True Muonium in fixed target experiments at current and future CERN facilities

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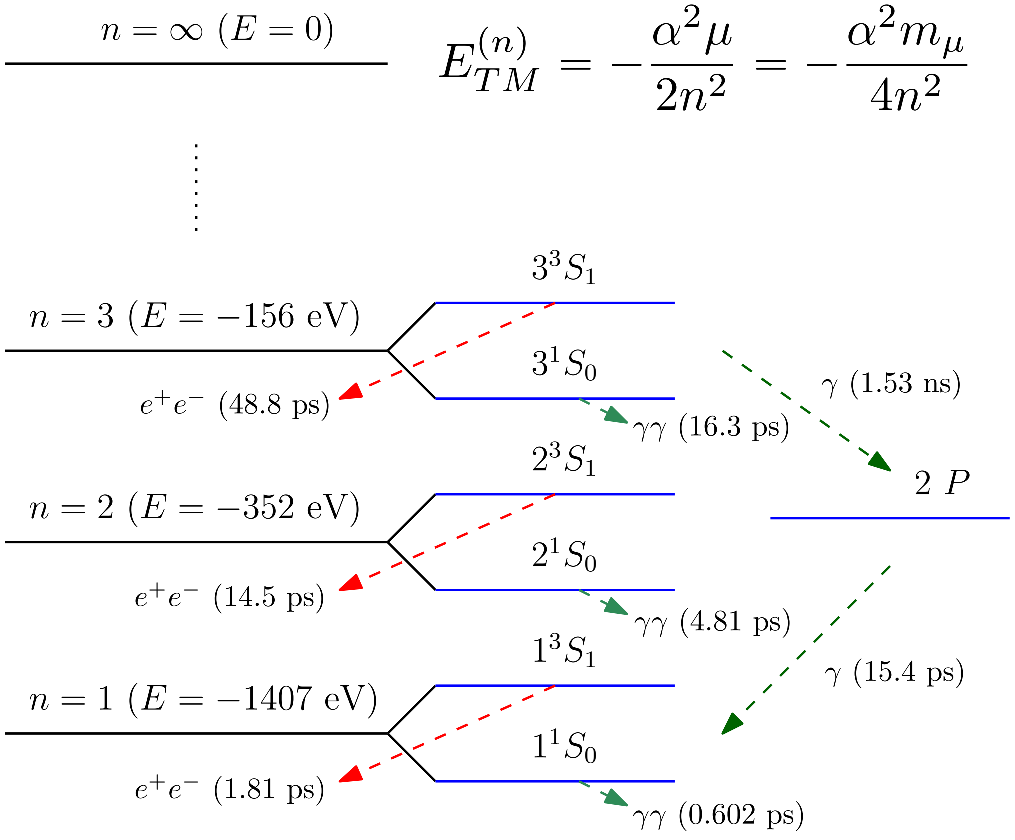
TRUE MUONIUM- properties

BOUND STATE OF μ+μ- VERY COMPACT QED OBJECT

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

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



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

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 $J^{PC} = 0^{-+}$

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,Mu which are
limited by mass suppression $\mathcal{O}(m_e/\Lambda_{BSM})$
or uncertainties of nuclear effects (H, μH)

PRODUCTION OF TM

MANY INTERESTING PROPOSALS:

$\pi p \to (\mu^+\mu^-)n,\ \gamma Z \to (\mu^+\mu^-)Z$ S.M. Bilenky, V.H. Nguyen, L.L. Nemenov, F.G. Tkebuchava, Yad. Fiz. 10, 812 (1969)

$eZ \to e(\mu^+\mu^-)$ Z E. Holvik, H.A. Olsen, Phys. Rev. D35, 2124 (1987)
and more recently at **fixed target (HPS@JLAB)**. A. Banburski, P. Schuster, Phys. Rev. D86, 093007 (2012)

$\mu^+\mu^- \to (\mu^+\mu^-)$ V. Hughes, B. Maglic, Bull. Am. Phys. Soc. 16, 65 (1971)

$e^+e^- \to (\mu^+\mu^-)$ **at Fool's Intersection Storage Rings**, S.J. Brodsky, R.F. Lebed, Phys. Rev. Lett. 102, 213401 (2009)

$e^+e^- \to (\mu^+\mu^-)\gamma$ S.J. Brodsky, R.F. Lebed, Phys. Rev. Lett. 102, 213401 (2009)

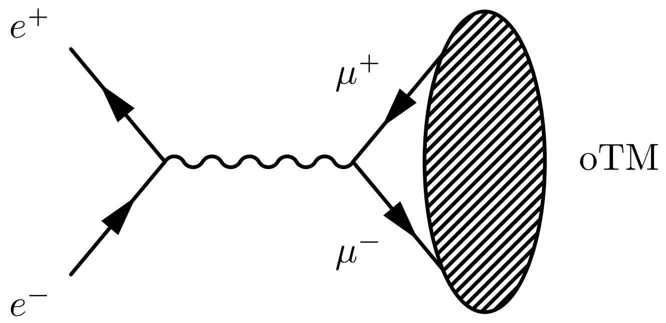
$\eta \to (\mu^+\mu^-)\gamma$ L. Nemenov, Yad. Fiz. 15, 1047 (1972), G. Kozlov, Sov. J. Nucl. Phys. 48, 167 (1988)
and **recently proposed for TM in LHCb,** Vidal et al. Phys. Rev. D 100, 053003 (2019)

$K_L \to (\mu^+\mu^-)\gamma$ J. Malenfant, Phys. Rev. D36, 863 (1987), Y. Ji and H. Lamm, Phys. Rev. D 98, 053008 (2018)

$Z_1Z_2 \to Z_1Z_2(\mu^+\mu^-)$ Ginzburg, U. Jentschura, S.G. Karshenboim, F. Krauss, V. Serbo et al., Phys. Rev. C58, 3565 (1998)

$q^+q^- \to (\mu^+\mu^-)g$ Y. Chen, P. Zhuang (2012), 1204.4389

1) PRODUCTION OF TM via annihilation channel at fixed targets



RATIO DIMUON **PAIR VS BOUND STATES** PRODUCTION

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

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

In **fixed targets**

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

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

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

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

σ ~ 6 orders of magnitude larger than $eZ \to e(\mu^+\mu^-)$ or $\pi p \to (\mu^+\mu^-)n$

PRODUCTION OF TM @ CERN SPS H4 beamline

PRODUCTION **RATE** OF TM

$$\frac{dN}{dt} = \Phi \cdot n \cdot L \cdot \sigma_p$$

To learn more about SPS secondary beams
see L. Gatignon CERN-ACC-NOTE-2020-004

where Φ is the flux of incoming particle per unit of time, n and L respectively the target density (number of electrons per unit volume) and target length.

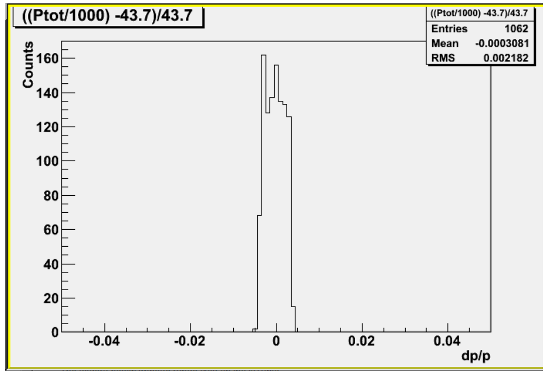
H4 A UNIQUE BEAMLINE:

- 1x10^7 POSITRONS per spill @43.7 GeV with (dp/p~1%) for 40 proton units on T2

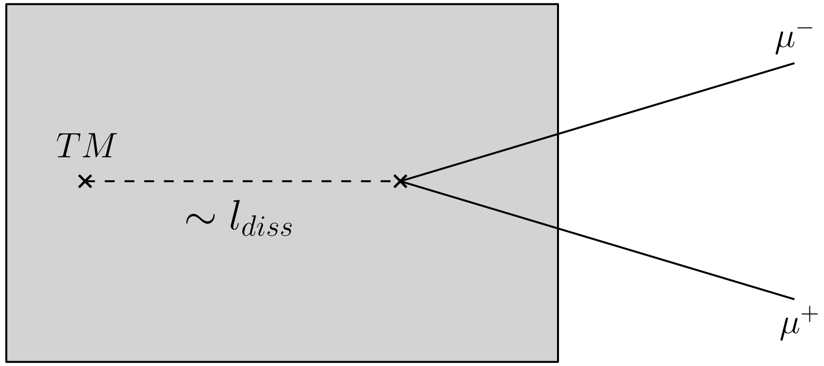
Estimated **RATE** OF TM ~$O(1)$ event/month (target optimisation ongoing)

Preliminary simulation (N. Charitonidis) very encouraging dp/p well below 1% should be achievable with moderate loss in the e$^+$ rate. **To be validated with measurements** during NA64 positron test beam at H4.

Possible **improvement of H4 flux** would require dedicated study.



DISSOCIATION OF TM



COLLINEAR DIMUON PAIRS

TM dissociation length

$$l_{\text{diss}} = \frac{1}{n\sigma_{\text{diss}}} = \frac{M}{\mathcal{N}_A \times \rho \times \sigma(\mu^+\mu^- + Z \to \mu^+ + \mu^- + Z)}$$

Dissociation **CROSS SECTION**

$$\sigma_{\text{diss}} \simeq Z^2 \times 1.3 \cdot 10^{-23}\ \text{cm}^2$$

	l_{diss} [cm]	X_0 [cm]	l/X_0
Pb	$3.71 \cdot 10^{-4}$	0.561	$6.12 \cdot 10^{-4}$
W	$2.23 \cdot 10^{-4}$	0.352	$6.34 \cdot 10^{-4}$
Al	$7.44 \cdot 10^{-3}$	8.90	$8.36 \cdot 10^{-4}$
Be	$3.89 \cdot 10^{-2}$	35.2	$1.11 \cdot 10^{-3}$

S. Mrowczynski, Interaction of Elementary Atoms With Matter, Phys. Rev. A33 (1986) 1549–1555.
S. Mrowczyński, Interaction of relativistic elementary atoms with matter. I. General formulas, Phys. Rev. D 36 (Sep, 1987) 1520–1528.
K. G. Denisenko and S. Mrowczyński, Interaction of relativistic elementary atoms with matter. II. Numerical results, Phys. Rev. D 36 (Sep, 1987) 1529–1537.

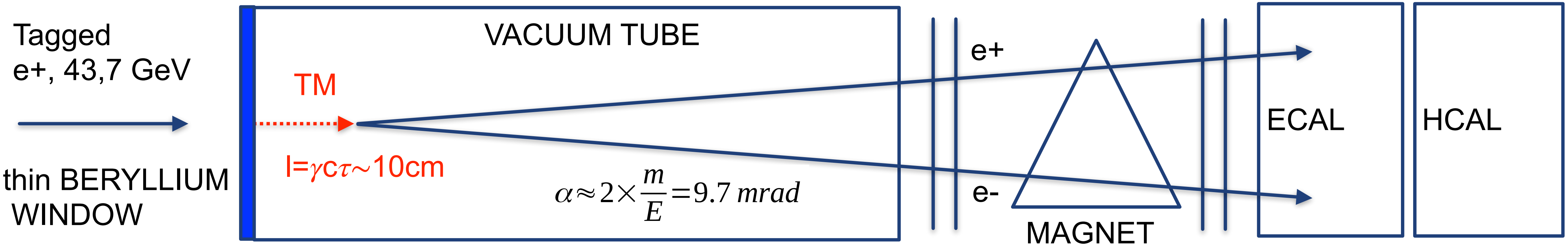
DETECTION OF TM IN NA64 VISIBLE SETUP (X17- search)

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

SIGNATURE:

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

See TALK of Gninenko on Tuesday



Tagged e+, 43,7 GeV

thin BERYLLIUM WINDOW

VACUUM TUBE

TM

$l=\gamma c\tau \sim 10\text{cm}$

$$\alpha \approx 2\times\frac{m}{E}=9.7\,mrad$$

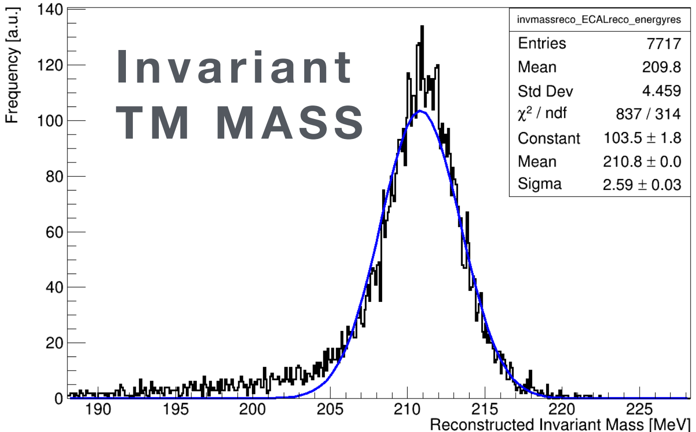
e+

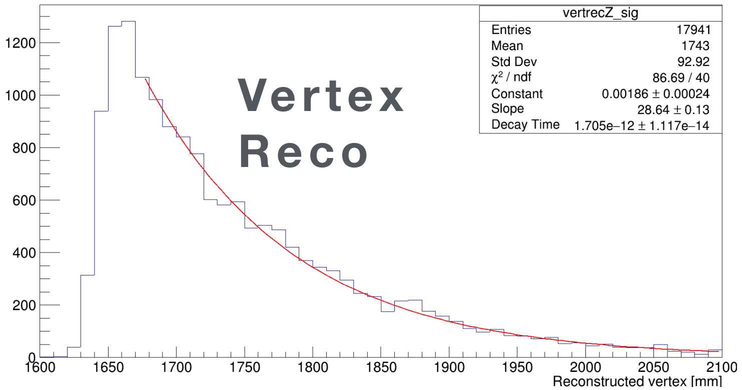
e-

MAGNET

ECAL

HCAL

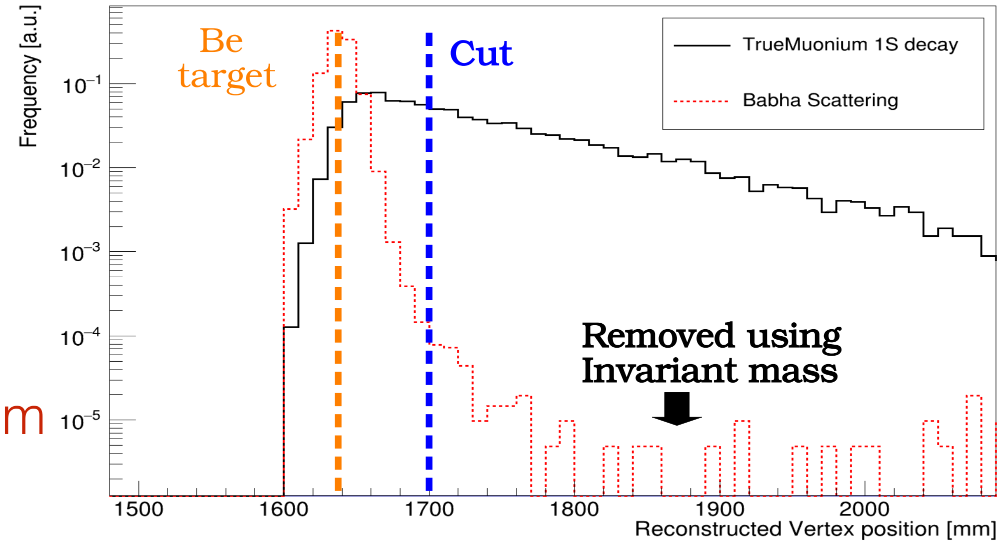


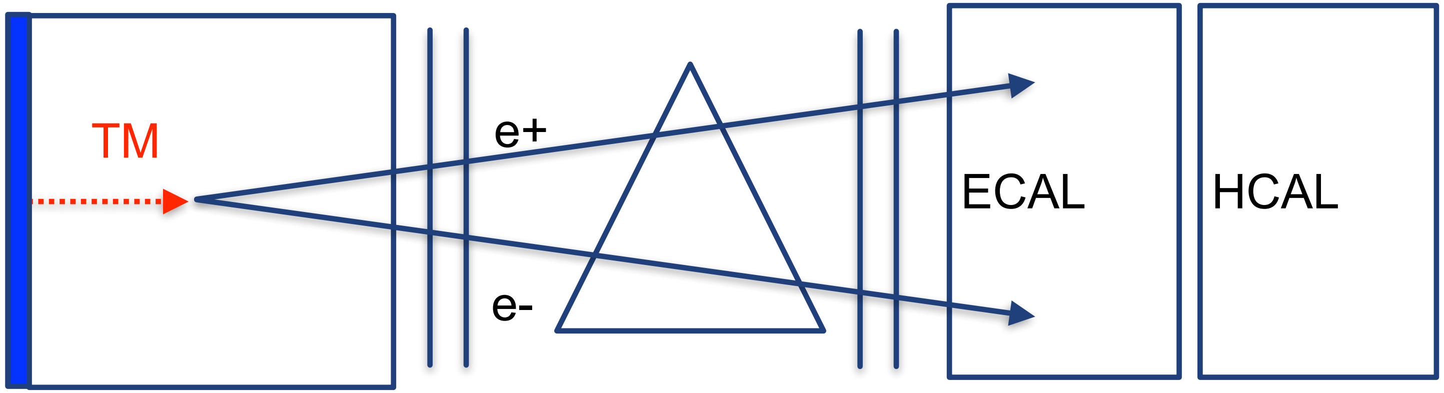


TM DECAY - BACKGROUND & DETECTION EFFICIENCY

SELECTION CRITERIA

1) Total energy detected in downstream ECAL larger than 40 GeV
2) No punch-through from the ECAL (no energy in HCAL and VETO)
3) Two clean tracks with a valid vertex are reconstructed in the decay volume
4) The vertex is displaced from the target 6.5 cm
5) Invariant mass is reconstructed between 190 and 220 MeV



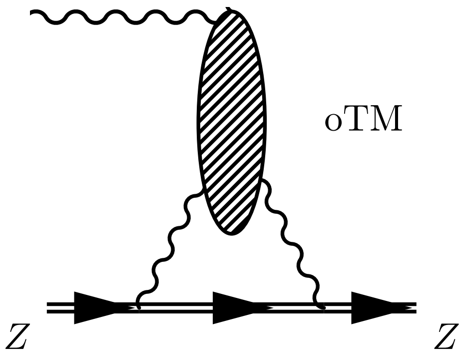


PRELIMINARY CONCLUSION

The experiment is background free at a level of 10^{11} positrons on target. The efficiency of detection is estimated to be 40%.

2) “Low energy” TM production @ the GAMMA Factory

See GF-TALK of Krasny on Monday



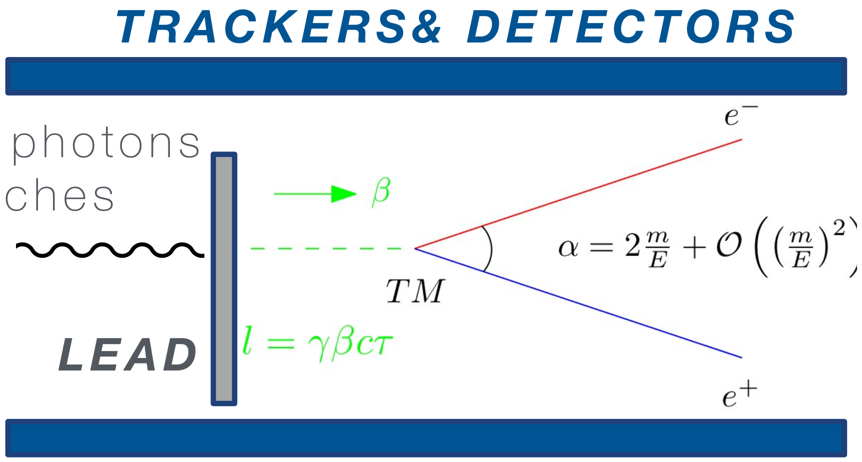
CROSS SECTION FOR TM PRODUCTION FOR E>>m_μ:

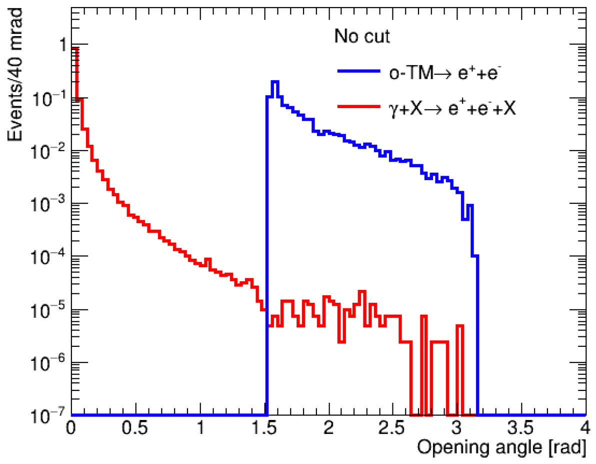
$$\sigma_{\gamma Z} = Z^2 \times 1.6 \cdot 10^{-40}\ \mathrm{cm}^2$$

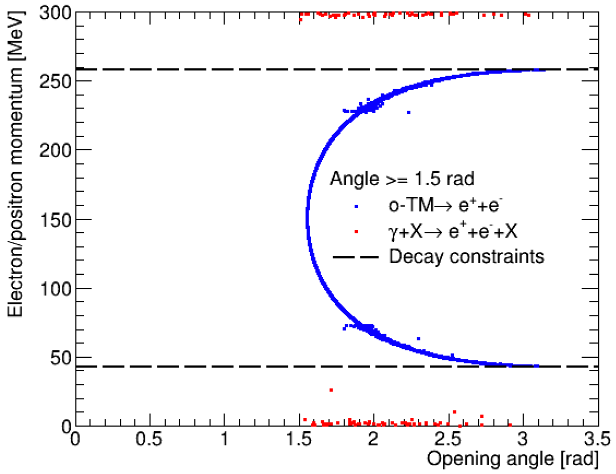
Ginzburg, et al., Phys. Rev. C58, 3565 (1998)

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

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



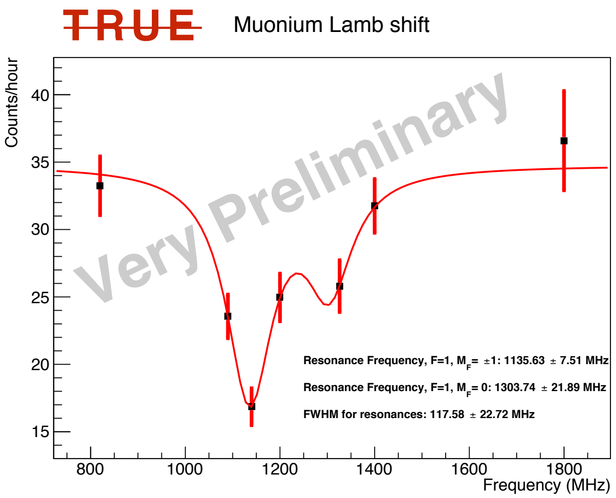




Estimated **RATE** OF ~$\mathcal{O}(10^4)$ TM (1^3S_1)/day and **~$\mathcal{O}(10^2$–$10^3)$ TM(2^3S_1)/day**

MEASUREMENT OF TM LAMB SHIFT AND FINE STRUCTURE

Similar measurement as for for μ^+e^-
(our data from last December beam time at PSI)



TRUE MUONIUM TRANSITIONS:

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

10 THz accessible via **LASER** (3 microns)
Natural line width of 20 GHz

GF- LASER-TALK of
Martends on Monday

SIGNATURE 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 ongoing:

  check H4 with positrons (2021), cross check simulation with data on NA64 visible setup (2022)

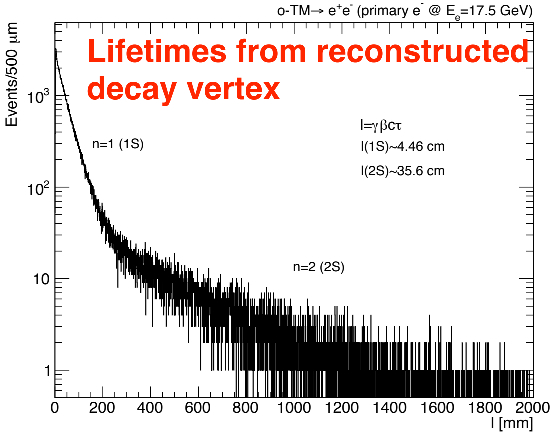
- Proof of principle in NA64 for measuring TM properties @ FUTURE CERN FACILITIES

e.g @LEMMA in beam dump mode: for 10^{16} e^+, dE=1 MeM, 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 TM/day”

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


Lifetimes from reconstructed decay vertex

Acknowledgments

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