
# 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 ($\delta^*$) 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*

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

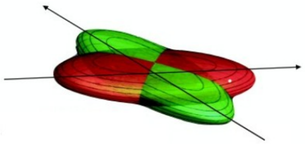
**..also a D, τ factory**

- **Clean environment** → lower background, high resolution
- **Hermetic detector** with excellent PID capability
- Efficient reconstruction of **neutrals** ($\pi^0$, $\eta$) 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**

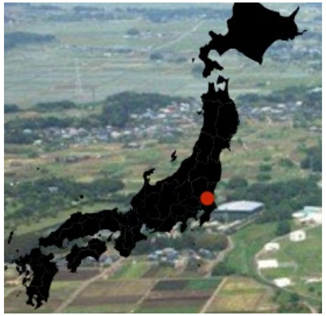
I (A): ~ 1.6/1.2 → **x 2** → I (A): ~ 3.6/2.6

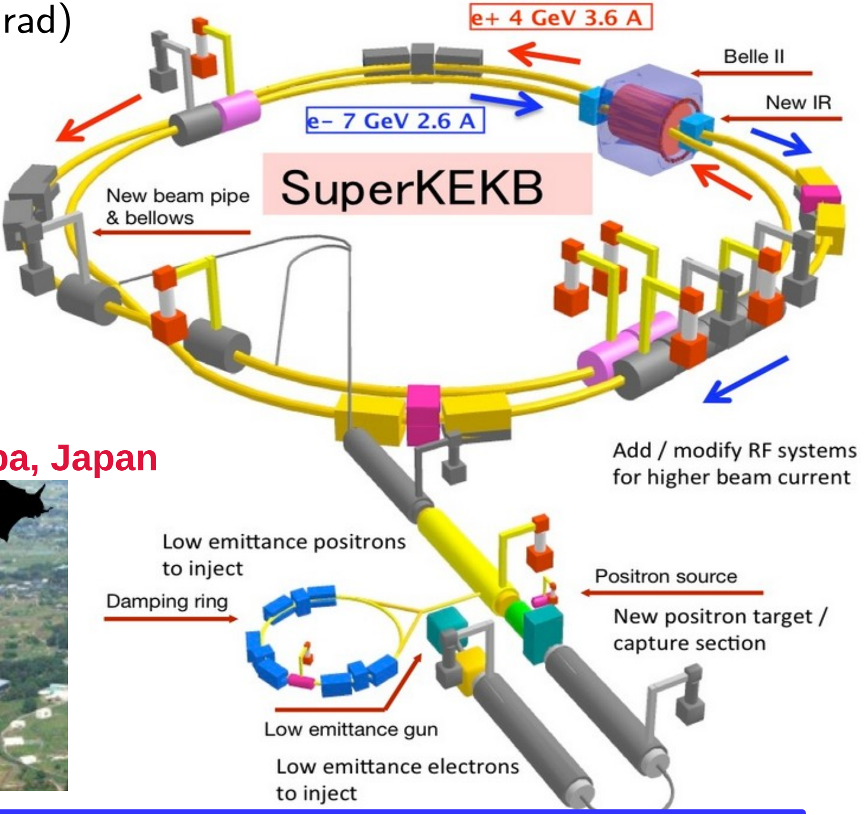
$\beta^*_y$ (mm): ~ 5.9/5.9 → **x 1/20** → $\beta^*_y$ (mm): ~ 0.27/0.3

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

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**





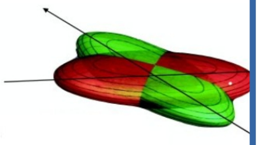

**30x KEKB peak luminosity: $\mathcal{L} = 6 \cdot 10^{35}$ cm$^{-2}$ s$^{-1}$**

# Breaking the wall of world highest luminosity

• **Wo**

*nano-beam s*

**KEKB**



I (A): ~ 1.6/1.

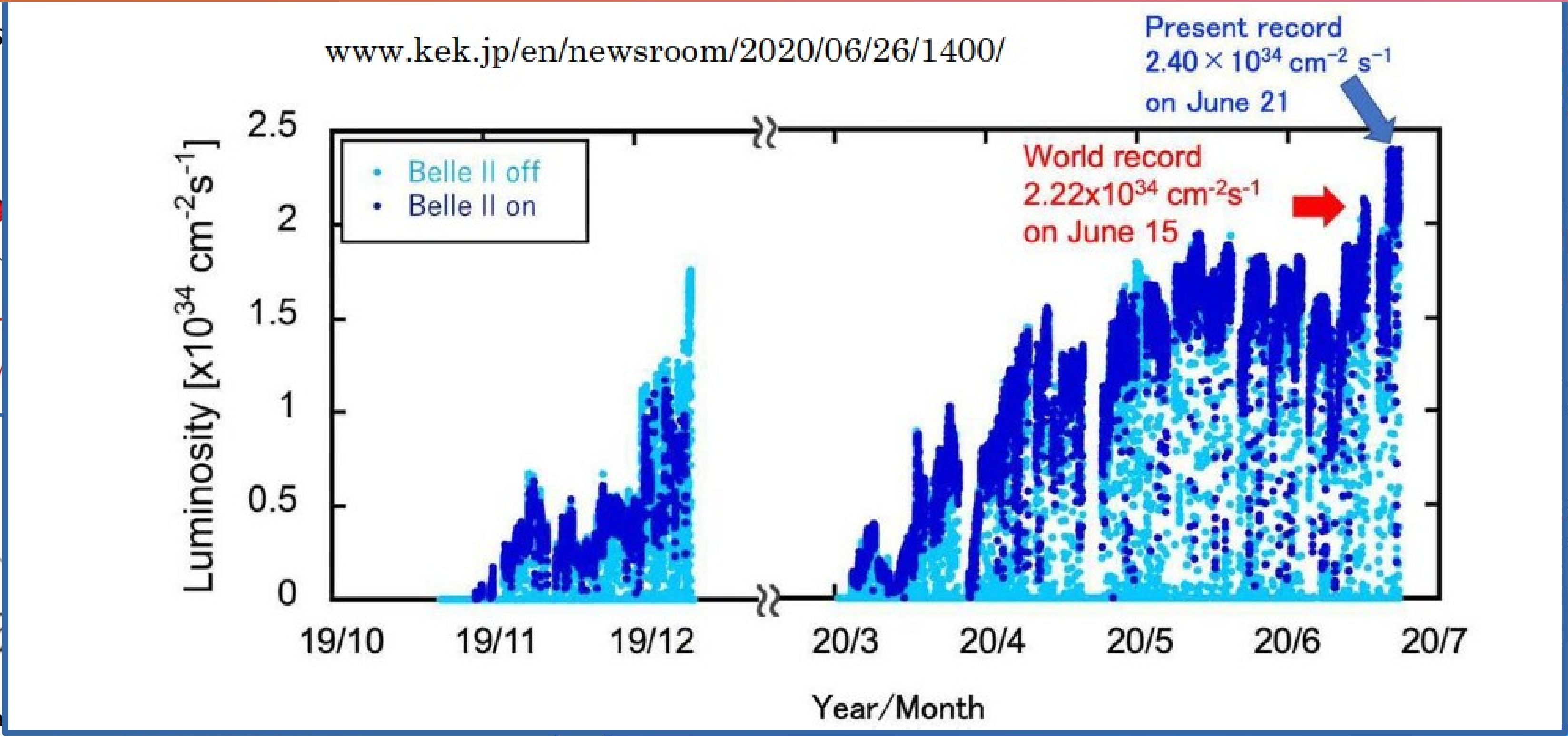
$\beta^*_y$ (mm): ~ 5.9/

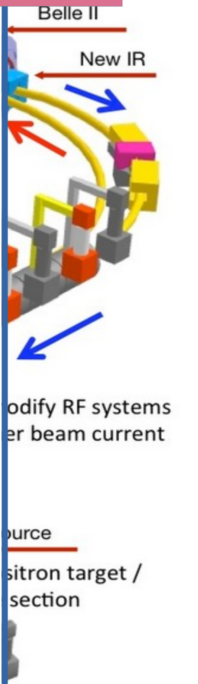
Lorentz factor

$L = $

beam a
ratio at the IP

at the IP

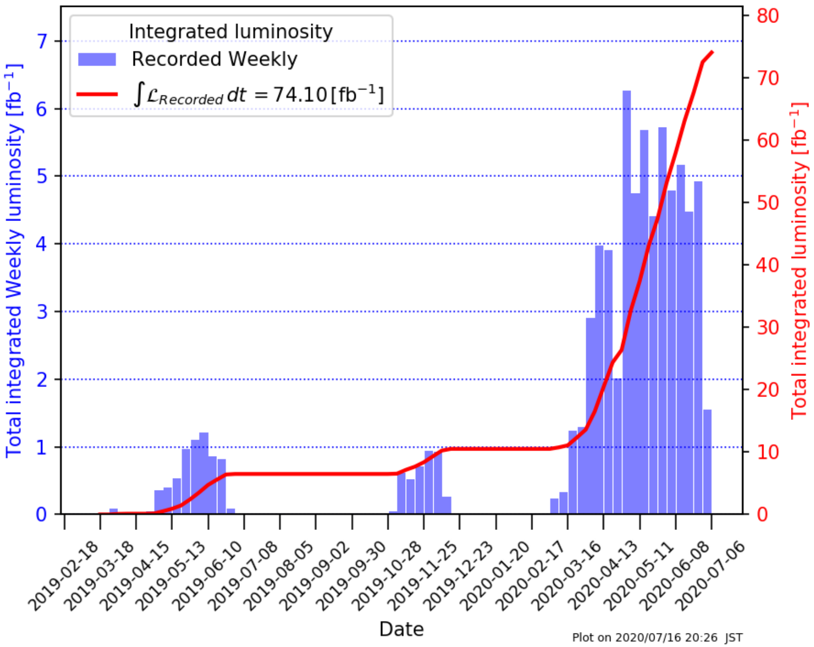


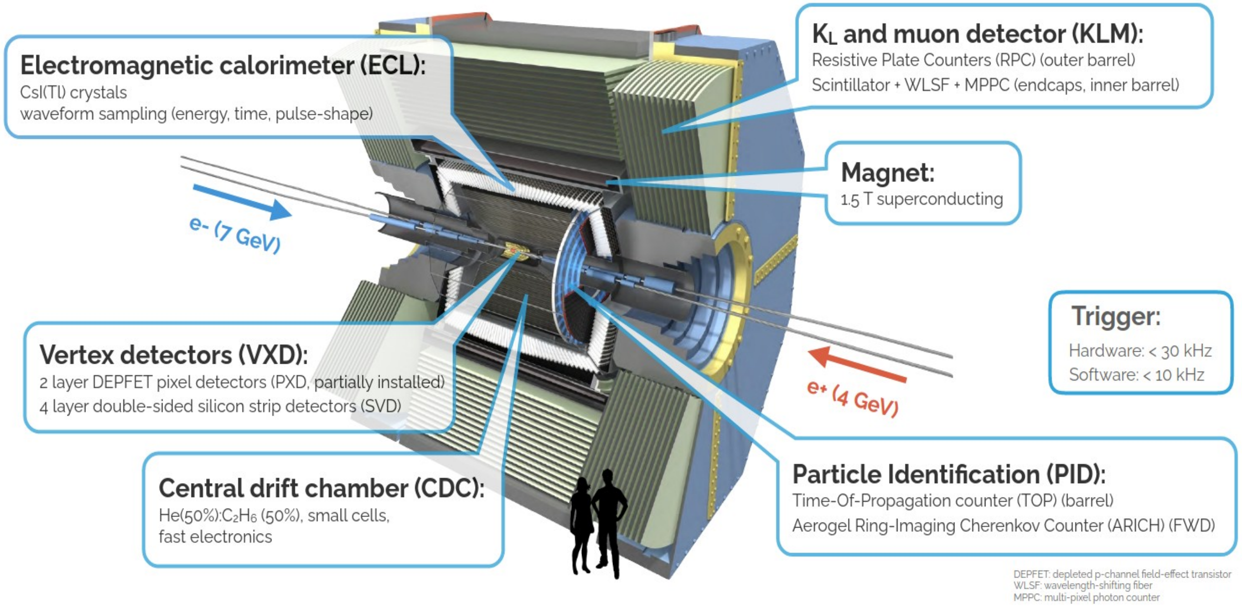




**30x KEKB peak luminosity: $\mathcal{L} = 6 \cdot 10^{35}$ cm$^{-2}$ s$^{-1}$**

# 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 $\Sigma q=\pm1$

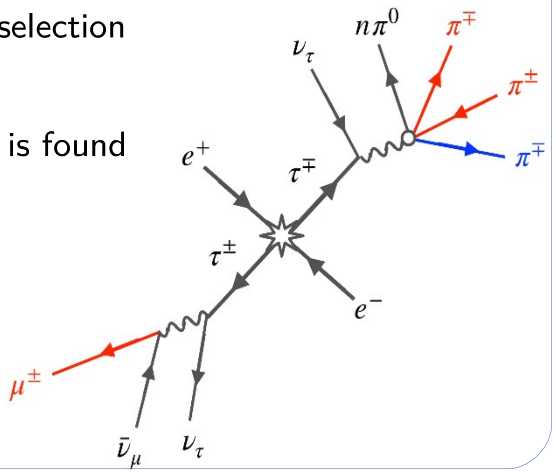
**PROBE**: 4th track in the event, satisfying looser selection requirements and conserving charge, $\Sigma q=0$.

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

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

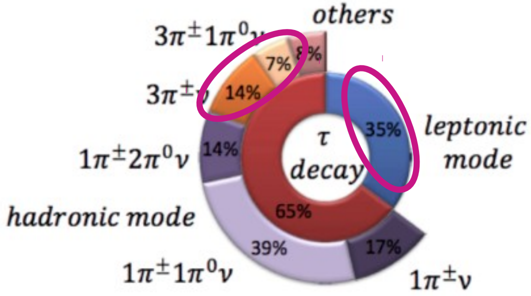
- A = detector acceptance,
- $\mathcal{E}$ = track reconstruction efficiency.

3x1-prong events




- 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*



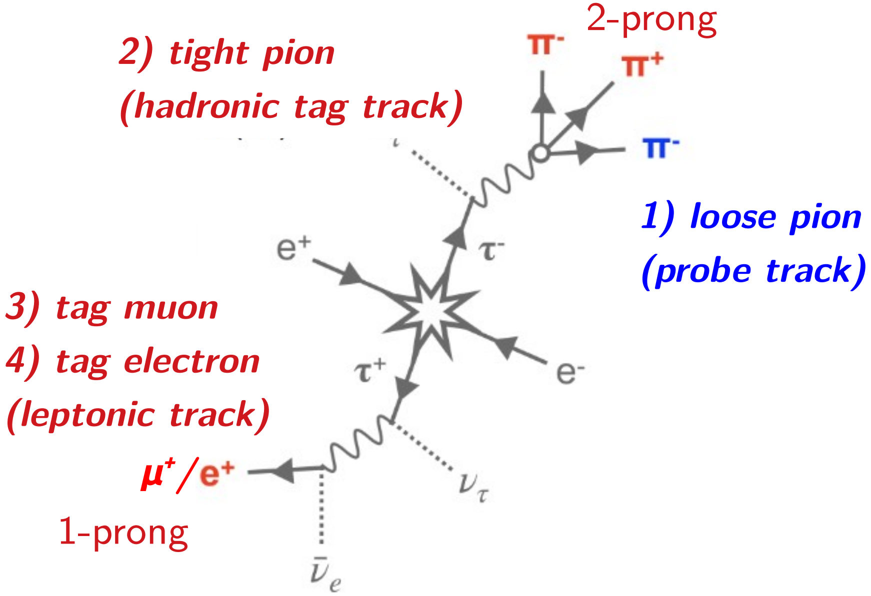

**All reprocessed 2019 data, $L_{int}$ =8.8 $fb^{-1}$**

**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***



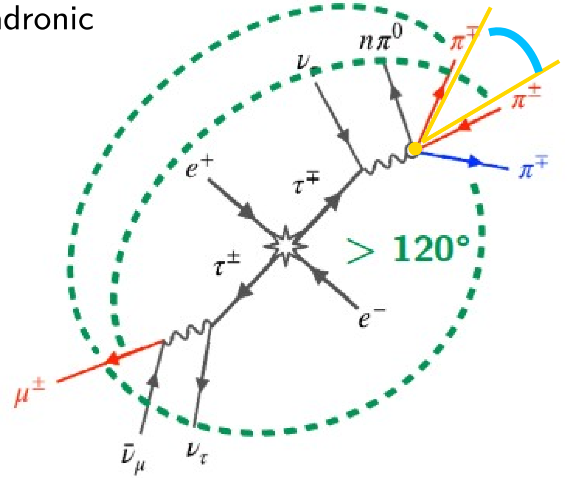

## Muon channel / Electron channel

| Muon channel N3 sample: | Muon channel N4 sample: | Electron channel N3 sample: | Electron channel 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 |

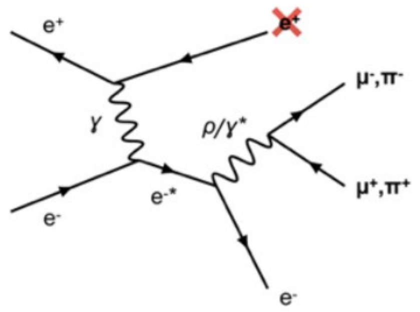
According to the charge of the 2-prong tracks we define:
- *Opposite Sign* sample (**OS**)
- *Same Sign* sample (**SS**)

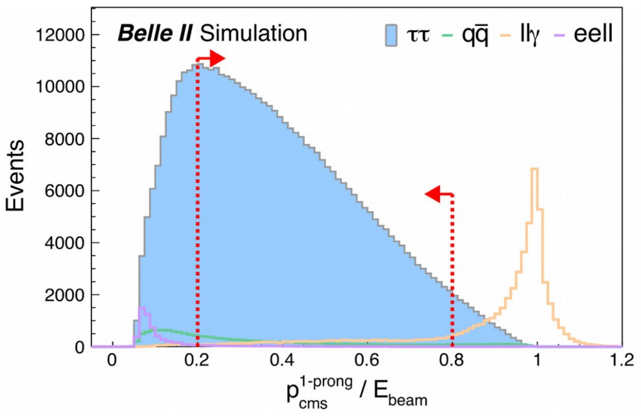
# Background suppression

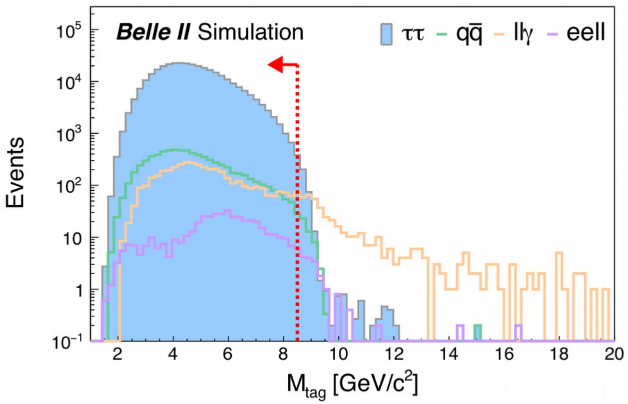
- ***Topology:*** require *angular isolation* of the 1-prong leptonic tag from all the other three hadronic tracks + good quality of the $\chi^2$ of the fit to the 2-prong tracks vertex




- ***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



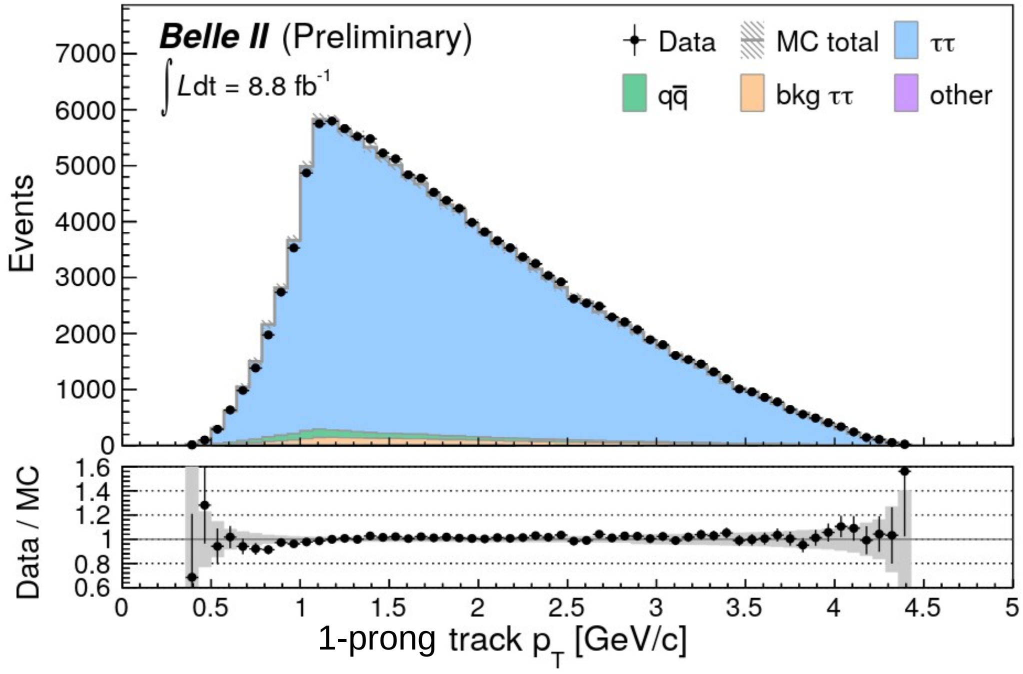



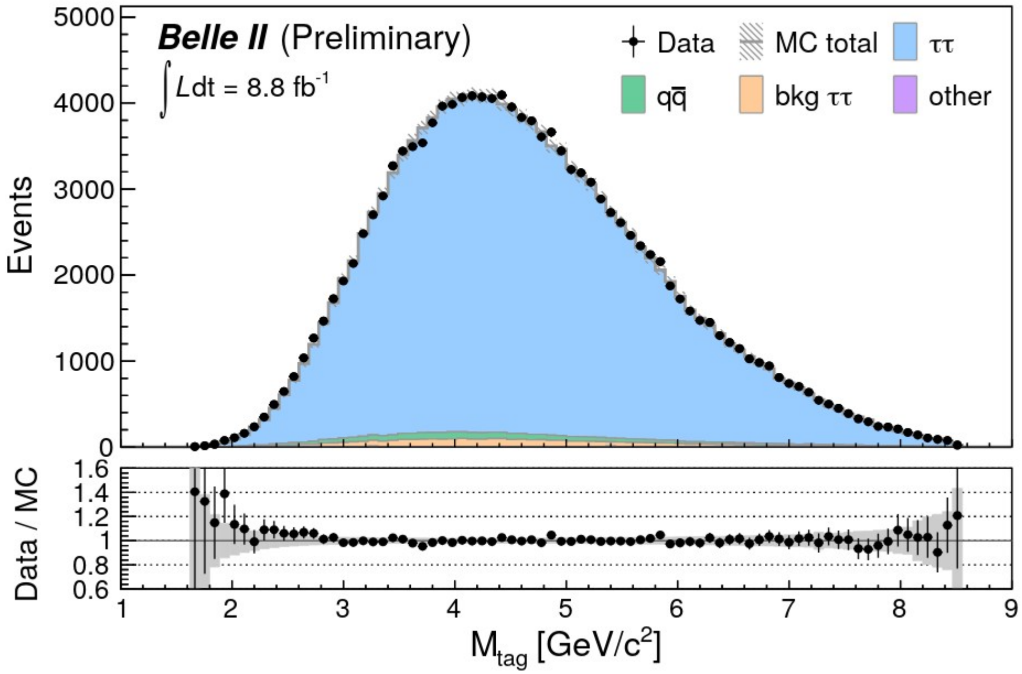



# Data -MC comparison

- 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)

details in backup



# Calibration procedure

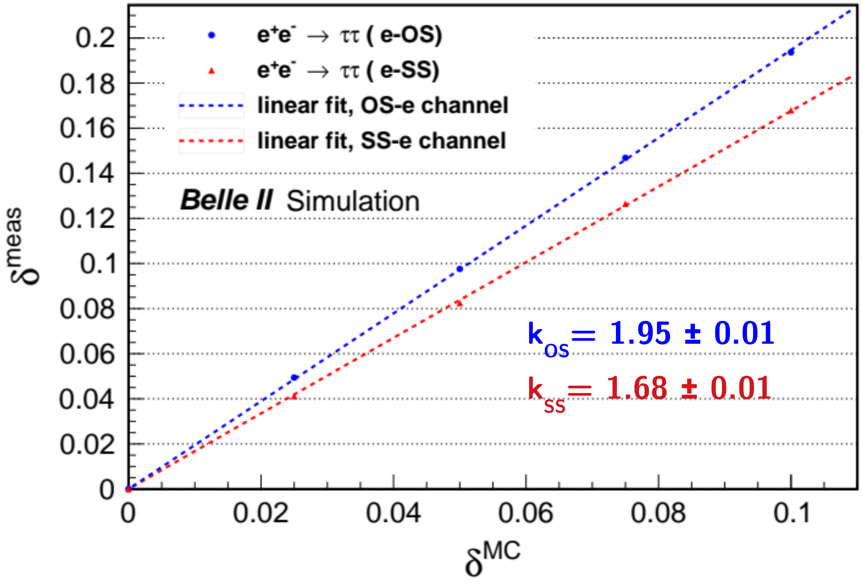
- Discrepancy estimator $\delta^{meas}$ calibrated to represent the true value ($\delta^*$)
- Introduce known *per track* inefficiencies in signal simulation, ττ sample ($\delta_{MC}$ = 2.5%, 5%, 7.5%, 10%)
- Extract **k-factors** from linear fits to the 2D distributions of $\boldsymbol{\delta^{meas}}$ **Vs.** $\boldsymbol{\delta_{MC}}$

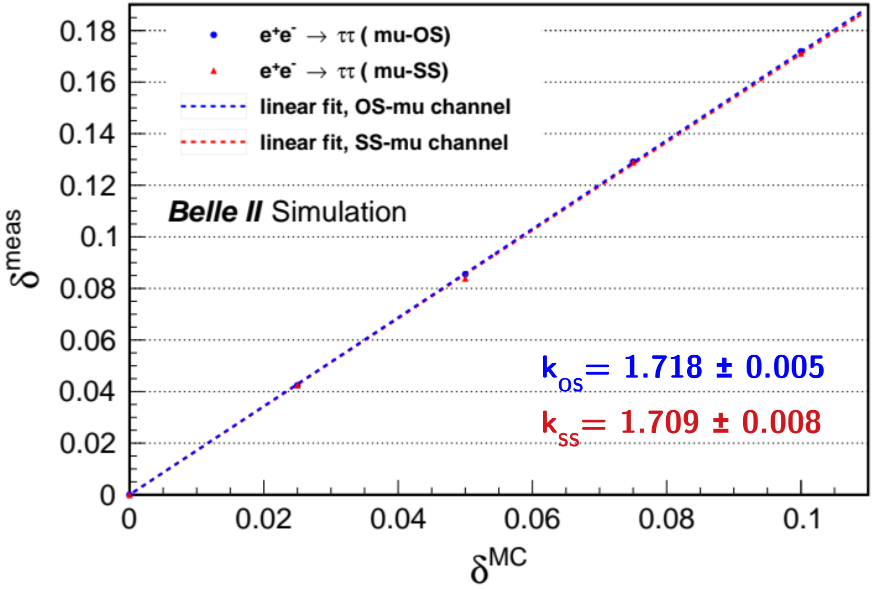
recall that: $\epsilon^{meas} = N_4/(N_3 + N_4)$

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

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

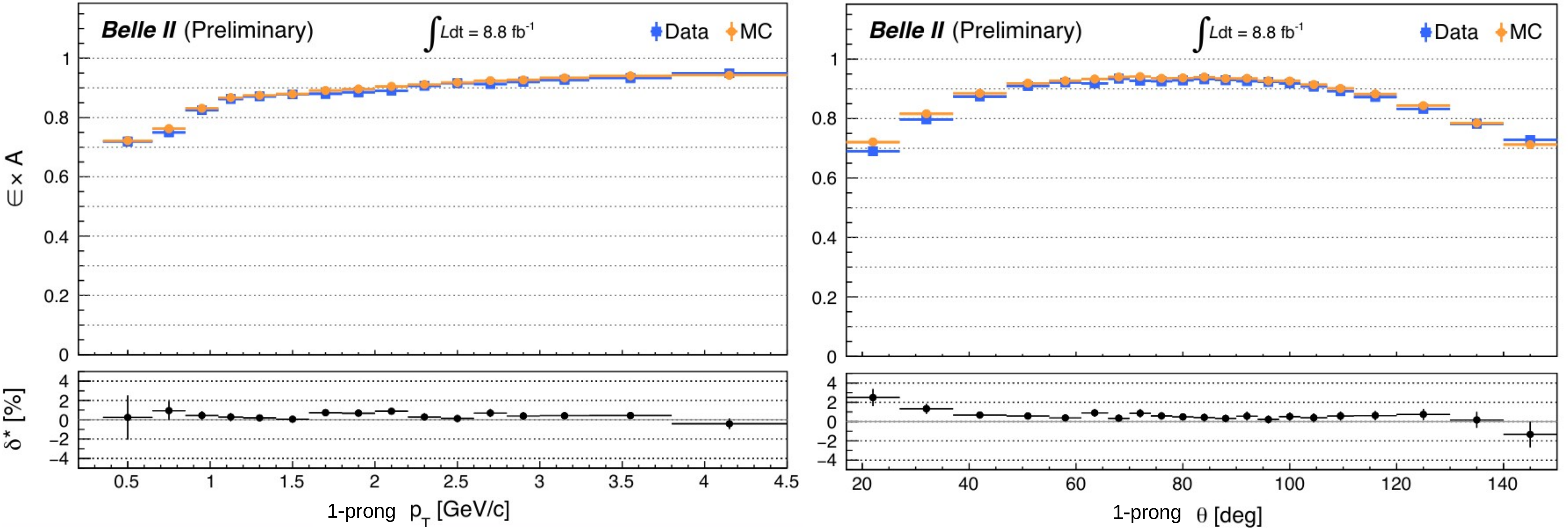
$$= \frac{1}{k}(1 - \epsilon^{meas}_{Data}/\epsilon^{meas}_{MC})$$



# εxA measurement

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



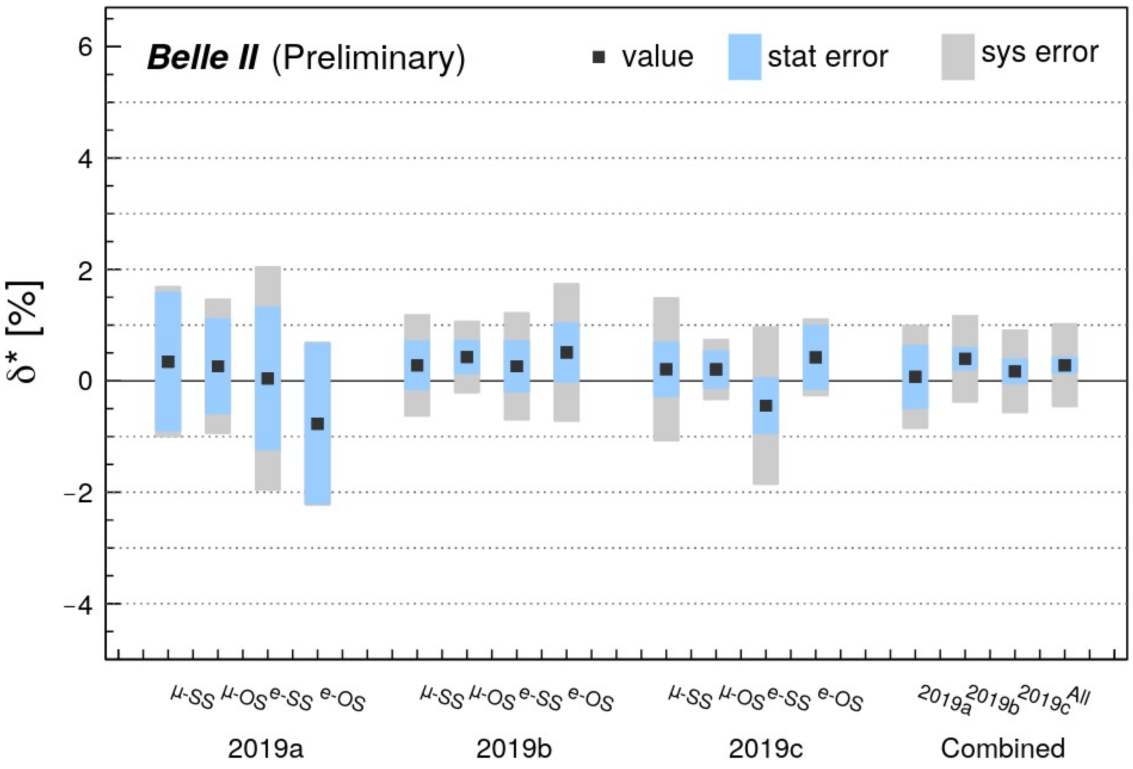
# Results: calibrated discrepancy

- 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 *charge dependence* → expected to be improved after a better understanding of *charge asymmetry* effects

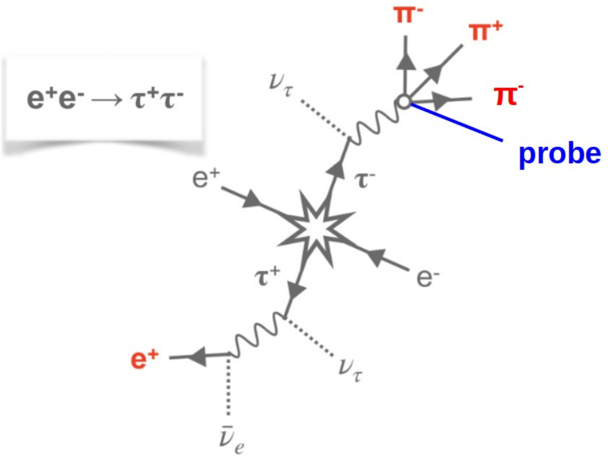
$\delta^*_{\text{overall}} = 0.28 \pm 0.15\ (\text{stat}) \pm 0.73\ (\text{sys})\ \%$

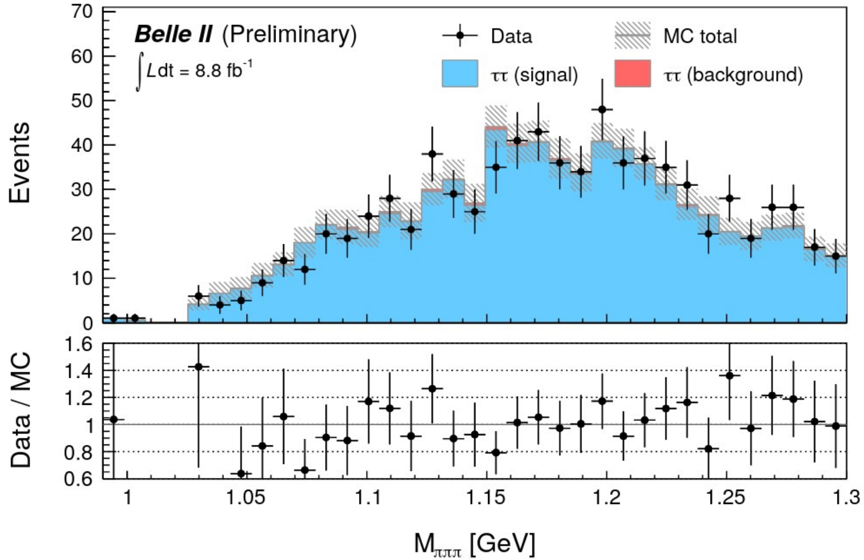


# Fake rate measurement

- 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 **$r_{fake}$=N5/(N4 + N5)**




- Exploit full event kinematics to increase signal purity (measured on simulation)
- Scale yields in data for the measured signal purity: **$r_{fake}$= 0.97 ± 0.34 (stat)%**
- Only preliminary evaluation of systematic uncertainty

# Summary

- **Belle II** is taking data since the beginning of **Phase 3**, and continued successfully for all 2020 run periods!
- With a sample of ~ 9 $fb^{-1}$ data (**Belle II 2019**), we devise the strategy to measure the quantity **ε x A** on data and simulation, by analyzing 3x1-prong τ-pair decays:

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

- The overall calibrated discrepancy $\delta^*$ is measured to be:

**0.28 ± 0.15 (stat) ± 0.73 (sys) %**

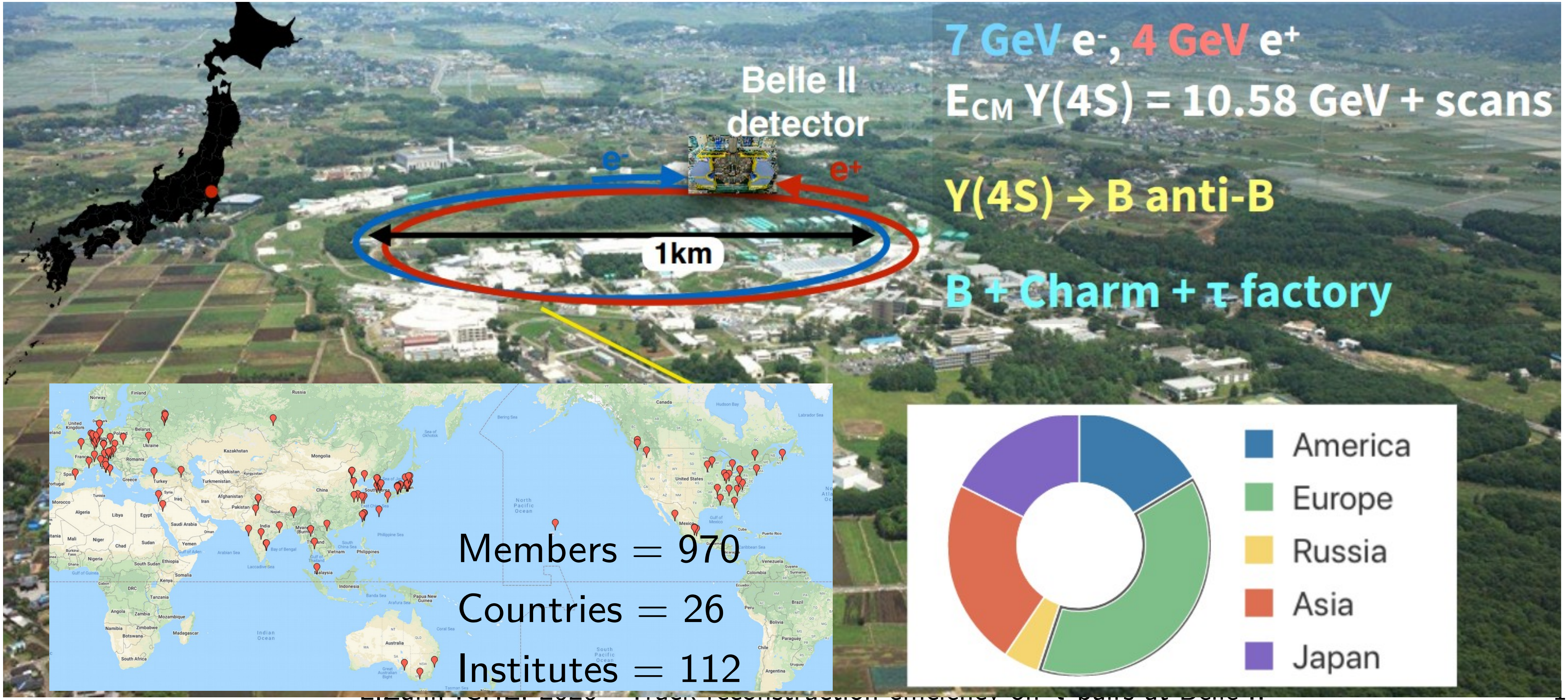
→ Prescription on how to assign systematic uncertainties for analyses dealing with tracks of transverse momentum $[0.2 < p_T < 3.5]$ GeV/c is provided

- 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) %** consistently with simulation.

Thanks for your attention!

# backup

# Belle II collaboration




Members = 970

Countries = 26

Institutes = 112

# Track selections

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

| | 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] | $< 1$ | $< 1$ | $< 1$ | $< 1$ |
| $\frac{E_{cluster}}{p}$ | $< 0.8$ | $< 0.6$ | $(0.8, 1.2)$ | $< 0.6$ |
| $E_{cluster}$ | – | $> 0$ | – | $> 0$ |
| 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.

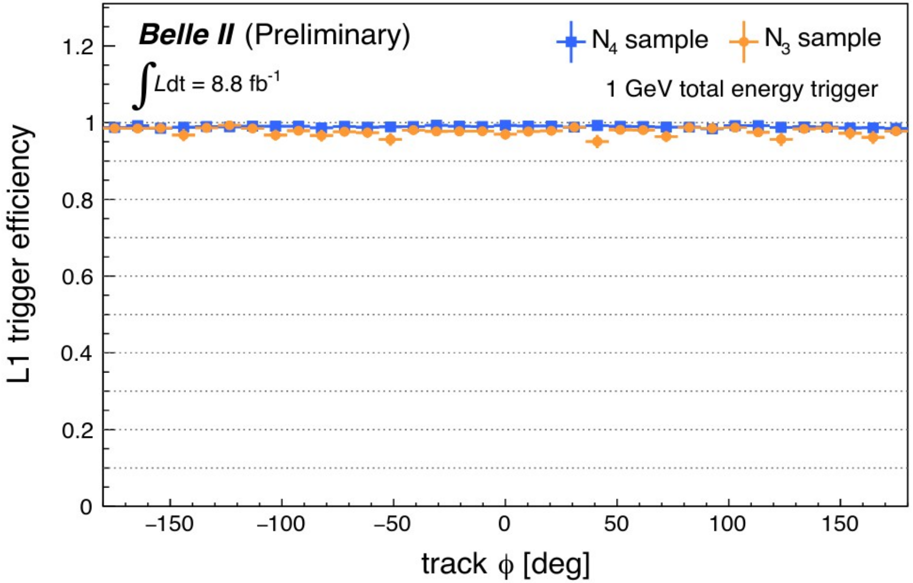
| | $N_{pion}^{probe}$ | $N_{pion}^{tag}$ | $N_{electron}^{tag}$ | $N_{muon}^{tag}$ |
|---|---|---|---|---|
| electron channel, 4-track sample | 3 | $\geq 2$ | 1 | 0 |
| electron channel, 3-track sample | 2 | 2 | 1 | 0 |
| muon channel, 4-track sample | 3 | $\geq 2$ | 0 | 1 |
| muon channel, 3-track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

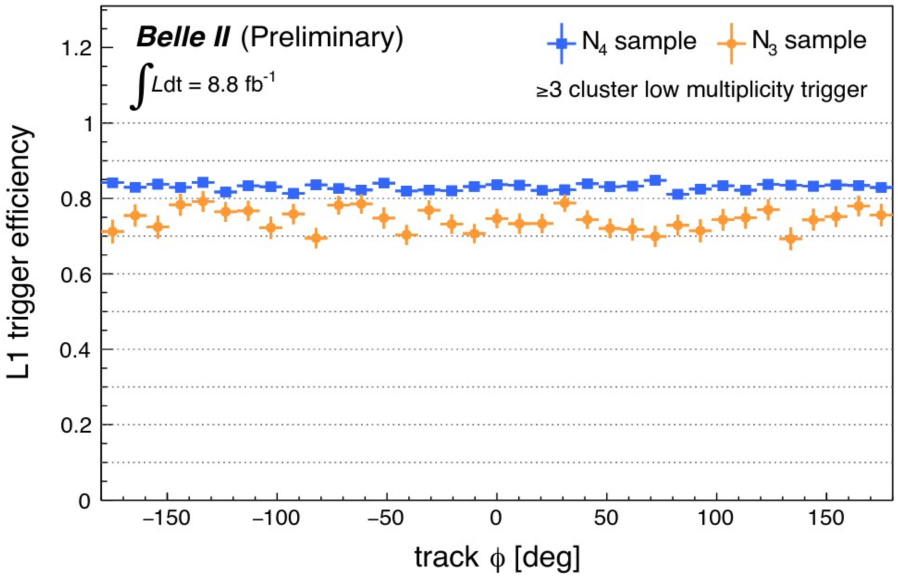
# Trigger selection

- 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.

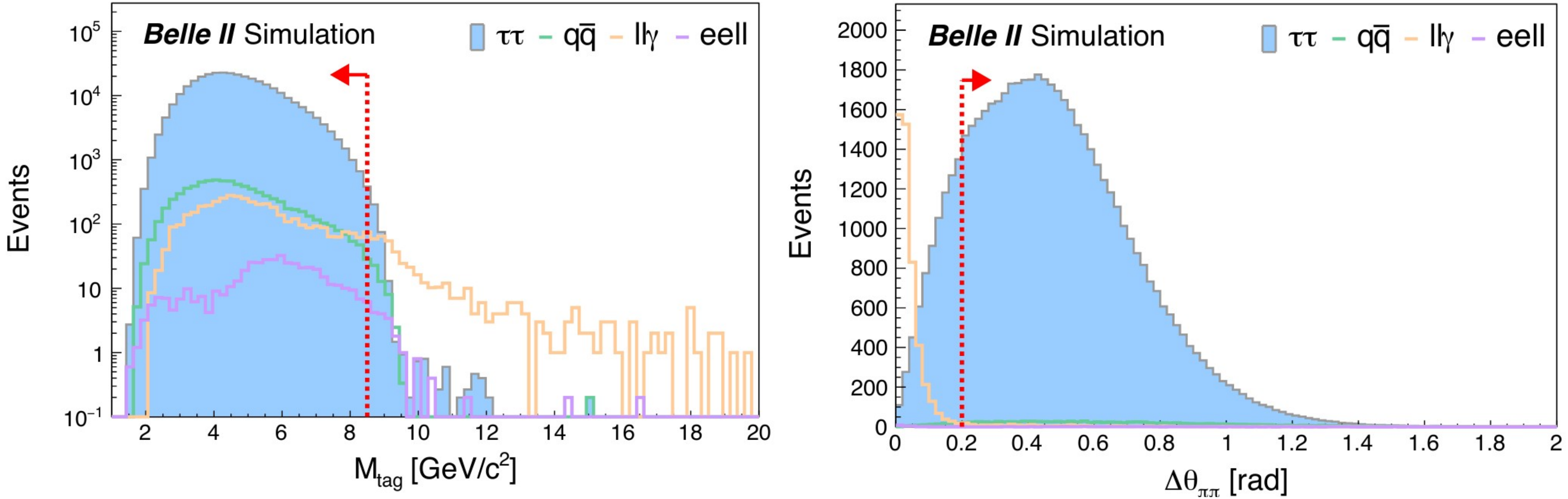
$$\epsilon_{bit_{ECL}} = \frac{N(bit_{ECL} \text{ AND } bit_{CDC})}{N(bit_{CDC})}$$



# Selections

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



# Calibration procedure: details

- The discrepancy estimator **$\delta^{meas}$** is overestimated due to 1) ***combinatorial effect*** + 2) ***effect of the applied selections***

  1) allow multiple N4 candidates when the *probe track* passes also the selections for *tight pions* (tag track):

  - possible swapping of tracks between tag and probe
  - do not select any best candidate not to bias the efficiency
  - average on all the possible combinations with 1/Ncand as event weight

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

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

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

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

- From a pure statistical approach the expected overestimate **k-factor** is 2, averaging on the sign of the probe track.

  2) The selections for background rejection may mitigate the effect, rejecting some N4 candidates:

  - no more possible to extract the k-factor from pure theoretical approach (binomial coefficient computation) $\rightarrow$ need a ***calibration procedure exploiting the simulation***

# Efficiency estimator: statistical interpretation

- The tag-and-probe method exploits charge conservation to imply the 4th track:

  **FOUND → N4**

  **NOT FOUND → N3**

  $\left.\right\}$ **ε x A = N4/(N3+N4)**

- Let's call **ε** the efficiency to find a track and assume we always have the 1-prong track (required by reconstruction, $\boldsymbol{\varepsilon_{\text{1-prong}} = 1}$)
- **N4 = $\boldsymbol{\varepsilon^3 N_{tot}\ (\varepsilon_{\text{1-prong}} * \Pi \mathcal{B})}$**
- **N3 = $\boldsymbol{3\ \varepsilon^2 (1-\varepsilon)\ N_{tot}\ (\varepsilon_{\text{1-prong}} * \Pi \mathcal{B})}$**

$$\boldsymbol{\varepsilon \times A = N4/(N3+N4)} = \frac{\epsilon^3}{\epsilon^3+2\epsilon^2(1-\epsilon)} = \frac{\epsilon}{2-\epsilon} = \frac{1-\delta}{1+\delta} \simeq 1 - 2\delta + o(\delta^2)$$