π^0 efficiency study with 3-prong τ decay

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Outline

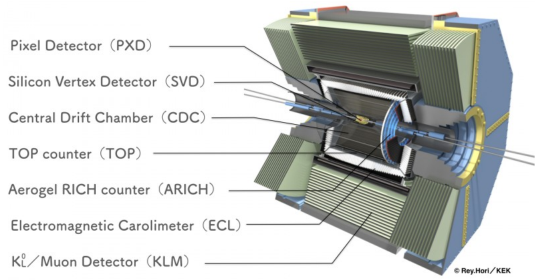
Belle II and SuperKEKB

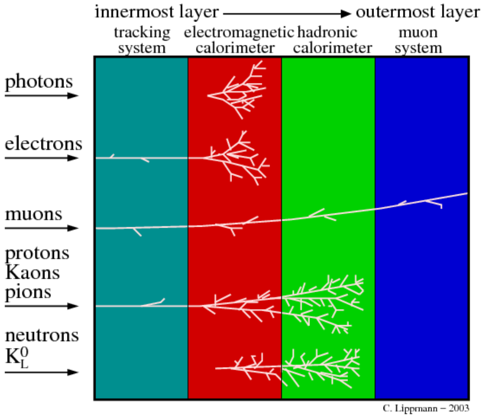
Belle II is the detector associated with SuperKEKB accelerator.

- Located at KEK in Tsukuba, Ibaraki (Japan)
- e^+e^- asymetric collider
- So-called B-factory
- Most recent achievement : New world record of instantaneous luminosity at $5.1.10^{34}\text{cm}^{-2}\text{s}^{-1}$ (27/12/2024)

Belle II

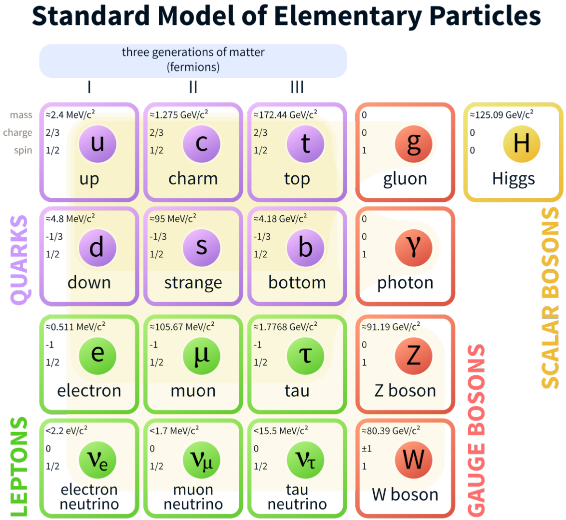
Belle II detector





π^0 efficiency is linked in great part to calorimeter efficiency : $\pi^0 \to \gamma\gamma$ ($> 98\%$)

$\tau \rightarrow \pi^-\pi^+\pi^-(n\pi^0)\nu_\tau$



3-prong = 3 charged tracks, mostly $\tau \rightarrow \pi^-\pi^+\pi^-(n\pi^0)\nu_\tau$

Meson are $q'\bar{q}$ particles :

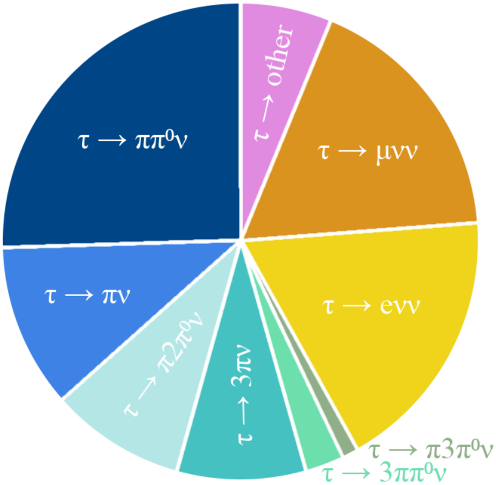
- $\pi^0 = u\bar{u} + d\bar{d}$
- $\pi^+ = u\bar{d}$
- $\pi^- = d\bar{u}$

τ is the heaviest lepton in SM and the only one able to decay to mesons/hadron

Belle II is called a B-factory because we produce massively B mesons.
But it is also a τ factory : Very active research at Belle II

τ lepton

τ decay modes



Looking for $e^+e^- \to \tau^+\tau^-$ events followed by $\tau^- \to \pi^-\pi^+\pi^-(n\pi^0)\nu_\tau$ on one side (signal side) and $\tau^- \to e^-\nu_\tau\bar{\nu}_e$ (tag side)

τ : $m_\tau = 1.77$ GeV, $\tau_\tau = 290.10^{-15}$s
π^0 : $m_{\pi^0} = 0.135$ GeV, $\tau_{\pi^0} = 8.10^{-17}$s

- BR $(\tau \to \pi^-\pi^+\pi^-\nu_\tau) \approx 9\%$
- BR $(\tau \to \pi^-\pi^+\pi^-\pi^0\nu_\tau) \approx 5\%$
- BR $(\tau \to \pi^-\pi^+\pi^-2\pi^0\nu_\tau) \approx 0.5\%$
- BR $(\tau \to \pi^-\pi^+\pi^-3\pi^0\nu_\tau) \approx 0.02\%$

Introduction

The aim is to get an efficiency correction given by the double ratio

$$\frac{\epsilon^{\mathrm{data}}}{\epsilon^{\mathrm{MC}}} = \frac{N_{\pi^0}^{\mathrm{data}}}{N_{\mathrm{event}}^{\mathrm{data}}} \div \frac{N_{\pi^0}^{\tau\bar{\tau}} + N_{\pi^0}^{q\bar{q}} + \ldots}{N_{\mathrm{event}}^{\tau\bar{\tau}} + N_{\mathrm{event}}^{q\bar{q}} + \ldots}$$

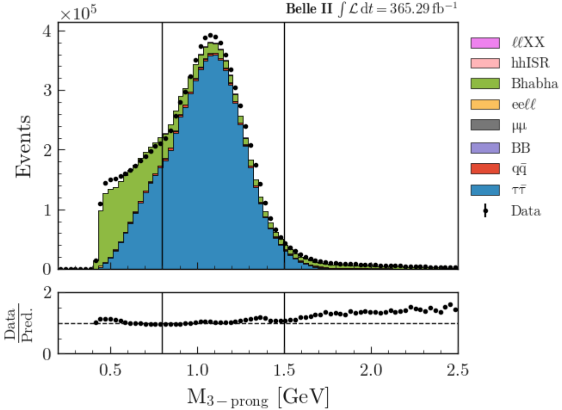
assuming an accurate simulation of τ decays.

We use the 3×1 prong topology :

- Signal side $\tau \to \pi^-\pi^+\pi^-(n\pi^0)\nu_\tau$
- Tag side $\tau \to e\nu_\tau\bar{\nu}_e$

We use 365.29fb^{-1} of data and MC15rd (up to 4x luminosity of data)
$\longrightarrow$ After selection : 6 276 946 events.

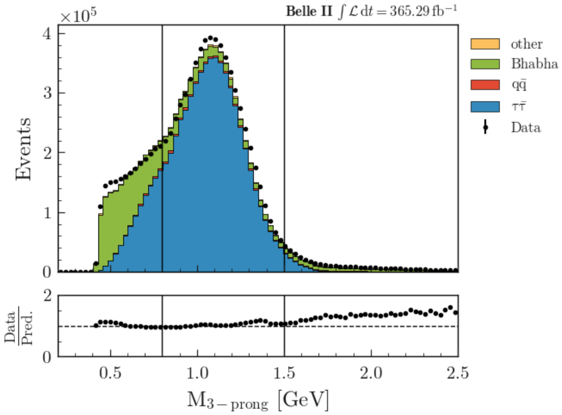
Make selection



Find discriminant variable that allows to select events we want and suppress background : Balance between

- Purity : signal/background
- Efficiency : signal left/signal available

Make selection



Find discriminant variable that allows to select events we want :
Balance between

- Purity : signal/background
- Efficiency : signal left/signal available

Purity and Efficiency

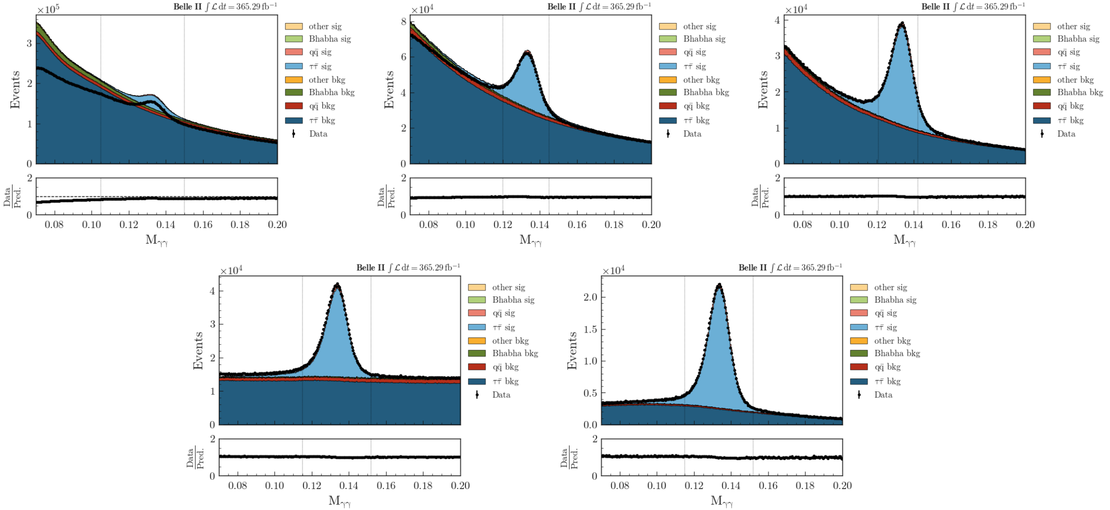
We can measure efficiency compared to tauThrust skimmed with topology requirement.

- taupair cut/topology : 6.3%
- data cut/topology 1.8%
- data events : 6 276 946
- Event data/MC : 97.04%

Process	$\tau\bar{\tau}$	$q\bar{q}$	Bhabha	other
Event purity (%)	91.33	1.08	7.01	0.58
events	5 562 709	65 569	427 270	35 539

We consider 7 different types of π^0 selection, TauNom, TauOpt, Eff50, Eff40, Eff30, Eff20, Eff10

π^0 mass distributions



mass distribution for π^0 selections : Eff50,Eff30,Eff20 (top) and Nom,Opt (bottom)

π^0 Purity - TauNom selection

We can measure purity for π^0 selections : Bhabha barely contributes to signal and is no longer that big

- N_{π^0} data (in $[70, 200]$ MeV) : 4 675 082
- N_{π^0} data/MC : 101.92%

Process	$\tau\bar{\tau}$	$q\bar{q}$	Bhabha	other
Event purity (%)	91.33	1.08	7.01	0.58
events	5 562 709	65 569	427 270	35 539
N_{π^0} purity (%)	91.65	6.72	1.22	0.41
N_{π^0}	4 203 594	308 279	55 960	18 981
$N_{\pi^0,sig}$ purity (%)	94.27	5.37	**0.01**	0.35
$N_{\pi^0,sig}$	878 332	50 021	60	3 272
$N_{\pi^0,bkg}$ purity (%)	90.98	7.07	1.53	0.43
$N_{\pi^0,bkg}$	3 325 263	258 258	55 900	15 709

π^0 candidates - template fit

N_{π^0} is determined from fit to $M_{\gamma\gamma}$

- Signal: histogram from $\tau^+\tau^-$ MC using truth matched π^0 candidates
- Background: Chebyshev polynomial. Order : beginning of χ^2 plateau (0 to 3)

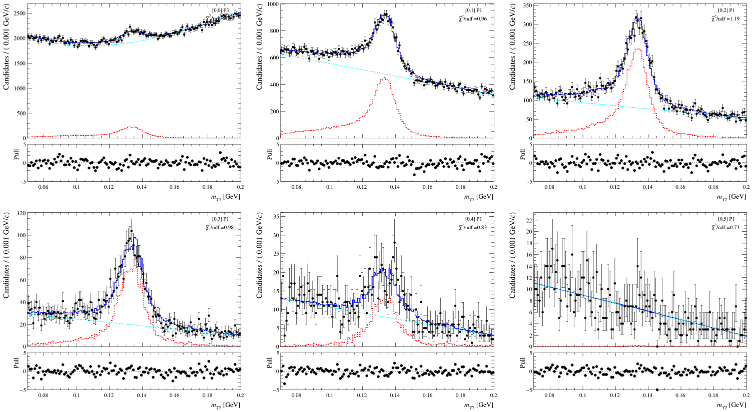
N_{π^0} is an integral of signal over selection mass window.

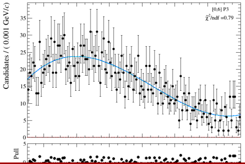
We use 7x7 bins in momentum and $\cos\theta$ of π^0 candidates:

$$p = [0, 0.5, 1, 1.5, 2, 2.5, 3, \mathrm{above}]\ \mathrm{GeV}$$

$$\cos\theta = [-1, -0.6, -0.3, 0, 0.3, 0.6, 0.8, 1]$$

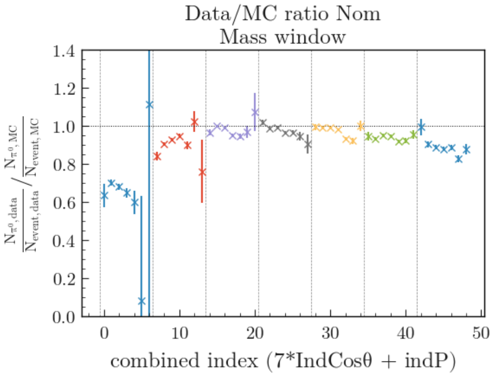
TauNom $M_{\gamma\gamma}$ template fit

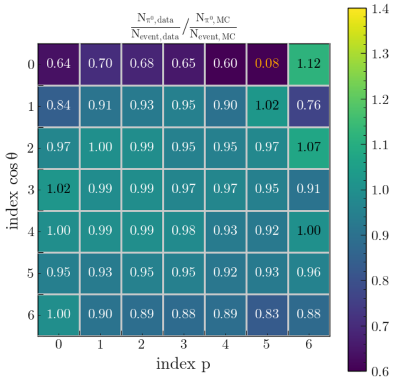




- $-1 < \cos\theta < -0.6$
- $p = [0, 0.5, 1, 1.5, 2, 2.5, 3, \text{above}]$ GeV
- PN indicates the order of background polynominal

Nom π^0 efficiency correction (preliminary)

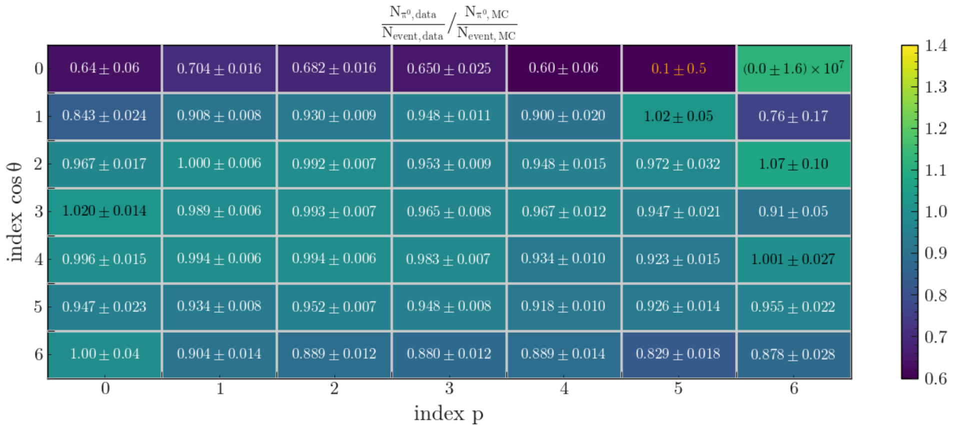




Efficiency correction factors in 1D and 2D of $\cos\theta$ and p bins.

- Error is statistical only

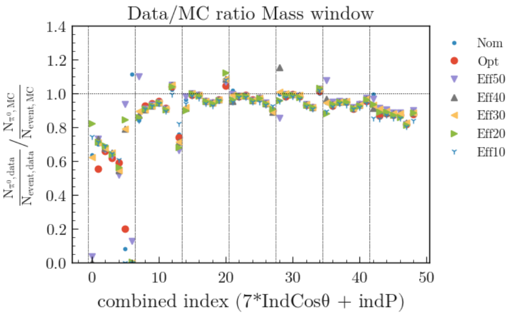
Nom π^0 efficiency correction (preliminary)

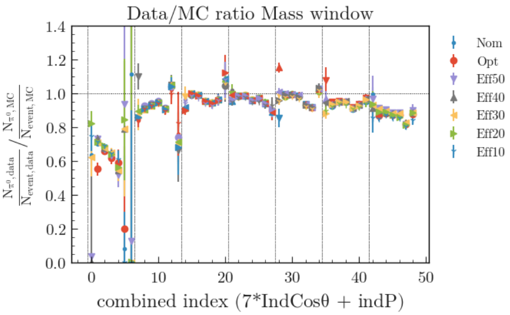


Detailed correction factors in 2D $\cos\theta$ and p bins.

- Error is statistical only

π^0 template fit efficiency correction comparison (preliminary)



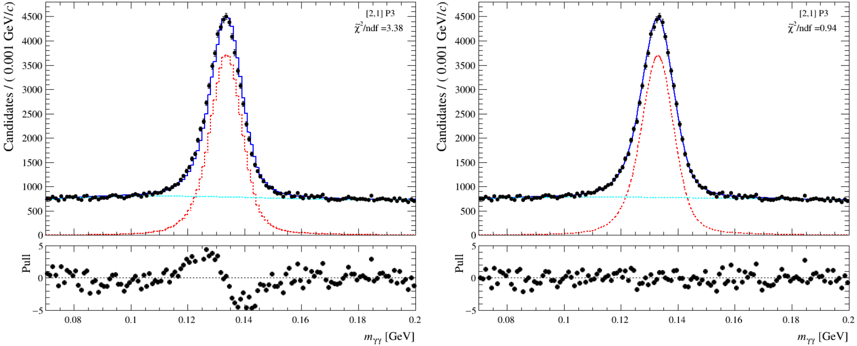


Comparison of correction factor for each selections depending on combined bin

- Error is statistical only

Convolution fit

Many fits on data suffer from shift of the peak. We suspect there may also be broadening effects : Try to fit them using template convoluted with gaussian $G(\mu, \sigma)$



TauNom distribution, data fit results for [2,1] bin without and with convolution ($\mu = -0.65$ MeV, $\sigma = 1$ MeV)

Outlook

Final result is then correction factor to improve MC/data disagreement.
Still things to do for this analysis :

- Reweighting to improve MC/data disagreement
- Systematics
- Change selection to suppress better background (then go back to step 1) ?

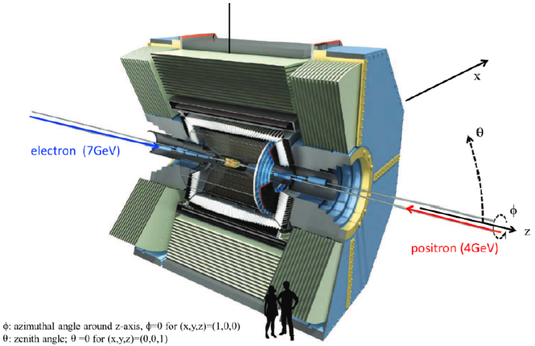
But close to the end

Questions ?

Backup slides

Other pictures

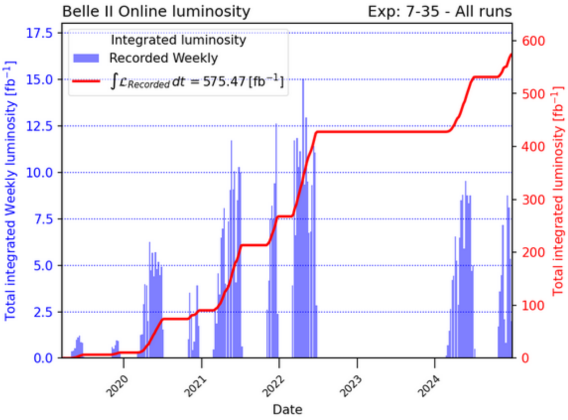
A bit more details on Belle II

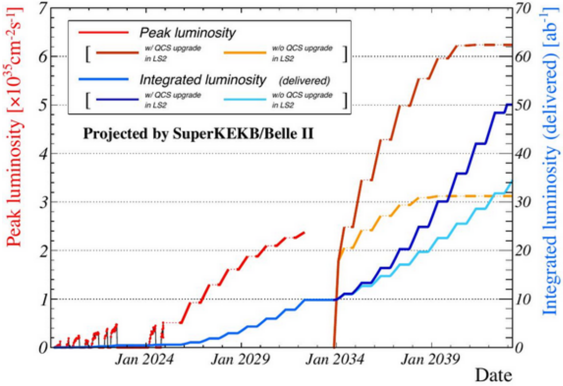


TOTAL INTEGRATED LUMINOSITY FOR GOOD RUNS

- Total integrated luminosity: **424 fb-1**
- Total integrated luminosity at the Y(4S) resonance: **363 fb-1**
- Total integrated luminosity below Y(4S) resonance: **42 fb-1**
- Total integrated luminosity above Y(4S) resonance: **19 fb-1**

A bit more details on Belle II





τ event selection

- tauThrust skim
- Trigger : stt || ffy || fyo ||ffo ||fff || lml0 || lml12 || hie
- Charged tracks
  - TrackCut: $|dz| < 3.0$ cm, $dr < 1.0$ cm
  - nGoodTrack=4
- Signal side
  - Considering PID for e veto, for now doing without
- Tag side
  - electronID: electronID_noSVD_noTOP > 0.8
- Slimming (background suppression)
  - $0.9 <$ thrust < 0.99
  - $2.0 <$visibleEnergyOfEventCMS$<$ 9.1 GeV
  - $0.8 < M_{3-\mathrm{prong}} < 1.55$ GeV (3 charged π invariant mass)
  - p_t cut on π in 3-prong : $p_t(\pi_1) > 0.5$ GeV, $p_t(\pi_2) > 0.2$ GeV, $p_t(\pi_3) > 0.2$ GeV
  - $N_{\mathrm{good}\ \gamma, 1-prong} < 1.5$

τ event selection - thrust

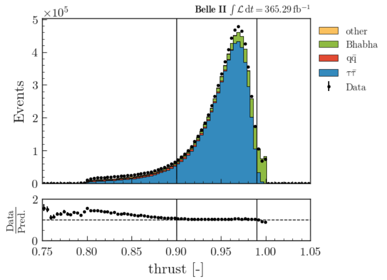
$$\text{thrust} = \max_{|n|=1} \frac{\sum_i |p_i . n|}{\sum_i |p_i|}$$

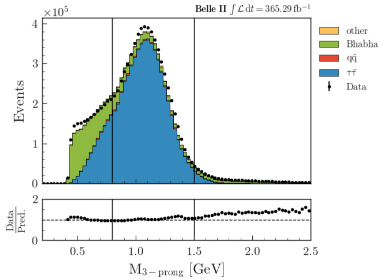
We need to choose particles to include in it : π^0 definition is not stable, we choose instead a "good" γ definition (including those coming from π^0)

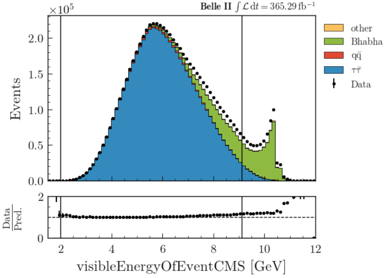
- $E_\gamma > 200$ MeV
- $0.8660 < \cos\theta < 0.9563$
- $|clusterTiming| < 200$ ns
- $clusterNHits > 1.5$

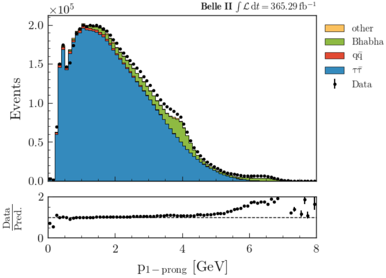
Introduced in Qiming's study. Harder than most studied π^0 selection photons.
Also used in tag-side photon veto.

Event plots


Belle II $\int \mathcal{L}\,dt = 365.29\,\mathrm{fb}^{-1}$
×10^5
Events
Data/Pred.
thrust [-]
other
Bhabha
$q\bar{q}$
$\tau\bar{\tau}$
Data


Belle II $\int \mathcal{L}\,dt = 365.29\,\mathrm{fb}^{-1}$
×10^5
Events
Data/Pred.
$M_{3-\mathrm{prong}}$ [GeV]
other
Bhabha
$q\bar{q}$
$\tau\bar{\tau}$
Data


Belle II $\int \mathcal{L}\,dt = 365.29\,\mathrm{fb}^{-1}$
×10^5
Events
Data/Pred.
visibleEnergyOfEventCMS [GeV]
other
Bhabha
$q\bar{q}$
$\tau\bar{\tau}$
Data


Belle II $\int \mathcal{L}\,dt = 365.29\,\mathrm{fb}^{-1}$
×10^5
Events
Data/Pred.
$p_{1-\mathrm{prong}}$ [GeV]
other
Bhabha
$q\bar{q}$
$\tau\bar{\tau}$
Data

π^0 selection I

We apply 7 different types of π^0 selection, TauNom, TauOpt, Eff50, Eff40, Eff30, Eff20, Eff10

	TauNom	TauOpt (1)
$E\gamma$ (MeV)	> 100	> 25
$\cos\theta$	$[-0.8660, 0.9563]$	
clusterNHits	> 1.5	
γ clusterTiming (ns)	–	< 200
$M_{\gamma\gamma}$ (MeV)	$[115, 152]$	

	TauOpt (2)			
	$E_{\gamma-\mathrm{lead}}$	$E_{\gamma-\mathrm{sub}}$	$(\cos\theta_{\gamma\gamma})_{\pi^0}$	p_{π^0} (MeV)
$E_{\gamma\gamma}$(FWD) MeV	562.5	162.5	945.8	944.4
$E_{\gamma\gamma}$(BRL) MeV	412.5	62.6	887.5	633.3
$E_{\gamma\gamma}$(BWD) MeV	412.5	112.5	870.8	611.1
E_{γ}(BRL), E_{γ}(FWD/BWD) MeV	362.5	87.5	887.5	588.9

π^0 selection II

We apply 7 different types of π^0 selection, TauNom, TauOpt, Eff50, Eff40, Eff30, Eff20, Eff10

	eff50	eff40	eff30	eff20	eff10
$E_{\gamma\gamma}$ (FWD) MeV	> 25	> 80	> 80	> 120	> 200
$E_{\gamma\gamma}$ (BRL) MeV	> 25	> 30	> 30	> 25	> 100
$E_{\gamma\gamma}$ (BWD) MeV	> 40	> 60	> 80	> 80	> 180
θ (rad)			$[0.2967, 2.6180]$		
clusterNHits			> 1.5		
$\lvert\Delta\phi\rvert$ (rad)			< 1.5		
Δ anagle (rad)			< 1.4		
$M_{\gamma\gamma}$ MeV	$[105, 150]$	$[120, 145]$	$[120, 145]$	$[121, 142]$	$[127, 139]$

π^0 Purity - Eff50 selection

For comparison, Eff50 (loosest selection, with highest Bhabha contribution)

- N_{π^0} data (in $[70, 200]$ MeV) : 34 542 788
- N_{π^0} data/MC : 82.47%

Process	$\tau\bar{\tau}$	$q\bar{q}$	Bhabha	other
Event purity (%)	91.33	1.08	7.01	0.58
events	5 562 709	65 569	427 270	35 539
N_{π^0} purity (%)	91.18	4.19	4.07	0.56
N_{π^0}	38 190 679	1 754 235	1 702 750	235 461
$N_{\pi^0,sig}$ purity (%)	92.35	7.19	**0.01**	0.45
$N_{\pi^0,sig}$	1 205 496	93 872	110	5 887
$N_{\pi^0,bkg}$ purity (%)	91.15	4.09	4.20	0.57
$N_{\pi^0,bkg}$	36 985 183	1 660 363	1 702 640	229 574

π^0 efficiency correction

We provide the results with the following 7 intervals

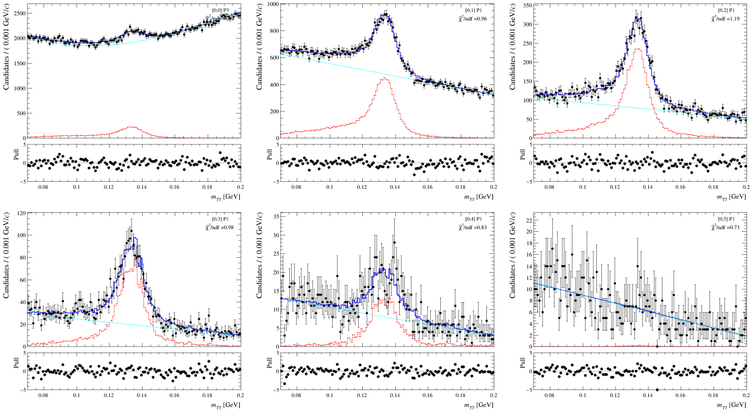
$$p = [0, 0.5, 1, 1.5, 2, 2.5, 3, \text{above}]\ \text{GeV}$$

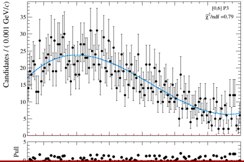
$$\cos\theta = [-1, -0.6, -0.3, 0, 0.3, 0.6, 0.8, 1]$$

We number the 49 bins as follows:

$-1 < \cos\theta < -0.6$	0	1	2	3	4	5	6
$-0.6 < \cos\theta < -0.3$	7	8	9	10	11	12	13
$-0.3 < \cos\theta < 0$	14	15	16	17	18	19	20
$0 < \cos\theta < 0.3$	21	22	23	24	25	26	27
$0.3 < \cos\theta < 0.6$	28	29	30	31	32	33	34
$0.6 < \cos\theta < 0.8$	35	36	37	38	39	40	41
$0.8 < \cos\theta < 1$	42	43	44	45	46	47	48
	$0 < p < 0.5$	$0.5 < p < 1$	$1 < p < 1.5$	$1.5 < p < 2$	$2 < p < 2.5$	$2.5 < p < 3$	$p > 3$

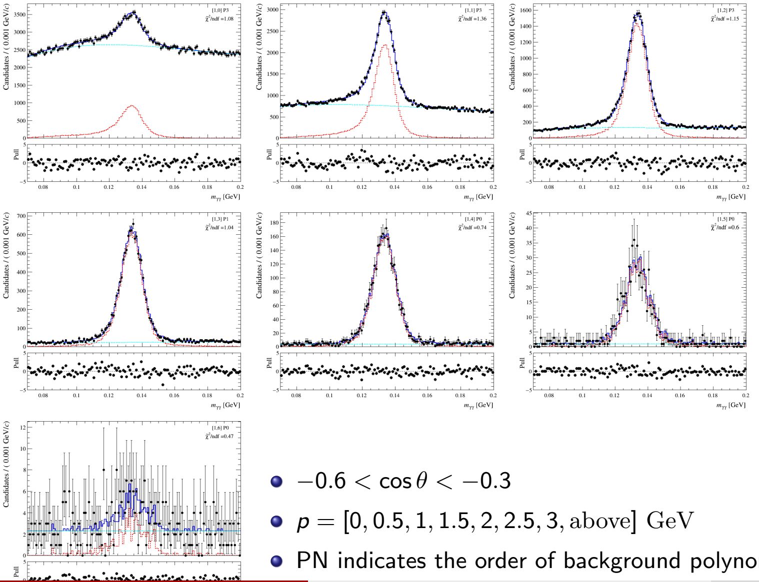
Nom $M_{\gamma\gamma}$ template fit





- $-1 < \cos\theta < -0.6$
- $p = [0, 0.5, 1, 1.5, 2, 2.5, 3, \text{above}]$ GeV
- PN indicates the order of background polynominal

Nom $M_{\gamma\gamma}$ template fit



- $-0.6 < \cos\theta < -0.3$
- $p = [0, 0.5, 1, 1.5, 2, 2.5, 3, \text{above}]$ GeV
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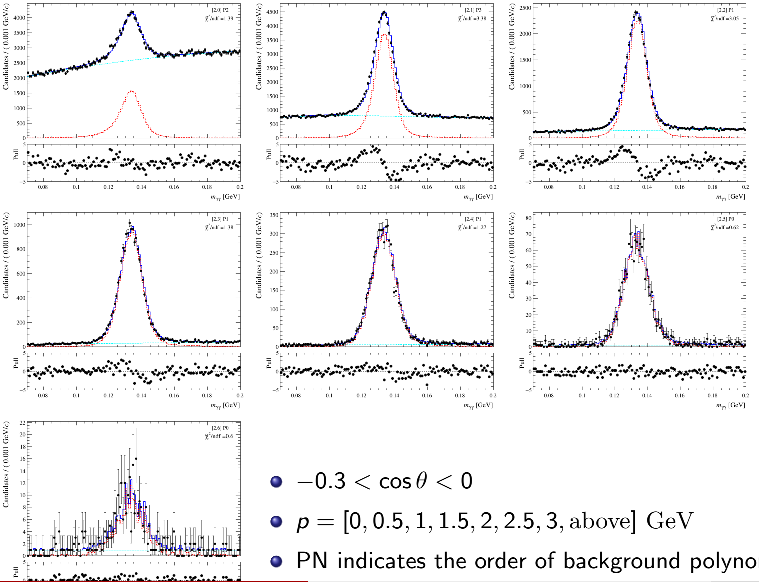
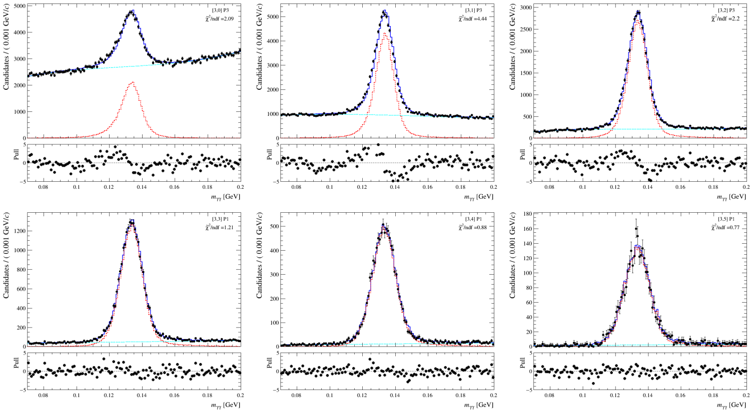
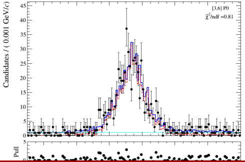
Nom $M_{\gamma\gamma}$ template fit



- $-0.3 < \cos\theta < 0$
- $p = [0, 0.5, 1, 1.5, 2, 2.5, 3, \text{above}]$ GeV
- PN indicates the order of background polynominal

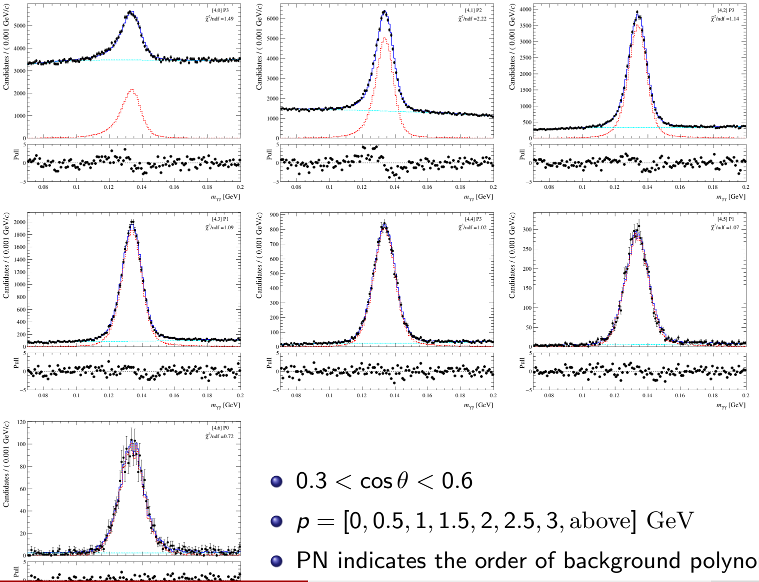
Nom $M_{\gamma\gamma}$ template fit





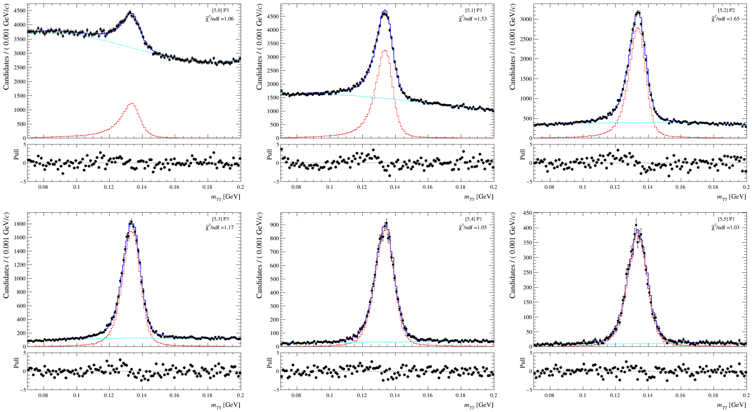
- $0 < \cos\theta < 0.3$
- $p = [0, 0.5, 1, 1.5, 2, 2.5, 3, \text{above}]$ GeV
- PN indicates the order of background polynominal

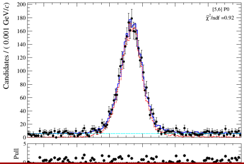
Nom $M_{\gamma\gamma}$ template fit



- $0.3 < \cos\theta < 0.6$
- $p = [0, 0.5, 1, 1.5, 2, 2.5, 3, \text{above}]$ GeV
- PN indicates the order of background polynominal

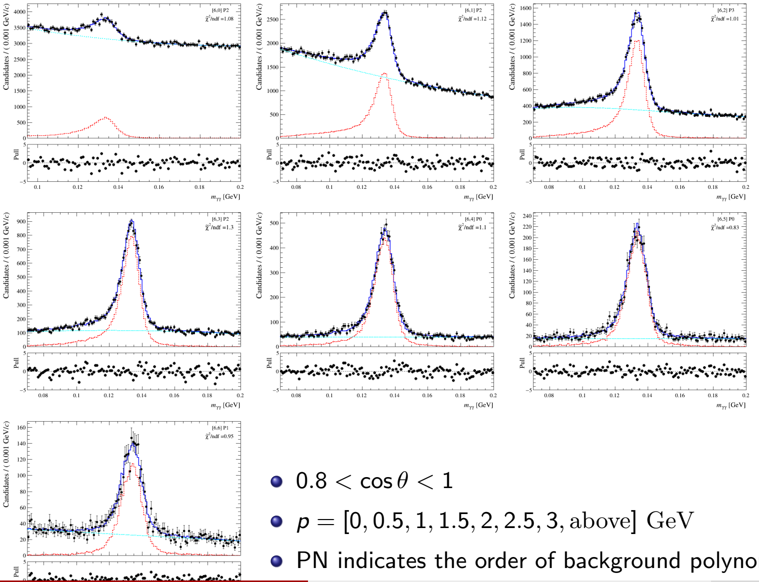
Nom $M_{\gamma\gamma}$ template fit





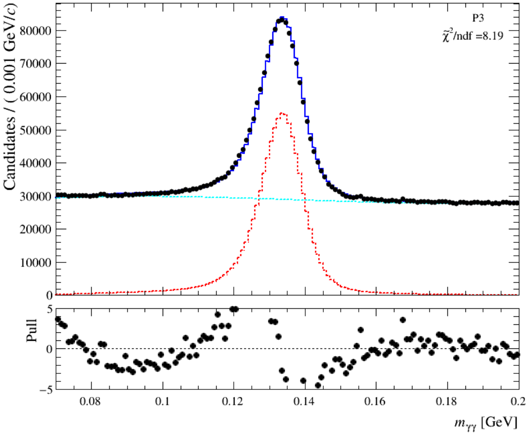
- $0.6 < \cos\theta < 0.8$
- $p = [0, 0.5, 1, 1.5, 2, 2.5, 3, \text{above}]$ GeV
- PN indicates the order of background polynominal

Nom $M_{\gamma\gamma}$ template fit



- $0.8 < \cos\theta < 1$
- $p = [0, 0.5, 1, 1.5, 2, 2.5, 3, \text{above}]$ GeV
- PN indicates the order of background polynominal

Nom $M_{\gamma\gamma}$ template fit



- Inclusive (sum of all regions of p and $\cos\theta$)
- P3 implies 3^{rd} order chebyshev background

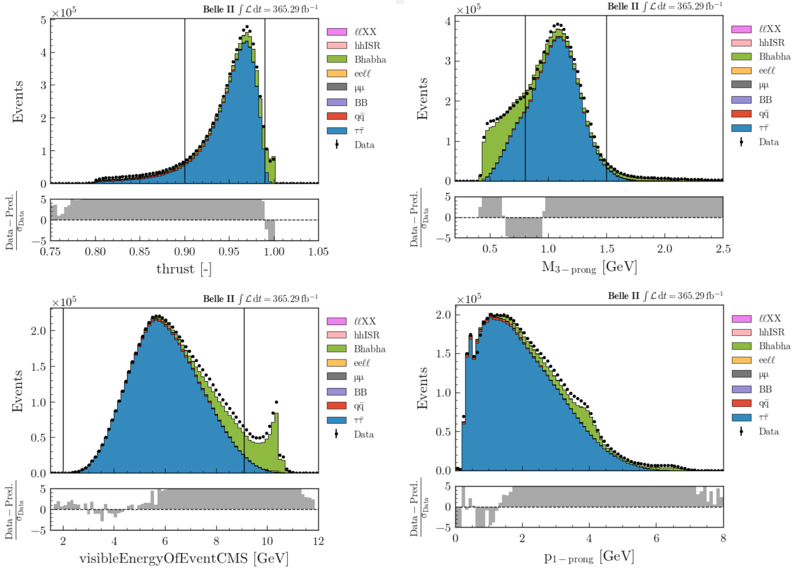
Event and π^0 purity - all channels

TauNom selection

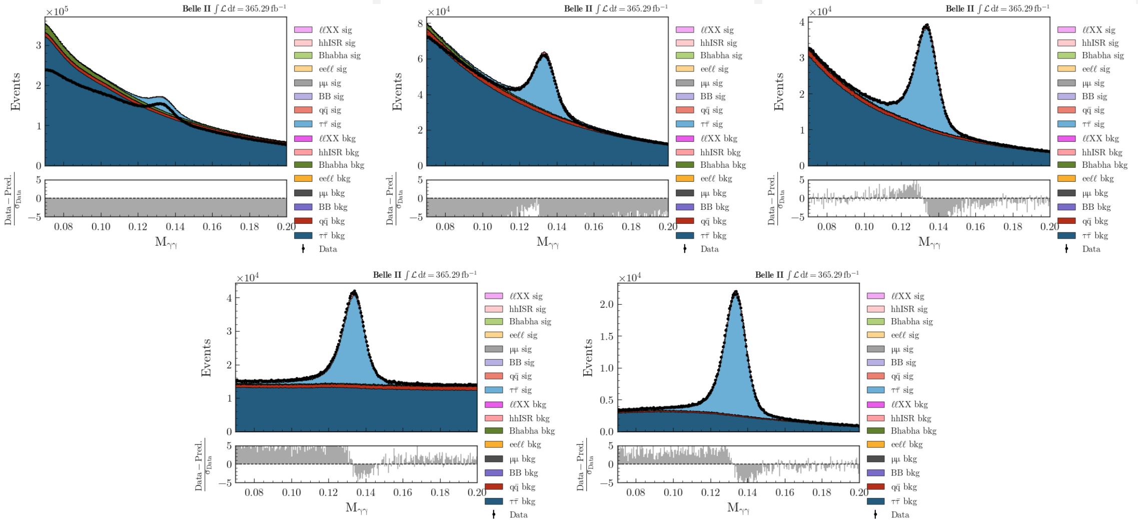
- N_{π^0} data (in $[0.07, 0.20]$ MeV) : 4 675 082
- N_{π^0} data/MC : 101.92%

Process	$\tau\bar{\tau}$	$q\bar{q}$	BB	$\mu\mu$	$ee\ell\ell$	**Bhabha**	hhISR	$\ell\ell$XX
Event purity (%)	91.33	1.08	0.02	5.10^{-4}	0.3	7.01	0.001	0.26
events	5 562 709	65 569	1331	31	17 957	427 270	83	16 137
N_{π^0} purity (%)	91.65	6.72	0.12	1.10^{-4}	0.05	1.22	7.10^{-4}	0.24
N_{π^0}	4 203 594	308 279	5 594	3	2 291	55 960	30	11 063
$N_{\pi^0,sig}$ purity (%)	94.27	5.37	0.08	0	2.10^{-4}	0.006	3.10^{-4}	0.27
$N_{\pi^0,sig}$	878 332	50 021	766	0	2	60	3	2 501
$N_{\pi^0,bkg}$ purity (%)	90.98	7.07	0.13	1.10^{-4}	0.06	1.53	7.10^{-4}	0.23
$N_{\pi^0,bkg}$	3 325 263	258 258	4 829	3	2 289	55 900	27	8 562

Event plots - all channels

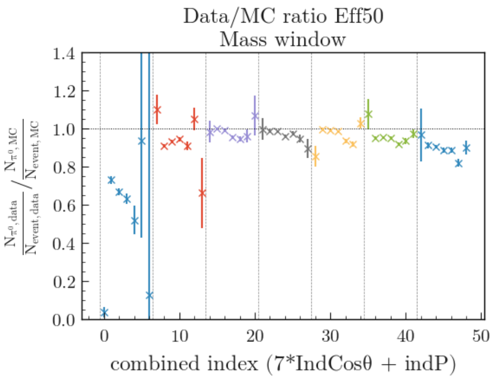


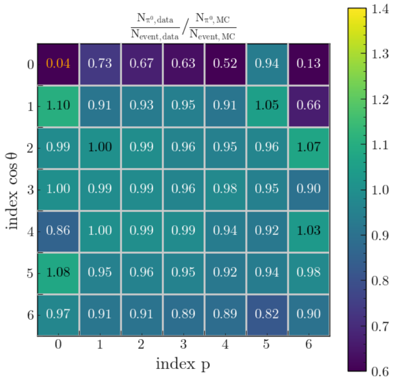
π^0 mass distributions - all channels



mass distribution for π^0 selections : Eff50,Eff30,Eff20 (top) and Nom,Opt (bottom)

Eff50 π^0 template fit efficiency correction (preliminary)

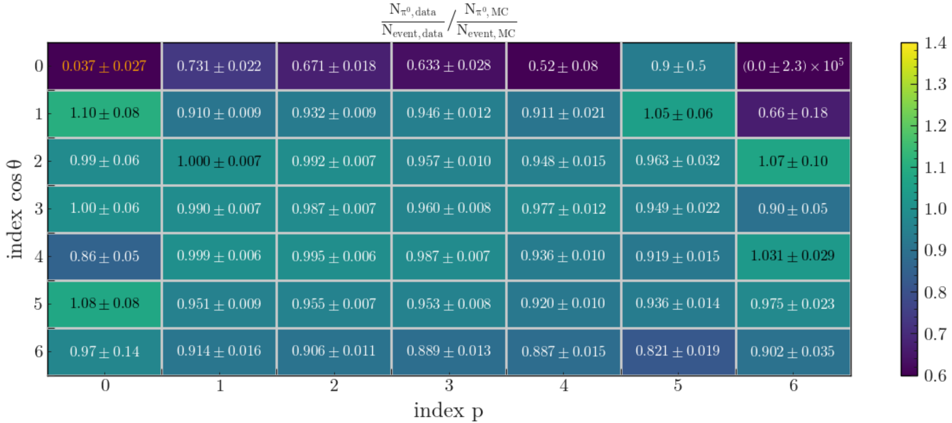




Efficiency correction factors in 1D and 2D of $\cos\theta$ and p bins.

- Error is statistical only

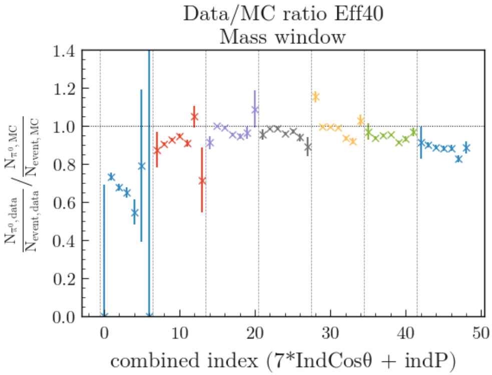
Eff50 π^0 template fit efficiency correction (preliminary)

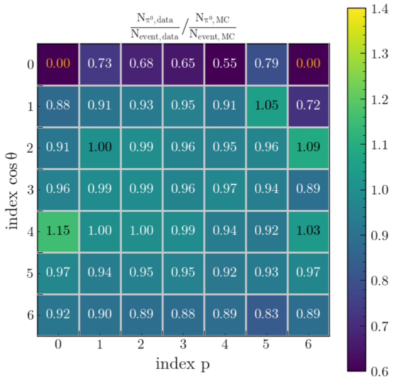


Detailed correction factors in 2D $\cos\theta$ and p bins.

- Error is statistical only

Eff40 π^0 template fit efficiency correction (preliminary)

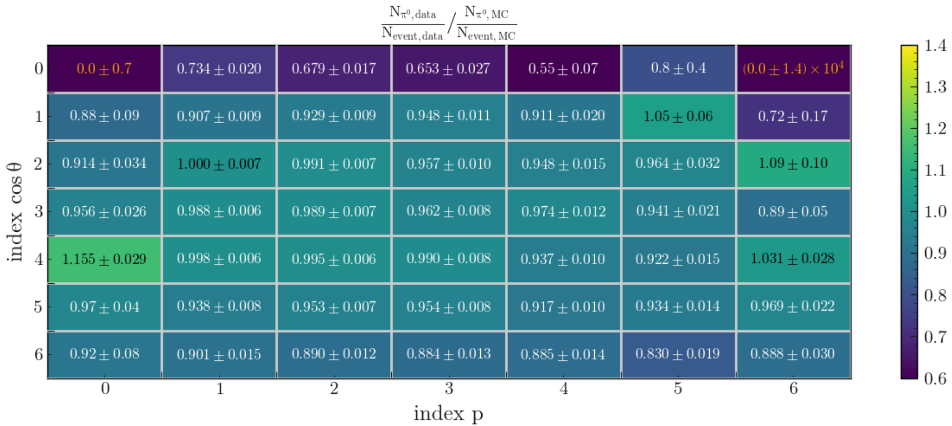




Efficiency correction factors in 1D and 2D of $\cos\theta$ and p bins.

- Error is statistical only

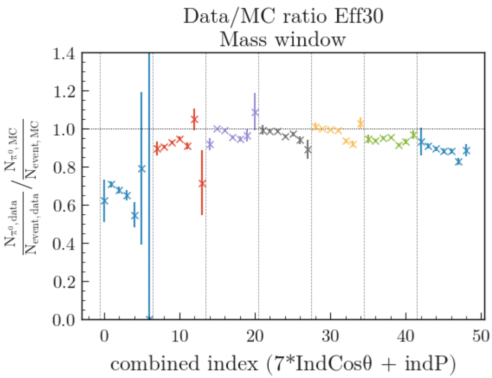
Eff40 π^0 template fit efficiency correction (preliminary)

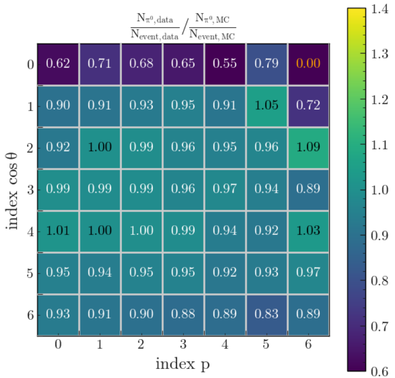


Detailed correction factors in 2D $\cos\theta$ and p bins.

- Error is statistical only

Eff30 π^0 template fit efficiency correction (preliminary)

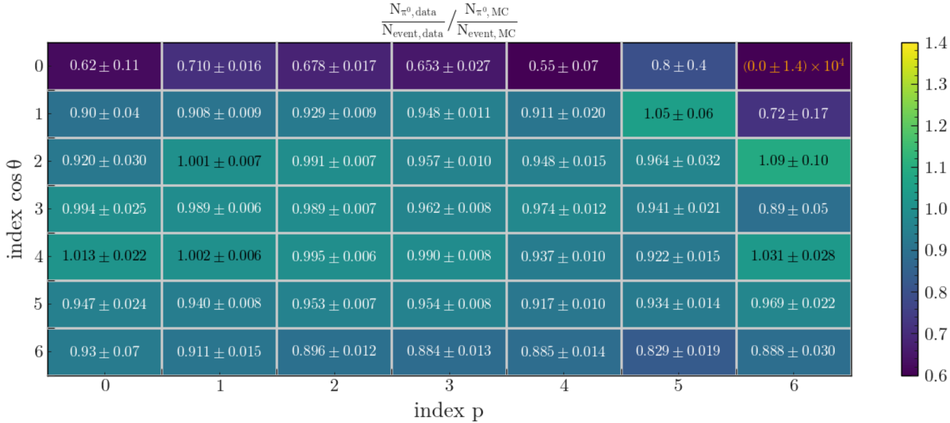




Efficiency correction factors in 1D and 2D of $\cos\theta$ and p bins.

- Error is statistical only

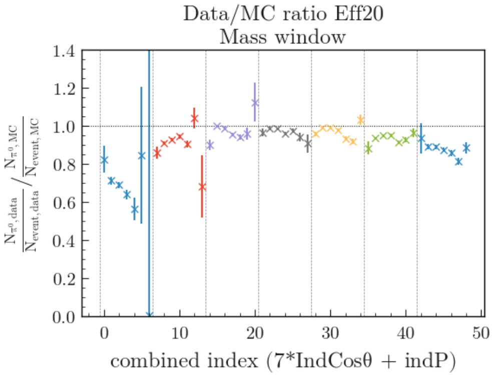
Eff30 π^0 template fit efficiency correction (preliminary)

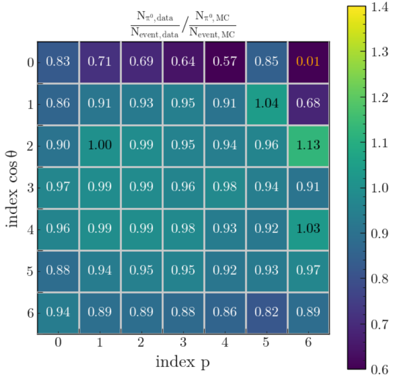


Detailed correction factors in 2D $\cos\theta$ and p bins.

- Error is statistical only

Eff20 π^0 template fit efficiency correction (preliminary)



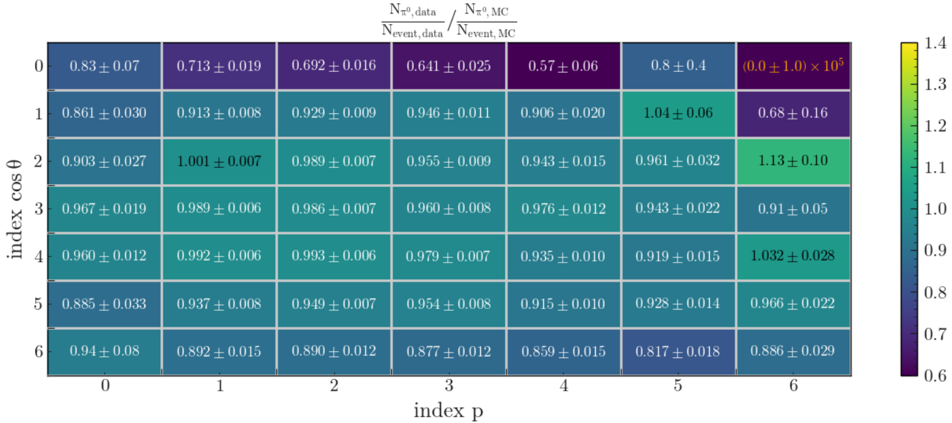


index cos θ \ index p	0	1	2	3	4	5	6
0	0.83	0.71	0.69	0.64	0.57	0.85	0.01
1	0.86	0.91	0.93	0.95	0.91	1.04	0.68
2	0.90	1.00	0.99	0.95	0.94	0.96	1.13
3	0.97	0.99	0.99	0.96	0.98	0.94	0.91
4	0.96	0.99	0.99	0.98	0.93	0.92	1.03
5	0.88	0.94	0.95	0.95	0.92	0.93	0.97
6	0.94	0.89	0.89	0.88	0.86	0.82	0.89

Efficiency correction factors in 1D and 2D of $\cos\theta$ and p bins.

- Error is statistical only

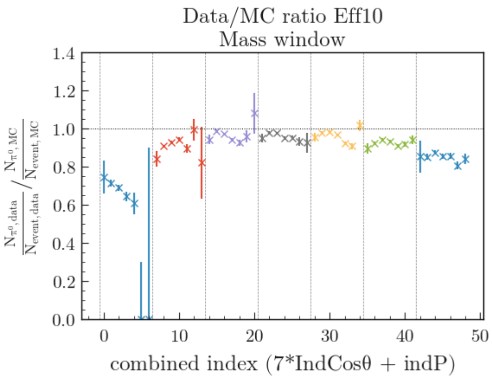
Eff20 π^0 template fit efficiency correction (preliminary)

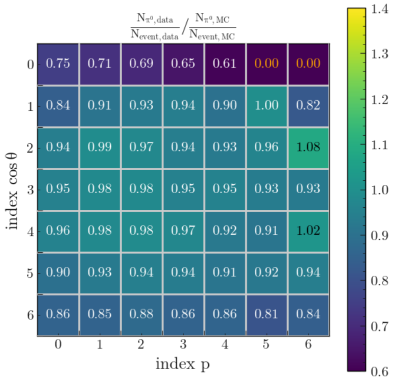


Detailed correction factors in 2D $\cos\theta$ and p bins.

- Error is statistical only

Eff10 π^0 template fit efficiency correction (preliminary)

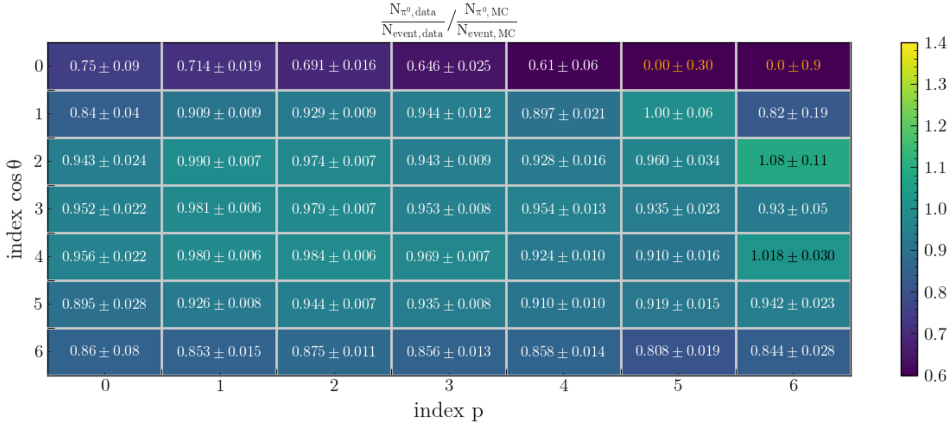




Efficiency correction factors in 1D and 2D of $\cos\theta$ and p bins.

- Error is statistical only

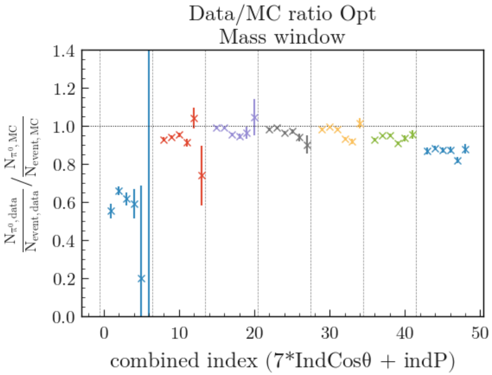
Eff10 π^0 template fit efficiency correction (preliminary)

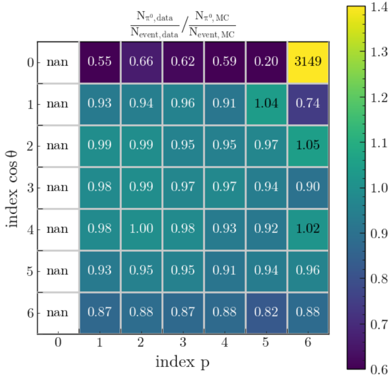


Detailed correction factors in 2D $\cos\theta$ and p bins.

- Error is statistical only

Opt π^0 template fit efficiency correction (preliminary)

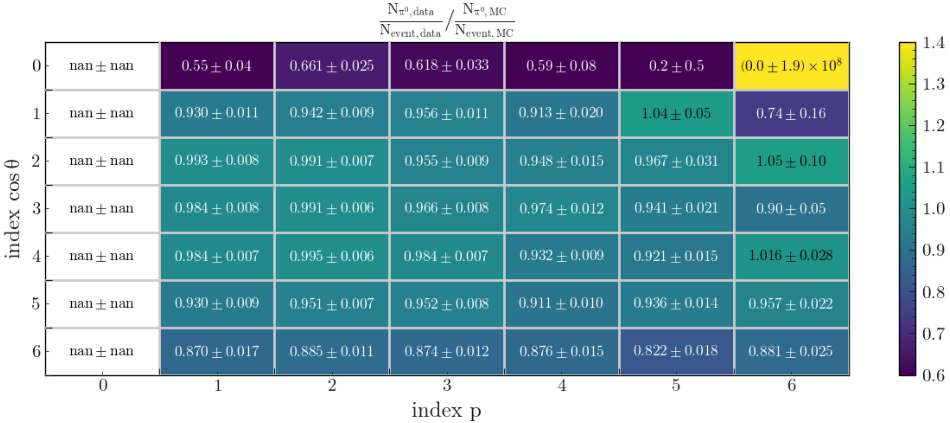




Efficiency correction factors in 1D and 2D of $\cos\theta$ and p bins.

- Error is statistical only

Opt π^0 template fit efficiency correction (preliminary)



Detailed correction factors in 2D $\cos\theta$ and p bins.

- Error is statistical only