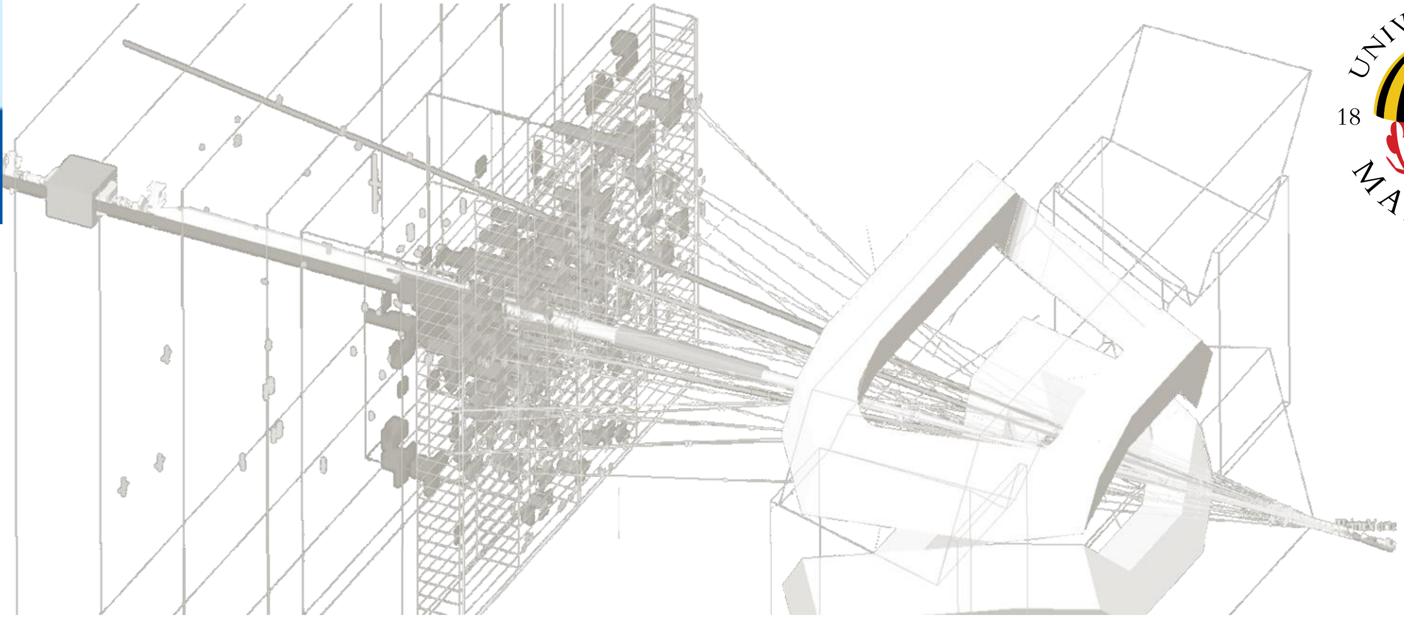


Testing lepton universality in rare and semileptonic B decays at LHCb

Experimental Seminar
SLAC National Accelerator Laboratory

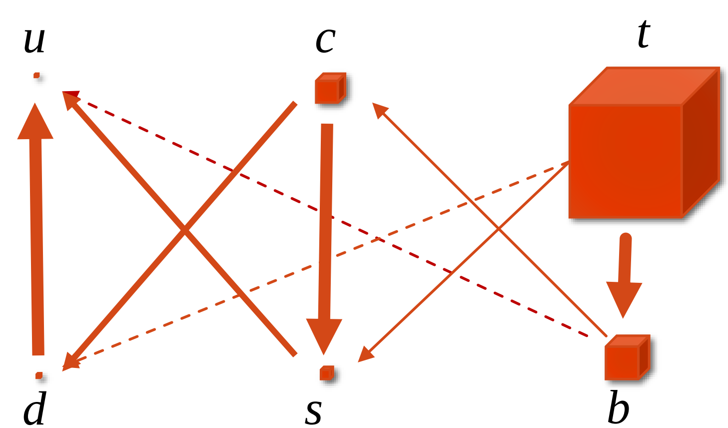
Tuesday 8 August 2017

Brian Hamilton

B Physics Basics

- Standard model flavor structure is described by the Cabibbo-Kobayashi-Maskawa mixing matrix
- V_{CKM} hierarchical & nearly diagonal
  - Quark flavor transitions mixing different generations suppressed
  - 3rd generation especially "isolated"
- This leads to suppression of all tree-level b quark decay amplitudes
  - $|Vcb|\sim 0.04$
  - Makes B physics quite sensitive to NP generically misaligned with CKM
- Also leads to long b quark lifetime: $c\tau_B \sim 400\mu m$! (= about 2x charm lifetime)
  - Very Important for hadron collider b tagging/reconstruction
  - Allows access to time-dependent phenomena

$$\begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \rightarrow$$

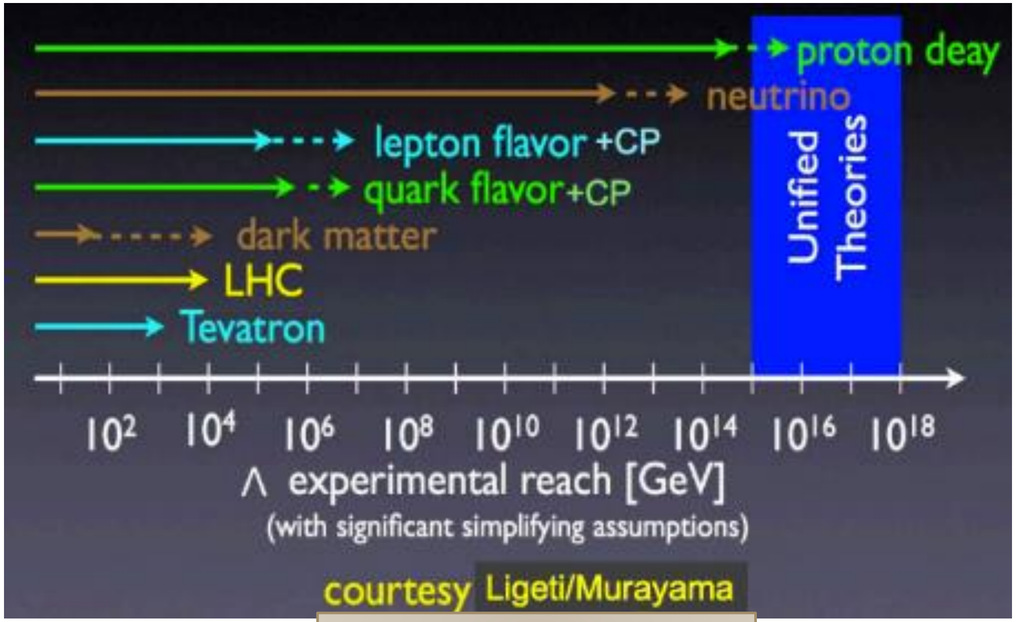


Flavor Physics Reach

- The reach of flavor physics comes from sensitivity to heavy intermediate states
  - These contribute in the form of higher dimension operators, eg

$$\frac{c(q'\Gamma q)(f'\Gamma f)}{\Lambda^2}$$

- Reach in Λ is potentially quite large (or, alternately, can probe very weak couplings at Λ~TeV)



H. Weerts, intensity frontier workshop

- **Study processes which are highly suppressed by small parameters or loop factors in the SM**
  - Smaller SM contribution → New Physics (NP) interference or enhancement easier to observe for larger $\Lambda_{\rm NP}$

Lepton universality

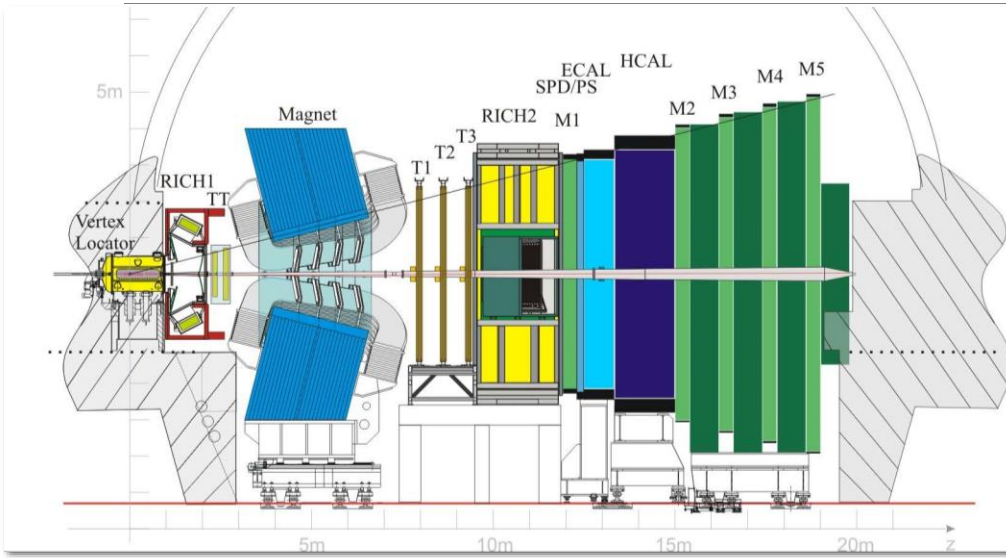
- In Standard Model (SM), charged lepton flavors are ***identical copies*** of one another
  - Electroweak couplings are trivially equal for all three flavors by construction, only Higgs Yukawa couplings differentiate them
  - Amplitudes for processes involving e, μ, τ must all be identical up to explicit 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...

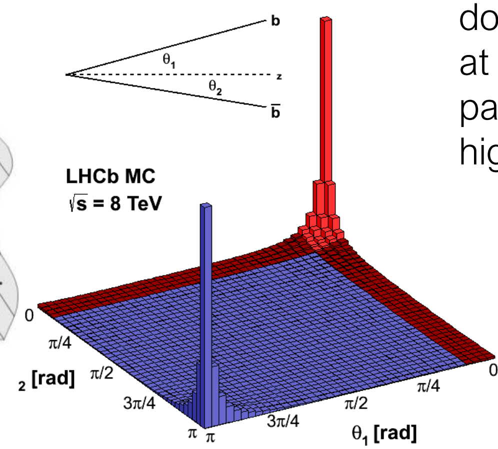
- Universality of the EW interactions does not necessarily imply universality of physics beyond the SM

- 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





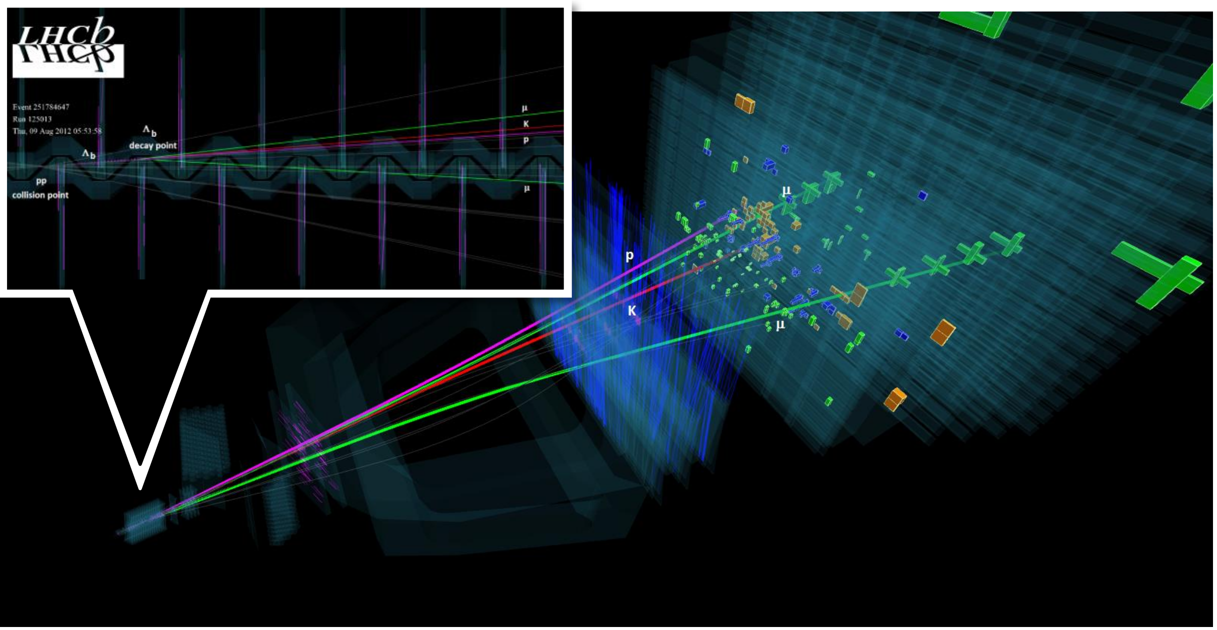
$b\bar{b}$ production dominantly at lower p_T: parton CM frame highly boosted

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 in multi-TeV collisions: cover 27% (25%) of (pair) production while instrumenting < 3% of the solid angle (value!)

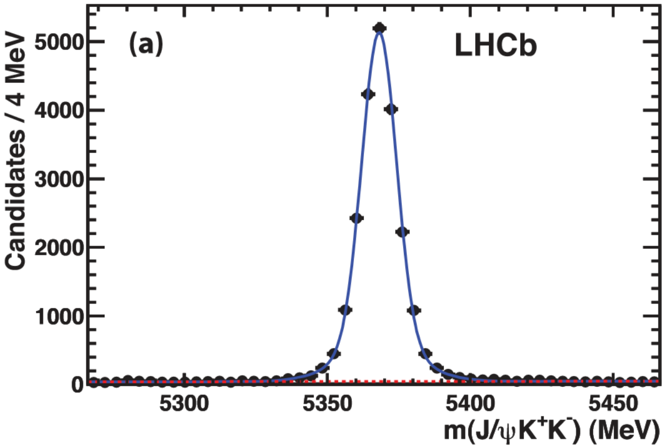
- Single arm spectrometer optimized for beauty and charm physics at large η:
  - Trigger: ~90% efficient for dimuon channels, ~30% for all-hadronic
  - Tracking: σ_p/p ~ 0.4%–0.6% (p from 5 GeV to 100 GeV), $\sigma_{IP} < 20$ μm
  - Vertexing: σ_τ ~ 45 fs for $B_s \to J/\psi\phi$
  - PID: 97% μ ID for 1-3% π→μ misID
  - Dipole magnet polarity periodically flipped to change the sign of many reconstruction asymmetries

LHCb Events



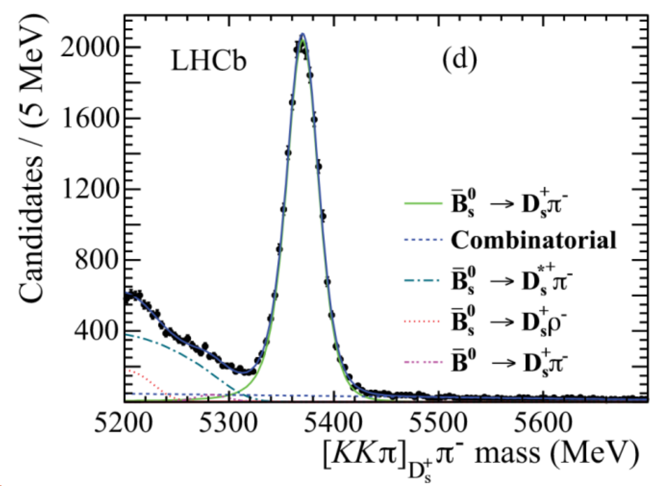
b →charmonium

[PRD 86, 052006 (2013)]



All hadronic

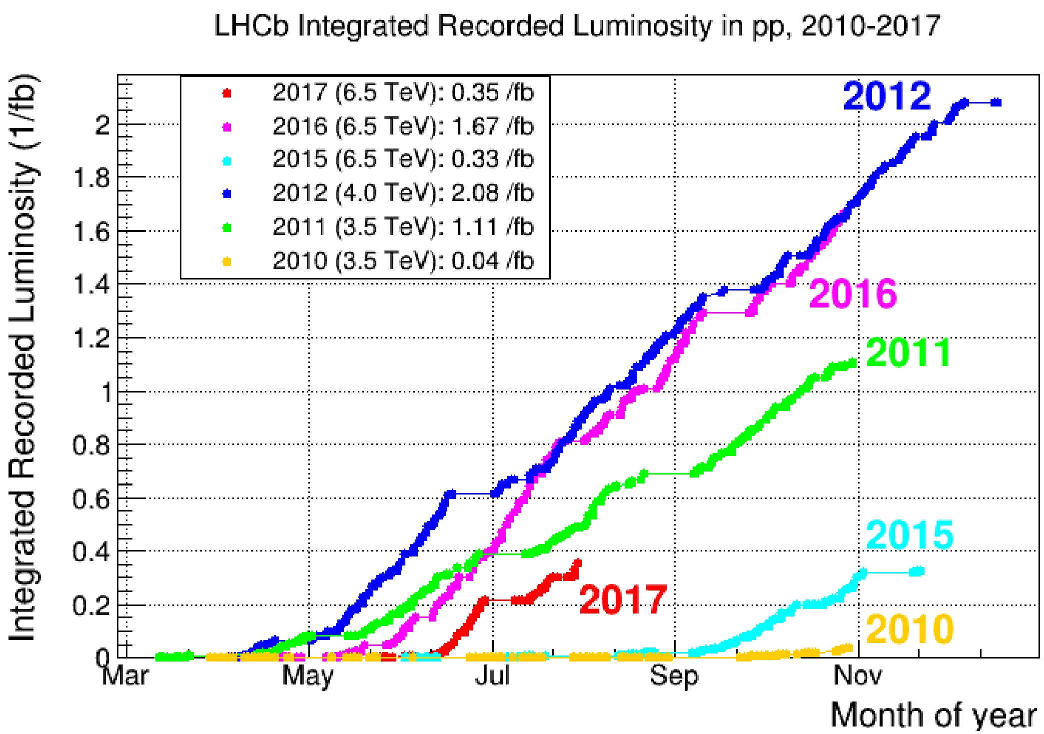
[PRL 113, 172001(2014)]

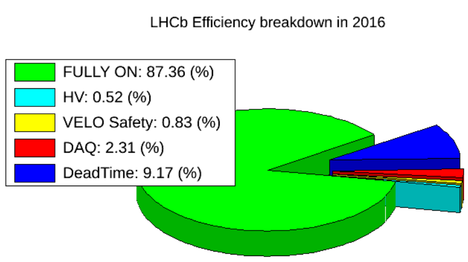


- Information from all subdetectors combined to form candidate charged particles and neutral clusters for analysis
  - Event display: sample $\Lambda_b^0 \rightarrow J/\psi pK$ candidate event
- Large number of B decay modes can be constructed very cleanly
  - Backgrounds in analysis tend to be mostly combinatoric, mis-identified daughters, or partially reconstructed decays (right)

Data taking status

- 13 TeV, 25ns data coming in smoothly
  - Heavy flavor cross section scales linearly in $\sqrt{s}$: Run2 dataset surpasses Run1 already!
- LHCb data taking inefficiency dominated by deadtime imposed by 1 MHz readout





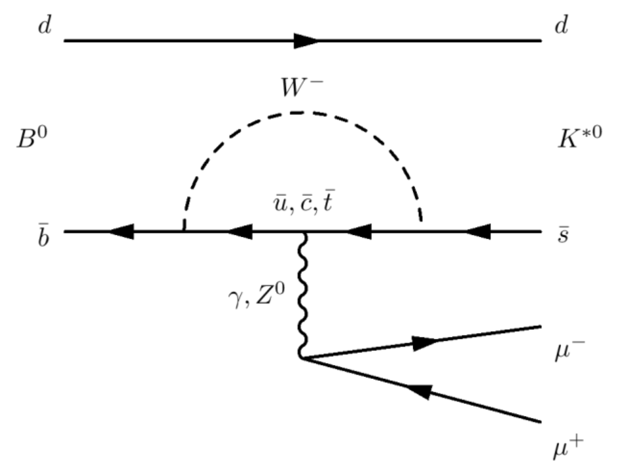
Rare Decays and Lepton Flavor Universality

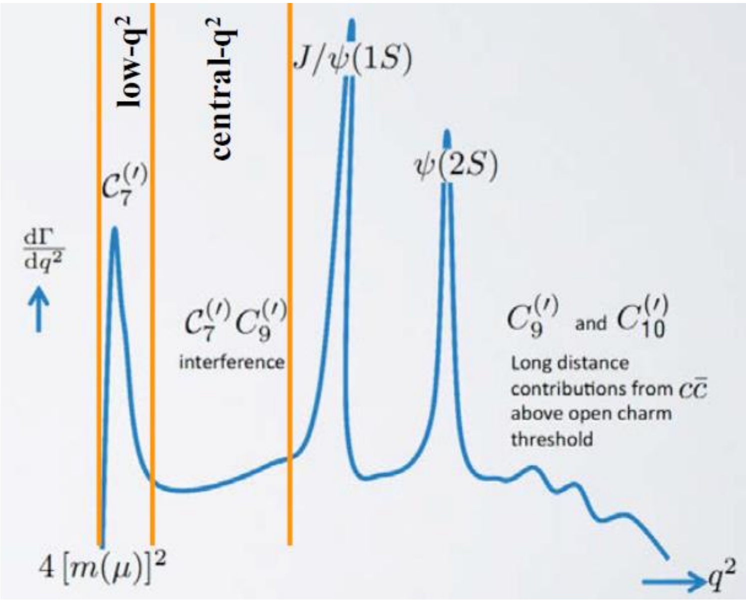
ARXIV:1705.05802

Electroweak Penguin Decays

- Penguin transitions stringently test the structure of the electroweak interaction
  - In SM: loop structure with almost all major SM 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 both LHCb and B-factories
  - Dilepton in final state allows for clean event selection
  - Rich phenomenology with scalar and vector hadronic final states ($K \; or \; K^*$)
  - SM calculations become unreliable near $m(\ell\ell) = m(J/\psi), m(\psi(2S))$
    - (tree-level $b \to c\bar{c}s$ amplitudes, $c\bar{c}$ vacuum polarization, long distance effects…)
    - Focus on $q^2 < 6 \text{ GeV}^2$ to avoid
      - Subdivided into $[0.045, 1.1] \text{ GeV}^2$ and $[1.1, 6.0] \text{ GeV}^2$
- Lepton universality test: general consensus in literature that if only SM fields participate

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





RK* event selection and raw yields

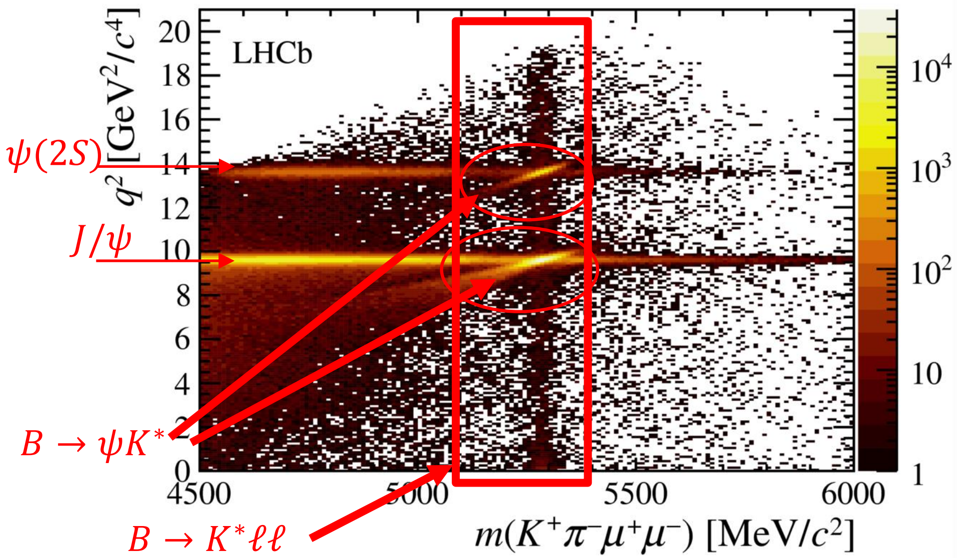
- Main challenge experimentally at LHCb: **electron reconstruction**
  - Electron momentum resolution is considerably worsened by bremsstrahlung
    - Charged particles at LHCb see $X/X_0 \approx 60\%$ before RICH2, $\approx 30\%$ before magnet
    - Recovery algorithms find the hardest pre-magnet emissions ($E_T > 75$ MeV)
    - Limitations of E_T threshold, unassociated clusters misidentified as brem. and inefficiency of isolation limit resolution
  - Dielectron mass resolution also strongly dependent on trigger path

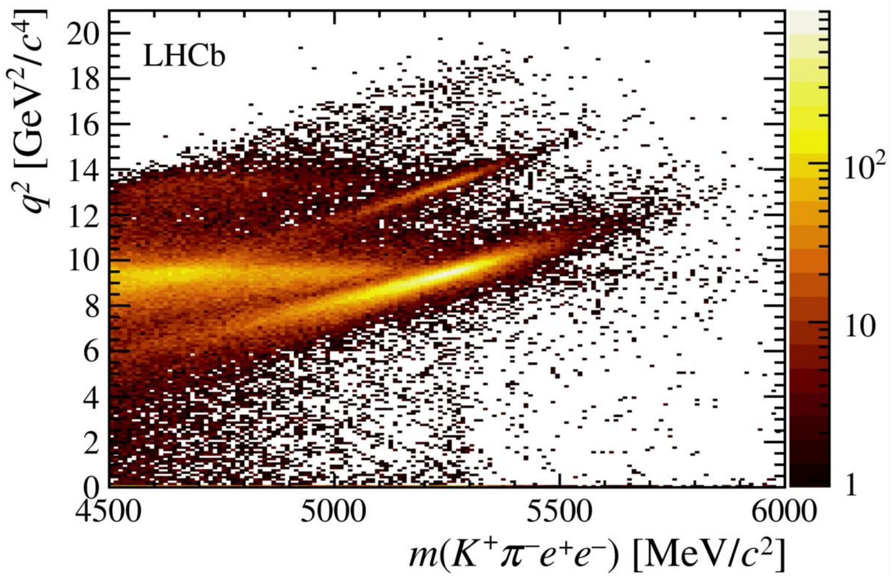
- Measure double ratio

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

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

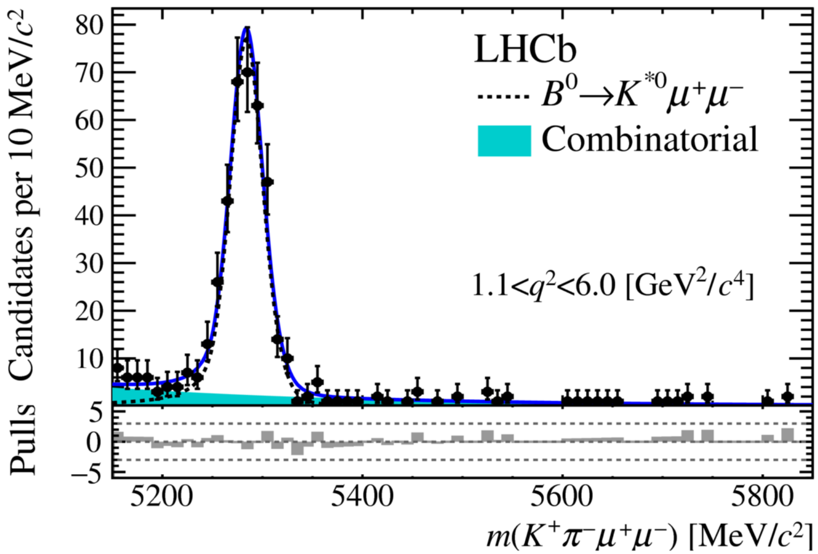
to minimize impact of reconstruction systematics on LFU observables

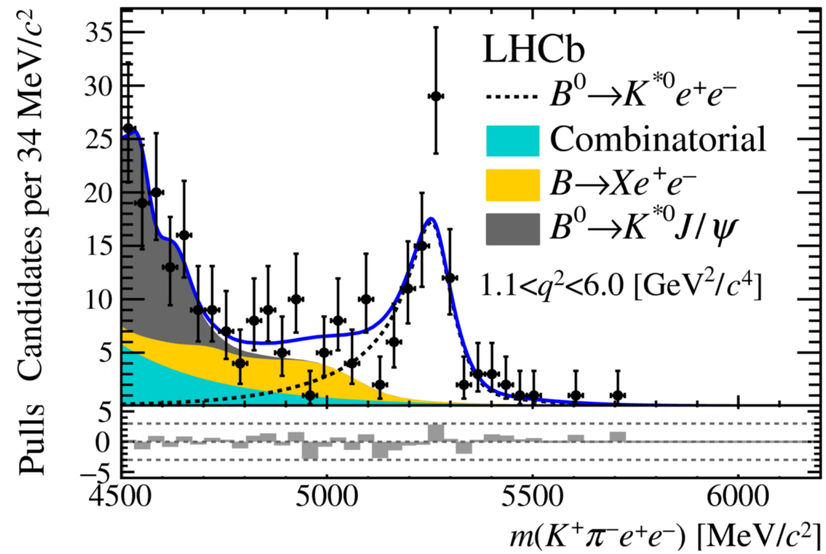




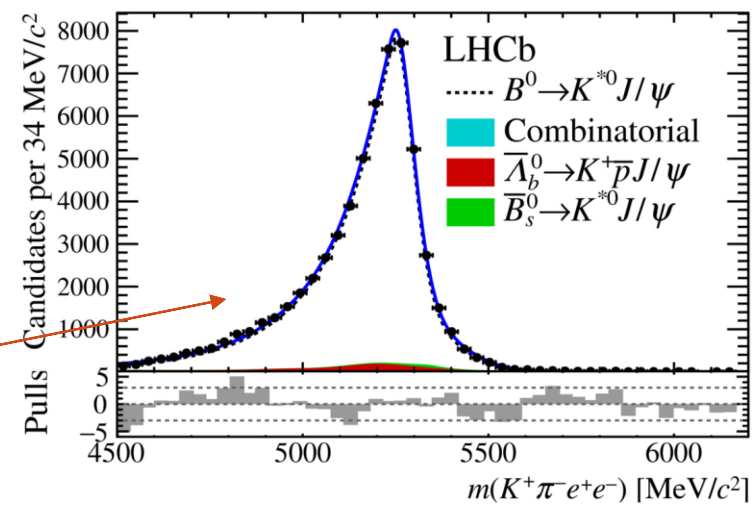
arXiv:1705.05802

R_{K^*} fit





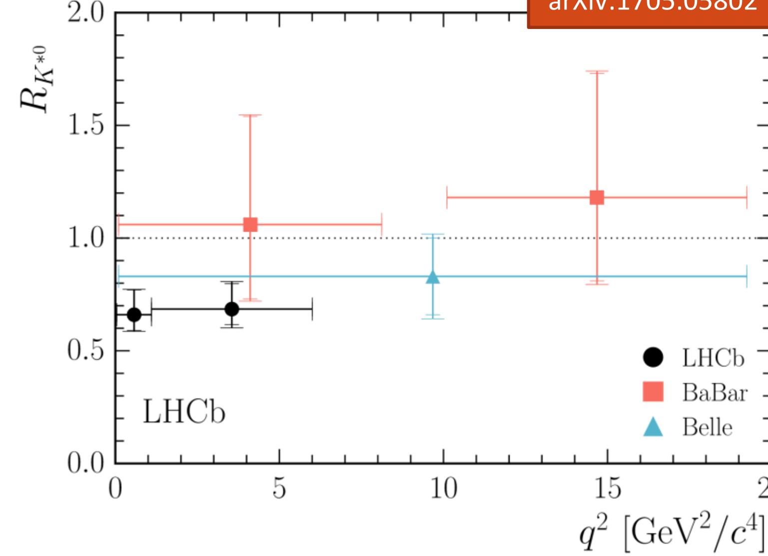
- Mass shape in electron mode is sum of shapes corresponding to zero, one, or two or more recovered photons
  - Fit separately in each of [electron triggered, kaon triggered, other] categories
  - Parameters fixed in signal decays to those obtained in fit to $B \to J/\psi\, K^*$

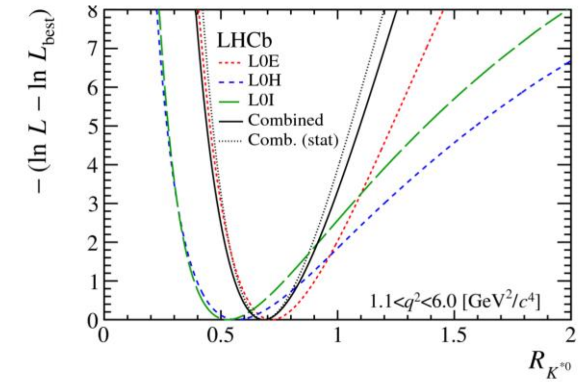


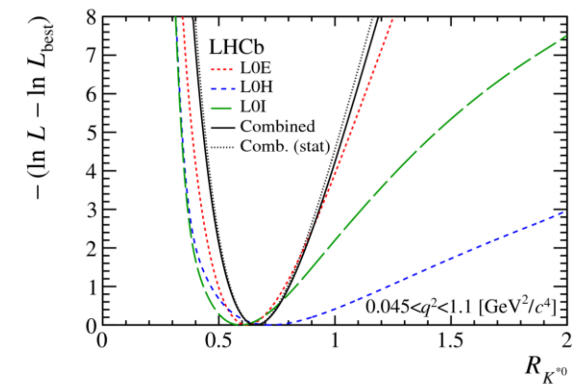
arXiv:1705.05802

RK* results

- This result:
  - $R_{K^*}(low\ q^2) = 0.66\ ^{+0.11}_{-0.07} \pm 0.03$
    - $2.1 - 2.3\sigma$ below predictions (~0.92)
  - $R_{K^*}(central\ q^2) = 0.69\ ^{+0.11}_{-0.07} \pm 0.05$
    - $2.4 - 2.5\sigma$ below predictions (~1.0)
- Previous LHCb result:
  - $R_{K,\ q^2<6\mathrm{GeV}^2} = 0.745^{+0.090}_{-0.074} \pm 0.036$
- Result cross-checked by studying the *single ratio* $r_{J/\psi} = \frac{\mathcal{B}(B\to J/\psi[\to\mu\mu]K^*)}{\mathcal{B}(B\to J/\psi[\to ee]K^*)} = 1.043 \pm 0.006 \pm 0.045$
  - Fewer cancellations than double ratio means it is more sensitive to systematic issues with efficiencies and yield extraction
  - Further cross-checks measure double ratio for $\psi(2S) \rightarrow$ result is 1 within 2%(=stat error)
- Consistent with $C_9/C_9 - C_{10}$-type new physics picture preferred by global fits to $b \rightarrow s\ell\ell$ data – eg
- Currently this is the “poster child” of statistics-limited measurements. Expect fast improvement with Run2!





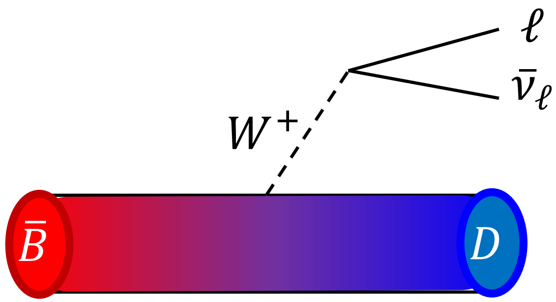


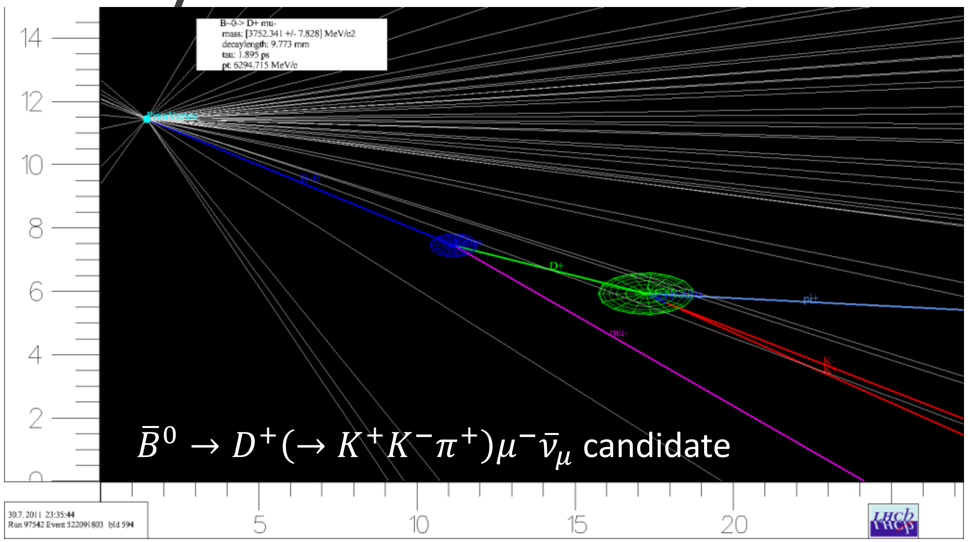
LFU in Semileptonic Decays

PRL 115, 11803 (2015)

LHCB-PAPER-2017-017 (IN PREPARATION)

Semileptonic B decays





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

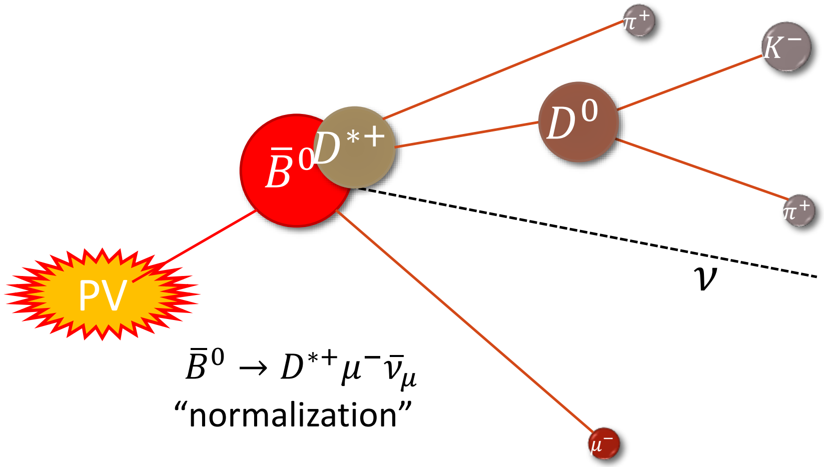
- Theoretically well-understood in the SM
  - Tree level virtual W emission – strong V-A structure
  - No QCD interaction between the lepton-neutrino system and the recoiling hadron(s)
    - $\bar{B} \to W^{*\pm}D^{(*)}$ half of the decay still needs non-perturbative input

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

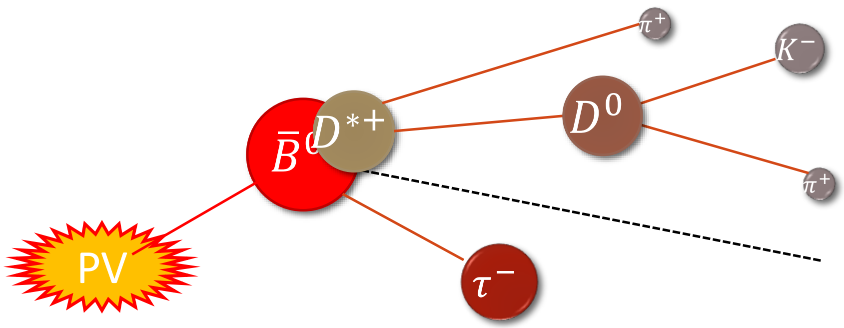
What we want to measure

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

- Theoretically clean due to cancellation of form factor uncertainties
  - Poorly-measured helicity suppressed amplitudes give dominant uncertainty
  - SM (HQET): $R(D^*) = 0.252(3)$ [PRD **85** 094025 (2012)]
- $\tau^- \to \mu^-\bar{\nu}_\ell\nu_\tau$
  - Automatic normalization from identical final state
  - Must be disentangled from $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$ using decay kinematics
- $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$
  - Clear signature: higher signal purity
  - Must be normalized to hadronic B decays (reliant on external measurements to get R(D*)
- Common Challenges: missing neutrinos with (mostly) unconstrained momentum
  - Don't have full B momentum
  - Large backgrounds from partially-reconstructed B decays



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



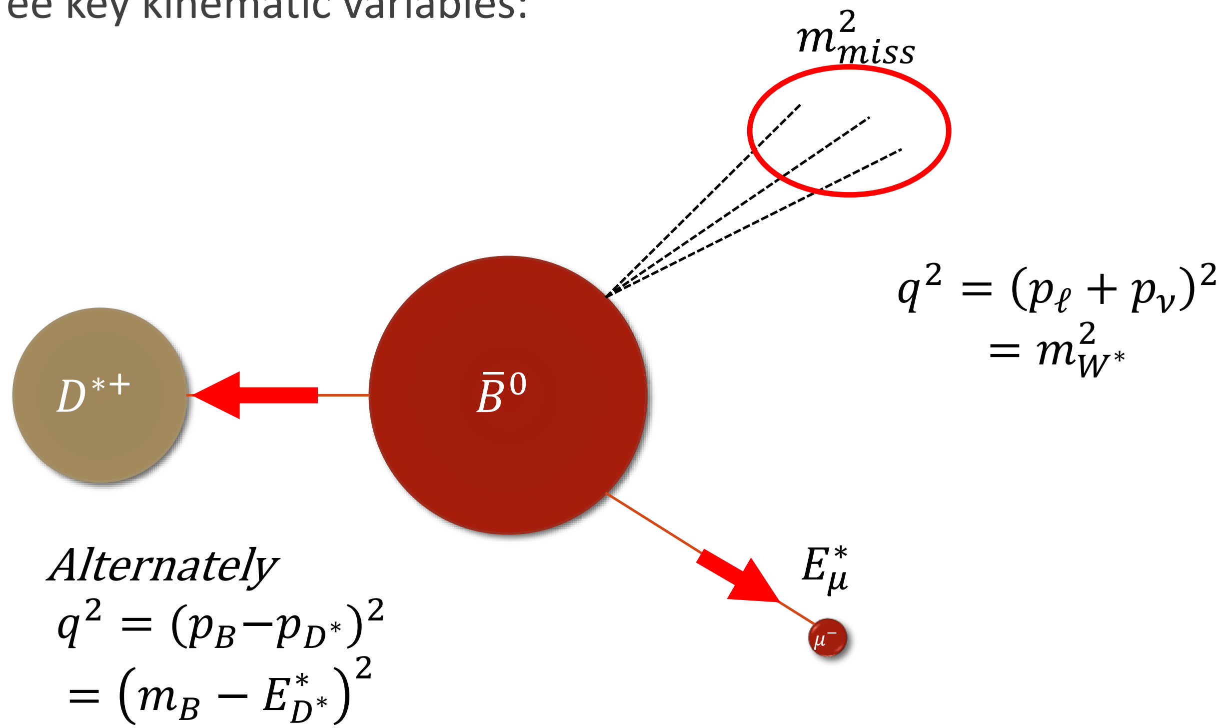
$\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$
"signal"

Measurement Using $\tau \to \mu\bar{\nu}\nu$

PRL 115, 11803 (2015)

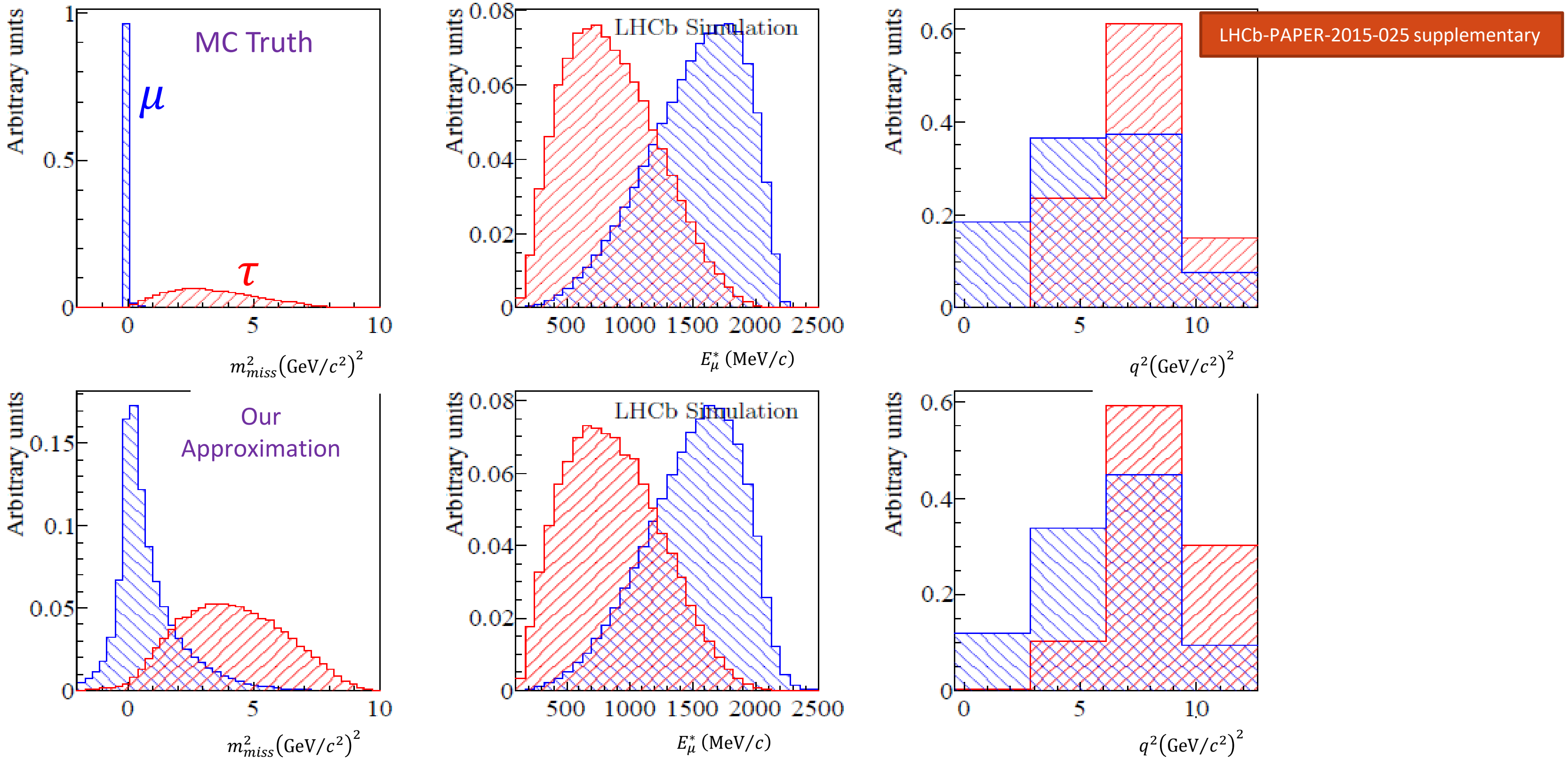
Distinguishing $b \to c\tau(\to \mu\nu\nu)\nu$ from $b \to c\mu\nu$

- In B rest frame, three key kinematic variables:



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

Rest frame approximation



- CHALLENGE: not enough constraints to close the kinematics at LHCb
- Key: Distributions are broad to begin with – a well-behaved approximation will still preserve differences between signal, normalization and backgrounds

Take $(\gamma\beta_z)_{\bar{B}} = (\gamma\beta_z)_{D^*\mu}$

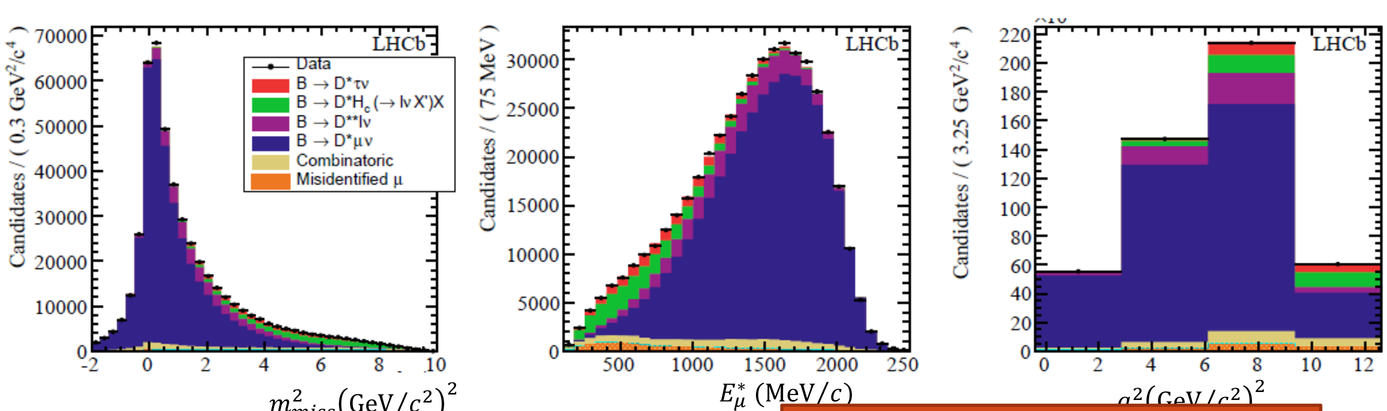
$$\Longrightarrow \quad (p_z)_{\bar{B}} = \frac{m_B}{m(D^*\mu)}(p_z)_{D^*\mu}$$

Fit

- Using rest frame approximation, construct 3D "template" histograms for each process contributing to $D^{*+}\mu^-$
  - Signal, normalization, and partially reconstructed backgrounds use simulated events, other backgrounds use control data
  - Templates are functions of any relevant model parameters via interpolation between histograms generated with different fixed values of those parameters

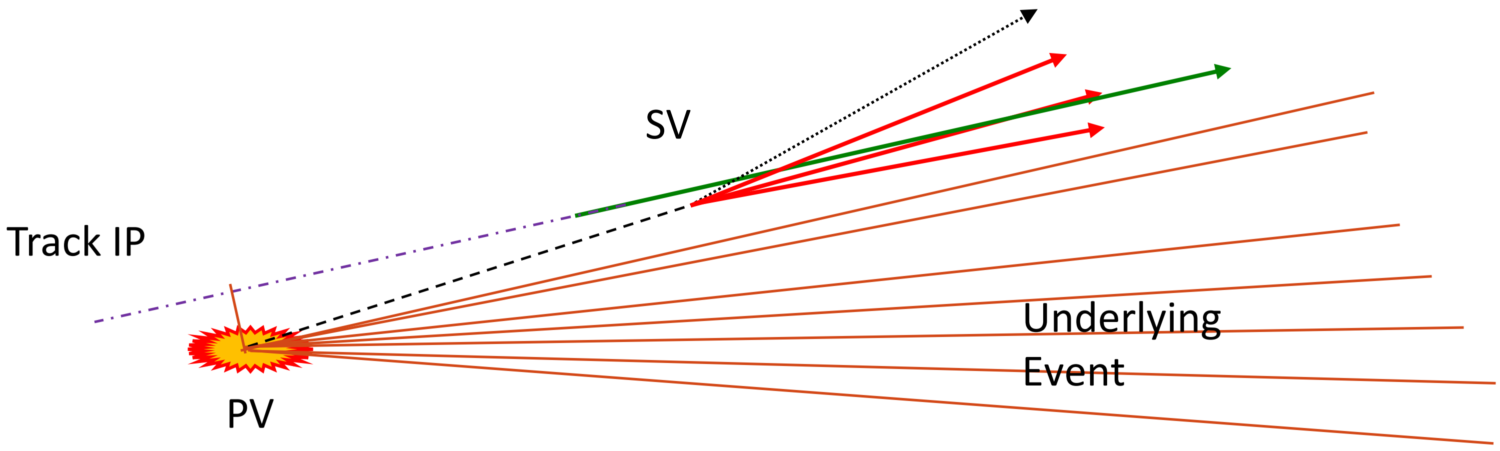
- These templates are then used as PDFs for a maximum likelihood fit to data

- -> distributions shown previously directly translate to one-dimensional projections of the 3D templates for signal and normalization



LHCb-PAPER-2015-025 supplementary

Reducing partially reconstructed backgrounds



- Make use of superb tracking system
  - Scan over every reconstructed track and compare against $D^{*+}\mu^-$ vertex
    - Check for vertex quality with PV and SV, change in displacement of SV, p_T, alignment of track and $D^{*+}\mu^-$ momenta

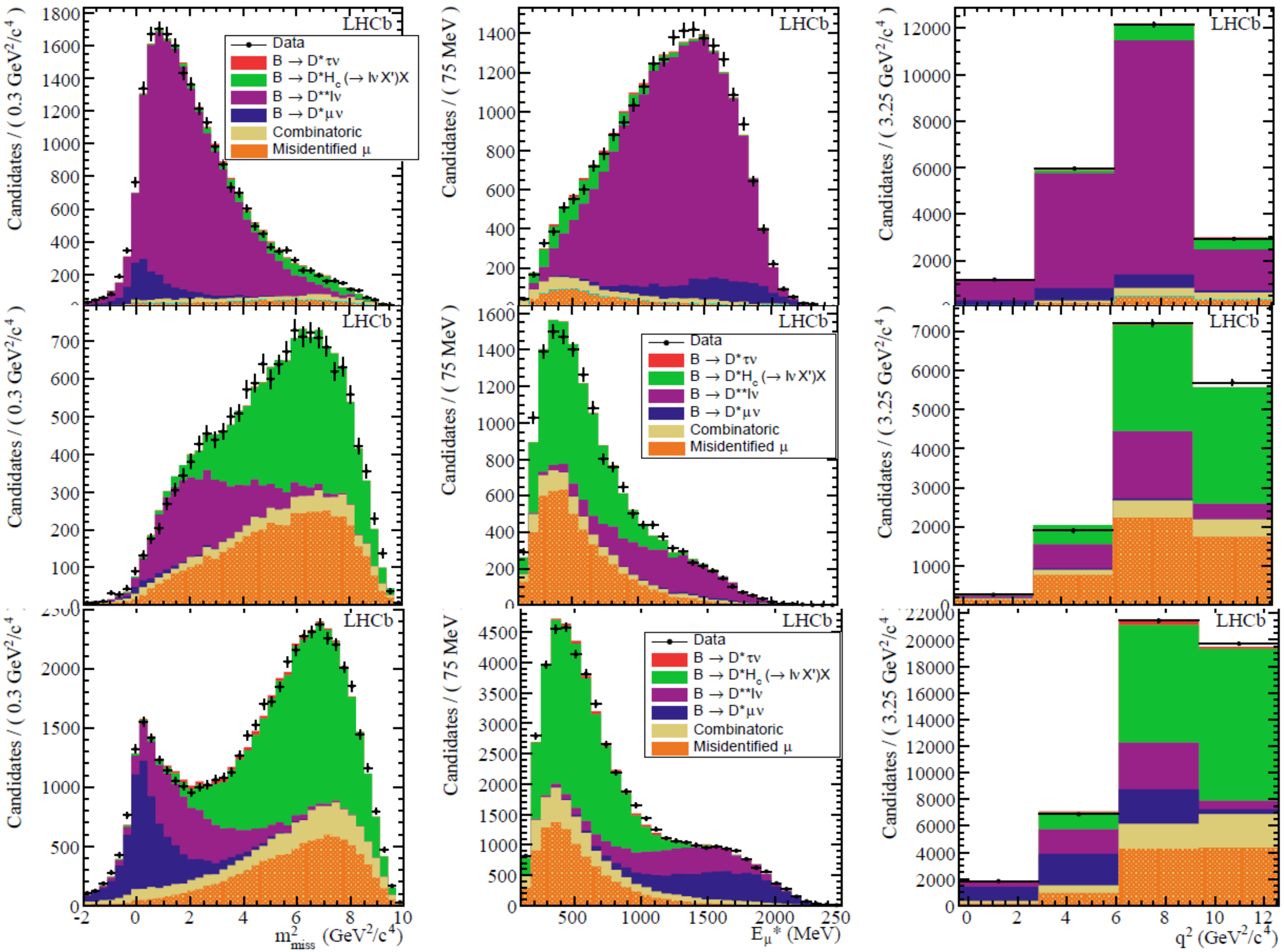
- Each track receives BDT score as "SV-like" (high) vs "PV-like" (low)
  - Cut on most SV-like track below threshold: get signal sample enriched in exclusive decays. Rejects 70% of events with 1 additional slow pion
  - Cut on most SV-like track(s) being above threshold: get control samples enriched in interesting backgrounds - $B \to D^{*+}\pi\mu\nu, B \to D^{*+}\pi\pi\mu\nu, B \to D^{*+}H_c(\to \mu\nu X')X$ (see backups for projections)

Control sample fits for BG shapes

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

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

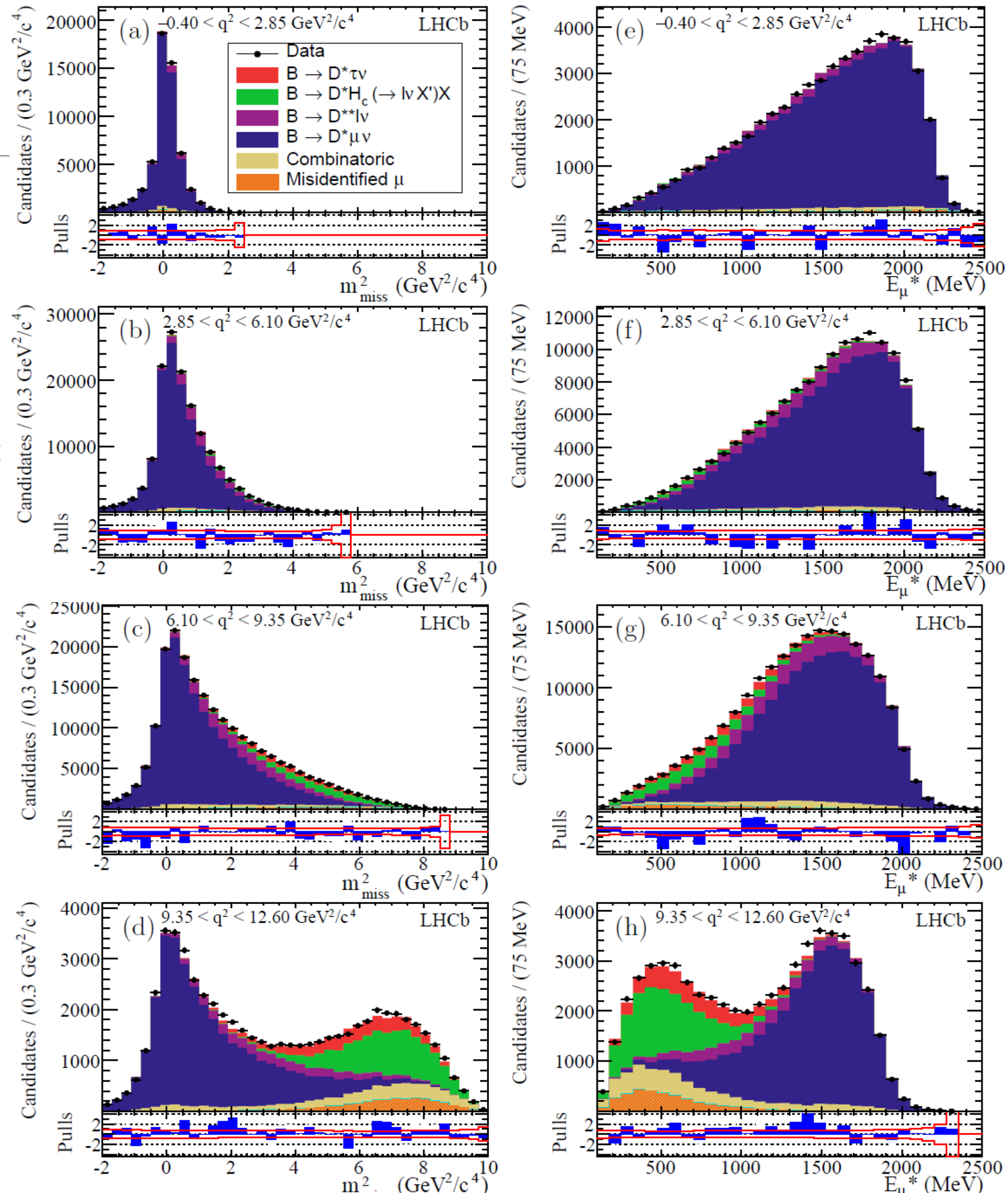
$D^{*+}\mu^-K^\pm$



LHCb-PAPER-2015-025 supplementary

Detailed fit projections

- Projections of (left) m^2_{miss} and (right) E^*_μ in bins of increasing q^2 from top to bottom
- Signal more clearly visible here in highest q^2 bin
  - Note different y scales, most signal actually in second-highest q^2 bin
- Final result:
  $R(D^*) = 0.336 \pm 0.027 \pm 0.030$
- Systematics dominated by MC statistics, treatment of hadron -> muon misID background
  - Other systematics smaller and driven by control sample size – lots of room for improvement!

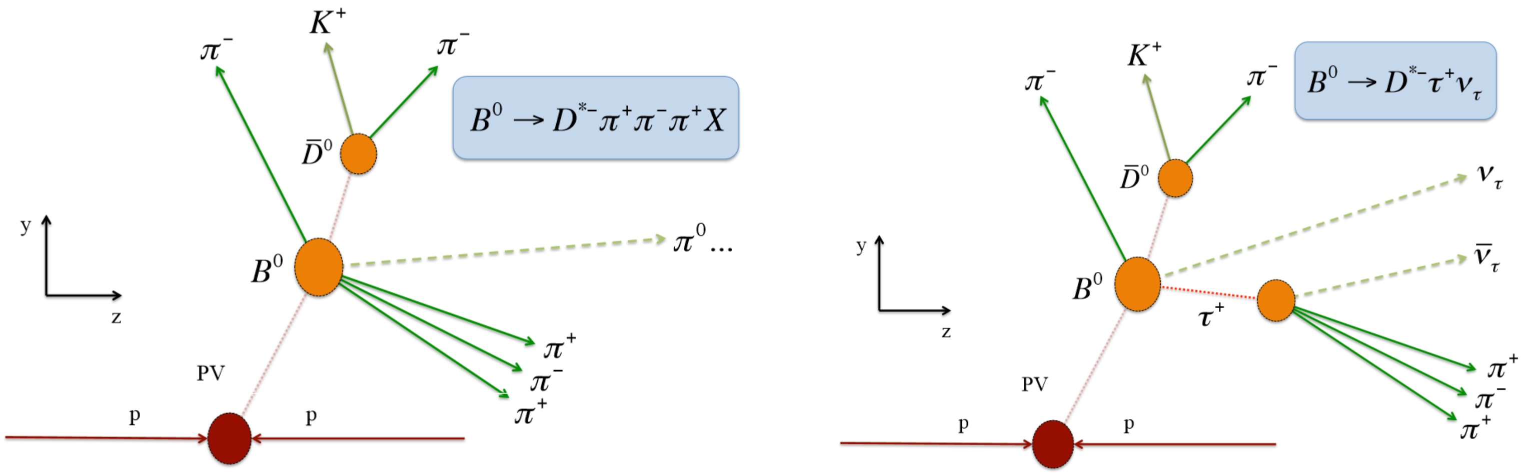


PRL 115 111803 (2015)

Measurement Using $\tau \to 3\pi(\pi^0)\nu$

LHCB-PAPER-2017-017 (IN PREPARATION)

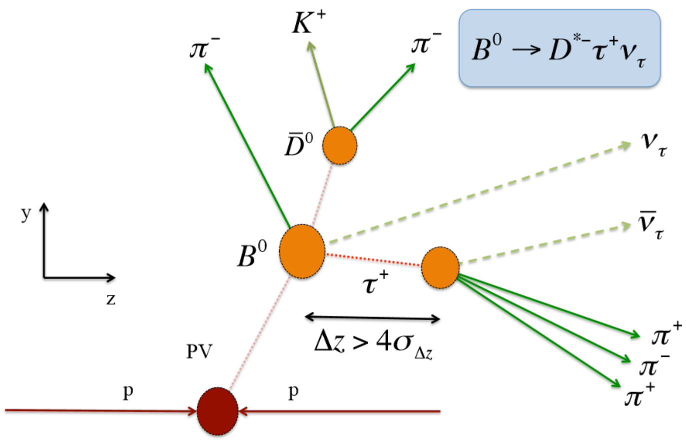
$\bar{B}^0 \to D^{*+}\tau\bar{\nu}$ with $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu$

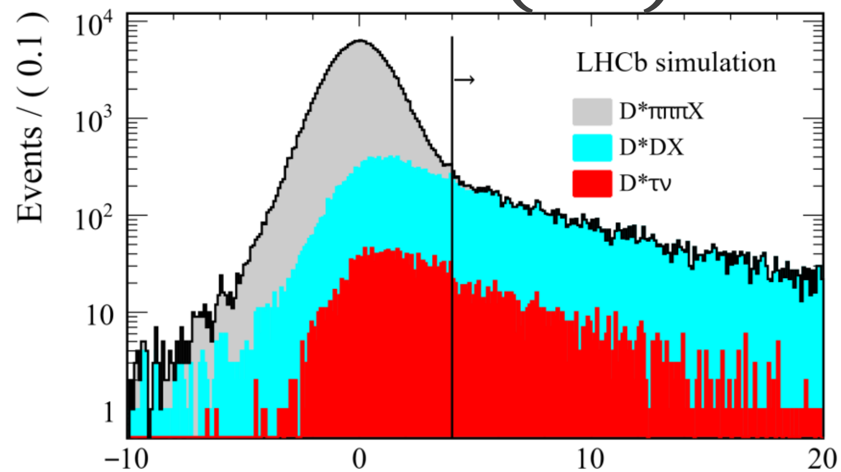


- $\bar{B}^0 \to D^{*+}\tau^-(\to \pi^-\pi^+\pi^-(\pi^0)\nu)\bar{\nu}$ reconstructed using both candidates from the $D^0 \to K^-\pi^+$ trigger and the 2,3,4-body topological triggers
  - In this case, the combination of the two paths has the most flat q^2 efficiency

- Normalize result using number of reconstructed $\bar{B}^0 \to D^{*+}\pi^-\pi^+\pi^-$ exclusive hadronic decays (left cartoon)

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





LHCb-PAPER-2017-017 (in preparation)

- 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

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!

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

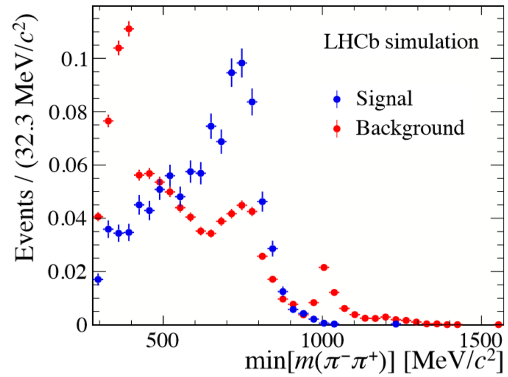
$$|\vec{p}_\tau| = \frac{(m_{3\pi}^2 + m_\tau^2)|\vec{p}_{3\pi}|\cos\theta_{\tau,3\pi} \pm E_{3\pi}\sqrt{(m_\tau^2 - m_{3\pi}^2)^2 - 4m_\tau^2|\vec{p}_{3\pi}|^2\sin^2\theta_{\tau,3\pi}}}{2(E_{3\pi}^2 - |\vec{p}_{3\pi}|^2\cos^2\theta_{\tau,3\pi})}$$

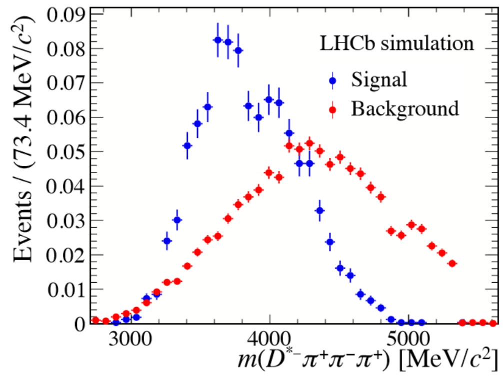
- Choose θ, θ' such that the ambiguity vanishes
  - Provides $\approx 10\%$ resolution on q^2

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

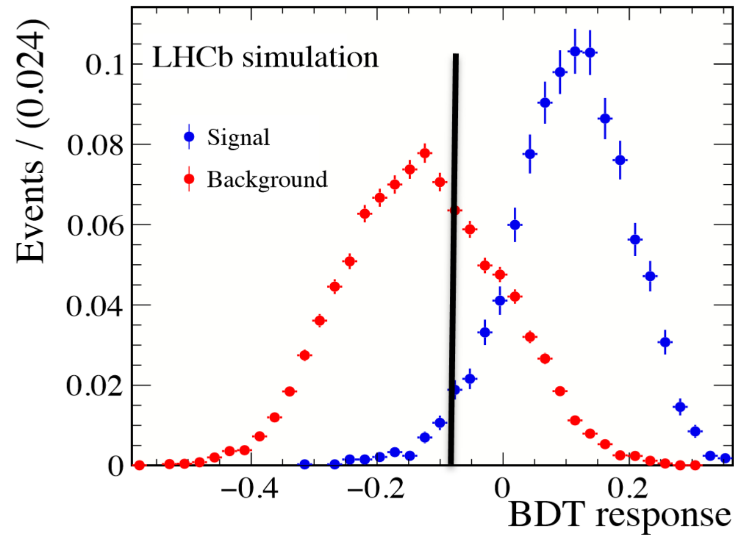
Signal BDT

- Train a dedicated BDT to distinguish signal from $\bar{B} \rightarrow D^{*+} D_s X$ background
  - Distinguishing variables:
    - Charged and neutral energy inside an η, ϕ cone
    - Masses and momenta under both reconstruction hypotheses
    - $m^{\max}_{\pi^+\pi^-}, m^{\min}_{\pi^+\pi^-}$
    - Transverse energy and flight distance of 3pi
    - $m_{D^* 3\pi}$





- Training is on MC samples



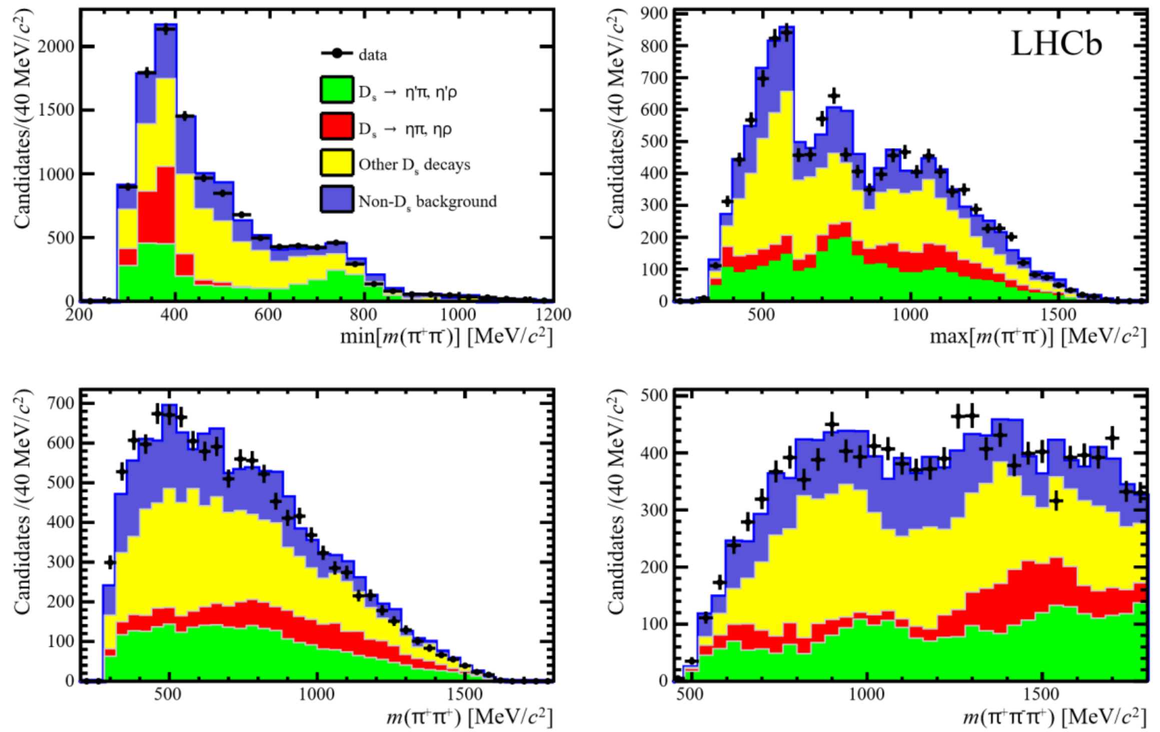
- Very important to use best possible info on $m^{\max}_{\pi^+\pi^-}, m^{\min}_{\pi^+\pi^-}$ and $m_{D^* 3\pi}$ for this to work
  - Control samples are key!

LHCb-PAPER-2017-017 (in preparation)

Controlling Ds backgrounds

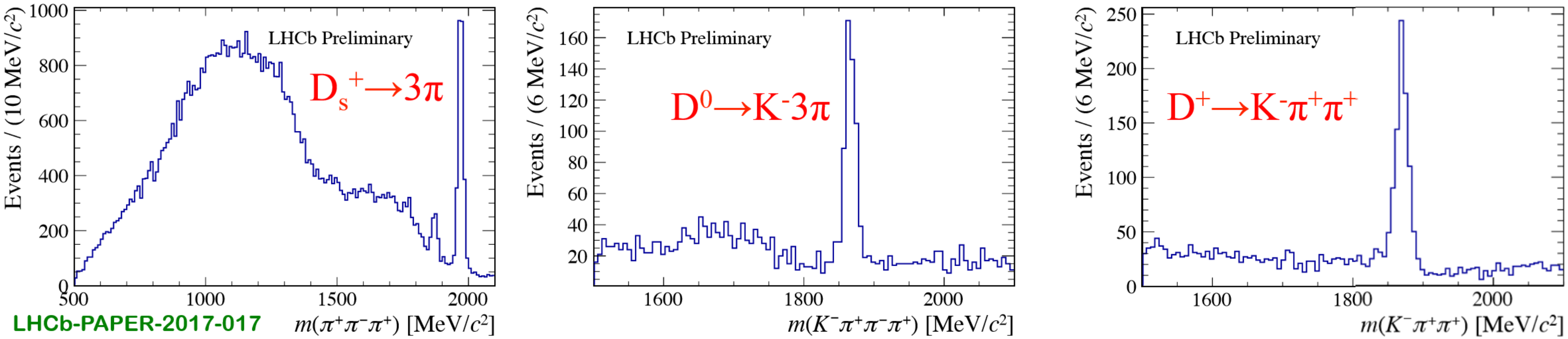
- Use of the 3pi dynamics in the BDT requires that the simulation modelling in D_s decays to 3π +neutrals be as good as possible
  - Most of the mismatch between data and simulation for these is due to incorrect relative branching ratios in MC

- Use BDT to select the most $\bar{B} \to D^{*+} D_s X$-like region and perform a fit to calibrate these relative contributions directly from the data



LHCb-PAPER-2017-017 (in preparation)

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

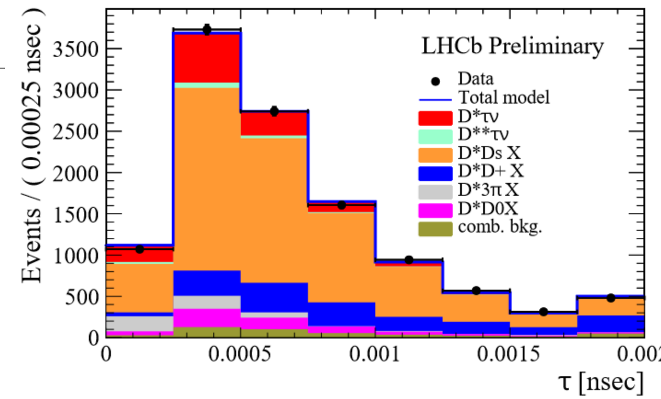
Fit

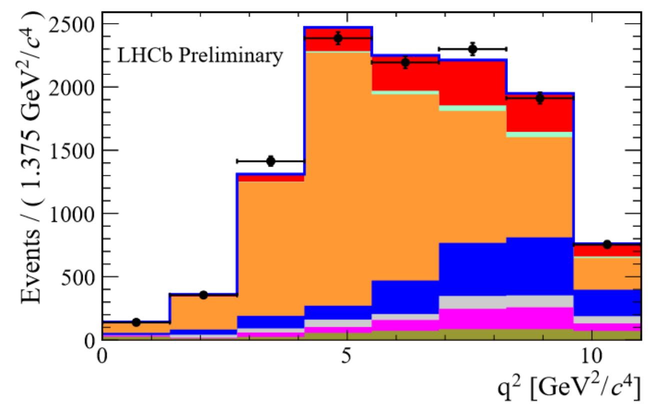
- 3-dimensional template fit (including all correlations) to BDT output, q^2 and estimated tau decay time

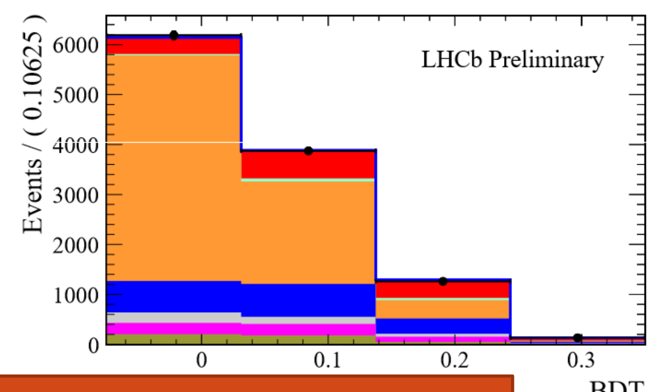
- Templates taken entirely from simulated data with corrections from control regions

- Free components:
  $\tau \to 3\pi\nu$ signal+ $\tau \to 3\pi\pi^0\nu$ signal (in fixed ratio)
  $X_b \to D^{**}\tau\nu$ (fixed ratio to signal)
  $B \to D^{*(*)}D_sX$ (subcomponents constrained by fit to $D_s \to 3\pi$ exclusive region)
  $B \to D^{*+}D^-X$
  $B \to D^{*+}D^0X$
  $B \to D^{*+}3\pi$ residual
  Combinatorial background

- **Result:** $0.285 \pm 0.019 \pm 0.025 \pm 0.013$
  - Splits the difference between SM and previous LHCb





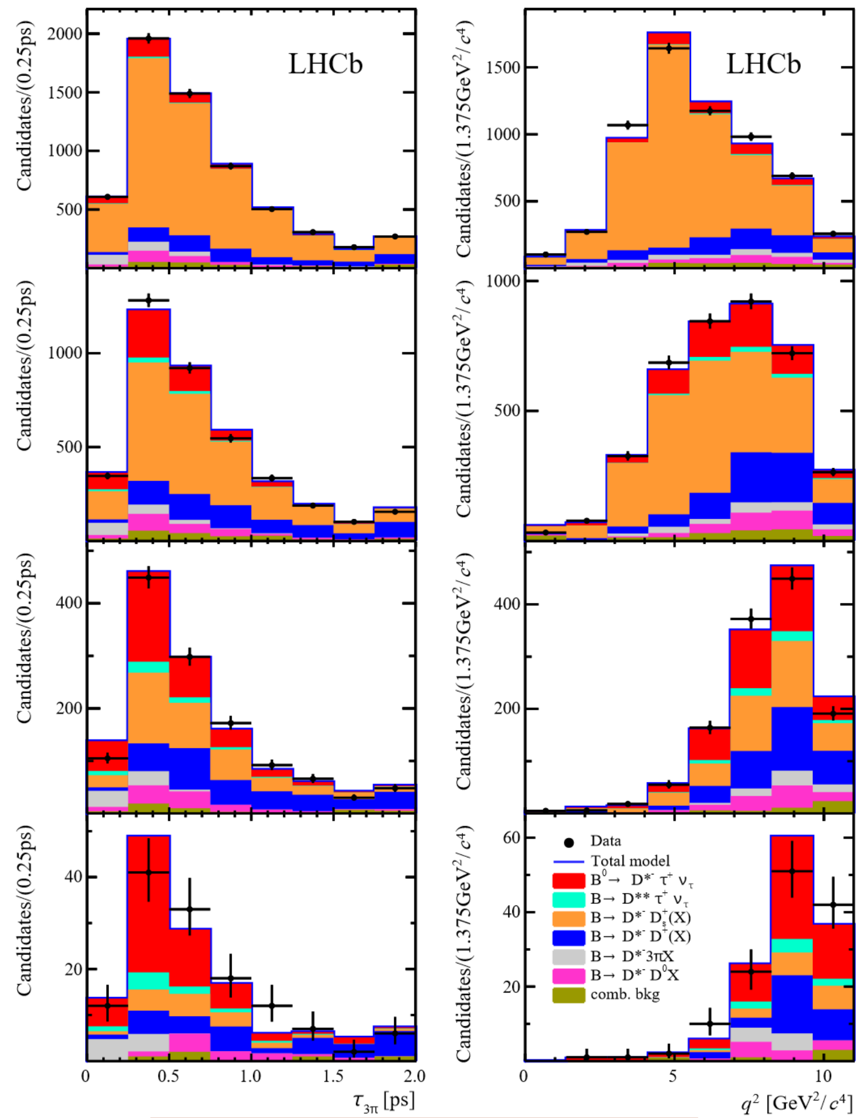


LHCb-PAPER-2017-017 (in preparation)

Systematic Uncertainties and Detailed Projections

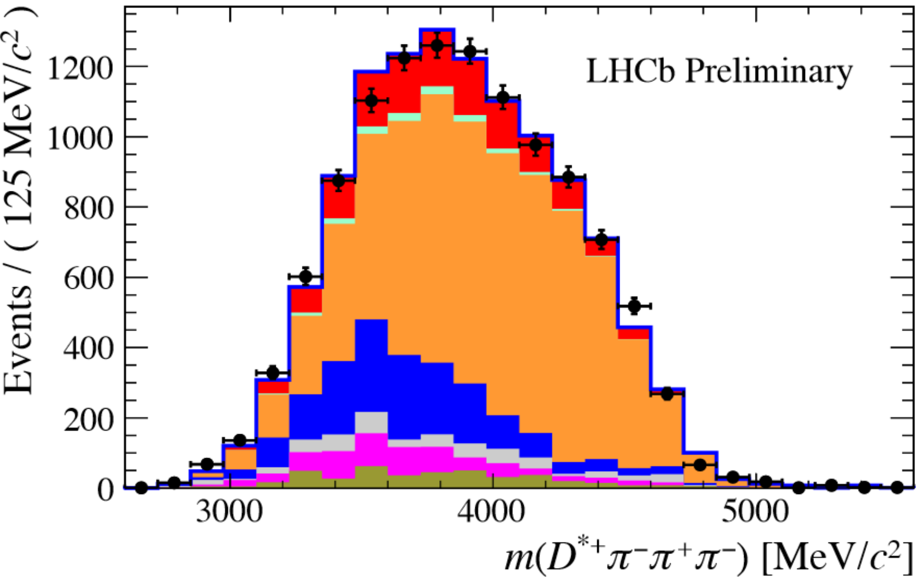
Source	$\delta R(D^{*-})/R(D^{*-})[\%]$
Simulated sample size	4.7
Signal decay model	1.8
$D^{**}\tau\nu$ and $D_s^{**}\tau\nu$ feeddowns	2.7
$D_s^+ \to 3\pi X$ decay model	2.5
$B \to D^{*-} D_s^+ X$, $B \to D^{*-} D^+ X$, $B \to D^{*-} D^0 X$ backgrounds	3.9
Combinatorial background	0.7
$B \to D^* 3\pi X$ 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 $\mathcal{B}(B^0 \to D^* \mu\nu_\mu)$	4.8

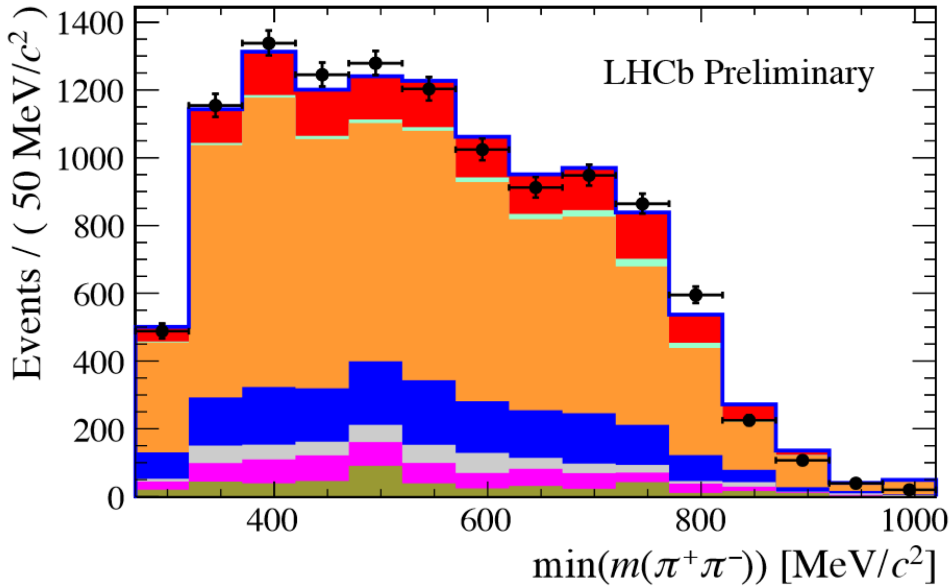
- Largest individual internal systematic is the size of the simulated templates
  - Already lots of CPU time used – work underway trying to find effective fast simulation for template fits
- Knowledge of the shape and 3pi dynamics for the various D decays will be key to driving down future uncertainty
  - Control samples will grow with data and help, but external input will be needed to reach ultimate sensitivity (perhaps with help of BESIII?)
- Normalization uncertainty still quite large despite recent BaBar measurement. More input needed here!



LHCb-PAPER-2017-017 (in preparation)

Post-fit BDT inputs

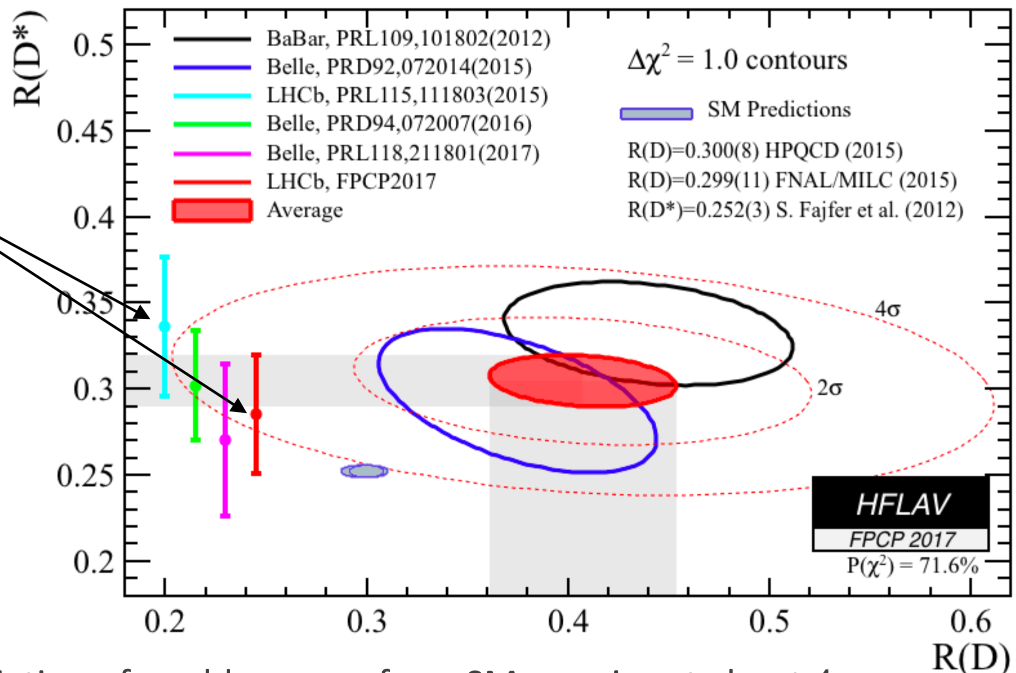




- Important sanity check: good fit to BDT output distribution at the correct minimum should imply good agreement in BDT *input* distribtuions.
- As before, most important are those sensitive to problems with the MC decay model, the 3pi mass and the variables encoding the 3pi dynamics
  - Quality of agreement very acceptable

$R(D^{(*)})$ World Average

This talk



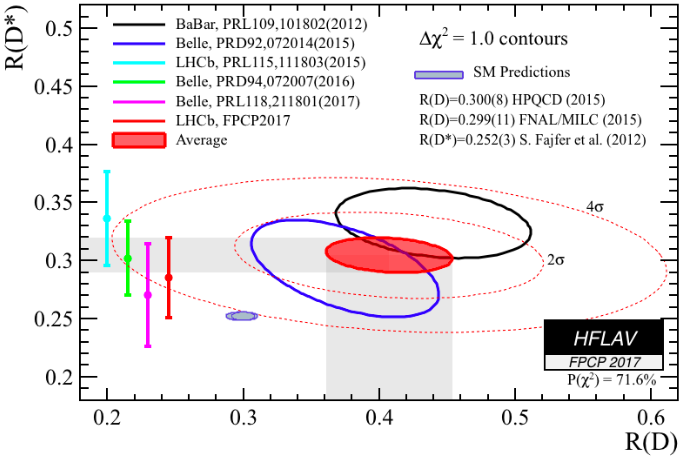
- With new LHCb result, deviation of world average from SM remains at about 4σ
  - Central value reduced very slightly, error bars shrunk by same – familiar story to those who follow, e.g., $|V_{ub}|$ inclusive vs exclusive

- To-Dos:
  - (community) improve R(D*) predictions (go beyond CLN?)
  - (LHCb) need results in baryons (different systematics, can begin to think about spin structure in plausible NP models)
  - (LHCb+Belle-II) better measurements in the R(D) channel (comparable precision here would drive us over 5 sigma at the current central value)

Followup Measurements

WHAT MORE CAN WE LEARN FROM RUN1

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



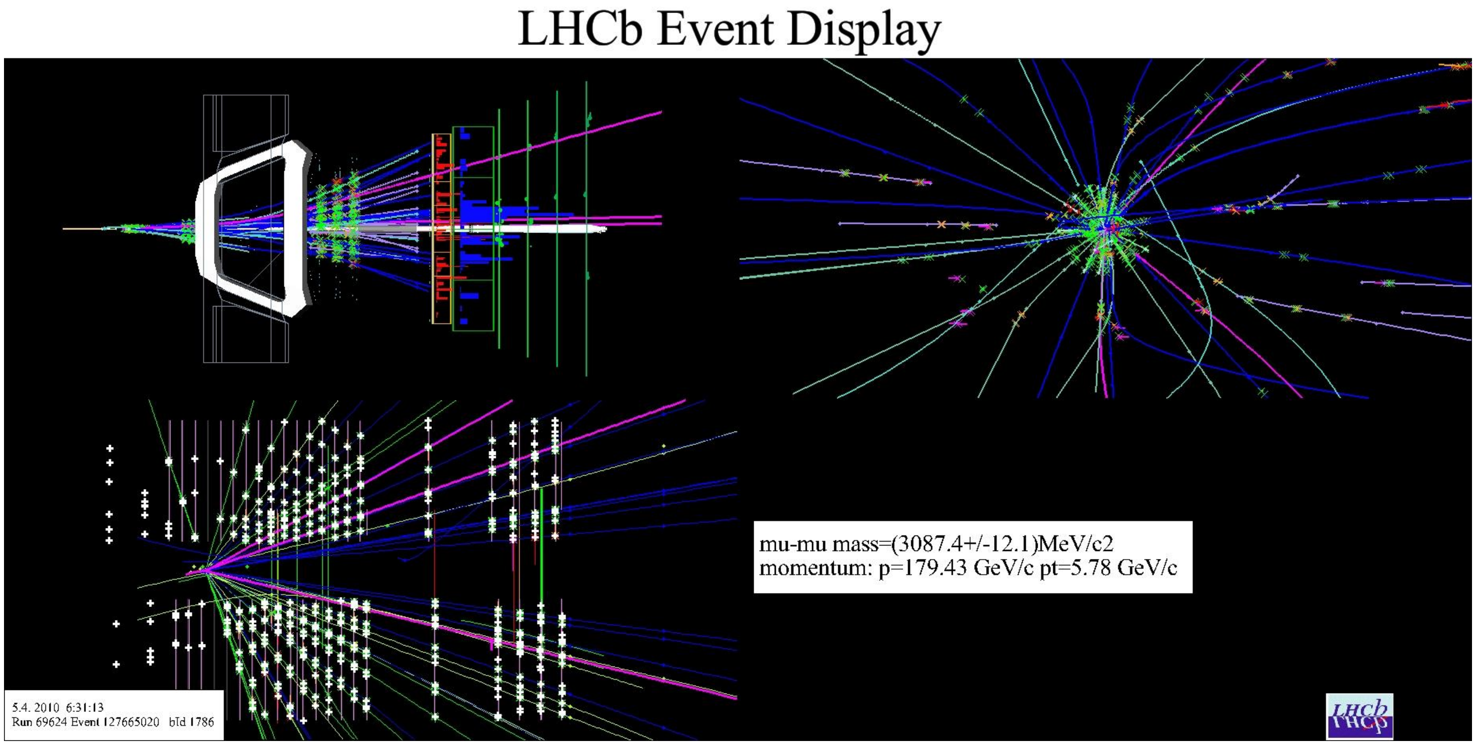
$$\frac{B^- \to D^{*0}[\to D^0(\pi^0/\gamma)]\mu\bar{\nu}}{B^- \to D^0\mu\bar{\nu}} \approx 2.5$$

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

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

- Muonic $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}$ served as a prototype due to simpler measurement structure, better handles on certain backgrounds
- $B^- \to D^0\tau^-\bar{\nu}$ perfectly possible at LHCb
  - Strategy: simultaneous fit to disjoint $D^0\mu^-$ and $D^{*+}\mu^-$ samples
    - Feed-down from D* always present in $D^0\mu^-$ sample → correlation in R(D) vs R(D*).
      - Simultaneously refitting $D^{*+}\mu^-$ sample helps control this
    - Low slow pion efficiency means $D^0\mu^-$ sample is 5x larger
      - 75% is D* feed down → expect big improvement along that direction
- $R(D^+)$ not feasible with Run1 dataset
  - Piggybacking on exclusive charm trigger only works for $D^0 \to h^+h^-$ selection
  - Run 2 adds dedicated triggers for $D^0\mu X$ these final states as well as $D^+\mu X,\ \Lambda_c^+\mu X,\ D_s^+\mu X$

$R(J/\psi) \quad (B_c^- \to J/\psi\tau^-\bar{\nu})$



- Production rate is very low, but trimuon final state is difficult to miss → huge reconstruction efficiency boost compared to $D^{*+}\mu$ final state
  - O(10^4) normalization events in Run1 dataset

- Main challenge is that $B \to J/\psi hX$ with h misidentified as μ is bigger than signal
  - 10^{-3} misID rate compensated by 100x bigger cross-section

“Hadronic tau” program

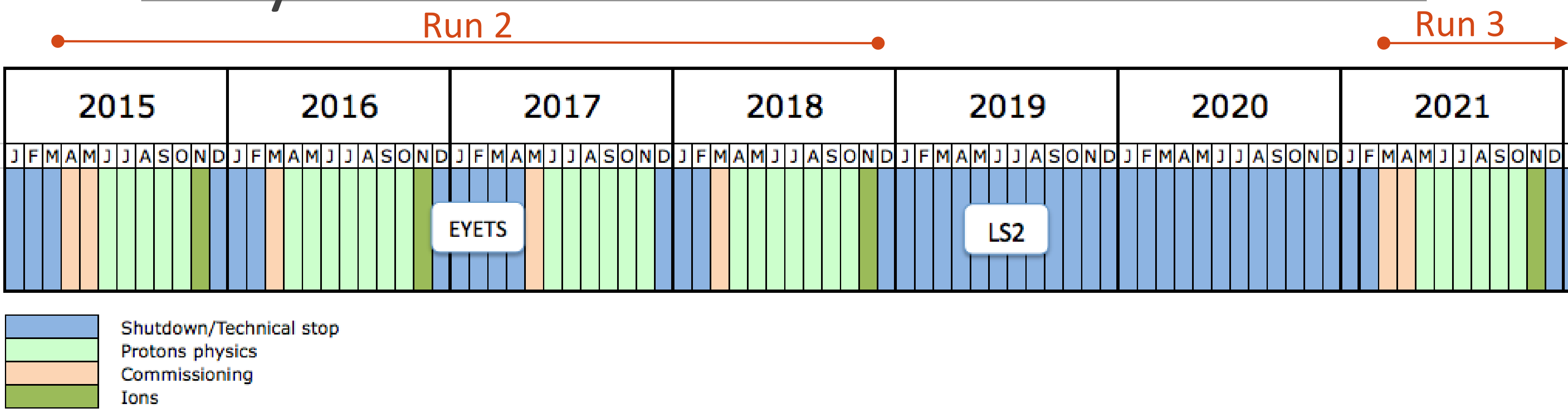
- Statistical uncertainty on $K_{had}(D^{*+}) = \frac{\mathcal{B}(D^{*+}\tau\nu)}{\mathcal{B}(D^{*+}\pi\pi\pi)}$ is expected to come down by a factor of two using the Run1+Run2 dataset
  - Recall internal systematic uncertainties are also mostly scaling with control sample size (=luminosity)
  - Work is already underway to adapt the present analysis to exploit the Run2 data with a combined analysis

- Along with more data, this analysis will also benefit greatly from the full alignment of offline and online reconstruction achieved in Run2
  - Trigger effects under much better control means smaller corrections with smaller uncertainties

- As in the muonic tau decay case, this analysis as a ‘proof-of-concept’ has launched a whole program across all accessible b hadron flavors

LHCb Upgrade

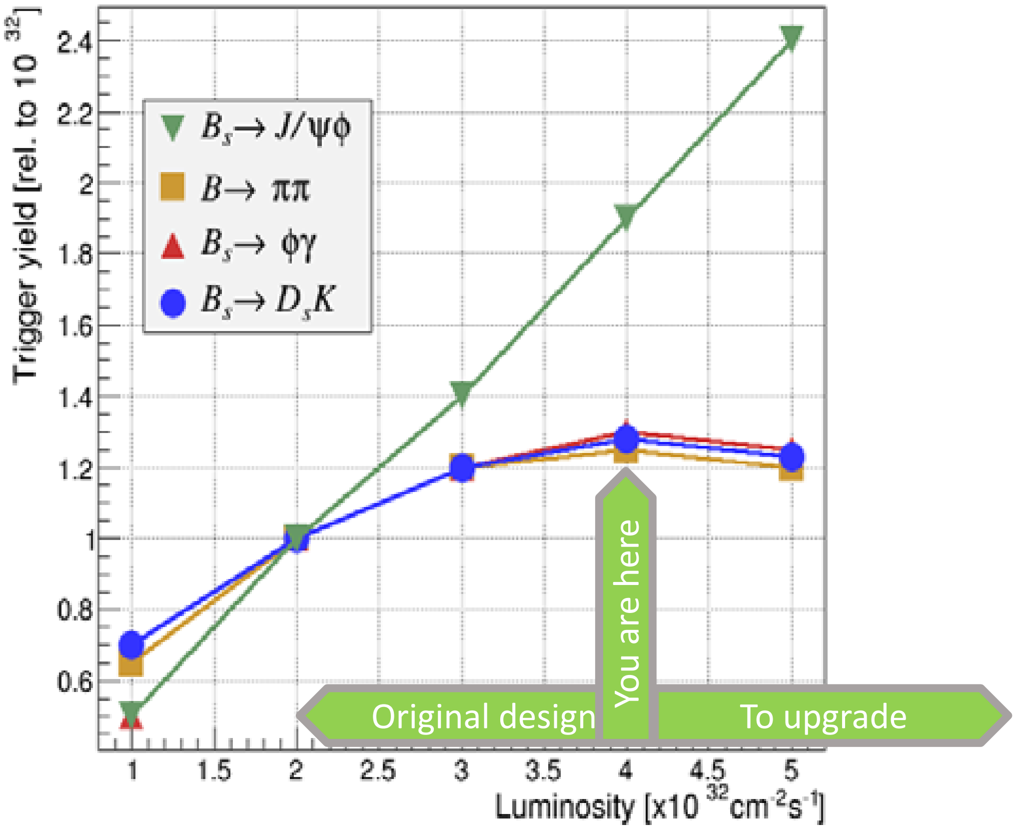
Beyond Run 2



- LHC will continue to operate through the next decade and more
- LHCb is on target to exceed 5/fb
  - After 5/fb and a two year break, its no longer clearly beneficial to keep integrating ~ 1.5/fb per year
    - Progress two incremental
    - Belle-II data-taking set to begin in earnest
  - Goal: increase dataset by an order of magnitude over next phase of running

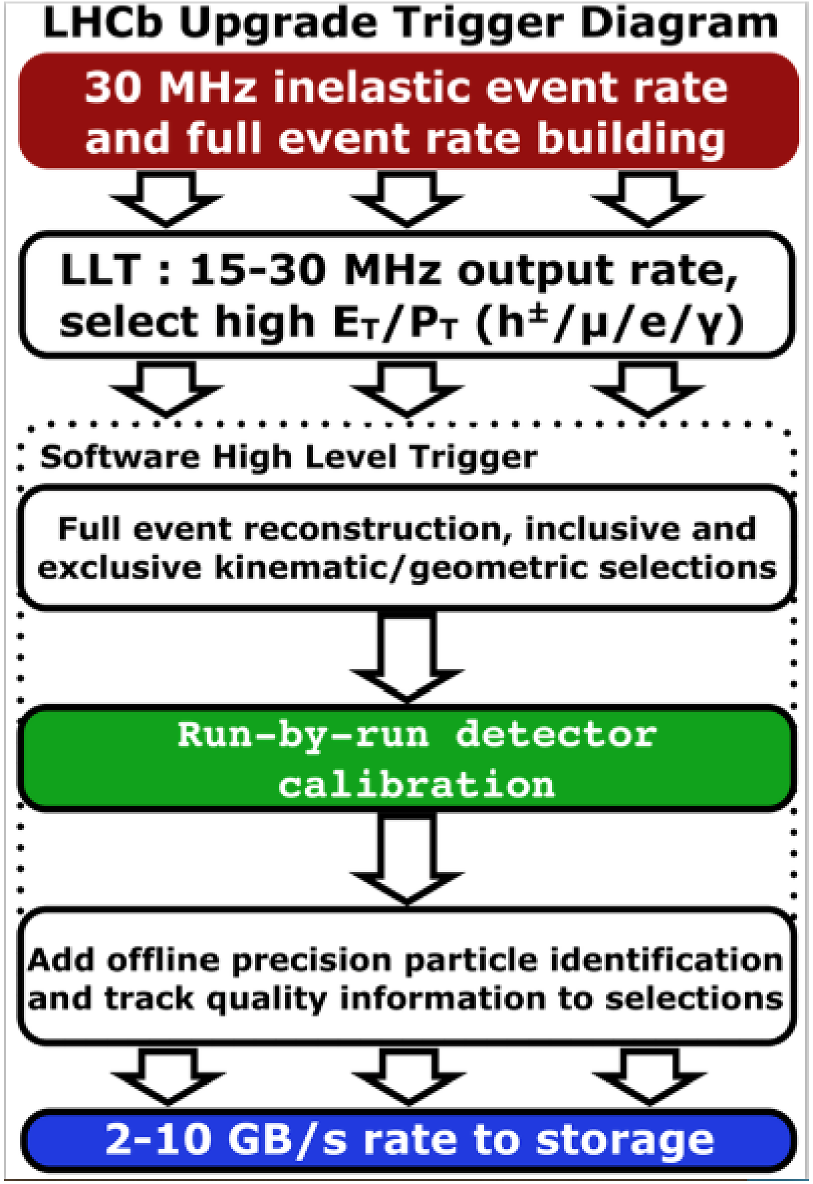
Challenges at high luminosity

- 26 kHz of beauty in acceptnace (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 will go up dramatically
    - All-new tracking system required
  - Cannot rely on hardware E_T thresholds and expect to make intelligent trigger decisions
    - See right: channels with no background-free selection (i.e. not charmonium signals) have already tapered off as thresholds have gone up
    - Need to do something new in the trigger!



Upgrade Trigger

- Hardware trigger will be completely removed, all subsystems read out at 40 MHz LHC clock and passed to all-software trigger
  - Software LLT allows option to throttle event rate
  - Initial HLT reconstruction to reduce below 1-2 MHz
  - Track fit, PID, selection applied to reduce to 20-100 kHz
- Run-by-run detector calibration and offline-quality reconstruction online already built and proven possible in Run2
  - Major milestone towards the next generation of flavor physics data-taking!



Flavor physics with 50/fb

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [30]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [32]	0.045	0.014	~ 0.01
	a_{sl}^s	6.4×10^{-3} [63]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$	0.17 [63]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [64]	0.025	0.008	0.02
	$s_0\ A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [64]	6 %	2 %	7 %
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [9]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [29]	8 %	2.5 %	$\sim 10\,\%$
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [4]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	$\sim 100\,\%$	$\sim 35\,\%$	$\sim 5\,\%$
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [40, 41]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\, K_S^0)$	0.8° [63]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [63]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [8]	0.65×10^{-3}	0.12×10^{-3}	–

- With 50/fb in hand, many CKM and CP violating observables will be pushed up to or beyond their respective theory uncertainty, providing powerful constraints on new physics

Beyond the (phase1) upgrade

- Possiblities being explored for supplemental upgrades on a longer timescale than LS2
  - TOF PID system using BaBar DIRC bars
  - “side chambers” in magnet to provide extra hits on low-momentum tracks bent out of acceptance

- Already studies underway to plot the way forward to a post-LHCb Upgrade which will collect 300/fb

Summary

- B physics experiments are pushing lepton universality tests into new and exciting territories beyond tests of the electroweak interaction, with LHCb playing a key role

- Measurements of LFU in electroweak penguin decays are reaching the 10% precision level with LHCb Run1
  - 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
    - No smoking gun yet! We've seen large deviations disappear in a puff of statistics before!
  - Large improvements expected with LHCb Run2 dataset
    - (Run2 L0 trigger configuration optimized with an eye towards not limiting $B \to K^{(*)}ee$ measurements – no worries about lower bandwidth with larger x-sections)

- 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, but limited by manpower and long lead times required for these systematics-sensitive analyses (template fits are tricky!)

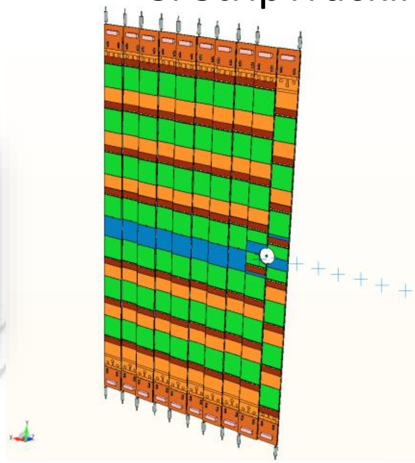
- After a very successful Run1, LHCb is smoothly integrating 13 TeV data
  - Faster rates to storage, higher cross-sections, offline-quality trigger reconstruction all promise to make this data extremely powerful for physics

- LHCb upgrade will allow continued progress on flavor observables at the current pace post-2020
  - Ideas already in the pipeline for late-2020's possibilities

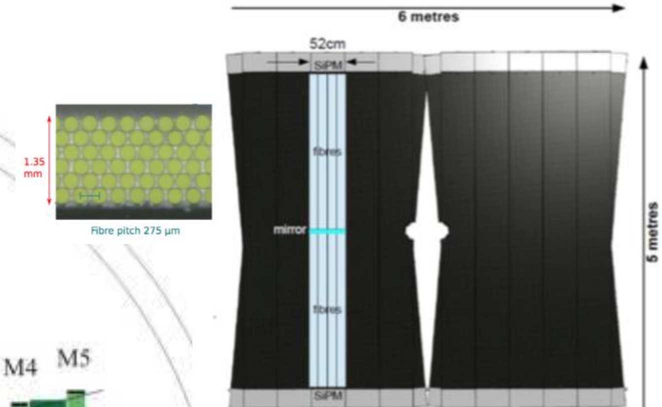
Backup

LHCb Upgrade Hardware

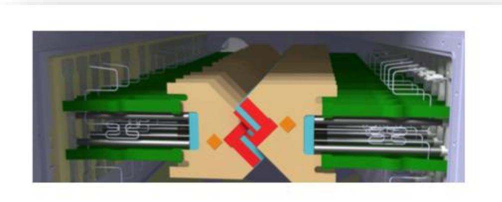
Improved Upstream Si StripTracking

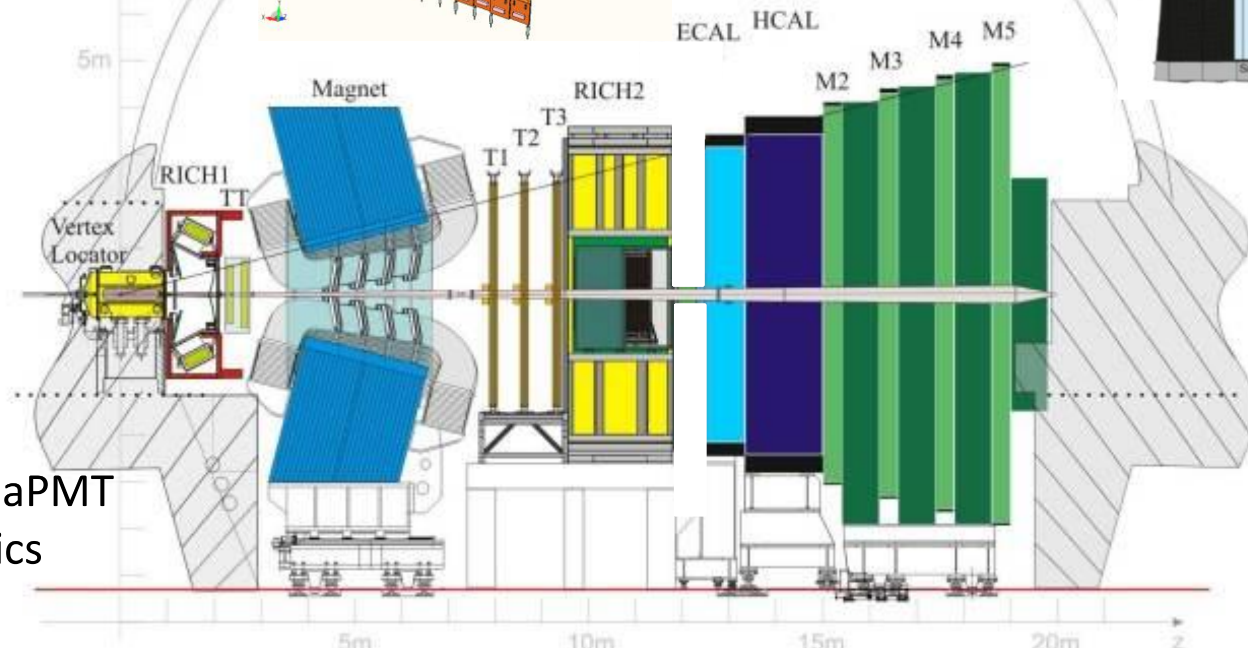


Scintillating Fibre Downstream Tracking



Pixel Velo

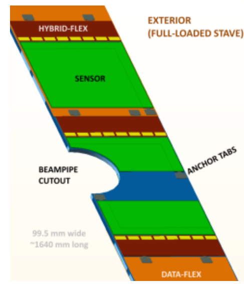


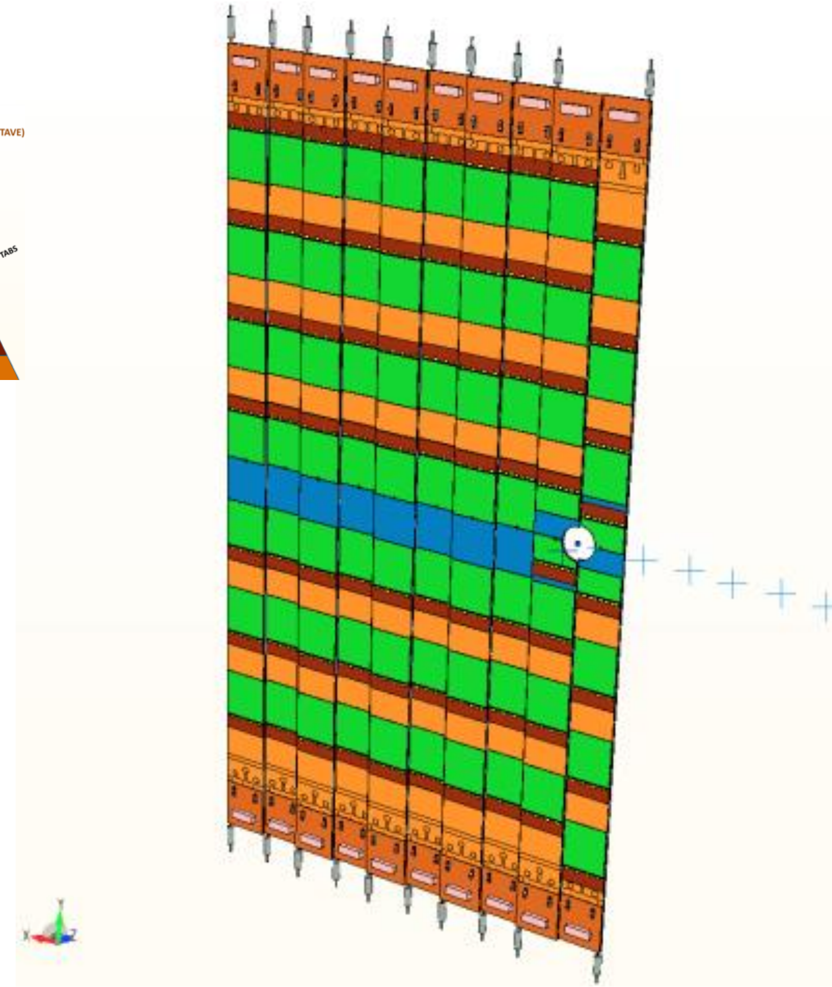


40MHz Muon Readout

New RICH MaPMT sensors+optics

LHCb Upgrade - UT





TT to be replaced with UT (Upstream Tracker)

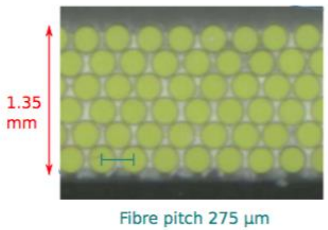
- Collaboration between US institutions (inc. UMD) and INFN, Zurich, AGH and CERN
- 4 planes of Si-strip detectors located ~2m from interaction point replacing current TT
  - Features improved segmentation, full fiducial coverage of every layer
  - FE electronics on ASIC at sensor – allows for zero-suppressed 40 MHz readout

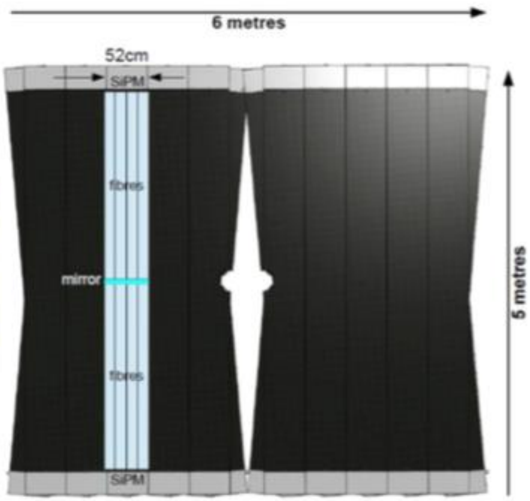
Will allow for fast reconstruction of track segments before extrapolating to downstream trackers, improving HLT tracking speed by a factor of 3

LHCb Upgrade - SciFi

Silicon+Straw tubes downstream tracking replaced by new detector based on <u>sci</u>ntillating <u>fi</u>bers

- 3x XUVX stations
- 250 µm fibers read out by SiPM arrays provide excellent spatial resolution (~65 µm)
- Split at y=0 with mirror to increase light yield

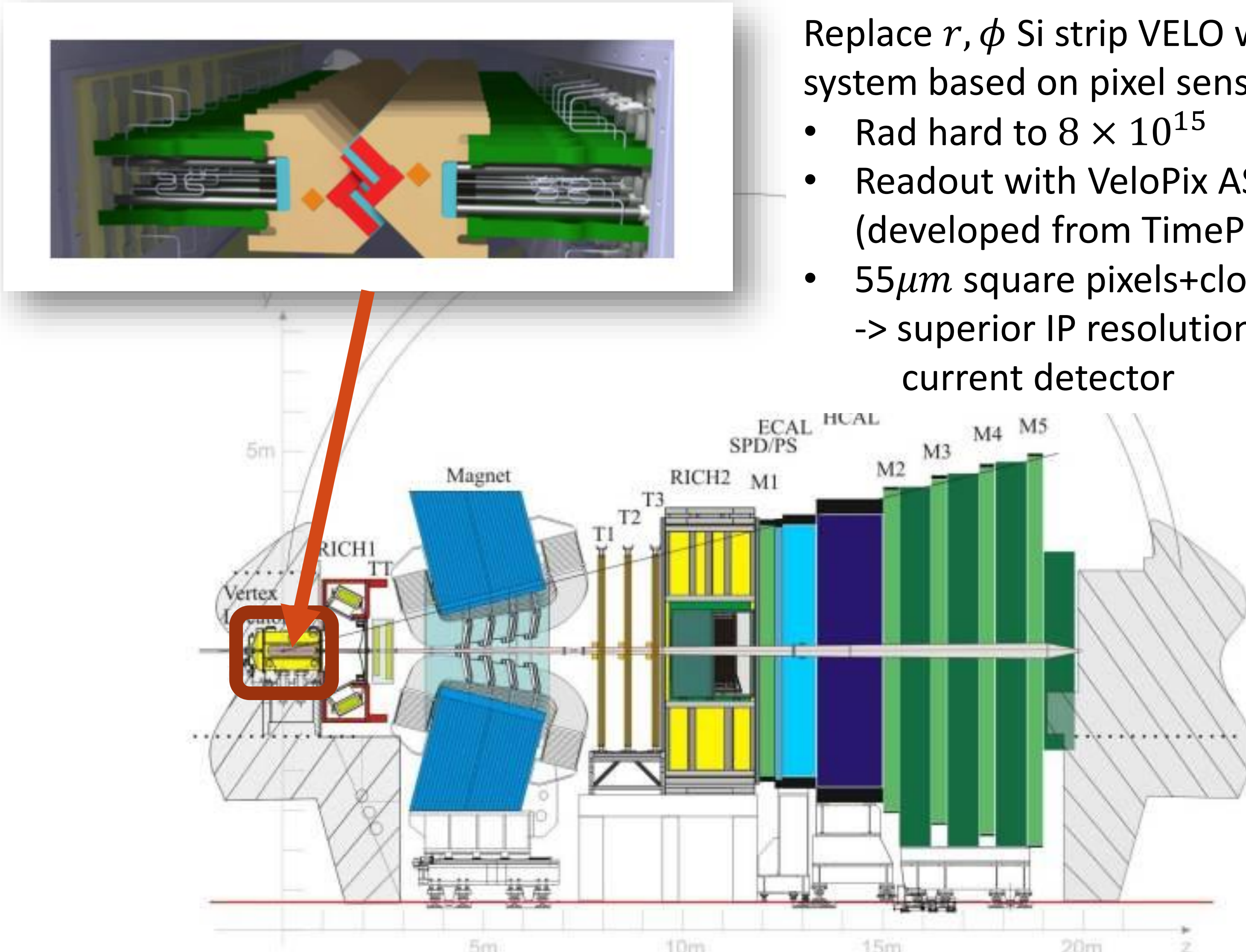




LHCb Upgrade - VELOPIX

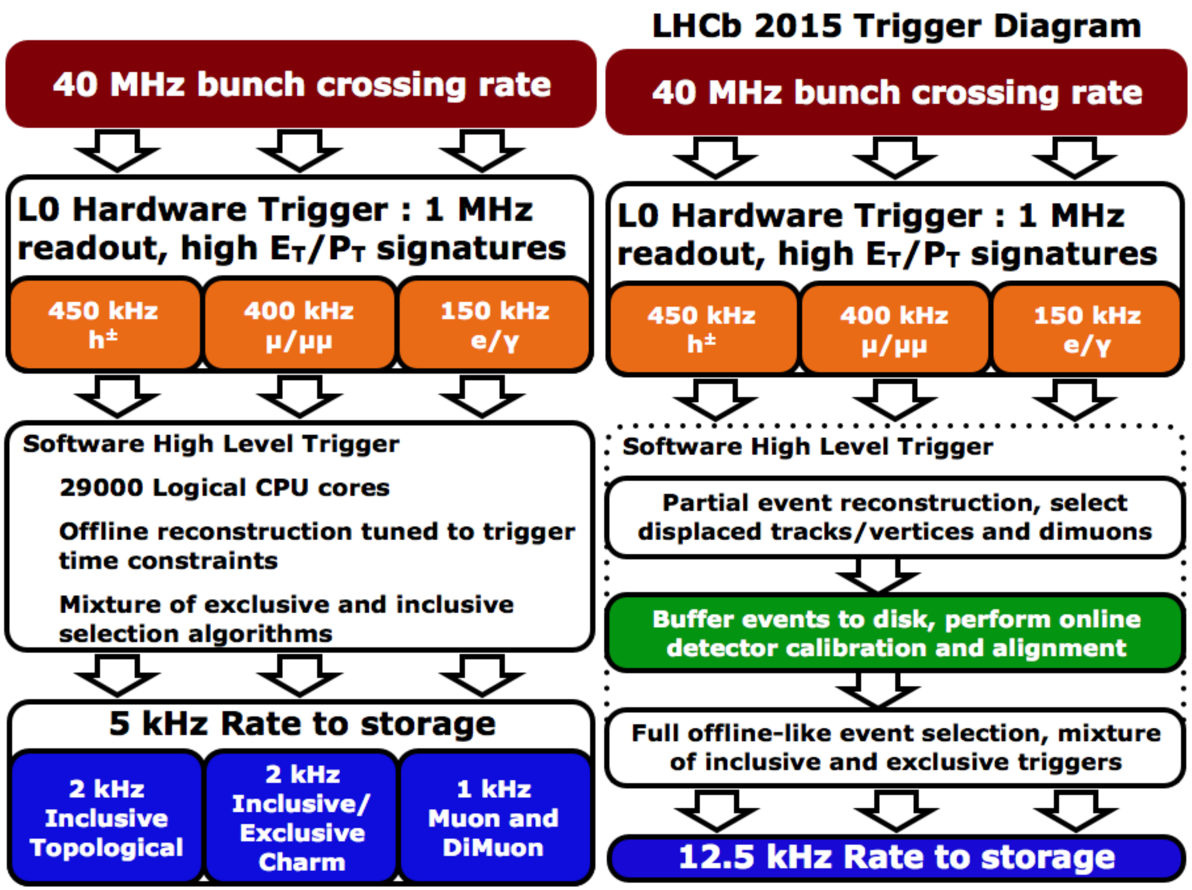
Replace r, ϕ Si strip VELO with new system based on pixel sensors

- Rad hard to 8×10^{15}
- Readout with VeloPix ASIC (developed from TimePix/MediPix family)
- $55\mu m$ square pixels+closer to the beam -> superior IP resolution compared to current detector

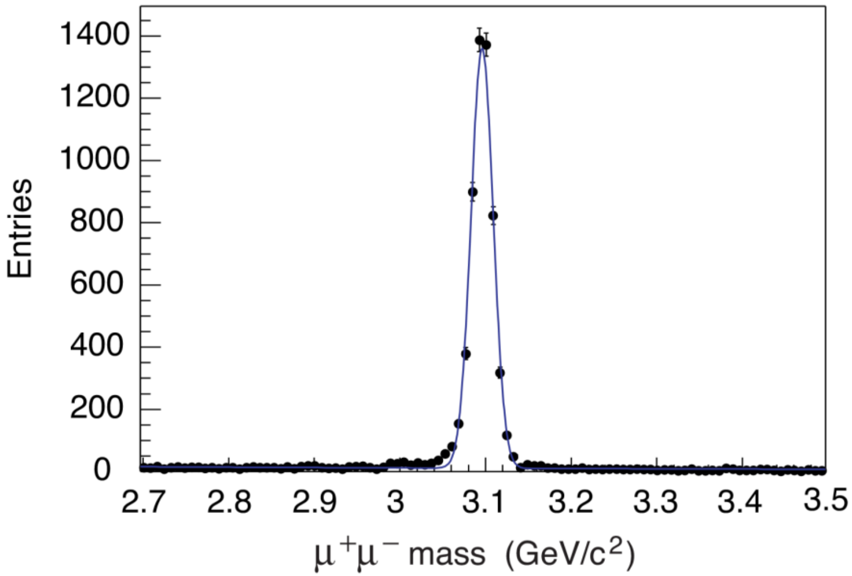


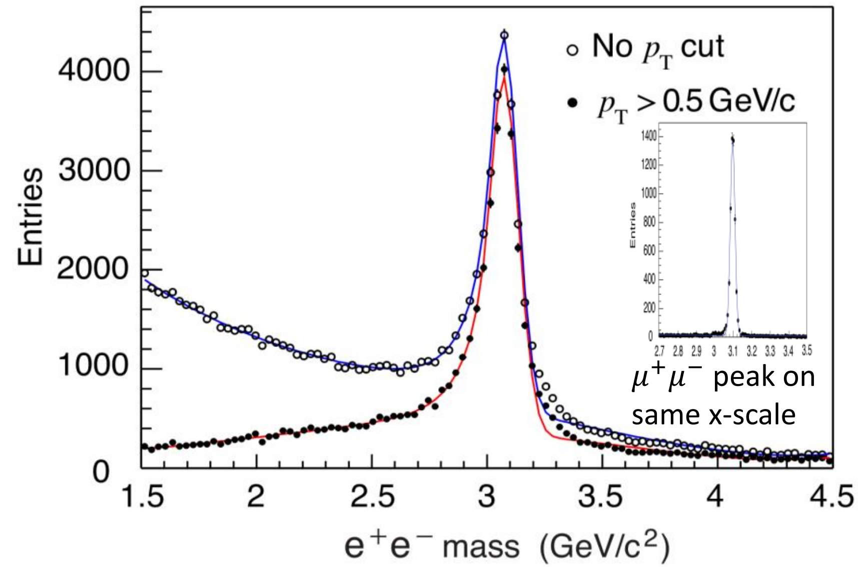
Triggering on Heavy Flavor

- Triggering inclusively as possible is *essential* in order to not limit the physics program
- Software high-level trigger performs full event reconstruction for all tracks above 300 MeV of p_T
  - First level searches for single high-impact parameter tracks with > 1.6 GeV of p_T
  - Mix of inclusive n-body displaced vertex and exclusive selections to arrive at trigger decision
  - Exclusive high-pt charm triggering for charm physics and access to alternate sample of b to c decays
- New in Run2: aggressive buffering of first-stage software trigger to provide offline-quality calibration and alignment in the trigger

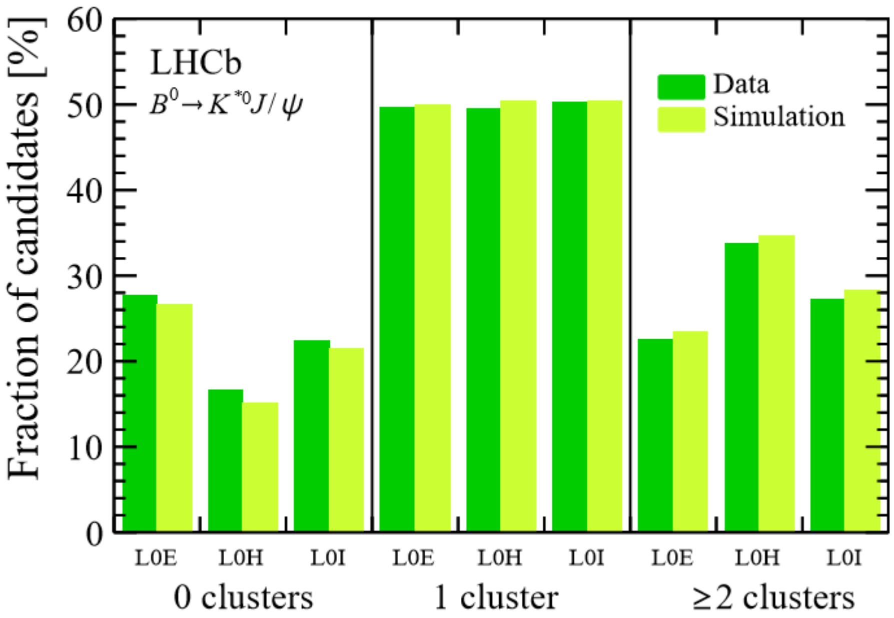


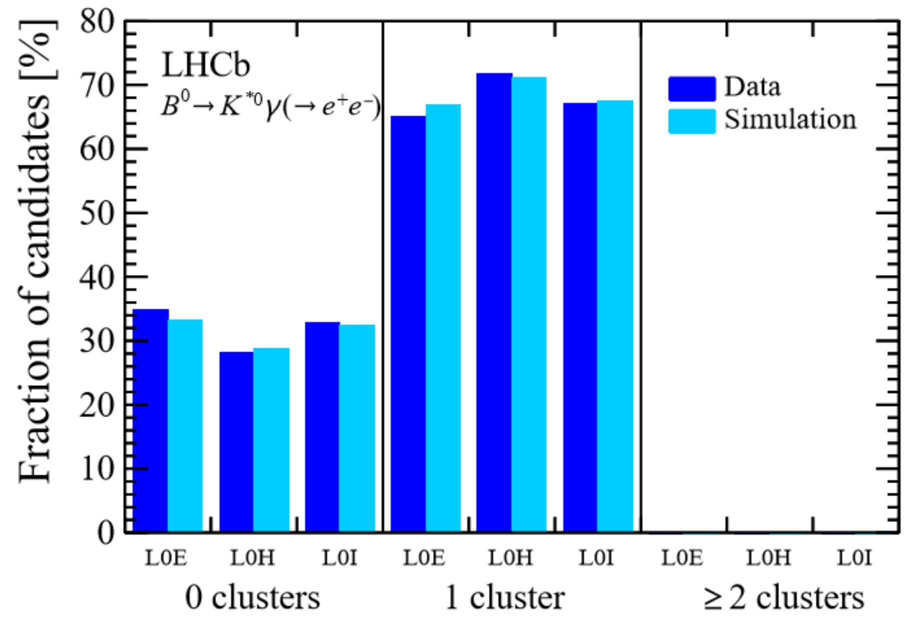
e vs μ reconstruction





K^*ee reconstruction paths





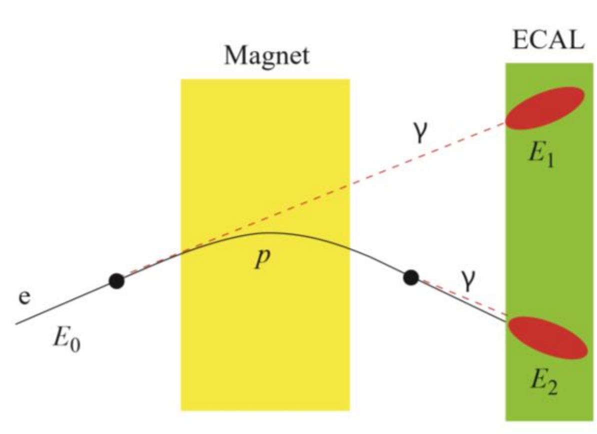
Low q2 = low opening angle means that separate clusters are not resolved

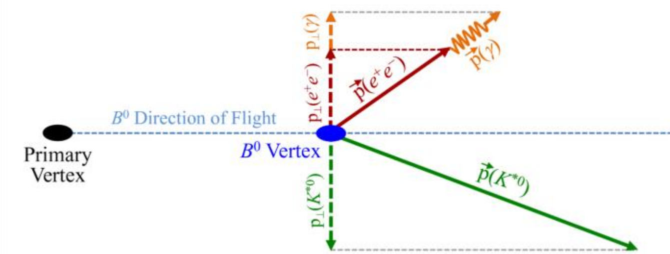
JINST 3 S08005 (2008)

arXiv:1705.05802

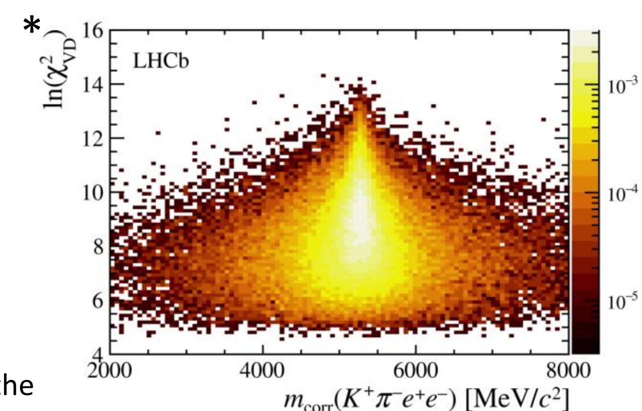
Electron mode tools

- 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



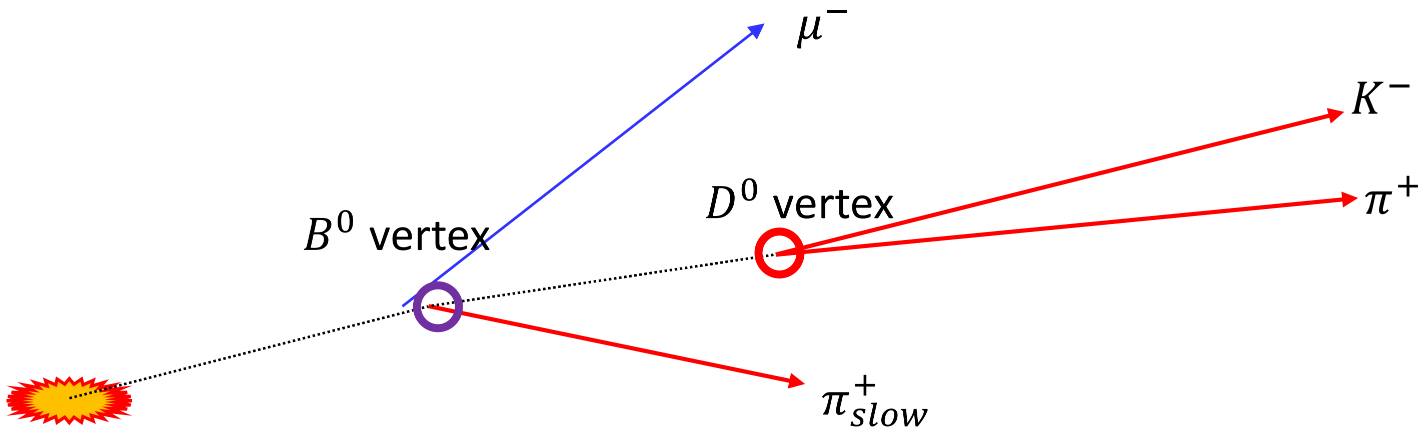


- Energy threshold and isolation requirement means not all large-angle bremsstrahlung is recovered
  - Can build a *corrected mass* to further distinguish backgrounds
    - Add p_γ (middle) to reconstructed B where $p_{\gamma_\perp} = p_{K^*{}_\perp} - p_{e^+e^-{}_\perp}$, recompute B mass
  - Resulting resolution vs candidate separation from PV shown bottom right (note the log scale)



* χ^2_{VD} = delta chi2 for the hypothesis that the candidate vertex is at the PV vs nominal position

Muonic RD* Event Selection



- Combine $D^0 \to K^-\pi^+$ candidate passing charm trigger with μ^- and π^+_{slow} (inclusive displaced vertex triggers biased in missing mass)
  - Require $D^0 \to K^-\pi^+$ decay vertex well-separated from PV
  - Require $\mu^-, K^-\pi^+$all to have significant impact parameter with respect to PV
  - Remove prompt charm background with impact parameter requirements on $D^0 \to K^-\pi^+$

Semileptonic Backgrounds

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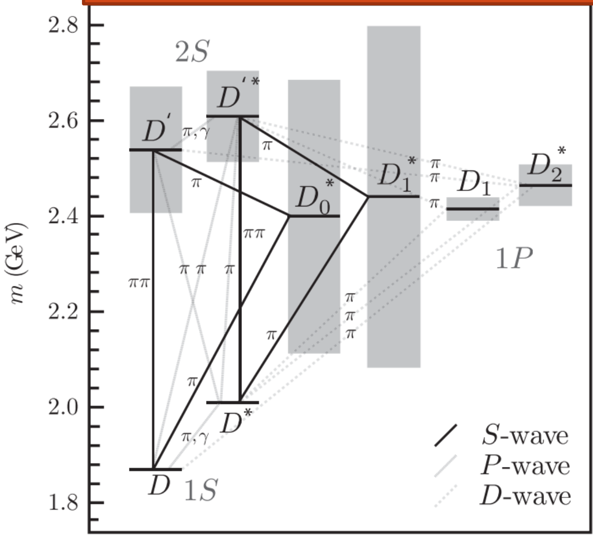
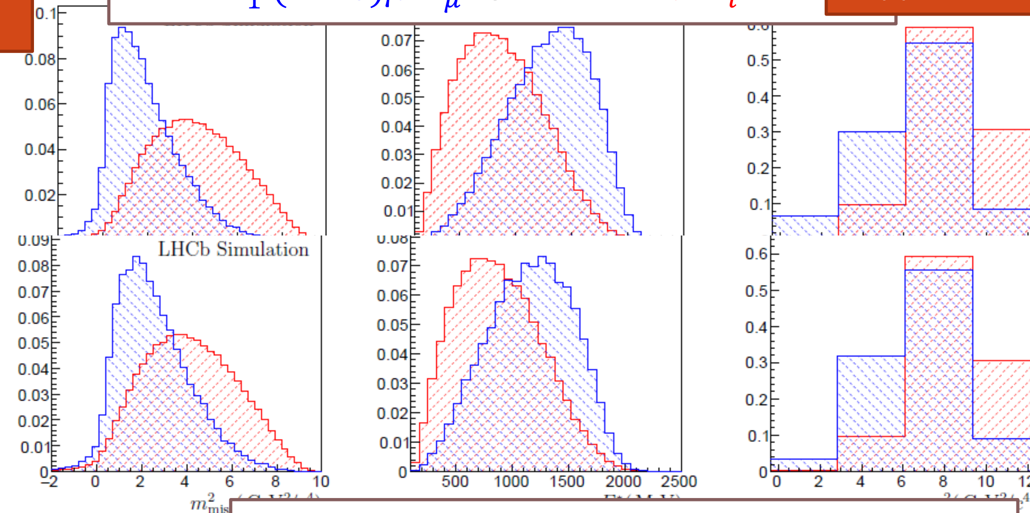
Bernlochner et al, PRD 85 094033 (2012)



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



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

- Contributions of excited charm states in the $B^{\pm,0} \to (c\bar{q})\mu\nu$ 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

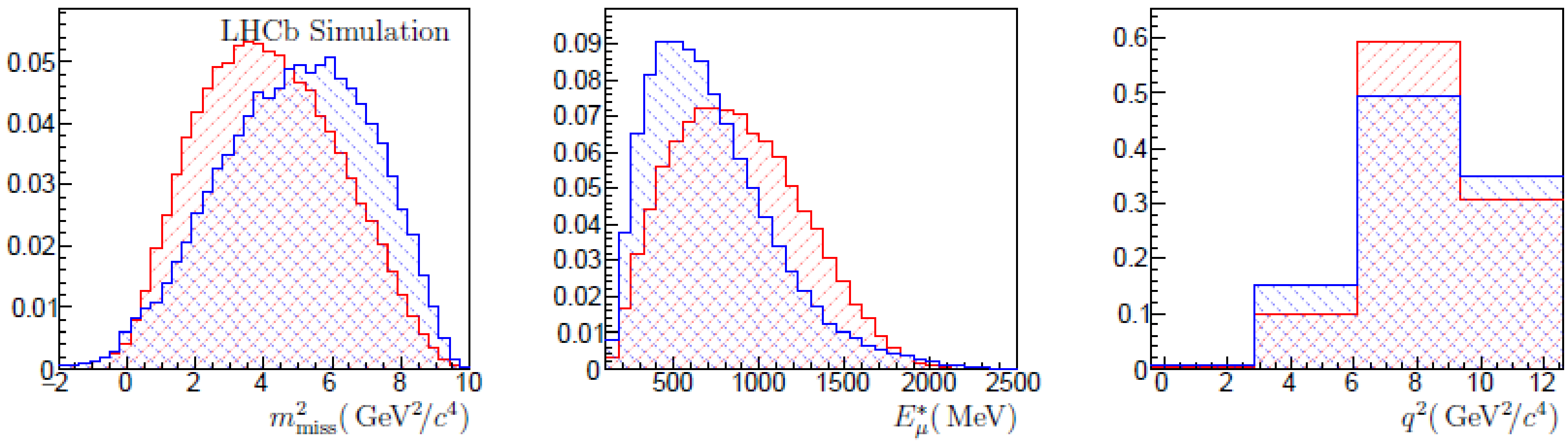
- Distinguishable by "edge" at missing mass $\approx (2)m_\pi$

- 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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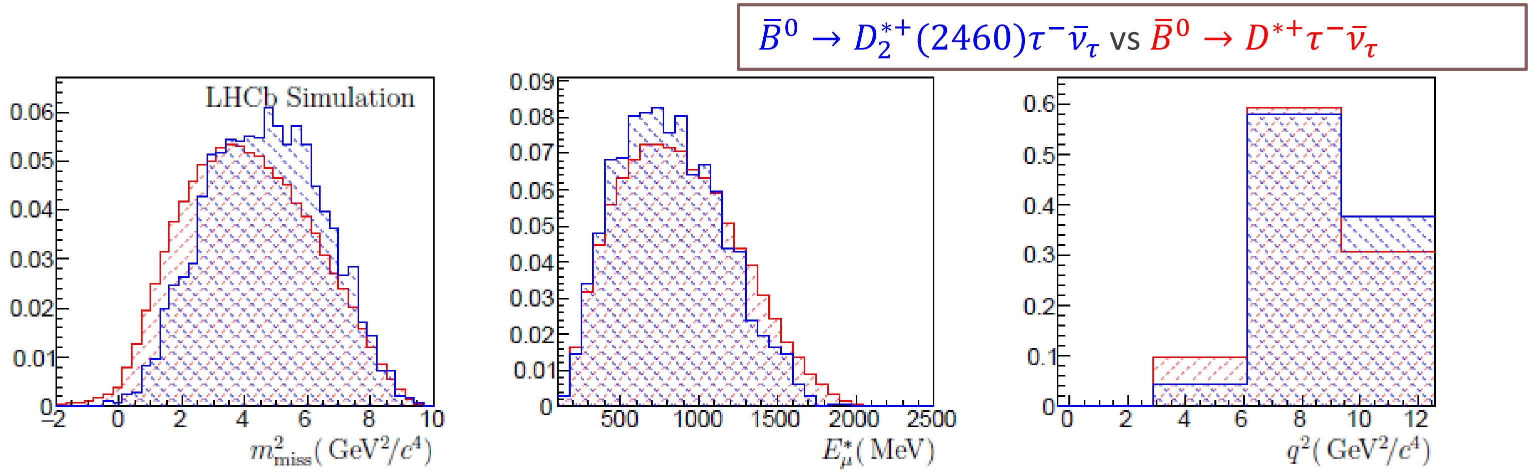
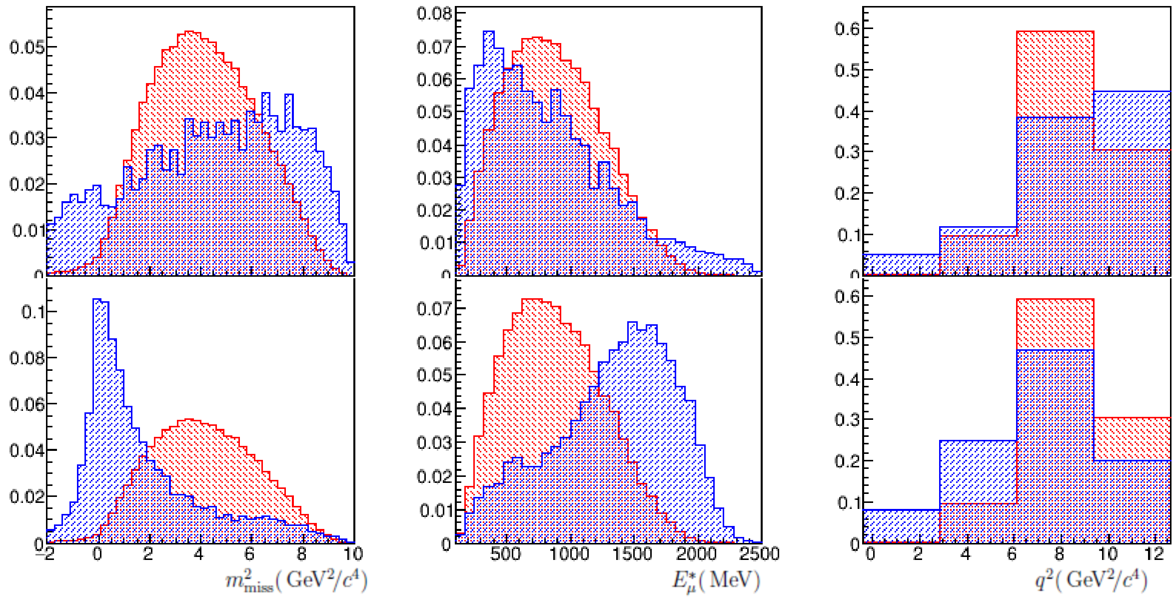
Tau backgrounds



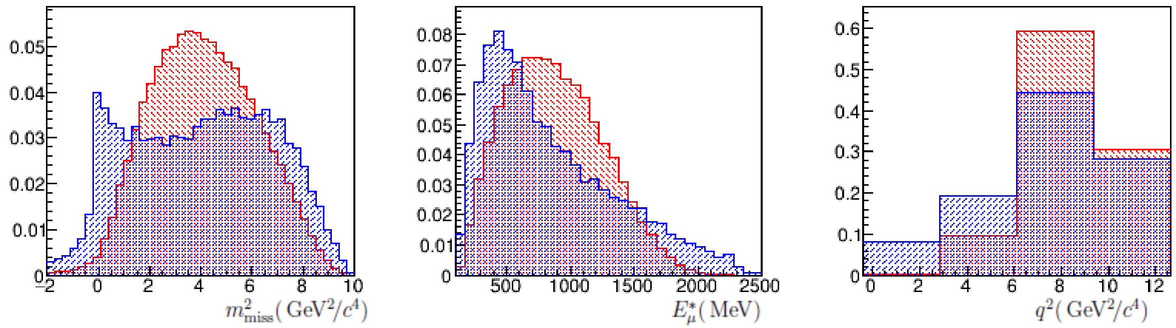
- All backgrounds with real $\tau \to \mu\bar{\nu}\nu$ decays are an order of magnitude (at least) smaller than the signal
  - Background contributions from $\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau$ are considered to be fixed relative to the corresponding decay modes to muons
    - Very small component, 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*)

Other backgrounds

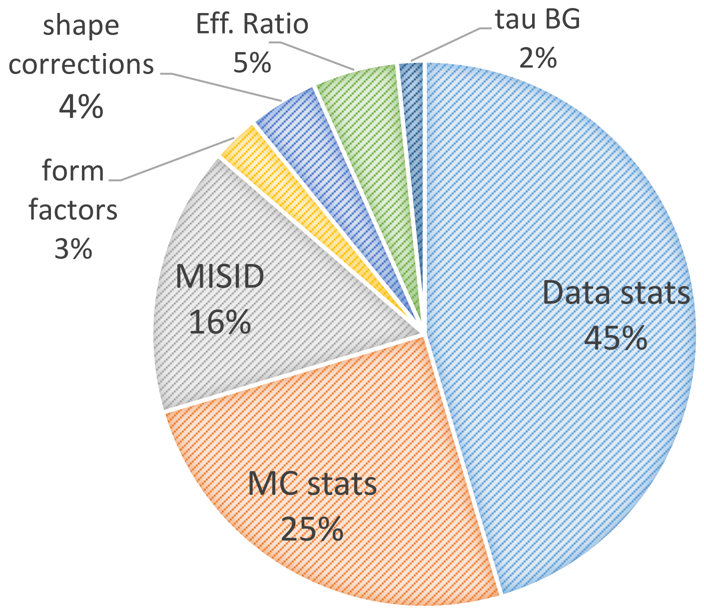
- Other backgrounds from “junk” reconstructed as $D^{*+}\mu^-$
  - combinatorial (top), fake D^{*+} candidates (middle), hadrons misidentified as muons (bottom), all derived from control samples



- Misidentification background particularly troublesome due to ambiguities in deriving fit shapes from the control sample



Muonic RD* Uncertainty Breakdown

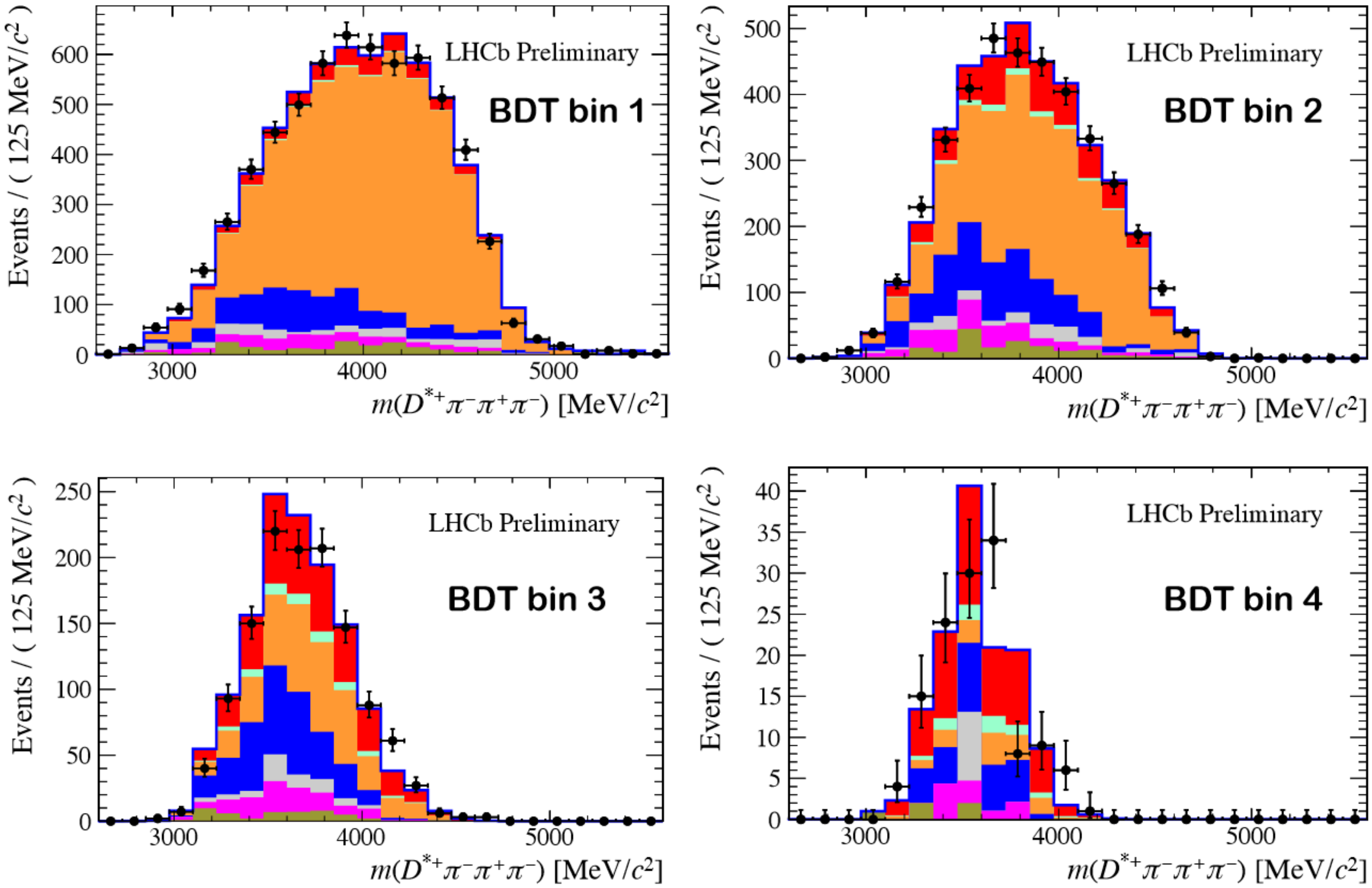


Contribution of each source to the squared total measurement uncertainty

- Systematic error bars are larger, but measurement is in fact statistics limited

- Good prospects for future improvement
  - Form factors, shape corrections all taken from fits to data – will reduce by themselves
  - MC stats simple (if CPU intensive) to reduce
  - Substantial progress on better data-driven misID templates for other analyses

Post-fit BDT


LHCb Preliminary
BDT bin 1
BDT bin 2
BDT bin 3
BDT bin 4
Events / (125 MeV/c^2)
$m(D^{*+}\pi^-\pi^+\pi^-)$ [MeV/c^2]

D** in data – 3pi

- Investigated creating a D**-enriched sample for the 3pi analysis

- Observed yield used to set upper limit and compare to theory expectation for $\mathcal{B}(B \to D^{*+}\tau\nu)/\mathcal{B}(B \to D^{**+}\tau\nu)$
  - Result is compatible with expected value