Colliding light to measure tau $g - 2$

Brookhaven Forum 2025

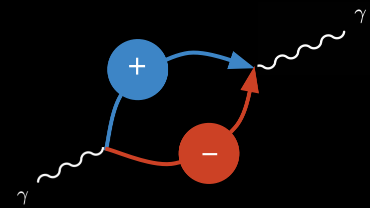
October 23, 2025

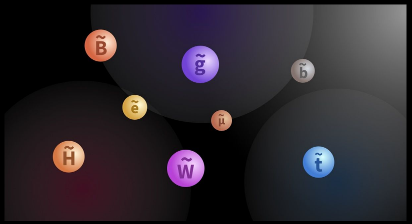
Jesse Liu

New York University

Introduction to $g-2$

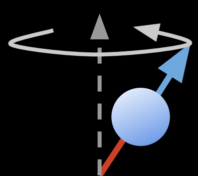
$$\mu_f \cdot \mathbf{B} = \frac{g_f e}{2m_f}\mathbf{S}\cdot\mathbf{B}$$

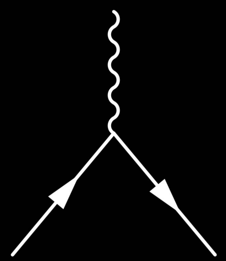




RELATIVISTIC QM → **QUANTUM FIELDS** → **NEW PARADIGMS?**

Antimatter exists | ***Vacuum is dynamical*** | ***Dark matter?***





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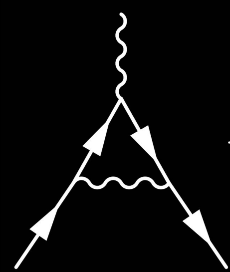

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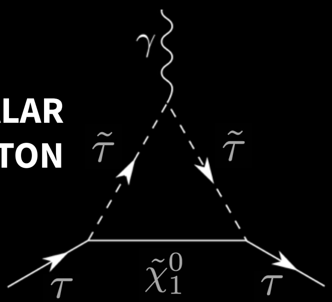


$$g = 2 + \frac{\alpha}{\pi}$$

Dirac 1928 | **Schwinger 1948** | **New physics?**

Dark photons A'
Scalar leptons $\tilde{\tau}$
Axion-like particles a
Neutralino dark matter $\tilde{\chi}$
Charge-parity violation d_τ
⋮

Electron *g* – 2: first measured in New York 1948

"Why measure to 3rd decimal place when theory predicts nothing?

PHYSICAL REVIEW VOLUME 74, NUMBER 3 AUGUST 1, 1948

The Magnetic Moment of the Electron†

P. KUSCH AND H. M. FOLEY
Department of Physics, Columbia University, New York, New York

(Received April 19, 1948)

A comparison of the g_J values of Ga in the $^2P_{3/2}$ and $^2P_{1/2}$ states, In in the $^2P_{1/2}$ state, and Na in the $^2S_{1/2}$ state has been made by a measurement of the frequencies of lines in the *hfs* spectra in a constant magnetic field. The ratios of the g_J values depart from the values obtained on the basis of the assumption that the electron spin gyromagnetic ratio is 2 and that the orbital electron gyromagnetic ratio is 1. Except for small residual effects, the results can be described by the statement that $g_L = 1$ and $g_S = 2(1.00119 \pm 0.00005)$. The possibility that the observed effects may be explained by perturbations is precluded by the consistency of the result as obtained by various comparisons and also on the basis of theoretical considerations.

Phys. Rev. 74 (1948) 250

Amid watershed 1947 Shelter Island Conference at birth of QED

Quantum field theory revolution: vacuum NOT static or empty!

BNL 2006: Muon *g* – 2 passes parts-per-million landmark

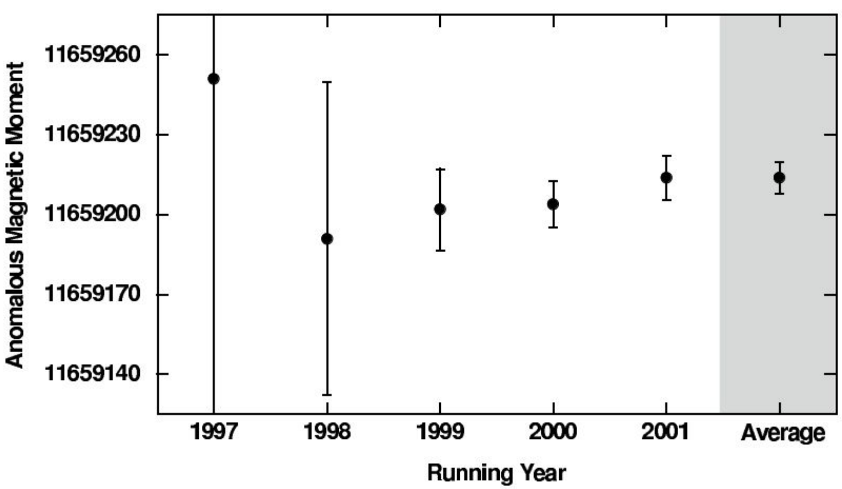
hep-ex/0602035

PHYSICAL REVIEW D **73,** 072003 (2006)

Final report of the E821 muon anomalous magnetic moment measurement at BNL

G. W. Bennett,[2] B. Bousquet,[10] H. N. Brown,[2] G. Bunce,[2] R. M. Carey,[1] P. Cushman,[10] G. T. Danby,[2] P. T. Debevec,[8] M. Deile,[13] H. Deng,[13] W. Deninger,[8] S. K. Dhawan,[13] V. P. Druzhinin,[3] L. Duong,[10] E. Efstathiadis,[1] F. J. M. Farley,[13] G. V. Fedotovich,[3] S. Giron,[10] F. E. Gray,[8] D. Grigoriev,[3] M. Grosse-Perdekamp,[13] A. Grossmann,[7] M. F. Hare,[1] D. W. Hertzog,[8] X. Huang,[1] V. W. Hughes,[13,*] M. Iwasaki,[12] K. Jungmann,[6,7] D. Kawall,[13] M. Kawamura,[12] B. I. Khazin,[3] J. Kindem,[10] F. Krienen,[1] I. Kronkvist,[10] A. Lam,[1] R. Larsen,[2] Y. Y. Lee,[2] I. Logashenko,[1,3] R. McNabb,[10,8] W. Meng,[2] J. Mi,[2] J. P. Miller,[1] Y. Mizumachi,[11] W. M. Morse,[2] D. Nikas,[2] C. J. G. Onderwater,[8,6] Y. Orlov,[4] C. S. Özben,[2,8] J. M. Paley,[1] Q. Peng,[1] C. C. Polly,[8] J. Pretz,[13] R. Prigl,[2] G. zu Putlitz,[7] T. Qian,[10] S. I. Redin,[3,13] O. Rind,[1] B. L. Roberts,[1] N. Ryskulov,[3] S. Sedykh,[8] Y. K. Semertzidis,[2] P. Shagin,[10] Yu. M. Shatunov,[3] E. P. Sichtermann,[13] E. Solodov,[3] M. Sossong,[8] A. Steinmetz,[13] L. R. Sulak,[1] C. Timmermans,[10] A. Trofimov,[1] D. Urner,[8] P. von Walter,[7] D. Warburton,[2] D. Winn,[5] A. Yamamoto,[9] and D. Zimmerman[10]

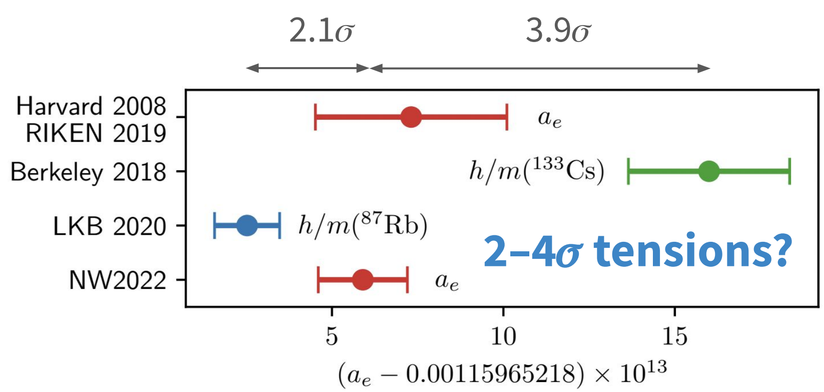
$$a_\mu(\text{Expt}) = 11\,659\,208.0(6.3) \times 10^{-10} \quad (0.54\,\text{ppm})$$



Magnet leaving Brookhaven for Fermilab…

FNAL/BNL

State of the art



Electron: 13 decimal places

"TRIUMPH OF MODERN PHYSICS!"

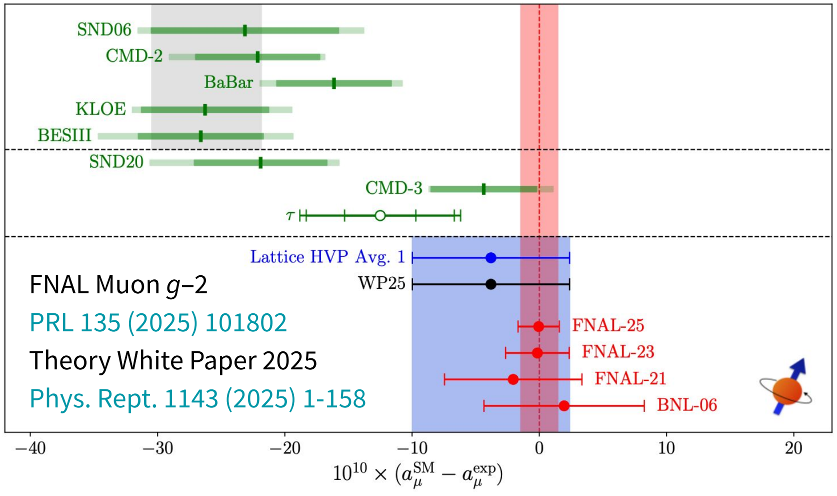
$$a_e^{\mathrm{exp}}(\text{cyclotron}) = 0.001\,159\,652\,180\,59\,(13)$$ ← Fan et al PRL 2023

↓ Morel et al Nature 2022

$$a_e^{\mathrm{theory}}\left(\alpha_{\mathrm{EM}}^{\mathrm{Rb}}\right) = 0.001\,159\,652\,182\,037\,(720)_{\alpha_{\mathrm{EM}}^{\mathrm{Rb}}}\,(11)_{\mathrm{theory}}\,(12)_{\mathrm{hadron}}$$

$$a_e^{\mathrm{theory}}\left(\alpha_{\mathrm{EM}}^{\mathrm{Cs}}\right) = 0.001\,159\,652\,181\,606\,(229)_{\alpha_{\mathrm{EM}}^{\mathrm{Cs}}}\,(11)_{\mathrm{theory}}\,(12)_{\mathrm{hadron}}$$

Parker et al Science 2018 ↑ ↑ Aoyama et al PRL 2012



FNAL Muon g–2

PRL 135 (2025) 101802

Theory White Paper 2025

Phys. Rept. 1143 (2025) 1-158

Muon: 10 decimal places

"THEORY IGNORANCE OR NEW PHYSICS?

$$a_\mu\,(\text{exp}) = 0.001\,165\,920\,72\,(15)$$

$$a_\mu\,(\text{pred}) = 0.001\,165\,920\,33\,(62)$$

0–5σ tensions?

Definition: $a = (g-2)/2$

What about tau *g* – 2?

SHOCKING EXPERIMENTAL IGNORANCE!

Pressing problem: PDG value from 2004

$$a_\tau^{\text{exp}} = -0.018\,(17)$$

$$a_{\tau,\,\text{SM}}^{\text{pred}} = 0.001\,177\,21\,(5)$$

a_{exp}: DELPHI [EPJC 35 (2004) 159], $a_{\text{SM pred}}$: Eidelman, Passera [MPLA 22 (2007) 159]

Not even testing 78 year old 1-loop QED 😱

Phys. Rev. 73 (1948) 416

On Quantum-Electrodynamics and the Magnetic Moment of the Electron

JULIAN SCHWINGER
Harvard University, Cambridge, Massachusetts
December 30, 1947

corresponds to an additional magnetic moment associated with the electron spin, of magnitude $\delta\mu/\mu = (\frac{1}{2}\pi)e^2/\hbar c = 0.001162$. It is indeed gratifying that recently acquired experimental data confirm this prediction. Measurements on the hyperfine splitting of the ground states of atomic hydrogen and deuterium[1] have yielded values that are definitely larger than those to be expected from the directly

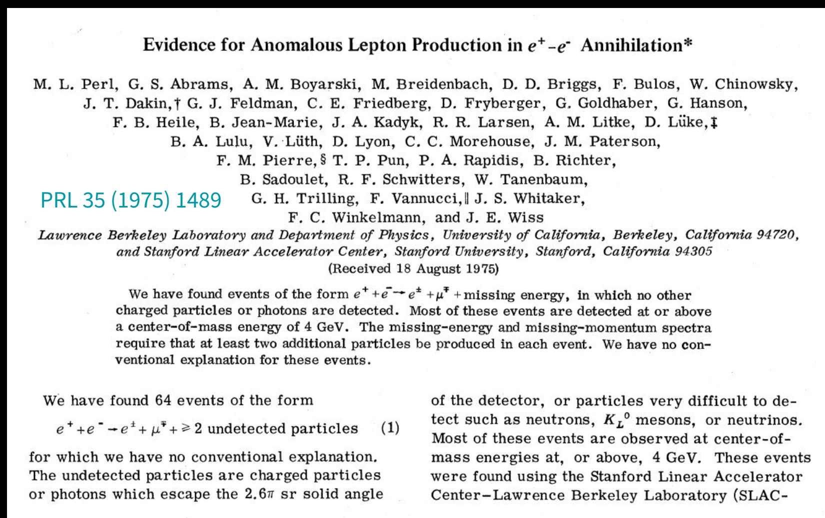
Much room for new physics beyond SM

$$\delta a_\ell \sim m_\ell^2 / M_{\text{SUSY}}^2 \qquad m_\tau^2 / m_\mu^2 \sim 280$$

Martin & Wells [PRD 64 (2001) 035003]

50 years after tau-lepton discovery

No evidence for 1-loop tau-photon coupling



Evidence for Anomalous Lepton Production in e^+-e^- Annihilation*

M. L. Perl, G. S. Abrams, A. M. Boyarski, M. Breidenbach, D. D. Briggs, F. Bulos, W. Chinowsky, J. T. Dakin,† G. J. Feldman, C. E. Friedberg, D. Fryberger, G. Goldhaber, G. Hanson, F. B. Heile, B. Jean-Marie, J. A. Kadyk, R. R. Larsen, A. M. Litke, D. Lüke,‡ B. A. Lulu, V. Lüth, D. Lyon, C. C. Morehouse, J. M. Paterson, F. M. Pierre,§ T. P. Pun, P. A. Rapidis, B. Richter, B. Sadoulet, R. F. Schwitters, W. Tanenbaum, G. H. Trilling, F. Vannucci,‖ J. S. Whitaker, F. C. Winkelmann, and J. E. Wiss

Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720, and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

PRL 35 (1975) 1489

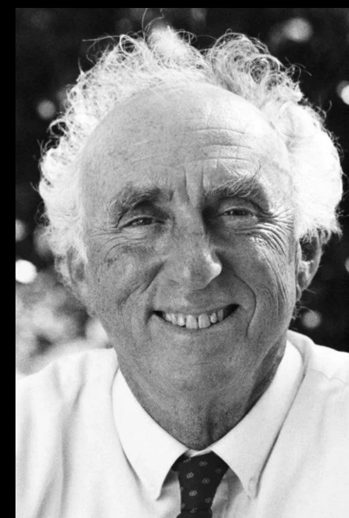
(Received 18 August 1975)

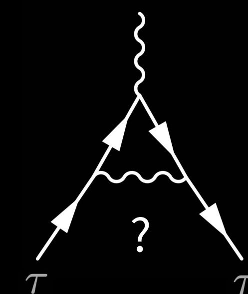
We have found events of the form $e^+ + e^- \to e^\pm + \mu^\mp +$ missing energy, in which no other charged particles or photons are detected. Most of these events are detected at or above a center-of-mass energy of 4 GeV. The missing-energy and missing-momentum spectra require that at least two additional particles be produced in each event. We have no conventional explanation for these events.

We have found 64 events of the form

$$e^+ + e^- \to e^\pm + \mu^\mp + \geq 2 \text{ undetected particles} \quad (1)$$

for which we have no conventional explanation. The undetected particles are charged particles or photons which escape the 2.6π sr solid angle of the detector, or particles very difficult to detect such as neutrons, K_L^0 mesons, or neutrinos. Most of these events are observed at center-of-mass energies at, or above, 4 GeV. These events were found using the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory (SLAC-





"It would be very nice to measure μ_τ with enough precision to check [the Schwinger term]…

At present such precision is a dream"

– Martin Perl in 1998 (Nobel Prize 1995, NYU Tandon alumnus)

"Crazy idea" launches new LHC program

PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

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New physics and tau $g-2$ using LHC heavy ion collisions

Lydia Beresford and Jesse Liu
Phys. Rev. D **102**, 113008 – Published 22 December 2020

PHYSICAL REVIEW LETTERS

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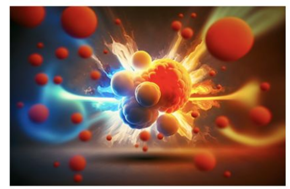


EDITORS' SUGGESTION

Observation of τ Lepton Pair Production in Ultraperipheral Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

The ATLAS and CMS experiments have separately measured photon-induced τ-lepton pair production in Pb+Pb collisions, providing a novel probe of the τ anomalous magnetic moment.

G. Aad *et al*. (ATLAS Collaboration)
Phys. Rev. Lett. **131**, 151802 (2023)

A. Tumasyan *et al.* (CMS Collaboration)
Phys. Rev. Lett. **131**, 151803 (2023)

Invent new analysis

Initiate LHC tau g – 2 renaissance

Beresford & JL PRD 102 (2020) 113008
ParticleBites coverage

Pioneer ATLAS & CMS results

First tau g – 2 measurement in 2 decades

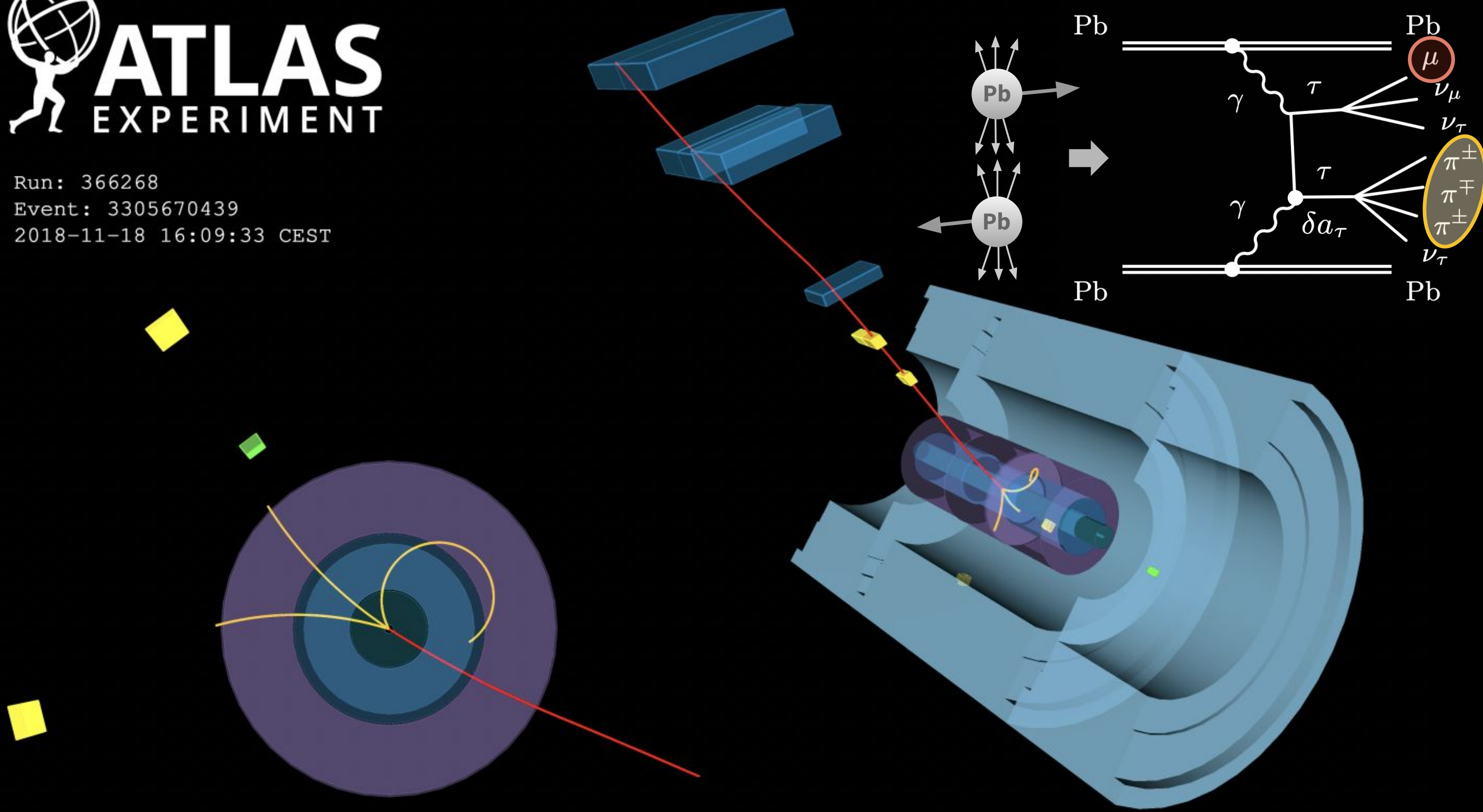
ATLAS (JL Editor) & CMS PRL 131 (2023) 151802 & 03
Joint *PRL Editors' Suggestion*, *The Conversation* feature

Creative pheno+analysis upended status quo

Tau g – 2 measurable without lepton collider

Foundational (B)SM tests hidden in LHC data

Observation of γɣ → $\tau\tau$ at hadron colliders



↑ "All charged-particle tracks above 100 MeV are shown"

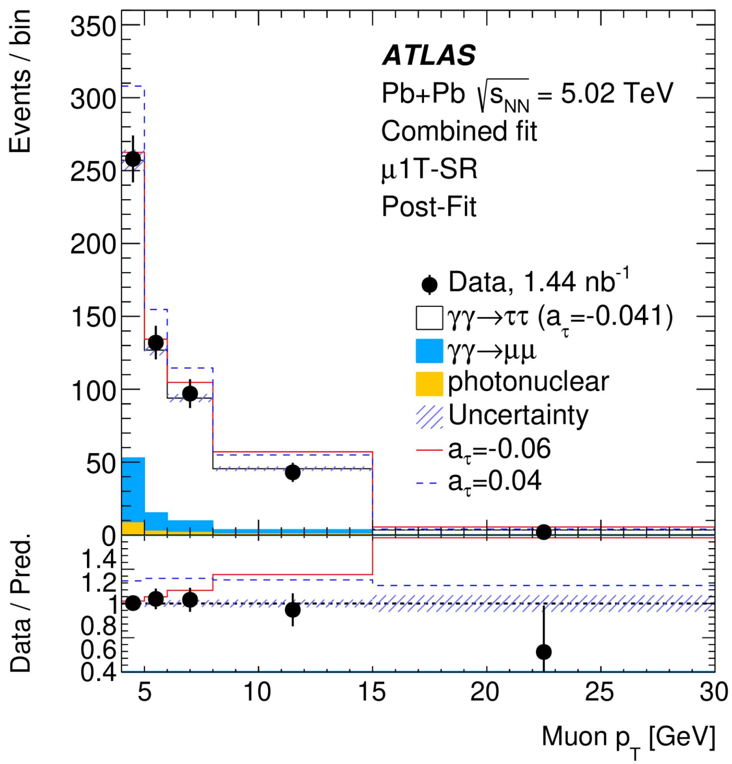
With Stony Brook + BNL collaborators | 0.01% pileup vs pp | $p_T(\mu)$ > 4 GeV trigger

ATLAS (JL Editor) PRL 131 (2023)151802

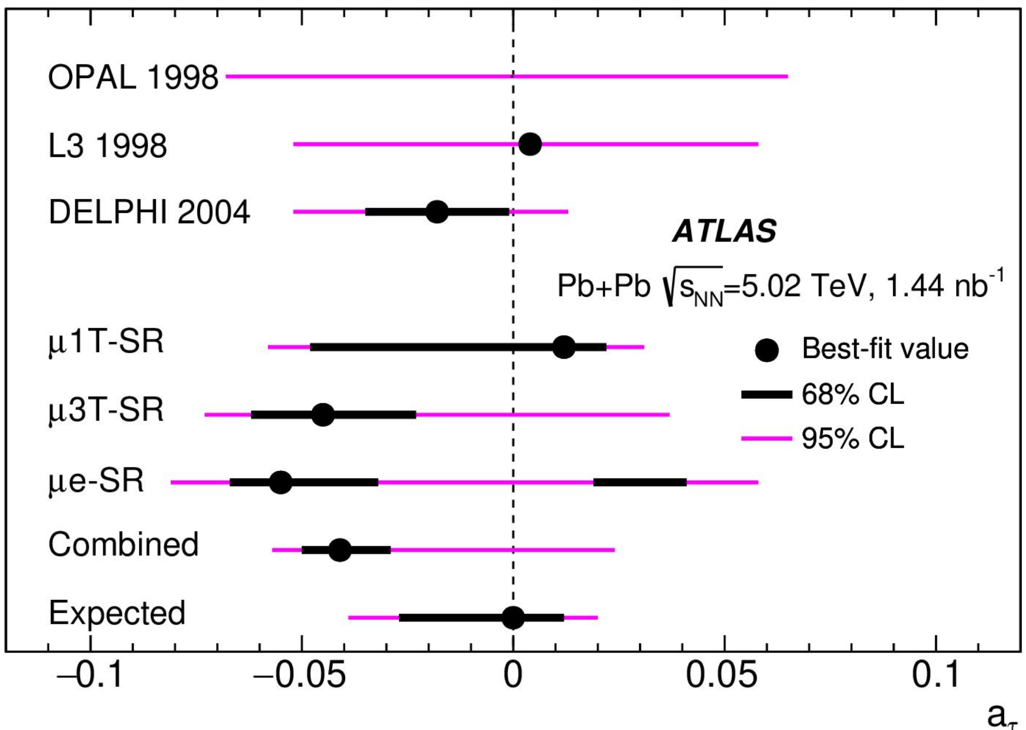
Groundbreaking results competitive with LEP

>10σ signal in existing data because **we were not looking!**

>10σ observation of taus in heavy-ion data

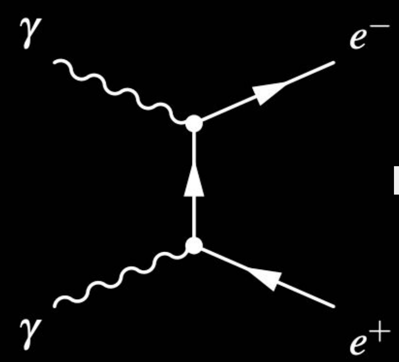


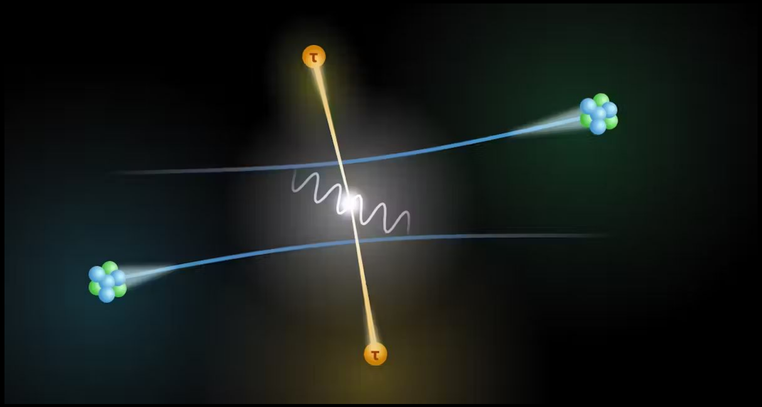
First hadron-collider tau *g* – 2 & first constraints in 2 decades



ATLAS (JL Editor) PRL 131 (2023)151802,
See also CMS PRL 131 (2023) 151803 used 2015 data

Photon collisions first calculated at NYU 91 years ago





DECEMBER 15, 1934 PHYSICAL REVIEW VOLUME 46

Collision of Two Light Quanta

G. BREIT* AND JOHN A. WHEELER,** *Department of Physics, New York University*

(Received October 23, 1934)

The recombination of free electrons and free positrons and its connection with the Compton effect have been treated by Dirac before the experimental discovery of the positron. In the present note are given analogous calculations for the production of positron electron pairs as a result of the collision of two light quanta. The angular distribution of the ejected pairs is calculated for different polarizations, and formulas are given for the angular distribution of photons due to recombination. The results are applied to the collision of high energy photons of cosmic radiation with the temperature radiation of interstellar space. The effect on the absorption of such quanta is found to be negligibly small.

Phys. Rev. 46 (1934) 1087

Next milestone: high-mass γγ → $\tau\tau$ in pp

PHYSICAL REVIEW D **110**, 092016 (2024)

Strategy to measure tau $g-2$ via photon fusion in LHC proton collisions

Lydia Beresford,[1,*] Savannah Clawson,[1,†] and Jesse Liu[2,‡]
[1]Deutsches Elektronen-Synchrotron DESY, Notkestrasse 85, 22607 Hamburg, Germany
[2]Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, United Kingdom

(Received 14 March 2024; accepted 16 October 2024; published 25 November 2024)

Measuring the tau-lepton (τ) anomalous magnetic moment $a_\tau = (g_\tau - 2)/2$ in photon fusion production ($\gamma\gamma \to \tau\tau$) tests foundational Standard Model principles. However, $\gamma\gamma \to \tau\tau$ eludes observation in LHC proton collisions (pp) despite enhanced new physics sensitivity from higher-mass reach than existing probes. We propose a strategy to measure pp $\to$ p($\gamma\gamma \to \tau\tau$)p by introducing the overlooked electron-muon signature with vertex isolation for signal extraction. Applying the effective field theory of dipole moments, we estimate 95% confidence level sensitivity of $-0.0092 < a_\tau < 0.011$ assuming 300 fb^{-1} luminosity and 5% systematics. This fourfold improvement beyond existing constraints opens a crucial path to unveiling new physics imprinted in tau-lepton dipoles.

DOI: 10.1103/PhysRevD.110.092016

PRD 110 (2024) 092016

I. INTRODUCTION

Precise measurements of electromagnetic (EM) dipoles are fundamental tests of the Standard Model (SM) that could reveal beyond-the-SM (BSM) physics. A cornerstone SM principle is lepton universality, where all three generations (electron e, muon μ, tau-lepton τ) couple equally to gauge bosons. The leading SM loop correction from quantum fluctuations is also flavor universal, shifting magnetic moments by the Schwinger term $\alpha_{\rm EM}/2\pi \simeq 0.0012$ [1,2]. The electron and muon anomalous magnetic moments $a_{e,\mu} = (g_{e,\mu} - 2)/2$ are now tested to 13 [3–12] and 10 decimal places [13–16], respectively. However, the tau-lepton counterpart a_τ is still compatible with zero to two decimal places [17] as its 0.3 ps proper lifetime [18–21] precludes storage-ring probes [15]. The existence of tau-lepton loop interactions with photons in nature thus remains untested.

The most precise single-experiment a_τ constraint is a $-0.052 < a_\tau^{\rm obs} < 0.013$ 95% confidence level (CL) limit by DELPHI [22] at the Large Electron Positron Collider (LEP), with similar precision by L3 and OPAL [23,24]. ATLAS and Compact Muon Solenoid (CMS) recently pioneered Large Hadron Collider (LHC) probes of a_τ using photon fusion production of tau-leptons ($\gamma\gamma \to \tau\tau$) in lead-lead (PbPb) data [25,26]; the ATLAS 95% CL limit is $-0.057 < a_\tau^{\rm obs} < 0.024$. Such large experimental uncertainties relative to the SM prediction $a_{\tau,\rm SM}^{\rm pred} = 0.00117721(5)$ [27] could conceal BSM dynamics, for example, those motivated by lepton sector tensions [28–44]. Specific models predict quadratic scaling $\delta a_\ell \propto m_\ell^2$ with lepton mass m_ℓ [45–47], implying $(m_\tau/m_\mu)^2 \simeq 280$ times larger effects for a_τ than a_μ. New physics can also violate charge-parity (CP) symmetry, inducing an electric dipole d_τ. Standard LHC proton-proton (pp) collisions reach higher $\mathcal{O}$(TeV) masses, enhancing BSM dipole sensitivity over $\mathcal{O}$(100 GeV) in PbPb [48–53]. Despite this key benefit, cross section yielding over 30 million events to date, and major photon-fusion advances [54–88], $\gamma\gamma \to \tau\tau$ remarkably evades observation in pp data.

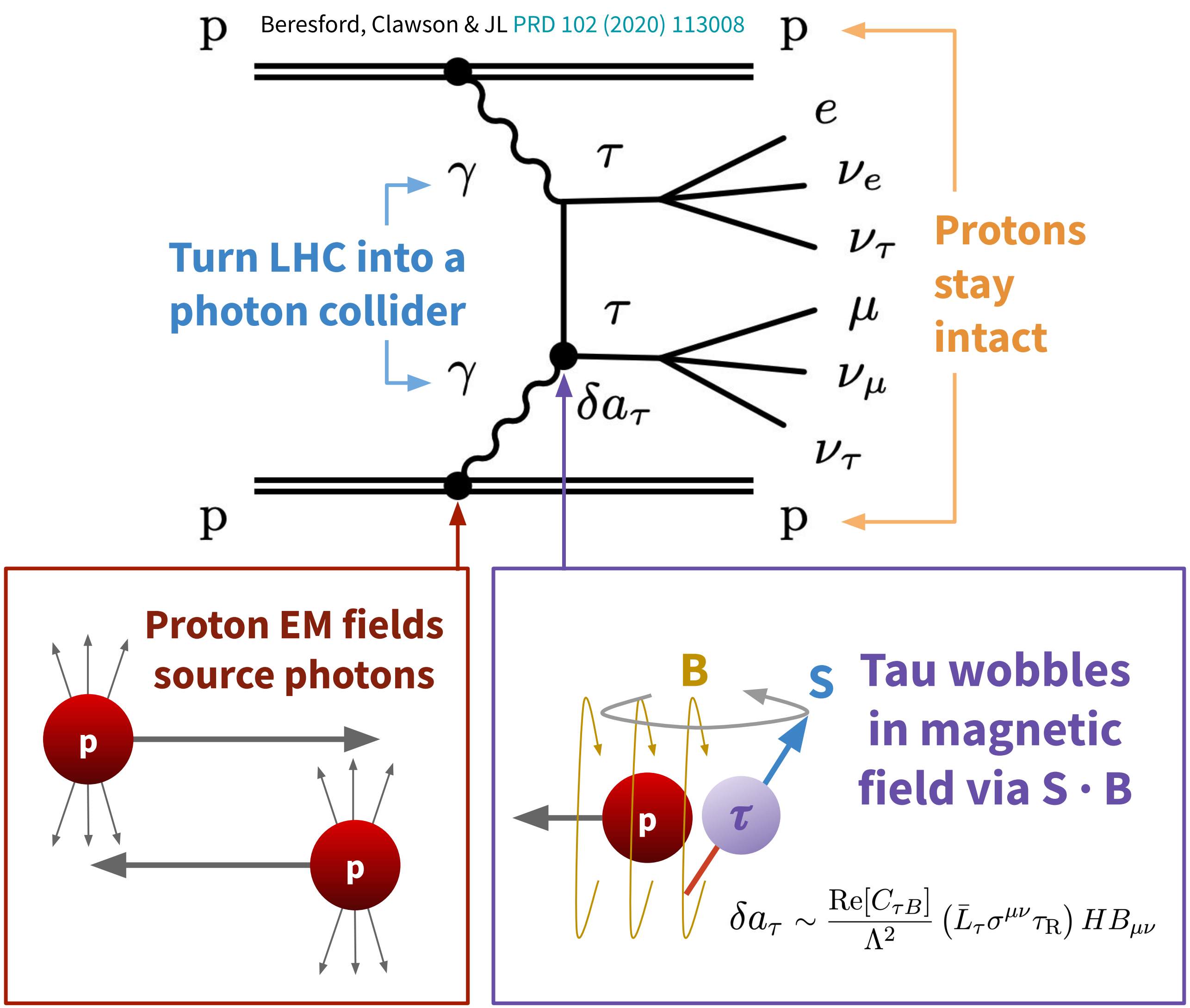
This paper proposes the strategy to measure $\gamma\gamma \to \tau\tau$ in the fully leptonic channel and tau-lepton EM dipoles in LHC pp collisions (Fig. 1). We initiate the first Monte Carlo (MC) simulation analysis of the pp $\to$ p($\gamma\gamma \to \tau\tau$)p signal

FIG. 1. Tau-leptons produced from photon fusion in proton beams with electron-muon $\tau\tau \to e\nu\nu\mu\nu\nu$ decays as a Feynman diagram (left) and detector signature illustrating the vertex isolation technique for the electron-muon vs pileup tracks (right). New physics can modify the magnetic moment δa_τ.

*Contact author: lydia.beresford@desy.de
†Contact author: savannah.clawson@desy.de
‡Contact author: jesseliu@hep.phy.cam.ac.uk

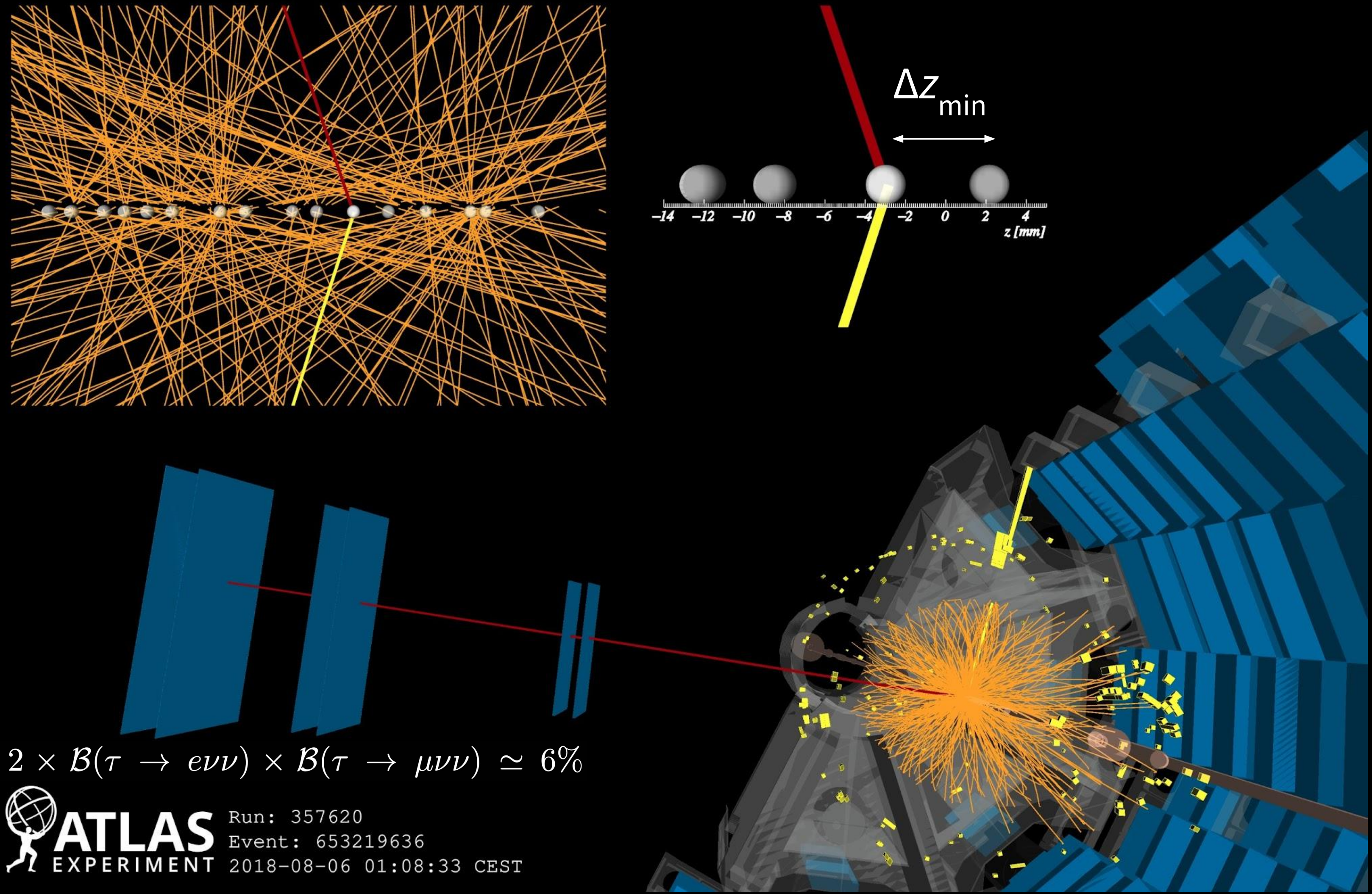
↑ **Savannah Clawson / JL / Lydia Beresford**

Central idea: collide light to measure tau g – 2



150 pb = 60 million events @ 400/fb

Unconventional signature: no proton breakup



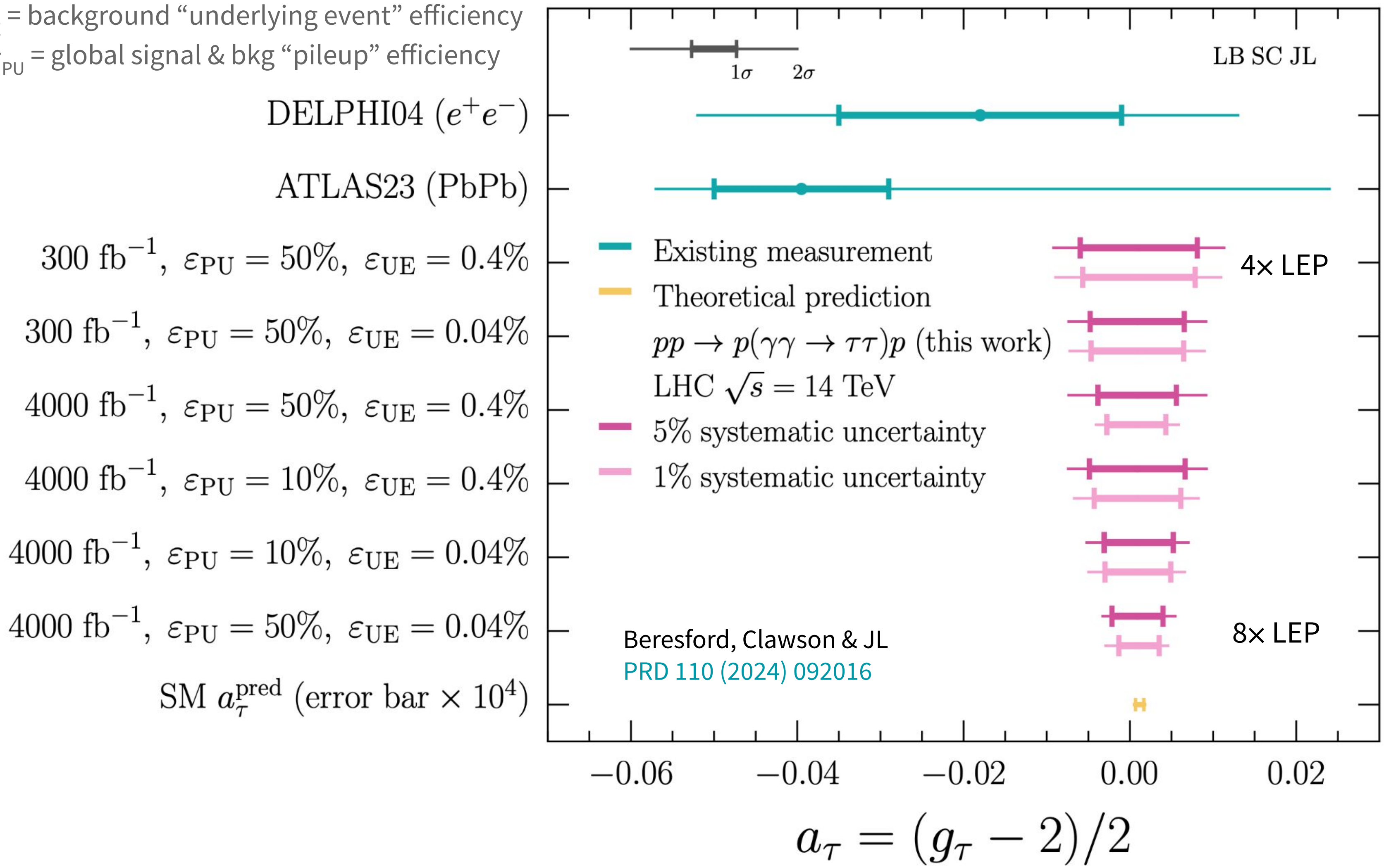
$$2 \times \mathcal{B}(\tau \to e\nu\nu) \times \mathcal{B}(\tau \to \mu\nu\nu) \simeq 6\%$$

Innovative "soft tracking" to reconstruct γγ → $\tau\tau$ → $e\nu\nu\mu\nu\nu$

ATLAS PLB 816 (2021) 136190

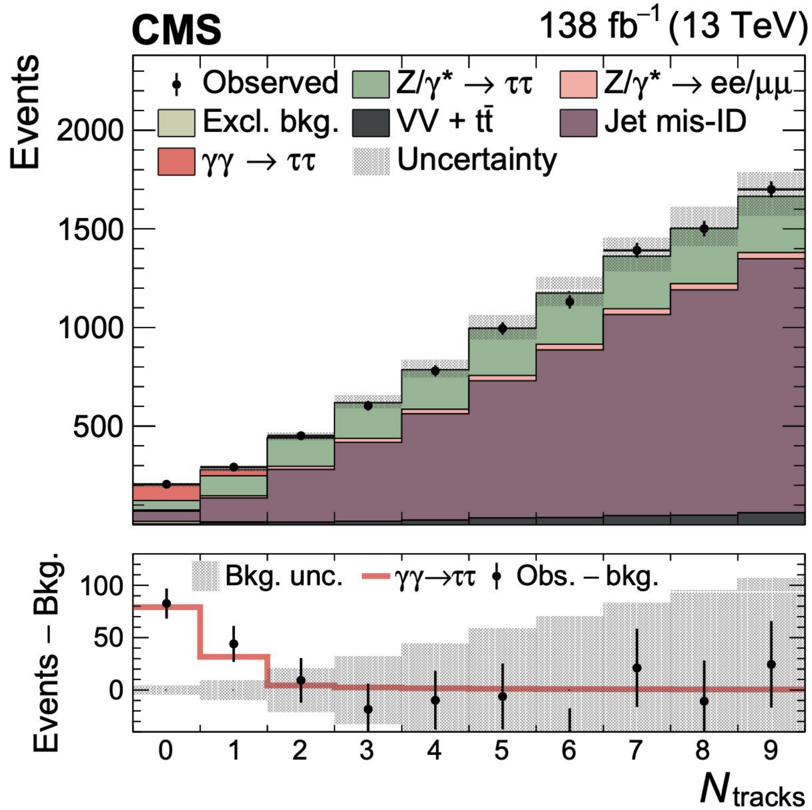
Sensitivity: 4× to 8× improvement via eμ alone

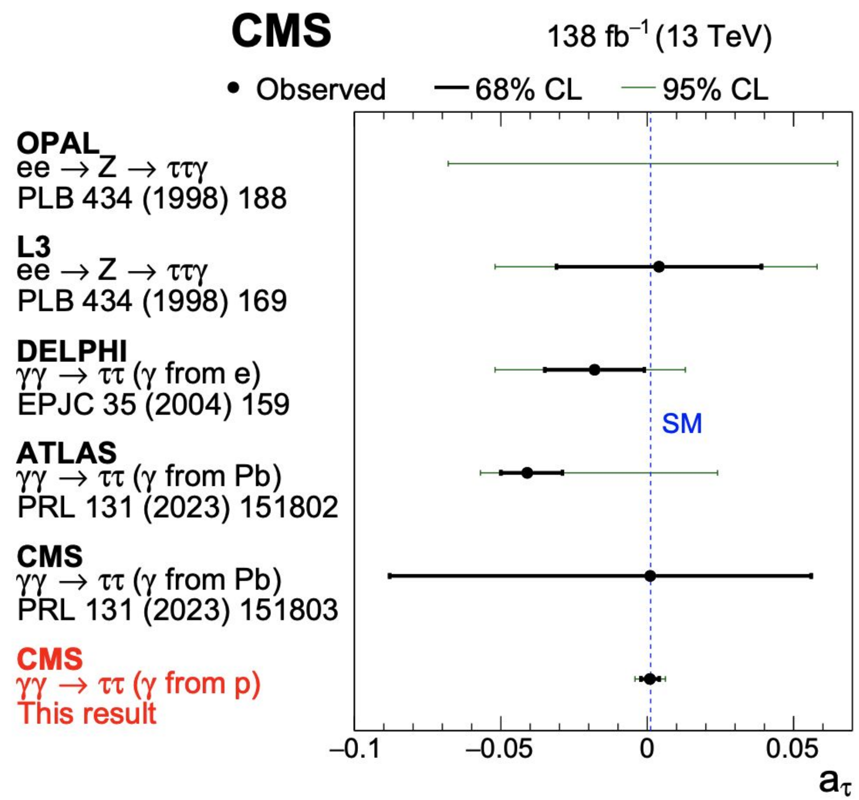
ε_{UE} = background “underlying event” efficiency
ε_{PU} = global signal & bkg “pileup” efficiency



CMS observation of γγ → $\tau\tau$ in pp

Observation of γγ → ττ in proton–proton collisions and limits on the anomalous electromagnetic moments of the τ lepton RPP (2024) 87 107801





γγ → $\tau\tau$ in pp: 5.3σ (6.5) obs (exp)

Tau *g* – 2: 5x improvement vs LEP

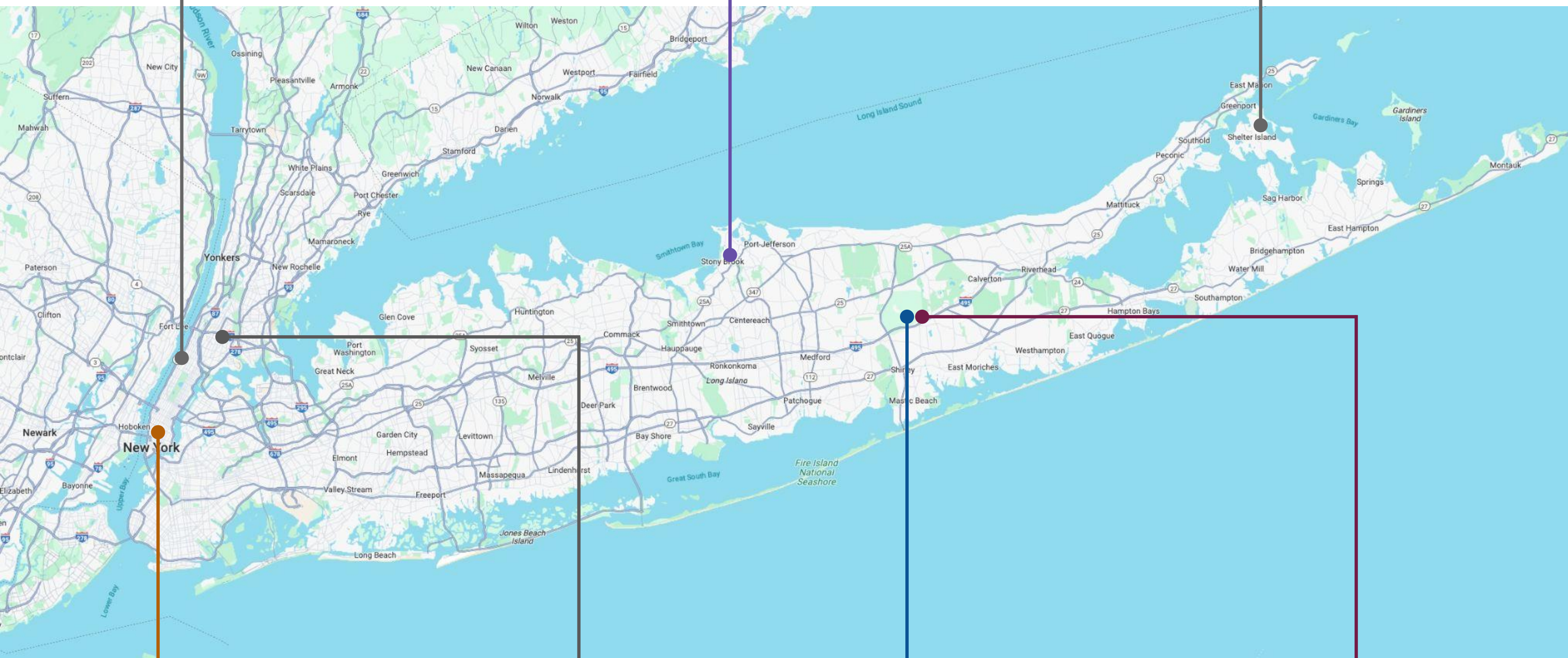
Nearing per-mille & stats limited: $a_\tau = 0.0009^{+0.0016}_{-0.0015}(\mathrm{syst})^{+0.0028}_{-0.0027}(\mathrm{stat})$

New York: long history unraveling quantum vacuum

1948: electron $g-2$
Kusch & Foley @ Columbia

2022: $\gamma\gamma \to \tau\tau$ @ PbPb
JL with Stony Brook+BNL

1947: 1-loop QED
Shelter Island conference



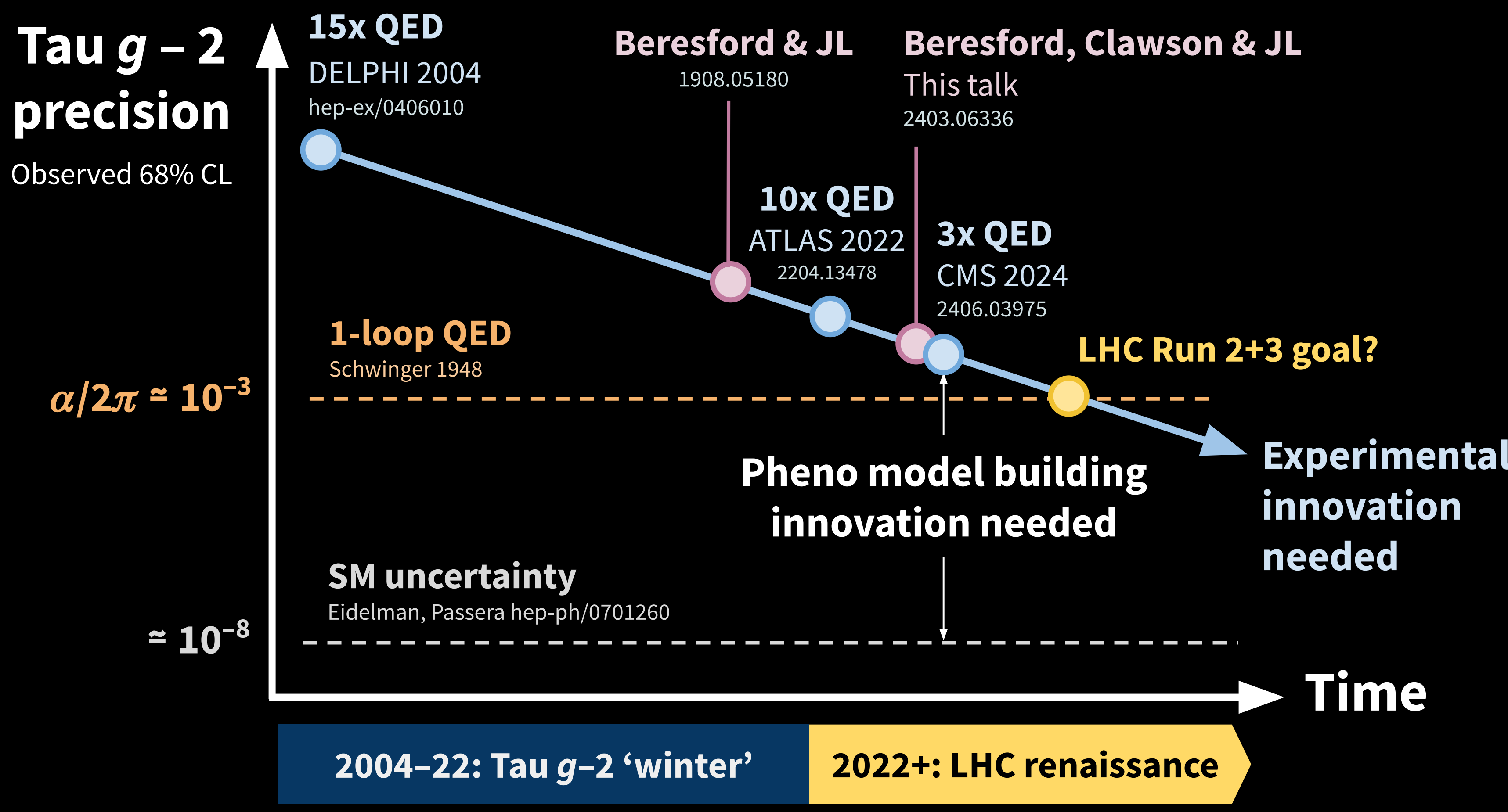
2025+: tau $g-2$ $\gamma\gamma \to \tau\tau$
JL's new group @ NYU

1934: $\gamma\gamma \to ee$
Breit & Wheeler @ NYU

2006: muon $g-2$
BNL ppm milestone

2025+: proton EDM
BNL storage ring R&D

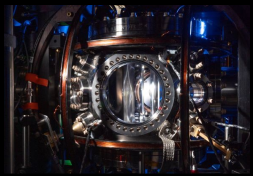
ROADMAP



Tau g – 2 precision
Observed 68% CL
15x QED
DELPHI 2004
hep-ex/0406010
Beresford & JL
1908.05180
Beresford, Clawson & JL
This talk
2403.06336
10x QED
ATLAS 2022
2204.13478
3x QED
CMS 2024
2406.03975
1-loop QED
Schwinger 1948
$\alpha/2\pi \simeq 10^{-3}$
LHC Run 2+3 goal?
Experimental innovation needed
Pheno model building innovation needed
SM uncertainty
Eidelman, Passera hep-ph/0701260
$\simeq 10^{-8}$
Time
2004–22: Tau g–2 'winter'
2022+: LHC renaissance

Vision: Coordinated US “Dipoles for Discovery” Program?

Currently disjoint AMO/HEP/NP experimental techniques, funding & communities



Cass/UColorado

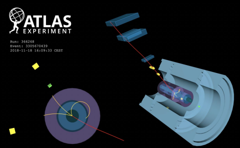
e

ELECTRON
Quantum
Atomic

FNAL/BNL

μ

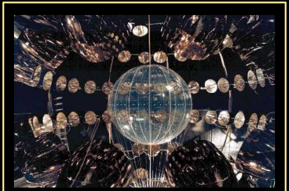
MUON
Precision
Lattice



ATLAS/CMS

τ

TAU-LEPTON
Collider
Electroweak



Borexino/INFN

ν

NEUTRINO
Nuclear
Intensity

pEDM/BNL

p

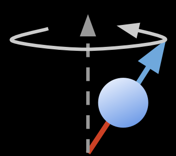
PROTON
pEDM
Storage Ring

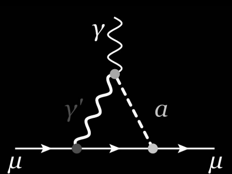
nEDM/ORNL

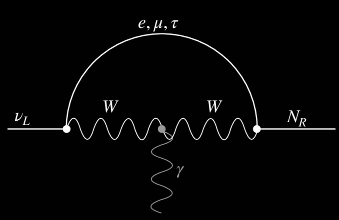
n

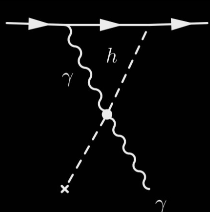
NEUTRON
Spallation
Neutrons

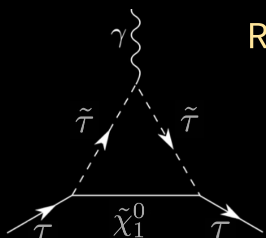
Communities rarely converse despite same fundamental physics goals











Right-handed neutrino N_R
Dark photons A'
Scalar leptons τ
Axion a Higgs h
Dark matter χ

c.f. US Dark Sectors: “low cost” but must cross disciplines in & outside HEP