Latest results on beauty and charm hadron decay at Belle II

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KEK High Energy Accelerator Research Organization

Belle II

Outline

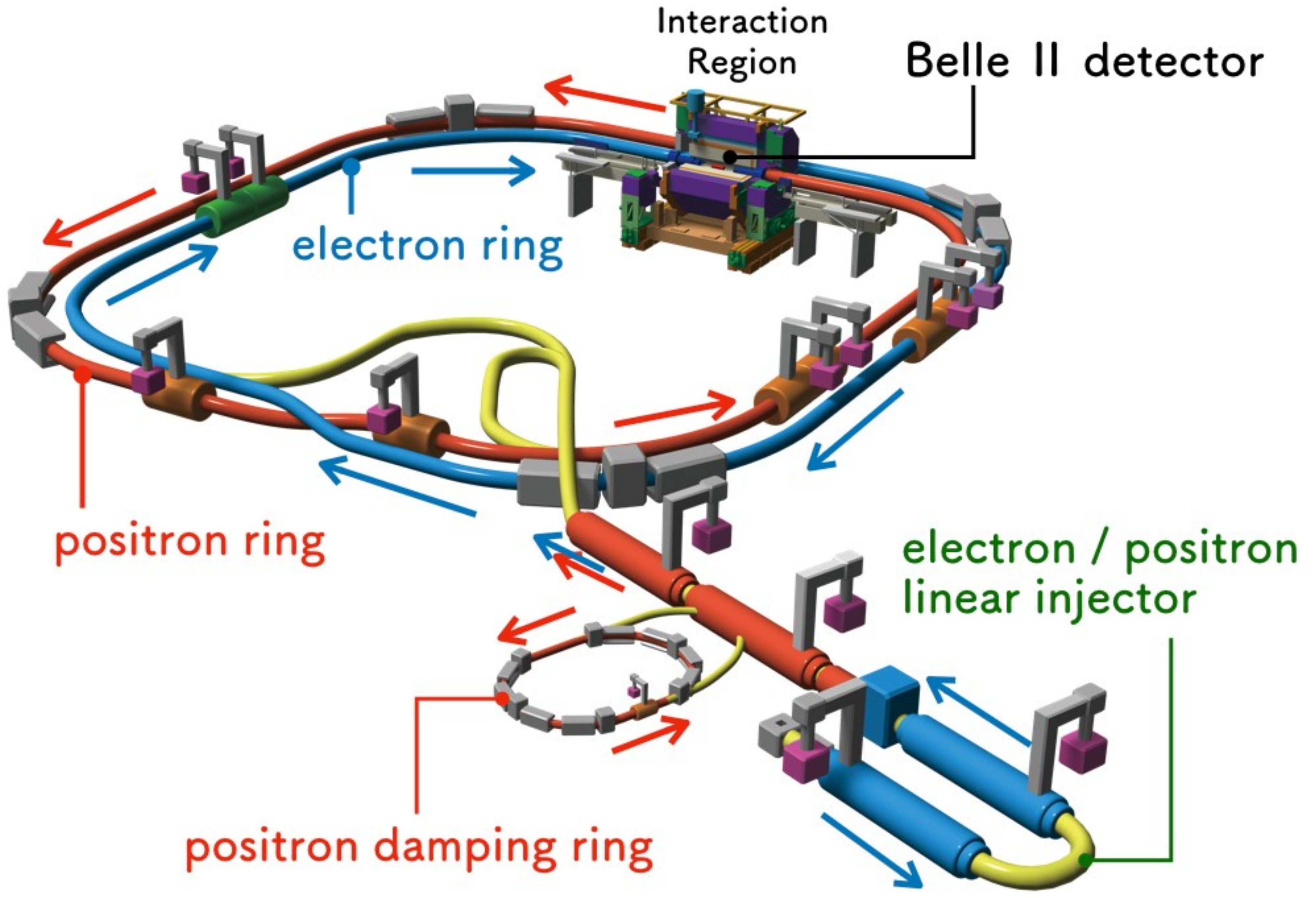
- B Physics
- Introduction to Belle II experiment
- Recent Results
  - Charm Lifetime
  - $B^+ \to K^+\ell^+\ell^-$ measurement
  - $B^+ \to K^+\nu\bar{\nu}$ measurement
  - ϕ_3/γ measurement with $B \to D^{(*)}h(h = K/\pi)$ decays
  - Semileptonic decays (Inclusive $B \to X_c\ell\nu$, Exclusive $B \to D^{(*)}\ell\nu$)
- Outlook

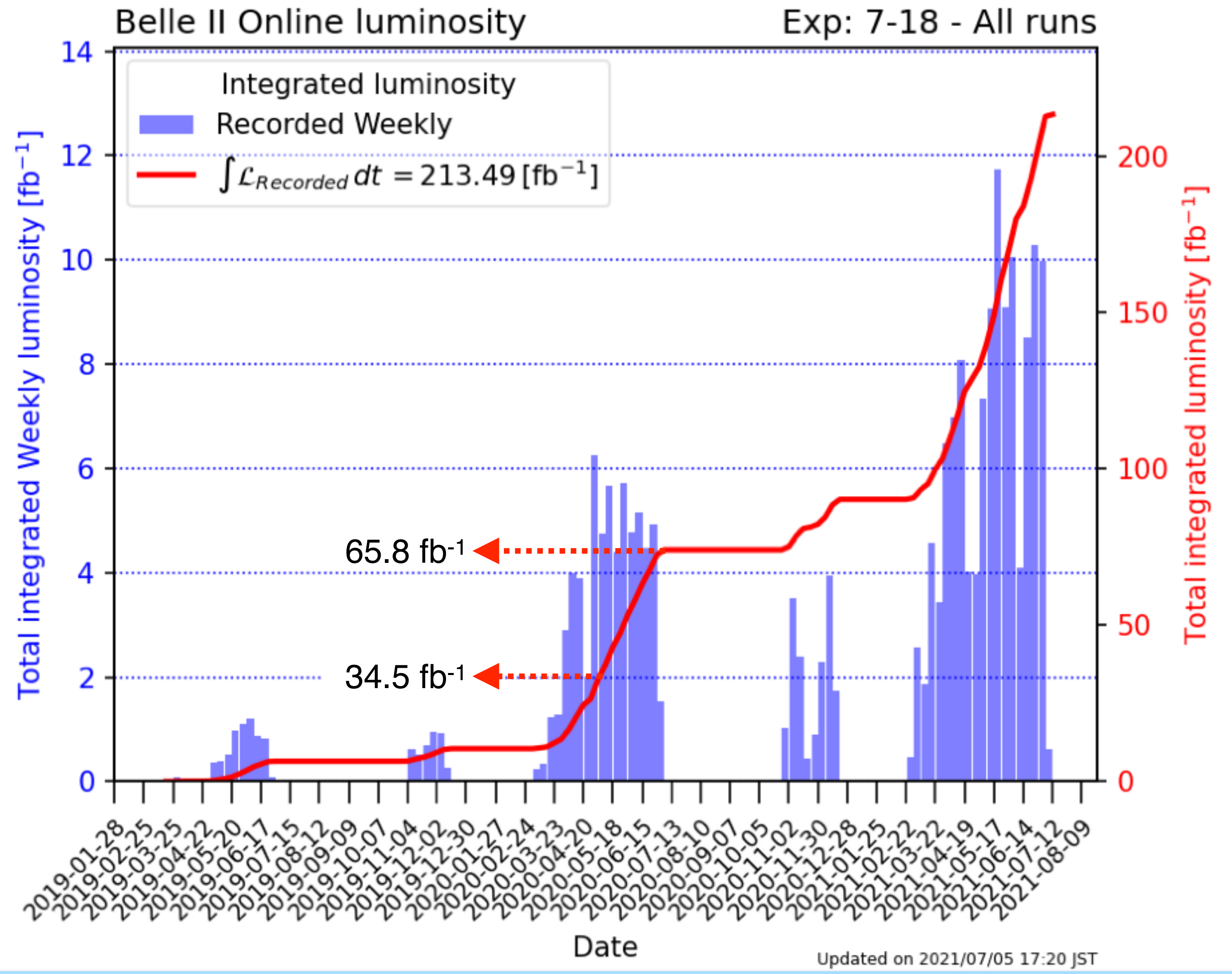
B Physics and B factories

- **Weak decays** of B meson → tests of the Standard Model and its parameters.
  - Determination of the weak mixing angles,
  - Test the unitarity of the Cabibbo- Kobayashi-Maskawa (CKM) matrix,
  - CP violation.
  - New Physics (beyond the Standard Model)
- e+e− experiments at the Υ(4S) resonance → a lot of information on heavy-quark decays
- B factories: SLAC, **KEK**, Cornell, and DESY
  - Clean environment → Efficient detection of neutrals (γ, π^0, η, …)
  - $B^0\bar{B}^0$ pairs → effective flavor tagging efficiency : ~34%(Belle II) ~5% (LHCb)
  - Large sample of τ leptons
  - Full reconstruction tagging possible → a powerful tool to measure
    - b→u semileptonic decays (CKM)
    - decays with large missing energy

SuperKEKB

- Asymmetric e^+e^-collider with center-of-mass energy at $B\bar{B}$ threshold (10.58 GeV)
- e^+e^- collisions very clean compared to pp collisions
- Aims at an integrated luminosity of $50\,\mathrm{ab}^{-1}$ (50 $\times$ Belle) $\rightarrow$Challenge harsh beam background conditions
- Plan to deliver collisions at a peak luminosity of $6.5 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- 30 $\times$ Luminosity of KEKB achieved by
  - $\times$ 1.5 beam current increase
  - $\times$ 20 beam size decrease

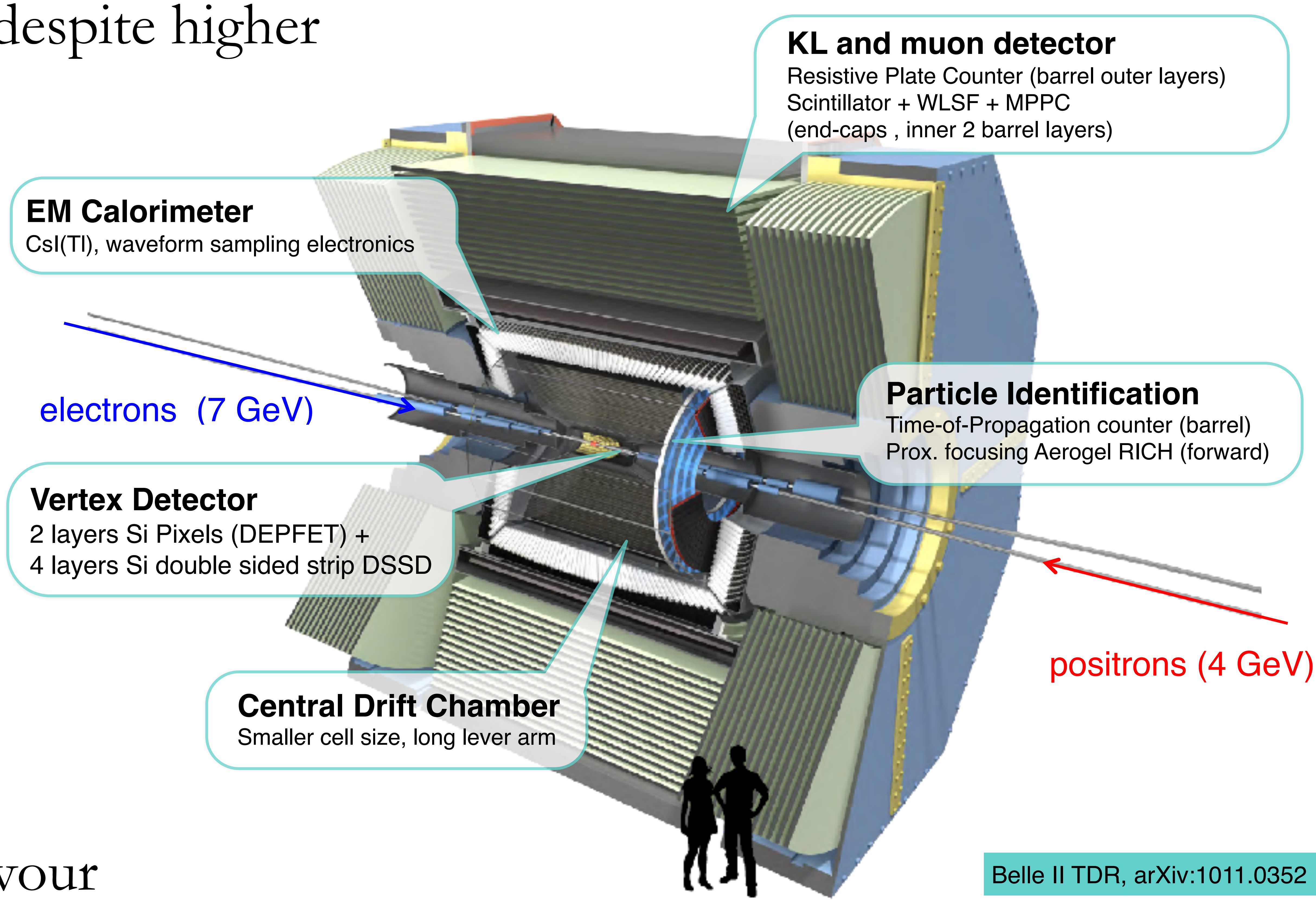




- Data taking till Summer run 2021: 213.49 fb^{-1}
- Peak luminosity record: $3.1 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

The Belle II Detector

- Designed to operate with a performance better than Belle despite higher backgrounds
- Belle II enables us
  - K/π separation compatible with Belle
  - High reconstruction efficiency with very low trigger bias
  - Better reconstruction of final states containing photons from π^0, $\boldsymbol{\rho}^{\pm}$, η
  - Neutral K_L mesons efficiently reconstructed.
  - Better K_s efficiency
  - Detection of the decay products of one B allows the flavour of the other B to be tagged.
  - Good vertex resolution
  - Analyses of missing mass since initial state perfectly known
  - Production of large sample of charm mesons and τ leptons



Belle II TDR, arXiv:1011.0352

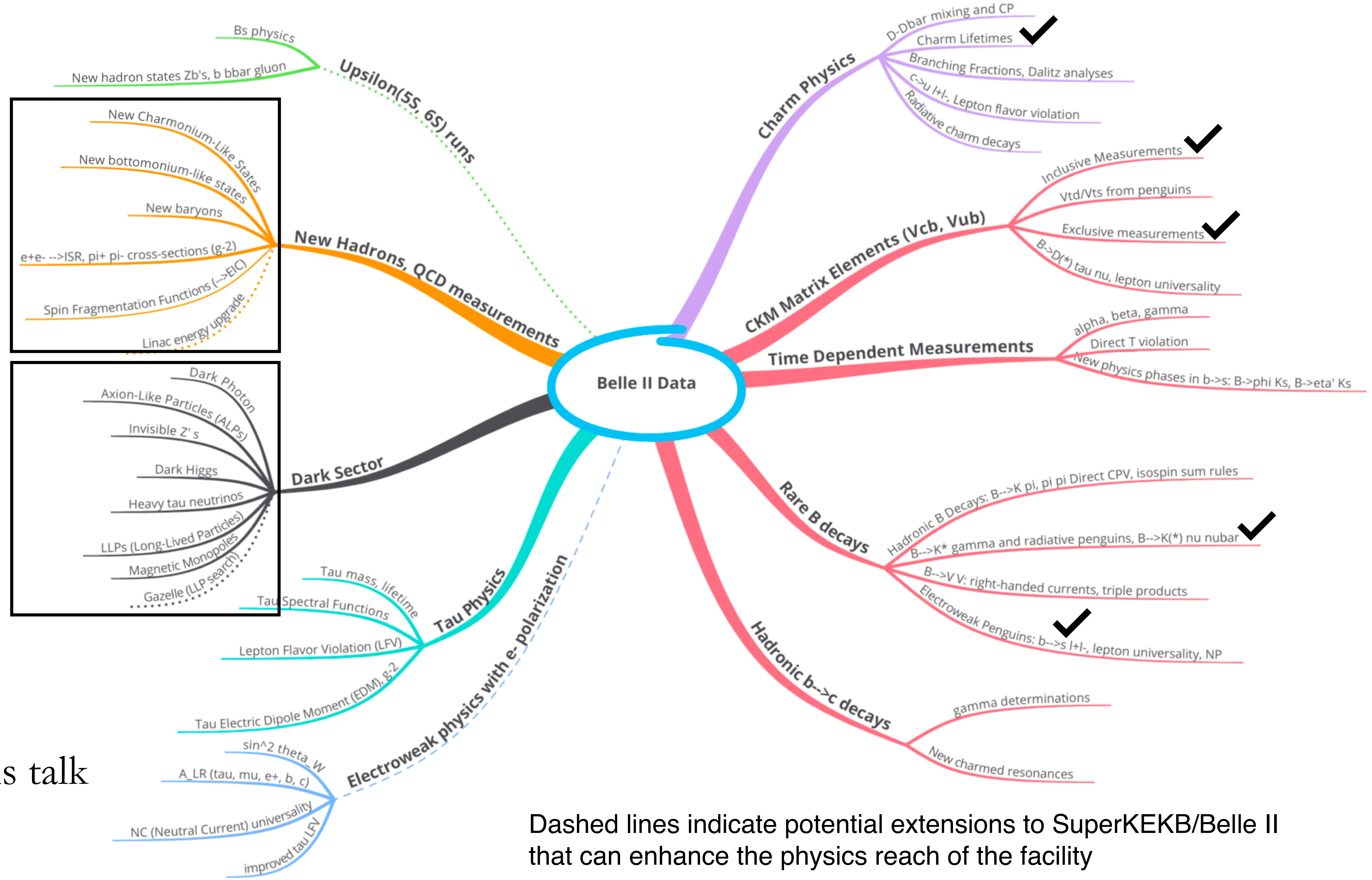
$$\Upsilon(4S) \rightarrow B^+B^-(\sim 51.5\%)$$
$$\Upsilon(4S) \rightarrow B^0\bar{B}^0(\sim 48.5\%)$$

Belle II Physics Program

Talk: "The Belle II prospects for charmonium and bottomonium studies" by **Pavel Krokovny**

Talk: "Latest results on the dark sector and tau physics at Belle II" by **Ewan Hill**

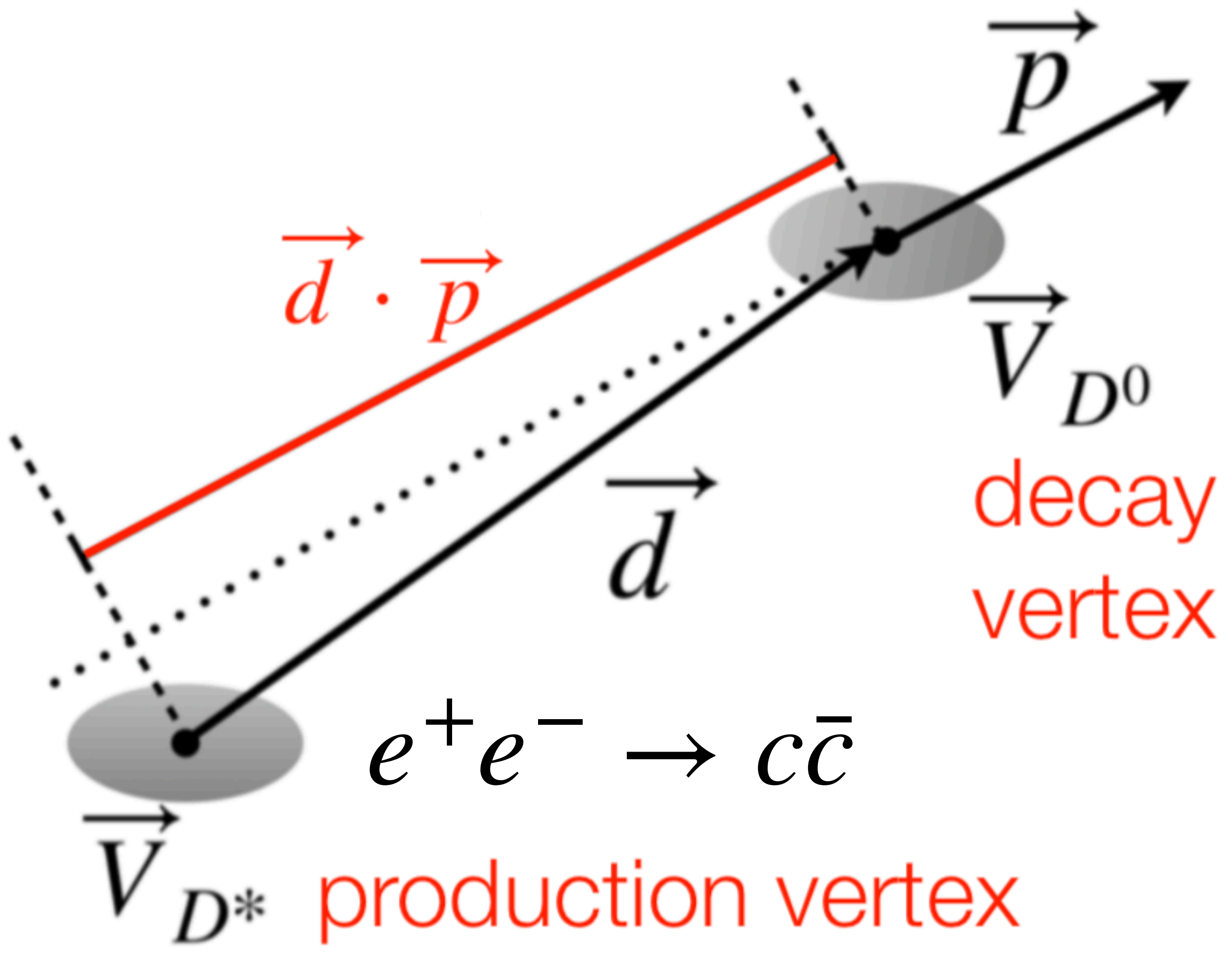
✔ Topics I will cover in this talk



Dashed lines indicate potential extensions to SuperKEKB/Belle II that can enhance the physics reach of the facility

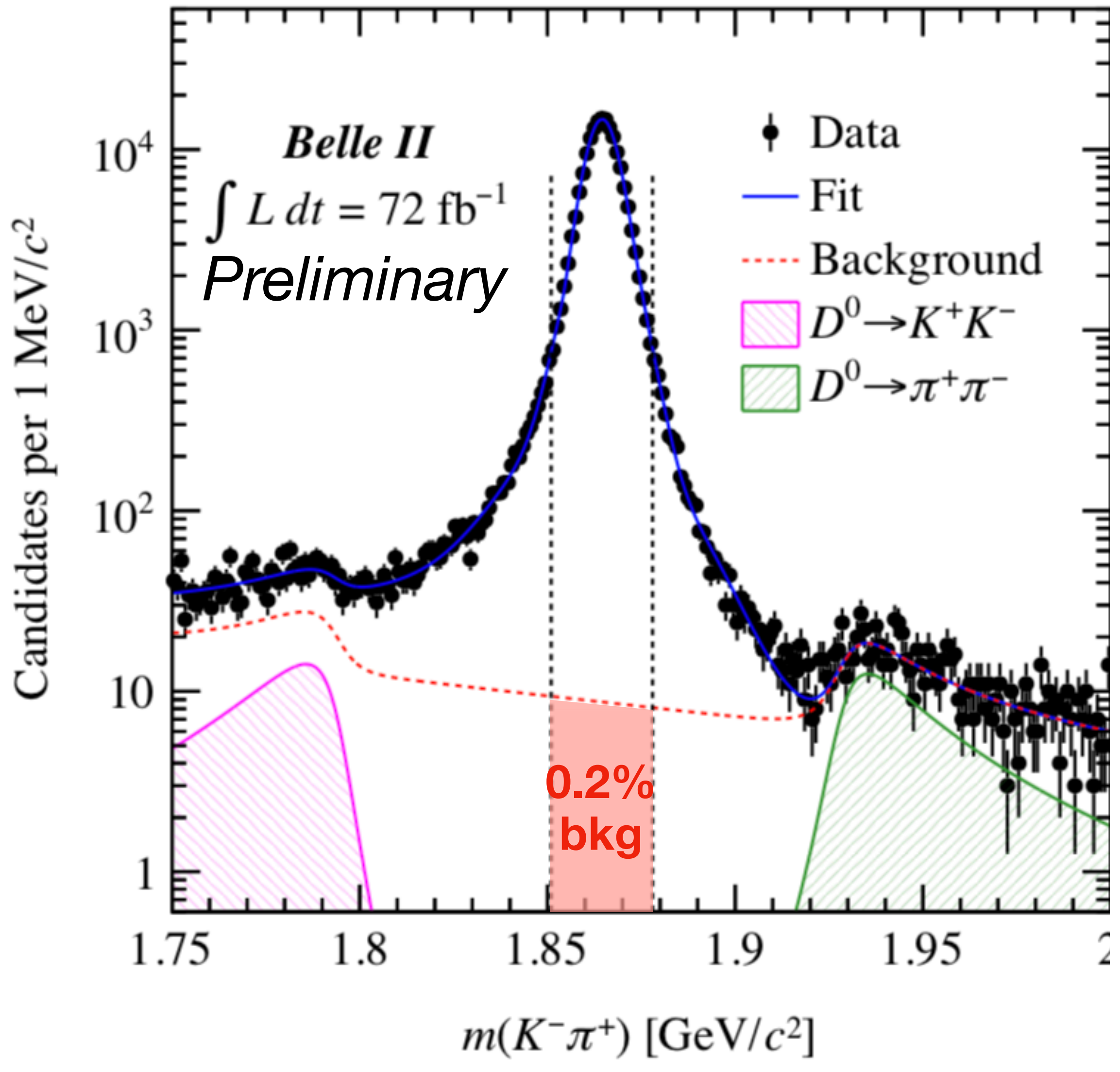
Charm Lifetime

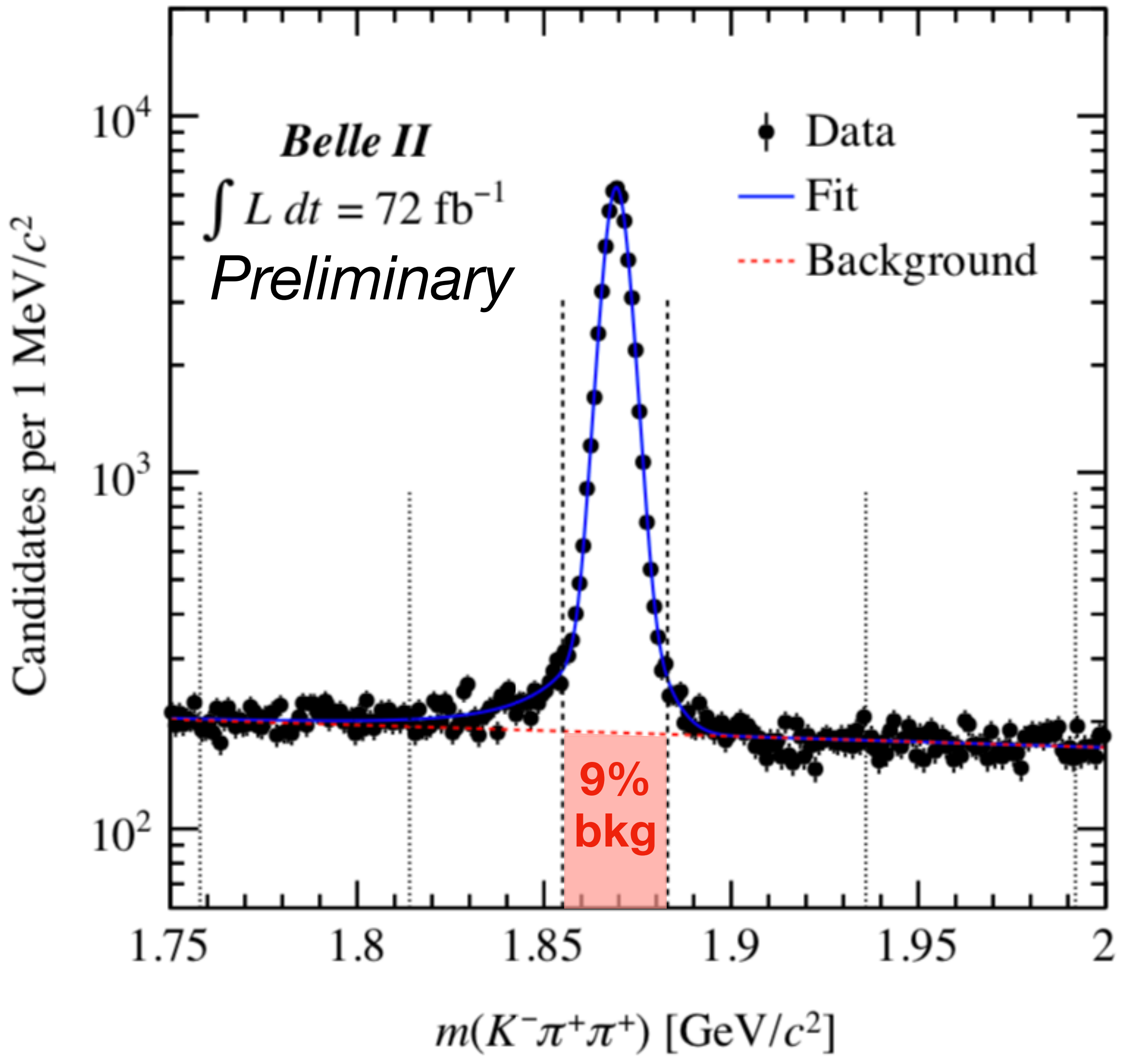
- High-precision measurement of $D^{0/+}$ lifetimes require
  - excellent vertex-detector alignment,
  - Precise calibration of final state particle momenta
  - Powerful background discrimination
- Early Belle II dataset already competitive → Challenge is to control systematics



$$t = m_D \frac{\vec{d}\cdot\vec{p}}{p^2 c}$$

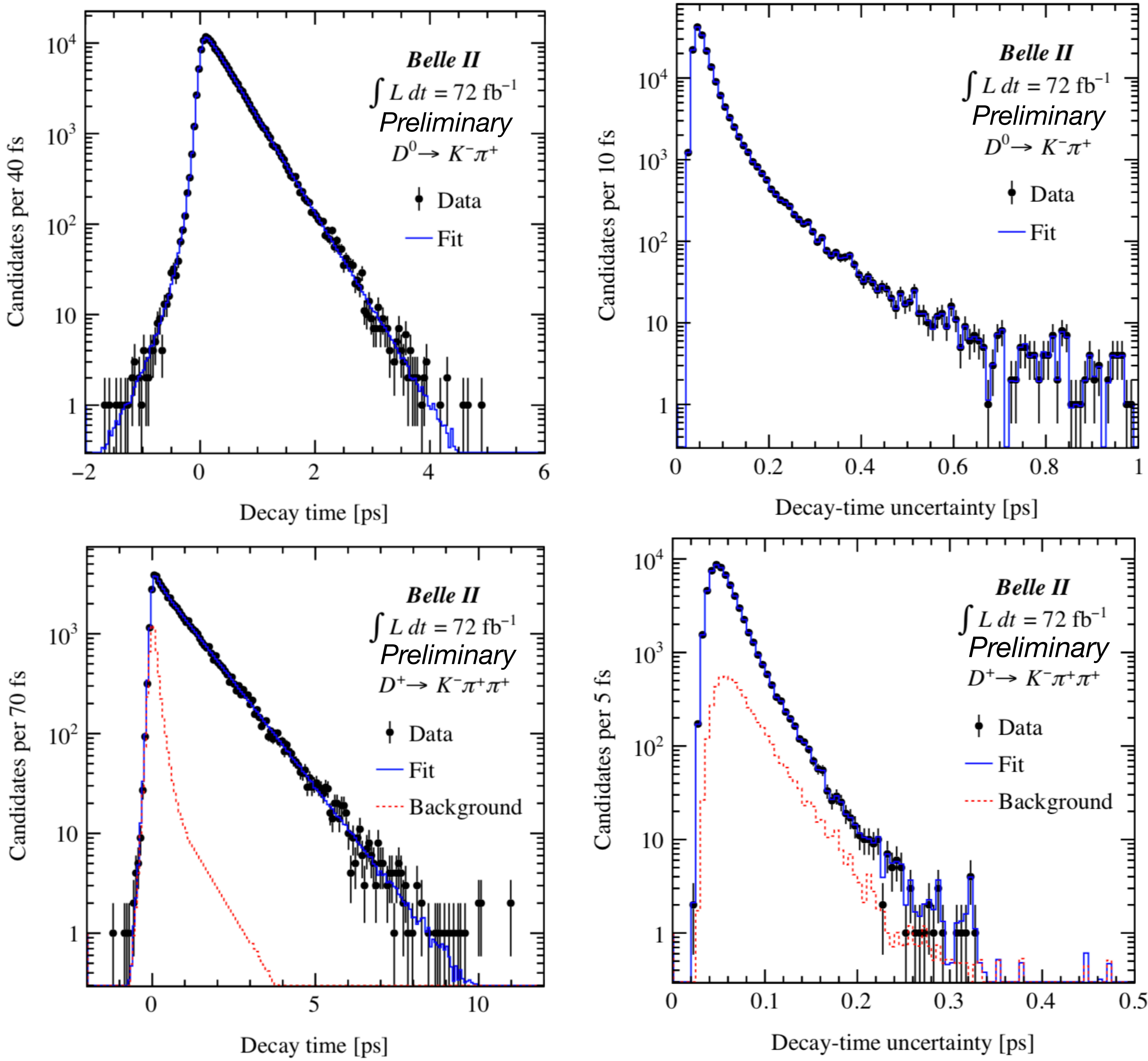
- Reconstructed $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ and $D^{*+} \to D^0(\to K^-\pi^+\pi^+)\pi^0$ from D^*-tagged.
- High-purity samples, selected to limit background-related systematic uncertainty.





Fit Strategy for Lifetime Measurement

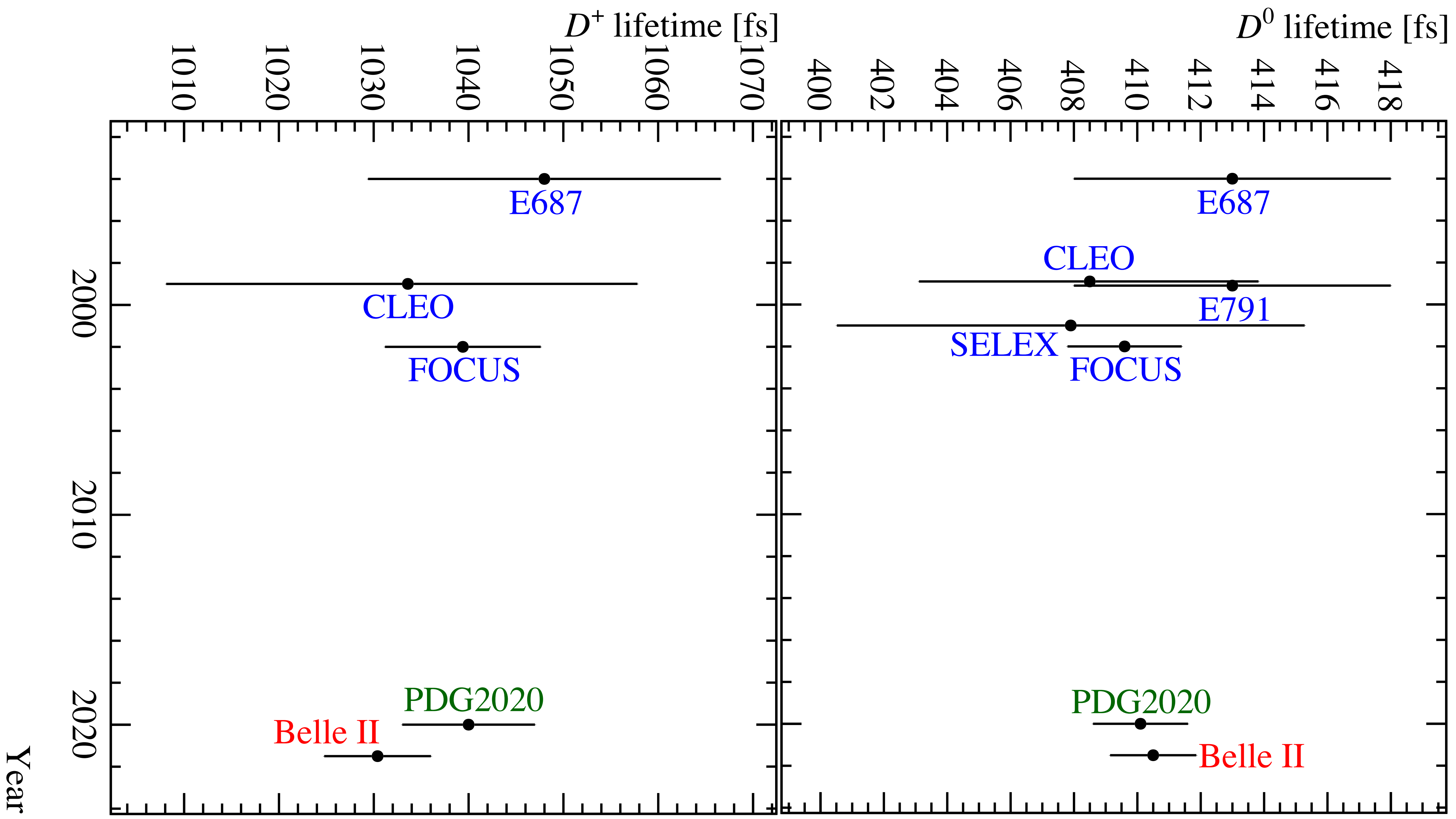
- Unbinned maximum-likelihood fits to the (t, σ_t)
  - [1.855, 1.833] GeV/c^2 for $m(K^-\pi^+\pi^+)$
  - [1.851, 1.878] GeV/c^2 for $m(K^-\pi^+)$
- For D^0 : background neglected in the fit → systematic assigned.
- For D$^+$: background included in fit → modeled using data sidebands
- Resolution function: → (2 gaussian for D^0, 1 gaussian for D$^+$) determined directly from fit
- Width: ~60-70 fs.
- Systematics:
  - Mostly from misalignment of vertex detector
  - Background modeling of D$^+$



Results (preliminary)

- Most precise to date and consistent with previous measurements
- Few-per-mille accuracy establishes excellent vertex capability of Belle II

$$\tau(D^0) = 410 \pm 1.1(\text{stat}) \pm 0.8(\text{syst})\ \text{fs}$$
$$\tau(D^+) = 1030.4 \pm 4.7(\text{stat}) \pm 3.1(\text{syst})\ \text{fs}$$



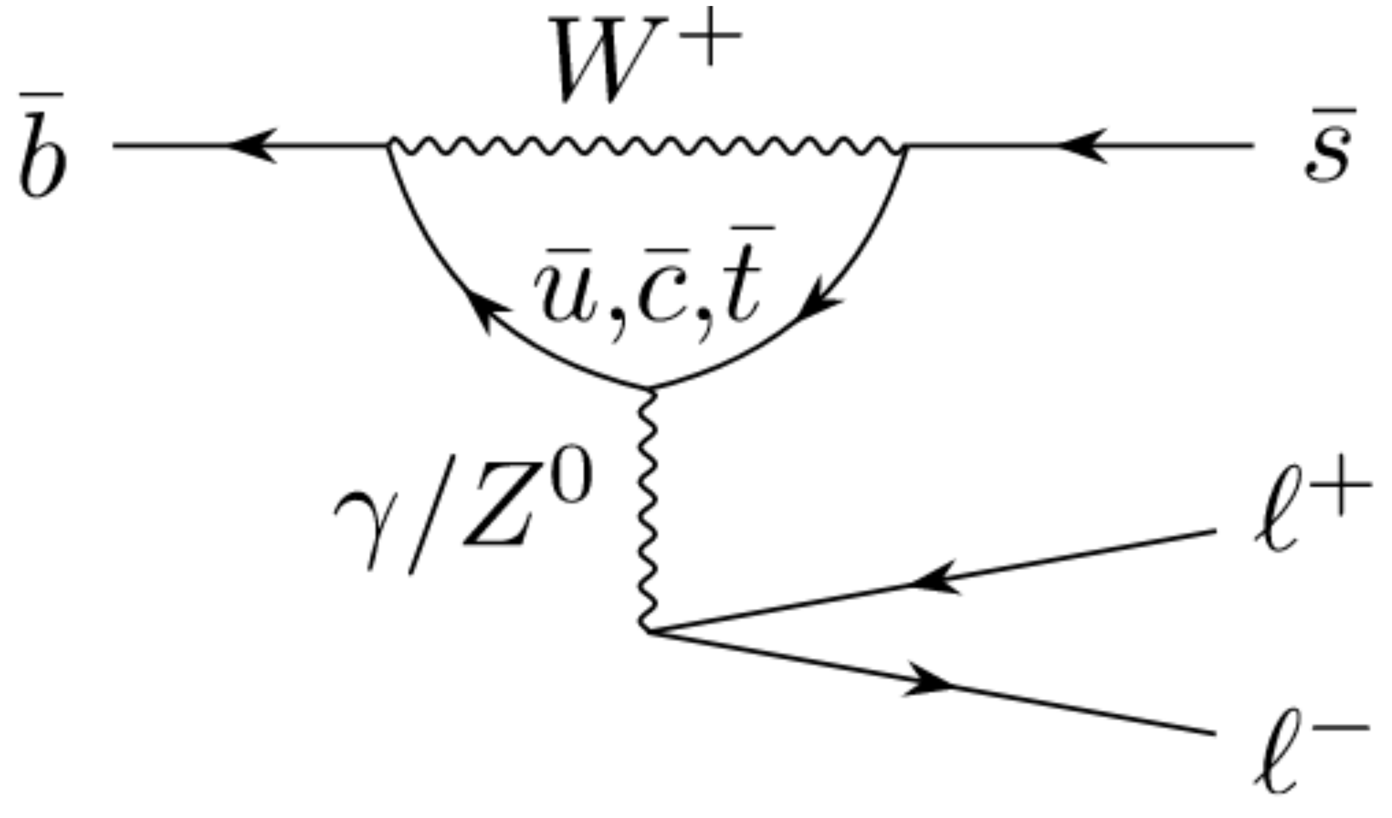
- Assuming all systematic uncertainties are fully correlated between $\tau(D^0)$ and $\tau(D^0)$ $\rightarrow$ correlation coefficient is 18%

$$\frac{\tau(D^+)}{\tau(D^0)} = 2.510 \pm 0.013(\text{stat}) \pm 0.007(\text{syst})\,.$$

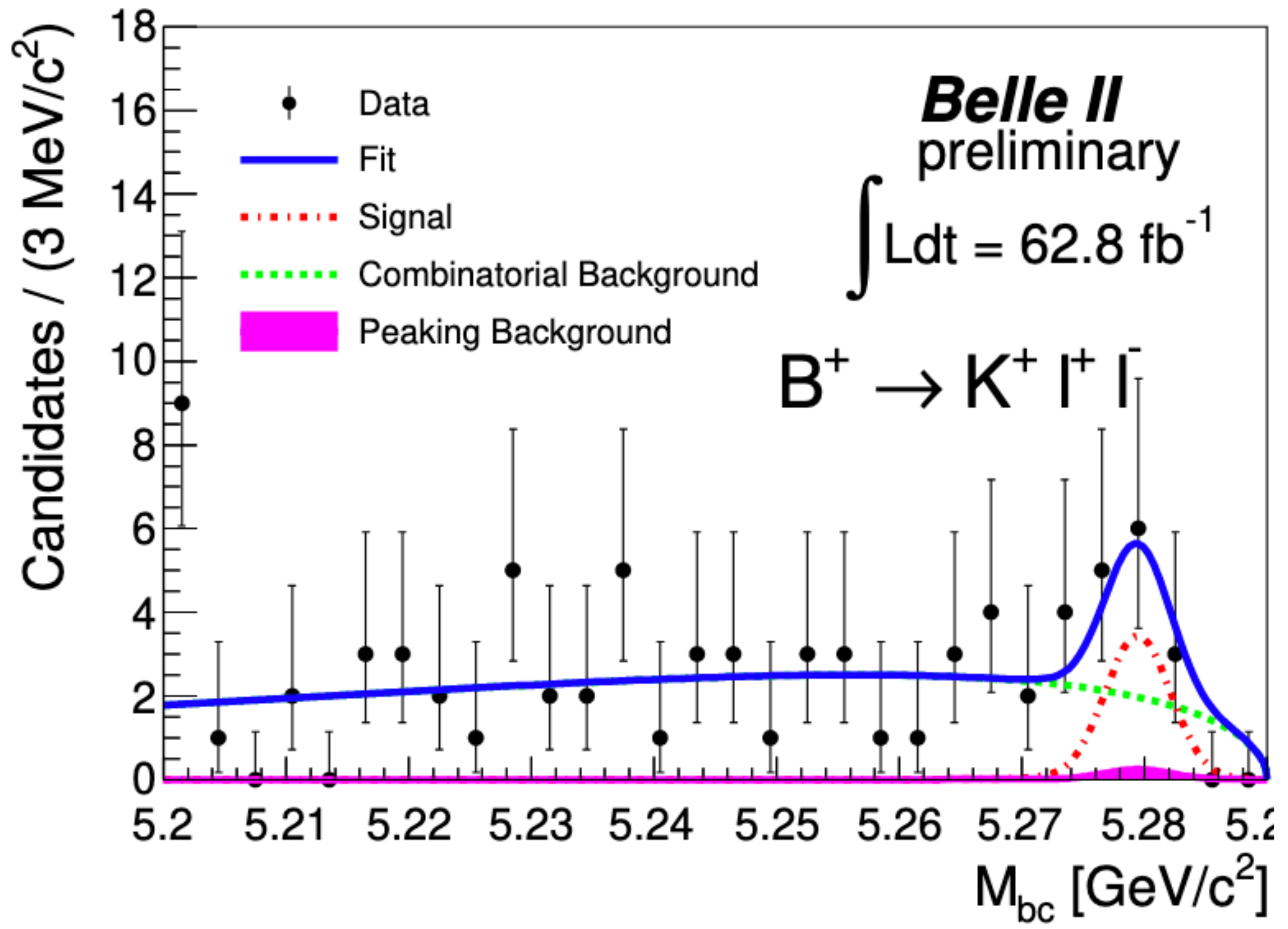
$B^+ \to K^+\ell^+\ell^-$ Measurement

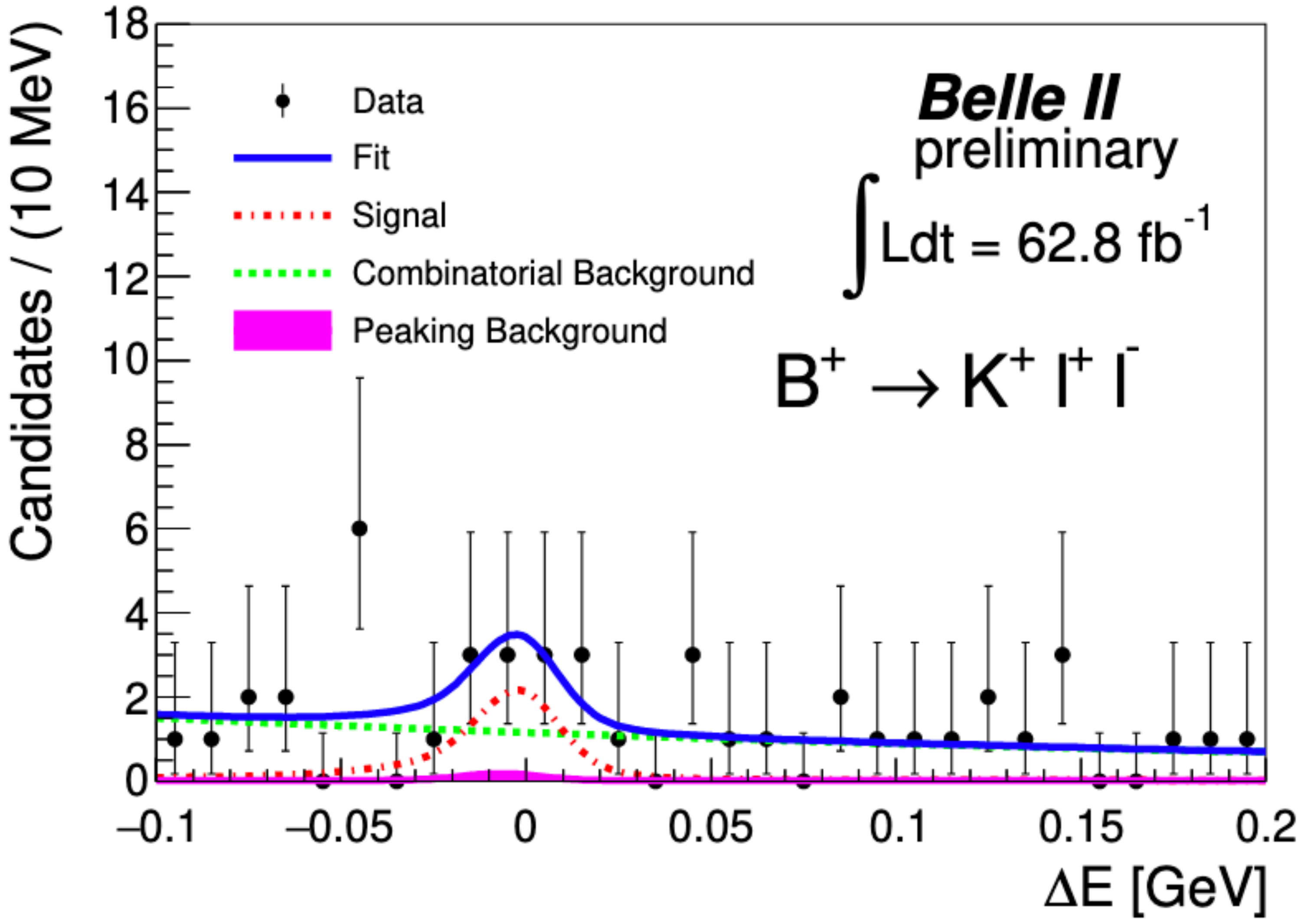
- Important FCNC decay measurement $B^+ \to K^+\ell^+\ell^-$(l = e, μ) sensitive to many SM extensions.
- Rediscovery of $B^+ \to K^+\ell^+\ell^-$
- BDT (event shape, vertex related and missing energy variables) to suppress background from **light quark** and **inclusive *B* decays**.
- First observation with just 63 fb^{-1} data

$\mathrm{B.F} \sim 10^{-7}$



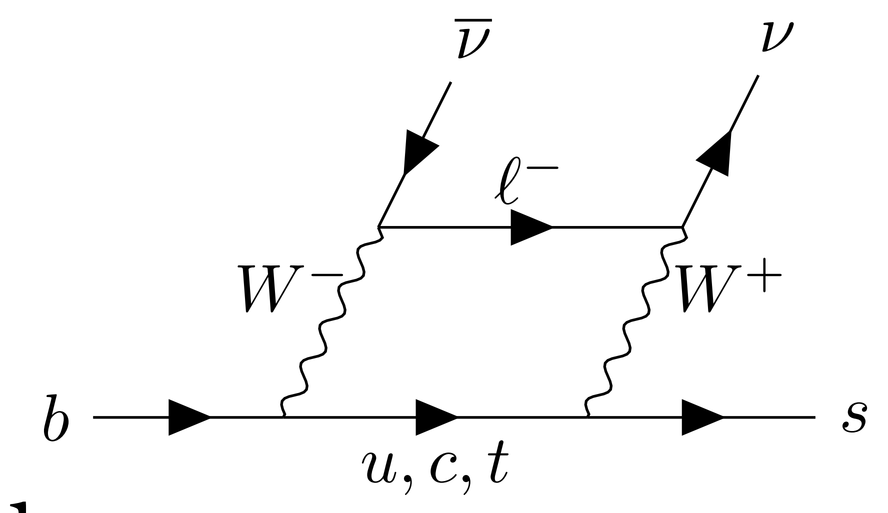
- 2D fit to $\Delta E = E_B^* - E_{beam}$ and $M_{bc} = \sqrt{E_{beam}^2 - \vec{p}_B^{\,2}}$ distribution
- Signal Yield : $\boxed{8.6^{+4.3}_{-3.9} \pm 0.4 \text{ events}}$
  - (2.7σ significane)
- More data needed for B.F measurement , R_K,



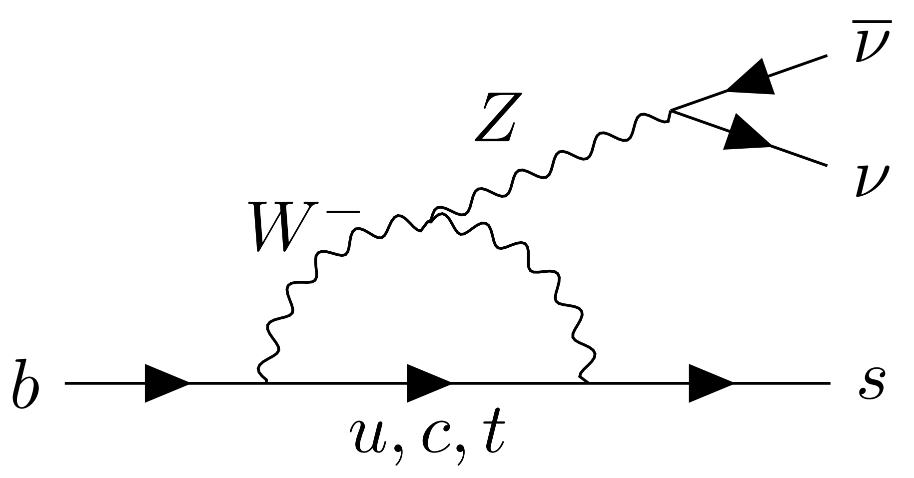


$B^+ \to K^+\nu\nu$ Measurement

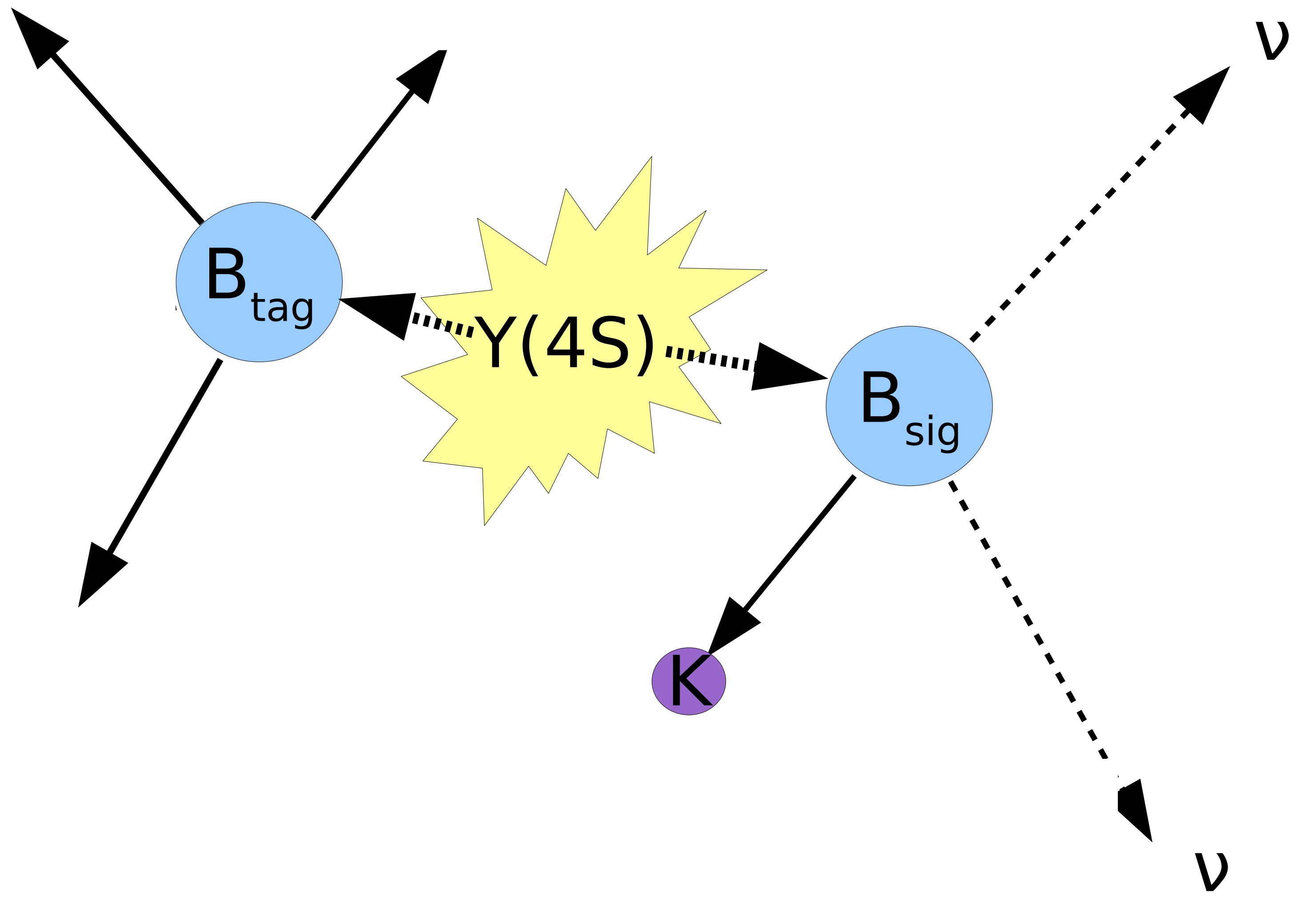
- Complementary probe of BSM physics scenarios proposed to explain flavour anomalies
- BSM models with lepto-quarks [PRD 102, 015023 (2020)], axions [PRD 101, 095006 (2020)], or DM [PRD 98, 055003 (2018)] can be constrained
- SM prediction for $\mathscr{B}(B^+ \to K^+\nu\nu) = (4.6 \pm 0.5) \times 10^{-6}$ [arXiv:1606.00919]
- Experimentally very challenging with two (escaping) neutrinos → information of the other B meson is required
- Measured using inclusive tagging approach
  - Exploit distinct topology and kinematics to achieve higher signal efficiency (~4%) → better compared to earlier approaches (semileptonic/hadronic tagging) used
  - Two boosted decision tree classifiers, of which the 2nd one is nested, to fight against various backgrounds



Box Diagram

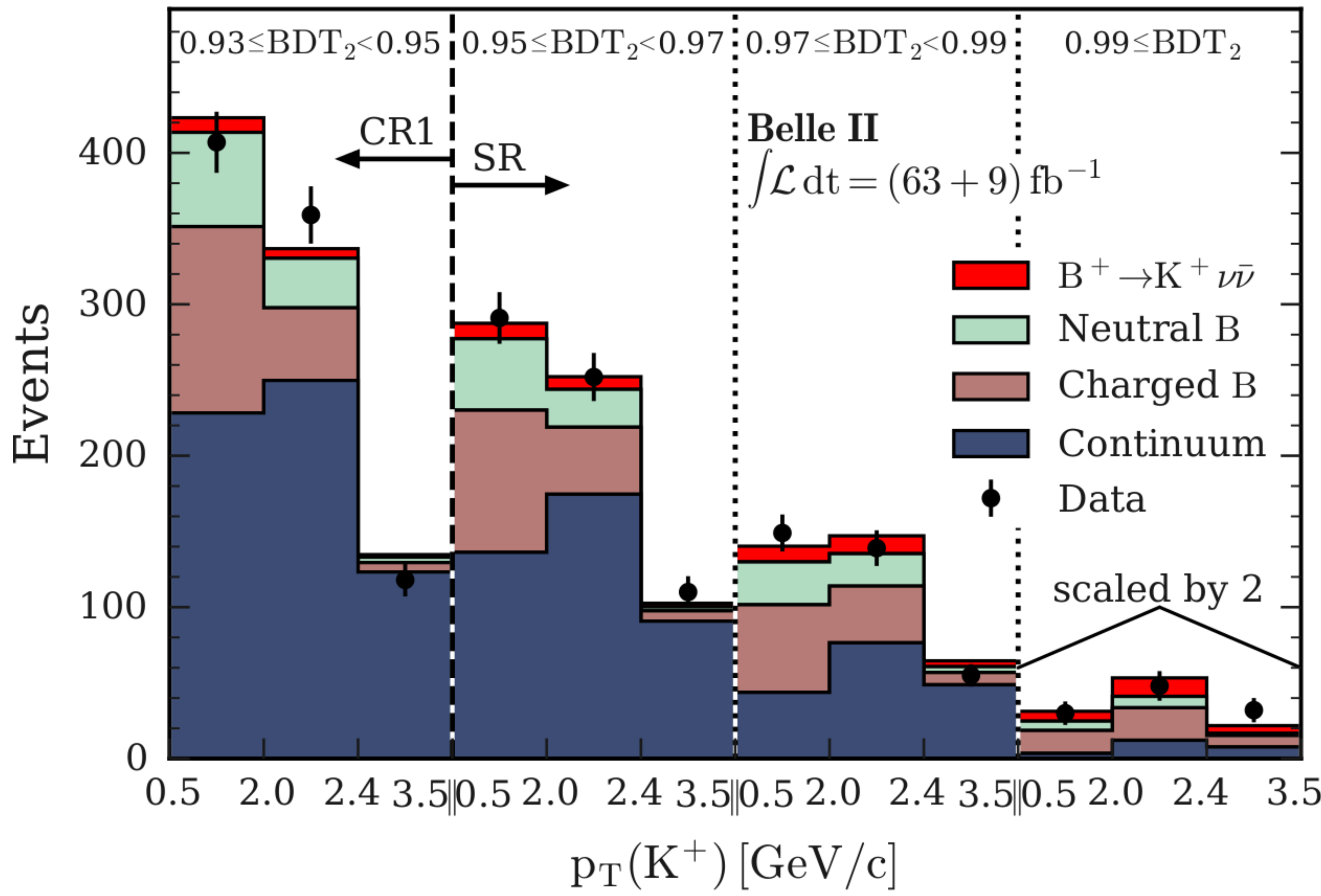


Penguin Diagram



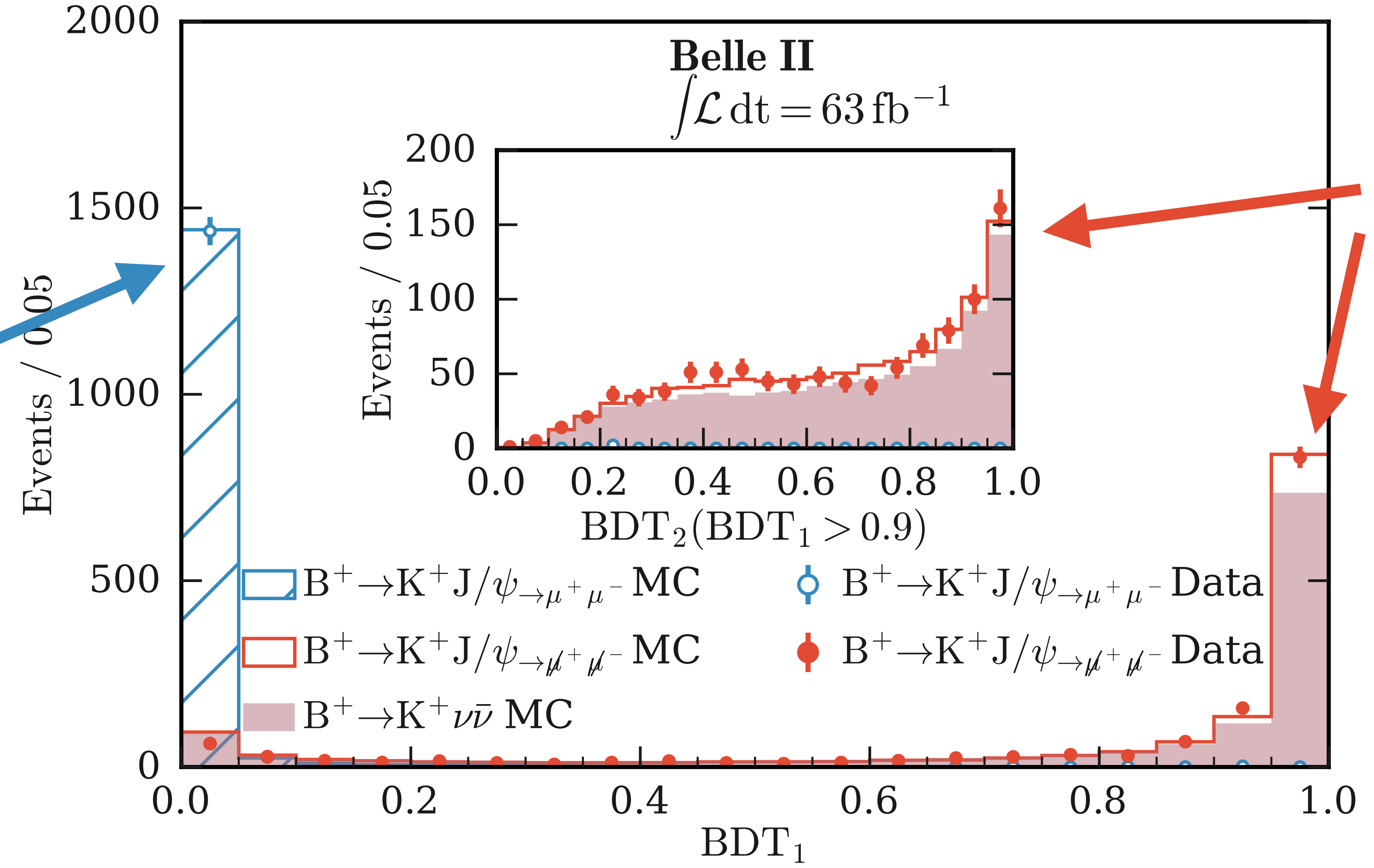
$B^+ \to K^+\nu\nu$ Measurement

- Select highest p_T track as signal kaon candidate
- Use off-resonance data to constrain yields from continuum processes $(q\bar{q}, \tau\bar{\tau})$
- Validate BDT: using data of $B^+ \to K^+J/\psi(\to \mu^+\mu^-)$ decays where the muons can be removed to mimic signal



- Compare response of BDTs in data and simulation
- Correct kaon momentum using simulated signal events
- Fraction of events in signal region (BDT2 > 0.95, data/simulation) =1.06 ± 0.10

BG-like sample (no muon removal)

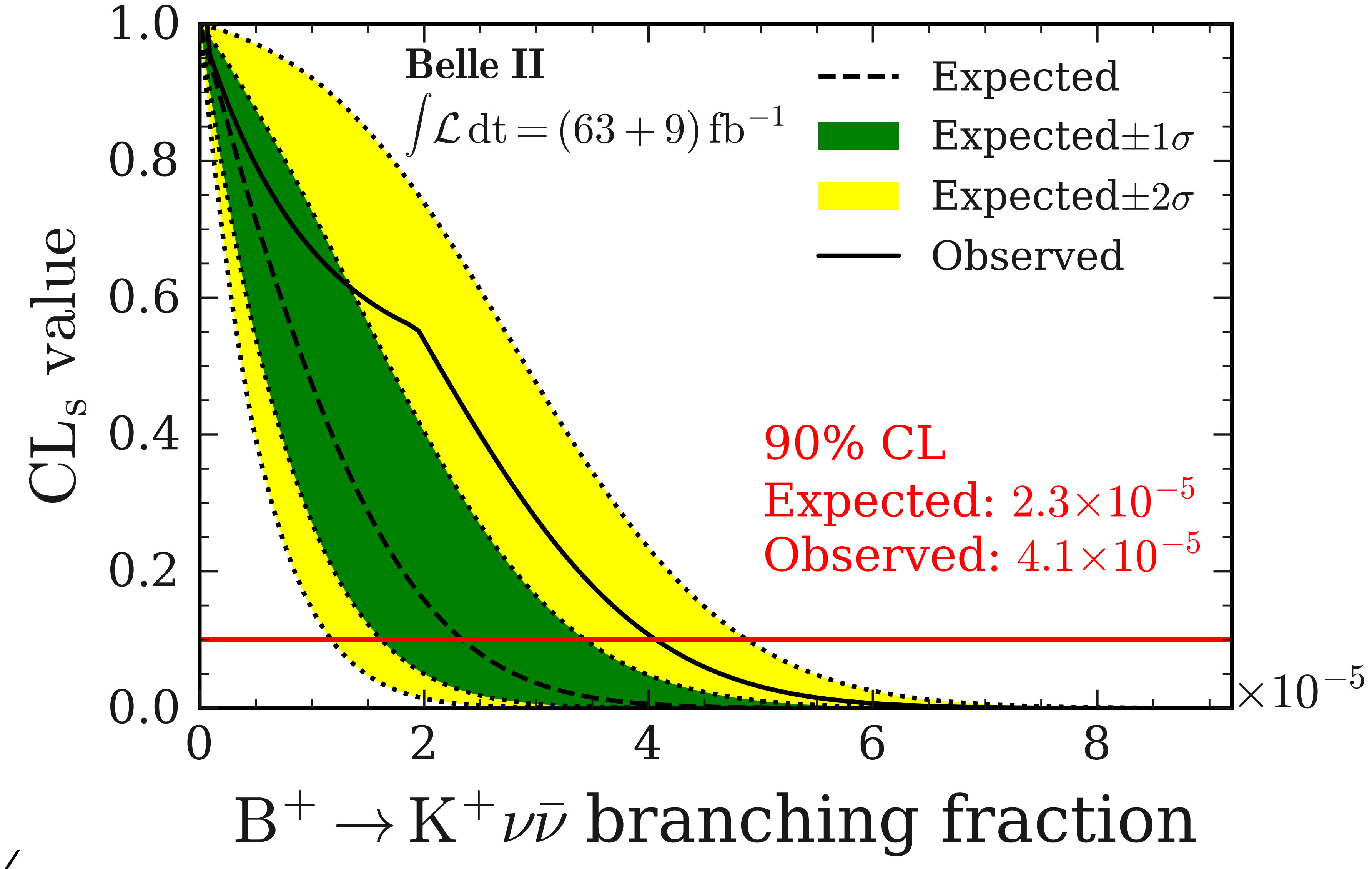


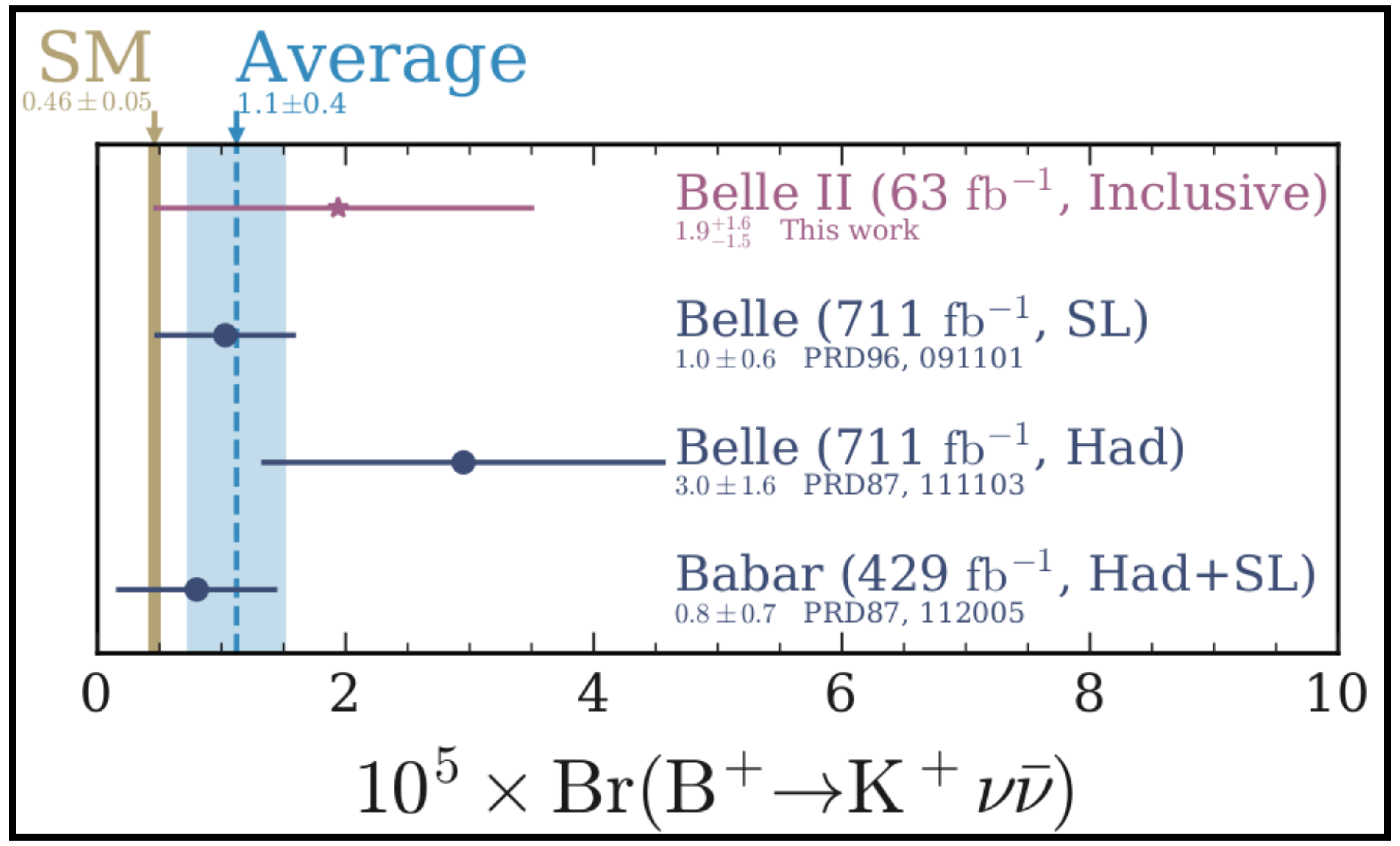
Signal-like sample (muon removal, momentum correction)

$B^+ \to K^+\nu\nu$ Results (preliminary)

- No signal observed; setting upper limit on BR using CLs method (assuming SM signal)

$$\boxed{\mathscr{B}(B^\pm \to K^\pm \nu\bar{\nu}) < (4.1 \pm 0.5) \times 10^{-5} \ @ \ 90\,\%\,\mathrm{CL}}$$





- When converted to the same luminosity, this measurement is better than
  - semileptonic tagging by 10-20%
  - hadronic tagging by a factor 3.5

- Future prospects:
  - more data
  - additional channels $B^0 \to K^{*0}\nu\bar{\nu}$, $B^0 \to K_S^0\nu\bar{\nu}$)
  - improved technique (neural net)
  - Expected to observe with ~5 ab^{-1} data

Work in progress to improve the inclusive tag method and employ the same strategy for other modes $B^0 \to K^*\nu\bar{\nu}$

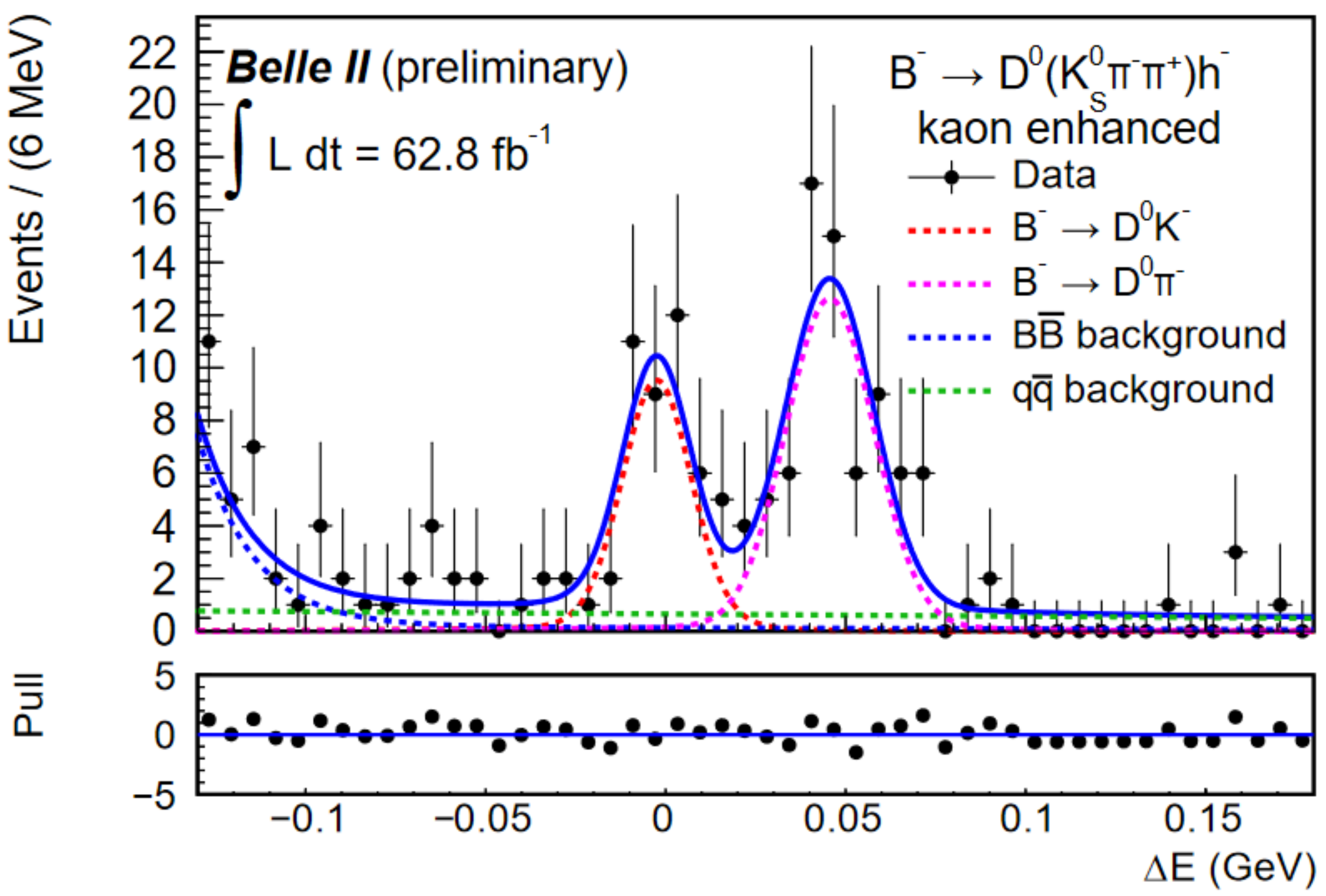
ϕ_3/γ Measurement with $B \to D^{(*)}h(h = K/\pi)$

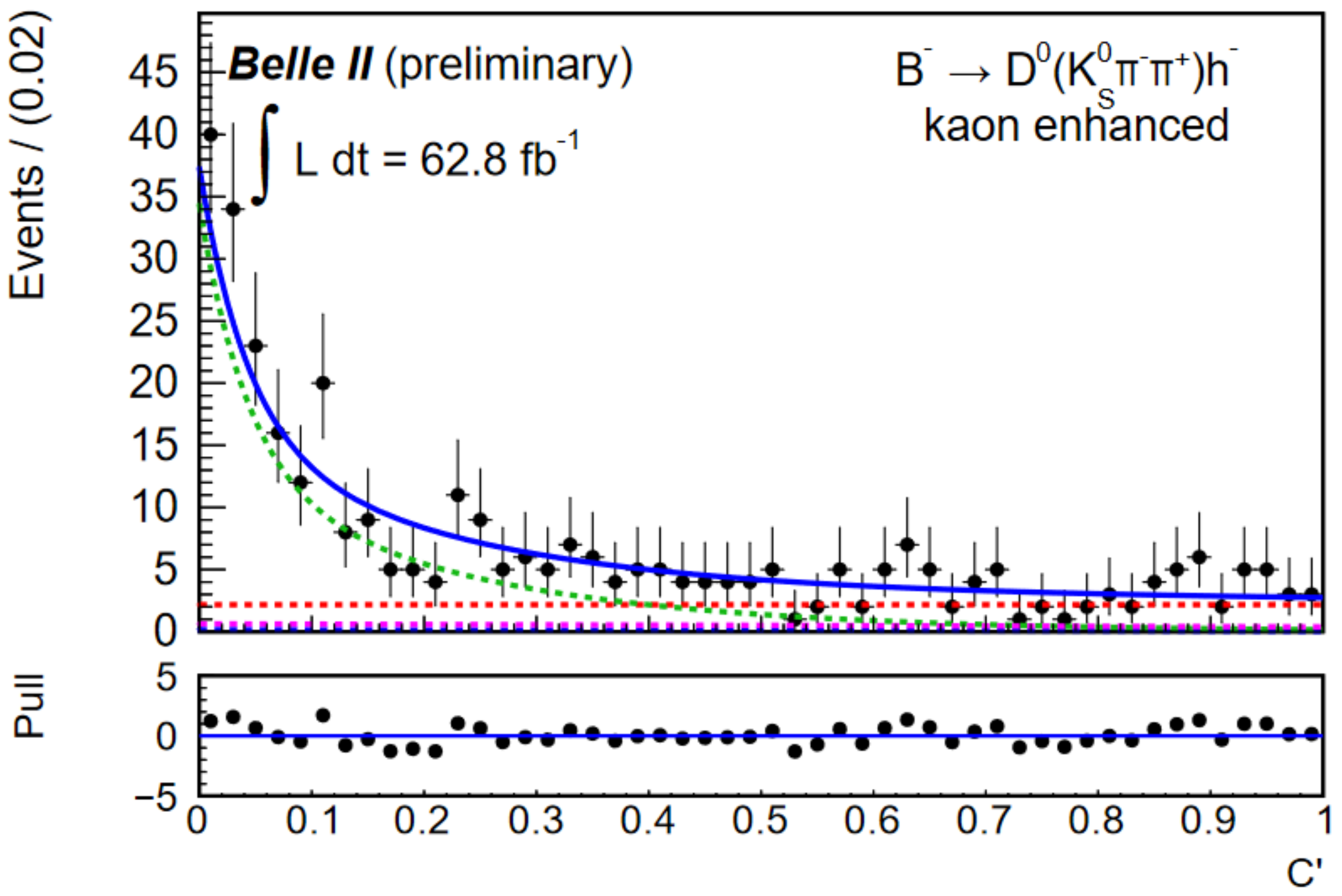
- Decays $B^- \to D^{(*)0}K^-$ are important for precise determination CKM angle γ/ϕ_3.
  - $B^- \to D^0(K_S^0\pi^+\pi^-)K^-$ is the golden mode for γ/ϕ_3 measurement for Belle/Belle II.
  - Dominant and clean decay $\underline{B^- \to D^{(*)0}\pi^-}$ and $\underline{B^0 \to D^{(*)+}\pi^-}$ provide good control sample.
- Signal enhanced with $M_{\rm bc} = \sqrt{E_{\rm beam}^2 - \vec{p}_B^{\,2}} > 5.27$ GeV/c^2 and PID to K/π from signal B,
- Unbinned ML fit in $\Delta E = E_B^* - E_{beam}$ and MVA output (with event shape variables).

$$\boxed{\frac{\mathscr{B}(\overline{B}^- \to D^0(K_s^0\pi^-\pi^+)K^-)}{\mathscr{B}(\overline{B}^- \to D^0(K_s^0\pi^-\pi^+)\pi^-)} = 6.32 \pm 0.81^{+0.09}_{-0.11}}$$

- Many systematics cancel in Ratio
- Results agree with PDG (LHCb)

Aiming for first Belle+Belle II for ϕ_3 combined result very soon





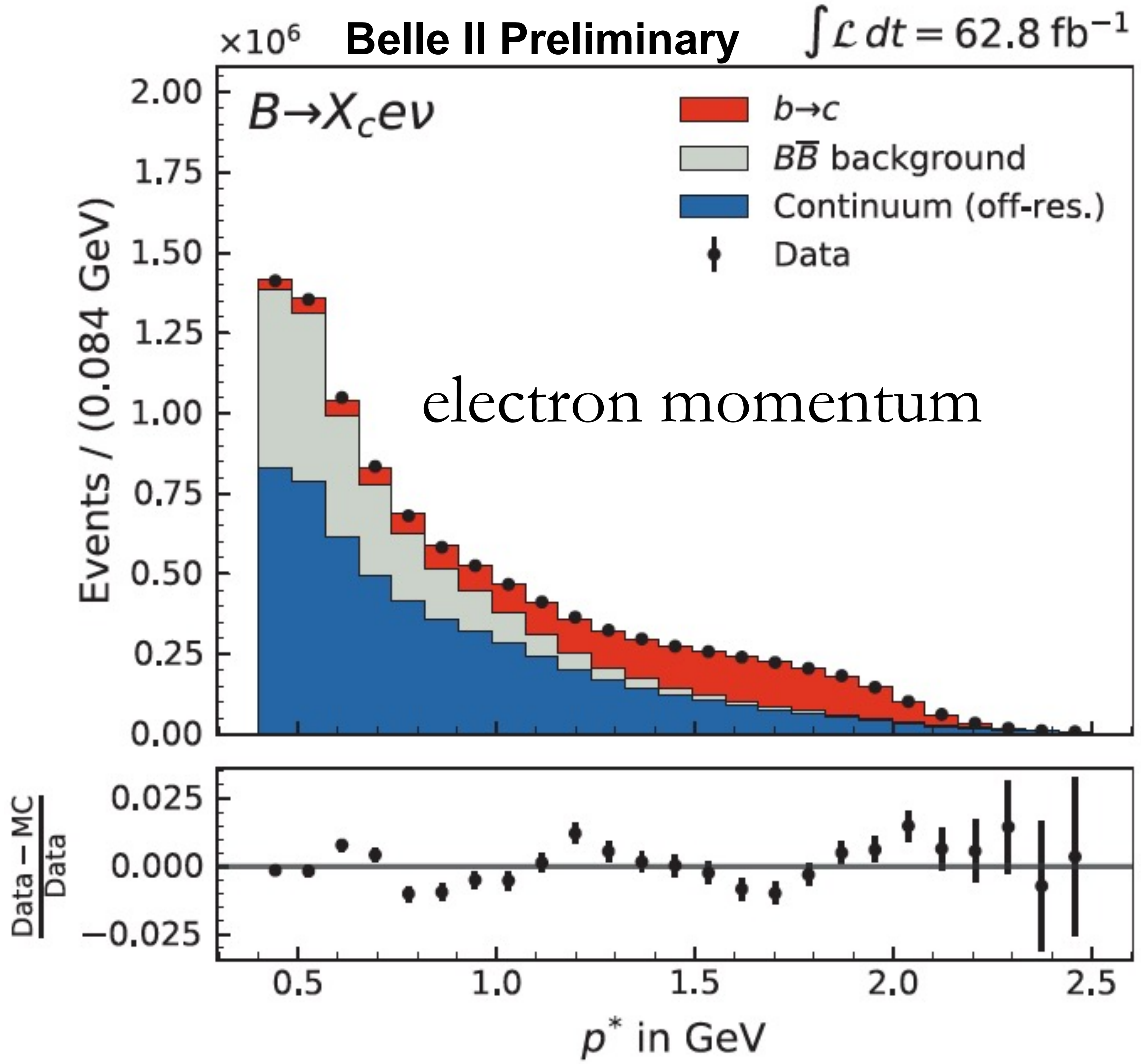
Inclusive $B \to X_c \ell \nu$

- Different analysis strategies will help resolve the inclusive/exclusive discrepancy in $b \to c\ell\nu$ and $b \to u\ell\nu$
- Measure the q²-moments (moments of lepton energy or hadronic mass) in order to simultaneously determine the non perturbative elements and $|V_{cb}|$
- Belle II performed both the untagged and the hadronic tagged analyses.

Untagged analysis

- Require one well identified lepton
- Exploit missing mass and momentum to reject backgrounds
- Measure the branching fraction with a fit to p^*_l

$$\mathscr{B}(B \to X_c \ell \nu) = (9.75 \pm 0.03(stat) \pm 0.47(syst))\ \%$$

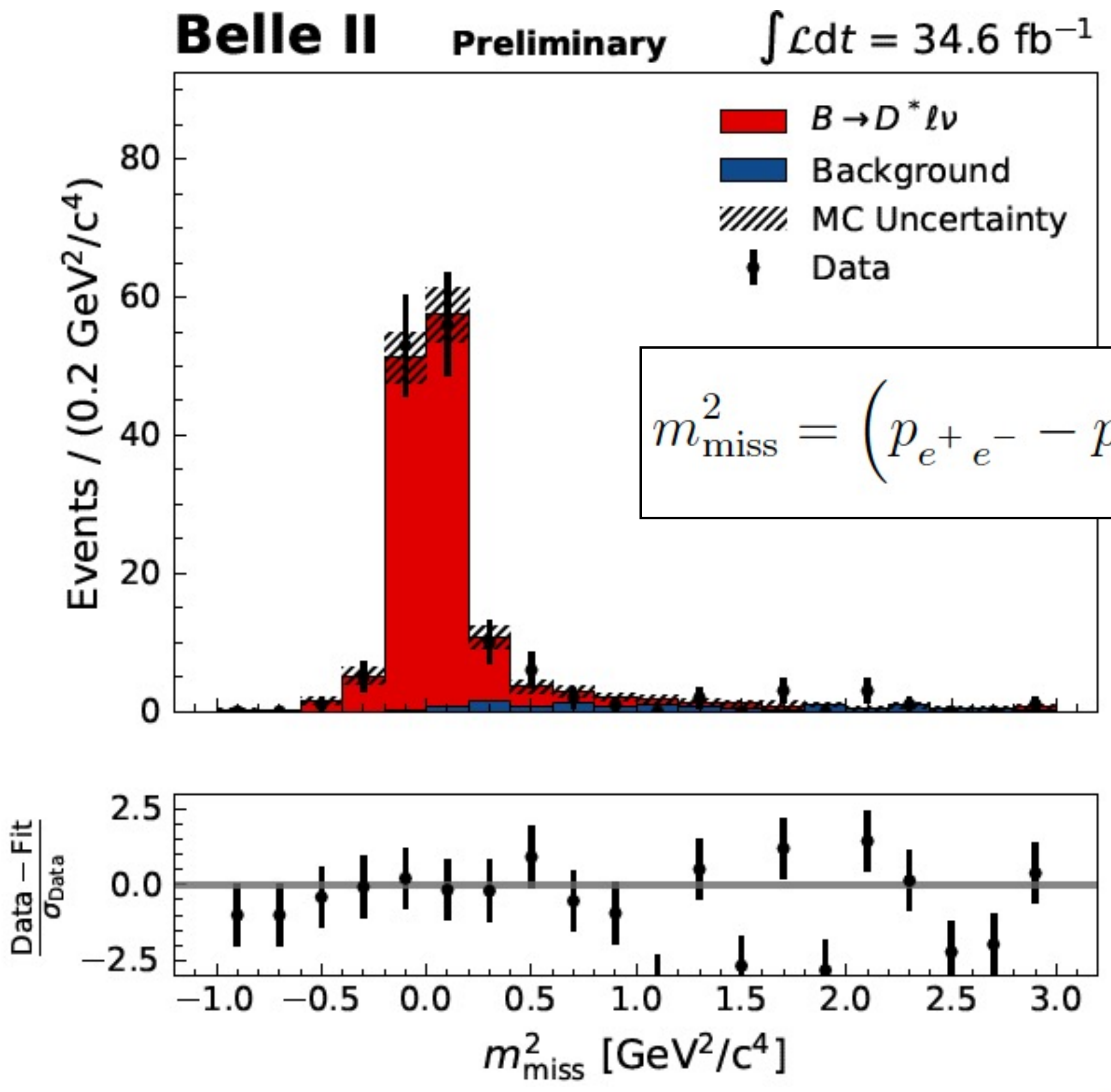


Exclusive $B \to D^{(*)}\ell\nu$

- $B \to D^{(*)}\ell\nu$ has been explored with both tagged and untagged approaches

- Tagged Analysis
  - Almost zero background after tag
  - Signal selection from D* and D⁰ invariant masses, and lepton momentum

$$\mathcal{B}(\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_l) = (4.51 \pm 0.41_{\text{stat}} \pm 0.27_{\text{syst}} \pm 0.45_{\pi_s})\,\%$$

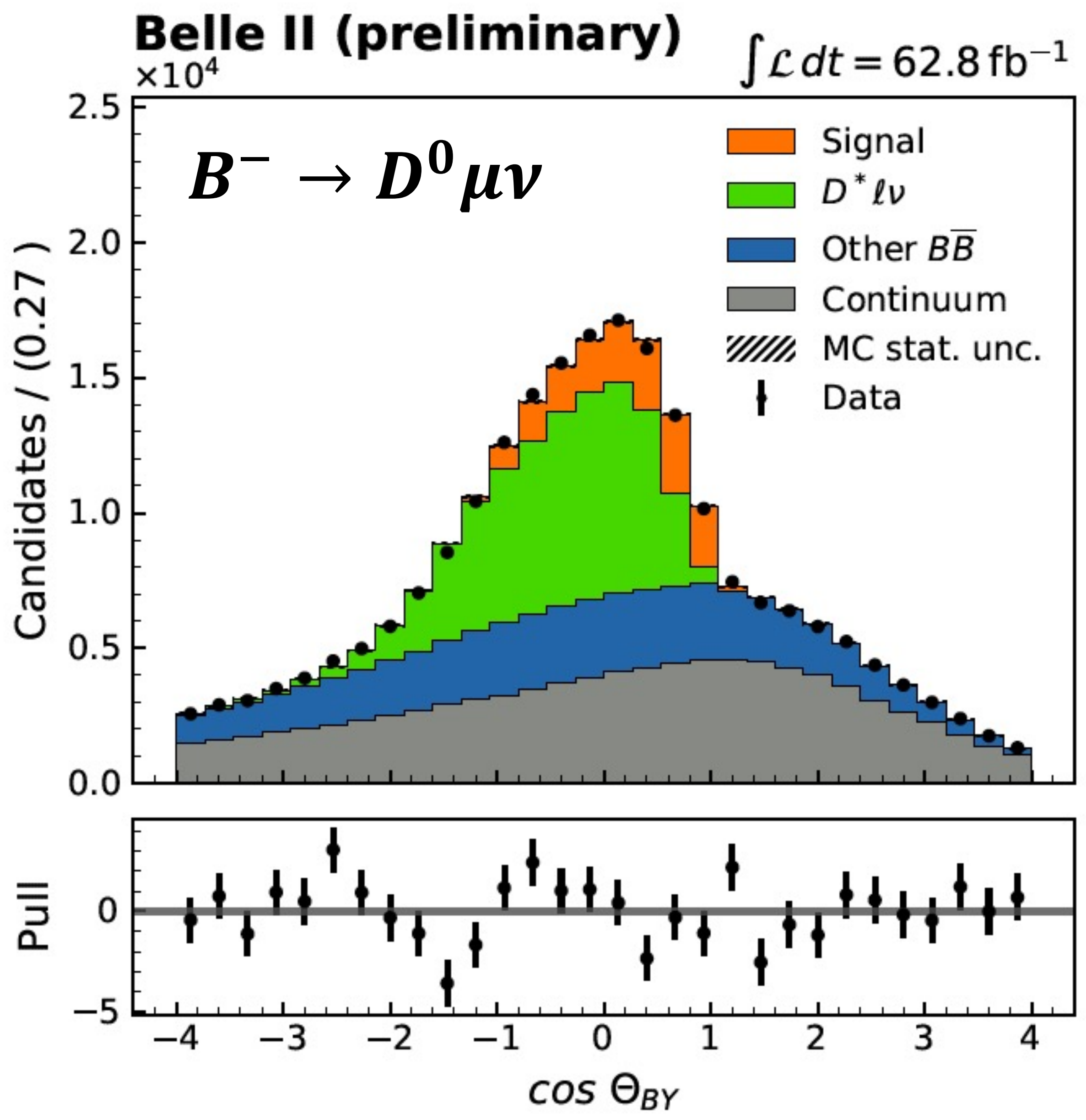


$$m^2_{\text{miss}} = \left(p_{e^+e^-} - p_{B_{\text{tag}}} - p_{D^*} - p_\ell\right)^2$$

- Untagged Analysis
  - Signal selection from $\cos\theta_{B,Y}$ where $\theta_{B,Y}$ is angle b/w B and direction of $D^*\ell/D^0\ell$ system

$$\mathcal{B}(B^- \to D^0\ell^-\overline{\nu}_l) = (2.29 \pm 0.05_{\text{stat}} \pm 0.08_{\text{syst}})\%$$

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



$|V_{cb}|$ measurement in progress …

Conclusions

- Belle II in great shape have already >200 fb^{-1} of data being analyzed → more new results coming soon
- Established excellent vertexing performance with world's best D lifetimes measurement.
- First excellent result of $B^+ \to K^+\nu\nu$ with prospects to measure $B^+ \to K^+\nu\nu$ very soon
- Re-optimization of Belle ϕ_3 analysis ongoing → aiming for first Belle+Belle II combined result
- Within the next years Belle II will be able to address the inclusive/exclusive $|V_{cb}|/|V_{ub}|$ tension by precisely measuring semileptonic B decays
- SuperKEKB has set a new world record in peak luminosity and is entering the regime of a "Super B factory"
- Belle II detector is working very well and is producing very promising physics results

Looking forward to an exciting era of discoveries and a healthy competition and complementarity of Belle II and LHCb

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Thank You