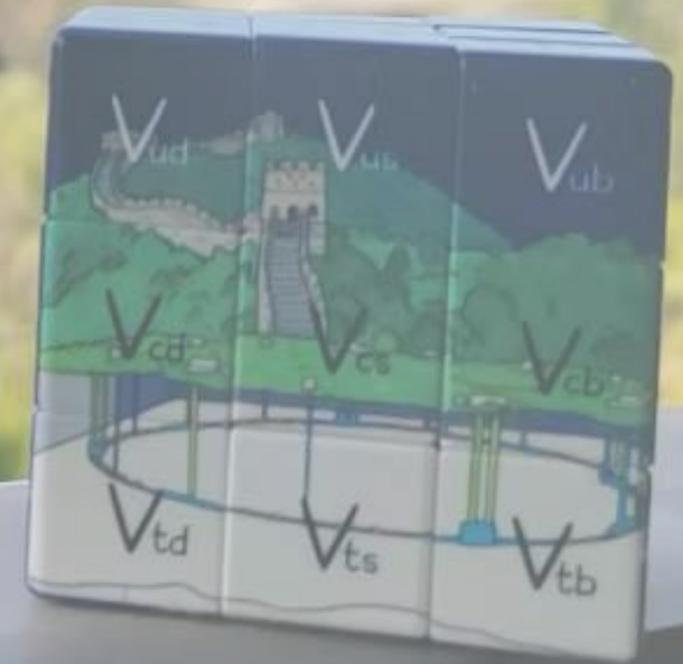
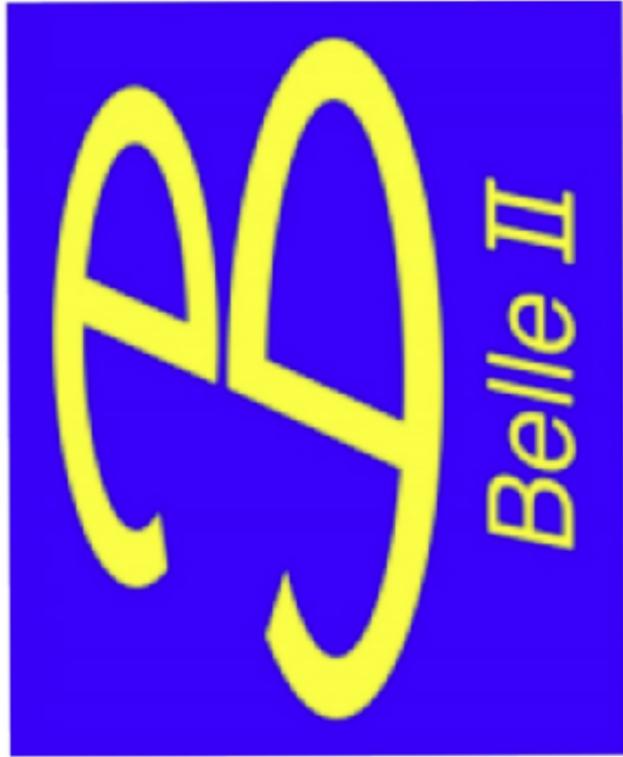


Belle II实验上CKM矩阵元和相角的测量

报告人：殷俊昊
南开大学物理科学学院



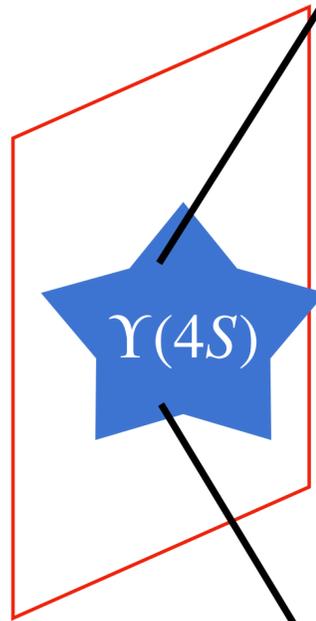
味物理前沿研讨会暨味物理讲座100期特别活动



Belle



“e⁻electron



B

\bar{B}

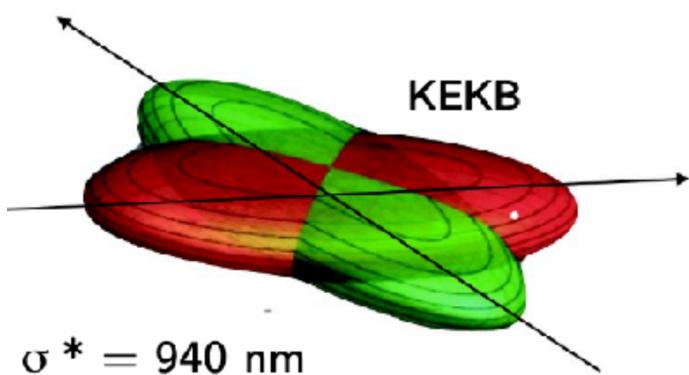
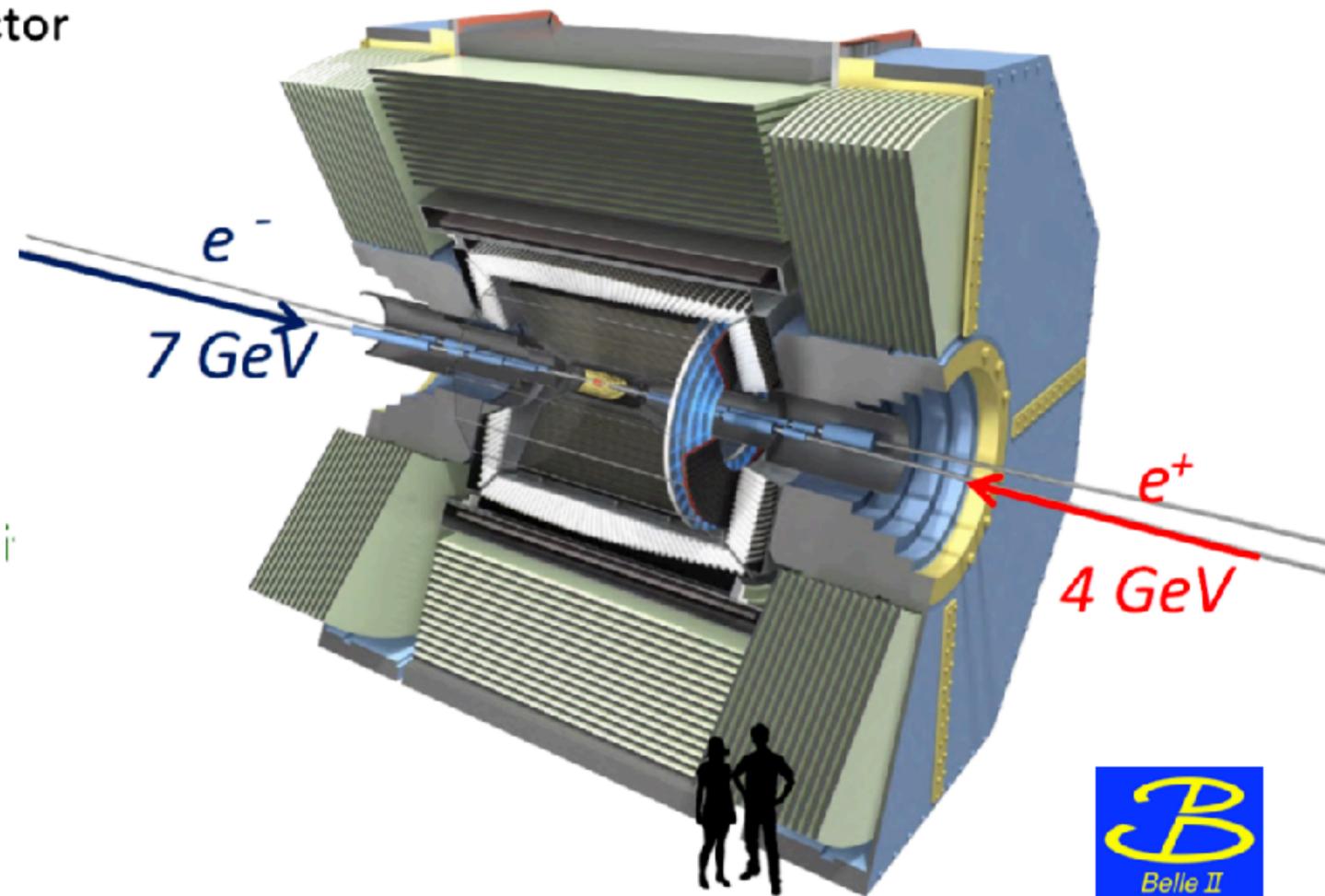
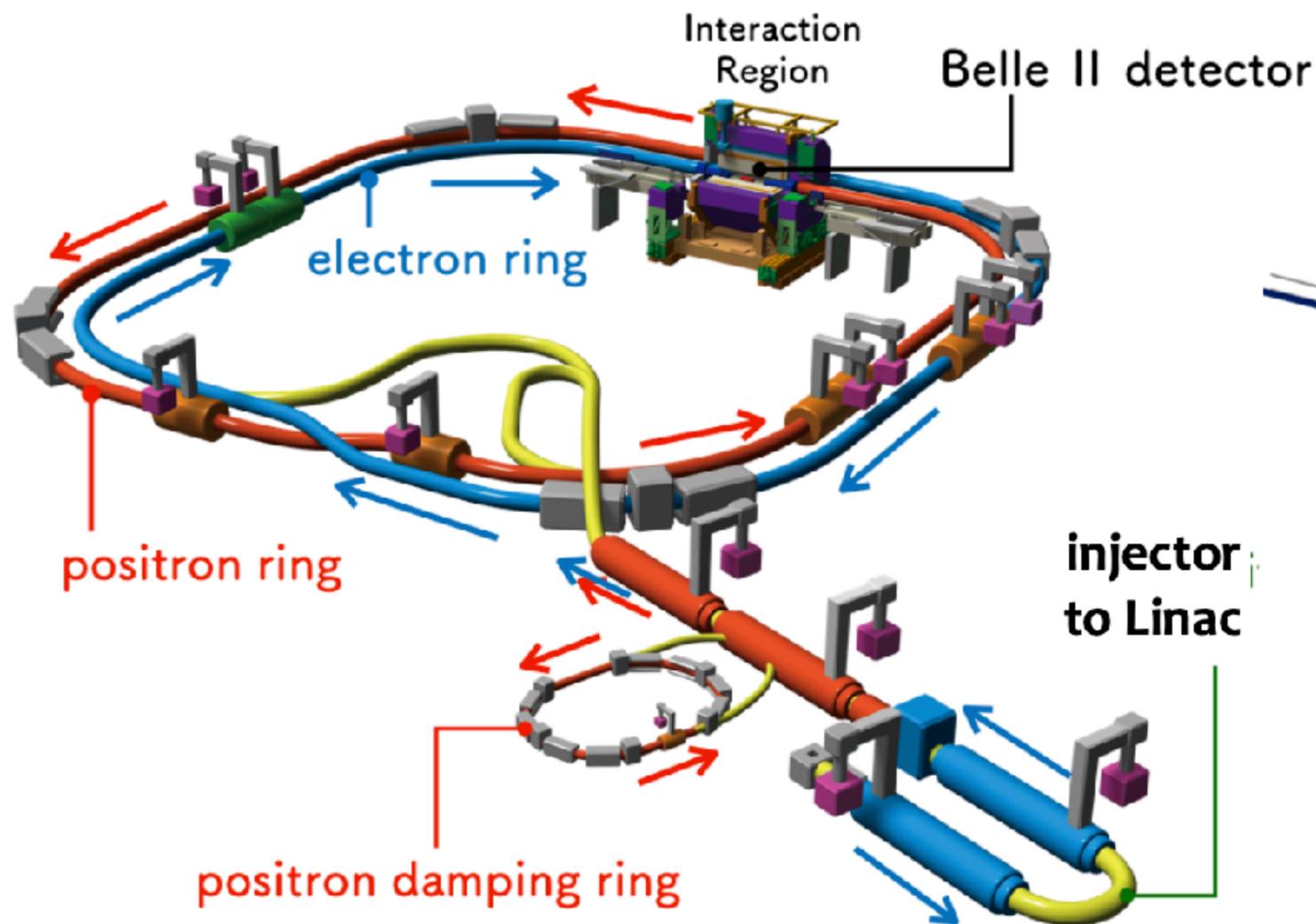


nortce “e⁺”

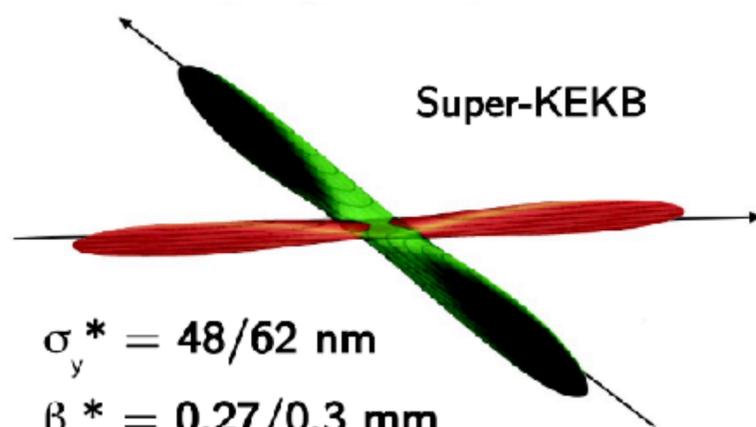
SuperKEKB

$$e^- \xrightarrow{7 \text{ GeV}} (\star) \xleftarrow{4 \text{ GeV}} e^+$$

Belle II



$$\begin{aligned} \sigma_y^* &= 940 \text{ nm} \\ \beta_y^* &= 5.9 \text{ mm} \\ \sigma_x^* &= 147/170 \text{ } \mu\text{m} \end{aligned}$$



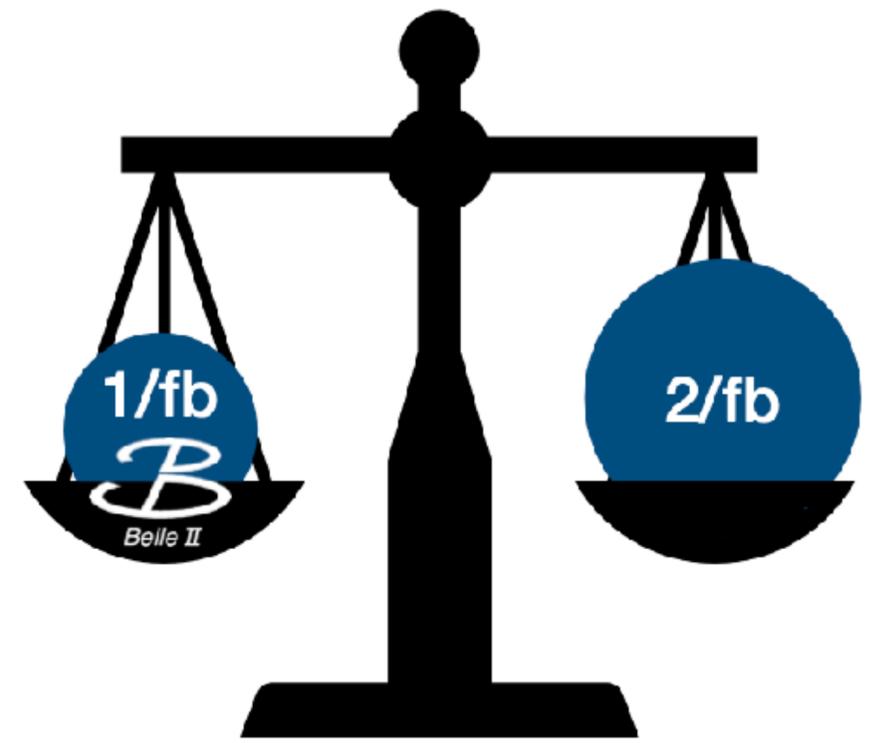
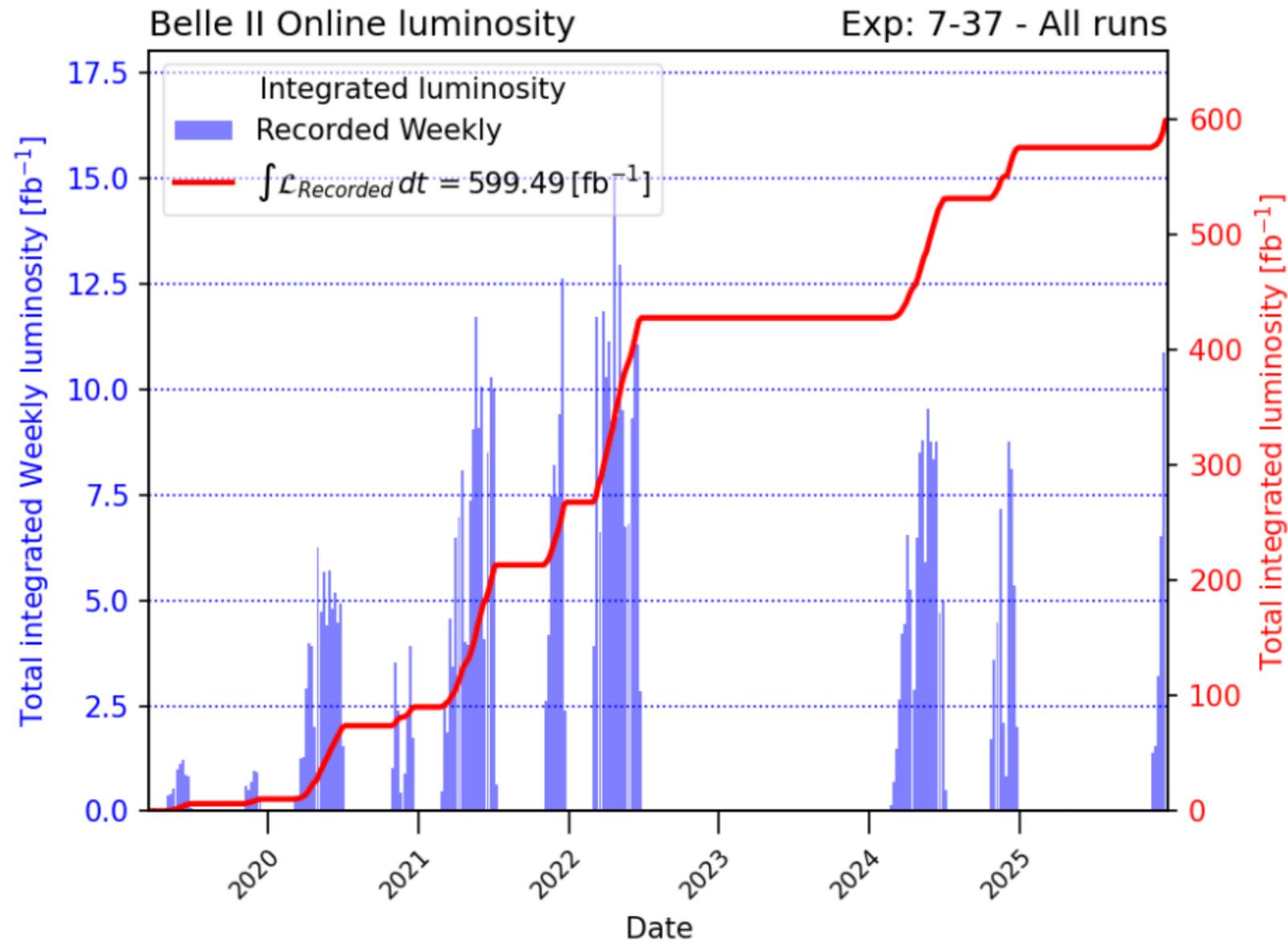
$$\begin{aligned} \sigma_y^* &= 48/62 \text{ nm} \\ \beta_y^* &= 0.27/0.3 \text{ mm} \\ \sigma_x^* &= 10.1/10.7 \text{ } \mu\text{m} \end{aligned}$$

Beam current: KEKB x ~1.5

$$L = \frac{\gamma_{\pm}}{2er_e} \left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right) \frac{I_{\pm} \xi_{\pm y}}{\beta_y^*} \left(\frac{R_L}{R_y}\right)$$

Beam squeeze: KEKB / ~20

RUN-I & II (2019-2025)

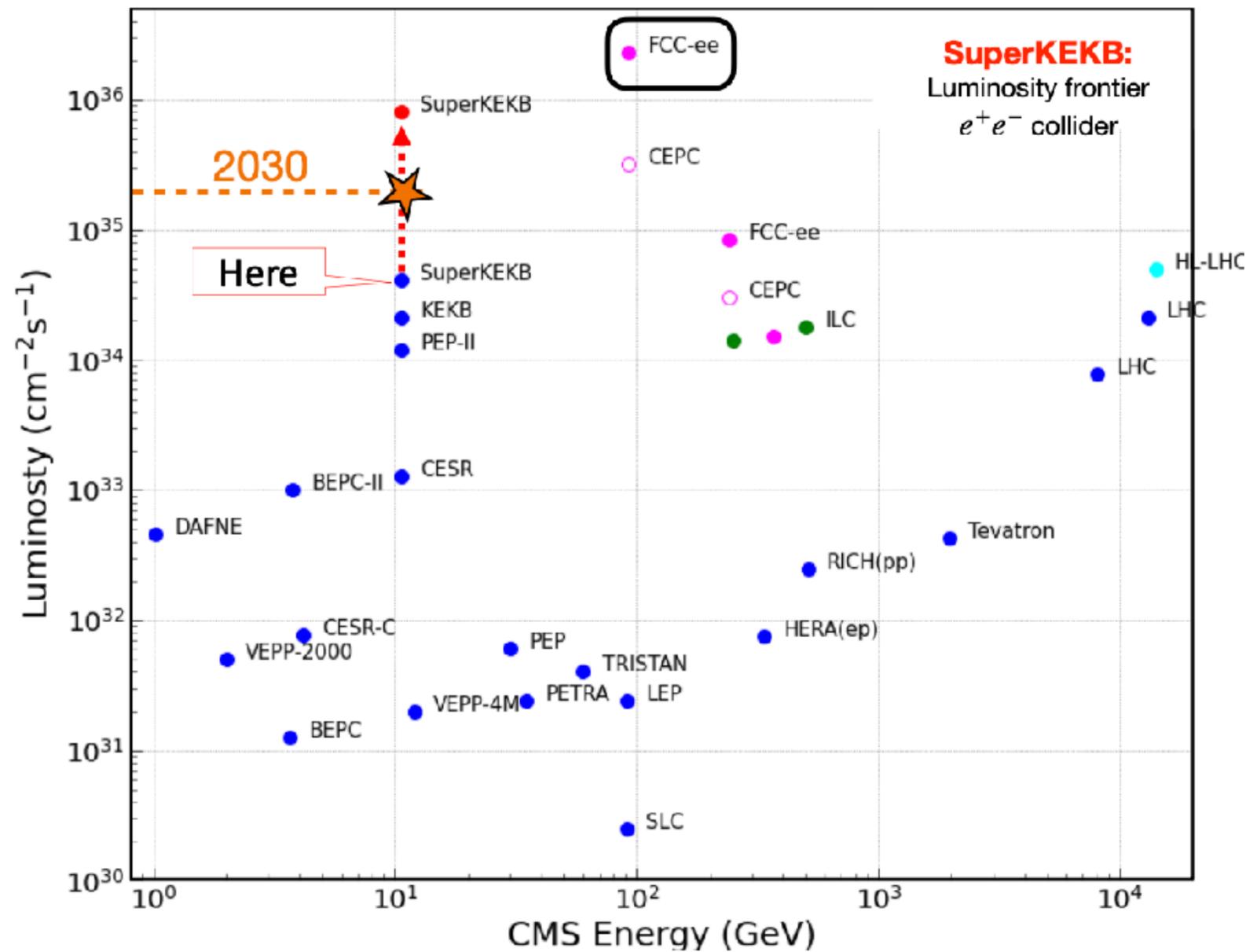


- **Belle II** achieves **higher statistical power** than Belle & BaBar due to improved detector & modern analysis techniques.
- **1/fb of Belle II** data is **worth 2/fb of BaBar or Belle** data*.
- Much effort ongoing to shift this fraction even further with new triggers, better reconstruction, novel ideas etc.

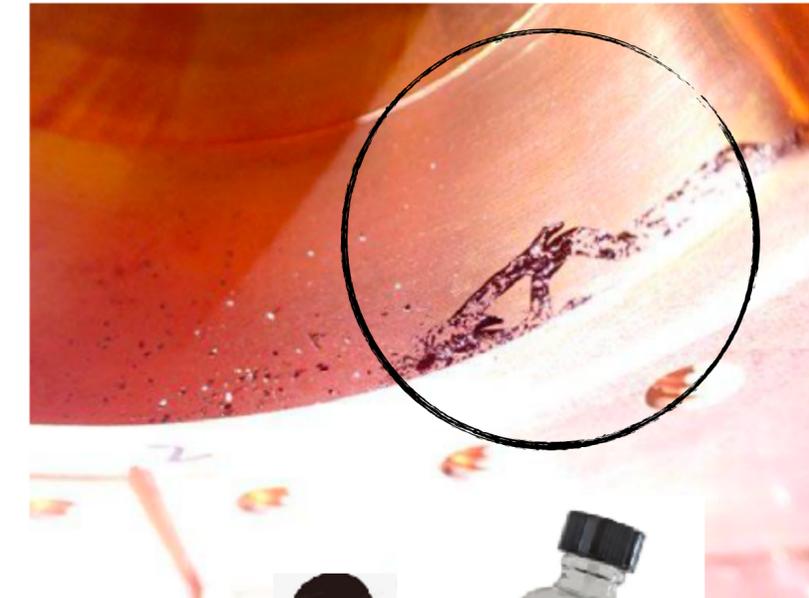
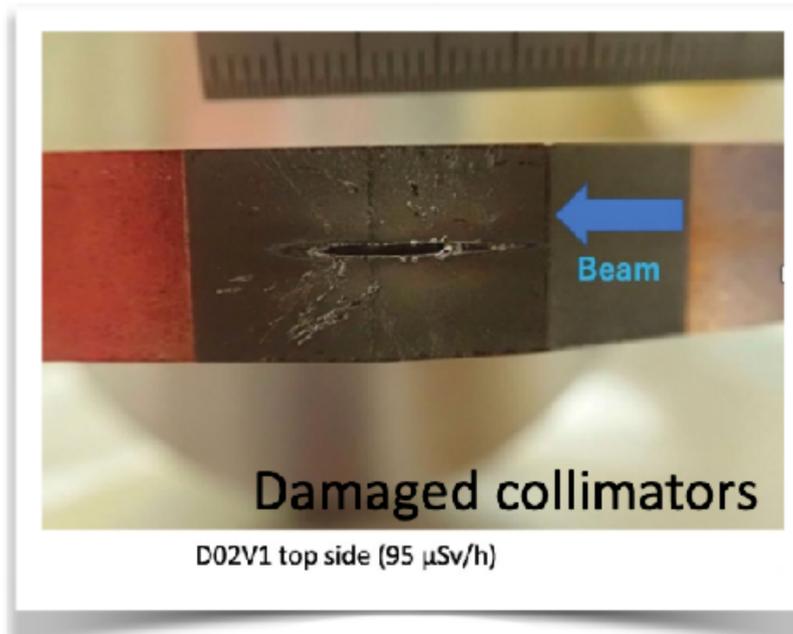
Run 2 of experiment started Jan 29th 2024

Collected ca. 0.55/ab = BaBar

→ During **Run 1**: Achieved world record inst. luminosity of $4.71 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$



- Devoted significant fraction of running time for machine studies to understand instabilities.
- Sudden beam loss leads not only low lumi. but also detector damage



vacuum sealant

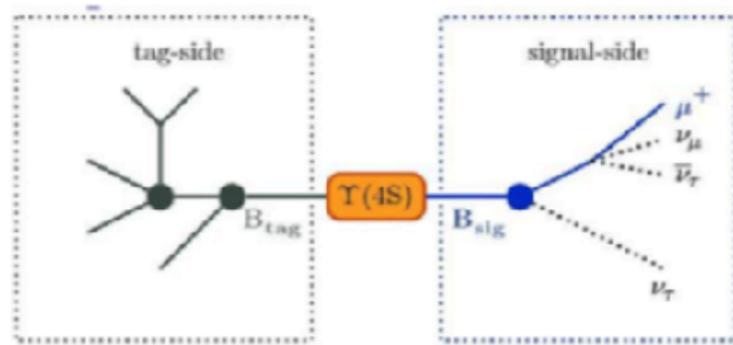
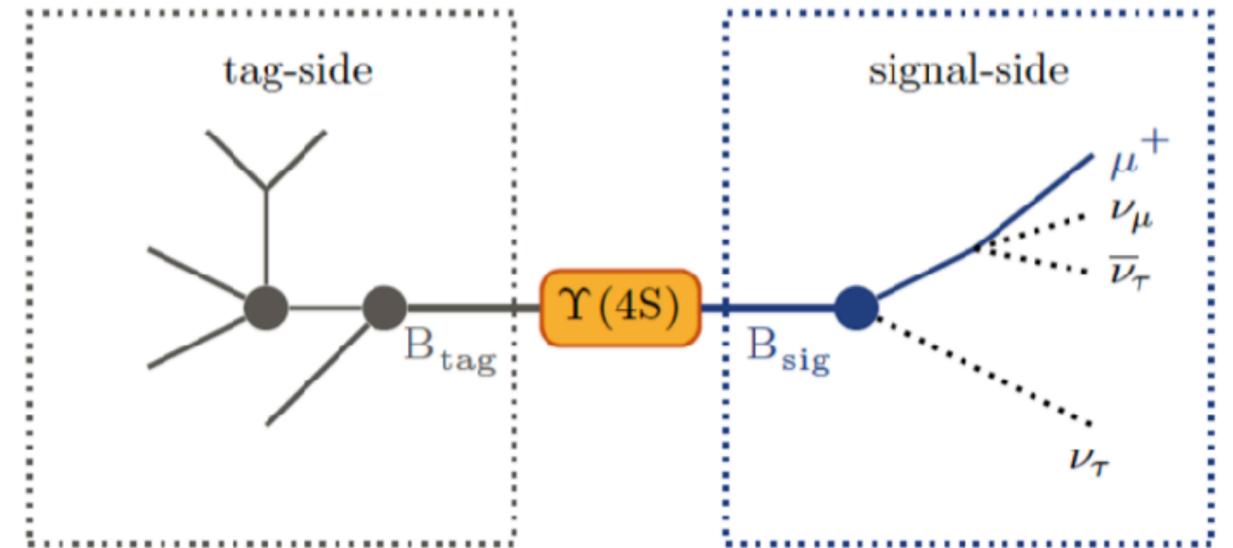
Removal improve beam stability

Accumulate $\sim 1/\text{ab}$ in 2026b, 4 days per 3 week for machine tuning, study...

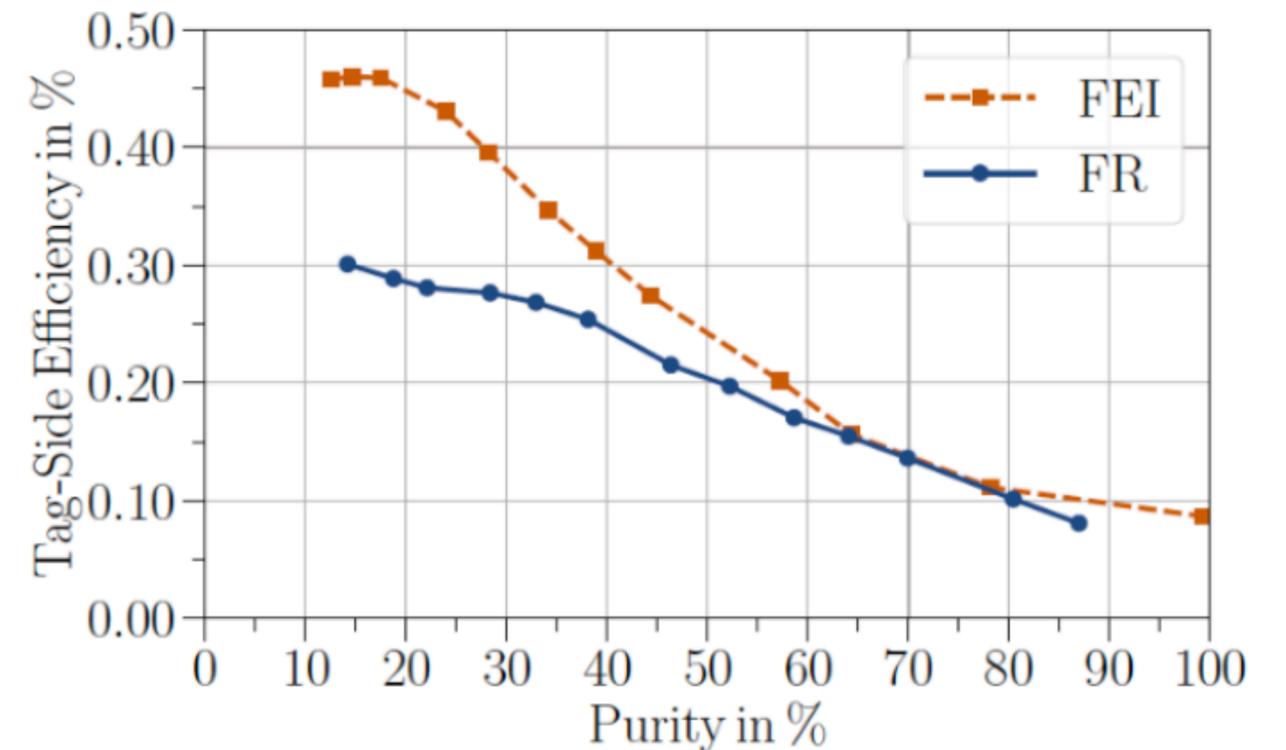
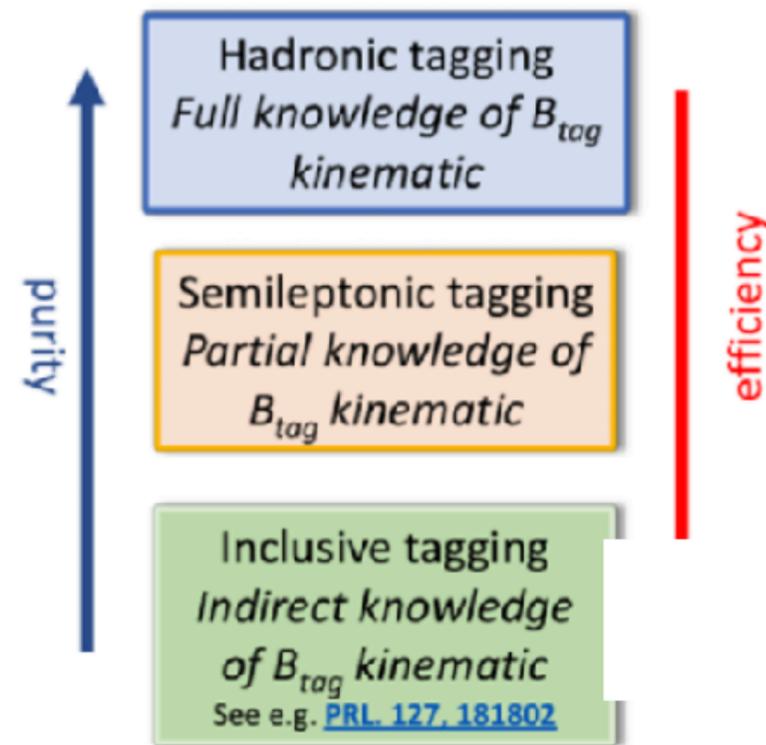
SuperKEKB & Belle II goals until 2032 \longrightarrow $\sim 2 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ & collect 5-10/ab

Full Event Interpretation (FEI)

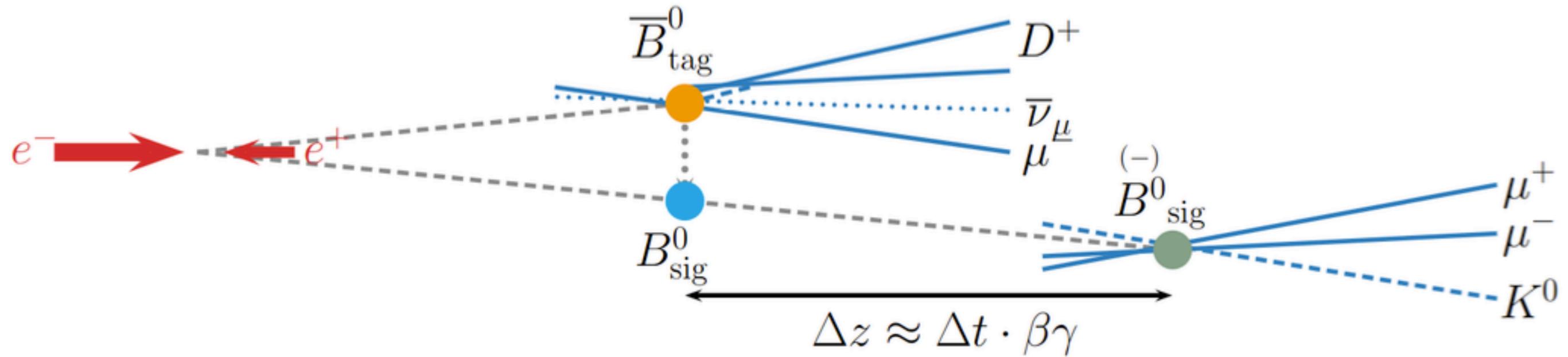
- Reconstructs this B_{tag} in roughly 10 000 channels
- First reconstructing low-level particles (K, π, \dots), then intermediate D mesons and finally B mesons.
- Most-likely particle candidates are selected using pre-trained multivariate classifiers



Full Event Interpretation (FEI)



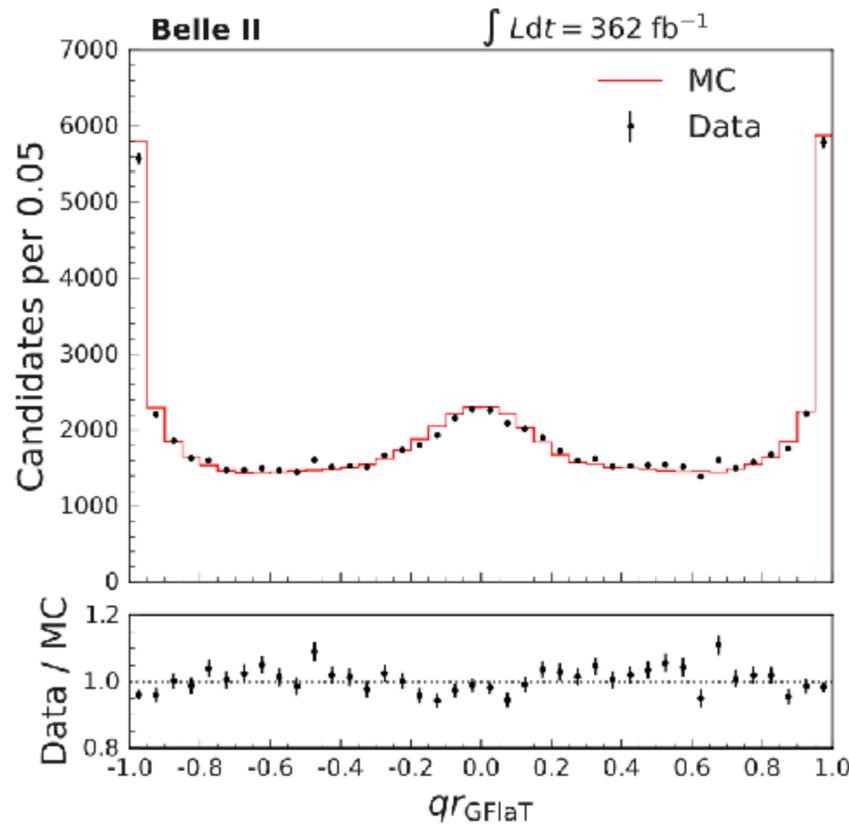
Belle II advantages



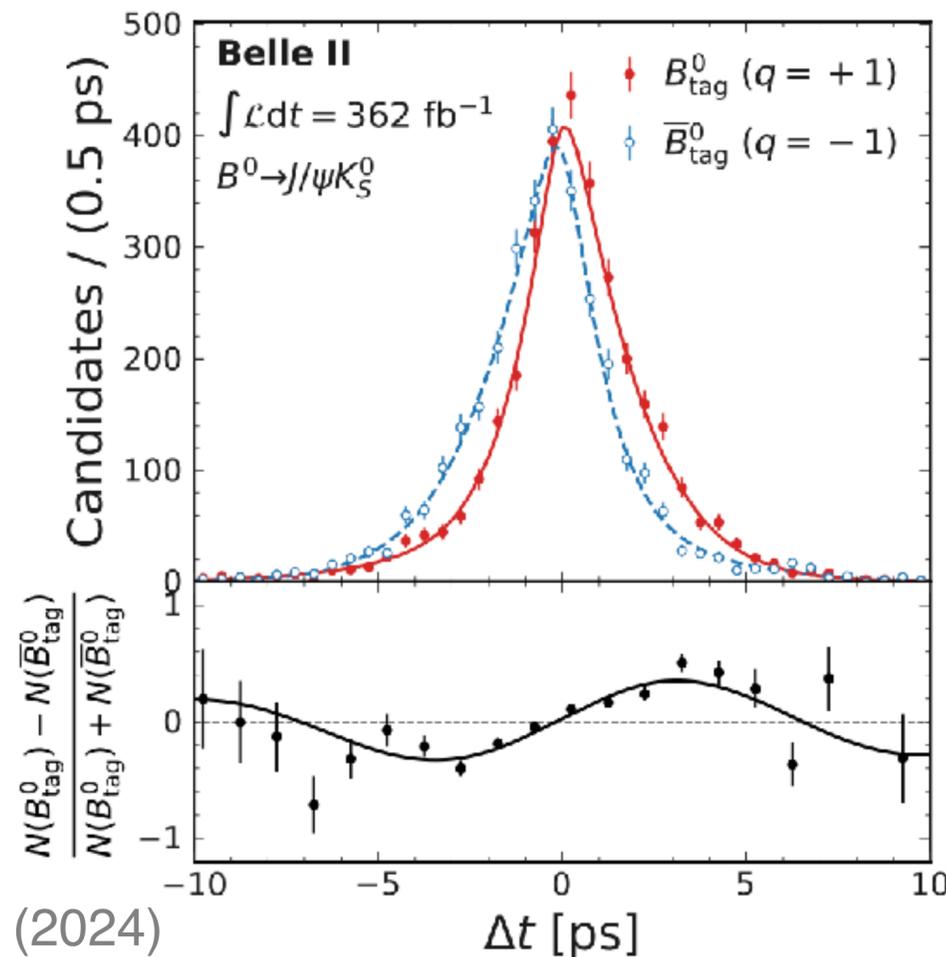
- Asymmetric collision (boost effect): better measurement on displacement. (Belle II: $\Delta z \approx 130\mu m$, Belle: $\Delta z \approx 200\mu m$)
- Good vertex resolution: $15\mu m$; 2 layers of PXD and 4 layers of SVD.
- Coherent $B\bar{B}$ pairs. Graph-neural-network based algorithm to determined the flavor of B^0/\bar{B}^0
- High tagging efficiency (Belle II: $\epsilon_{tag} = (31.7 \pm 0.4)\%$; Belle: $\epsilon_{tag} = (30.1 \pm 0.4)\%$)

$B^0 \rightarrow K_S J/\psi$ ANA 101

- GFlaT, Graph-neural-network based algorithm to determined the flavor of B^0/\bar{B}^0
- Use info. of all charged and the relation between them



PRD 110, 012001 (2024)



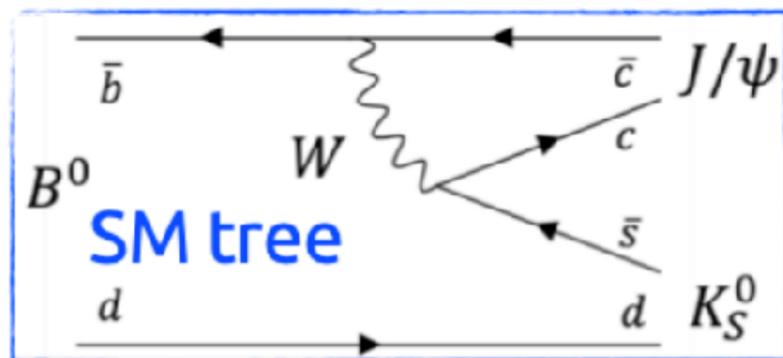
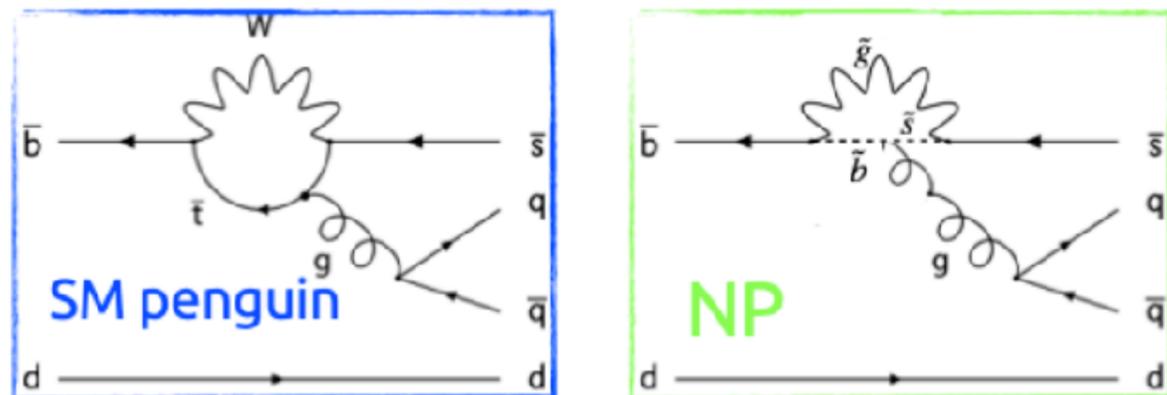
CPV par.	Belle II (362 fb ⁻¹) PRD 119, 012002 (2024)	Belle (711 fb ⁻¹) PRL 108, 171802 (2012)
S	$0.724 \pm 0.035 \pm 0.009$	$0.670 \pm 0.029 \pm 0.013$
C	$-0.035 \pm 0.026 \pm 0.029$	$-0.015 \pm 0.021^{+0.045}_{-0.023}$

Comparable uncert. with Belle.

Extract $\phi_1 = (23.2 \pm 1.5 \pm 0.6)^\circ$

ϕ_1/β measurement

- It's the most precise angle $(22.2 \pm 0.7)^\circ$, what can we do more?
- $b \rightarrow s\bar{q}q$ ($q = d, s$), gluonic penguin process. More sensitive to **New Physics**.



- $S^{eff} = \sin(2\phi_1) + \Delta S$, ΔS may come from SM or NP.
- Using precise W.A. $\sin(2\phi_1) = 0.699 \pm 0.017$, measure ΔS , compare with SM's $\Delta S \rightarrow$ hint from NP.

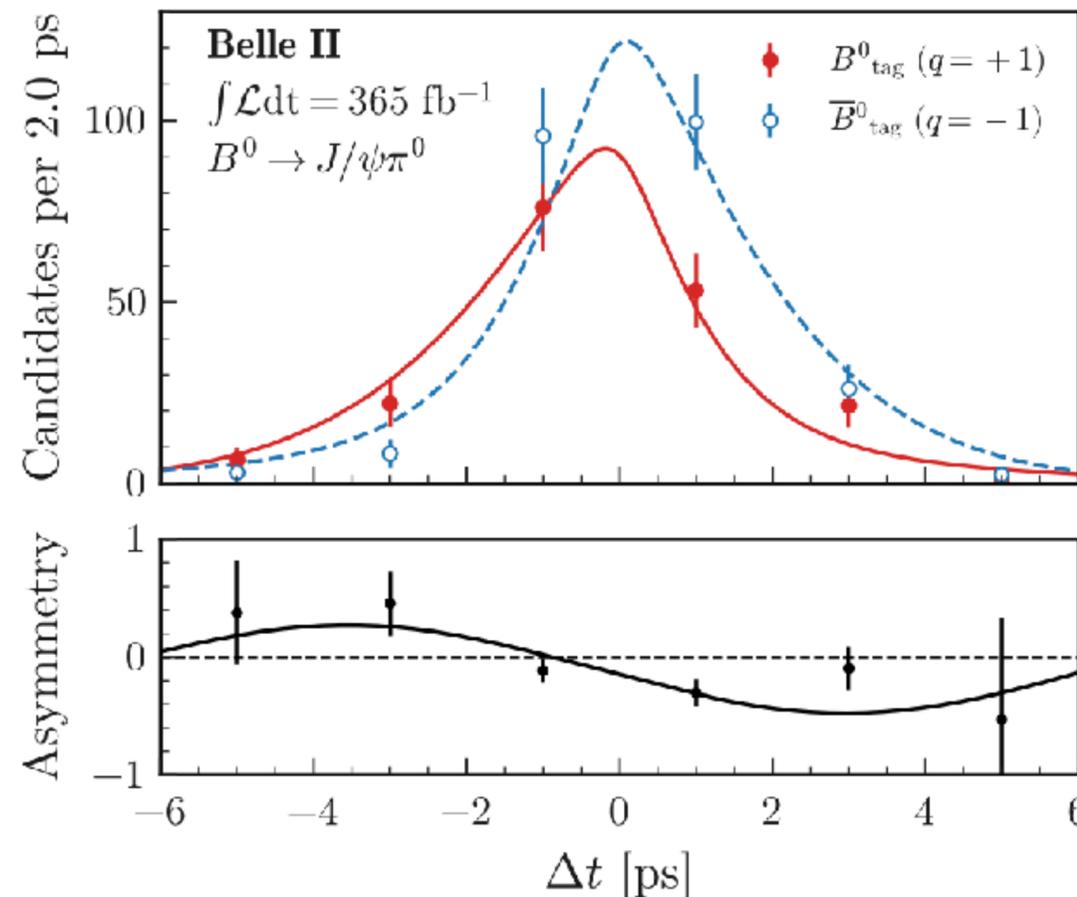
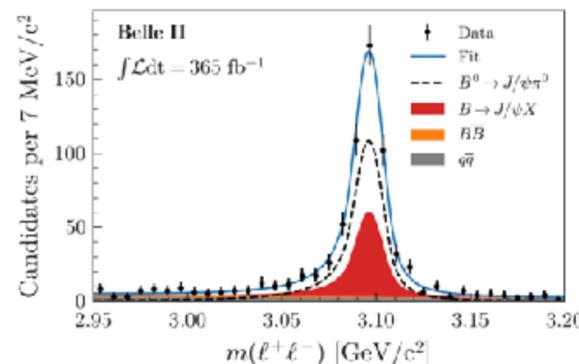
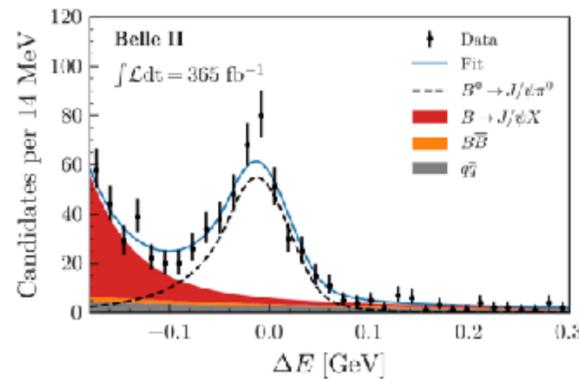
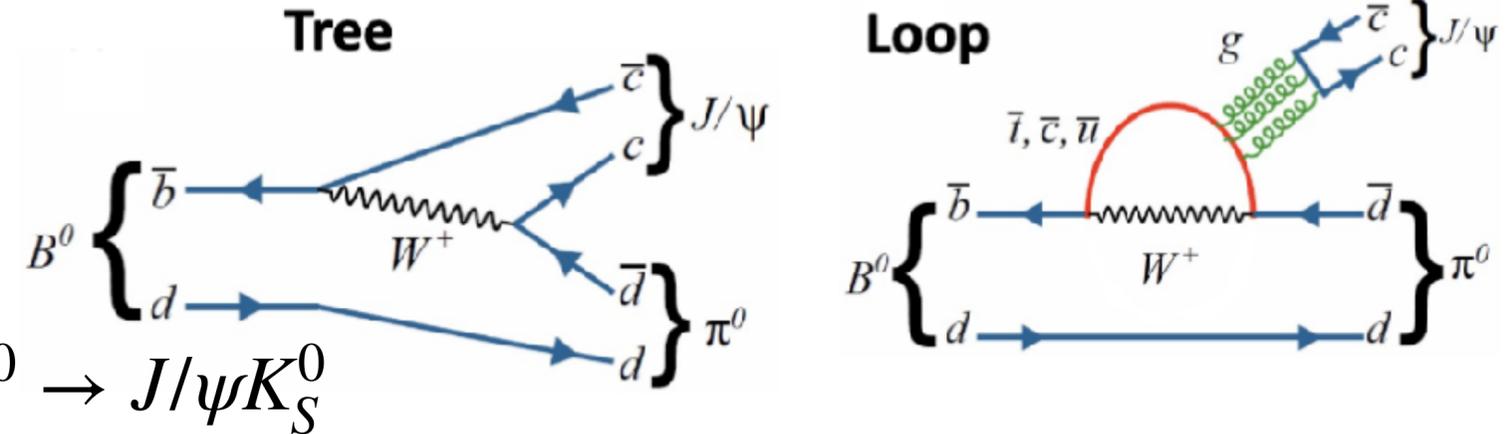
channel	S_meas	C_meas	
$B^0 \rightarrow K_S^0 \pi^0 \gamma$	$0.04_{-0.44}^{+0.45} \pm 0.10$	$-0.06 \pm 0.25 \pm 0.07$	PRL 134 , 011802(2025)
$B^0 \rightarrow \eta' K_S^0$	$0.67 \pm 0.10 \pm 0.04$	$-0.19 \pm 0.08 \pm 0.03$	PRD 110, 112002 (2024)
$B^0 \rightarrow \pi^0 K_S^0$	$0.75_{-0.23}^{+0.20} \pm 0.04$	$-0.04_{-0.15}^{+0.14} \pm 0.05$	PRL 131, 111803 (2023)
$B^0 \rightarrow \phi K_S^0$	$0.54 \pm 0.26_{-0.08}^{+0.06}$	$-0.31 \pm 0.20 \pm 0.05$	PRD 108, 072012 (2023)
$B^0 \rightarrow K_S^0 K_S^0 K_S^0$	$-1.86_{-0.46}^{+0.91} \pm 0.09$	$-0.22_{-0.27}^{+0.30} \pm 0.04$	arXiv: 2209.09547

- **Consistent with world average and SM expectation.**
- $B^0 \rightarrow \eta' K_S^0$ provides the most sensitive results up to date.
- Smaller data size but equivalent uncertainties, sometimes better.

$\sin 2\phi_1: B^0 \rightarrow \pi^0 J/\psi$

Belle II, *PRD* 111 (2025) 1, 012011

- $S = -\sin 2\phi_1$, $C = 0$ if there is only tree amplitude
- Tree is color and CKM suppressed.
 - Can be used to understand the loop contribution in $B^0 \rightarrow J/\psi K_S^0$
- Improved sensitivity by the better π^0 selection and GFlaT
- $\Delta E - M(\ell^+\ell^-)$ fit to extract signal.



$S = -0.88 \pm 0.17 \pm 0.03$,
first observation (5σ) of non-zero S
(mixing-induced CPV) in this mode

$C = 0.13 \pm 0.12 \pm 0.03$,

$\mathcal{B} = (2.02 \pm 0.12 \pm 0.10) \times 10^{-5}$

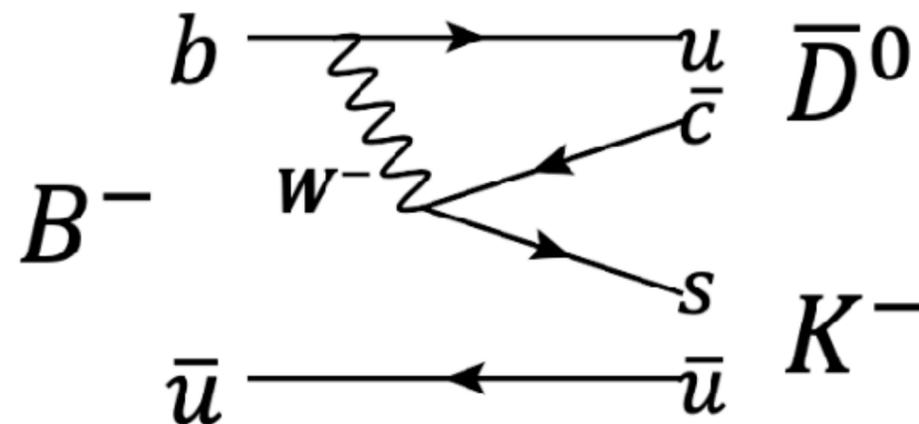
Consistent with WA & comparable precision

ϕ_3 measurement $B^+ \rightarrow D^{(*)}h^+$

$$\phi_3 = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$$

appears in CPV parameter of $b \rightarrow u\bar{c}s$ and $b \rightarrow c\bar{u}s$ tree decay interference.

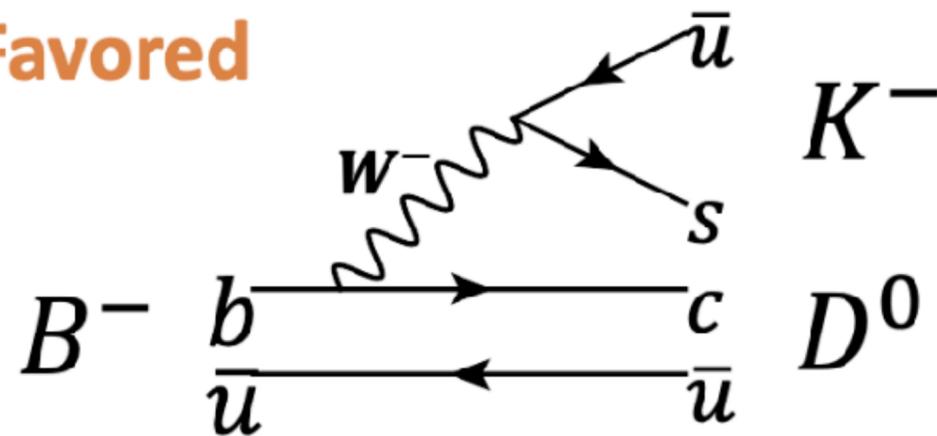
Suppressed



$$\frac{\mathcal{A}(\bar{D}^0 K^-)}{\mathcal{A}(D^0 K^-)} = r_B \exp(i(\delta_B - \phi_3))$$

$r_B = |\mathcal{A}(\bar{D}^0 K^-)|/|\mathcal{A}(D^0 K^-)| \simeq c_f |V_{cs}V_{ub}^*/V_{us}V_{cb}^*| \simeq 0.1$ (c_f : Color suppression factor)
 δ_B : Strong phase difference between 2 modes

Favored



Methods to measure ϕ_3 using different D^0 decays

- GLW method: $D^0 \rightarrow K^+K^-, K_S^0\pi^0$ (CP eigenstates)
- BPGGSZ method: self conjugate multibody decay, ex.) $D^0 \rightarrow K_S^0 h^+ h^-$
- GLS method: $D^0 \rightarrow K_S^0 K^\pm \pi'^{\mp}$ (singly Cabibbo-suppressed decays)
- ADS method: $D^0 \rightarrow K^\pm \pi^{\mp}$

ϕ_3 measurement $B^+ \rightarrow D^{(*)}h^+$

First Belle + Belle II combined ϕ_3 analysis

Combined analysis using 4 methods

Fit results

Parameters	$\phi_3(^{\circ})$	r_B^{DK}	$\delta_B^{DK}(^{\circ})$	$r_B^{D\pi}$	$\delta_B^{D\pi}(^{\circ})$	$r_B^{D^*K}$	$\delta_B^{D^*K}(^{\circ})$
Best-fit value	75.2	0.115	137.8	0.0165	347.0	0.229	342
68.3% interval	[67.7, 82.3]	[0.102, 0.127]	[128.0, 146.3]	[0.0113, 0.0220]	[337.4, 355.7]	[0.162, 0.297]	[326, 356]
95.4% interval	[59, 89]	[0.089, 0.138]	[116, 154]	[0.006, 0.027]	[322, 366]	[0.10, 0.37]	[306, 371]

Inputs for ϕ_3 measurement

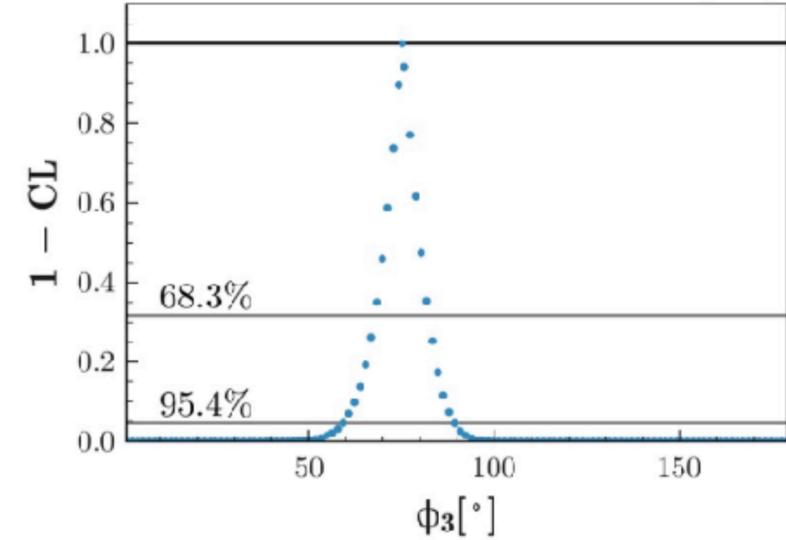
B decay	D decay	Method	Data set (Belle + Belle II)[fb $^{-1}$]
$B^+ \rightarrow Dh^+$	$D \rightarrow K_S^0\pi^0, K^-K^+$	GLW	711 + 189 Belle II
$B^+ \rightarrow Dh^+$	$D \rightarrow K^+\pi^-, K^+\pi^-\pi^0$	ADS	711 + 0
$B^+ \rightarrow Dh^+$	$D \rightarrow K_S^0K^-\pi^+$	GLS	711 + 362 Belle II
$B^+ \rightarrow Dh^+$	$D \rightarrow K_S^0h^-h^+$	BPGGSZ (m.i.)	711 + 128 Belle II
$B^+ \rightarrow Dh^+$	$D \rightarrow K_S^0\pi^-\pi^+\pi^0$	BPGGSZ (m.i.)	711 + 0
$B^+ \rightarrow D^*K^+$	$D^* \rightarrow D\pi^0, D \rightarrow K_S^0\pi^0, K_S^0\phi, K_S^0\omega, K^-K^+, \pi^-\pi^+$	GLW	210+0
$B^+ \rightarrow D^*K^+$	$D^* \rightarrow D\pi^0, D\gamma, D \rightarrow K_S^0\pi^-\pi^+$	BPGGSZ (m.d.)	605 + 0

Belle + Belle II :

[JHEP 10 \(2024\) 143](#)

$$\phi_3 = (75.2 \pm 7.6)^{\circ}$$

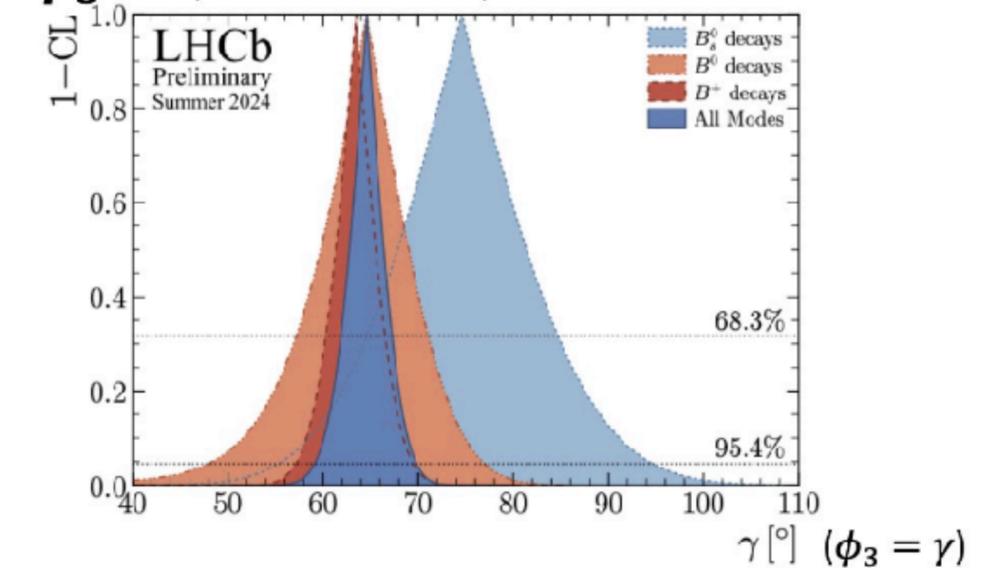
Belle + Belle II (2024)



LHCb:

[LHCb-CONF-2024-004](#)

$$\phi_3 = (64.6 \pm 2.8)^{\circ}$$



Dominated by LHCb, but Belle+Belle II does improve the precision.

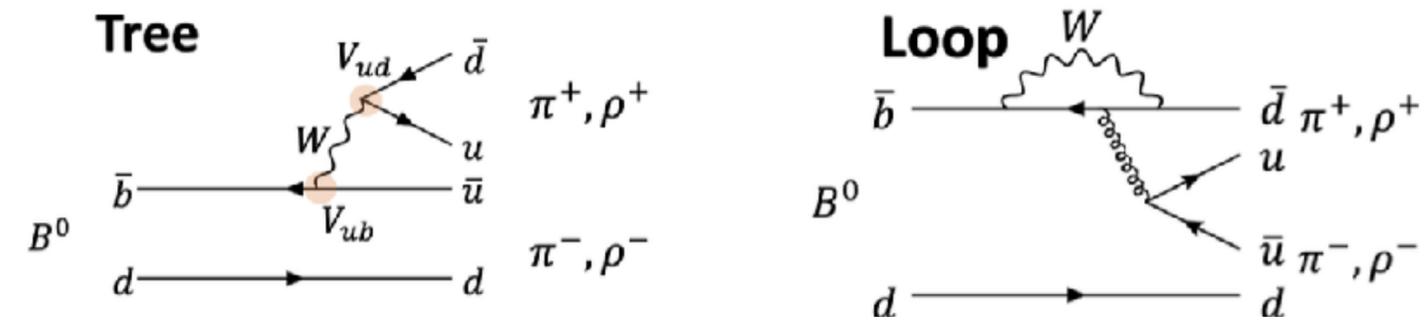
Uncertainty could be reduced to 3.5° with 5 ab^{-1} Belle II data

ϕ_2/α measurement

- Least well known CKM angle with WA $(84.1_{-3.8}^{+4.5})^\circ$,
Uncertainty dominated by $\mathcal{B}(B^0 \rightarrow \pi^0\pi^0)$ and \mathcal{A}_{CP}
- Extract from $b \rightarrow u\bar{u}d$ process, like $B \rightarrow \pi\pi, \rho\rho, \rho\pi$

$$\frac{\Gamma(\bar{B}^0 \rightarrow f) - \Gamma(B^0 \rightarrow f)}{\Gamma(\bar{B}^0 \rightarrow f) + \Gamma(B^0 \rightarrow f)} = -C \cdot \cos \Delta m_d \Delta t + S \cdot \sin \Delta m_d \Delta t$$

- Using $b \rightarrow u$ tree decays (e.g. $B^0 \rightarrow \pi^+\pi^-, \rho^+\rho^-$),
 $S = \sin 2\phi_2$ and $C = 0$.
- Due to the interference between tree and loop $b \rightarrow d$,
 $S = \sin 2\phi_2 + 2\Delta\phi_2$, and $C \neq 0$



Isospin relations

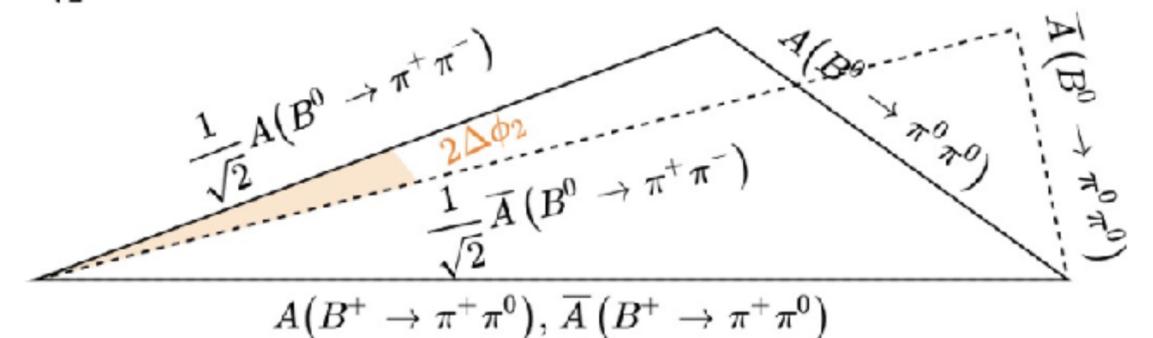
	Tree	Loop	
$\pi^+\pi^-$	○	○	○: Large contribution ×: No contribution △: Smaller contribution
$\pi^+\pi^0$	○	×	
$\pi^0\pi^0$	△	○	

(color suppressed)

Granou-London isospin relations

$$\frac{1}{\sqrt{2}}A(B^0 \rightarrow \pi^+\pi^-) - A(B^0 \rightarrow \pi^0\pi^0) = A(B^+ \rightarrow \pi^+\pi^0)$$

$$\frac{1}{\sqrt{2}}\bar{A}(B^0 \rightarrow \pi^+\pi^-) - \bar{A}(B^0 \rightarrow \pi^0\pi^0) = \bar{A}(B^+ \rightarrow \pi^+\pi^0)$$

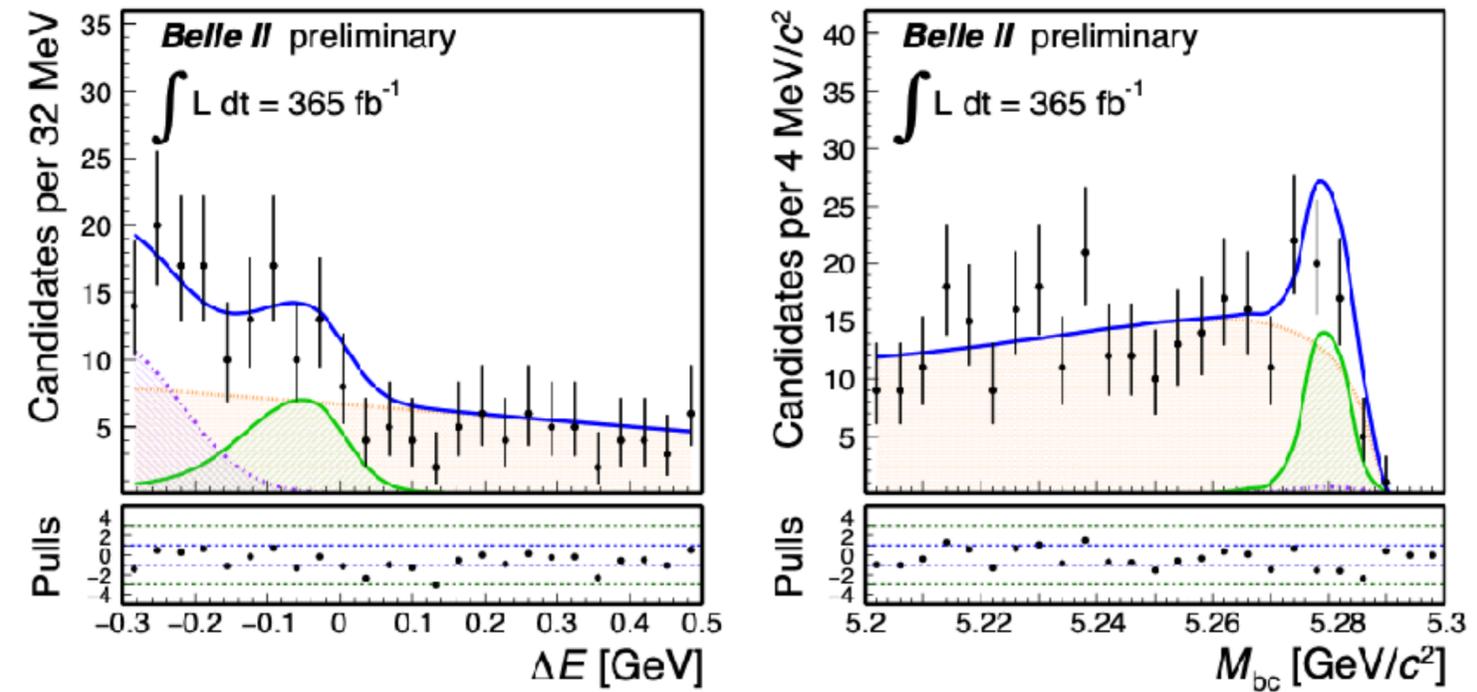


$\Delta\phi_2$ can be extracted using this relationship

ϕ_2/α measurement

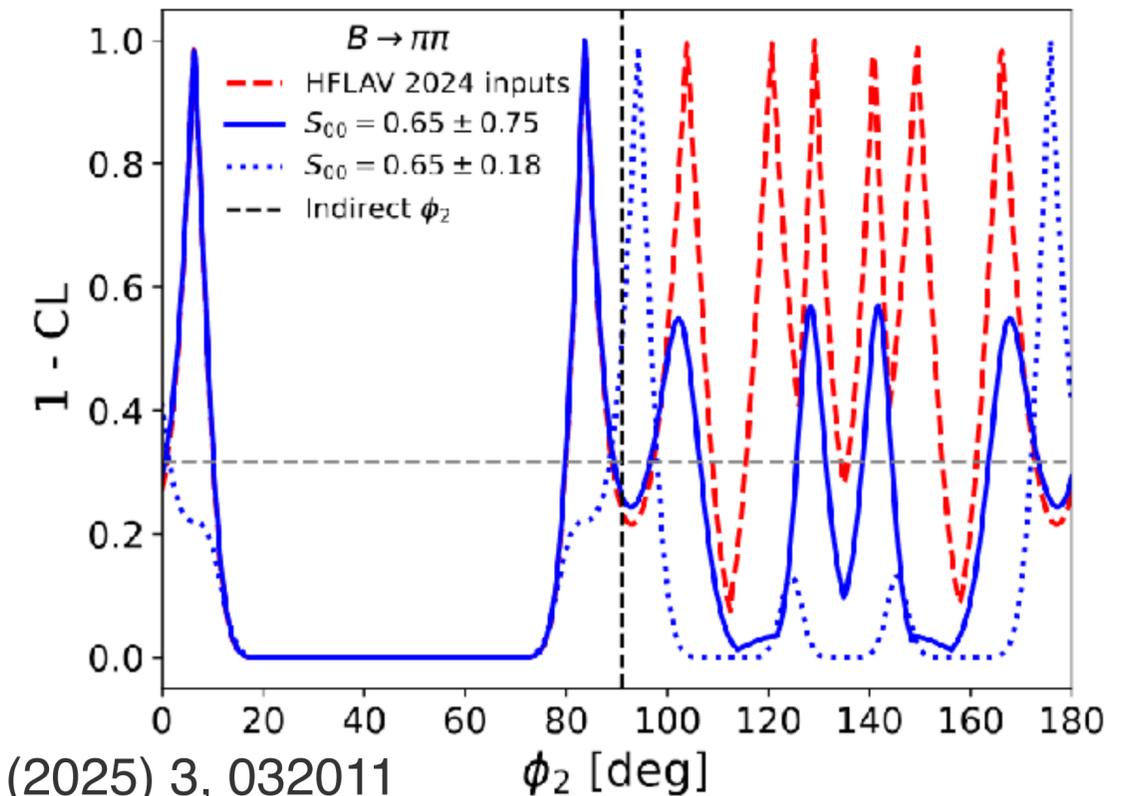
$$B^0 \rightarrow \pi^0 \pi^0$$

- Use 365/fb Belle II data
- Photon-BDT to reduce fake photon & beam BKG
- Calibrate B^0 flavor with $B^0 \rightarrow D^{(*)-} \pi^+$



	$B(10^{-6})$	A_{CP}	$N_{B\bar{B}}$
Belle II	$1.25 \pm 0.20 \pm 0.11$	$0.03 \pm 0.30 \pm 0.04$	388×10^6
Belle	$1.31 \pm 0.19 \pm 0.19$	$0.14 \pm 0.36 \pm 0.10$	772×10^6

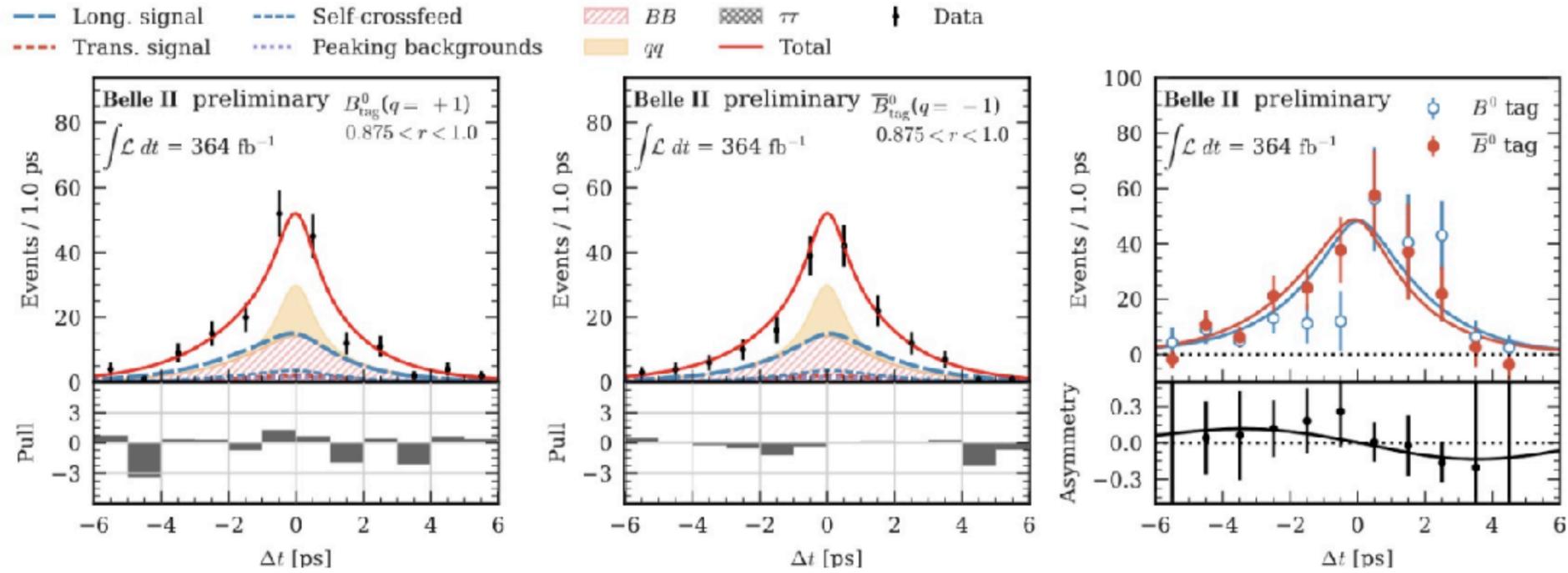
- Clear impact on ϕ_2 from $\pi\pi$ system
 - Reduce interval @68% C.L. by 10°
 - 30% improvement on ϕ_2 precision.



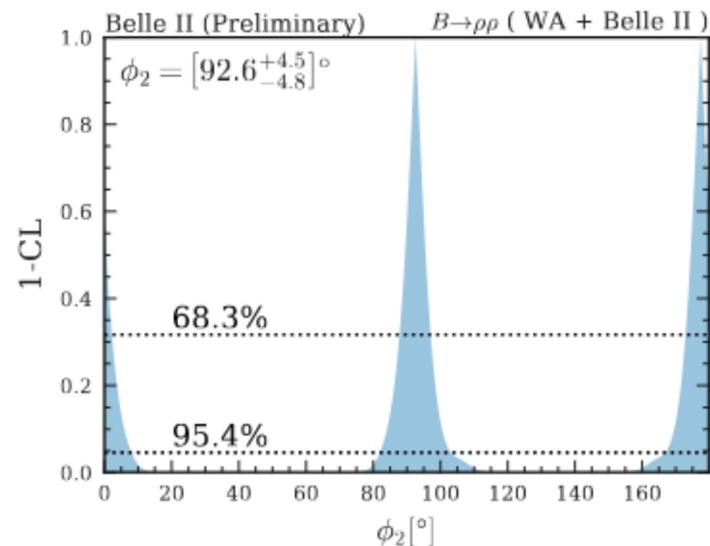
ϕ_2/α measurement



- Smaller contribution from loop than $B \rightarrow \pi\pi, \rho\pi, a_1\pi$
- More stringent constraint on ϕ_2
- Two step fit
 - Extended fit to $\Delta E, m_{\pi^\pm\pi^0}, \cos\theta_{\rho^\pm}, \mathcal{T}_C$ to extract \mathcal{B}, f_L
 - fit to $\Delta t, q, r$ to extract S, C



	$\mathcal{B}(10^{-6})$	f_L	S	C
Belle II	$29.0^{+2.3}_{-2.2} \begin{smallmatrix} +3.1 \\ -3.0 \end{smallmatrix}$	$0.921^{+0.024}_{-0.025} \begin{smallmatrix} +0.017 \\ -0.015 \end{smallmatrix}$	$-0.26 \pm 0.19 \pm 0.08$	$-0.02 \pm 0.12 \begin{smallmatrix} +0.06 \\ -0.05 \end{smallmatrix}$
Belle	$28.3 \pm 1.5 \pm 1.5$	$0.988 \pm 0.012 \pm 0.006$	$-0.13 \pm 0.15 \pm 0.05$	$0.00 \pm 0.10 \pm 0.06$
BABAR	$25.5 \pm 2.1 \begin{smallmatrix} +3.6 \\ -3.9 \end{smallmatrix}$	$0.992 \pm 0.024 \begin{smallmatrix} +0.026 \\ -0.013 \end{smallmatrix}$	$-0.17 \pm 0.20 \begin{smallmatrix} +0.05 \\ -0.06 \end{smallmatrix}$	$0.01 \pm 0.15 \pm 0.06$



$B \rightarrow \rho\rho$ world average

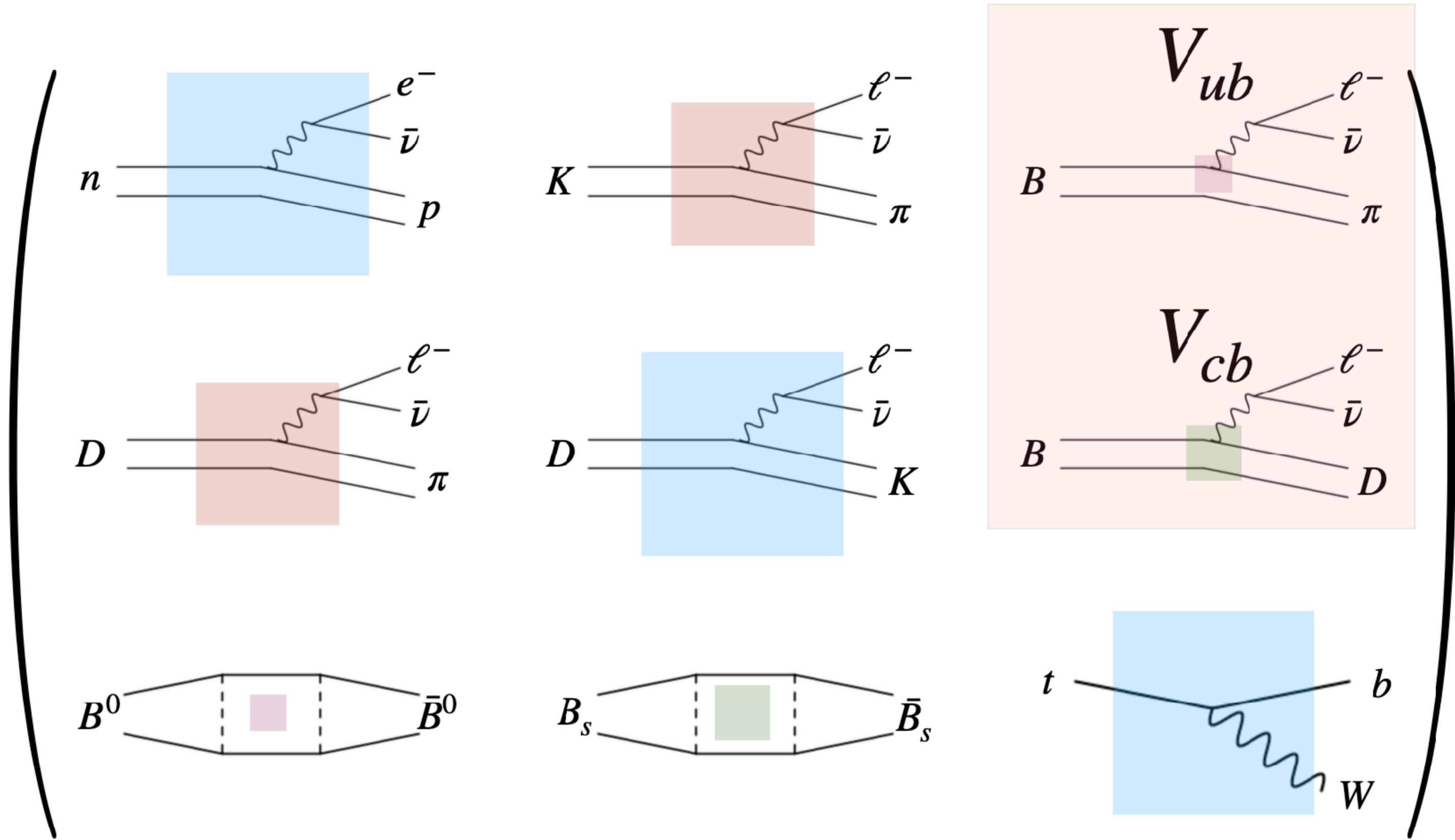
$$\phi_2 = (91.5^{+4.5}_{-5.4})^\circ$$

$B \rightarrow \rho\rho$ world average

+ Belle II $\rho^+ \rho^-$ results

$$\rightarrow \phi_2 = (92.6^{+4.5}_{-4.8})^\circ$$

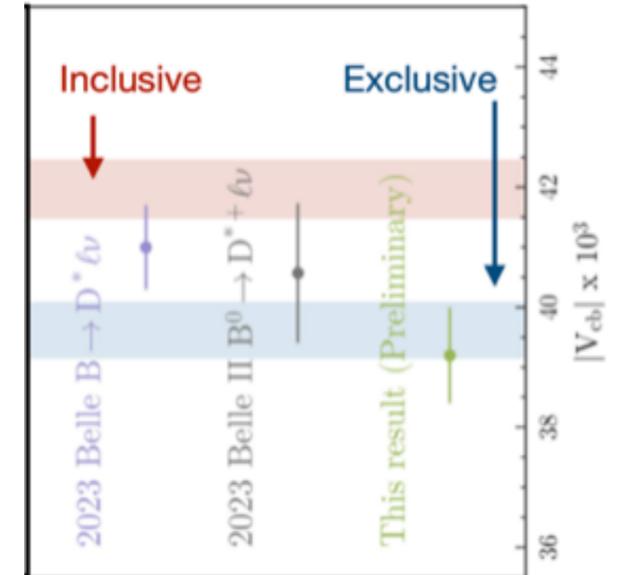
6% ↑



$|V_{cb}|$ measurement

q^2 in $B \rightarrow X_c \ell \nu$

- A longstanding discrepancy btw. $|V_{cb}|_{\text{incl.}}$ and $|V_{cb}|_{\text{exc.}}$ about 3σ

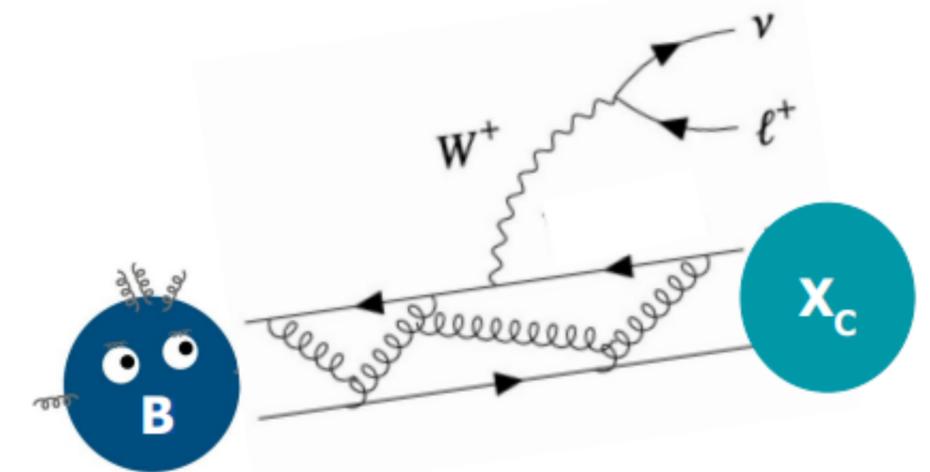
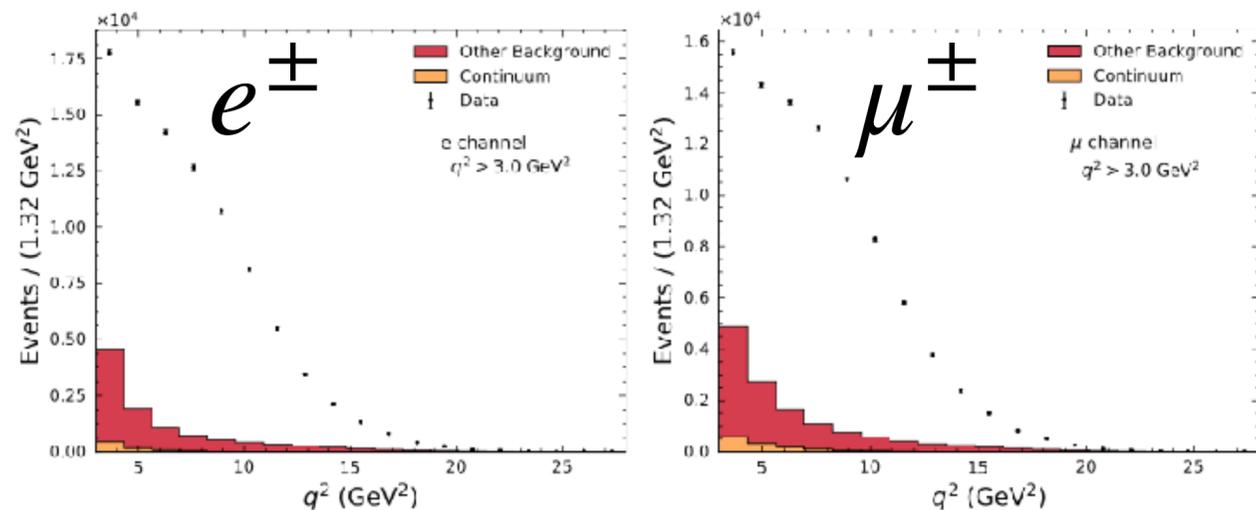


JHEP01, 147 (2014)

- A novel and alternative method to determine $|V_{cb}|_{\text{incl.}}$ to avoid proliferation of theoretical parameters, but need spectral moments of the lepton mass squared $q^2 \equiv (p_\ell + p_\nu)^2 = (p_B - p_X)^2$.

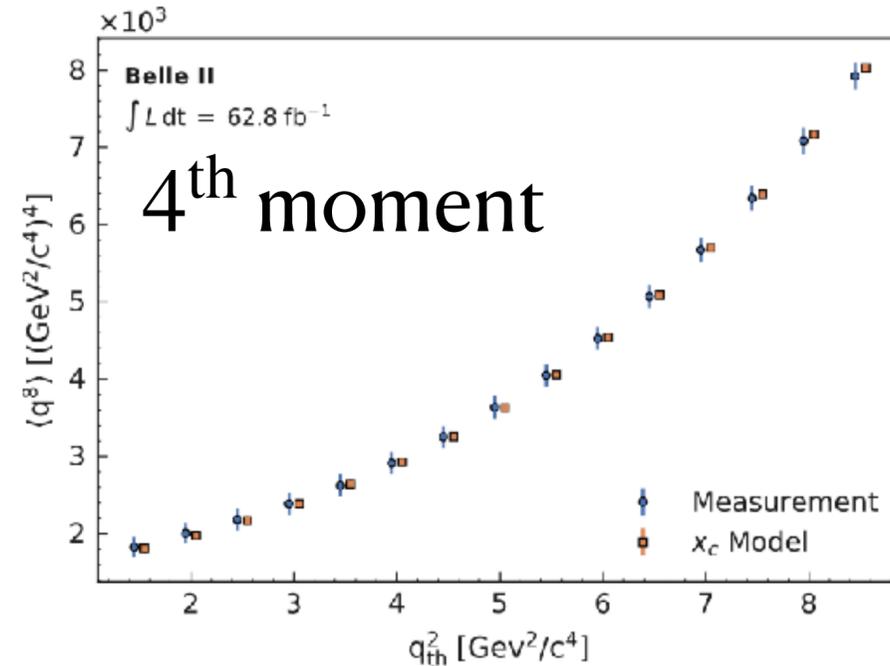
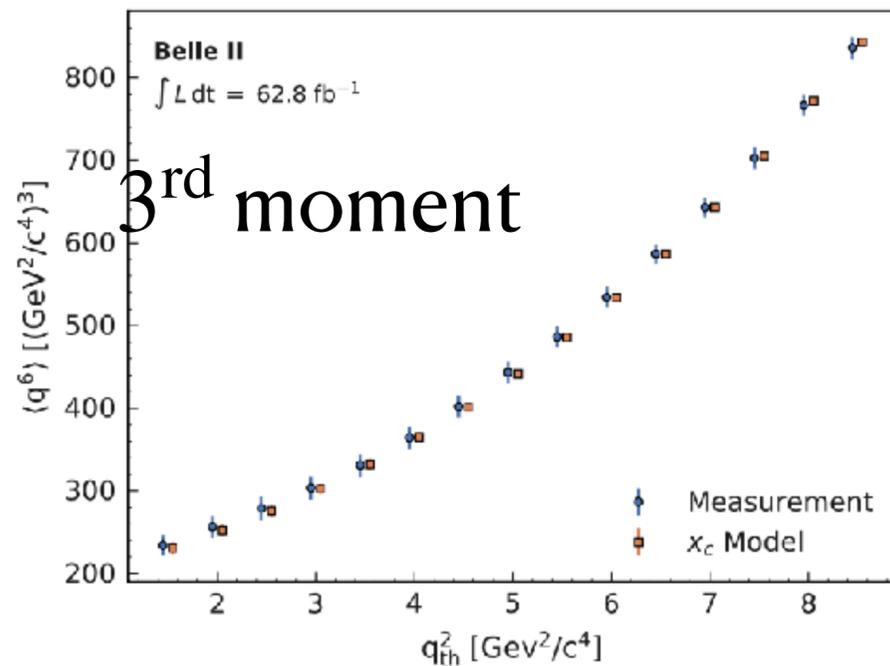
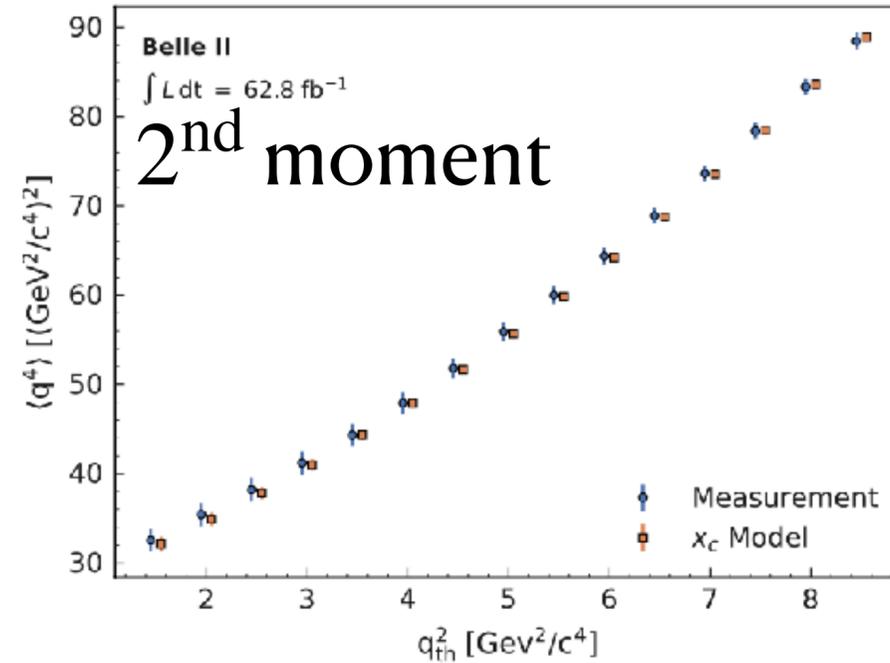
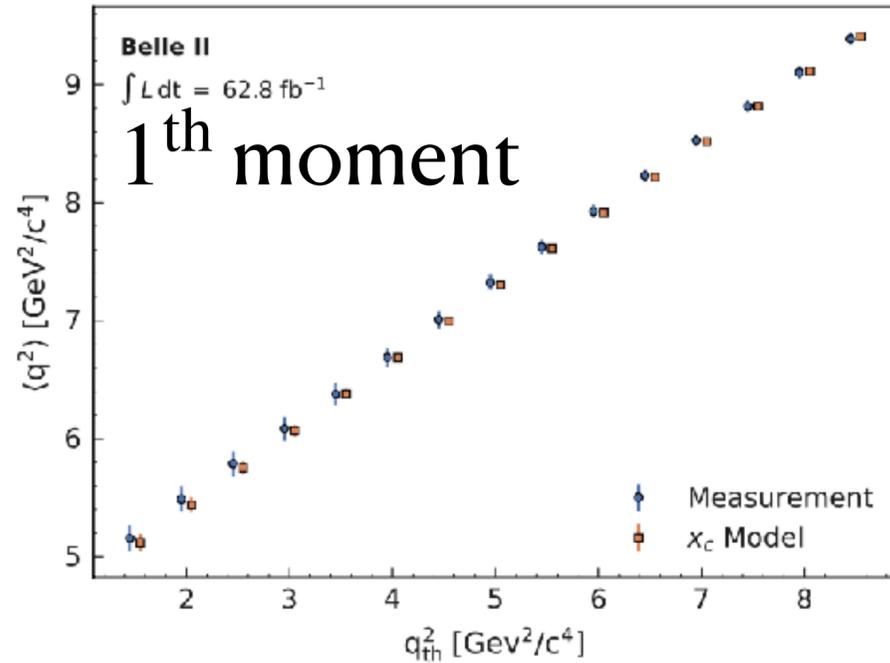
- Belle reported q^2 measurement for $q^2 > 4 \text{ GeV}^2/c^4$, covering 58% accessible phase space, with full Belle data ($772 \times 10^6 B\bar{B}$ events)

PRD 104(2021) 112011



- Similarly work was done with $q^2 > 1.5 \text{ GeV}^2/c^4$, covering 77% accessible phase space, with 62.8 fb^{-1} data collected at Belle II.

[PRD 107 \(2023\) 7, 072002](#)



With the q^2 moment provided by Belle and Belle II, $|V_{cb}|_{\text{incl.}}$ reported as:

- $|V_{cb}|_{\text{incl.}} = (41.69 \pm 0.63) \times 10^{-3}$

[JHEP 10 \(2022\) 068](#)

- $|V_{cb}|_{\text{incl.}} = (41.97 \pm 0.48) \times 10^{-3}$

[JHEP 02 \(2024\) 206](#)

where the latter includes $O(\alpha_s^2 \beta_0)$ corrections.

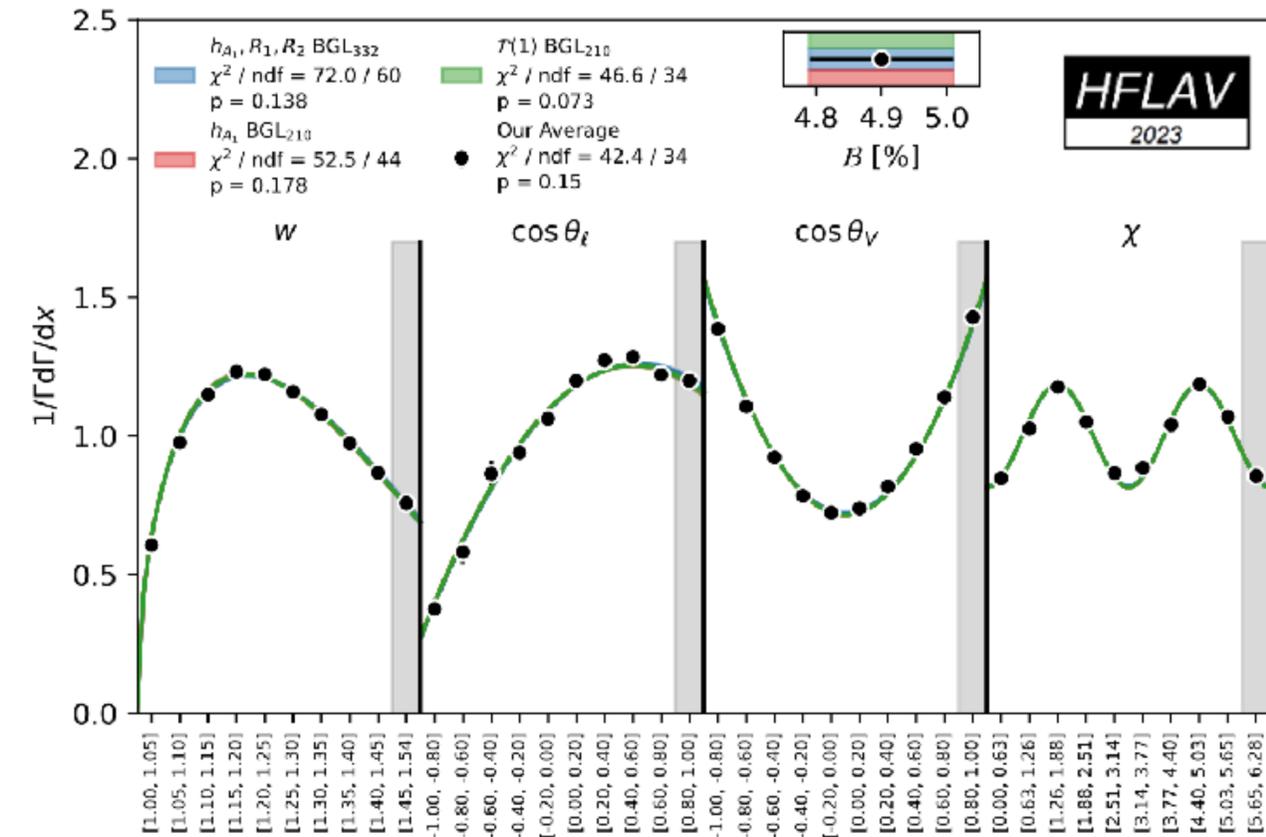
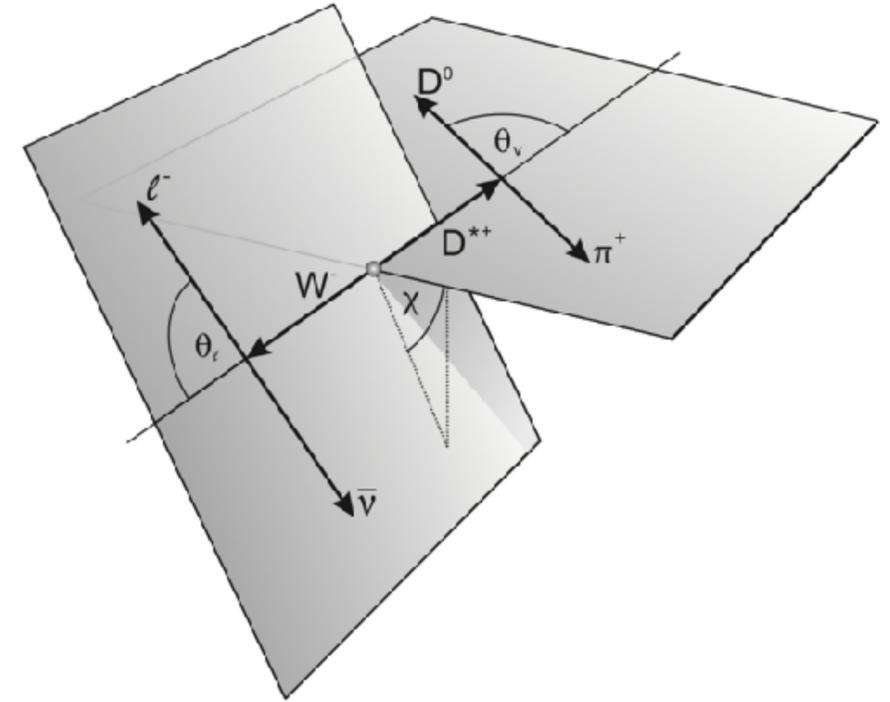
$|V_{cb}|$ measurement

$|V_{cb}|$ with $B \rightarrow D^* \ell \nu$

- $B \rightarrow D^* \ell \nu$ provide most precise $|V_{cb}|$ measurement
- $B \rightarrow D^* \ell \nu$ is parameterized with the recoil parameter (w) and three decay angles ($\theta_\ell, \chi, \theta_V$).
- Extract signal yields in each $(w, \theta_\ell, \chi, \theta_V)$ bin.
- Combined Belle and Belle II measurements and fit (HFLAV2023)

PRD 108 (2023) 092013
PRD 108 (2023) 012002

 - extract $|V_{cb}|$ in different LQCD input scenarios



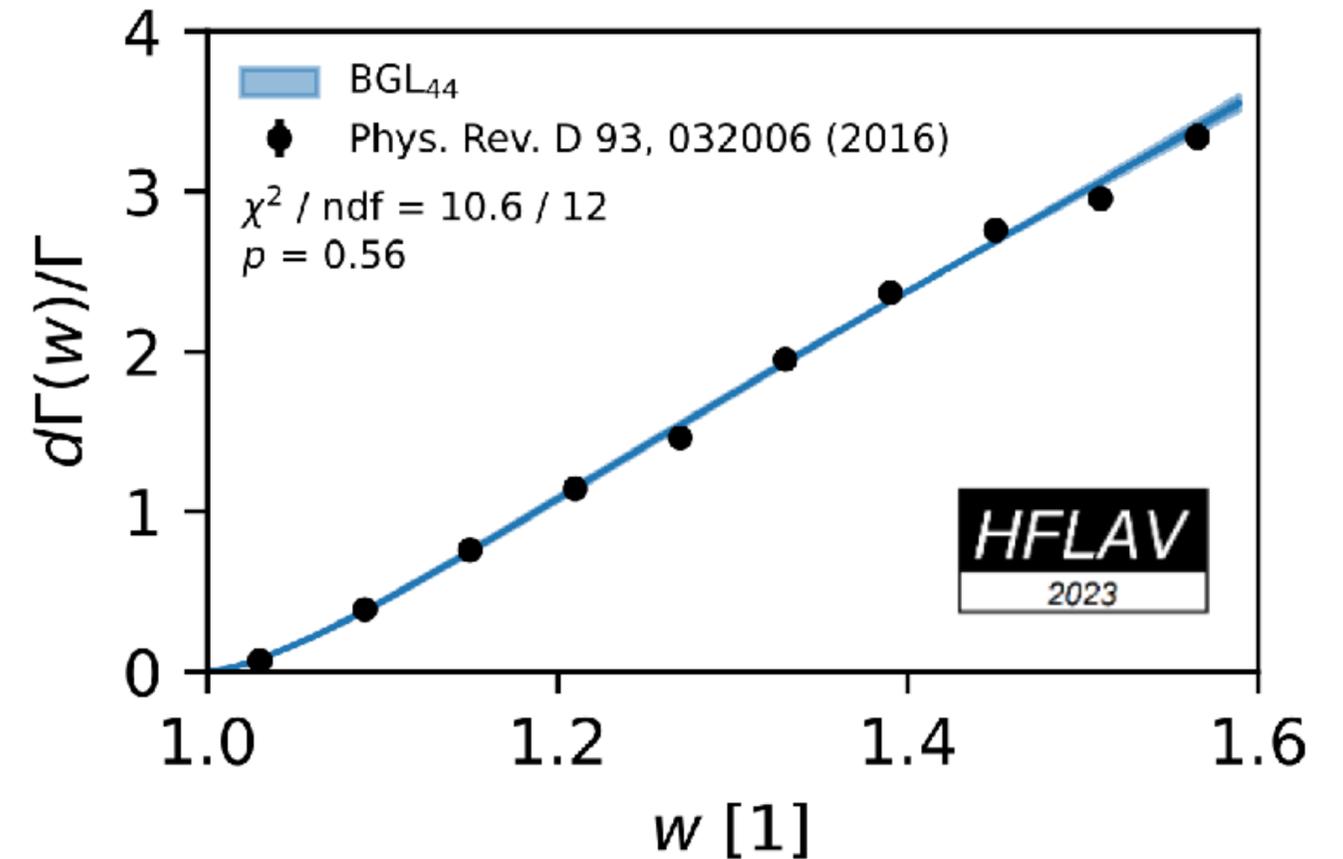
BGL	$ V_{cb} \times 10^3$	$ V_{cb} \times 10^3 \times \mathcal{F}(1)$	$\mathcal{F}(1)$	LQCD Input
332	40.0 ± 0.7	36.0 ± 0.5	0.900 ± 0.008	$h_{A_1}(w), R_1(w), R_2(w)$
210	40.2 ± 0.6	36.0 ± 0.4	0.897 ± 0.009	$h_{A_1}(w)$
210	40.2 ± 0.6	36.0 ± 0.4	0.895 ± 0.007	$h_{A_1}(1) = \mathcal{F}(1)$

$|V_{cb}|$ measurement

$|V_{cb}|$ with $B \rightarrow D\ell\nu$

- Disadvantages:
 - Smaller BF ($\sim 2\%$, $\sim 5\%$ of $B \rightarrow D^*\ell\nu$)
 - Background from $B \rightarrow D^*\ell\nu$.
- Advantages:
 - Smaller theoretical uncertainty in form factor.
 - Smaller experimental systematic uncertainty.

$$\frac{d\Gamma(\bar{B} \rightarrow D\ell^-\bar{\nu}_\ell)}{dw} = \frac{G_F^2 m_D^3}{48\pi^3} (m_B + m_D)^2 (w^2 - 1)^{3/2} \eta_{EW}^2 \mathcal{G}^2(w) |V_{cb}|^2,$$



With Belle result, HFLAV give

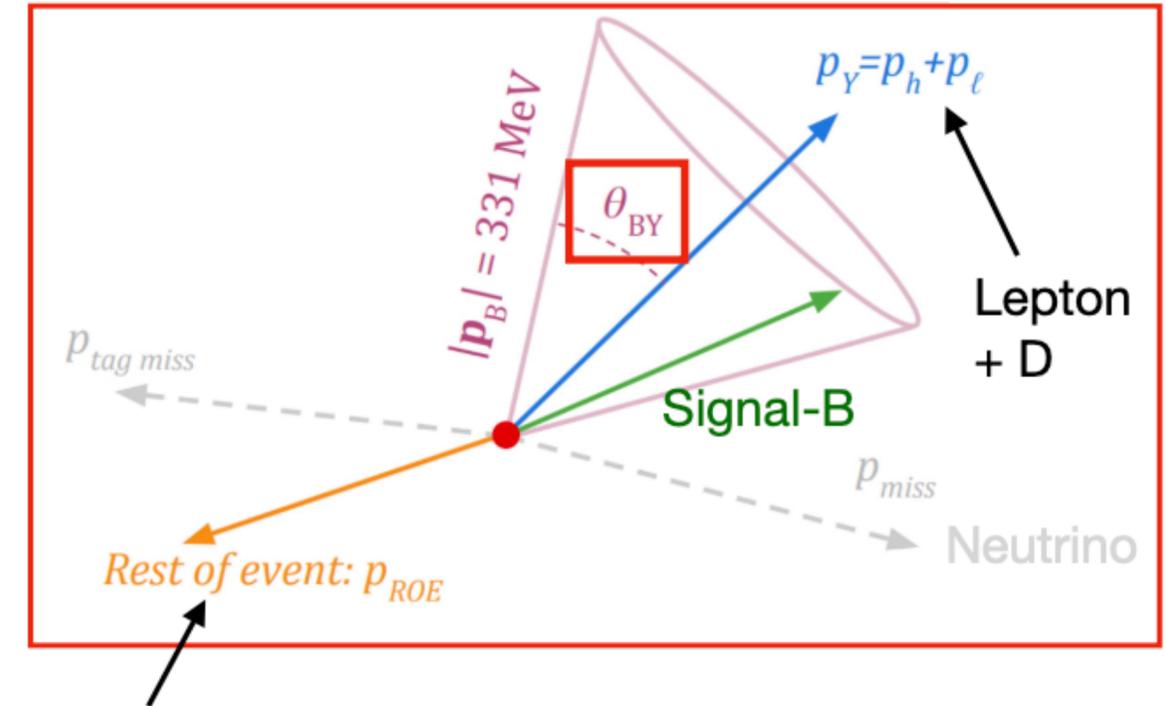
$$|V_{cb}| = (38.9 \pm 0.7) \times 10^{-3}$$

$|V_{cb}|$ measurement

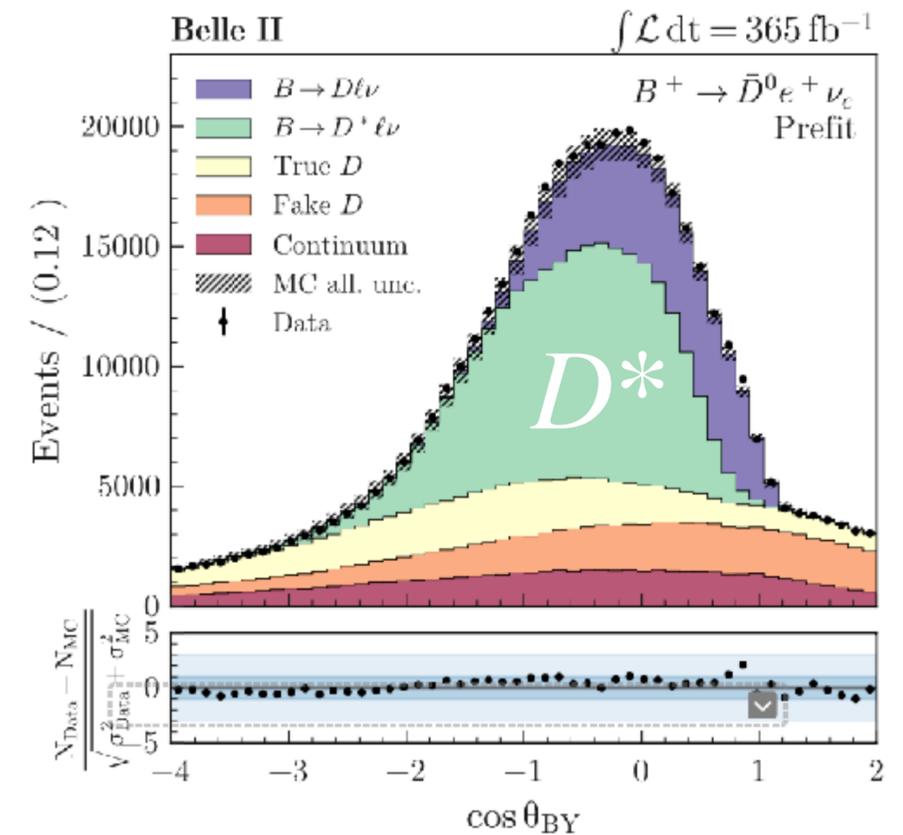
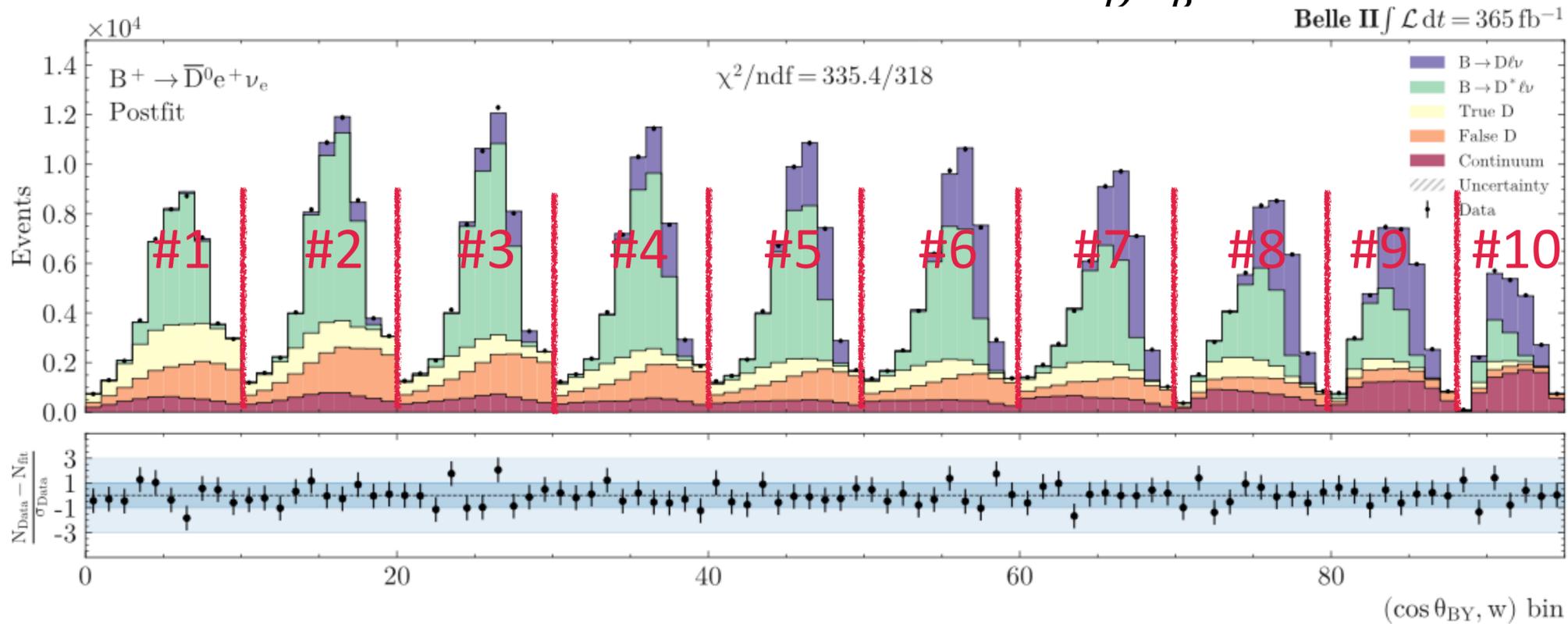
$|V_{cb}|$ with $B \rightarrow D\ell\nu$ PRD 112 (2025) 112009

- With 365 fb^{-1} $\Upsilon(4S)$ data collected at Belle II
- After $B \rightarrow D^*\ell\nu$ and continuum suppression, S:B = 1:4

- Reconstruct in bins of $w = v_B \cdot v_D = \frac{m_B^2 + m_D^2 - q^2}{2m_D m_B} \in [1, 1.5]$



From inclusive tag

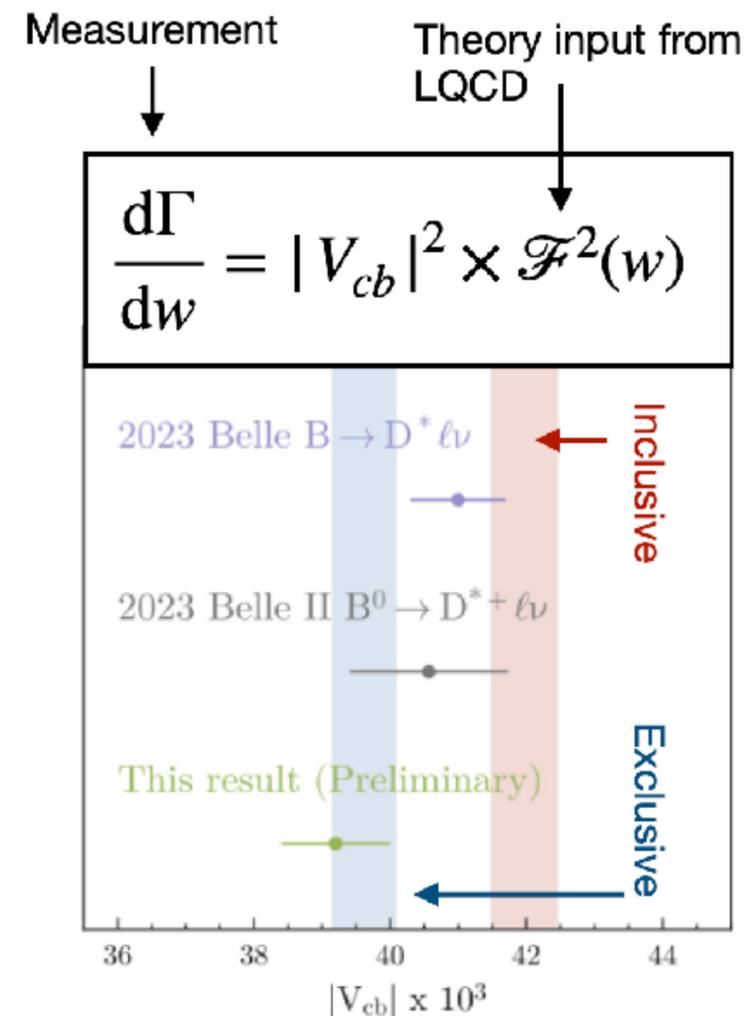
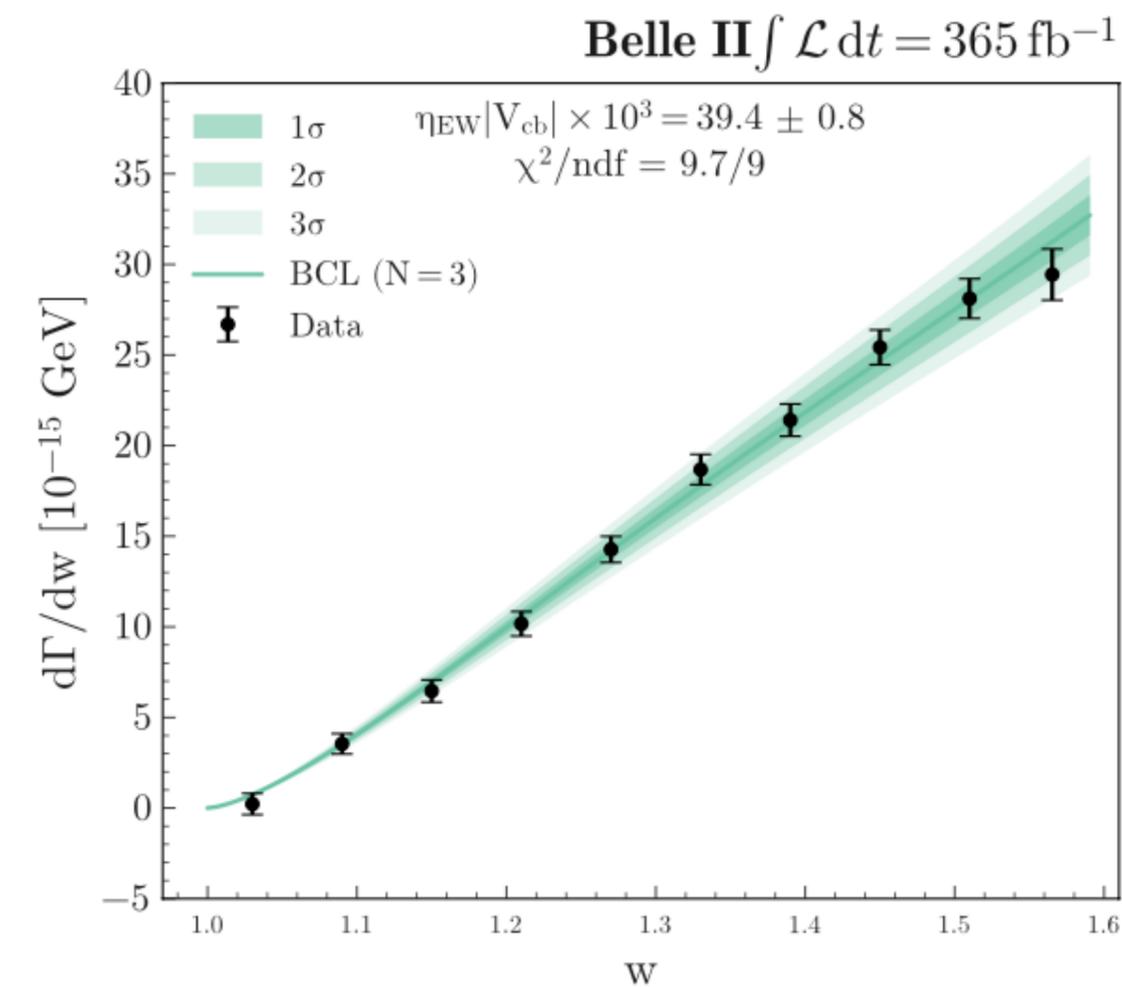


- Summing differential decay width over w , we get
 - $\mathcal{B}(B^+ \rightarrow \bar{D}^0 \ell^+ \nu_\ell) = (2.31 \pm 0.04 \pm 0.09) \%$
 - $\mathcal{B}(B^0 \rightarrow D^- \ell^+ \nu_\ell) = (2.06 \pm 0.05 \pm 0.10) \%$

- Lepton flavour universality

$$R^{\ell/\mu} \equiv \frac{\mathcal{B}(B \rightarrow D \ell \nu)}{B \rightarrow D \mu \nu}$$

$$= 1.020 \pm 0.020 \pm 0.022$$



Use BCL expansion of the form factor, we obtain

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

stat. syst. theo.

- Consistent with Belle and BaBar's results, but 2.1% total uncertainty improves.
- World's most precise fully exclusive determination of $|V_{cb}|$!

New measurement of inclusive $|V_{ub}|$

$$B \rightarrow X_u \ell \nu$$

[arXiv:2512.08056](https://arxiv.org/abs/2512.08056)

- $|V_{ub}|$ is hard due to background from $B \rightarrow X_c \ell \nu$
 - $\times \mathcal{O}(100)$ more abundant
 - Very similar signature
 - high momentum lepton, hadronic system, etc.
- Clear separation only in corners of phase space
 - high E_ℓ , low M_X

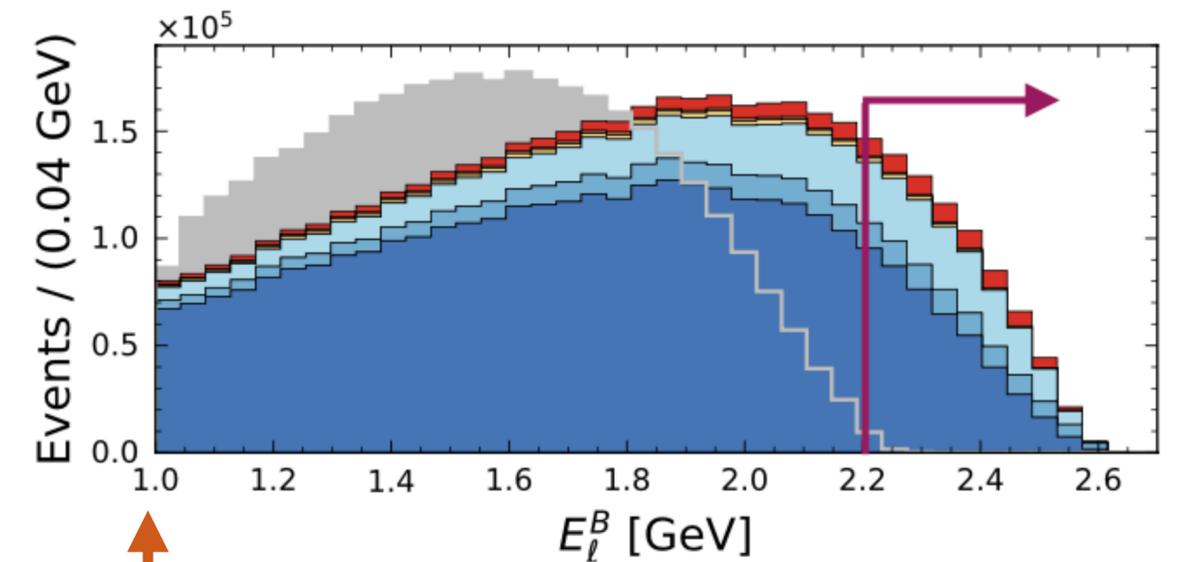
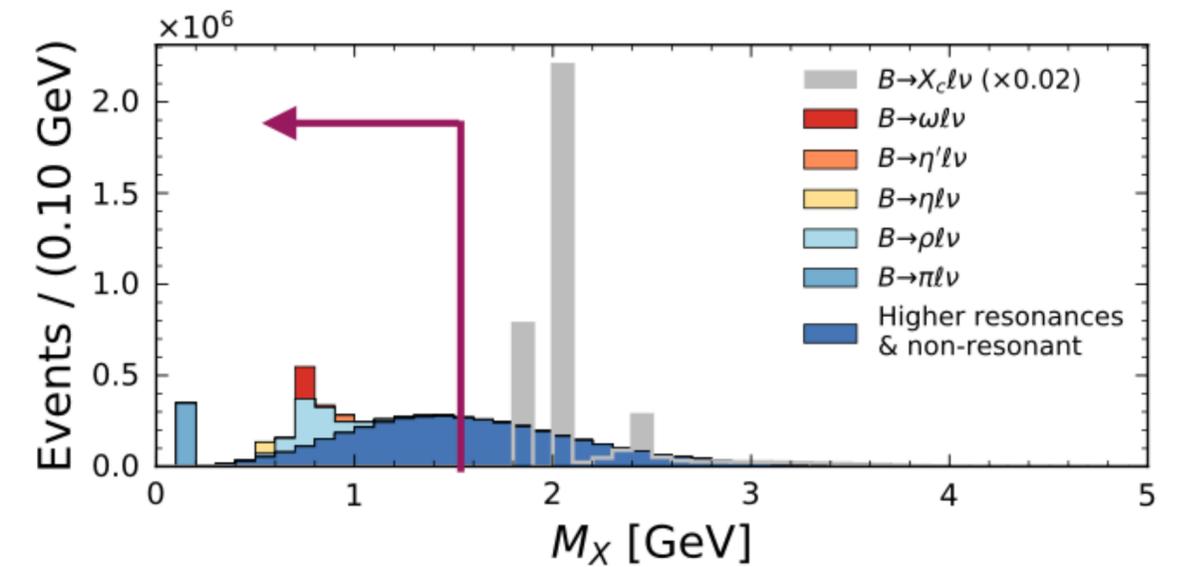
Theory error gets large
Experimental uncert. small

high cut

Theory error gets small
Experimental uncert. large

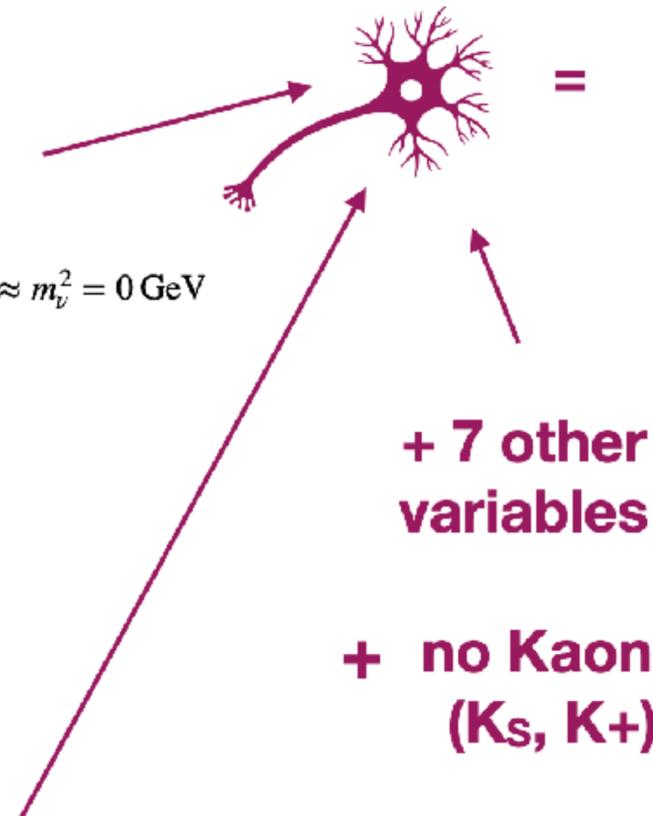
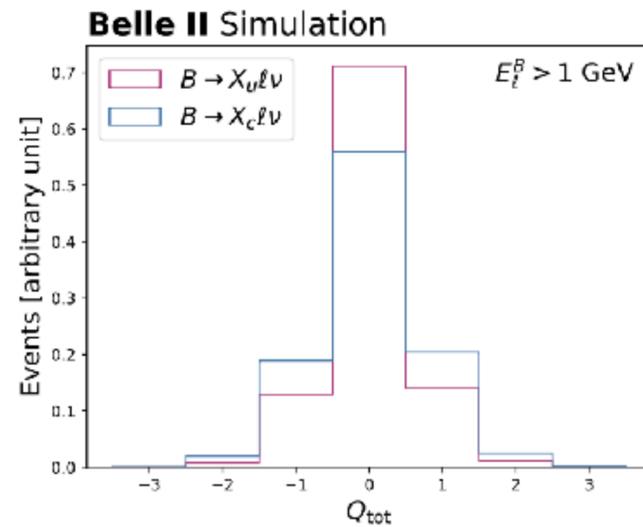
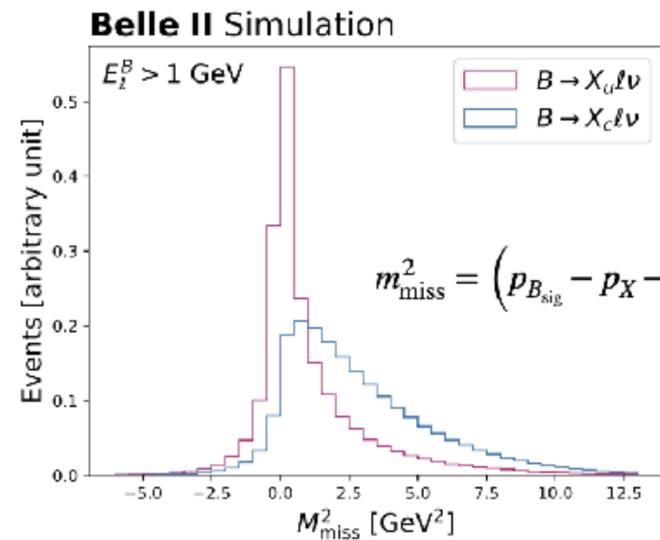
low cut

24

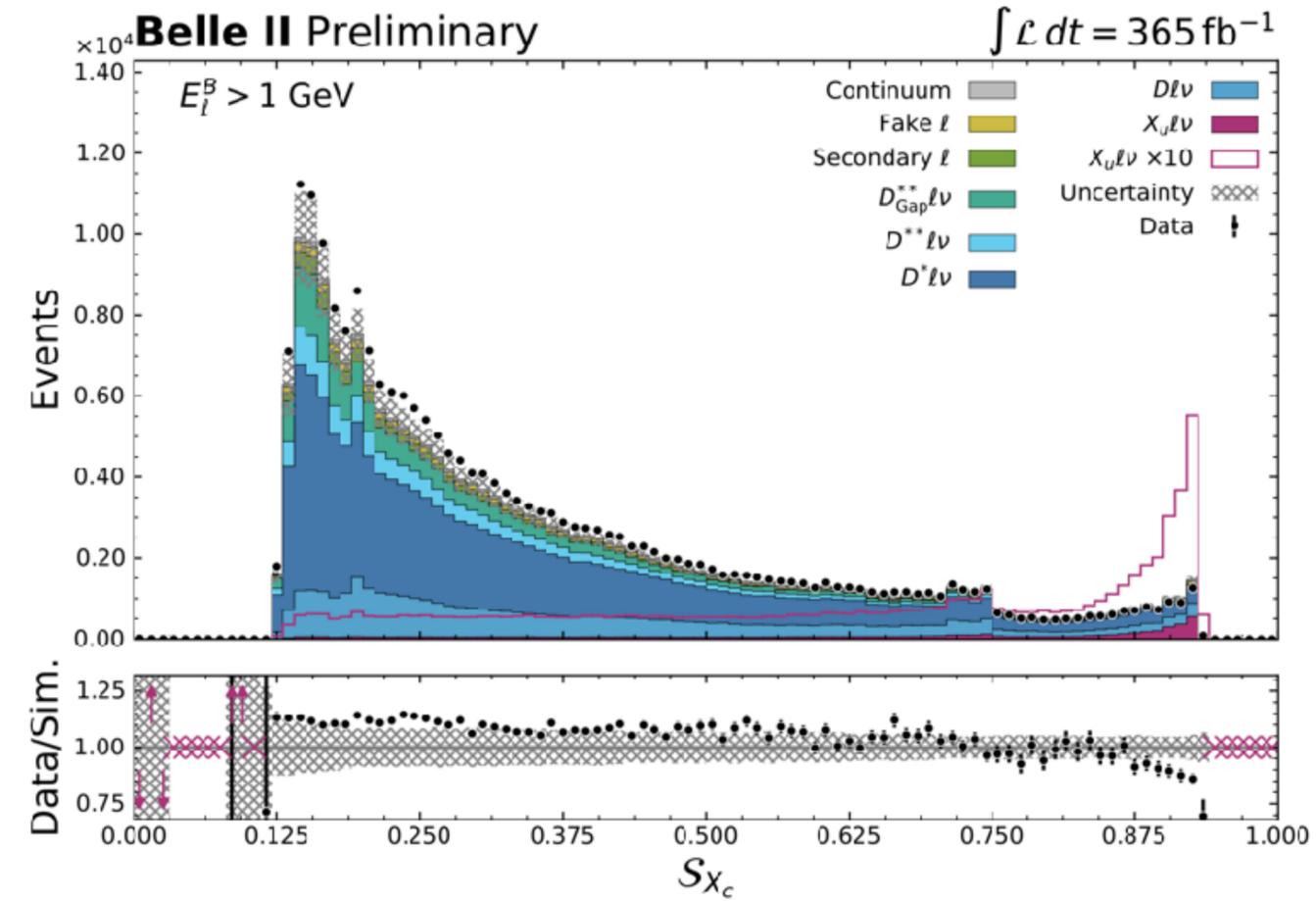


Start from 1.0 GeV, rejects events populated by continuum and fake secondary lepton events.

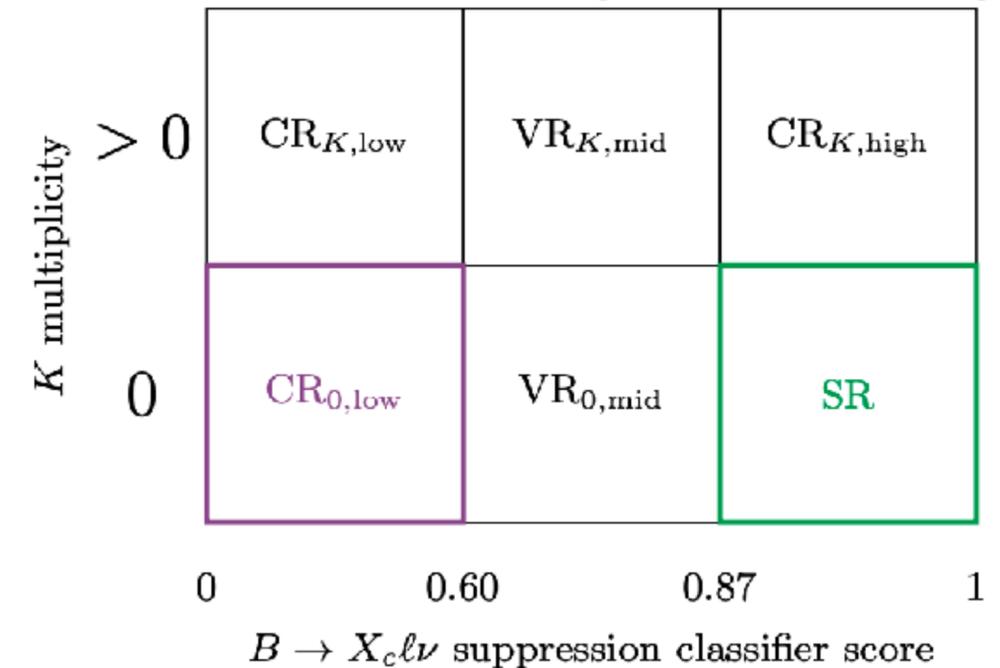
- 30 variables based MLP to reduce **continuum background**.
 - reject 95% of continuum and retain 68% of X_u
- 9 variables based MLP to reduce $B \rightarrow X_c \ell \nu$



Reject 98% of X_c and retain 25% of X_u

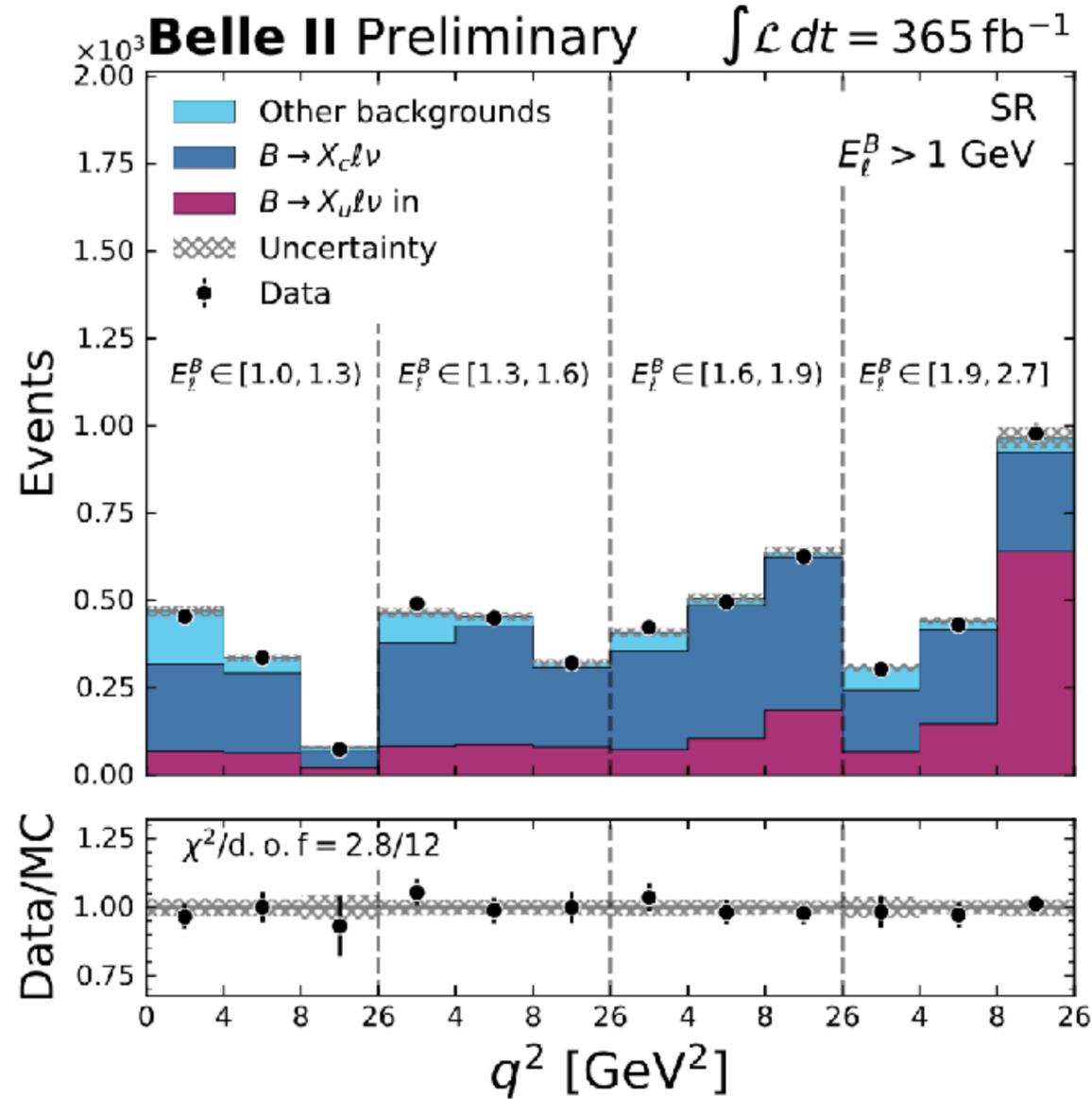


Data driven background modeling



Two dimensional fit in $q^2 : E_\ell$

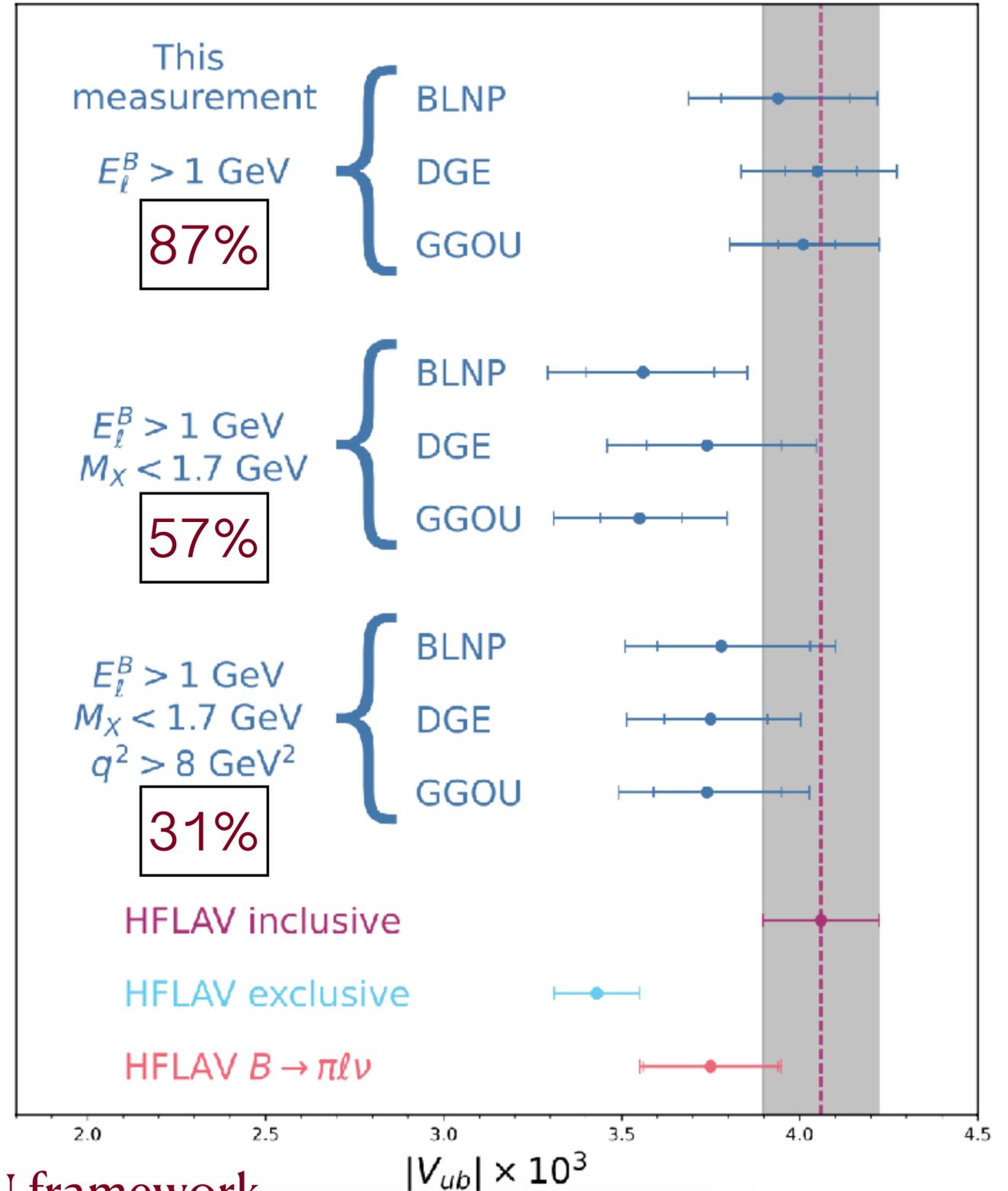
With $E_\ell^B > 1$ GeV:



$$\Delta\mathcal{B}(B \rightarrow X_{u\ell\nu}) = (1.54 \pm 0.08 \pm 0.12) \times 10^{-3}$$

$$|V_{ub}| = (4.01 \pm 0.11 \pm 0.16_{-0.08}^{+0.07}) \times 10^{-3} \text{ in GGOU framework}$$

Belle II Preliminary



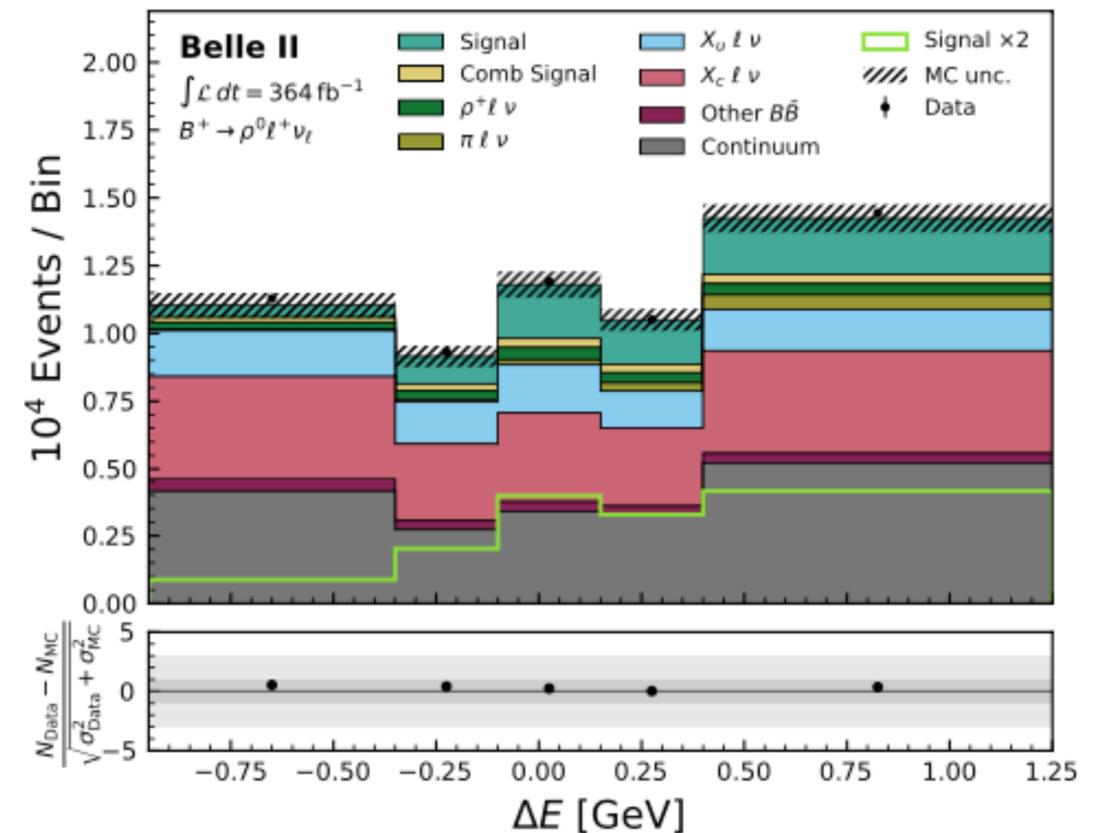
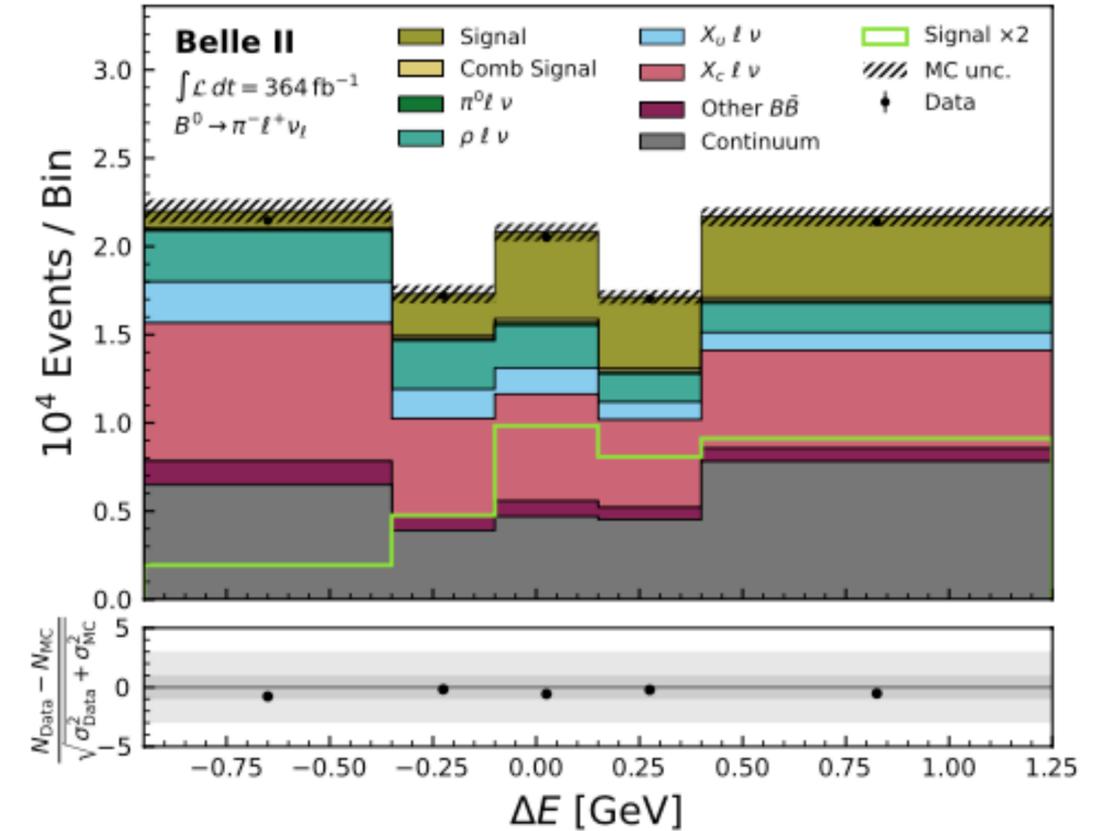
$|V_{ub}|$ measurement

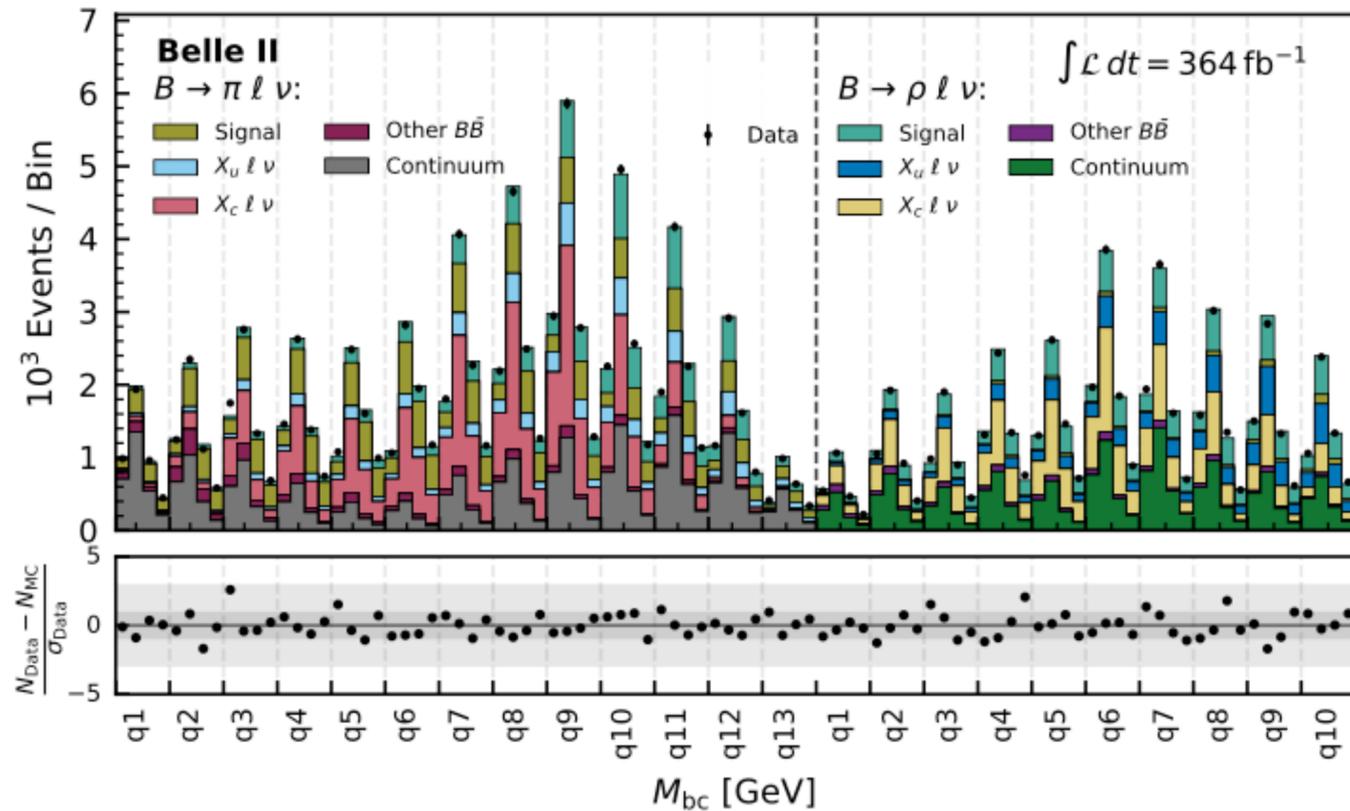
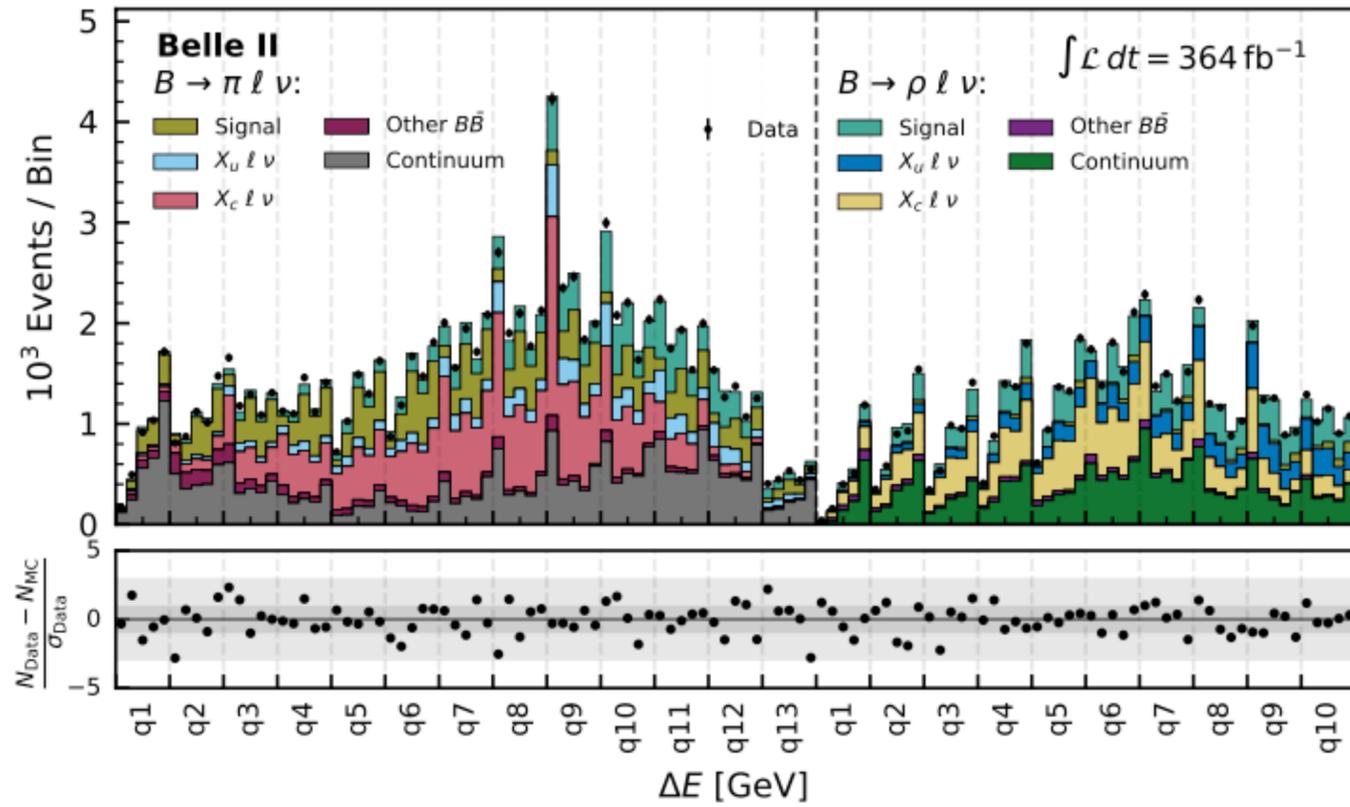
$$B^0 \rightarrow \pi^- \ell^+ \nu \quad \& \quad B^+ \rightarrow \rho^0 \ell^+ \nu \quad \text{PRD 111(2025), 112009}$$

- Easily mis-identified each other. Simultaneous measurement provide additional constraints.
- `Untag` partner B meson. High efficiency but low purity.
- Estimate p_ν by attributing E & p from Rest of Event (ROE)

$$(E_{\text{miss}}^*, \vec{p}_{\text{miss}}^*) = (E_{\Upsilon(4S)}^*, \vec{p}_{\Upsilon(4S)}^*) - \left(\sum_i E_i^*, \sum_i \vec{p}_i^* \right)$$

- Very restrict to reduce beam background / acceptance loss, etc.
- BDT to suppress continuum background, variables including event shape, kinematic and topological variables are used.





- Simultaneous fit to ΔE , M_{bc} and q^2 in 460 q^2 bins, (13+10) of q^2 , X 5 of ΔE , X 4 of M_{bc} .

Signal yields are obtained in bins of q^2

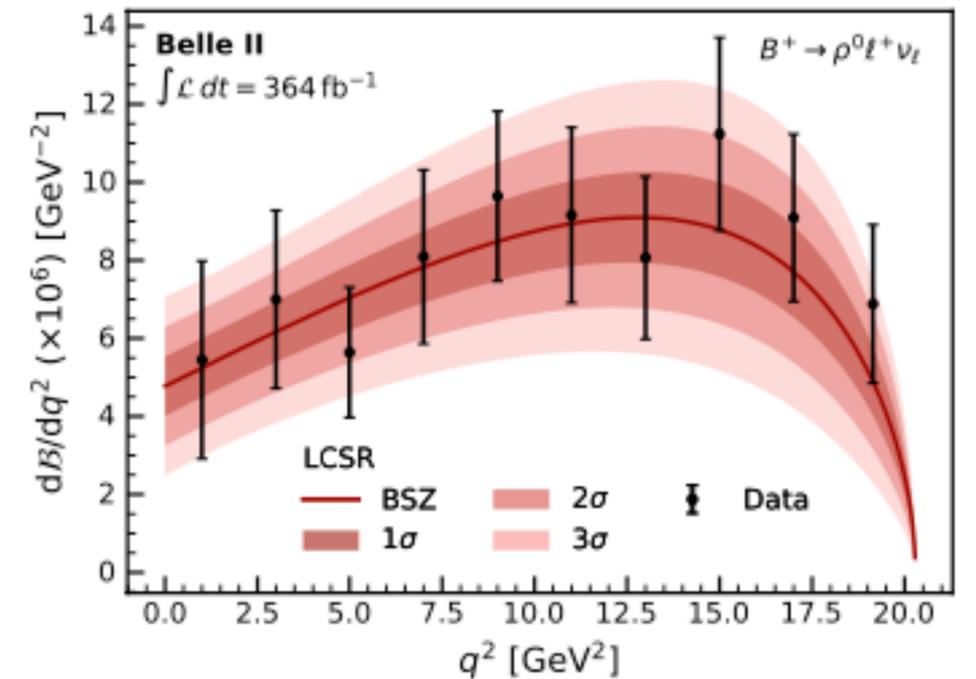
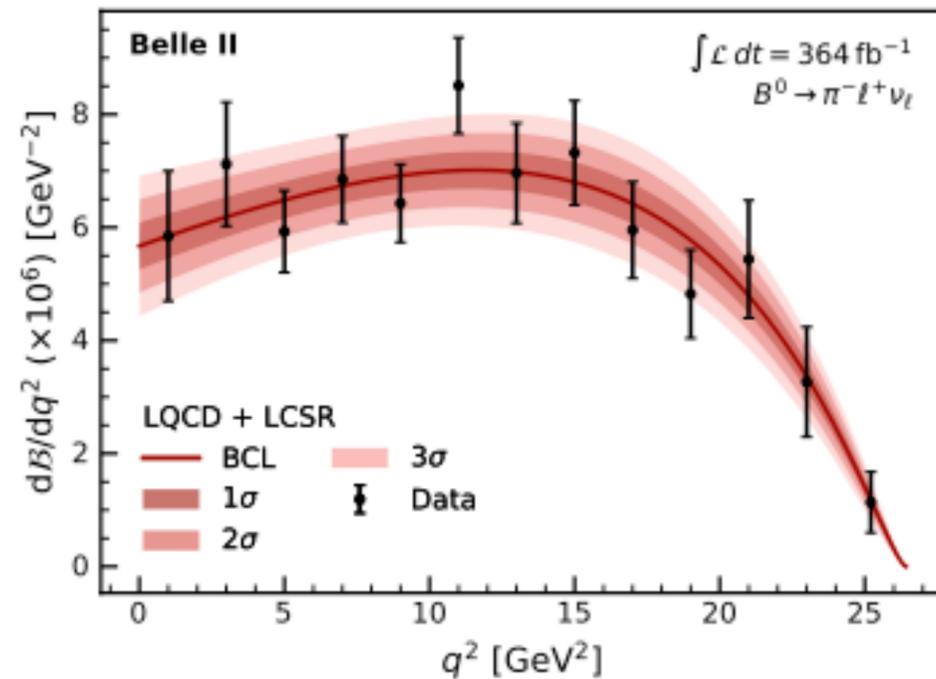
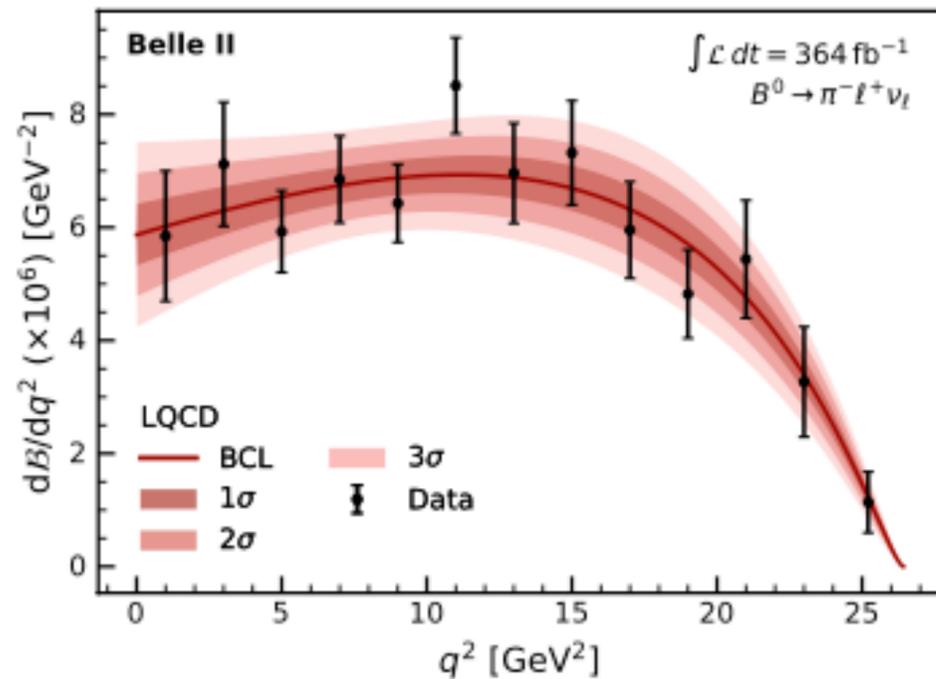
Total BFs determined from the sum of partial BFs:

- $\mathcal{B}(B^0 \rightarrow \pi^- \ell^+ \nu_\ell) = (1.516 \pm 0.042 \pm 0.059) \times 10^{-4}$
- $\mathcal{B}(B^+ \rightarrow \rho^0 \ell^+ \nu_\ell) = (1.625 \pm 0.079 \pm 0.180) \times 10^{-4}$

Consistent with SM.

Determine $|V_{ub}|$ by minimizing $\chi^2 = \sum_{i,j=1}^N (\Delta B_i - \Delta\Gamma_i\tau)C_{ij}^{-1}(\Delta B_j - \Delta\Gamma_j\tau) + \chi_{\text{theory,m}}^2$

PRD 111(2025), 112009



LQCD only: $|V_{ub}|_{B \rightarrow \pi \ell \nu_\ell} = (3.93 \pm 0.09 \pm 0.13 \pm 0.19) \times 10^{-3}$

LQCD + LCSR: $|V_{ub}|_{B \rightarrow \pi \ell \nu_\ell} = (3.73 \pm 0.07 \pm 0.07 \pm 0.16) \times 10^{-3}$

$|V_{ub}|_{B \rightarrow \rho \ell \nu_\ell} = (3.19 \pm 0.12 \pm 0.17 \pm 0.26) \times 10^{-3}$

Both consistent with previous exclusive measurements, despite of a lower $|V_{ub}|_{B \rightarrow \rho \ell \nu_\ell}$.

Large uncertainty from limited off-resonance data & $B \rightarrow \pi \ell \nu_\ell$.

$|V_{ub}|/|V_{cb}|$ determination

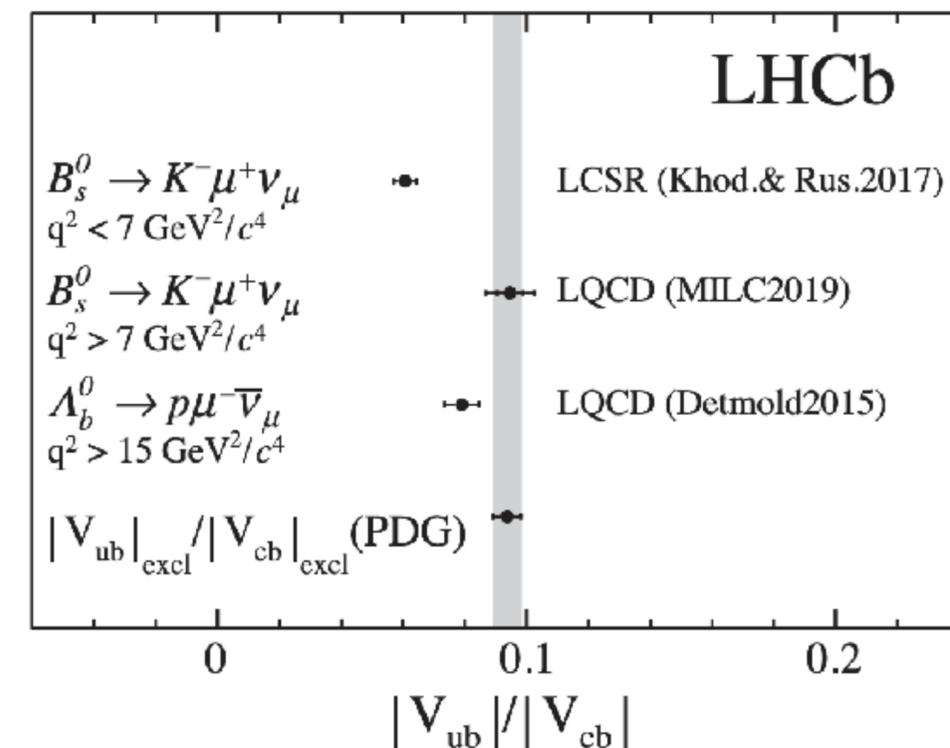
- Despite that $|V_{ub}|$ and $|V_{cb}|$ differ significantly by inclusive and exclusive measurement, $|V_{ub}|/|V_{cb}|$ from inclusive and exclusive in excellent agreement.

- LHCb reported $|V_{ub}|/|V_{cb}|$ with $B_s^0 \rightarrow K^- \mu^+ \nu_\mu$ and $\Lambda_b^0 \rightarrow p \mu^- \nu_\mu$.

$$|V_{ub}|/|V_{cb}|_{\text{exc}} = (9.4 \pm 0.5) \times 10^{-2},$$

$$|V_{ub}|/|V_{cb}|_{\text{inc}} = (9.8 \pm 0.6) \times 10^{-2},$$

$$|V_{ub}|/|V_{cb}|_{\text{LHCb}} = (8.4 \pm 0.7) \times 10^{-2}.$$



- $|V_{ub}|/|V_{cb}|$ determined with full Belle data, converted into Belle II data format

PRD 111, 092016 (2025)

- Use Belle II software technique, FEI, to tag hadronic B .
- BDT to reduce duplicated tracks with low momentum / continuum background.

Calibrate non-continuum background:

Secondary & fake lepton enriched area:

$$E_\ell^{B_{\text{sig}}} \in [0.7, 1.8] \text{ GeV} \ \& \ M_X > 2.0 \text{ GeV}$$

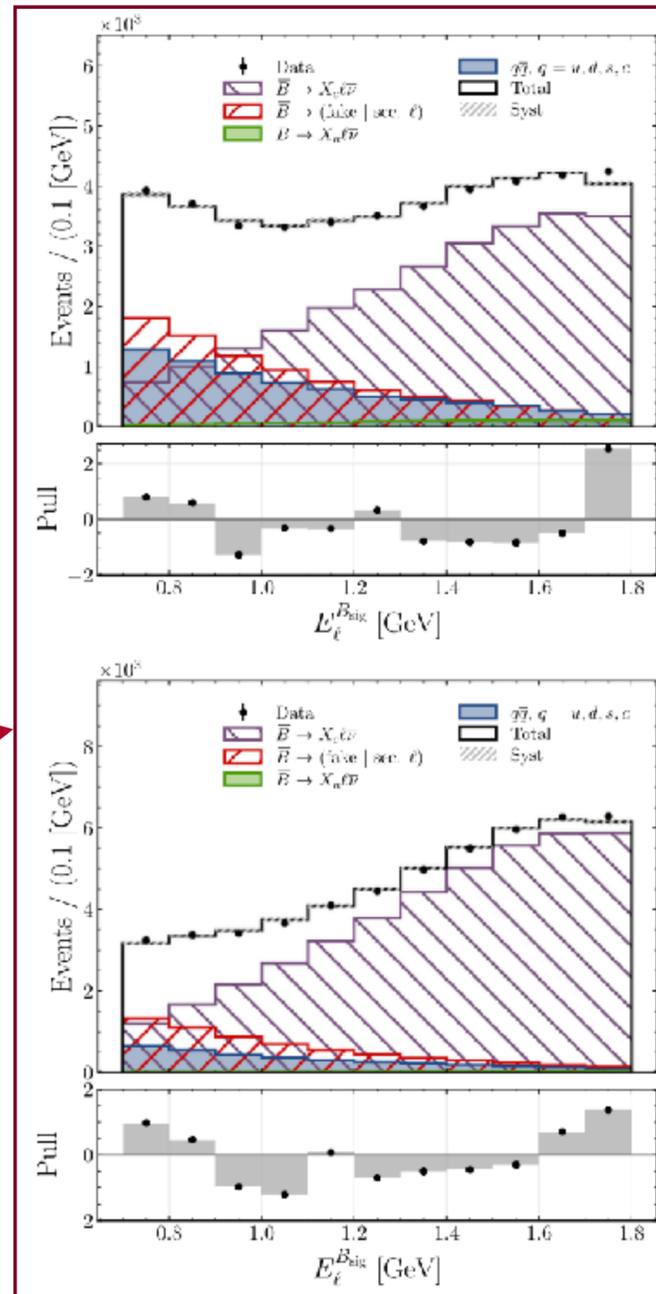
Slow pion veto:

Find a slow pion, then $E_{D^*} \propto E_\pi$.

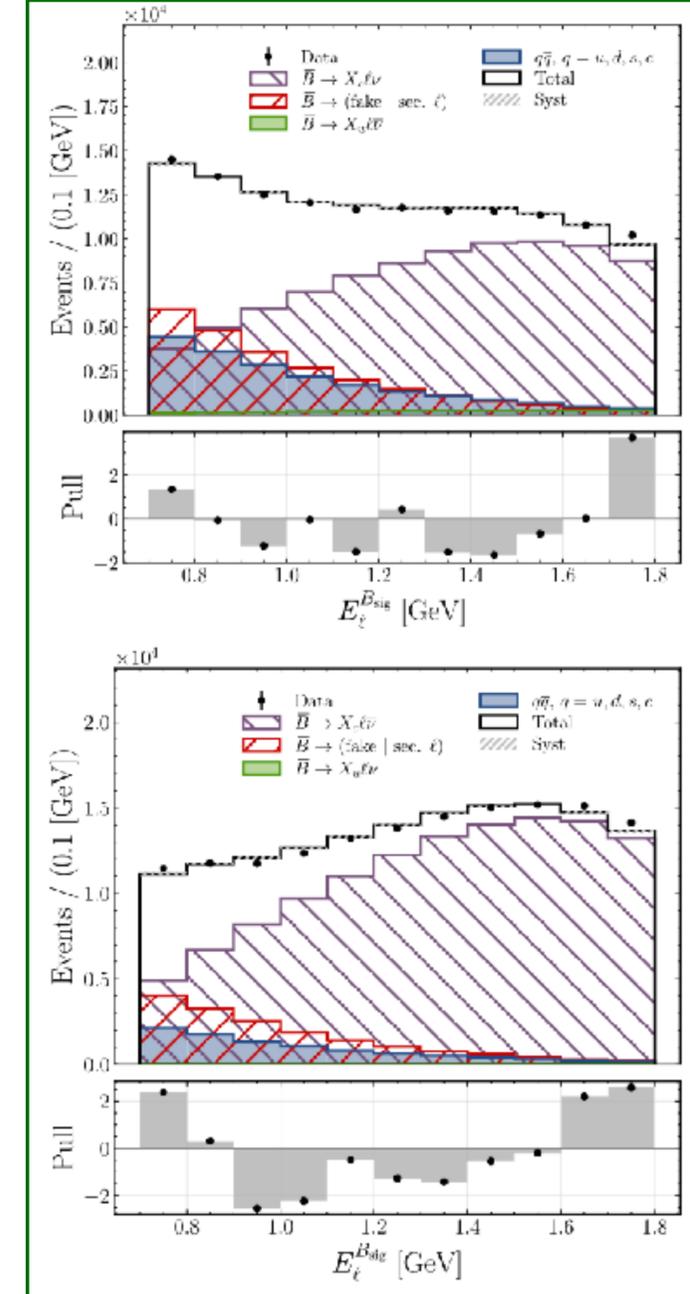
$$M_{\text{miss}}^2(D^*) > -2 \text{ GeV}^2$$



X_u yield sample



X_c yield sample



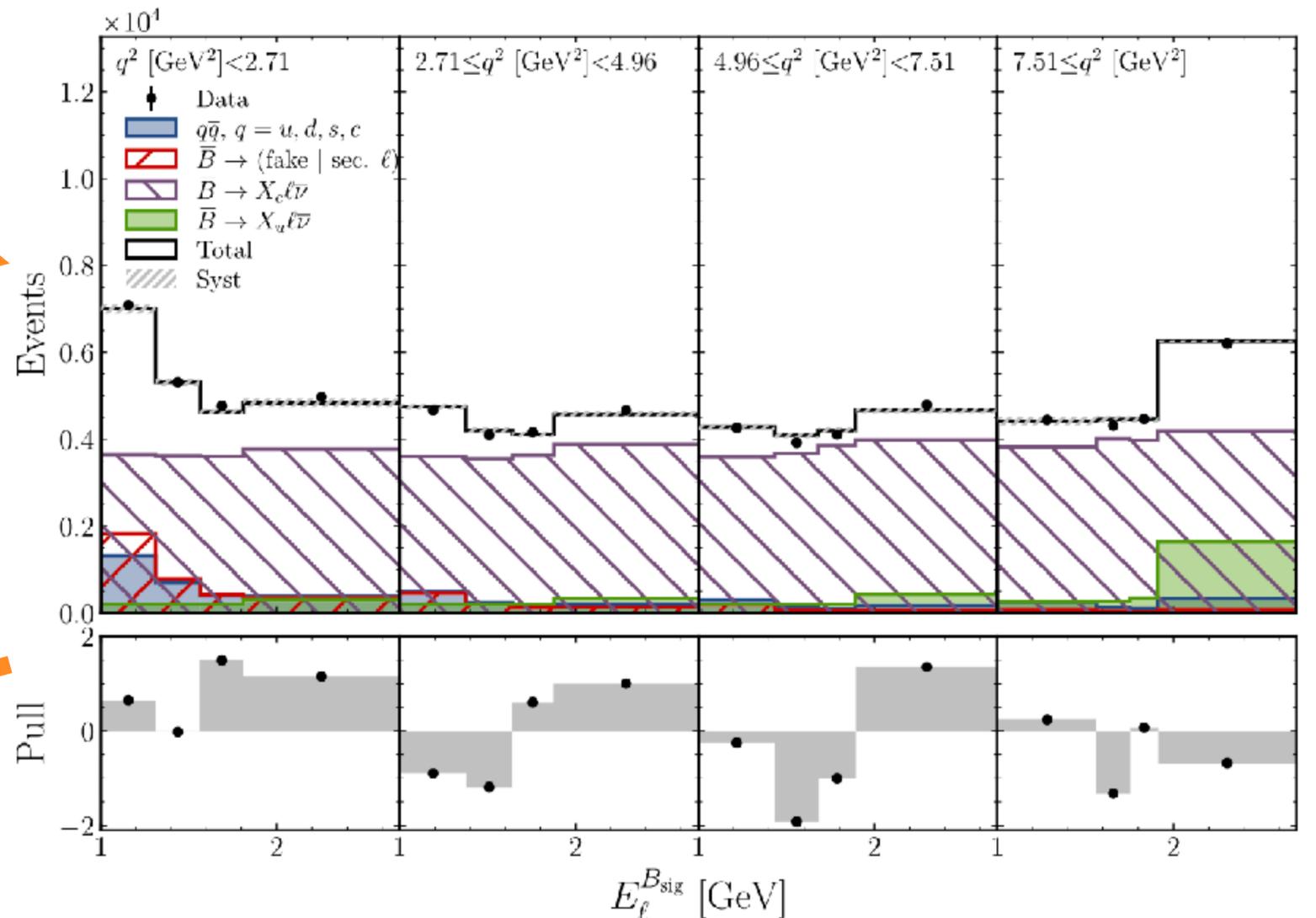
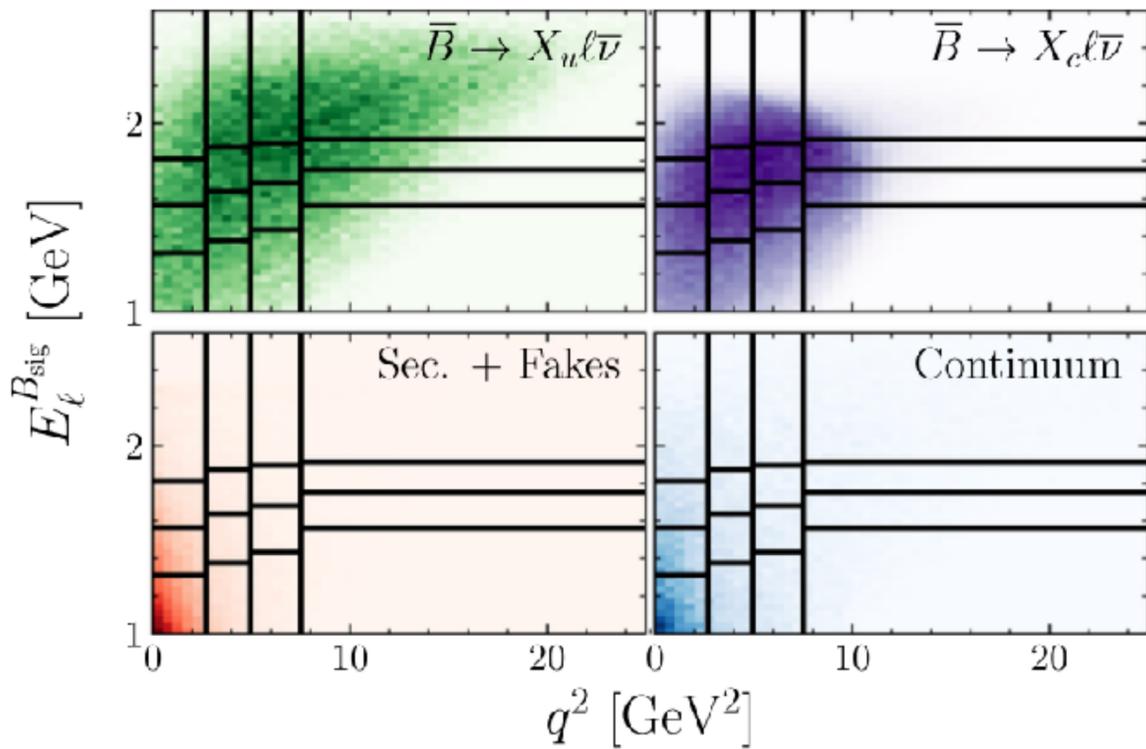
No kaons

X_u enhanced

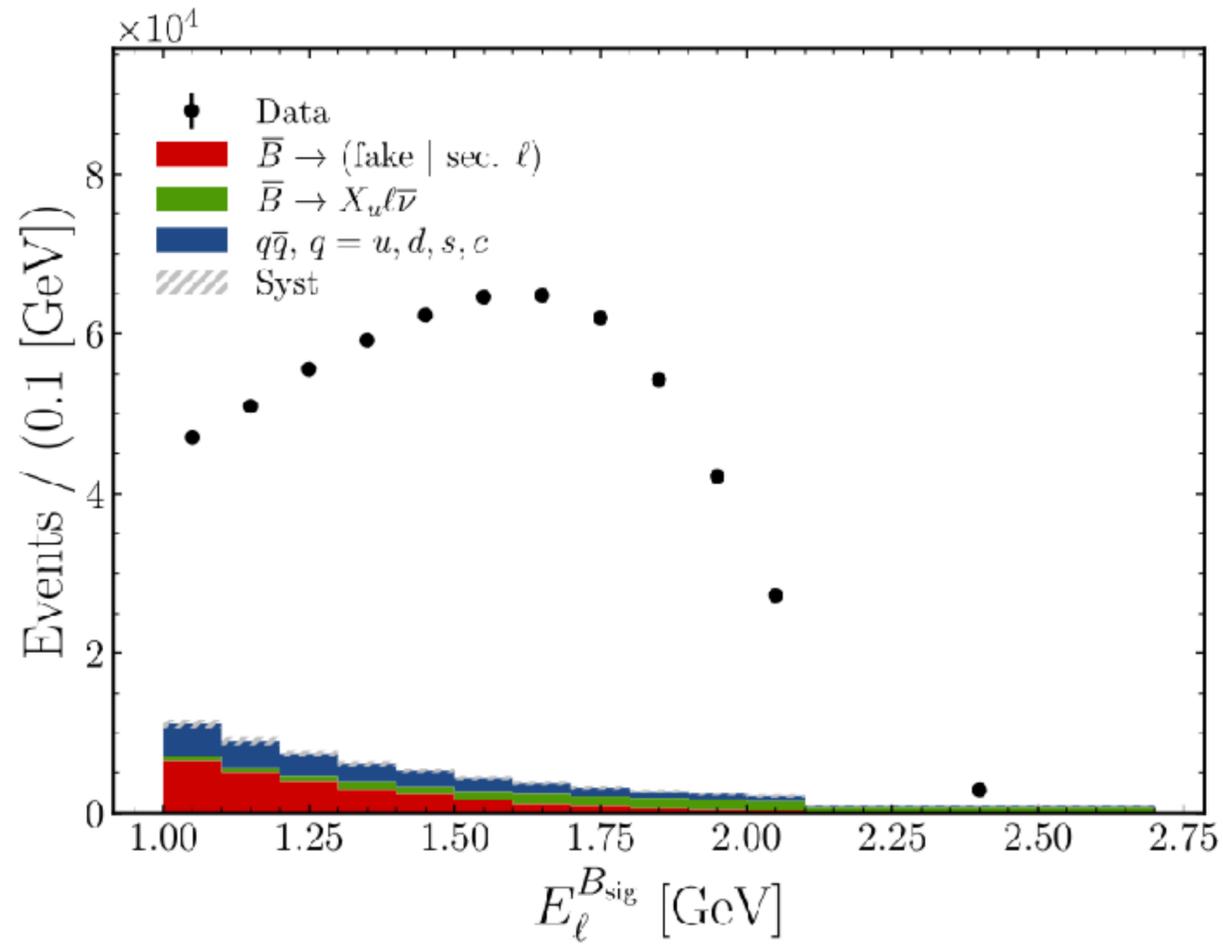
Contain kaon
depleted

Constrain $B \rightarrow X_c \ell \nu$ contribution in $B \rightarrow X_u \ell \nu$

- Poor agreement btw. data&MC in kinematic quantities modeling.
- Divided into 4X4 bins with equal X_c yield to ensure each sample is large enough for a data-driven approach to constrain $B \rightarrow X_c \ell \nu$ contribution in $B \rightarrow X_u \ell \nu$.



Yield $N^{X_u \ell \nu} = 5430 \pm 450_{\text{stat.}} \pm 350_{\text{syst.}}$



Yield $N^{X_u \ell \bar{\nu}} = N^{\text{data}} - \eta^{q\bar{q}} - \eta^{\text{Sec.Fakes}} - a\eta^{X_u \ell \bar{\nu}}$ by **counting**

$$\frac{\Delta\mathcal{B}(\bar{B} \rightarrow X_u \ell \bar{\nu})}{\Delta\mathcal{B}(\bar{B} \rightarrow X_c \ell \bar{\nu})} = \frac{\epsilon^{X_c \ell \bar{\nu}} N^{X_u \ell \bar{\nu}}}{\epsilon^{X_u \ell \bar{\nu}} N^{X_c \ell \bar{\nu}}},$$

$$\frac{|V_{ub}|}{|V_{cb}|} = \sqrt{\frac{\Delta\mathcal{B}(\bar{B} \rightarrow X_u \ell \bar{\nu}) \Delta\Gamma(\bar{B} \rightarrow X_c \ell \bar{\nu})}{\Delta\mathcal{B}(\bar{B} \rightarrow X_c \ell \bar{\nu}) \Delta\Gamma(\bar{B} \rightarrow X_u \ell \bar{\nu})}},$$

Consider two predictions of partial rate:
BLNP & GGOU

$$\frac{|V_{ub}|}{|V_{cb}|}^{\text{BLNP}} = (9.81 \pm 0.42_{\text{stat}} \pm 0.38_{\text{syst}} \pm 0.51_{\Delta\Gamma(\bar{B} \rightarrow X_u \ell \bar{\nu})} \pm 0.20_{\Delta\Gamma(\bar{B} \rightarrow X_c \ell \bar{\nu})}) \times 10^{-2},$$

$$\frac{|V_{ub}|}{|V_{cb}|}^{\text{GGOU}} = (10.06 \pm 0.43_{\text{stat}} \pm 0.39_{\text{syst}} \pm 0.23_{\Delta\Gamma(\bar{B} \rightarrow X_u \ell \bar{\nu})} \pm 0.20_{\Delta\Gamma(\bar{B} \rightarrow X_c \ell \bar{\nu})}) \times 10^{-2},$$

$|V_{ub}|$ measurement

Extract $|V_{ub}|$ with $B^+ \rightarrow \tau^+ \nu_\tau$

PRD 112, 072002 (2025)

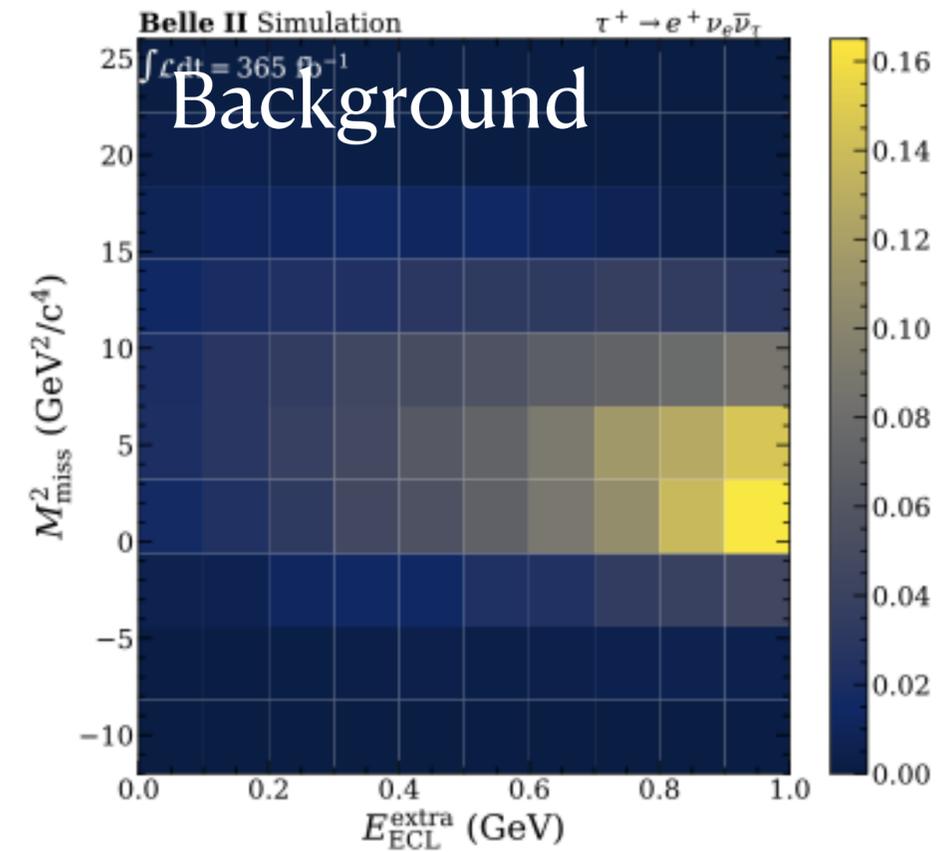
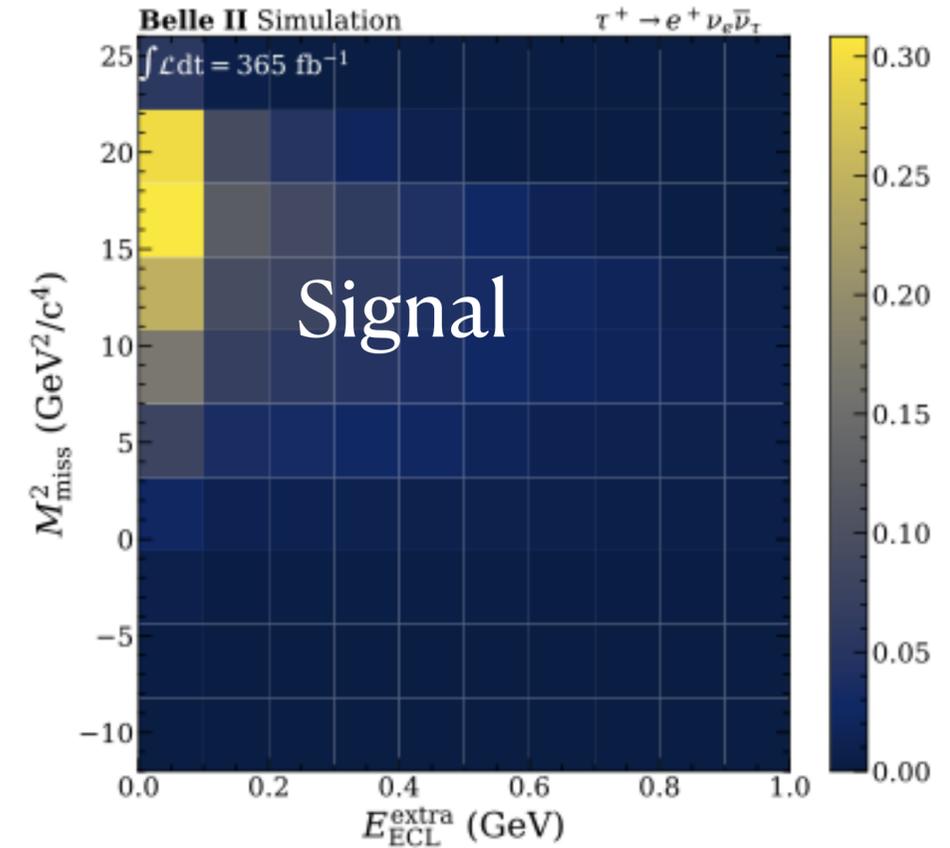
- In SM, branching fractions of $B^+ \rightarrow \tau^+ \nu_\tau$ provide direct measurement of $|V_{ub}|$, independent of in- and exclusive semi-leptonic $B \rightarrow X_u \ell \nu$.

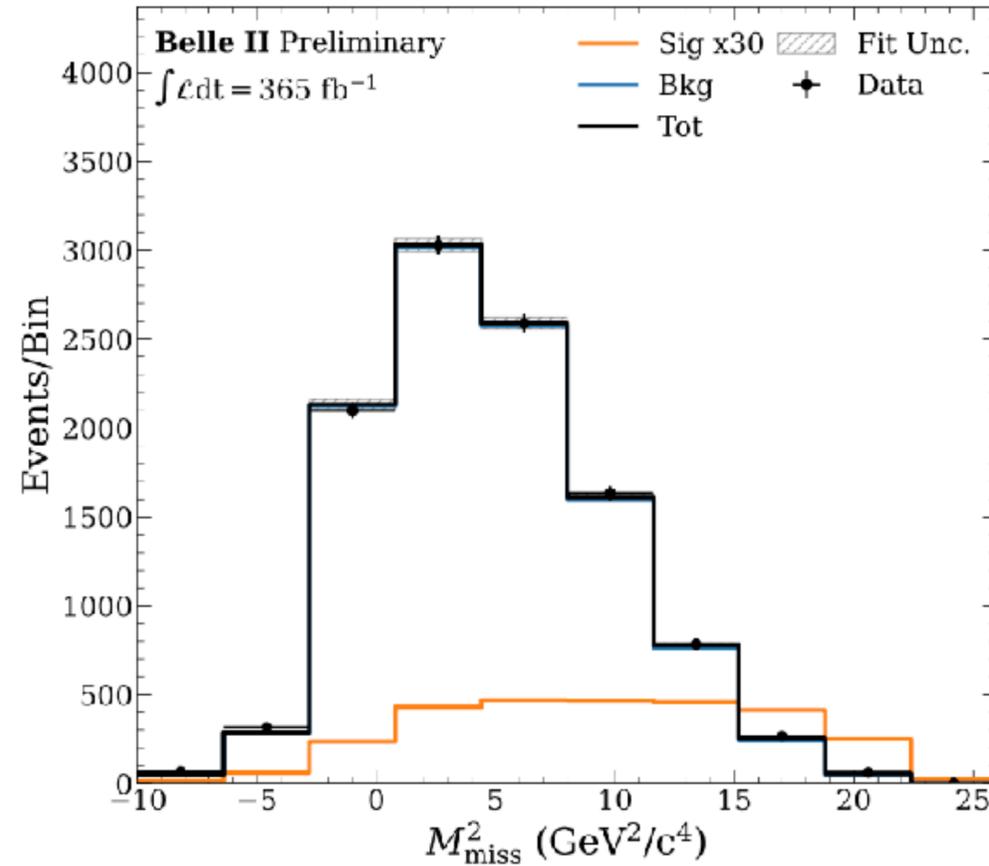
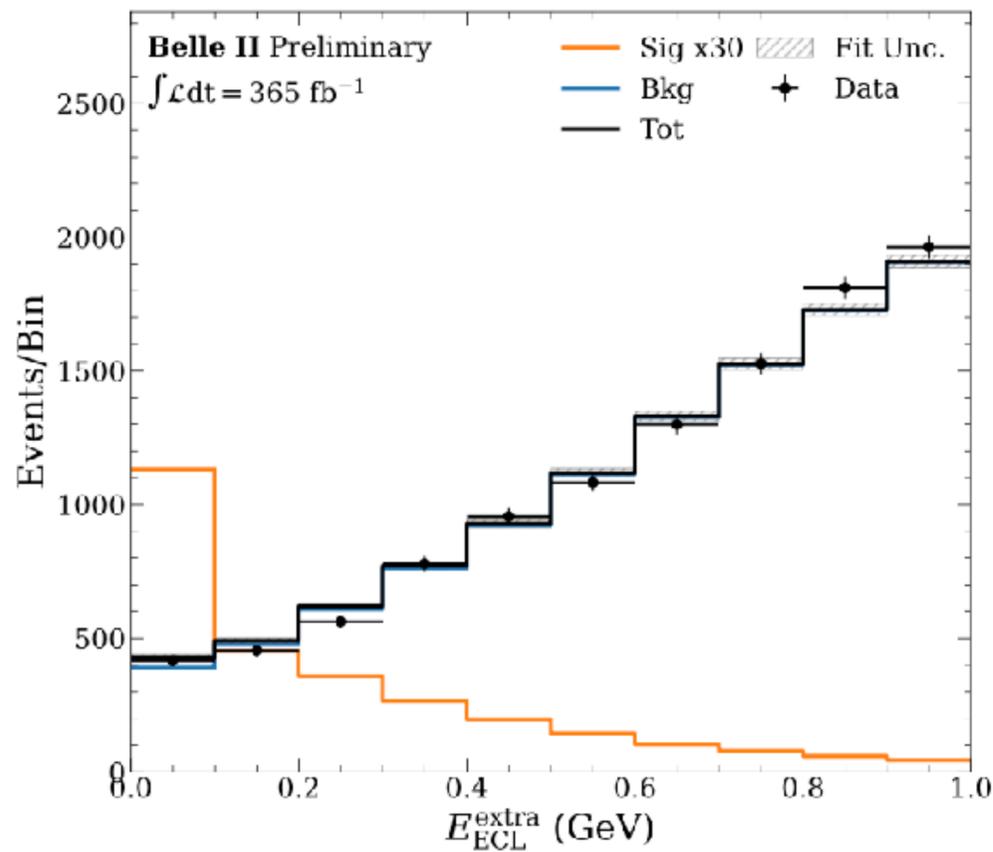
$$B(B^+ \rightarrow \tau^+ \nu_\tau) = \frac{G_F^2 m_B m_\tau^2}{8\pi} \left[1 - \frac{m_\tau^2}{m_B^2} \right]^2 f_B^2 |V_{ub}|^2 \tau_B,$$

- With $(387 \pm 6) \times 10^6 \Upsilon(4S)$ events collected on Belle. covering 72% of τ decays

$$\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau, \tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau, \tau^+ \rightarrow \pi^+ \nu_\tau, \text{ and } \tau^+ \rightarrow \rho^+ \bar{\nu}_\tau,$$

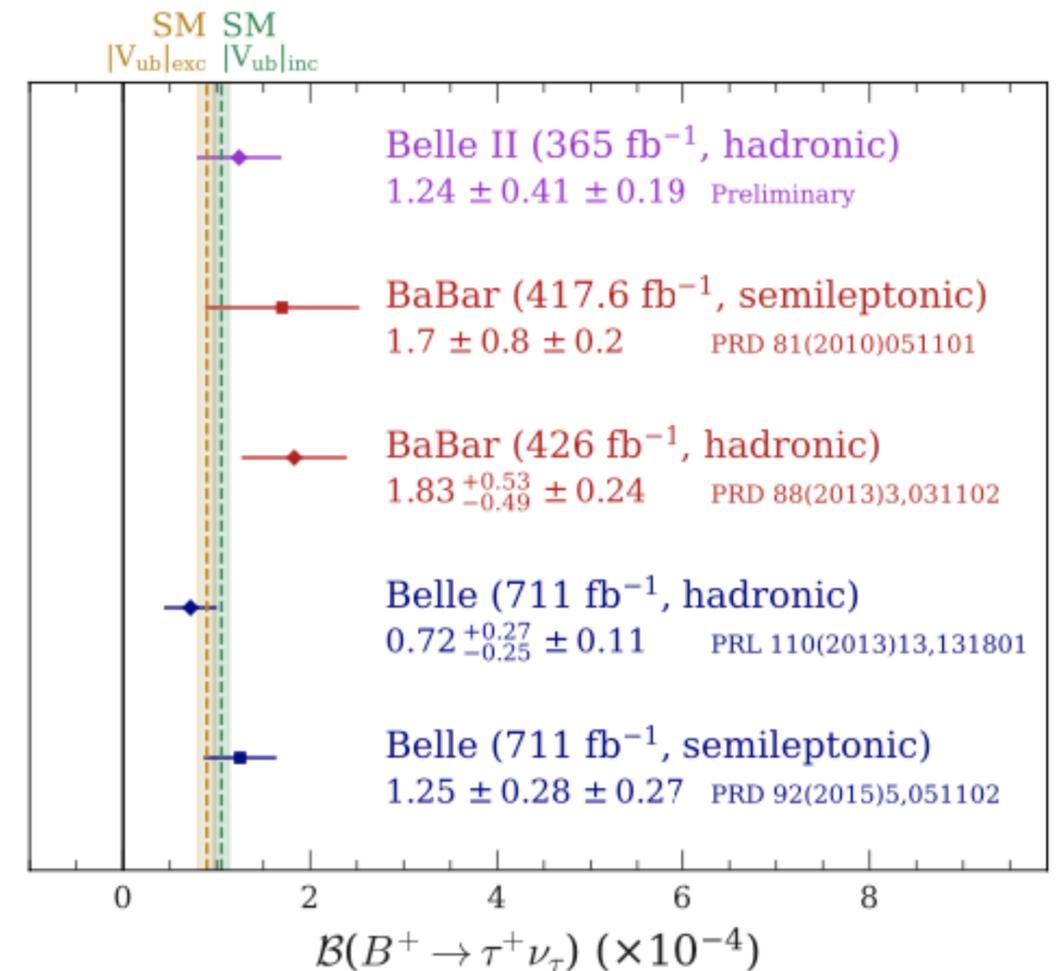
- Separate signal/background with 2D-fit: E_{ECL}^{extra} and M_{miss}^2





PRD 112, 072002 (2025)

94 ± 31 signal yields



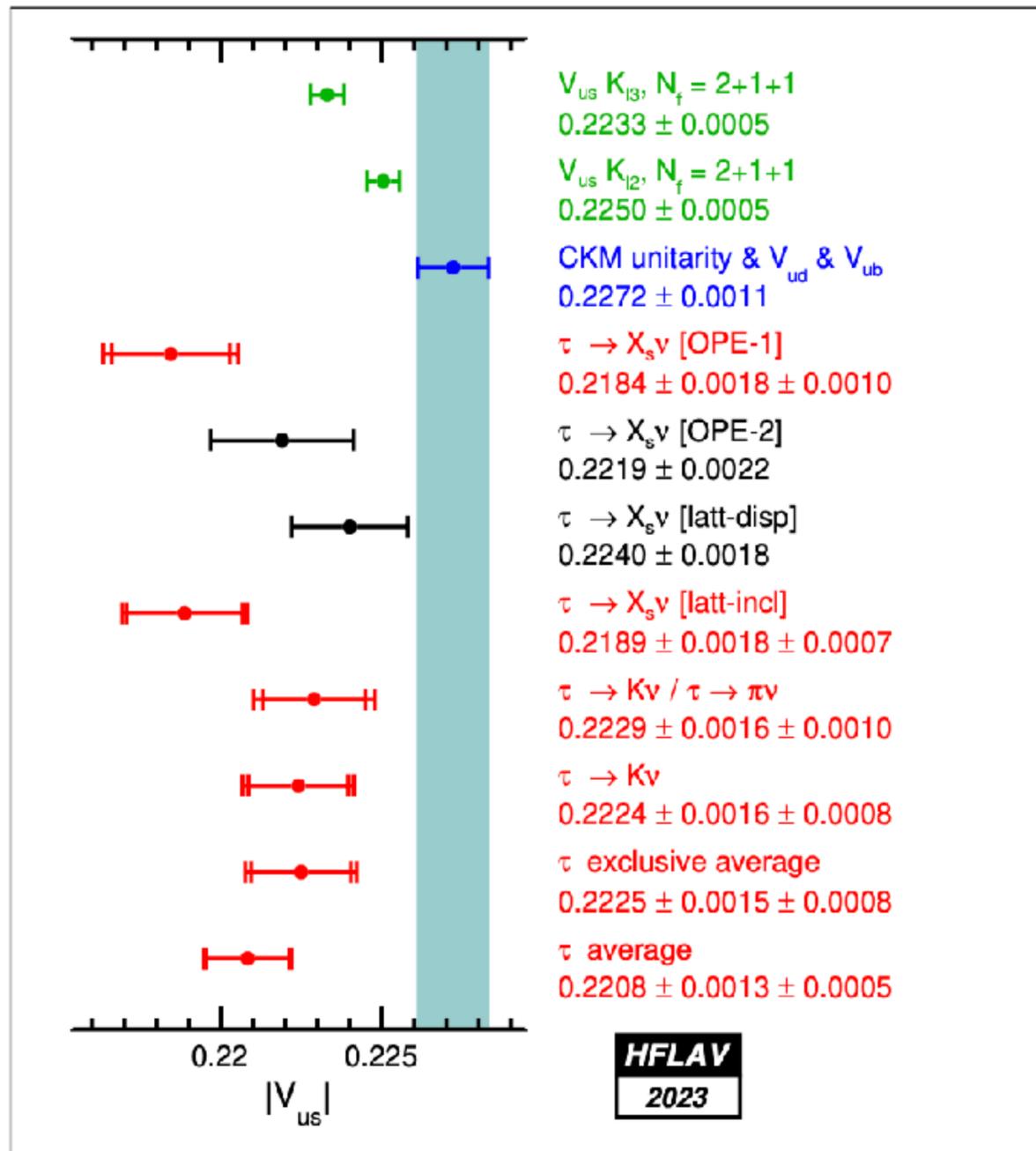
◦ Evidence (3σ) for signal with

$$\mathcal{B} = [1.24 \pm 0.41 (\text{stat.}) \pm 0.19 (\text{syst.})] \times 10^{-4}$$

◦ Use $f_B = (190.0 \pm 1.3) \text{ MeV}$, extract

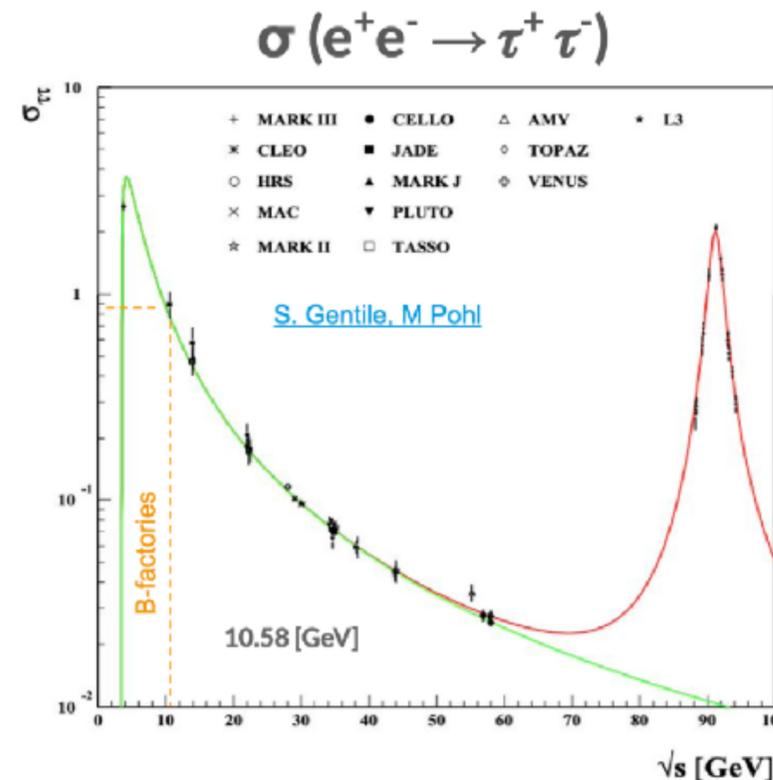
$$|V_{ub}|_{B^+ \rightarrow \tau^+ \nu_\tau} = [4.41^{+0.74}_{-0.89}] \times 10^{-3}.$$

$|V_{us}|$ with τ decays



- τ decay provide an alternative approaches to $|V_{us}|$
- All τ based $|V_{us}|$ determinations are lower than kaon and CKM unitarity results.
- Measured BF's of $\tau \rightarrow K(\pi)\nu$ are lower than predictions.

B factory is also a τ factory



Smaller cross section but high \mathcal{L}

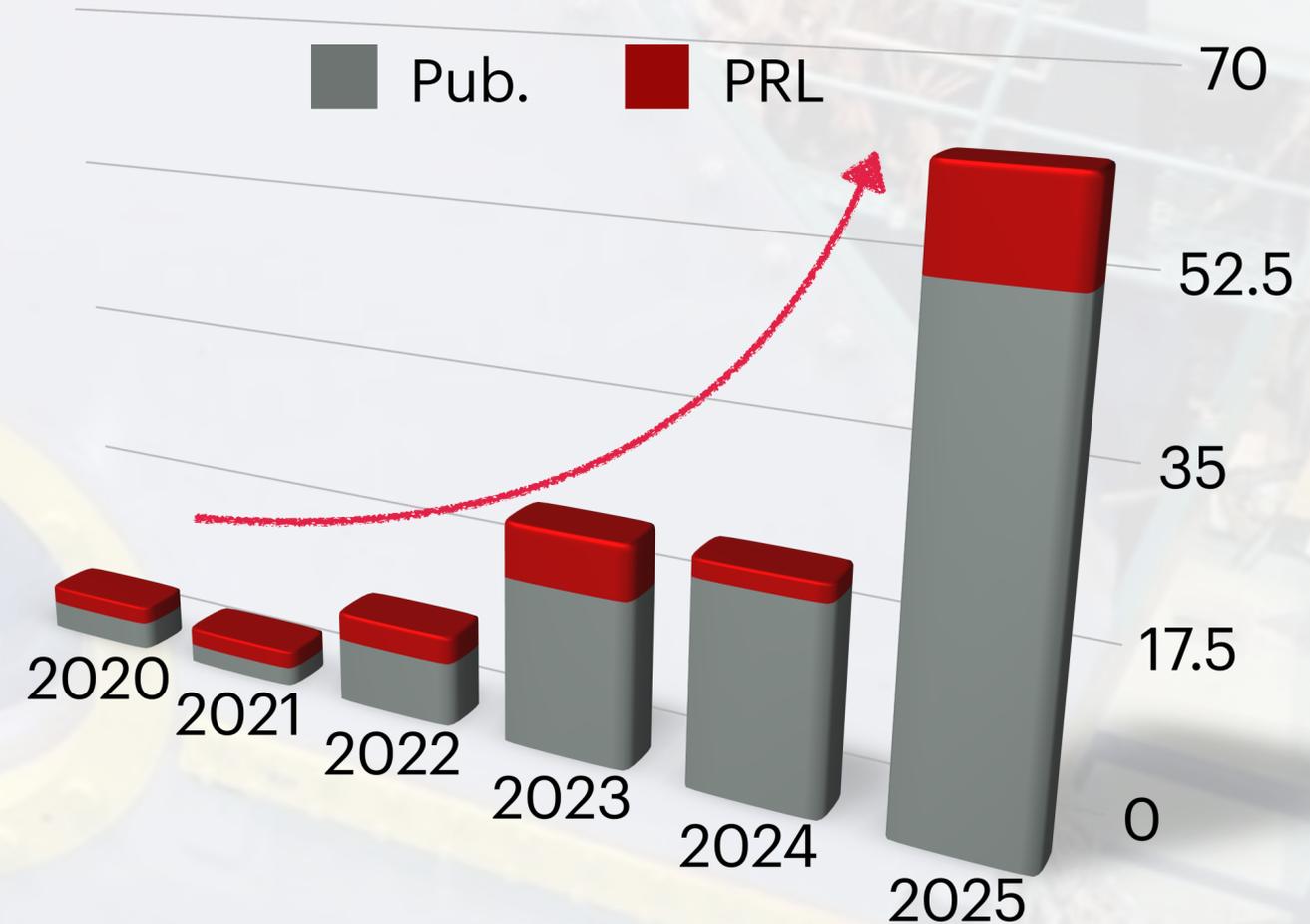
Specific designed τ trigger

→ More accurate measurement of τ decays and help to better constrain $|V_{us}|$.

Summary

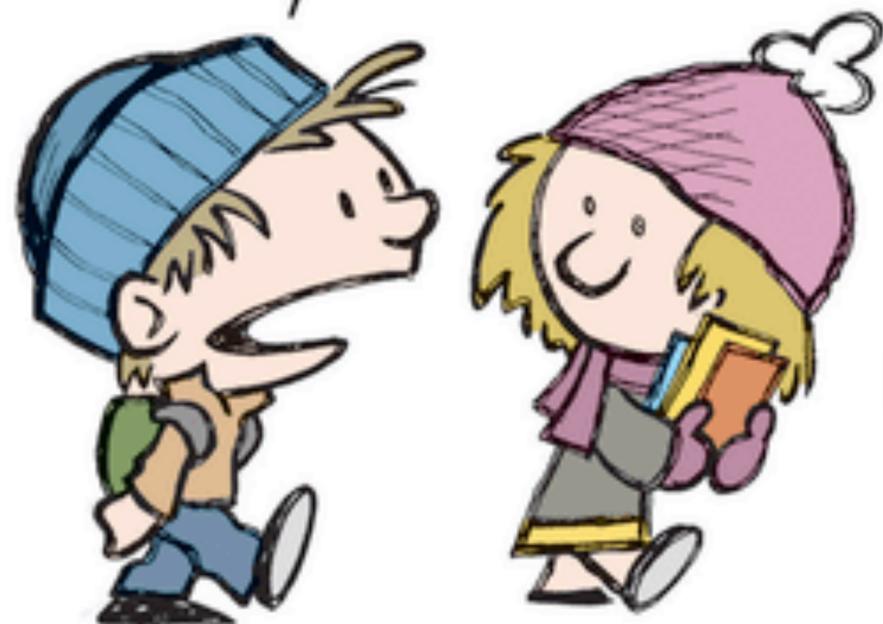
- Experienced many challenges: operation, rising cost...
- But, still lots of achievement! >50 publication in 2025.
- Make good use of Belle II unique advantages.
- Now ~600/fb data, push to 1/ab before July.
5-10/ab till 2032
- Provide more stringent constraints to CKM elements & angles.

Belle II publication per year



Thanks!

THE GOOD NEWS
IS THAT MY DAD
HELPED ME WITH
MY MATH
HOMEWORK.



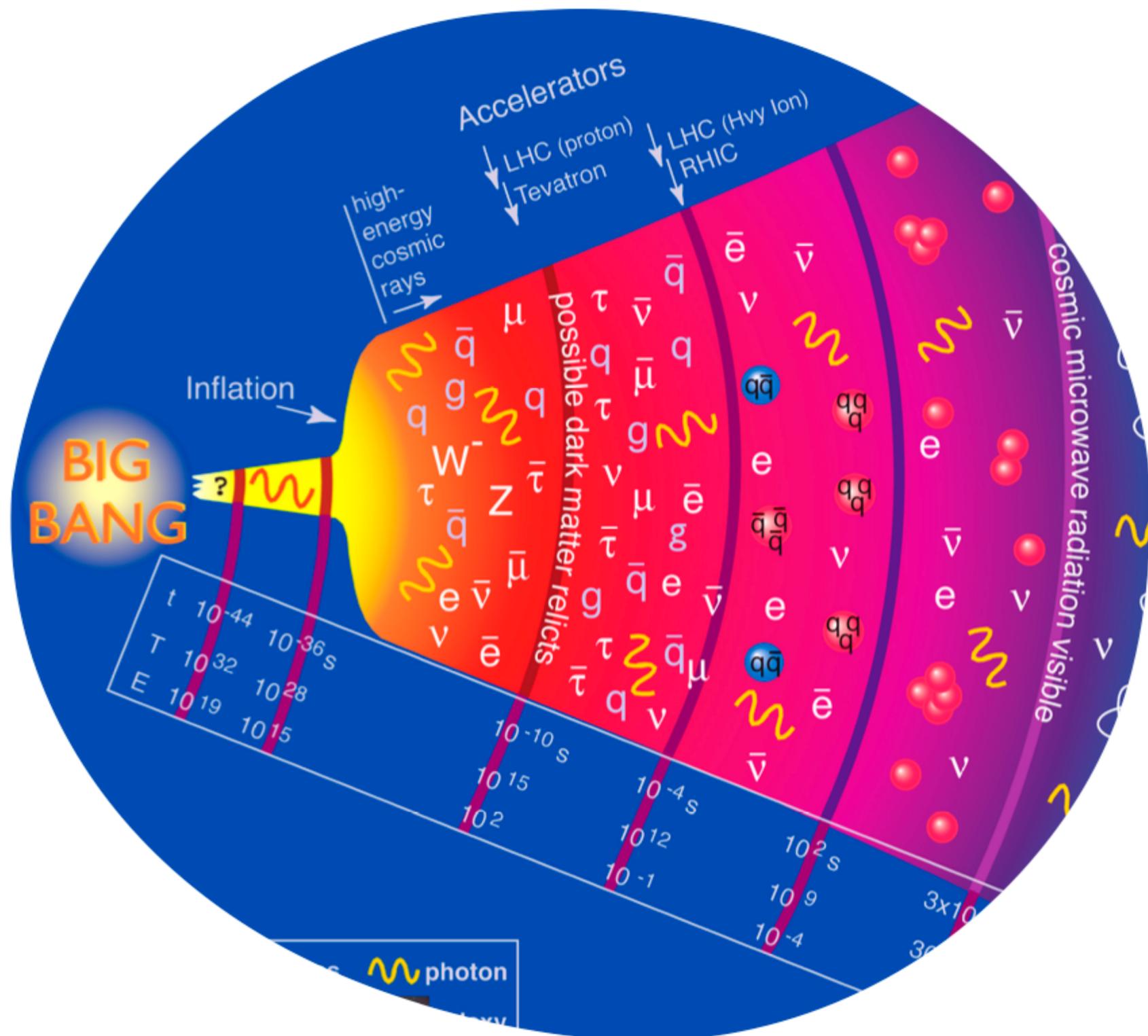
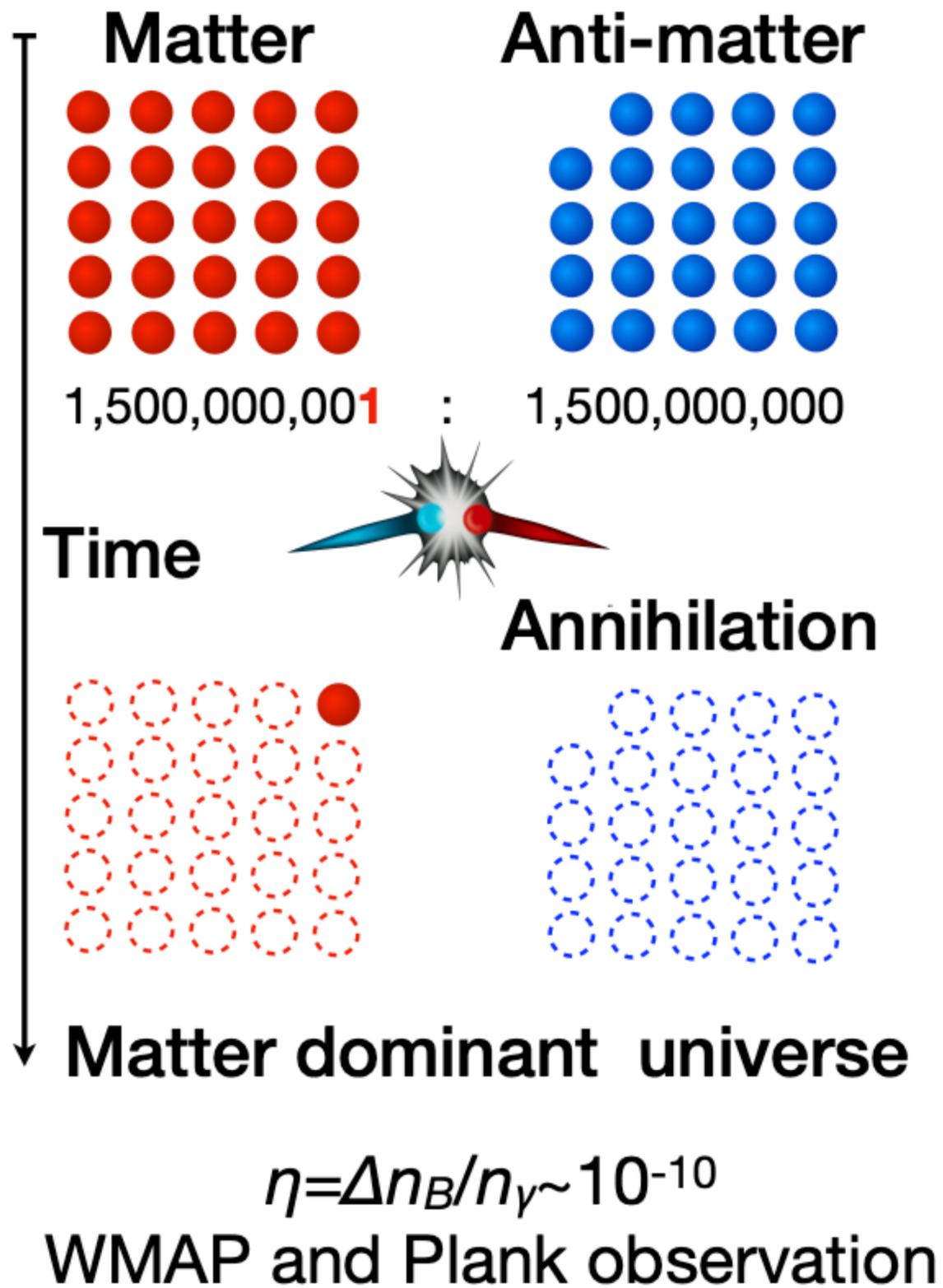
SO, WHAT'S
THE BAD NEWS?



THE BAD NEWS
IS THAT HE
WORKS AT
THE FED.

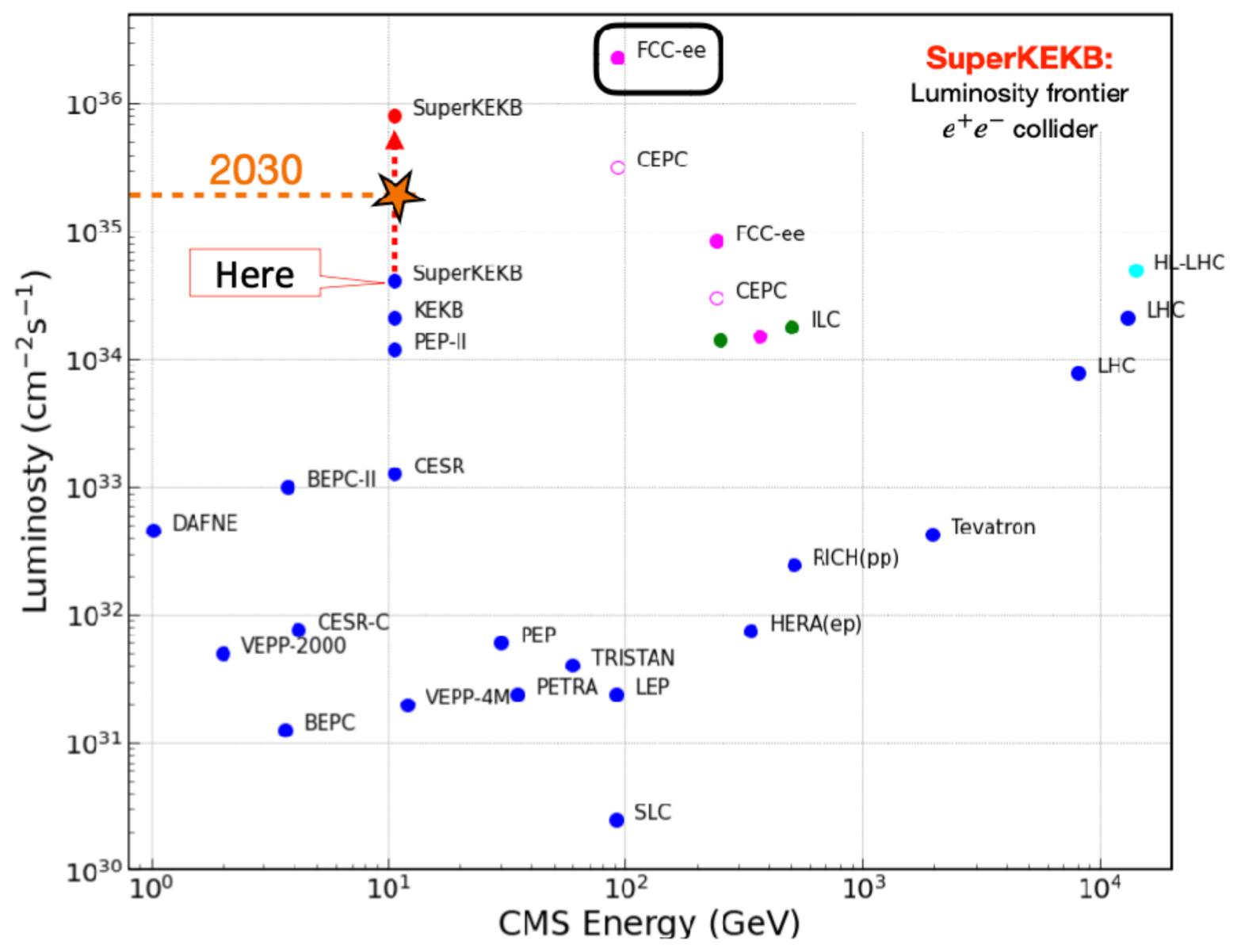


Why matter dominant universe





SuperKEKB & Belle II goals until 2032 → $\sim 2 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ & collect 5-10/ab



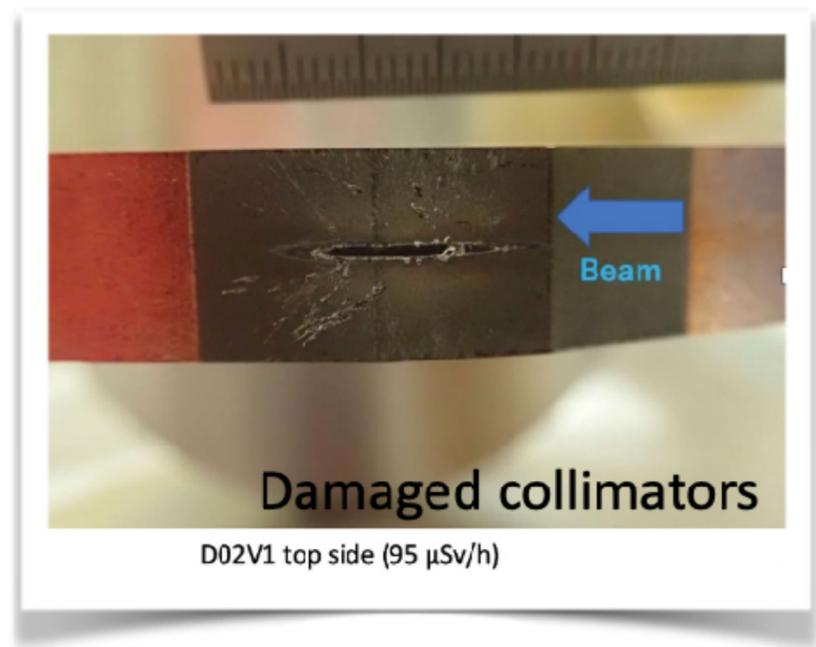
SBL...

Sudden beam losses of unknown origin hinder the collider to reach stable operations

→ Cause damage to collimators & detector

Other challenges to reach high luminosities:

- Low injection eff.
- Low beam lifetime
- Vertical emittance growth



→ Devoted significant fraction of running time for machine studies to understand instabilities



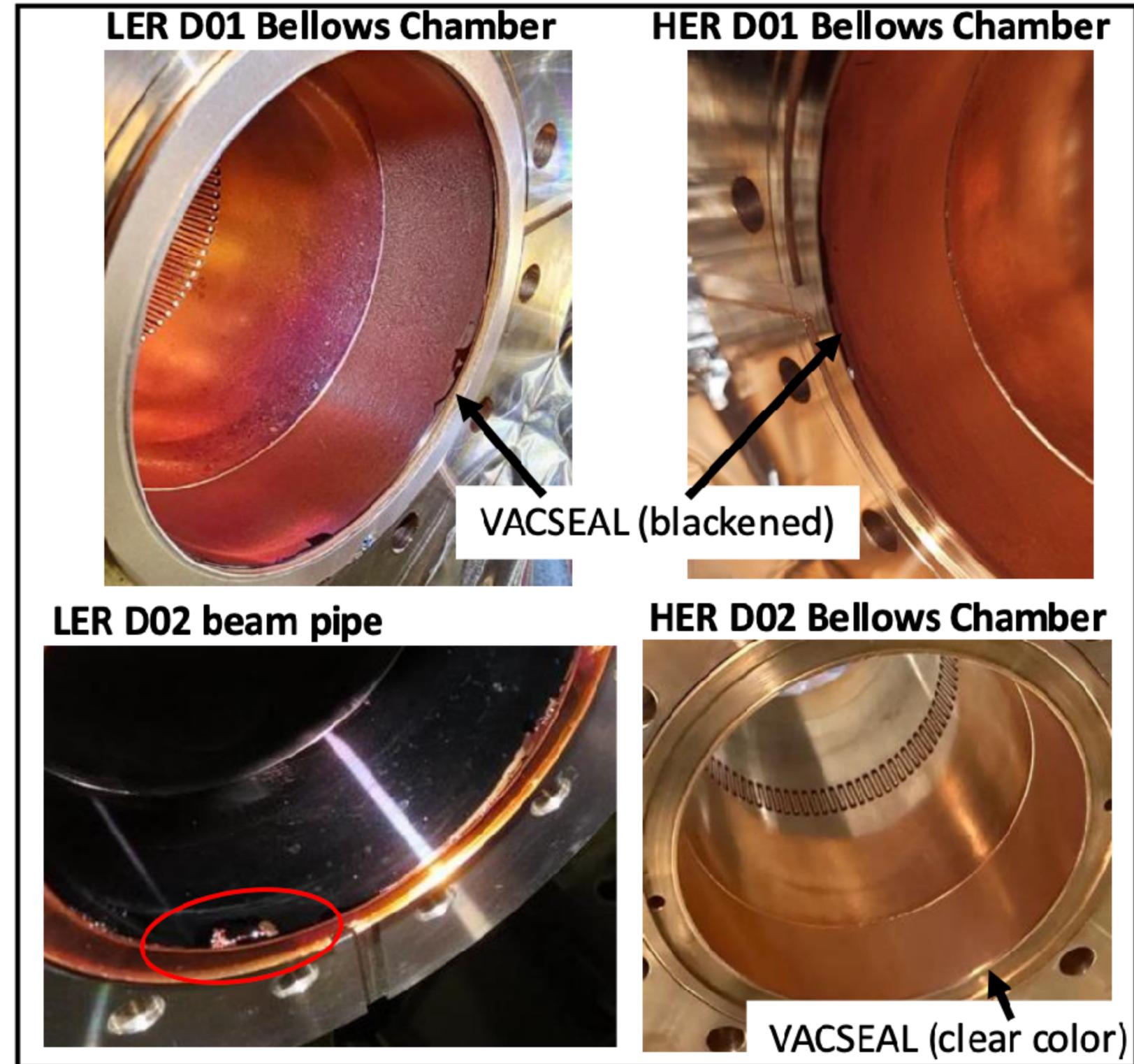
During the construction vacuum sealant was used in many places

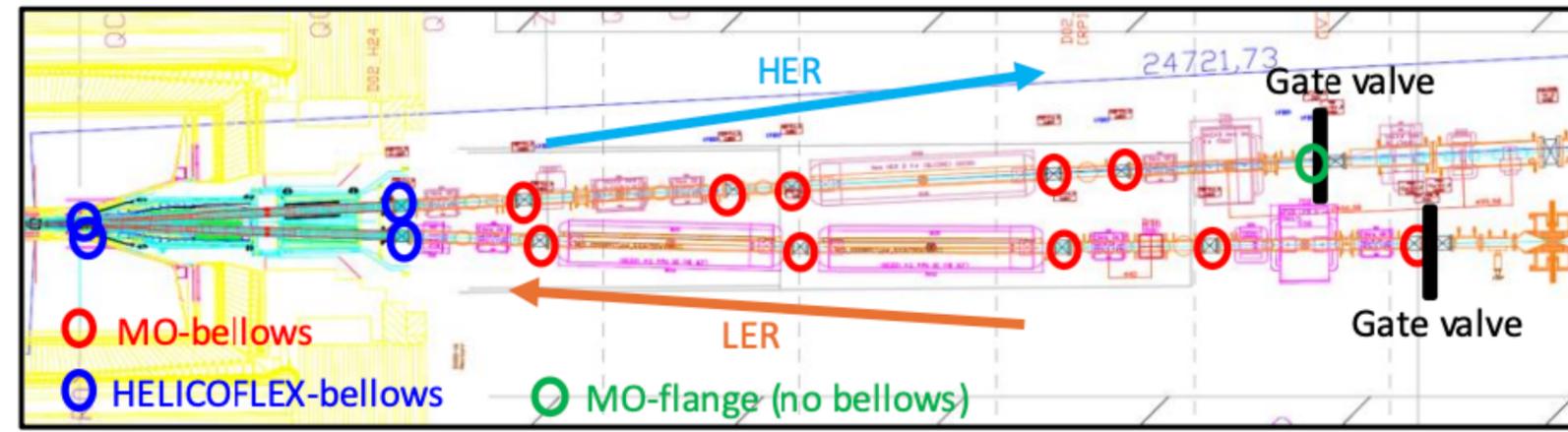
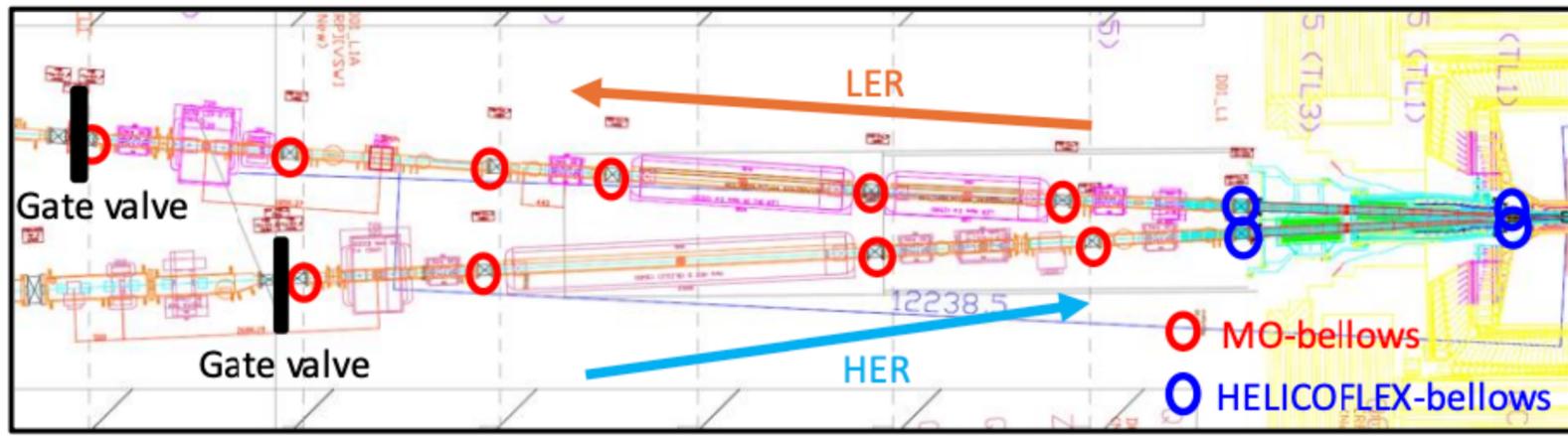
Leaked into interior, extended radiation created blackened stains that outgas

Removal significantly improves beam stability

Confirmed Locations:

- Near IR
- But also in HER & LER straight and wiggler sections in MO bellows

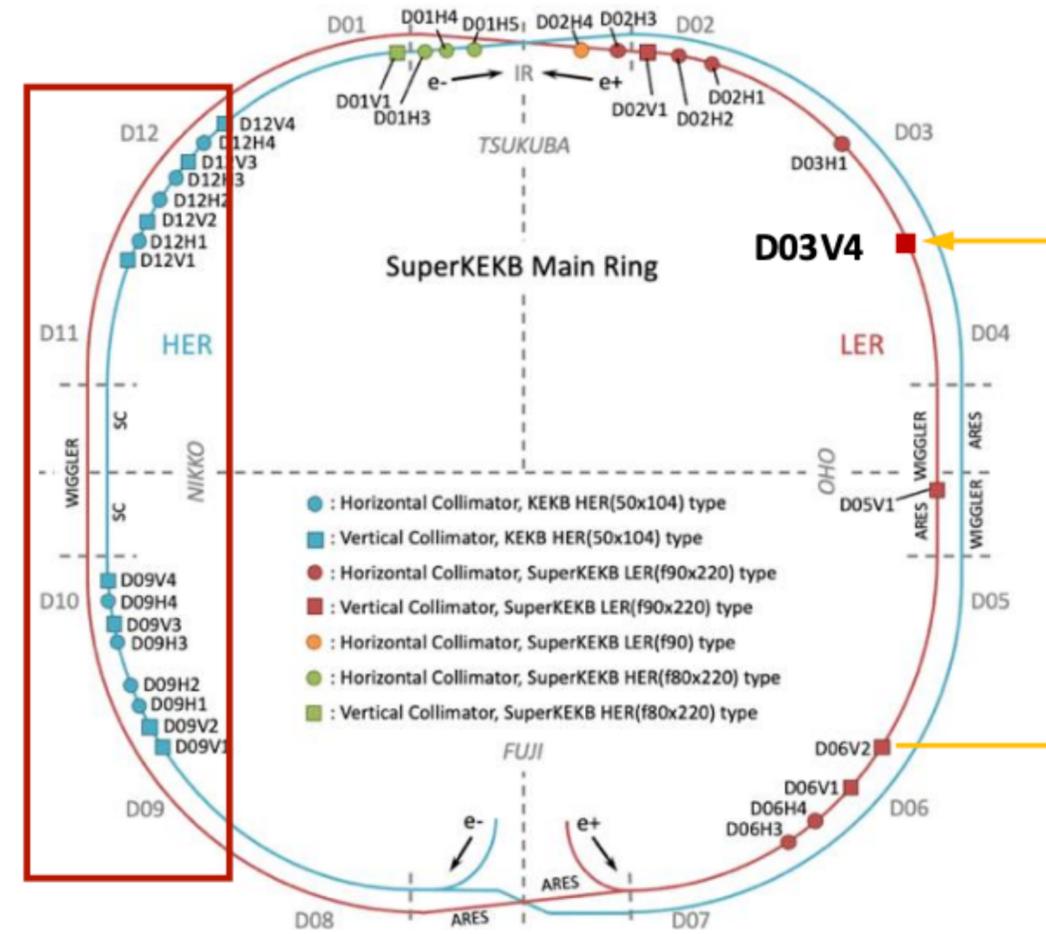




Impact of cleaning in Nikko straight section during last run (2024c)

Number of pressure bursts and beam aborts **significantly reduced after cleaning (!)**

Location of collimators



The next run has **two goals** :

Push our recorded dataset to **1/ab**



Need close communication with SuperKEKB team to balance this; **physics** will be **priority**

← 80% of running time dedicated to physics

Reach luminosities of **$\sim 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$**

Will have for the first time a connected

7 month run

Schedule:

- * SuperKEKB Main Ring operations plan to start **Nov 5th**
- * Brief Christmas shutdown **Dec 24th - Jan 7th**
- * Continue run until **end of May**

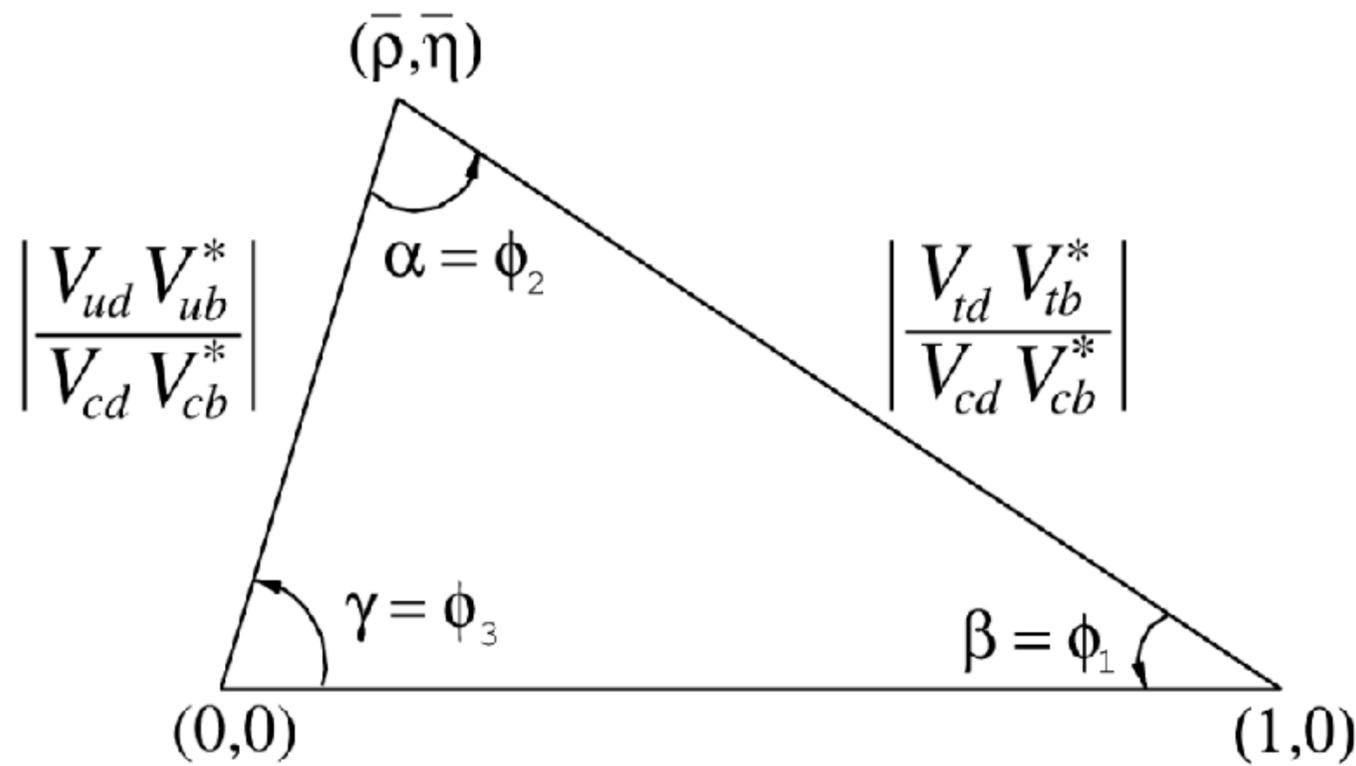
CP violation and the CKM matrix

Quark mixing via charged-current interactions



- Kobayashi and Maskawa predict three generations of quarks
 - Three mixing angles **and one CP violating phase**
 - Unitarity condition represented as triangles, e.g.

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



Interaction eigenstates

Mass eigenstates

$$\begin{pmatrix} d_W \\ s_W \\ b_W \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d_m \\ s_m \\ b_m \end{pmatrix}$$

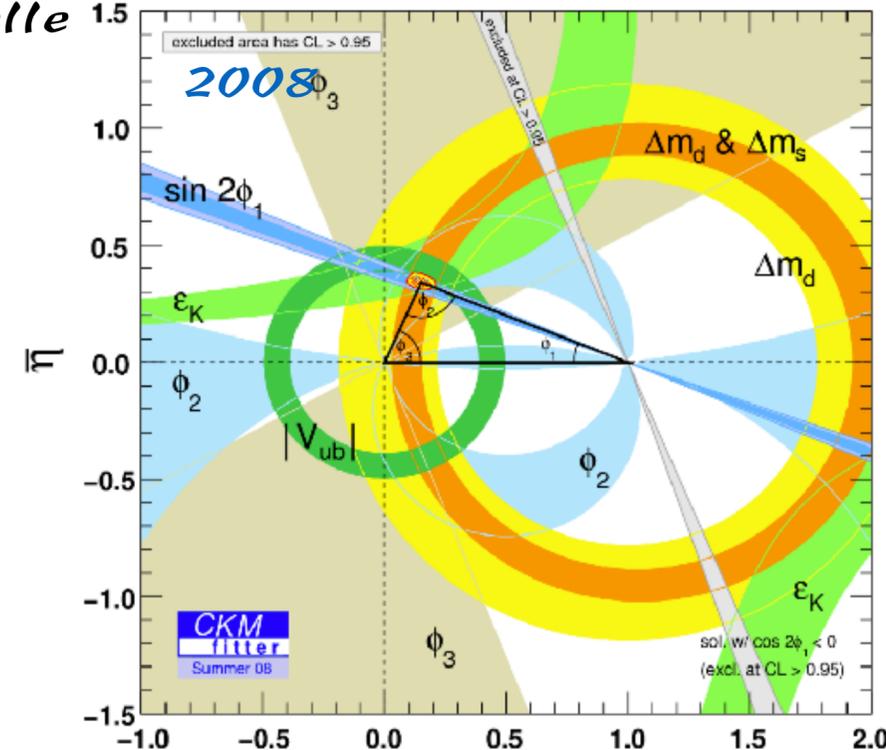
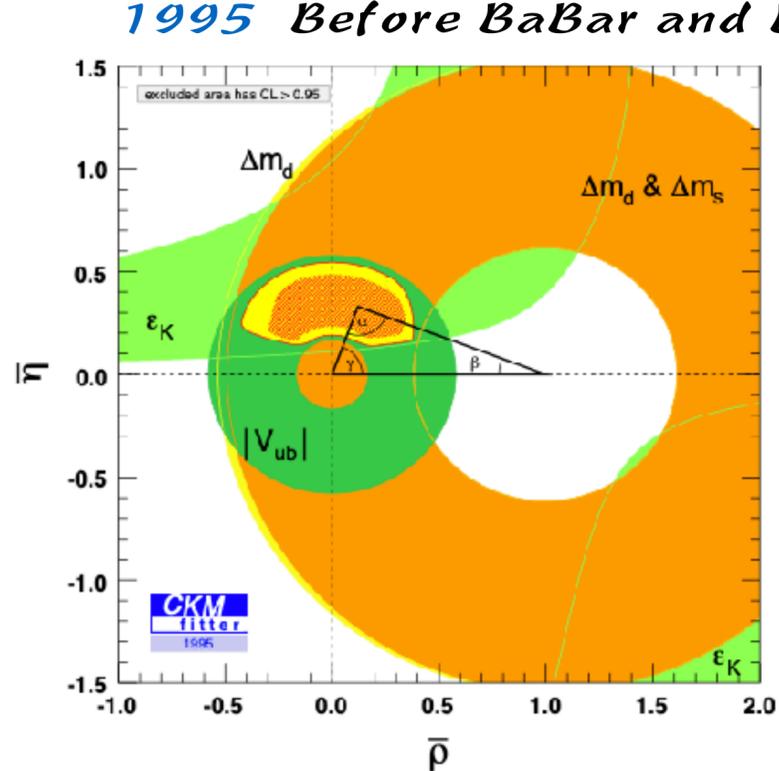
- Common CKM parameterization: Wolfenstein
 - Exploit hierarchy of matrix elements

$$V_{\text{CKM}} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

↑ ↑
scaled apex parameters

Is the triangle closed? (Hint of New Physics?)

1995 Before BaBar and Belle



- With results from BaBar, Belle, and LHCb's Run1,2 data, the triangle is still closed.

- $\phi_1 = \beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right), (22.2 \pm 0.7)^\circ$

- $\phi_2 = \alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right), (85.2^{+4.8}_{-4.3})^\circ$

- $\phi_3 = \gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right), (66.2^{+3.4}_{-3.6})^\circ$
HFLAV

- With much more data from LHCb and Belle II, we could shrink the uncertainty, test this triangle and look for hints from new physics.

