**New physics must exist:**
- dark matter, hierarchy problem, matter-antimatter asymmetry, neutrino masses, gravity....

...but where is it??

### ATLAS SUSY Searches - 95% CL Lower Limits

<table>
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<tr>
<th>Model</th>
<th>$\mu, \tau, 3 \text{ jets}$</th>
<th>Jets</th>
<th>$\sqrt{s} = 7, 8, 13 \text{ TeV}$</th>
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*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, i.e. cuts, for the assumptions made.*
New physics must exist:  
- dark matter, hierarchy problem, matter-antimatter asymmetry, neutrino masses, gravity....
...but where is it??

---

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

---

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

---

**Precise measurements vs precise calculations**
**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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The magnetic moment of charged leptons:
- exactly 2 at tree level (Dirac’s prediction)
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**The magnetic moment of charged leptons:**
- exactly 2 at tree level (Dirac’s prediction)

- first loop calculated by Schwinger in 1948
  \[ g = 2 + \frac{\alpha}{2\pi} + \ldots \]

- state of the art: \textit{O(5) in QED}
  12,762 diagrams! arXiv:1712.06060
For electrons, a determined by QED loops

A recent measurement of $\alpha$

$\frac{1}{\alpha} = 137.035999046(27)$

$\rightarrow$ new prediction of $a_e = 0.00115965218161(23)$

compared to measured $a_e = 0.00115965218073(28)$

$\rightarrow 2.5\sigma$ difference
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compared to measured $a_e = 0.00115965218073(28)$
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For muons:
- larger muon mass → QCD and EWK loops contribute
- a long-standing disagreement with experiment:
  - $a = 0.00116592089(63)$ (measured)
  - $a \sim 0.00116591821(36)$ (prediction)
PRD 73(2006)072003, KNT18, PRD97, 114025
→ 3.7$\sigma$ difference

Comparison of SM & BNL Measurement

Jegerlehner (2017) -4.1$\sigma$
DHMZ (2017) -3.5$\sigma$
DHMZ (2011) -3.6$\sigma$
KNT (2017) -3.9$\sigma$
HLMNNT (2011) -3.3$\sigma$
BNL (2004)
FNAL expected 0.14 ppm

$a_\mu - a_\mu (BNL)$ x10^{-11}
Electron and muon discrepancies in opposite directions...

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

...a model with a large muon EDM..?

- arXiv:1807.11484
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...so a lepton-flavour violating dark photon..?

...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

“Follow that ambulance!”
Put muons in a magnetic field, measure precession frequency

\[ \omega_s = \frac{g qB}{2m} = \frac{(2 + 2a) qB}{2m} \]
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Use a circular magnetic storage ring (7.1 m radius)

Cyclotron frequency:

\[
\omega_c = \frac{qB}{m} \rightarrow \omega_a = \omega_s - \omega_c = \frac{a qB}{m}
\]

\[\mu\]
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Cyclotron frequency:

\[ \omega_c = \frac{q B}{m} \rightarrow \omega_a = \omega_s - \omega_c = \frac{a q B}{m} \]

Use “magic momentum” 3.09 GeV

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

Actually measure ratio of two frequencies:

\[ a_\mu = \frac{\omega_a}{\tilde{\omega}_p} \frac{\mu_p}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2} \]

3ppb, 22ppb, 0.0003ppb
Decay $\text{e}^+$

Top down view of ring section

Vacuum Chamber

Calorimeters

Tracker

Highest energy positrons when spin and momentum are aligned.

60 hour dataset, preliminary

$\sigma_s$ statistical precision: 1.2 ppm
BNL → FNAL
\[ 50 \text{ (stat)} + 33 \text{ (syst)} \rightarrow 11 \text{ (stat)} + 11 \text{ (syst)} \] \times 10^{-11}

**BNL magnet moved to Fermilab in 2013**
- higher intensity, cleaner beam
- new trackers & calorimeters
- lots more stats
22 June → 26 July 2013
Need highly uniform B-field around the storage ring
- magnetic field was shimmed to high precision
- constantly monitored using NMR probes

\[ \omega_a = \frac{a q B}{m} \]

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)
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
Include vertical and horizontal beam motion, pile-up, muon losses and energy scale.
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
→ could push significance to ~5-10σ
**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?
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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[T. Blum et al., arXiv:1311.2198]
g-2 theory

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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→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)

Up to 20 Be targets + Si detectors
downstream calorimeters + muon PID
**SUSY?**

- Needs $\mu > 0$, ‘light’ SUSY-scale $\Lambda$ and/or large $\tan \beta$
  - ...excluded by LHC for simplest (like CMSSM)
  - causes large $\chi^2$ 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

\[ a_{\mu}^{SUSY} \approx \text{sgn}(\mu) 130 \times 10^{-11} \tan \beta \left( \frac{100 \text{ GeV}}{\Lambda_{SUSY}} \right)^2 \]
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Many other ideas out there, eg:
- 2 Higgs doublet model, Stockinger et al., JHEP 1701 (2017) 007
- 1 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 $\pi^0$ 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!
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...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.

→ EDMs
→ cLFV experiments
Fundamental particles can also have an EDM
→ zero in SM, slightly non-zero due to loops

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

\[ \omega_a = \frac{e}{mc} \left[ \left( \alpha - \frac{1}{\gamma^2 + 1} \right) \vec{\beta} \times \vec{E} \right] \]  

cancels completely using \( p = 0.7 \text{ GeV} \)

\[ \omega_\eta = -\eta \frac{Qe \vec{E}}{2mc} \]  

leaves precession due to EDM

Part “Physics Beyond Colliders” programme → 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 → low rate process
- *a la* beta decay with the massive W boson
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Neutrino oscillations violate lepton flavour conservation
→ technically possible in charged lepton sector
...but suppressed by $\sim 10^{-50}$

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

There is no “floor”!
- current limits $\sim 10^{-12}$
- sensitivity purely experimental limitation

→ any observation of cLFV is new physics!
Effective Lagrangian

de Gouvea & Vogel, arXiv 1303.4097

\[ \mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + h.c. \]

\[ \frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma_\mu u_L + \bar{d}_L \gamma_\mu d_L) + h.c. \]
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\]

**Next generation experiments can reach BSM physics at masses of 10,000 TeV**

...the LHC direct reach is ~10 TeV

**Can help resolve model dependency in g-2:**

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

\[
a_\mu \sim g^2 \times \left( \frac{m_\mu}{\Lambda} \right)^2
\]
MEG-II @ PSI:
- physics in 2019
- aiming for x10 on limit
  \[ \to 10^{-14} \text{ with 3 years running} \]
- 11 institutes, 75 collaborators
- no UK involvement

Mu2e @ FNAL
- starting 2022 (after g-2)
- aiming for x10^4 on limit
  \[ \to 10^{-17} \text{ with } \approx 4/5 \text{ years running} \]
- COMET @ J-PARC similar
- 40 institutes, 242 collaborators
- Liverpool, Manchester, UCL

Mu3e @ PSI
- phase 1 (2020) & 2 (2025)
- aiming for x10^4 on limit
  \[ \to 10^{-16} \text{ after phase 2} \]
- 11 institutes, 60 collaborators
- Liverpool, Bristol, Oxford, UCL
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

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Searching for one cLFV interaction in $10^{16}$ muon decays
...looking for one specific grain of sand...
$\mu N \rightarrow eN$

**Stop muons on an Al target**
- x-ray emission from capture $\rightarrow$ normalisation

**Signal of neutrino-less conversion:**
mono-energetic electron

$$E_e = m_\mu - E_{bind} - E_{recoil}$$
$$= 105.67 - 0.47 - 0.22 \text{ MeV}$$
$$= 104.98 \text{ MeV}$$
\[ \mu N \rightarrow eN \]

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Stat. errors only

\[ N_{\text{POT}} = 3.6 \times 10^{20} \]
\[ R_{\mu\nu} = 10^{-16} \]
\[ N_{\text{CE}} = 3.72 \pm 0.01 \]
\[ N_{\text{DIO}} = 0.20 \pm 0.02 \]

Signal Window

\[ 103.35 < p < 105.10 \text{ MeV/c} \]

No PID selection applied
**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

8 GeV protons (8 kW)

20 m downstream Stopping Target Monitor

Proton pulse on Production target

Muons at Stopping target

Live Window

8 GeV protons (8 kW)
Mu3e @ PSI
DC beam of up to $10^{10}$ μ/s on target, triggerless DAQ.
**Mu3e @ PSI**

DC beam of up to $10^{10}$ μ/s on target, triggerless DAQ.

**Combinatorics, Michel decay + photon conversion:**
- Scintillating fibres (1ns) and tiles (100ps)
- Vertex resolution 200 μm

**Michel decay + internal conversion**
- Momentum resolution 0.5 MeV

**Recurling tracks in 1T field,**
scattering dominated regime (E<53 MeV)
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
  → 0.1% $X_0$ per tracking layer

Timing detectors reduce combinatorics
- tracking on GPUs to keep up with muon rate
Currently under construction, first data 2020
**New physics must be out there... but where?**

→ 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 $10^4$ improvement in sensitivity over current limits
  - probe mass scales up to $\sim 10^4$ 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!