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, μ, τ 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

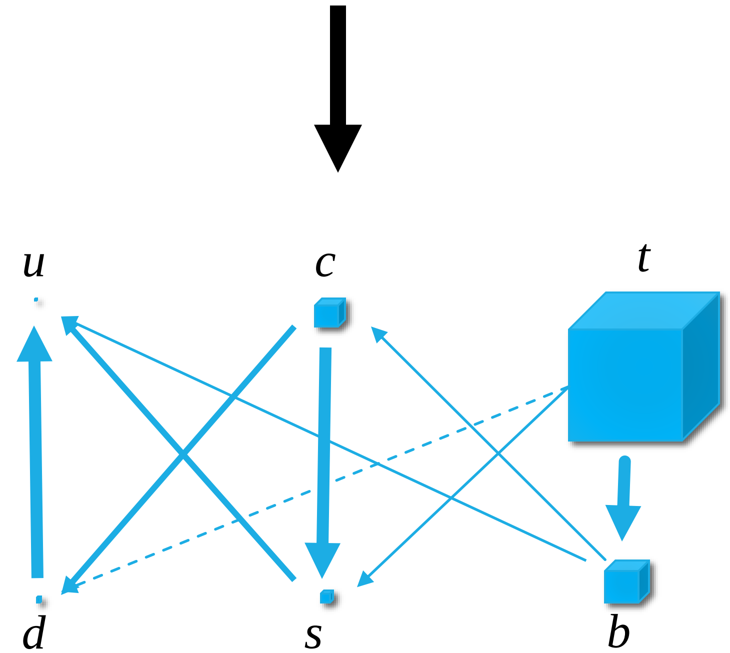
- Universality of the EW interactions does not necessarily imply universality of physics beyond the SM
- In particular, new physics preferentially coupling to the 3rd generation is usually less well-constrained, and can modify SM charged and neutral currents
  - Examples: $A^0, H^{\pm}$, new vectors coupled to SM Higgs doublet, leptoquarks
- Many 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

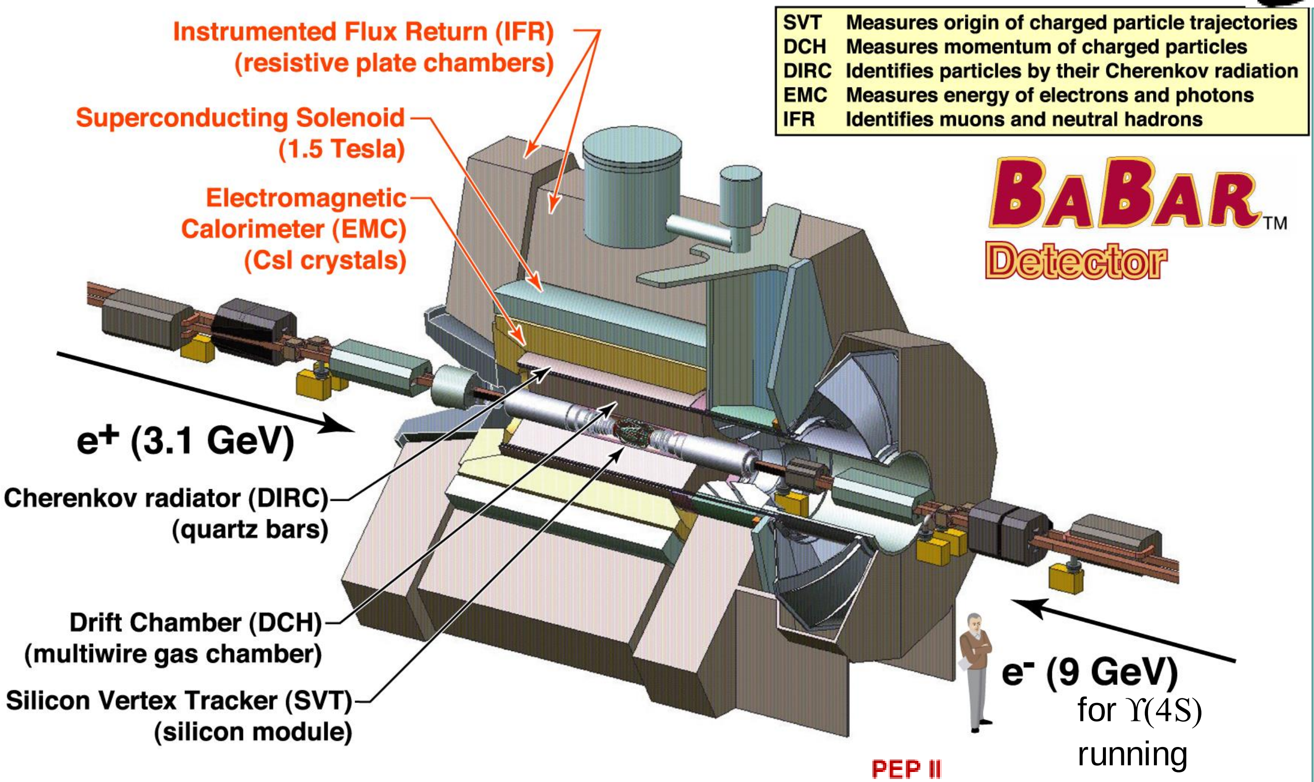
$$\begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

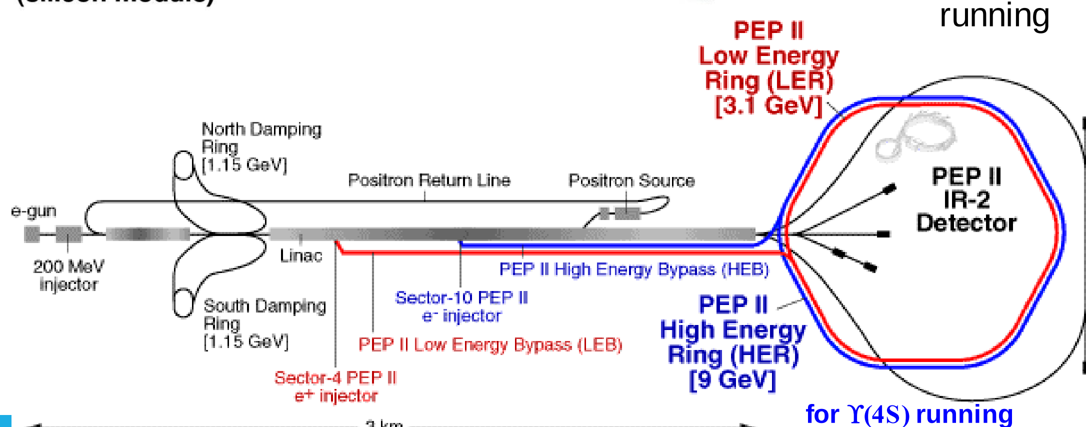
- V_{CKM} hierarchical & nearly diagonal
  - Quark flavor transitions mixing different generations suppressed
  - 3rd generation especially "isolated"
- This leads to suppression of all tree-level b quark decay amplitudes
  - $|V_{cb}|$~0.04
  - Makes B physics quite sensitive to NP generically misaligned 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



The players

Cast (1/3): *BaBar*/PEP-II

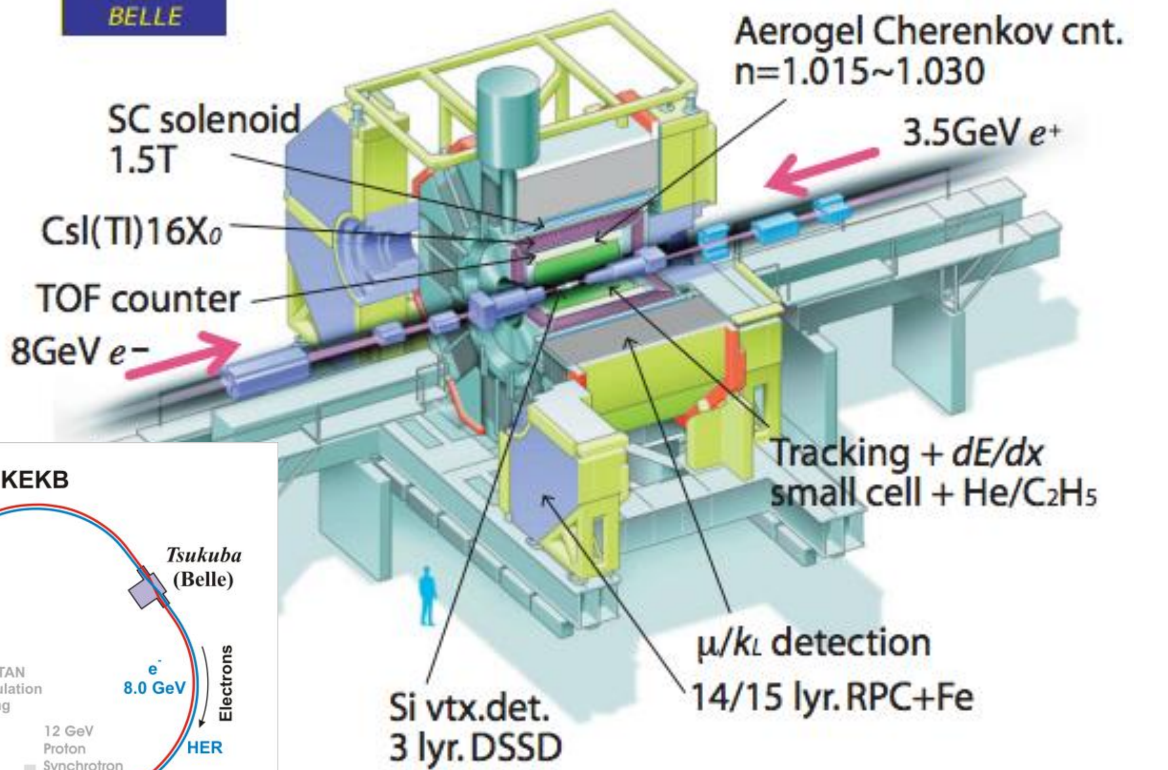


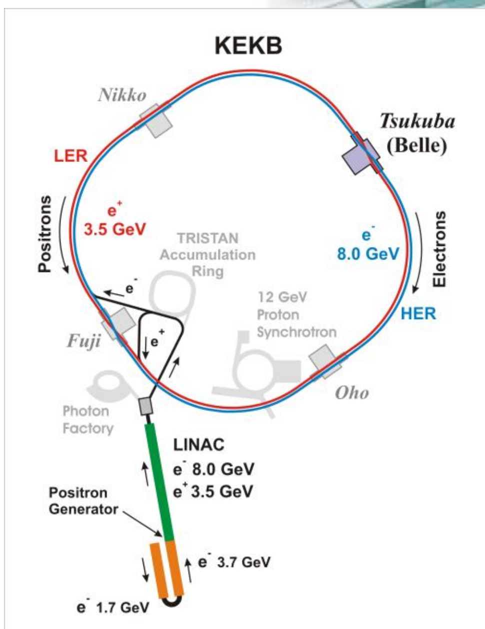


- 5-layer inner silicon strip tracker (SVT) plus 40-layer multicell drift chamber (DCH) in a 1.5 Tesla axial B field
- Dedicated Cherenkov PID system with quartz (n~1.474) radiator
  - PID at low p from dE/dx in both DCH and SVT
- CsI(Tl) crystal calorimeter
- Magnet flux return instrumented with RPCs and/or LSTs (depending on run period)
- $\Upsilon(4S)$ dataset: $\approx 470 \times 10^6 B\bar{B}$ pairs

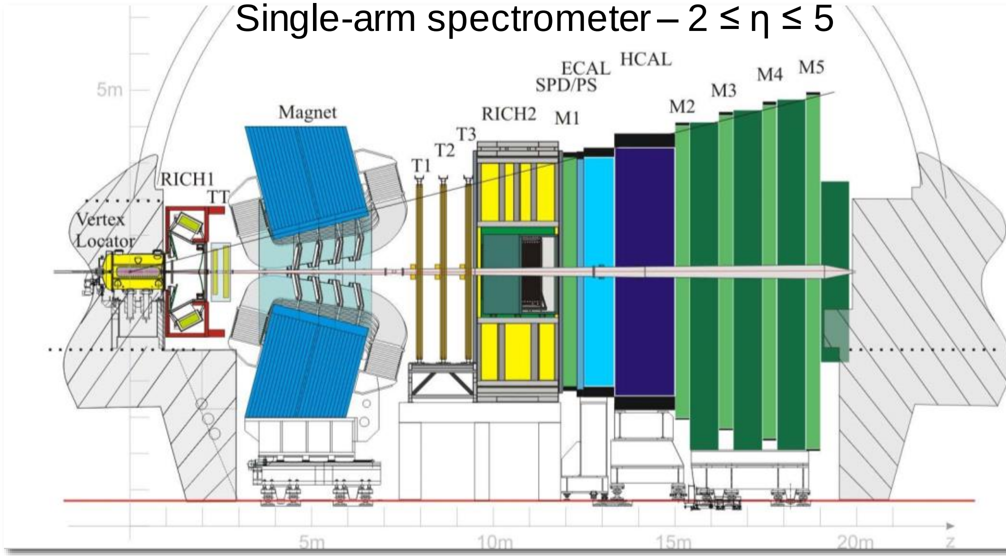
Cast (2/3): Belle/KEKB

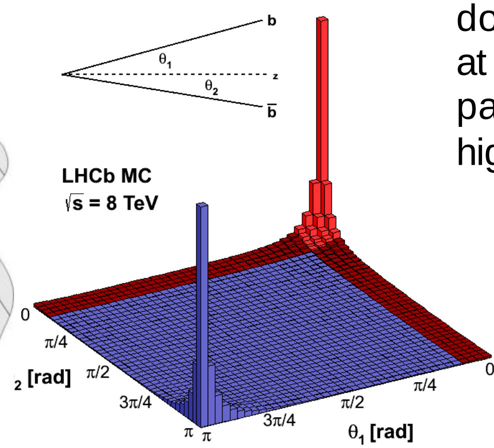
- 3/4-layer double-sided Silicon Tracker plus drift chamber
- Particle ID via measurements of time of flight and Cherenkov counter
- Excellent μ/K_L detection
- CsI(Tl) crystal calorimeter measures photon energies and assists in PID
- $\Upsilon(4S)$ dataset: $\approx 770 \times 10^6 B\bar{B}$ pairs





Cast (3/3) LHCb/LHC





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

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

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

b hadron production

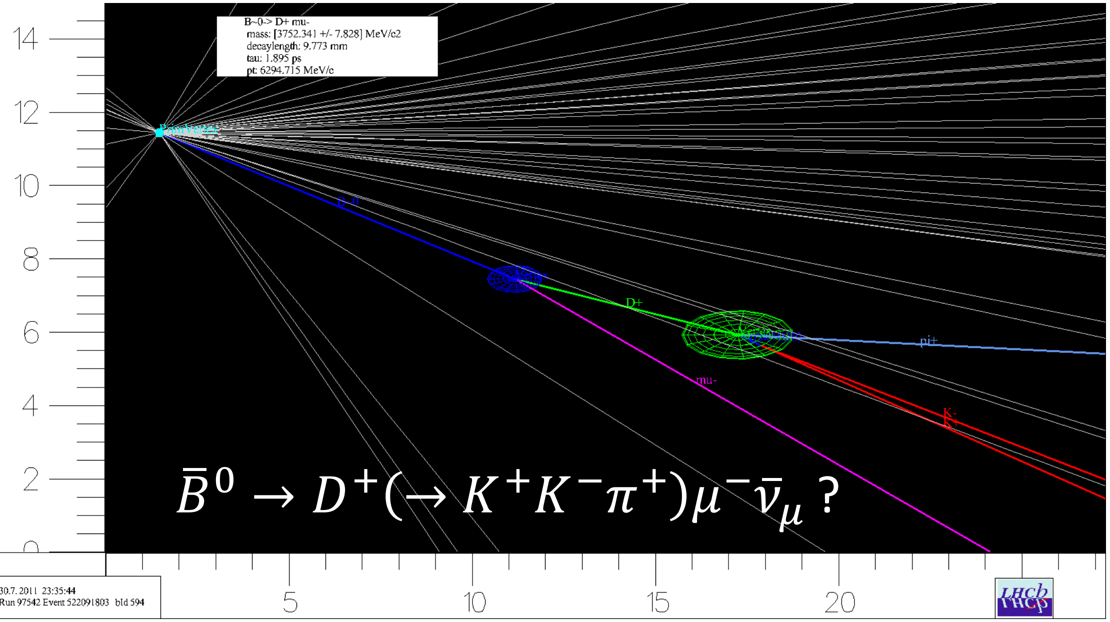
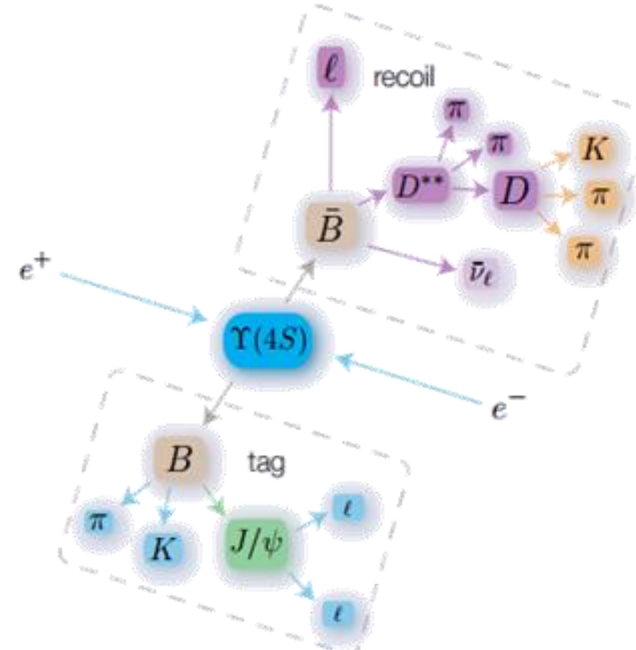


Figure from T. Lück's talk at ICHEP 2014



- B-factories: exploit clean BB **production** from Y(4S)
  - Event shape discriminates $B\bar{B}$ vs $e^+e^- \to q\bar{q},\ q = u, d, s, c$
  - 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 $gg \to b\bar{b} + MPI + showering + ISR + \cdots$, very messy

Selected Results

Tau

- B-factory measurements in $e^+e^- \to \tau^+\tau^-$ 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:

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

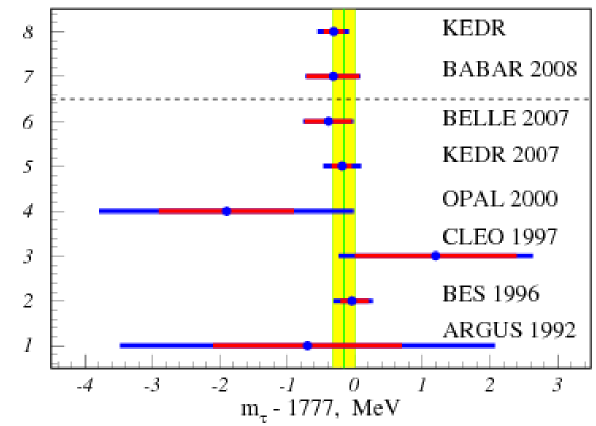
$$\frac{\Gamma_{\tau\to \mu}}{\Gamma_{\mu\to e}} \propto \left(\frac{g_\tau}{g_e}\right)^2 = \frac{\tau_\mu}{\tau_\tau}\mathscr{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)\left(\frac{m_\mu}{m_\tau}\right)^5 \frac{f(m_e^2/m_\mu^2)r_{EW}^\mu}{f(m_\mu^2/m_\tau^2)r_{EW}^\tau}$$

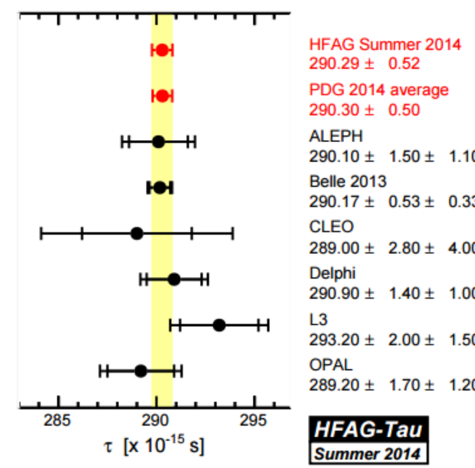
$$\frac{\Gamma_{\tau\to e}}{\Gamma_{\tau\to \mu}} \propto \left(\frac{g_e}{g_\mu}\right)^2 = \frac{\mathscr{B}(\tau^- \to e^-\bar{\nu}_\mu\nu_\tau)}{\mathscr{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)}\frac{f(m_\mu^2/m_\tau^2)}{f(m_e^2/m_\tau^2)}$$

- 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

arxiv 1112.3815





HFAG 2014

average.

EW penguin decays

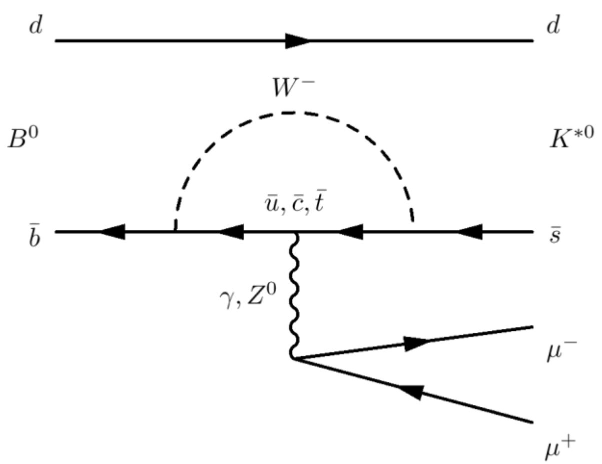
PRL 113 (2014) 151601

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, γ, t
  - New particles connected to EWSB can appear and introduce q^2- or angular-dependent interference



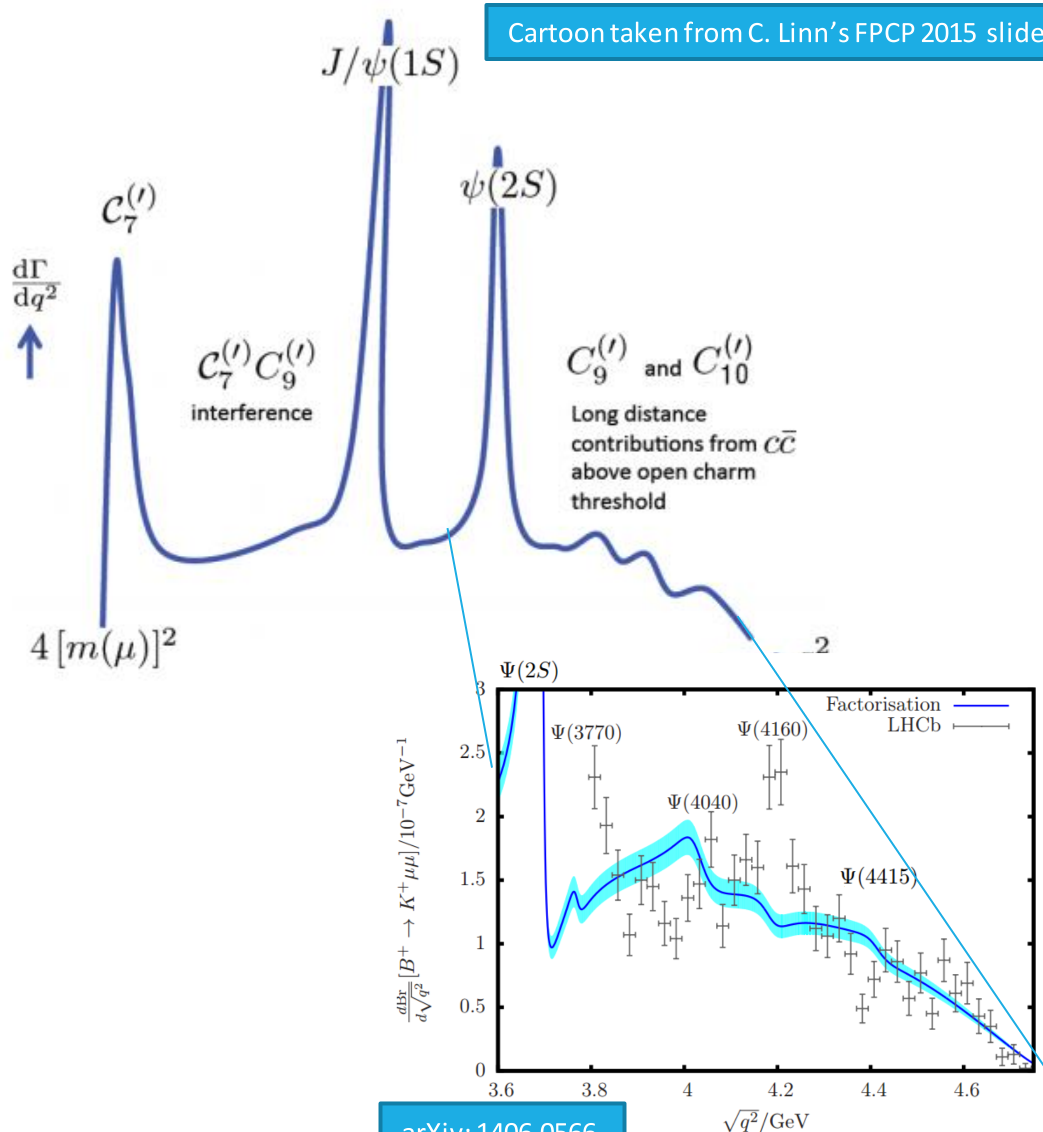
- Excellent targets for both LHCb and B-factories
  - Dilepton in final state allows for clean event selection
  - Rich phenomenology with scalar and vector hadronic final states (K or K^*)
  - SM calculations become unreliable near $m(\ell\ell) = m(J/\psi), m(\psi(2S))$
    - (tree-level $b \to c\bar{c}s$ amplitudes, $c\bar{c}$ vacuum polarization, long distance effects…)
- Lepton universality test: standard lore is that

$$R(K) \equiv \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)} = 1 \pm \mathcal{O}(10^{-3})$$ if only γ, 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 $q^2 < 6\ \mathrm{GeV}^2$
  - ψ 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

BABAR

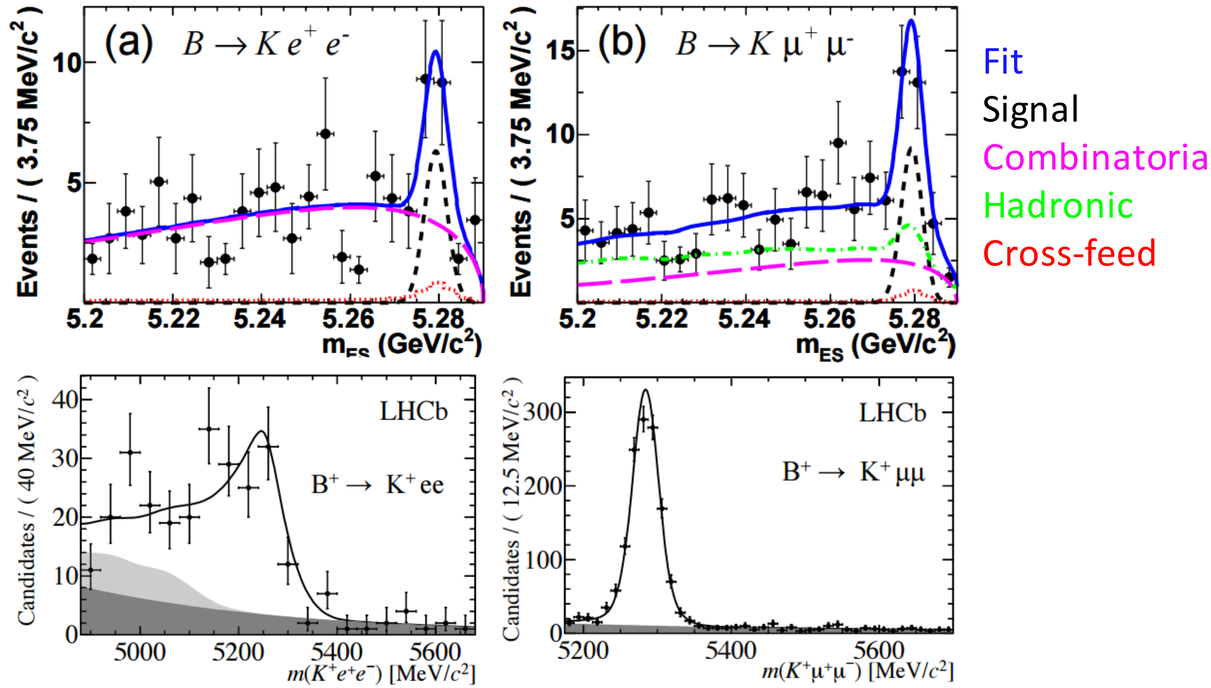
(high q2)

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

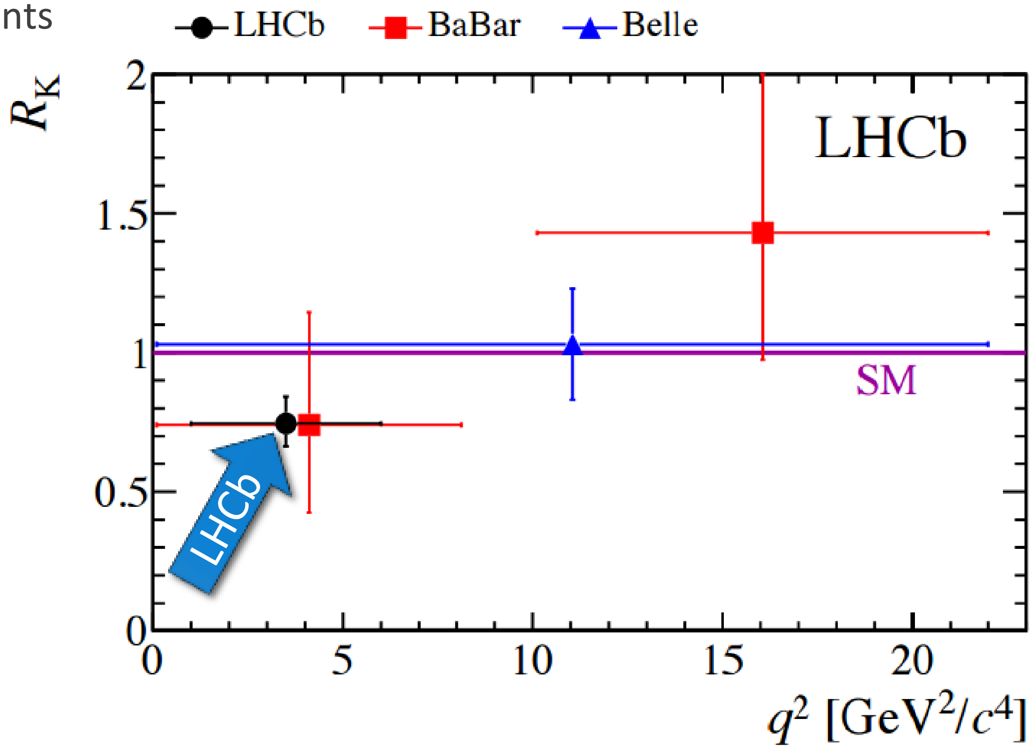
  B-factories: cut on $E - E_{beam}$, fit in $m_{ES,BC} \equiv \sqrt{\left(\frac{E^*_{CM}}{2}\right)^2 - (p^*_B)^2}$

    - Belle additionally fits in θ_B=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:
    $$R_{K,\ q^2<8.12\mathrm{GeV}^2} = 0.74^{+0.40}_{-0.31} \pm 0.06$$
    $$R_{K,\ q^2>10.11\mathrm{GeV}^2} = 1.43^{+0.65}_{-0.44} \pm 0.12$$
  - LHCb:
    $$R_{K,\ q^2<6\mathrm{GeV}^2} = 0.745^{+0.090}_{-0.074} \pm 0.036$$



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

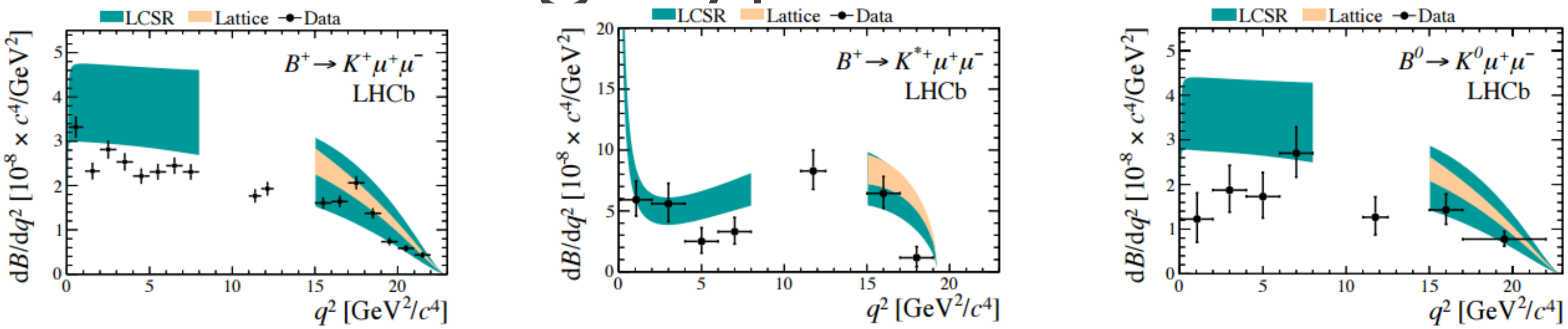
- Related results:
  - Belle:
    $$R_{K^*} = 0.83 \pm 0.17 \pm 0.08$$
  - BaBar:
    $$R_{K^*,\ q^2<8.12\mathrm{GeV}^2} = 1.06^{+0.48}_{-0.33} \pm 0.08$$
    $$R_{K^*,\ q^2>10.11\mathrm{GeV}^2} = 1.18^{+0.55}_{-0.37} \pm 0.11$$
  - LHCb:
    analysis ongoing

PRL 113 (2014) 151601

PRD 86 (2012) 032012

PRL 103 (2009) 171801

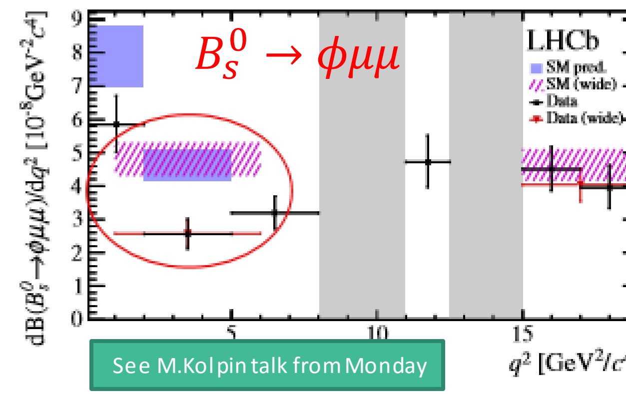
Entertaining hypotheticals…



JHEP 06 (2014) 133

SM predictions: JHEP 07 (2011) 067; JHEP 01 (2012) 107; \Phys. Rev. Lett. 111 (2013) 162002

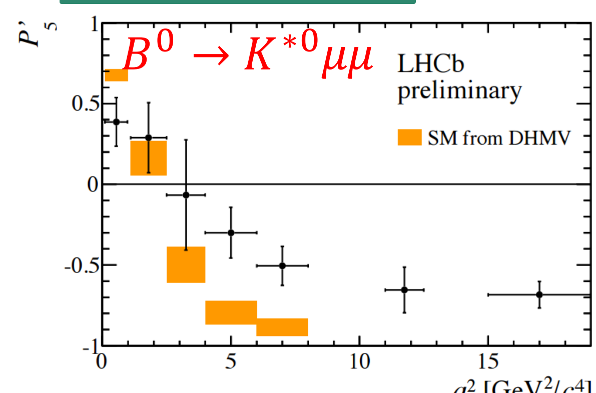
- Other similarly-sized deviations across $b \to s\mu\mu$ measurements:
  - Branching fractions consistently below expectations at low q^2
  - Angular variable $P_5{}'$ in poor agreement



LHCb-PAPER-2015-023

- Combined fit to $b \to s\mu\mu$ gives P=~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…



LHCb-CONF-2015-002

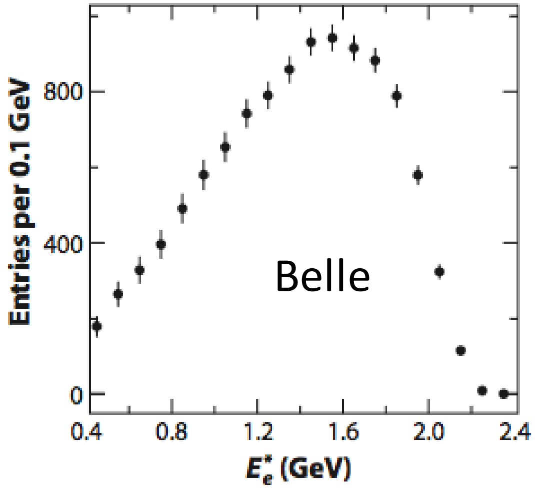
Semileptonic decays

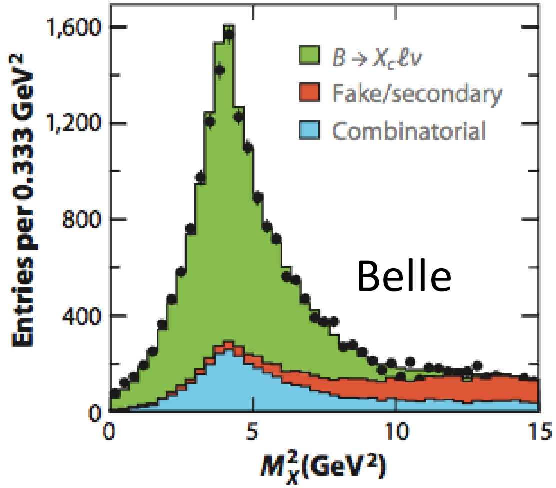
PRL 109 (2012) 101802
PRD 88 (2013) 072012

arXiv: 1506.08614
Submitted to PRL

arXiv: 1507.03233
Submitted to PRD

Semileptonic B decays





Luth, V.G. Annual Review of Nuclear Science, **61** (2011) 119-148

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

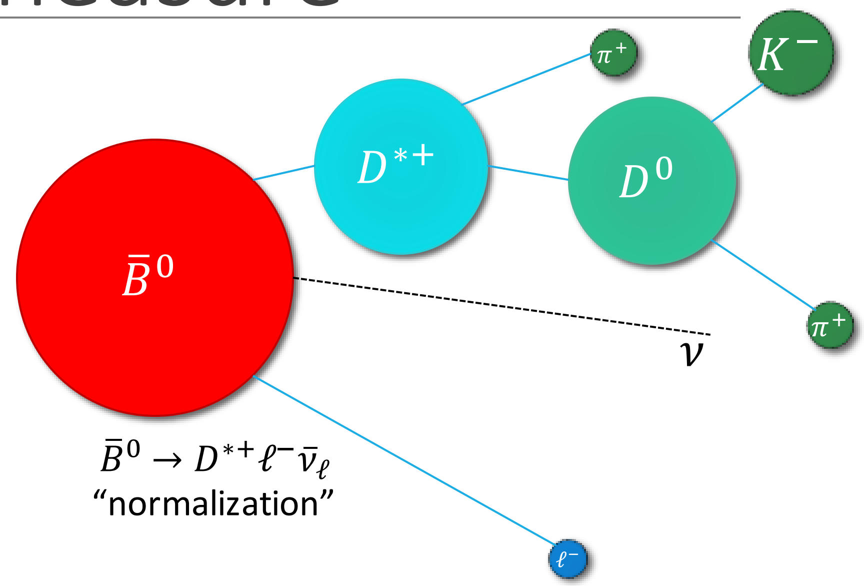
- Theoretically well-understood in the SM
  - Tree level virtual W emission – strong V-A structure
  - No QCD interaction between the lepton-neutrino system and the recoiling hadron(s)
    - $\bar{B} \to W^{*\pm} D^{(*)}$ half of the decay still needs non-perturbative input

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

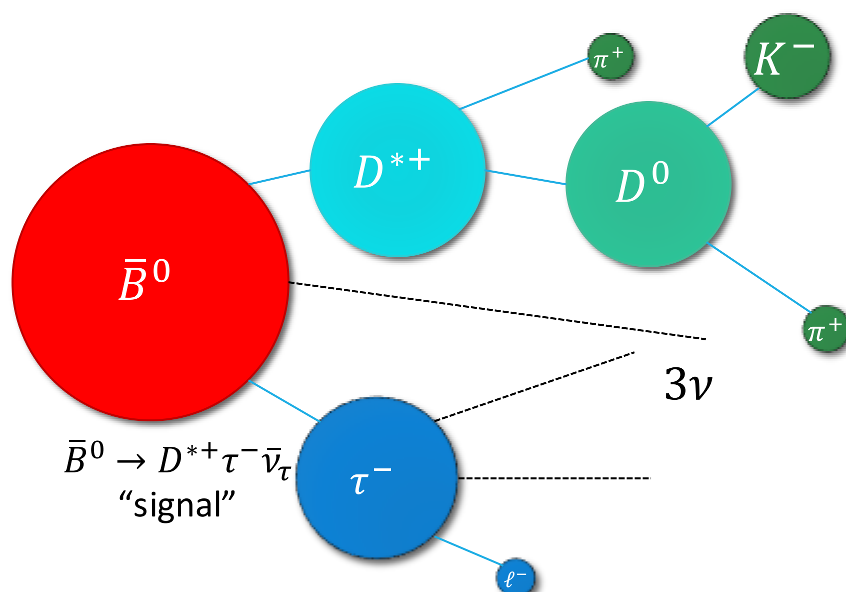
What we want to measure

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

- 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

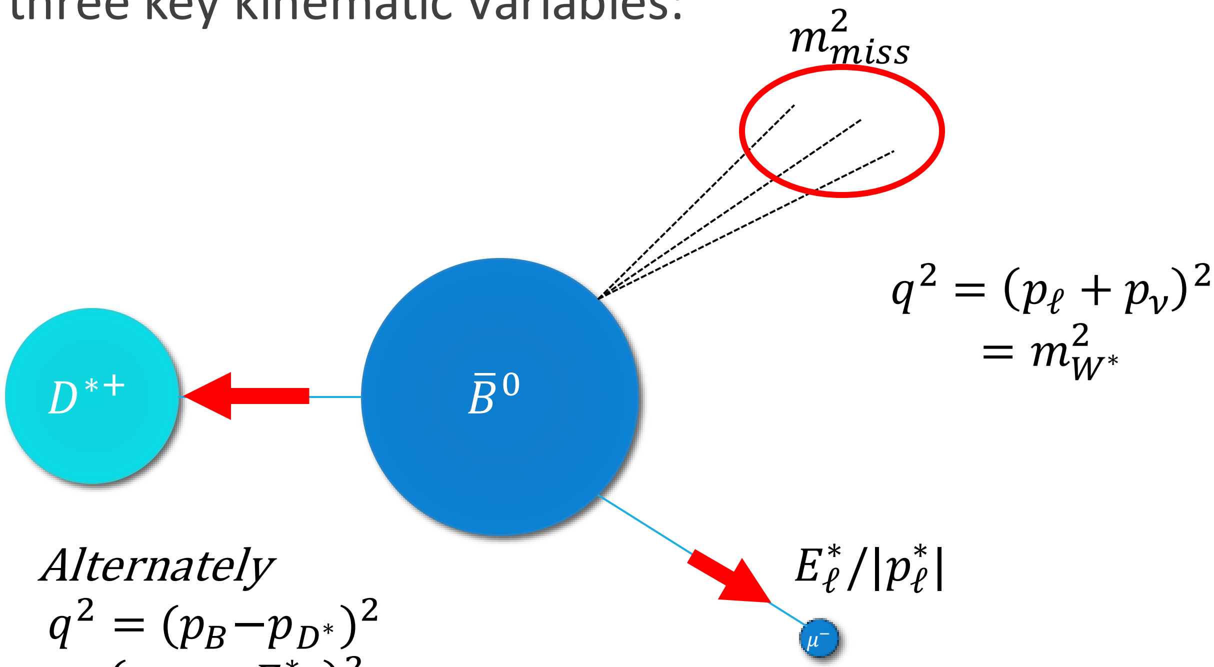


- Experimentally nice with $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau$
  - Results in identical (visible) final state
  - large, well-measured BF:
    $\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau) = (17.41 \pm 0.04)\%$
    - Expected (signal)/(normalization)=0.439%
  - Disentangle from $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\mu$ 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:



Alternately

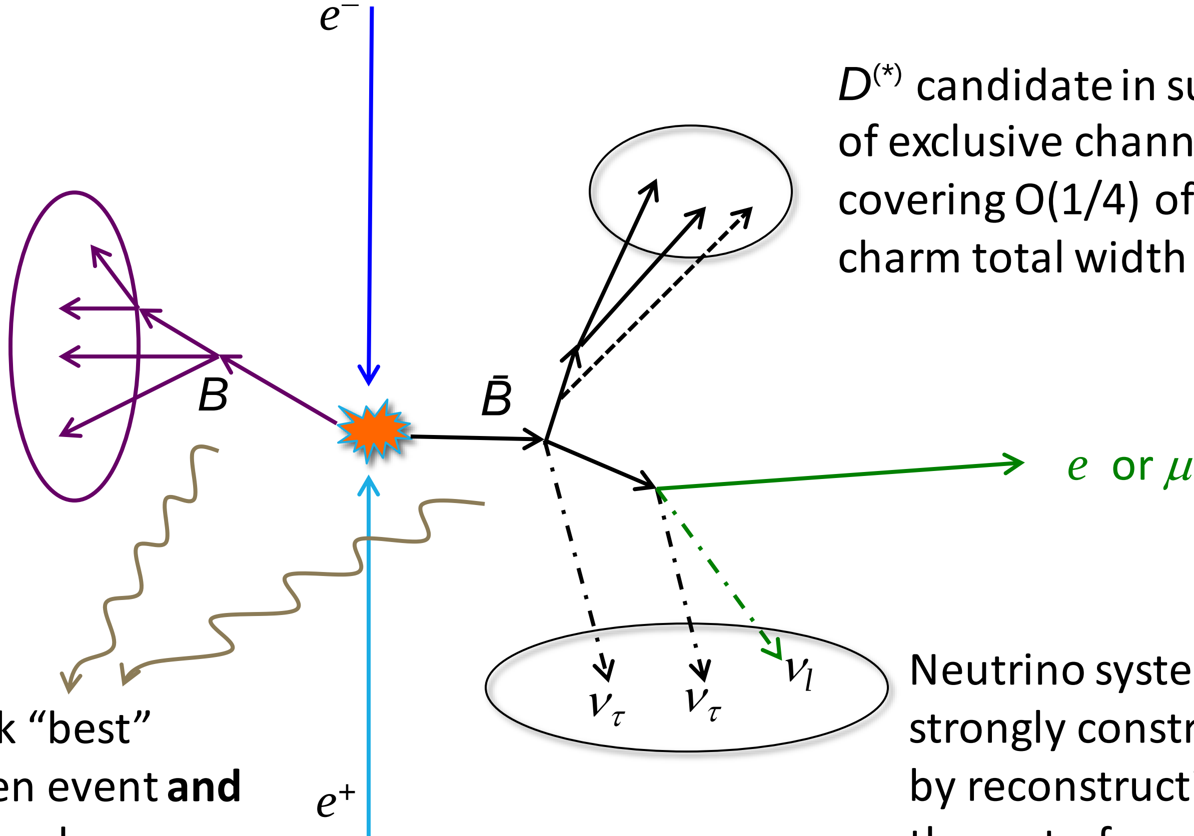
$$q^2 = (p_B - p_{D^*})^2$$
$$= (m_B - E^*_{D^*})^2$$

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

B-factory techniques (continued)

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

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

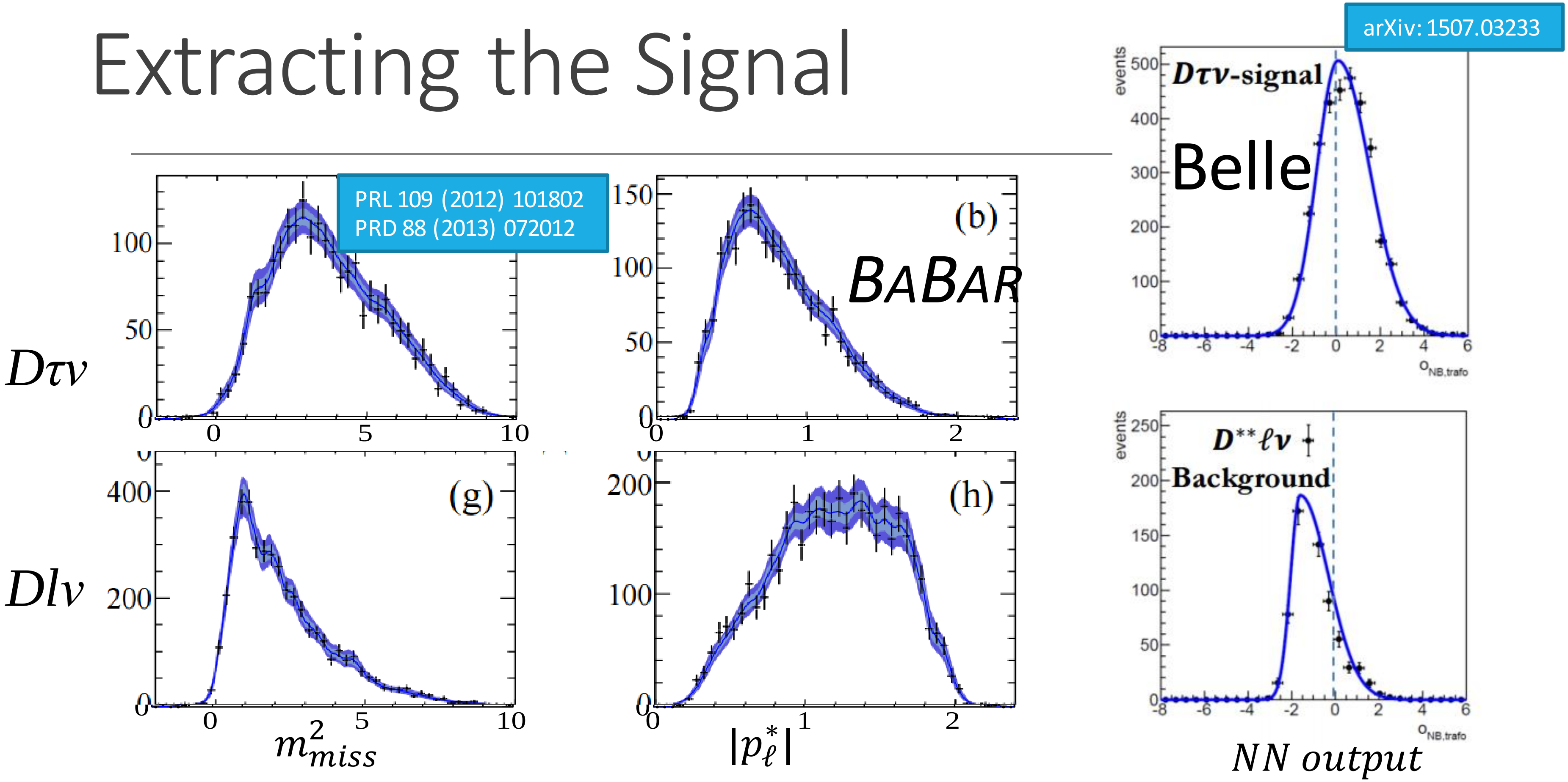


EMC energy used to pick "best" reconstruction for a given event **and** to select D*π control sample

Neutrino system strongly constrained by reconstruction of the rest of event m^2_{miss}

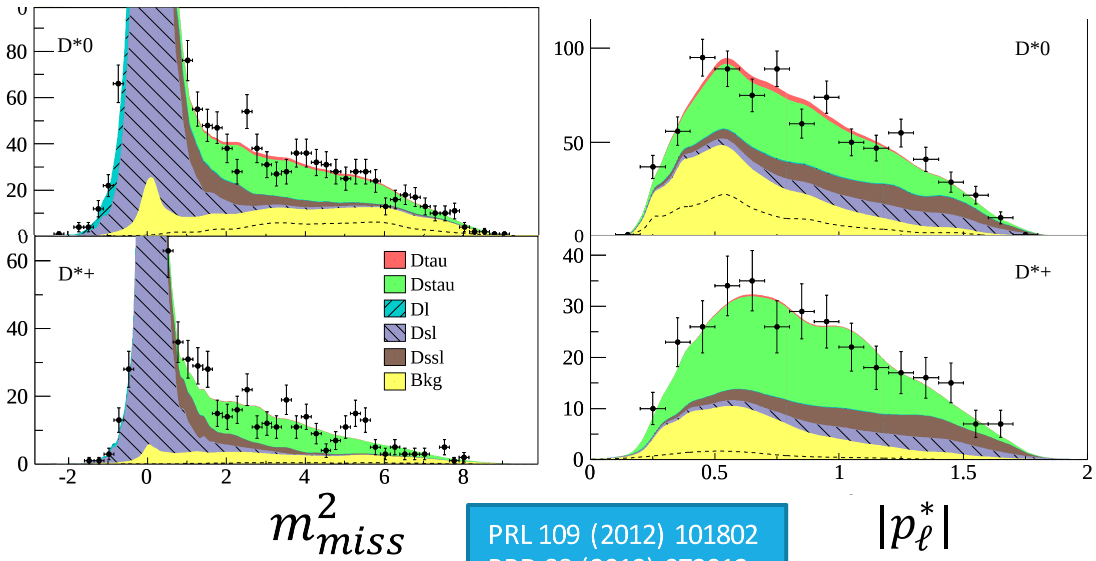
- Select events with $q^2 = (p_\ell + p_{\text{miss}})^2 = (p_B - p_D)^2 > 4\ \text{GeV}^2$

Extracting the Signal

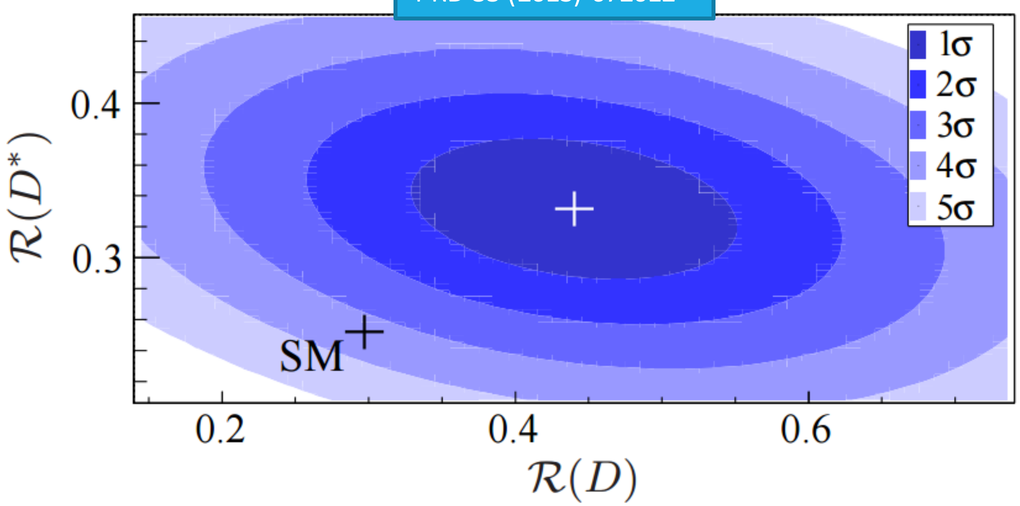


- Fit is performed in mass squared of invisible system vs lepton momentum in B frame
  - Split between D^0, D^+, D^{*0}, D^{*+} samples
- Distributions for fit taken from simulation
  - Missing mass squared best discriminator of signal from normalization ($D^{(*)}\ell\nu$)
  - Backgrounds separated in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

Fits – BaBar



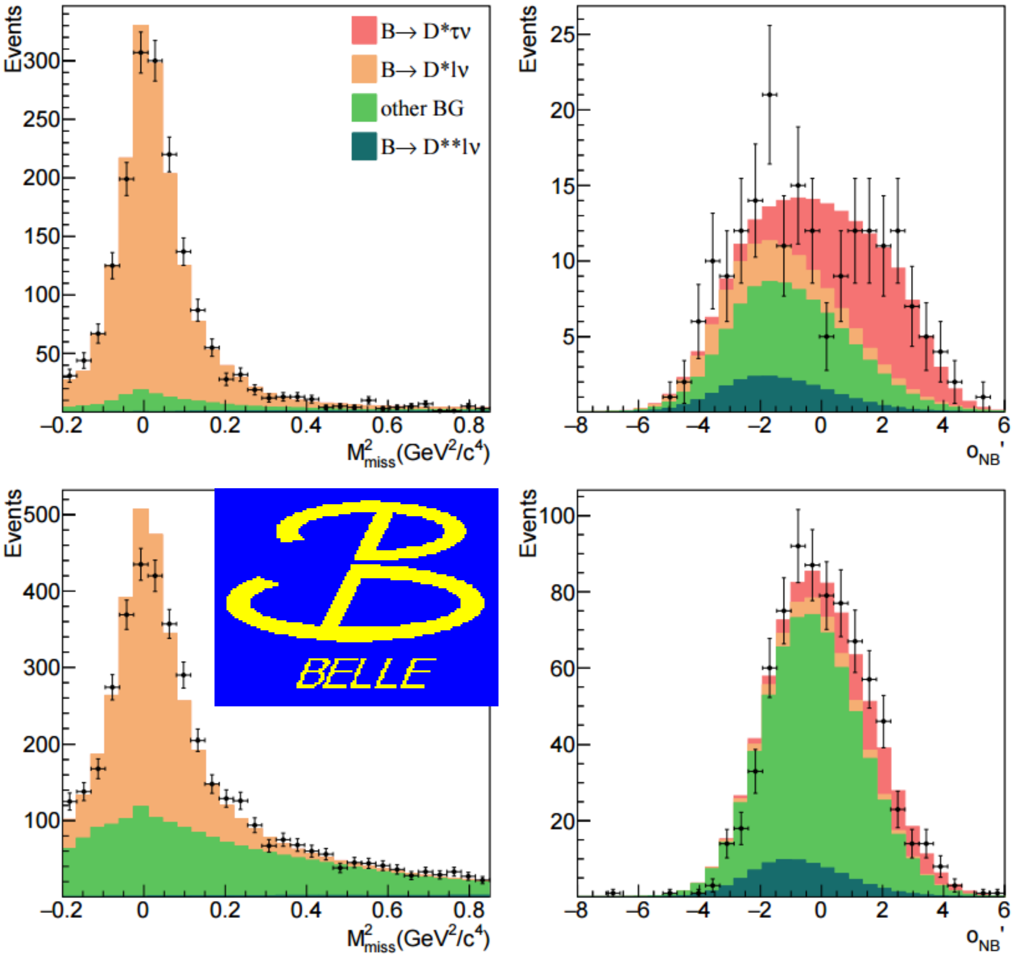
PRL 109 (2012) 101802
PRD 88 (2013) 072012



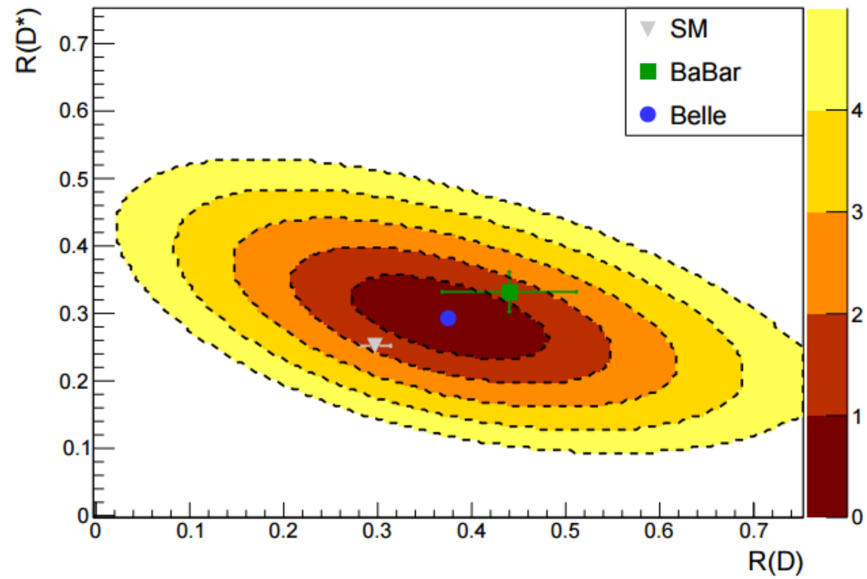
- BaBar published their hadronically-tagged result on the final dataset in 2012/2013 (PRL+detailed PRD)
- Result showed tantalizing tension with SM: 3.4 sigma including correlations!
- This is where things stood until FPCP this year, when *two* new measurements were released!

NEW

New R(D(*)) Results



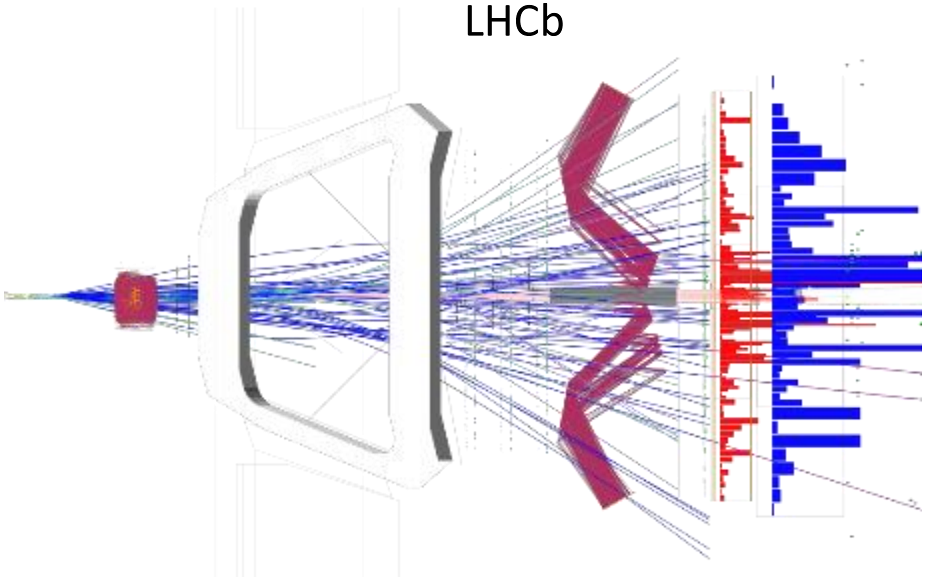
arXiv: 1507.03233



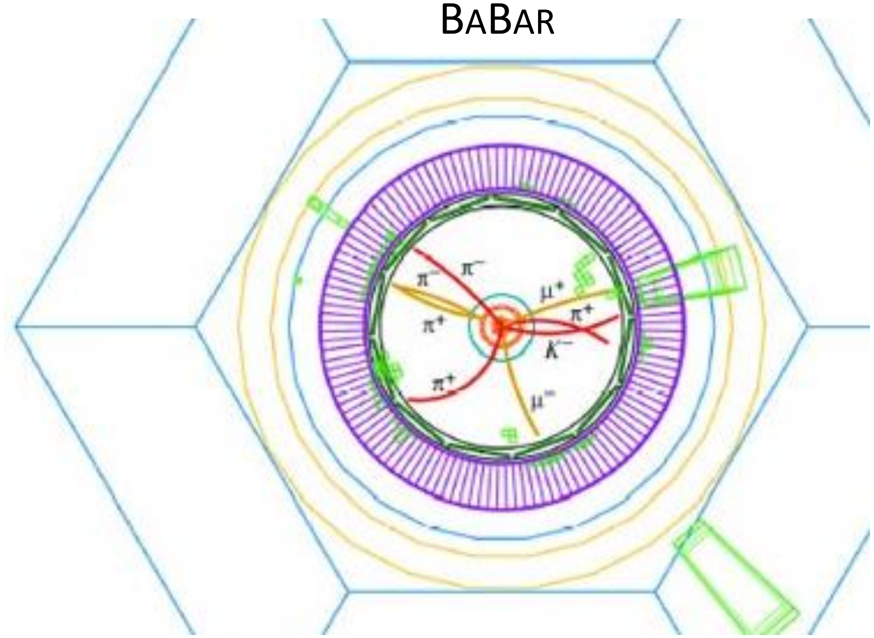
- At FPCP2015, Belle weighed in with their full dataset
  - Result shows no serious tension with either BaBar or SM (almost splits the difference by eye)

What about LHCb?

LHCb



BABAR

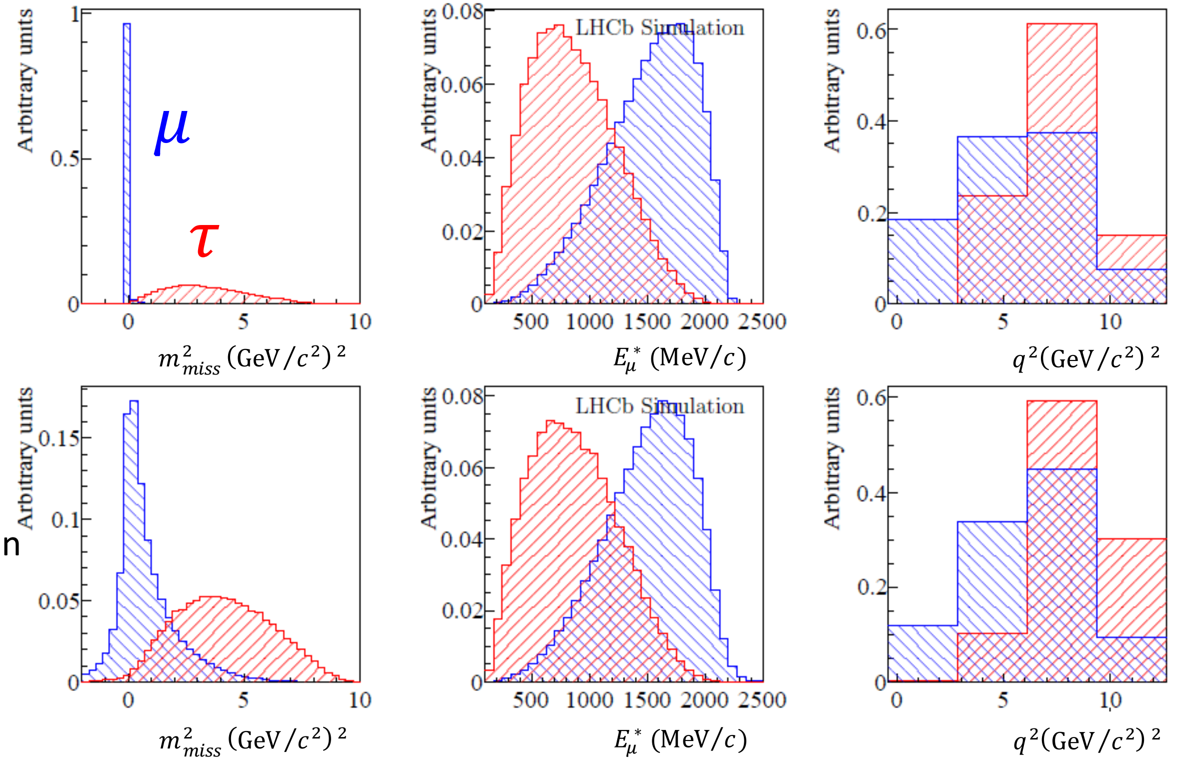


- In hadron collisions, things are not nearly as “nice” as in $\Upsilon(4S)$ decay
  - Unknown CM frame for $gg \to b\bar{b}$ production
  - Lots of additional particles in the event (showering, MPI etc)
- Different handles are needed to deal with (1) missing neutrinos and underconstrained kinematics as well as (2) large backgrounds from partially-reconstructed B decays

Rest frame approximation at LHCb

MC Truth

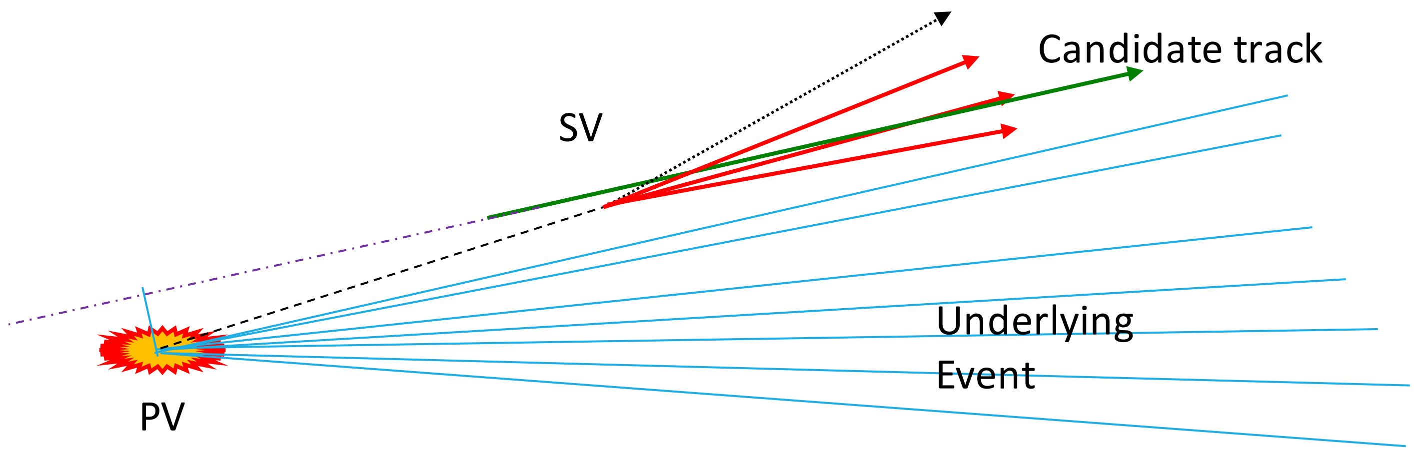
Our Approximation



- 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 $(\gamma\beta_z)_{\bar{B}} = (\gamma\beta_z)_{D^*\mu} \implies (p_z)_{\bar{B}} = \frac{m_B}{m(D^*\mu)}(p_z)_{D^*\mu}$
- 18% resolution on B momentum approximation gives excellent shapes to use for fit

Fit

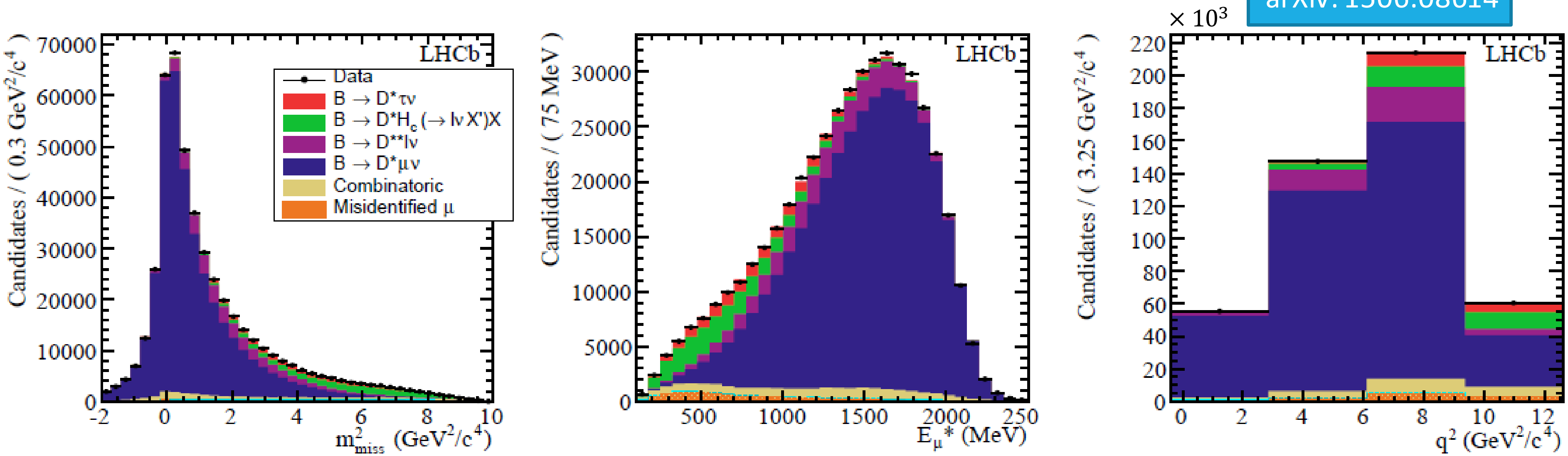
- Using rest frame approximation, construct 3D "template" histograms for each process contributing to $D^{*+}\mu^-$ sample
  - Signal, normalization, and partially reconstructed backgrounds use simulated events, other backgrounds use control data
- Reduce partially constructed backgrounds with LHCb's 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)



Fit Result – Full projections

NEW

arXiv: 1506.08614



- Projections of (left) m_{miss}^2 and (middle) E_μ^* and (right) q^2
- Signal clearly much smaller than normalization, as expected from phase-space suppression combined with $\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau) \cong 17\%$
- Result: $R(D^*) = 0.336 \pm 0.027 \pm 0.030$

Systematics

NEW

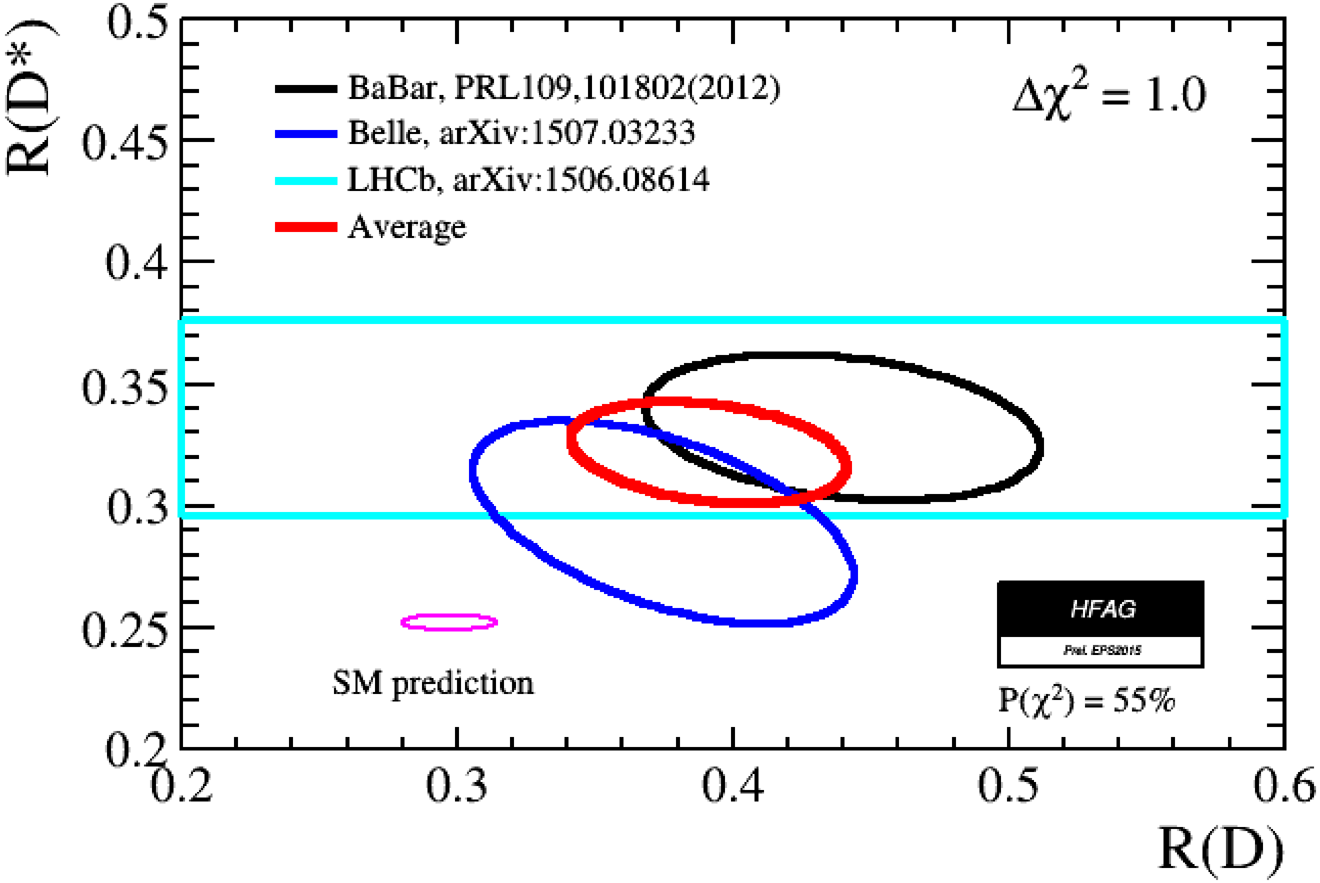
Model uncertainties	Absolute size ($\times 10^{-2}$)
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ form factors	0.6
$\overline{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu)$	0.5
$\overline{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\overline{B} \to D^{**}(\to D^{*+}\pi)\mu^-\overline{\nu}_\mu$ form factors	0.3
$\overline{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form-factors	0.2
$\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

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

Will scale down with more data (Run2)

Combined R(D*) data

NEW



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

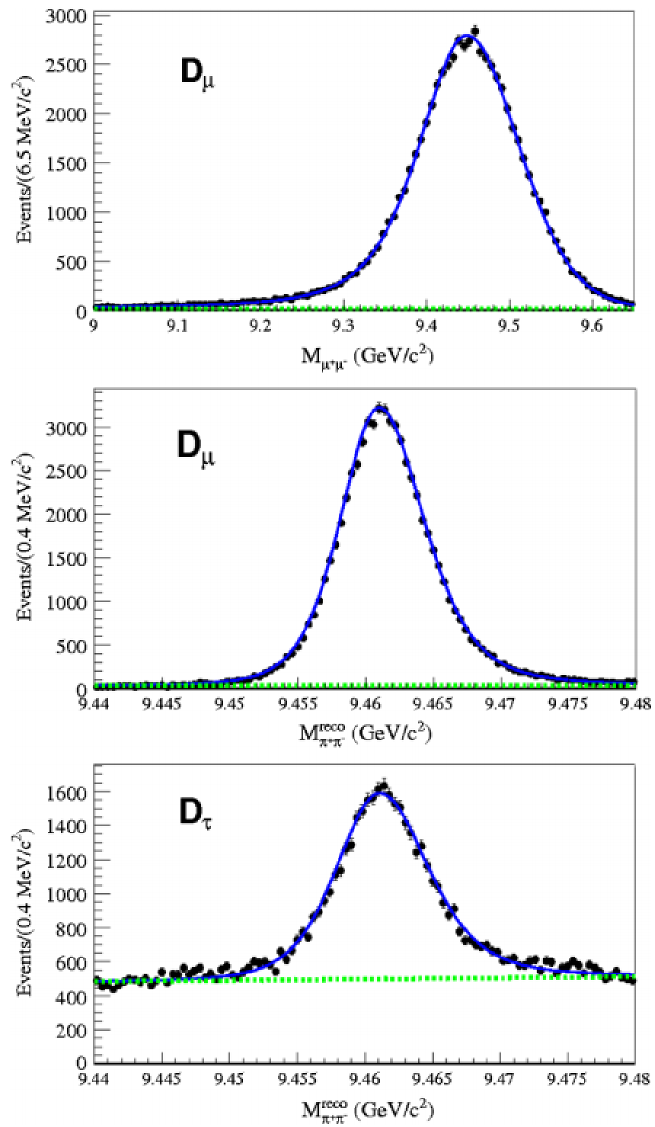
- Plot and average from HFAG
  - SM p-value = $1.1 \times 10^{-4} \rightarrow \approx 3.9\sigma$

Other results of note

$\Upsilon(1S)$ decay

PRL 104 (2010) 191801

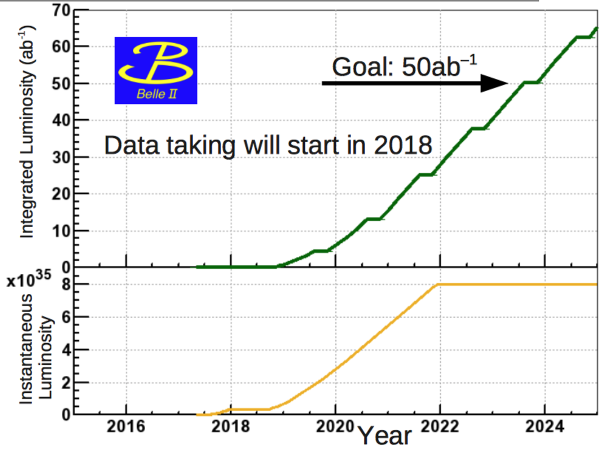
- Nonuniversal effects in $\Upsilon(1S) \to \mu\mu/\tau\tau$ can be induced by pseudoscalar Higgs A^0 (directly or via mixing with η_b)
- BaBar searched in $\Upsilon(3S) \to \Upsilon(1S)\pi\pi$
  - $\Upsilon(1S) \to \mu\mu$ is fully reconstructed
  - $\Upsilon(1S) \to \tau\tau$ is selected based on missing energy after the $\Upsilon(3S) \to \Upsilon(1S)\pi\pi$ dipion system is identified
- Result:
  - $R_{\mu\tau} = 1.005 \pm 0.013 \pm 0.022$



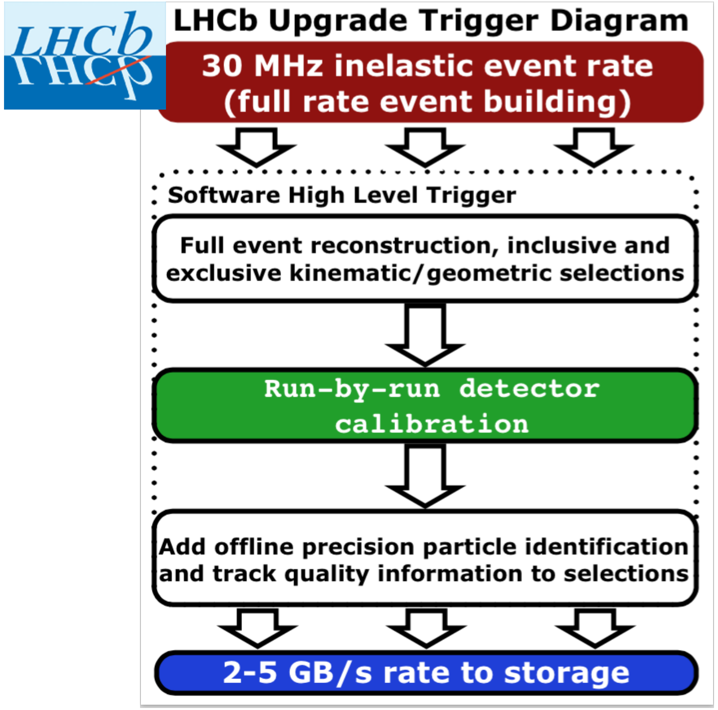
Looking Ahead…

Future Heavy Flavor Experiments

- e^+e^-
  - Belle-II / Super-KEKB
    - Nanobeams, improved final focus, and doubled beam currents to reach 8×10^{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



- pp
  - 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



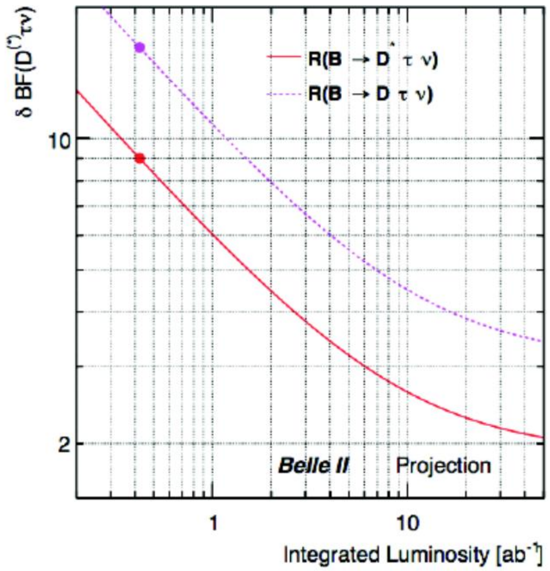
$R(K)$ future prospects

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

- Naievely 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)

Model uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ form factors	0.6
$\overline{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu)$	0.5
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$\overline{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form-factors	0.2
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Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

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

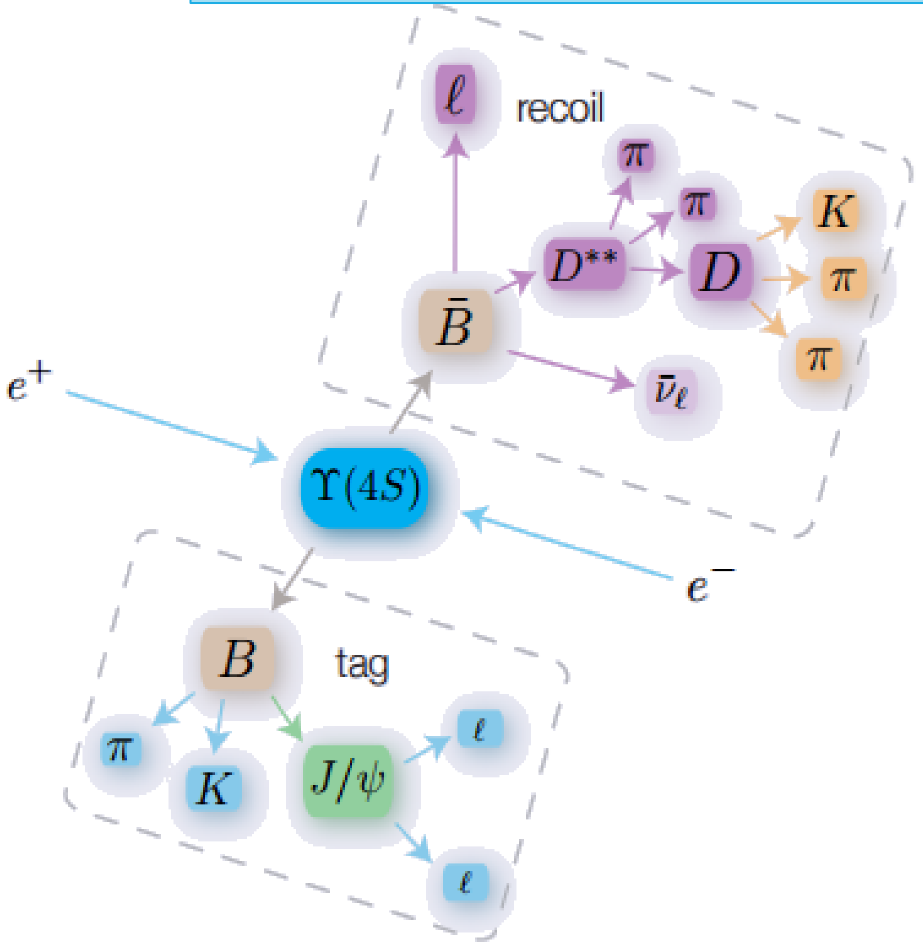
Backup

B-factory measurements

- Exploiting the simple kinematics of the $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ 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 $e^+e^- \to c\bar{c}$ 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

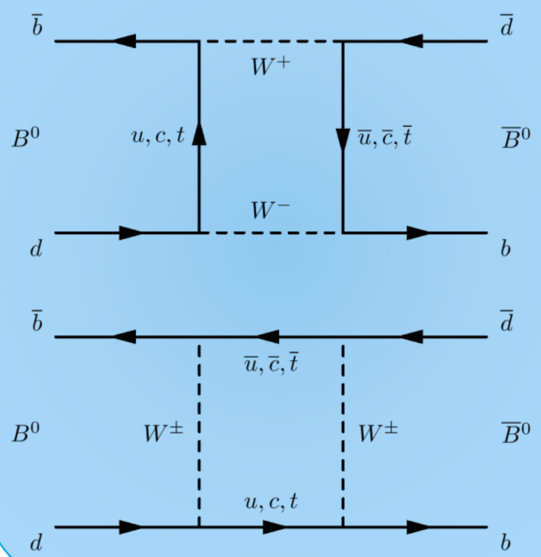


FCNC generalities

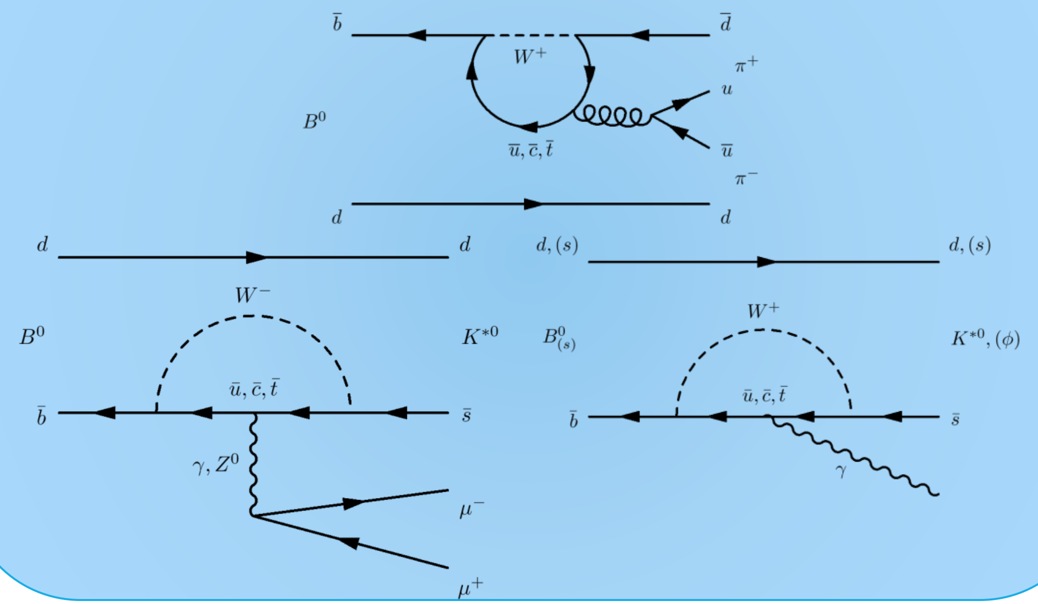
- Flavor-changing Neutral Currents (FCNC) are forbidden at tree-level in the SM
  - Ensured by GIM mechanism, assuming Higgs Yukawas are the only source of flavor violation

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

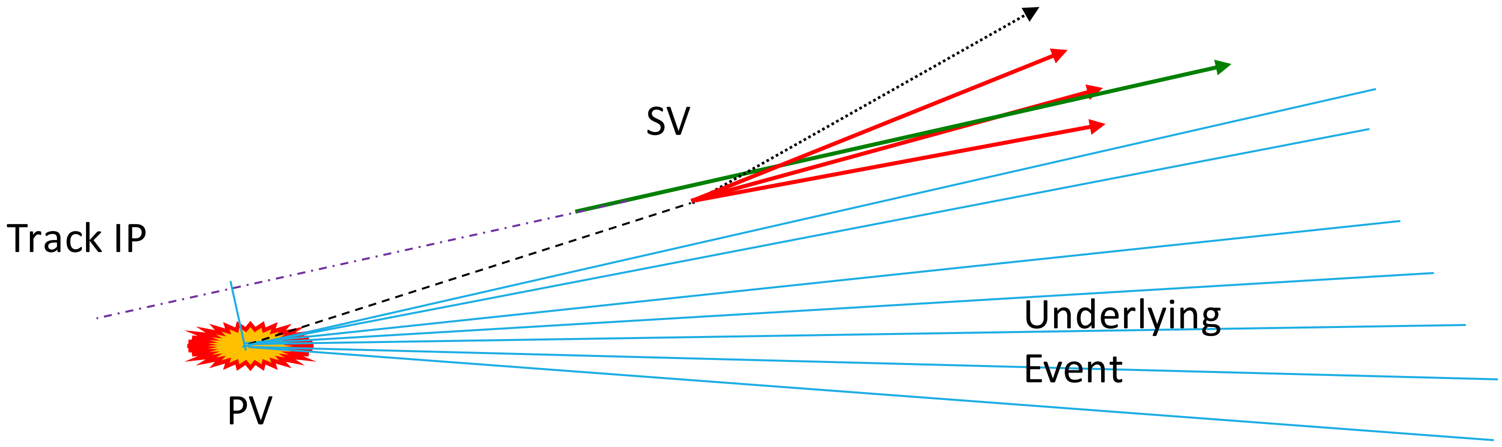
$\Delta F = 2$ “box” diagrams



$\Delta F = 1$ “penguin” diagrams



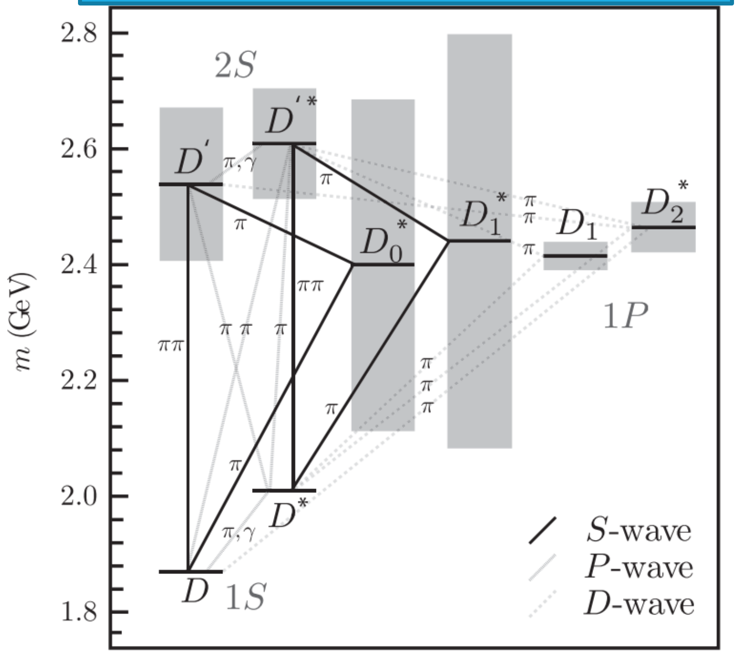
Reducing partially reconstructed backgrounds



- 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 (B2dstst, B2hc)

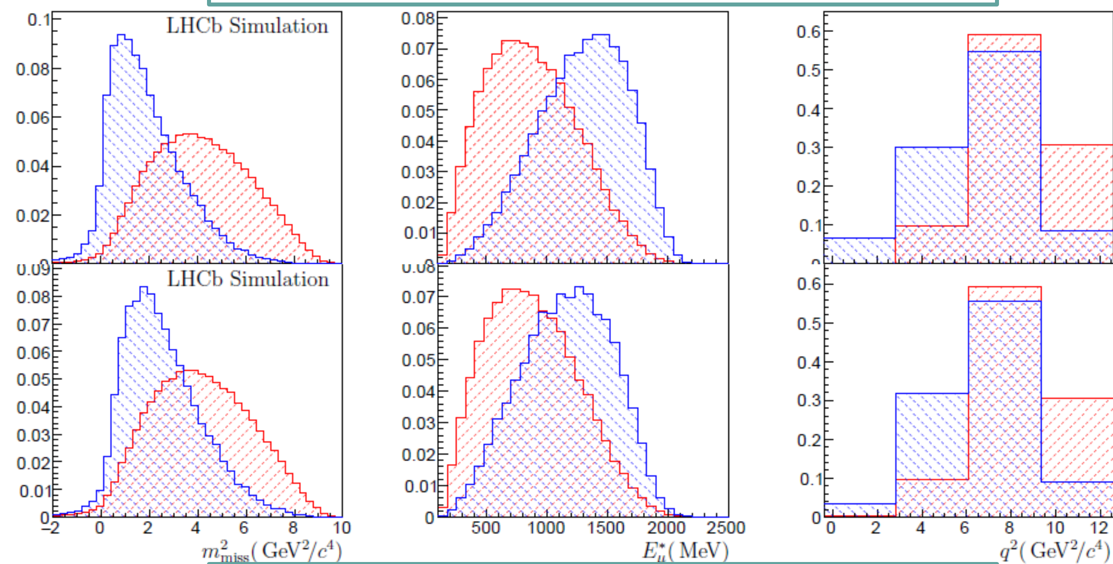
Semileptonic Backgrounds

Bernlochner et al, PRD 85 094033 (2012)



LHCb-PAPER-2015-025

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



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

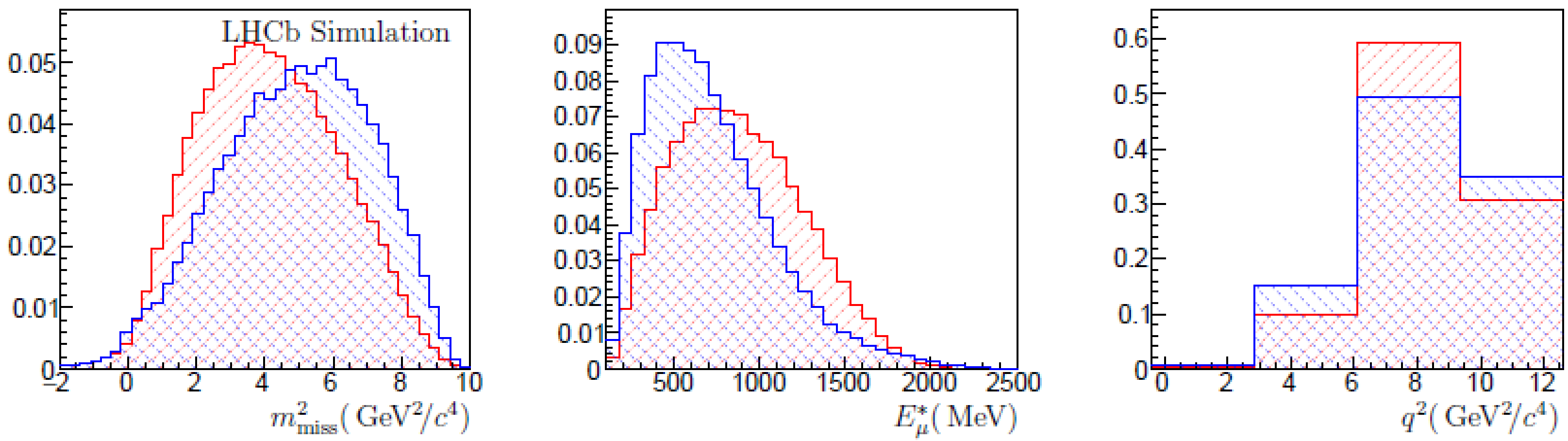
- Contributions of excited charm states in the $B^{\pm,0} \to (c\bar{q})\mu\nu$ transition are large
  - 1P states decaying as $D^*\pi$ known and reasonably well-described by theory (HQET)
    - $D^{*+}\mu^-\pi^-$ control sample sets nonperturbative shape parameters for input to signal fit
  - States 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 $\approx (2)m_\pi$

$B \to D^{*+} H_c(\to \mu\nu X')X$ 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)
  - 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 $D^* DK(n \geq 0\ \pi)$ final states are not well-simulated
  - Dedicated $D^{*+}\mu^- K^{\pm}$ control sample used to improve the template to match data

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



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Big picture $\bar{B} \to D^{*}\tau\nu$

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

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

$\bar{B}^0 \to D^{**+}\mu^-\bar{\nu}_\mu + \bar{B}^0 \to D^{**+}\tau^-\bar{\nu}_\tau$
$\bar{B}^- \to D^{**0}\mu^-\bar{\nu}_\mu + \bar{B}^- \to D^{**0}\tau^-\bar{\nu}_\tau$
$D^{**} \to D^{*+}\pi$ (3 states each, 6 PDFs)

$\bar{B}^0_s \to D_s^{**+}\mu^-\bar{\nu}_\mu$
$D_s^{**+} \to D^{*+}K_S^0$, (2 states, 1 free param)

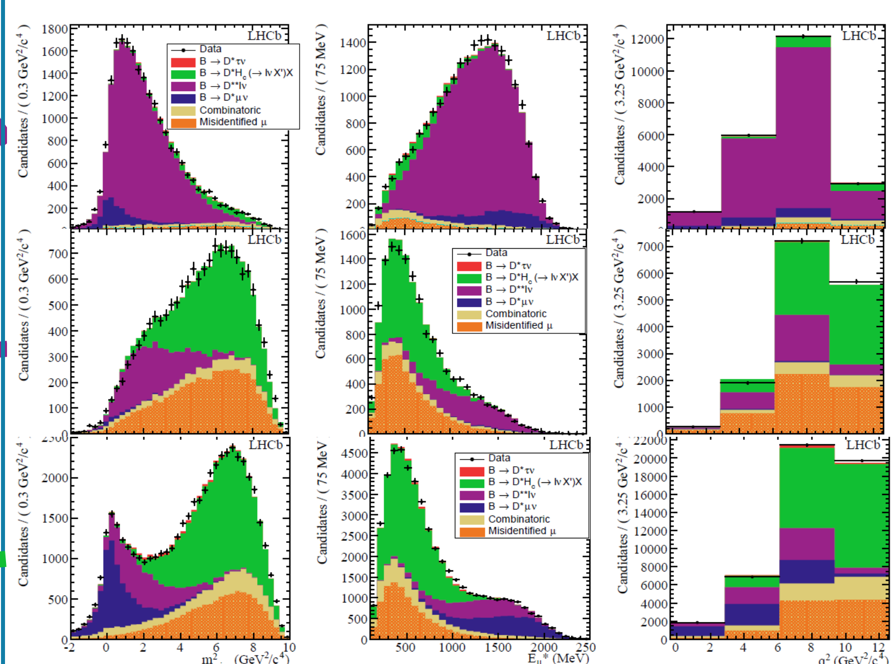
$B^{+,0} \to \bar{D}^{**}\mu^+\nu_\mu$
$\bar{D}^{**} \to D^{*-}\pi\pi$, (cocktail)

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

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

$h \to \mu$ misidentification

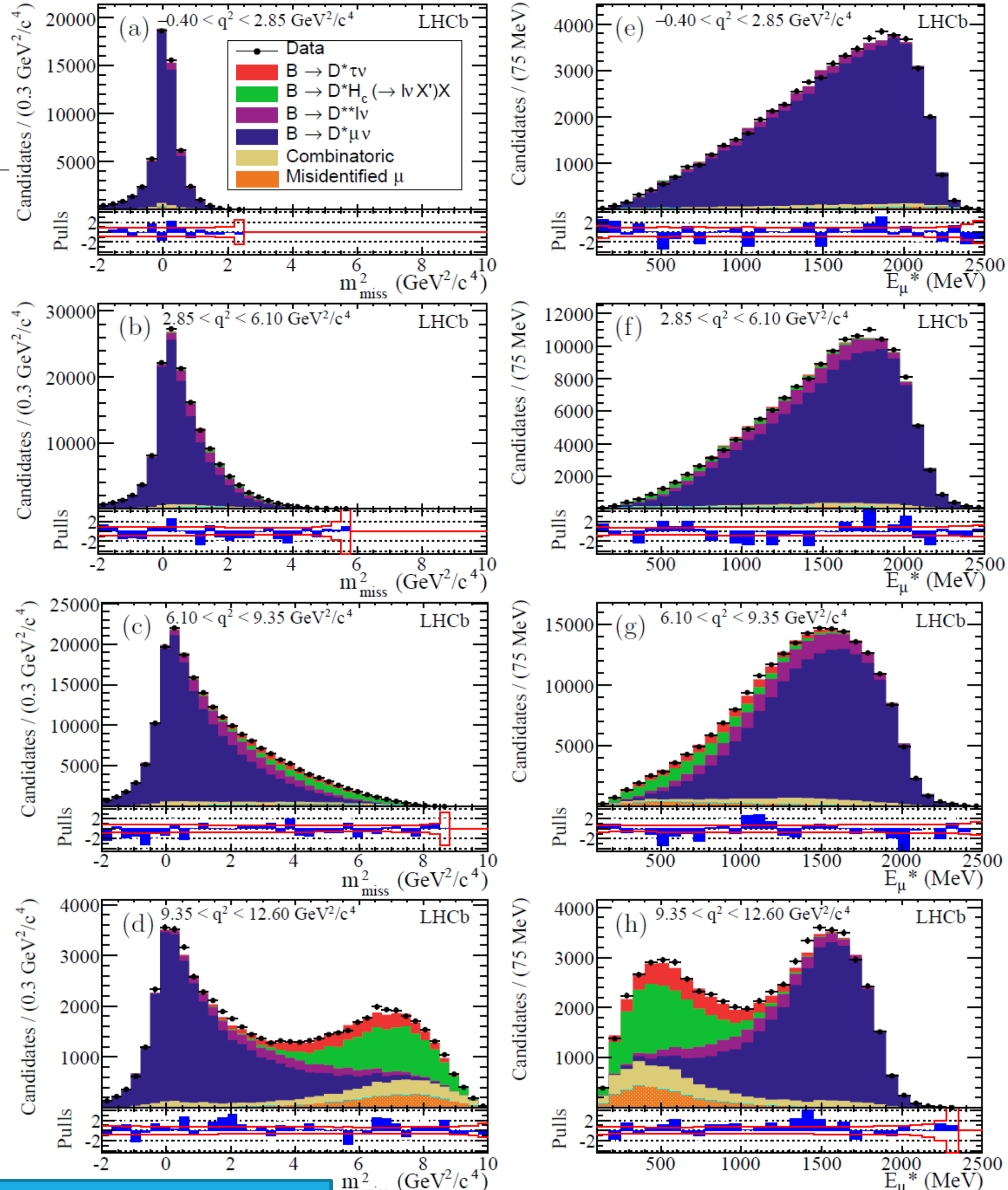
Control sample fits to constrain shapes



LHCb-PAPER-2015-025

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



arXiv:1506.08614 [hep-ex]