Predicting and Discovering True Muonium

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UNIVERSITY OF MARYLAND

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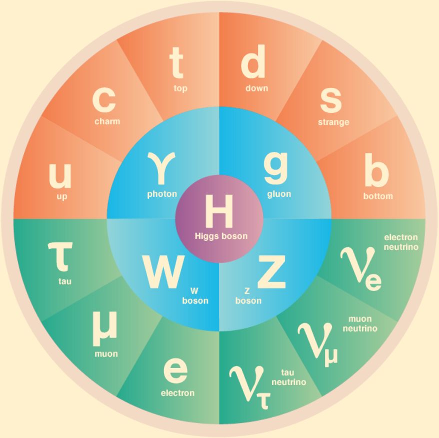
Outline



t
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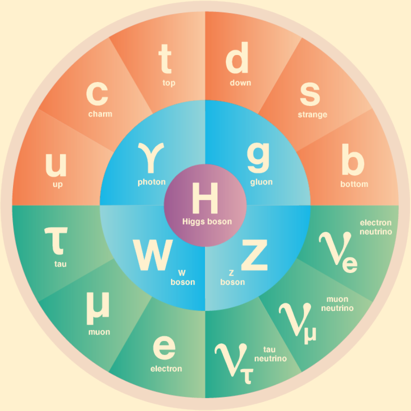
Who ordered that?



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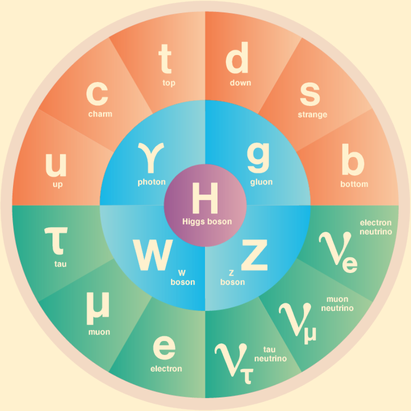
In Standard Model, *lepton universality* is only broken by Higgs



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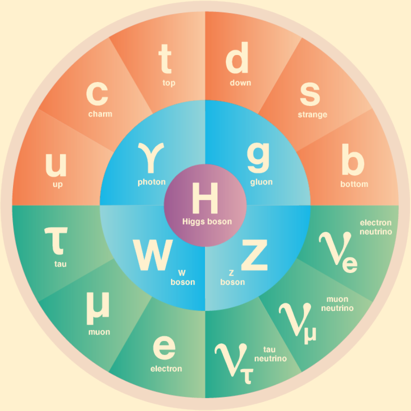
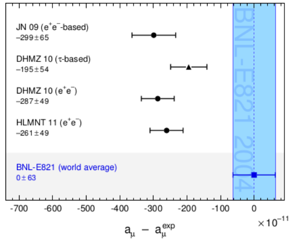
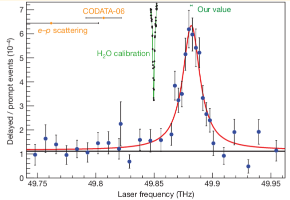


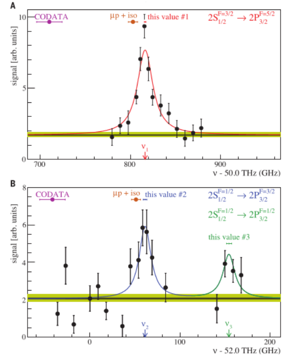
ν_ℓ require modification beyond Standard Model, so at some level lepton universality is violated

What's the deal with muon physics?[1][2][3]

mu·on prob·lem: (n) the curious observation that discrepancies exist in muon sector when compared to other leptons





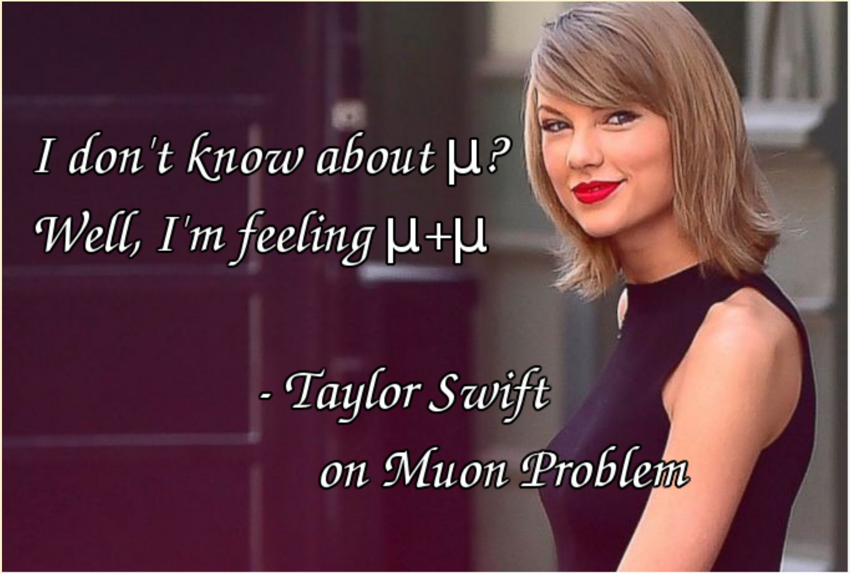


[1] G. Bennett et al. "Final Report of the Muon E821 Anomalous Magnetic Moment Measurement at BNL". . In: *Phys. Rev.* D73 (2006), p. 072003. arXiv: hep-ex/0602035 [hep-ex].

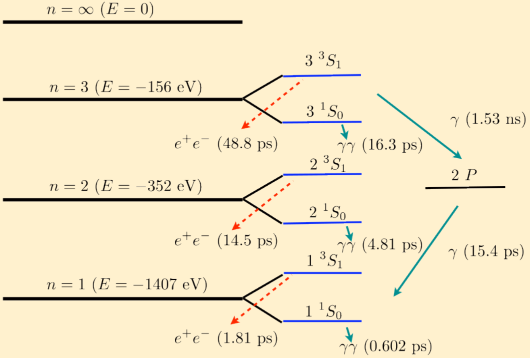
[2] A. Antognini et al. "Proton Structure from the Measurement of $2S - 2P$ Transition Frequencies of Muonic Hydrogen". In: *Science* 339 (2013), pp. 417–420.

[3] R. Pohl et al. "Laser spectroscopy of muonic deuterium". In: *Science* 353.6300 (2016), pp. 669–673.

Building a new streetlight: True Muonium



Wait? I can bind muons?



- $(\mu^+\mu^-)$ proposed in 1961, still undetected

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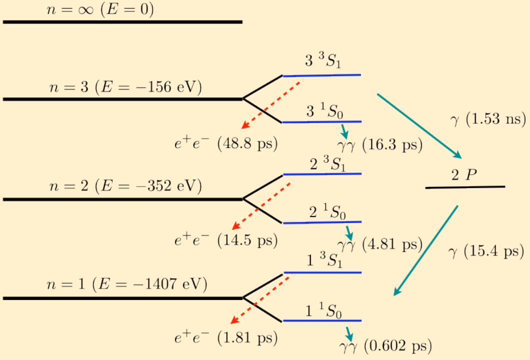

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The true muonium ($\mu^+\mu^-$) and true tauonium ($\tau^+\tau^-$) [and the much more difficult to produce "mu-tauonium" ($\mu^\pm\tau^\mp$)] bound states are not only the heaviest, but also the most compact pure QED systems [the ($\mu^+\mu^-$) Bohr radius is 512 fm]. The relatively rapid weak decay of the τ unfortunately makes the observation and study of true tauonium more difficult, as quantified below. In the case of true muonium the proposed production mechanisms include $\pi^- p \to (\mu^+\mu^-)n$ [6], $\gamma Z \to (\mu^+\mu^-)Z$ [6], $eZ \to e(\mu^+\mu^-)Z$ [12], $Z_1Z_2 \to Z_1Z_2(\mu^+\mu^-)$ [13] (where Z indicates a heavy nucleus), direct $\mu^+\mu^-$ collisions [7], $\eta \to (\mu^+\mu^-)\gamma$ [14], and $e^+e^- \to (\mu^+\mu^-)$ [15]. In addition, the properties of true muonium have been studied in a number of papers [9,16,17].

- ($\mu^+\mu^-$) proposed in 1961, still undetected
- Leptonic QED bound state analogous to Ps or Quarkonium
- **...but many channels suggested**[4]

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What's in a name?

Bimuonium is first name in published article[5], but only used in the one.

Name	Year	Refs.	Au.

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...but clearly wrong are Muononium and Muonic Muonium

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Bimuoniu... is firs... ...n the one.

†10 of these ar...

...but clearl... wr... ...onium

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...because if you did[8][9][10][11][12][13][14][15][16][17][18][19]

[8] A. Badertscher et al. "An Improved Limit on Invisible Decays of Positronium". In: *Phys. Rev.* D75 (2007), p. 032004. arXiv: hep-ex/0609059 [hep-ex].

[9] J. Jaeckel and S. Roy. "Spectroscopy as a test of Coulomb's law: A Probe of the hidden sector". In: *Phys. Rev.* D82 (2010), p. 125020. arXiv: 1008.3536 [hep-ph].

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[12] D. Tucker-Smith and I. Yavin. "Muonic hydrogen and MeV forces". In: *Phys. Rev.* D83 (2011), p. 101702. arXiv: 1011.4922 [hep-ph].

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[19] H. Lamm. "Applying Bayesian Inference to Galileon Solutions of the Muon Problem". In: *Phys. Rev.* D94.11 (2016), p. 115007. arXiv: 1609.07520 [hep-ph].

Hard to hide new physics due to s-channel

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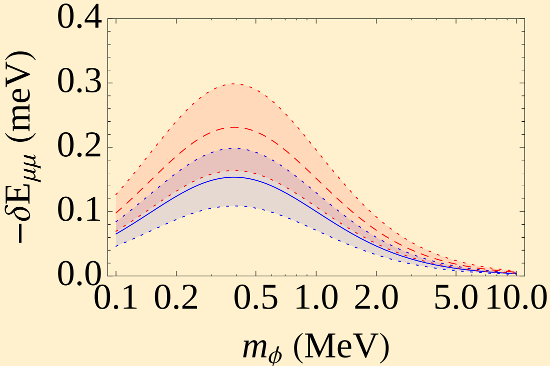

ΔE_{Lamb} for S and V^μ solving a_μ[20]

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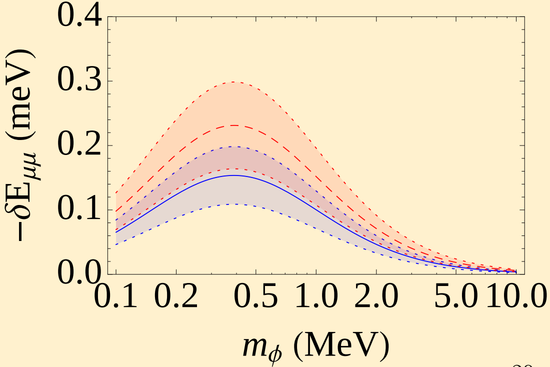

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Annihilation channel through Fierz identity enhances suppressed interactions

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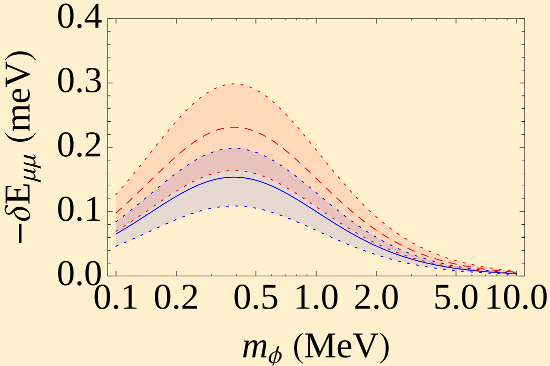

ΔE_{Lamb} for S and V^{μ} solving a_{μ}[20]

Annihilation channel through Fierz identity enhances suppressed interactions

$$\delta a_{\mu} \approx 2 \times 10^{-9} \left(\frac{2\text{TeV}}{M_x/g}\right)^2 \qquad \delta E \approx \frac{g^2}{M_x^2}|\psi(0)|^2 = \mathbf{100\ MHz} \left(\frac{1\text{TeV}}{M_x/g}\right)^2$$

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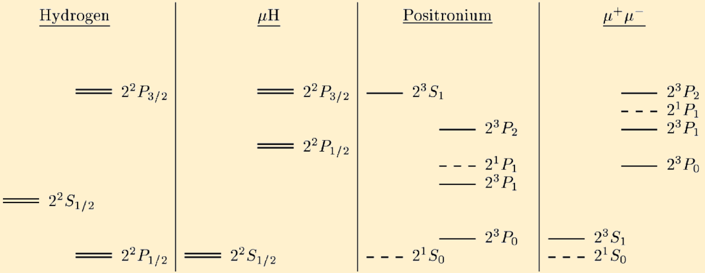

Hydrogen
$2^2P_{3/2}$
$2^2S_{1/2}$
$2^2P_{1/2}$
μH
$2^2P_{3/2}$
$2^2P_{1/2}$
$2^2S_{1/2}$
Positronium
2^3S_1
2^3P_2
2^1P_1
2^3P_1
2^3P_0
2^1S_0
$\mu^+\mu^-$
2^3P_2
2^1P_1
2^3P_1
2^3P_0
2^3S_1
2^1S_0

Goal: $\mathcal{O}$(100 MHz) true muonium predictions

Obs.	E[MHz] 2000	E[MHz] 2017
Lamb	$1.37(5)\times 10^{7}$	$1.3813(14)\times 10^{7}$
$1s-2s$	$2.55(5)\times 10^{11}$	—
hfs	$42329604(800)_{\text{had}}(1200)_{\text{miss}}$	$42329435(16)_{\text{had}}(90)_{\text{ind}}(700)_{\mu}$

- Unlike Positronium e, had, τ loops contribute appreciably $\frac{\alpha m_\mu}{m_e} \approx 1.5$.

[21] HL and NR, in prep.

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- Technology exist for these computations diagram by diagram

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Improving the hfs prediction

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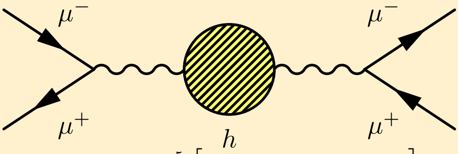
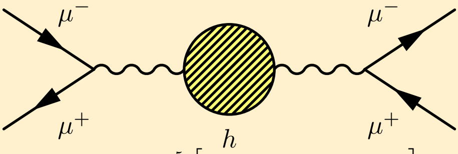


$$\Delta E_{1,\mathrm{hvp}} = \frac{m_\mu \alpha^5}{n^3 \pi} \left[m_\mu^2 \int_{4m_\pi^2}^{\infty} \mathrm{d}s \frac{R(s)}{3s(4m_\mu^2 - s)} \right]$$

10^{-4} vs 10^{-7} in Mu, helpful with a_μ

Improving the hfs prediction



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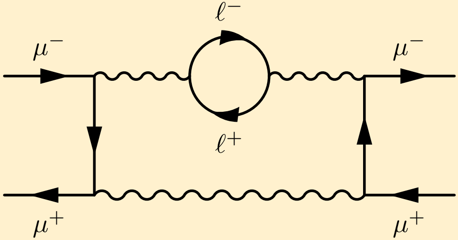
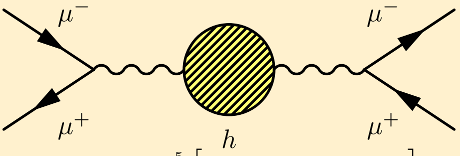


$$\Delta E_{\mathrm{eVP},0} = \frac{m_\mu \alpha^6}{n^3 \pi^2}\left[\frac{\beta(-31 + 15 \ln \beta)}{150} + \mathcal{O}(\beta^2)\right]$$

$\beta \equiv \left(\frac{m_\mu}{m_e}\right)^2$, Modifies decay rate as well

Improving the hfs prediction



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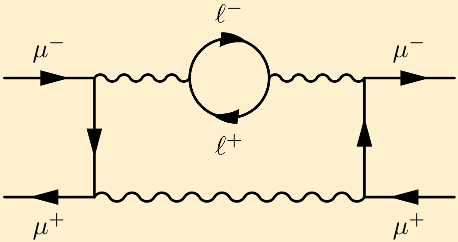

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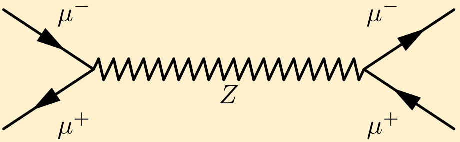
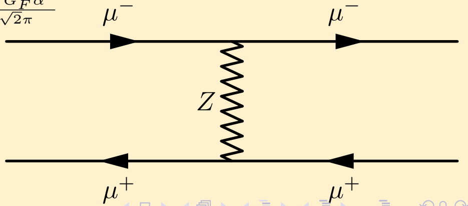
Low energy extraction of $\sin\theta_W$

$\Delta E_Z = -\frac{3}{8}\frac{m^3 G_F \alpha^3}{\sqrt{2}\pi}$



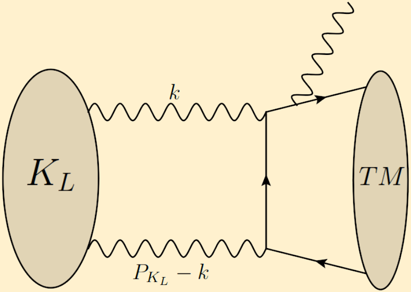


The current state of hfs in true muonium

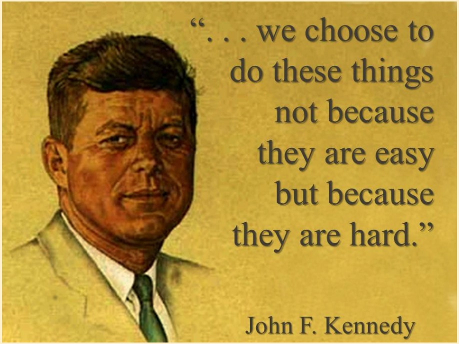
$\mathcal{O}(m\alpha^n)$	C_n		$\delta E^{1s}_{\text{hfs}}$[MHz]	
$m\alpha^4$	$\frac{7}{12}$		42260692	
$\frac{m\alpha^5}{\pi}$	$-\frac{1}{2}\ln(2)-\frac{8}{9}$		-207904	
$\frac{m\alpha^5}{\pi}\vert_\mu$	0.81650(9)	1611.04258	137400(16)	QCD
$\frac{m\alpha^6}{\pi^2}$	$-\frac{52}{32}\zeta(3)+\left(\frac{221}{24}\ln(2)-\frac{5197}{576}\right)\zeta(2)+\frac{1}{2}\ln(2)+\frac{1367}{648}$		-1515	
$\frac{m\alpha^6}{\pi^2}\vert_\mu$	350.572533*	1607.07059,1701.04362	137034*(700)	QED
$m\alpha^6\ln\left(\frac{1}{\alpha}\right)$	$\frac{5}{24}$		3954	
$\frac{m\alpha^7}{\pi^3}$	160*		145*(90)	
$\frac{m\alpha^7}{\pi}\ln\left(\frac{1}{\alpha}\right)$	$-\frac{17}{3}\ln(2)+\frac{217}{90}$		-67	
$\frac{m\alpha^7}{\pi}\ln^2\left(\frac{1}{\alpha}\right)$	$-\frac{7}{8}$		-190	
$\frac{m^3G_F\alpha^3}{\sqrt{2}\pi}$	$-\frac{3}{8}$	1502.03841	-109	EW
$\frac{m\alpha^7}{\pi^3}\vert_\mu$	-5.324248*	1507.07841	-5*(40)	
Total			42329435(16)(90)(700)	

$|_\mu$ indicates true muonium corrections missing from positronium, which depend upon m_μ/m_e. Errors consists of (1) hadronic model dependence, (2) missing mass-independent QED contributions at $\mathcal{O}(m\alpha^7)$, (3) missing mass-dependent QED contributions at $\mathcal{O}(m\alpha^6)$. $*$ indicate partial terms.

Outline



Time for the bad news



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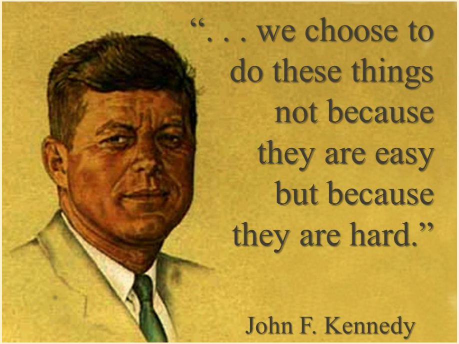

- Analogous to pion production, but $\propto \left(\frac{\alpha_{em}}{\alpha_S}\right)^3$

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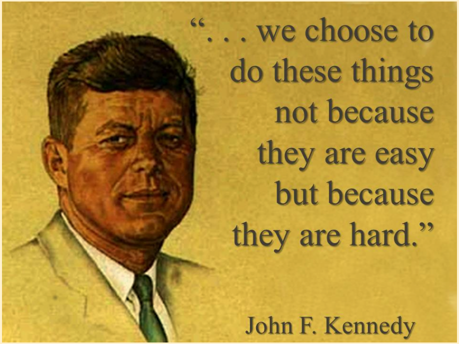

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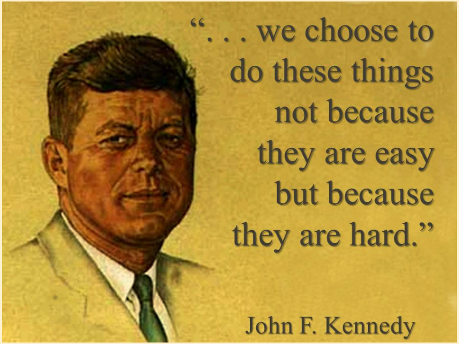

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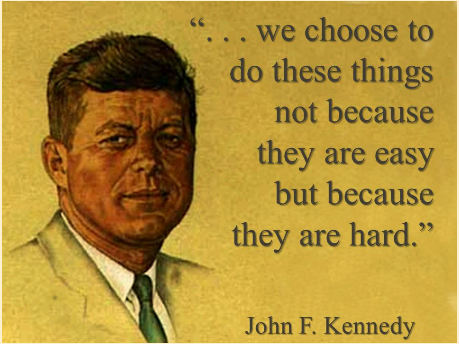

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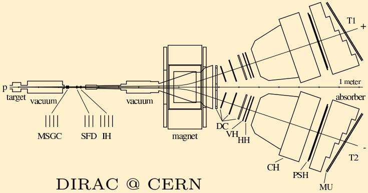
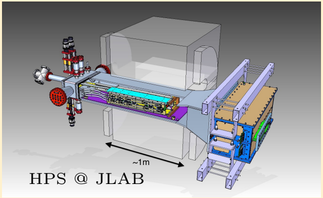
- ...but true muonium is likely to be **relativistic**
- Truly an **intensity** frontier proposition

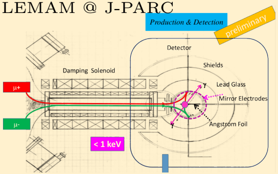
Near future experimental efforts to detect possible



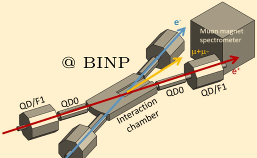
DIRAC @ CERN



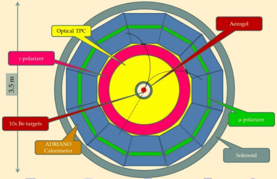
LEMAM @ J-PARC



@ BINP



REDTOP @ Fermilab



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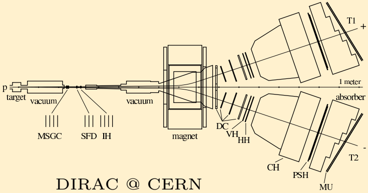

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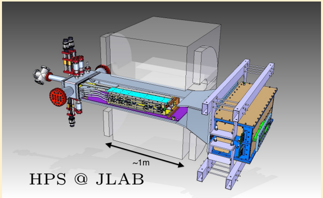

HPS @ JLAB

- Exist: DIRAC, HPS are fixed targets

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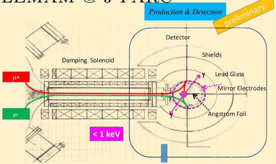

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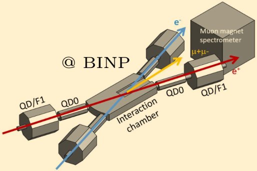
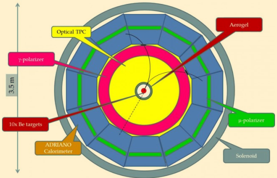


REDTOP @ Fermilab



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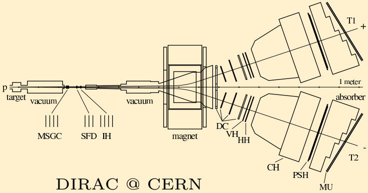

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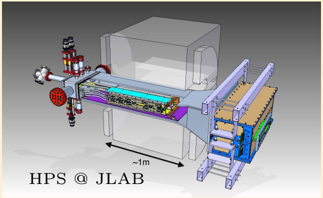

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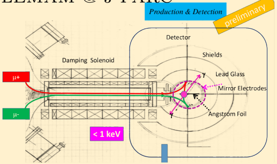
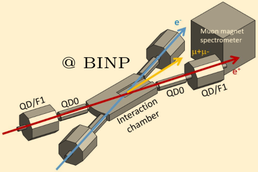
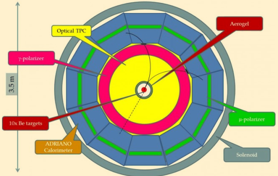




REDTOP @ Fermilab



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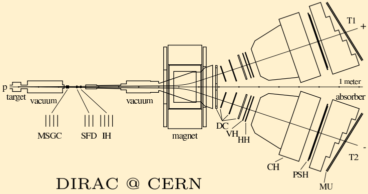

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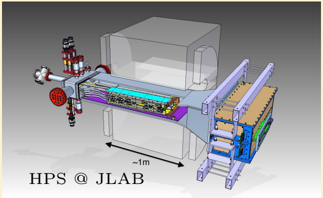

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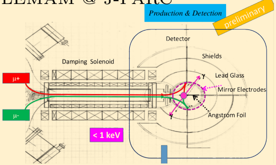

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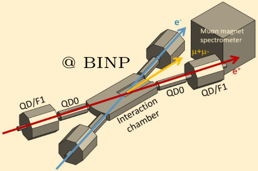
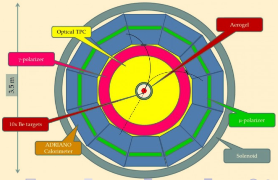


REDTOP @ Fermilab



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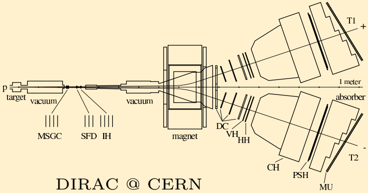

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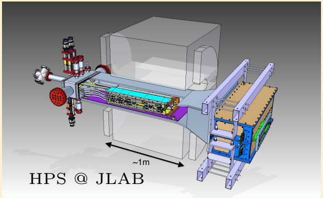

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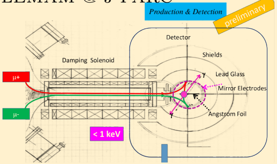
- Proposed: e^+e^- collider at BINP
- Proposed: **REDTOP is a η/η' factory**

LEMAM @ J-PARC



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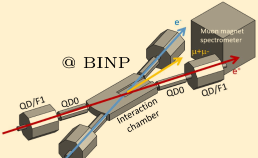
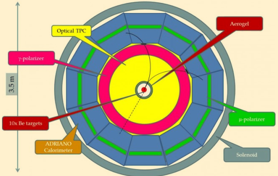


REDTOP @ Fermilab



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Rare meson decay may open the path

Proposals for rare decay searches, like REDTOP, would be capable of detecting true muonium+γ. Large $\mathcal{O}(\alpha)$ corrections and $F_{\gamma^*}(q^2)$ dependence needed

$$\frac{\mathcal{B}(\eta \to \gamma(\mu^+\mu^-))}{\mathcal{B}(\eta \to \gamma\gamma)} = 1.476(5)_{\text{stat}}(4)_{\text{sys}} \times 10^{-9}$$

$$\frac{\mathcal{B}(\eta' \to \gamma(\mu^+\mu^-))}{\mathcal{B}(\eta' \to \gamma\gamma)} = 1.761(7)_{\text{stat}}(2)_{\text{sys}} \times 10^{-9}$$

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[24] YJ and HL, in prep.

[25] Y. Ji and H. Lamm. "Discovering True Muonium in $K_L \to (\mu^+\mu^-)\gamma$". In: (2017). arXiv: 1706.04986 [hep-ph].

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Discovery would constrain on $F_{\gamma^*}(q^2)$

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Outline

The future looks bright

- Your favorite **new physics** can be severely constrained with true muonium
- A theoretical program is underway to reduce the **uncertainty** in observables to $\mathcal{O}(100\text{ MHZ})$
- Contributions possible to a_μ and $\sin\theta_W$
- Most promising experimental outlook in 56 years!