PHYSICS AT THE PRECISION FRONTIER

THEN, NOW, AND TOMORROW

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RADCOR-LoopFest 2021

Outline

- Precision at the Frontier: Examples
  - Kepler’s Battle With Mars
  - The Neutron Electric Dipole Moment
  - Gravitational Waves
  - g-2
  - The LHC
- The Frontier Tomorrow
- Summary

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Kepler’s Battle With Mars

Tycho Brahe
1546 – 1601

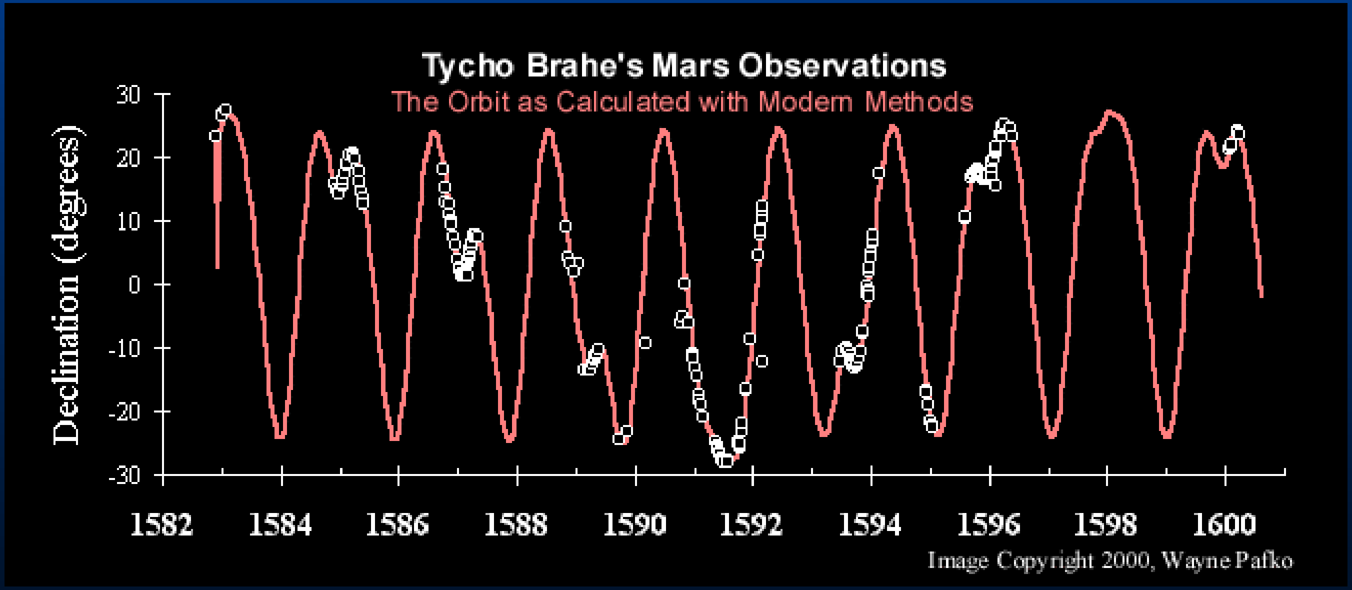
“Tycho has the world’s finest observations, but he only lacks an architect to construct an edifice out of them.”

Johannes Kepler

Brahe’s data, obtained with the naked eye, were indeed accurate: to 1/30th the angular size of the Moon.

Kepler’s Battle With Mars

Kepler was hired by Brahe in 1600 and thought he would have access to all of Brahe’s data. However, his new boss gave Kepler the data on Mars only and told him to work out that planet’s orbit.



From Wayne Pafko: http://www.pafko.com/tycho/home.html

Kepler’s Battle With Mars

Tycho Brahe’s data were so precise, it quickly became clear that neither the Ptolemaic nor the Copernican systems fit the data well.

However, although the Copernican system was the less precise model, Kepler, accepted the heliocentric hypothesis.

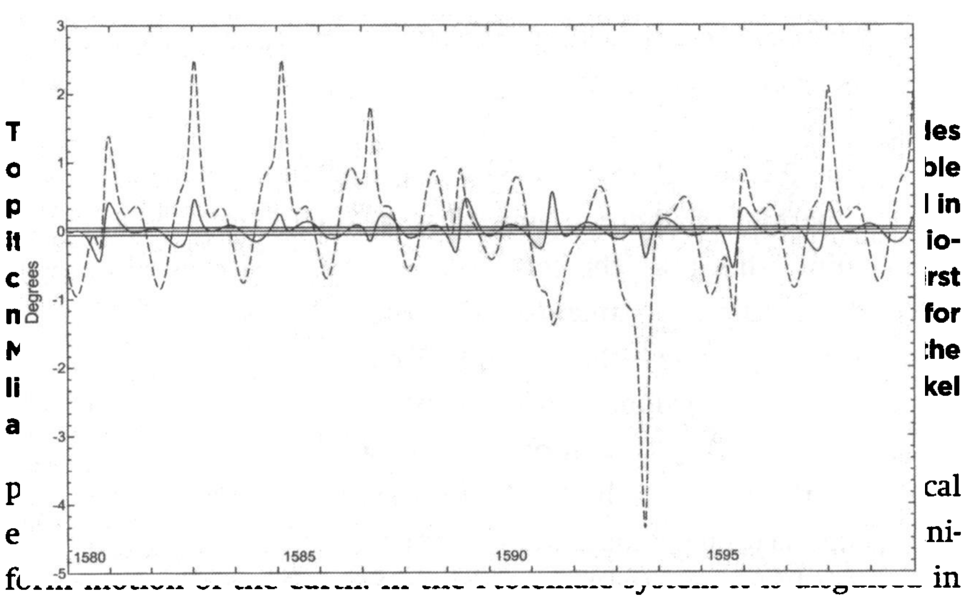
He first used the observations of Mars to obtain the orbit of Earth.

Then, he mapped the Martian data from the geocentric frame to a heliocentric frame with the Sun displaced from the center of the orbit of Mars, which he took to be circular.

Kepler’s Battle With Mars

The model worked much better than both the Ptolemaic and Copernican systems, but discrepancies between data and the model remained. However, by examining how the speed of Mars changed in its orbit Kepler concluded that

a different curve would work much better, and the rest, as they say, is history.



Owen Gingerich and James R. Voelkel
https://www.jstor.org/stable/40972003

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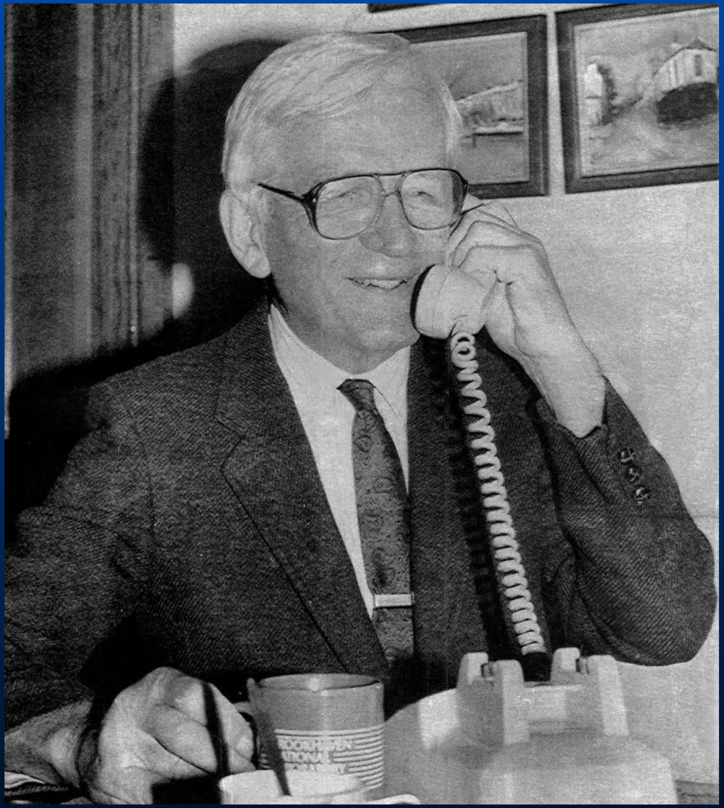
The Neutron Electric Dipole Moment

Norman Ramsey 1915 – 2011



Associated Press 1989

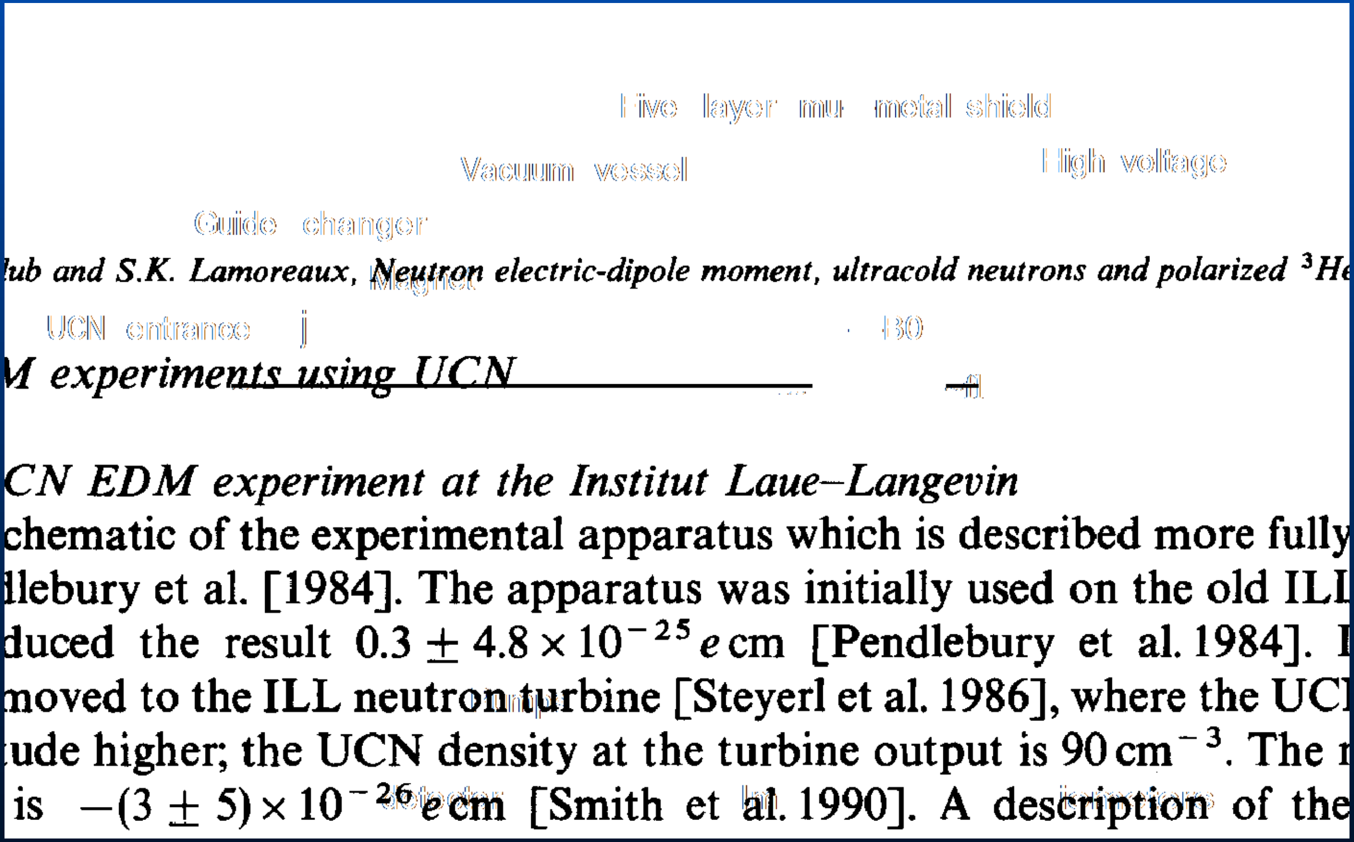
Norman Ramsey argued that the question: does a particle have an electric dipole moment (EDM) is one to be answered experimentally.

In 1951, he, Smith, and Purcell established that the neutron EDM (nEDM) $|d_n|$:

$$< (0.1 \pm 2.4) \times 10^{-20}\ \mathrm{ecm}$$

Experiments to measure the nEDM using the Ramsey method are sensitive to energy changes of $10^{-21}\ \mathrm{eV}$, but probe physics beyond the TeV scale.

The Neutron Electric Dipole Moment



lub and S.K. Lamoreaux, *Neutron electric-dipole moment, ultracold neutrons and polarized ^{3}He*

M experiments using UCN

CN EDM experiment at the Institut Laue–Langevin

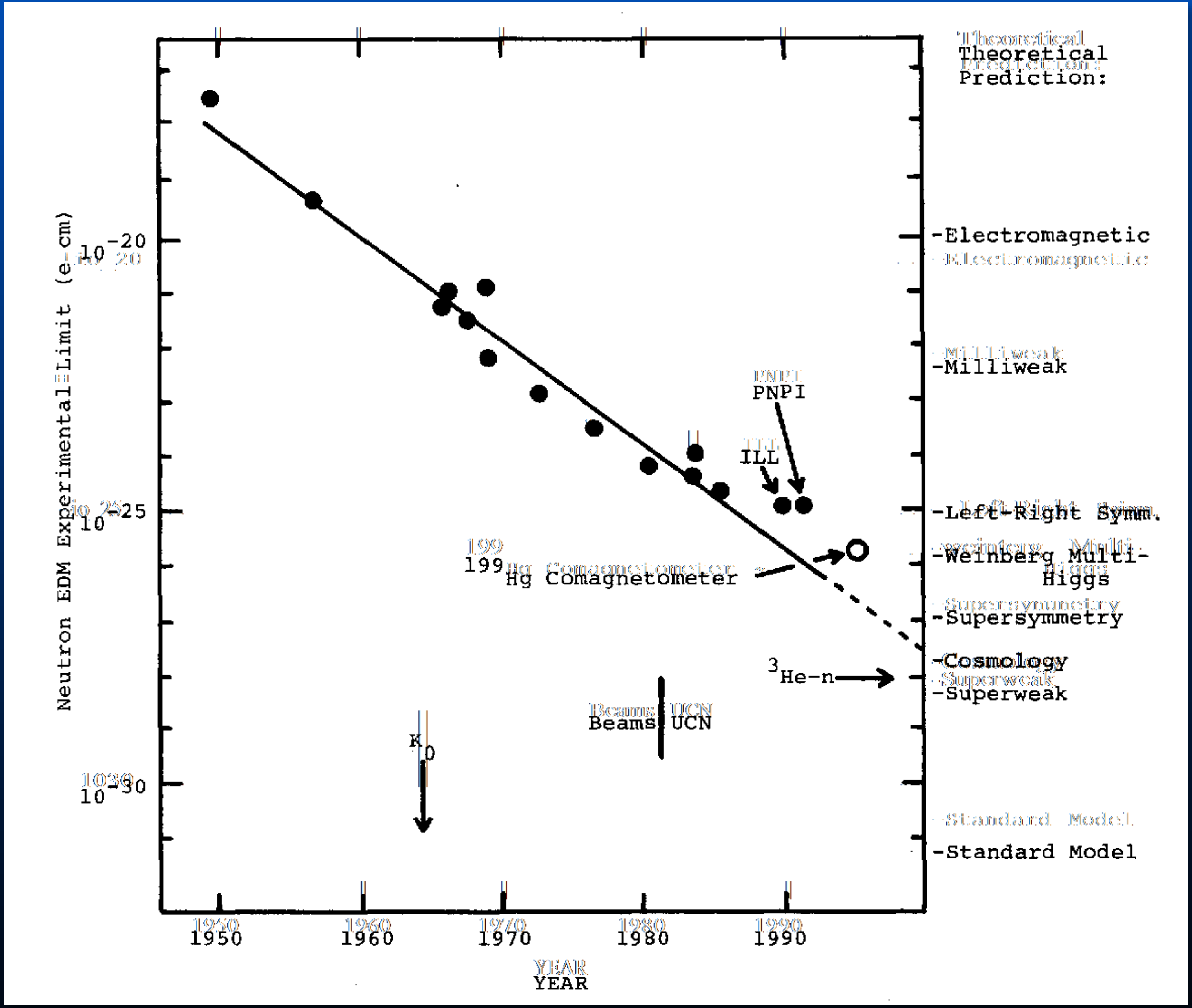
chematic of the experimental apparatus which is described more fully llebury et al. [1984]. The apparatus was initially used on the old ILL duced the result $0.3 \pm 4.8 \times 10^{-25}\,e\,\mathrm{cm}$ [Pendlebury et al. 1984]. I moved to the ILL neutron turbine [Steyerl et al. 1986], where the UC ude higher; the UCN density at the turbine output is $90\,\mathrm{cm}^{-3}$. The r is $-(3 \pm 5) \times 10^{-26}\,e\,\mathrm{cm}$ [Smith et al. 1990]. A description of the

By 1990, the limit had reduced to

$< \ 12 \times 10^{-26}$ ecm @ 90% CL

K. F. Smith, N. Crampin, J. M. Pendlebury, D. J. Richardson, D. Shiers, K. Green, A. I. Kilvington, J. Moir, H. B. Prosper, B. D. Thompson, N. F. Ramsey, B. R. Heckel *et al.*, *A search for the electric dipole moment of the neutron*, Phys. Lett. B **234**, 191 (1990)

The Neutron Electric Dipole Moment



Best limit to date

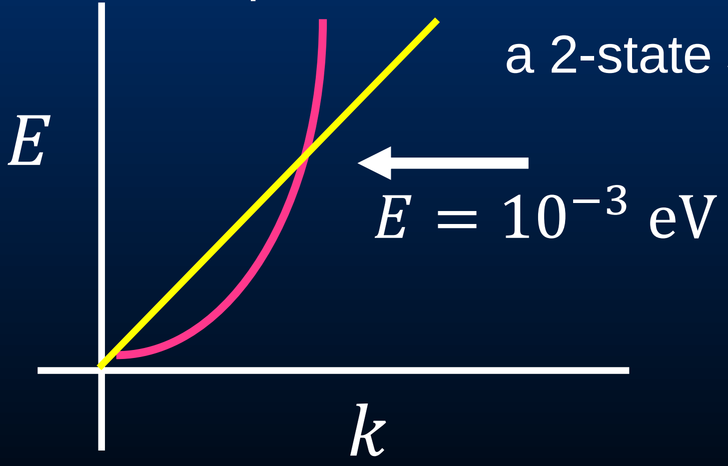
1.8×10^{-26} ecm

Review of Particle Physics at PSI
doi:10.21468/SciPostPhysProc.2 (2021)

The Neutron Electric Dipole Moment

A proposal by the nEDM* collaboration could reach 10^{-27} ecm (https://www.psi.ch/en/nedm)

Another proposal, made some time ago by Golub and Huffman (J. Res. Natl. Inst. Stand. Technol. 110, 169-172 (2005)), to create ultra cold neutrons in superfluid ^{4}He potentially could reach 10^{-29} ecm. The dispersion curves of the neutrons and phonons form a 2-state system which makes it possible for cold neutrons to down scatter to ultra cold ones (UCN).



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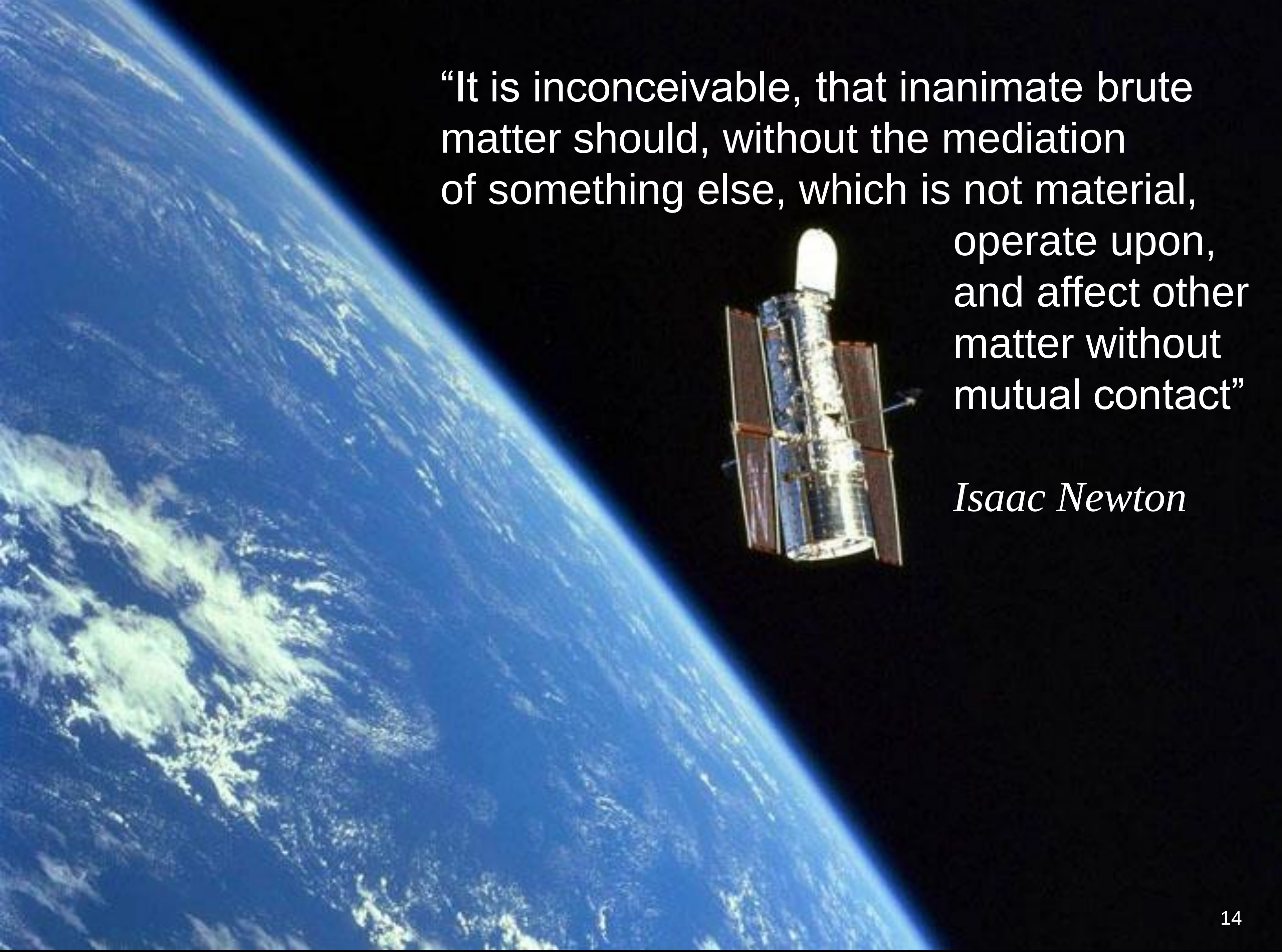


“It is inconceivable, that inanimate brute matter should, without the mediation of something else, which is not material, operate upon, and affect other matter without mutual contact”

Isaac Newton

Gravitational Waves

Virgo, Italy

Livingston, USA

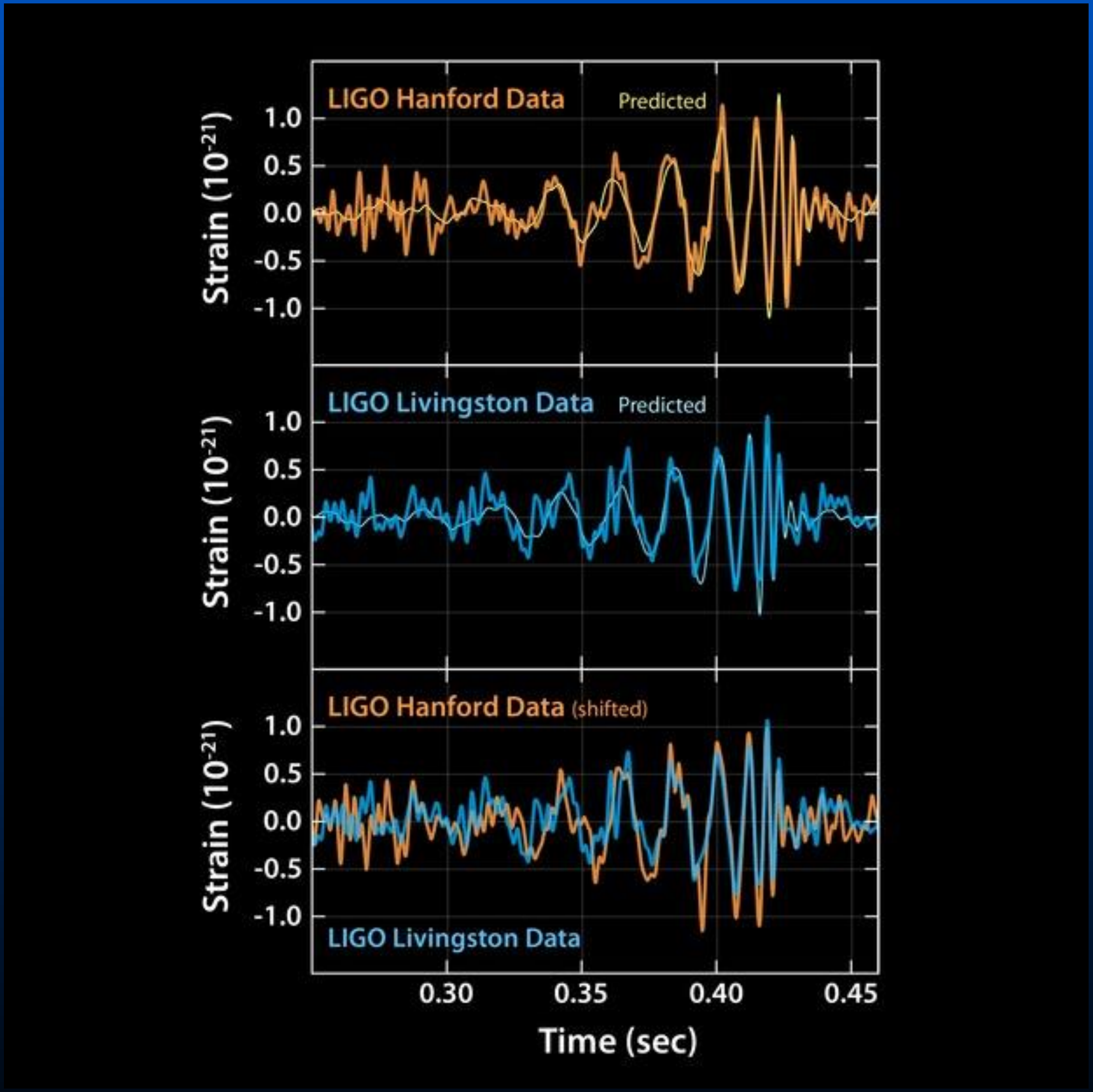
Hanford, USA

- The Field Equations of Gravitation, Albert Einstein, November 25, 1915

- First direct detection of gravitational waves September 14, 2015 5:51 a.m. EDT.

- In order to detect these waves, a displacement of 10^{-4} fm over ~ 4 km must be measured.

Image Credit: Caltech/MIT/LIGO Lab



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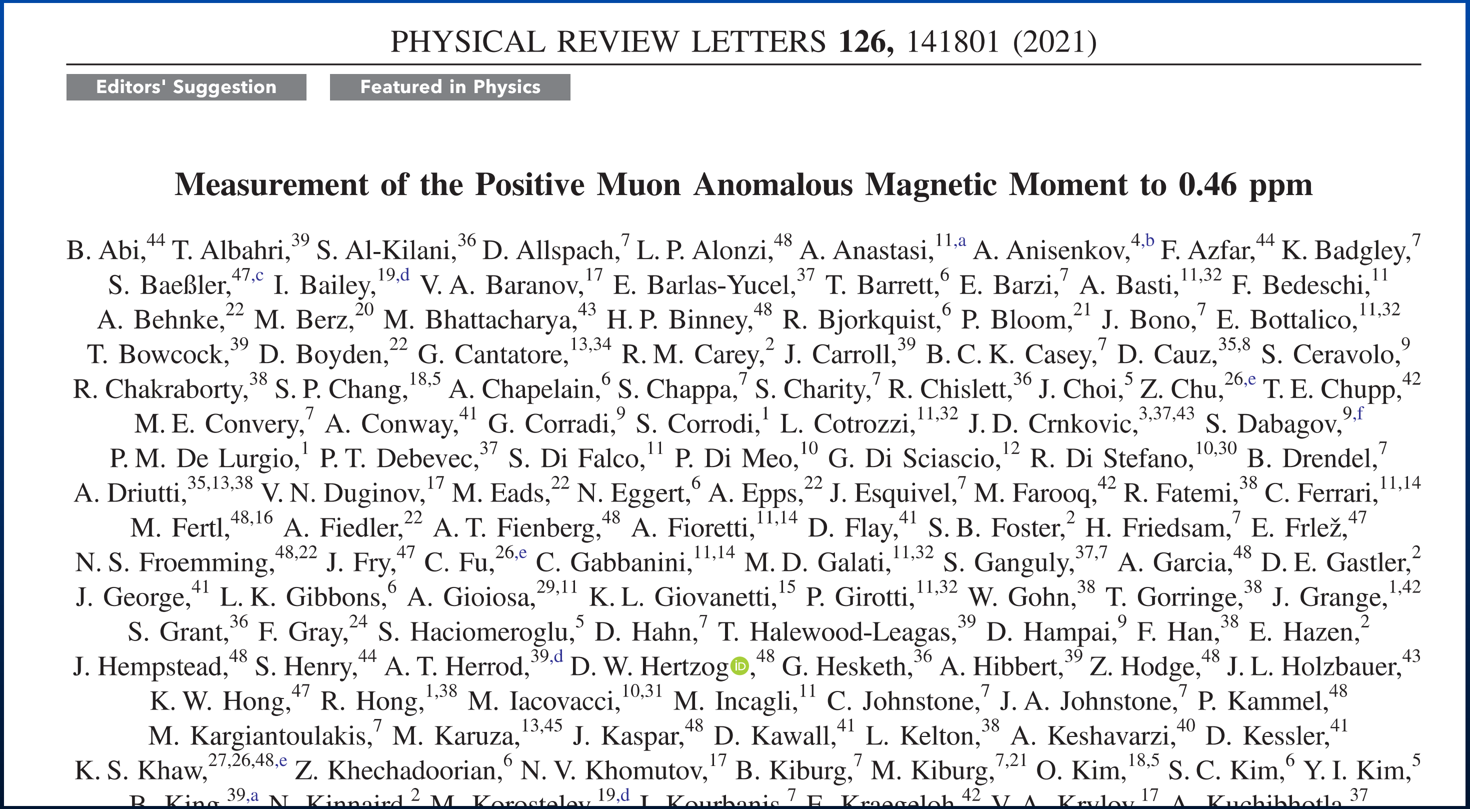
g – 2 of Muon



PHYSICAL REVIEW LETTERS **126,** 141801 (2021)

Editors' Suggestion **Featured in Physics**

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

B. Abi,[44] T. Albahri,[39] S. Al-Kilani,[36] D. Allspach,[7] L. P. Alonzi,[48] A. Anastasi,[11,a] A. Anisenkov,[4,b] F. Azfar,[44] K. Badgley,[7]
S. Baeßler,[47,c] I. Bailey,[19,d] V. A. Baranov,[17] E. Barlas-Yucel,[37] T. Barrett,[6] E. Barzi,[7] A. Basti,[11,32] F. Bedeschi,[11]
A. Behnke,[22] M. Berz,[20] M. Bhattacharya,[43] H. P. Binney,[48] R. Bjorkquist,[6] P. Bloom,[21] J. Bono,[7] E. Bottalico,[11,32]
T. Bowcock,[39] D. Boyden,[22] G. Cantatore,[13,34] R. M. Carey,[2] J. Carroll,[39] B. C. K. Casey,[7] D. Cauz,[35,8] S. Ceravolo,[9]
R. Chakraborty,[38] S. P. Chang,[18,5] A. Chapelain,[6] S. Chappa,[7] S. Charity,[7] R. Chislett,[36] J. Choi,[5] Z. Chu,[26,e] T. E. Chupp,[42]
M. E. Convery,[7] A. Conway,[41] G. Corradi,[9] S. Corrodi,[1] L. Cotrozzi,[11,32] J. D. Crnkovic,[3,37,43] S. Dabagov,[9,f]
P. M. De Lurgio,[1] P. T. Debevec,[37] S. Di Falco,[11] P. Di Meo,[10] G. Di Sciascio,[12] R. Di Stefano,[10,30] B. Drendel,[7]
A. Driutti,[35,13,38] V. N. Duginov,[17] M. Eads,[22] N. Eggert,[6] A. Epps,[22] J. Esquivel,[7] M. Farooq,[42] R. Fatemi,[38] C. Ferrari,[11,14]
M. Fertl,[48,16] A. Fiedler,[22] A. T. Fienberg,[48] A. Fioretti,[11,14] D. Flay,[41] S. B. Foster,[2] H. Friedsam,[7] E. Frlež,[47]
N. S. Froemming,[48,22] J. Fry,[47] C. Fu,[26,e] C. Gabbanini,[11,14] M. D. Galati,[11,32] S. Ganguly,[37,7] A. Garcia,[48] D. E. Gastler,[2]
J. George,[41] L. K. Gibbons,[6] A. Gioiosa,[29,11] K. L. Giovanetti,[15] P. Girotti,[11,32] W. Gohn,[38] T. Gorringe,[38] J. Grange,[1,42]
S. Grant,[36] F. Gray,[24] S. Haciomeroglu,[5] D. Hahn,[7] T. Halewood-Leagas,[39] D. Hampai,[9] F. Han,[38] E. Hazen,[2]
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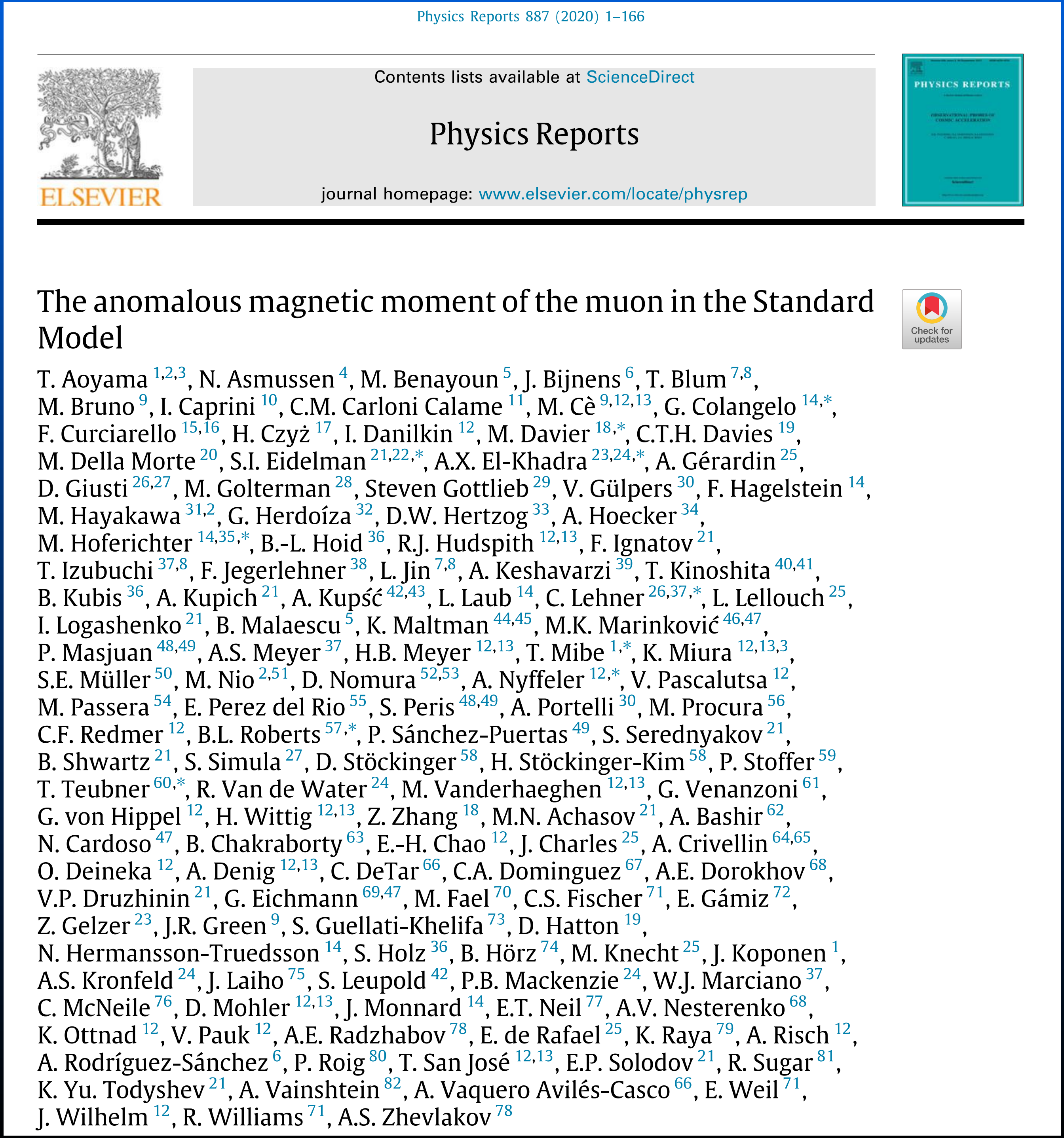
K. W. Hong,[47] R. Hong,[1,38] M. Iacovacci,[10,31] M. Incagli,[11] C. Johnstone,[7] J. A. Johnstone,[7] P. Kammel,[48]
M. Kargiantoulakis,[7] M. Karuza,[13,45] J. Kaspar,[48] D. Kawall,[41] L. Kelton,[38] A. Keshavarzi,[40] D. Kessler,[41]
K. S. Khaw,[27,26,48,e] Z. Khechadoorian,[6] N. V. Khomutov,[17] B. Kiburg,[7] M. Kiburg,[7,21] O. Kim,[18,5] S. C. Kim,[6] Y. I. Kim,[5]
R. King,[39,a] N. Kinnaird,[2] M. Korostelev,[19,d] I. Kourbanis,[7] E. Kraegeloh,[42] V. A. Krylov,[17] A. Kuchibhotla,[37]



Physics Reports 887 (2020) 1–166

Contents lists available at ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama [1,2,3], N. Asmussen [4], M. Benayoun [5], J. Bijnens [6], T. Blum [7,8],
M. Bruno [9], I. Caprini [10], C.M. Carloni Calame [11], M. Cè [9,12,13], G. Colangelo [14,*],
F. Curciarello [15,16], H. Czyż [17], I. Danilkin [12], M. Davier [18,*], C.T.H. Davies [19],
M. Della Morte [20], S.I. Eidelman [21,22,*], A.X. El-Khadra [23,24,*], A. Gérardin [25],
D. Giusti [26,27], M. Golterman [28], Steven Gottlieb [29], V. Gülpers [30], F. Hagelstein [14],
M. Hayakawa [31,2], G. Herdoíza [32], D.W. Hertzog [33], A. Hoecker [34],
M. Hoferichter [14,35,*], B.-L. Hoid [36], R.J. Hudspith [12,13], F. Ignatov [21],
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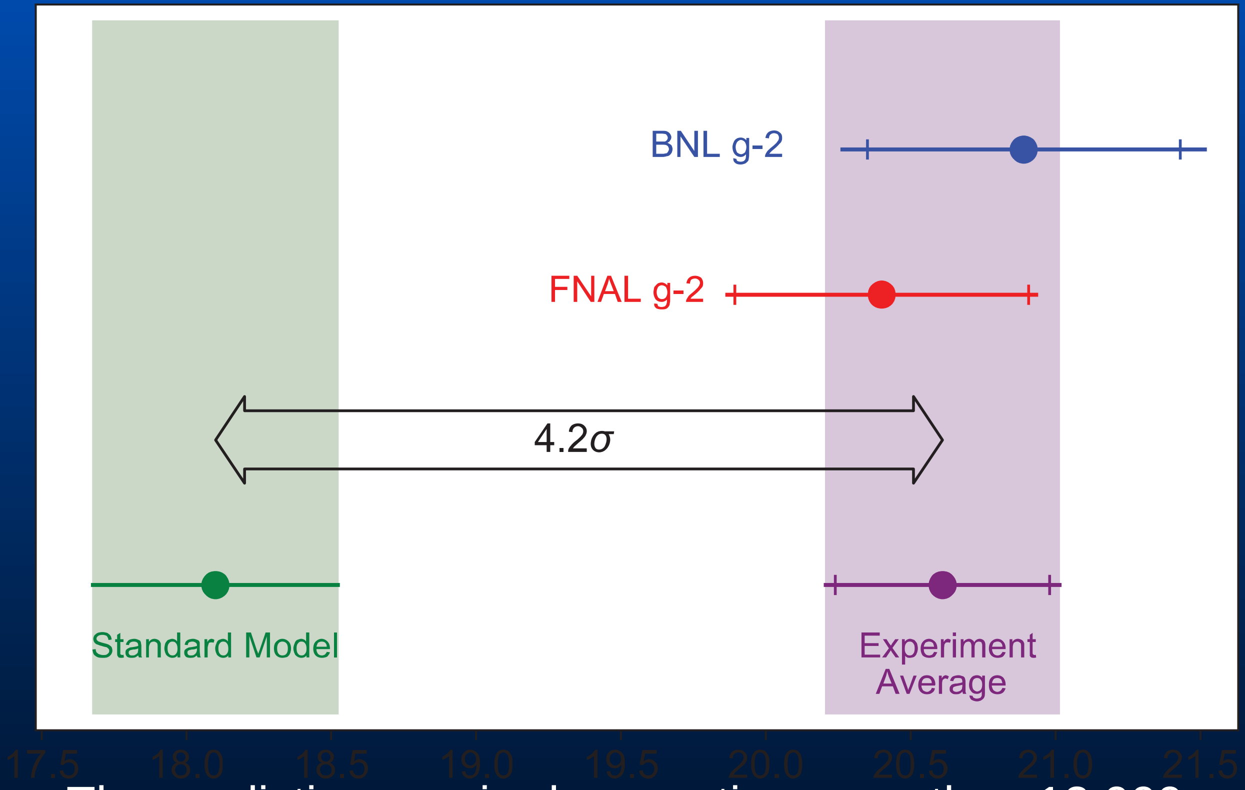
I. Logashenko [21], B. Malaescu [5], K. Maltman [44,45], M.K. Marinković [46,47],
P. Masjuan [48,49], A.S. Meyer [37], H.B. Meyer [12,13], T. Mibe [1,*], K. Miura [12,13,3],
S.E. Müller [50], M. Nio [2,51], D. Nomura [52,53], A. Nyffeler [12,*], V. Pascalutsa [12],
M. Passera [54], E. Perez del Rio [55], S. Peris [48,49], A. Portelli [30], M. Procura [56],
C.F. Redmer [12], B.L. Roberts [57,*], P. Sánchez-Puertas [49], S. Serednyakov [21],
B. Shwartz [21], S. Simula [27], D. Stöckinger [58], H. Stöckinger-Kim [58], P. Stoffer [59],
T. Teubner [60,*], R. Van de Water [24], M. Vanderhaeghen [12,13], G. Venanzoni [61],
G. von Hippel [12], H. Wittig [12,13], Z. Zhang [18], M.N. Achasov [21], A. Bashir [62],
N. Cardoso [47], B. Chakraborty [63], E.-H. Chao [12], J. Charles [25], A. Crivellin [64,65],
O. Deineka [12], A. Denig [12,13], C. DeTar [66], C.A. Dominguez [67], A.E. Dorokhov [68],
V.P. Druzhinin [21], G. Eichmann [69,47], M. Fael [70], C.S. Fischer [71], E. Gámiz [72],
Z. Gelzer [23], J.R. Green [9], S. Guellati-Khelifa [73], D. Hatton [19],
N. Hermansson-Truedsson [14], S. Holz [36], B. Hörz [74], M. Knecht [25], J. Koponen [1],
A.S. Kronfeld [24], J. Laiho [75], S. Leupold [42], P.B. Mackenzie [24], W.J. Marciano [37],
C. McNeile [76], D. Mohler [12,13], J. Monnard [14], E.T. Neil [77], A.V. Nesterenko [68],
K. Ottnad [12], V. Pauk [12], A.E. Radzhabov [78], E. de Rafael [25], K. Raya [79], A. Risch [12],
A. Rodríguez-Sánchez [6], P. Roig [80], T. San José [12,13], E.P. Solodov [21], R. Sugar [81],
K. Yu. Todyshev [21], A. Vainshtein [82], A. Vaquero Avilés-Casco [66], E. Weil [71],
J. Wilhelm [12], R. Williams [71], A.S. Zhevlakov [78]

g – 2 of Muon



The prediction required computing more than 12,000 diagrams, the use of non-perturbative data-driven methods, and the use of lattice QCD.

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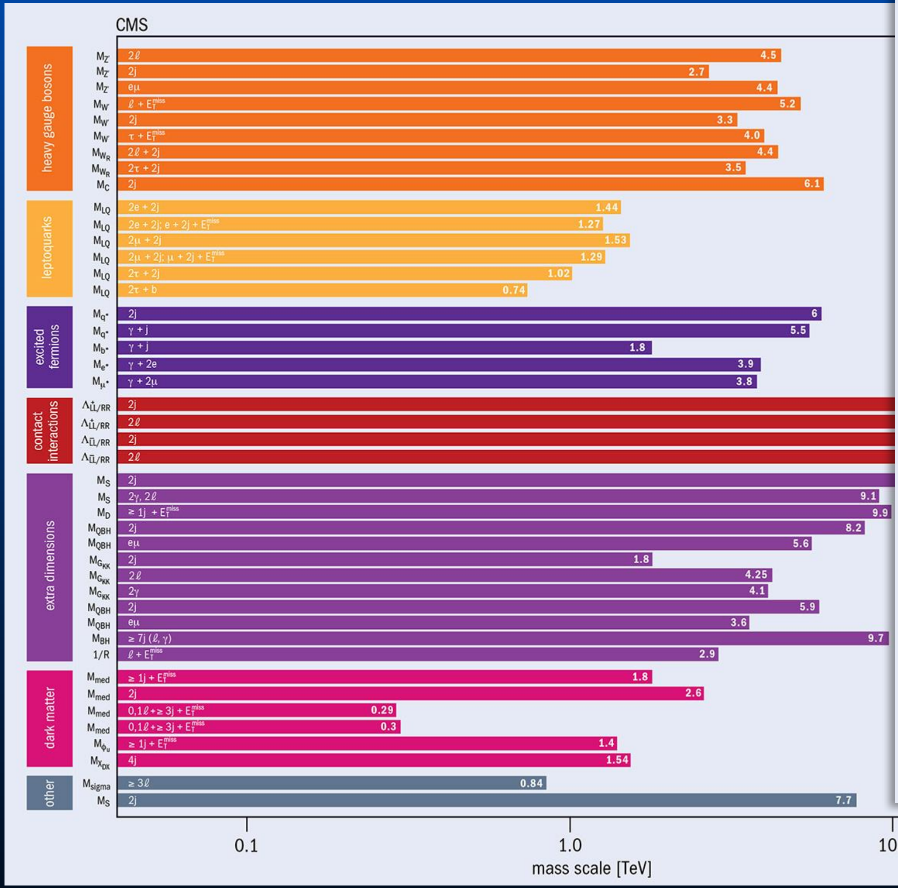
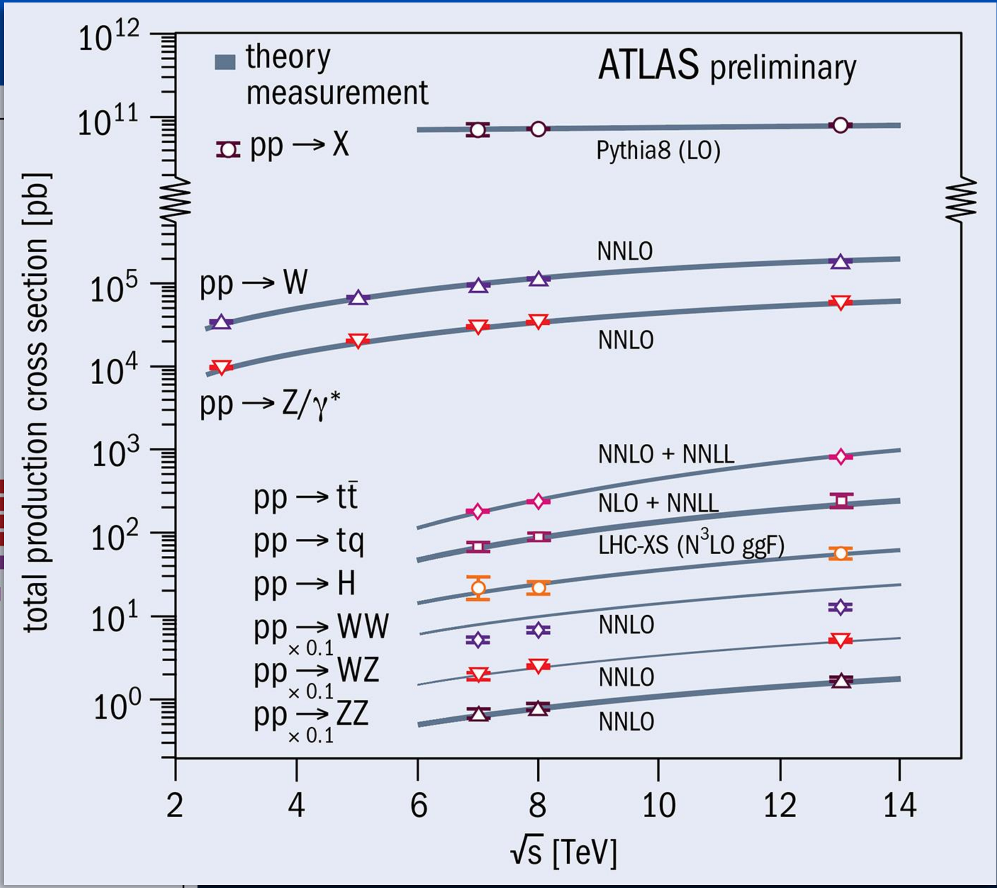
The LHC

To date, more than 2700 peer-reviewed physics papers have been published by the seven running LHC experiments (ALICE, ATLAS, CMS, LHCb, LHCf, MoEDAL and TOTEM). Approximately 10% of these are related to the Higgs boson, and 30% to searches for BSM phenomena.

CERN Courier 9 March 2020

The LHC





Source: CMS/CERN Courier 2020

Source: ATL-PHYS-PUB-2019-024/ CERN Courier 2020

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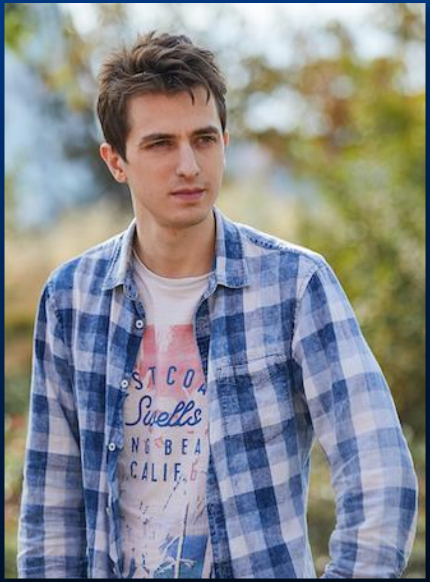
The Frontier Tomorrow

Here are some points to ponder:

1. By 2038, when the LHC era ends, the precision of measurements across many subfields of physics, not just collider physics, will have improved considerably.
2. Precision will be needed everywhere: QFT-based predictions, PDF and hadronization modeling, detector simulations.
3. Significant progress in physics may require the analysis of data across multiple sub-fields, which in turn will require the associated high-precision predictions.
4. The bright young theorists of 2038 are not yet in High School!
5. If you want to stay in the game, you won’t be able to avoid AI…

The Frontier: Symbolic Mathematics

In December 2019, Guillaume Lample and François Charton* at Facebook AI Research, Paris, announced: “*We achieve results that outperform commercial Computer Algebra Systems such as Matlab or Mathematica*.”



Lample

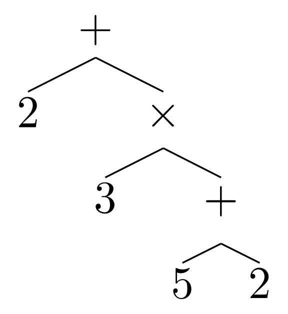
Charton

G. Lample and F. Charton, Deep Learning for Symbolic Mathematics, arXiv: 1912.01412v1.

The Frontier: Symbolic Mathematics

Their key idea is to take the idea of mathematics as a *language* seriously. Then, solving a mathematical problem symbolically is analogous to translating from one language to another or rephrasing a sentence.

Consider the expression $2 + 3 \times (5 + 2)$. It is first written as a tree:



Next, the tree is converted to a sequence:

$[+2\ \times\ 3 + 5\ 2]$.

Operators, functions, or variables are modeled with specific tokens.

The Frontier: Symbolic Mathematics

The authors' system simplifies, integrates functions, and solves 1st and 2nd order differential equations.

The training data are pairs (x, t) of correctly formed, *randomly generated*, expressions x with associated solutions t.

For example, for integration, at least two approaches are used:

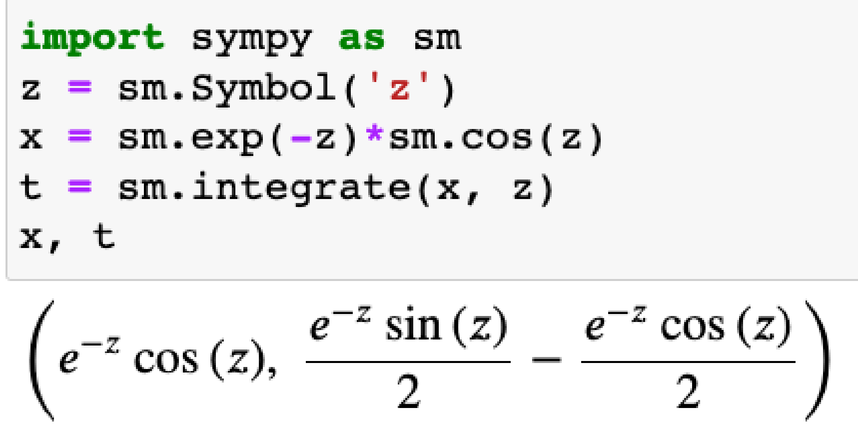
1. Forward: (x, t) where $t = \int x$
2. Backward: (x, t) where $x = Dt$

The Facebook toolkit seq2seq is used to translate one mathematical sequence into another.
https:// github.com/facebookresearch/fairseq

The Frontier: Symbolic Mathematics

…and here is why you won’t be able to avoid AI…

The authors trained their model using the subset of randomly generated functions that sympy can integrate, e.g.,



```
import sympy as sm
z = sm.Symbol('z')
x = sm.exp(-z)*sm.cos(z)
t = sm.integrate(x, z)
x, t
```

$$\left(e^{-z} \cos{\left(z \right)}, \frac{e^{-z} \sin{\left(z \right)}}{2} - \frac{e^{-z} \cos{\left(z \right)}}{2}\right)$$

…and found, amazingly, that the model was able to integrate functions that sympy could not!

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Summary

- Precise observation, experimentation, and calculation has been the hallmark of many important advances in physics.
- We may get lucky before 2038 and find a spectacular, unexpected, bump in a distribution, or a single spectacular event that heralds an unambiguous discovery of new physics.
- But by far the most important result from the LHC to date is the continuing extraordinary success of the Standard Model.
- It is, therefore, likely that the only realistic way towards the New Standard Model is with precision as our guide.