Search for the Electric Dipole Moment and anomalous magnetic moment of the tau lepton at tau factories

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Outline

- Introduction and current best results
- Track impact parameters and neutrino reconstruction
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- Expected sensitivities
- Theoretical constraints
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Introduction

- 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:

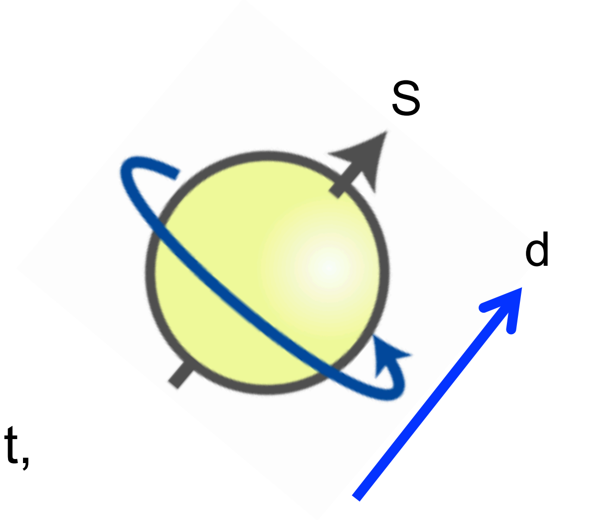
$$\Gamma^{\mu}_{d_\ell}(q^2) = ie\frac{\sigma^{\mu\nu}q_\nu}{2m_\ell}F_3^{NP}(q^2)\gamma^5$$

  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 ~10^{-38} e•cm, way smaller than the sensitivity of any experiment, e.g., ACME

Introduction

- 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:

$$\Delta a_\mu(\text{exp.} - \text{SM}) = (2.87 \pm 0.8) \times 10^{-9}$$ [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: $e^+e^- \rightarrow \tau^+\tau^-$

- Detect BSM through loop diagrams, and through its interference with the SM process – high statistics is needed. Ideal experiments: current (Belle-II) or future tau factories

Current best measured results

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

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

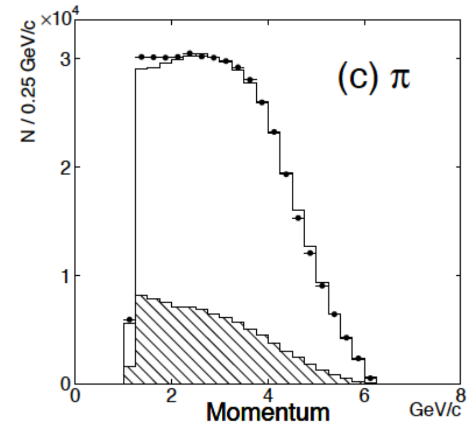
$$-0.052 < a_\tau < 0.013.$$ DELPHI $e^+e^- \to e^+e^-\tau^+\tau^-$

[EPJC 35 (2004) 159]

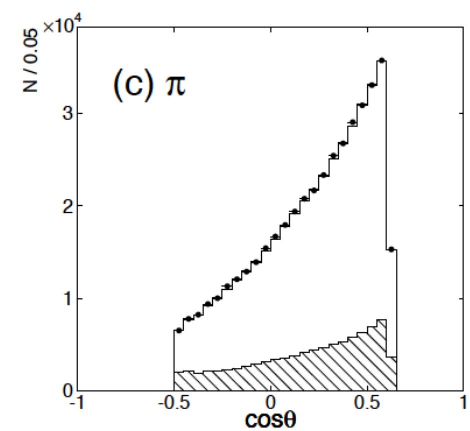
To be compared to theory:

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

which is an order of magnitude more precise than the measurement



[Phys. Lett. B551 (2003) 16]



- 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

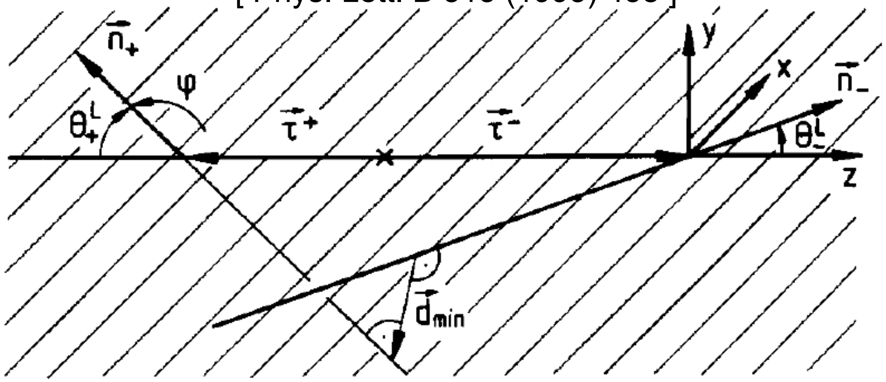
$$\mathcal{M}^2_{\rm prod} = \mathcal{M}^2_{\rm SM} + Re(d_\tau)\mathcal{M}^2_{Re} + Im(d_\tau)\mathcal{M}^2_{Im} + |d_\tau|^2\mathcal{M}^2_{d^2},$$

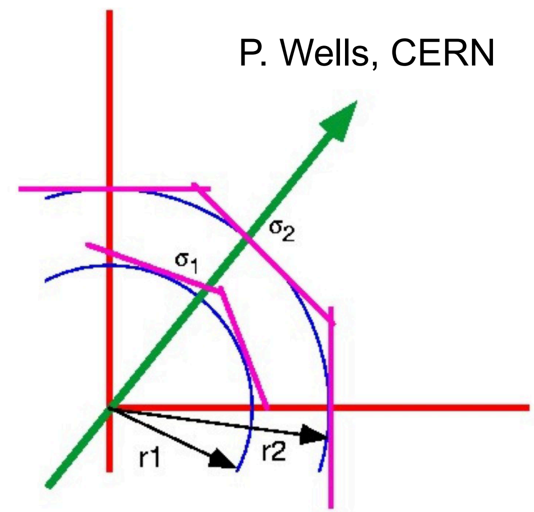
$$\mathcal{O}_{Re} = \frac{\mathcal{M}^2_{Re}}{\mathcal{M}^2_{\rm SM}}$$

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 asymmetric beam energy too, such as Belle-II (7 GeV + 4 GeV), when the tau flight directions are not aligned. The ISR/FSR effects can also deviate the back-to-back topology. In addition, the interaction point (IP) is hard to get in ditau final states

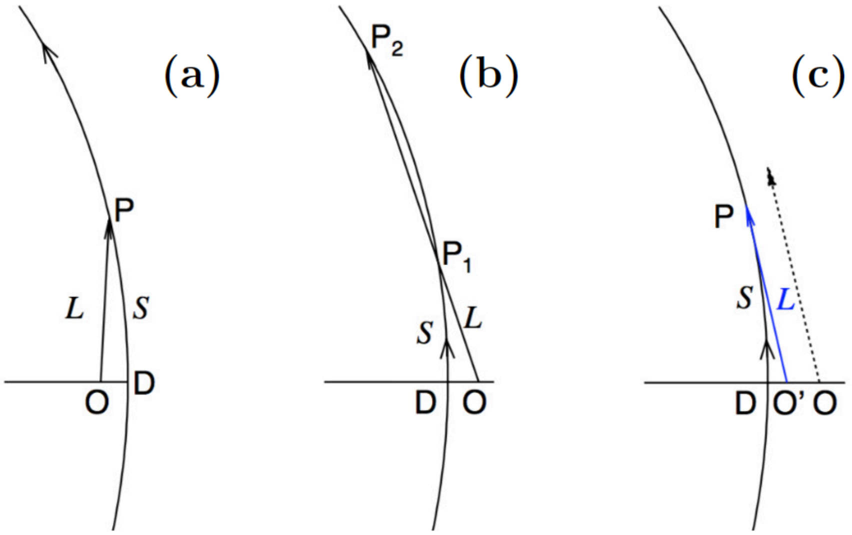
  - The resolution of tracking (p_T and direction) and impact parameters, can render null or wrong solutions, which has to be addressed

  - 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

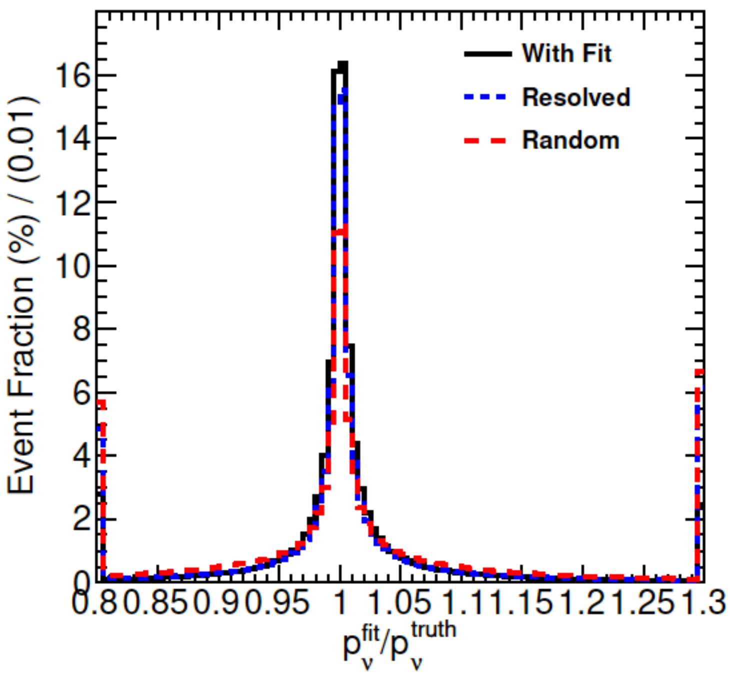
$$\chi^2_{\mathrm{IP}} = \left(\frac{d_0^{\mathrm{fit}} - d_0}{\sigma_{d_0}}\right)^2 + \left(\frac{z_0^{\mathrm{fit}} - z_0}{\sigma_{z_0}}\right)^2$$

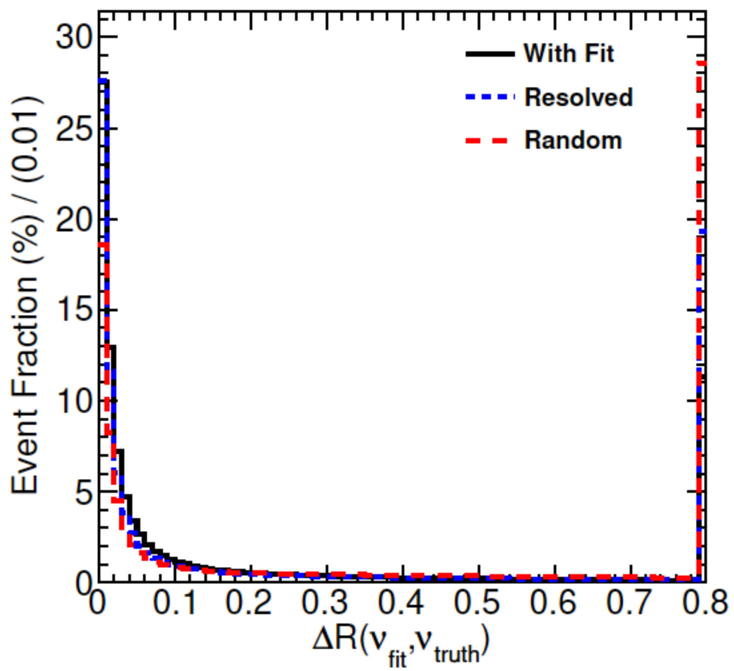
- Once the intersection point is found in the transverse plane, the z_0 can be extrapolated: $z_0^{\mathrm{fit}} = L \sinh \eta_\tau - S \sinh \eta_{\mathrm{track}}$

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

Neutrino momentum

- 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

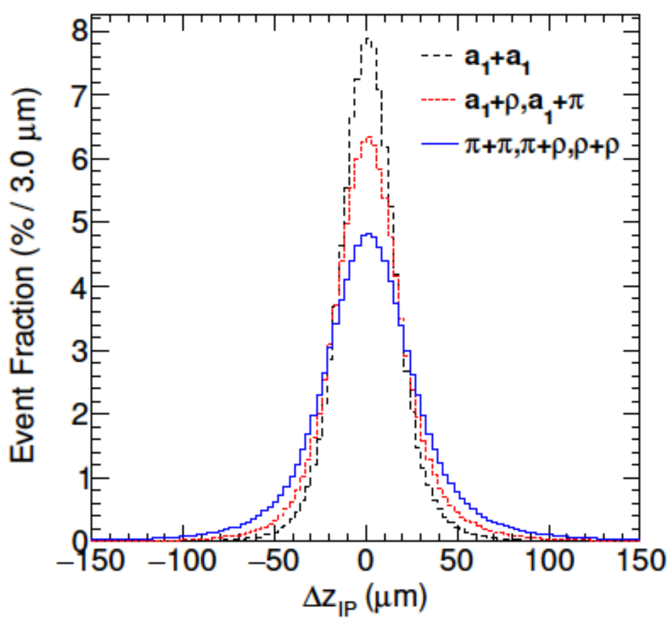


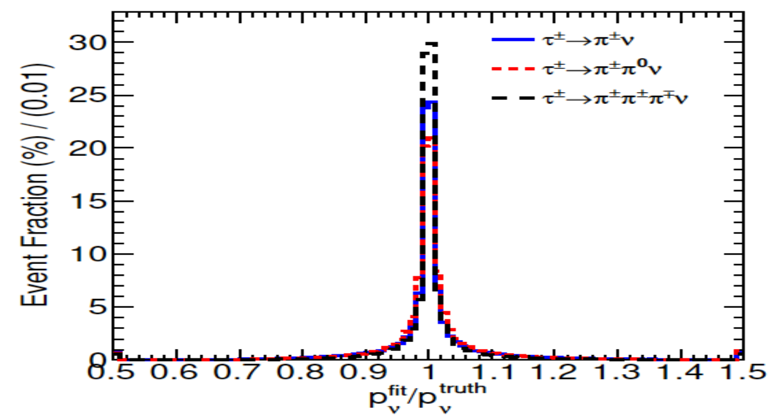


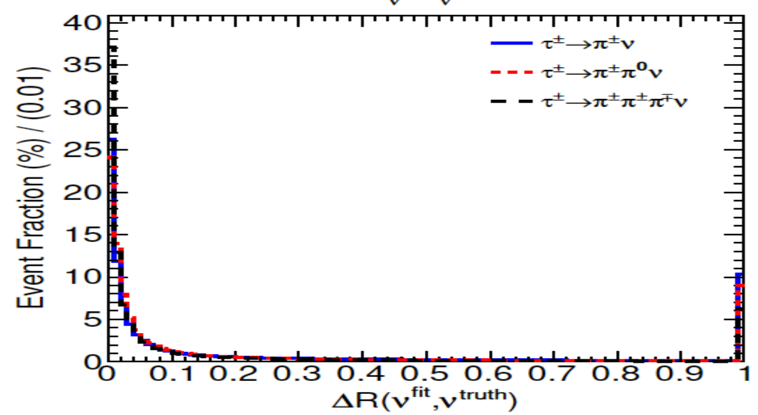
The fractions of good reconstructed neutrinos: 42% → 59% → 65%

PV incorporated

- 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 $z_0^{fit} = z_{IP} + L' \sinh \eta_\tau - S \sinh \eta_{track}$
- The z_{IP} is well fitted for all decays







Data simulation

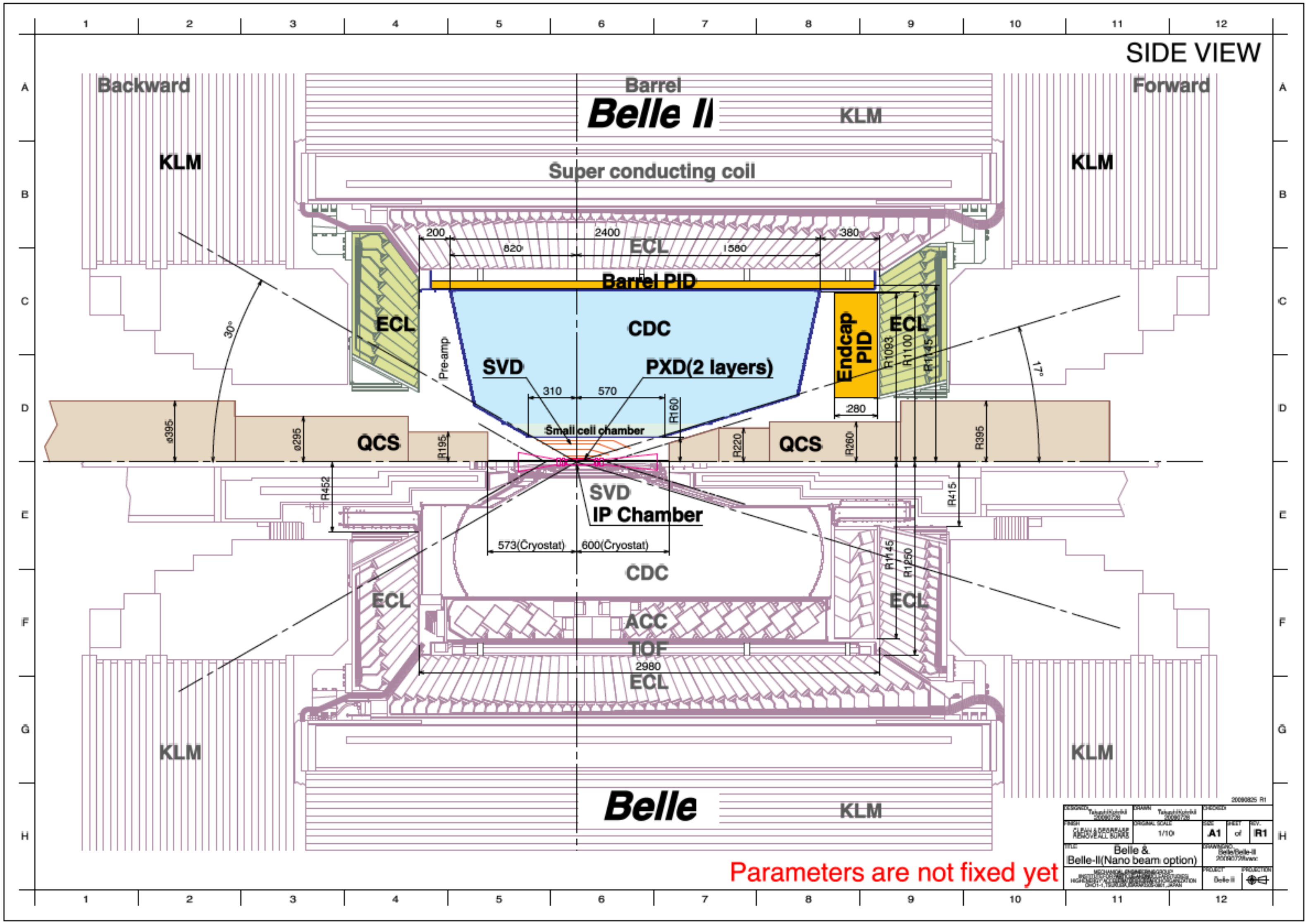
- $\tau\tau$ signal and qq continuum are generated with MadGraph5, parton showered and hadronized by Pythia8. BB events are generated with EvtGen. The truth particles are pass through DELPHES for detector simulation. TauDecay package [EPJC 73 (2013) 2489] is used to decay taus in MG5 with their spin correlation preserved, for three main hadronic modes:

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

- Tracking and calorimeter volume roughly restricted to $-1.32<\eta<1.90$ in a 1.5T field. Track momentum resolution $0.3\% \oplus 0.1\% p_T$
- Particle ID efficiency is generally high and mis-ID rate is low. When parameters no explicitly available in Belle-II TDR, the ones from BaBar is used, especially for low p_T objects where dE/dx can be used
- The tracks from tau should have $p_T>0.2$ GeV, and $p_T>0.4$ GeV for the leading one. The neutral clusters should have $p_T>0.1$ GeV

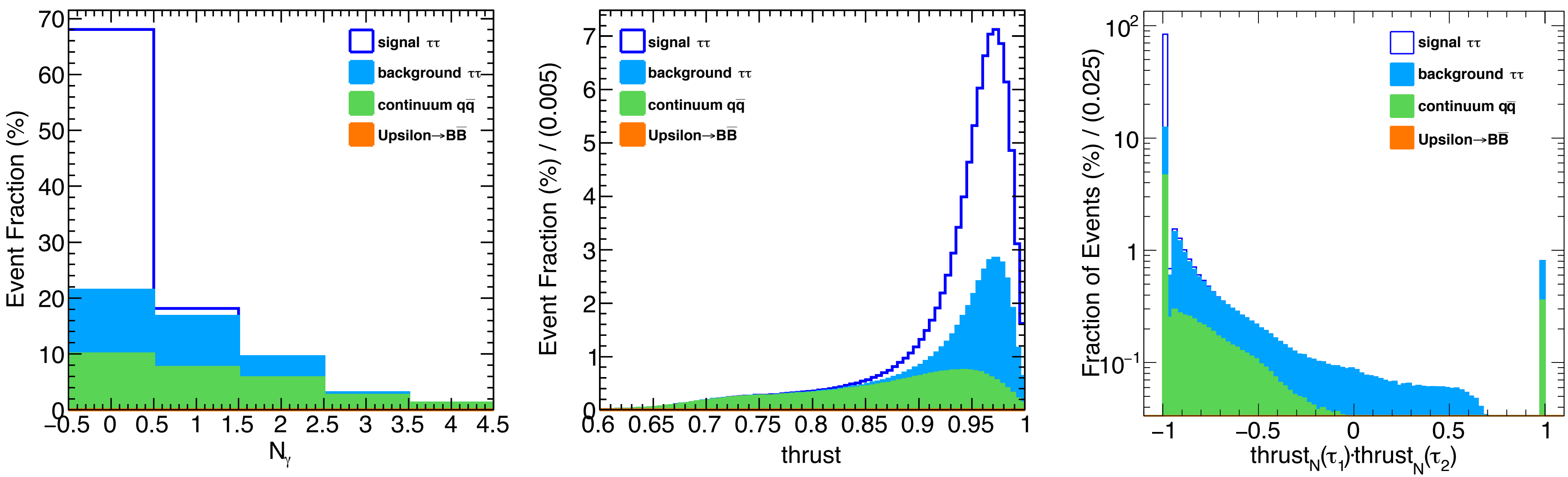
Belle-II detector

[arXiv:1011.0352]



Event reconstruction and selection

- For 3-prongs taus and events with neutral pions, the combinations with masses closest to a_1 and ρ mesons are chosen, and The net charge of the tau pair should be ±1
- In the $\tau\tau$ signal, there are events with extra photons from π^0 decay or unidentified π^0 (background $\tau\tau$), and the continuum can be largely removed by cutting on the thrust



- Each tau's visible decay products are required to be on each hemisphere of the thrust axis, to further suppress the backgrounds

Expected event yields

- 3 tau decay modes and 6 ditau decay combinations:

Expected cross sections after all the selection cuts

Mode	Signal $\tau\tau$ (pb)	Background $\tau\tau$ (pb)	Continuum (pb)	Upsilon (fb)
$a_1 + a_1$	3.09	0.00	0.22	0.37
$a_1 + \rho$	16.14	0.39	0.73	1.16
$a_1 + \pi$	9.30	0.70	0.42	0.59
$\pi + \pi$	7.42	2.50	0.51	0.68
$\pi + \rho$	24.13	3.16	0.98	1.01
$\rho + \rho$	20.96	1.20	0.73	1.19
total	81.04	7.95	3.58	4.99

- The upsilon process is severely suppressed by kaon veto and thrust cut

- After all the cuts, one is left with a clean sample of well reconstructed $\tau\tau$ events (background contamination ~13%) for BSM search

ME and OO

- 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,

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

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

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

$$J^\mu_\pm(\tau^\pm \to \pi^\pm \nu) = p^\mu_{\pi^\pm},$$

$$J^\mu_\pm(\tau^\pm \to \pi^\pm \pi^0 \nu) = p^\mu_{\pi^\pm} - p^\mu_{\pi^0},$$

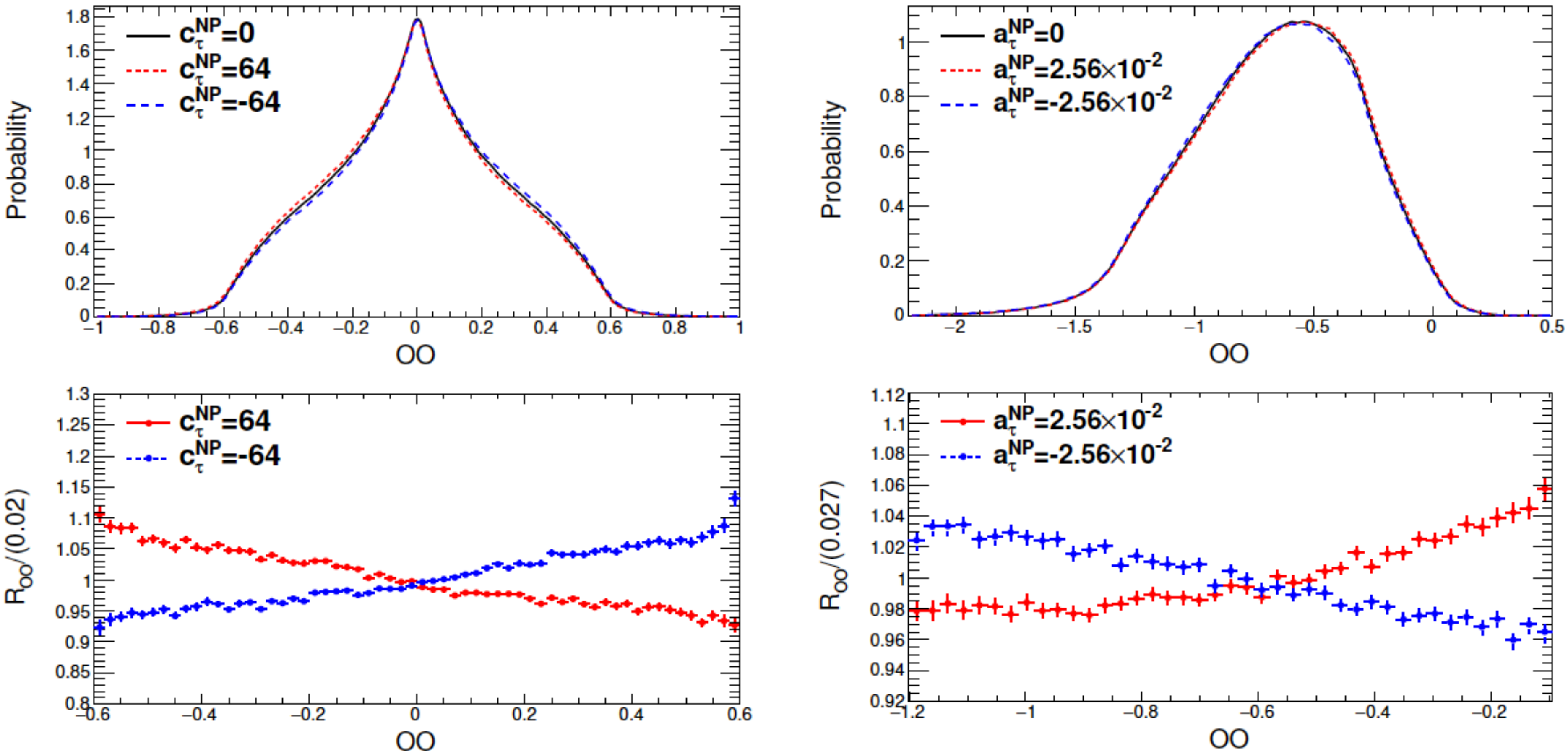
$$J^\mu_\pm(\tau^\pm \to \pi_1^\pm \pi_2^\pm \pi_3^\mp \nu) = F^{13}(q_1^\mu - q_3^\mu - G^{13}Q^\mu) + (1 \leftrightarrow 2),$$

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

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

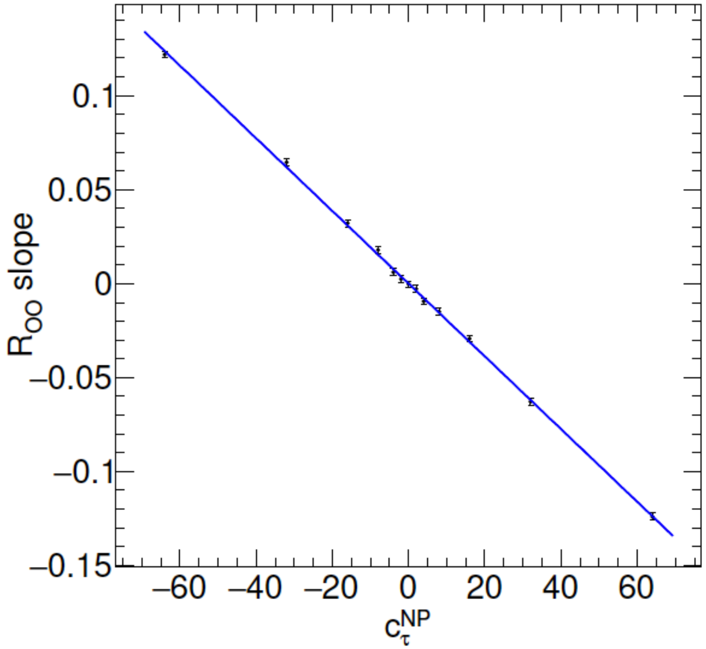
with higher order terms M_2 neglected

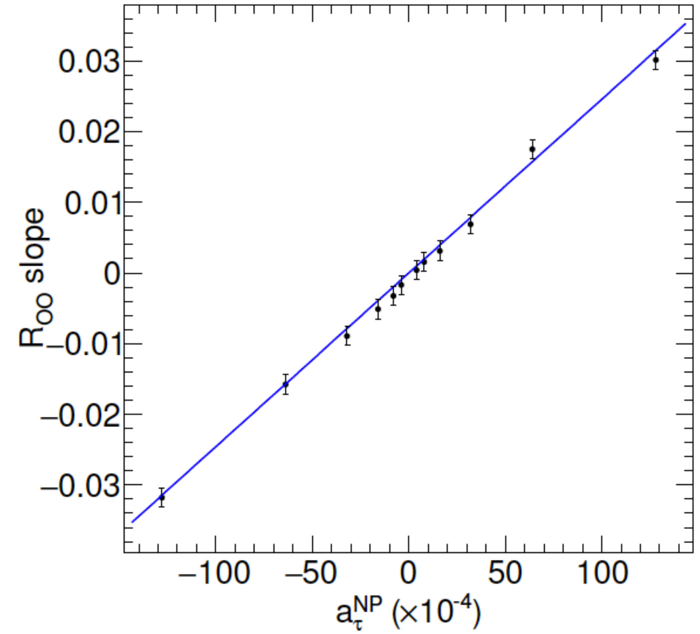
OO distributions



- 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



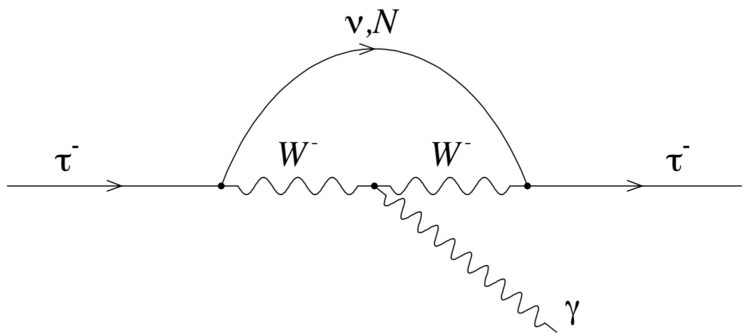


- The slope can be obtained as a function of different values of c_τ and a_τ, and with the fitted 1σ CL error for the slope b, the corresponding 1σ precisions for c_τ and a_τ can be obtained

$\mathcal{L}$	1 ab^{-1}	10 ab^{-1}	50 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}

Constraints on mirror neutrinos

- 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]

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

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

- The currents with the W boson now become

$$J^\mu = (\cos^2\theta + \sin^2\theta e^{-i\chi})\bar{\nu}_1\gamma^\mu\tau_1 - (\cos^2\theta - \sin^2\theta e^{-i\chi})\bar{\nu}_1\gamma^\mu\gamma_5\tau_1$$
$$+\cos\theta\sin\theta(e^{i\chi}-1)\bar{\nu}_2\gamma^\mu\tau_1 - \cos\theta\sin\theta(e^{i\chi}+1)\bar{\nu}_2\gamma^\mu\gamma_5\tau_1$$

- Neglecting terms prop. to m_τ/m_W and m_τ/m_N, the EDM can be written

$$d_\tau^{NP} = \frac{eG_F m_N}{4\sqrt{2}\pi^2}\int_0^1 dz \frac{(1-z)(4-4z+rz)\sin^2\theta\cos^2\theta\sin\Delta\chi}{1-z+rz}$$

where $r = m_N^2 / m_W^2$, and χ is the CP phase difference between two sectors. When $\chi=\pm\pi/2$ and $m_N >> m_W$,

$$|d_\tau| = \frac{eG_F m_N\cos^2\theta\sin^2\theta}{8\sqrt{2}\pi^2}$$

- As χ goes from $\pi/2$ to 0, $|d_\tau|$ goes down, and $|\Delta a_\tau|$ goes up. In the case of $\chi=0$:

$$a_\tau = \frac{G_F m_\tau^2\sin^2(2\theta)}{8\sqrt{2}\pi^2}\int_0^1 dz(1-z)\frac{(4-2z)(1-z)+4\frac{m_N}{m_\tau}(1-z)+\frac{m_N^2}{m_W^2}(1+z)z+\frac{m_N^3}{m_W^2 m_\tau}z}{1-z+\frac{m_N^2}{m_W^2}z}$$

Constraints on mirror neutrinos

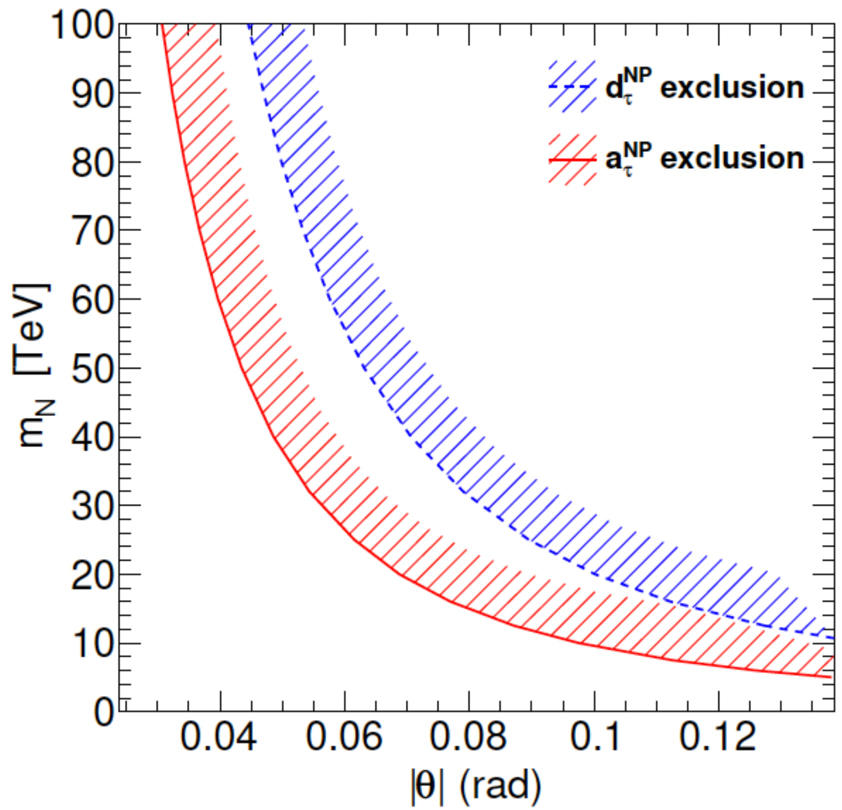
- When $m_N \gg m_W$,

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

- 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

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

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1 + h_1^0 + i a_1^0}{\sqrt{2}} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2 + h_2^0 + i a_2^0}{\sqrt{2}} \end{pmatrix}, \quad S = \frac{1}{\sqrt{2}}(\omega + \phi_4 + i\phi_5),$$

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

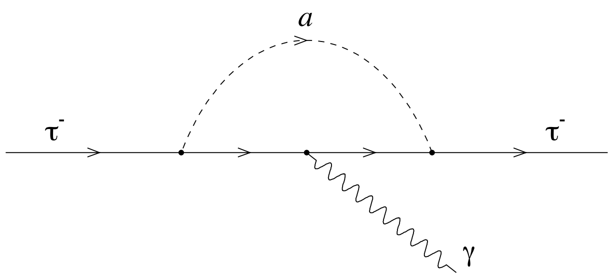
$$\hat{\Phi}_1 = \begin{pmatrix} G^+ \\ \frac{v + \phi_1 + iG^0}{\sqrt{2}} \end{pmatrix}, \quad \hat{\Phi}_2 = \begin{pmatrix} H^+ \\ \frac{\phi_2 + i\phi_3}{\sqrt{2}} \end{pmatrix}, \quad \hat{S} = \frac{1}{\sqrt{2}}(\omega + \phi_4 + i\phi_5)$$

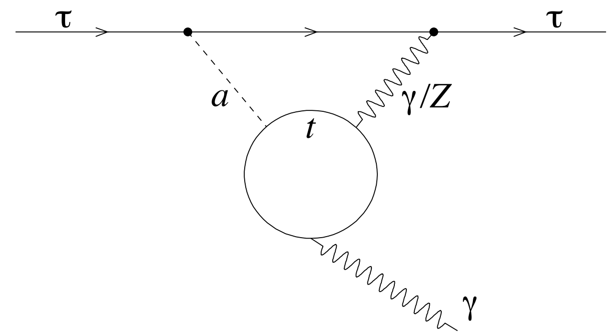
- In general, the neutral scalars can mix: $\phi_i = R_{ij} h_j$, and the Yukawa couplings are

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

- 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





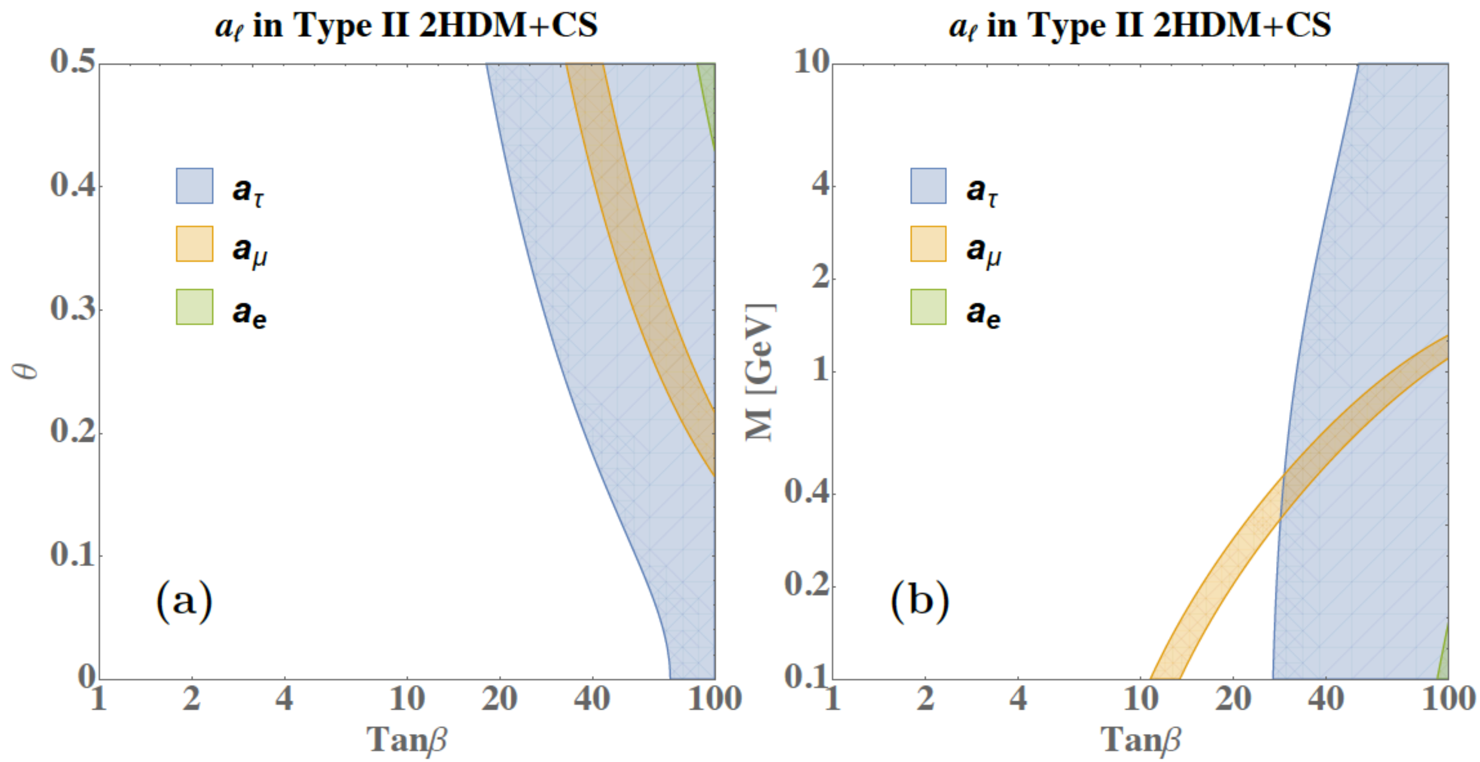
- Beside the one-loop contributions, two-loops (Bar-Zee diagrams) can also contribute (for electrons and muons)
- Direct search channels at LHC: $h \to aa \to \mu\mu\tau\tau$
- However, in the $e^+e^- \to \tau^+\tau^-$ process, what we measure is the magnetic form factors (arXiv:0707.2496). The real part of it is

$$\Re[F_2(\theta)] = -\frac{|y_\ell|^2}{4\pi^2 \sinh\theta} \int_0^1 dx \int_0^{\frac{\theta}{2}} dy \frac{x^3 - kx^2}{x^2 + z(1-x)\left(\frac{\sinh y}{\sinh\frac{\theta}{2}}\right)^2}$$

where $k = 2[\Re(y_\ell)]^2/|y_\ell|^2,\ z = m_a^2/m_\tau^2,\ \theta = \ln[(1+\beta)/(1-\beta)]/2$ with β being the tau velocity. At Y(4S) energy (β=1.75486), $R(F_2)$ only drops to about 90% of the Schwinger value (for e/μ, it is close to 0)

Constraints on a light scalar

- 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 $e^+e^-\rightarrow\tau^+\tau^-$ factories is proposed. Matrix element method is used to get the best sensitivity
- With 50 ab-1 of data to be delivered by the Belle-II experiment, a tauEDM search with a 1σ level CL of $|d_\tau|<2.04\times10^{-19}$ e•cm, and g-2 search with $|\Delta a_\tau|<1.75\times10^{-5}$ (1.5% of the SM prediction), can be expected
- The result can put an upper bound on the heavy mirror neutrino mass, which can escape direct search at hadron colliders. It can also constrain models containing a light scalar with mass at O(1 GeV), which can explain the current muon g-2 anomaly as well