Stato dell'esperimento Belle II e primi risultati di fisica

Giacomo De Pietro

INFN ROMA TRE

for the Belle II Collaboration

Belle II

Congresso della Società Italiana di Fisica @ Online

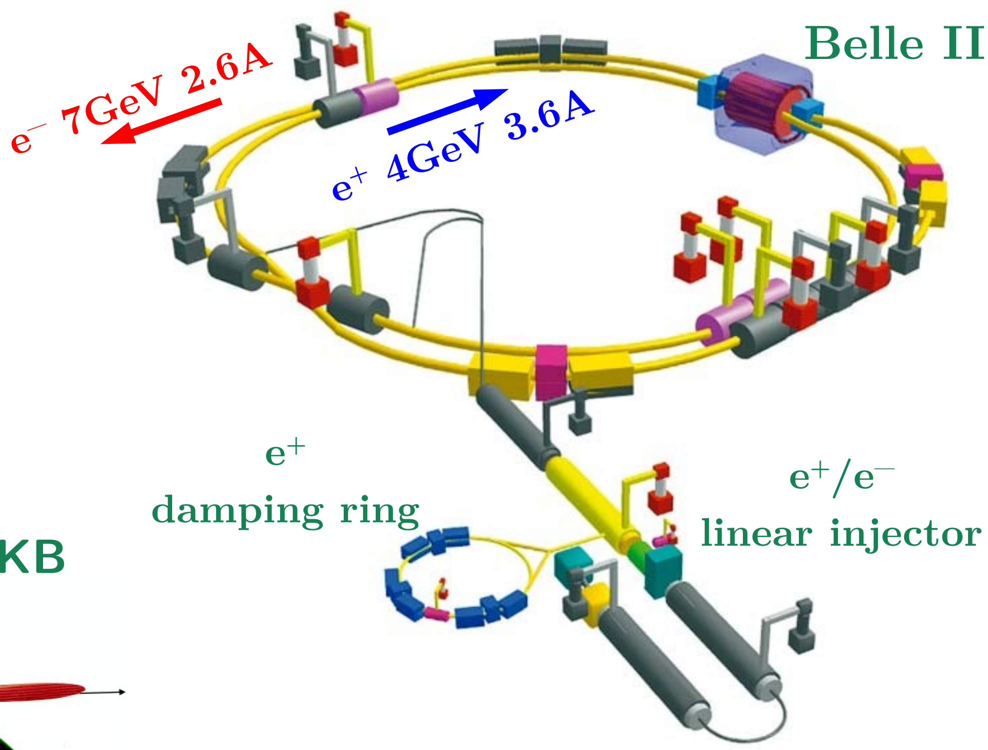
14 - 18 September 2020

SuperKEKB and Belle II

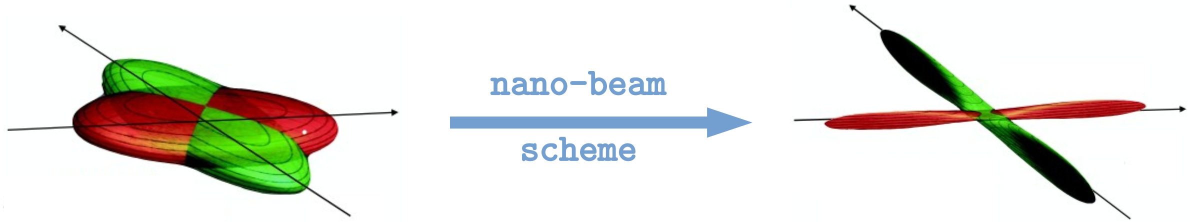
SuperKEKB: an Intensity Frontier machine

SuperKEKB is a super B-factory
located at KEK (Tsukuba, Japan)

It's an asymmetric e^+e^- collider
operating mainly at **10.58 GeV**
(**Υ(4S)**, but possible runs from Υ(2S) to Υ(6S))



KEKB | **SuperKEKB**



KEKB: I (A): ~ 1.6/1.2
β^*_y (mm): ~ 5.9/5.9

SuperKEKB: I (A): ~ 2.8/2.0
β^*_y (mm): ~ 0.27/0.3

30x peak luminosity: $6 \cdot 10^{35}$ cm^{-2} s^{-1}

SuperKEKB: an Intensity Frontier machine

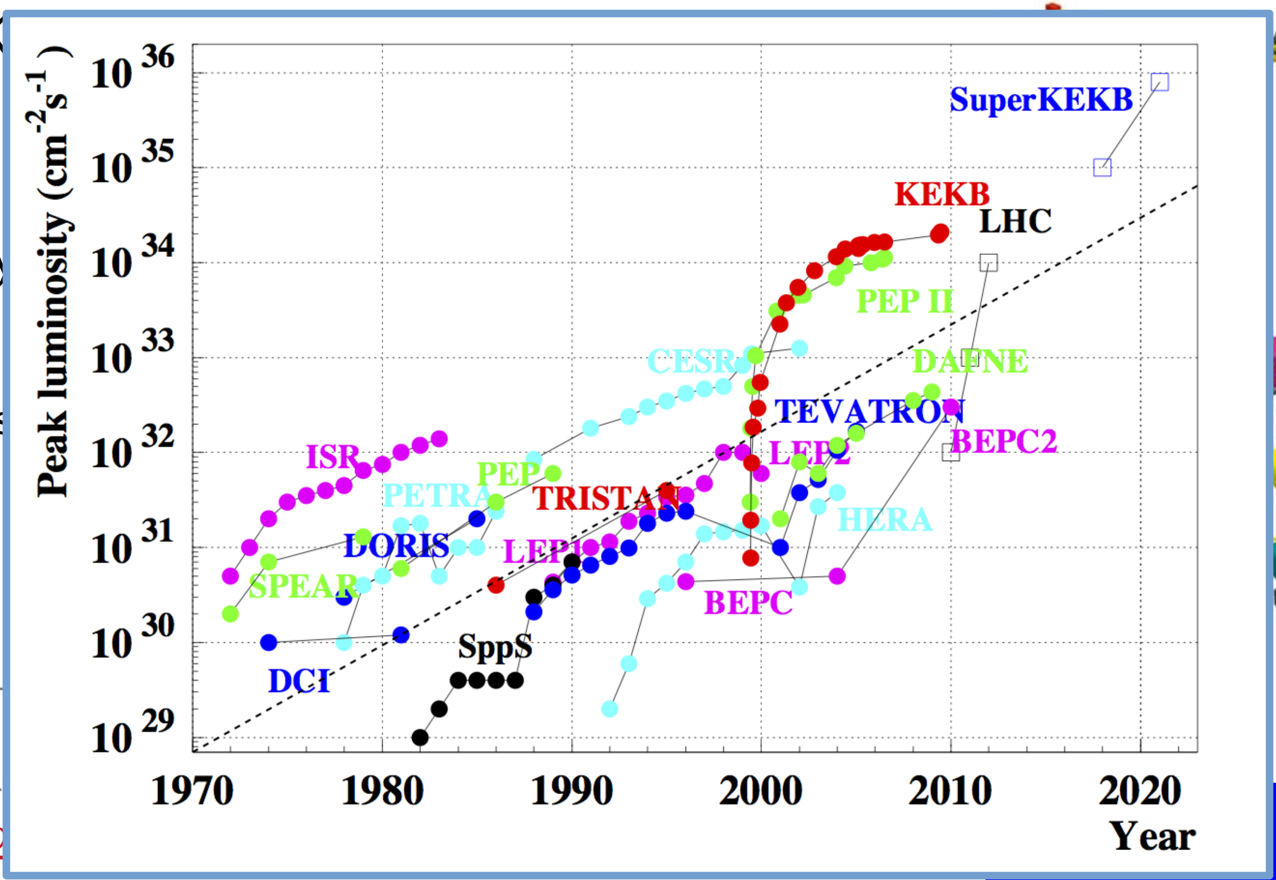
SuperKEK

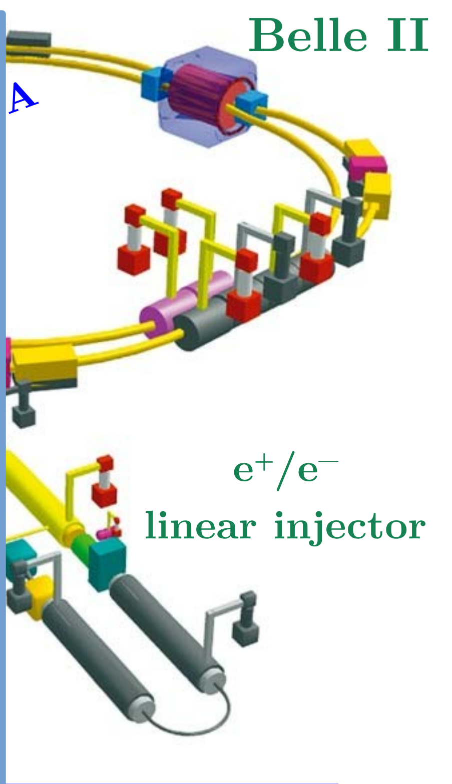
located at

It's an asy

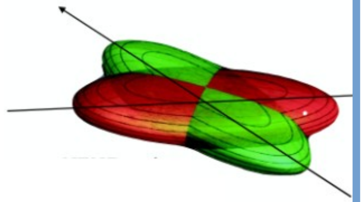
operating

(Υ(4S), but poss





KEKB



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β^*_y (mm): ~ 5.9/5.9

β^*_y (mm): ~ 0.27/0.3

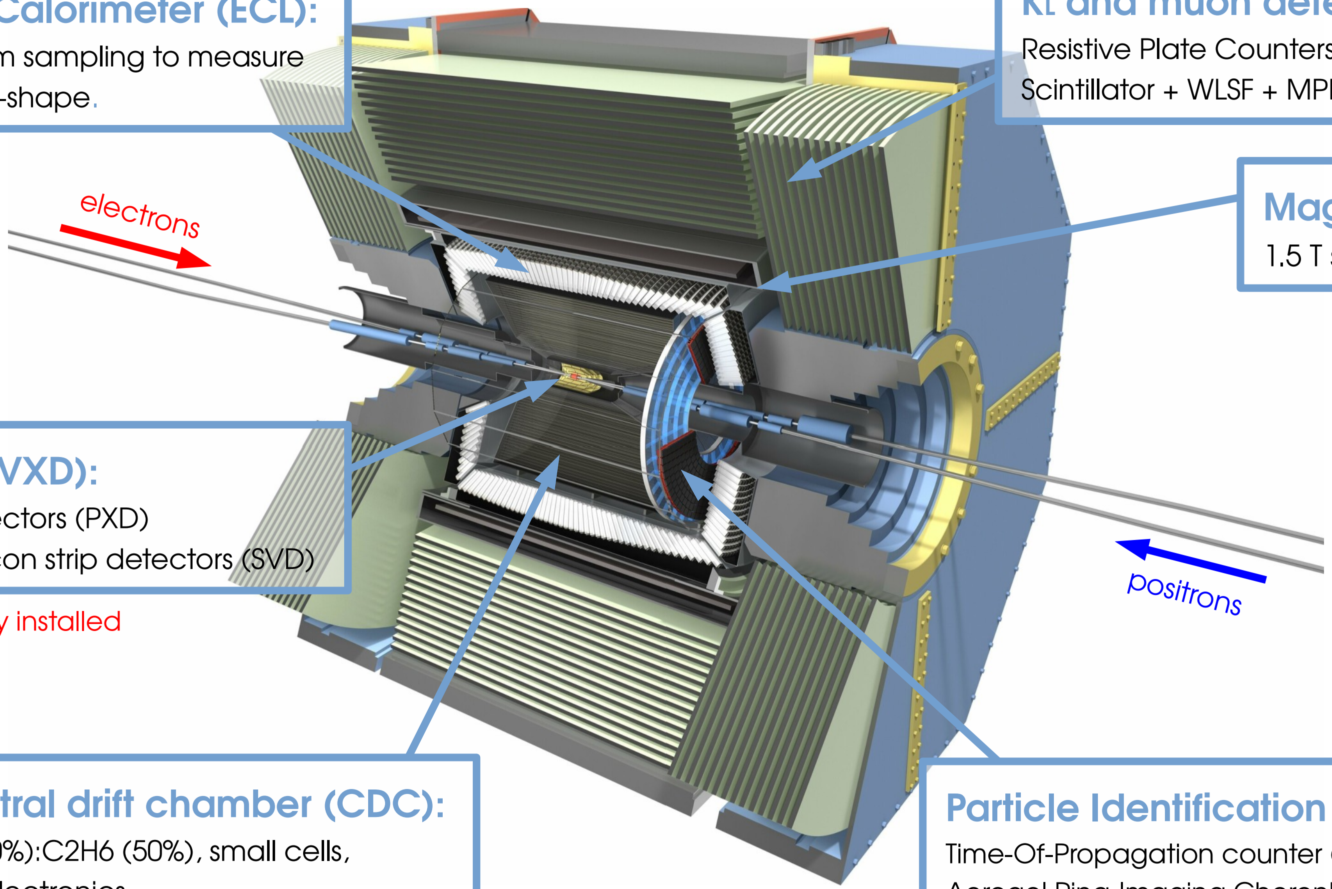
luminosity:
$6 \cdot 10^{35}$ cm^{-2} s^{-1}

Belle II detector

Electromagnetic Calorimeter (ECL):
CsI(Tl) crystals, waveform sampling to measure time, energy, and pulse-shape.

K_L and muon detector (KLM):
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (endcaps, inner barrel)

Magnet:
1.5 T superconducting



Vertex detectors (VXD):
2 layer DEPFET pixel detectors (PXD)
4 layer double-sided silicon strip detectors (SVD)

* 2nd PXD layer is partially installed

Trigger:
Hardware: < 30 kHz
Software: < 10 kHz

Central drift chamber (CDC):
He(50%):C2H6 (50%), small cells, fast electronics

Particle Identification (PID):
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)

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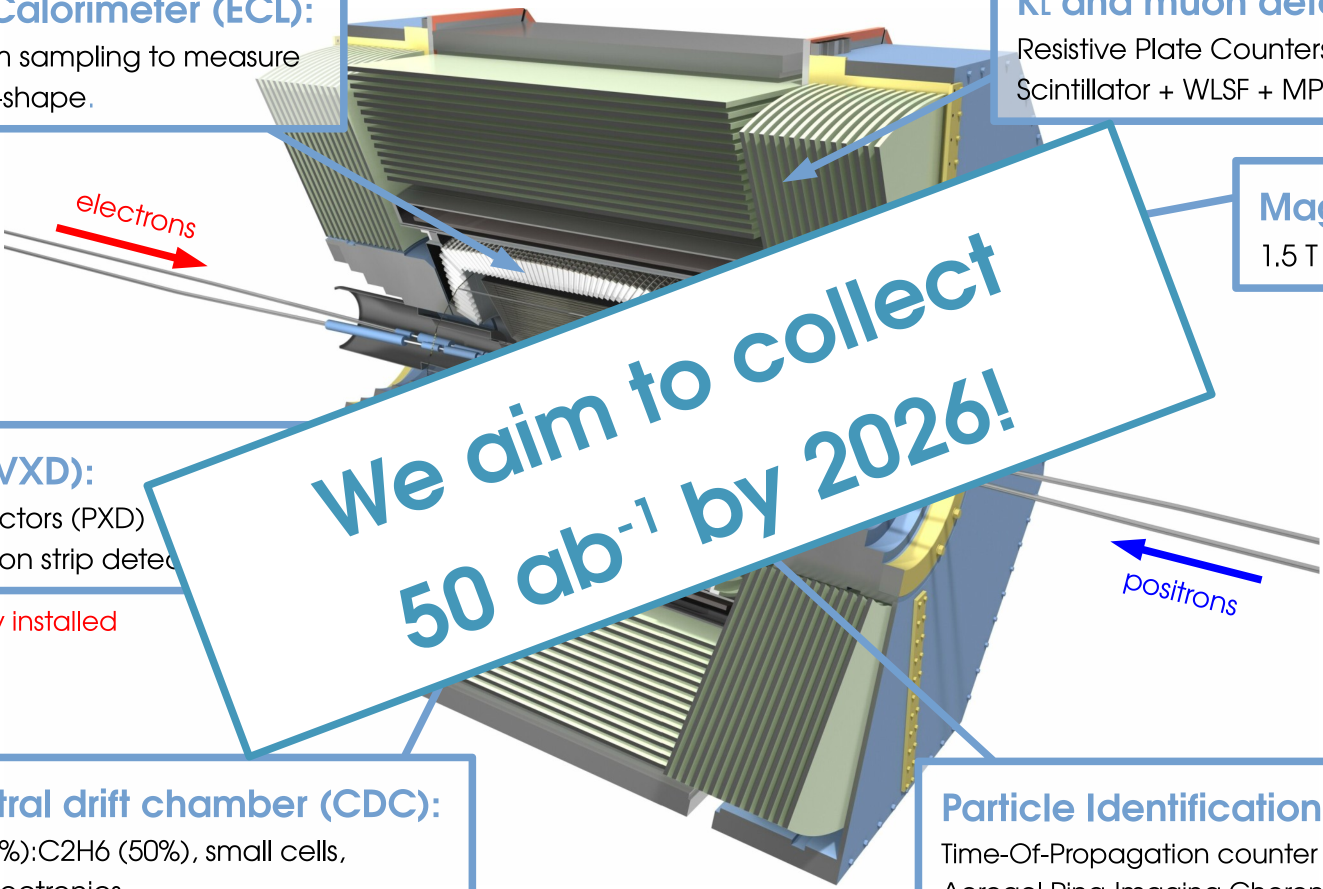

We aim to collect $50\ ab^{-1}$ by 2026!

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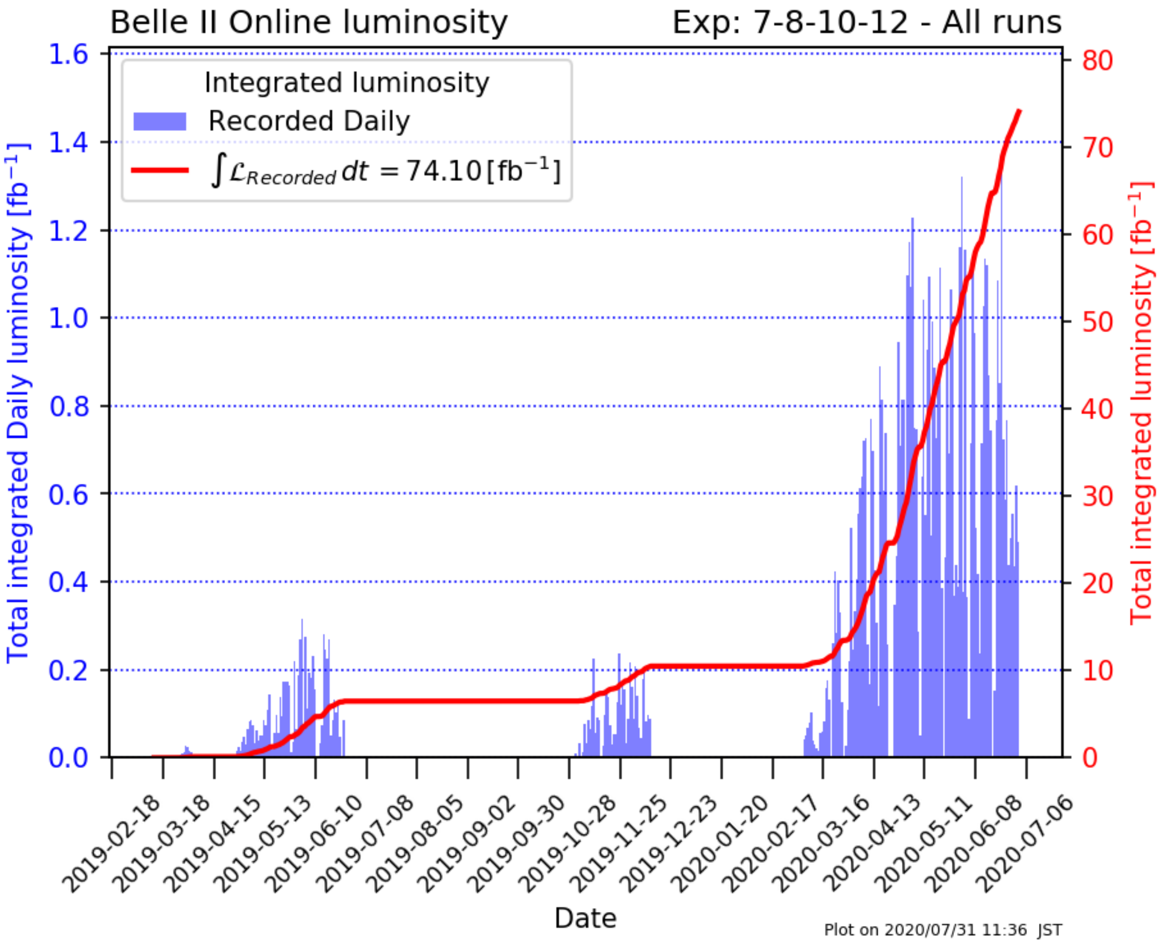
Luminosity status

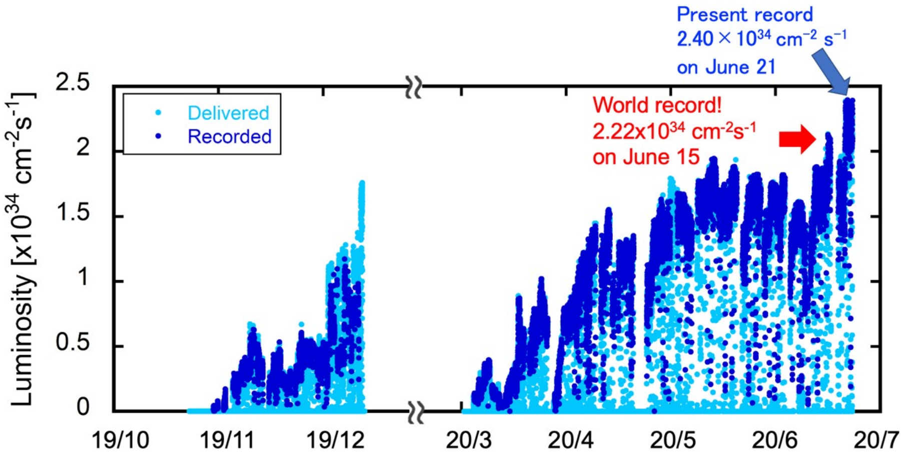


We collected:

- **0.5 fb^{-1} in 2018**;
- **74 fb^{-1} since 2019**.

On June 21st 2020, SuperKEKB set a new **luminosity world record**:

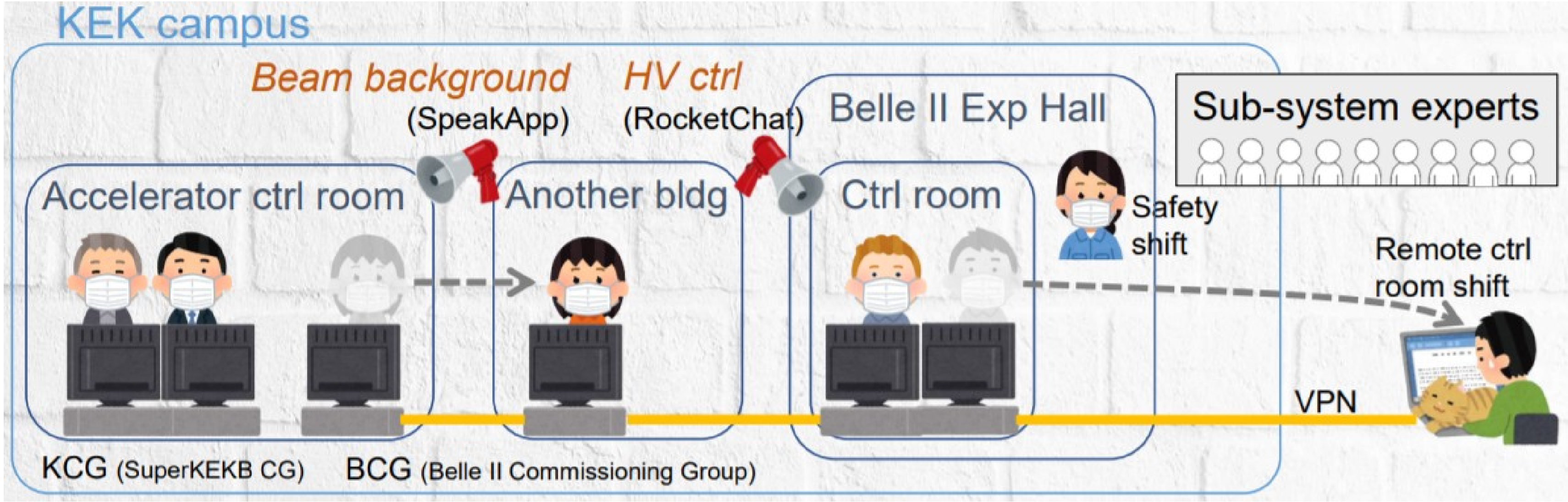
$$2.4 \cdot 10^{34}\ cm^{-2}\ s^{-1}$$



Taking data during the 2020 pandemic...

Non-stop operations with COVID-19 pandemic:

- social distancing requirements;
- strong developments for close to or fully **remote sub-system operations**;
- **huge commitments from japanese colleagues and residents in Japan**;
    - $\rightarrow$ only 40 persons on site from March to July.



courtesy of K. Matsuoka

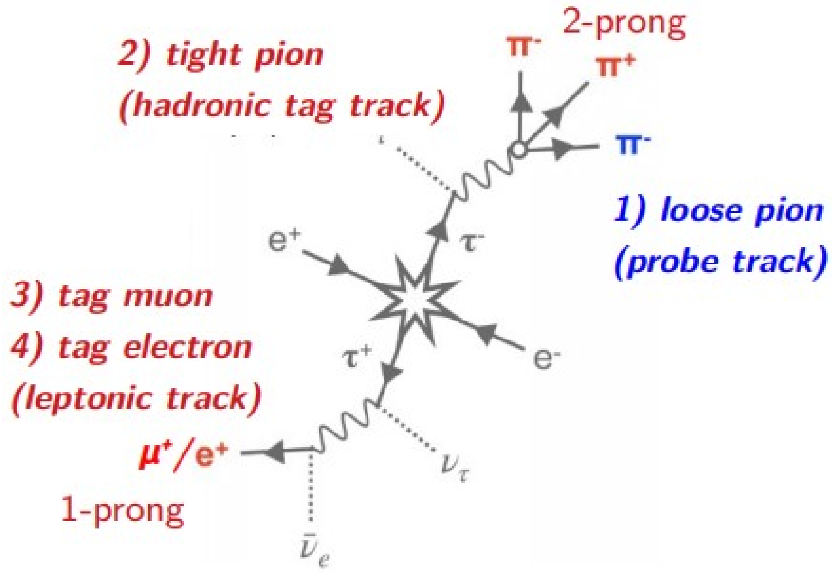
Belle II data taking efficiency: **85%**

Detector performance

Tracking performance

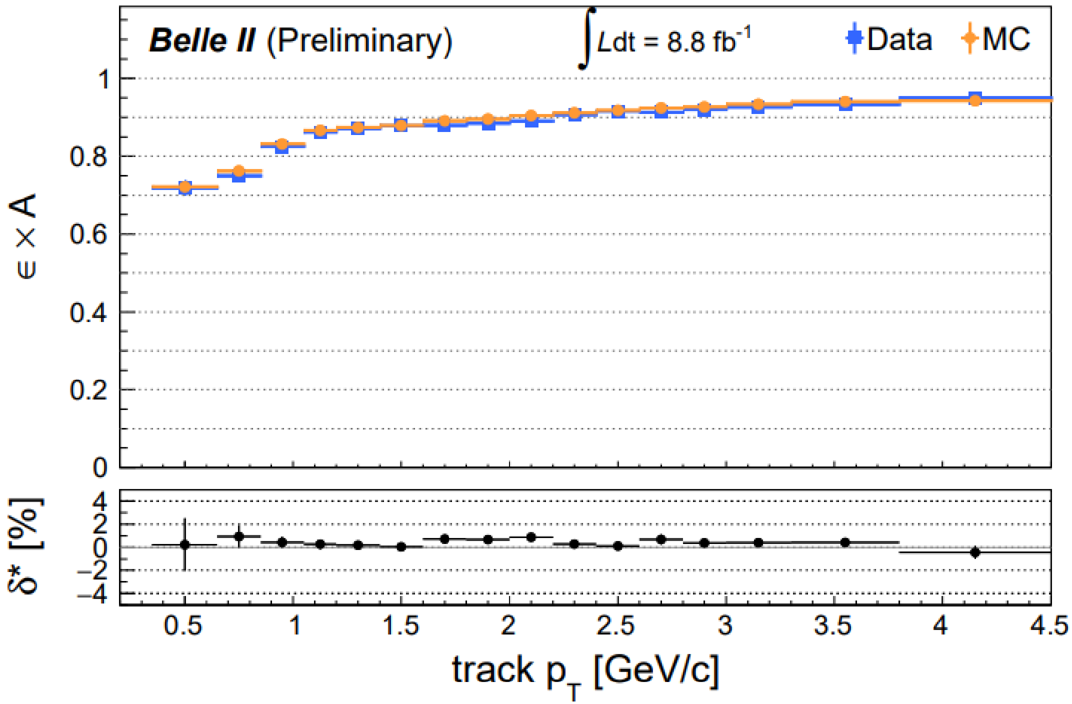
Tag & probe technique with events $e^+e^- \to \tau^+\tau^-$:

- 4 charged tracks expected;
- leptonID tags the event;
- 3 prongs provide the probe.



$\varepsilon = N_{evts}(4\ tracks)\ /\ [N_{evts}(4\ tracks) + N_{evts}(3\ tracks)]$

Track finding paper: arXiv:2003.12466
Performance plots: BELLE2-NOTE-PL-2020-014



Similar technique to evaluate **fake rate per track**:

$$r_{fake} = (0.97 \pm 0.34_{stat} \pm 0.06_{syst})\ \%$$

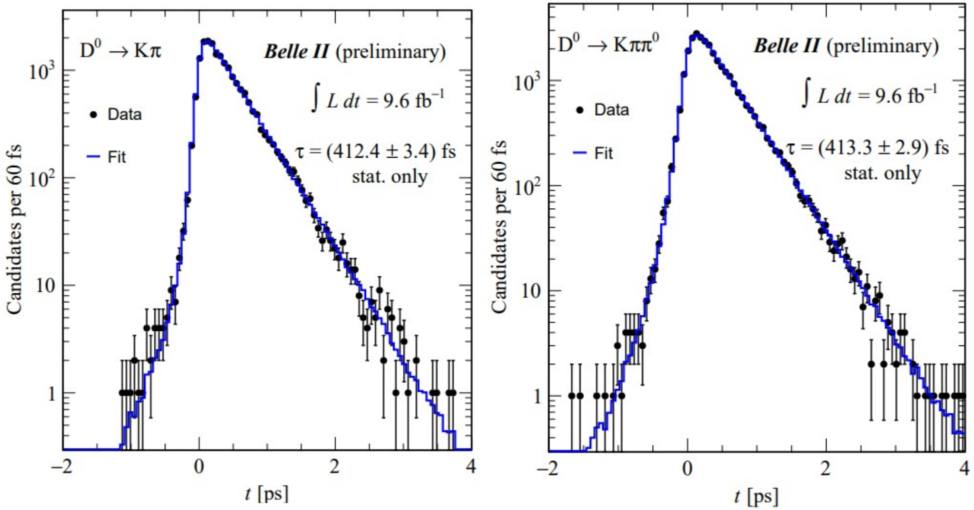
Vertexing performance

D^0 lifetime:

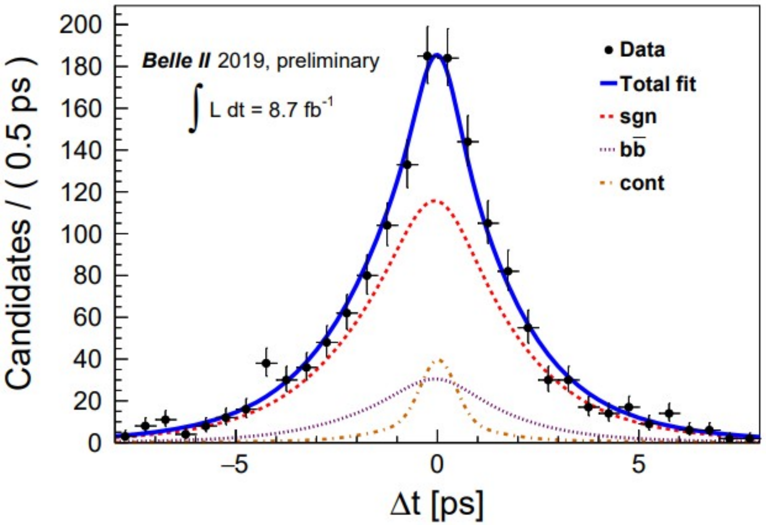
- measurement with 3 channels: $K^-\pi^+$, $K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$;
- estimated vertex resolution: $\sim$ **40 μm**;

$\rightarrow \tau(D^0) = (412.3 \pm 2.0_{stat})$ fs

(world average: (410.1 ± 1.5) fs



arXiv:2005.07507



B^0 lifetime:

- smaller boost $\beta\gamma$: 0.42 (Belle) $\rightarrow$ 0.28 (Belle II);
- average distance between B-mesons: 200 μm $\rightarrow$ 130 μm;
- hadronic channels: $B^0 \rightarrow D^{(*)-}\pi^+/\rho^+$;
- estimated resolutions: $\Delta t \sim 1$ ps $\rightarrow$ $\Delta z \sim$ **80 μm**

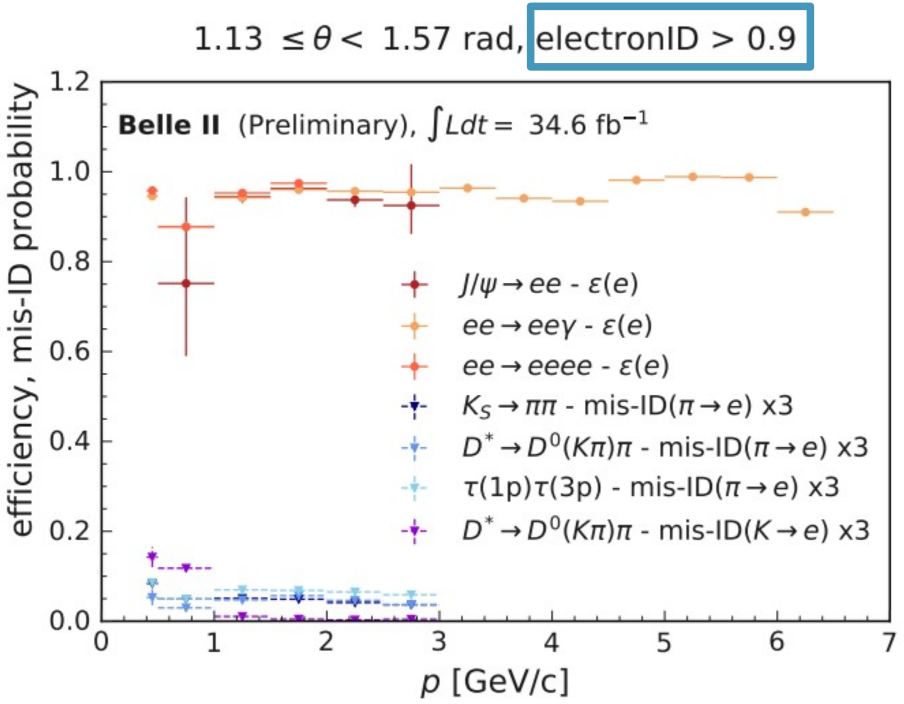
$\rightarrow \tau(B^0) = (1.48 \pm 0.28_{stat} \pm 0.06_{syst})$ ps

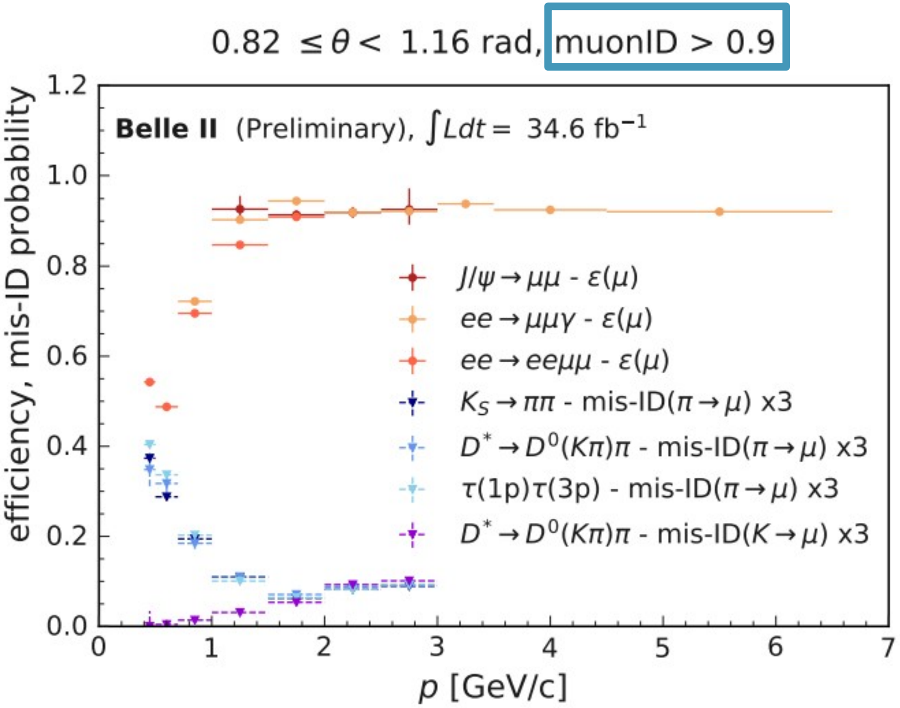
(world average: (1.519 ± 0.004) ps

Particle identification: leptons

Several fully reconstructed channels are used:

- extract both efficiency & mis-ID probability **from data**;
- measured for various leptonID and angular acceptance.



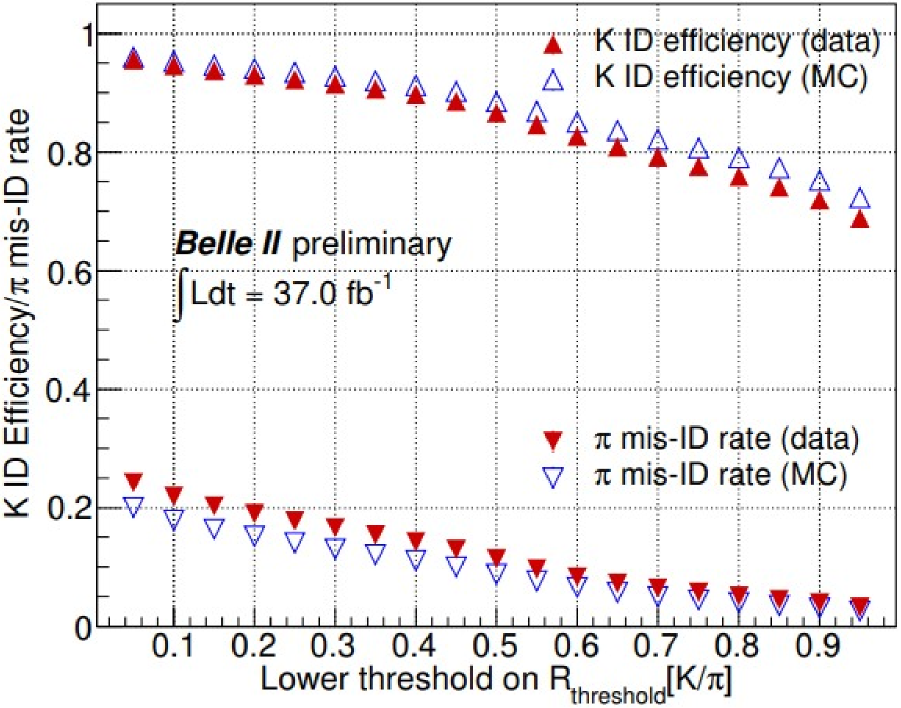


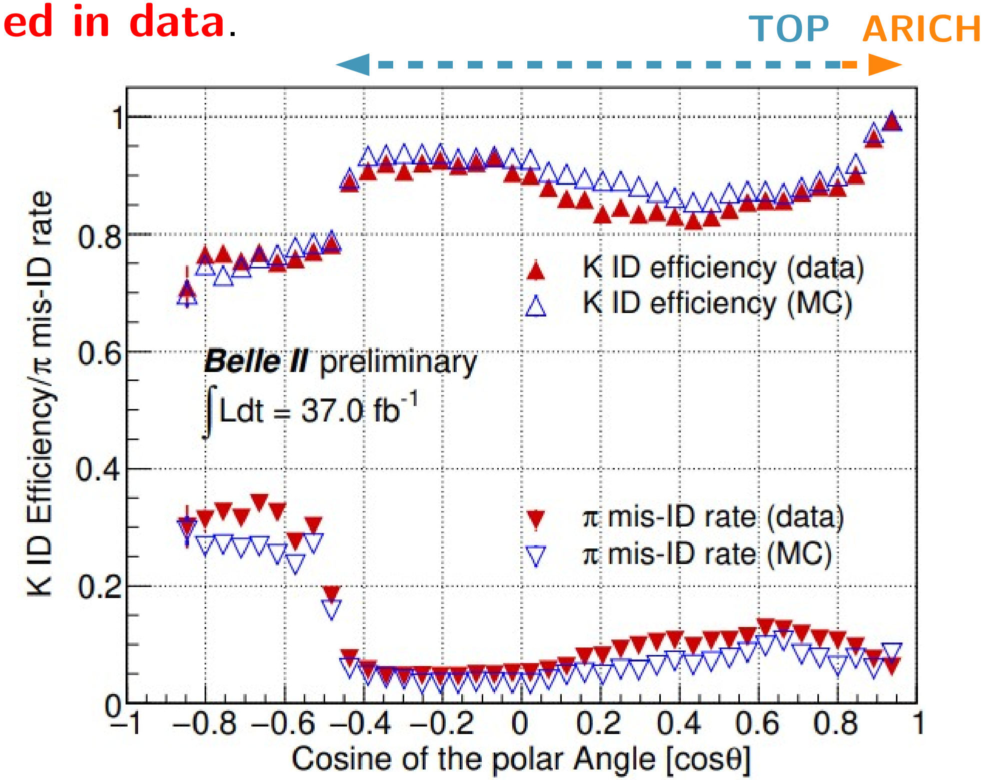
$$\text{leptonID} = \mathcal{L}_{\text{lepton}} \,/\, (\mathcal{L}_e + \mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_K + \mathcal{L}_p)$$

Particle identification: hadrons

Fully reconstructed channels are used:

- $D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\pi^+$;
- slow π tags the D^0 flavour $\rightarrow$ K and π **identified in data**.





$$K/\pi\text{-ID} = \mathcal{L}_{K/\pi} \,/\, (\mathcal{L}_\pi + \mathcal{L}_K)$$

Some physics results

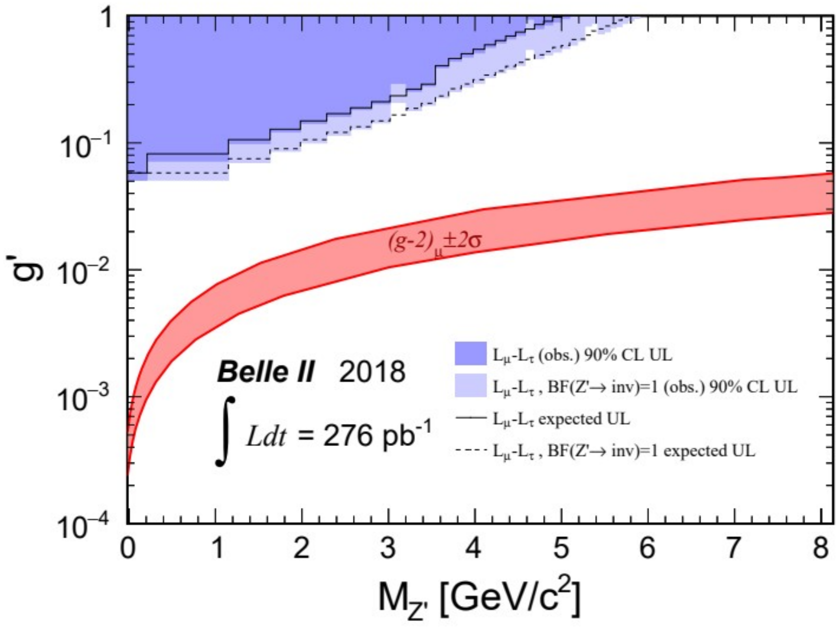
Dark sector physics and first Belle II papers

Major tool for:

- direct probe for DM and NP.

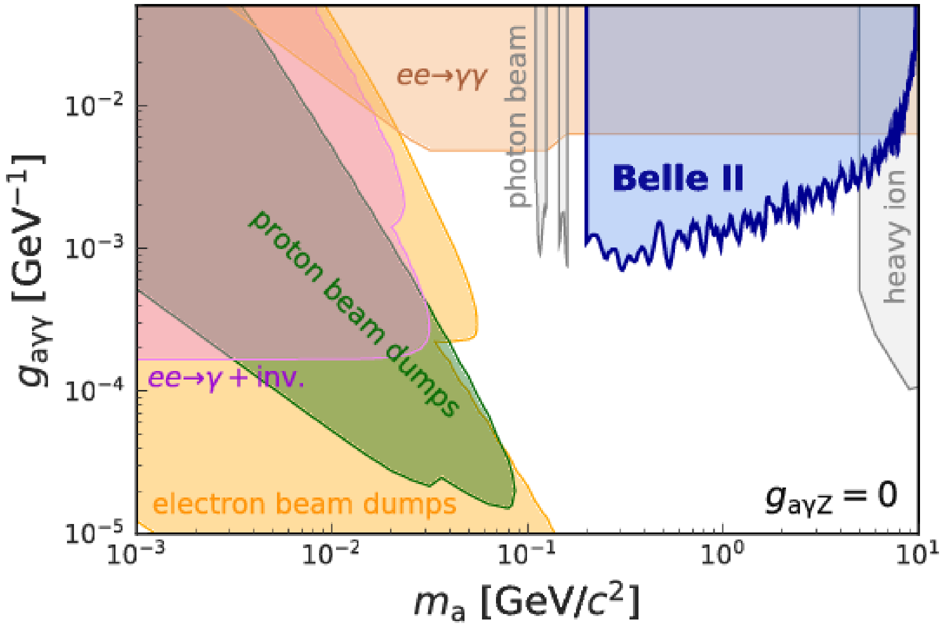
First Belle II physics papers, more infos in M. Campajola "comunicazione".

Search for an invisibly decaying Z' boson:



Phys. Rev. Lett. 124, 141801 (2020)

Search for an Axion-Like Particle decaying to γγ:

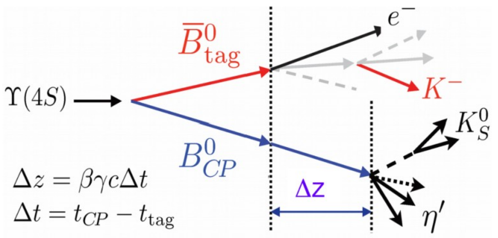


arXiv:2007.13071,
accepted few days ago by PRL

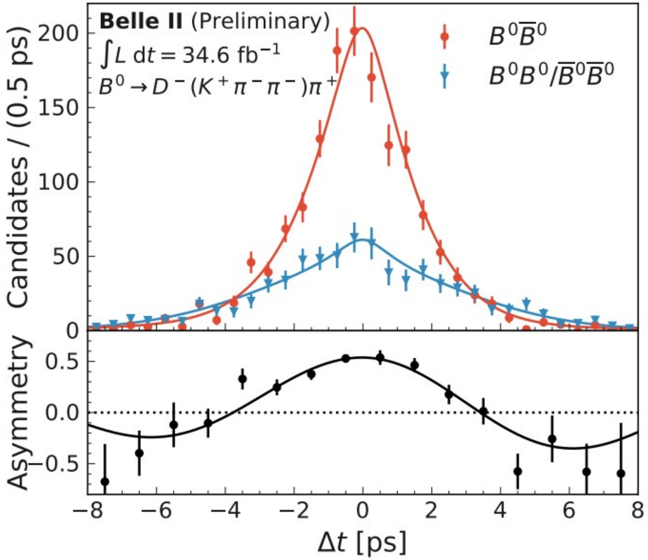
Time-dependent analysis for B-physics

Major tool for:

- SM precision test, CP violation (φ_1);
- NP sensitivity in $b \to q\bar{q}s$ transitions.



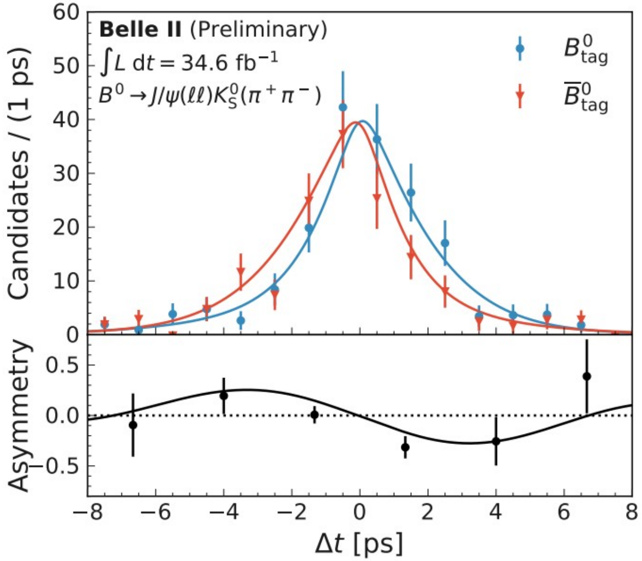
Mixing $B^0 \to D^- \pi^+$:



$\to \Delta m_d(B^0) = (0.531 \pm 0.046_{stat} \pm 0.013_{syst})$ ps

(world average: (0.5065 ± 0.019) ps)

Initial $\sin(2\varphi_1)$ measurement $B^0 \to J/\Psi\, K_S$:



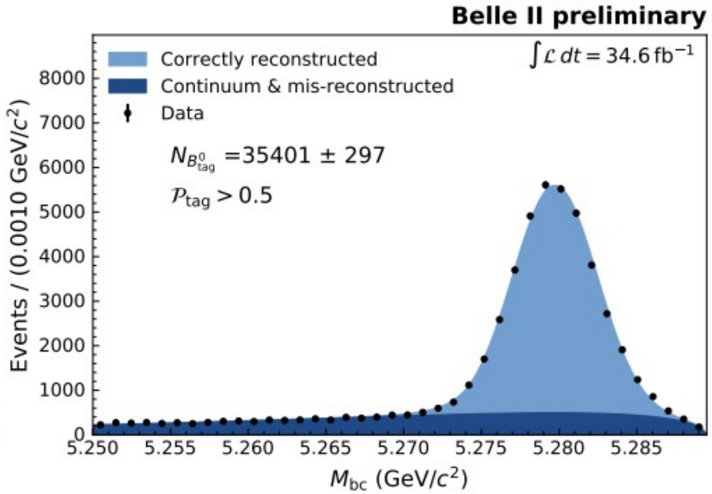
$\to \sin(2\varphi_1) = 0.55 \pm 0.21_{stat} \pm 0.04_{syst}$

(world average: (0.5065 ± 0.019) ps)

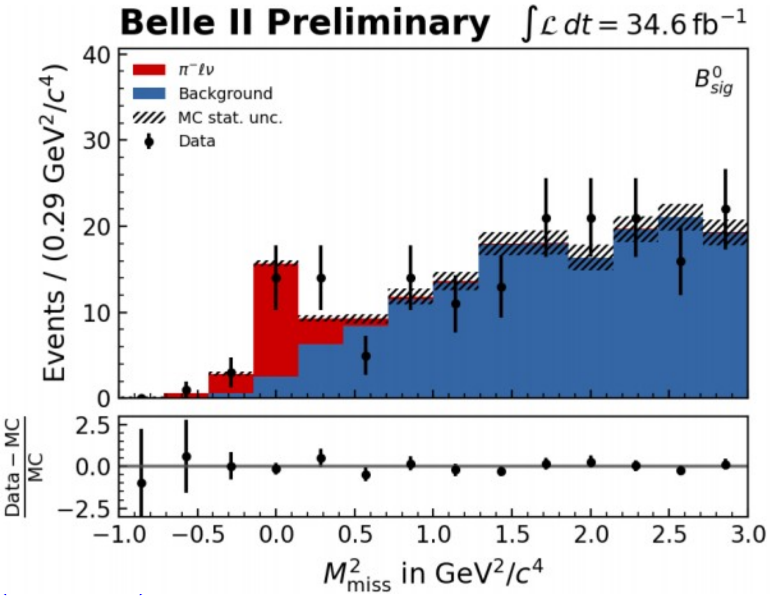
Full Event Interpretation

B exclusive reconstruction in tag-side:

- critical tool for signal channels with missing particles;
- 10^4 channels identified via successive BDTs;
  - → provides classifier with efficiency and purity calibrated on data;
- tag-side with **fully hadronic or semileptonic decays**.



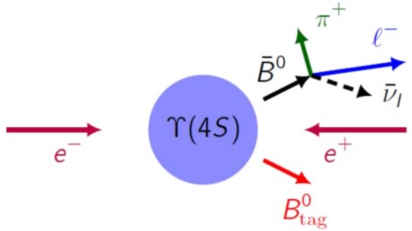
arXiv:2008.06096



arXiv:2008.08819

Rediscovery of semileptonic B decay:

- missing 4-momenta → $\mathbf{M}^2_{\mathbf{miss}}$.



$\rightarrow \mathcal{B}(\mathrm{B}^0 \rightarrow \pi^- l^+ \nu_l) = (\mathbf{1.58 \pm 0.43_{stat} \pm 0.07_{syst}}) \cdot \mathbf{10^{-4}}$

(world average: $(1.50 \pm 0.06) \cdot 10^{-4}$)

Semileptonic B-decays

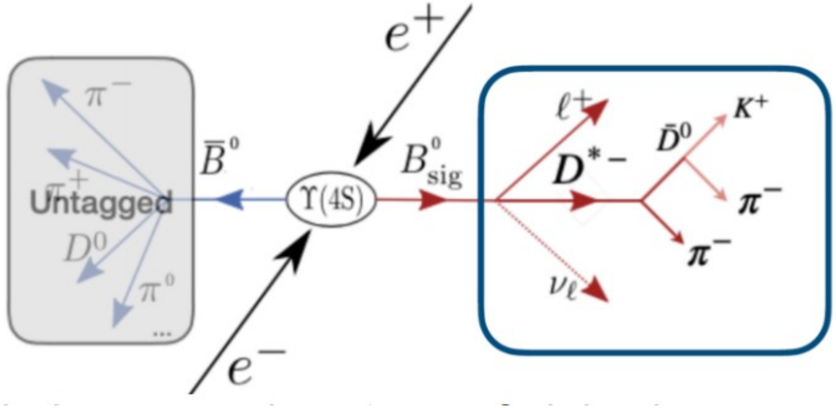
Major tool for:

- SM precision test, CKM elements $|V_{ub}|$ and $|V_{cb}|$;
- Lepton Flavour Universality test.

Untagged exclusive analysis:

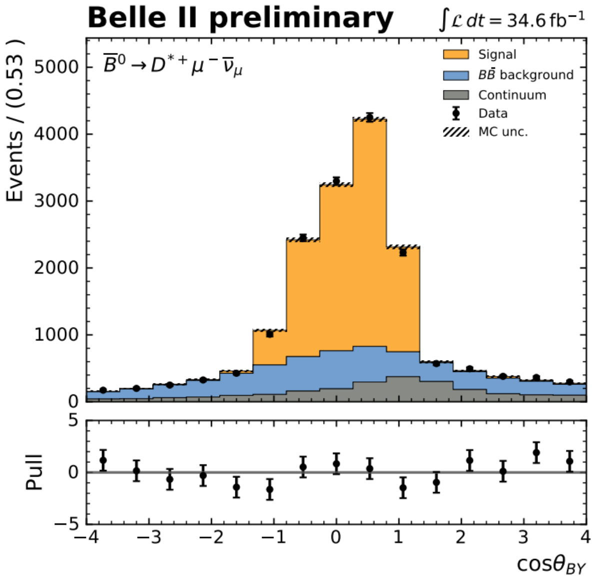
- 2 channels: $B^0 \to D^{*-} l^+ \nu_l$ and $B^+ \to \overline{D}^0 l^+ \nu_l$;

arXiv:2008.07198



$\to \mathcal{B}(B^0 \to D^{*-} l^+ \nu_l) = (4.60 \pm 0.05_{stat} \pm 0.17_{syst} \pm 0.45_{\pi s})\%$

(world average: $(5.05 \pm 0.14)\%$)

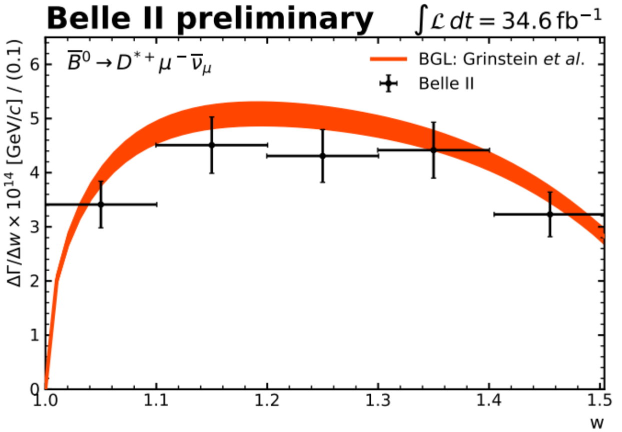


Build the $Y = D^* l$ system to separate signal from bkg.

Partial decay rates $\Delta\Gamma$ unfolded over hadronic recoil parameter w:

$$w = \frac{m_B^2 + m_{D^*}^2 - (p_B - p_{D^*})^2}{2 m_B m_{D^*}}$$

It will allow a precise $|V_{cb}|$ extraction



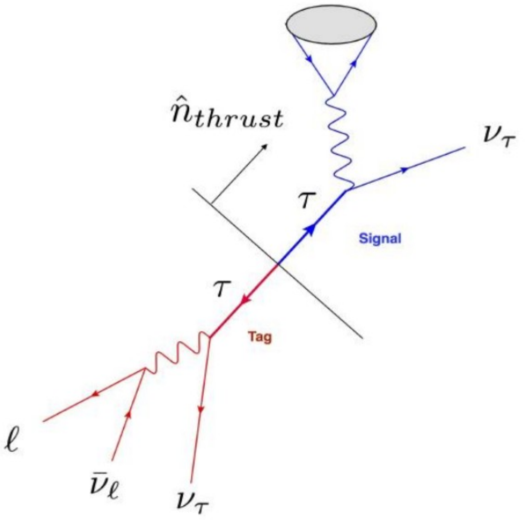
Tau physics

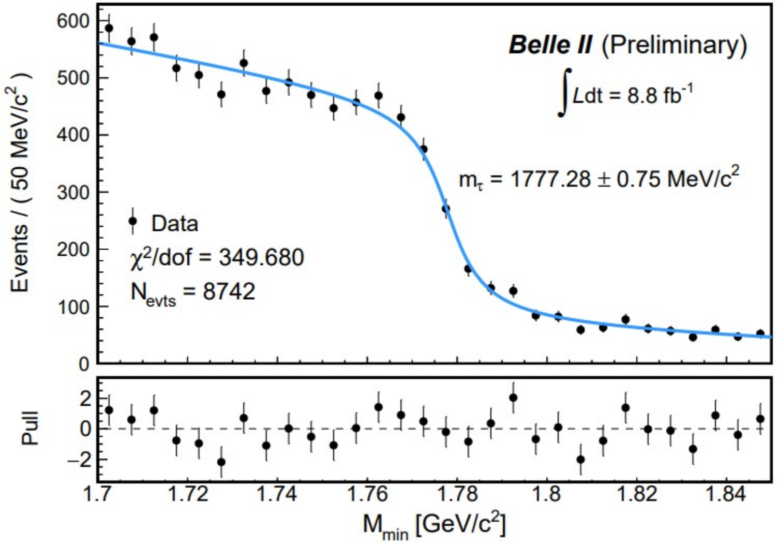
Major tool for:

- Lepton Flavour Violation with various decays;
- SM precision test by measuring τ properties.

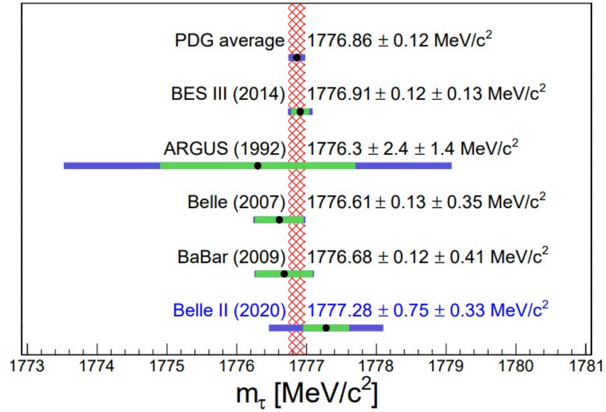
Tau mass measurement

- pseudomass technique (from ARGUS)
- event selection: 3 charged-π & 1 prong ($+\ \pi^0$)





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



arXiv:2008.06096

... and many other results!

Many other Belle II results and prospects are covered by four “comunicazioni”:

First measurements on charmless B decays at Belle II
by Sebastiano Raiz (TS)

Study of charmless decay $B \to \eta' K_S$ at Belle II
by Valeria Fioroni (PD)

Lepton Flavour Violation searches in τ decays at Belle II
by Alberto Martini (RM3)

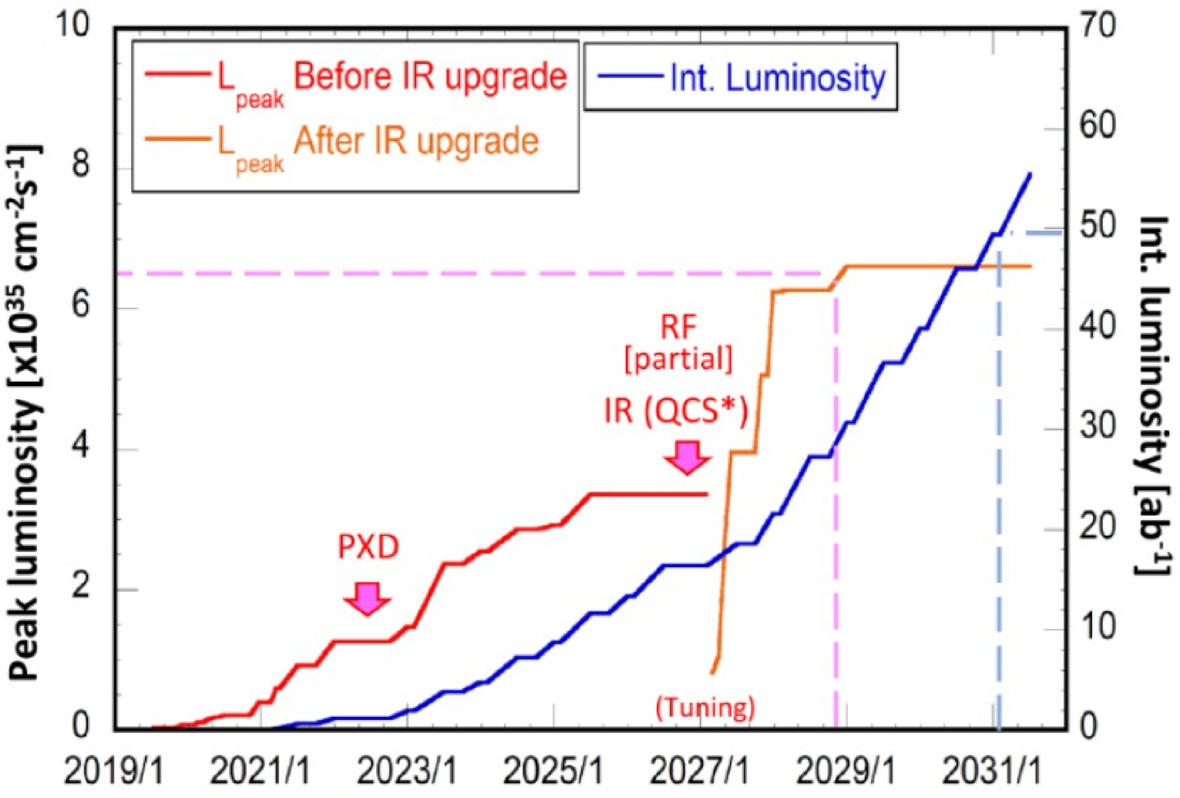
First results and prospects for dark sector searches at Belle II
by Marcello Campajola (NA)

Prospects and summary

SuperKEKB schedule overview

Until 2026:

- continuous machine tuning;
  → beam optics ($\beta_y^* \to 0.5$ mm)
- beam background mitigation (current limiting factor in 2020);
  → new collimators.



Upgrade foreseen in 2026:

- "long" shutdown;
- new final focusing magnets;
- new beam pipe for the interaction region;
- partial RF power upgrade.
  → **nominal luminosity $6 \cdot 10^{35}$ cm^{-2} s^{-1}.**

Prospects for Belle II

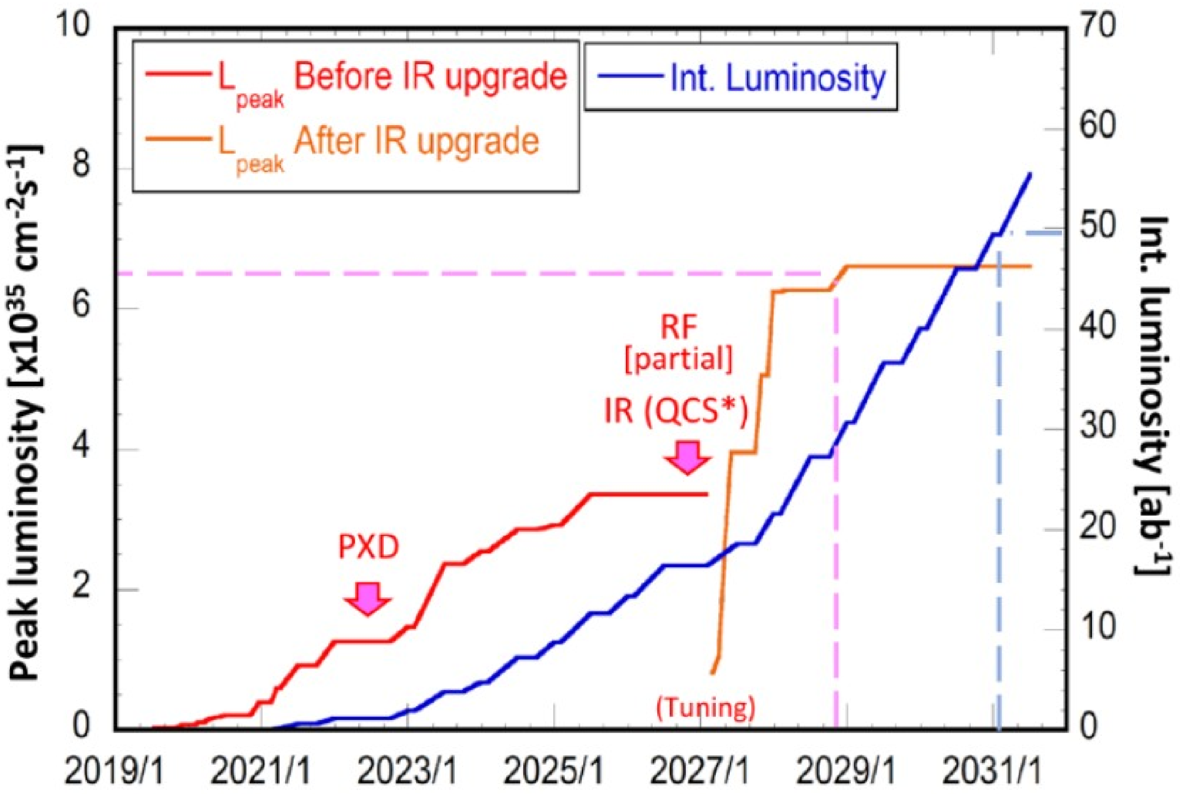
Continuous improvement with 2 major steps:

2022 shutdown:

- on-going DAQ boards replacement;
- renew PXD: complete two inner layers and with new beam-pipe shielding;
- TOP PMT replacement for longevity against the beam background.

2026 shutdown:

- opportunity for detector upgrades;
  - $\rightarrow$ better resilience from beam-background;
  - $\rightarrow$ improve some performance;
- nine Letters of Interest submitted for Snowmass 2021.



Summary

- SuperKEKB and Belle II have a clear plan to deliver and accumulate 50 ab^{-1}
- Current analysis performances similar or better than Belle
- Many measurements delivered and on-going: already some competitive results
- First two physics papers about Dark Sector searches already published

Thank you for your attention

Backup slides

SuperKEKB machine parameters

Parameter	KEKB Design	KEKB Achieved	SuperKEKB Design
Energy (GeV) (LER/HER)	3.5/8.0	3.5/8.0	4.0/7.0
β_y^* (mm)	10/10	5.9/5.9	0.27/0.30
β_x^* (mm)	330/330	1200/1200	32/25
ε_x (nm)	18/18	18/24	3.2/5.3
$\frac{\varepsilon_y}{\varepsilon_x}$ (%)	1	0.85/0.64	0.27/0.24
σ_y (μm)	1.9	0.94 → 1/20 →	0.048/0.062
ξ_y	0.052	0.129/0.090	0.09/0.081
σ_z (mm)	4	6/7	6/5
I_{beam} (A)	2.6/1.1	1.64/1.19 → x2 →	3.6/2.6
$N_{bunches}$	5000	1584	2500
Luminosity ($10^{34} cm^{-2} s^{-1}$)	1.0	2.11 → x40 →	80

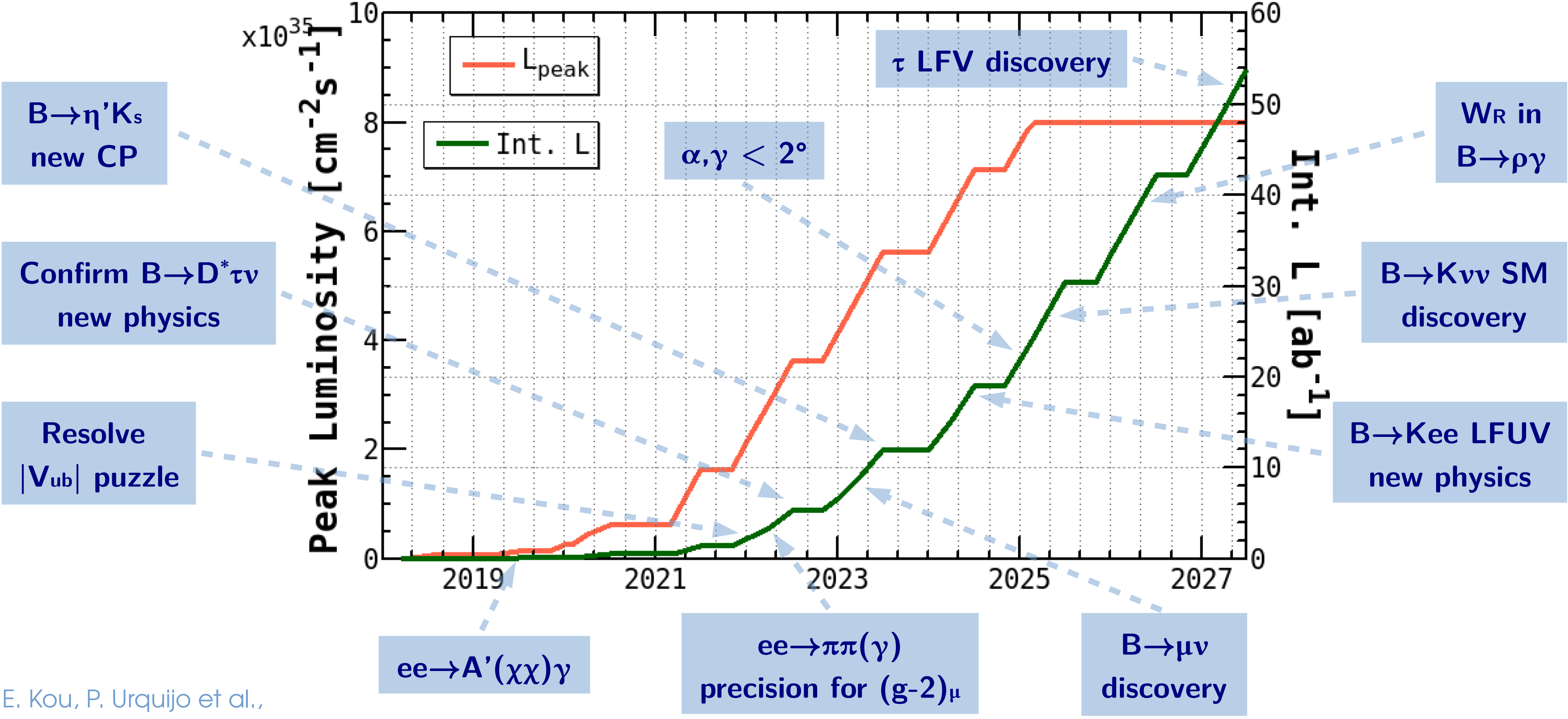
$$L = \frac{\gamma_\pm}{2er_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_{y\pm}}}\right)$$

Cross sections at a B-factory

Physics process	Cross section [nb]	Selection Criteria	Reference
$\Upsilon(4S)$	1.110 ± 0.008	-	[2]
$u\bar{u}(\gamma)$	1.61	-	KKMC
$d\bar{d}(\gamma)$	0.40	-	KKMC
$s\bar{s}(\gamma)$	0.38	-	KKMC
$c\bar{c}(\gamma)$	1.30	-	KKMC
$e^+e^-(\gamma)$	300 ± 3 (MC stat.)	$10° < \theta_e^* < 170°$, $E_e^* > 0.15$ GeV	BABAYAGA.NLO
$e^+e^-(\gamma)$	74.4	$p_e > 0.5$ GeV/c and e in ECL	-
$\gamma\gamma(\gamma)$	4.99 ± 0.05 (MC stat.)	$10° < \theta_\gamma^* < 170°$, $E_\gamma^* > 0.15$ GeV	BABAYAGA.NLO
$\gamma\gamma(\gamma)$	3.30	$E_\gamma > 0.5$ GeV in ECL	-
$\mu^+\mu^-(\gamma)$	1.148	-	KKMC
$\mu^+\mu^-(\gamma)$	0.831	$p_\mu > 0.5$ GeV/c in CDC	-
$\mu^+\mu^-\gamma(\gamma)$	0.242	$p_\mu > 0.5$ GeV in CDC, $\geq 1\ \gamma$ ($E_\gamma > 0.5$ GeV) in ECL	-
$\tau^+\tau^-(\gamma)$	0.919	-	KKMC
$\nu\bar{\nu}(\gamma)$	0.25×10^{-3}	-	KKMC
$e^+e^-e^+e^-$	39.7 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5$ GeV/c^2	AAFH
$e^+e^-\mu^+\mu^-$	18.9 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5$ GeV/c^2	AAFH

E. Kou, P. Urquijo et al., arXiv:1808.10567

A rich program for many reaches



E. Kou, P. Urquijo et al., arXiv:1808.10567

Z' to invisible

References:
Shuve et al. (2014), arXiv:1403.2727
Altmannshofer et al. (2016) arXiv:1609.04026

A bit of Theory

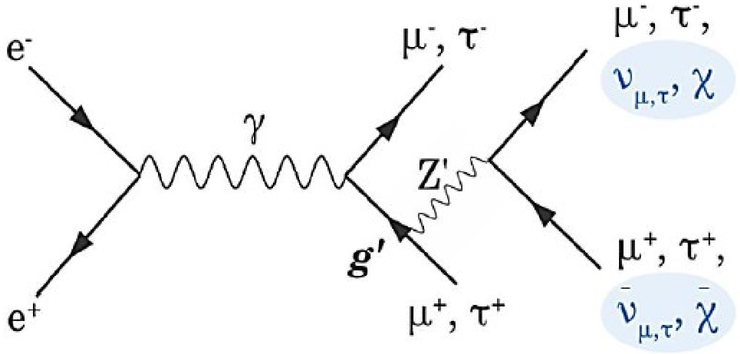
New light gauge boson Z' coupling only to the 2nd and 3rd generation of leptons ($L_\mu - L_\tau$ model);

This model may explain:

- DM puzzle;
- $(g\text{-}2)_\mu$ anomaly;
- $B \to K(^*)\mu\mu$, R_K, R_{K^*} anomalies;

Several experimental signature:

- Visible decay into a muon/tau pair. (constrained by BaBar)
- Invisible decay into SM neutrinos or DM if kinematically accessible, e.g., sterile neutrinos, light Dirac fermions. (Never explored before)



@ Belle II: looking for an invisibly decaying Z' produced with a pair of muons.

$$e^+e^- \to \mu^+\mu^- Z'$$
$\hookrightarrow$ *invisible*

Looking for:

- A peak in the mass distribution of the recoiling system against $\mu\mu$ pair;
- Nothing else in the rest of event

4

SIF 2020 – First results and prospects for Dark Sector searches at Belle II (M. Campajola)

Z' to invisible

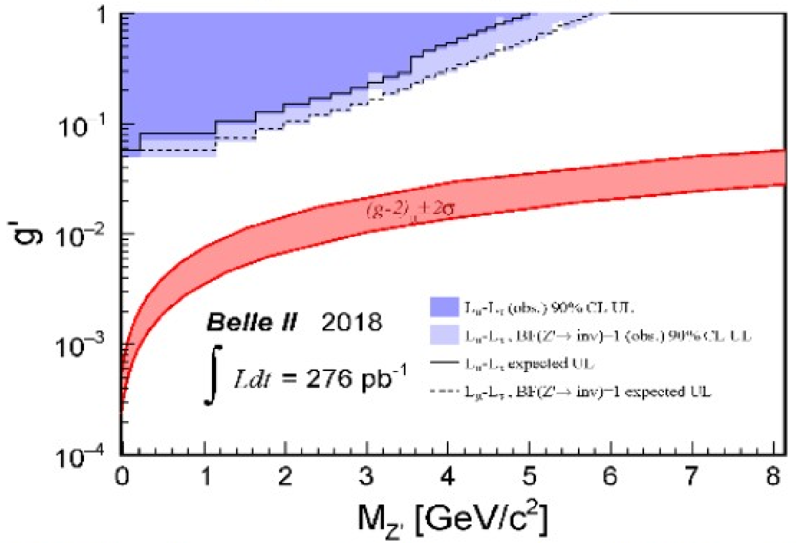
Results

Measurement performed with 2018 pilot run data.

- First results ever for the Z' to invisible decay.
- Searched also for a LFV Z' in $e\mu + missing$ final state.

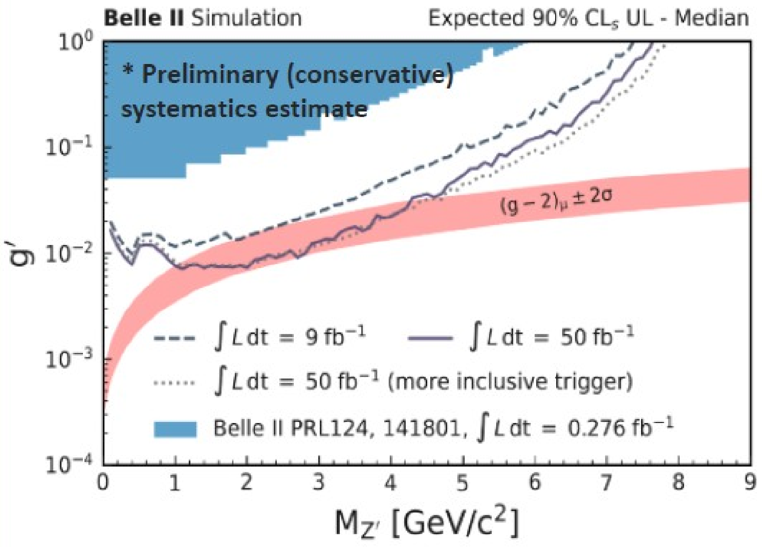
First physics paper by Belle II
[PRL 124 (2020) 141801](PRL 124 (2020) 141801)

90% CL upper limit on the g' coupling constant.



Short term luminosity projection with new data (2019/20)

- Starting to probe the $(g-2)_\mu$ band



SIF 2020 – First results and prospects for Dark Sector searches at Belle II (M. Campajola)

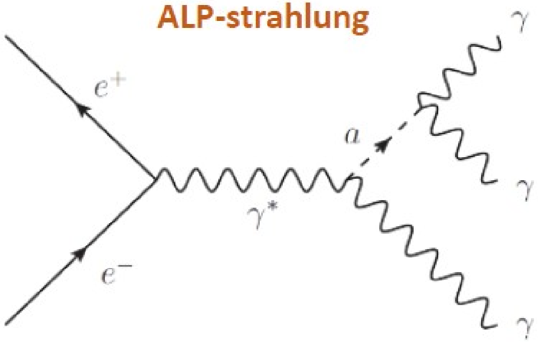
Axion Like Particles

A bit of theory

Axion Like Particles (ALPs) are pseudo-scalars particles (*a*) that couple to bosons.

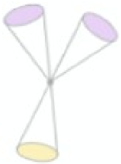
- They can be DM candidates or mediators and appear in many BSM scenarios.

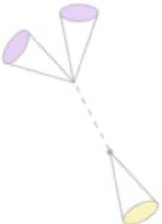
ALP-strahlung



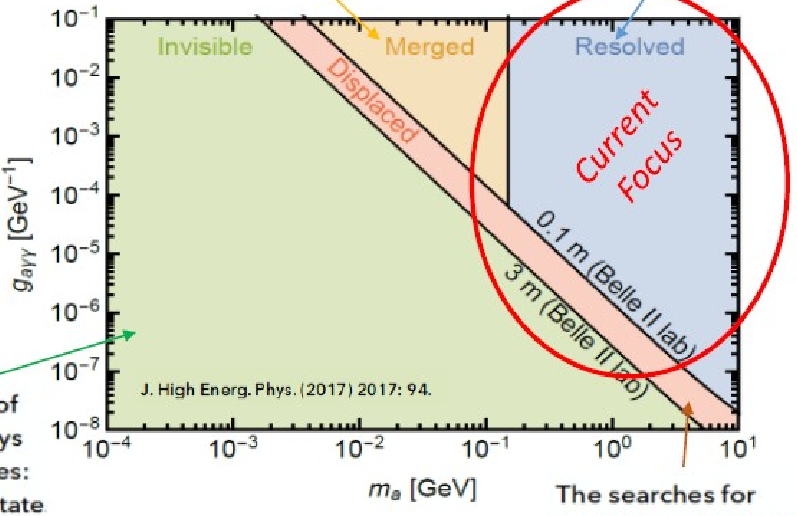
Two of the photons overlap or **merge**.

Three **resolved**, high energetic photons.





ALP decays outside of the detector or decays into **invisible** particles: Single photon final state



The searches for invisible and visible ALP decays veto this region.

@ Belle II exploring photon coupling $g_{a\gamma\gamma}$ in ALP-strahlung
First search at B-factories.

Exploring the 3γ resolved final state:

- 3γ that add up to the beam energy;
- bump on di-photon mass;

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SIF 2020 – First results and prospects for Dark Sector searches at Belle II (M. Campajola)

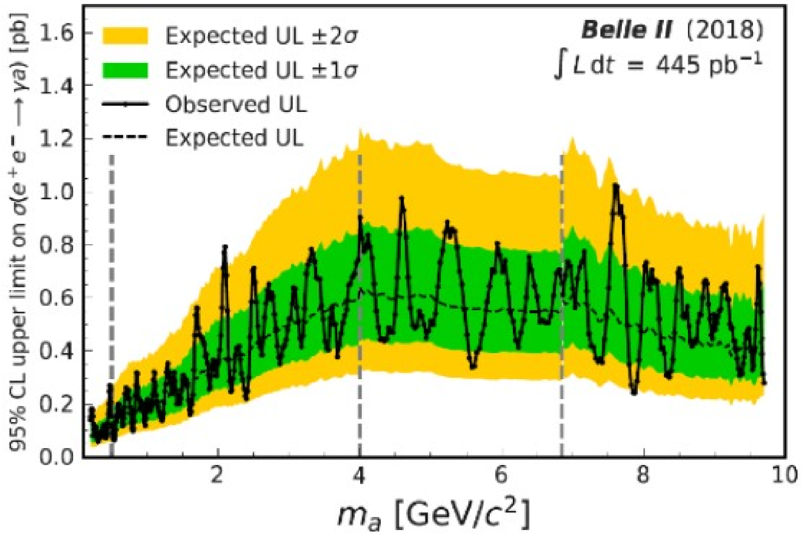
Axion Like Particles

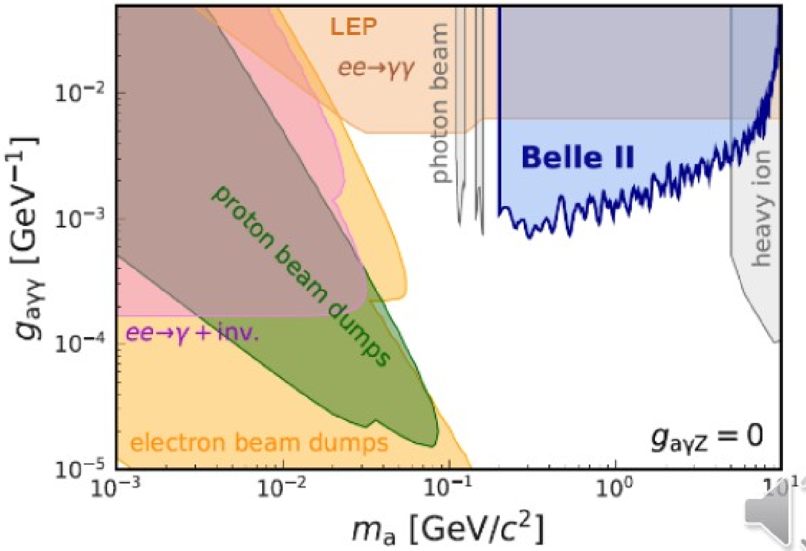
Results

Second physics paper by Belle II
Submitted to PRL [arXiv:2007.13071]

Measurement performed with 2018 pilot run data.

- Explored mass range $0.2 < m_a < 9.7\ \mathrm{GeV}/c^2$
- 95% CL upper limit on the cross section and then translated in terms of the $g_{a\gamma\gamma}$ coupling constant.

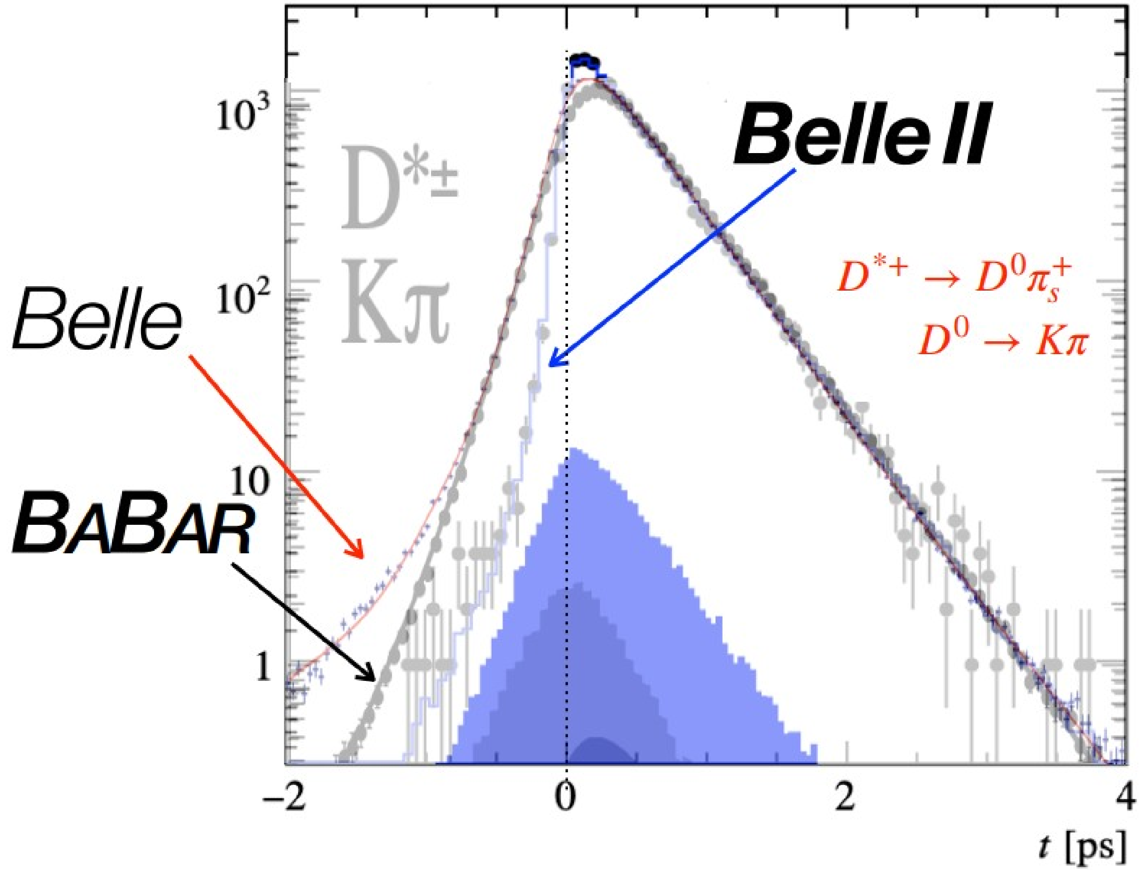




SIF 2020 – First results and prospects for Dark Sector searches at Belle II (M. Campajola)

Vertexing performance

Proper time resolution at Belle II is a factor 2 better than Belle & BABAR.



Full Event Interpretation

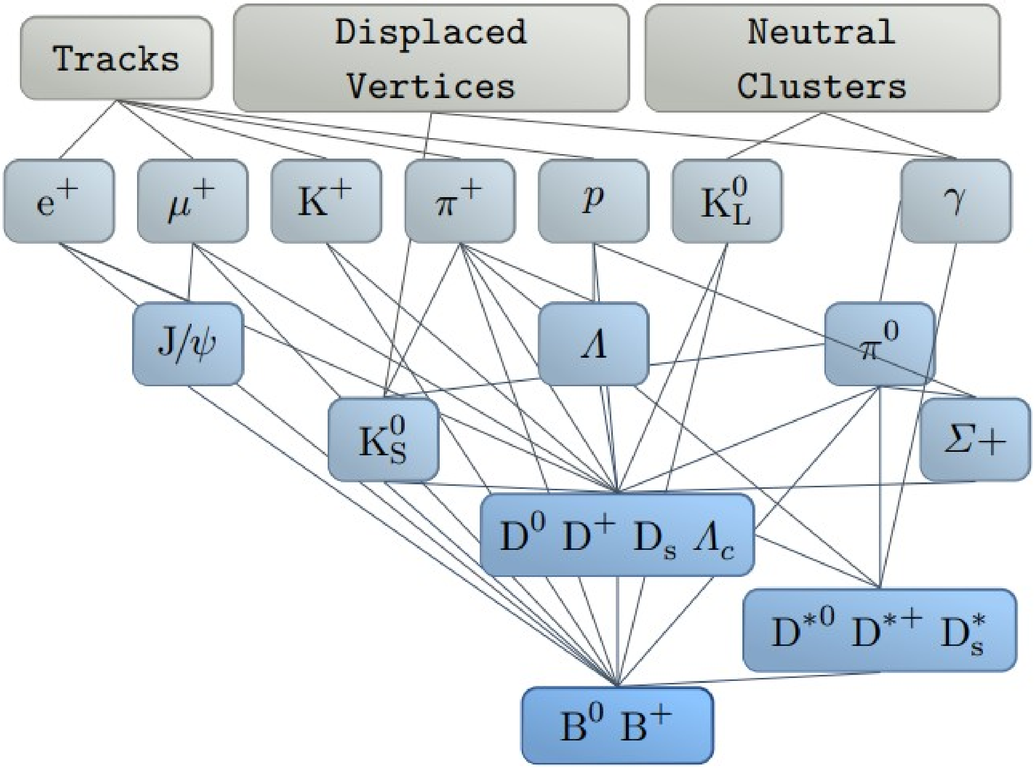
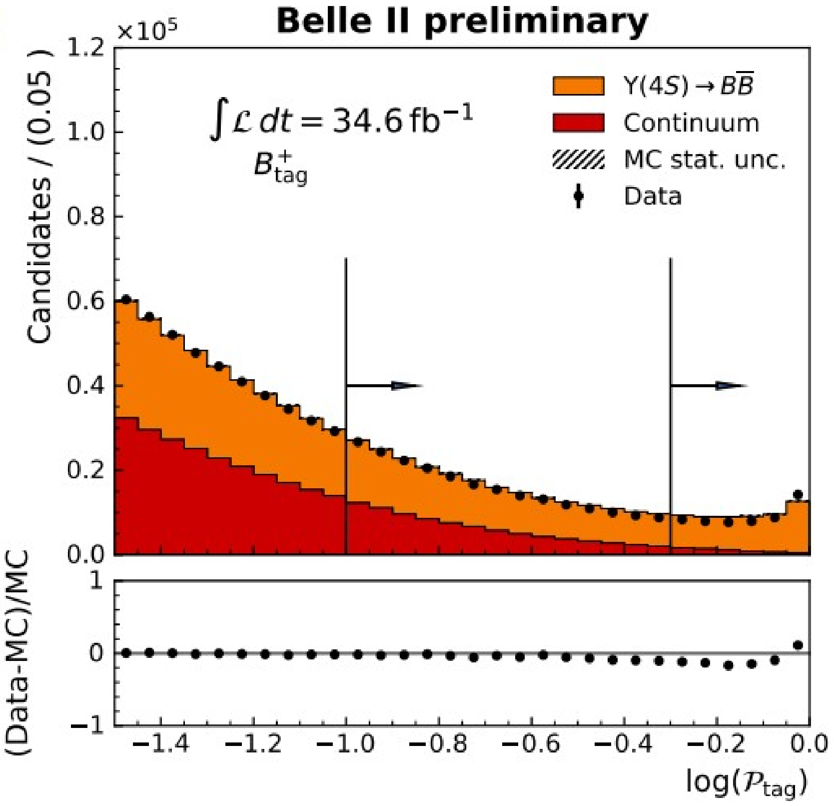


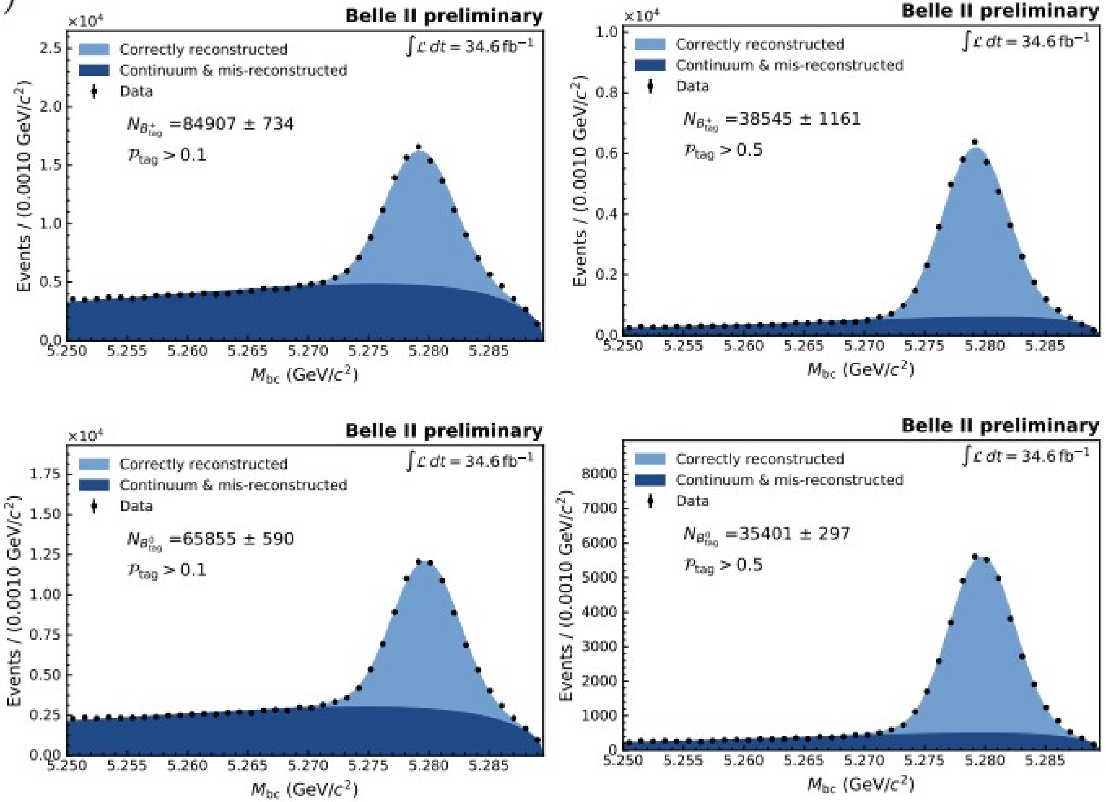
FIG. 1. The stages of reconstruction employed by Full Event Interpretation.

Full Event Interpretation

a)



(b)



Flavour Tagging

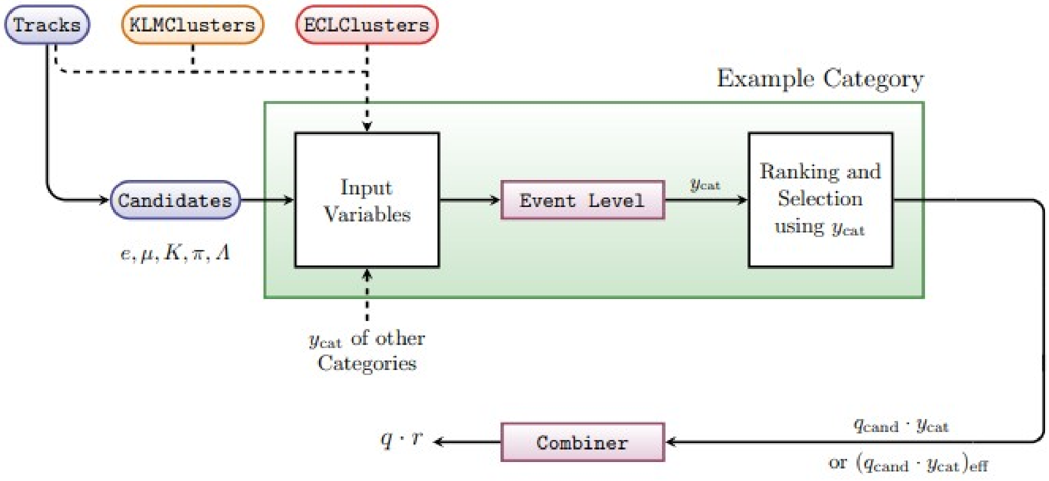


TABLE V. Partial efficiencies ε_i and wrong-tag fractions w_i obtained with the Belle II flavor tagger in 2019 Belle II data and with the Belle flavor tagger in Belle data [10] taken with the second silicon-vertex detector configuration (SVD2). Statistical and systematical uncertainties are added in quadrature. All values are given in percent.

$B^0 \to D^{(*)-}h^+$	$\varepsilon_i \pm \delta\varepsilon_i$		$w_i \pm \delta w_i$		$\varepsilon_{\text{eff},i} \pm \delta\varepsilon_{\text{eff},i}$	
r- Interval	Belle II	Belle	Belle II	Belle	Belle II	Belle
0.000 – 0.100	20.3 ± 1.8	22.2 ± 0.4	47.4 ± 4.2	50.0	0.1 ± 0.2	0.0
0.100 – 0.250	17.4 ± 0.9	14.5 ± 0.3	42.8 ± 4.4	41.9 ± 0.4	0.4 ± 0.4	0.4 ± 0.1
0.250 – 0.500	21.2 ± 1.0	17.7 ± 0.4	26.9 ± 3.7	31.9 ± 0.3	4.5 ± 1.5	2.3 ± 0.1
0.500 – 0.625	11.1 ± 0.7	11.5 ± 0.3	16.7 ± 5.5	22.3 ± 0.4	4.9 ± 1.7	3.5 ± 0.1
0.625 – 0.750	9.6 ± 0.9	10.2 ± 0.3	9.2 ± 6.5	16.3 ± 0.4	6.4 ± 2.1	4.6 ± 0.2
0.750 – 0.875	7.0 ± 0.6	8.7 ± 0.3	1.2 ± 5.7	10.4 ± 0.4	4.0 ± 1.2	5.5 ± 0.1
0.875 – 1.000	13.4 ± 0.8	15.3 ± 0.3	0.0 ± 3.3	2.5 ± 0.3	13.4 ± 1.9	13.8 ± 0.3
Total	$\varepsilon_{\text{eff}} = \sum_i \varepsilon_i \cdot (1 - 2w_i)^2 =$				33.8 ± 3.9	30.1 ± 0.4

arXiv:2008.08819