McGill

Semileptonic decays at Belle and Belle II

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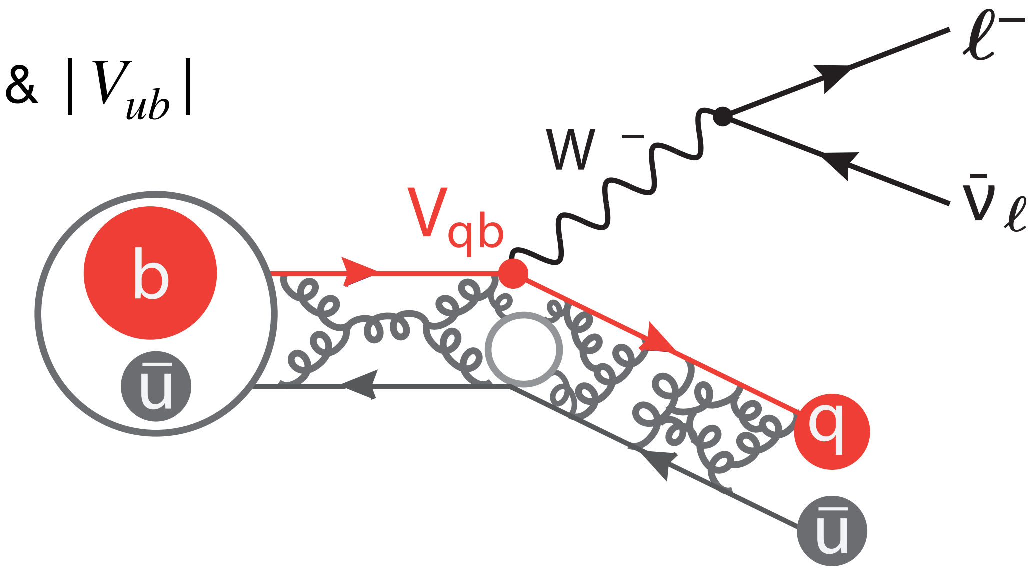
Lake Louise Winter Institute 2024

BELLE

Belle II

Semileptonic decays

- SL B decays ideal to extract CKM Matrix elements $|V_{cb}|$ & $|V_{ub}|$
- $|V_{qb}|$ limiting the constraining power of global fits.
- Important inputs in predictions of SM rates for ultra-rare decays.
- Significant tension between inclusive & exclusive determinations poses a longstanding puzzle.



Exclusive $|V_{ub}|$

$\bar{B} \to \pi \ell \bar{\nu}_\ell$

Exclusive $|V_{cb}|$

$\bar{B} \to D \ell \bar{\nu}_\ell, \bar{B} \to D^* \ell \bar{\nu}_\ell$

$$\mathcal{B} \propto |V_{qb}|^2 f^2$$ ← Form Factors

Inclusive $|V_{ub}|$

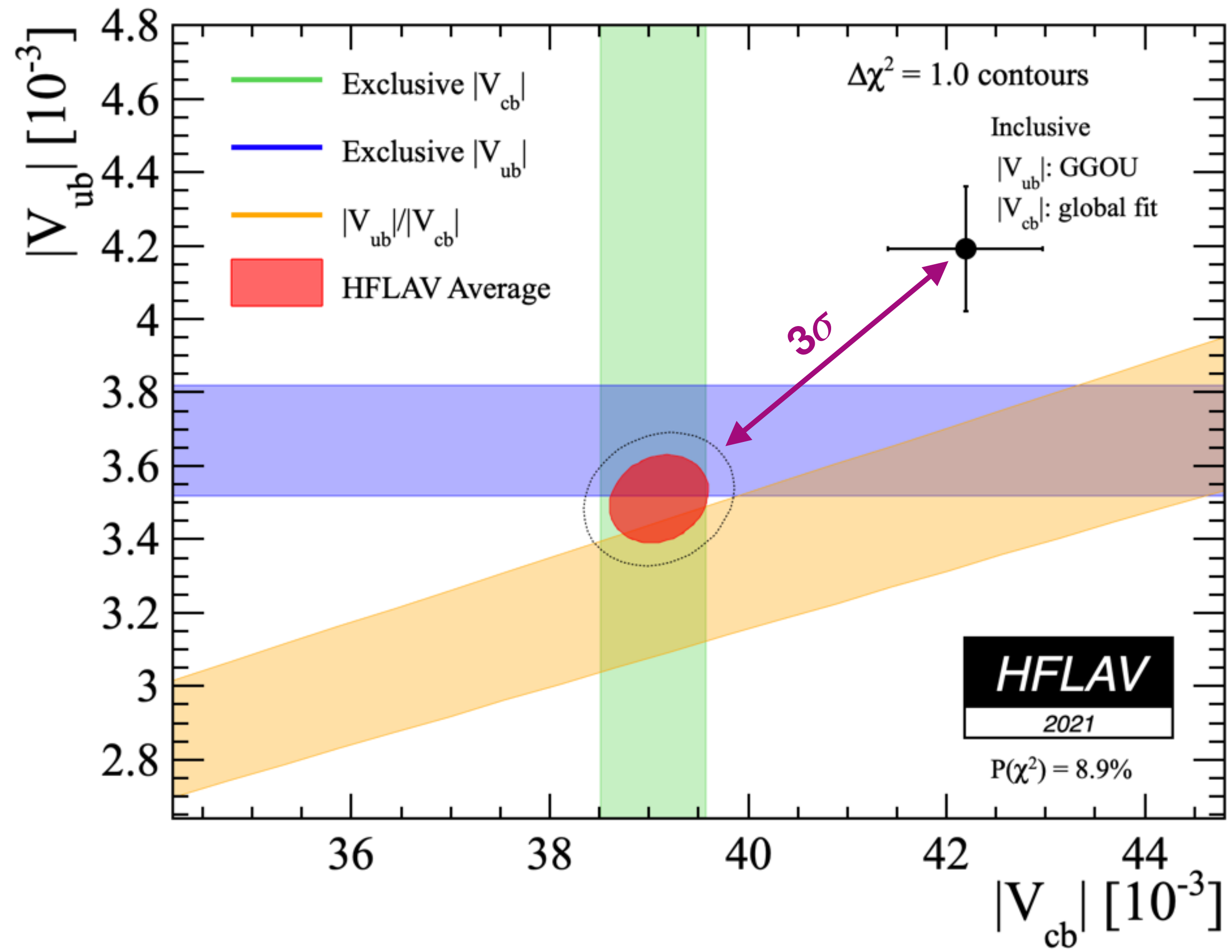
$\bar{B} \to X_u \ell \bar{\nu}_\ell$

Inclusive $|V_{cb}|$

$\bar{B} \to X_c \ell \bar{\nu}_\ell$

Heavy Quark Expansion

$$\mathcal{B} = |V_{qb}|^2 \left[\Gamma(b \to q\, \ell\, \bar{\nu}_\ell) + 1/m_{c,b} + \alpha_s + \ldots \right]$$



Lepton Flavour Universality

- Semileptonic decays also provide theoretically clean SM probes in Lepton Flavour Universality (LFU) tests.
- Differences in angular asymmetries for different lepton flavours are also sensitive to non-SM physics.
- Form factors and experimental uncertainties partially cancel in measurements of ratios of decay rates.

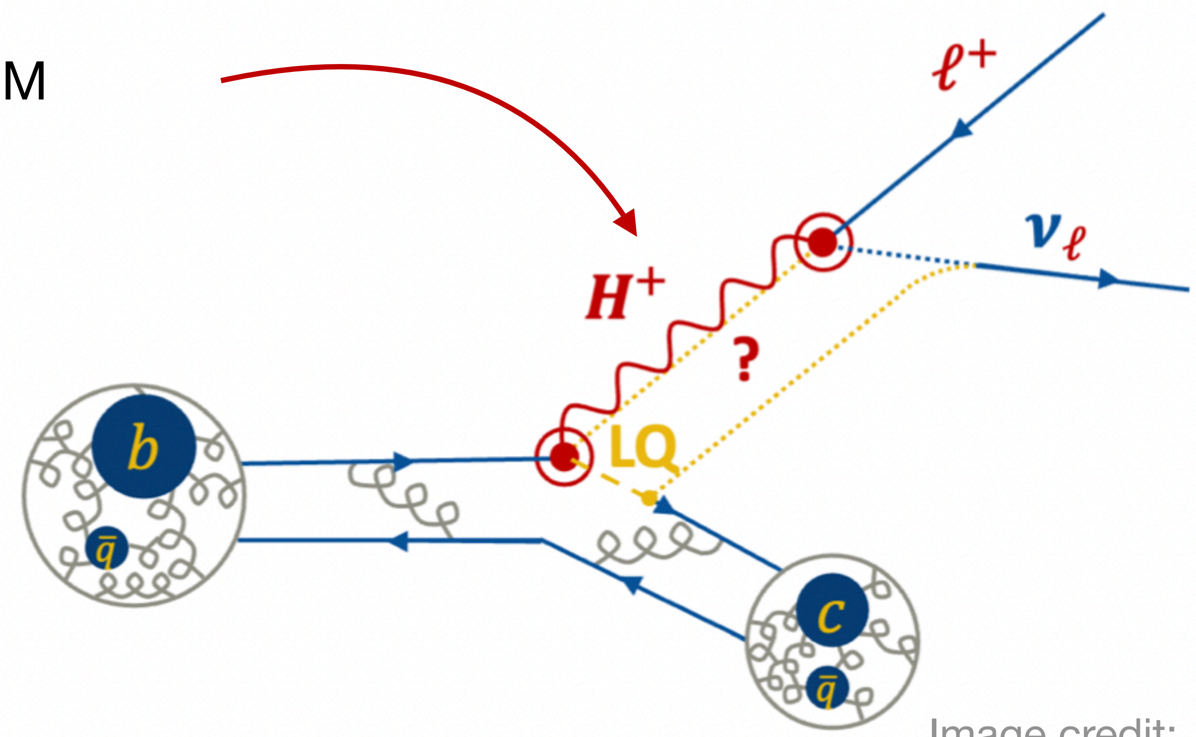
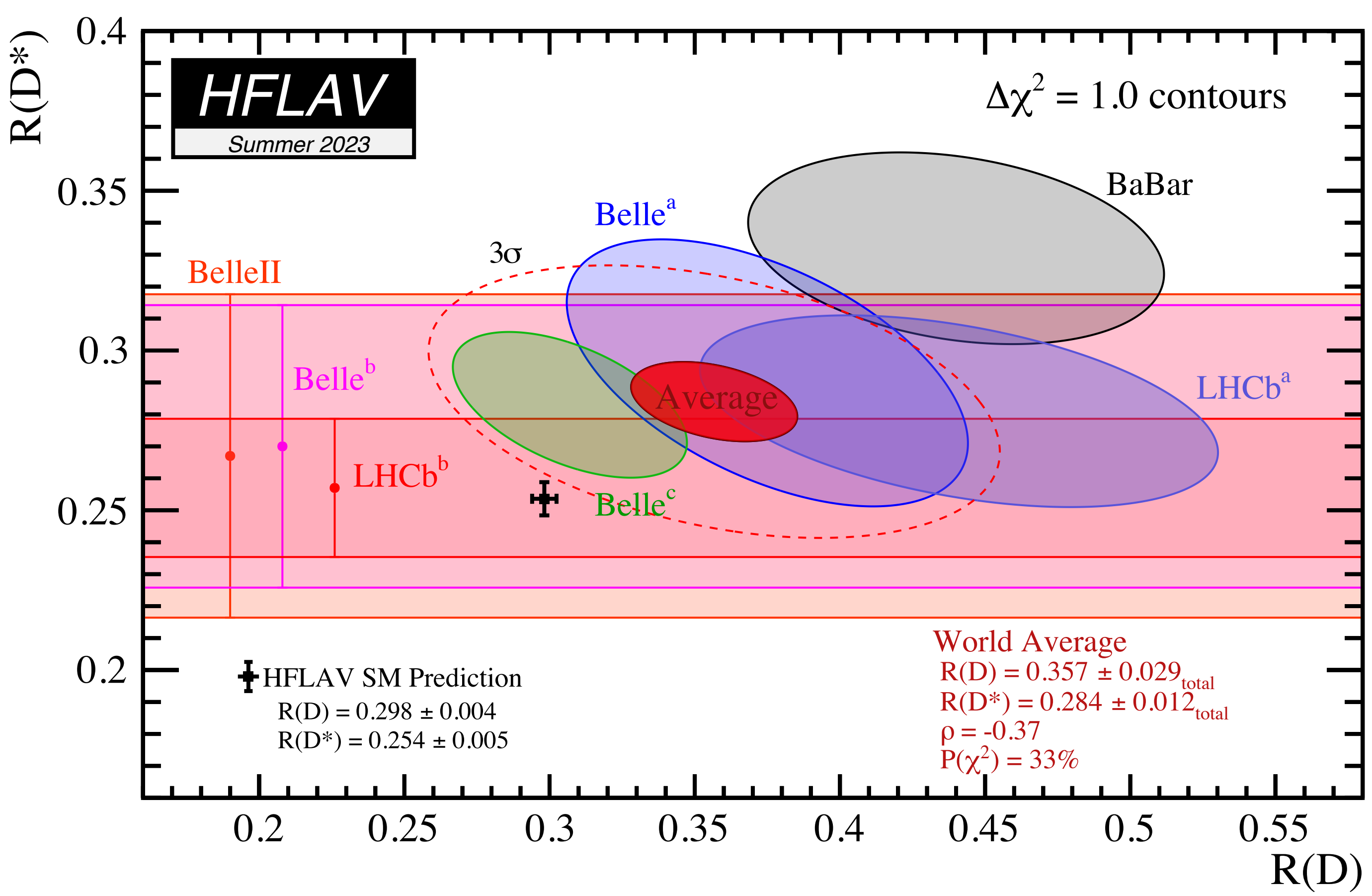


Image credit: H. Junkerkalefeld

Long-standing tension between LFU-sensitive quantities $R(D^{(*)})$ and SM predictions!



Exclusive approach:

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

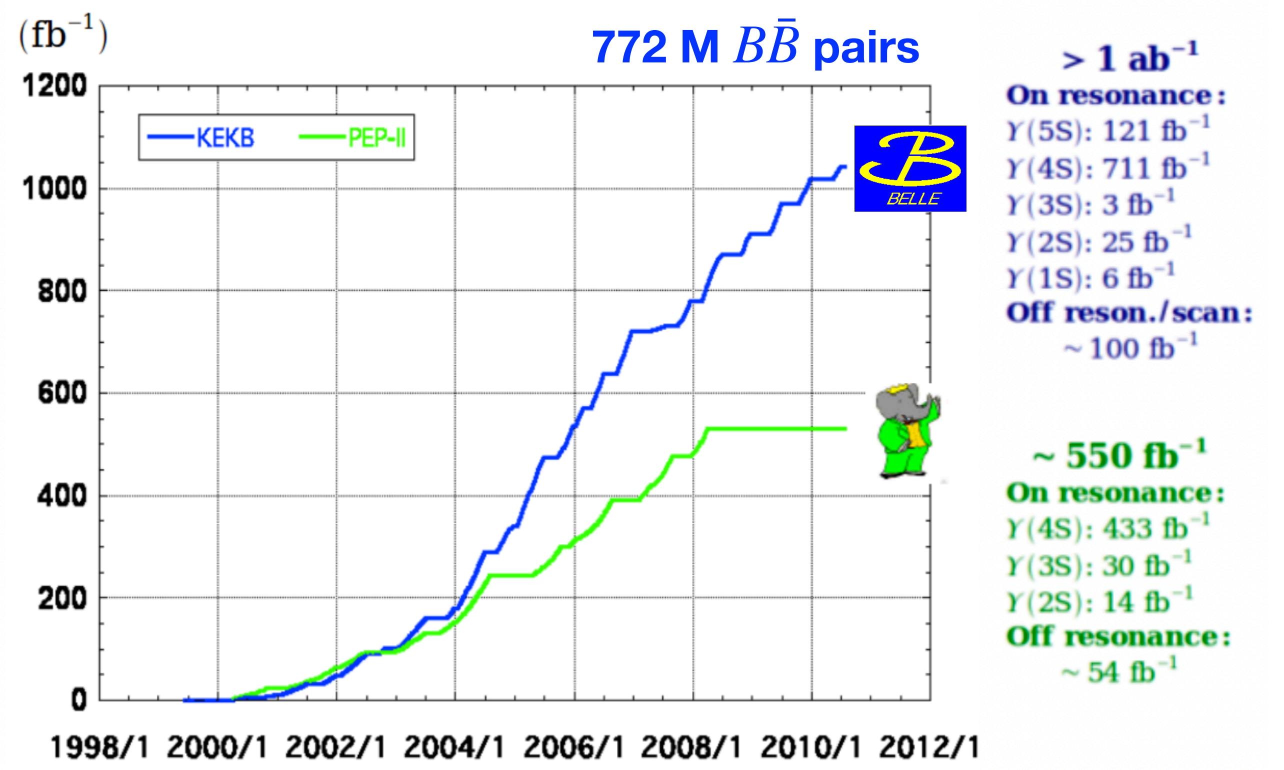
Complementary inclusive approach:

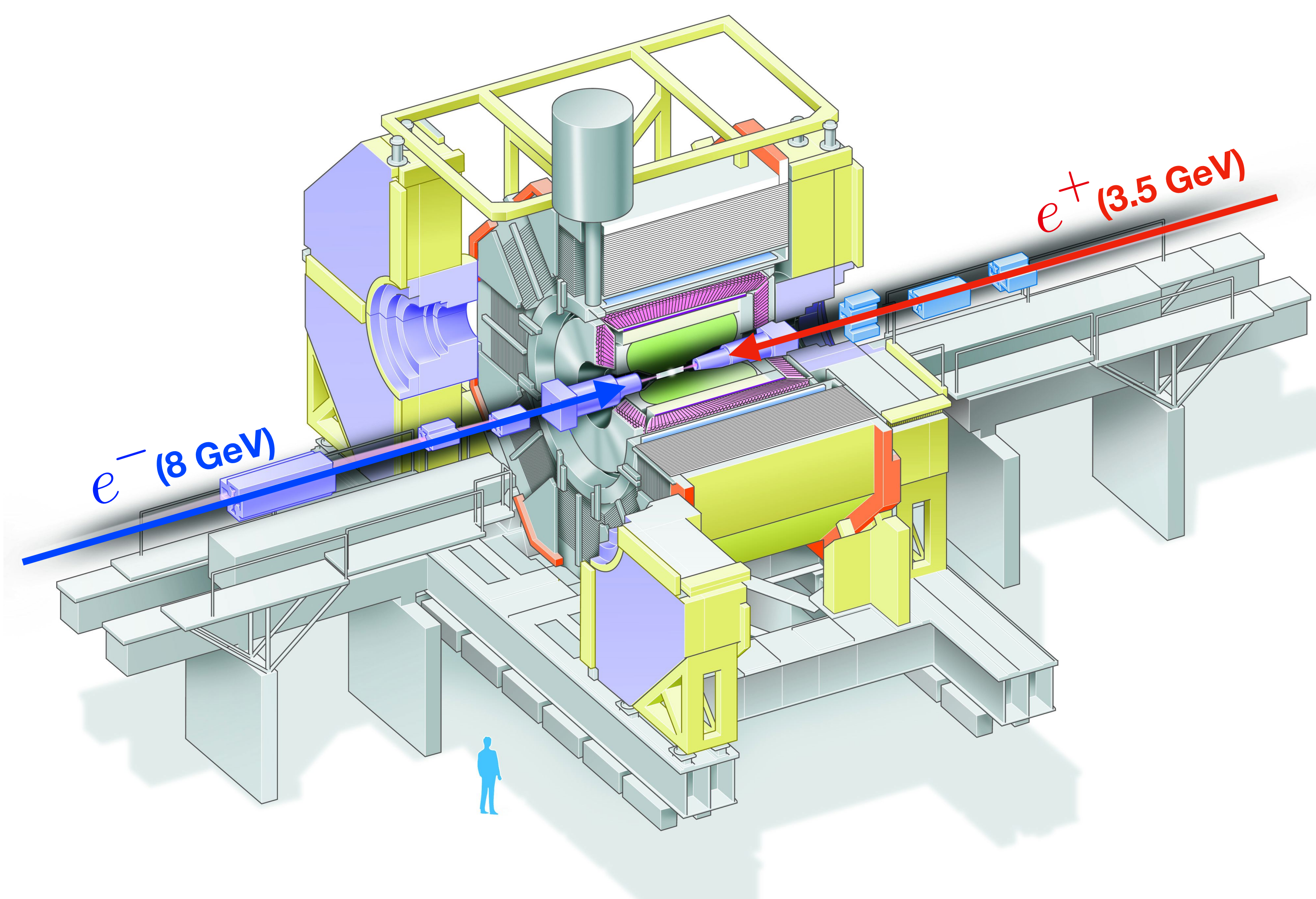
$$R(X_{\tau/\ell}) = \frac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)} \qquad \ell = e, \mu$$

Experimental uncertainties differ for $R(X_{\tau/\ell})$ & $R(D^{(*)})$

From Belle

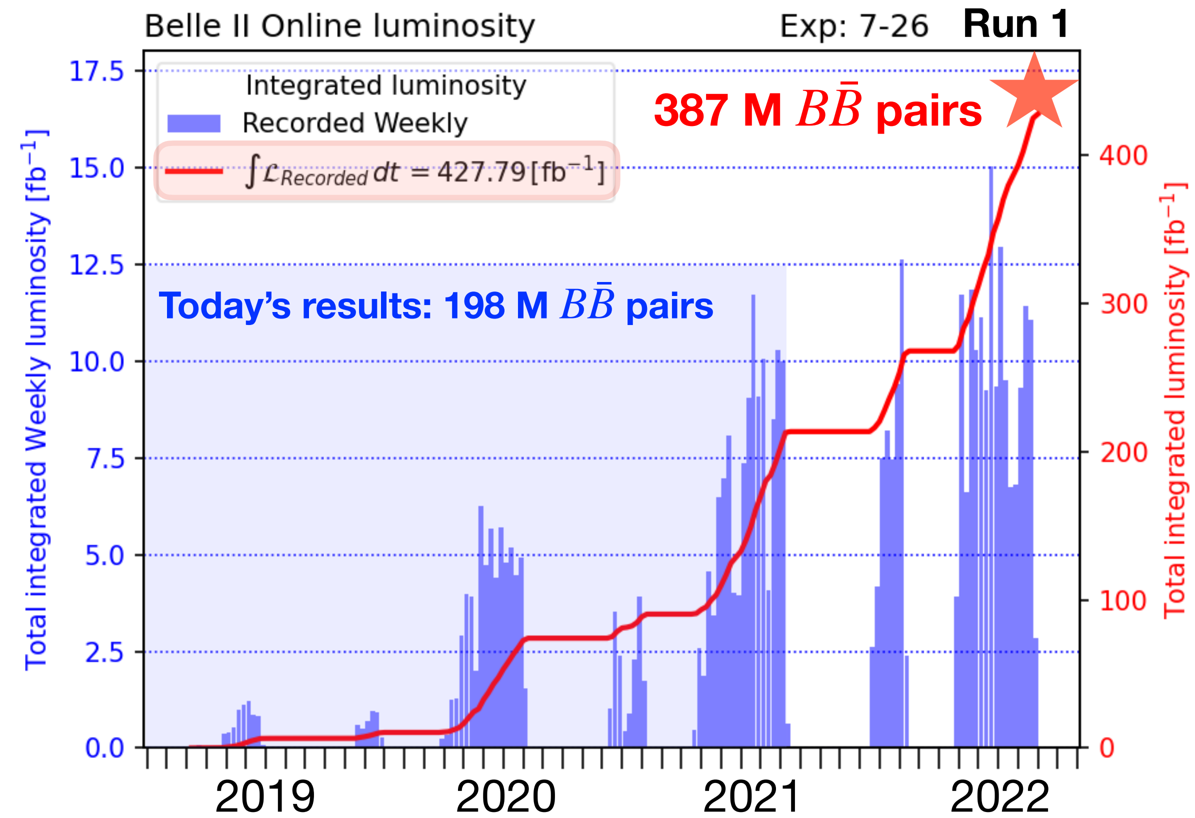
- Operated from 1999 to 2010 at KEK in Tsukuba, Japan.
- Asymmetric e^+e^- collider.
- Collected data at $\sqrt{s} = 10.58\ \mathrm{GeV}$ corresponding to the $\Upsilon(4S)$ resonance.
- Large solid angle coverage.
- Very successful — still produces results!

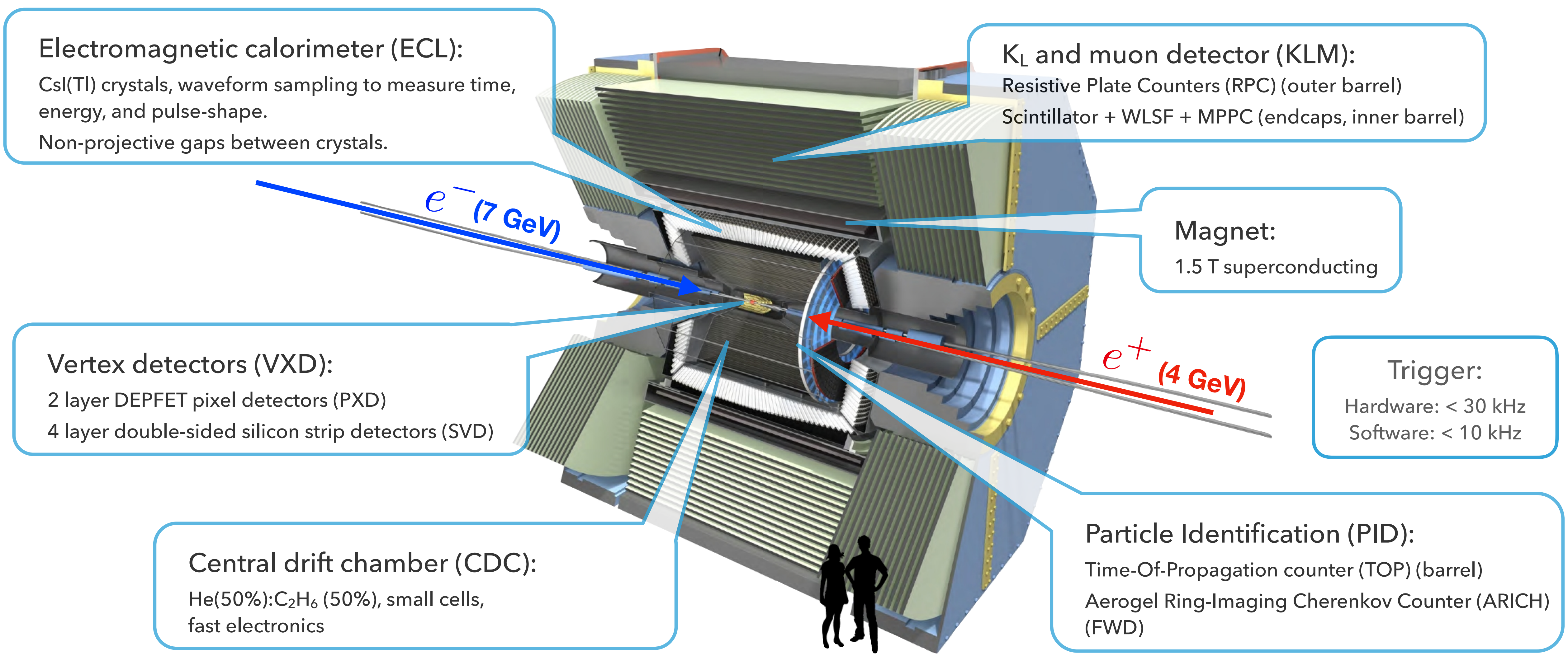




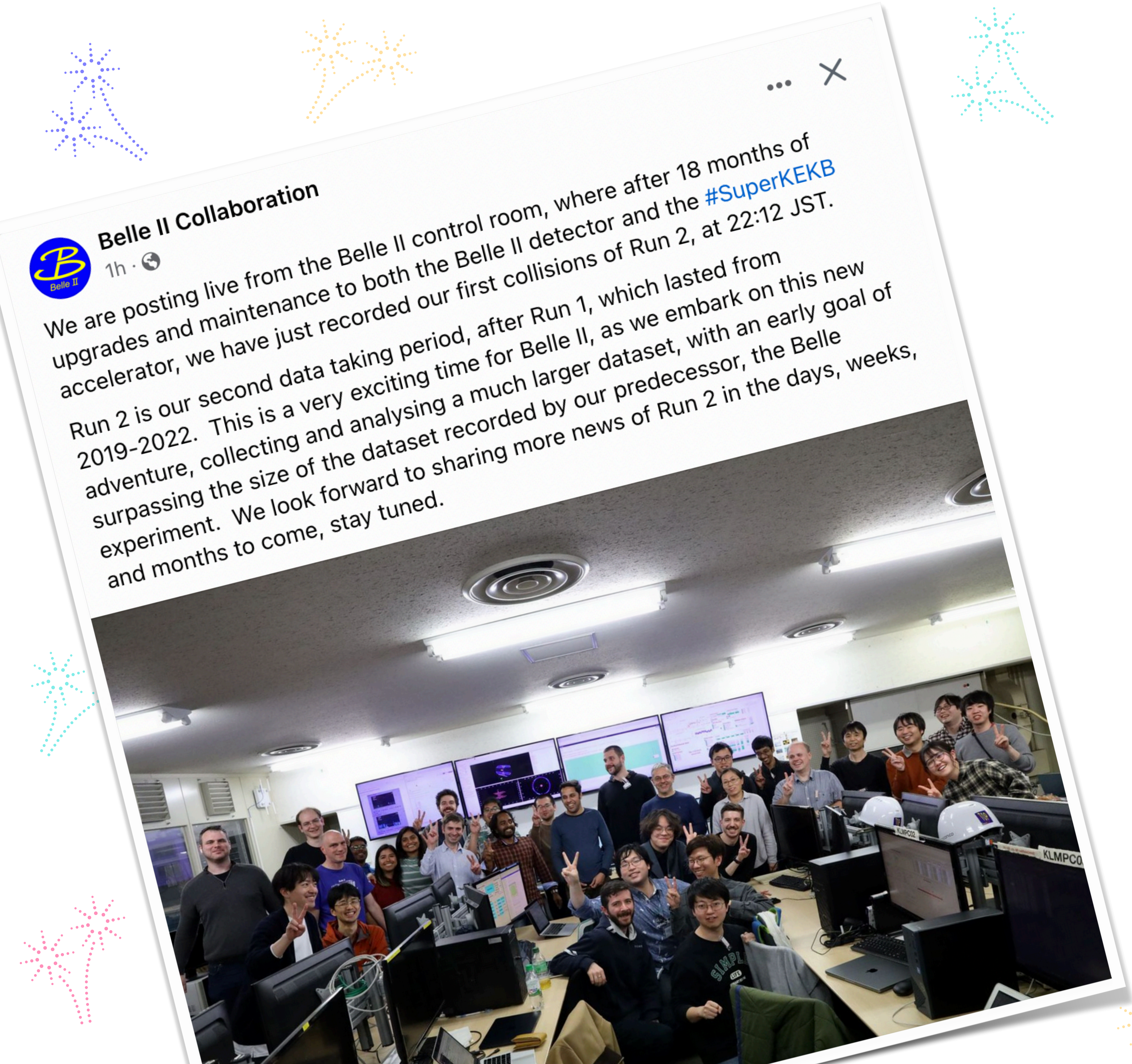
From Belle…to Belle II

- Starting Run 2 after installing two-layer pixel detector and machine maintenance.
- Re-utilized from Belle: only the structure, superconducting magnets, calorimeter crystals and outer barrel of K_L & μ detector.
- Practically a brand new detector with better vertexing/tracking than Belle.





First collisions of Run 2: 20 February 2024 22:12 JST



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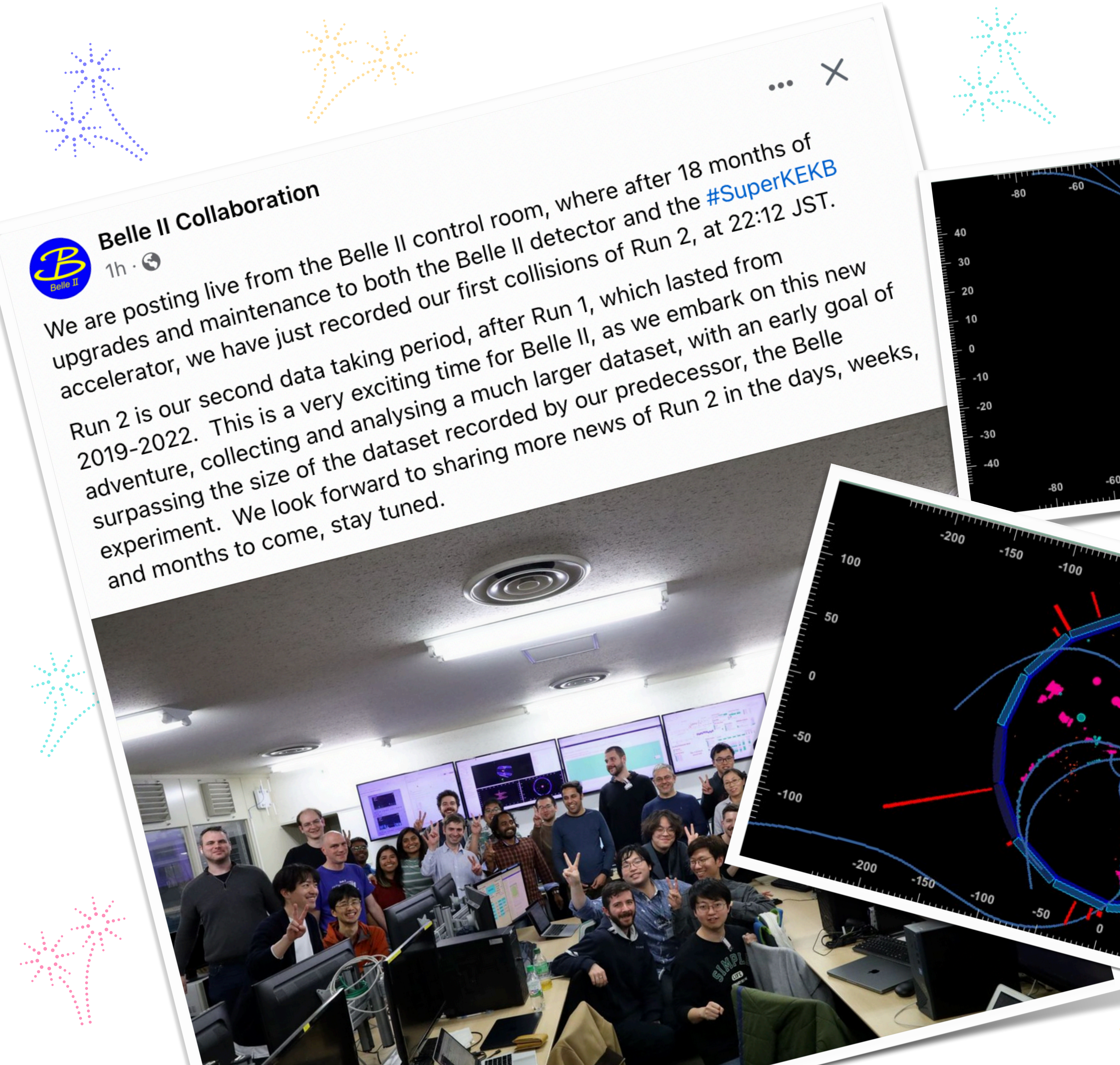
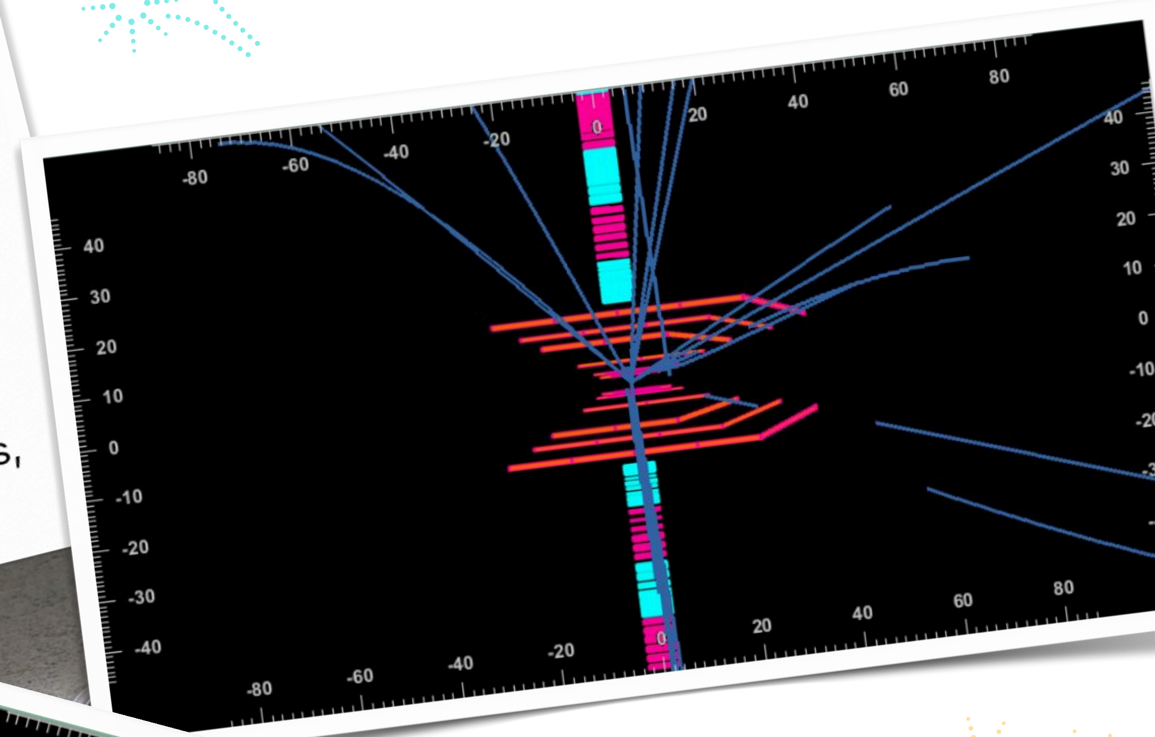
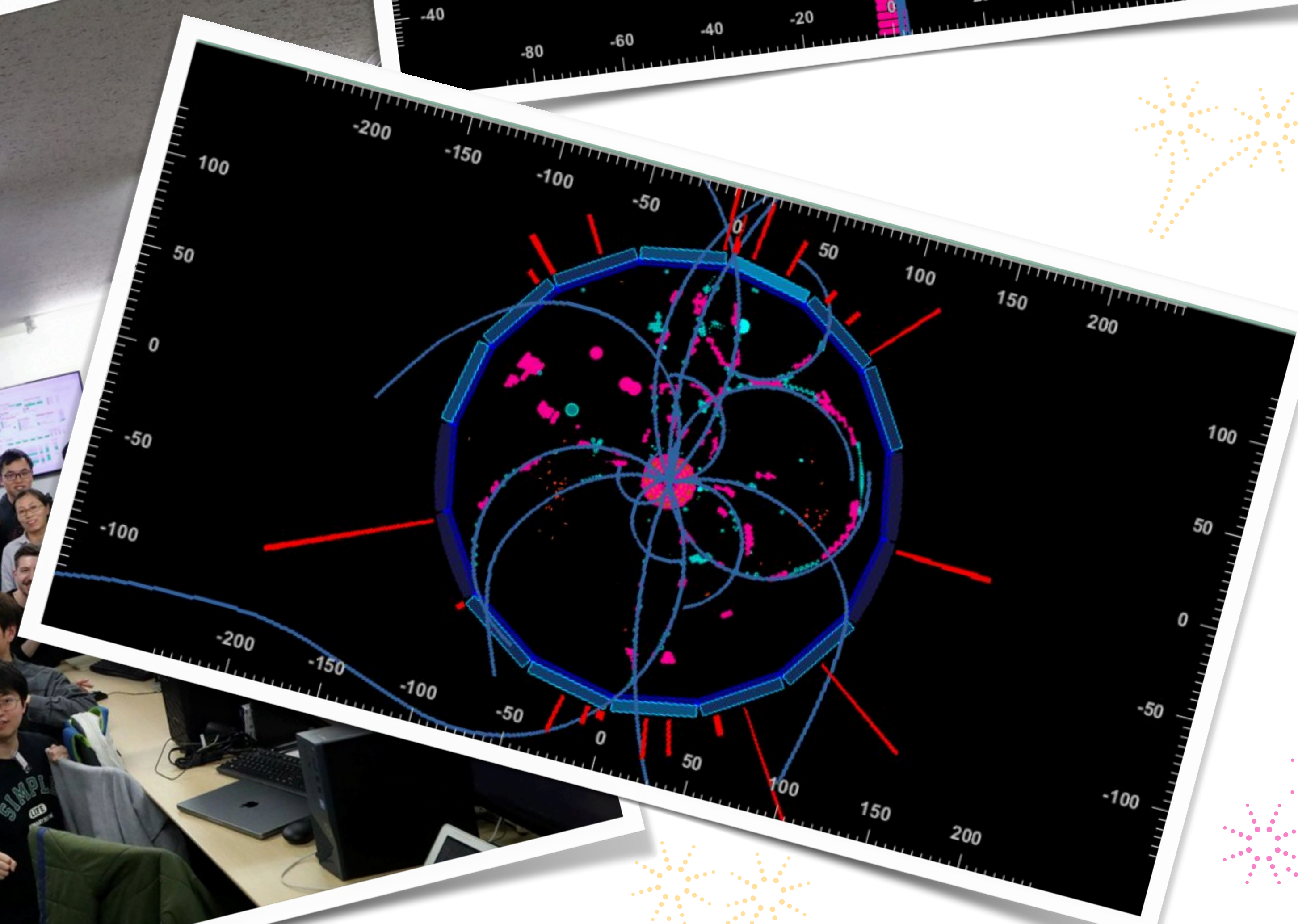


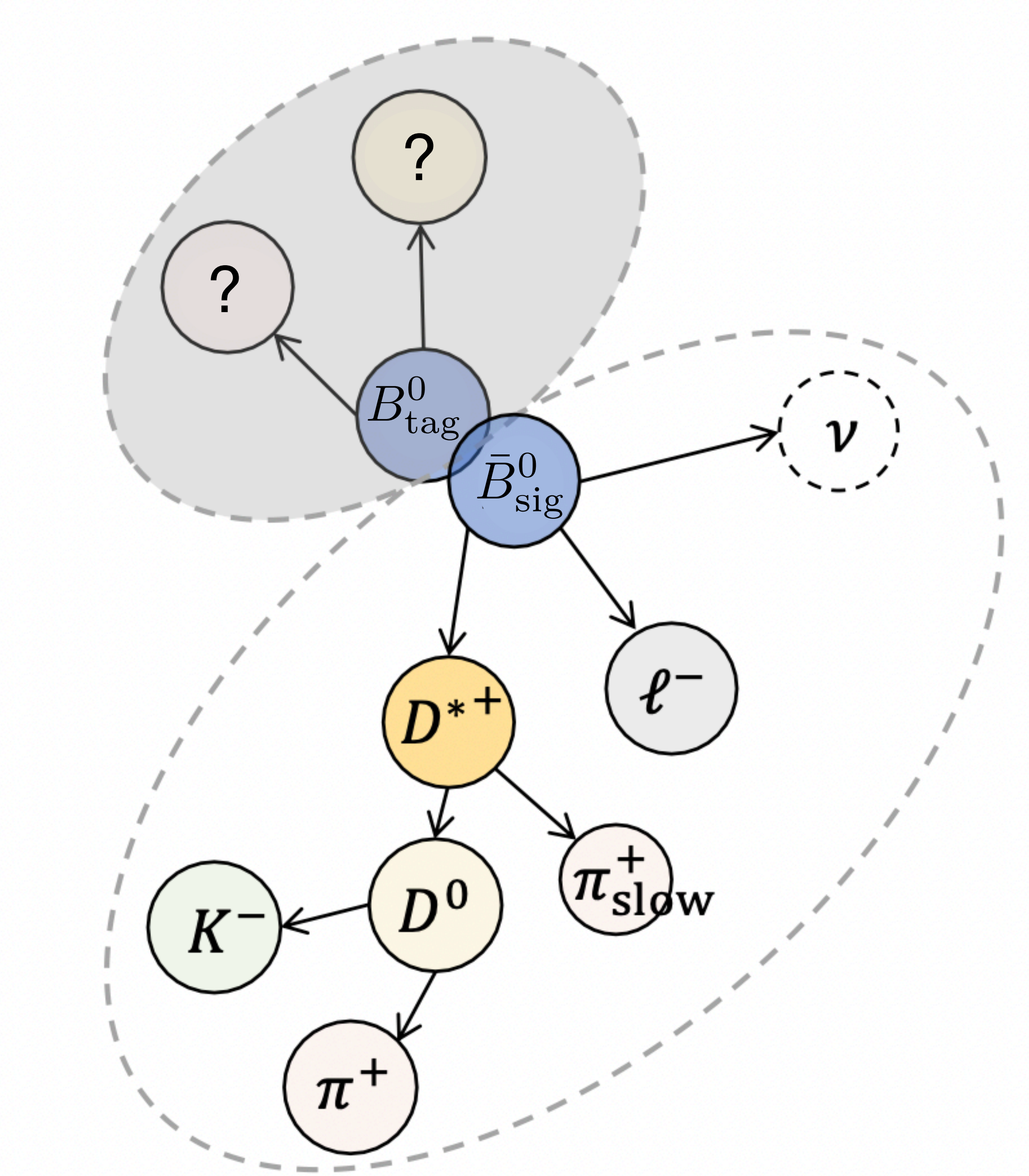




Reconstruction at B-Factories

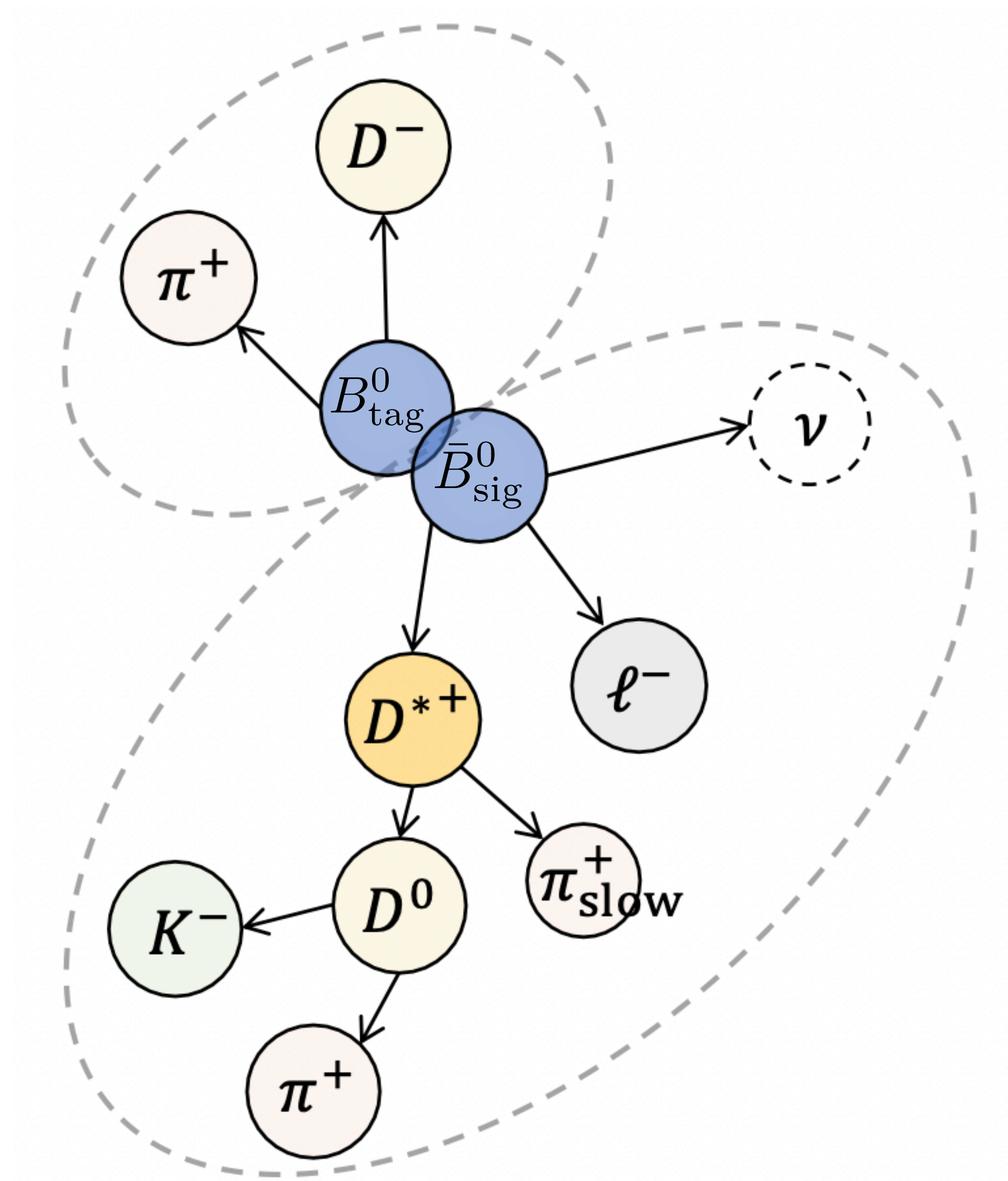
Untagged

Only reconstruct the signal B meson (B_{sig}).



Tagged

Reconstruct B_{tag} with hadronic decay modes.



← Efficiency, backgrounds

Purity, available observables →

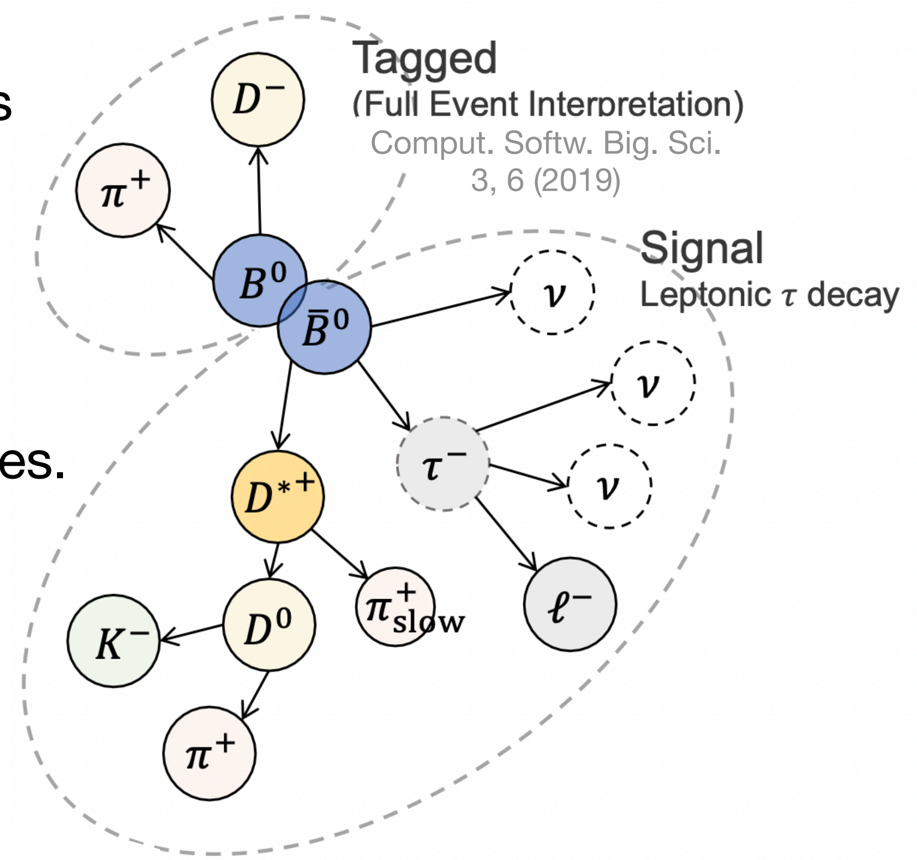
Image credit: K. Kojima

Measurement of $R(D^*)$

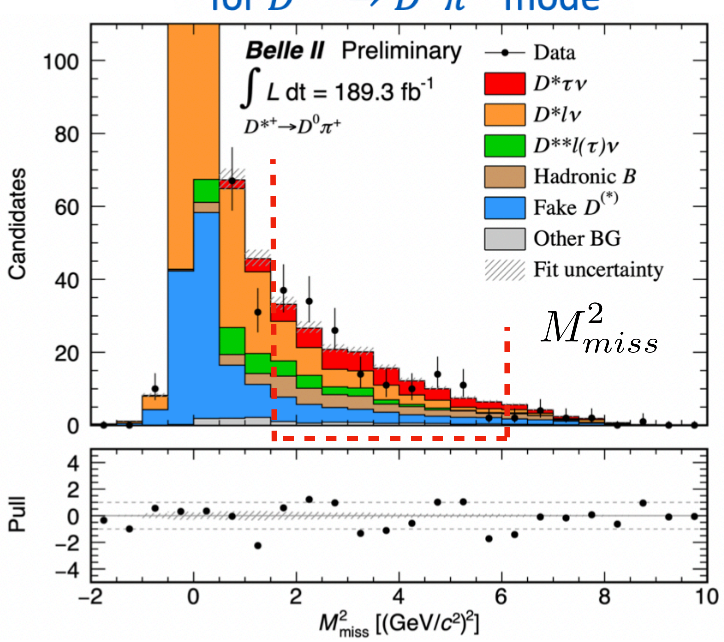
arXiv:2401.02840

Measure: $R(D^*) = \frac{\mathcal{B}(B \to D^* \tau \nu_\tau)}{\mathcal{B}(B \to D^* \ell \nu_\ell)}$ to cancel many systematics

- Consider three signal modes: $D^{*+} \to D^0 \pi^+$ and $D^+ \pi^-$, $D^{*0} \to D^0 \pi^0$
- Identify lepton from $\tau \to \ell \nu \bar{\nu}$
- Completeness constraint require **no additional tracks** or π^0 candidates.
- **Main challenge:** understand significant & poorly known $B \to D^{**} \ell \nu$ background decays.
  - **Data-driven validation** of background and signal modelling based on studies of sideband regions.
- **Extract signal** with 2D fit to residual energy in the calorimeter E_{ECL} & mass of undetected neutrinos $M^2_{miss} = (p_{e^+e^-} - p_{B_{tag}} - p_{D^*} - p_\ell)^2$



Zoom of M^2_{miss} projection for $D^{*+} \to D^0 \pi^+$ mode



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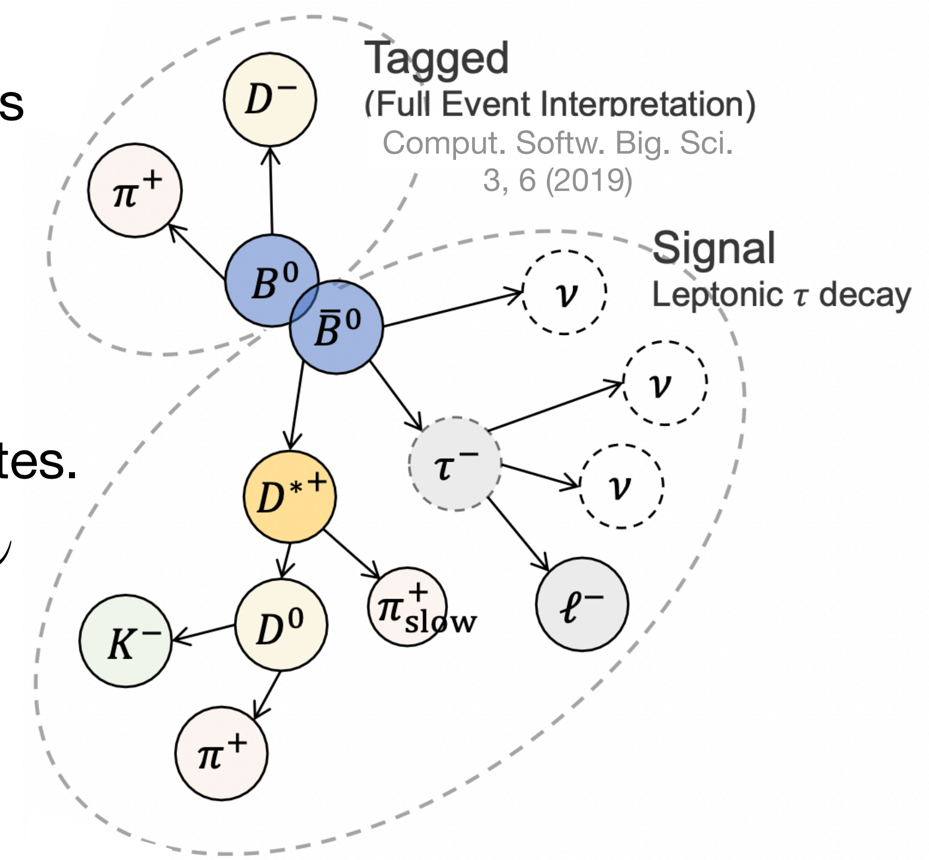

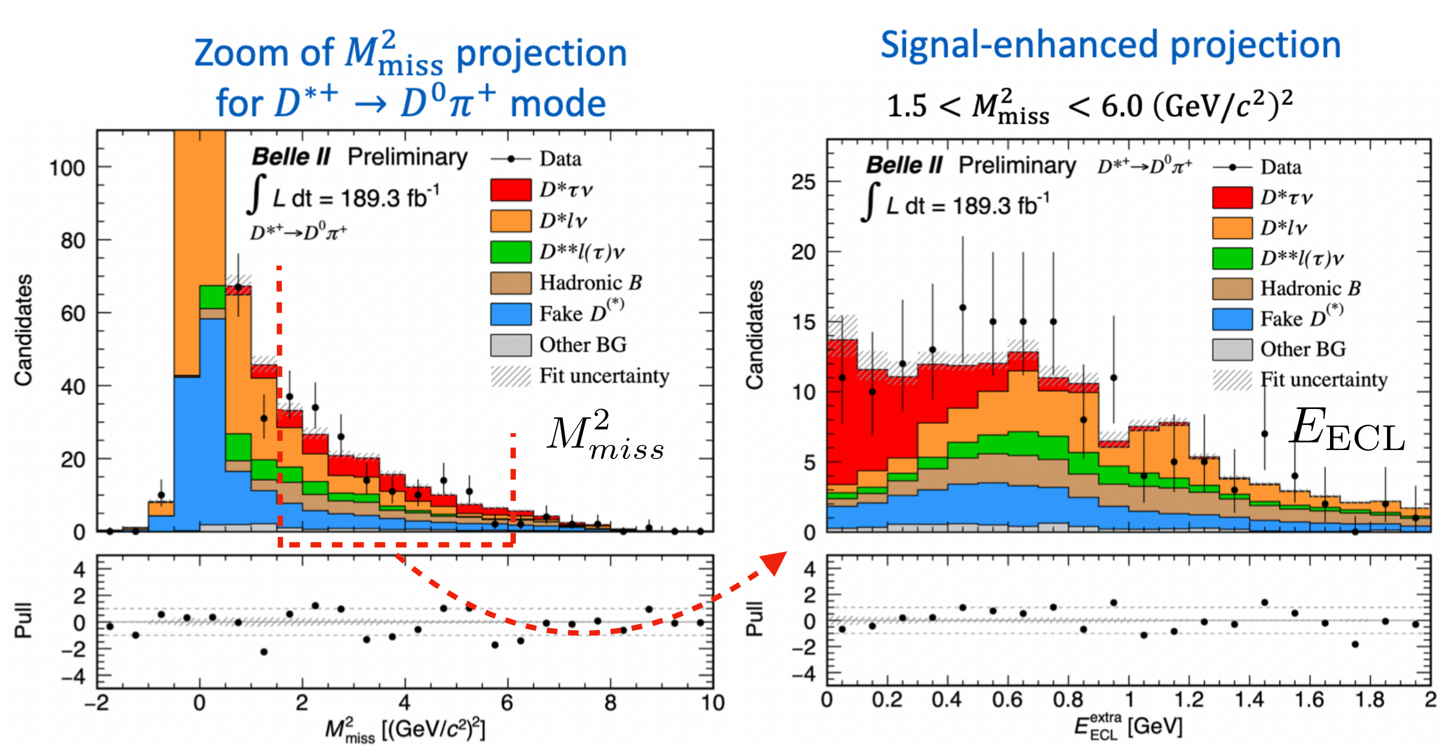

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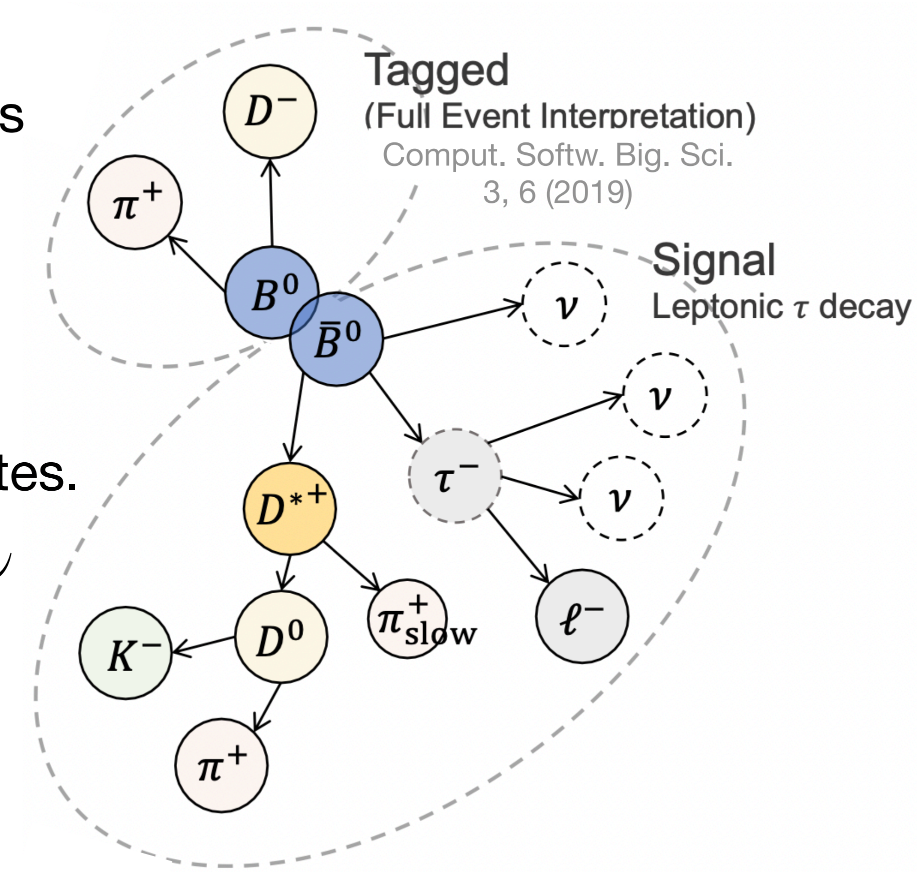

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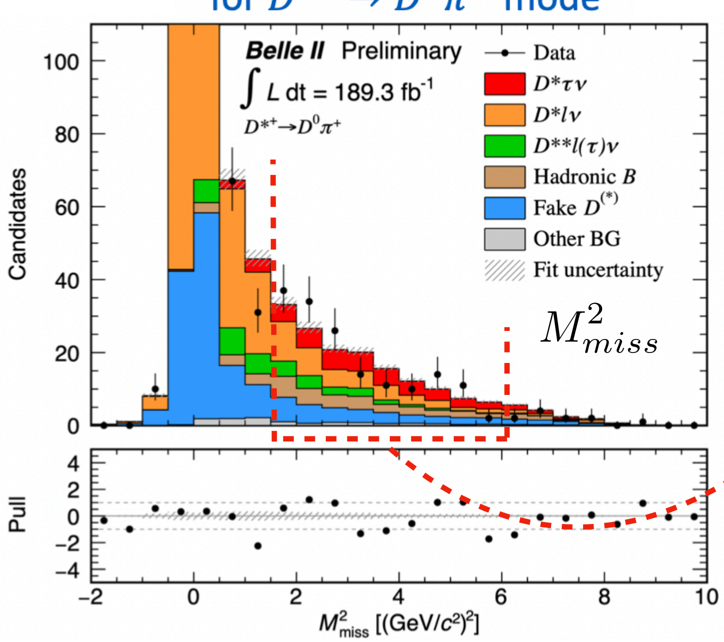
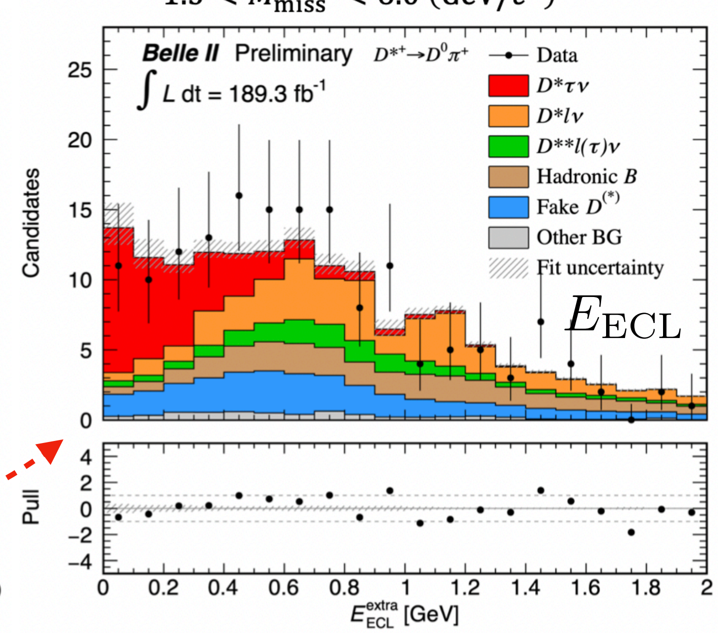


Signal-enhanced projection

$1.5 < M^2_{miss} < 6.0\ (\mathrm{GeV}/c^2)^2$



Leading systematics:
MC statistics, E_{ECL} PDF shape,
D^{**} modelling

$$R(D^*) = 0.262^{+0.041}_{-0.039}(\mathrm{stat.})^{+0.035}_{-0.032}(\mathrm{syst.})$$

SM prediction: $R(D^*) = 0.254 \pm 0.005$

HFLAV 23: $R(D^*) = 0.284 \pm 0.013$

Eur. Phys. J. C 81, 226 (2021)

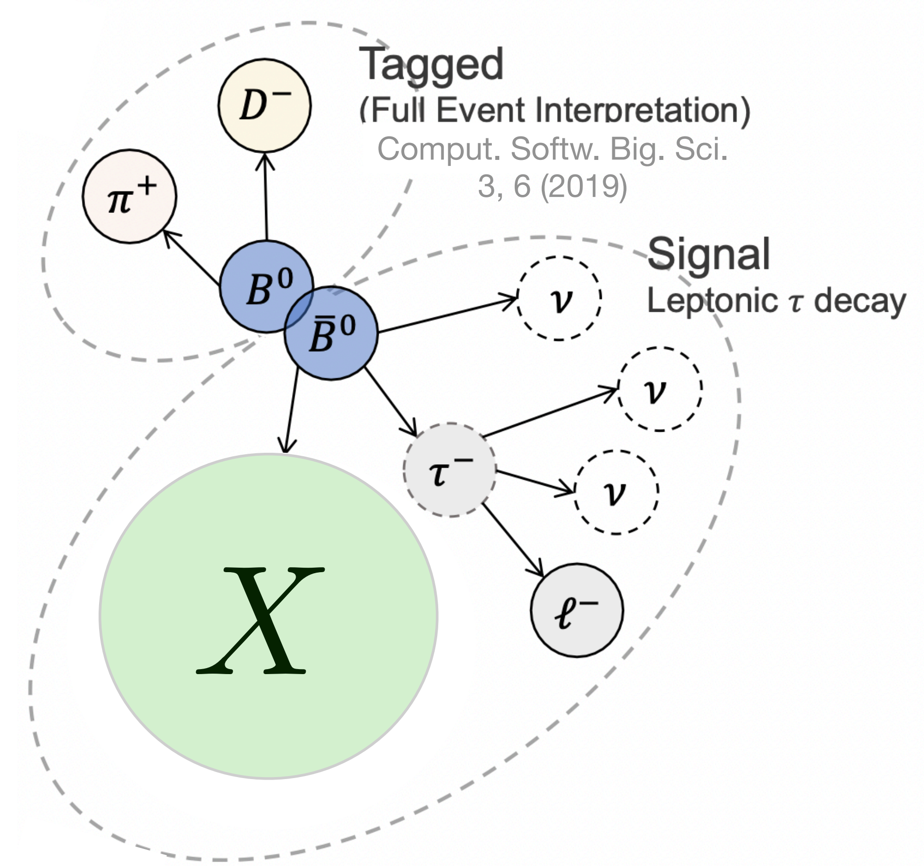
Consistent with SM and previous measurements!

Measurement of $R(X_{\tau/\ell})$

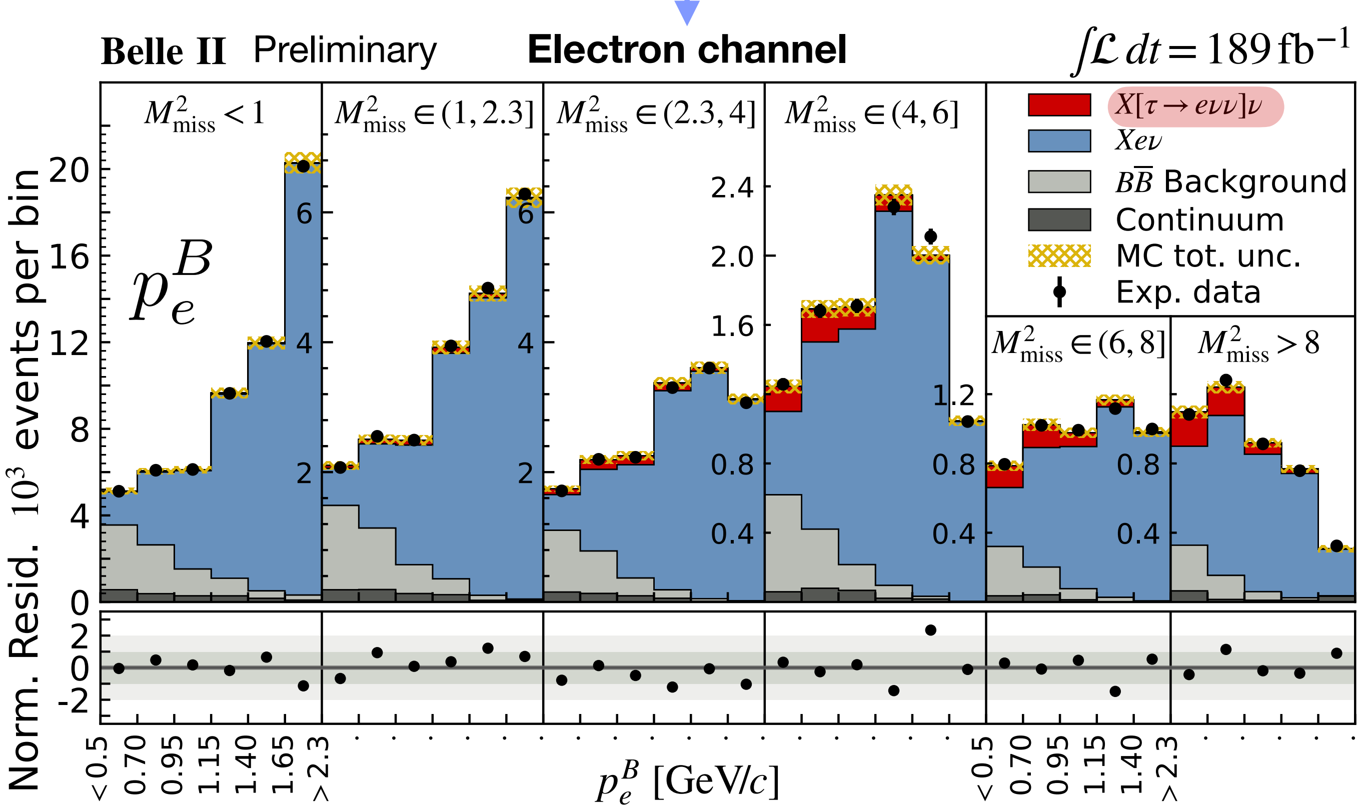
Belle II

arXiv:2311.07248

Complementary inclusive study: $R(X_{\tau/\ell}) = \dfrac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)}$



- **First measurement at a B-Factory with the $\Upsilon(4S)$!**
- **Main challenge:** Modelling & characterising backgrounds arising from $b \to c \to \ell$, $e^+e^- \to q\bar{q}$ (continuum) and mis-identified leptons.
  - **Data-driven $X\ell\nu$ modelling** using M_X distribution in high-lepton momentum ($p_\ell^B > 1.4$ GeV) sideband region.
  - Systematics dominated by $X_c\ell\nu$ modelling and M_X reweighting.
- **Extract signal** with 2D fit to lepton momentum p_ℓ^B (in the signal B rest frame) & mass of undetected neutrinos M^2_{miss}



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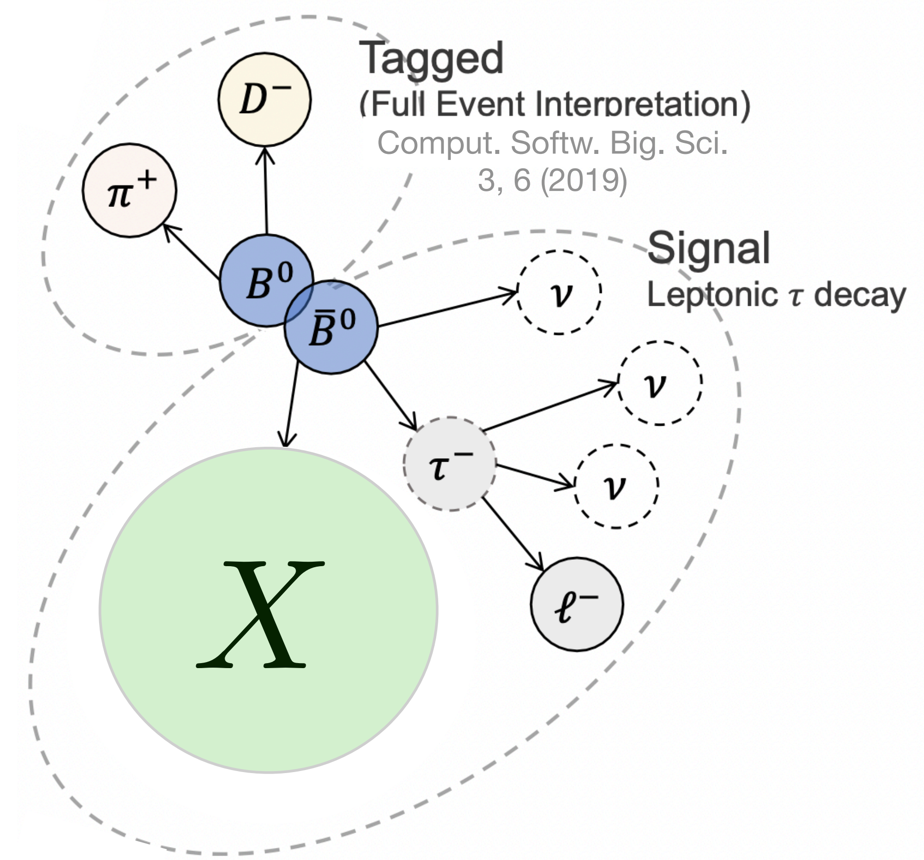

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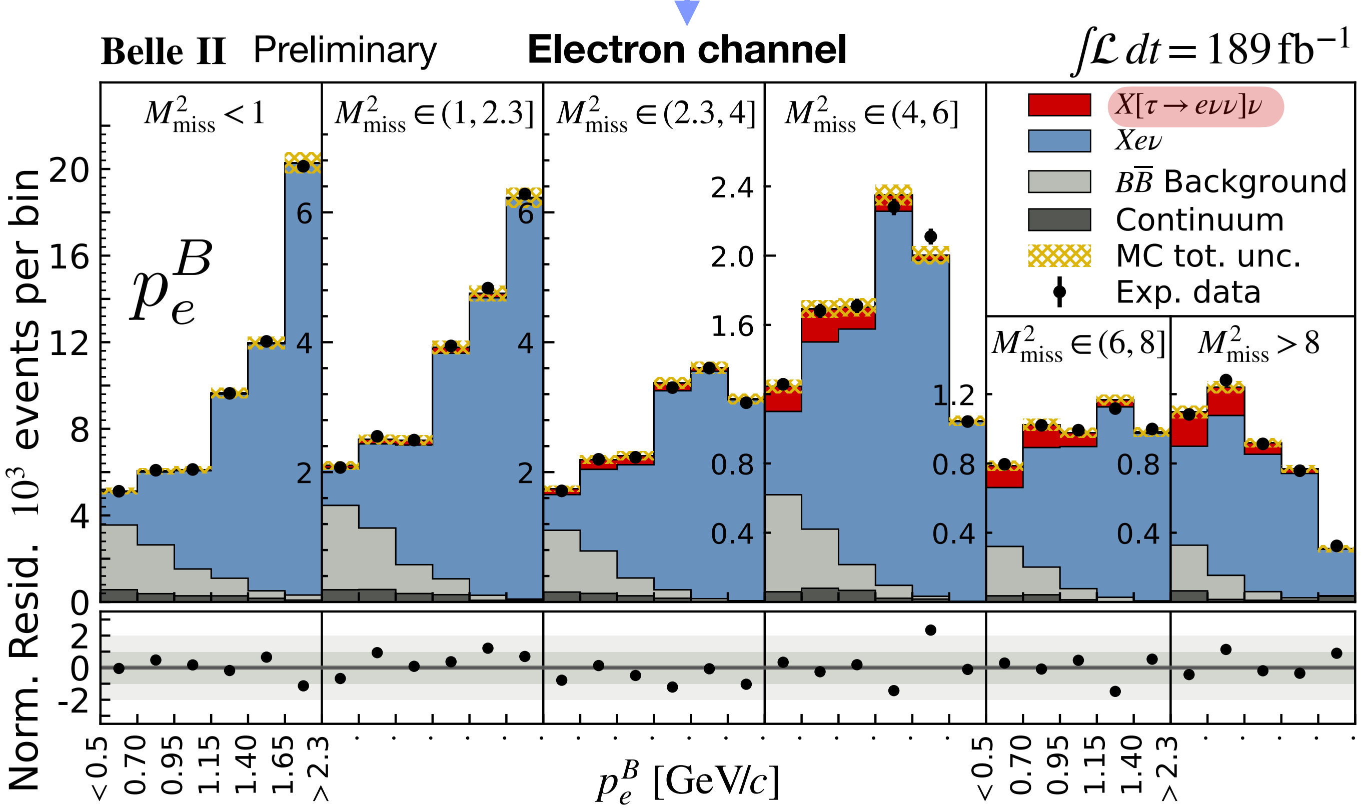


(average of electron and muon channels)

$$R(X_{\tau/\ell}) = 0.228 \pm 0.016\ (\mathrm{stat.}) \pm 0.036\ (\mathrm{sys.})$$

SM prediction: $R(X)$ = 0.223 ± 0.005

J. High Energ. Phys. 2022, Phys. Rev. D 92, 054018, Phys. Rev. D 105, 073009

Compatible with SM and $R(D^{(*)})$ measurements

$|V_{cb}|$ from untagged $B^0 \to D^{*+}\ell^-\nu$

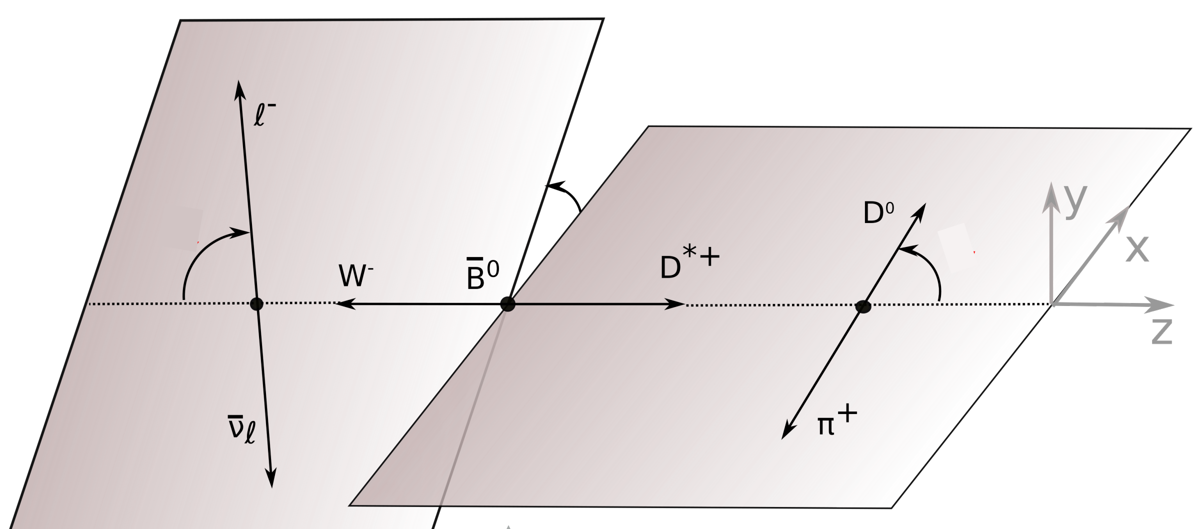
Belle II

PRD 108, 092013 (2023)

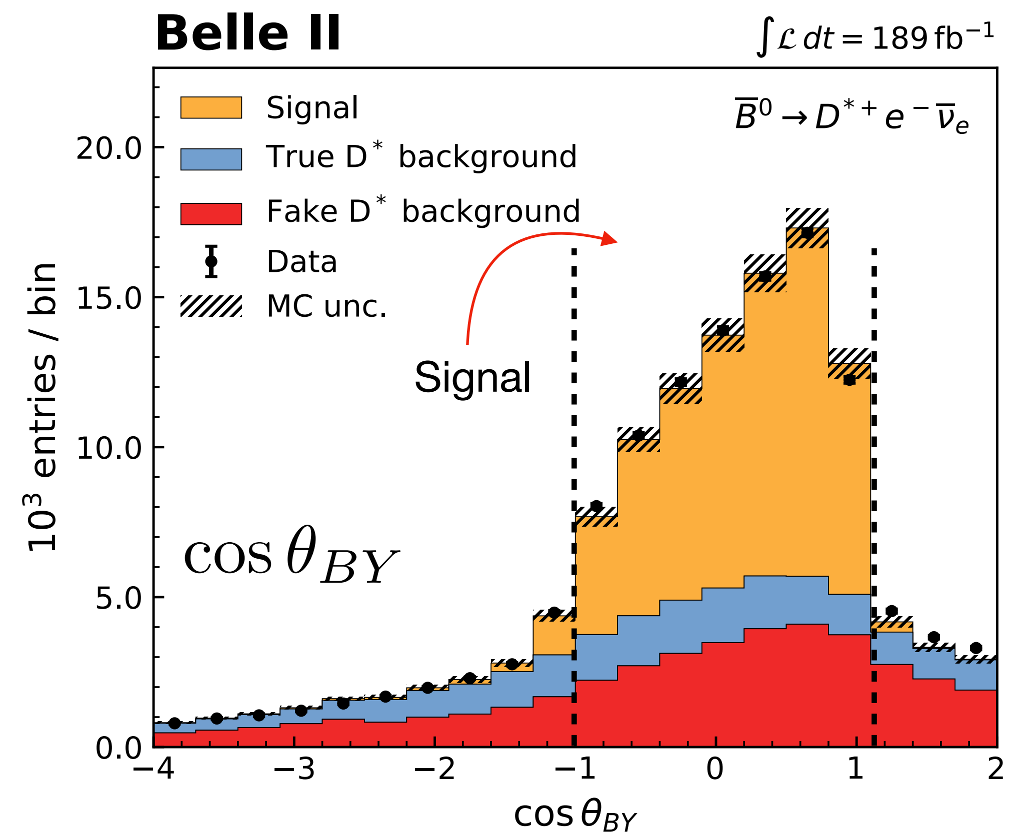
- **Reconstruct** $D^{*+} \to D^0(\to K^-\pi^+)\pi^+_{\text{slow}}$ and combine with appropriately **charged lepton** ($\ell = e$ or μ).
- **Main challenge:** accurate background model, slow pion (p < 0.4 GeV) tracking and statistical correlations between bins.
- Reconstruct the angle between B and $Y = D^*\ell$:

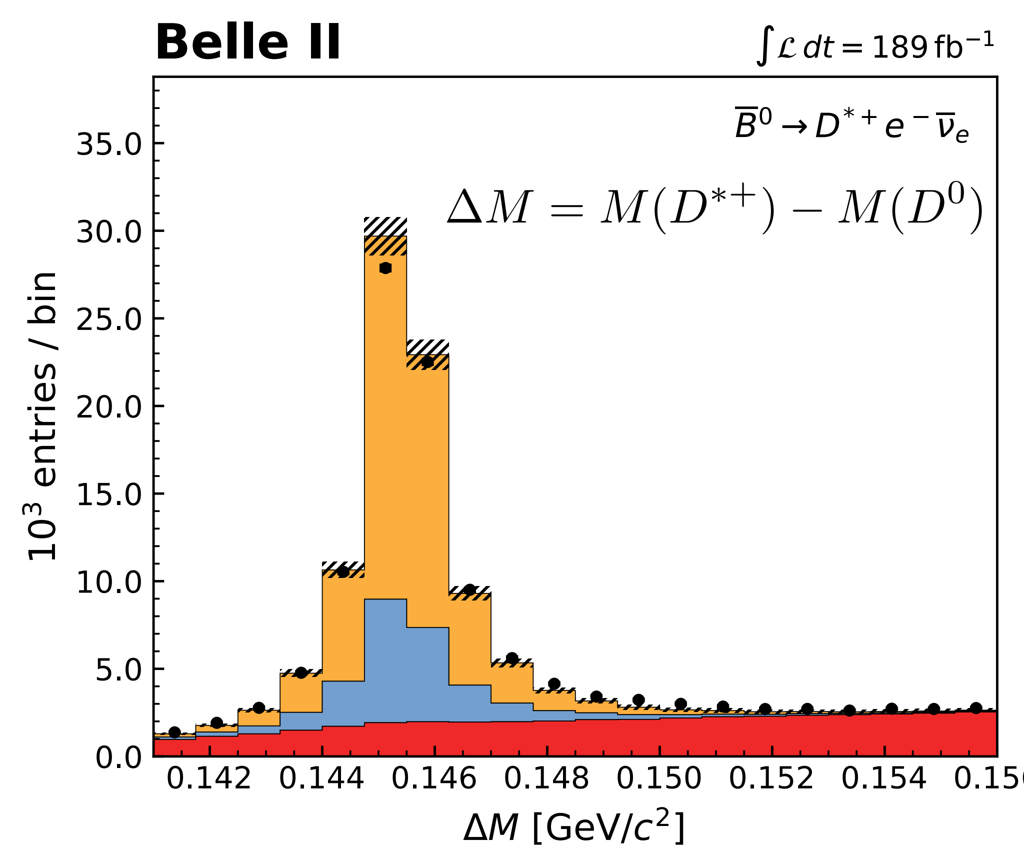
$$\cos\theta_{BY} = \frac{2E^*_B E^*_Y - m^2_B - m^2_Y}{2|p^*_B||p^*_Y|}$$

- **Extract signal yield** with 2D fit to $\cos\theta_{BY}$ and $\Delta M = M(D^{*+}) - M(D^0)$ in bins of…



Signal B rest frame





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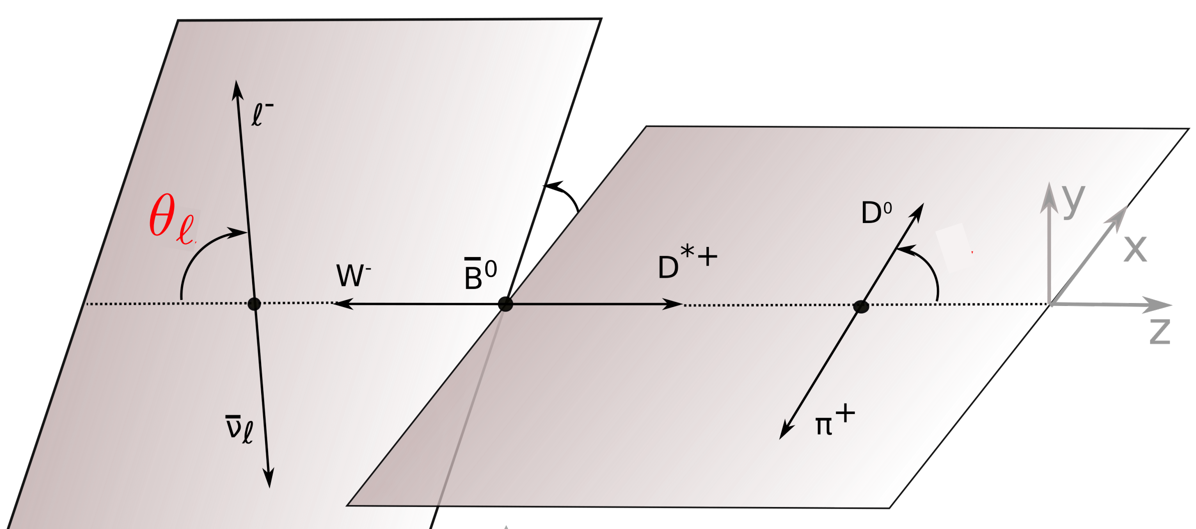

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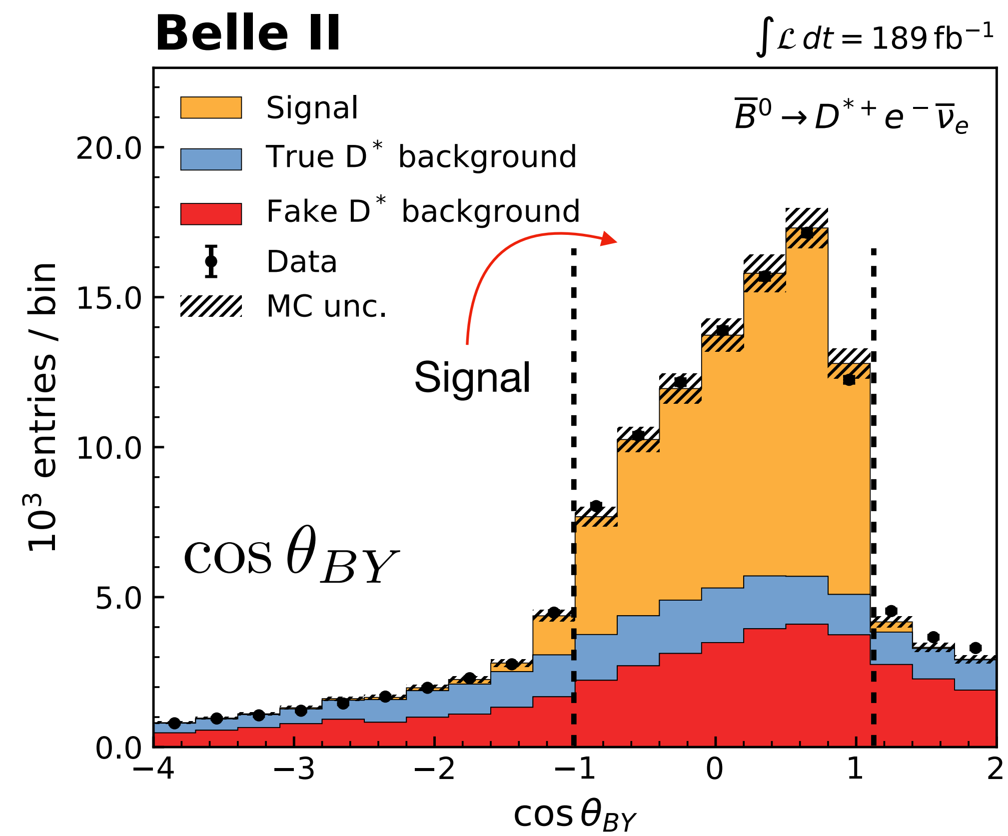

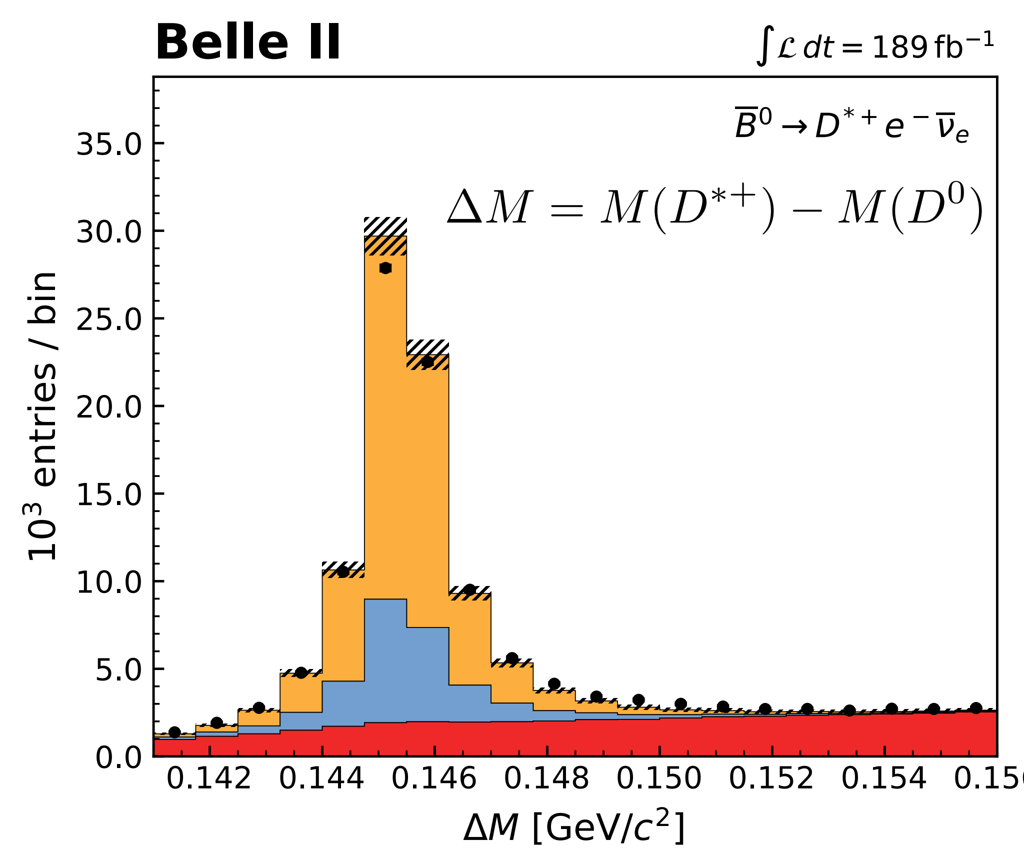

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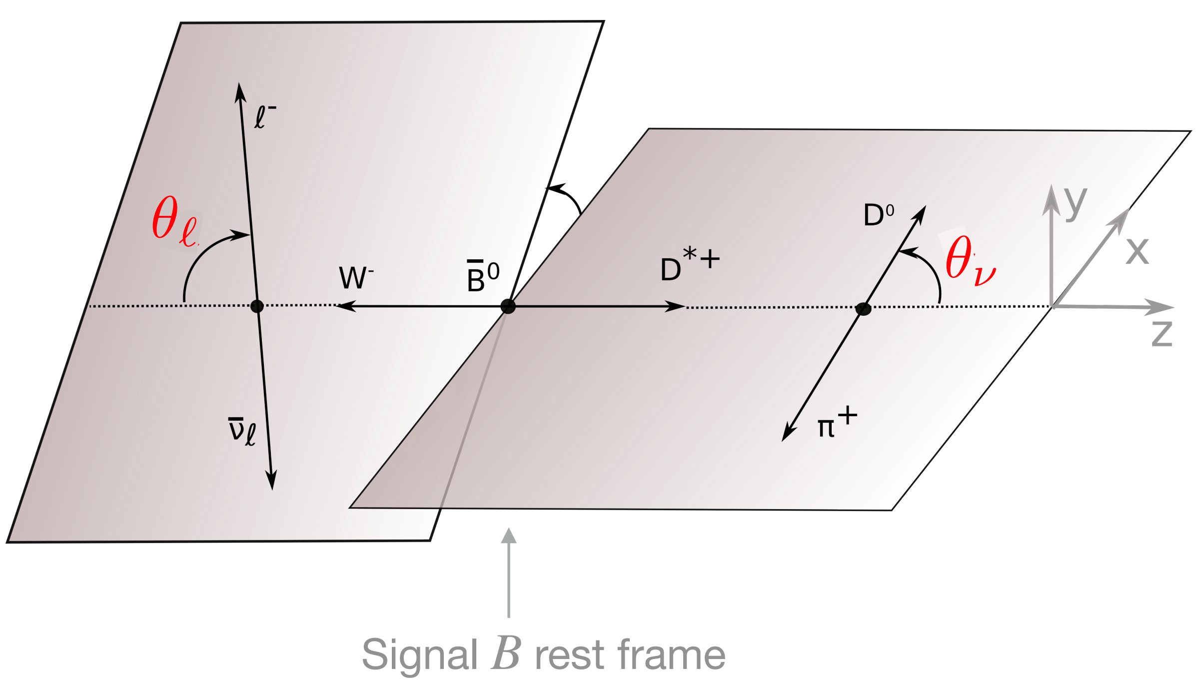

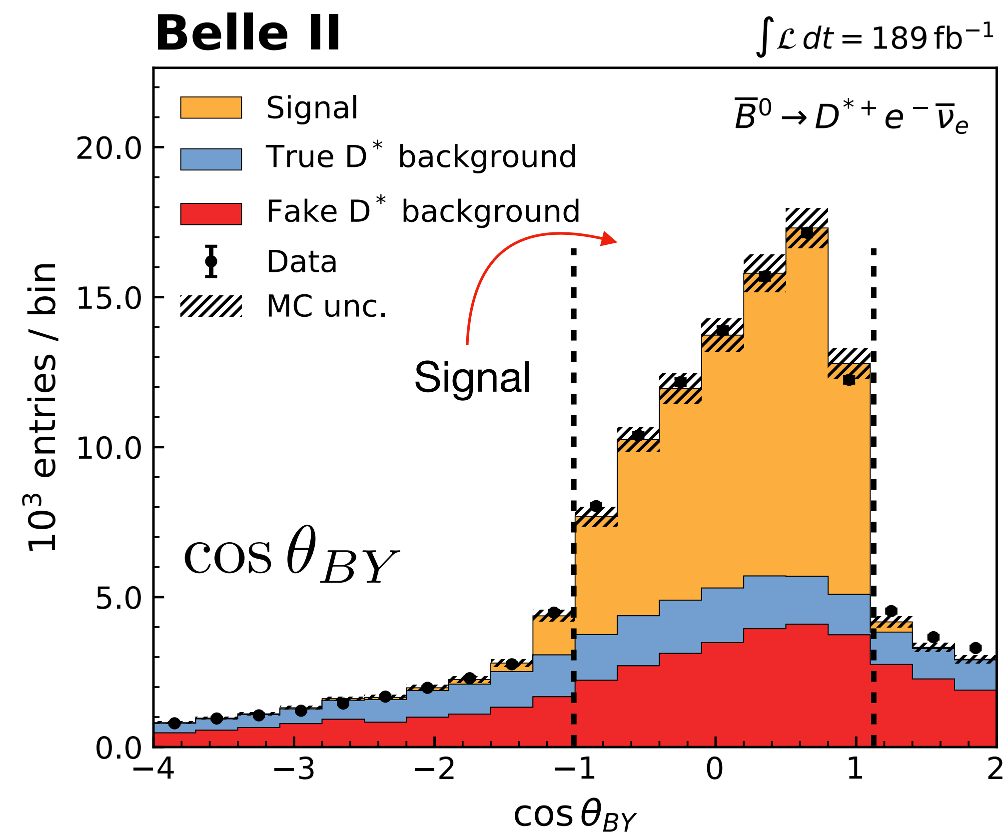

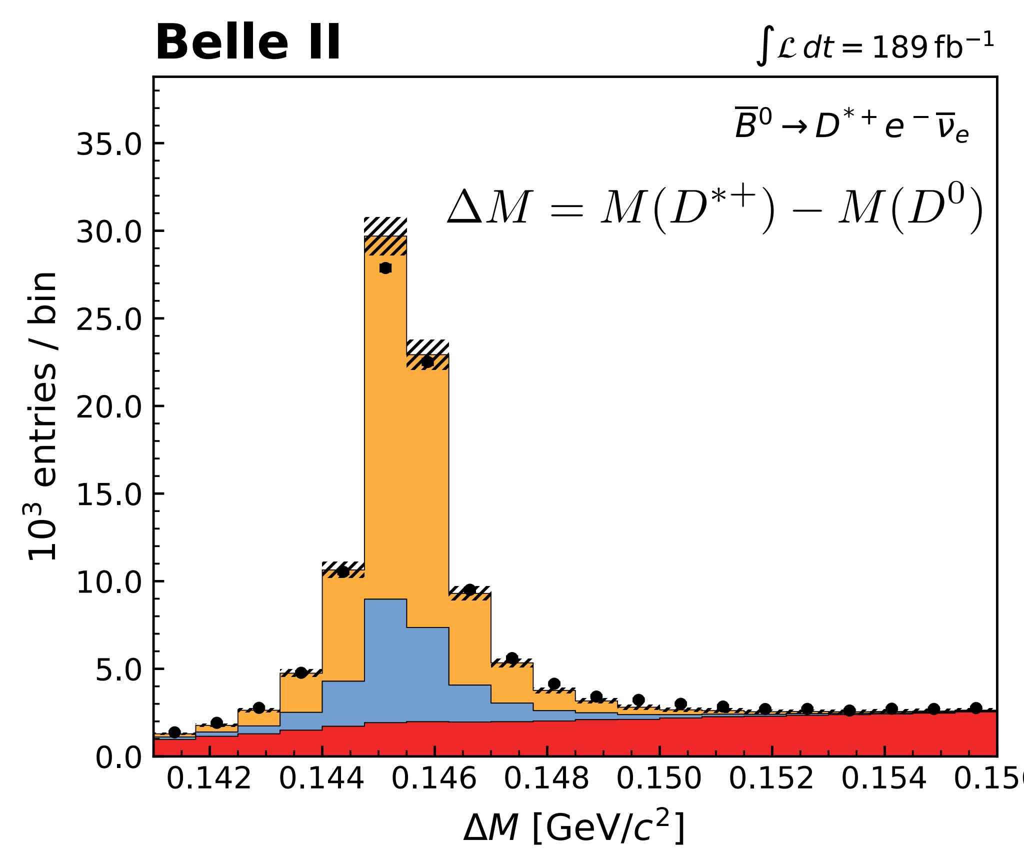

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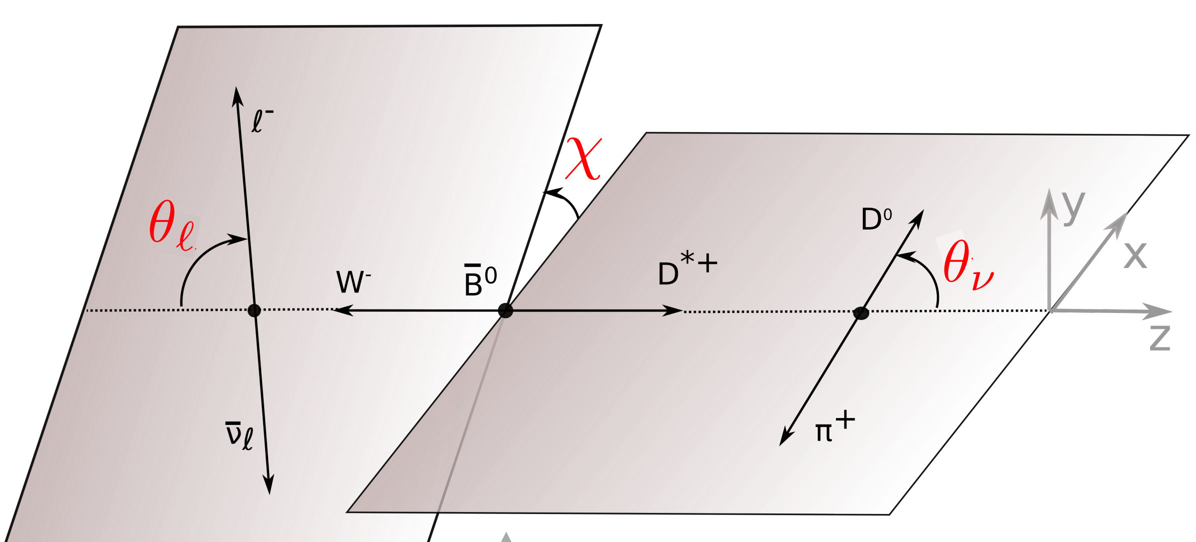

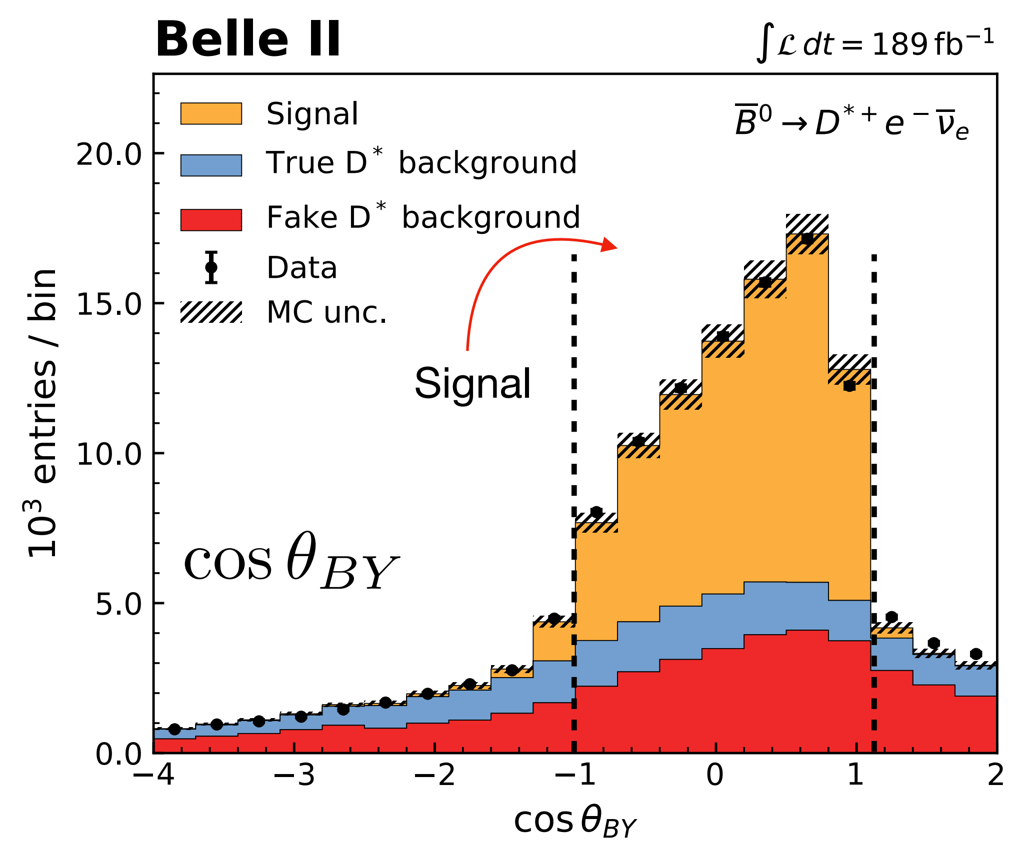

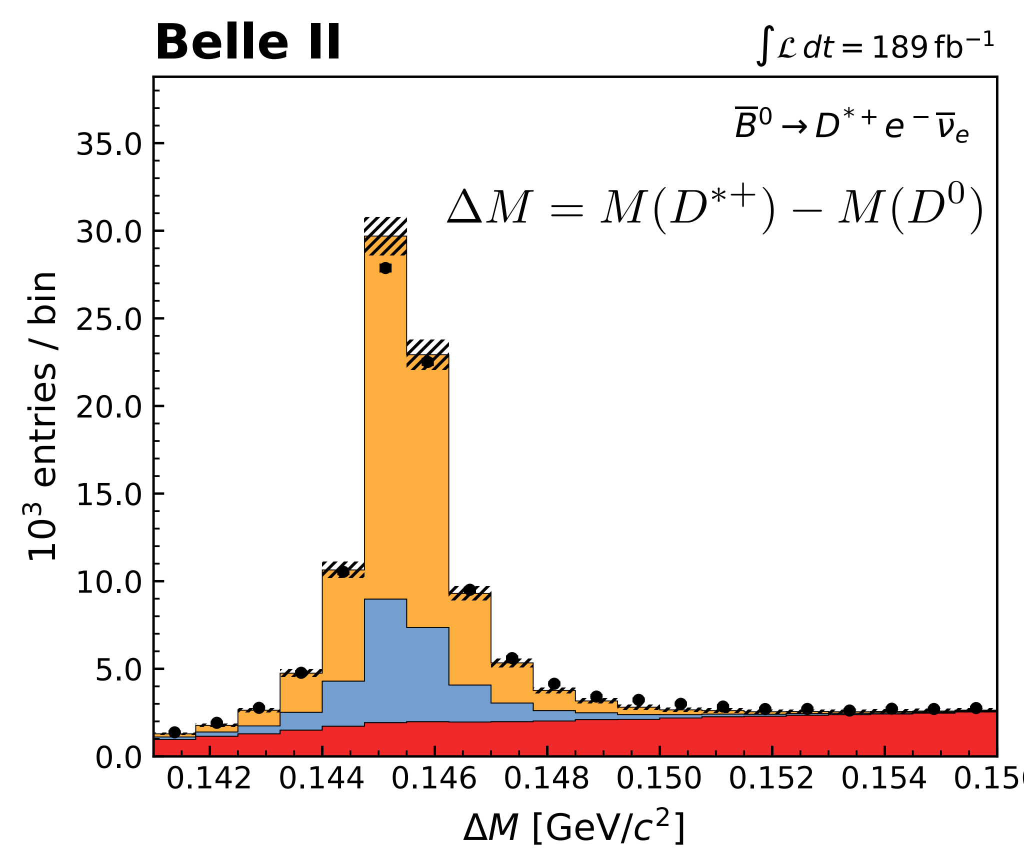

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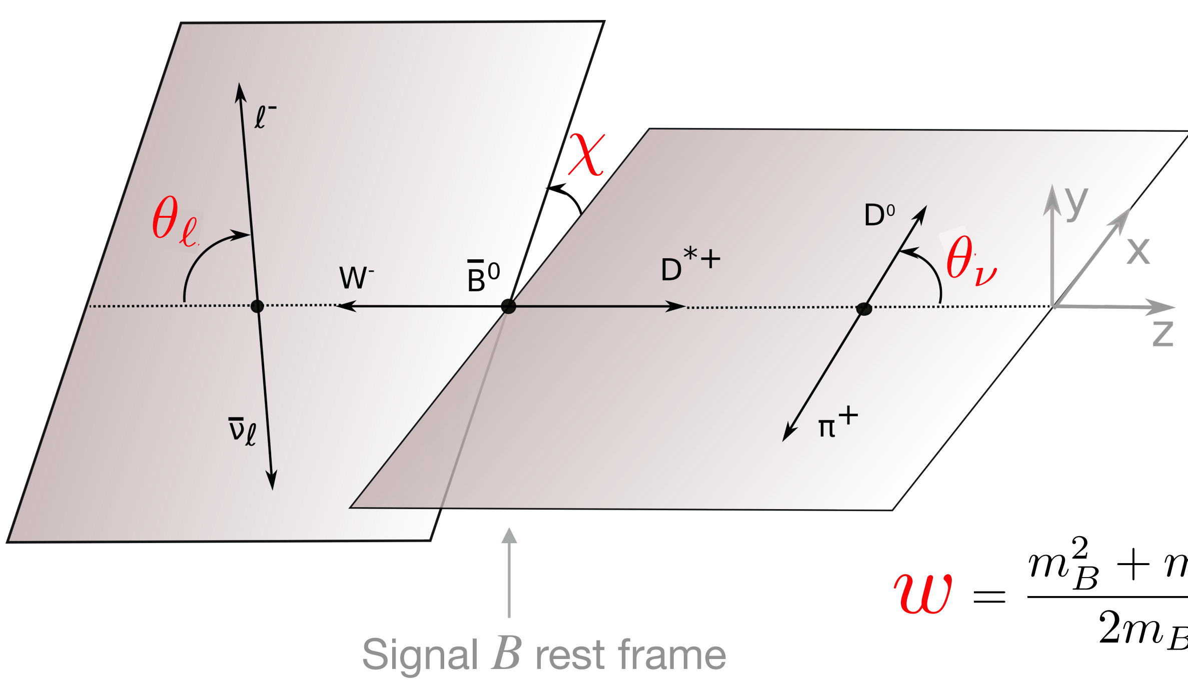
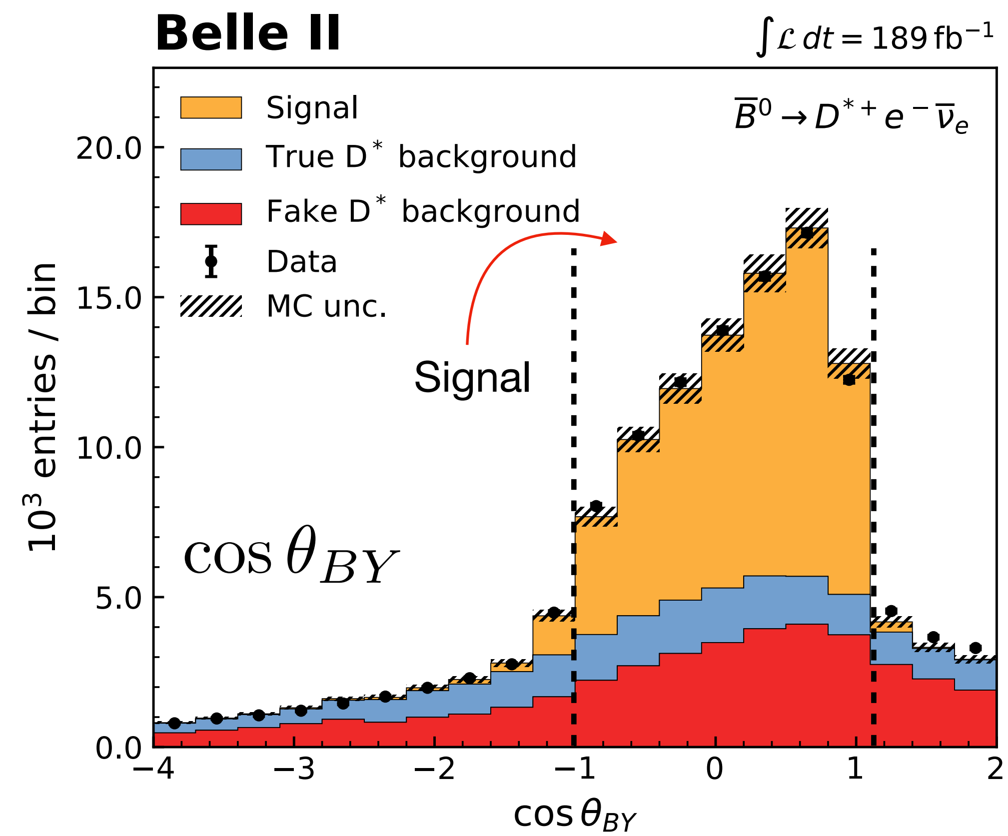
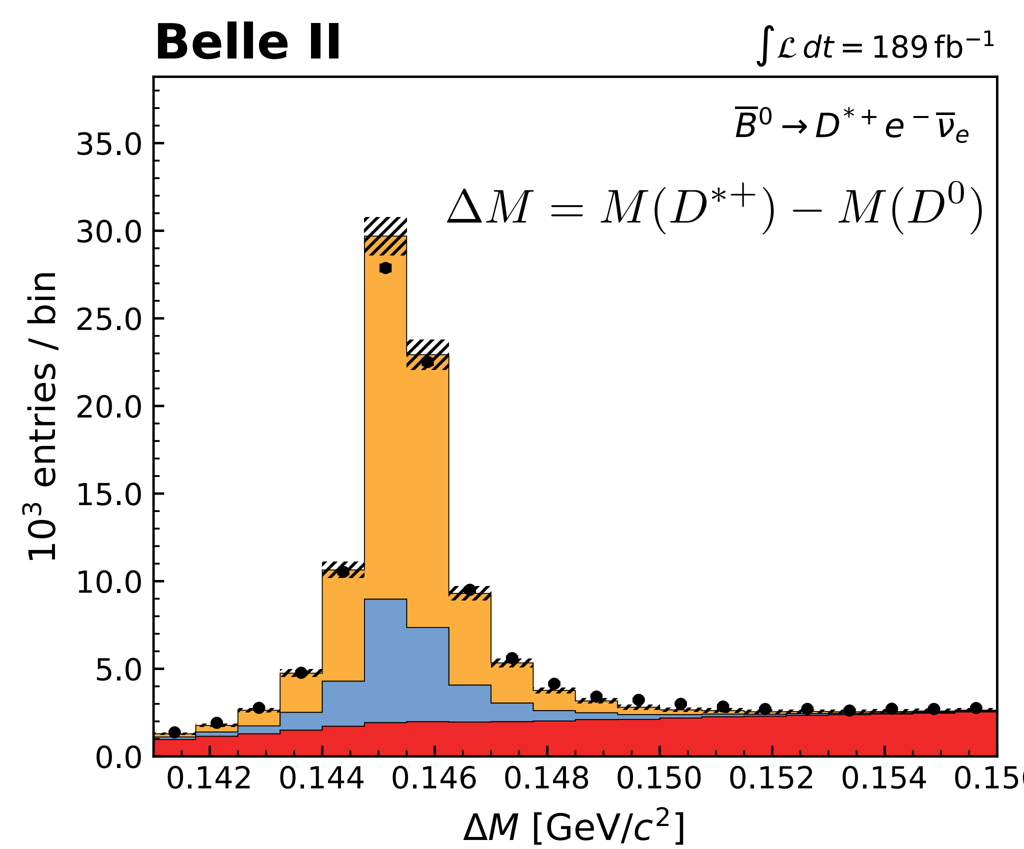


$$w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$$





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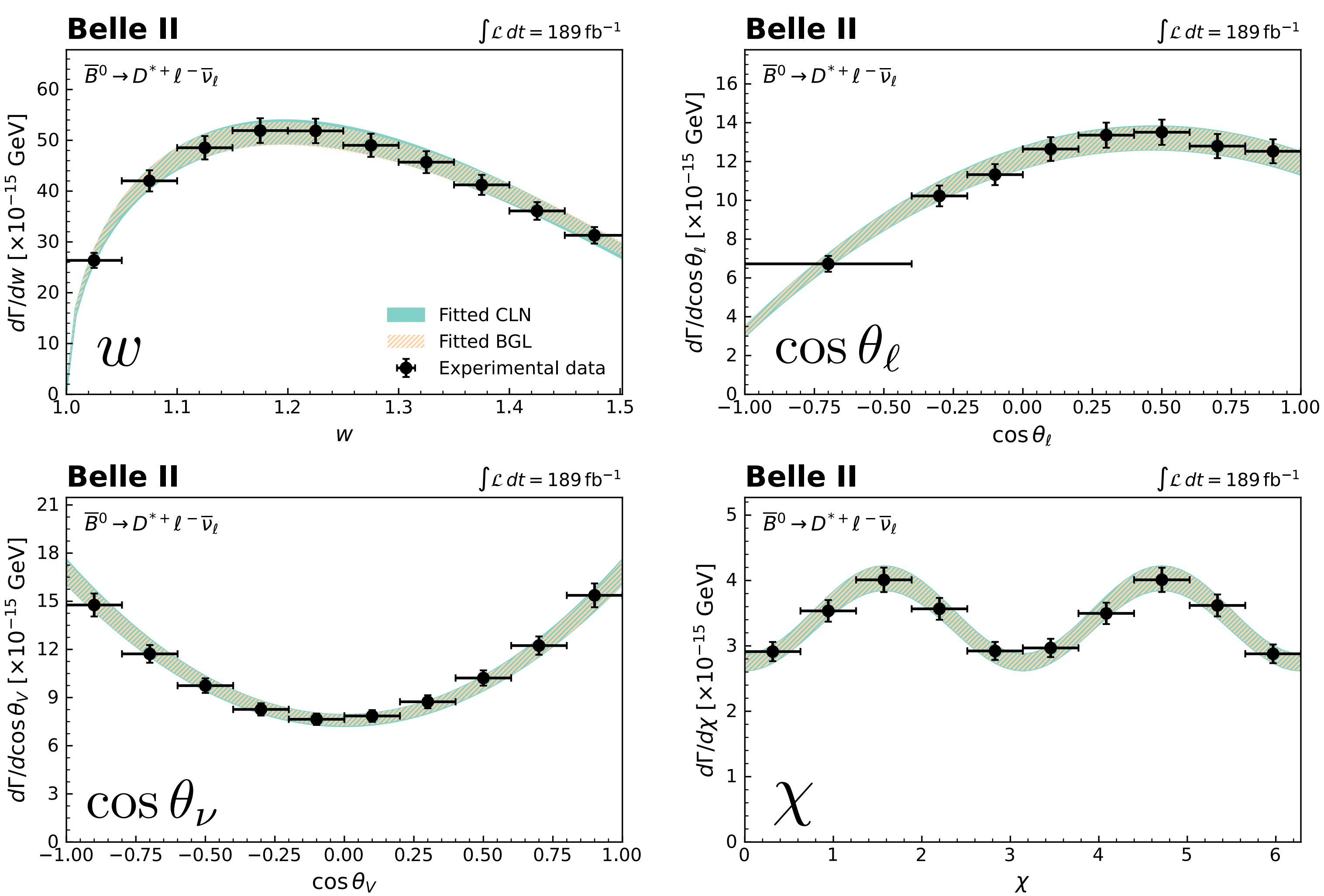
- Convert to partial branching fractions $\Delta\Gamma_i$ using **reconstruction efficiencies**.
- **Fit differential shapes** with different form factor expansions to obtain $|V_{cb}|$.
- Use FNAL/MILC lattice QCD data at zero recoil ($w = 1$) for **normalisation.** Phy. Rev. D 89 (2014) 114504



e mode: $\mathcal{B}(\bar{B}^0 \to D^{*+}e^-\bar{\nu}_e) = (4.92 \pm 0.03 \pm 0.22)\%$

μ mode: $\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu) = (4.93 \pm 0.03 \pm 0.23)\%$

Ratio $R(D^*_{e/\mu}) = 0.998 \pm 0.009 \pm 0.020$

$$\frac{d^4\Gamma}{dw\,d\cos\theta_\ell\,d\cos\theta_\nu\,d\chi} \propto |V_{cb}|^2 F^2(w, \cos\theta_\ell, \cos\theta_\nu, \chi)$$

$$|V_{cb}|_{\mathrm{BGL}} = (40.6 \pm 0.3 \pm 1.0 \pm 0.6) \times 10^{-3}$$

$$|V_{cb}|_{\mathrm{CLN}} = (40.1 \pm 0.3 \pm 1.0 \pm 0.6) \times 10^{-3}$$

Slow pion eff. plays leading role in syst.

Input from LQCD at zero-recoil F(1)

Fom factor parameterizations:

Caprini-Lellouch-Neubert (CLN) parameterization
Phy. Rev. D 56 (1997) 6895

Boyd-Grinstein-Lebed (BGL) parameterization
Nucl. Phy. B 530 (1998) 152

$|V_{cb}|$ from untagged $B^0 \to D^{*+}\ell^-\nu$

Belle II

PRD 108, 092013 (2023)

- Convert to partial branching fractions $\Delta\Gamma_i$ using **reconstruction efficiencies**.
- **Fit differential shapes** with different form factor expansions to obtain $|V_{cb}|$.
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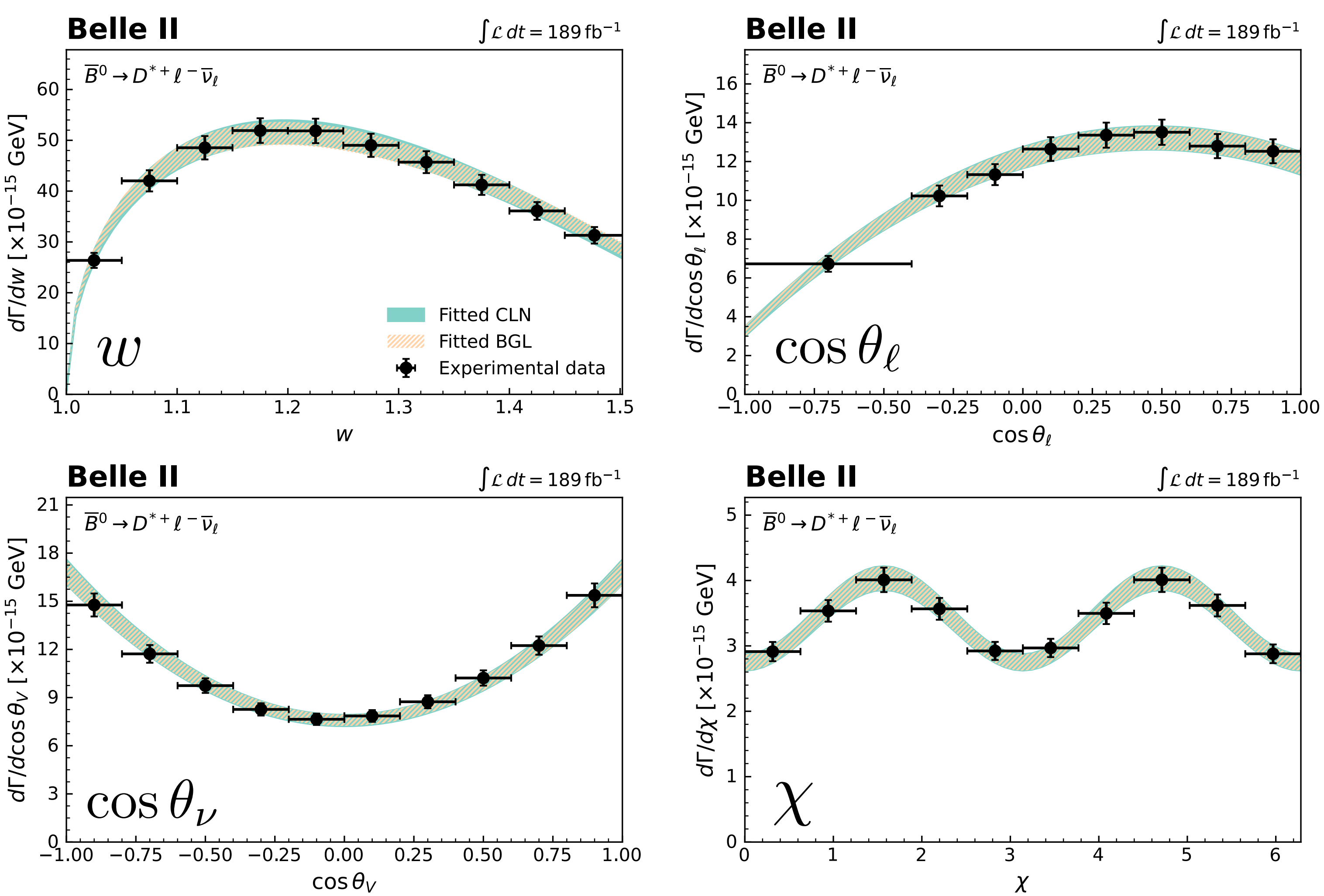

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WA values (HFLAV 21):

$|V_{cb}|_{\mathrm{Excl.}}$ = (39.10 ± 0.50) x 10^{-3}

$|V_{cb}|_{\mathrm{Incl.}}$ = (42.19 ± 0.78) x 10^{-3}

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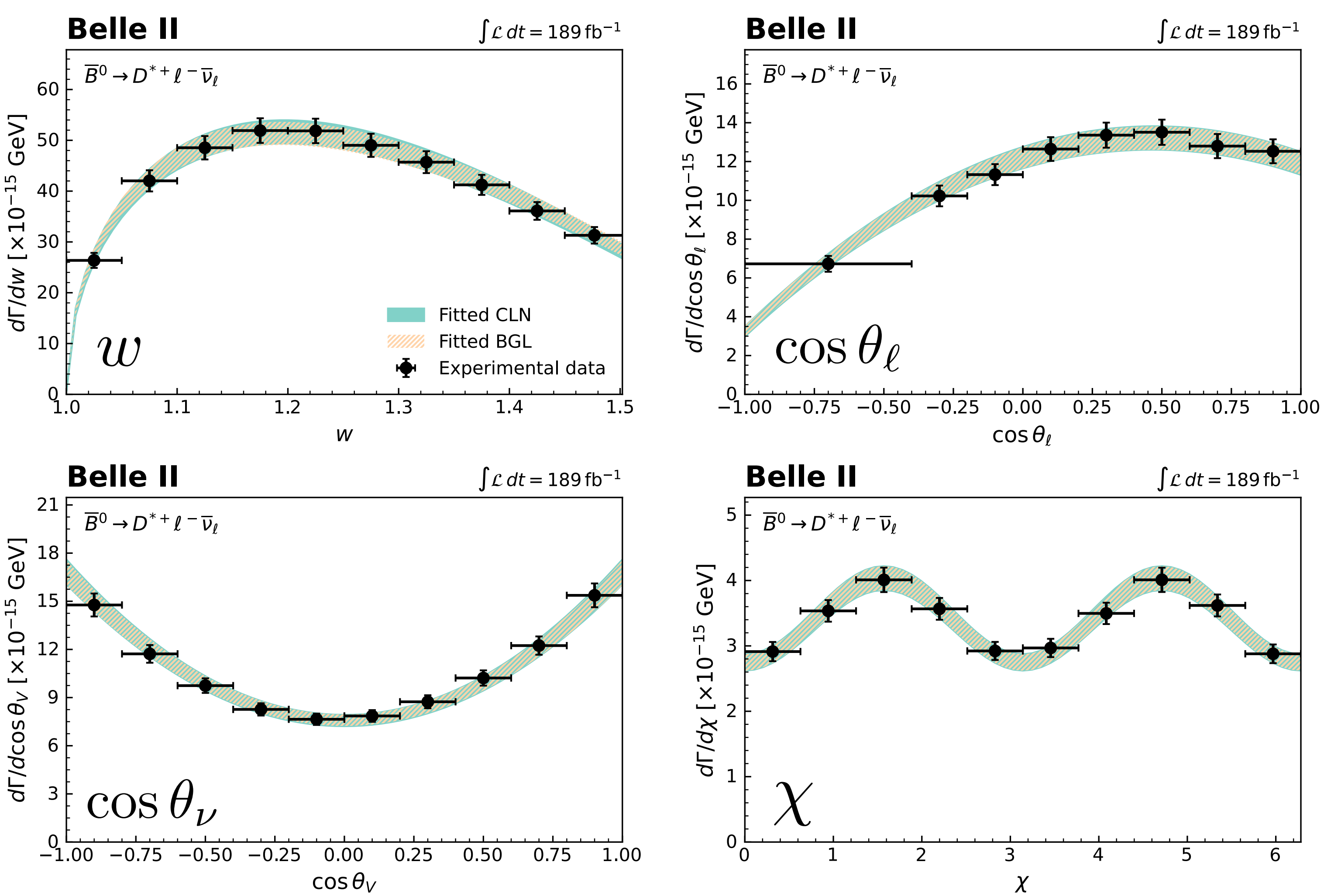

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Shifts exclusive average closer to inclusive average

Fom factor parameterizations:

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Nucl. Phy. B 530 (1998) 152

$B^0 \to D^{*-}\ell\nu$ angular asymmetries

Belle II

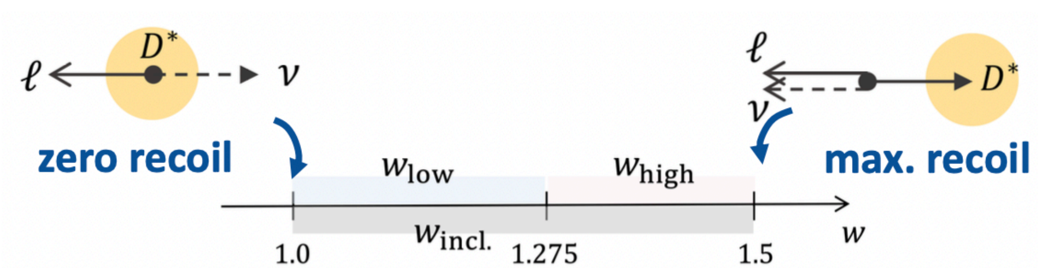
PRL 131, 181801 (2023)

- Measure angular asymmetries separately for $B \to D^* e\nu$ & $B \to D^*\mu\nu$ final states; their differences are sensitive to LFU violation.

$$A_x(w) = \left(\frac{d\Gamma}{dw}\right)^{-1}\left[\int_0^1 - \int_{-1}^0\right] dx \frac{d^2\Gamma}{dwdx}$$

+	-	
		$\mathcal{A}_{FB}(w)$ $dx \to d(\cos\theta_\ell)$
		$\mathcal{S}_3(w)$ $dx \to d(\cos 2\chi)$
		...

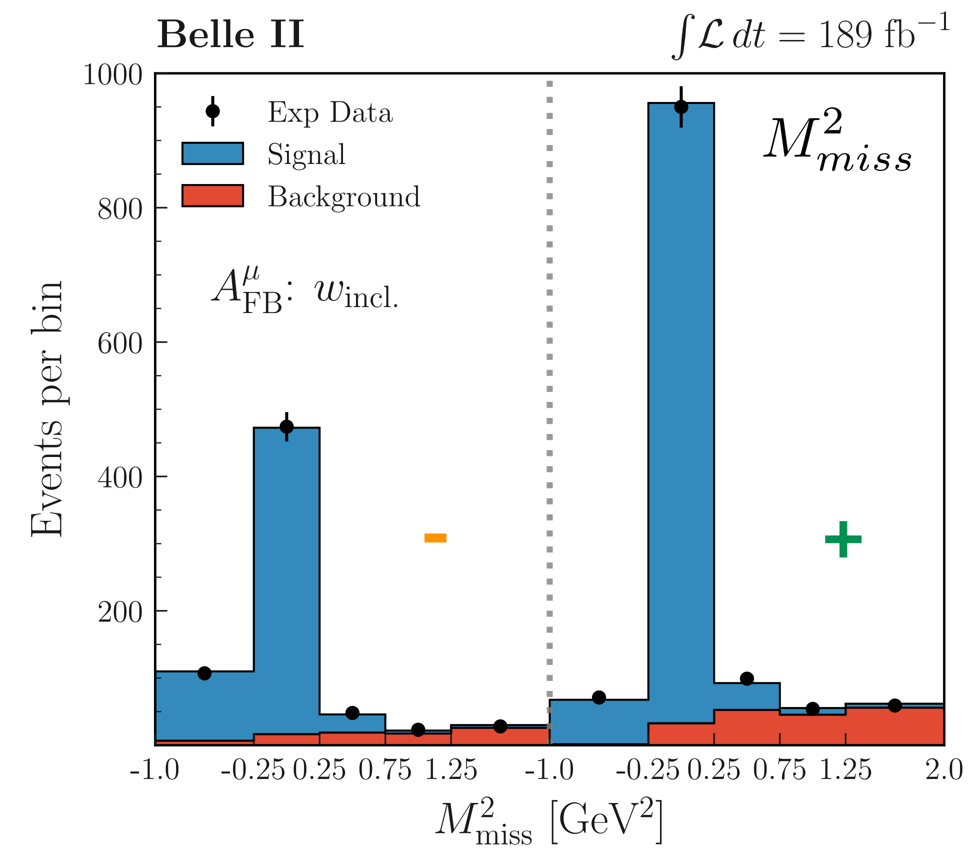
- Simultaneous determination of all asymmetries in different w ranges:

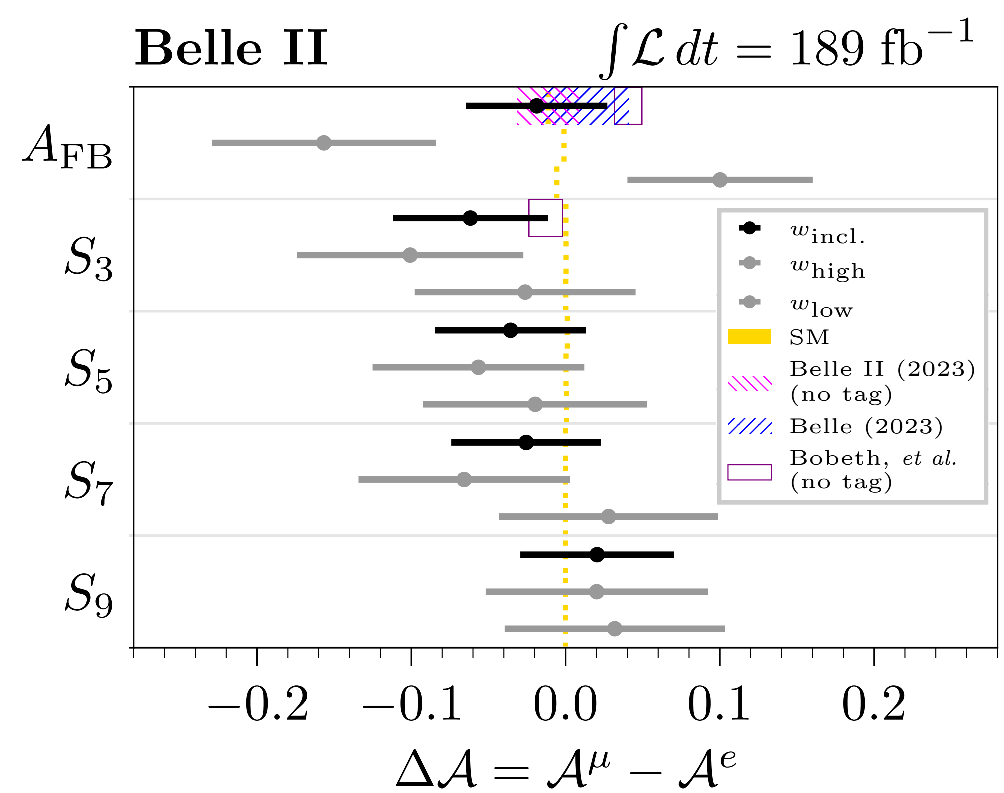


- Signal yields extracted from fits to M^2_{miss}

All asymmetry measurements are statistics limited!

Agrees well with SM, no evidence for LFU violation



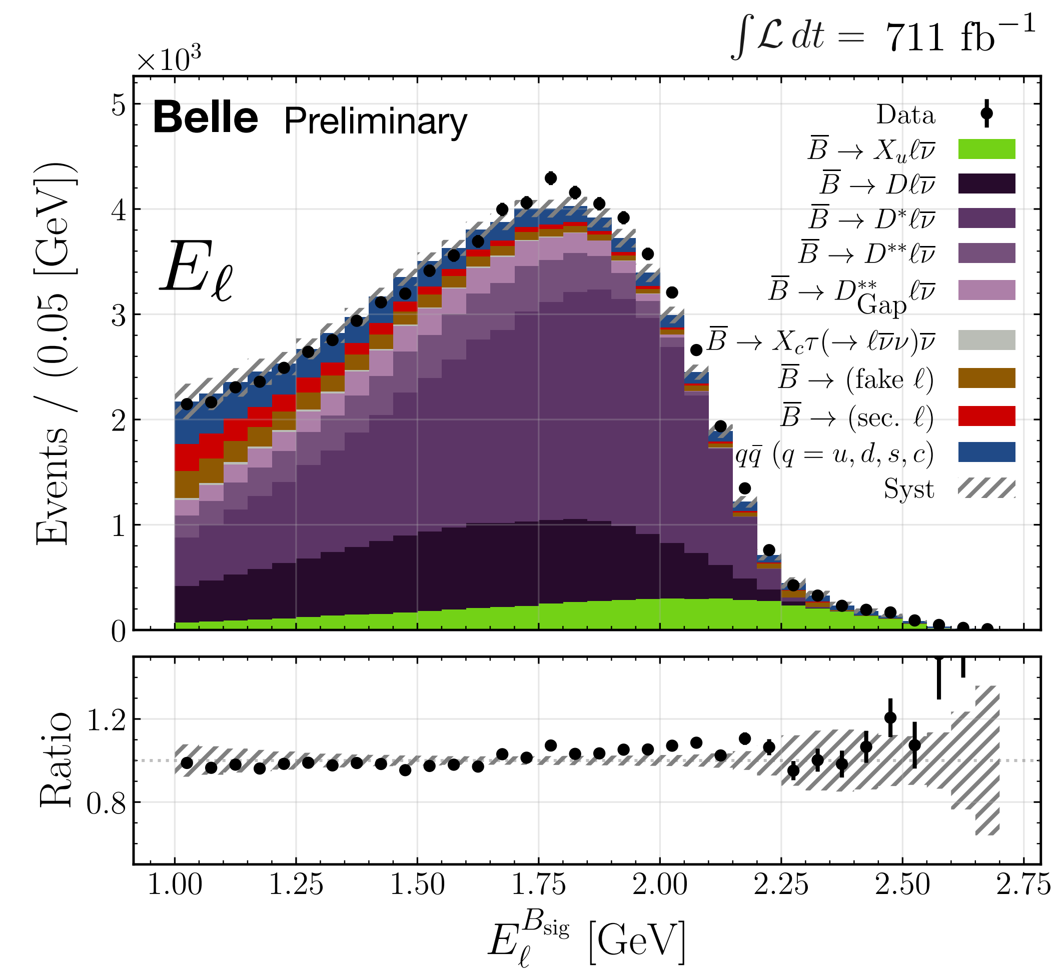


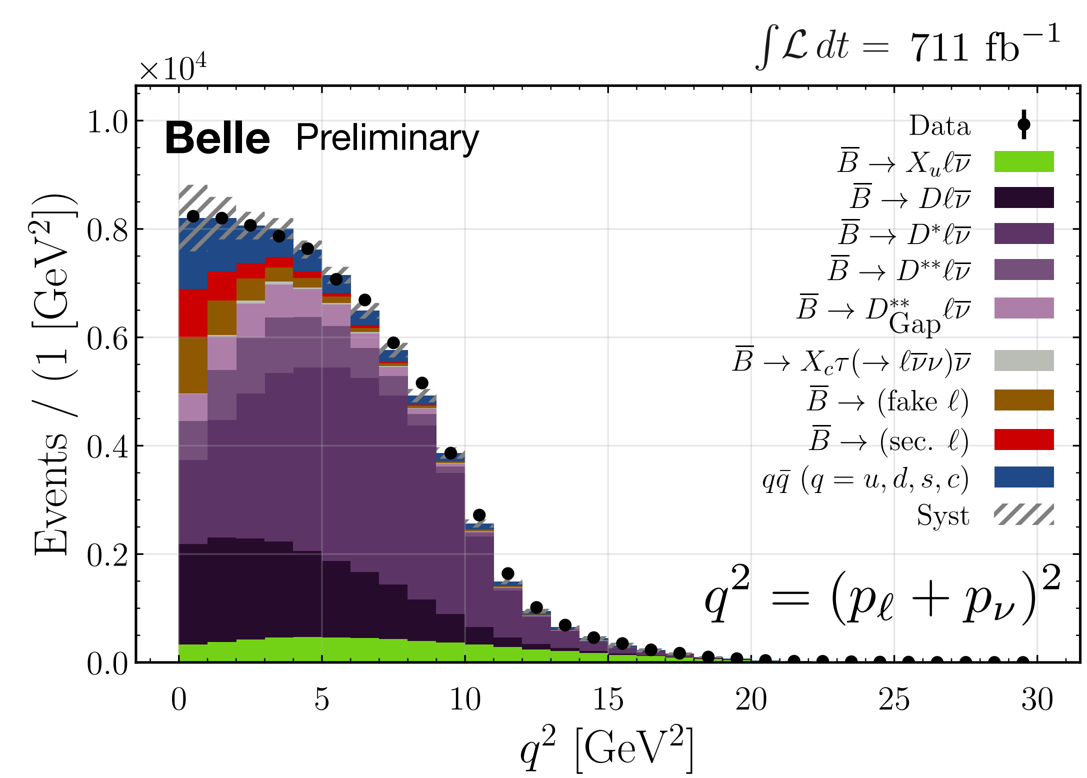
Ratio of $|V_{ub}|$ and $|V_{cb}|$ from inclusive decays

BELLE

arXiv:2311.00458

- Measuring $B \to X_u \ell \nu$ is challenging due to large background component from $B \to X_c \ell \nu$.
- Clear separation only possible in corners of phase space.





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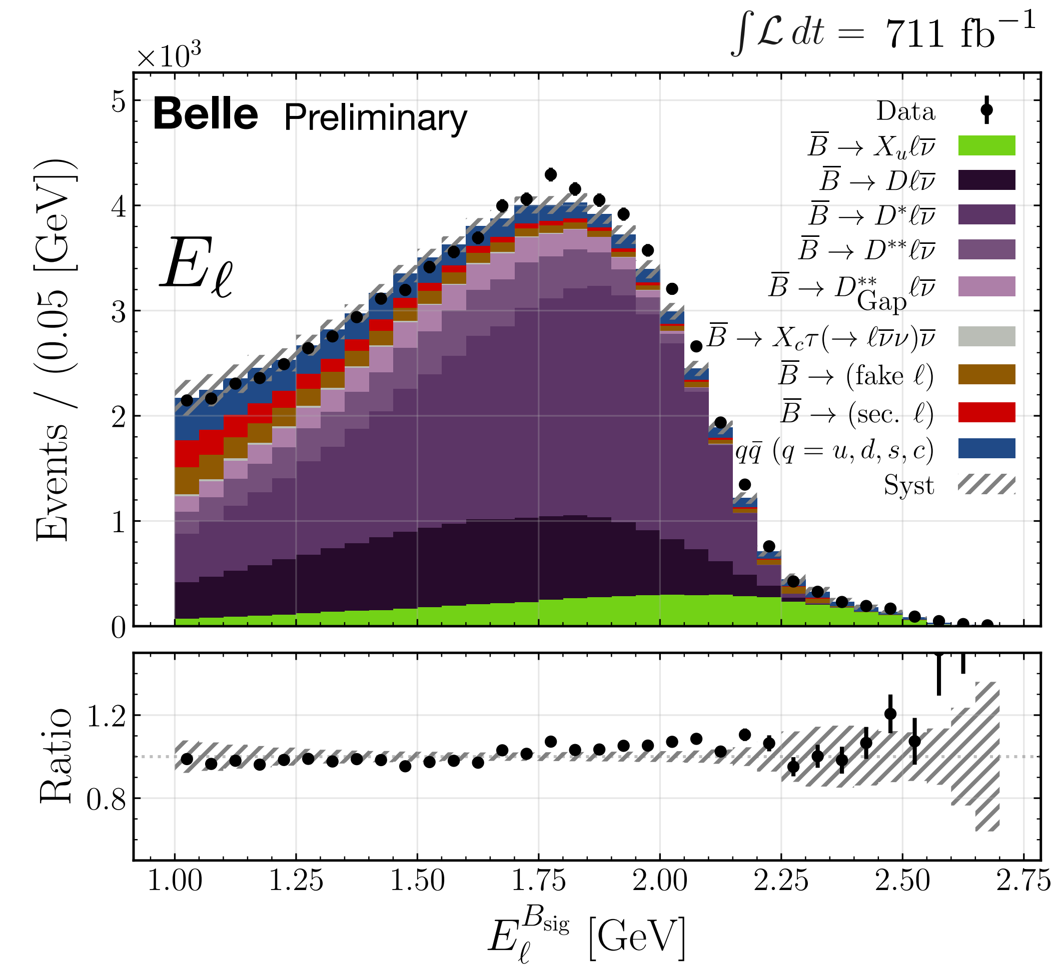
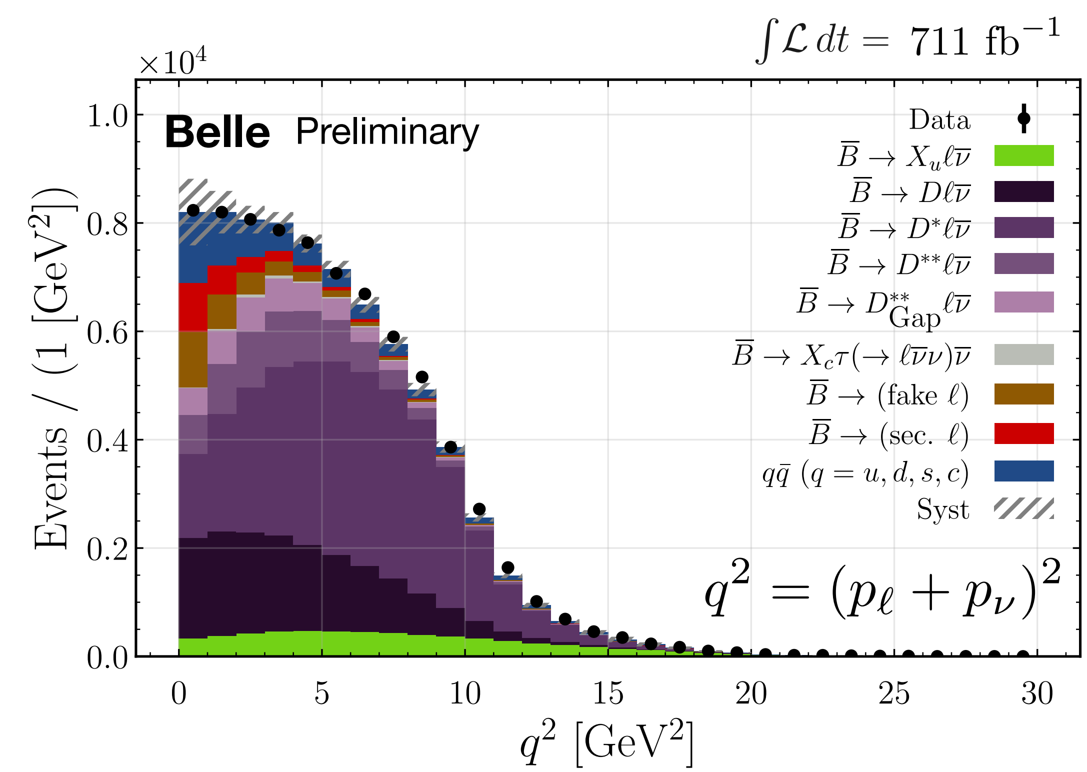
  - Up to 50% higher efficiency than previous Belle Full Reconstruction.
- Extract $B \to X_u \ell \nu$ yield from 2D fit to lepton energy E_ℓ & $q^2 = (p_B - p_X)^2 = (p_\ell + p_\nu)^2$





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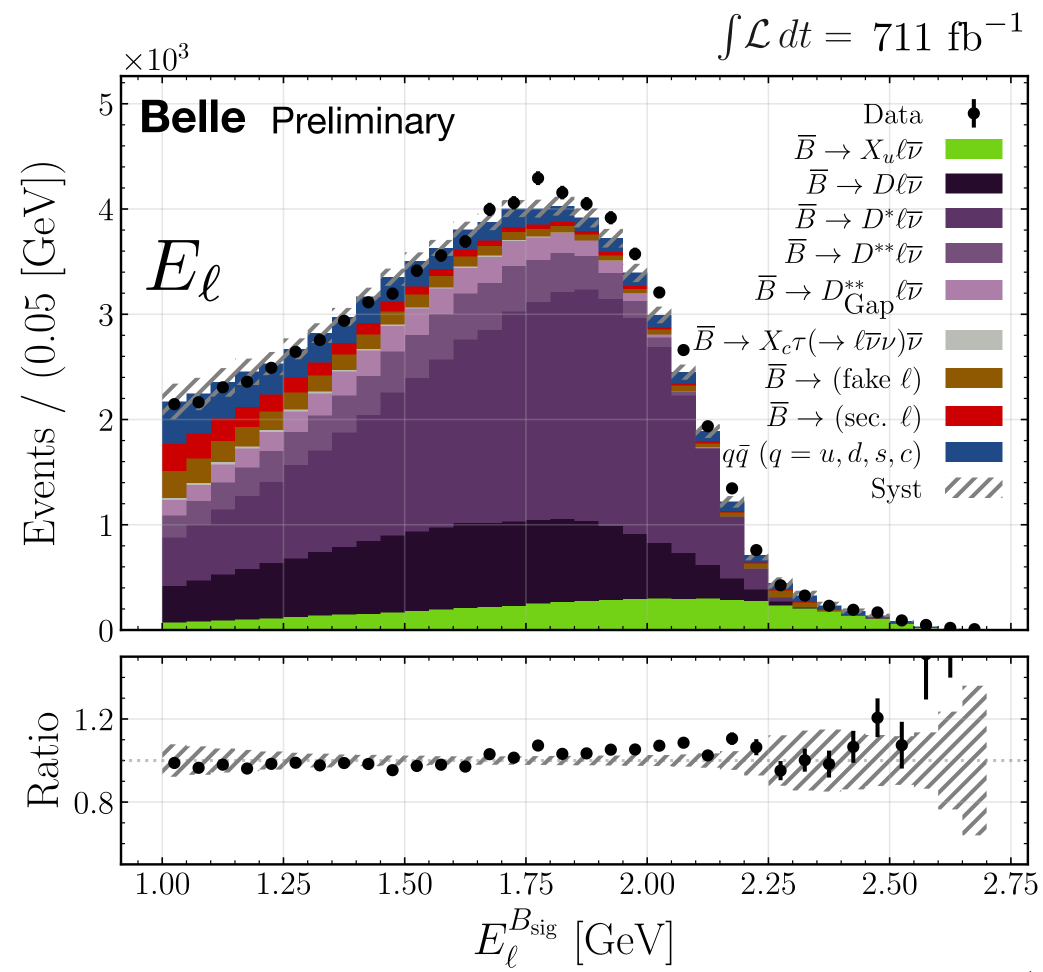

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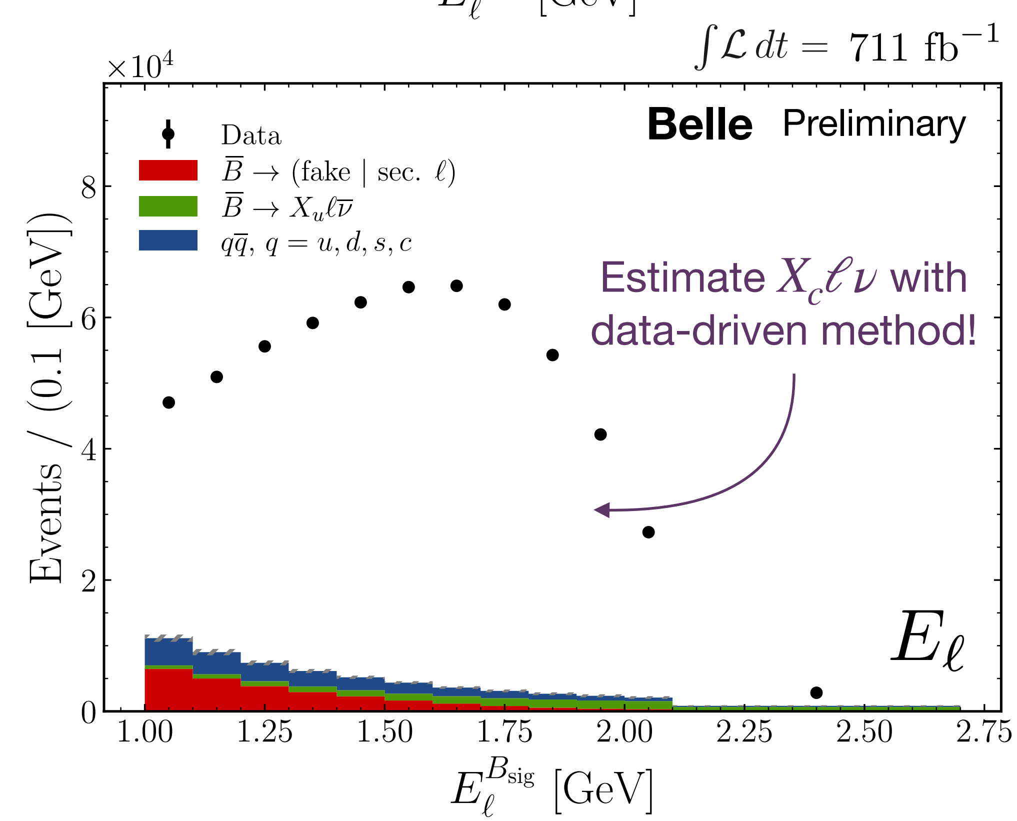

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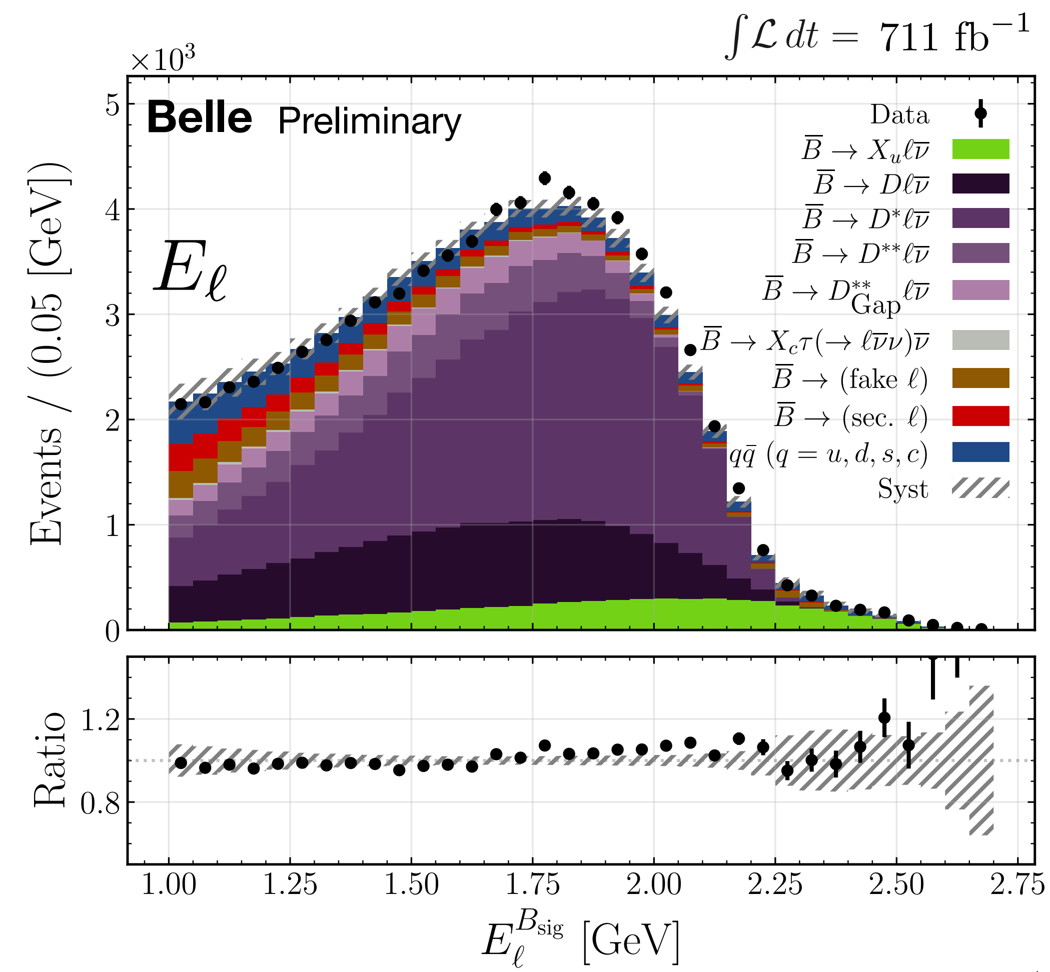
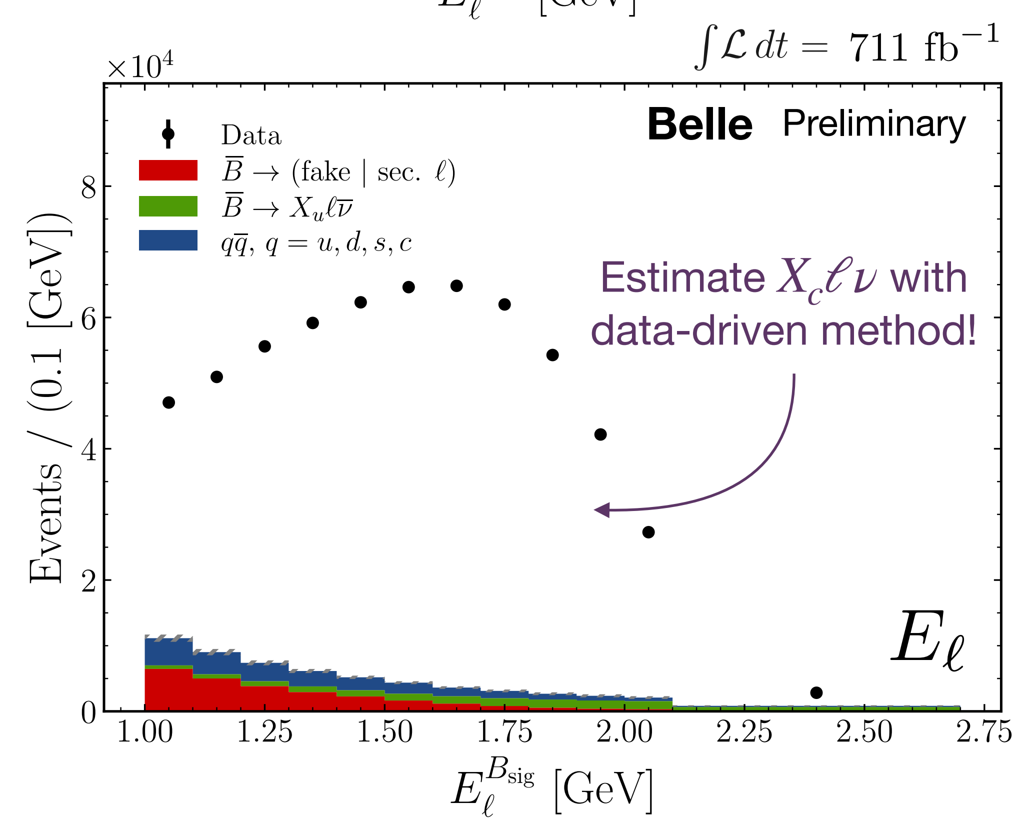
Measure partial BF for the region $E_\ell^B > 1$ GeV:

$$\frac{\Delta\mathcal{B}(\bar{B} \to X_u \ell \bar{\nu})}{\Delta\mathcal{B}(\bar{B} \to X_c \ell \bar{\nu})} = 1.96(1 \pm 8.4\%_{\rm stat} \pm 7.9\%_{\rm syst}) \times 10^{-2}$$

Leading systematics:
Modelling of $B \to X_u \ell \nu$ component &
composition of fake leptons and secondary decays



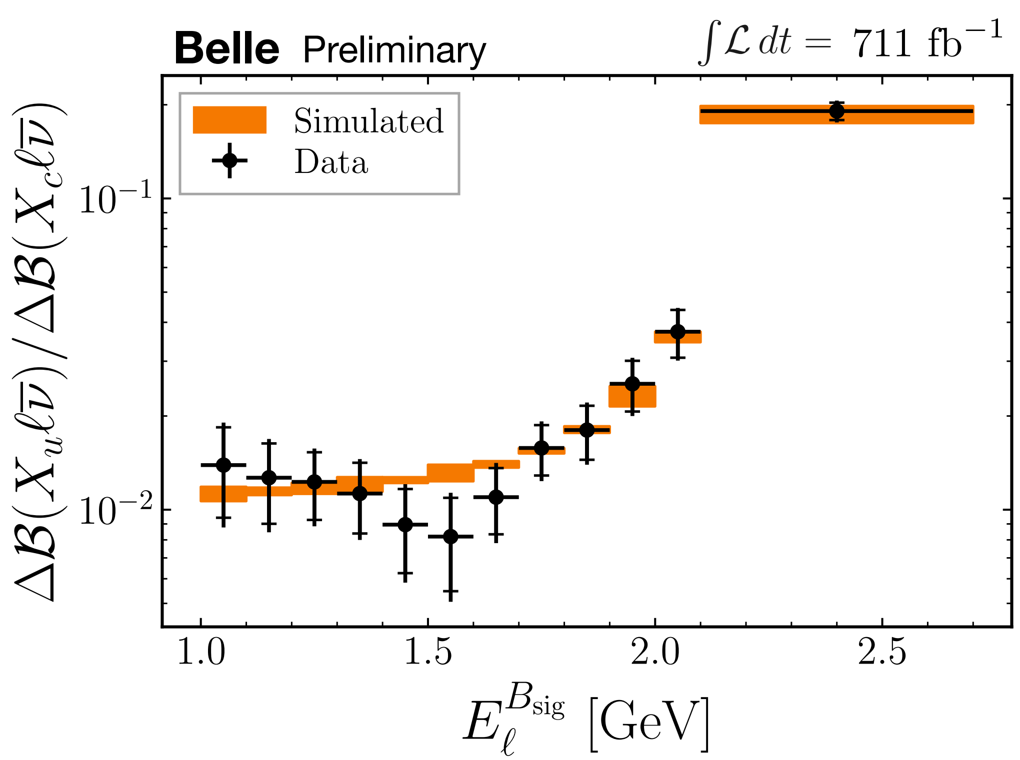


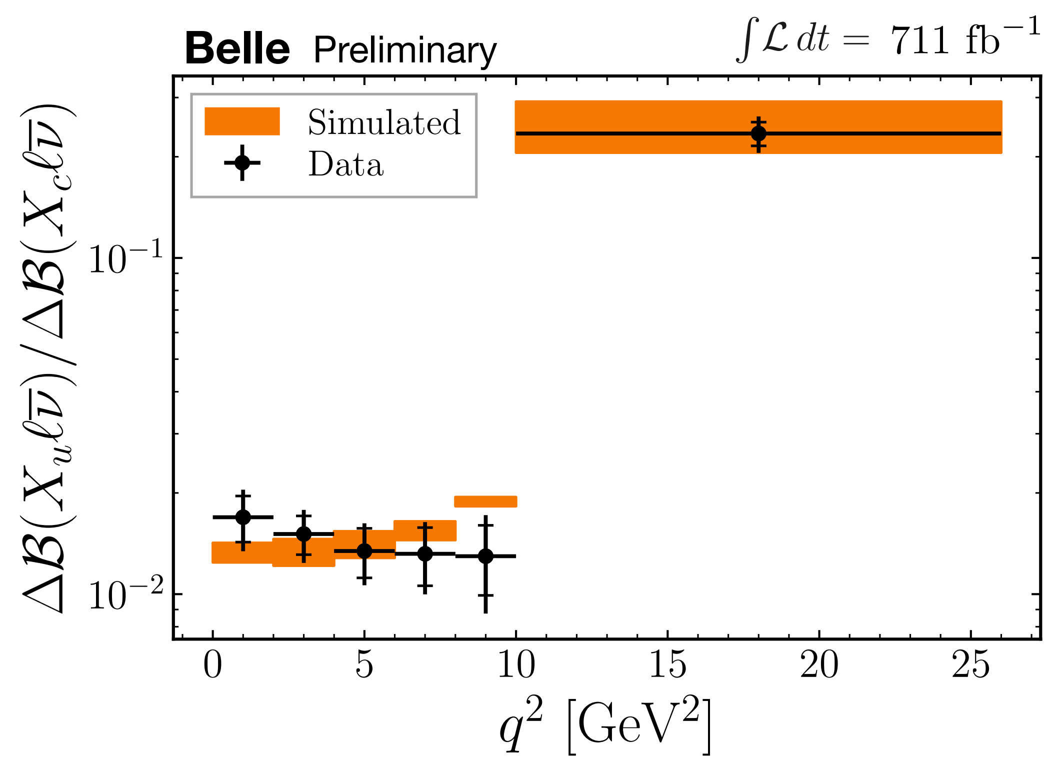
Ratio of $|V_{ub}|$ and $|V_{cb}|$ from inclusive decays

BELLE

arXiv:2311.00458

- Unfold $B \to X_u \ell \nu$ & $B \to X_c \ell \nu$ yields via singular value decomposition (SVD). arXiv:hep-ph/9509307
- Take ratio and correct for efficiency to form differential ratios.





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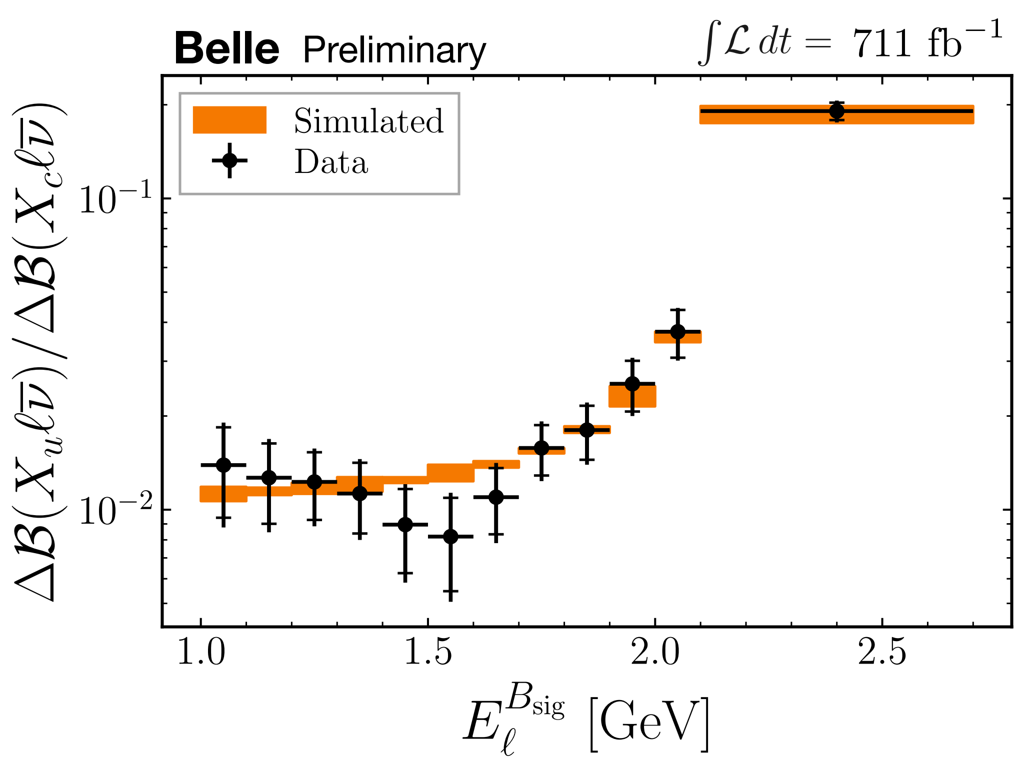

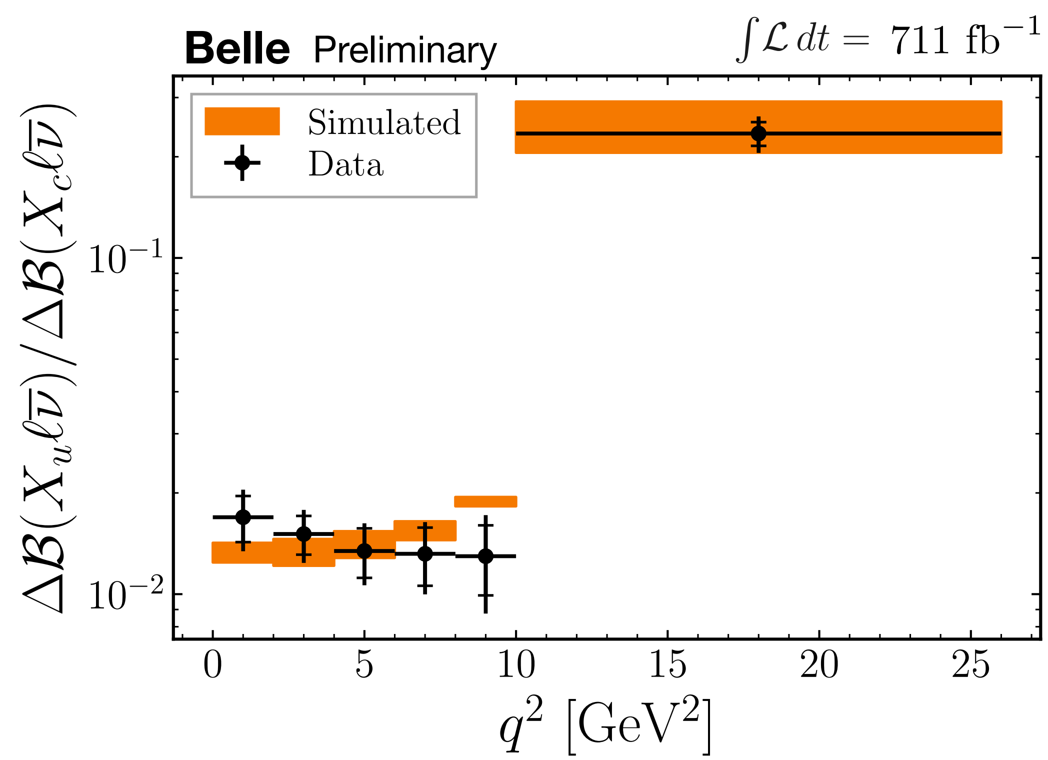

Final step: Extract $|V_{ub}|/|V_{cb}|$ with **partial BF**

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

Theo. decay rates:

J. High Energ. Phys. 10 (2007) 058 $\Delta\Gamma^{\mathrm{GGOU}}(B \to X_u \ell \nu) = 58.5^{+2.7}_{-2.3}\ \mathrm{ps}^{-1}$

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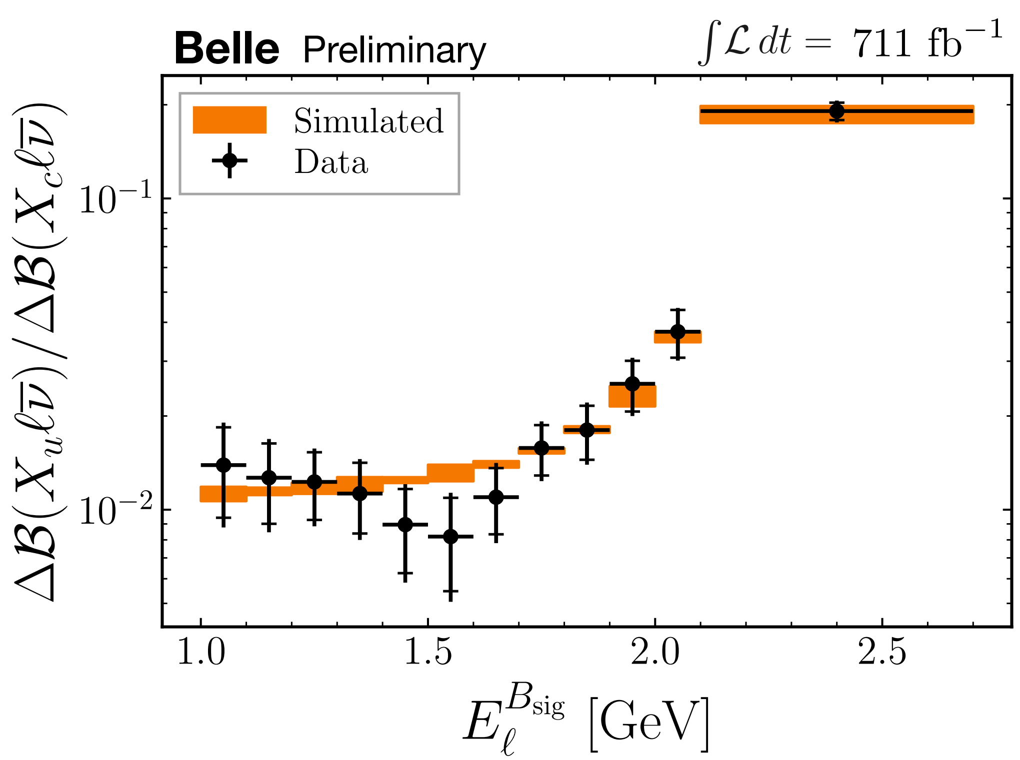

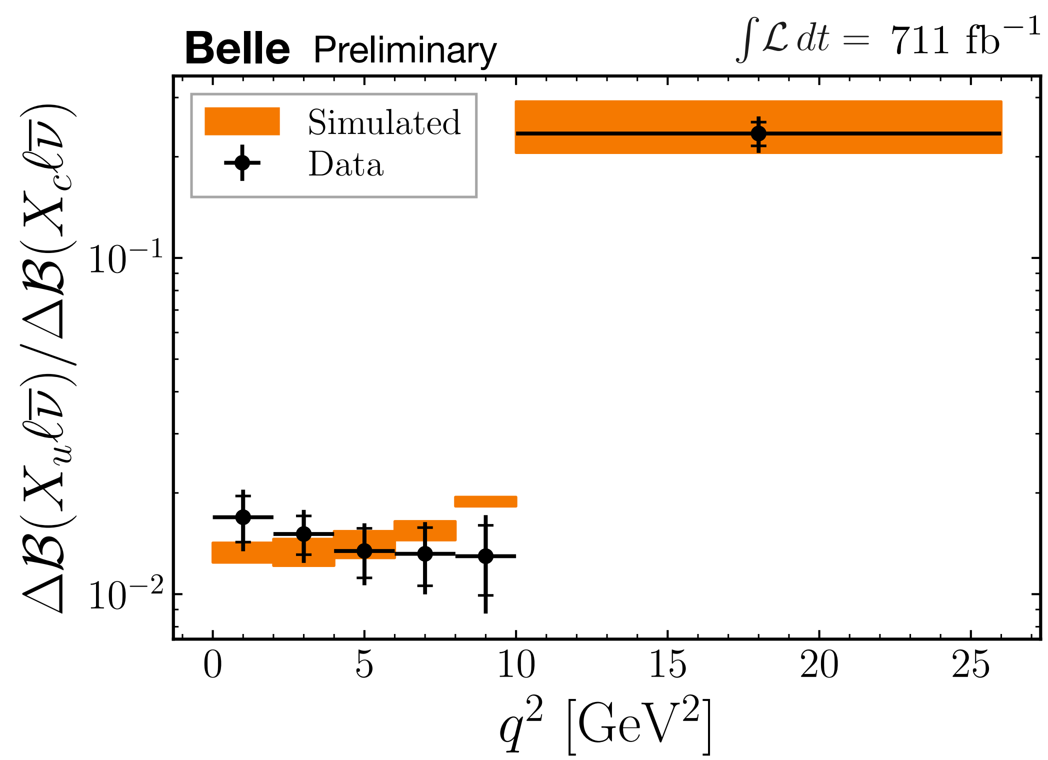

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$$\frac{|V_{ub}|}{|V_{cb}|}^{\mathrm{BLNP}} = 0.0972(1 \pm 4.2\%_{\mathrm{stat}} \pm 3.9\%_{\mathrm{syst}} \pm 5.2\%_{\Delta\Gamma(\bar{B}\to X_u\ell\bar{\nu})} \pm 2.0\%_{\Delta\Gamma(\bar{B}\to X_c\ell\bar{\nu})})$$

$$\frac{|V_{ub}|}{|V_{cb}|}^{\mathrm{GGOU}} = 0.0996(1 \pm 4.2\%_{\mathrm{stat}} \pm 3.9\%_{\mathrm{syst}} \pm 2.3\%_{\Delta\Gamma(\bar{B}\to X_u\ell\bar{\nu})} \pm 2.0\%_{\Delta\Gamma(\bar{B}\to X_c\ell\bar{\nu})})$$

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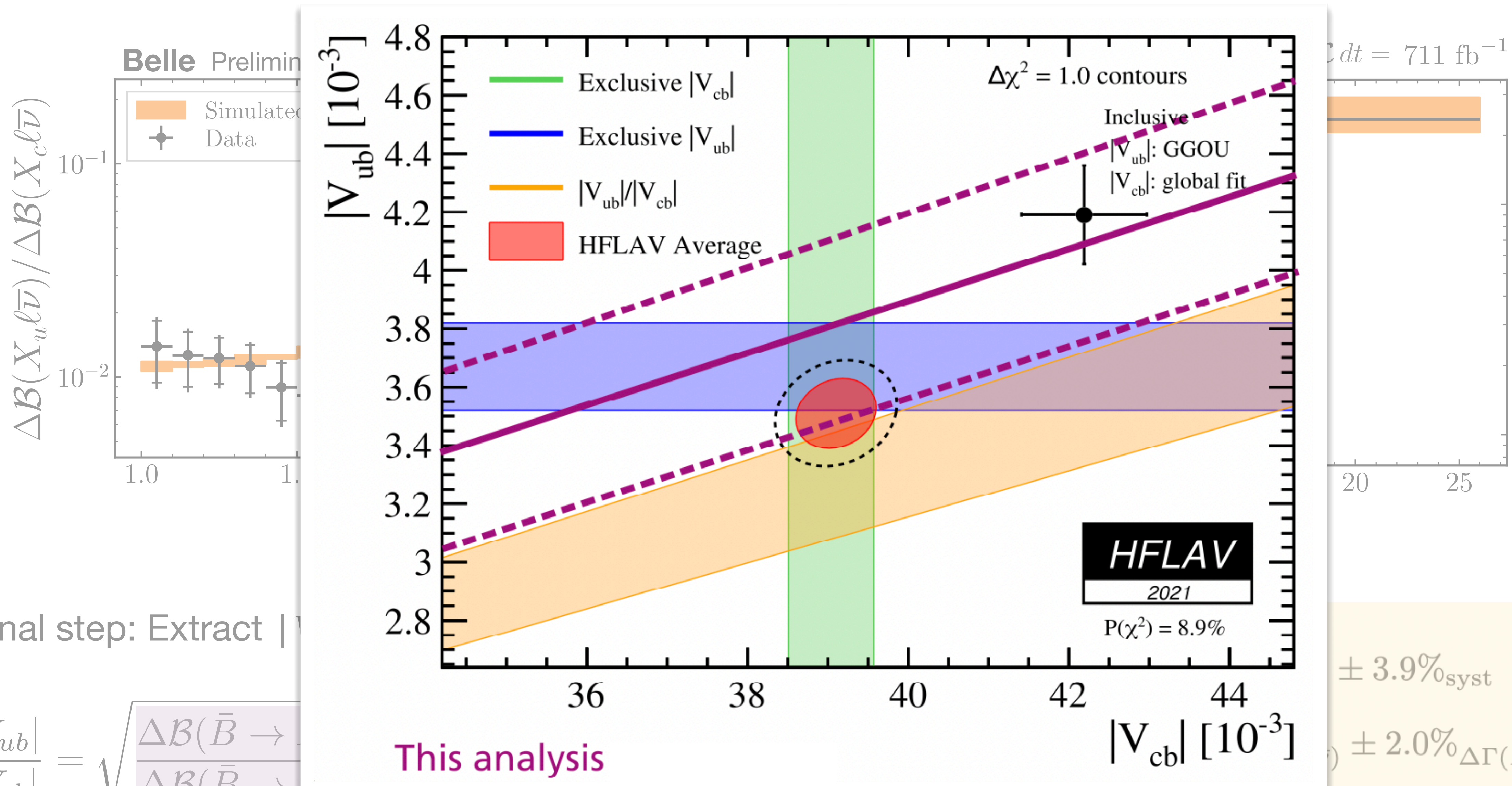

Final step: Extract |

$$\frac{|V_{ub}|}{|V_{cb}|} = \sqrt{\frac{\Delta\mathcal{B}(\bar{B} \to}{\Delta\mathcal{B}(\bar{B} \to}}$$

$\pm 3.9\%_{\text{syst}}$

$\pm 2.0\%_{\Delta\Gamma(\bar{B}\to X_c\ell\bar{\nu})})$

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Conclusion & Outlook

- Many new, **exciting measurements** from both Belle and Belle II!
- Only presented a **subset of results**.
- With half of the collected data set ($189\ \text{fb}^{-1}$), Belle II already produces **world-leading and unique** results!
  - New LFU tests from Belle II consistent with SM.
  - Most recent $|V_{cb}|$ results from $B \to D^*\ell\nu$ shift exclusive closer to inclusive average.
- The well-understood Belle data set is still used to squeeze out **innovative measurements.**
  - Ratio of inclusive $|V_{ub}|$ & $|V_{cb}|$ agrees with exclusive average.

Thank you for your attention!

BELLE	Belle II
Simultaneous determination of Incl. & Excl. $|V_{ub}|$ Phys. Rev. Lett. 131 (2023) 21	Test of LFU with inclusive $R(X_{e/\mu})$ Phys. Rev. Lett. 131 (2023) 5
Differential distributions of $B \to D^*\ell\nu$ Phys. Rev. D 108 (2023) 1	Lepton mass squared moments of $B \to X_c\ell\nu$ Phys. Rev. D 107 (2023) 7
Angular coefficients of $B \to D^*\ell\nu$ arXiv:2310.20286	$|V_{ub}|$ from untagged $B \to \pi\ell\nu$ arXiv:2210.04224
Branching fractions of $B \to D^{(*)}\pi(\pi)\ell\nu$ Phys. Rev. D 107 (2023) 9	$|V_{ub}|$ from tagged $B \to \pi\ell\nu$ arXiv:2206.08102
q^2 moments of $B \to X_c\ell\nu$ Phys. Rev. D 104 (2021) 11	$|V_{cb}|$ from $B \to D\ell\nu$ arXiv:2210.13143
...	...

More exciting **results** are on the way!

Additional slides

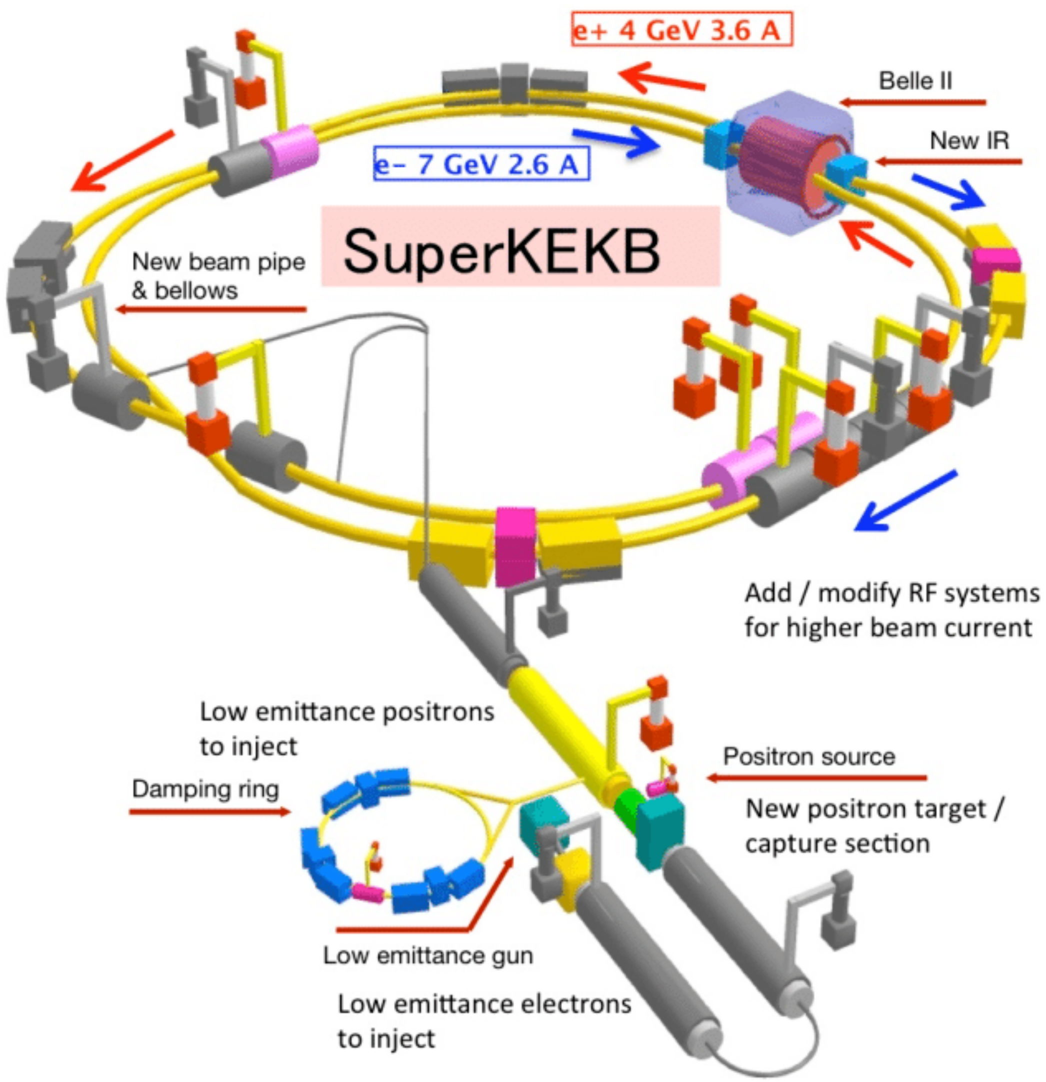
SuperKEKB in a nutshell

$\mathcal{L}_{\text{Belle}} = 2.11 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$

x30!

Goal: Achieve instantaneous luminosity of $\mathcal{L}_{\text{Belle II}} = 6 \times 10^{35}\,\text{cm}^{-2}\,\text{s}^{-1}$

with record $4.7 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$ already achieved!

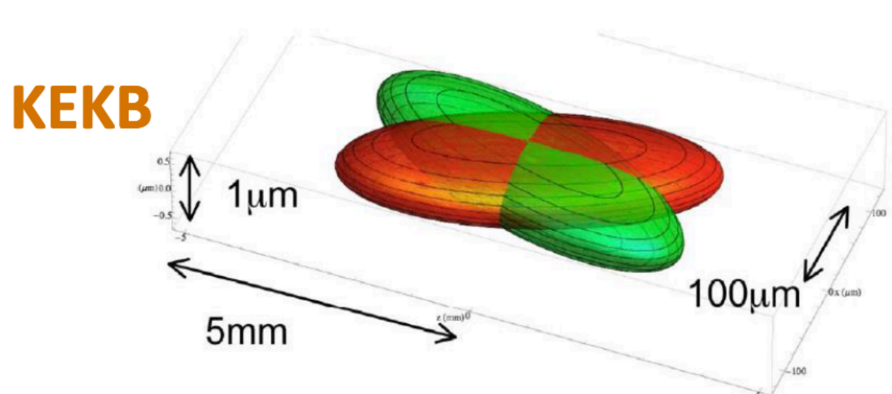


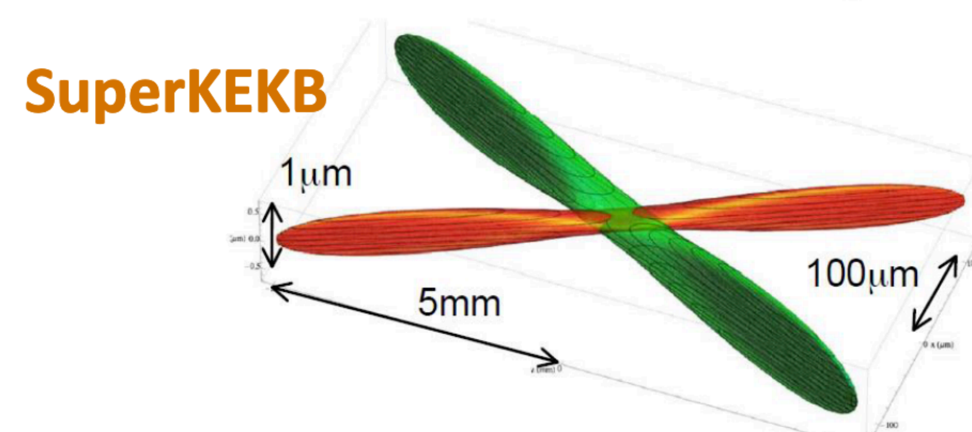
How to increase luminosity:

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

- Lorentz factor
- Beam current **x 1.5**
- Beam-beam parameter
- Beam size
- Vertical β function **x 1/20**
- Geometric factors

Nano-beam scheme: Squeeze vertical beam spot size down to ≈ 50 nm using superconducting focusing magnets.





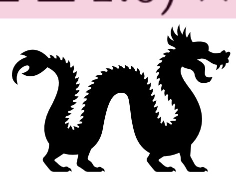
$B \to X_c \ell \nu$ modelling & composition

A **leading systematic** in incl. semileptonic analyses:

$$\mathcal{B}(\mathrm{B}^+ \to X_c^0 \ell^+ \nu_\ell) \approx 10.79\,\%$$

$\mathrm{D}^0 \ell^+ \nu_\ell$	$\mathrm{D}^{*0} \ell^+ \nu_\ell$	$\mathrm{D}^{**0} \ell^+ \nu_\ell$ + Other	Gap
$2.31\,\%$	$5.05\,\%$	$2.38\,\%$	$\sim 1.05\,\%$

Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D\,\ell^+\,\nu_\ell$	$(2.4 \pm 0.1) \times 10^{-2}$	$(2.2 \pm 0.1) \times 10^{-2}$
$B \to D^*\,\ell^+\,\nu_\ell$	$(5.5 \pm 0.1) \times 10^{-2}$	$(5.1 \pm 0.1) \times 10^{-2}$
$B \to D_1\,\ell^+\,\nu_\ell$	$(6.6 \pm 0.1) \times 10^{-3}$	$(6.2 \pm 0.1) \times 10^{-3}$
$B \to D_2^*\,\ell^+\,\nu_\ell$	$(2.9 \pm 0.3) \times 10^{-3}$	$(2.7 \pm 0.3) \times 10^{-3}$
$B \to D_0^*\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.8) \times 10^{-3}$	$(3.9 \pm 0.7) \times 10^{-3}$
$B \to D_1'\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.9) \times 10^{-3}$	$(3.9 \pm 0.8) \times 10^{-3}$
$B \to D\pi\pi\,\ell^+\,\nu_\ell$	$(0.6 \pm 0.9) \times 10^{-3}$	$(0.6 \pm 0.9) \times 10^{-3}$
$B \to D^*\pi\pi\,\ell^+\,\nu_\ell$	$(2.2 \pm 1.0) \times 10^{-3}$	$(2.0 \pm 1.0) \times 10^{-3}$
$B \to X_c \ell \nu_\ell$	$(10.8 \pm 0.4) \times 10^{-2}$	$(10.1 \pm 0.4) \times 10^{-2}$



→ Fairly well known.

→ Broad states based on 3 measurements. (BaBar, Belle, DELPHI)

→ Some hints from BaBar & recent Belle result.

Image credit: F. Metzner

A tale of two 'gap' models

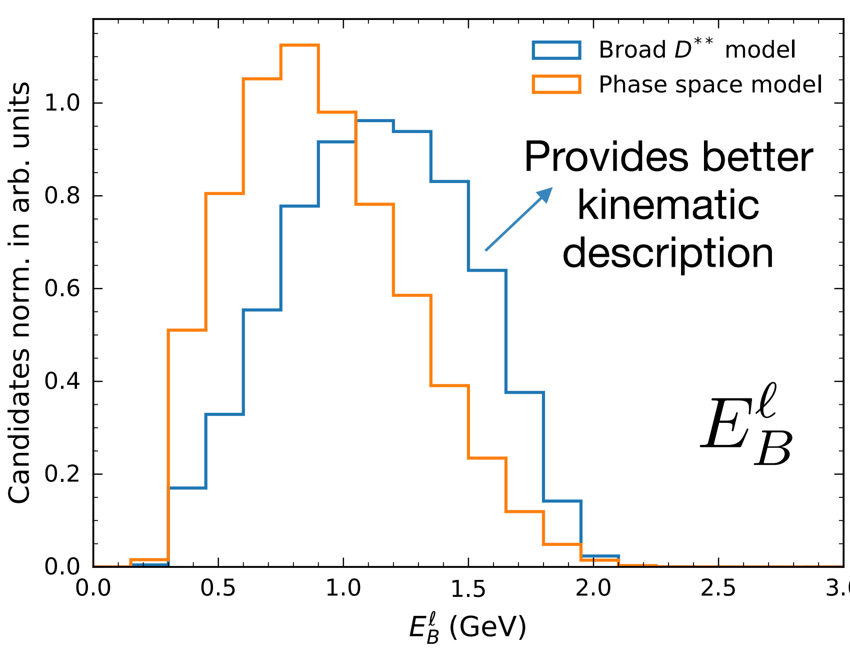
Model 1:
Equidistribution of all final state particles in phase space

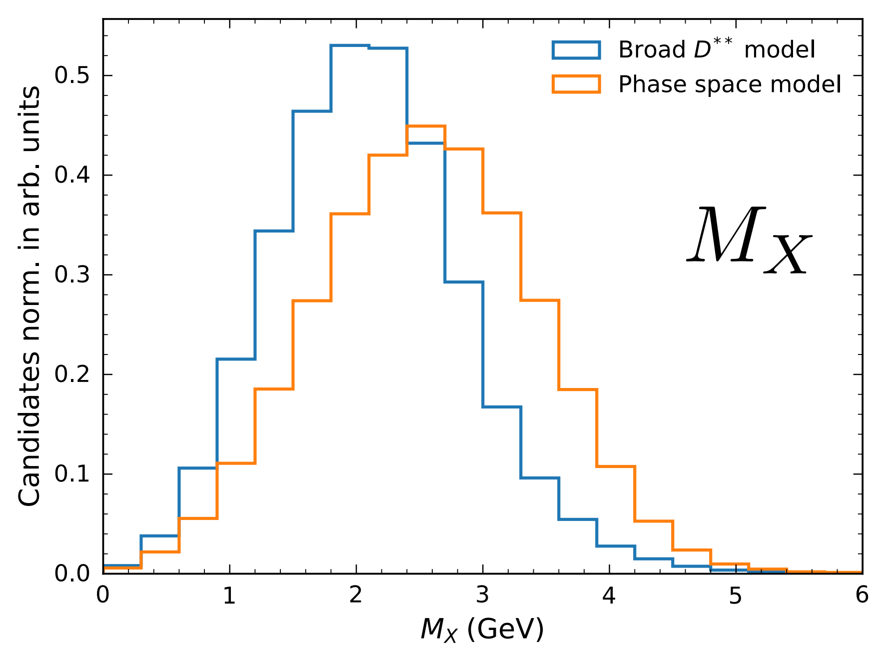
Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D\,\ell^+\,\nu_\ell$	$(2.4 \pm 0.1) \times 10^{-2}$	$(2.2 \pm 0.1) \times 10^{-2}$
$B \to D^*\,\ell^+\,\nu_\ell$	$(5.5 \pm 0.1) \times 10^{-2}$	$(5.1 \pm 0.1) \times 10^{-2}$
$B \to D_1\,\ell^+\,\nu_\ell$	$(6.6 \pm 0.1) \times 10^{-3}$	$(6.2 \pm 0.1) \times 10^{-3}$
$B \to D_2^*\,\ell^+\,\nu_\ell$	$(2.9 \pm 0.3) \times 10^{-3}$	$(2.7 \pm 0.3) \times 10^{-3}$
$B \to D_0^*\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.8) \times 10^{-3}$	$(3.9 \pm 0.7) \times 10^{-3}$
$B \to D_1'\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.9) \times 10^{-3}$	$(3.9 \pm 0.8) \times 10^{-3}$
$B \to D\pi\pi\,\ell^+\,\nu_\ell$	$(0.6 \pm 0.9) \times 10^{-3}$	$(0.6 \pm 0.9) \times 10^{-3}$
$B \to D^*\pi\pi\,\ell^+\,\nu_\ell$	$(2.2 \pm 1.0) \times 10^{-3}$	$(2.0 \pm 1.0) \times 10^{-3}$
$B \to D\eta\,\ell^+\,\nu_\ell$	$(4.0 \pm 4.0) \times 10^{-3}$	$(4.0 \pm 4.0) \times 10^{-3}$
$B \to D^*\eta\,\ell^+\,\nu_\ell$	$(4.0 \pm 4.0) \times 10^{-3}$	$(4.0 \pm 4.0) \times 10^{-3}$
$B \to X_c\ell\nu_\ell$	$(10.8 \pm 0.4) \times 10^{-2}$	$(10.1 \pm 0.4) \times 10^{-2}$

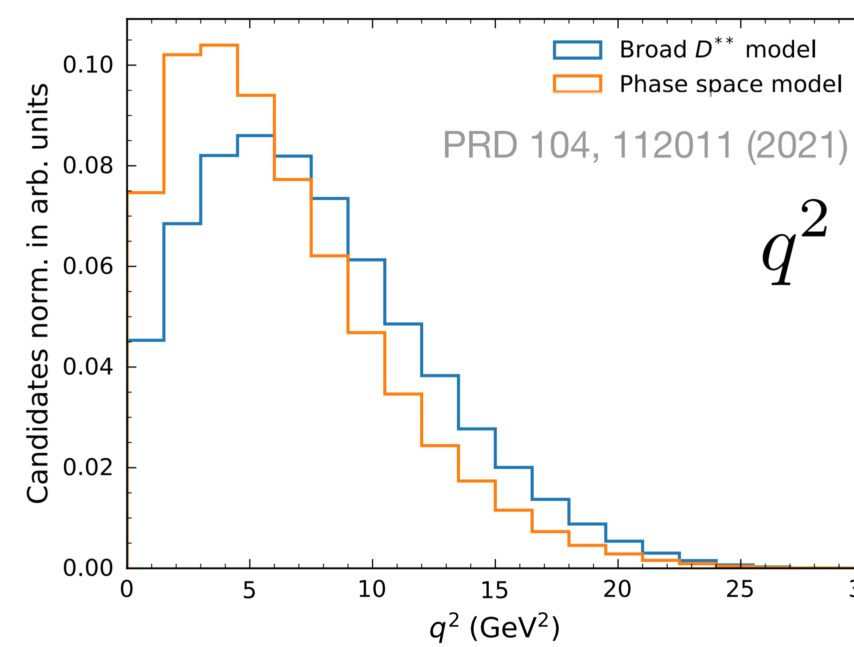
Model 2:
Decay via intermediate broad D^{**} state

Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D_0^*\,\ell^+\,\nu_\ell$ ($\hookrightarrow D\pi\pi$)	$(0.03 \pm 0.03) \times 10^{-2}$	$(0.03 \pm 0.03) \times 10^{-2}$
$B \to D_1^*\,\ell^+\,\nu_\ell$ ($\hookrightarrow D\pi\pi$)	$(0.03 \pm 0.03) \times 10^{-2}$	$(0.03 \pm 0.03) \times 10^{-2}$
$B \to D_0^*\pi\pi\,\ell^+\,\nu_\ell$ ($\hookrightarrow D^*\pi\pi$)	$(0.108 \pm 0.051) \times 10^{-2}$	$(0.101 \pm 0.048) \times 10^{-2}$
$B \to D_1^*\pi\pi\,\ell^+\,\nu_\ell$ ($\hookrightarrow D^*\pi\pi$)	$(0.108 \pm 0.051) \times 10^{-2}$	$(0.101 \pm 0.048) \times 10^{-2}$
$B \to D_0^*\,\ell^+\,\nu_\ell$ ($\hookrightarrow D\eta$)	$(0.396 \pm 0.396) \times 10^{-2}$	$(0.399 \pm 0.399) \times 10^{-2}$
$B \to D_1^*\,\ell^+\,\nu_\ell$ ($\hookrightarrow D^*\eta$)	$(0.396 \pm 0.396) \times 10^{-2}$	$(0.399 \pm 0.399) \times 10^{-2}$

(Assign 100% BR uncertainty in systematics covariance matrix)







Diamond frame reconstruction

- Estimate the momentum direction of the signal B meson, p_B, for untagged analyses using a modified ***diamond frame*** approach:

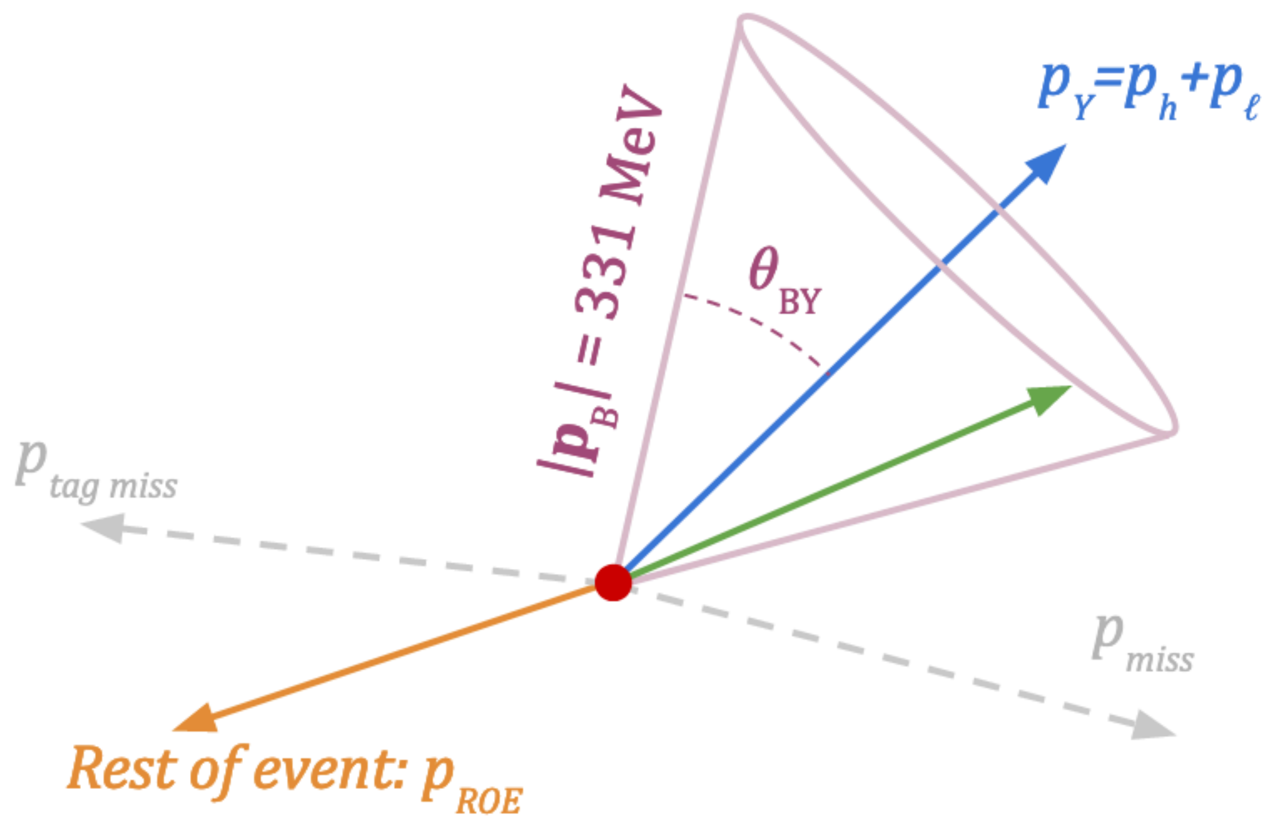


Image credit: P. Lewis