Production of “True Muonium” at Super-Tau-Charm factory

S.J. Brodsky, R.F.Lebed, PRL 102, 213401 (2009)
1209.0060 [hep-ph]

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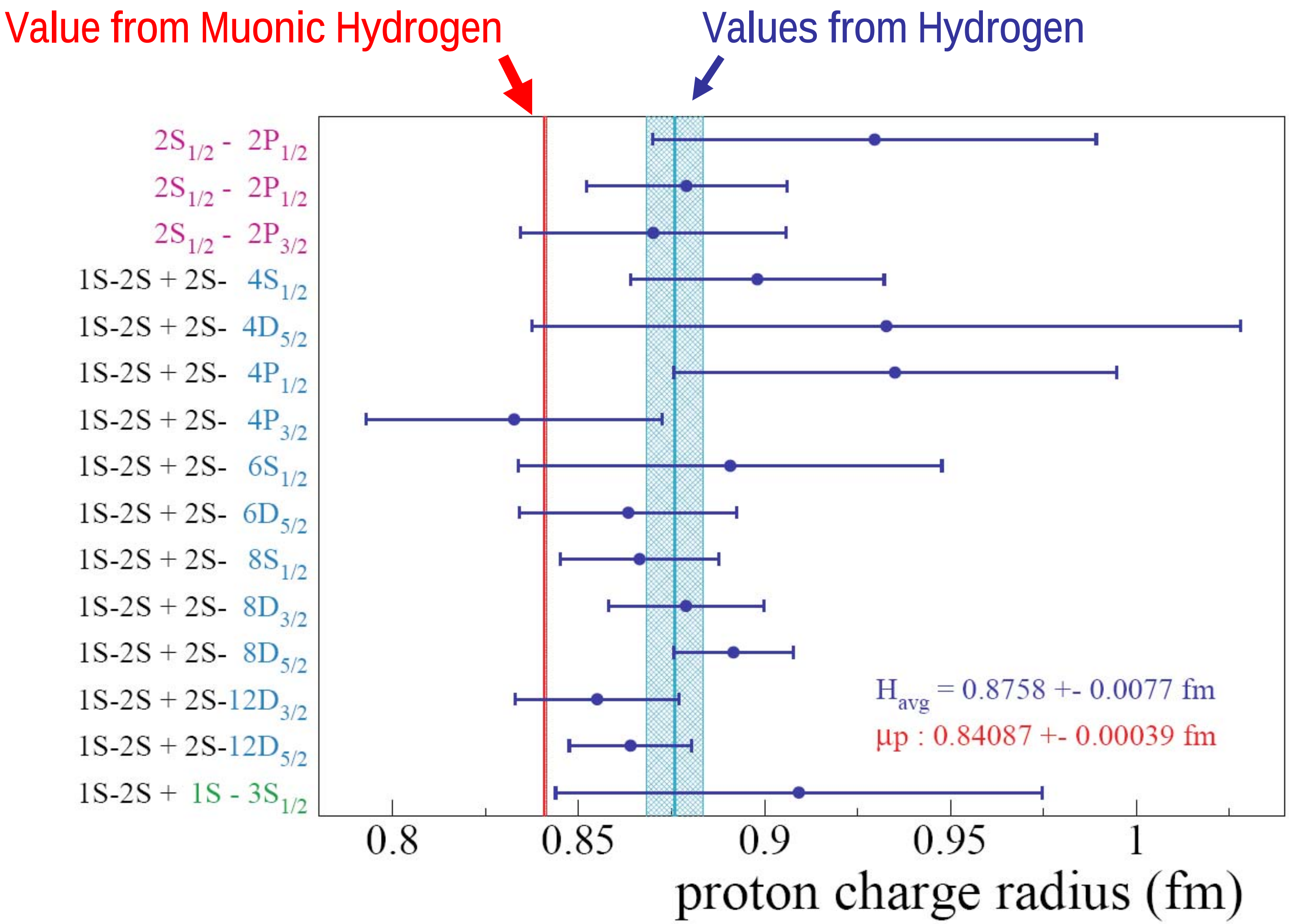
Motivation

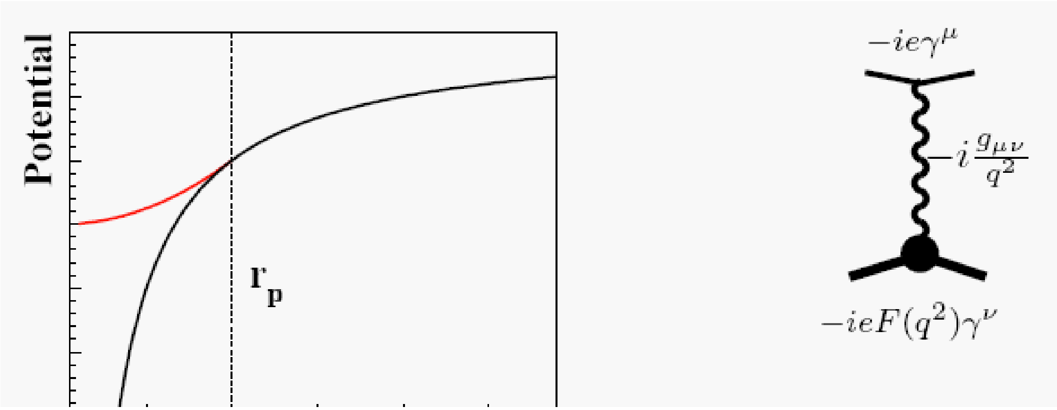


The puzzle of proton charged radius.

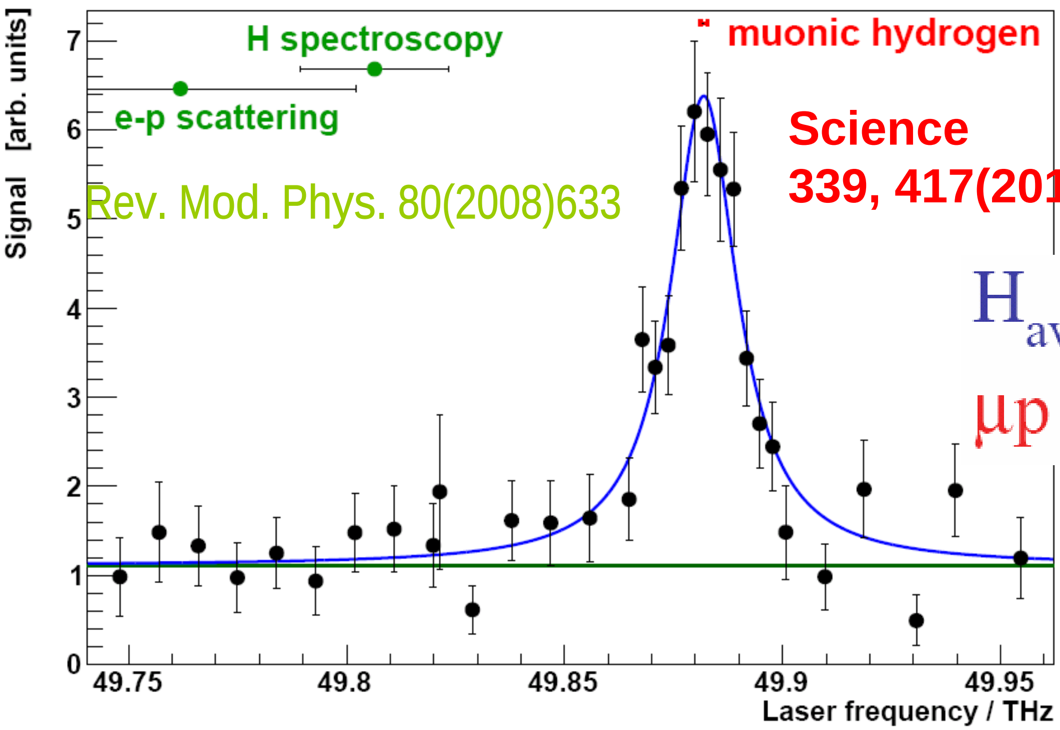
Nature 466, 213(2010),
Science 339, 417(2013)

Muonic hydrogen Lamb shift

so different from what was expected! New force for muons?



Contribution of r_p is much larger in ^1H because the muon is 200 times closer to the nucleus.



H_{avg} = 0.8758 +- 0.0077 fm

μp : 0.84087 +- 0.00039 fm

Motivation

- Any new force exchanges between muon and proton, which is lepton-flavor dependent?
- $(\mu^+\mu^-)[n^3S_1]\rightarrow\gamma^*\rightarrow e+e-$ is allowed and sensitive to the vacuum polarization corrections via the time-like running coupling $\alpha(q^2>0)$
- It should be related to the g-2 (discrepancy between theoretical prediction and measurement)?
- It should be also correlated with $\mu\rightarrow e\gamma$ transition?
- Lepton-flavor dependence: study property of $(\mu^+\mu^-)$, which may be different from positronium (e+e-)? IT IS IMPORTANT!

PRL 102, 213401 (2009)
1209.0060 [hep-ph]

"True Muonium"

- Positronium (e+e-): M. Deutsch, Phys. Rev. 82, 455 (1951):
- Muonium: (μ+e–):, Phys. Rev. Lett. 5, 63 (1960):
- (μπ) atom: Phys. Rev. Lett. 37, 249 (1976);
- No observation of ($\mu^+\mu^-$) yet, but it was predicted in 1969.
- Many proposals for the production of the ($\mu^+\mu^-$) :

$$\pi^- p \to (\mu^+\mu^-)n \qquad eZ \to e(\mu^+\mu^-)Z$$

$$\gamma Z \to (\mu^+\mu^-)Z \qquad Z_1 Z_2 \to Z_1 Z_2(\mu^+\mu^-)$$

$$\eta \to (\mu^+\mu^-)\gamma \qquad e^+e^- \to (\mu^+\mu^-)$$

$$e^{+}e^{-} \longrightarrow (\mu^{+}\mu^{-})$$

- It is hard to produce "true Muonium" in the e+e- head-to-head collision at threshold of "true muonium"
- The luminosity is low, hence the statistical is low;
- The decay products of "true muonium" is hard since the final states are low momentum.
- Proposal was made to produce the "true muonium " in a machine, in which the $(\mu^{+}\mu^{-})$ is strongly boosted, and easy to detect or identify.

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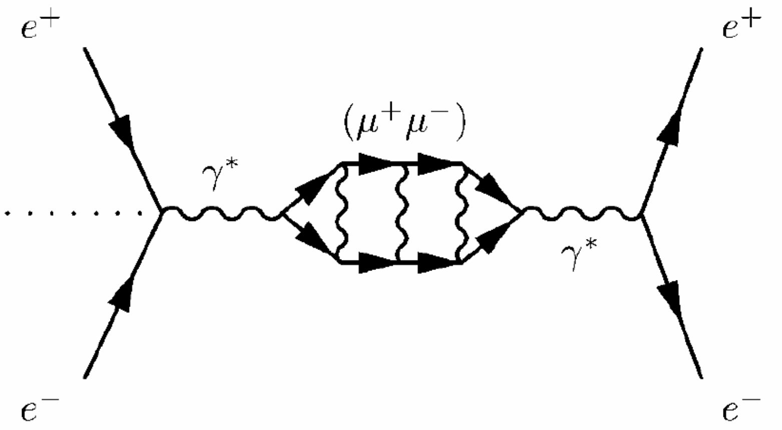
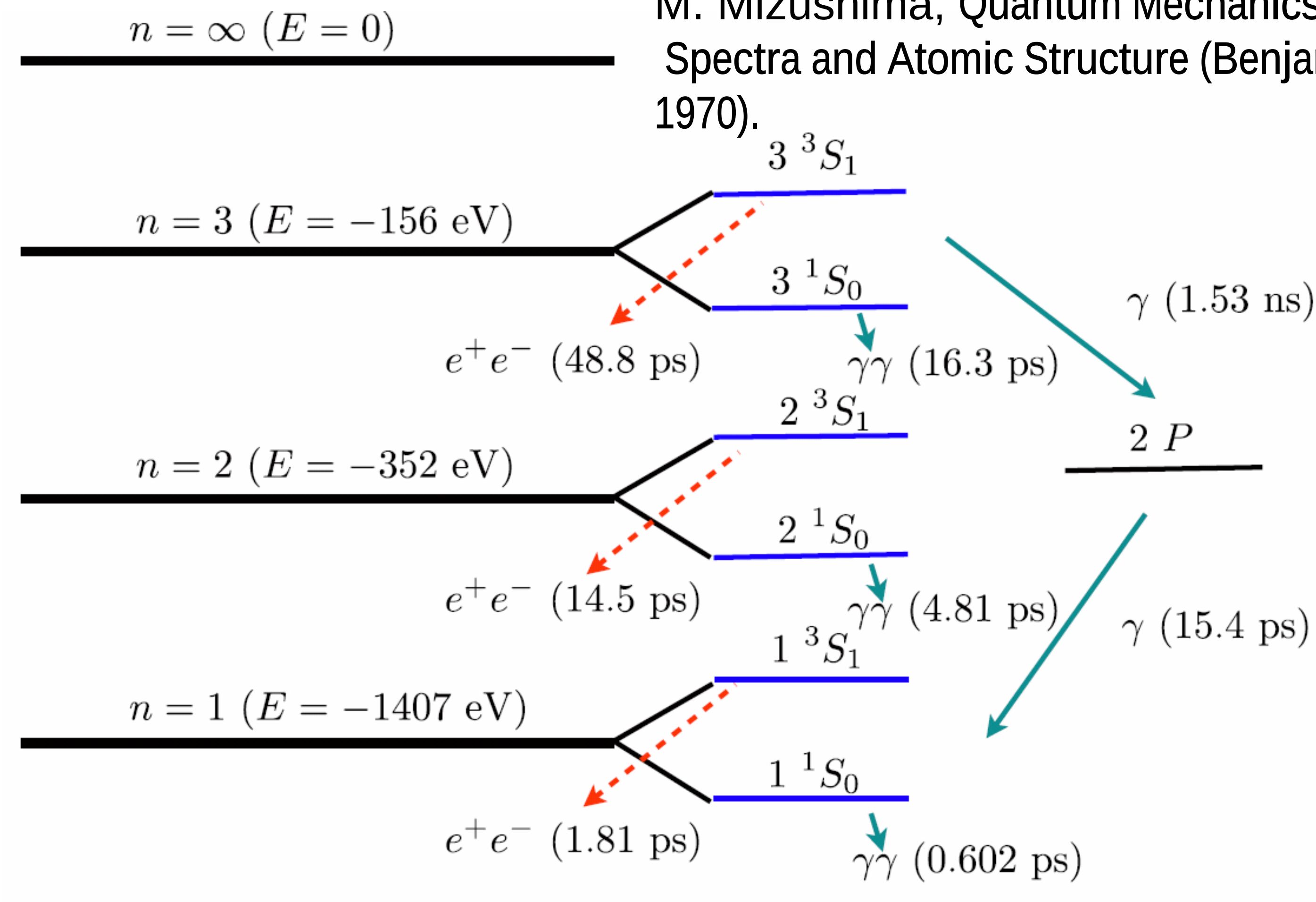


The open angle between e+ and e- beams is 2θ, CM energy $s = (p_{e+} + p_{e-})^2 = 2E_+E_-(1-\cos(2\theta)) \approx 4\, m_\mu^2$.

$\theta=5^o$, $E_\pm=1.212$ GeV, p(mu+mu-) = 2.415 GeV, $\gamma=11.5$

Spectroscopy of the "true Muonium"

M. Mizushima, Quantum Mechanics of Atomic Spectra and Atomic Structure (Benjamin, New York, 1970).

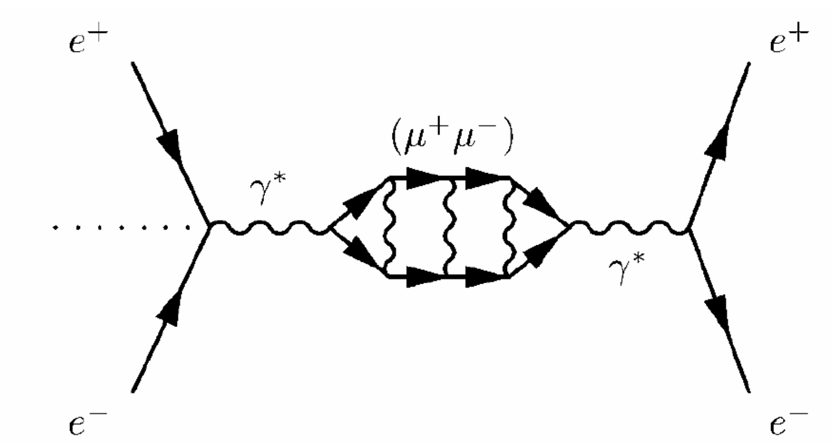


Bohr binding energy $-m_\mu \alpha^2/4n^2$

Lifetime and stability of ($\mu^+\mu^-$)true Muonium

- The free μ is unstable and has lifetime of 2.6 μs, meaning that the ($\mu^+\mu^-$) (0.62ps [$^1S_0$] and 1.8 ps[$^3S_1$]) annihilates long before its constituents weakly decay;
- The free τ lifetime is 291 fs, the true tauonium is about 38 fs and 107 fs for $^0S_1$ and $^3S_1$, respectively, tauonium is not a pure QED states, and hard to produced;
- True Muonium is unique as heaviest metastable state possible for precision QED tests.

Production cross-section of “true Muonium” near threshold



After considering the Sommerfeld-Schwinger-Sakahorov (SSS) threshold enhance factor from Coulomb rescattering:

$$\sigma = \frac{2\pi\alpha^2\beta}{s}\left(1-\frac{\beta^2}{3}\right)S(\beta)$$

$$S(\beta) = \frac{X(\beta)}{1-\exp[-X(\beta)]} \qquad X(\beta) = \pi\alpha\sqrt{1-\beta^2}/\beta$$

The open angle between e+ and e⁻ beams is 2θ, CM energy $s = (p_{e+} + p_{e-})^2 = 2E_+E_-(1-\cos(2\theta)) \approx 4\, m_\mu^2$, for example”

$\theta=5^o$, $E_\pm$=1.212GeV, $p(\mu^+\mu^-)$ = 2.415GeV, γ=11.5

β is the velocity of μ^+ or μ^- in their central of mass system, $\beta \to 0$ near threshold.

The average decay length in the lab for True Muonnium (TM):

3^3S_1(TM)→ e+e-: 16.6 cm
2^3S_1 (TM)→e+e-: 4.9 cm
1^3S_1 (TM)→e+e-: 0.6 cm

After considering the beam spread of 1 MeV:

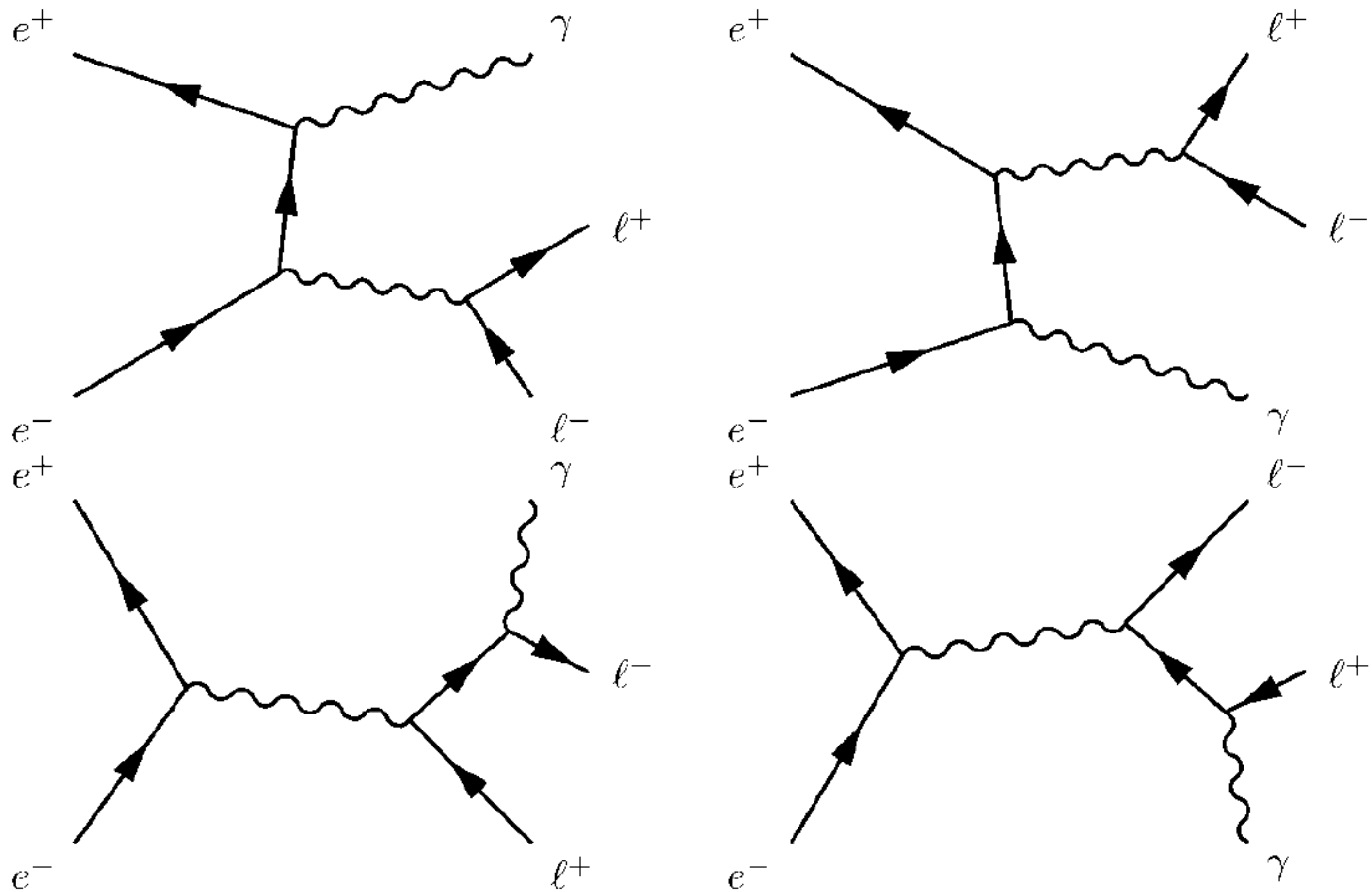
$$\boldsymbol{R = \frac{\sigma(e^+e^- \to (\mu^+\mu^-))}{\sigma(e^+e^- \to \mu^+\mu^-)} = 5\times 10^{-5}}$$

The production cross-section is about 0.1 nb
The Luminosity could be 1×10^{32} /cm^2/s,
about 1×10^5 TM will be produced per year!

Production of “true Muonium” at super-tau-charm factory

C = –

C = +



Diagrams for $e^+e^- \to \gamma\ (\mu^+\mu^-)$

Production of “true Muonium” at super-tau-charm factory

At STCF, it has advantage that the production rate is independent of the beam resolution , and removes the ($\mu^+\mu^-$) (TM) completely from the beam line since the atom recoils against a coproduced hard γ. While the reproduction of the real γ costs an additional factor of α in the rate .

After considering all bound states and SSS effects:

$$\frac{d\sigma}{ds_1} = 2\pi\left[\ln\left(\frac{1+c_0}{1-c_0}\right) - c_0\right]\frac{\alpha^4}{ss_1}.$$

The relevant range of ds_1 is just that where bound Bohr states occur, which begin at energy $\alpha^2 m_\mu/4$ below the pair creation threshold $s_1 = 4m_\mu^2$, and thus give rise to $ds_1 \simeq m_\mu^2\alpha^2$. Thus one obtains

$$\sigma \simeq \frac{\pi}{2}\left[\ln\left(\frac{1+c_0}{1-c_0}\right) - c_0\right]\frac{\alpha^6}{s}$$

Production of "true Muonium" at super-tau-charm factory

In e+e- collision at central of mass s ($s \gg 4m_\mu^2$), the ratio is defined as

$$R = \frac{\sigma^{part}(e^+e^- \to \gamma(\mu^+\mu^-))}{\sigma^{part}(e^+e^- \to \mu^+\mu^-)} \approx 1\times 10^{-8}$$

Part: integrate within the detector coverage only, not the whole phase space.

For example, at the BEPCII, assuming 0.5×10^{33} /cm^2/s at sqrt(s)=2 GeV,
In one years data taking, only about 5 true Muonium events are produced.
While at super-tau-charm, 500 events will be produced at **sqrt(s)=2 GeV.**
At ψ(3770) peak, 314 events are expected.

The average decay length in the lab
E_beam = 1.0 GeV for True Muonnium (TM):
3^3S_1(TM)→ e+e-: 8.3 cm
2^3S_1 (TM)→e+e-: 2.5 cm
1^3S_1 (TM)→e+e-: 0.3 cm

The average decay length in the lab
E_beam = 1.89 GeV for True Muonnium (TM):
3^3S_1(TM)→ e+e-: 16.0 cm
2^3S_1 (TM)→e+e-: 4.5 cm
1^3S_1 (TM)→e+e-: 0.5 cm

Production of "true Muonium" at super-tau-charm factory

In J/ψ decay

Assuming the ratio of BR($J/\psi \to \gamma(\mu^+\mu^-)$) to BR($J/\psi \to \mu^+\mu^-$) is:

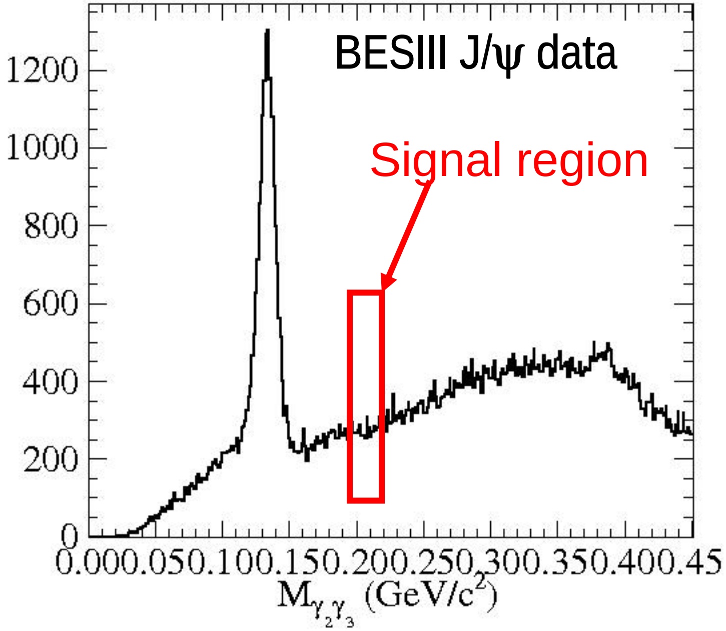
C = +

$$R = \frac{BR(J/\psi \to \gamma(\mu^+\mu^-))}{BR(J/\psi \to \mu^+\mu^-)} \approx 1 \times 10^{-8}$$

Each year, we have about 3×10^{12} J/ψ decay events, about 1800 events/year will be expected for spin singlet states $^0S_1$(TM)→ γγ ,

Signal: $J/\psi \to \gamma(\mu^+\mu^-)$, $(\mu^+\mu^-) \to \gamma\gamma$

Backgrounds: $J/\psi \to \gamma\pi^0$, $\pi^0 \to \gamma\gamma$



Summary

- It is possible to search for the true Muonium at Super-tau-charm factory
- The spin-triplet states can be reached in $e^+e^- \rightarrow \gamma(\mu\mu)$
- The spin-singlet states can be reached in the $J/\psi \rightarrow \gamma(\mu\mu)$
- The lifetime of true Muonium may be measured
- A fast MC simulation is needed.

Decay time and their ratios for true Muonium decays.

$$\tau(n^3S_1 \to e^+e^-) = \frac{6\hbar n^3}{\alpha^5 mc^2}, \qquad \tau(n^1S_0 \to \gamma\gamma) = \frac{2\hbar n^3}{\alpha^5 mc^2},$$

$$\tau(2P \to 1S) = \left(\frac{3}{2}\right)^8 \frac{2\hbar}{\alpha^5 mc^2}, \qquad \tau(3S \to 2P) = \left(\frac{5}{2}\right)^9 \frac{4\hbar}{3\alpha^5 mc^2},$$

$$\frac{\tau(n^3S_1 \to e^+e^-)}{\tau(n^1S_0 \to \gamma\gamma)} = 3, \qquad \frac{\tau(2P \to 1S)}{\tau(n^1S_0 \to \gamma\gamma)} = \left(\frac{3}{2}\right)^8 \frac{1}{n^3} = \frac{25.6}{n^3},$$

$$\frac{\tau(3S \to 2P)}{\tau(2P \to 1S)} = \left(\frac{5}{3}\right)^9 = 99.2.$$