

# Summary of Heavy Flavors and the CKM Matrix Track

Frank Meier

on behalf of the conveners Rafael Silva Coutinho (Syracuse), Frank Meier (Duke),  
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15th Conference on the Intersections of Particle and Nuclear Physics  
9 – 13 June 2025



Research supported by



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# Heavy Flavors and the CKM Matrix

- ▶ wide range of topics that could be covered
  - ▶ Decays, mixings, lifetimes, and CP asymmetries of charmed and b-flavored hadrons
  - ▶ QCD, Hadron Spectroscopy, and Exotics
  - ▶ QCD calculations that aid in the determination of the CKM matrix
  - ▶ Interpretations of non-standard model effects and extensions
  - ▶ BES3, CLEO, BaBar and Belle results
  - ▶ LHC flavor physics results
  - ▶ Rare decays
  - ▶ Lattice QCD calculations of heavy quark physics
  - ▶ BSM contributions to flavor physics
- ▶ at CIPANP 2021: 10 talks in parallel sessions and 8 more in joint sessions with High Intensities track
- ▶ at CIPANP 2025: only one parallel session with two presentations: one by ATLAS, one by Belle II
- ▶ what happened?
  - ▶ had invited contributions from ALICE, BaBar, BES III, CMS, LHCb as well as several theorists
  - ▶ received feedback that experiments have difficulty to find speakers willing to come to the US
  - ▶ competing conferences: 23rd FPCP (Flavor Physics and CP Violation) last week in Cincinnati and 30th International Workshop on Weak interactions and Neutrinos this week in Sussex, UK



Differential cross-section measurements of  $D^\pm$  and  $D_s^\pm$  meson production in proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector

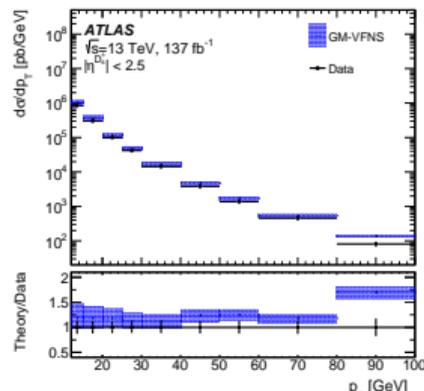
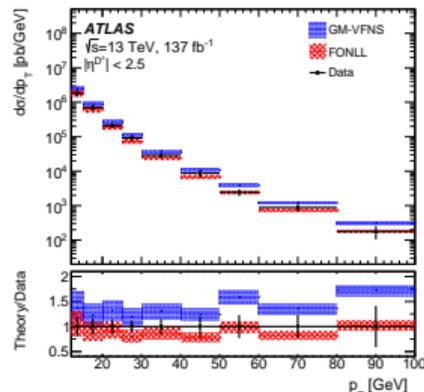
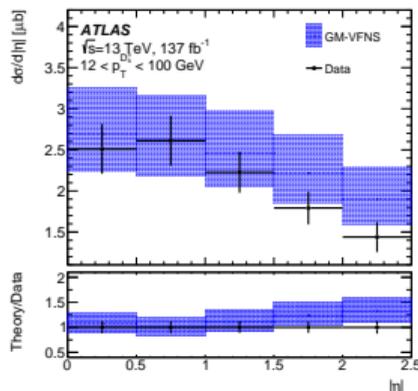
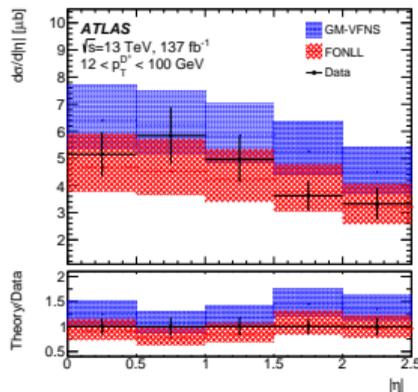
arXiv:2412.15742 (submitted to JHEP)

# Production cross-section of $D^\pm$ and $D_s^\pm$

Andrew Gentry  
(University of New Mexico)



- Good agreement for both models at low  $p_T$  for  $D^\pm$ , GM-VFNS is higher at high  $p_T$
- Only GM-VFNS available for  $D_s^\pm$ , predicts higher value throughout, increasing with  $p_T$

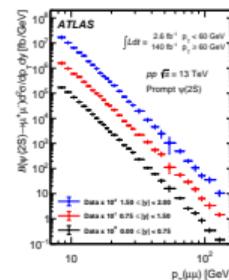
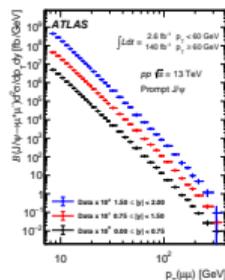


$D^\pm$

$D_s^\pm$

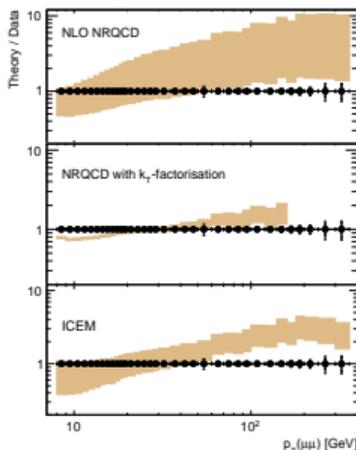
Measurement of the production cross section of  $J/\psi$   
and  $\psi(2S)$  mesons in pp collisions at  $\sqrt{s} = 13$  TeV  
with the ATLAS detector

EPJC 84, 169 (2024)

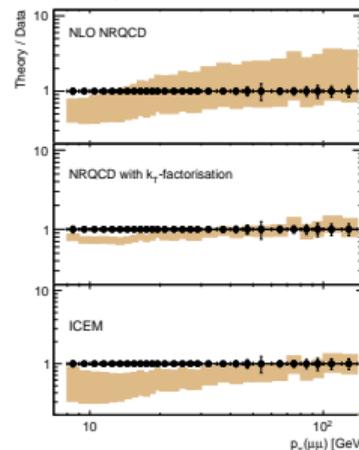


- Comparisons made to theory for prompt production w/ 3 different models
- Generally good agreement, at low  $p_T$  worse at high  $p_T$  for  $J/\psi$
- Some underestimation at low  $p_T$  for  $\psi(2S)$

**ATLAS**  
 $pp \sqrt{s} = 13 \text{ TeV}$   $\int L dt = 2.6 \text{ fb}^{-1}$   $p_T < 60 \text{ GeV}$   
 $0 \leq |y| < 0.75$   $140 \text{ fb}^{-1}$   $p_T \geq 60 \text{ GeV}$   
 Prompt  $J/\psi$



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 Prompt  $\psi(2S)$

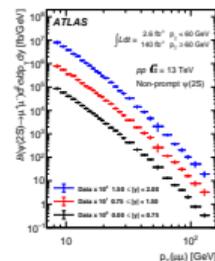
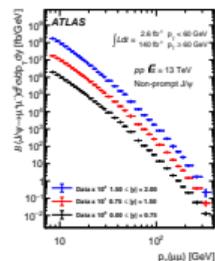


# Non-prompt results



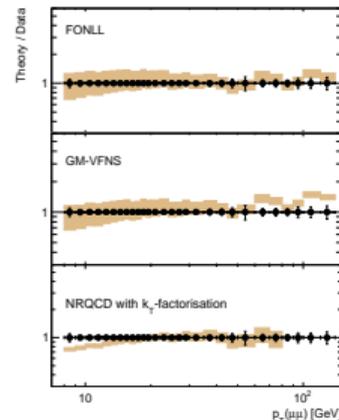
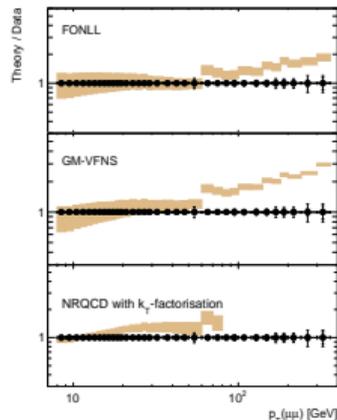
Andrew Gentry  
(University of New Mexico)

- Similar results for non-prompt cross section
- Larger divergence at high- $p_T$  for  $J/\psi$



ATLAS  
 $pp \sqrt{s} = 13 \text{ TeV}$   $\int L dt = 2.6 \text{ fb}^{-1}$   $p_T < 60 \text{ GeV}$   
 $0 \leq |y| < 0.75$   $140 \text{ fb}^{-1}$   $p_T \geq 60 \text{ GeV}$   
Non-prompt  $J/\psi$

ATLAS  
 $pp \sqrt{s} = 13 \text{ TeV}$   $\int L dt = 2.6 \text{ fb}^{-1}$   $p_T < 60 \text{ GeV}$   
 $0 \leq |y| < 0.75$   $140 \text{ fb}^{-1}$   $p_T \geq 60 \text{ GeV}$   
Non-prompt  $\psi(2S)$



# Precision measurement of the $B^0$ meson lifetime using $B^0 \rightarrow J/\psi K^{*0}$ decays with the ATLAS detector

arXiv:2411.09962 (accepted by EPJC)

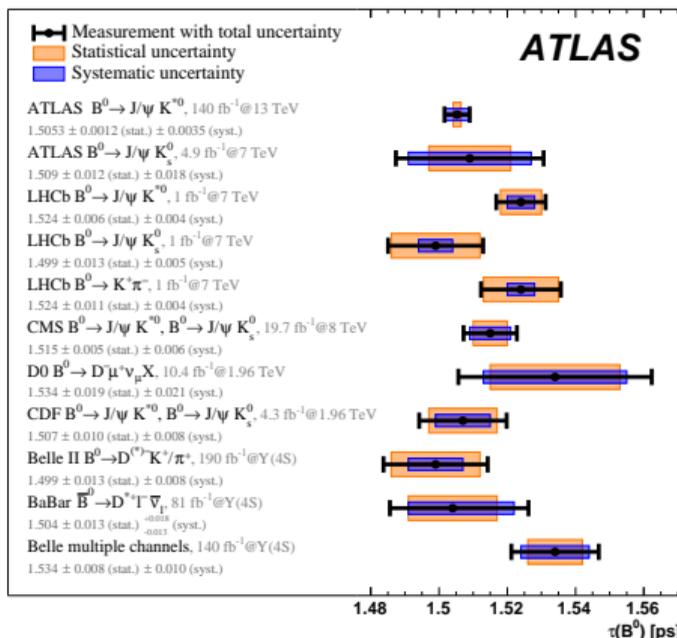
# $B^0$ lifetime with $B^0 \rightarrow J/\psi K^{*0}$



$$\tau_B^0 = 1.5053 \pm 0.0012(\text{stat.}) \pm 0.0035(\text{syst.})\text{ps}$$

$$\Gamma_d = 0.6639 \pm 0.0005(\text{stat.}) \pm 0.0016(\text{syst.}) \pm 0.0038(\text{ext.})\text{ps}^{-1}$$

$$\frac{\Gamma_d}{\Gamma_s} = 0.9905 \pm 0.0022(\text{stat.}) \pm 0.0036(\text{syst.}) \pm 0.0057(\text{ext.})$$



- External uncertainty comes from HFLAV uncertainties from parameters used in the  $\Gamma$  calculations
- Previous ATLAS measurement of  $\Gamma_s$  was used
- This measurement is the most precise to date, compatible with theory and previous measurements

Model	$\Gamma_d/\Gamma_s$
HQE	1.003 ± 0.006
Lattice QCD	1.00 ± 0.02

# Cabibbo-Kobayashi-Maskawa matrix

- ▶ Mass eigenstates  $\neq$  eigenstates of weak interaction
- ▶ Superposition described via complex CKM matrix
- ▶ Quark transition proportional to matrix elements
- ▶ Irreducible phase of CKM matrix = source of  $CP$  violation
- ▶ Unitarity of CKM matrix:

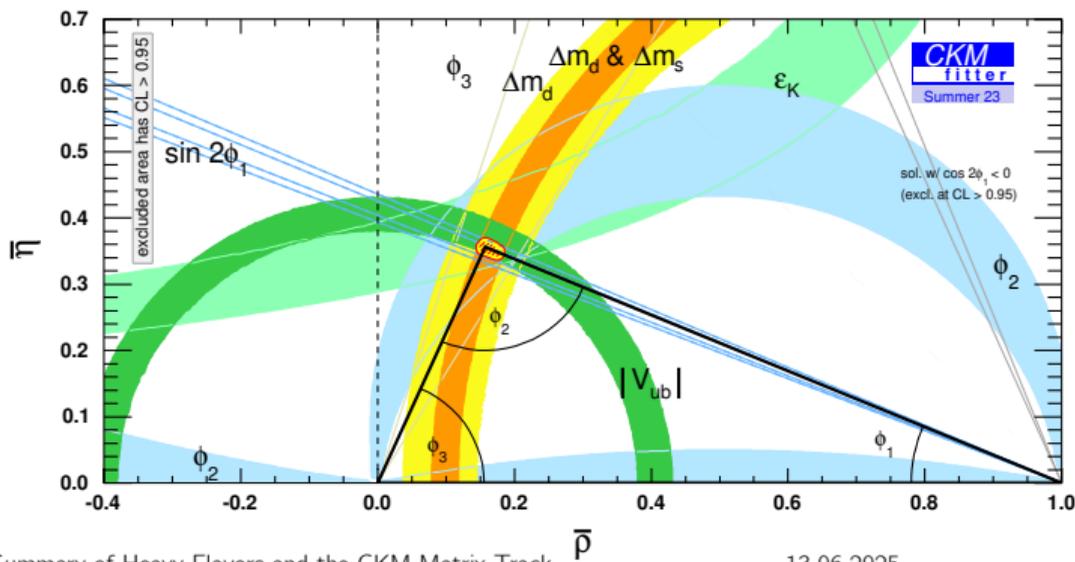
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$\phi_1 = \beta \equiv \arg \left( -\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right)$$

$$\phi_2 = \alpha \equiv \arg \left( -\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*} \right)$$

$$\phi_3 = \gamma \equiv \arg \left( -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right)$$



# Determination of $|V_{cb}|$ using $B \rightarrow \bar{D}\ell^+\nu_\ell$ Decays at Belle II

to be submitted to PRD

# Concept

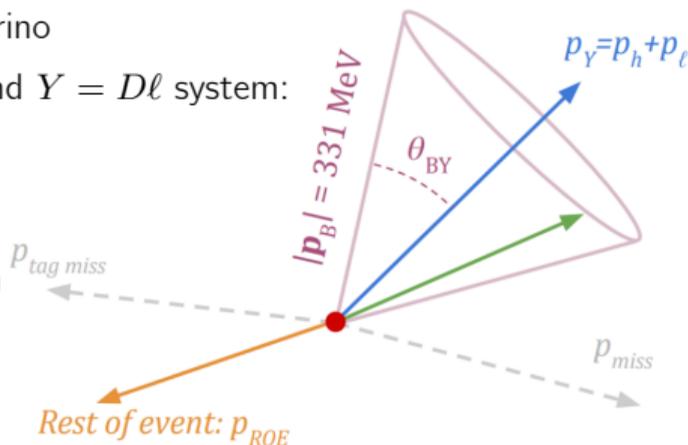
- ▶ Differential measurement of  $B \rightarrow \bar{D}\ell^+\nu_\ell$  decay width as a function of recoil variable  $w = \frac{m_B^2 + m_D^2 - q^2}{2m_B m_D}$
- ▶  $w$  boundaries
  - ▶  $w_{\min} = 1$  for  $D$  at rest in  $B$  rest frame
  - ▶  $w_{\max} = \frac{m_B^2 + m_D^2}{2m_B m_D} \approx 1.59$  for lepton at rest in  $B$  rest frame

$$\frac{d\Gamma(B \rightarrow \bar{D}\ell^+\nu_\ell)}{dw} \propto (w - 1)^{3/2} \eta_{EW}^2 (1 + \delta_C^{+,0}) \mathcal{G}^2(w) |V_{cb}|^2$$

- ▶ Reconstruction of  $w$  challenging because of undetected neutrino
- ▶ Weighted average over multiple configurations on cone around  $Y = D\ell$  system:

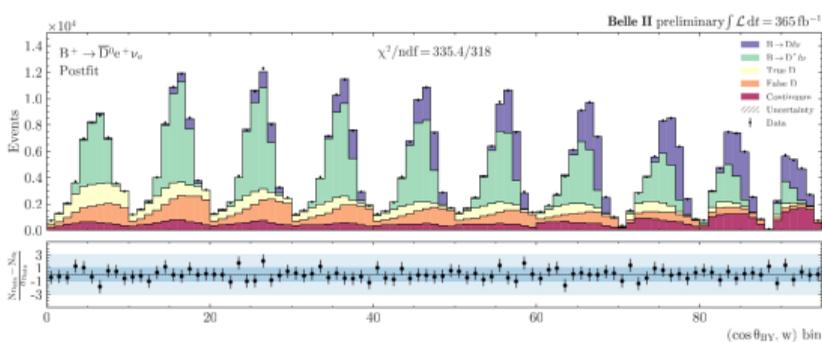
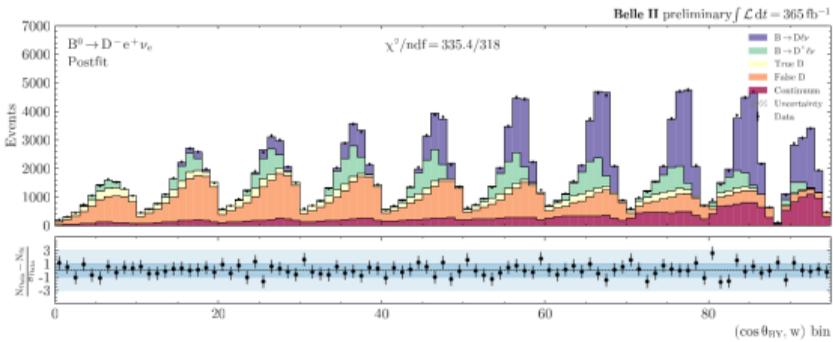
$$\cos \theta_{BY} = \frac{2E_{\text{beam}} E_Y - m_B^2 - m_Y^2}{2|\vec{p}_B||\vec{p}_Y|}$$

- ▶ Using weights  $\frac{1}{2}(1 - \hat{p}_B^* \cdot \hat{p}_{ROE}^*) \sin^2 \theta_B^*$ 
  - ▶  $\hat{p}_{ROE}^*$ : unit vector in CM frame of sum of all particles in event not used in  $Y$  reconstruction
  - ▶  $\theta_B^*$ : angle in CM frame of  $B$  meson wrt beam axis



# Signal extraction

- ▶ Maximum likelihood fit to 10 bins of  $\cos\theta_{BY}$  in range  $[-4, 2]$
- ▶ Simultaneously extract signal yield in 10 equidistant  $w$  bins for neutral and charged modes
- ▶ Fit templates from MC for five components:
  - ▶  $B \rightarrow \bar{D}\ell^+\nu_\ell$  signal
  - ▶ Feed-down background from  $B \rightarrow \bar{D}^*\ell^+\nu_\ell$
  - ▶ Combinatorial background with correctly reconstructed  $D$  meson
  - ▶ Combinatorial background with fake  $D$  meson
  - ▶ Continuum background

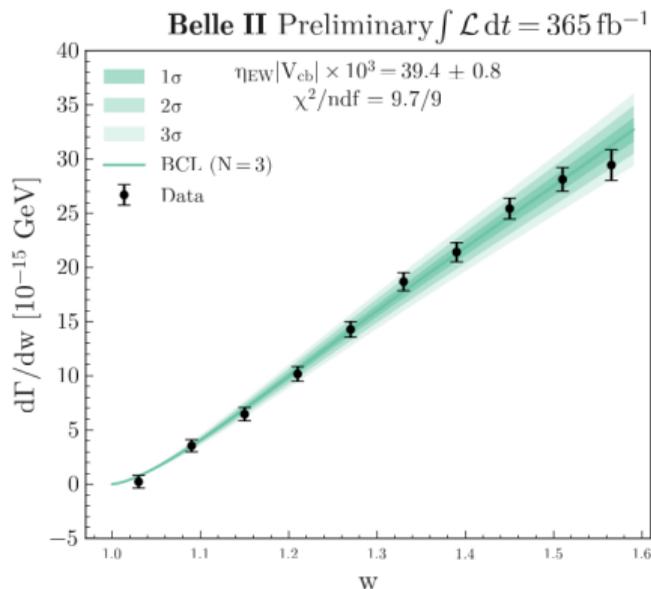


- ▶ Signal yield converted to differential decay width via 
$$\frac{\Delta\Gamma_i}{\Delta w} = \frac{N_i}{N_B \mathcal{B}(D) \varepsilon_i \tau_B (1 + \delta_C^{+,0}) \Delta w}$$

# Determination of $|V_{cb}|$

- ▶ Truncate BCL expansion of vector and scalar form factors at  $N = 3 \rightarrow$  five free parameters
- ▶ Minimize  $\chi^2 = \sum_{i,j}^{10} \left( \frac{\Delta\Gamma_i}{\Delta w} - \frac{\Delta\Gamma_{i,BCL}}{\Delta w} \right) C_{ij}^{-1} \left( \frac{\Delta\Gamma_j}{\Delta w} - \frac{\Delta\Gamma_{j,BCL}}{\Delta w} \right) + \sum_{k,l}^5 (c_k - c_{k,FLAG}) D_{kl}^{-1} (c_l - c_{l,FLAG})$
- ▶ Coefficients of BCL expansion constrained to FLAG average [arXiv:2411.04268] of FNAL/MILC [PRD 92, 034506 (2015)] and HPQCD [PRD 92, 054510 (2015)] calculations of  $B \rightarrow \bar{D}\ell^+\nu_\ell$  form factor

	Values		Correlation Coefficients			
$a_0$	$0.8959 \pm 0.0092$	1	0.26	-0.38	0.95	0.51
$a_1$	$-8.03 \pm 0.15$		1	0.17	0.33	0.86
$a_2$	$49.3 \pm 3.1$			1	-0.31	0.16
$b_0$	$-0.7813 \pm 0.0073$				1	0.47
$b_1$	$-3.38 \pm 0.15$					1



# Results

$$|V_{cb}| = (39.2 \pm 0.4 (\text{stat}) \pm 0.6 (\text{syst}) \pm 0.5 (\text{th})) \times 10^{-3}$$



- ▶ Signal branching fractions from sum over  $w$  bins:

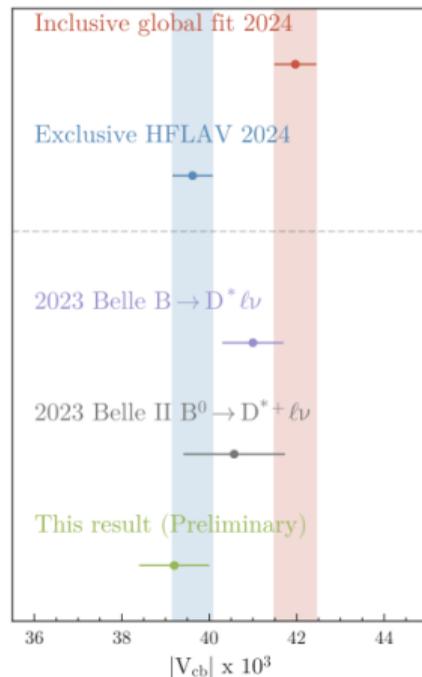
$$\mathcal{B}(B^0 \rightarrow D^- \ell^+ \nu_\ell) = (2.06 \pm 0.05 (\text{stat}) \pm 0.10 (\text{syst}))\%$$

$$\mathcal{B}(B^+ \rightarrow \bar{D}^0 \ell^+ \nu_\ell) = (2.31 \pm 0.04 (\text{stat}) \pm 0.09 (\text{syst}))\%$$

$$\text{WA: } 2.12 \pm 0.06\% (B^0 \rightarrow D^- \ell^+ \nu_\ell) / 2.21 \pm 0.06\% (B^+ \rightarrow \bar{D}^0 \ell^+ \nu_\ell)$$

- ▶ Test of lepton flavor universality:

$$\frac{\mathcal{B}(B \rightarrow \bar{D} e^+ \nu_e)}{\mathcal{B}(B \rightarrow \bar{D} \mu^+ \nu_\mu)} = 1.020 \pm 0.020 (\text{stat}) \pm 0.022 (\text{syst})$$

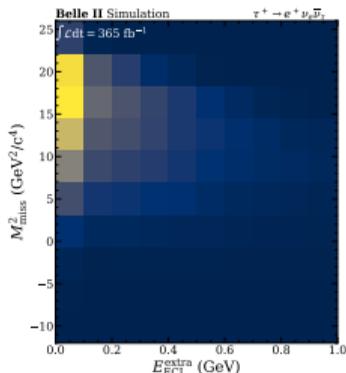


# Measurement of $B^+ \rightarrow \tau^+ \nu_\tau$ branching ratio with a hadronic tagging method at Belle II

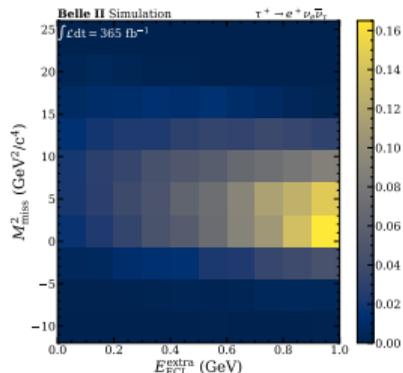
arXiv:2502.04885 (submitted to PRD)

# Overview

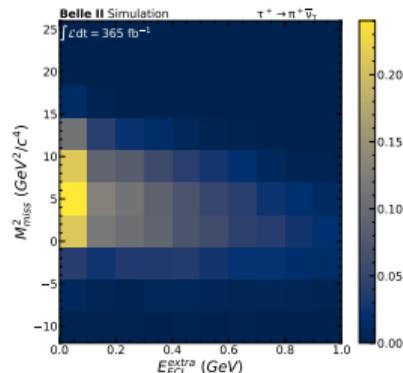
- ▶ In the standard model  $\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau) = \frac{G_F^2 m_B m_\tau^2}{8\pi} \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$
- ▶ Allows direct measurement of  $|V_{ub}|$  independent of exclusive and inclusive semileptonic  $B \rightarrow X_u \ell \nu_\ell$  decays
- ▶ Branching fraction enhanced (or suppressed) in beyond-the-standard-model physics like models with charged Higgs or Higgs Doublet Model
- ▶ Reconstruct  $\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$ ,  $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$ ,  $\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$ , and  $\tau^+ \rightarrow \rho^+ \bar{\nu}_\tau$  (72% of  $\tau$  decay modes covered)
- ▶ Reconstruct other  $B$  meson in hadronic decays using Full Event Interpretation [Comput. Softw. Big Sci. 3 \(2019\)](#)
- ▶ Extract branching fraction from 2D fit to residual energy in calorimeter and missing mass squared



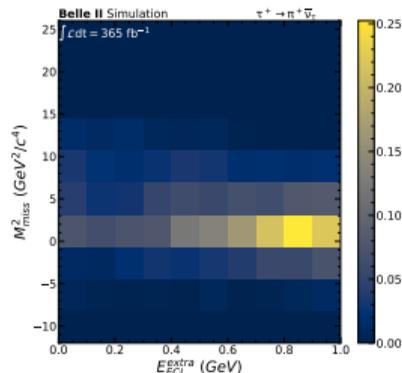
▶ signal e channel



▶ bkg e channel



▶ signal  $\pi$  channel



▶ bkg  $\pi$  channel

# Results

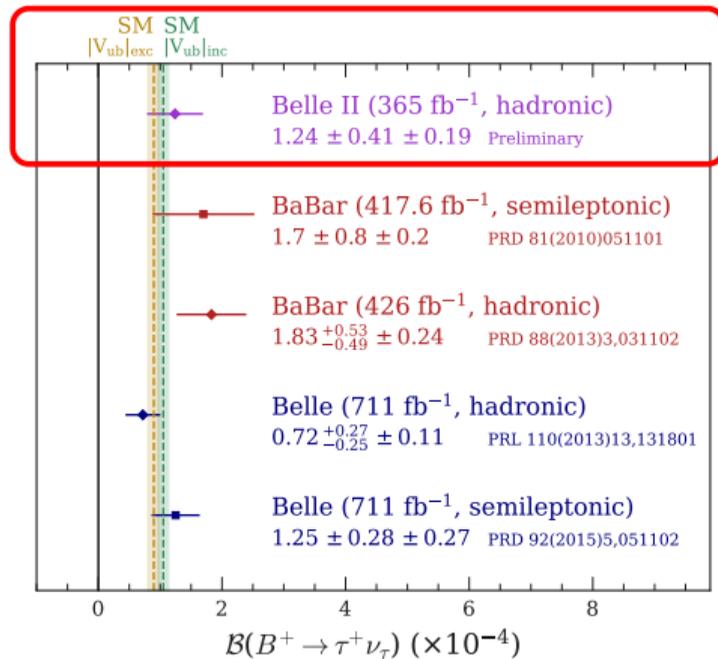


Decay mode	$n_s$	$\mathcal{B}$ ( $10^{-4}$ )
Simultaneous	$94 \pm 31$	$1.24 \pm 0.41$
$e^+ \nu_e \bar{\nu}_\tau$	$13 \pm 16$	$0.51 \pm 0.63$
$\mu^+ \nu_\mu \bar{\nu}_\tau$	$40 \pm 20$	$1.67 \pm 0.83$
$\pi^+ \bar{\nu}_\tau$	$31 \pm 13$	$2.28 \pm 0.93$
$\rho^+ \bar{\nu}_\tau$	$6 \pm 25$	$0.42 \pm 1.82$

- Assuming SM and  $f_B = (190.0 \pm 1.3)$  MeV

$$|V_{ub}|_{B^+ \rightarrow \tau^+ \nu_\tau} = (4.41^{+0.74}_{-0.89}) \times 10^{-3}$$

- $|V_{ub}|_{\text{SM (exclusive)}}: (3.75 \pm 0.06 \pm 0.19) \times 10^{-3}$
- $|V_{ub}|_{\text{SM (inclusive)}}: (4.06 \pm 0.12 \pm 0.11) \times 10^{-3}$



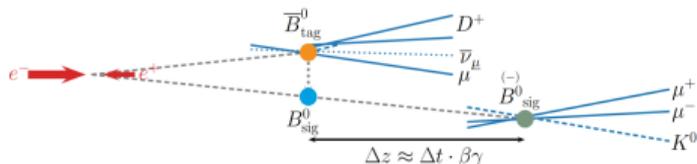
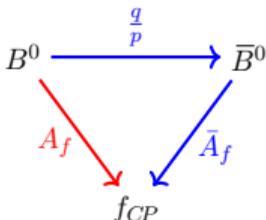
Measurement of the branching fraction, polarization,  
and time-dependent  $CP$  asymmetry in  $B^0 \rightarrow \rho^+ \rho^-$   
decays and constraint on the CKM angle  $\phi_2$

PRD 111, 092001 (2025)

# Time-dependent $CP$ violation measurement

- ▶  $CP$  violation in the interference between

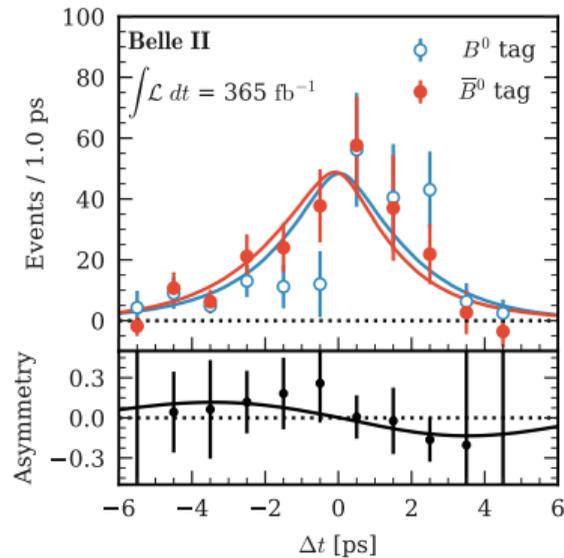
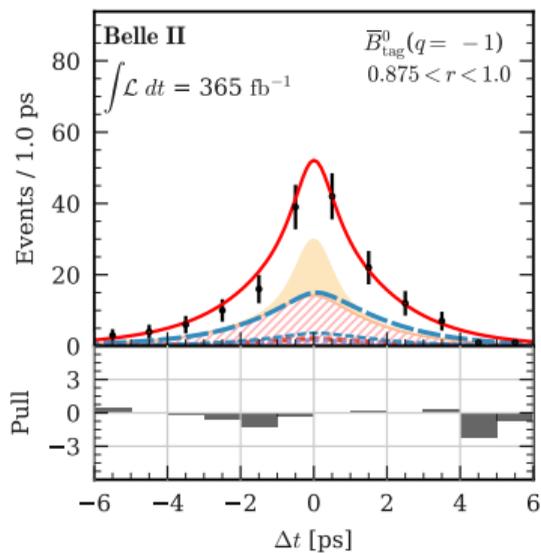
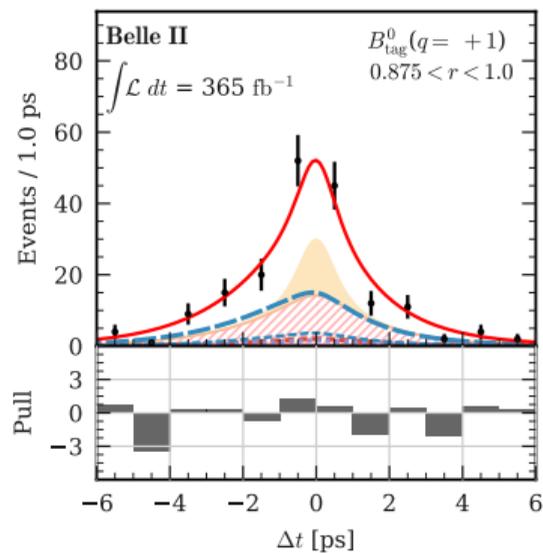
- ▶ direct decay
- ▶ decay after mixing



$$\mathcal{A}(\Delta t) \equiv \frac{\Gamma(\bar{B}^0(\Delta t) \rightarrow f_{CP}) - \Gamma(B^0(\Delta t) \rightarrow f_{CP})}{\Gamma(\bar{B}^0(\Delta t) \rightarrow f_{CP}) + \Gamma(B^0(\Delta t) \rightarrow f_{CP})} = S_f \sin(\Delta m \Delta t) - C_f \cos(\Delta m \Delta t)$$

- ▶ Initial flavor  $\rightarrow$  flavor tagging
  - ▶ Introduces diluting mistag fraction
- ▶ Proper-time difference  $\rightarrow$  reconstruction of distance between  $B_{\text{sig}}$  and  $B_{\text{tag}}$  vertices
  - ▶ Requires description of proper-time resolution, often via per-event uncertainties  $\sigma_{\Delta t}$
- ▶  $CP$  observables  $\rightarrow$  parameters of interest
  - ▶  $S_{b \rightarrow u\bar{u}d} = \sqrt{1 - C^2} \sin(2\phi_2 + \Delta\phi_2)$ : loop amplitude obstructs clean extraction of  $\phi_2$
- ▶ Mixing parameters  $\rightarrow$  from external measurements

# Time-dependent $CP$ -asymmetry fit

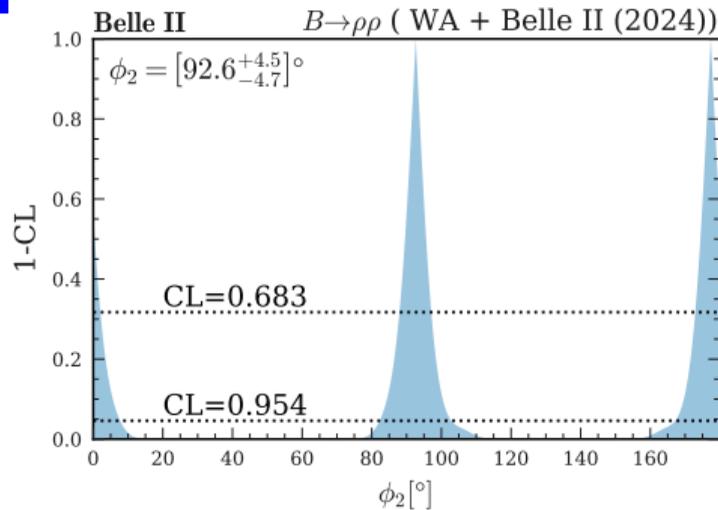
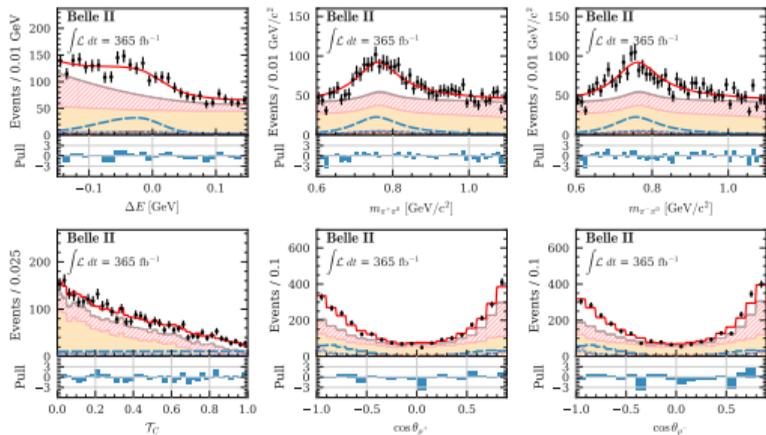


$$S = -0.26 \pm 0.19 \pm 0.08$$

$$C = -0.02 \pm 0.12_{-0.05}^{+0.06}$$



# Results of $B^0 \rightarrow \rho^+ \rho^-$



$$\mathcal{B}(B^0 \rightarrow \rho^+ \rho^-) = \left( 2.89^{+0.23}_{-0.22} (\text{stat})^{+0.29}_{-0.27} (\text{syst}) \right) \times 10^{-5}$$

$$f_L = 0.921^{+0.024}_{-0.025} (\text{stat})^{+0.017}_{-0.015} (\text{syst})$$

- ▶ Combining results from Belle, BaBar, and LHCb of  $B^0 \rightarrow \rho^+ \rho^-$ ,  $B^0 \rightarrow \rho^0 \rho^0$ , and  $B^+ \rightarrow \rho^+ \rho^0$

- ▶ Uncertainty dominated by S parameters of  $B^0 \rightarrow \rho\rho$

- ▶ two solutions, though second excluded by  $\phi_1$ ,  $\phi_3$ , and unitarity

$$\phi_2 = (92.6^{+4.5}_{-4.7})^\circ \quad \Delta\phi_2 = (2.4^{+3.8}_{-3.7})^\circ$$

$$\phi_2 = (177.4^{+4.7}_{-4.5})^\circ \quad \Delta\phi_2 = (-2.4^{+3.7}_{-3.8})^\circ$$

# Conclusion



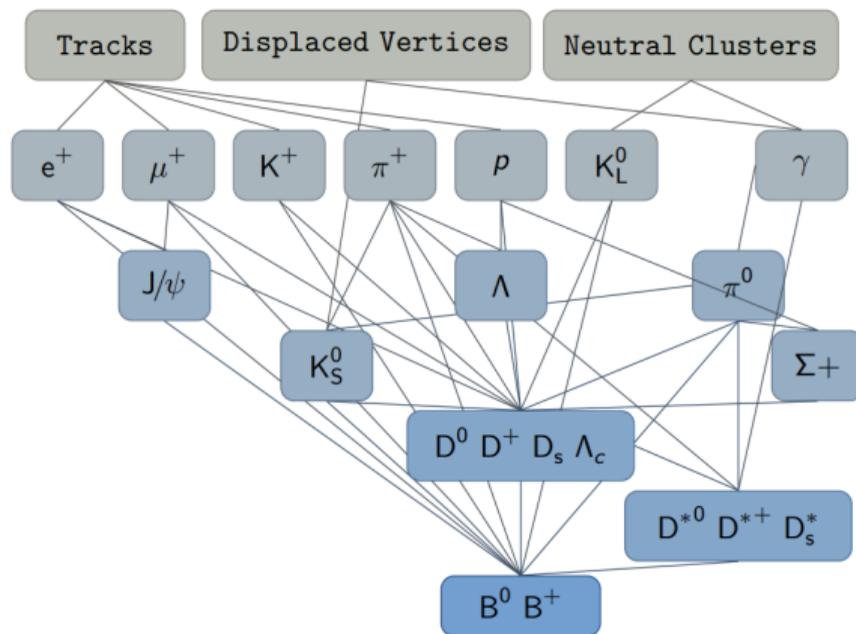
# Backup

# Full Event Interpretation *Comput. Softw. Big Sci.* 3 (2019)

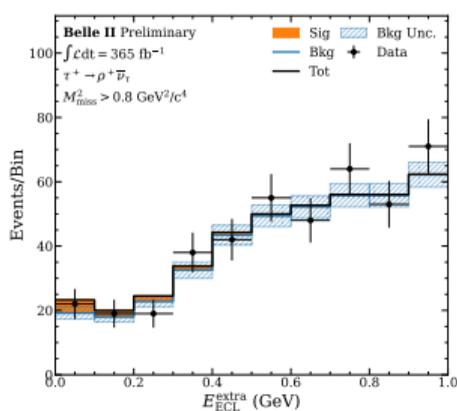
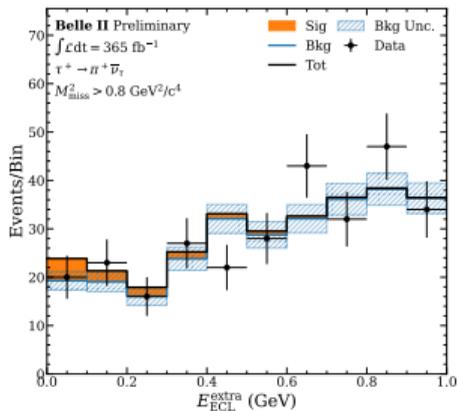
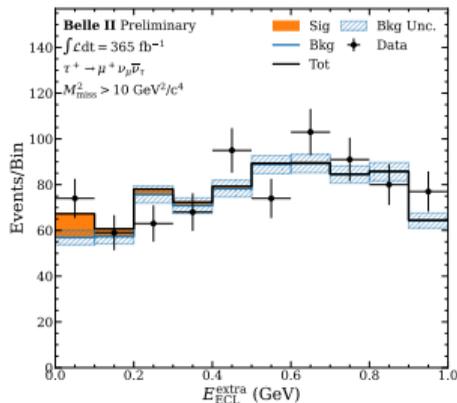
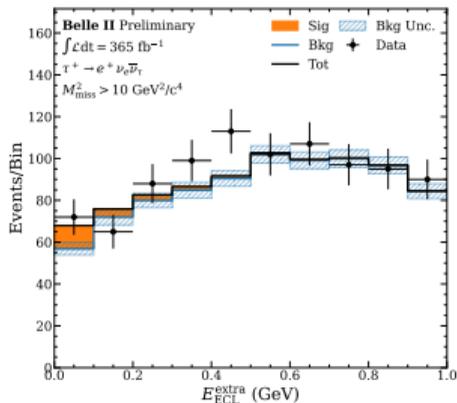
- ▶ Fully reconstruct one of the  $B$  mesons (tag-side) in many exclusive modes
- ▶ Train BDT for each stage  
⇒ signal probability
- ▶ Fraction of  $\Upsilon(4S)$  events with correctly reconstructed charged  $B_{\text{tag}}$  candidate  $\approx 0.30\%$  with purity of 29%
- ▶ Reduce misreconstructed events with requirements on beam-constrained mass  $M_{\text{bc}}$  and energy difference  $\Delta E$

$$M_{\text{bc}} = \sqrt{(E_{\text{beam}}^*)^2 - |\vec{p}_{\text{tag}}^*|^2}$$

$$\Delta E = E_{\text{tag}}^* - E_{\text{beam}}^*$$



# Fit of $B^+ \rightarrow \tau^+ \nu_\tau$



- ▶ Simultaneous binned maximum likelihood fit to all the four  $\tau$  categories
- ▶ Floating parameters in fit:  $\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau)$  and background yields of each category
- ▶ Signal yields related via efficiencies

Source	Syst. (%)
<b>Simulation statistics</b>	<b>13.3</b>
<b>Fit variables PDF corrections</b>	<b>5.5</b>
<b>Decays branching fractions in MC</b>	<b>4.1</b>
Tag $B^-$ reconstruction efficiency	2.2
Continuum reweighting	1.9
$\pi^0$ reconstruction efficiency	0.9
Continuum normalization	0.7
Particle identification	0.6
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Number of produced $\mathcal{T}(4S)$	1.5
Fraction of $B^+B^-$ pairs	2.1
Tracking efficiency	0.2
<hr/>	
Total	15.5