Measurements of CKM Parameters at Belle II

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(On behalf of the Belle II Collaboration)

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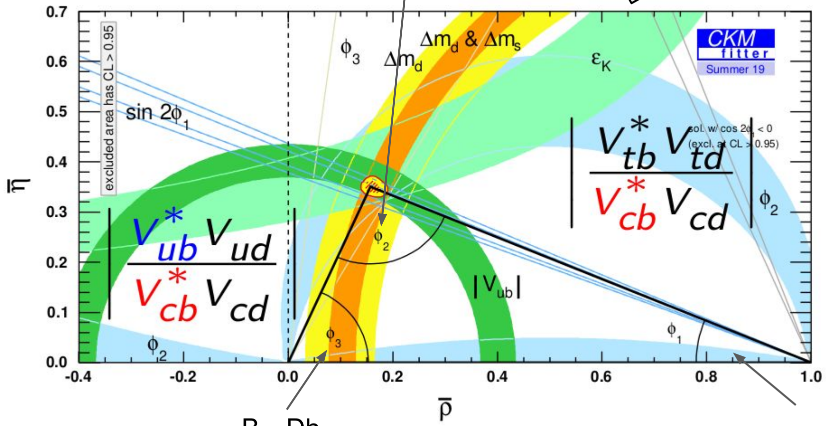
CKM matrix and unitarity triangle

Complex phase cause CP violation

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A^2\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$$V^\dagger V = 1 \Rightarrow V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

$$\lambda^3 \cdot 1 \quad \lambda^2 \cdot \lambda \quad 1 \cdot \lambda^3$$



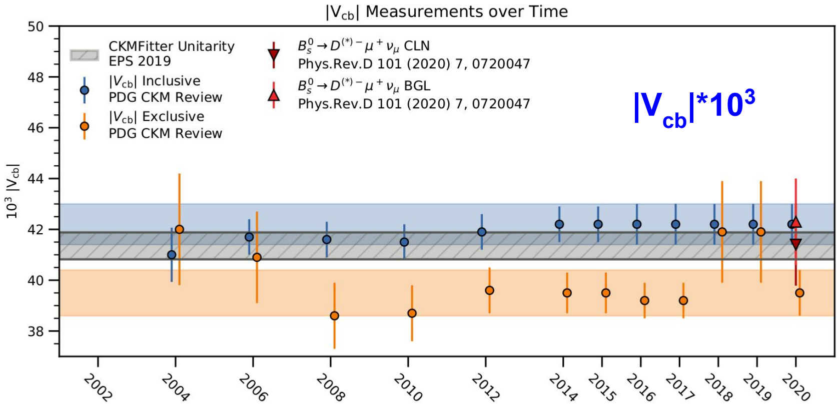
The Belle II Physics Book

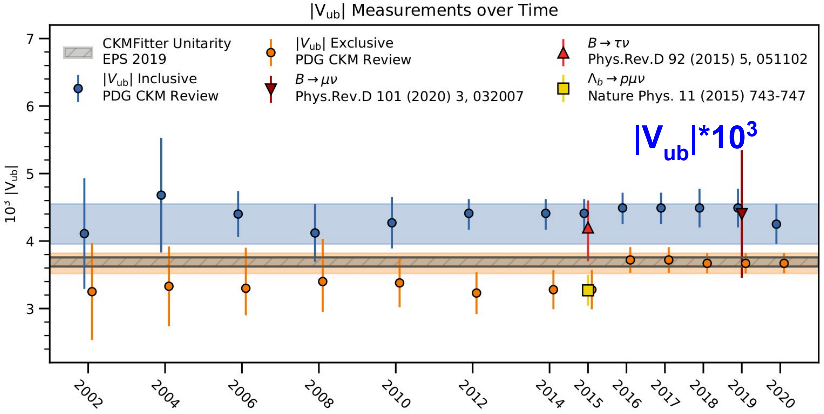
arXiv:1808.10567

Observables	Expected the. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	LHCb/Belle II
$\lvert V_{cb}\rvert$ incl.	***	1%	Belle II
$\lvert V_{cb}\rvert$ excl.	***	1.5%	Belle II
$\lvert V_{ub}\rvert$ incl.	**	3%	Belle II
$\lvert V_{ub}\rvert$ excl.	**	2%	Belle II/LHCb

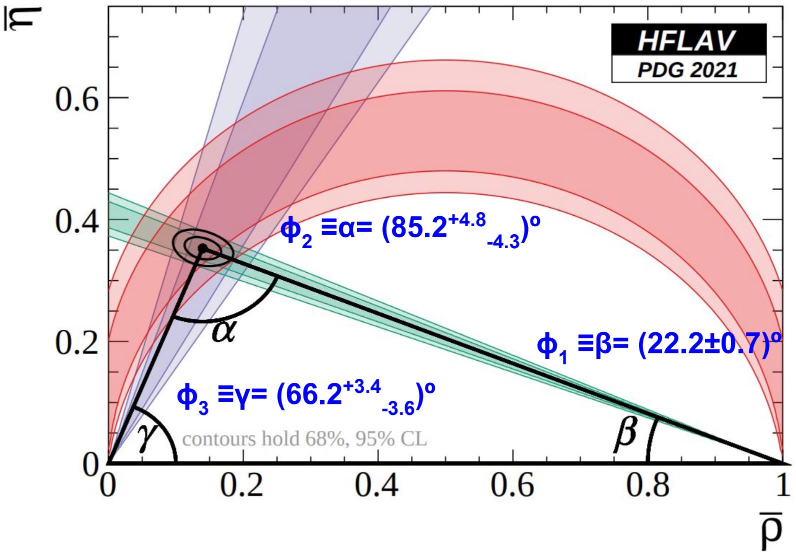
Status

※ **Tension of $|V_{cb}|$ and $|V_{ub}|$ measurements between inclusive and exclusive processes.**





※ **Status of $\sin(2\phi_1)$, ϕ_2 and ϕ_3 measurement**

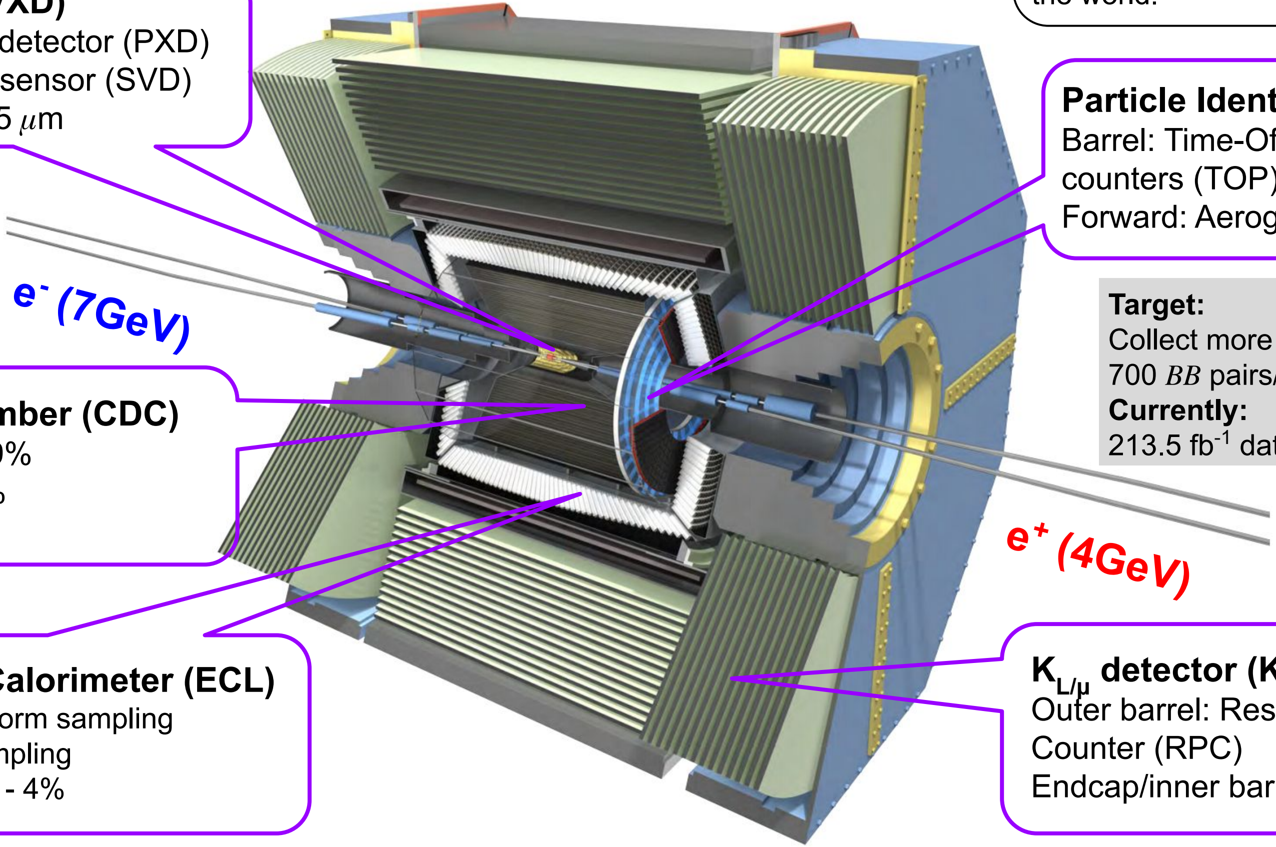


Precision of angles and sides of the unitarity triangle is an important test for the standard model.

The Belle II detector

Features:
Energy-asymmetric e^+e^- collider →low background.
Highest luminosity ($3.1\times10^{34}cm^{-2}s^{-1}$) in the world.

Vertex detector (VXD)
Inner 2 layers: pixel detector (PXD)
Outer 4 layers: strip sensor (SVD)
Vertex resolution : 15 μm



Particle Identification
Barrel: Time-Of-Propagation counters (TOP)
Forward: Aerogel RICH (ARICH)

Target:
Collect more than 50 ab^{-1} data;
700 BB pairs/second
Currently:
213.5 fb^{-1} data are collected.

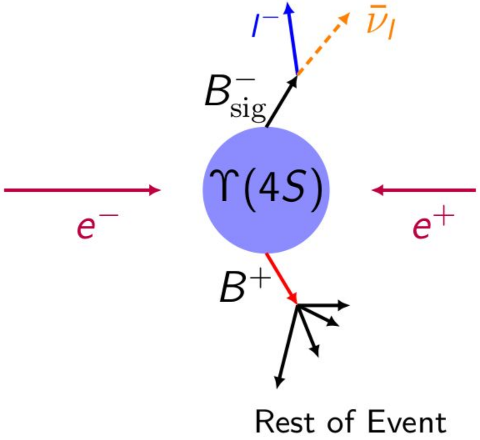
Central Drift Chamber (CDC)
Track efficiency ~ 99%
dE/dx resolution : 5%
p_T resolution : 0.4 %

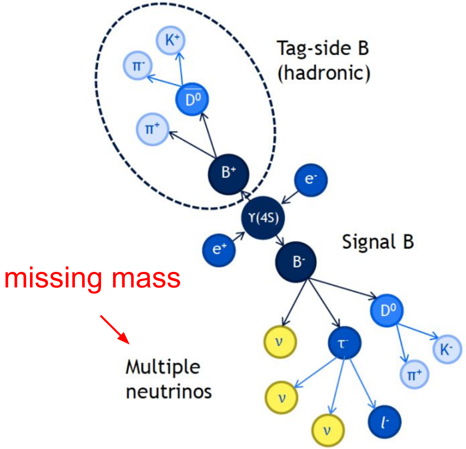
ElectroMagnetic Calorimeter (ECL)
Barrel: CsI(TI) + waveform sampling
Endcap: waveform sampling
Energy resolution : 1.6 - 4%

$K_{L/\mu}$ detector (KLM)
Outer barrel: Resistive Plate Counter (RPC)
Endcap/inner barrel: Scintillator

B decay reconstruction

- Collide e^+ and e^- at the threshold energy (10.58 GeV) to make Y(4S) particles
- Y(4S) decays to B^+B^- and B^0B^0 >96% of the time.
- Untagged approach:
  - Reconstruct signal first.
  - Inclusively sum over all tracks and clusters in remaining event or use only signal side information
  - High efficiency but large background
- Tagged approach:
  - Reconstruct one B meson as tag-side (B_{tag})
  - Study remaining B meson as signal (B_{sig})
  - Flavour and kinematic constraints: $B_{tag} \Rightarrow B_{sig}$

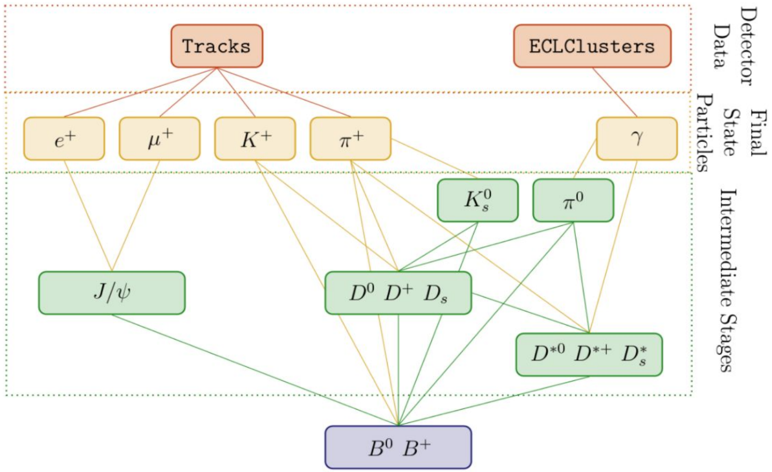




Full Event Interpretation (FEI)

Advanced tagging technique

The FEI uses a **multivariate technique** to reconstruct the B-tag side (hadronic or semileptonic) through O(10^3) decay modes in a Υ(4S) decay.



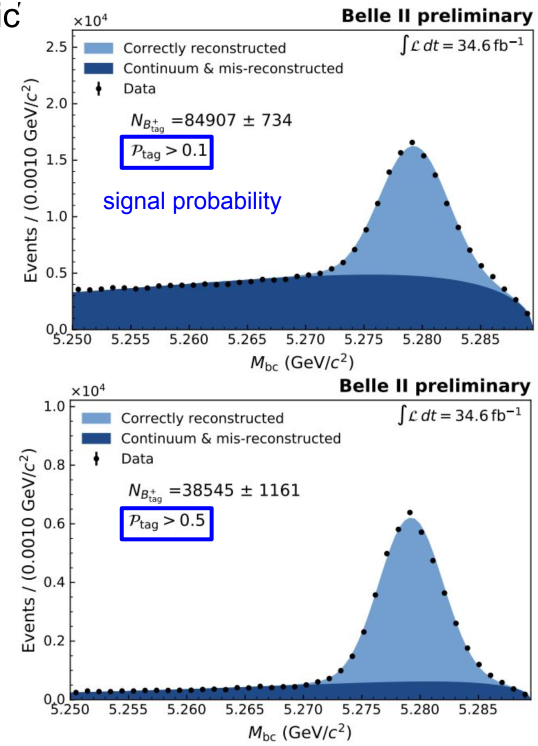
Tagging efficiency of FEI (evaluated on Belle MC)

ε_{tag} for had.: 0.78%(B^+), 0.46%(B^0)
ε_{tag} for SL: 1.80%(B^+), 2.04%(B^0)

Comput Softw Big Sci (2019) 3: 6

Had. tagging with Belle II data

arXiv:2008.06096

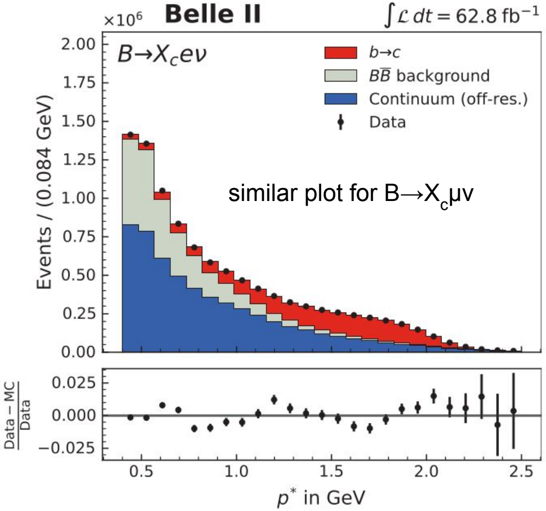


Determine the correctly reconstructed tag-side yield by fitting $m_{bc} = \sqrt{E^2_{beam}/4 - p^{*2}_{B_{tag}}}$.

Inclusive $|V_{cb}|$ measurement

- Measure the **spectral moments** (moments of lepton energy or hadronic mass) in order to simultaneously determine the non-perturbative elements and $|V_{cb}|$. Details about this approach: JHEP02(2019)177

Untagged $B \to X_c \ell \nu$ arXiv:2103.02629



similar plot for $B \to X_c \mu \nu$

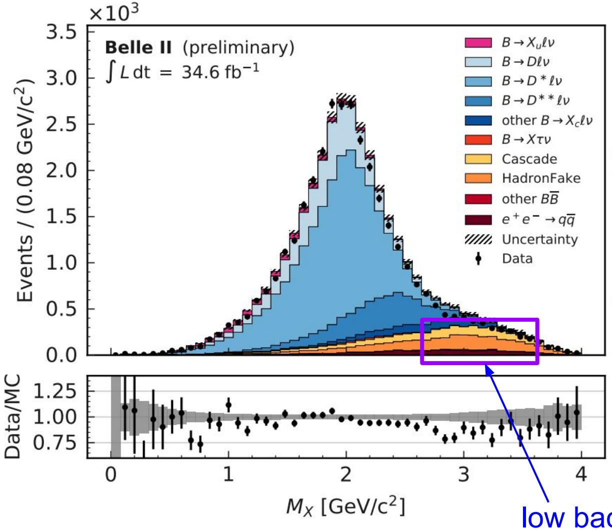
Demand one well-identified lepton.

Exploit missing mass and momentum to reject backgrounds.

Obtained BF($B \to X_c \ell \nu$): $(9.75 \pm 0.03_{stat} \pm 0.47_{sys})\%$

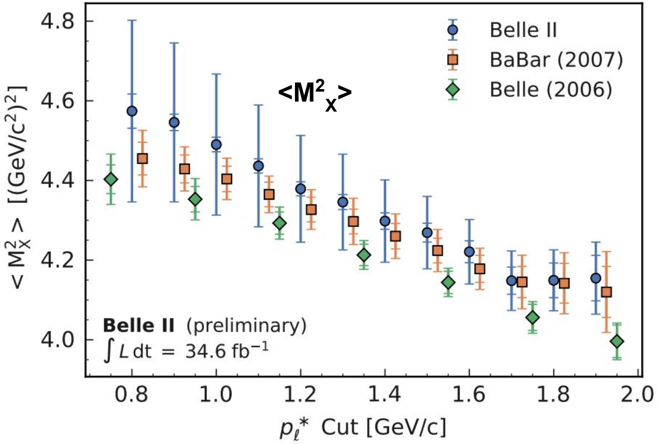
Main source: the knowledge of $B \to X_c \ell \nu$ composition.

Had. Tagged $B \to X_c \ell \nu$ arXiv:2009.04493



low background

Measured $\langle M^2_X \rangle$ moments as a function of different p^*_l cuts

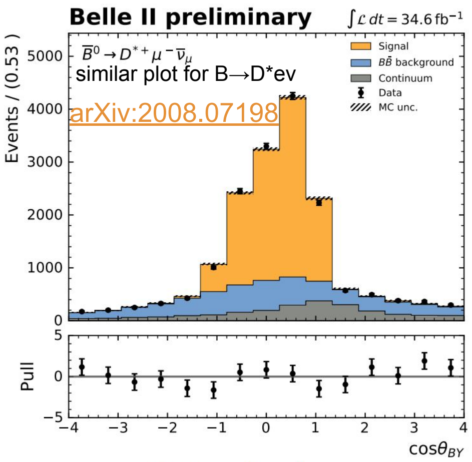


Measure the first six **hadronic mass moments.**

Next: $|V_{cb}|$ extraction from $q^2=(p_B-p_X)^2$ moments.

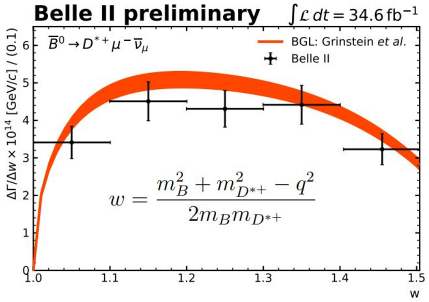
Exclusive $|V_{cb}|$ measurement

Untagged $B^0 \to D^{*-}\ell^+\nu$



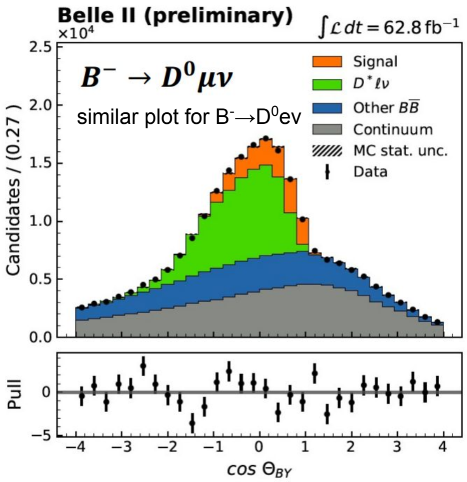
$$\cos\theta_{BY} = \frac{2E_B^* E_Y^* - m_B^2 - m_Y^2}{2|p_B^*||p_Y^*|}$$

Y: D*ℓ system



Unfolded w spectrum agrees with previous analysis well.

Untagged $B^- \to D^0\ell^-\nu$



Measured BR($B^- \to D^0\ell^-\nu$):

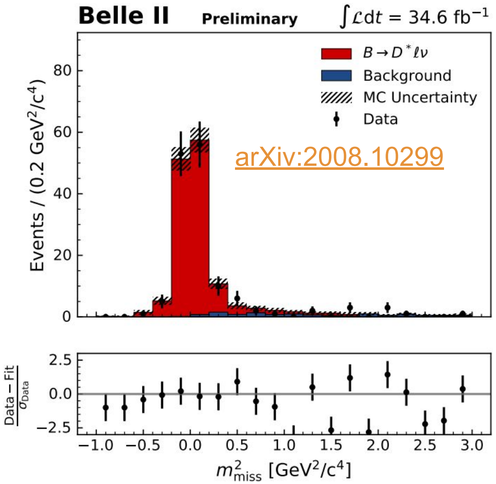
$$(2.29 \pm 0.05_{\text{stat}} \pm 0.08_{\text{syst}})\%$$

PDG value:

$$(2.35 \pm 0.09)\%$$

Plan: $|V_{cb}|$ measurement, analysis of angular observables, e.g., A_{FB}.

Hadronically tagged $B^0 \to D^{*-}\ell^+\nu$



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

Measured BR($B^0 \to D^{*-}\ell^+\nu$):

Untagged: $(4.60 \pm 0.05_{\text{stat}} \pm 0.17_{\text{syst}} \pm 0.45_{\pi_s})\,\%$

Tagged: $(4.51 \pm 0.41_{\text{stat}} \pm 0.27_{\text{syst}} \pm 0.45_{\pi_s})\,\%$

BR($B^0 \to D^{*-}\ell^+\nu$) PDG value:

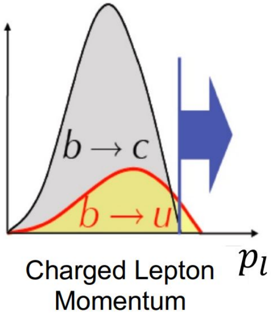
$$(5.05 \pm 0.14)\,\%$$

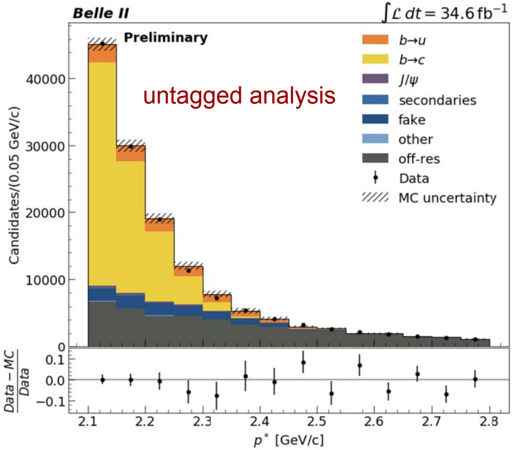
Inclusive $|V_{ub}|$ measurement

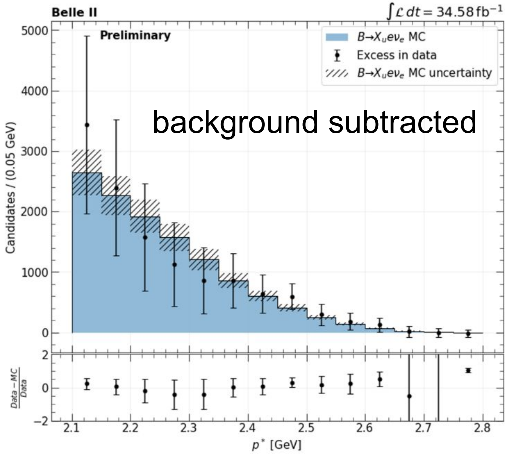
BELLE2-NOTE-PL-2020-026

- Challenge in the measurement of $B \to X_u \ell \nu$:
  - large background from $b \to c$ events
- To suppress charm decay, exploit the lepton momentum endpoint, where $b \to c$ component is relatively small

- Analysis strategy:
  - select one well-identified electron
  - extract signal yield by fitting electron momentum in the center-of-mass frame







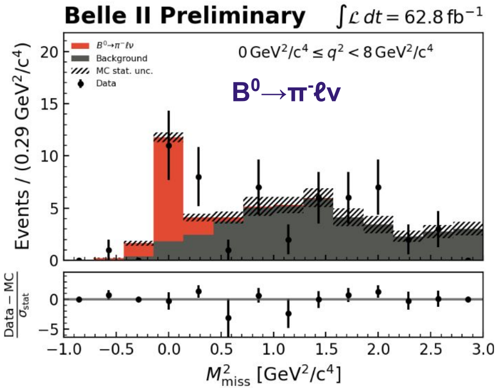
- Background substracted distribution is consistent with $B \to X_u \ell \nu$ prediction. The significance of the yield is 3σ.

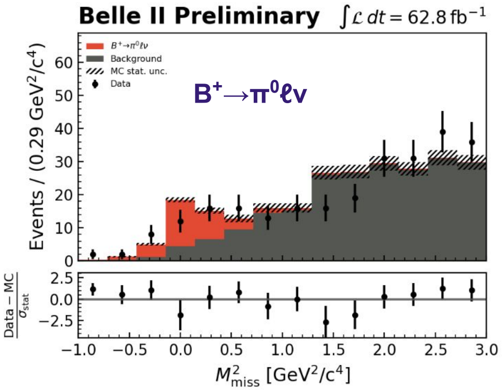
Capable of measuring $|V_{ub}|$ with more data.

Exclusive $|V_{ub}|$ measurement

BELLE2-CONF-PH-2021-013

Hadronically tagged $B \to \pi \ell \nu$





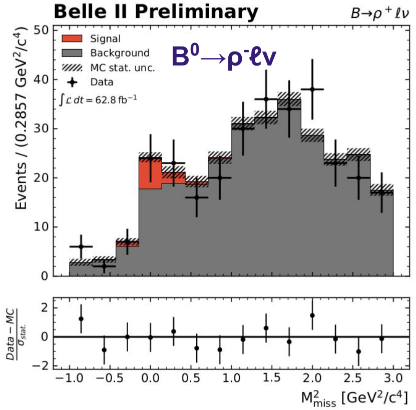
$B \to \pi^+ \ell \nu$ in first q^2 bin

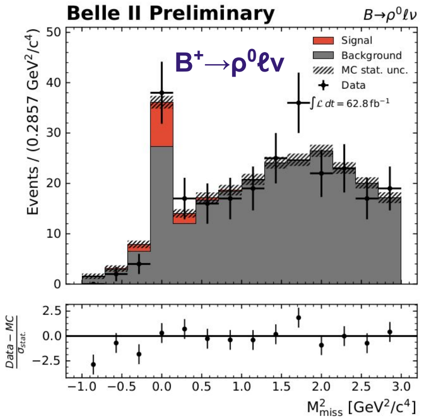
$\mathcal{B}(B^0 \to \pi^- \ell \nu) = (1.47 \pm 0.29_{stat} \pm 0.05_{sys})\%$

$\mathcal{B}(B^+ \to \pi^0 \ell \nu) = (8.29 \pm 1.99_{stat} \pm 0.46_{sys})\%$

Calculate the sum of the partial branching fractions in three bins of q^2.

Hadronically tagged $B \to \rho \ell \nu$





$\mathcal{B}(B^0 \to \rho^- \ell \nu) = (1.51 \pm 1.13_{stat} \pm 0.09_{sys})\%$

$\mathcal{B}(B^+ \to \rho^0 \ell \nu) = (9.26 \pm 6.33_{stat} \pm 0.38_{sys})\%$

relatively lower statistical uncertainty → promising for precise $|V_{ub}|$ measurement

- Extract signal yield for each channel by fitting m^2_{miss}.
- All branching ratios are in agreement with PDG values.
- Untagged exclusive $|V_{ub}|$ measurement is also on-going.

Measurement of $\sin(2\phi_1)$

BELLE2-NOTE-PL-2020-11

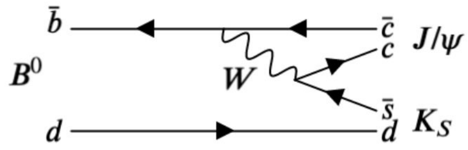
$$\mathcal{A}_f(\Delta t) = \frac{\Gamma(\bar{B}^0 \to J/\psi K_S^0) - \Gamma(B^0 \to J/\psi K_S^0)}{\Gamma(\bar{B}^0 \to J/\psi K_S^0) - \Gamma(B^0 \to J/\psi K_S^0)} = S_f \sin(\Delta m_B \Delta t) + A_f \cos(\Delta m_B \Delta t)$$

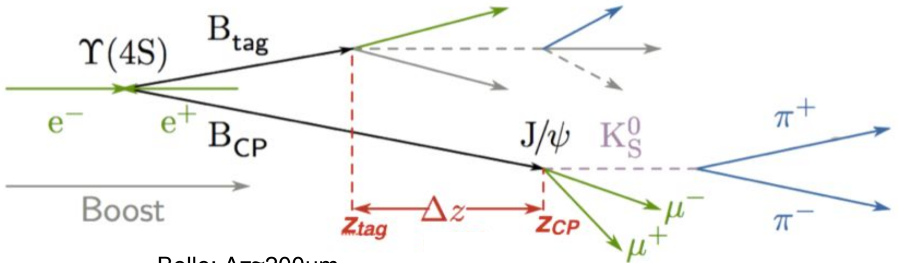
Δm_B is meaused by $B^0 B^0$ mixing

Assume no direct CPV: Af ~ 0

Golden mode: $B^0 \to J/\psi K^0$

(tree-level decay)





Belle: $\Delta z \approx 200\mu m$

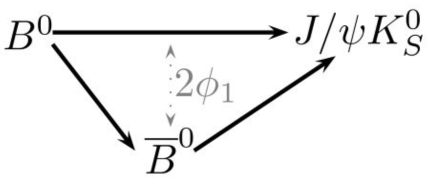
Belle II: $\Delta z \approx 130\mu m$

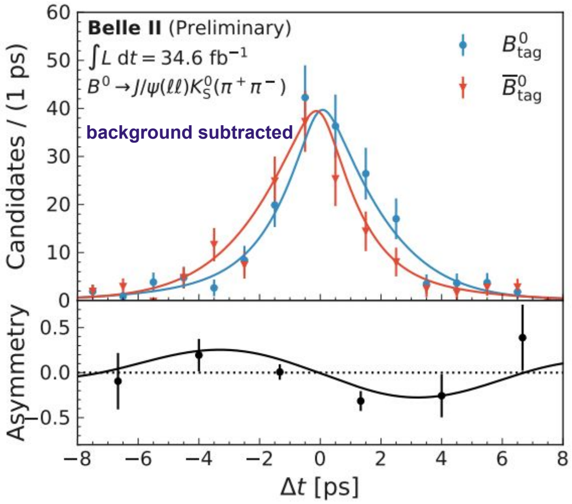
with better Δz resolution

distance measurement

$\Delta t = \Delta z / (\beta\gamma c)$

time measurement





$\sin(2\phi_1) \approx Sf = 0.55 \pm 0.21_{stat} \pm 0.04_{sys}$

world average: 0.699 ± 0.017

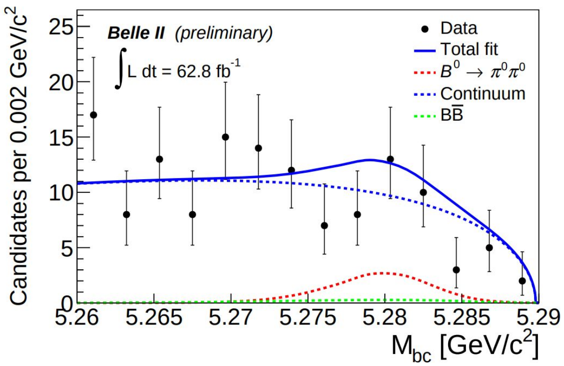
Toward ϕ_2

Unique Belle II capability to study all the $B \to \pi\pi$, $\rho\rho$ partner decays to determine ϕ_2

$B^0 \to \pi^0\pi^0$: very challenging because four γ's.
Train BDT to suppress background photons.
3D fit of ΔE-Mbc-continuum suppression BDT.
Unique Belle II reach.

$\mathcal{B}(B^0 \to \pi^0\pi^0) = (0.98^{+0.48}_{-0.39}(\text{stat}) \pm 0.27(\text{syst})) \times 10^{-6}$

arXiv:2107.02373



$B^+ \to \rho^+\rho^0$: π-only final state, large background because of ρ mass width. Additional challenge of angular analysis→6D fit including helicity angles.

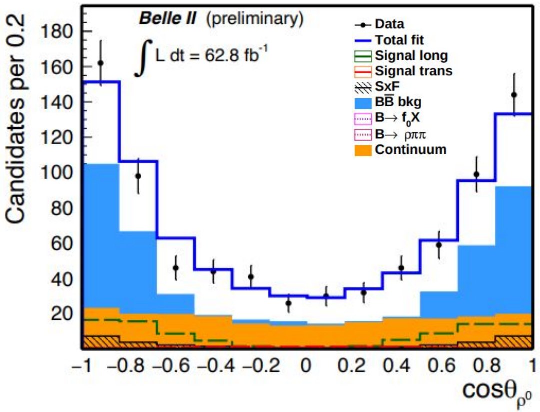
longitudinal polarization fraction

$f_L(B^+ \to \rho^+\rho^0) = (0.936^{+0.049}_{-0.041}(\text{stat}) \pm 0.021(\text{syst}))$

$\mathcal{B}(B^+ \to \rho^+\rho^0) = (20.6 \pm 3.2(\text{stat}) \pm 4.0(\text{syst})) \times 10^{-6}$

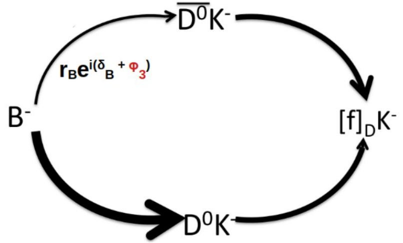
arXiv:2109.11456

20% precision improvement wrt Belle on the same lumi!



On track to measure the CKM angle ϕ_2 at Belle II

Toward ϕ_3



important set of observables:

$$R^{(*)0} = \frac{\Gamma(B^- \to D^{(*)0}K^-)}{\Gamma(B^- \to D^{(*)0}\pi^-)}$$

$$R^{(*)+} = \frac{\Gamma(\bar{B}^0 \to D^{(*)+}K^-)}{\Gamma(\bar{B}^0 \to D^{(*)+}\pi^-)}$$

$$\frac{\mathcal{A}^{\text{suppr.}}(B^- \to \overline{D^0}K^-)}{\mathcal{A}^{\text{favor.}}(B^- \to D^0K^-)} = r_B e^{i(\delta_B + \phi_3)}$$

The most sensitive mode to determine ϕ_3

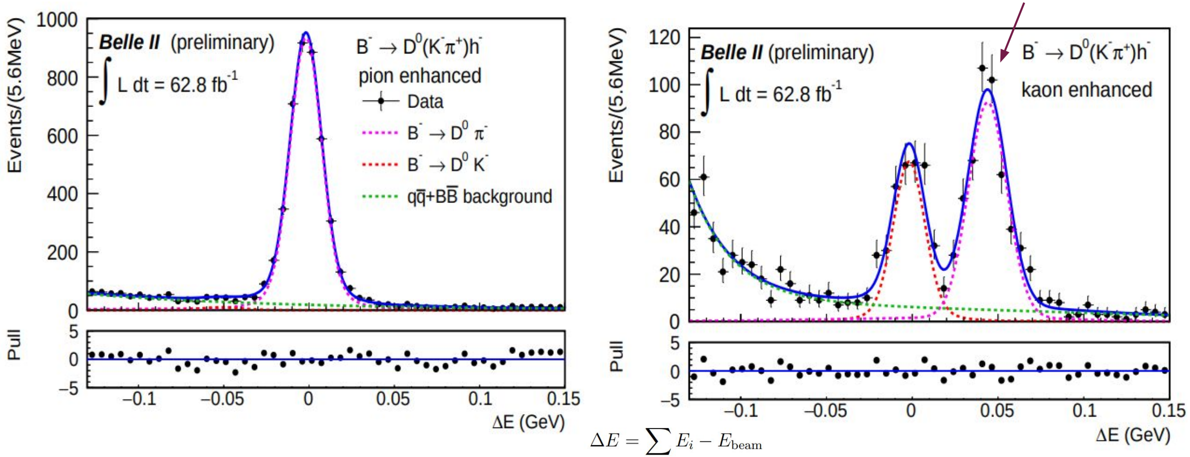
$$B^- \to D^0(K_S^0\pi^+\pi^-)K^-$$

for this mode, fit not only ΔE but also the output from fast boosted decision tree

arXiv:2104.03628

simultaneous fit to pion and kaon enhanced samples

misidentification of the charged pion as a kaon



$$\Delta E = \sum_i E_i - E_{\text{beam}}$$

results comparsion

	$B^- \to D^0(K^-\pi^+)h^-$	$B^- \to D^0(K_S^0\pi^+\pi^-)h^-$	$\bar{B}^0 \to D^+h^-$
Belle II $R^{+/0}$ ($\times 10^{-2}$)	$7.66 \pm 0.55\ ^{+0.11}_{-0.08}$	$6.32 \pm 0.81\ ^{+0.09}_{-0.11}$	$9.22 \pm 0.58 \pm 0.09$
LHCb $R^{+/0}$ ($\times 10^{-2}$)	$7.77 \pm 0.04 \pm 0.07$	$7.77 \pm 0.04 \pm 0.07$	$8.22 \pm 0.11 \pm 0.25$

Expect 1.6° precision on ϕ_3 with 50 ab^{-1} dataset.

Summary and prospects

- Precision measurement of CKM parameters is a keystone of Belle II program
- Intensive activity ongoing on early data to prepare measurements of UT angles and sides
- Preliminary results are reported based on 30-60/fb on BF for determining |Vcb| and |Vub|, $\sin(2\phi_1)$, $B \to DK$ parameters sensitive to ϕ_3, and $B \to \pi^0\pi^0/\rho^+\rho^0$ parameters sensitive to ϕ_2

Backup

Comparison with LHCb

Property	LHCb	Belle II
$\sigma_{b\bar{b}}$ (nb)	~150,000	~1
$\int L\,dt$ (fb^{-1})	~25	~50,000
Background level	High	Low
Typical efficiency	Low	High
π^0, K_S efficiency	Low	High
Initial state	Not well known	Well known
Decay-time resolution	Excellent	Good
Collision spot size	Large	Tiny
Heavy bottom hadrons	B_s, B_c, b-baryons	Partly B_s
τ physics capability	Limited	Excellent
B-flavor tagging efficiency	3.5 - 6%	36%