Status and Prospects for Tau Property Measurements at Belle II.

Michel Hernández Villanueva
DESY

On behalf of the Belle II collaboration

The 16th International Workshop on Tau Lepton Physics (TAU 2021)
Sep 27, 2021

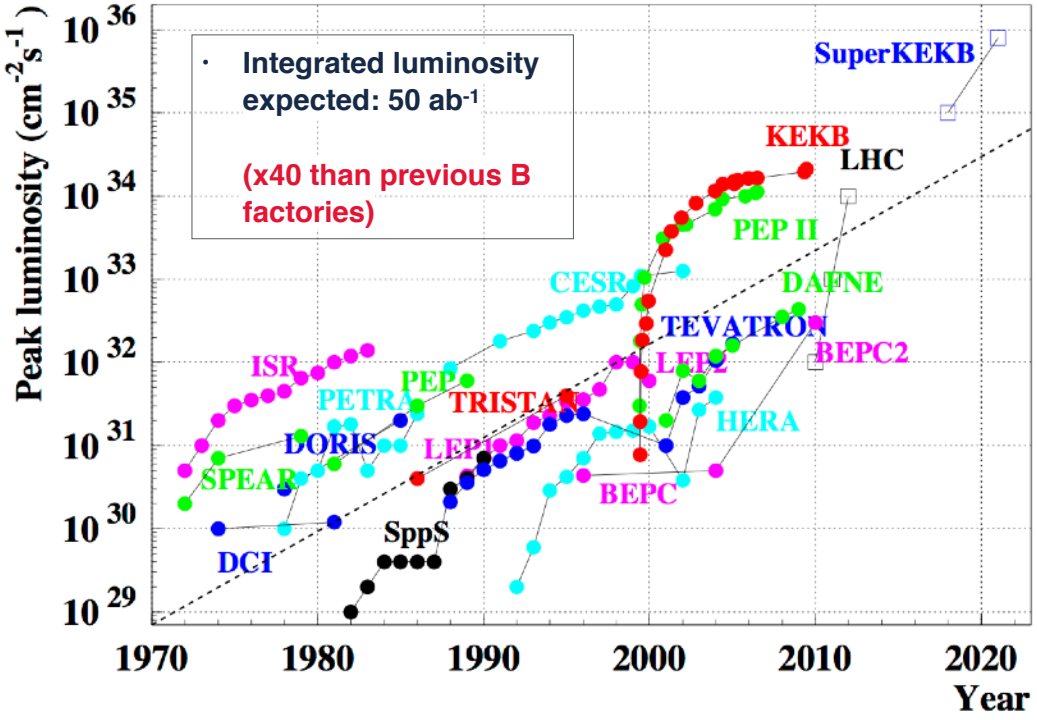
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Belle II

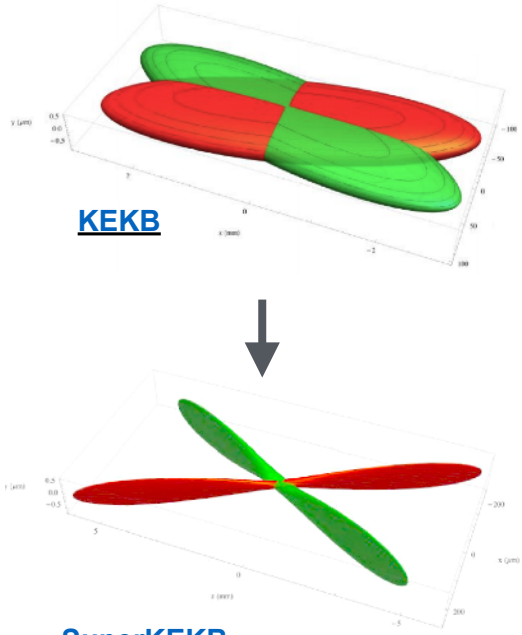
DESY.

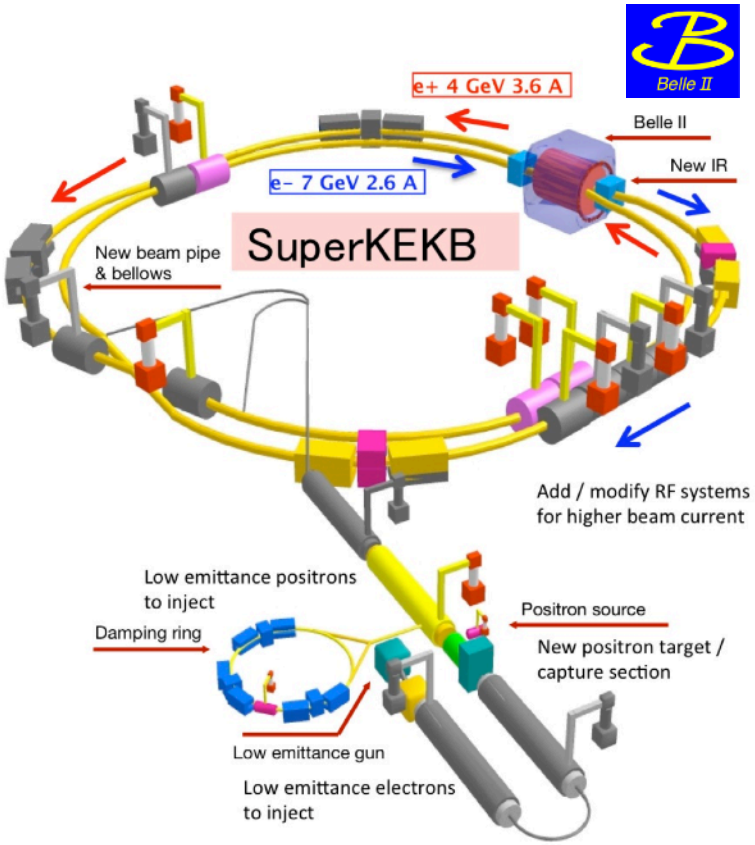
SuperKEKB

A B factory of next generation



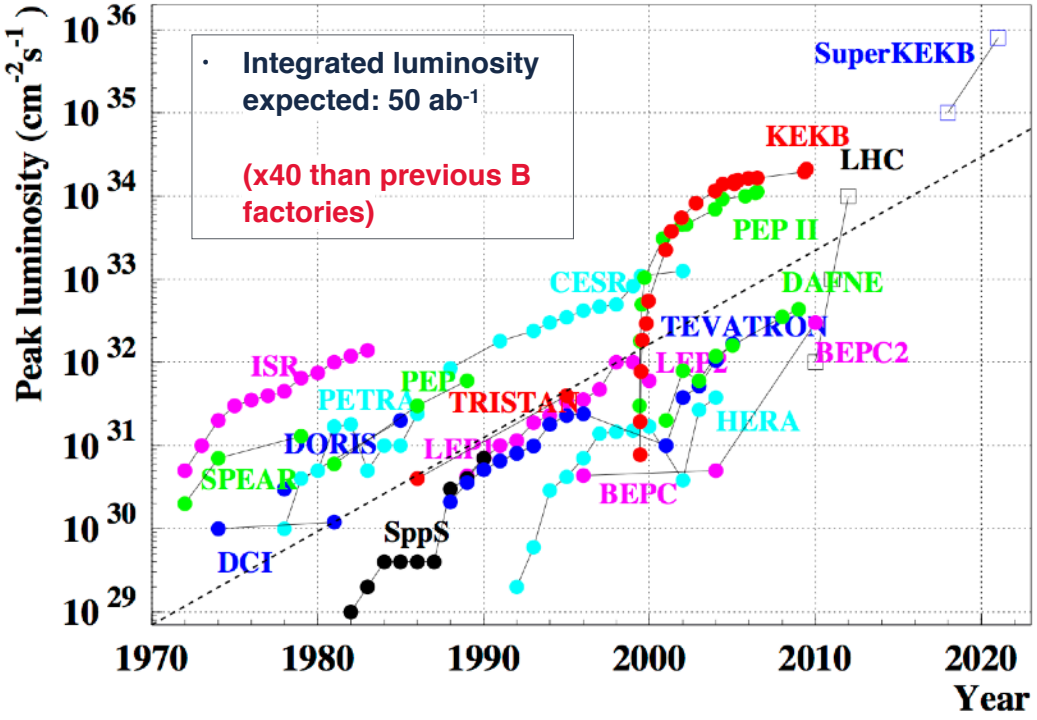
"Nano-beams": vertical beam size is 50nm at the IP.





SuperKEKB

A B factory of next generation



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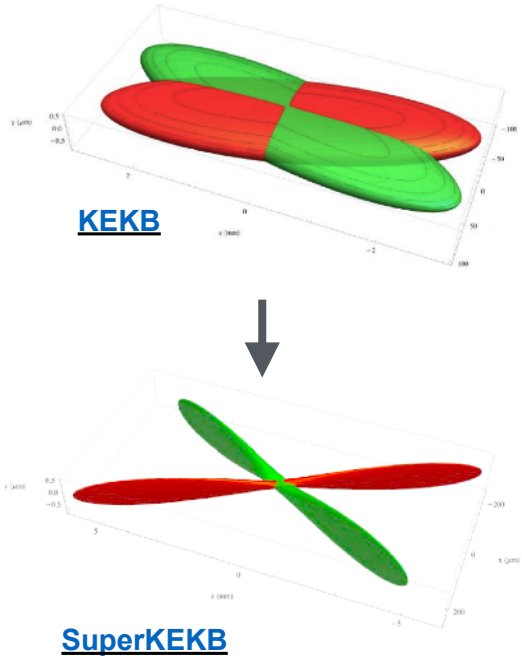
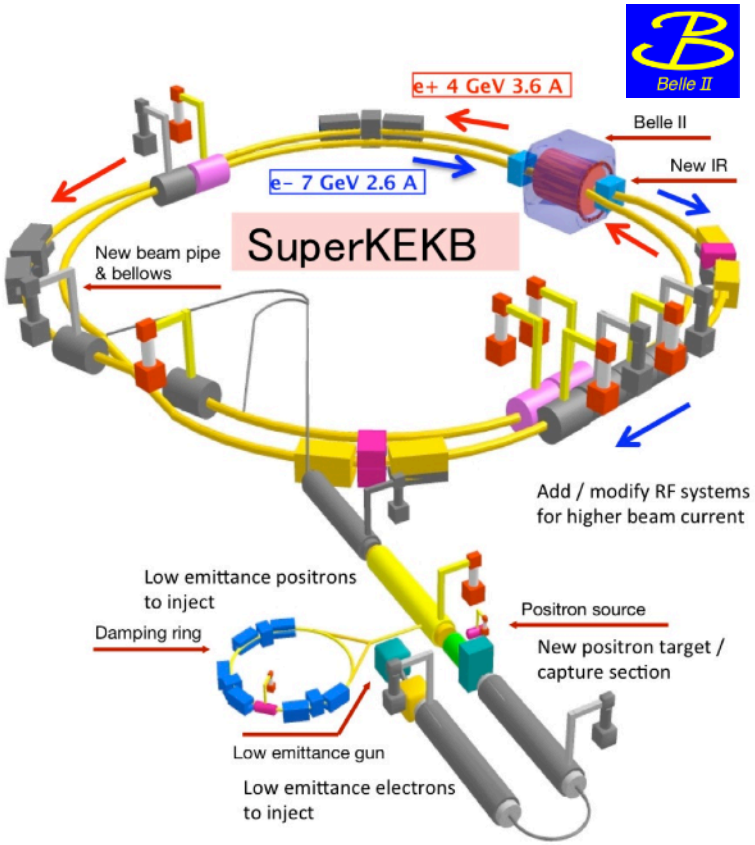
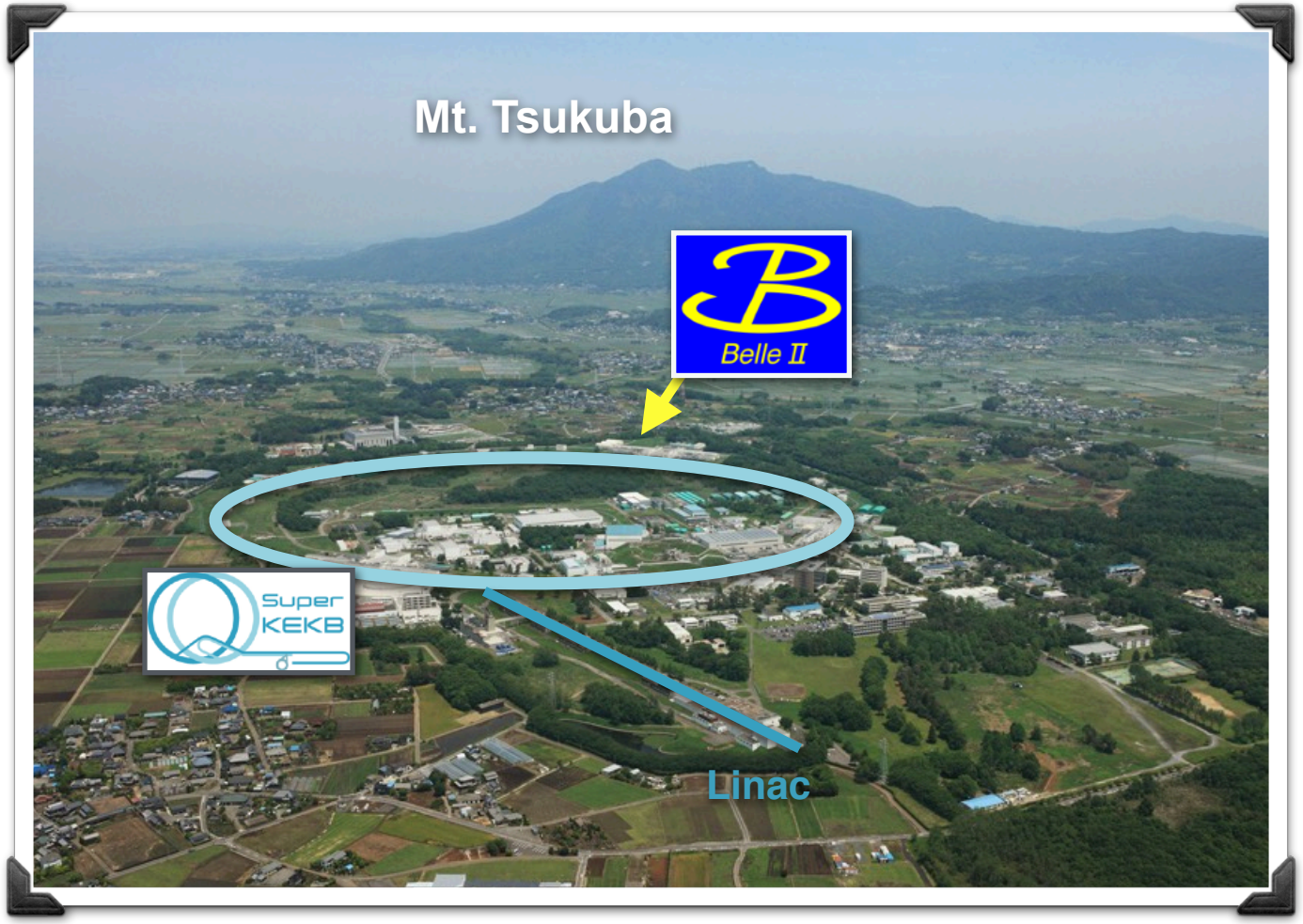




- Challenges at L=6.5x10^{35} cm^{-2} s^{-1}:
  - **Higher background** (Radiative Bhabha, Touschek, beam-gas scattering, etc.).
  - **Higher trigger rates** (High performance DAQ, computing).

The Belle II Collaboration

1100 members, 123 institutions, 26 countries



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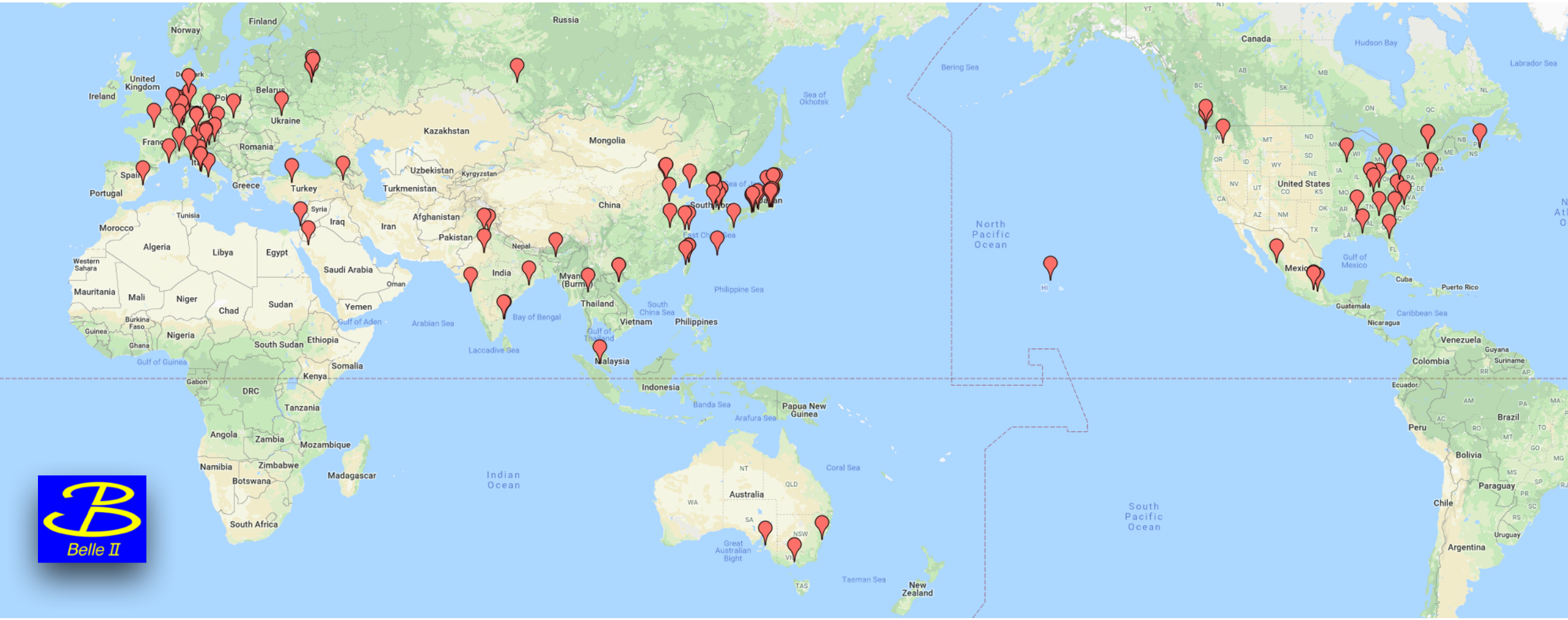
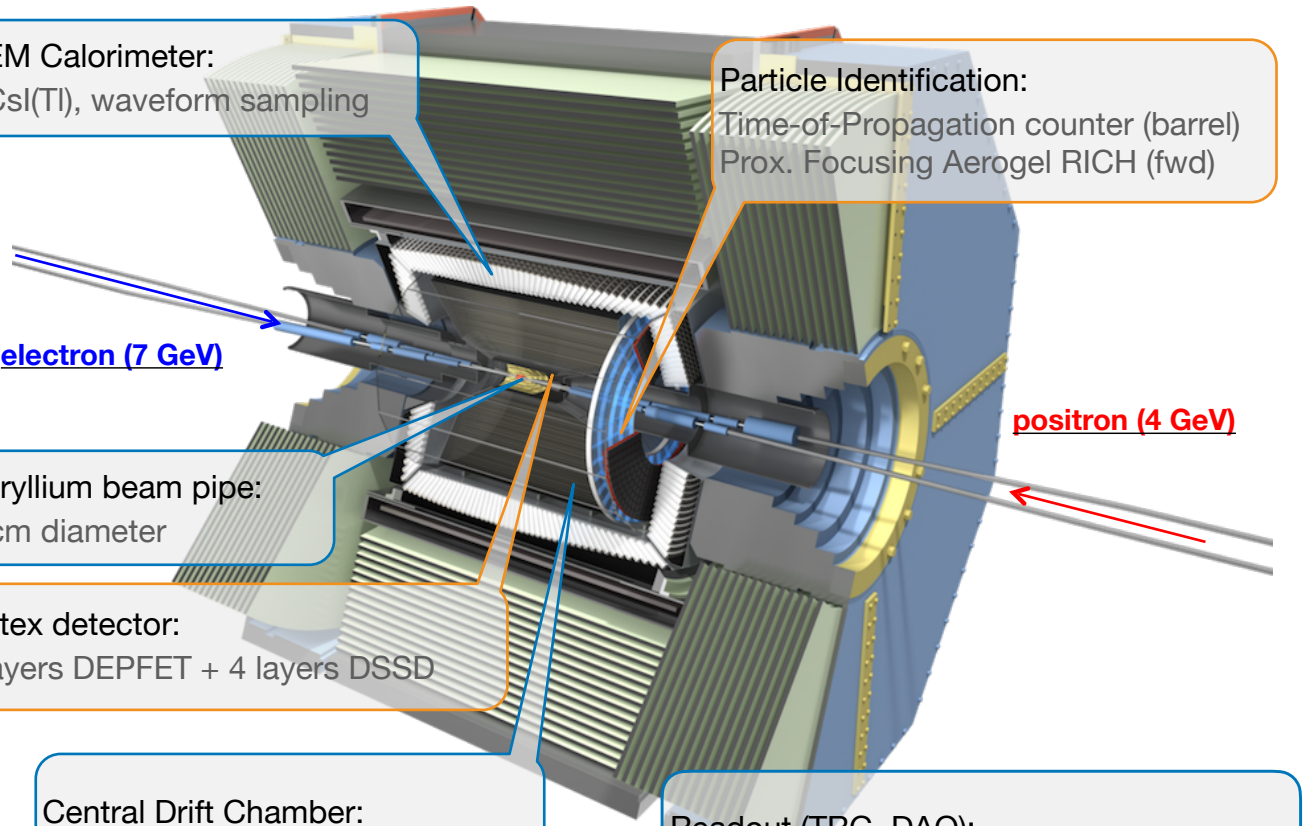


The Belle II Experiment

EM Calorimeter:
CsI(Tl), waveform sampling

Particle Identification:
Time-of-Propagation counter (barrel)
Prox. Focusing Aerogel RICH (fwd)



electron (7 GeV)

positron (4 GeV)

Beryllium beam pipe:
2 cm diameter

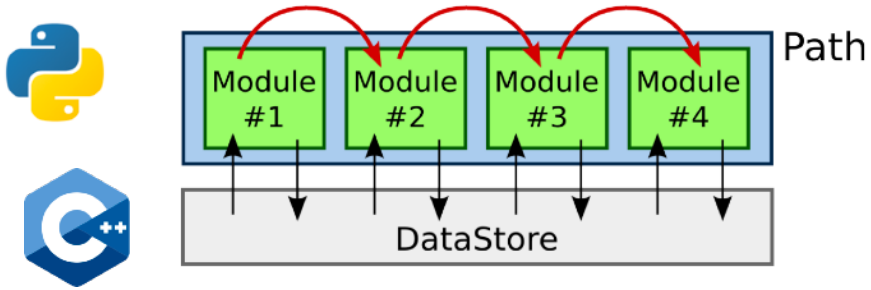
Vertex detector:
2 layers DEPFET + 4 layers DSSD

Central Drift Chamber:
He(50%):C_2H_6(50%), Small cells, long lever arm, fast electronics

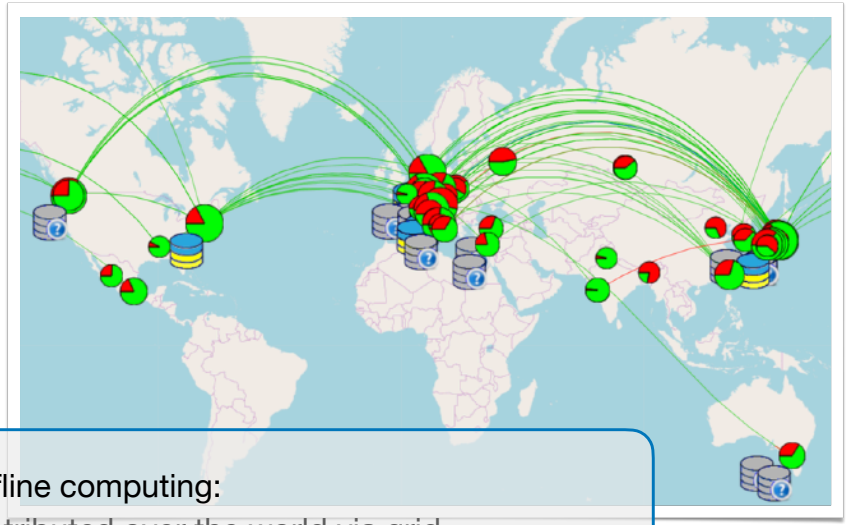
Readout (TRG, DAQ):
Max. 30kHz L1 trigger
~100% efficient for hadronic events.
1MB (PXD) + 100kB (others) per event
- over 30GB/sec to record

arXiv:1011.0352 [physics.ins-det]

Software:
Open-source sophisticated algorithms for simulation, reconstruction, visualization, and analysis.



Comput. Softw. Big Sci. 3 1 (2019)



Offline computing:
Distributed over the world via grid.

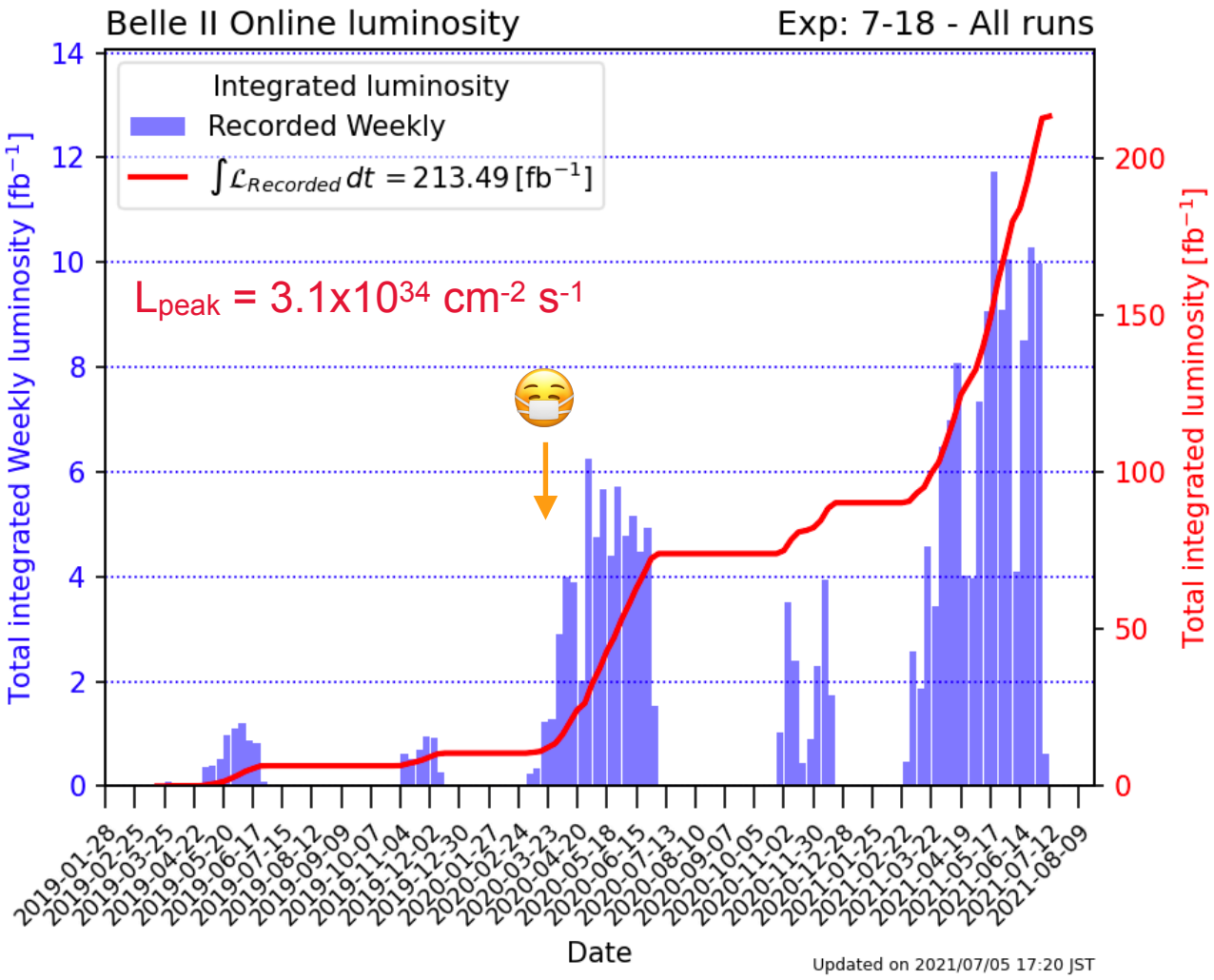
EPJ Web Conf., 245 (2020) 11007

Belle II

DESY.

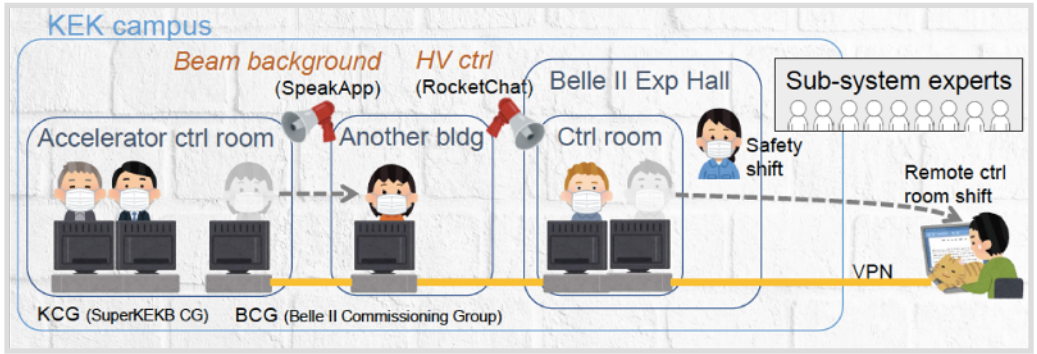
Integrated Luminosity

Today



- **Super B-factory performance levels**, despite a global pandemic.
  - World records:
    - 1.96 fb^{-1}/day,
    - 12 fb^{-1}/week,
    - 40 fb^{-1}/month
  - Luminosity above the B factories and LHC, with a product of beam currents 3.5 times lower than KEKB.

- "Social distancing" scheme for on-site shifts, and mobilized remote shifters around the world



Integrated Luminosity

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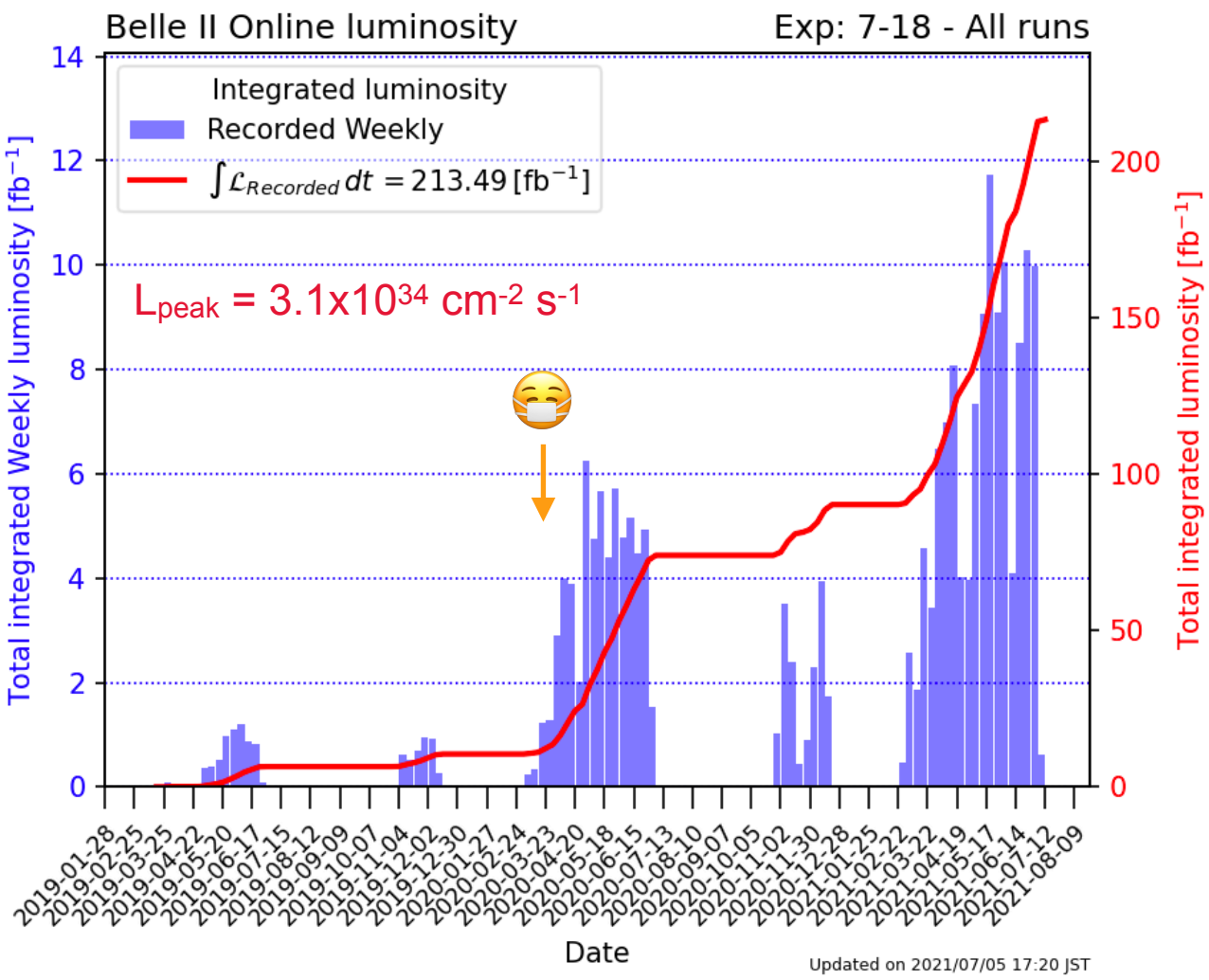


ACCELERATORS | NEWS

SuperKEKB raises the bar

22 August 2021

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

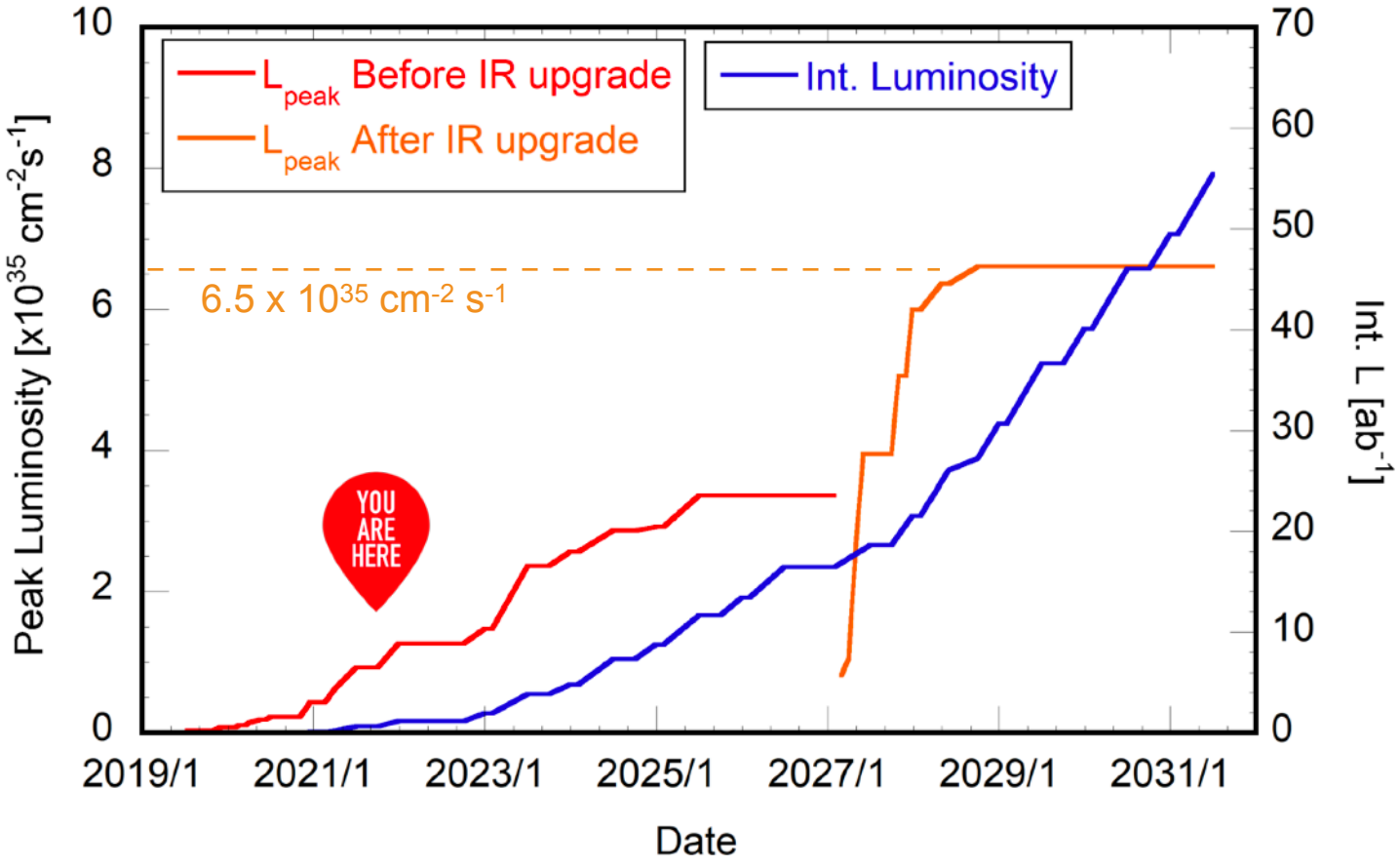
On 22 June, the SuperKEKB accelerator at the KEK laboratory in Tsukuba, Japan set a new world record for peak luminosity, reaching 3.1 × 10^{34} cm^{-2} s^{-1} in the Belle II detector. Until last year, the luminosity record stood at 2.1 × 10^{34} cm^{-2} s^{-1}, shared by the former KEKB accelerator and the LHC. In the summer of 2020, however, SuperKEKB/Belle II surpassed this value with a peak luminosity of 2.4 × 10^{34} cm^{-2} s^{-1}.

https://cerncourier.com/a/superkekb-raises-the-bar/

Integrated Luminosity

Projections

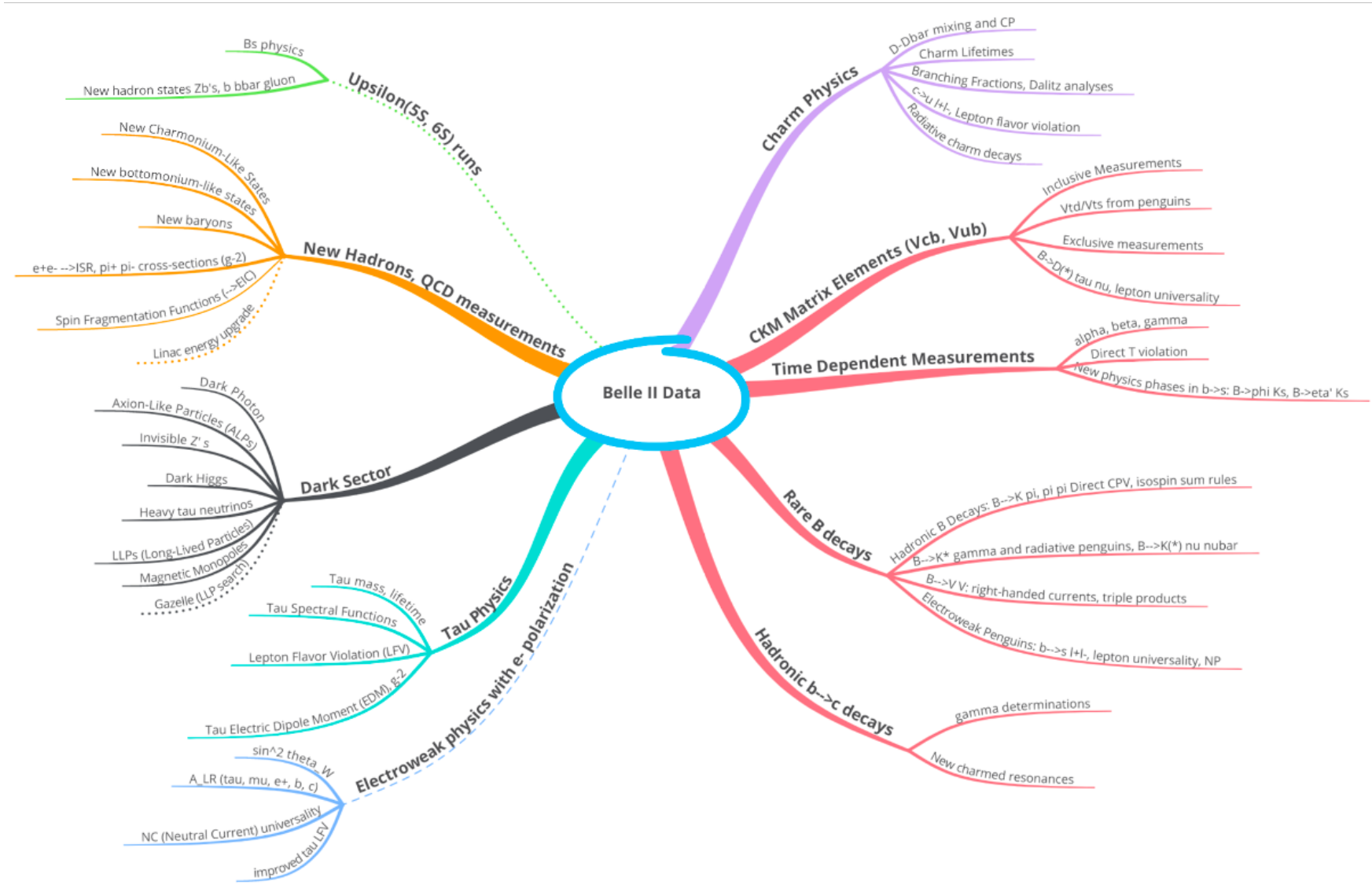
Target: **x40** the integrated luminosity collected by the previous B-factories.



- Milestones:
  - **~500 fb^{-1}** by the next summer (2022).
  - **O(10 ab^{-1})** by the upgrade of the IR (2026).
  - **50 ab^{-1}** after the upgrade, by 2030.

Belle II Physics Program

- The physics program of Belle II covers measurements in B decays, charm, dark sectors, exotic particles, etc.
- Further details can be found in “The Belle II Physics Book”: PTEP 2019 (2019) 12, 123C01
- The enormous number of e+e- collisions features a unique environment for the study of τ physics with high precision.



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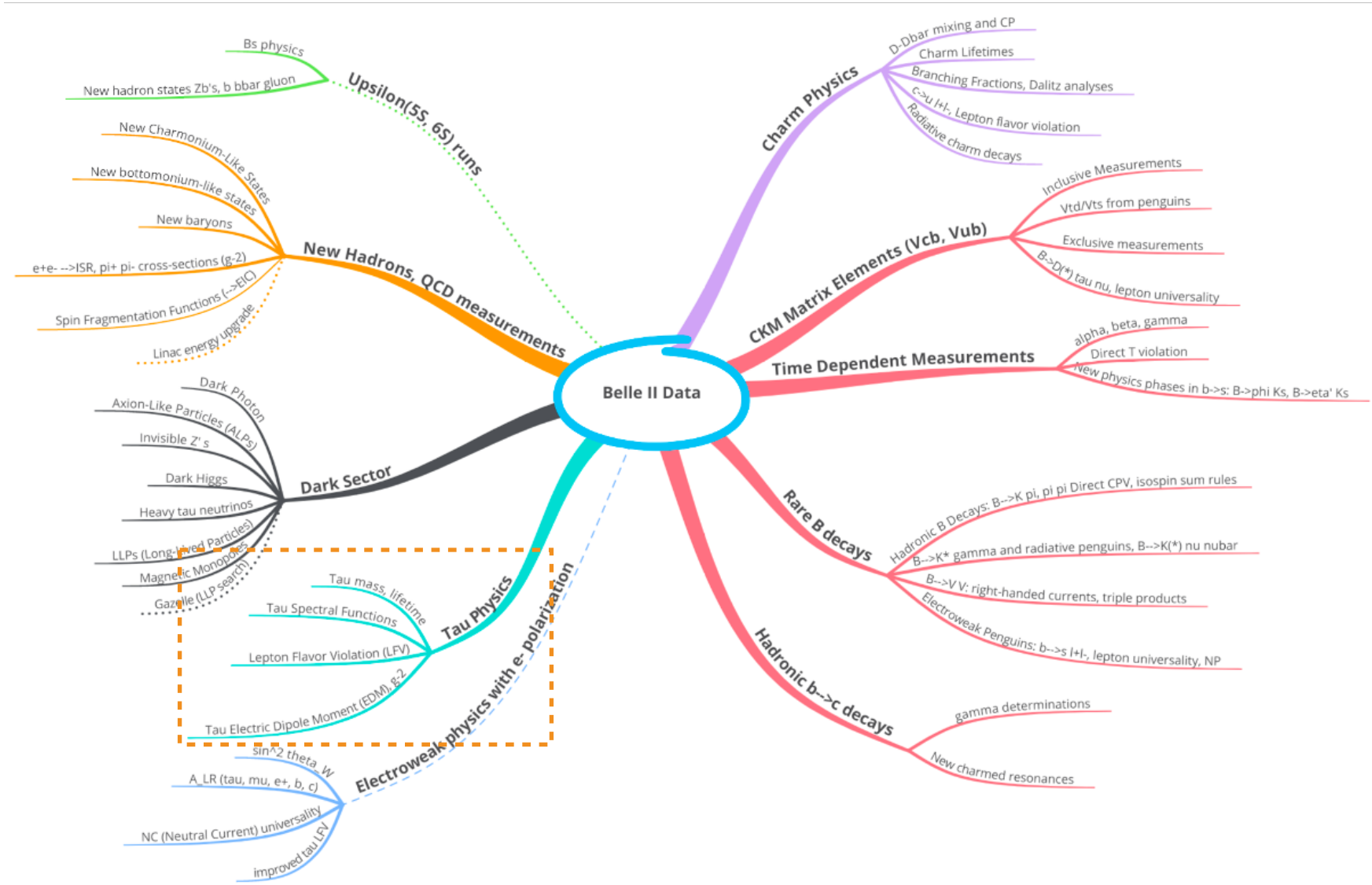
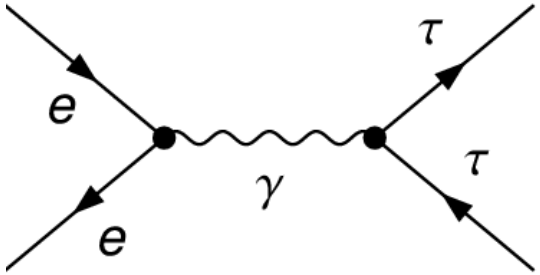


Tau leptons at the B factories

Let's talk about the tau



- At Y(4S):

  $\sigma(e^+e^- \dashrightarrow B\bar{B}) = 1.05$ nb

  $\sigma(e^+e^- \dashrightarrow \tau^+\tau^-) =$ **0.92 nb**

- Approximately 1M tau pairs per fb^{-1}

- **B-Factories are also τ-factories**

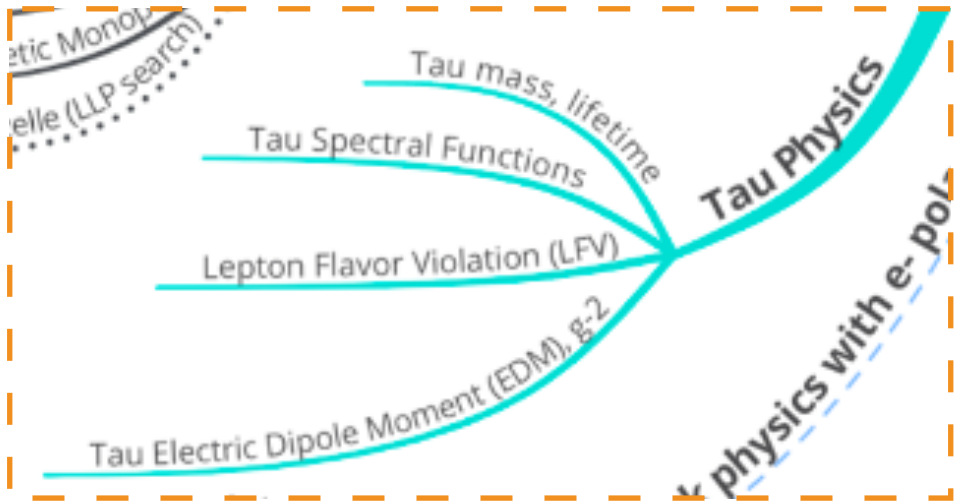
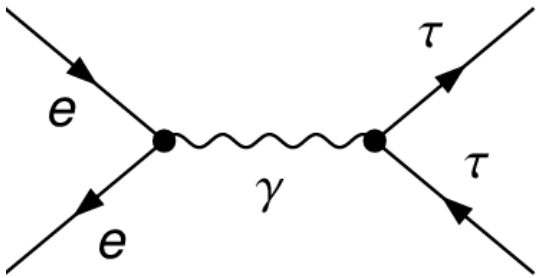


Figure: The particle zoo.

Tau leptons at the B factories

Let's talk about the tau

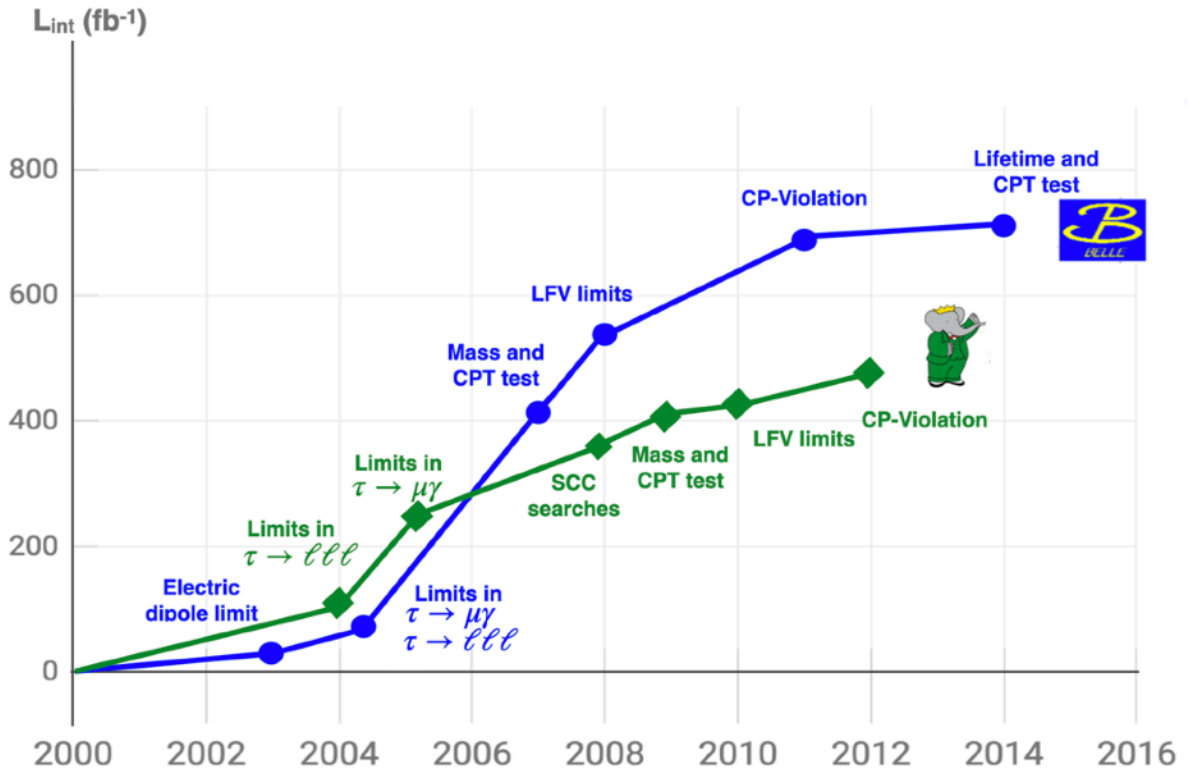


- B-Factories are also τ-factories

- **Features of a B-Factory:**
  - Well-defined initial state.
  - High vertex resolution.
  - Excellent calorimetry.
  - Sophisticated particle ID.

providing a great environment for the study of tau lepton decays.

- B-Factories of first generation provided (and keep providing!) many interesting results as the luminosity increased:



Most of these results will be updated with the Belle II data set.

Contributions during TAU 2021 by Belle II

Join us!

Tuesday 28/09

Searches for violation of Lepton Flavor Universality at Belle II — *Alberto Martini*
Virtual, Indiana University 17:35 - 17:55

First results and prospects for tau LFV decay tau -> e + alpha(invisible) at Belle II — *Alejandro De Yta Hernandez*
Virtual, Indiana University 20:20 - 20:40

Friday 01/10

Tau lifetime measurement at Belle II
tbd
Virtual, Indiana University
16:50 - 18:50

The tau mass measurement at Belle II
tbd
Virtual, Indiana University
16:50 - 18:50

Future directions on tau physics with Belle II — *Ami Rostomyan*
Virtual, Indiana University 19:50 - 20:15

Physics Prospects of Beam Polarization at Belle II — *Michael Roney*
Virtual, Indiana University 21:35 - 22:00

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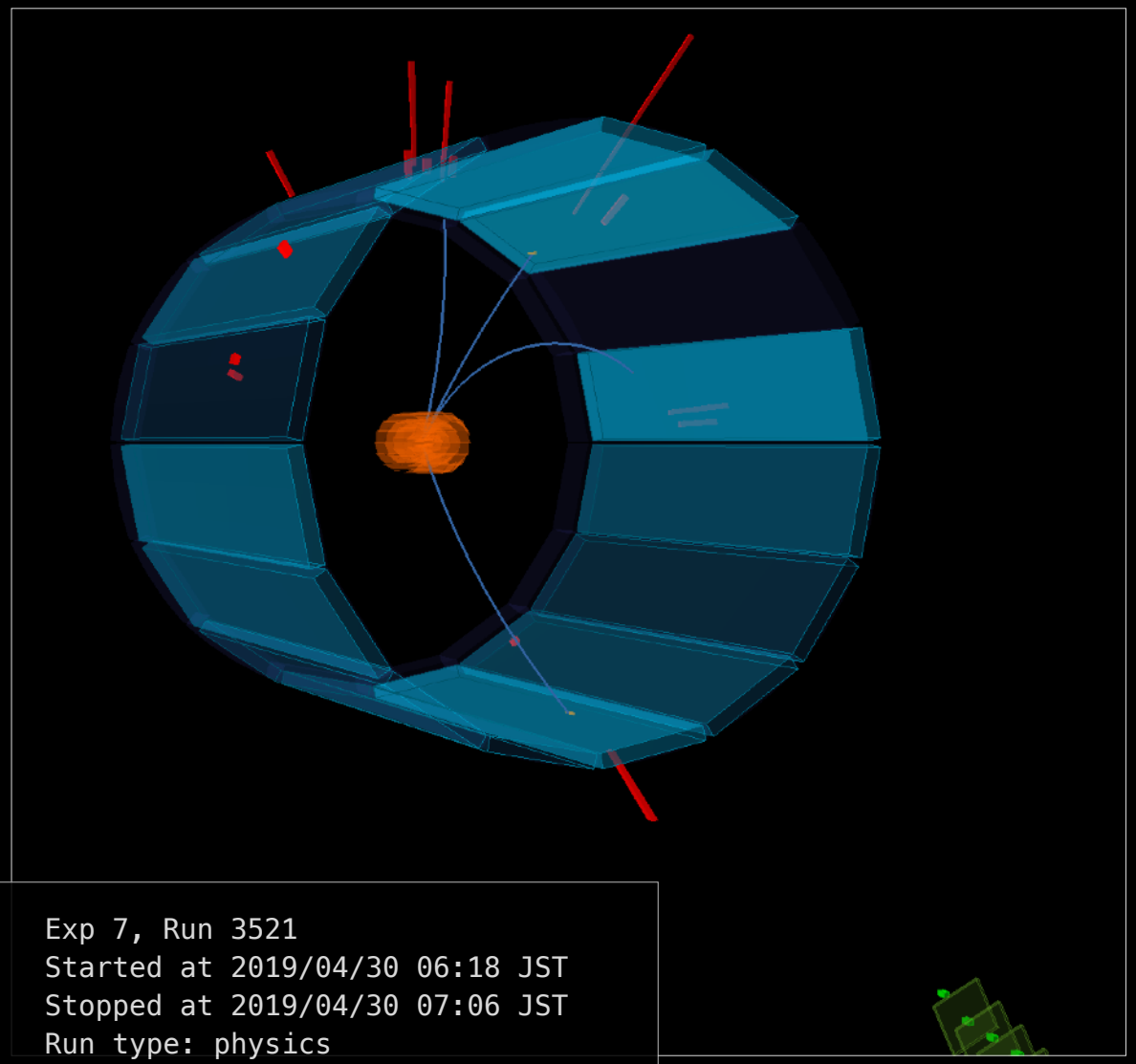
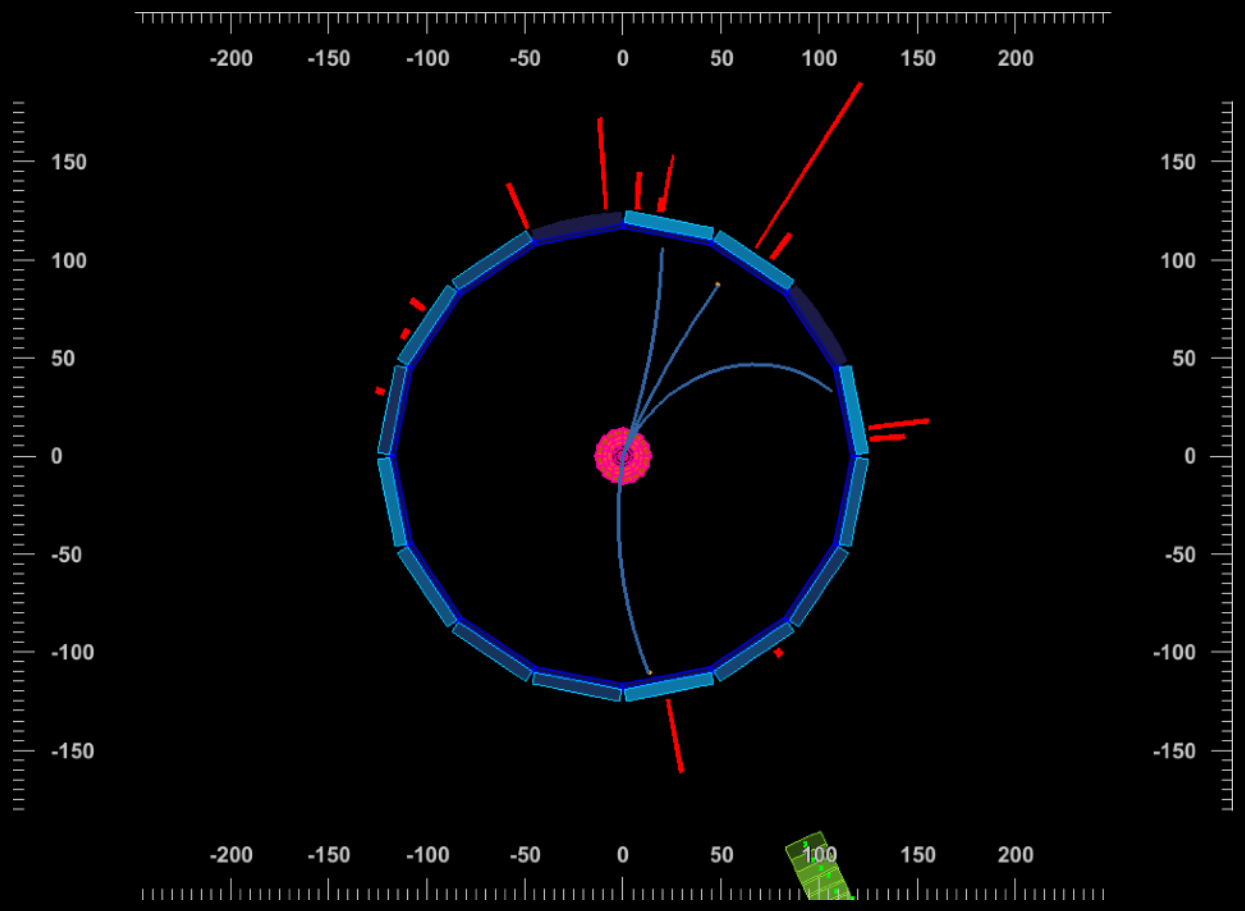
Note: Times in CET

Tau decay event in early Belle II data



Exp 7, Run 3521
Started at 2019/04/30 06:18 JST
Stopped at 2019/04/30 07:06 JST
Run type: physics



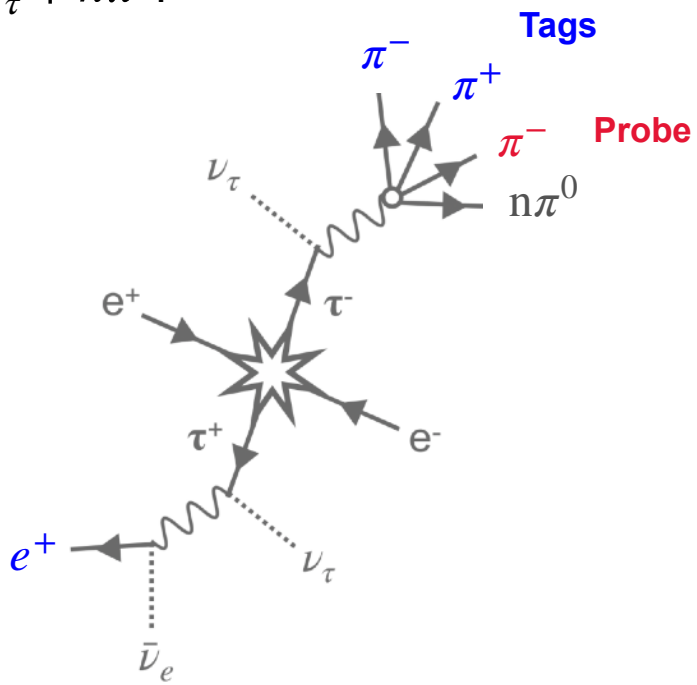
Performance

Towards precision measurements in tau lepton physics

- Tau pairs are not only tools for the comprehension of fundamental physics, but also for the understanding of our detector.

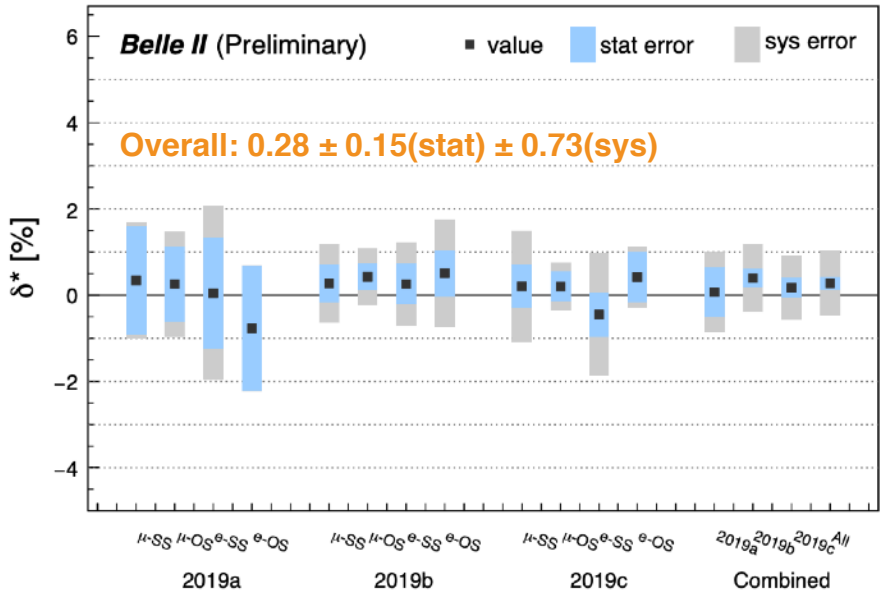
Tracking efficiency

- Tracking efficiency and fake rates have been measured using $\tau\tau$ events, with one of the leptons decaying to $\tau^- \to 3\pi^{\pm}\nu_\tau + n\pi^0$.



Calibrated discrepancy between data/MC:

$\delta^* = 1 - \epsilon_{\text{data}}/\epsilon_{\text{MC}}$



BELLE2-NOTE-PL-2020-014

Performance

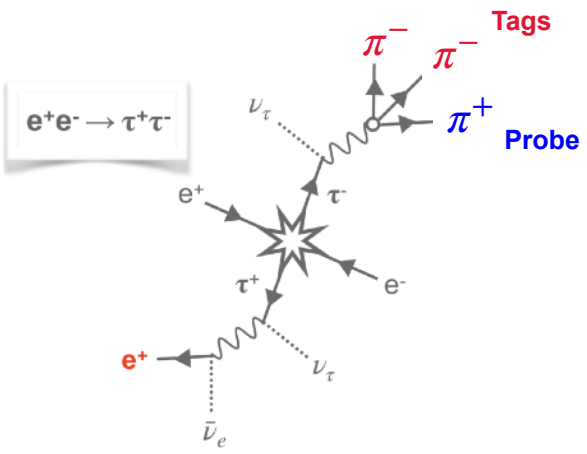
Towards precision measurements in tau lepton physics

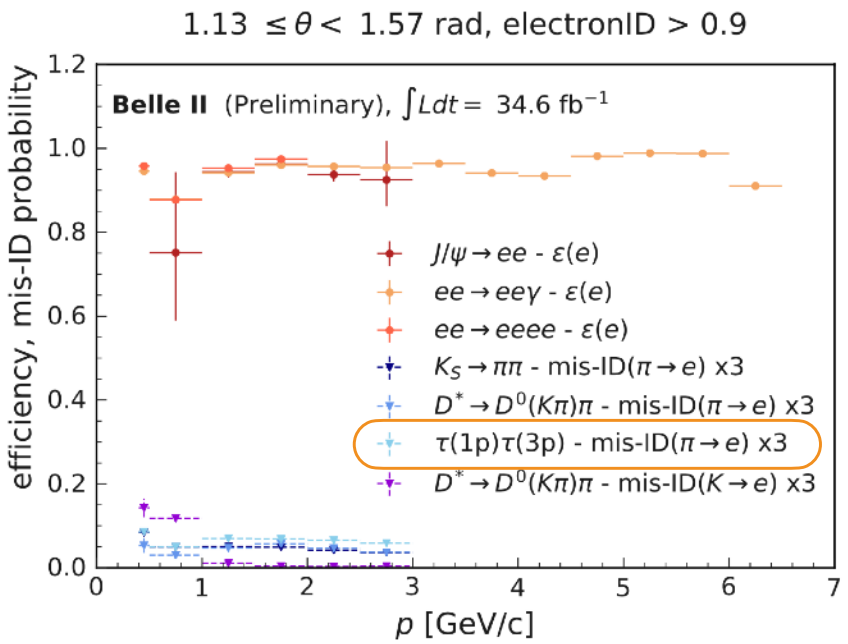
Lepton ID performance

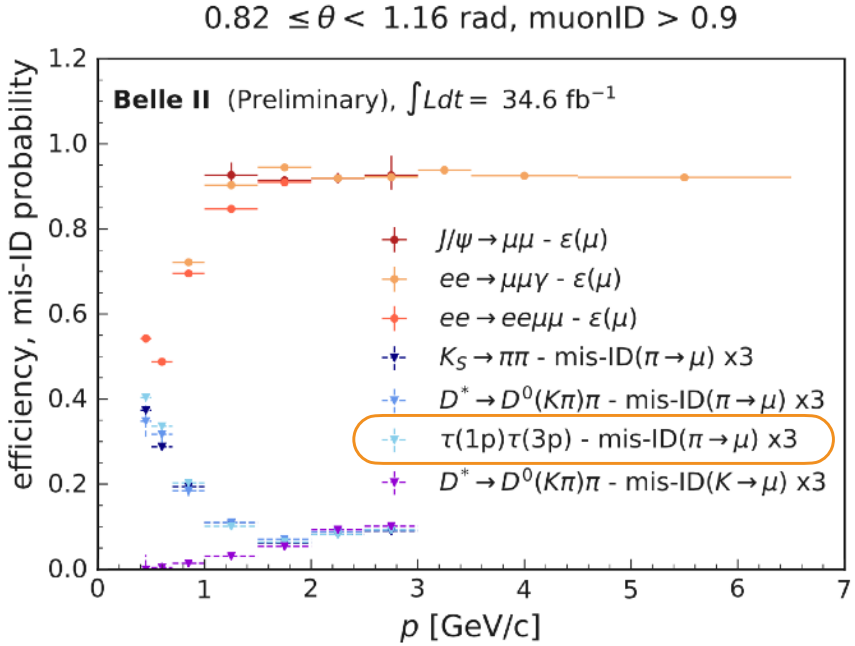
- Particle identification is based on the global likelihood ratio from all sub detectors.

$$\ell \text{ ID} = \frac{\mathcal{L}_\ell}{\mathcal{L}_e + \mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_K + \mathcal{L}_p}$$

- With the same tag-and-probe approach, lepton misidentification rates are calculated with pions from the 3-prong decay $\tau^- \to 3\pi^\pm + \nu_\tau$







BELLE2-NOTE-PL-2020-027

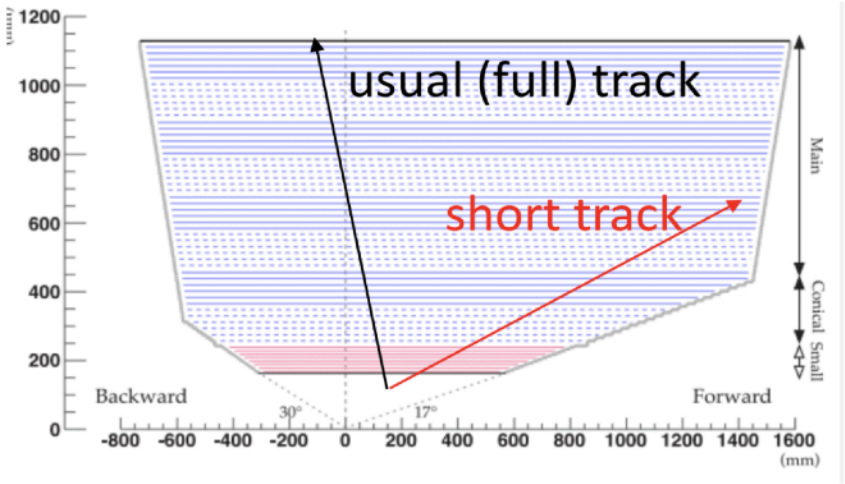
Performance

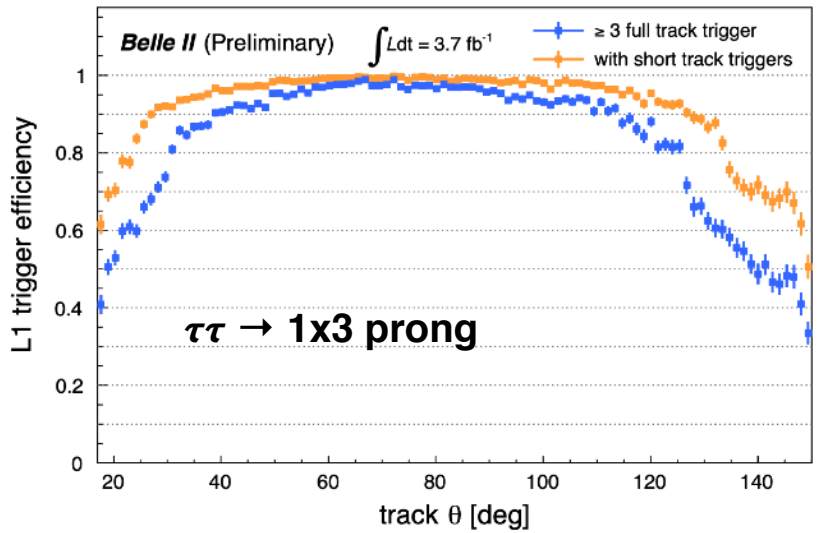
Towards precision measurements in tau lepton physics

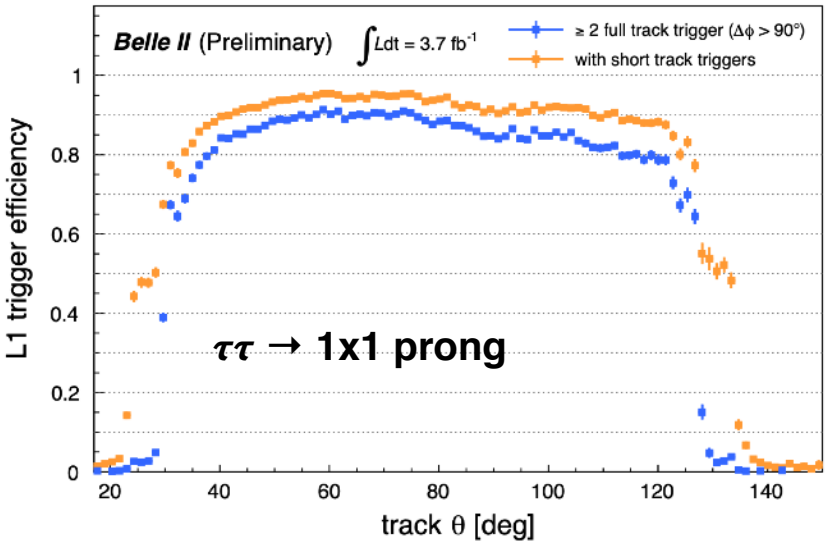
Trigger efficiencies

- The Level 1 trigger efficiency has been studied using $e^+e^- \rightarrow \tau^+\tau^-$ events with 1x1 and 3x1 topologies.
- Full track triggers present low efficiency in endcaps.
- To compensate, the CDC trigger also searches for **short tracks,** providing a significant gain in efficiency for endcaps/low p_T.
- Identification of tau events with 1x1 topologies still represents a challenge.

(More details on Tuesday by A. Martini).





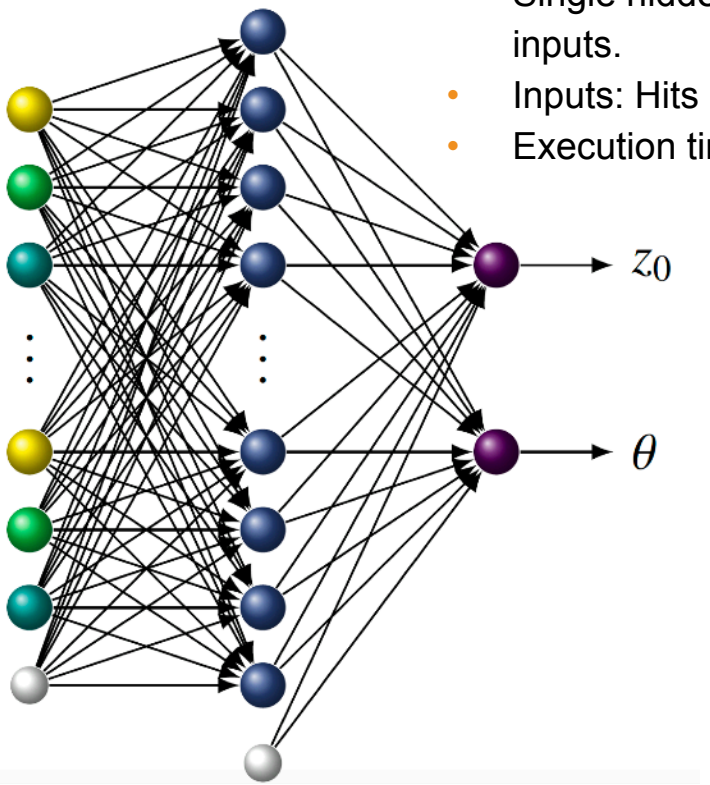


BELLE2-NOTE-PL-2020-015

Single Track Trigger

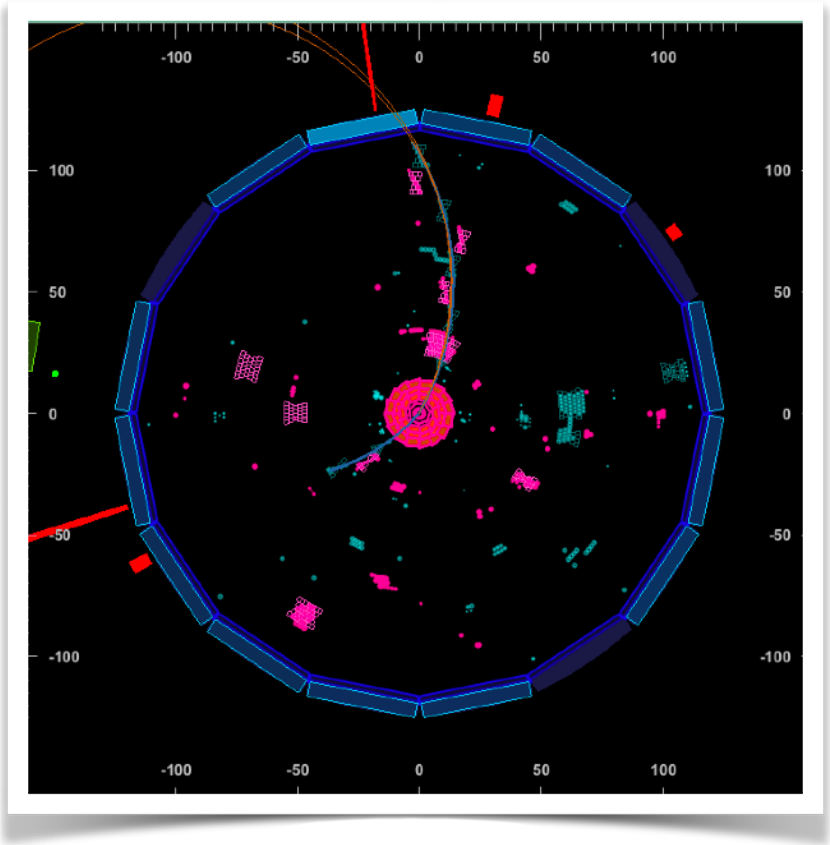
Neural-net based hardware track trigger

- A neural-ned based hardware trigger (“y trigger”) is now operational, showing great performance.
- It fires if it finds a track within 15 cm from the collision vertex and a momentum larger than 700 MeV.



- Single hidden layer with 81 neurons and 27 inputs.
- Inputs: Hits on wires of the CDC.
- Execution time: 300 ns

First results coming, with promising results.



Measurement of tau properties at Belle II

Mass, lifetime, leptonic decays

- Lepton Flavor Universality test:
  - $$B_{\tau\ell} \propto B_{\mu e} \frac{\tau_\tau}{\tau_\mu} \frac{m_\tau^5}{m_\mu^5}$$
- Inputs from tau decays:
  - Tau mass m_τ
  - Tau lifetime τ_τ
  - Leptonic BR $B_{\tau\ell}$
- Belle II has the potential of provide precise measurements of these parameters.
- "Wait, did you just say LFU?"
  Join us on Tuesday!

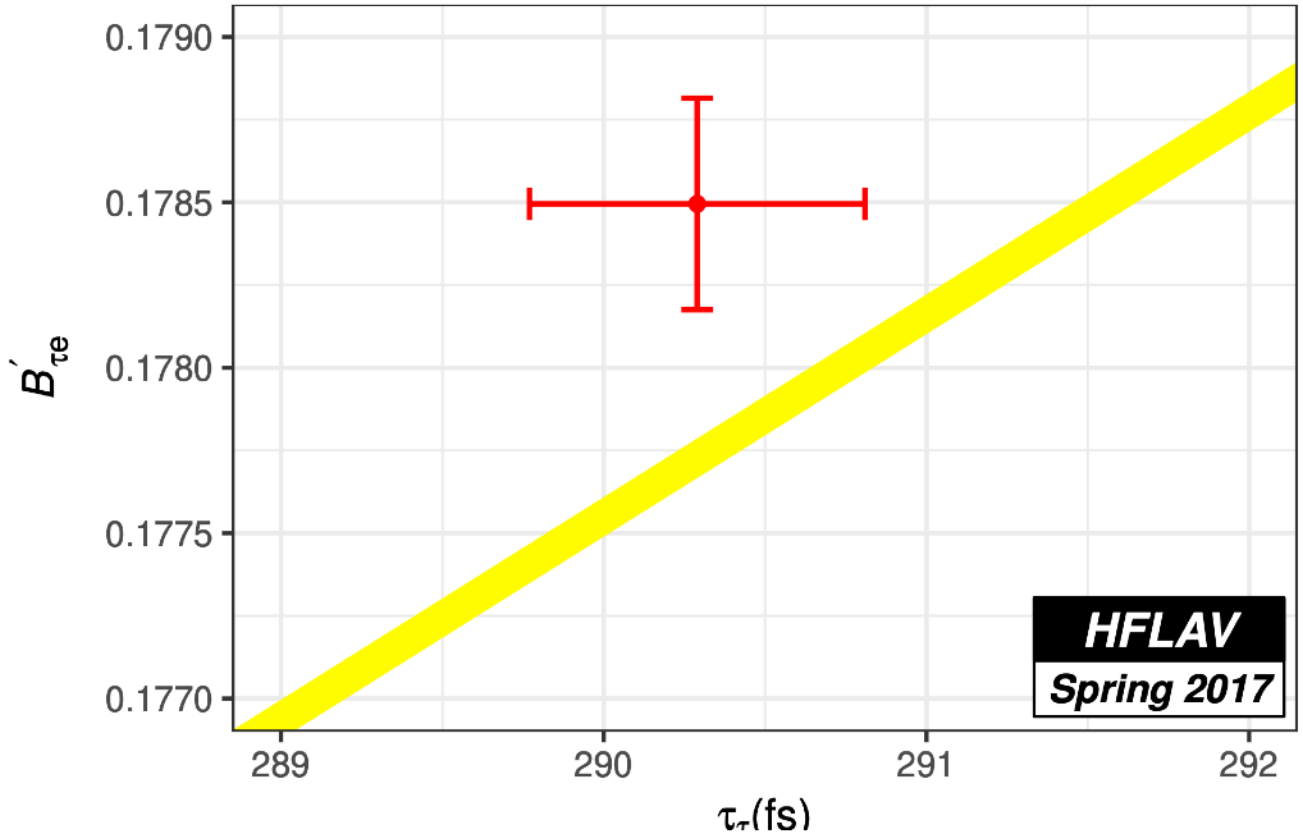


Figure: EPJ Web Conf., 218 (2019) 05002

Searches for violation of Lepton Flavor Universality at Belle II	*Alberto Martini*
Virtual, Indiana University	17:35 - 17:55

Tau Lepton Mass Measurement

Historical overview

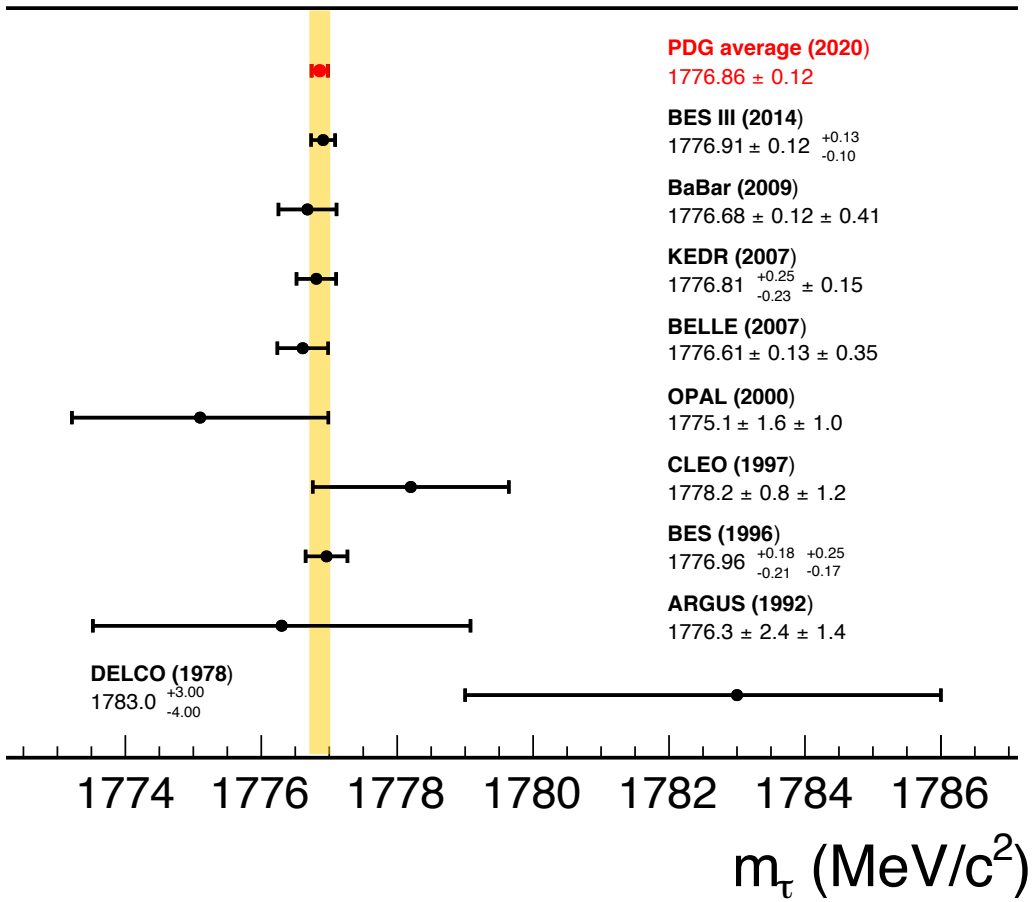
- The lepton masses are fundamental parameters of the SM:

$$m_e = (0.5109989461 \pm 0.0000000031)\ \text{MeV},$$
$$m_\mu = (105.6583745 \pm 0.0000024)\ \text{MeV},$$
$$m_\tau = (1776.86 \pm 0.12)\ \text{MeV}.$$

- Precision of m_τ have consequences in LFU tests.

- Two methods for measuring m_τ:
  - Measurement in the production threshold (DELCO, BES, KEDR, **BES III**).
  - Pseudomass distribution (ARGUS, OPAL, BaBar, **Belle**).

- The latter will be exploited in Belle II.



Tau Lepton Mass Measurement

Pseudomass distribution

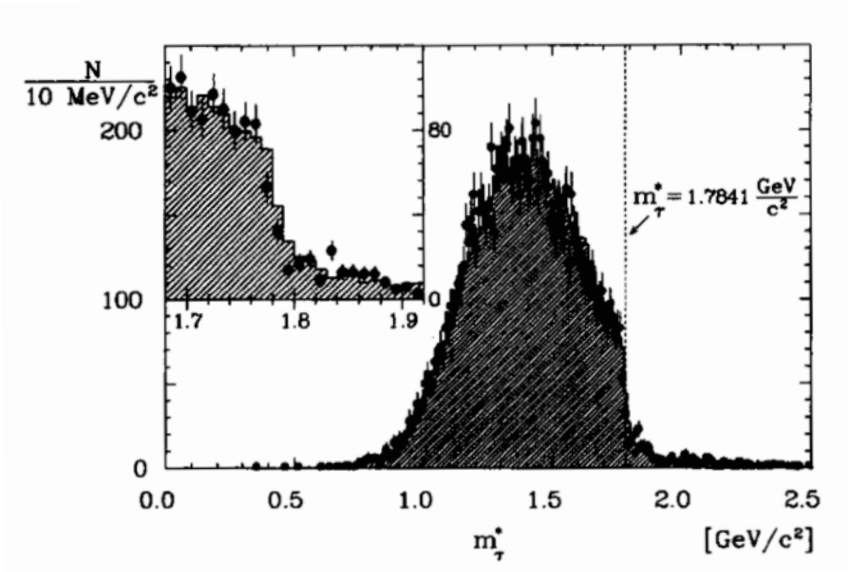
- Measured in the decay mode $\tau \rightarrow 3\pi\nu$, using a pseudomass technique developed by the **ARGUS** collaboration.
- The tau mass can be calculated as

$$m_\tau^2 = (p_h + p_\nu)^2$$
$$= 2E_h(E_\tau - E_h) + m_h^2 - 2|\vec{p}_h|(E_\tau - E_h)\ \cos(\vec{p}_h, \vec{p}_\nu)$$

- As the direction of the neutrino is not known, the approximation $\cos(\vec{p}_\nu, \vec{p}_h) = 1$ is taken, resulting in

$$M_{\min}^2 = 2E_h(E_\tau - E_h) + m_h^2 - 2|\vec{p}_h|(E_\tau - E_h) < m_\tau^2$$

- Then, the distribution of the pseudomass is fitted to an empirical edge function, and the position of the cutoff indicates the value of the mass.



Phys. Lett. B 292 (1992) 221-228

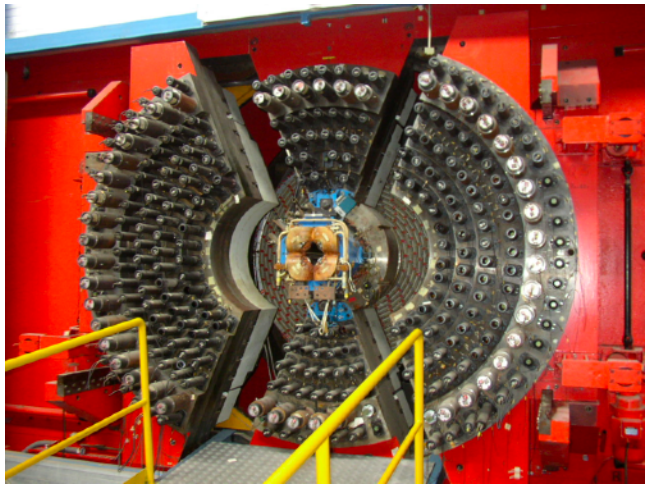


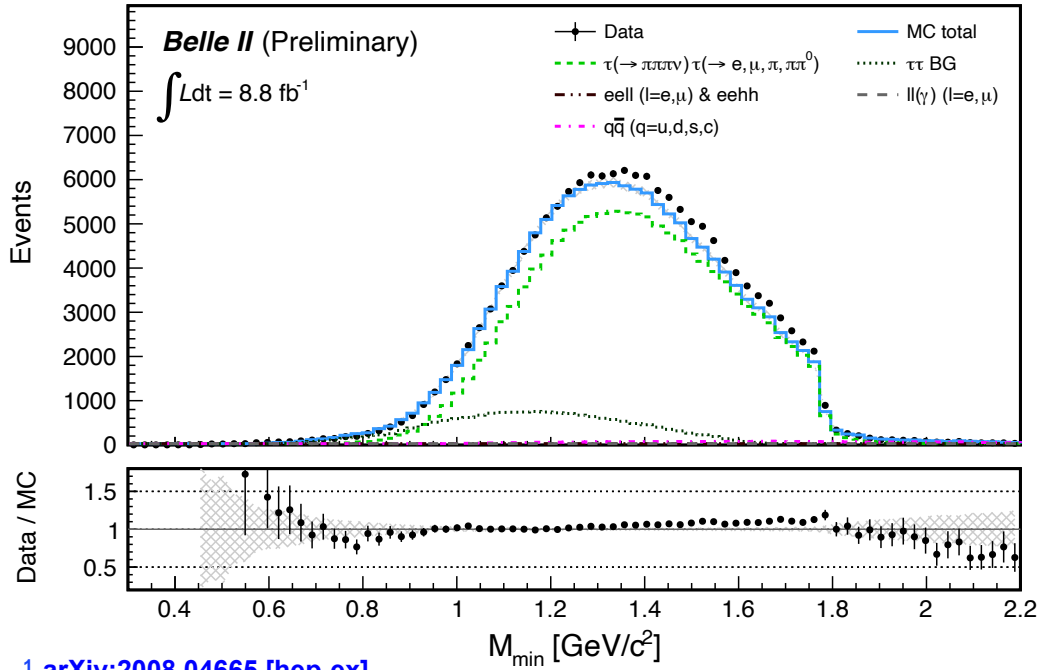
Figure: The ARGUS detector at DESY

Tau Lepton Mass Measurement

Performance test @ 8.76 fb^{-1}

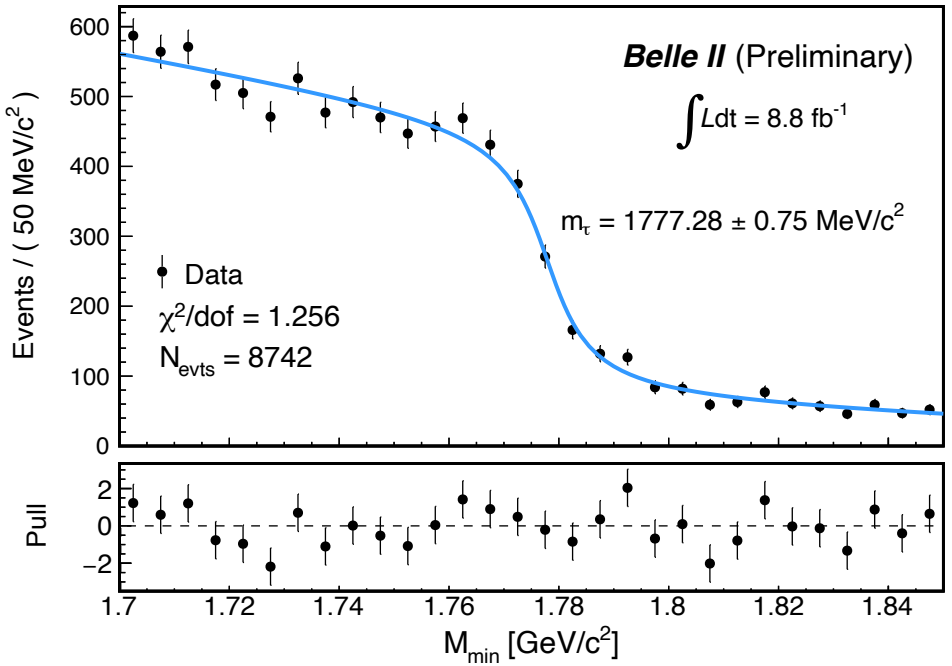
- Our latest result[1] (8.76 fb^{-1}, ICHEP 2020): **1777.28 ± 0.75 ± 0.33 MeV/c².**
- Main systematic sources:
  - Momentum shift due to imperfections on the B-Field map: 0.29 MeV/c².
  - Bias of the mτ estimator: 0.12 MeV/c².

Pseudomass distribution, data vs MC



Fit to edge p.d.f. in the cutoff region

$$F(M_{\min}, \vec{P}) = (P_3 + P_4 M_{\min}) \cdot \tan^{-1}[(M_{\min} - P_1)/P_2] + P_5 M_{\min} + 1$$

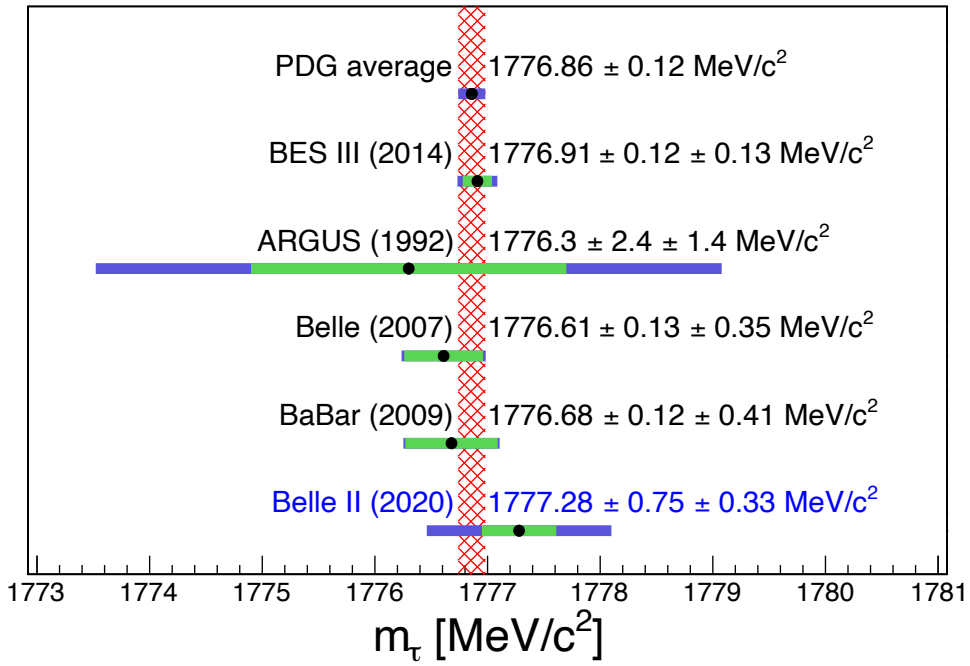


[1] arXiv:2008.04665 [hep-ex]

Tau Mass Measurement at Belle II

Projection towards high luminosity

- Our result is still dominated by statistical uncertainty, and consistent with previous measurements:



Blue: statistical; **Green: systematic**

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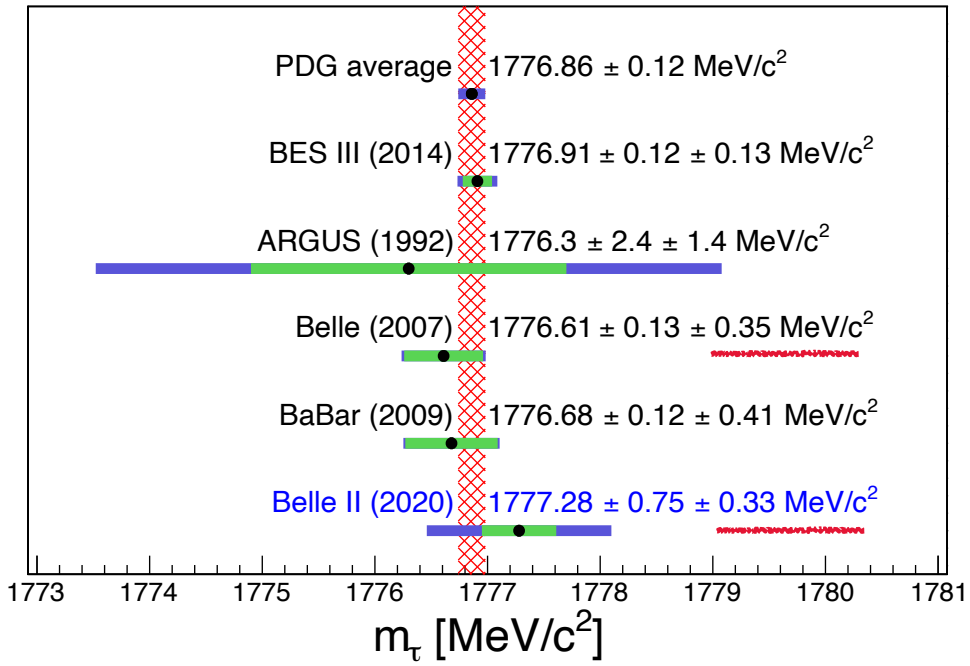

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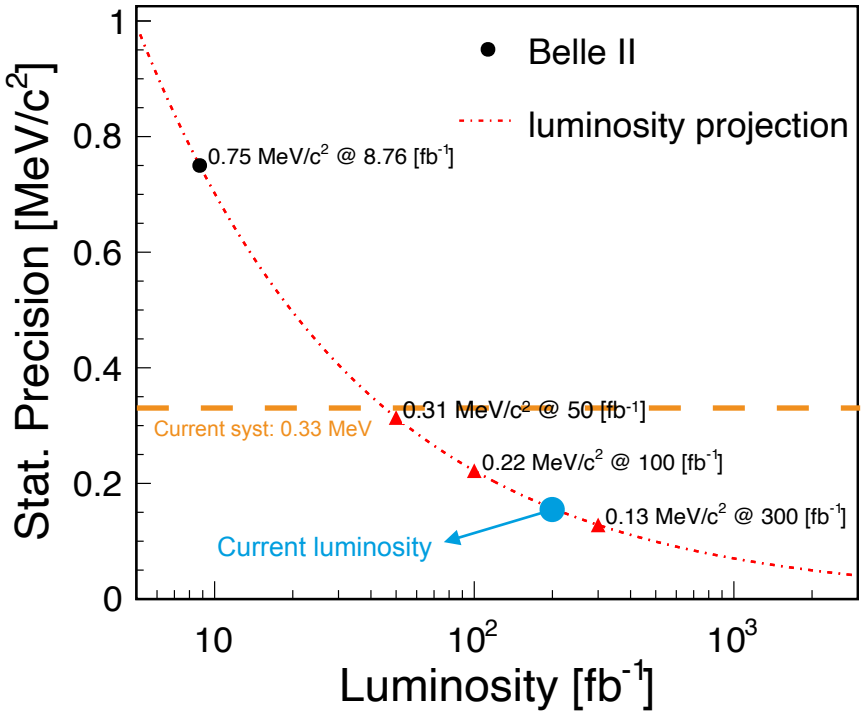
- We expect significant reduction in the main systematic uncertainties.

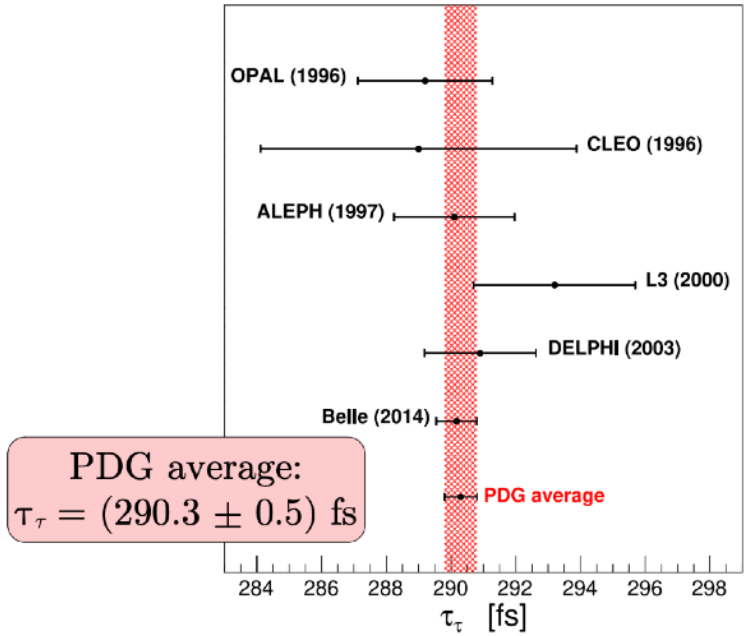


"Can wait to see more details!"
Join us on Friday!

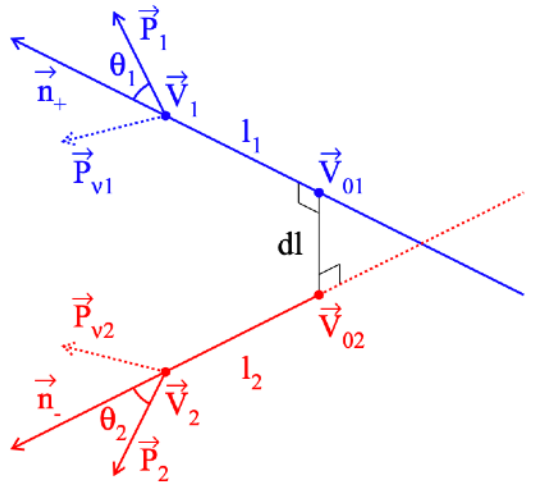
Tau Lifetime Measurement

Exploiting the nano-beam scheme

- Important SM parameter. Its precision has implications in LFU, $\alpha_s(m_\tau)$, etc.
- Previous measurements:
  - Z-peak: LEP (DELPHI, L3, ALEPH, OPAL).
  - Y-peak: CLEO, BaBar, **Belle** [1].



- The world-leading measurement by Belle[1] uses a **3x3 topology**, with both tau leptons decaying to $3\pi\nu_\tau$.
  - **τ_τ = 290.17 ± 0.53(stat) ± 0.33(syst) fs**



[1] PRL 112, 031801 (2014), arXiv:1310.8503 [hep-ex]

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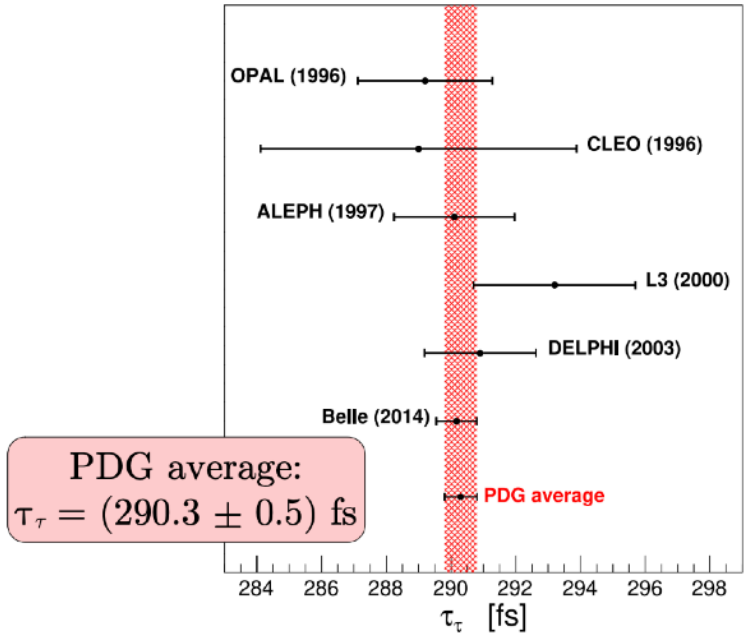

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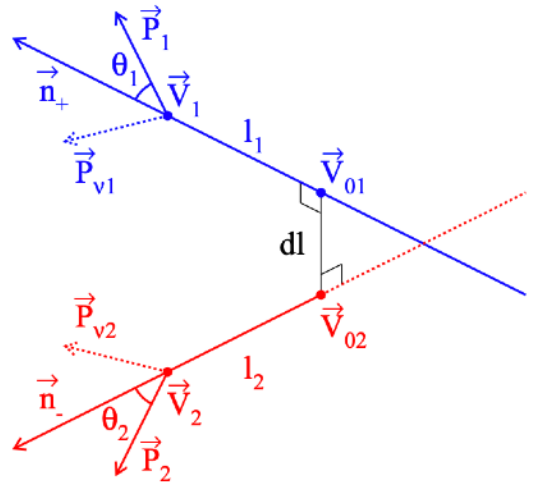
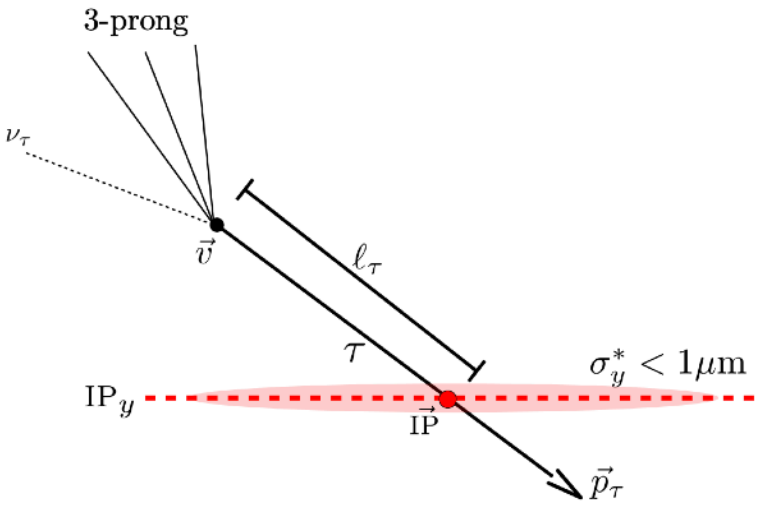


- **Strategy at Belle II:**
  1. Reconstruct vertex for 3-prong τ.
     Only one 3-prong = higher statistics.
  2. Estimate the τ momentum $\vec{p}_\tau$.
     Hadronic decays in both sides.
  3. Find the production vertex.
     Intersection of $\vec{p}_\tau$ with the plane IP_y.



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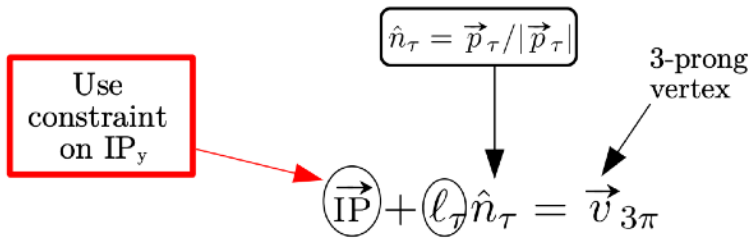
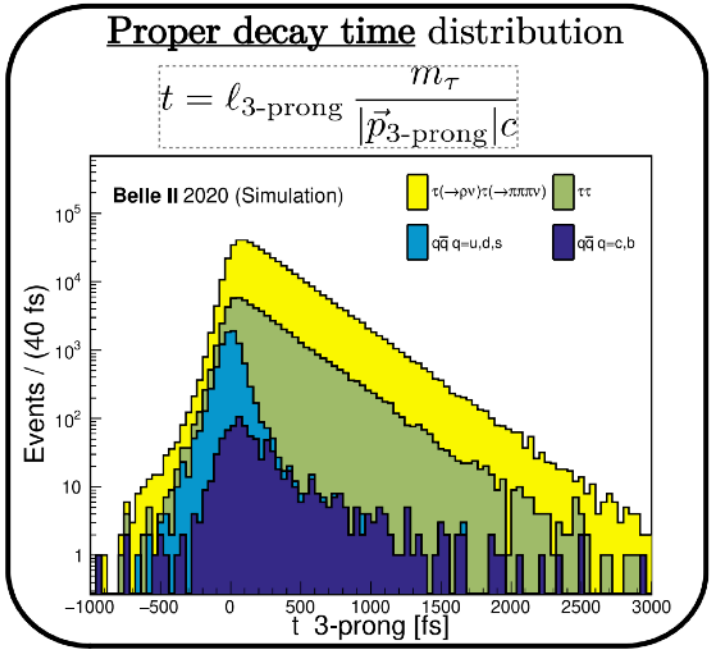
Tau Lifetime Measurement

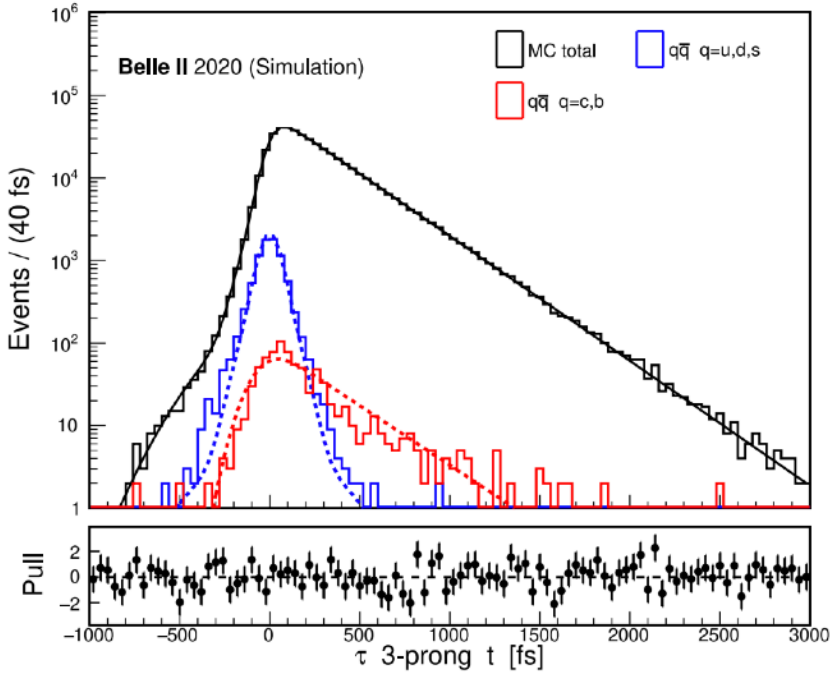
Sensitivity at 200 fb^{-1}

- ℓ_τ reconstruction and IP constrain:





- Lifetime extraction:
  - **τ_τ = 287.2 ± 0.5 (stat) fs**
  - Same statistical uncertainty of Belle. (200 fb^{-1} vs 711 fb^{-1})



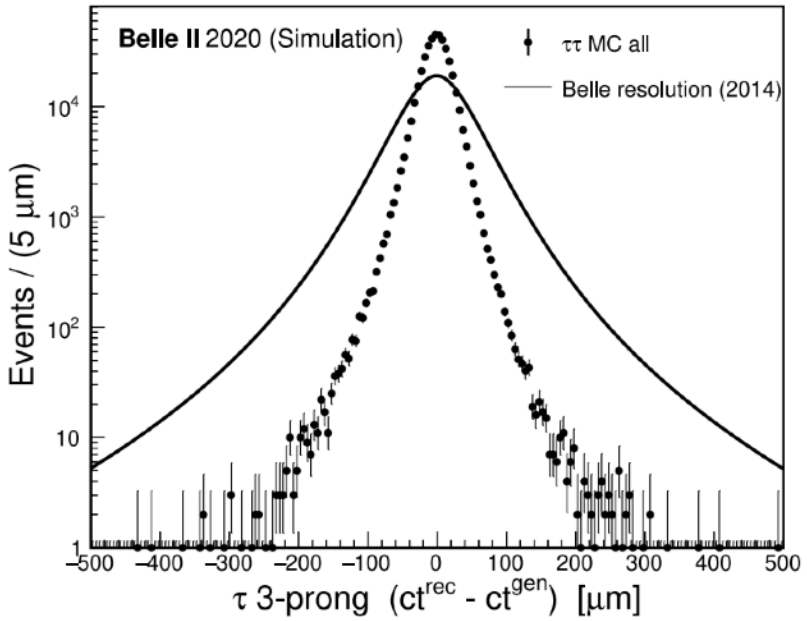
- τ_τ presents ≃ 3 fs bias. (Generated lifetime: 290.57 fs)
  - ISR/FSR losses = underestimation of the proper time.
  - And intrinsic bias in the measurement.
- Further studies to estimate systematics:
  - Test dependence from resolution function in the fit
  - Beam-spot position
  - ISR/FSR simulation
  - Vertex detector alignment (dominant at Belle and Babar)

Tau Lifetime Measurement

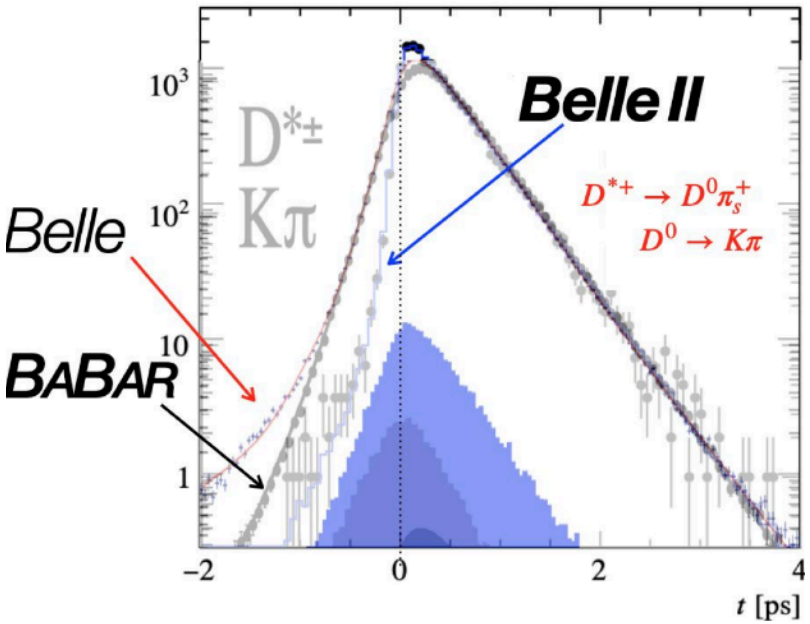
Detector performance

- In MC simulations, the Belle II proper time resolution is **~2x better than Belle.**
  - Due to PXD and smaller beam pipe diameter.

Proper decay time resolution:



- For comparison, the D meson lifetime measurement by Belle II was recently published[1].
  - Improvement in resolution is confirmed



$$\tau(D^0) = 410.5 \pm 1.1(\text{stat}) \pm 0.8(\text{syst}) \text{ fs}$$

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

[1] arXiv:2108.03216 [hep-ex] (submitted to PRL)

- "Awesome! How to know more?"
  Join us on Friday!

Summary

- In 2021, SuperKEKB has set a new record in peak luminosity at L_{peak} = 3.1x10^{34} cm^{-2} s^{-1}.
- To the date, 213 fb^{-1} of collision data have been recorded by Belle II. By summer, we expect to collect of the order of ~ BaBar data set.
- Since its discovery, the tau lepton has been studied at new every e^+e^- collider into operation, improving the measurements with every upgrade.
  - In Belle II we are very motivated, and ready to reach new limits in the precision.
- **Tau mass studies** with the early data show potential for an update in the measurement of m_τ using the pseudomass technique.
- The **lifetime measurements** at Belle II show the potential of the nano-beam scheme with an upgraded vertex detection system. First studies of τ_τ very promising, with an update in the measurement feasible in the coming months.

Thank you

Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

Michel Hernandez Villanueva
michel.hernandez.villanueva@desy.de
Orcid: 0000-0002-6322-5587