Track reconstruction efficiency measurement using $e^+e^- \to \tau^+\tau^-$ events at Belle II

Prague 2020 - Laura Zani *

On behalf of the Belle II collaboration

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Outline

- Motivation
- Experimental context: Belle II at SuperKEKB collider
- Measurement strategy:
  - Event selection and background suppression
  - Comparison to simulation
  - Calibration procedure
- Results

Motivation

→ Track reconstruction efficiency is a key performance driver for **Belle II physics...**

- Real detector != simulated detector
- *GOAL: assess the systematic uncertainty due to track finding in physics analyses, based on the measured discrepancy (δ*) in track reconstruction efficiency between simulation and data*

Discrepancy, $\delta^* = 1 - \varepsilon_{DATA}/\varepsilon_{MC}$

- **B-factories**: dedicated experiments at e^+e^- *asymmetric-energy colliders*

$$e^+e^- \rightarrow \Upsilon(4S)\ [10.58\ \text{GeV}] \rightarrow B\bar{B}$$

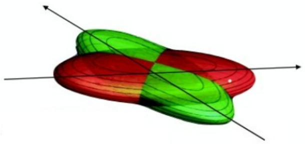
..also a D, τ factory

- **Clean environment** → lower background, high resolution
- **Hermetic detector** with excellent PID capability
- Efficient reconstruction of **neutrals** (π^0, η) and ***missing energy*** final states

SuperKEKB accelerator

- **World highest luminosity,** applying the large crossing angle (83 mrad) *nano-beam scheme* [arXiv:0709.0451].

KEKB



SuperKEKB

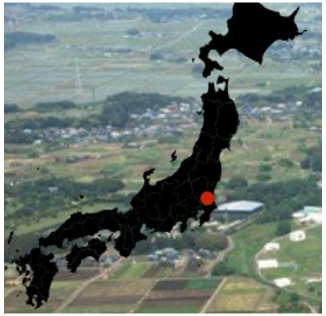
I (A): ~ 1.6/1.2 → **x 2** → I (A): ~ 3.6/2.6

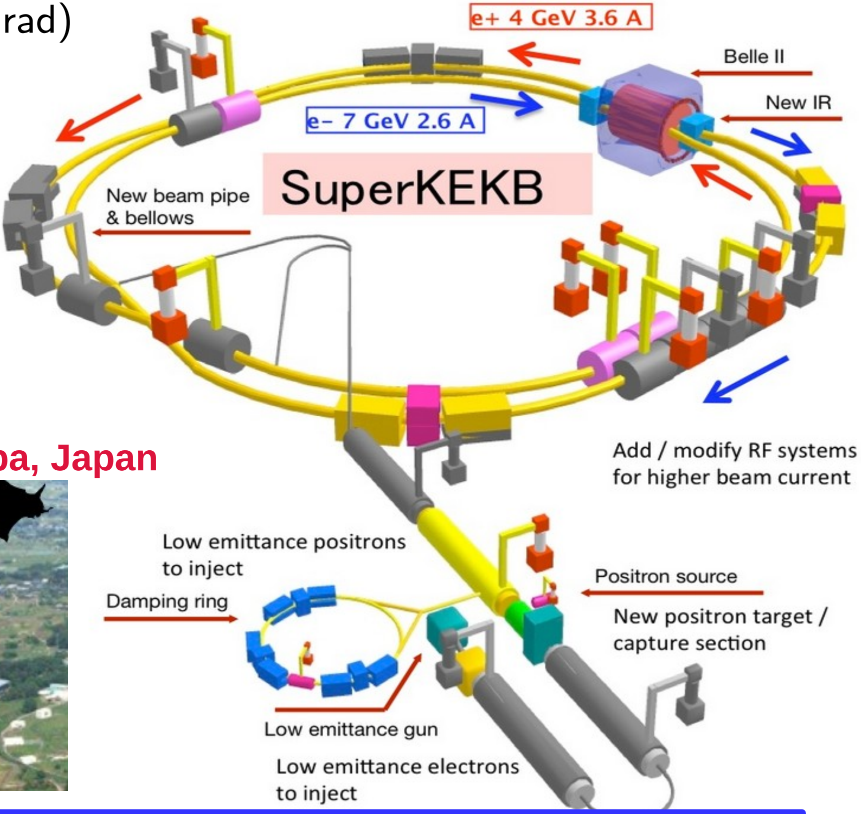
β^*_y (mm): ~ 5.9/5.9 → **x 1/20** → β^*_y (mm): ~ 0.27/0.3

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

- Lorentz factor
- beam current
- beam-beam parameter
- geometrical reduction factors
- beam aspect ratio at the IP
- vertical beta-function at the IP

KEK
Tsukuba, Japan





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

Breaking the wall of world highest luminosity

- **Wo**

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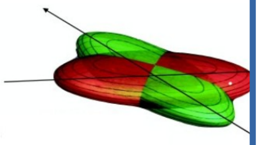
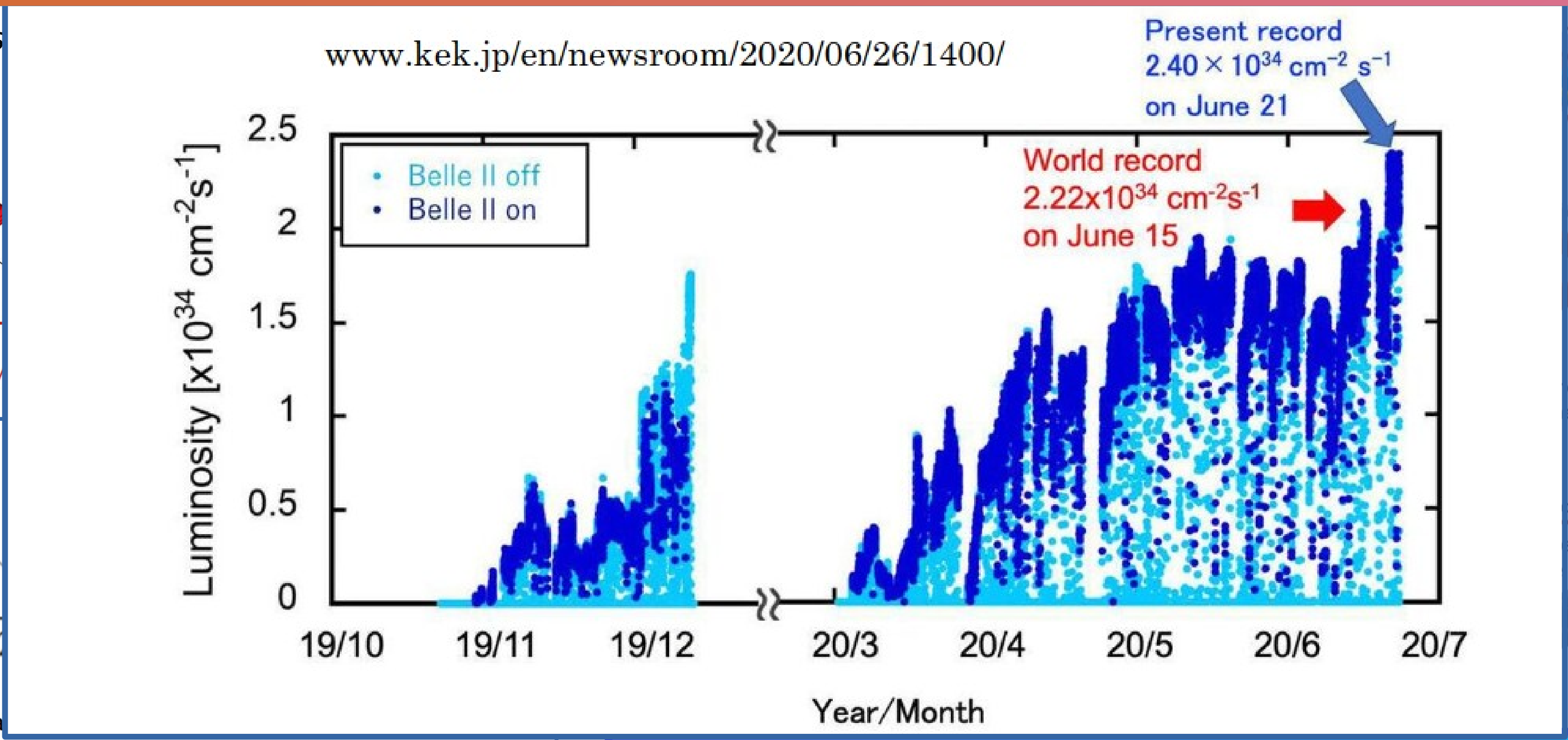
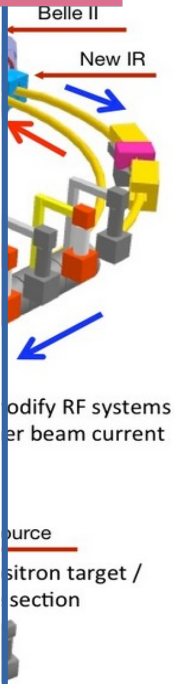
KEKB



I (A): ~ 1.6/1.

β^*_y (mm): ~ 5.9/





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sitron target /
section

Lorentz factor

$L = $

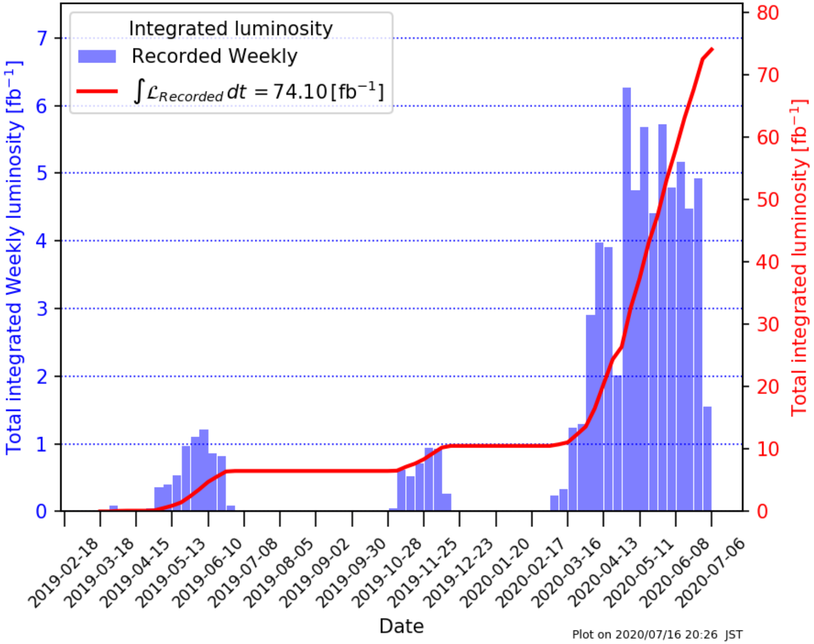
beam a
ratio at the IP

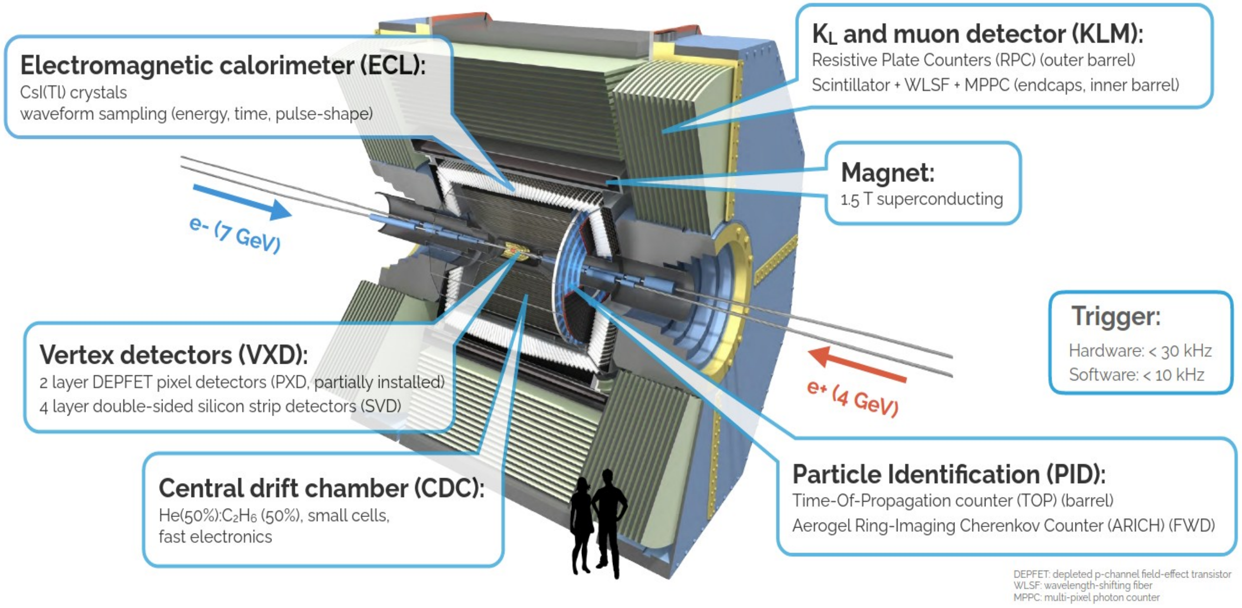
at the IP

40x KEKB peak luminosity: $\mathcal{L} = 8 \cdot 10^{35}$ cm^{-2} s^{-1}

Belle II detector

Phase 3: March 2019 – ...





Phase 3 FINAL GOAL : 50 ab^{-1}

Measurement strategy

Tag & probe method on $e^+e^- \to \tau^+\tau^- \to (\, l + \nu\, \bar{\nu}\,)\ (3\pi^\pm + \nu + n\pi^0)$

TAG: three *good quality* tracks with minimal requirements for particle identification (PID), satisfying $\Sigma q = \pm 1$

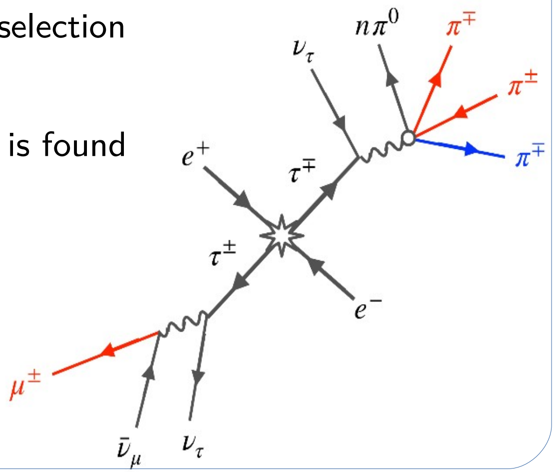
3x1-prong events

PROBE: 4th track in the event, satisfying looser selection requirements and conserving charge, $\Sigma q = 0$.

Count the number of events were the probe track is found (**N4**) and not found (**N3**):

$$\mathbf{A \times \mathcal{E} = N4/(N4 + N3)}$$

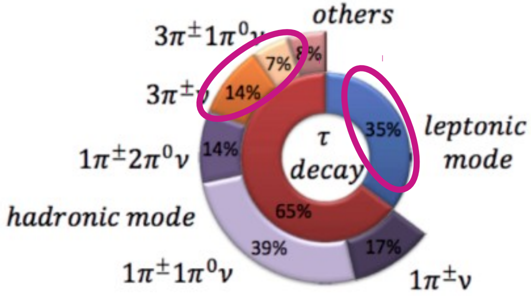
- A = detector acceptance,
- Ɛ = track reconstruction efficiency.



- Low multiplicity but high track density (boosted events)
- Investigate wide medium-momentum range (0.2 – 3.5 GeV/c)

$\sigma_{\tau\tau}$ (10.58 GeV) ~ 0.92 nb

$\to$ x BF x L_{int} = 1.2 M events



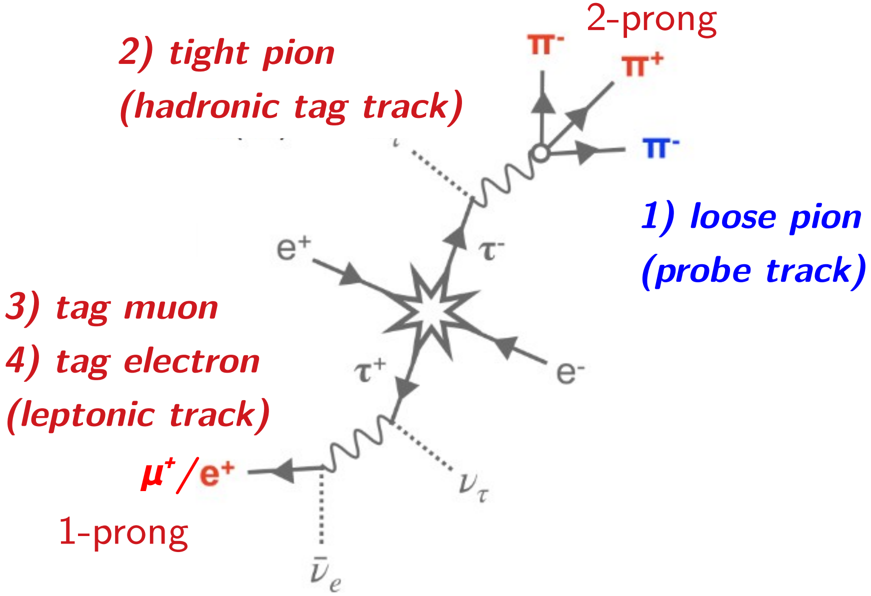
All reprocessed 2019 data, L_{int} = 8.8 fb^{-1}

100 fb^{-1} Monte Carlo official production:
Signal: $e^+e^- \to \tau^+\tau^-$,
Background: $e^+e^- \to q\bar{q}$ + low multiplicity

Event selection

- ***ECL triggers*** fired on data to provide unbiased samples
- ***Track Selection***: define **4 track lists** starting from *good quality* tracks (= coming from the interaction point, IP)
  - NO further selection on the *probe track*, not to bias the efficiency measurement
  - Tight pions (tag hadronic tracks) are a subset of loose pions
  - Apply PID to make lists orthogonal

→ ***Constrain the #candidates per list, but NOT the total #tracks***

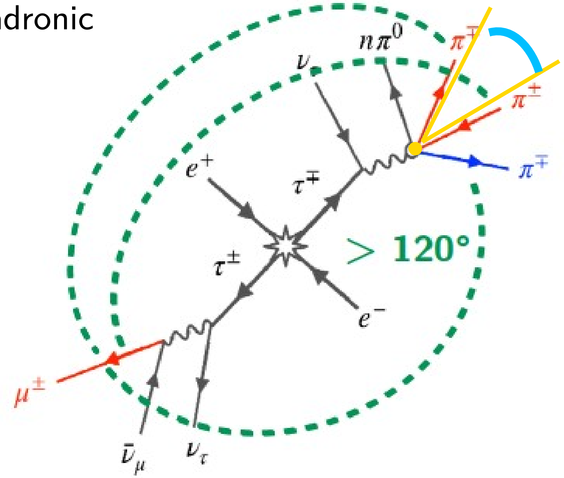


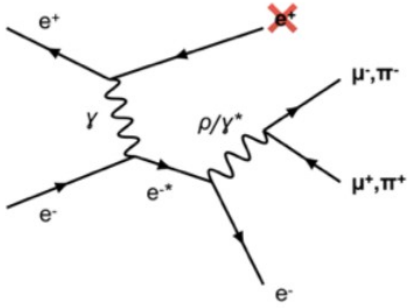
Muon channel		Electron channel	
N3 sample:	**N4 sample:**	**N3 sample:**	**N4 sample:**
#loose pion = 2	#loose pion = 3	#loose pion = 2	#loose pion = 3
#tight pion = 2	#tight pion >= 2	#tight pion = 2	#tight pion >= 2
#muon = 1	#muon = 1	#muon = 0	#muon = 0
#electron = 0	#electron = 0	#electron = 1	#electron = 1

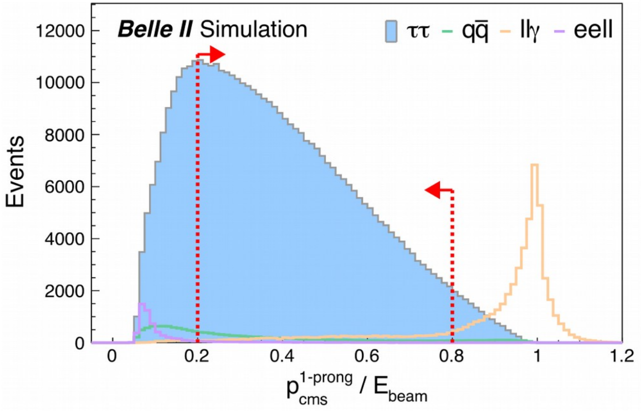
According to the charge of the 2-prong tracks we define:
- *Opposite Sign* sample (**OS**)
- *Same Sign* sample (**SS**)

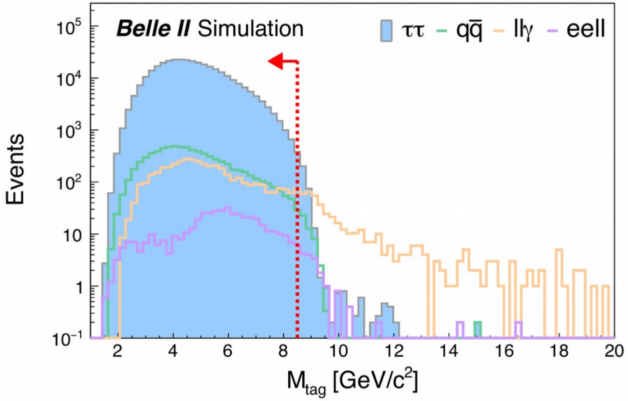
Background suppression

- ***Topology:*** require *angular isolation* of the 1-prong leptonic tag from all the other three hadronic tracks + good quality of the χ^2 of the fit to the 2-prong tracks vertex
- ***Radiative QED and continuum $q\bar{q}$ rejection:***
  - 1-prong track momentum within 20% and 80% of the beam energy ($\sqrt{s}/2$)
  - constrain number of neutral pions and photons per event
  - minimum opening angle between the two tag pions
  - Selections on the invariant mass of the tag tracks and of the 2-prong tracks
- ***Data-driven veto*** against two-photon event contamination, $ee\gamma^* \rightarrow$ affecting the *Opposite Sign (OS)* electron channel



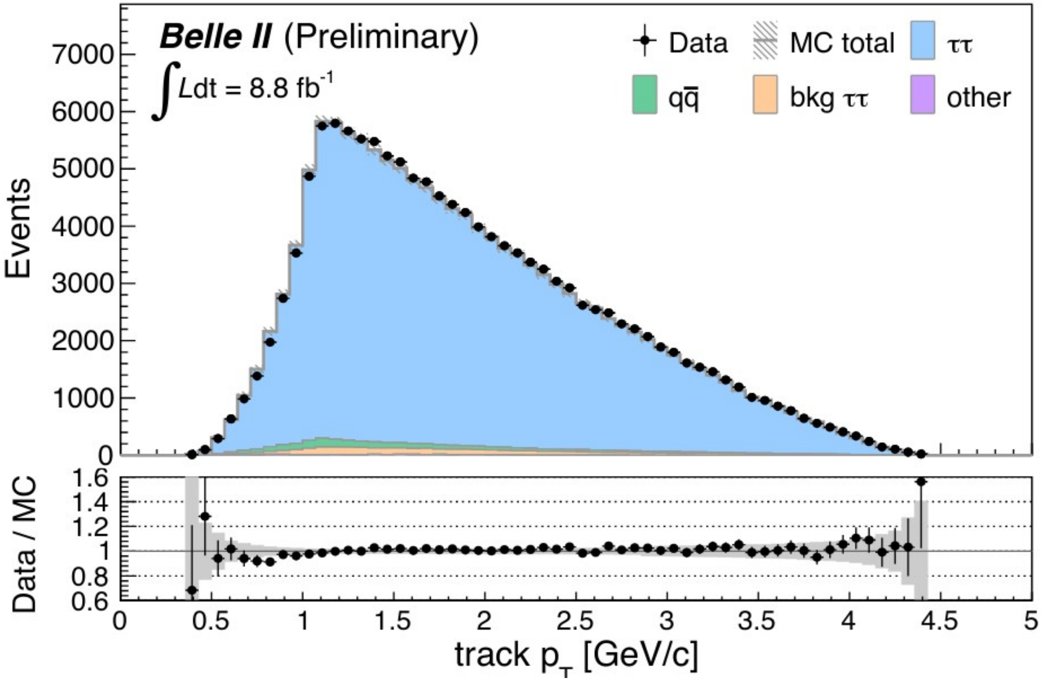


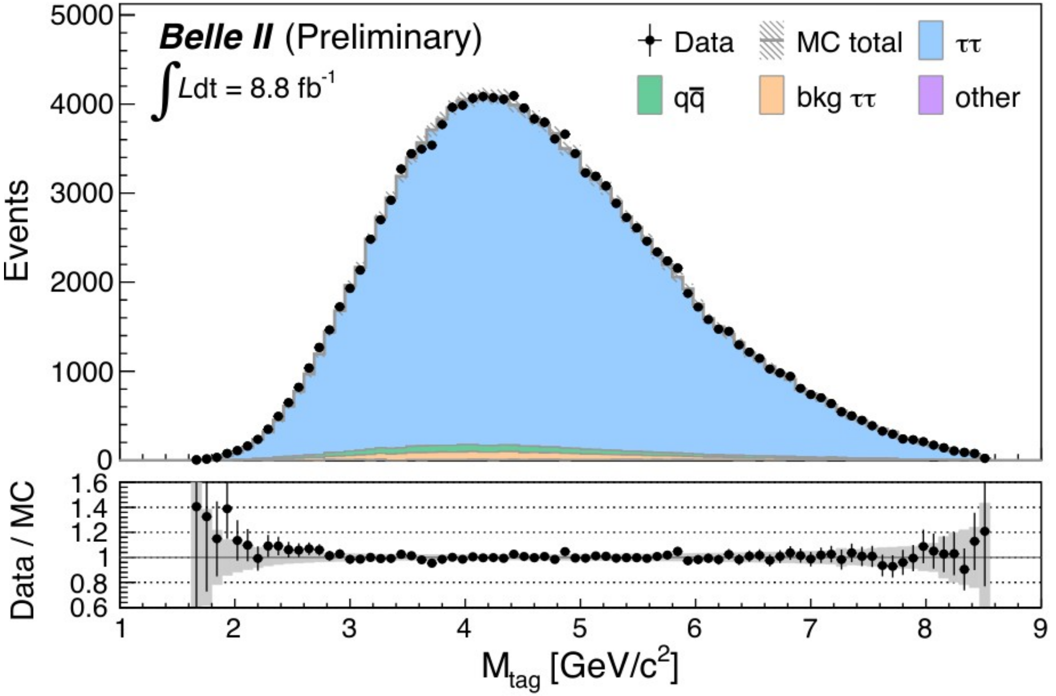




Data -MC comparison

- Data and simulation (signal + background) are compared after all selections
- Simulation scaled to data luminosity (8.8 fb^{-1}) and weighted bin-by-bin with the measured ***trigger efficiency*** on data (see P.Rados talk from yesterday Operation performance session)





Calibration procedure

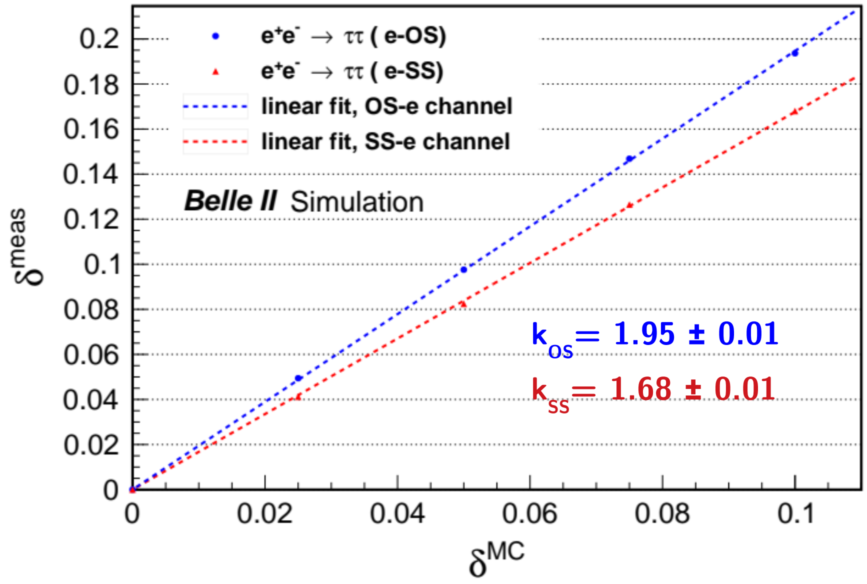
- Discrepancy estimator δ^{meas} calibrated to represent the true value (δ^*):
  - Combinatorial effects
  - Impact of charge dependent selection (e.g., eeγ^* veto for OS-electron channel)
- Introduce known *per track* inefficiencies in signal simulation, ττ sample (δ_{MC} = 2.5%, 5%, 7.5%, 10%)
- Extract calibration k-factors from linear fits to the 2D distributions of **δ^{meas} Vs. δ_{MC}**

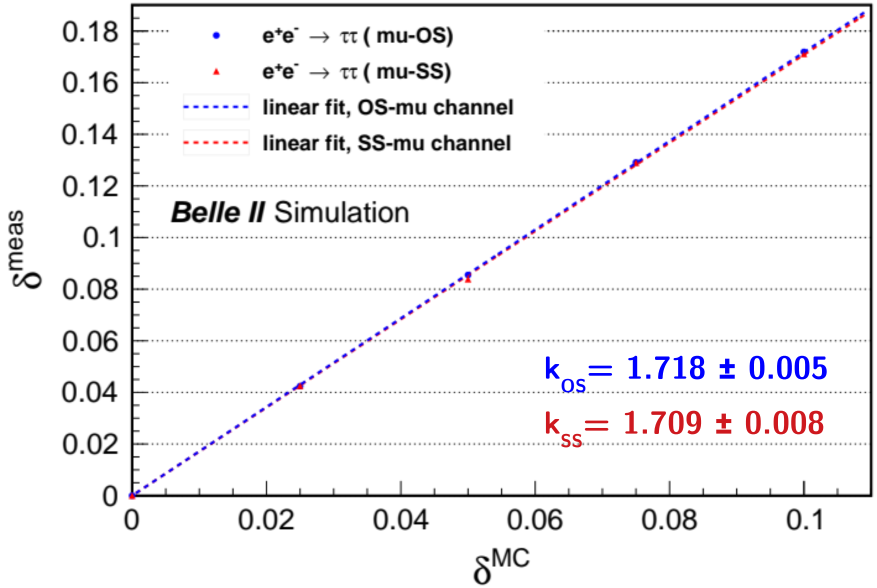
recall that: $\epsilon^{meas} = N_4/(N_3 + N_4)$

$$\delta^{meas} = 1 - \epsilon^{meas}_{Data}/\epsilon^{meas}_{MC} = k \cdot \delta^*$$

$$\delta^* = 1 - \epsilon^*_{Data}/\epsilon^*_{MC}$$

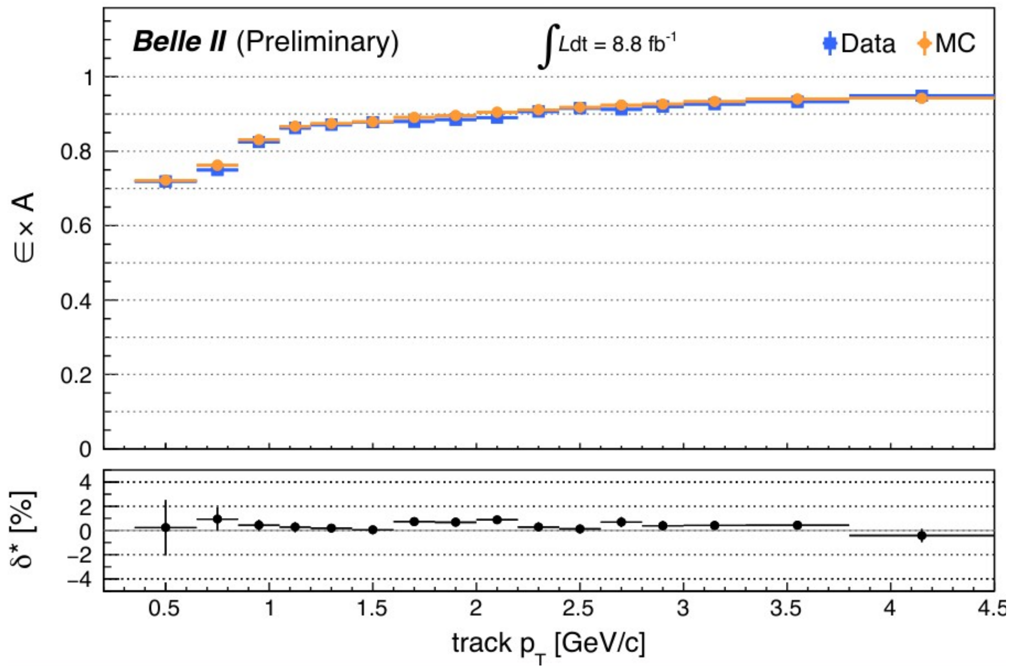
$$= \frac{1}{k}(1 - \epsilon^{meas}_{Data}/\epsilon^{meas}_{MC})$$

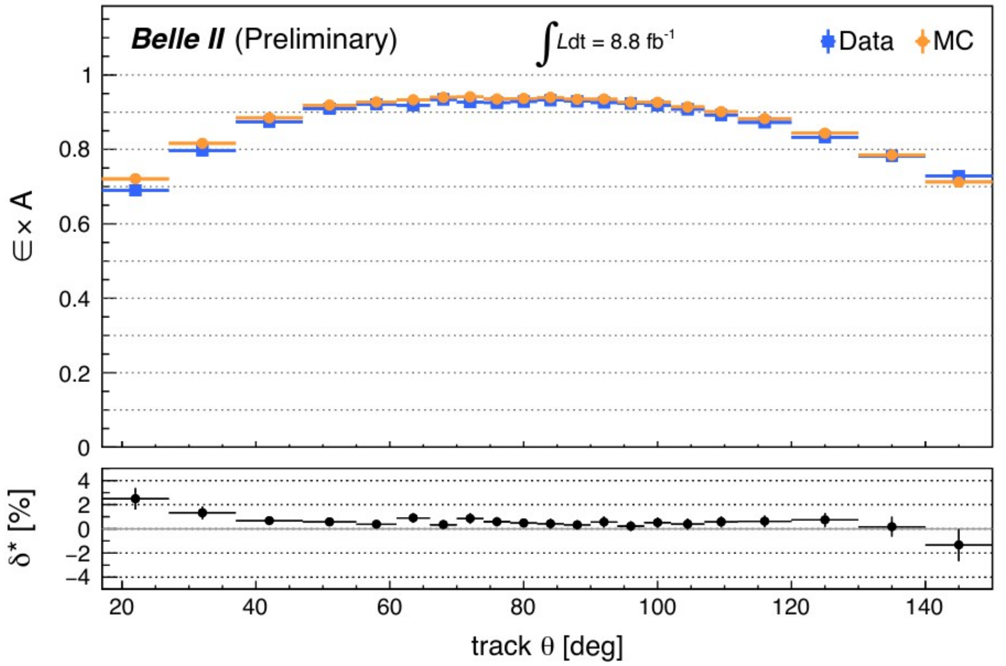




ɛxA measurement

- Remaining background estimated from simulation → background subtraction applied to data
- Efficiency ɛxA computed from the ratio N4/(N4 + N3) for data and simulation, as well as calibrated discrepancies δ^*.





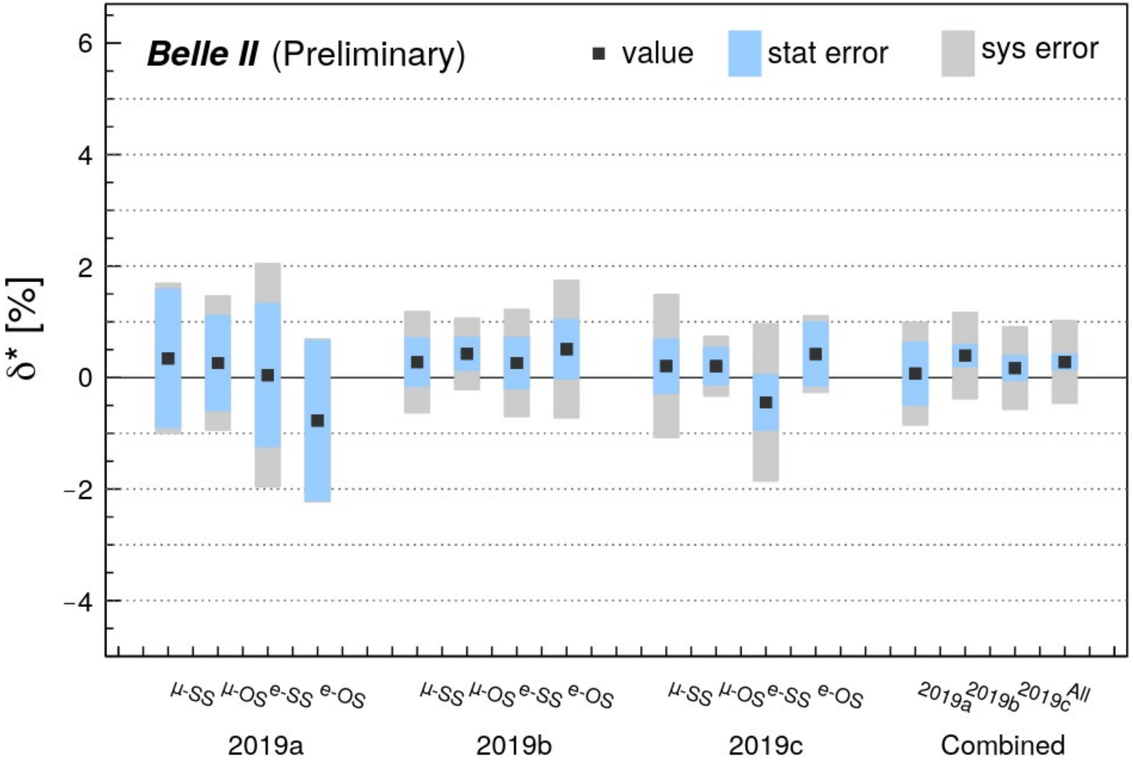
Results: calibrated discrepancy

- Calibrated data-MC discrepancies:

$$\delta^* = 1 - \epsilon^*_{Data}/\epsilon^*_{MC} = \frac{1}{k}(1 - \epsilon^{meas}_{Data}/\epsilon^{meas}_{MC})$$

- Systematic uncertainty contributions are included
- Dominated by trigger efficiency uncertainty and charge dependence

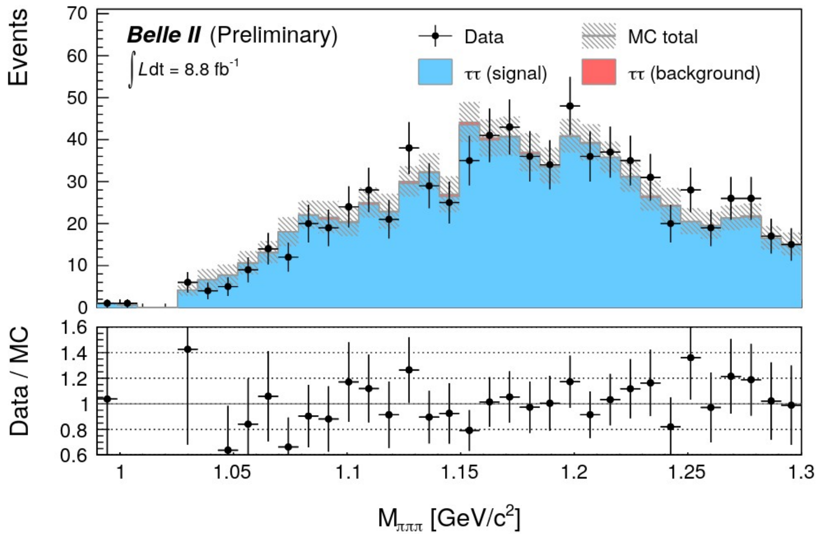
$\delta^*_{overall} = 0.28 \pm 0.15\ (\mathrm{stat}) \pm 0.73\ (\mathrm{sys})\ \%$

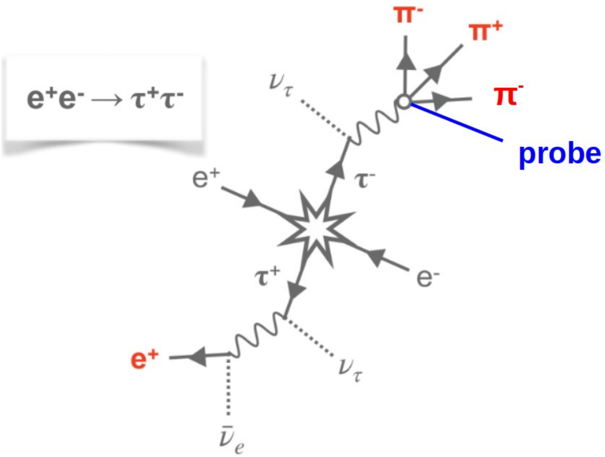


Fake rate measurement

- Estimate the probability to reconstruct a *fake track* coming from: random combination of (beam) background hits; low-momentum tracks curling inside the detector without being merged (*clone tracks*)

- Analogue *tag-and-probe* technique
  - Fully reconstruct a 3x1 τ-pair event by requiring 4 tracks (tag)
  - Look for the 5th track (probe)
  - Compute the fake rate as $\mathbf{r_{fake}=N5/(N4 + N5)}$





- Exploit full event kinematics to increase signal purity (measured on simulation)
- Scale yields in data for the measured signal purity: $\mathbf{r_{fake} = 0.97 \pm 0.34\ (stat) \pm 0.06\ (sys)\ \%}$

Summary

- Belle II successfully took data for all 2020 run periods
- With a sample of ~ 9 fb^{-1} data (**Belle II 2019**) we devise the strategy to measure the quantity **εxA** on data and simulation, by analyzing ~ 1.2M processes:

$$e^+e^- \rightarrow \tau^+\tau^- \rightarrow (l + \nu \bar{\nu}) (3\pi^\pm + \nu + n\pi^0)$$

- The overall calibrated (first time this calibration procedure is applied!) discrepancy is measured to be

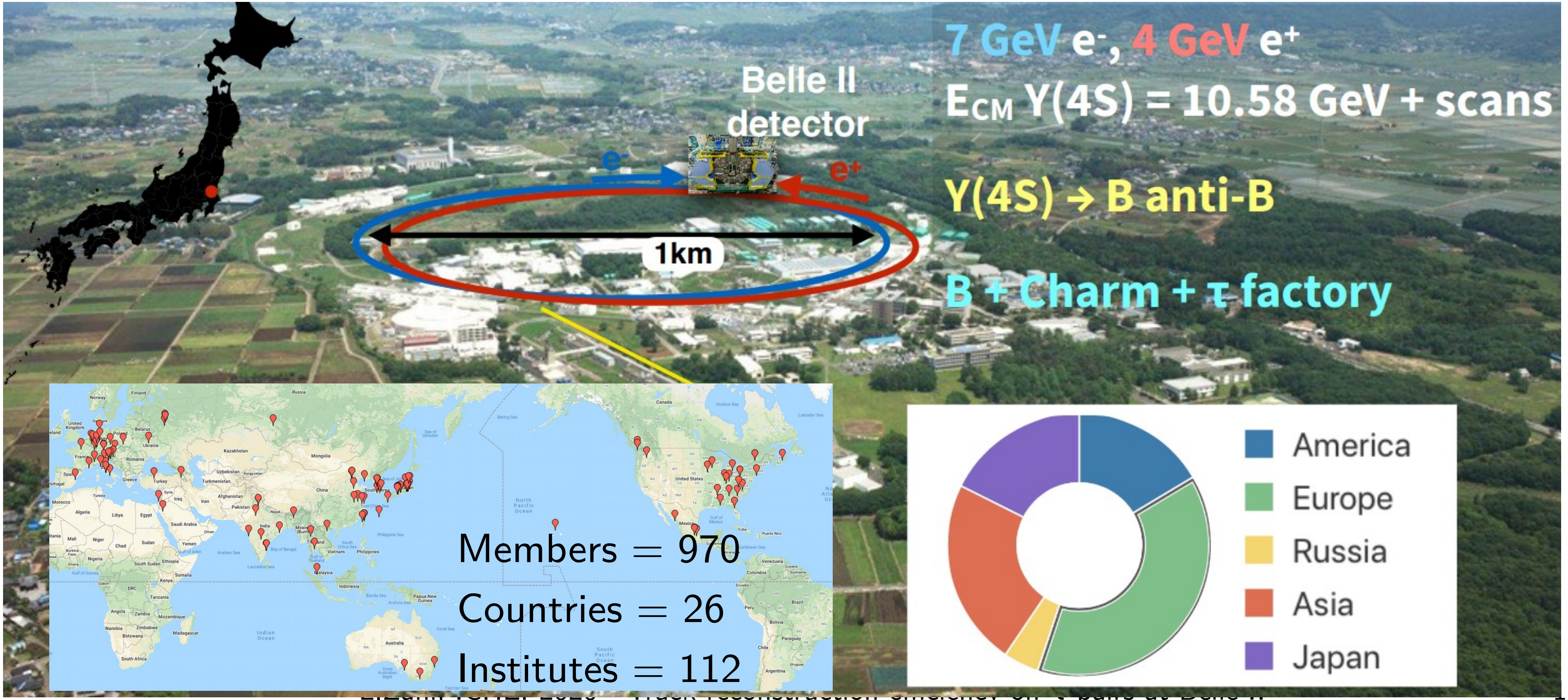
0.28 ± 0.15 (stat) ± 0.73 (sys) %

→ Prescription on how to assign systematic uncertainties for analyses dealing with tracks of transverse momentum [0.2 < pT <3.5] GeV/c is provided

- The track reconstruction fake rate in Belle II data has been also measured exploiting τ-pair events and found to be **0.97 ± 0.34 (stat) ± 0.06 (sys) %** consistently with simulation.

backup

Belle II collaboration



Track selections

- The tighter *pion tag* candidates also satisfied the selections as looser *pion probe* candidate.
- N3 samples: no additional pion probe is needed $\rightarrow$ $N_{pion}^{probe} = N_{pion}^{tag}$

	Probe pion track	Tag pion track	Tag electron track	Tag muon track
p_T [MeV]	–	> 200	> 200	> 200
$\|z_0\|$ [cm]	< 3	< 3	< 3	< 3
$\|d_0\|$ [cm]	< 1	< 1	< 1	< 1
$\frac{E_{\text{cluster}}}{p}$	< 0.8	< 0.6	$(0.8, 1.2)$	< 0.6
E_{cluster}	–	> 0	–	> 0
muonID	–	< 0.9	–	> 0.9

TABLE III: Track selection criteria. The first three lines in the table are the selections which define the *good tracks* used for this analysis.

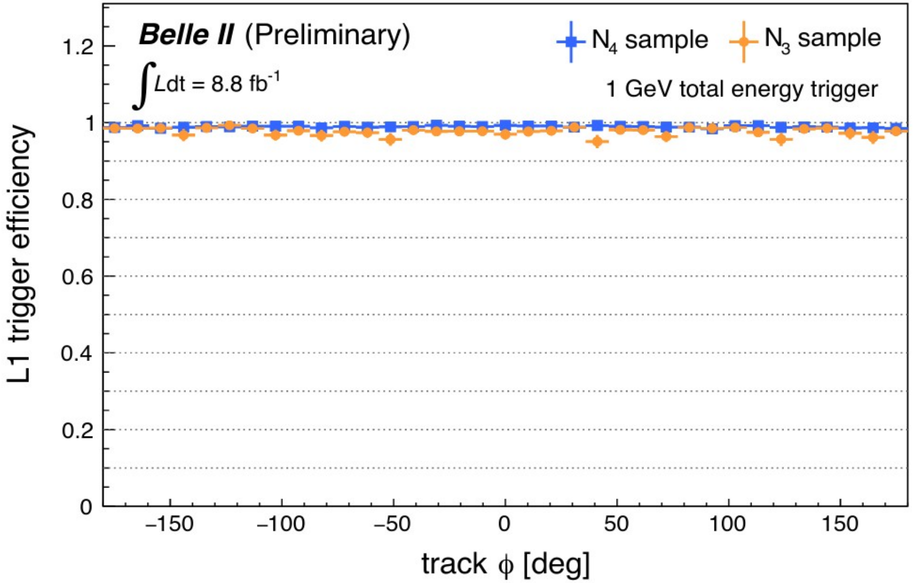
	$N_{\text{pion}}^{\text{probe}}$	$N_{\text{pion}}^{\text{tag}}$	$N_{\text{electron}}^{\text{tag}}$	$N_{\text{muon}}^{\text{tag}}$
electron channel, 4-track sample	3	≥ 2	1	0
electron channel, 3-track sample	2	2	1	0
muon channel, 4-track sample	3	≥ 2	0	1
muon channel, 3-track sample	2	2	0	1

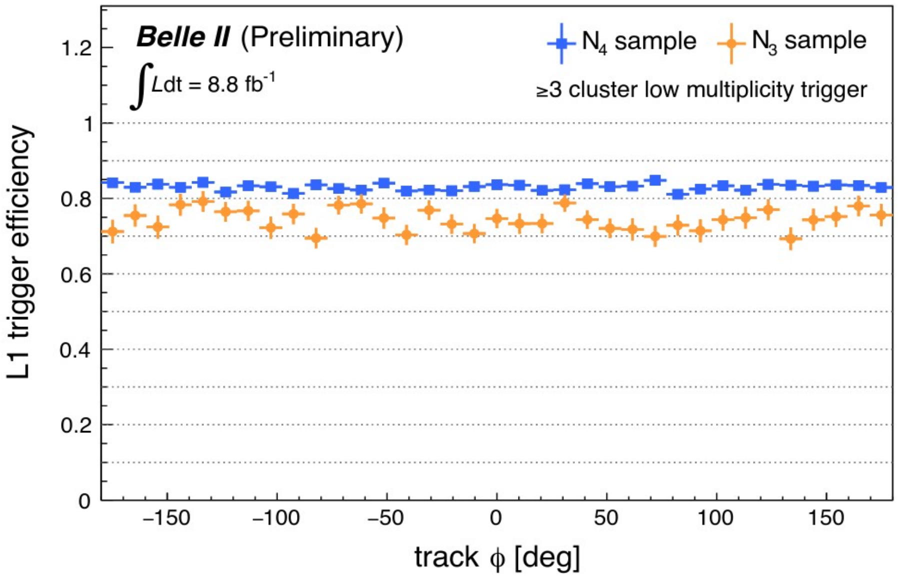
Trigger selection

- Different hardware (Level 1, L1) trigger lines based on ECL cluster properties are used to select events according to the channel:
  - Electron channel: energy deposit in ECL >1 GeV $+$ Bhabha veto
  - Muon channel: low multiplicity trigger with minimum 3 ECL clusters, at least one above 300 MeV $+$ Bhabha veto
- Reference L1 trigger line to measure the ECL trigger efficiency: CDC trigger lines

For details on trigger efficiency measurement: P. Rados's talk.

$$\epsilon_{bit_{ECL}} = \frac{N(bit_{ECL} \text{ AND } bit_{CDC})}{N(bit_{CDC})}$$





Selections

- Selection optimization is performed on simulated MC samples for signal and background