New Physics with Muons



Gavin Hesketh YETI 2019 7/1/19





New physics must exist: - dark matter, hierarchy problem, matter-antimatter asymmetry, neutrino masses, gravity.... ...but where is it??

JU	y 2018	e II T N	late	Emiss	60 140	-11	Ма	a a lineit			E T D T N	E 10 T-11	$\sqrt{s} = 7, 8, 13$
_	Model	ε,μ,ι,γ	Jets	T	JLaten	1	Ma	iss limit			$\sqrt{s} = 7, 8 \text{ TeV}$	$v_s = 13$ lev	Heierence
I	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_{1}^{0}$	0 mono-jet	2-6 jets 1-3 jets	Yes Yes	36.1 36.1	$\tilde{q} = [2x, 8x \text{ Degen}]$ $\tilde{q} = [1x, 8x \text{ Degen}]$]	0.43	0.71	9	1.55	$m(\tilde{\chi}_{1}^{0}) < 100 \text{ GeV}$ $m(\tilde{q}) \cdot m(\tilde{\chi}_{1}^{0}) = 5 \text{ GeV}$	1712.02332 1711.03301
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q \tilde{q} \tilde{\chi}_{1}^{0}$	0	2-6 jets	Yes	36.1	ğ ğ			Forbidde	n	2.0 0.95-1.6	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 900 \text{ GeV}$	1712.02332 1712.02332
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell \ell)\tilde{\chi}_{1}^{0}$	3 e, μ ee, μμ	4 jets 2 jets	- Yes	36.1 36.1	ili ili				1.	1.85	m($\tilde{\chi}_{1}^{0}$)<800 GeV m($\tilde{\chi}_{1}^{0}$)=50 GeV	1706.03731 1805.11381
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_{1}^{0}$	0 3 <i>e</i> , µ	7-11 jets 4 jets	Yes	36.1 36.1	ğ ğ			(.98	1.8	$m(\tilde{\chi}_{1}^{0}) < 400 \text{ GeV}$ $m(\tilde{g}) \cdot m(\tilde{\chi}_{1}^{0}) = 200 \text{ GeV}$	1708.02794 1706.03731
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t \tilde{t} \tilde{\chi}_{1}^{0}$	0-1 e,μ 3 e,μ	3 b 4 jets	Yes	36.1 36.1	Ë Ë				1.	2.0	m($\tilde{\chi}_1^0$)<200 GeV m(\tilde{g})-m($\tilde{\chi}_1^0$)=300 GeV	1711.01901 1706.03731
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1{\rightarrow}b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple Multiple Multiple		36.1 36.1 36.1	$egin{array}{c} eta_1\ ebbe_1\ $	Forbidden	Forbidden Forbidden	0. 0.58-0.82 0.7	9	$m(\tilde{\chi}_{1}^{0}) = 200$	$m(\tilde{\chi}_{1}^{0})=300 \text{ GeV}, BR(b\tilde{\chi}_{1}^{0})=1$ =300 GeV, BR(b\tilde{\chi}_{1}^{0})=BR(t\tilde{\chi}_{1}^{0})=0.5 : GeV, $m(\tilde{\chi}_{1}^{0})=300 \text{ GeV}, BR(t\tilde{\chi}_{1}^{0})=1$	1708.09266, 1711.03301 1708.09266 1706.03731
	$\tilde{b}_1\tilde{b}_1,\tilde{t}_1\tilde{t}_1,M_2=2\times M_1$		Multiple Multiple		36.1 36.1	τ ₁ τ ₁ Forbidd	en		0.7	Ð		$m(\tilde{\chi}_1^0)=60 \text{ GeV}$ $m(\tilde{\chi}_1^0)=200 \text{ GeV}$	1709.04183, 1711.11520, 1708.0324 1709.04183, 1711.11520, 1708.0324
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0 \text{ or } t \tilde{\chi}_1^0$ $\tilde{t}_1 \tilde{t}_1, \tilde{H} \text{ LSP}$	0-2 e, µ (0-2 jets/1-2 Multiple Multiple	b Yes	36.1 36.1 36.1	\tilde{t}_1 \tilde{t}_1 \tilde{t}_1	Forbidden		0.4-0. 0.6-0.8	1.0 9	$m(\tilde{\chi}_1^0)=150$ $m(\tilde{\chi}_1^0)=300$	$m(\tilde{\chi}_1^0)=1 \text{ GeV}$ 0 GeV, $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)=5 \text{ GeV}$, $\tilde{r}_1 \approx \tilde{r}_L$ 0 GeV, $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)=5 \text{ GeV}$, $\tilde{r}_1 \approx \tilde{r}_L$	1506.08616, 1709.04183, 1711.1152 1709.04183, 1711.11520 1709.04183, 1711.11520
	$\tilde{t}_1 \tilde{t}_1$, Well-Tempered LSP $\tilde{t}_1 \tilde{t}_1$, $\tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{c} \tilde{c}$, $\tilde{c} \rightarrow c \tilde{\chi}_1^0$	0	Multiple 2c	Yes	36.1 36.1	\tilde{t}_1 \tilde{t}_1 \tilde{t}_1		0.46	0.48-0.84 0.85		$m(\tilde{\chi}_1^0)=150$	$GeV, m(\tilde{\chi}_1^a)-m(\tilde{\chi}_1^0)=5 GeV, \tilde{r}_1 \approx \tilde{r}_L$ $m(\tilde{\chi}_1^0)=0 GeV$ $m(\tilde{r}_1, \tilde{c})-m(\tilde{\chi}_1^0)=50 GeV$	1709.04183, 1711.11520 1805.01649 1805.01649
	7.7. 7	0	mono-jet	Yes	36.1	<i>ī</i> 1 7		0.43	0 22 0 85			$m(\tilde{t}_1, \tilde{c}) \cdot m(\tilde{t}_1^0) = 5 \text{ GeV}$	1711.03301
	¥±¥ ⁰ μia WZ	2-3 e. u	+0	Yes	36.1	$\tilde{X}^{\pm}/\tilde{X}^{0}$		_	0.6		in,	m(2 ⁰)-0	1403.5294, 1806.02293
	A 1 A 2 VIG # 2	ее, µµ	≥ 1	Yes	36.1	$\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0}$ 0.17						$m(\tilde{\chi}_1^{\pm}) \cdot m(\tilde{\chi}_1^{0}) = 10 \text{ GeV}$	1712.08119
	$ \begin{split} \tilde{\chi}_{1}^{\pm} \tilde{\chi}_{2}^{0} \ \text{via} \ Wh \\ \tilde{\chi}_{1}^{\pm} \tilde{\chi}_{1}^{\mp} / \tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{+} {\rightarrow} \tilde{\tau} \nu(\tau \tilde{\nu}), \tilde{\chi}_{2}^{0} {\rightarrow} \tilde{\tau} \tau(\nu \tilde{\nu}) \end{split} $	<i>ℓℓ/ℓγγ/ℓbb</i> 2 τ		Yes Yes	20.3 36.1	$\frac{\tilde{\chi}_{1}^{*}/\tilde{\chi}_{2}^{'}}{\tilde{\chi}_{1}^{*}/\tilde{\chi}_{2}^{0}}$ $\tilde{\chi}_{1}^{*}/\tilde{\chi}_{2}^{0}$	0.26		0.76		$m(\hat{\chi}_{1}^{\pm})-m(\hat{\chi}_{1}^{0})=1$	$m(\tilde{\chi}_{1}^{0})=0$ $n(\tilde{\chi}_{1}^{0})=0, m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{\pm})+m(\tilde{\chi}_{1}^{0}))$ 10 GeV, $m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{\pm})+m(\tilde{\chi}_{1}^{0}))$	1501.07110 1708.07875 1708.07875
	$\tilde{\ell}_{L,R} \tilde{\ell}_{L,R}, \tilde{\ell} {\rightarrow} \ell \tilde{\chi}_1^0$	2 e,μ 2 e,μ	0 ≥ 1	Yes Yes	36.1 36.1	ℓ ℓ 0.18		0.5	5			$m(\tilde{\ell}_1^0)=0$ $m(\tilde{\ell}_1)-m(\tilde{\chi}_1^0)=5 \text{ GeV}$	1803.02762 1712.08119
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 4 e, µ	$\geq 3b$ 0	Yes Yes	36.1 36.1	<u>Й</u> 0.1 Й	3-0.23 0.3		0.29-0.88			$BR(\tilde{\chi}_{1}^{0} \rightarrow h\tilde{G})=1$ $BR(\tilde{\chi}_{1}^{0} \rightarrow Z\tilde{G})=1$	1806.04030 1804.03602
	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$ \tilde{\chi}_{1}^{\pm} \\ \tilde{\chi}_{1}^{\pm} = 0.15 $		0.46				Pure Wino Pure Higgsino	1712.02118 ATL-PHYS-PUB-2017-019
	Stable g R-hadron	SMP		-	3.2	ğ					1.6		1606.05129
	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$		Multiple		32.8	$\tilde{g} = [\tau(\tilde{g}) = 100 \text{ ns},$	0.2 ns]				1.6 2.4	m($\tilde{\chi}_{1}^{0}$)=100 GeV	1710.04901, 1604.04520
	GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$, long-lived $\tilde{\chi}_1^0$ $\tilde{a} \tilde{\chi}_1^0 \rightarrow eev euv uuv$	2 γ displ. ee/eu/u	- u -	Yes -	20.3	X ₁ ğ		0.44			1.3	$1 < \tau(\tilde{\chi}_1^0) < 3 \text{ ns, SPS8 model}$ $ < c \tau(\tilde{\chi}_1^0) < 1000 \text{ mm, m}(\tilde{\chi}_1^0) = 1 \text{ TeV}$	1409.5542 1504.05162
	LFV $pp \rightarrow \tilde{v}_r + X, \tilde{v}_r \rightarrow eu/et/ut$	eu.et.pt			3.2	P.					19	Au =0.11. Augustar=0.07	1607 08079
	$\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp}/\tilde{\chi}_{2}^{0} \rightarrow WW/Z\ell\ell\ell\ell\nu\nu$	4 e, µ	0	Yes	36.1	$\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} = [\lambda_{i33} \neq 0,$	$l_{12k} \neq 0$		0.82		1.33	m($\tilde{\ell}_{1}^{0}$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow qqq$	0 4	5 large- <i>R</i> je Multiple	ets -	36.1 36.1	$\tilde{g} = [m(\tilde{\chi}_{1}^{0})=200 \text{ Ge} \\ \tilde{g} = [\lambda''_{112}=2e-4, 2e-4]$	V, 1100 GeV] 5]			1.05	1.3 1.9 2.0	Large $\lambda_{112}^{\prime\prime}$ m $(\tilde{\chi}_1^0)$ =200 GeV, bino-like	1804.03568 ATLAS-CONF-2018-003
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow tbs / \tilde{g} \rightarrow tt\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow tbs$		Multiple		36.1	ğ [ℓ ^{''} ₃₂₃ =1, 10-2]					1.8 2.1	$m(\tilde{\ell}_1^0)$ =200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow tbs$		Multiple		36.1	g [A"323=2e-4, 1e-	2]	0.40	0.55	1.05		$m(\tilde{\chi}_1^0)$ =200 GeV, bino-like	ATLAS-CONF-2018-003
	$i_1i_1, i_1 \rightarrow bs$ $\tilde{i}_1\tilde{i}_1, \tilde{i}_1 \rightarrow b\ell$	20.11	2 jets + 2 l		36.7	7. [qq, bs]		0.42	0.01		4-1.45	BB(1>he(hu)>20%	1710.07171

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made. Mass scale [TeV

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- dark matter, hierarchy problem, matter-antimatter asymmetry, neutrino masses, gravity.... ...but where is it??

	Model	e, μ, τ, γ	Jets	$E_{\mathrm{T}}^{\mathrm{miss}}$	∫ <i>L dt</i> [fb	-1]	Mass limit		\sqrt{s} = 7, 8 TeV	$\sqrt{s} = 13 \text{ TeV}$	Reference
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q \tilde{\chi}_{1}^{0}$	0 mono-jet	2-6 jets 1-3 jets	Yes Yes	36.1 36.1	 <i>q̃</i> [2×, 8× Degen.] <i>q̃</i> [1×, 8× Degen.] 	0.43	0.9	1.55	m($\tilde{\chi}_{1}^{0}$)<100 GeV m(\tilde{q})-m($\tilde{\chi}_{1}^{0}$)=5 GeV	1712.02332 1711.03301
Inclusive Searches	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_{1}^{0}$	0	2-6 jets	Yes	36.1	ğ ğ		Forbidden	2.0 0.95-1.6	m($\tilde{\chi}_{1}^{0}$)<200 GeV m($\tilde{\chi}_{1}^{0}$)=900 GeV	1712.02332 1712.02332
	$\tilde{g}\tilde{g}, \tilde{g} {\rightarrow} q \bar{q}(\ell \ell) \tilde{\chi}_1^0$	3 e, μ ee, μμ	4 jets 2 jets	- Yes	36.1 36.1	it is a second s			1.85	m(𝔅 ⁰)<800 GeV m(𝔅)-m(𝔅 ⁰)=50 GeV	1706.03731 1805.11381
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_{1}^{0}$	0 3 e, µ	7-11 jets 4 jets	Yes	36.1 36.1	ğ ğ		0.98	1.8	m(x̃ ₁ ⁰) <400 GeV m(č)⋅m(x̃ ₁ ⁰)=200 GeV	1708.02794 1706.03731
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t t \tilde{\chi}_1^0$	0-1 e, μ 3 e, μ	3 b 4 jets	Yes	36.1 36.1	an Ba			2.0	m(ℓ ₁ ⁰)<200 GeV m(ĝ)-m(ℓ ₁ ⁰)=300 GeV	1711.01901 1706.03731
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1{\rightarrow}b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple Multiple Multiple		36.1 36.1 36.1	$egin{array}{ccc} & & & & & & \\ & & & & & & \\ & & & & & $	den Forbidden Forbidden	0.9 0.58-0.82 0.7	m($\tilde{\chi}_{1}^{0}$)=200	$m(\tilde{t}_1^0)=300 \text{ GeV}, BR(b\tilde{t}_1^0)=1$ =300 GeV, $BR(b\tilde{t}_1^0)=BR(b\tilde{t}_1^+)=0.5$ GeV, $m(\tilde{t}_1^+)=300 \text{ GeV}, BR(b\tilde{t}_1^+)=1$	1708.09266, 1711.03301 1708.09266 1706.03731
ion	$\tilde{b}_1\tilde{b}_1,\tilde{t}_1\tilde{t}_1,M_2=2\times M_1$		Multiple Multiple		36.1 36.1	71 71 Forbidden		0.7	m($\tilde{\chi}_{1}^{0}$)=60 GeV m($\tilde{\chi}_{1}^{0}$)=200 GeV		1709.04183, 1711.11520, 1708.03247 1709.04183, 1711.11520, 1708.03247
o gen. squar direct producti	$ \begin{array}{l} \tilde{\imath}_1 \tilde{\imath}_1, \tilde{\imath}_1 {\rightarrow} W b \tilde{\chi}_1^0 \text{ or } t \tilde{\chi}_1^0 \\ \tilde{\imath}_1 \tilde{\imath}_1, \tilde{H} \text{ LSP} \end{array} $	0-2 e, µ (0-2 jets/1-2 l Multiple Multiple	> Yes	36.1 36.1 36.1	τ ₁ τ ₁ τ ₁ Forbide	den	1.0 0.4-0.9 0.6-0.8	$\begin{array}{l} m(\tilde{k}_{1}^{0}) \!=\! 150 \mathrm{GeV}, m(\tilde{k}_{1}^{1}) \!=\! 5 \mathrm{GeV}, \tilde{t}_{1} \approx \tilde{t}_{L} \\ m(\tilde{k}_{1}^{0}) \!=\! 300 \mathrm{GeV}, m(\tilde{k}_{1}^{1}) \!=\! m(\tilde{k}_{1}^{0}) \!=\! 5 \mathrm{GeV}, \tilde{t}_{1} \approx \tilde{t}_{L} \end{array}$		1506.08616, 1709.04183, 1711.11520 1709.04183, 1711.11520 1709.04183, 1711.11520
	$\tilde{t}_1 \tilde{t}_1$, Well-Tempered LSP	0	Multiple	Vac	36.1	71 7		0.48-0.84	$m(\tilde{\chi}_{1}^{0})=150 \text{ GeV}, m(\tilde{\chi}_{1}^{0})-m(\tilde{\chi}_{1}^{0})=5 \text{ GeV}, \tilde{r}_{L} \approx \tilde{r}_{L}$ $m(\tilde{\chi}_{1}^{0})=0 \text{ GeV}$		1709.04183, 1711.11520
	$\eta\eta, \eta \rightarrow \alpha_1 / cc, c \rightarrow \alpha_1$	0	mono-jet	Yes	36.1		0.46 0.43	0.00		$m(\tilde{x}_1)=0 \text{ GeV}$ $m(\tilde{x}_1,\tilde{c})-m(\tilde{\chi}_1^0)=50 \text{ GeV}$ $m(\tilde{t}_1,\tilde{c})-m(\tilde{\chi}_1^0)=5 \text{ GeV}$	1805.01649 1711.03301
	$\tilde{t}_2\tilde{t}_2,\tilde{t}_2{\rightarrow}\tilde{t}_1+h$	1-2 e, µ	4 b	Yes	36.1	ĩ ₂		0.32-0.88	m(i	$(\tilde{t}_{1}^{0})=0 \text{ GeV}, m(\tilde{t}_{1})\cdot m(\tilde{t}_{1}^{0})=180 \text{ GeV}$	1706.03986
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via WZ	2-3 e, μ ee, μμ	- ≥ 1	Yes Yes	36.1 36.1	$ \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} \\ \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{1}^{0} $ 0.17		0.6		$m(\tilde{\chi}_{1}^{\pm})=0$ $m(\tilde{\chi}_{1}^{\pm})-m(\tilde{\chi}_{1}^{0})=10 \text{ GeV}$	1403.5294, 1806.02293 1712.08119
ect	$\begin{array}{l} \tilde{\chi}_{1}^{\pm}\tilde{\chi}_{2}^{0}\textit{via}\;Wh \\ \tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp}/\tilde{\chi}_{2}^{0},\tilde{\chi}_{1}^{+}{\rightarrow}\tilde{\tau}\nu(\tau\tilde{\nu}),\tilde{\chi}_{2}^{0}{\rightarrow}\tilde{\tau}\tau(\nu\tilde{\nu}) \end{array}$	<i>ℓℓ/ℓγγ/ℓbb</i> 2 τ	:	Yes Yes	20.3 36.1	$ \frac{\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0}}{\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0}} $ 0.26 $ \frac{\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0}}{\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0}} $ 0.22		0.76	$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)=10$	$m(\tilde{\chi}_{1}^{0})=0$ $(\tilde{\chi}_{1}^{0})=0, m(\tilde{\tau}, \tilde{\tau})=0.5(m(\tilde{\chi}_{1}^{\pm})+m(\tilde{\chi}_{1}^{0}))$ 10 GeV, $m(\tilde{\tau}, \tilde{\tau})=0.5(m(\tilde{\chi}_{1}^{\pm})+m(\tilde{\chi}_{1}^{0}))$	1501.07110 1708.07875 1708.07875
<u>ج</u> ر	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} {\rightarrow} \ell \tilde{\chi}_1^0$	2 e,μ 2 e,μ	0 ≥ 1	Yes Yes	36.1 36.1	ℓ ℓ 0.18	0.5			$m(\tilde{\ell}_1^0)=0$ $m(\tilde{\ell})-m(\tilde{\chi}_1^0)=5 \text{ GeV}$	1803.02762 1712.08119
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 4 e, µ	$\geq 3b$ 0	Yes Yes	36.1 36.1	Й 0.13-0.23 Й	0.3	0.29-0.88		$BR(\tilde{\chi}_1^0 \rightarrow h\tilde{G})=1$ $BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G})=1$	1806.04030 1804.03602
	$\text{Direct}\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$ \tilde{\chi}_{1}^{\pm} \\ \tilde{\chi}_{1}^{\pm} = 0.15 $	0.46			Pure Wino Pure Higgsino	1712.02118 ATL-PHYS-PUB-2017-019
icles	Stable g R-hadron	SMP			3.2	<u>ğ</u>			1.6		1606.05129
art	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$		Multiple		32.8	$\tilde{g} = [\tau(\tilde{g}) = 100 \text{ ns}, 0.2 \text{ ns}]$			1.6 2.4	m($\tilde{\chi}_{1}^{0}$)=100 GeV	1710.04901, 1604.04520
1 11	GMSB, $\chi_1^{\circ} \rightarrow \gamma G$, long-lived χ_1° $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow eev/e\mu v/\mu\mu v$	2 γ displ. ee/eµ/μ	μ-	Yes -	20.3	X ₁ ğ	0.44		1.3 6	$1 < \tau(\tilde{\chi}_{1}^{0}) < 3 \text{ ns, SPS8 model}$ $< c\tau(\tilde{\chi}_{1}^{0}) < 1000 \text{ mm, m}(\tilde{\chi}_{1}^{0}) = 1 \text{ TeV}$	1409.5542 1504.05162
	$LFV\ pp{\rightarrow}\tilde{v}_{\tau} + X, \tilde{v}_{\tau}{\rightarrow}e\mu/e\tau/\mu\tau$	εμ,ετ,μτ	-	-	3.2	$\tilde{\nu}_{\tau}$			1.9	λ'_{311} =0.11, $\lambda_{132/133/233}$ =0.07	1607.08079
	$\tilde{\chi}_{1}^{\pm} \tilde{\chi}_{1}^{\mp} / \tilde{\chi}_{2}^{0} \rightarrow WW/Z\ell\ell\ell\ell\nu\nu$	4 e, µ	0	Yes	36.1	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ $[\lambda_{i33} \neq 0, \lambda_{12k} \neq 0]$		0.82	1.33	m($\tilde{\chi}_{1}^{0}$)=100 GeV	1804.03602
RPV	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qqq$	0 4	 5 large-R je Multiple 	ts -	36.1 36.1	$\tilde{g} = [m(\tilde{\chi}_{1}^{0})=200 \text{ GeV}, 1100 \text{ GeV}]$ $\tilde{g} = [\chi''_{112}=2e-4, 2e-5]$	1	1.0	1.3 1.9 5 2.0	Large $\lambda_{112}^{\prime\prime}$ m($\tilde{\chi}_1^0$)=200 GeV, bino-like	1804.03568 ATLAS-CONF-2018-003
	$\tilde{g}\tilde{g}, \tilde{g} \to tbs / \tilde{g} \to t \tilde{t} \tilde{\chi}_1^0, \tilde{\chi}_1^0 \to tbs$		Multiple		36.1	ĝ [ℓ ^{''} ₃₂₃ =1, 1e-2]			1.8 2.1	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow tbs$		Multiple		36.1	ğ [A''_323=2e-4, 1e-2]	0.5	5 1.0	5	$m(\tilde{\chi}_1^0)$ =200 GeV, bino-like	ATLAS-CONF-2018-003
	$t_1t_1, t_1 \rightarrow bs$ $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\ell$	0 2 e. u	∠ jets + 2 b 2 h		36.7 36.1	$I_1 = [q\bar{q}, b\bar{s}]$	0.42	0.61	0.4-1.45	$BR(\bar{i}_1 \rightarrow be/bu) > 20\%$	1710.07171 1710.05544

Surprises from the lepton sector: - neutrino masses - some ~3σ effects: R(K), R(D) - 3.8σ effect in muon g-2

So, how do we learn more? - Fermilab Muon g-2 - Mu3e ...+several other experiments

Precise measurements vs precise calculations

g-2



Larmor Precession:

- the magnetic moment of a particle rotates around a B-field

$$\omega_{s} = \frac{g q B}{2 m} = \frac{(2 + 2a) q B}{2 m}$$



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g-2



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Larmor Precession:

- the magnetic moment of a particle rotates around a B-field

$$\omega_{s} = \frac{g qB}{2 m} = \frac{(2 + 2a) qB}{2 m}$$

The magnetic moment of charged leptons:

- exactly 2 at tree level (Dirac's prediction)





D

Larmor Precession:

- the magnetic moment of a particle rotates around a B-field

g-2

$$\omega_{s} = \underbrace{g qB}_{2 m} = \underbrace{(2+2a) qB}_{2 m}$$

The magnetic moment of charged leptons:

- exactly 2 at tree level (Dirac's prediction)







- first loop calculated by Schwinger in 1948 $g = 2 + \alpha/2\pi + \dots$

- state of the art: *O(5) in QED* 12,762 diagrams! arXiv:1712.06060





For electons, a determined by QED loops

A recent measurement of α $I/\alpha = 137.035999046(27)$ Science, 13 Apr 2018: Vol. 360, Issue 6385, pp. 191-195 → new prediction of $a_e = 0.00115965218161(23)$ compared to measured $a_e = 0.00115965218073(28)$ PRD 97(2018)036001, PRL 100(2008)120801 → 2.50 difference

For electons, a determined by QED loops

A recent measurement of α $I/\alpha = 137.035999046(27)$ Science, 13 Apr 2018: Vol. 360, Issue 6385, pp. 191-195 → new prediction of $a_e = 0.00115965218161(23)$ compared to measured $a_e = 0.00115965218073(28)$ PRD 97(2018)036001, PRL 100(2008)120801 → 2.50 difference

Comparison of SM & BNL Measurement

Jegerlehner (2017) -4.1 o



- larger muon mass \rightarrow QCD and EWK loops contribute - a long-standing disagreement with experiment: - a = 0.00116592089(63) (measured) - a ~ 0.00116591821(36) (prediction) PRD 73(2006)072003, KNT18, PRD97, 114025 \rightarrow 3.70 difference



Electron and muon discrepancies in opposite directions...

...so a lepton-flavour violating dark photon..?

...a model with a large muon EDM..? - arXiv:1807.11484



Electron and muon discrepancies in opposite directions...

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...a model with a large muon EDM..?
- arXiv:1807.11484
```

... or experimental effects..?

Fermilab Muon g-2 experiment:

- factor 4 improvement over BNL result
- should resolve (at 5-10 σ level) or resolve muon discrepancy

34 institutes, 185 collaborators UK: Lancaster, Liverpool, Manchester, UCL



GIZMODO

VIDEO REVIEW SCIENCE IO9 FIELD GUIDE EARTHER DESIGN PALEOFUTURE

PHYSICS

Why Particle Physicists Are Excited About This Mysterious Inconsistency





The magnetism of muons is measured as the short-lived particles circulate in a 700-ton ring. FERMILAB

Renewed measurements of muon's magnetism could open door to new physics

Forbes

6,854 views | Sep 8, 2018, 10:00am

Ask Ethan: Does The Measurement Of The Muon's Magnetic Moment Break The Standard Model?

Ethan Siegel Senior Contributor Starts With A Bang Senior Contributor Science The Universe is out there, waiting for you to discover it.



Scientific breakthrough could be as simple as measuring the wobble of a muon

By Don Lincoln

CINNI

① Updated 1648 GMT (0048 HKT) February 13, 2018







Gravitational effect: the e-2 magnet arrives at Fermilab to h

experiment



We Asked Celeb Physicist Brian Cox About Flat Earth Conspiracies, the ... gizmodo.com

Measuring Muon g-2

UCL

Put muons in a magnetic field, measure precession frequency

$$\omega_{s} = \frac{g q B}{2 m} = \frac{(2 + 2a) q B}{2 m}$$



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Use a circular magnetic storage ring (7.1 m radius)

Cyclotron frequency:

$$\begin{array}{ccc} \omega_{c} = qB & \rightarrow & \omega_{a} = \omega_{s} - \omega_{c} = a \underline{qB} \\ m & & m \end{array}$$





Measuring Muon g-2

UCL

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Cyclotron frequency:
$$\omega_c = qB \rightarrow \omega_a = \omega_s - \omega_c = a qB m$$

m

$$\omega_{a} = -\frac{q}{m} \left[a_{\mu} B - \left(a_{\mu} - \frac{1}{\gamma^{2} - 1} \right) \frac{\beta \times E}{c} \right]$$

Actually measure ratio of two frequencies: $\begin{array}{c} 3ppb & 22ppb \\ \hline & & & \\ a_{\mu} = \frac{\omega_{a}}{\widetilde{\omega}_{p}} \frac{\mu_{p}}{\mu_{e}} \frac{m_{\mu}}{m_{e}} \frac{g_{e}}{2} \end{array} \quad 0.0003ppb$







Eelectron



15



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 $BNL \rightarrow FNAL$

 $[50 (stat) + 33 (syst) \rightarrow II (stat) + II (syst)] \times IO^{-II}$

A long journey

BNL magnet moved to Fermilab in 2013 - higher intensity, cleaner beam - new trackers & calorimeters

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- lots more stats







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B-field





Need highly uniform B-field around the storage ring - magnetic field was shimmed to high precision - constantly monitored using NMR probes



B-field uniformity 3x better than BNL (2x was the goal)

Simplest fit: 5 parameters

- exponential decay (2 parameters)

- with a superimposed sine wave (3 parameters)



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New Trackers

Main positron energy measurement made using 24 calorimeters - fast response lead-flouride Cherenkov crystals (9x6 array, each crystal 25x25x140mm)

- resolution 2.3% at 3 GeV

UK contributed new tracking detectors in front of two calorimeters









beam position video





Improved Wiggle





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First data-taking run complete:

- 5 months running, > 2x Brookhaven stats (took 5 years!)

- publish in 2019

Runs in 2019/20 will accumulate ~20 x BNL \rightarrow could push significance to ~5-10 σ



Comparison of SM & BNL Measurement



Planned g-2 experiment at J-PARC

- provide completely independent measurement

How about the theory?



Planned g-2 experiment at J-PARC

- provide completely independent measurement

How about the theory?





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g-2 theory

•	_

	Value $(\times 10^{-11})$ units
QED $(\gamma + \ell)$	$116584718.951\pm0.009\pm0.019\pm0.007\pm0.077_{\alpha}$
HVP(lo) [20]	6923 ± 42
HVP(lo) [21]	6949 ± 43
HVP(ho) [21]	-98.4 ± 0.7
HLbL	105 ± 26
\mathbf{EW}	154 ± 1
Total SM $[20]$	$116591802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}(\pm 49_{\text{tot}})$
Total SM $[21]$	$116591828\pm43_{\rm H\text{-}LO}\pm26_{\rm H\text{-}HO}\pm2_{\rm other}(\pm50_{\rm tot})$

[T. Blum et al., arXiv:1311.2198]

 \rightarrow need x2 improvement to keep up with experiment

Muon g-2 Theory Initiative underway https://indico.fnal.gov/event/13795/

Lattice starting to contribute to LBL & HVP

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MUonE experiment @ CERN:

- space-like (free of resonances) e-mu scattering

- basically a 150 GeV muon structure-function experiment

-> new, independent input to HVP calculations (used ee \rightarrow hadrons to date)

Schedule:

2018: 2 modules in CERN M2 Beam Line 2019: LOI to SPSC 2020/1: construction & installation 2021/2: start data taking (for 2 years)



 \rightarrow need x2 improvement to keep up with experiment

Muon g-2 Theory Initiative underway https://indico.fnal.gov/event/13795/

Lattice starting to contribute to LBL & HVP



SUSY?

- Needs $\mu > o$, 'light' SUSY-scale Λ and/or large tan β - ...excluded by LHC for simplest (like CMSSM)

- causes large χ^2 in simultaneous SUSY-fits with LHC data and g-2
- However, SUSY does not have to be minimal
 - could have large mass splittings (with lighter sleptons), be hadrophobic/leptophilic



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Many other ideas out there, eg:

- 2 Higgs doublet model, Stockinger et al., JHEP 1701 (2017) 007

- I TeV Leptoquark Bauer + Neubert, PRL 116 (2016)

- single new scalar could solve g-2, B-factory anomalies and still satisfy limits from LEP and LHC...

- axion-like particle contributing like π° in HLBL Marciano et al, PRD 94 (2016) 115033

- inevitably, a dark photon eg Feng et al, PRL 117 (2016) 071803

If the discrepancy goes away, will set tight limits on these new physics scenarios

See Thomas Teubner's talk at the UK HEP Forum, Nov 2018



It may not be the clear sign of new physics we wanted... ...but it may be the sign we get!



It may not be the clear sign of new physics we wanted... ...but it may be the sign we get!

To identify the new physics model, need to determine - couplings - quantum numbers - mass

Continued non-observation at the LHC will rule out some scenarios ...but need other observations to pin this down.

 \rightarrow EDMs \rightarrow cLFV experiments 34 G. Hesketh

 $\vec{d} = \eta \frac{Qe}{2} \vec{s}$

Fundamental particles can also have an EDM \rightarrow zero in SM, slightly non-zero due to loops

Existence of $EDM \rightarrow additional$ source of CP violation



A non-zero muon EDM would lead to out-of-plane precession
 - can be measured using trackers
 → 100x improvement in limit from Fermilab g-2
 - an upgrade would push limit further...



 $\mu = g \frac{1}{2mc} s$

Proton EDM

UCL

The proton EDM can be measured using similar techniques to g-2 - but use all electric storage ring

$$\omega_a = \frac{e}{mc} \left[\left(a_{\mu} - \frac{1}{\gamma^2 + 1} \right) \vec{\beta} \times \vec{E} \right] \quad \text{cancels of}$$

$$\omega_{\eta} = -\eta \frac{Qe}{2m} \frac{\vec{E}}{c}$$

leaves precession due to EDM



Part "Physics Beyond Colliders" programme \rightarrow expect 5 orders of magnitude in limit.

Development work ongoing at Juelich.



Many BSM models include charged lepton flavour violation

- leptoquarks, compositeness, Higgs doublets, heavy neutrinos... ...or invoke it for leptogenesis of matter-antimatter asymmetry

Heavy mediator \rightarrow low rate process

- *a la* beta decay with the massive W boson

cLFV

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Neutrino oscillations violate lepton flavour conservation
→ techincally possible in charged lepton sector
...but suppressed by ~10⁻⁵⁰

Put one of these models in a loop, rate may increase...

There is no "floor"! - current limits ~10⁻¹² - sensitivity purely experimental limitation

 \rightarrow any observation of cLFV is new physics!

Contact



Dipole

Updated from A. de Gouvea, P. Vogel, arXiv:1303.4097

N

 10^{2}

Contact

10



Limits are at 90% C.L.

 10^{-1}

 10^{-2}

Dipole

Dates are time the last data was taken for existing limits or the start of data taking (where known) for projected limits

Updated from A. de Gouvea, P. Vogel, arXiv:1303.4097

Can help resolve model dependency in g-2:

Rate (CLFV)
$$\sim g^2 \times \theta_{e\mu}^2 \times \left(\frac{m_{\mu}}{\Lambda}\right)^2$$

 $a_{\mu} \sim g^2 \times \left(\frac{m_{\mu}}{\Lambda}\right)^2$



MEG-II @ PSI:
physics in 2019
aiming for X10 on limit

→ 10⁻¹⁴ with 3 years running

II institutes, 75 collaborators

no UK involvement



cLFV

Muze @ FNAL
starting 2022 (after g-2)
aiming for x10⁴ on limit

→ 10⁻¹⁷ with ~4/5 years running
COMET @ J-PARC similar

40 institutes, 242 collaborators
Liverpool, Manchester, UCL



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The coming 5 years sees a step-change in sensitivity to cLFV!

Complementary experiments:

- Mu2e involves quark and lepton couplings - Mu3e purely leptonic, can also search for dark photons etc



Searching for one cLFV interaction in 10¹⁶ muon decays ...looking for one specific grain of sand...

Allen Bernsteit







Stop muons on an Al target - x-ray emission from capture \rightarrow por

- x-ray emission from capture \rightarrow normalisation

Signal of neutrino-less conversion: mono-energetic electron



 $E_e = m_{\mu} - E_{bind} - E_{recoil}$ = 105.67 - 0.47 - 0.22 MeV $= 104.98 \, \text{MeV}$



Stop muons on an Al target

- x-ray emission from capture \rightarrow normalisation

Signal of neutrino-less conversion: mono-energetic electron



Mu2e

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Mu2e

Proton pulse on

Production target

Live Window

Muons at

Stopping target 1700 ns

900 ns

700 ns

Prompt backgrounds

- (radiative nuclear capture, d.i.f., pions, protons).
- Curved solenoid transport channel
- Pulsed beam strong extinction factor ($<10^{-9}$)

Cosmics: cosmic veto detector

Muon decay in orbit $(\mu N \rightarrow evvN)$ - precise momentum resolution







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Mu3e

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1.1 m² pixel tracker - first HV-CMOS tracker in particle physics!

Material budget critical: - 50 μm HV-MAPS - 25 μm support - 25 μm flex-print - 12 μm aluminium traces

- 10 µm adhesive

 \rightarrow 0.1% X $_{_{\rm o}}$ per tracking layer

Timing detectors reduce combinatorics - tracking on GPUs to keep up with muon rate







A [TeV]

Currently under construction, first data 2020





Updated from A. de Gouvea, P. Vogel, arXiv:1303.4097

UCL

New physics must be out there... but where?

 \rightarrow reach further through loops, with high precision measurements

Muon physics complements and extends major research themes:

- BSM searches, CPV in the lepton sector and leptogenesis of matter-antimatter asymmetry

g-2: - first publication in 2019, running for 2 more years, 20x BNL stats.

- options for extended / upgraded running, and follow-on measurements incl EDM

cLFV:

Mu2e and Mu3e aiming for 10⁴ improvement in sensitivity over current limits
 probe mass scales up to ~10⁴ TeV

- complementary physics, and complementary to g-2

Going to be an exciting few years!

We may need new ideas and new experiments to really identify new physics - this is a great time to be joining the field!