Colliding light, tau $g - 2$, and axion dark matter

University of Sydney
Consortium for Particle Physics and Cosmology Seminar
4 May 2023

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University of Cambridge

TRINITY COLLEGE CAMBRIDGE

UNIVERSITY OF CAMBRIDGE

Today: two pioneering Letters

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

CERN

Submitted to: Phys. Rev. Lett.

CERN-EP-2022-079
November 28, 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

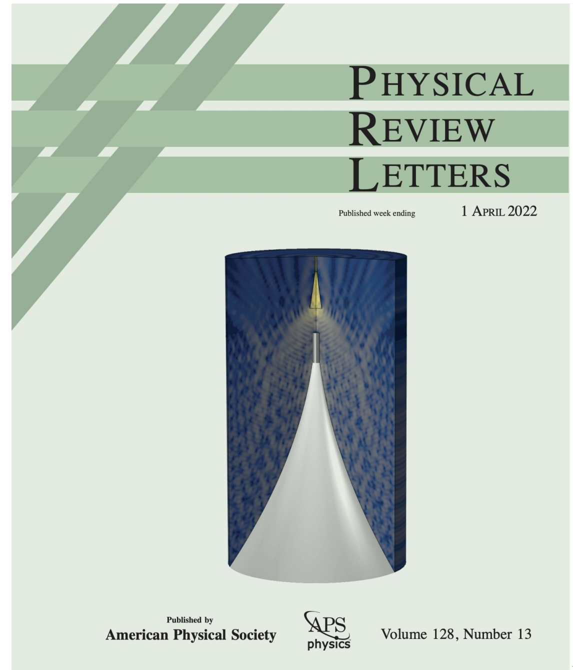
This Letter reports the observation of τ-lepton pair production in ultraperipheral lead–lead collisions, Pb+Pb $\to$ Pb($\gamma\gamma \to \tau\tau$)Pb, and constraints on the τ-lepton anomalous magnetic moment, a_τ. The dataset corresponds to an integrated luminosity of 1.44 nb^{-1} of LHC Pb+Pb collisions 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 $\mu_{\tau\tau} = 1.03^{+0.06}_{-0.05}$ 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 interval for a_τ is $-0.057 < a_\tau < 0.024$.

Colliding light for tau g – 2

Bridge nuclear physics with new physics via precision

ATLAS (JL Editor) 2204.13478

Accepted by PRL, Editors' Suggestion



BREAD: meV axion detector

Bridge astroparticle physics with quantum technology

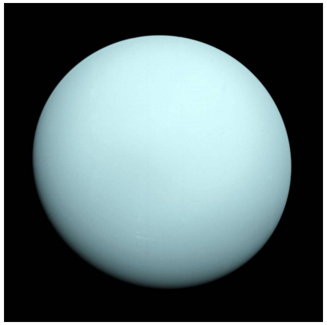
JL, Dona et al 2111.12103

PRL 2022, On the Cover & Editors' Suggestion

PROLOGUE

A TALE OF TRANSFORMATIVE DISCOVERY SCIENCE

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



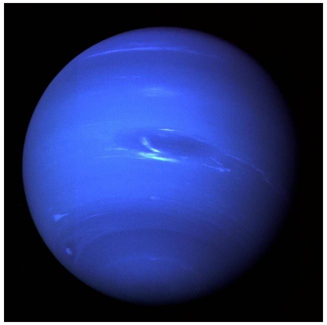
NASA/JPL-Caltech

Uranus

Herschel 1781

Planet never seen before

Measure for 65 years



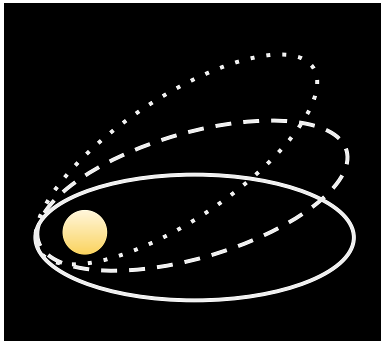
NASA/JPL-Caltech

Neptune

Le Verrier, Galle, d'Arrest 1846

Discover on same night

Within 1° of prediction



Mercury

Le Verrier 1859, Einstein 1915

43 arcseconds/century anomaly

Null search for Planet Vulcan

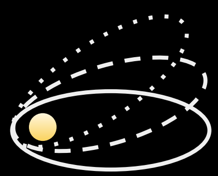
LESSON

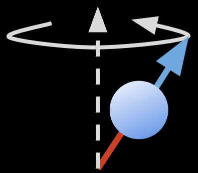
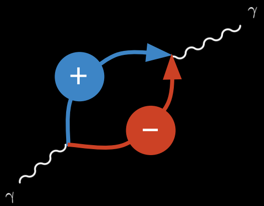
Precision measurements revolutionise science

GR: SPACETIME IS DYNAMICAL

Discover new planets: unchanged physical laws

But planet known since antiquity transformative



QFT: VACUUM IS DYNAMICAL

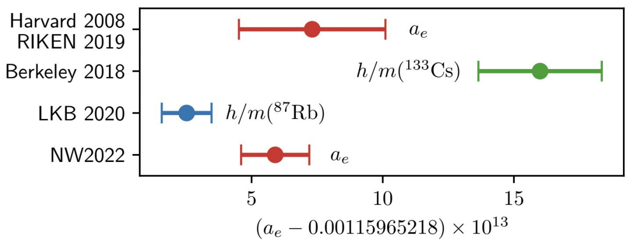
Per mille precession of electron: no new particles

But groundbreaking evidence of quantum loops

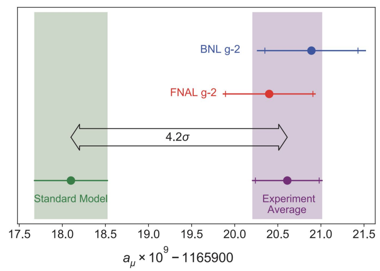
The ordinary harboured extraordinary surprises

Persistent widespread indirect evidence for new physics

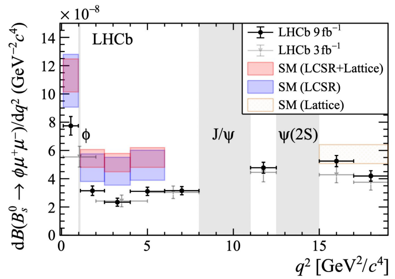
Electron *g* – 2 (2.5σ)
[PRL 2023, FIPs2022, Science 2018]



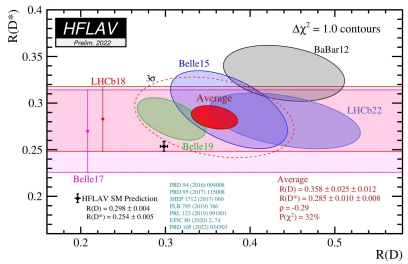
Muon *g* – 2 (4.2σ)
[PRL 2021, Phys Rept 2020]



$B_s \to \phi\mu\mu$ (3.6σ)
[PRL 2021]



$B \to D\tau\nu$ (3.2σ)
[HFLAV 2022]

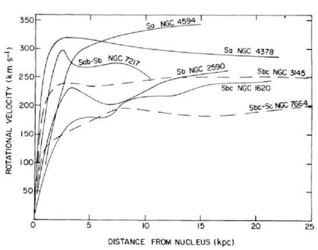


LEPTON ANOMALIES ↑

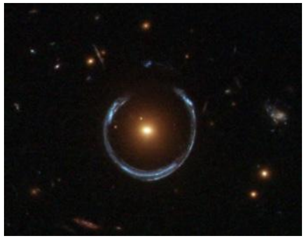
Several laboratories across all flavours
New particles via quantum fluctuations

↓ *DARK MATTER*

Sub-galactic to cosmological scales
New particles via gravitational force

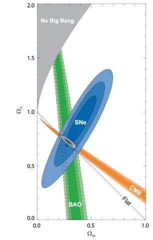


Galaxy rotation
[ApJ 1978]

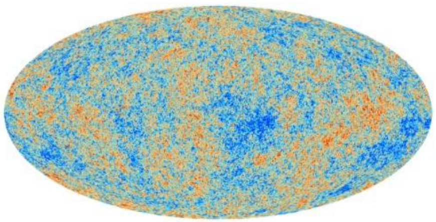


Lensing
[ESA/Hubble & NASA]

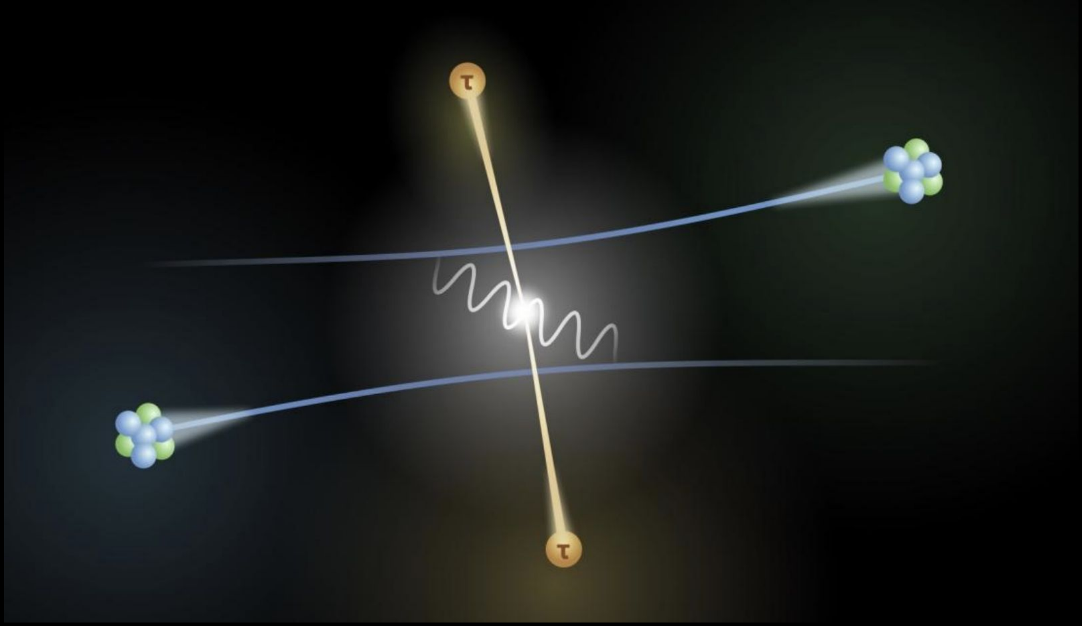
Bullet cluster
[NASA/CXC/CfA/STScI/ESO WFI]



BAO
[ApJ 2008]



Cosmic microwave bkg
[ESA/Planck]



OUTLINE

PART 1

Colliding light for tau $g - 2$

PART 2

BREAD axion detector R&D

April 2021: *g* – 2 recaptures international attention

The New York Times

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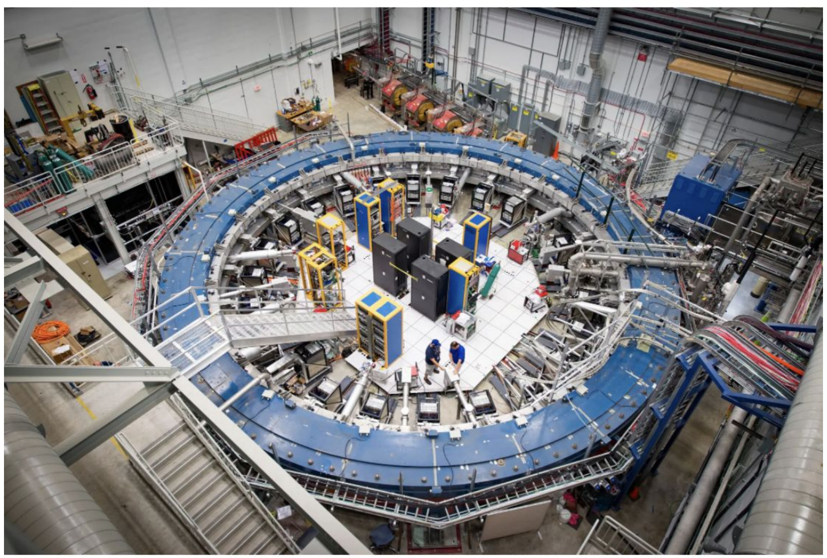
OUT THERE

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

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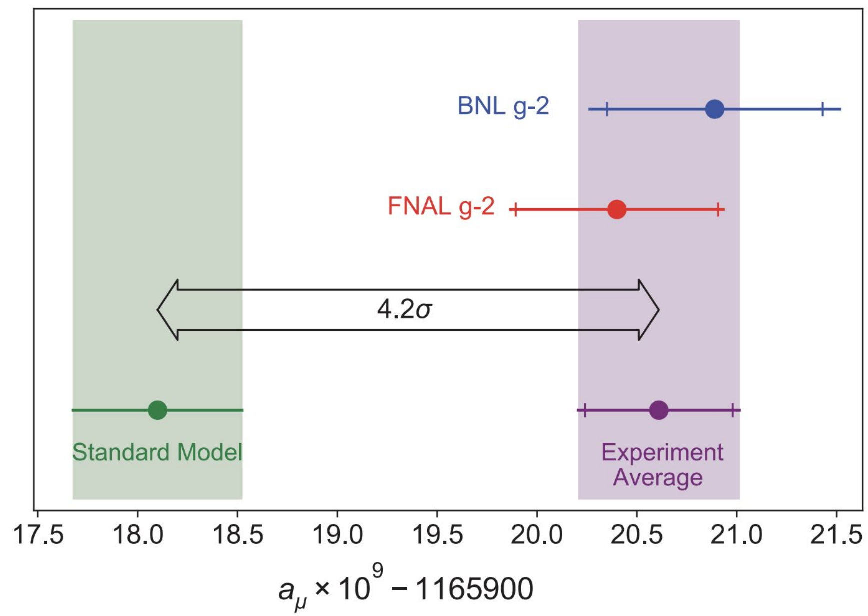
NEWS | 07 April 2021

Is the standard model broken? Physicists cheer major muon result

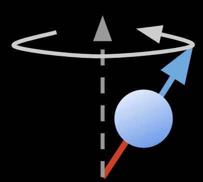
The muon's magnetic moment is larger than expected — a hint that new elementary particles are waiting to be discovered.

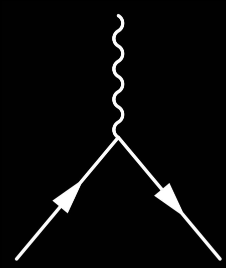


Muon *g*–2 Experiment [PRL 2021]

g – 2: foundational test of QFT

"How does light interact with matter?"





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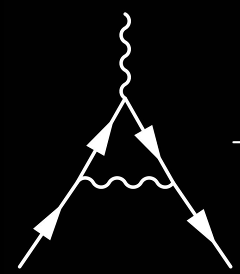

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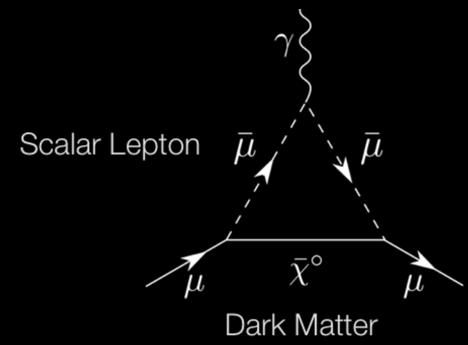


$$g = 2 + \frac{\alpha}{\pi}$$

Dirac (1928) **Schwinger (1948)** **New particles?**

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

Electron & muon magnetic moments

Extraordinary precision: scientific triumph!

Electron g – 2: known to 13 decimal places

Fan et al [PRL 2023], Morel et al [Nature 2022], Parker et al [Science 2018]

$$a_e \text{ (exp)} = 0.001\,159\,652\,180\,59(13)$$

$$a_e \text{ (pred)} = 0.001\,159\,652\,181\,61(23)$$

$$a_\mu \text{ (exp)} = 0.001\,165\,920\,61(41)$$

$$a_\mu \text{ (pred)} = 0.001\,165\,918\,10(43)$$

Muon g – 2: known to 10 decimal places

FNAL Muon *g*–2 [PRL 2021], Muon *g*–2 theory [Phys Rept 2020], Lattice *g*–2 [Nature 2021]

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

What about tau g – 2?

SHOCKING EXPERIMENTAL IGNORANCE!

Pressing problem: PDG value from 2004

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

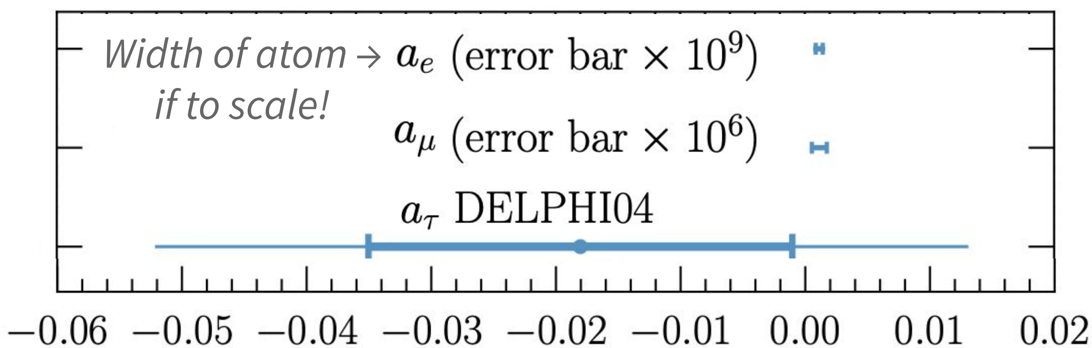
$$a_{\tau,\,\text{SM}}^{\text{pred}} = 0.001\,177\,21\,(5)$$

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

Not even testing 70 year old 1-loop QED

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

Schwinger [1948]



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

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

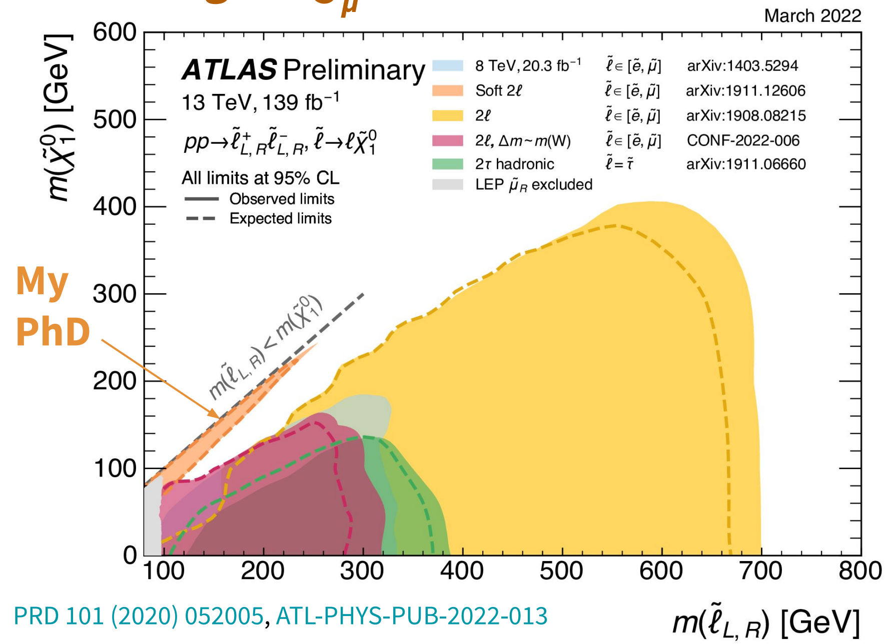
to new physics

than muon *g* – 2

No shortage of e & μ *g* – 2 model building

Martin, Wells [hep-ph/0103067]; Czarnecki, Marciano [hep-ph/0102122]; Pospelov [0811.1030]; Cahill-Rowley et al [1407.4130]; Ajaib et al [1505.05896]; Allanach et al [1511.07447]; Han et al [1511.05162]; Batell et al [1606.04943]; Di Chiara et al [1704.06200]; Poh, Raby [1705.07007]; Li et al [1808.02424]; Liu et al [1810.11028]; Dutta, Mimura [1811.10209]; Mohlabeng [1902.05075]; Endo, Wen [1906.08768]; Bauer et al [1908.00008]…

No shortage of g_μ – 2 motivated searches



PRD 101 (2020) 052005, ATL-PHYS-PUB-2022-013

Tau *g* – 2: no consensus how to progress

Future electron–positron colliders (Belle-II/CLIC/ILC/FCC-ee)

Eidelman et al [1601.07987], Chen, Wu [1803.00501], Köksal et al [1804.02373] Howard et al [1810.09570]; Köksal [2104.01003], Crivellin et al [2111.10378]

Future electron–proton colliders (LHeC/FCC-eh)

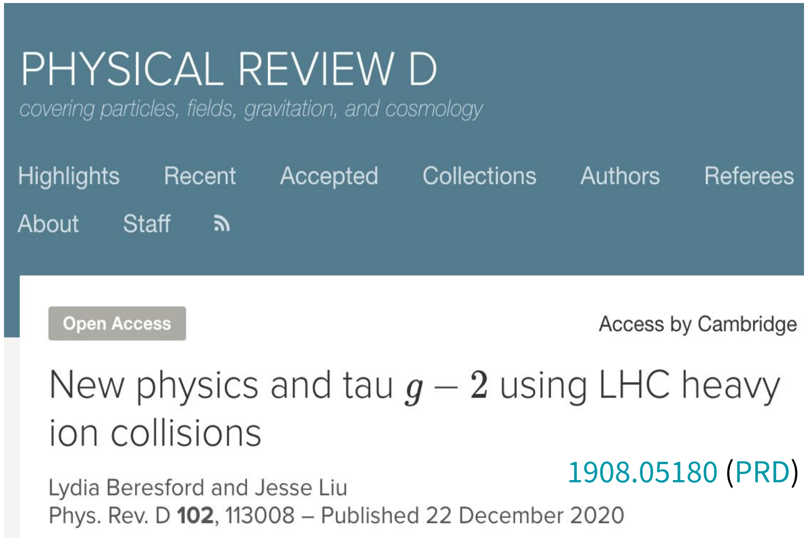
Köksal [1809.01963]; Gutiérrez-Rodríguez et al [1903.04135]

Proposed proton fixed target & bent crystals

Fomin et al [1810.06699]; Fu et al [1901.04003]

THINK DIFFERENT

Invent new heavy-ion strategy


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

1908.05180 (PRD)

Creative theory paper overcame status quo

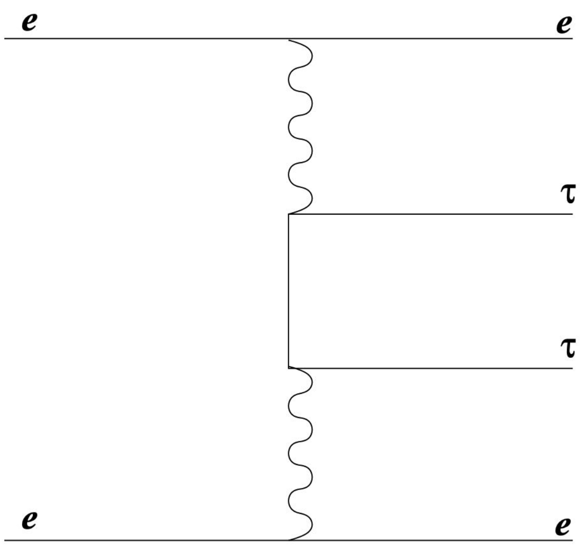
Tau g – 2 measurable without lepton collider

Heavy ions interesting for BSM via precision

Lydia Beresford → now DESY Staff funded by €1.5m Helmholtz Young Investigator Grant
Leading group with Savannah Clawson (DESY Fellow) & Weronika Stanek (PhD student)

How can we see γγ → $\tau\tau$ at hadron colliders?

Best constraint of tau *g* – 2



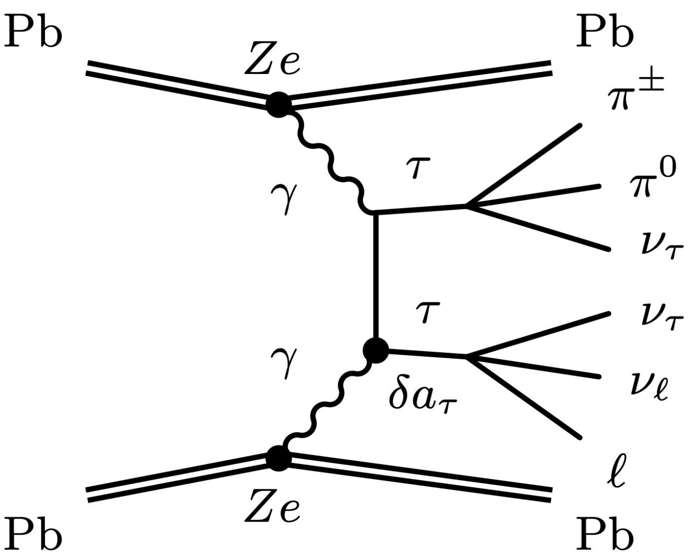
Large Electron Positron collider

σ ~ 400 pb

⇒ 200 000 events all years

DELPHI [EPJC 35 (2004) 159]
Also L3 [PLB 1997)], OPAL [ZPC 1993]

Proceed analogously @ LHC?



Not even observed at hadron collider

σ ~ Z^4 ~ 500 000 nb (Z_{Pb} = 82)

⇒ 1 million events per month

Beresford & JL [1908.05180]
Also de Aguila et al [PLB 1991], Dyndal et al [2002.05503]

🥳 Now: CMS & ATLAS breakthroughs realize our idea 🎉

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

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

CMS-HIN-21-009

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 ultraperipheral 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

CMS 2206.05192

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Phys. Rev. Lett.

CERN-EP-2022-079
November 28, 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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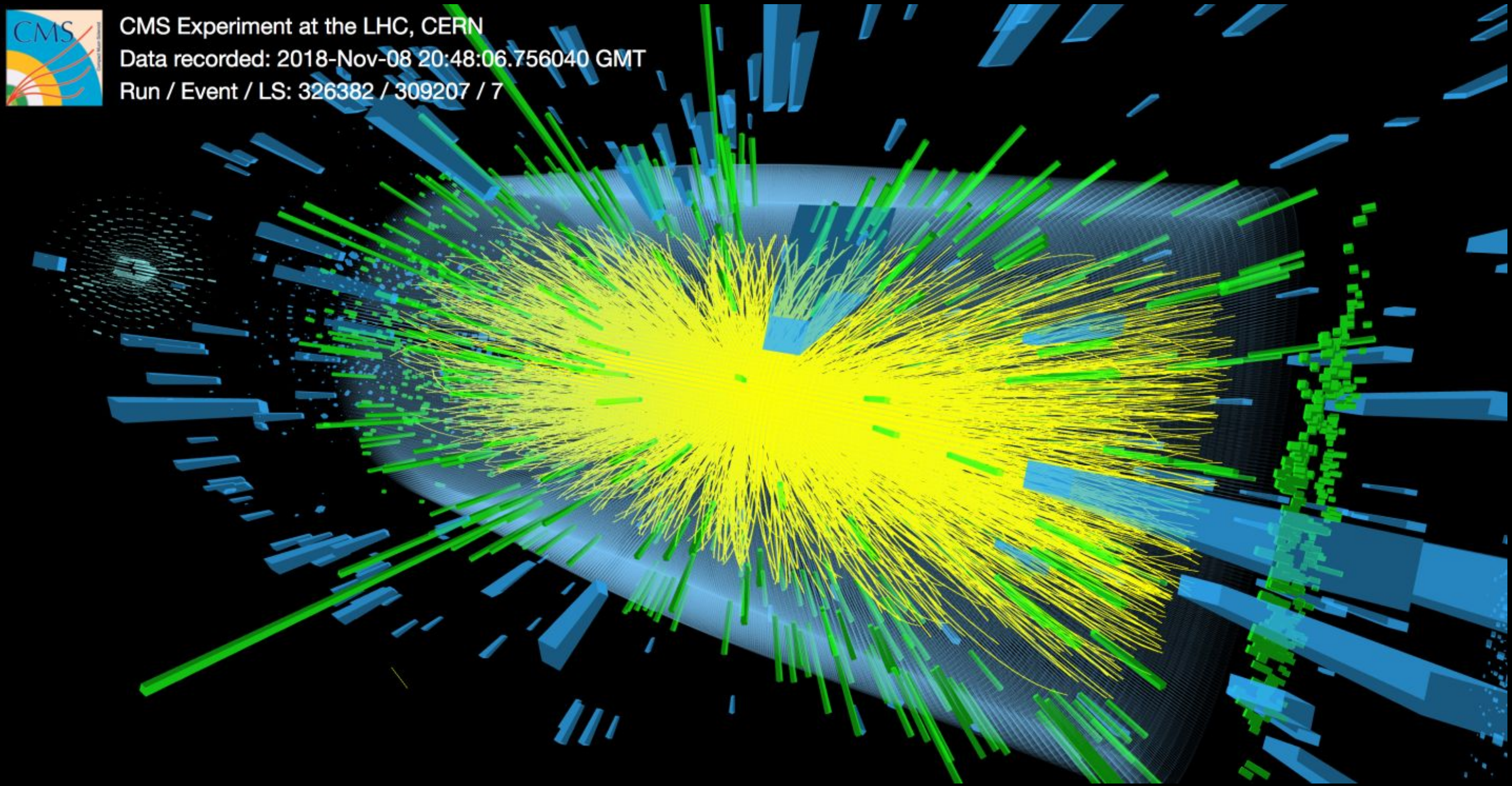
This Letter reports the observation of τ-lepton pair production in ultraperipheral lead–lead collisions, Pb+Pb $\to$ Pb($\gamma\gamma \to \tau\tau$)Pb, and constraints on the τ-lepton anomalous magnetic moment, a_τ. The dataset corresponds to an integrated luminosity of 1.44 nb^{-1} of LHC Pb+Pb collisions 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 $\mu_{\tau\tau} = 1.03^{+0.06}_{-0.05}$ 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 interval for a_τ is $-0.057 < a_\tau < 0.024$.

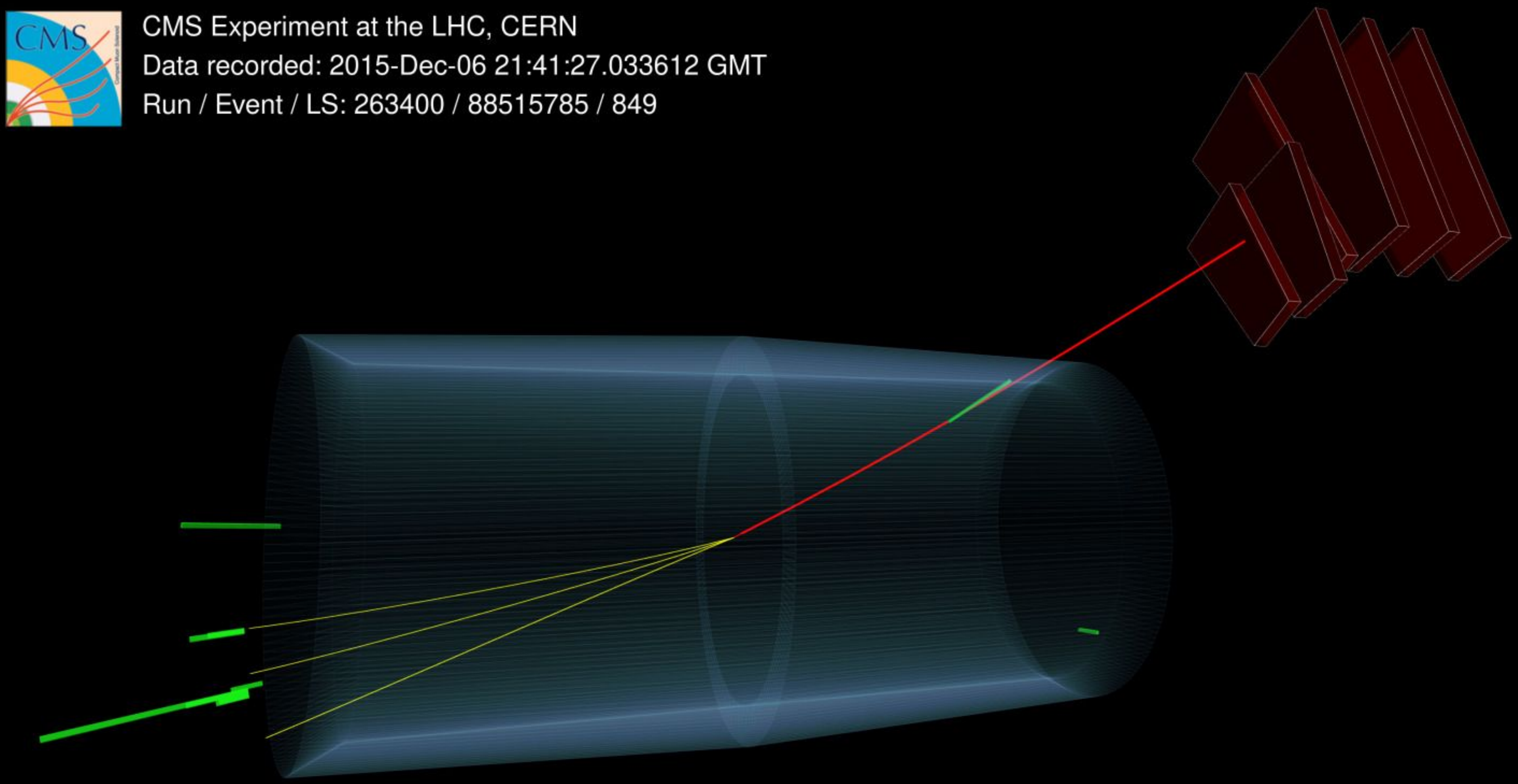
ATLAS (JL Editor) 2204.13478
Accepted by PRL, Editors' Suggestion

Heavy-ion collisions: what usually comes to mind



CMS [PHO-EVENTS-2018-009]

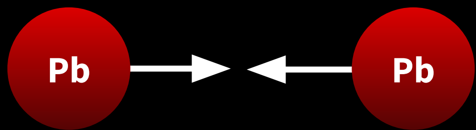
Heavy-ion collisions: breathtakingly clean

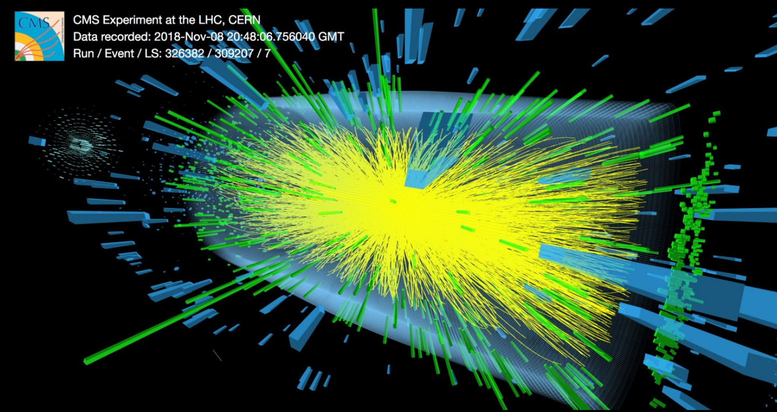


[CMS News Briefing]

Colliding light at LHC

Head-on collisions

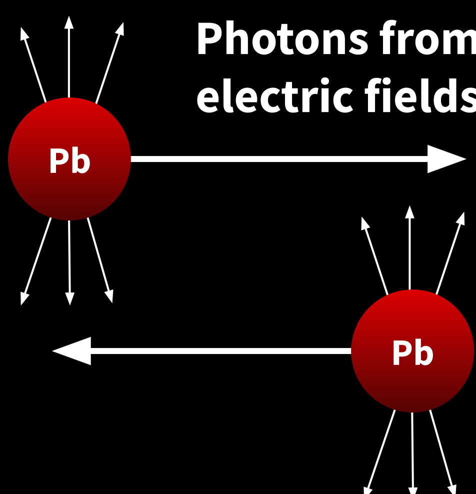


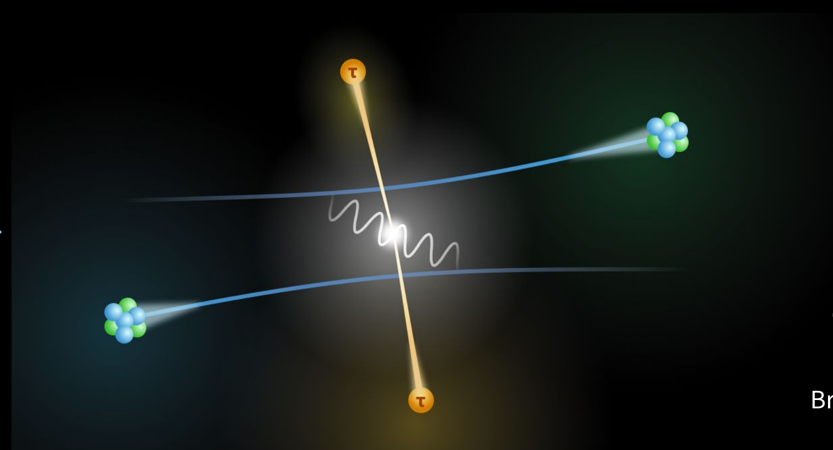


Quark gluon plasma

Busza et al review [1802.04801]

Photons from electric fields

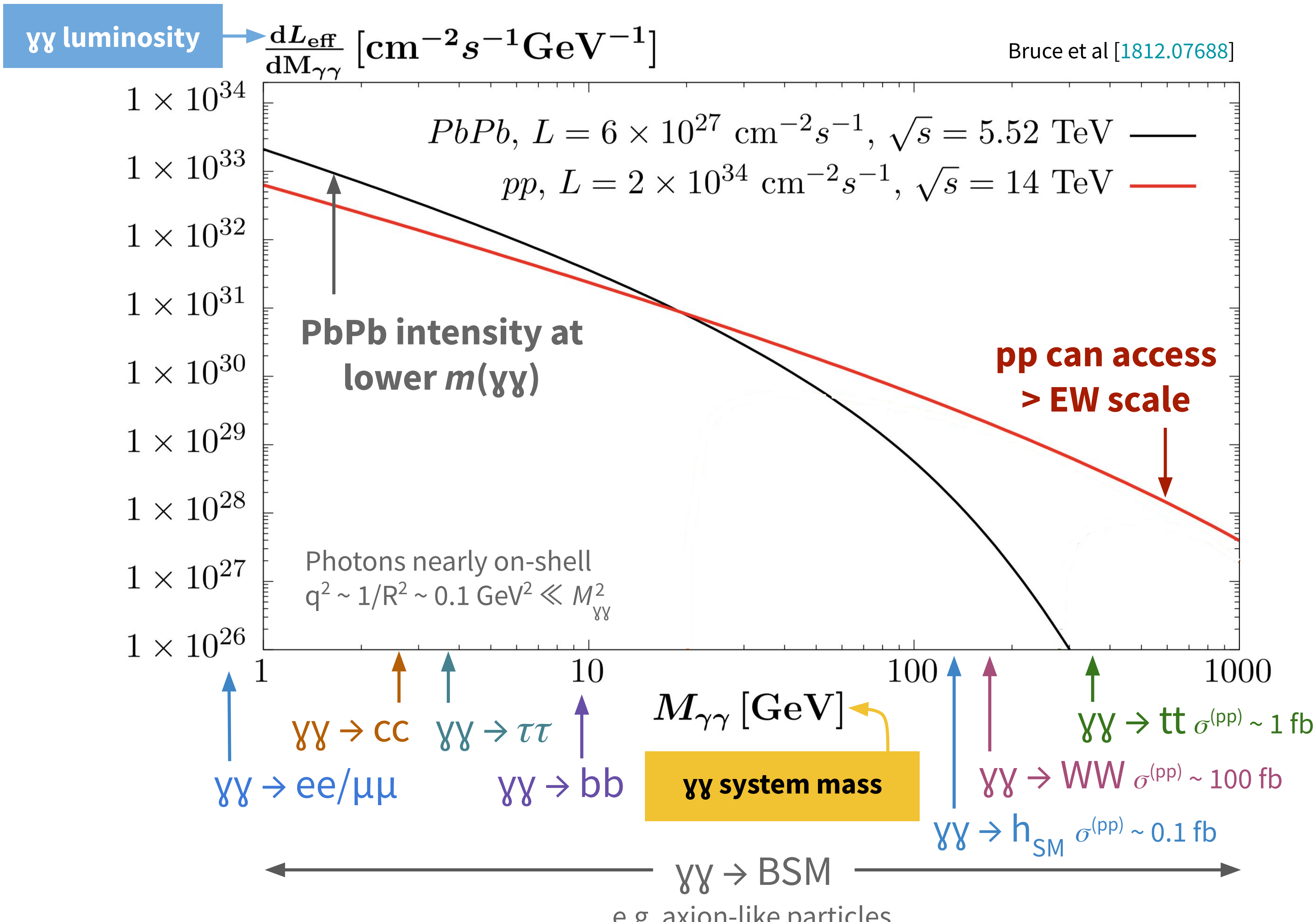




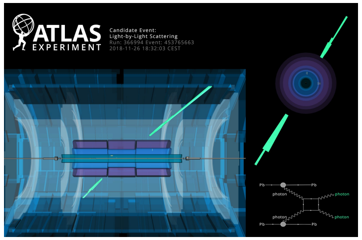
LHC as photon collider

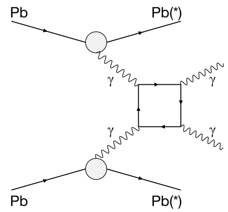
Bruce et al review [1812.07688]

LHC is a broadband γγ collider



Recent breakthroughs open rich science program

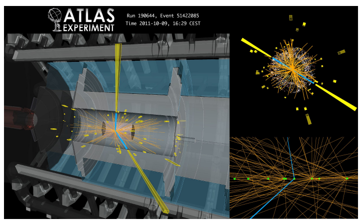


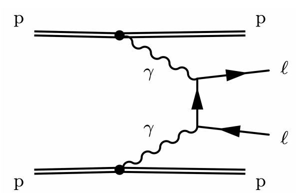


Observation of light-by-light scattering in ultraperipheral Pb+Pb collisions with the ATLAS detector

Probe photon self-coupling & axion-like particles

PRL 123 (2019) 052001

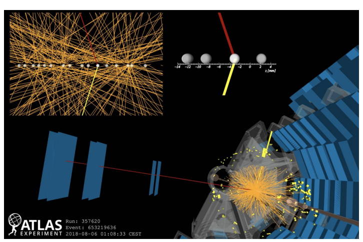


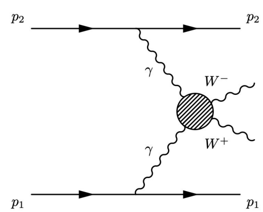


Observation and measurement of forward proton scattering in association with lepton pairs produced via the photon fusion mechanism at ATLAS

Pioneer forward proton scattering at weak scale

PRL 125 (2020) 261801 (JL Editor)

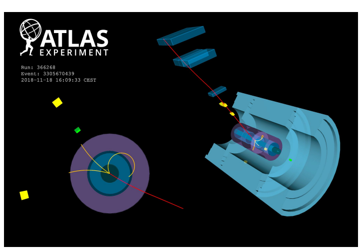


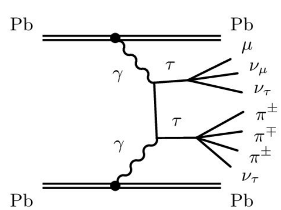


Observation of photon-induced W^+W^- production in pp collisions at $\sqrt{s}$ = 13 TeV using the ATLAS detector

Create electroweak mass states via photon fusion

PLB 816 (2021) 136190





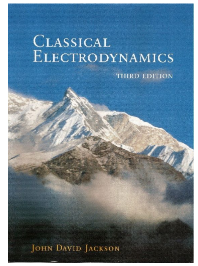
Observation of the $\gamma\gamma \to \tau\tau$ process in Pb+Pb collisions and constraints on the τ-lepton anomalous magnetic moment with the ATLAS detector

First tau $g - 2$ measurement in 2 decades

2204.13478, Accepted PRL (JL Editor)

Theory: how to calculate γγ → ττ cross-sections

Beresford & JL [1908.05180]



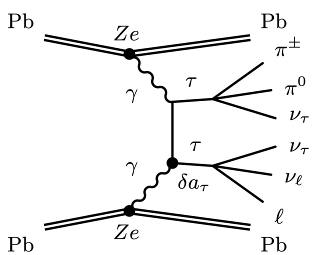
Classical field theory of relativistic charge

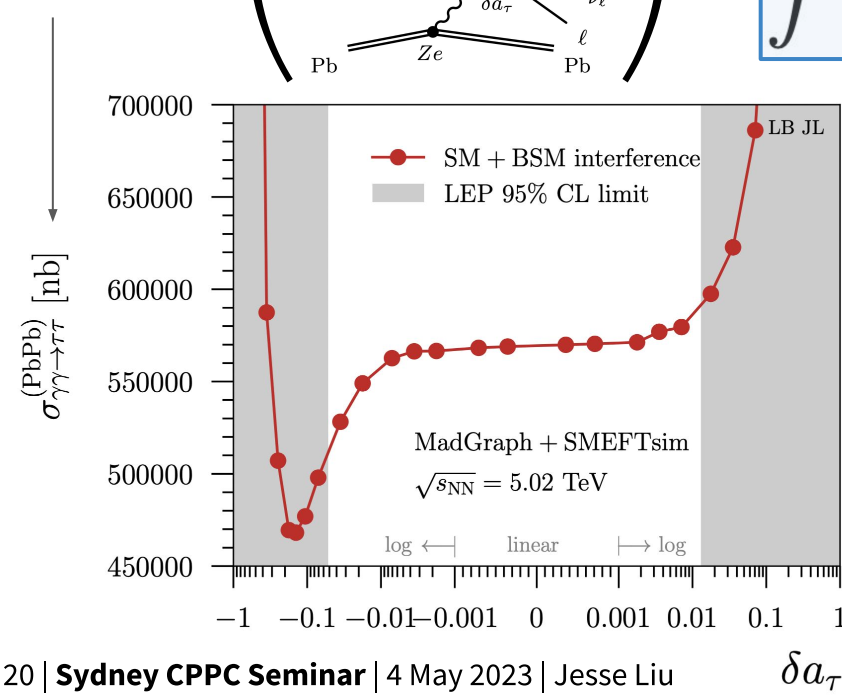
Add Jackson §15.4 into MadGraph 2.6.5 Fortran software

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

Monte Carlo | **Photon flux** | **Quantum process**

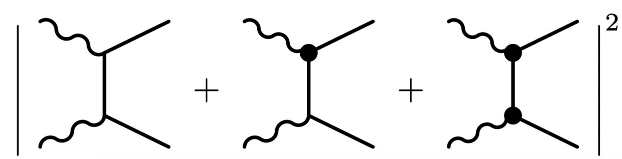
$$\sigma^{(\mathrm{PbPb})}_{\gamma\gamma\to XX}\left(\quad \right) = \int \mathrm{d}x_1 \mathrm{d}x_2 \, n(x_1) n(x_2) \, \sigma_{\gamma\gamma\to XX}$$





Vary a_τ using effective field theory

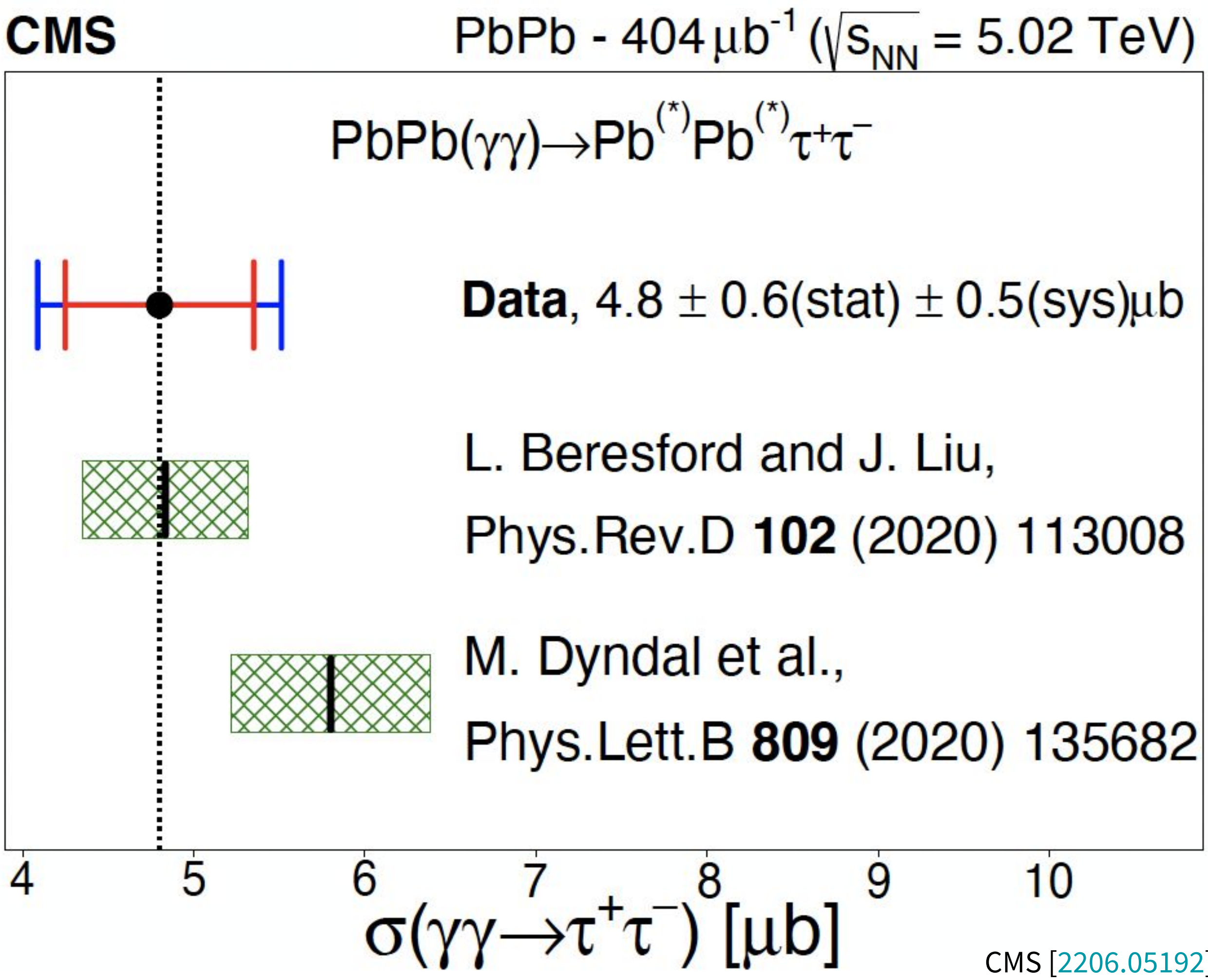
SMEFT: Grzadkowski et al [1008.4884]; Brivio, Jiang, Trott [1709.06492]



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

Complex C ⇒ non-zero CP-violating electric dipole moment δd_τ

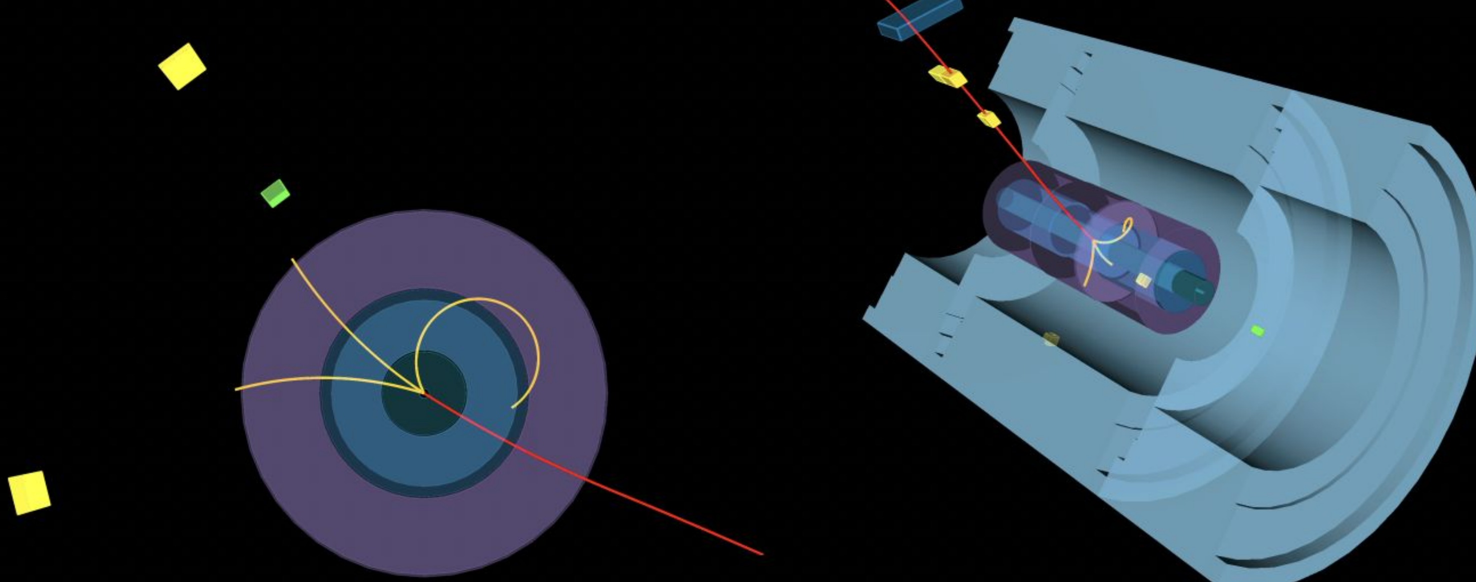
First PbPb → Pb(γγ → $\tau\tau$)Pb measurement

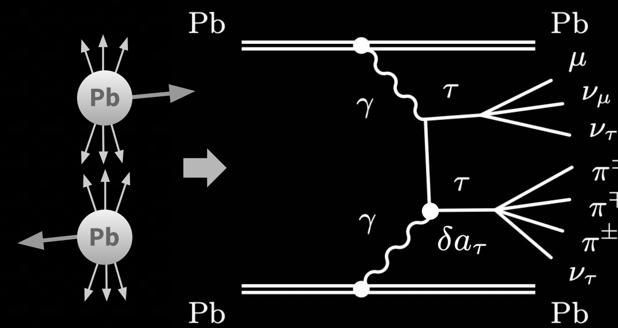


CMS [2206.05192]

Remarkable result using 2015 data 🤩 …and just getting started!

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

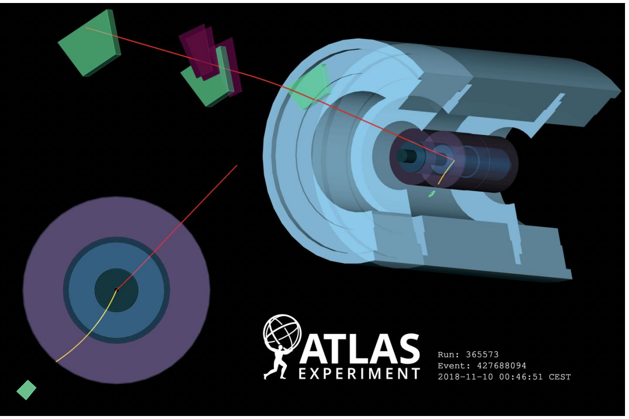


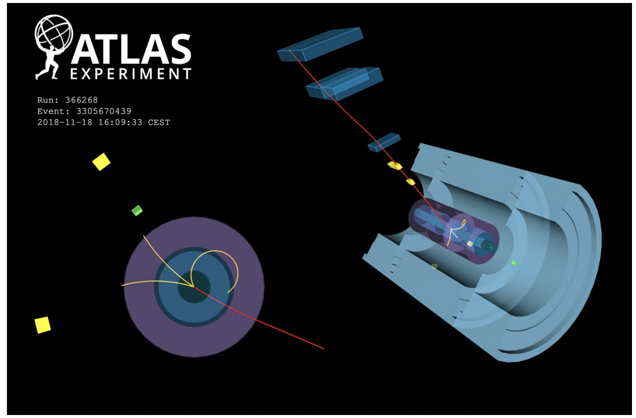


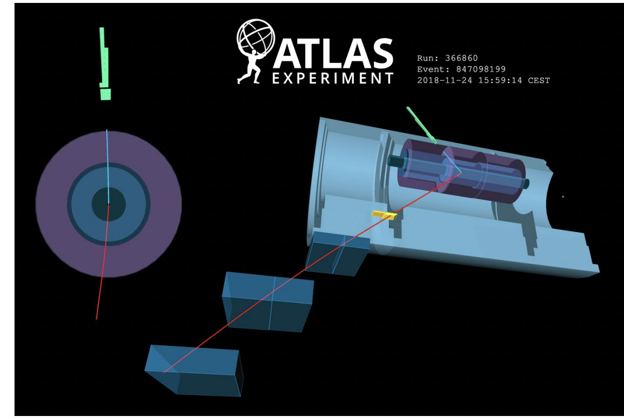
↑ *All charged-particle tracks above 100 MeV are shown*

1 month to double dataset | 10^4 smaller pileup vs pp | $p_T(\mu)$ > 4 GeV trigger

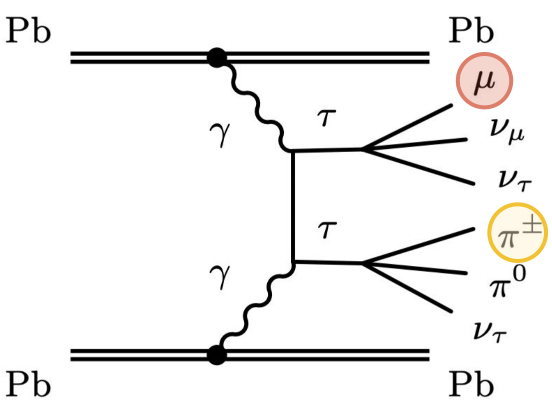
ATLAS analyzes 2018 data in our 3 proposed channels







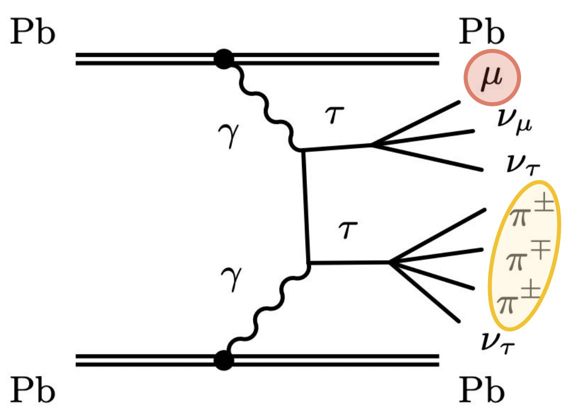
1 muon + 1 track (μ1T-SR)



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

S/B = 5.3

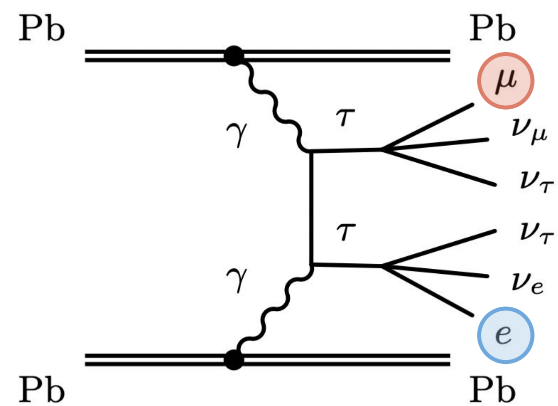
1 muon + 3 tracks (μ3T-SR)



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

S/B = 7.5

1 muon + 1 electron (μe-SR)

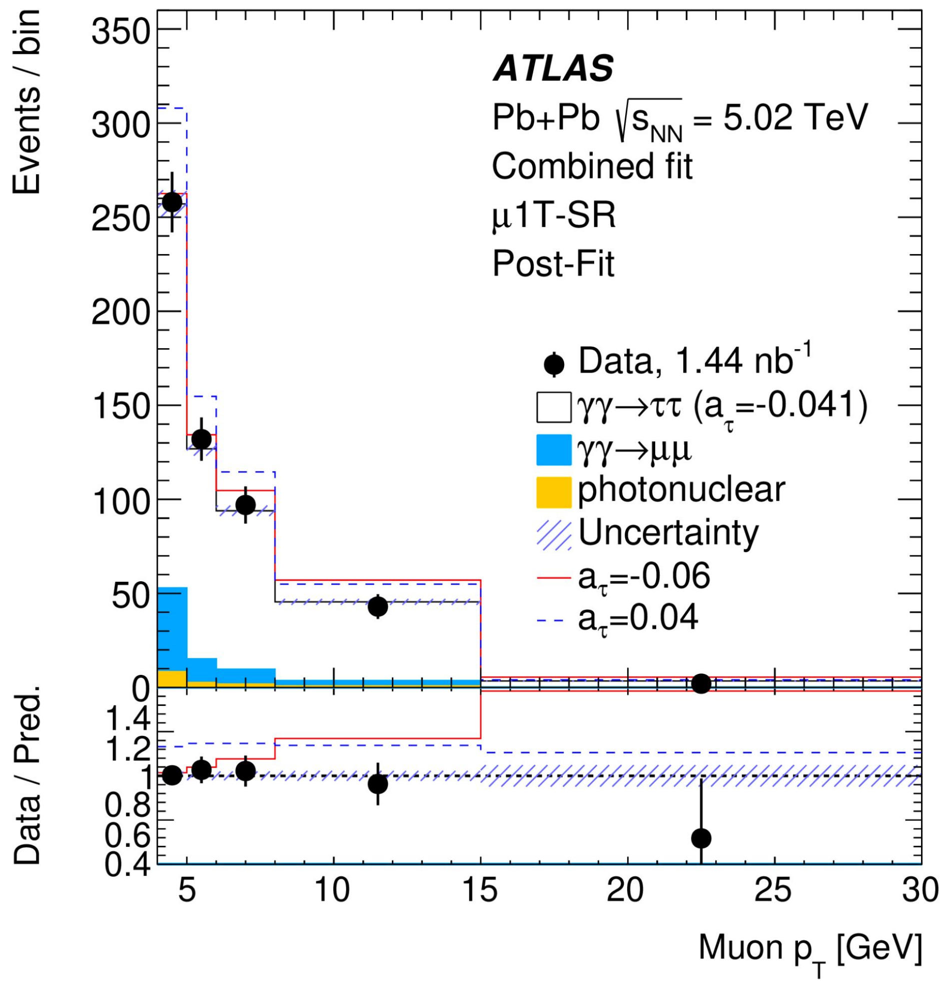


$N_{obs} = 39$, $N_{bkg} = 2.8 \pm 0.7$

S/B = 13

ATLAS (JL Editor) 2204.13478, Accepted PRL

Identify muons down to 4 GeV detectability threshold



Muons lose ~3 GeV of energy before reaching muon chambers

Use μμ events to control photon flux theory modelling systematics

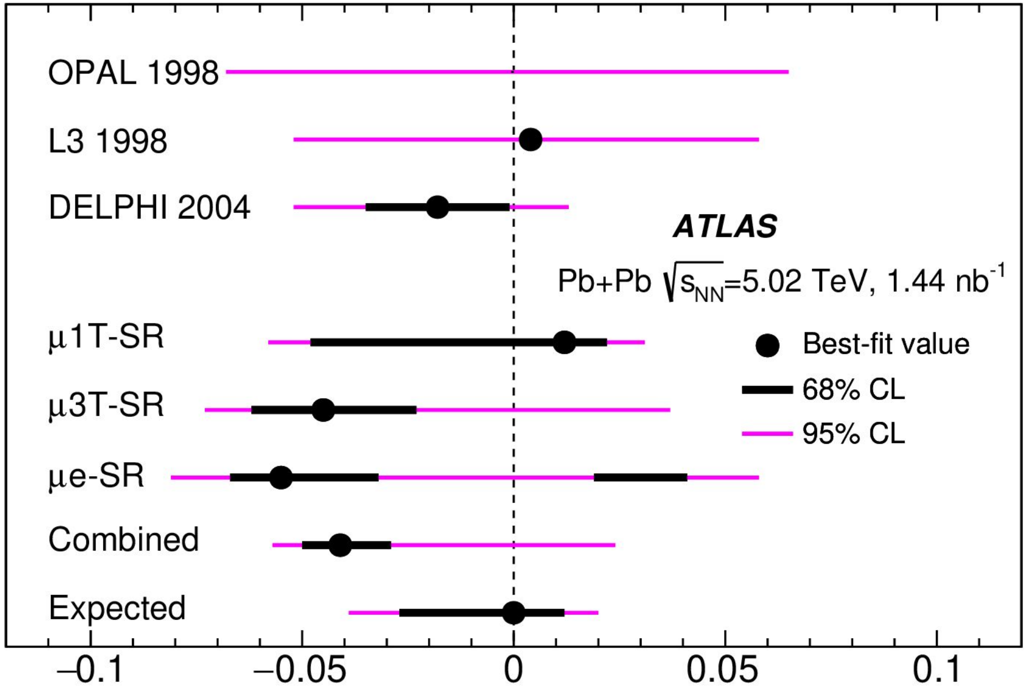
ATLAS (JL Editor) 2204.13478, Accepted PRL

Groundbreaking results competitive with LEP

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

First time taus analyzed in heavy ion collisions

Heavy ions enabled 5% measurement of QED g_τ



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

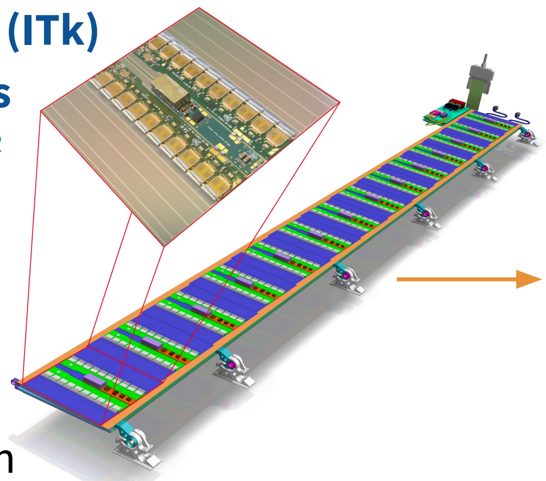
ATLAS (JL Editor) 2204.13478, Accepted PRL

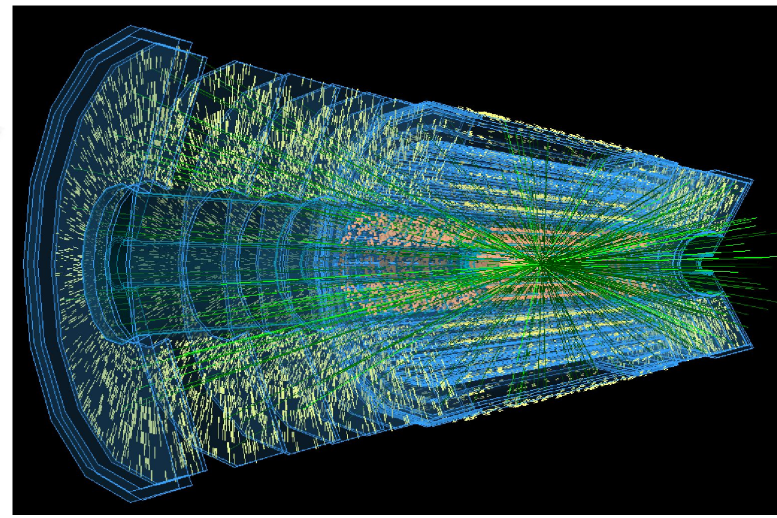
High-Luminosity LHC: 20x data over 20 years

New silicon cameras: ultra-granular images probing microcosm

ATLAS Inner Tracker (ITk) silicon strips sensors

ATLAS ITk Simulation, ITk Strips TDR





Today → Upgrade

60 m^2 → 165 m^2 silicon

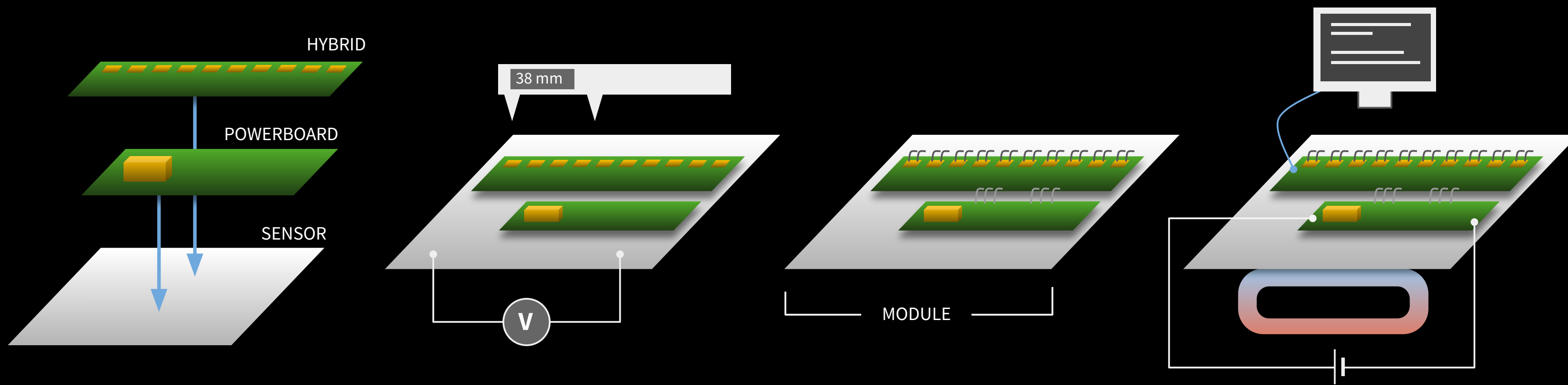
6 million → 60 million readout channels

Prototyping → **Pre-production** → **Production** → **Integration**

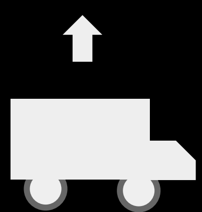
Today's undergrads become postdocs

[lhc-commissioning.web.cern.ch]

ITk Strips barrel module production



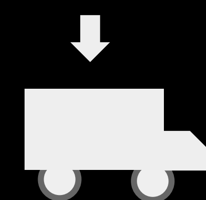
Glue boards ➡ **Metrology** ➡ **Wire bond** ➡ **Test & thermal cycle**



Receive parts

Sensors: Hamamatsu
Hybrids: Birmingham
Powerboards: Berkeley

Cambridge deliverables
Test 3000 sensors
Build 1000 modules
+ 10% yield



Ship Modules → RAL

2 × 14 modules per stave
11k modules on 392 staves

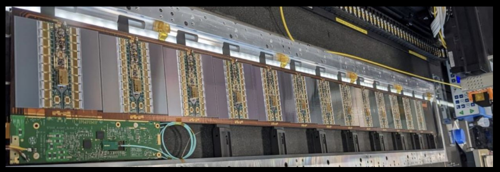
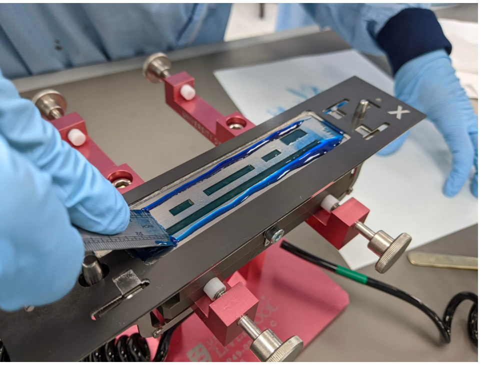


Photo: STFC

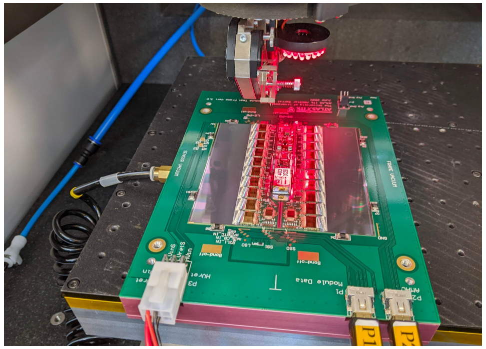
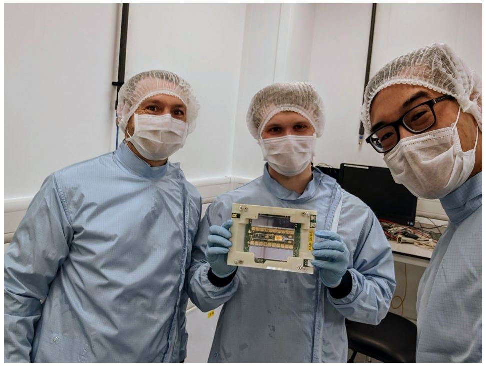
Build next-gen ATLAS silicon camera at Cambridge 🧑‍🔬

GLUE

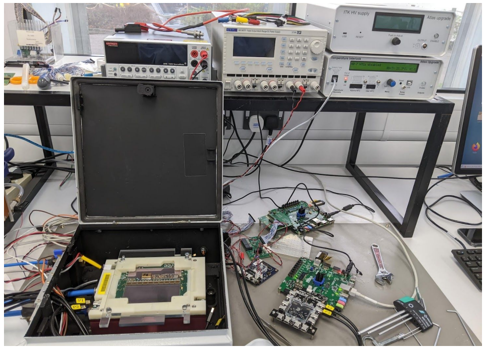




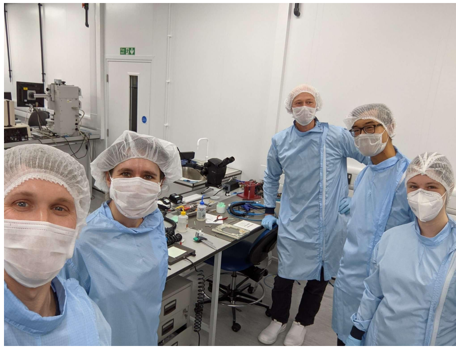
WIRE BOND

TEST & PACKAGE



GROUP PICS



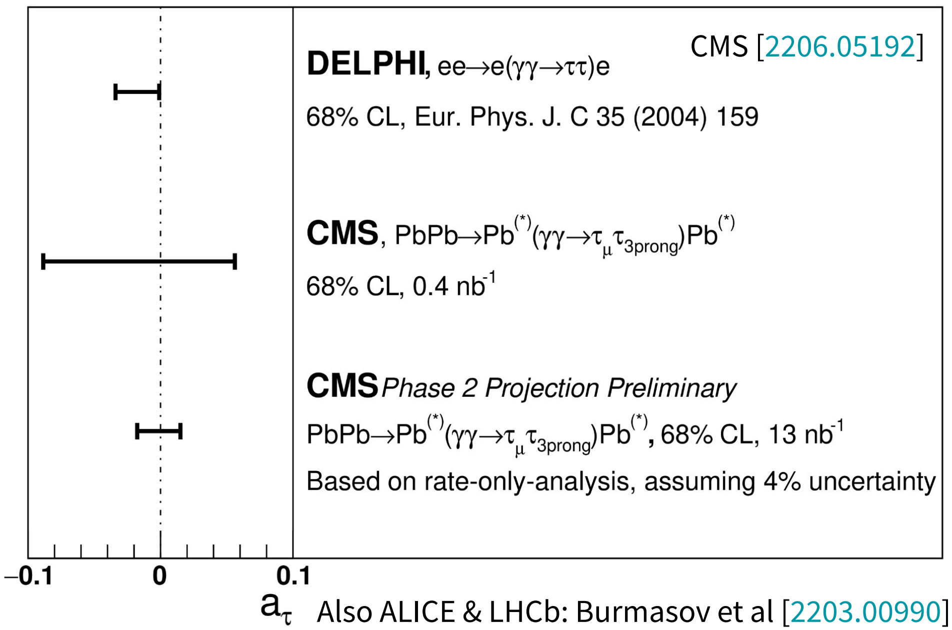
Featuring staff: Bart Hommels, Will Fawcett, Val Gibson, Kosala Kariyapperuma, JL, Sarah Williams;
PhD student: Anna Mullin; Visitors: Alan Barr (Oxford), Lydia Beresford (DESY)

Every innovation strengthens HL-LHC science

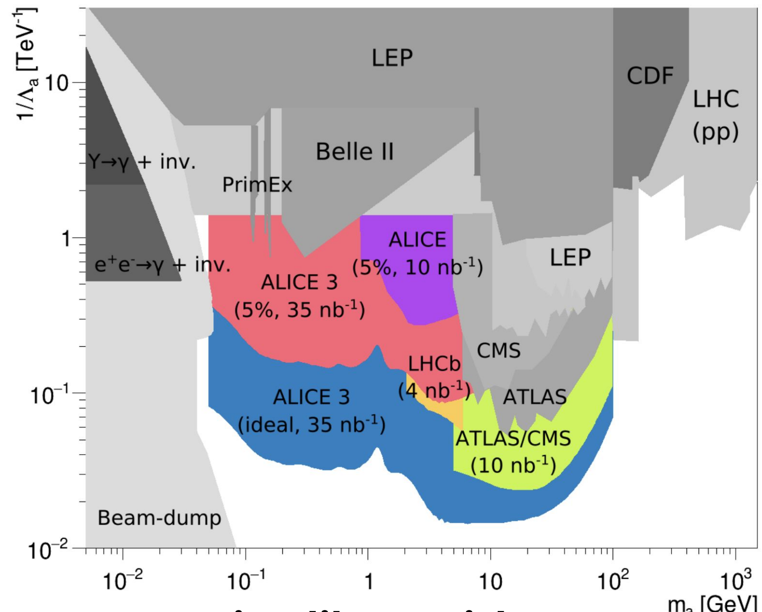
Snowmass 2021 whitepaper: d'Enterria et al [2203.05939]

Opportunities for new physics searches with heavy ions at colliders

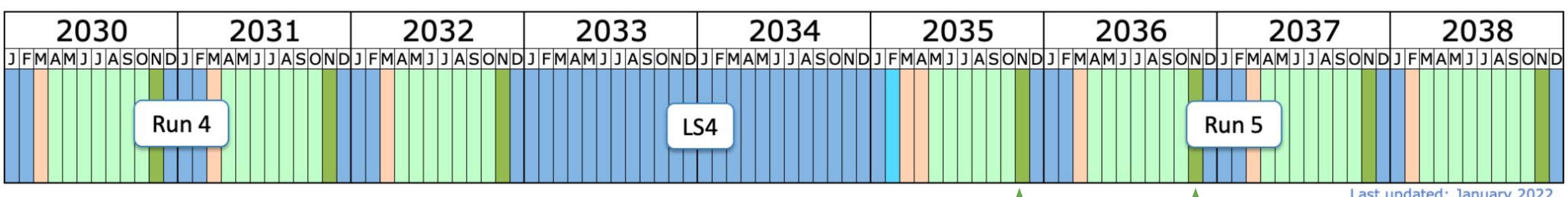
David d'Enterria, Marco Drewes, Andrea Giammanco, Jan Hajer, Elena Bratkovskaya, Roderik Bruce, Nazar



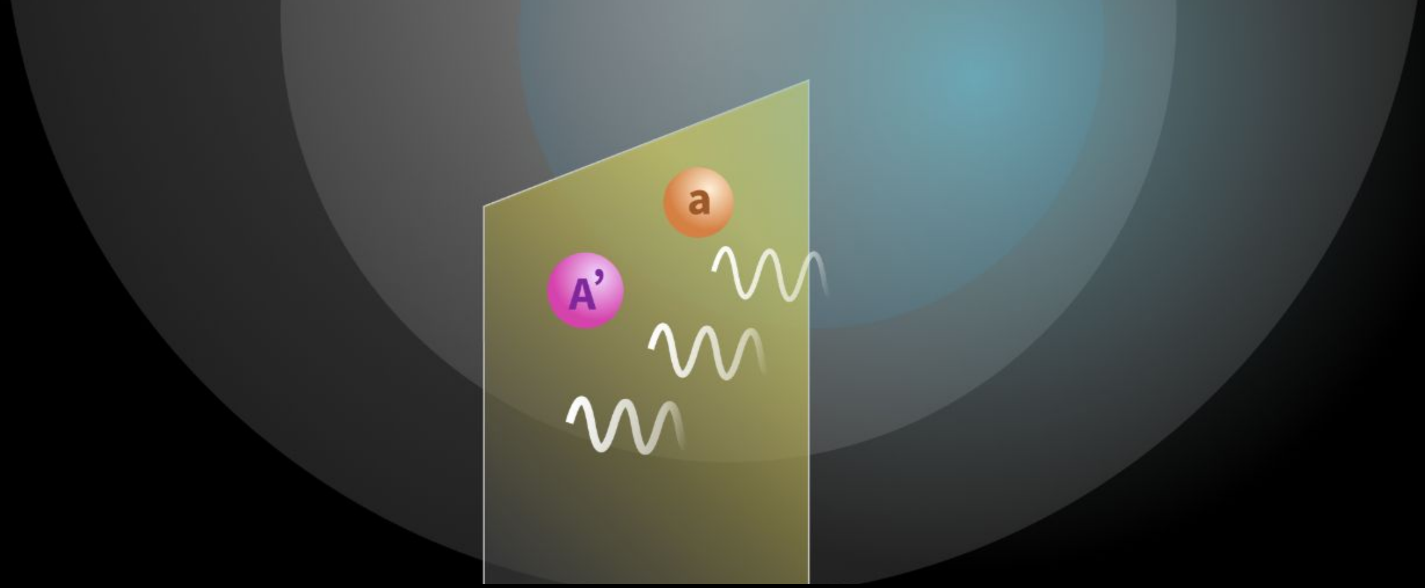
Also ALICE & LHCb: Burmasov et al [2203.00990]



γγ → axion-like particle → γγ



Photon collider physics motivates heavy ions @ HL-LHC



OUTLINE

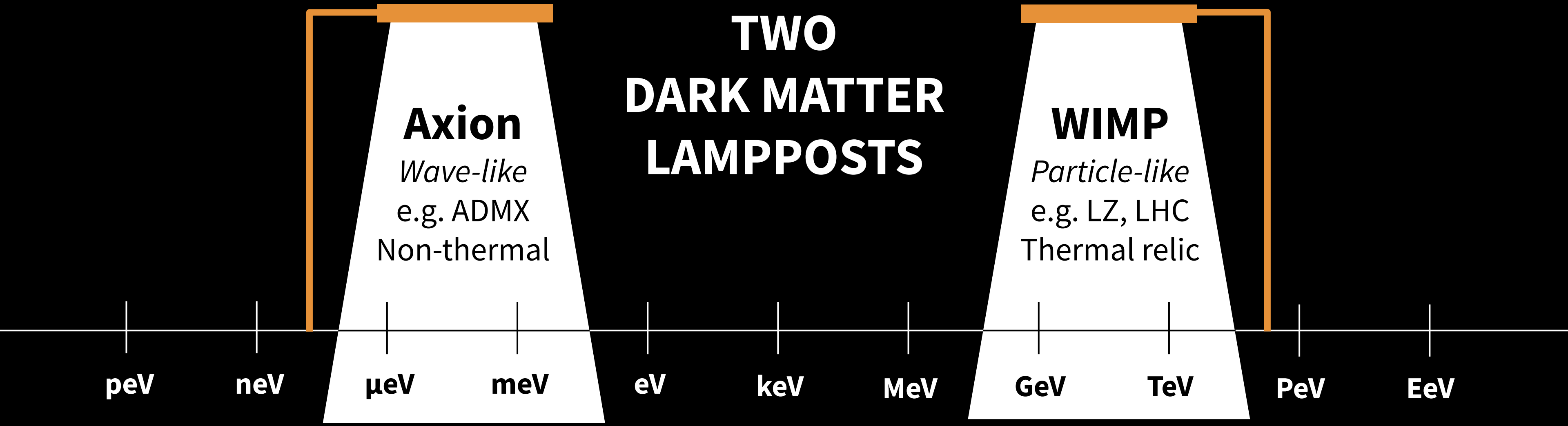
PART 1

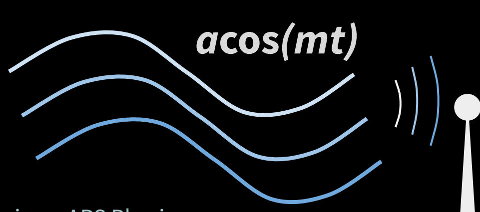
Colliding light for tau $g - 2$

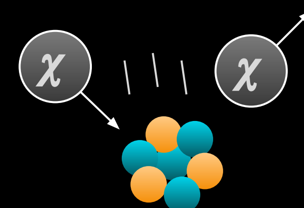
PART 2

BREAD axion detector R&D

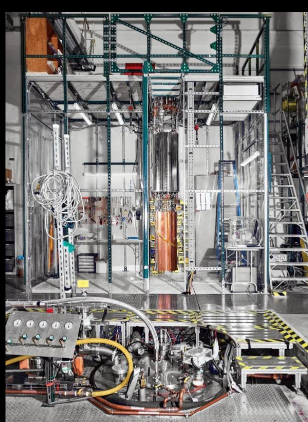
TWO DARK MATTER LAMPPOSTS

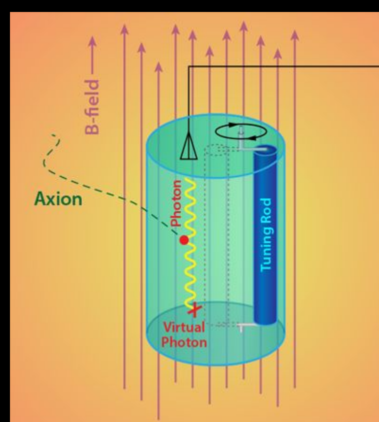




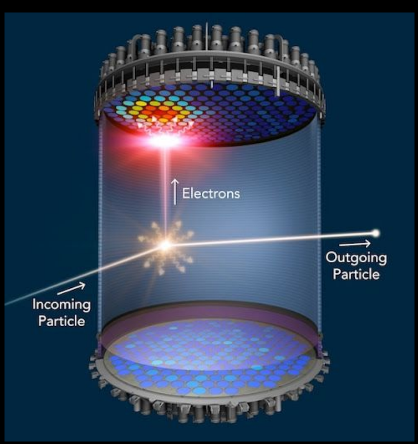


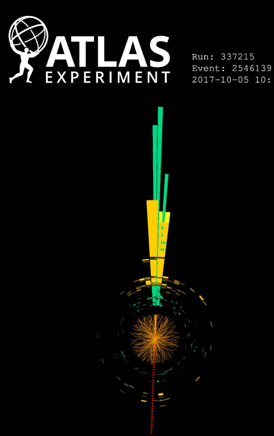
Scientific American, APS Physics





lz.ac.uk, 2102.10874





Axion motivation: resolve two mysteries

CP Conservation in the Presence of Pseudoparticles*

R. D. Peccei and Helen R. Quinn†
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305
(Received 31 March 1977)

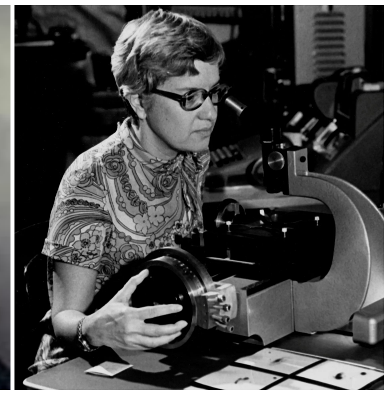
We give an explanation of the *CP* conservation of strong interactions which includes the effects of pseudoparticles. We find it is a natural result for any theory where at least one flavor of fermion acquires its mass through a Yukawa coupling to a scalar field which has nonvanishing vacuum expectation value.

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

Vera C. Rubin† and W. Kent Ford, Jr.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡
Received 1969 July 7; revised 1969 August 21

UCLA

Franklin Institute



Carnegie via NYT

APS

Strong CP problem

PARTICLE PHYSICS

Why strong force conserves charge–parity symmetry & neutron lacks electric dipole

Peccei & Quinn [PRL 38 (1977) 1440]

Neutron EDM: $|d_{obs}/d_{QCD}| \lesssim 10^{-10}$

Abel et al [PRL 124 (2020) 081803]

Dark matter problem

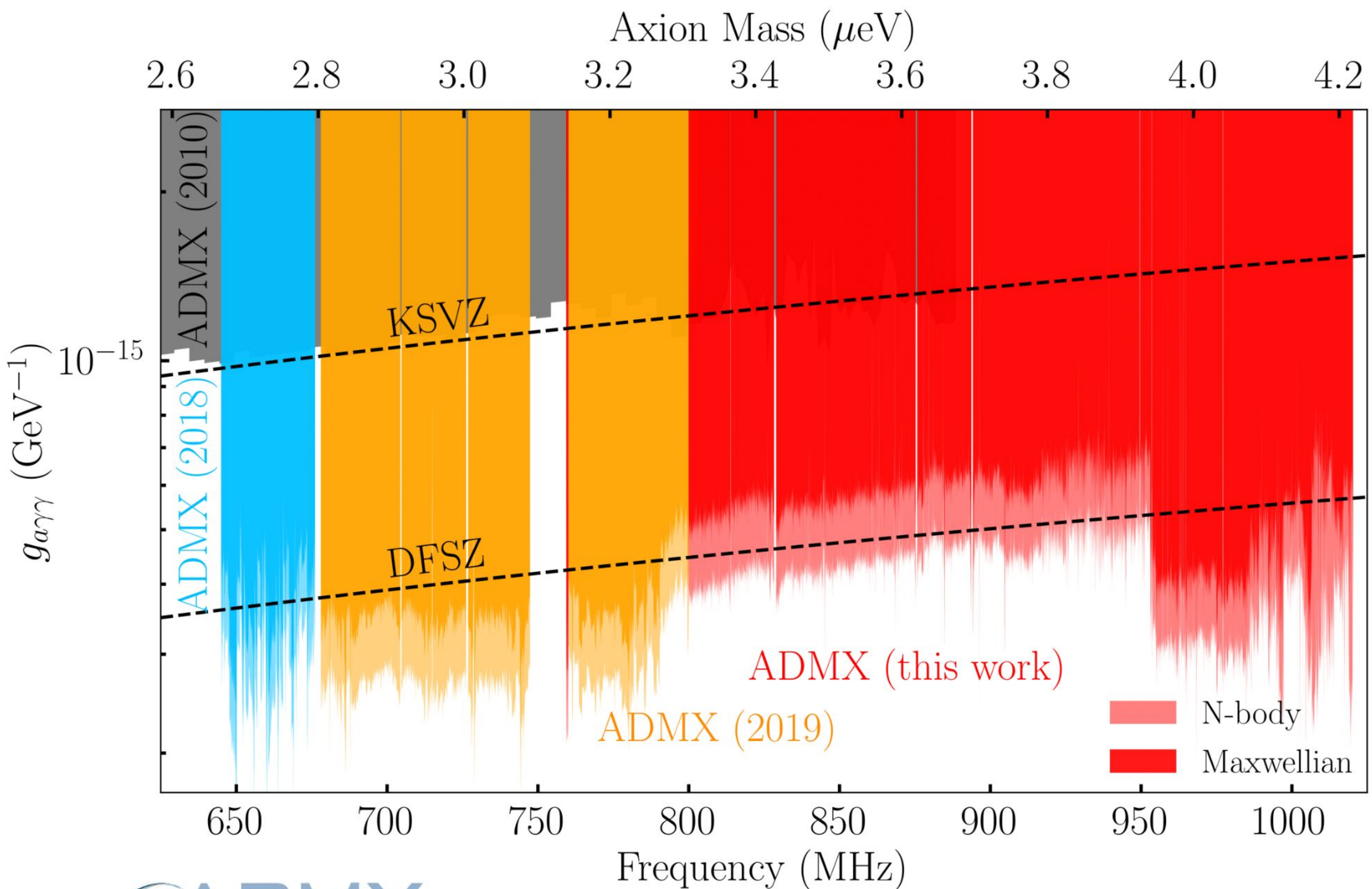
ASTROPHYSICS

Rotation curves of Andromeda Galaxy too high for measured luminous matter

Rubin & Ford

[ApJ 159 (1970) 379]

Success story: decisively test canonical axion targets

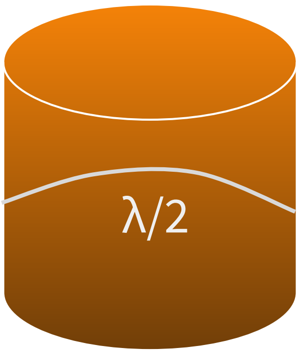


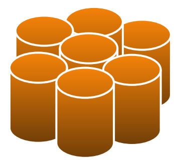
AXION DARK MATTER EXPERIMENT

Bartram et al (ADMX) PRL 127 (2021) 261803

Problem: signal power falls rapidly vs mass

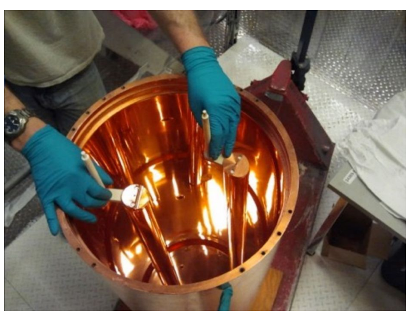
m = 4 μeV	m = 40 μeV	m = 400 μeV
GHz, λ ~ 30 cm	10 GHz, λ ~ 3 cm	100 GHz, λ ~ 0.3 cm
Power	**Power x 10^{-3}**	**Power x 10^{-6}**

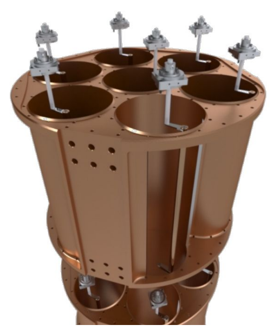




ADMX AXION DARK MATTER EXPERIMENT G2 multicavity

??



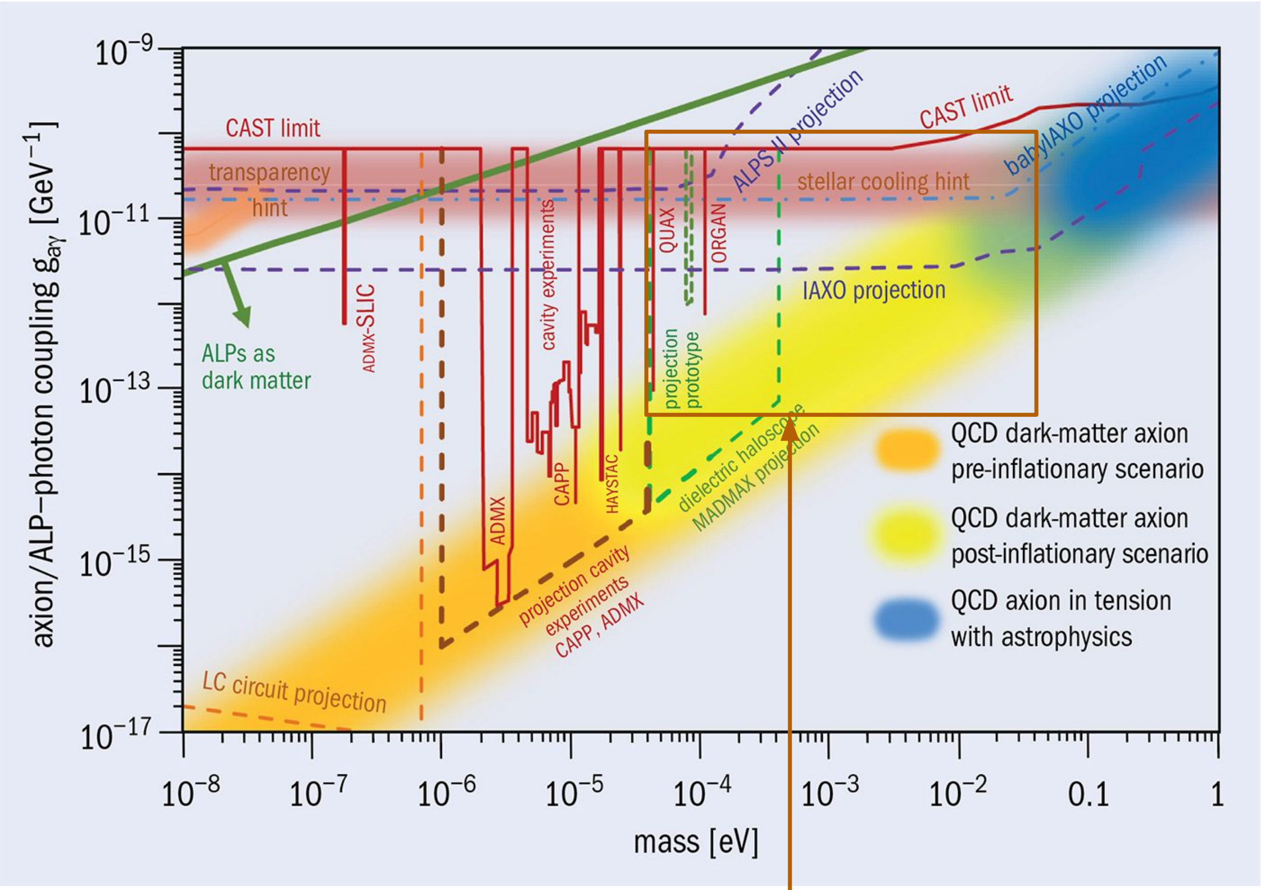


Signal power ~ cavity volume
N(cavities) ~ mass^3
Impractical for m ≳ 50 μeV

$$P_{a\to\gamma} = (1.9\times10^{-22}\mathrm{W})\left(\frac{V}{136\ \mathrm{L}}\right)\left(\frac{B}{6.8\ \mathrm{T}}\right)^2\left(\frac{C_{nlm}}{0.4}\right)\left(\frac{g_\gamma}{0.97}\right)^2\left(\frac{\rho_a}{0.45\ \mathrm{GeV/cm^3}}\right)\left(\frac{f_a}{650\ \mathrm{MHz}}\right)\left(\frac{Q}{50000}\right)$$

Khatitada et al (ADMX) Rev. Sci. Instrum. 92 (2021) 124502

Opening the terahertz axion window



CERN Courier 2021

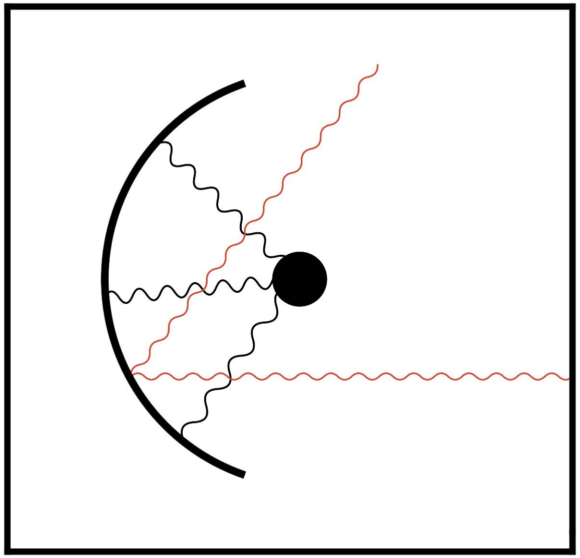
Desire broadband but cavity haloscopes narrowband $\Delta m/m \ll 1$

Desire high mass but scan rate $R \sim m^{-14/3}$ impractical for $m > 50\ \mu\text{eV}$

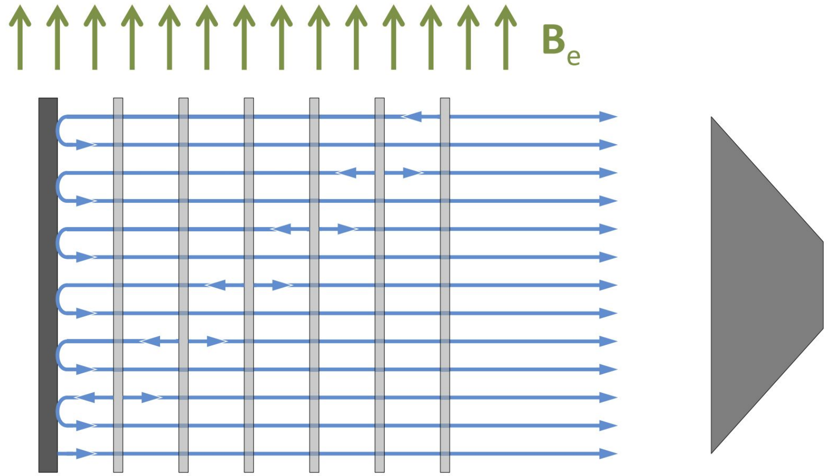
NEED CREATIVITY TO OVERCOME BOTH LONGSTANDING OBSTACLES

Innovative ideas for m ≳ 50 μeV

Power ~ coupling^2 × Area



Power ~ coupling^2 × Area × (disks boost)



DISH ANTENNA

Mirror creates & focuses signal

Truly broadband: no resonance

Horns et al JCAP 04 (2013) 016

DIELECTRIC STACK

Mirror+disks create & boost signal

Enhance signal coherently via N disks

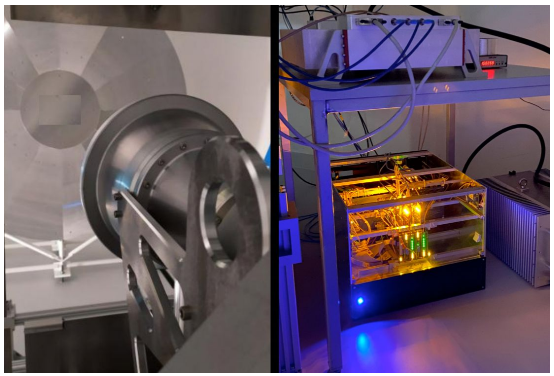
Caldwell et al (MADMAX) PRL 118 (2017) 091801

No resonant cavity enhancement but no longer suffer volume scaling

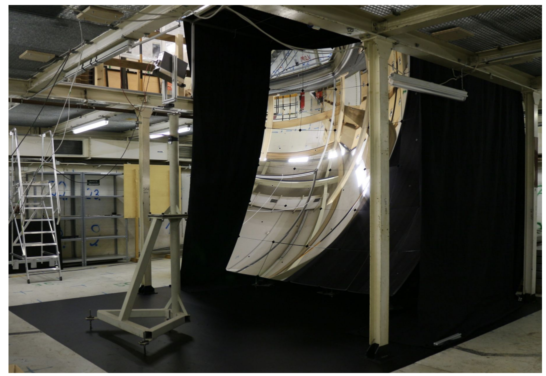
Proof-of-principle pilots worldwide

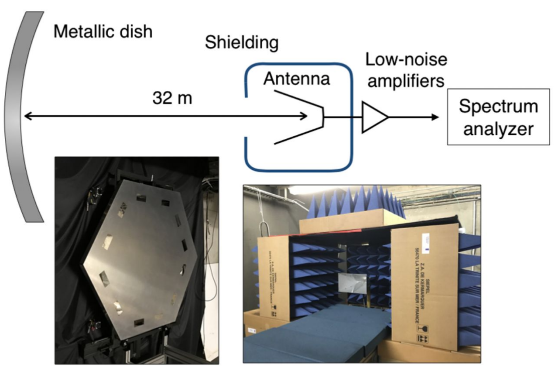
DISH ANTENNA

BRASS
Broadband Radiometric Axion SearcheS
Hamburg, Germany
Nguyen et al (BRASS) PATRAS 2022

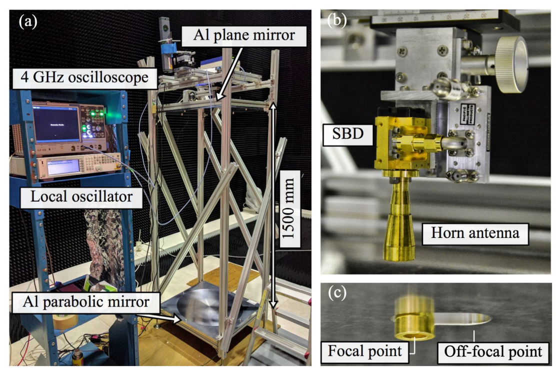


FUNK
Finding U(1)s of a Novel Kind
Karlsruhe, Germany
Andrianavalomahefa et al PRD 102 (2020) 042001





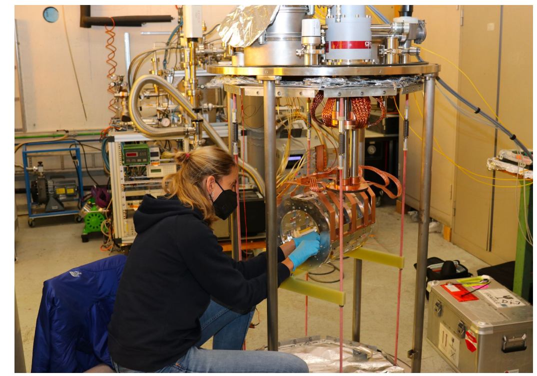
SHUKET
SearcH for U(1) darK matter with Electromagnetic Telescope
Paris, France
Brun et al PRL 122 (2019) 201801

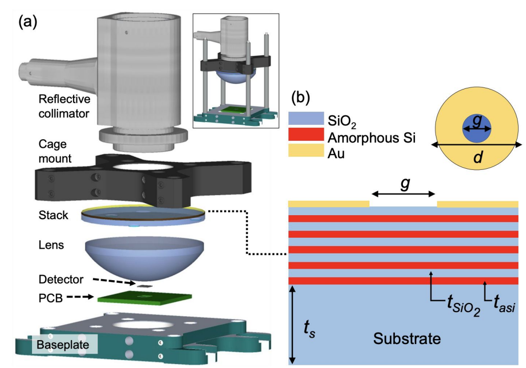


Tokyo
No official name except location
Tokyo, Japan
Knirck et al JCAP 11 (2018) 031

DIELECTRIC STACK

MADMAX
MAgnetized Disk and Mirror Axion eXperiment
Hamburg, Germany/CERN, Switzerland
Egge et al (MADMAX) EPJC 80 (2020) 392





LAMPOST
Light A' Multilayer Periodic Optical SNSPD Target
Boulder, Colorado, USA
Chiles et al PRL 128 (2022) 231802

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

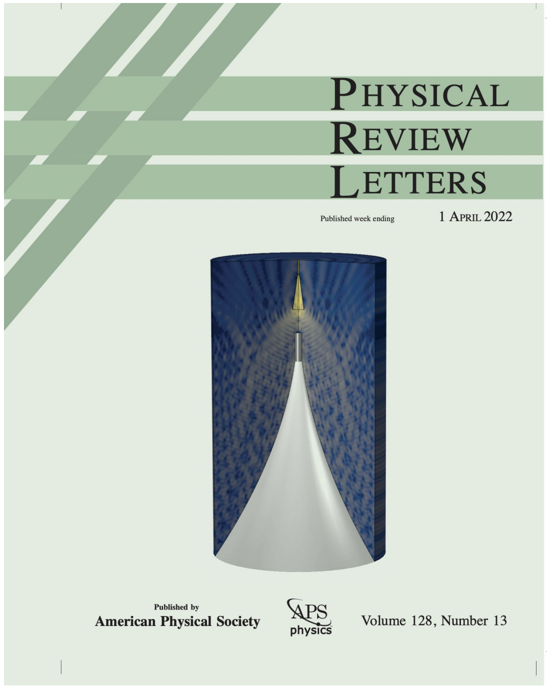
Simulation of the full electric field inside the conceptual design of the Broadband Reflector Experiment for Axion Detection (BREAD). Selected for an Editors' Suggestion.

Jesse Liu *et al.*

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

Issue 13 Table of Contents | More Covers

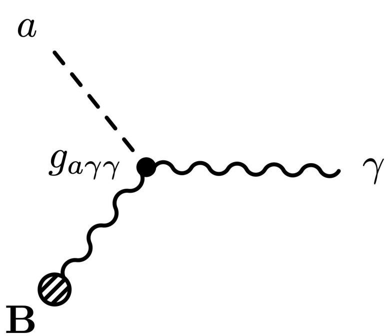
Jesse Liu, Kristin Dona, Gabe Hoshino, Stefan Knirck, Noah Kurinsky, Matthew Malaker, David W. Miller, Andrew Sonnenschein, Mohamed H. Awida, Peter S. Barry, Karl K. Berggren, Daniel Bowring, Gianpaolo Carosi, Clarence Chang, Aaron Chou, Rakshya Khatiwada, Samantha Lewis, Juliang Li, Sae Woo Nam, Omid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



Step 1: convert DM to photons

Axion–photon coupling

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

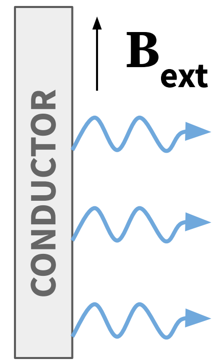


Augment Ampère–Maxwell

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

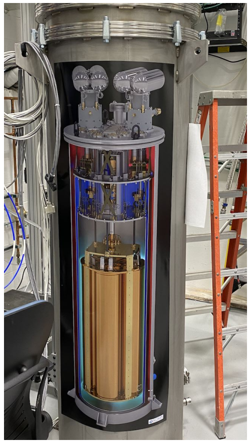
$$g_{a\gamma\gamma}\sqrt{2\rho_{\mathrm{DM}}}\mathbf{B}^{\parallel}_{\mathrm{ext}} \cos(m_a t)$$

Emit photons



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

Geometry



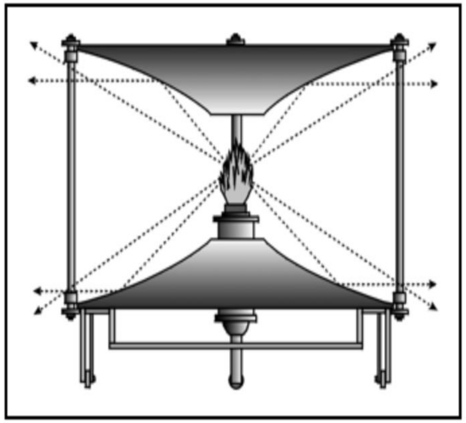
Broadband: no resonant tuning to unknown mass

Dish antenna concept proposed in Horns et al [1212.2970]

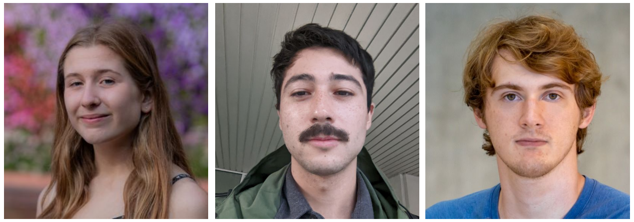
Cryostat & solenoid pic: Kristin Dona, Andrew Sonnenschein

Step 2: collect photons

Historical inspiration: classical lighthouse



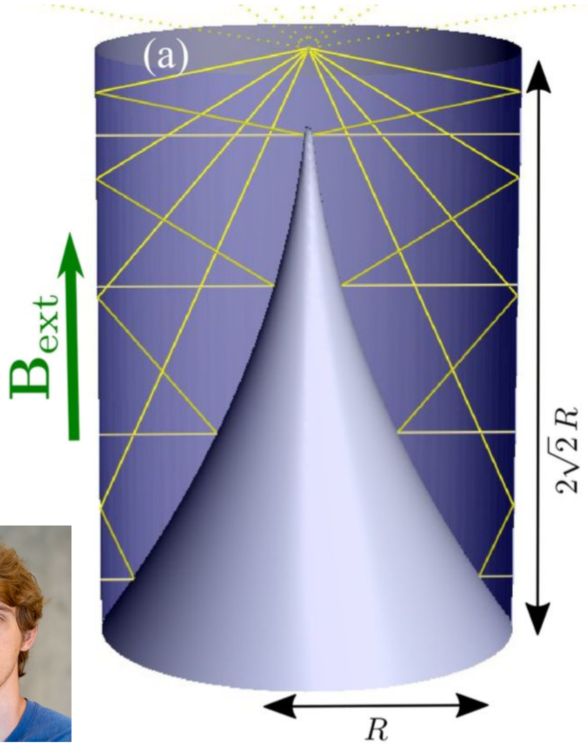
Bordier-Marcet 1811 [uslhs.org]



Kate Azar (Wellesley)
Gabe Hoshino (Yale)
Matthew Malaker (IIT)

Fermilab undergraduate summer students led initial simulation studies

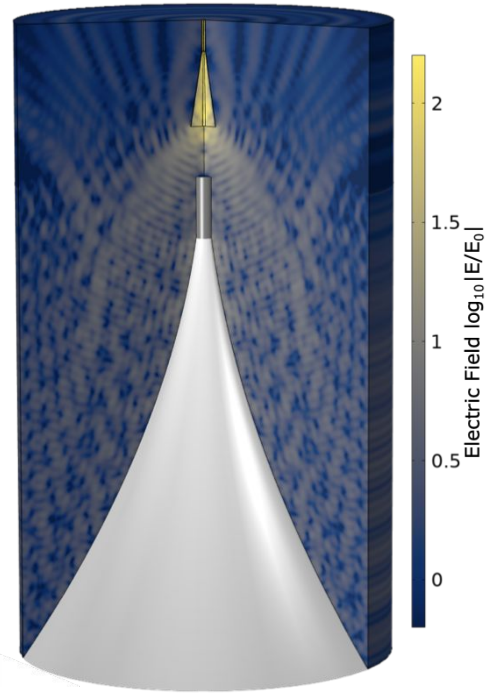
High mass: infrared ray optics



Shot-noise limited

Focal spot smeared by non-zero halo velocity

Low mass: coherent microwave field



Diffraction limited

Numerical Maxwell's equations (COMSOL) for 15 GHz signal

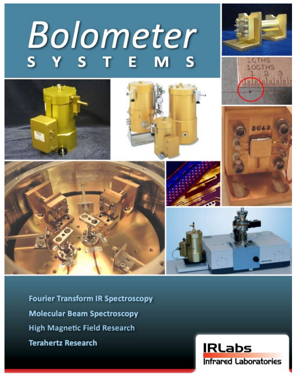
JL, Dona et al [PRL 128 (2022) 131801]

BREAD COLLABORATION

Step 3: detect photons

gentec-eo.com

irlabs.com

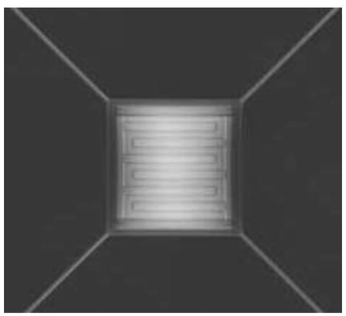


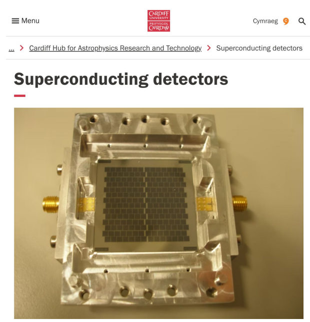
Commercial bolometers

Lower noise is better ↓

Photosensor	E (meV)	T_{op} (K)	NEP ($\text{W}/\sqrt{\text{Hz}}$)	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	$\frac{\text{DCR}}{\text{Hz}} = 4$	0.06^2
SNSPD [103, 104]	[124, 830]	0.3	$\frac{\text{DCR}}{\text{Hz}} = 10^{-4}$	0.4^2

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

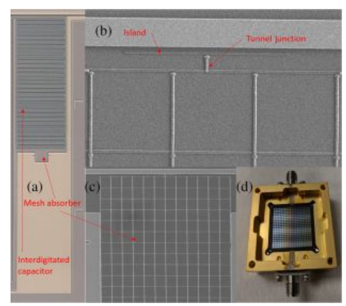


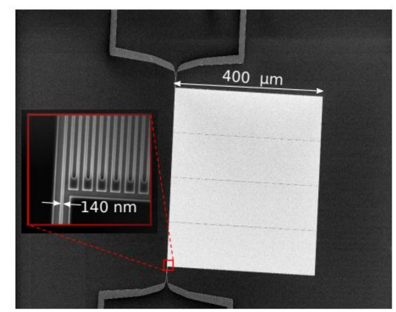


Transition Edge Sensor
Goldie et al [JLTP 2016]

Kinetic Inductance Detector
Baselmans et al [A&A 2017]

Established technology for astronomy





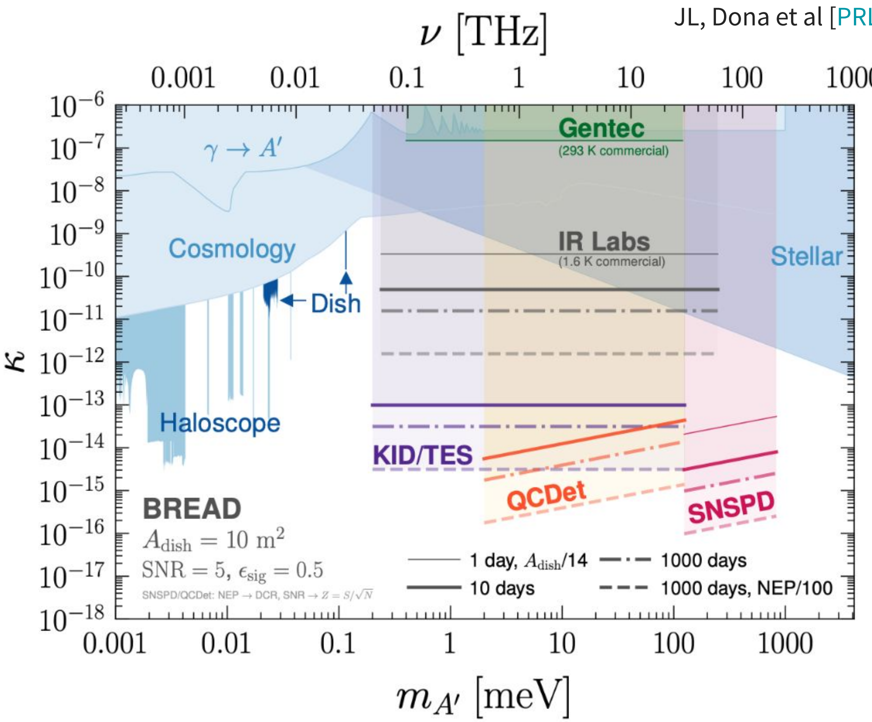
Quantum Capacitance Detector
Echternach et al [JATIS 2021]

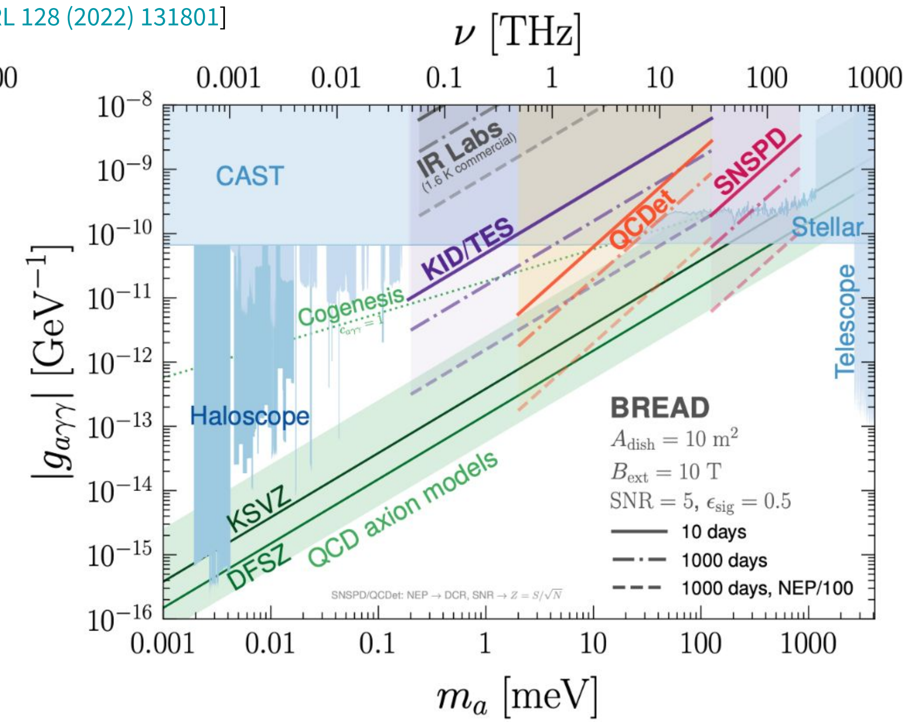
Superconducting Nanowire Single Photon Detector
Hochberg et al (MIT) [PRL 2019]

Emerging technology for infrared photon counting

Science program: pilot → full scale

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





DARK PHOTON (VECTOR)

Preparing “sourdough starter” pilots

Near term: first data ~ this year

AXION (PSEUDOSCALAR)

Requires significant sensor R&D

Longer term: 5+ year timescale

BREAD COLLABORATION

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

Vision: towards flagship axion facility

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

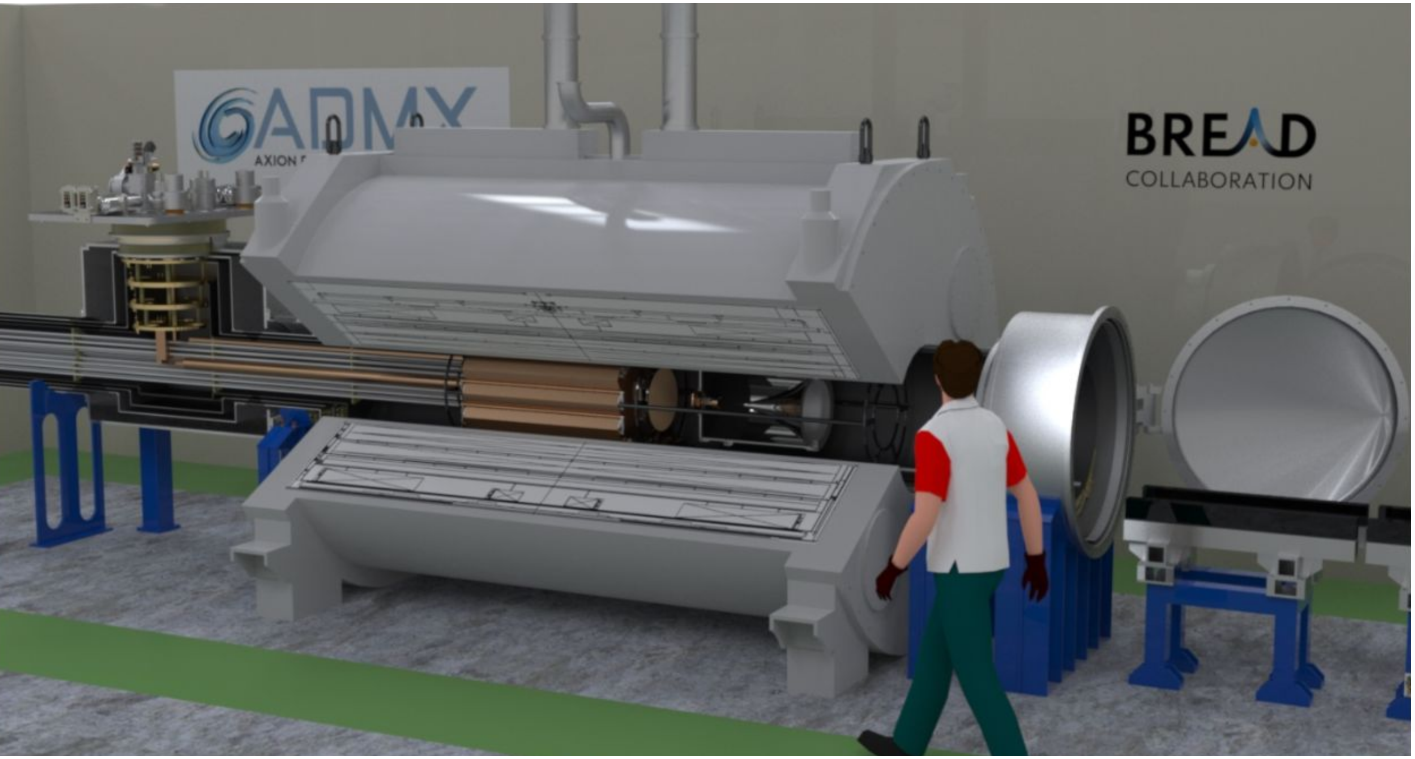
BREAD	Pilot	Stage 1	Stage 2a	Stage 2b
Axion a	—	✓	✓	✓
Dark photon A'	✓	✓	✓	✓
Experimental parameters				
$A_{\rm dish}$ [m^2]	0.7	10	10	10
$B_{\rm ext}$ [T]	—	10	10	10
ϵ_s	0.5	0.5	0.5	0.5
Δt [days]	10	10	1000	1000
NEP [W Hz$^{-1/2}$]	10^{-14}	10^{-18}	10^{-20}	10^{-22}

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

Joerg Jaeckel, Gray Rybka, Lindley Winslow Editors
(JL contributing author) 2203.14923

Snowmass 2021 White Paper Axion Dark Matter

Don Mitchell (FNAL) designing support structures & fixtures for mounting in cryostat



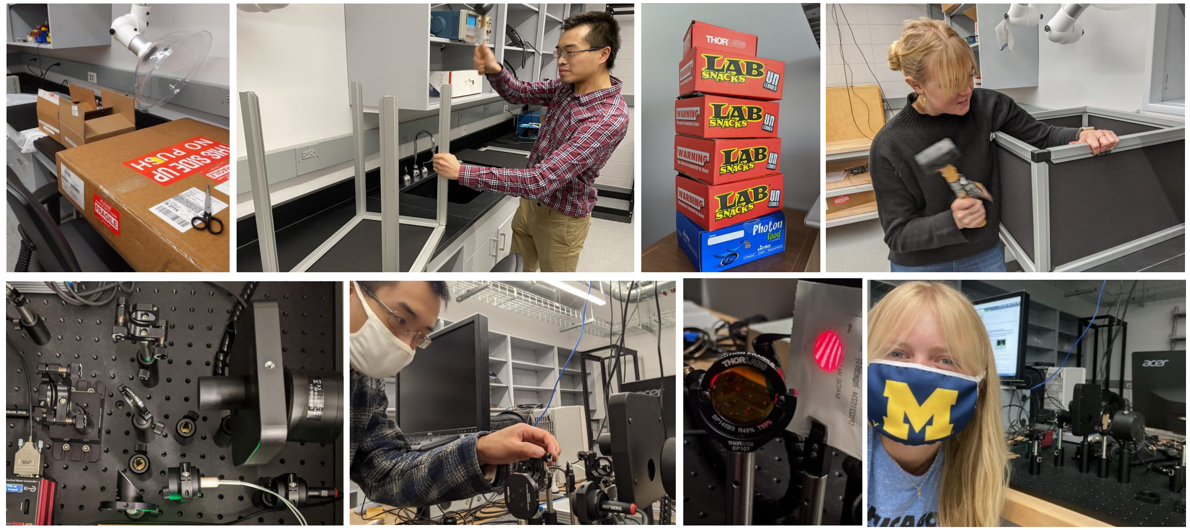
Hands on 1: build spectrometer for calibration optics

JANUARY 2020
Hardware arrival & assembly

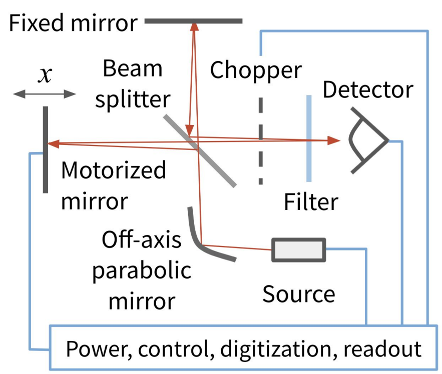
AUGUST
Alignment & operations

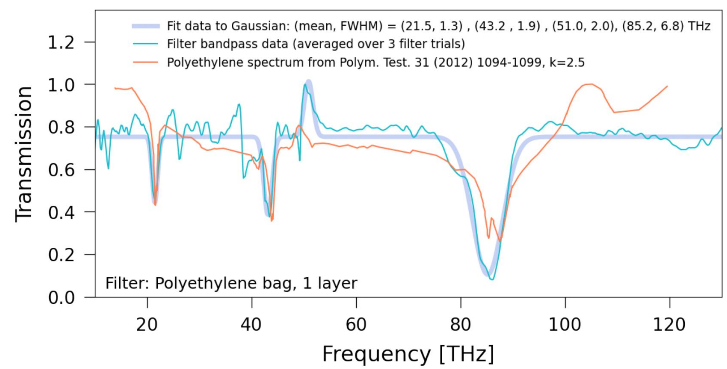
OCTOBER
Measurements & analysis

APRIL 2021
Write up & publish
2104.07157 (JINST)



← Kristin Dona (UChicago)





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

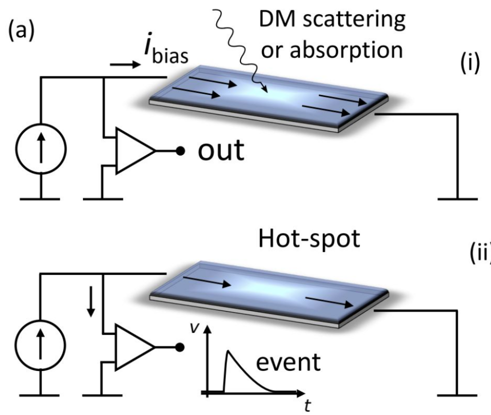
Kristin Dona,[1,*] Jesse Liu,[1,†] Noah Kurinsky,[2,3,‡] David Miller,[1,§]
Pete Barry,[2,4] Clarence Chang,[2,4] and Andrew Sonnenschein[3,¶]
[1]*Department of Physics, University of Chicago, Chicago IL 60637, USA*
[2]*Kavli Institute for Cosmological Physics, University of Chicago, Chicago IL 60637,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

Supported by Department of Energy HEP-QIS QuantISED grant

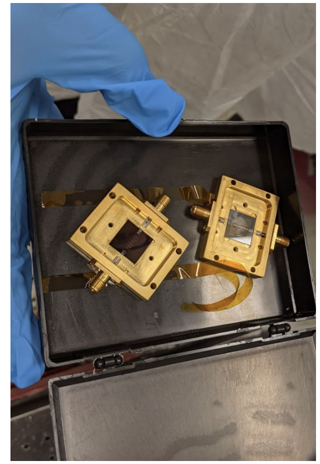
Hands on 2: quantum sensor testing

JL & Kristin @ Fermilab SiDet

Superconducting nanowires

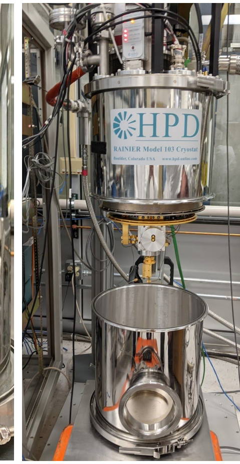


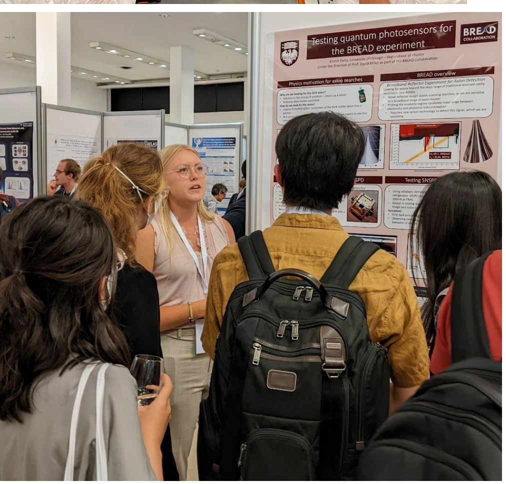
MIT nanowires



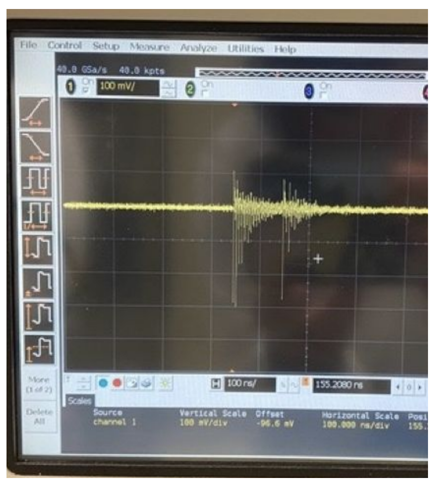
Window

Cryostat



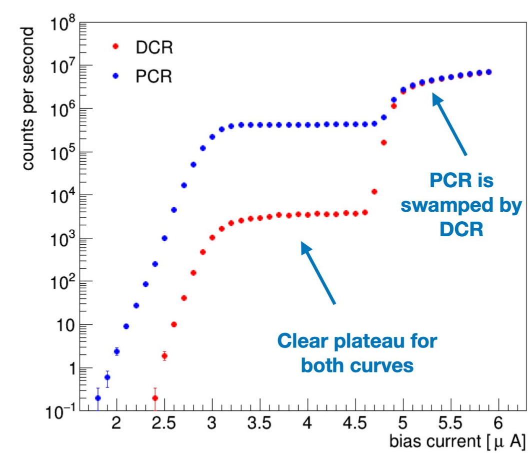


Kristin's ICHEP poster



First photosensor clicks

Christina Wang (Caltech)

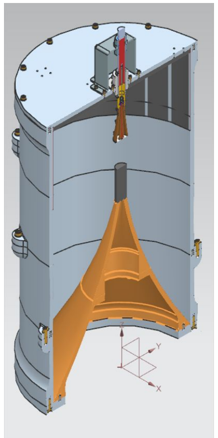


Photon/dark count rates

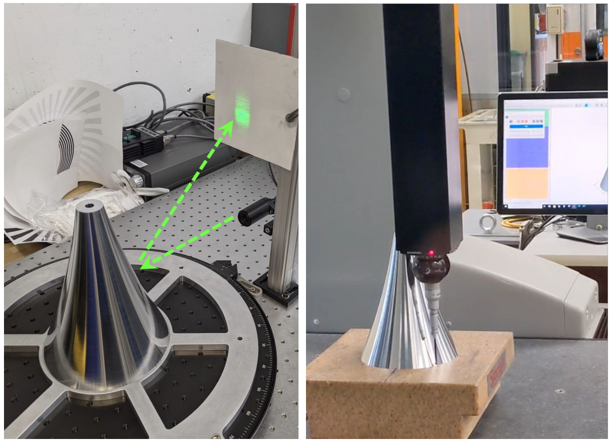
Hands on 3: reflector engineering & infrastructure

Pilot reflector assembly

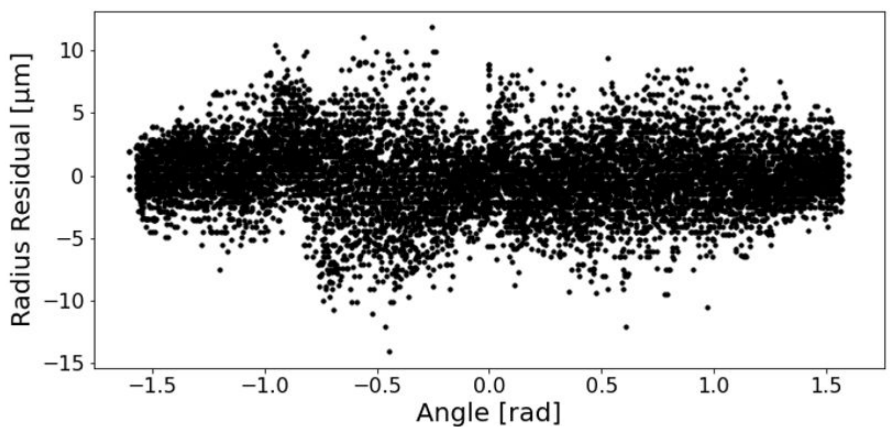
Pilot CAD



Reflectometry & touch-probe metrology

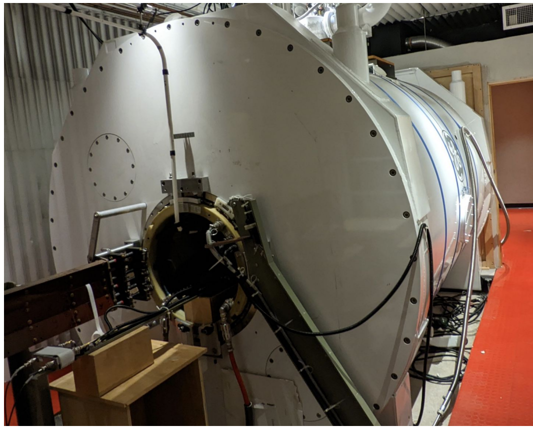


Huma Jafree
(Randolph-Macon)



Metrology residuals vs design

Andrew Sonnenschein @ Argonne



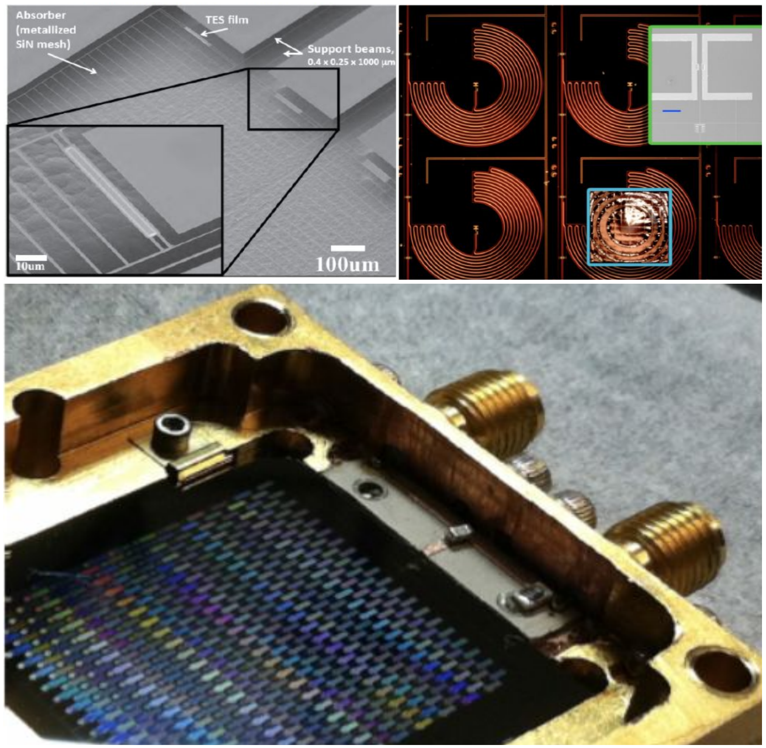
9.4 T 80 cm bore solenoid @ UIC

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

Pics: origins.ipac.caltech.edu | Space IR telescope recommended in Astro2020 Decadal Survey

EPILOGUE

Neutron magnetic moment

When Nature laughed in our 1930s faces

Paul Dirac 1928

Irène and Frédéric Joliot-Curie 1932

James Chadwick 1932

Theory: zero as it's neutral & pointlike

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

Goudsmit & Bacher (1933), Tamm & Altshuler (1934), Breit & Rabi (1934), Alvarez & Bloch (1940), CODATA (2018)

Completely confounded expectation!

Pics: Britannica

TRANSFORMATIVE

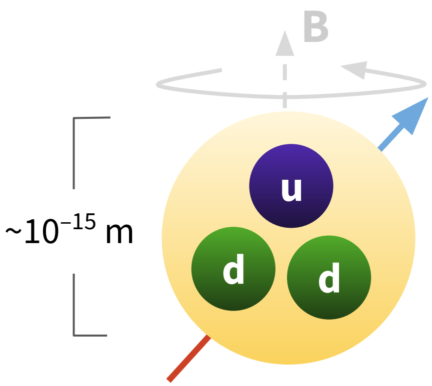
Neutron magnetic moment

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

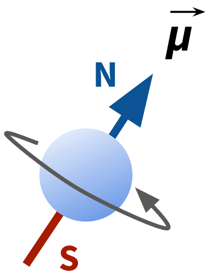
opens new problem with EDM

MAGNETIC DIPOLE MOMENT (MDM)

Expectation: Dirac theory ⇒ $g = 0$

Reality: huge & negative! :O

Solved: new physics → QCD ✔

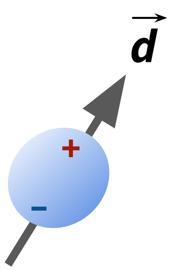


ELECTRIC DIPOLE MOMENT (EDM)

Expectation: strong CP violation ⇒ large

Reality: 0 to ten decimal places! :O

Solution: new physics → axions…?



THANK YOU

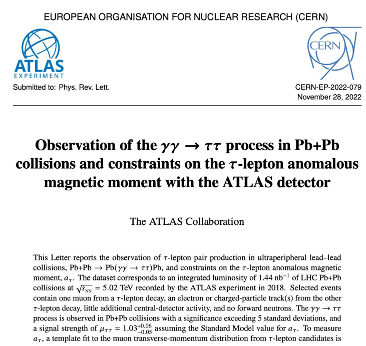
Colliding light for tau $g - 2$

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)

Submitted to: Phys. Rev. Lett.

CERN-EP-2022-079
November 28, 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 $\mu_{\tau\tau} = 1.03^{+0.06}_{-0.05}$ 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