EDM and anomalous magnetic moment of tau at CEPC

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The 2019 International Workshop on the High Energy CEPC

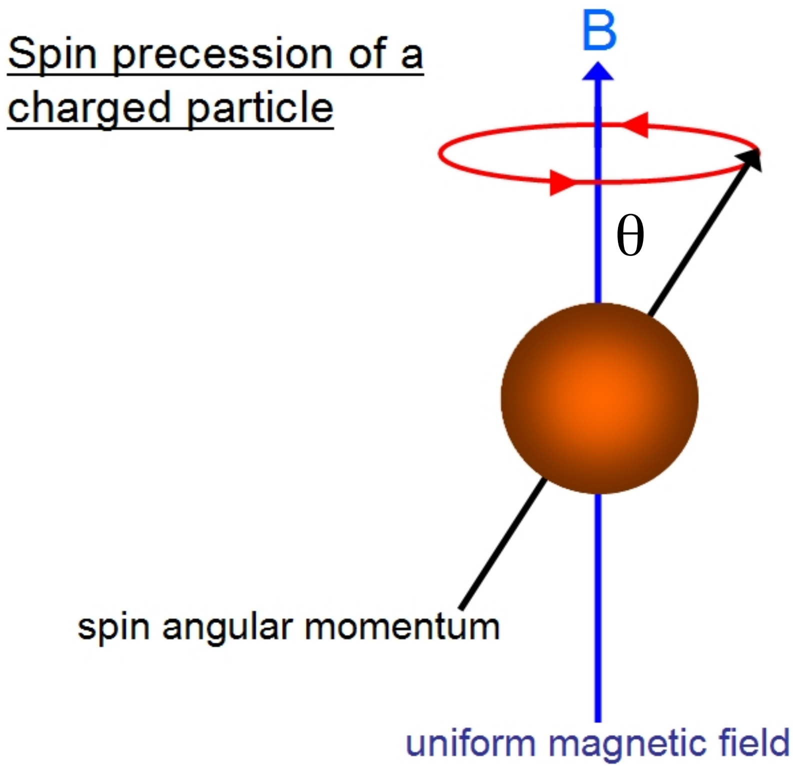
11/18-20, 2019, IHEP, Beijing

Outline

- Introduction and current best results
- Track impact parameters and neutrino reconstruction
- Matrix element extraction of BSM and OO distributions
- Expected sensitivities
- Theoretical constraints
  - ✓ Constraints on a mirror neutrino
  - ✓ Constraints on a light scalar
- Summary

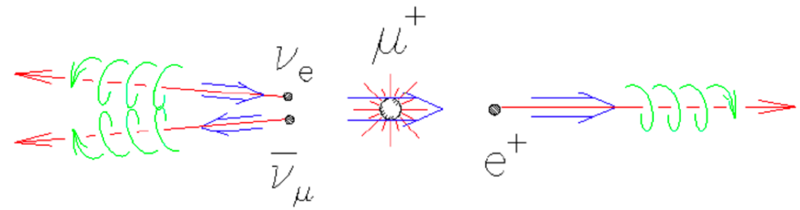
Anomalous magnetic moment (g-2)

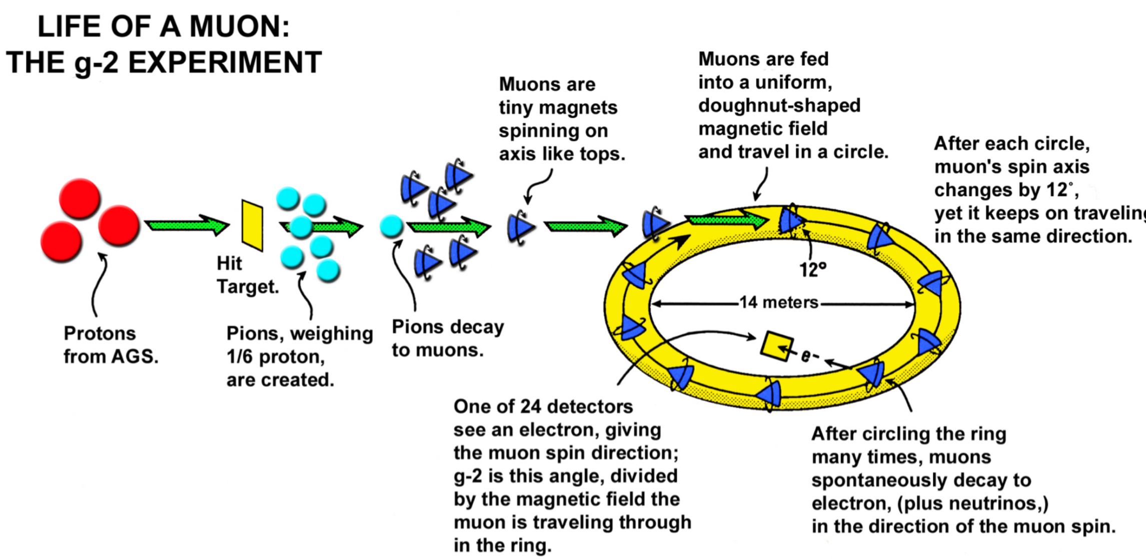
$$\frac{d}{dt}\vec{S} = \frac{1}{i\hbar}\overline{\left[\hat{\vec{S}}, \hat{H}\right]} = gB\hat{\vec{S}}\times\vec{e}_B = \vec{\mu}_s \times \vec{B}$$



Muon (g-2)


g-2 muon storage ring


ν_e
μ^+
e^+
$\bar{\nu}_\mu$


LIFE OF A MUON:
THE g-2 EXPERIMENT
Protons from AGS.
Hit Target.
Pions, weighing 1/6 proton, are created.
Pions decay to muons.
Muons are tiny magnets spinning on axis like tops.
Muons are fed into a uniform, doughnut-shaped magnetic field and travel in a circle.
After each circle, muon's spin axis changes by 12°, yet it keeps on traveling in the same direction.
12°
14 meters
e-
One of 24 detectors see an electron, giving the muon spin direction; g-2 is this angle, divided by the magnetic field the muon is traveling through in the ring.
After circling the ring many times, muons spontaneously decay to electron, (plus neutrinos,) in the direction of the muon spin.

EDM

- CP violation is a necessary condition for baryogenesis, a process leading to matter-antimatter imbalance in the universe. If extra BSM CP violation enters the lepton-photon-lepton vertex, the lepton can possess an Electric Dipole Moment (EDM), which in EFT form:

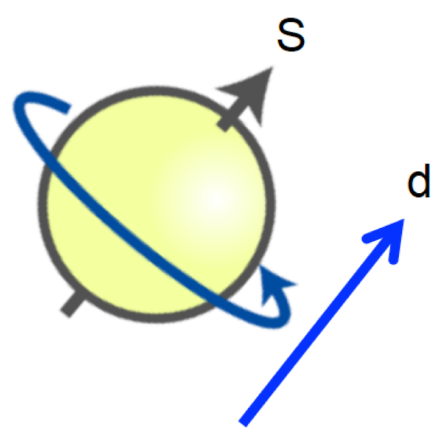
$$\Gamma^{\mu}_{d_\ell}(q^2) = ie\frac{\sigma^{\mu\nu}q_\nu}{2m_\ell}F_3^{NP}(q^2)\gamma^5$$

  where Λ is the BSM energy scale much larger than the experiment reach so that terms of the order q^2/Λ^2 can be neglected in the Wilson coefficient

- In the nonrelativistic limit, this operator can be reduced to

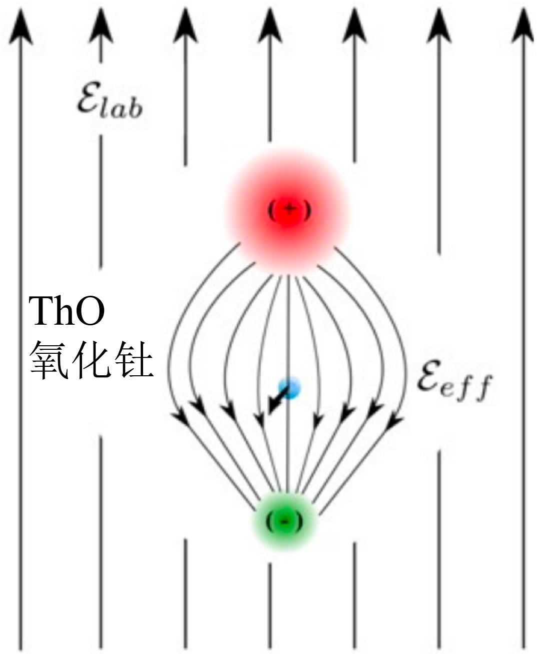
$$\mathcal{L}_{d_\ell} = d_\ell \chi_\ell^\dagger \vec{\sigma}\chi_\ell \cdot \vec{E},$$

  which gives a lepton EDM aligned with its spin



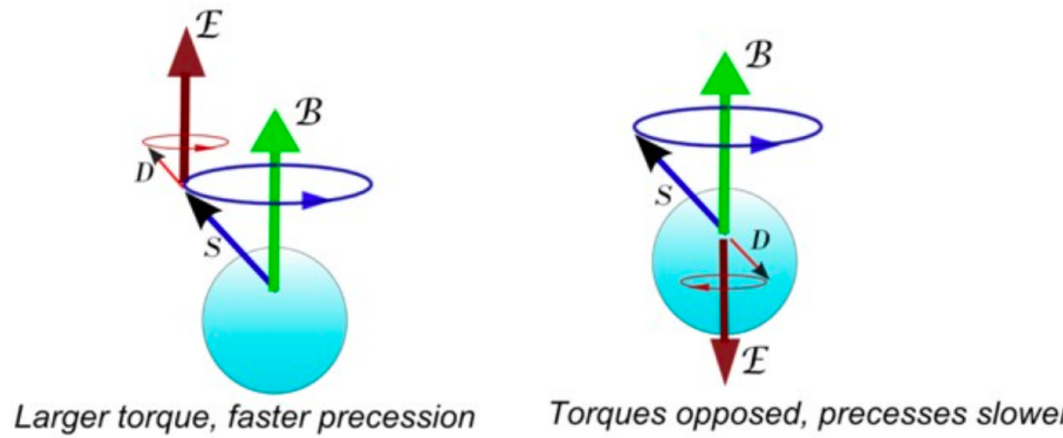
- In SM, electron EDM is at a level of $\sim 10^{-38}$ e·cm, way smaller than the sensitivity of any experiment, e.g., ACME

Electron EDM



$\boldsymbol{\varepsilon}_{\mathrm{eff}} \sim 78$ GV/cm

EDM can change electron precession frequency (Larmor frequency)



Best electron EDM limit from ACME-II [Harvard, Nature 562 (2018) 355]: $|d_e| < 1.1 \times 10^{-29} e\,\mathrm{cm}$

Tau EDM and g-2

- The EDM operator is closely related to another one which gives the anomalous magnetic moment in case of CP conservation:

$$\Gamma^{\mu}_{a_\ell}(q^2) = -e\frac{\sigma^{\mu\nu}q_\nu}{2m_\ell}F_2^{NP}(q^2)$$

where $a_\ell = (g-2)/2$. The muon g-2 measured by BNL is ~3.6σ deviation from SM:

$$\Delta a_\mu(\exp. - \mathrm{SM}) = (2.87 \pm 0.8) \times 10^{-9}$$ [arXiv:1311.2198]

- If BSM exists in the lepton sector, tau lepton is an ideal test case, since it is expected to couple more strongly to BSM

- Unlike electrons or muons whose EDM or g-2 can be detected though spin precession effect, tau lepton is highly unstable (decays as soon as it is produced). Use electron-positron colliders where tau pairs are copiously produced via virtual photon: $e^+e^- \to \tau^+\tau^-$

- Detect BSM through loop diagrams, and through its interference with the SM process – high statistics is needed. Experiments: current or future tau factories such as CEPC, super tau-charm, Belle-II…

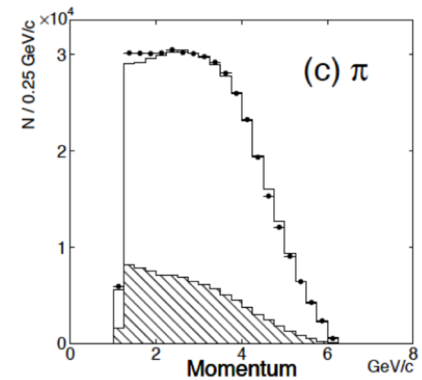
Current best measured results

- The current best measurements of a_τ and d_τ are from Belle and DELPHI

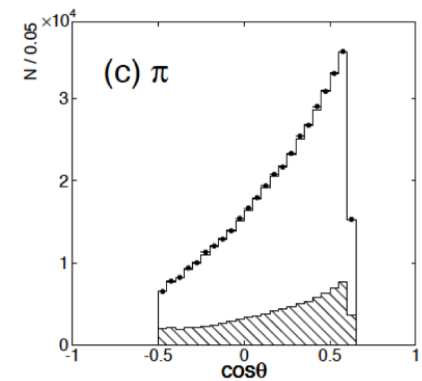
$$-2.2 < \Re(d_\tau) < 4.5\ (10^{-17}\mathrm{e\cdot cm}), \qquad \text{Belle}$$

$$-0.052 < a_\tau < 0.013. \qquad \text{DELPHI}\ \ \mathrm{e^+e^- \to e^+e^-\tau^+\tau^-}$$

[EPJC 35 (2004) 159]



[Phys. Lett. B551 (2003) 16]



To be compared to theory:

$$a_\tau = 117721(5) \times 10^{-8},$$ [Mod.Phys.Lett. A22 (2007) 159]

which is an order of magnitude more precise than the measurement

- The Belle measurement tried to detect the interference effect of effective d_τ with the SM process using the optimal observable (OO [Phys. Lett. B306,1993, 411]). Since the neutrinos from tau decays are not detected, the OO is calculated by averaging all possible kinematic configurations

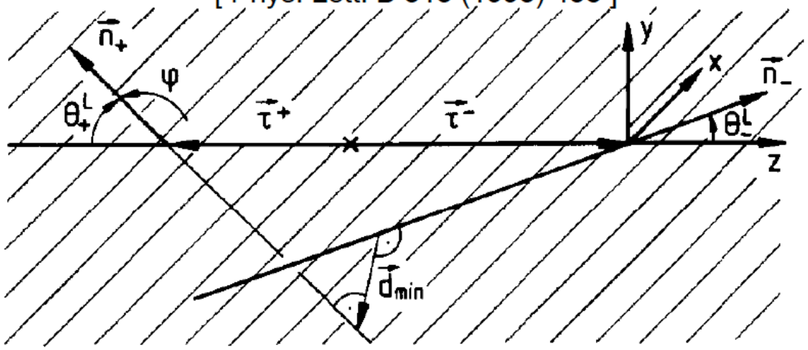
$$\mathcal{M}^2_{\rm prod} = \mathcal{M}^2_{\rm SM} + Re(d_\tau)\mathcal{M}^2_{Re} + Im(d_\tau)\mathcal{M}^2_{Im} + |d_\tau|^2\mathcal{M}^2_{d^2},$$

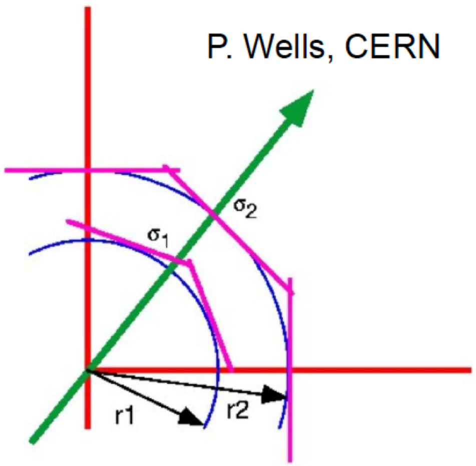
$$\mathcal{O}_{Re} = \frac{\mathcal{M}^2_{Re}}{\mathcal{M}^2_{\rm SM}}$$

Measurements at e^+e^- colliders

- It has been shown that neutrinos can be reconstructed, and the ambiguity in the solutions can be resolved with impact parameters of tracks from tau decay:

[Phys. Lett. B 313 (1993) 458]





$$\sigma^2(d_0) = \frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}$$

- The advancement in silicon trackers over the last few decades has significantly improved the resolutions on the precision of tracking and the impact parameters. The relevant parameters for Belle-II:

[arXiv:1011.0352]

mm	a	b
d_0	0.015	0.007
z_0	0.020	0.010

Multiple scattering introduces also p_T dependence:

$$a \oplus b/(p_T \sin\theta^{1/2})$$

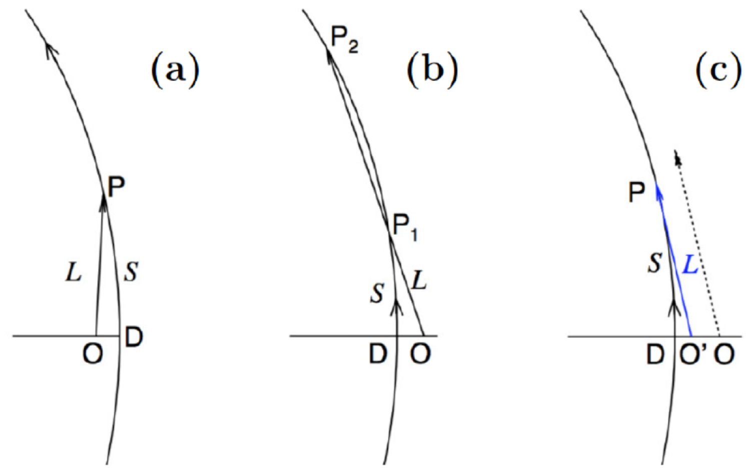
Measurements at e^+e^- colliders

- We try to improve the previous ideas to reconstruct the neutrino from hadronic tau decays

- Deal with either asymmetric (Belle-II) or symmetric (BESIII, CEPC) beam energy. The ISR/FSR effect can deviate the back-to-back topology. In addition, the interaction point (IP) is hard to get in ditau final states
- The resolution of tracking (p_T and direction) and impact parameters, can render null or wrong solutions, which has to be addressed
- The impact parameters, not only can resolve the ambiguity in solutions, but can also improve the reconstruction of the neutrinos. This is tried at hadron colliders as well
- The neutrinos (combined) from leptonic tau decays can be also reconstructed, but not for each of them and the unknown degrees of freedom have to be integrated out

The impact parameters

- We consider the impact parameters as extra auxiliary measurements of the tau flight diections
- If no intersection between tau flight direction and track trajectory, it is assumed to be due to resolution effect and translated to the tangential position



[EPJC 77 (2017) 697]

- When there are two interactions (solutions), both are checked which gives the smallest χ^2

$$\chi^2_{\mathrm{IP}} = \left(\frac{d_0^{\mathrm{fit}} - d_0}{\sigma_{d_0}}\right)^2 + \left(\frac{z_0^{\mathrm{fit}} - z_0}{\sigma_{z_0}}\right)^2$$

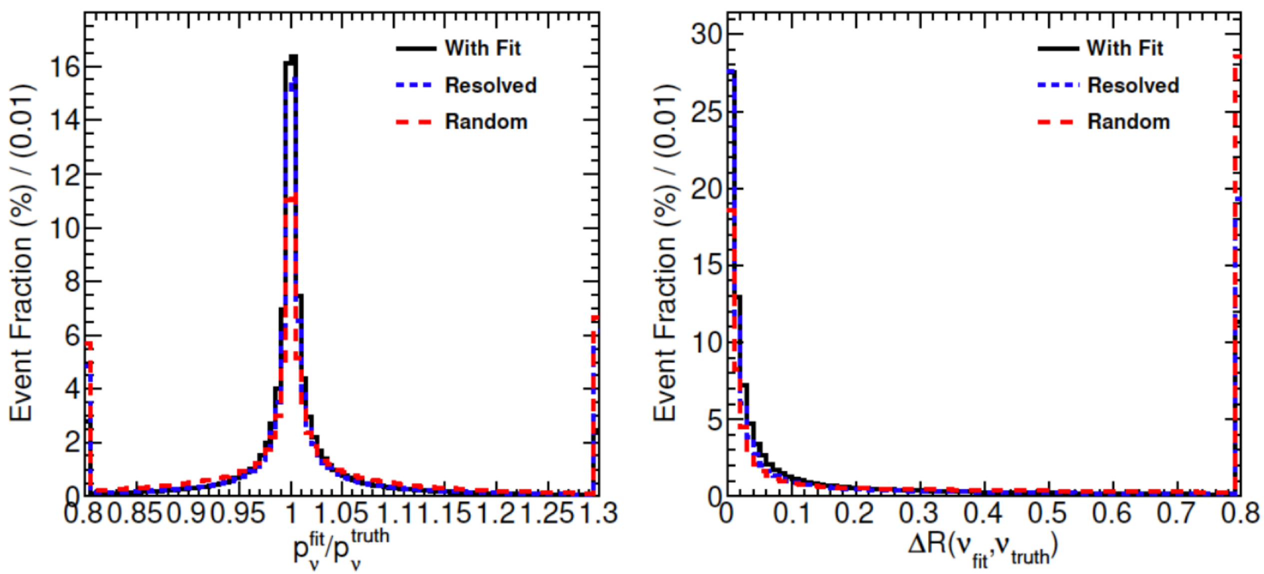
- Once the intersection point is found in the transverse plane, the z_0 can be extrapolated: $z_0^{\mathrm{fit}} = L \sinh \eta_\tau - S \sinh \eta_{\mathrm{track}}$

  This can be compared with the original measured z_0 as an auxiliary measurement

Neutrino momentum

[JHEP 10 (2019) 089]

- The momenta of neutrinos from taus can be reconstructed by minimizing χ^2 constraints per event
- The performance can be also compared with the two other cases:
  - ❖ Random: choose one out of two solutions randomly (PLB 313, 458)
  - ❖ Resolved: no fit, but use our χ^2 to resolve the two-fold ambiguity

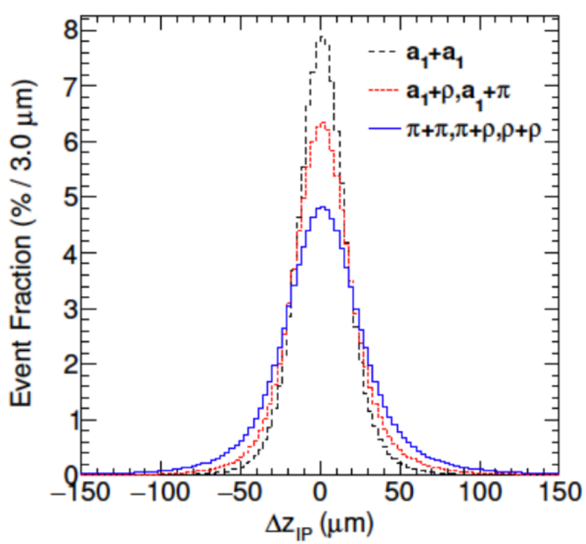


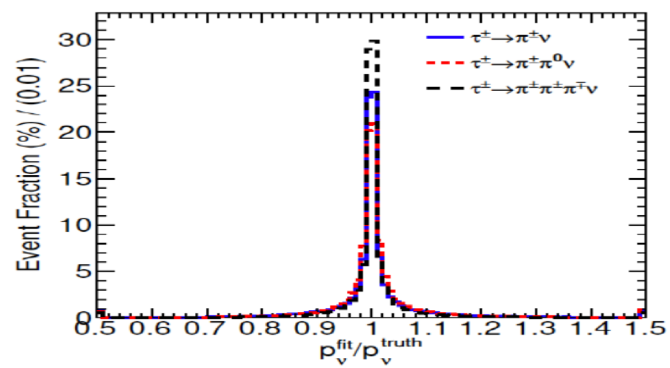
The fractions of good reconstructed neutrinos: 42% → 59% → 65%

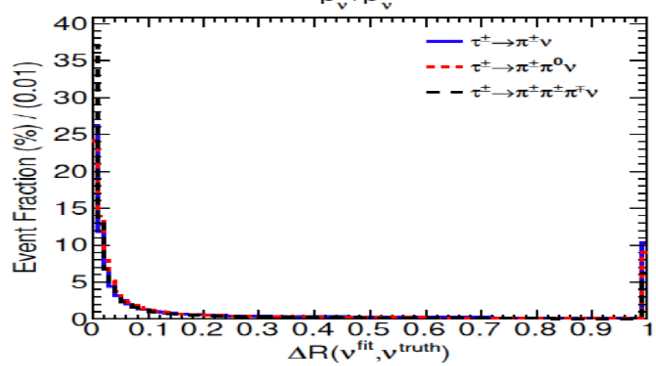
PV incorporated

[JHEP 10 (2019) 089]

- Unlike in LHC, where primary vertex (PV) can be reconstructed from underlying event tracks or jets, in $e^+e^- \to \tau^+\tau^-$, only limited number of tracks are available. The PV position is also important for determining the momentum of neutral particles such as π^0
- The beam spot size for Belle-II is (10μm, 60nm, 6mm) in (x, y, z) directions. The impact parameters can be still defined w.r.t. the origin, and the z_0 is now calculated as $z_0^{\text{fit}} = z_{\text{IP}} + L' \sinh\eta_\tau - S\sinh\eta_{\text{track}}$
- The z_{IP} is well fitted for all decays







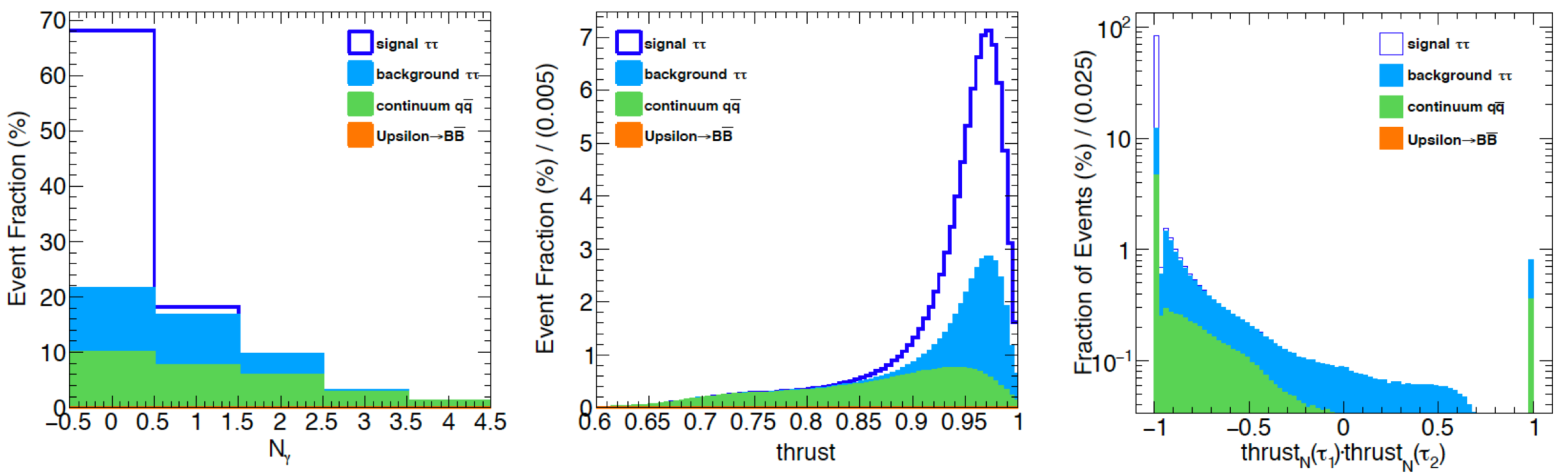
Sample selection

[JHEP 10 (2019) 089]

- We can get relative clean ditau event samples from CEPC, Z-pole, Belle-II and BESIII (background contamination at the level of 10-20%)
- Only hadronic channels are use for the sake of neutrino reconstruction

$$\tau^{\pm} \to \pi^{\pm}\nu \quad (10.8\%),$$
$$\tau^{\pm} \to \pi^{\pm}\pi^{0}\nu(\rho^{\pm}) \quad (25.4\%),$$
$$\tau^{\pm} \to \pi^{\pm}\pi^{\pm}\pi^{\mp}\nu(a^{\pm}) \quad (9.3\%),$$

- Background control at low energy e^+e^- collider:



ME and OO

[JHEP 10 (2019) 089]

- Expand the matrix element for $e^+e^-\to\tau^+\tau^-\to\pi^\pm\pi^0\ldots$, where the initial beam particles are unpolarized, in powers of c_τ and a_τ,

$$|\mathcal{M}|^2_{d_\tau} \propto M_0^d - M_1^d \frac{c_\tau}{\Lambda} + M_2^d \left(\frac{c_\tau}{\Lambda}\right)^2 ,$$

(c_τ linearly depends on d_τ)

$$|\mathcal{M}|^2_{a_\tau} \propto M_0^a + M_1^a \frac{a_\tau}{2m_\tau} + M_2^a \left(\frac{a_\tau}{2m_\tau}\right)^2 ,$$

- Using Spin Projector [Acta Phys. Polon. B16 (1985) 483] to calculate the amplitudes. The charged currents are adapted from TauDecay package:

$$J^\mu_\pm(\tau^\pm \to \pi^\pm \nu) = p^\mu_{\pi^\pm},$$
$$J^\mu_\pm(\tau^\pm \to \pi^\pm \pi^0 \nu) = p^\mu_{\pi^\pm} - p^\mu_{\pi^0},$$
$$J^\mu_\pm(\tau^\pm \to \pi^\pm_1 \pi^\pm_2 \pi^\mp_3 \nu) = F^{13}(q_1^\mu - q_3^\mu - G^{13} Q^\mu) + (1 \leftrightarrow 2),$$

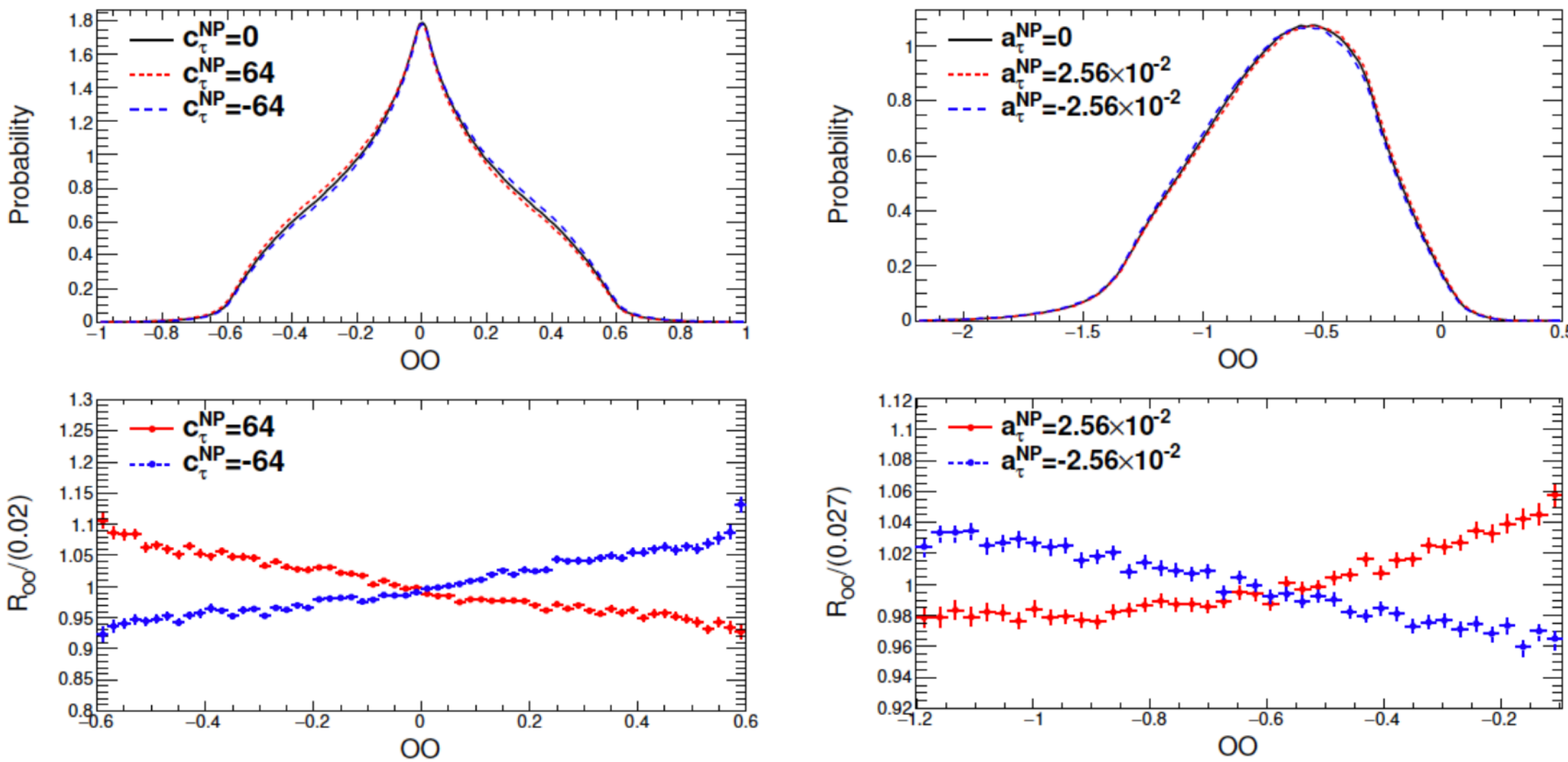
where F^{13} is the form factor used in the a_1 channel

- The OO is simply defined as $\mathcal{O}\mathcal{O}^{(i)} \equiv \dfrac{(M_1^i/\mathrm{GeV})}{M_0^i}$

with higher order terms M_2 neglected

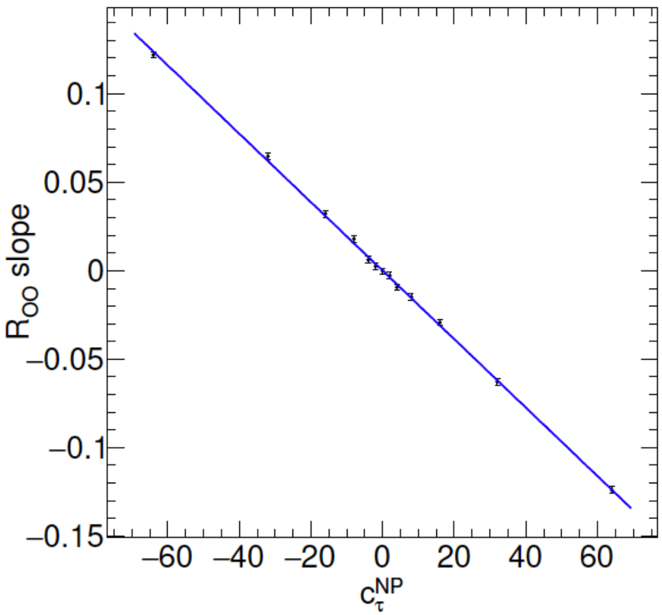
OO distributions

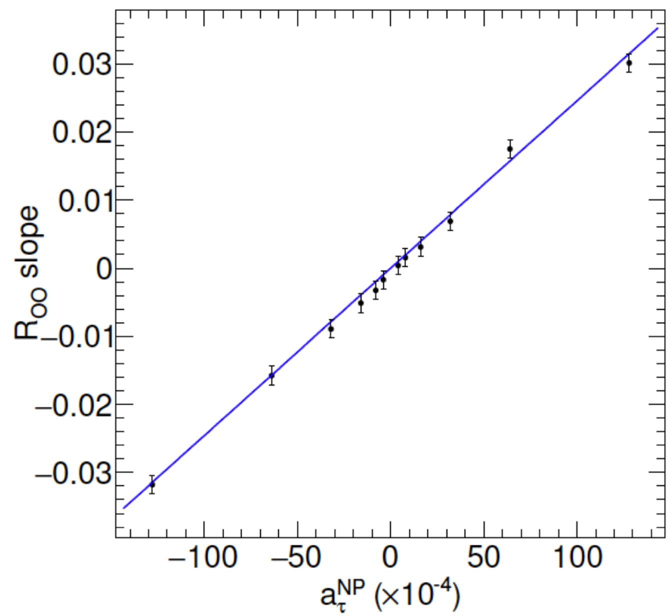
[JHEP 10 (2019) 089]



➢ For small enough c_τ and a_τ, the ratio of distributions of different c_τ and a_τ w.r.t. can be parametrized with $R_{\mathcal{OO}} = 1 + b(\mathcal{OO} - x_0)$, where b is the slope

Sensitivities at low energy e^+e^- [JHEP 10 (2019) 089]





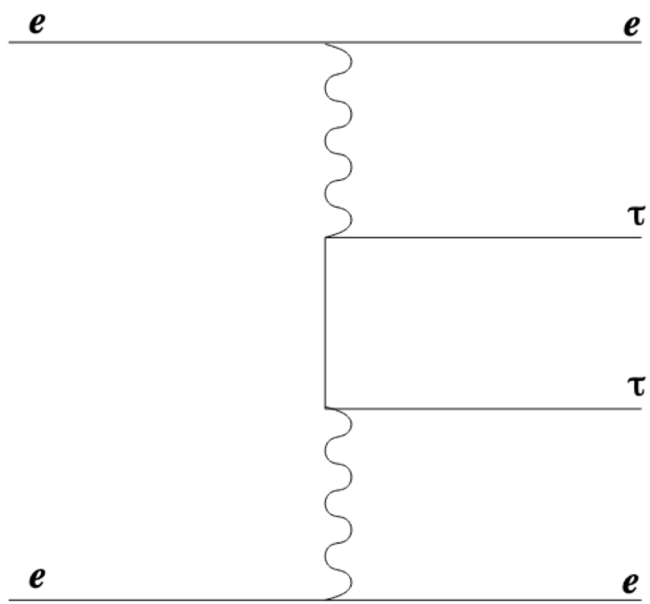
- The slope can be obtained as a function of different values of cτ and aτ, and with the fitted 1σ CL error for the slope b, the corresponding 1σ precisions for c_τ and a_τ can be obtained:

Belle-II estimation

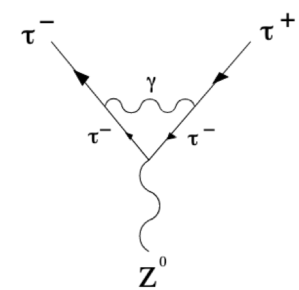
$\mathcal{L}$	$1\ \mathrm{ab}^{-1}$	$10\ \mathrm{ab}^{-1}$	$50\ \mathrm{ab}^{-1}$
$\lvert d_\tau^{NP}\rvert$ (e·cm)	1.44×10^{-18}	4.56×10^{-19}	2.04×10^{-19}
$\lvert a_\tau^{NP}\rvert$	1.24×10^{-4}	3.92×10^{-5}	1.75×10^{-5}

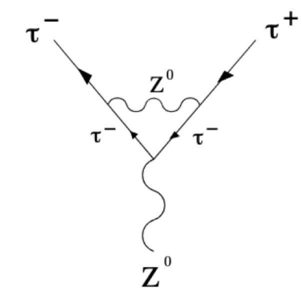
Tau EDM and g-2 at CEPC and Z-pole

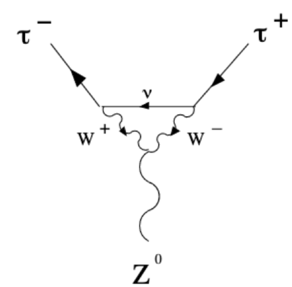
At CEPC 240 GeV energy, the process searched by LEP can be used:



At Z-pole, the weak dipole moment and g-2 can be measured:







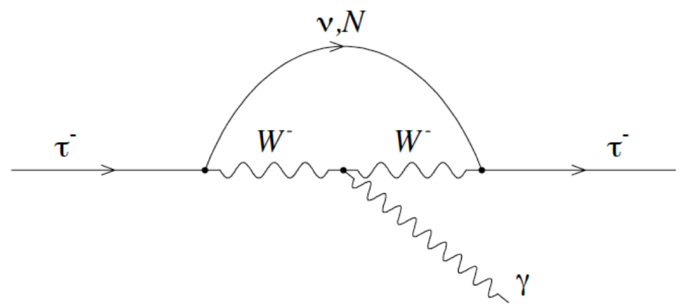
$Re(a_\tau^W)$
$< 1.1\times 10^{-3}$

$Re(d_\tau^W)$
$< 0.50\times 10^{-7} e\cdot cm$

Our method in [JHEP 10 (2019) 089] can be well adapted for these two cases

Constraints on mirror neutrinos [JHEP 10 (2019) 089]

- Large tau EDM and g-2 can be realized in models with mirror leptons arising from GUT, extended SUSY or Kaluza-Klein theories. These particles have V+A type of couplings to the SM leptons, and mixing among them is possible



- Bi-unitary transformations between the weak and mass eigenstates of the leptons [Phys. Rev. D81 (2010) 033007]

$$D_{L,R}^{\tau,\nu} = \begin{pmatrix} \cos\theta & e^{-i\chi}\sin\theta \\ -e^{i\chi}\sin\theta & \cos\theta \end{pmatrix} \equiv D,$$

where θ is the mixing angle, and χ is the CP phase angle. For simplicity, assume the same mixing angle for charged and neutral sectors:

$$\begin{pmatrix} \tau \\ E_\tau \end{pmatrix} = D \begin{pmatrix} \tau_1 \\ \tau_2 \end{pmatrix}, \quad \begin{pmatrix} \nu \\ N \end{pmatrix} = D \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

ν_1: SM light neutrino
ν_2: heavy mirror neutrino

Constraints on mirror neutrinos [JHEP 10 (2019) 089]

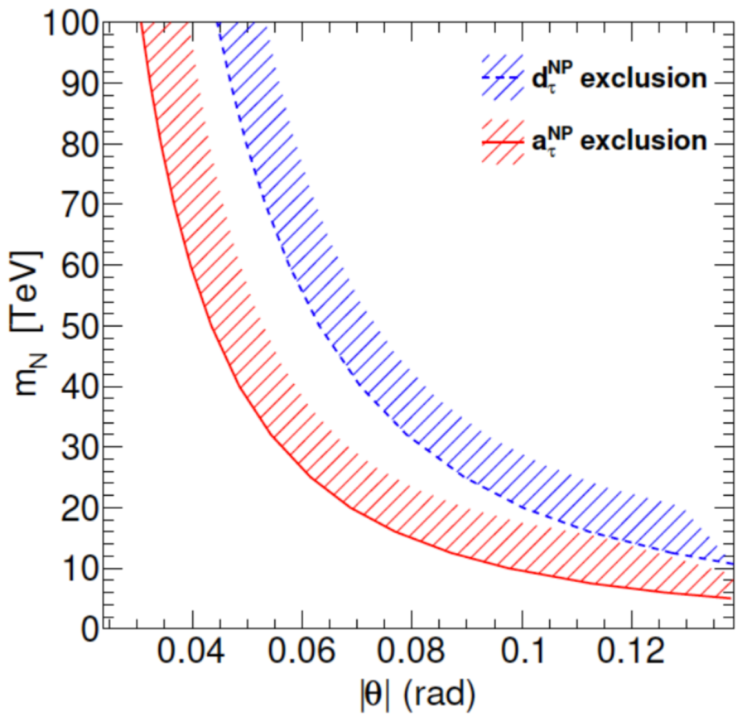
- When $m_N >> m_W$,

$$a_\tau = \frac{G_F m_\tau m_N \cos^2\theta \sin^2\theta}{4\sqrt{2}\pi^2}$$

- Exclusion can be set on the m_N vs. θ plane, for EDM ($\Delta\chi=\pi/2$) and g-2 ($\Delta\chi=0$)

- For small enough θ that is still compatible with tau decay data, one can exclude m_N about O(100 TeV)

- The EDM and g-2 sensitivities can be combined without overlap, since they are mutually exclusive



Constraints on a light scalar

[JHEP 10 (2019) 089]

- Enhancement of EDM and g-2 could also be observed in a model with extra scalars, such as 2HDM + a complex scalar:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1+h_1^0+ia_1^0}{\sqrt{2}} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2+h_2^0+ia_2^0}{\sqrt{2}} \end{pmatrix}, \quad S = \frac{1}{\sqrt{2}}(\omega + \phi_4 + i\phi_5),$$

- After rotating into the Higgs basis where only one double gets VEV:

$$\hat{\Phi}_1 = \begin{pmatrix} G^+ \\ \frac{v+\phi_1+iG^0}{\sqrt{2}} \end{pmatrix}, \quad \hat{\Phi}_2 = \begin{pmatrix} H^+ \\ \frac{\phi_2+i\phi_3}{\sqrt{2}} \end{pmatrix}, \quad \hat{S} = \frac{1}{\sqrt{2}}(\omega + \phi_4 + i\phi_5)$$

- In general, the neutral scalars can mix: $\phi_i = R_{ij}h_j$, and the Yukawa couplings are

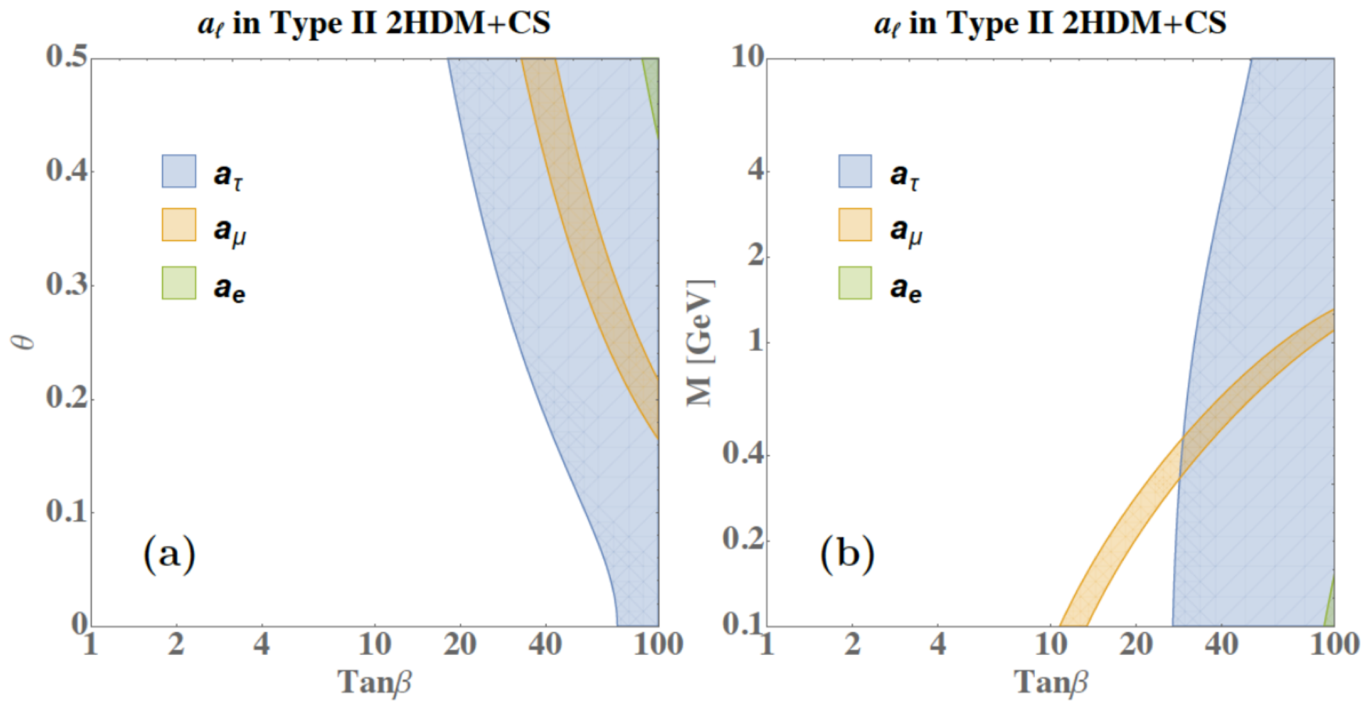
$$\begin{aligned} y_d^{h_i} &= \frac{m_d}{v}\left(R_{1i} + \xi_d(R_{2i} + iR_{3i})\right), \\ y_\ell^{h_i} &= \frac{m_\ell}{v}\left(R_{1i} + \xi_\ell(R_{2i} + iR_{3i})\right), \\ y_u^{h_i} &= \frac{m_u}{v}\left(R_{1i} + \xi_u(R_{2i} - iR_{3i})\right). \end{aligned}$$

- In Type-II Yukawa coupling, where down-type and charged lepton couple to Φ_2 and up-type couples to Φ_1: $\xi_{d,\ell} = -\tan\beta$, $\xi_u = \cot\beta$.

Constraints on a light scalar

[JHEP 10 (2019) 089]

- Limits can be set on a_τ in the tanβ vs. θ plane assuming light scalar mass of 1 GeV, or in the tanβ vs. M_a plane if assuming θ=0.25



The blue and green region are excluded by τ and e lepton measurement respectively. The orange band is the region that could explain the muon g-2 anomaly

Summary

- Precise measurement of the Electric Dipole Moment (EDM) and anomalous magnetic moment (g-2) of the tau lepton are important tests of BSM at the intensity frontier

- A new method to reconstruct the neutrinos from the hadronic decays of tau pairs produced at $e^+e^-\to\tau^+\tau^-$ factories (CEPC, Z-pole and low energy) is proposed. Matrix element method is used to get the best sensitivity

- The high statistics of ditau events at current or future tau factories can significantly improve the current experimental sensitivity for EDM and g-2 of tau by several orders of magnitude

- New physics can be revealed at loop level through the EDM and g-2 precision measurements