Karlsruher Institut für Technologie

Walter Benjamin-Programm

DFG Deutsche Forschungsgemeinschaft

BELLE

Belle II

Semileptonic & leptonic decays at Belle II

Raynette van Tonder
on behalf of the Belle & Belle II Collaborations

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Mt. Tsukuba

SuperKEKB
(HER + LER)

Damping ring
(e^+)

Linac

KEK Tsukuba
Campus

Mt. Tsukuba

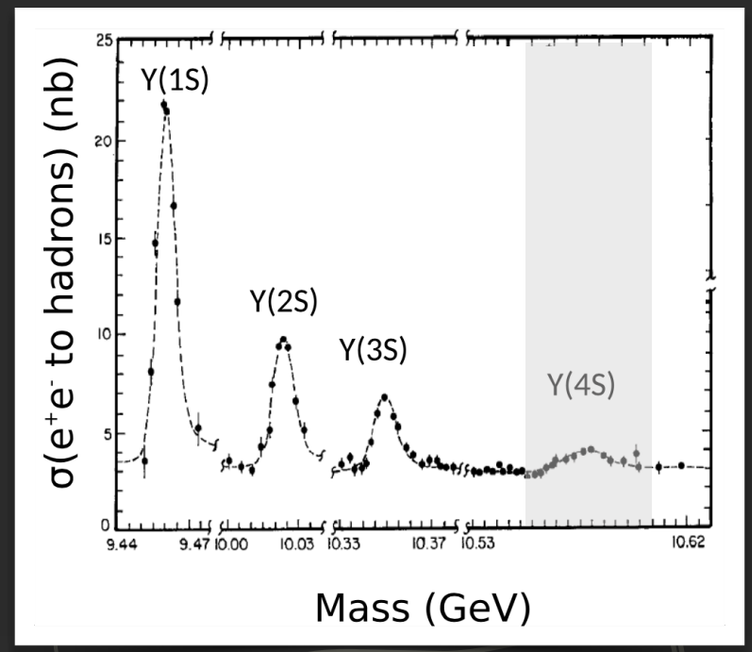
SuperKEKB
(HER + LER)

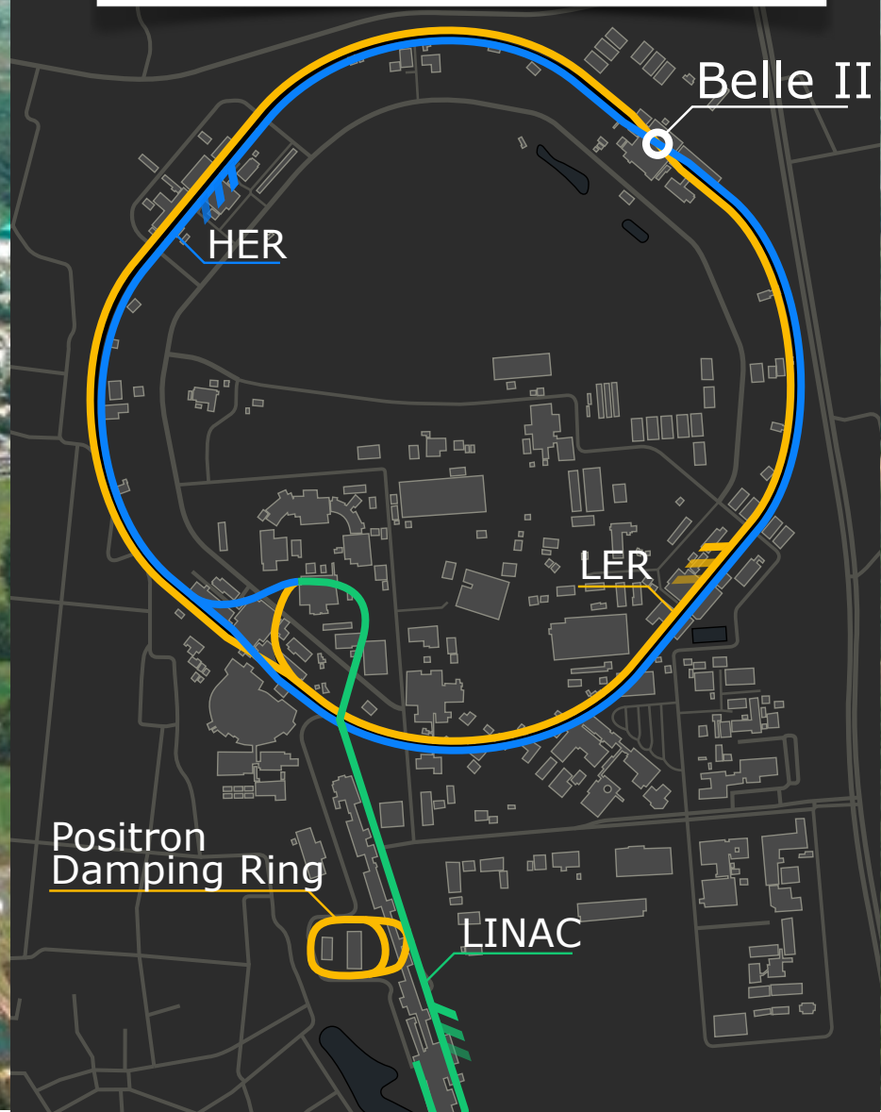
Damping ring
(e^+)

Linac

$\sqrt{s} = 10.58$ GeV

$e^+e^- \to \Upsilon(4S) \to B\bar{B}$





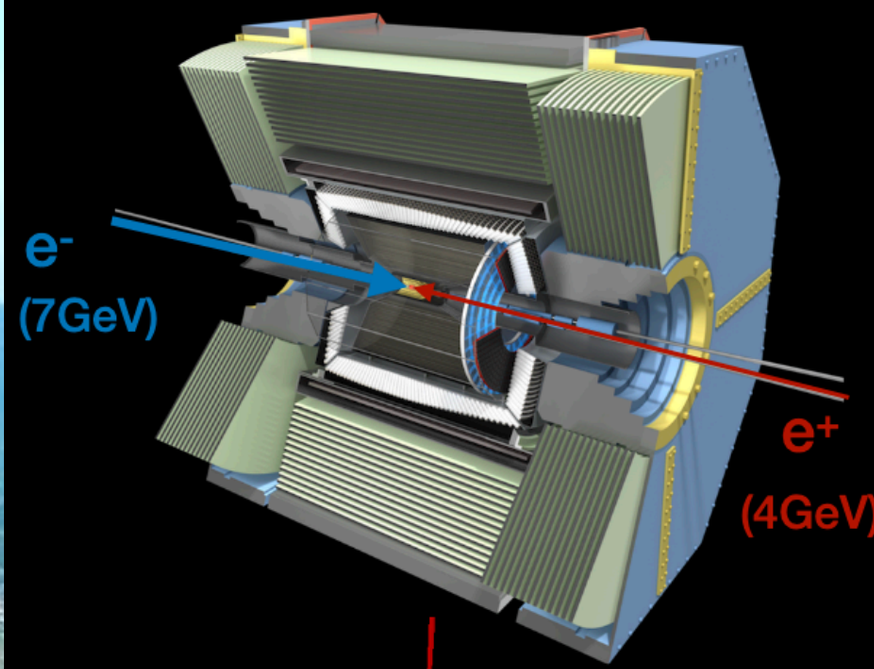
Mt. Tsukuba

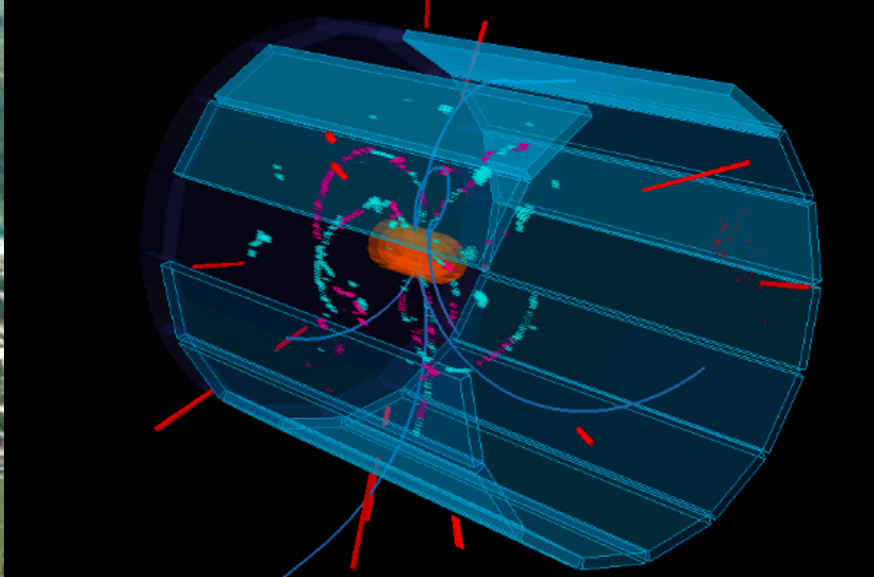
Belle (II)
Detector

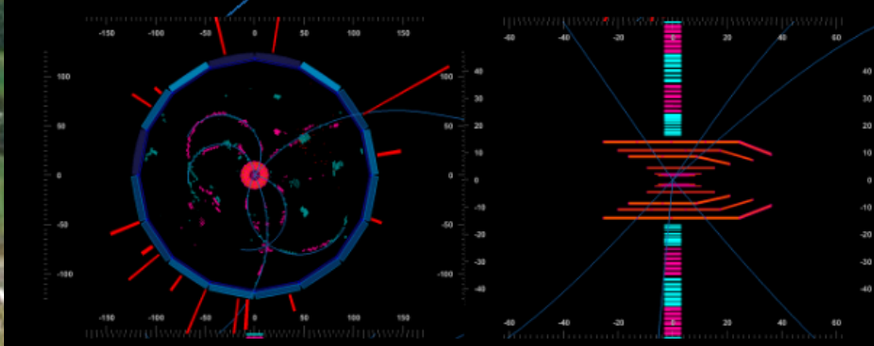
SuperKEKB
(HER + LER)

Damping ring
(e^+)

Linac



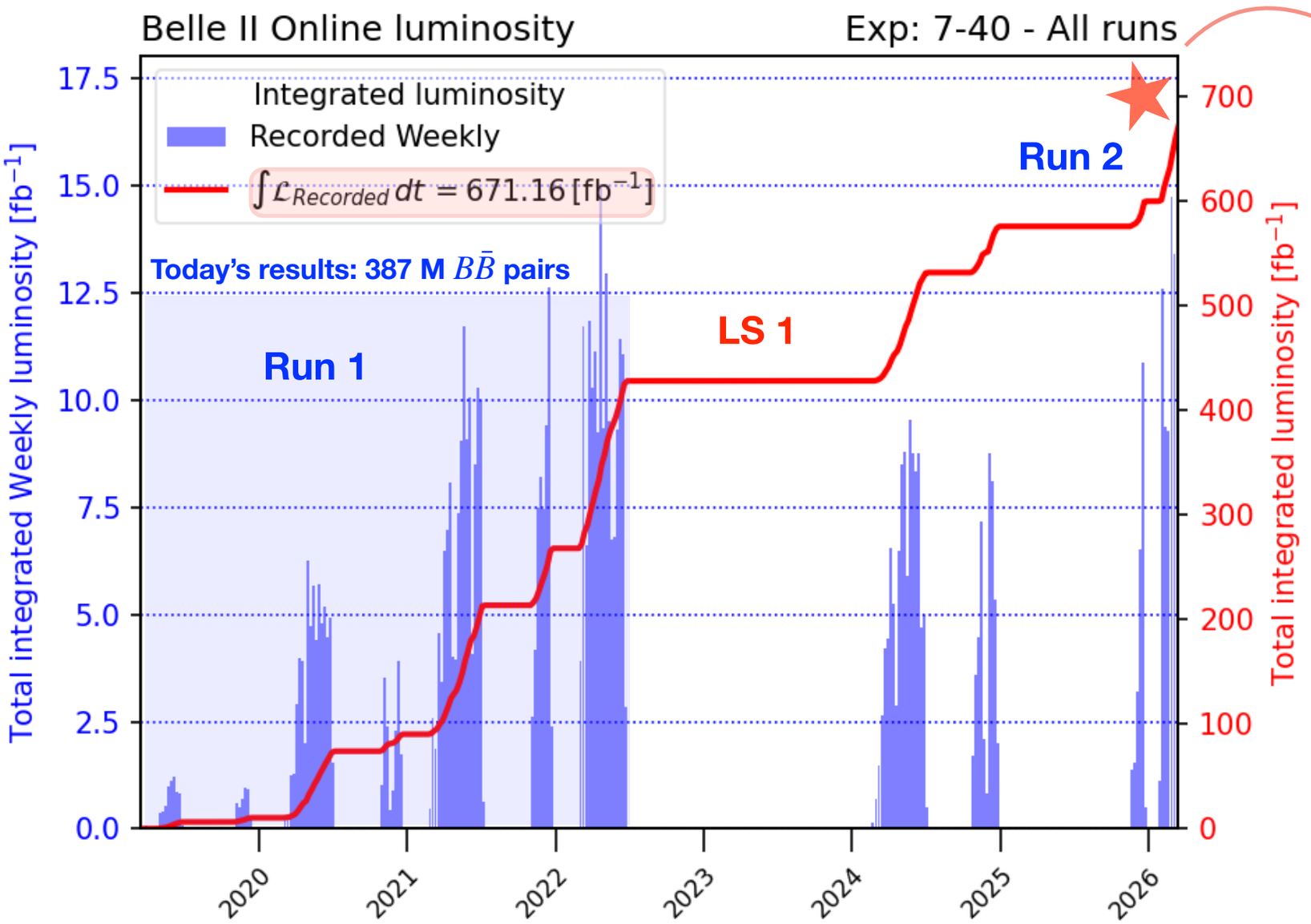




Accumulated dataset

Online Luminosity

- Belle II has recorded a **total integrated luminosity** of 660 fb^{-1} since March 2019
  - (Belle 988 fb^{-1}, BaBar 513 fb^{-1})
- Results shown today based on **Run 1 dataset** (365 fb^{-1})



World record!

Instantaneous luminosity:

L_{peak} = 5.1 x 10^{34} cm^{-2} s^{-1}

Integrated luminosity (so far):

~519 fb^{-1} recorded at $\Upsilon(4S)$

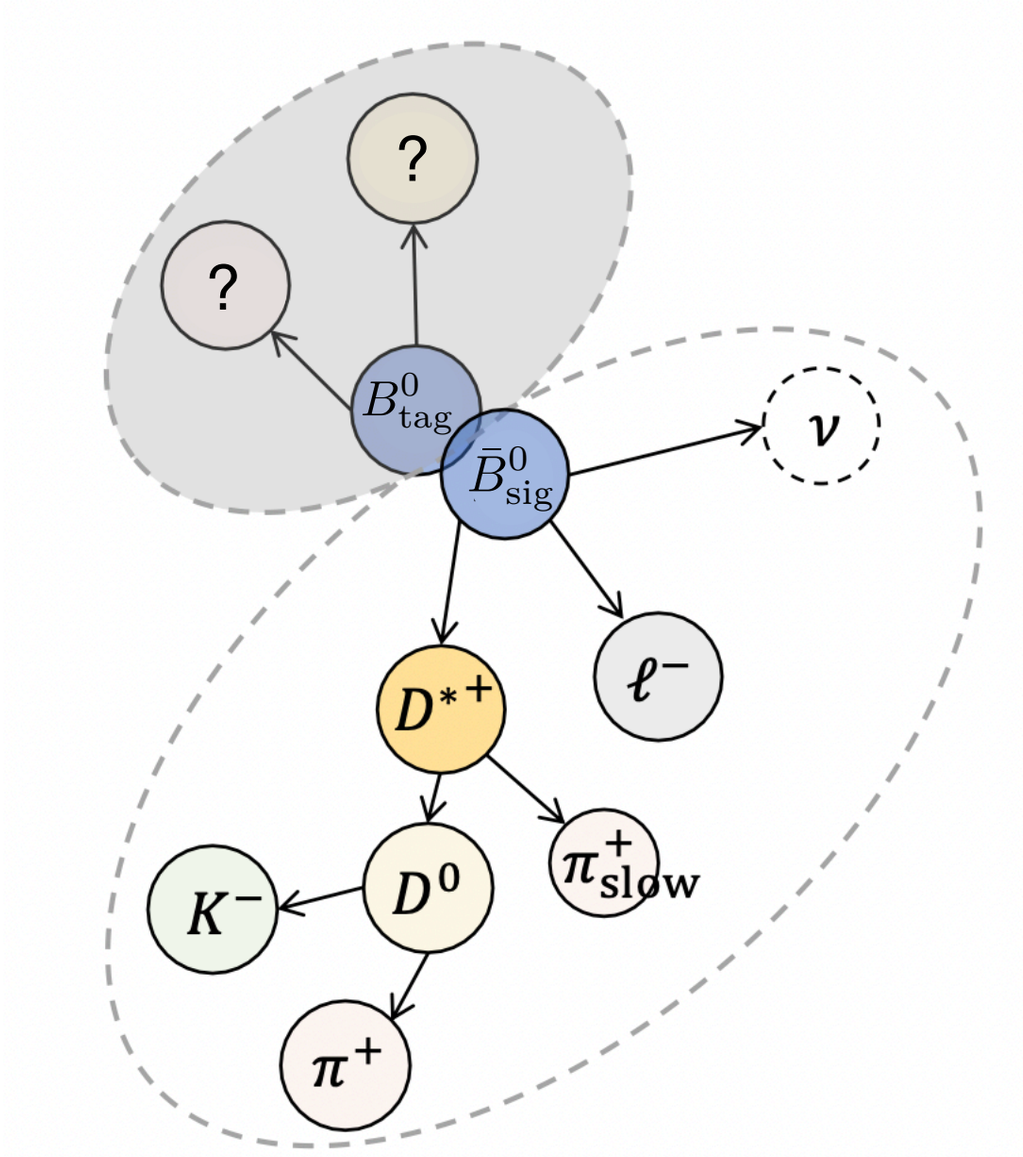
~59 fb^{-1} recorded 60 MeV below $\Upsilon(4S)$ (background studies)

~19 fb^{-1} recorded at 10.8 GeV (exotic hadron searches)

Tagging strategies at B-Factories

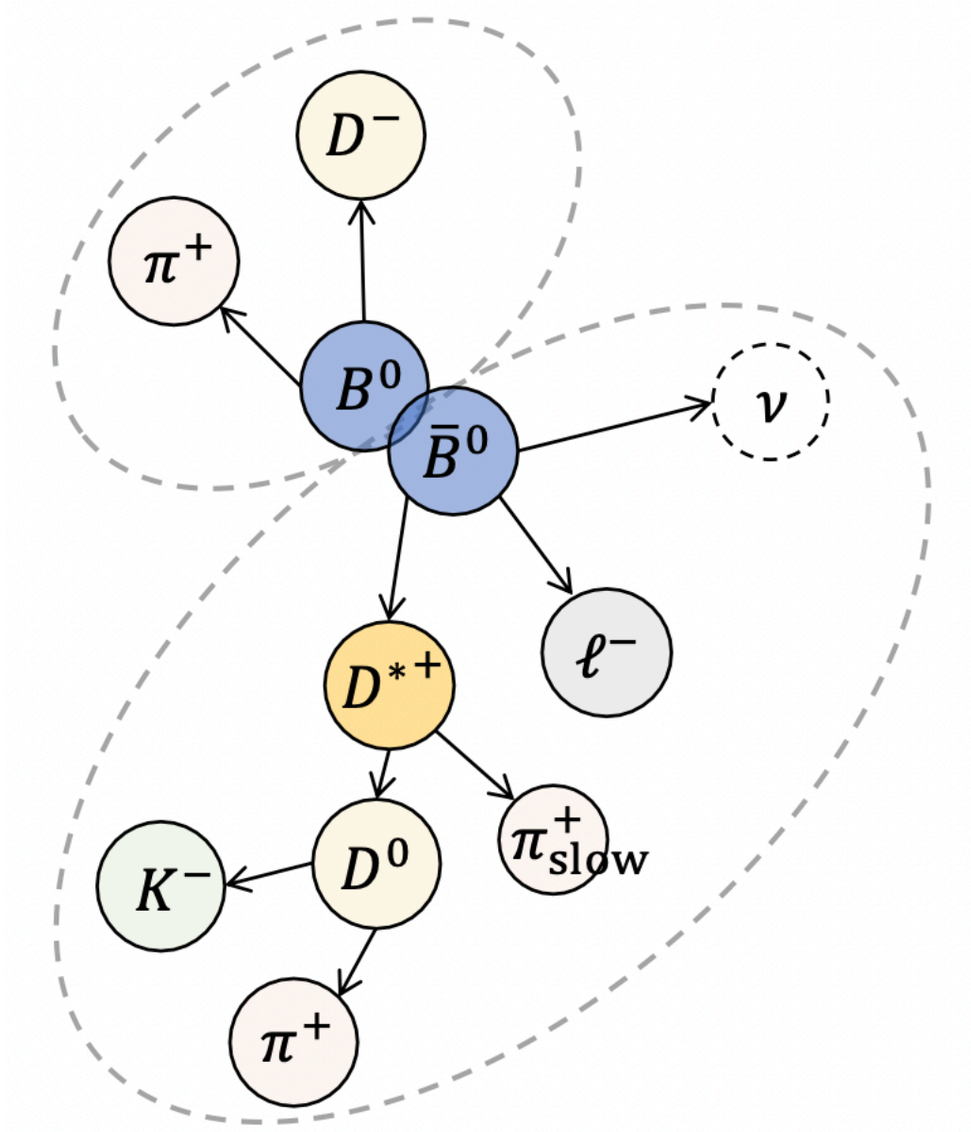
Untagged

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

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.

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

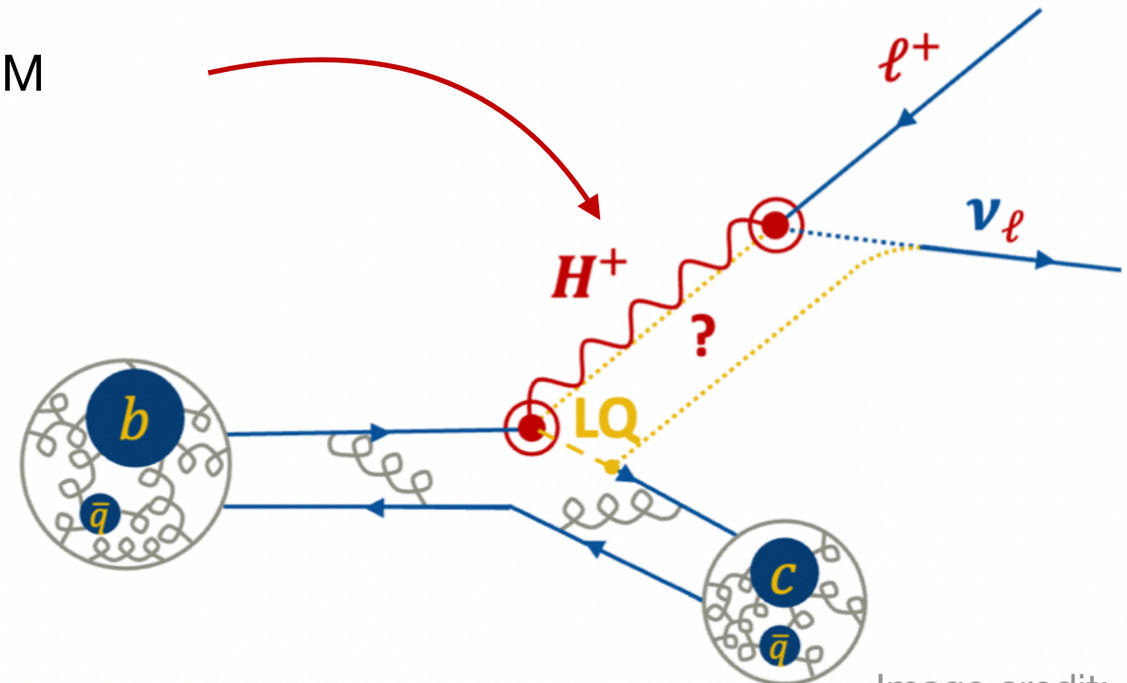
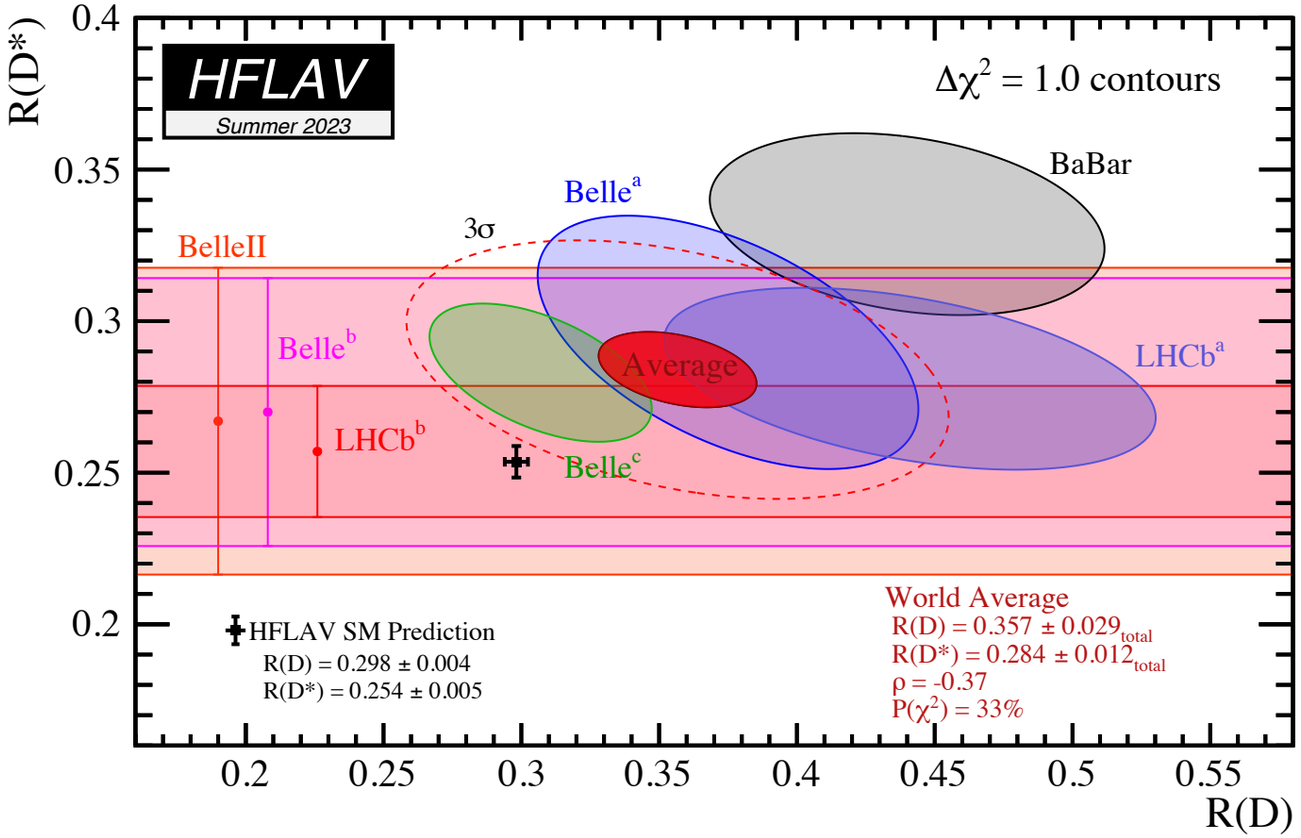


Image credit: H. Junkerkalefeld



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 $R(X_{\tau/\ell})$ & $R(D^{(*)})$

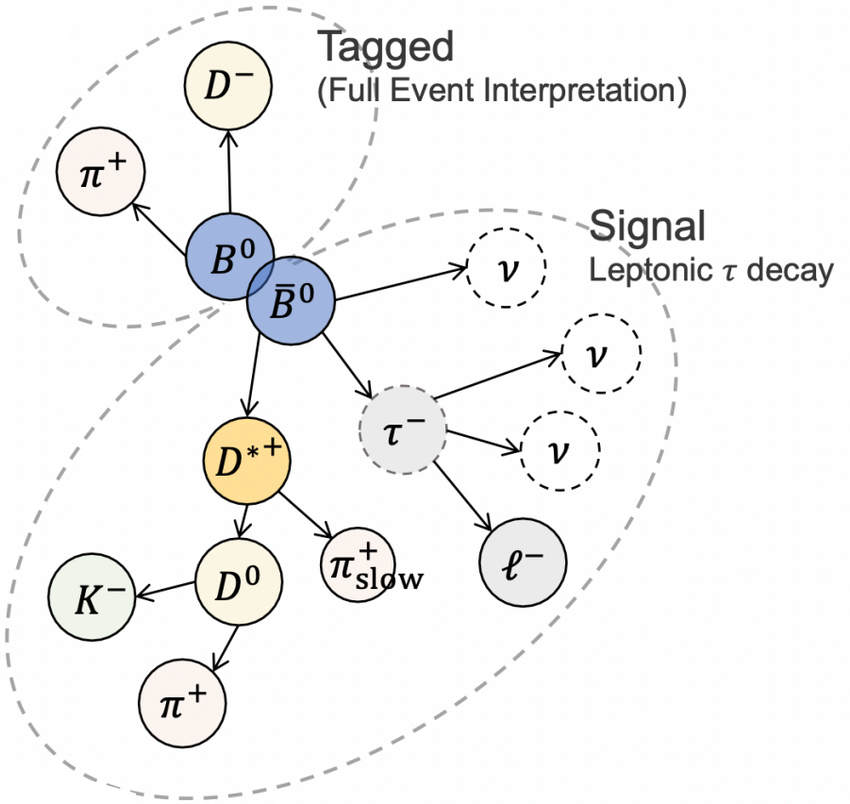
$R(D^{(*)})$ with hadronic tag

$R(D^{(*)})$ with hadronic tag

To be submitted

Supersedes previous hadronic tag $R(D^*)$ result by using the full Run 1 dataset:

- Previous Belle II $R(D^*)$ result used only **half of the dataset** (189 fb^{-1}) PRD 110 (2024) 7, 072020
- Identify lepton from $\tau \to \ell\nu\bar{\nu}$
- **Efficiency is maximised** by reconstructing all D^* decay modes and 13 D decay modes
  - $D^{*\pm} \to D^0\pi^\pm, D^\pm\pi^0$
  - $D^{*0} \to D^0\pi^0, D^0\gamma$
- Extend analysis to include $R(D)$



Signal

Normalisation modes

Dominant backgrounds

Twice the data!

	D^{*+}	$D^*_{[D^0\pi^0]}{}^0$	$D^*_{[D^0\gamma]}{}^0$	D^0	D^+
$B \to D^*\tau\nu$	124 ± 10	64 ± 5	107 ± 8	380 ± 30	63 ± 5
$B \to D\tau\nu$	0 ± 0	2 ± 0	32 ± 4	340 ± 43	148 ± 19
$B \to D^*\ell\nu$	2899 ± 66	1417 ± 32	2598 ± 59	10638 ± 235	1624 ± 37
$B \to D\ell\nu$	4 ± 0	7 ± 0	215 ± 7	2882 ± 87	1226 ± 37
$B \to D^{**}\tau/(\ell)\nu$	60 ± 31	29 ± 24	191 ± 58	731 ± 134	294 ± 64
gap modes	21 ± 25	42 ± 15	53 ± 50	240 ± 94	90 ± 46
hadronic B decay	86 ± 25	4 ± 12	166 ± 38	469 ± 95	126 ± 25
continuum	3	2	33	181	84
other backgrounds	0	0	0	1	4
Total	3197	1567	3395	15862	3659

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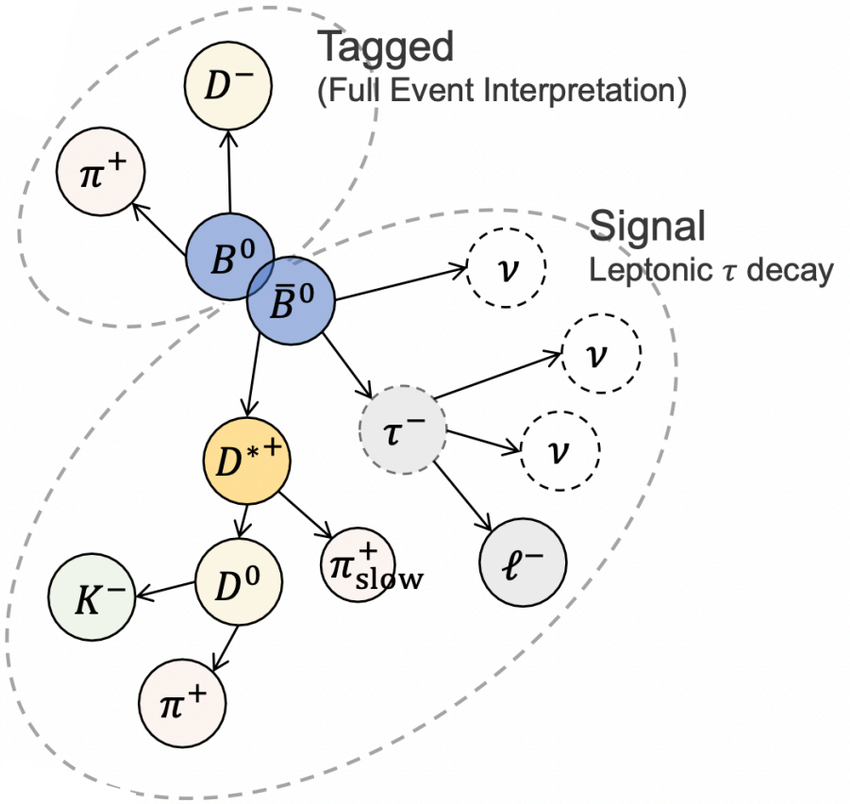
  - $D^{*\pm} \to D^0\pi^\pm, D^\pm\pi^0$
  - $D^{*0} \to D^0\pi^0, D^0\gamma$ ← **New mode for this analysis!**
- Extend analysis to include $R(D)$



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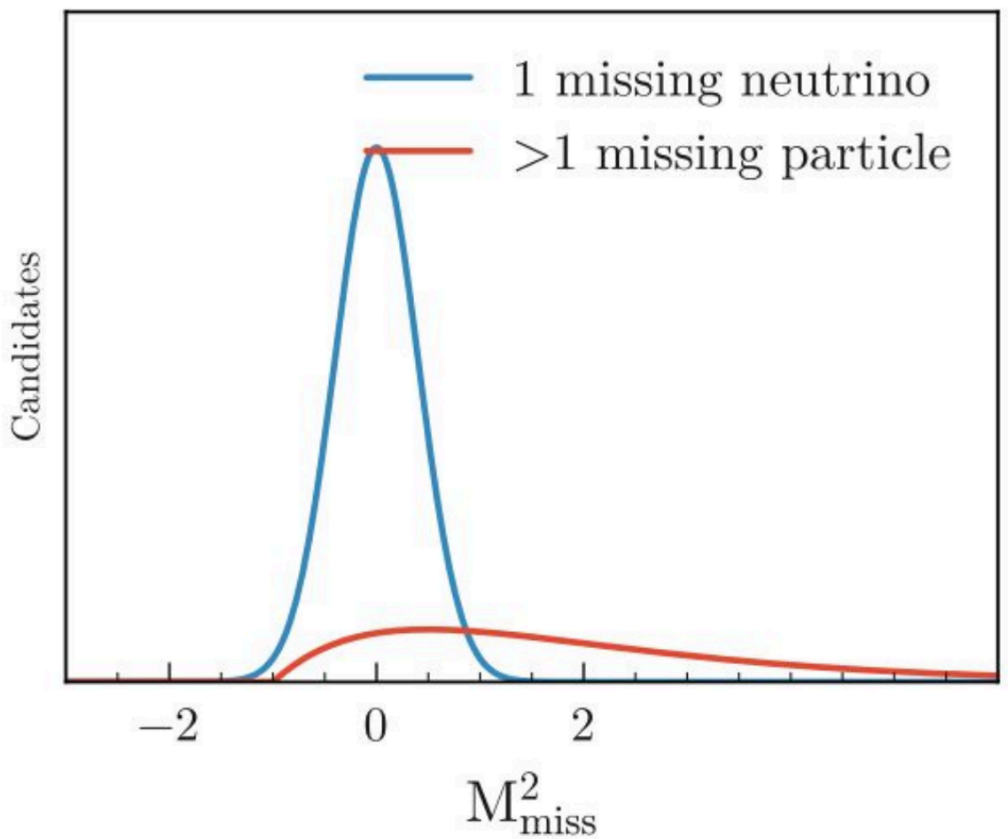
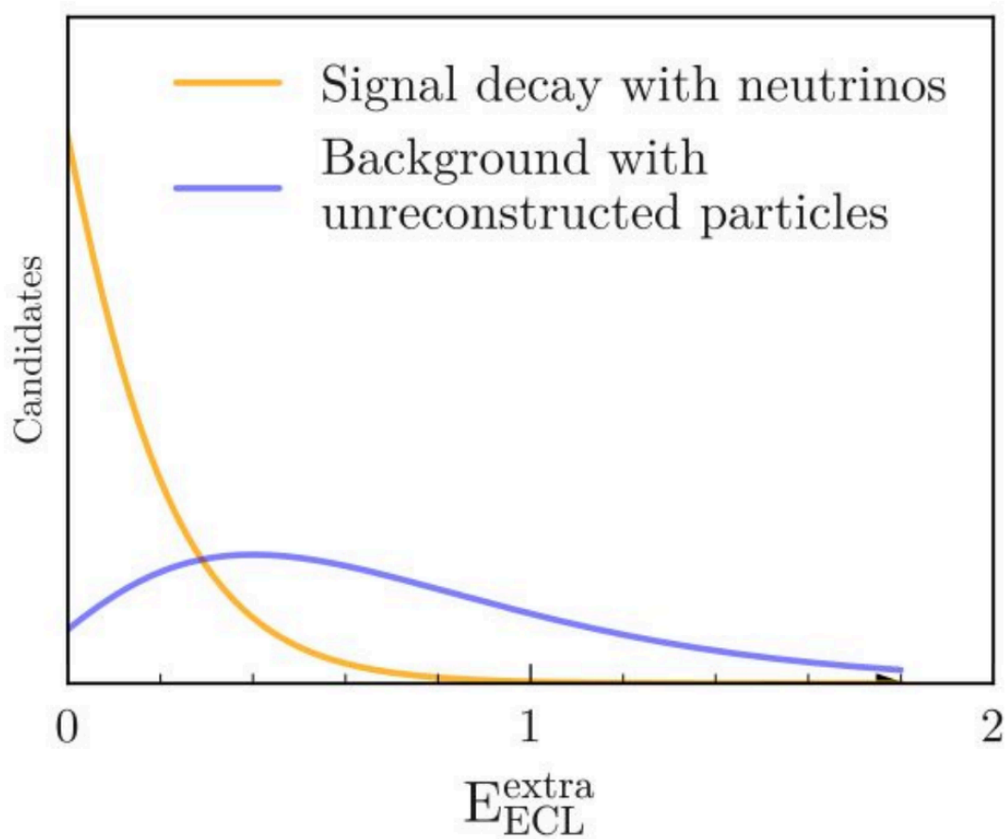
- **Main challenge:** understand significant & poorly known $B \to D^{**}\ell\nu$ background decays.
  - Reduce background through completeness constraint that **require no additional tracks**
  - **Data-driven validation** of background and signal modelling based on studies of sideband regions.
- **Extract signal** with 2D fit to residual energy in the calorimeter E_{ECL} & invariant mass of undetected neutrinos $M^2_{miss} = (p_{e^+e^-} - p_{B_{tag}} - p_{D^*} - p_\ell)^2$

Dealing with missing energy



Reducing background



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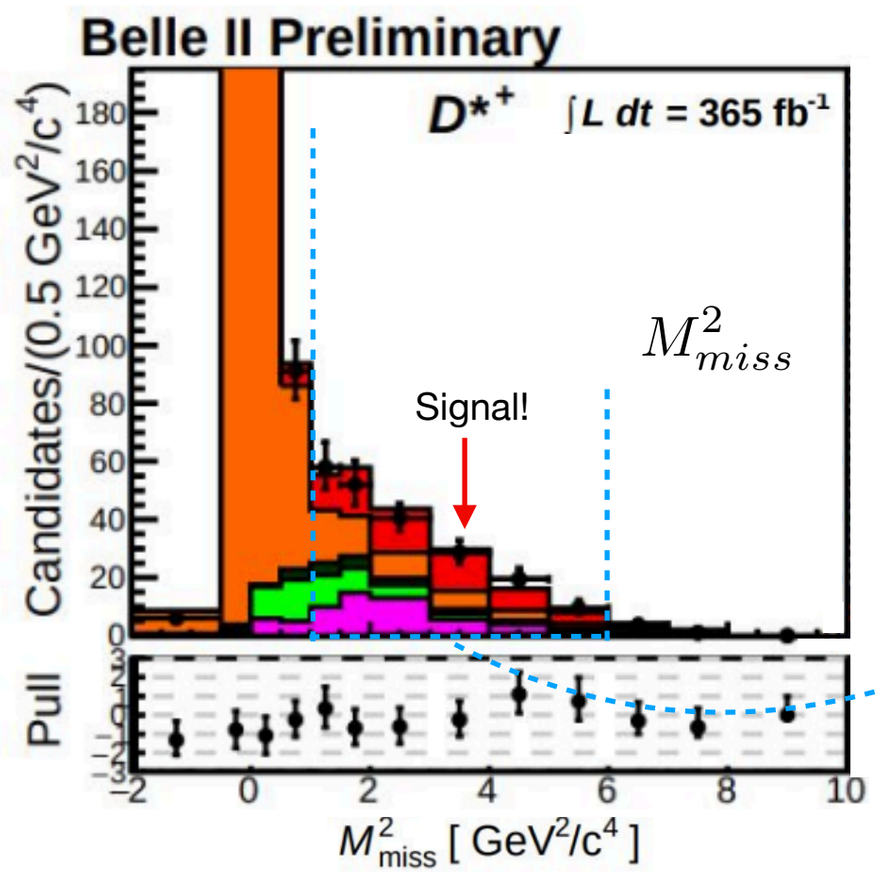

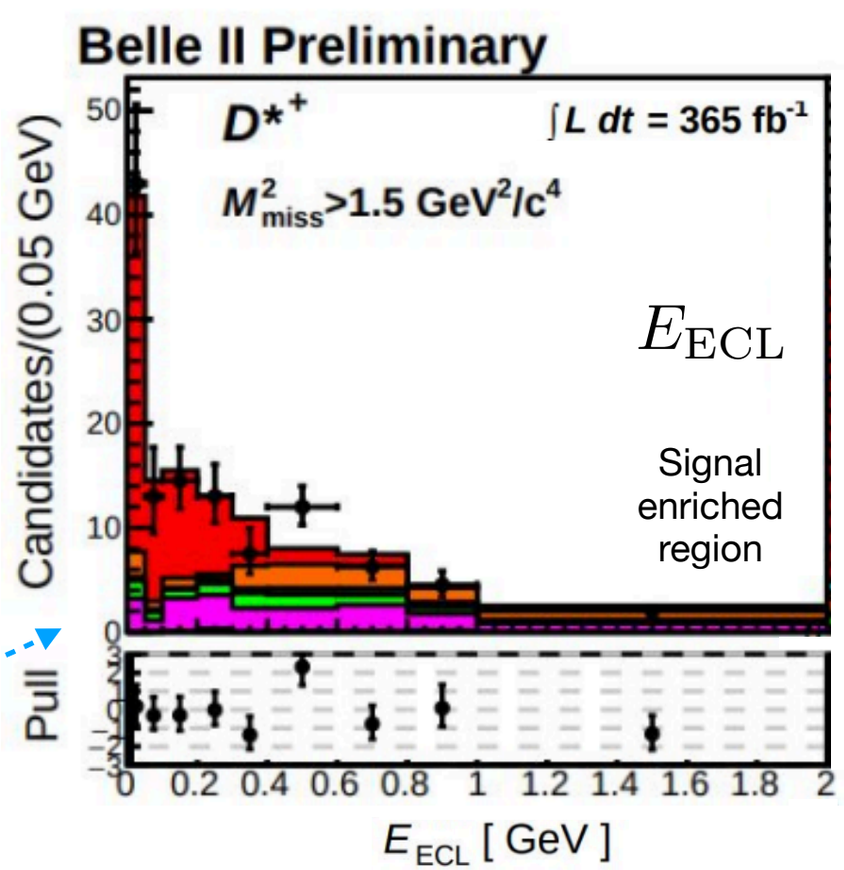

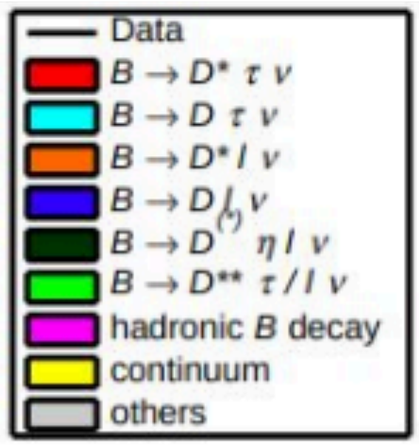

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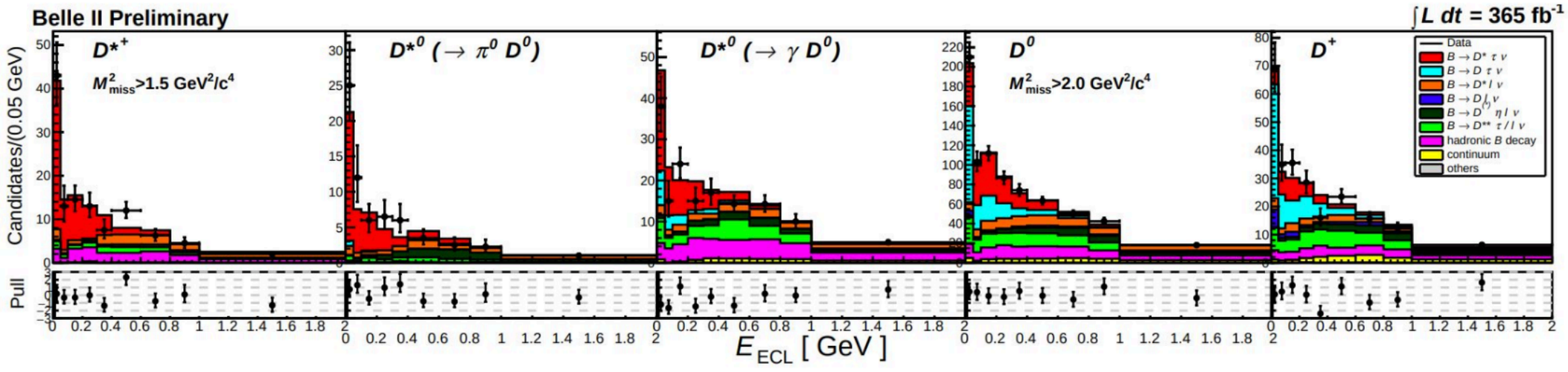
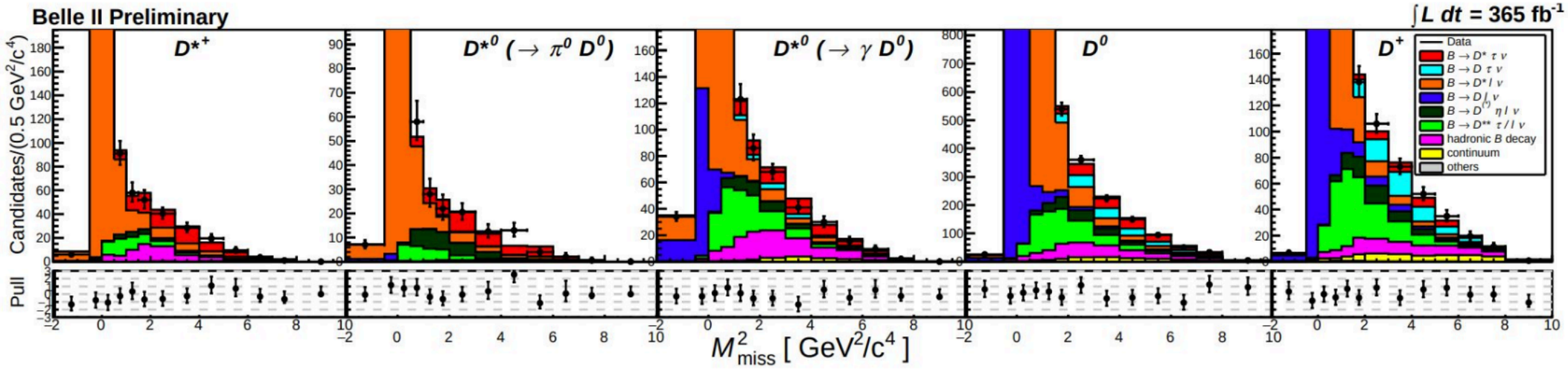


$B \to D^*\tau\nu$

$B \to D\tau\nu$



$B \to D^*\ell\nu$

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$R(D^{(*)})$ with hadronic tag

To be submitted

Most precise determination of $R(D^{(*)})$ with hadronic tagging!

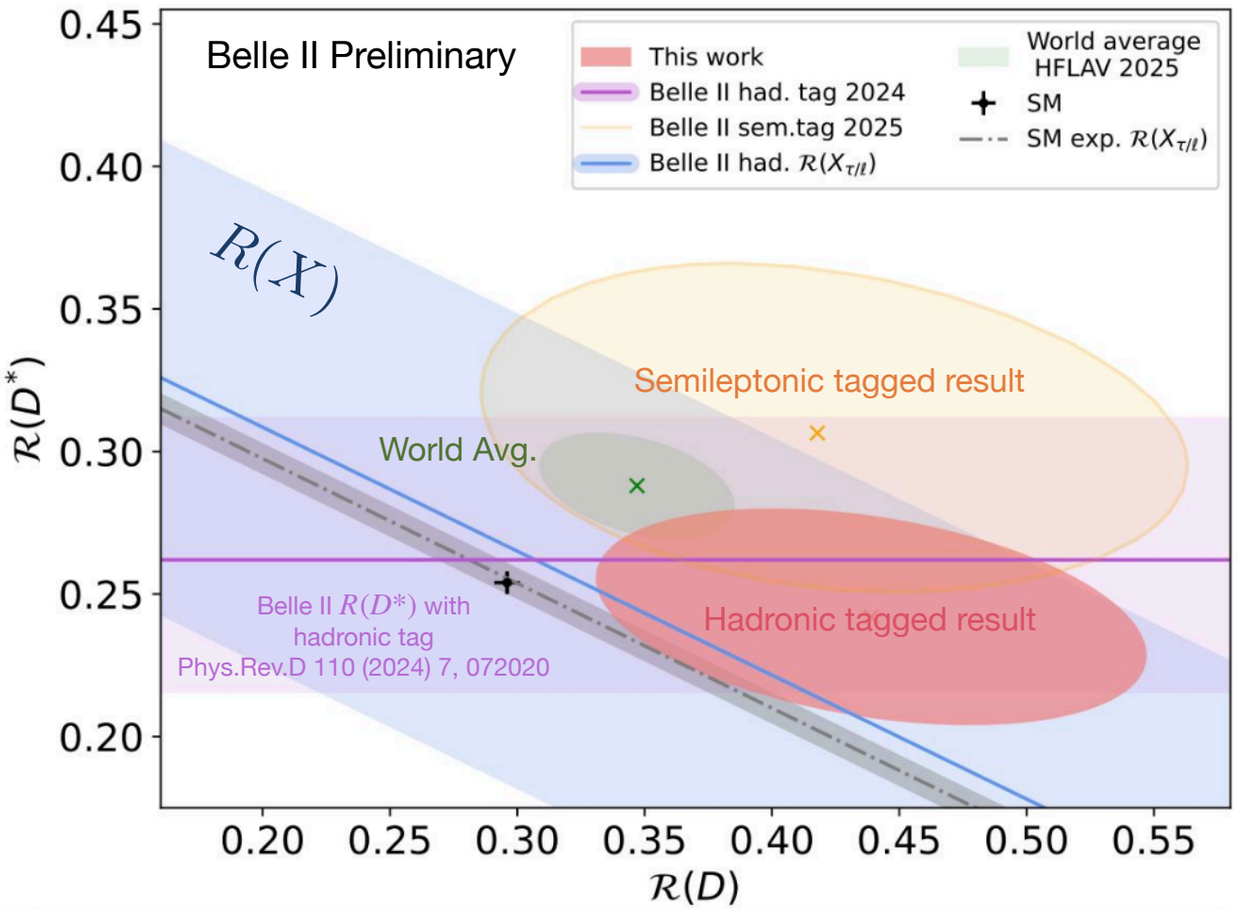
$$R(D) = 0.439 \pm 0.055(\text{stat.}) \pm 0.045(\text{syst.})$$

$$R(D^*) = 0.242 \pm 0.019(\text{stat.}) \pm 0.016(\text{syst.})$$

$$\rho = -0.52$$

SM prediction: $R(D^*)$ = 0.254 ± 0.005
HFLAV 23: $R(D^*)$ = 0.284 ± 0.013
Eur. Phys. J. C 81, 226 (2021)

- $R(D)$ consistent with SM within 2σ
- $R(D^*)$ consistent with SM within 0.5σ
- Consistent with SM expectation within 1.5σ
- Consistent with world average within 1.3σ



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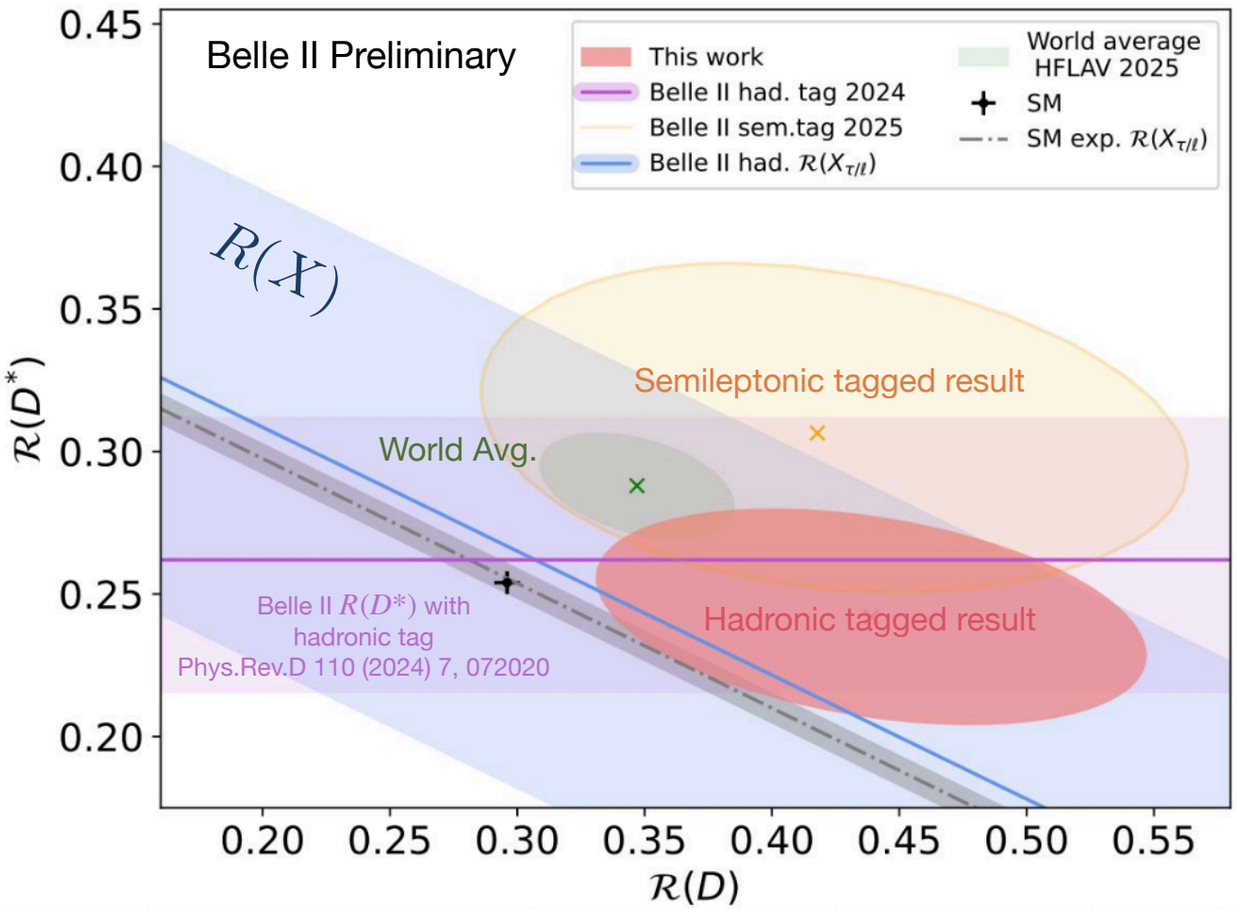
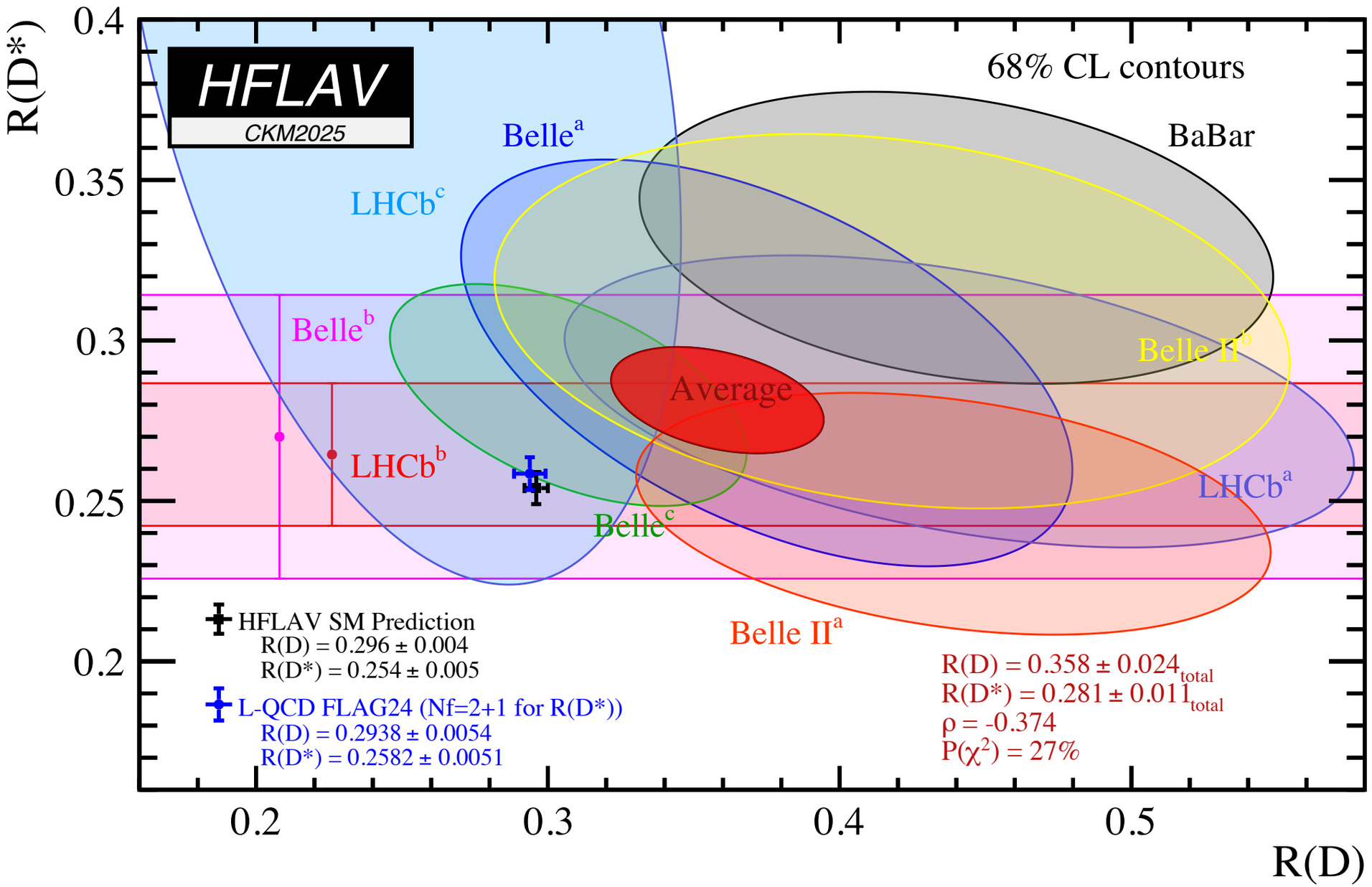


Source	$R(D^*)$	$R(D)$	ρ
Simulation sample size	4.8%	8.4%	−0.44
gap-mode branching fraction	2.6%	2.6%	0.00
$\bar{B} \to D^{**}\tau^-/(\ell^-)\bar{\nu}_\ell$ branching fractions	0.3%	1.3%	0.25
Hadronic B decay branching fractions	1.6%	1.5%	−0.26
Form factors	0.5%	0.9%	−0.70
Fraction of misreconstructed $D^{(*)}$	0.5%	1.2%	0.00
Continuum background	2.4%	2.1%	0.93
Fit biases	0.3%	1.2%	0.00
Low-momentum π^0, γ efficiency	2.2%	2.4%	0.99
Other efficiency corrections	0.7%	1.4%	0.92
B-tagging efficiency of data	0.9%	1.8%	−1.00
B-tagging efficiency of $B \to D\tau\nu$	0.1%	1.8%	1.00
M^2_{miss} resolution	0.5%	0.8%	0.48
Total systematic uncertainty	6.7%	10.2%	−0.20
Statistical uncertainty	8.3%	16.3%	−0.40

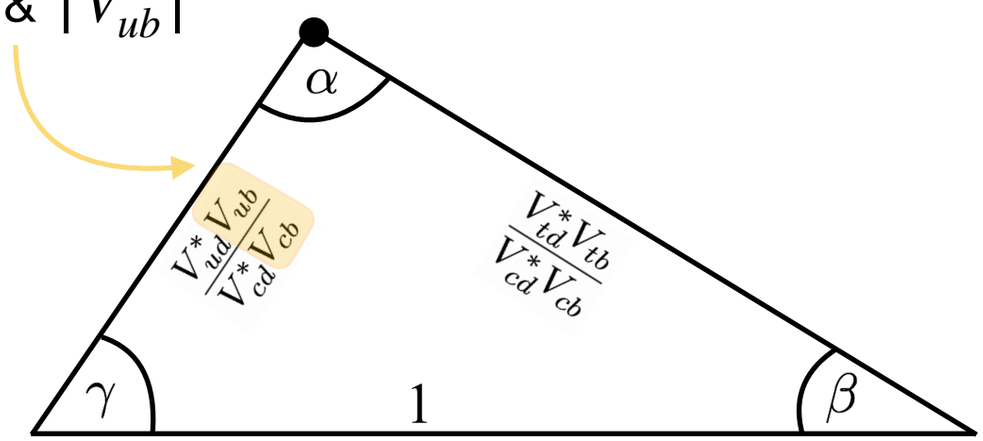
Global status

Deviation of world average from SM prediction increases to 3.8σ



CKM matrix elements

- SL B decays ideal to extract CKM Matrix elements $|V_{cb}|$ & $|V_{ub}|$
- $|V_{qb}|$ limiting the constraining power of global fits.
- Important inputs to 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 $|V_{ub}|$

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

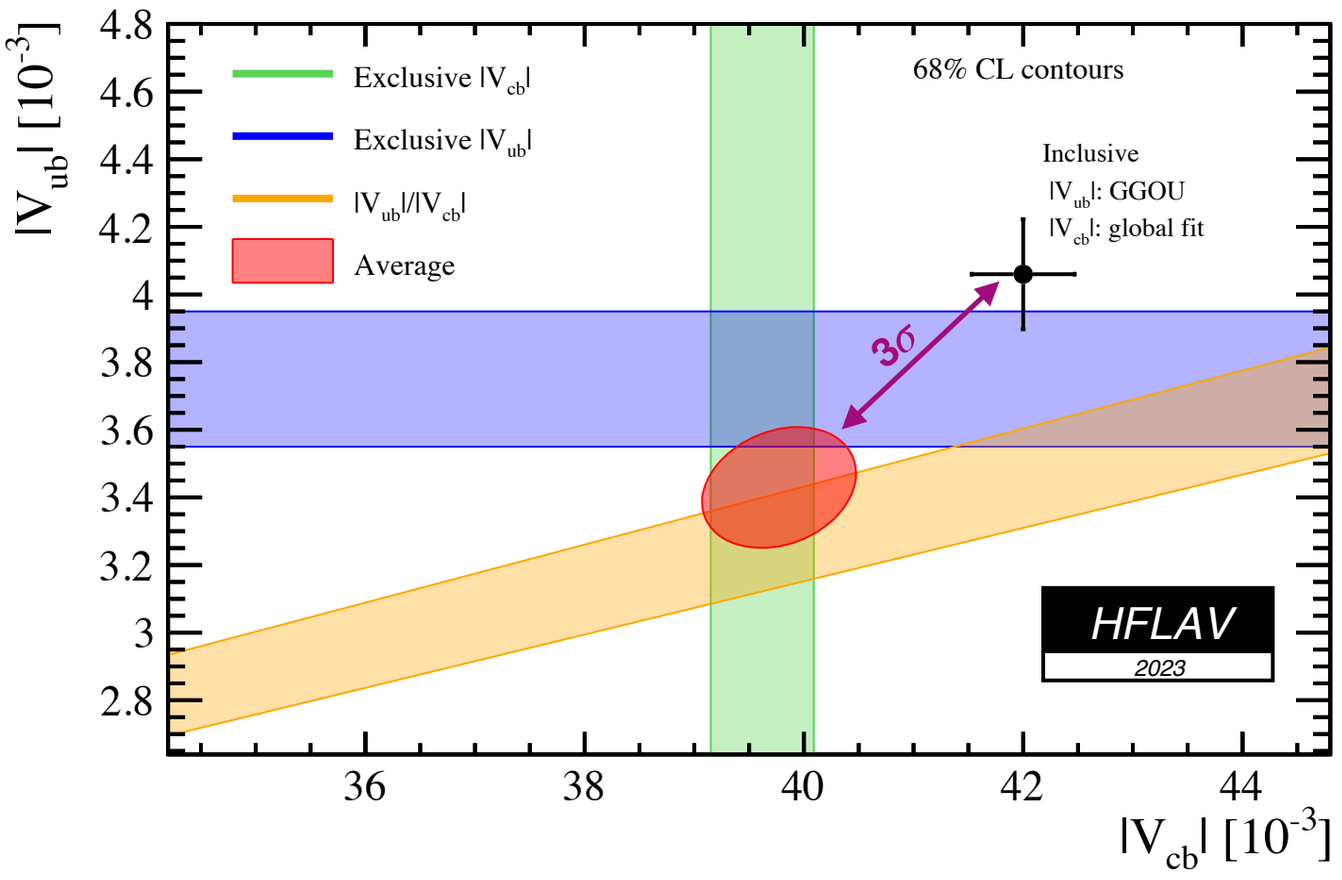
Inclusive $|V_{cb}|$

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

Heavy Quark Expansion

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

A longstanding tension…

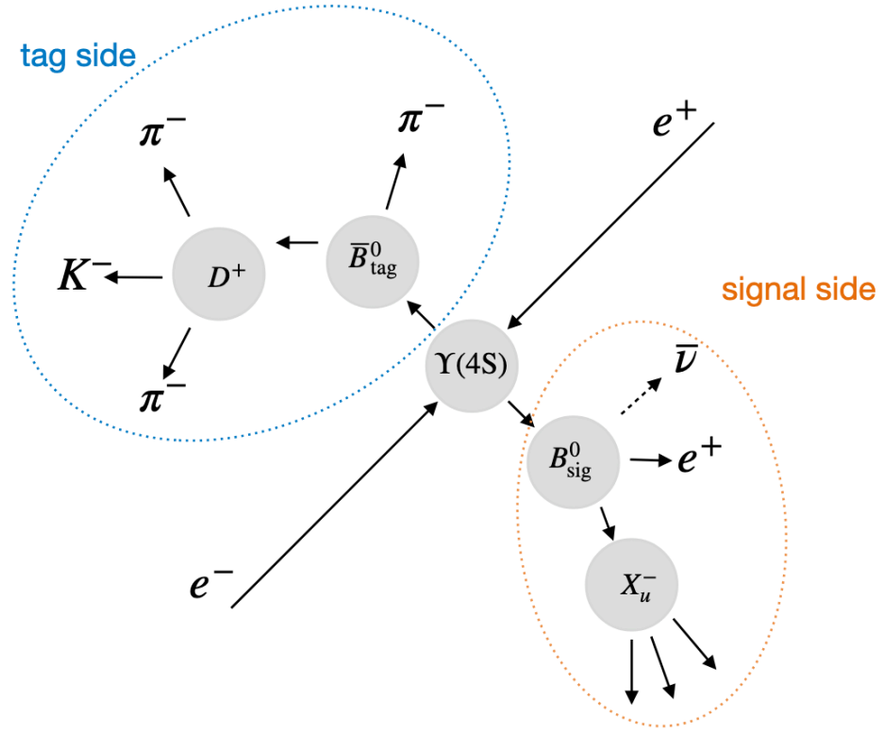


Inclusive $|V_{ub}|$ from $B \to X_u \ell \nu$

Inclusive $B \to X_u \ell \nu$

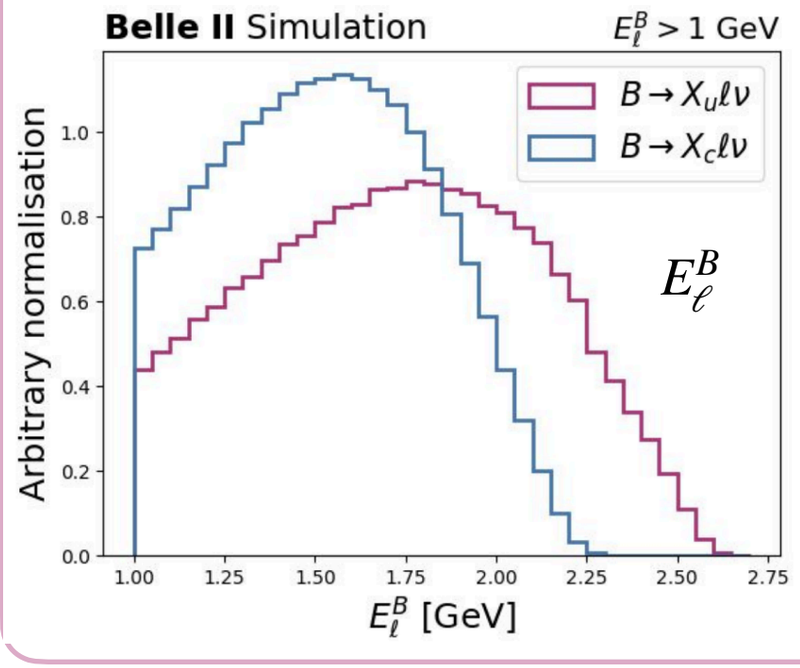
PRD 113 (2026) 3, 032004

- **Reconstruct:** Combined signal lepton on the **signal side** with fully reconstructed hadronic B on **tag side**
- **Large backgrounds** from dominant $B \to X_c \ell \nu$ decays
  - Efficiently suppressed with MLP using different event shape variables
  - Normalization and shape mismodelling **corrected** using **control regions** in data

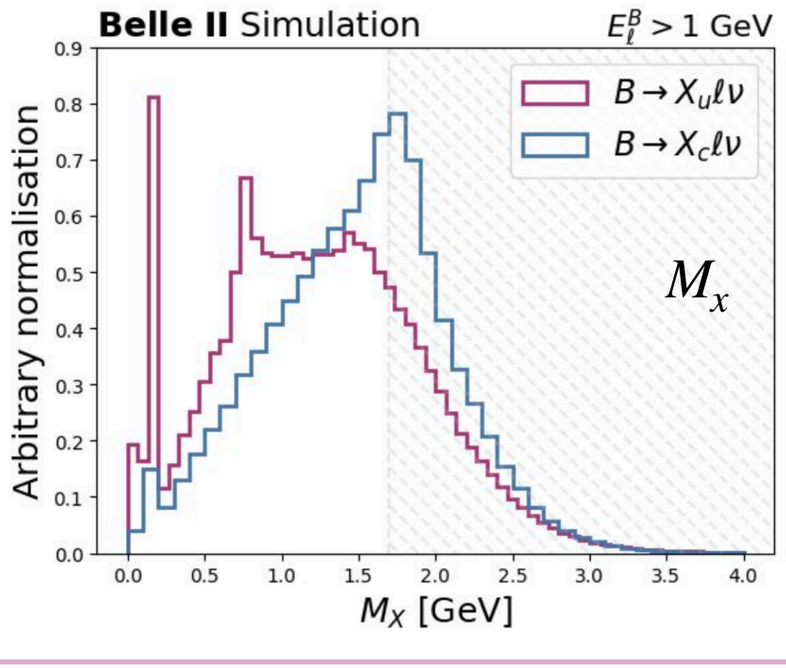


Key inclusive variables:

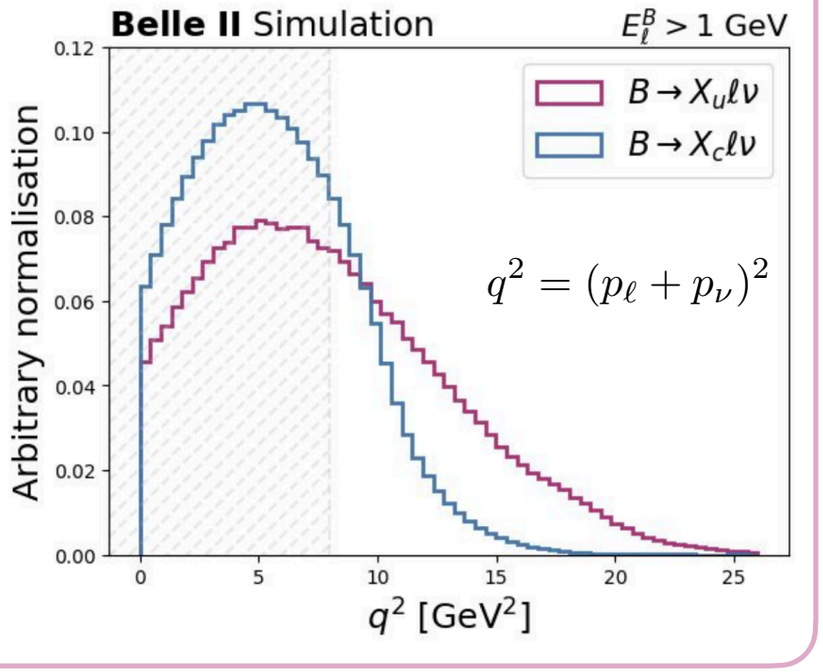
Lepton energy in B rest frame



Mass of hadronic system



Lepton invariant mass squared



Inclusive $B \to X_u \ell \nu$

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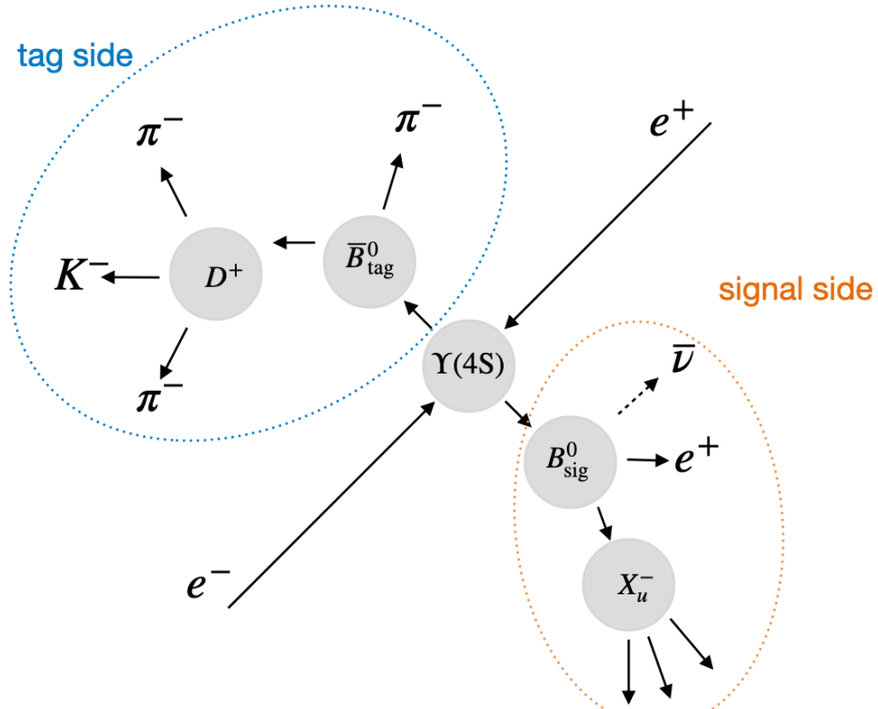

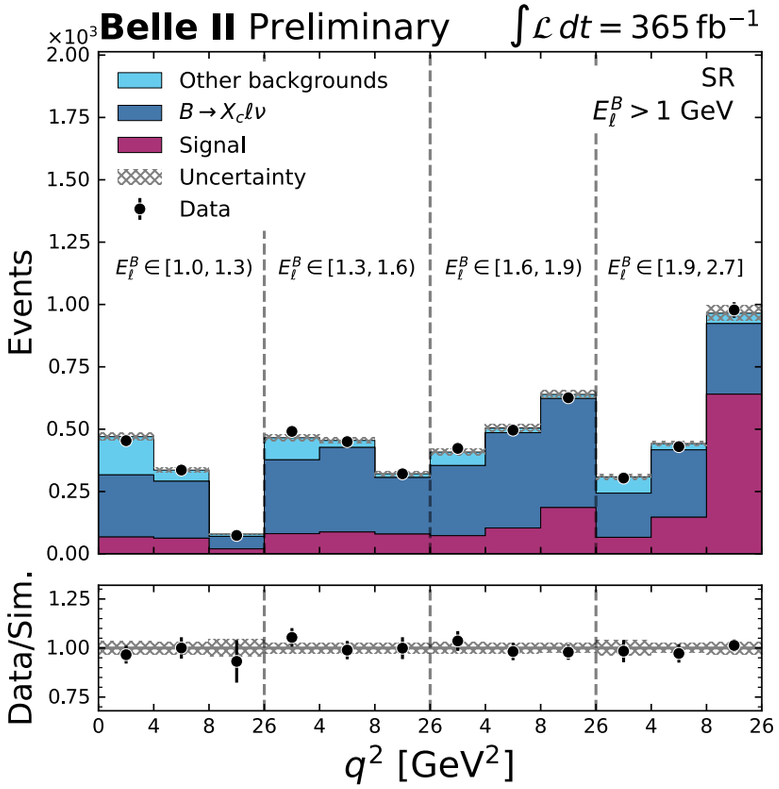

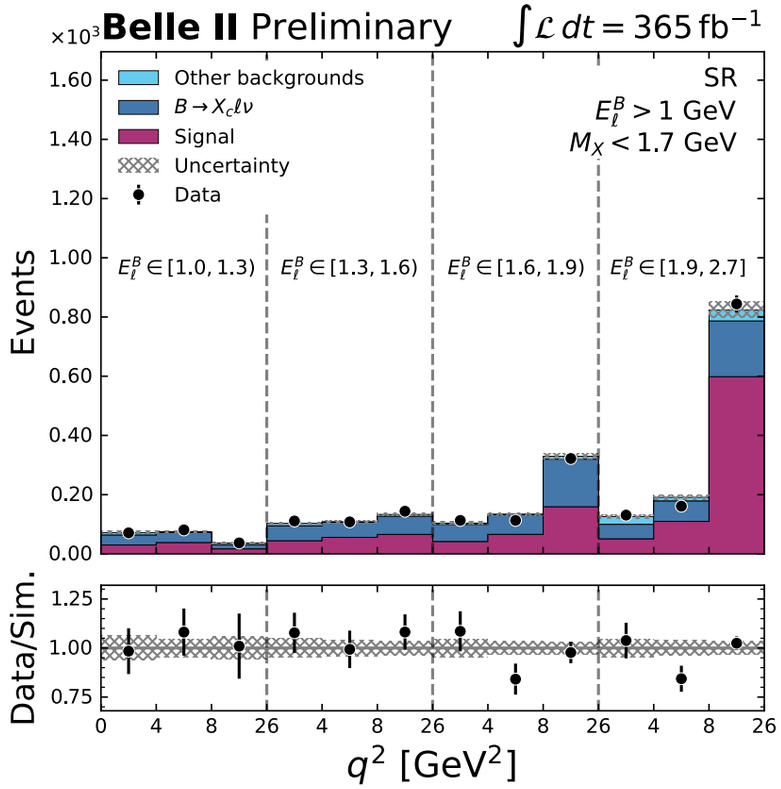

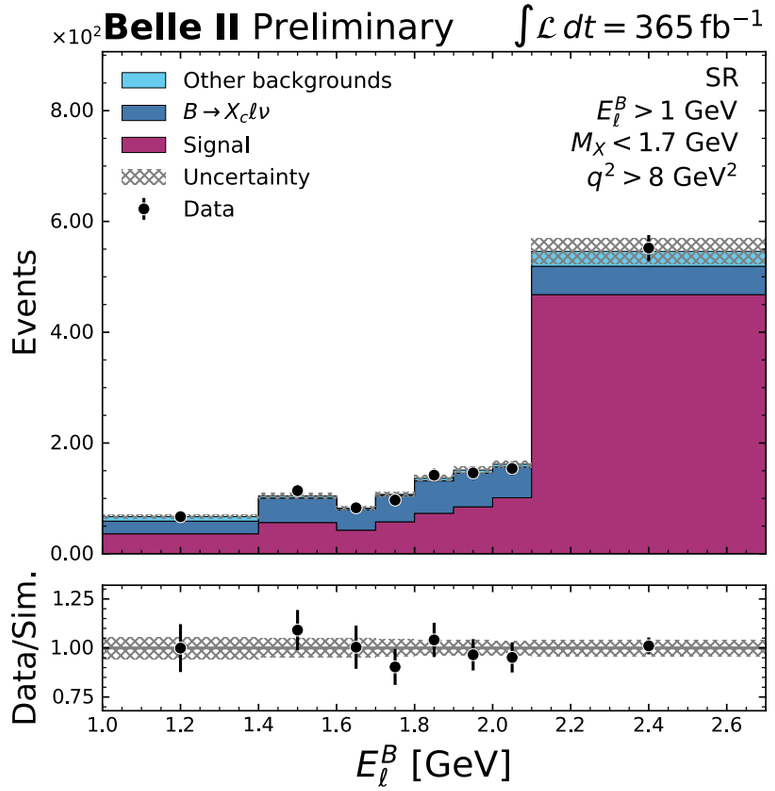

Acceptance / Purity

Inclusive $B \to X_u \ell \nu$

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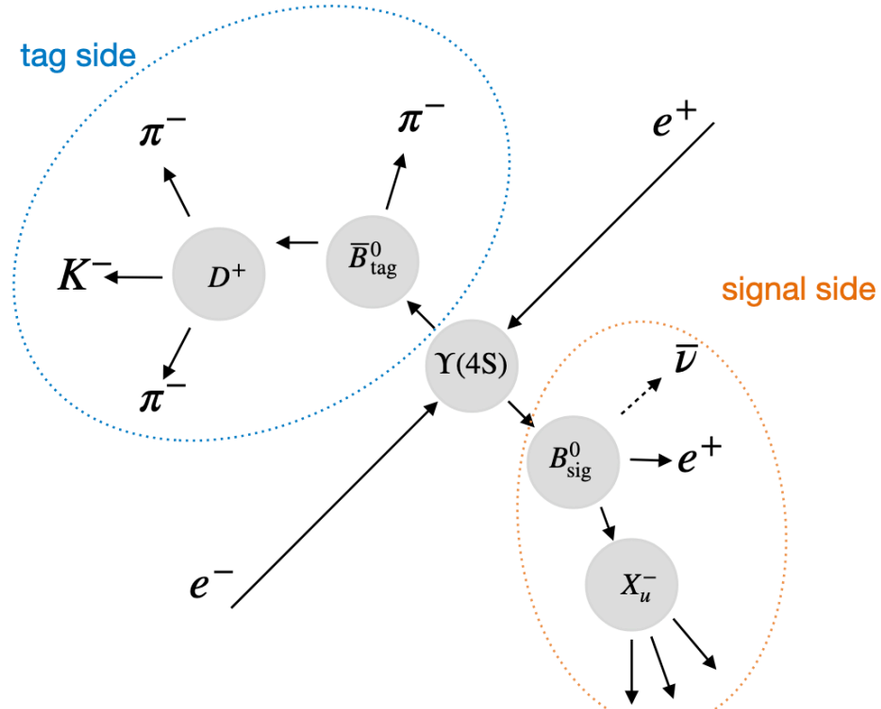
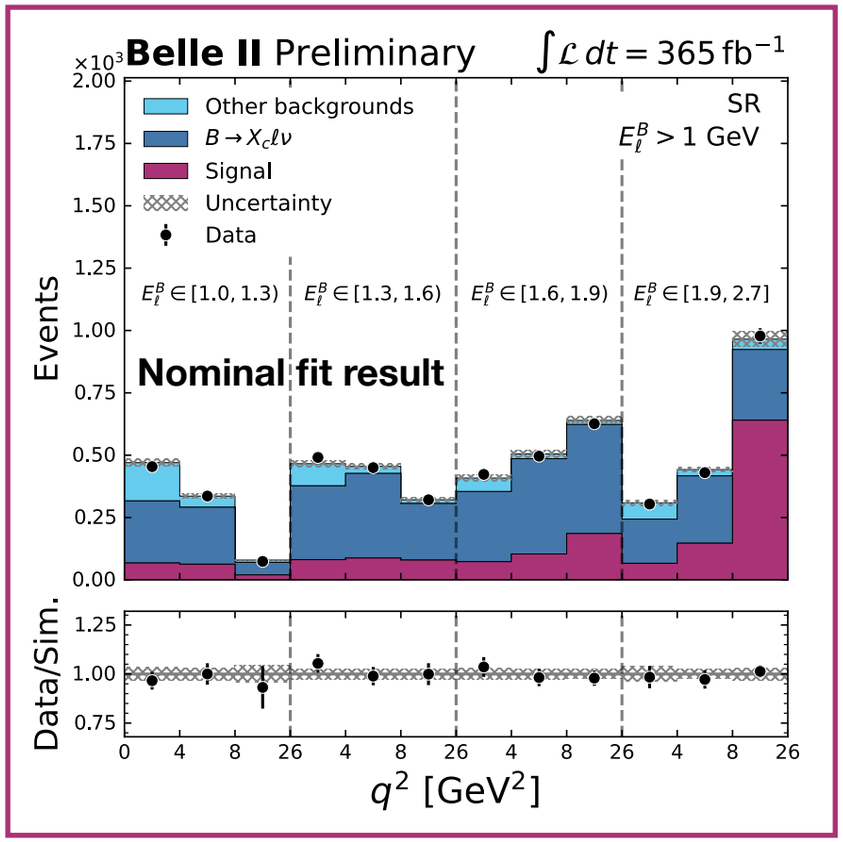
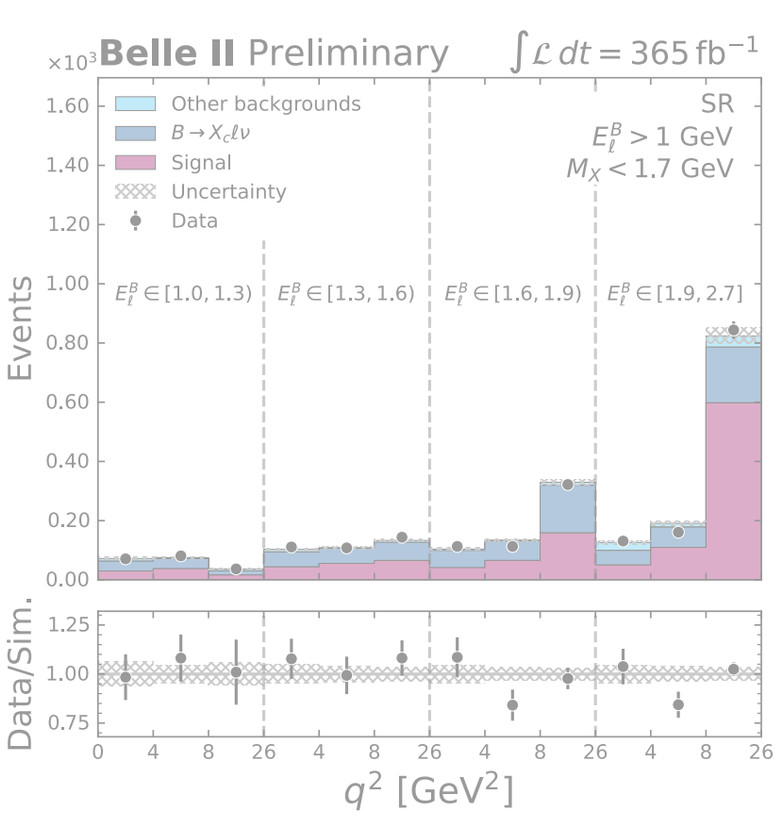
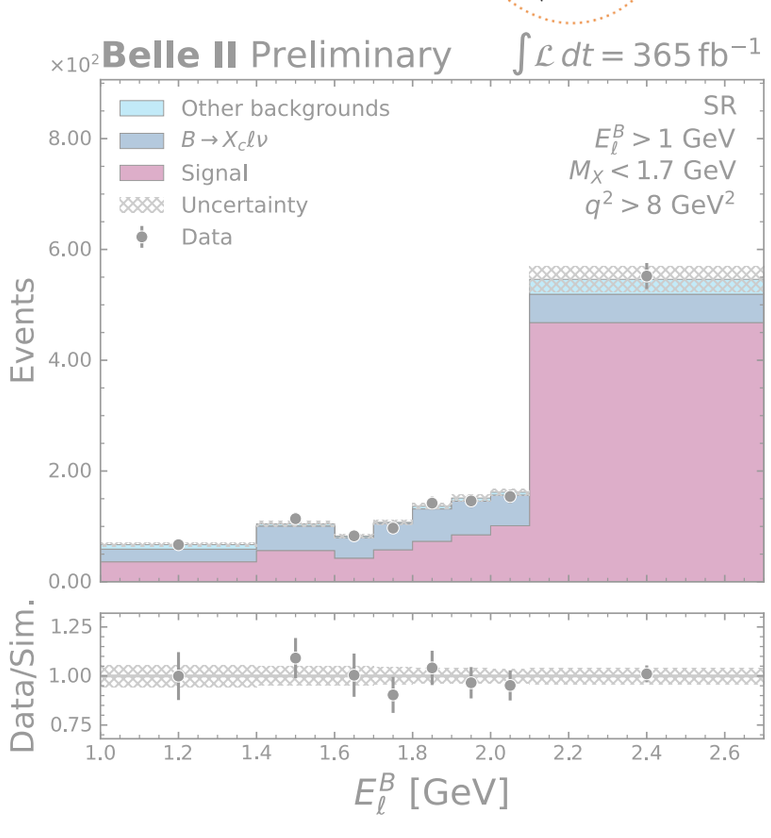
  - Normalization and shape mismodelling **corrected** using **control regions** in data
- **Extract signal** with 2D fit to lepton energy in B restframe E_ℓ^B & momentum transfer $q^2 = (p_\ell + p_\nu)^2$







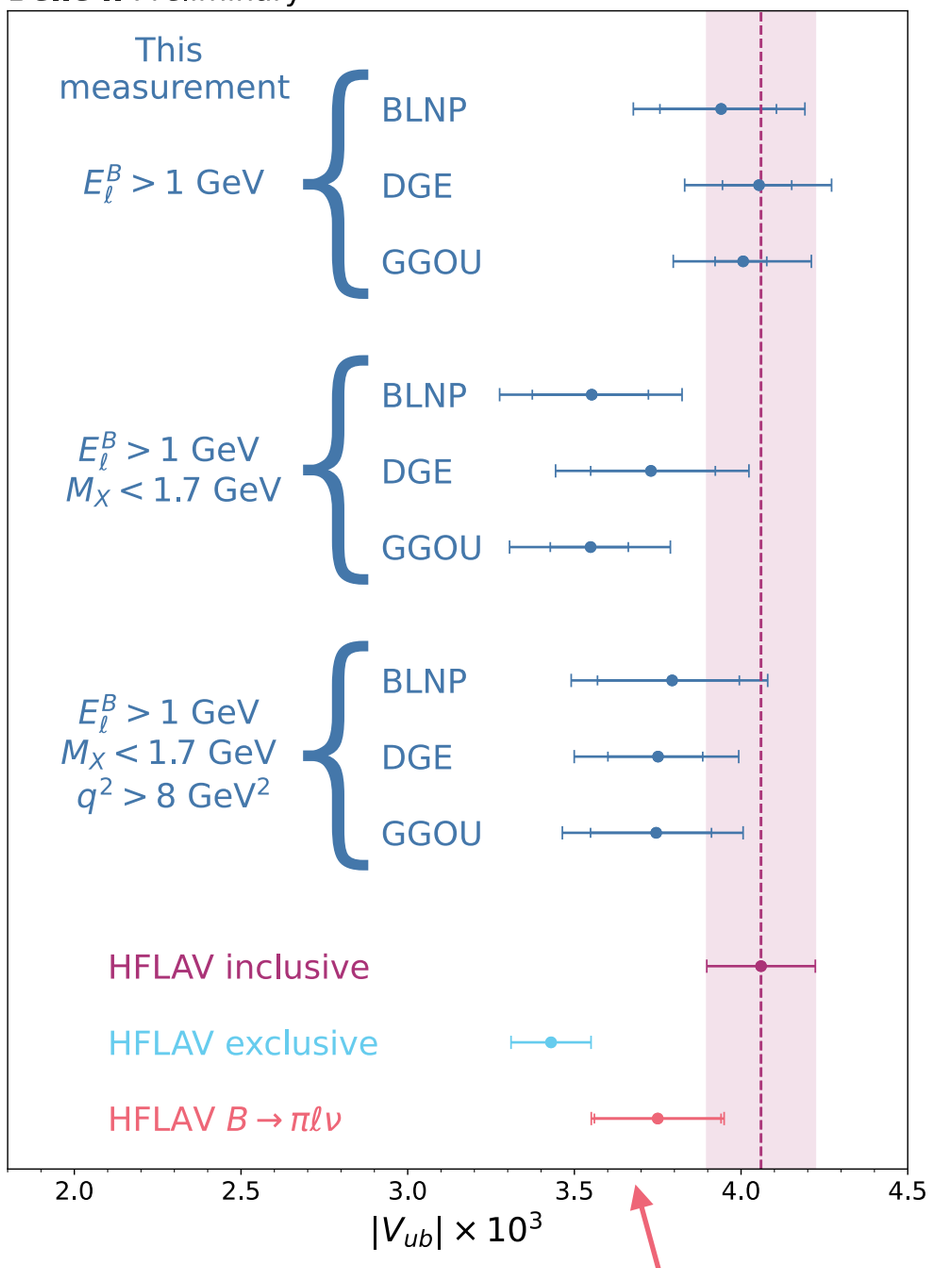


Acceptance / Purity

Inclusive $B \to X_u \ell \nu$

PRD 113 (2026) 3, 032004

Predictions of the partial rate



Exclusive Average for $B \to \pi \ell \nu$:

$$|V_{ub}| = (3.75 \pm 0.06_{\text{exp}} \pm 0.19_{\text{theo}}) \times 10^{-3}$$

Determine $|V_{ub}|$ from the measured **partial branching fractions** in the 3 different phase space regions:

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u \ell^+ \nu_\ell)}{\tau_B \cdot \Delta\Gamma(B \to X_u \ell^+ \nu_\ell)}}$$

Nominal result: $E_\ell^B > 1$ GeV with GGOU

$$|V_{ub}| = 4.01 \pm 0.11(\text{stat.}) \pm 0.16(\text{syst.})^{+0.07}_{-0.08}(\text{theo})$$

Covering 87% of phase space

Dominant systematics:

- $B \to X_u \ell \nu$ modelling: (m_b, a) where $a = f(m_b, \mu_\pi^2)$ in Kagan-Neubert scheme
- $B \to X_c \ell \nu$ composition differences between SR and CR
- X_u fragmentation modelling

Competitive with previous measurements!

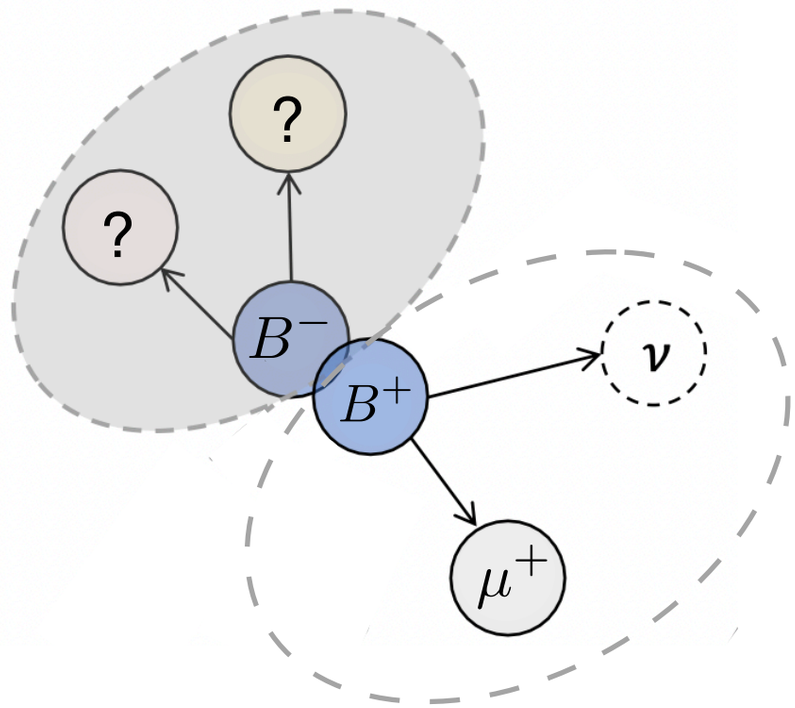
Inclusive $B^+ \to \mu^+ \nu$

Inclusive $B^+ \to \mu^+\nu$

arXiv:2602.09800

Submitted to PRD

- **Combines** Run 1 Belle II dataset with published Belle analysis
  - Update $b \to c$ & $b \to u$ modelling for Belle results
  - Total dataset: 1.1 ab^{-1}
- **Experimental signature:** mono-energetic ~2.64 GeV muon in the B-sig rest frame



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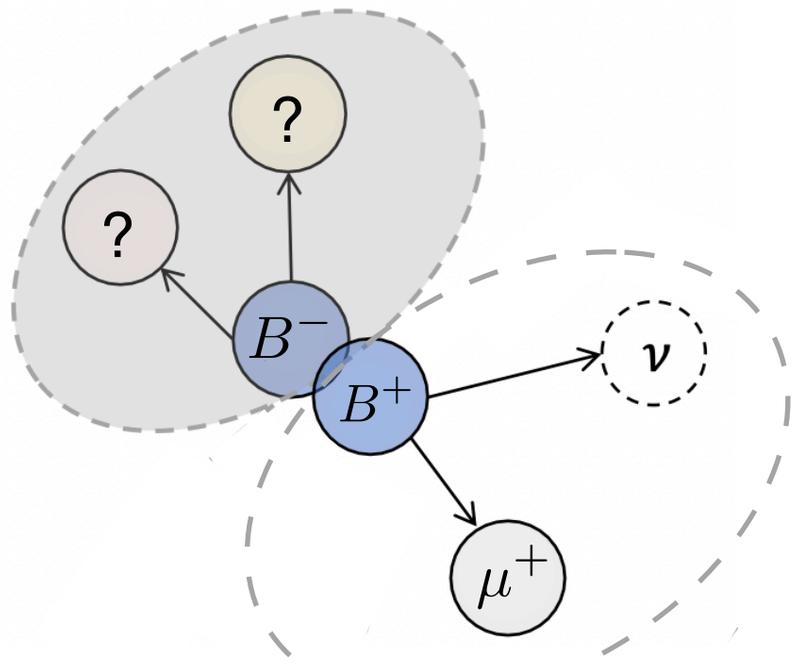
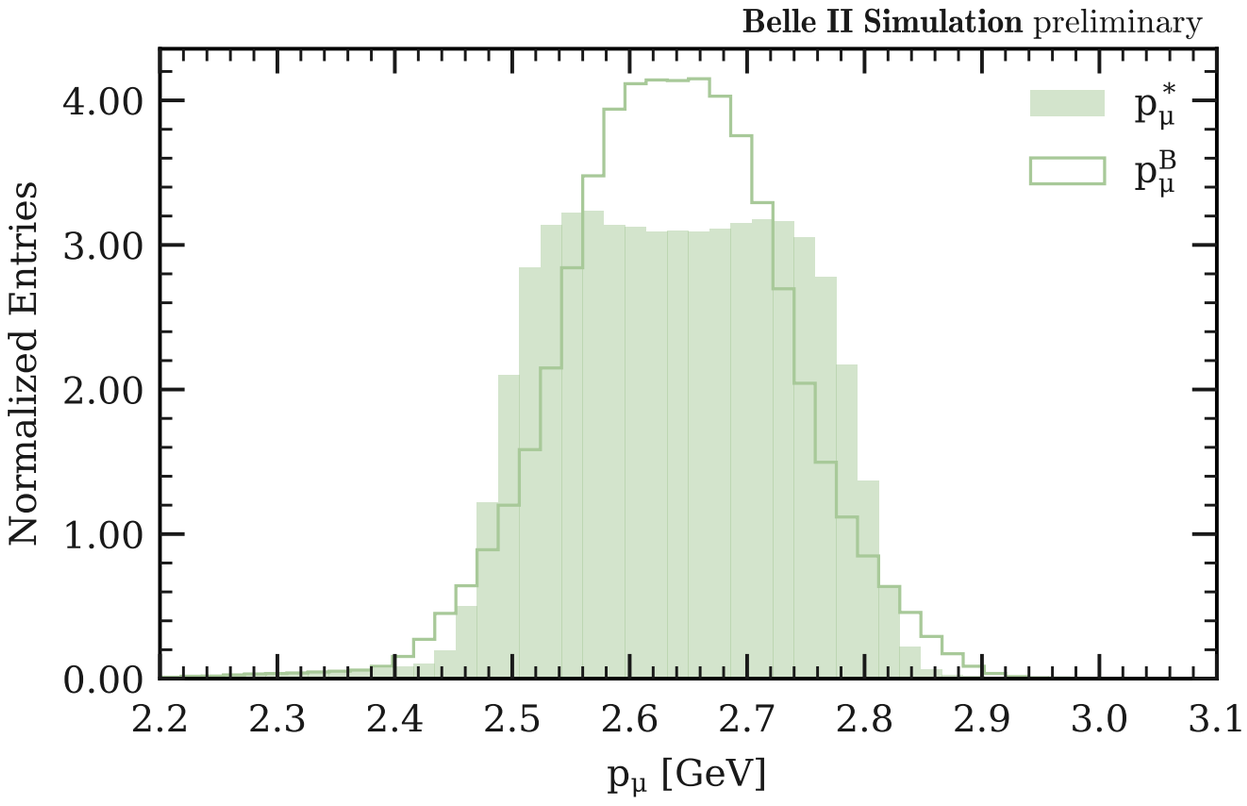
  - Inclusive B-tag reconstruction to boost in the approximate B-sig rest frame
  - Validated with $B^+ \to \bar{D}^0\pi^+$ data.





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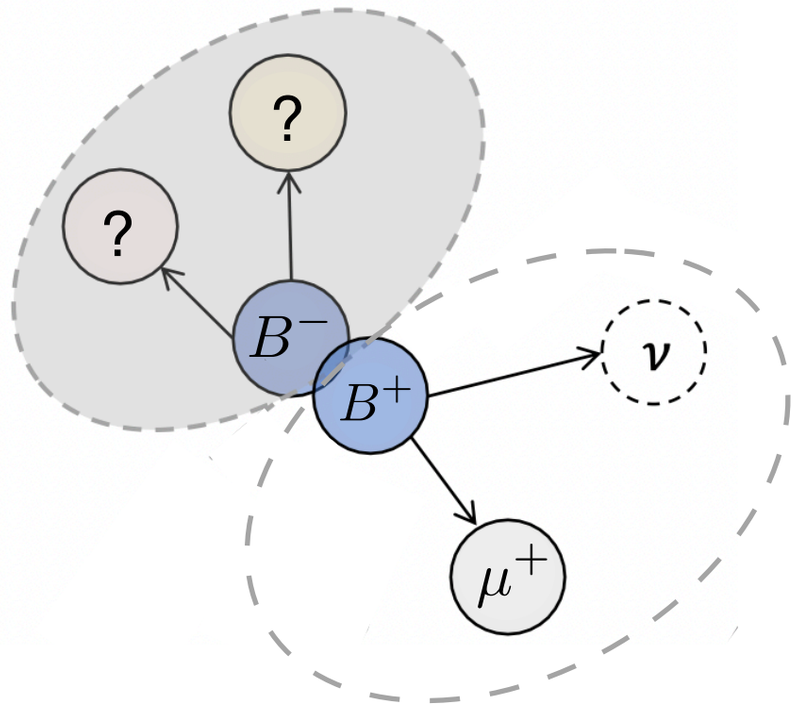
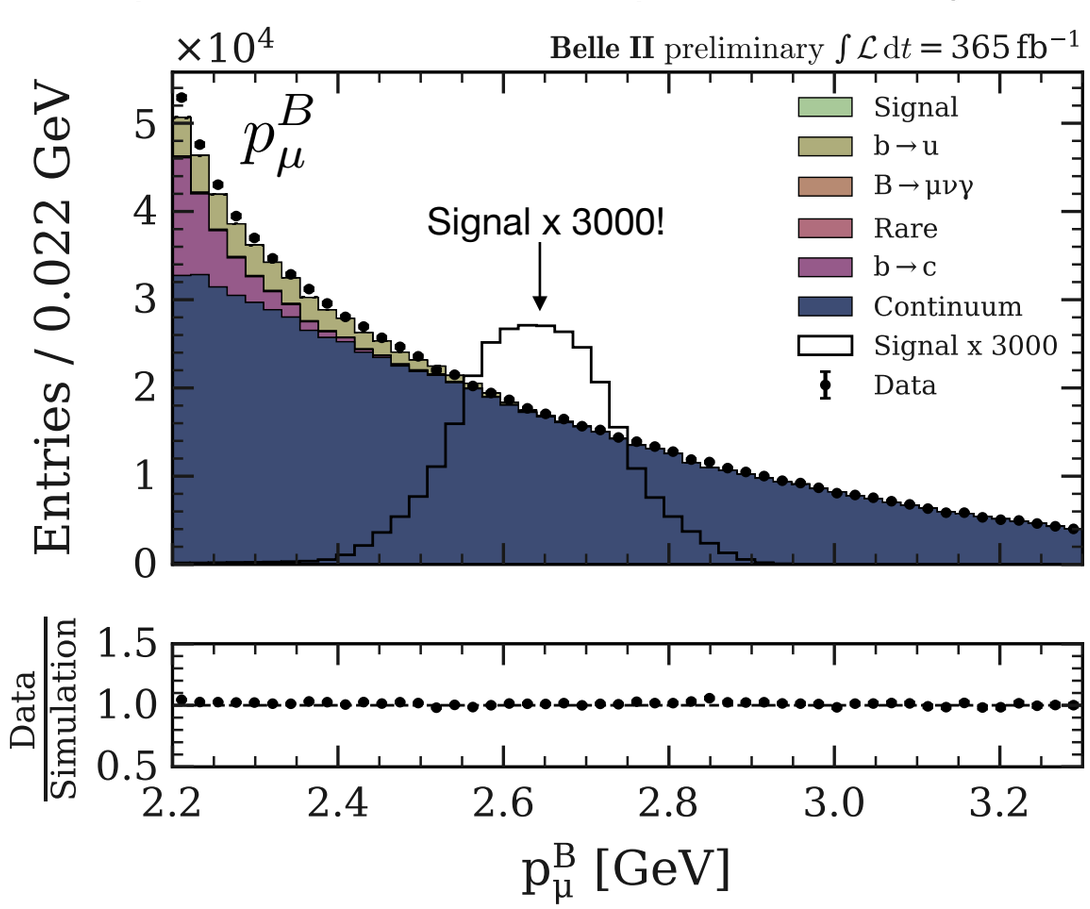
- **Challenging due to large backgrounds** from light quark production and semileptonic B decays





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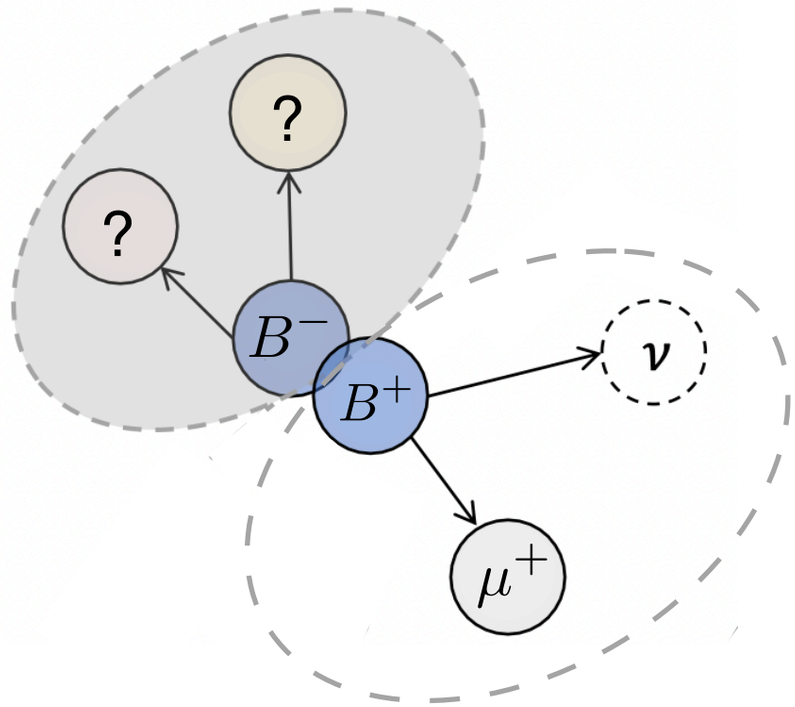
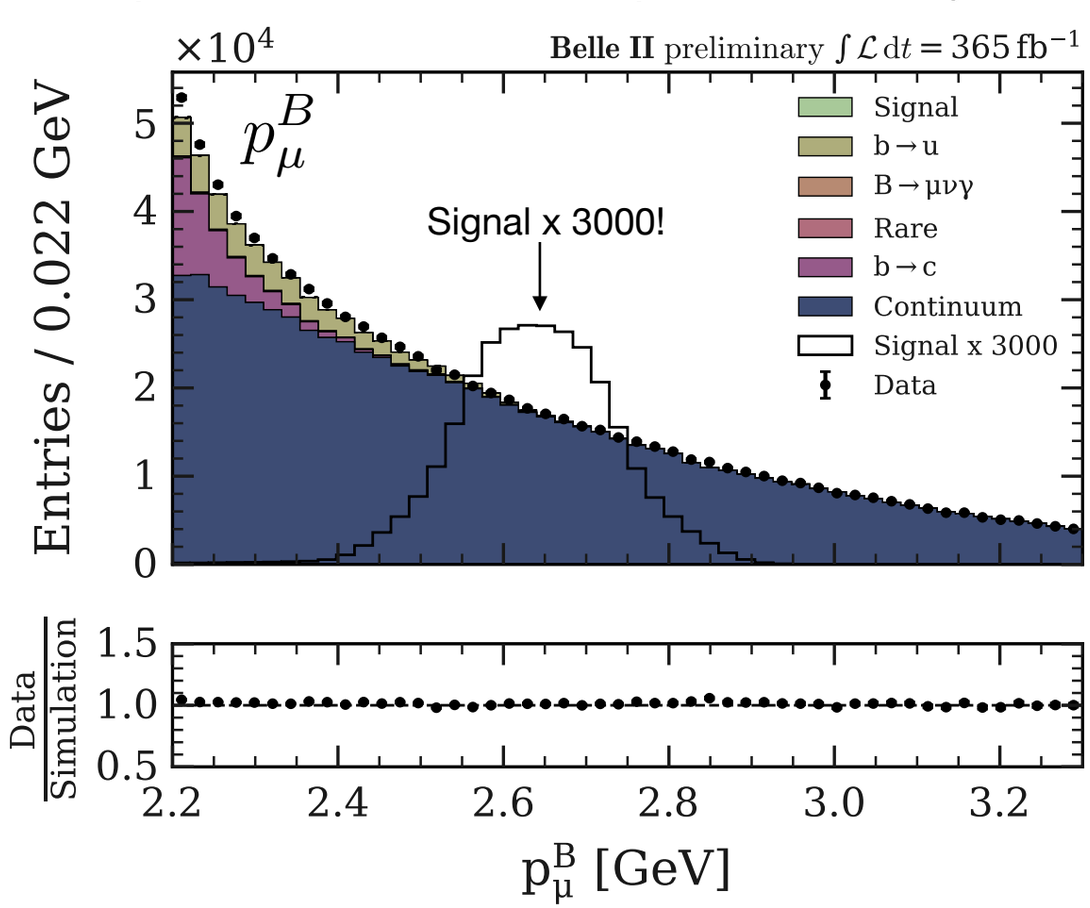
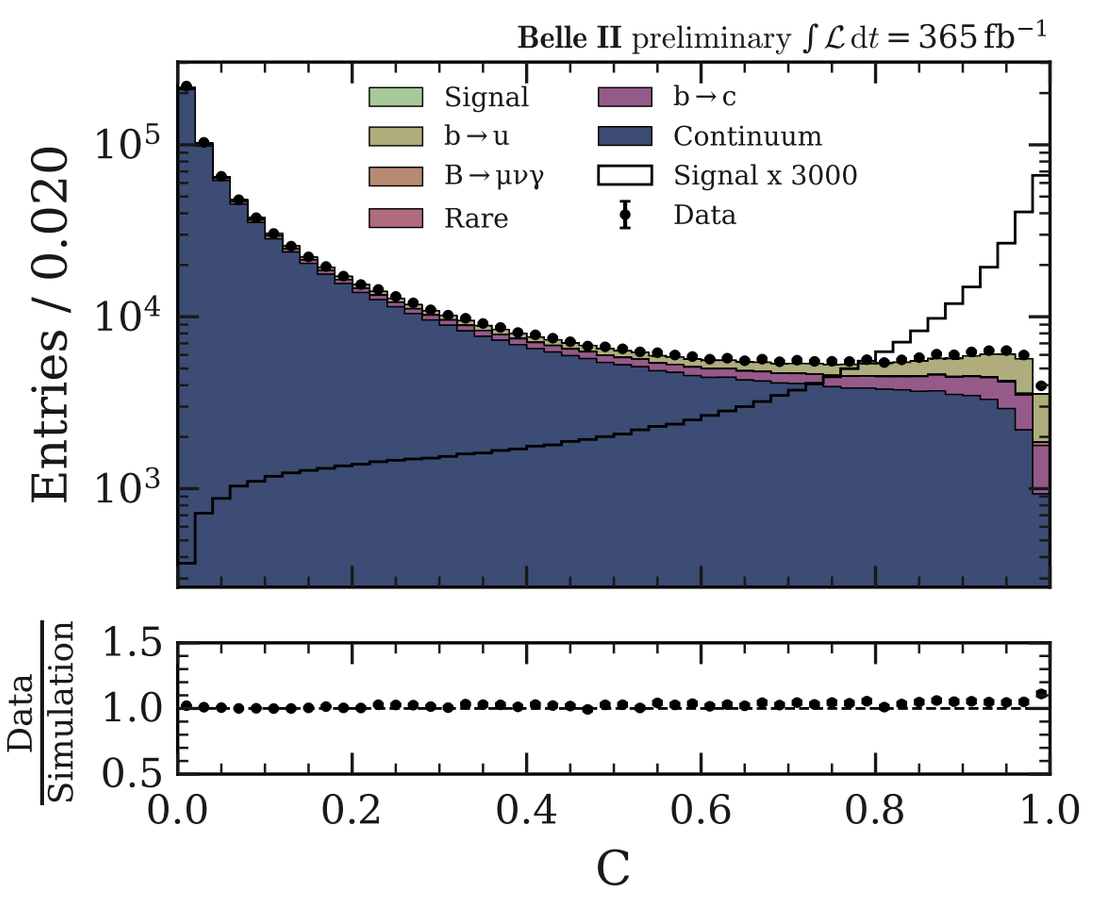




Suppress

with BDT!



Inclusive $B^+ \to \mu^+\nu$

arXiv:2602.09800

Submitted to PRD

- **Signal extraction:** Combined binned fit of p_μ^B in 4 (Belle) + 4 (Belle II) categories based on BDT output

Most precise measurement to date:

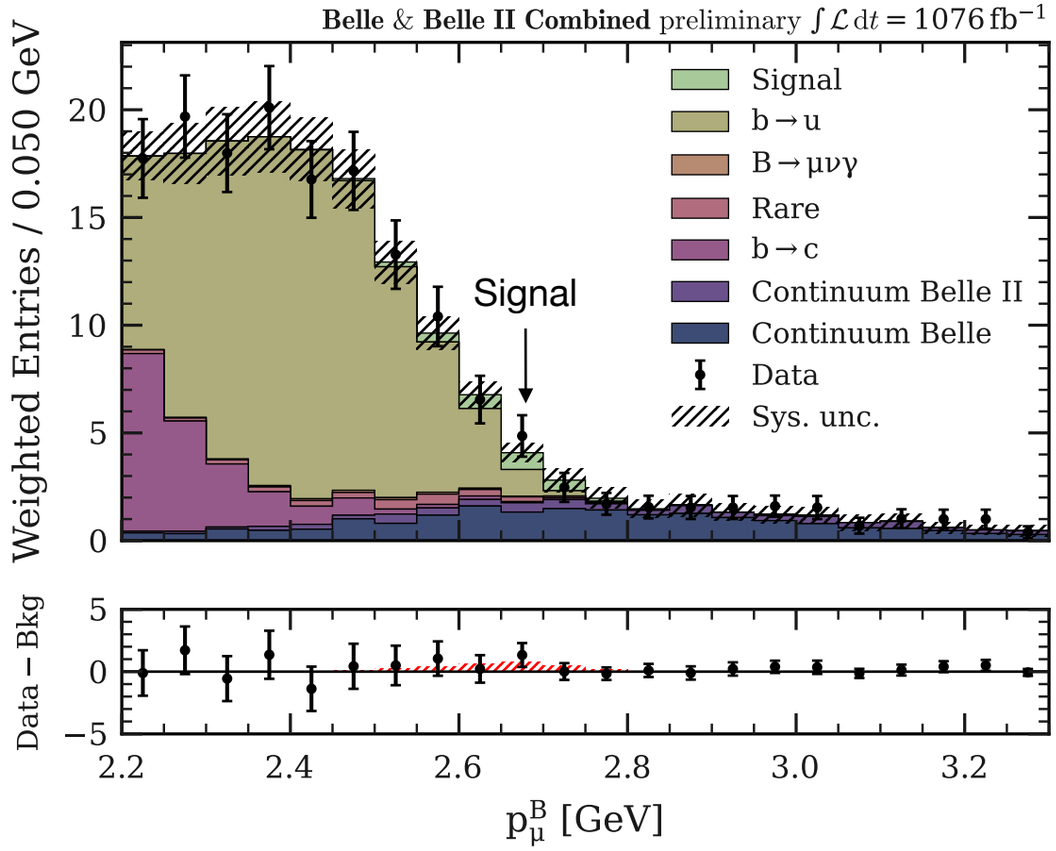
$$\mathcal{B}(B^+ \to \mu^+\nu_\mu) = (4.4 \pm 1.9 \pm 1.0) \times 10^{-7}$$

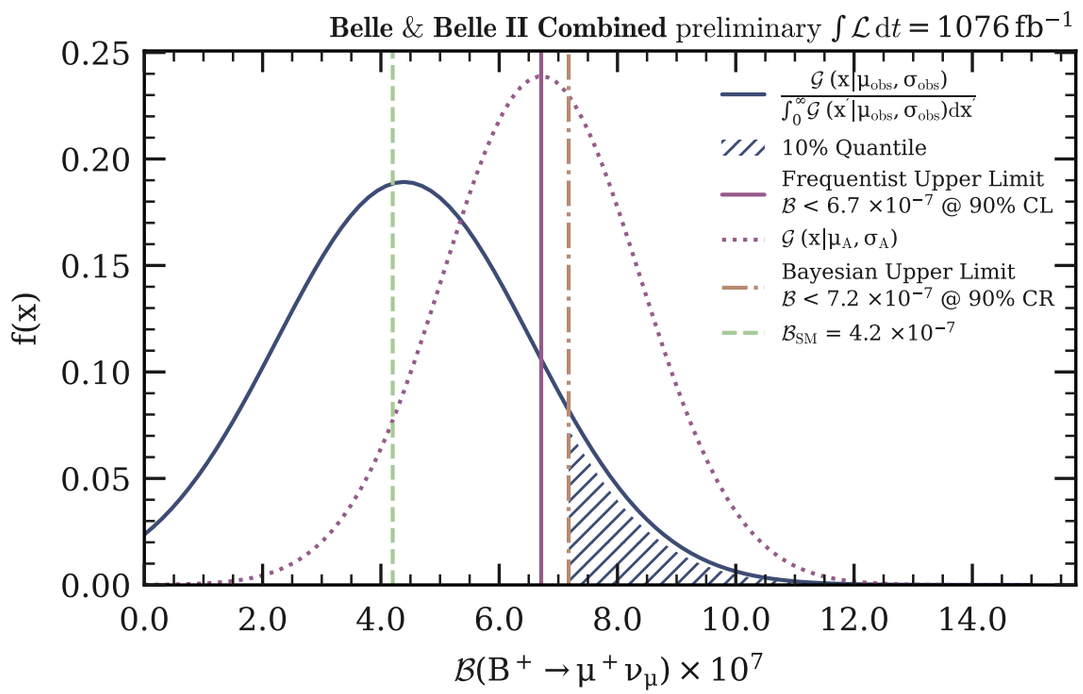
- 150 ± 73 signal events
- 2.4σ over background-only hypothesis
- Leading systematics:
  - $B \to u\ell\nu$ modelling
  - Continuum

Determination of exclusive $|V_{ub}|$

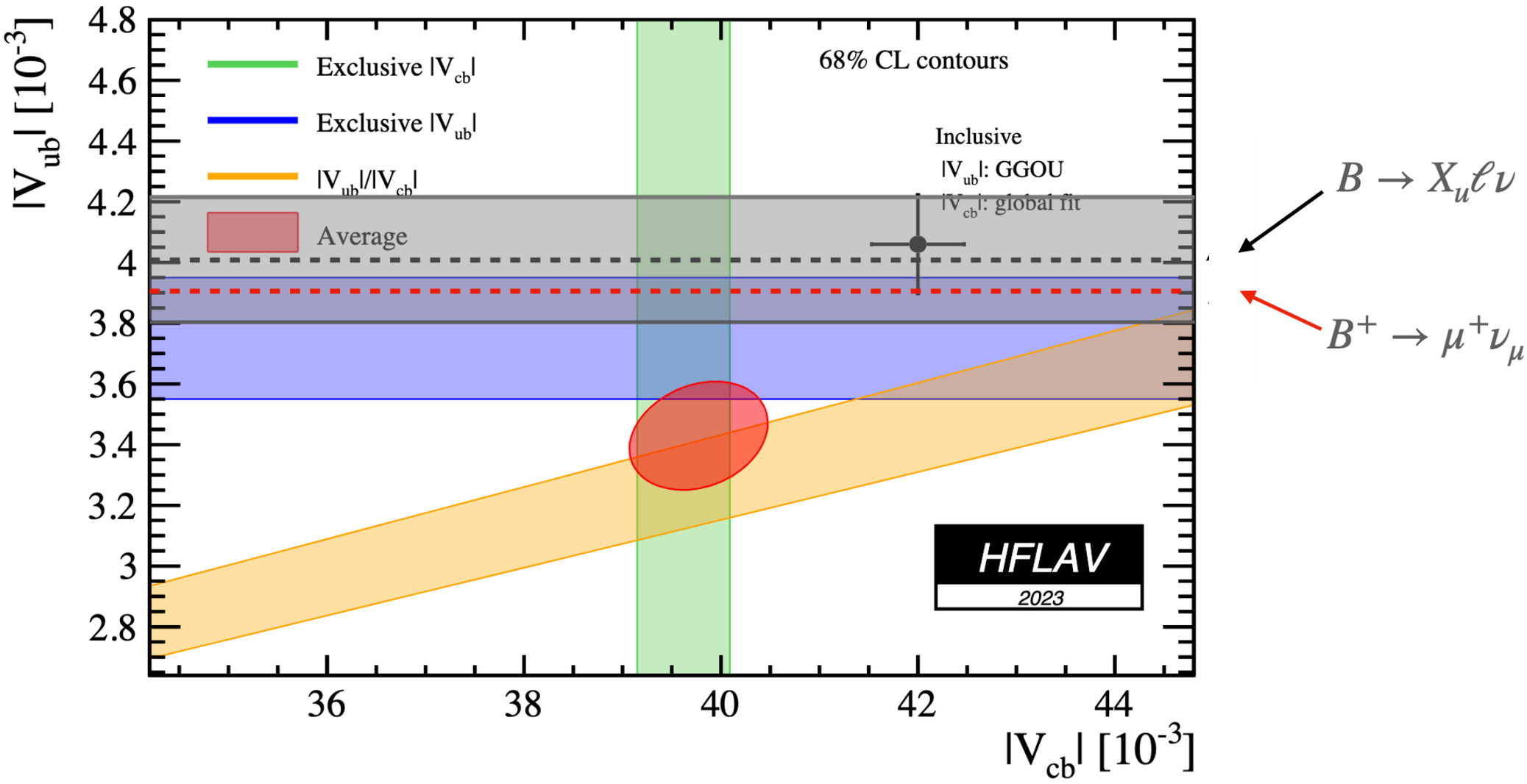
$$|V_{ub}| = 3.92^{+0.77}_{-0.96}(\text{stat.})^{+0.44}_{-0.49}(\text{syst.}) \pm 0.03(\text{theo})$$

Compatible with both inclusive and exclusive determinations





$|V_{ub}|$ results in context



$B \to X_u \ell \nu$: $|V_{ub}| = (4.01 \pm 0.11 \pm 0.16^{+0.07}_{-0.08}) \times 10^{-3}$

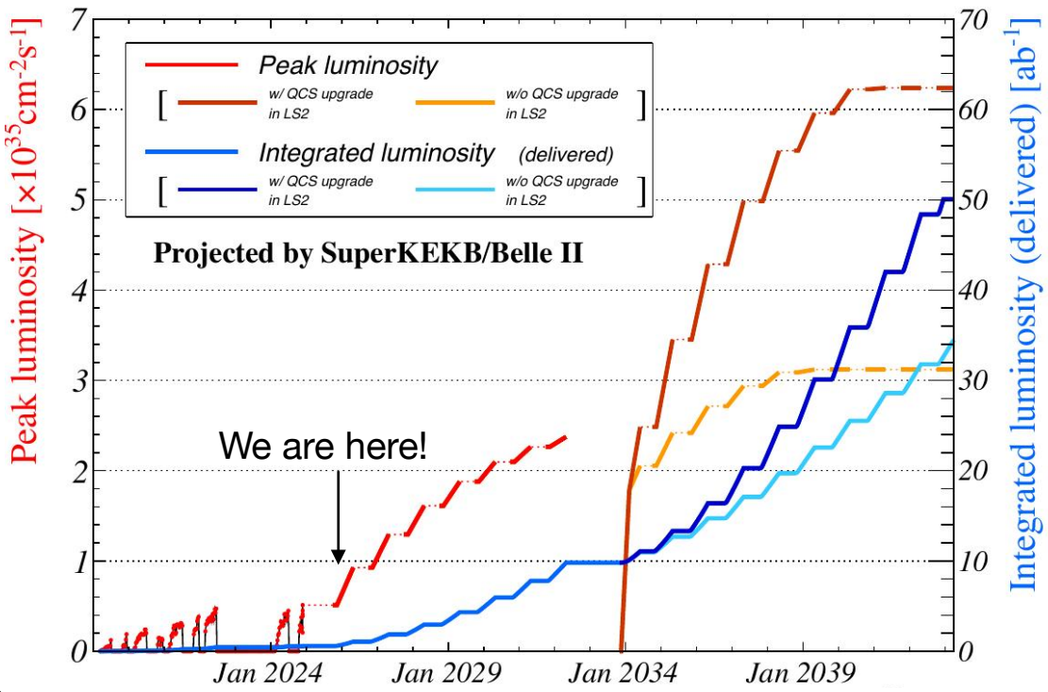
$B \to \mu \nu$: $|V_{ub}| = \left(3.90^{+0.77}_{-0.96}\,(\text{stat.})^{+0.43}_{-0.49}\,(\text{sys.}) \pm 0.03\,(\text{theo.})\right) \times 10^{-3}$

Conclusion & Outlook

Belle II offers a unique and fertile environment for precision measurements of semileptonic B decays.

Very active field, with **innovative strategies** of measuring V_{ub}, V_{cb} and tests of lepton flavour universality.

- With the current collected data set, Belle II already produces **world-leading and unique** results!
- The well-understood Belle data set is still used to squeeze out **interesting measurements**.
- Collaboration between **theory and experiment** crucial to solve ongoing puzzles!



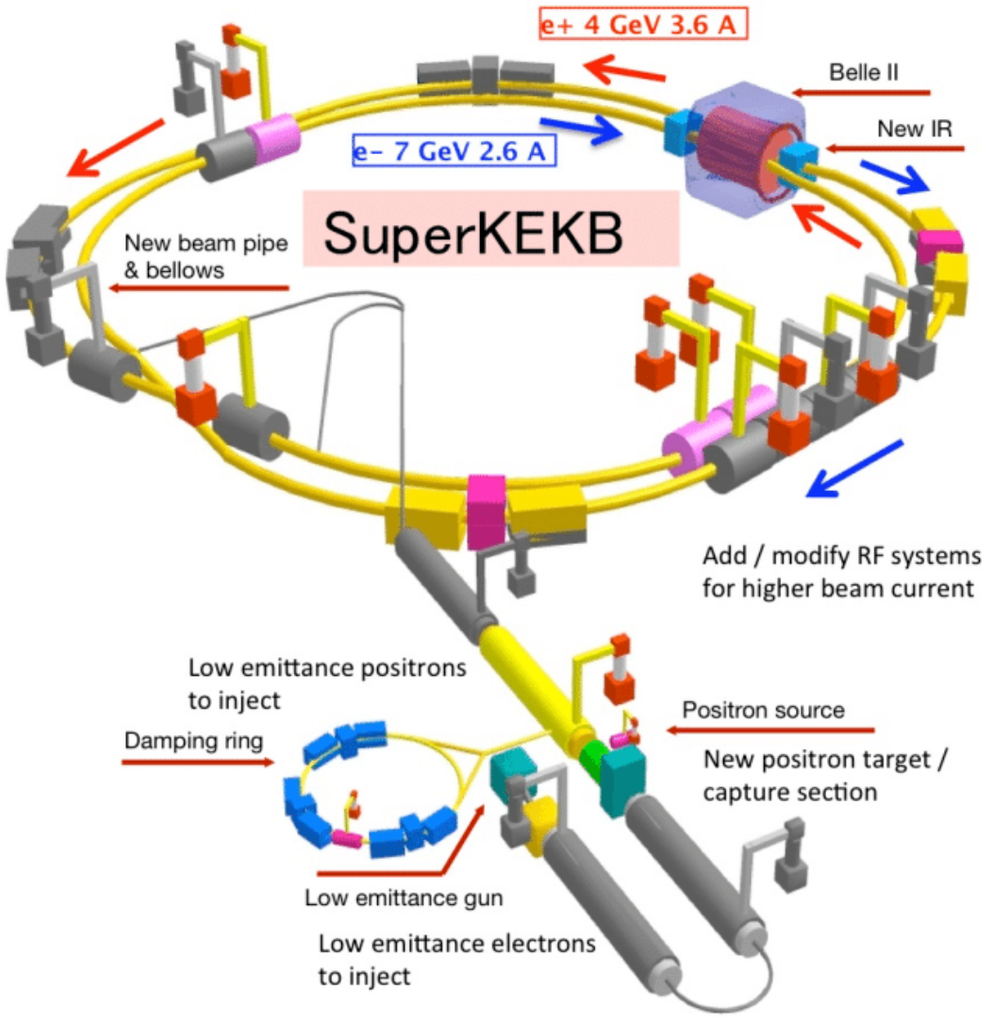
Exciting, new **results** are on the way!

SuperKEKB in a nutshell

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

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

with record 5.1 x 10^{34} $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ already achieved!



How to increase luminosity:

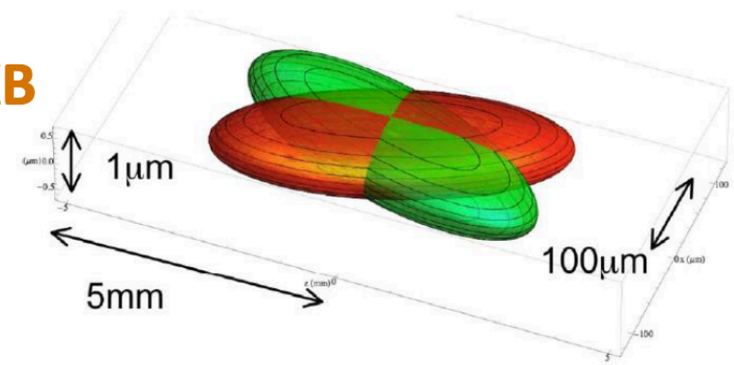
Beam current **x 1.5**

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

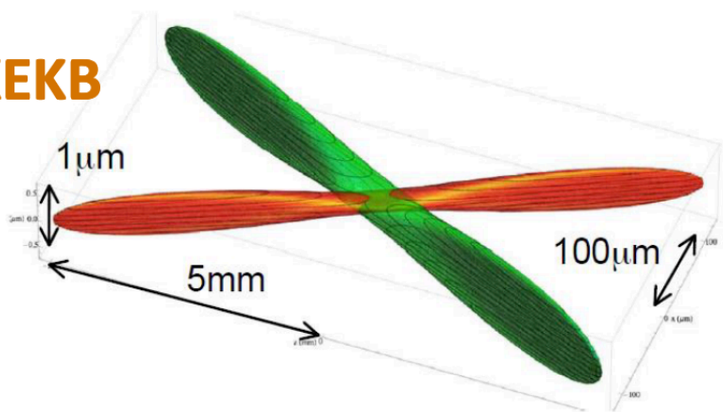
Vertical β function **x 1/20**

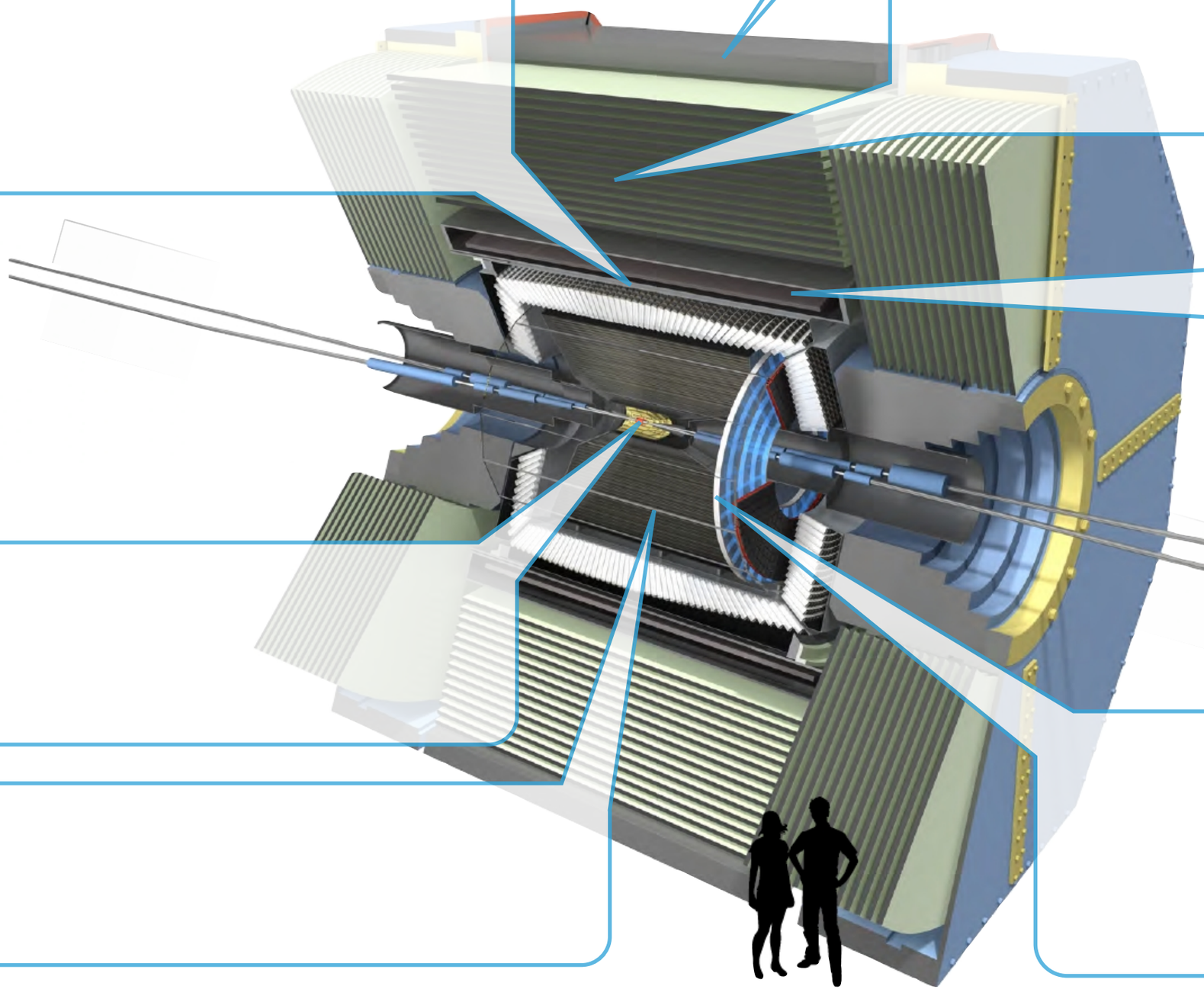
Nano-beam scheme: Squeeze vertical beam spot size down to ≈ 50 nm using superconducting focusing magnets.

KEKB



SuperKEKB





Trigger:

Hardware: < 30 kHz

Software: < 10 kHz