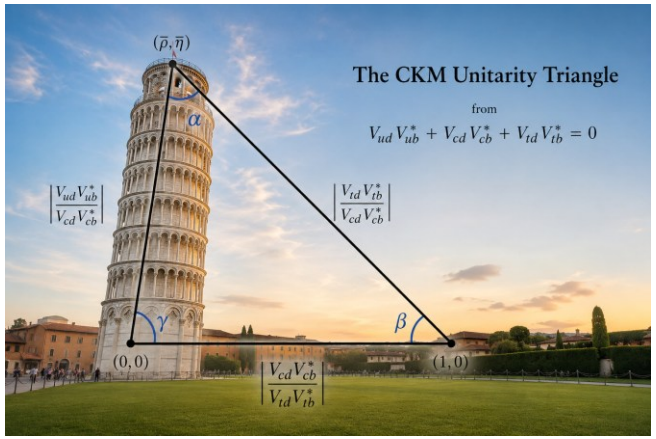
B physics at Belle II
Phi to Psi 2026

Jim Libby on behalf of Belle II

Indian Institute of Technology Madras



Images generated with OpenAI ChatGPT (GPT-5.5) image generation, based on prompts by the author.

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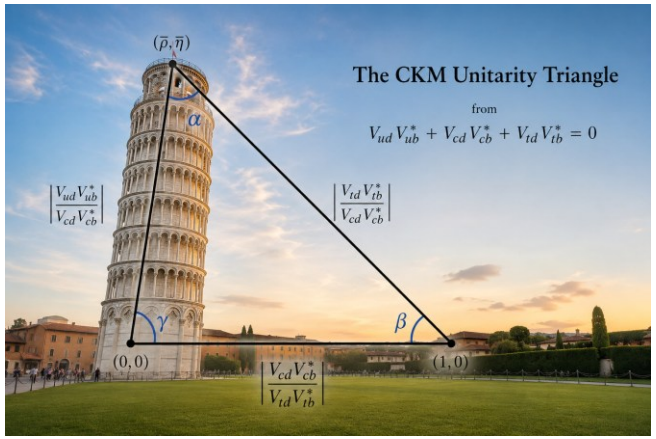

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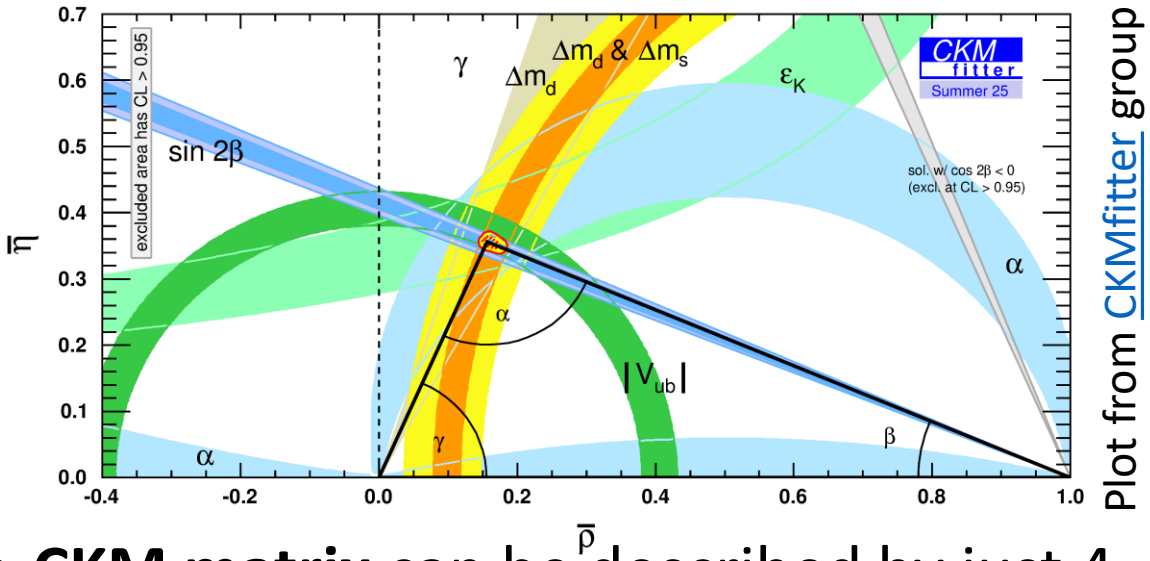
Outline

- *B* physics motivation
  - Cabibbo-Kobayashi-Maskawa (CKM) matrix measurements
  - Indirect searches for beyond-the-standard physics
- BelleII: detector, data set and tools
- Recent highlights
  - Time-dependent CP violation in $B \to \pi^0 \pi^0$
  - Semi-tauonic *B* decay: $B \to D^{(*)} \tau \nu$
  - Electroweak penguin decays: $b \to s \tau \tau$ and $b \to s \nu \nu$
- Conclusion and outlook

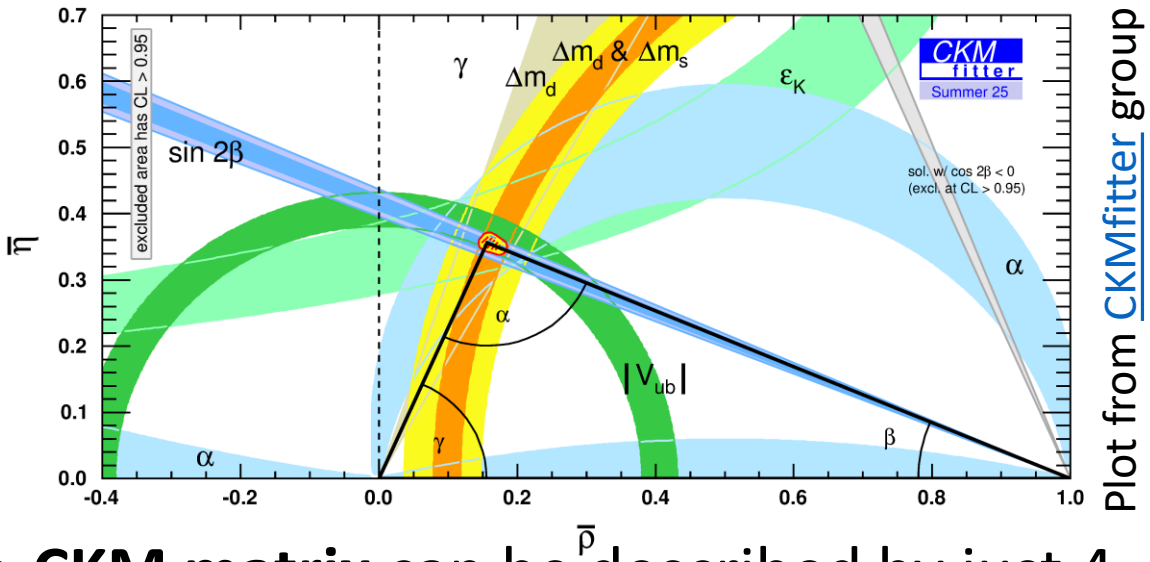
B physics motivation



Plot from CKMfitter group

- **CKM matrix** can be described by just 4 parameters in the standard model (SM) – *A*, λ, ρ and η
  - Unitarity triangles visualize the amount of CP violation
- Many measurements of sides and angles possible in B decay
  - Deviations amongst measurements a sign of beyond-the-SM physics

B physics motivation



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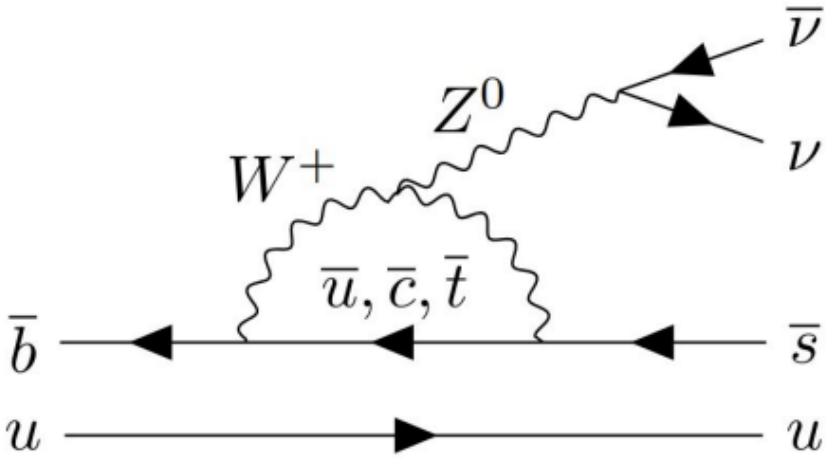
- **Indirect searches for beyond-the-SM physics**
  1. Measurements of lepton universality in semileptonic B decay, e.g., $B \to D^{(*)} \tau \nu$
  2. Searches for rare flavour-changing neutral currents that proceed only at loop level



Why *B* physics at the Υ(4S)?

- The process $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ has comparable cross section to $e^+e^- \to q\bar{q}, q = u, d, s, c$ a.k.a. continuum

Why *B* physics at the Y(4S)?

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- **Advantages compared to proton-proton**
  - Low average multiplicity – neutral reconstruction
  - Constrained kinematics – good missing momentum reconstruction
  - Correlated $B^0\bar{B}^0$ - high flavour-tagging efficiency
  - Open trigger – 100% efficient for almost all *B* decays

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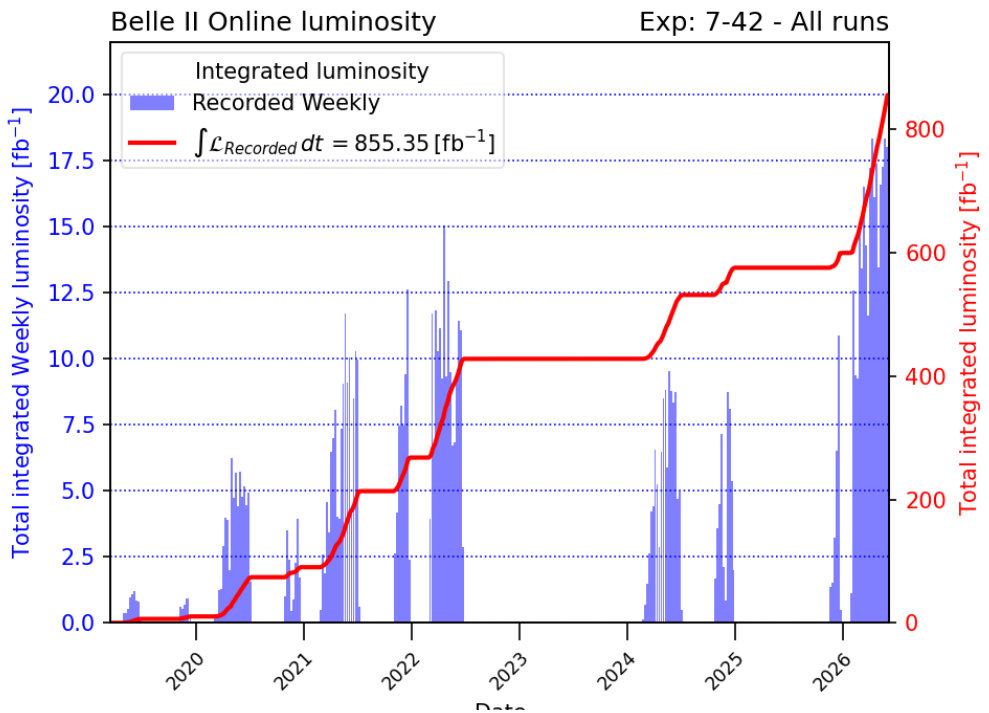
  - Open trigger – 100% efficient for almost all *B* decays
- **Disadvantages compared to proton-proton**
  - **Cross section – 150,000 times smaller**
  - No B_s, B_c, or Λ_b produced
  - No boost in the c.m. frame – **partially overcome by the asymmetric beams**

Data sample and detector

- SuperKEKB and luminosity
  - nanobeam scheme to increase instantaneous luminosity by factor 30 to collect multi-ab^{-1} sample
  - **World record instantaneous luminosity March 2026**
    - **5.2×10^{34} cm^{-2}s^{-1}**
    - Target 6×10^{35} cm^{-2}s^{-1}
  - Run 1 2019-2022
    - 365 fb^{-1} at Y(4S) + 42 fb^{-1} off-resonance to characterize continuum
  - Run 2 2024-
    - + ~500 fb^{-1} so far and exceeded the Belle Y(4S) dataset



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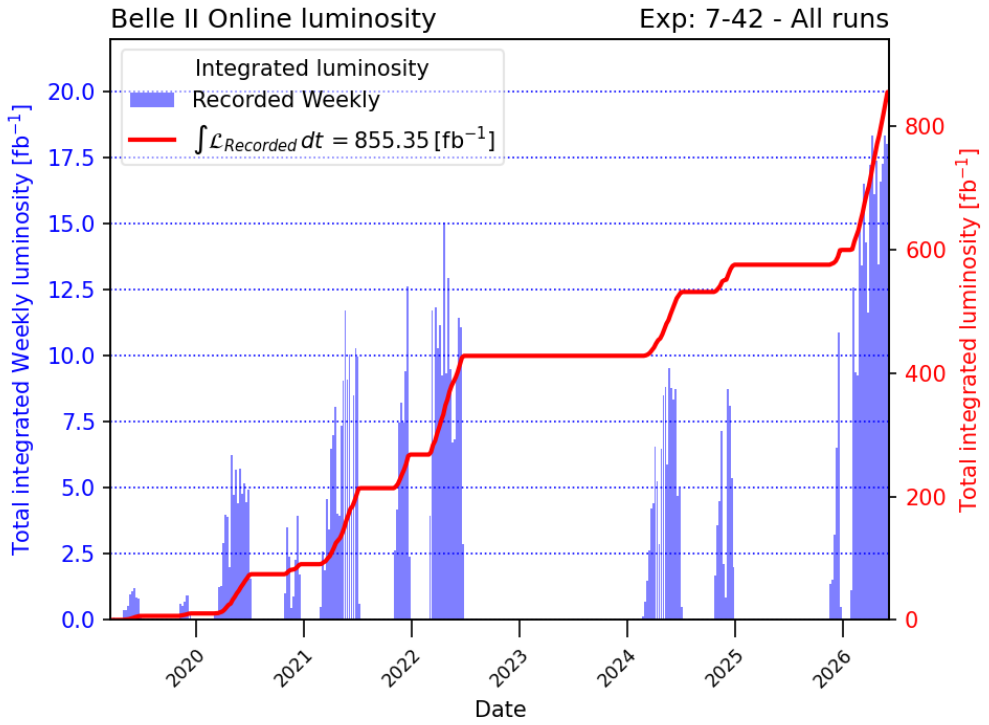
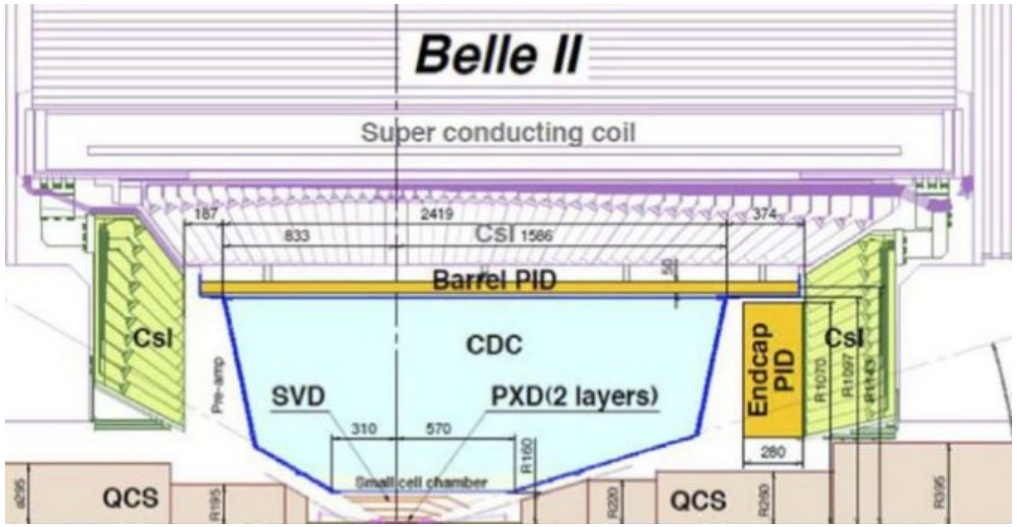
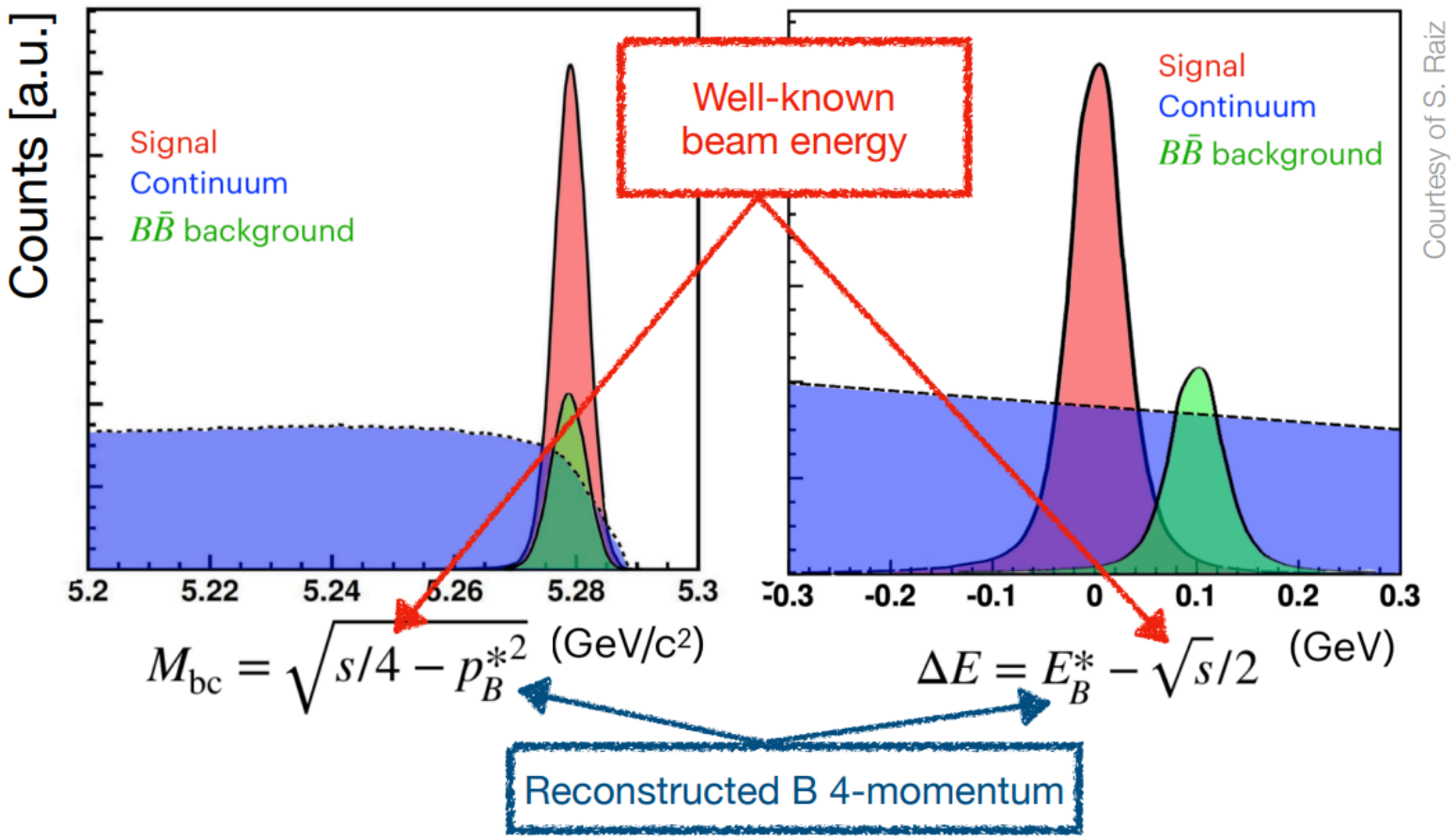
- Belle II detector
  - Si vertexing, low-mass tracking, particle ID, and crystal calorimetry
  - beam-background mitigation key



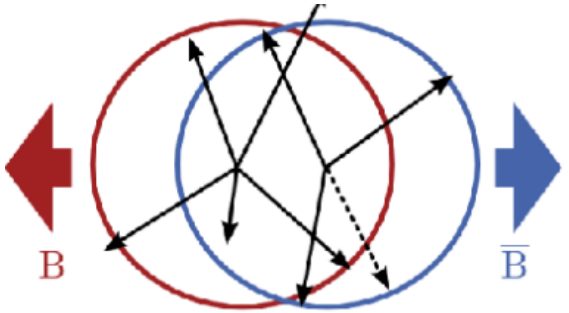


Belle II analysis essentials 1 – beam constrained kinematics

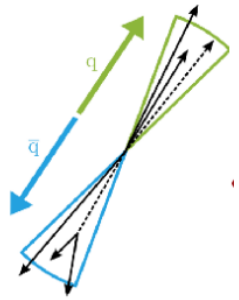


Belle II analysis essentials 2 – continuum suppression

- In the c.m. frame B mesons almost at rest when they decay
  - isotropic distribution of particles
- In the c.m. frame continuum qq back-to-back
  - jetlike distribution of particles



vs.



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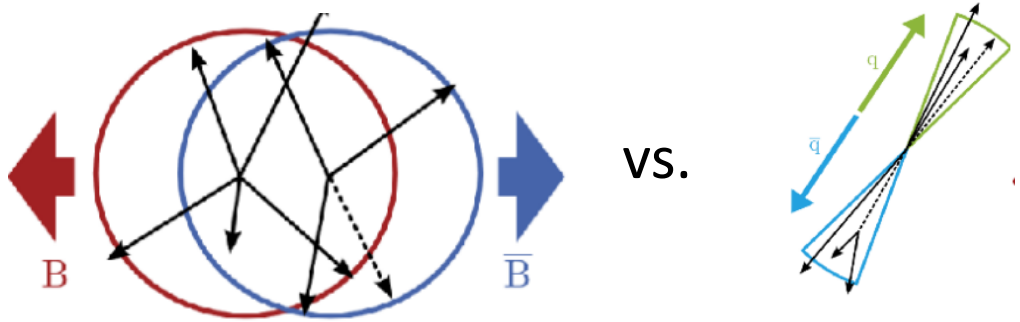
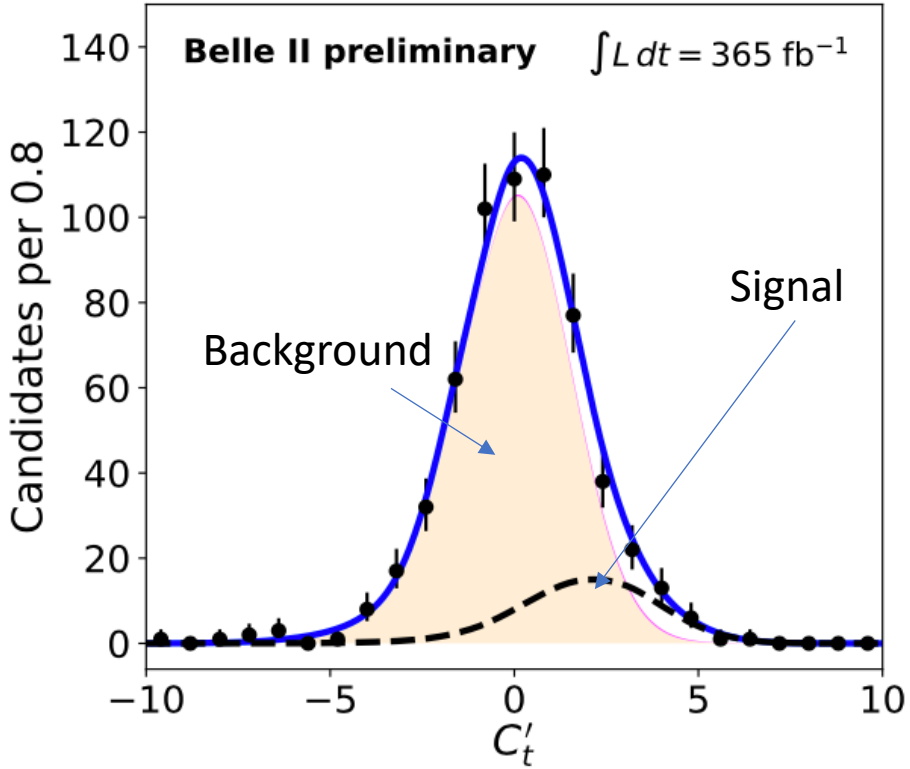
- In the c.m. frame B mesons almost at rest when they decay
  - isotropic distribution of particles
- In the c.m. frame continuum qq back-to-back
  - jetlike distribution of particles
- Shape variables, e.g., thrust and Fox-Wolfram moments, help distinguish topologies
- Ideal task for machine-learning
- Output often used as a fit variable

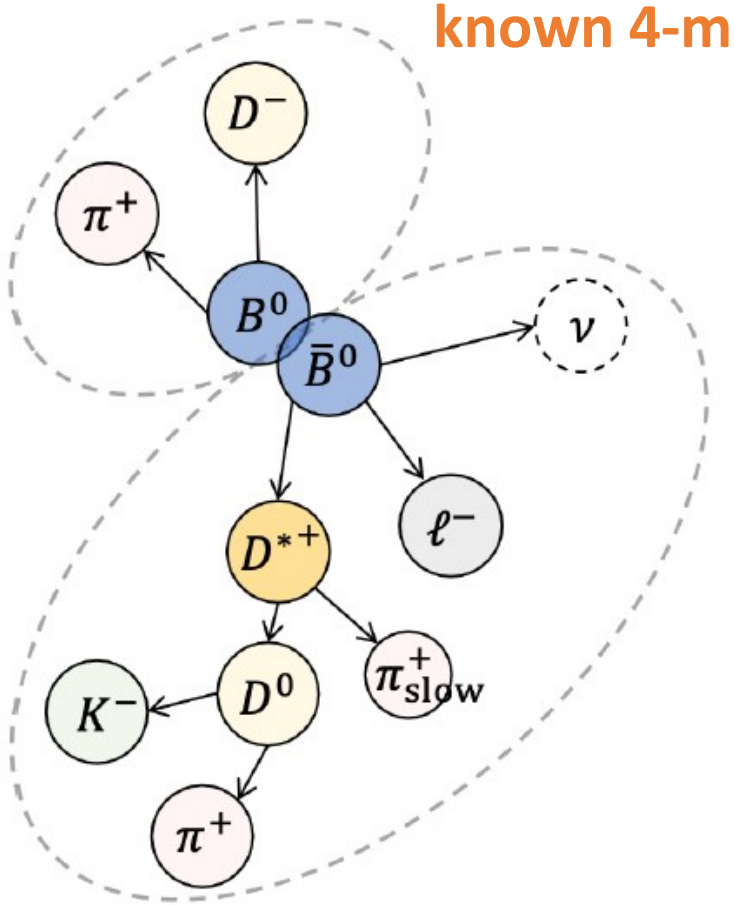




Belle II analysis essentials 3: hadronic tag

- Full-reconstruction of one B decay in a large number of high BF modes on one side
  - $B \rightarrow D^{(*)0}\, m\pi^{\pm} n\pi^{0}$, where $m \geq 1$ $n \geq 0$
- Reconstruct other B as signal with missing energy

B→Dπ tag decay – known 4-momentum



Belle II analysis essentials 3: hadronic tag

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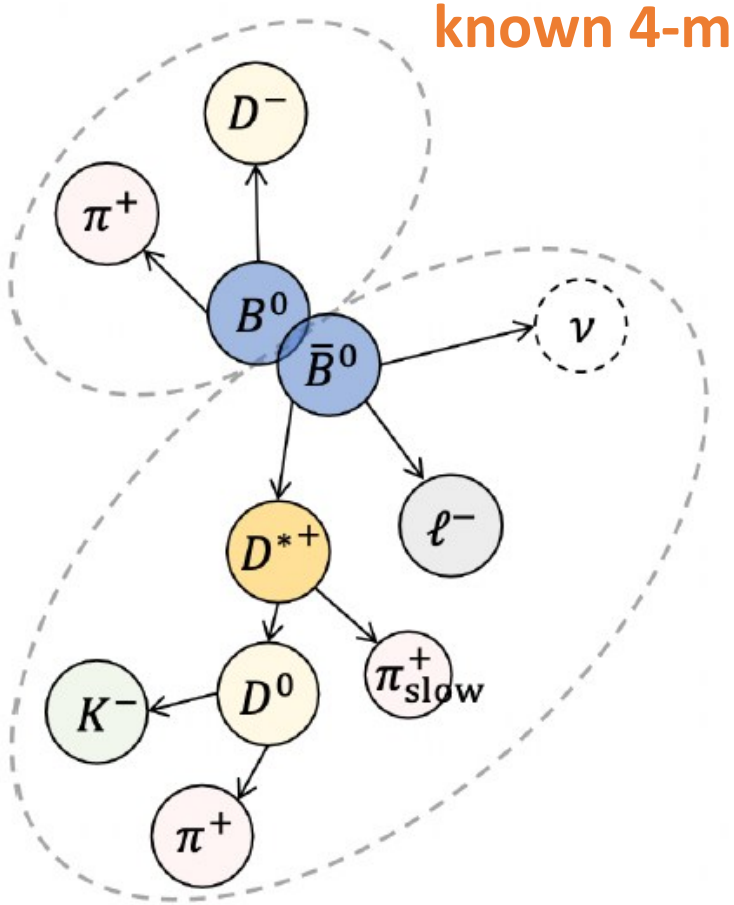
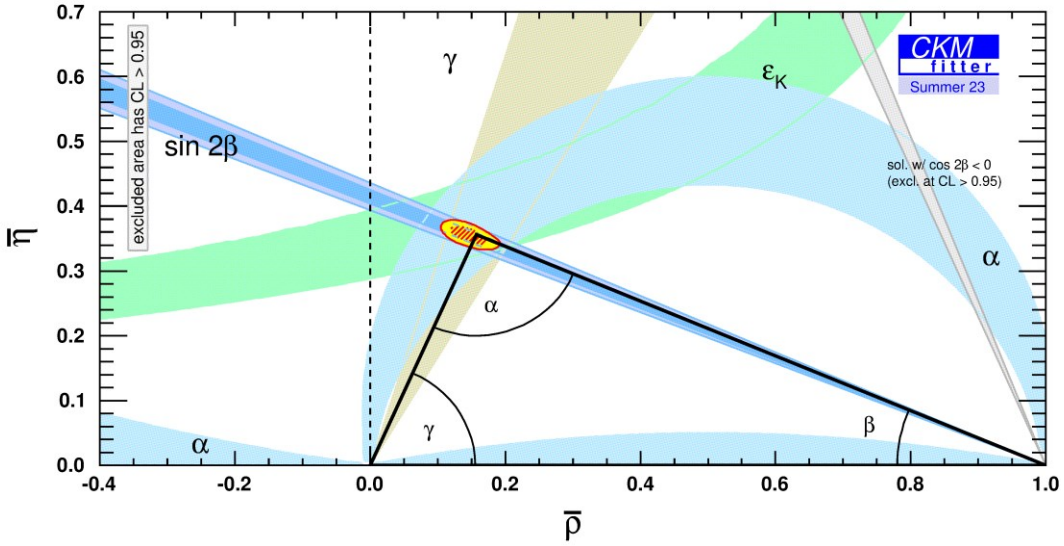
  - B → $D^{(*)0}$ mπ±nπ0 , where m≥1 n ≥0
- Reconstruct other B as signal with missing energy
- Machine learning algorithm used to boost efficiency as much as possible
  - Comput. Softw. Big Sci. 3 (2019) 1, 6
- Total efficiency < 1% but a powerful tool
- Requires calibration
- **Essential 4: flavour tagging but will discuss with the first measurement**

B→Dπ tag decay – known 4-momentum



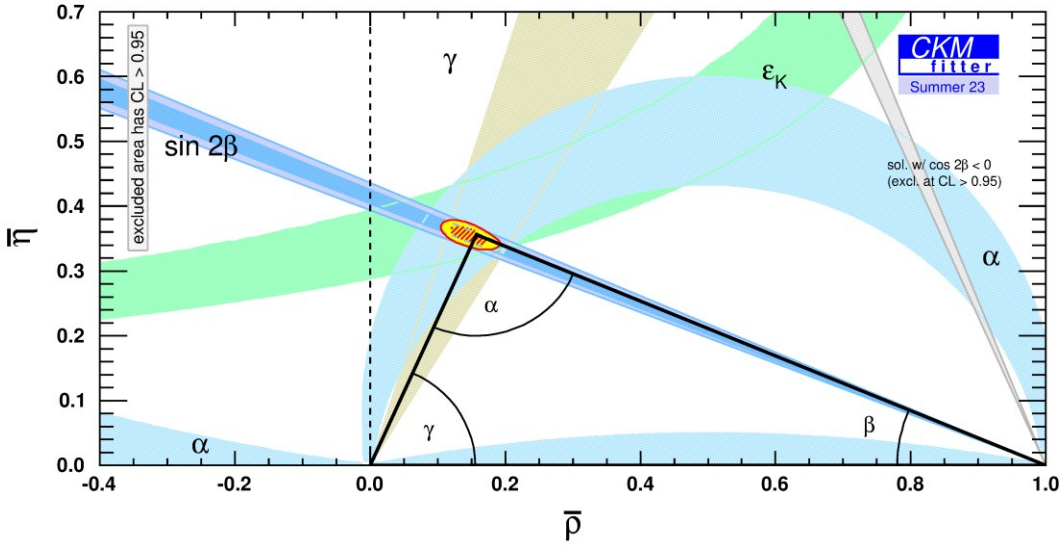
α/ϕ_2: $B^0 \to \pi^0\pi^0$

- α/ϕ_2 now the least precise angle of the unitarity triangle



α/ϕ_2: $B^0 \to \pi^0\pi^0$

- α/ϕ_2 now the least precise angle of the unitarity triangle
- Isospin relations among all $B \to \pi\pi$, $B \to \rho\rho$ and $B \to \rho\pi$ branching fractions and *CP* asymmetries provide constraints
  - **e.g, Gronau and London PRL 65 3381 (1990)**



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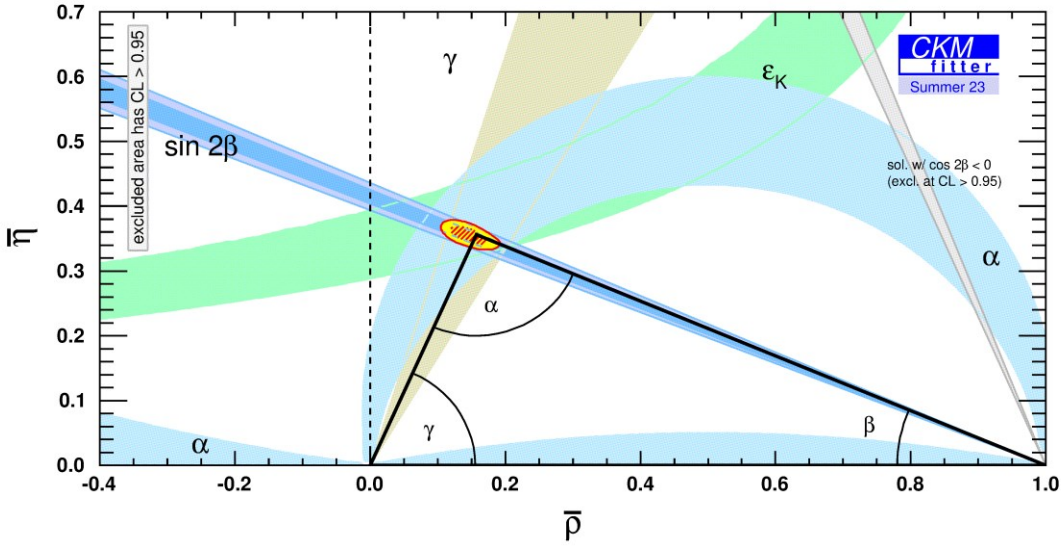
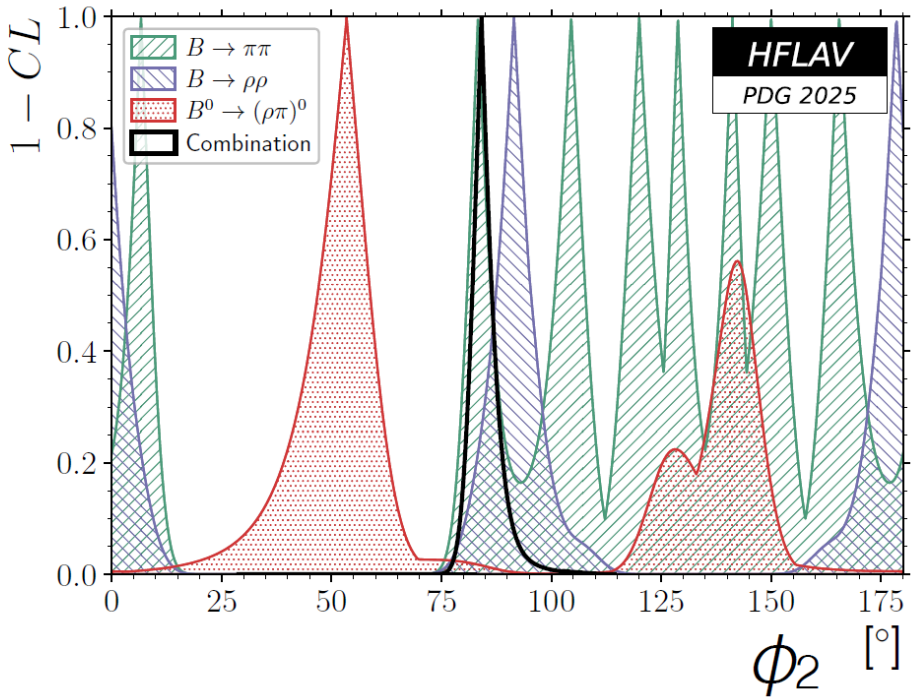
  - **e.g, Gronau and London PRL 65 3381 (1990)**
- Experimental situation is messy
- $B \to \pi\pi$ impact limited because time-dependent *CP* violation measurement $B^0 \to \pi^0\pi^0$ had not been performed

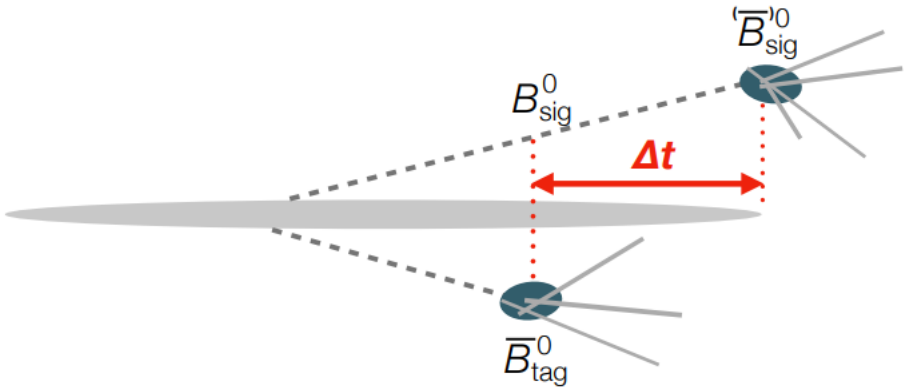




Time-dependent measurement of $B \to \pi^0\pi^0$

Usual B factory method is to measure the time difference between signal and tag B meson

Flavour tagging by lepton charge, kaon charge, and other quantities via a multivariate



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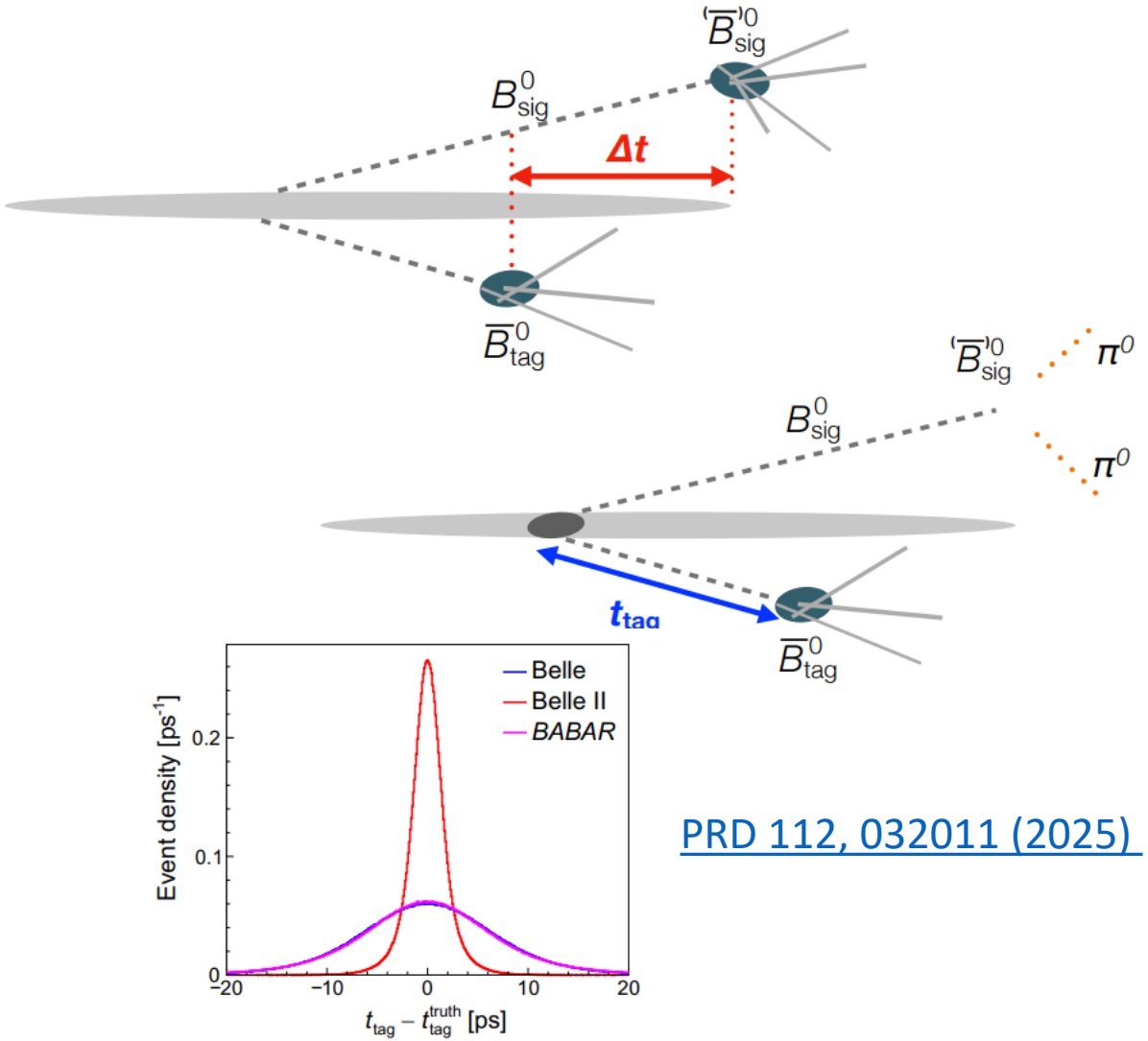
- However, no signal vertex for $B \to \pi^0\pi^0$ unless one $\pi^0 \to e^+e^-\gamma$, which is ~2% of the time
- New at Belle II luminous region small and pixel detector means t_{tag} can be measured well



PRD 112, 032011 (2025)

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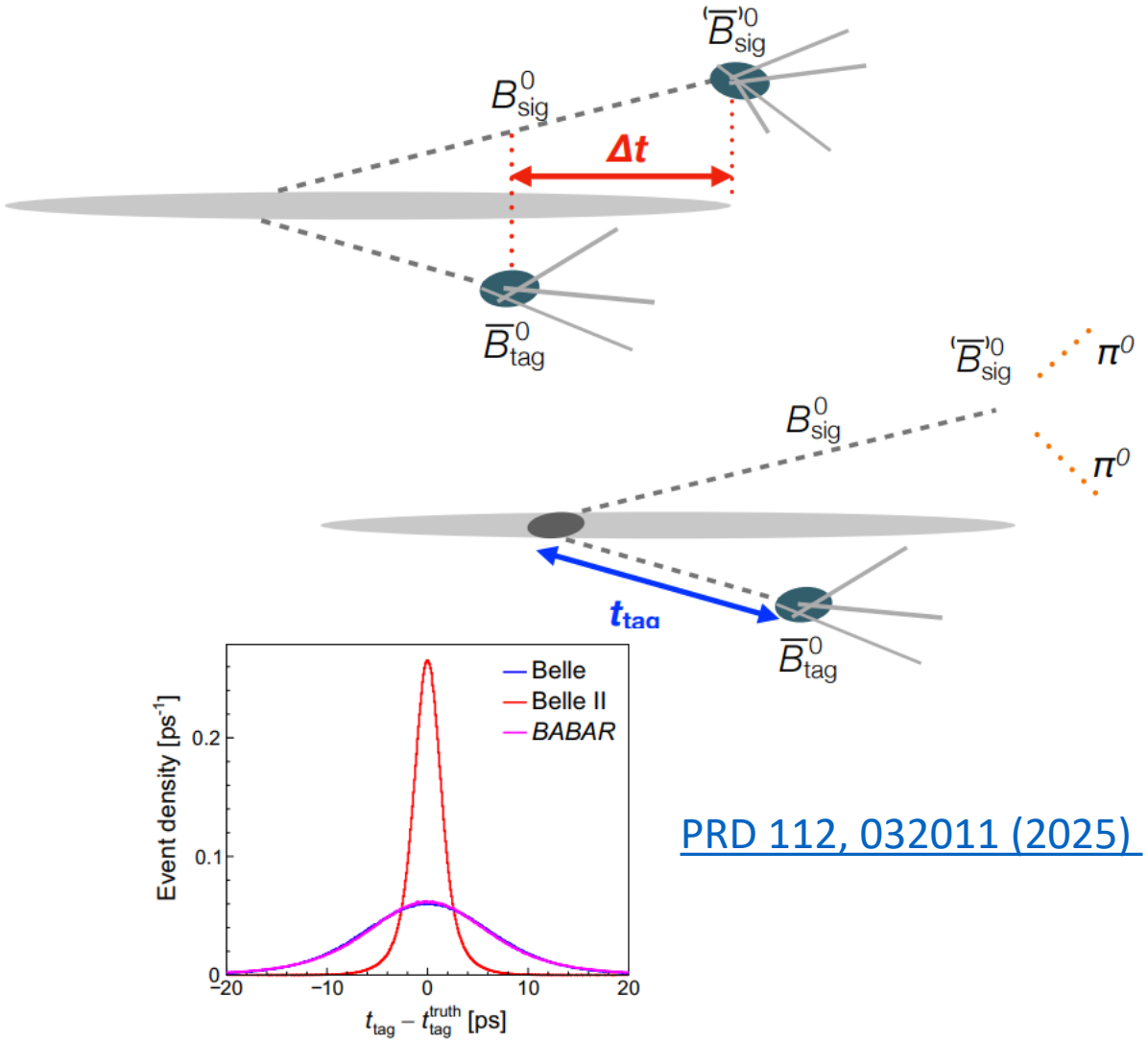
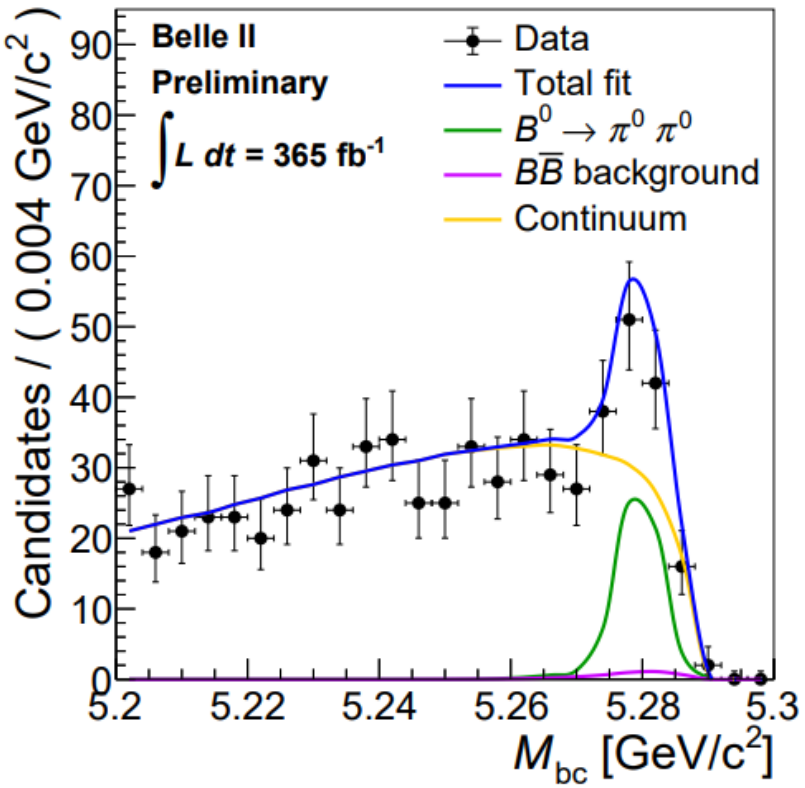
- Quantum-correlation of neutral B mesons from Y(4S) means that the *CP* asymmetry information influences the t_{tag} distribution



PRD 112, 032011 (2025)

$B \to \pi^0\pi^0$ results



Fit to M_{bc}, ΔE, wrong-flavour probability, continuum suppression variable, t_{tag} and $\sigma(t_{tag})$

171 ± 24 signal events

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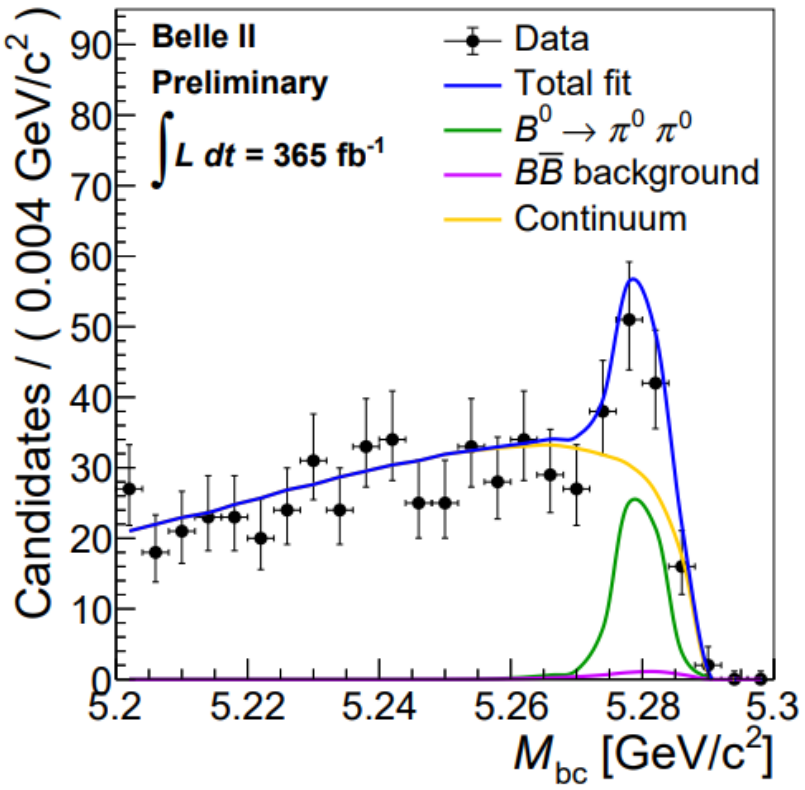

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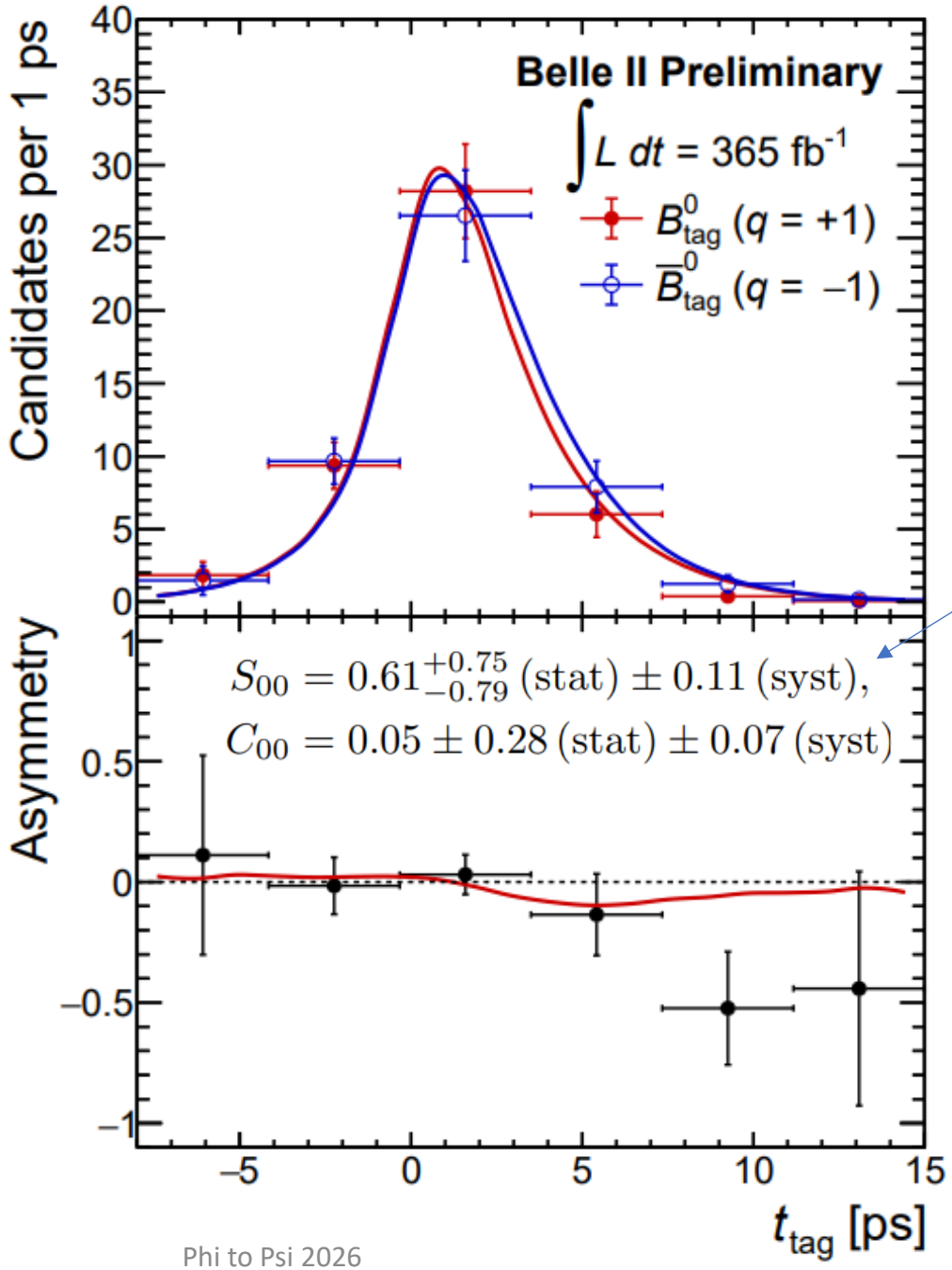
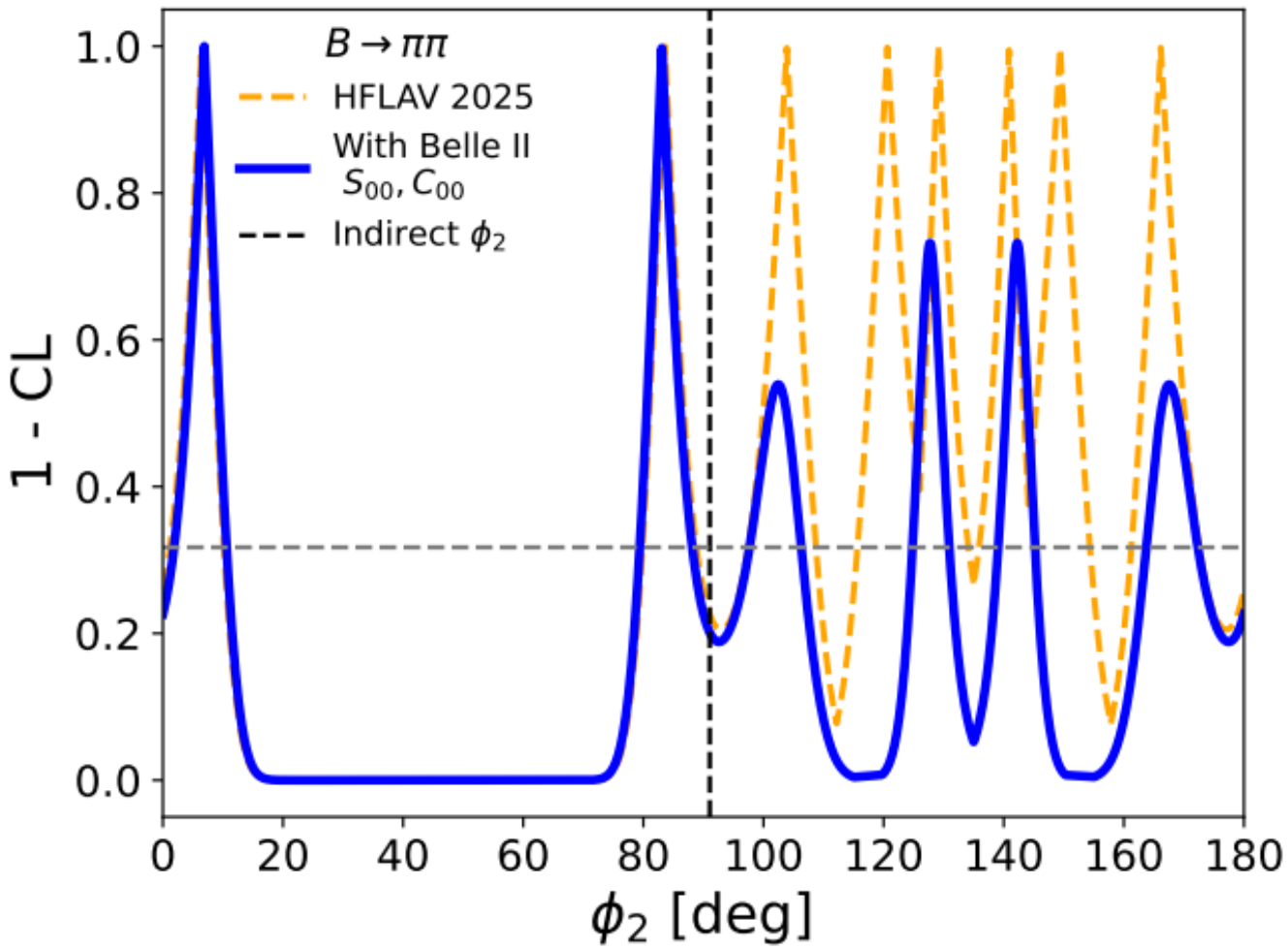


First information related to CP violation in the interference between mixing and decay

$B \to \pi^0\pi^0$: impact and outlook

Paper in preparation



Clear impact on the possible values of ϕ_2 with just 0.37 ab^{-1}

Control samples for the t_{tag} resolution model which is largest systematic uncertainty

Therefore, significant improvement will be made with a large Belle II data sample

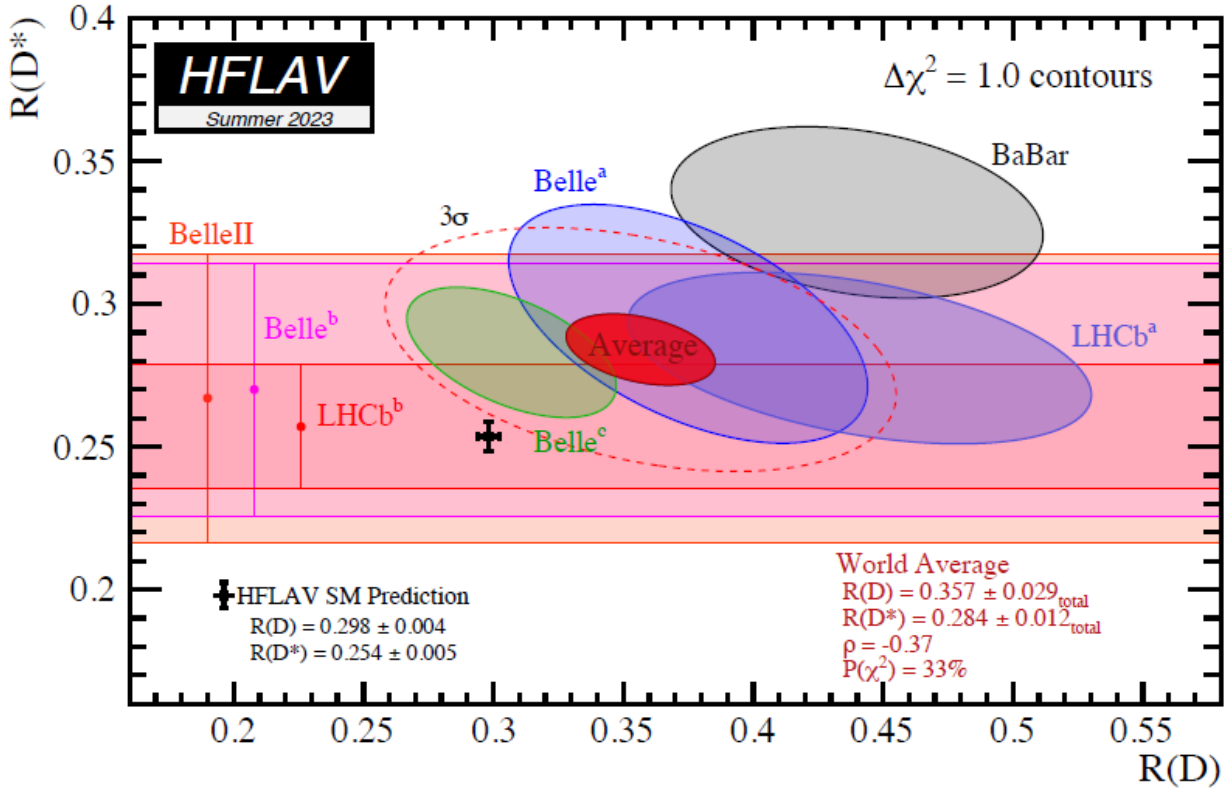
$B \to D^{(*)} \tau \nu$

- Long standing tension in the ratio

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)} \tau \nu_\tau)}{\mathcal{B}(B \to D^{(*)} \ell \nu_\ell)} \qquad \ell = e, \mu$$

compared to the expectation from lepton universality

- Beyond-the-SM tree-level physics, e.g., charged Higgs or leptoquark
  - Third-generation only effect may not have clear high-p_T signatures though



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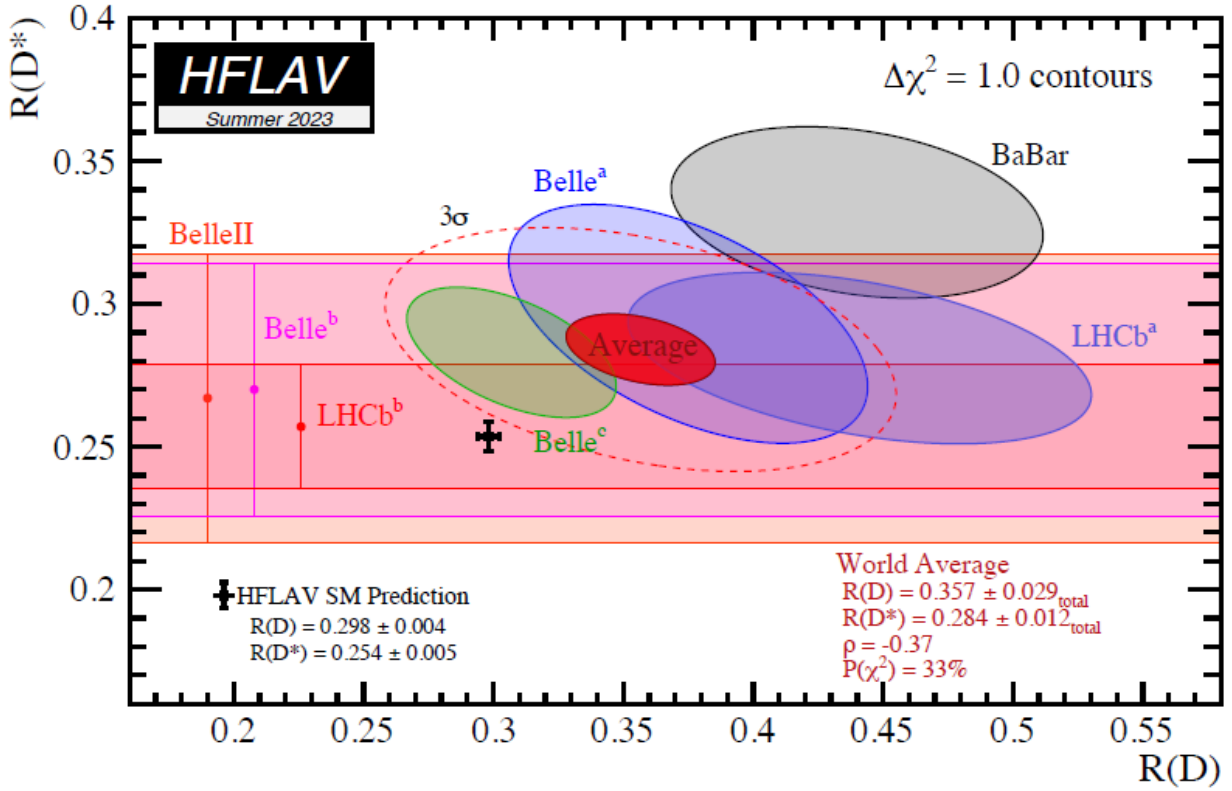
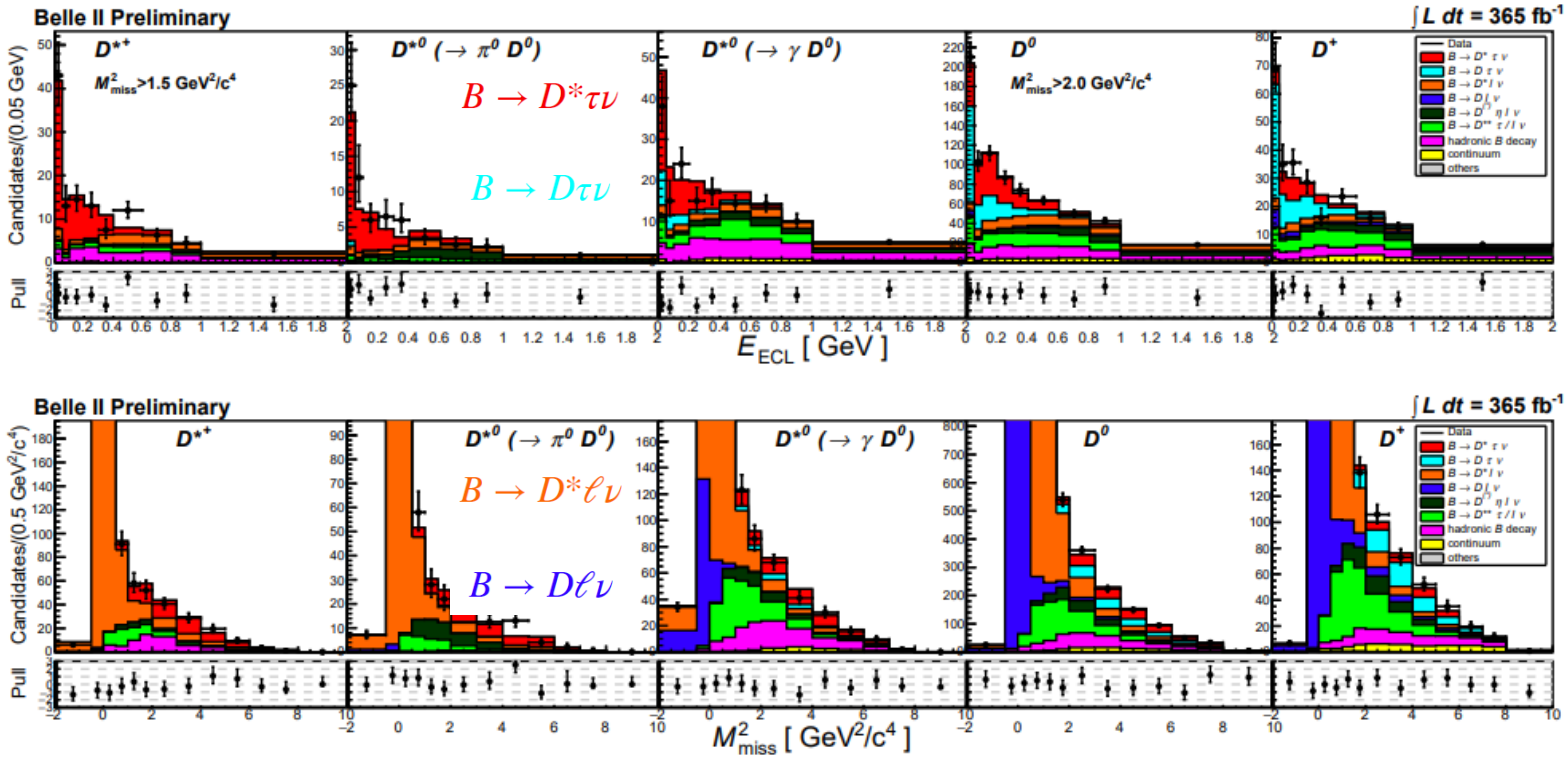
  - Third-generation only effect may not have clear high-p_T signatures though
- **Additional measurements required to clarify the situation**



$B \to D^* \tau \nu$ - hadronic tag

- Recent result from Belle II using hadronic tagging method
  - Fully constrained kinematics means reconstruction missing-mass squared
    - Non-zero for B→D*τν but zero for B→D*lν (normalization)
  - Full reconstruction means addition energy in calorimeter $E_{ECL} \sim 0$



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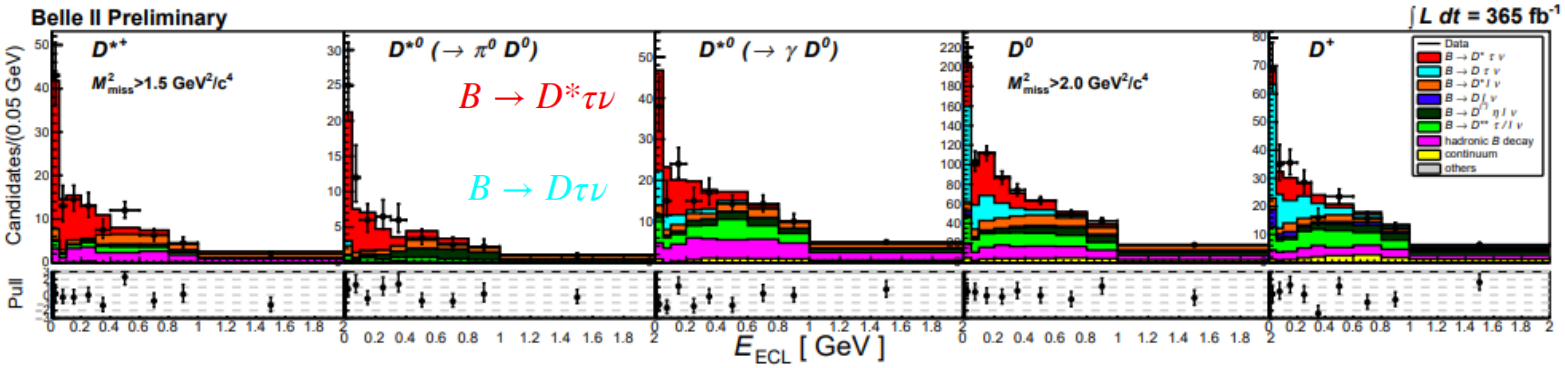
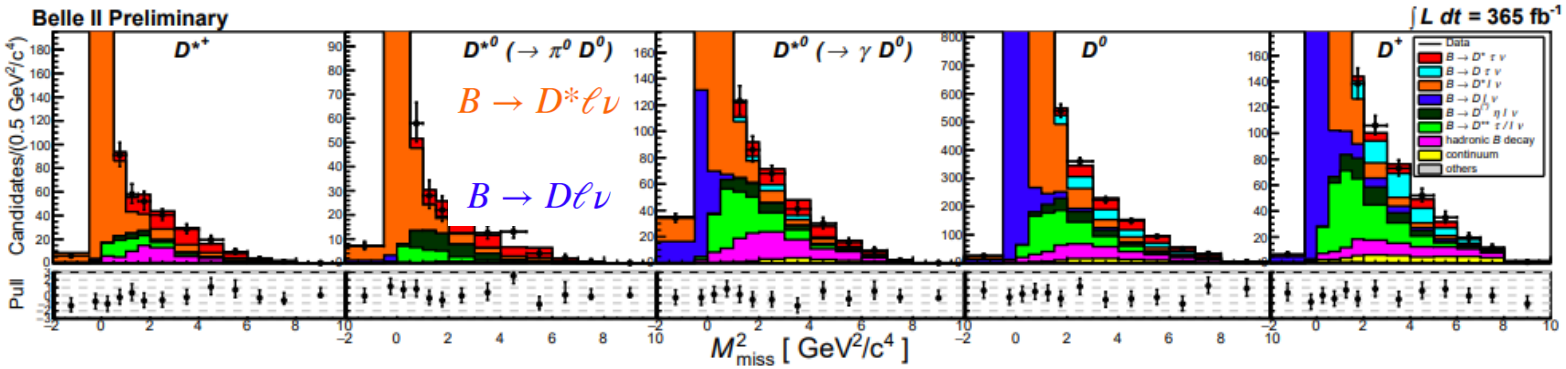




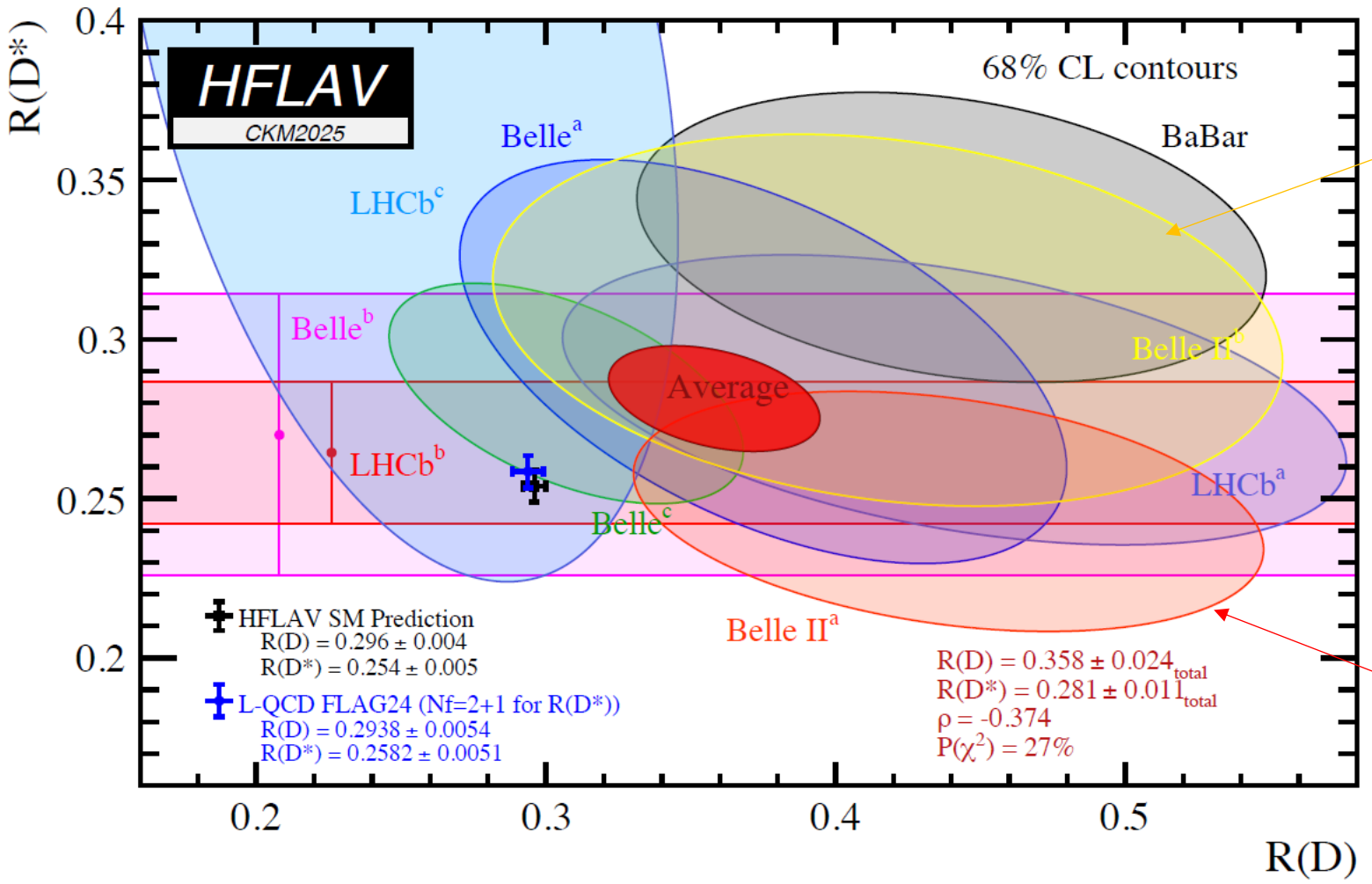
$$R(D) = 0.439 \pm 0.055(\text{stat.}) \pm 0.045(\text{syst.})$$

$$R(D^*) = 0.242 \pm 0.019(\text{stat.}) \pm 0.016(\text{syst.})$$

Systematics – simulation sample size for templates, *D* model, neutral efficiency**

Comparison with other results

3.8 sigma tension



Semileptonic tag
PRD **112**, 032010

This result

$B^+ \to K^+ \nu\bar{\nu}$

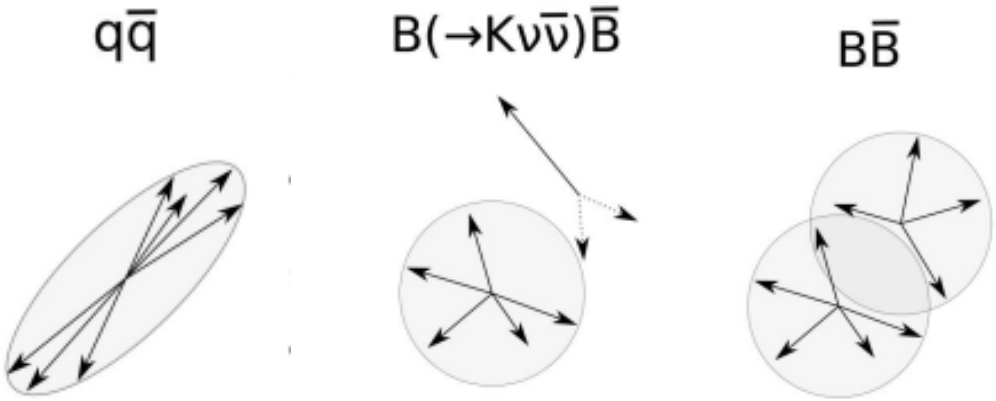
PRD 109, 112006 (2024)

- Theoretically clean and third generation sensitive flavour changing neutral current *b→sll* transition

$B^+ \to K^+ \nu\bar{\nu}$

PRD 109, 112006 (2024)

- Theoretically clean and third generation sensitive flavour changing neutral current *b→sll* transition
- Inclusive tag developed that exploits topology
  - 8% efficiency



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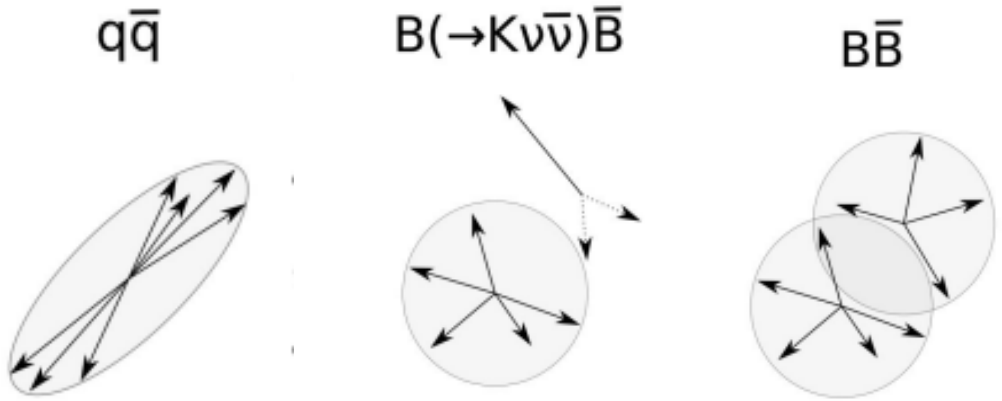
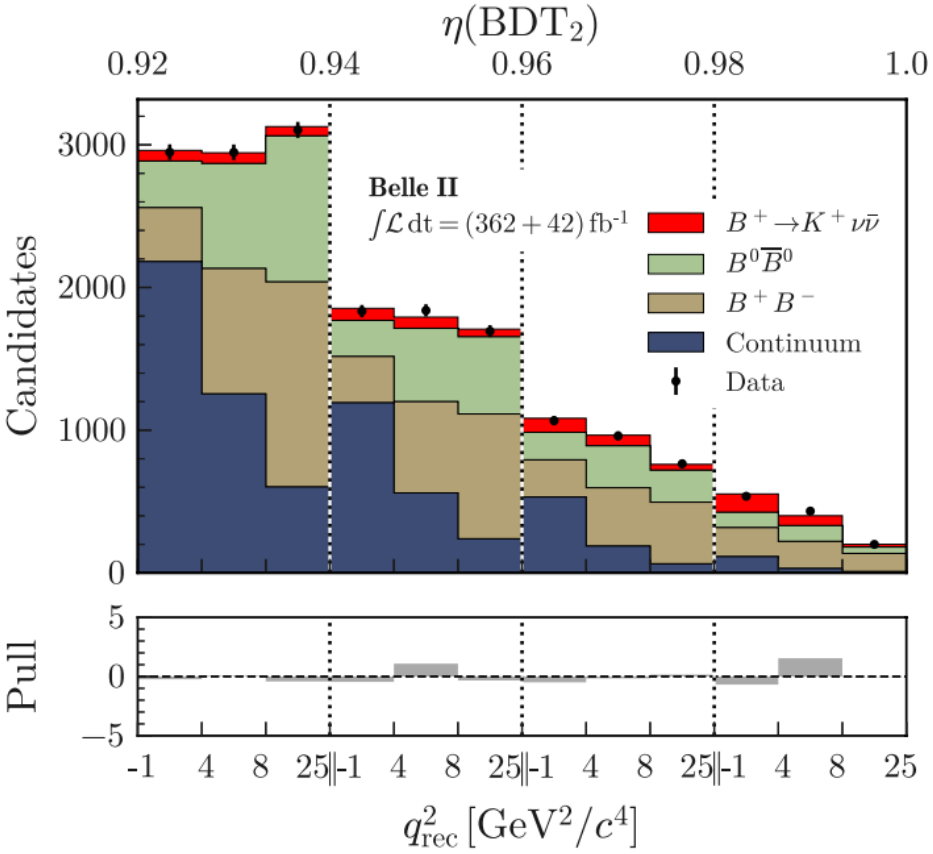


- Fit to invariant mass of neutrinos (q^2) and classifier
  - Checked and combined with lower efficiency hadronic *B* tag

$$\mathbf{B}(B^+ \to K^+ \nu\bar{\nu}) = \left(2.3 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})\right) \times 10^{-5}$$

PRD 109, 112006 (2024)

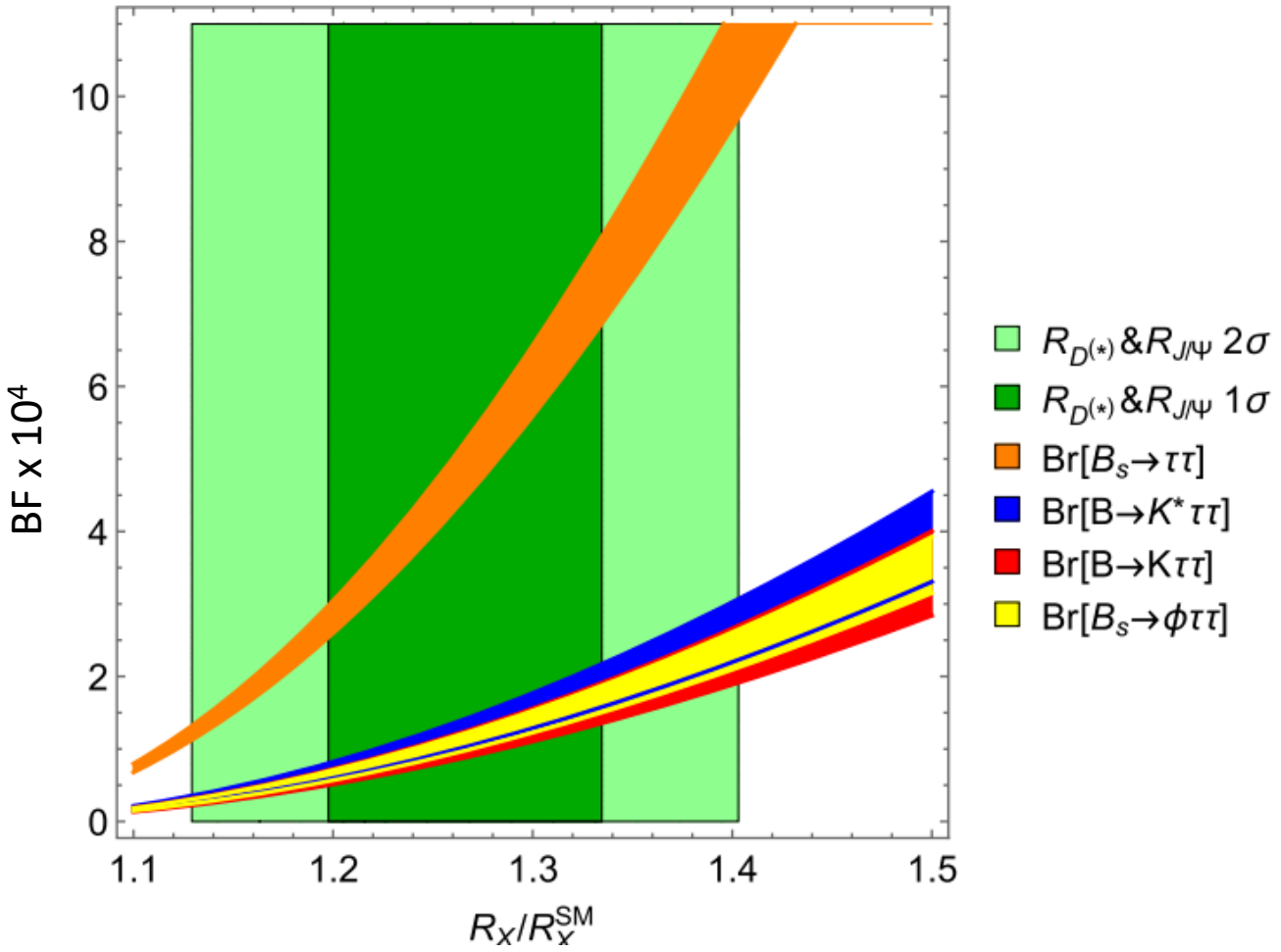


Evidence @ 3.5σ
Tension with SM prediction of 0.6×10^{-5} @ 2.7σ

$B^+ \to K^+\tau^+\tau^-$ and $B^+ \to K_S^0\tau^+\tau^-$

- Very sensitive to explanations of the other anomalies
  - SM branching fraction prediction 10^{-7}

PRL **120**, 181802 (2018)



$B^+ \to K^+\tau^+\tau^-$ and $B^+ \to K_S^0\tau^+\tau^-$

- Very sensitive to explanations of the other anomalies
  - SM branching fraction prediction 10^{-7}
- Belle + Belle II Run 1 data
  - $\sim 1.1\ ab^{-1}$
- Hadronic B tagging
- Tau reconstruction decay
  - leptonic for $B^+ \to K^+\tau^+\tau^-$
  - single-prong $B^0 \to K_S^0\tau^+\tau^-$

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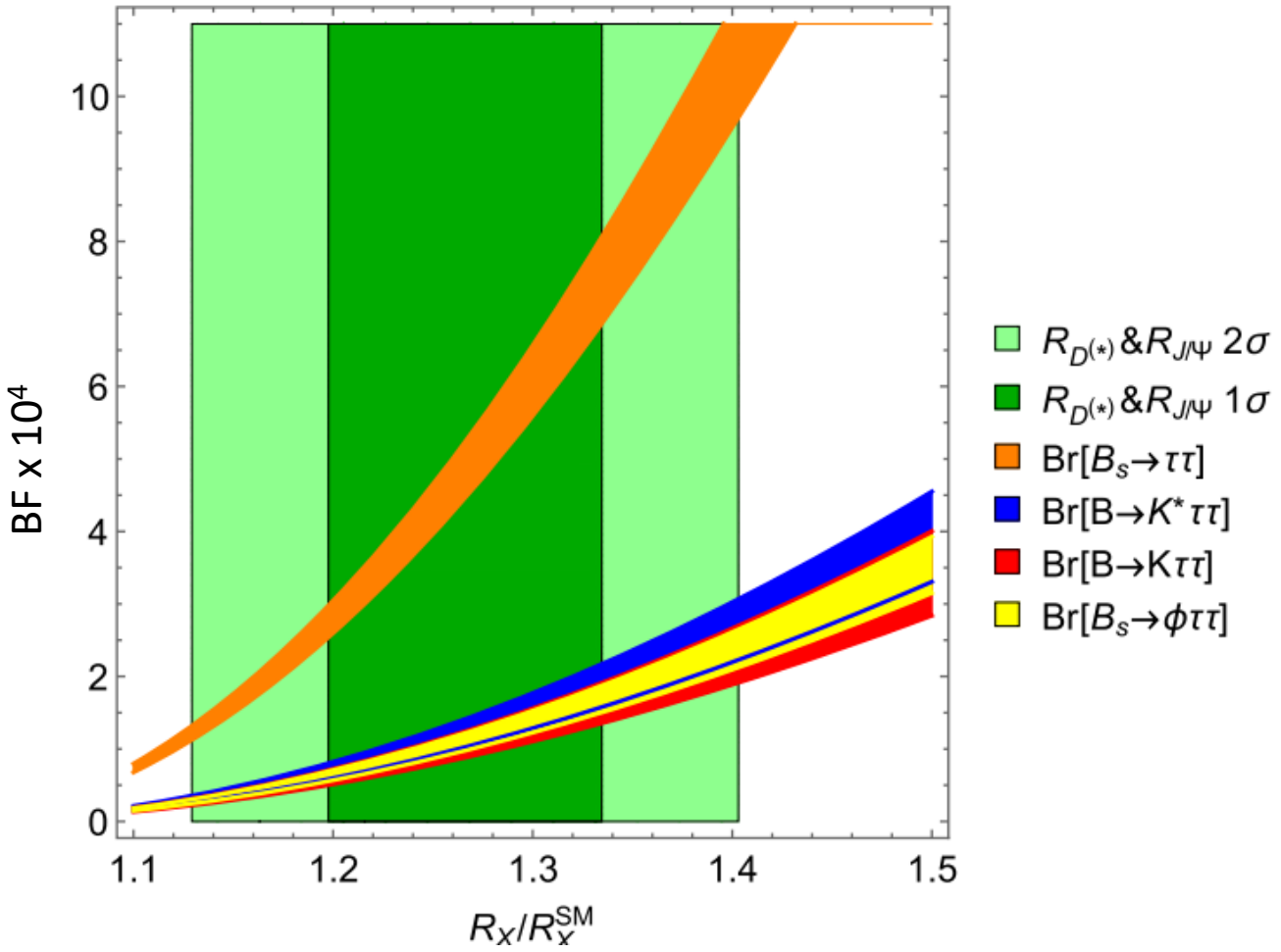
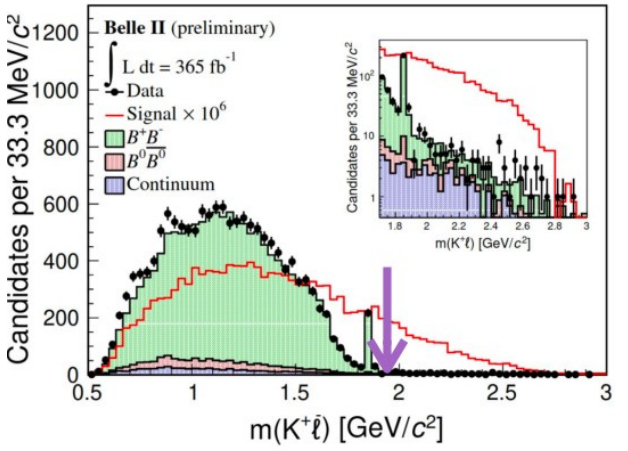


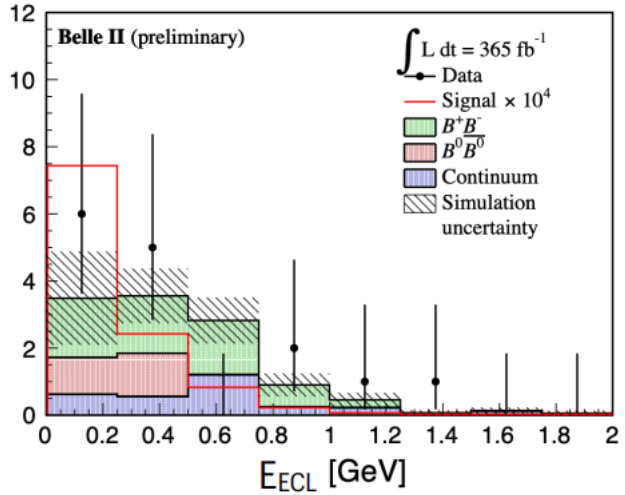
Submitted to PRL

$B^+ \to K^+\tau^+\tau^-$



m(Kl)>1.9 GeV/c²

Removes D background

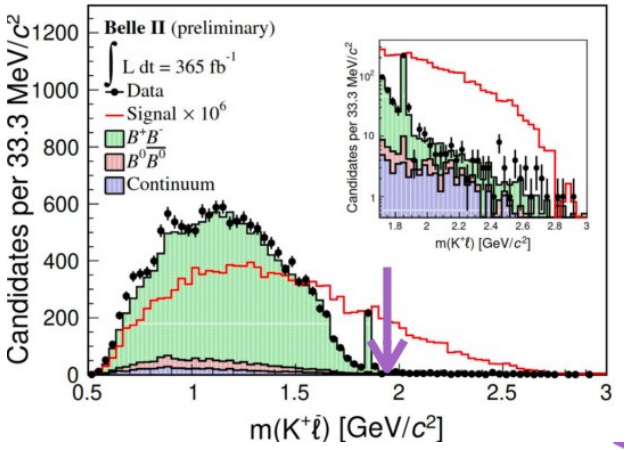


Template fit to E_{ECL}

No signal – BF < 5.6×10^{-4} at 90% C.L.

Submitted to PRL

$B^+ \to K^+\tau^+\tau^-$



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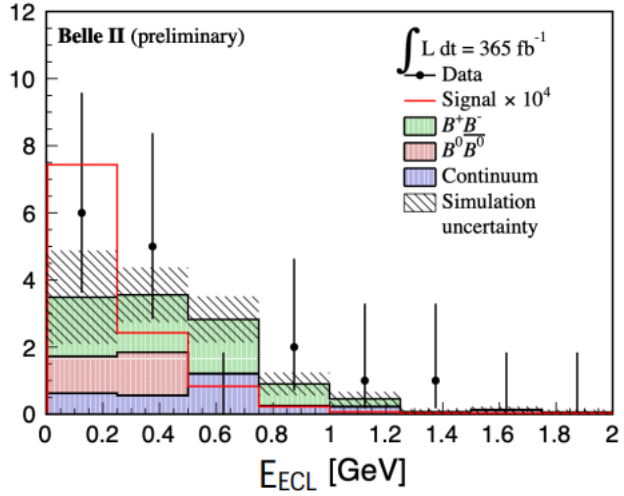


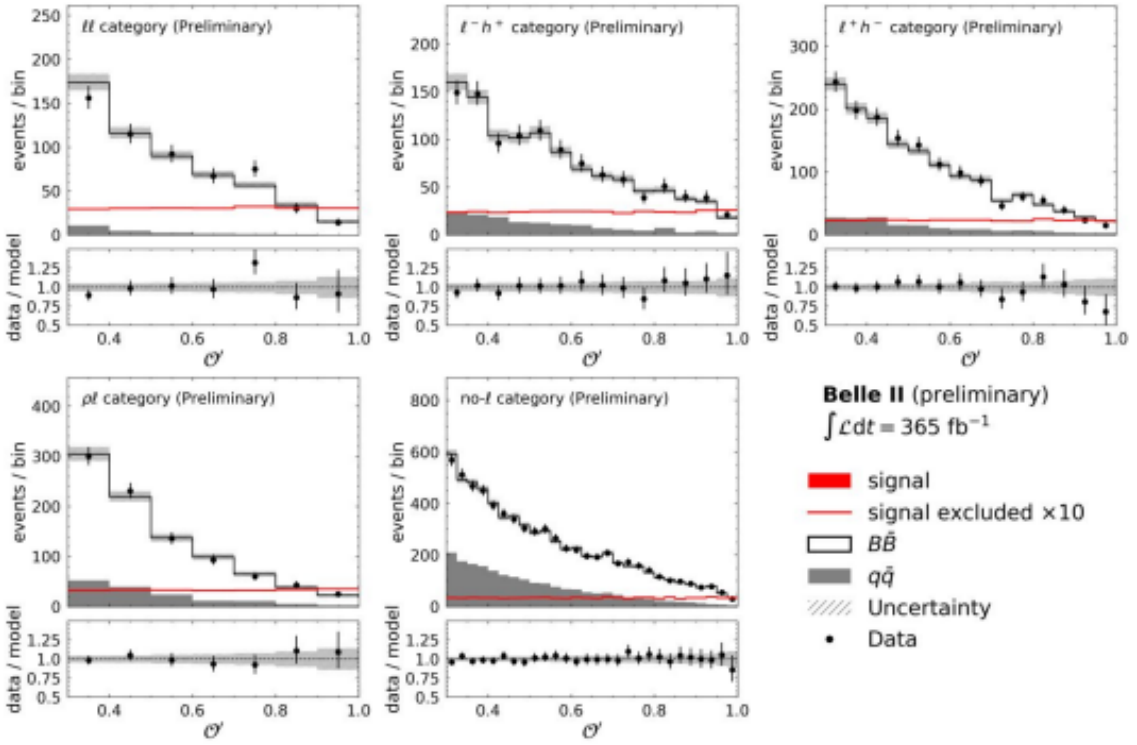
Template fit to E_{ECL}

No signal – BF < 5.6×10^{-4} at 90% C.L.

Paper in preparation

$B^0 \to K^0_S\tau^+\tau^-$

Multivariate classifier output template fit



No signal – BF < 8.4×10^{-4} at 90% C.L.

Most stringent limits to date for both

Conclusion and outlook

- *B*-physics central part of Belle II programme
  - CKM measurements – new constraints on α
  - Tests of lepton universality – tensions persist in $B \to D^{(*)}\tau\nu$
  - New beyond-the-SM sensitive $b \to s\tau\tau$ limits

Conclusion and outlook

- *B*-physics central part of Belle II programme
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- Just scratching the surface
  - 45 B physics publications submitted or accepted
  - Another ~500 fb^{-1} recorded
  - Long term plans, inc. upgrade, to obtain multi-ab^{-1} datasets