CKM Matrix related measurements at Belle II

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on behalf of Belle II collaborations

International Workshop on Weak Interactions and Neutrinos
University of Sussex – 2025, 11th June

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CKM Matrix and the Unitary Triangle

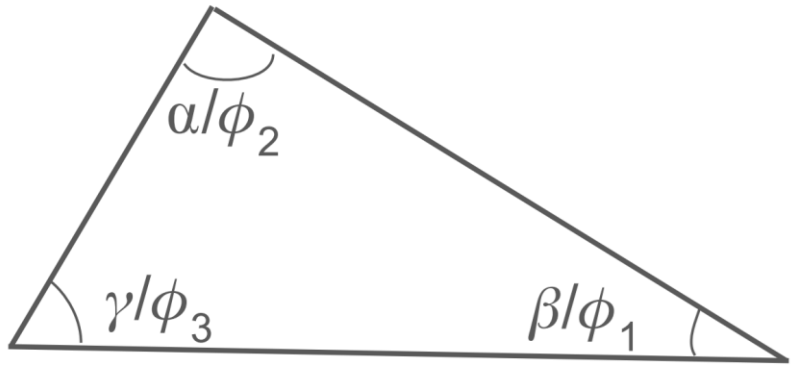
CKM Matrix

Describes *flavor-changing* weak interaction of the quarks.
Each matrix element determines the *strength* of quark–level *transition*.
3 *mixing angles* and 1 *CP-violating* phase.

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

Unitary Triangle

Unitarity of the CKM matrix leads to 6 unitary triangles.



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

Measurements at B Factories with B mesons

- CKM matrix elements: $|V_{ub}|$ and $|V_{cb}|$
  - Leptonic and Semileptonic B decays
- Angles of the Unitary Triangle: ϕ_1/β and ϕ_2/α
  - $B \to \pi\pi$, $B \to \rho\rho$, $B \to J/\psi\pi^0$

CKM Matrix Elements

Determination of the *CKM Element* $|V_{qb}|$ via (Semi)Leptonic B Decays

Measurements of $|V_{qb}|$ are crucial to constrain the unitarity triangle of the *CKM matrix*.

(Semi)Leptonic B decays are studied to determine the *CKM element* $|V_{qb}|$.

Exclusive decays:

Single, fully reconstructed final state *(e.g.,* $B \to \pi \ell \nu$, $B \to \rho \ell \nu$, $B \to D^{(*)} \ell \nu$*).*

Experimentally *clean*, theoretically **challenging**

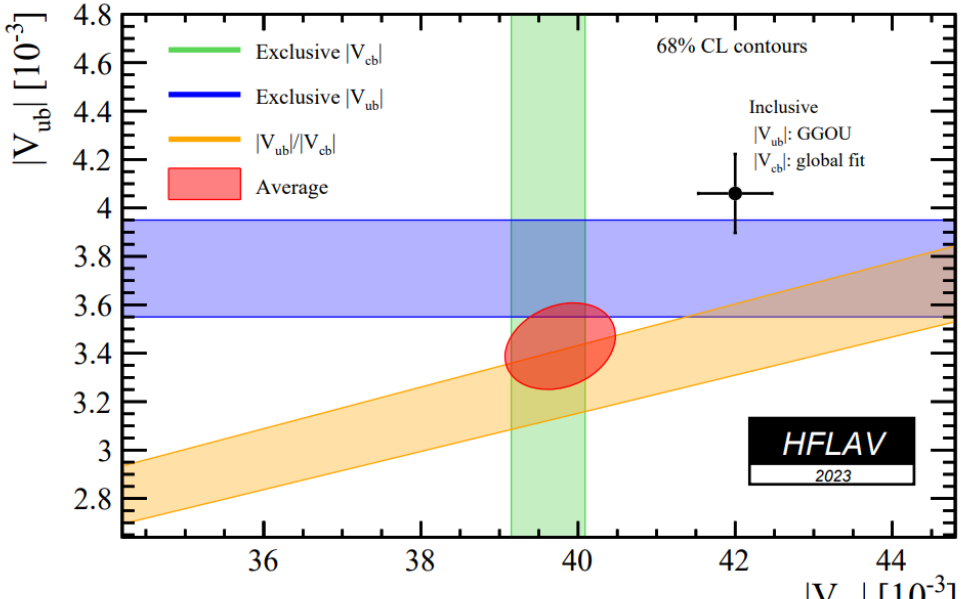
Inclusive decays:

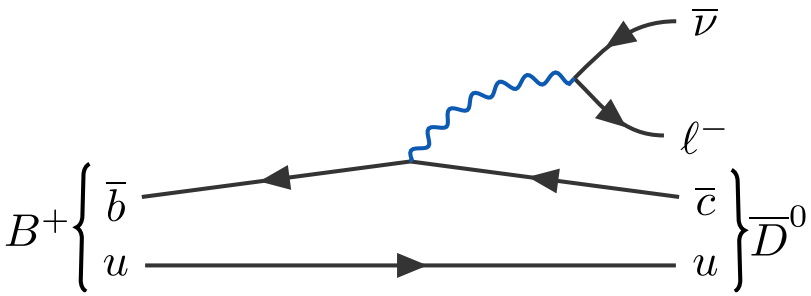
Final hadronic states not reconstructed

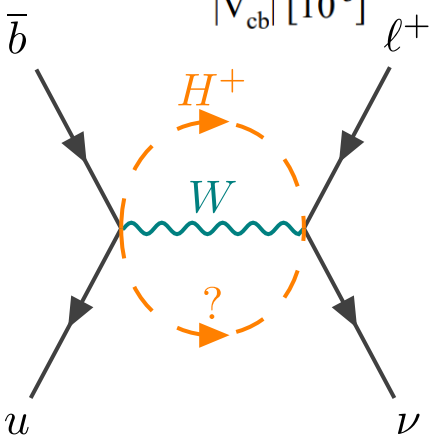
(e.g., $B \to X_u \ell \nu$, $B \to X_c \ell \nu$*)*

Experimentally **challenging**, theoretically *cleaner*

A long standing tension *arXiv:2411.18639*







2025, 11th June

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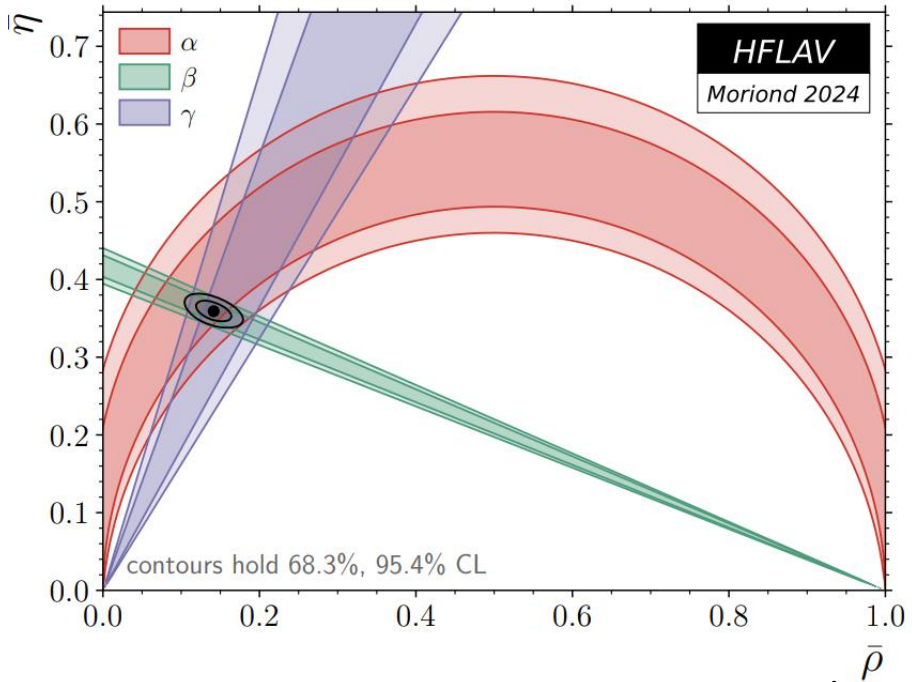
Angles of Unitary Triangle

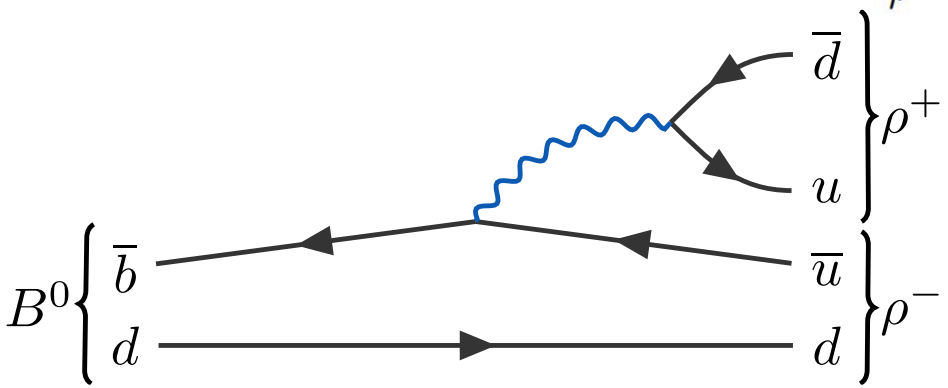
Determination of the *Angles* ϕ_1/β and ϕ_2/α via Hadronic B Decays

- UT constructed from CKM matrix has angles which are well-defined (physical) quantities.
- New Physics can cause inconsistency in the triangle parameters or inconsistency between tree-dominated and loop-dominated modes.

***CP Violation* in beauty:**

- ϕ_1/β: measured in $b \to c\bar{c}d$ transitions, precision close to effect of penguin amplitudes, controlled with $B \to J/\psi\pi^0$
- ϕ_2/α: least known experimentally, determined from isospin analysis of $B \to \rho\rho$ and $B \to \pi\pi$

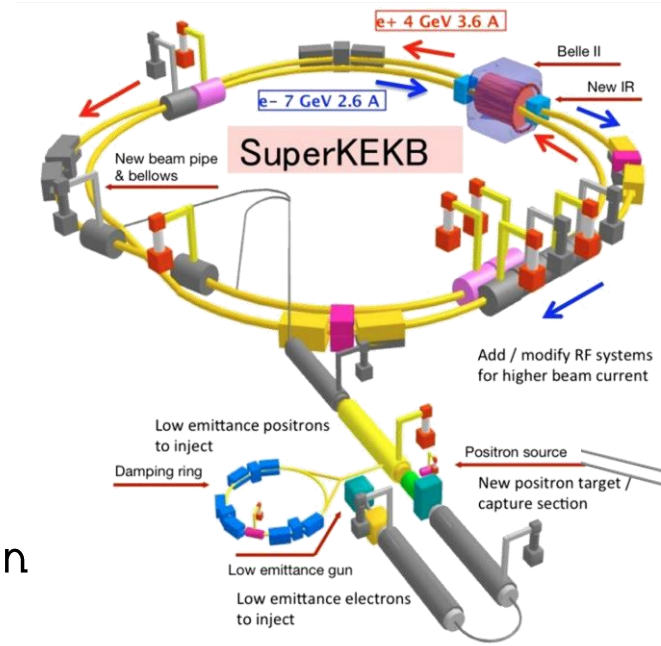


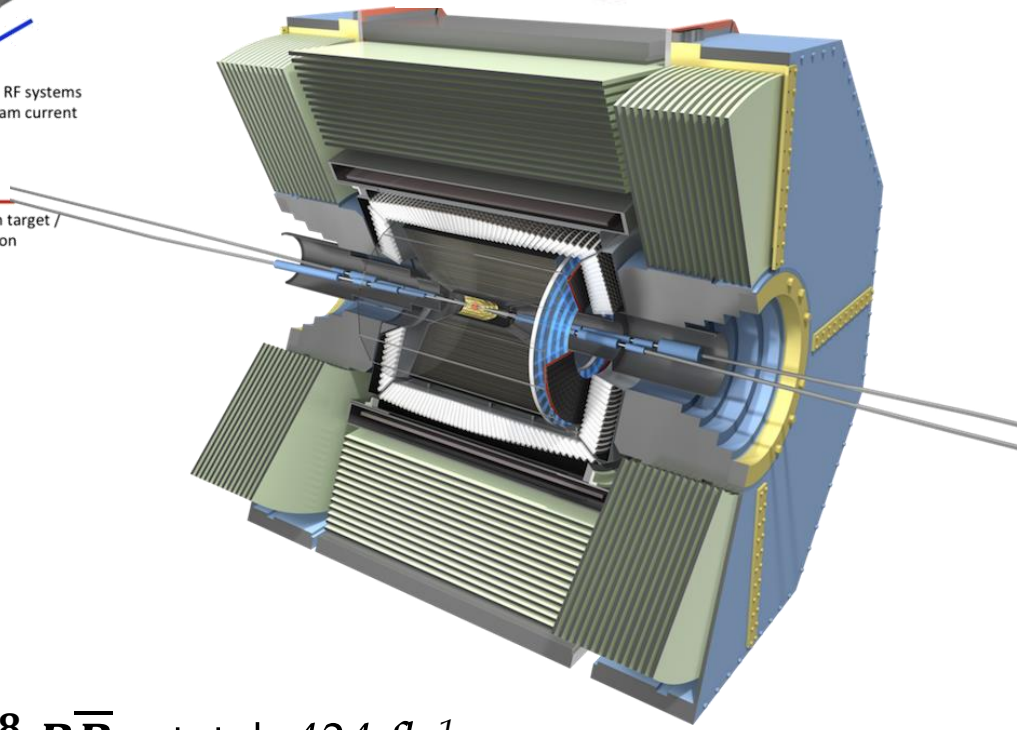


Belle II and SuperKEKB

SuperKEKB

- e^+e^- collider with energies 4 GeV and 7 GeV operating around $\Upsilon(4S)$ resonance.
- Achieved world-record peak Luminosity of $L = 4.7 \times 10^{34} cm^{-2} s^{-1}$





Belle II

- Nearly 4π detector coverage
- Tracking, PID and photon reconstruction capabilities
- Similar performance for electrons and muons
- Well-suited to measure decays with missing energy, π^0 in the final state, inclusive measurement
- From 2019 – 2024, $500\ fb^{-1}$ of data was collected.

RUN1: Data at $\Upsilon(4S)$: $365\ fb^{-1}$, about $\mathbf{4 \times 10^8}\ \boldsymbol{B\overline{B}}$ – total: $424\ fb^{-1}$

Statistics similar to *BaBar* e about half of *Belle*

$|V_{cb}|$ *from untagged* $B \to D\ell\nu$

Analysis Workflow

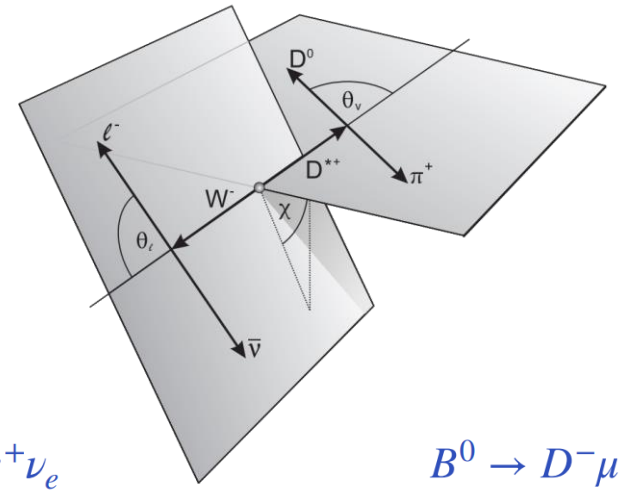
- Candidate $B \to D\ell\nu$ are formed from $\ell(e,\ \mu)$ and a D $(D \to K\pi,\ D \to K\pi\pi)$
- Exploit *isospin symmetry* to analyze B^0 and B^+ decays simultaneously and reduce experimental uncertainties.
- *Signal variable* using available kinematic constant

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

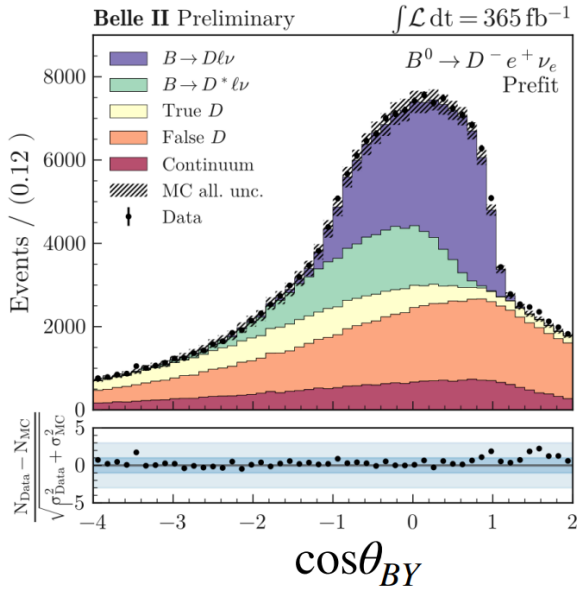
$Y = D\ell$

$$w = \frac{m_B^2 + m_D^2 - q^2}{2m_B m_D}$$

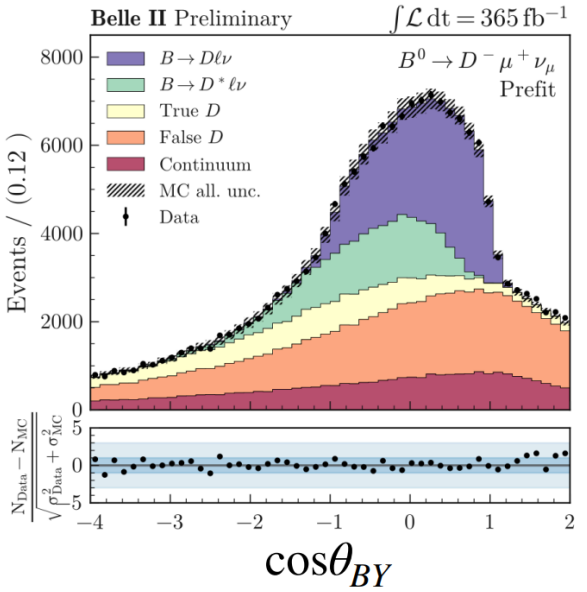
- **Main Backgrounds**
  - $B \to D^*\ell\nu$
  - Continuum events $e^+e^- \to q\bar{q}$



$B^0 \to D^- e^+ \nu_e$



$B^0 \to D^- \mu^+ \nu_\mu$

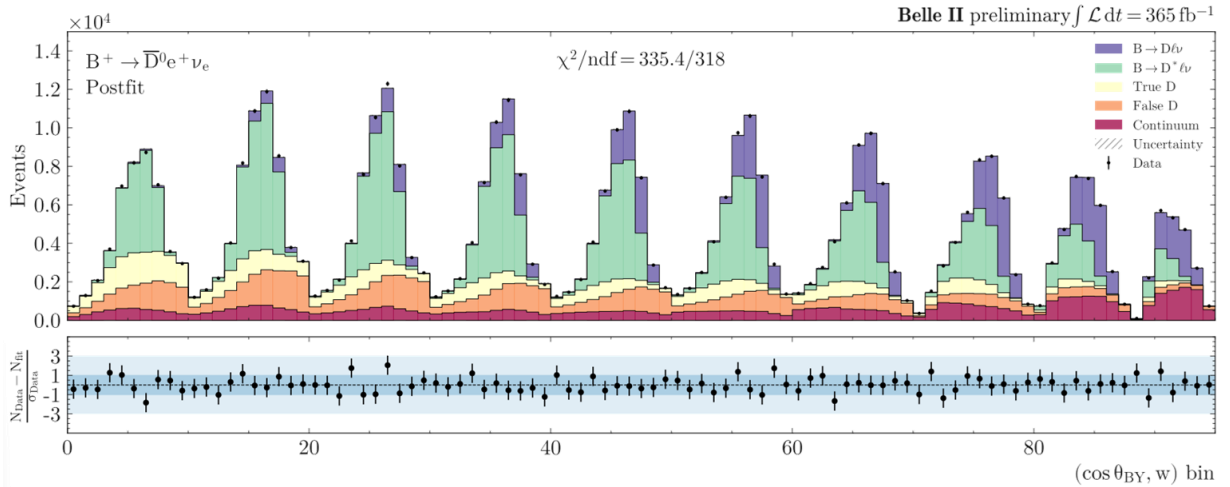


$|V_{cb}|$ from untagged $B \to D\ell\nu$

Signal Extraction

The branching fractions of each of the two modes were measured with a fit on $cos\theta_{BY}$ in bins of w.

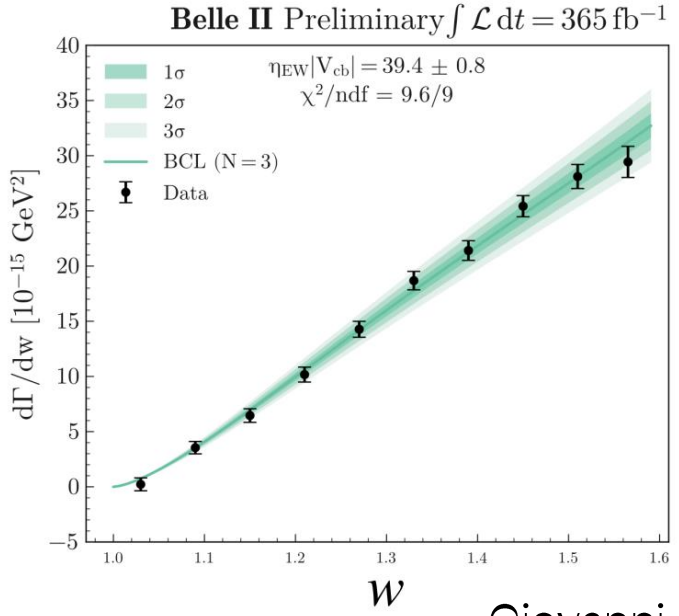
$$\mathcal{B}(B^0 \to D^- \ell^+ \nu_\ell) = (2.06 \pm 0.05\,(\text{stat.}) \pm 0.10\,(\text{sys.}))\%$$
$$\mathcal{B}(B^+ \to \bar{D}^0 \ell^+ \nu_\ell) = (2.31 \pm 0.04\,(\text{stat.}) \pm 0.09\,(\text{sys.}))\%$$



$|V_{cb}|$ extraction

Fit differential decay rates using *Bourrely-Caprini-Lellouch (BCL)* parameterization of form factor

$$|V_{cb}|_{\text{BCL}} = (39.2 \pm 0.4\,(\text{stat.}) \pm 0.6\,(\text{sys.}) \pm 0.5\,(\text{th.})) \times 10^{-3}$$

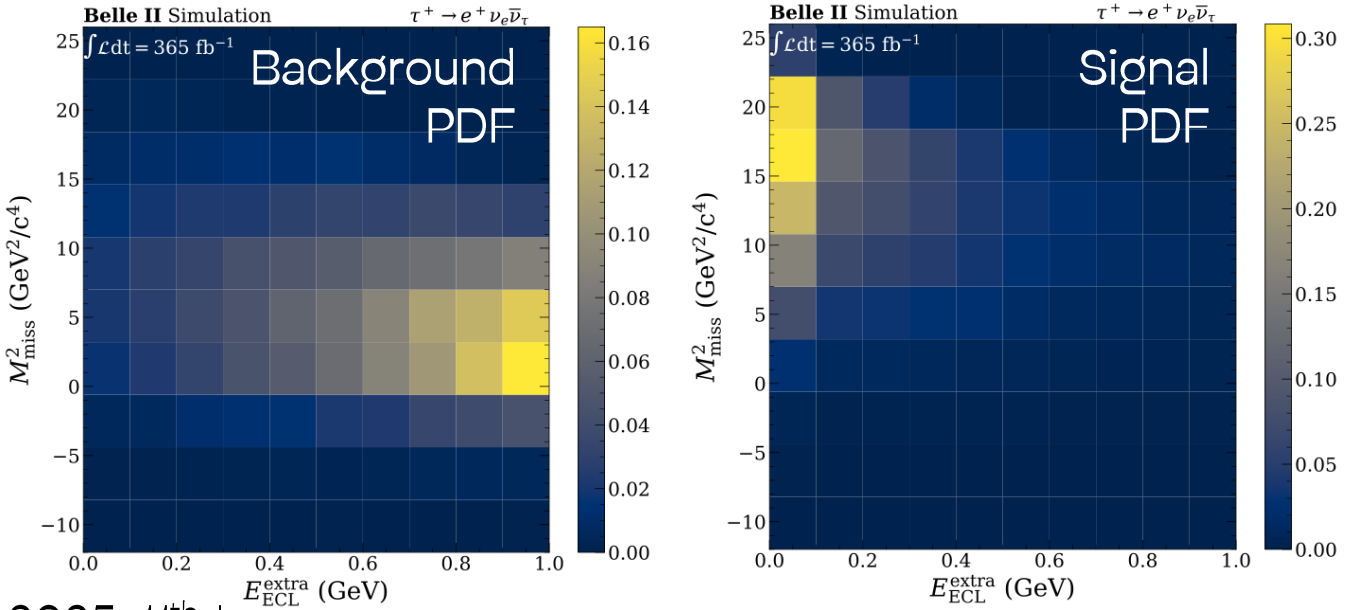


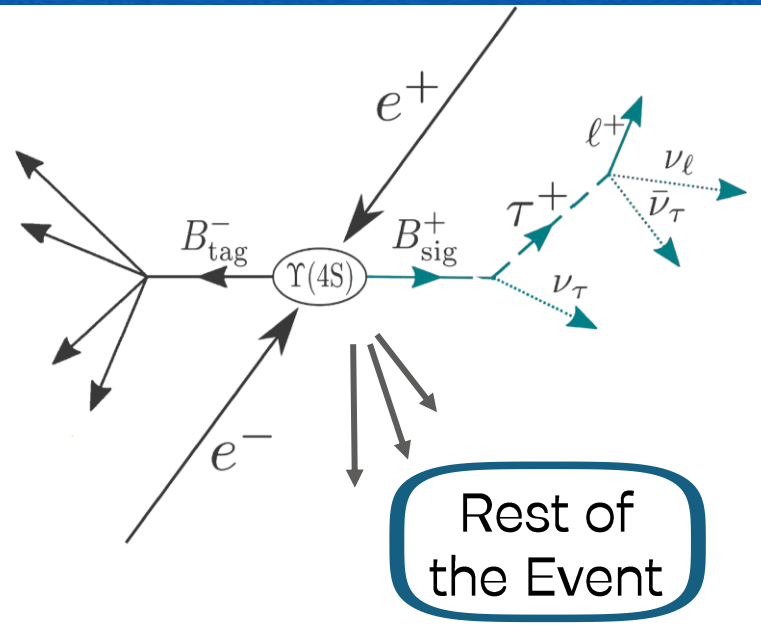
Most precise measurement to date using $B \to D\ell\nu$ decays

$|V_{ub}|$ from hadronic tagged $B \to \tau\nu$

Analysis Workflow

- Reconstruction of the tag B meson with hadronic decays
- Reconstruction of τ decays using 1 prong decays *(~70%)*
- Build of *Extra Event:*
  - Sum of all the cleaned clusters energy → $\boldsymbol{E_{ECL}^{extra}}$.
  - $p_{miss} = p_{beams} - p_{B_{tag}} - p_{track} - p_{ROE}$





Signal Extraction

- It is crucial to reject fake photons in the ECL from background
- We use the Extra ECL Energy and the missing mass squared to extract the signal yield

$|V_{ub}|$ from hadronic tagged $B \to \tau\nu$

Submitted to PRD: ***arXiv:2502.04885***

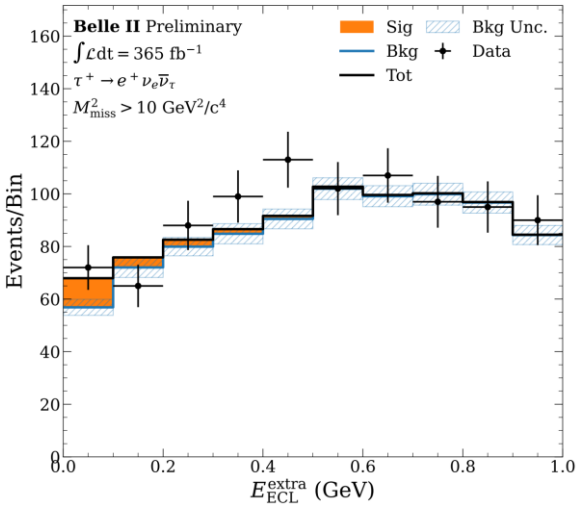
Branching Ratio Extraction

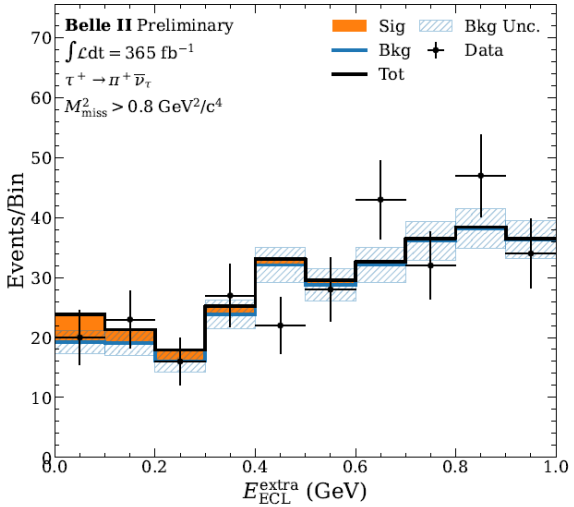
3.0σ with respect to background-only hypothesis

$|V_{ub}|$ extraction

Assuming the SM, and using $f_B = 190.0 \pm 1.3$ MeV from Lattice QCD:

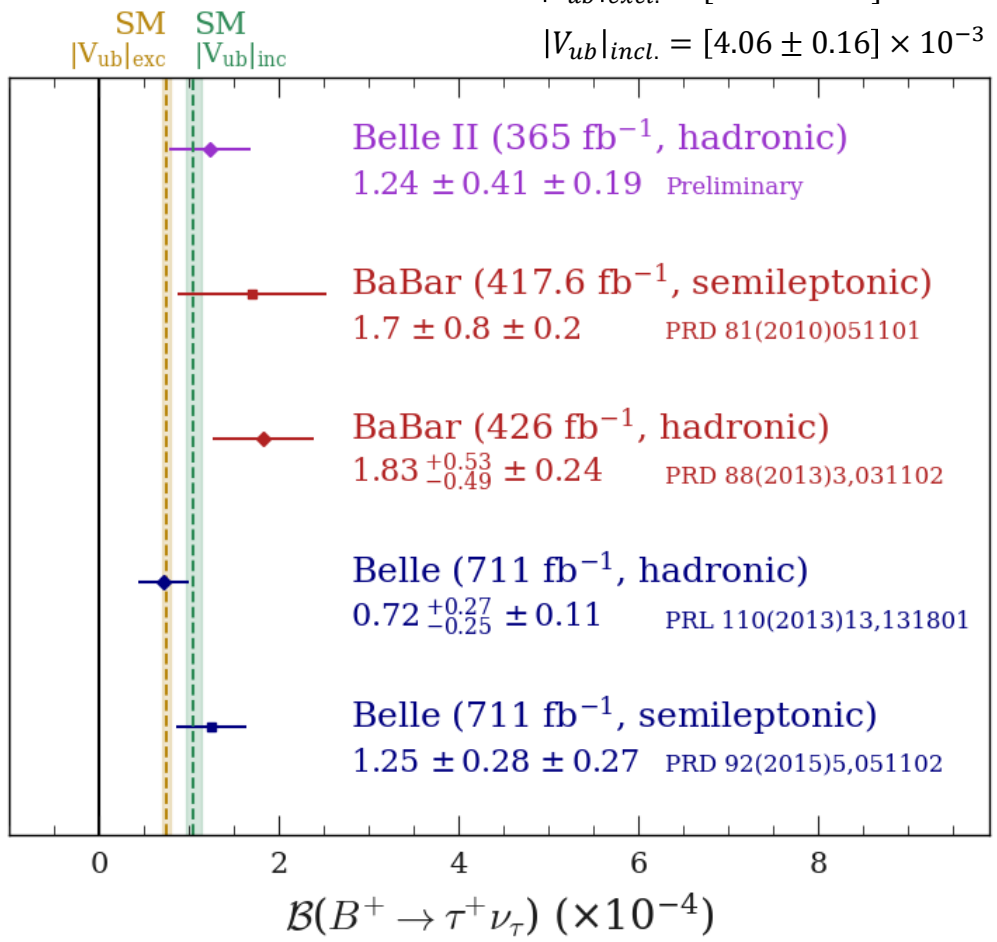
$$|V_{ub}| = \left(4.41^{+0.74}_{-0.89}\right) \times 10^{-3}$$





$|V_{ub}|_{excl.} = [3.43 \pm 0.12] \times 10^{-3}$

$|V_{ub}|_{incl.} = [4.06 \pm 0.16] \times 10^{-3}$

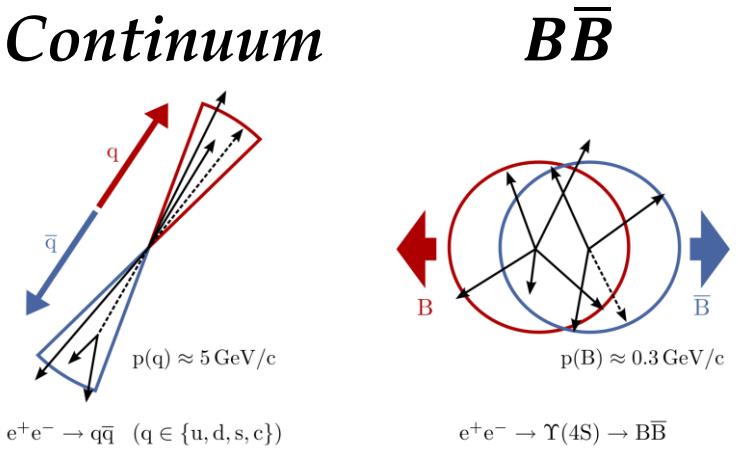


$$\mathcal{B}(B^+ \to \tau^+ \nu) = (1.24 \pm 0.41(\text{stat.}) \pm 0.19(\text{syst.})) \times 10^{-4}$$

CPV measurements at B factories

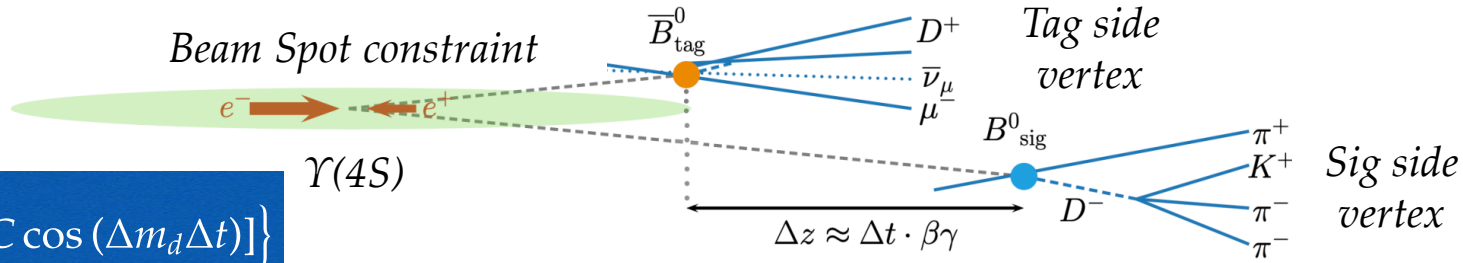
Essential ingredients for CPV analysis

- Kinematics variables and geometry of the events.
- Tag initial flavor from partially reconstructed tag-side B^0 [PRD 110, 012001 (2024)]
  - Improved efficiency with *Graph-NN* (31.7% → 37.4%)
- Exploit correlation of $B^0\overline{B^0}$ pairs to measure Δt asymmetries
  - Improved Δt resolution from pixel detector and constraint from nano-beams



$$\Delta E = E_B^* - \sqrt{s}/2$$

$$M_{bc}c^2 = \sqrt{s/4 - (p_B^* c)^2}$$



$$P(\Delta t, q_{tag}) = \frac{e^{-|\Delta t|/\tau}}{4\tau}\left\{1 + q_{tag}(1-2w)\left[S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)\right]\right\}$$

ϕ_2 from $B^0 \to \rho^+\rho^-$

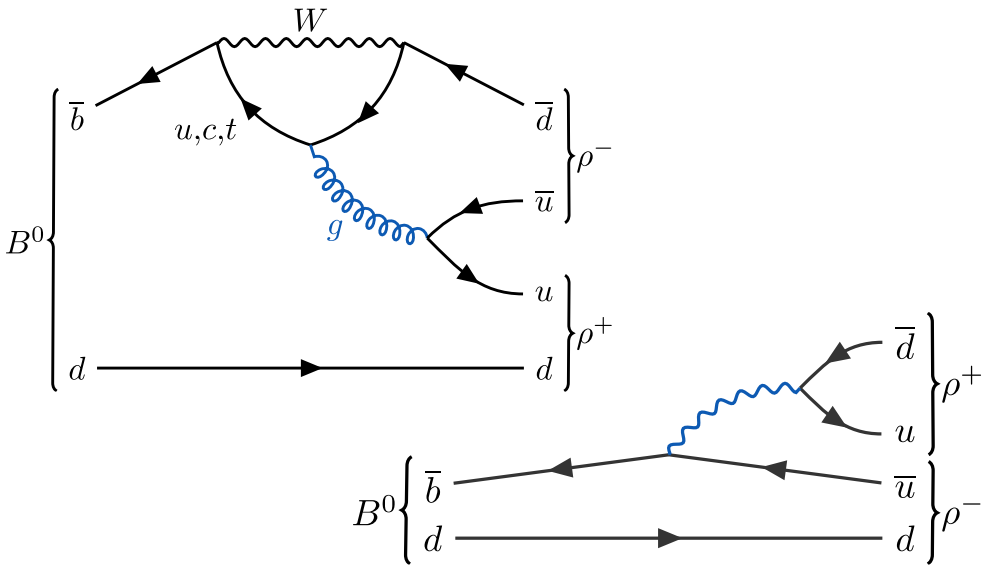
Goal: Constrain CKM angle ϕ_2 via $B^0 \to \rho^+\rho^-$

CP–violation from *direct CP violation (C)* and *mixing induced CP violation (S)*. $B^0 \to \rho\rho$ dominates precision on ϕ_2 due to smal loop contribution

Experimentally reconstruct $2\pi^0$ in the final state and angular analysis to separate longitudinal/transverse polarization in $P \to VV$ decays.

Measurements dominated by BaBar and Belle ($\mathcal{B}$, CP, polarisation)

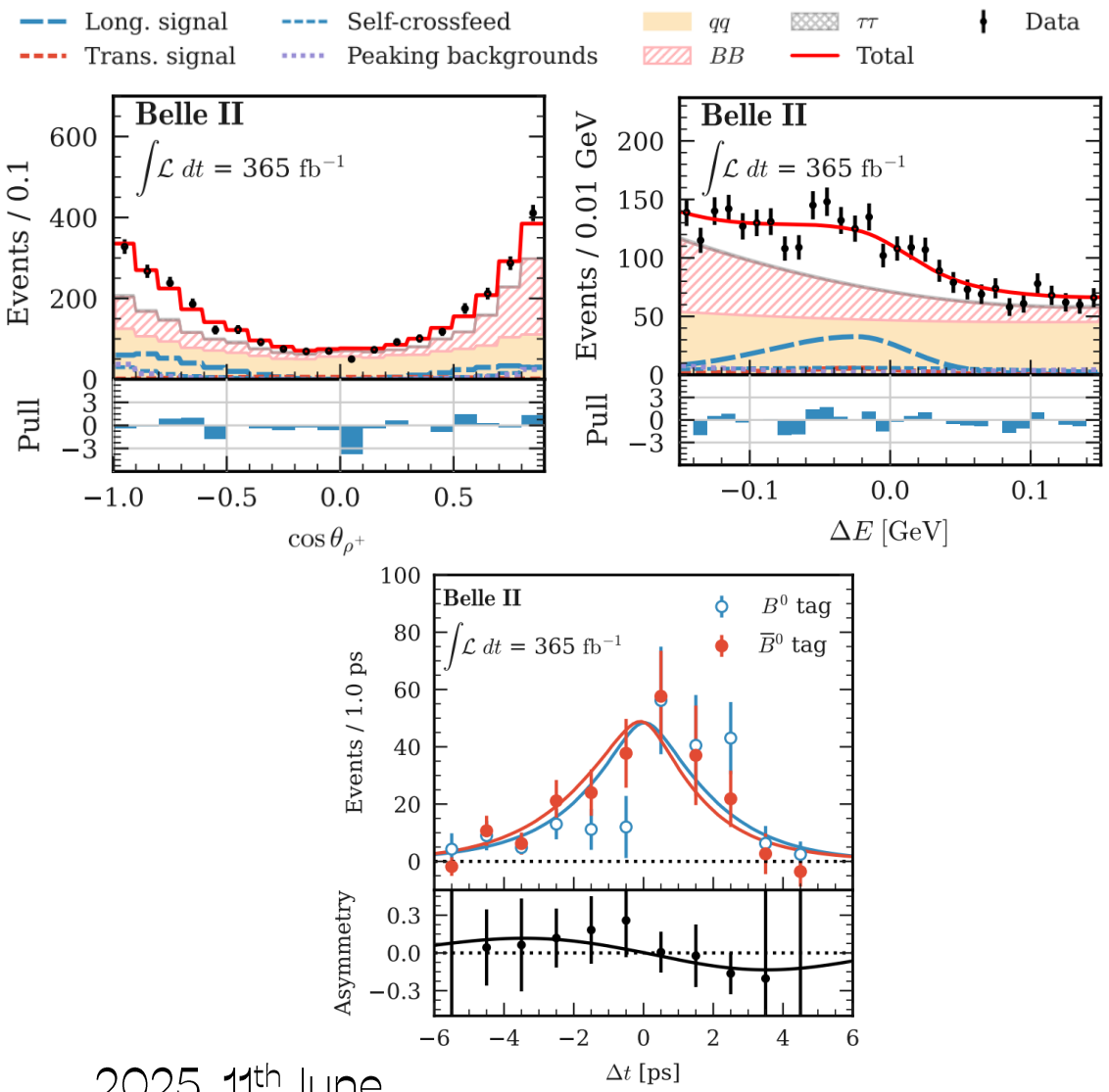
Challenging due to presence of *4 photons* in the final state.



Longitudinal polarisation fraction

$$\frac{1}{\Gamma}\frac{\partial^2\Gamma}{\partial\cos\theta_{\rho^+}\partial\cos\theta_{\rho^-}} = \frac{9}{4}\left[\frac{1}{4}(1-f_L)\sin^2\theta_{\rho^+} + \right.$$
$$\left. + \sin^2\theta_{\rho^-} + f_L\cos^2\theta_{\rho^+}\cos^2\theta_{\rho^-}\right]$$

ϕ_2 from $B^0 \to \rho^+\rho^-$: Results



Boosted Decision Tree (BDT) based separation of photons from hadronic clusters

Signals are discriminated from backgrounds via M_{bc} and ΔE

Found *436±35* longitudinally polarized signal candidates, from which competitive precision on Δt–dependent *CP*–asymmetries is achieved

- *~8%* relative improvement on the precision of ϕ_2 from *$B \to \rho\rho$ isospin analysis*

$$\mathcal{B}(B^0 \to \rho^+\rho^-) = (2.89^{+0.23+0.29}_{-0.22-0.27}) \times 10^{-5}$$
$$f_L = 0.921^{+0.024+0.017}_{-0.025-0.015}$$
$$\phi_2 = \left(91.5^{+4.8}_{-5.2}\right)^\circ$$

Phys. Rev. D 111, 092001, 2025

Conclusions

Belle II continues to provide essential inputs to test the *CKM structure* of the Standard Model.

Several *world leading results* and mostly *unique measurements* with neutrals and missing energy.

Other CKM Belle II new relevant results not presented today:

- *$B \to \pi^0\pi^0$ at Belle II* → *Phys. Rev. D **111**, L071102 (2025)*
- *$B^0 \to J/\psi\pi^0$ at Belle II* → *Phys. Rev. D 111, 012011 (2025)*
- *$B^\pm \to D_{CP\pm}K^\pm$ at Belle and Belle II* → *JHEP05(2024)212*
- *$B^0 \to K_S\pi^0\gamma$ at Belle II* → *PhysRevLett.134.011802 (2025)*
- *$B^0 \to \eta' K_S$ at Belle II* → *PhysRevD.110.112002 (2024)*

Stay tuned for other important results from Belle II people

That's all!

Thanks for the attention

Backup Slides

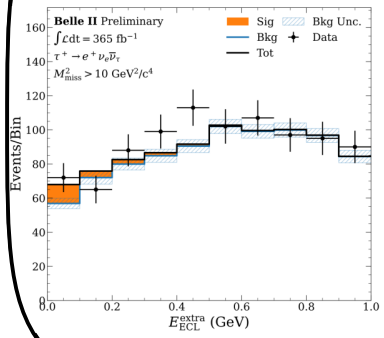
Hadronic Tag at B factories

It allows you to reconstruct decays with neutrinos (*missing energy*) in the final state or *inclusive* decays at Belle and Belle II.

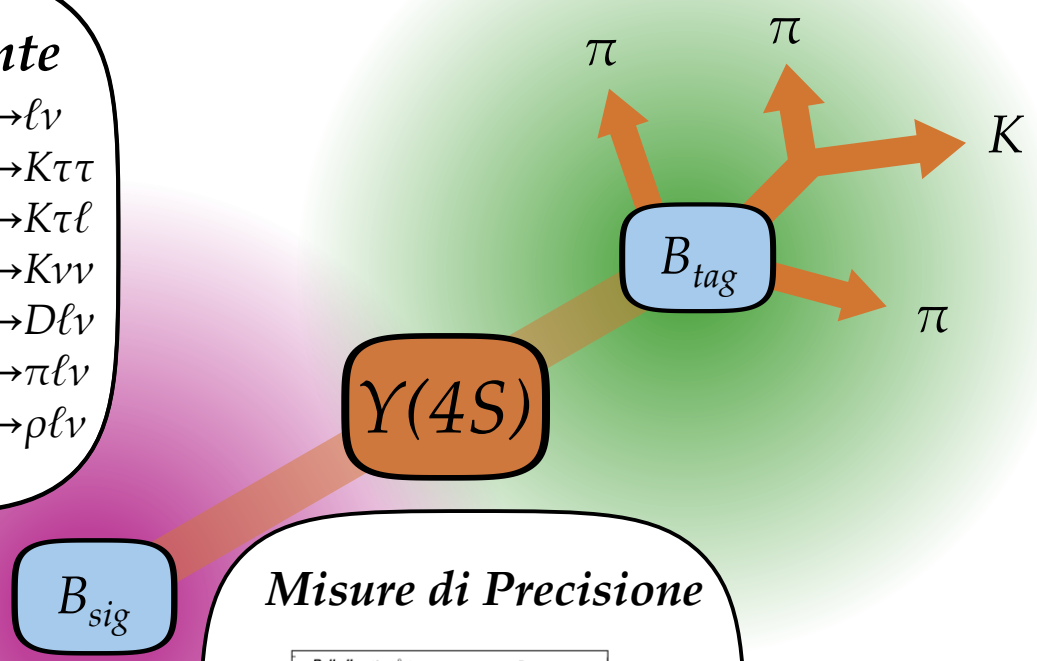
Filter out $B\overline{B}$ events with *high purity*.

It can provide the *direction of the signal B meson* and the residual energy (only for e^+e^- colliders).

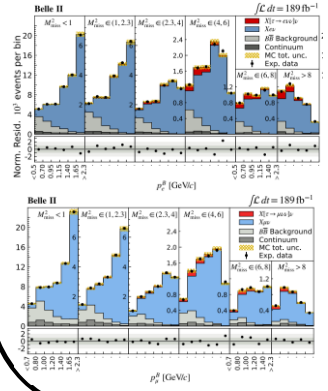
Energia Mancante



$B \to \ell\nu$
$B \to K\tau\tau$
$B \to K\tau\ell$
$B \to K\nu\nu$
$B \to D\ell\nu$
$B \to \pi\ell\nu$
$B \to \rho\ell\nu$

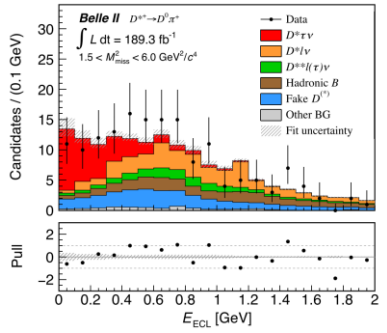


Canali Inclusivi



$B \to X_s\gamma$
$B \to X_s\nu\nu$
$B \to X\ell\nu$
$B \to X_u\ell\nu$
$B \to X\tau\nu$

Misure di Precisione



$|V_{ub}|$
$|V_{cb}|$
$R(D)$
$R(D^*)$

2025, 11th June

Giovanni Gaudino

ϕ_2 from $B^0 \to \pi^0\pi^0$ decays

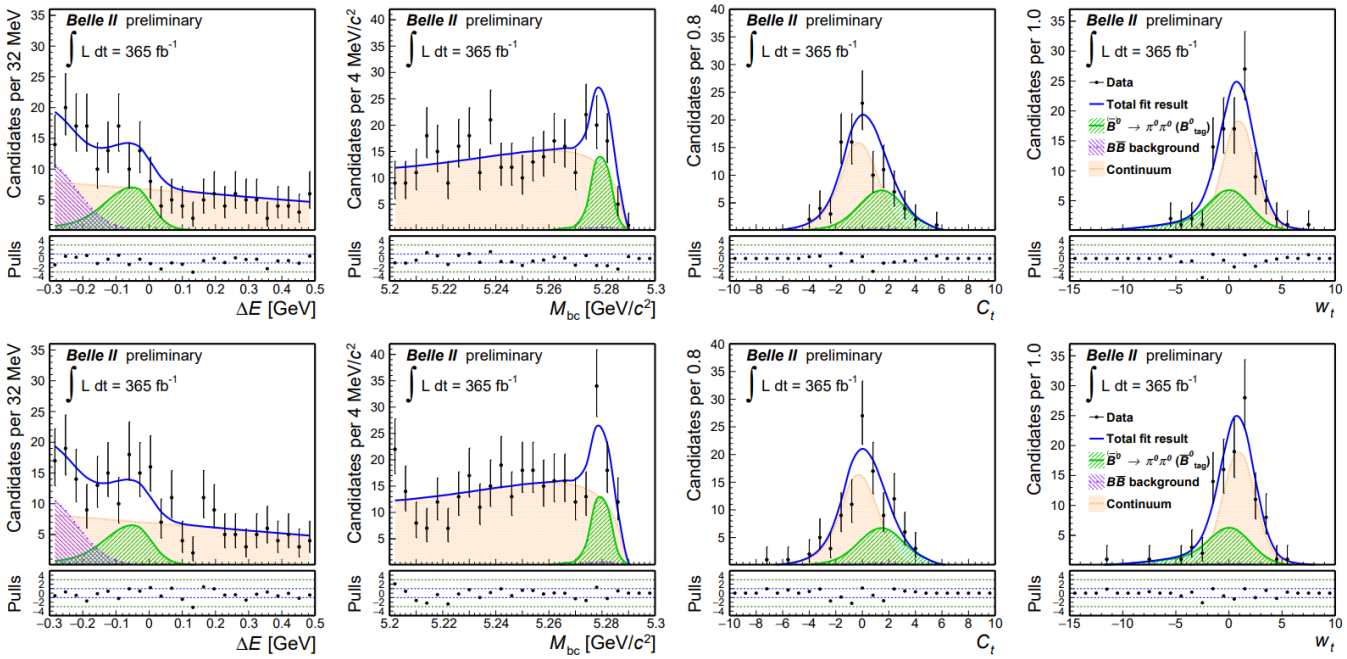
Published to PRDL: *PRD* **111, L071102**

Knowledge of Branching Fractions and CP asymmetries in $B^0 \to \pi^0\pi^0$ limits the precision on ϕ_2 extracted from the $B \to \pi\pi$ system.

Experimentally reconstruct $2\pi^0$ (*i.e.* 4 photons and no vertex) among large continuum background

Found 126 ± 20 signal candidates, achieving competitive precision on Branching Fraction and A_{CP}

- $\sim 30\%$ fractional increase in ϕ_2 precision from $B \to \pi\pi$ system including this result.



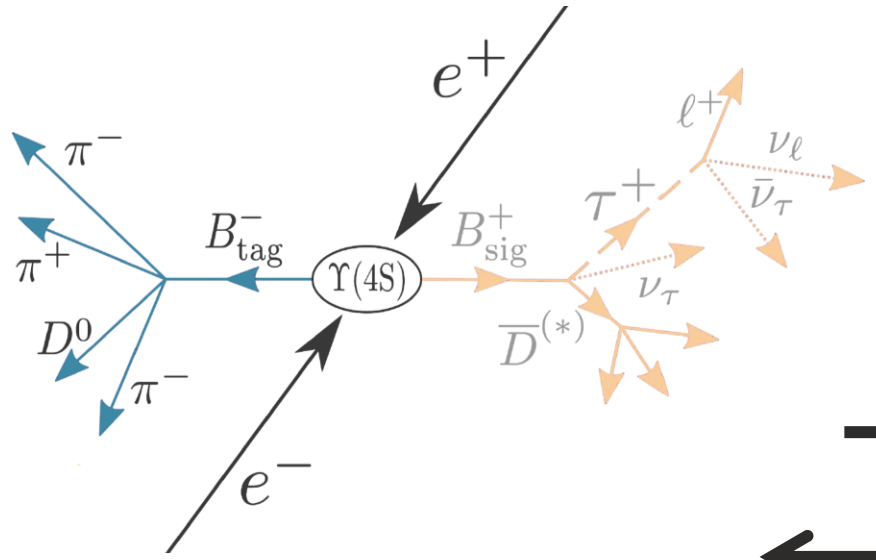
$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.25 \pm 0.20 \pm 0.11) \times 10^{-6}$$
$$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) = (0.03 \pm 0.30 \pm 0.04)$$

Missing Energy decays at Belle II

Two different algorithms to reconstruct events with at least one neutrino in the final state

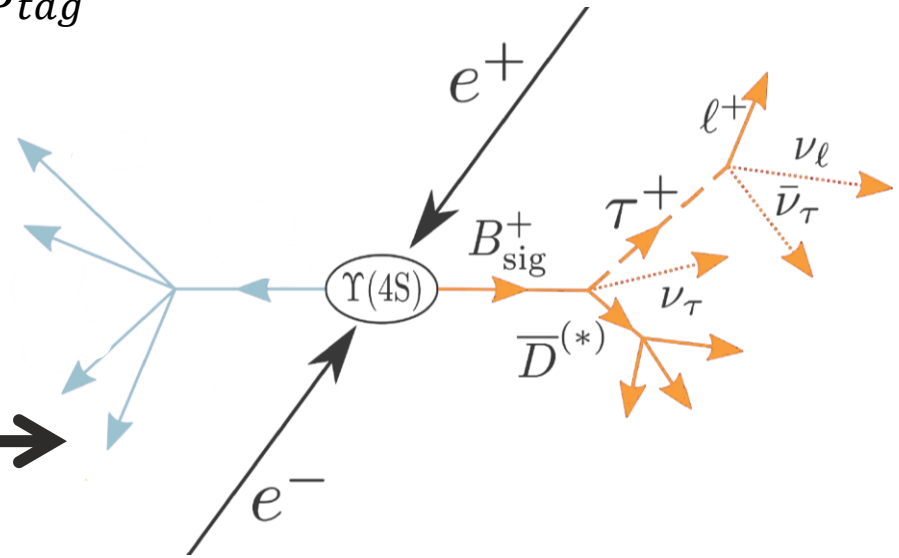
Full Event Interpretation (FEI):

1. Reconstruct all the decay chain of a B meson (both hadronic and semileptonic ways)
2. Search for the signal signature in the B_{tag} recoil



Inclusive Tag or Untagged:

1. Reconstruct the signal signature, identifying the B_{sig}
2. All the remaining tracks and clusters represent the B_{tag}



Efficiency →

← *Purity*