Flavour Physics Overview

Greg Ciezarek,
on behalf of the LHCb collaboration

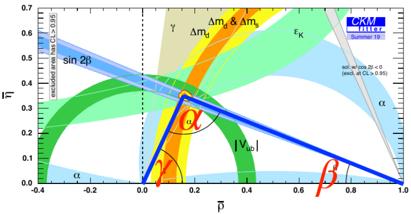
November 04, 2021

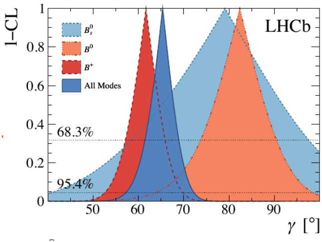
Overview

- CP violation
- Spectrosopy: presented yesterday by Emanuele Santovetti
- $b \to s\ell\ell$
- $b \to c\tau\nu$

CKM fit

LHCb-PAPER-2021-033



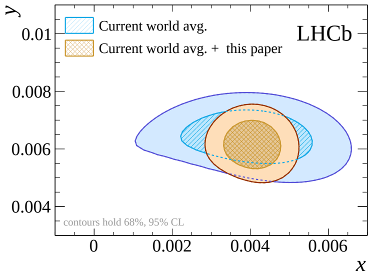


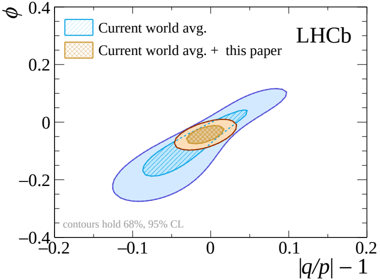
$$\gamma = (65.4^{+3.8}_{-4.2})^\circ$$
$$x = (4.00^{+0.52}_{-0.53}) \times 10^{-3}$$
$$y = (6.30^{+0.33}_{-0.30}) \times 10^{-3}$$

- Gamma combination now updated with many new/improved measurements
  - Most precise single measurement of gamma!
  - For the first time, combine together with related charm parameters
- First gamma measurement from Belle II (together with Belle data)
  - $\gamma = 78.4 \pm 11.4 \pm 0.5 \pm 1.0$, arXiv:2110.12125

Charm mixing in $D^0 \to K^0_S \pi^+\pi^-$

LHCb-PAPER-2021-033

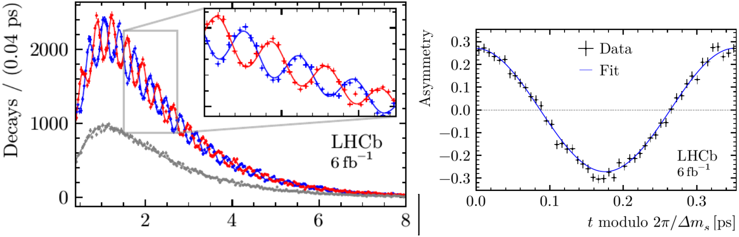




- First observation of mass difference between eigenstates
  - Considerable improvement in precision on mixing parameters
- No evidence for CP violation in mixing with significant improvement in precision
  - Direct CP violation observed: LHCb-PAPER-2019-006

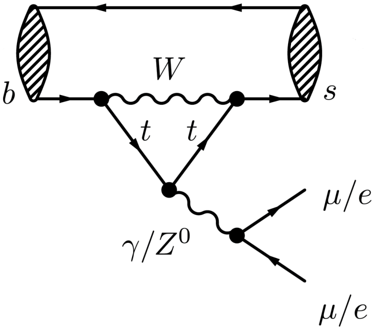
B mixing in $B_s^0 \to D_s^- \pi^+$

LHCb-PAPER-2021-005



- World's most precise measurement of the B_s mixing frequency, Δm_s
  - $\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032\,\mathrm{ps}^{-1}$
- Directly enters CKM fit

$b \to s\ell\ell$ introduction



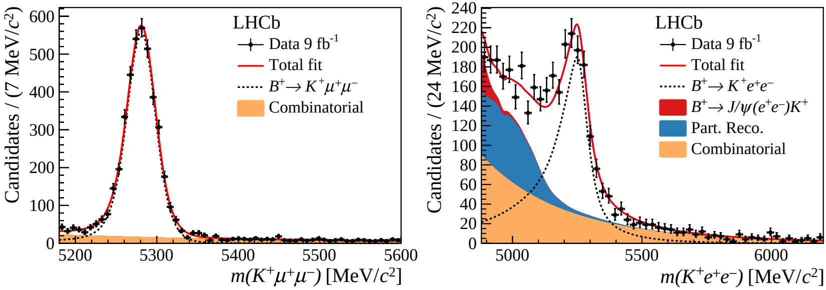
- $b \to s\ell\ell$ is highly suppressed in the SM
- Long history as a probe for new physics
  - Branching fractions, angular distributions, lepton universality...
- Hadronizes to many different channels:
  $B \to K(*)\ell\ell$,$B_s \to \phi\ell\ell$,$\Lambda_b \to pK\ell\ell$.... But one underlying process
  - Also includes $B_s \to \mu\mu$

Lepton universality

- Test lepton universality via $R(K^{(*)}) = \frac{\mathcal{B}(B\to K^{(*)}\mu\mu)}{\mathcal{B}(B\to K^{(*)}ee)}$
- In the SM, QCD effects cancel to $\mathcal{O}(10^{-4})$, $\sim 1\%$ uncertainty from radiative corrections: Bordone, Isidori, Pattori
  - Theoretically clean!

$R(K)$ signal

LHCb-PAPER-2021-004

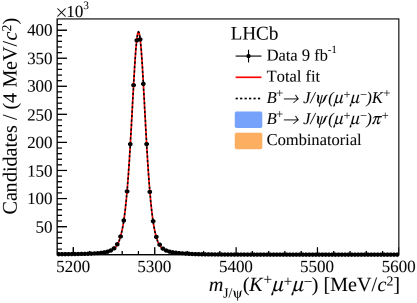


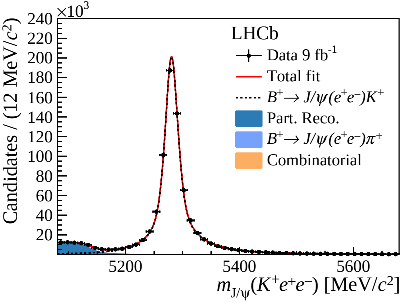
- LHCb signals for $B \to K^+\mu^+\mu^-$ (left) and $B \to K^+e^+e^-$ right
- Differences due to bremsstrahlung:
  - Worse mass resolution
  - Lower reconstruction and selection efficiencies
  - Different PID, different trigger
- Key challenge is controlling the efficiency difference from these effects

$R(K)$ normalisation

‘

LHCb-PAPER-2021-004

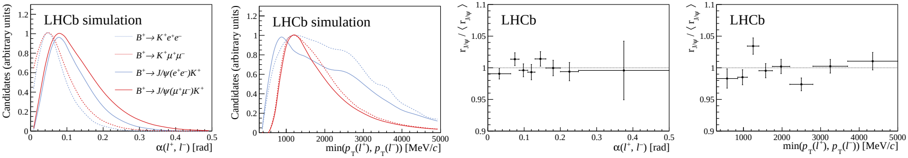




- Control channels: $B \to J/\psi\, K^+$, $J/\psi \to e^+e^-$or $\mu^+\mu^-$
  - J/ψ decay known to be lepton universal within 4 per mille
  - Construct double ratio $\frac{B\to K^+(J/\psi \to e^+e^-)/B\to K^+e^+e^-}{B\to K^+(J/\psi \to \mu^+\mu^-)/B\to K^+\mu^+\mu^-}$ $\to$ cancel efficiency differences
  - Then check efficiency corrections give $r_{J/\psi} = \frac{J/\psi \to e^+e^-}{J/\psi \to \mu^+\mu^-} = 1$

$R(K)$ normalisation

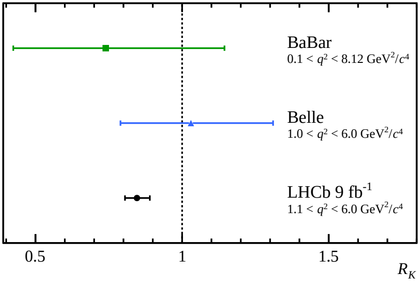
LHCb-PAPER-2021-004



- Integrated $r_{J/\psi} = 0.981 \pm 0.020$
- Check $r_{J/\psi}$ as a function of lepton opening angle and kinematic variables
  - These are different between $B \to J/\psi K^+$ and the signal modes $\to$ propagate the level of agreement as a systematic uncertainty
- Cross-check with heavier $\psi(2S)$: $r_{\psi(2S)} = 0.997 \pm 0.0110$

$R(K)$ result

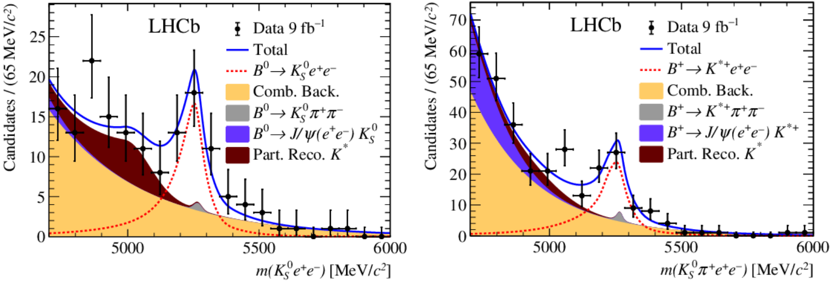
LHCb-PAPER-2021-004



- Measure $R(K) = 0.846\ ^{+0.042}_{-0.039}\ ^{+0.013}_{-0.012}$ in range $1 < q^2 < 6\,\mathrm{GeV}/c^2$ $(q2 = M(\ell\ell))$
- 3.1 sigma below SM expectation

$R(K^{(*)})$ with K^0_S

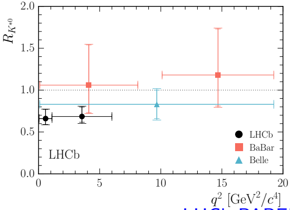
LHCB-PAPER-2021-038



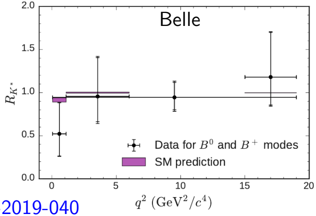
- Most recent: measure $R(K^{(*)})$ in more challenging decay modes: $B \to K^0_S \ell\ell$ and $B \to K^{*+}(\to K^0_S \pi)\ell\ell$
- K^0_S decays later in the detector
  - Lower reconstruction efficiency
  - Worse background rejection
- $R(K^0_S) = 0.66\ ^{+0.20}_{-0.14}\ ^{+0.02}_{-0.04}$
- $R(K^{*+}) = 0.70\ ^{+0.18}_{-0.13}\ ^{+0.03}_{-0.04}$
- Together: 2.0 sigma agreement with SM

$R(x)$ results

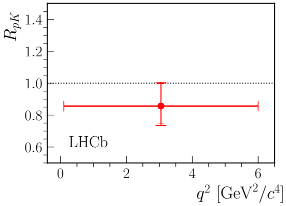
LHCb-PAPER-2017-013



Phys. Rev. Lett. 126, 161801 (2021)



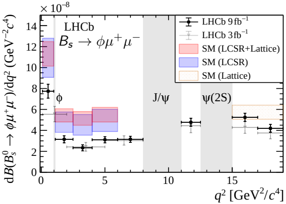
LHCb-PAPER-2019-040



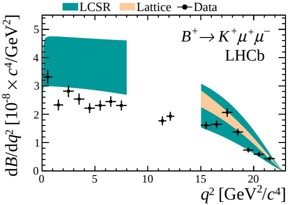
- Similar tensions in $R(K^{*0})$ and $R(pK)$ measurements

Branching fractions

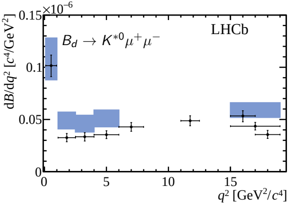
LHCb-PAPER-2021-014



LHCb-PAPER-2014-006



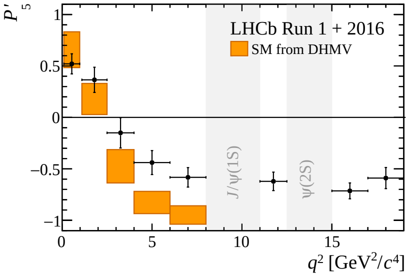
LHCb-PAPER-2016-012



- Branching fractions are consistently low
- BUT: one theoretical uncertainty cannot be controlled - virtual charm loops
  - Lepton universal

$B \to K^*\ell\ell$

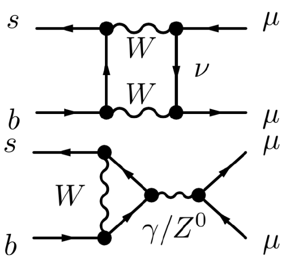
LHCb-PAPER-2020-002

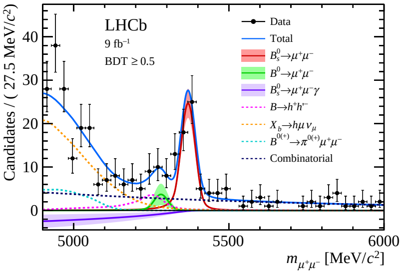


- Angular distributions of $B \to K^*\ell\ell$ sensitive to new physics
- Various combinations of polarisations created to minimise theoretical uncertainties ("P_5'") - and many other observables
  - Now have measurements in a full basis of observables, with correlations
- BUT: charm loops issue equally present here $\to$ can't trust significances

$B_{(s)} \to \mu\mu$

LHCb-PAPER-2021-007

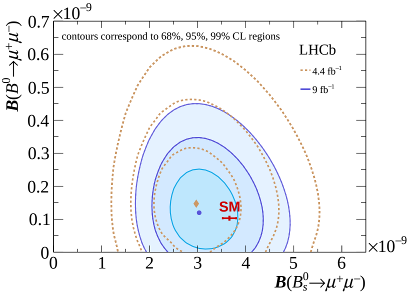




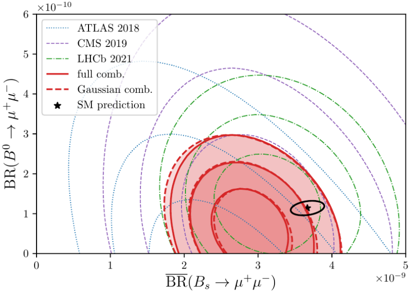
- Related by crossing: $B_{(s)} \to \mu\mu$
- Even more suppressed in the SM
- Need a huge suppression of combinatorial and misidentified backgrounds

$B_{(s)} \to \mu\mu$

LHCb-PAPER-2021-007



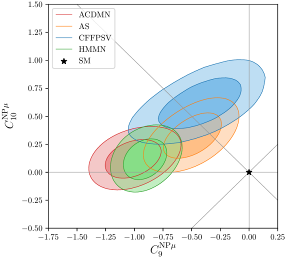
Altmannshofer, Stangl



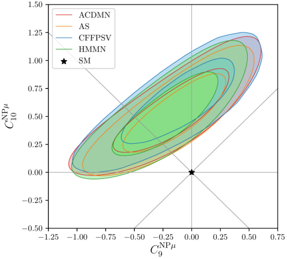
- LHCb legacy run1+2 result (left)
- Combination of LHCb, ATLAS and CMS in 2.3 sigma agreement with SM ($B_s \to \mu\mu$ and $B_d \to \mu\mu$ together)

Combined significance

Capdevila, Fedele, Nestapour, Stangl - Flavour Anomaly Workshop



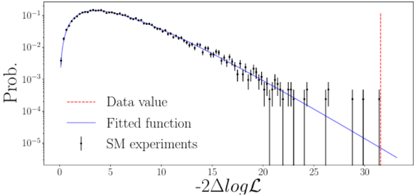
global fit



fit to LFU observables + $B_s \to \mu\mu$

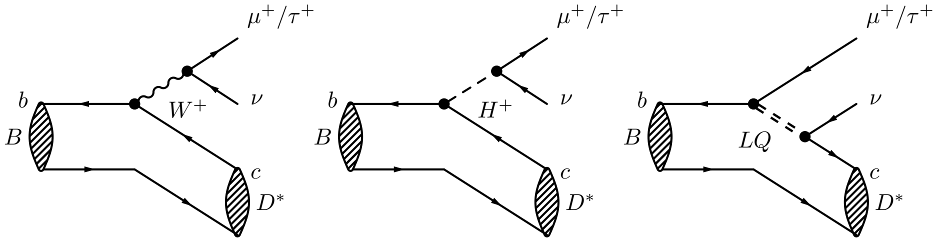
- How to combine the information from so many observables and channels? Fit Effective Field Theory coefficients
  - "Wilson coefficients" encode the strength of a coupling with a given Lorentz structure
- Fits from several groups, after many years of discussions achieved a remarkable level of agreement
  - Left: including observables sensitive to charm loops → more variation from theory approaches, significances not to be taken seriously
  - Right: only theoretically clean observables

Combined significance



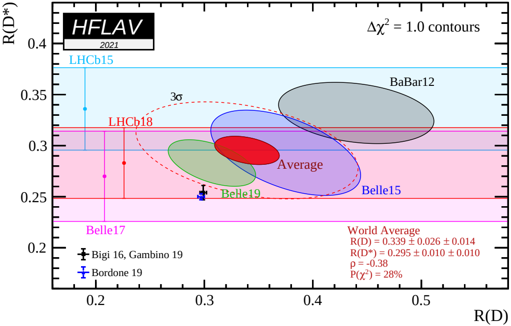
- Best estimate of combined global significance: 4.3 sigma from SM (Isidori,Lancierini,Mathad,Owen,Serra,Silva Coutinho)
    - Include only theoretically clean information: charm loop effect treated as an unconstrained nuisance parameter
    - Consider the probability for a pair of Effective Field Theory coefficients to $\to$ "look elsewhere" factor of ~ 7

$B \to D^{(*)}\tau\nu$



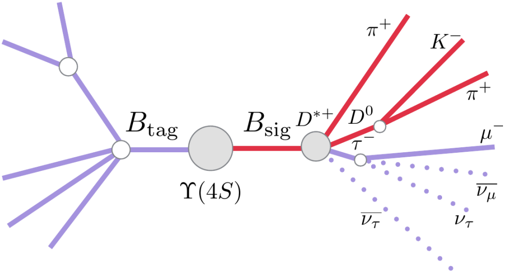
- In the Standard model, the only difference between $B \to D^{(*)}\tau\nu$ and $B \to D^{(*)}\mu\nu$ is the mass of the lepton
  - Form factors mostly cancel in the ratio of rates (except helicity suppressed amplitude)
- Ratio R($D^{(*)}$) = $\mathcal{B}(B \to D^{(*)}\tau\nu)$ / $\mathcal{B}(B \to D^{(*)}\mu\nu)$ is sensitive to e.g charged Higgs, leptoquark

Where do we stand?



- Official HFLAV combination of $\mathcal{R}(D)$and $\mathcal{R}(D^*)$
- Excellent consistency between results
- Combined: **3.4σ tension with SM**

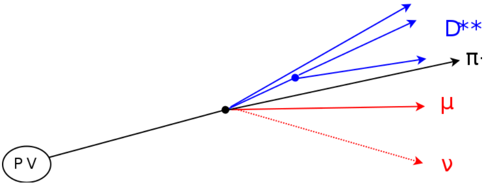
Experimental challenge

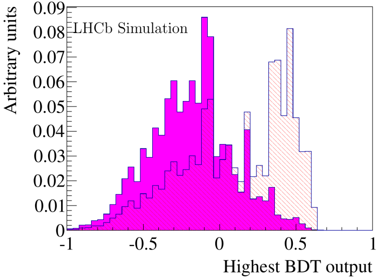


- Difficulty: neutrinos - 2 for $(\tau \to \pi(\pi\pi)\nu)\nu$, 3 for $(\tau \to \mu\nu\nu)\nu$
  - No narrow peak to fit (in any distribution)
- Main backgrounds: partially reconstructed B decays
  - $B \to D^*\mu\nu, B \to D^{**}\mu\nu$, $B \to D^*DX$, $B \to D^*\pi\pi\pi X$ ...
- Also combinatorial, misidentified background
- Method at B factories: "tag reconstruction"
  - Reconstruct other B: precisely measure recoil
  - Can make very precise measurements at Belle II - see later

Isolation

Phys. Rev. Lett. 115 (2015) 111803



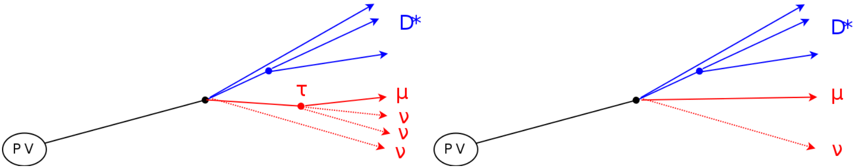


- Reject physics backgrounds with additional charged tracks
- MVA output distribution for $B \to D^{**}\mu^+\nu$ background (hatched) and signal (solid)
- Inverting the cut gives a sample hugely enriched in background $\to$ control samples

Muonic tau strategy

Phys. Rev. Lett. 115 (2015) 111803

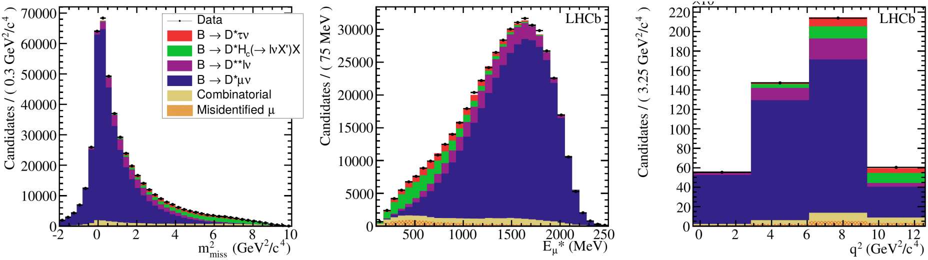
$B \to D^* \tau \nu$ $B \to D^* \mu \nu$



- Can use B flight direction to measure transverse component of missing momentum
- No way of measuring longitudinal component $\to$ use approximation to access rest frame kinematics
  - Assume $\gamma\beta_{z,visible} = \gamma\beta_{z,total}$
  - $\sim$20% resolution on B momentum, long tail on high side
- Can then calculate rest frame quantities - $m^2_{missing}$, E_μ, q^2

Muonic tau fit strategy

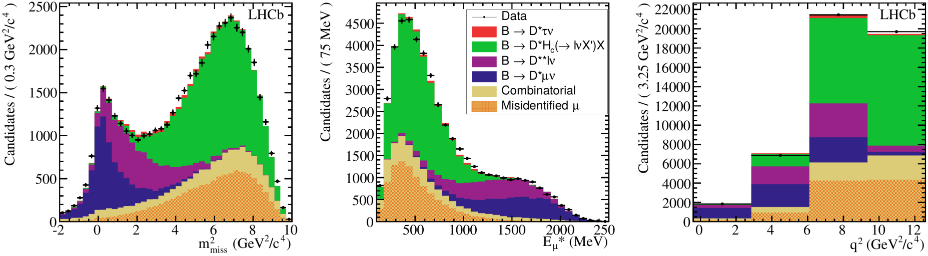
Phys. Rev. Lett. 115 (2015) 111803



- Three dimesional template fit in E_μ (left), $m^2_{missing}$ (middle), and q^2
  - Projections of fit to isolated data shown
- All uncertainties on template shapes incorporated in fit:
  - Continuous variation in e.g different form factor parameters

Background strategy

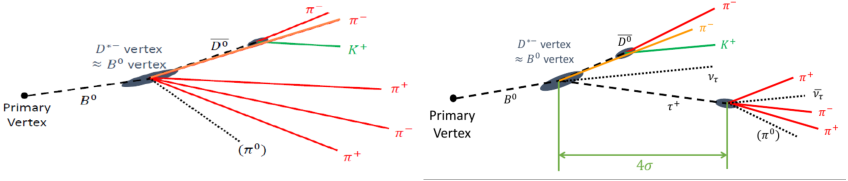
Phys. Rev. Lett. 115 (2015) 111803



- All major backgrounds modelled using control samples in data
  - Dedicated samples for different backgrounds
  - Quality of fit used to justify modelling
  - Data-driven systematic uncertainties
- All combinatorial or misidentified backgrounds taken from data

Hadronic tau strategy

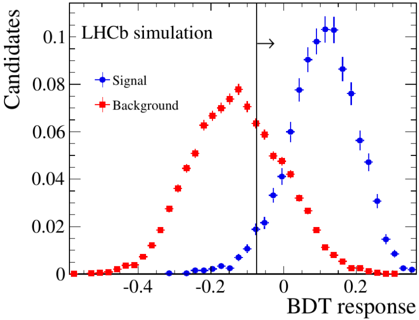
LHCb-PAPER-2017-017, LHCb-PAPER-2017-027



- Control experimental efficiencies by measuring rate relative to $B \to D^*\pi\pi\pi$
- Can use decay topology to remove direct $B \to D^*\pi\pi\pi X$ decays:
- If the $\pi\pi\pi$ vertex is displaced from the B vertex, cannot be direct $B \to D^*\pi\pi\pi X$
- Can remove a large, poorly measured background
  - And control the remainder
- $B \to D^*DX$ major physics background remaining

Dealing with $B \to D^* DX$

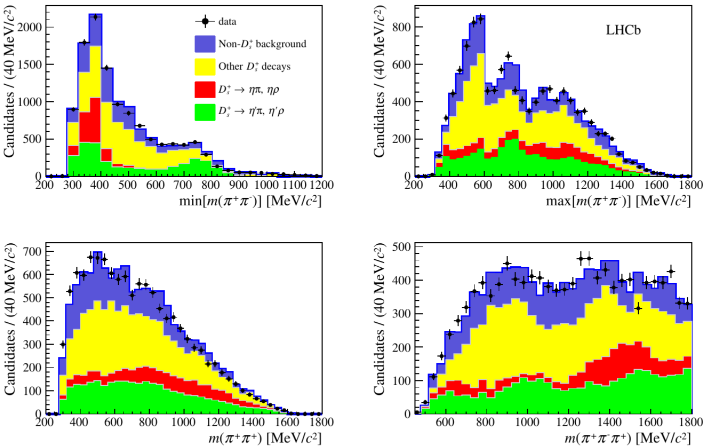
LHCb-PAPER-2017-017, LHCb-PAPER-2017-027



- $[\pi\pi\pi]$ lifetime discriminates between tau and $B \to D^* DX$
- Can use partial reconstruction techniques to reconstruct D peak in $B \to D^{*+} D$ (not $B \to D^* DX$)
- $\tau \to \pi\pi\pi\nu$ is mostly $a1(1260)$, $D \to \pi\pi\pi X$ mostly isn't
  - Use the $\pi\pi\pi$ (sub) structure to separate $B \to D^* \tau\nu$ from $B \to D^* DX$
  - Shown: control region for $D_s \to \pi\pi\pi X$
- Put everything in an MVA: kinematics, Dalitz, partial reconstruction,

$D \to \pi\pi\pi X$

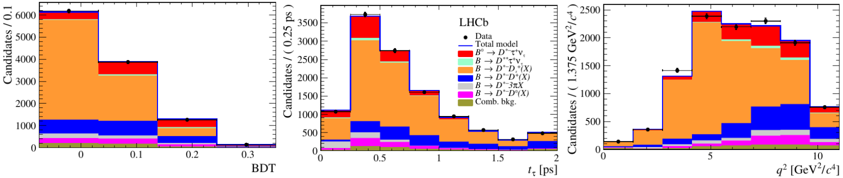
LHCb-PAPER-2017-017, LHCb-PAPER-2017-027



- Again, use data to control background modelling
- Use low BDT region to control $D_s \to \pi\pi\pi X$ substructure

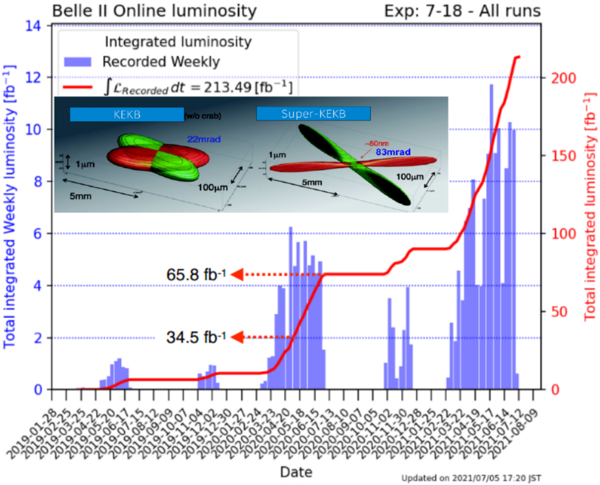
Hadronic tau fit

LHCb-PAPER-2017-017, LHCb-PAPER-2017-027



- 3D template fit in BDT,q^2, tau lifetime to determine signal yield

Belle II status



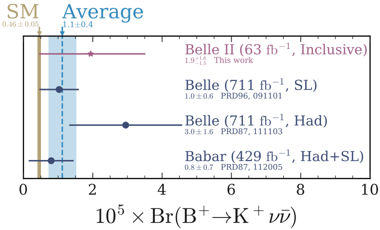
- Luminosity record reclaimed
- Early Belle II results presented yesterday by Hulya Atamacan

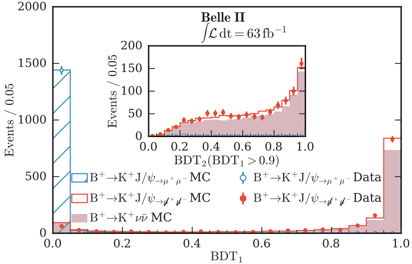
Belle II prospects

Belle II Physics Book

Observable	Current Belle/ Babar	2019 LHCb	Belle II ($5\ ab^{-1}$)	Belle II ($50\ ab^{-1}$)
CKM precision, new physics in CP Violation				
$\sin 2\beta/\varphi_1$ ($B \to J/\psi K_S$)	0.03	0.04	0.012	0.005
γ/φ_3	13°	5.4°	4.7°	1.5°
α/φ_2	4°	–	2	0.6°
$\|V_{ub}\|$ (Belle) or $\|V_{ub}\|/\|V_{cb}\|$ (LHCb)	4.5%	6%	2%	1%
φ_s	–	49 mrad	–	–
S_{CP}($B \to \eta' K_S$, gluonic penguin)	0.08	○	0.03	0.015
A_{CP}($B \to K_S \pi^0$)	0.15	–	0.07	0.04
New physics in radiative & EW Penguins, LFUV				
S_{CP}($B_d \to K^* \gamma$)	0.32	○	0.11	0.035
R($B \to K^* l^+ l^-$) ($1<q^2<6$ GeV$^2/c^2$)	0.24	0.1	0.09	0.03
R($B \to D^* \tau\nu$)	6%	10%	3%	1.5%
Br($B \to \tau\nu$), Br($B \to K^* \nu\nu$)	24%, –	–	9%, 25%	4%, 9%
Br($B_d \to \mu\mu$)	–	90%	–	–
Charm and τ				
ΔA_{CP}(KK-$\pi\pi$)	–	8.5×10^{-4}	–	5.4×10^{-4}
A_{CP}($D \to \pi^+\pi^0$)	1.2%	–	0.5%	0.2%
Br($\tau \to e\gamma$)	$<120\times10^{-9}$	–	$<40\times10^{-9}$	$<12\times10^{-9}$
Br($\tau \to \mu\mu\mu$)	$<21\times10^{-9}$	$<46\times10^{-9}$	$<3\times10^{-9}$	$<3\times10^{-9}$

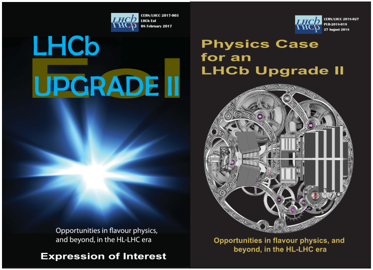
$B \to K\nu\nu$





- First flavour physics publication from Belle II: Phys. Rev. Lett. 127, 181802 (2021)
- Improved analysis methods give higher sensitivity than previously
- BDT containing tagging, event shape information
  - Simulation validated using control channels: $B \to J/\psi(\to \mu^+\mu^-)K$ with the muons discarded
- Belle II measurements discussed yesterday by Markus Prim

LHCb Upgrade-II



- Framework TDR in preparation - strong support:
  - LHCC -Expression of interest (2017), Physics Case (2018)
  - Strong support in European Strategy (2020)
- Applications from new groups actively encouraged!
- Wide and growing physics program: flavour, EW, soft QCD, gas target, light direct searches,...
- Technical Associate membership: physics on other experiments while pursuing R&D on LHCb
  - Rad. hard CMOS detector, Small pixel precision timing vertex detector, ECAL with precision timing, Hadron PID with fast timing, Cryogenic cooled SiPMs, GPU based triggering, ...

Conclusion

- Precision of CP violation measurements in beauty and charm ever improving
- 4.3 sigma tension with SM in $b \to s\ell\ell$ decays
- 3.4 sigma tension with SM in $B \to D^*\tau\nu$ decays
- In both cases, lepton non-universal
- I've tried to convince you of why we believe our uncertainties
- LHCb, Belle-II, CMS and ATLAS will all have a lot to say in the near future