Belle II at SuperKEKB: Status and perspectives

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(On behalf of the Belle II Collaboration)

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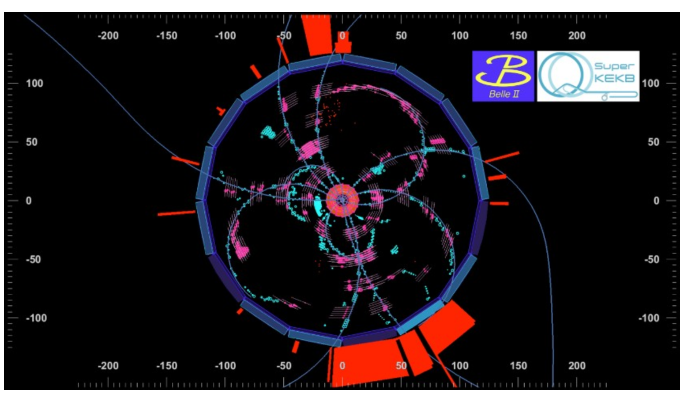
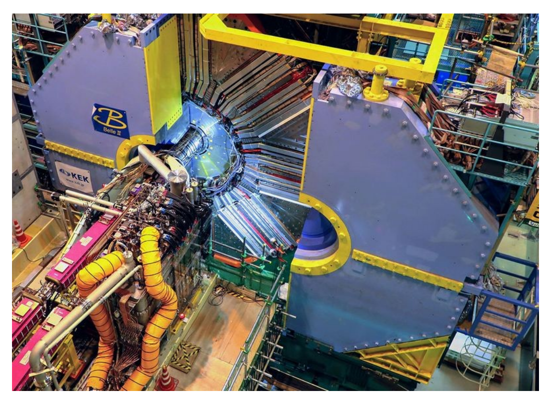
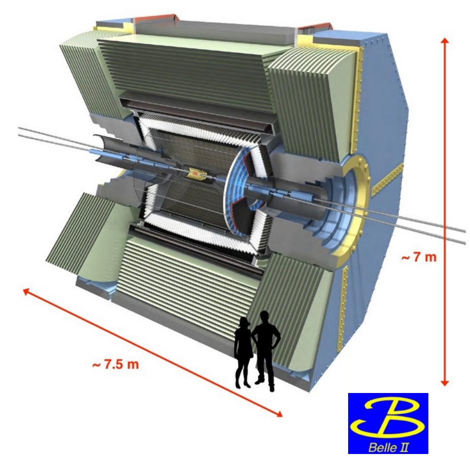
Outline

- Introduction, physics motivation
- The experimental setup: SuperKEKB/Belle II detector
- Selected recent results
- Prospects
- Summary and conclusions



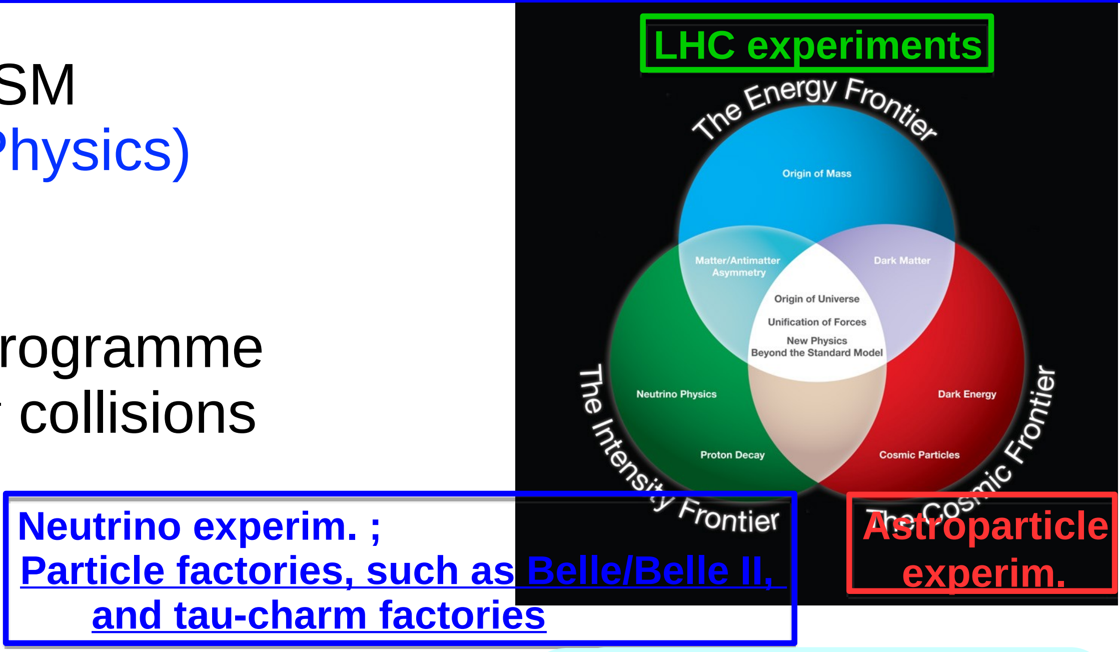




Beyond the SM physics

Belle II

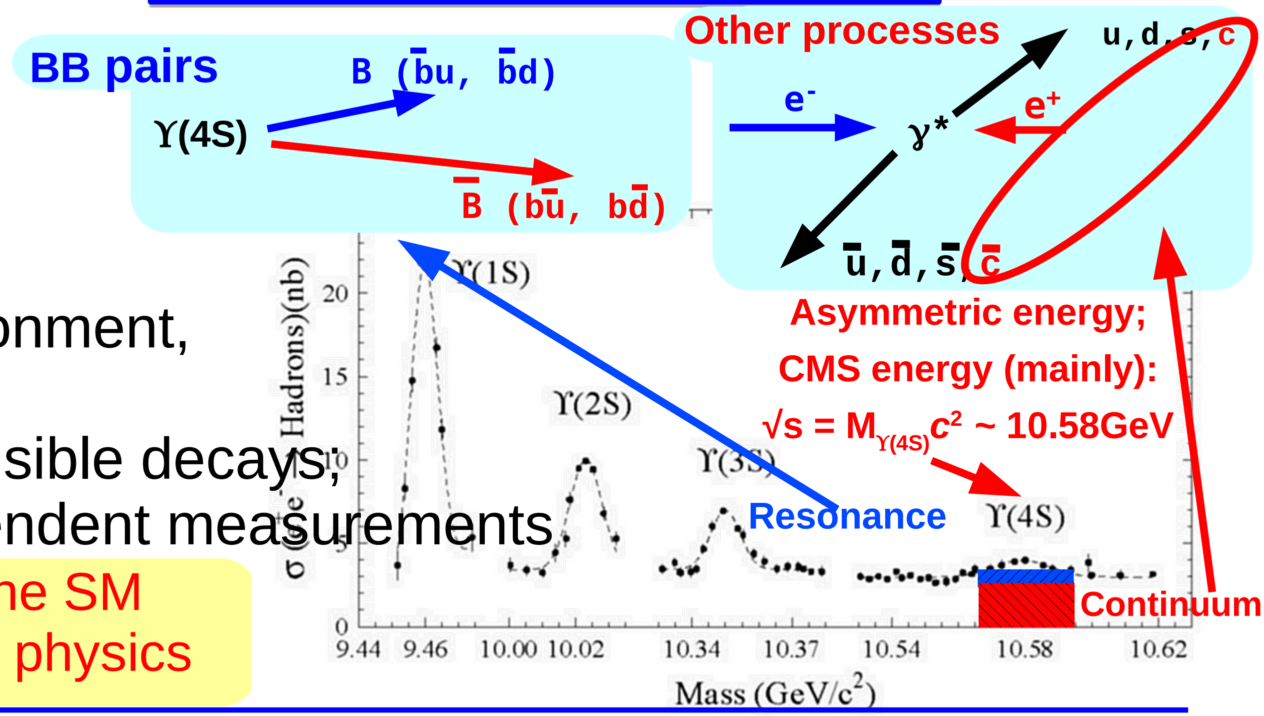
Open questions not explained by the SM
→ Beyond the SM Physics (New Physics)



Belle II: a flavour factory,
with an extensive physics programme
→ The plan is to collect 50 ab^{-1} of e^+e^- collisions
at/around $\Upsilon(4S)$ resonance :
(NB: Belle 1 ab^{-1}; BaBar ~ 0,5 ab^{-1})

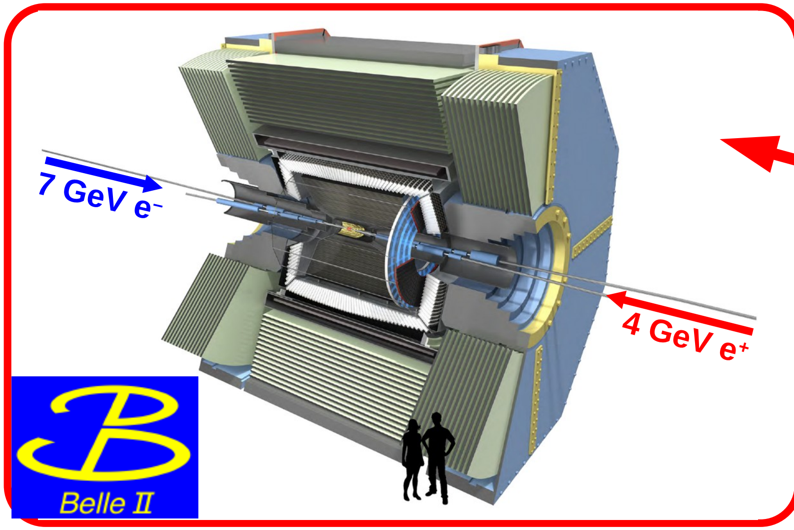
- (Super) B factory:
  ~ $1.1 \cdot 10^9$ $B\bar{B}$ pairs / 1ab^{-1}
- (Super) charm factory:
  ~ $1.3 \cdot 10^9$ $c\bar{c}$ pairs / 1ab^{-1}
- (Super) tau factory:
  ~ $0.9 \cdot 10^9$ $\tau^+\tau^-$ pairs / 1ab^{-1}

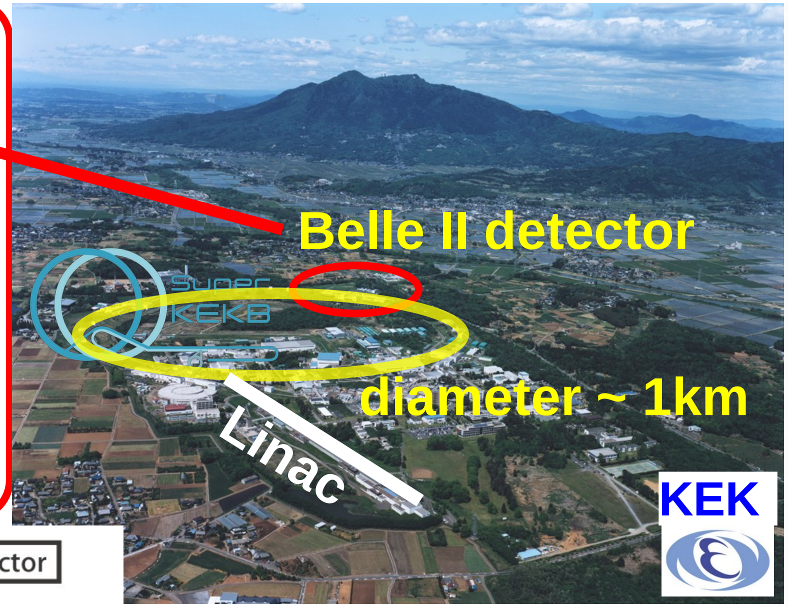
→ Clean experimental e^+e^- environment,
well-known initial conditions;
hermetic detector for neutral/invisible decays;
boosted c.m.s. allows time-dependent measurements

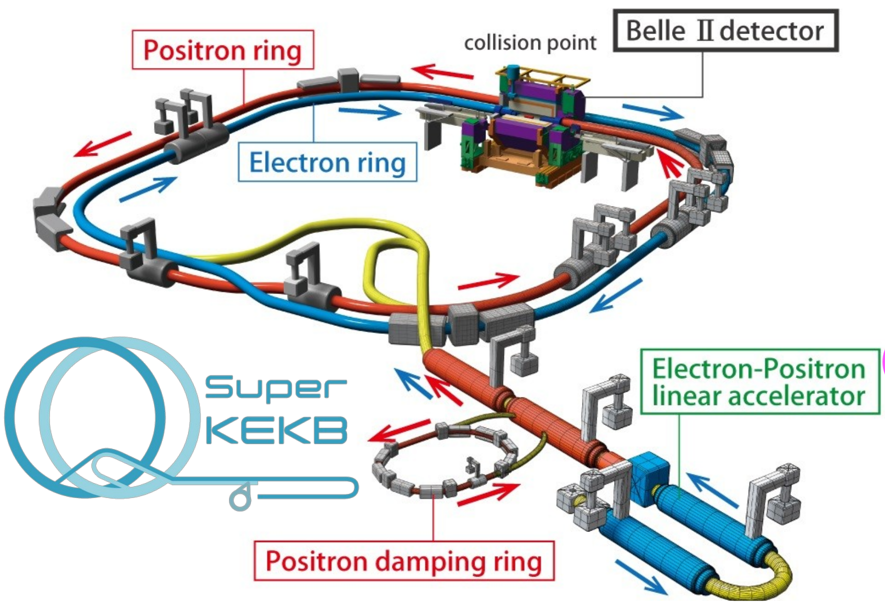


➡ Possibilities for stress-testing the SM
and sensitively probing new physics

SuperKEKB/Belle II experimental set-up







Target:

$$\int Ldt = 50\ ab^{-1}$$

$$L_{peak} = 6 \times 10^{35}\ cm^{-2}s^{-1}$$

Achieved:

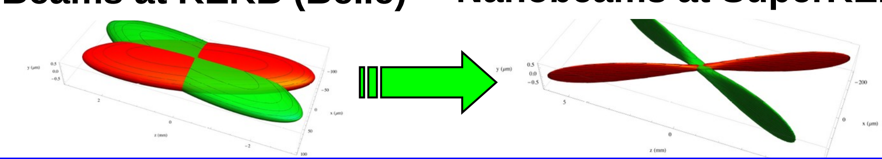
$$\int Ldt > 530\ fb^{-1}$$

(WR!)

$$L_{peak} = 4.7 \times 10^{34}\ cm^{-2}s^{-1}$$

(KEKB: 2.11×10^{34} cm^{-2}s^{-1};
PEP-II: 1.21×10^{34} cm^{-2}s^{-1})

Beams at KEKB (Belle) **Nanobeams at SuperKEKB (Belle II)**

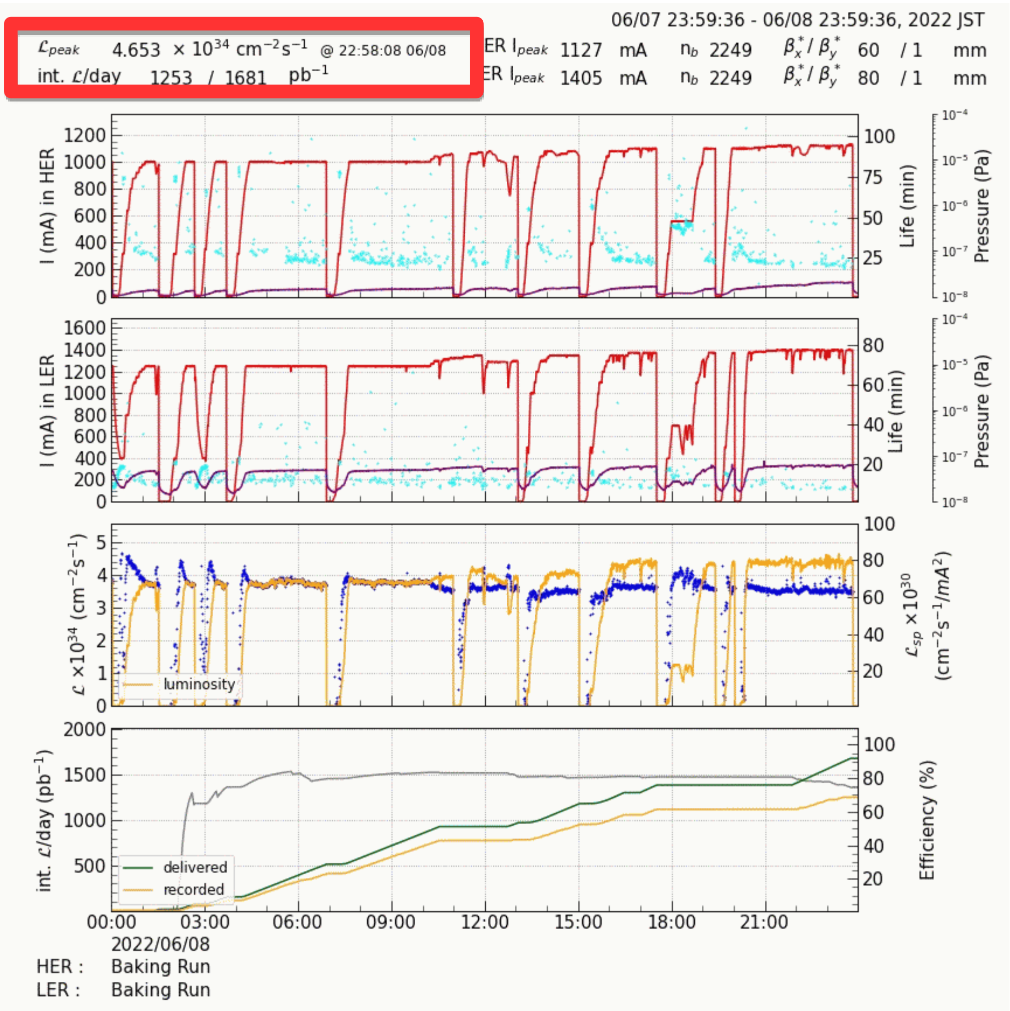


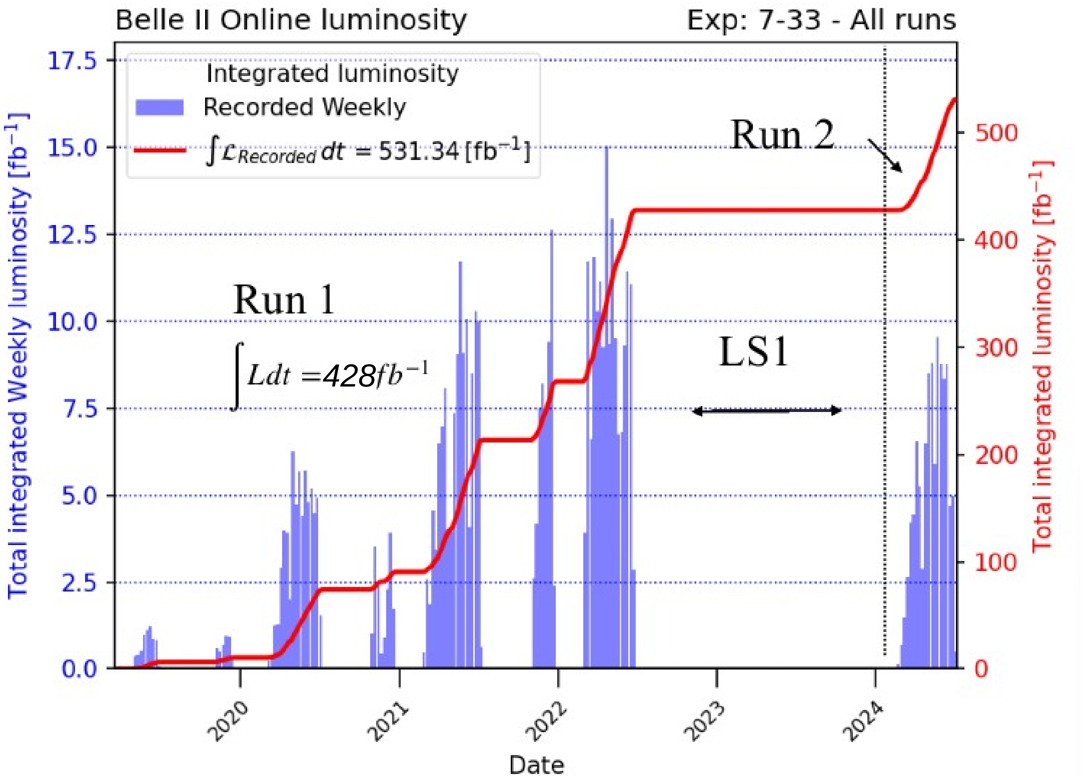
Belle II data-taking: Run 1 , LS1, Run 2, ...

- **Run 1** (2019/03 to 2022/06)
- **LS1** (2022/07 to 2024/02)
- **Run 2** (2024/03 → …) resumes now!

Run 1 luminosity : arXiv:2407.00965 (accepted by Chin. Phys. C)

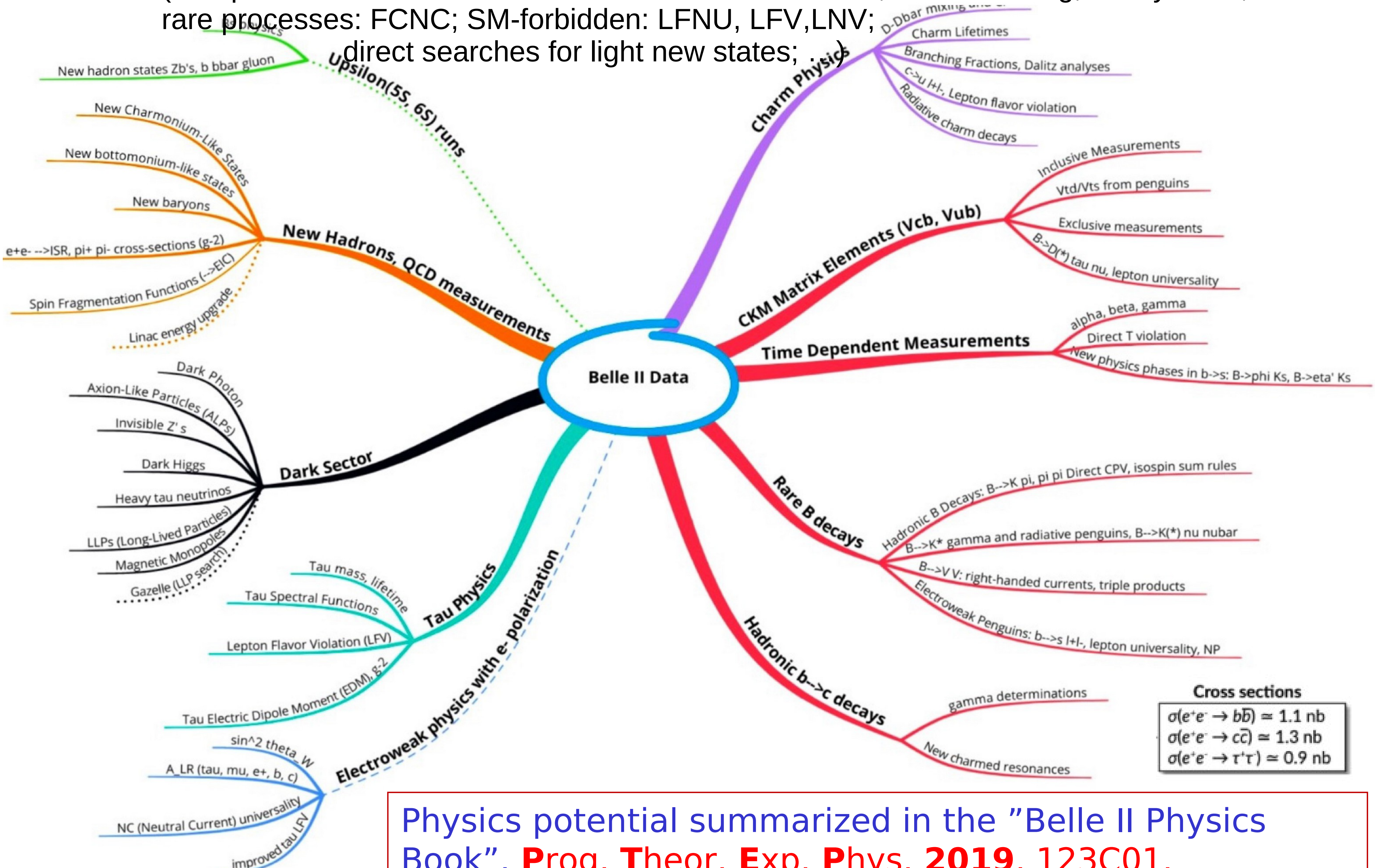
Type	$\sqrt{s}$ (GeV)	$\mathcal{L}$ (fb^{-1})
$\Upsilon(4S)$	10.580	365.37 ± 1.70
off-$\Upsilon(4S)$	10.517	42.74 ± 0.20
$\Upsilon(5S)$ scan	10,657	3.54 ± 0.03
	10.706	1.63 ± 0.02
	10.751	9.88 ± 0.06
	10.810	4.71 ± 0.03
Total	—	427.87 ± 2.01





Physics programme

(Prosperous measurements: CKM measurements: CPV, meson mixing, decay rates; rare processes: FCNC; SM-forbidden: LFNU, LFV, LNV; direct searches for light new states; ...)



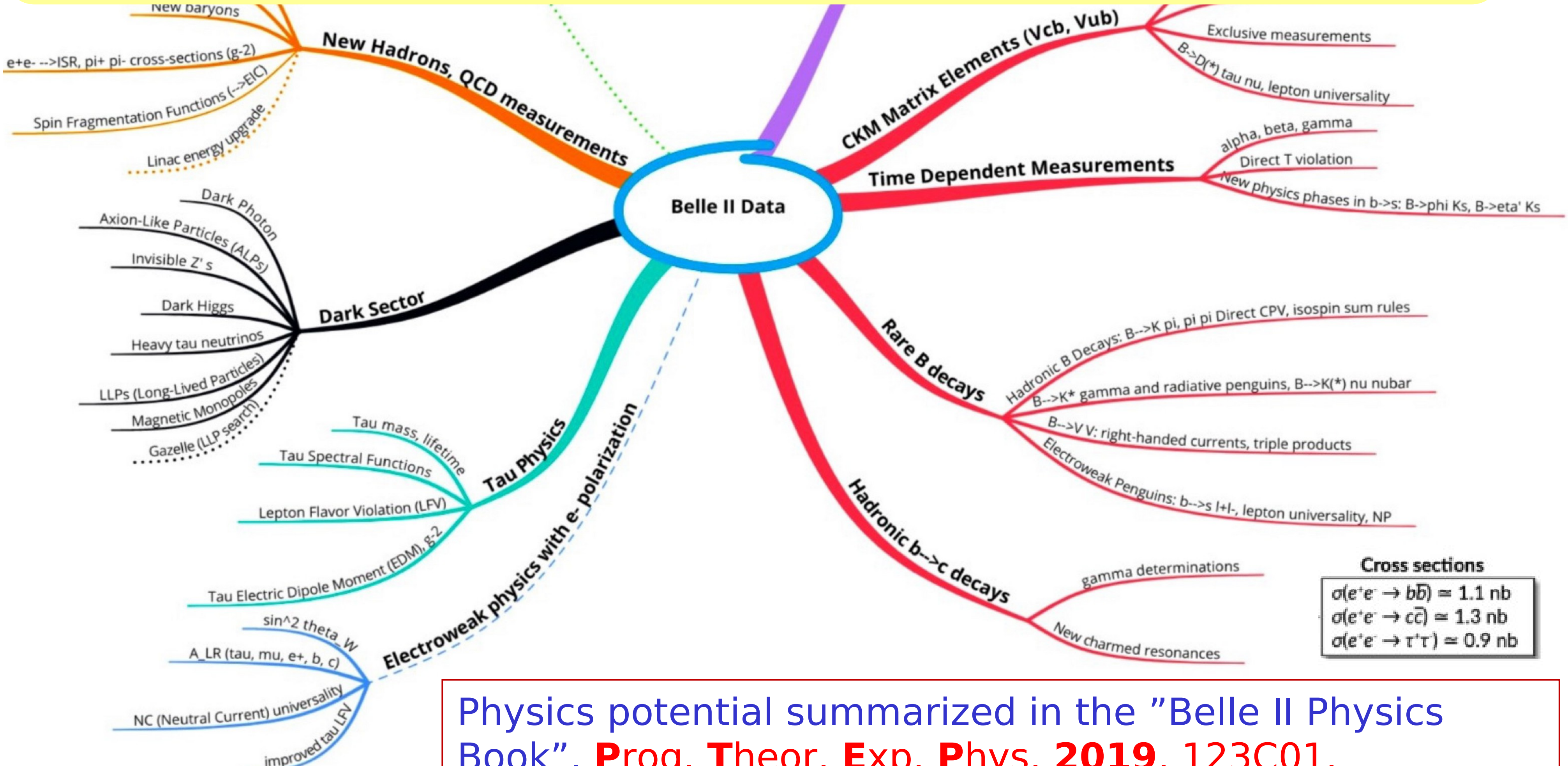
Cross sections

$\sigma(e^+e^- \to b\bar{b}) \simeq 1.1$ nb
$\sigma(e^+e^- \to c\bar{c}) \simeq 1.3$ nb
$\sigma(e^+e^- \to \tau^+\tau^-) \simeq 0.9$ nb

Physics potential summarized in the "Belle II Physics Book", **P**rog. **T**heor. **E**xp. **P**hys. **2019**, 123C01.

Physics programme

Only a subselection of recent results is presented in this talk ...

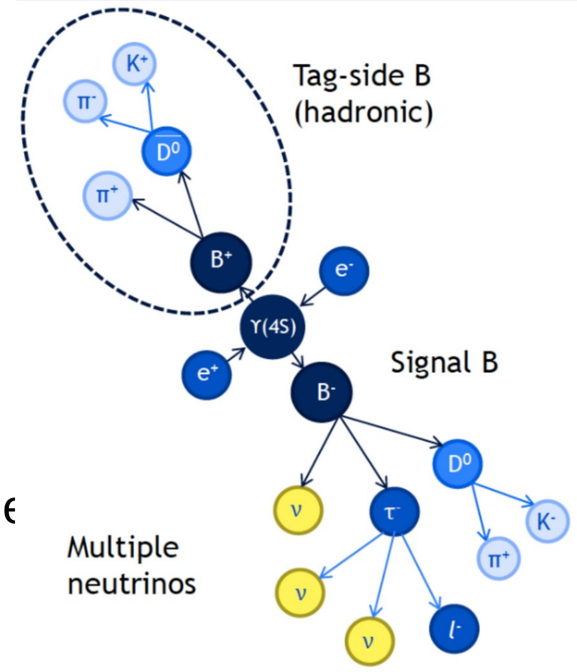


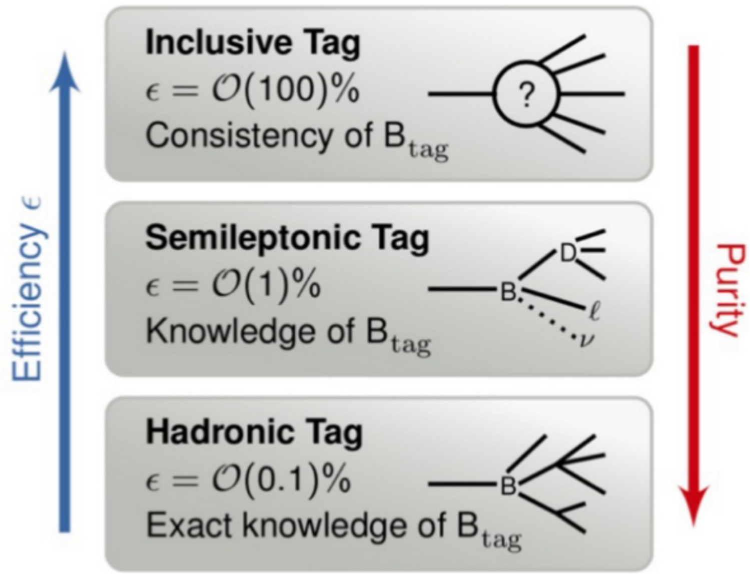
Physics potential summarized in the "Belle II Physics Book", **P**rog. **T**heor. **E**xp. **P**hys. **2019**, 123C01.

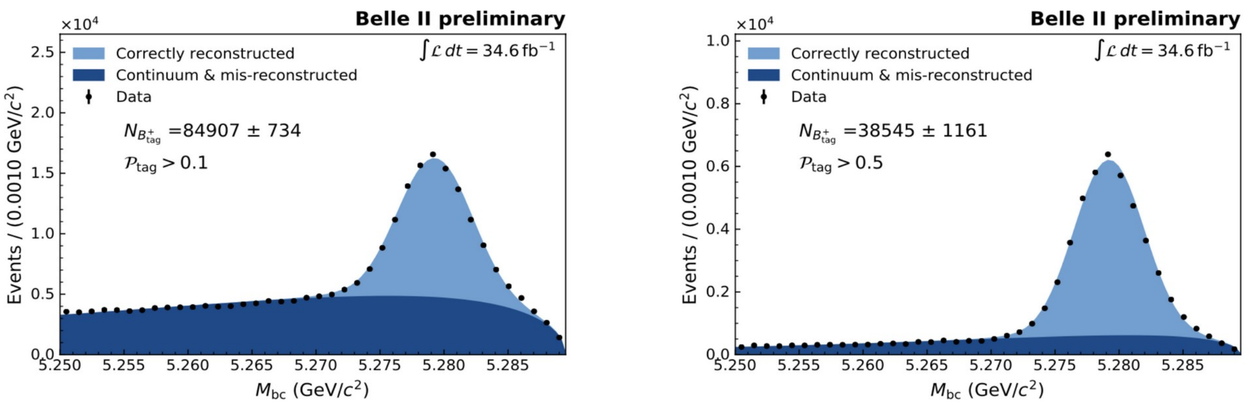
The tools: Missing energy and B-tagging

Many B-physics studies involve modes with <u>the missing energy</u> ($D^{(*)}\tau\nu$, $K\tau\ell$, $K^{(*)}\tau\tau$, $K^{(*)}\nu\nu$, $\pi\ell\nu$, $\tau\ell$, $\tau\nu$, $\mu\nu$, ...) and <u>require B-tagging</u>

→ One can profit from the fact that exactly two B mesons are produced in e^+e^- collisions : Full Event Interpretation (FEI)
- hierarchical multivariate technique (>200 BDTs) to reconstruct the B-tag side (<u>semi-leptonic</u> or <u>hadronic</u>) through $O(10^3)$ different decay modes
- results in a significantly increased tagging efficiency compared to Belle (semileptonic eff. ~2%; hadronic eff. <1%)



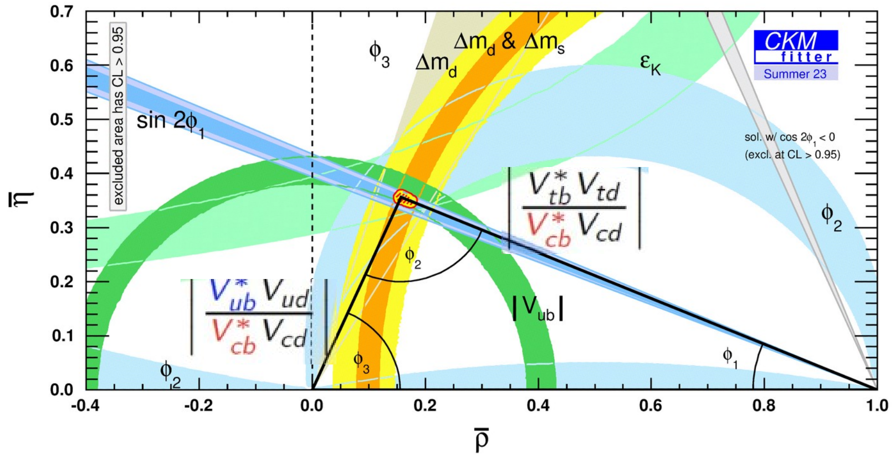




$$M_{bc} = \sqrt{E_{beam}^2/4 - (p_{B_{tag}}^{cm})^2} > 5.27\ \mathrm{GeV}/c^2$$

Precision CKM measurements

- Determine the $|V_{ub}|$ *and* $|V_{cb}|$:



Exclusive : $B \to \pi l\nu, B \to D^{(*)}l\nu$, etc

Inclusive : $B \to X_u l\nu, B \to X_c l\nu$

Different measures carried out by Belle and Belle II

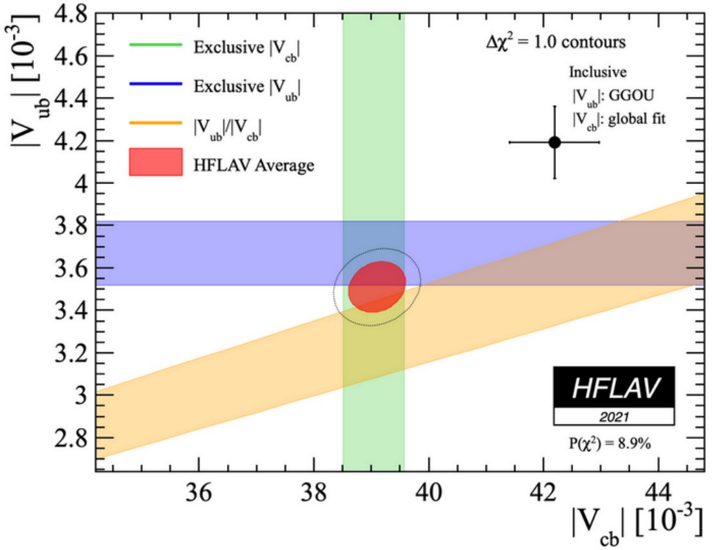
- $|V_{cb}|$ angular coefficient of $B \to D^* l\nu$ Belle arXiv.2310.20286 (PRL accepted)

  $|V_{cb}|$ = (41.0 +/- 0.7)x10[-3] (with 711fb[-1] @Belle)

- $|V_{ub}|$
  - a. from $B \to (\pi/\rho)l\nu$ simultaneous analysis arXiv.2407.17403 submitted to PRD
  - b. Simultaneous inclusive and exclusive $|V_{ub}|$ Belle PRL.131.211801

$$|V_{ub}^{\text{excl.}}| = (3.78 \pm 0.23 \pm 0.16 \pm 0.14) \times 10^{-3}$$
$$|V_{ub}^{\text{incl.}}| = (3.88 \pm 0.20 \pm 0.31 \pm 0.09) \times 10^{-3}$$

(with 711fb[-1] @Belle)



Simultaneous measurement of $B^0 \to \pi^- \ell^+ \nu$ and $B^+ \to \rho^0 \ell^+ \nu$

arxiv.2407.17403 (submitted to PRD)

New measurements from Belle II

Full Run1 data of 364 fb^{-1} with inclusive tagging strategy

- Extract signal yield by combined fit of M_{bc} and ΔE for each bin of q^2:
  - 13 bins for π-mode
  - 10 bins of ρ-mode
  - Build up BDT discriminator to suppress $B \to X_c l \nu$ and continuum

$$M_{\rm bc} = \sqrt{E^{*\,2}_{\rm beam} - |\vec{p}^{\,*}_B|^2}$$

$$\Delta E = E^*_B - E^*_{beam}$$

$$\mathscr{B}(B^0 \to \pi^- l \nu_l) = (1.516 \pm 0.042(stat) \pm 0.059(sys)) \times 10^{-4}$$

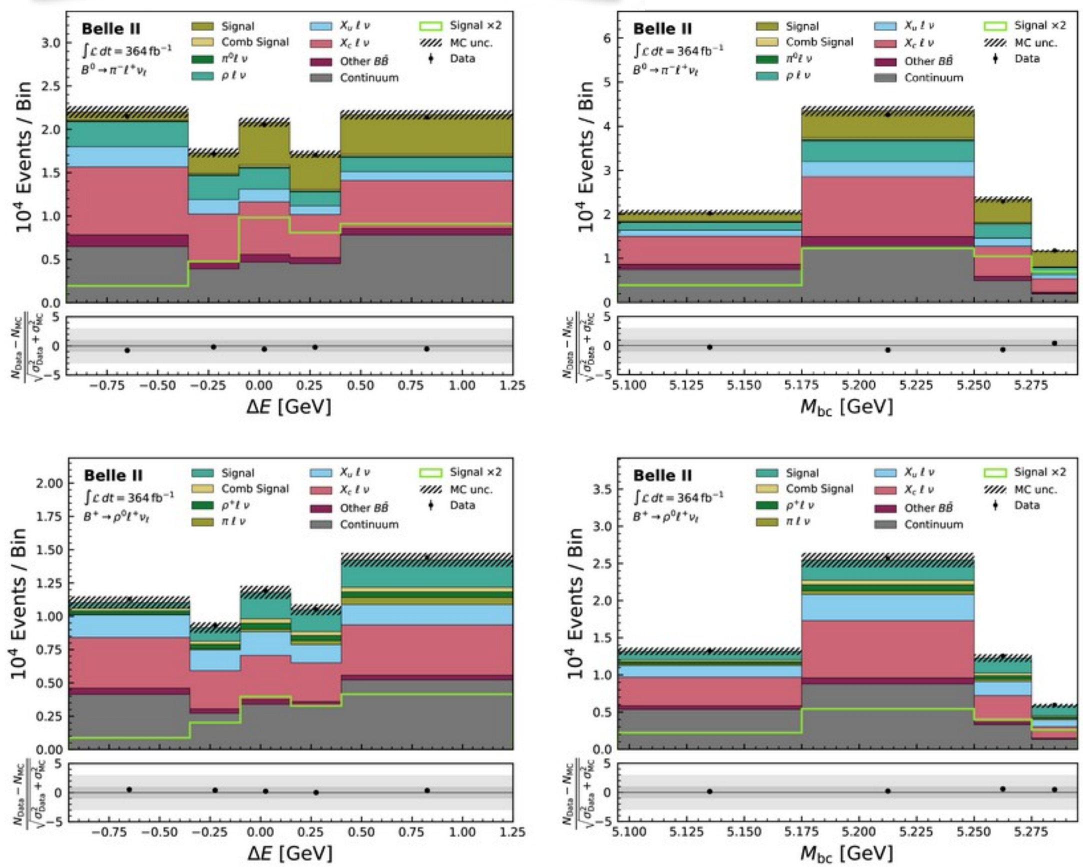
$$\mathscr{B}(B^0 \to \rho^0 l^+ \nu_l) = (1.625 \pm 0.079(stat) \pm 0.180(sys)) \times 10^{-4}$$

(BRs are consistent with the Was.

Precision compatible w.r.t. Belle and BaBar.)

$$|V_{ub}|_{B \to \pi l \nu} = (3.73 \pm 0.07(stat) \pm 0.07(sys) \pm 0.16(theo)) \times 10^{-3}$$

$$|V_{ub}|_{B \to \rho l \nu} = (3.19 \pm 0.12(stat) \pm 0.17(sys) \pm 0.26(theo)) \times 10^{-3}$$



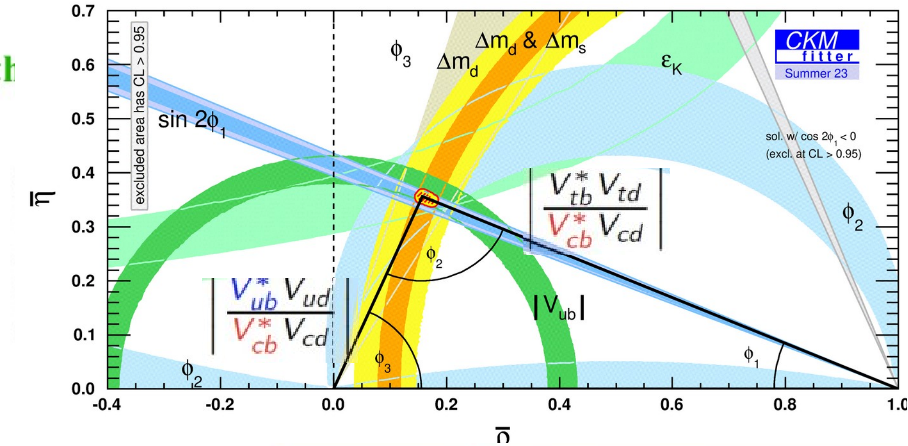
Measurement of $B^0 \to \pi^0\pi^0$

Results are preliminary; paper is being prepared. *Belle II*

Tree level $b \to u$ **processes** allow extraction of ϕ_2 (or α) (least precise CKM angle)

Build upon previous Belle II effort and extend to full **RUN1 data sample with**

- Improved photon selection
- Bkg mostly from continuum and $B^+ \to \rho^+\pi^0; B^0 \to K_s\pi^0$



- Statistical and systematic uncertainty reduced by 10% and 50% respectively on BF and absolute uncertainty on A_{CP}

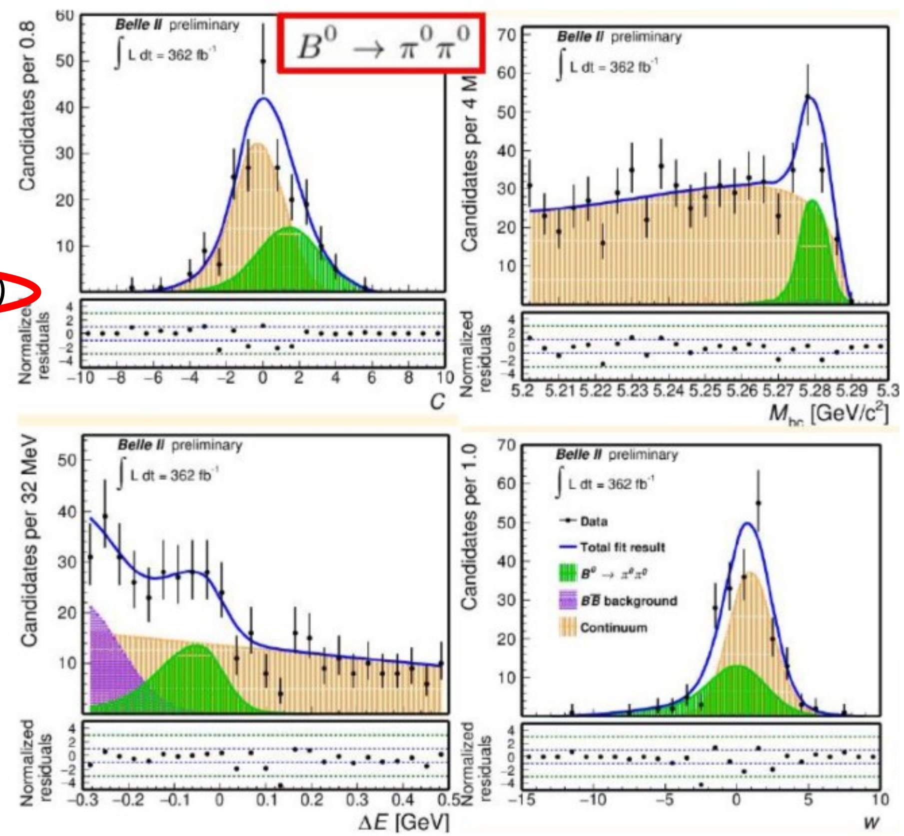
- Simultaneous fit to $M_{bc}, \Delta E, C, w$: - where C is the continuum variable

  - and w is the wrong tag probability

$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.26 \pm 0.20 \pm 0.12) \times 10^{-6}$$

$$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) = (0.06 \pm 0.30 \pm 0.05)$$

(with 365 fb^{-1} @Belle II)



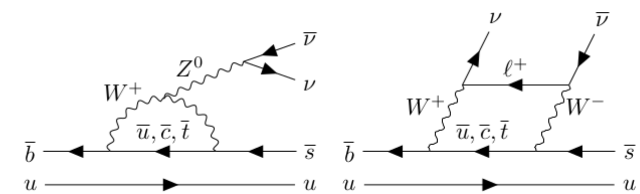
- Agreement with previous measurements
- Comparable precision with world best result from BaBar

Rare decays: $B^+ \to K^+\nu\bar{\nu}$

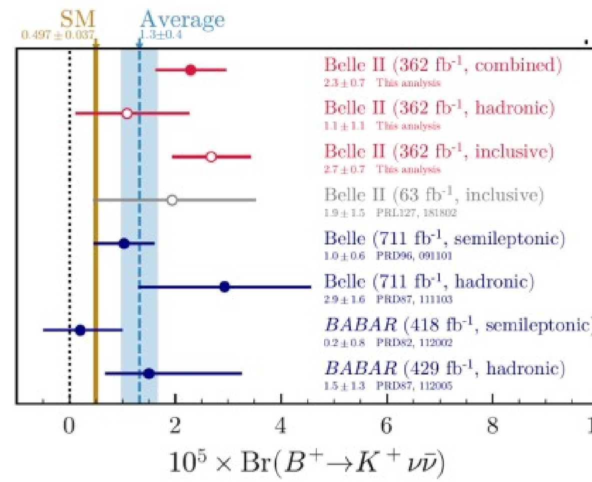
Belle II

PRD.109.112006 (2024)

- $b \to s\nu\bar{\nu}$ are highly ***suppressed*** in the SM Highly sensitive to non-SM contributions

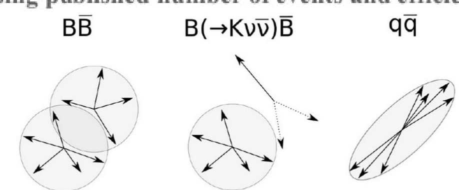


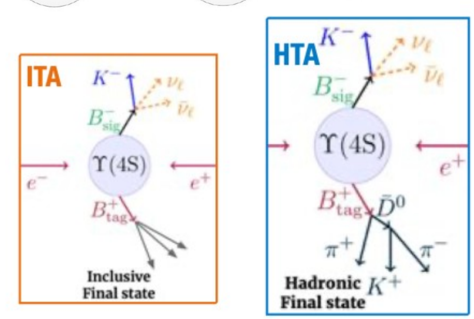
- Precise prediction in the SM: $\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = (5.6 \pm 0.4) \times 10^{-6}$ arXiv 2207.13371
  - Leading theoretical uncertainties from hadronic form factors
  - Existing results are from BaBar (PhysRevD.87.112005) and first analysis with Belle II (Phys.Rev.Lett.127.181802)



Belle reports upper limits only; branching fractions are estimated using published number of events and efficiency

- Experimental challenges: **Low BF with 2 neutrinos in the final state and high bkg contamination mainly from continuum**
  - **Used two complementary B tag approaches: low purity-high efficiency** (0.8%-8%) **and its opposite** (3.5%-0.4%)
  - Signal selection combines kaon, event topology and the rest of the event properties in MVA classifiers
  - Bkg validation : from semileptonic B-decays: $(B^+ \to K^+ n\bar{n}, B^+ \to K^+K^0\bar{K}^0)$





- **Inclusive method validated by** closure test by measuring. $\mathscr{B}(B^+ \to \pi^+K^0)$

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

Belle II

- Parameter of interest: $\mu = \dfrac{\mathscr{B}(B^+ \to K^+\nu\bar{\nu})}{\mathscr{B}_{SM}(B^+ \to K^+\nu\bar{\nu})}$
- **Binned fit** to extract μ:
  - ITA : 2D fit on a classifier output [$\eta(BDT_2)$] bins and q^2 bins
  - HTA: fit on a classifier output $\eta(BDT_h)$
- **Combining ITA & HTA** we have a 10% increase in precision w.r.t ITA alone

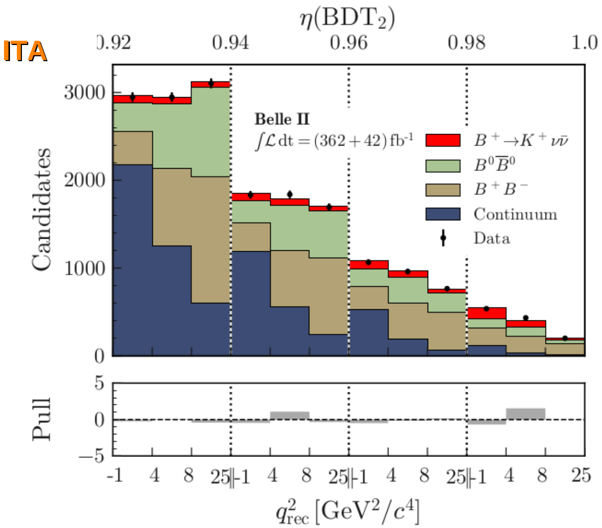
Combined: $\mu = 4.6 \pm 1.0(stat) \pm 0.9(sys)$

3.5 σ significance w.r.t bkg-only hypothesis

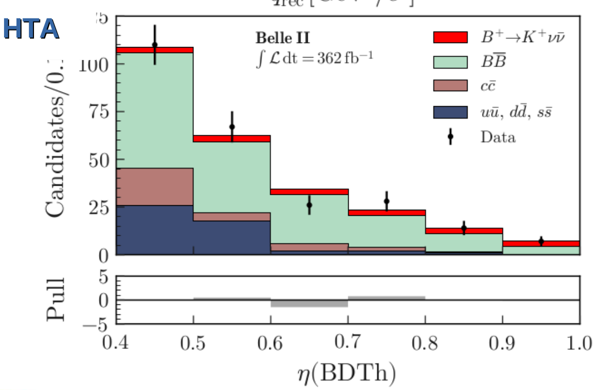
2.7 σ deviation above SM predictions

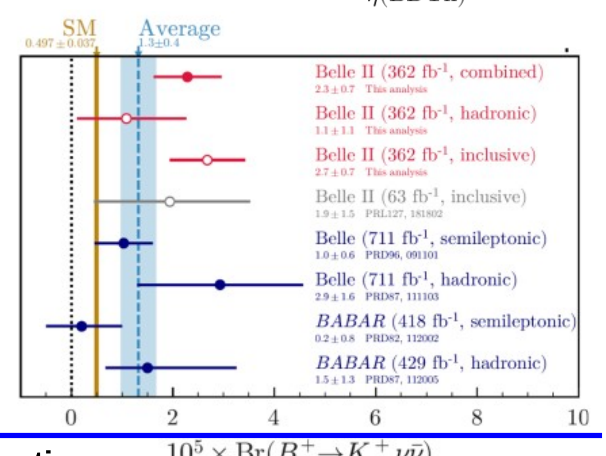
First evidence of $B^+ \to K^+\nu\bar{\nu}$ process

ITA



HTA





PRD.109.112006 (2024)

Rare decays: $B^0 \to K^{*0}\tau^+\tau^-$

Belle II

Results are preliminary; paper is being prepared.

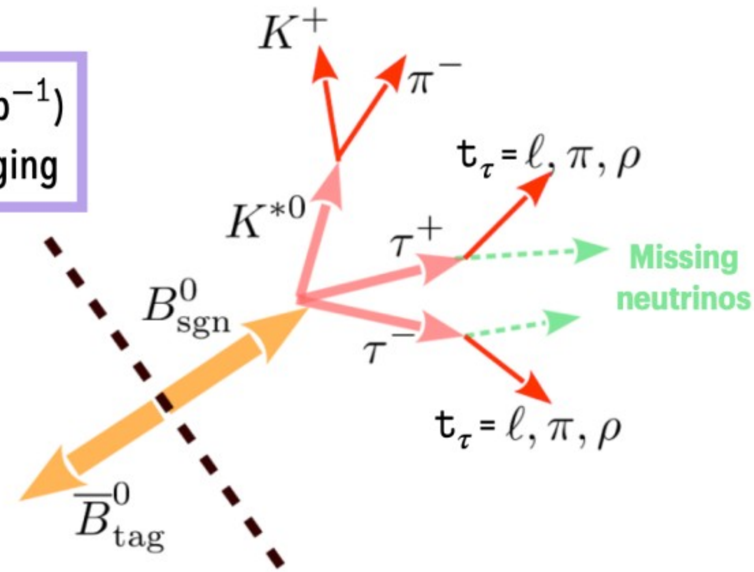
- These processes are suppressed in the SM and occur only at loop level

  $\mathcal{B}_{SM} = (0.98 \pm 0.10) \times 10^{-7}$

- Sensitive to new physics models accommodating the $b \to c\tau\nu$ anomalies
  - Might correlate with enhanced $b \to s\tau\tau$ decay rates

- **Belle (711 fb^{-1}) : $\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 3.1 \times 10^{-3}$ @ 90% C.L.**

Belle II (364 fb^{-1})
hadronic B-tagging



Experimental challenges:

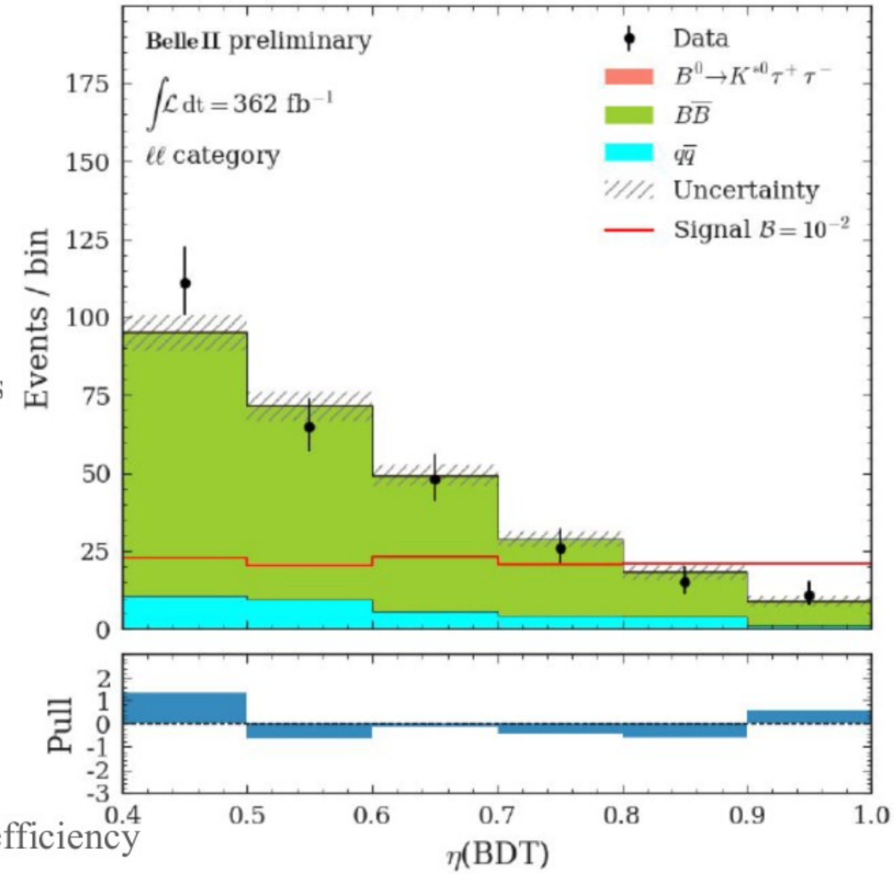
- Low branching fraction
- No signal peaking kinematic observable
- Large background + more than 3 prompt tracks
- Up to 4 neutrinos originating from τ
- K^{*0} has low momentum due to the phase space

Results are preliminary; paper is being prepared.

- Combination of charged particle from τ decay lead to 4 categories:

$$ll, l\pi, \pi\pi, \rho X$$

- **BDT** is trained using missing energy, extra cluster energy in EM calorimeter, $M(K^{*0}t_\tau)$, q^2,etc
- BDT output $\eta(BDT)$ is used to extract the signal yield with simultaneous fit to 4 categories



$$\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-) = 1.8 \times 10^{-3} \quad @\ 90\%\ C.L$$

(with 365 fb^{-1} @Belle II)

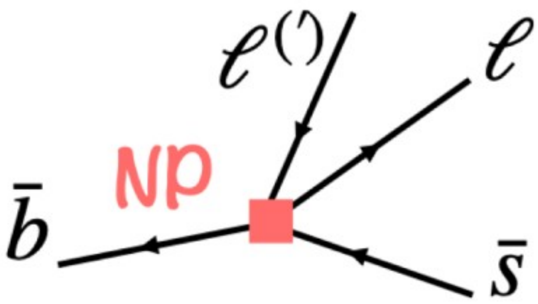
- **Twice better with only half sample w.r.t Belle :** better tagging & signal efficiency

- **The most stringent limit on the $B^0 \to K^{*0}\tau^+\tau^-$ decay and in general on $b \to s\tau\tau$ transition**

LFV searches: $B^0 \to K_S^0 \tau^\pm \ell^\mp$ (ℓ=e , μ)

Results are preliminary; paper is being prepared.

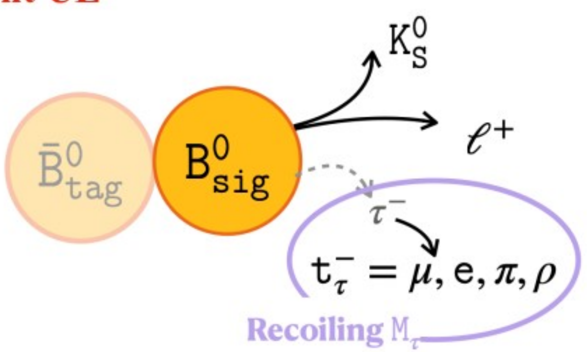
- New heavy particles might accommodate the $\mathscr{B}(B^\pm \to K^\pm \bar{\nu}\nu)$ excess and $b \to c\tau\nu$ anomalies
  - new physics coupling preferentially to 2nd and 3rd generation leptons could result in observable decays to $b \to s\tau l$ (Lepton Flavor Violation-LFV)



- BaBar (428 fb^{-1}) : $B^+ \to K^+\tau^\pm l^\mp$ PRD.86.012004
- LHCb (9 fb^{-1}) : $B^+ \to K^+\tau^+\mu^-$, $B^0 \to K^{*0}\tau^\pm\mu^\mp$ JHEP.06.129, arXiv.2209.09846
- Belle (711 fb^{-1}) : $B^+ \to K^+\tau^\pm l^\mp$ PRL.130.261802

Most stringent UL

- **First search in $B^0 \to K_s^0\tau^\pm l^\mp$**

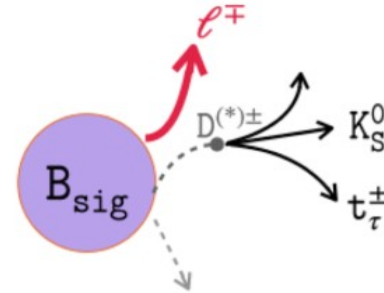


- Belle + Belle II (711+364 fb^{-1}) + hadronic B-tagging

Strategy and results for $B^0 \to K_S^0 \tau^\pm \ell^\mp$ ($\ell = e, \mu$) decays

Belle II

- Final states involving **presence of neutrinos** $\longrightarrow$ **can compute recoil mass of τ**
- K_S^0 reconstructed from a pair of opposite charged pions $\longrightarrow$ after selections more than **98% purity**
- Semileptonic B decays are primarily **background**
- The remaining background is treated with the use of a **BDT**



90% U.L. are derived:

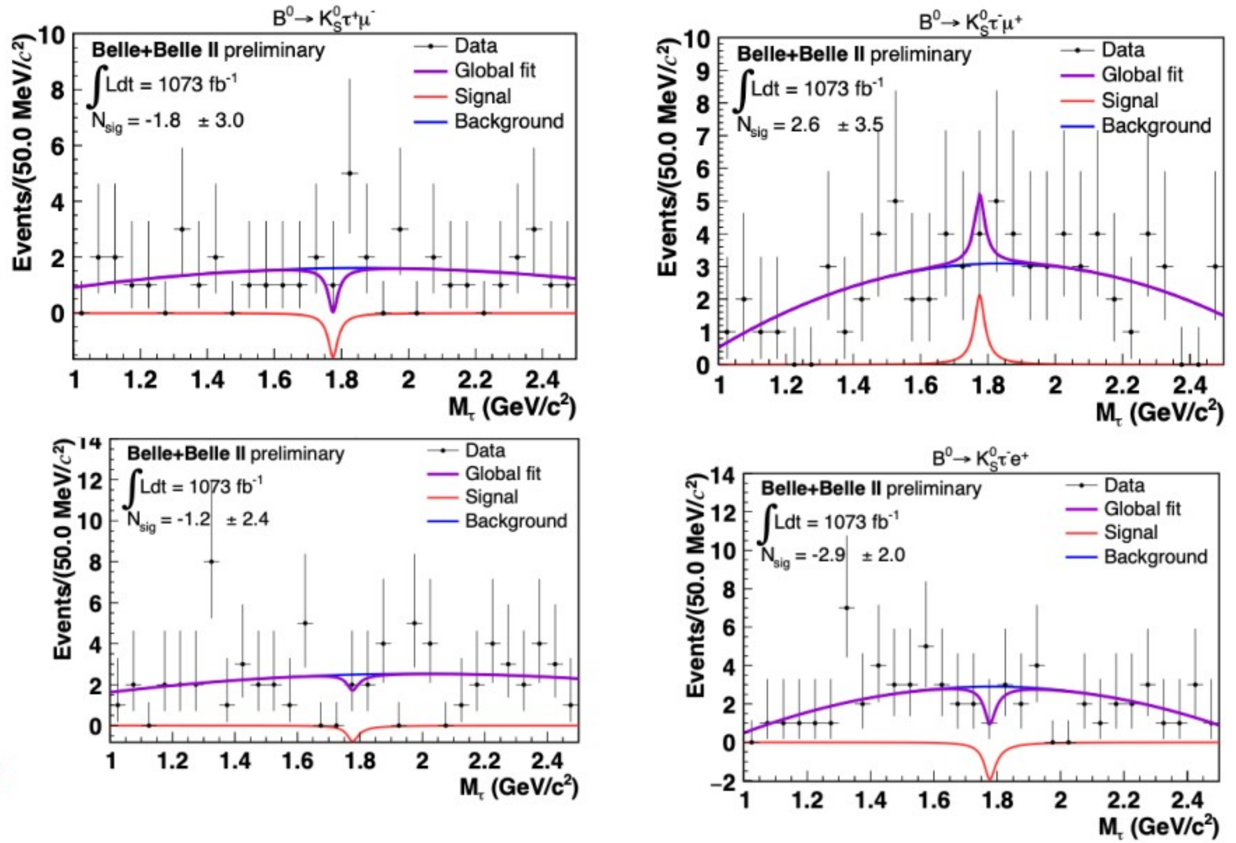
$$\mathcal{B}(B^0 \to K_S^0 \tau^+ \mu^-) < 1.1 \times 10^{-5}$$

$$\mathcal{B}(B^0 \to K_S^0 \tau^- \mu^+) < 3.6 \times 10^{-5}$$

$$\mathcal{B}(B^0 \to K_S^0 \tau^+ e^-) < 1.5 \times 10^{-5}$$

$$\mathcal{B}(B^0 \to K_S^0 \tau^- e^+) < 0.8 \times 10^{-5}$$

The results are among the most stringent limits



LFU tests: Light lepton universality in τ decays

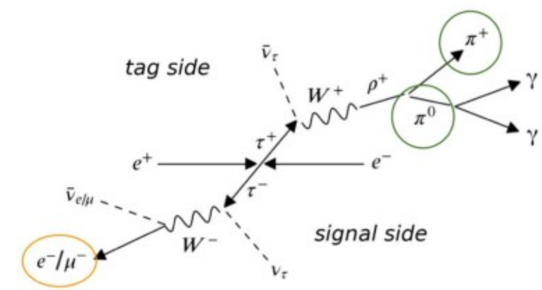
JHEP 08 2024, 205 (2024)

In the SM all charged leptons have equal coupling strength ($g\ell$) to the W boson: LFU → may be violated by new forces [1]

For each $B\bar{B}$ event we get ~ a $\tau\tau$ pair
→ Belle II optimal for τ physics too

$$R_\mu = \frac{\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)}{\mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)}$$

$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{R_\mu \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$$



- **Test of μ/e universality in τ decays**
  - In the $e^+e^- \to \tau^+\tau^-$ one can separate the event in two hemispheres: tag τ, and signal τ

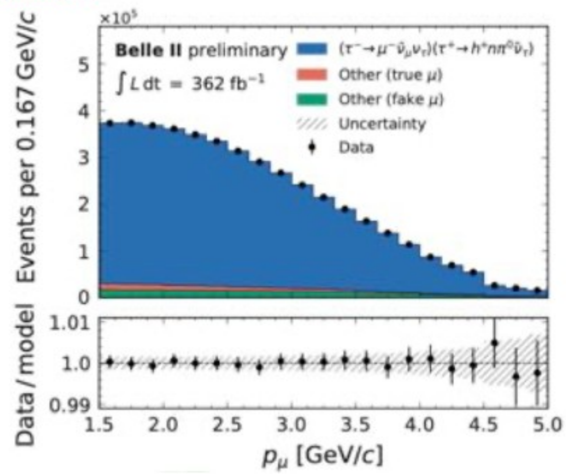
Full Belle II RUN1 data sample 364 fb^{-1}

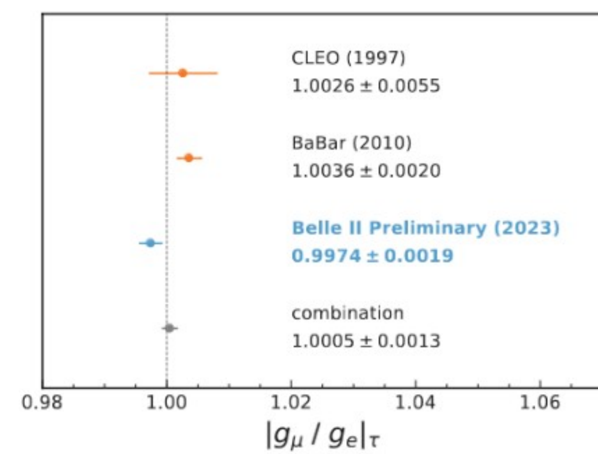
-Signal side: e or μ

-Tag side: 1 charged hadron + $\geq 1\pi^0$

- Background suppression using a Neural Network
- Systematics dominated by eID and trigger

Purity 96% and 92% for electron and muon channels





R_μ obtain by binned maximum likelihood fit on momentum spectra on μ/e

Most precise test of light lepton universality in τ decays

$$R_\mu = 0.9675 \pm 0.0007(stat) \pm 0.0036(sys)$$

$$g_\mu/g_e = 0.9974 \pm 0.0019$$

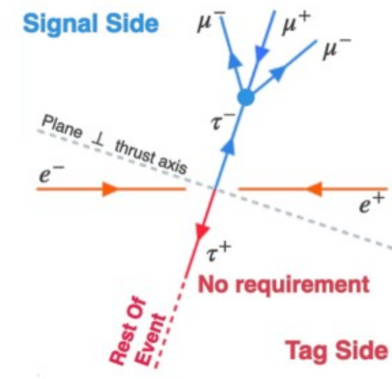
Search for LFV decays: $\tau \to \mu\mu\mu$

JHEP 09 2024, 062 (2024) Belle II
arXiv:2405.07386

A lot of interest in LFV decays at e^+e^- colliders, with ~ 50 modes: $\tau \to l\gamma, \tau \to l\phi, \tau \to lll$

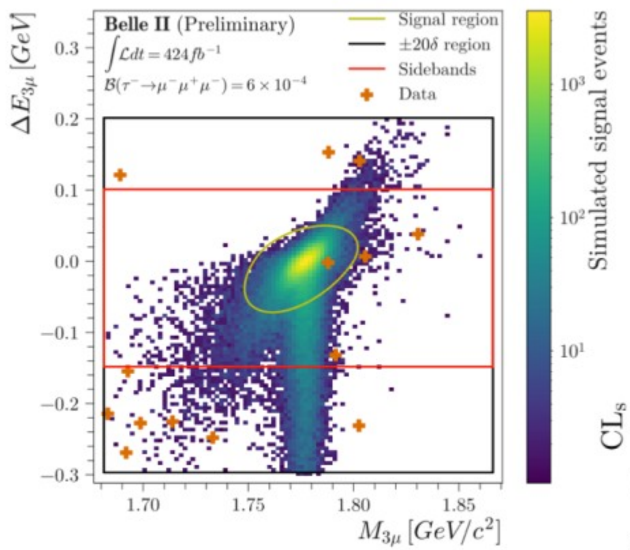
These are rare decays : it's all about **maximising the statistics!**

- Almost free from SM background
- Very good resolution on the energy and the momentum



Signal:
- reconstruction of signal candidate by combining three muons

Background:
- Selections to remove low-multiplicity events
- BDT to reject $q\bar{q}$ events

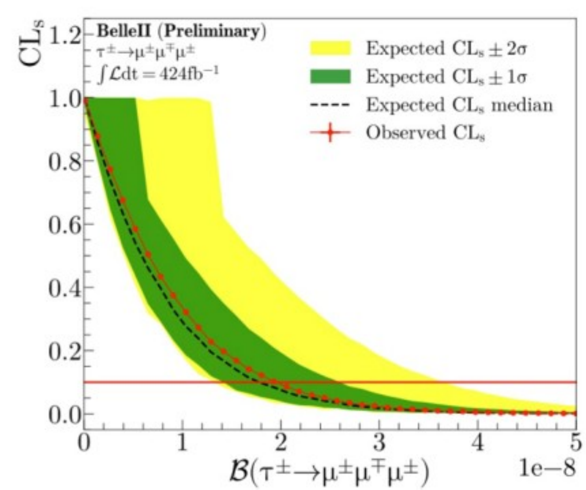


90% CL upper limit on Branching Fraction

$$\mathscr{B}(\tau \to \mu\mu\mu) < 1.9 \times 10^{-8}$$

World's best limit!!!

No excess is found!



Summary and Conclusions

- Belle II has collected and will continue to collect high quality data for a rich physics programme
- The data collected with Belle is also used, usually combined with the Belle II sample

- The field is very active: Many measurements are in progress
  (few dozens of them, with ~400 fb^{-1} Run 1 data from Belle II)

- In this talk only selected results are presented;

More information can be found on our public publications page :
https://www.belle2.org/research/physics/publications

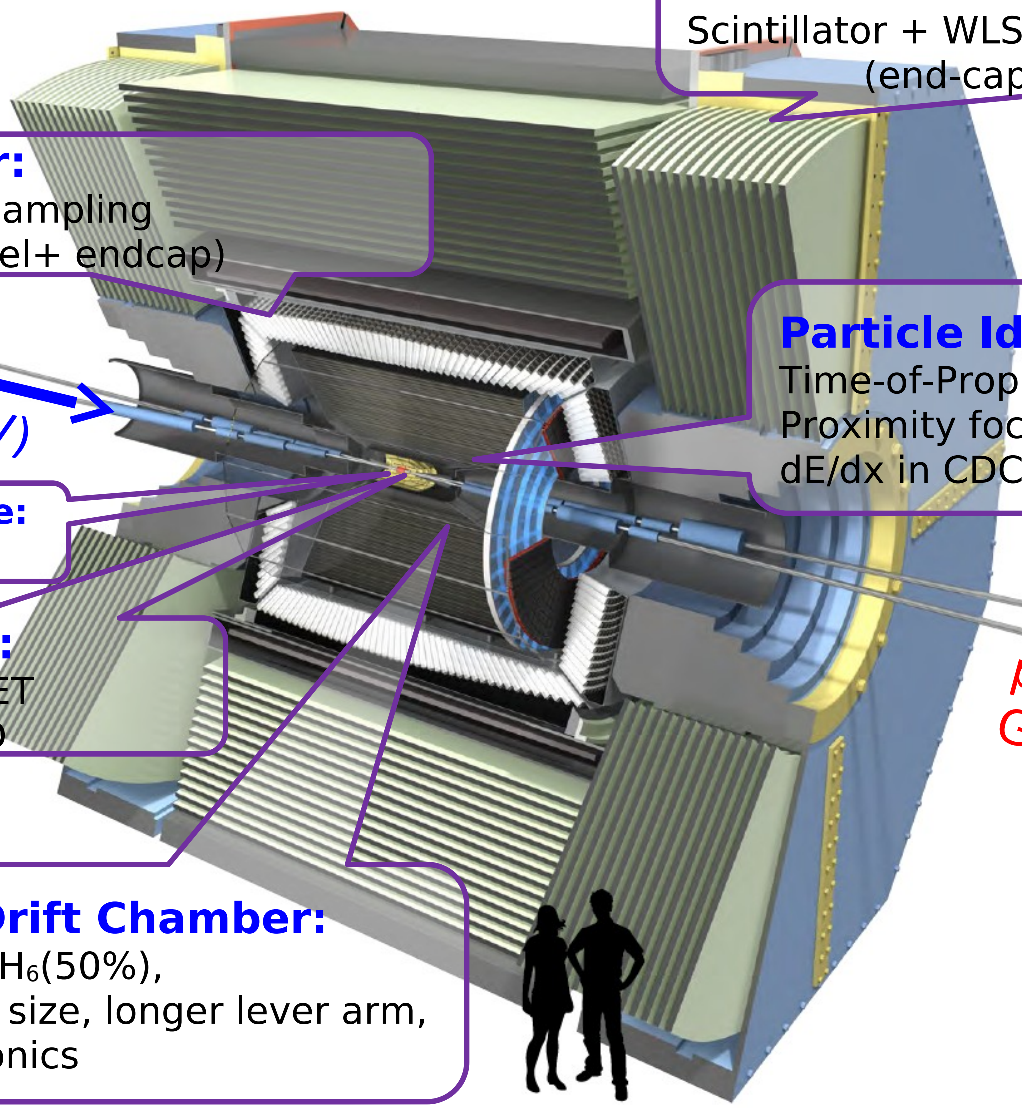
- Belle II has restarted collecting data from its Run2 in 2024,

aiming at a significant increase of the data sample (50 ab^{-1}) in the next years (~2035)

→ **Our results are eagerly awaited by the HEP community.**

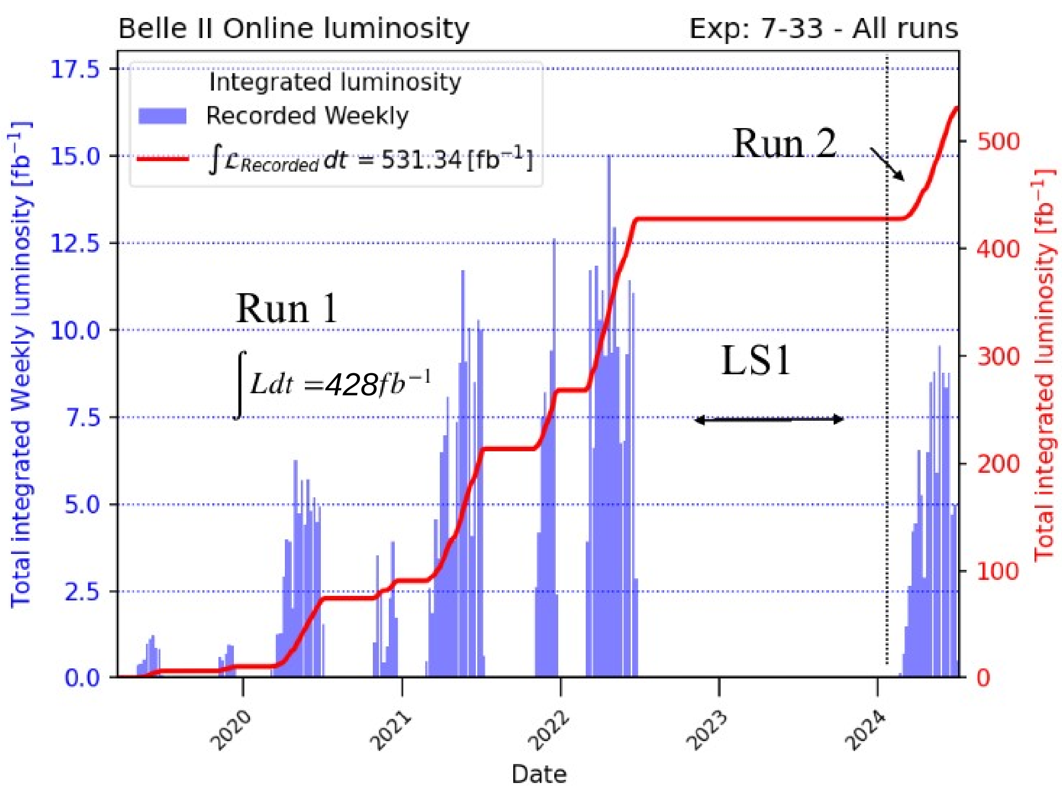
Backup Slides

Belle II detector



Belle II data-taking: Run 1 , LS1, Run 2, …

- Run 1 (March 2019 to June 2022)
- LS 1 (autumn 2022 to spring 2024)
- Run 2 (March 2024 to …) will resume in October 2024



Operation status (beginning of Run 2):

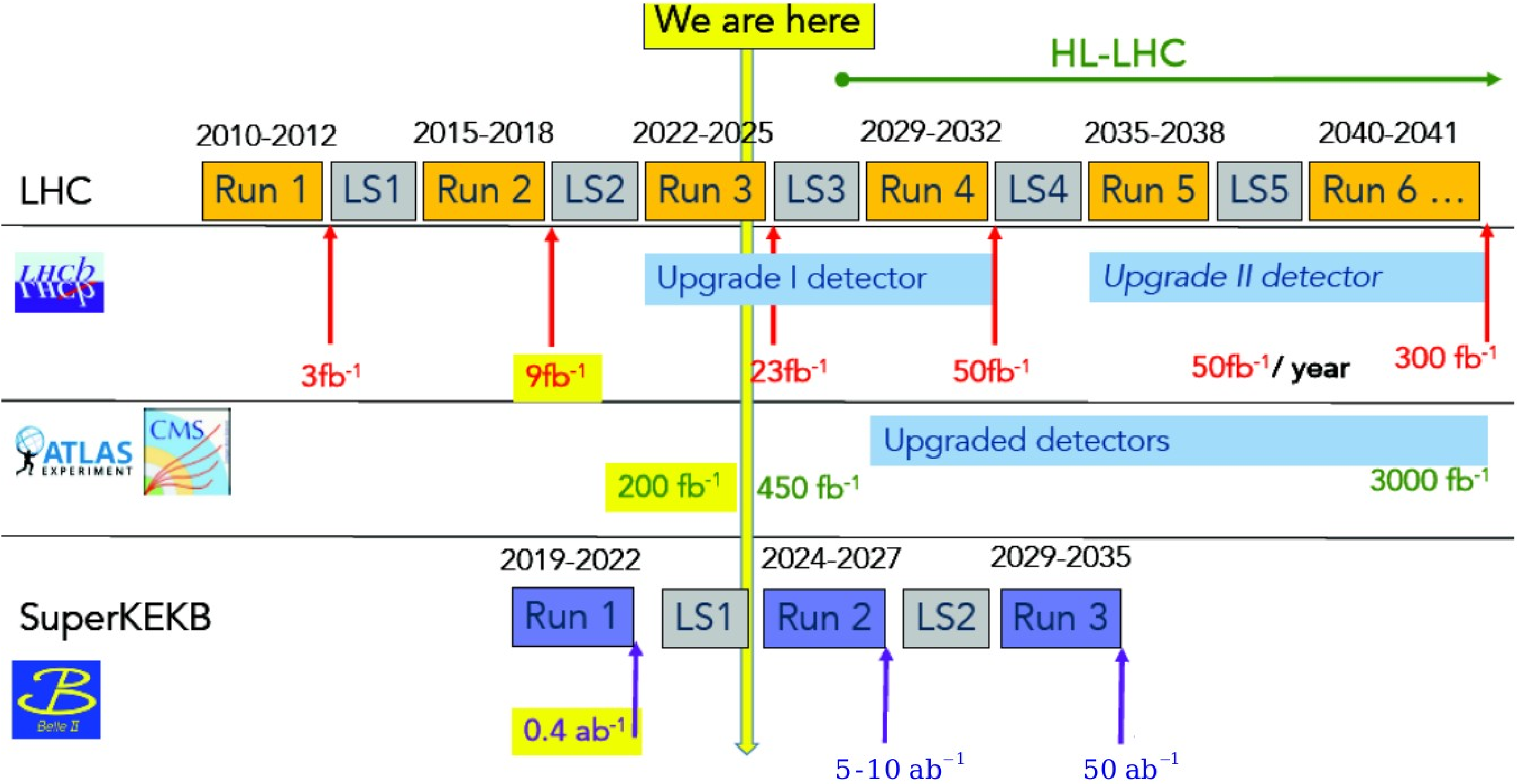
We are suffering from **sudden beam loss events**, with large doses at the interaction region.

In a couple of them two channels of **PXD were damaged**

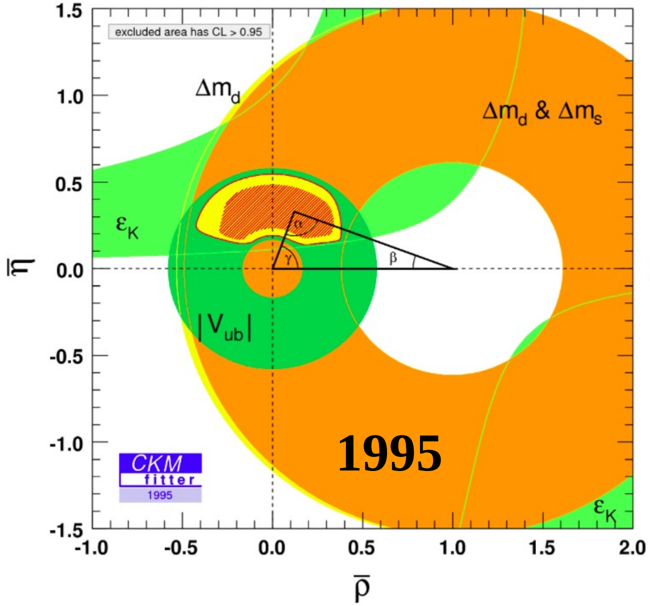
- as a precaution, it has been decided to **keep PXD off** while investigating the sources of the sudden beam loss and implement countermeasures to stabilize the beam operation

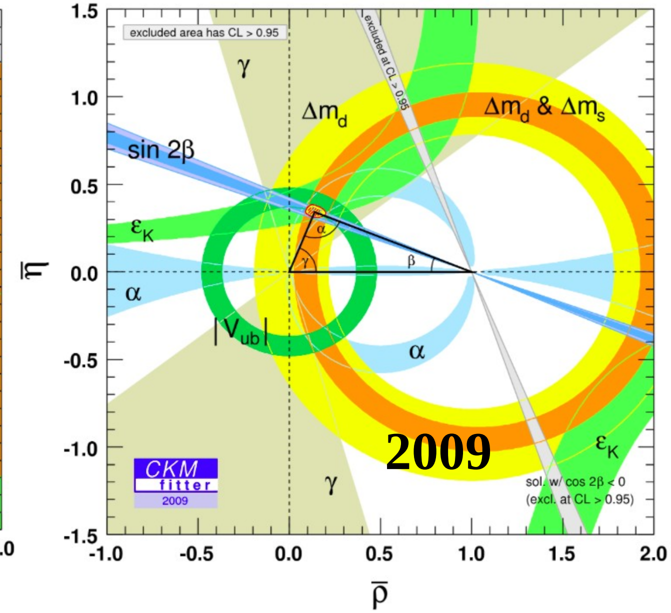
LHCb / Belle II data-taking: status & plans

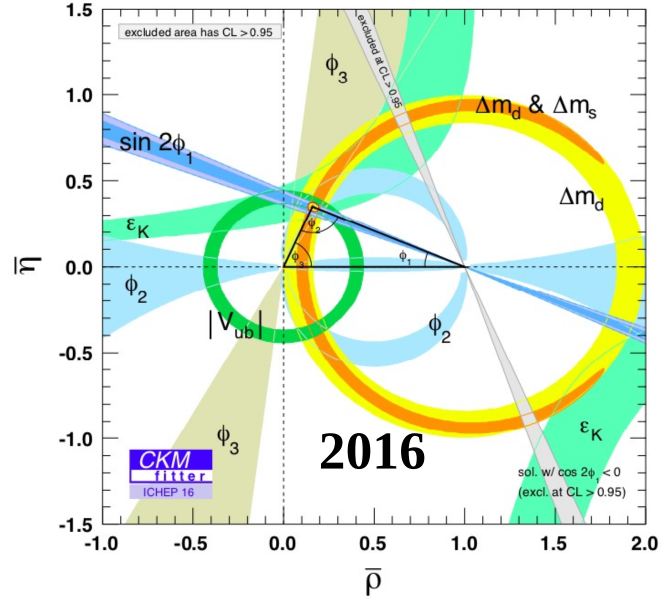
K. Trabelsi
(M.H. Schune)

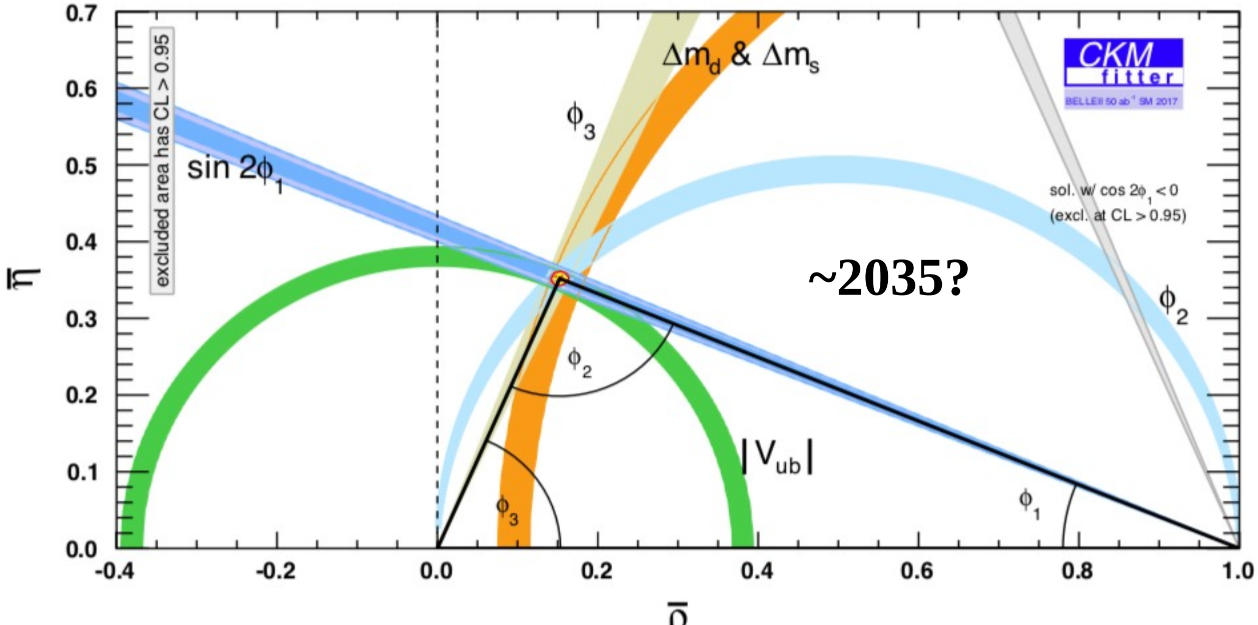


Precision of CKM unitarity triangle









Belle II 50 ab^{-1} projection, all constraints