Update from Belle II

Petar Rados
on behalf of the DESY Belle II group

90th PRC Meeting Open Session

5/11/2020

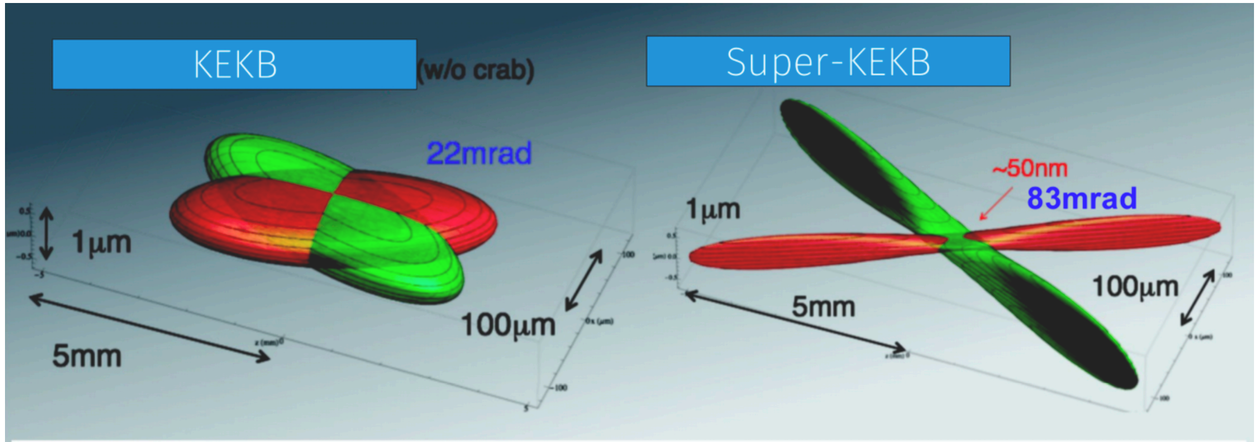
DESY.

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

Belle II

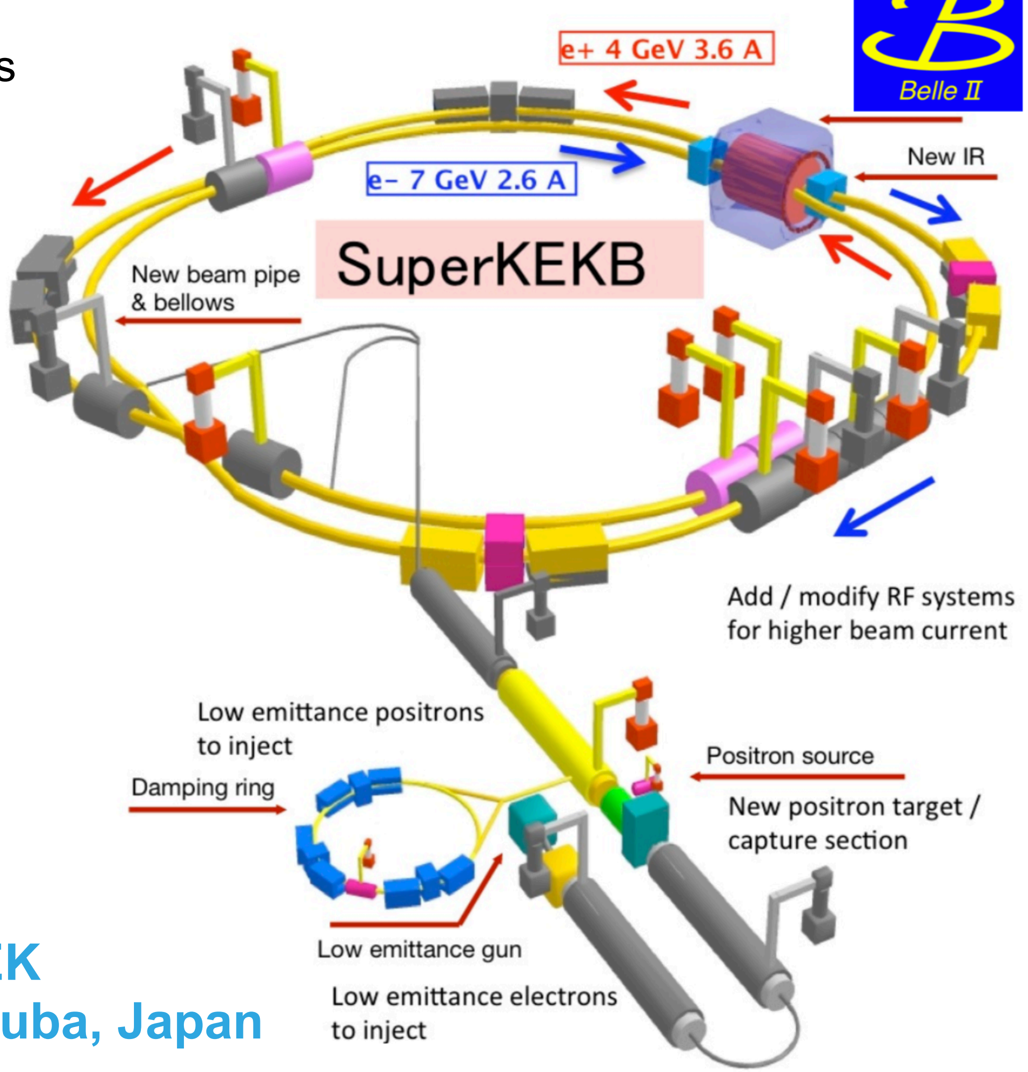
SuperKEKB Accelerator

- Next generation B-factory: $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$, $\sqrt{s} \approx 10.58$ GeV
  + rich program of dark sector, tau and other low-multiplicity physics



	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

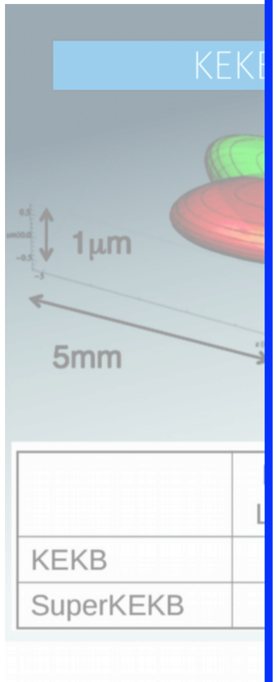
factor 20 factor 2-3

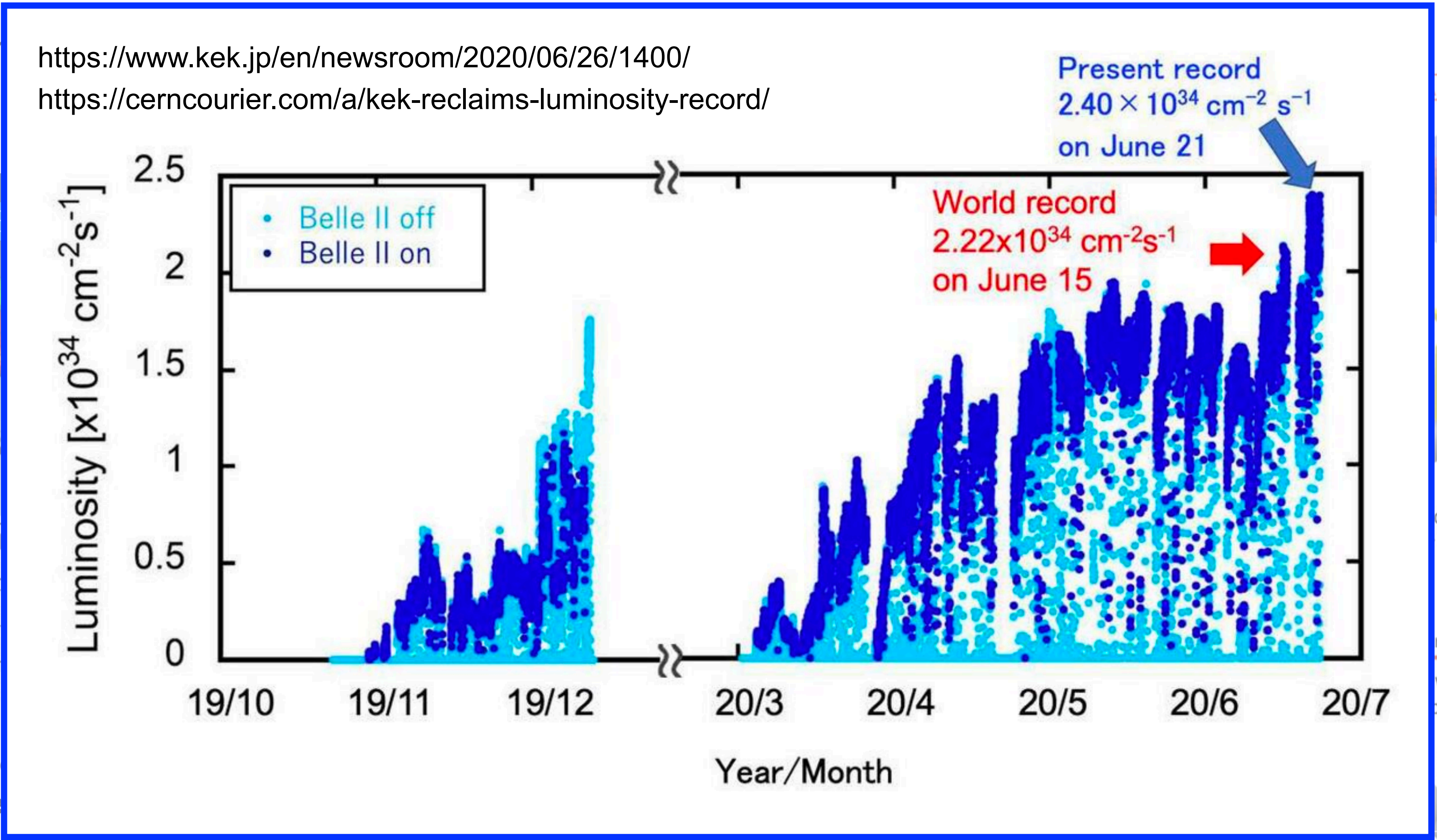


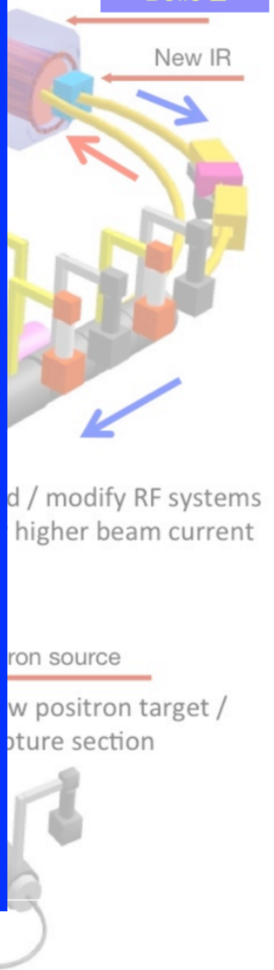
- Unprecedented target luminosity of ~6×10^{35} $cm^{-2}s^{-1}$ (↓25% due to relaxed beam currents goals)
- Broke the world lumi record earlier this year

@KEK
Tsukuba, Japan

- Next gener
  + rich prog





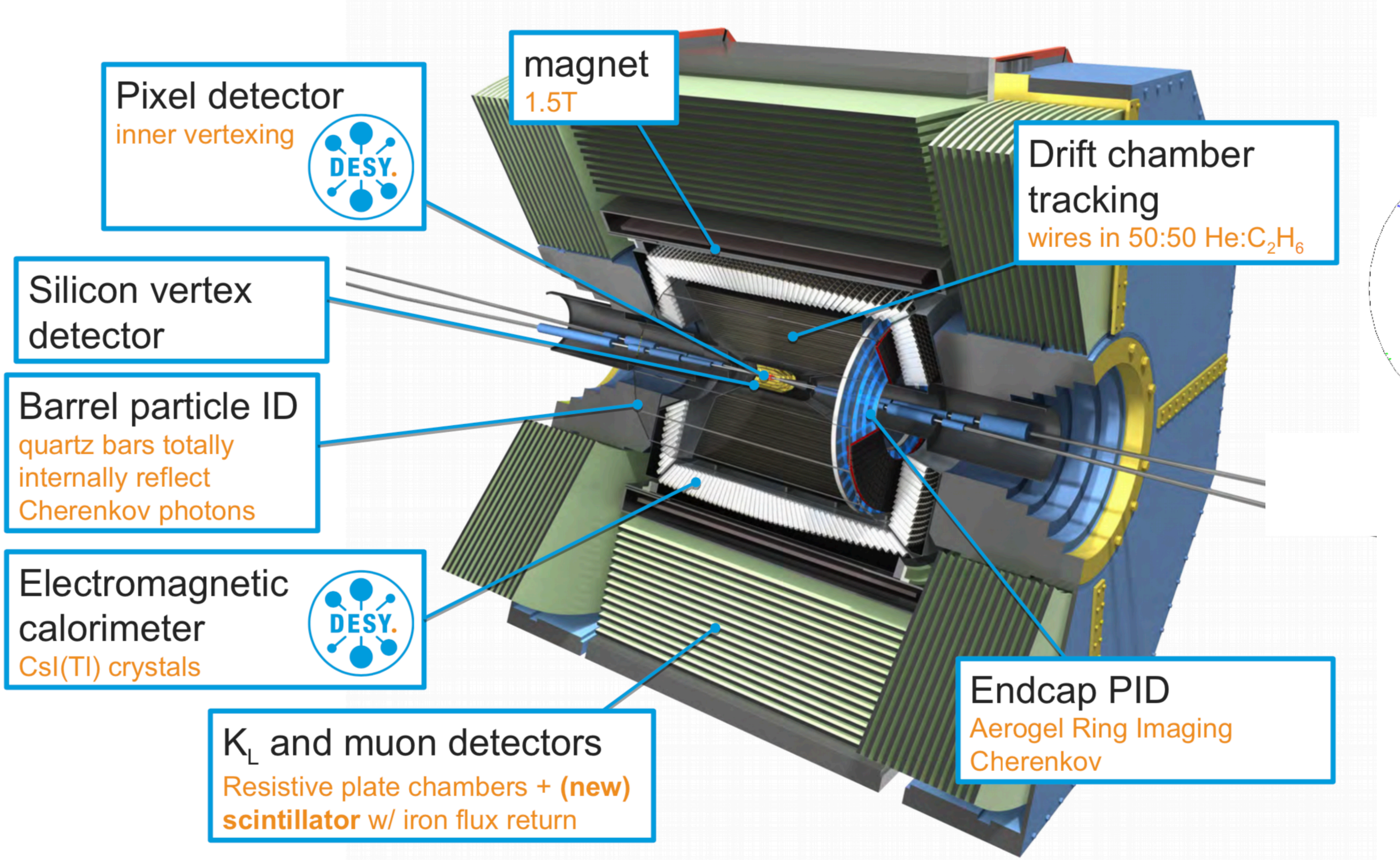


- Unpreced
  (↓25% due

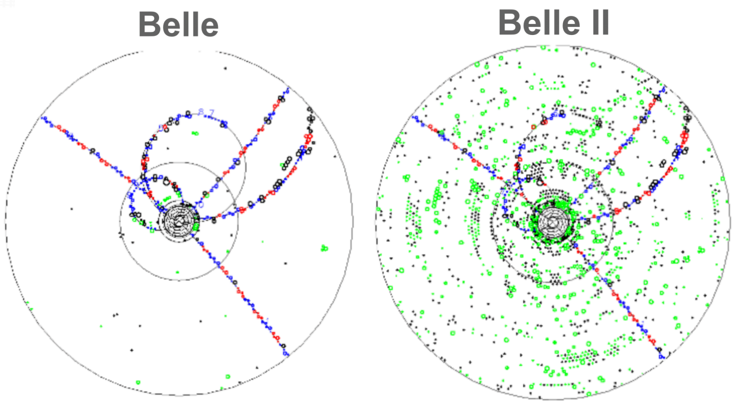
Tsukuba, Japan

- **Broke the world lumi record earlier this year**

Belle II Detector



- Increased beam backgrounds

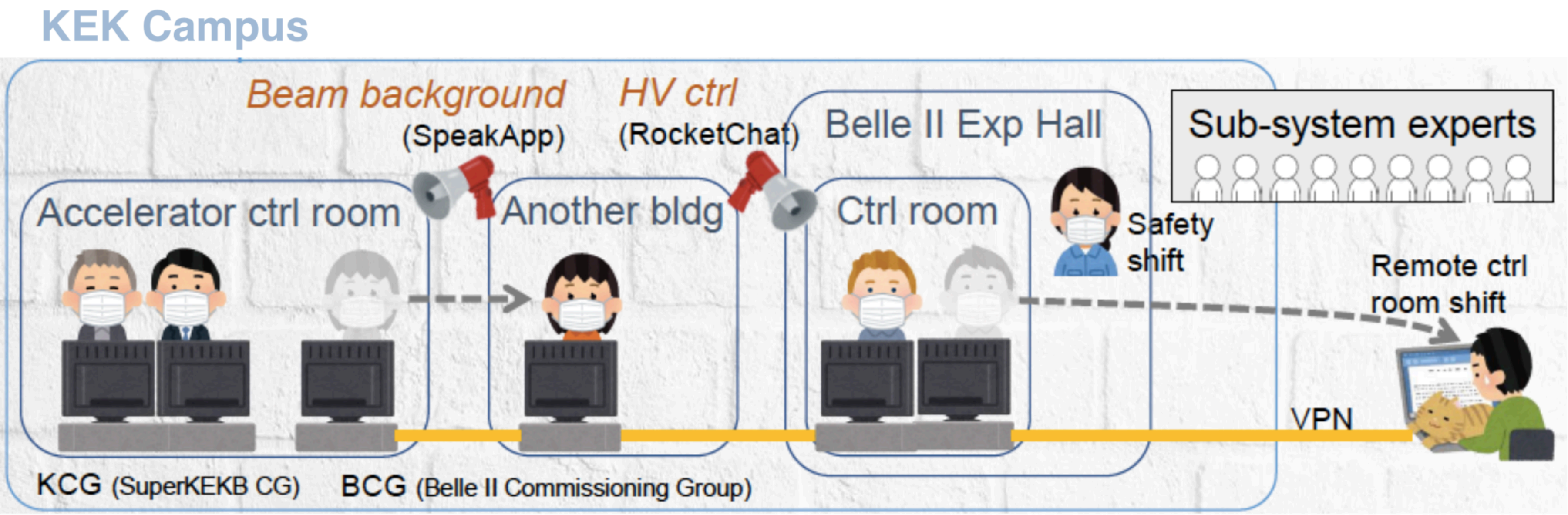


⇒ upgraded trigger system and sub-detectors

- Rolled in: April 2017
- First collision in April 2018

Belle II Operations in 2020

- SuperKEKB/Belle II has been operating during the COVID-19 pandemic with protocols in place to maximize safety and minimize the risk of infection
    - minimize person-to-person contact
    - remote control room shifts and expert shifts
    - online meetings
- Travel restrictions resulted in very heavy load on local crew at KEK (~40 people)
    - in upcoming runs try to relieve local CR shifters by having 2 remote CR shifters



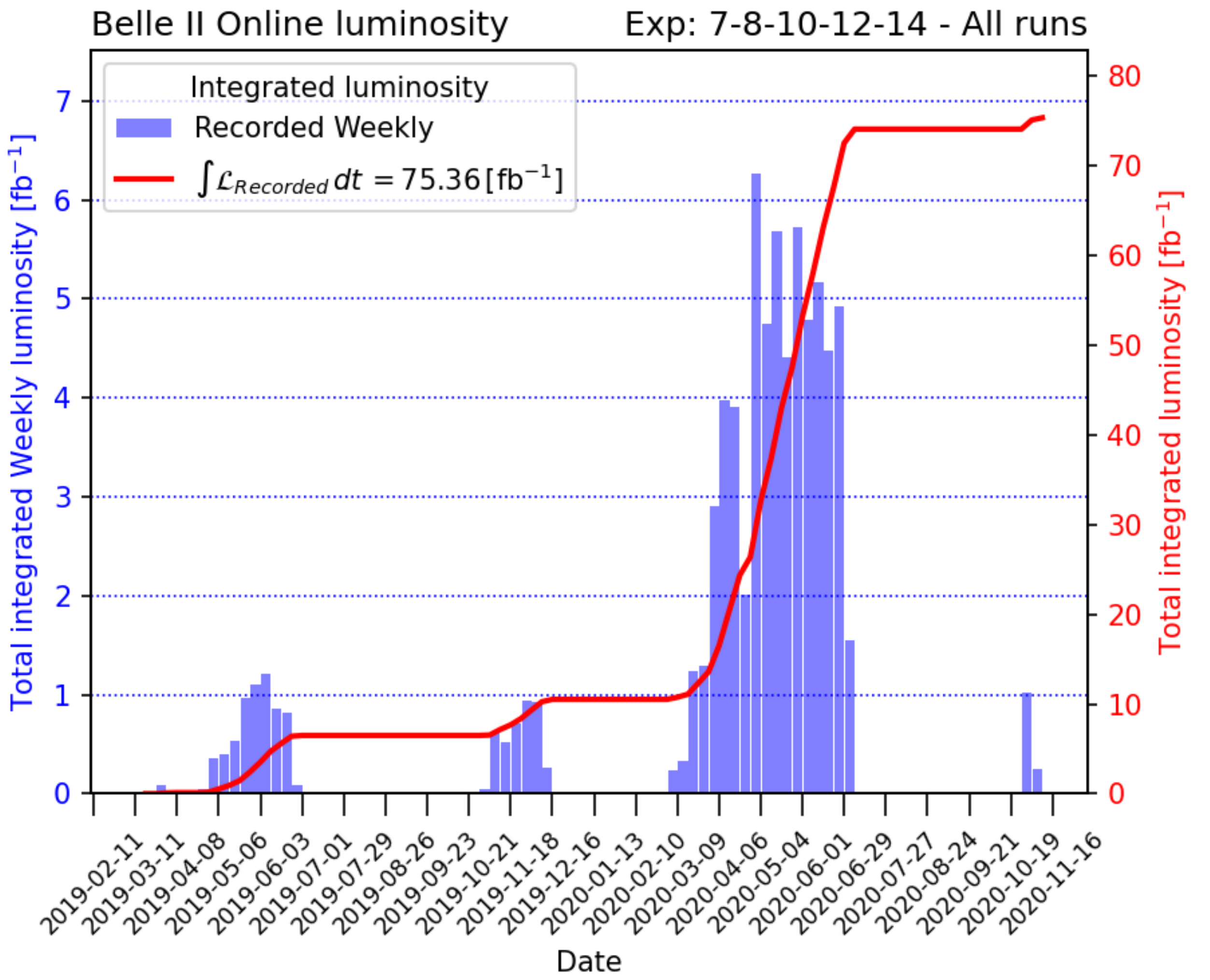
Luminosity status

- Despite challenges brought about by COVID-19, data-taking continues:
  - **74 fb^{-1}** total (8fb^{-1} off-resonance) from March 2019 to July 2020
  - started again in October 2020

- Cumulative data taking efficiency:
  - March-July 2020: 84%
  - since Oct 2020: 90%

- Aiming for **50 ab^{-1}** over the next ~10 years (50 x Belle dataset).

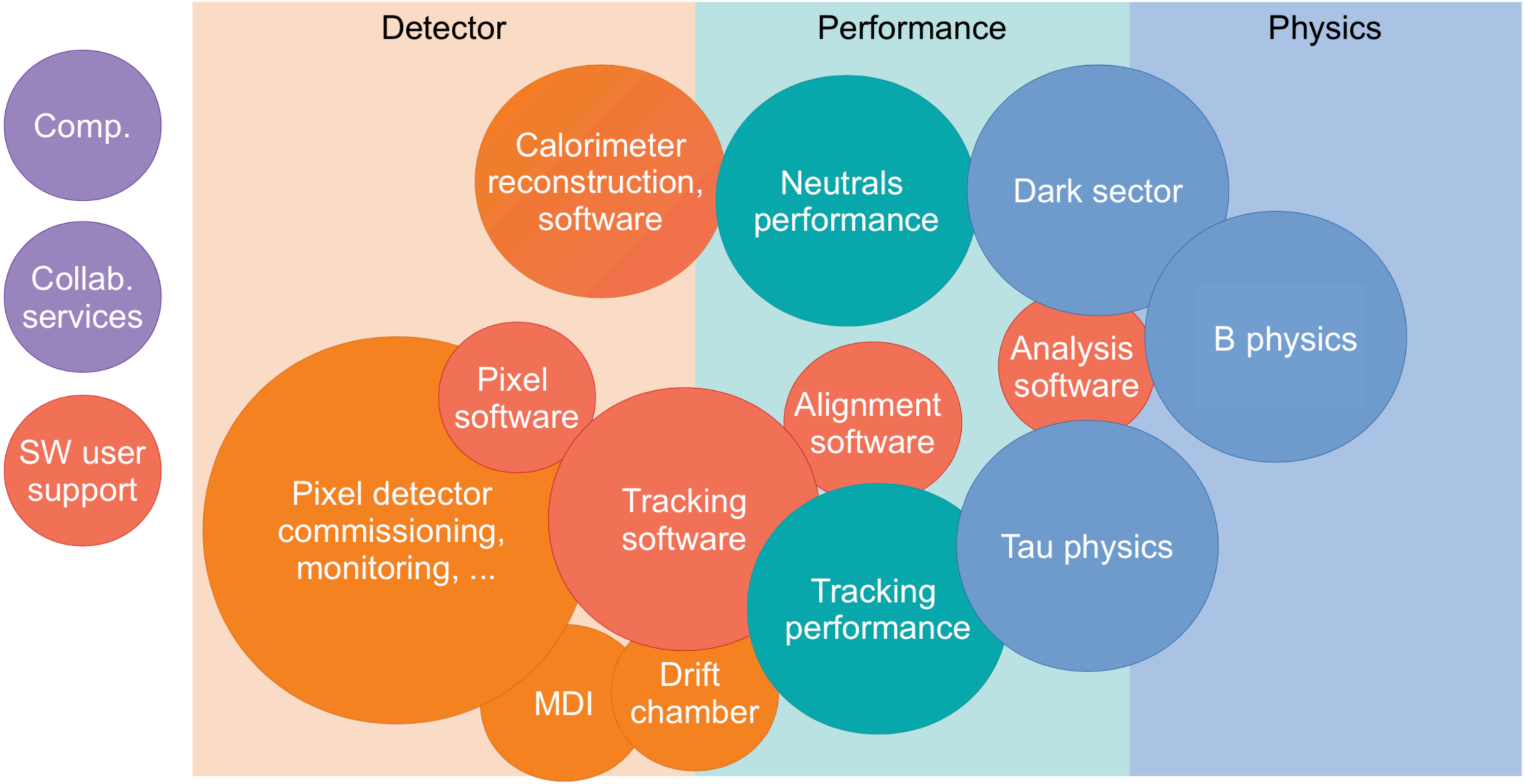
⇒ long way to go: machine performance and background



https://confluence.desy.de/display/BI/Belle+II+Luminosity

DESY group activities

taken from S. Cunliffe



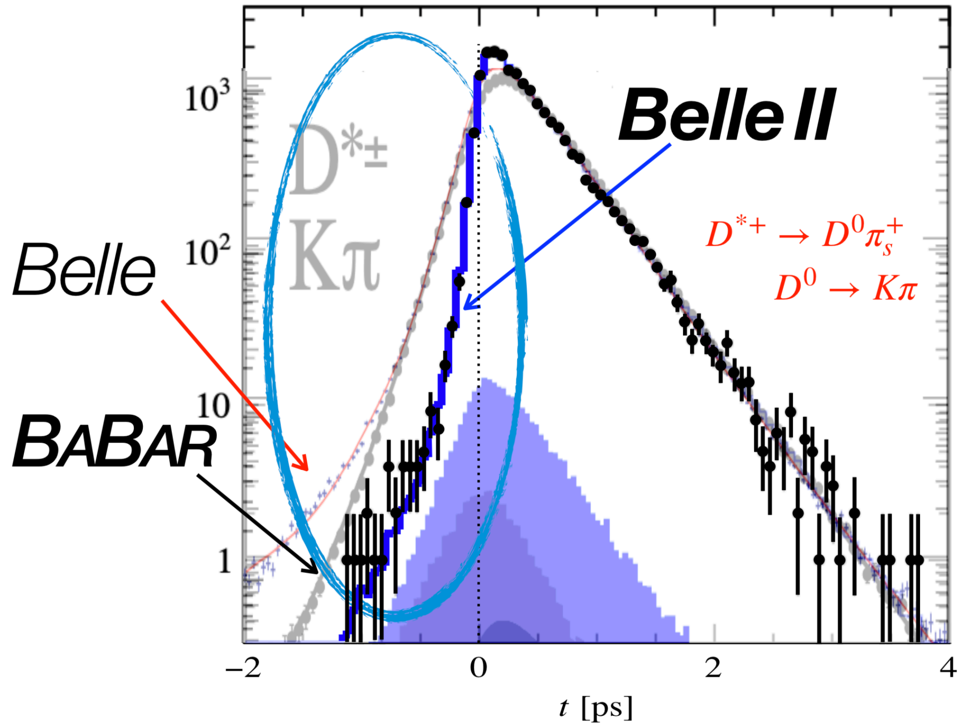
Pixel Detector

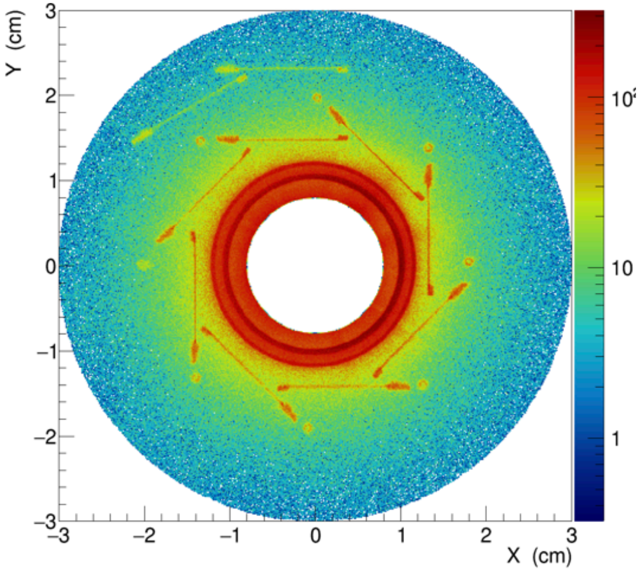
Pixel detector

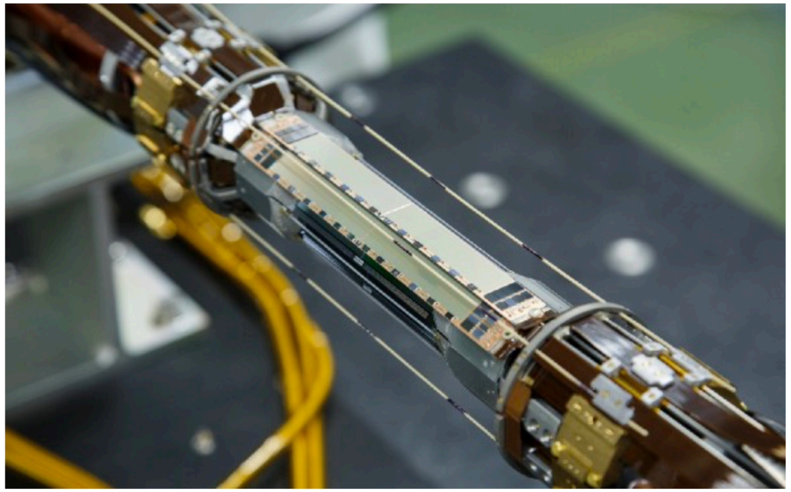
- Pixel detector (PXD):
  - 2 layers: 8 (inner) + 12 (outer) ladders
  - DEPFET sensor modules (2 per ladder)

- Full inner layer + partial outer layer installed end of 2018

BELLE2-NOTE-PL-2020-008





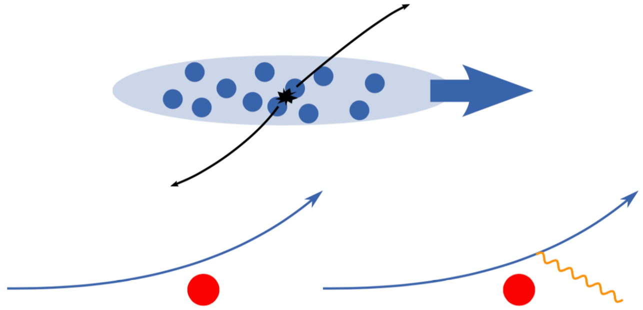


- PXD is stably running
  - hit ε > 99% (excluding inefficient rows from beam loss incidents)
  - SNR 40-50, σ(d_0) ~ 14 μm (BELLE2-NOTE-PL-2019-011)

- Operational challenges
  - radiation damage from beam loss incidents (~2.5% of full PXD)
    ⇒ emergency protection scheme now greatly improved
  - several modules reached power supply limit
    ⇒ limit increased (>2mA) during summer shutdown

PXD backgrounds

- **Single-beam backgrounds**
  - Touschek scattering
  - beam-gas scattering
  - Synchrotron radiation
  - injection background

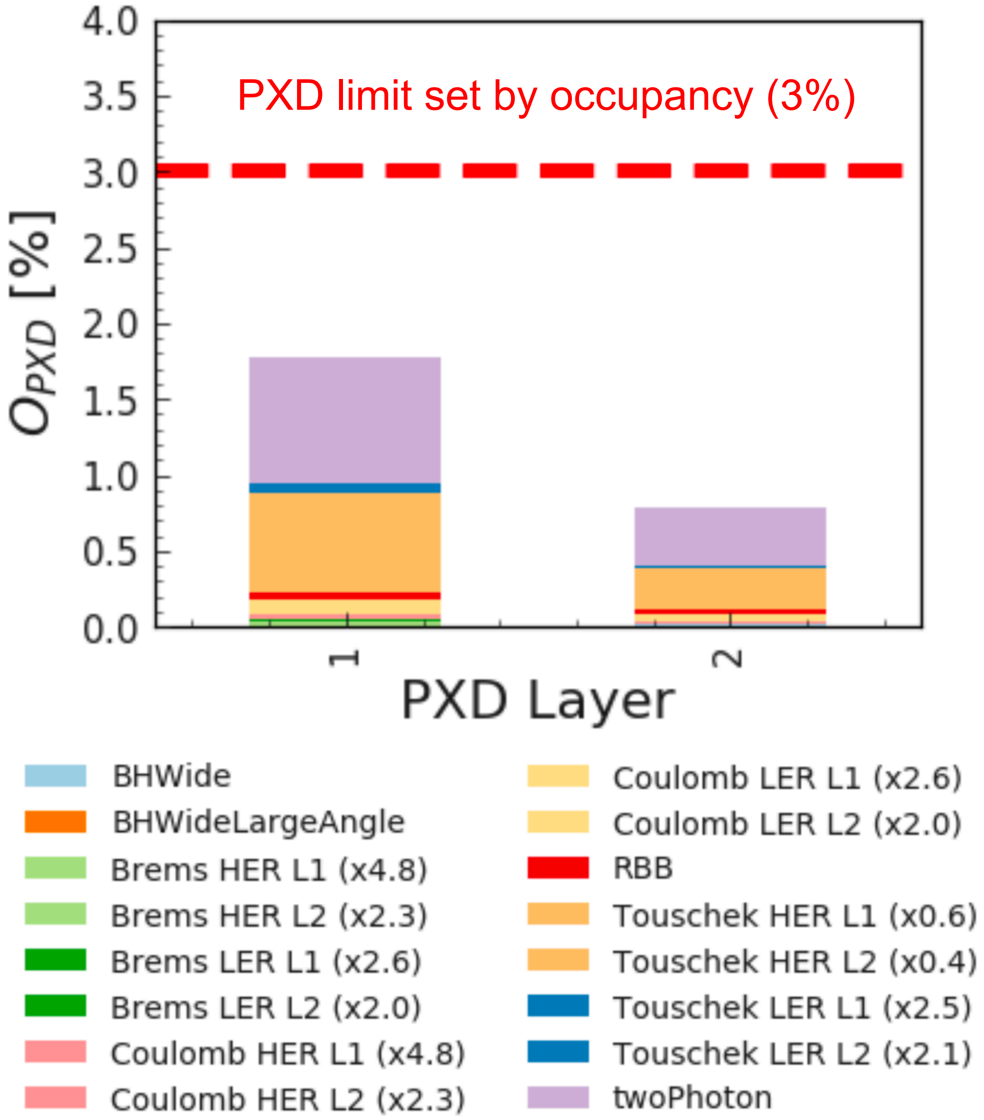


- **Luminosity backgrounds** (irreducible): mainly two-photon

- Background decomposition performed in single-beam and luminosity runs
  - Data/MC factors ϵ [0.5, 5] → correct design simulation
  - lumi background in excellent agreement with simulation

Study indicates we should be well within $\mathcal{O}_{\mathrm{PXD}} < 3\%$ at the original design optics.

- Note: extrapolation missing for injection and SR backgrounds, however SR currently has acceptable contribution to $\mathcal{O}_{\mathrm{PXD}}$

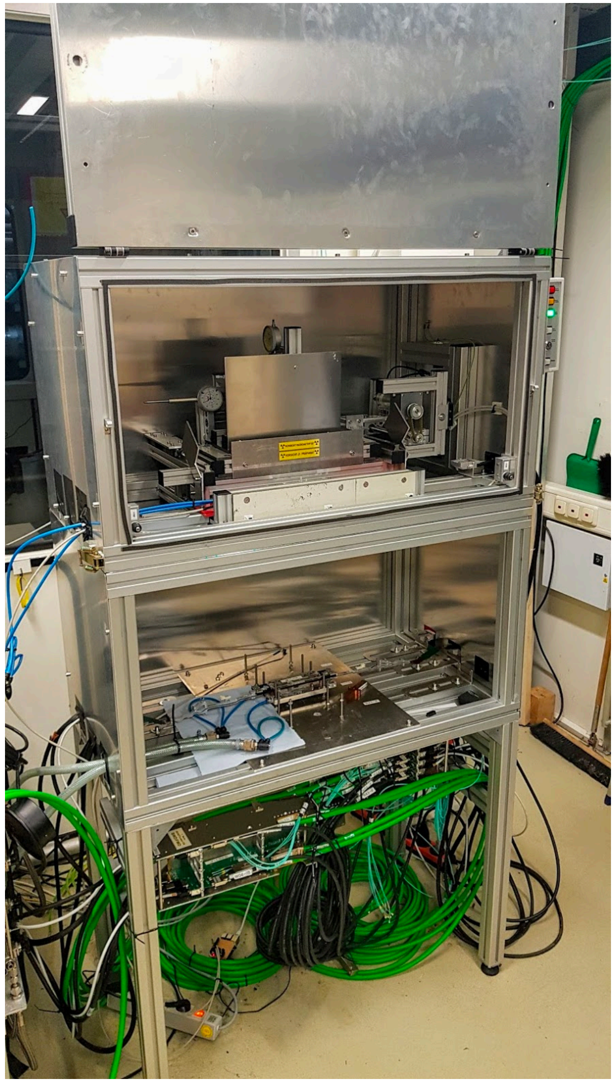


PXD 2022

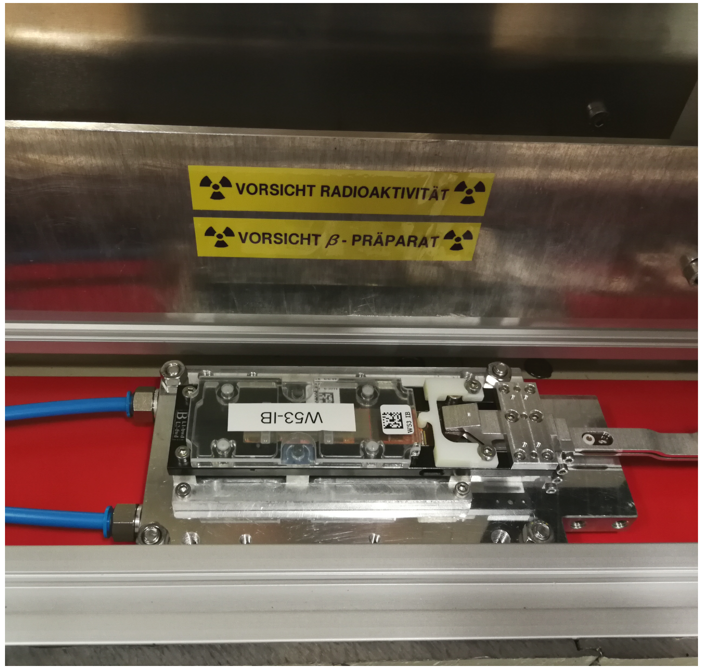
- Towards full 2-layer PXD detector
  - module production ongoing @ **MPP**, **HLL**
  - module testing ongoing @ **DESY**
  - improved beam pipe construction @ **KEK**

- Installation planned during the 2022 long shutdown

- DESY continues to play a leading role in the Belle II PXD project:
  - detector characterization, commissioning and operation
  - performance studies, background estimation, calibration and software development

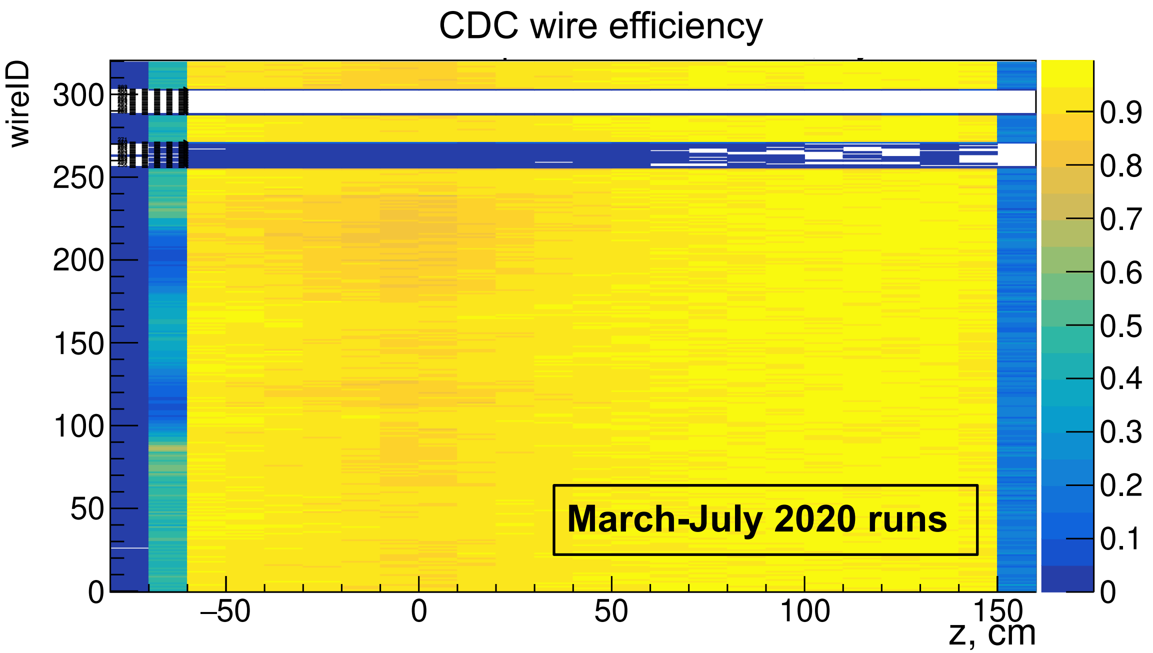


PXD module mass-testing setup @DESY



Tracking

- DESY plays a leading role in tracking:
  - tracking software development
  - support for tracking alignment using Millepede
  - tracking efficiency measurements
  - monitoring CDC wire efficiency
  - monitoring relative VXD/CDC efficiency



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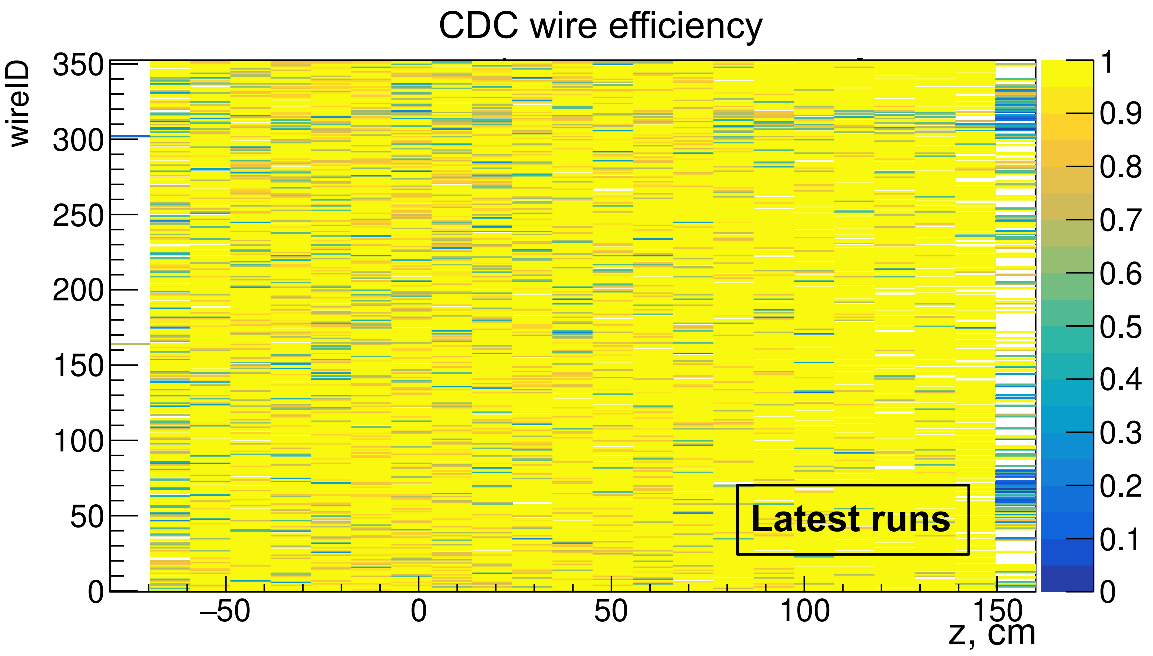

⇒ improvements are due to work on the CDC readout electronics

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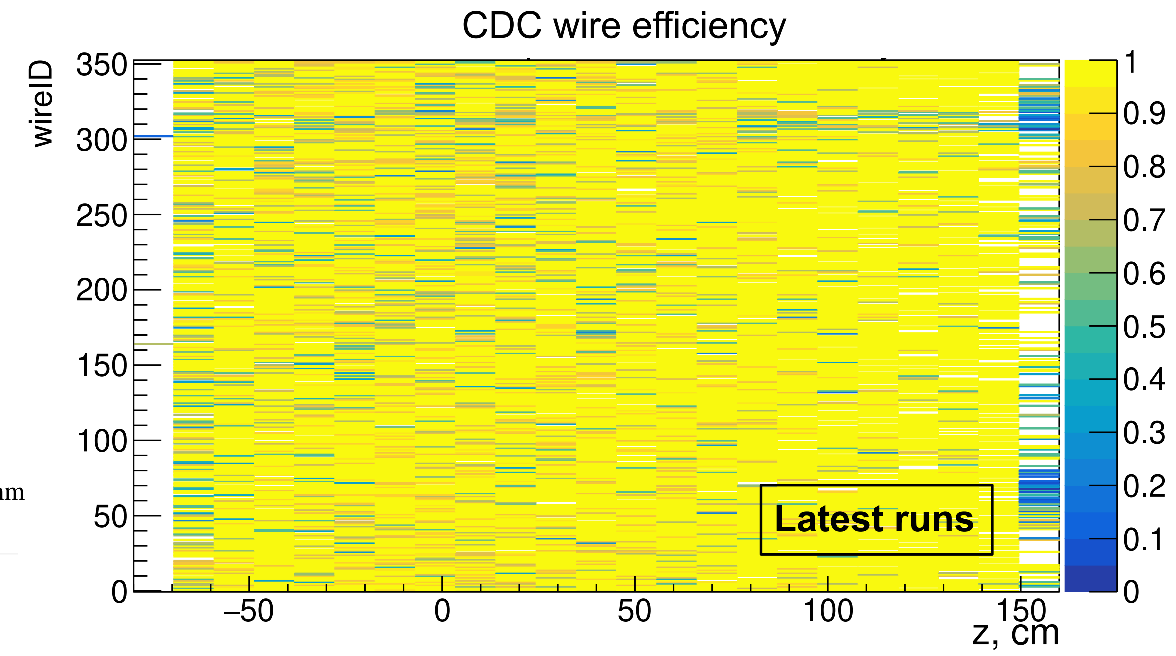
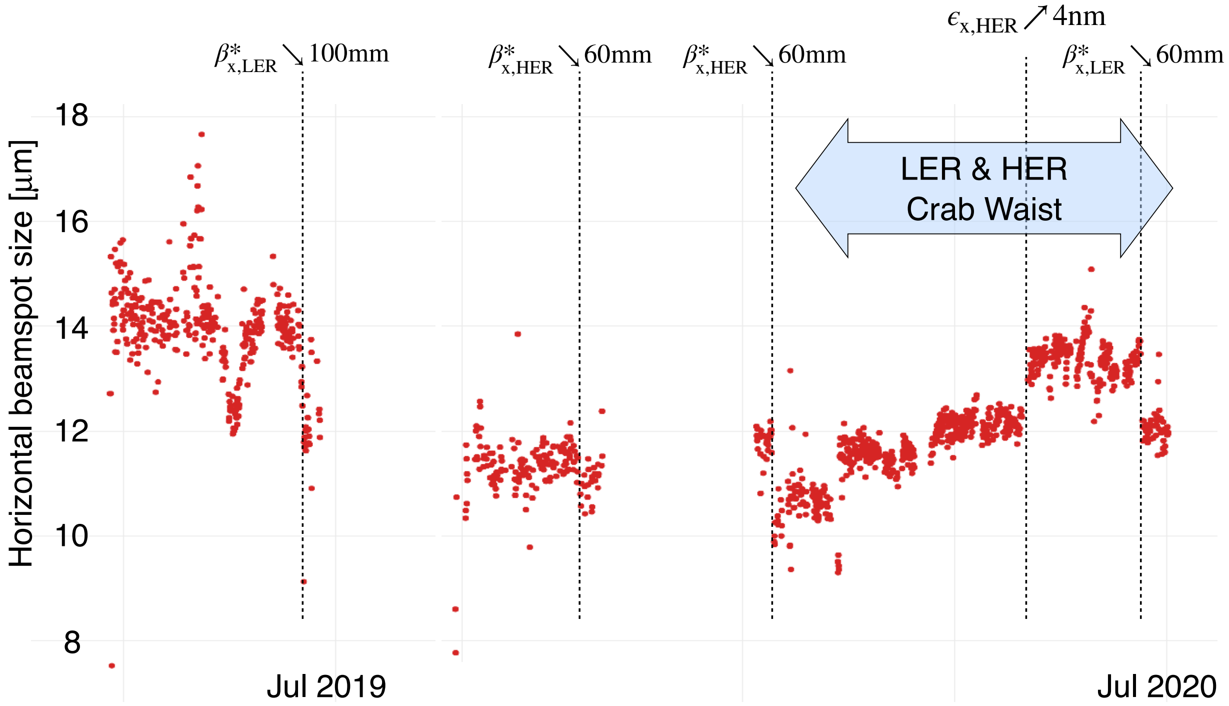




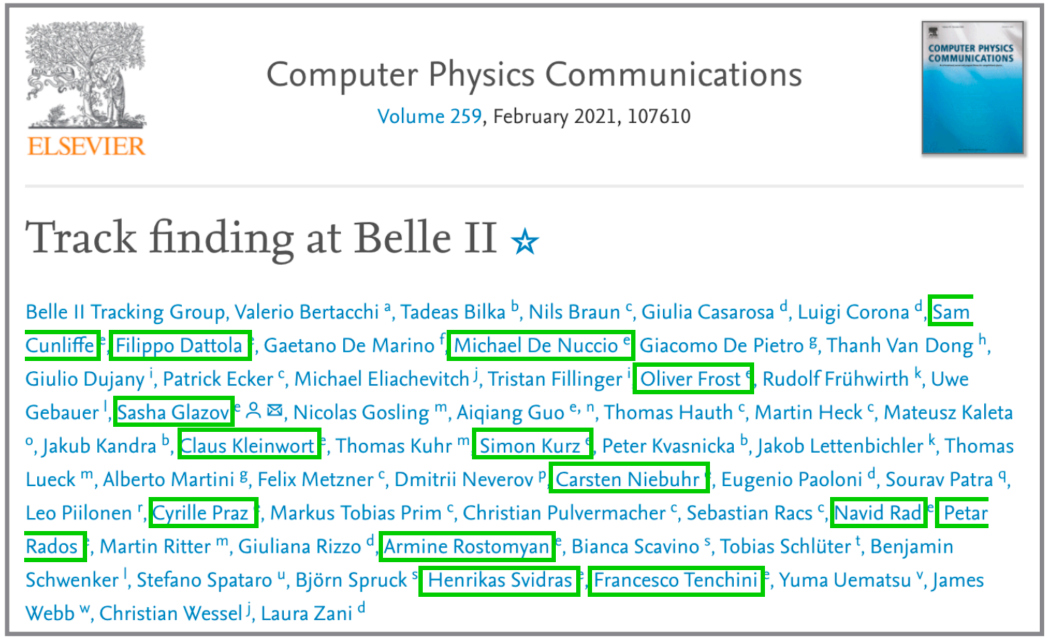
⇒ improvements are due to work on the CDC readout electronics

- Through tracking we are able to follow changes in beam optics and provide valuable feedback to the machine group

Tracking activities

- Tracking paper on algorithms and MC performance is **now published!**
- Strong contribution from DESY

https://doi.org/10.1016/j.cpc.2020.107610



ELSEVIER

Computer Physics Communications

Volume 259, February 2021, 107610

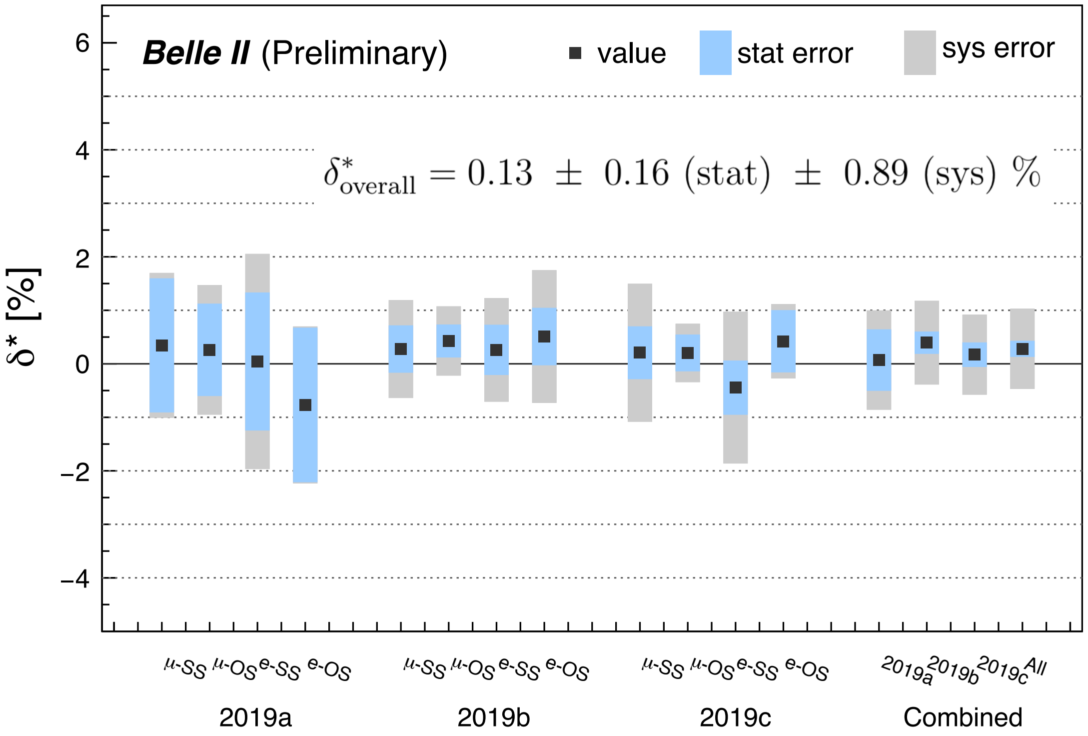
COMPUTER PHYSICS COMMUNICATIONS

Track finding at Belle II ☆

Belle II Tracking Group, Valerio Bertacchi [a], Tadeas Bilka [b], Nils Braun [c], Giulia Casarosa [d], Luigi Corona [d], Sam Cunliffe [e], Filippo Dattola [e], Gaetano De Marino [f], Michael De Nuccio [e], Giacomo De Pietro [g], Thanh Van Dong [h], Giulio Dujany [i], Patrick Ecker [c], Michael Eliachevitch [j], Tristan Fillinger [i], Oliver Frost [e], Rudolf Frühwirth [k], Uwe Gebauer [l], Sasha Glazov [e], Nicolas Gosling [m], Aiqiang Guo [e, n], Thomas Hauth [c], Martin Heck [c], Mateusz Kaleta [o], Jakub Kandra [b], Claus Kleinwort [e], Thomas Kuhr [m], Simon Kurz [e], Peter Kvasnicka [b], Jakob Lettenbichler [k], Thomas Lueck [m], Alberto Martini [g], Felix Metzner [c], Dmitrii Neverov [p], Carsten Niebuhr [e], Eugenio Paoloni [d], Sourav Patra [q], Leo Piilonen [r], Cyrille Praz [e], Markus Tobias Prim [c], Christian Pulvermacher [c], Sebastian Racs [c], Navid Rad [e], Petar Rados [e], Martin Ritter [m], Giuliana Rizzo [d], Armine Rostomyan [e], Bianca Scavino [s], Tobias Schlüter [t], Benjamin Schwenker [l], Stefano Spataro [u], Björn Spruck [s], Henrikas Svidras [e], Francesco Tenchini [e], Yuma Uematsu [v], James Webb [w], Christian Wessel [j], Laura Zani [d]

- Paper on performance in early data: **coming soon!**
- Tracking efficiency measurement using tag-and-probe method with $ee \to \tau\tau \to$ 1x3 prong events

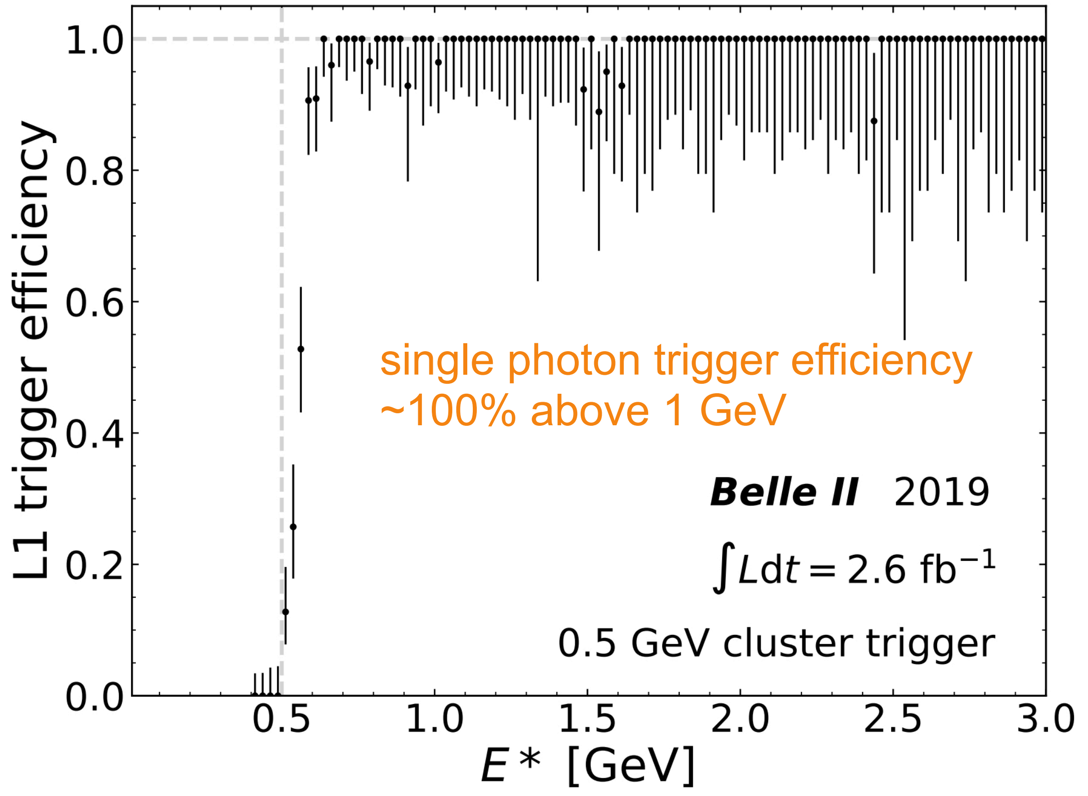
BELLE2-NOTE-PL-2020-014



Neutrals

- DESY members leading several areas of neutrals software + performance:
  - photon efficiency and resolution measurement
  - π^0 performance
  - particle identification with pulse shape discrimination
  - single photon triggering
  - calorimeter software

BELLE2-NOTE-PL-2020-009



- Neutrals performance paper: **coming soon!**

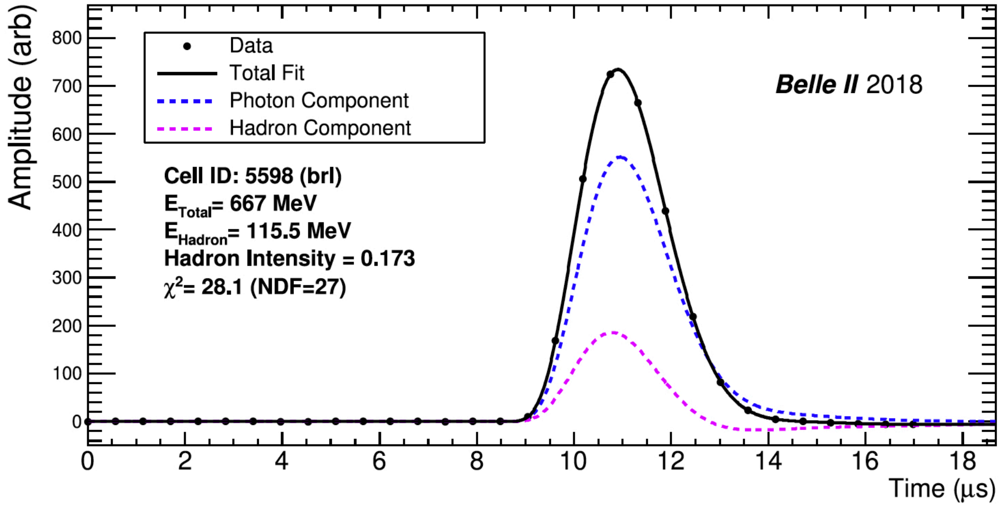
- Important input for several DESY-led physics results:
  - Axion-like particle search: **Published!** Phys. Rev. Lett. 125, 161806
  - Single photon search: **coming soon!**
  - $B \to X_s \gamma$: **coming soon!**

Pulse shape discrimination

- Using CsI(Tl) scintillation pulse shape to identify hadronic vs. electromagnetic showers at Belle II. Significantly improves γ/K_L^0 separation.

- First time applied for particle identification at an e^+e^- collider.

https://doi.org/10.1016/j.nima.2020.164562



Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 982, 1 December 2020, 164562

CsI(Tl) pulse shape discrimination with the Belle II electromagnetic calorimeter as a novel method to improve particle identification at electron–positron colliders

S. Longo [a], J.M. Roney [a, e], C. Cecchi [j, k], S. Cunliffe [b], T. Ferber [b], H. Hayashii [c], C. Hearty [d, e], A. Hershenhorn [d], A. Kuzmin [f, g], E. Manoni [k], F. Meier [m], K. Miyabayashi [c], I. Nakamura [i, h], M. Remnev [f, g], A. Sibidanov [a], Y. Unno [l], Y. Usov [f, g], V. Zhulanov [f, g]

- **Paper is now published!**

  Major contributions coming from DESY

Pulse shape discrimination

- PIER Seed Grant **successful**:

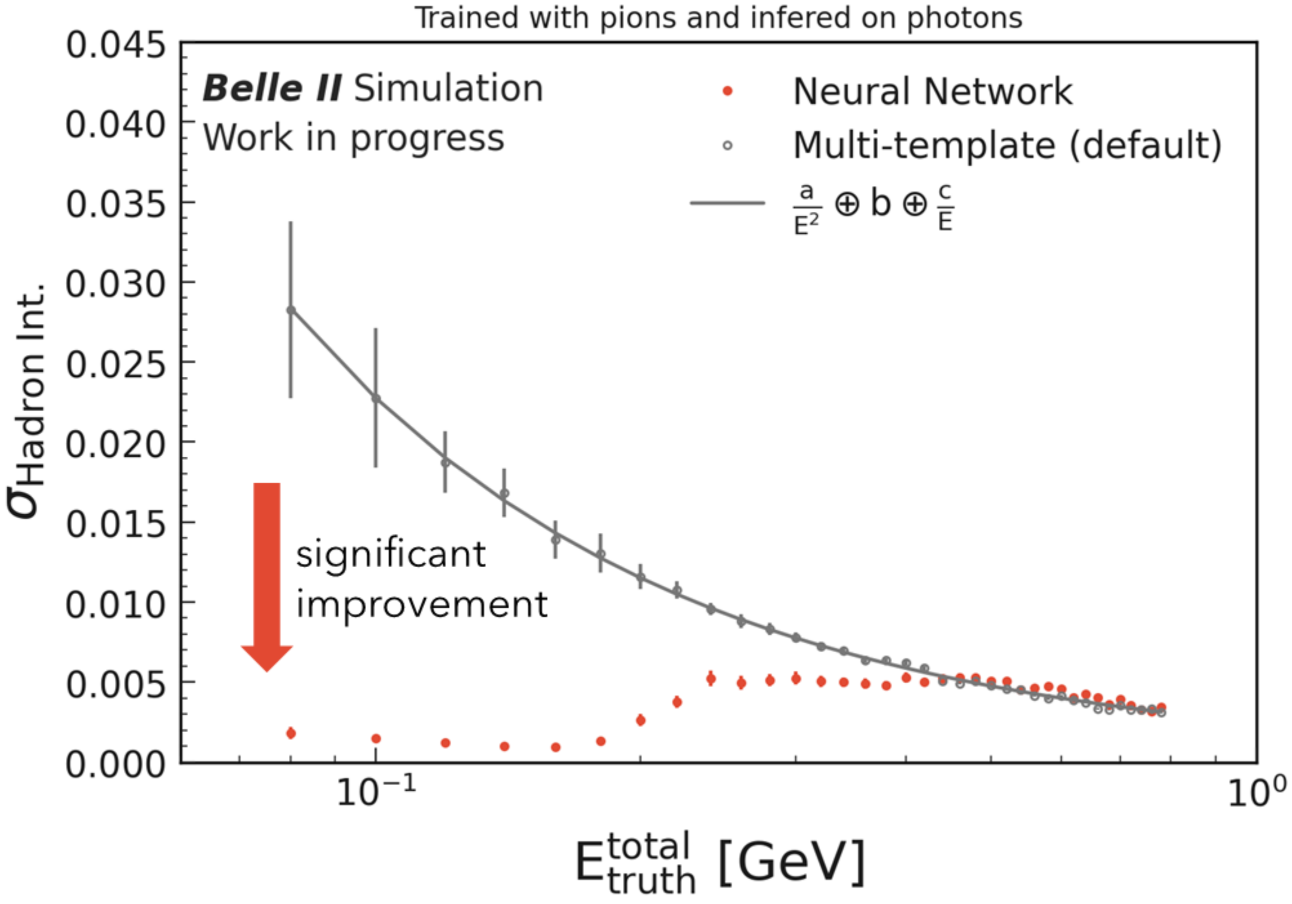
  "*Machine Learning with FPGAs for real-time characterization of fast scintillation signals*"
  (T. Ferber, B. von Krosigk, S. Longo)

- Collaboration with U. Hamburg/DESY SuperCDMS group.

- Ongoing work on PSD using ML on FPGAs

  ⇒ Neural Network provides **significantly improved** energy resolution of hadron component, for pulse shapes with lower energy deposits

- Plan to bring this improvement to the L1 trigger level



Physics

Second published physics paper from Belle II!

PHYSICAL REVIEW LETTERS

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Access by Deutsches Elek. Synch

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

F. Abudinén *et al.* (Belle II Collaboration)

Phys. Rev. Lett. **125**, 161806 – Published 14 October 2020

Article | References | No Citing Articles | Supplemental Material | PDF | HTML | Export Citation

Dark Sector Physics

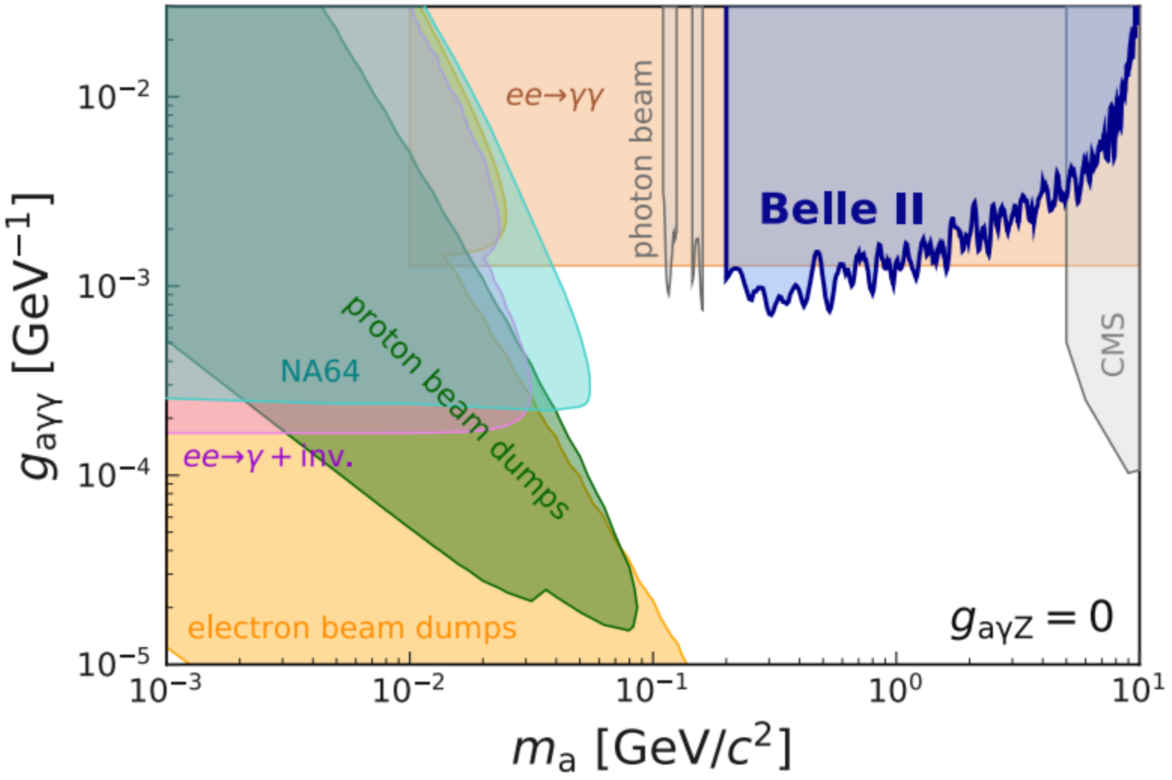
- ALP search published with 2018 data.
  Analysis driven entirely by DESY!

- Four active analyses in DESY dark-sector group (more are planned):
  (1) Search for single photon events.
  (2) Search for inelastic dark-matter.
  (3) Search for long-lived scalar in b → s.
  (4) Improvements to ALP search.

- (1) & (2) are competitive with ~70 fb^{-1} of data collected so far in 2020.

- Long-lived particle workshop (10-11 Dec) joint with theory, via **ErUM-FSP T09 Belle II**.

Phys. Rev. Lett. 125, 161806



FSP Workshop (online): Long-lived particles at Belle II

10 Dec 2020, 14:00 → 11 Dec 2020, 18:20 Europe/Berlin

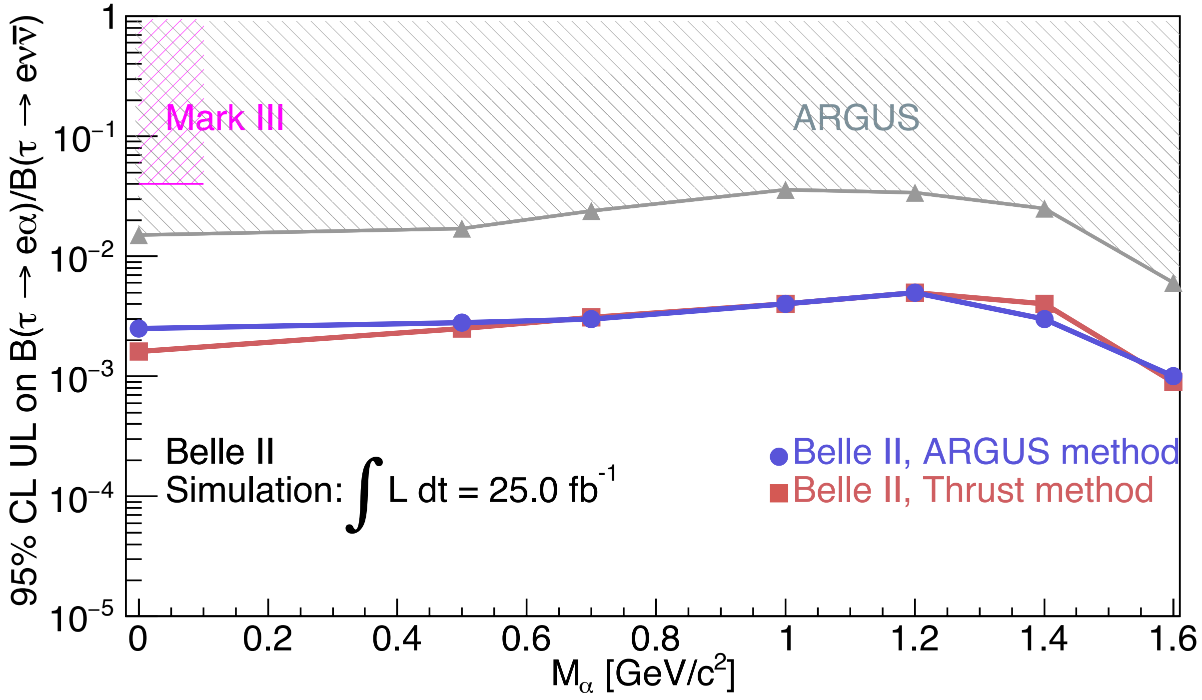
Susanne Westhoff (University Heidelberg), Torben Ferber (DESY)

Description: The goal of the workshop is to bring together experimentalist and theorists to discuss new ideas for searches at Belle II that involve long-lived particles. The workshop is organized in the context of the "Forschungsschwerpunk Belle II (FSP T09 Belle II)" in Germany, but we invite every interested person to join! Due to the current covid-19 related travel restrictions, this will be a purely online event via Zoom: https://desy.zoom.us/j/94098584828 (Passcode: 471873)

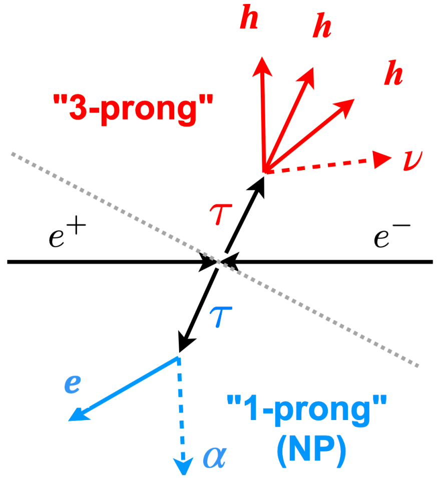
Tau Physics

- **B-factories are also τ-factories**
  - $\sigma(e^+e^- \to \Upsilon(4s)) = 1.05$ nb
  - $\sigma(e^+e^- \to \tau^+\tau^-) = 0.92$ nb

⇒ Belle II provides a unique environment to study tau physics with high precision!



- Several active analyses in DESY tau physics group:
  (1) Search for LFV decays **τ→lα**, μμμ and eɣ.
  (2) Tau mass measurement.
  (3) Electric Dipole Moment (CP/T violation)
  (4) Dalitz analysis.



Search for LFV τ→lα

- Search for 2-body decay, α unobserved (E_{miss})
- Signal will manifest in the (approximated) τ rest frame. Bump in p_l on top of SM τ→lνν.
- With only 25 fb^{-1} we can push forward the current bounds by an order of magnitude!
  BELLE2-NOTE-PL-2020-018
- **Aiming for paper on 2020 dataset**

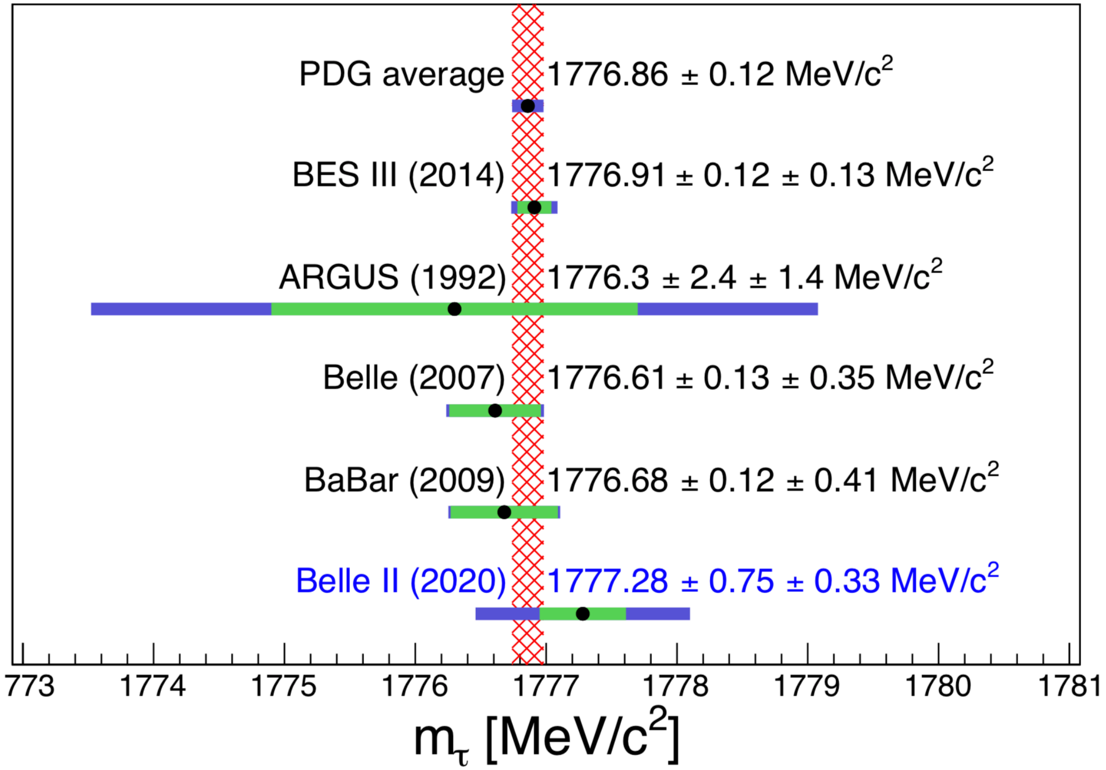
Tau mass measurement

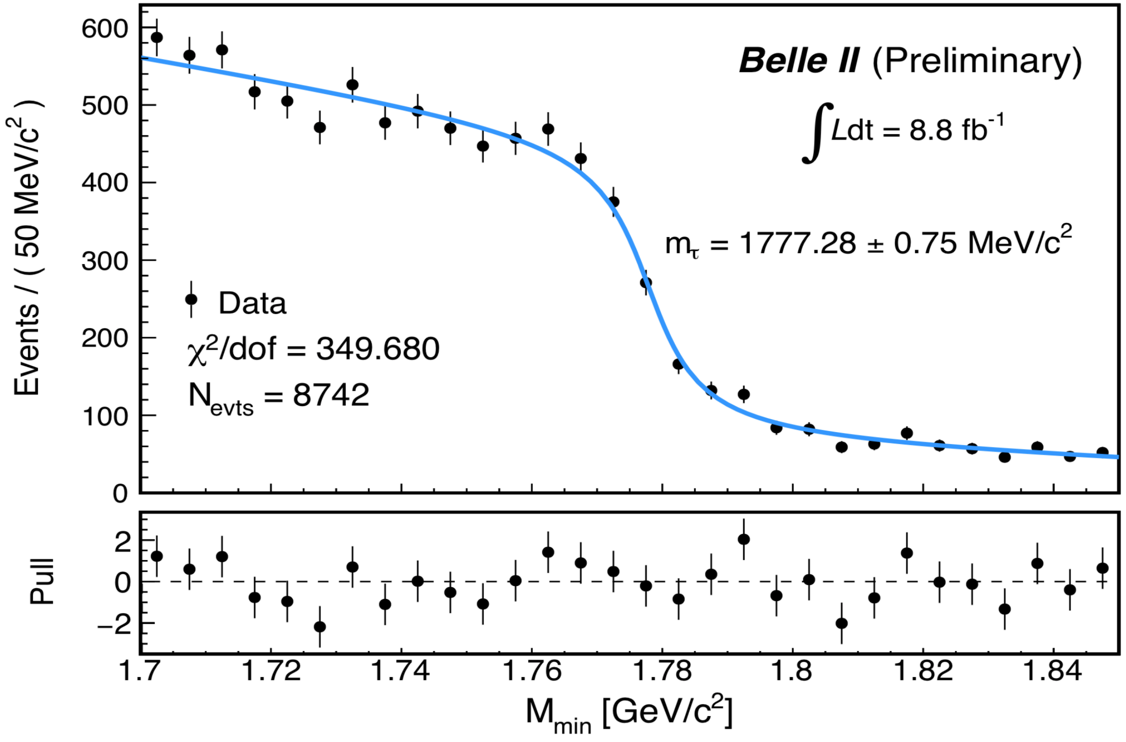
- m_τ measurement in 2019 data: BELLE2-CONF-PH-2020-010
- Using a pseudomass technique on $\tau \to 3\pi\nu$ decays

$$M_{min} = \sqrt{M_{3\pi}^2 + 2(E_{beam} - E_{3\pi})(E_{3\pi} - P_{3\pi})}$$

- sharp threshold behaviour in region close to m_τ

arXiv:2008.04665

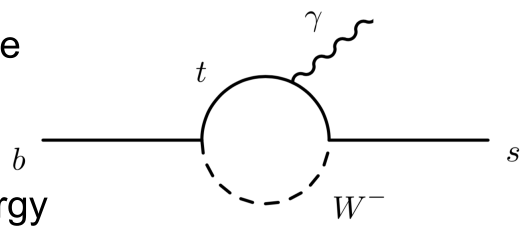




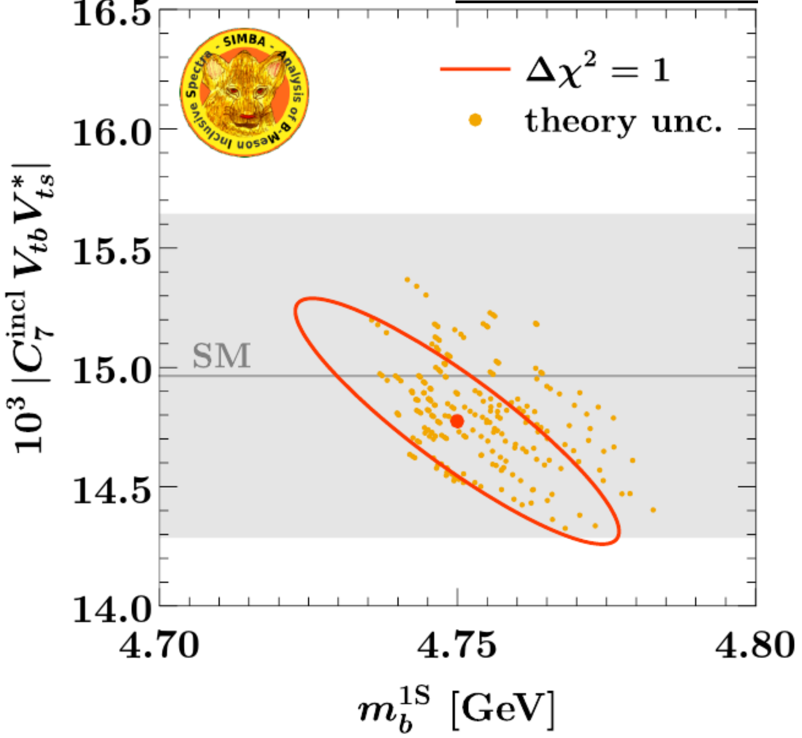
- Total systematic uncertainty comparable to Belle/BaBar (dominated by momentum scale → will improve!)
- **Goal**: have the best m_τ precision amongst the pseudomass techniques. **Possible with 150-300 fb^{-1}**.

B→$X_s\gamma$

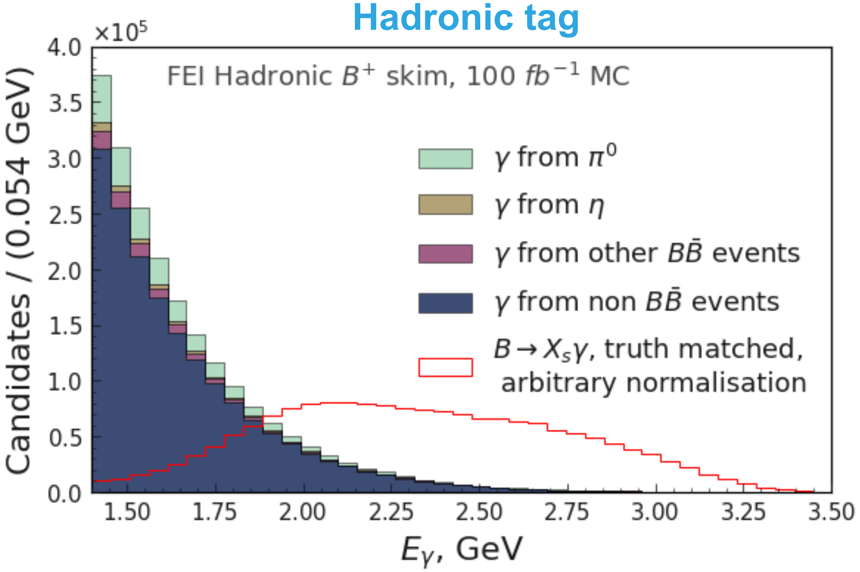
- Measurement of rare radiative decay B→$X_s\gamma$
  - Decay rate + CP asymmetries sensitive to BSM physics via EW penguin loop
  - Shape of photon energy spectrum sensitive to m_b.



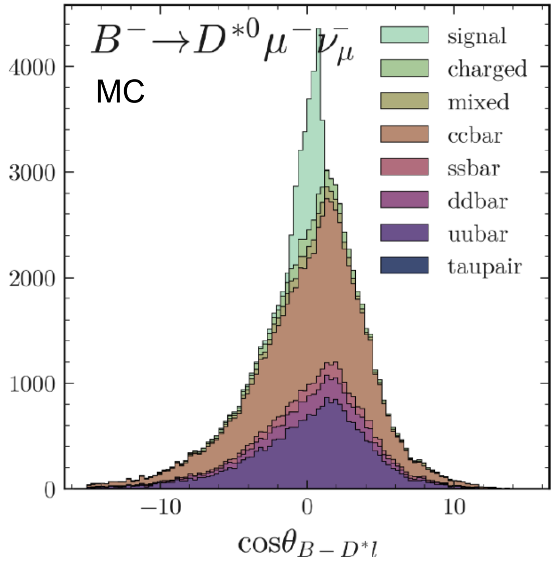
arXiv:2007.04320



Hadronic tag



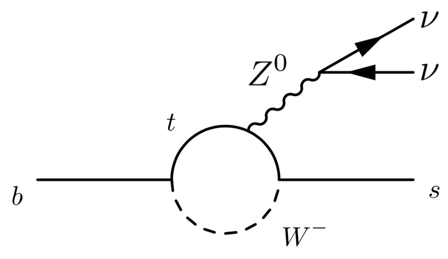
Semileptonic tag



- Data prospects for 10-100 fb^{-1}
  - Investigating several options regarding B-tagging and background suppression
  - Working on semileptonic tagging and photon efficiency measurement
  - Investigating analysis on Belle data w/ Belle II tagging tools
  - **Aiming for a public result using 2020 dataset**

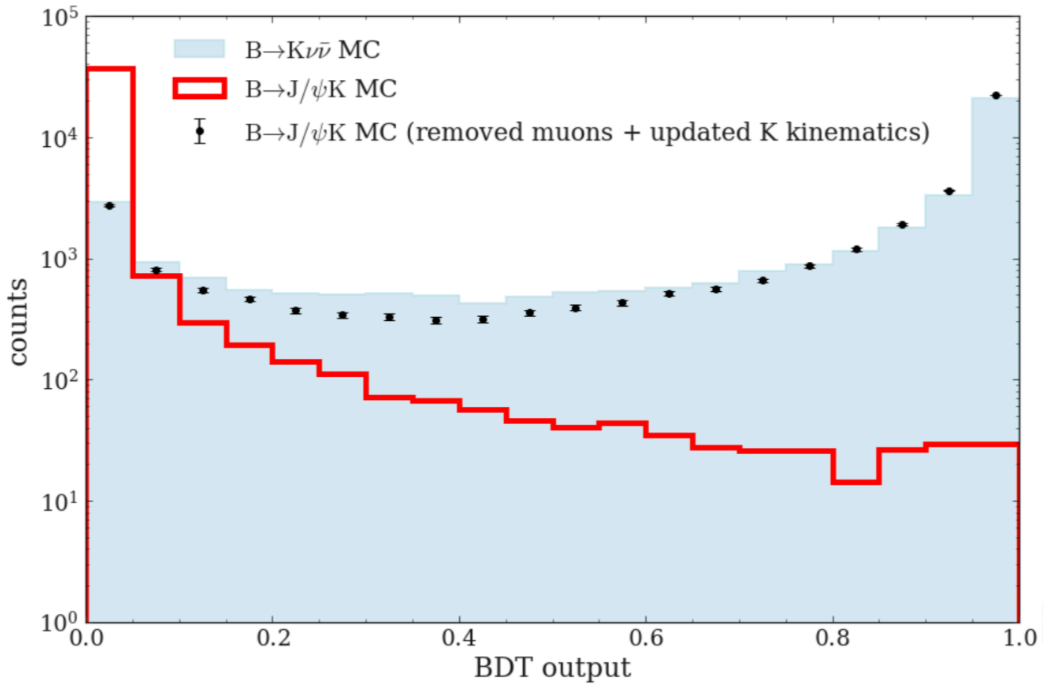
- Global fit paper now released (Belle + BaBar): arXiv:2007.04320 [hep-ph]
  - **SIMBA**: collaboration b/w DESY Belle II + theory group
  - Larger uncertainties suggest modelling and theory uncertainties underestimated in previous approaches ⇒ leaves more room for new physics

- Inclusive search for rare decay $B \to K\nu\bar{\nu}$
  - FCNC process with clean SM computation:



$$\mathcal{B} = (4.6 \pm 0.5) \times 10^{-6}$$

Not observed yet!
Highly sensitive to NP.



- **Novel DESY-pioneered method** without B tagger!
  - Select highest p_T kaon candidate, and rely on event topology, E_{miss} and vertex separation
  - **ε~5.0%** (vs ~0.2% with B-tagger), but larger bkg contamination
    ⇒ **BDT to maximise sensitivity**
  - Validating with $B \to J/\psi(\to \mu\mu)K$ with μμ veto and signal-like kaon kinematics

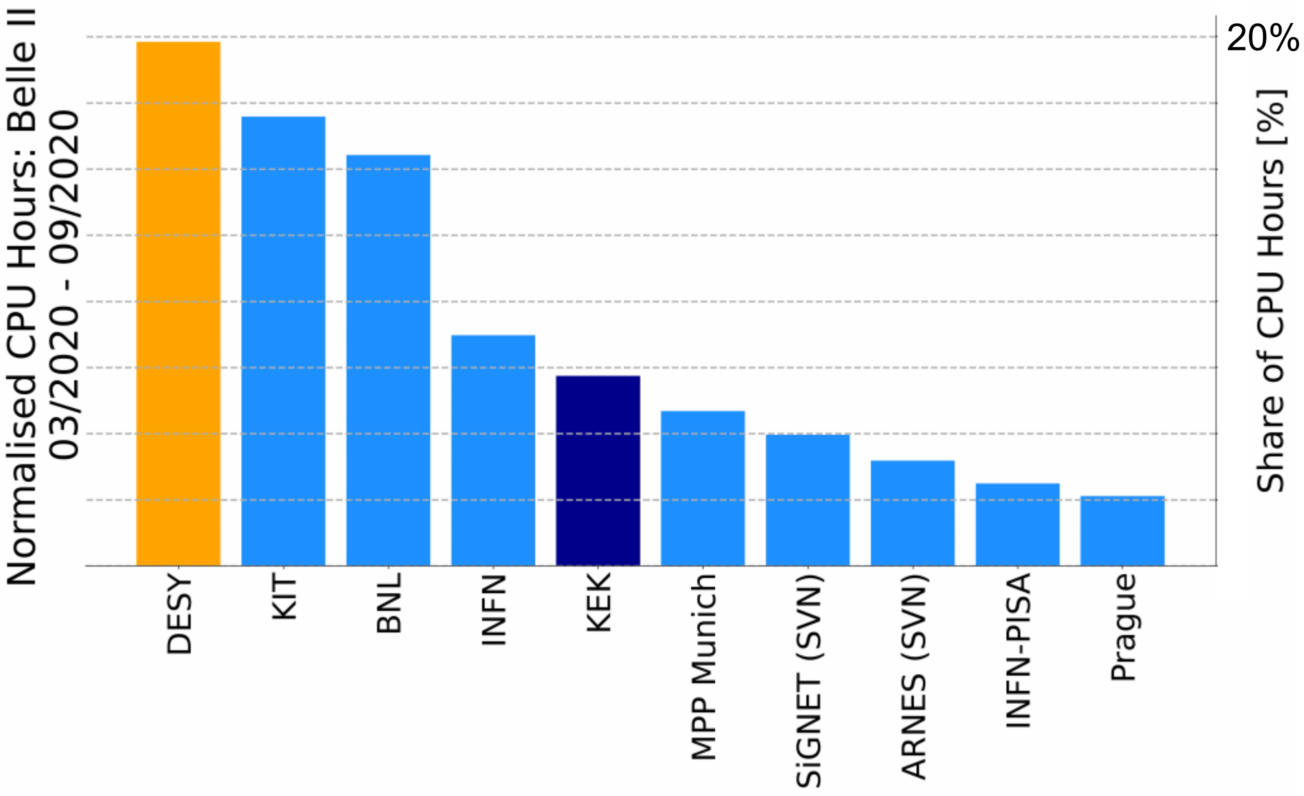
- Highlights and prospects:
  - Belle II data shows very high data-quality
  - Multivariate techniques heavily validated and optimised
  - New control channels (off-resonance, BDT-sideband) to constrain leading-order systematics
  - Sensitivity with 2020 data is close to previous measurements + using a novel method.

    ⇒ **Aim for paper with 2019+2020(summer) data**

Collaborative services & computing

Computing, collaborative services

- DESY continues to be a major GRID site for the belle VO ⇒ **largest** in current data processing
- Collaborative services/tools hosted at DESY remain a crucial part of the Belle II infrastructure
- From 2021 onward:
  - DESY will act as a Raw Data Centre for Belle II, storing 10% of the 2nd copy of RAW data (1st full copy at KEK)
  - DESY will become the recalibration centre for Belle II (succeeding BNL)
- ~200 Belle II users world-wide request access to NAF; a few ten are regular users including Jupyter hub



Summary

- **SuperKEKB luminosity is ramping up. Still a long way to go with challenges to overcome.**

- **DESY group plays a leading role in many areas critical to Belle II**
  - PXD operation, performance, background studies, software development and PXD 2022.
  - Tracking and neutrals software development, calibration and performance studies.
  - Computing and collaborative services.

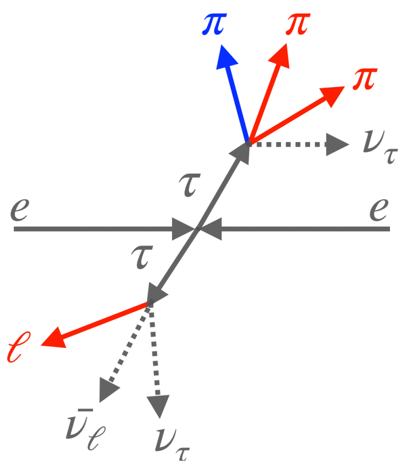
- **Many DESY-led physics results are in the pipeline**
  - ALPS search has been published. Second physics paper from Belle II, driven entirely by DESY!
  - Aiming for several publication on 2020 dataset in Dark Sector, Tau and B- Physics.

- **Exciting times are ahead!** Thanks for your attention!

BACKUP

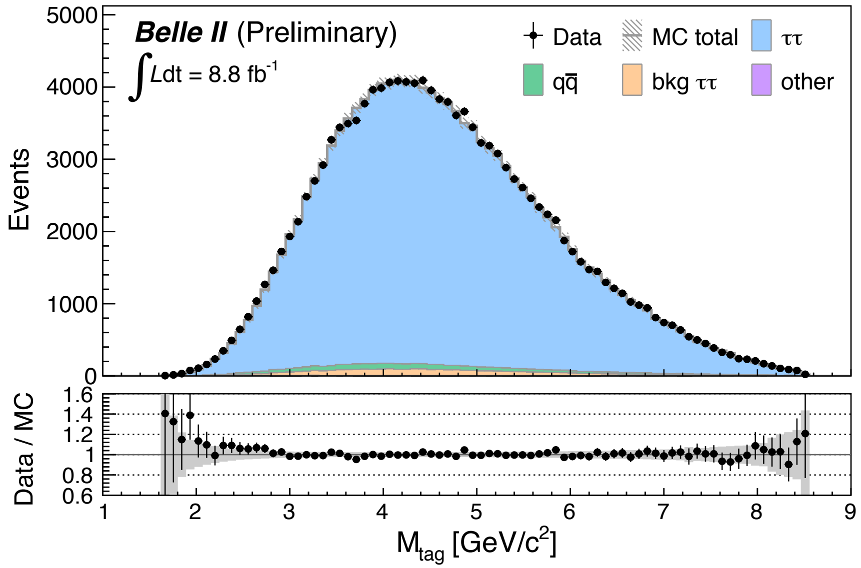
Tracking efficiency measurement

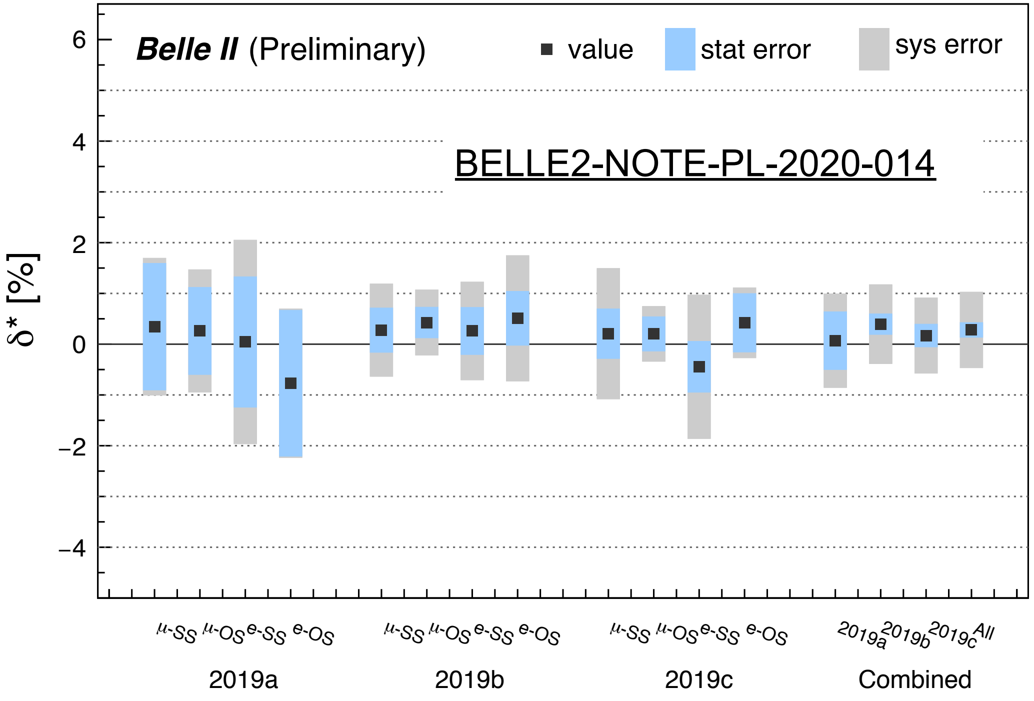
- Tag-and-probe method targeting ee → $\tau\tau$ → 1x3 prong events



- low multiplicity but high track density, wide momentum range (0.2 - 4 GeV)
- **tag**: 3 good quality tracks (∑q = ±1)
- **probe**: look for a loose 4th track that conserves charge

$$\epsilon \cdot A = \frac{N_4}{N_3 + N_4}$$





- Calibrated data-MC discrepancy for the overall efficiency:

$$\delta^*_{\text{overall}} = 0.13 \ \pm\ 0.16\ (\text{stat})\ \pm\ 0.89\ (\text{sys})\ \%$$

- Important input for many physics results. Aim to publish this study as part of upcoming tracking performance paper.

$B \to X_s \gamma$ global fit

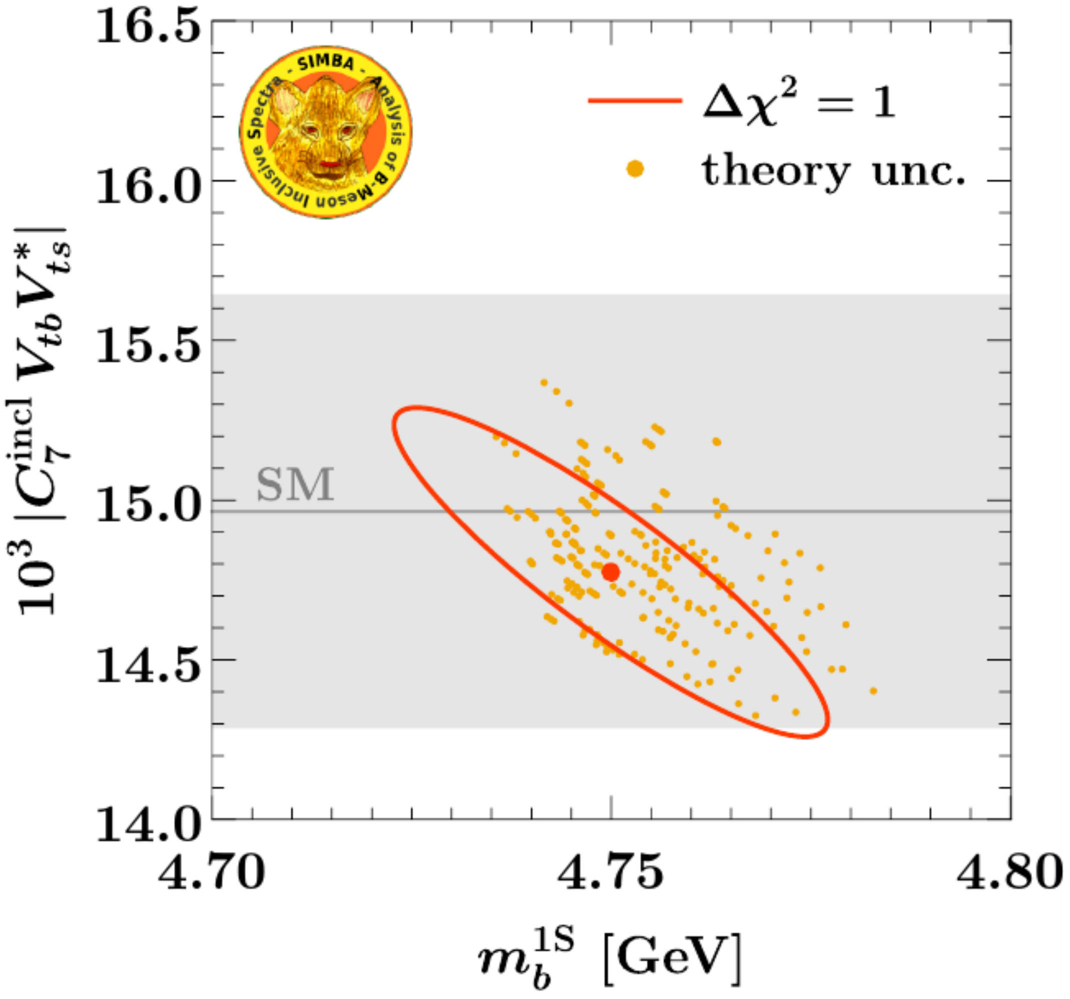
- $B \to X_s \gamma$ decay rate (prop. to $|C_7^{incl}|^2$) is sensitive to NP, and the photon energy spectrum is sensitive to m_b and nonperturbative physics

- Global fit paper released this summer: arXiv:2007.04320 [hep-ph]
  ⇒ **SIMBA**: *collaboration b/w Belle II + theory group*

- Fit to 4 photon energy spectra from Belle and BABAR
  - New approach: nonperturbative physics ("shape function") systematically parametrized
  - Larger uncertainties suggest that modelling and theory uncertainties underestimated in previous approaches

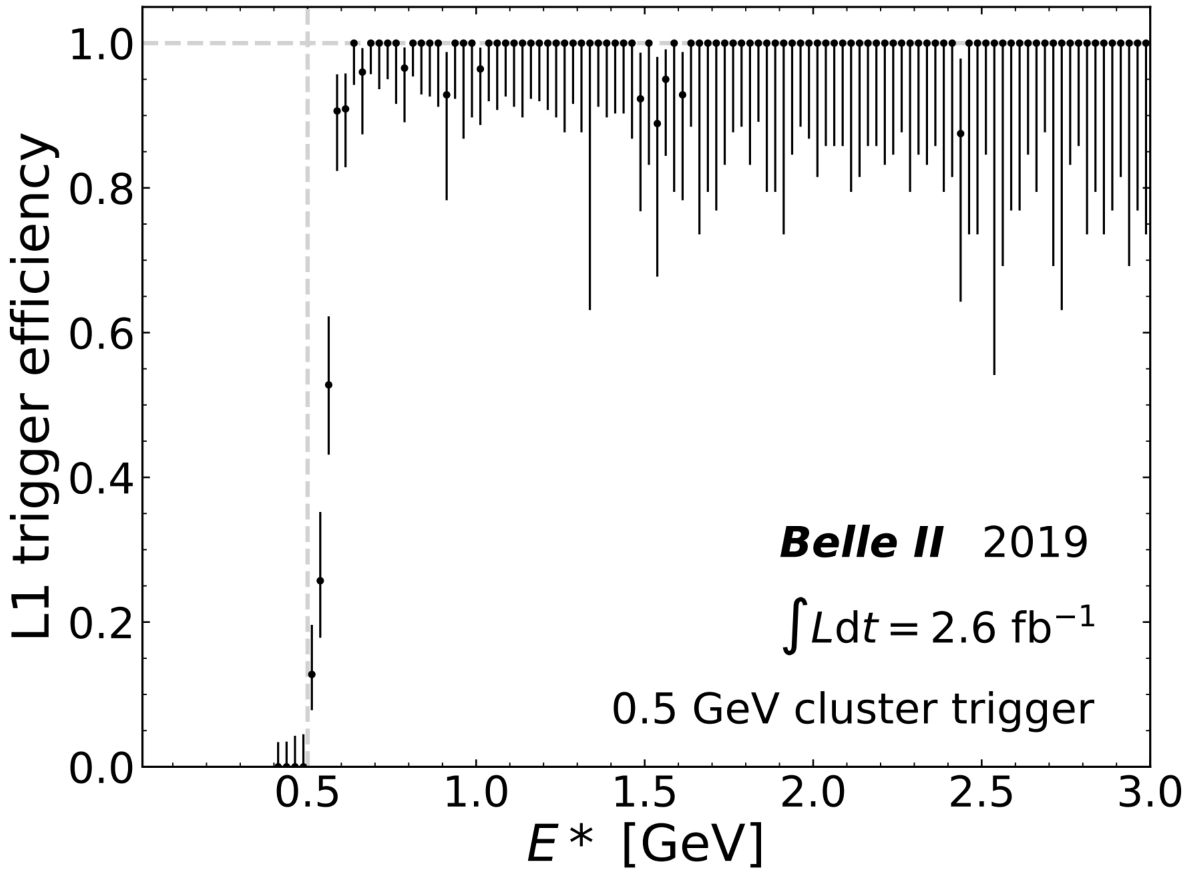
  ⇒ **leaves more room for new physics**

arXiv:2007.04320 [hep-ph]

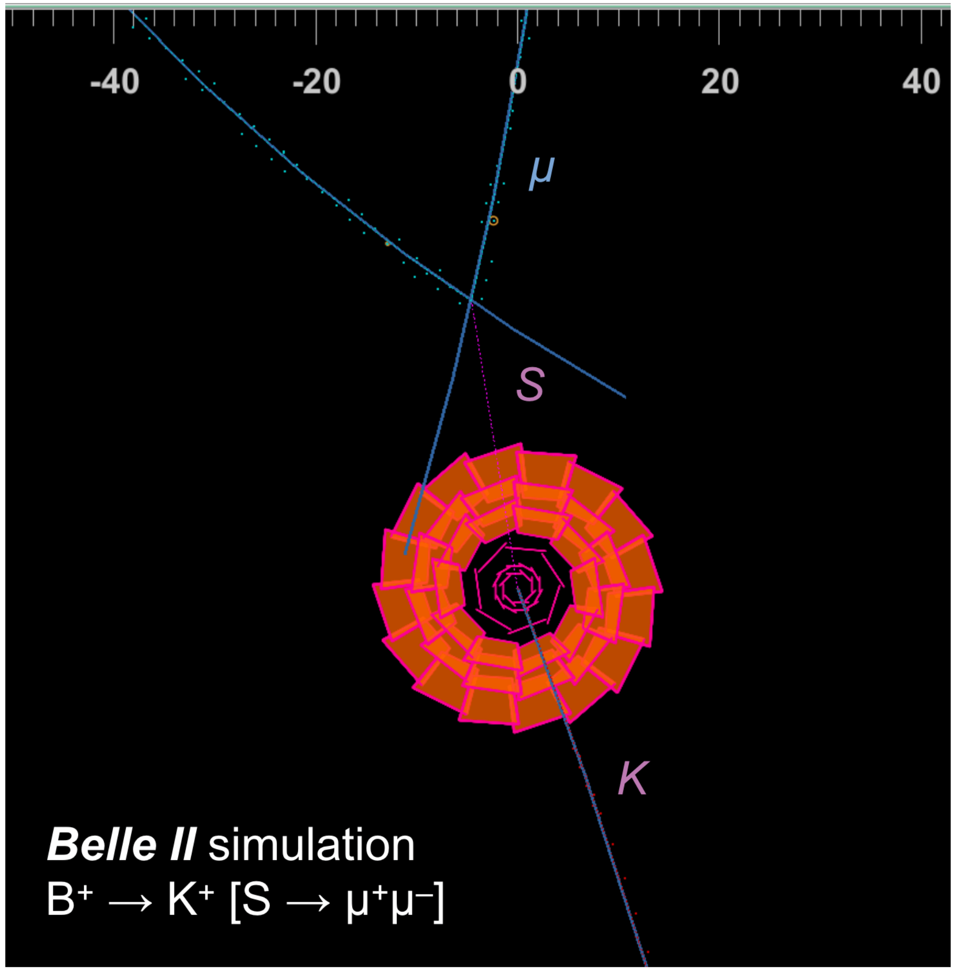


Dark Sector Physics

- Search for **single photon events**:
  trigger efficiency in data ~100% above 1 GeV

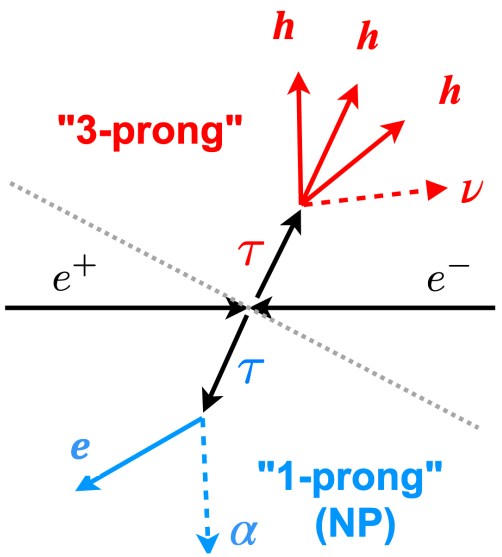


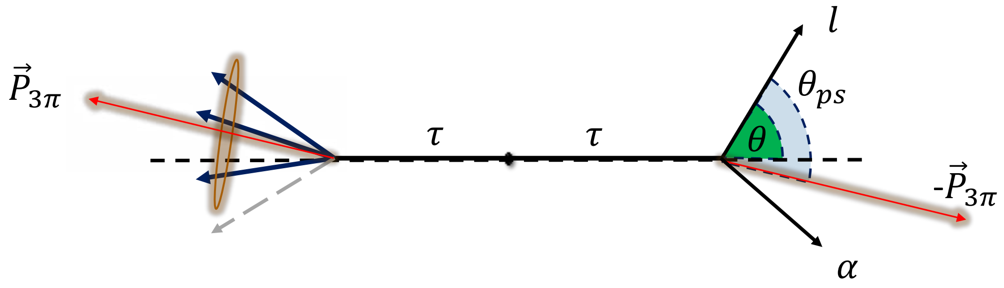
- **B→KS**: understanding displaced vertex efficiency and backgrounds (K_S^0, Λ^0, ..)



Search for LFV τ→lα

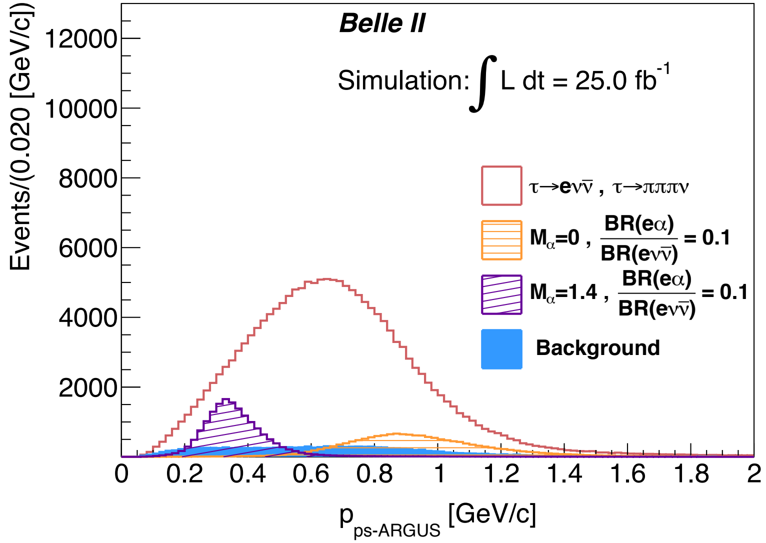
- Search for two body decay **τ→ e/μ + α**, where α is unobserved (missing energy)
- LFV process that appears in several NP models (Goldstone boson, LFV Z', light ALP, …)
- Previously studied at MARK III (9.5 pb^{-1}) and ARGUS (476 pb^{-1})

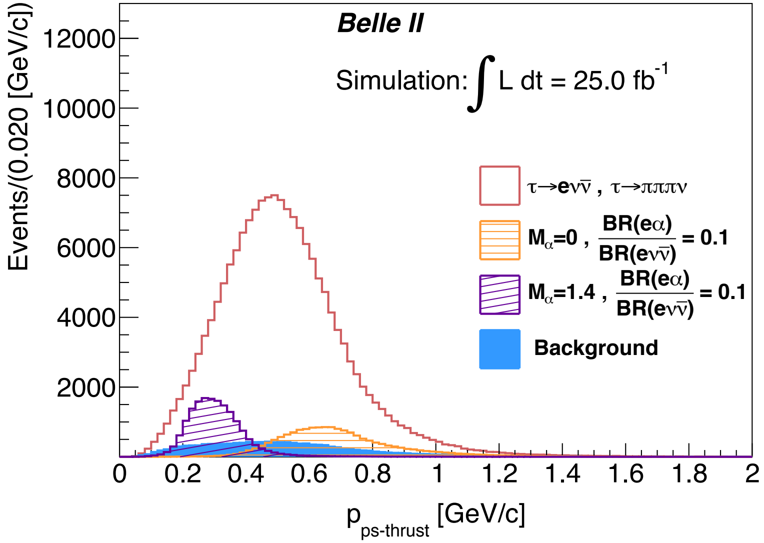




- Signal will manifest as a peak in the τ rest frame, against the SM τ→lνν background

BELLE2-NOTE-PL-2020-018





- cannot access τ rest frame directly due to neutrino
- approximate with the following assumptions:
  - $E_\tau = \sqrt{s}/2$
  - ARGUS method: $\overrightarrow{p_\tau} \approx -\overrightarrow{p_{3\pi}}$
  - Thrust method: $\overrightarrow{p_\tau} \approx \overrightarrow{T}$

Search for LFV τ→lα

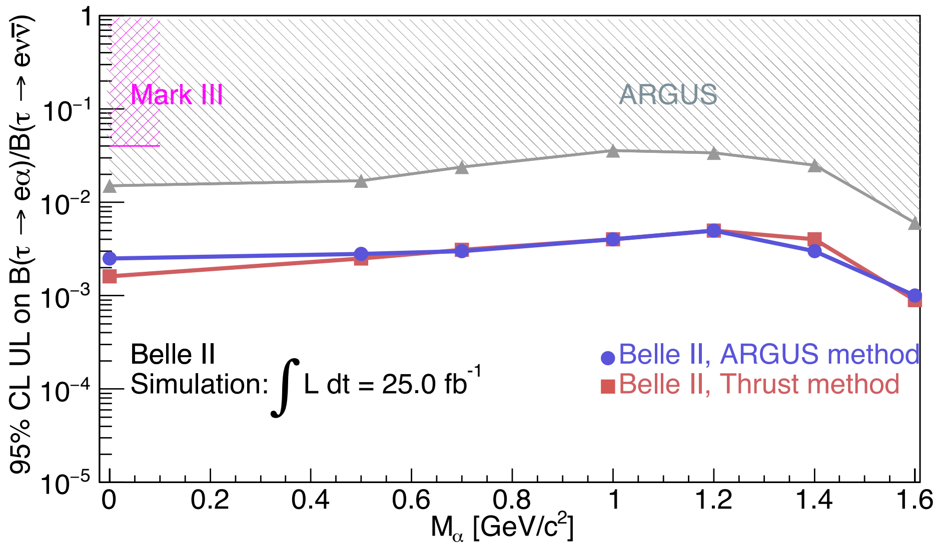
- UL estimation for the ratio **Br(τ→eα) / Br(τ→evv)** was shown at ICHEP (no systematics) BELLE2-NOTE-PL-2020-018

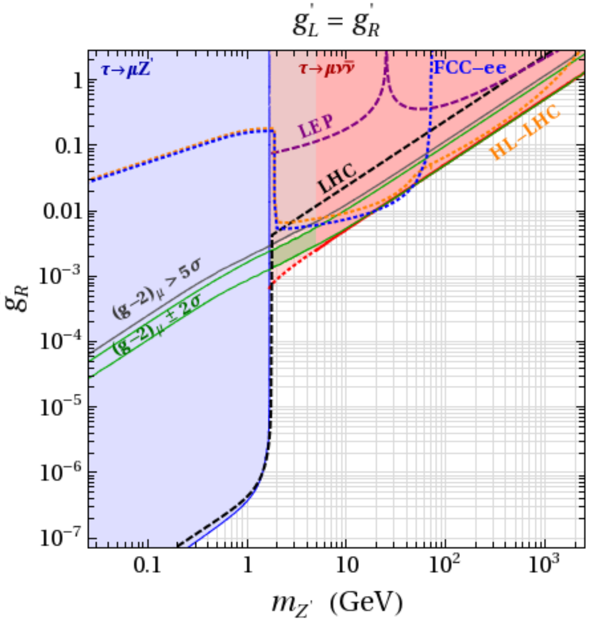
- **With only 25 fb^{-1} we can push forward current bounds by an order of magnitude!** Aiming for a paper in early-mid 2021.

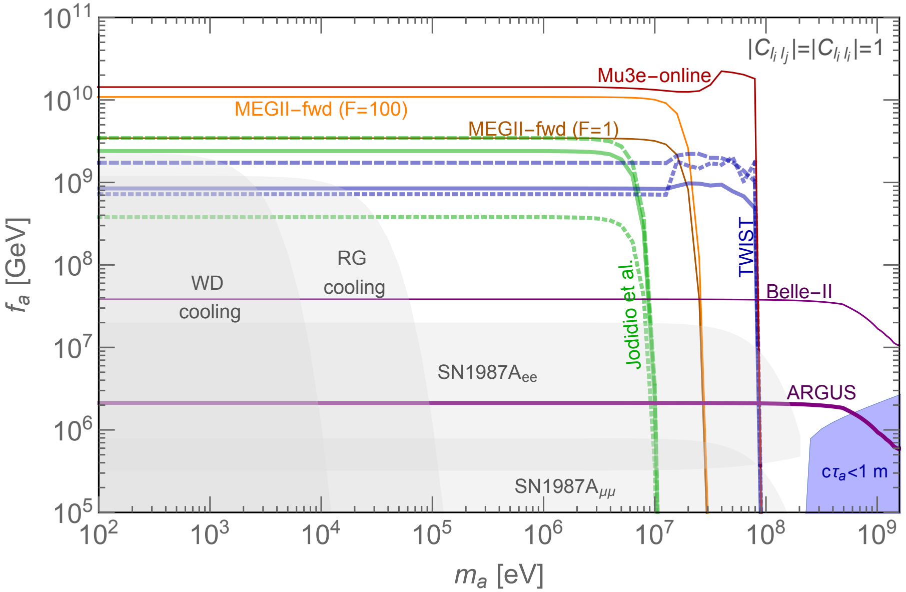
- Current status of the analysis:
  - including systematics uncertainties
  - include τ→μα channel
  - development of BDT, and better 3-prong selection (see earlier)
  - UL cross-check using Bayesian approach

Can set strong constraints on NP models, e.g:

- LFV Z' ⇒ strong bound already set from ARGUS for $m_{Z'} \lesssim m_\tau - m_\mu$
- light ALP ⇒ exploring regions of parameter space not reachable by other experiments





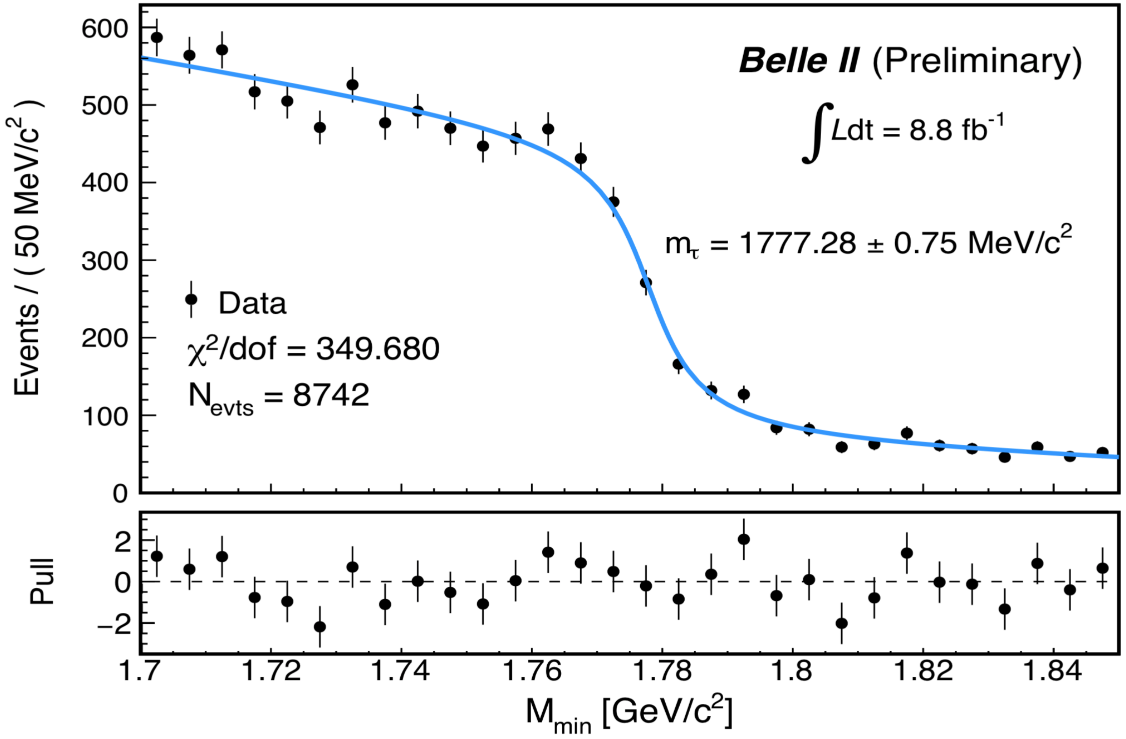


Tau Mass Measurement

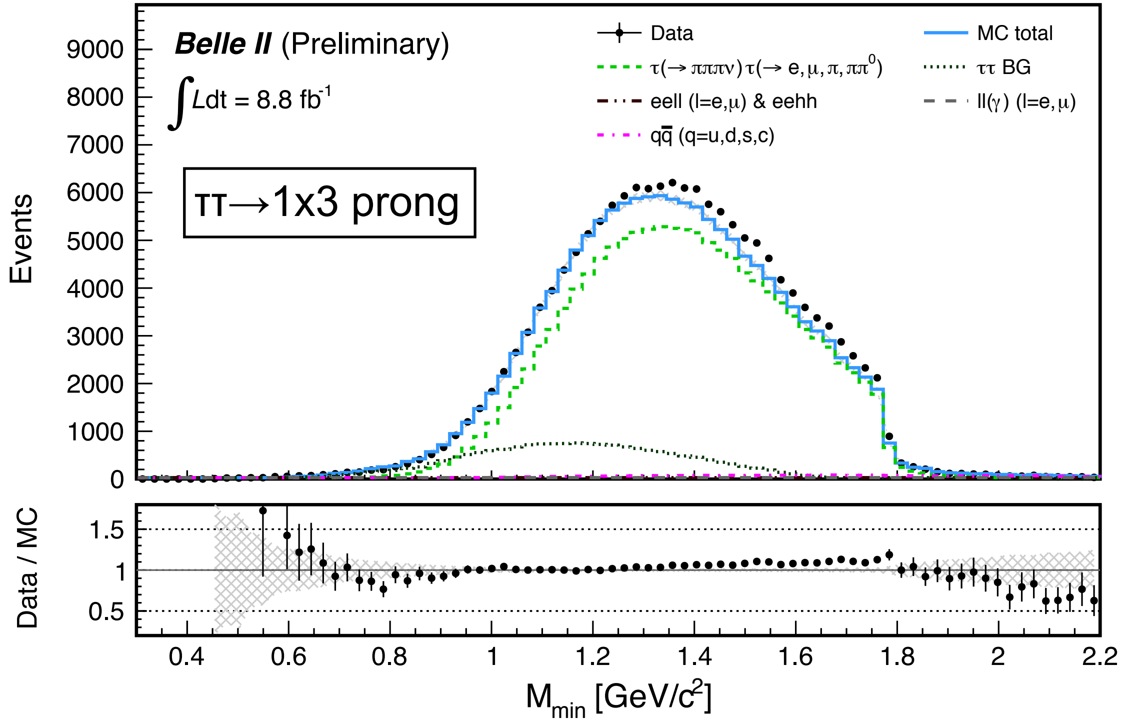
- Tau mass measurement in early Belle II data (8.8 fb-1)
- Using a pseudomass technique on $\tau \to 3\pi\nu$ decays

$$M_{min} = \sqrt{M_{3\pi}^2 + 2(E_{beam} - E_{3\pi})(E_{3\pi} - P_{3\pi})}$$

- sharp threshold behaviour in region close to m_τ



arXiv:2008.04665



- M_{min} is fitted to an empirical mass function ($P_1 \Rightarrow m_\tau$) within a 1.7-1.85 GeV window:

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

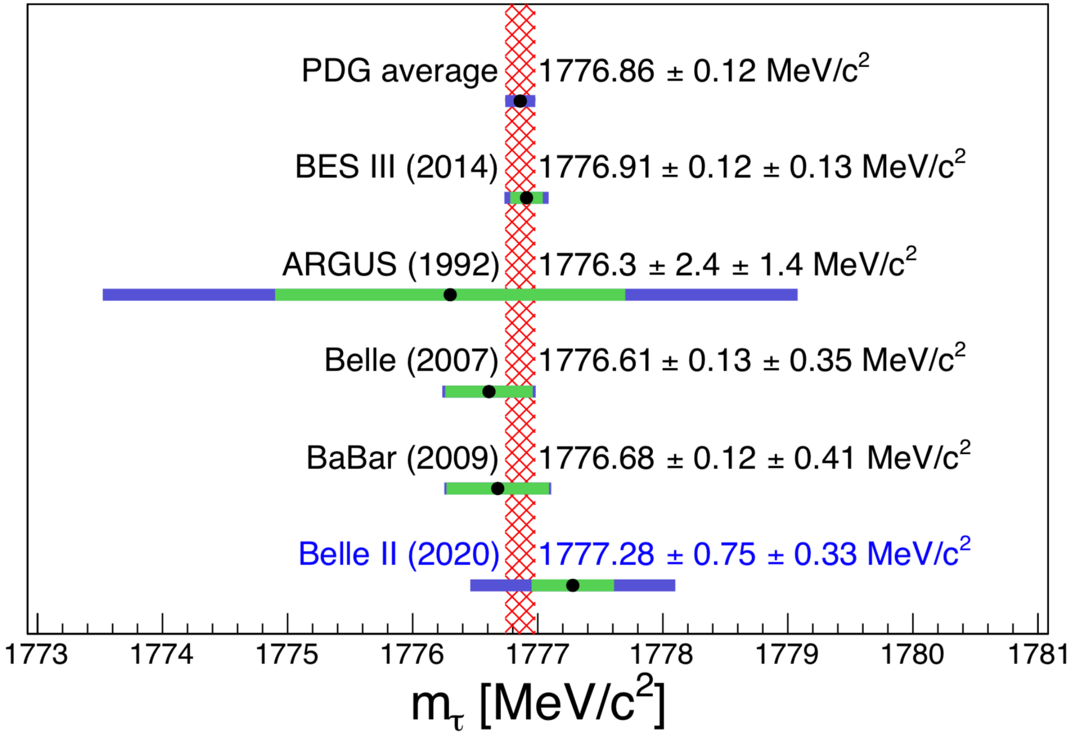
$$\boxed{m_\tau = 1777.28 \pm 0.75\ (\text{stat}) \pm 0.33\ (\text{sys})\ \text{MeV}}$$

Tau Mass Measurement

- **Belle II** in good agreement with previous measurements
- Current best result comes from **BES III** from pair production at threshold energy
- Best measurement from psuedomass technique comes from **Belle**

Systematic uncertainty	MeV/c^2
Momentum shift due to the B-field map	0.29
Estimator bias	0.12
Choice of p.d.f.	0.08
Fit window	0.04
Beam energy shifts	0.03
Mass dependence of bias	0.02
Trigger efficiency	≤ 0.01
Initial parameters	≤ 0.01
Background processes	≤ 0.01
Tracking efficiency	≤ 0.01

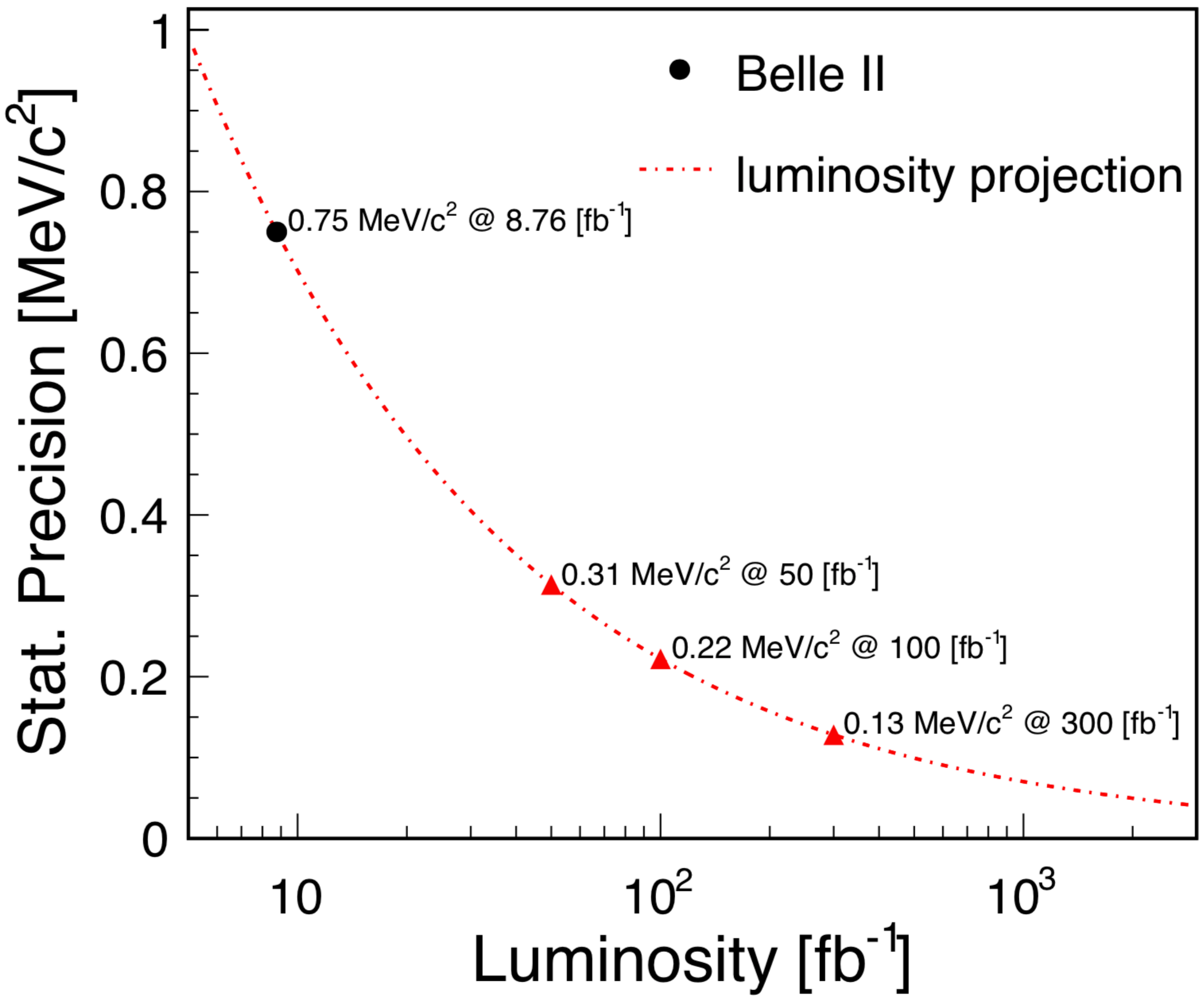
arXiv:2008.04665



- **Belle II** currently has similar systematic error as last generation B-factory results
- **B-field maps** will be updated soon, significantly reducing the dominant uncertainty

Tau Mass Prospects

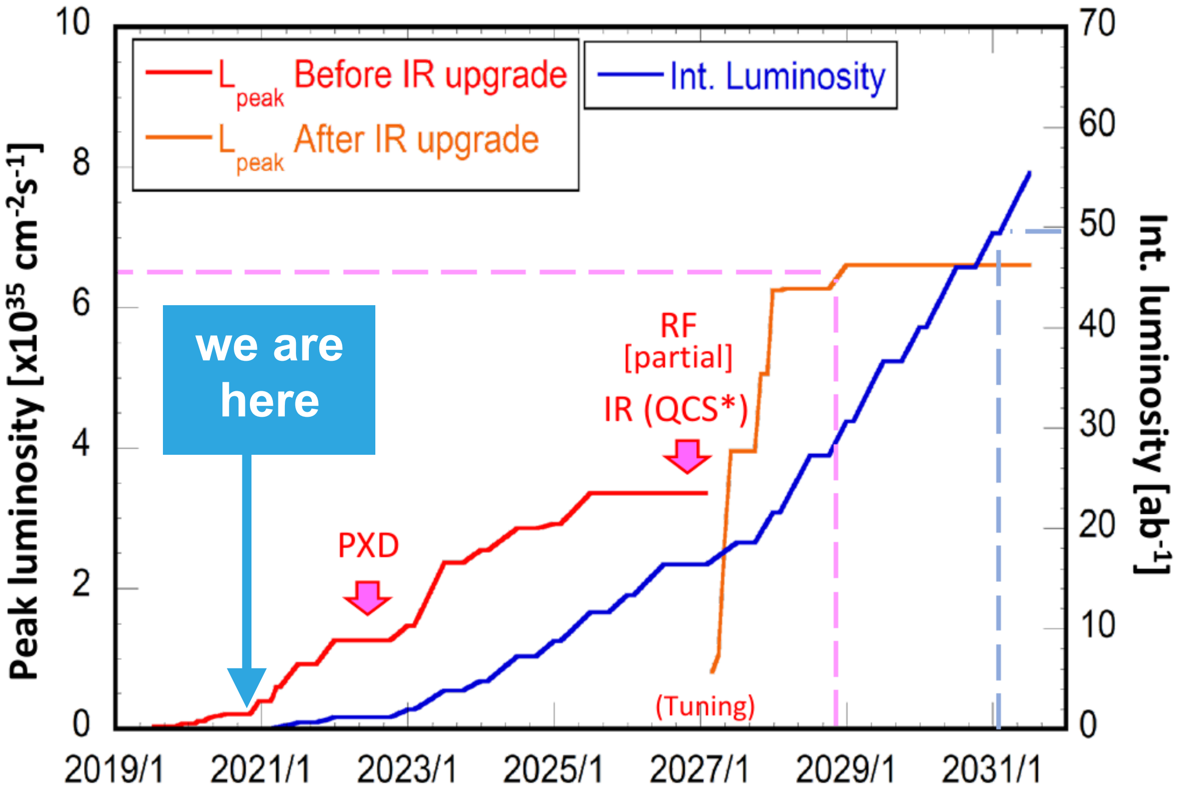
arXiv:2008.04665



Luminosity status and goals

- So far we have collected **~74 fb^{-1}** during Phase 3, with the 2020c data taking period starting this month.

- Aiming for **50 ab^{-1}** over the next ~10 years (50 x Belle dataset)



Challenges in PXD operation:

- Several modules reached the power supply limit due to increased backplane currents.

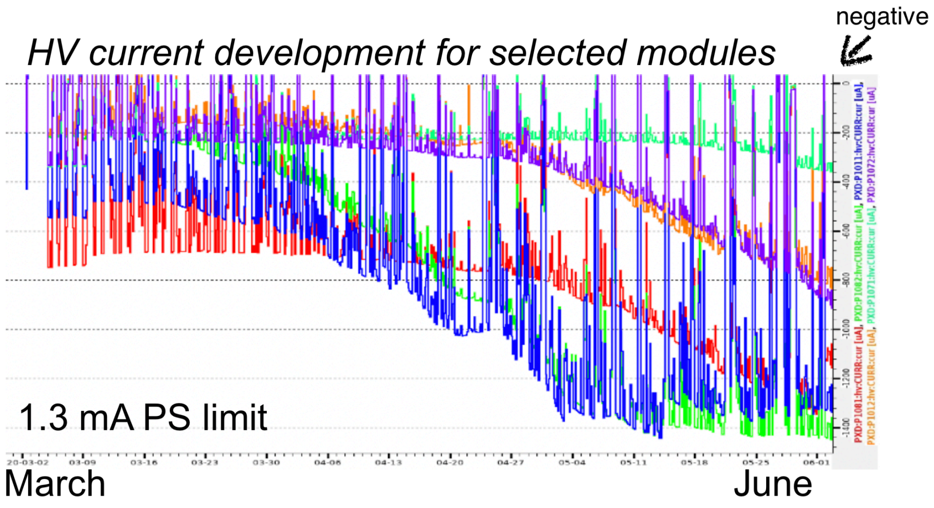
⇒ Limit was increased (>2mA) during summer shutdown.

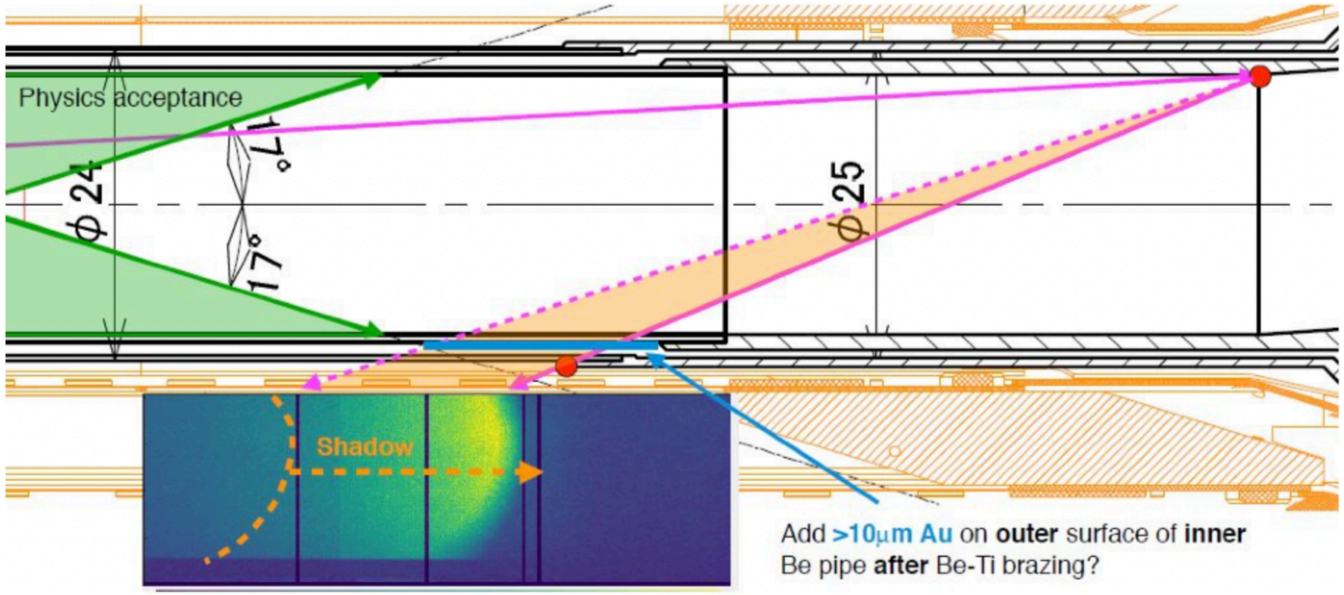
- Beam loss incidents sometimes not detected early enough. Radiation damage → inefficient rows from dead gates (~2% of full PXD).

⇒ Emergency protection scheme has since been greatly improved.

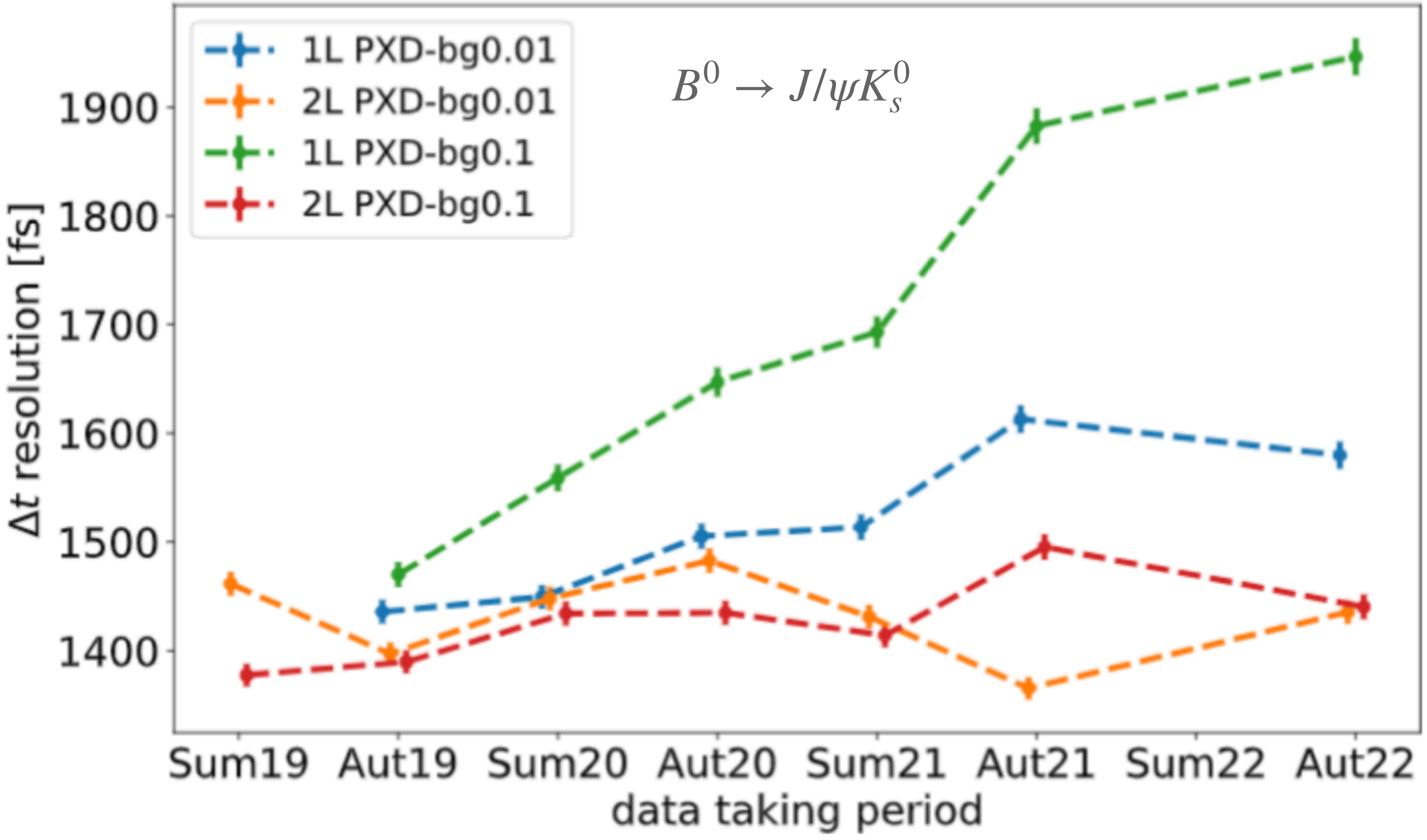
- Several modules with large Synchrotron radiation during beam injections. Could result in high occupancy and data loss.

⇒ To be studied in upcoming run period. Mitigated by new beam pipe (2022).





Impact of PXD backgrounds



- Δt resolution with projected backgrounds:
  - with single PXD layer, expect a significant degradation already in next 2 years
  - can be recovered by adding the second PXD layer