# Measurement of the $\tau$ lepton dipole moments exploiting the longitudinal polarization


Joan Ruiz Vidal

IFIC (Universitat de València-CSIC)


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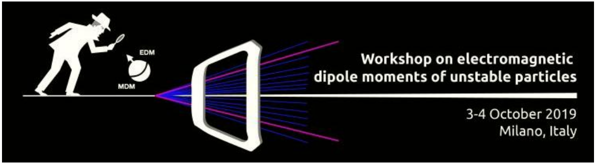
*based on the work of*
J. Fu, M.A. Giorgi, L. Henry, D. Marangotto, F. Martínez Vidal, A. Merli, A. Negre Simó, N. Neri, J.R.V.



# Overview

- Motivation: MDM and EDM of the $\tau$
- Experiment concept
- New challenges
  - Production and initial polarization
  - Polarization extraction
  - Backgrounds
- Possible realization and sensitivity
  - @LHC
  - @SPS
- Conclusions

# Motivation: $\tau$ lepton anomalous magnetic moment

- Astonishing sensitivity on electron and muon $g-2$

$$(g-2)/2_{e} = 0.00115965218091(26) \qquad (g-2)/2_{\mu} = 0.0011659209(6)$$

- Never measured for the $\tau$
  Only modest bounds from DELPHI through $e^+e^- \to e^+e^-\tau^+\tau^-$

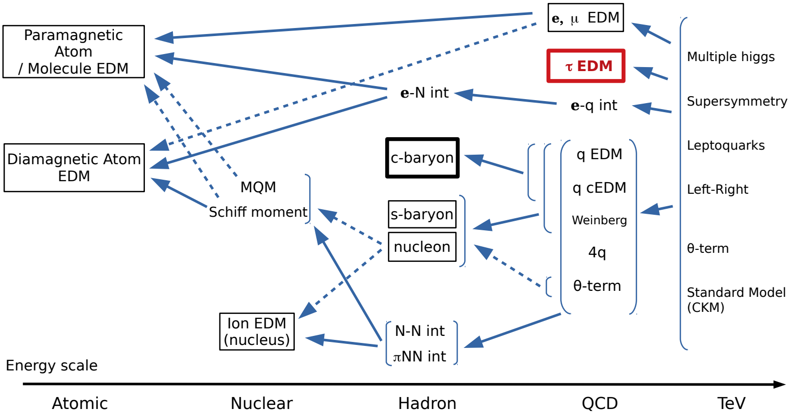
$$-0.052 < (g-2)/2_{\tau} < 0.013$$

- New Physics effects enhanced for heavy fermions, $\propto m^{1,2,3}$

$$m_\tau/m_e \sim 3500 \qquad m_\tau/m_\mu \sim 17$$

- Fundamental particle: free from hadronic uncertainties

# Motivation: EDMs



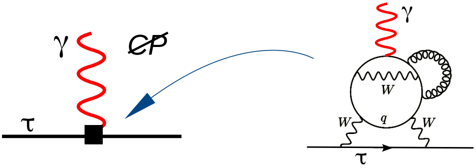

Based on N. Yamanaka. Springer Theses (2014),

- **Any** signal of EDM **originates in new physics** (in current/planned experiments)
- Direct **interpretation** for the $\tau$ EDM

see talks by M.Jung and P.Schmidt-Wellenburg

# Motivation: EDMs

**Standard Model** has its leading contribution at **4-loop** level




PRD 89 (2014) 056006

$d_\tau \sim 10^{-41} e\text{cm}$

negligible

**Beyond SM** predictions

$d_\tau \sim 10^{-17} e\text{cm}$ JHEP 1901 (2019) 069 **Scalar leptoquarks**

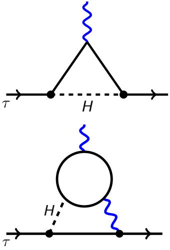
$d_\tau \sim 10^{-17} e\text{cm}$ J.Phys. G40 (2013) 035001 **331 models**

$d_\tau \sim 10^{-17} e\text{cm}$ Mod.Phys.Lett. A25 (2010) 703 **Little Higgs**

$d_\tau \sim 10^{-18} e\text{cm}$ Phys.Rev. D81 (2010) 033007 **Vector-like multiplets**

$d_\tau \sim 10^{-20} e\text{cm}$ EPJ C44 (2005) 411 **2HDM extra dim.**

... ...




Caveats: non-perturbativity of large couplings; not full phenom. analyses

**Indirect bounds**

$d_\tau < 4.5 \times 10^{-17} e\text{cm}$ Phys.Lett. B551 (2003) 16 $e^+e^- \to \tau^+\tau^-$, ang. dist.

$d_\tau \lesssim 5 \times 10^{-17} e\text{cm}$ Nuc.Phys.B 821 (2009) 285 $d_e$ through lbl diagrams

$d_\tau < 3 \times 10^{-17} e\text{cm}$ Nucl.Phys.Proc.S. 189 (2009) 257 $e^+e^- \to \tau^+\tau^-$, total $\sigma$

# Experiment concept: requirements

- A source of **polarized particles**
- **Electromagnetic field** intense enough to induce precession
- A **detector** to measure the polarization

# Experiment concept: requirements

Case of **short-lived $\tau^+$ leptons**

- A source of **polarized particles**

  Weak decays of charmed mesons, $\boldsymbol{D_s^+ \to \tau^+ \nu_\tau}$
  (longitudinal polarization)

- **Electromagnetic field** intense enough to induce precession

  Interatomic electric field
  in **bent crystals**

- A **detector** to measure the polarization

  Full kinematic information of the $3\pi^\pm$ system, $\tau^+ \to 3\pi^\pm \bar{\nu}$,
  in a multi-variate classifier. **Future dedicated experiment**

  PRL 123 (2019) 011801

# Spin precession

- Very short-lived $\rightarrow$ Need large EM field of $\sim 10^3$ T
- Electric field between atomic planes of a bent crystal
- Precession induced by the net EM field

$$s_X \approx -s_{0,Z}\frac{d'}{a'_d}\sin\Phi + s_{0,Y}\frac{d'a'}{{a'_d}^2}\left(1-\cos\Phi\right),$$

$$s_Y \approx s_{0,Z}\frac{a'}{a'_d}\sin\Phi + s_{0,Y}\left(\frac{{d'}^2}{{a'_d}^2}+\frac{{a'}^2}{{a'_d}^2}\cos\Phi\right),$$

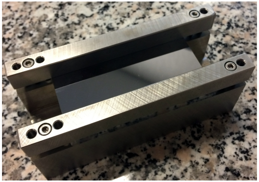
$$s_Z \approx s_{0,Z}\cos\Phi - s_{0,Y}\frac{a'}{a'_d}\sin\Phi,$$

$$a' = a + \frac{1}{1+\gamma},$$

$$d' = d/2,$$

$$a'_d = \sqrt{{a'}^2+{d'}^2},$$

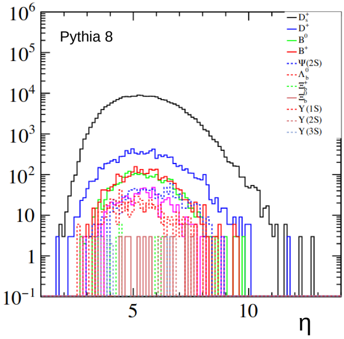
$$\Phi = \gamma\theta_C a'_d$$



# Production and initial polarization

## Production of $\tau$'s

- Similar experiment concept proposed initially using $B^+ \to \tau^+ \nu_\tau$ PRL 67 (1991) 668
- $D_s^+ \to \tau^+ \nu_\tau$ vastly dominates the $\tau$ production in hadronic machines
- Simulations in Pythia 8 with p-target collisions at 115 GeV in c.m.



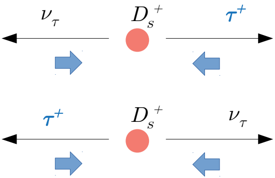

- Production channel in agreement with JHEP03 (2019) 156 , see Fomin's talk

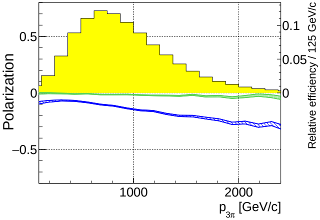
# Production and initial polarization

## Initial polarization

- $\tau^+$ polarization well defined in the $D_s^+$ rest frame.
- Not accessible from the lab frame due to missing energy
  $\rightarrow$ use kinematical constraints to enrich the polarization

## Longitudinal polarization, $s_z$

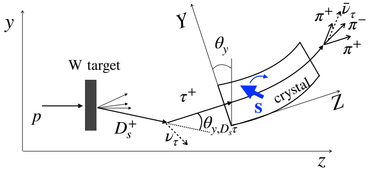


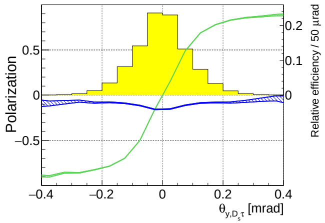




- Momentum cut (required for bkg separation) + channeling conditions
  $\rightarrow$ select a sample of $\tau$'s with $s_z \sim$ -18 %

# Production: Tagging for transverse polarization

## Transvere polarization, $s_y$



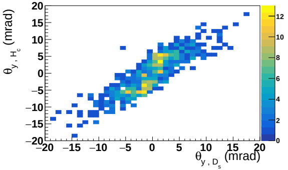

- The transverse polarization is highly **correlated to** $\theta_{\mathbf{y},\mathbf{D_s}\tau}$
- Variable in the **invisible part of the event** (only $\nu_\tau$ associated to the vertex)
- Use the rest of the event to get statistical information on the $D_s$ direction: $\theta_{\mathbf{y},\mathbf{D_s}}$**-tagging**
- Alternatively: double-crystal scheme to fix $D_s$ direction
  see Fomin's talk

# Production: Tagging for transverse polarization II

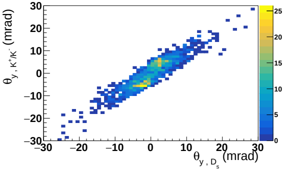
Very preliminar

- The $\theta_{\mathbf{y},\mathbf{D_s}}$ angle is correlated to the $\theta_{\mathbf{y},\mathbf{X}}$ of other particles from the same origin vertex

$X =$ *charm hadron*




$X =$ charged tracks




- Correlations of $\approx 85\%$!
- Tagging efficiency defined through the sign ($\theta^+_{y,D_s}/\theta^+_{y,X}$ ✓ $\theta^+_{y,D_s}/\theta^-_{y,X}$ $\times$)
- Fixing the $\tau$ direction to the crystal axis $\pm$ lindhard angle (channeled $\tau$'s) $\rightarrow$ vertical window on $\theta_{y,D_s}$ $\rightarrow$ dilutes correlations
- **WIP**: Combination of several taggers & MVA techniques

# Production and initial polarization

Estimation of the sensitivity

- From the spin equations of motion (TBMT)
- Assuming small precession angle $\Phi$

**Longitudinal polarization**, $s_{0,Z}$

$$\sigma_a \approx \frac{1}{S_Y s_{0,Z} \gamma \theta_C} \frac{1}{\sqrt{N_{\tau^+}^{\text{rec}}}}, \quad \sigma_d \approx \frac{2}{S_X s_{0,Z} \gamma \theta_C} \frac{1}{\sqrt{N_{\tau^+}^{\text{rec}}}}.$$

**Transverse polarization**, $s_{0,Y}$

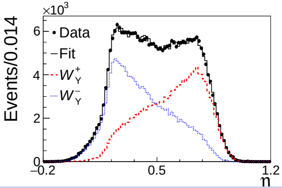
$$\sigma_a \approx \frac{1}{S_Z s_{0,Y} \gamma \theta_C} \frac{1}{\sqrt{N_{\tau^+}^{\text{rec}}}}, \quad \sigma_d \approx \frac{2}{S_X s_{0,Y} (\gamma \theta_C)^2 a'} \frac{1}{\sqrt{N_{\tau^+}^{\text{rec}}}},$$

Best sensitivity to $\tau$ **EDM** achived only with **longitudinal polarization**.
Factor of difference $1/(\gamma \theta_C a') \sim 100$

# Polarization reconstruction

See talk Marangotto's talk

- Kinematics of the $\tau^+$ decay cannot be fully reconstructed: Known methods in the literature cannot be applied
- Use a **multivariate classifier** with the available information.
  - Sensitive variables:
    - angles between $p_{3\pi}$ in $\tau^+$ rest frame and crystal axes
    - angles of $3\pi$ plane in $3\pi$ rest frame and crystal axes
    - $m(2\pi^\pm)$, $m(3\pi^\pm)$
  - Training samples
    - Events with full $\pm1$ polarization along the 3 crystal axes (3 classifiers)
  - Classifier response:
    - 1-D variable $\eta$
    - Functions $\mathcal{W}_i^+(\eta)$ and $\mathcal{W}_i^-(\eta)$ for $\pm$ polarization (*templates*)

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# Polarization reconstruction

See Marangotto's talk

- **Extract the polarization**
  - Display the data in $\eta$
  - Fit to the combination of $\mathcal{W}_i^+(\eta)$ and $\mathcal{W}_i^-(\eta)$

$$\mathcal{W}_i(\eta) = \frac{1}{2}\left[(1+s_i)\mathcal{W}_i^+(\eta) + (1-s_i)\mathcal{W}_i^-(\eta)\right],$$

  - The relative weight determines the sample polarization $s_i$

- **Event information**
  - The separation between $\mathcal{W}_i^+(\eta)$ and $\mathcal{W}_i^-(\eta)$ accounts for the uncertainty on $s_i$

$$S_i^2 = \frac{1}{N_{\tau^+}^{\mathrm{rec}}\sigma_i^2} = \left\langle \left( \frac{\mathcal{W}_i^+(\eta) - \mathcal{W}_i^-(\eta)}{\mathcal{W}_i^+(\eta) + \mathcal{W}_i^-(\eta)} \right)^2 \right\rangle$$

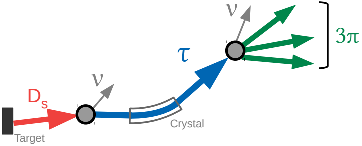
  - Achieved event information

$$S_X \approx S_Y \approx 0.42 \quad , \qquad S_Z \approx 0.23$$

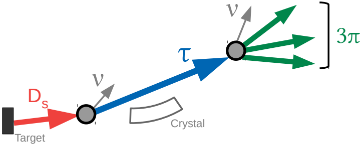
Ideal case, with complete event kinematics, $S_i = 0.58$

# Background categories

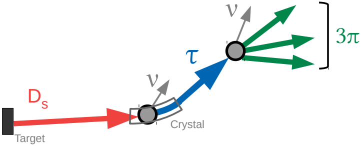
- $\tau^+$-*backgrounds*:
  Signal decays $D_s^+ \to \tau^+[3\pi^\pm\bar{\nu_\tau}]\nu_\tau$ which aren't fully channeled
- *physical backgrounds*:
  Other modes (e.g. $D^+ \to 3\pi^\pm\pi^0$) with similar signature



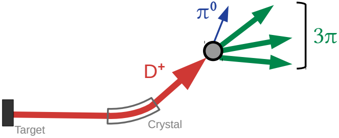

signal




crystal-transparent



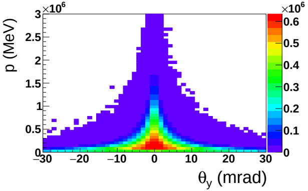

partially-channeled



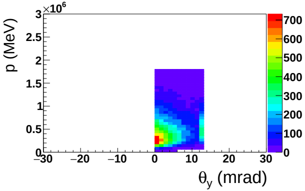

physical backgrounds

# $\tau$-backgrounds

crystal-transparent




crystal-induced (incl. fully-channeled)

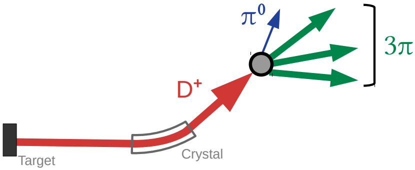



- Cuts: $p_{3\pi} > 800\text{GeV/c}$ , $\theta_y \in \theta_C \pm 1.5\text{mrad}$ , decay vertex after the crystal
- Partially-channeled background
  - $\tau^+$ produced inside the crystal, $p \lesssim 800\text{GeV}$
  - $\tau^+$ decaying inside the crystal, $\theta_y < \theta_C$
  - $\tau^+$ dechanneled $\theta_y < \theta_C$
  - (Combinations of the above)

This contamination is almost fully channeled $\rightarrow$ similar spin precession

| *Signal gain* | Small precession bias |
|---|---|
| $+39\%$ | $\approx 1.4\%$ |

# Physical backgrounds



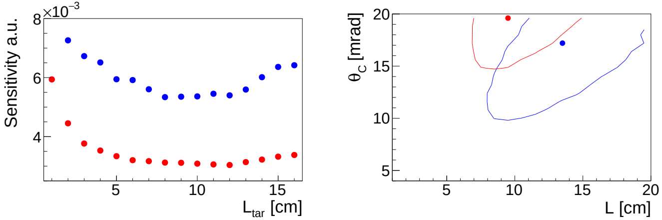

| Mother | channel |
|---|---|
| $D^+$ | $D^+ \to 2\pi^+\pi^-\pi^0/\gamma$ |
| | $D^+ \to 2\pi^+\pi^-\pi^0\pi^0/\gamma$ |
| | $D^+ \to 2\pi^+\pi^- K^0_S$ |
| $D^+_s$ | $D^+_s \to 2\pi^+\pi^-\pi^0/\gamma$ |
| | $D^+_s \to 2\pi^+\pi^-\pi^0\pi^0/\gamma$ |
| | $D^+_s \to 2\pi^+\pi^- K^0_S$ |
| | $D^+_s \to 2\pi^+\pi^-\phi[\to K^0_L K^0_S]$ |
| $\Lambda^+_c$ | $\Lambda^+_c \to 2\pi^+\pi^-\Lambda$ |
| | $\Lambda^+_c \to 2\pi^+\pi^-\pi^0\Lambda$ |
| | $\Lambda^+_c \to 2\pi^+\pi^-\Sigma^0$ |

- Background discrimination strongly depends on the final setup
- **target-crystal separation**: Can be optimized to favor long decays ($D^+_s$ + $\tau^+$)
- High granularity calorimeters: Reconstruct and **veto neutral particles**
- **PID systems**: avoid contamination from other charged particles $\neq \pi^\pm$

**Work in progress**

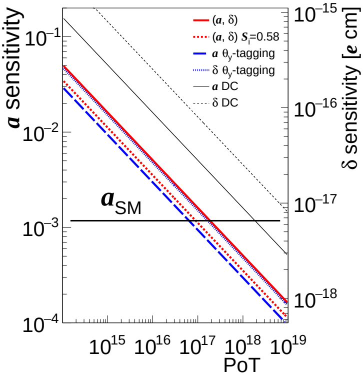
# Optimization

- Optimization of the setup based on final sensitivity
  - Multi-dimensional with fast simulations
  - Step-by-step scans with full simulations (Pythia+EvtGen)
    → in agreement
  - Variables:
    - ★ $p_{3\pi}$ cut
    - ★ crystal tilt wrt beam
    - ★ target-crystal distance ($L_{tar}$)
    - ★ crystal length (L)
    - ★ bending ($\theta_c$)




Sensitivity scans for crystals made of **Germanium** and **Silicon**

# Sensitivity @LHC




Parameters of the optimal setup for Si (Ge)

$$p_{3\pi} > 800 \text{ GeV/c}$$

$$\text{tilt} = 0.1 \text{ mrad} \qquad L_{tar} = 12\text{cm}$$

$$\theta_C = 16 \text{ mrad} \qquad L = 8(11) \text{ cm}$$

- The SM prediction of the $\tau$ MDM with $10^{17}$ protons on target
- EDM of the $\tau$ probed below $10^{-17}\,e\,\text{cm}$ with the same data set

- $10^{17}$ protons ≈ 10% of LHC protons during a decade of operation

# Possibilities @SPS

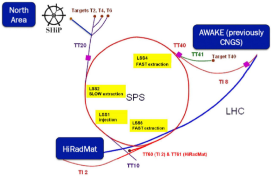
- Higher proton flux potentially available

M.Lamont IPAC2017 (TUPVA126)

CERN-PBC-REPORT-2018-007

Table 1: Key Beam Parameters Foreseen for SHiP

| | |
|---|---|
| Momentum [GeV/c] | 400 |
| Beam Intensity per cycle [$10^{13}$] | 4.2 |
| Cycle length [s] | 7.2 |
| Spill duration [s] | 1 |
| Expected r.m.s. spot size (H/V) [mm] | 6/6 |
| Avg. beam power on target [kW] | 400 |
| Avg. beam power on target during spill [kW] | 2900 |
| Protons on target (POT)/year | $4\times10^{19}$ |
| Total POT in 5 year's data taking | $2\times10^{20}$ |




- Smaller energies $E_p = 400$ GeV/c $\quad (\gamma_{SPS}/\gamma_{LHC} \approx 6\%)$
- $(\rightarrow)$ Smaller charm prod. $\sigma(pp \rightarrow c\bar{c}@SPS) \approx 91.1\mu$b, $\quad (\sigma^{c\bar{c}}_{SPS}/\sigma^{c\bar{c}}_{LHC} \approx 24\%)$
- $(\rightarrow)$ Smaller flight distance (shorter crystals? coupled to channeling eff.)
- $(\rightarrow)$ Larger angular spread $\propto 1/\gamma$ $\quad\rightarrow$ smaller trapping efficiency

Many effects $\rightarrow$ need a **full optimization study**

# Sensitivity @SPS

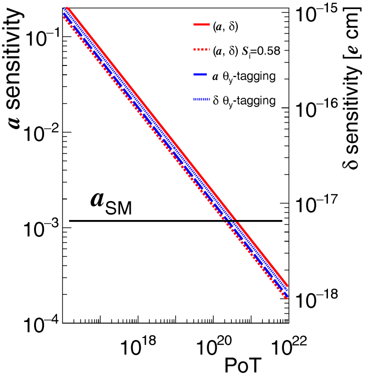
Very preliminar

Optimal setup parameters for Ge

$$p_{3\pi} > 60 \text{ GeV/c}$$

$$\text{tilt} = 1 \text{ mrad} \qquad L_{tar} = 0.25\text{cm}$$

$$\theta_C = 36 \text{ mrad} \qquad L = 1.25 \text{ cm}$$




1 LHC proton
≈ 2500 SPS protons

- SM prediction of $(g-2)_\tau$ tested with $10^{21}$ protons on target
- EDM of the $\tau$ probed below $10^{-17} e\,\text{cm}$ with the same data set

# Conclusions

- Direct spin precession on **$\tau$ leptons**
- First direct measurement of the anomalous magnetic moment $(\boldsymbol{g-2})_{\tau}$
- First direct **EDM** search , at $\approx 10^{-17}$ecm with $10^{17}$ PoT at the LHC

PRL 123 (2019) 011801

Different studies in progress:

- Possibilities at the SPS
- Determination of $D_s$ direction $\rightarrow$ improvement of $g-2$ sensitivity
- Rejection of physical backgrounds with cutting-edge detector technologies