Prospects of $\tau^- \to \pi^-\pi^0\nu_\tau$ at Belle II

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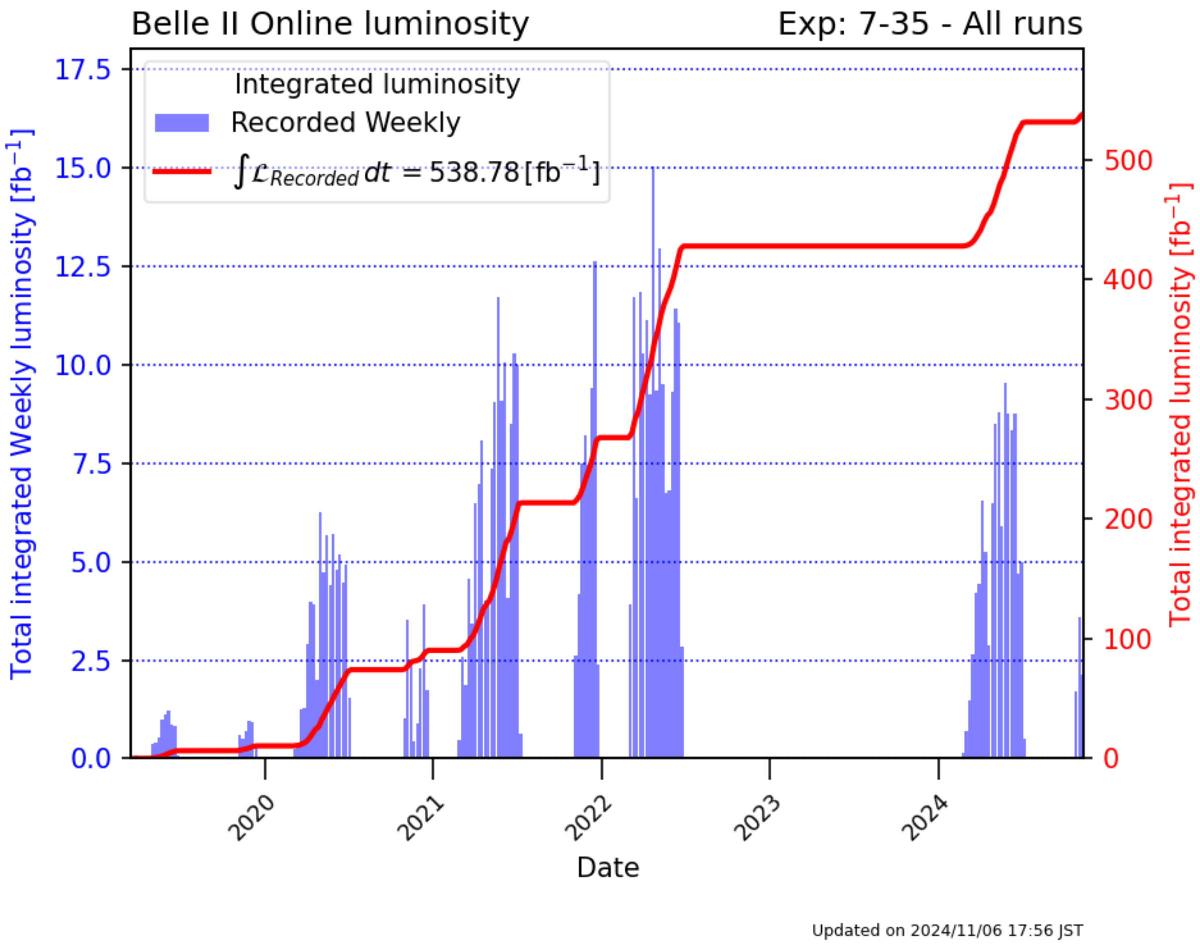
Belle II data



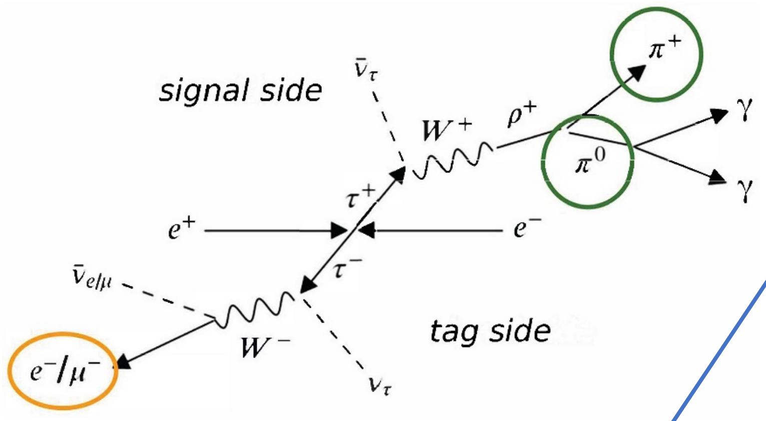
- ~540 fb^{-1} on tape
- 424 fb^{-1} data have been used for physics
- Publications on τ physics with tagged τ's
  - Test of light-lepton universality in τ decays with Belle II, 2405.14625, 365 fb^{-1} ($h\pi^0$, $h2\pi^0$ tag)
  - Measurement of the τ-lepton mass with the Belle II experiment, 2305.19116, 190 fb^{-1}, (e, μ, h, $h\pi^0$ tag)
  - Search for lepton-flavor-violating τ decays to a lepton and an invisible boson at Belle II, 2212.03634, 63 fb^{-1} (3h tag)
- Belle II trigger & data quality are suitable for high precision τ analyses

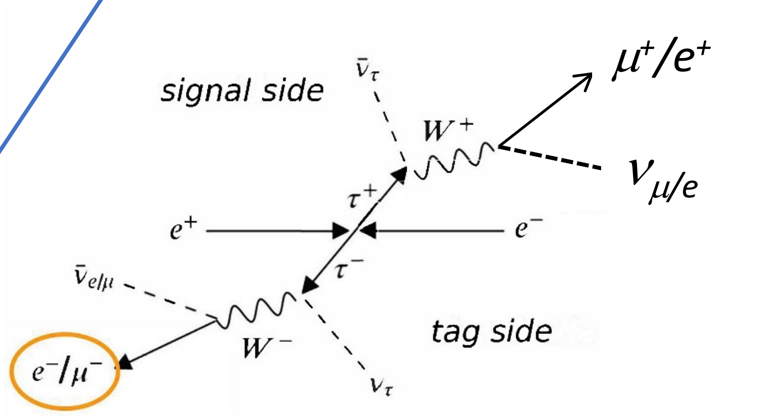
Strategy of BF and SF measurements

Measure the ratio of the BFs directly

Normalized $\pi\pi^0$ invariant mass distribution

$$v_1(s) \equiv \frac{m_\tau^2}{6\,|V_{ud}|^2\,S_{\mathrm{EW}}} \frac{B(\tau^- \to V^- \nu_\tau)}{B(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} \times \frac{\mathrm{d}N_V}{N_V\,\mathrm{d}s} \left[\left(1 - \frac{s}{m_\tau^2}\right)^2 \left(1 + \frac{2s}{m_\tau^2}\right) \right]^{-1}$$





Statistics are large enough in the 365 fb^{-1} data sample

Belle II: Test of light-lepton universality in τ decays with Belle II, 2405.14625, 365 fb^{-1} ($h\pi^0$, $h2\pi^0$ tag)

- The data were recorded between 2019 and 2022 at a center-of-mass energy of 10.58 GeV and correspond to about 333x10^6 $e^+e^-\to\tau^+\tau^-$ events.

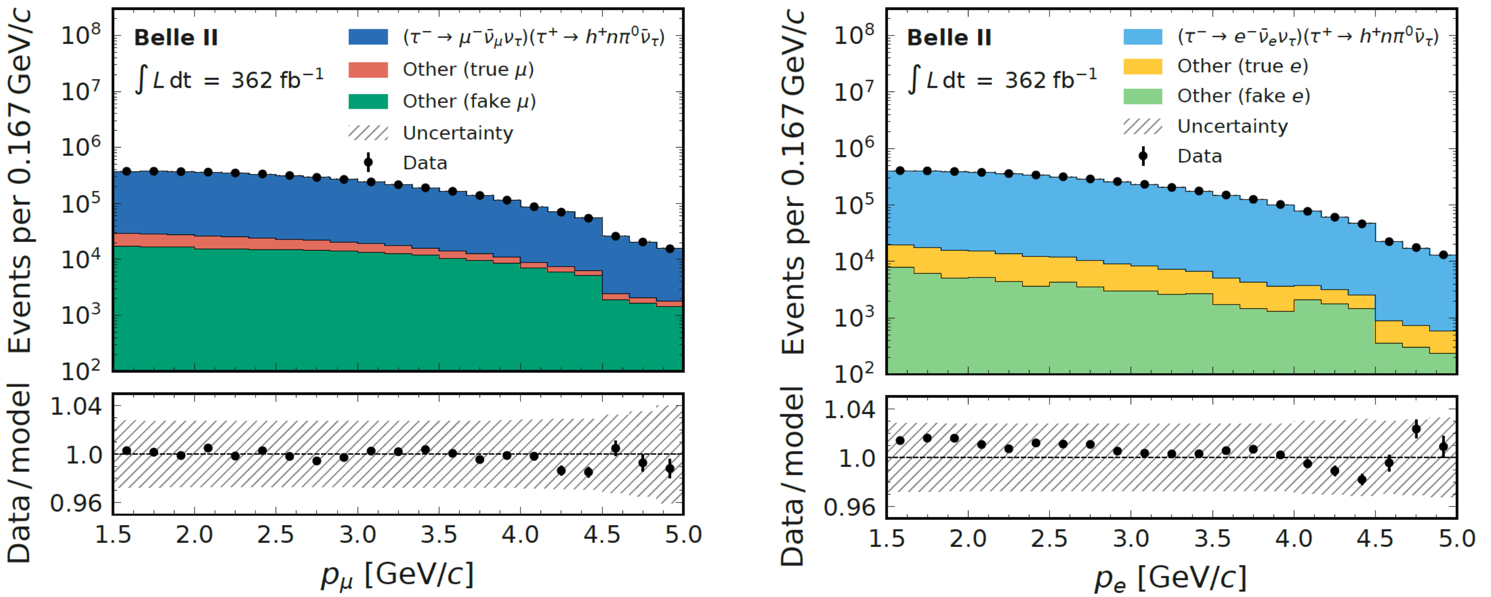
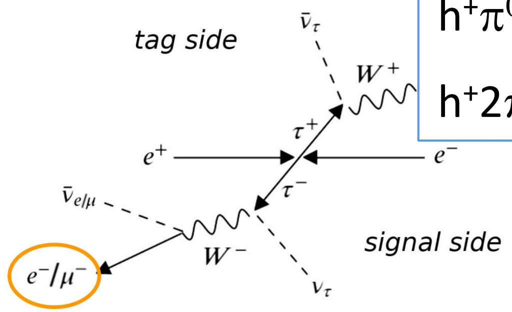


Figure 3. Observed momentum distribution for muon (left) and electron (right) candidates with simulation expectations overlaid. The lower panel shows the ratio between data and expectations with systematic uncertainties (hatched).



$h^+\pi^0$ or

$h^+2\pi^0$

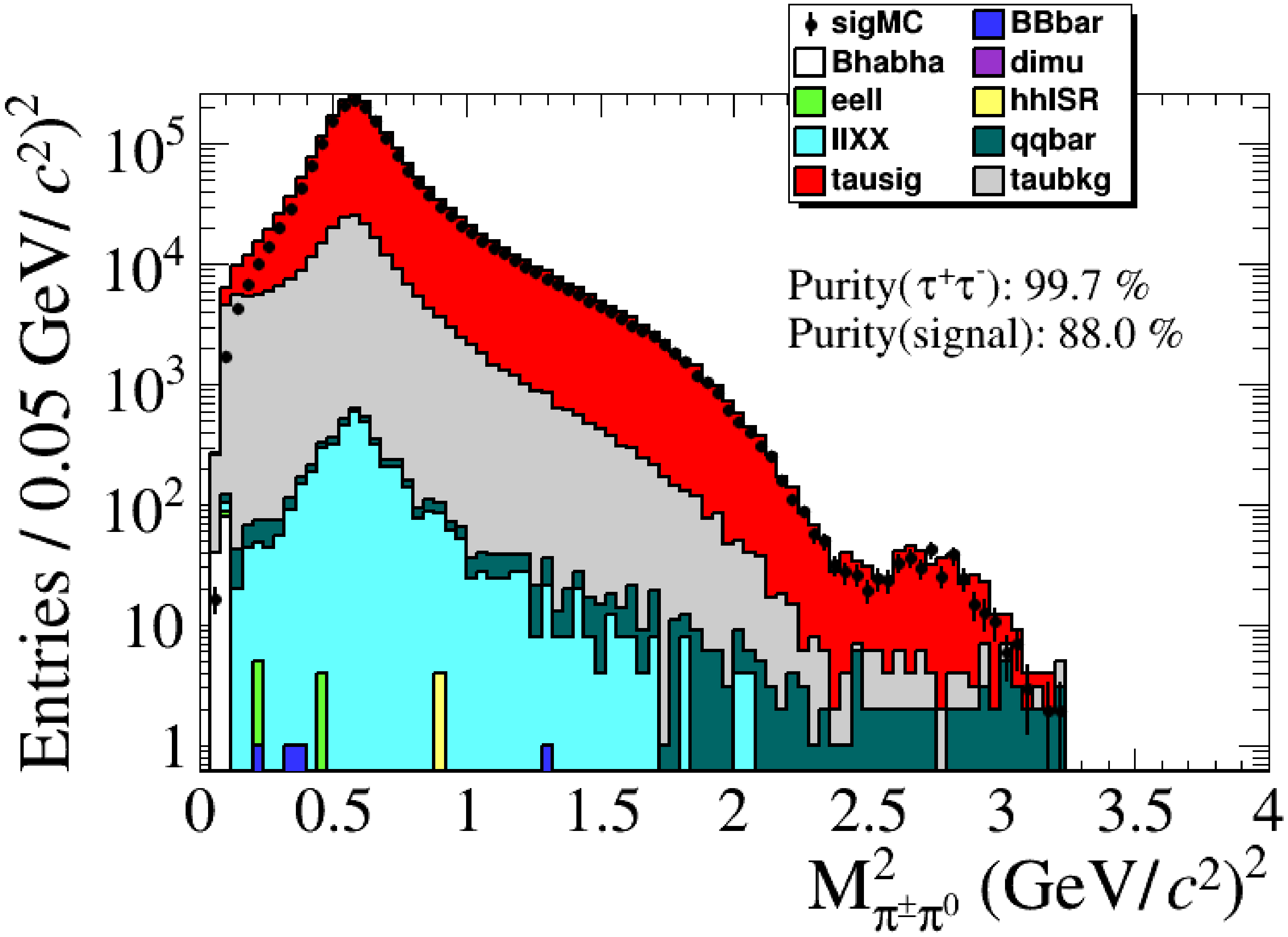
The signal yields are 4,156,500 for $\tau^-\to e^-\nu\nu$ and 4,000,190 for $\tau^-\to\mu^-\nu\nu$.

$h\pi^0$ is about 2/3 of the $h\pi^0$+$h2\pi^0$ tags
Expect ~5x10^6 e/μ-tagged $h\pi^0$ events
Expect ~2x10^6 eμ events

Statistical uncertainty in the ratio of the BFs is O(10^{-4})

Belle II: $R_\mu = 0.9675 \pm 0.0007(stat.) \pm 0.0036(sys.)$

Very rough MC study



Efficiencies and systematic uncertainties

- Trigger
- Tracking
- Particle ID
- Photon ID and π^0 reconstruction
- Background
- Unfolding
- ……

Trigger/tracking/PID

Belle II: Test of light-lepton universality in τ decays with Belle II, 2405.14625, 365/fb (hπ^0, h2π^0 tag)

- **Trigger:**

The trigger efficiency is measured with a reference sample selected by independent triggers based on the number of particles reconstructed in the CDC. The trigger efficiency in data is 99.8 % for $\tau^- \to e^-\bar{\nu}_e\nu_\tau$ and 96.6 % for $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ decays, which is primarily driven by the tag hemisphere. In simulation, the corresponding efficiencies are 98.6 % and 95.4 %, respectively. To account for imperfection in the simulation of the trigger, we apply correction factors as ratios of efficiencies in data and simulation to our simulated samples. The correction

- **Tracking:**

Differences between the track finding efficiencies in simulation and data have been measured in $e^+e^- \to \tau^+\tau^-$ events with one of the τ leptons decaying to three charged hadrons. A per-track systematic uncertainty of 0.24 % is included as a normalisation uncertainty of the templates to account for these differences. The associated systematic uncertainty on R_μ is 0.01 %.

- **Particle ID:**

  - e, μ:

Source	Uncertainty [%]
Charged-particle identification:	0.32
Electron identification	0.22
Muon misidentification	0.19
Electron misidentification	0.12
Muon identification	0.05

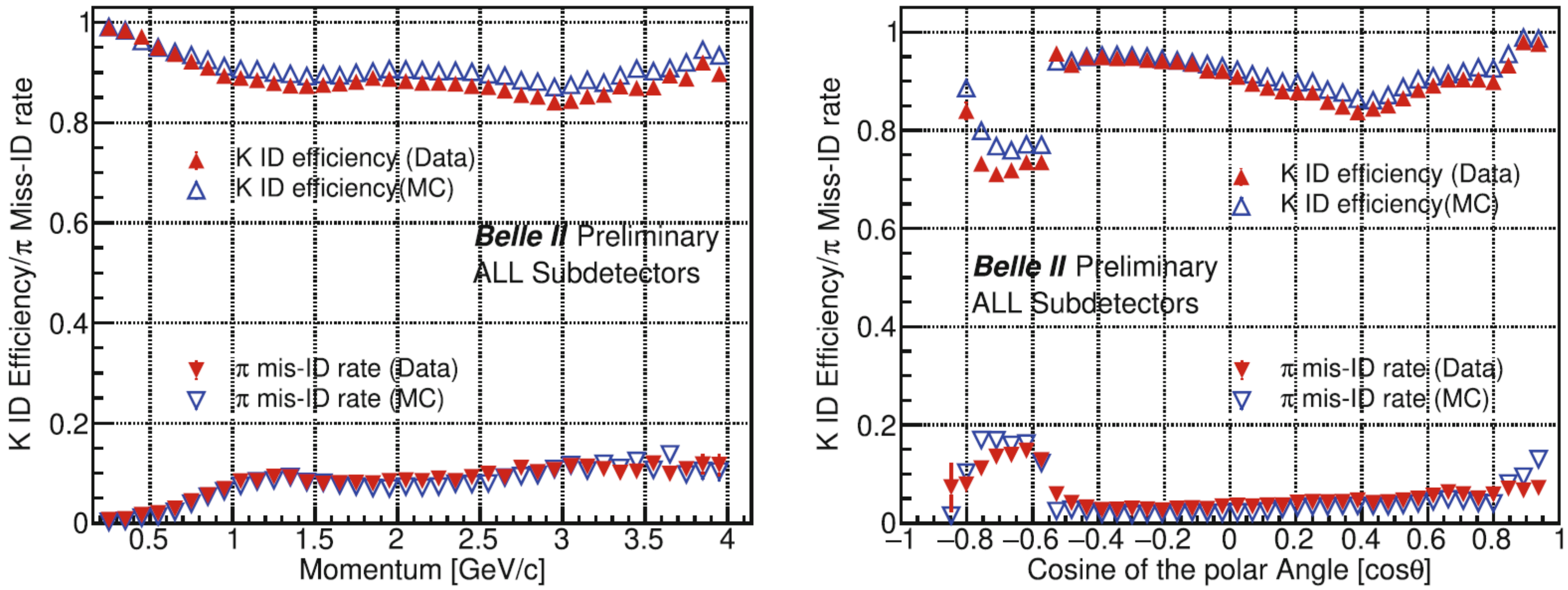
  - π: many studies (D, Ks, … decays), good precision can be achieved (next page)

π ID

Belle II: Charged Particle Identification Performances in Belle II, https://doi.org/10.1007/978-981-97-0289-3_35

Belle II incorporates two specialized sub-detectors: the Time-of-Propagation counter (TOP) and the Aerogel RICH counter (ARICH), both designed for efficient particle identification (PID). The PID capabilities of TOP and ARICH rely on Cerenkov angle measurements, while the Central Drift Chamber (CDC) utilizes specific ionization (dE/dx) to provide complementary PID information.

Control samples: $D^{*+} \to D^0[\to K^-\pi^+\pi^0]\pi^+$



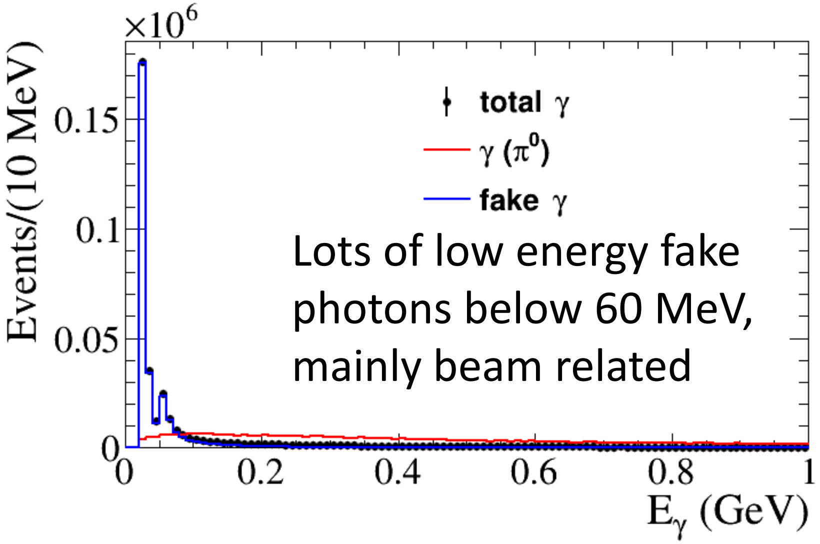
$$\mathcal{R}_{K/\pi} = \frac{\mathcal{L}_K}{\mathcal{L}_K + \mathcal{L}_\pi}$$

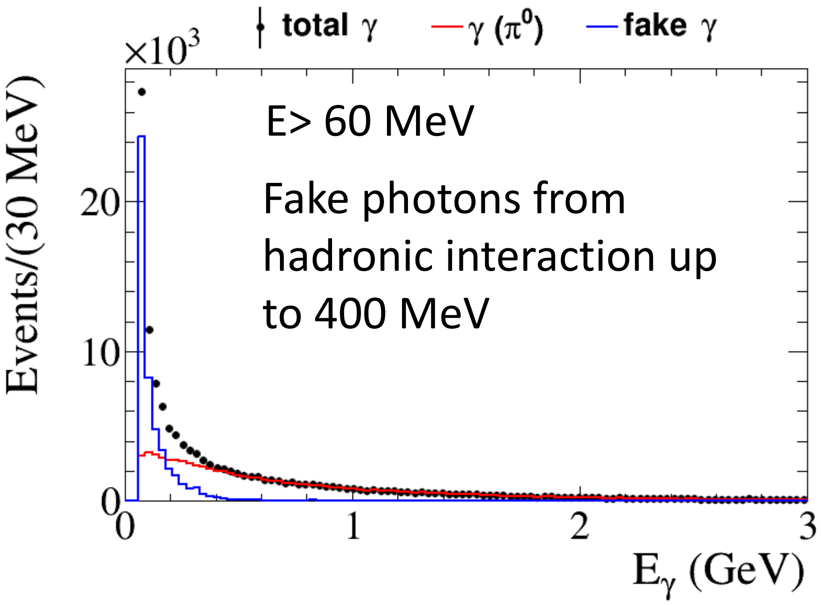
$R_{K/\pi} > 0.5$ for K-ID

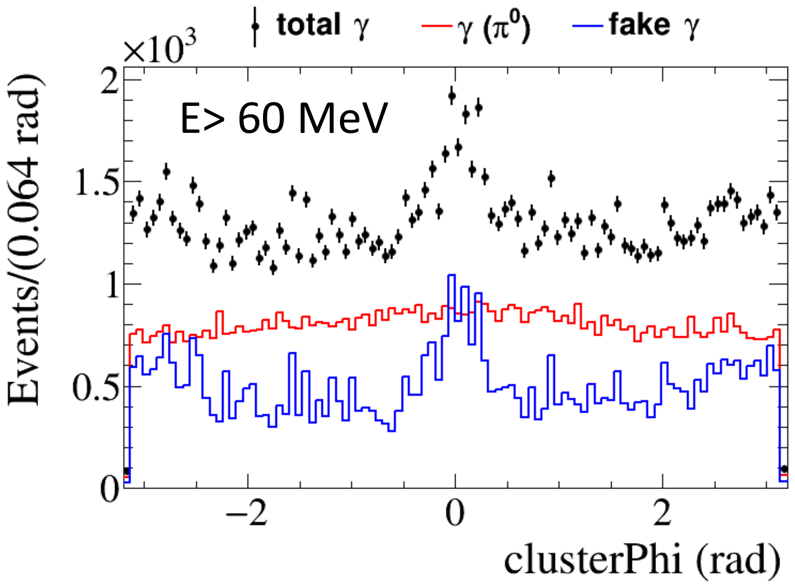
$\varepsilon_{K\to K} = (89.20\pm0.04)\%$

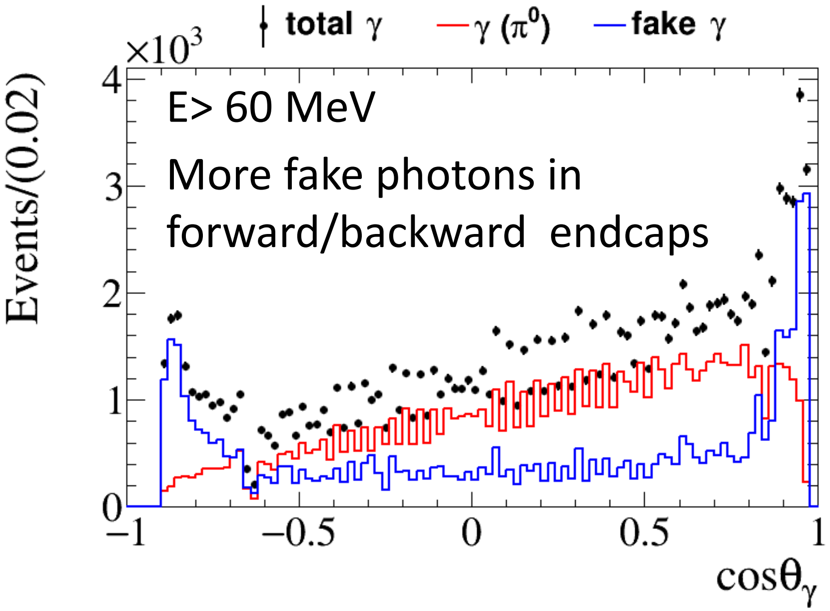
$\varepsilon_{\pi\to K} = (\ 5.08\pm0.02)\%$

Photon and π^0 selection

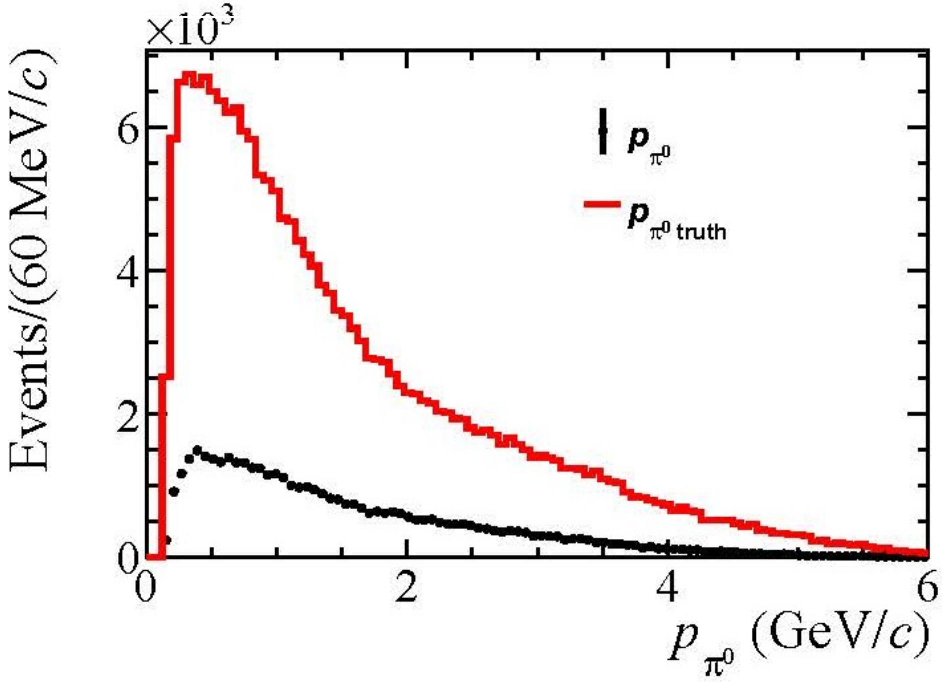


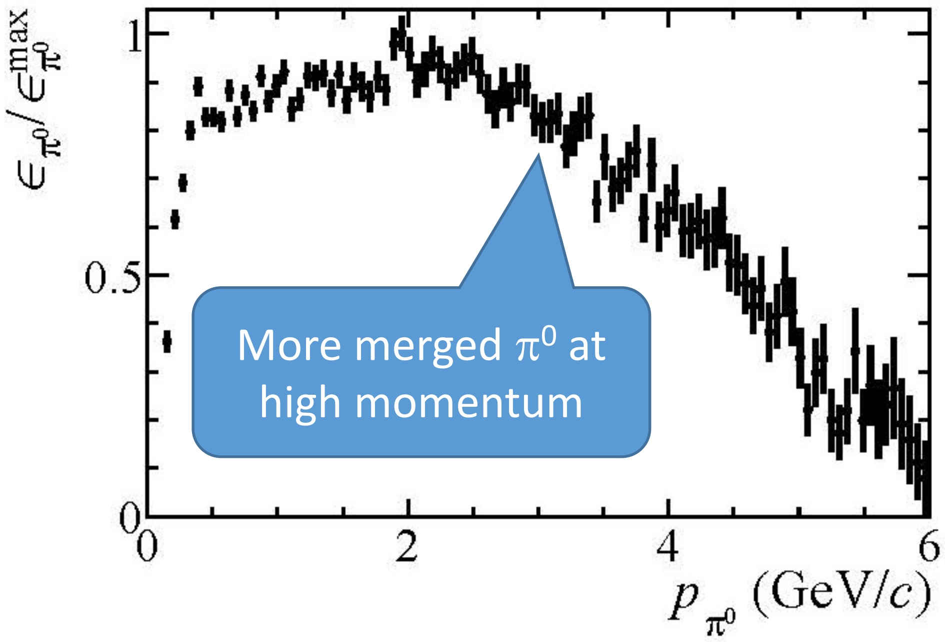




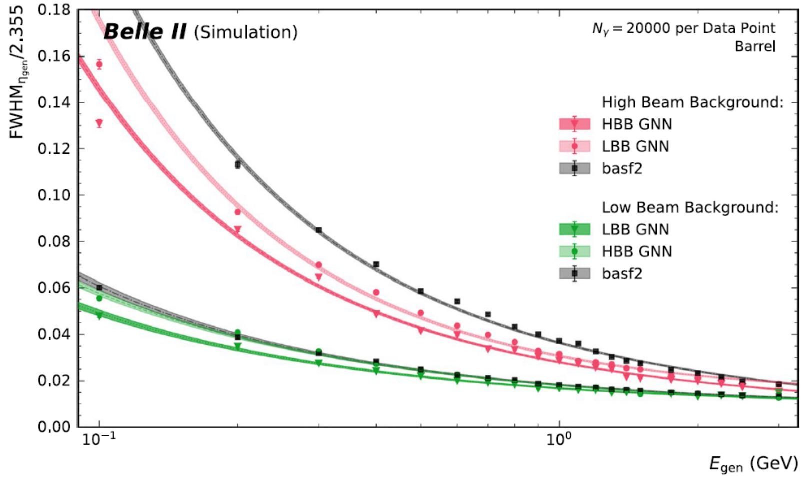


π^0 efficiency ($\pi^0 \to \gamma\gamma$)



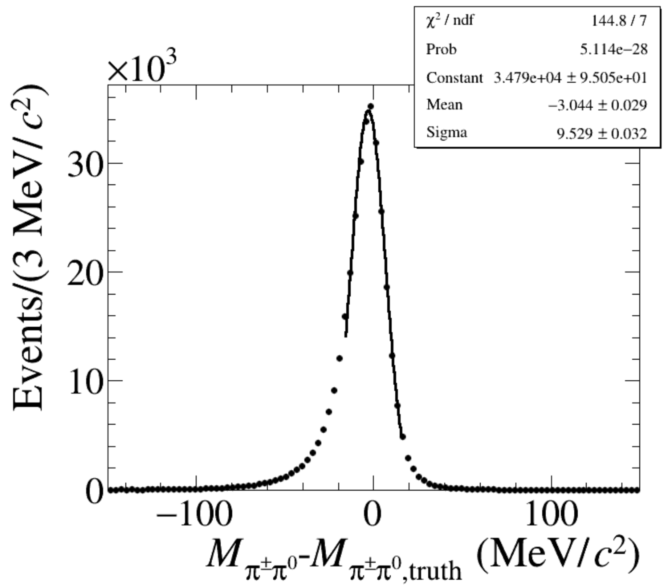


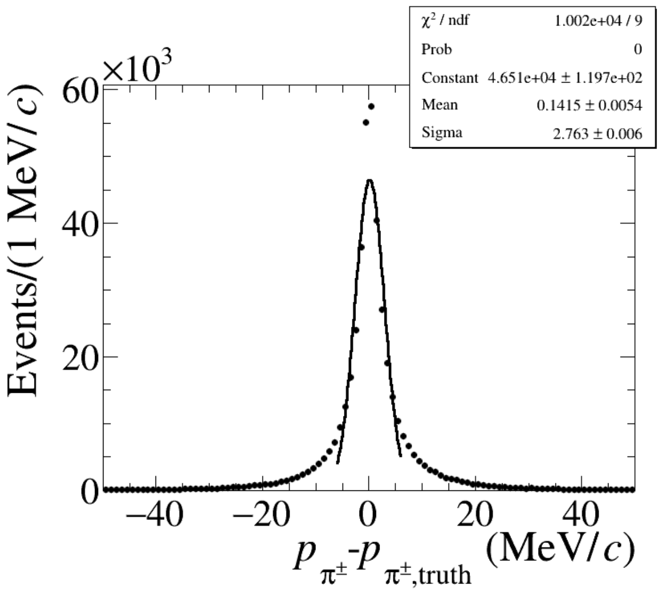
Belle II: Photon Reconstruction in the Belle II Calorimeter Using GNN, https://doi.org/10.1007/s41781-023-00105-w

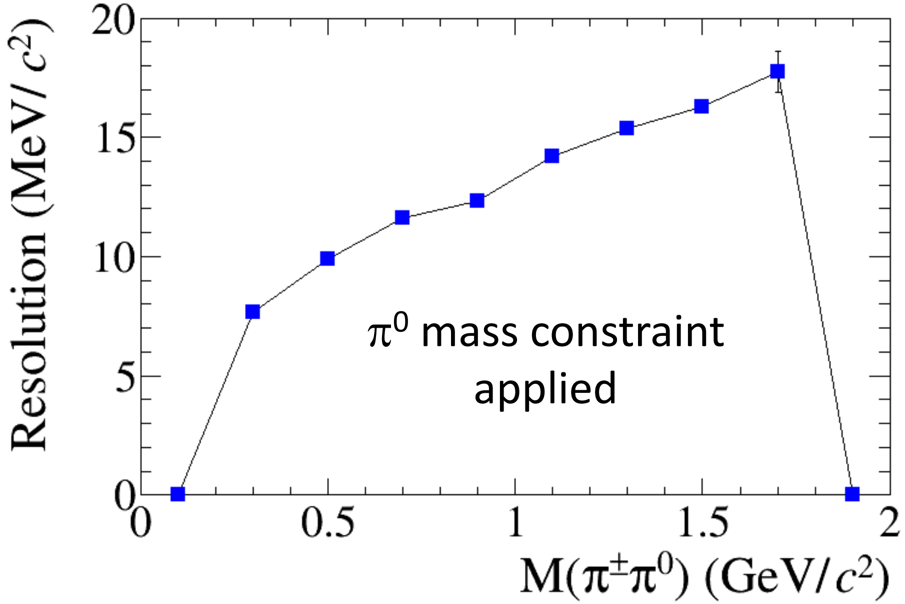


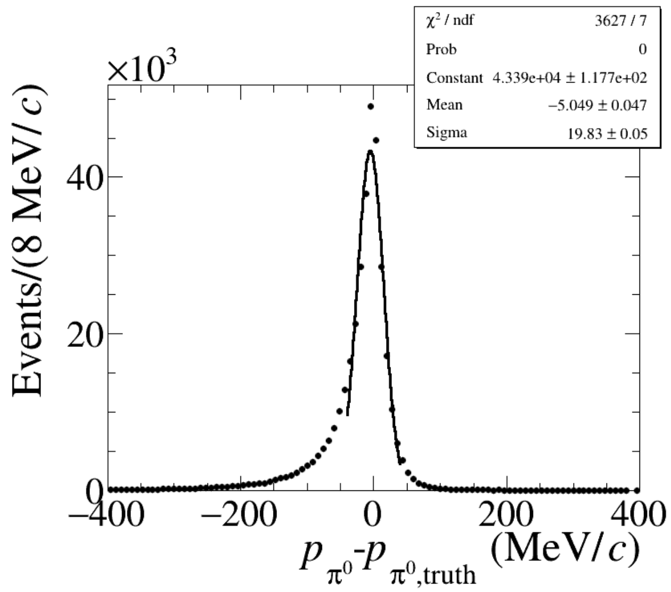
Better understanding the photon selection and π^0 reconstruction is essential: fake photon suppression, gamma-conversion reconstruction, merged-π^0 resolution, …

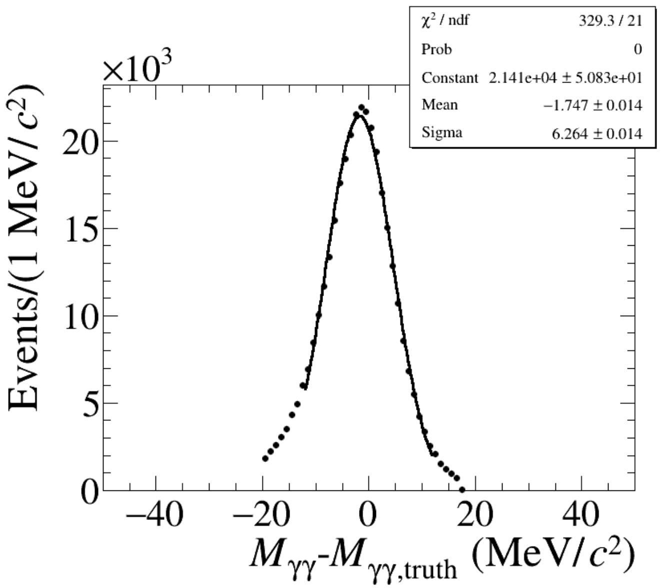
Photon and π^0 resolutions

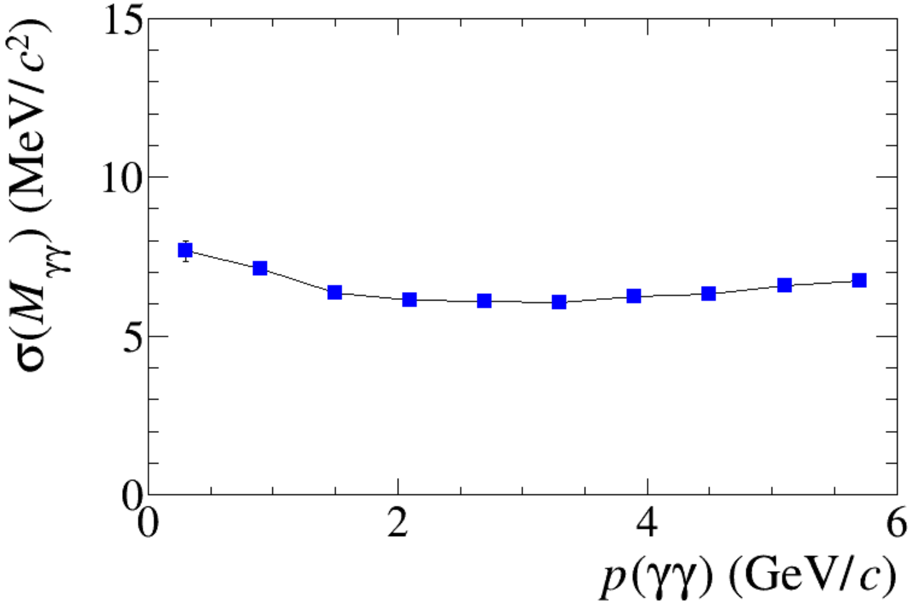












Backgrounds & unfolding

- Background:
  - Non-tau background should be studied in a data-driven method
  - Tau background, mainly from $h2\pi^0$, depends strongly on π^0 reconstruction, $h2\pi^0$ invariant mass distribution and intermediate states, can be studied with data
- Unfolding:
  - π^- momentum and resolution calibration
  - π^0 energy and resolution calibration
  - A few unfolding softwares are available

Summary

- No solid estimation on the final precision Belle II can achieve
- New techniques may be developed for photon-ID and π^0 reconstruction
- Lots of efforts needed to understand all the sources of systematic uncertainties reliably
- May extend the analysis to more Belle II data

Thank you very much!

More data are being accumulated ……