ETH zürich

IPA

Progress on the true muonium front

PBC general meeting 03.12.2021

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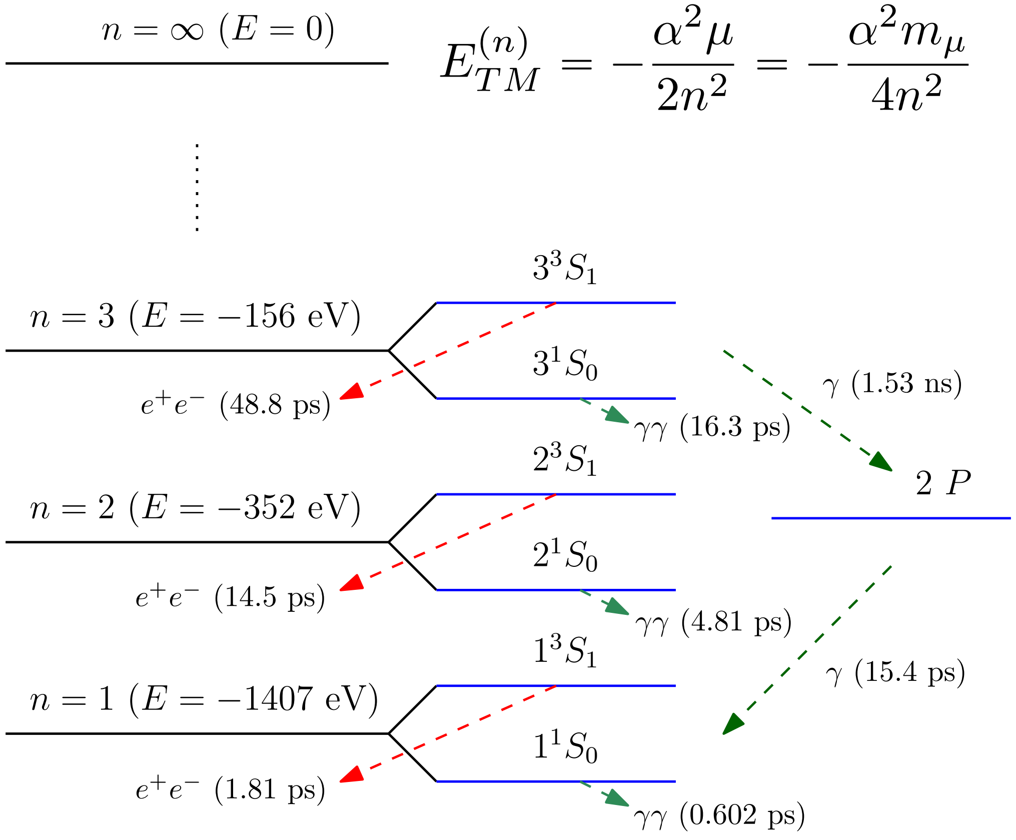
TRUE MUONIUM- properties

BOUND STATE OF μ+μ- VERY COMPACT QED OBJECT

$$a^0_{TM} = 2/(\alpha m_\mu) \simeq 512 \text{ fm}$$

$$\mu = m_\mu/2 \simeq 53 \text{ MeV}$$

$$E^{(n)}_{TM} = -\frac{\alpha^2 \mu}{2n^2} = -\frac{\alpha^2 m_\mu}{4n^2}$$



For a review on the theory see e.g H. Lamm and Y. Ji, EPJ Web Conf. 181 (2018) 01016, [arXiv:1712.0342].

$$E_{n,l,j,s} = -\frac{m_\mu \alpha^2}{4n^2} + m_\mu \alpha^4 \Big[C_0 + C_1 \frac{\alpha}{\pi} + C_{21}\alpha^2 \ln\left(\frac{1}{\alpha}\right) + C_{20}\left(\frac{\alpha}{\pi}\right)^2 + C_{32}\frac{\alpha^3}{\pi}\ln^2\left(\frac{1}{\alpha}\right) + C_{31}\frac{\alpha^3}{\pi}\ln\left(\frac{1}{\alpha}\right) + C_{30}\left(\frac{\alpha}{\pi}\right)^3 + \cdots \Big],$$

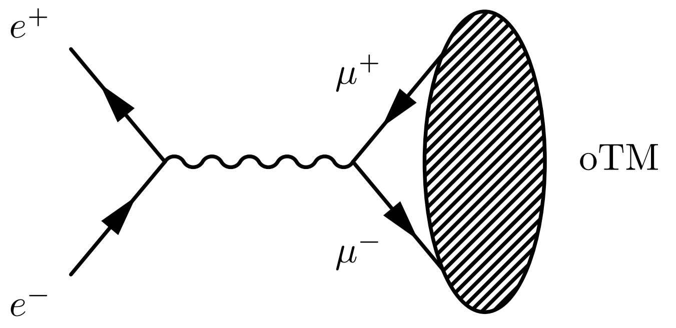
C_{ij} indicate the coefficient of the term proportional to $(\alpha)^i \ln^j(1/\alpha)$

ENHANCED SENSITIVITY TO BSM
compared to Ps,M which are limited by mass suppression $\mathcal{O}(m_e/\Lambda_{BSM})$
or uncertainties of nuclear effects (H, μH)

the triplet, ortho-true-muonium $(o - TM)$, 1^3S_1 with $J^{PC} = 1^{--}$
the singlet, para-true-muonium $(p - TM)$, 1^1S_0 with $J^{PC} = 0^{-+}$

1) PRODUCTION OF TM via annihilation channel at SPS-H4

RATIO DIMUON **PAIR VS BOUND STATES** PRODUCTION



$$R = \frac{\sigma^{e^+e^-\to\mu^+\mu^-}(s_B)}{\sigma_{\rm rel}^{e^+e^-\to\mu^+\mu^-}(s_B)} \simeq \frac{\sigma^{e^+e^-\to(\mu^+\mu^-)}}{\sigma_{\rm rel}^{e^+e^-\to\mu^+\mu^-}} \simeq \frac{3\pi\alpha}{2} \simeq 0.03$$

S. J. Brodsky and R. F. Lebed,, Phys. Rev. Lett. 102 (2009) 213401

In **fixed targets**

$$\sigma^{e^+e^-\to\mu^+\mu^-}(E_+) = \frac{2\pi^3\alpha^2}{m_\mu^2}\sqrt{1-\frac{E_{\rm th}}{E_+}} = \frac{2\pi^4\alpha^3}{\mu^2} \simeq 2.65\cdot 10^{-30}\ {\rm cm}^2$$

Production of **TM** close to threshold in **FIXED TARGET** experiments

$$\sigma_{(n)}^{e^+e^-\to(\mu^+\mu^-)}(E_+) = \frac{3\pi\alpha}{2}\frac{\delta E_n}{\Delta E_+} \times \sigma^{e^+e^-\to\mu^+\mu^-}(E_+) \simeq \frac{\delta E_n}{\Delta E_+} \times 9.11\cdot 10^{-32}\ {\rm cm}^2$$

where $\delta E_n = \alpha^2 m_\mu/(4n^2)$ is the effective energy window to produce the bound states and ΔE the beam energy resolution

H4 A UNIQUE BEAMLINE:
- $>10^7$ POSITRONS per spill @43.7 GeV with (dp/p<1%)

See TALK of Nikos C.

Estimated **RATE** OF TM ~*O*(1) event/month (target optimisation ongoing)

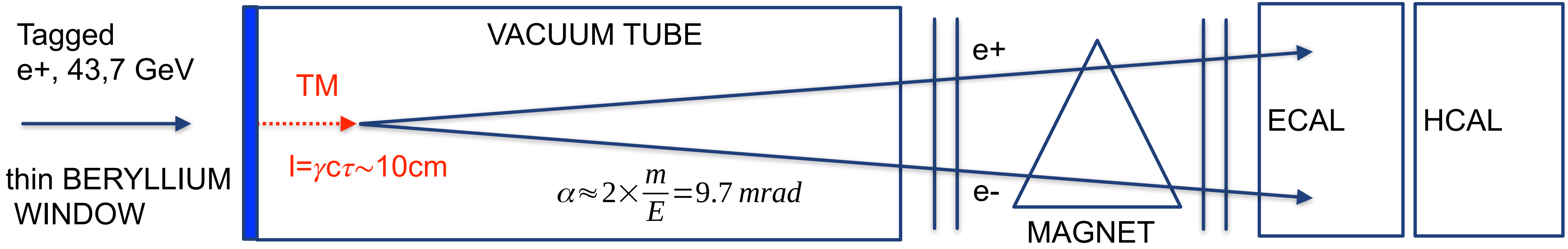
DETECTION OF TM IN NA64 VISIBLE SETUP (X17- search)

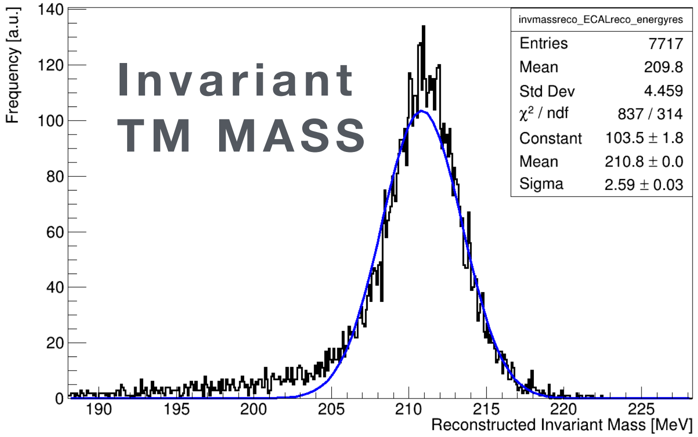
Phys.Rev.Lett. 120 (2018) 23, 231802, *Phys.Rev.D* 101 (2020) 7, 071101, *Eur.Phys.J.C* 80 (2020) 12, 1159

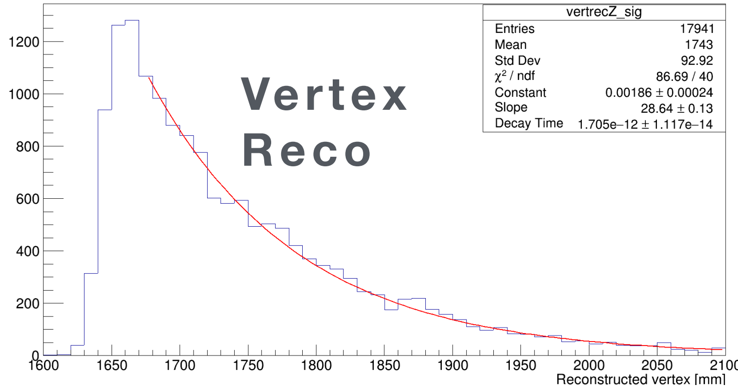
See NA64-TALK of Dima K.

SIGNATURE:

1) HIGH P_T e^+e^- PAIR WITH $2m_\mu$ INVARIANT MASS
2) RECONSTRUCTED DISPLACED VERTEX







PRELIMINARY CONCLUSION

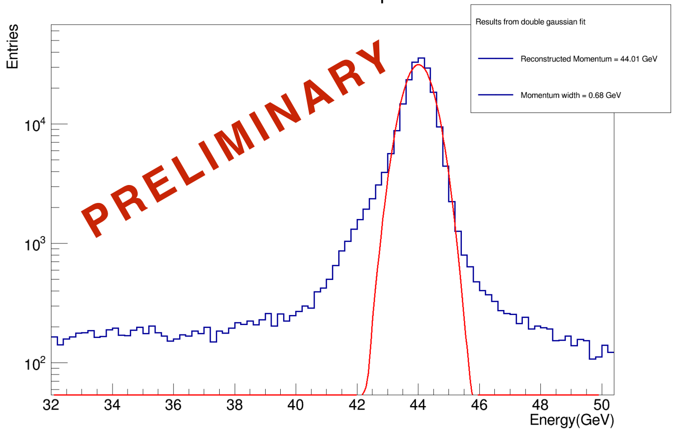
The experiment is background free at a level of 10^{12} positrons on target. The efficiency of detection is estimated to be 40%.

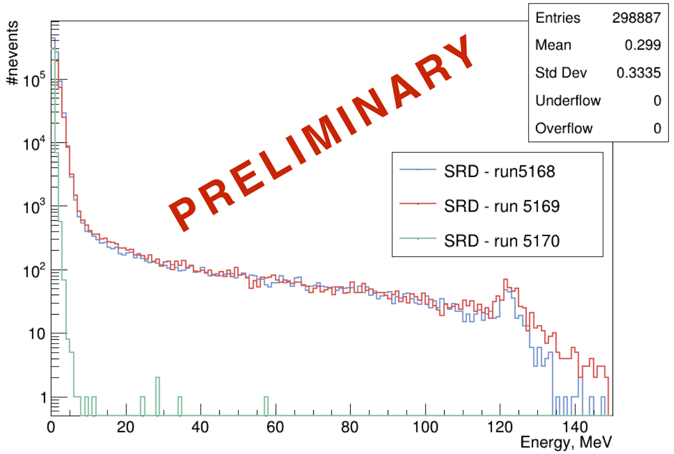
UPDATE- 43.7 GeV positron beam in H4 at SPS

1st QUICK TEST (2 hours) DURING NA64 BEAMTIME (September 2021)

GOAL: Cross check beam simulation, i.e. **positron intensity, momentum resolution** and measure **hadron contamination**

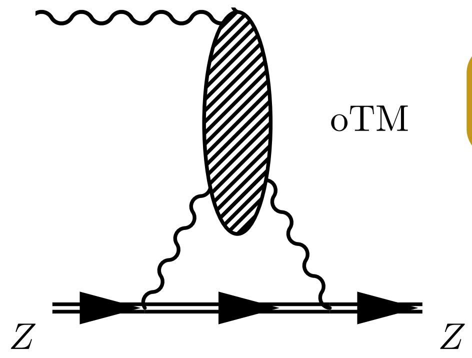
Run	Type	Spills	Intensity
5168	e^+	30	1.7×10^6
5169	e^+	20	7.7×10^6
5170	hadron	90	5×10^3





Preliminary results are encouraging: ~10^7 POSITRONS per spill @43.7 GeV with (dp/p<1%). New measurements in 2022 are planned including background measurements in visible setup.

2) "Low energy" TM production @ the GAMMA Factory



CROSS SECTION FOR oTM PRODUCTION FOR E>>m_μ:

$$\sigma_{\gamma Z} = Z^2 \times 2.4 \cdot 10^{-39}\mathrm{cm}^2$$

Ginzburg, et al., Phys. Rev. C58, 3565 (1998)

Dimuons production in G4 now extended down to the muon pair production threshold on request of GF design group

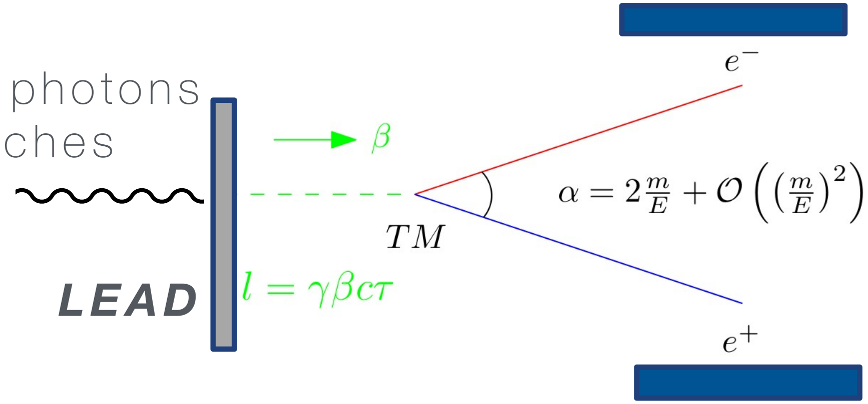
EPJ Web of Conferences **245**, 02009 (2020)

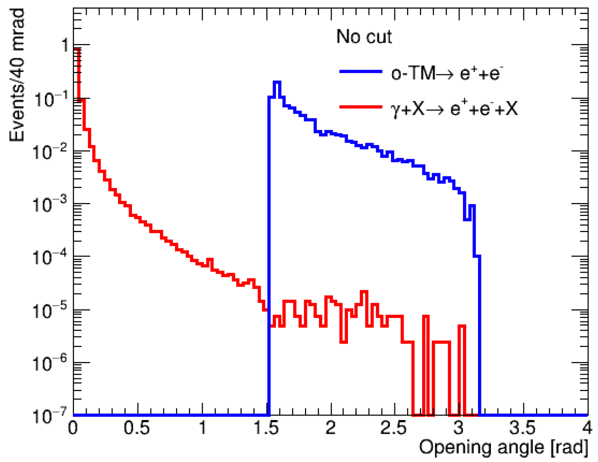
Production & detection of **TM** at GAMMA FACTORY:

See GF-TALK of M. Gorshteyn

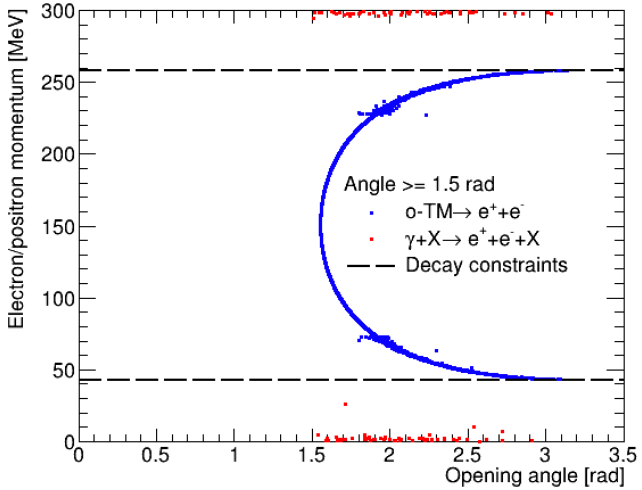
TRACKERS& DETECTORS

300 MeV 10^9 photons in 500 ps bunches at 20 MHz





10^{11} photons



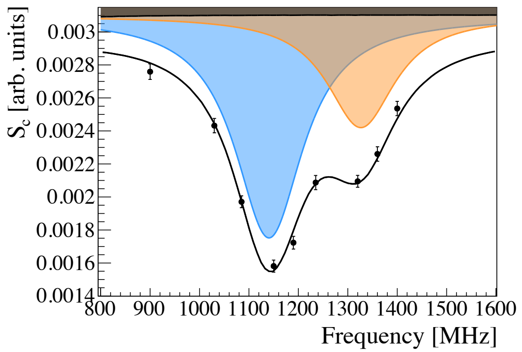
Estimated **RATE** OF ~***O*(10^{4-5}) TM (1^3S_1)/day** and ~***O*(10^{2-3}) TM(2^3S_1)/day**

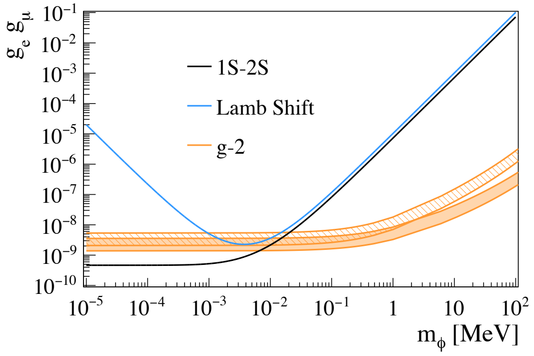
MEASUREMENT OF TM LAMB SHIFT AND FINE AND HFS STRUCTURE

Similar measurement
as for μ^+e^-

PAUL SCHERRER INSTITUT PSI

~~TRUE~~ MUONIUM





https://arxiv.org/abs/2108.12891

TRUE MUONIUM TRANSITIONS:

Transition	E_{theory} [MHz]
$1^3S_1 - 1^1S_0$	$42329355(51)_{had}(700)$
$2^3S_1 - 1^3S_1$	$2.550014(16) \times 10^{11}$
$2^3P_0 - 2^3S_1$	$1.002(3) \times 10^7$
$2^3P_1 - 2^3S_1$	$1.115(3) \times 10^7$
$2^3P_2 - 2^3S_1$	$1.206(3) \times 10^7$
$2^1P_1 - 2^3S_1$	$1.153(3) \times 10^7$

42 THz **HFS accessible via 7 micron LASER**
(e.g. with Quantum Cascade Lasers,P. Täschler et al., *Nat. Photon.* **15,** 919–924 (2021).)
Natural line width of 350 GHz

LS 10 THz, Natural line width of 20 GHz

SIGNATURE HFS or 2S-2P TRANSITIONS: COUNT NUMBER OF HIGH P_T e^+e^- PAIRS VS LASER FREQUENCY

SUMMARY AND OUTLOOK

- Feasibility of TM DETECTION WITH NA64 VISIBLE SETUP:

  - analysis of H4 with 43.7 GeV positrons ongoing,

  - cross check simulation with data on NA64 visible setup (2022)

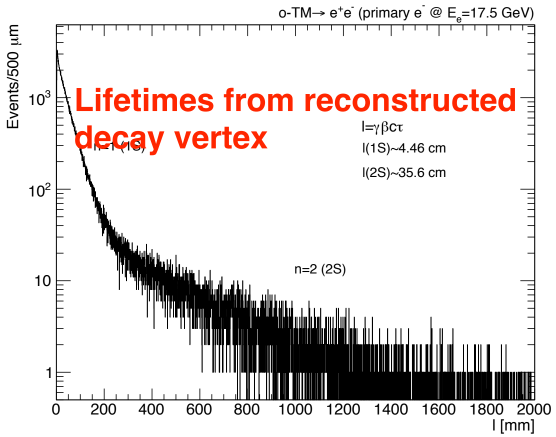
- Proof of principle in NA64 for measuring TM properties @ FUTURE CERN FACILITIES

e.g @LEMMA in beam dump mode: for 10^{16} e^+, dE=1 MeV, 10^4 TM

M. Boscolo et al. Phys.Rev.Accel.Beams 21 (2018) 6, 061005 N. Amapane *et al* 2020 *JINST* **15** P01036

or @GAMMA FACTORY (10^{17} gamma/s @up to 400MeV),10^{4-5} TM/day"

Precision study of TM properties such as decay rate, Lamb shift, Fine and HFS structure



IN PBC CONTEXT

- Complementarity of TM to search for NP in muonic sector
- Synergies (simulation/detectors/calculations) with other projects at the high intensity frontier

Acknowledgments

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