Study of $\tau^- \to h^-\pi^0\nu_\tau$

Shanshan Li[1], Shulei Zhang[1], Xiaolin Kang[2], Huijing Li[3], Xiaorong Zhou[4]

[1]Hunan University

[2]China University of Geosciences

[3]Henan Normal University

[4]University of Science and Technology of China

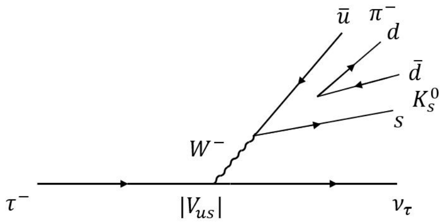
2026.7.2

Outline

- Motivation
- MC sample
- $\tau^- \to K_S^0 \pi^- \nu_\tau$
  - Event selection
  - Branching fraction measurement
  - CP violation
- $\tau^- \to \pi^-/K^- \pi^0 \nu_\tau$
  - Event selection
  - Branching fraction measurement
  - The strong coupling constant α_s
- Summary

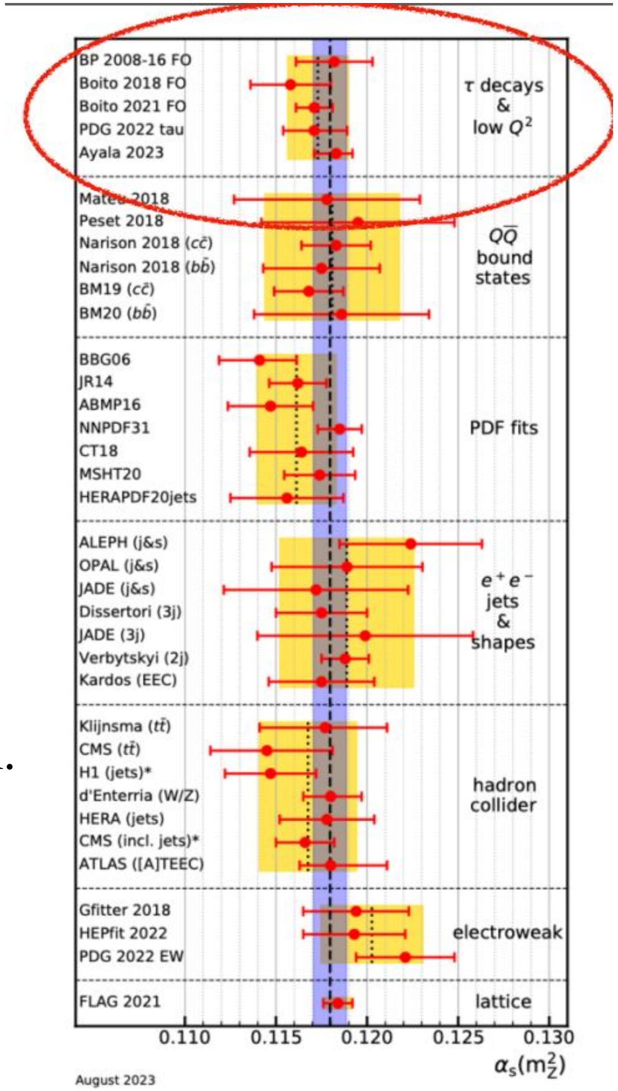
Motivation – $\tau^- \to K^0_S \pi^- \nu_\tau$

- CP violation is one of the key ingredients required to explain the matter–antimatter asymmetry in the Universe. In the Standard Model(SM), the CP asymmetry in $\tau^- \to K^0_S \pi^- \nu_\tau$ originates from $K^0 - \overline{K^0}$ mixing, with a predicted value of $A_{CP}^{SM} = (0.33 \pm 0.01)\%$.
- The BaBar Collaboration reported $A_{CP} = (-0.36 \pm 0.23 \pm 0.11)\%$, corresponding to a 2.8σ deviation from the Standard Model prediction. An independent measurement with higher precision is therefore highly motivated.
- The $\tau^- \to K^0_S \pi^- \nu_\tau$ decay is one of the dominant strange hadronic τ decay modes and provides an important probe of weak and strong interaction dynamics. Precise measurements of this channel can improve our understanding of the hadronic form factors and contribute to tests of the Standard Model through comparisons with theoretical predictions.



Motivation – $\tau^- \to \pi^-/K^-\pi^0\nu_\tau$

- The strong coupling constant α_s is a fundamental parameter of the SM of particle physics and Quantum Chromodynamics (QCD). Measuring the branching ratio of $\tau^- \to \pi^-\pi^0\nu_\tau$ the decay process provides significant experimental input for determining α_s .
- Meanwhile, the study of $\tau^- \to \pi^-\pi^0\nu_\tau$ can help to clarify the so-called "***ee* − *τ* puzzle**", which refers to the discrepancy between the hadronic vacuum polarization contributions to the muon anomalous magnetic moment a_μ derived from the $e^+e^- \to \pi^+\pi^-$ cross-section and from the $\tau^- \to \pi^-\pi^0\nu_\tau$ mass spectrum.
- The τ lepton decays to hadronic final states occur via W - exchange, and the decay rates to final states containing a strange quark suppressed by the factor $(|V_{us}|/|V_{ud}|)^2$. The $\tau^- \to K^-\pi^0\nu_\tau$ decay mode contributes to the inclusive strange τ-decay width, which is used to determine $|V_{us}|$.



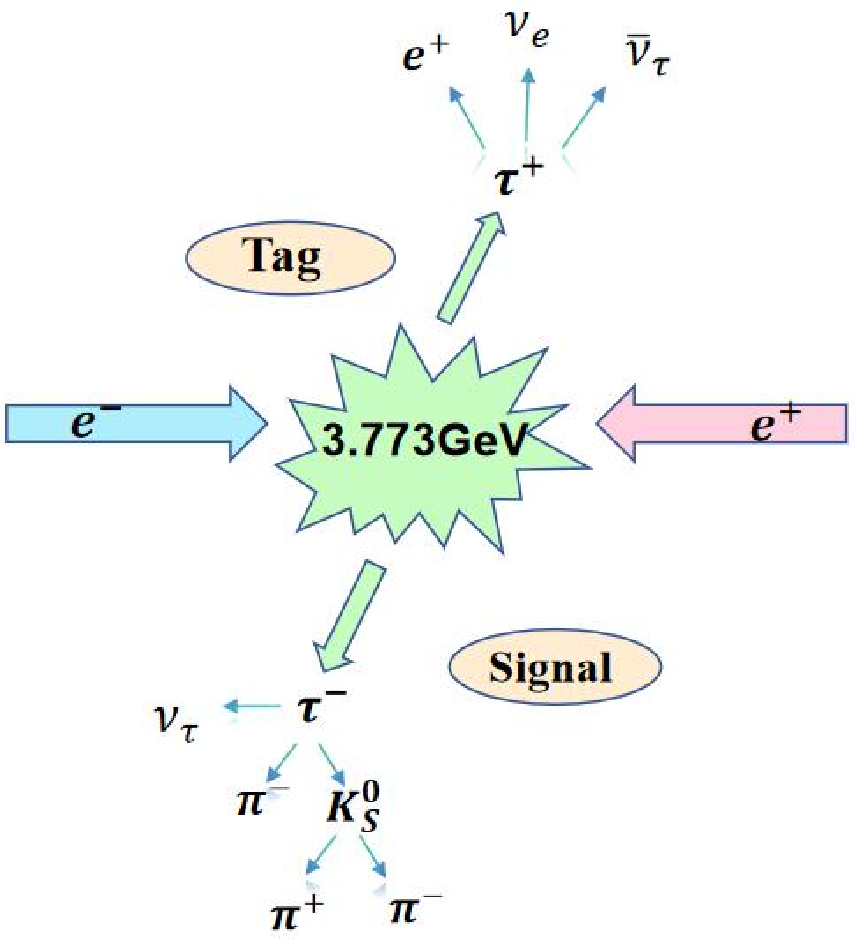
MC sample

$\sqrt{s}$= **4.260 GeV**

- Ditau MC : 98907000
- Ditau MC Generator model: madgraph5 + pythia8.
- signal MC : from Ditau MC.

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

Double tag method – $\tau^- \to K_S^0\pi^-\nu_\tau$



$$B(\tau^- \to K_S^0\pi^-\nu_\tau) = \frac{N_{\mathrm{sig}}}{2N_{\tau\tau}\varepsilon B(K_S^0 \to \pi^+\pi^-)B(\pi^0 \to \gamma\gamma)}$$

N_{sig}: Signal yields

$N_{\tau\tau}$: from ditau MC

ε : $\tau^+ \to e^+\overline{\nu}_\tau\nu_e$ and $\tau^- \to K_S^0\pi^-\nu_\tau$ efficiency

Parameter	value	from
$B(\tau^+ \to e^+\overline{\nu}_\tau\nu_e)$	0.1785±0.0004	PDG
$B(K_S^0 \to \pi^+\pi^-)$	0.6920 ± 0.0005	PDG

Event selection– $\tau^- \to K_S^0\pi^-\nu_\tau$

- **Charge tracks**

(Except for those decaying from K_S^0)

V_{xy}<1cm, $|V_z|$ <10cm

$\cos\theta$<0.93

- **PID requirement**

Using PID system: Global PID

e :$Prob_e > Prob_\pi; Prob_e > Prob_K$

π :$Prob_\pi > Prob_e; Prob_\pi > Prob_K$

(exclusion for those decaying from K_S^0)

N_π =1, $N_e = 1$。

- **K_S^0 selection**

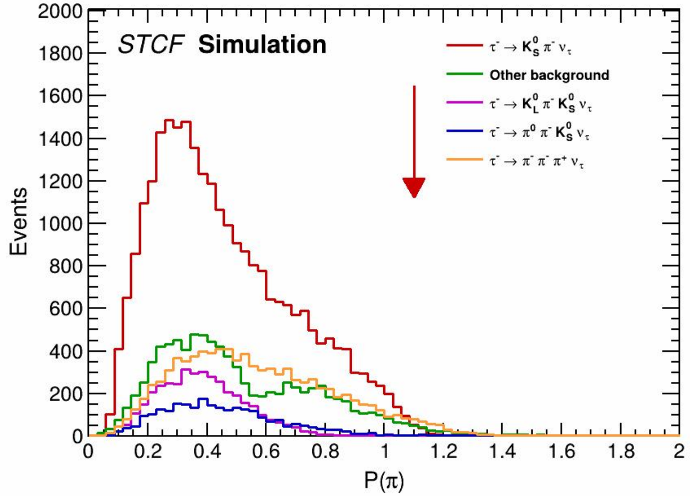
$|V_z| < 20$cm ; $\cos\theta < 0.93$

$0.4826 < M_{\pi^+\pi^-} < 0.5126$

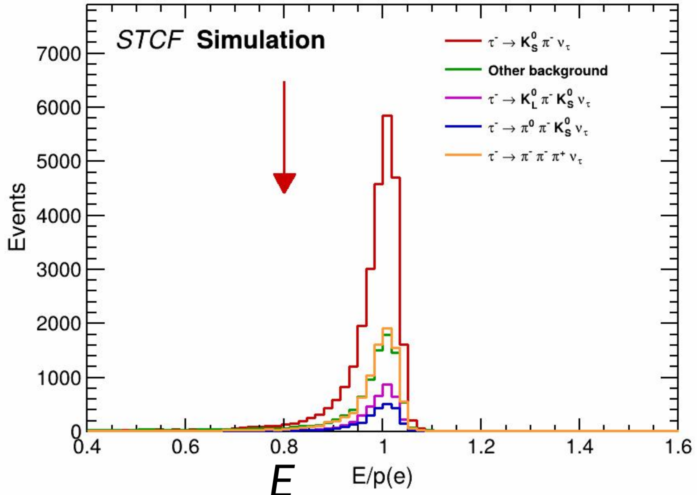
χ^2<200 (Vertex Fitting)

χ^2<200 (Secondary Vertex Fitting)

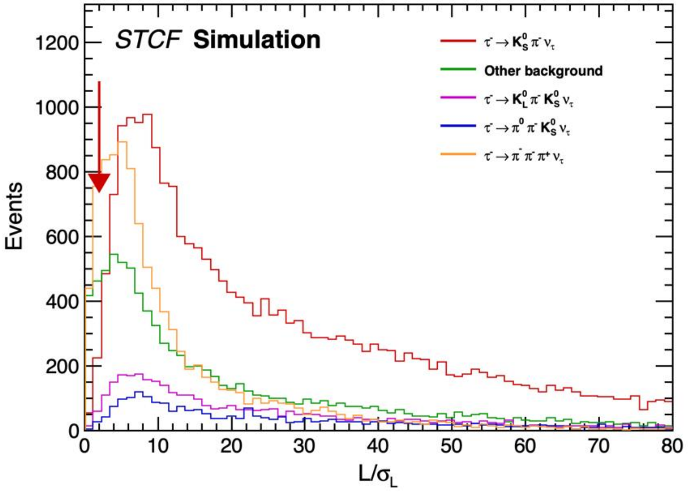
Event selection– $\tau^- \to K_S^0 \pi^- \nu_\tau$



$P_\pi < 1.1\text{GeV}/c$

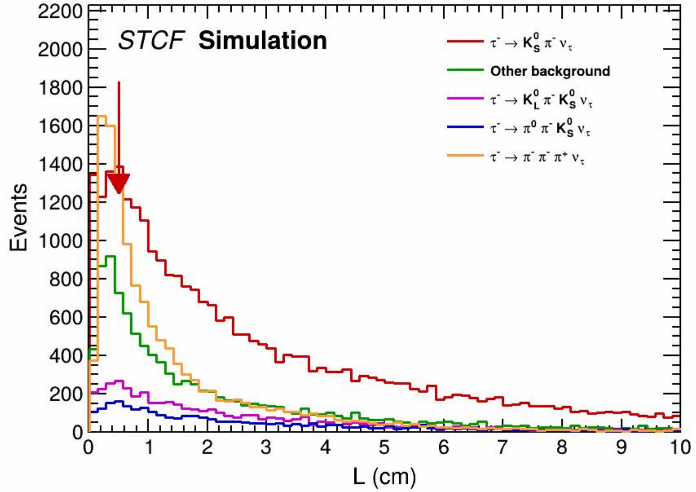


$\frac{E}{P}(e) > 0.8$

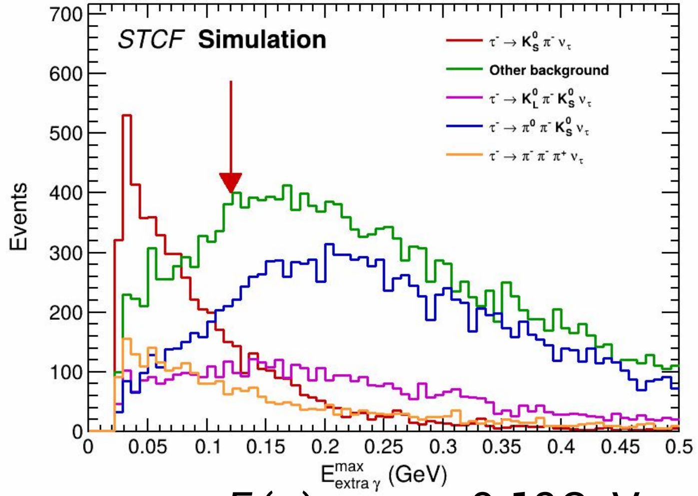


L/σ_L

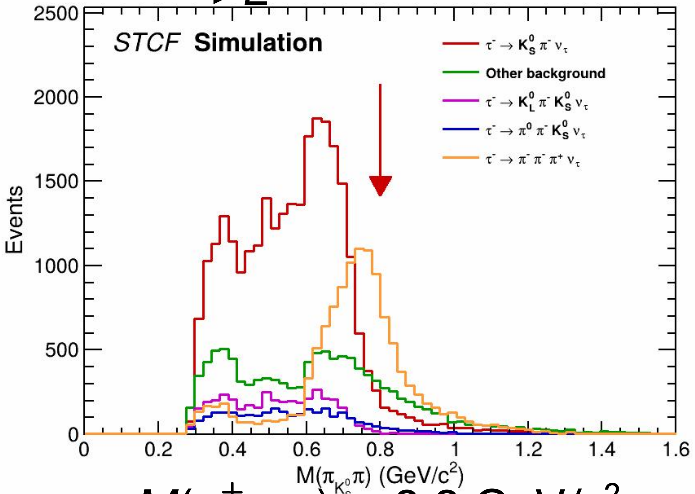
>2



L



$exE(\gamma)_{max} < 0.12\text{GeV}$

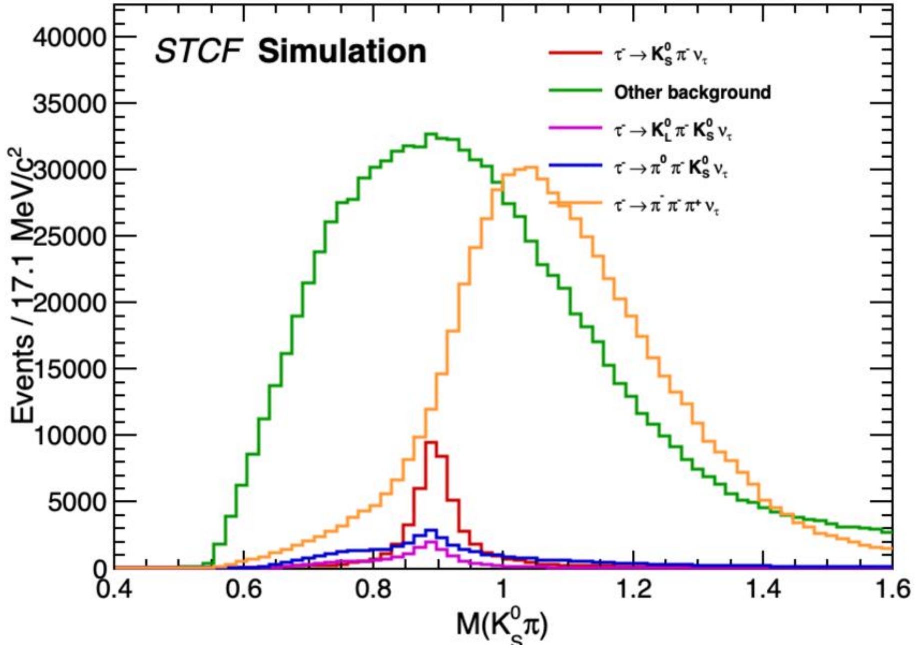


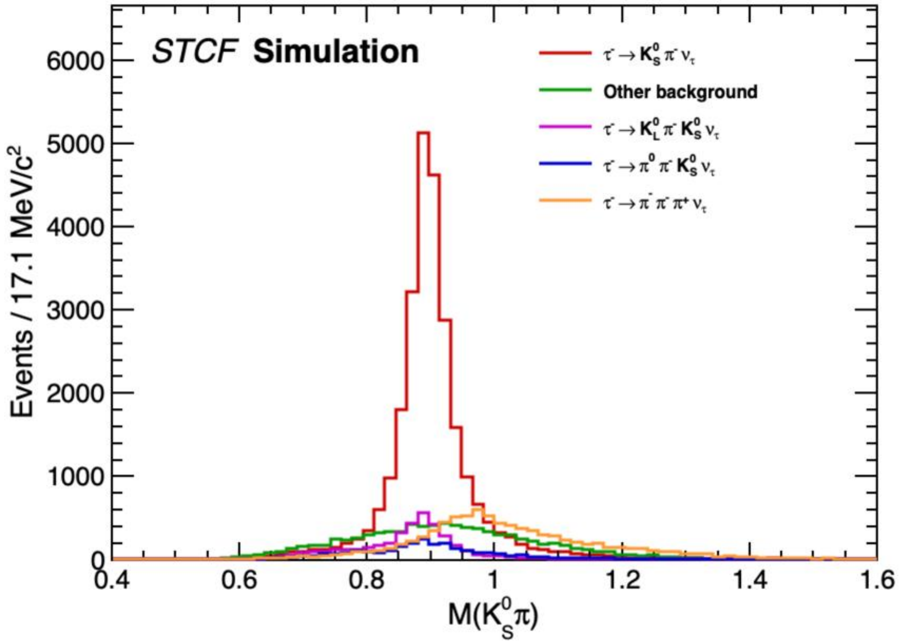
$M(\pi^+_{K_S^0}\pi^-) < 0.8\ \text{GeV}/c^2$

> 0.5

Signal selection criteria

At $\sqrt{s} = 4.26\ GeV$, m($K_S^0\pi^-$) is used to identify semileptonic decay, combined tag and signal selection .





Event selection– $\tau^- \to K_S^0 \pi^- \nu_\tau$

		Signal MC				bkg		
Initial number of events		101630	Rest efficiency ε(%)	Cut efficiency ε(%)	BESIII	101630	Rest efficiency ε(%)	Cut efficiency ε(%)
After the algorithm		49771	48.97%	48.97%	29.88%	1788838	97.29%	97.29%
Further event selection	$P_\pi < 1.1\text{GeV}/c$	49500	99.46%	48.71%	29.76%	1698735	94.96%	97.17%
	$\frac{E}{P}(e) > 0.8$	43877	88.64%	43.17%	27.47%	1266293	74.54%	96.65%
	$L/\sigma_L > 2$, $L > 0.5$	28988	66.07%	28.52%	18.54%	68556	5.41%	70.28%
	$exE(\gamma)_{max} <$ 0.12GeV	27247	93.99%	26.81%	16.98%	29758	43.41%	52.20%
	$M(\pi^+_{K_S^0}\pi^-) < 0.8$ GeV/c^2	26172	96.05%	25.75%	16.48%	23821	80.05%	47.65%

Systematic uncertainty– $\tau^- \to K_S^0 \pi^- \nu_\tau$

- tracking efficiency for $\pi^\pm$ and $e^\pm$ — 0.2%
- PID efficiency for $\pi^\pm$ and $e^\pm$ — 0.2%
- K_S^0 Reconstruction — 0.2%

Estimated from BESIII

- Lumisnosity — 0.1%

→ from 1ab^{-1} data volume at STCF

- MC statistics — 0.2%
- Input branching fractions — 0.2%

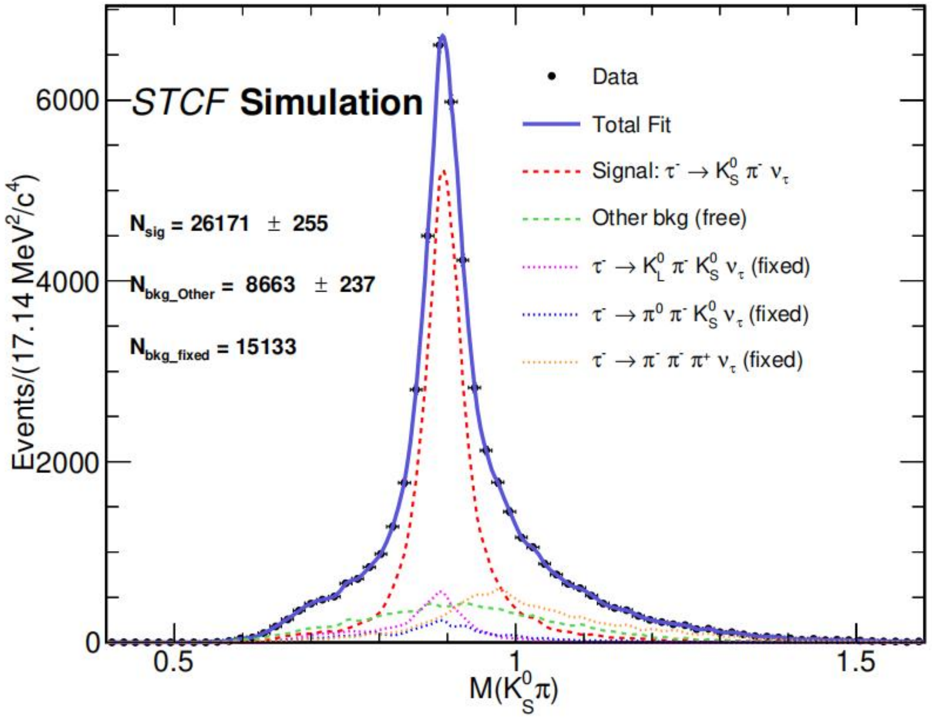
Symbol	Value
$\mathcal{B}(\tau^+ \to e^+ \nu_e \bar{\nu}_\tau)$	$(17.85 \pm 0.04)\%$
$\mathcal{B}(K_S^0 \to \pi^+ \pi^-)$	$(69.20 \pm 0.05)\%$

Branching fraction measurement– $\tau^- \to K_S^0\pi^-\nu_\tau$

Signal Fit

$\sqrt{s}$= 4.260 GeV

- Signal shape: From ditau MC;
- Background shape: From ditau MC;
- Data: ditau MC serve as data.



$$B(\tau^- \to K_S^0\pi^-\nu_\tau) = (4.18 \pm 0.05) \times 10^{-3}$$

Systematic uncertainty– $\tau^- \to K_S^0\pi^-\nu_\tau$

➢ m($K_S^0\pi^-$) fit

- Fixed background — 0.5%

  The fixed background yields are varied according to their branching–fraction uncertainties. PDG uncertainties are used for $\tau^- \to \pi^0 K_S^0\pi^-\nu_\tau$ and $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$, while for $\tau^- \to K_L^0 K_S^0\pi^-\nu_\tau$, a dedicated STCF estimate based on the expected statistical precision of this analysis and an assumed 5% systematic uncertainty is used instead of the current PDG uncertainty (22%).

- Signal shape — 0.1%

  The signal shape in the fit is determined from a signal MC sample generated according to phase space. The corresponding variation in the measured branching fraction is taken as the systematic uncertainty due to signal modeling.

Systematic uncertainty– $\tau^- \to K_S^0 \pi^- \nu_\tau$

Source	Uncertainty (%)
Tracking efficiency	0.2
Particle identification	0.2
K_S^0 reconstruction	0.2
Luminosity	0.1
MC statistics	0.2
Input branching fractions	0.2
Fit for signal shape	0.1
Fit for fixed background	0.5
Total	0.7

CP violation– $\tau^- \to K_S^0 \pi^- \nu_\tau$

- After correcting for the selection efficiency, signal yields from separate fits:

$$N_{\tau^+} = 51029 \pm 746 \qquad N_{\tau^-} = 50594 \pm 749$$

$$A_{CP} = \frac{N_{\tau^+} - N_{\tau^-}}{N_{\tau^+} + N_{\tau^-}} \qquad \delta A_{CP} = \sqrt{\left(\frac{\partial A_{CP}}{\partial N_{\tau^+}}\delta N_{\tau^+}\right)^2 + \left(\frac{\partial A_{CP}}{\partial N_{\tau^-}}\delta N_{\tau^-}\right)^2}$$

- Current sensitivity: δACP = 1.04×10^{-2},
- Projected to 1 ab^{-1} ($1/\sqrt{L}$scaling): δACP ≈ 1.73×10^{-3},
- Projected to 10 ab^{-1} ($1/\sqrt{L}$scaling): δACP ≈ 5.5×10^{-4}

CP violation– $\tau^- \to K_S^0 \pi^- \nu_\tau$

- Systematic uncertainty

Sourece	Absolute Uncertainty
detector	0.04%
fit	0.01%
$K^0/\overline{K}^0$interaction	0.01%
ToTal	0.04%

→ $$\left|\frac{\epsilon_{\tau^-} - \epsilon_{\tau^+}}{\epsilon_{\tau^-} + \epsilon_{\tau^+}}\right| = 0.039\%.$$

→ Estimated from BaBar

Summary– $\tau^- \to K_S^0 \pi^- \nu_\tau$

➢ The integrated comparative results are as follows:

	data volume	Bf ($\times 10^{-3}$)	stat.	sys.
Our work (4.260GeV)	98907000 MC	4.18	0.05(1.20%)	0.03(0.7%)
	Estimated cumulative retrieval 1ab^{-1}	4.18	0.006(0.14%)	0.03(0.7%)
Belle	669 fb^{-1}	4.16	0.01(0.24%)	0.08(1.9%)

Summary– $\tau^- \to K_S^0 \pi^- \nu_\tau$

- The sensitivity to CP violation

	1 ab^{-1}	10 ab^{-1}
Fast Simulation (arXiv:2012.06241)	9.7×10^{-4}	3.1×10^{-4}
Full Simulation (This work) (*35.97 estimate)	1.73×10^{-3}	5.5×10^{-4}

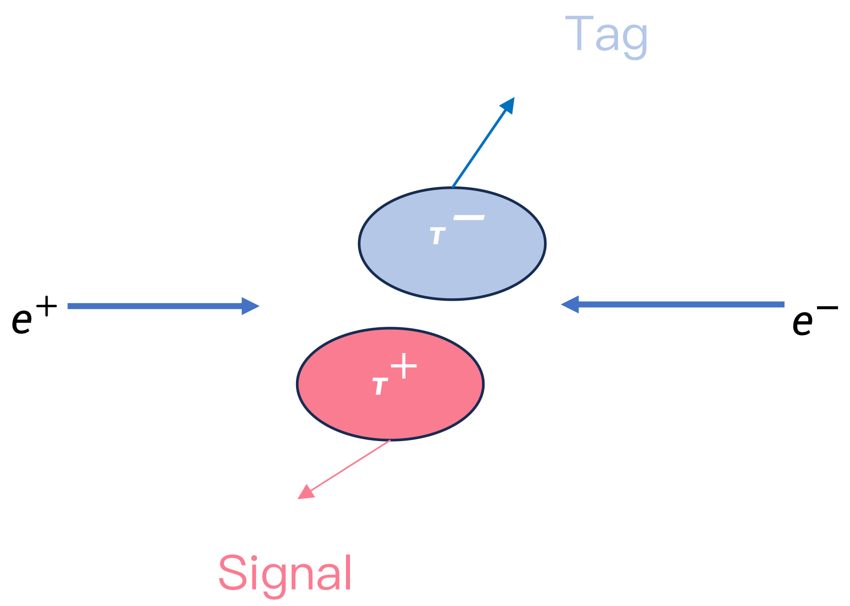
- With its clean $\tau^+\tau^-$ production environment and large integrated luminosity, STCF is expected to reach a sensitivity of $\delta A_{CP}(10\ ab^{-1}) \approx 0.055\%$. Taking into account the systematic uncertainty of 0.04%, this measurement would provide a useful test of the Standard Model prediction.

	$A_{CP}(\%)$
theory	0.33 ± 0.01
BaBar	$-0.36 \pm 0.23(stat) \pm 0.11(sys)$
Belle II	$0.71 \pm 0.26(stat) \pm 0.06(sys) \pm 0.15(unf)$

- Memo is completed.

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

Double tag method– $\tau^- \to \pi^-/K^-\pi^0\nu_\tau$



Tag: $\tau^+ \to e^+\overline{\nu}_\tau\nu_e$
Signal: $\tau^- \to \pi^-/K^-\pi^0\nu_\tau,\ \pi^0 \to \gamma\gamma$

$$B = \frac{N_{\text{sig}}}{2N_{\tau\tau}\varepsilon B(\tau^+ \to e^+\overline{\nu}_\tau\nu_e)B(\pi^0 \to \gamma\gamma)}$$

N_{sig}: Signal yields

$N_{\tau\tau}$: from ditau MC

ε : $\tau^+ \to e^+\overline{\nu}_\tau\nu_{\boldsymbol{e}}$ and $\tau^- \to \pi^-/K^-\pi^0\nu_\tau$ efficiency

Parameter	value	from
$B(\tau^+ \to e^+\overline{\nu}_\tau\nu_{\boldsymbol{e}})$	0.1785±0.0004	PDG
$B(\pi^0 \to \gamma\gamma)$	0.9880±0.00034	PDG

Event selection– $\tau^- \to \pi^-/K^-\pi^0\nu_\tau$

- Charge tracks

V_{xy}<1cm, $|V_z|$ <10cm

cosθ<0.93;

- Photon selection

E_γ> 0.025 GeV in the barrel section

E_γ> 0.050 GeV in the end cap

0 $\leq$ TDC $\leq$ 14(×50ns)

$N_\gamma \geq 2$

- π^0 Reconstruction

χ^2<200(1-c kinematic)

- PID requirement

Using PID system: Global PID

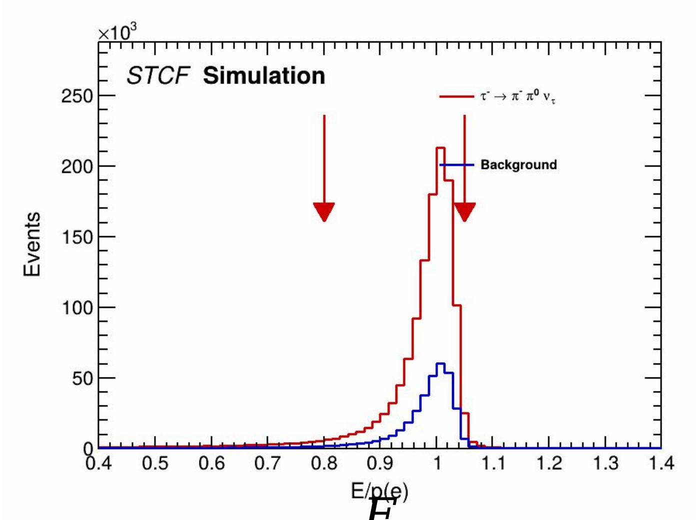
e :$Prob_e$>$Prob_\pi$;$Prob_e > Prob_K$

π :$Prob_\pi$>$Prob_e$;$Prob_\pi > Prob_K$

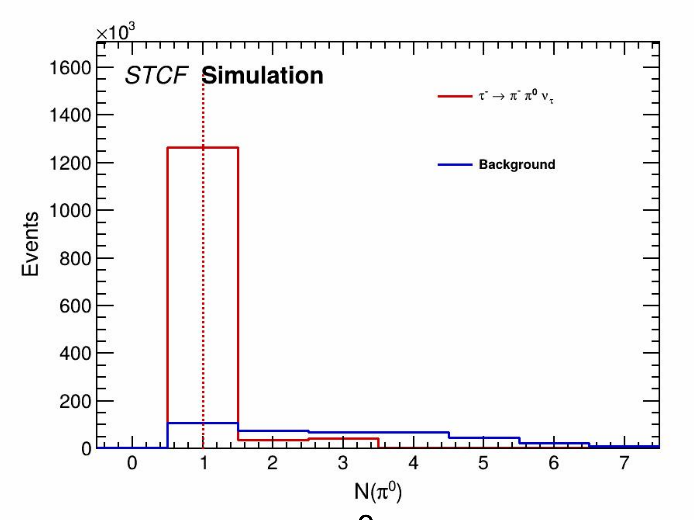
K: $Prob_k$>$Prob_e$;$Prob_k > Prob_\pi$

N_π/N_K =1, $N_e = 1$

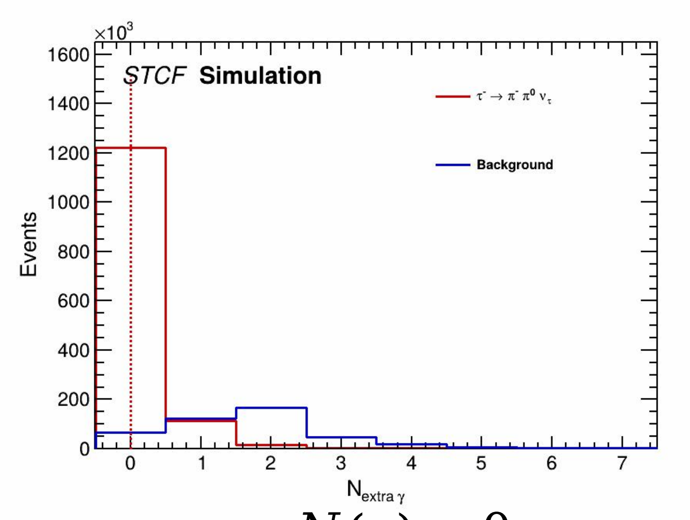
Event selection– $\tau^- \to \pi^-\pi^0\nu_\tau$



$0.8 < \frac{E}{P}(e) < 1.05$



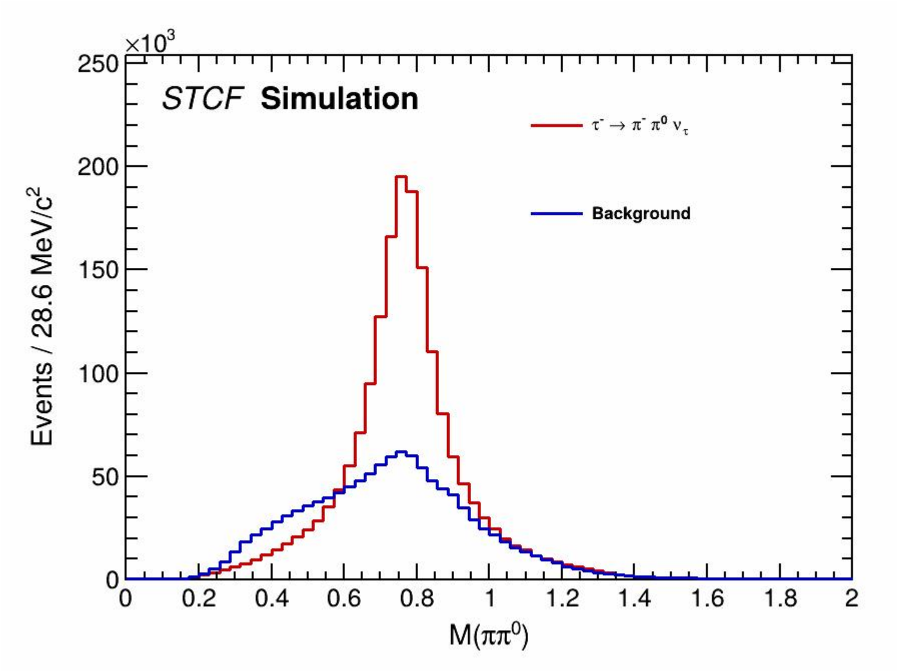
$N(\pi^0) = 1$

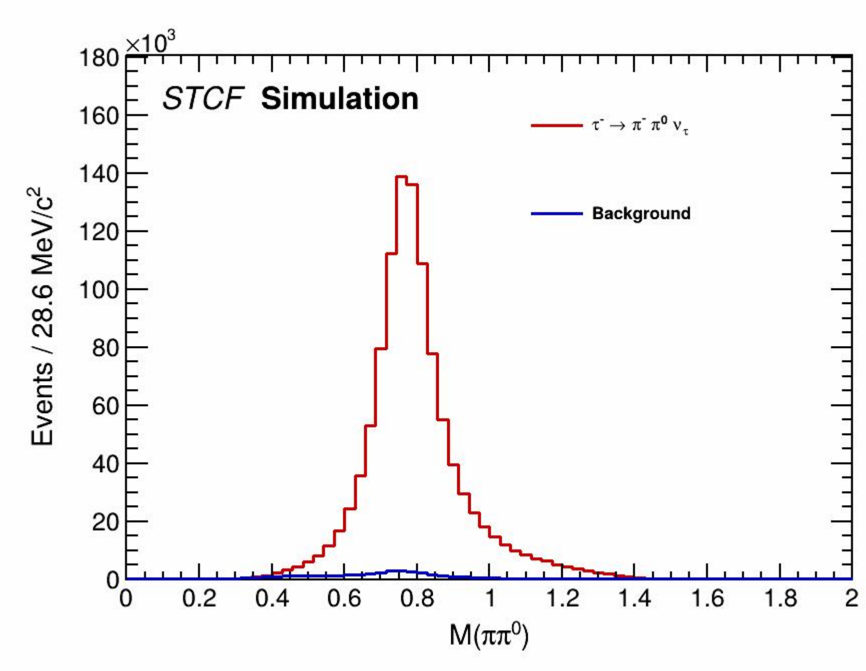


$exN(\gamma) = 0$

Signal selection criteria

At $\sqrt{s} = 4.26\ GeV$, m($\pi^-\pi^0$) is used to identify semileptonic decay, combined tag and signal selection .





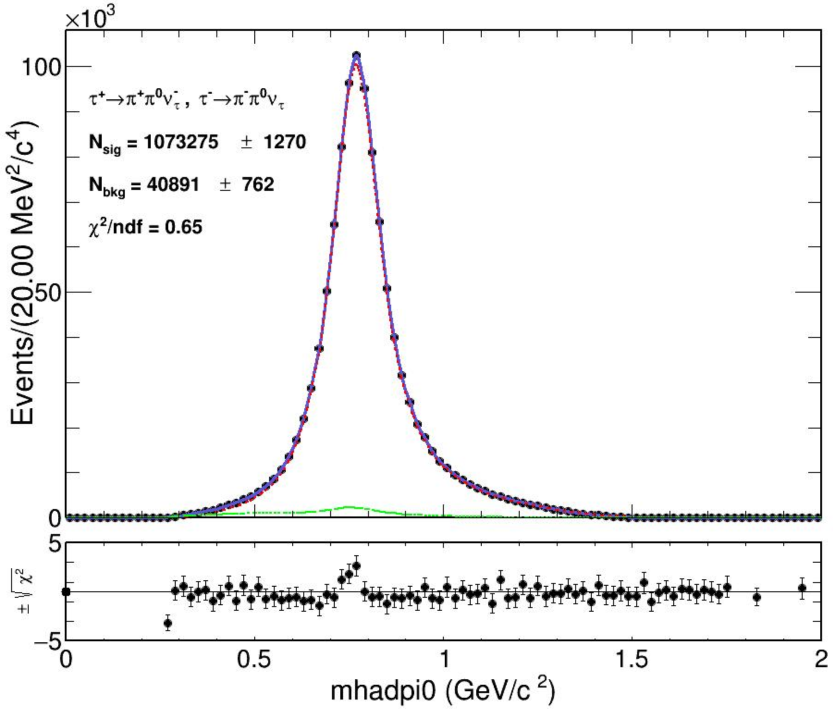
Event selection– $\tau^- \to \pi^-\pi^0\nu_\tau$

	ditau sigMC num	Efficiency	BESIII efficiency	ditau bkgMC num	bkg ratio
No cut	1751478	55.91%	48.3%	1075784	38.05%
0.115< $m(\pi^0)$ <0.15	1353175	43.20%	45.0%	427787	24.02%
$0.8 < \frac{E}{P}(e) < 1.05$	1172780	37.44%	40.8%	335647	22.25%
$N(\pi^0)=1$, $e\,x\,N(\gamma)=0$	1073266	34.26%	31.1%	40943	3.67%

Signal Fit

$\sqrt{s}$= 4.260 GeV

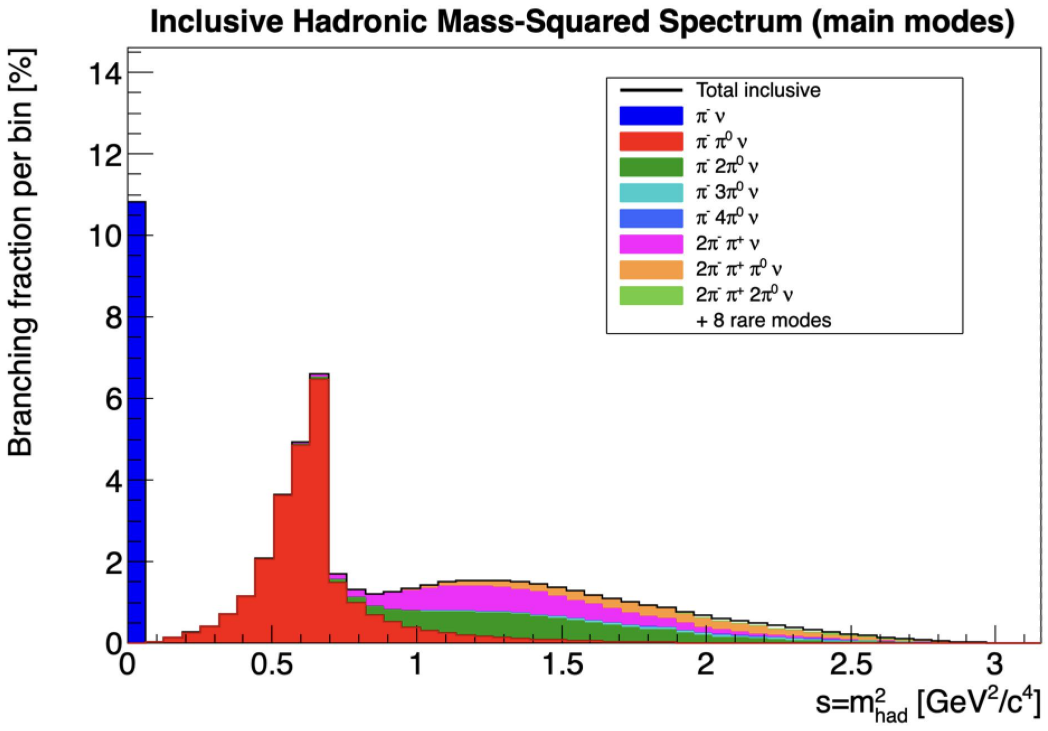
- Signal shape: From ditau MC;
- Background shape: From ditau MC;
- Data: ditau MC serve as data.



$$B(\tau^- \to \pi^-\pi^0\nu_\tau) = (25.43 \pm 0.039)\%$$

Mass spectrum

- The inclusive hadronic mass-squared spectrum is constructed by combining the pion-pole contribution, the unfolded and efficiency-corrected ($\tau^- \to \pi^-\pi^0\nu_\tau$) spectrum, and MC-truth shapes of other hadronic modes normalized to their branching fractions.



The strong coupling constant α_s

- The results are summarized in the following tables. The spectral moments D_{10}, D_{11}, D_{12} and D_{13} are obtained from the inclusive hadronic mass-squared spectrum. Together with the external input of $R_\tau = 3.475 \pm 0.011$, these moments are used in a simultaneous fit to extract the strong coupling constant α_s.

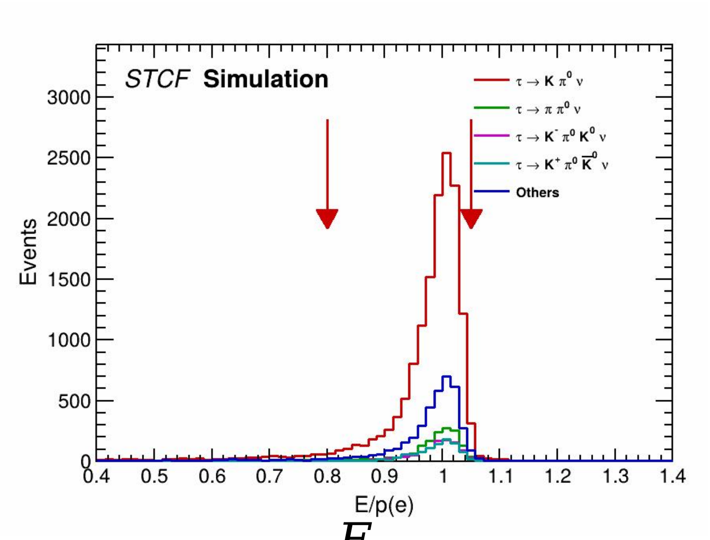
Observable	Current	Projected 1 ab^{-1}
D^{10}	0.714818 ± 0.000094	0.714818 ± 0.000009
D^{11}	0.160603 ± 0.000027	0.160603 ± 0.000003
D^{12}	0.059314 ± 0.000023	0.059314 ± 0.000002
D^{13}	0.026843 ± 0.000016	0.026843 ± 0.000002
$\alpha_s(m_\tau^2)$	0.32036 ± 0.00863	0.32036 ± 0.00862

The strong coupling constant α_s

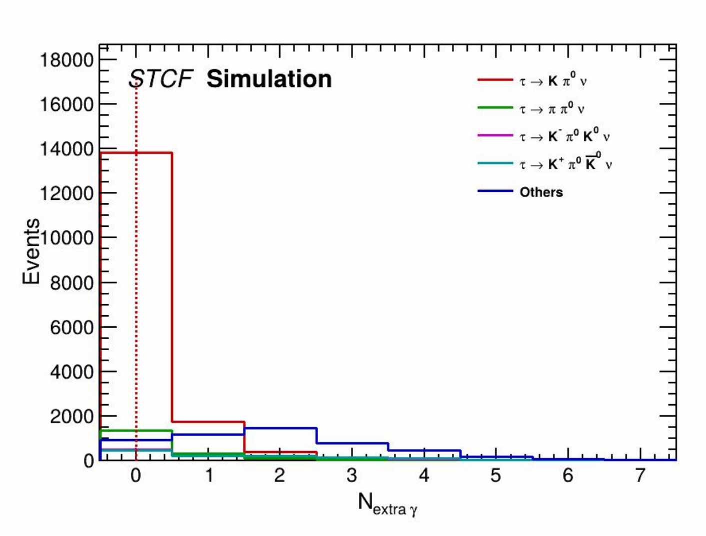
- The fit includes perturbative QCD contributions, non-perturbative OPE corrections, and the theoretical covariance matrix. For the projected 1ab^{-1} STCF sample, the result is summarized in the following tables.

Source	Current	Projected 1 ab^{-1}
Inclusive spectrum shape statistics	0.000099	0.000010
External R_τ input	0.00413	0.00413
Theory covariance	0.00757	0.00757
Total	0.00863	0.00862

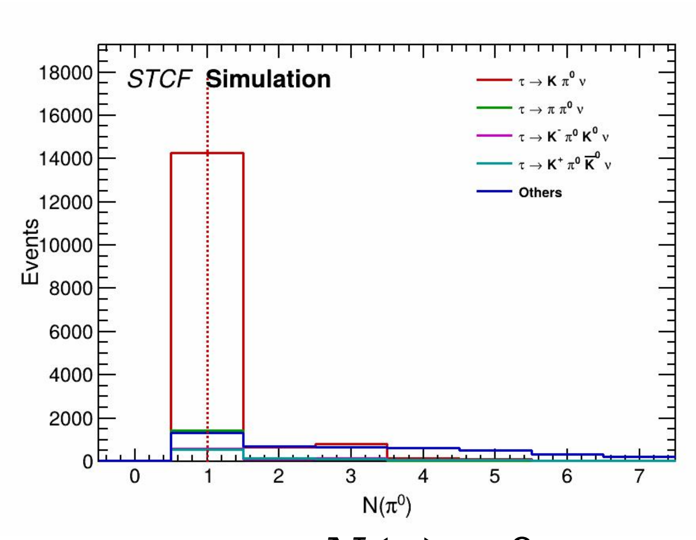
Event selection– $\tau^- \to K^-\pi^0\nu_\tau$



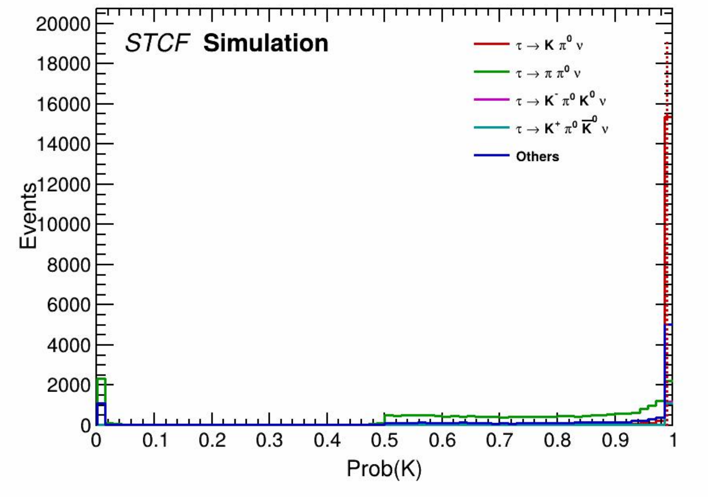
$0.8 < \frac{E}{P}(e) < 1.05$



$N(\pi^0) = 1$



$exN(\gamma) = 0$

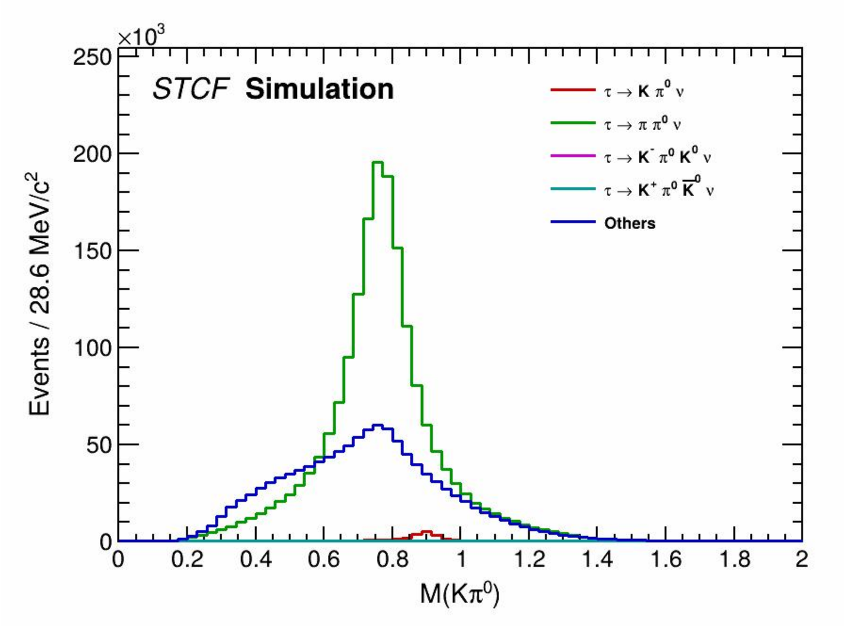


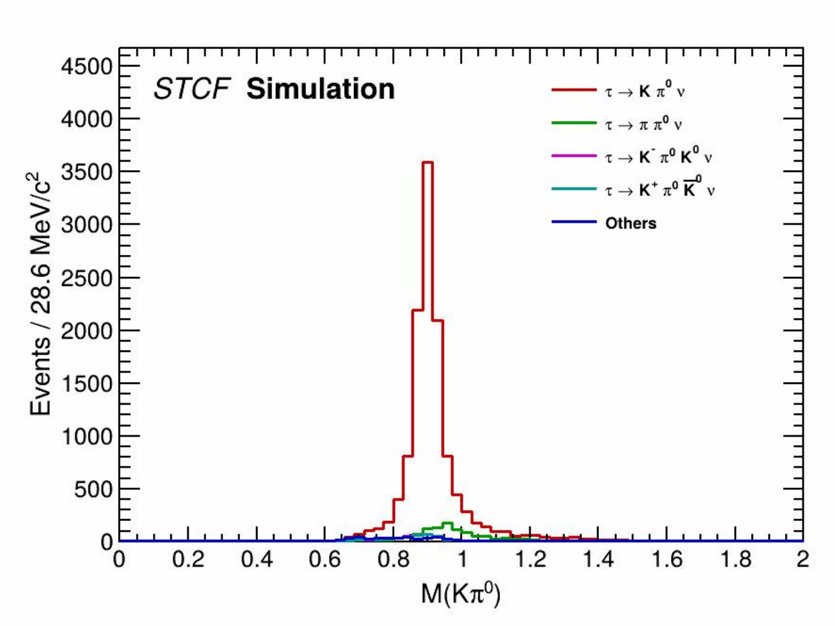
prob(k)>0.99

Event selection– $\tau^- \to K^-\pi^0\nu_\tau$

Signal selection criteria

At $\sqrt{s} = 4.26\ GeV$, m($K^-\pi^0$) is used to identify semileptonic decay, combined tag and signal selection .





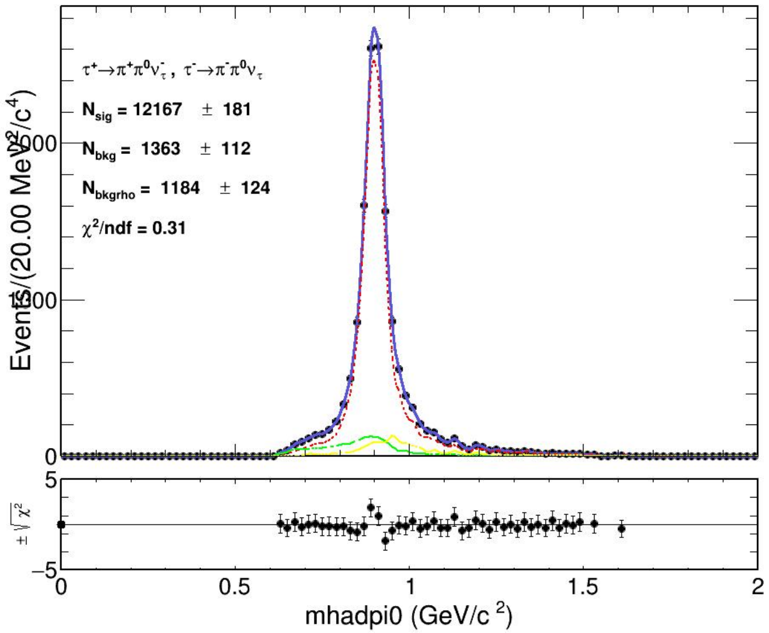
Event selection– $\tau^- \to K^-\pi^0\nu_\tau$

	ditau sigMC num	Efficiency	BESIII efficiency	ditau bkgMC num	bkg ratio
routine cut	24534	46.50%	41.7%	78707	76.24%
$0.115 < m(\pi^0) < 0.15$	17558	33.28%	37.9%	37936	68.36%
$0.8 < \frac{E}{P}(e) < 1.05$	15230	28.87%	34.3%	31192	67.19%
$N(\pi^0) = 1,\ e x N(\gamma) = 0$	13219	25.06%	22.3%	18473	58.29%
prob(k)>0.99	12166	23.06%		2550	17.33%

Signal Fit

$\sqrt{s}$= 4.260 GeV

- Signal shape: From ditau MC;
- Background shape: From ditau MC;
- Data: ditau MC serve as data.



$$B(\tau^- \to K^-\pi^0\nu_\tau) = (4.28 \pm 0.075) \times 10^{-3}$$

Summary

➢ The integrated comparative results are as follows:

$\tau^- \to \pi^-\pi^0\nu_\tau$	data volume	Bf(%)	stat.	input sys./sys.
This work	34,985,000 ditau MC	25.43	0.039(0.15%)	0.058(0.23%)
	Estimated cumulative retrieval 1ab^{-1}	25.77	0.0034(0.01%)	0.058(0.23%)
ALEP	155 pb^{-1}	25.47	0.097(0.38%)	0.085(0.33%)
Belle	72.2 fb^{-1}	25.24	0.01(0.04%)	0.39(1.55%)
$\tau^- \to K^-\pi^0\nu_\tau$	data volume	Bf(10^{-3})	stat.	input sys./sys.
This work	34,985,000 ditau MC	4.28	0.075(1.8%)	0.010(0.23%)
	Estimated cumulative retrieval 1ab^{-1}	4.28	0.005(0.12%)	0.010(0.23%)
BABR	230.2 fb^{-1}	4.16	0.03(0.72%)	0.18(4.33%)
ALEP	155 pb^{-1}	4.71	0.59(12.53%)	0.23(4.88%)
CLEO	3.5 fb^{-1}	4.44	0.26(5.86%)	0.24(5.41%)

Summary

- For the STCF projection, the total uncertainty is obtained by combining theprojected inclusive-spectrum statistical uncertainty, the external R_τ input uncertainty, and the theory covariance in quadrature. The projected spectrum-shape statistical uncertainty alone is 1×10^{-5} and is much smaller than the R_τ and theory uncertainties.

Experiment / Analysis	$\alpha_s(m_\tau^2)$	Remark
ALEPH (1998)	0.334 ± 0.022	$V + A$ moments
OPAL (1998)	$0.348 \pm 0.009_{\mathrm{exp}} \pm 0.019_{\mathrm{th}}$	CIPT
ALEPH update (2007)	$0.345 \pm 0.004_{\mathrm{exp}} \pm 0.009_{\mathrm{th}}$	updated analysis
STCF projection	$0.32036 \pm 0.00001_{\mathrm{stat}} \pm 0.00413_{R_\tau} \pm 0.00757_{\mathrm{th}}$	this work

Thanks for your attention！