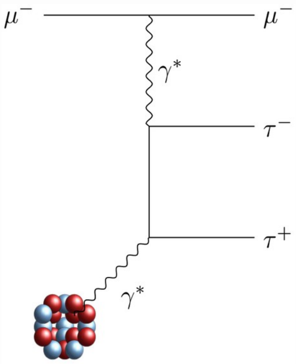
Muon-Induced Di-Tau Production as a Probe of New (Pseudo)scalars

Sebastian Trojanowski
National Centre for Nuclear Research (NCBJ)
AstroCeNT, Nicolaus Copernicus Astronomical Center (CAMK PAN)

SCALARS 2025
25/09/2025

Based on:
B. Batell, H. Davoudiasl, R. Marcarelli, E.T. Neil, ST, 2407.15942 (PRD)
S. Das, L. Kupari, M.H. Reno, ST (in preparation)

Outline



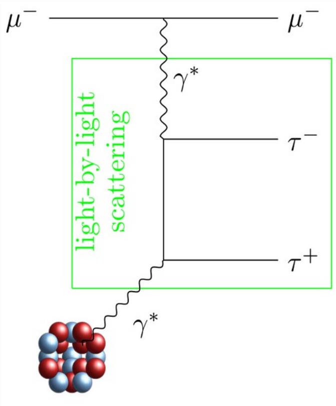
- **Muon-induced Di-Tau Production Process**
  - Process in the SM
  - Potential new physics effects
  - Experiments

- **BSM examples**
  - Leptophilic scalar
  - Lepton Flavor Violating ALPs
  - New physics in the $\gamma\tau\tau$ vertex; connections to $(g\text{-}2)_\tau$

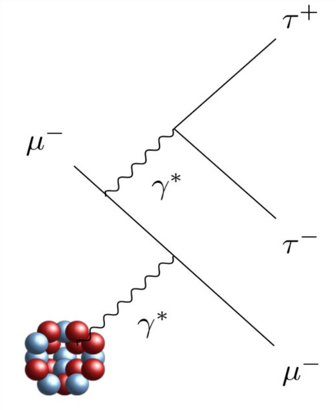
$\mu N \rightarrow \mu \tau \tau N$ PROCESS

SM predictions

- Two main types of diagrams
- Dominant Bethe-Heitler



Bethe-Heitler type

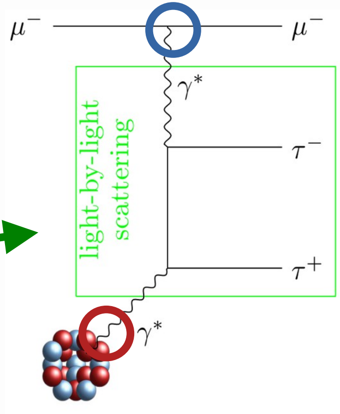


Muon ISR & FSR

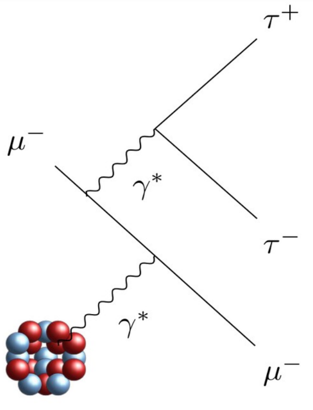
SM predictions

- Two main types of diagrams
- Dominant Bethe-Heitler

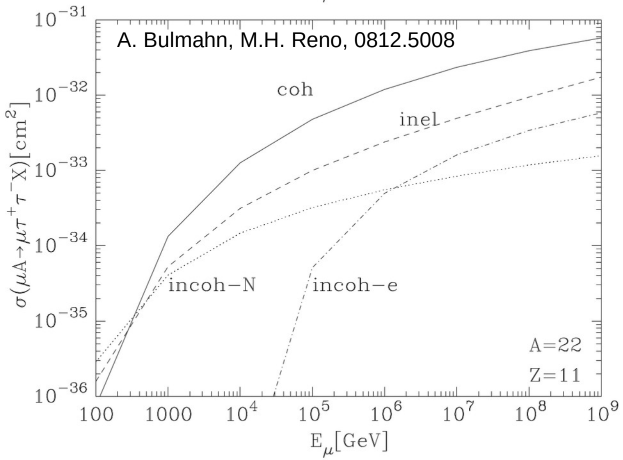
$$d\sigma = \frac{4\pi M_t}{2\sqrt{\lambda_s}} A_{\alpha\beta} B^{\alpha\beta}_{\mu\nu} W^{\mu\nu} \frac{e^8}{q^4 Q^4} \delta^4(k+q-k_1-p_+-p_-) d^4 q \times \frac{d^3 k_1}{2k_1^0 (2\pi)^3} \frac{d^3 p_+}{2p_+^0 (2\pi)^3} \frac{d^3 p_-}{2p_-^0 (2\pi)^3}$$



Bethe-Heitler type



Muon ISR & FSR



Muonic vertex

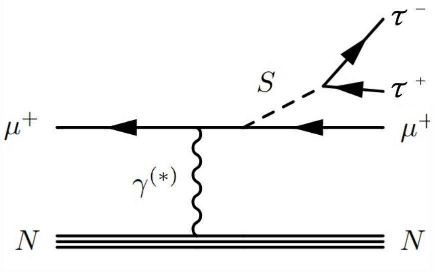
Light-by-light scattering – sensitive to $\gamma\ \tau\ \tau$

Hadronic vertex – sensitive to nucleon/nuclear form factors

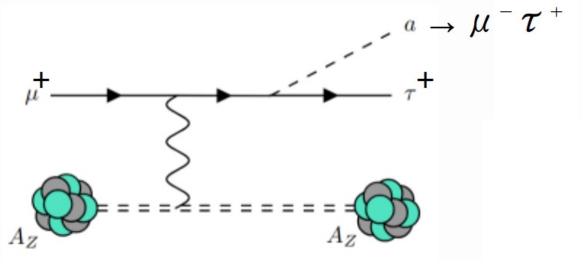
Coherent process dominates

New physics & muon-induced di-tau production

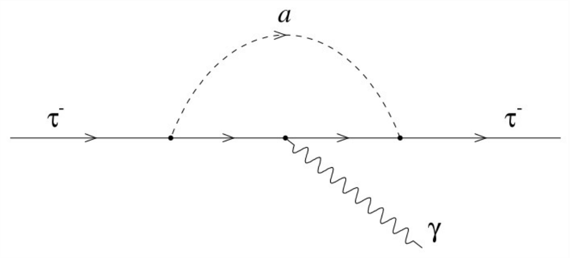
A) Bremsstrahlung followed by decay to $\tau\ \tau$



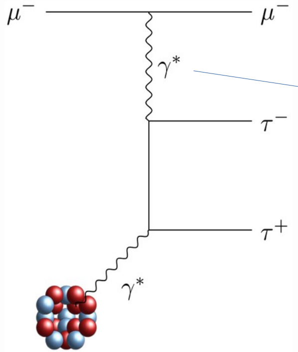
B) Muon charge flip due to LFV interactions



C) Modifications of the $\gamma\ \tau\ \tau$ vertex (a_τ, d_τ)



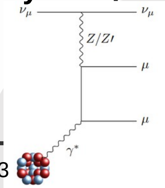
D) Modifications of the 2 → 4 scattering rates & kinematics



Z' ?

direct analogy with neutrino tridents

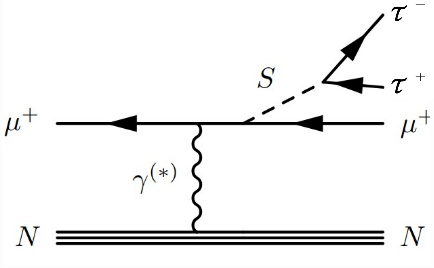
less attractive: no heavy med.



ν Tridents @ LHC: W. Altmannshofer etal (with ST), 2406.16803

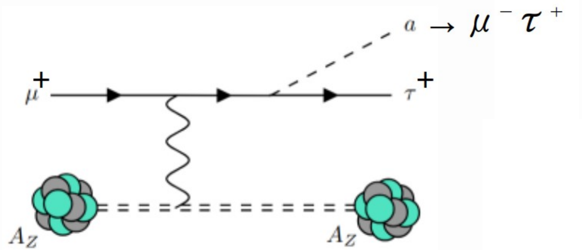
New physics & muon-induced di-tau production

A) Bremsstrahlung followed by decay to $\tau\ \tau$

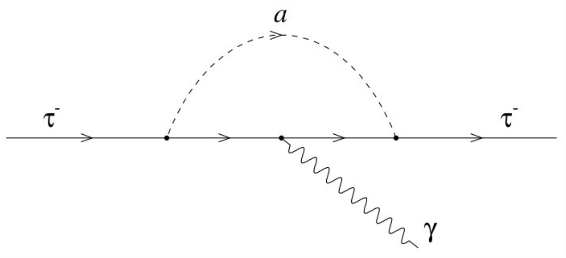


THIS TALK

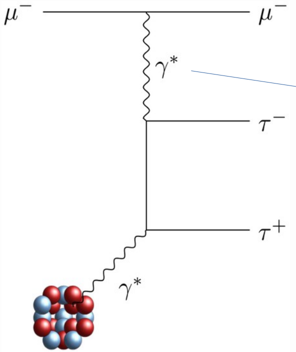
B) Muon charge flip due to LFV interactions



C) Modifications of the $\gamma\ \tau\ \tau$ vertex (a_τ, d_τ)



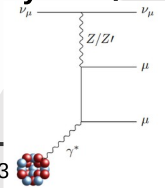
D) Modifications of the 2 → 4 scattering rates & kinematics



Z' ?

direct analogy with neutrino tridents

less attractive: no heavy med.

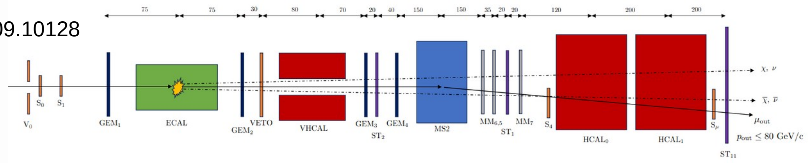


ν Tridents @ LHC: W. Altmannshofer etal (with ST), 2406.16803

Experiments: high-energy muon beams

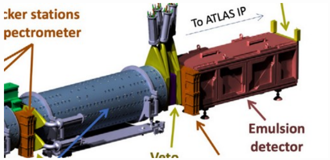
- **Ongoing:** NA64-μ
  - 160 GeV μ beam dumped on lead-scintillator target material (projected 10^{13} MOT)
  - Missing energy / momentum technique

NA64-μ, 2409.10128



- **Ongoing & future:** FASER & SND@LHC
  - FASER collaboration: BSM sensitivity study for PBC benchmarks prior to FASER approval
  - Up to a few TeV μ, both μ+ and μ- (“mixed”)
  - Precision high-energy (TeV) muon physics possible

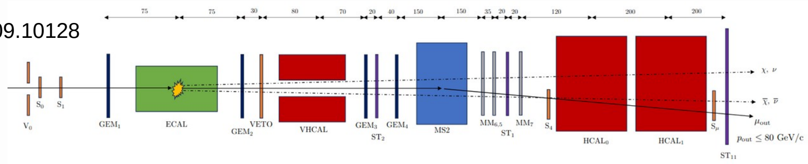
FASER, 2207.11427



Experiments: high-energy muon beams

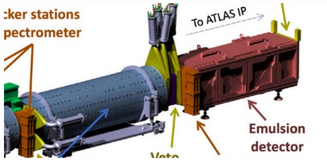
- **Ongoing:** NA64-μ
  - 160 GeV μ beam dumped on lead-scintillator target material (projected 10^{13} MOT)
  - Missing energy / momentum technique

NA64-μ, 2409.10128



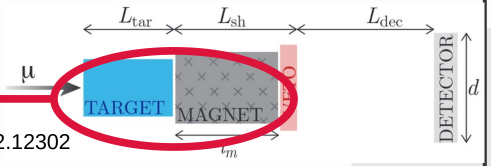
- **Ongoing & future:** FASER & SND@LHC
  - FASER collaboration: BSM sensitivity study for PBC benchmarks prior to FASER approval
  - Up to a few TeV μ, both μ+ and μ- (“mixed”)
  - Precision high-energy (TeV) muon physics possible

FASER, 2207.11427



- **Further future (?):** FPF@HL-LHC; Muon Collider & preparations
  - Proposed **Forward Physics Facility (FPF)@ HL-LHC** (up to a few TeV μ, both μ+ and μ-)
  - Muno dump @ Muon Collider (1.5-5 TeV μ, 10^{16} MOT for ~1h MAP operation, separate μ+ and μ-)
  - **Single high-energy muon beam enough to realize the search discussed here**
  - Idea: μTRISTAN, 1 TeV μ^+ beam; Y. Hamada etal, 2201.06664

Muon beam dump @ MuCol 10^{20} MOT)
Idea: operate with active target for a fraction of time (10^{16} – 10^{18} MOT)



C. Cesarotti, 2202.12302

EXAMPLES

Leptophilic dark sectors

(g-2)μ & neutrino masses: E. Ma etal, 0110146
Pheno: M. Bauer, P. Foldenauer, J. Jaeckel, 1803.05466
(g-2)μ & DM: J. Heeck, A. Thapa, 2202.08854
Cosmology: M. Escudero etal, 1901.02010
& many more…

- **Gauging one of the SM global symmetries:** L_μ-L_τ, L_e-L_τ, L_μ-L_e

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} Z'^{\alpha\beta} Z'_{\alpha\beta} + \frac{m_{Z'}^2}{2} Z'_\alpha Z'^\alpha + Z'_\alpha J^\alpha_{\mu-\tau}$$

with

$$J^\alpha_{\mu-\tau} = g_{\mu-\tau}\left(\bar\mu\gamma^\alpha\mu + \bar\nu_\mu\gamma^\alpha P_L\nu_\mu - \bar\tau\gamma^\alpha\tau - \bar\nu_\tau\gamma^\alpha P_L\nu_\tau\right)$$

  - Additionally motivated by $(g\text{-}2)_\mu$ & other anomalies, could be DM mediator, rich pheno

- **Leptophilic scalars**

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 - \sum_{\ell=e,\mu,\tau} g_\ell S \bar\ell \ell \quad \longleftarrow \quad \frac{c_i}{\Lambda} S \bar L_i H E_i$$

(g-2)μ: C.-Y. Chen etal, 1511.04715, B. Batell etal, 1606.04943
NA64μ: C.-Y. Chen, J. Kozaczuk, Y.-M. Zhong, 1807.03790
Electron beam dumps: L. Marcisiano etal, 1812.03829
& more…

  - Minimal Flavor Violation (MFV) → $g_e : g_\mu : g_\tau = m_e : m_\mu : m_\tau$

G. D'Ambrosio, G.F. Giudice, G. isidori, A. Strumia, 0207036

- **Lepton Flavor Violation (LFV) and ALPs**

B. Batell etal (with ST), 2407.15942

$$\mathcal{L} \supset -i\frac{a}{\Lambda}\sum_{i,j} \bar\ell_i[(m_j - m_i)v_{ij} + (m_j + m_i)a_{ij}\gamma^5]\ell_j$$

$$-\frac{\partial_\mu a}{\Lambda}\sum_{f,i,j} \bar f_i \gamma^\mu (v_{ij}^f - a_{ij}^f\gamma_5) f_j$$

real v_{ij}, a_{ij} →

$$\mathcal{L} \supset -i g_{\mu\tau} a \bar\mu \left[\sin\theta + \cos\theta\,\gamma^5\right]\tau + \text{h.c.}$$

LFV ALPs: M. Bauer etal, 1908.00008
C. Cornella etal, 1911.06279
L. Calibbi etal, , 2006.04795
H. Davoudiasl etal, 2112.04513
& more…

  - Potential clear signature of new physics

Leptophilic (pseudo)scalars & dark matter

- **Leptophilic scalar + dark matter (DM)**

$$\mathcal{L} \supset -g_\chi S \bar{\chi}\chi$$

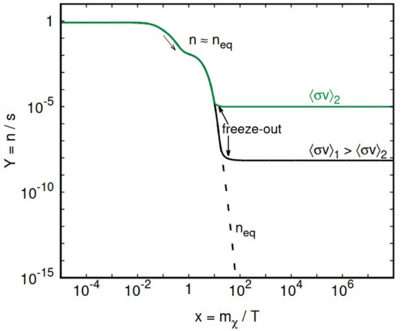
  - Thermal relic target (freeze out)
  - Annihilations into muons or taus, or **secluded, $\chi\bar{\chi} \to$ SS**
  - Yukawa-like couplings, $\chi e \to \chi e$ scatterings suppressed

- **LFV ALPs + dark matter**

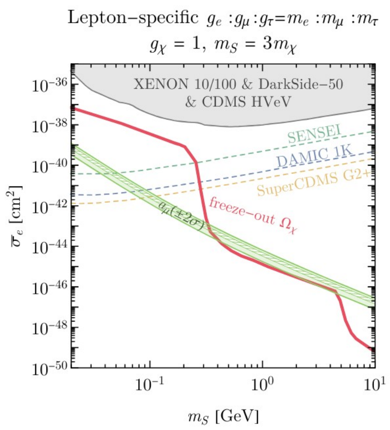
$$\mathcal{L} \supset -i\frac{C_\chi}{\Lambda_\chi} 2m_\chi a\bar{\chi}\gamma^5\chi = -ig_\chi a\bar{\chi}\gamma^5\chi$$

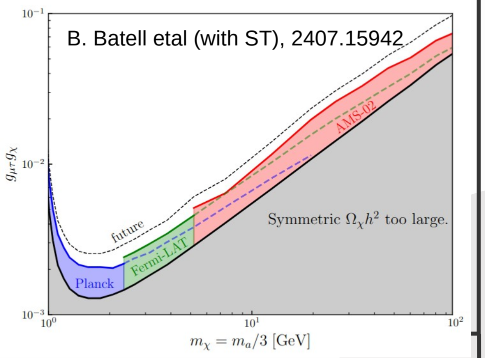
  - Annihilations into $\mu\ \tau$ or secluded $\chi\bar{\chi} \to aa$
  - For $\chi\bar{\chi} \to \mu\ \tau$, strong DM indirect detection bounds, but...
  - ... can be asymmetric DM
  - Relic density + DM indirect det. constrain low couplings

E.M. Sessolo, L. Roszkowski, ST, 1707.06277



C.-Y. Chen etal, 1807.03790

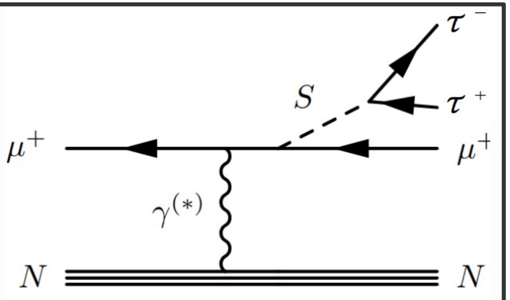


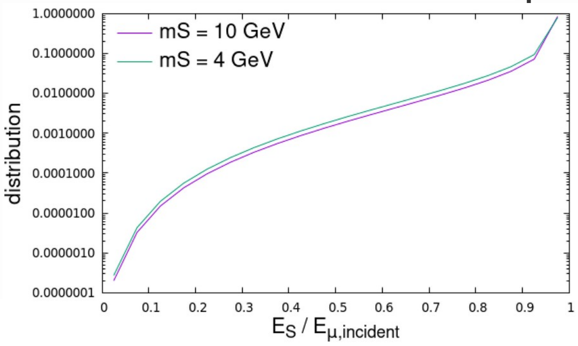


S. Das (with ST), (In preparation)

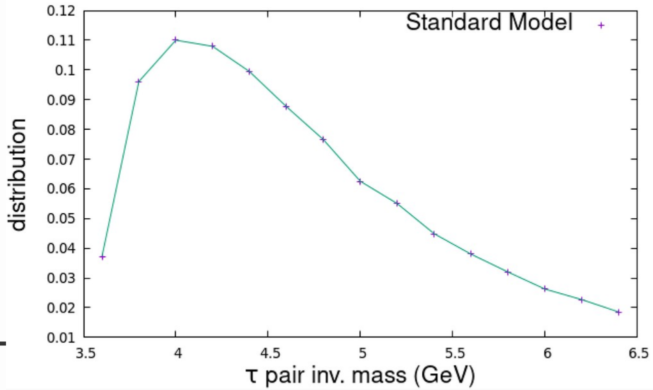
Search for leptophilic scalar

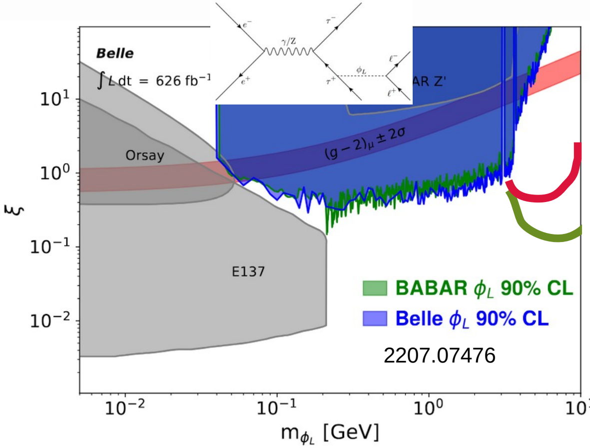
- **S brem (2→3)**
  - High-energy incident muon to produce heavy S
  - Heavy S carries away most of incident μ energy (soft outgoing μ)
  - Different than in the SM process
- **S decays dominantly & promptly into $\tau\ \tau$**
  - Above the di-tau threshold, assuming Yukawa-like couplings
  - Invariant mass of the di-tau system reconstructed from muons
  - Possible resonance search





Preliminary (μ→di-tau prod.)





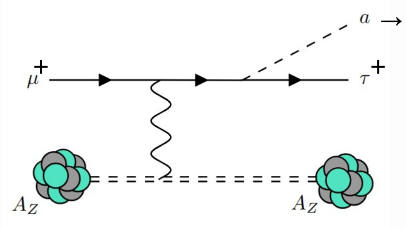
Outgoing E_μ < 10 GeV

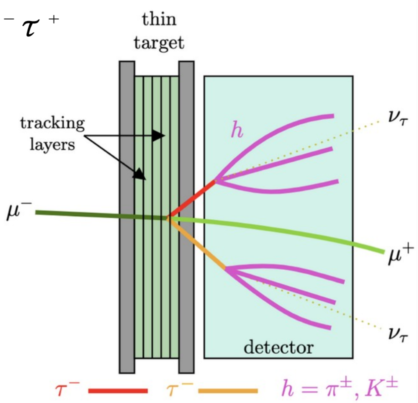
Resonance

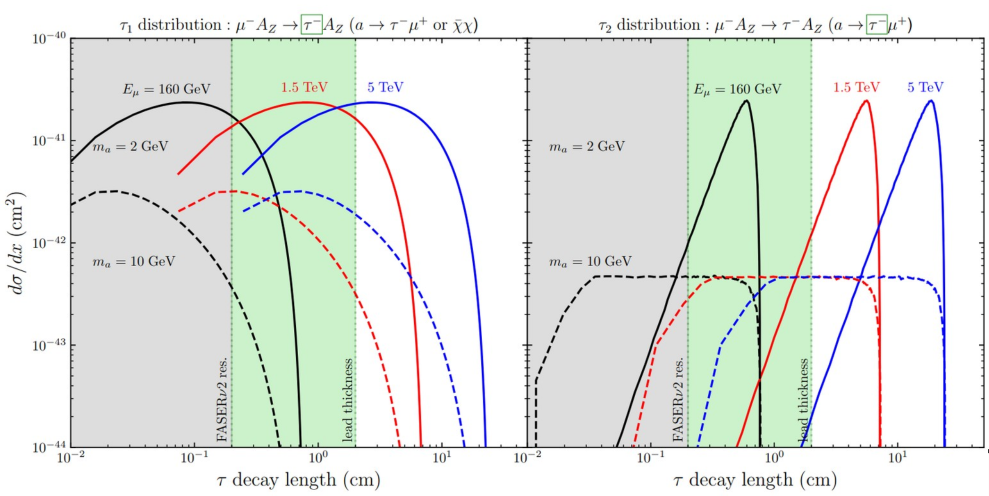
B. Batell etal (with ST), 2407.15942

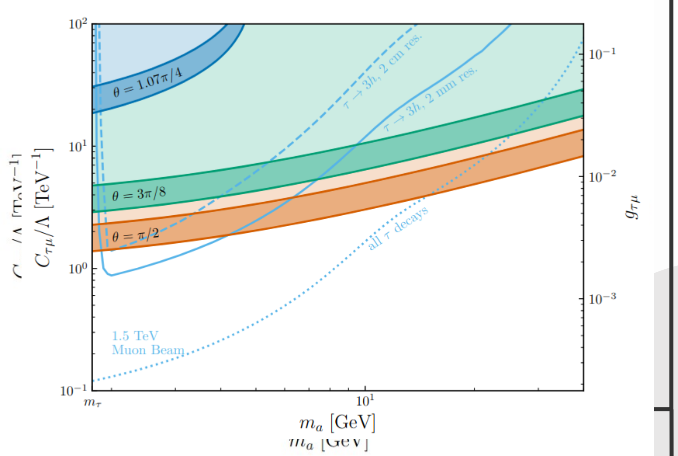
LFV ALPs: muon charge flip signature

- Probe LFV ALPs via muon charge flip
  - 50% chance to flip
  - τ ID needed & incident muon charge
  - O(mm-cm) track precision to reconstruct both intermediate τ tracks before they decay
  - Final state contains additional charged mesons or muons from τ decays
  - Close the gap between $(g-2)_\mu$ and DM bounds with intense ~1TeV μ beam

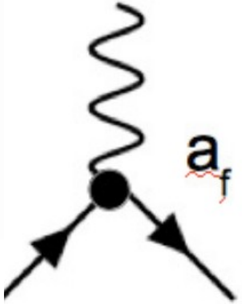








Photon-tau-tau vertex & (g-2)$_\tau$



- General gauge-invariant $\gamma\ \tau\ \tau$ vertex

$$\langle f(p_-)\bar{f}(p_+)|\, J^\mu(0)\,|0\rangle =$$

$$e\,\bar{u}(p_-)\left[\gamma^\mu\ F_1 + \frac{1}{2m_f}(i\,F_2 + F_3\gamma_5)\sigma^{\mu\nu}q_\nu + \left(q^2\gamma^\mu - q^\mu\ \not{q}\right)\gamma_5 F_A\right] v(p_+)$$

charge

dipole

$$d_f = \frac{e}{2m_f}F_3(0),$$

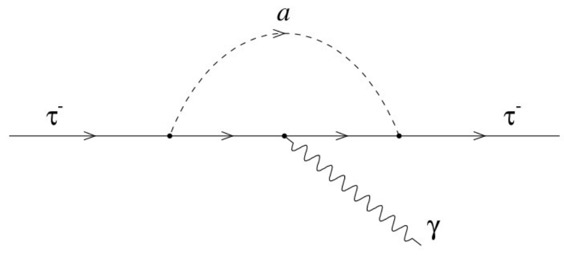
anapole

anomalous magnetic moment

$$F_2(0) = a_f; \quad \mu_f = (1+a_f)\frac{e}{2m_f}$$

- a_τ could be measured in the zero-momentum transfer limit; naive BSM sensitivity $a_\tau / a_\mu \sim m_\tau^2/m_\mu^2$
- Schwinger term (basic SM prediction) $a_\tau^{\rm SM} = 117\,721\,(5) \times 10^{-8}$. S. Eidelman, M. Passera, 0701260
- CMS bounds $a_\tau = 0.0009^{+0.0032}_{-0.0031}$ CMS PAS SMP-23-005

F_2 as a probe of new physics



- In general, the form factors F_2, F_3 are not probed at strictly $q^2 \to 0$
- The q^2 dependence might indicate new physics

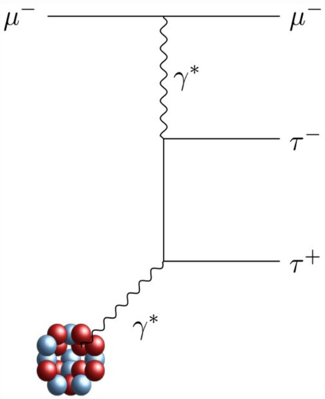
$$\Re[F_2(\theta)] = -\frac{|y_\ell|^2}{4\pi^2 \sinh\theta} \int_0^1 dx \int_0^{\frac{\theta}{2}} dy \frac{x^3 - kx^2}{x^2 + z(1-x)\left(\frac{\sinh y}{\sinh\frac{\theta}{2}}\right)^2}$$

$$z = m_a^2/m_\tau^2,\ \theta = \ln[(1+\beta)/(1-\beta)]/2$$

X. Chen, Y. Wu, 1803.00501

- β is the tau velocity in the $\tau\ \tau$ rest frame
- As $\beta \to 0$, $q^2 \to 0$ (on-shell photons)
- F_2 with BSM scalar contribution decreases for growing β, but...

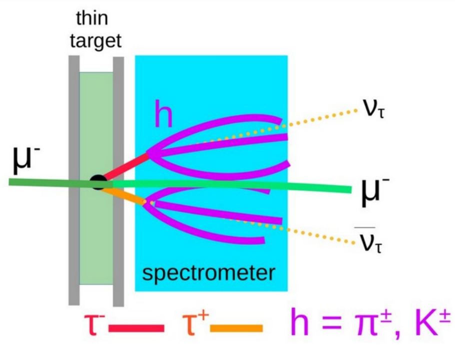
  ...the decrease is slower than the QED form factor in the SM
- Impact on the di-tau production rate and kinematics



τ reconstruction & 0ptimal Observable

- **Reconstructing τ lepton momenta**
  - Measuring all charged tracks in the final state and tau tracks
  - Overconstrained system → access to all momenta

J.H. Kuhn, 9307269



- **Invariant matrix element reconstruction**
- **Optimal Observable** (best constraining power)

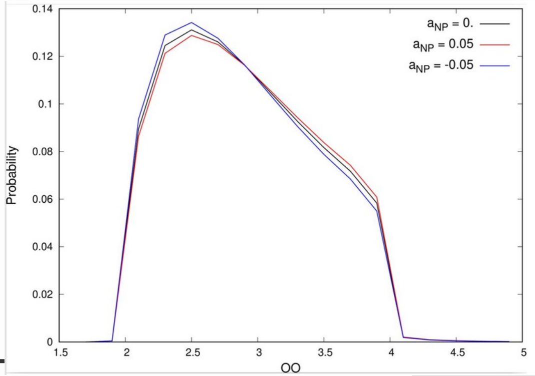
$$\mathcal{OO}^{(i)} \equiv \frac{(M_1^i/\mathrm{GeV})}{M_0^i}$$

D. Atwood etal, 9201381

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

a_τ^{NP} is F_2 form factor contribution from BSM

Preliminary: precision of O(10%) SM value of a_τ

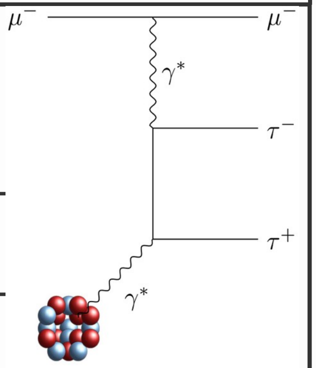


- **OO distribution → powerful tool to constrain new physics**

See also 1803.00501

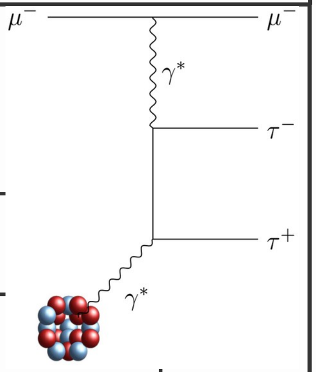
- **In practice: limited by momentum resolution (smearing)**

Summary



Process	Muon-induced Di-Tau Production
Requirements	High-energy & intense muon beam Dedicated detectors (active target, τ ID)
Experiments	One muon beam is sufficient, but can be realized in the forward region of future colliders Intense muon beams currently: SPS, LHC; future: MuCol?, μTRISTAN?
Characteristics	Dominant: coherent scattering off nucleus (relatively clean) Rare in the SM, within the reach of future experiments
BSM	Leptophilic dark sectors: - Resonant search for S → ττ - Muon charge flip (LFV) Impact via a_τ

Summary



Process	Muon-induced Di-Tau Production
Requirements	High-energy & intense muon beam Dedicated detectors (active target, τ ID)
Experiments	One muon beam is sufficient, but can be realized in the forward region of future colliders Intense muon beams currently: SPS, LHC; future: MuCol?, μTRISTAN?
Characteristics	Dominant: coherent scattering off nucleus (relatively clean) Rare in the SM, within the reach of future experiments
BSM	Leptophilic dark sectors: - Resonant search for S → ττ - Muon charge flip (LFV) Impact via a_τ

1) LFV dark matter & neutron stars
Jaime Hoefken Zink talk on Wed

2) Muon-induced forward neutrinos & BSM
Jyotismita Adhikary talk on Wed

T H A N K Y O U !

Funded with the NCN grant: No. 2021/42/E/ST2/00031

BACKUP