EXPERIMENTAL OVERVIEW OF LEPTON NONUNIVERSALITY RESULTS AND PROSPECTS FROM B PHYSICS

DPF2015 Ann Arbor, MI
August 7, 2015

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(on behalf of the LHCb Collaboration, including results from BaBar and Belle)
Lepton universality

- In 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 $e, \mu, \tau$ must all be identical up to effects depending on lepton mass (these effects can be large!)
    - Examples:
      - $\mathcal{B}(Z \to e^+e^-) = \mathcal{B}(Z \to \mu^+\mu^-) = \mathcal{B}(Z \to \tau^+\tau^-)$
      - $\mathcal{B}(\psi(2S) \to e^+e^-) = \mathcal{B}(\psi(2S) \to \mu^+\mu^-) = \mathcal{B}(\psi(2S) \to \tau^+\tau^-)/0.3885$

- Observation of violations of lepton universality would be a clear sign for physics beyond the standard model
  - Searches have been underway for violations 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...
  - These provide very strong limits on nonuniversality in the SM electroweak interactions
Nonuniversality in NP

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

- In particular, new physics preferentially coupling to the 3\textsuperscript{rd} 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 models are strongly constrained by high-Pt searches, but can be tuned to evade these bounds while preserving their effect on heavy flavor searches

- LFU measurements in heavy flavor decay provide additional constraining power beyond light flavor and tau decay measurements
SM flavor structure and B physics basics

- Standard model flavor structure is described by the Cabibbo-Kobayashi-Maskawa mixing matrix.

- $V_{	ext{CKM}}$ 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
  - $|V_{cb}| \sim 0.04$
  - Makes B physics quite sensitive to NP generically misaligned with CKM

- Also leads to long $b$ quark lifetime: $c\tau_B \sim 400\mu m! (= \text{about } 2x \text{charm lifetime})$
  - Very Important for hadron collider $b$ tagging/reconstruction
  - Allows access to time-dependent phenomena
The players
Cast (1/3): BABAR/PEP-II

- 5-layer inner silicon strip tracker (SVT) plus 40-layer multicell drift chamber (DCH) in a 1.5 Tesla axial B field
- Dedicated Cherenkov PID system with quartz (n~1.474) radiator
  - PID at low p from dE/dx in both DCH and SVT
- CsI(Tl) crystal calorimeter
- Magnet flux return instrumented with RPCs and/or LSTs (depending on run period)
- Υ(4S) dataset: ≈ 470 × 10⁶ BB̅ pairs
Cast (2/3): Belle/KEKB

- 3/4-layer double-sided Silicon Tracker plus drift chamber
- Particle ID via measurements of time of flight and Cherenkov counter
- Excellent $\mu/K_L$ detection
- CsI(Tl) crystal calorimeter measures photon energies and assists in PID
- $\Upsilon(4S)$ dataset: $\approx 770 \times 10^6 B\bar{B}$ pairs
Single-arm spectrometer – $2 \leq \eta \leq 5$

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

- Instruments $\lesssim 3\%$ of the solid angle to cover 27% of the b-quark cross-section

- Run1 dataset: 3fb$^{-1}$, Run2 datataking has already begun with 50ns ramp

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

At 7 TeV:
- $\sigma_{\text{inel}} \sim 70$ mb
- $\sigma_{c\bar{c}} \sim 6$ mb
- $\sigma_{b\bar{b}} \sim 280$ mb
b hadron production

B-factories: exploit clean BB production from Y(4S)
- Event shape discriminates $B\bar{B}$ vs $e^+e^- \rightarrow q\bar{q}$, $q = u, d, s, c$
- B mesons fly together, easy to cross-feed tracks between the two B mesons

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 $gg \rightarrow b\bar{b} + MPI + showering + ISR + \ldots$, very messy
Selected Results
B-factory measurements in $e^+e^- \rightarrow \tau^+\tau^-$ have been used to set tight limits on nonuniversality in the electroweak interaction.

$\tau^{\pm}$ decays to different charged leptons are calculable in the SM and naturally have negligible hadronic uncertainty. Thus:

$$\frac{\Gamma_{\tau \rightarrow e}}{\Gamma_{\mu \rightarrow e}} \propto \left( \frac{g_\tau}{g_\mu} \right)^2 = \frac{\tau_{\tau}}{\tau_{\mu}} \mathcal{B}(\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau) \left( \frac{m_\mu}{m_\tau} \right)^5 \frac{f(m_e^2/m_\mu^2) r^\mu_{EW}}{f(m_e^2/m_\tau^2) r^\tau_{EW}}$$

$$\frac{\Gamma_{\tau \rightarrow \mu}}{\Gamma_{\mu \rightarrow e}} \propto \left( \frac{g_\tau}{g_\mu} \right)^2 = \frac{\tau_{\tau}}{\tau_{\mu}} \mathcal{B}(\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau) \left( \frac{m_\mu}{m_\tau} \right)^5 \frac{f(m_e^2/m_\mu^2) r^\mu_{EW}}{f(m_e^2/m_\tau^2) r^\tau_{EW}}$$

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Waverage values with uncertainty of $\mathcal{O}(1.5 \times 10^{-3})$ have been obtained using information from B-factory measurements (esp. mass, lifetime)

PoS:KAON 054 2008 + HFAG 2014
EW penguin decays

PRL 113 (2014) 151601
PRD 86 (2012) 032012
PRL 103 (2009) 171801
Electroweak Penguins

- Penguin transitions stringently test the structure of the electroweak interaction
  - Loop structure with almost all major SM players at once: $W, Z, \gamma, t$
  - New particles connected to EWSB can appear and introduce $q^2$- or angular-dependent interference

- 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 $b \rightarrow c\bar{c}s$ amplitudes, $c\bar{c}$ vacuum polarization, long distance effects...)

- Lepton universality test: standard lore is that
  $$R(K) \equiv \frac{\mathcal{B}(B \rightarrow K\mu^+\mu^-)}{\mathcal{B}(B \rightarrow Ke^+e^-)} = 1 \pm \mathcal{O}(10^{-3})$$  if only $\gamma, Z$ participate
More on decay structure

- R(K) measurements can be performed anywhere in $q^2$
  - B factory measurements in high and low regions

- LHCb only measures below to $q^2 < 6$ GeV$^2$
  - $\psi$ resonances may dilute out NP contributions
  - high $q^2$ is very poorly modeled by naïve factorization

Cartoon taken from C. Linn’s FPCP 2015 slides

arXiv: 1406.0566
Analysis

\[ B\bar{A}B\bar{A}R \]
(high q2)

PRD 86 (2012) 032012

\[ LHCb \]
(left: electron triggered category)

PRL 113 (2014) 151601

- Analysis is (relatively) straightforward at all facilities
  - Fully reconstructed final state
  - LHCb: fit directly in reconstructed mass
  - B-factories: cut on \( E - E_{\text{beam}} \), fit in \( m_{ES,BC} \equiv \sqrt{\left( \frac{E_{CM}^*}{2} \right)^2 - (p_B^*)^2} \)
    - Belle additionally fits in \( \theta_B = \text{angle between B and beam in CM frame} \)
- Non-B background suppressed by multivariate classifiers in all experiments
Results

- Good compatibility between various experiments (by eye)
  - Belle: \[ R_K = 1.03 \pm 0.19 \pm 0.06 \]
  - BaBar:
    \[
    R_K, q^2 < 8.12 \text{GeV}^2 = 0.74^{+0.40}_{-0.31} \pm 0.06
    \]
    \[
    R_K, q^2 > 10.11 \text{GeV}^2 = 1.43^{+0.65}_{-0.44} \pm 0.12
    \]
  - LHCb:
    \[
    R_K, q^2 < 6 \text{GeV}^2 = 0.745^{+0.090}_{-0.074} \pm 0.036
    \]

- More data clearly needed here to clarify the situation and set harder limits in this system

Related results:
- Belle:
  \[ R_{K^*} = 0.83 \pm 0.17 \pm 0.08 \]
- BaBar:
  \[
  R_{K^*}, q^2 < 8.12 \text{GeV}^2 = 1.06^{+0.48}_{-0.33} \pm 0.08
  \]
  \[
  R_{K^*}, q^2 > 10.11 \text{GeV}^2 = 1.18^{+0.55}_{-0.37} \pm 0.11
  \]
- LHCb:
  analysis ongoing
Entertaining hypotheticals...

- Other similarly-sized deviations across $b \to s \mu \mu$ measurements:
  - Branching fractions consistently below expectations at low $q^2$
  - Angular variable $P_5'$ in poor agreement

- Combined fit to $b \to s \mu \mu$ gives $P \approx 0.02$ for standard model
  - Preferred NP operators contribute left handed $b \to s$ FCNC [PRD 90 (2014) 054014]

- But high-scale dynamics that generates these must be $SU(3)_C \times SU(2)_L \times U(1)_Y$ invariant!
  - Implies related charged currents... (arxiv 1412.7164, 1506.01705, 1506.02661)
  - Ok, half conspiracy theory, half convenient segue...
Semileptonic decays

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

arXiv: 1506.08614
Submitted to PRL

arXiv: 1507.03233
Submitted to PRD
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)
    - $\bar{B} \rightarrow W^{*\pm} D(\ast)$ half of the decay still needs non-perturbative input

- Charged lepton universality implies branching fractions for semileptonic decays to $e, \mu, \tau$ differ only phase space and helicity-suppressed contributions

What we want to measure

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

- **Theoretically clean** due to cancellation of form factor uncertainties
  - Poorly-measured helicity suppressed amplitudes give dominant uncertainty
  - SM: \( R(D^*) = 0.252(3) \) PRD 85 094025 (2012)
  - \( R(D) = 0.300(8) \) arxiv:1505.03925

- **Experimentally nice with** \( \tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau \)
  - Results in identical (visible) final state
  - Large, well-measured BF: \( \mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau) = (17.41 \pm 0.04)\% \)
  - Expected (signal)/(normalization)=0.439%
  - Disentangle from \( \bar{B}^0 \to D^{*+} \ell^- \bar{\nu}_\ell \) using invariant mass of invisible system, lepton energy spectrum
Distinguishing $b \to c\tau(\to \ell\nu\nu)\nu$ from $b \to c\ell\nu$

- In B rest frame, three key kinematic variables:

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

  \[ q^2 > 0 \]

  \[ m_{miss}^2 > 0 \]

  \[ E_\ell^* / |p_\ell^*| \]

  \[ m_\tau^2 \leq q^2 \leq 10.6 \text{ GeV}^2 \]

<table>
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<tr>
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<td>$E_\ell^*$ spectrum is soft</td>
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<tr>
<td>$m_\tau^2 \leq q^2 \leq 10.6 \text{ GeV}^2$</td>
<td>$\approx 0 \leq q^2 \leq 10.6 \text{ GeV}^2$</td>
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“Hadronic tagging” algorithms semi-inclusively reconstruct a hadronically decaying B meson

EMC energy used to pick “best” reconstruction for a given event and to select D*π control sample

- Select events with $q^2 = (p_\ell + p_{\text{miss}})^2 = (p_B - p_D)^2 > 4 \text{ GeV}^2$

$D^{(*)}$ candidate in sum of exclusive channels covering $O(1/4)$ of charm total width

Neutrino system strongly constrained by reconstruction of the rest of event $m^2_{\text{miss}}$
Extracting the Signal

- **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

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

arXiv: 1507.03233
Fits – BaBar

- BaBar published their hadronically-tagged result on the final dataset in 2012/2013 (PRL+detailed PRD)

- Result showed tantalizing tension with SM: 3.4 sigma including correlations!

- This is where things stood until FPCP this year, when two new measurements were released!
New $R(D(*))$ Results

At FPCP2015, Belle weighed in with their full dataset
- Result shows no serious tension with either BaBar or SM (almost splits the difference by eye)

arXiv: 1507.03233
What about LHCb?

- In hadron collisions, things are not nearly as “nice” as in $\Upsilon(4S)$ decay
  - Unknown CM frame for $g g \rightarrow b\bar{b}$ production
  - Lots of additional particles in the event (showering, MPI etc)

- Different handles are needed to deal with (1) missing neutrinos and underconstrained kinematics as well as (2) large backgrounds from partially-reconstructed $B$ decays
Rest frame approximation at LHCb

- Resolution on rest frame variables doesn’t matter much because distributions are broad to begin with
  - A well-behaved approximation will still preserve differences between signal, normalization and backgrounds
  - Take \((\gamma \beta_z)_{\bar{B}} = (\gamma \beta_z)_{D^* \mu} \implies \langle p_z \rangle_{\bar{B}} = \frac{m_B}{m(D^* \mu)} \langle p_z \rangle_{D^* \mu}\)

- 18% resolution on B momentum approximation gives excellent shapes to use for fit
• Using rest frame approximation, construct 3D “template” histograms for each process contributing to \( D^{*+}\mu^- \) sample
  ◦ Signal, normalization, and partially reconstructed backgrounds use simulated events, other backgrounds use control data

• Reduce partially constructed backgrounds with LHCb’s excellent tracking
  ◦ Scan over every reconstructed track and compare against \( D^{*+}\mu^- \) vertex
  ◦ 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 (\( \bar{B} \to D^{**}\ell\nu, B \to D^*H_c(\to \mu\nu X')X, H_c = \) any open charm)
• Projections of (left) $m_{miss}^2$ and (middle) $E_\mu^*$ and (right) $q^2$

• Signal clearly much smaller than normalization, as expected from phase-space suppression combined with $\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau) \approx 17\%$

• Result: $R(D^*) = 0.336 \pm 0.027 \pm 0.030$
### Systematics

#### Model uncertainties

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Expected to be reduced for future $R(D) + R(D^*)$

Will scale down with more data (Run2)
Combined R(D*) data

\[ \Delta \chi^2 = 1.0 \]

\[ R(D^*)_{avg} = 0.322 \pm 0.022 \]
\[ R(D)_{avg} = 0.391 \pm 0.050 \]
\[ \rho = -0.29 \]

- Plot and average from HFAG
  - SM p-value = \(1.1 \times 10^{-4}\) \(\rightarrow\approx 3.9\sigma\)
Other results of note
\( \Upsilon(1S) \) decay

- Nonuniversal effects in \( \Upsilon(1S) \rightarrow \mu\mu/\tau\tau \) can be induced by pseudoscalar Higgs \( A^0 \) (directly or via mixing with \( \eta_b \))

- BaBar searched in \( \Upsilon(3S) \rightarrow \Upsilon(1S)\pi\pi \)
  - \( \Upsilon(1S) \rightarrow \mu\mu \) is fully reconstructed
  - \( \Upsilon(1S) \rightarrow \tau\tau \) is selected based on missing energy after the \( \Upsilon(3S) \rightarrow \Upsilon(1S)\pi\pi \) dipion system is identified

Result:
- \( R_{\mu\tau} = 1.005 \pm 0.013 \pm 0.022 \)
Looking Ahead...
Future Heavy Flavor Experiments

- $e^+ e^-$
  - Belle-II / Super-KEKB
    - Nanobeams, improved final focus, and doubled beam currents to reach $8 \times 10^{35}$ Hz/cm$^2$
    - Physics data to begin in 2018, with a goal of $50 \text{ab}^{-1} \approx 6 \times 10^{10} B\bar{B}$ pairs

- $p\bar{p}$
  - LHCb Run 2:
    - 13TeV with 25ns spacing
    - LHCb to collect $5 \text{fb}^{-1} \approx 6 \times 10^{11} b\bar{b}$ in acceptance
  - LHCb Upgrade:
    - LHCb detector to be upgraded for increased instantaneous luminosity running in LS2(2018/2019)
      - All-new tracking system to cope with increased occupancy
      - 40MHz synchronous readout plus all-software triggering
    - $50 \text{fb}^{-1} \approx 6 \times 10^{12} b\bar{b}$ in acceptance
**$R(K)$ future prospects**

- $b \rightarrow s\ell\ell$ still largely statistically limited (particularly in $B^+ \rightarrow K^+ e^+ e^-$)

- Naively scaling statistical error bars:
  - LHCb 2018: $R(K) = x.xx \pm 0.04 \pm 0.04$
    - Assumes no systematic uncertainty improvement—very pessimistic assumption
    - Systematics currently dominated by trigger efficiencies. Can be reduced by dedicated study
  - Belle II: $R(K) = x.xx \pm 0.03\pm$?
    - Systematics currently codominated by a variety of sources. Probably can be controlled with careful study...
  - LHCb Upgrade: $R(K) = x.xx \pm 0.02\pm$?
    - Here we will be dealing with an all-new trigger scheme. How well can we nail the relative efficiency down?
\[ R(D^{(*)}) \]

- **Belle II:**
  - Analysis is limited by the statistics available after hadronic B-tagging.
  - Expected scaling given on right
    - Could reach 2% sensitivity after full luminosity is collected

- **LHCb:**
  - Situation is more subtle. Currently systematics dominated, but dominated by MC stats
  - Most systematics (e.g. shape uncertainties) scale with data or control samples
  - Systematic from misidentified muon background requires more effort to reduce
    - Uncertainty on \( R(D^*) \) of 7%-9% could be possible with Run2 data, 3%-4% with upgrade
      - Depends on how trigger efficiencies evolve
      - (Assumes BaBar central value for comparison with above plot)

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Summary

- B physics experiments are pushing lepton universality tests into new and exciting territories beyond tests of the Electroweak interaction.

- $R_K$ measurements from electroweak penguin decays are reaching the 10% precision level with LHCb Run1.
  - Further improvements expected to be rapid with LHCb Run2, Belle-II, LHCb Upgrade datasets.
  - Small tension in LHCb result can be related back to other tensions in branching ratios at low $q^2$.
    - SM still provides a very respectable fit, but possibilities are tantalizing!

- Semitauonic branching fractions remain too large relative to SM expectations.
  - P-level with respect to HQET+Lattice now at $10^{-4}$ level.
Backup
B-factory measurements

- Exploiting the simple kinematics of the $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ reaction
  - Small Q-value means no additional hadrons produced

- "Hadronically-tagged" analyses preferred in channels with multiple neutrinos
  - Reconstruct 2nd $B$ meson in decay mode with no missing particles
  - Provides precise knowledge of kinematics of missing system
  - Reduces backgrounds from $e^+e^- \rightarrow c\bar{c}$ and from background partially-reconstructed $B$ decays
  - Allows use of calorimeter to veto events with
  - Efficiency of few $10^{-3}$ -- costly!

Figure from T. Lück’s talk at ICHEP 2014
FCNC generalities

- Flavor-changing Neutral Currents (FCNC) are forbidden at tree-level in the SM
  - Ensured by GIM mechanism, assuming Higgs Yukawas are the only source of flavor violation

- FCNCs in standard model first appear at second order in the weak interaction:

\[ \Delta F = 2 \text{ “box” diagrams} \]

\[ \Delta F = 1 \text{ “penguin” diagrams} \]
Reducing partially reconstructed backgrounds

- Make use of superb tracking system
  - Scan over every reconstructed track and compare against $D^{*+}\mu^-\pi^-$ 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 (B2dstst, B2hc)
Contributions of excited charm states in the $B^{\pm,0} \rightarrow (c\bar{q})\mu\nu$ transition are large

- 1P states decaying as $D^*\pi$ known and reasonably well-described by theory (HQET)
  - $D^{*+}\mu^\mp\pi^-$ control sample sets nonperturbative shape parameters for input to signal fit
  - 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

- Distinguishable by “edge” at missing mass $\approx (2)m_\pi$
\[ B \rightarrow D^{*+} H_c (\rightarrow \mu \nu X') X \] background

- \( b \rightarrow c \bar{c} q \) decays can lead to very similar shapes to the semitauonic decay (e.g. \( B^0 \rightarrow D^{*+} D_s^- (\rightarrow \phi \mu \nu) \) +many others)
- Highly suppressed in B-factory analyses due to complete event reconstruction, but very important at LHCb
- Branching fractions well-cataloged, but detailed descriptions of the \( D^* D K (n \geq 0 \pi) \) final states are not well-simulated
  - Dedicated \( D^{*+} \mu^- K^\pm \) control sample used to improve the template to match data

\[ B^0 \rightarrow D^{*+} H_c (\rightarrow \mu \nu X') X \text{ vs } B^0 \rightarrow D^{*+} \tau^- \nu_\tau \]
Big picture $\bar{B} \rightarrow D^*\tau\nu$

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

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

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

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

$D^{**} \rightarrow D^{*+}\pi$ (3 states each, 6 PDFs)

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

$D_s^{**} \rightarrow D^{*+}K_s^0$, (2 states, 1 free param)

$B^{+,0} \rightarrow \bar{D}^{**}\mu^+\nu_\mu$

$\bar{D}^{**} \rightarrow D^{*-}\pi\pi$, (cocktail)

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

$+\bar{B} \rightarrow D^{*+}D_s^- (\rightarrow \tau^-\bar{\nu}_\tau)X$

Control sample fits to constrain shapes

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

$h \rightarrow \mu$ misidentification
Detailed fit projections

- Projections of (left) $m_{miss}^2$ and (right) $E_\mu^*$ 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.