DEEP DIVE INTO SEMILEPTONIC ANALYSES

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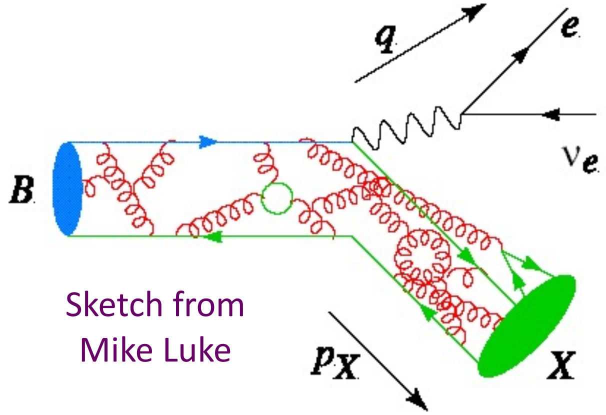
Motivation

Why study semileptonic decays?

- Provide access to fundamental CKM parameters $|V_{cb}|$ and $|V_{ub}|$
- Probe charged weak b decays:
  - Allow tests of lepton universality
  - Allow tests of structure (pure $V-A$ or not?)
- Are more abundant (but less clean) than purely leptonic decays
- Are better understood theoretically than fully hadronic decays (but they're harder to reconstruct due to missing neutrino(s))

$$\langle X|\bar{b}\gamma^{\mu}q|B\rangle_{SM}$$

$$\langle X|\mathcal{O}|B\rangle_{NP?}$$



Sketch from Mike Luke

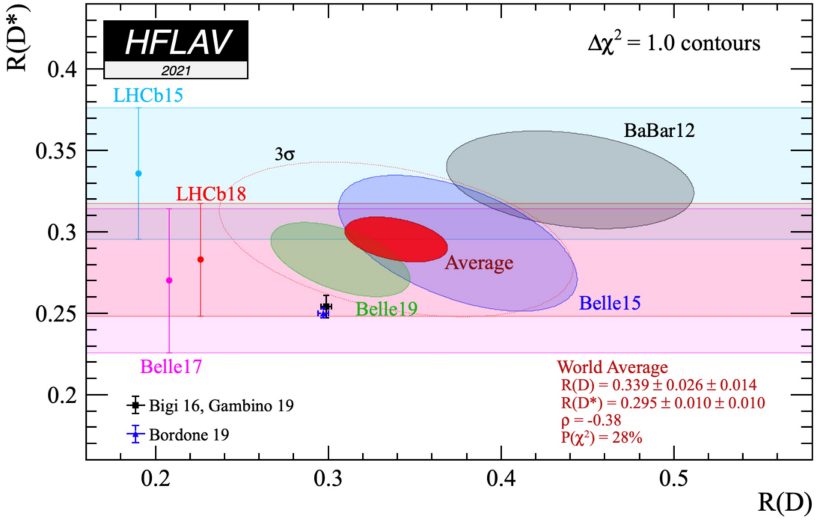
SM ← Physics goals → NP

- $|V_{cb}|$
  - Abundant $B \to X_c \ell \nu$ decay modes ($\approx 24\%$ of all B decays)
- $|V_{ub}|$
  - Rarer ($\approx 0.5\%$ of all B decays)
  - Large potential background from $b \to c$ transitions
- Form factors

- Lepton flavor universality: measure e, μ, τ decay rates separately
- Look for contributions that aren’t pure $V - A$

SM input to NP

Lepton flavor universality tests



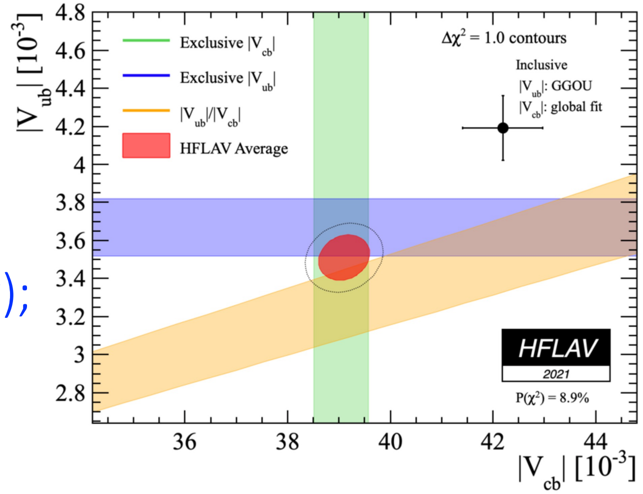
- A fundamental assumption in the SM is that spin-1 bosons couple *only* to charge; for flavor-changing interactions this means weak isospin
- As a result, e, μ and τ decay rate differences arise only due to phase space → the SM makes precise predictions about their ratios
- Ratios like $\mathcal{R}_D = \frac{\Gamma(B\to D\tau\nu)}{\Gamma(B\to D\ell\nu)}$ provide stringent tests, since uncertainties from form factors and experimental sources partially cancel in the ratio
- Many such $\mathcal{R}$ measurements are of interest; the ones with the precision to test the SM to date are $\mathcal{R}_D$ and $\mathcal{R}_{D^*}$ (a first measurement of $\mathcal{R}_{J/\psi}$ from B_c^+ was made by LHCb)
- Other quantities (e.g. τ polarization) are also useful probes
- Much more detail in RMP article:
  "Semitauonic b-hadron decays: A lepton flavor universality laboratory", F. Bernlochner, M. F. Sevilla, D. J. Robinson, G. Wormser, [arXiv: 2101.08326]

High priority measurements for Belle II

- Semi-tauonic decays ($B \rightarrow X\tau\nu$) as measured by BaBar, Belle and LHCb are in some tension with SM expectations
  - we must establish whether this is due to “New Physics” or “Nuisance Parameters”
- And there’s our friendly competition with LHCb…

- Inclusive/exclusive puzzle:

  $|V_{cb}|$ and $|V_{ub}|$ can be determined using *inclusive* or *exclusive* decays (the methods are complementary); the results don’t agree well



- Missing modes:

  The measured exclusive modes do not saturate the inclusive BF (the gap is $\sim 1.2 \pm 0.4\%$); how does what is missing impact important measurements?

Inclusive and exclusive SL decays

Theory uncertainties arise from different sources

Inclusive $B \to X_q \ell \nu$

- Theory Relies on Heavy Quark Expansion (OPE), a systematic expansion in Λ_{QCD}/m_b; non-perturbative coefficients can be determined from data (via fit to moments in $E_e, m_X, \ldots$)
- Measurement allows for unreconstructed "X" and represents a sum over all modes that involve the reconstructed particles
- E.g., $\bar{B} \to D(X)\ell\nu = \sum_j \bar{B} \to D X_j \ell \nu$ ("X_j" can be null, a pion, a photon, two pions, etc.)

Exclusive $B \to H \ell \nu$

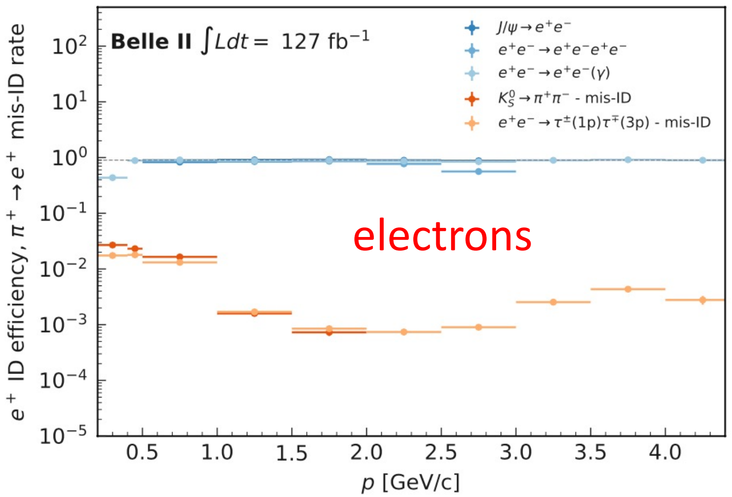
- Theory requires form factors $F(q^2)$; shape can in principle be measured but normalization must be come from theory (LQCD)
- Measure a specific decay (or simultaneously measure multiple decays); everything else is treated as background
- E.g., $\bar{B}^0 \to D^{*+}\ell^-\nu$, or $B^- \to \pi^0 \ell^- \nu$

The basics

Electrons and muons in Belle II

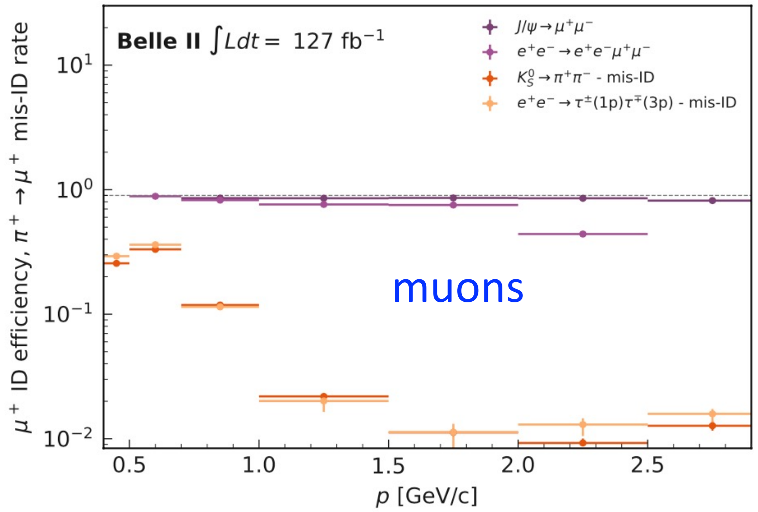
Electrons

- High identification efficiency and low misID background down to ≈ 0.3 GeV
- Affected by radiative corrections (in production/decay) and bremsstrahlung (in detector). Brem corrections are helpful but it is essential to quantify the *uncertainty* due to brems



Muons

- High identification efficiency and low misID above ≈ 1 GeV; large π/K misID at low p



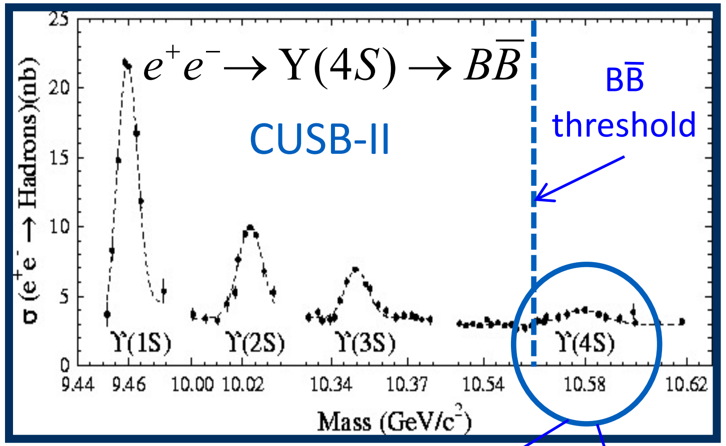
Dedicated analyses determine efficiencies and misID rates

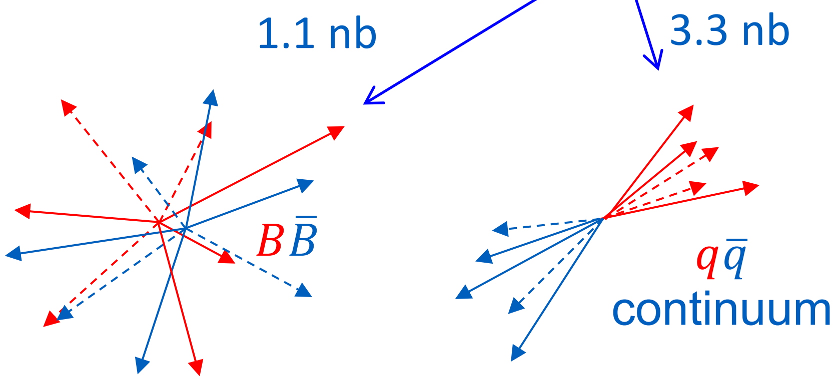
Sources of electrons and muon candidates

- Prompt leptons from weak b, c hadron decay
- Backgrounds from hadron mis-ID, detector interactions
- Production cross-sections/BFs at 10.58 GeV:

	$b\bar{b}$	$c\bar{c}$	$q\bar{q}\ (q = u, d, s)$
$\sigma(e^+e^- \to q\bar{q})$	1.1 nb	1.3 nb	2.0 nb
BF $\left(H_q \to X\ell\nu\right)$	0.11	(0.07—0.18)	(only fakes)

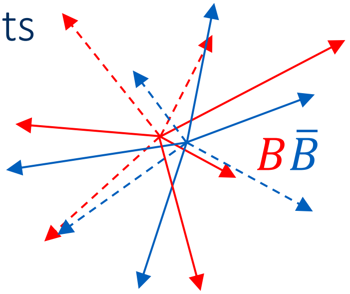
- Leptons from $B \to J/\psi \to \ell^+\ell^-$ ($\sim 0.013\ \ell/B$) matter for $b \to u\ell\nu$ studies
- Event shapes help with continuum suppression



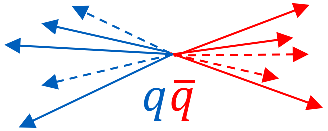


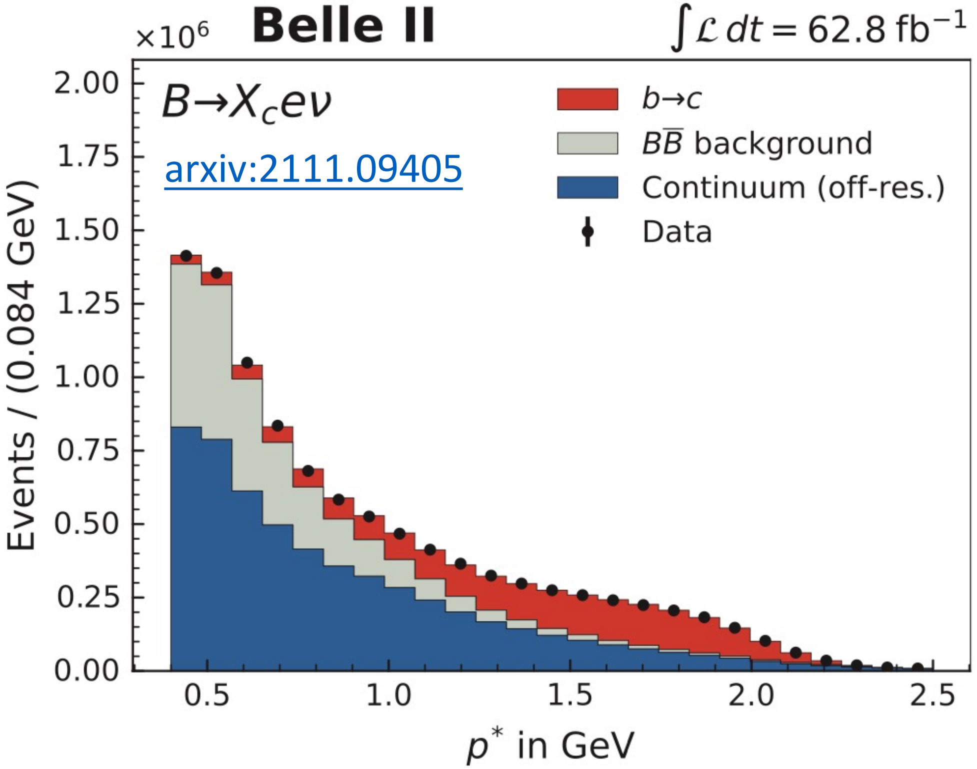
Electrons and muons at $\Upsilon(4S)$

- In CM, B mesons are nearly at rest; the decay products are isotropic and each B decays independently

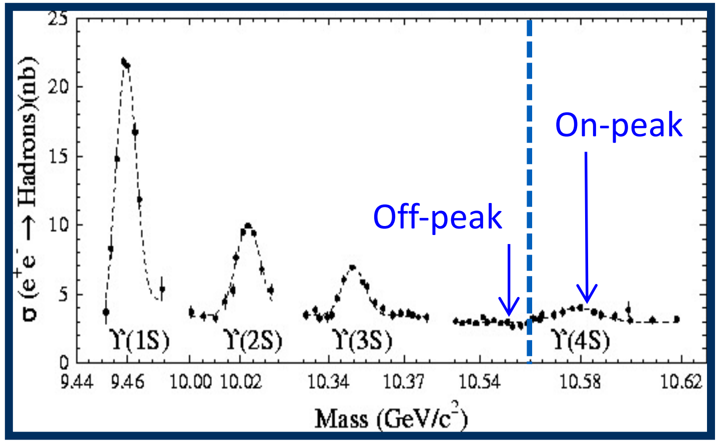


- Both B and charm weak decays have significant SL BFs; charmonium contributes less, but can give high p leptons
- Leptons from $B \to \ell$ are harder than cascades $B \to D/\tau \to \ell$
- Charge correlations: $b \to \ell^-$ but $b \to c/\tau \to \ell^+$ and $b \to \bar{c} \to \ell^-$; primary leptons tag b (and B) flavor
- Real leptons in continuum come primarily from $c\bar{c}$, but other $q\bar{q}$ are a source of fake leptons (mis-ID)
- In CM the charm mesons are boosted leading to more collimation (jet-like)

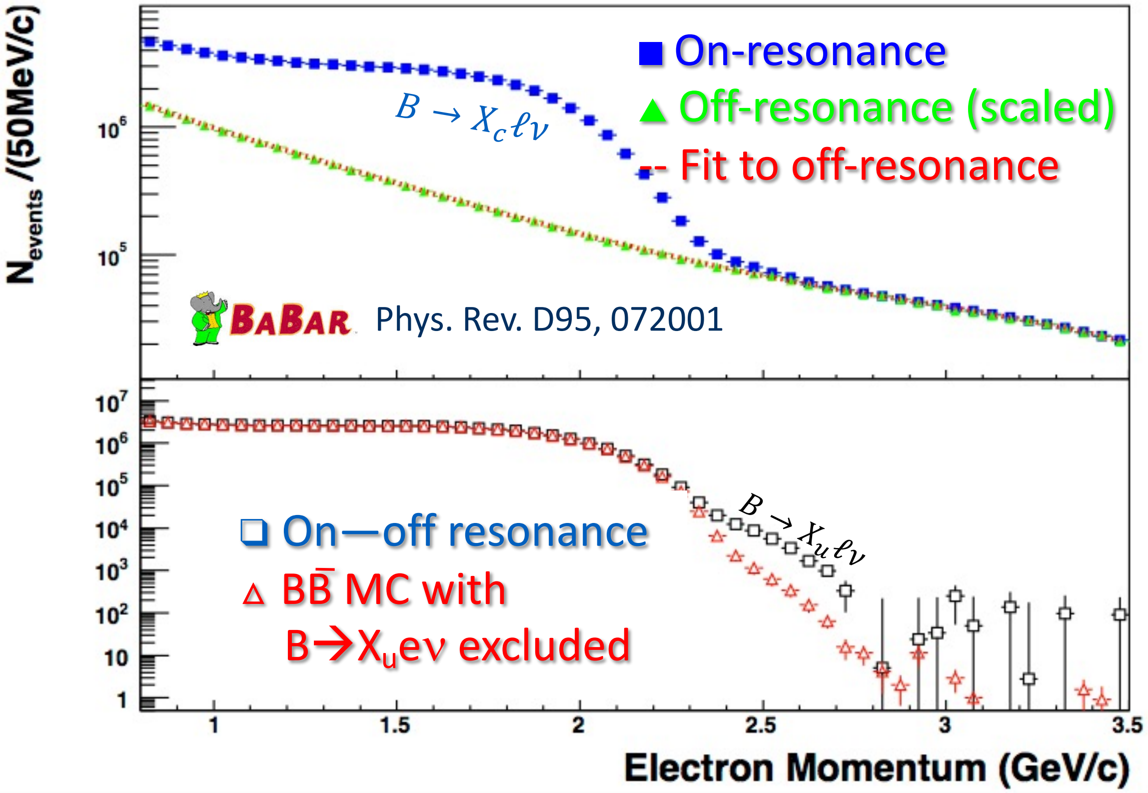




Electrons spectrum from $B\bar{B}$ and $q\bar{q}$



- Off-resonance data (scaled for luminosity and cross-section differences) provides an excellent control sample for modeling the continuum background
- $B \to X_c \ell \nu$ decays dominate over continuum and over $B \to X_u \ell \nu$: $\mathrm{BF}(B \to X_c \ell \nu) \sim 50 * \mathrm{BF}(B \to X_u \ell \nu)$
- $B \to X_u \ell \nu$ can be measured in regions ($p_\ell \gtrsim 2.4$ GeV, $q^2 > 11.7$ GeV^2) forbidden to $B \to X_c \ell \nu$
- Continuum background is also significant for $B \to X_u \ell \nu$ decays (note region around $p = 2.5$ GeV where continuum has $\sim 10^5$ events/bin and $B \to X_u \ell \nu$ has $\sim 10^4$)
- Many analyses use dedicated continuum suppression methods (often MVA)



Phys. Rev. D95, 072001

Measurement strategies

Untagged

- High efficiency 👍
- Weak/no kinematic constraints 👎
- Kinematic acceptance is limited by backgrounds (details depend on mode) 👎

- Large background from $e^+e^- \to q\bar{q}$
- Due to backgrounds, only cleanest decay modes (e.g. $D^+ \to K^-\pi^+\pi^+$) are used

B-Tagged

- Low overall efficiency (including tag) 👎
- Strong kinematic constraints for 1ν modes 👍
- Kinematic acceptance usually better than untagged 👍

- Other complications will be discussed later

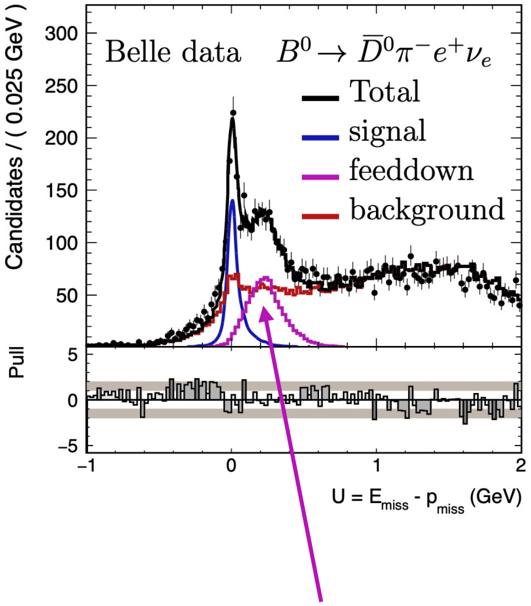
Missing neutrinos

If only one neutrino is missing in the event, kinematic constraints are useful.
If you have >1 missing particle, the kinematics are not constrained

- For hadronic tags

  $p_{miss} = p_{e^+e^-} - \sum_{j=1}^{N_{obs}} p_j$
  so $U \equiv E_{miss} - |\vec{p}_{miss}|$
  should be ≈ 0 ($\sigma_U \sim 40$MeV)

  Alternatively,
  $m_{miss}^2 = U(E_{miss} + |\vec{p}_{miss}|)$,
  but this mixes resolution and physics

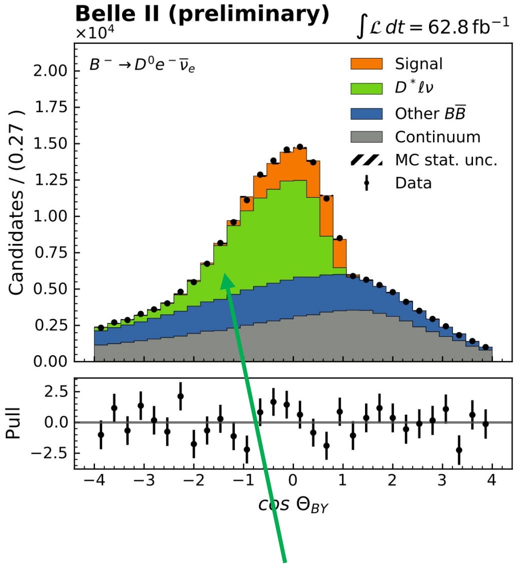


Additional missing particle(s)

- For untagged analyses or semileptonic tags[*],

  $$\cos\theta_{BY} \equiv \frac{2E_B^* E_Y^* - m_B^2 - m_Y^2}{2|\vec{p}_B^*||\vec{p}_Y^*|}$$

  lies in $[-1,1]$ for $B \to Y\ell\nu$ decays. Missing particles (e.g. slow pions) push this to $\sim[-3,1]$, but still allow useful discrimination



Additional missing particle(s)

[*] One can define another variable in events where signal and tag each have one missing neutrino; I leave it as an exercise

Kinematics exercises

The “traditional” variable, $\cos\theta_{BY} \equiv \frac{2E_B^* E_Y^* - m_B^2 - m_Y^2}{2|\vec{p}_B^*||\vec{p}_Y^*|}$, is a calculated angle in the CM frame (we should probably call it $\cos\theta_{BY}^*$). Since the B mesons are not at rest, the $\cos\theta_{BY}$ distribution has more entries near +1 than near -1 (the Y is boosted forward)

1. Show that a related variable gives the angle in the *rest frame of the decaying* B *meson*:

$$\cos\theta_{BY}^B = \frac{2E_Y^* - E_B^*(1 + r^2)}{|\vec{p}_B^*|(1 - r^2)}$$

   $\left(r \equiv \frac{m_Y}{m_B}\right)$. This quantity is distributed uniformly on $[-1,1]$ for true $B \rightarrow Y\nu$ decays

2. Show that when both B mesons from $\Upsilon(4S)$ decay semileptonically, the following must be satisfied (γ is the angle between Y_1 and Y_2):

$$\cos^2\phi_B = \frac{\cos^2\theta_{BY_1} + \cos^2\theta_{BY_2} + 2\cos\theta_{BY_1}\cos\theta_{BY_2}\cos\gamma}{\sin^2\gamma} \epsilon\ [0,1]$$

Exclusive decay landscape

- Measure branching fractions or ratios of BFs; use to determine $|V_{qb}|$
- Measure form factors as function of q^2 (with good resolution) and angles
- Where possible, measure all the relevant kinematic variables over the full phase space
- Deal with feed-down or feed-across from related decay modes; these can be large effects

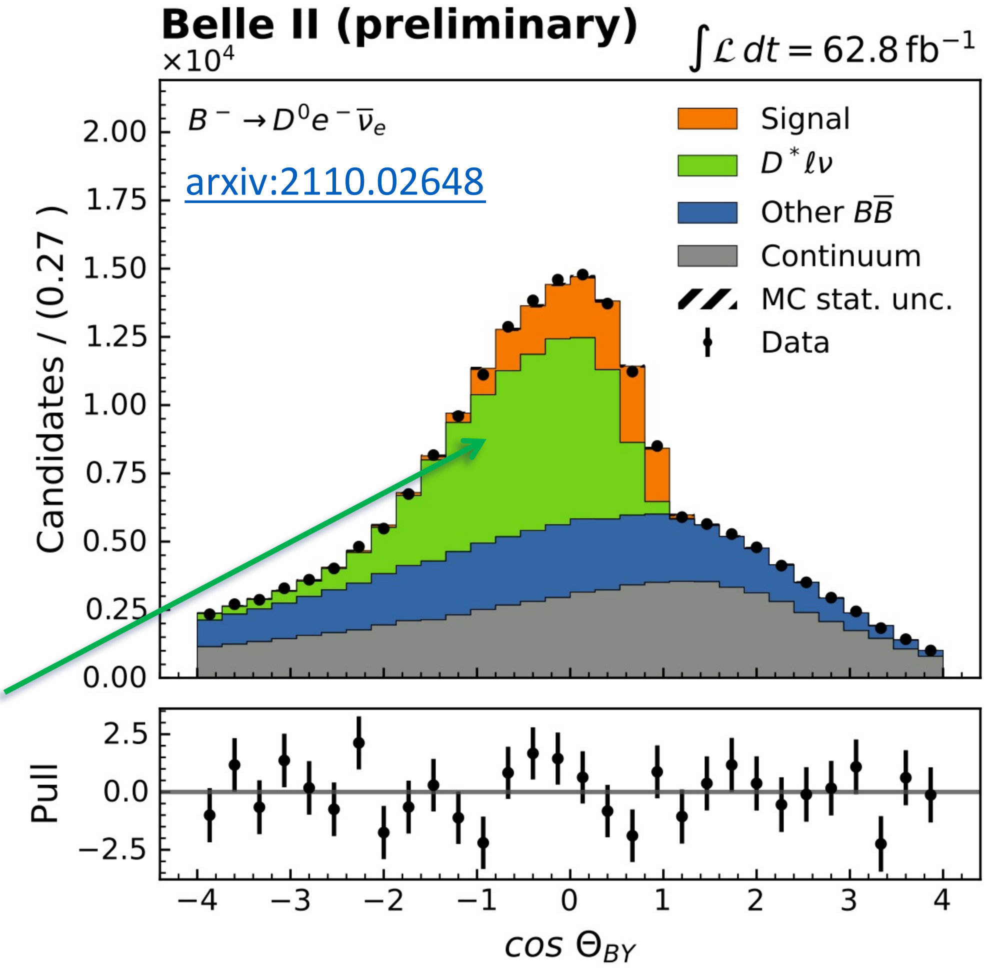
- For details on theory, see. Review of Modern Physics article by F. Bernlochner, M. F. Sevilla, D. J. Robinson, G. Wormser, arXiv: 2101.08326

$B \to D\ell\nu$ analyses

- Fully differential decay rate depends only on q^2, or $w = \frac{m_B^2+m_D^2-q^2}{2m_B m_D}$, or $z(q^2) = \frac{\sqrt{t_+-q^2}-\sqrt{t_+-t_0}}{\sqrt{t_+-q^2}+\sqrt{t_+-t_0}}$ (t_+ and t_0 are constants)
- FF parameterized as function of $w \in [1,1.6]$ (or $z \in [-0.032,0.032]$). BGL form based on analyticity and unitarity is commonly used:

$$f_+(z) = \frac{1}{P_+(z)\phi_+(z)}\sum_{n=0}^{N} a_{+,n} z^n$$

- Lattice QCD calculations provide $O(1\%)$ precision at large q^2 and also provide shape information; $|V_{cb}|$ and FF parameter determination done with simultaneous fit to lattice+experiment
- Challenge: large feed-down from $B \to D^*\ell\nu$ decays with missing π, γ
- A second FF (f_0) arises for massive leptons (τ)
- To improve resolution, kinematic fits are used in tagged analyses and the “diamond frame” is used for q^2 in untagged analyses

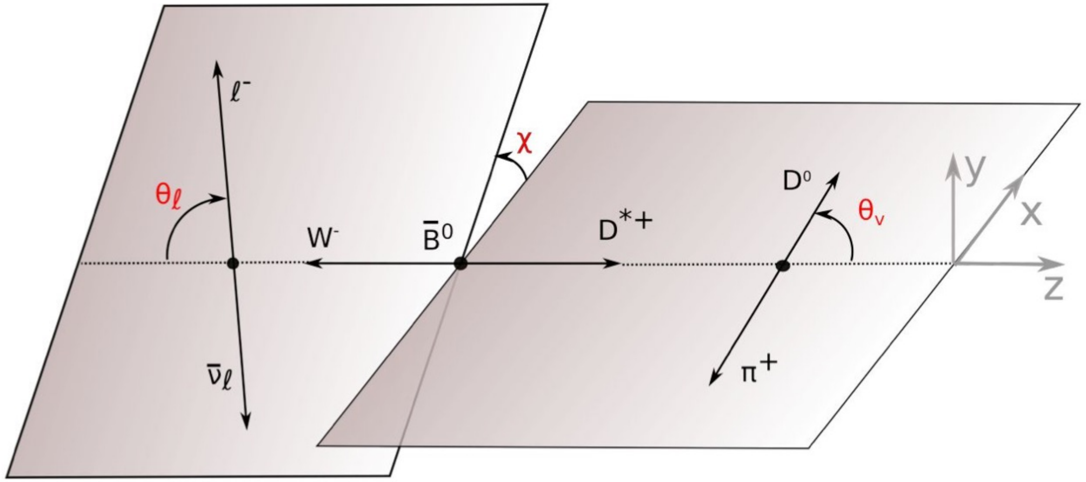


arxiv:2110.02648

$B \to D^* \ell \nu$ analyses

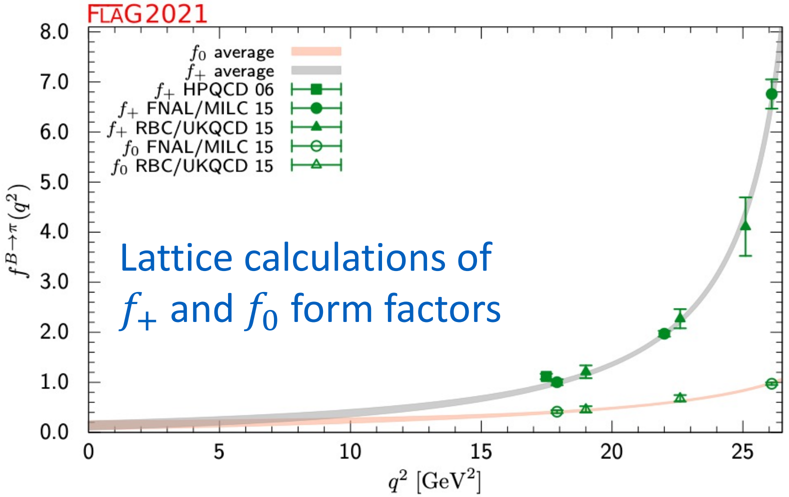
- Fully differential rate depends on angles $(\theta_\ell, \theta_V, \chi)$ and q^2 or w or z; there are three form factors for light leptons, parameterized in different ways ($\{A_1, A_2, V\}$; $\{f, F_1, g\}$; …)
- Measurement of the full 4D experimental rate requires high stats and good modeling of acceptance
- Again, $\ell = \tau$ again brings in an additional FF
- Lattice QCD provides $O(1\%)$ predictions at large q^2 and shape information; the $D^*: D: \pi$ coupling makes this calculation more challenging than for $B \to D$
- Combined expt+lattice fits are used to determine $|V_{cb}|$ and the FF parameters

- Heavy Quark Effective Theory offers a useful framework, relating all FFs to a universal “Isgur-Wise” function, but HQET constraints are no longer needed to interpret data

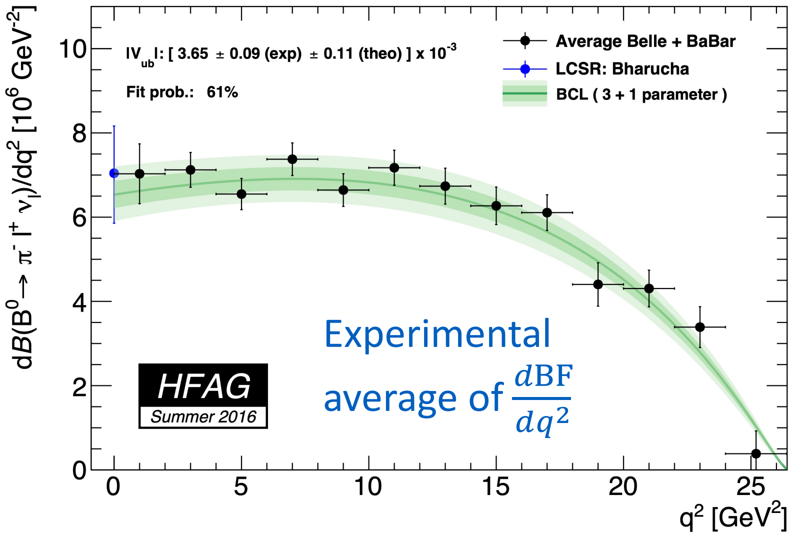


$B \to \pi \ell \nu$ analyses

- Fully differential decay rate depends only on q^2
- Lattice calculations provide ~3% precision for $q^2 > 16\ \mathrm{GeV}^2$
- Challenge: untagged analyses have large backgrounds from continuum and from feed-down ($B \to \rho \ell \nu$) decays
- Tagged analyses are much cleaner but have low yields (tag efficiency times $\mathrm{BF}(B \to \pi \ell \nu) < 10^{-6}$)
- While untagged analyses have large background, especially at high q^2 (where $|\vec{p}_\pi|$ is small), they still dominate current $|V_{ub}|$ determinations (this will be true until we have many ab^{-1})



Lattice calculations of f_+ and f_0 form factors



Experimental average of $\frac{d\mathrm{BF}}{dq^2}$

Inclusive decay landscape

For lack of time I’m not going to talk much about inclusive decays.

- The semileptonic $B \to X_c \ell \nu$ BF is a crucial element in determining $|V_{cb}|$
- Moments of the $E_e,\ m_h$ and q^2 distributions in $B \to X_c \ell \nu$ decays are important inputs in determining coefficients of the Heavy Quark Expansion, on which the determination of $|V_{cb}|$ is based

- The semileptonic $B \to X_u \ell \nu$ BF has a theoretically robust relation to $|V_{ub}|$; unfortunately, the full BF is not easily measure, and partial BFs in restricted regions of phase space bring in larger theory uncertainties

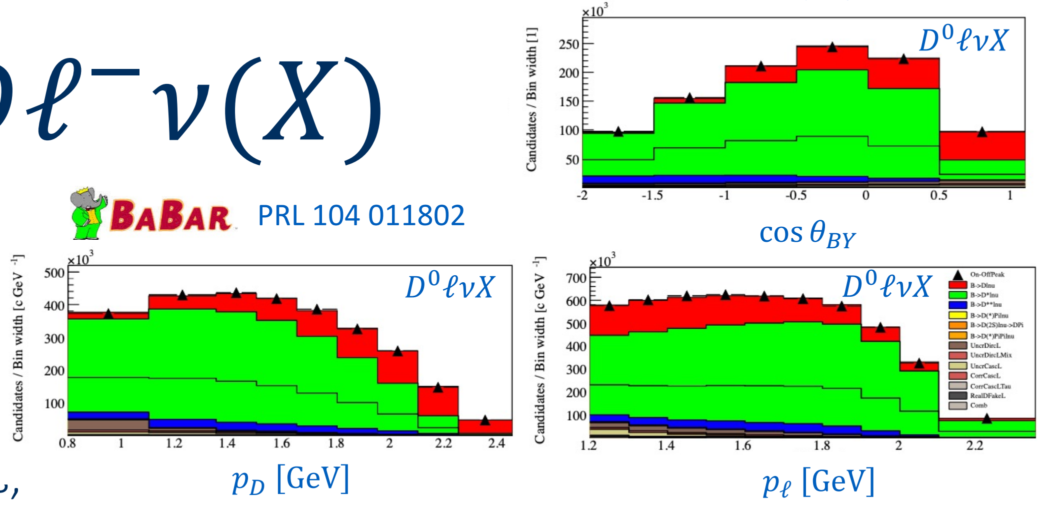
- These topics are discussed in many places, including in the PDG review article on semileptonic B decays, https://pdg.lbl.gov/2021/web/viewer.html?file=https://pdg.lbl.gov/2021/reviews/rpp2020-rev-vcb-vub.pdf

Untagged analyses - examples

Global fit to untagged $B \rightarrow D\ell^{-}\nu(X)$

- High statistics: about 8000 $D\ell^{-}$ pairs / fb^{-1}
- Three independent variables for B decays: $p_D, p_\ell, \cos\theta_{BY}$
- W helicity state populations differ for $B \rightarrow D$ and $B \rightarrow D^*$ transitions, leading to different p_D and p_ℓ distributions; $\cos\theta_{BY}$ is also shifted. Decays to heavier X_c states shift p_D, p_ℓ and $\cos\theta_{BY}$ to still lower values
- Global fit to $B \rightarrow D\ell^{-}\nu X$ can determine BFs and FF slopes for both $B \rightarrow D\ell^{-}\nu$ and $B \rightarrow D^*\ell^{-}\nu$ ***without ever reconstructing soft π^+/π^0***
- Leading uncertainties arise from modeling of heavier X_c states, D decay BFs and detector modeling
- 2009 measurement (207 fb^{-1}) still gives world-leading precision on BF($B^{-} \rightarrow D^{*0}\ell^{-}\nu$) (4%) and BF($B^{-} \rightarrow D^{0}\ell^{-}\nu$) (5.5%)

Electron fit projections



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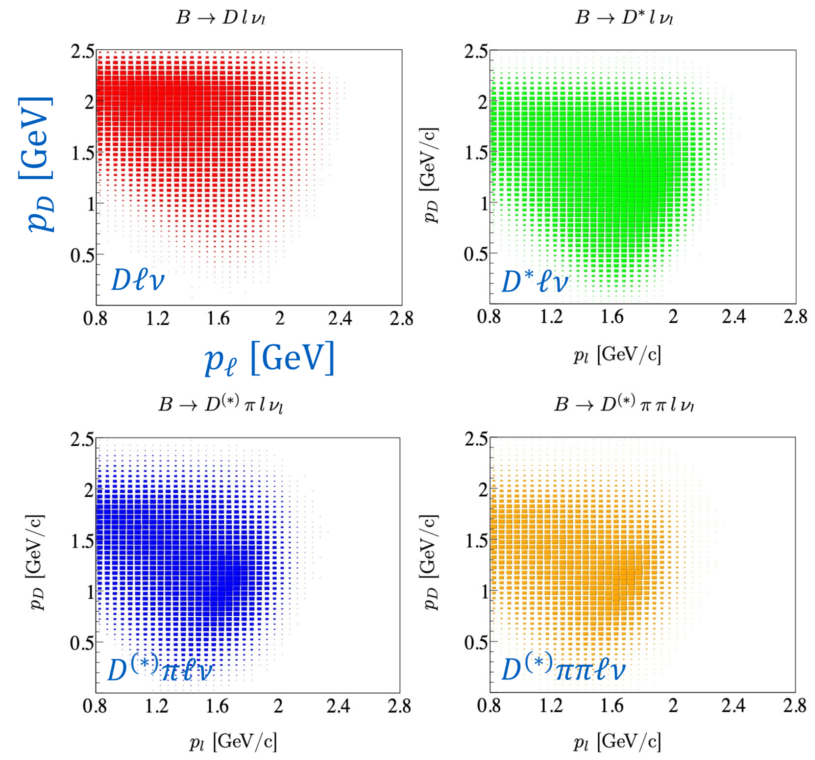


Tagged analyses – which tag?

- Tagged analysis strategy:
  - Require that tag+signal decays use *all* good tracks (N_{Extra}^{trk}=0);
  - Measure how much neutral calorimeter activity is not part of either tag or signal (E_{Extra}, a.k.a. E_{ECL})

Hadronic tags

- Tag side fully reconstructed – we know p_{tag} ($\therefore p_{miss}$) and calculate $U = E_{miss} - |\vec{p}_{miss}|$
- For high efficiency, we include tag decays with high multiplicity ⇒ lots of activity in the detector, which increases E_{Extra}
- High multiplicity tag modes are also less clean ⇒ many candidates per event

Semileptonic tags

- Tag side has neutrino – we don't know $\vec{p}_{B_{tag}}$
- Less activity in the detector from visible tag-side particles (helps with E_{Extra})
- Lower multiplicity and visible energy compensates for weaker kinematic constraint (use $\cos\theta_{BY}$ to select tag)

B tagging: the fine print

Tagging (Full Event Interpretation in Belle II) is powerful but has challenges

- Purity – is the “best” tag the true one?
  - The answer depends on the signal side decay mode and multiplicity
  - Unfortunately, the overall tag+signal efficiency depends on purity: if you choose the wrong tag you can fail to reconstruct the signal from the ROE (“rest of event”)
  - The hardest case is for analyses where the ROE is unconstrained (e.g. when we try to measure the X_c system in $B \to X_c \ell \nu$)

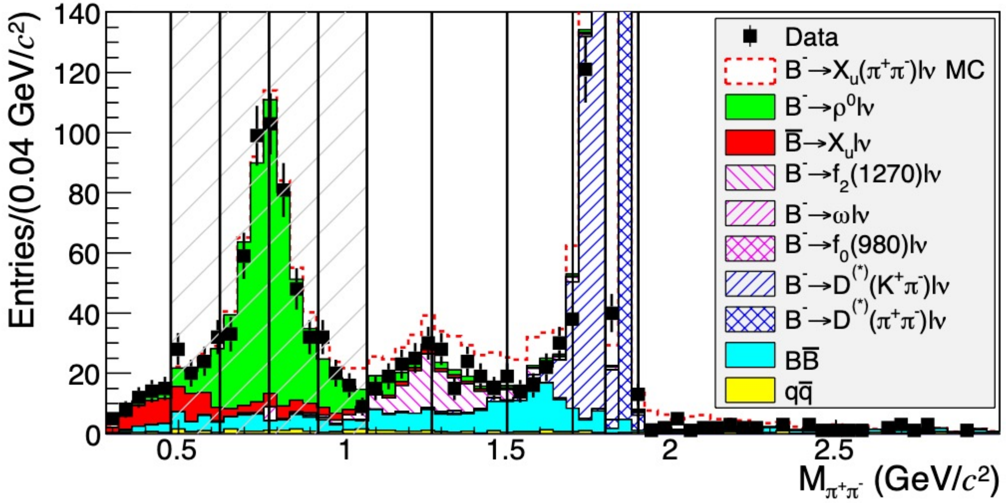
- Calibration
  - B decays involve millions of individual modes $\Rightarrow$ EVTGEN does not agree with data when we sum over reconstructed B decay chains
  - The modeling of the detector is also imperfect
  - We therefore “calibrate” (compare data with MC) to correct the simulated FEI efficiency; these calibration factors are large ($\sim 30\%$)
  - Unfortunately, we have very few high-stats calibration channels and the correction differs (in principle) for different signal modes

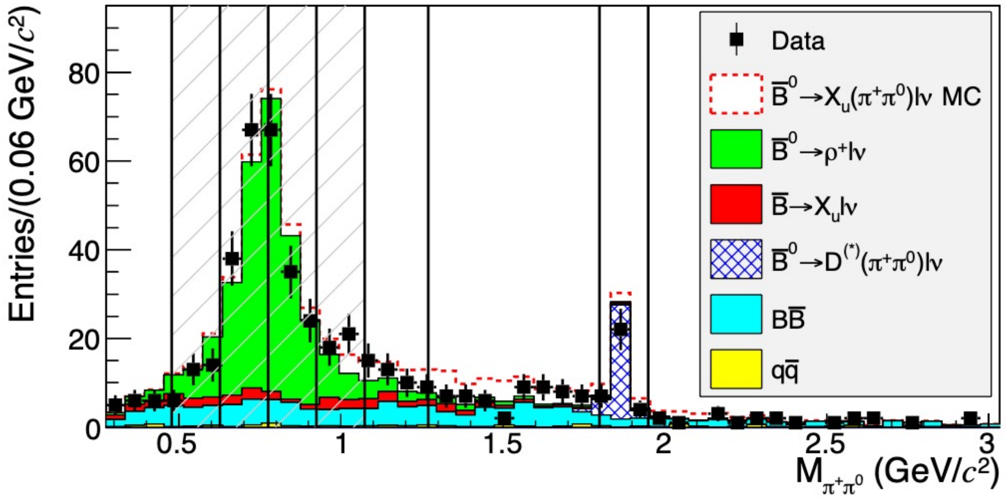
Tagged analyses - examples

$B \to X_u \ell \nu$ with hadronic tag

Belle paper (PhysRevD.88.032005) is current state-of-the-art

- Measures many modes: $B \to h\ell\nu$ with $h = \pi^+, \pi^0, \rho^+, \rho^0, \omega$ Recall from isospin $\mathrm{BF}(B^0 \to h^+\ell\nu) = 2\times\mathrm{BF}(B^- \to h^0\ell\nu)$
- Require tag+signal topology, fit M^2_{miss} spectra
- Largest systematic uncertainty: tag calibration (4.5%); cross-feed from other $X_u\ell\nu$ modes also important for $\rho^+\ell\nu$
- Cleanliness of $B \to \rho\ell\nu$ allows comparison of $\pi^+\pi^-\ell\nu$ and $\pi^+\pi^0\ell\nu$ composition with simulation (see plot); this is impossible in untagged analyses

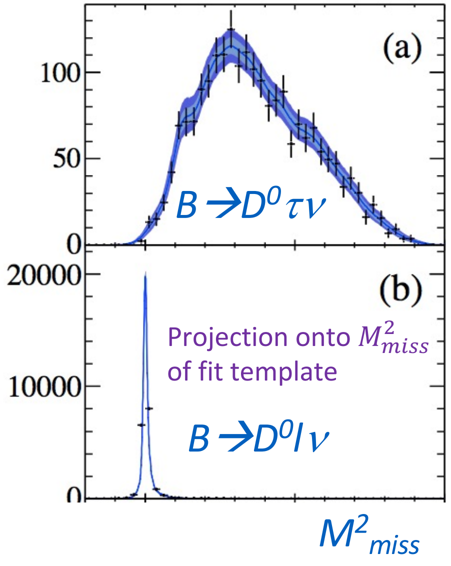




BaBar $R(D^{(*)})$ with hadronic tag

BaBar 2012 result (arXiv:1303.0571)

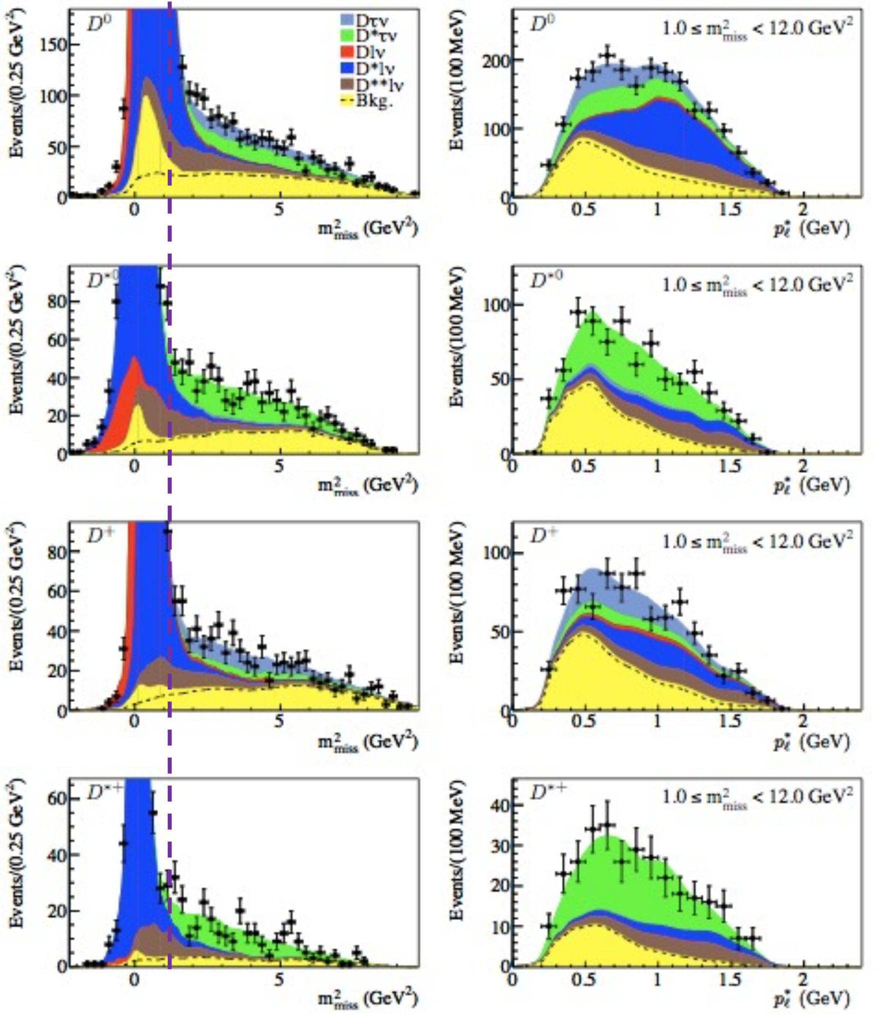
- Fit to m_{miss}^2 and p_ℓ to both signal ($B \to D^{(*)}\tau\nu$) and normalization ($B \to D^{(*)}\ell\nu$) modes
- Use $B \to D^{(*)}\pi^0\ell\nu$ mode to control D^{**} (i.e. higher-mass X_c states) systematics
- Leading systematics from D^{**} modeling, other background and MC statistics (56 2D-templates needed for fit…)



Projection onto M_{miss}^2 of fit template

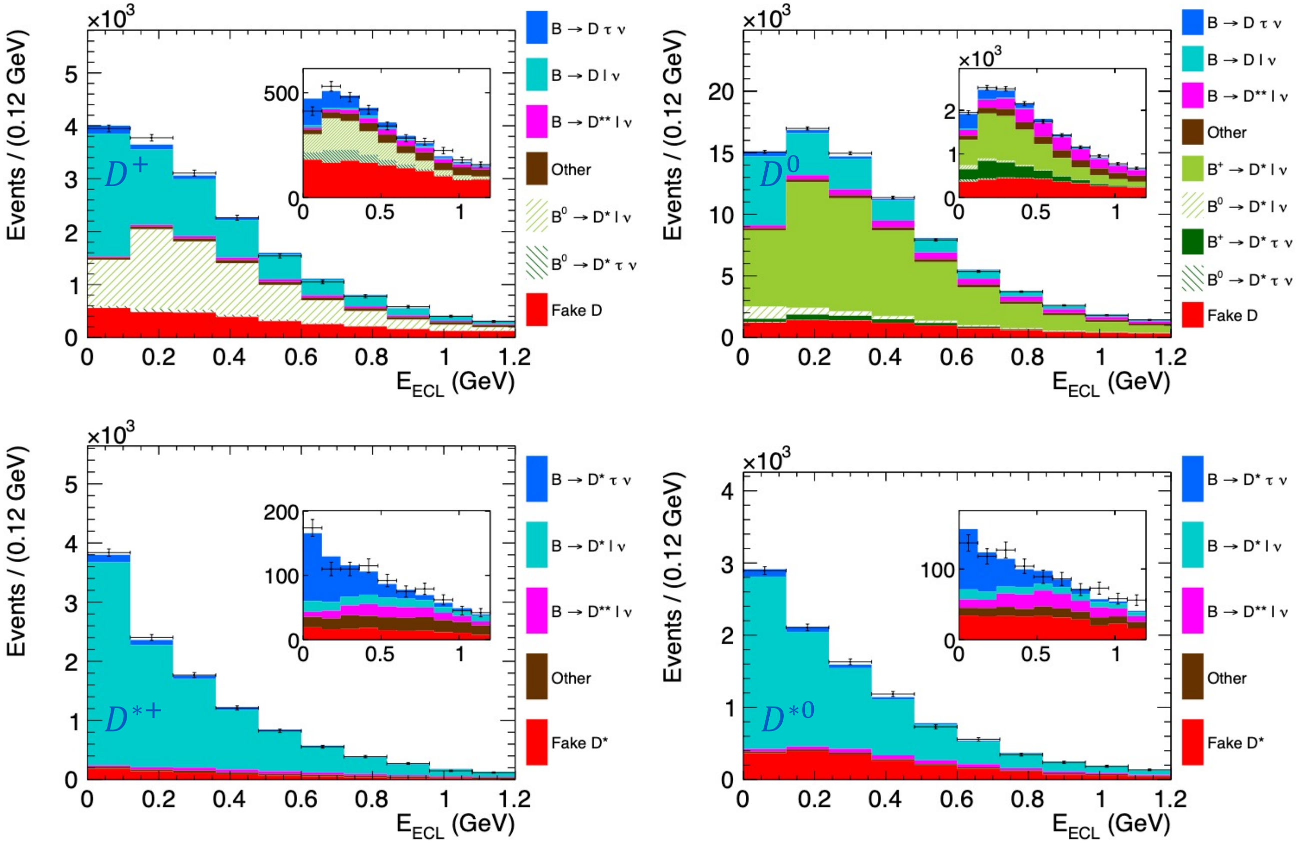
Normalization modes (off scale)

Fit projections for $(D^0, D^{*0}, D^+, D^{*+})\,\ell/\tau\,\nu$



Belle $R(D^{(*)})$ with semileptonic tag

- arXiv:1910.05864 – highest precision to date
- Semileptonic $B \to D^{(*)}\ell\nu$ tags and leptonic decays $\tau \to \ell\nu\bar{\nu}$ are selected
- Tag selected based on tag BDT and $\cos\theta_{BY}$
- No additional tracks allowed; E_{ECL} measured
- MVA used to select signal region; graph insets show selected regions
- Syserrs: PDF shapes (sig and bkg modeling), feed-down ($D^* \to D\pi$), relative efficiency factors (sig/norm)



Systematic uncertainties

Experimental uncertainties

The usual suspects:

- Particle identification
- Bremsstrahlung
- Tracking efficiency and resolution
- Photon efficiency, resolution and background
- Backgrounds from the accelerator and interactions in detector material (E_{extra})

Theoretical/external uncertainties

- Uncertainty on BF and FF for particles in the signal decay chain (e.g. D meson decays) and for decay modes that contribute to backgrounds
- Simulation of semileptonic decays
  - Modelling form factors (and their uncertainty) for exclusive decays
  - Filling the gap between known exclusive modes and the inclusive semileptonic BF (requires assumptions about resonances and decay modes that have never been measured)
  - Modelling inclusive $b \to u\ell\nu$ decays
  - Combining inclusive and exclusive $B \to X_u\ell\nu$ samples
  - Modeling radiative corrections

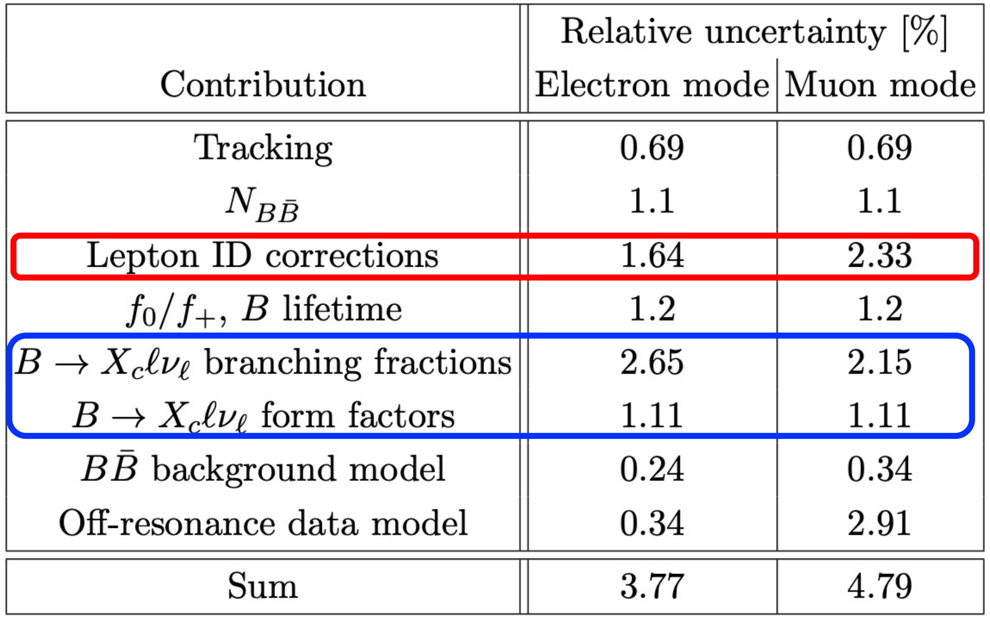
Systematic uncertainties – example 1

- Systematic uncertainties on inclusive SL BF [BELLE2-CONF-PH-2021-012]
- The BF is determined in a template fit to $b \to c\ell\nu$, other $B\bar{B}$ ($b \to u\ell\nu, b \to c(\tau) \to \ell$), continuum, fakes
- BF determined as

$$\mathrm{BF}(B \to X_c\ell\nu) = (9.75 \pm 0.03 \pm 0.47)\%$$

- Even on $62.8\mathrm{fb}^{-1}$ this measurement is already completely dominated by systematic uncertainties (world's best measurement has 2% uncertainty)
- Shape of dominant $b \to c\ell\nu$ component is leading uncertainty

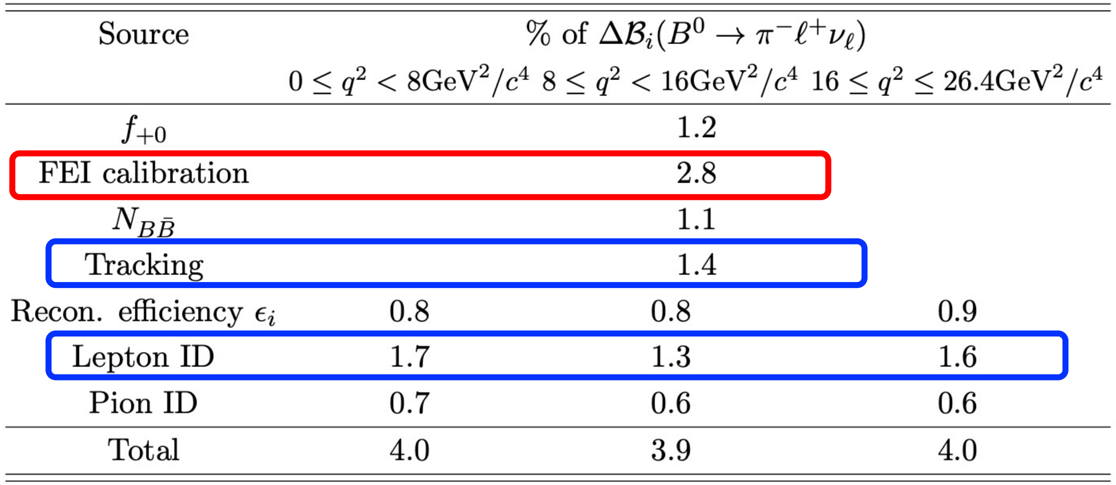
- Lepton ID (eff, fakes) significant
- Off-res uncertainty taken as difference between fixing and floating continuum normalization



Contribution	Relative uncertainty [%] Electron mode	Relative uncertainty [%] Muon mode
Tracking	0.69	0.69
$N_{B\bar{B}}$	1.1	1.1
Lepton ID corrections	1.64	2.33
f_0/f_+, B lifetime	1.2	1.2
$B \to X_c\ell\nu_\ell$ branching fractions	2.65	2.15
$B \to X_c\ell\nu_\ell$ form factors	1.11	1.11
$B\bar{B}$ background model	0.24	0.34
Off-resonance data model	0.34	2.91
Sum	3.77	4.79

Systematic uncertainties – example 2

- Systematic uncertainties on exclusive BF for $\bar{B}^0 \to \pi^+ \ell^- \nu$ [BELLE2-CONF-PH-2021-013]
- Hadronic tagging (FEI) used on 62.8fb^{-1}
- Major uncertainty is FEI calibration
- Lepton ID and tracking efficiency are next
- Determining the number of $B^0\bar{B}^0$ events produced gives $\sim 1.6\%$ uncertainty



Source	% of $\Delta\mathcal{B}_i(B^0 \to \pi^- \ell^+ \nu_\ell)$		
	$0 \le q^2 < 8\text{GeV}^2/c^4$	$8 \le q^2 < 16\text{GeV}^2/c^4$	$16 \le q^2 \le 26.4\text{GeV}^2/c^4$
f_{+0}	1.2		
FEI calibration	2.8		
$N_{B\bar{B}}$	1.1		
Tracking	1.4		
Recon. efficiency ϵ_i	0.8	0.8	0.9
Lepton ID	1.7	1.3	1.6
Pion ID	0.7	0.6	0.6
Total	4.0	3.9	4.0

From the paper:

"For $B \to \pi l \nu$ decays, the systematic uncertainties from the modeling of $B \to X_u l \nu$ are expected to be small compared to other systematic uncertainties."

This will not be the case for other modes, such as $B \to \rho l \nu$

Recommendation for Belle II semileptonic analyses

- Both physics and experimental factors are common amongst many individual decay modes and analyses – this suggests grouping channels together into larger analyses to get the most from our data
- Good examples are the BaBar global fit to $B \to D^{(*)}\ell\nu(X)$ and Belle $B \to X_u\ell\nu$ hadronic tag analyses discussed here
- Another good example of such a multi-channel analysis is the recent Belle result circulated internally by Frank Meier (BN1569); it's a *lot* of work but has impact

Summary

- Semileptonic decays offer a valuable tool for testing and further quantifying the SM and in looking for new physics
- Many semileptonic analyses are systematics limited (and most of those that aren't now will be in a few years) ➔ good ideas and hard work needed to make progress
- Grouping related channels together brings real benefits – but may require tighter coordination amongst analysts (bigger teams)
- Belle II has great potential in this area

Backup

Some useful references

- Much more detail on tauonic decays and the theory of exclusive semileptonic decays in RMP article
  "Semitauonic b-hadron decays: A lepton flavor universality laboratory,", F. Bernlochner, M. F. Sevilla, D. J. Robinson, G. Wormser, [arXiv: 2101.08326]
- Inclusive semileptonic decays are discussed in the PDG review article
  https://pdg.lbl.gov/2021/web/viewer.html?file=https://pdg.lbl.gov/2021/reviews/rpp2020-rev-vcb-vub.pdf
- References on B tagging (FEI)
  https://confluence.desy.de/pages/viewpage.action?pageId=35004501
- References on efficiency (tracking, photon, PID) determination
  https://confluence.desy.de/display/BI/Physics+Performance+Webhome

Modeling charmless semileptonic B decays

- Low-lying resonances are modelled using FFs, BFs
- Higher mass contributions (by rate the majority) are generated using an inclusive quark-level model followed by hadronization
- These two very different samples must be mixed together
  - Preserving the BFs and FFs of resonant states
  - Trying to maintain the overall kinematics (q^2, E_ℓ, M_{X_u}) of inclusive sample
- Apart from low-multiplicity modes (e.g. 2 pions) we don’t have good tests of whether this modeling provides a good description of reality

Using off-peak data to model continuum

The modeling of fragmentation and hadronization at these low energies is far from perfect; this motivates collecting an **experimental control sample** with similar $e^+e^- \rightarrow q\bar{q}$ production but no $B\bar{B}$ production.

- The off-peak sample will always be statistically limited (luminosity ratio $\frac{\mathcal{L}_{on}}{\mathcal{L}_{off}} \sim 15$)
- Annihilation cross-section falls as $1/s$; need to scale off-peak by $\frac{s_{off}}{s_{on}} \sim 0.99$
- Momenta of particles must also be scaled, but not just by $\sqrt{\frac{s_{on}}{s_{off}}}$, since multiplicity also changes; need to simulate $e^+e^- \rightarrow q\bar{q}$ at both s_{on} and s_{off} to gauge the impact

$B \to Xe\nu$ (untagged) for $|V_{ub}|$

BABAR Phys. Rev. D95, 072001

- High-statistics e spectrum; event-shape-based continuum suppression; simultaneous fit to on-peak and off-peak data. Fit for $0.8 < E_e < 2.7$ GeV determines continuum and normalizations for 6 $B \to X_c e\nu$ modes and a $B \to X_u e\nu$ model
- Systematic uncertainties: modeling (FFs, higher resonances) of $B \to X_c e\nu$, electron ID/misID, radiative corrections, modeling of $B \to X_u e\nu$
- Experimental sensitivity only for $E_e \gtrsim 2.1$ GeV; attempts to determine the partial BF for lower E_e depend sensitively on the $B \to X_u e\nu$ model assumed
- To extract $|V_{ub}|$ one needs a theory model for $\Delta\Gamma = \int_{E>E_0} \frac{d\Gamma}{dE}$ to compare with the *corresponding* partial BF ΔB