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Disclaimer: Following results are preliminary

Tau Physics at CEPC

ALPs x Flavor Crossover Edition

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(QCD) Axion



Strong CP Problem: Measurement of neutron EDM $\implies \bar{\theta} < 10^{-10}$

Possible solution: Make $\bar{\theta}$ dynamical Breaking $U(1)_{PQ}$ symmetry (at energy scale f_a) gives pNGB (axion)

Extension: Invisible axion (KSVZ, DFSZ) when $f_a \gg \Lambda_{\rm EW}$.

Additionally: DM candidate!

Axion-Like Particles (ALPs)

QCD Axion is quite constrained!

Class of similar models (ALPs):

- pNGB from breaking of global symmetry, enjoy $a \rightarrow a + \text{const.}$
 - Global lepton number symmetry → Majoron
 - Global family symmetry → Familon

Pheno: Interesting effect with Flavor Physics(?)

ALP-Lepton interactions (@ Z-pole)



ALP-Tau interactions

Theoretically:

- BSM (more likely) has greater impact on heavy states.
- Larger event yields (compared with electron, muon)

[See 2006.04795]

for simplicity we neglected the mass of the final-state lepton

$$\Gamma(\ell_i \to \ell_j a) = \frac{1}{16\pi} \frac{m_{\ell_i}^3}{F_{\ell_i \ell_j}^2} \left(1 - \frac{m_a^2}{m_{\ell_i}^2}\right)^2$$

$$F_{\ell_i \ell_j} = \frac{2f_a}{\sqrt{|C_{\ell_i \ell_j}^V|^2 + |C_{\ell_i \ell_j}^A|^2}}$$

[See 2212.02818]

$$\sigma(e^+e^- \rightarrow \ell^+\ell^-a)$$

$$\ell = e \qquad 7.1 \times 10^{-9} \text{ pb}$$

$$\ell = \mu \qquad 7.6 \times 10^{-5} \text{ pb}$$

$$\ell = \tau \qquad 1.1 \times 10^{-2} \text{ pb}$$

LO cross sections of signal (for $f_a/C_{\ell\ell}^A = 100$ GeV, $m_a = 10^{-6}$ GeV)

ALP-Tau interactions

Phenomenologically (@CEPC):

Many tau naire	Particle	Belle II	CEPC $(4 \times \text{Tera-}Z)$
· Marry lau pairs	$ au^{\pm}$	$4.5 \times 10^{10} (50 \text{ ab}^{-1} \text{ on } \Upsilon(4S))$	$1.2 imes 10^{11}$

- More boosted tau pairs (vs B factories) from $Z \rightarrow \tau^+ \tau^-$
- Excellent tracking for tau 3-prongs decay $\tau^{\pm} \rightarrow \pi^{\pm}\pi^{\pm}\pi^{\mp}\nu$ (or 5-prongs).
- ALP-Electron/Muon can be done in other experiments, ALP-Tau is unique opportunity for CEPC!

Sim. & Vertex Reco.



- Pythia \rightarrow Delphes (IDEA card)
- Vertexing is VERY importance here
 - Need to fit the tau decay vertex!
 - Using delphes/external/TrackCovariance/VertexFit.cc

Can do more realistic vertexing with fast simulation!

Sim. & Vertex Reco. Nowadays

Simple assumption: Fast but not super realistic

(e.g. manually smear the truth level vertex)



Full simulation: Sophisticated but time-consuming





Can do more realistic vertexing with fast simulation!

Can vary detector parameters Can study detector design!

Relevant part in the detector card:

delphes/cards/delphes_card_IDEA.tcl

barrel	name	zmin	zmax	r	w (m)	X0	n_meas	th_up (rad)	th_down (rad)	reso_up (m)	reso_down (m)	flag
1	PIPE	-100	100	0.01	0.00235	0.35276	0	0	0	0	0	0
1	VTXLOW	-0.0965	0.0965	0.012	0.00028	0.0937	2	0	1.5708	3.00E-06	3.00E-06	1
1	VTXLOW	-0.1609	0.1609	0.02	0.00028	0.0937	2	0	1.5708	3.00E-06	3.00E-06	1
1	VTXLOW	-0.2575	0.2575	0.031525	0.00028	0.0937	2	0	1.5708	3.00E-06	3.00E-06	1
1	VTXLOW	-0.1609	0.1609	0.15	0.00028	0.0937	2	0	1.5708	3.00E-06	3.00E-06	1
1	VTXHIGH	-0.3263	0.3263	0.315	0.00047	0.0937	2	0	1.5708	7.00E-06	7.00E-06	1
1	DCHCANI	-2.125	2.125	0.345	0.0002	0.237223	0	0	0	0	0	0
1	DCH	-2	2	0.36	0.014775	1400	1	0.0203738	0	0.0001	0	1
1	DCH	-2	2	0.374775	0.014775	1400	1	-0.0212097	0	0.0001	0	1

Pheno (Off Diagonal Channel)



Off Diagonal Channel (cLFV)

Extra theoretical interest of cLFV: [See 2006.04795]

• Current cLFV searches ($\mu \rightarrow e\gamma, \tau \rightarrow \ell\gamma, \mu \rightarrow eee, \tau \rightarrow \ell\ell\ell, ...$) are related to dim-6 operators $\implies BR \sim 1/\Lambda^4$

• ALPs searches ($\mu \rightarrow ea, \tau \rightarrow \ell a$)

are relates to dim-5 operators \implies BR $\sim 1/f_a^2$

Off Diagonal Channel (cLFV)

Constraints:

- T_{Tag} decay vertex
- (assuming) PV=0
- Z boson 2 body decay
- т on-shell
- Energy momentum conversation (assuming no ISR)

Can solve:

4-momentum $p(\tau_{Sig})$, thus p(a)



$$q^2 \equiv (p_{\tau_{\rm Sig}} - p_\ell)^2$$









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$$q^2 \equiv (p_{\tau_{\rm Sig}} - p_\ell)^2$$





The narrower the peak, the better the constraints

But how to understand the resolution here?

More Realistic Collider Picture





More Realistic Collider Picture





Pheno (Diagonal Channel)



Diagonal Channel (radiation)

Constraints:

- T_{Tag,1}, T_{Tag,2} decay vertices
- (assuming) PV=0
- т on-shell
- Energy momentum conversation (assuming no ISR)

Can solve:

4-momenta $p(T_{Tag,1})$, $p(T_{Tag,2})$, thus p(a)

More advanced methods: χ^2 fit, Machine Learning







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Take Home Message



- ALPs are nice <u>hypothetical</u> particle but still no evidence yet.
- ALP-Lepton gives interesting pheno.
 - Especially ALP-Tau
- CEPC is a unique playground and can put strong limit.

Backup

Some Features of the Exclusion Limit



Some Features of the Exclusion Limit



Some Features of the Exclusion Limit





