Study on the process of

$\tau^- \to a_1(1260)^- \upsilon_\tau \to \rho^0 \pi^- \upsilon_\tau \to \pi^+ \pi^- \pi^- \upsilon_\tau$

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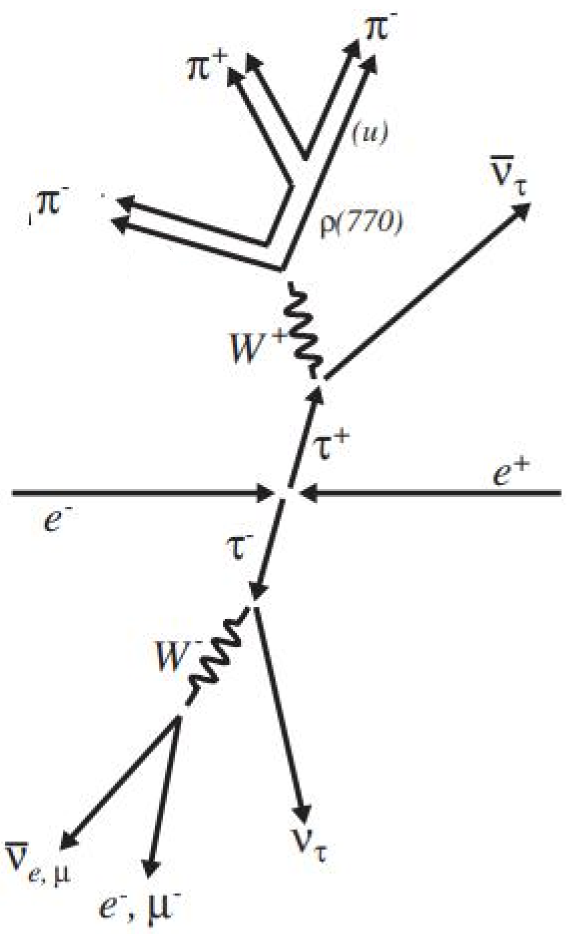
Motivation

- The branching fraction of the $\tau^- \rightarrow \pi^+\pi^-\pi^-\upsilon_\tau$ process from PDG is $(9.31 \pm 0.05)\%$, provided by HFLAV (Heavy Flavor Averaging Group).
- The measurement of the resonance parameters of $a_1(1260)^-$ using the charmonium decays suffers a lot from the high background, while this issue can be effectively avoided via the decay $\tau^- \rightarrow \pi^+\pi^-\pi^-\upsilon_\tau$, providing a unique opportunity for the $a_1(1260)^-$ relevant measurements.



Motivation

- Theoretical prediction ($\tau^- \to \pi^- \rho^0 \nu_\tau$)
  - S-wave: 7.68×10^{-2}
  - P-wave: 3.90×10^{-3}
- Mechanism is not clear.
- Comparison between experiment and theroy helps reveal the hadronization mechanism of W boson[1].

[1]Phys.Rev.D 99 (2019) 1, 016021

Datasets

- Boss version: 7.0.9
- Data sample: 2.7 billion $\psi(2S)$ events (2009+2012+2021)
- Inclusive MC sample: 2.7 billion $\psi(2S)$ events (2009+2012+2021)
- Signal MC sample: 3M events (09:12:21=4:13:83)

Decay	Generator
$\psi(2S) \to \tau^+\tau^-$	PHOTOS VLL
$\tau^+ \to e^+ \bar{\upsilon}_\tau \upsilon_e$	PHOTOS TAULNUNU
$\tau^- \to a_1^- \upsilon_\tau$	PHSP
$a_1^- \to \rho^0\pi^-$	PHSP
$\rho^0 \to \pi^+ \pi^-$	VSS

Event selection

◆ Charged track

- $|V_r| < 1cm, |V_z| < 10cm;$
- $|cos\theta| < 0.93;$
- $N_{good} = 4;$
- $N_{\pi^+} = 1, N_{\pi^-} = 2, N_{e^+} = 1;$

◆ Neutral track (to veto events with additional π^0)

- Barrel: $E > 25MeV, |cos\theta| < 0.8$;

  Endcap: $E > 50MeV, 0.86 < |cos\theta| < 0.92$;
- $0 < T_{Emc} < 14$;
- $\theta(\gamma, trk) > 10°;$
- $N_\gamma = 0;$

◆ PID pion:

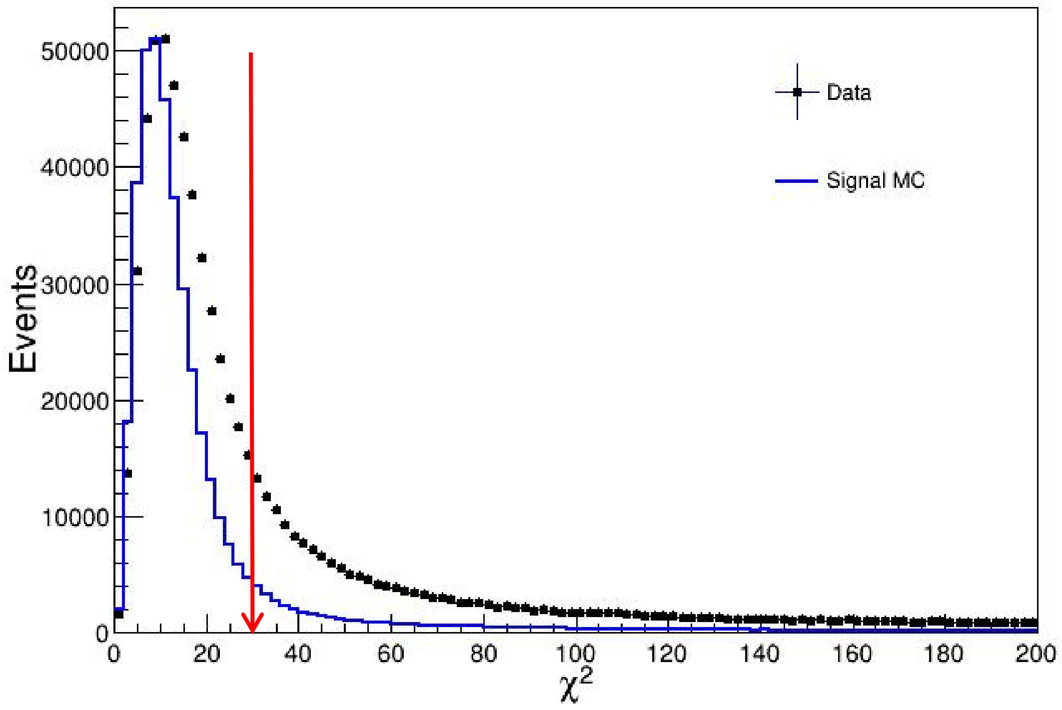
- $Prob_\pi > 0.001;$
- $Prob_\pi > Prob_e \& Prob_\pi > Prob_\mu \& Prob_\pi > Prob_K \& Prob_\pi > Prob_p;$

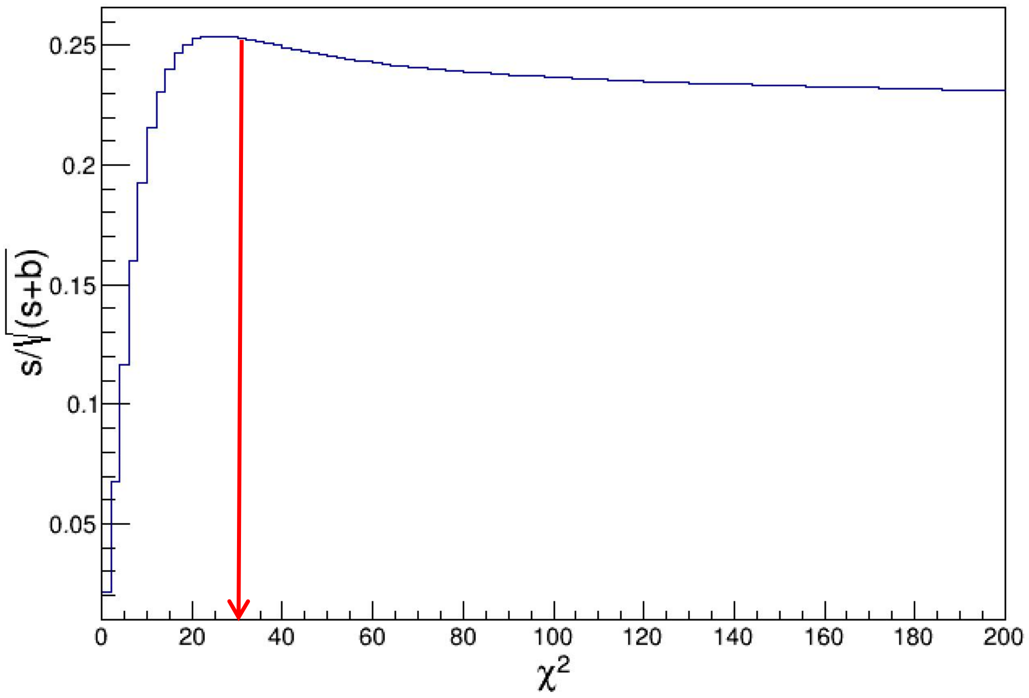
◆ PID electron:

- $0.8 < E/p < 1.2;$
- $Prob_e > 0.001;$
- $Prob_e > Prob_\pi \& Prob_e > Prob_\mu \& Prob_e > Prob_K \& Prob_e > Prob_p;$

Event selection

➢ vertex fit ($\pi^+\pi^-\pi^-e^+$): $\chi^2 < 30$





The figure illustrates the selection and optimization of χ^2

Background analysis

Inclusive MC after all selections:

Table 1: Decay trees and their respective initial-final states.

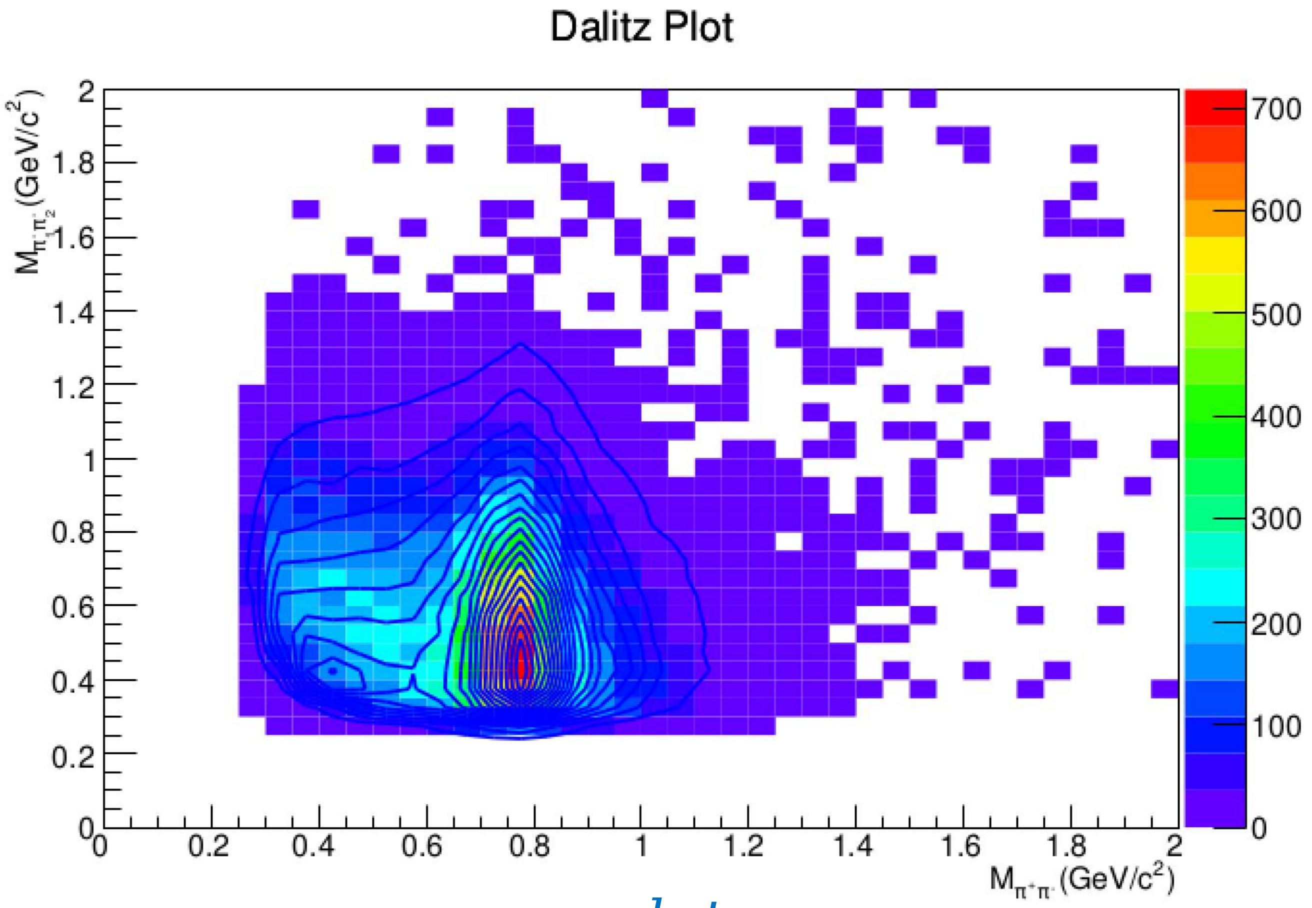
rowNo	decay tree (decay initial-final states)	iDcyTr	iDcyIFSts	nEtr	nCEtr
1	$\psi' \to \tau^+\tau^-, \tau^+ \to e^+\nu_e\bar{\nu}_\tau, \tau^- \to \nu_\tau\pi^+\pi^-\pi^-$ $(\psi' \dashrightarrow e^+\nu_e\nu_\tau\bar{\nu}_\tau\pi^+\pi^-\pi^-)$	0	0	9503	9503
2	$\psi' \to \tau^+\tau^-, \tau^+ \to e^+\nu_e\bar{\nu}_\tau, \tau^- \to \nu_\tau\pi^-\omega, \omega \to \pi^0\pi^+\pi^-$ $(\psi' \dashrightarrow e^+\nu_e\nu_\tau\bar{\nu}_\tau\pi^0\pi^+\pi^-\pi^-)$	33	8	48	9551
3	$\psi' \to \tau^+\tau^-, \tau^+ \to e^+\nu_e\bar{\nu}_\tau, \tau^- \to \nu_\tau\pi^-\bar{K}^0, \bar{K}^0 \to K^0_S, K^0_S \to \pi^+\pi^-$ $(\psi' \dashrightarrow e^+\nu_e\nu_\tau\bar{\nu}_\tau\pi^+\pi^-\pi^-)$	1	0	43	9594
4	$\psi' \to \tau^+\tau^-, \tau^+ \to e^+\nu_e\bar{\nu}_\tau, \tau^- \to \nu_\tau\pi^0\pi^+\pi^-\pi^-$ $(\psi' \dashrightarrow e^+\nu_e\nu_\tau\bar{\nu}_\tau\pi^0\pi^+\pi^-\pi^-)$	10	8	41	9635
5	$\psi' \to \tau^+\tau^-, \tau^+ \to e^+\nu_e\bar{\nu}_\tau, \tau^- \to \nu_\tau\pi^-\omega, \omega \to \pi^+\pi^-$ $(\psi' \dashrightarrow e^+\nu_e\nu_\tau\bar{\nu}_\tau\pi^+\pi^-\pi^-)$	14	0	32	9667
6	$\psi' \to \pi^+\pi^-J/\psi, J/\psi \to \pi^+\pi^-n\bar{n}$ $(\psi' \dashrightarrow \pi^+\pi^+\pi^-\pi^-n\bar{n})$	65	25	21	9688
7	$\psi' \to \tau^+\tau^-, \tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau, \tau^- \to \nu_\tau\pi^+\pi^-\pi^-$ $(\psi' \dashrightarrow \mu^+\nu_\mu\nu_\tau\bar{\nu}_\tau\pi^+\pi^-\pi^-)$	11	9	19	9707
8	$\psi' \to \tau^+\tau^-, \tau^+ \to \bar{\nu}_\tau\pi^+\pi^+\pi^-, \tau^- \to \nu_\tau\pi^-$ $(\psi' \dashrightarrow \nu_\tau\bar{\nu}_\tau\pi^+\pi^+\pi^-\pi^-)$	37	14	18	9725
9	$\psi' \to \pi^+\pi^-J/\psi, J/\psi \to e^+e^-$ $(\psi' \dashrightarrow e^+e^-\pi^+\pi^-)$	21	15	17	9742
10	$\psi' \to \pi^+\pi^-J/\psi, J/\psi \to \pi^0\rho^0, \rho^0 \to \pi^+\pi^-$ $(\psi' \dashrightarrow \pi^0\pi^+\pi^+\pi^-\pi^-)$	70	7	16	9758
11	$\psi' \to \chi_{c0}\gamma, \chi_{c0} \to \pi^+\pi^+\pi^-\pi^-$ $(\psi' \dashrightarrow \pi^+\pi^+\pi^-\pi^-\gamma)$	6	4	15	9773
12	$\psi' \to \pi^+\pi^-J/\psi, J/\psi \to \pi^+\pi^+\pi^-\pi^-$ $(\psi' \dashrightarrow \pi^+\pi^+\pi^+\pi^-\pi^-\pi^-)$	17	13	14	9787
13	$\psi' \to \pi^+\pi^-J/\psi, J/\psi \to \pi^+\Delta^-\bar{n}, \Delta^- \to \pi^-n$ $(\psi' \dashrightarrow \pi^+\pi^+\pi^-\pi^-n\bar{n})$	77	25	14	9801
14	$\psi' \to \pi^+\pi^+\pi^-\pi^-K^+K^-$ $(\psi' \dashrightarrow \pi^+\pi^+\pi^-\pi^-K^+K^-)$	12	3	13	9814
15	$\psi' \to \pi^+\pi^-J/\psi, J/\psi \to \pi^+\rho^-, \rho^- \to \pi^0\pi^-$ $(\psi' \dashrightarrow \pi^0\pi^+\pi^+\pi^-\pi^-)$	9	7	12	9826
16	$\psi' \to \pi^0\pi^+\pi^+\pi^-\pi^-$ $(\psi' \dashrightarrow \pi^0\pi^+\pi^+\pi^-\pi^-)$	66	7	11	9837
17	$\psi' \to \chi_{c0}\gamma, \chi_{c0} \to \rho^0\pi^+\pi^-, \rho^0 \to \pi^+\pi^-$ $(\psi' \dashrightarrow \pi^+\pi^+\pi^-\pi^-\gamma)$	20	4	10	9847

- Total: 10213 events
- Signal: 9503 events

  (the highlighted green part)

Background: 6.95%

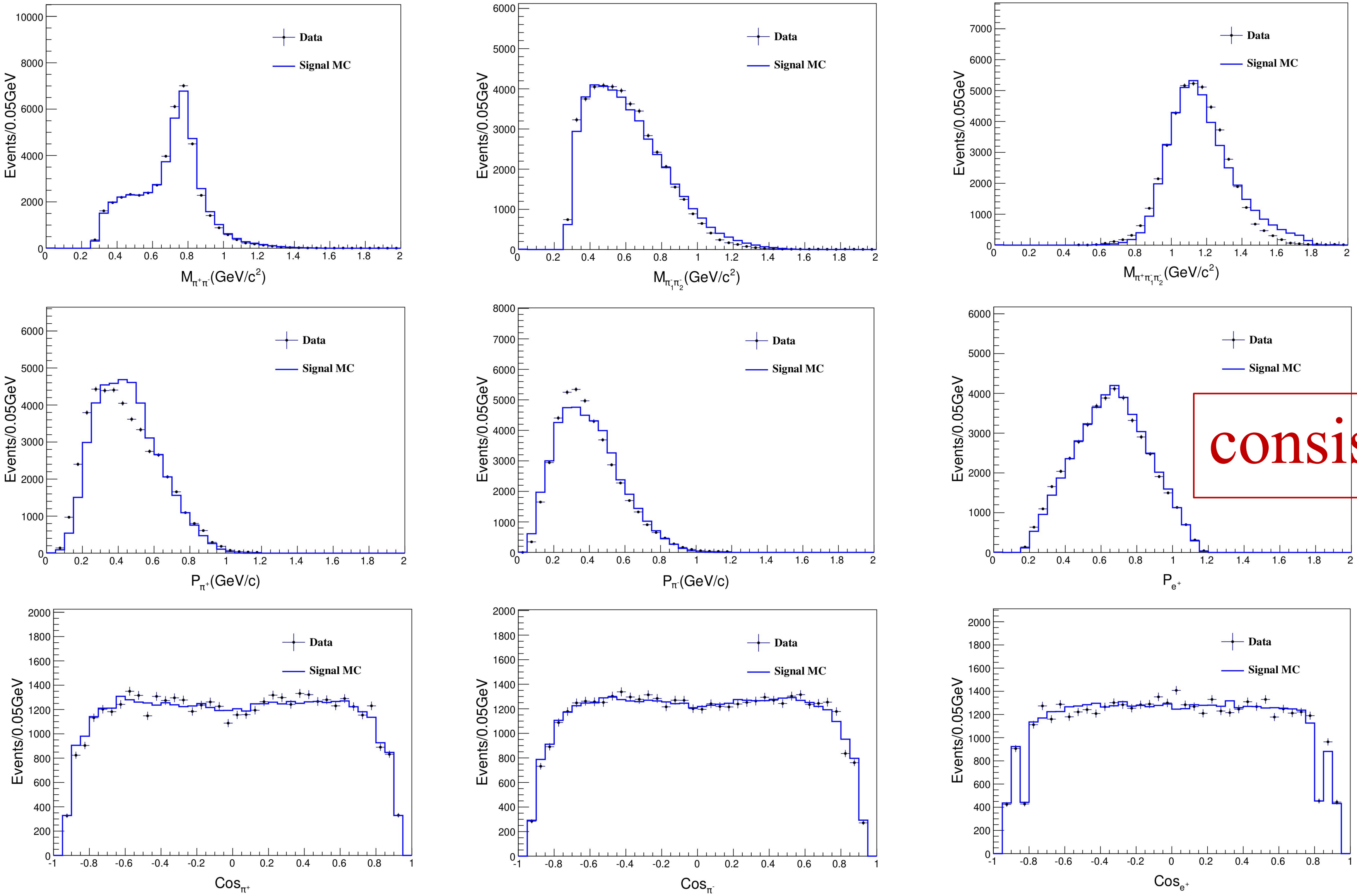
MC reweight



$$\frac{data}{signal\ mc}$$

Signal MC sample is reweighted into the data according to the Dalitz plot to obtain the correct efficiency.

Comparison of data and MC (after reweight)



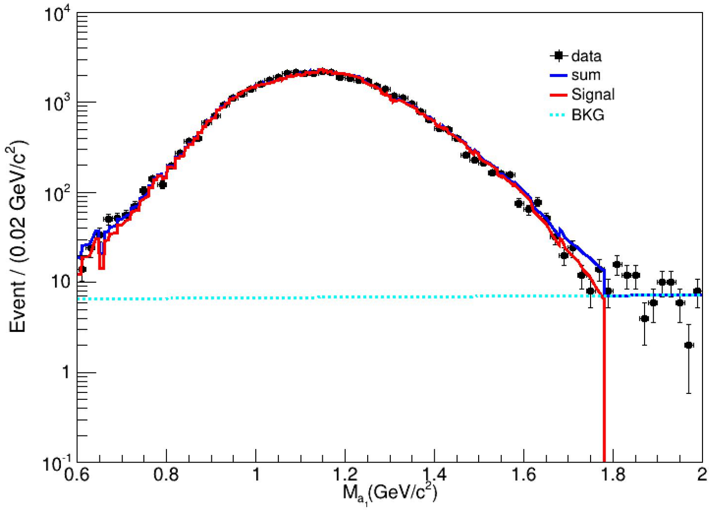
consistent well

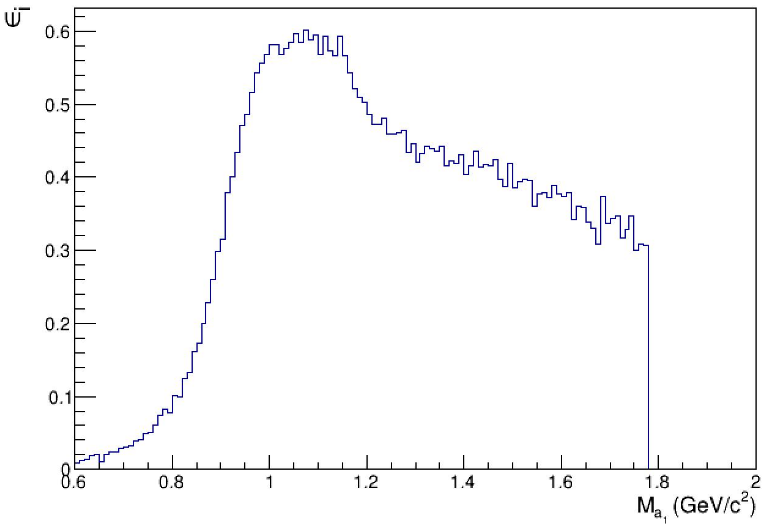
MC efficiency

criteria	events	efficiency
total events	3000000	100%
good charged tracks	1987252	66.24%
PID, $\boldsymbol{N_\pi = 3, N_e = 1}$	712183	23.74%
verterx fit	681774	22.73%
$\boldsymbol{N_\gamma = 0}$	254496	8.48%
$\boldsymbol{\chi^2_{vertex\,fit} \leq 30}$	210041	7%

The cut flow shown in this table is unreweighted, the total efficiency of signal MC is 7%. And the reweighted total efficiency of signal MC is 6.93%.

Fitting result





The results are obtained by fitting invariant mass spectrum of $\pi^+\pi^-\pi^-$

PDF:

- Signal: $\varepsilon_i \times ffc \times |BW + C_0 PHSP|^2$
- Background: 1st Chebyshev polynomial
- $N_{fit}=(2.154 \pm 0.015) \times 10^4$ events

$$\varepsilon_i = \frac{m_{rec(3\pi)}}{m_{truth(3\pi)}} \qquad ffc(form\ factor) = e^{-\frac{|s-m_0^2|}{\Lambda^2}} \quad (\Lambda = 1)^{[2]}$$

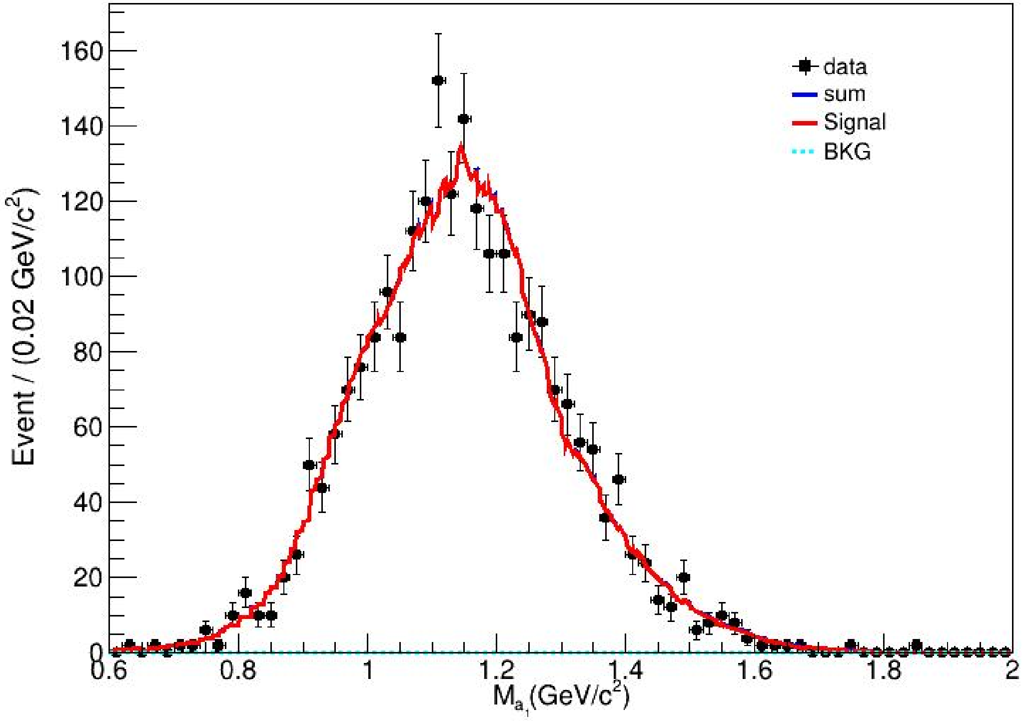
$$PHSP = \frac{\sqrt{[s-(m_{\rho(1450)}+m_\pi)^2][s-(m_{\rho(1450)}-m_\pi)^2]}}{2\sqrt{s}}$$

$$BW = \frac{g^2}{m_0^2-s-im_0\Gamma(s)}, \Gamma(s) = \Gamma_0\left(\frac{q(s)}{q(m_0^2)}\right)^{2L+1}\frac{m_0}{\sqrt{s}}F_L^2(q) \quad (L=0\ \ F_L=1)^{[3]}$$

[2]CPC(HEP & NP), 2009, 33(8): 617—621
[3]Phys.Rev.D 98 (2018) 9, 092003

QED contribution

QED contribution is normalized from 3.65 GeV



PDF:

- Signal: $\varepsilon_i \times ffc \times |BW + C_0 PHSP|^2$
- Background: 1st Chebyshev polynomial
- $N_{fit} = 1188$ events
- $N_{QED} = N_{fit} \times \frac{\mathcal{L}_{3686}}{\mathcal{L}_{3650}} = (1.123 \times 10^4)$ events

  $(\mathcal{L}_{3686} = 3877\ \mathrm{pb}^{-1}; \mathcal{L}_{3650} = 410\ \mathrm{pb}^{-1})$

Measurement

	This work	PDG
Br	$(\quad \pm 0.04)\%$ $(\tau^- \to a_1(1260)^-\upsilon_\tau \to \rho_0\pi^-\upsilon_\tau \to \pi^+\pi^-\pi^-\upsilon_\tau)$	$(9.31 \pm 0.05)\%$ $(\tau^- \to \pi^+\pi^-\pi^-\upsilon_\tau)$
Pole $M_{a_1(1260)}$	$(\quad \pm 0.9)\ MeV/c^2$	$(1.23 \pm 0.04)\ GeV/c^2$
Pole $\Gamma_{a_1(1260)}$	$(\quad \pm 1.0)\ MeV$	$(0.38 \pm 0.08)\ GeV$

Pole $M_{a_1(1260)}$、$\Gamma_{a_1(1260)}$:

$$m_0^2 - s - im_0\Gamma(s) = 0\,; \quad pole = m - \frac{\Gamma}{2}i$$

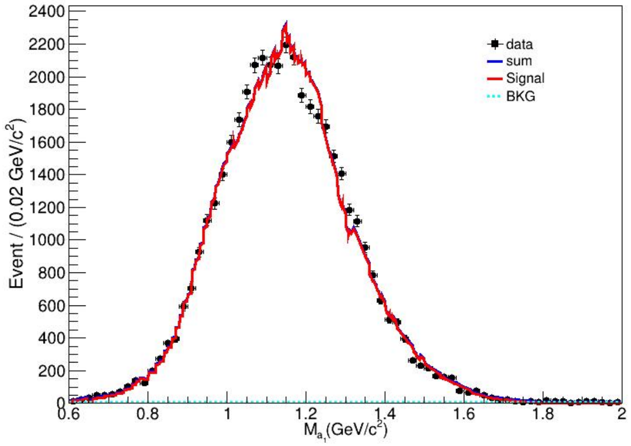
Systematic uncertainty

- Tracking efficiency — 4.00% (1% per track)
- $\psi(2S)$ total number — 0.50%
- PID — 4.00% (1% per track)
- Branching fraction (PDG/arXiv:2502.19850) — 12.91% / 3.22%

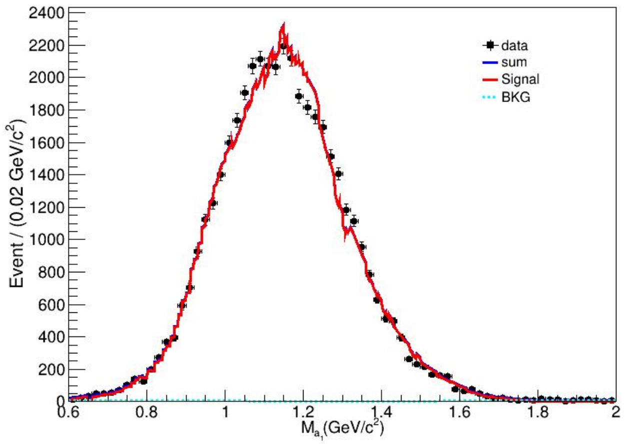
  $(\psi(2S) \to \tau^+\tau^-; \tau^+ \to e^+\upsilon_e\bar{\upsilon}_\tau)$
- MC statistics $\sqrt{(1-\epsilon)/N\epsilon}$ — 0.21%
- Weight $\frac{\epsilon-\epsilon_{weight}}{\epsilon}$ — 0.10%

Systematic uncertainty

Background shape



1^{st} Chebyshev polynomial

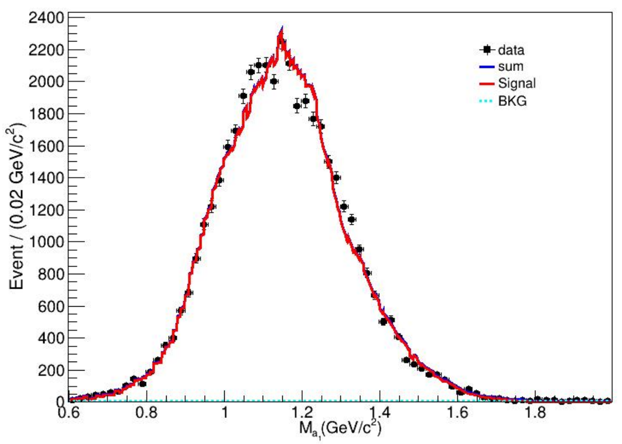


2^{nd} Chebyshev polynomial

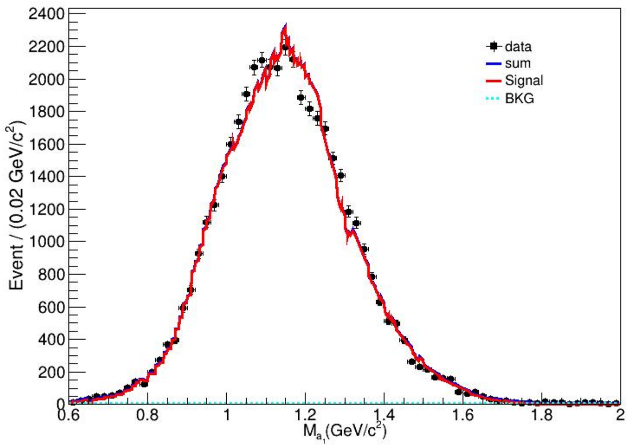
Background shape	1^{st}	2^{nd}
N_{sig}	21541	21595
Branching fraction	(9.50 ± 0.04)%	(9.55 ± 0.04)%
Uncertainty	0.53%	
$M_{a_1(1260)}$	$1.211 GeV/c^2$	$1.212 GeV/c^2$
Uncertainty	0.08%	
$\Gamma_{a_1(1260)}$	$0.426 GeV$	$0.427 GeV$
Uncertainty	0.23%	

Systematic uncertainty

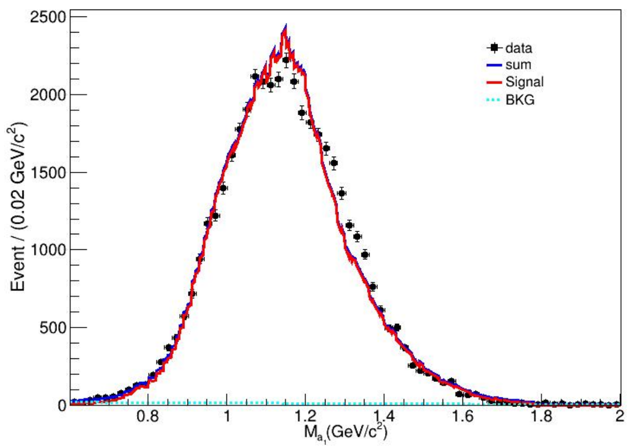
$\pi^+\pi^-\pi^-$ fitting range



(0.598,1.998)



(0.600,2.000)



(0.602,2.002)

Fitting Range	(0.598,1.998)	(0.6,2.0)	(0.602,2.002)
N_{sig}	21556	21541	21528
Branching fraction	$(9.51 \pm 0.04)\%$	$(9.50 \pm 0.04)\%$	$(9.49 \pm 0.04)\%$
Uncertainty	0.15%		
$M_{a_1(1260)}$	$1.214GeV/c^2$	$1.211GeV/c^2$	$1.211GeV/c^2$
Uncertainty	0.30%		
$\Gamma_{a_1(1260)}$	0.430GeV	0.426GeV	0.425GeV
Uncertainty	0.41%		

Systematic uncertainty

Branching fraction

Source	Uncertainty(%)
Tracking efficiency	4.00
$\psi(2S)$ total number	0.50
PID	4.00
Branching fraction(PDG/arXiv:2502.19850) ($\psi(2S) \to \tau^+\tau^-; \tau^+ \to e^+\nu_e\bar{\nu}_\tau$)	12.91/3.22
MC statistics	0.21
Weight	1.00
Background shape	0.53
Fitting range	0.15
Total	14.15/6.6

Systematic uncertainty

$M_{a_1(1260)}$

Source	Uncertainty(%)
Background	0.08
Fitting range	0.30
Total	0.31

$\Gamma_{a_1(1260)}$

Source	Uncertainty(%)
Background	0.23
Fitting range	0.41
total	0.47

Summary & Next to do

[4]Phys.Rev.D 99 (2019) 1, 016021

- The branching fraction of the decay $\tau^- \to a_1(1260)^-\upsilon_\tau \to \rho^0\pi^-\upsilon_\tau \to \pi^+\pi^-\pi^-\upsilon_\tau$ has been measured preliminary.

  $PDG: Br(\tau^- \to a_1(1260)^-\nu_\tau \to \rho^0\pi^-\nu_\tau \to \pi^+\pi^-\pi^-\nu_\tau) = ($[redacted]$\pm 0.04 \pm 1.34)\%$

  $arXiv: 2502.19850: Br(\tau^- \to a_1(1260)^-\nu_\tau \to \rho^0\pi^-\nu_\tau \to \pi^+\pi^-\pi^-\nu_\tau) = ($[redacted]$\pm 0.04 \pm 0.63)\%$

- The mass and width of $a_1(1260)$ has been measured preliminary.

  $M_{a_1(1260)} = ($[redacted]$\pm 0.9 \pm 3.8) MeV/c^2$; $\Gamma_{a_1(1260)} = ($[redacted]$\pm 1.0 \pm 2.0) MeV$

- For $\tau \to \pi\rho^0\nu_\tau$ process, we found $\tau^- \to \pi^-\rho^0\nu_\tau$ happens mostly through the process $\tau^- \to a_1(1260)^-\nu_\tau \to \rho^0\pi^-\nu_\tau \to \pi^+\pi^-\pi^-\nu_\tau$. By measuring the branching fraction of this process and comparing it with the theoretical prediction, $\tau \to \pi\rho^0\nu_\tau$ is more consistent with the *S*-wave assumption[4].

	s-wave production	p-wave production
Br	7.68×10^{-2}	3.90×10^{-3}

Next to do:

- Further study background
- Further study systematic uncertainty
- Consider the charge conjugated channel
- Prepare the memo

Thanks!