Study of the τ lepton decays at the Belle II experiment

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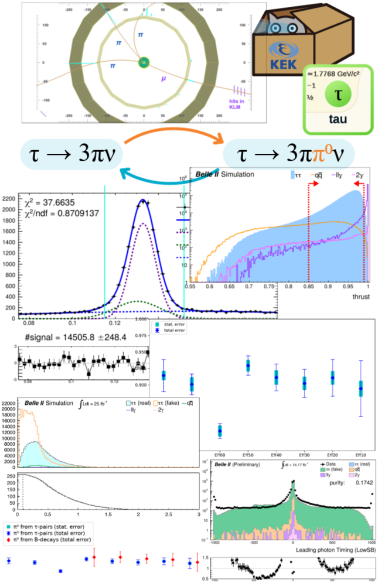
Overview

» **main topic:** measurement of the π^0 reconstruction efficiency correction using τ-pair events from the Belle II experiment

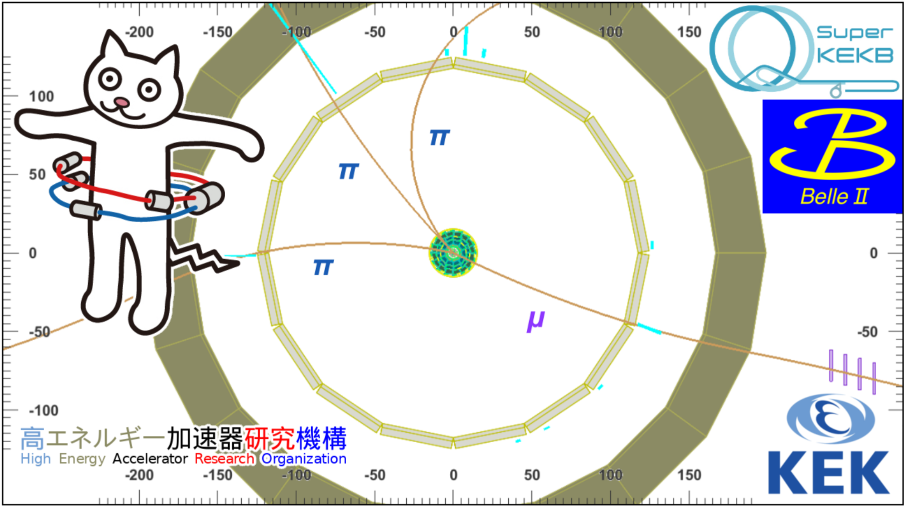
» **outline:**

- Belle II experiment
- τ leptons
- π^0 reconstruction efficiency
- analysis
- signal yields
- average and momentum dependent correction
- optimized π^0 selection
- photon timing study
- summary



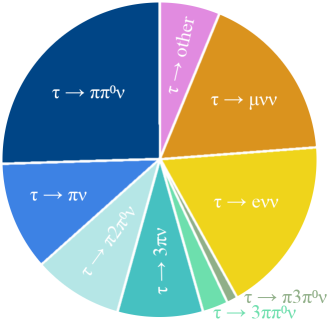
Belle II experiment

- **SuperKEKB:** asymmetric e^+e^- collider, $\sqrt{s} = 10.58$ GeV, Tsukuba, Japan
  B-, D-factory, but also τ-**factory**



τ leptons

タウオン

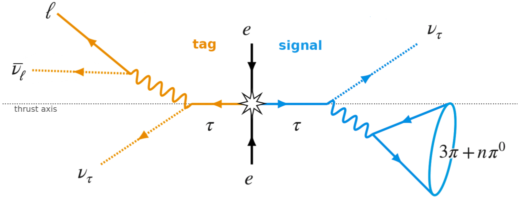


» τ **mass:** (1776.86 ± 0.12) MeV

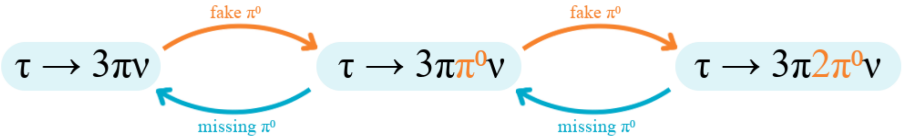
» τ **lifetime:** $(2.903 \pm 0.005) \times 10^{-13}$ s

» **studied events:** 3x1-prong τ decays

- signal side: $\tau \to 3\pi n\pi^0\nu_\tau$
- tag side: $\tau \to e\bar{\nu}_e\nu_\tau$ or $\tau \to \mu\bar{\nu}_\mu\nu_\tau$



π^0 reconstruction efficiency



- π^0 **mass:** (134.9770 ± 0.0005) MeV
- π^0 **lifetime:** $(8.52 \pm 0.18) \times 10^{-17}$ s
- **dominant decay mode:** $\pi^0 \rightarrow 2\gamma$ (almost 99 %)
- π^0 **efficiency correction:** double ratio method

$$\eta_{\pi^0} = \frac{\epsilon_{\pi^0}^{data}}{\epsilon_{\pi^0}^{MC}} = \frac{N^{data}(\tau\to 3\pi\pi^0\nu_\tau)}{N^{MC}(\tau\to 3\pi\pi^0\nu_\tau)} \div \frac{N^{data}(\tau\to 3\pi\nu_\tau)}{N^{MC}(\tau\to 3\pi\nu_\tau)}$$

$N_{\pi^0} = 0 \rightarrow$ extract $\tau \rightarrow 3\pi\nu_\tau$

$N_{\pi^0} \geq 1 \rightarrow$ extract $\tau \rightarrow 3\pi\pi^0\nu_\tau$

- similar measurement by the BaBar collaboration → arXiv:1305.3560 [physics.ins-det]

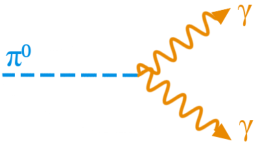
Event selection and π^0 selection

» **used data:** 62.79 fb^{-1} (collected at Belle II between 2019-2020)

» **event selection:** suppressing background by imposing requirements on variables with good signal/background separation, more details in backup

» π^0 **selection:** eight different selections

- nominal working points:
  "Eff60", "Eff50", "Eff40", "Eff30", "Eff20", "Eff10"
  - π^0 selections with given efficiency, recommended by the Belle II Neutrals Performance Group
  - optimized for π^0 from B-decays



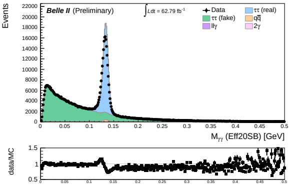
- **"Nom"** π^0 selection
  - what is currently used in the Belle II Tau Physics Group

- **"Low"** π^0 selection
  - same as "Nom" but lower E_γ threshold

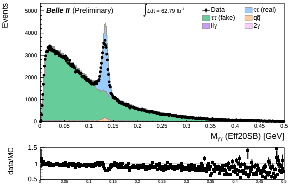
» **signal:** $\pi^0_{lead}+\pi^0_{sub}+\pi^0_{third}$

- summing the signals from the distributions of three reconstructed π^0s with the highest energy

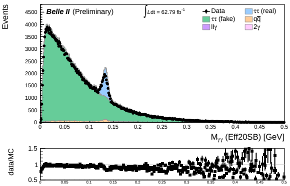
leading π^0



subeading π^0



third π^0



("$\tau\tau$ (real)" – truth-matched π^0; "$\tau\tau$ (fake)" – fake π^0, either one or both of the photons are background photons)

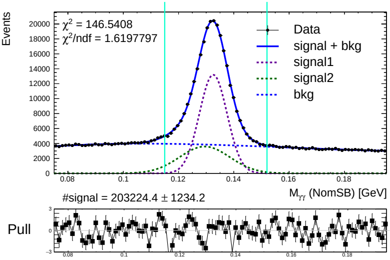
» π^0 **mass distribution fit:**

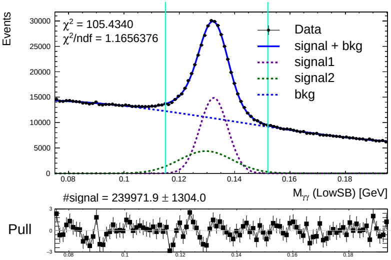
- peak: double Gaussian
- background: 3rd order polynomial

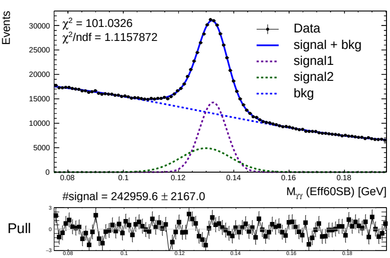
» **#signal:** integral over the double Gaussian within mass window

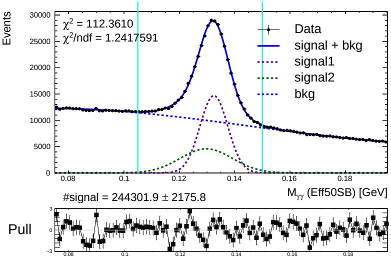
π^0 type	M_{min} (GeV)	M_{max} (GeV)
'Eff10'	0.127	0.139
'Eff20'	0.121	0.142
'Eff30'	0.120	0.145
'Eff40'	0.120	0.145
'Eff50'	0.105	0.150
'Eff60'	0.03	–
'Nom'	0.115	0.152
'Low'	0.115	0.152

$M_{\gamma\gamma}$ fits



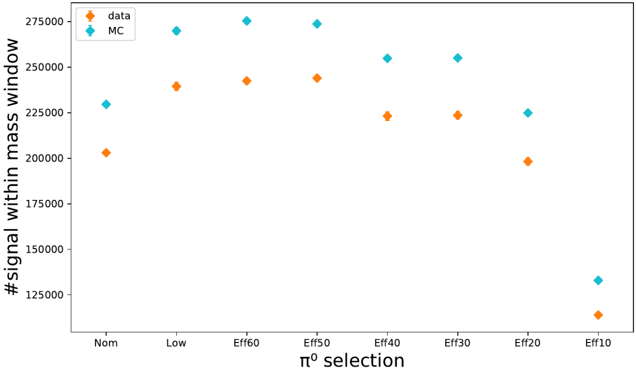






Signal yield of $\tau \to 3\pi\pi^0\nu$

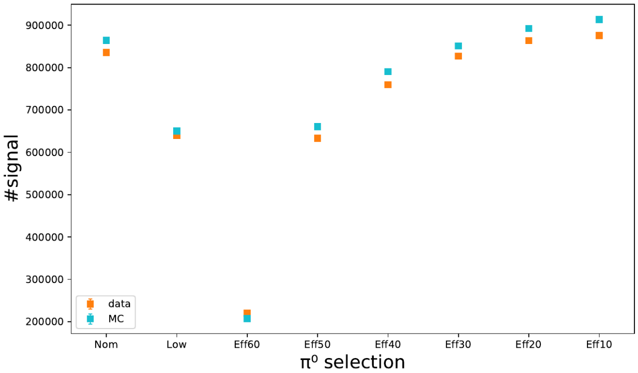
$$\eta_{\pi^0} = \frac{\epsilon_{\pi^0}^{data}}{\epsilon_{\pi^0}^{MC}} = \frac{N^{data}(\tau \to 3\pi\pi^0\nu_\tau)}{N^{MC}(\tau \to 3\pi\pi^0\nu_\tau)} \div \frac{N^{data}(\tau \to 3\pi\nu_\tau)}{N^{MC}(\tau \to 3\pi\nu_\tau)}$$



- #signal for $\tau \to 3\pi\pi^0\nu$ was calculated from the fits of the $M_{\gamma\gamma}$ distribution, using events with $N_{\pi^0} \geq 1$

Signal yield of $\tau \to 3\pi\nu$

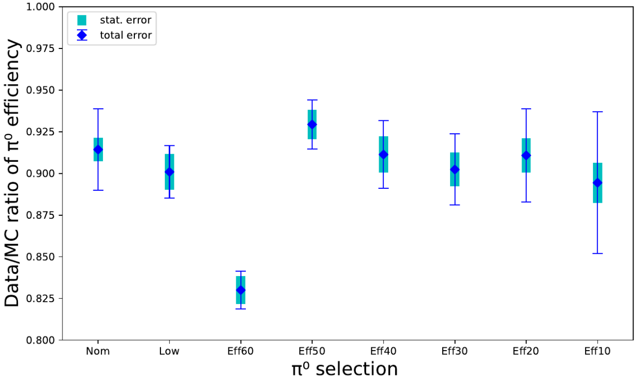
$$\eta_{\pi^0} = \frac{\epsilon_{\pi^0}^{data}}{\epsilon_{\pi^0}^{MC}} = \frac{N^{data}(\tau\to 3\pi\pi^0\nu_\tau)}{N^{MC}(\tau\to 3\pi\pi^0\nu_\tau)} \div \frac{N^{data}(\tau\to 3\pi\nu_\tau)}{N^{MC}(\tau\to 3\pi\nu_\tau)}$$



- #signal for $\tau \to 3\pi\nu$ was determined from events with $N_{\pi^0} = 0$
- MC yield = τ-pair originating from $\tau \to 3\pi\nu$ (truth-matching)
- data yield = data - MC background

π^0 efficiency correction

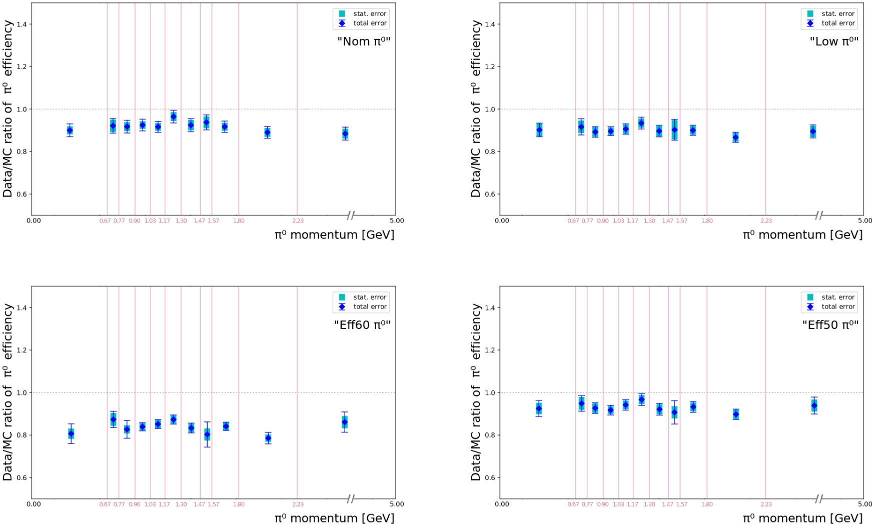
$$\eta_{\pi^0} = \frac{\epsilon_{\pi^0}^{data}}{\epsilon_{\pi^0}^{MC}} = \frac{N^{data}(\tau \to 3\pi\pi^0\nu_\tau)}{N^{MC}(\tau \to 3\pi\pi^0\nu_\tau)} \div \frac{N^{data}(\tau \to 3\pi\nu_\tau)}{N^{MC}(\tau \to 3\pi\nu_\tau)}$$



- **total uncertainty:** $\sigma^2_{\mathrm{total}} = \sigma^2_{\mathrm{stat}} + \sigma^2_{\mathrm{total\ syst}}$
  - systematics sources: fit function, luminosity, trigger efficiency, leptonID efficiency, leptonID fake rate, BR uncertainty, tracking efficiency

Momentum dependent correction

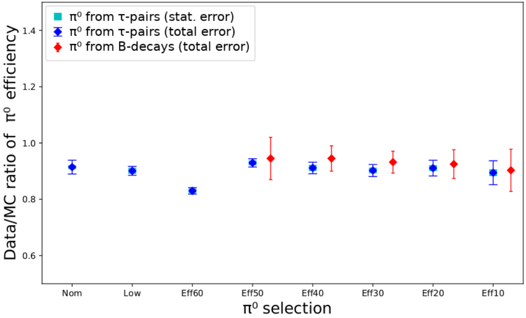
- momentum dependent correction is important for physics analyses with different energy spectrum of π^0s

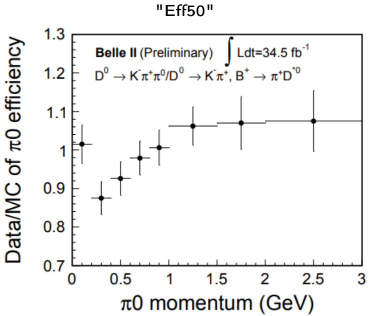


π^0 efficiency measurement discussion

» results were compared with π^0 efficiency measurement from B decays

- average π^0 efficiency corrections are in agreement
- significant discrepancy is observed in the momentum dependent correction





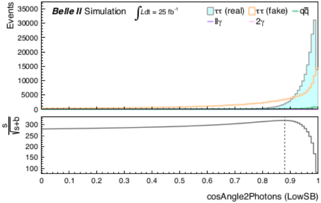
» **next steps:**

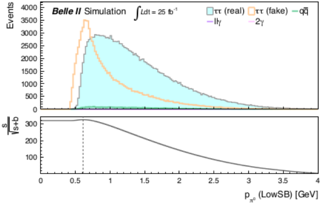
- investigate the discrepancy between the τ and B measurements
- measure the π^0 correction as a function of the θ angle

Optimized π^0 selection

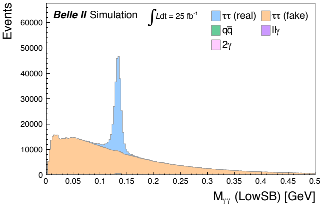
- improved π^0 selection optimized for τ analyses
- based on "Low" π^0 selection
- imposing additional requirements on photon energies, angle between the photons and π^0 momentum, more details in backup

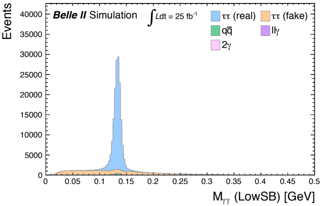
example optimization plots with FOM





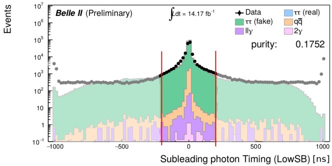
$M_{\gamma\gamma}$ distribution before and after optimized selections

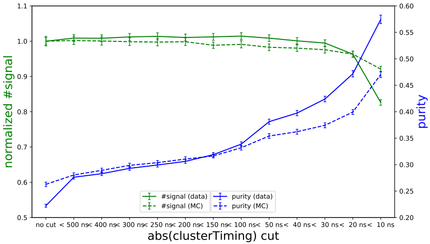


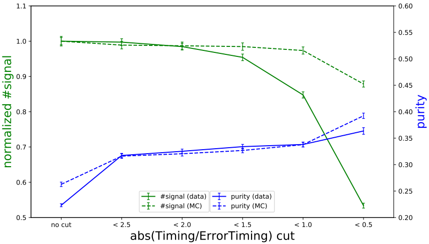


Photon timing study

- » out-of-time clusters were not modelled properly in Belle II simulation software
  → simulation will improve
  → imposing requirements on photon timing will be even more important to reject this background
- » more details in backup







- » **timing selection recommendations:**
- loose timing selection: abs(`clusterTiming`) $<$ 200 ns
- tight timing selection: abs(`clusterTiming`) $<$ 200 ns & abs(`Timing/ErrorTiming`) $<$ 2.0
  → these are currently the official photon timing selection recommendations for the Belle II collaboration

π^0 selection results discussion

» new π^0 selection: (see previous slides)

- **"Opt":** "Low" + optimized selections

  "OptLoose", "OptTight": "Opt" + recommended timing selections

	"Nom"	"Eff30"	"Eff10"	"Opt"	"OptLoose"	"OptTight"
efficiency (%)	25.69	29.84	9.81	24.82	24.80	24.47
purity (%)	55.42	29.78	69.25	87.53	87.84	88.13

» compared to "Nom", "Opt" π^0 selection has **significanly higher purity while maintaining comparable efficiency**

» "OptLoose" selection has already been used also in the measurement of the τ EDM using 1x1-prong τ-pair events

» **next steps:**

- finalize the selection and make it the new default π^0 selection for Belle II τ analyses
- measure the π^0 efficiency correction for the new selections
  $\rightarrow$ aim to have these results in the upcoming neutrals performance Belle II paper

Summary

» main goal of this thesis was to measure **π^0 efficiency correction** using τ-pair events:
- eight different π^0 selections were studied
- average and momentum dependent correction was measured
- results were compared with an independent measurement from B decays

» **new π^0 selection** with significantly higher purity was optimized for τ analyses

» photon timing study was performed, providing **photon timing selection recommendations**

» progress and results were regularly presented at the Belle II Tau Physics and Neutrals Performance Group meetings, as well as at the Belle II General Meeting (B2GM)

» among the **next steps** are:
- θ dependent correction measurement
- optimized π^0 selection finalization
- measuring π^0 efficiency correction for the new selection
- presenting the results at the next B2GM
- aim to have these results in the upcoming neutrals performance Belle II paper

Thank you

additional information and material

Event selections

» event selection: 4 good quality tracks that are 3x1 w.r.t. thrust axis

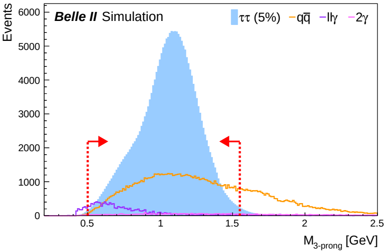
- π^0 allowed only on 3-prong side
- 1-prong is either electron or muon

» particle selection:

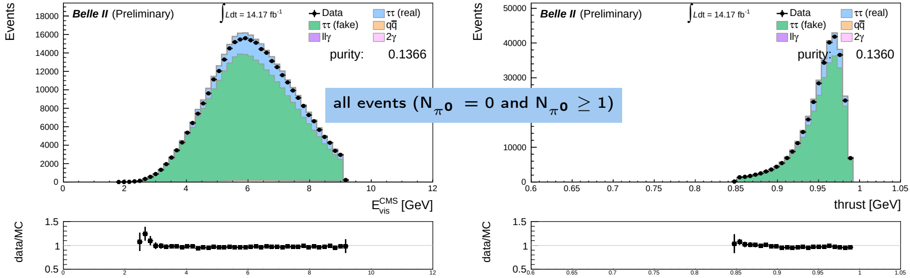
- **electron**:
  -3 $<$ dz $<$ 3 cm
  dr $<$ 1 cm
  electronID $>$ 0.9
- **muon**:
  -3 $<$ dz $<$ 3 cm
  dr $<$ 1 cm
  muonID $>$ 0.9
- **pion** (3-prong):
  -3 $<$ dz $<$ 3 cm
  dr $<$ 1 cm
  E/p $<$ 0.8
- **good photon**:
  E $>$ 200 MeV
  $-0.8660 < \cos\theta < 0.9563$
  clusterNHits $>$ 1.5
  not π^0 photon

» cuts:

- leading track $p_T > 0.5$ GeV
- subleading track $p_T > 0.2$ GeV
- third track $p_T > 0.05$ GeV
- 1-prong $N_{\pi^0} = 0$ and $N_\gamma \leq 1$
- $0.85 <$ thrust < 0.99
- $1.7 <$ total E (CMS) < 9.1 GeV
- $0.5 < M_{\text{3-prong}} < 1.55$ GeV

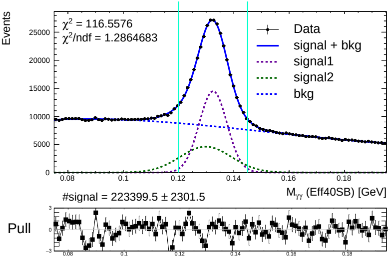


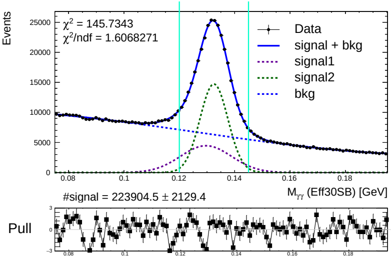
Data/MC agreement

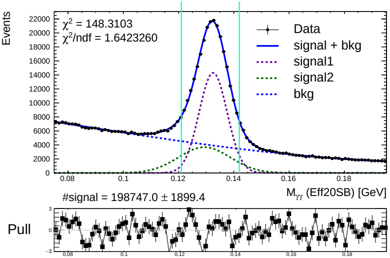


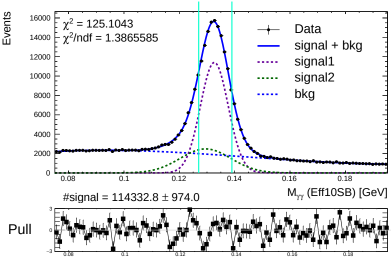
- $\tau\tau$ (real) – truth-matched "LowSB π^0"
- $\tau\tau$ (fake) – fake "LowSB π^0", either one or both of the photons are background photons
- "SB" – with side-bands, i.e. with the $M_{\gamma\gamma}$ window cut dropped

$M_{\gamma\gamma}$ fits



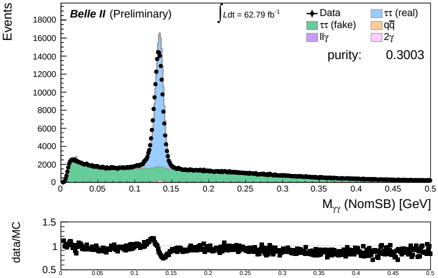




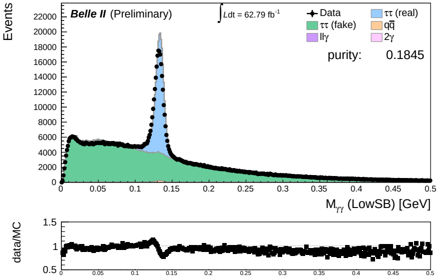


$M_{\gamma\gamma}$ distributions

"NomSB"



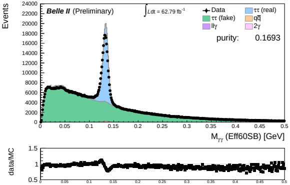
"LowSB"



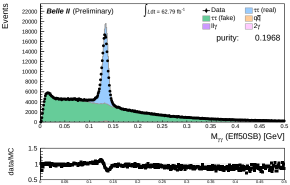
- mass of the reconstructed π^0 with the highest energy
- "SB" – mass distributions with side-bands

$M_{\gamma\gamma}$ distributions

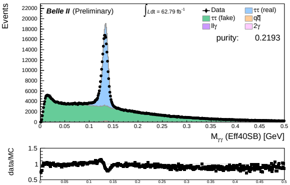
"Eff60SB"



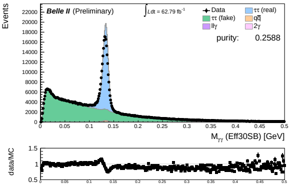
"Eff50SB"



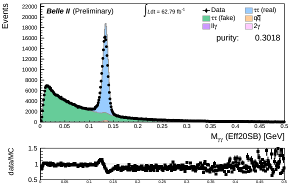
"Eff40SB"



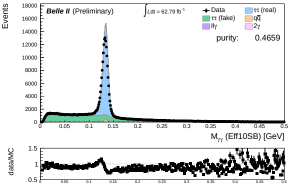
"Eff30SB"



"Eff20SB"

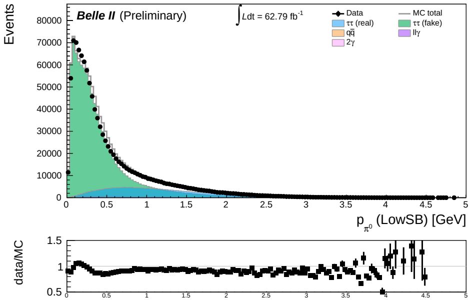


"Eff10SB"



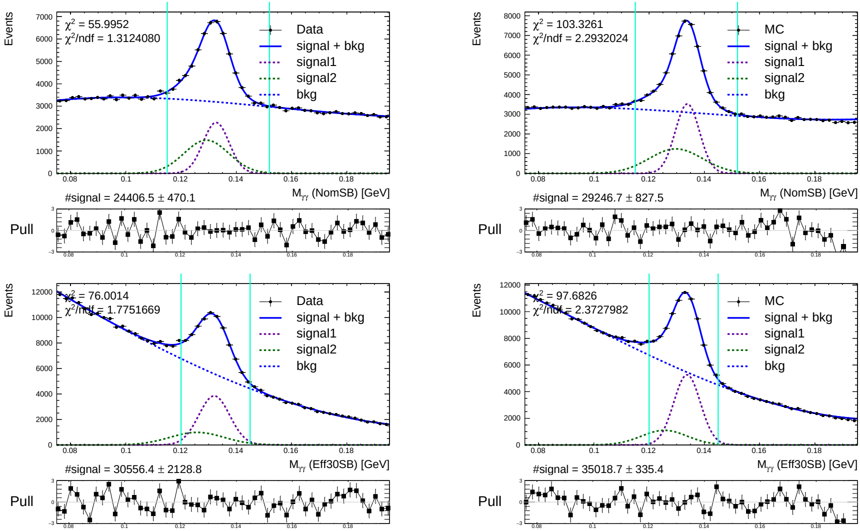
» **11 momentum bins:**

p_{π^0} bin	p_{π^0} range [GeV]
p_1	< 0.67
p_2	[0.67, 0.77]
p_3	[0.77, 0.90]
p_4	[0.90, 1.03]
p_5	[1.03, 1.17]
p_6	[1.17, 1.30]
p_7	[1.30, 1.47]
p_8	[1.47, 1.57]
p_9	[1.57, 1.80]
p_{10}	[1.80, 2.23]
p_{11}	> 2.23

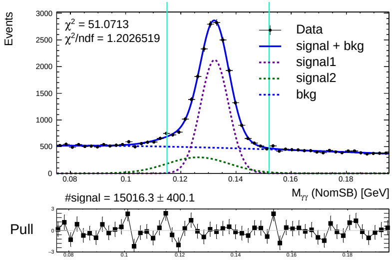


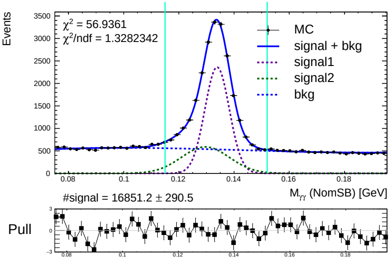
» signal yields and efficiency correction was determined in each momentum bin using the same procedure as in the momentum averaged case (examples in backup)

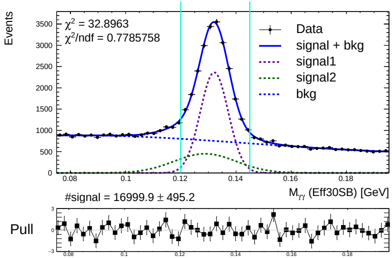
Fits for $p_{\pi^0} < 0.67$ GeV (examples)

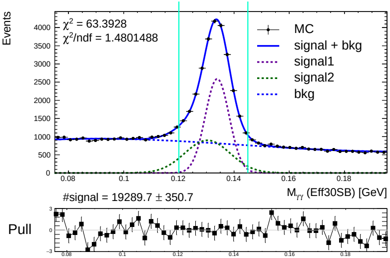


Fits for $0.67 < p_{\pi^0} < 0.77$ GeV (examples)

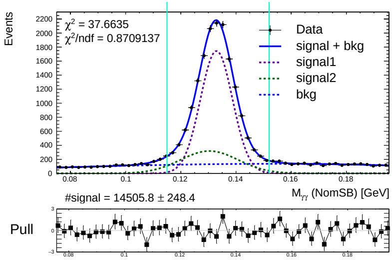


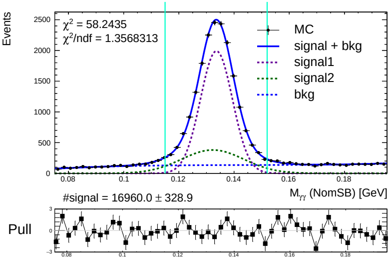


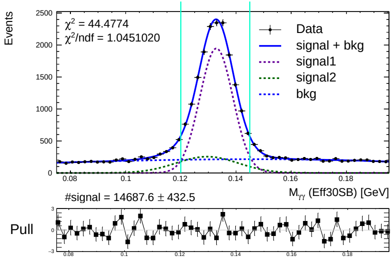


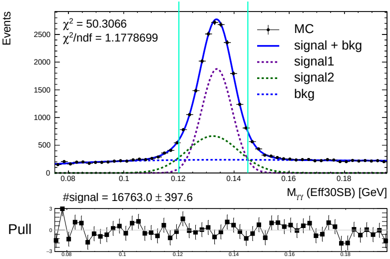


Fits for $p_{\pi^0} > 2.23$ GeV (examples)

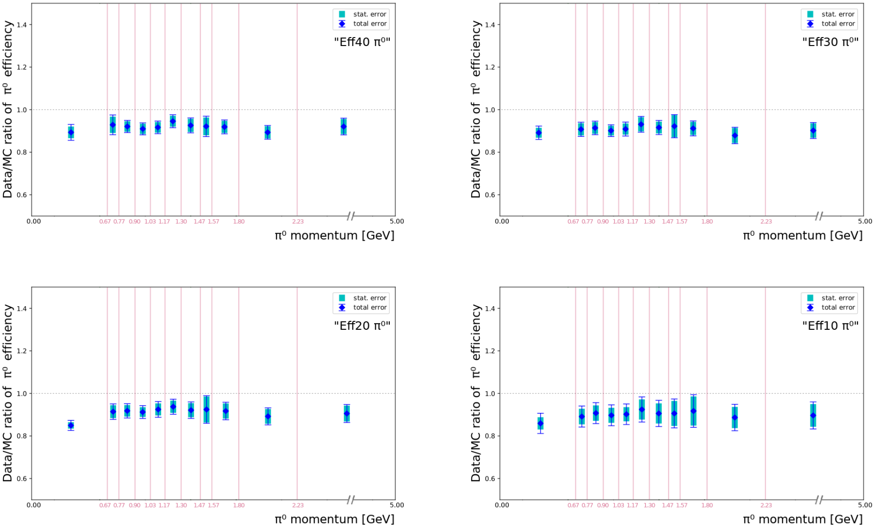






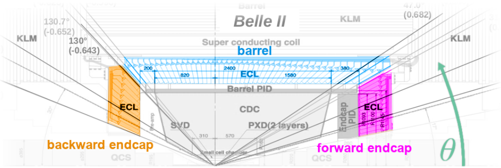


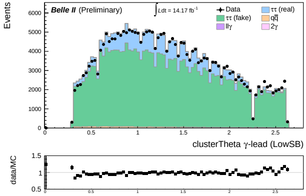
Momentum dependent correction

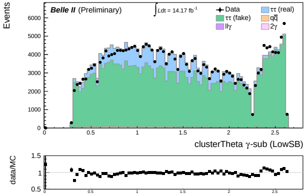


» additional requirements optimized in four different ECL regions:

- both photons in FWD
- both photons in BRL
- both photons in BWD
- one photon in BRL + other photon in FWD or BWD







Region	$E_{\gamma-lead}$ [GeV]	$E_{\gamma-sub}$ [GeV]	π^0 cos($\gamma\gamma$ angle)	p_{π^0} [GeV]
whole detector	> 0.3375	> 0.0875	> 0.8792	> 0.6111
$\gamma\ \gamma$ FWD	> 0.5625	> 0.1625	> 0.9458	> 0.9444
$\gamma\ \gamma$ BRL	> 0.4125	> 0.0625	> 0.8875	> 0.6333
$\gamma\ \gamma$ BWD	> 0.4125	> 0.1125	> 0.8708	> 0.6111
γ BRL, γ FWD/BWD	> 0.3625	> 0.0875	> 0.8875	> 0.5889

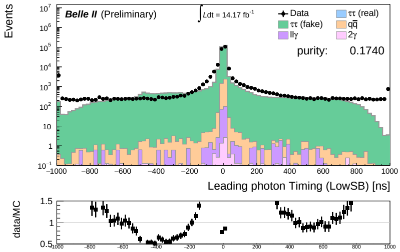
Photon timing study

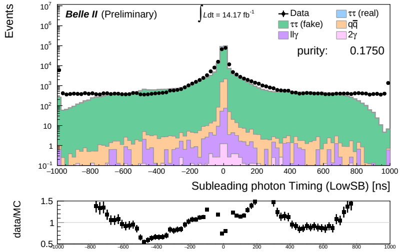
» photon `clusterTiming` - time of the photon ECL cluster

- in MC simulation, out-of-time clusters were not modelled properly in Belle II simulation software
- the simulation of photon timing will be improved in the next release
  $\rightarrow$ significant increase in out-of-time background clusters in MC
  $\rightarrow$ imposing threshold on photon timing can reject this backgrounds

» **studied thresholds:**

- abs(`clusterTiming`) $< \{500, 400, 300, 250, 200, 150, 100, 50, 40, 30, 20, 10\}$ ns





Photon timing ratio

- photon `clusterErrorTiming` - ECL cluster's timing uncertainty that contains 99 % of the real photons
  $\rightarrow$ abs(`clusterTiming/clusterErrorTiming`) < 1 is designed to give a 99% timing efficiency for the real photons

- **studied thresholds:**

- abs(`clusterTiming/clusterErrorTiming`) $< \{2.5, 2.0, 1.5, 1.0, 0.5\}$