Belle II experiment: status and prospects

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For the Belle II Collaboration

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JAPAN SOCIETY FOR THE PROMOTION OF SCIENCE
日本学術振興会

KEK High Energy Accelerator Research Organization

Outline

- The case for probing non Standard Model physics in Belle II
- Introduction to Belle II
- Recent results
  - Charm lifetimes
  - CKM unitarity triangle angle ϕ_2/α and ϕ_3/γ (B to charm and charmless decays)
  - $B^+ \to K^+\ell^+\ell^-$ and $B^+ \to K^+\nu\bar{\nu}$ (Rare decays)
  - Inclusive $B \to X_c\ell\nu$, Exclusive $B \to D^{(*)}\ell\nu$ (Semileptonic B decays)
- Outlook

The case for probing non SM Physics in Belle II

Issues addressable at flavour factory

→ NP beyond the direct reach of the LHC

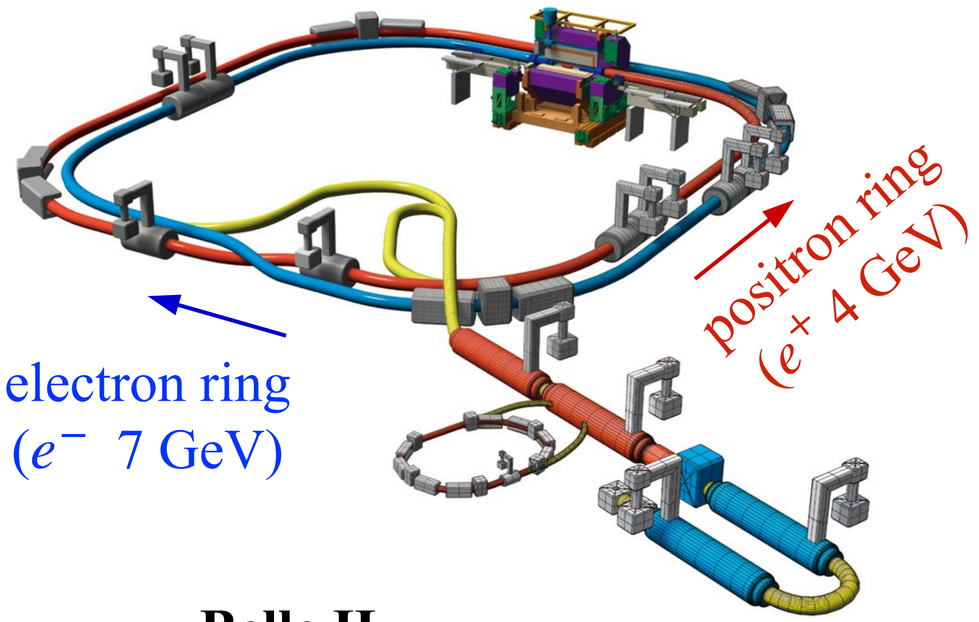
- Baryon asymmetry in cosmology
  → New sources of CPV in quarks and charged leptons
- Finite neutrino masses
  → Tau LFV.
- Quark and lepton flavour & mass hierarchy
  → higher symmetry, massive new particles, extended gauge sector
- Hidden and dark sectors at the GeV scale.

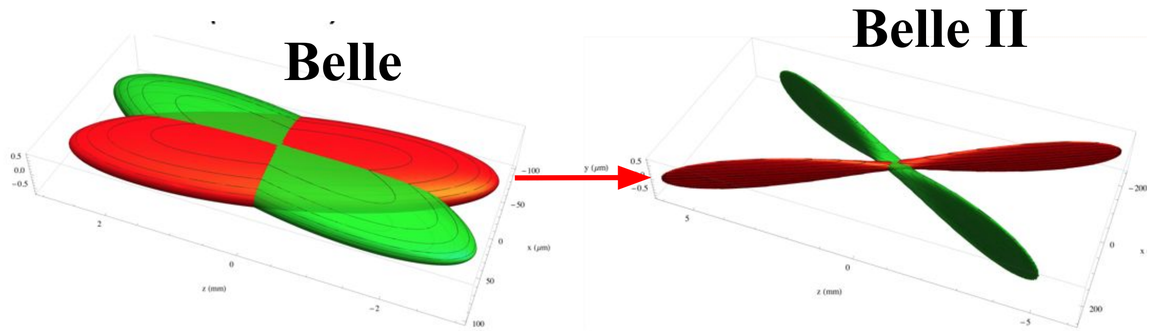
- **Direct** production at **energy frontier (LHC)** yielded no non-SM Physics evidence at the TeV scale
- **But *indirect*** searches at the **intensity frontier (Belle/BaBar)** probe higher scales.

BaBar + Belle experiments collected ~1.5 ab^{-1} at the first generation of B factories led to many discoveries

SuperKEKB

- Asymmetric e^+e^-collider with main center-of-mass energy at $B\bar{B}$ threshold (10.58 GeV)
- Upgrade of KEKB
- Aims at an integrated luminosity of 50 ab^{-1} (50 × Belle)
  →Challenging harsh beam background conditions
- 30 × KEKB best instantaneous luminosity is achieved by
  - × 1.5 beam current increase
  - × 20 beam size decrease



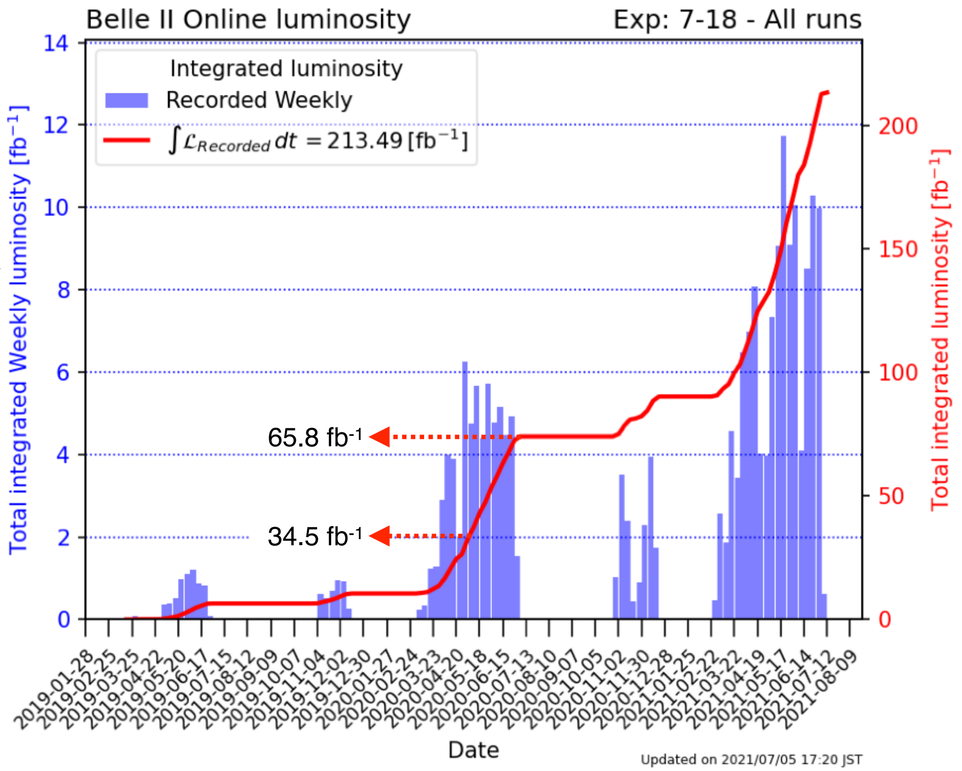


e^+e^- collisions very clean compared to pp collisions

Data Taking at Belle II

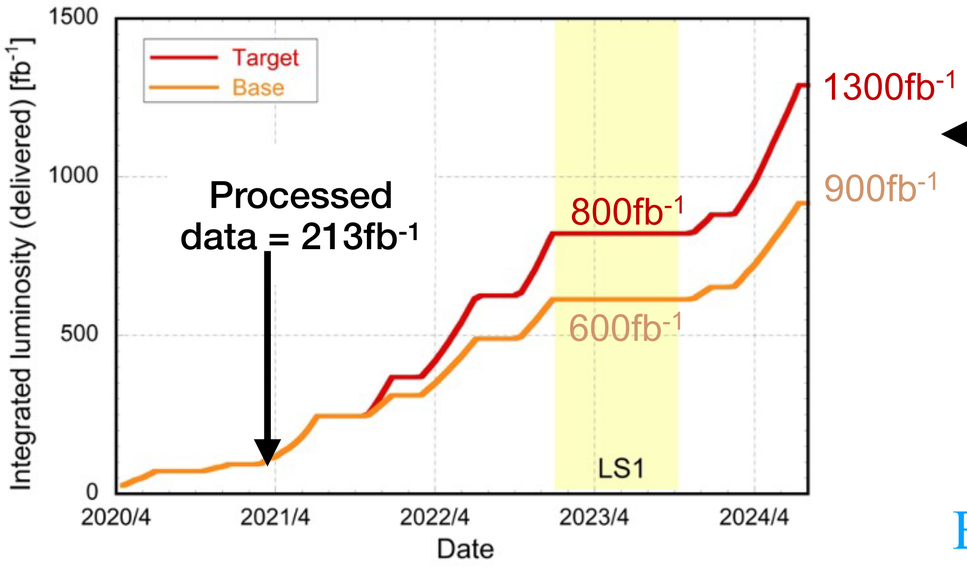
- Operation started in 2019
- Plan peak luminosity of $6.5 \times 10^{35} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Peak luminosity
  - $\mathscr{L}_{\mathrm{peak}}^{\mathrm{KEKB}} = 2.1 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \rightarrow \mathscr{L}_{\mathrm{peak}}^{\mathrm{SKEKB}} = 3.1 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

  (World record set on 22nd June 2021)



Data taking till Summer run 2021: 213.49 fb^{-1} with ~90% data taking efficiency

Data taking plan for next 5 years



1300fb^{-1}

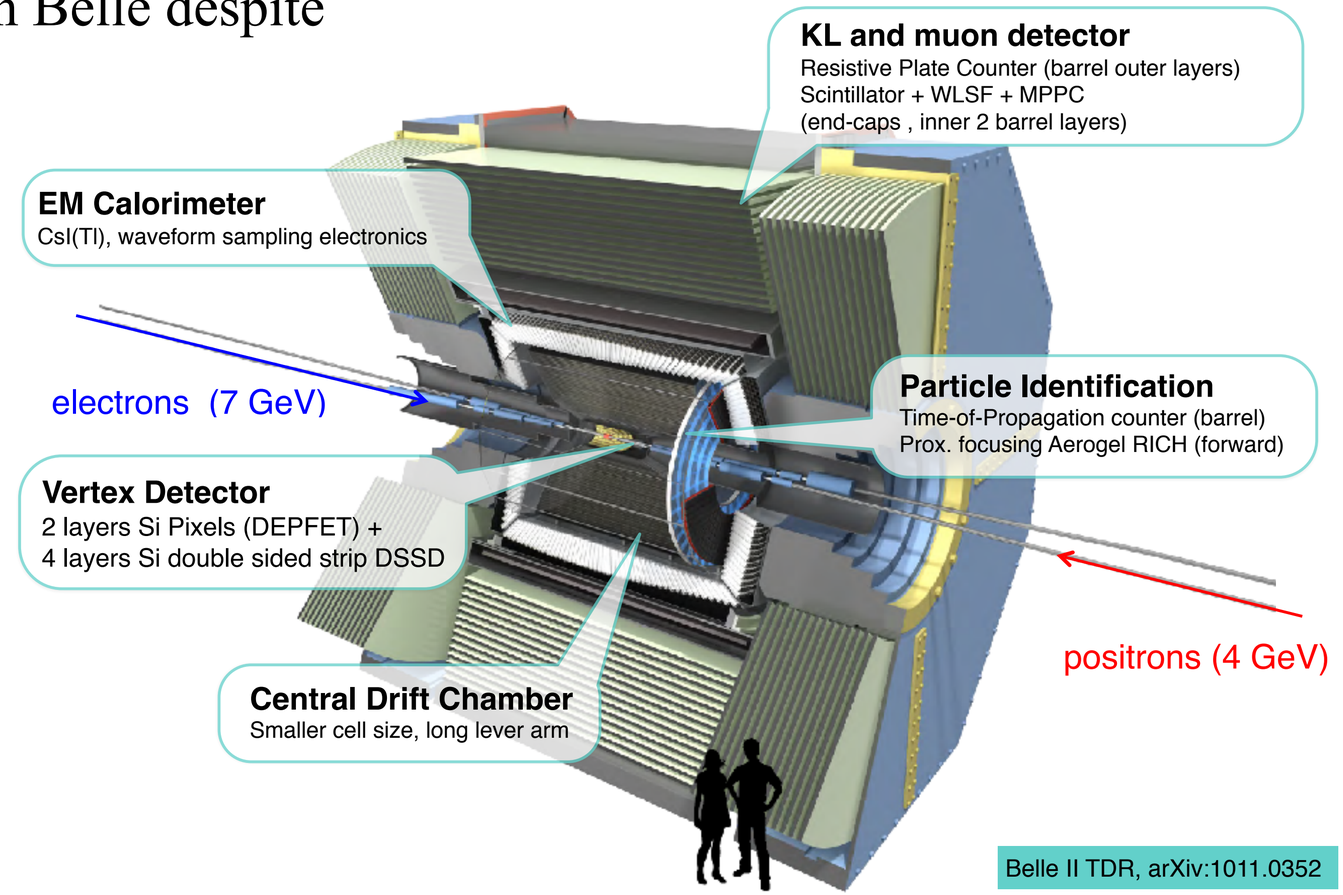
900fb^{-1}

$nB\bar{B} = 10^{11}$

Belle II has started taking after summer 2021 break ..

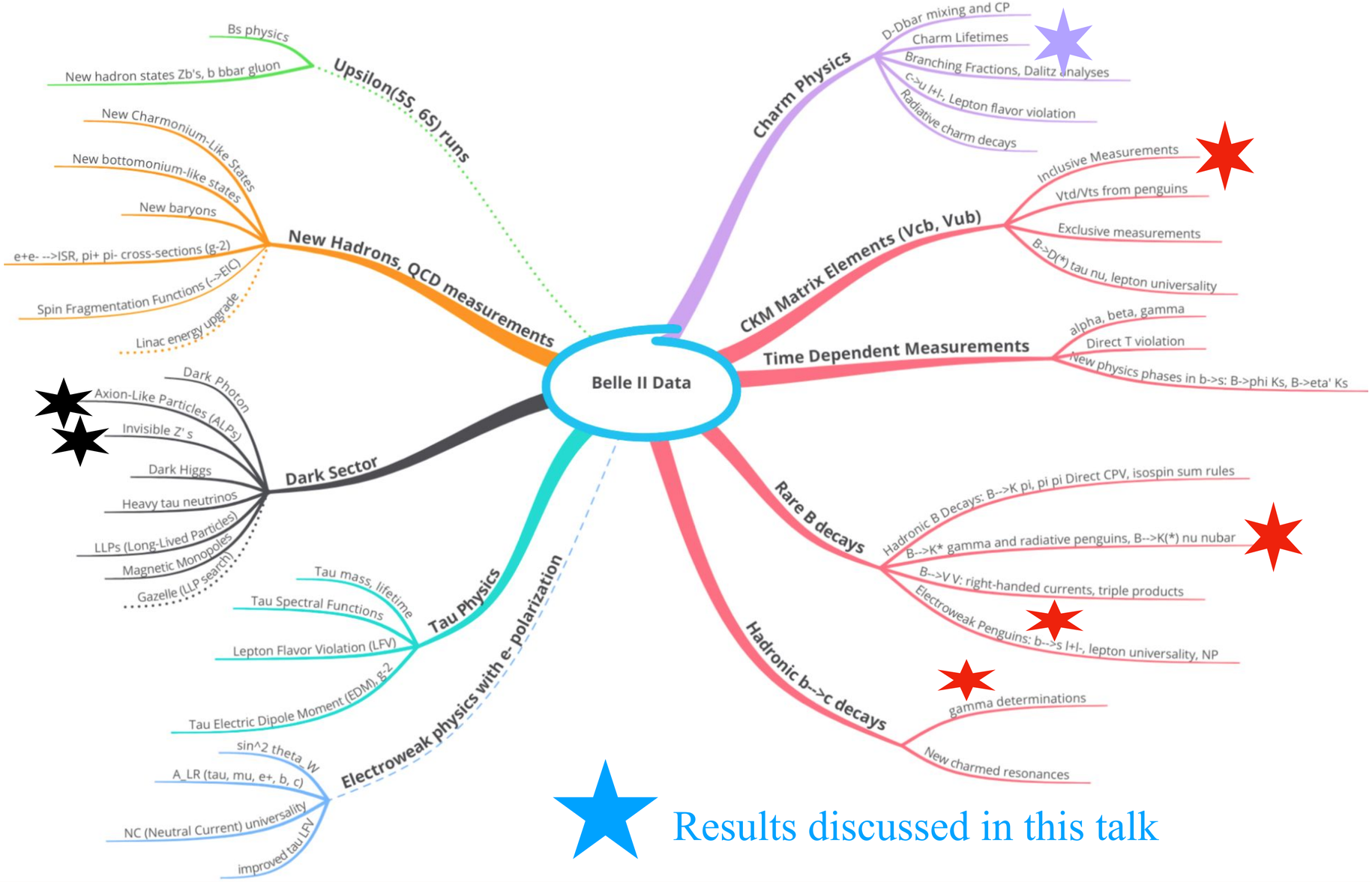
The Belle II Detector

- Designed to operate with a performance better than Belle despite higher beam backgrounds
- Belle II enables us
  - High reconstruction efficiency with very low trigger bias
  - Uniform performance in reconstruction of final states containing photons from π^0, $\rho^{\pm}$, η, K_S etc
  - Good vertex resolution
  - Analyses of missing mass since initial state perfectly known
  - Production of large sample of charm mesons and τ leptons



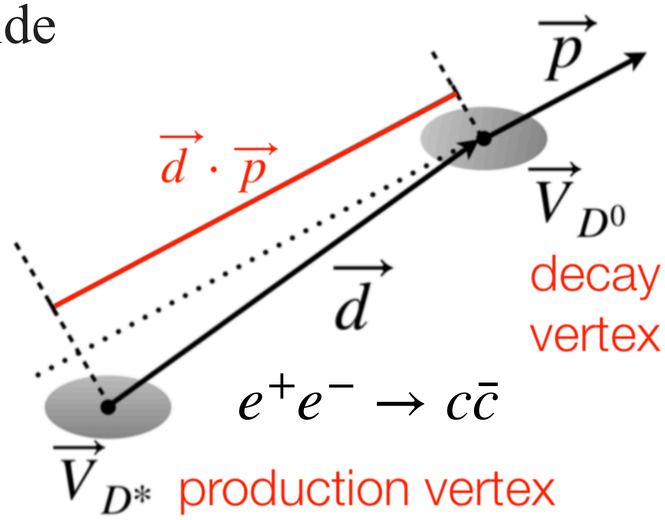
Belle II TDR, arXiv:1011.0352

The Belle II Physics Program

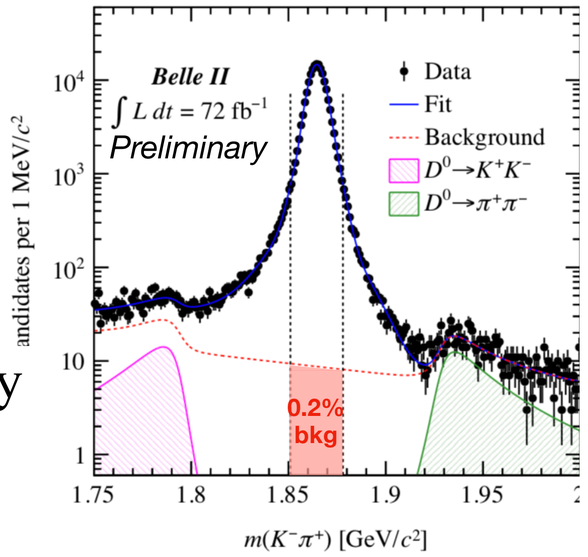


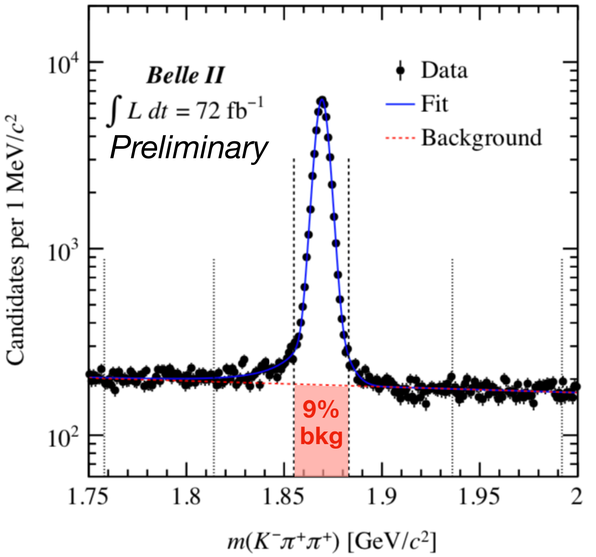
Charm Lifetimes

- Lifetimes measurements test non-perturbative QCD and provide guidance to describe strong interactions
- High-precision measurement of $D^{0/+}$ lifetimes rely on
  - excellent vertex-detector alignment,
  - Precise calibration of final state particle momenta
- Early Belle II dataset already competitive → Challenge is to control systematics
- High-purity samples, large BF decay modes selected to limit background-related systematic uncertainty.
- Reconstructed $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ and $D^{*+} \to D^+(\to K^-\pi^+\pi^+)\pi^0$ from D^*-tagged.
- Removing D from B decays (originating from a secondary vertex) with $p(D^{*+}) > 2.5(2.6)$ GeV requirement avoids bias in $D^0(D^+)$ production vertex position



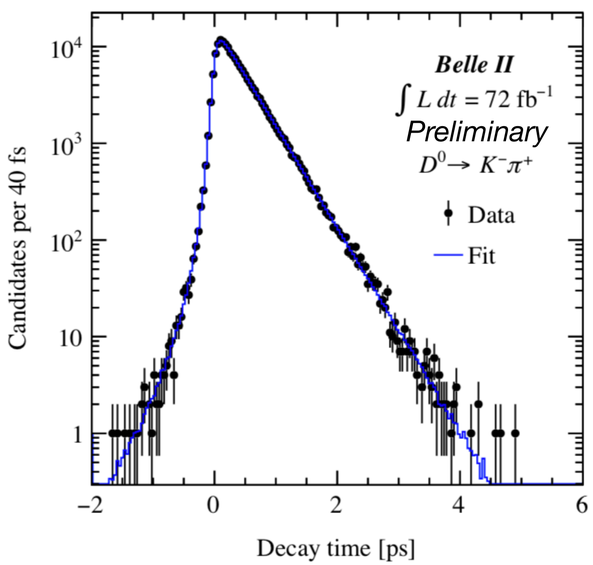
$$t = m_D \frac{\vec{d} \cdot \vec{p}}{p^2 c}$$

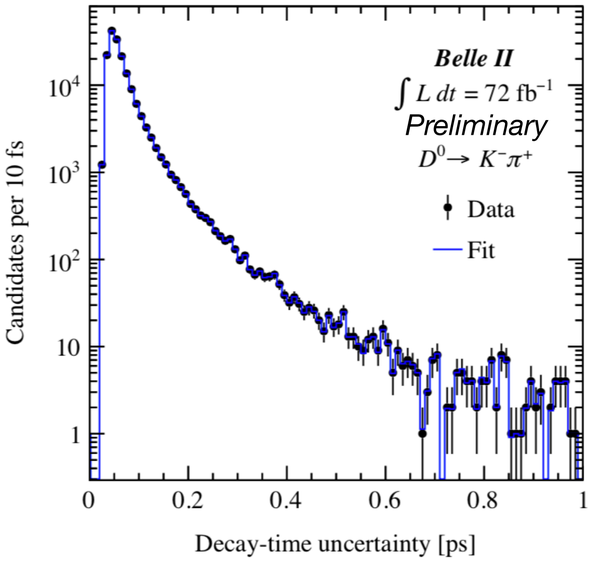


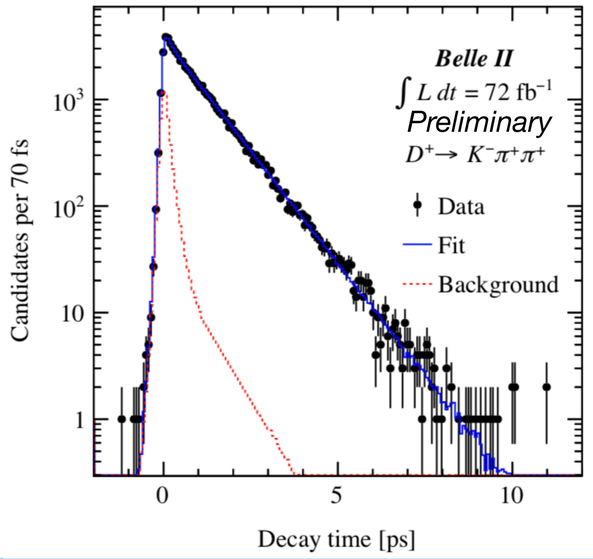


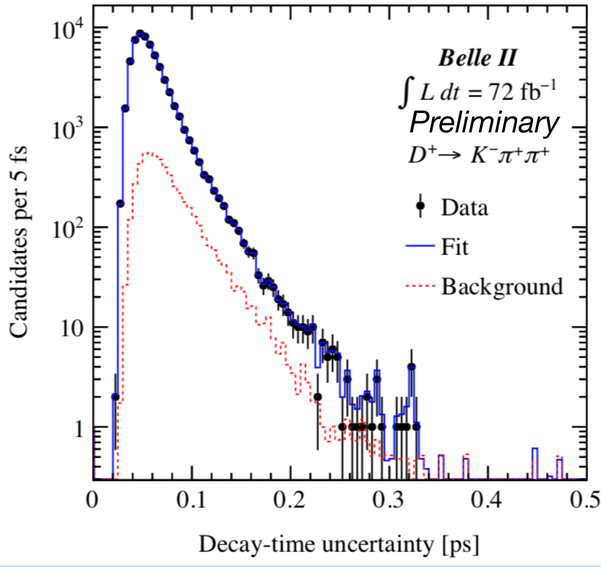
Fit Strategy for Lifetime Measurement

- 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 $m(K^-\pi^+)$
- Resolution function: → (2 gaussians for D^0, 1 gaussian for D^+) determined directly from fit
- For D^0 : background neglected in the fit → systematic assigned.
- For D^+: background included in fit → modeled using data sidebands
- Width: ~60-70 fs.
- Systematics:
  - Mostly from misalignment of vertex detector
  - Background modeling of D^+







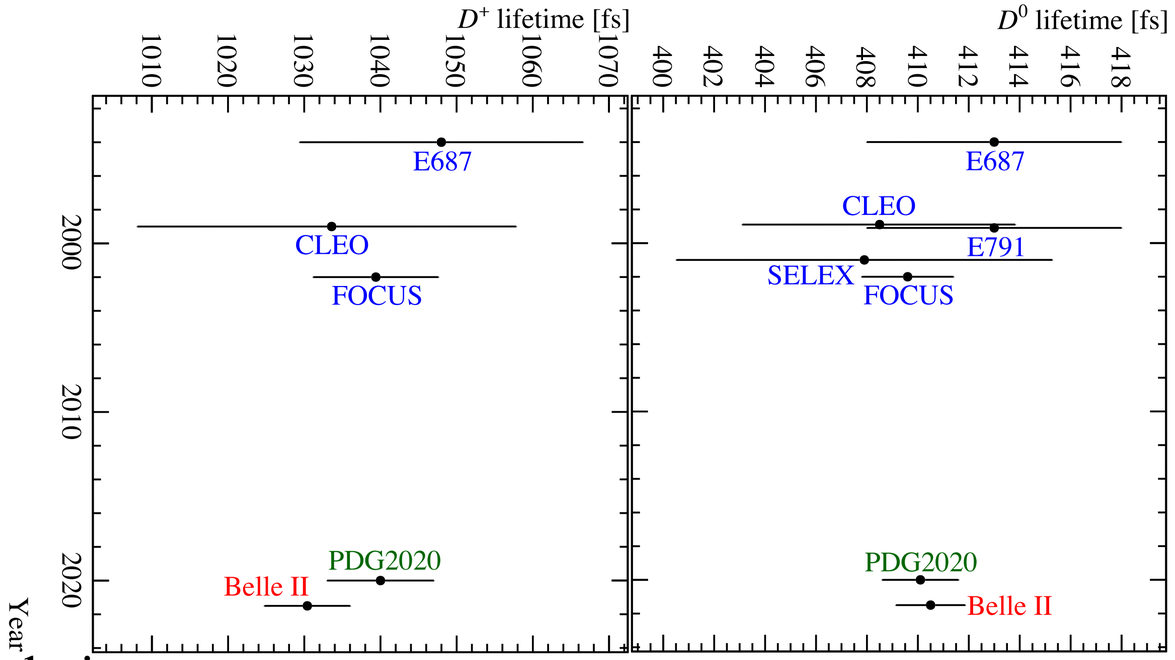


Results

- Most precise and consistent with previous measurements
- Few-per-mille accuracy excellent vertexing capability

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

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



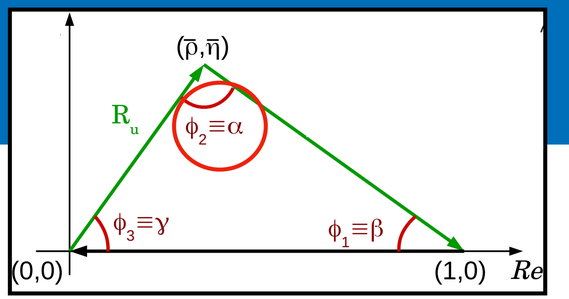
- Assuming systematic uncertainties fully correlated → correlation coefficient is 18%

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

Phys, Rev. Lett. 127 (2021) 211801

Expected excellent vertexing performance is established and will guarantee improved precision of time-dependent measurement, beyond the increase of luminosity

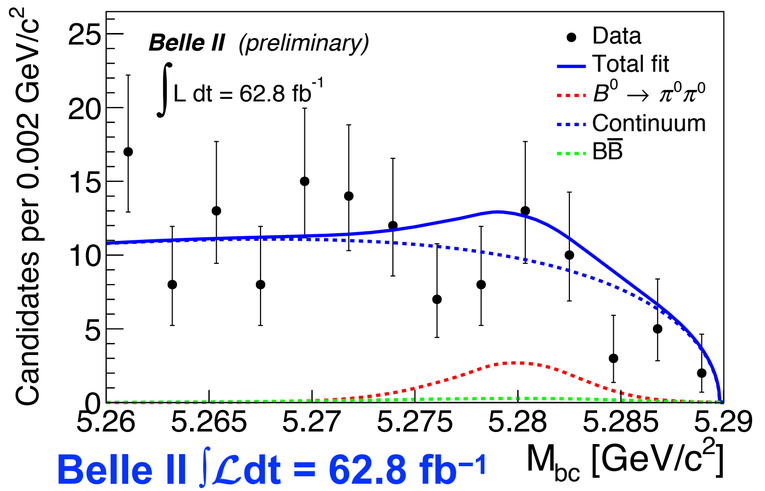
Towards ϕ_2/α



- Accessible via $b \to u$ transitions with large contribution from penguin ($b \to d$) diagrams
- Unique Belle II capability to determine ϕ_2/α by $B^0 \to \pi^0\pi^0$, $B^+ \to \rho^+\rho^0$
- $B^0 \to \pi^0\pi^0$ is very challenging due to four photons in final state
  - Main background is from continuum π^0
  - Dedicated MVA for photon selection

arXiv:2107.02373

- $\mathcal{B}(B^0 \to \pi^0\pi^0) = [0.98^{+0.48}_{-0.39}(\text{stat}) \pm 0.27(\text{syst})] \times 10^{-6}$



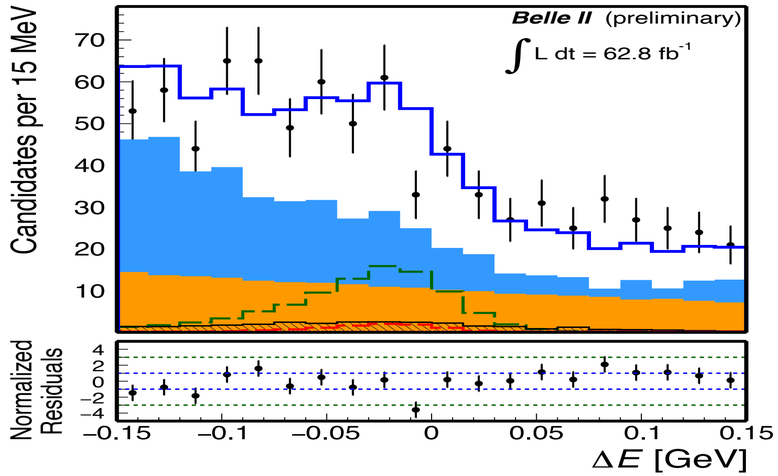
- $B^+ \to \rho^+\rho^0$ is pion only final state
  - Main background due to ρ mass width
  - Branching ratio is compatible with WA

$$\Delta E = E_B^* - E_{beam}$$

$$M_{\text{bc}} = \sqrt{E_{\text{beam}}^2 - \vec{p}_B^{\,2}}$$

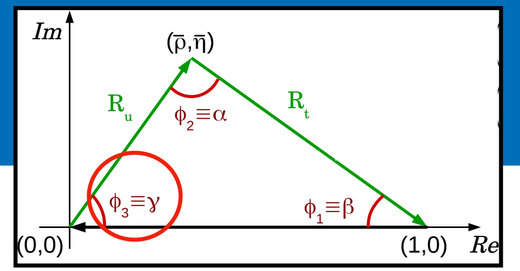
arXiv:2109.11456v2

- $\mathcal{B}(B^+ \to \rho^+\rho^0) = [20.6 \pm 3.2(\text{stat}) \pm 4.0(\text{syst})] \times 10^{-6}$



First reconstruction in Belle II data→preparing for measurement of α/ϕ_2

ϕ_3/γ Measurement with Combined Belle + Belle II Data

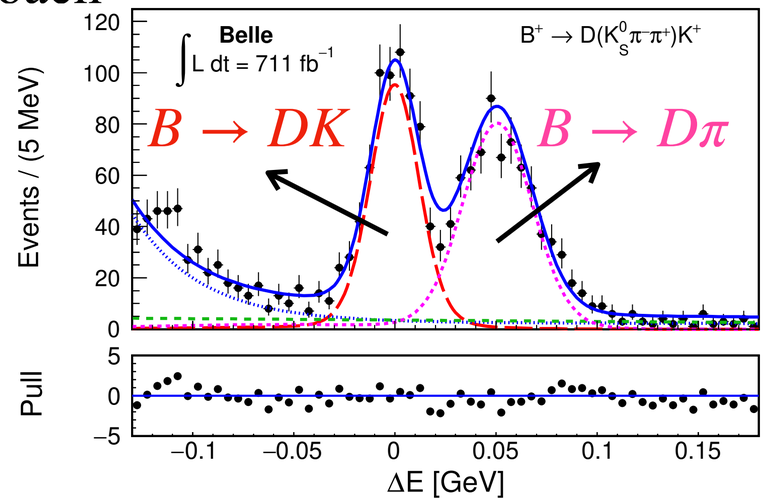


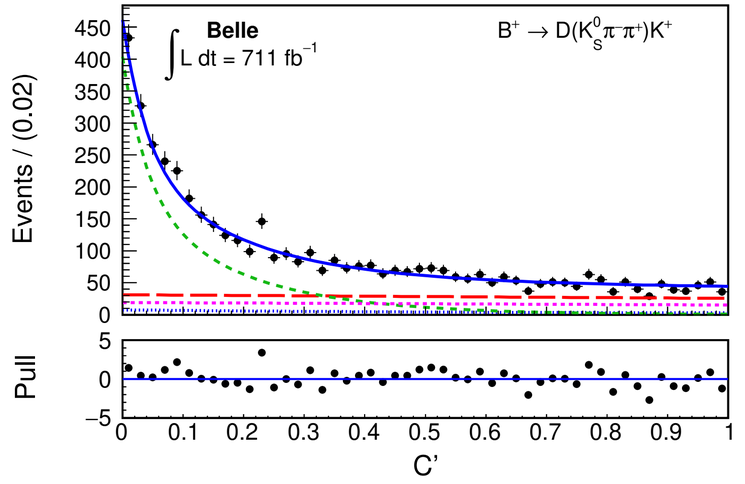
- $B^- \to D^0(K^0_S\pi^+\pi^-)K^-$ is the golden mode for γ/ϕ_3 measurement for Belle/Belle II.
- Using BPGGSZ model independent approach

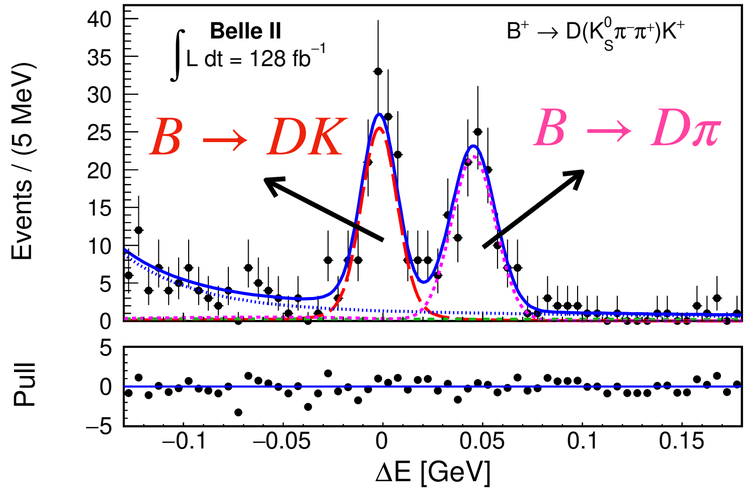
$$\frac{\mathcal{A}^{suppr.}(B^- \to \overline{D^0}K^-)}{\mathcal{A}^{favor.}(B^- \to D^0K^-)} = r_B e^{i(\delta_B+\phi_3)}$$

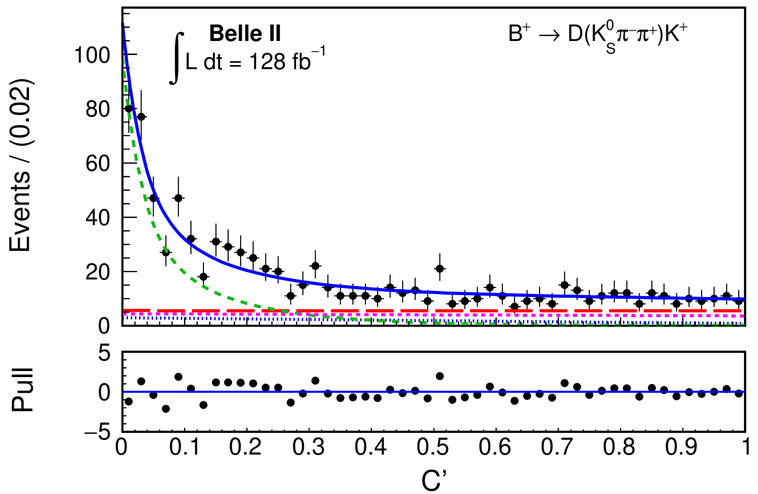
- r_B: magnitude of the ratio of amplitudes
- δ_B: strong phase difference

- Dominant and clean decay $B^- \to D^{(*)0}\pi^-$ and $B^0 \to D^{(*)+}\pi^-$ provide good control sample.
  Signal enhanced with $M_{\rm bc} > 5.27$ GeV/c^2 and PID to K/π from signal B
- Unbinned ML fit in ΔE and MVA output (with event shape variables).









ϕ_3/γ Measurement with Combined Belle + Belle II Data

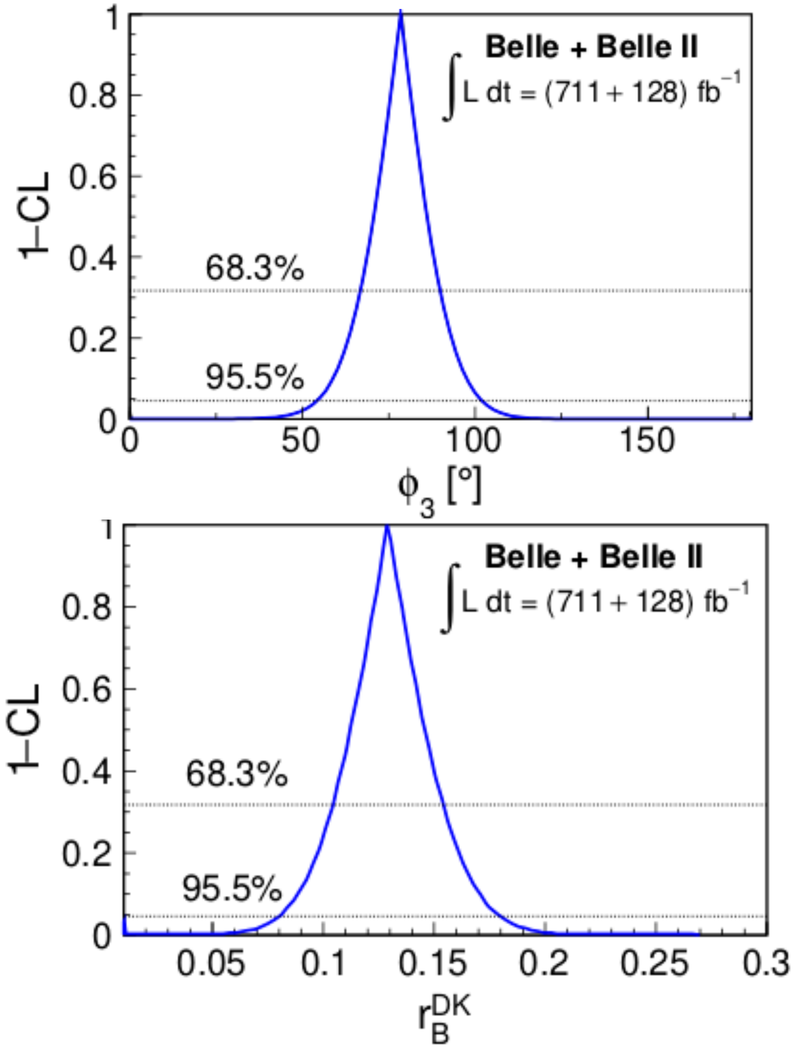
- First Belle and Belle II combined measurement

Belle+Belle II $\int\mathcal{L}dt$ = (711 + 128) fb^{-1}

$$\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ ,$$
$$r_B^{DK} = 0.129 \pm 0.024 \pm 0.001 \pm 0.002,$$
$$\delta_B^{DK} = (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^\circ .$$

- Statistical uncertainty improved by 30 % with just 20 % more data
- Experimental systematics reduced from 4° to 0.5°
- Systematics associated with inputs reduced from 4° to 1° due to recent updates from by BESIII

arXiv:2110.12125
Submitted to JHEP

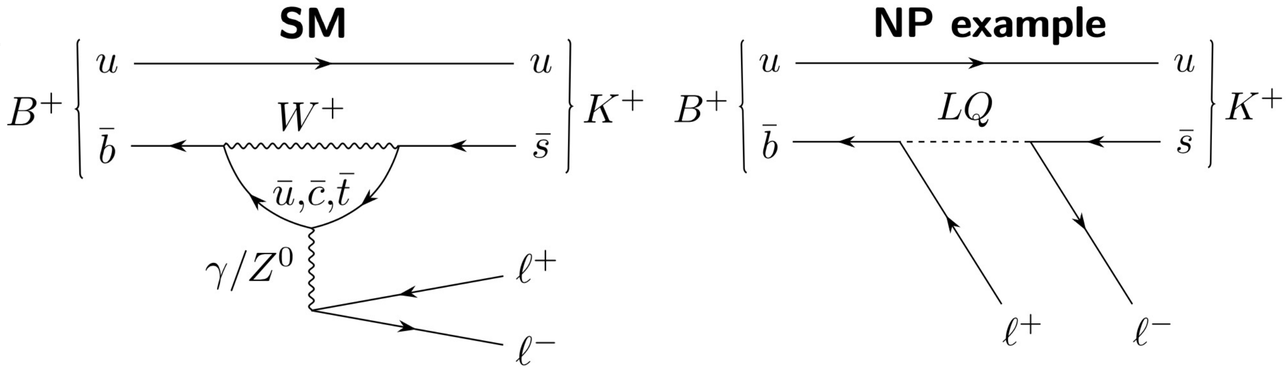


$B^+ \to K^+\ell^+\ell^-$

B . F ~ 10^{-7}

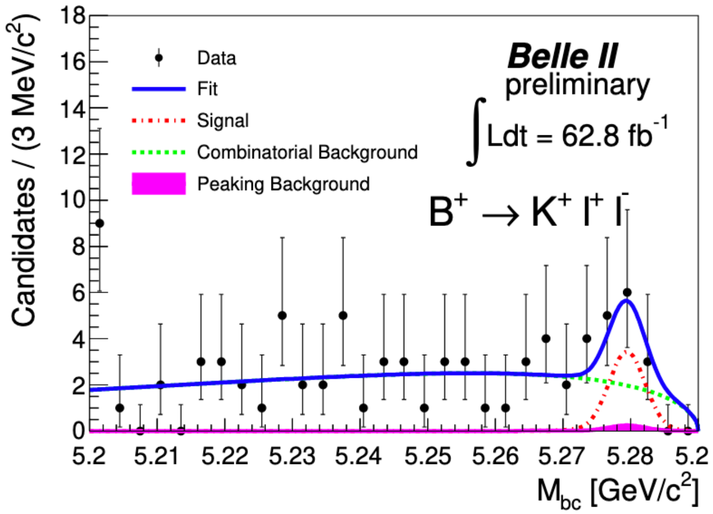
- Important FCNC decay measurement $B^+ \to K^+\ell^+\ell^-$ (l = e, μ) sensitive to many SM extensions.
- BDT (event shape, vertex related and missing energy variables) to suppress background from **light quark** and **inclusive *B* decays**.
- First look with 63 fb^{-1} data
- 2D fit to $\Delta E = E_B^* - E_{beam}$ and $M_{\rm bc} = \sqrt{E_{\rm beam}^2 - \vec{p}_B^{\,2}}$ distribution
- Signal Yield : $8.6^{+4.3}_{-3.9} \pm 0.4$ events

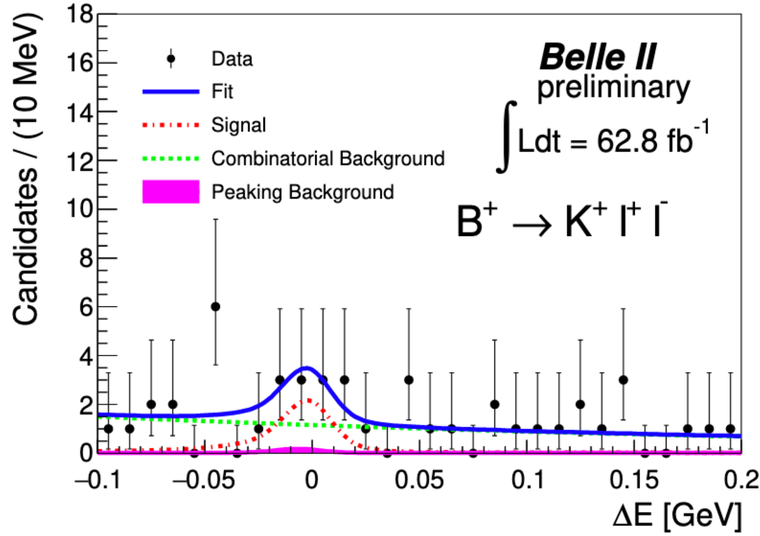
More data needed for $\mathcal{B}$ and R_K measurement



$$R_{K^{(*)}} := \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \overset{\rm SM}{\cong} 1$$

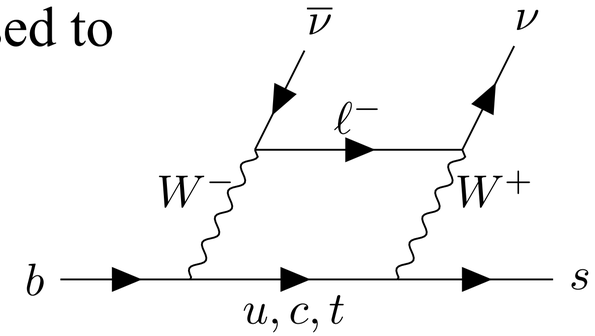
Any significant deviation is hint for non-SM Physics!!



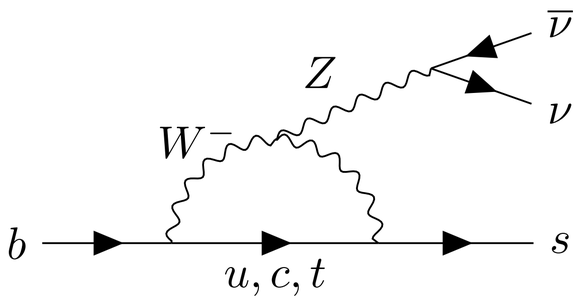


$B^+ \to K^+\nu\bar{\nu}$

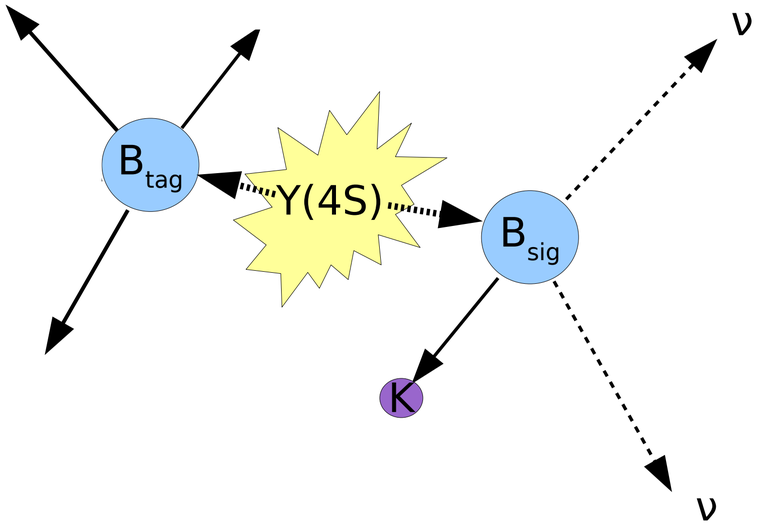
- Complementary probe of BSM physics scenarios proposed to explain anomalies observed in $b \to sl\bar{l}$ transitions
- Not observed yet
- SM prediction: $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = (4.6 \pm 0.5) \times 10^{-6}$
- but BSM could enhance its B.F
- Experimentally very challenging with two neutrinos
- Previously measured using tagging (semileptonic, hadronic) approach
- Belle II approach: measured using inclusive tagging
  - Exploit distinct topology and kinematics to achieve higher signal efficiency (~4%) → better compared to earlier approaches
  - Two nested boosted decision tree classifiers, to suppress various backgrounds



Box Diagram

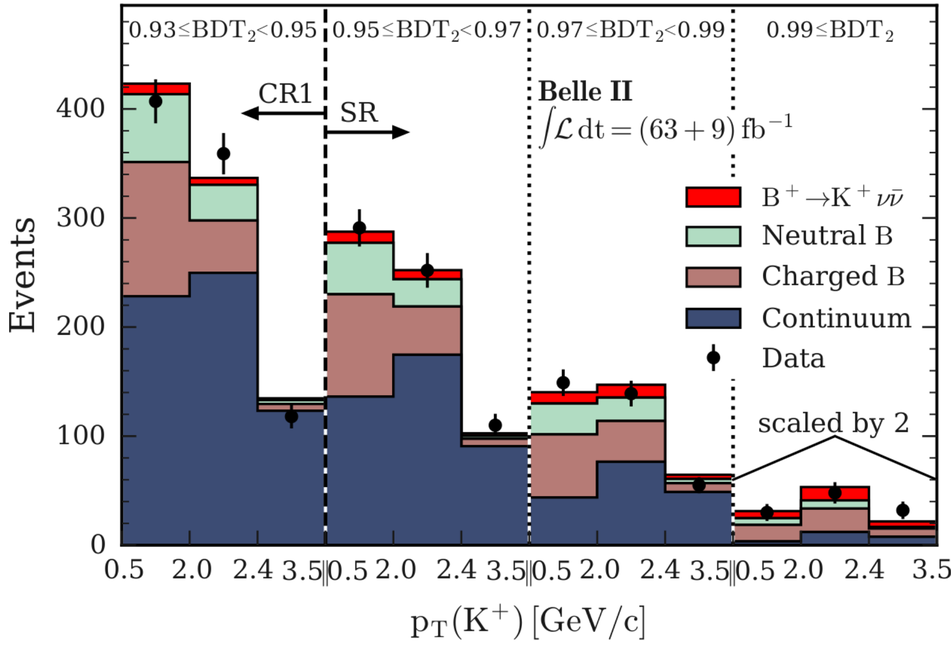


Penguin Diagram

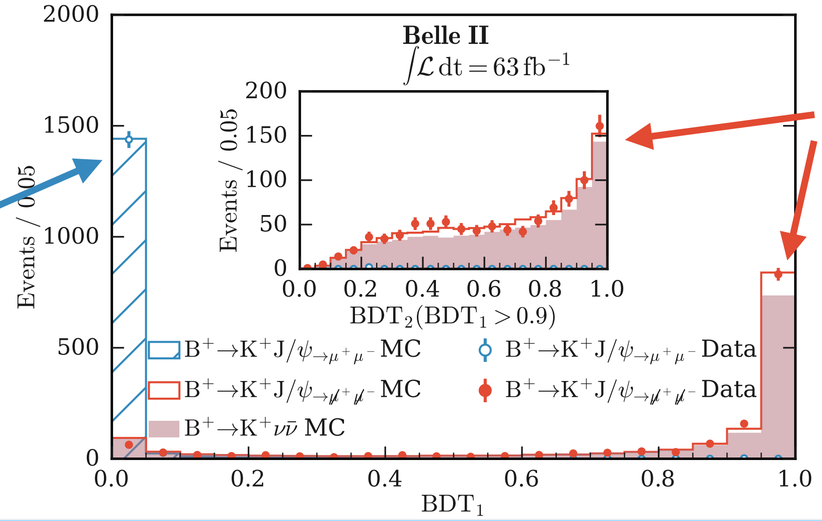


$B^+ \to K^+\nu\bar{\nu}$

- 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
- 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)

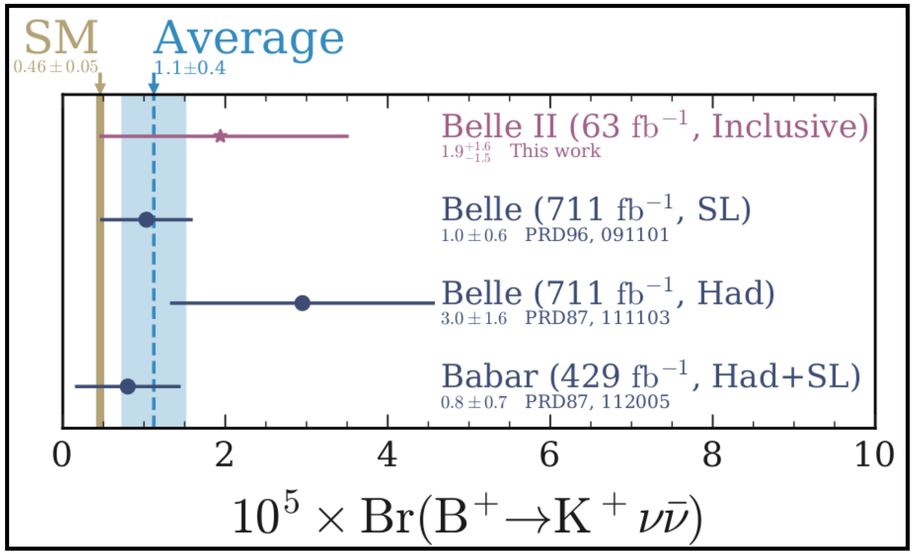
$B^+ \to K^+ \nu\bar{\nu}$ Results

- No signal observed; CLs limit (assuming SM signal)

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

- better than
  - semileptonic tagging by $10 - 20\,\%$
  - hadronic tagging by a factor 3.5

- Future prospects:
  - more data
  - additional channels $B^0 \to K^{*0}\nu\bar{\nu}$, $B^0 \to K^0_S \nu\bar{\nu}$, $B^+ \to K^{*+}\nu\bar{\nu}$
  - improved technique (neural net)



Phys. Rev. Lett. 127 (2021) 181802

Work in progress to improve the inclusive tag method and employ the same strategy for other modes $b \to s\nu\bar{\nu}$

Inclusive $B \to X_c \ell \nu$

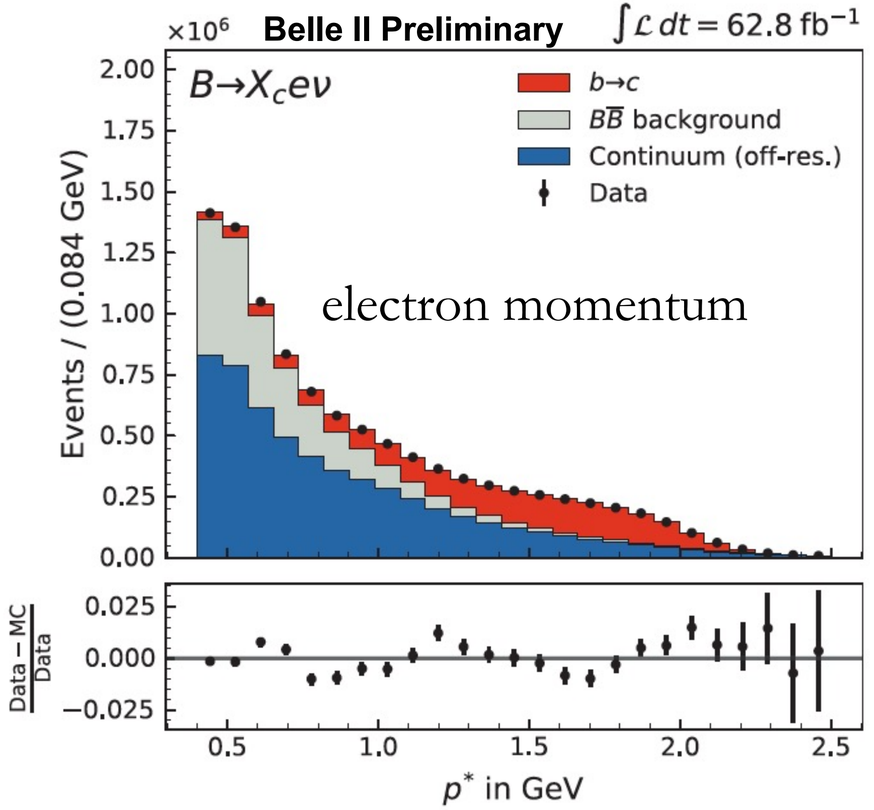
- Different strategies may help resolve the inclusive/exclusive discrepancy in $b \to c\ell\nu$ and $b \to u\ell\nu$
- Measure q^2-moments (moments of lepton energy or hadronic mass) to simultaneously determine non perturbative elements and $|V_{cb}|$

arXiv: 2109.01685

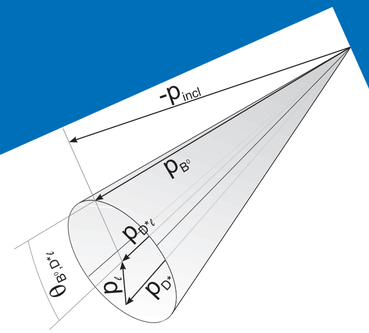
- Belle II performed both the untagged and the hadronic tagged analyses.
- **Untagged analysis**
- Require one well identified lepton
- Exploit missing mass and momentum to reject backgrounds
- Measure the branching fraction with a fit to p_l^*

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

Next: $|V_{cb}|$ from q^2 moments



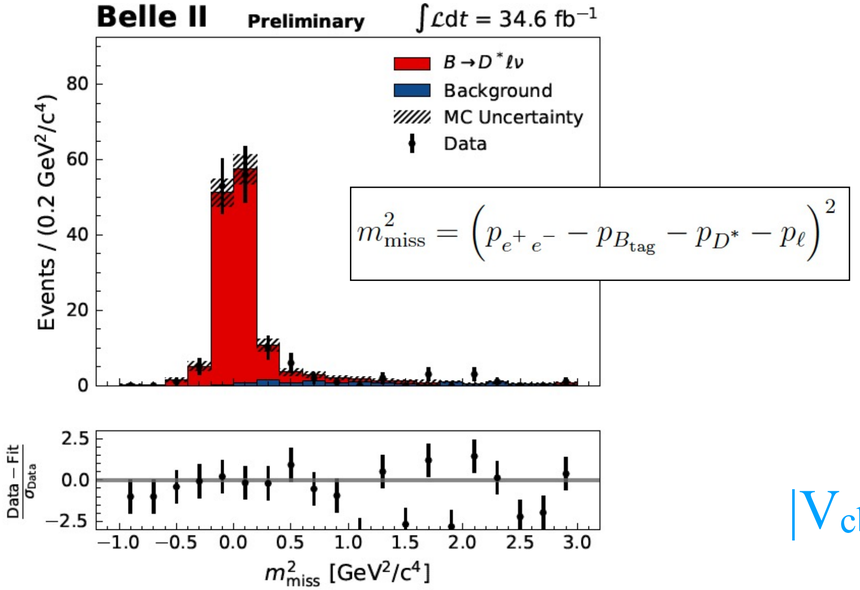
Exclusive $B \to D^{(*)}\ell\nu$



- $B \to D^{(*)}\ell\nu$ has been explored with both tagged and untagged approaches
- Tagged analysis
  - Almost zero background after tag
  - Signal selection from D^* and D^0 invariant masses, and lepton momentum
- 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

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

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

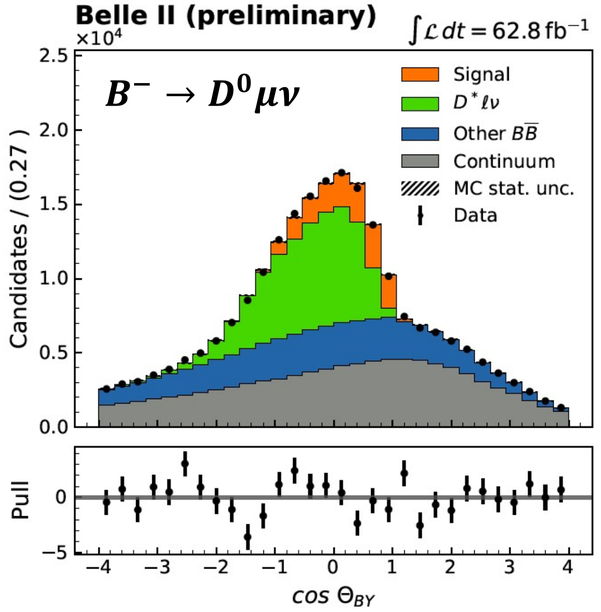


$$m^2_{\text{miss}} = \left(p_{e^+e^-} - p_{B_{\text{tag}}} - p_{D^*} - p_\ell\right)^2$$

arXiv:2008.10299v4

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

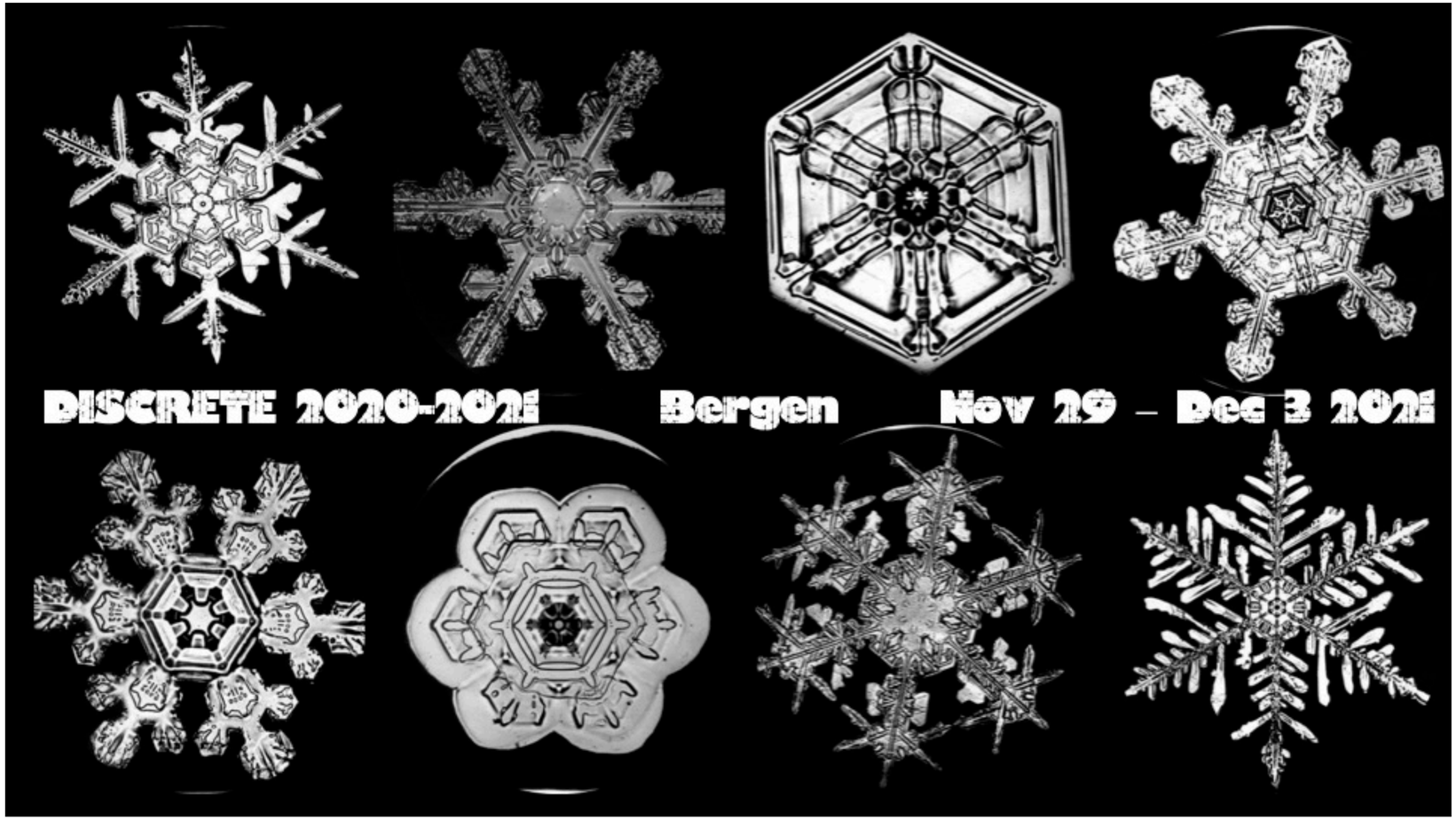
$|V_{cb}|$ measurement in progress …



Conclusions

- Belle II in great shape, has already >200 fb^{-1} of data being analyzed → more new results coming soon
- Established excellent vertexing performance with world's best D lifetimes measurement
- Belle II preparing for a leading role in ϕ_2 measurement and first combined Belle + Belle II ϕ_3 measurement
- First observation of $B^+ \to K^+\ell^+\ell^-$ and $B^+ \to K^+\nu\bar{\nu}$ with just 63 fb^{-1} data with prospects to do full measurement
- 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
- Very active and wide range program of searches for dark sector; Belle II will be leading the field of light Dark Matter searches in the GeV range in the coming years
- SuperKEKB has set a new world record in peak luminosity and is entering the regime of a "Super B factory"
- We have restarted data taking for winter 2021-2022 from mid October

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



Thank You

Backup

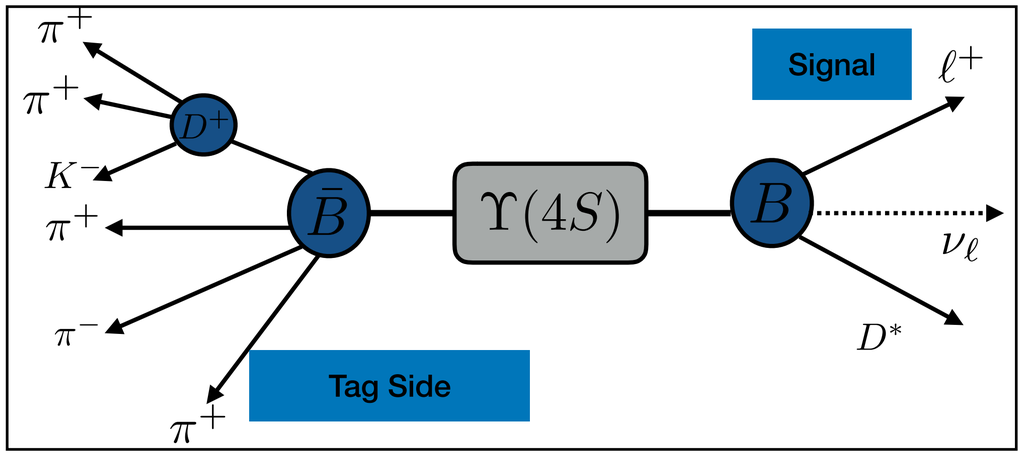
Tagging Techniques at Belle II

Tagged Measurement

One B reconstructed completely in a known b→c mode without ν. "B-meson Beam"

Provide background suppression

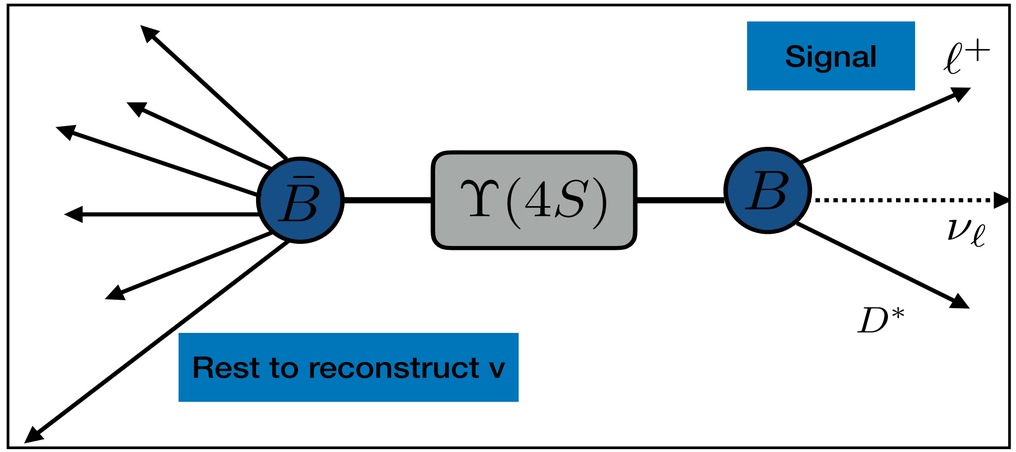
- **High purity, very small background**
- **Low Efficiency , large stat. errors**



Untagged Measurement

Initial 4 momentum known, missing 4-momentum = ν
Reconstructed B → Xq lν
Other side information to constrain B flight direction

- **High efficiency**
- **Low purity, large background**



Efficiency

Purity

Summary of the Sensitivities: $B^+ \to K^+ \nu\bar{\nu}$

Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B^+ \to K^+ \nu\bar{\nu})$	$< 450\%$	30%	11%
$\mathrm{Br}(B^0 \to K^{*0} \nu\bar{\nu})$	$< 180\%$	26%	9.6%
$\mathrm{Br}(B^+ \to K^{*+} \nu\bar{\nu})$	$< 420\%$	25%	9.3%
$F_L(B^0 \to K^{*0} \nu\bar{\nu})$	–	–	0.079
$F_L(B^+ \to K^{*+} \nu\bar{\nu})$	–	–	0.077
$\mathrm{Br}(B^0 \to \nu\bar{\nu}) \times 10^6$	< 14	< 5.0	< 1.5
$\mathrm{Br}(B_s \to \nu\bar{\nu}) \times 10^5$	< 9.7	< 1.1	–

The Belle II Physics Book, PTEP 2019 (2019) 12

Comparison with LHCb

Property	LHCb	Belle II
$\sigma_{b\bar{b}}$ (nb)	~150,000	~1
$\int L\,dt$ (fb^{-1})	~25	~50,000
Background level	High	Low
Typical efficiency	Low	High
π^0, K_S efficiency	Low	High
Initial state	Not well known	Well known
Decay-time resolution	Excellent	Good
Collision spot size	Large	Tiny
Heavy bottom hadrons	B_s, B_c, b-baryons	Partly B_s
τ physics capability	Limited	Excellent
B-flavor tagging efficiency	3.5 - 6%	36%