Recent Belle II results on the CKM parameters $|V_{cb}|$ and $|V_{ub}|$

July 8, 2022 ICHEP

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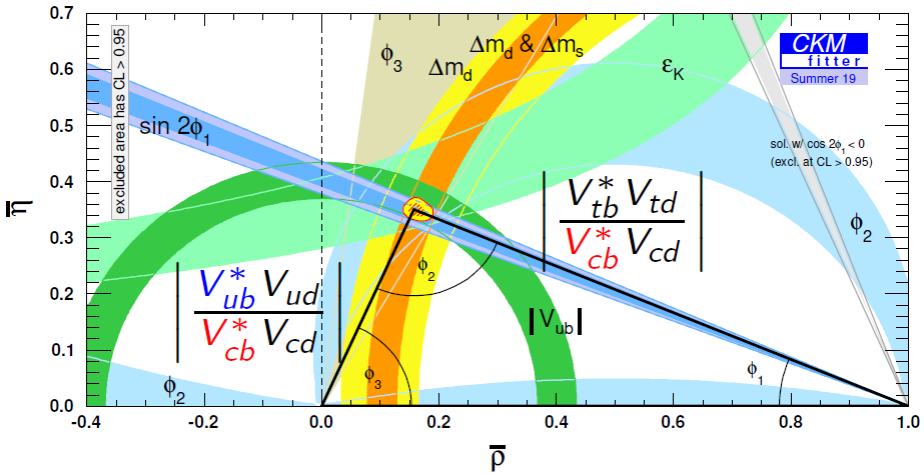
Determination of CKM parameters

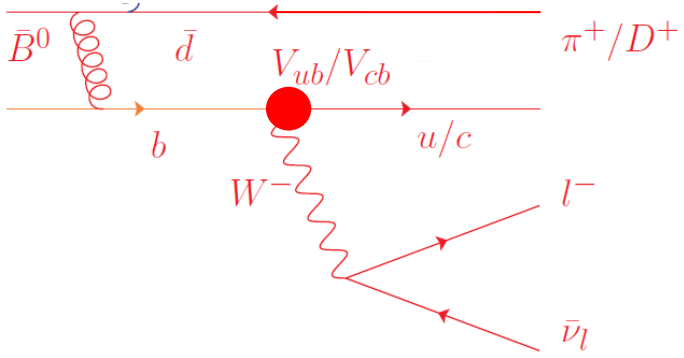
-Essential references for the standard model quark dynamics

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

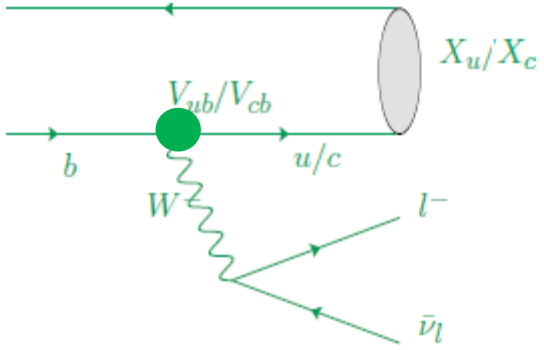


-$|V_{cb}|$ and $|V_{ub}|$ are measured precisely with semileptonic B decays

Exclusive: B→π/ρ ℓν, B→D(*)ℓν etc.



Inclusive: B→X_uℓν, B→X_cℓν



Parameter	Exclusive	Inclusive
$\|V_{cb}\| \times 10^{-3}$	39.10±0.50	42.19±0.78
$\|V_{ub}\| \times 10^{-3}$	3.51±0.12	4.19±0.12

HFLAV, arXiv:2206.07501

discrepancy between inclusive and exclusive

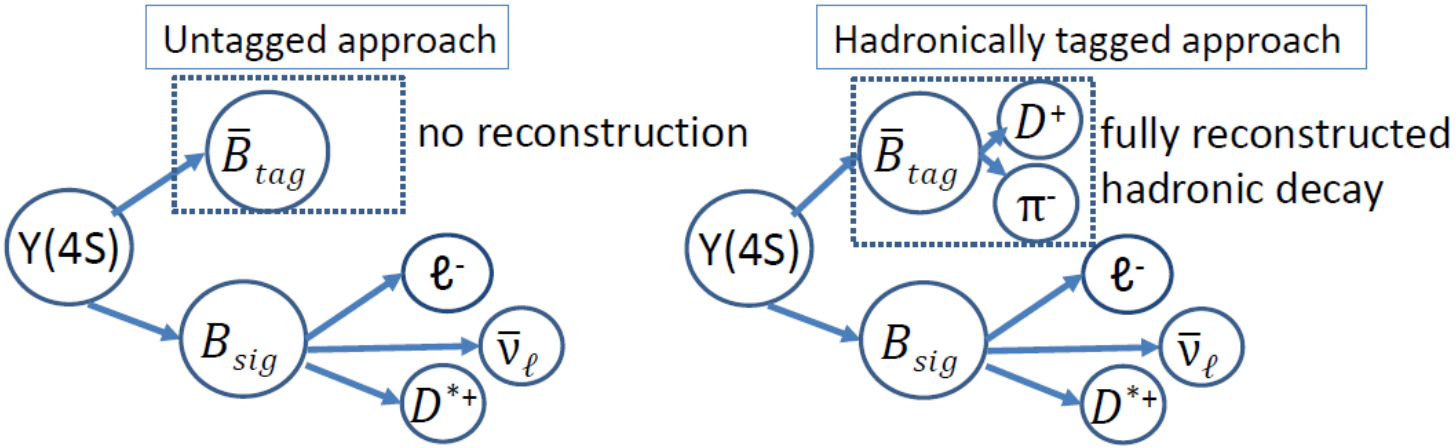
Measurement of $|V_{cb}|$ and $|V_{ub}|$ at Belle II

-Belle II at SuperKEKB: on-threshold $B\bar{B}$ production from $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B_{sig}\,\bar{B}_{tag}$, reconstructed with hermetic detector

-Today: four results based on exclusive signal reconstruction with and without reconstructing partner B_{tag}

$\lvert V_{xb}\rvert$	Signal B (B_{sig}) decay	Other B (B_{tag}) decay	Latest result
$\lvert V_{cb}\rvert$	$B_{sig} \rightarrow D\ell\nu$ (ℓ=e,μ)	untagged	ICHEP 2022
$\lvert V_{cb}\rvert$	$B^0_{sig} \rightarrow D^*\ell\nu$ (ℓ=e,μ)	hadronically tagged	Moriond 2022
$\lvert V_{ub}\rvert$	$B^0_{sig} \rightarrow \pi\ell\nu$ (ℓ=e,μ)	untagged	ICHEP 2022
$\lvert V_{ub}\rvert$	$B_{sig} \rightarrow \pi e\nu$	hadronically tagged	Moriond 2022

190fb^{-1}

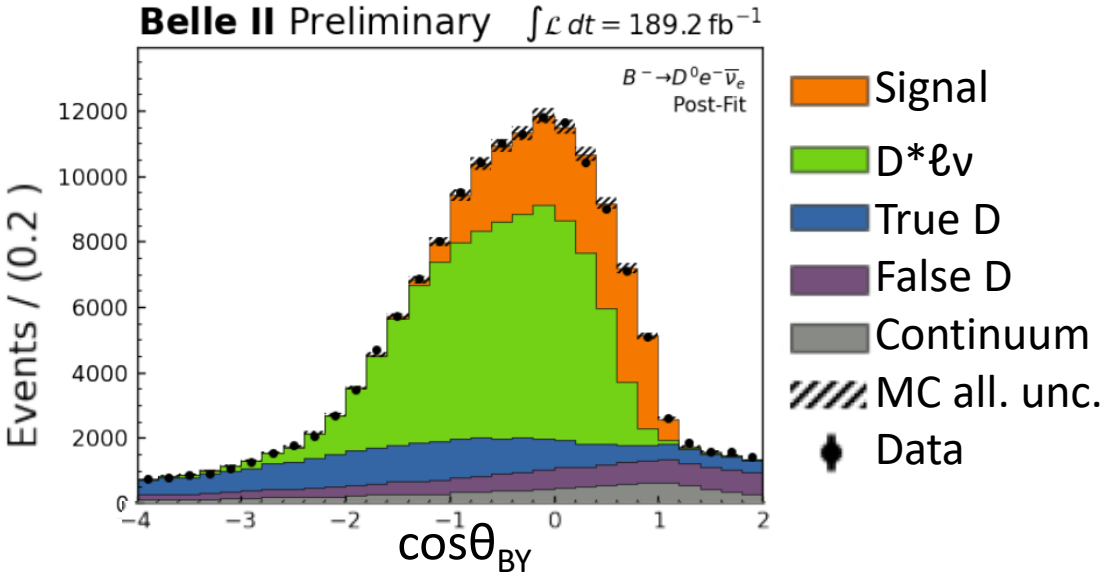


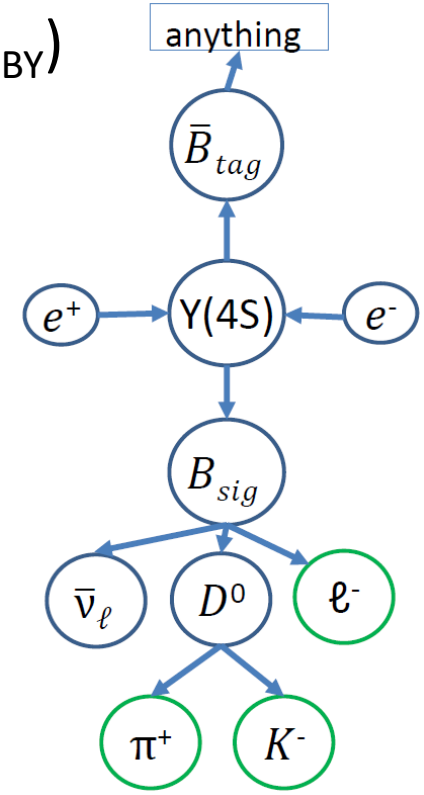
Untagged B→Dℓν: selection

-Challenge: large background from continuum and B decays

- -$B^0 \to D^- \ell^+ \nu_\ell$, $B^+ \to \bar{D}^0 \ell^+ \nu_\ell$ and cc. (ℓ=e,μ) with $D^0 \to K^- \pi^+$ or ($D^- \to K^+ \pi^- \pi^-$)
- -K, π, ℓ: reconstructed by tracking and particle ID detectors
- -D: reconstruct mass with K and π
- -D* veto: reject B→D*ℓν candidates
- -Event shape and energy cuts for background rejection

-Signal is extracted from angle between B and Dℓ ($\cos\theta_{BY}$)





	$B^- \to D^0 e^- \bar{\nu}_e$	$B^- \to D^0 \mu^- \bar{\nu}_\mu$	$B^0 \to D^- e^+ \nu_e$	$B^0 \to D^- \mu^+ \nu_\mu$
Signal yield	27485	29015	22824	24568

Untagged B→Dℓν: result

-Differential decay width is fitted to extract $|V_{cb}|$ and form factors

-BGL parametrization (N=3) (Phys. Rev. D **56**, 6895(1997)) with lattice QCD by FNAL/MILC (Phys. Rev. D 92, 034506 (2015)), HPQCD (Erratum: Phys.Rev.D 93, 119906 (2016))

$$\frac{d\Gamma}{dw} = \frac{G_F^2 m_D^3}{48\pi^3}(m_B + m_D)^2 (w^2-1)^{3/2} \eta_{EW}^2 \mathcal{G}^2(w) |V_{cb}|^2$$

$\mathcal{G}(w)$: form factor

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

w: normalized momentum transfer, minimized at 1 with $q^2=(m_B-m_D)^2$

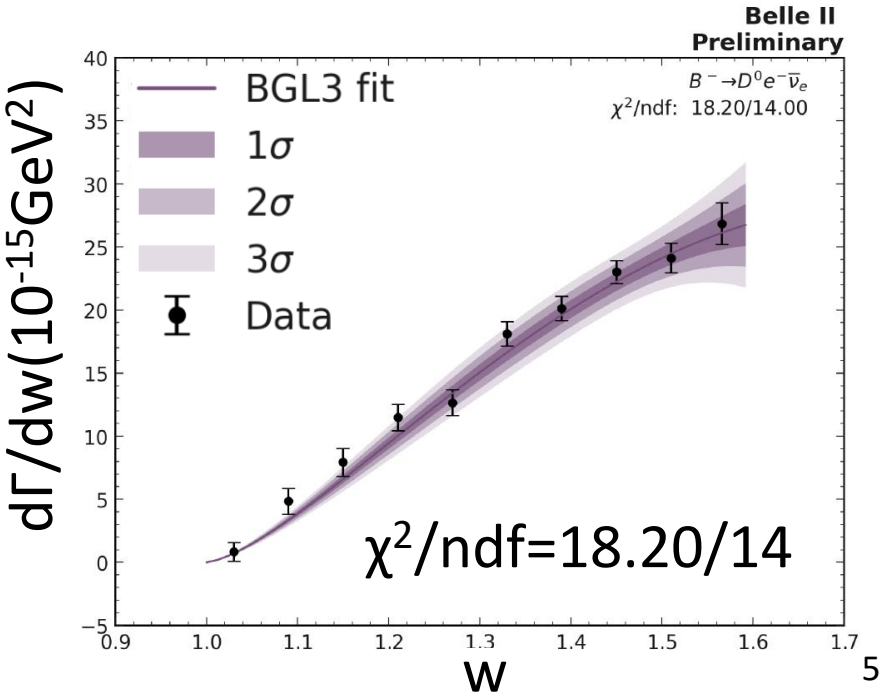
η_{EW}: electroweak correction

$$\eta_{EW}|V_{cb}| = (38.53 \pm 1.15) \times 10^{-3}$$

stat.+sys.+theo.

-~3% error, comparable to the past measurements

-Consistent with the exclusive world average



Tagged $B^0 \to D^* \ell \nu$: hadronic tag

-Challenge: low reconstruction efficiency of B_{tag}

-Full Event Interpretation algorithm to reconstruct B_{tag}

(*Comput Softw Big Sci* **3,** 6 (2019))

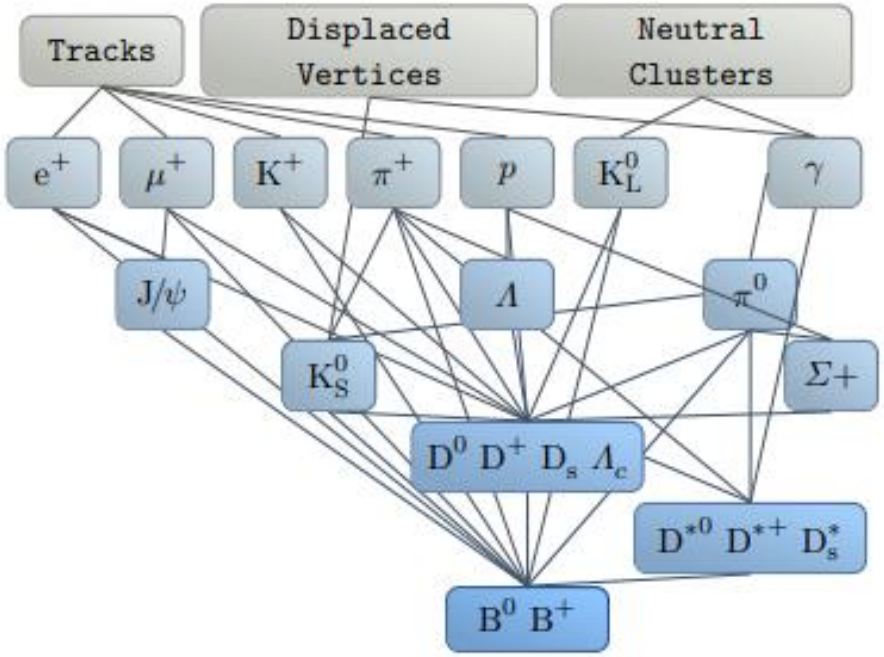
-Reconstruct B candidate with all combination of daughters

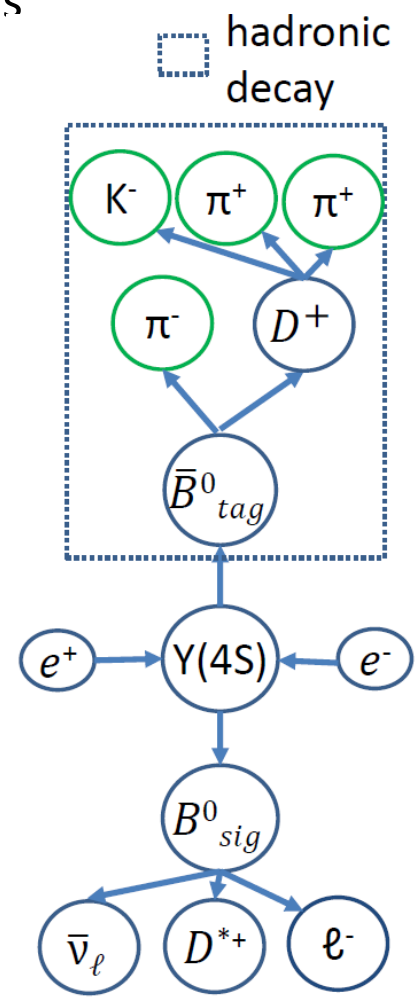
-Calculate signal probability with multivariate classifier.

Input for training: vertex, momentum, PID of daughters

-B_{tag} efficiency is ~0.27%, purity is ~15%

-calibrated with $B \to X \ell \nu$





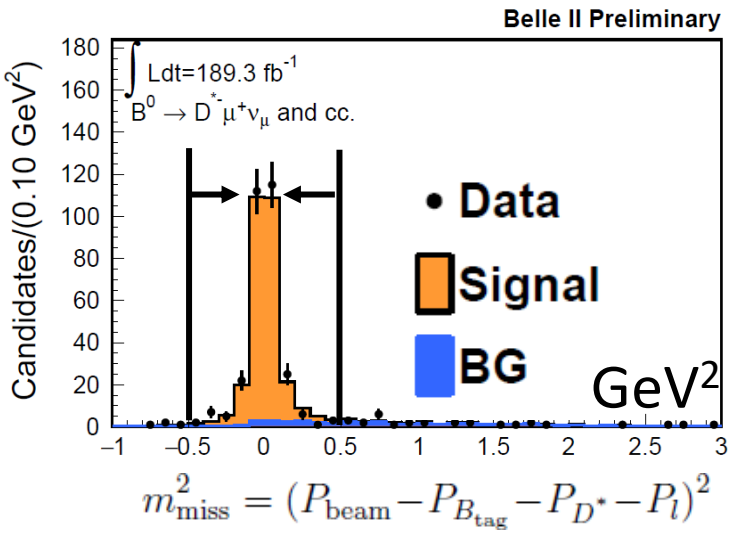
Tagged $B^0 \to D^* \ell \nu$: signal selection

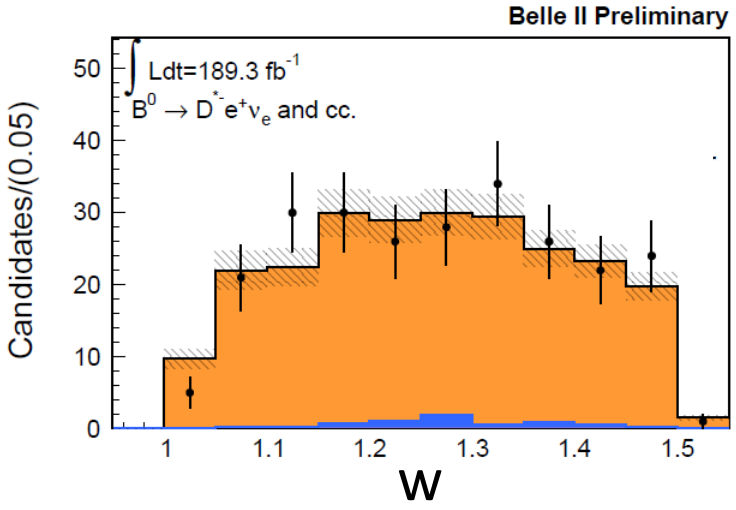
-Challenge: reconstruct low momentum pions from D*

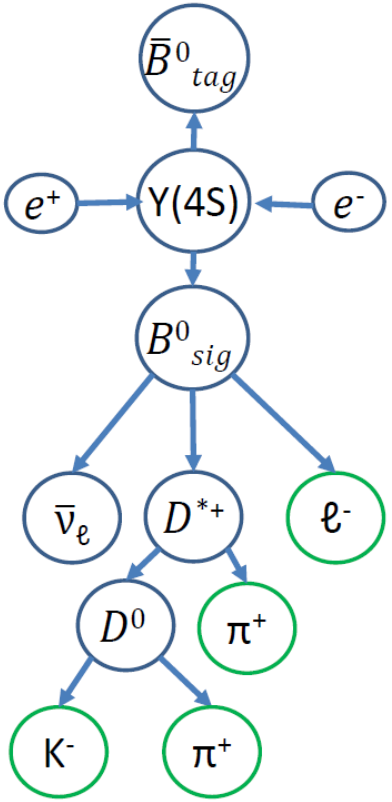
-calibrated with $B \to D^* \pi$

-$B^0 \to D^* \ell \nu$ and cc. (ℓ=e,μ) are reconstructed for $|V_{cb}|$

-Squared invariant mass of unreconstructed signal decay product (m^2_{miss}) is estimated with D*, ℓ, B_{tag} and initial beam energy







	Data	MC signal	MC BG	MC total
#selected events	545	505.6	29.4	535.0

Tagged $B^0 \to D^* \ell \nu$: result

-Differential decay width is fitted to extract $|V_{cb}|$ and form factors

-CLN parametrization

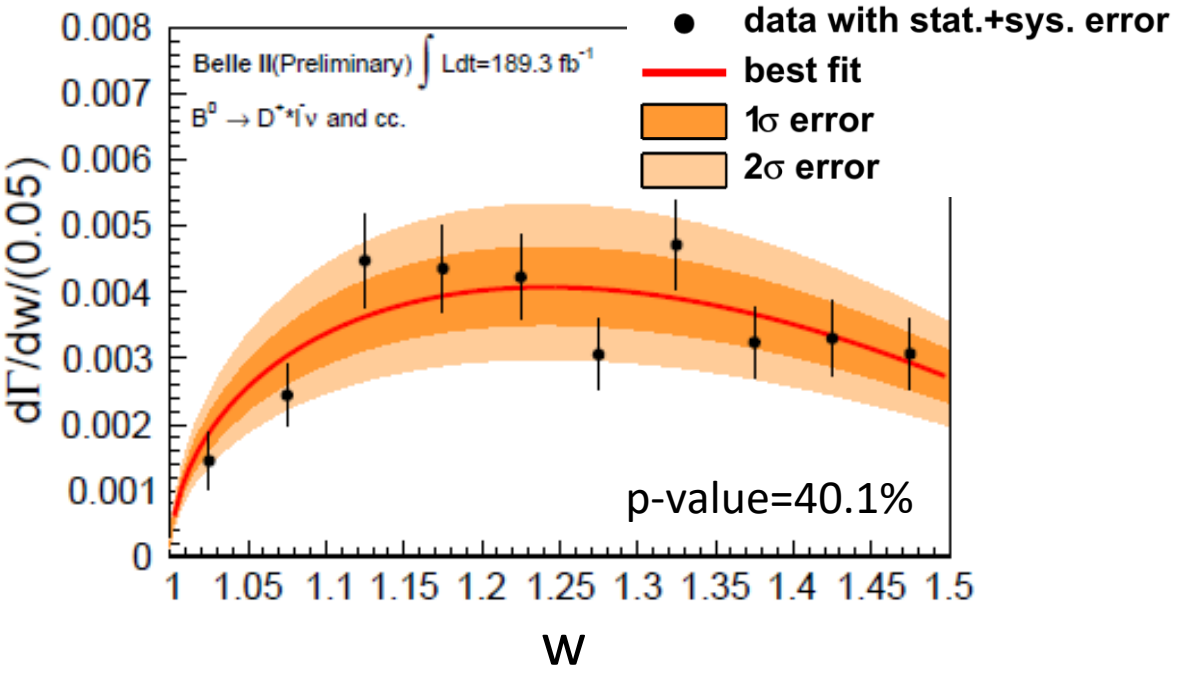
(Nuclear physics B, 530, 153 (1998))

$$\frac{d\Gamma}{dw} = \frac{\eta_{EW}^2 G_F^2}{48\pi^3} m_{D^*}^3 (m_B - m_{D^*})^2 g(w) F^2(w) |V_{cb}|^2$$

$$\eta_{EW}|V_{cb}| = (38.2 \pm 2.8) \times 10^{-3}$$

stat.+sys.+theo.

-Consistent with the exclusive world average



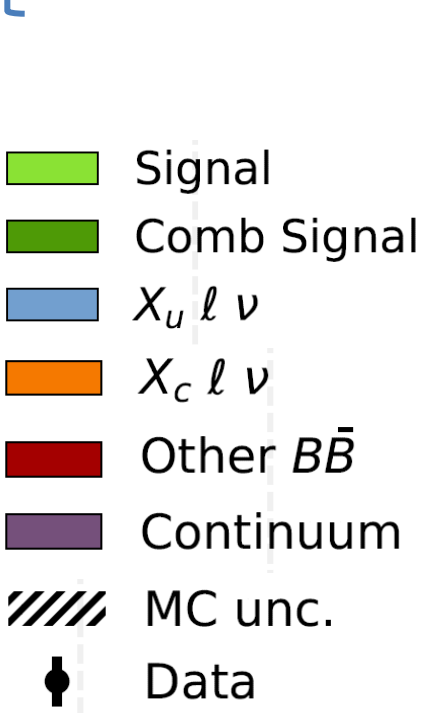
Untagged $B^0 \to \pi \ell \nu$: selection

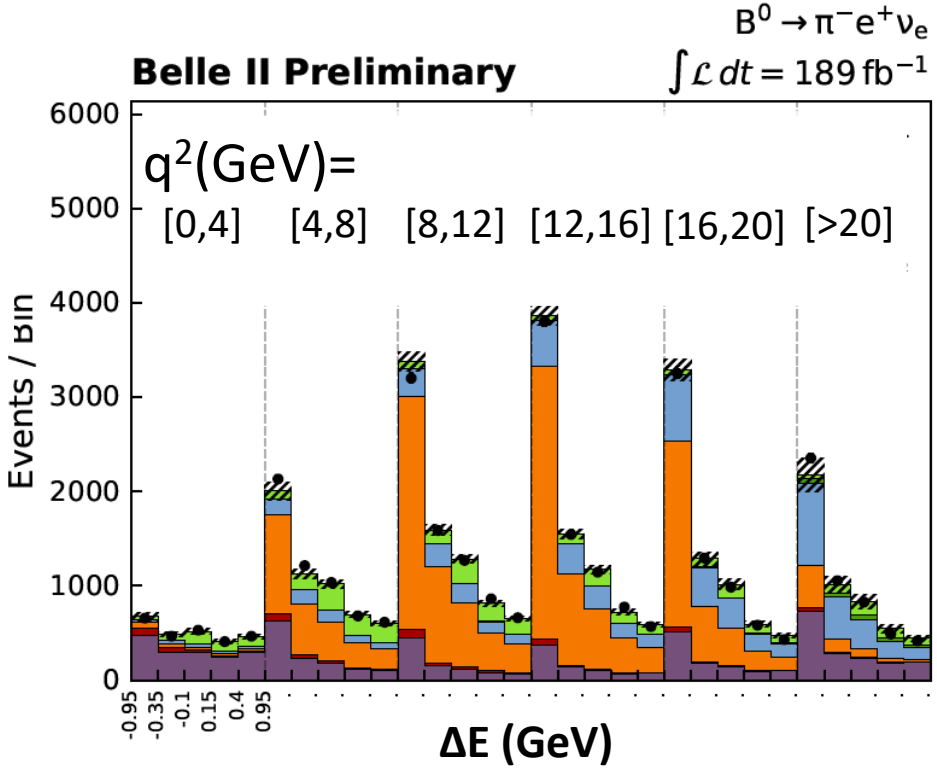
-Challenge: large background from continuum and B decays

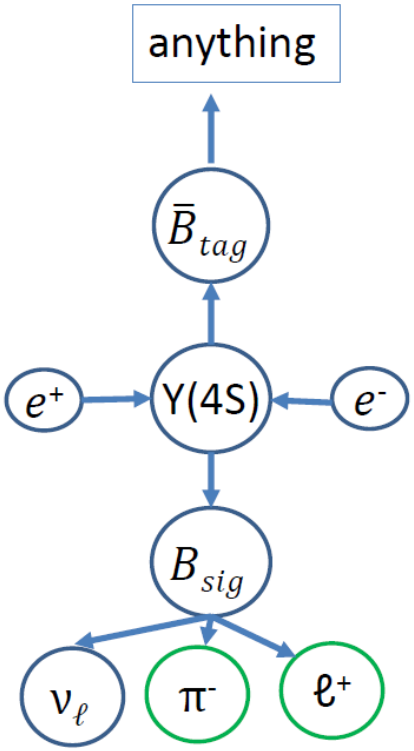
- -$B^0 \to \pi \ell \nu$ (ℓ=e,μ) and cc. are reconstructed for $|V_{ub}|$
- -continuum and B background rejection with multivariate classifier (Boosted decision trees)

-Signal is extracted by fitting M_{bc} and ΔE distributions

- - M_{bc} : Invariant B candidate mass where energy is replaced by half of collision energy
- -ΔE: difference between expected and observed B energy







Untagged $B^0 \to \pi l \nu$: result

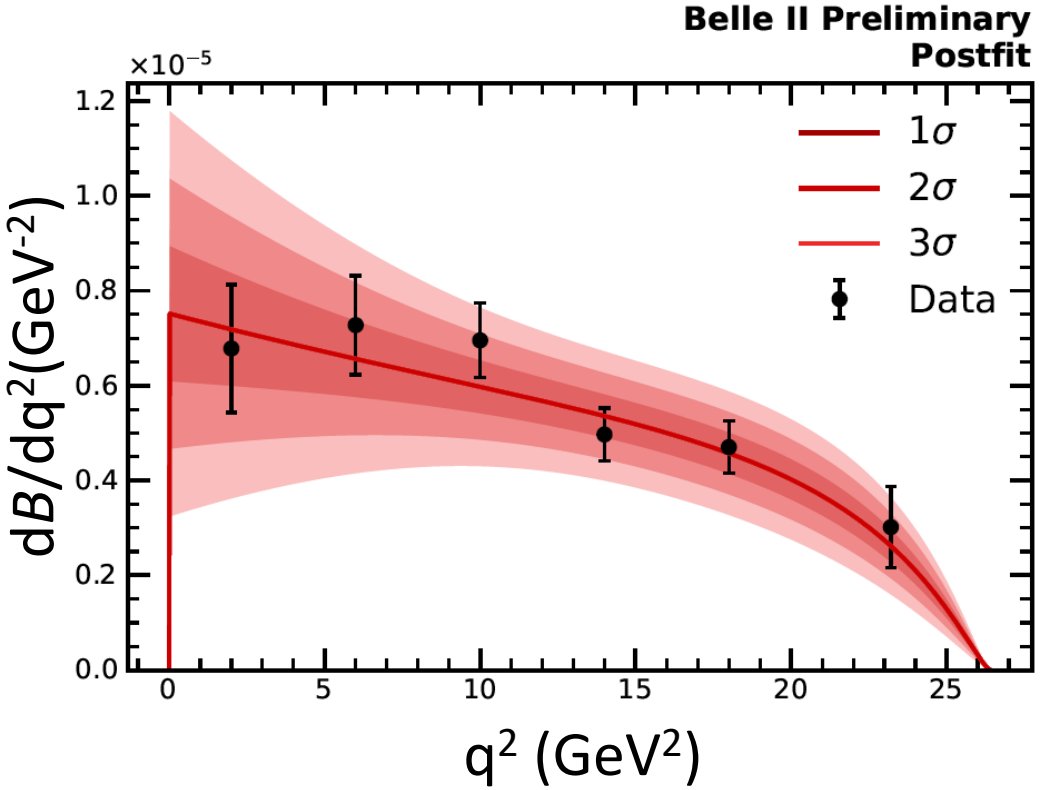
-Differential decay width is fitted to extract $|V_{ub}|$ and form factors

-BCL parametrization (Phys. Rev. D 79, 013008 (2009)) with lattice QCD calculation by FNAL/MILC (Phys. Rev. D 92, 014024 (2015)),

$$\frac{d\Gamma(B \to \pi \ell \nu)}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{24\pi^3} |\boldsymbol{p}_\pi|^3 |f_+(q^2)|^2$$

$$|V_{ub}|_{B^0 \to \pi^- \ell^+ \nu_\ell} = (3.54 \pm 0.12_{\text{stat}} \pm 0.15_{\text{sys}} \pm 0.16_{\text{theo}}) \times 10^{-3}$$

-consistent with the exclusive world average

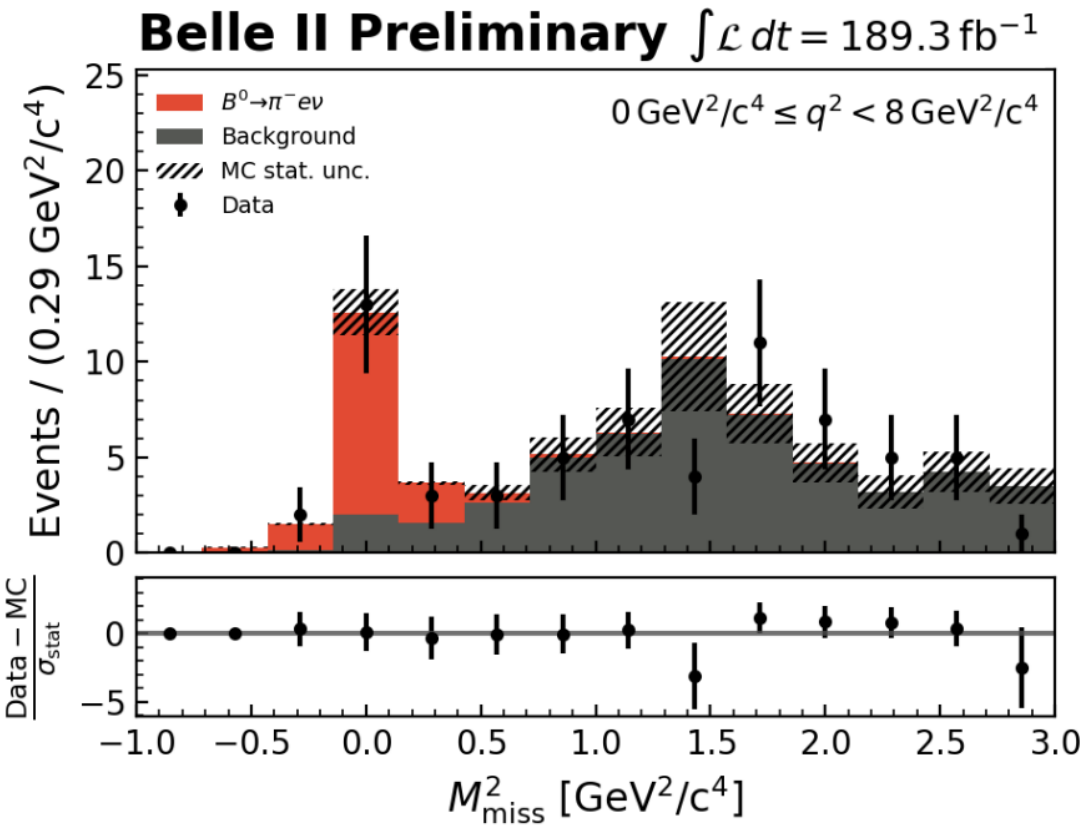


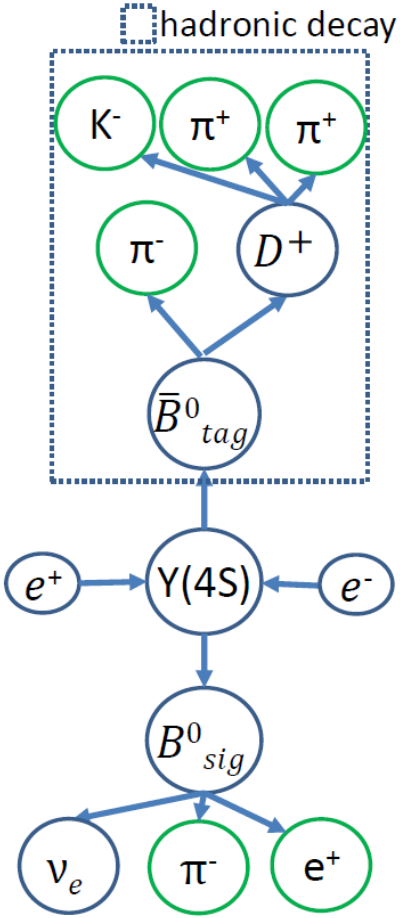
Tagged B→πeν: selection

-$B^0 \to \pi^- e^+ \nu_e$, $B^+ \to \pi^0 e^+ \nu_e$ and cc. are reconstructed for $|V_{ub}|$

-B_{tag} is fully reconstructed with Full Event Interpretation algorithm

-Signal is extracted by fitting missing mass squared distribution





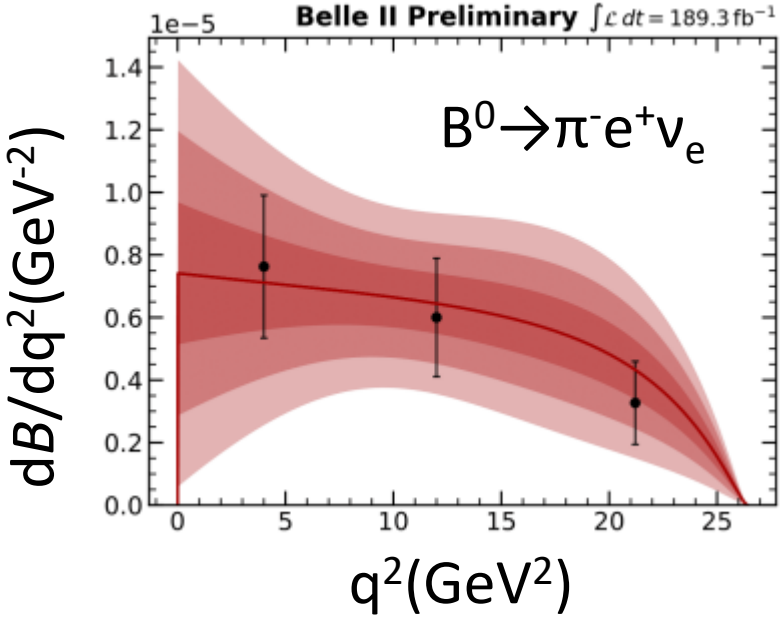
Tagged B→πeν: result

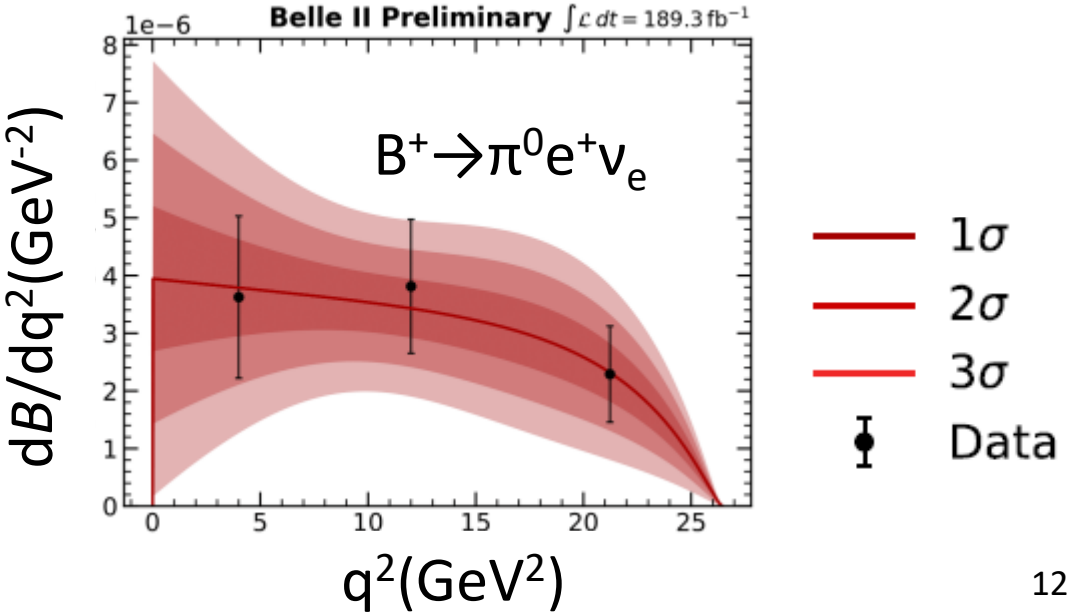
-Differential decay width is fitted to extract $|V_{ub}|$ and form factors

-BCL parametrization (Phys. Rev. D 79, 013008 (2009)) with lattice QCD calculation by FNAL/MILC (Phys. Rev. D 92, 014024 (2015)), $\frac{d\Gamma(B \to \pi \ell \nu)}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{24\pi^3} |\boldsymbol{p}_\pi|^3 |f_+(q^2)|^2$

$|V_{ub}| \times 10^3 = 3.88 \pm 0.45$ (stat.+sys.+theo.)

-Consistent with the world average





BF of B→ρℓν

-B→ρℓν is another channel to measure $|V_{ub}|$

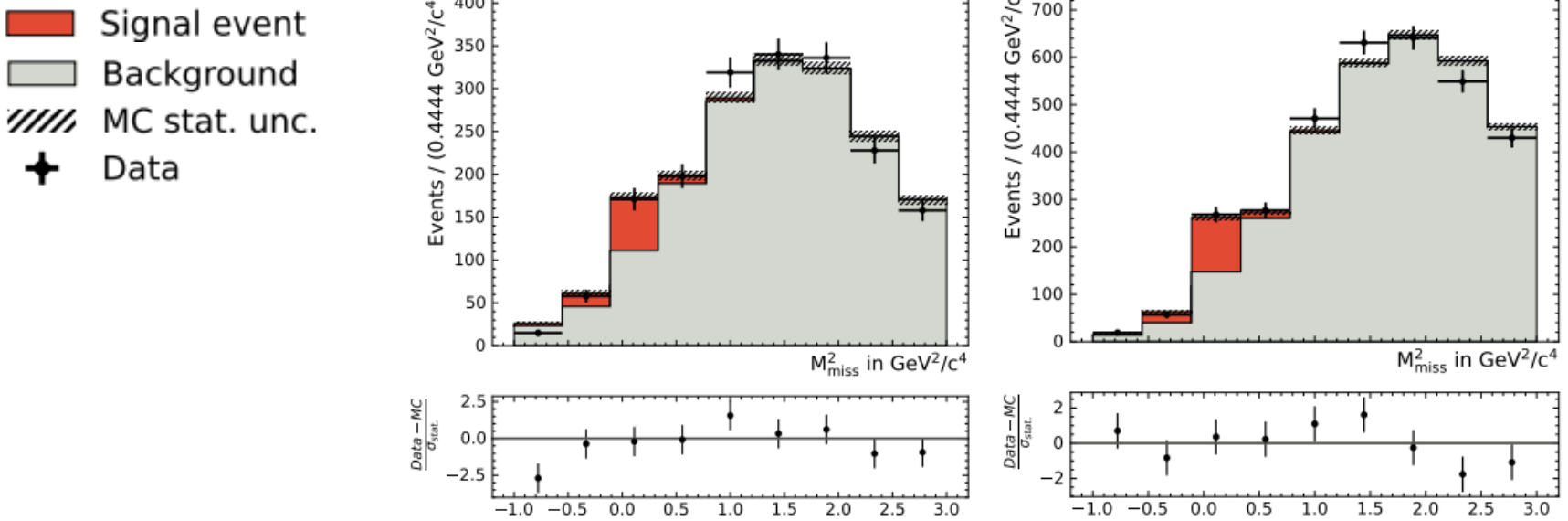
-independent samples from B→πlν

-tension observed between measurements of $B^0 \to \rho^- \ell^+ \nu$ and $B^+ \to \rho^0 \ell^+ \nu$

-BF is measured with the hadronic tag method

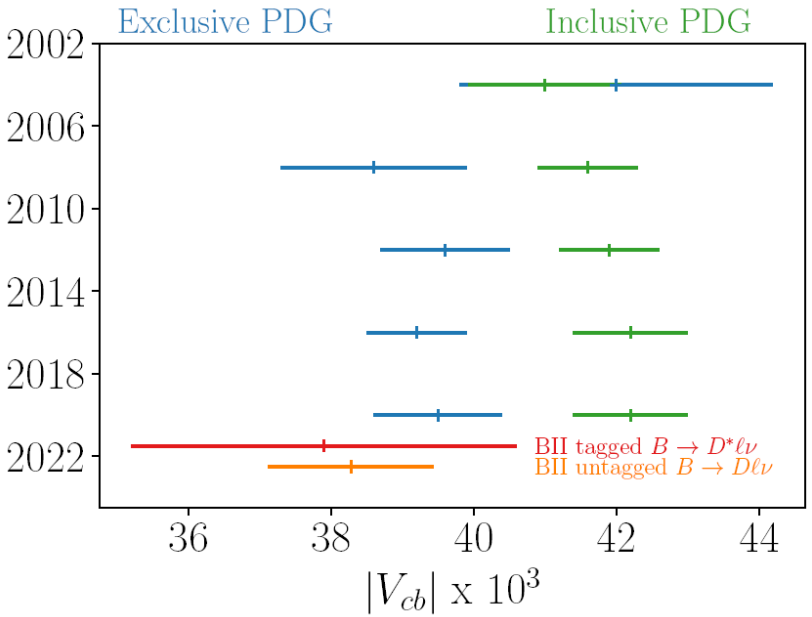
-Signal is extracted from missing mass squared and invariant mass of two pions

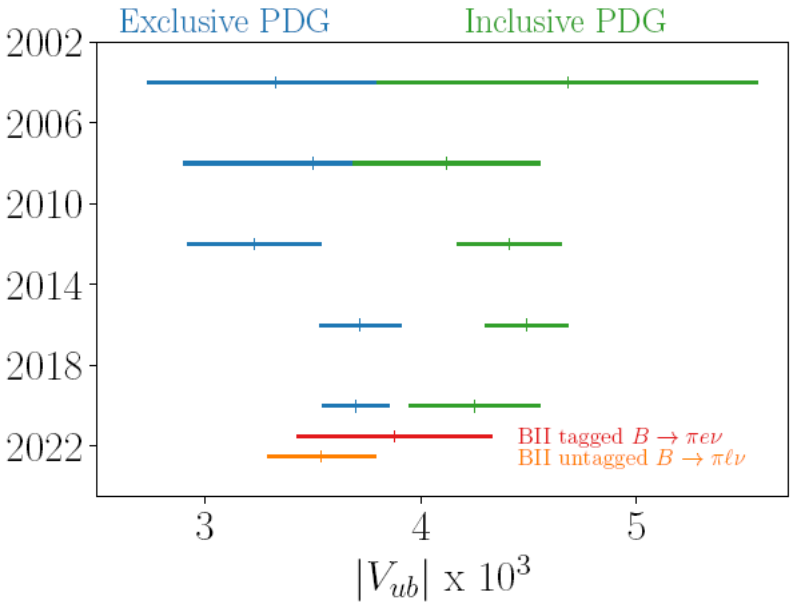
	$B^0 \to \rho^- \ell^+ \nu$	$B^+ \to \rho^0 \ell^+ \nu$
$\mathcal{B}$	$(4.12 \pm 0.64_{\text{stat}} \pm 1.16_{\text{sys}}) \times 10^{-4}$	$(1.77 \pm 0.23_{\text{stat}} \pm 0.36_{\text{sys}}) \times 10^{-4}$
$\mathcal{B}_{\text{PDG}}$	$(2.94 \pm 0.11 \pm 0.18) \times 10^{-4}$	$(1.58 \pm 0.11) \times 10^{-4}$



Summary

- Improved measurements of $|V_{cb}|$ and $|V_{ub}|$ are essential to increase the constraining power of the Unitarity triangle fit
- Known initial state kinematics and hermetic detector make Belle II ideal for these studies
- Today new analyses based on B→D(*)ℓnu, B→πℓnu
- Results consistent with previous measurements and approaching their precision





Backup

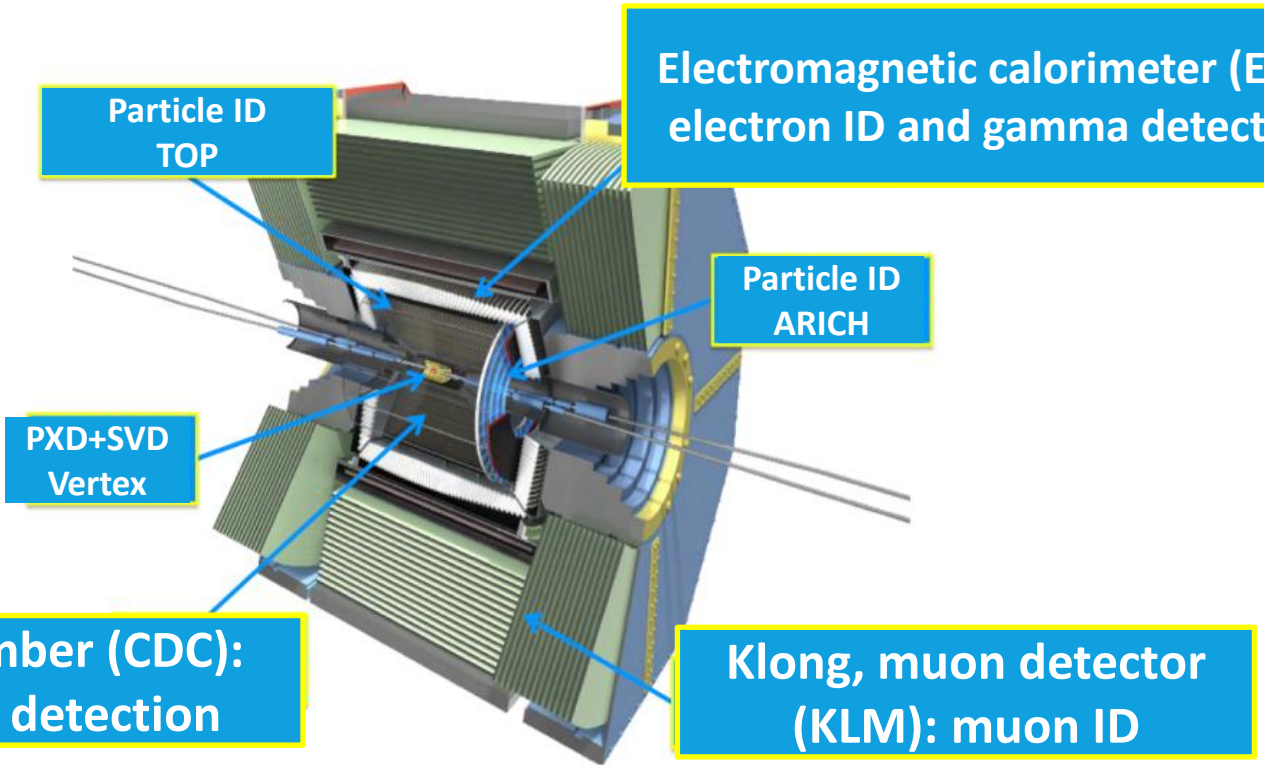
Belle II experiment

-Super-B factory

-SuperKEKB + Belle II detector:
energy-asymmetric e^-(7 GeV) e^+(4 GeV) collider at Y(4S)

-Achieved peak luminosity: $4.7 \times 10^{34}\,cm^2s^{-1}$

-Integrated luminosity: 424 fb^{-1}



Measurement of $|V_{cb}|$ and $|V_{ub}|$ at Belle II

-In this time, Belle II measures $|V_{cb}|$ and $|V_{ub}|$ exclusively

- $|V_{cb}|$: $B \to D(*)l\nu$, $|V_{ub}|$: $B \to \pi l\nu$ (l=e,μ)
- 189 fb^{-1} dataset accumulated in 2019-2021

-$|V_{cb}|$ and $|V_{ub}|$ are extracted from differential decay width:

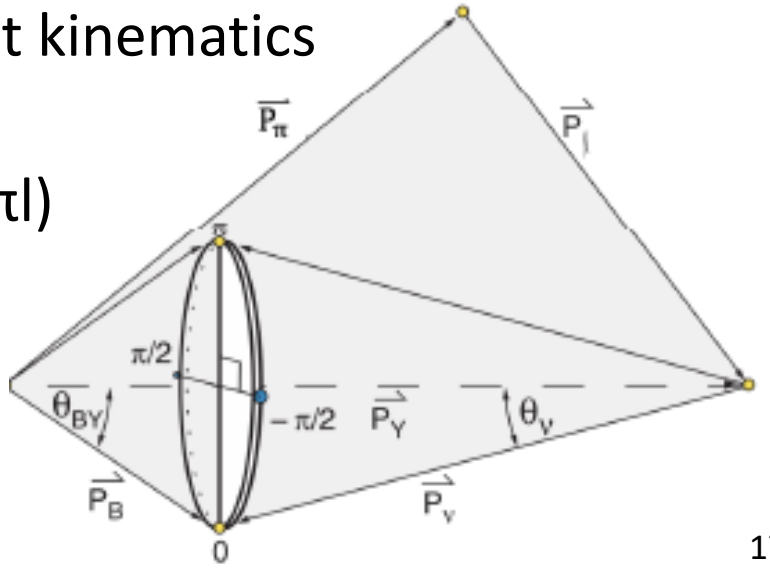
$$\frac{d\Gamma(B \to \pi l\nu)}{dq^2} \propto |V_{ub}|^2 \times |FF(q^2)|^2$$

FF: Form factor
q^2: Momentum transfer

-q^2 is reconstructed by daughter and event kinematics

$$\cos\theta_{BY} = \frac{2E_B^* E_Y^* - m_B^2 - m_Y^2}{2|p_B^*||p_Y^*|}$$ (Y=Dl, πl)

with known initial beam state
and clean environment at Belle II



untagged B→Dlv: BF estimation and systematic errors

-Branching fraction of B→Dlv is estimated from the signal yield:

	$B^- \to D^0 e^- \overline{\nu}_e$	$B^- \to D^0 \mu^- \overline{\nu}_\mu$	$B^0 \to D^- e^+ \nu_e$	$B^0 \to D^- \mu^+ \nu_\mu$
$\mathcal{B}(D\ell\nu)[\%]$	$2.21 \pm 0.03 \pm 0.08$	$2.22 \pm 0.03 \pm 0.10$	$1.99 \pm 0.04 \pm 0.08$	$2.03 \pm 0.04 \pm 0.09$
	Contributions to the systematic uncertainty [%]			
Tracking	0.90	0.90	1.20	1.20
N_{BB}	1.91	1.91	1.91	1.91
$\mathcal{B}(D \to K\pi(\pi))$	0.78	0.78	1.71	1.71
HadronID	0.61	0.60	0.15	0.15
LeptonID	1.21	3.11	0.91	1.93
$D\ell\nu$ FF	0.07	0.12	0.10	0.06
$D^*\ell\nu$ FF	0.14	0.17	0.02	0.02
$X_c\ell\nu$ BRs	1.86	1.86	0.40	0.32
False D shape	1.38	1.47	2.97	2.80
Continuum normalization	0.19	0.19	0.12	0.12
Total	3.51	4.56	4.23	4.44

-Systematic error is estimated with detector response, signal and background modeling

B→Dlν: $|V_{cb}|$ extraction

-Differential decay width of B→Dlν:

$$\frac{\Delta\Gamma(B \to D\ell\nu_\ell)}{\Delta w} = \frac{G_F^2 m_D^3}{48\pi^3}(m_B + m_D)^2 (w^2-1)^{3/2} \eta_{EW}^2 \mathcal{G}^2(w) |V_{cb}|^2$$

-m: mass
-G_F: Fermi constant
-η_{EW}: electroweak correction
-g(w) : form factor

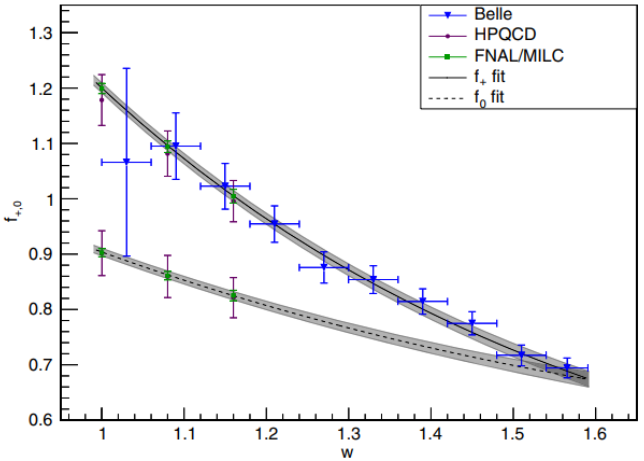
$$w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$$

-binned likelihood with form factor and $|V_{cb}|$

-Boyd-Grinstein-Lebed parametrization (N=3)

$$f_i(z) = \frac{1}{P_i(z)\phi_i(z)} \sum_{n=0}^{N} a_{i,n} z^n, \quad i = +, 0$$

-f_+, f_0 from lattice QCD calculation by FNAL/MILC, HPQCD are used as constraints



untagged B→πlν: BF estimation and systematic errors

-Estimated branching fraction of B→πlν:

stat. sys.

$$\mathcal{B}_{B^0\to\pi^-\ell^+\nu_\ell} = (1.421 \pm 0.056 \pm 0.126) \times 10^{-4}$$

-Systematic error is estimated with detector response, signal and background modeling

Systematic error of BR in each q^2 bin

TABLE II: Systematic uncertainties in % on the yields split by source.

Source	$B^0 \to \pi^- e^+ \nu_e$						$B^0 \to \pi^- \mu^+ \nu_\mu$					
	$q1$	$q2$	$q3$	$q4$	$q5$	$q6$	$q1$	$q2$	$q3$	$q4$	$q5$	$q6$
Detector	1.2	1.0	1.1	1.4	2.3	2.4	2.3	3.2	3.3	1.2	1.9	3.8
MC Stat.	4.0	2.0	2.4	2.8	3.9	5.6	3.9	2.0	2.3	2.7	3.4	4.8
Continuum	13.1	5.5	4.4	7.8	10.5	33.9	53.3	8.8	3.2	4.5	8.0	11.4
$B \to \rho\ell\nu$	9.5	12.5	9.7	6.9	3.4	12.9	8.7	11.6	8.6	6.3	3.3	14.3
$B \to X_u\ell\nu$	3.3	1.9	2.1	2.1	1.8	3.7	3.4	2.3	2.0	2.3	2.1	6.0
$B \to X_c\ell\nu$	2.3	3.0	1.1	0.8	0.5	2.4	2.4	1.5	1.5	0.8	0.5	2.2
Total Sys.	17.2	14.3	11.2	11.1	12.0	37.0	53.4	15.2	10.3	8.7	9.7	20.3
Stat.	10.2	6.01	6.86	8.08	10.3	13.2	10.4	6.0	6.4	7.8	9.7	13.4
Total	20.2	15.5	13.2	13.7	15.9	39.2	54.5	16.4	12.2	11.6	13.7	24.3