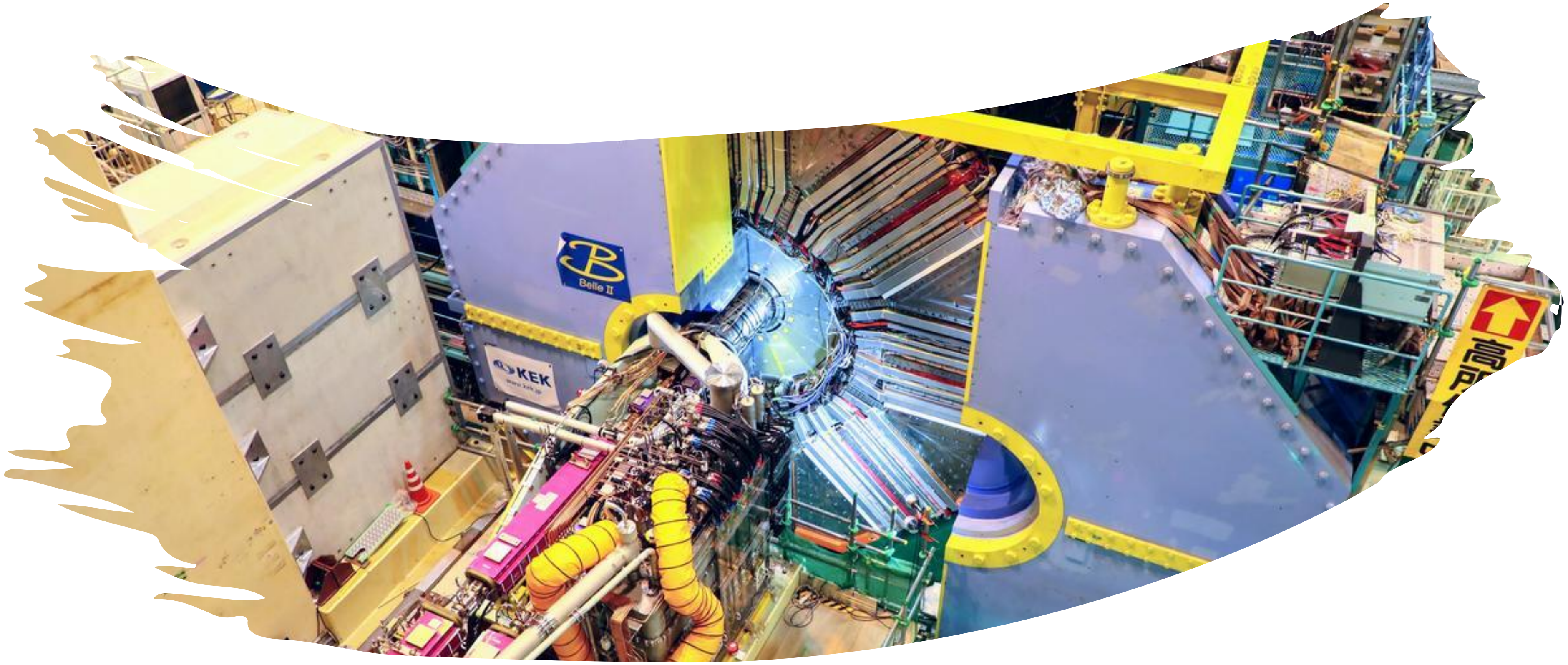

Non-EWP decays with missing energy aka (semi)leptonic decays

Markus Prim
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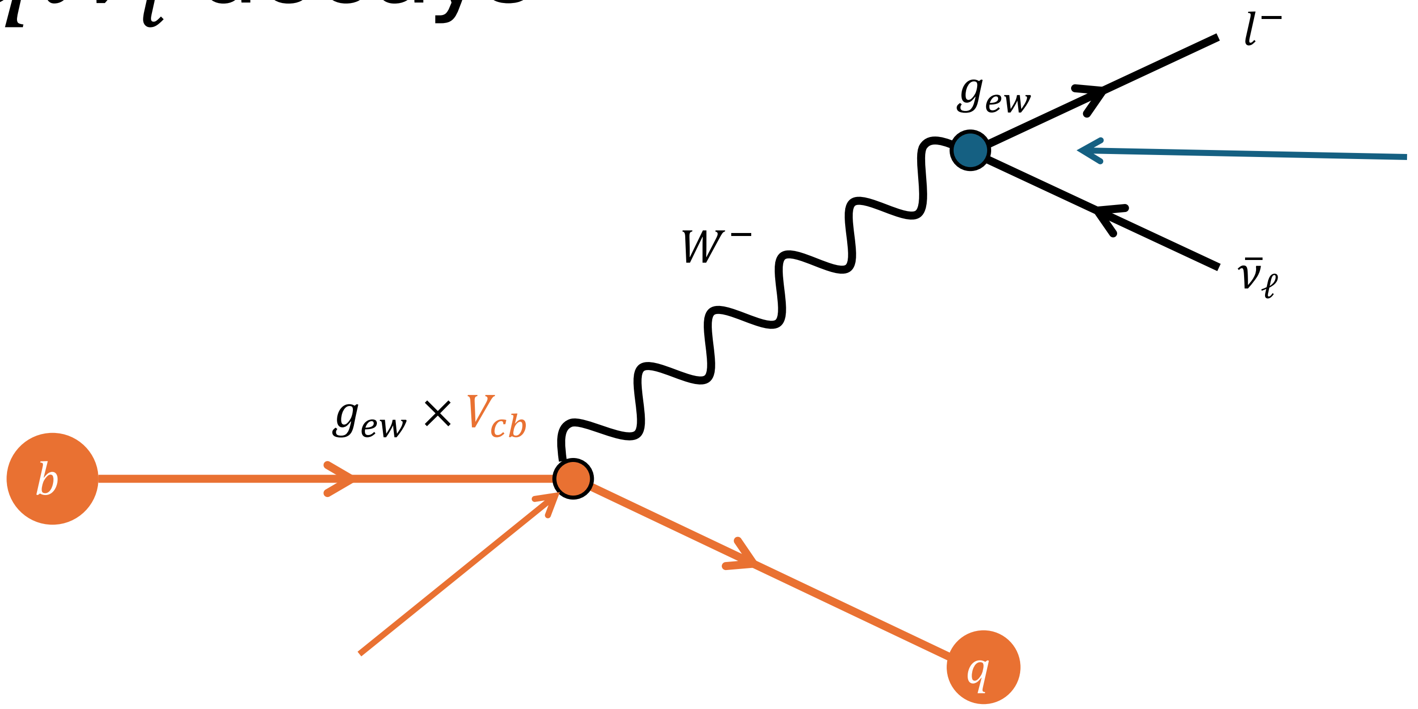
color meets flavor

UNIVERSITÄT BONN

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

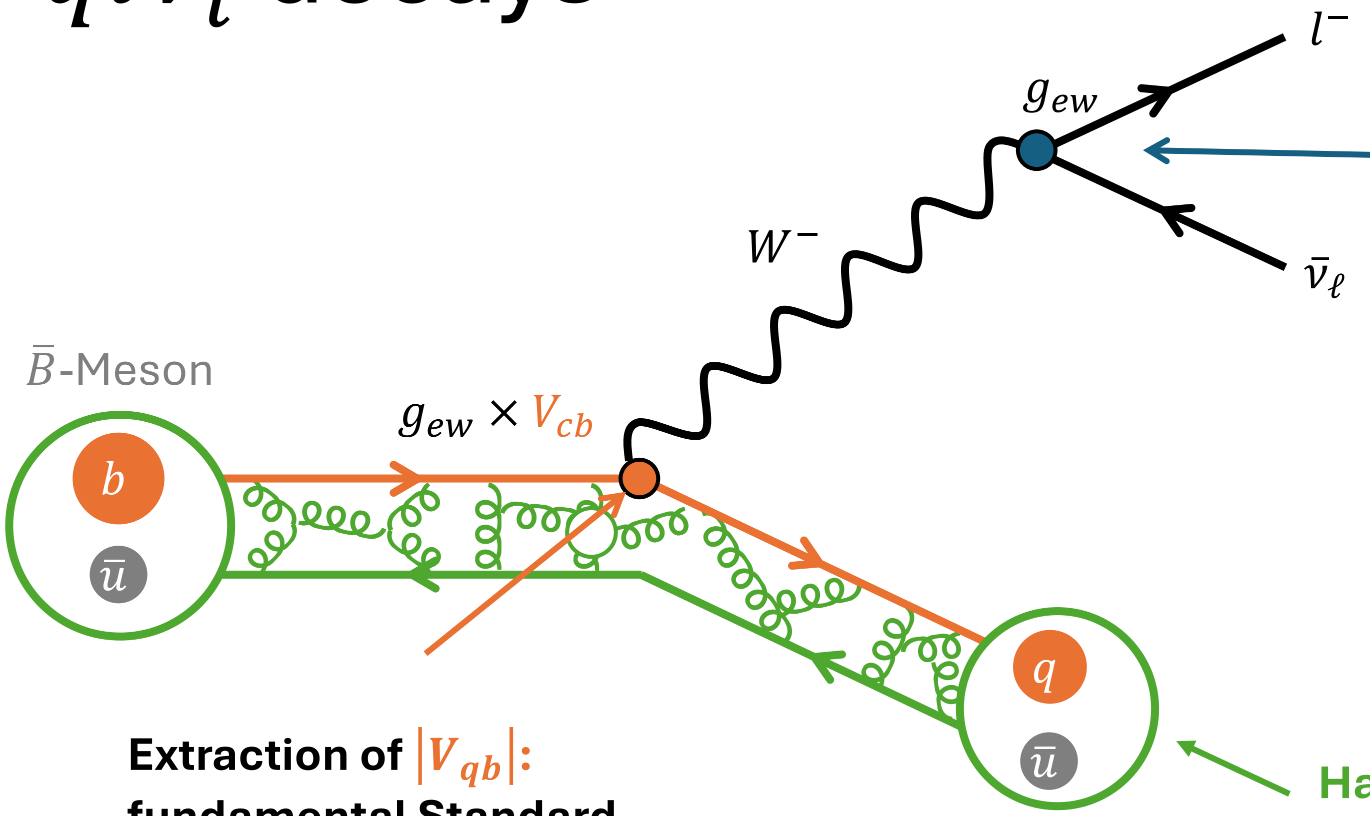
$b \to q l \bar{\nu}_l$ decays



Measuring the universality of couplings: test of the Standard Model

Extraction of $|V_{qb}|$: fundamental Standard Model parameter

$b \to q l \bar{\nu}_l$ decays



Measuring the universality of couplings: test of the Standard Model

Extraction of $|V_{qb}|$: fundamental Standard Model parameter

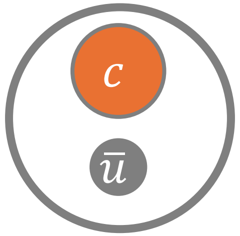
Hadronic system

$$X_c = \{D, D^*, D^{**}, D\pi, D^*\pi, \ldots\}$$

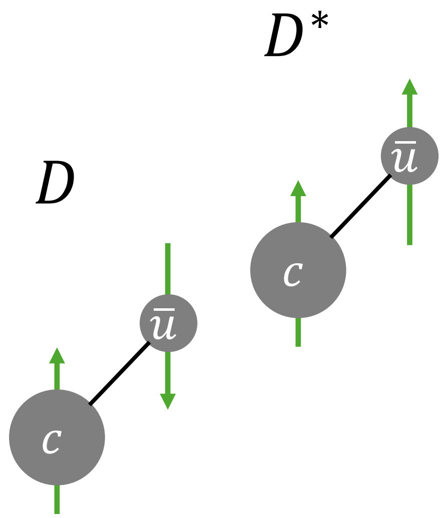
$$X_u = \{\pi, \rho, \omega, \pi\pi, \ldots\}$$

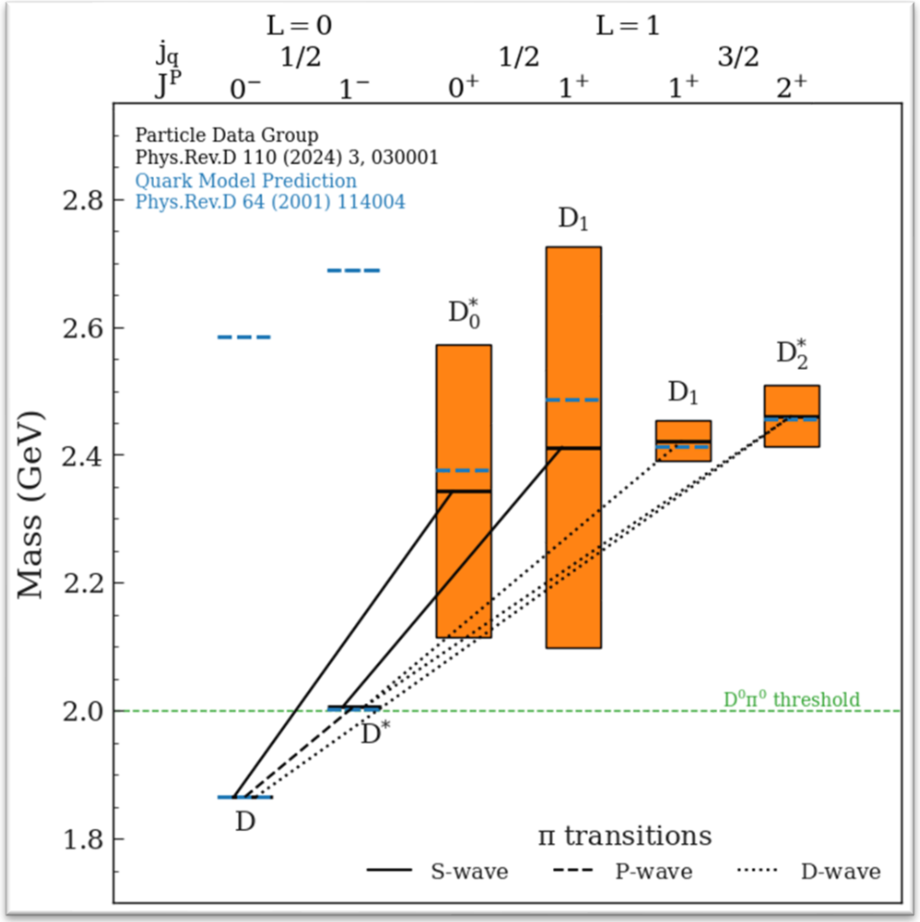
Understanding the hadronic system plays a crucial role for precision measurements of flavor observables!

D-Meson Spectrum

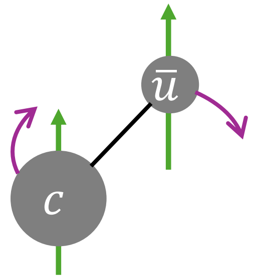


Excited states like in the hydrogen atom, but QCD instead of QED potential



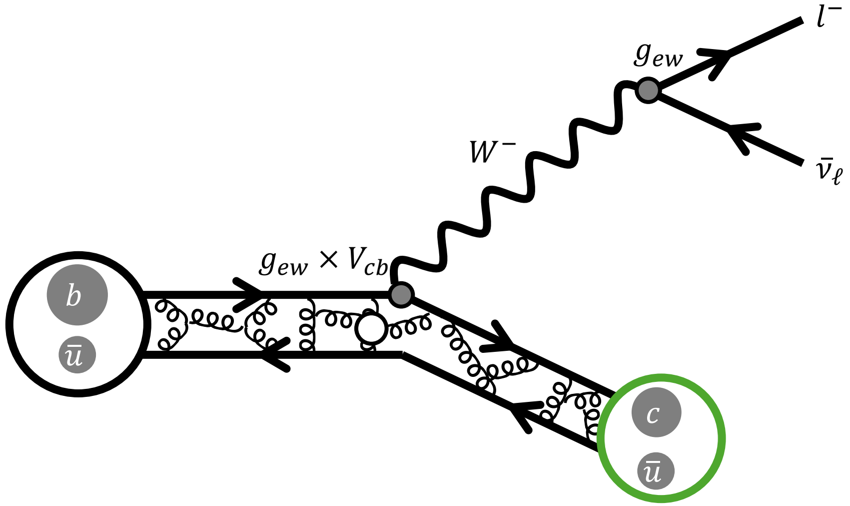


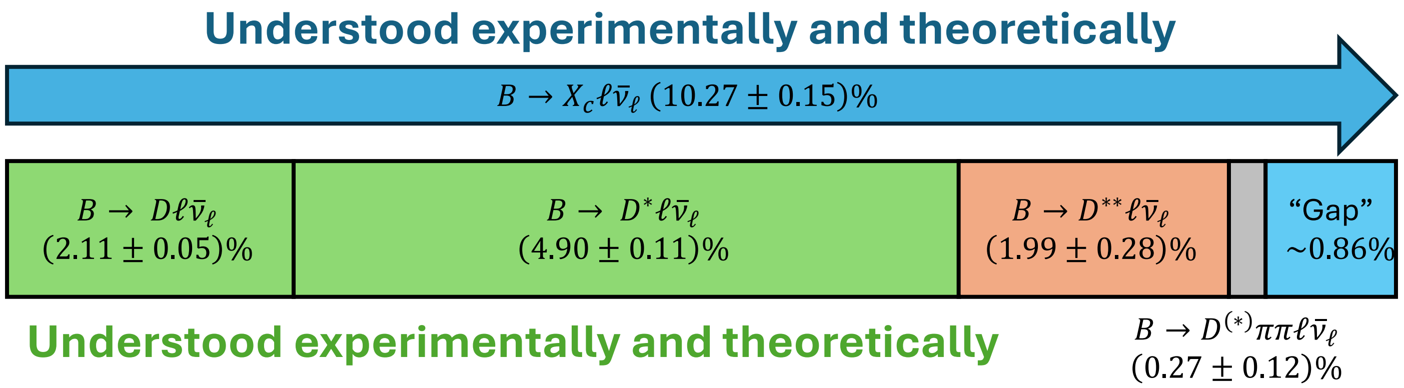
$$D^{**} = D_0^*, D_1^*, D_1, D_2^*$$



- HQET allows grouping into spin-symmetry doublets based on the quantum numbers of the light degrees of freedom
- Quark model has predictive power over the spectrum

$\bar{B} \to X_c \ell \bar{\nu}_\ell$ Decays





Problems with $B \to D^{**} \ell \bar{\nu}_\ell$

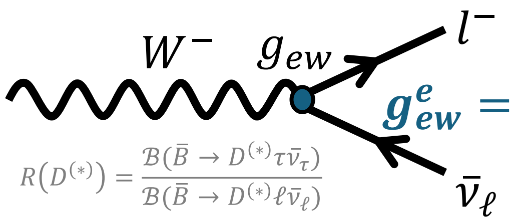
- Form factors assume narrow widths of the resonances
- ${}^1/_2 \leftrightarrow {}^3/_2$ puzzle
- Tension across experiments

Inclusive $\neq$ Sum of exclusive

- Unknown decay modes?
- Ad-hoc filled with $\bar{B} \to (D^{(*)} \eta) \ell \bar{\nu}_\ell$ decays to reproduce the p_ℓ spectrum

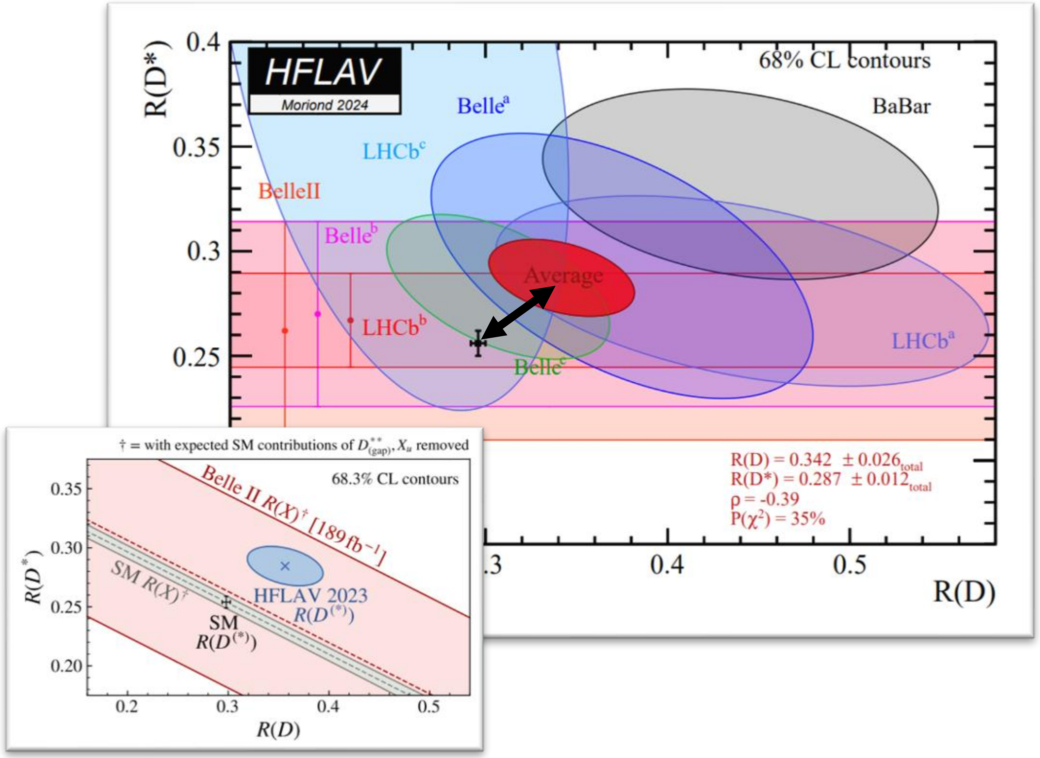
Open problems in tree-level $b \to c l \bar{\nu}_l$ decays

Signs of lepton flavor violation

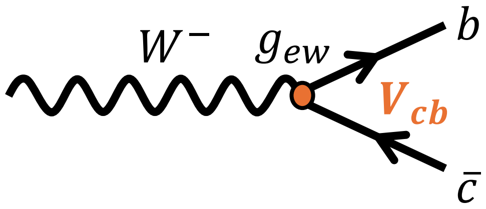


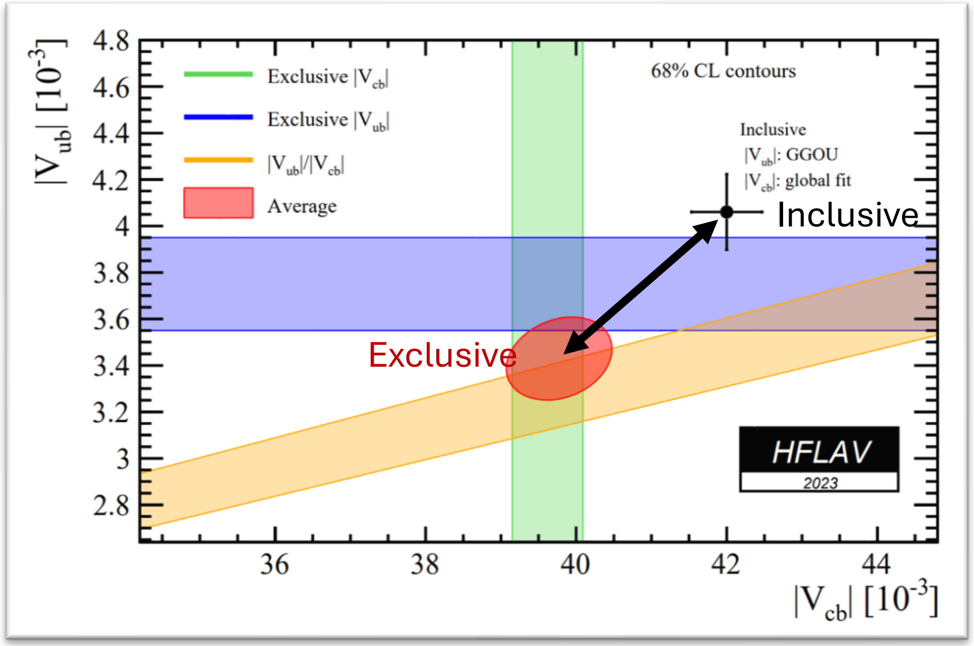
$g_{ew}^e = g_{ew}^\mu = g_{ew}^\tau$

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

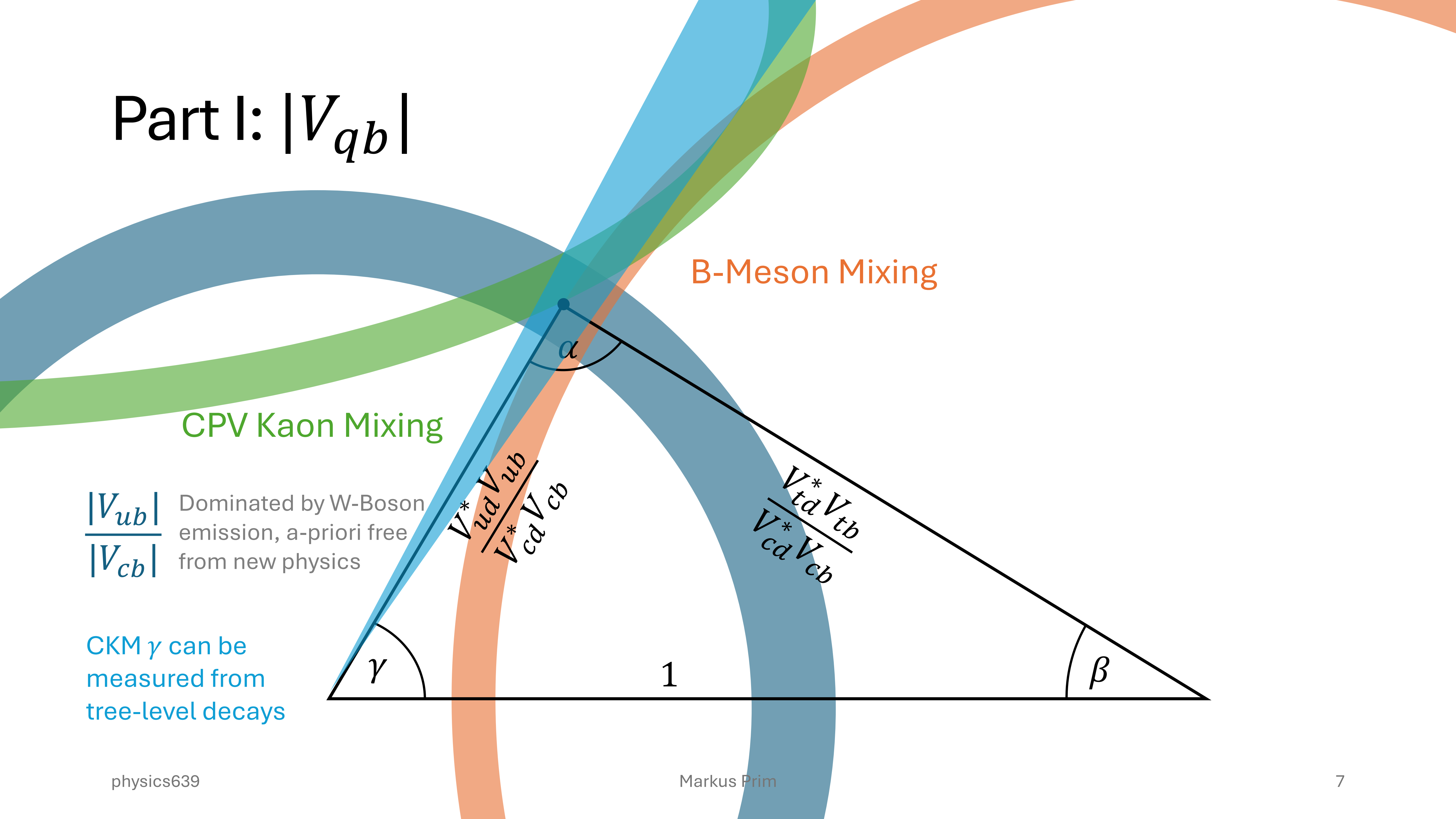


Unsolved inclusive vs. exclusive $|V_{cb}|$ discrepancy





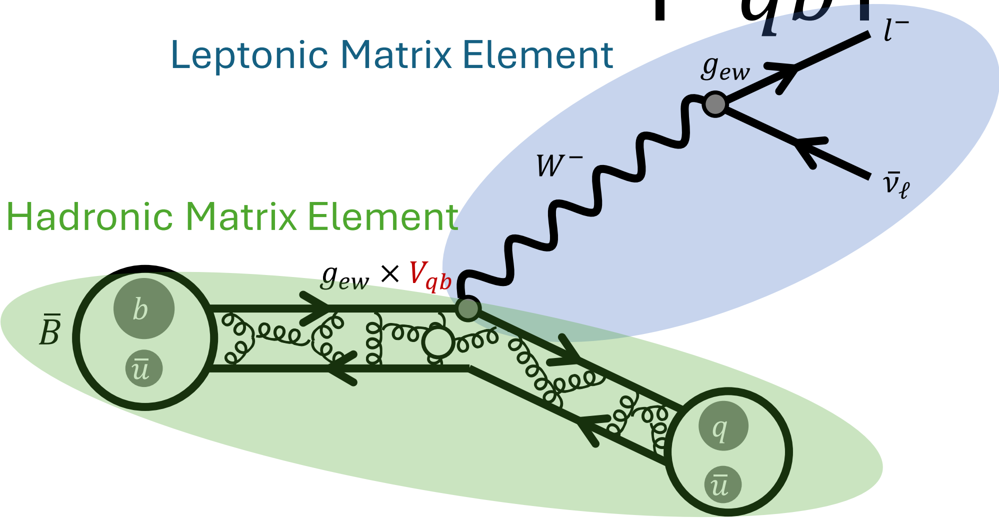
Part I: $|V_{qb}|$



$\frac{|V_{ub}|}{|V_{cb}|}$ Dominated by W-Boson emission, a-priori free from new physics

CKM γ can be measured from tree-level decays

Access to $|V_{qb}|$



Inclusive $|V_{ub}|$

$\bar{B} \to X_u \ell \bar{\nu}_\ell$

Fermi Motion / Shape Function

Inclusive $|V_{cb}|$

$\bar{B} \to X_c \ell \bar{\nu}_\ell$

Operator Product Expansion

$$\boxed{\mathcal{B} \propto \left|V_{qb}\right|^2 \left(\Gamma(b \to q\ell\bar{\nu}_\ell) + \frac{1}{m_{c,b}} + \alpha_s + \cdots \right)}$$

Leptonic $|V_{ub}|$

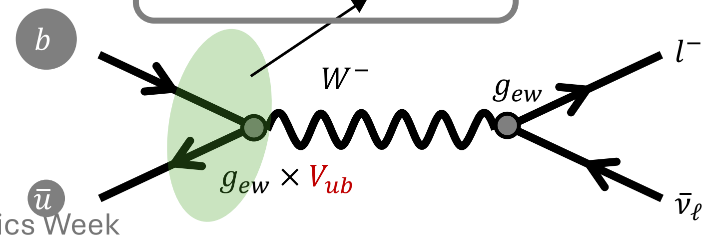
$\bar{B} \to l \bar{\nu}_\ell$

B-Meson Decay Constant

$\mathcal{B}(B^- \to \mu\bar{\nu}_\mu) = \mathcal{O}(10^{-7})$

$\mathcal{B}(B^- \to \tau\bar{\nu}_\tau) = \mathcal{O}(10^{-4})$

$$\boxed{\mathcal{B} \propto |V_{ub}|^2 f_B^2 m_\ell^2}$$



Exclusive $|V_{ub}|$

$\bar{B} \to \pi \ell \bar{\nu}_\ell, \Lambda_b \to p \mu \bar{\nu}_\mu$

Form Factors

Exclusive $|V_{cb}|$

$\bar{B} \to D^{(*)} \ell \bar{\nu}_\ell$

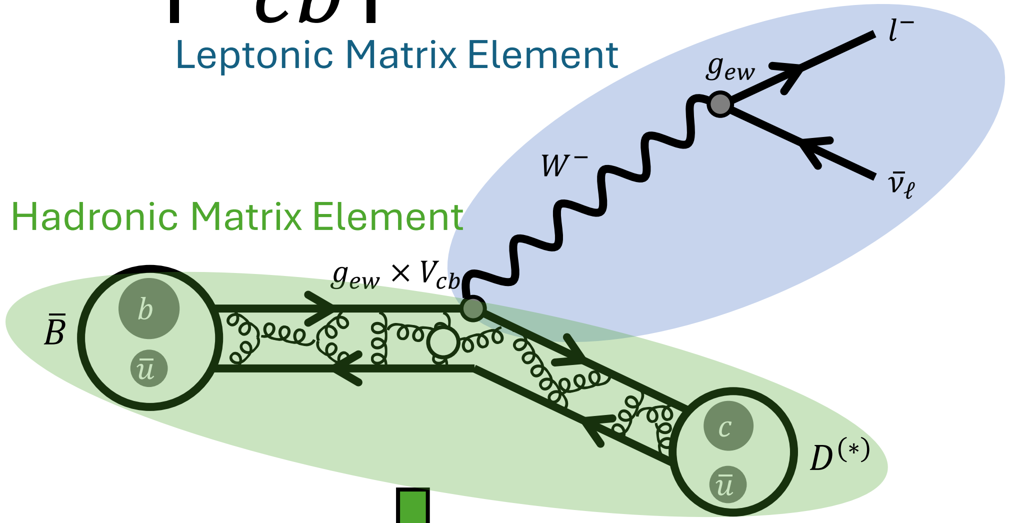
Form Factors

$$\boxed{\mathcal{B} \propto \left|V_{qb}\right|^2 f^2}$$

Remember: $\bar{B} \to D^{(*)} \ell \bar{\nu}_\ell$

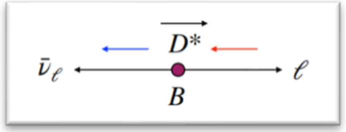
$\langle B | H_\mu | D \rangle = (p + p')_\mu f_+$

$|V_{cb}|$ from $\bar{B} \to D\ell\bar{\nu}_\ell$ vs $\bar{B} \to D^*\ell\bar{\nu}_\ell$

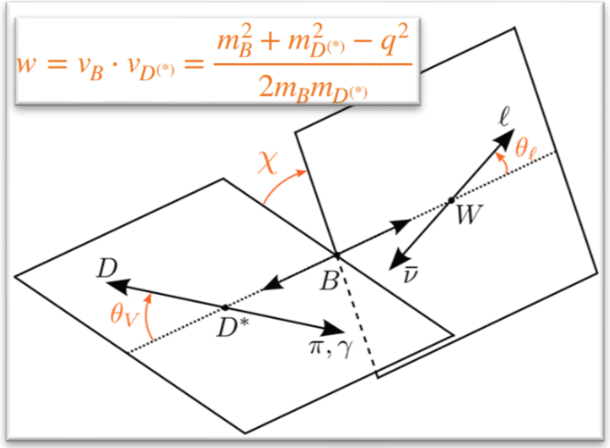


$$\Gamma(\bar{B} \to D\ell\bar{\nu}_\ell) \propto |V_{cb}|^2 \times (w^2 - 1)^{\frac{3}{2}} \times \mathcal{G}(1)$$

$$\Gamma(\bar{B} \to D^*\ell\bar{\nu}_\ell) \propto |V_{cb}|^2 \times (w^2 - 1)^{\frac{1}{2}} \times \mathcal{F}(1)$$



- D^* carries spin, so can make sure that angular momentum is conserved
- D^* has larger rate (3 spin states), naively $\Gamma_{D^*} = 3 \times \Gamma_D$
- Drawback: additional Lorentz structures → more complex form factors
- Additional degrees of freedom, total rate depends also on the helicity angles



Hadronic Matrix Elements can not be calculated from first principles
→ Can be parameterized with form factors $h_X = h_X(w)$ and **extracted from data**
→ Theory must provide (at least) inputs on their normalization

$$\frac{\langle D(p')|V^\mu|B(p)\rangle}{\sqrt{m_B m_D}} = h_+(v + v')^\mu + h_-(v - v')^\mu$$

$$\frac{\langle D^*(p')|V^\mu|B(p)\rangle}{\sqrt{m_B m_{D^*}}} = h_V \epsilon^{\mu\nu\alpha\beta} \epsilon^*_\nu v'_\alpha v_\beta$$

$$\frac{\langle D^*(p')|A^\mu|B(p)\rangle}{\sqrt{m_B m_{D^*}}} = h_{A_1}(w+1)\epsilon^{*\mu} - h_{A_2}(\epsilon^* \cdot v)v^\mu - h_{A_3}(\epsilon^* \cdot v)v'^\mu$$

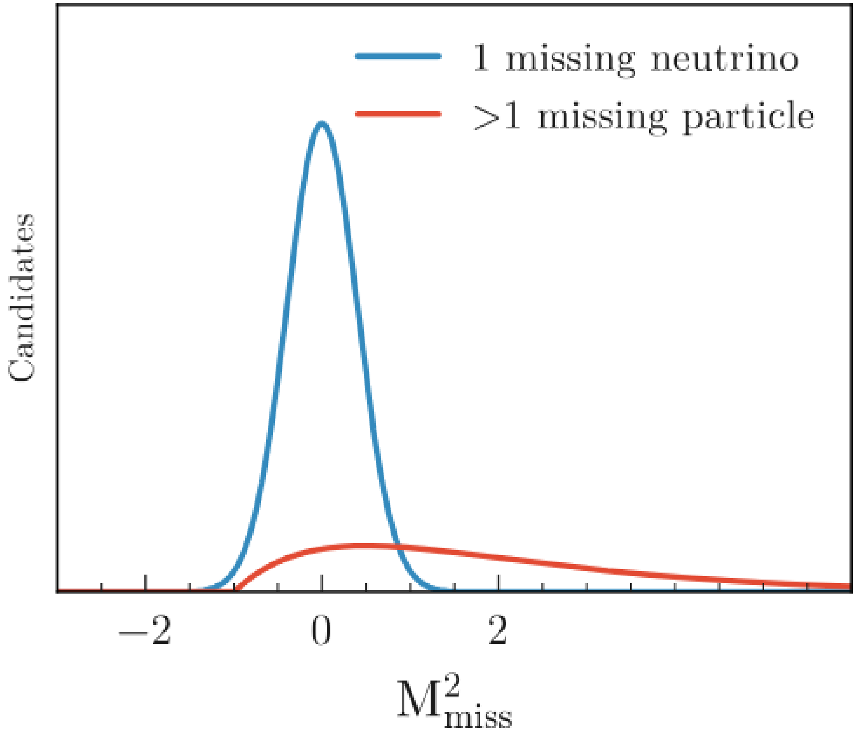
$$V^\mu = \bar{c}\gamma^\mu b$$
$$A^\mu = \bar{c}\gamma^\mu\gamma_5 b$$

Heavy Quark Symmetry Basis

Two key variables for $b \to q\ell\bar{\nu}_\ell, \ell = e, \mu$

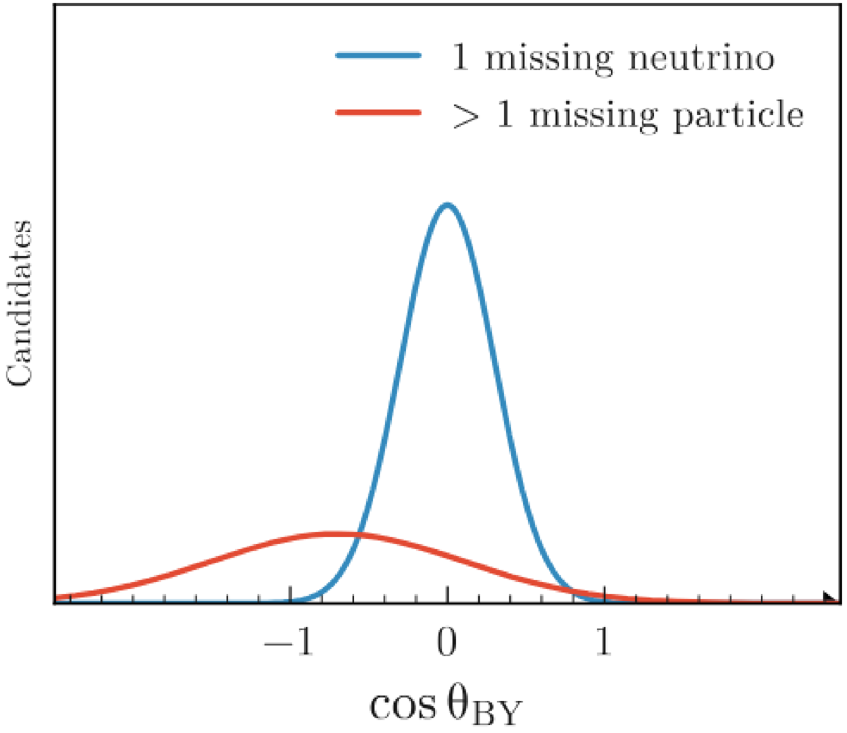
$$M_{miss}^2 = \left(p_{e^+e^-} - p_{B_{tag}} - p_{D^{(*)}\ell}\right)^2$$

Squared 4-momentum of the undetected neutrino(s)



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

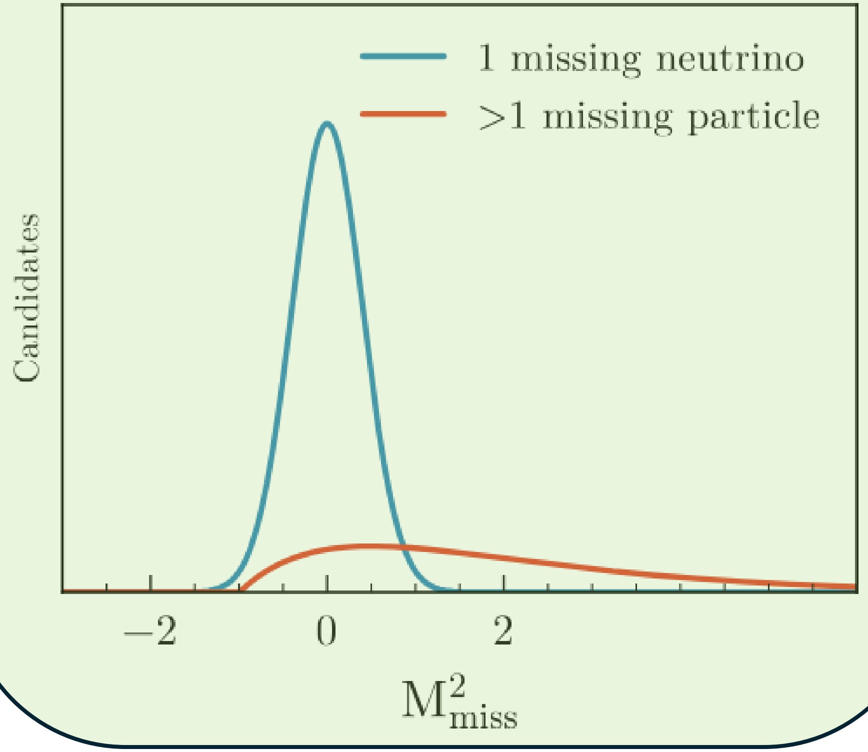
Angle between B and $Y = D^{(*)}\ell$



Two key variables for $b \to q\ell\bar{\nu}_\ell, \ell = e, \mu$

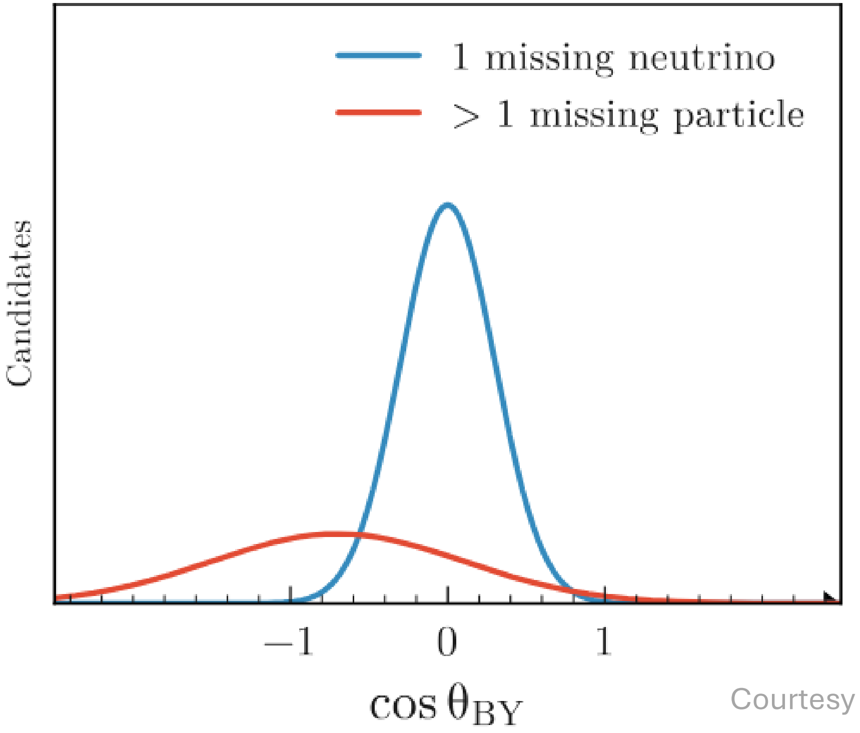
$$M^2_{miss} = \left(p_{e^+e^-} - p_{B_{tag}} - p_{D^{(*)}\ell}\right)^2$$

Squared 4-momentum of the undetected neutrino(s)



$$\cos\theta_{BY} = \frac{2E^*_B E^*_Y - m^2_B - m^2_Y}{2|\vec{p}^{\,*}_B||\vec{p}^{\,*}_Y|}$$

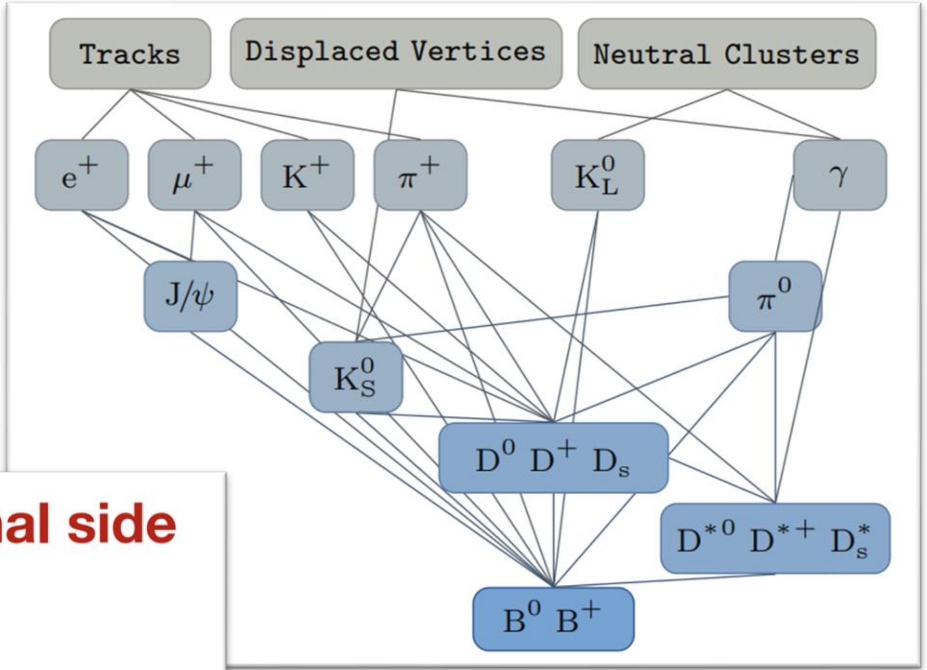
Angle between B and $Y = D^{(*)}\ell$



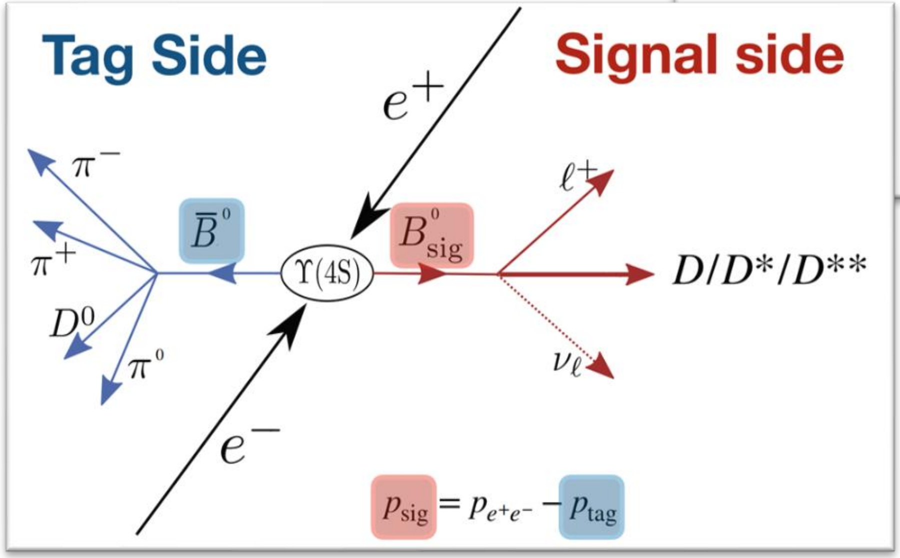
Courtesy from Philipp Horak

Tag-side reconstruction

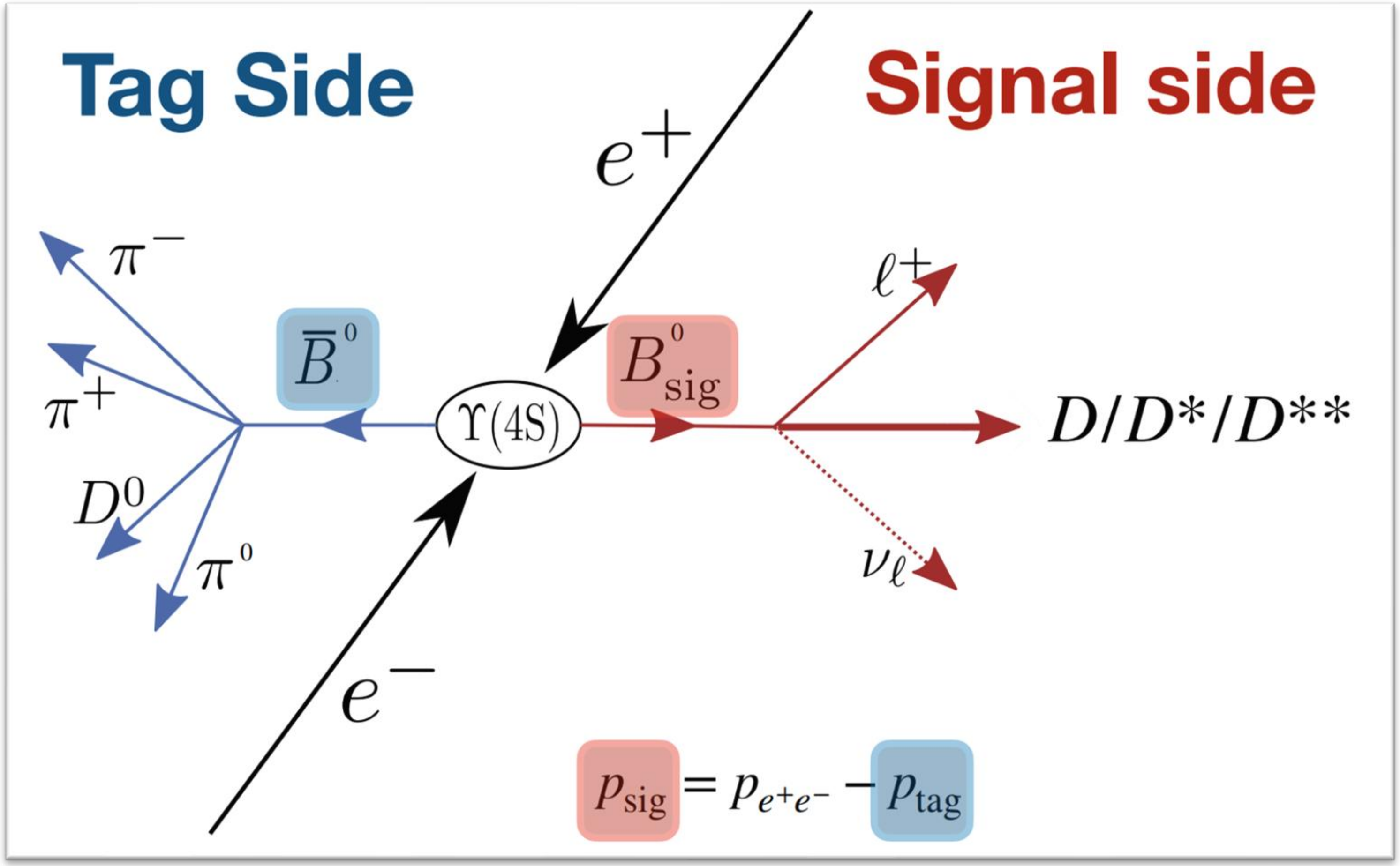
- Reconstruct accompanying B-meson (the tag-side) to infer (kinematic) information for the signal side
- Algorithmic problem: Reconstruct many tag-sides and select the best/correct one
- Set of multivariate classifiers to select correctly reconstructed intermediate particles and B-mesons



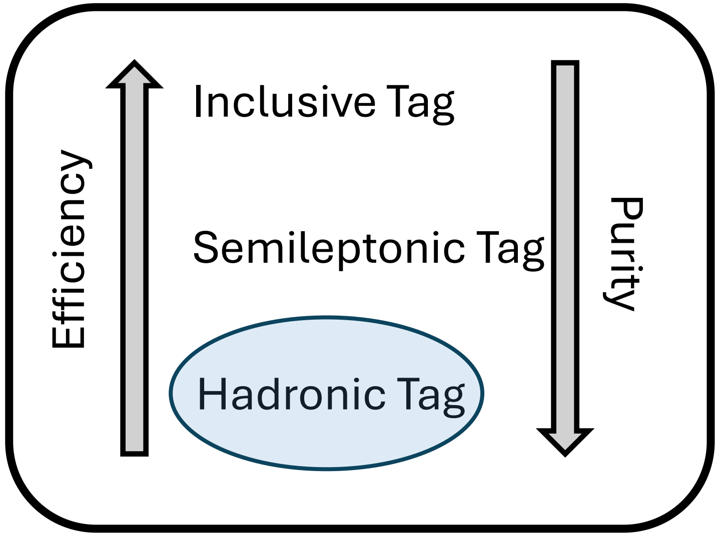
[Comput.Softw.Big Sci. 3 (2019) 1, 6]



Event reconstruction at Belle (II)

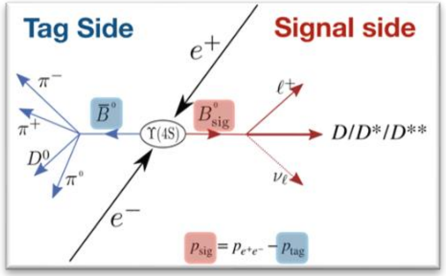


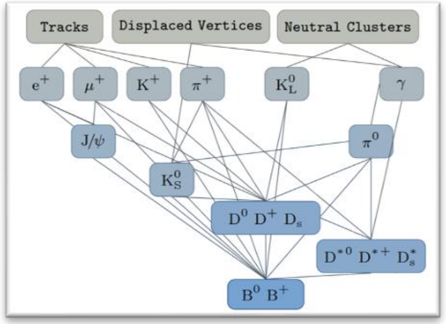
- **Exclusive measurements:** Explicit reconstruction of the final state hadron
- **Inclusive measurements:** Agnostic with respect to the hadronic system (unique for B-factories)

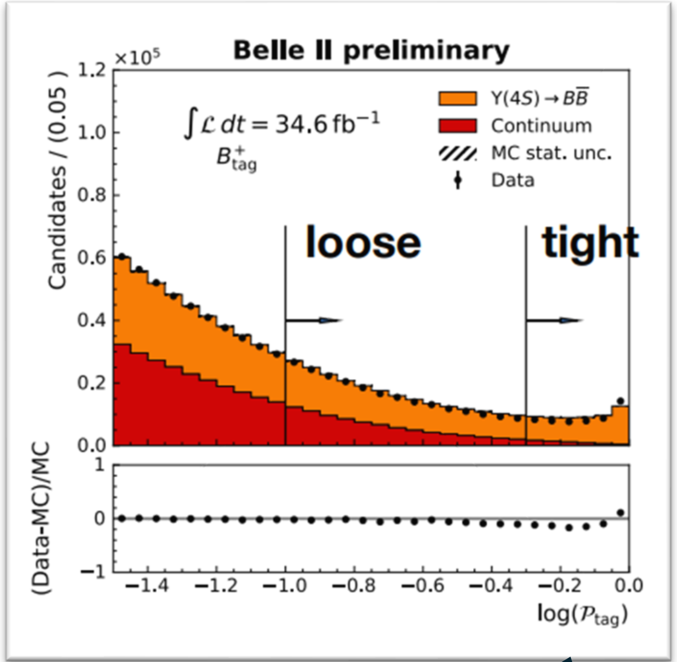


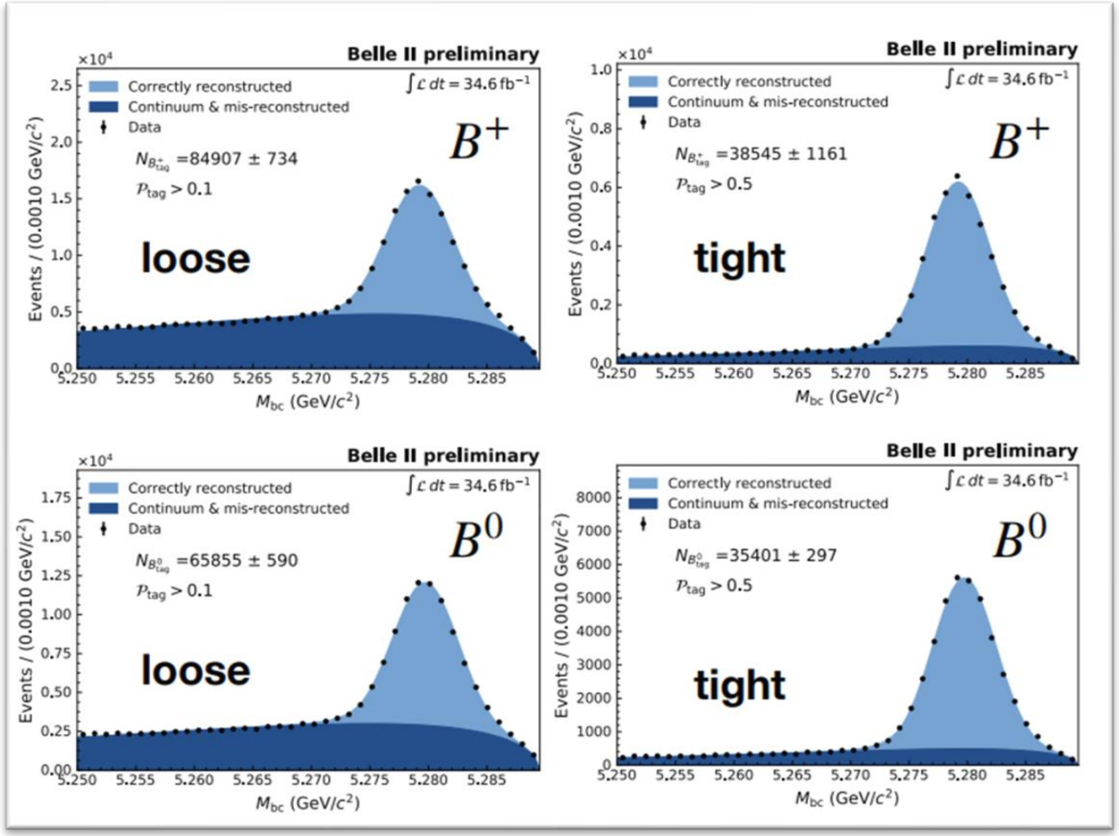
Tag-side reconstruction

- $M_{bc} = \sqrt{E_{beam}^2 - (p_{tag})^2}$ is the beam-constrained mass
- $E_{beam} = \sqrt{s}/2$ is precisely known ($\mathcal{O}(10^{-4})$ or better)



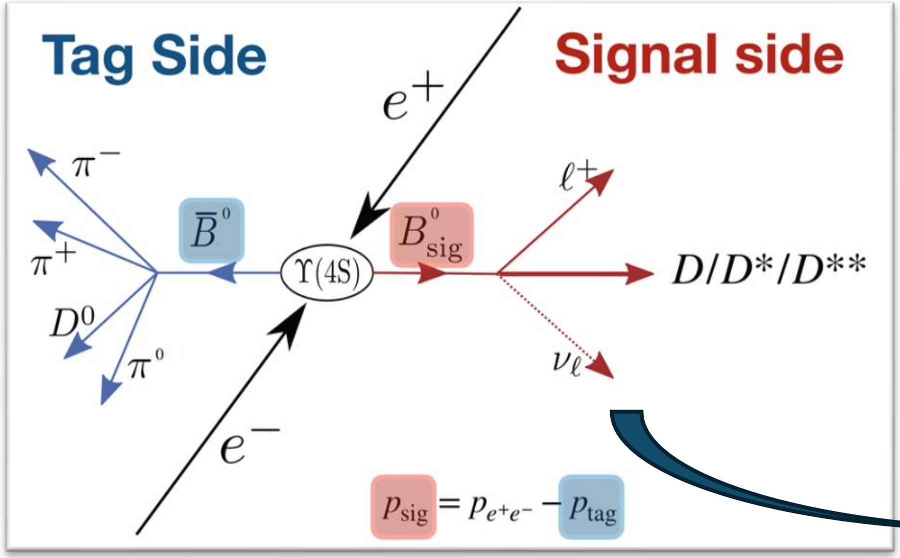


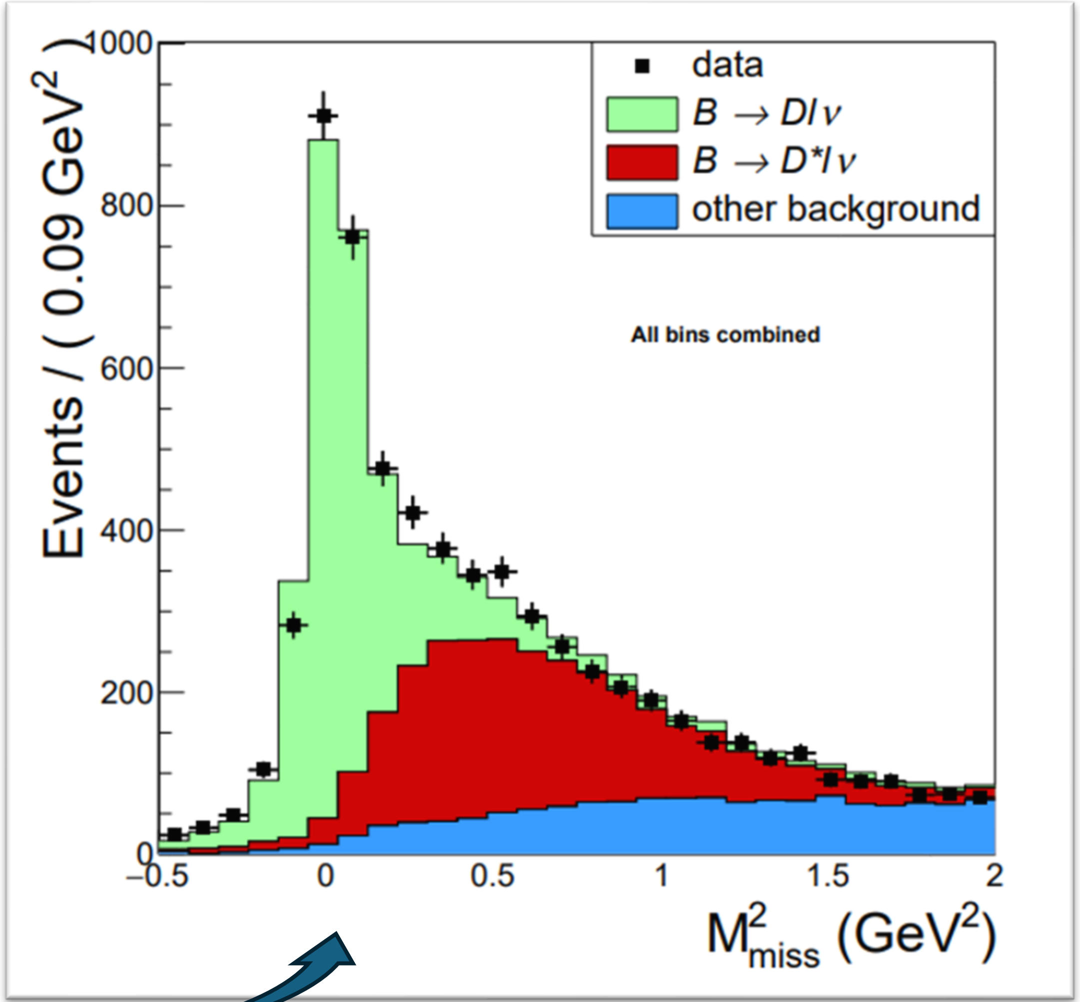




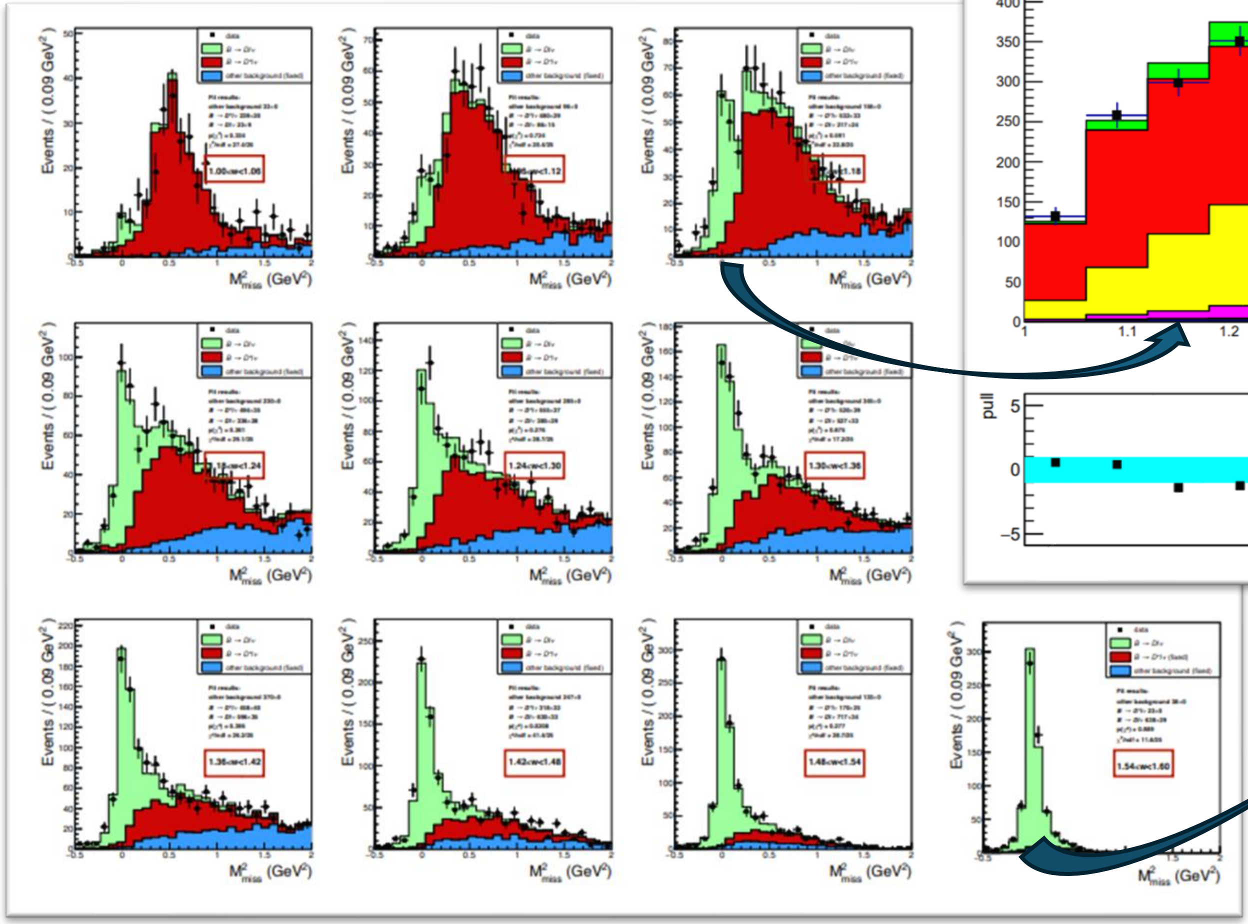
Event kinematics

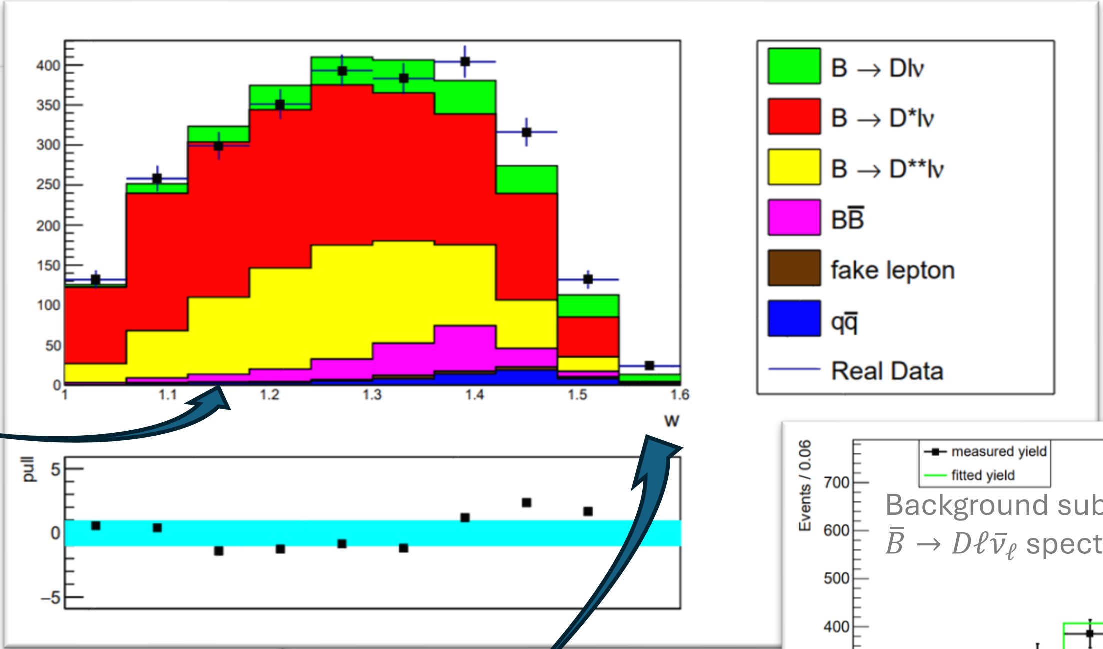
- $M_{miss}^2 = (p_{sig} - p_D - p_\ell)^2 \approx p_\nu^2 = 0$
  is the missing mass squared
- Peaks at zero for events with only one neutrino
- (Almost) model-independent variable, which is useful for signal extraction

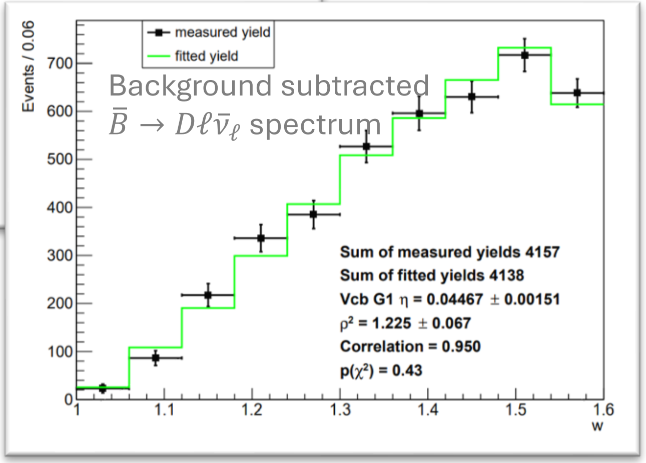




Signal yield extraction







Likelihood function:

$$\mathcal{L} = \left(M^2_{miss}; \nu_D, \nu_{D^*}, \nu_{bkg}\right) = \Pi_i \mathcal{P}(n_i; \nu_i)$$

$$\nu_i = \mathrm{f}_{\mathrm{i}}^{\mathrm{D}} \nu_D + f_i^{D^*} \nu_{D^*} + f_i^{bkg} \nu_{bkg}, \mathcal{P}(n, \nu) = \frac{\nu^n}{n!} e^{-\nu}$$

Resolution and efficiency

- Correction for migration (reconstructed w not same as true w)

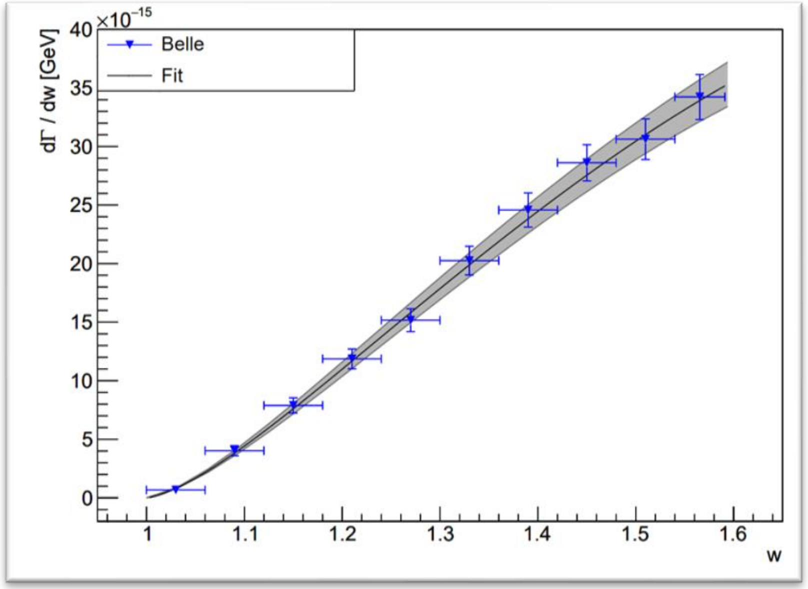
$$\mathcal{M}_{ij} = \mathcal{P}(\text{reco bin } i \mid \text{true bin } j)$$

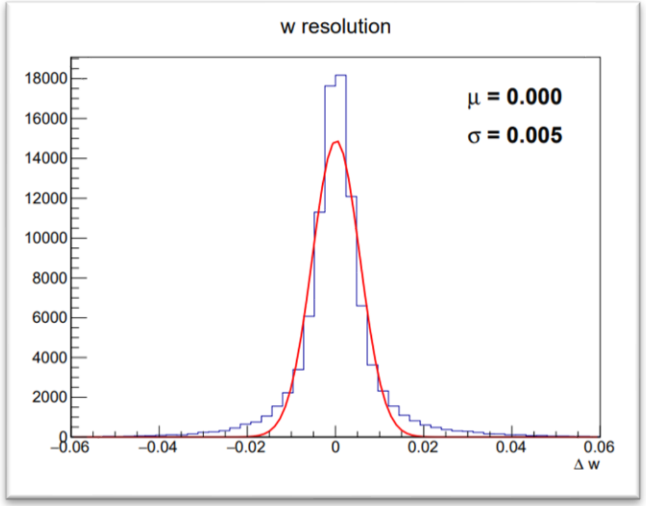
- Correction for efficiency

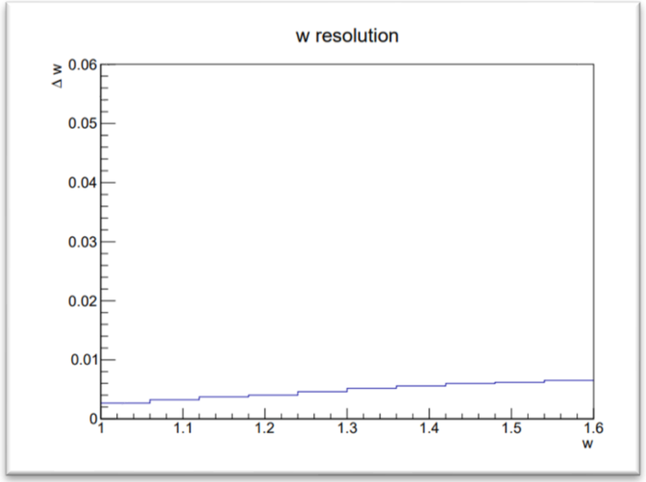
$$\left(\epsilon_{reco}\epsilon_{tag}\right)_{jj} = \mathcal{A}(\text{true bin } j)$$

$$\frac{\Delta\mathcal{B}}{\Delta x} = \left(\epsilon_{reco}\epsilon_{tag}\right)^{-1} \times \mathcal{M}^{-1} \times \nu_{sig} \times 1/4N_{B\bar{B}}$$

$\mathcal{B} = \Gamma \times \tau$



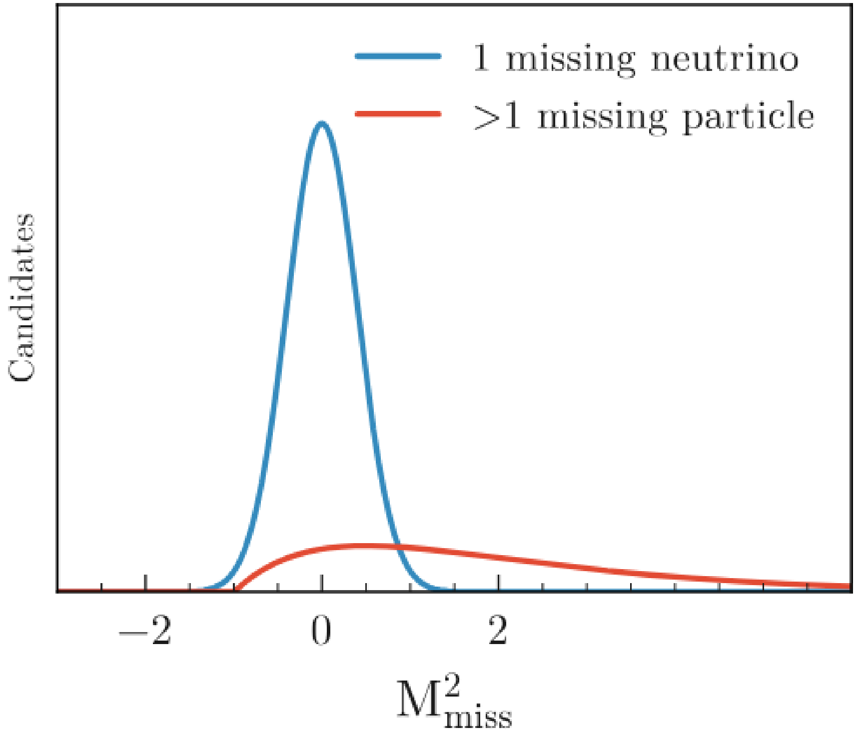




Two key variables for $b \to q\ell\bar{\nu}_\ell, \ell = e, \mu$

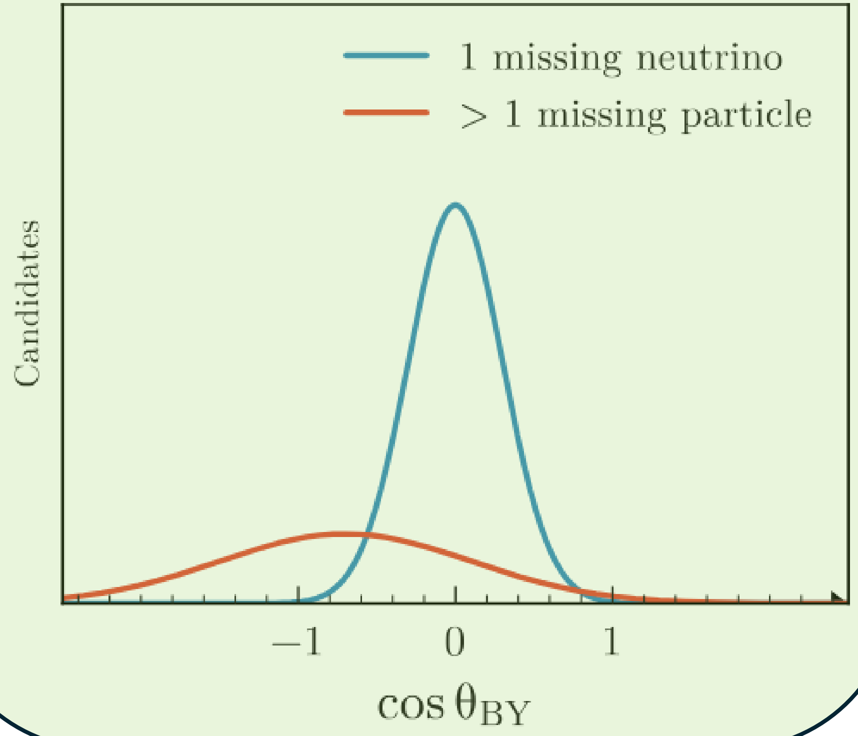
$$M_{miss}^2 = \left(p_{e^+e^-} - p_{B_{tag}} - p_{D^{(*)}\ell}\right)^2$$

Squared 4-momentum of the undetected neutrino(s)



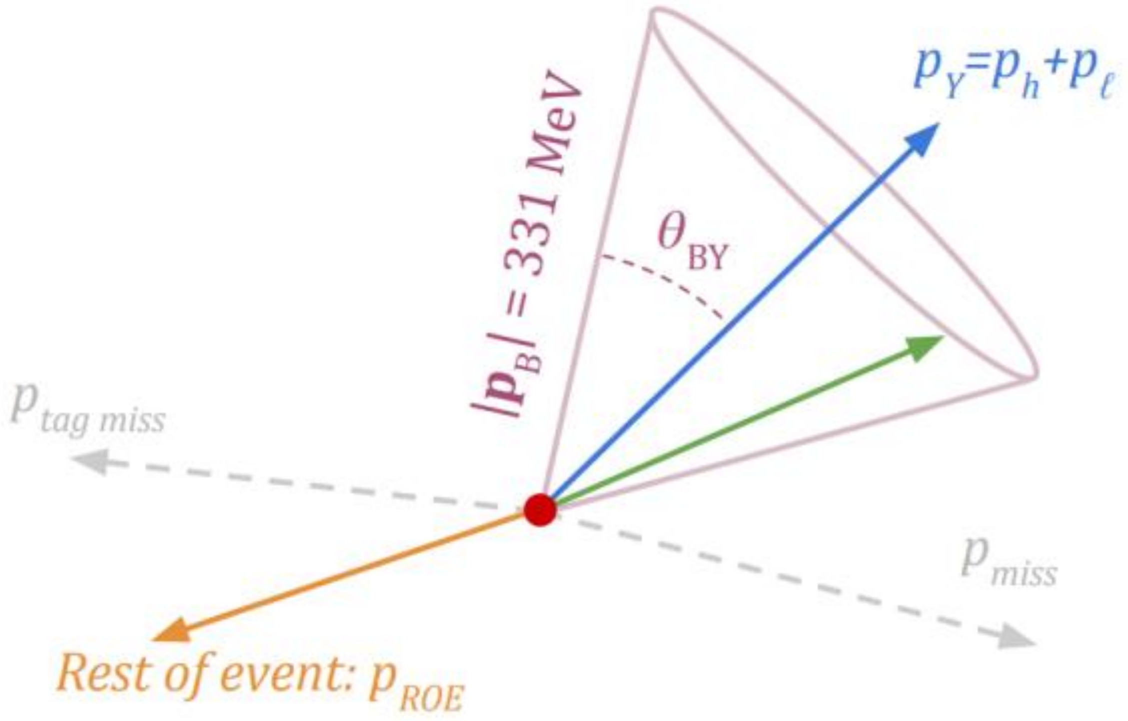
$$\cos\theta_{BY} = \frac{2E_B^* E_Y^* - m_B^2 - m_Y^2}{2|\vec{p}_B^*||\vec{p}_Y^*|}$$

Angle between B and $Y = D^{(*)}\ell$



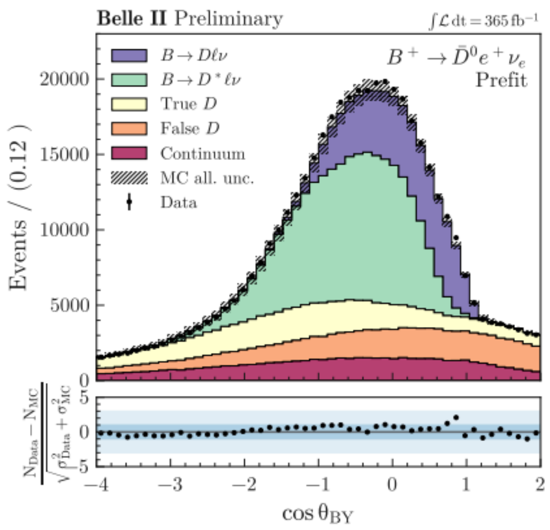
How to reconstruct q^2 $(or\ w)$ without B_{tag}

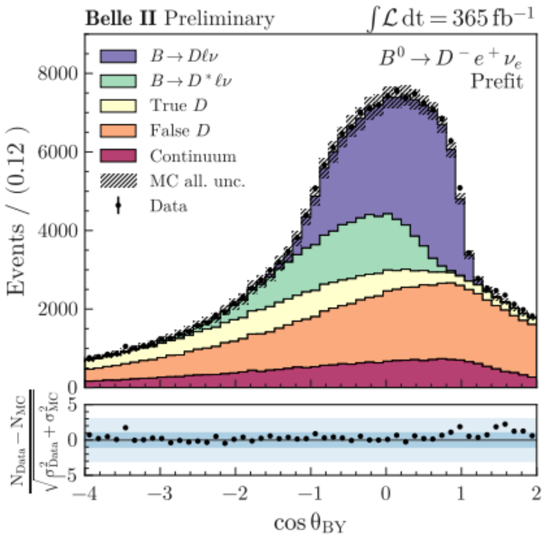
- Angle $\cos\theta_{BY}$ between B and $Y = D\ell$ from reconstructed particles
- B meson angular distribution + ROE momentum
  $$\frac{1}{2}(1 - \hat{p}_B^* \, \hat{p}_{ROE}^*) \sin^2 \theta_B^*$$
- Weighted average over different B meson momenta on the cone span by θ_{BY}



Courtesy from Philipp Horak

Main backgrounds



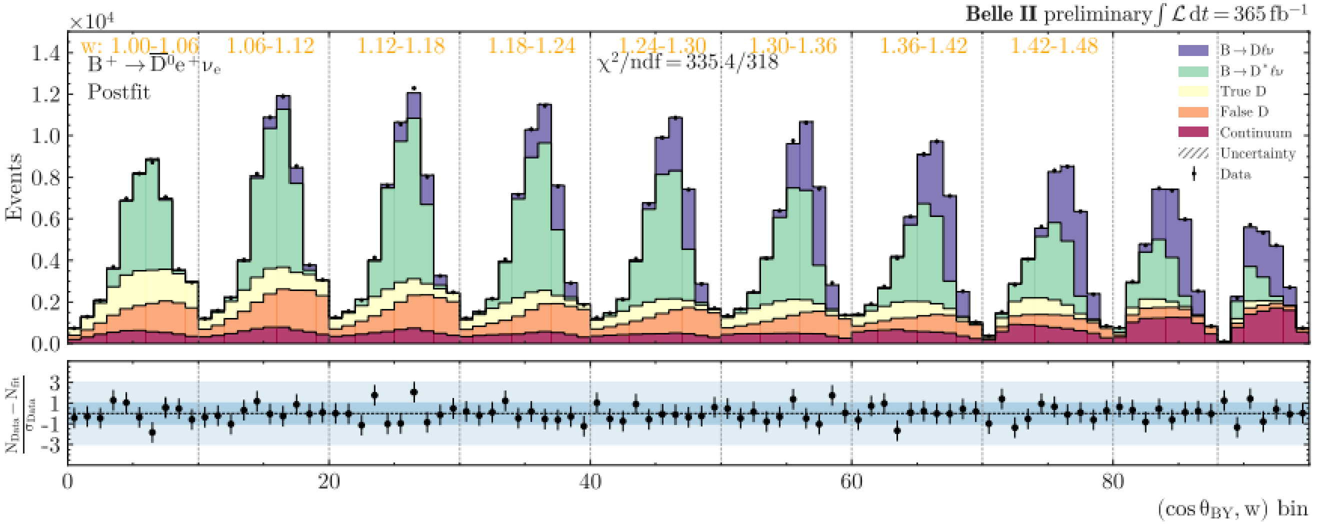


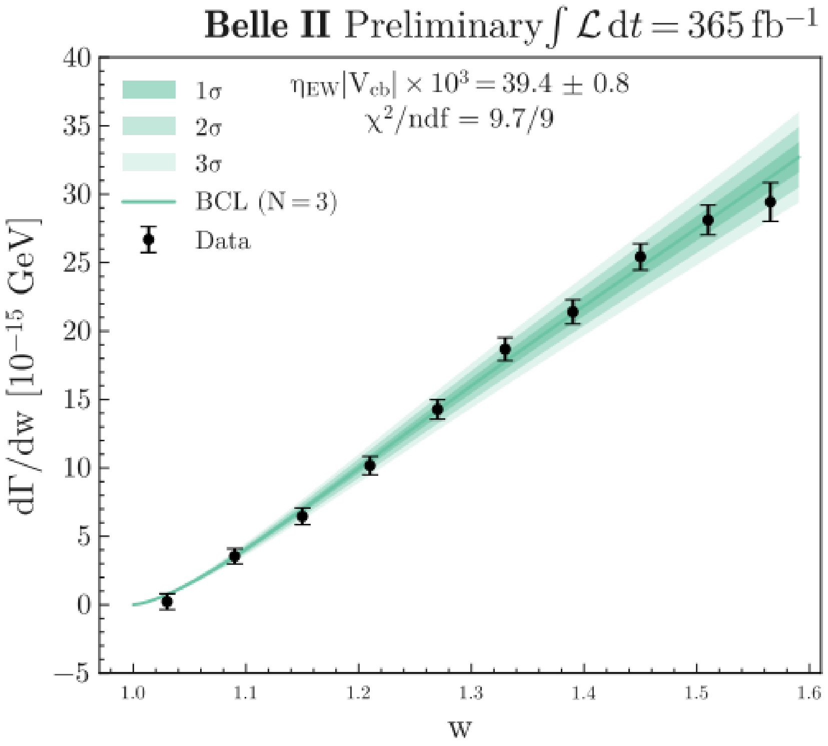
Main backgrounds

- $B \to D^*\ell\nu$ down-feed
- Fake D: Combinatorial backgrounds
- True D: SL backgrounds and $B \to X_c \to \ell$ secondaries
- Continuum: $e^+e^- \to q\bar{q}$ where $q \in [u, d, s, c]$

- Suppress background with selection on ROE, lepton helicity angle, event shape variables, $D^*\ell\nu$ veto
- Control samples to validate signal and backgrounds

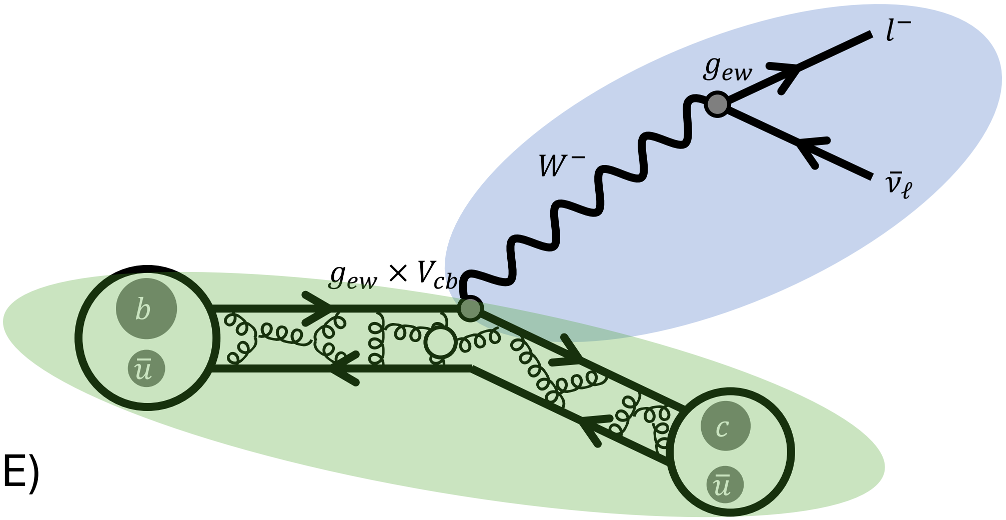
Signal extraction





- 2d binned fit in $\cos\theta_{BY}$ and w
- All systematic uncertainties as nuisance parameters
- Bin-by-bin migration baked into the fit (forward folding)

Inclusive $B \to X_c \ell \bar{\nu}_\ell$



Agnostic with respect to the hadronic system

The theoretical framework is the Heavy Quark Expansion (HQE)

$$d\Gamma = d\Gamma_0 + d\Gamma_{\mu_\pi} \frac{\mu_\pi^2}{m_b^2} + d\Gamma_{\mu_G} \frac{\mu_G^2}{m_b^2} + d\Gamma_{\rho_D} \frac{\rho_D^3}{m_b^3} + d\Gamma_{\rho_{LS}} \frac{\rho_{LS}^3}{m_b^3} + \mathcal{O}(1/m_b^4)$$

$d\Gamma$ are calculated perturbatively

Available at $\mathcal{O}(\alpha_s^3)$

M. Fael, K. Schönwald, M. Steinhauser [Phys. Rev. D 104, 016003 (2021)]

$\mu_\pi, \mu_G, \rho_D, \rho_{LS}$ encapsulate non-perturbative dynamics

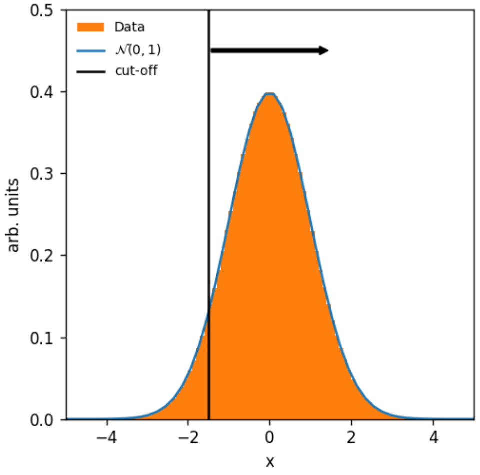
HQE parameters must be extracted from data

requires the **moments** of the $B \to X_c \ell \nu$ rate

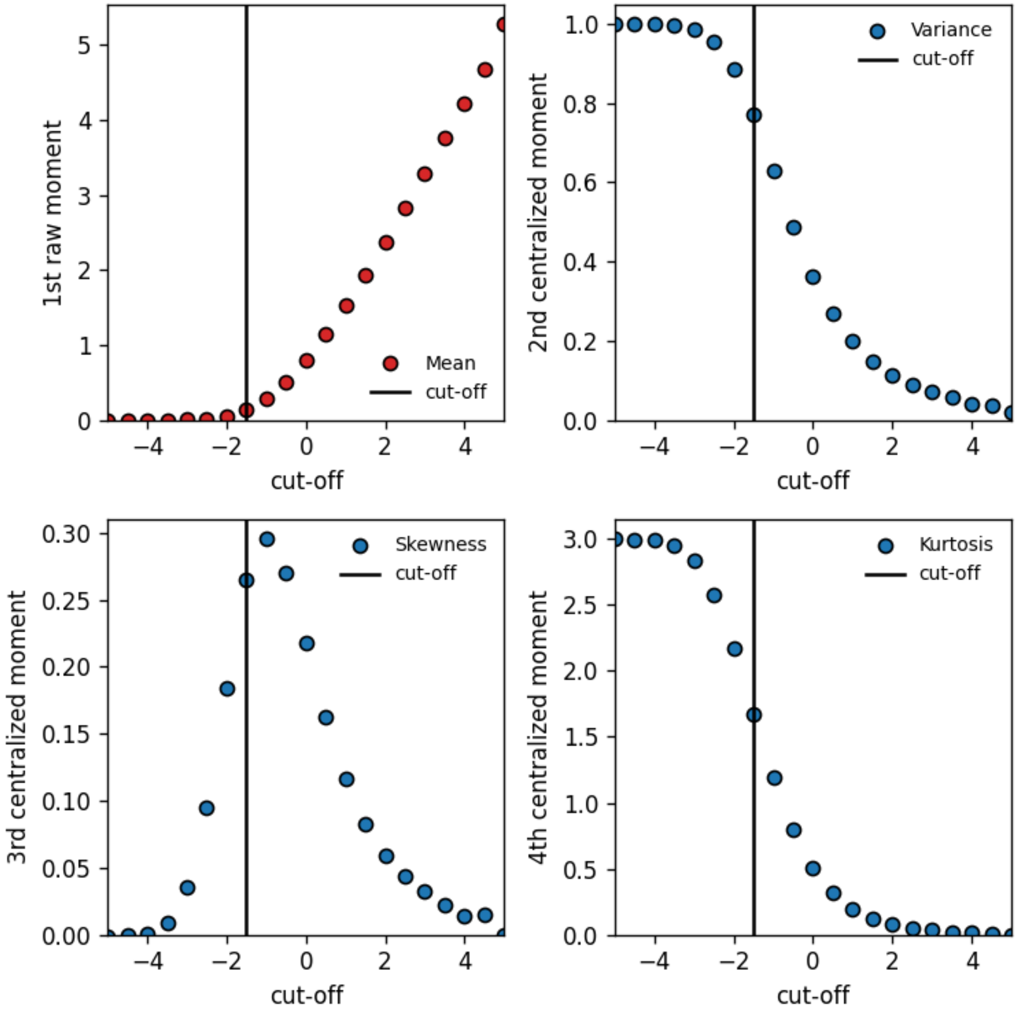
The theory cannot predict the differential decay rate, but the moments of the distribution

Challenge: Proliferation of HQE parameters at higher order

Moments of a Distribution



- The moments are measured with cut-offs in the distribution
- Data points are highly-correlated



$$\mu_n = \int_{-\infty}^{-\infty} (x - c)^n f(x) dx$$

Raw moment: $c = 0$

Central moment: $c = \mathrm{Mean}$

First raw moment: Mean

Measures the location

Second central moment: Variance

Measures the spread

Third central moment: Skewness

Measures asymmetry

Fourth central moment: Kurtosis

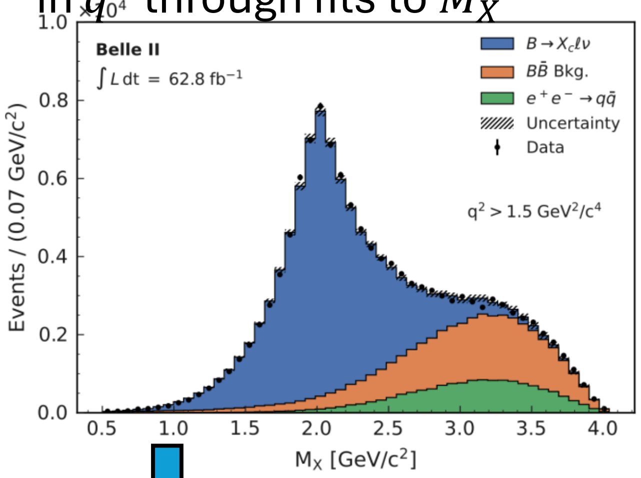
Measures "tailedness"

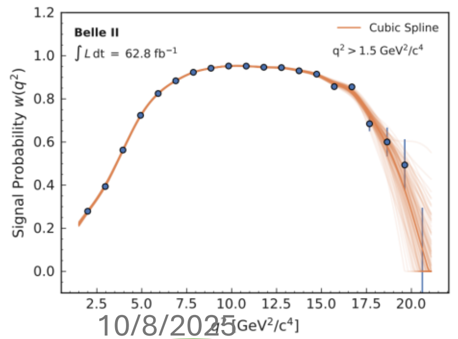
$\langle q^2 \rangle$ Moments – Background Subtraction

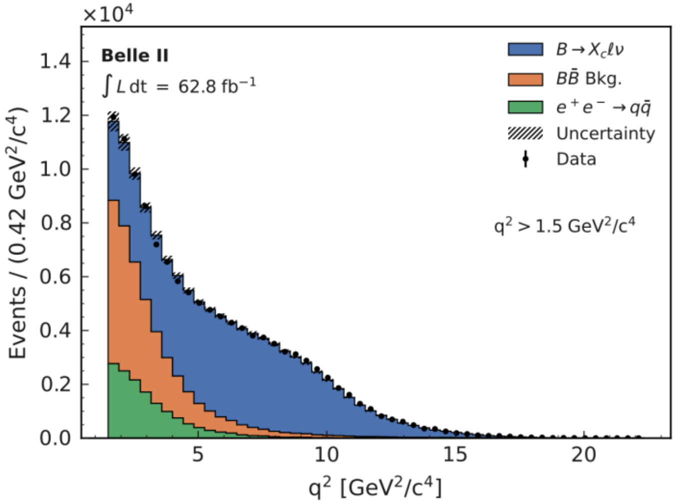
Event-wise master formula

$$\langle q^{2n} \rangle = \frac{\Sigma_{i=0}^{N_{data}} w(q_i^2) \times q_{calib,i}^{2n}}{\Sigma_{j=0}^{N_{data}} w(q_j^2)} \times \mathcal{C}_{calib} \times \mathcal{C}_{gen}$$

Determine background normalization in q^2 through fits to M_X







Calculate event-wise signal probability

- Linear calibration function
  $q_{calib}^{2n} = (q_{reco}^{2n} - c_n)/m_n$
- Bias from assumed linearity
  $\mathcal{C}_{calib} = \langle q_{gen,sel}^{2n} \rangle / \langle q_{calib}^{2n} \rangle$
- Reconstruction effects & final state radiation
  $\mathcal{C}_{gen} = \langle q_{gen}^{2n} \rangle / \langle q_{gen,sel}^{2n} \rangle$

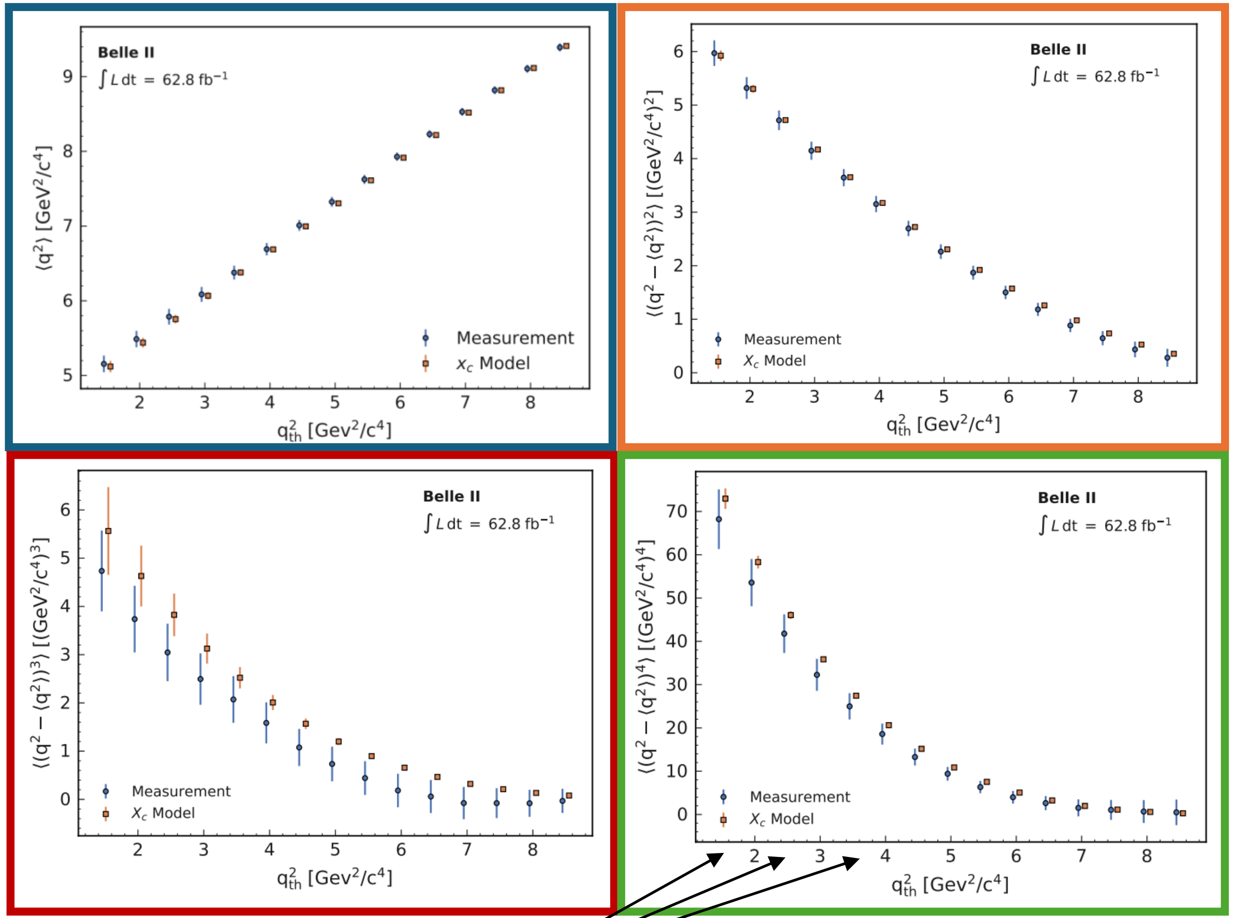
$\langle q^2 \rangle$ Moments – Result

$$\mu_n = \int_{-\infty}^{-\infty} (x-c)^n f(x)dx$$

Raw moment: $c = 0$

Central moment: $c = \text{Mean}$

$\langle q^2 \rangle$ Moments



cut-offs

First raw moment: Mean

Measures the location

Second central moment: Variance

Measures the spread

Third central moment: Skewness

Measures asymmetry

Fourth central moment: Kurtosis

Measures "tailedness"

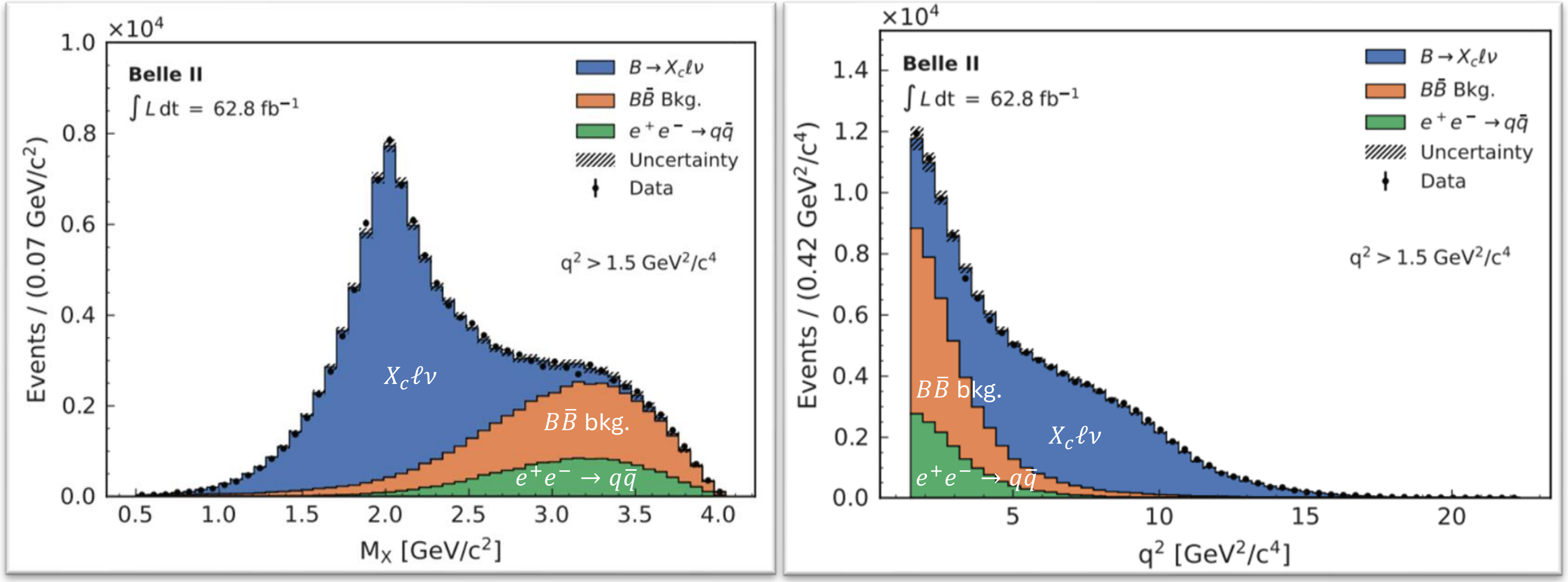
Systematics

- Background yields and shape
- Composition of the X_c system
- Simulated detector resolution

Belle II Collaboration
[Phys.Rev.D 107 (2023) 7, 072002]

Spectral moments: $\langle q^{2n} \rangle$

Also measured: $\langle M_X^n \rangle, \langle E_\ell^n \rangle$

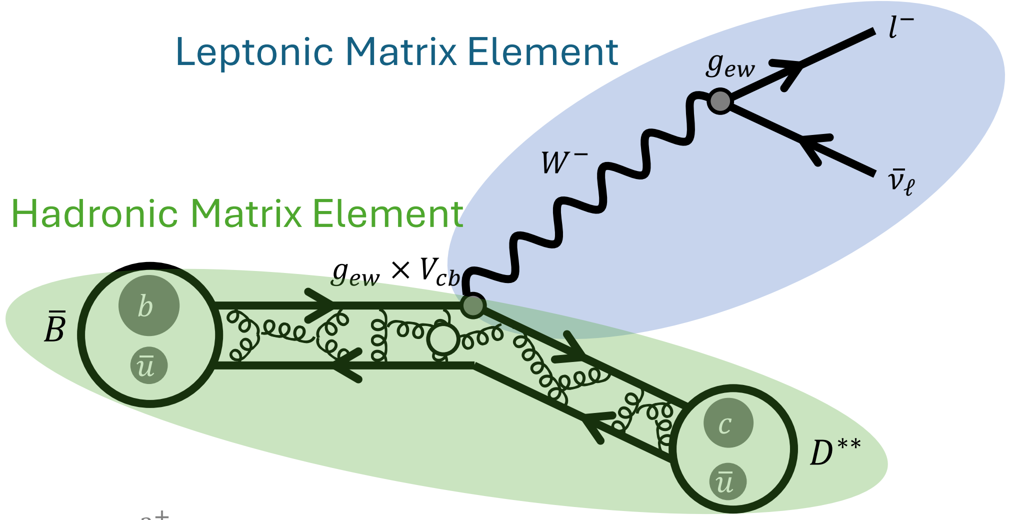


Sizeable uncertainty on the measured spectral moments from the $B \to X_c \ell \bar{\nu}_\ell$ modelling:

- Branching ratios
- Form factors
- Filling “the gap”

Any bias in the measurement is amplified at moments of higher order

Exclusive $\bar{B} \to D^{**} \ell \bar{\nu}_\ell$



$\frac{3}{2}^+$ states

$$\frac{\langle D_1(v',\epsilon)|V^\mu|B(v)\rangle}{\sqrt{m_B m_{D_1}}} = f_{V_1}\epsilon^{*\mu} + (f_{V_2}v^\mu + f_{V_3}v'^\mu)(\epsilon^* \cdot v)$$

$$\frac{\langle D_1(v',\epsilon)|A^\mu|B(v)\rangle}{\sqrt{m_B m_{D_1}}} = i f_A \epsilon^{\mu\alpha\beta\gamma}\epsilon^*_\alpha v_\beta v'_\gamma$$

$$\frac{\langle D_2^*(v',\epsilon)|A^\mu|B(v)\rangle}{\sqrt{m_B m_{D_2^*}}} = k_{A_1}\epsilon^{*\mu\alpha}v_\alpha + \left(k_{A_2}v^\mu + k_{A_3}v'^\mu\right)\epsilon^*_{\alpha\beta}v^\alpha v^\beta$$

$$\frac{\langle D_2^*(v',\epsilon)|V^\mu|B(v)\rangle}{\sqrt{m_B m_{D_2^*}}} = i k_V \epsilon^{\mu\alpha\beta\gamma}\epsilon^*_{\alpha\sigma}v^\sigma v_\beta v'_\gamma$$

$\frac{1}{2}^+$ states

$$\frac{\langle D_0^*(v')|V^\mu|B(v)\rangle}{\sqrt{m_B m_{D_0^*}}} = 0$$

$$\frac{\langle D_0^*(v')|A^\mu|B(v)\rangle}{\sqrt{m_B m_{D_0^*}}} = g_+(v^\mu + v'^\mu) + g_-(v^\mu - v'^\mu)$$

$$\frac{\langle D_1^*(v')|V^\mu|B(v)\rangle}{\sqrt{m_B m_{D_1^*}}} = g_{V_1}\epsilon^{*\mu} + (g_{V_2}v^\mu + g_{V_3}v'^\mu)(\epsilon^* \cdot v)$$

$$\frac{\langle D_1^*(v')|A^\mu|B(v)\rangle}{\sqrt{m_B m_{D_1^*}}} = i g_A \epsilon^{\mu\alpha\beta\gamma}\epsilon^*_\alpha v_\beta v'_\gamma$$

Stronger assumptions in the D^{**} system:

- Narrow-width approximation for the form factors
- Form factors defined at the nominal mass are applied over the full invariant mass spectrum

In the heavy quark limit ($m_b, m_c \to \infty$) with both b and c quark at rest:

- $\frac{\Gamma\left(B \to D_{0,1}^{\frac{1}{2}}\ell\nu\right)}{\Gamma\left(B \to D_{1,2}^{\frac{3}{2}}\ell\nu\right)} = \frac{\left|\tau_{\frac{1}{2}}\right|^2}{\left|\tau_{\frac{3}{2}}\right|^2}$
- HQET Predicts: $\Gamma\left(B \to D_{1,2}^{\frac{3}{2}}\ell\nu\right) \gg \Gamma\left(B \to D_{0,1}^{\frac{1}{2}}\ell\nu\right)$
- Observed: $\Gamma\left(B \to D_{1,2}^{\frac{3}{2}}\ell\nu\right) \approx \Gamma\left(B \to D_{0,1}^{\frac{1}{2}}\ell\nu\right)$

This is the so-called $\boldsymbol{\tau_{3/2} - \tau_{1/2}}$ puzzle

At zero-recoil ($v = v'$), only g_+, g_{V_1}, and f_{V_1} contribute to the differential decay rate

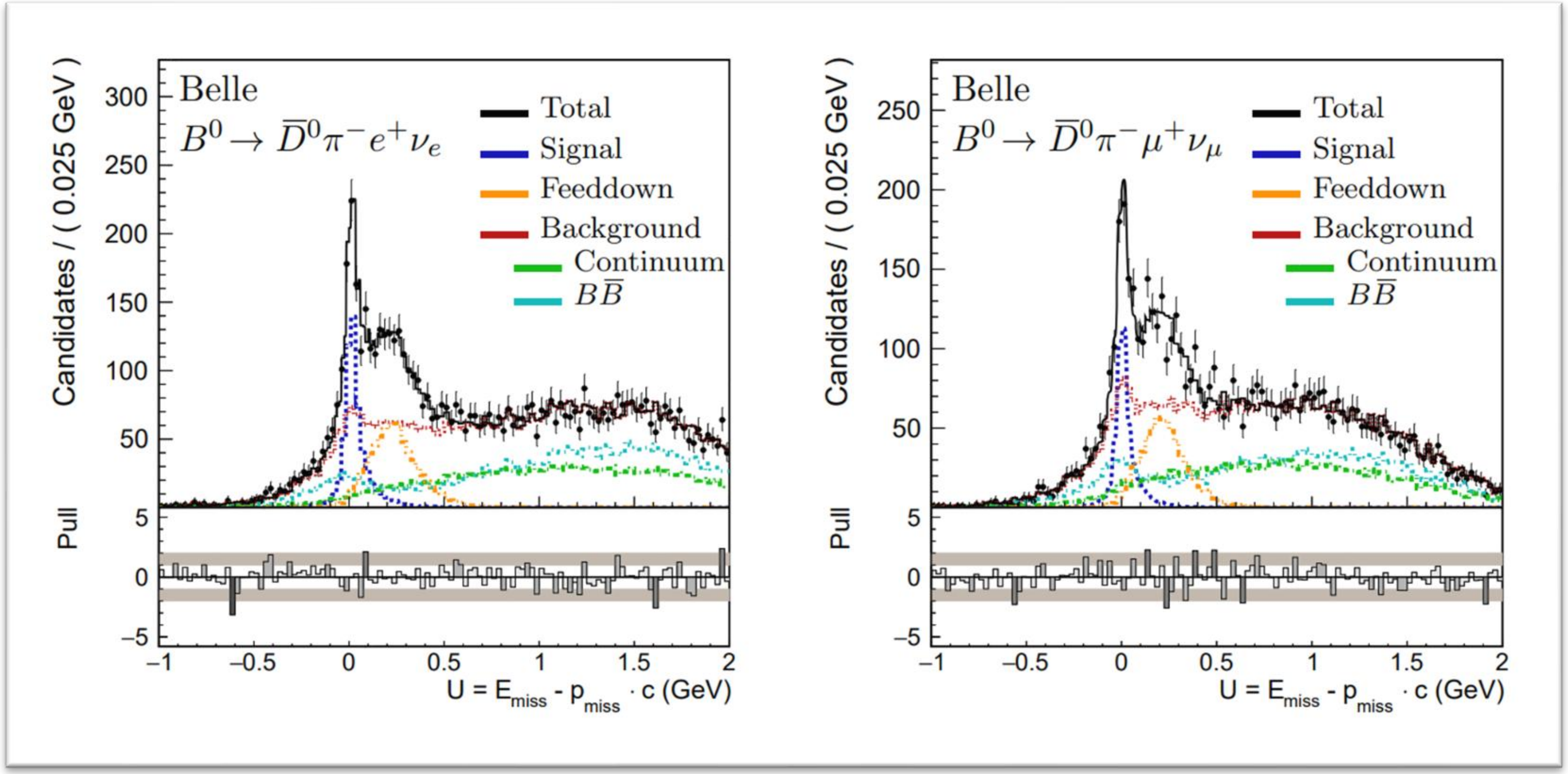
$B \to D^{**}\ell\bar{\nu}_\ell$ Decays

Belle Collaboration
[*Phys.Rev.D* 107 (2023) 9, 092003]

Extraction Method:

$$U = E_{miss} - p_{miss}c$$

with $E_{miss} = E_{e^+e^-} - E_{tag} - E_{D^{**}} - E_\ell$



$D^{**} = (D_0^*, D_1, D_1', D_2^*)$ Composition

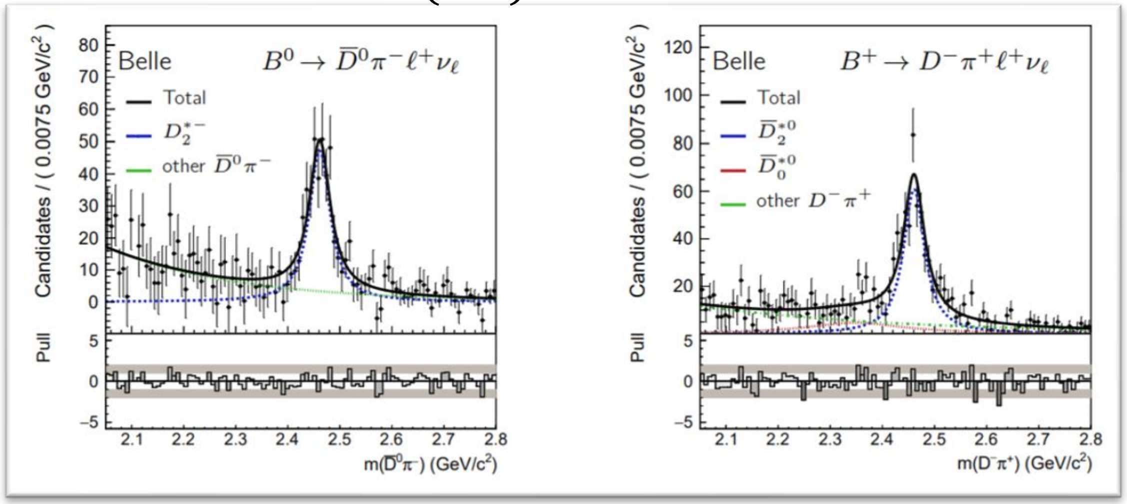
Belle Collaboration
[*Phys.Rev.D* 107 (2023) 9, 092003]

Based on signal weights from previous fits to U

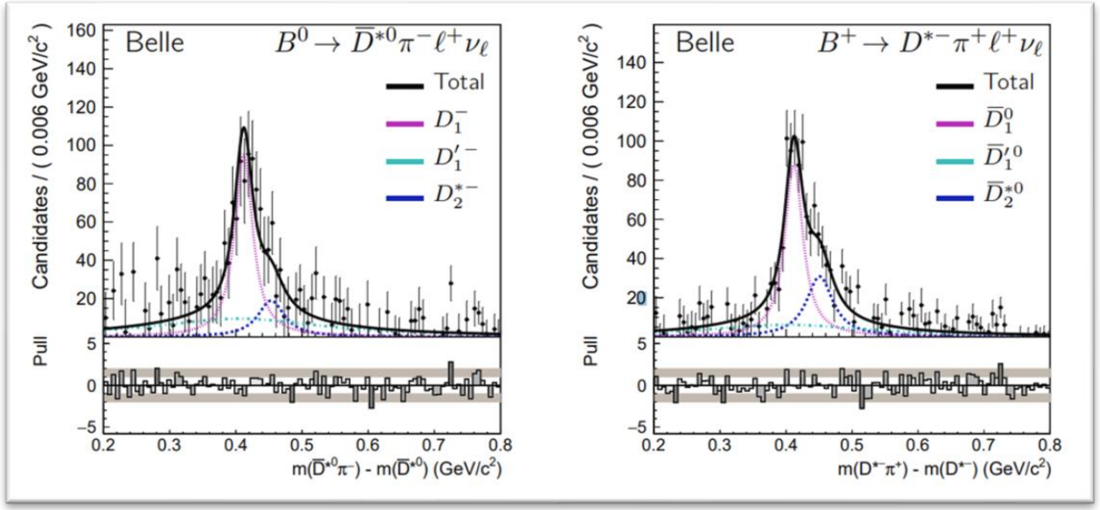
Custom Orthogonal Weight functions

Model: Breit-Wigner functions convolved with Gaussian

$m(D\pi)$ Distribution



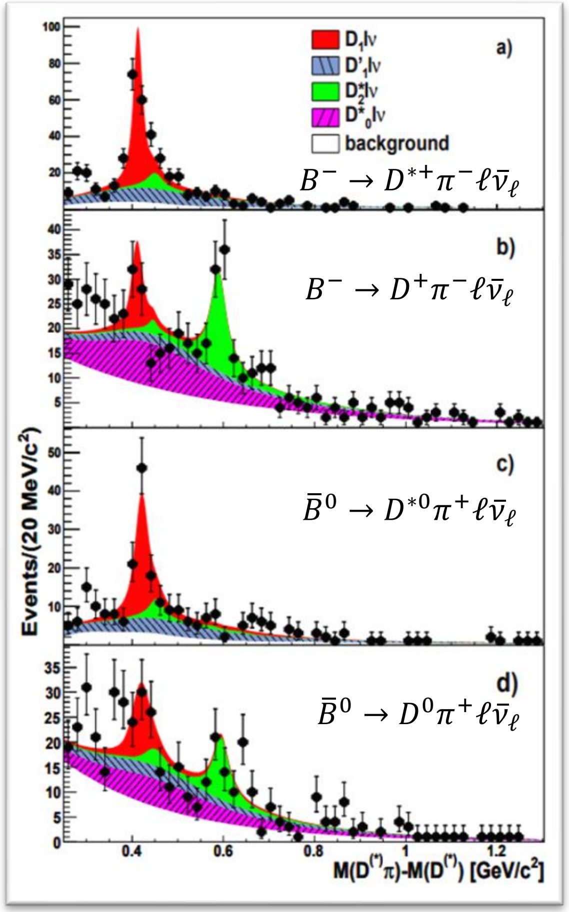
$m(D^*\pi)$ Distribution

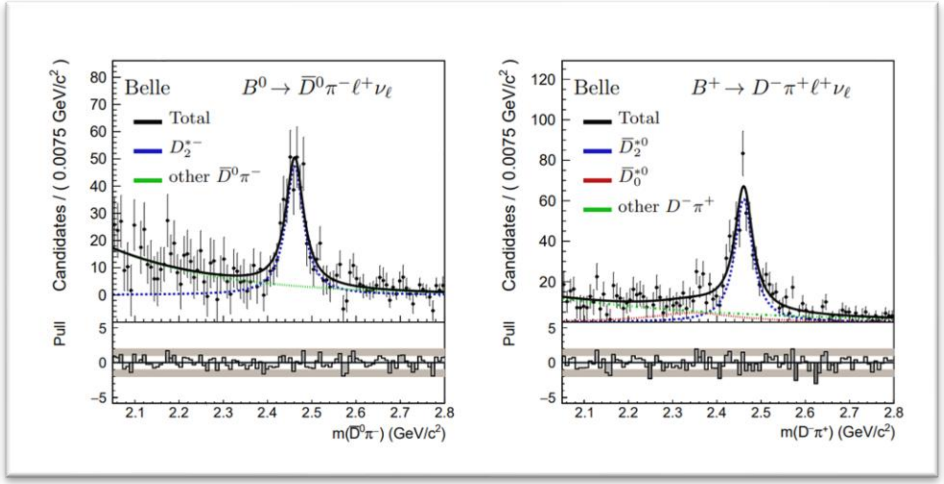


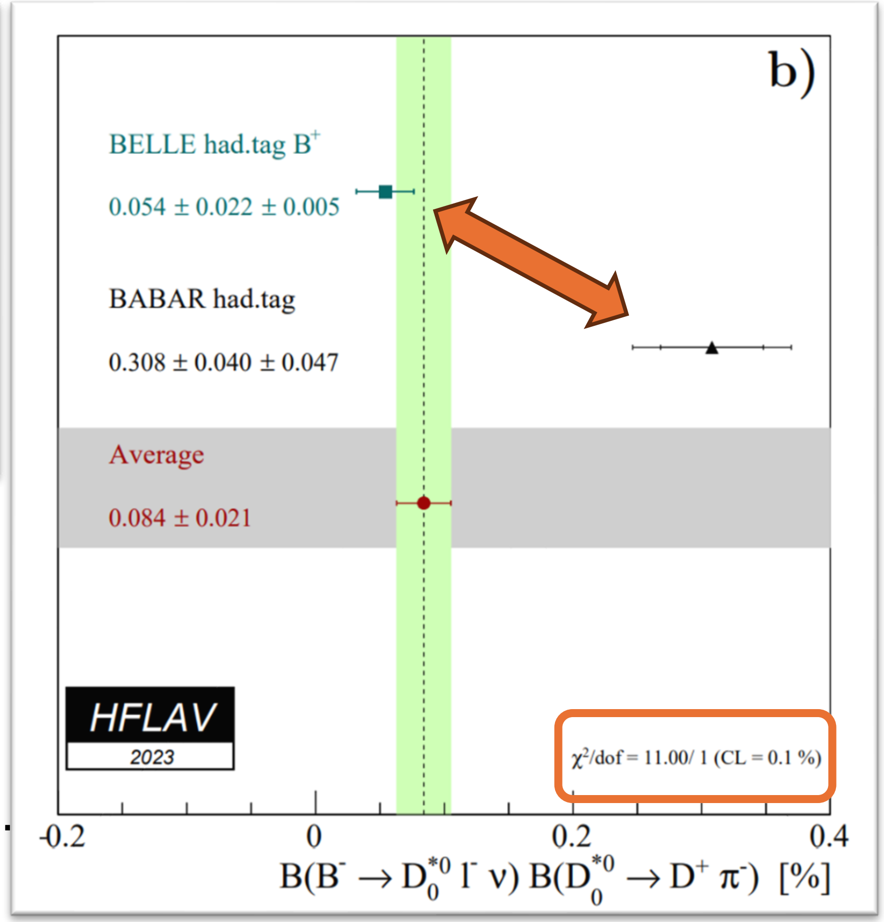
	yield	branching fraction [%]	PDG [%]
$B^0 \to D_0^{*-}\ell^+\nu_\ell$ with $D_0^{*-} \to \bar{D}^0\pi^-$	-	<0.044 at 90% CL	0.30 ± 0.12
$B^0 \to D_2^{*-}\ell^+\nu_\ell$ with $D_2^{*-} \to \bar{D}^0\pi^-$	457 ± 45	$0.157 \pm 0.015\,(\text{stat}) \pm 0.005\,(\text{syst})$	0.121 ± 0.033
other $B^0 \to \bar{D}^0\pi^-\ell^+\nu_\ell$	547 ± 45	-	
$B^+ \to \bar{D}_0^{*0}\ell^+\nu_\ell$ with $\bar{D}_0^{*0} \to D^-\pi^+$	180 ± 72	$0.054 \pm 0.022\,(\text{stat}) \pm 0.005\,(\text{syst})$	0.25 ± 0.05
$B^+ \to \bar{D}_2^{*0}\ell^+\nu_\ell$ with $\bar{D}_2^{*0} \to D^-\pi^+$	590 ± 39	$0.163 \pm 0.011\,(\text{stat}) \pm 0.008\,(\text{syst})$	0.153 ± 0.016
other $B^+ \to D^-\pi^+\ell^+\nu_\ell$	520 ± 70	-	

	yield	branching fraction [%]	PDG [%]
$B^0 \to D_1^-\ell^+\nu_\ell$ with $D_1^- \to \bar{D}^{*0}\pi^-$	866 ± 142	$0.306 \pm 0.050\,(\text{stat}) \pm 0.029\,(\text{syst})$	0.280 ± 0.028
$B^0 \to D_1'^-\ell^+\nu_\ell$ with $D_1'^- \to \bar{D}^{*0}\pi^-$	523 ± 173	$0.206 \pm 0.068\,(\text{stat}) \pm 0.025\,(\text{syst})$	0.31 ± 0.09
$B^0 \to D_2^{*-}\ell^+\nu_\ell$ with $D_2^{*-} \to \bar{D}^{*0}\pi^-$	145 ± 114	$0.051 \pm 0.040\,(\text{stat}) \pm 0.010\,(\text{syst})$	0.068 ± 0.012
$B^+ \to \bar{D}_1^0\ell^+\nu_\ell$ with $\bar{D}_1^0 \to D^{*-}\pi^+$	698 ± 65	$0.249 \pm 0.023\,(\text{stat}) \pm 0.015\,(\text{syst})$	0.303 ± 0.020
$B^+ \to \bar{D}_1'^0\ell^+\nu_\ell$ with $\bar{D}_1'^0 \to D^{*-}\pi^+$	353 ± 93	$0.138 \pm 0.036\,(\text{stat}) \pm 0.009\,(\text{syst})$	0.27 ± 0.06
$B^+ \to \bar{D}_2^{*0}\ell^+\nu_\ell$ with $\bar{D}_2^{*0} \to D^{*-}\pi^+$	382 ± 74	$0.137 \pm 0.026\,(\text{stat}) \pm 0.009\,(\text{syst})$	0.101 ± 0.024

Exclusive $\bar{B} \to D^{**}\ell\bar{\nu}_\ell$







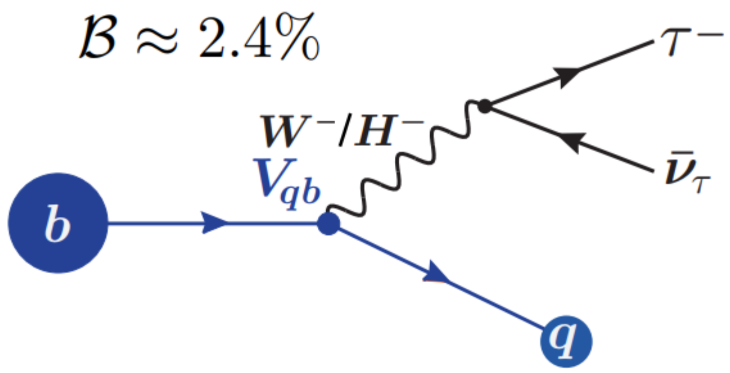
Strong tension in $B \to D_0^*\ell\bar{\nu}_\ell$ measurements

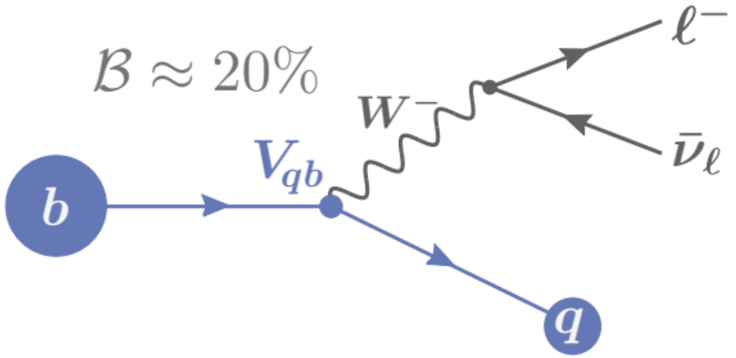
The way forward:

- Belle II measurements will be important
- Utilize semileptonic tagging
- Provide differential data in $m(D^{(*)}\pi), q^2, \ldots$

Choice of S-wave lineshape has a large impact on the extracted branching ratio

Part II: Semileptonic decays with τ





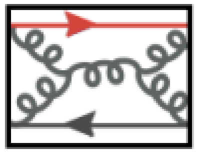
Observable of choice:

$$R = \frac{b \to q\tau\bar{\nu}_\tau}{b \to q\ell\bar{\nu}_\ell}$$

$$\to R(D^{(*)}, \pi, \mathrm{J}/\Psi)$$

Benefits:

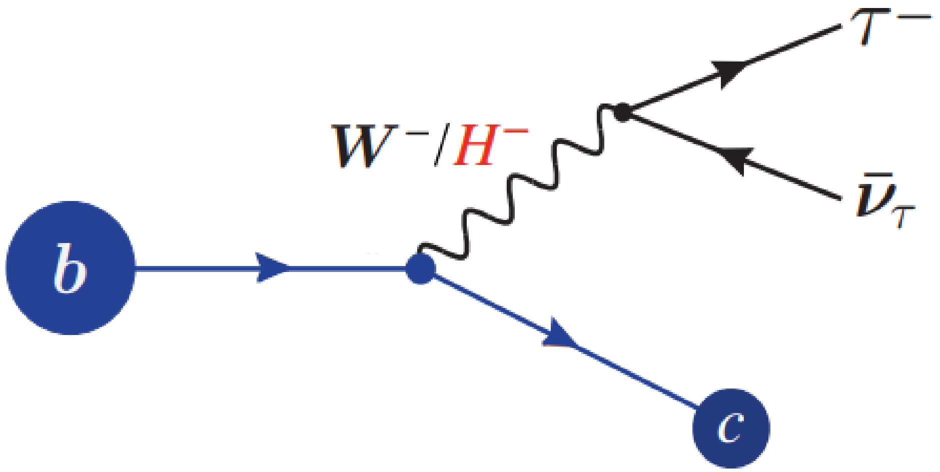
- Experimental systematics **cancel in the ratio**
- Theoretical uncertainties **cancel in the ratio**

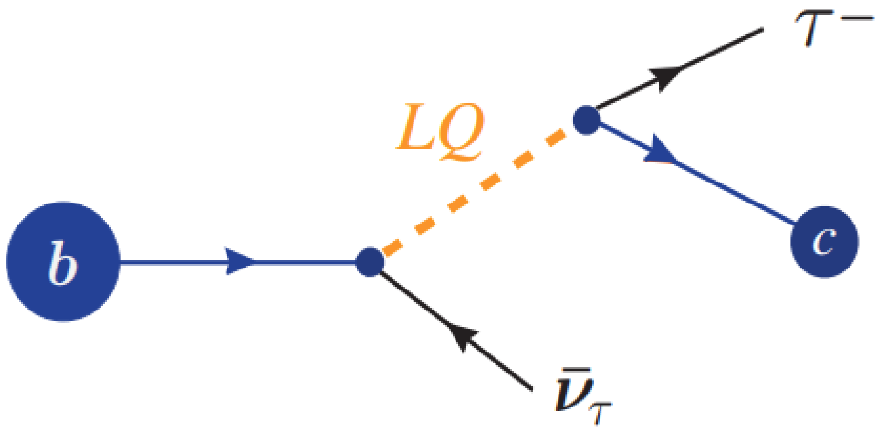


Semileptonic decays with τ

Sensitive probe to physics beyond the Standard Model:

- Charged Higgs bosons
- Leptoquark



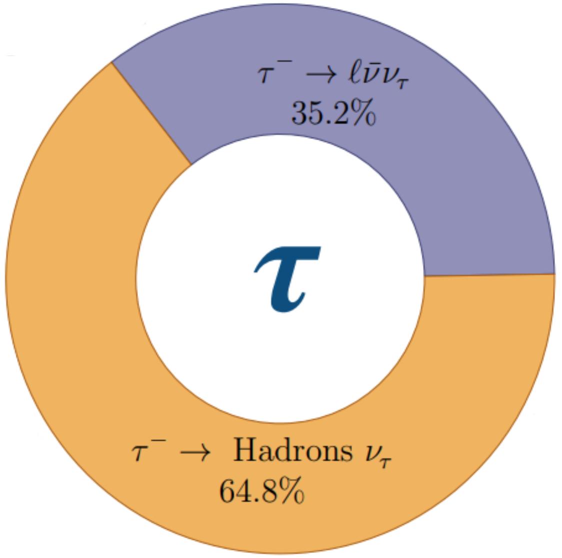


Experimental aspects

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

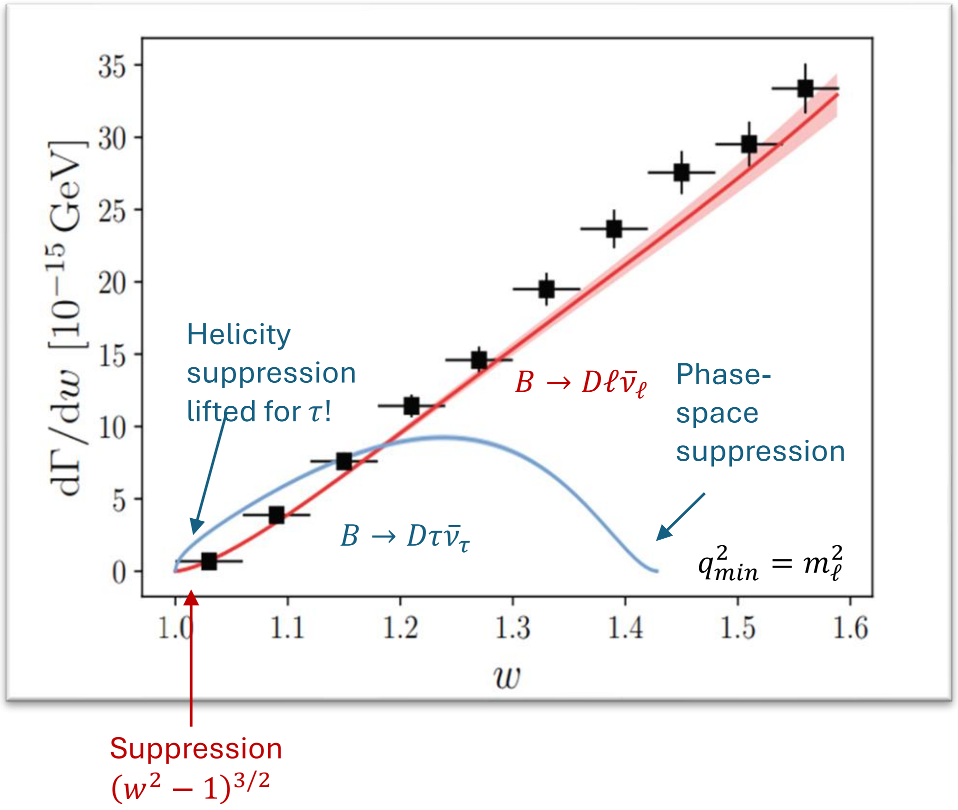
Leptonic or hadronic τ decays?

- Some properties only accessible with hadronic decays, e.g. τ polarization
- Leptonic τ decays are experimentally cleaner

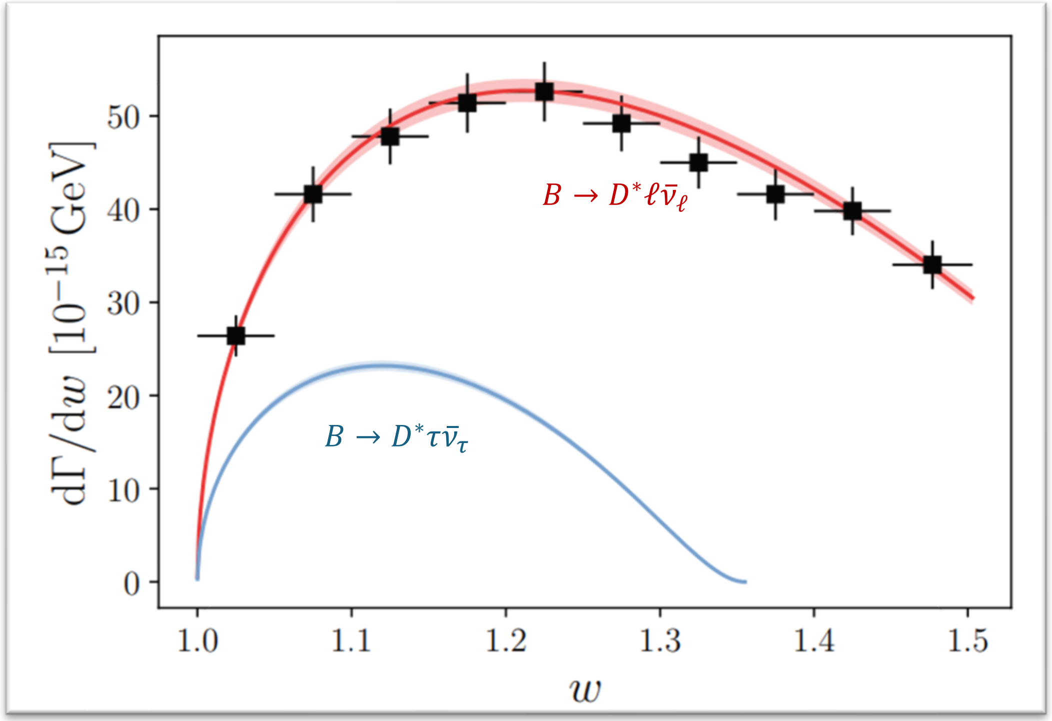


Semileptonic decays are abundant, but the τ decay is **difficult** to separate from normalization and backgrounds

- LHCb: Isolation criteria, displacement of $D^{(*)}$ and τ, kinematics
- B-factories: Full reconstruction of the event (Tagging), matching topology, kinematics



$d\Gamma/dw\ [10^{-15}\ \mathrm{GeV}]$
w
Helicity suppression lifted for τ!
$B \to D\ell\bar{\nu}_\ell$
Phase-space suppression
$B \to D\tau\bar{\nu}_\tau$
$q^2_{min} = m^2_\ell$
Suppression $(w^2-1)^{3/2}$



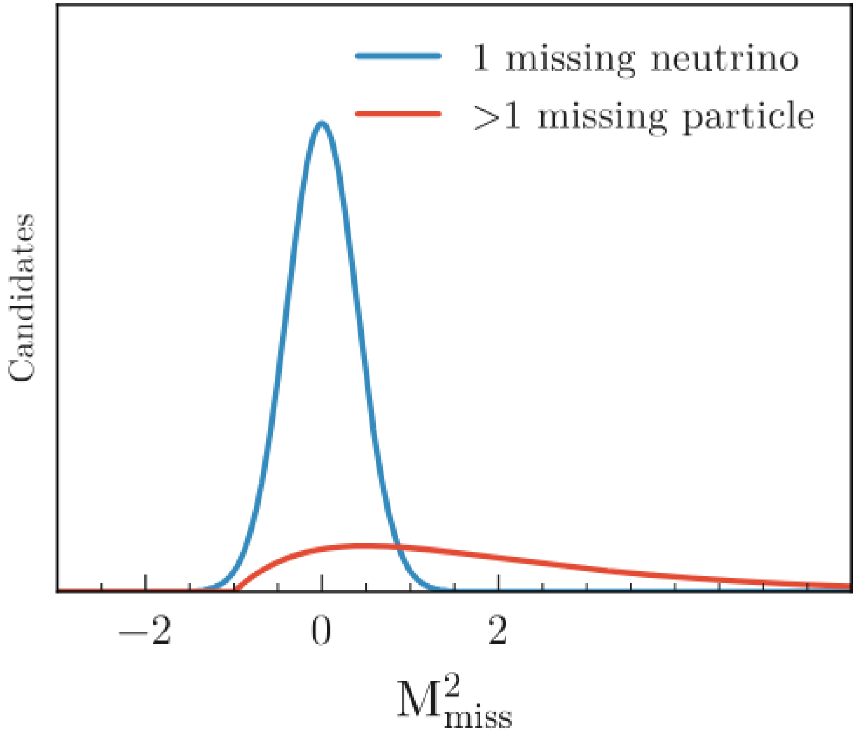
$d\Gamma/dw\ [10^{-15}\ \mathrm{GeV}]$
w
$B \to D^*\ell\bar{\nu}_\ell$
$B \to D^*\tau\bar{\nu}_\tau$

Solving the 3-class classification problem

In general, identify 2 variables that have discriminating power in three classes: signal normalization, background

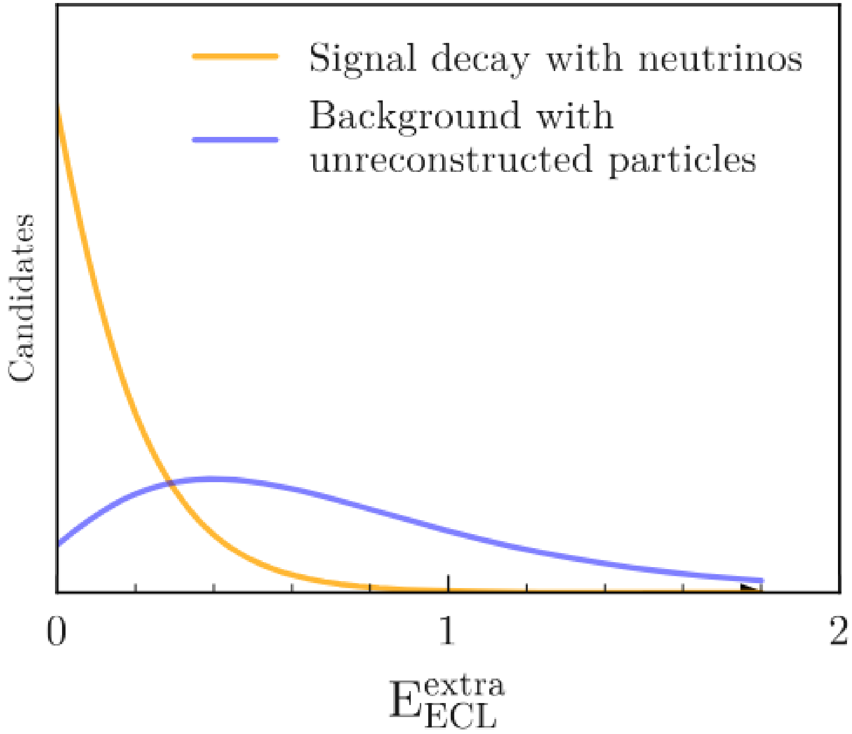
$$M^2_{miss} = \left(p_{e^+e^-} - p_{B_{tag}} - p_{D^{(*)}\ell}\right)^2$$

Squared 4-momentum of the undetected neutrino(s)



For tau final states, at least 2 neutrinos are present in the event, and signal decays look very similar to background

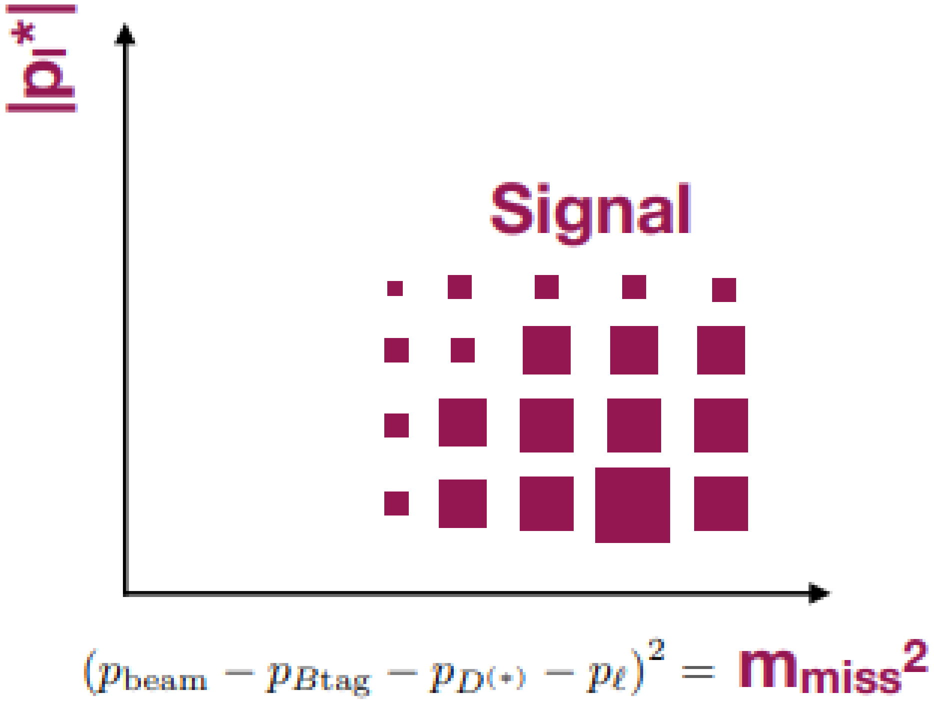
Sum of unassigned energy in the electromagnetic calorimeter

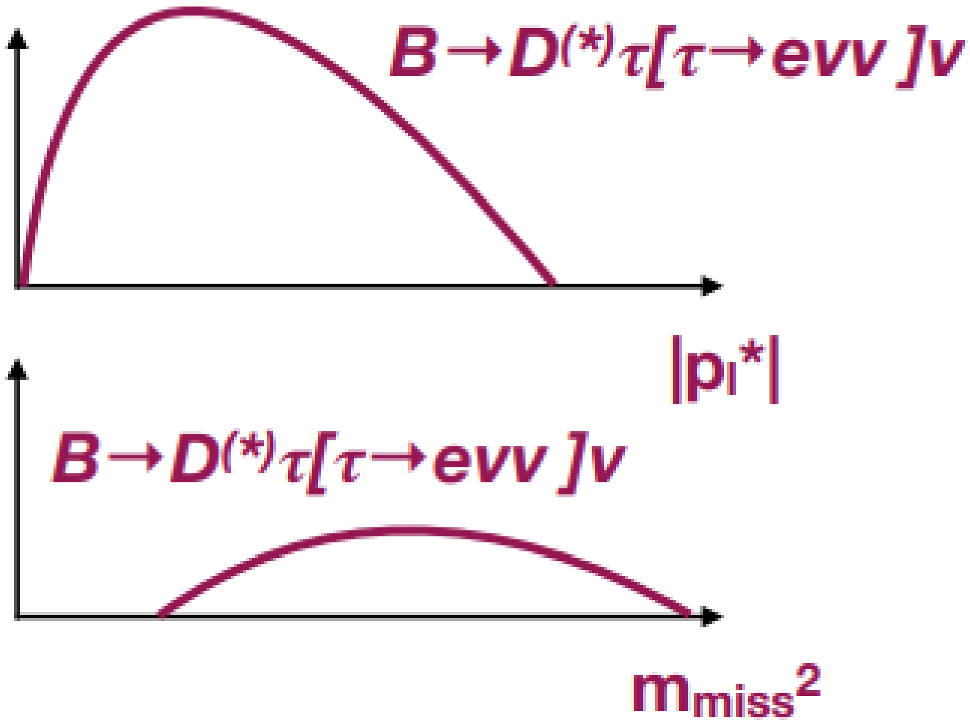


Works, because during the full reconstruction, if correctly done, all energy deposits have been assigned

BaBar measurement of $R(D^{(*)})$

Belle commonly uses the variables M_{miss}^2 and E_{ECL}





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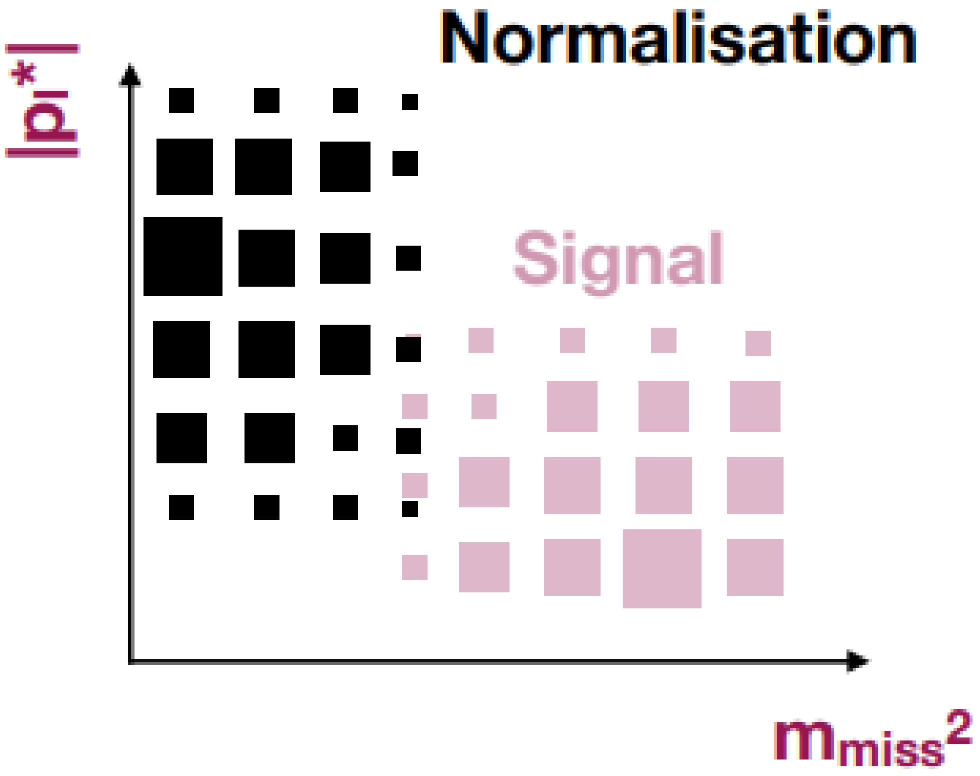

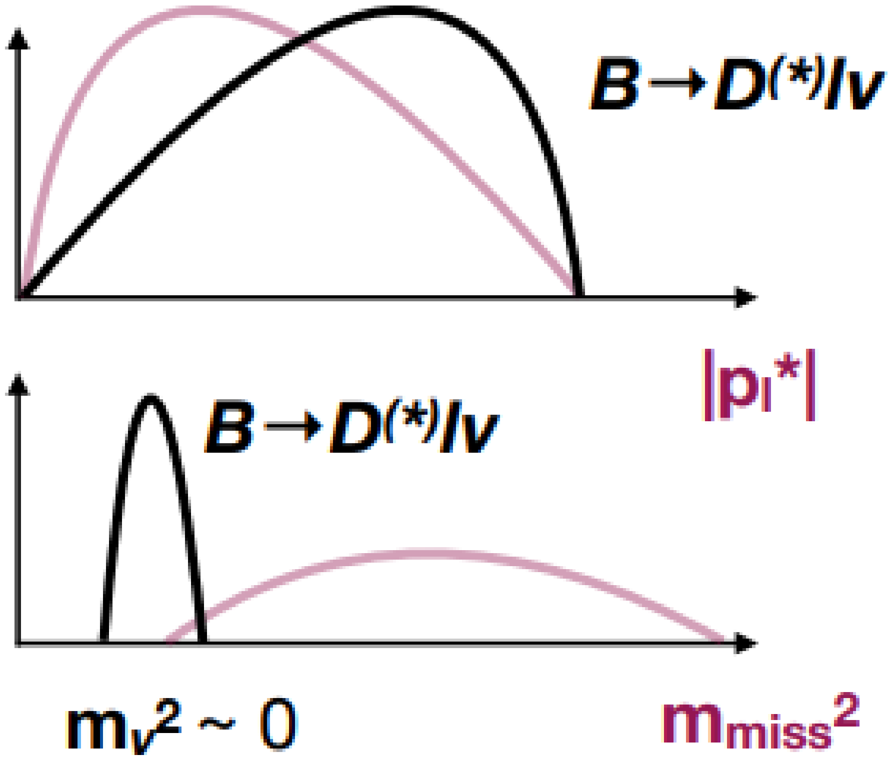

BaBar measurement of $R(D^{(*)})$

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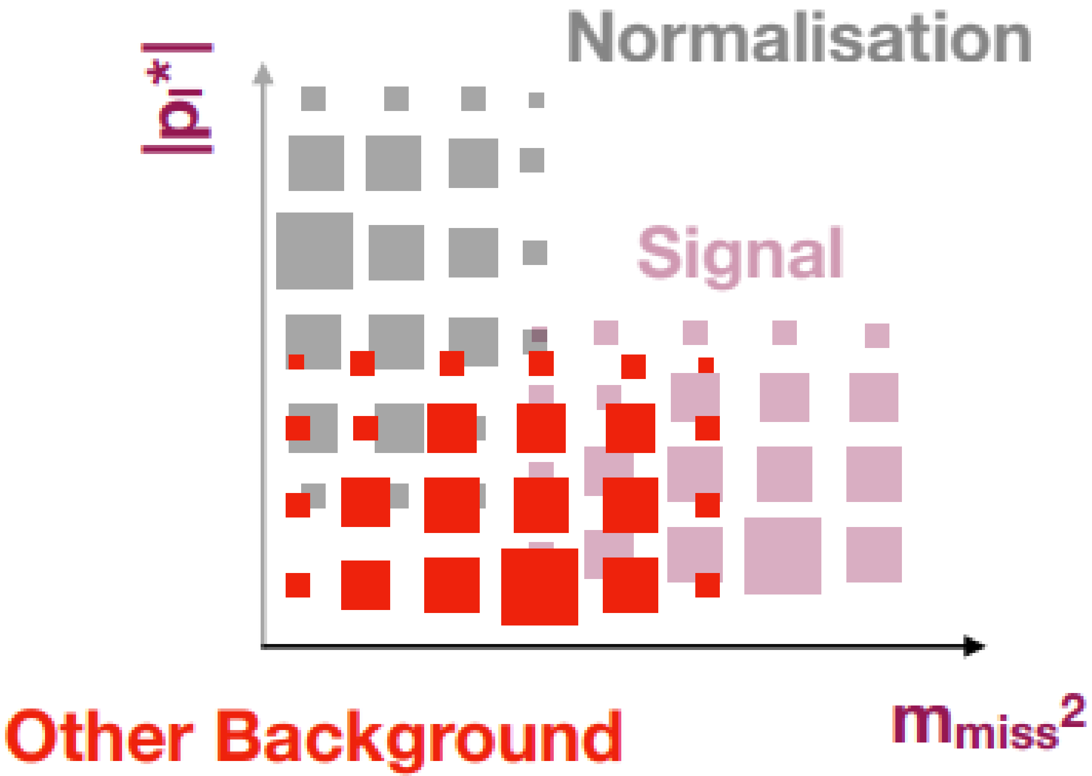
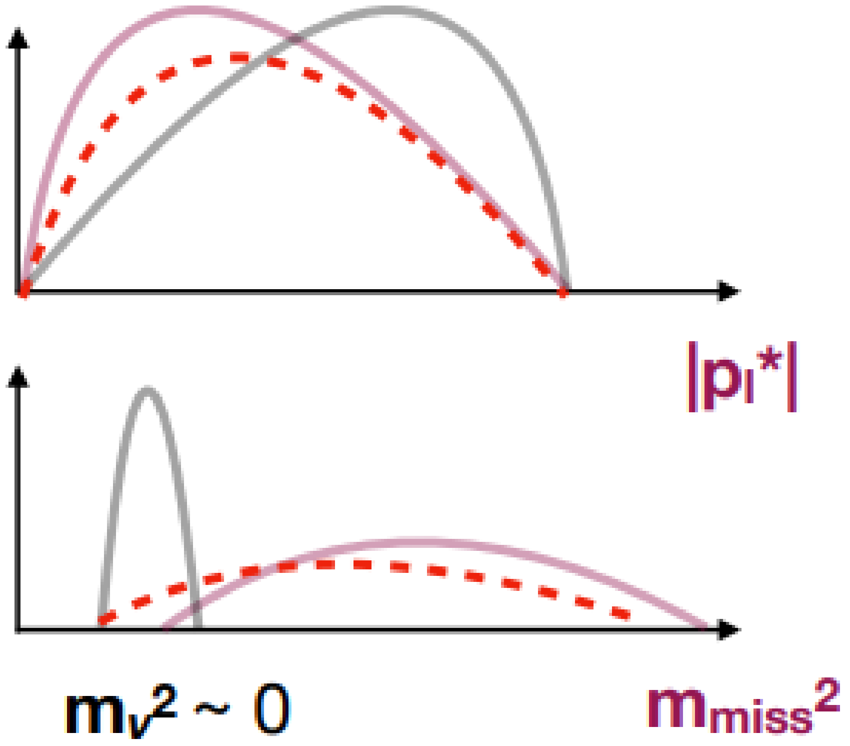
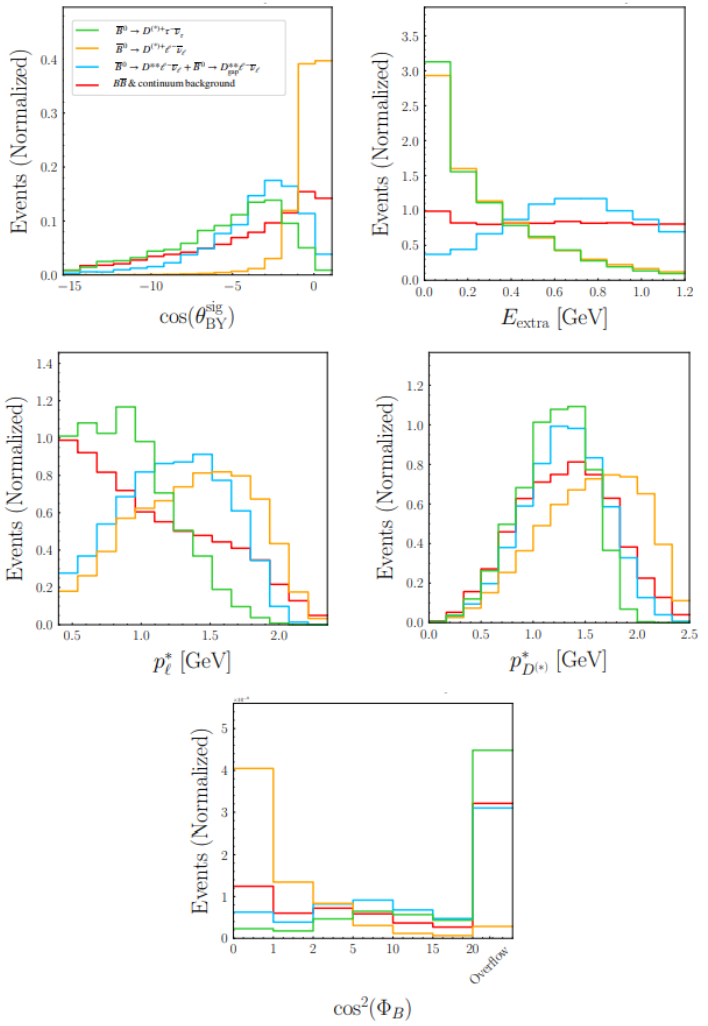
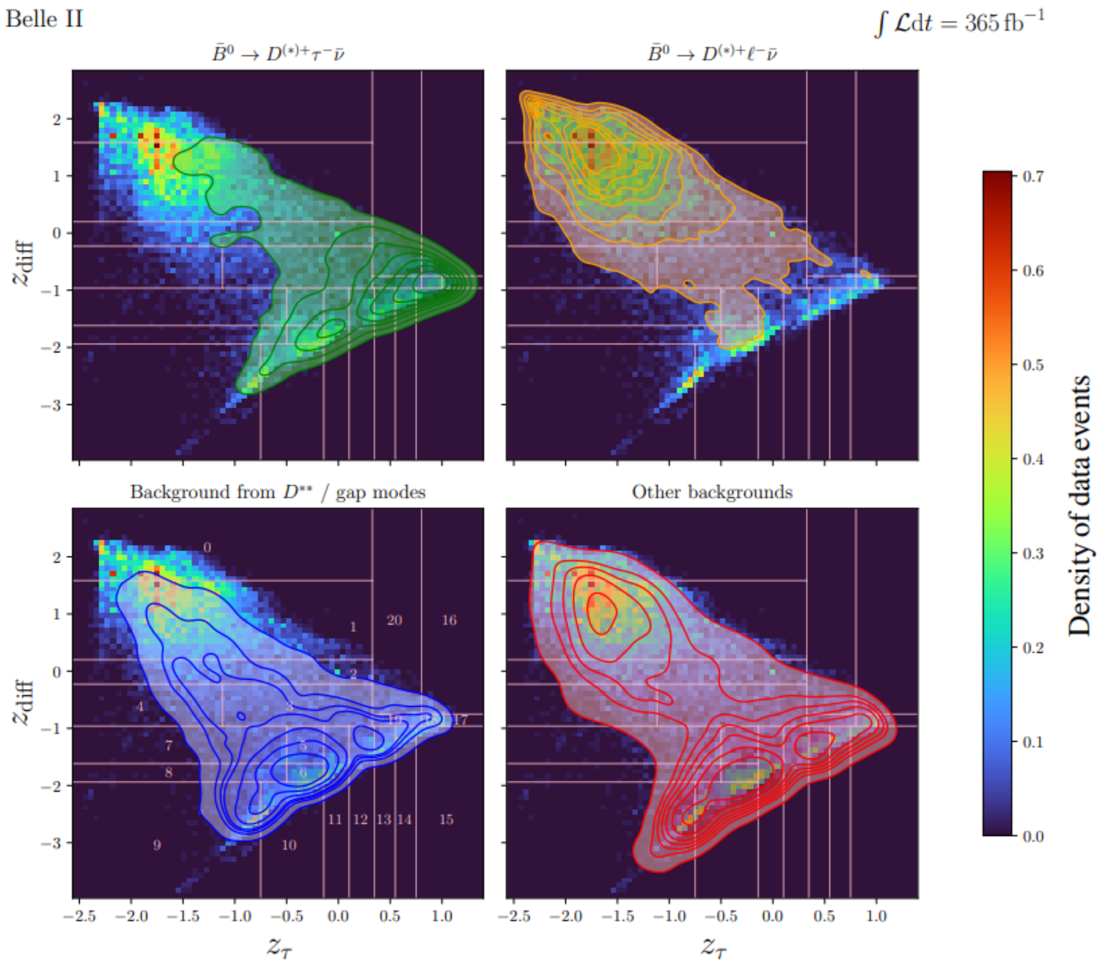




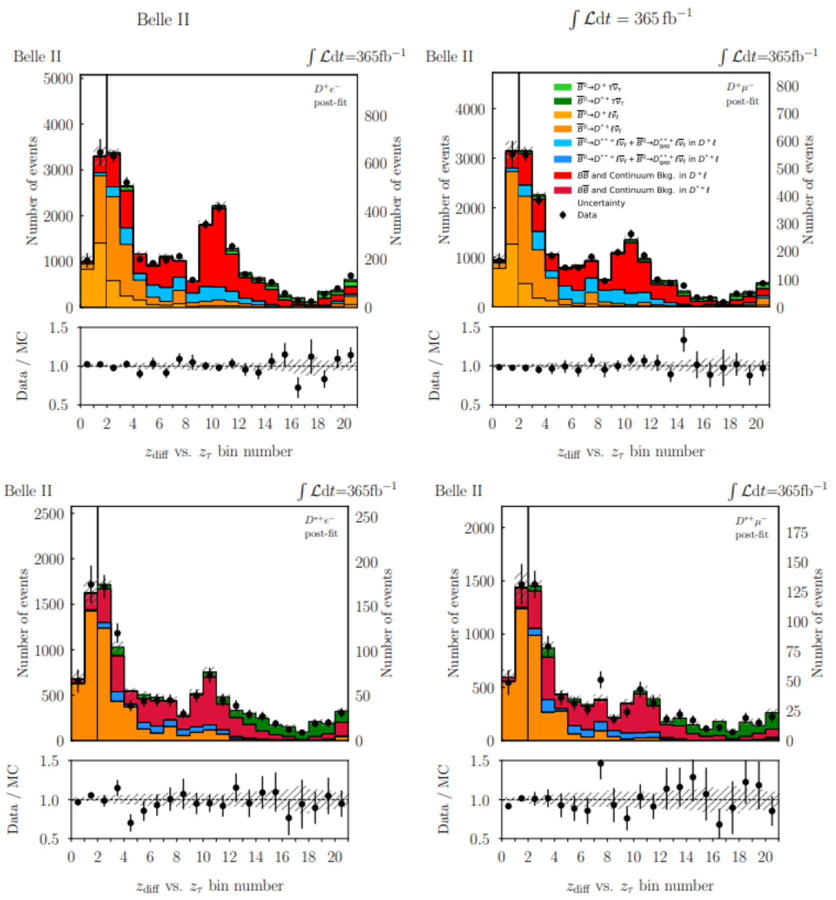
3-class classification at Belle II

Here: Semileptonic tag side, leptonic tau decays

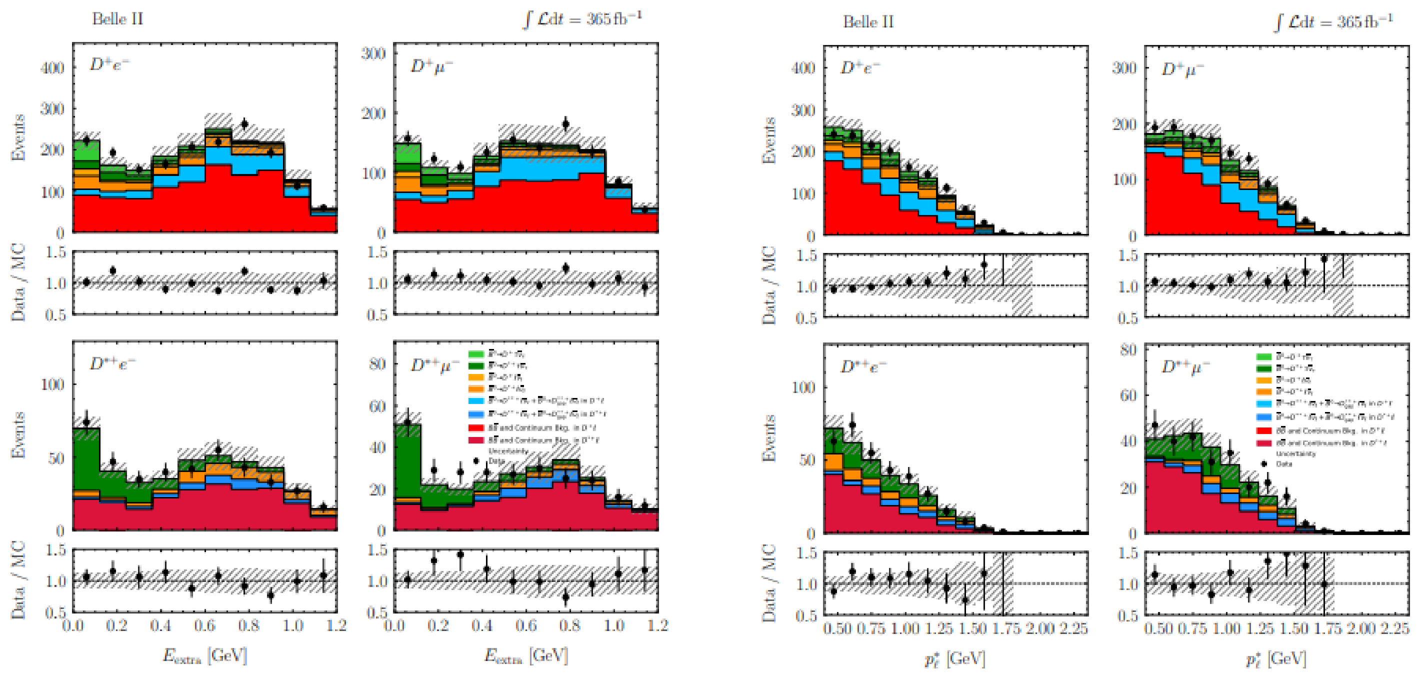




3-class classification in practice

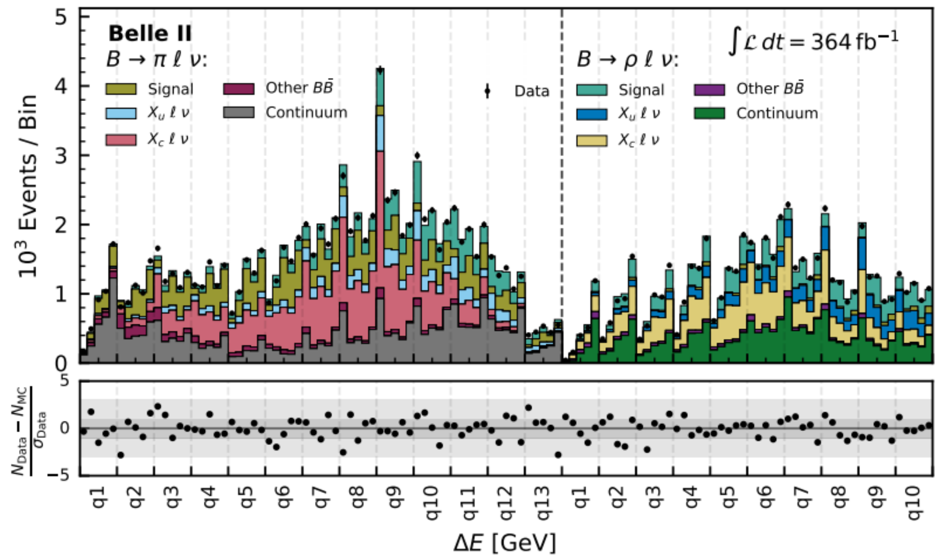


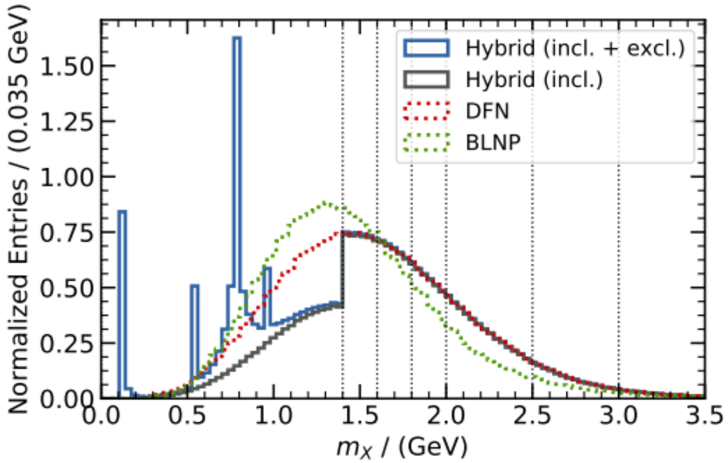
Signal enriched region

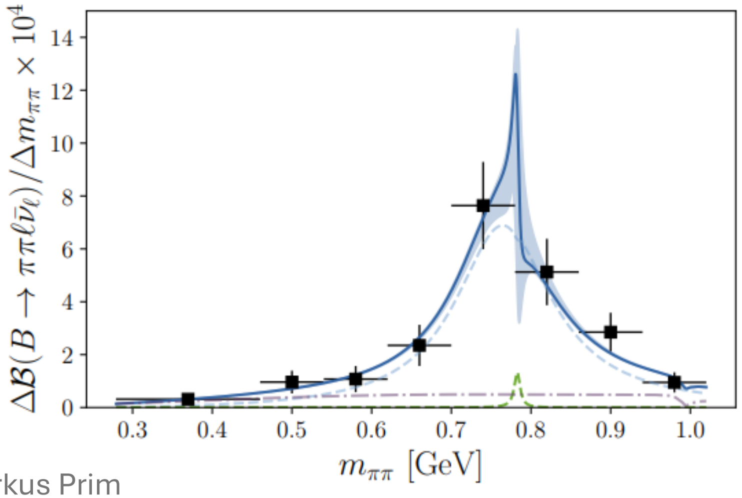


Only a glance at $b \to u\ell\bar{\nu}_\ell$

- $b \to u\ell\bar{\nu}_\ell$ are underrepresented in this talk, but equally important!
  - $B \to \pi\ell\bar{\nu}_\ell, B \to \rho\ell\bar{\nu}_\ell, B \to \omega\ell\bar{\nu}_\ell$
- Most of the things can be directly applied to $b \to u\ell\bar{\nu}_\ell$ decays, except one must manage the $b \to c\ell\bar{\nu}_\ell$ background, which is much more abundant due to $\left|\frac{V_{ub}}{V_{cb}}\right| \ll 1$
- Gap problem does not exist in $b \to u\ell\bar{\nu}_\ell$, but
  - we must construct the so-called hybrid MC
  - Consider the $\rho - \omega$ interference







Take-aways

Key variables

- M_{miss}^2
- $\cos\theta_{BY}$
- E_{ECL} (when analyzing τ)

Common problems / systematics

- Modelling:
  - Gap, Resonances ($b \to c\ell\bar{\nu}_\ell$)
  - Hybrid MC, Interference ($b \to u\ell\bar{\nu}_\ell$)
- MC statistics when using tag-side reconstruction
- Particle identification

Thanks for listening!

Time for question ☺

$\bar{B} \to D^*\ell\bar{\nu}_\ell$ Channels and the slow pion

$\bar{B}^0 \to D^{*+}(\to D^0\pi_s^+, D^+\pi_s^0)\ell\bar{\nu}_\ell$

$B^- \to D^{*0}(\to D^0\pi_s^0)\ell\bar{\nu}_\ell$