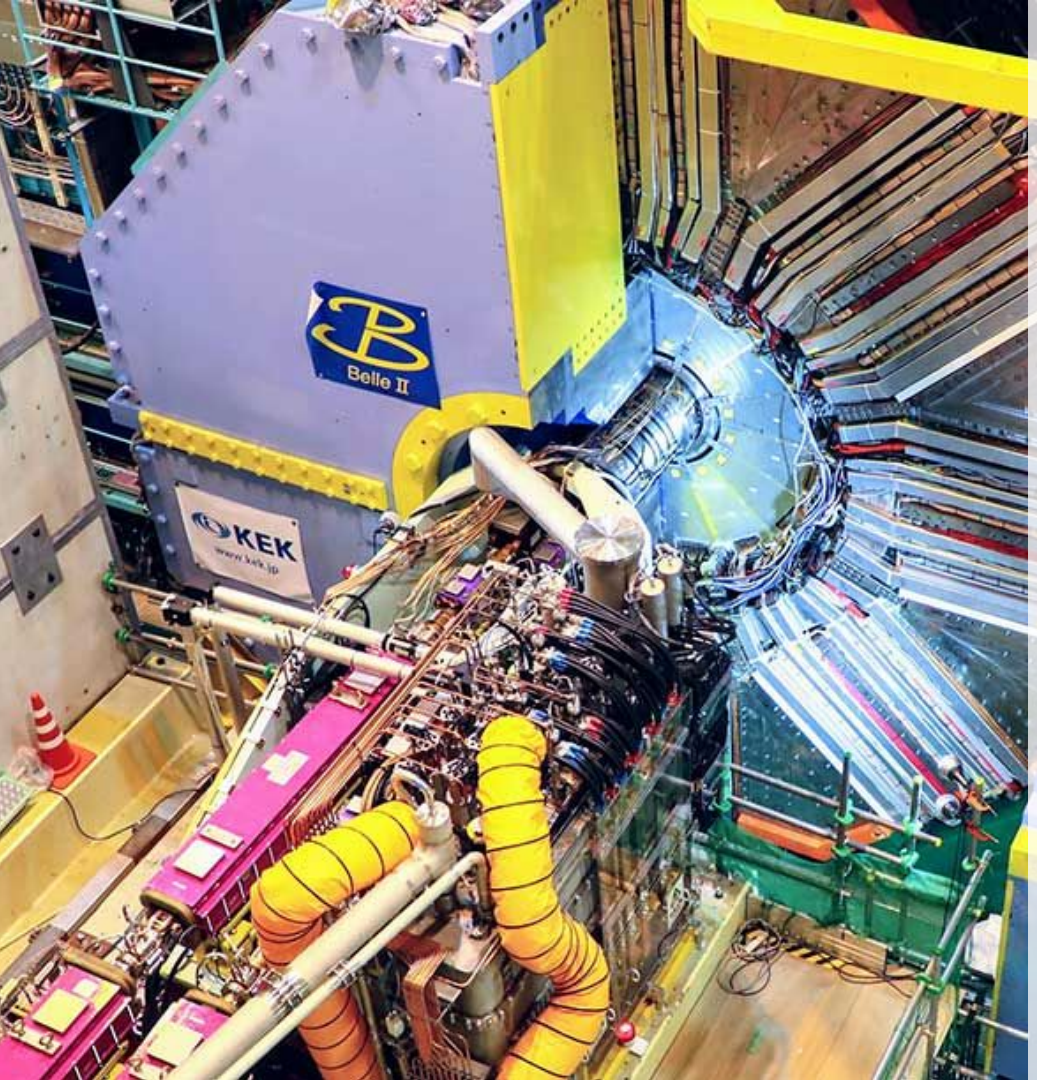


Belle II: status and prospects

NUCLEUS-2021

Peter M. Lewis on behalf of the Belle II collaboration

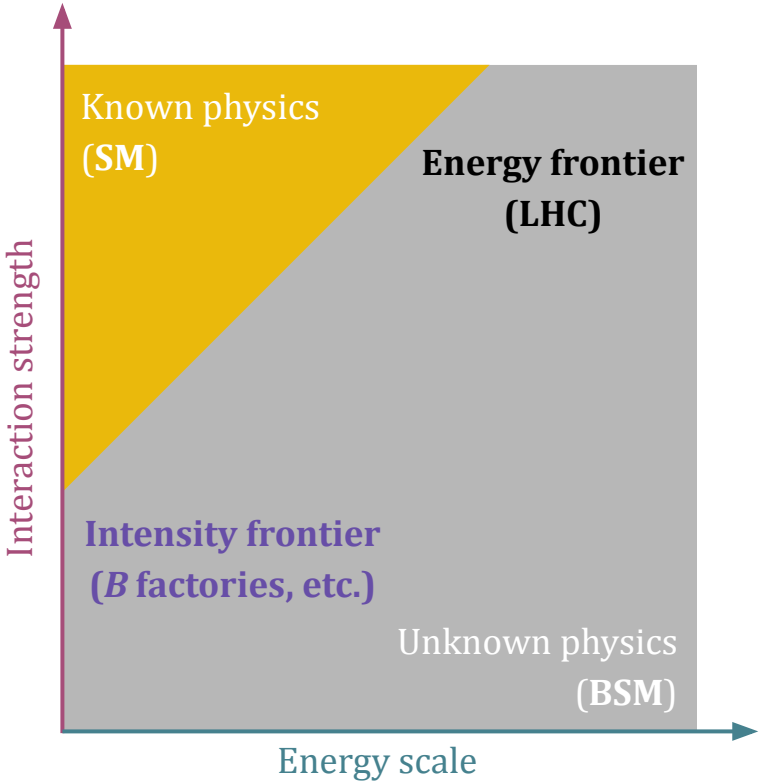
Belle II

UNIVERSITÄT BONN

Standard Model

Decades of precision tests

- Enormous progress on measuring parameters and verifying predictions
- But SM is **not complete**
  - Ongoing search for **BSM physics**
- **Direct** production at **energy frontier** has yielded no unambiguous evidence
  - Nothing from ATLAS, CMS...

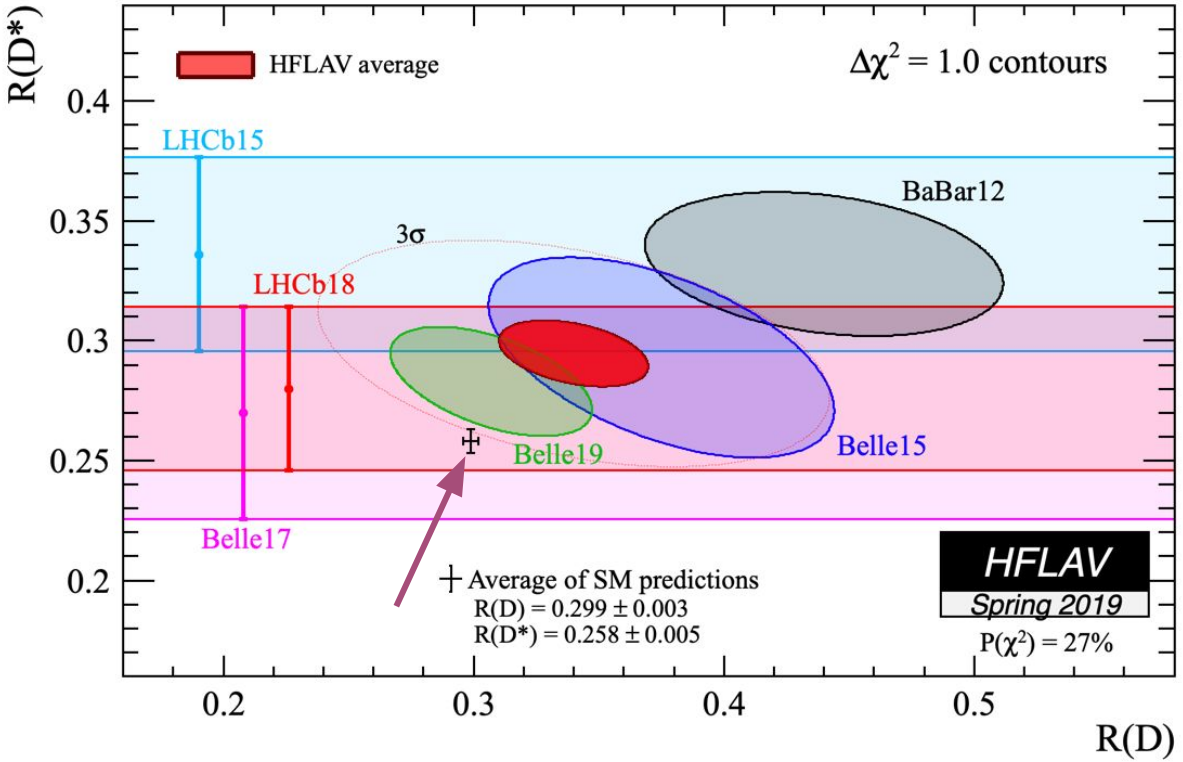


But *indirect* searches at the **intensity frontier** have uncovered intriguing **flavor anomalies**...

Flavor anomalies

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

$$(\ell = e, \mu)$$



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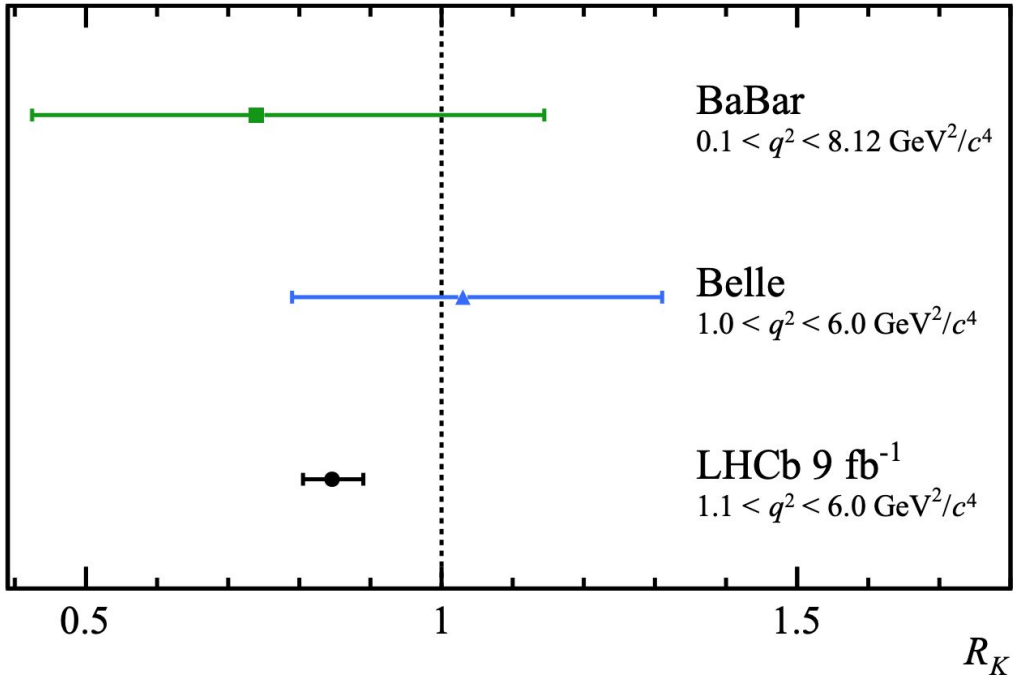
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$



Flavor anomalies

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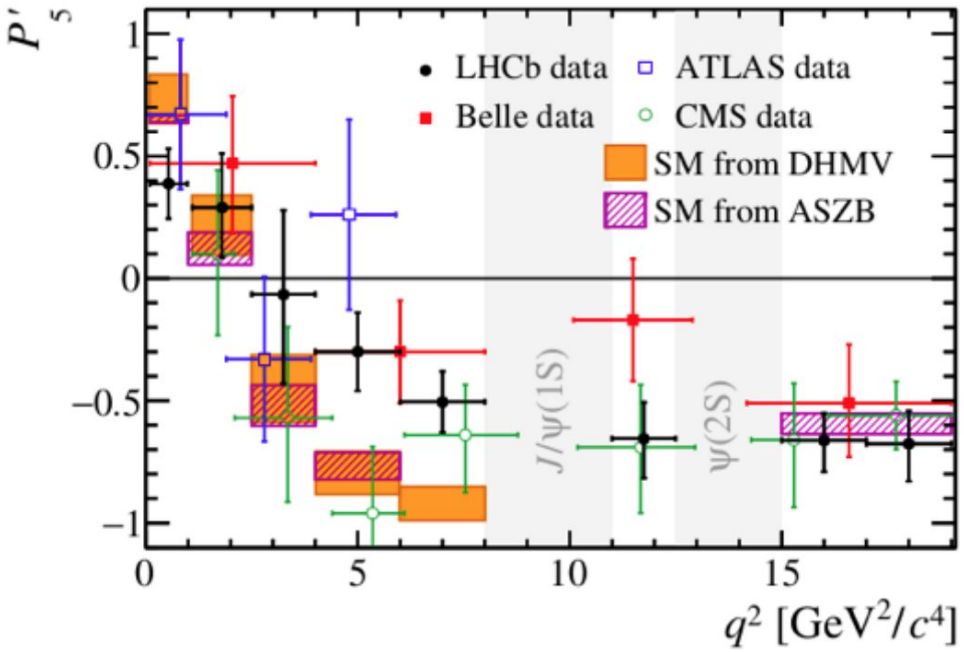


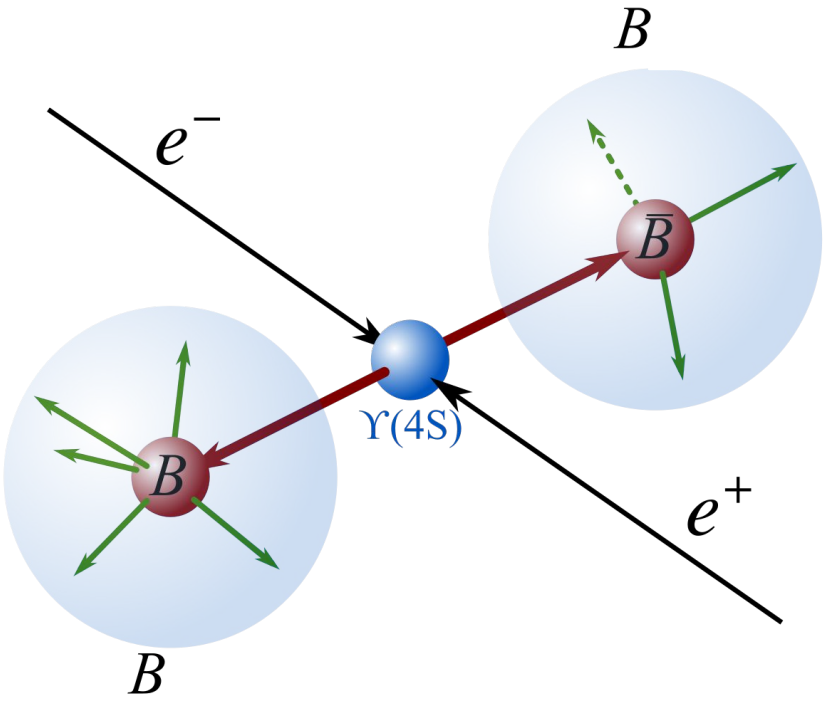
Other $b \to s\ell\ell$ anomalies in angular observables.
Global tension may be over 5σ

A coherent picture is emerging… lots of excitement! Need more data...

Intensity frontier

More data to confirm anomalies

- These anomalies are seen in **rare *B* meson decays**
- We need **huge**, **pure** collections of ***B* mesons...**
- At the *B Factories*, a pair of *B* mesons is produced in "clean" events $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\overline{B}$
  - BaBar (1999-2008): 433 fb^{-1} (470M $B\overline{B}$)
  - Belle (1999-2010): 711 fb^{-1} (771M $B\overline{B}$)
- LHCb (current) is largely **complementary**

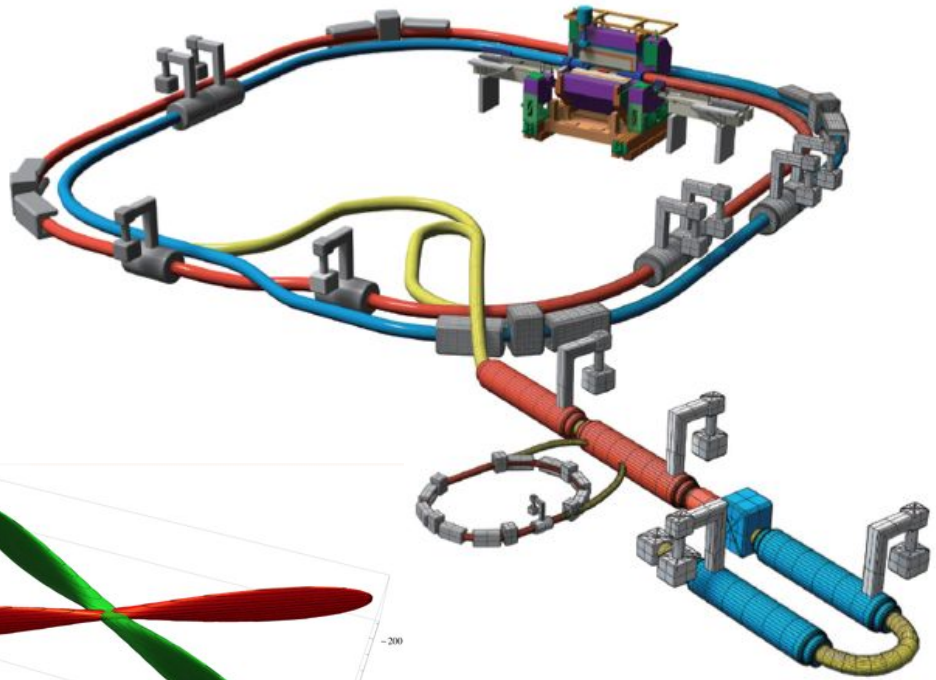


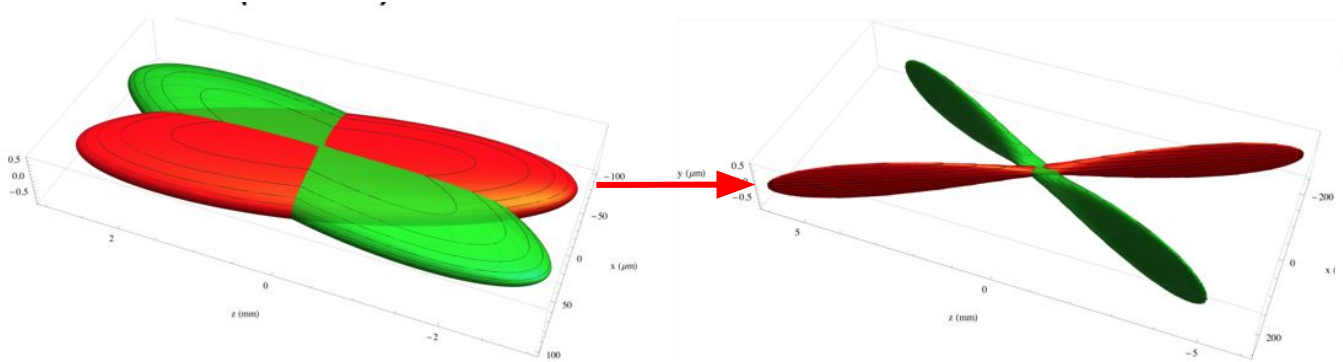
A luminosity upgrade to Belle...

SuperKEKB

Upgrade to KEKB

- Asymmetric e^+e^- collider at 10.58 GeV [$\Upsilon(4S)$]
- Increase instantaneous luminosity by **30**
- Largely accomplished via **nanobeam scheme**
  - σ_y^*: 940 → ~50 nm





Luminosity

Plan and records

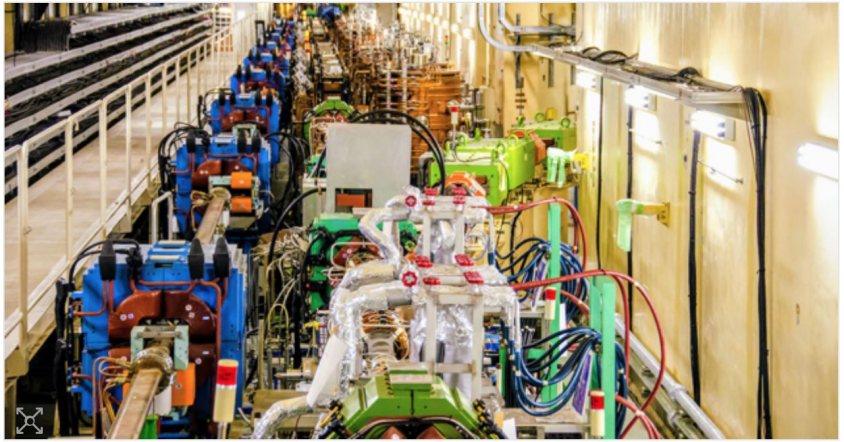
- Goal: **50ab^{-1}** integrated (>50**Bn** $B\overline{B}$)
- Operating since 2018
- World record instantaneous luminosity set by ~50%
  - *Was*: **2.1**x10^{34}cm^{-2}s^{-1}
  - *Now*: **3.1**x10^{34}cm^{-2}s^{-1}
- A long way to go!
- Will review some **early results** and **near-term prospects** today...

CERNCOURIER

ACCELERATORS | NEWS

SuperKEKB raises the bar

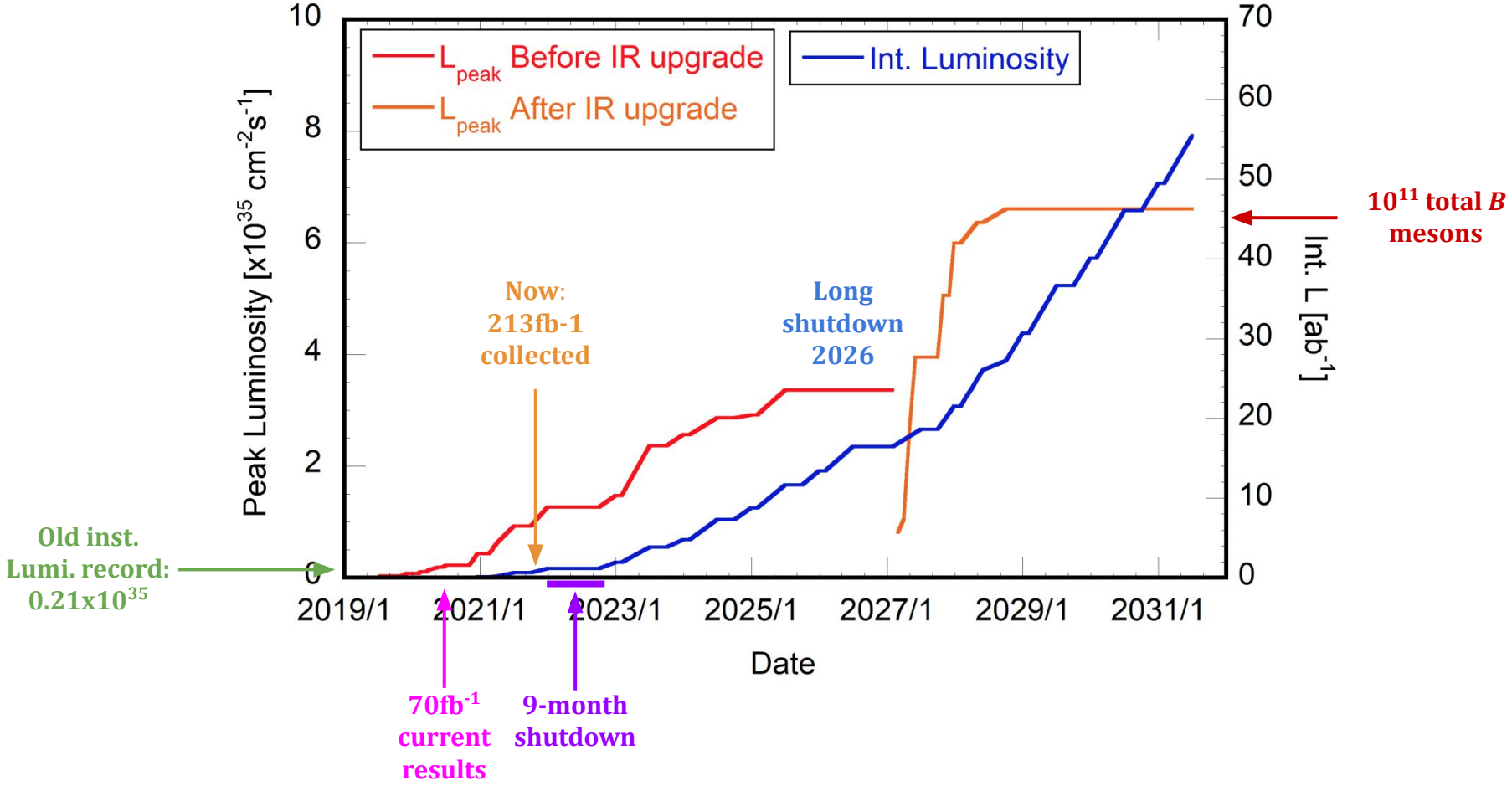
22 August 2021



Record breaker The SuperKEKB accelerator at the KEK laboratory in Tsukuba, Japan. Credit: S. Takahashi / KEK

On 22 June, the SuperKEKB accelerator at the KEK laboratory in Tsukuba, Japan set a new world record for peak luminosity, reaching 3.1 × 10^{34} cm^{-2} s^{-1} in the Belle II detector. Until last year, the luminosity record stood at 2.1 × 10^{34} cm^{-2} s^{-1}, shared by the

Luminosity plan



Belle II upgrades

Central beam pipe: decreased diameter from 3cm to 2cm (Beryllium)

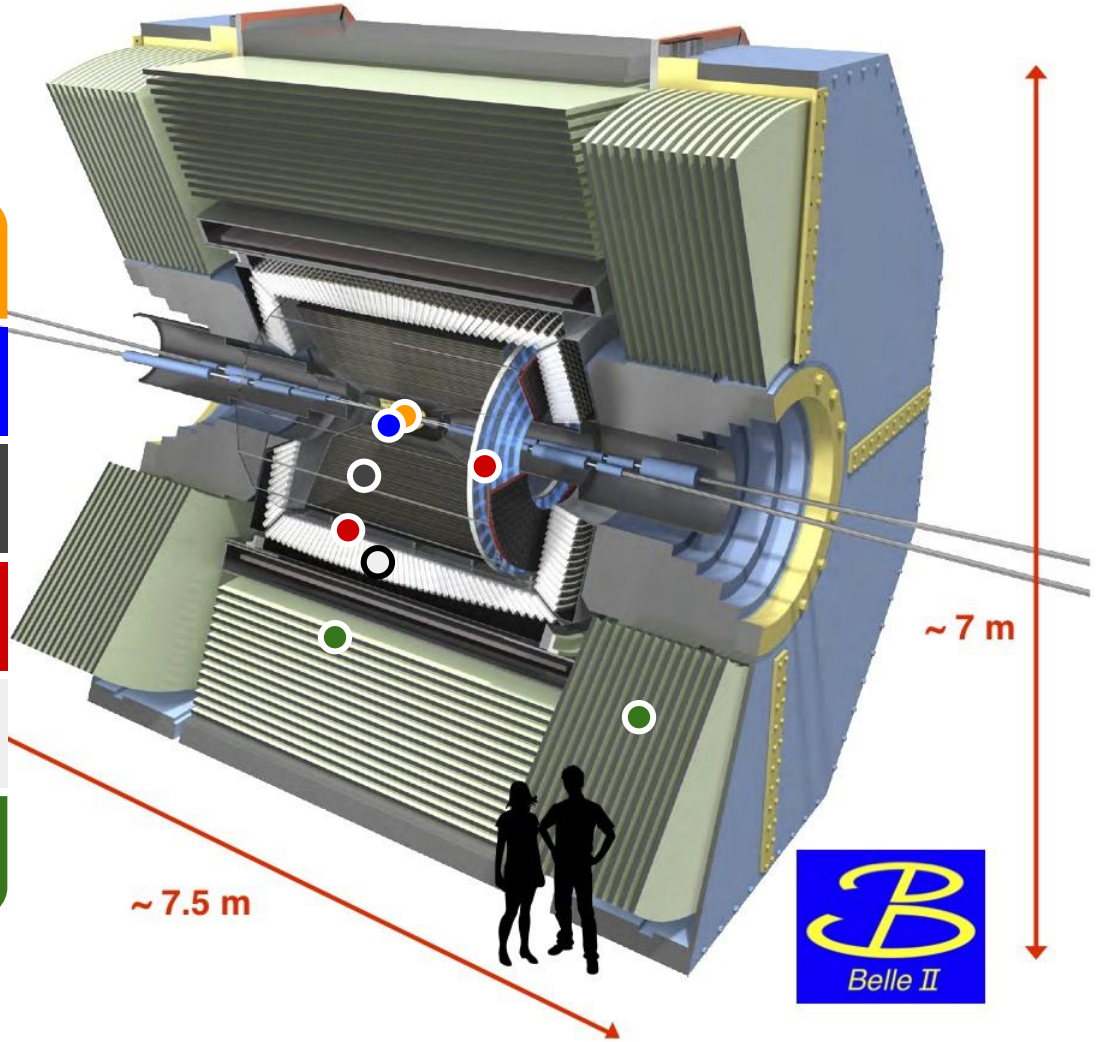
Vertexing: new 2 layers of pixels, upgraded 4 double-sided layers of silicon strips

Tracking: drift chamber with smaller cells, longer lever arm, faster electronics

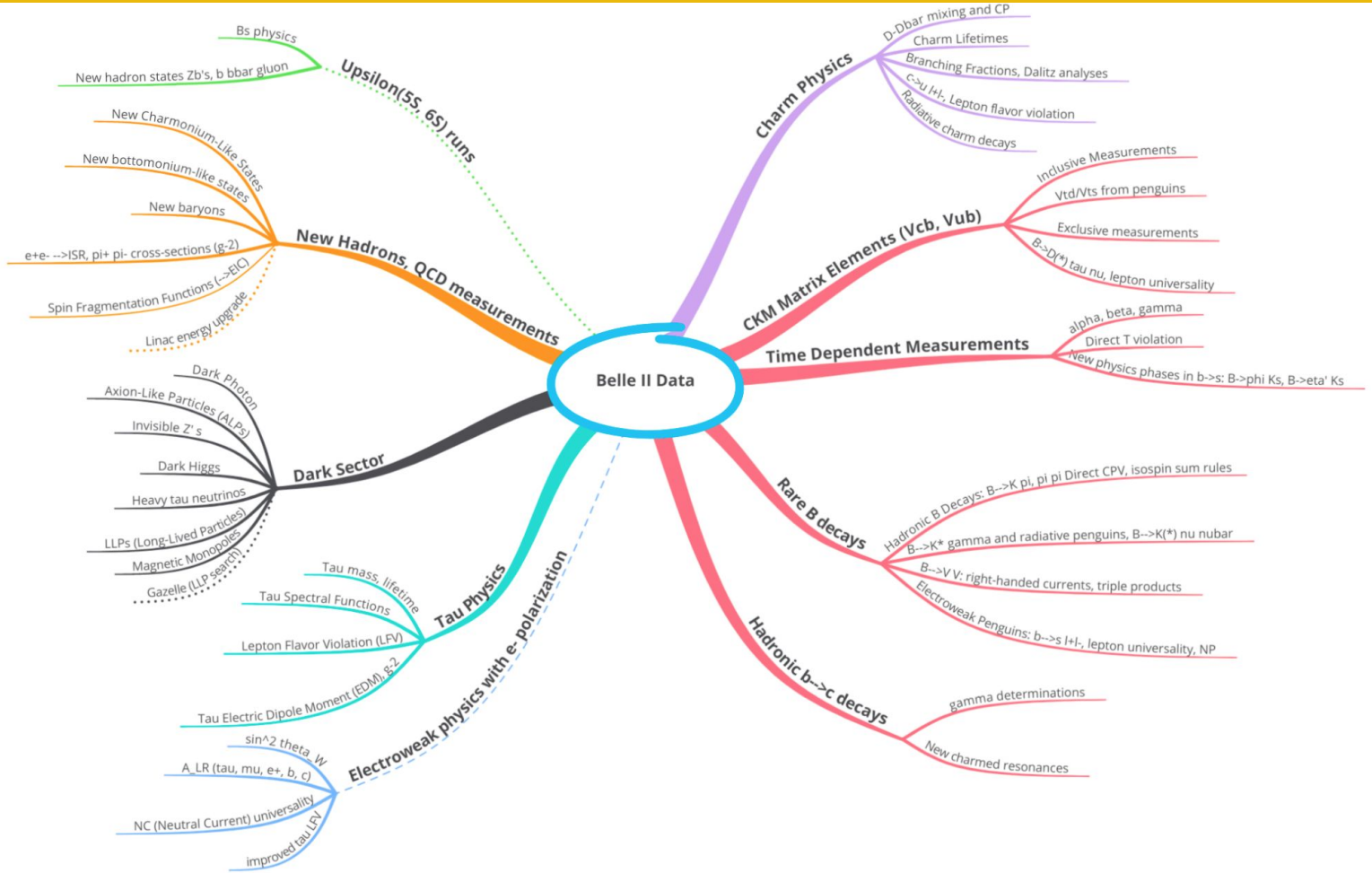
PID: new time-of-propagation (barrel) and proximity focusing aerogel (endcap) Cherenkov detectors

EM calorimetry: upgrade of electronics and processing with legacy CsI(Tl) crystals

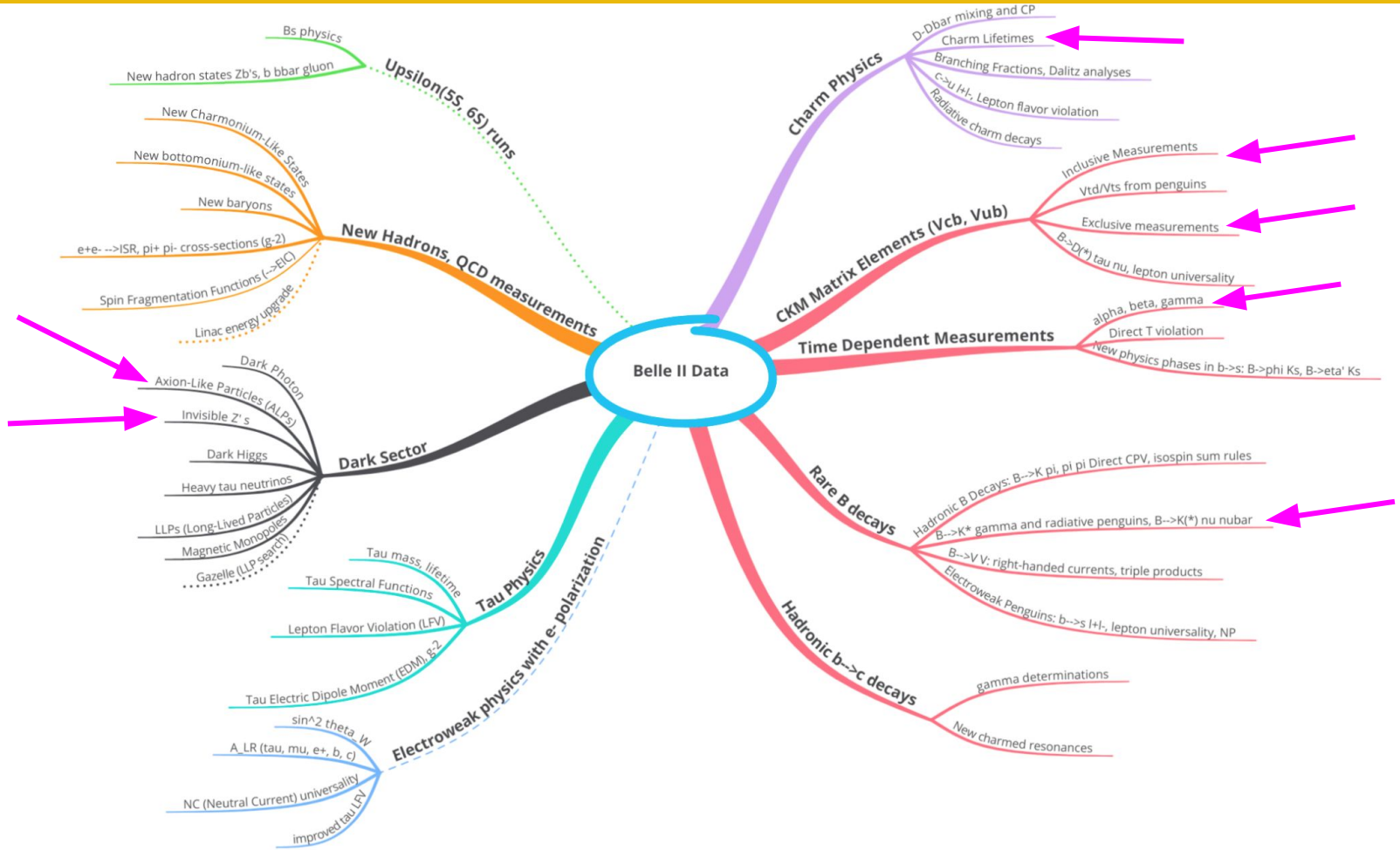
K_L and μ: scintillators replace RPCs (endcap and inner two layers of barrel)



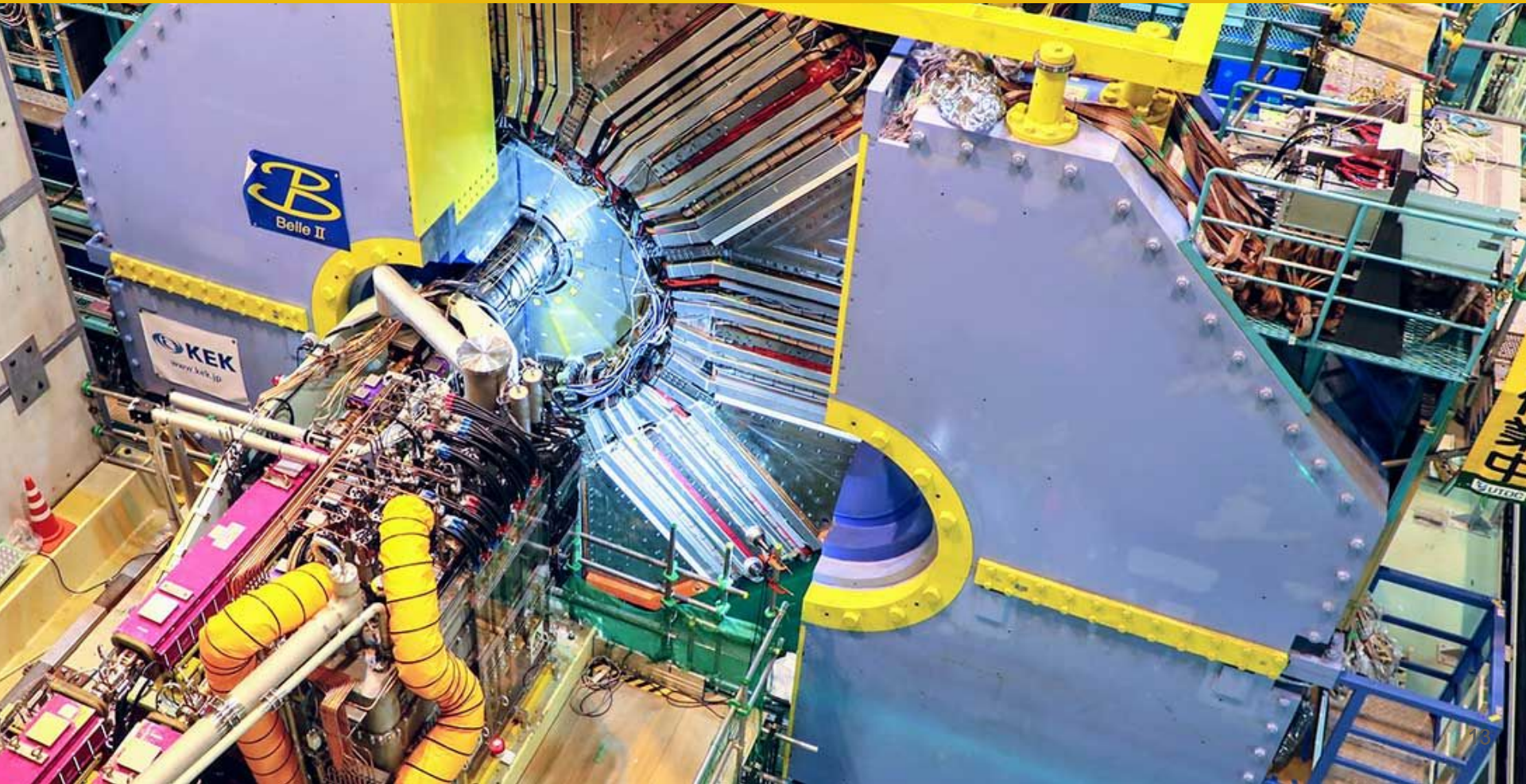
Belle II physics program: not just flavor anomalies



Belle II physics program: not just flavor anomalies



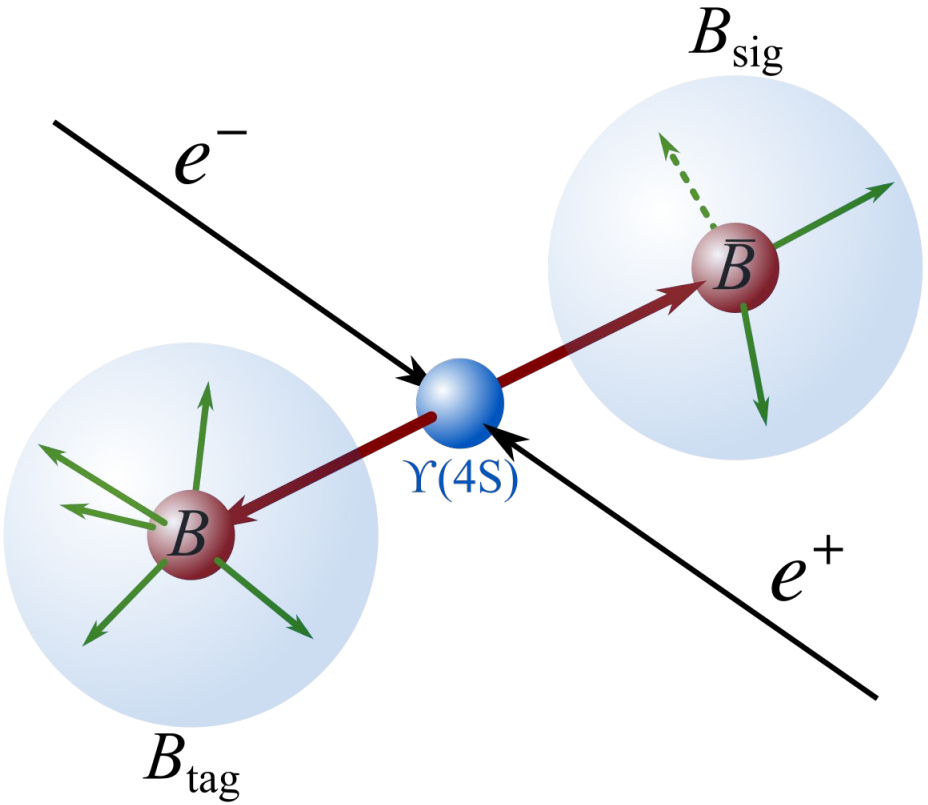
B factory essentials



Kinematics

Basics

- $p_{\Upsilon(4S)} = p_{e-} + p_{e+}$
- $\Upsilon(4S)$ frame (COM) is **static**
  - But **boosted** in lab frame
  - $B\bar{B}$ fly back-to-back in COM frame (p_T exaggerated in figure)
  - *B frame* is not *a priori* known
- Full kinematic reconstruction of a **single neutrino** is possible
- Boost allows for identification of **displaced *B* vertex**



Kinematics

Key metrics of kinematic consistency

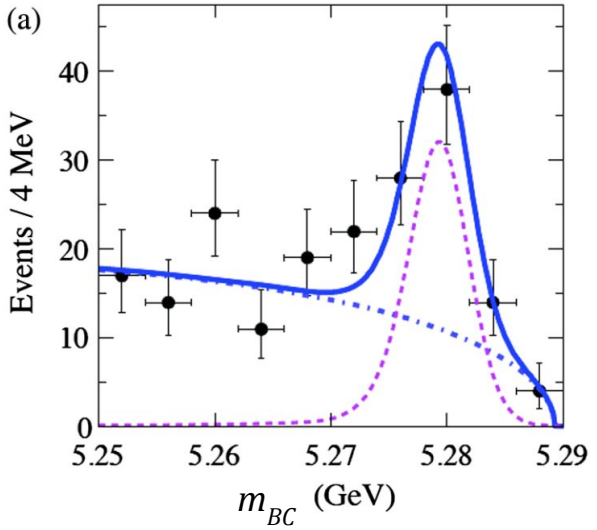
- *Beam constrained mass* ($m_{bc} = m_B$ for correctly reconstructed B)

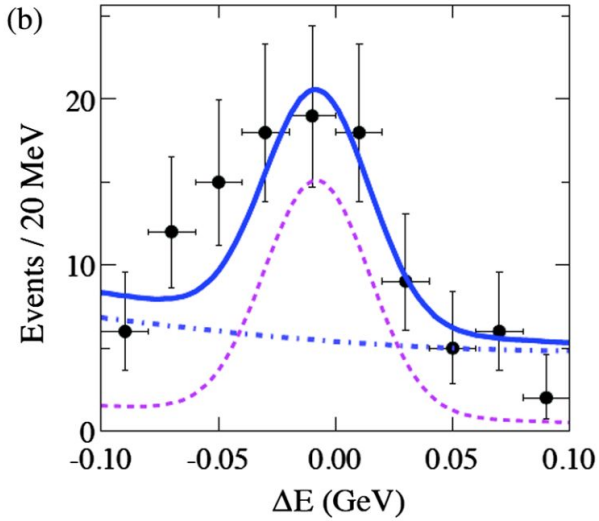
$$m_{\mathrm{bc}} = \sqrt{E^{\star 2}_{\mathrm{beam}} - \boldsymbol{p}^{\star 2}_{B}}$$

- *Energy difference* ($\Delta E = 0$ for correctly reconstructed B)

$$\Delta E = E^{\star}_{B} - E^{\star}_{\mathrm{beam}}$$

- *Missing mass squared* ($\boldsymbol{m}_{miss}^{\ 2} = 0$ if reconstruction is complete/correct except for a single **missing massless**)

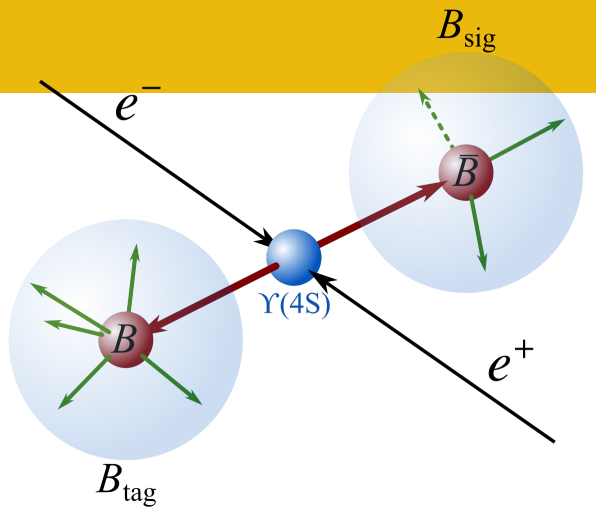


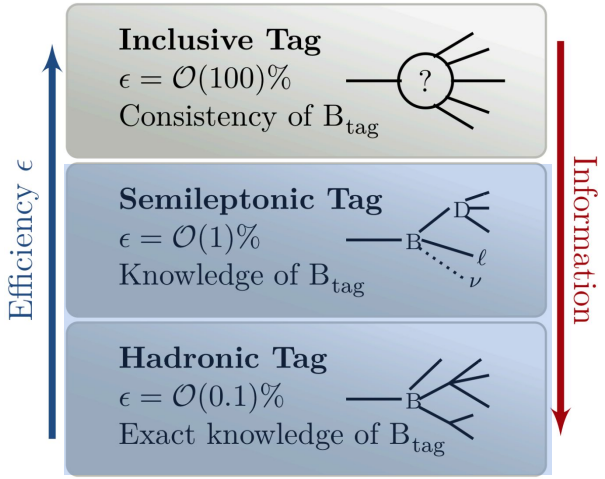


B tagging

Overview

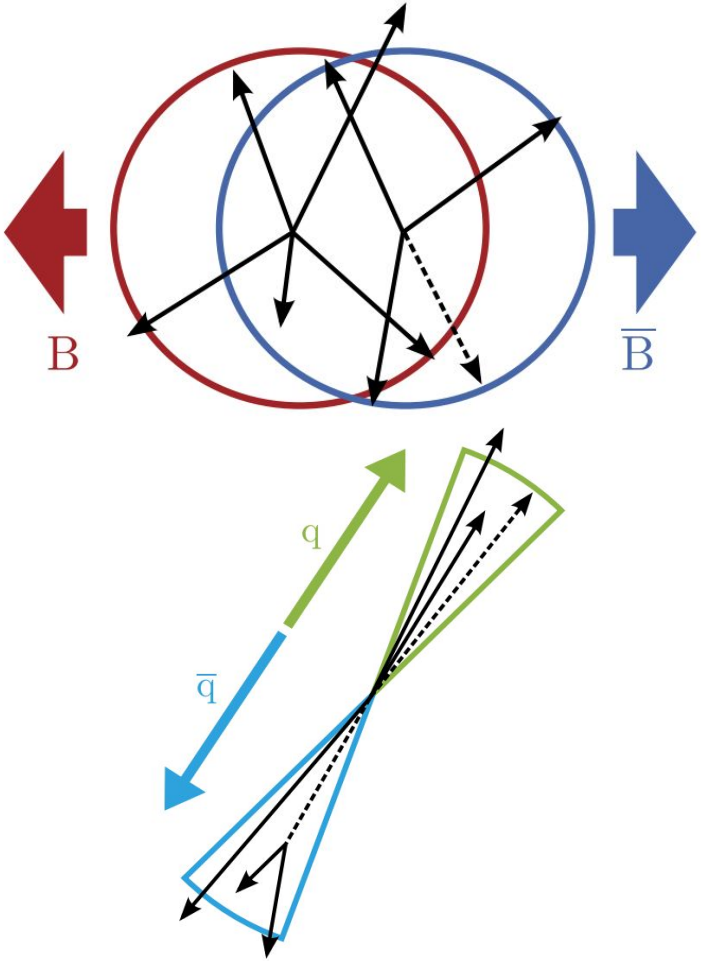
- **Identify** $B\overline{B}$ by reconstructing one of them
  - **Isolate** B_{tag}
  - B_{tag} **information** constrains B_{sig}
- Always a trade-off between **efficiency** and **information** (incl. **purity**, signal-side kinematic **resolution**, etc.)
- In Belle II, **Full Event Interpretation** (FEI):
  - Hierarchical reconstruction of ~10,000 decay modes
  - Extensive use of machine learning
  - Semileptonic and hadronic tag modes
  - Increase in **efficiency**, comparable **purity**



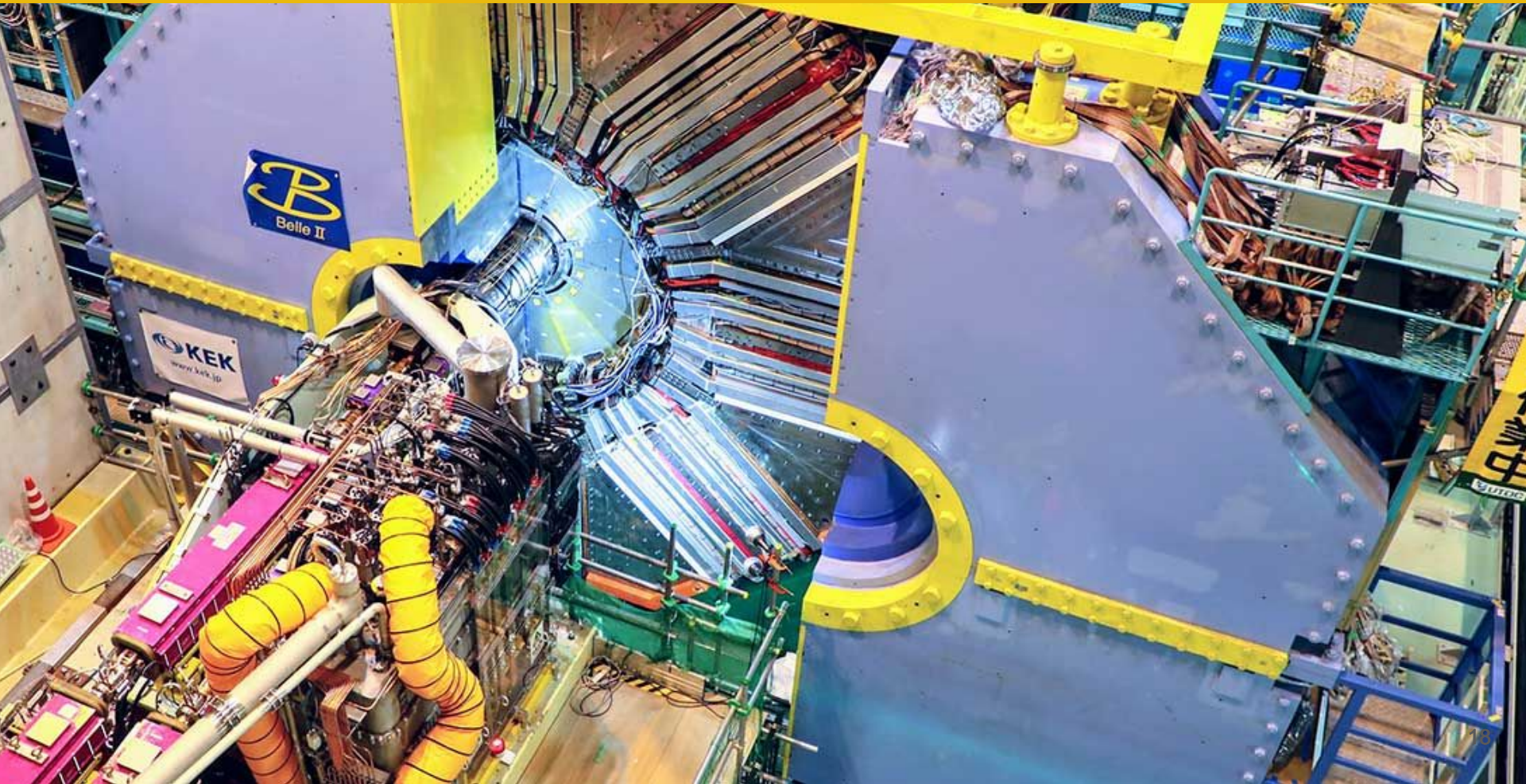


Continuum

- Copious production of $e^+e^- \rightarrow q\bar{q}$
- $B\bar{B}$ events are typically **spherical** while $q\bar{q}$ are typically more **back-to-back**
- *Continuum suppression* typically employs machine learning trained on many **event shape variables**
- **Tagging** can also substantially reduce continuum
- **Off-resonance** data used to describe and constrain continuum



Early physics results



$B \to K\nu\nu$

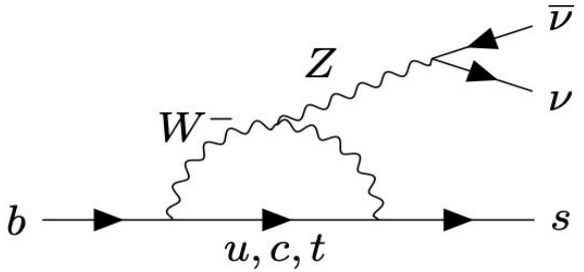
arXiv: 2104.12624

Search for $B^+ \to K^+\nu\bar{\nu}$ decays using an inclusive tagging method at Belle II

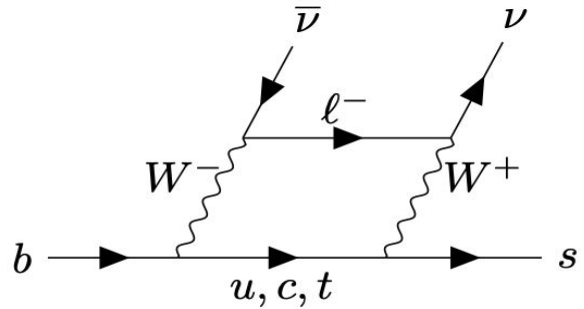
F. Abudinén,[44] I. Adachi,[21,19] K. Adamczyk,[66] P. Ahlburg,[98] H. Aihara,[114] N. Akopov,[120] A. Aloisio,[87,37] N. Anh Ky,[34,12] D. M. Asner,[2] H. Atmacan,[100] T. Aushev,[23] V. Aushev,[79] A. Baur,[10] V. Babu,[10] S. Baehr,[48]

First *B*-physics paper at Belle II

- Search for **flavor-changing neutral current**
- Complementary probe to BSM from $b \to s\ell\ell$
- A channel **unique** to Belle II
- A new technique for this analysis: **inclusive tagging**
- Train signal classifier based on **event shape**
- Signal extracted from 2D fit in p_T vs. classifier bins



(a) Penguin diagram



(b) Box diagram

$B \to K\nu\nu$

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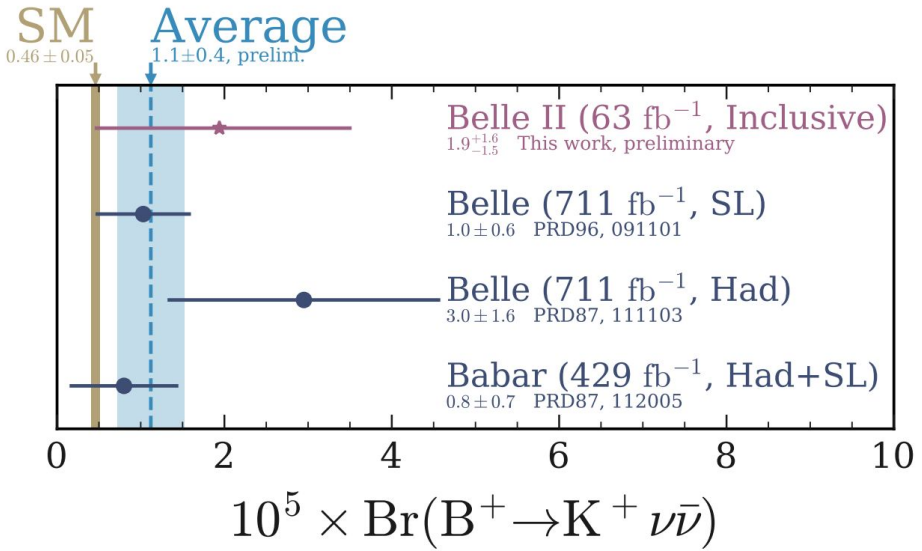
Results

- Results **competitive** with previous measurements despite **1/10th data**
- Statistically limited for now



D^0 and D^+ lifetimes

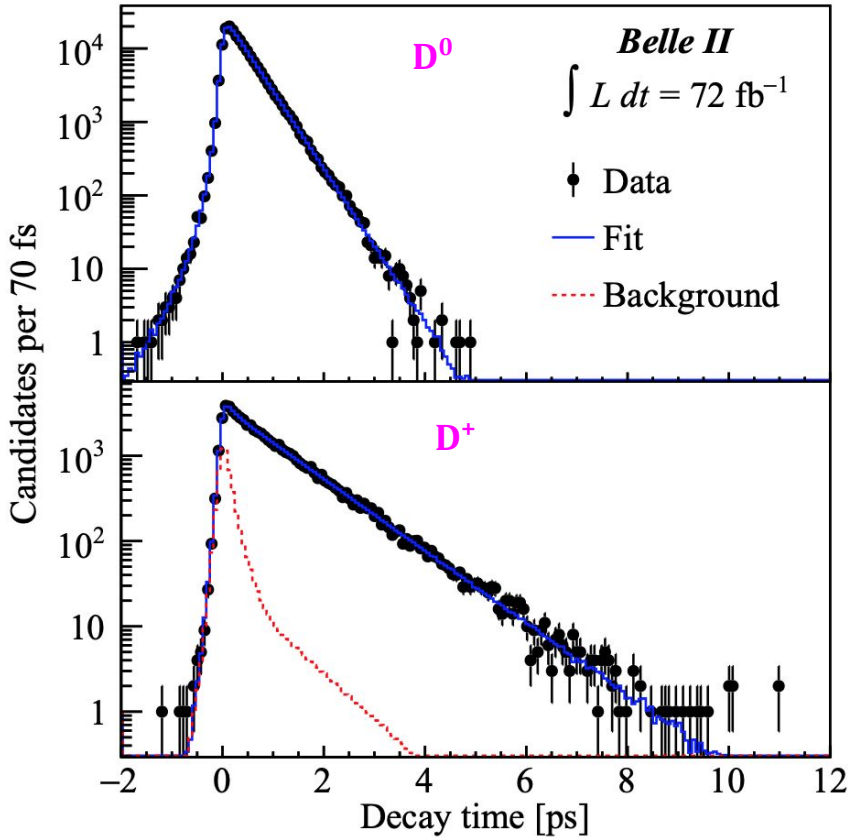
arXiv: 2108.03216

Precise measurement of the D^0 and D^+ lifetimes at Belle II

F. Abudinén,[31] I. Adachi,[21,18] K. Adamczyk,[66] L. Aggarwal,[73] H. Ahmed,[76] H. Aihara,[112] N. Akopov,[2] A. Aloisio,[88,25] N. Anh Ky,[40,13] D. M. Asner,[3] H. Atmacan,[99] V. Aushev,[81] V. Babu,[11] S. Bacher,[66] H. Bae,[112]

Analysis

- Lifetimes of D mesons using:
  - $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$
  - $D^{*+} \to D^+(\to K^-\pi^+\pi^+)\pi^0$
- Existing lifetimes are **systematics-limited**: a precision test of Belle II **vertexing capabilities + knowledge of interaction region**
- D^* decays at collision point; distance to D decay vertex gives lifetime
- Fit to time distribution with decaying exponential convolved with resolution function



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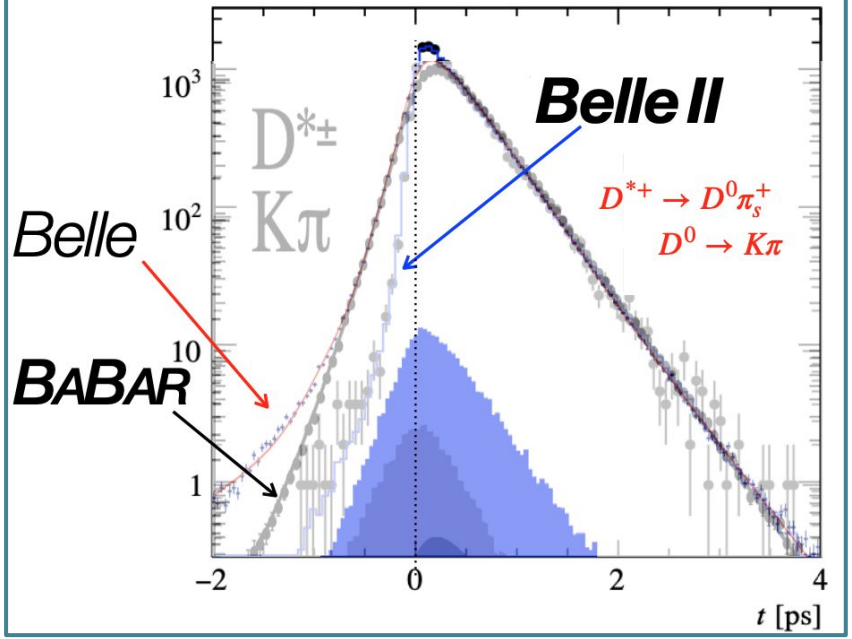
Results

- Proper time resolution at Belle II is a **factor of 2** better than Belle and BaBar due to better vertexing

- resolution improvement visible at $t < 0$:



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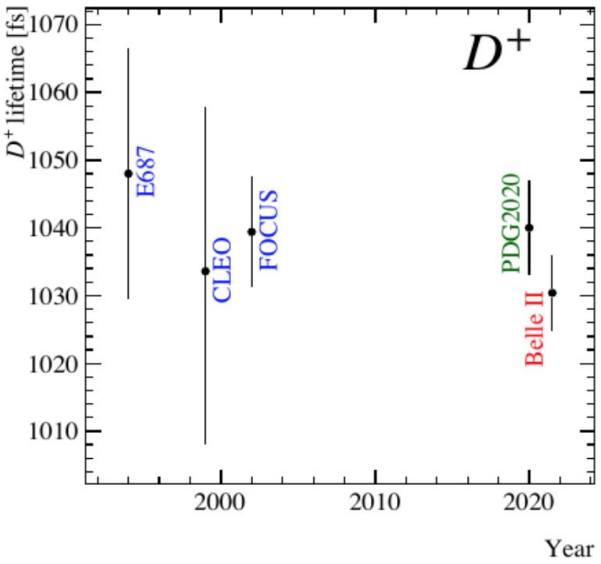
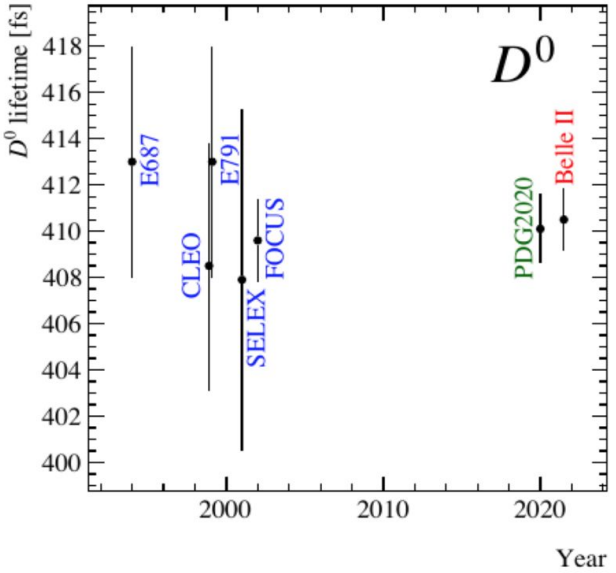
Results

- First updates to D lifetimes in 20 years
- Provides important reference to LHCb charm lifetime measurements
- Still **statistics-limited**
- **Vertex performance excellent**: good sign for time-dependent mixing and CPV measurements





Axion-Like Particles

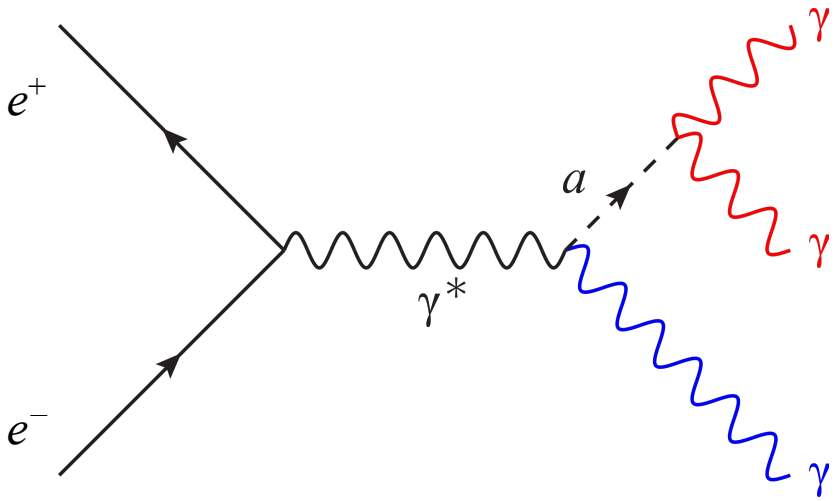
PHYSICAL REVIEW LETTERS **125,** 161806 (2020)

Search for Axionlike Particles Produced in e^+e^- Collisions at Belle II

F. Abudinén,[42] I. Adachi,[21,18] H. Aihara,[115] N. Akopov,[121] A. Aloisio,[87,35] F. Ameli,[39] N. Anh Ky,[32,11] D. M. Asner,[2] T. Aushev,[23] V. Aushev,[77] V. Babu,[9] S. Bacher,[46] S. Bahinipati,[25] P. Bambade,[96] Sw. Banerjee,[105] S. Bansal,[68] J. Baudot,[97]

Concept

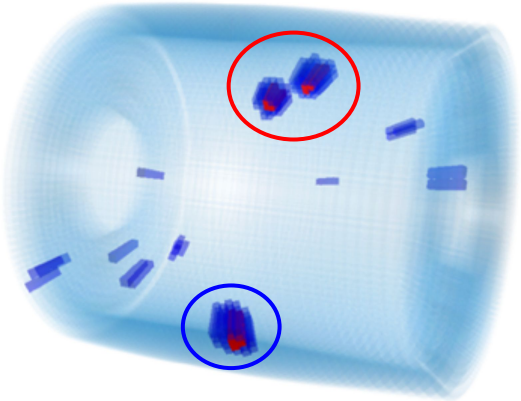
- **ALPs:** portal to dark sector
  - Mediator or DM candidate
  - Light pseudoscalar interacting with SM gauge bosons
- Search using **445pb^{-1}** of early data without complete detector
- Look for a **mono-energetic photon** recoiling against a **resonant photon pair**

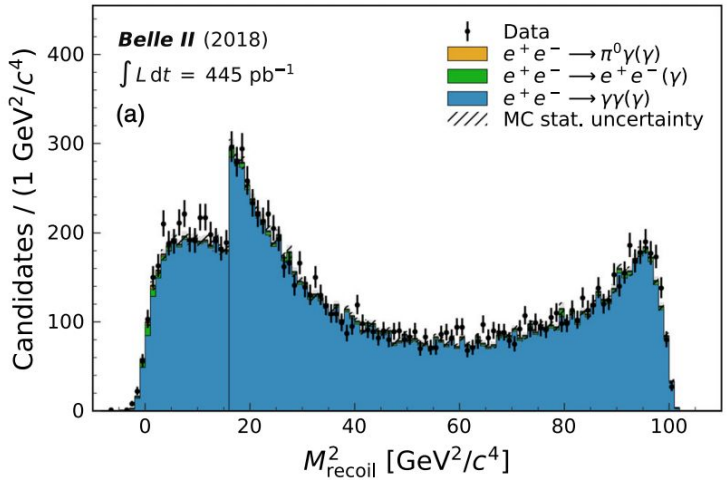


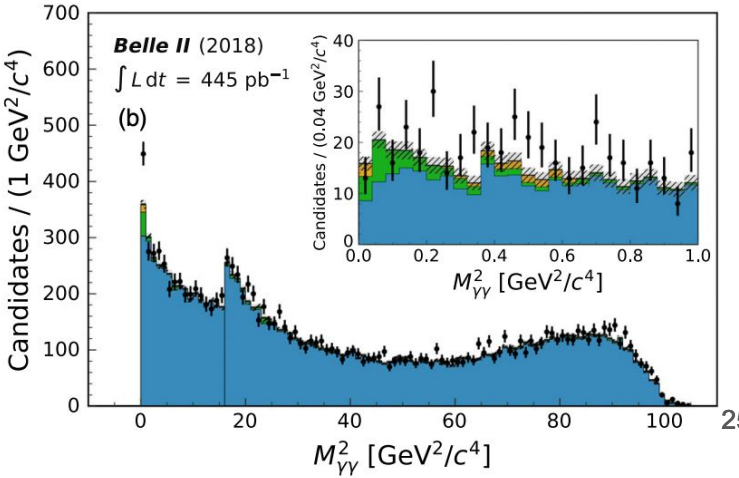
Axion-Like Particles

Analysis

- Find **three-photon events**
- Two signatures in **EM calorimeter**:
  - Peak in mass recoiling against γ, *or*
  - Peak in $\gamma\gamma$ invariant mass







Axion-Like Particles

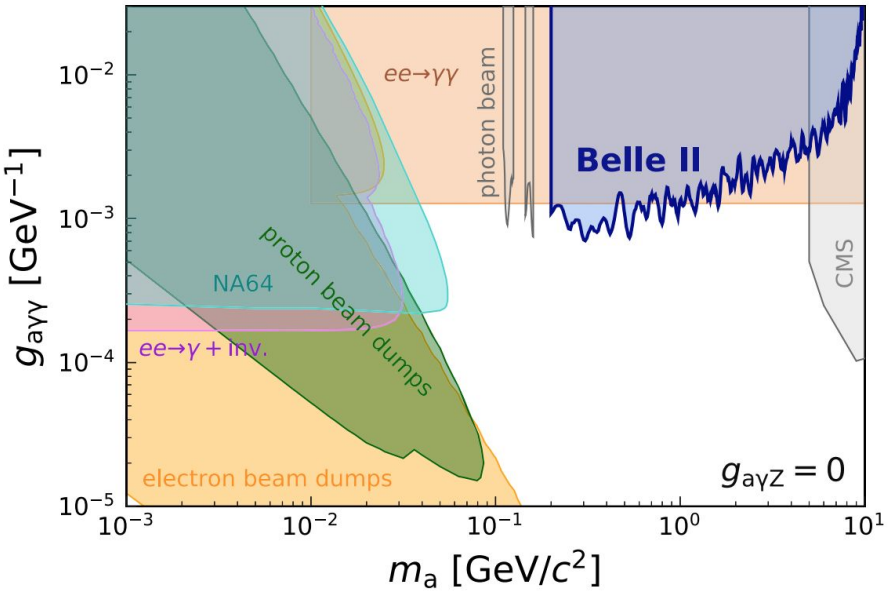
Results

- First-ever ALPs search at a *B* factory
- Already excluding **new parameter space** in region unconstrained by cosmological considerations
- More than one order of magnitude improvement on $g_{a\gamma\gamma}$ expected with **better stats**

PHYSICAL REVIEW LETTERS **125,** 161806 (2020)

Search for Axionlike Particles Produced in e^+e^- Collisions at Belle II

F. Abudinén,[42] I. Adachi,[21,18] H. Aihara,[115] N. Akopov,[121] A. Aloisio,[87,35] F. Ameli,[39] N. Anh Ky,[32,11] D. M. Asner,[2] T. Aushev,[23] V. Aushev,[77] V. Babu,[9] S. Baehr,[46] S. Bahinipati,[25] P. Bambade,[96] Sw. Banerjee,[105] S. Bansal,[68] J. Baudot,[97]



Invisibly decaying Z'

PHYSICAL REVIEW LETTERS **124,** 141801 (2020)

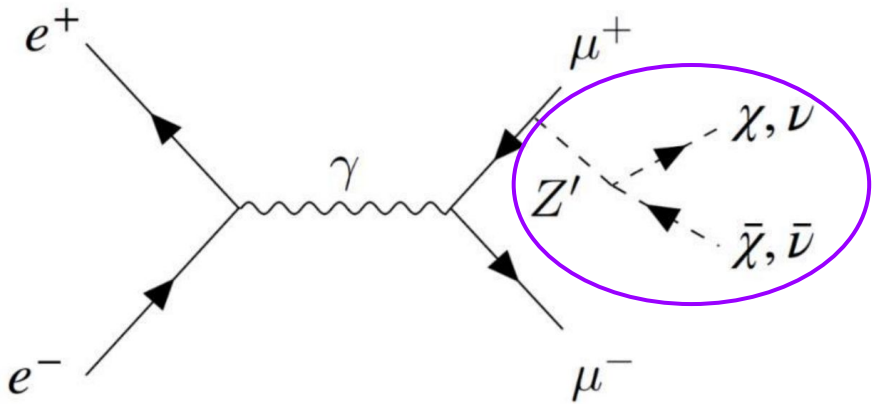
Editors' Suggestion | Featured in Physics

Search for an Invisibly Decaying Z' Boson at Belle II in $e^+e^- \to \mu^+\mu^-(e^\pm\mu^\mp)$ Plus Missing Energy Final States

I. Adachi,[21,18] P. Ahlburg,[95] H. Aihara,[111] N. Akopov,[117] A. Aloisio,[86,33] N. Anh Ky,[30,12] D. M. Asner,[2] H. Atmacan,[97] T. Aushev,[56] V. Aushev,[78] T. Aziz,[79] V. Babu,[10] S. Baehr,[44] P. Bambade,[49] Sw. Banerjee,[100] V. Bansal,[69] M. Barrett,[21]

Analysis

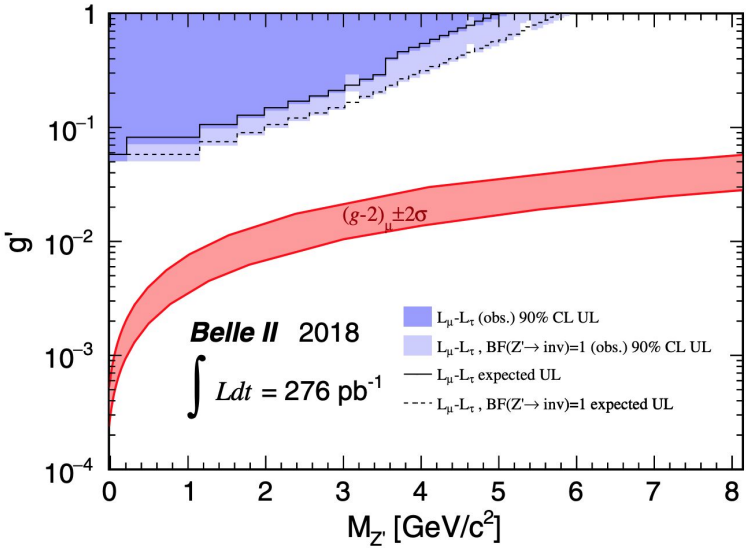
- Testing the L_μ-L_τ extension of the SM
  - New vector boson Z' that couples to SM only through μ, τ, ν_μ, ν_τ
  - Possible explanation for $(g\text{-}2)_\mu$, $b \to s\mu\mu$ anomalies and DM candidate
- First ever search for $Z' \to$ *invisible*
  - Peak in mass recoiling against $\mu\mu$
  - Also search for **LFV** Z' with eμ
  - 276**p**b^{-1} of early data

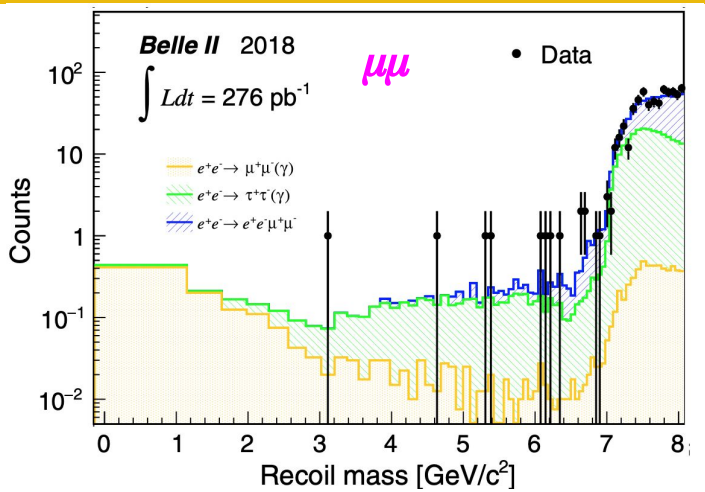


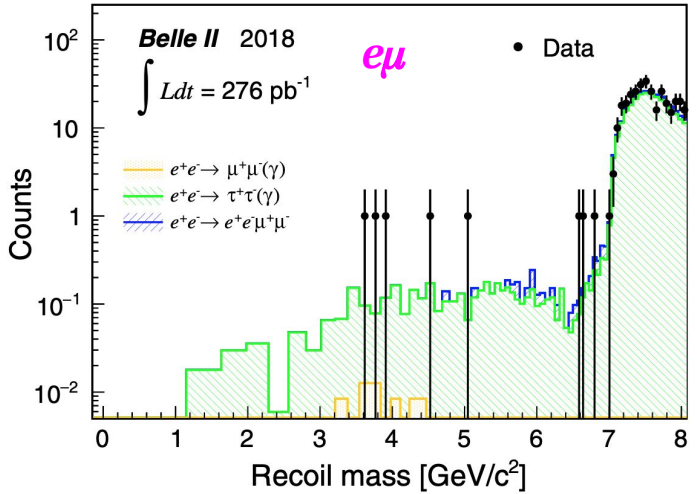
Invisibly decaying Z'

Results

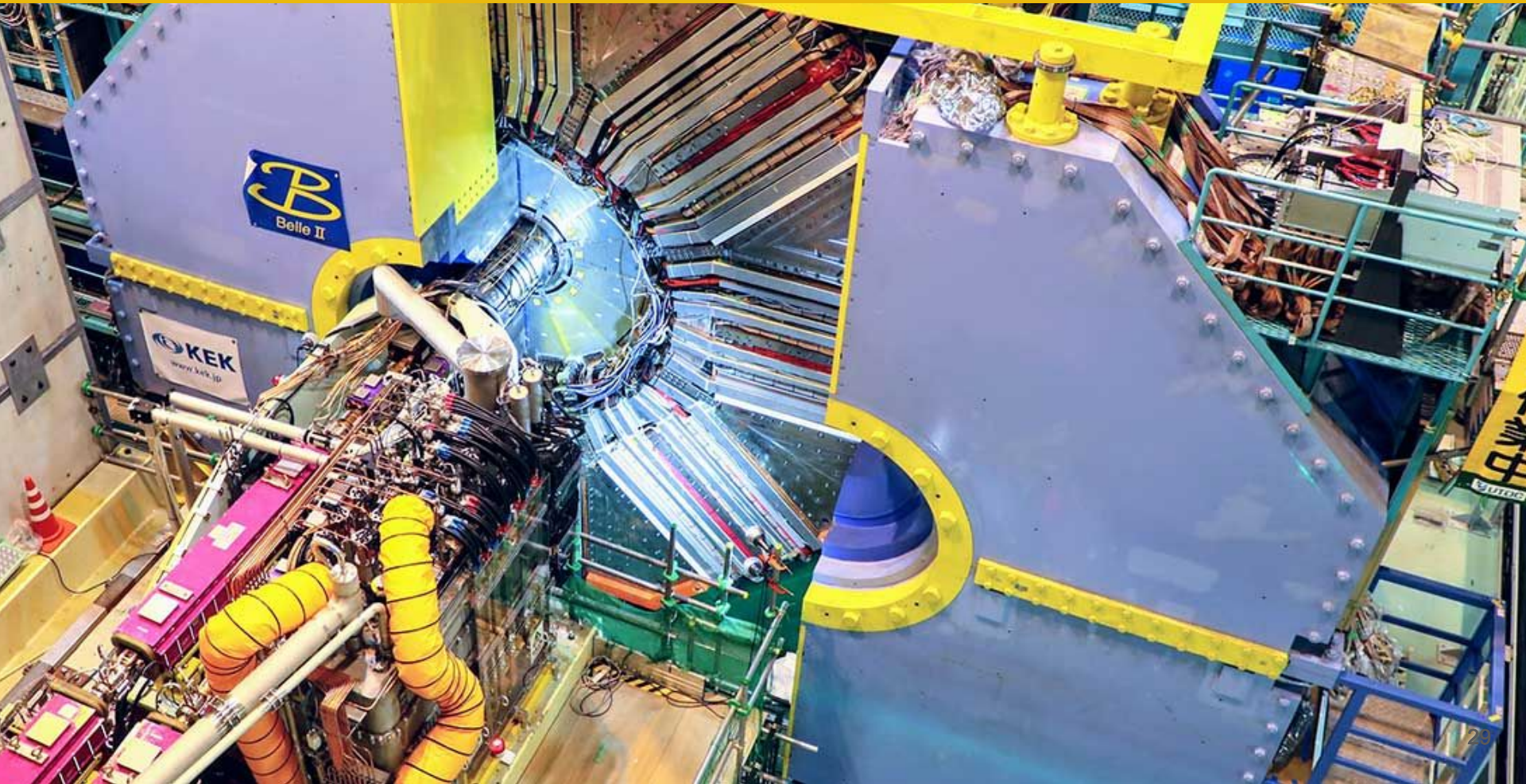
- New limits set
- Extension to $(g\text{-}2)_\mu$ region possible with $50fb^{-1}$







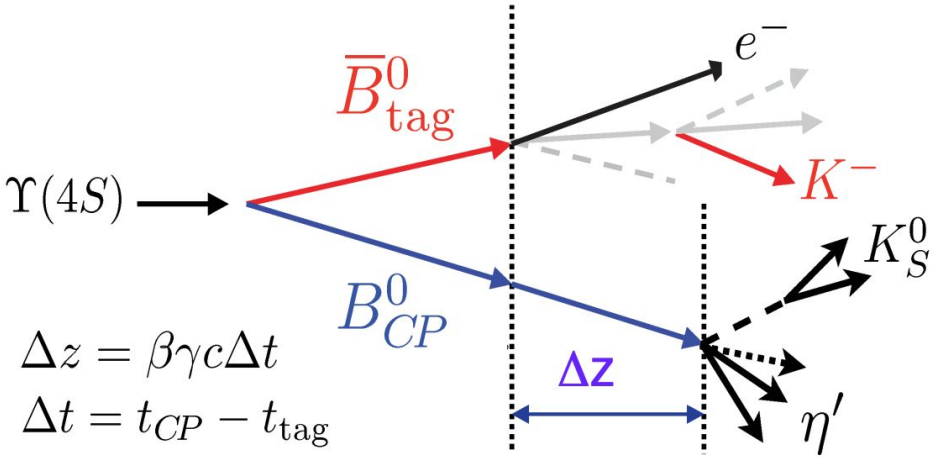
Selected other public preliminary results



Time-dependent CPV in *B* decays

The flagship *B* factory measurement

- SuperKEKB/Belle II **optimized** for this measurement
- *CP* asymmetries in **proper time** distribution of decays measure ϕ_1 (Unity Triangle angle)
- Look at **BF asymmetry** between tag and **quantum-entangled CP eigenstate** vs. time:
  - *Mixing frequency* from mass difference Δm_B
  - Mixing-induced asymmetries (indirect)
  - Direct CP asymmetries
- Some looks at early results...



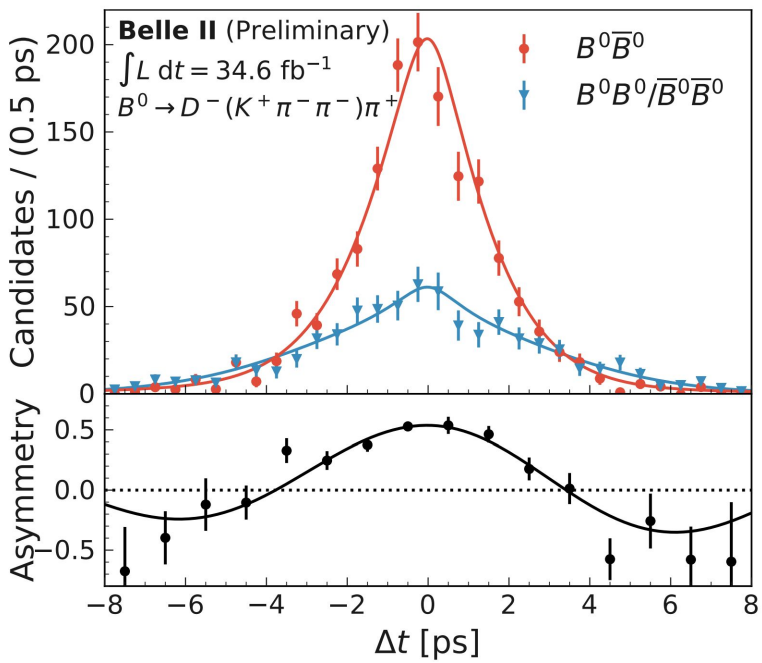
<Δz> ~ 130 μm at Belle II

$$\mathcal{A}_f(\Delta t) = \frac{\Gamma(\overline{B}^0(\Delta t) \to \eta' K^0_S) - \Gamma(B^0(\Delta t) \to \eta' K^0_S)}{\Gamma(\overline{B}^0(\Delta t) \to \eta' K^0_S) + \Gamma(B^0(\Delta t) \to \eta' K^0_S)} = S_f \sin(\Delta m_B \Delta t) + A_f \cos(\Delta m_B \Delta t)$$

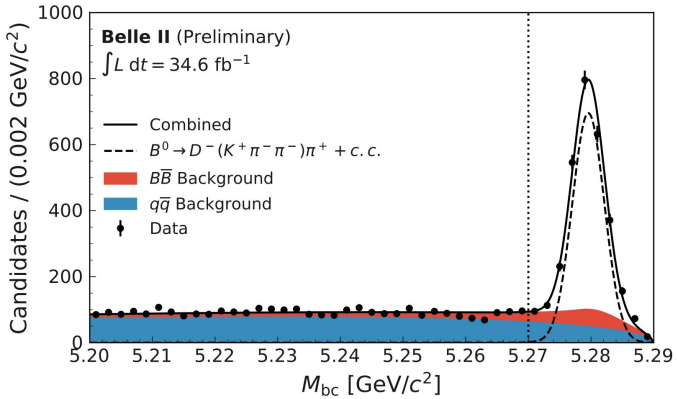
Time-dependent CPV in *B* decays

$$B^0 \to D^-(K^+\pi^-\pi^-)\pi^+$$

- Observation of direct CP violation with 34.6fb^{-1}
- Obtain Δm_B



BELLE2-NOTE-PL-2020-011

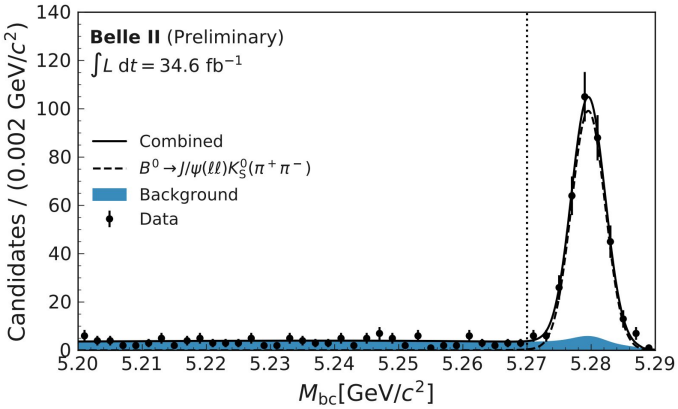


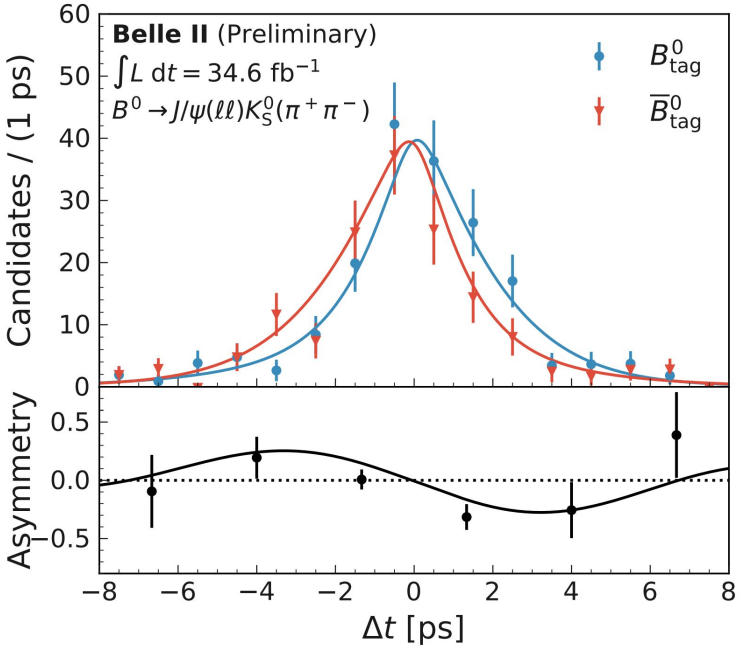
$$\begin{aligned}\mathcal{A}_f(\Delta t) &= \frac{\Gamma(\overline{B}^0(\Delta t) \to \eta' K_S^0) - \Gamma(B^0(\Delta t) \to \eta' K_S^0)}{\Gamma(\overline{B}^0(\Delta t) \to \eta' K_S^0) + \Gamma(B^0(\Delta t) \to \eta' K_S^0)} \\ &= S_f \sin(\Delta m_B \Delta t) + A_f \cos(\Delta m_B \Delta t)\end{aligned}$$

Time-dependent CPV in *B* decays

$$B^0 \to J/\psi(e^-e^+/\mu^-\mu^+)K_S$$

- Assume no direct CPV
- Extract TD CPV parameter S_f with 2.7σ significance
- Expect **factor of 5** improvement ultimately in CKM parameters ϕ_1 and ϕ_2





BELLE2-NOTE-PL-2020-011

$$\begin{aligned}\mathcal{A}_f(\Delta t) &= \frac{\Gamma(\overline{B}^0(\Delta t) \to \eta' K_S^0) - \Gamma(B^0(\Delta t) \to \eta' K_S^0)}{\Gamma(\overline{B}^0(\Delta t) \to \eta' K_S^0) + \Gamma(B^0(\Delta t) \to \eta' K_S^0)} \\ &= S_f \sin(\Delta m_B \Delta t) + A_f \cos(\Delta m_B \Delta t)\end{aligned}$$

Toward V_{ub} and V_{cb}

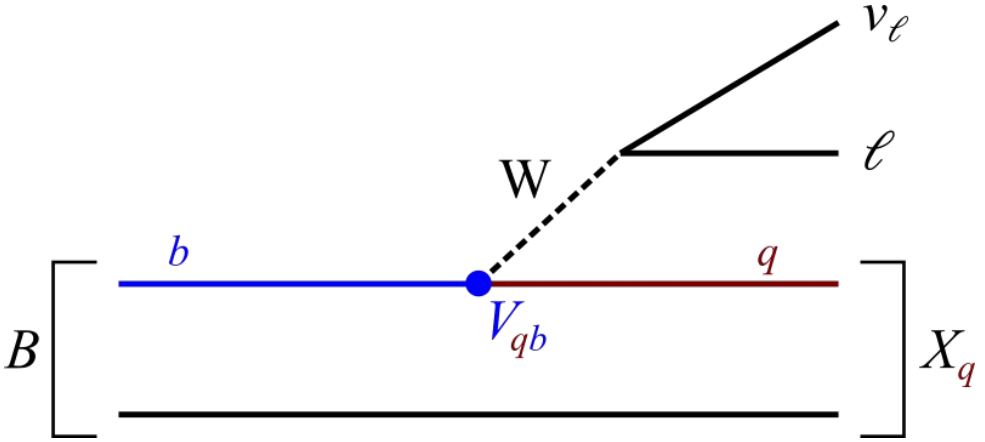
Semileptonic decays

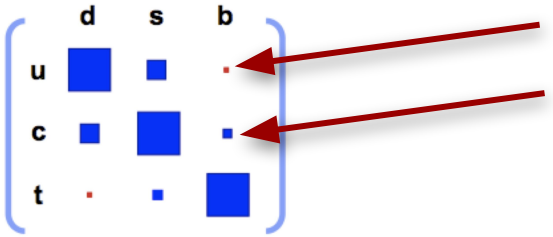
- **Semileptonic** decays provide clean access to V_{ub} and V_{cb} CKM elements
- Two major current areas of excitement:
  - Excess in $R(D^{(*)})$: LFU implications
  - Inclusive/exclusive disagreement in $|V_{ub}|$ and $|V_{cb}|$ at 3.3σ level

$$\frac{d\Gamma}{dq^2} \propto |V_{xb}|^2 |f(q^2)|^2$$

$$q^2 = (p_\ell + p_\nu)^2$$

- A large number of upcoming results...

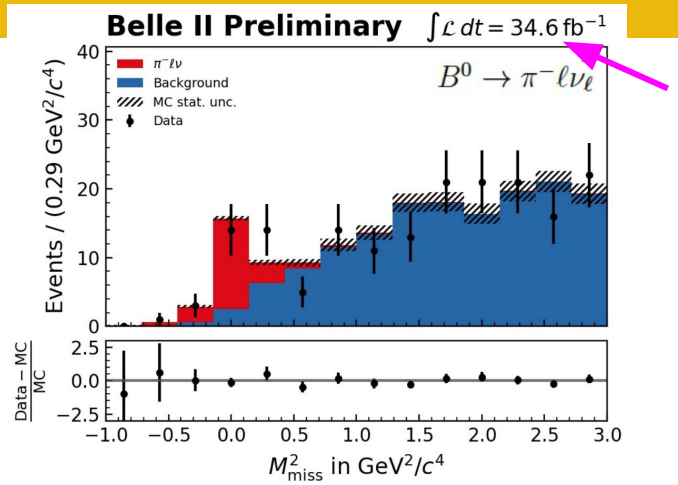


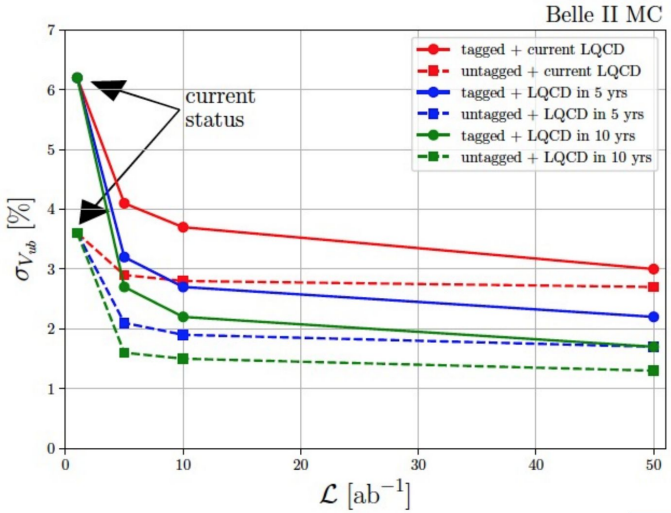


"Rediscovery" of $B \to \pi \ell \nu$

Toward $|V_{ub}|$ extraction

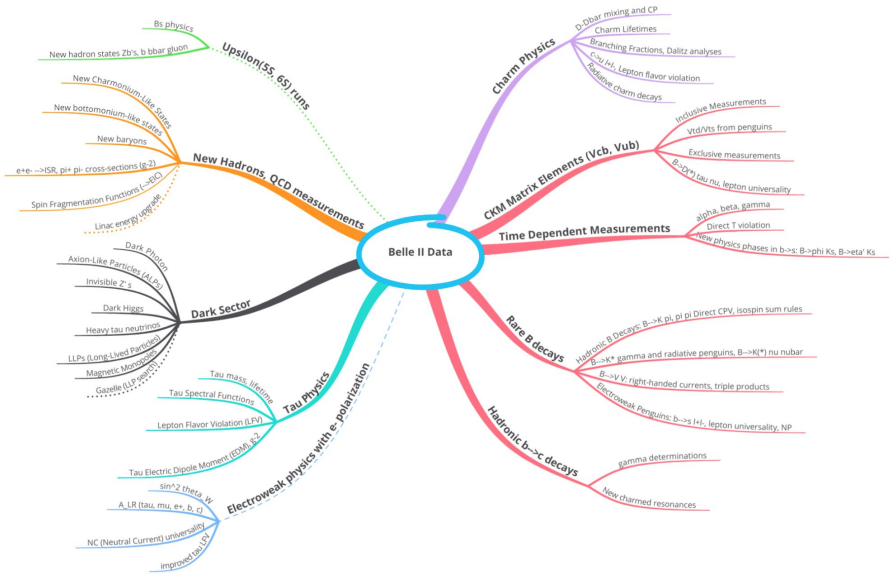
- Hadronic-tagged $B \to \pi \ell \nu$ gives best constraints on $|V_{ub}|$
  - Requires extraction of Γ in $\boldsymbol{q^2}$ **bins**
  - **Very low statistics** (hadronic tagging efficiency and $|V_{ub}|^2$)
- *Observed* with significance **>5σ**
- "Rediscovery" shows: Belle II soon capable of competitive inclusive and exclusive V_{ub} and V_{cb}





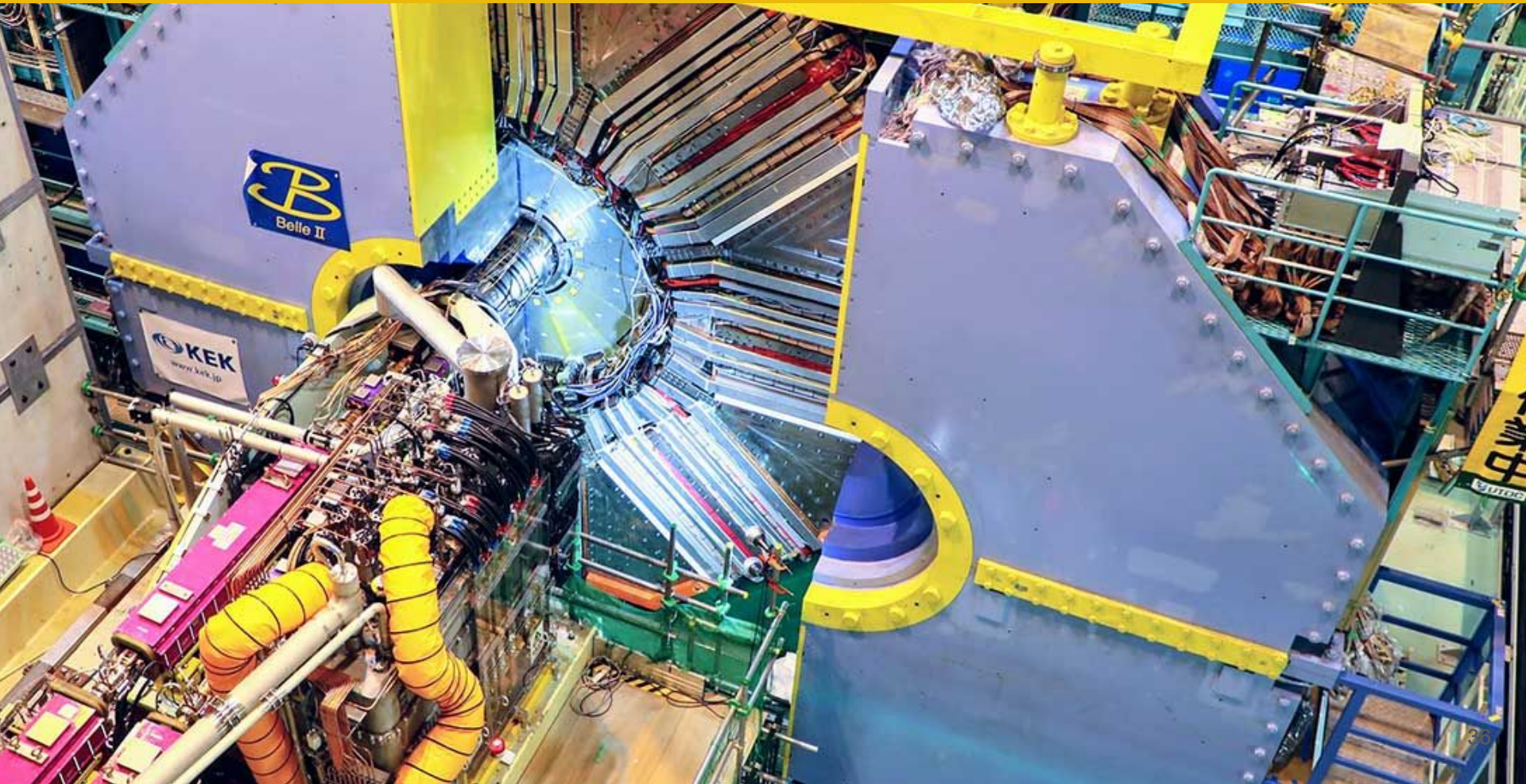
Status and prospects

- SuperKEKB is delivering world-record luminosities
- First *trickle* of physics results show excellent performance and physics potential
- Expect a ***flood*** of diverse results as Belle II dataset grows to comparable size with BaBar/Belle



Thank you!

Additional slides



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%