Feasibility study of radiative decay $\tau \to \pi\gamma\nu_\tau$ at STCF

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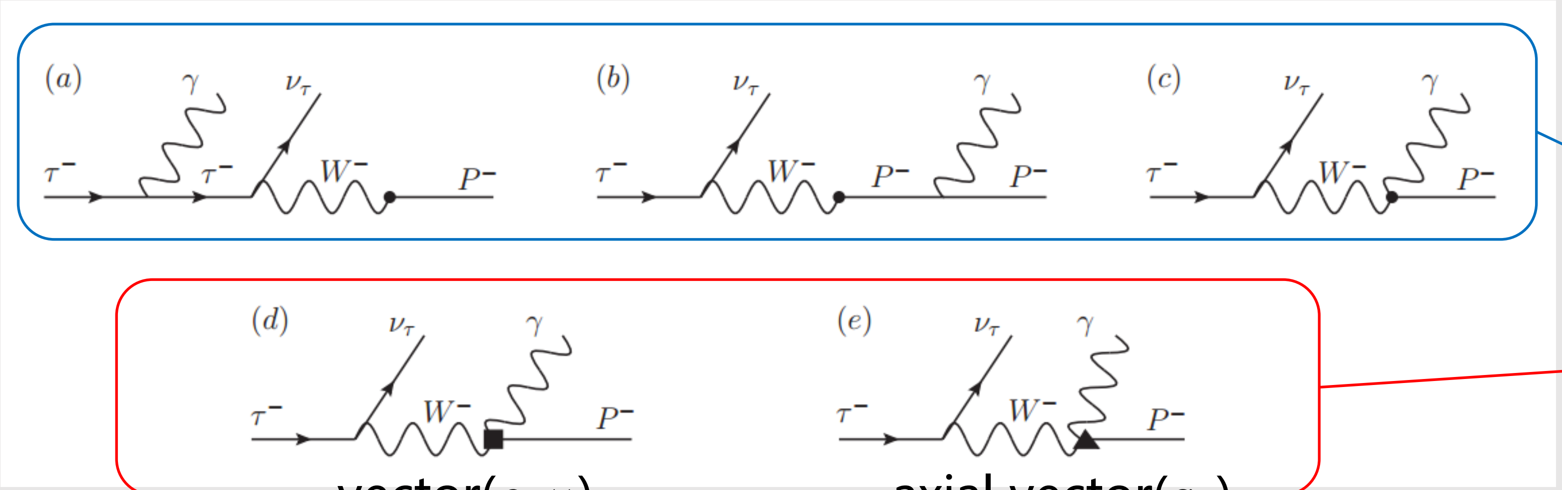
Motivation



Internal bremsstrahlung (IB)

Structure dependent (SD)

vector(ρ, ω) axial vector(a_1)

- None of the radiative tau decays have been measured before.
- Radiative correction becomes crucial for precision tau physics ,such as the lepton universality test in hadronic tau decays, calculation of muon g-2 using tau decays.
- Search for tau radiative decay $\tau \to \pi\gamma v_\tau$.
- Challenge : signal has much lower branching ratio than backgrounds ($Br_{(\tau^- \to \pi^- \gamma \nu_\tau)} / Br_{(\tau^- \to \pi^- \nu_\tau)} \sim 10^{-2}$.
- ML technique is being explored to distinguish signal from backgrounds.

Signal modelling

- Model DIY
- Theoretical calculation
- Validation

Signal generator

Boss Version : 7.0.3

BesEvtGen-00-03-90

4.11 DIY

Author: Rong-Gang Ping

Usage:

BrFr daughter 1 daughter 2... DIY;

Explanation:

The model Doing It Yourself (DIY) is created for user to generate event by supplying decay amplitude. The DIY model is useful for the user to generate event using partial wave analysis results, or implementing coherent effects in decays, or parameterizing the physical quantities in amplitude. The DIY generates events according the decay mode specified by user with pure phase space and passing the four-vector momentum to the amplitude and calculate the decay amplitude. The maximal value of the amplitude is singled out in 20,000 events. Then it uses the reject-accepted sampling method to generate event.

Theoretic decay rate

One-meson radiative tau decays

Zhi-Hui Guo and Pablo Roig
Phys. Rev. D **82**, 113016 – Published 28 December 2010

$$\frac{d^2\Gamma_{IB}}{dx\,dy} = \frac{\alpha}{2\pi} f_{IB}\left(x,y,r_P^2\right) \frac{\Gamma_{\tau^-\to\nu_\tau P^-}}{\left(1-r_P^2\right)^2},$$

$$\frac{d^2\Gamma_{SD}}{dx\,dy} = \frac{\alpha}{8\pi}\frac{M_\tau^4}{F_P^2}\left[|F_V(t)|^2 f_{VV}\left(x,y,r_P^2\right) + 4\Re e(F_V(t)F_A^\star(t)) f_{VA}\left(x,y,r_P^2\right) + 4|F_A(t)|^2 f_{AA}(x,y,r_P^2)\right]\frac{\Gamma_{\tau^-\to\nu_\tau P^-}}{(1-r_P^2)^2},$$

$$\frac{d^2\Gamma_{INT}}{dx\,dy} = \frac{\alpha}{2\pi}\frac{M_\tau^2}{F_P}\left[f_{IB-V}\left(x,y,r_P^2\right)\Re e(F_V(t)) + 2 f_{IB-A}\left(x,y,r_P^2\right)\Re e(F_A(t))\right]\frac{\Gamma_{\tau^-\to\nu_\tau P^-}}{\left(1-r_P^2\right)^2}$$

$$f_{IB}\left(x,y,r_P^2\right) = \frac{\left[r_P^4(x+2) - 2r_P^2(x+y) + (x+y-1)\left(2-3x+x^2+xy\right)\right]\left(r_P^2-y+1\right)}{\left(r_P^2-x-y+1\right)^2 x^2}$$

$$f_{VV}\left(x,y,r_P^2\right) = -\left[r_P^4(x+y) + 2r_P^2(1-y)(x+y) + (x+y-1)\left(-x+x^2-y+y^2\right)\right],$$

$$f_{AA}\left(x,y,r_P^2\right) = f_{VV}\left(x,y,r_P^2\right),$$

$$f_{VA}\left(x,y,r_P^2\right) = -\left[r_P^2(x+y) + (1-x-y)(y-x)\right]\left(r_P^2-x-y+1\right),$$

$$f_{IB-V}\left(x,y,r_P^2\right) = -\frac{\left(r_P^2-x-y+1\right)\left(r_P^2-y+1\right)}{x},$$

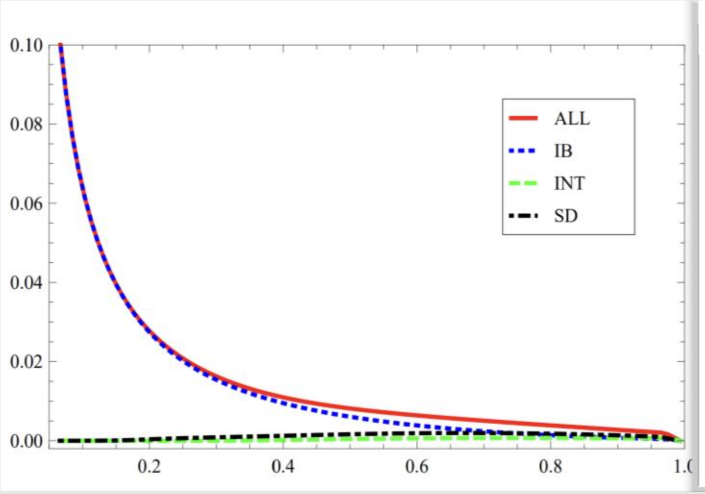
$$f_{IB-A}\left(x,y,r_P^2\right) = -\frac{\left[r_P^4 - 2r_P^2(x+y) + (1-x+y)(x+y-1)\right]\left(r_P^2-y+1\right)}{\left(r_P^2-x-y+1\right)x}.$$

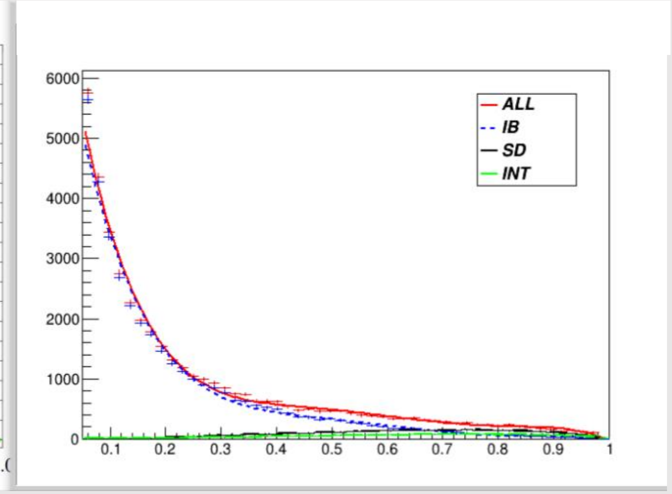
$$\begin{aligned} F_V^\pi(t) = & -\frac{N_C}{24\pi^2F_\pi} + \frac{2\sqrt{2}F_V}{3F_\pi M_V}\left[(c_2-c_1-c_5)t + (c_5-c_1-c_2-8c_3)m_\pi^2\right]\times \\ & \left[\frac{\cos^2\theta}{M_\phi^2}\left(1-\sqrt{2}\mathrm{tg}\theta\right) + \frac{\sin^2\theta}{M_\omega^2}\left(1+\sqrt{2}\mathrm{cotg}\theta\right)\right] \\ & + \frac{2\sqrt{2}F_V}{3F_\pi M_V}D_\rho(t)\left[(c_1-c_2-c_5+2c_6)t + (c_5-c_1-c_2-8c_3)m_\pi^2\right] \\ & + \frac{4F_V^2}{3F_\pi}D_\rho(t)\left[d_3 t + (d_1+8d_2-d_3)m_\pi^2\right]\times \\ & \left[\frac{\cos^2\theta}{M_\phi^2}\left(1-\sqrt{2}\mathrm{tg}\theta\right) + \frac{\sin^2\theta}{M_\omega^2}\left(1+\sqrt{2}\mathrm{cotg}\theta\right)\right]. \end{aligned}$$

$$F_A^\pi(t) = \frac{F_V^2}{2F_\pi M_\rho^2}\left(1-\frac{2G_V}{F_V}\right) - \frac{F_A^2}{2F_\pi}D_{a_1}(t) + \frac{\sqrt{2}F_AF_V}{F_\pi M_\rho^2}D_{a_1}(t)\left(-\lambda'' t + \lambda_0 m_\pi^2\right)$$

Model validation

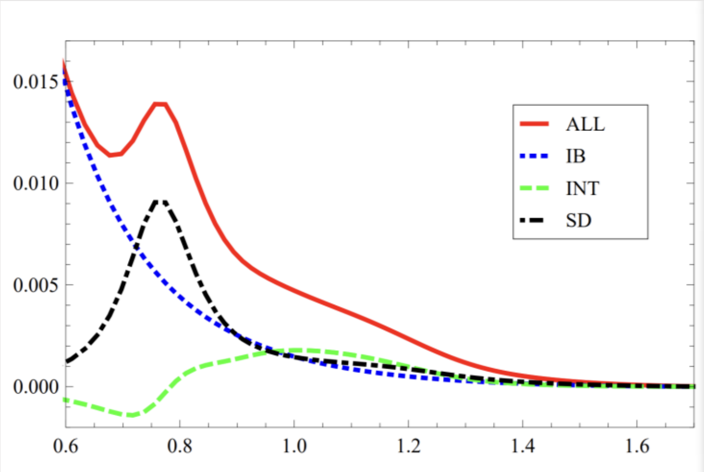
theory predict | simulation result

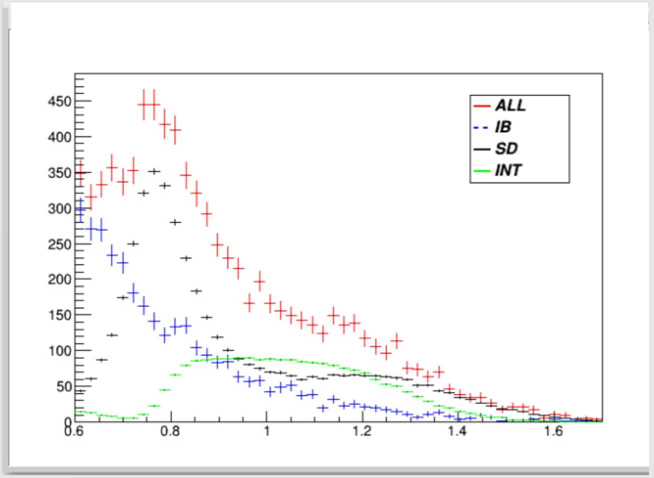




$$x := \frac{2p_\tau \cdot k}{M_\tau^2}$$

In the tau rest frame x is the photon energy Eγ





$$t = P^2 = (p_2 + k)^2$$

The variable t is the invariant mass square of the pion-photon system

Study of event selection using BESIII detector

- Background processes
- Event selection
- Upper limit

Inclusive MC sample at BESIII

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Boss Version : 7.0.3

$\sqrt{s}$ =4.23GeV

Inclusive sample :

di-tau samples : tau pair generated with KKMC decay of tau with EvtGen

di-muon samples : generated with BABAYAGA

Hadronic samples : generated with LUNDARLW

Luminosity(pb^{-1}) = 1100.91

	$\sigma(nb)$	$N_{exp}(10^6)$
di-tau	9.86	10.85
di-muon	5.18	5.7
hadronic	20.32	22.37
gamma gamma	19.73	21.72
Bhabha	415.41	457.33

Primary selection

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Tag side : $\tau^+ \to \mu^+ \bar{\nu}_\tau \nu_\mu$

Prob side : $\tau^- \to \pi^- \gamma \nu_\tau$

Note : The event selection is studied with BESIII detector for now

Criteria for selection：

Good Mdc track = 2
(Interaction Point and Exit Angle)

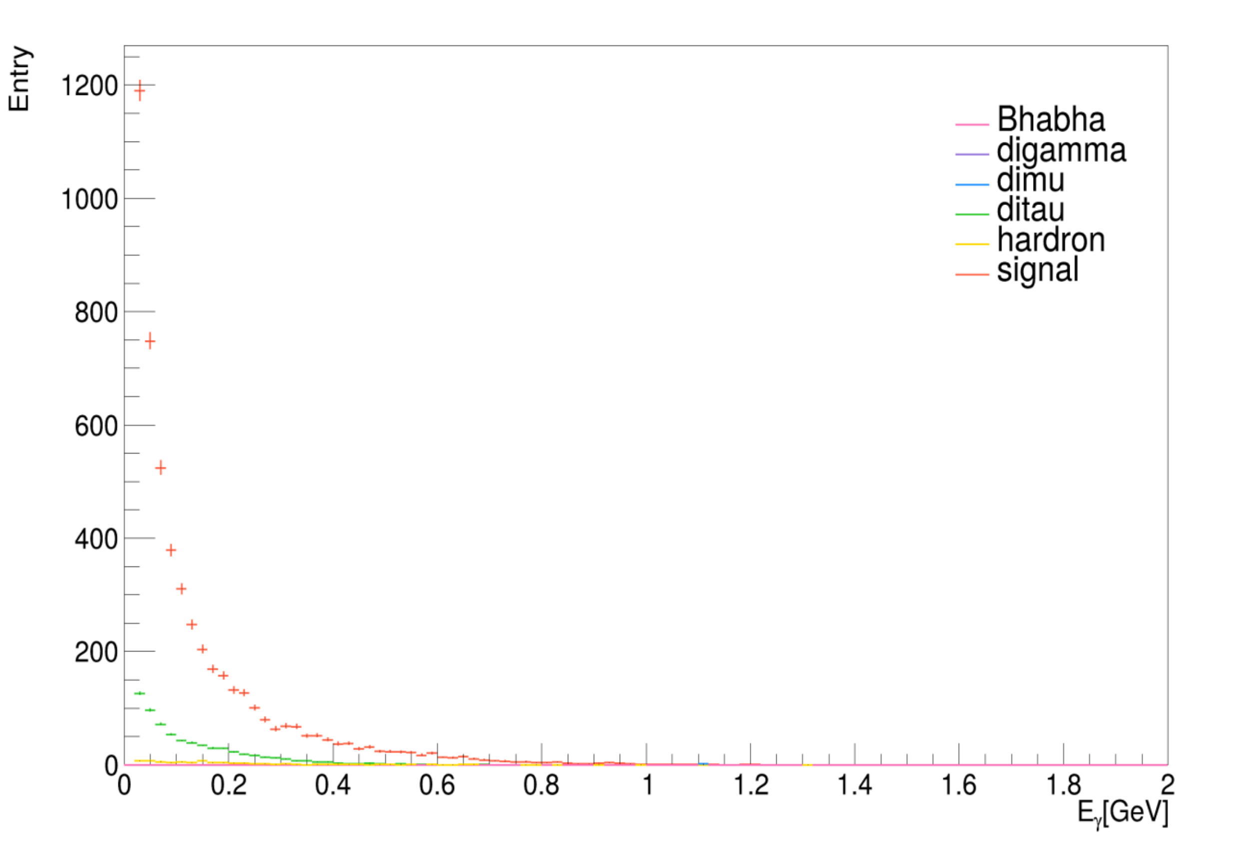
Total charge = 0

PID two track is pion and muon

Good Emc track = 2
(With Valid Shower)

Final event selection

signal is scaled by 100 for better visibility

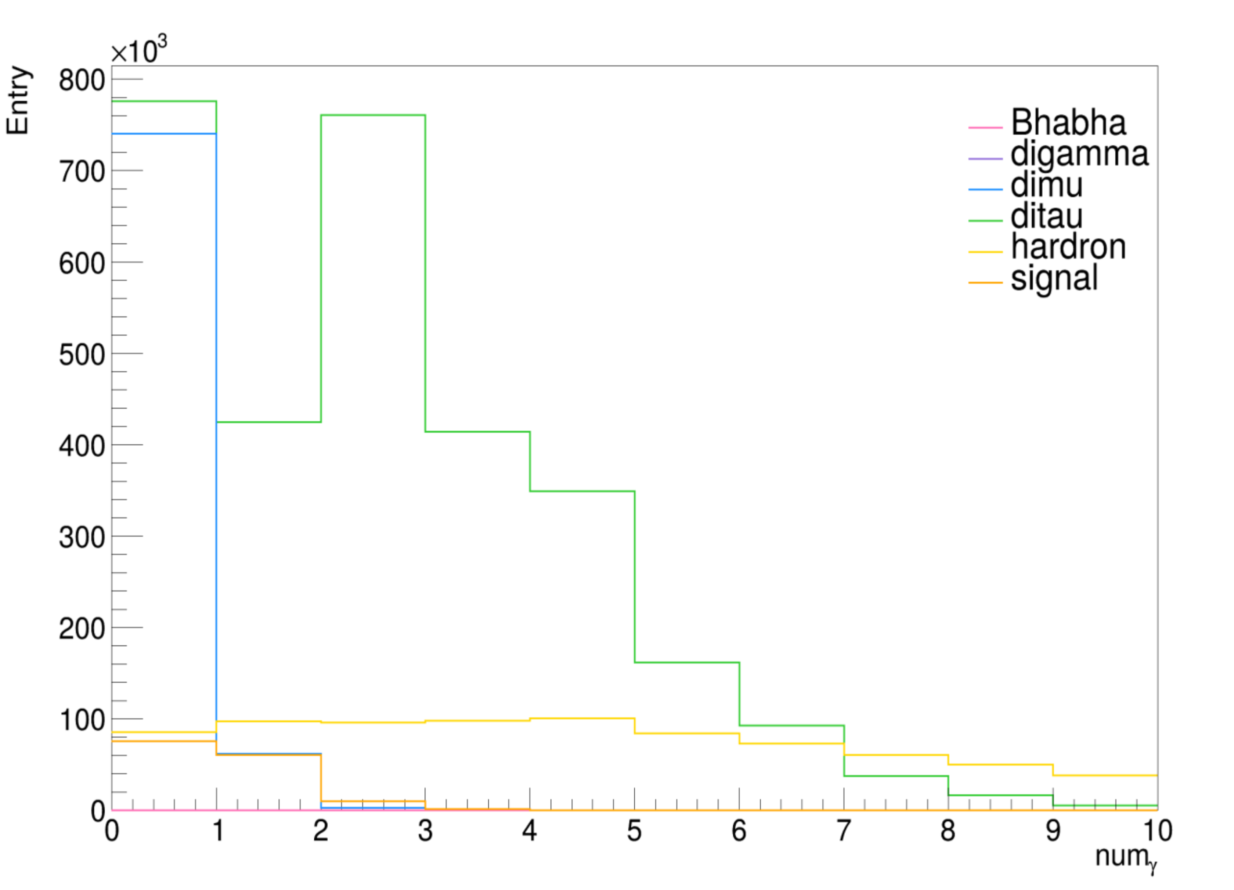


The energy distribution of photons

$E_\gamma > 0.4$ GeV

Criteria for selection
E/p < 0.2
Angle(γ,π) < 40
-140 < θ_{acop} < 140
${M^2}_{miss} > 2$ GeV^2
$N_\gamma = 1$
$E_\gamma > 0.4$ GeV
Not considered conjugate process

Photon number constraint



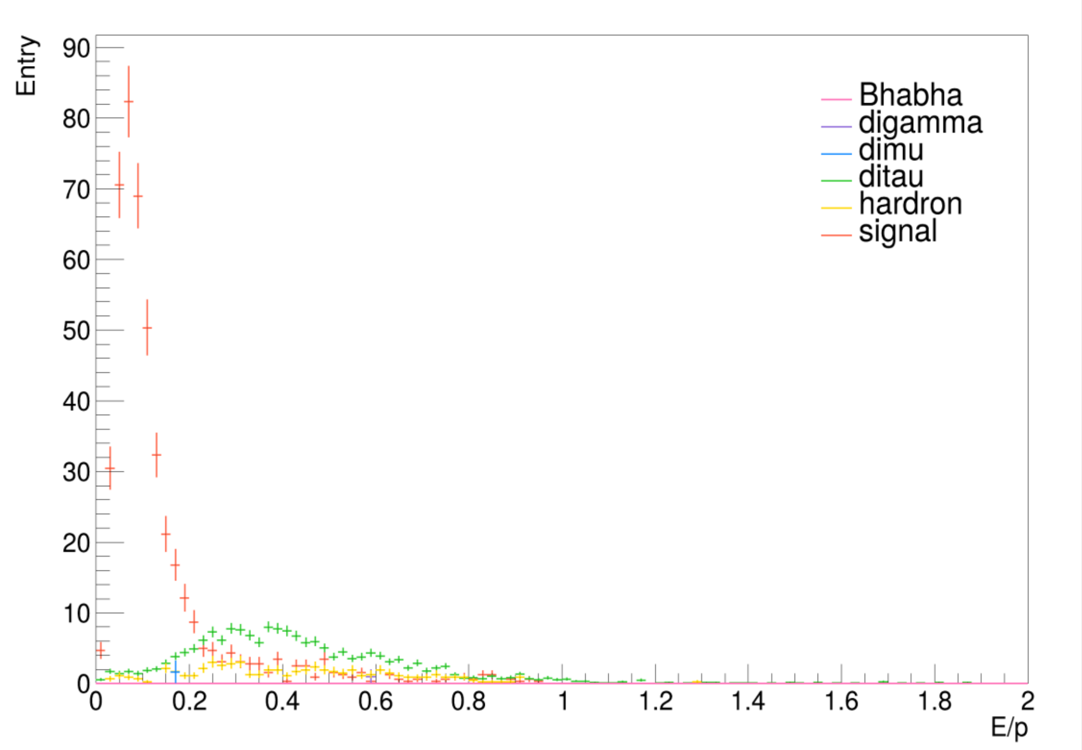
Photon number distribution

Constraint the number of photon = 1

Most of the di-muon process, di-tau process and hardronic process are removed

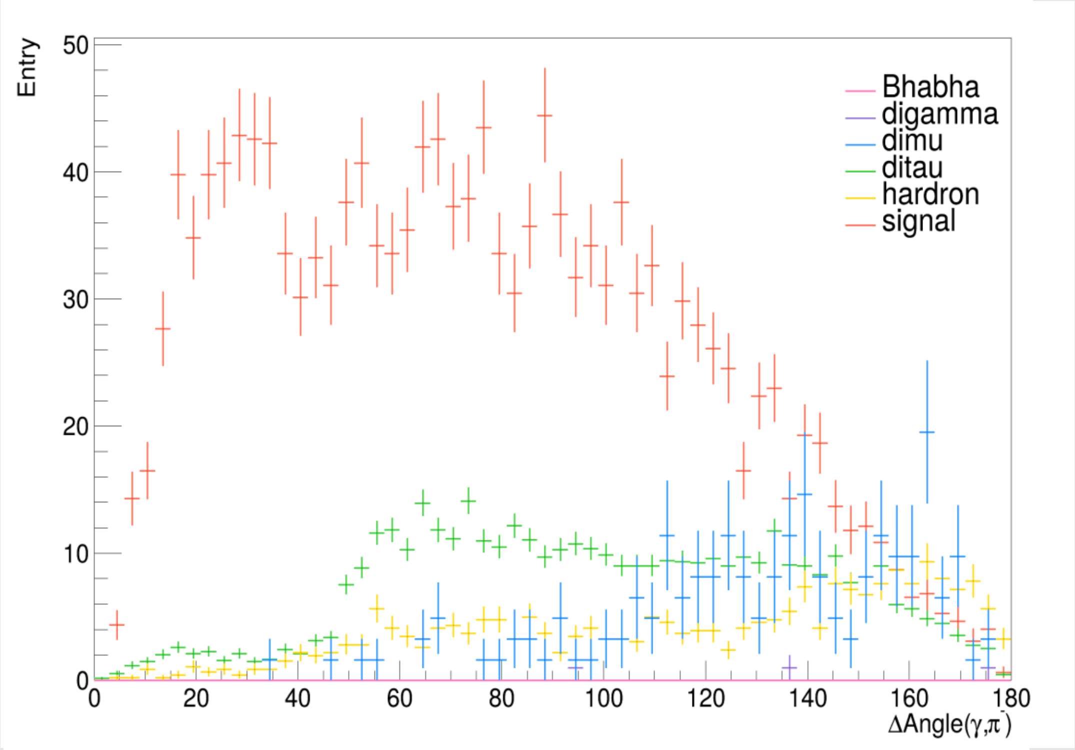
About half of the signal has been removed, and a large number of di-tau processes are still retained.

Parameter about π^-



E/P of prob π^- (E is the deposited energy in EMC and p is the momentum of the track)

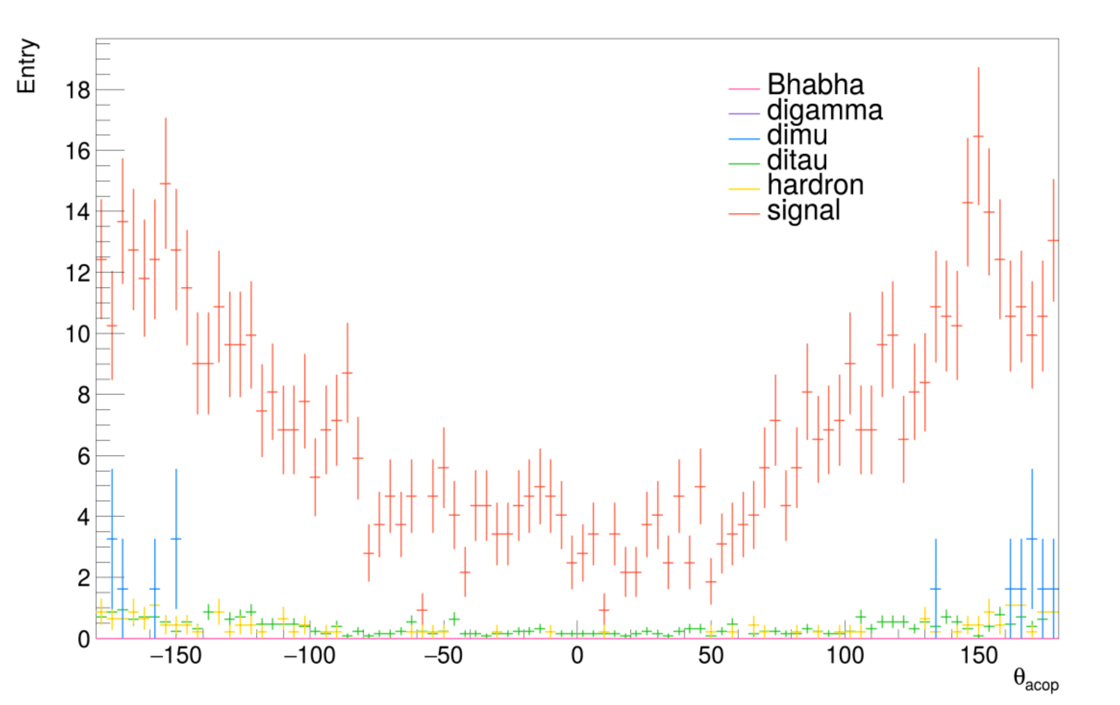
$E/p < 0.2$



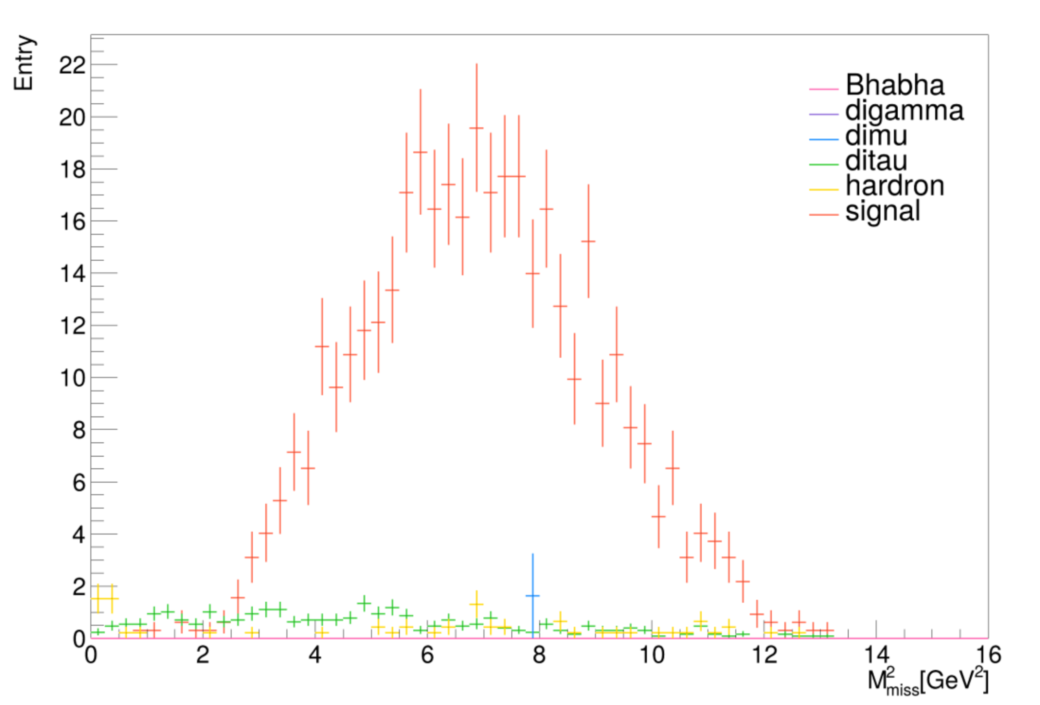
Angle between γ and prob π^-

$\text{Angle}(\gamma, \pi) < 40$

Parameter about system



Acoplanarity angle (the angle between the planes formed by the momenta of two particles involved in the interaction.) -140 < θ_{acop} < 140



Missing mass squared

$$M_{miss}^2 = (\sum E_{initial} - \sum E_{final})^2 - (\sum \vec{p}_{initial} - \sum \vec{p}_{final})^2$$

$$M_{miss}^2 > 2\ \mathrm{Ge}V^2$$

Expected upper limit

Theoretical articles give relational formulas :

(PHYSICAL REVIEW D 103, 056017(2021))

$$\frac{\Gamma_{(\tau^- \to \pi^- \gamma \nu_\tau)}}{\Gamma_{(\tau^- \to \pi^- \nu_\tau)}} = (1.61 \pm 0.06) \times 10^{-2}$$

The branching ratio of non-radiative process can be quoted from PDG:

$$Br_{(\tau^- \to \pi^- \nu_\tau)} = (10.82 \pm 0.05)\%$$

So upper limit on the signal can be calculated by :

$$\mu_{sig}^{up} = Br_{(measured)} \,/\, Br_{(\text{theoretical})}$$
$$= Br_{sig}^{up} \,/\, (Br_{(\tau^- \to \pi^- \nu_\tau)} \times 1.6 \times 10^{-2})$$

μ_{sig}^{up} is the signal strength

Physics potential at the STCF

An STCF operating at CMEs ranging from 2 to 7GeV would be of great importance to the entire field of elementary particle physics.

It would address a very broad range of physics topics, including QCD tests, hadron spectroscopy, precise tests of the electroweak sector of the SM, and searches for new physics beyond the SM.

The proposed luminosity of the STCF is above $\mathbf{0.5 \times 10^{35} cm^{-2} s^{-1}}$, at this level, it is expected to deliver more than $\mathbf{1 ab^{-1}}$ of data samples each year.

CME (GeV)	Lumi (ab^{-1})	Samples	σ(nb)	No. of Events	Remarks
4.230	1	$J/\psi\pi^+\pi^-$	0.085	8.5×10^7	
		$\tau^+\tau^-$	3.6	3.6×10^9	
		$\gamma X(3872)$			

Compared with BESIII, the luminosity of STCF is increased by nearly three orders of magnitude, and although the cross-section is one-third of BESIII at the central mass of 4.23 GeV, the number taken is about 300 times that of BESIII

Expected upper limit

μ_{sig}^{up} and luminosity have such a relationship :

$$\mu_{sig}^{up} \propto \frac{1}{\sqrt{\mathcal{L}}}$$

	Lumi(4.23Gev)	μ_{sig}^{up}@95% $C.L$	Br_{sig}^{up}@95% $C.L$	Expected signal significance
BESIII	1100.81 pb^{-1}	3.357	5.82×10^{-2}	0.6σ
STCF(Assuming the same detection efficiency as BESIII)	1 ab^{-1}(expected)	0.108	1.94×10^{-3}	19.7σ

A Bayesian-based maximum likelihood estimator, extended from the profile likelihood approach, is used to determine the upper limit of the signal strength. Nucl. Instrum. Meth. A 551, 493–503(2005), arXiv:physics/0403059

Event selection optimization using CNN

- Sample generation
- Traditional selection
- CNN method

Tau decay mode

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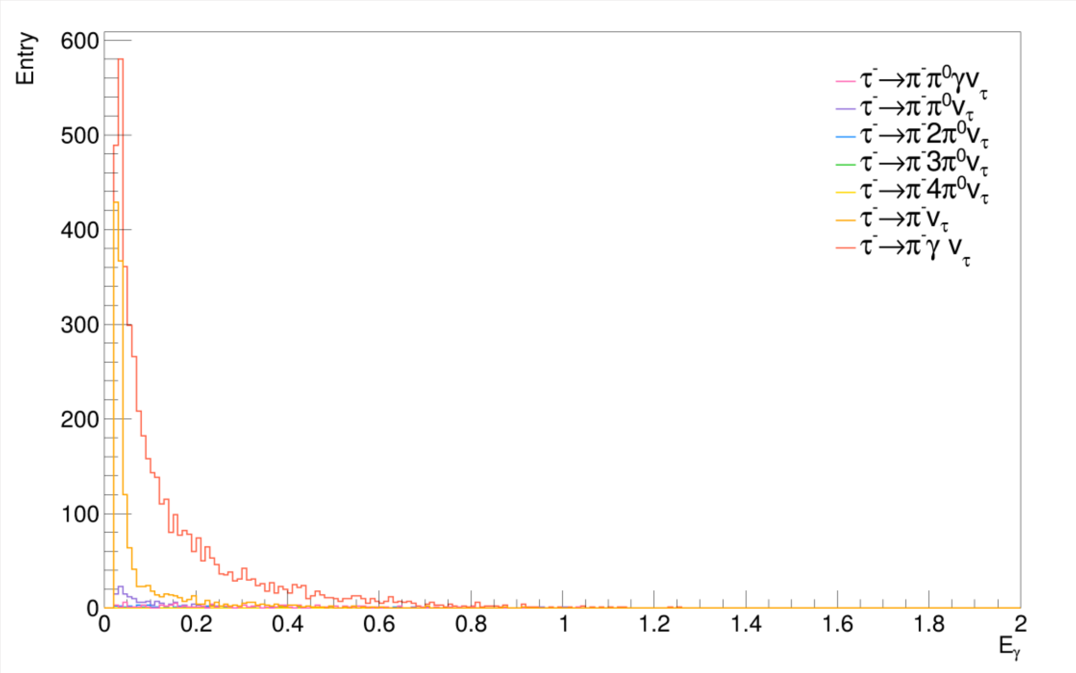
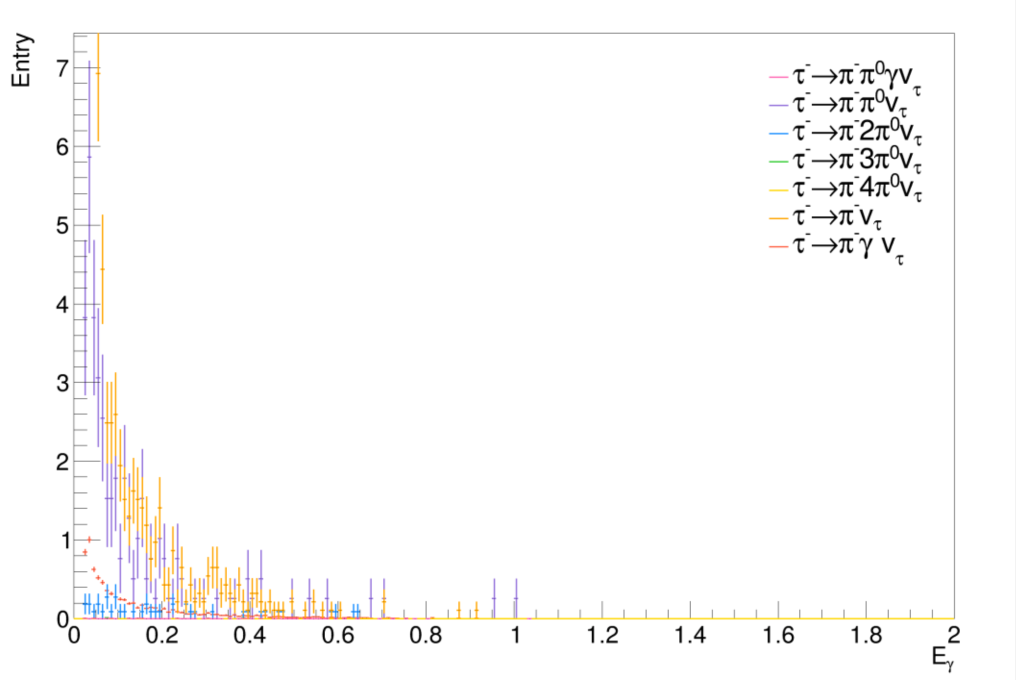
Modes with one charged particles	Branch ratio		
$\mu\bar{\nu}_\mu\nu_\tau$	$(17.39 \pm 0.04)\%$	$\pi^-2\pi^0\nu_\tau$	$(17.39 \pm 0.04)\%$
$\mu\bar{\nu}_\mu\nu_\tau\gamma$	$(3.67 \pm 0.08) \times 10^{-3}$	$K^-2\pi^0\nu_\tau$	$(6.5 \pm 2.2) \times 10^{-4}$
$e\bar{\nu}_e\nu_\tau$	$(17.82 \pm 0.04)\%$	$\pi^-3\pi^0\nu_\tau$	$(1.04 \pm 0.07)\%$
$e\bar{\nu}_e\nu_\tau\gamma$	$(1.83 \pm 0.05)\%$	$h^-4\pi^0\nu_\tau$	$(1.6 \pm 0.4) \times 10^{-3}$
$\pi^-\nu_\tau$	$(10.82 \pm 0.05)\%$	$a_1(1260)\nu_\tau \rightarrow \pi^-\gamma\nu_\tau$	$(4.0 \pm 1.5) \times 10^{-4}$
$K^-\nu_\tau$	$(6.96 \pm 0.10) \times 10^{-3}$		
$\pi^-\pi^0\nu_\tau$	$(25.49 \pm 0.09)\%$		
$K^-\pi^0\nu_\tau$	$(4.33 \pm 0.15) \times 10^{-3}$		

Event selection using cuts to variables

The same number of main process events were generated with KKMC and decay of tau with EvtGen.
The distribution of photon energy is plotted using the same selection conditions as before.



Before scale



Scale by branch ratio

Event selection using cuts to variables

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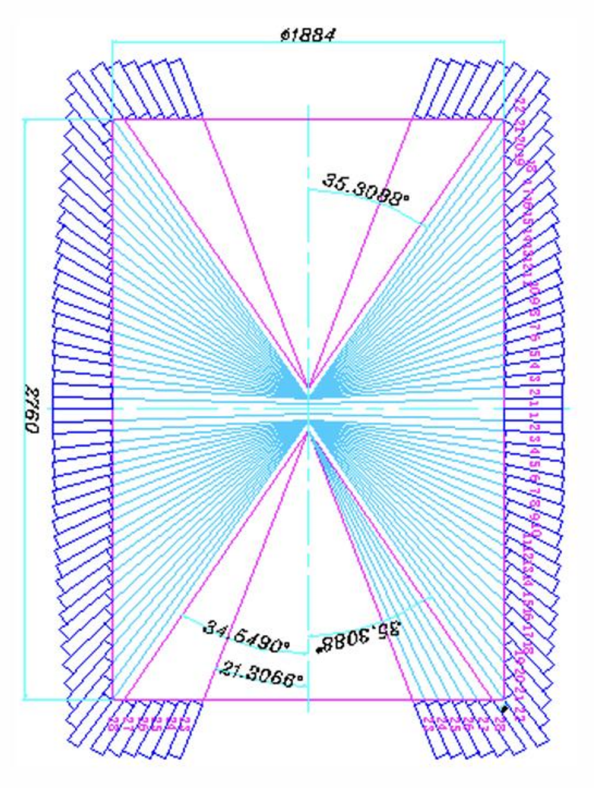
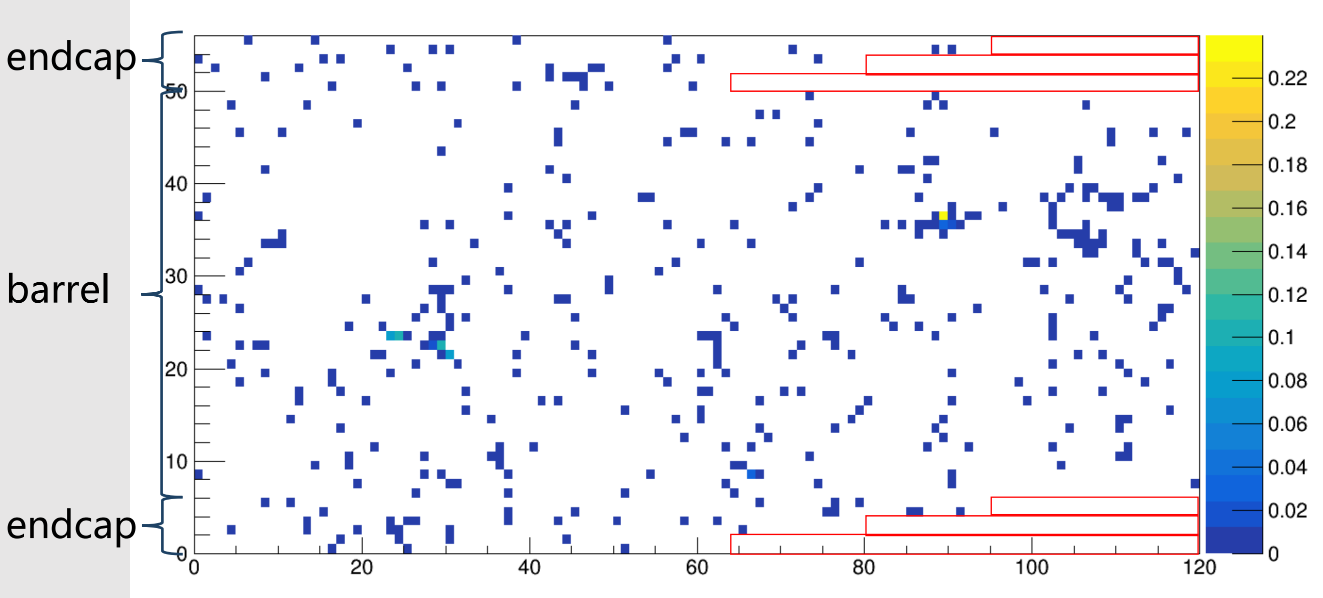
	N_{gen}	N_{reco}	Br	$eff = N_{reco}/N_{gen}$	$ratio = eff_{sig}/eff_{bkg}$	$scale - factor$	N_{scale}
$\tau^- \rightarrow \pi^- \gamma v_\tau$	100000	4551	0.0017	0.04551	1	0.0321	146.04
$\tau \rightarrow \pi^- \pi^0 v_\tau$	100000	158	0.2549	0.00158	28.8	4.8116	760.25
$\tau \rightarrow \pi^- \pi^0 \gamma v_\tau$	100000	98	0.0014	0.00098	46	0.0264	2.58
$\tau \rightarrow \pi^- 2\pi^0 v_\tau$	100000	41	0.0926	0.00041	111	1.7480	73.42
$\tau \rightarrow \pi^- 3\pi^0 v_\tau$	100000	2	0.0104	0.00002	2275	0.1963	0.39
$\tau \rightarrow \pi^- 4\pi^0 v_\tau$	100000	0	0.0016	0	0	0.0302	0
$\tau^- \rightarrow \pi^- v_\tau$	100000	1247	0.1082	0.01247	3.65	2.0424	2549.96

BESIII EMC





The EMC is divided into a barrel part and two endcaps

barrel : 120×44=5280， endcap : 2×(96,96,80,80,64,64) =960

CNN model

The signal and one of the backgrounds are mixed

$\tau^- \to \pi^- \gamma \nu_\tau$

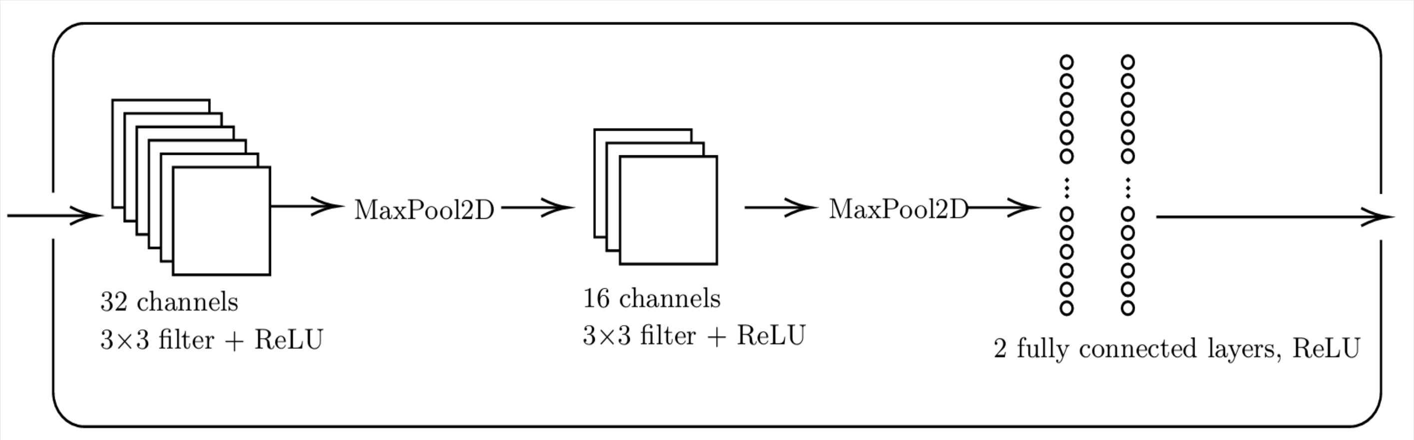
$\tau \to \pi^- \pi^0 \nu_\tau$

$\tau \to \pi^- \pi^0 \gamma \nu_\tau$

$\tau \to \pi^- 2\pi^0 \nu_\tau$

$\tau \to \pi^- 3\pi^0 \nu_\tau$

$\tau \to \pi^- 4\pi^0 \nu_\tau$



$P(\pi^- \gamma \nu_\tau)$

$P(background)$

Currently, binary classification between signal and each backgrounds is used. Will identify between signal and inclusive ditau MC events.

Comparison with traditional methods

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	$ratio_{trad}$	N_{scale}^{trad}	$ratio_{CNN}$	N_{scale}^{CNN}
$\tau^- \to \pi^- \gamma \upsilon_\tau$	1	146.04	1	229
$\tau \to \pi^- \pi^0 \upsilon_\tau$	28.8	760.25	7.61	16018
$\tau \to \pi^- \pi^0 \gamma \upsilon_\tau$	46	2.58	178.19	3.83
$\tau \to \pi^- 2\pi^0 \upsilon_\tau$	111	73.42	459.92	92.99
$\tau \to \pi^- 3\pi^0 \upsilon_\tau$	2275	0.39	1195.32	5.57
$\tau \to \pi^- 4\pi^0 \upsilon_\tau$	0	0	1314.54	0.82
$\tau^- \to \pi^- \upsilon_\tau$	3.65	2549.96	NA	NA

CNN can suppress the backgrounds with ≥ 3 photons more effectively.

Therefore, we want to use more means to improve the classification ability

Summary

- The event selection of radiative decay of $\tau \to \pi\gamma v_\tau$ is studied at BESIII
- The ditau backgrounds are difficult to remove due to very similar signature as signal.

- The expected upper limit of branch fraction of $\tau \to \pi\gamma v_\tau$ is derived at BESIII and STCF(currently using the event selection at BESIII). Expected measurement in STCF is $Br_{sig}^{up}@95\%\ C.L = 1.94 \times 10^{-3}$.
- Simulation and reconstruction using STCF detector will be performed

- Machine Learning technique is being explored to improve the background rejection
- Need to reproduce the inclusive MC samples with EMC hit map info

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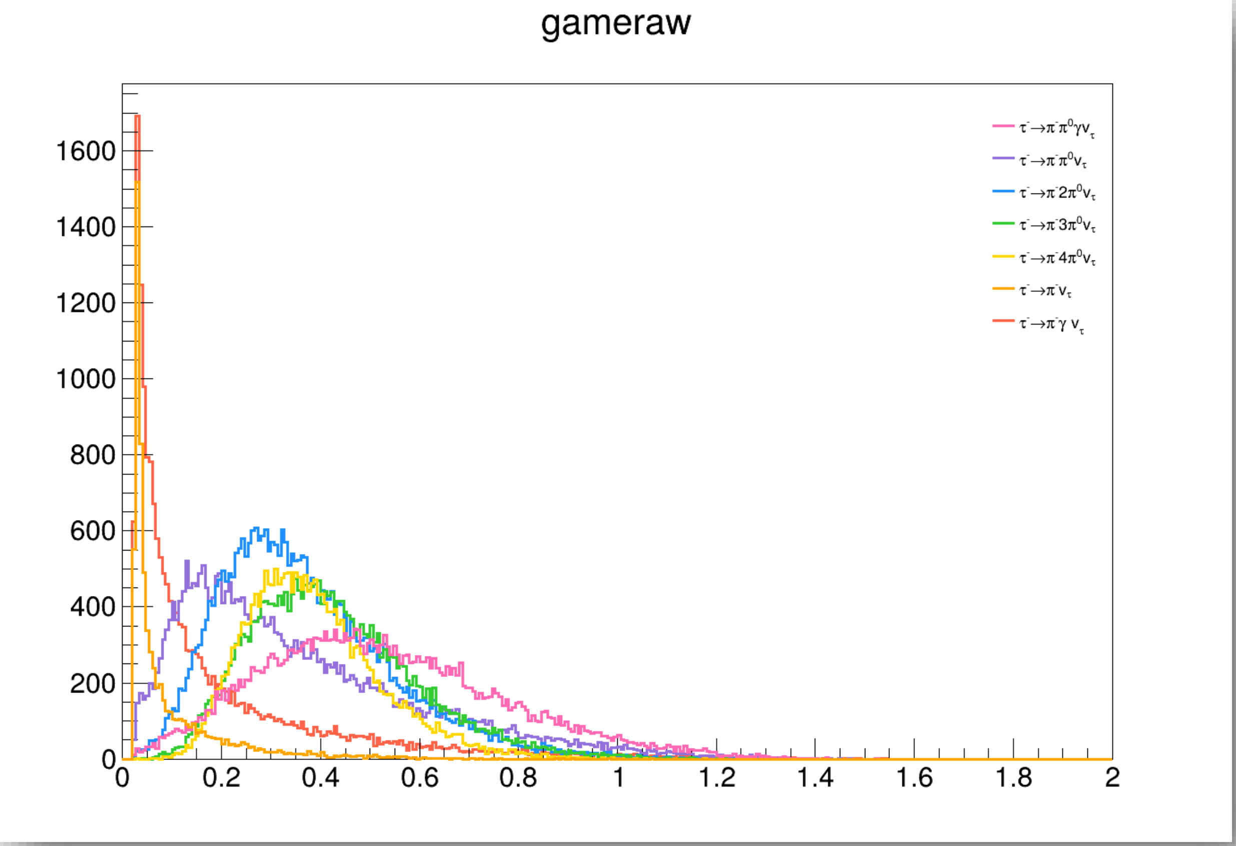
Thanks

Backup

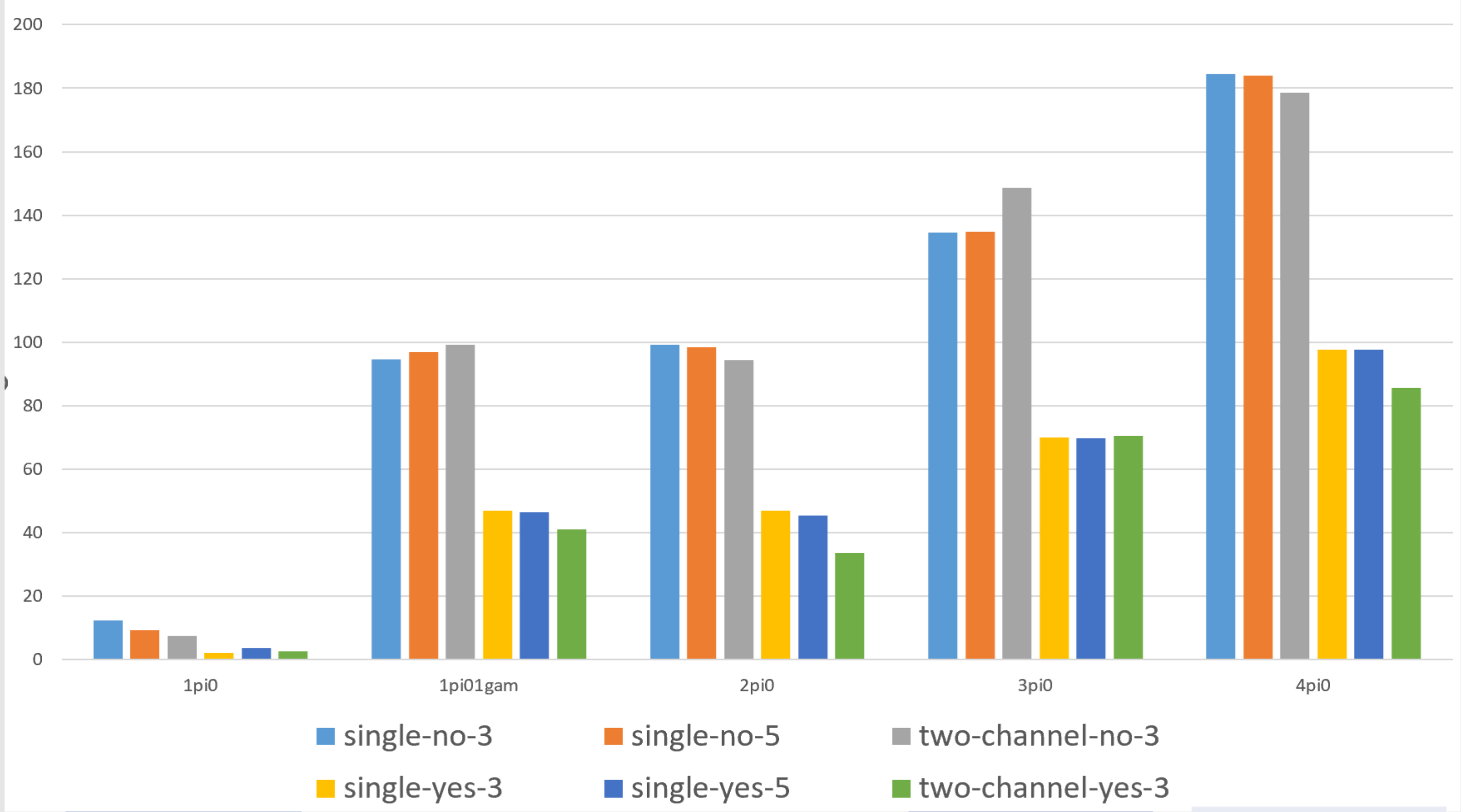
	Ngen	Nreco
di-tau	50,031,418	5,471,656
di-muon	3,503,867	1,464,702
hadronic	103,054,340	1,579,726
gamma gamma	21,532,505	394
Bhabha	3,794,461	770
signal	380,000	152,358

Primary efficiency



di-tau sample gamma energy

Data Cleansing



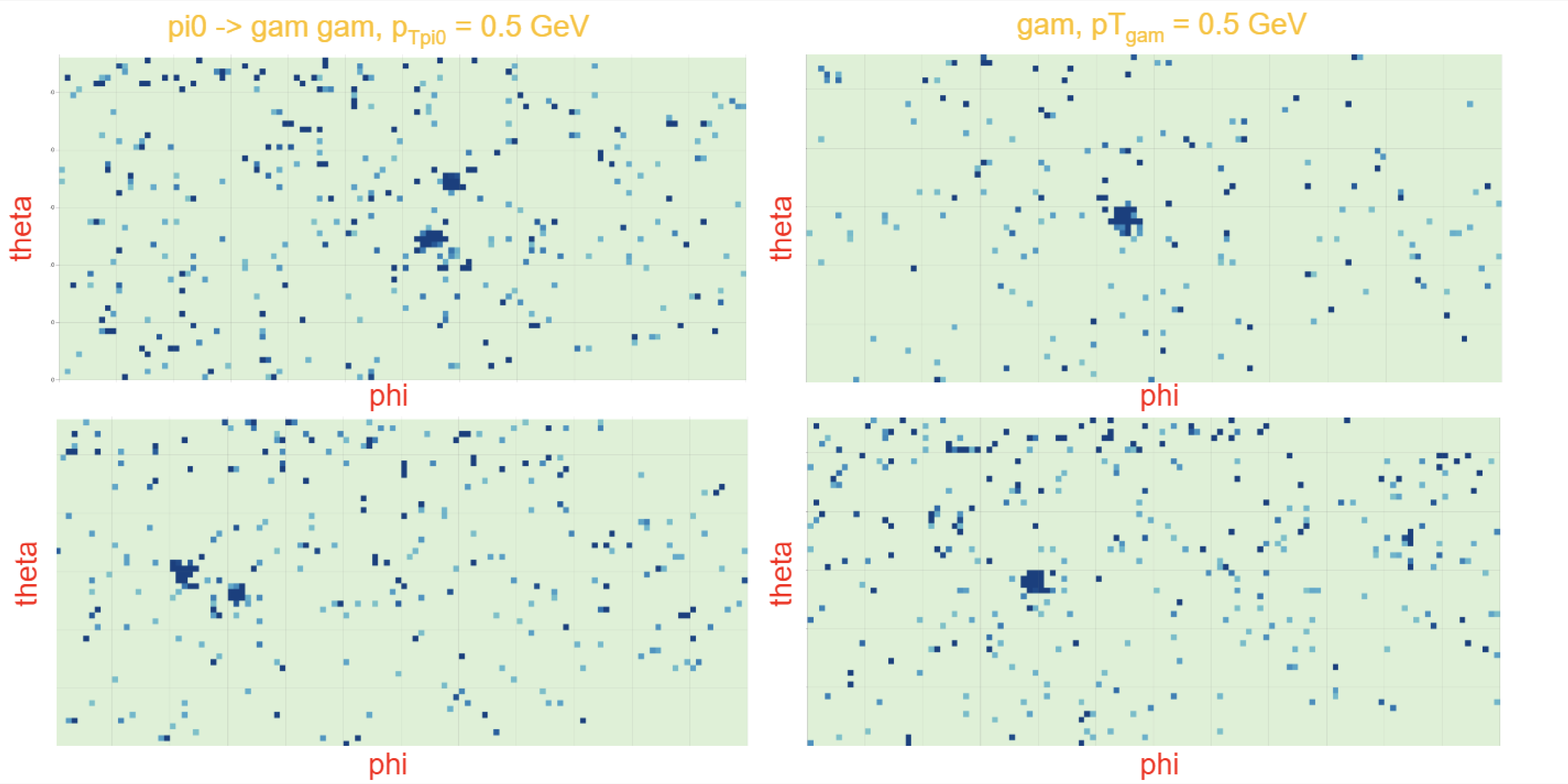
$\tau \to \pi^- \pi^0 \upsilon$ | $\tau \to \pi^- \pi^0 \gamma \upsilon$ | $\tau \to \pi^- 2\pi^0 \upsilon$ | $\tau \to \pi^- 3\pi^0 \upsilon$ | $\tau \to \pi^- 4\pi^0 \upsilon$

Generate samples via SingleParticleGun to remove the effect of tag side.

Record the center position of the charged track in the EMC, and remove the hit information of the surrounding 3x3 cells

Constraint the number of photon > 0

Pi0 and gamma binary separation



Possible backgrounds

di-tau:

$\tau^+ \to \mu^+ \upsilon_\mu \bar{\upsilon}_\tau \gamma$	$\tau^- \to \pi^- \upsilon_\tau$	signal photon is misidentified from radiative photon of tag side
$\tau^+ \to \pi^+ \pi^0 \bar{\upsilon}_\tau$	$\tau^- \to \mu^- \bar{\upsilon}_\mu \upsilon_\tau$	π^0 not successfully reconstructed and the daughter photons are regarded as signal photon (ditau process)
$\tau^+ \to \mu^+ \upsilon_\mu \bar{\upsilon}_\tau \gamma$	$\tau^- \to \mu^- \bar{\upsilon}_\mu \upsilon_\tau$	one muon is misidentified as signal pion
$\tau^+ \to \pi^+ \gamma \bar{\upsilon}_\tau$	$\tau^- \to \pi^- \upsilon_\tau$	one pion is misidentified as tag muon

di-mu with ISR: $\mu^+ \mu^- \gamma$	one muon is misidentified as tag pion, signal photon is misidentified from radiative photon (dimu process)
hadronic: $\pi^+ \pi^- + (\geq 1)\pi^0$	signal muon is misidentified from charged pion and π^0 not successfully reconstructed (hadronic process)