Colliding light, tau $g-2$, & broadband axion detection

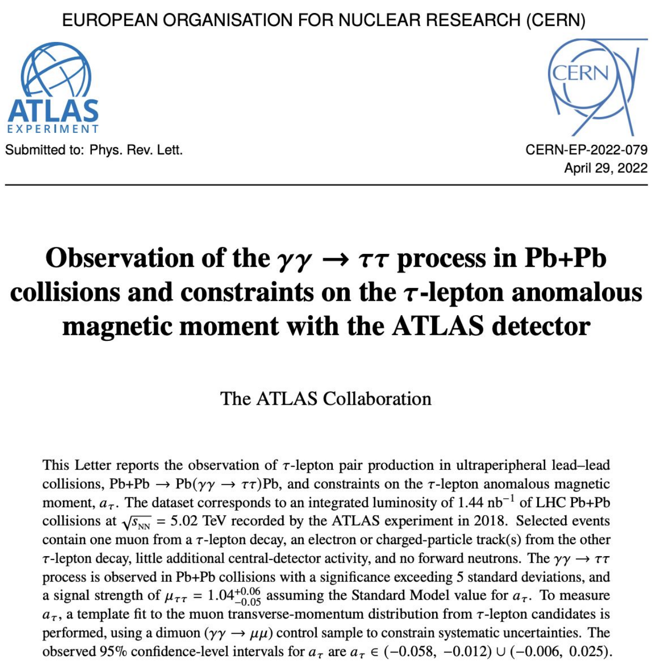
University of Liverpool
High Energy Physics Seminar
16 November 2022

Jesse Liu
University of Cambridge

TRINITY COLLEGE CAMBRIDGE

UNIVERSITY OF CAMBRIDGE

Today: two groundbreaking Letters


EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

Submitted to: Phys. Rev. Lett.

CERN-EP-2022-079
April 29, 2022

Observation of the $\gamma\gamma \to \tau\tau$ process in Pb+Pb collisions and constraints on the τ-lepton anomalous magnetic moment with the ATLAS detector

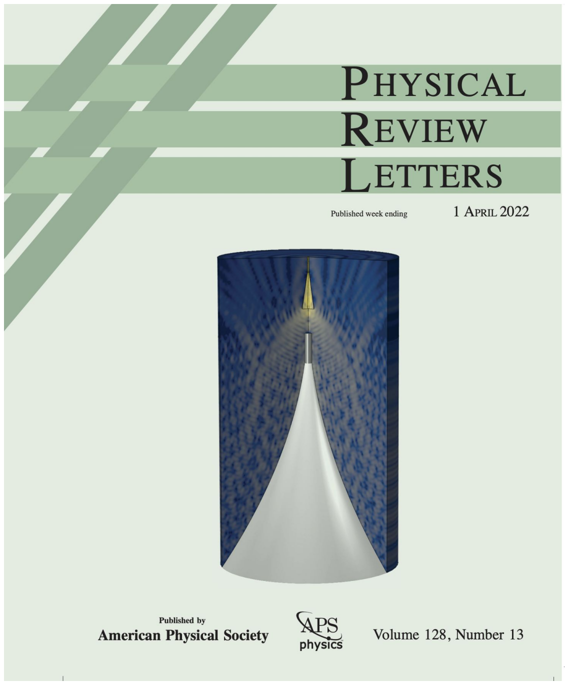
The ATLAS Collaboration

This Letter reports the observation of τ-lepton pair production in ultraperipheral lead–lead collisions, Pb+Pb $\to$ Pb($\gamma\gamma \to \tau\tau$)Pb, and constraints on the τ-lepton anomalous magnetic moment, a_τ. The dataset corresponds to an integrated luminosity of 1.44 nb^{-1} of LHC Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV recorded by the ATLAS experiment in 2018. Selected events contain one muon from a τ-lepton decay, an electron or charged-particle track(s) from the other τ-lepton decay, little additional central-detector activity, and no forward neutrons. The $\gamma\gamma \to \tau\tau$ process is observed in Pb+Pb collisions with a significance exceeding 5 standard deviations, and a signal strength of $\mu_{\tau\tau} = 1.04^{+0.06}_{-0.05}$ assuming the Standard Model value for a_τ. To measure a_τ, a template fit to the muon transverse-momentum distribution from τ-lepton candidates is performed, using a dimuon ($\gamma\gamma \to \mu\mu$) control sample to constrain systematic uncertainties. The observed 95% confidence-level intervals for a_τ are $a_\tau \in (-0.058, -0.012) \cup (-0.006, 0.025)$.

Colliding light for tau g – 2

Pioneer heavy-ion probe of new physics via precision

ATLAS (JL Editor) 2204.13478, Accepted PRL



BREAD: new axion detector

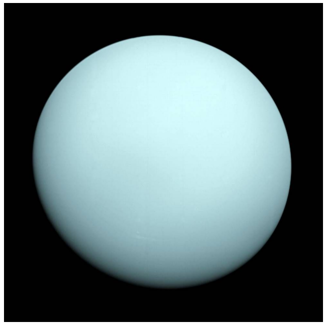
meV dark matter observatory using quantum sensors

JL, Dona et al 2111.12103 (PRL, On the Cover)

PROLOGUE

A TALE OF TRANSFORMATIVE DISCOVERY SCIENCE

Discovery as new probe | **Spectacular predictivity** | **Paradigm shift**



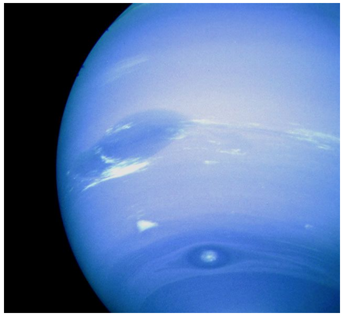
NASA/JPL-Caltech

Uranus

Herschel 1781

Planet never seen before

Measure for 65 years



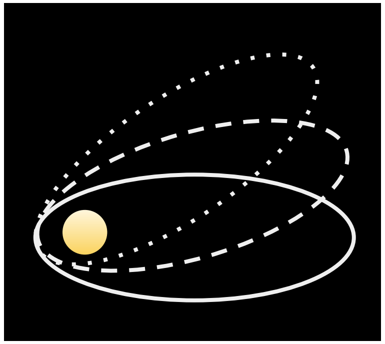
NASA/JPL-Caltech

Neptune

Le Verrier, Galle, d'Arrest 1846

Discover on same night

Within 1° of prediction



General Relativity

Le Verrier 1859, Einstein 1915

43 arcseconds/century anomaly

Null search for Planet Vulcan

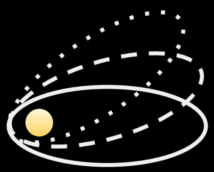
LESSON

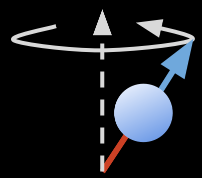
Precision measurements revolutionise science

GR: SPACETIME IS DYNAMICAL

Discover new planets: unchanged physical laws

But planet known since antiquity transformative





QFT: VACUUM IS DYNAMICAL

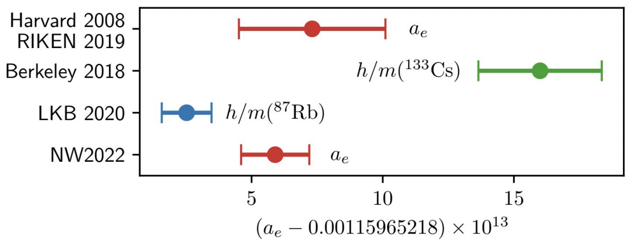
Per mille precession of electron: no new particles

But groundbreaking evidence of physical loops

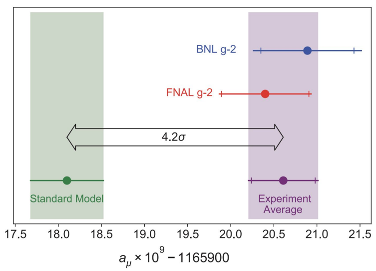
The ordinary harboured extraordinary surprises

Persistent widespread indirect evidence for new physics

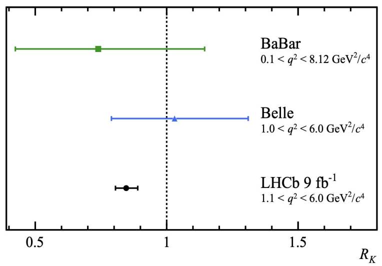
Electron $g-2$ (2.5σ)
[Science 2018]



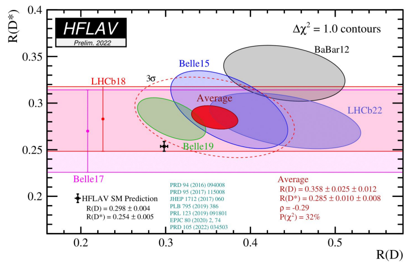
Muon $g-2$ (4.2σ)
[PRL 2021]



B → Kℓℓ (3.1σ)
[Nat Phys 2022]



B → D$\tau\nu$ (3.2σ)
[HFLAV 2022]

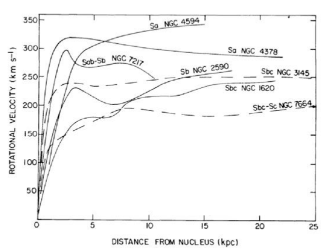


LEPTON ANOMALIES ↑

Involves e/μ/τ across different labs
Indirect evidence of new particles

↓ *DARK MATTER*

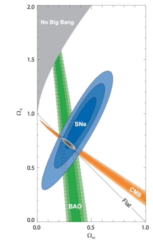
Sub-galactic to cosmological scales
Indirect evidence for particle nature



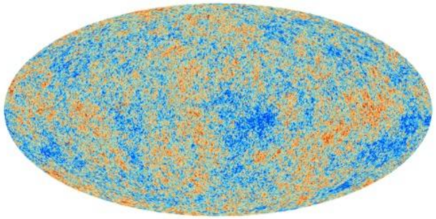
Galaxy rotation
[ApJ 1978]

Lensing
[ESA/Hubble & NASA]

Bullet cluster
[NASA/CXC/CfA/STScI/ESO WFI]



BAO
[ApJ 2008]



CMB
[ESA/Planck]

April 2021: $g - 2$ recaptures international attention

The New York Times

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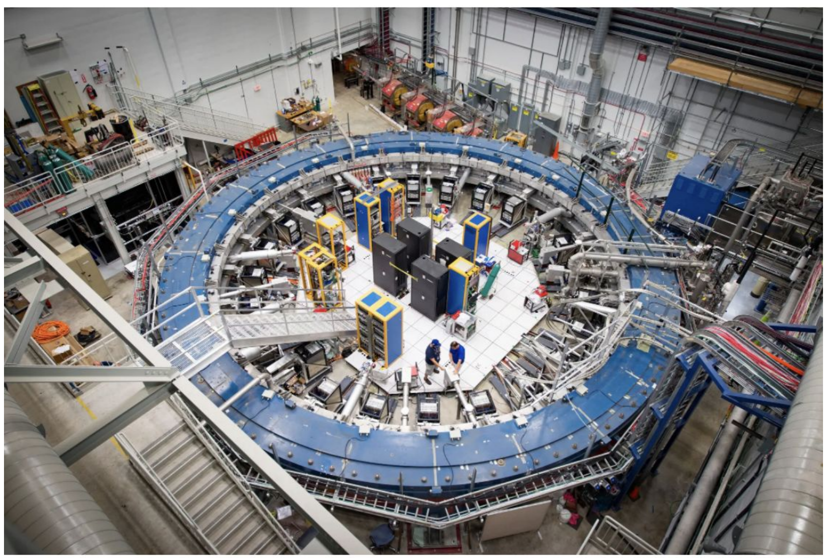
OUT THERE

A Tiny Particle's Wobble Could Upend the Known Laws of Physics

Experiments with particles known as muons suggest that there are forms of matter and energy vital to the nature and evolution of the cosmos that are not yet known to science.

535



The Muon g-2 ring, at the Fermi National Accelerator Laboratory in Batavia, Ill., operates at minus 450 degrees Fahrenheit and studies the wobble of muons as they travel through the magnetic field. Reidar Hahn/Fermilab, via U.S. Department of Energy

nytimes.com

nature

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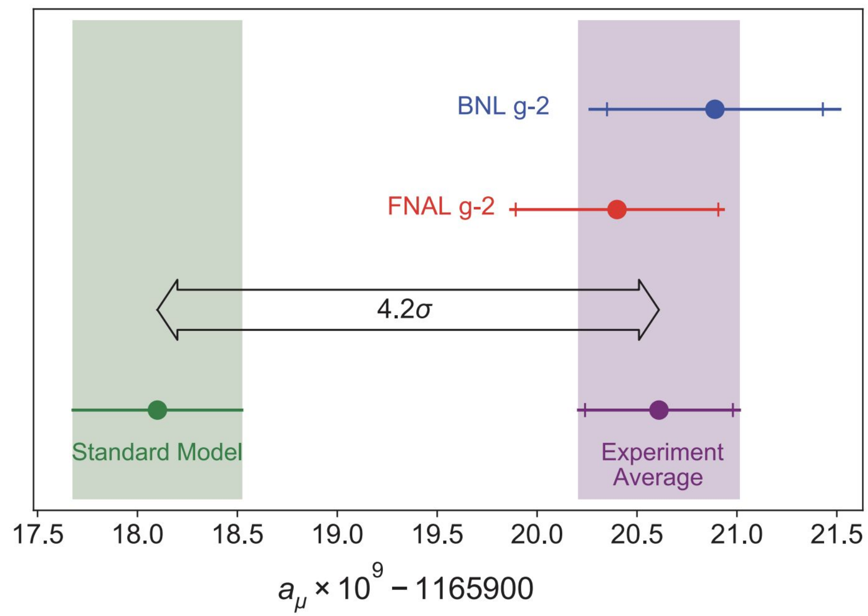
NEWS | 07 April 2021

Is the standard model broken? Physicists cheer major muon result

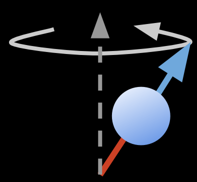
The muon's magnetic moment is larger than expected — a hint that new elementary particles are waiting to be discovered.

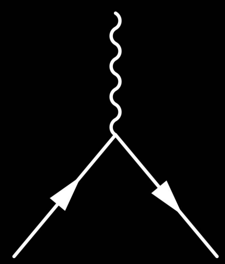


Muon g–2 Experiment [PRL 2021]

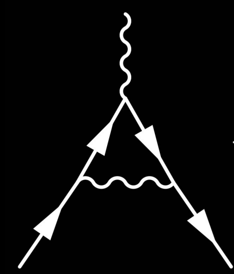
$g - 2$: foundational test of QFT

"How does light interact with matter?"

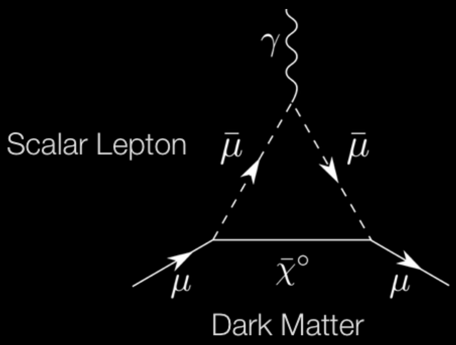




$+$



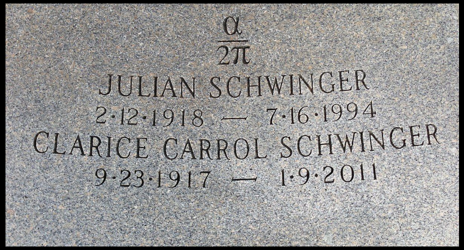
$+$



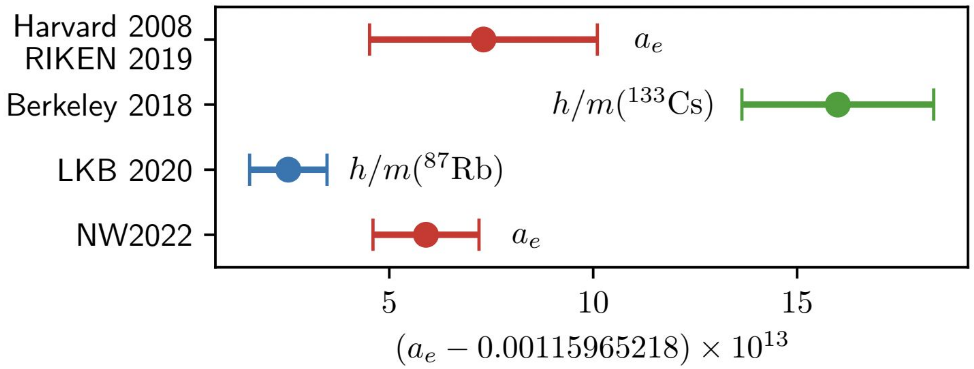
$$g = 2 + \frac{\alpha}{\pi}$$

Dirac (1928) **Schwinger (1948)** **BSM?**

$$\boldsymbol{\mu}_f \cdot \mathbf{B} = \frac{g_f e}{2m_f} \mathbf{S} \cdot \mathbf{B}$$



Today: cracks at the heart of Standard Model?



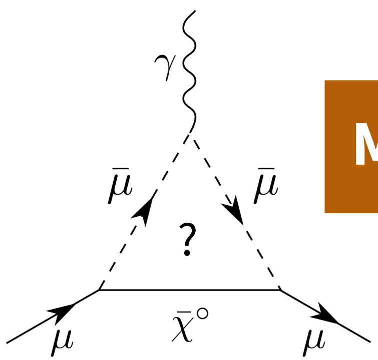
↑ ***Error bars width of atom if drawn to scale!***

Electron *g* – 2 (–2.5σ?)

Odom, Hanneke, D'Urso, Gabrielse [PRL (2006)]
Bouchendira et al [PRL (2011)]
Aoyama, Hayakawa, Kinoshita, Nio [PRL 2018]
Parker, Yu, Zhong, Estey, Müller [Science (2018)]
Morel et al [Nature 2022]
Fan, Myers, Sukra, Gabrielse [2209.13084]
Cladé [FIPs2022]

0.1 parts per billion

"Triumph of quantum electrodynamics"

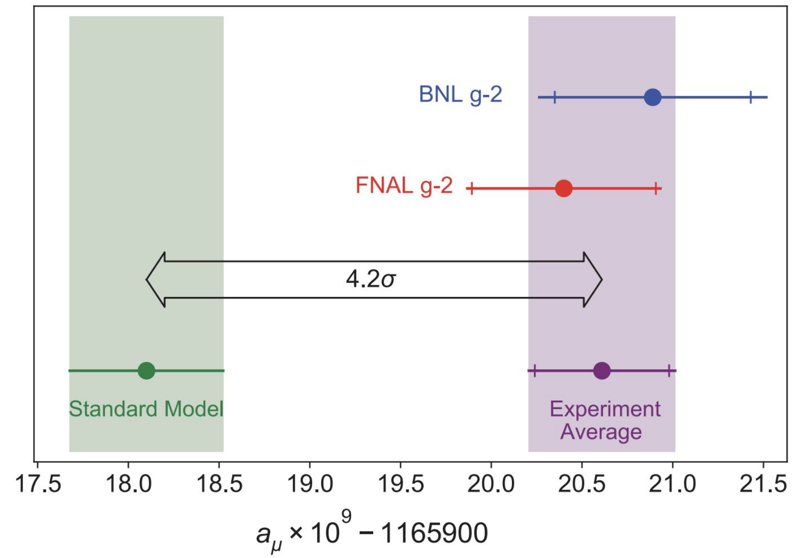


Muon *g* – 2 (+4.2σ?)

BNL E821 [PRD 2006]
Fermilab E989 [1501.06858]
J-PARC [1901.03047]
Keshavarzi, Nomura, Teubner [PRD 2018]
Davier, Hoecker, Malaescu, Zhang [EPJC 2020]
Muon *g*–2 theory initiative [Phys Rept 2020]
FNAL Muon g–2 [PRL 2021]

0.5 parts per million

"Hadronic ignorance or harbinger of new physics?"



What about tau *g* – 2?

SHOCKING EXPERIMENTAL IGNORANCE!

Current PDG value is by DELPHI 2004

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

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

a_{exp}: DELPHI [hep-ex/0406010], $a_{\text{SM pred}}$: Eidelman, Passera [hep-ph/0701260]

Pressing problem: barely measured!

Not even testing 70 year old 1-loop QED!

$$\alpha/2\pi = 0.001162$$

QED: lepton–photon universality at tree-level *AND* 1-loop [Schwinger 1948]

Pressing & *interesting* open problem

Huge uncertainty

⇒ huge room for new physics

$$\delta a_\ell \sim m_\ell^2 / M_{\text{SUSY}}^2$$

$$m_\tau^2 / m_\mu^2 \sim 280$$

Martin, Wells [hep-ph/0103067]

280× more sensitive

to new physics

than muon *g* – 2

e & μ *g* – 2: no model shortage pre-FNAL

Martin, Wells [hep-ph/0103067]
Czarnecki, Marciano [hep-ph/0102122]
Pospelov [0811.1030]
Cahill-Rowley, Hewett, Ismail, Rizzo [1407.4130]
Ajaib, Dutta, Ghosh, Gogoladze, Shafi [1505.05896]
Allanach, Queiroz, Strumia, Sun [1511.07447]
Han, Kang, Sayre [1511.05162]
Batell, Lange, McKeen, Pospelov, Ritz [1606.04943]
Di Chiara, Fowlie, Fraser, Marzo, Marzola, Raidal, Spethmann [1704.06200]
Poh, Raby [1705.07007]
Cherchiglia, Stöckinger, Stöckinger-Kim [1711.11567]
Davoudiasl, Marciano [1806.10252]
Crivellin, Hoferichter, Schmidt-Wellenburg [1807.11484]
Li, Li, Yang [1808.02424]
Liu, Wagner, Wang [1810.11028]
Dutta, Mimura [1811.10209]
Mohlabeng [1902.05075]
Endo, Wen [1906.08768]
Badziak, Sakurai [1908.03607]
Bauer, Neubert, Renner, Schnubel, Thamm [1908.00008]
…

How can we measure tau *g* – 2?

Belle-II/CLIC/ILC/FCC-ee:
Eidelman, Epifanov, Fael, Mercolli, Passera [1601.07987]
Chen, Wu [1803.00501]
Köksal, Billur, Gutierrez-Rodriguez, Hernandez-Ruiz [1804.02373]
Howard, Rajaraman, Riley, Tait [1810.09570]
Köksal [2104.01003]
Crivellin, Hoferichter, Michael Roney [2111.10378]
LHeC/FCC-eh:
Köksal [1809.01963],
Gutiérrez-Rodríguez, Köksal, Billur, Hernández-Ruíz [1903.04135]
Proton fixed target & bent crystals:
Fomin, Korchin, Stocchi, Barsuk, Robbe [1810.06699]
Fu et al [1901.04003]

THINK DIFFERENT

Invent new heavy-ion analysis

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 — 1908.05180 (PRD)
Phys. Rev. D **102**, 113008 – Published 22 December 2020

Creative pheno paper overcame status quo

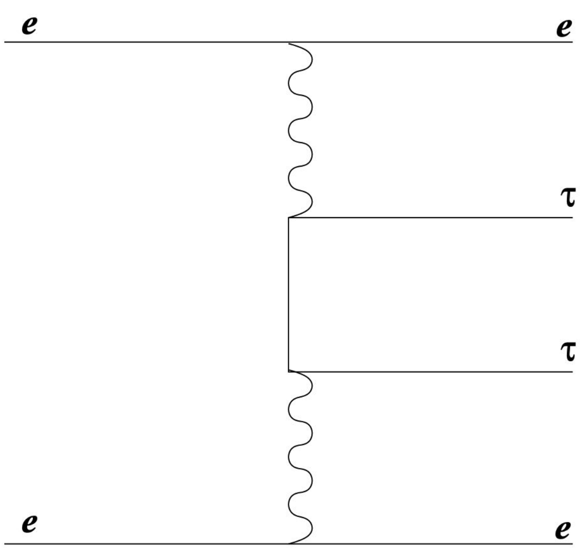
Tau g – 2 measurable without lepton collider

Heavy ions interesting for BSM via precision

See also our pp papers: Beresford & JL 1811.06465 (PRL), ATLAS (Beresford & JL editors) 2009.14537 (PRL)

How can we see $\gamma\gamma \to \tau\tau$ at LHC?

PDG constraint of tau *g* – 2



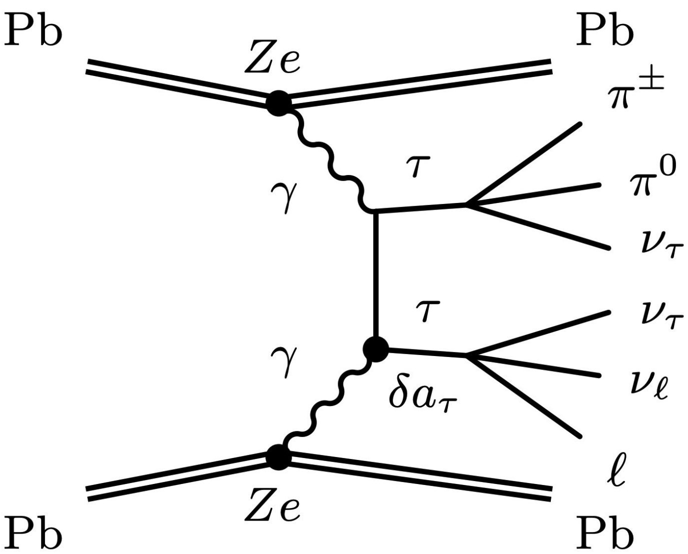
LEP photon collisions

σ ~ 400 pb

⇒ 200k events all years

DELPHI [EPJC 35 (2004) 159-170]

Proceed analogously @ LHC today?



Never measured at LHC

σ ~ Z^4 ~ 500 000 nb (Z_{Pb} = 82)

⇒ 1 million events *already*

Beresford, JL [1908.05180]

Also de Aguila et al [PLB 1991], Dyndal et al [2002.05503]

🥳 Now: CMS & ATLAS breakthroughs realizing our idea 🎉

Creative collaborations bridging nuclear, flavour & BSM physics communities

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CMS-HIN-21-009

CERN-EP-2022-098
2022/06/13

Observation of τ lepton pair production in ultraperipheral lead-lead collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

The CMS Collaboration

Abstract

We present an observation of photon-photon production of τ lepton pairs in ultra-peripheral lead-lead collisions. The measurement is based on a data sample with an integrated luminosity of 404 μb^{-1} collected by the CMS experiment at a nucleon-nucleon center-of-mass energy of 5.02 TeV. The $\gamma\gamma \to \tau^+\tau^-$ process is observed for $\tau^+\tau^-$ events with a muon and three charged hadrons in the final state. The measured fiducial cross section is $\sigma(\gamma\gamma \to \tau^+\tau^-) = 4.8 \pm 0.6\,(\mathrm{stat}) \pm 0.5\,(\mathrm{syst})\,\mu$b, in agreement with leading-order QED predictions. Using $\sigma(\gamma\gamma \to \tau^+\tau^-)$, we estimate a model-dependent value of the anomalous magnetic moment of the τ lepton of $a_\tau = 0.001^{+0.055}_{-0.089}$ at a 68% confidence level.

Submitted to Physical Review Letters

↑ Announced Moriond EWK 2022

CMS 2206.05192

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Phys. Rev. Lett.

CERN-EP-2022-079
April 29, 2022

Observation of the $\gamma\gamma \to \tau\tau$ process in Pb+Pb collisions and constraints on the τ-lepton anomalous magnetic moment with the ATLAS detector

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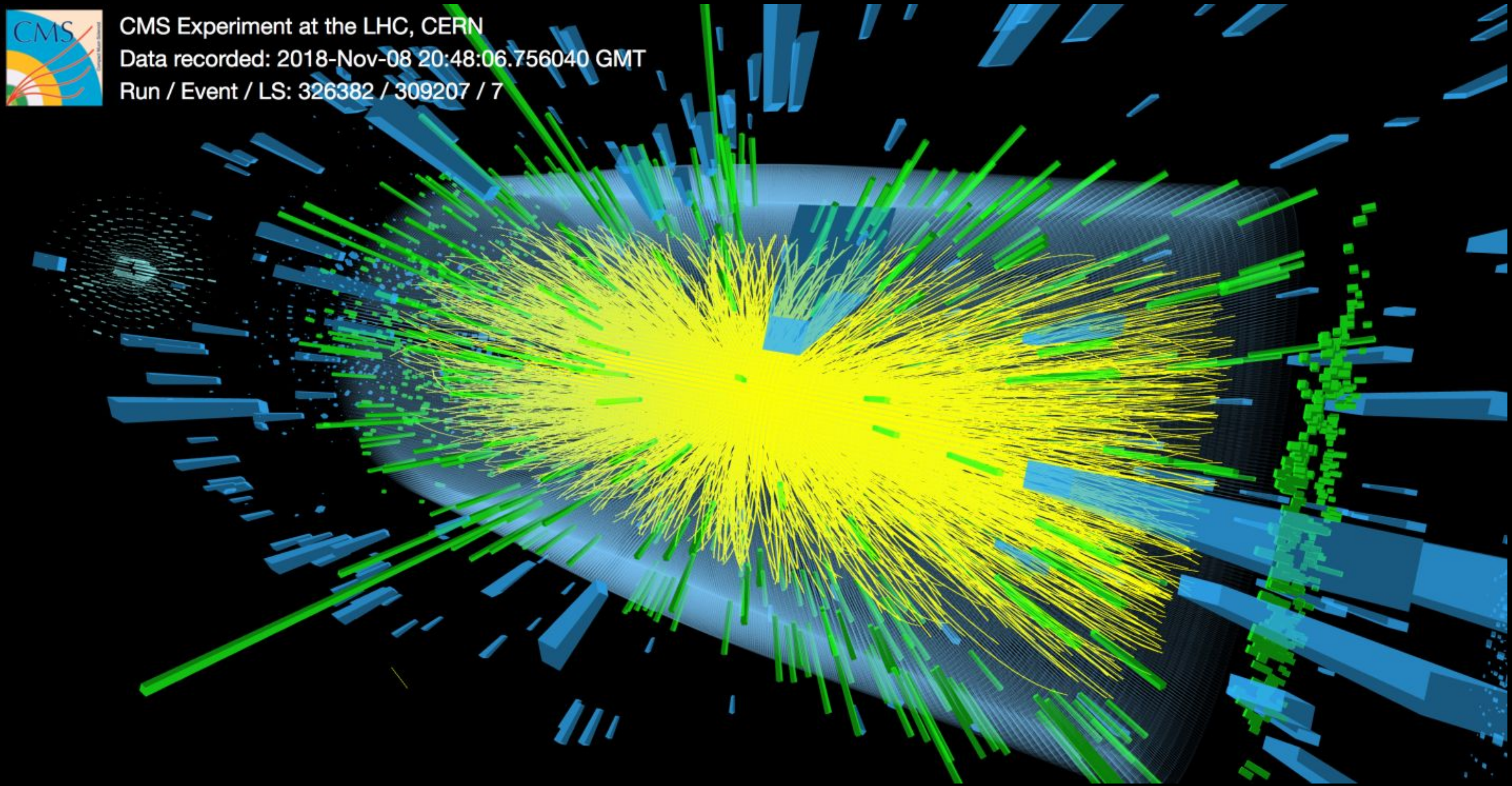
↑ Announced Quark Matter 2022

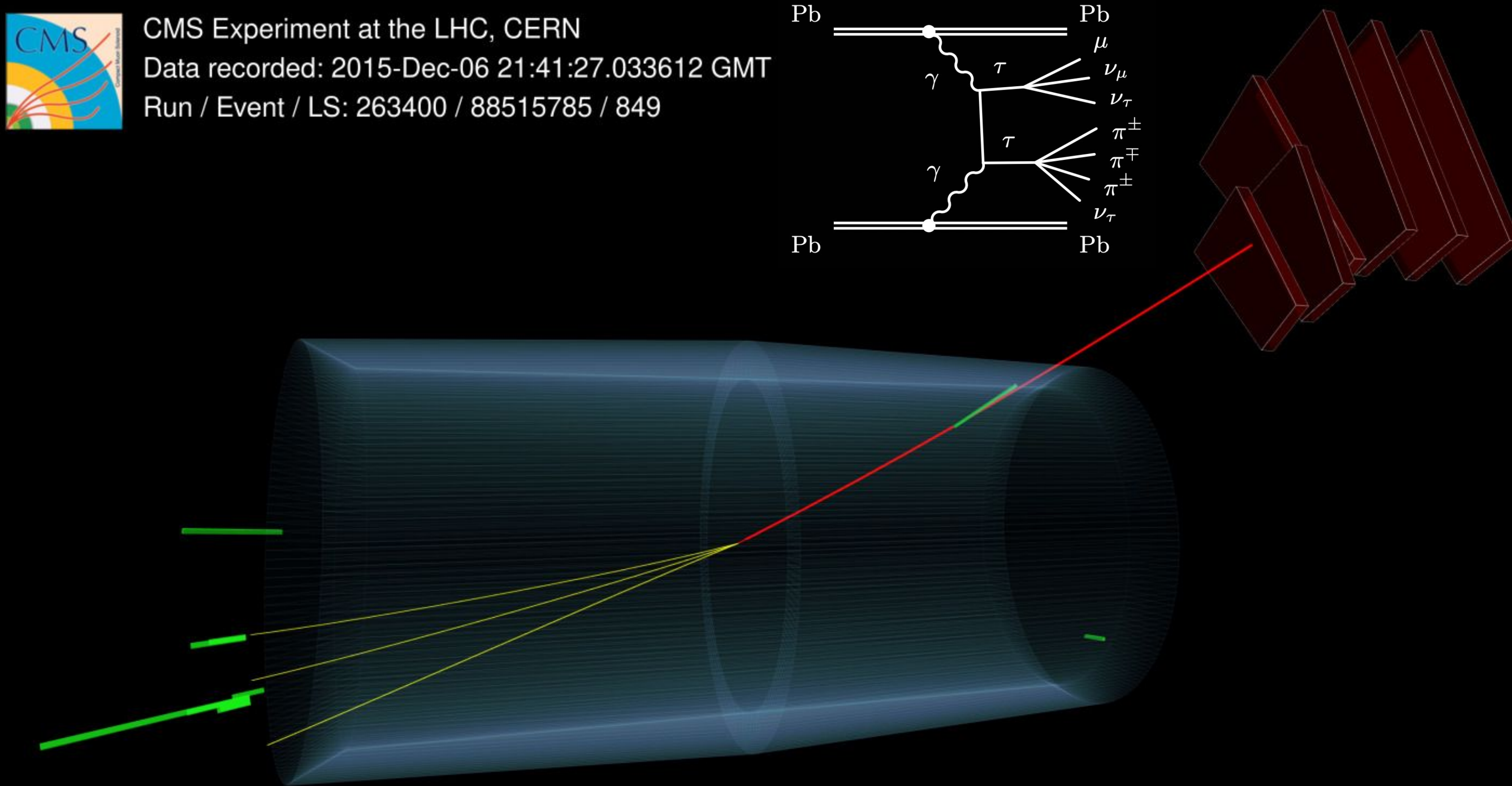
ATLAS (JL Editor) 2204.13478, Accepted PRL

Heavy-ion collisions: what usually comes to mind



CMS [PHO-EVENTS-2018-009]

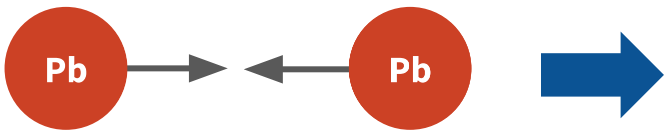
Heavy-ion collisions: breathtakingly clean

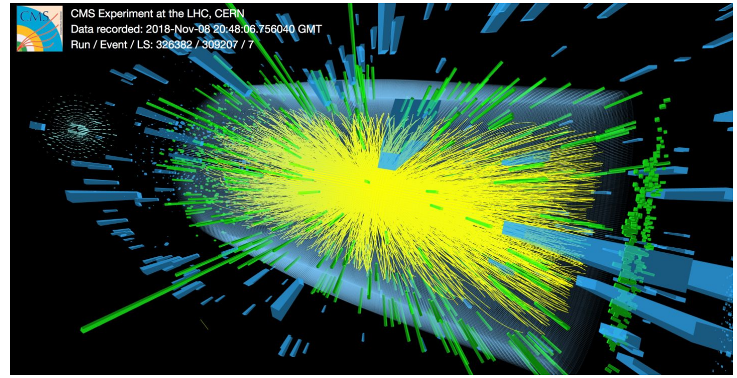


“Using light to make cousins of the electron” [CMS News Briefing]

Colliding light @ LHC

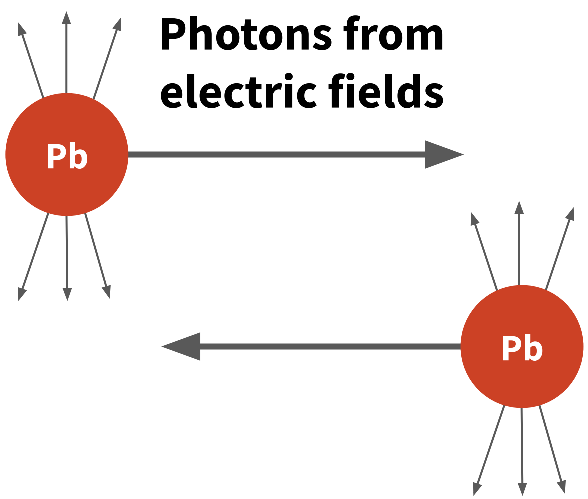
Head-on Pb–Pb collisions

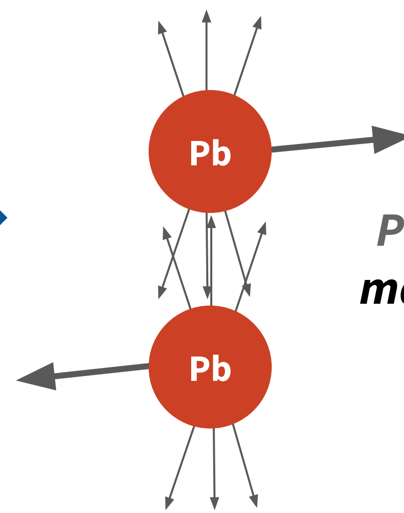




***Partons* collide to make new particles**

Photons from electric fields



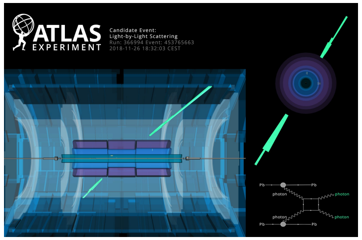


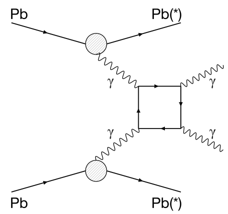
***Photons* collide to make new particles**

EQUIVALENT PHOTON APPROXIMATION

Fermi (1925) [hep-th/0205086], Weizsäcker (1934), Williams (1934), Schwinger (1952), Budnev, Ginzburg, Meledin, Serbo (1975)
ATLAS [ATLAS HION Event Display], Bruce et al [1812.07688]

Recent experimental breakthroughs

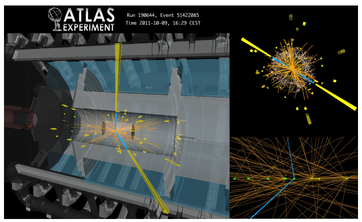


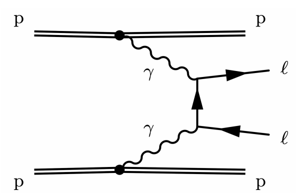


Observation of light-by-light scattering in ultraperipheral Pb+Pb collisions with the ATLAS detector

Probe photon self-coupling & axion-like particles

PRL 123 (2019) 052001

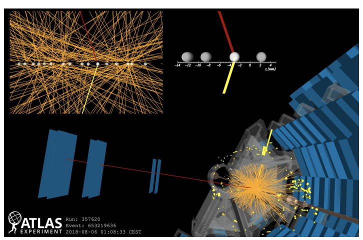


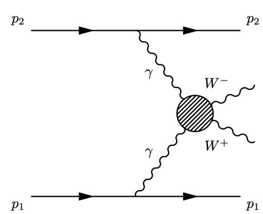


Observation and measurement of forward proton scattering in association with lepton pairs produced via the photon fusion mechanism at ATLAS

Pioneer ATLAS Forward Proton at weak scale

PRL 125 (2020) 261801 (JL Editor)

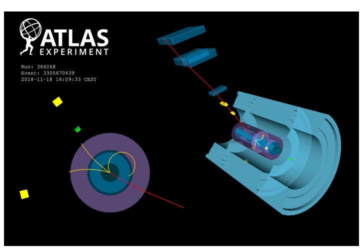


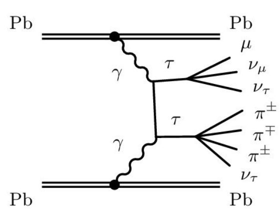


Observation of photon-induced W^+W^- production in pp collisions at $\sqrt{s}$ = 13 TeV using the ATLAS detector

Create electroweak mass states via photon fusion

PLB 816 (2021) 136190



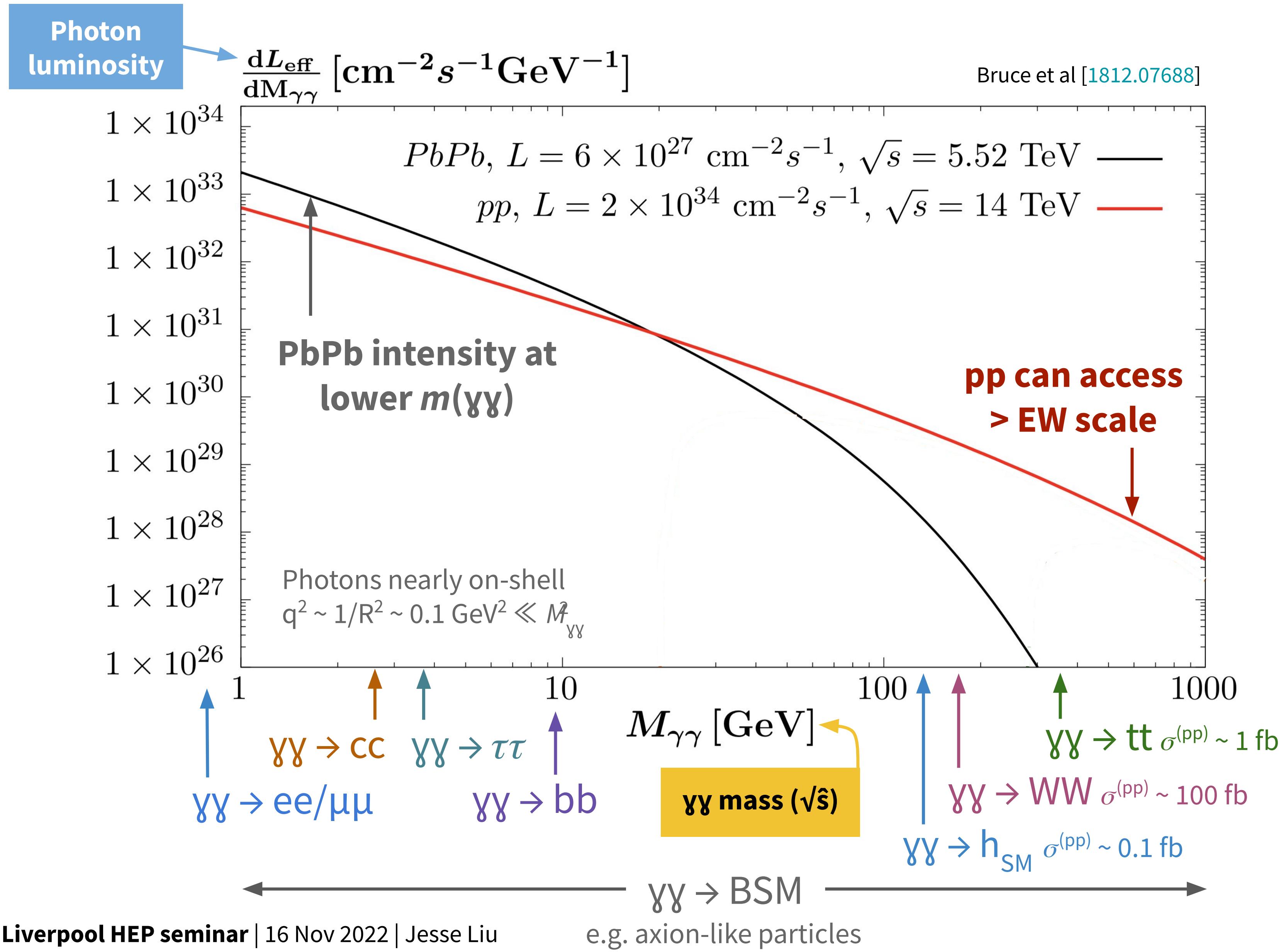


Observation of the $\gamma\gamma \to \tau\tau$ process in Pb+Pb collisions and constraints on the τ-lepton anomalous magnetic moment with the ATLAS detector

First tau g – 2 measurement in 2 decades

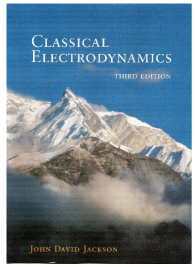
2204.13478, Accepted PRL (JL Editor)

Colliding ɣɣ spectrum



Photon collisions using MadGraph & SMEFTsim

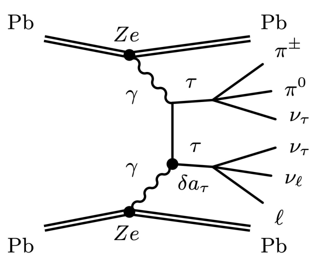
Follow MadGraph EPA prescription
d'Enterria, Lansberg [0909.3047]
Knapen, Lin, Lo, Melia [1607.06083]
Superchic 3
Harland-Lang, Khoze, Ryskin [1810.06567]



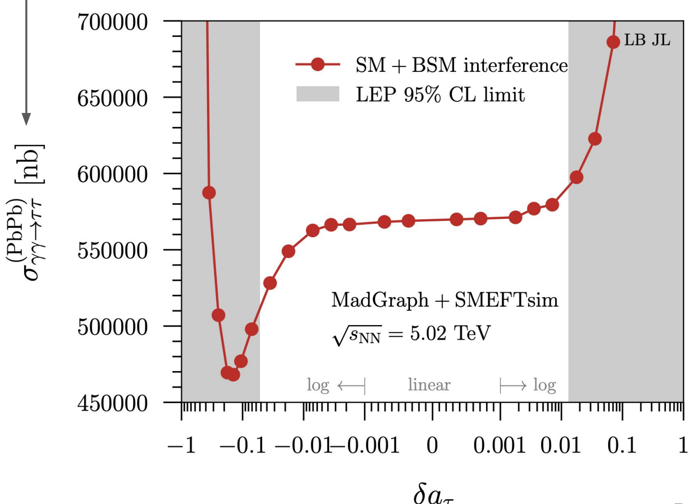
Photon flux: classical field theory

Add Chapter 15 §4 into MadGraph 2.6.5 with Fortran77

$$n(x) = \frac{2Z^2\alpha}{x\pi}\left\{\bar{x}K_0(\bar{x})K_1(\bar{x}) - \frac{\bar{x}^2}{2}\left[K_1^2(\bar{x}) - K_0^2(\bar{x})\right]\right\}$$

$\sigma^{(\mathrm{PbPb})}_{\gamma\gamma\to XX}$ () = $\int \mathrm{d}x_1 \mathrm{d}x_2\, n(x_1) n(x_2)\, \sigma_{\gamma\gamma\to XX}$

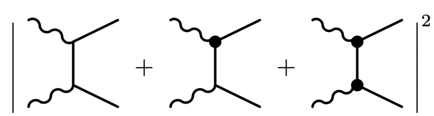
MadGraph | **Jackson** | **SMEFTsim**



BSM a_τ variations: dim-6 SMEFTsim

Grzadkowski, Iskrzyński, M. Misiak, Rosiek [1008.4884]
Alloul, Christensen, Degrande, Duhr, Fuks [1310.1921]
Brivio, Jiang, Trott [1709.06492]

Include interference up to 2 BSM couplings



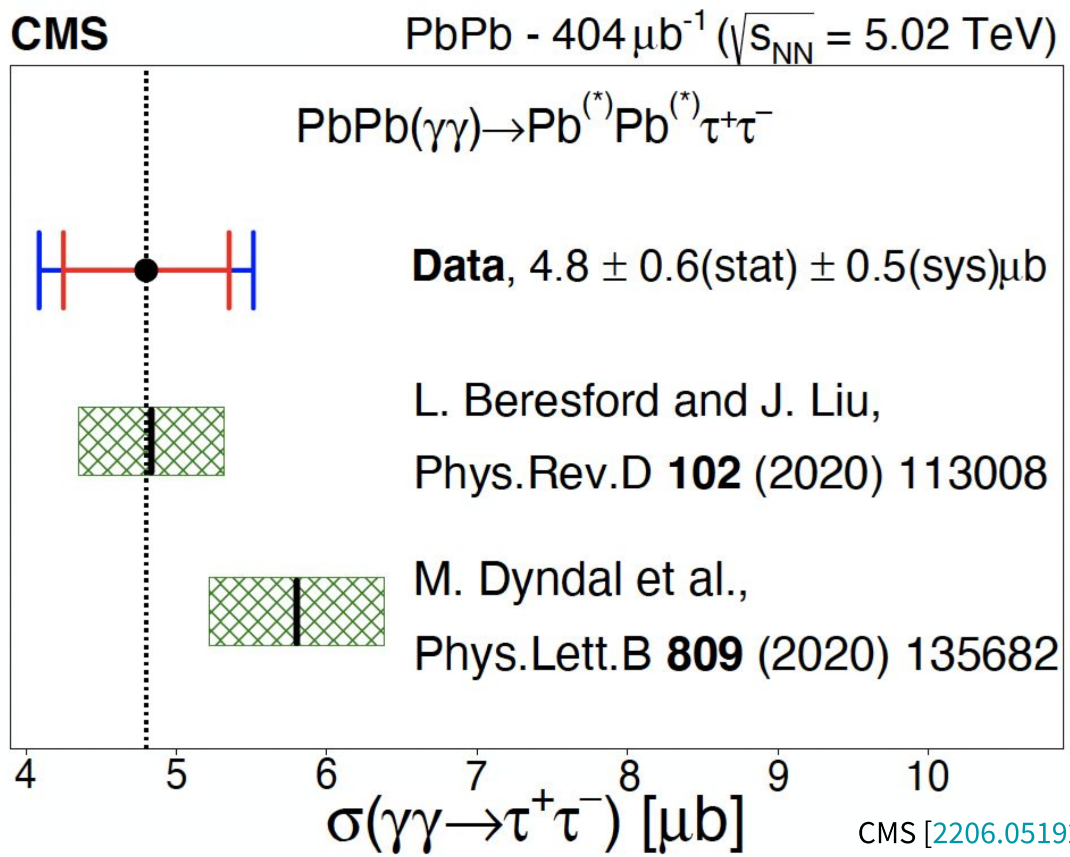
$$\delta a_\tau \sim \frac{C}{\Lambda^2}\left(\bar{L}_\ell \sigma^{\mu\nu}\ell_R\right) H \left(\partial_\mu A_\nu\right)$$

Beresford, JL [1908.05180]

1st PbPb → Pb(γγ → ττ)Pb cross-section measurement

Only μb *visible* cross-section ∵ soft tau acceptance x efficiency very low →

→ Jackson Electrodynamics works! 😅

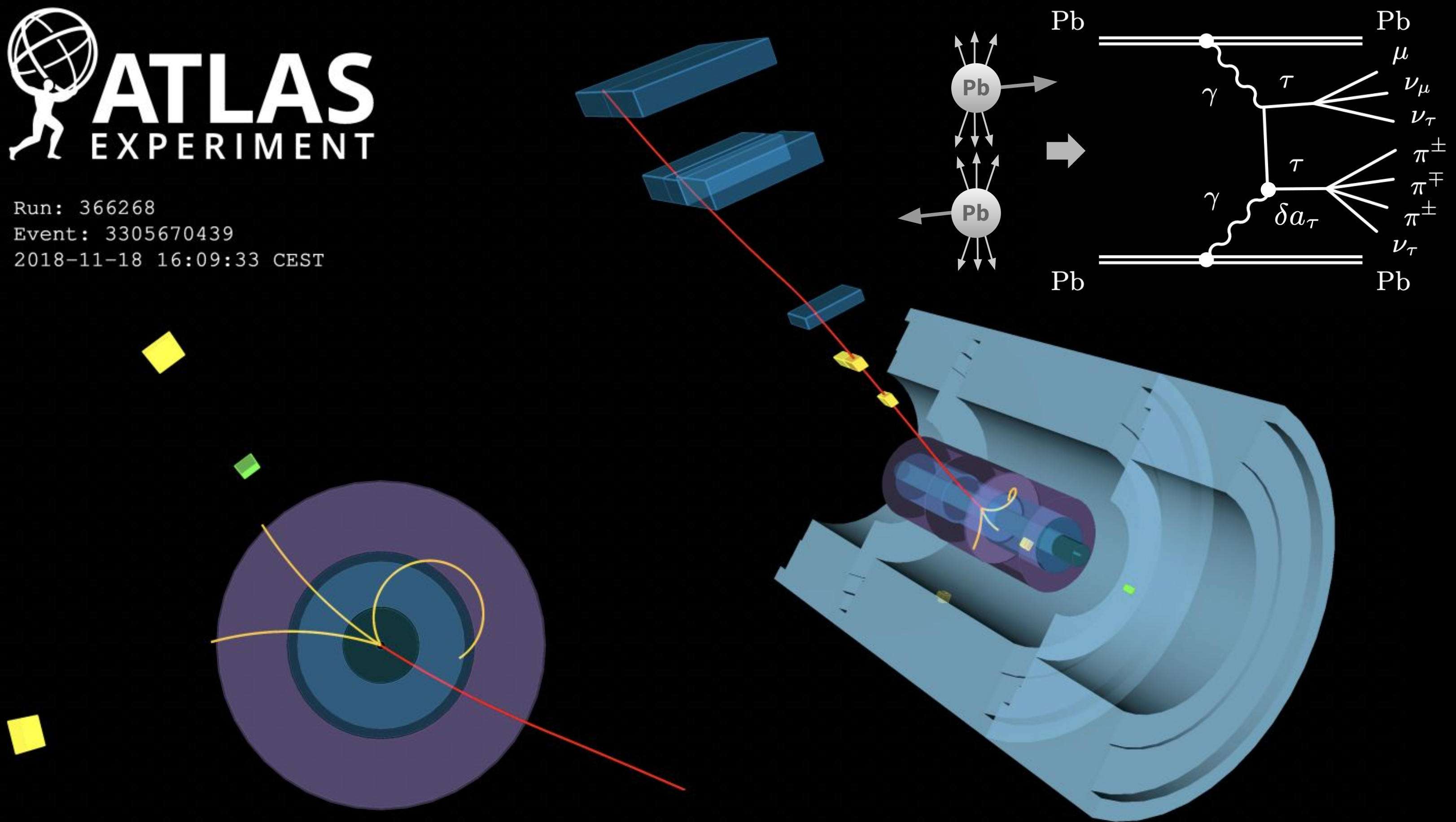


CMS [2206.05192]

Remarkable result 🤩 …and just getting started!

2015 data | dominant systematics: muon efficiency (6.7%), luminosity (5%), pion efficiency (3.6%)

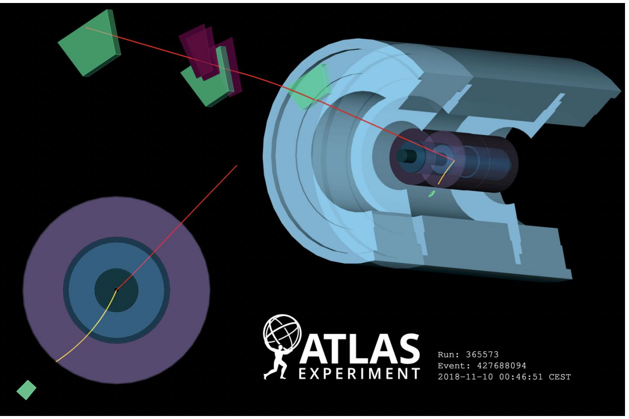
ATLAS observation of PbPb → Pb (γγ → $\tau\tau$) Pb

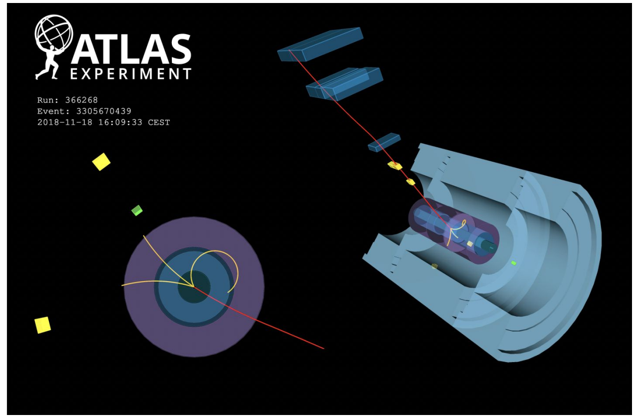


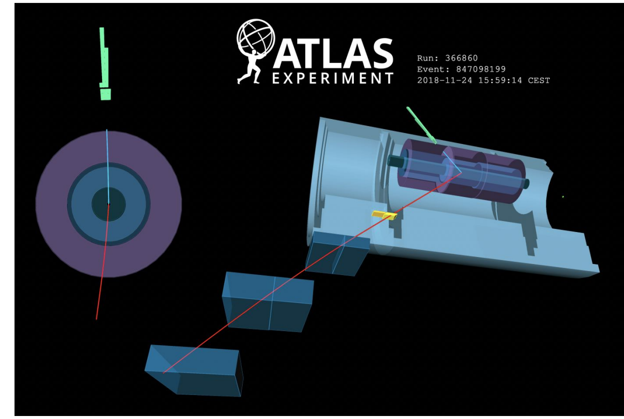
↑ *All charged-particle tracks above 100 MeV are shown*

1 month to double dataset | Pileup μ ~ 0.003 | $p_T(\mu)$ > 4 GeV trigger

ATLAS analyzes 2018 data in our 3 proposed channels



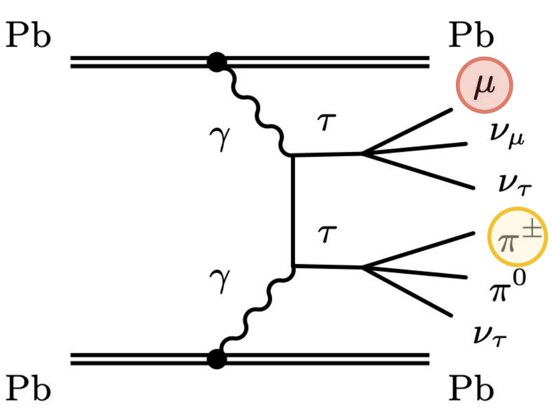


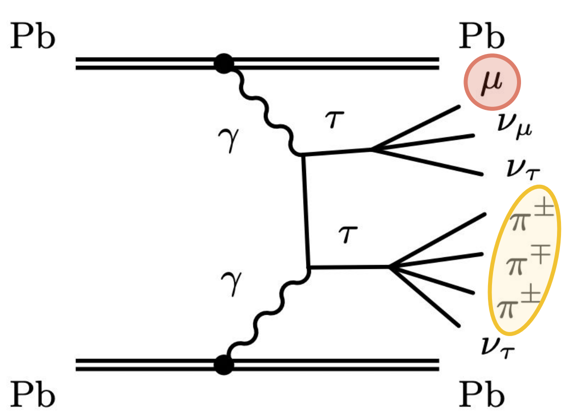


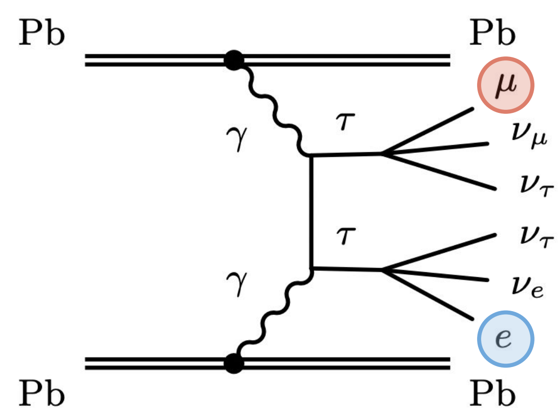
1 muon + 1 track (μ1T-SR)

1 muon + 3 tracks (μ3T-SR)

1 muon + 1 electron (μe-SR)







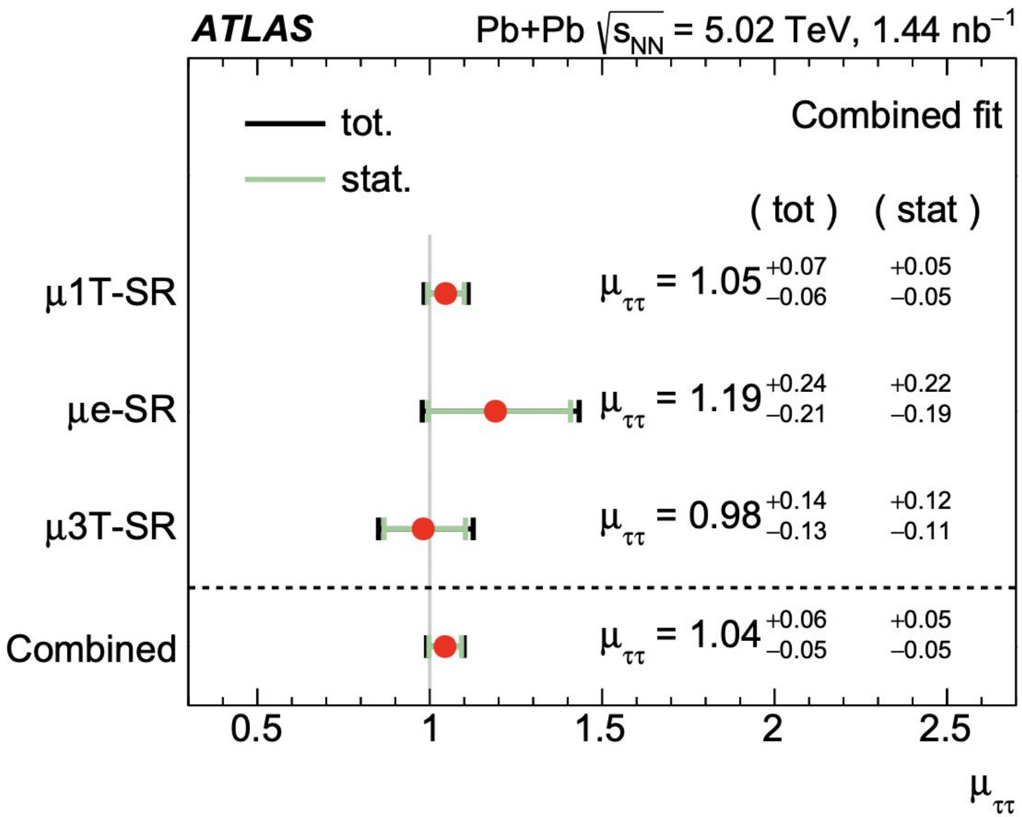
$N_{obs} = 532$, $N_{bkg} = 84 \pm 19$

$N_{obs} = 85$, $N_{bkg} = 10 \pm 3$

$N_{obs} = 39$, $N_{bkg} = 2.8 \pm 0.7$

ATLAS (JL Editor) 2204.13478, Accepted PRL

Precision currently limited by data sample size

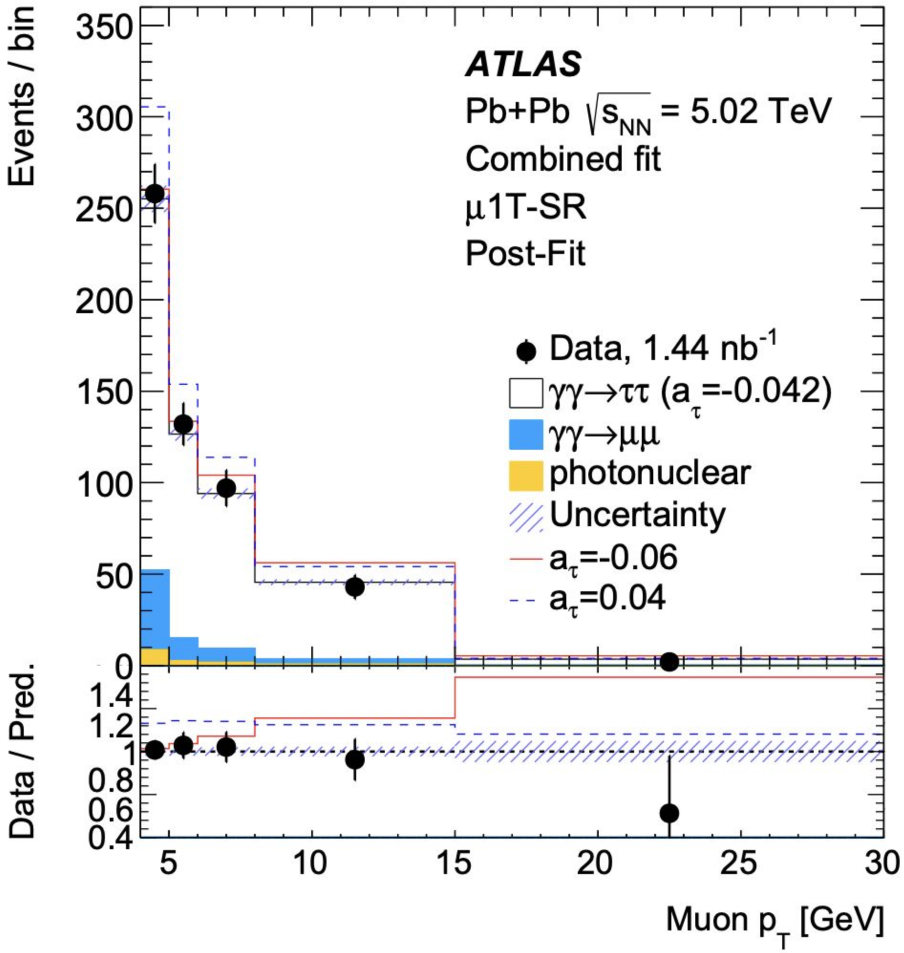


Signal strength $\mu_{\tau\tau}$ = observed rate / expected SM rate

$$\mathcal{B}(\tau^\pm \to \ell^\pm \nu_\ell \nu_\tau) = 35\%,$$
$$\mathcal{B}(\tau^\pm \to \pi^\pm \nu_\tau + \text{neutral pions}) = 45.6\%,$$
$$\mathcal{B}(\tau^\pm \to \pi^\pm \pi^\mp \pi^\pm \nu_\tau + \text{neutral pions}) = 19.4\%.$$

ATLAS (JL Editor) 2204.13478, Accepted PRL

Very soft: muon p_T > 4 GeV, track p_T > 100 MeV



Use μμ events to control photon flux modelling systematics

Muons lose ~3 GeV of energy before reaching muon chambers

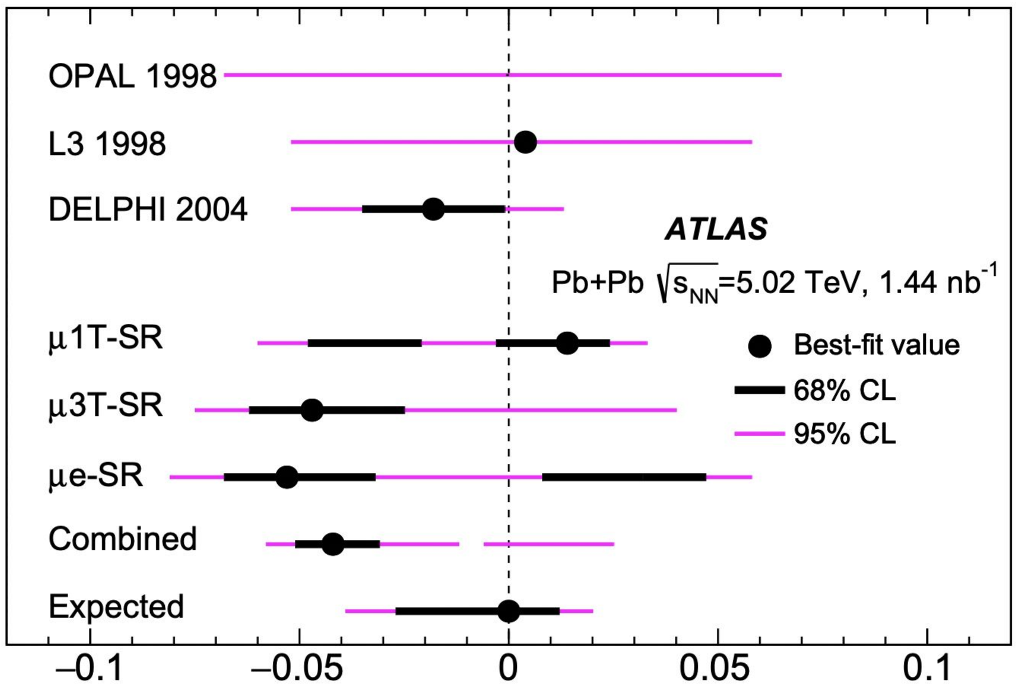
ATLAS (JL Editor) 2204.13478, Accepted PRL

Groundbreaking results competitive with LEP

First lab measurement of tau $g-2$ in 2 decades

First time taus analysed in heavy ion collisions

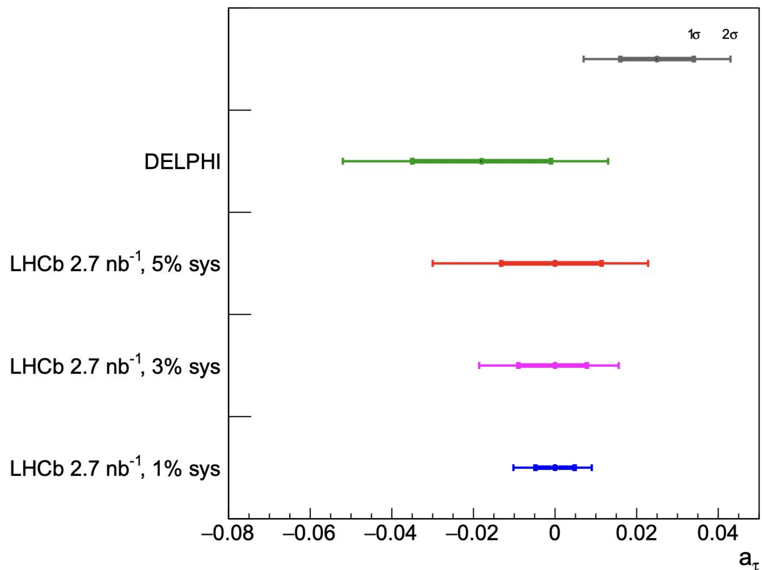
Heavy ions enabled 5% measurement of QED g_τ



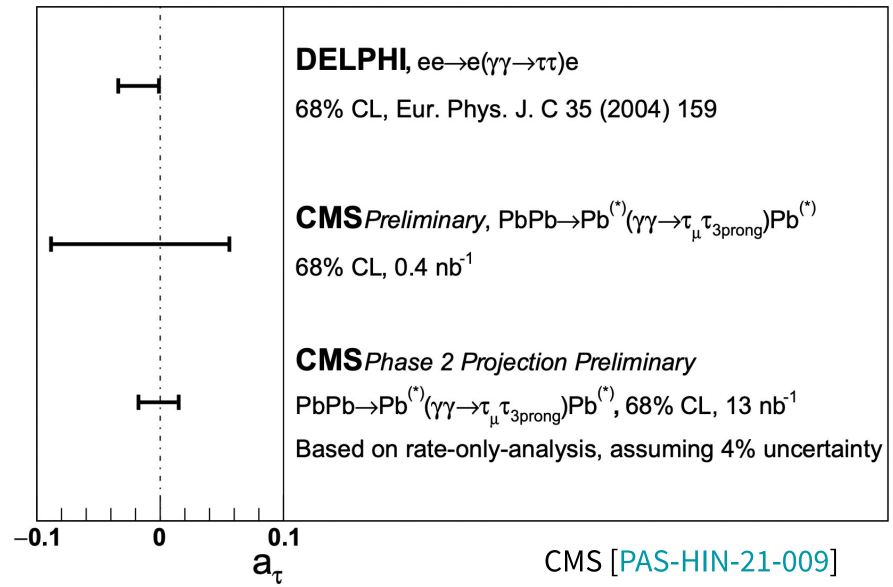
$a_\tau = (g_\tau - 2)/2$

ATLAS (JL Editor) 2204.13478, Accepted PRL

Every innovation strengthens HL-LHC science



LHCb+ALICE too! Burmasov et al [2203.00990]

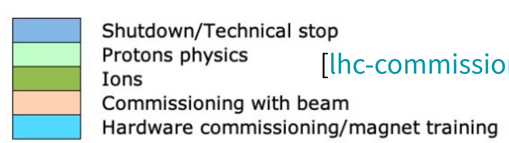


CMS [PAS-HIN-21-009]

d'Enterria et al [2203.05939]

Pb-Pb	runtime	ATLAS/CMS	ALICE	LHCb
	1 month	2.1–2.5 nb^{-1}	2.5–2.8 nb^{-1}	< 0.5 nb^{-1}
	5 months	10.5–12.5 nb^{-1}	12.5–14.0 nb^{-1}	< 2.5 nb^{-1}

Today's undergrads become postdocs



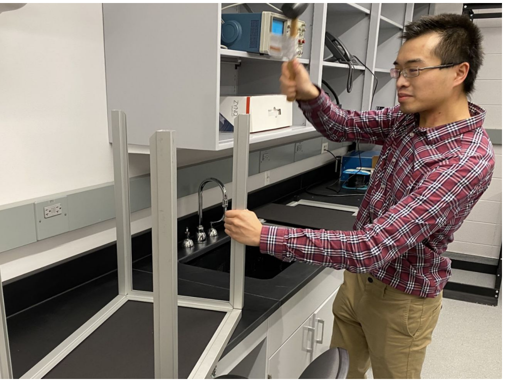
[lhc-commissioning.web.cern.ch]

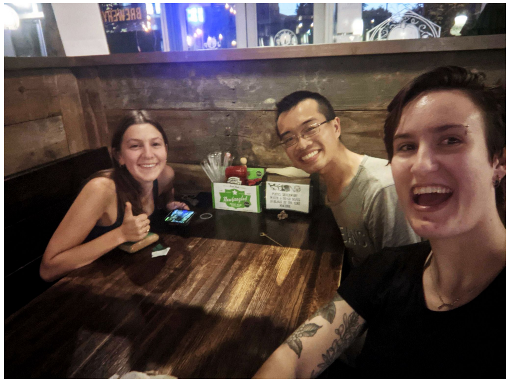
Build next-gen ATLAS silicon camera (ITk) at Cambridge 🧑‍🔬

Cambridge leading barrel sensor and module assembly & quality control

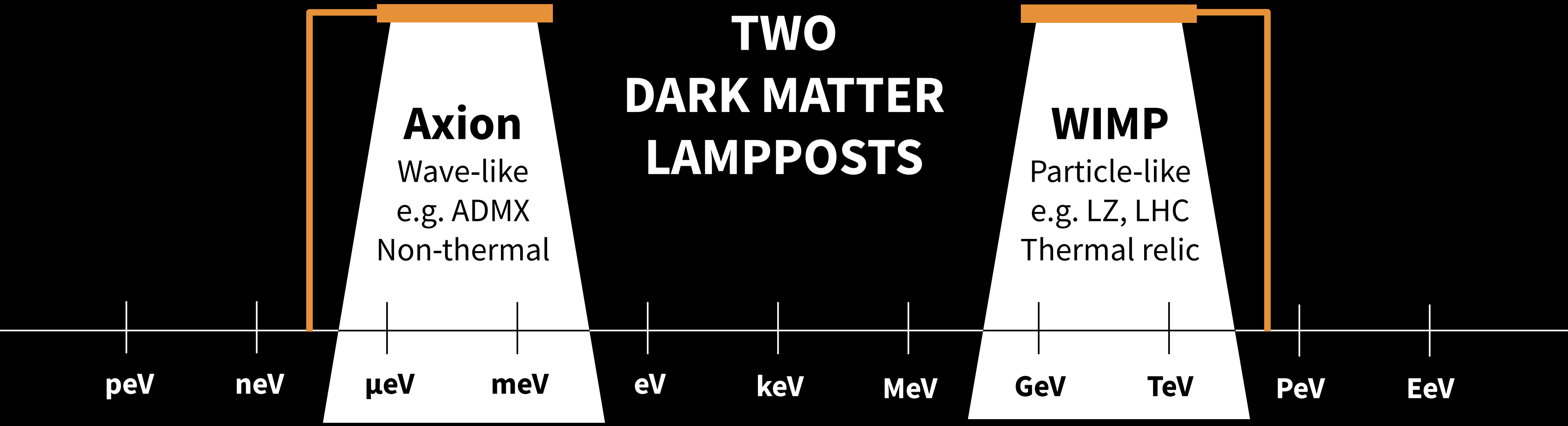
Featuring Alan Barr, Lydia Beresford Bart Hommels, Will Fawcett, Val Gibson, Kosala Kariyapperuma, JL, Anna Mullin, Sarah Williams; Photo credits: Bart Hommels, Val Gibson, Will Fawcett

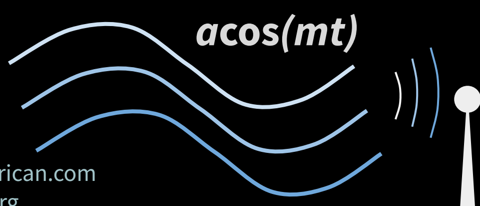
POSTDOC YEARS @ THE UNIVERSITY OF CHICAGO (2019–21)

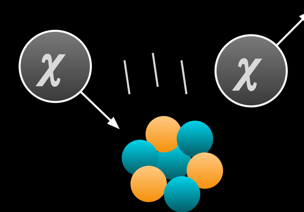




TWO DARK MATTER LAMPPOSTS

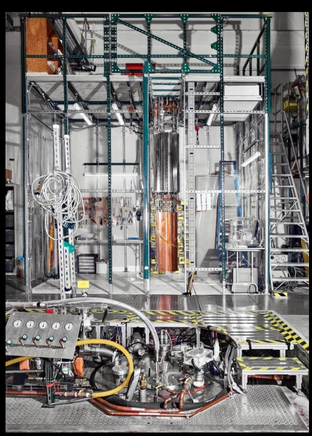


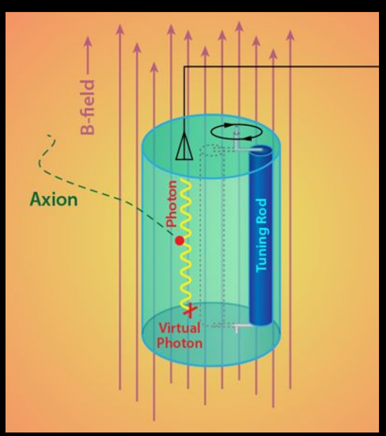


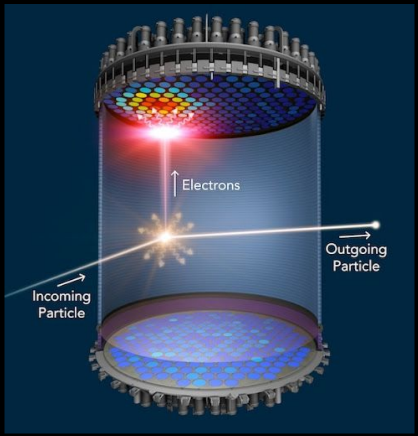


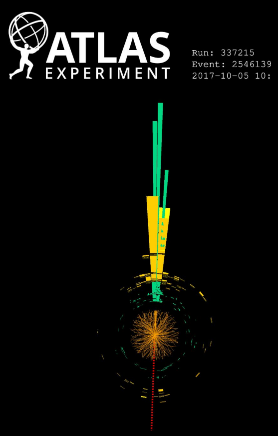
scientificamerican.com
physics.aps.org

lz.ac.uk
2102.10874

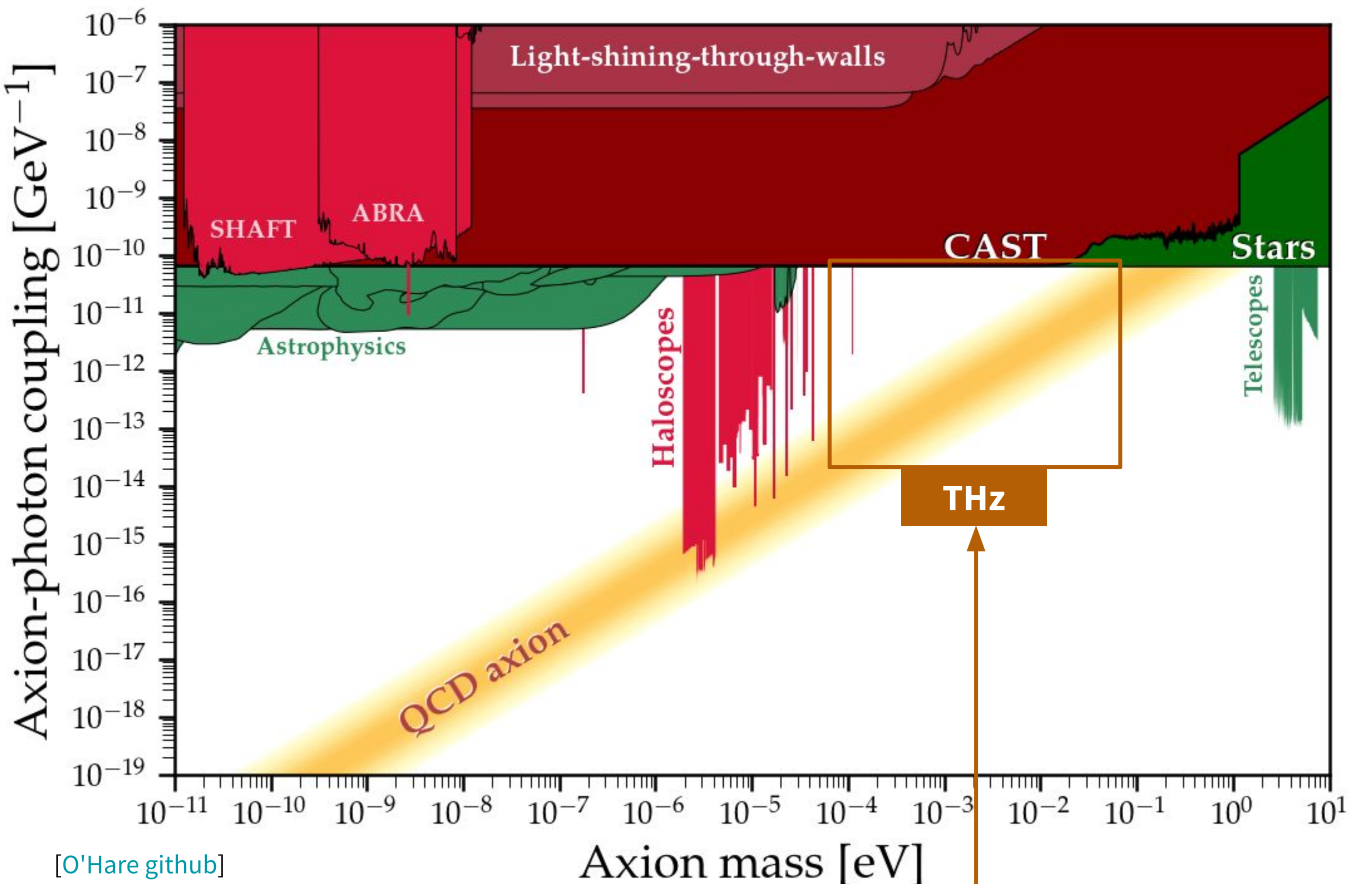








The milli-eV/terahertz axion search problem



[O'Hare github]

Problem 1: Desire broadband but cavity haloscopes narrowband $\Delta m/m \ll 1$

Problem 2: Desire high mass but scan rate* $R \sim f^{-14/3}$ impractical for $m > 50$ μeV

NEED CREATIVITY TO OVERCOME BOTH LONGSTANDING OBSTACLES

*See e.g. Backes et al [2008.01853] for how to overcome this scaling in HAYSTAC

Broadband Reflector Experiment for Axion Detection

🥳 My proposal paper on the cover of PRL & Editors' Suggestion 🎉

BREAD COLLABORATION

SLAC, NIST, Lawrence Livermore National Laboratory, The University of Chicago, University of Cambridge, Argonne National Laboratory, Fermilab, MIT, NASA Goddard Space Flight Center, Illinois Tech

PHYSICAL REVIEW LETTERS

JL, Dona et al [2111.12103]

Highlights | Recent | Accepted | Collections | Authors | Referees | Search | Press

ON THE COVER

Broadband Solenoidal Haloscope for Terahertz Axion Detection

March 28, 2022

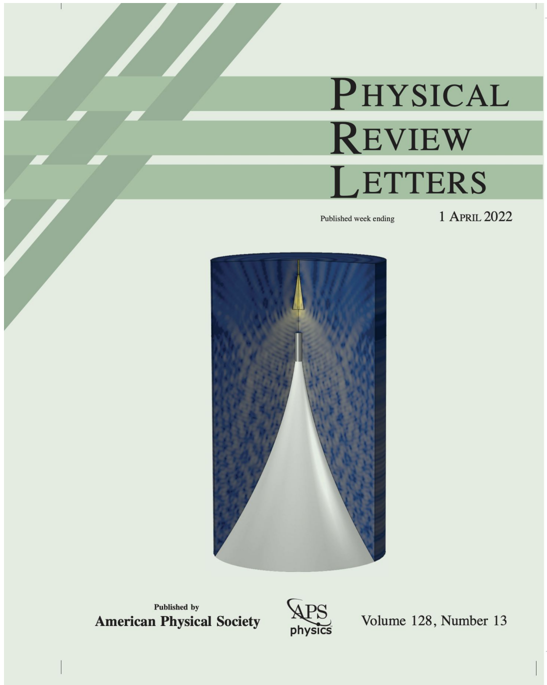
Simulation of the full electric field inside the conceptual design of the Broadband Reflector Experiment for Axion Detection (BREAD). Selected for an Editors' Suggestion.

Jesse Liu *et al.*

Phys. Rev. Lett. **128**, 131801 (2022)

Issue 13 Table of Contents | More Covers

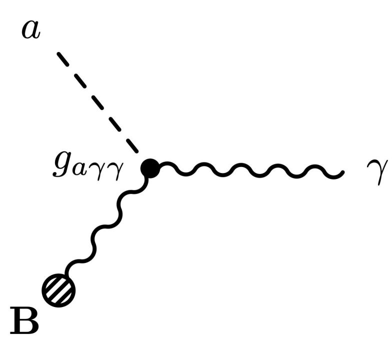
Jesse Liu, Kristin Dona, Gabe Hoshino, Stefan Knirck, Noah Kurinsky, Matthew Malaker, David W. Miller, Andrew Sonnenschein, Mohamed H. Awida, Peter S. Barry, Karl K. Berggren, Daniel Bowring, Gianpaolo Carosi, Clarence Chang, Aaron Chou, Rakshya Khatiwada, Samantha Lewis, Juliang Li, Sae Woo Nam, Omid Noroozian, and Tony X. Zhou (BREAD Collaboration)



Step 0: dish antenna foundations

Axion–photon coupling

$$g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

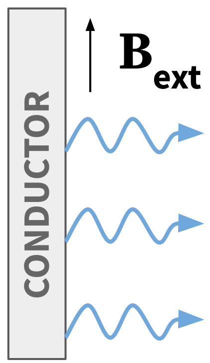


Augment Ampère–Maxwell

$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \mathbf{J}_{\mathrm{DM}}$$

$$g_{a\gamma\gamma}\sqrt{2\rho_{\mathrm{DM}}}\mathbf{B}^{\parallel}_{\mathrm{ext}} \cos(m_a t)$$

Photon conversion



$$\mathbf{E}_{\parallel} = 0$$

Broadband: no resonant tuning to unknown mass

Concept proposed in Horns et al [1212.2970]

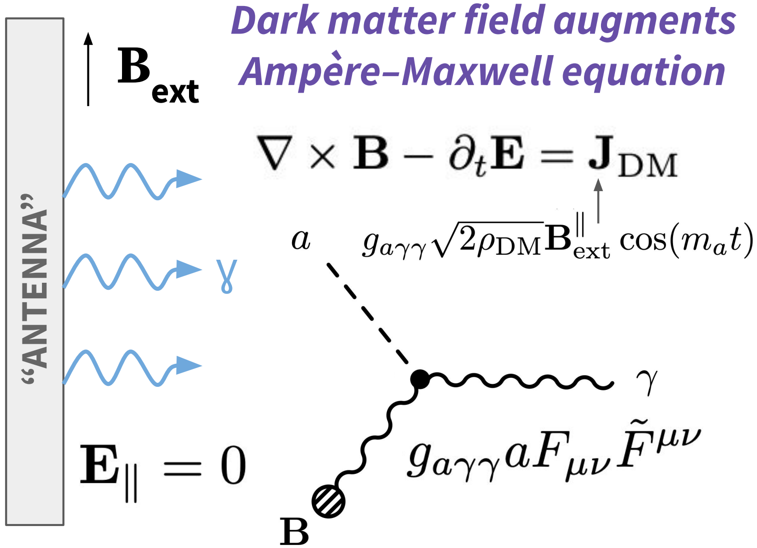
Step 1: convert DM to photons

a) Oscillating axion field makes conductor emit photons

Dark matter field augments Ampère–Maxwell equation

$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \mathbf{J}_{\rm DM}$$

$$g_{a\gamma\gamma}\sqrt{2\rho_{\rm DM}}\mathbf{B}^{||}_{\rm ext}\cos(m_a t)$$



INHERENTLY BROADBAND

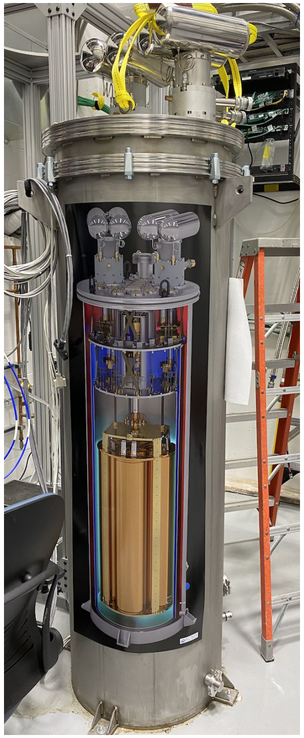
No tuning to unknown DM mass

Concept proposed in Horns et al [1212.2970]

b) Make cylindrical to embed in standard solenoids & cryostats

→ Fridge for ADMX science at FNAL
(Photo by Kristin Dona)

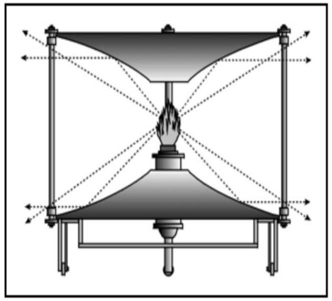
↓ Solenoids for Magnetic Resonance Imaging
hopkinsmedicine.org



See also Mark Bird (2020)
"Ultra-High Field Solenoids and Axion Detection"

Step 2: collect photons

Historical inspiration → **Novel parabolic reflector design focuses photons** → **3D-printed prototype @ FNAL** → **Proposed dark photon pilot design**

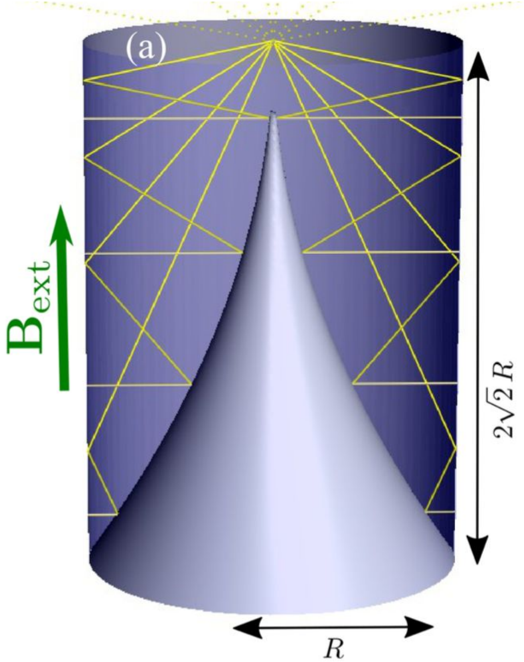


Inverse of 19th century lighthouse

Bordier-Marcet 1811

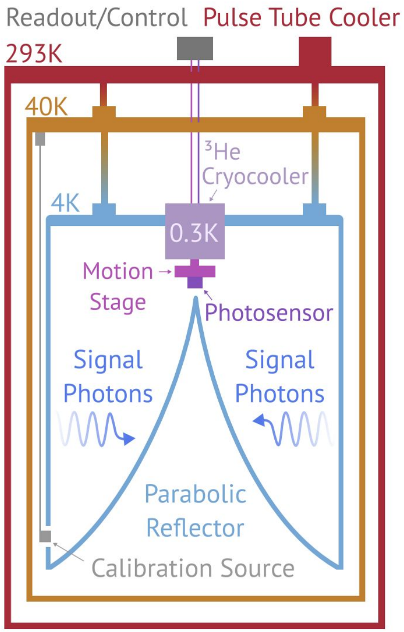
Cylindrically symmetric co-parallel rays from point source

uslhs.org



Ray tracing simulation

Gabe Hoshino led in situ measurements with antenna



Status: iterating reflector design with engineers

BREAD COLLABORATION

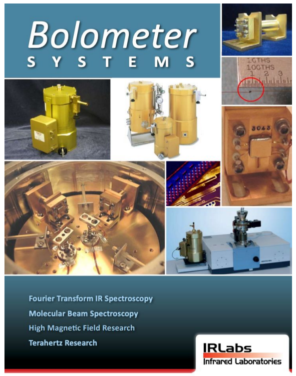
Kate Azar, Matthew Malaker, Gabe Hoshino (summer students) led detailed simulation studies

JL, Dona et al [PRL 128 (2022) 131801]

Step 3: detect photons

gentec-eo.com

irlabs.com

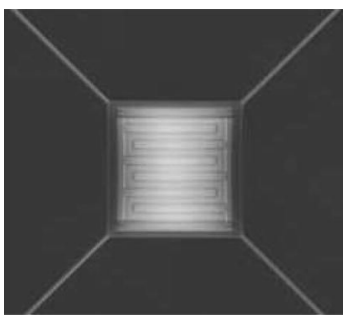


Commercial bolometers

Lower noise is better ↓

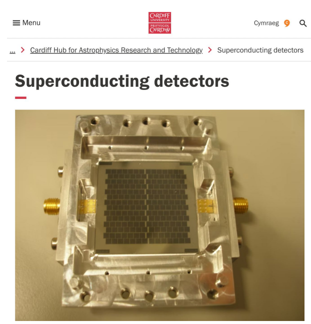
Photosensor	E / meV	T_{op} / K	NEP / $\mathrm{W}/\sqrt{\mathrm{Hz}}$	A_{sens} / mm^2
GENTEC [97]	[0.4, 120]	293	$1 \cdot 10^{-8}$	$\pi 2.5^2$
IR LABS [98]	[0.24, 248]	1.6	$5 \cdot 10^{-14}$	1.5^2
KID/TES [99, 100]	[0.2, 125]	0.3	$2 \cdot 10^{-19}$	0.2^2
QCDet [101, 102]	[2, 125]	0.015	$\frac{\mathrm{DCR}}{\mathrm{Hz}} = 4$	0.06^2
SNSPD [103, 104]	[124, 830]	0.3	$\frac{\mathrm{DCR}}{\mathrm{Hz}} = 10^{-4}$	0.4^2

JL, Dona et al [PRL 128 (2022) 131801]



Transition Edge Sensor

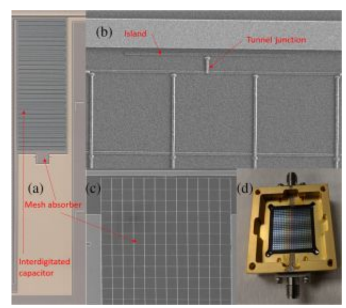
Goldie et al [JLTP 2016]



Kinetic Inductance Detector

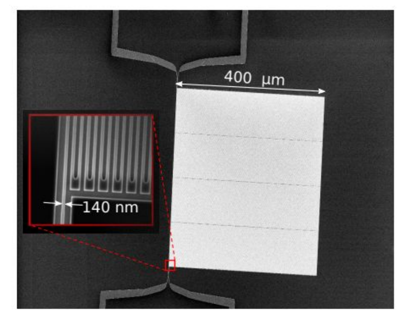
Baselmans et al [A&A 2017]

Established technology for astronomy/CMB*



Quantum Capacitance Detector

Echternach et al [JATIS 2021]



Superconducting Nanowire Single Photon Detector

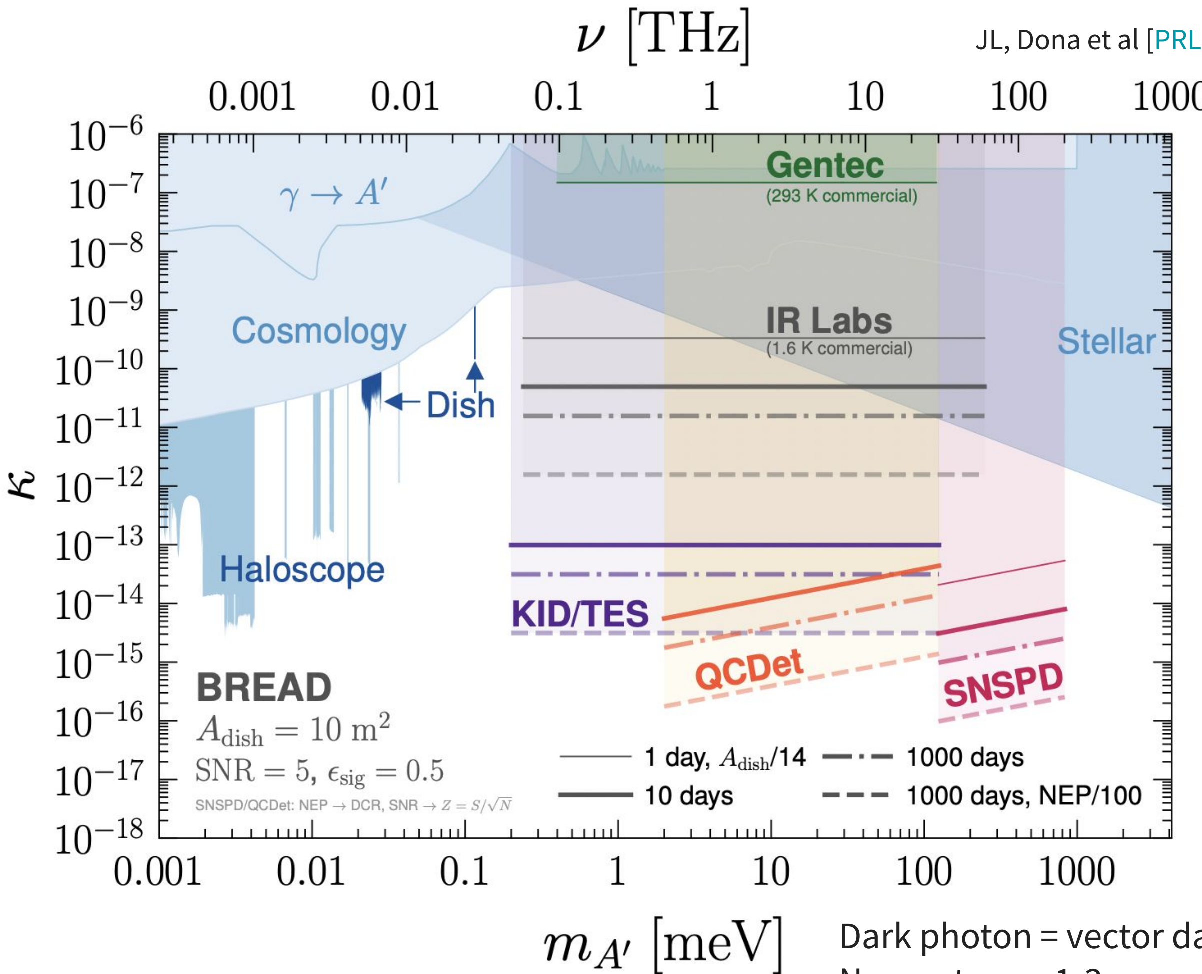
Hochberg et al [1903.05101]

Emerging technology for infrared photon counting

*E.g. UK efforts: TES @ Cambridge (S Withington et al), KID @ Cardiff (Pete Barry et al)

Sensitivity: dark photon pilot "sourdough starter"

JL, Dona et al [PRL 128 (2022) 131801]



Dark photon = vector dark matter A'

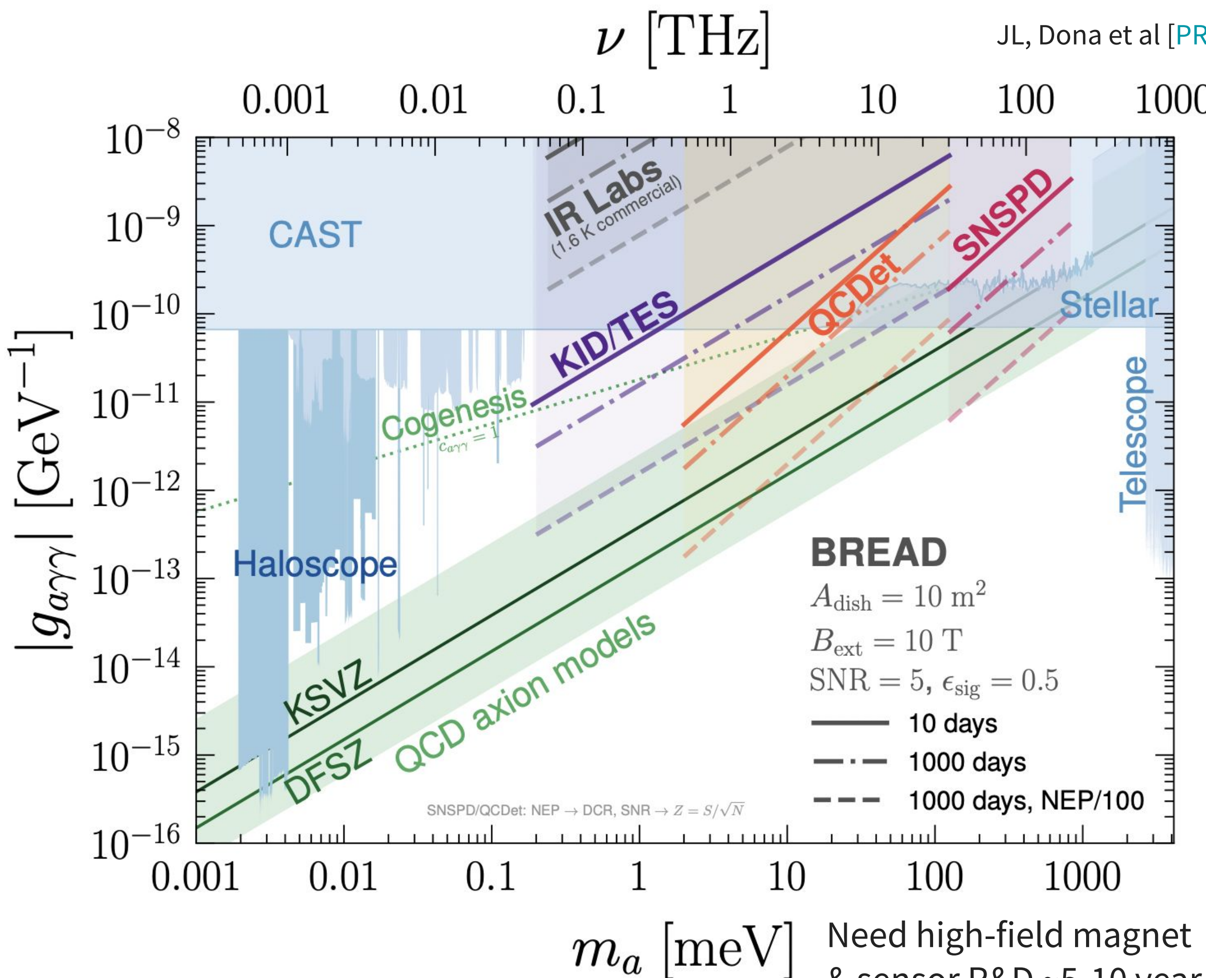
Nearer-term ~1-3 year pilots ongoing

BREAD COLLABORATION

$$\left\{\begin{matrix}\left(\frac{g_{a\gamma\gamma}}{10^{-12}}\right)^2 \\ \left(\frac{\kappa}{10^{-15}}\right)^2\end{matrix}\right\} = \left\{\begin{matrix}\frac{3.0}{\mathrm{GeV}^2}\left(\frac{m_a}{\mathrm{meV}}\right)^3\left(\frac{10\,\mathrm{T}}{B_\mathrm{ext}}\right)^2 \\ 11.9\frac{2/3}{\alpha_\mathrm{pol}^2}\frac{m_{A'}}{\mathrm{meV}}\end{matrix}\right\}\left(\frac{\mathrm{hour}}{\Delta t}\right)^{1/2}\frac{10\,\mathrm{m}^2}{A_\mathrm{dish}}\frac{Z}{5}\frac{0.5}{\epsilon_s}\left(\frac{\mathrm{DCR}}{10^{-2}\,\mathrm{Hz}}\right)^{1/2}\frac{0.45\,\mathrm{GeV/cm}^3}{\rho_\mathrm{DM}}$$

Sensitivity: axion science programme

JL, Dona et al [PRL 128 (2022) 131801]



Need high-field magnet
& sensor R&D ~5-10 year timescale

BREAD COLLABORATION

$$\left\{\begin{matrix}\left(\frac{g_{a\gamma\gamma}}{10^{-12}}\right)^2 \\ \left(\frac{\kappa}{10^{-15}}\right)^2\end{matrix}\right\} = \left\{\begin{matrix}\frac{3.0}{\mathrm{GeV}^2}\left(\frac{m_a}{\mathrm{meV}}\right)^3\left(\frac{10\,\mathrm{T}}{B_\mathrm{ext}}\right)^2 \\ 11.9\,\frac{2/3}{\alpha_\mathrm{pol}^2}\,\frac{m_{A'}}{\mathrm{meV}}\end{matrix}\right\}\left(\frac{\mathrm{hour}}{\Delta t}\right)^{1/2}\frac{10\,\mathrm{m}^2}{A_\mathrm{dish}}\,\frac{Z}{5}\,\frac{0.5}{\epsilon_s}\left(\frac{\mathrm{DCR}}{10^{-2}\,\mathrm{Hz}}\right)^{1/2}\frac{0.45\,\mathrm{GeV/cm}^3}{\rho_\mathrm{DM}}$$

BREAD roadmap to flagship next-gen axion experiment

BREAD	Pilot	Stage 1	Stage 2a	Stage 2b
Axion a	—	✓	✓	✓
Dark photon A'	✓	✓	✓	✓
Experimental parameters				
$A_{\rm dish}$ [m^2]	0.7	10	10	10
$B_{\rm ext}$ [T]	—	10	10	10
ϵ_s	0.5	0.5	0.5	0.5
Δt [days]	10	10	1000	1000
NEP [W Hz$^{-1/2}$]	10^{-14}	10^{-18}	10^{-20}	10^{-22}
Coupling sensitivity (SNR = 5)				
$\lvert g_{a\gamma\gamma}/g_{a\gamma\gamma}^{\rm KSVZ}\rvert$	—	280	9.0	0.90
$\lvert g_{a\gamma\gamma}/g_{a\gamma\gamma}^{\rm DFSZ}\rvert$	—	740	23	2.3
$\kappa/10^{-14}$	8400	22	0.7	0.07

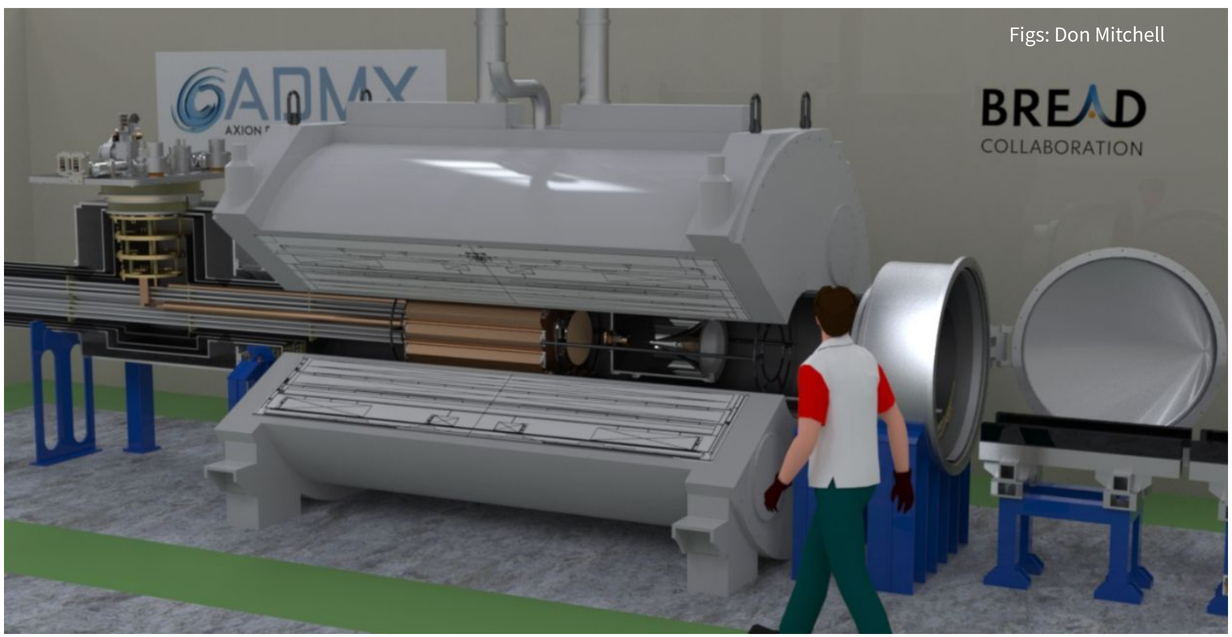
Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

2203.14923 (JL contributing author)

Snowmass 2021 White Paper
Axion Dark Matter

J. Jaeckel[1], G. Rybka[2], L. Winslow[3], and the Wave-like Dark Matter Community [4]

[1]Institut fuer theoretische Physik, Universitaet Heidelberg, Heidelberg, Germany
[2]University of Washington, Seattle, WA, USA
[3]Laboratory of Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA, USA
[4]Updated Author List Under Construction



Figs: Don Mitchell

Well-aligned with UK Quantum Sensors for the Hidden Sector (PI: Ed Daw et al, qshs.org)
See also UK Quantum Technologies for Fundamental Physics, Strategic Detector R&D proposal

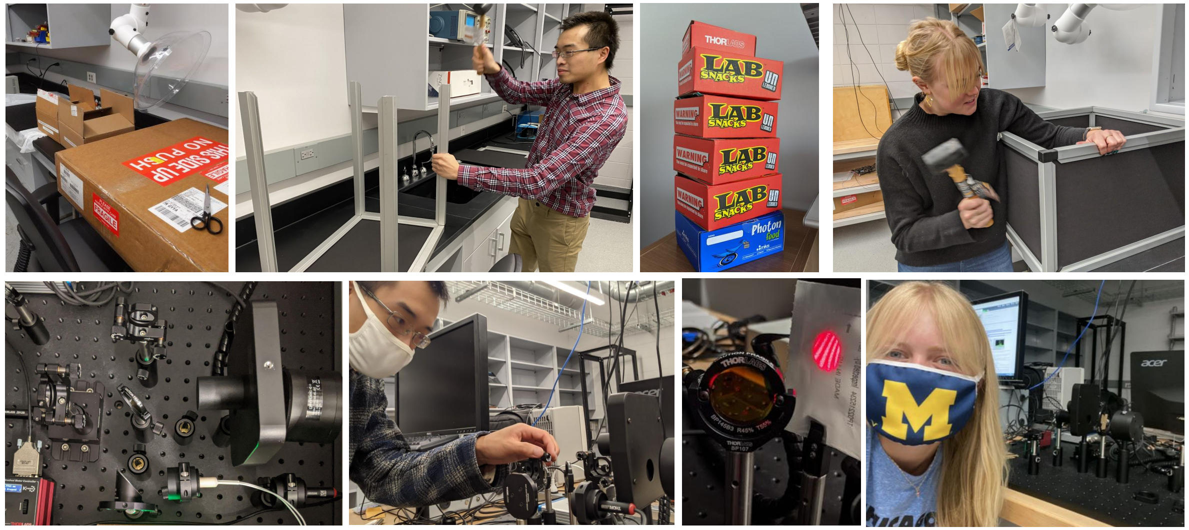
Hands on 1: build spectrometer to characterize optics

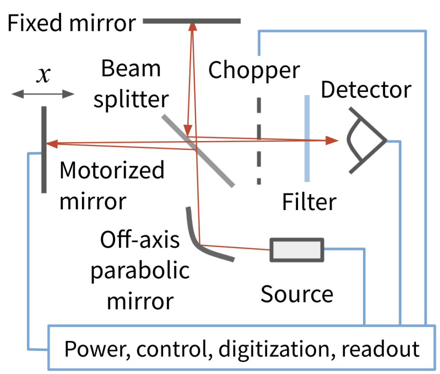
JANUARY 2020
Hardware arrival & assembly

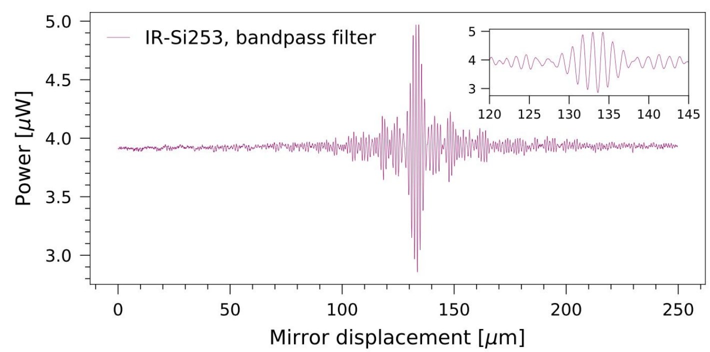
AUGUST
Laser alignment

OCTOBER
Begin measurements

APRIL 2021
Write up
2104.07157 (JINST)





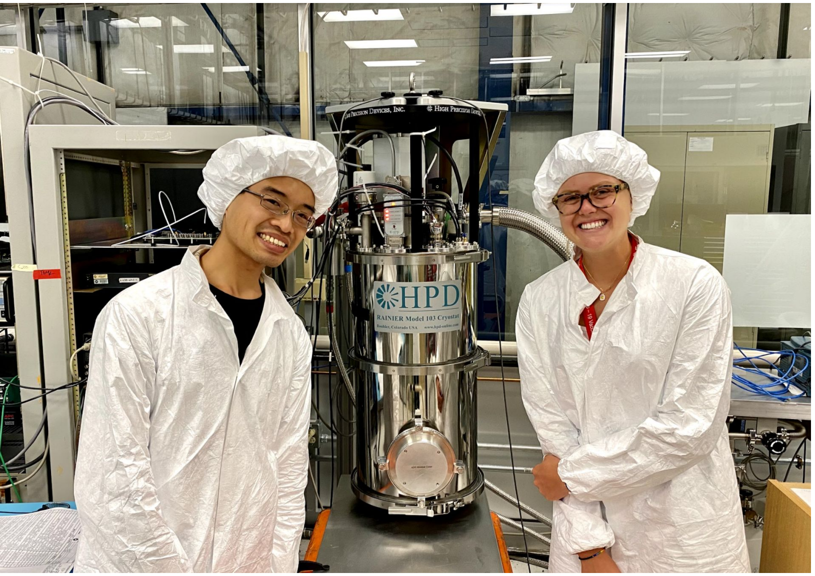


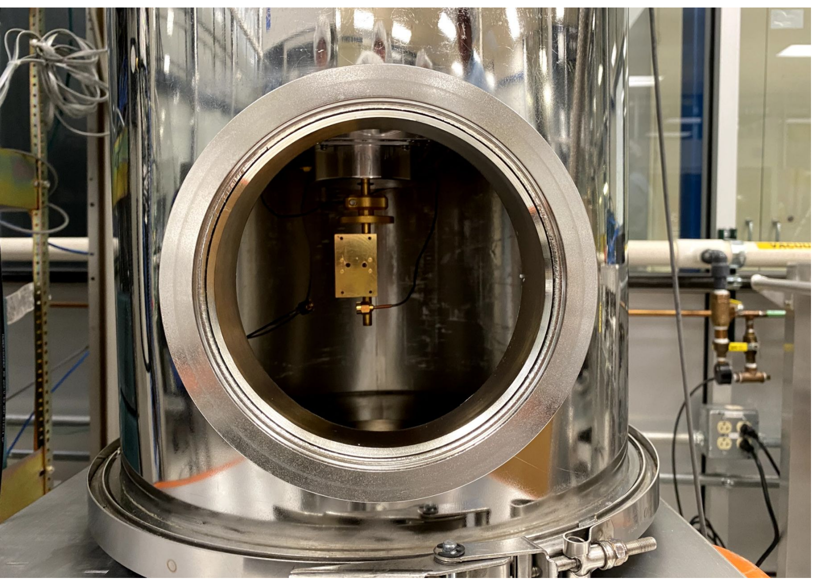
Design and performance of a multi-terahertz Fourier transform spectrometer for axion dark matter experiments

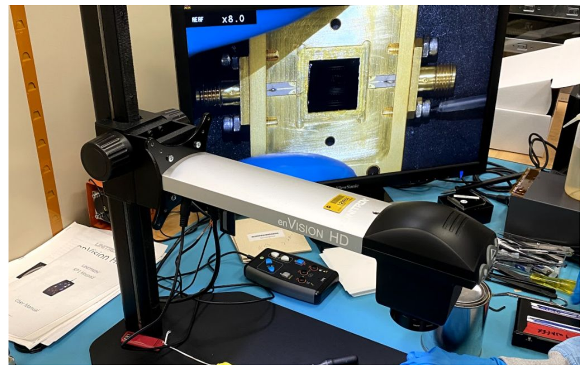
Kristin Dona,[1,*] Jesse Liu,[1,†] Noah Kurinsky,[2,3,‡] David Miller,[1,§]
Pete Barry,[2,4] Clarence Chang,[2,4] and Andrew Sonnenschein[3,¶]
[1] *Department of Physics, University of Chicago, Chicago IL 60637, USA*
[2] *Kavli Institute for Cosmological Physics, University of Chicago, Chicago IL 60637, USA*
[3] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[4] *Argonne National Laboratory, Lemont, IL 60439, USA*

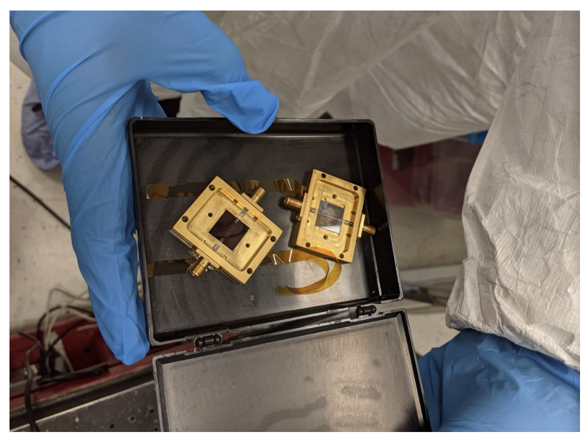
Funded by DOE HEP-QIS QuantISED grant with FNAL and Argonne collaborators

Hands on 2: quantum photosensor testing @ Fermilab







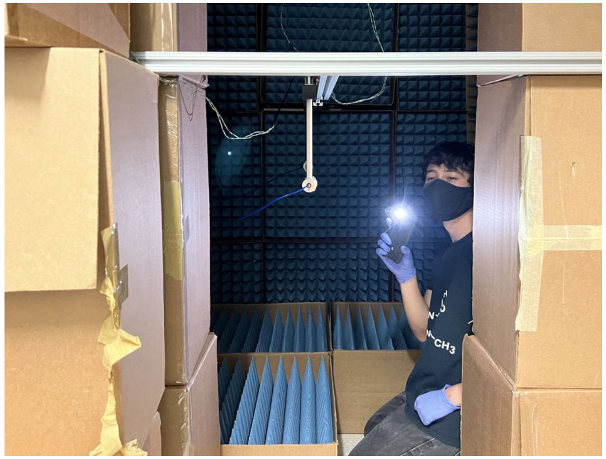


Kester Anyang, Aaron Chou, Kristin Dona, Israel Hernandez, Rakshya Khatiwada, Stefan Knirck, Robert McDermott, David Miller, Max Olberding, Cristián Peña, David Harrison, Andrew Sonnenschein, Christina Wang, Jialin Yu, Tony Zhou, et al

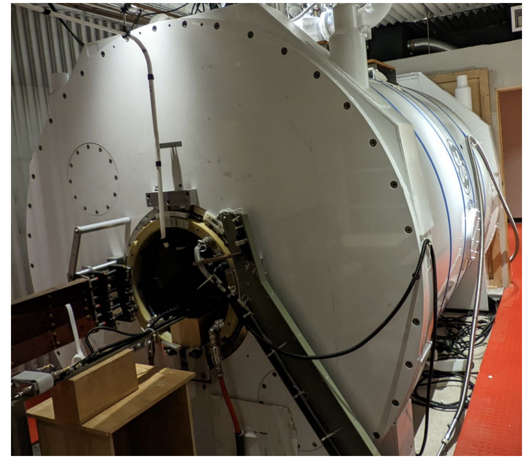
Hands on 3: horn receiver, pilot reflector, magnet scouting

GHz horn receiver

Gabe Hoshino @ Chicago RF isolation room

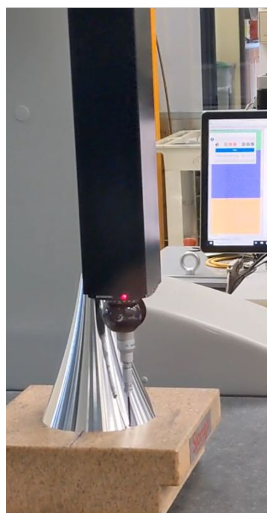


9.4 T MRI magnet @ UIC



BREAD meeting 🍞

Pilot dish antenna & reflector



Touch probe CMM

4 T MRI magnet @ Argonne

1st BREAD Collaboration meeting (Aug 2022)

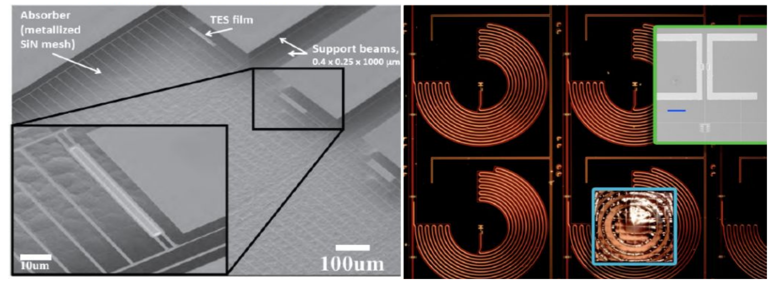
Photos: Stefan Knirck, Andrew Sonnenschein

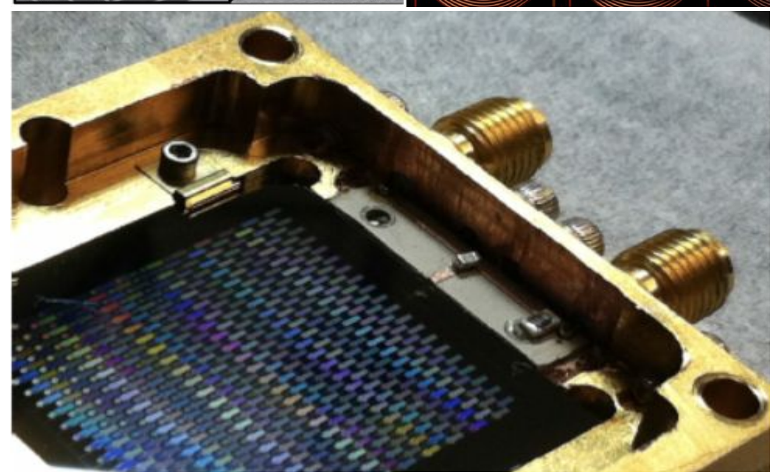
Innovation at interdisciplinary interfaces

ASTRONOMY
Origins of habitability & life

↔ **BREAD** COLLABORATION ↔

QUANTUM TECHNOLOGY
Information & sensing





**"Think *Inside*, Think *Outside* the box.
Make connections to other fields"**
NSF Program Director at Snowmass Oct 2020

"Synergies between particle and astroparticle physics should be strengthened"
European Strategy Update Jun 2020

Images: origins.ipac.caltech.edu
Space-based far-IR mission recommended in US Astro 2020 Decadal Survey

EPILOGUE

Neutron magnetic moment

When nature laughed in our 1930s faces

***Theory*: zero as it's neutral & pointlike**

***Nature*: large *AND* negative haha ($g - 2 = -5.8$)**

Chadwick (1932), Bacher (1933), Tamm & Altshuler (1934), Rabi (1934), Alvarez & Bloch (1940), CODATA (2018)

Completely confounded expectation!

TRANSFORMATIVE

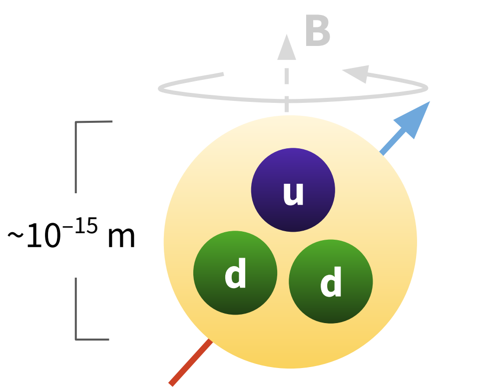
Neutron magnetic moment

When nature laughed in our 1930s faces

Theory: zero as it's neutral & pointlike

Nature: large *AND* negative haha ($g - 2 = -5.8$)

Chadwick (1932), Bacher (1933), Tamm & Altshuler (1934), Rabi (1934), Alvarez & Bloch (1940), CODATA (2018)



NUCLEAR SUBSTRUCTURE

New confining strong force

hopkinsmedicine.org

Today nuclear moments save lives with MRI medical imaging

Nobel prize in Physiology or Medicine 2003

CLIFFHANGER

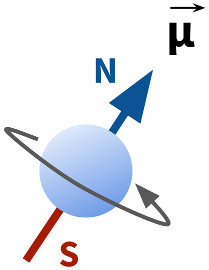
However, solution for neutron MDM **opens new problem with EDM**

MAGNETIC DIPOLE MOMENT (MDM)

Expectation: $g - 2 = 0$ (Dirac theory)

Reality: huge & negative! :O

Solved: new physics → QCD ✔

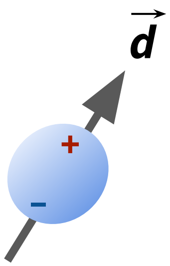


ELECTRIC DIPOLE MOMENT (EDM)

Expectation: large (strong CP violation)

Reality: 0 to 1 part per billion! :O

Solution: new physics → axions…?

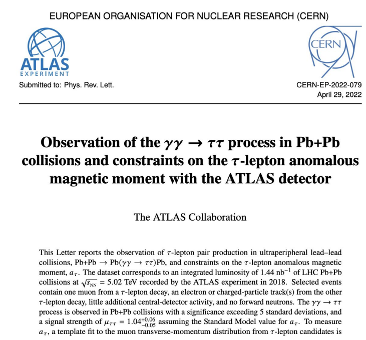


THANK YOU

Colliding light for tau $g - 2$
ATLAS (JL Editor) 2204.13478, Accepted PRL

BREAD: new axion detector
JL, Dona et al PRL 128 (2022) 131801

We must keep looking at Nature in unprecedented ways
Even if – especially if – it completely defies expectation


EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

CERN

Submitted to: Phys. Rev. Lett.

CERN-EP-2022-079
April 29, 2022

Observation of the $\gamma\gamma \to \tau\tau$ process in Pb+Pb collisions and constraints on the τ-lepton anomalous magnetic moment with the ATLAS detector

The ATLAS Collaboration

This Letter reports the observation of τ-lepton pair production in ultraperipheral lead–lead collisions, Pb+Pb $\to$ Pb($\gamma\gamma \to \tau\tau$)Pb, and constraints on the τ-lepton anomalous magnetic moment, a_τ. The dataset corresponds to an integrated luminosity of 1.44 nb^{-1} of LHC Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV recorded by the ATLAS experiment in 2018. Selected events contain one muon from a τ-lepton decay, an electron or charged-particle track(s) from the other τ-lepton decay, little additional central-detector activity, and no forward neutrons. The $\gamma\gamma \to \tau\tau$ process is observed in Pb+Pb collisions with a significance exceeding 5 standard deviations, and a signal strength of $\mu_{\tau\tau} = 1.04^{+0.06}_{-0.05}$ assuming the Standard Model value for a_τ. To measure a_τ, a template fit to the muon transverse-momentum distribution from τ-lepton candidates is