Colliding light to measure tau $g - 2$

Warwick University
Elementary Particle Physics Seminar
9 June 2022

Jesse Liu
University of Cambridge

TRINITY COLLEGE CAMBRIDGE

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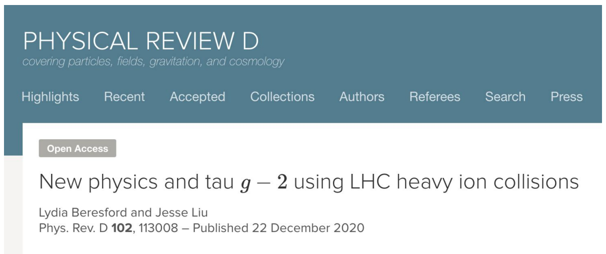
TODAY

Two stories of creative interdisciplinary science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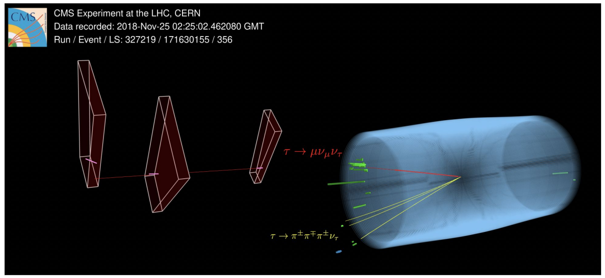
New physics and tau $g-2$ using LHC heavy ion collisions
Lydia Beresford and Jesse Liu
Phys. Rev. D **102**, 113008 – Published 22 December 2020

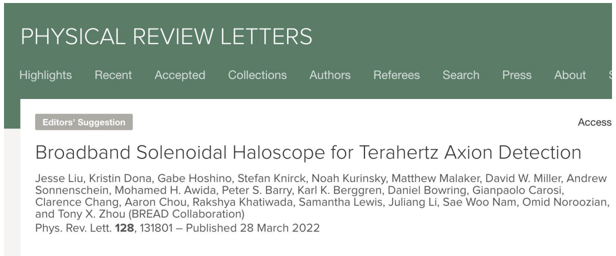


Colliding light for tau g – 2

Invent heavy-ion probe of precision EWK & new physics

Beresford & JL [1908.05180]

ATLAS [2204.13478], CMS [PAS-HIN-21-009]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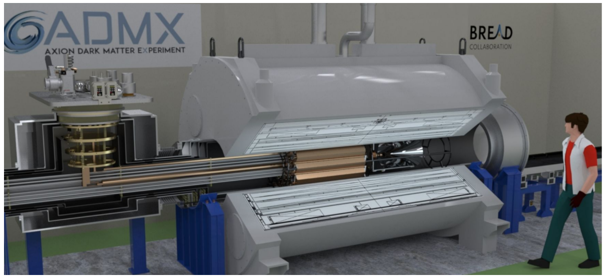
Broadband Solenoidal Haloscope for Terahertz Axion Detection
Jesse Liu, Kristin Dona, Gabe Hoshino, Stefan Knirck, Noah Kurinsky, Matthew Malaker, David W. Miller, Andrew Sonnenschein, Mohamed H. Awida, Peter S. Barry, Karl K. Berggren, Daniel Bowring, Gianpaolo Carosi, Clarence Chang, Aaron Chou, Rakshya Khatiwada, Samantha Lewis, Juliang Li, Sae Woo Nam, Omid Noroozian, and Tony X. Zhou (BREAD Collaboration)
Phys. Rev. Lett. **128**, 131801 – Published 28 March 2022



BREAD: new axion detector

meV dark matter observatory using quantum sensors

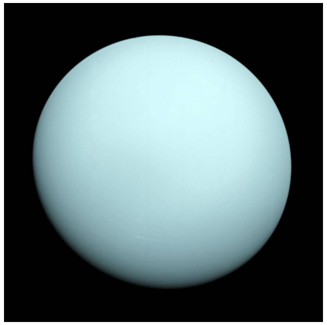
JL, Dona et al [2111.12103]

Dona, JL et al [2104.07157]

PROLOGUE

A TALE OF TRANSFORMATIVE DISCOVERY SCIENCE

Self-consistency tests | **Spectacular predictive power** | **Transformative precision**



Credits: NASA/JPL-Caltech

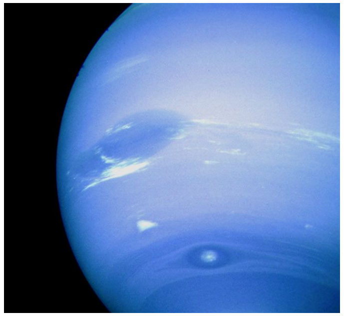
Uranus

Herschel 1781

Planet never seen before

65 years of measuring

[Precision electroweak]



Credits: NASA/JPL-Caltech

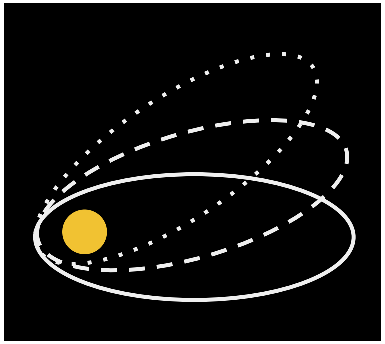
Neptune

Le Verrier, Galle, d'Arrest 1846

Discover on same night

within 1° of prediction

[Higgs boson discovery]



General Relativity

Le Verrier 1859, Einstein 1915

43 arcseconds/century deviation

Null search for Planet Vulcan

[Witnessing this today?]

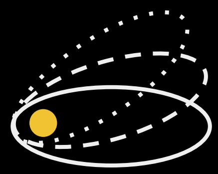
LESSON

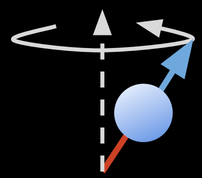
Precision measurements revolutionise science

GR: SPACETIME IS DYNAMICAL

Discover new planets: unchanged physical laws

But planet known since antiquity transformative





QFT: VACUUM IS DYNAMICAL

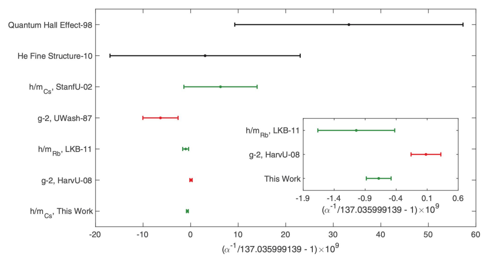
Per mille precession of electron: no new particles

But groundbreaking evidence of physical loops

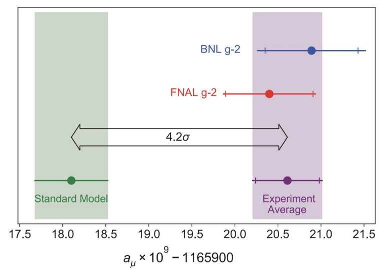
The ordinary harboured extraordinary surprises

Persistent widespread indirect evidence for new physics

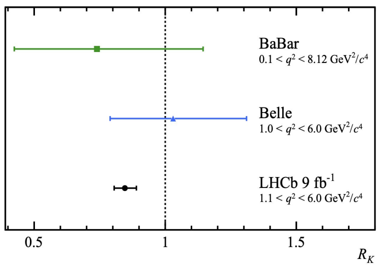
Electron $g-2$ (2.5σ)
[Science 2018]



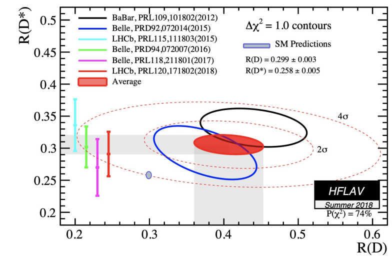
Muon $g-2$ (4.2σ)
[PRL 2021]



B → K$\ell\ell$ (3.1σ)
[2103.11769]



B → D$\tau\nu$ (3σ)
[HFLAV 2018]

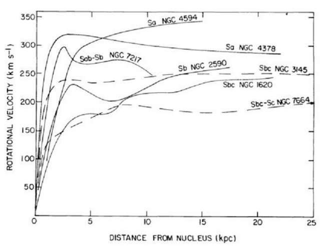


LEPTON ANOMALIES ↑

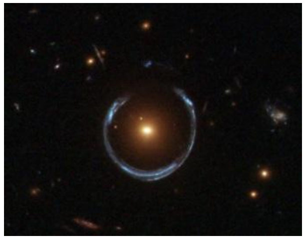
Involves e/μ/τ across different labs
Indirect evidence of new particles

↓ *DARK MATTER*

Sub-galactic to cosmological scales
Indirect evidence for particle nature

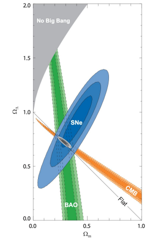


Galaxy rotation
[ApJ 1978]

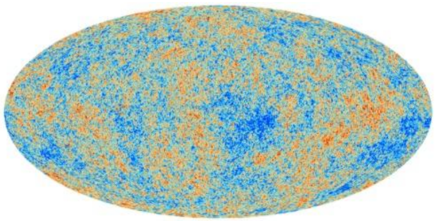


Lensing
[ESA/Hubble & NASA]

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



BAO
[ApJ 2008]



CMB
[ESA/Planck]

PART 1

Colliding light to measure tau *g* – 2

FROM PHENO PROPOSAL | **TO EXPERIMENTAL REALITY**

High Energy Physics – Phenomenology

[Submitted on 14 Aug 2019]

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

Lydia Beresford, Jesse Liu

The anomalous magnetic moment of the tau lepton $a_\tau = (g_\tau - 2)/2$ strikingly evades measurement, but is highly sensitive to new physics such as compositeness or supersymmetry. We propose using ultraperipheral heavy ion collisions at the LHC to probe modified magnetic δa_τ and electric dipole moments δd_τ. We introduce a suite of one electron/muon plus track(s) analyses, leveraging the exceptionally clean photon fusion $\gamma\gamma \to \tau\tau$ events to reconstruct both leptonic and hadronic tau decays sensitive to $\delta a_\tau, \delta d_\tau$. Assuming 10% systematic uncertainties, the current 2 nb^{-1} lead-lead dataset could already provide constraints of $-0.0080 < a_\tau < 0.0046$ at 68% CL. This surpasses 15 year old lepton collider precision by a factor of three while opening novel avenues to new physics.

2019: Propose innovative idea

Lydia Beresford & JL [1908.05180]

High Energy Physics – Experiment

[Submitted on 28 Apr 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

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 $\sqrt{s_{\text{NN}}} = 5.02$ 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 $a_\tau \in (-0.058, -0.012) \cup (-0.006, 0.025)$.

🥳 **Groundbreaking measurement!** 🎉

ATLAS Collaboration [2204.13478]

(Lydia Beresford, Mateusz Dyndal, Jakub Kremer, JL Editors)

April 2021: *g* – 2 recaptures international attention

The New York Times

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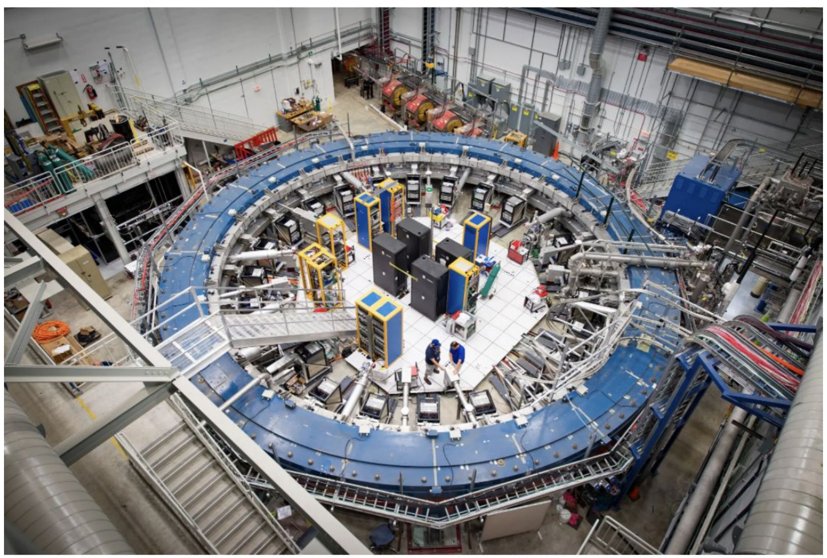
OUT THERE

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

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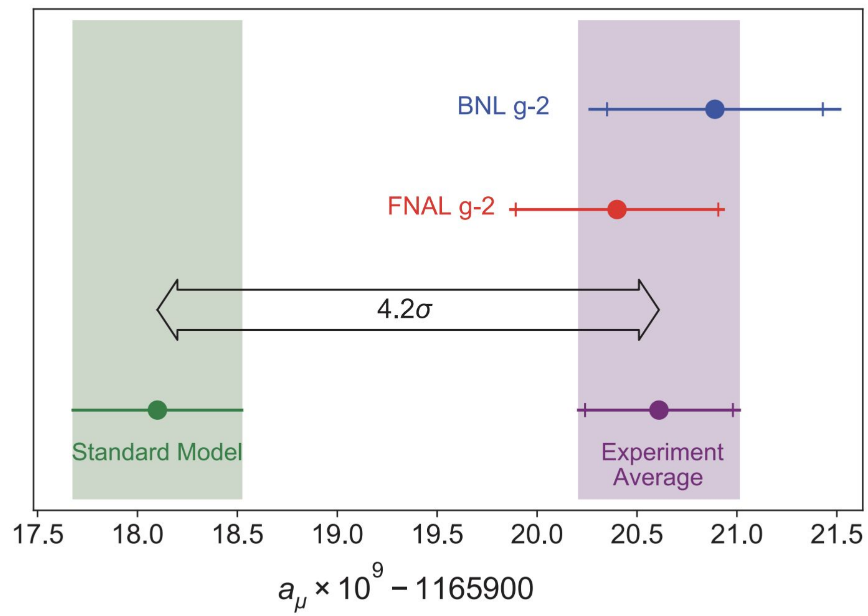
NEWS | 07 April 2021

Is the standard model broken? Physicists cheer major muon result

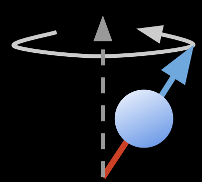
The muon's magnetic moment is larger than expected — a hint that new elementary particles are waiting to be discovered.

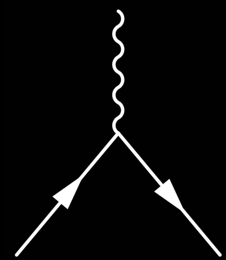


Muon g–2 Experiment [PRL 2021]

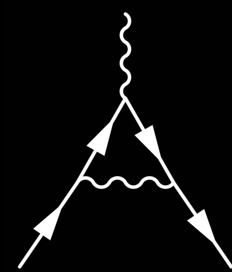
g – 2: foundational test of QFT

“How does light interact with matter?”

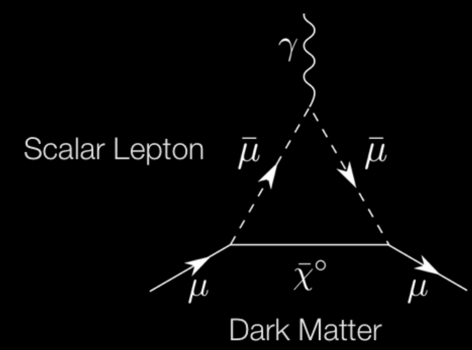




$+$



$+$



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

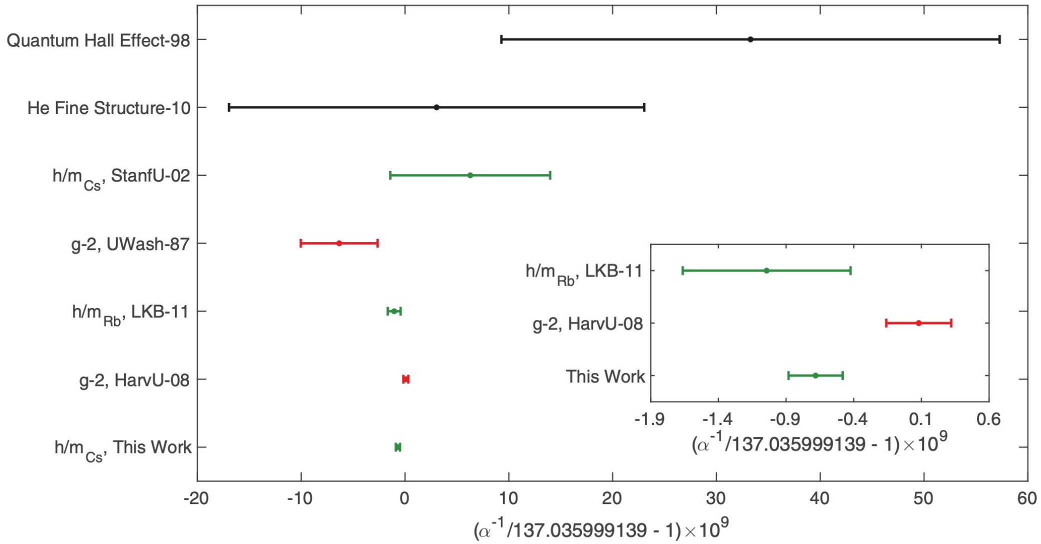
Dirac (1928)

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?



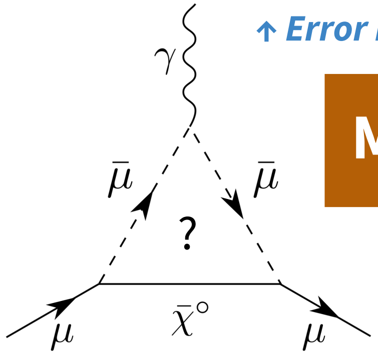
Electron $g - 2$ (−2.5σ?)

Odom, Hanneke, D'Urso, Gabrielse [PRL (2006)]
Bouchendira et al [PRL (2011)]
Aoyama, Hayakawa, Kinoshita, Nio [1205.5368]
Parker, Yu, Zhong, Estey, Müller [Science (2018)]

0.2 parts per billion

"Triumph of quantum electrodynamics"

↑ Error bars width of atom if drawn to scale!

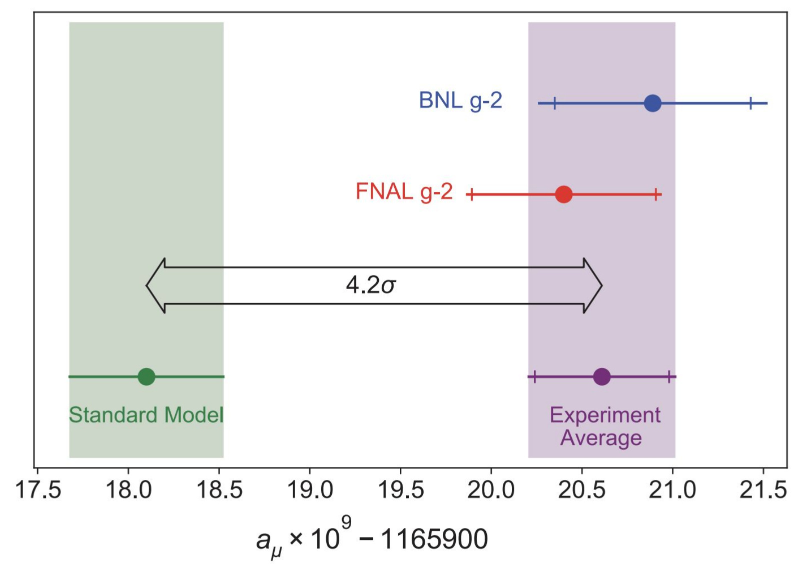


Muon $g - 2$ (+4.2σ?)

BNL E821 [hep-ex/0602035]
Fermilab E989 [1501.06858]
J-PARC [1901.03047]
Keshavarzi, Nomura, Teubner [1802.02995]
Davier, Hoecker, Malaescu, Zhang [1908.00921]
Muon g–2 theory initiative [2006.04822]
FNAL Muon g–2 [2104.03281]

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

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

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

DELPHI [hep-ex/0406010], 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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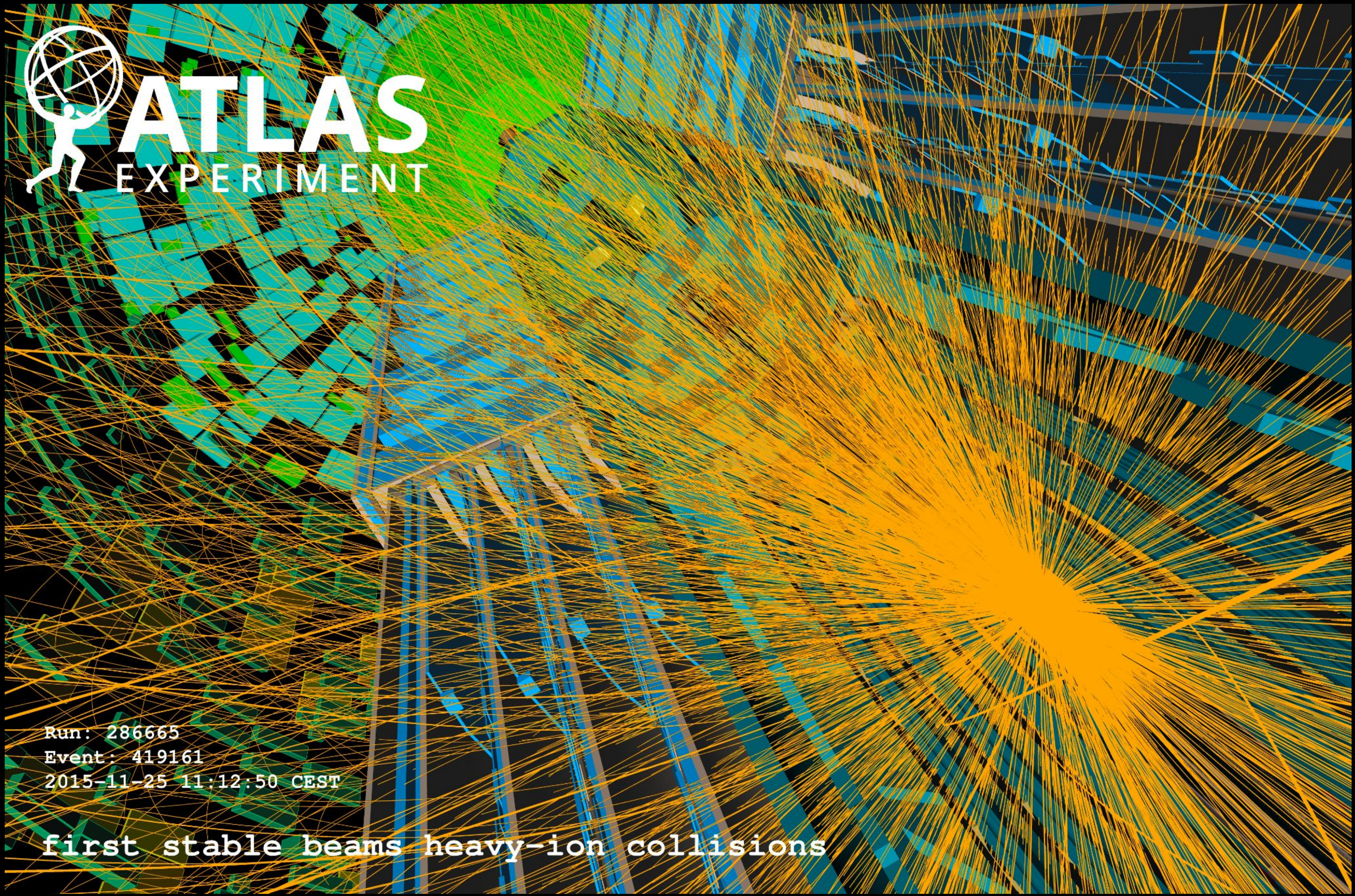
New physics and tau $g-2$ using LHC heavy ion collisions

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

1908.05180

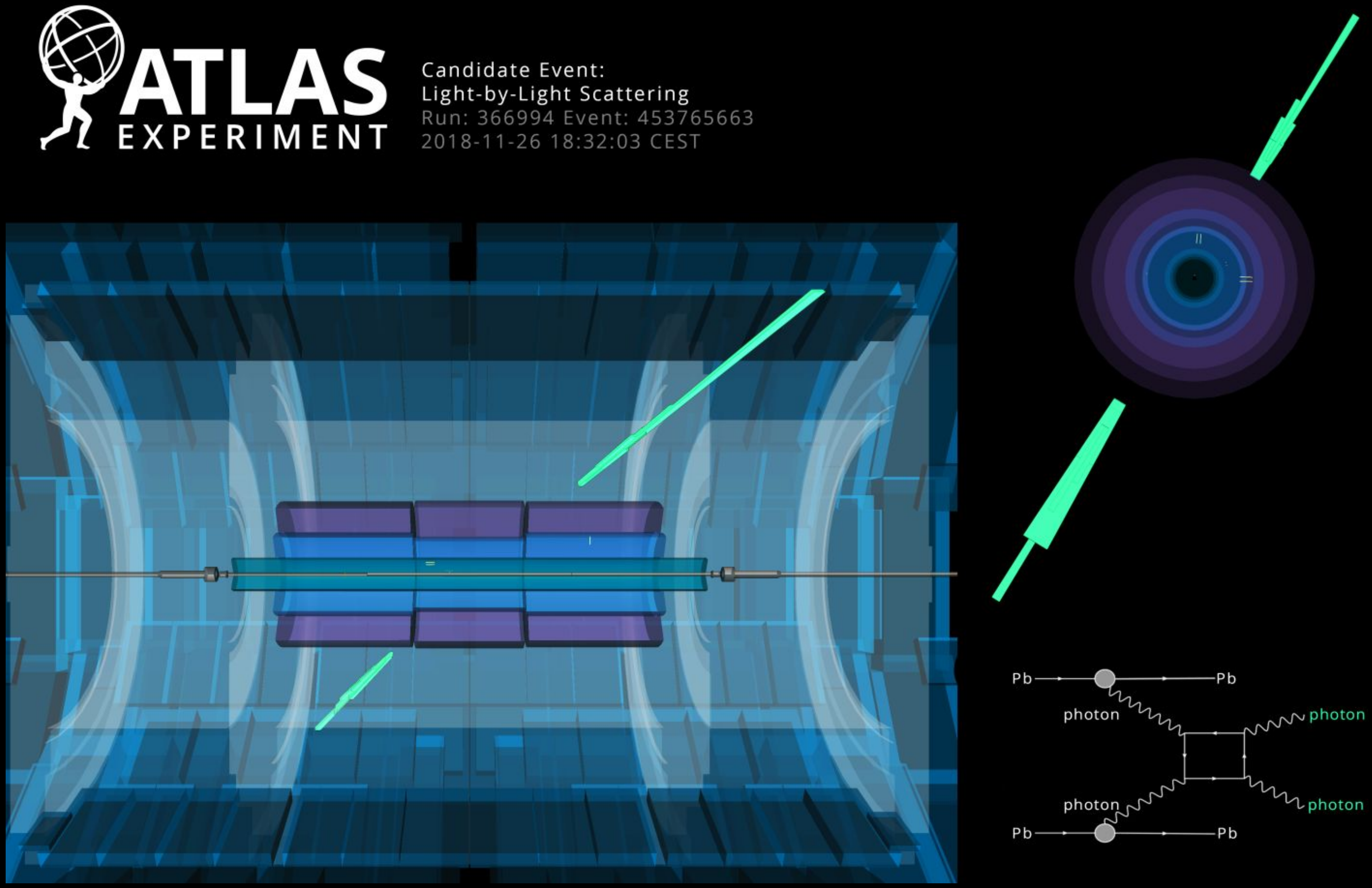
Creative bridge across **electroweak/flavour/BSM** & **nuclear physics** communities

Heavy-ion collisions: what usually comes to mind



ATLAS HION Event Display

Heavy-ion collisions: exquisitely clean

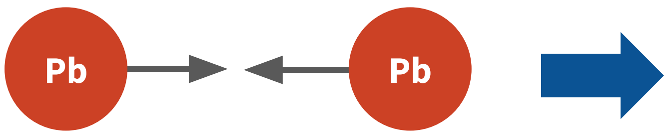


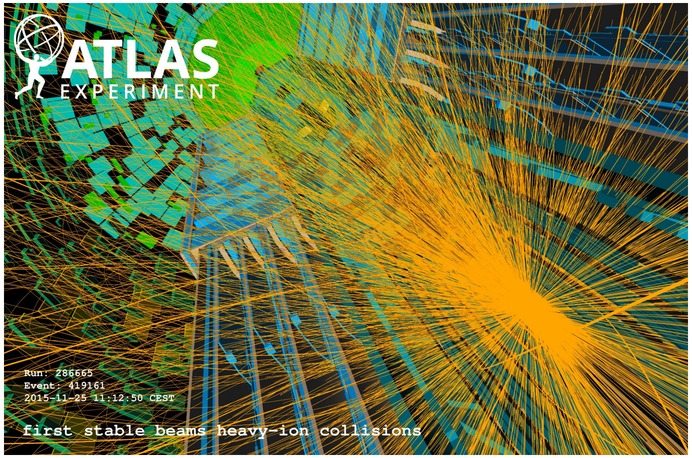
"All charged-particle tracks with p_T > 100 MeV are shown"

ATLAS light-by-light observation [1904.03536] (PRL)

Colliding light @ LHC

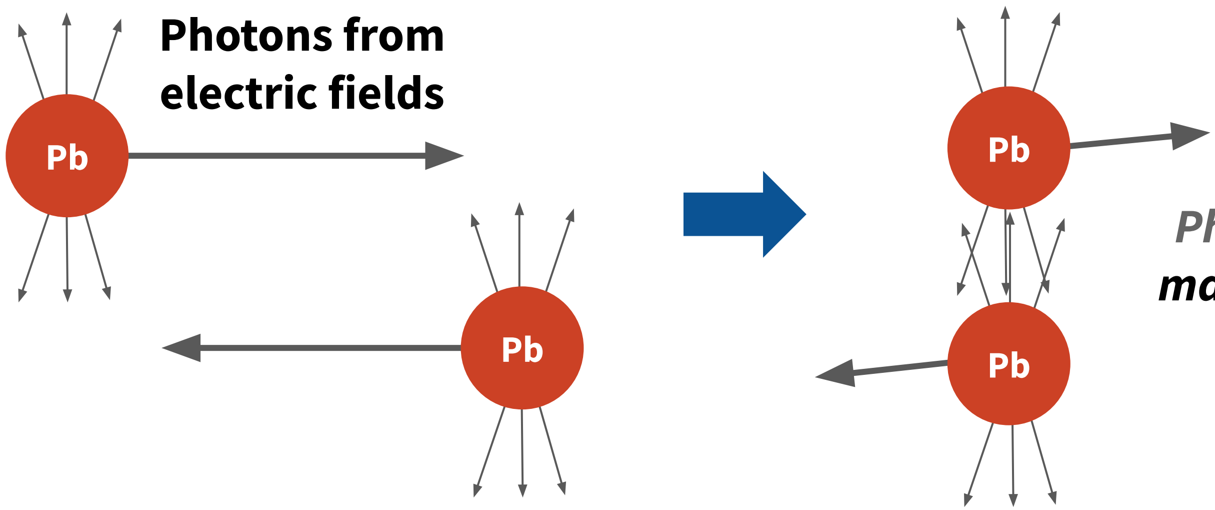
Head-on Pb–Pb collisions





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

Photons from electric fields

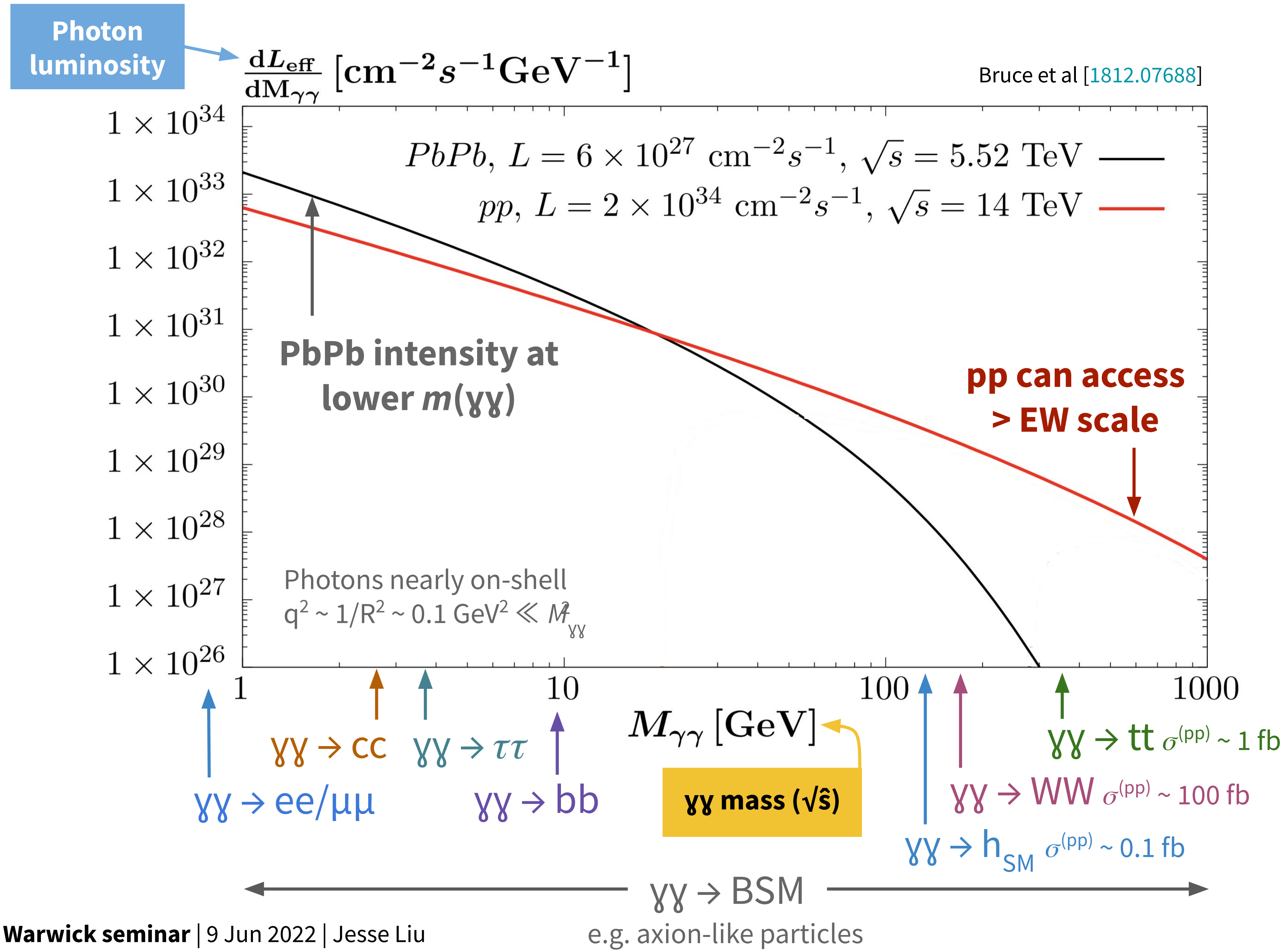


***Photons* collide to make new particles**

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]

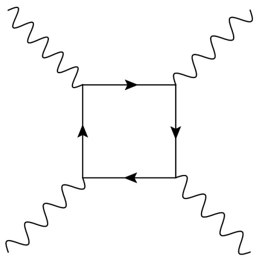
Colliding γγ spectrum



Vibrant LHC photon collider programme growing

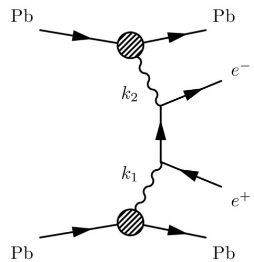
TODAY'S FOCUS

PbPb (5.02 TeV)



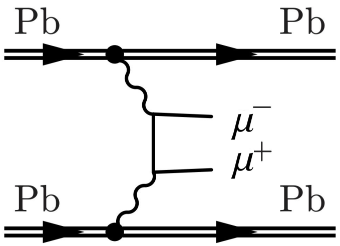
γγ → (*a*) → γγ

ATLAS [1702.01625, 1904.03536*, 2008.05355], CMS [1810.04602]



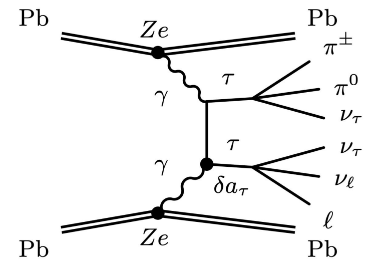
γγ → ee

ATLAS [CONF-2022-025]



γγ → μμ

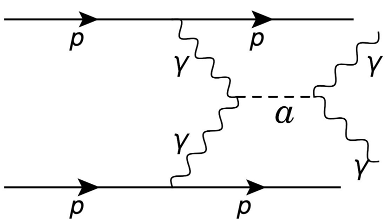
ATLAS [1806.08708*, 2011.12211]
CMS [2011.05239*]



γγ → ττ

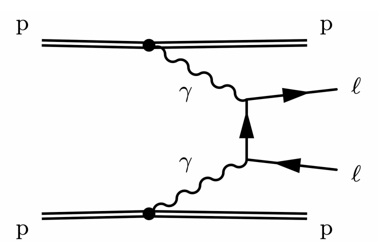
ATLAS [2204.13478*]
CMS [PAS-HIN-21-009*]

pp (13 TeV)



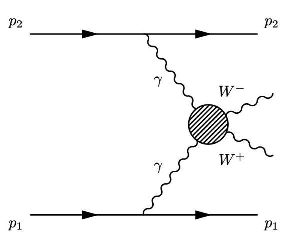
γγ → γγ

CMS [2110.05916]



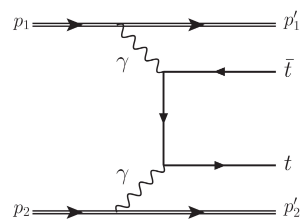
γγ → ee/μμ

CMS [1209.1666*, 1803.04496*]
ATLAS [1506.07098, 1708.04053, 2009.14537*]



γγ → WW

ATLAS [1607.03745, 2010.04019*]
CMS [1305.5596, 1604.04464]



γγ → tt

CMS [PAS-TOP-21-007]

*** = "Observation" in title**

2 years ago: led landmark (γγ → ee/μμ)+p result

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Observation and Measurement of Forward Proton Scattering in Association with Lepton Pairs Produced via the Photon Fusion Mechanism at ATLAS

G. Aad *et al.* (ATLAS Collaboration)

Phys. Rev. Lett. **125**, 261801 – Published 23 December 2020

ATLAS (Lydia Beresford, JL Editors) [2009.14537]

Physics Briefing

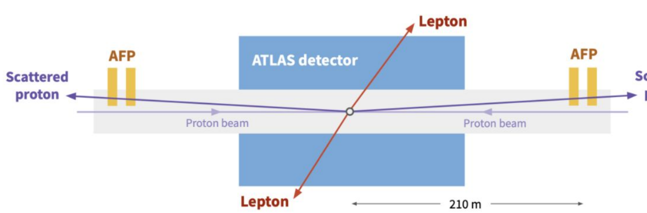
[ATLAS Physics Briefing]

Tags: Physics Results, ICHEP2020, ICHEP, forward detectors

Looking forward: ATLAS measures proton scattering when light turns into matter

By ATLAS Collaboration, 30th July 2020

Today, at the International Conference for High Energy Physics (ICHEP 2020), the ATLAS Collaboration announced first results using the ATLAS Forward Proton (AFP) spectrometer (Figure 1). With this instrument, physicists directly observed and measured the long sought-after prediction of proton scattering when particles of light turn into matter.



ENERGY FRONTIERS

[CERN Courier Sep/Oct 2020]

Reports from the Large Hadron Collider experiments

ATLAS

The LHC as a photon collider

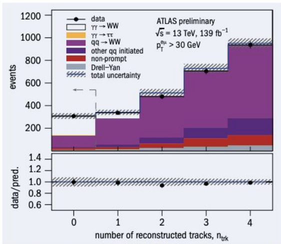


Fig. 1. *To isolate a sample of γγ→WW interactions, events with no additional reconstructed charged-particle tracks in the vicinity of the electron–muon pair (n_{trk} = 0) are selected.*

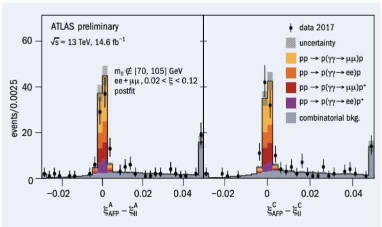


Fig. 2. *A sample of γγ→ℓℓ events can be isolated by observing a scattered proton in the AFP spectrometer. Here, the proton energy loss measured in the AFP installed either side (A and C) of the collision point (ξ_{AFP}, dimensionless) is shown to agree with that predicted from measurements of the lepton pair in the main detector ($\xi_{\ell\ell}$).*

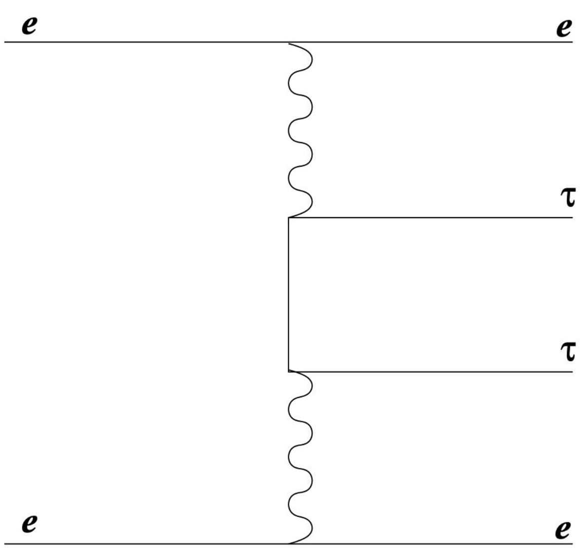
Protons accelerated by the LHC generate a large flux of quasi-real high-energy photons that can interact to produce particles at the electroweak scale. Using the LHC as a photon collider, the ATLAS collaboration recently announced a set

pairs – are the only particles detected in the vicinity. However, if charged particles arise from nearby proton–proton collisions, the clean γγ→WW signal can be missed. The main background is W boson pairs produced in head-on proton–

side of the collision point, the AFP can detect protons that have been scattered in photon–photon collisions but which have nevertheless been focused by the LHC's magnets. Its pioneering results so far analyse a standard-candle pro–

How about γγ → $\tau\tau$? Bring LEP success to LHC

PDG constraint of tau $g - 2$



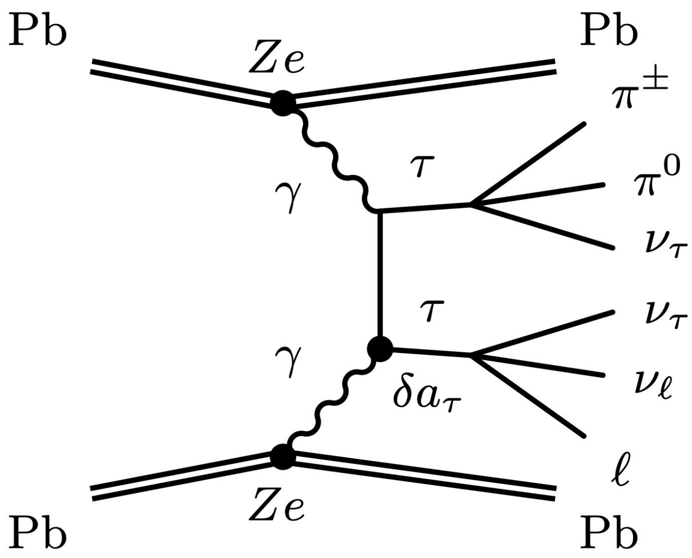
LEP photon collisions

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)

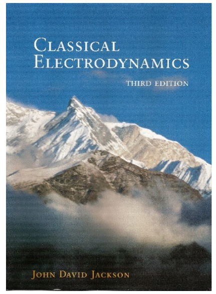
⇒ 1 million events *already*

Beresford, JL [1908.05180]

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

Photon collisions using MadGraph & SMEFTsim

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



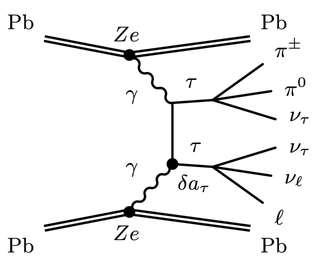
Photon flux: classical field theory

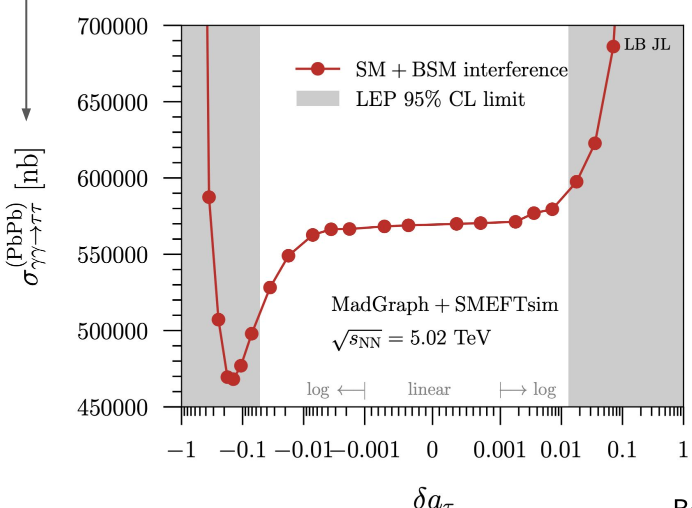
Add Chapter 15 §4 into MadGraph 2.6.5 with Fortran77

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

MadGraph **Jackson** **SMEFTsim**

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

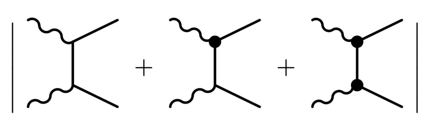




SMEFTsim: implement dim-6 in Feynrules

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



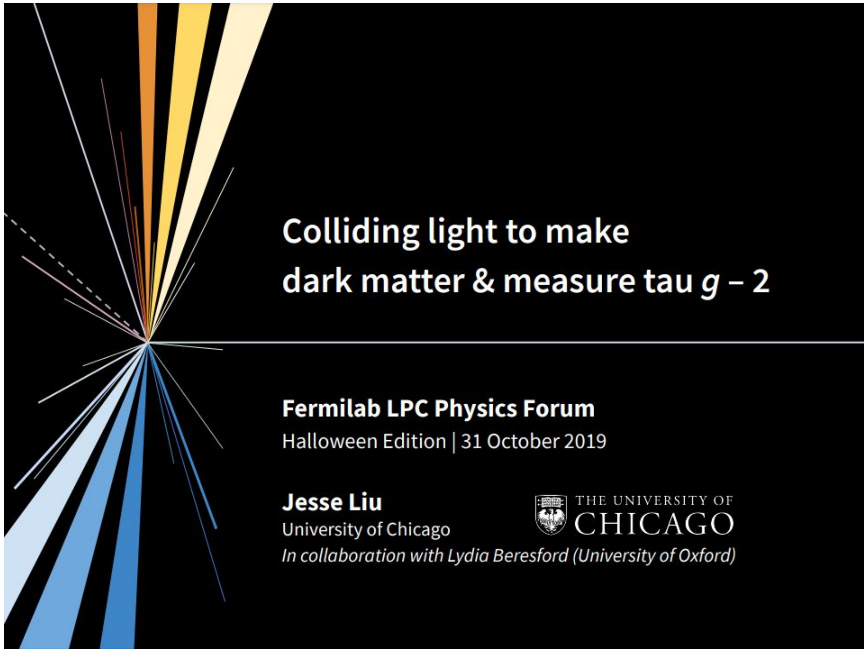
$$\delta a_\tau \sim \frac{C}{\Lambda^2}\left(\bar{L}_\ell\sigma^{\mu\nu}\ell_R\right)H\left(\partial_\mu A_\nu\right)$$

Beresford, JL [1908.05180]

31 OCT 2019: AN OCEAN APART

Lydia & I gave seminars proposing new idea

Lydia's Warwick seminar



My Fermilab seminar

🥳 Now: CMS & ATLAS breakthroughs realizing our idea 🎉

Available on the CERN CDS information server **CMS PAS HIN-21-009**

CMS Physics Analysis Summary

Contact: cms-pag-conveners-heavyions@cern.ch 2022/03/17

Observation of τ lepton pair production in ultraperipheral nucleus-nucleus collisions

The CMS Collaboration

Abstract

The first observation of τ lepton pair production in ultraperipheral nucleus-nucleus collisions, a pure quantum electrodynamics (QED) process, is presented. The measurement is based on a data sample collected by the CMS experiment at a per nucleon center-of-mass energy of 5.02 TeV, and corresponding to an integrated luminosity of 404 μb^{-1}. The photon-induced $\gamma\gamma \to \tau^+\tau^-$ production is observed with a statistical significance of at least five standard deviations for $\tau^+\tau^-$ events with a muon and three charged hadrons in the final state. The cross section is measured in a fiducial phase space region, and is found to be $\sigma(\gamma\gamma \to \tau^+\tau^-) = 4.8 \pm 0.6 (\text{stat}) \pm 0.5 (\text{syst})\ \mu b$, in agreement with leading-order QED predictions. The measurement, produced with a fraction of the expected integrated luminosity of the LHC program, establishes the potential for a substantially more precise determination of the anomalous magnetic moment of the τ lepton, which is currently poorly constrained.

↑ Announced Moriond EWK 2022

CMS-PAS-HIN-21-009

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Phys. Rev. Lett.

CERN-EP-2022-079
April 29, 2022

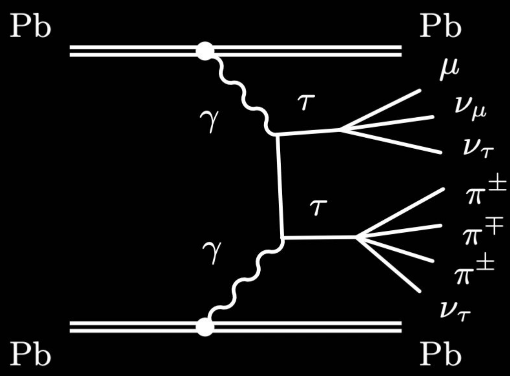
Observation of the $\gamma\gamma \to \tau\tau$ process in Pb+Pb collisions and constraints on the τ-lepton anomalous magnetic moment with the ATLAS detector

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 $\sqrt{s_{\text{NN}}} = 5.02$ 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 $a_\tau \in (-0.058, -0.012) \cup (-0.006, 0.025)$.

↑ Announced Quark Matter 2022

ATLAS (JL Editor) 2204.13478



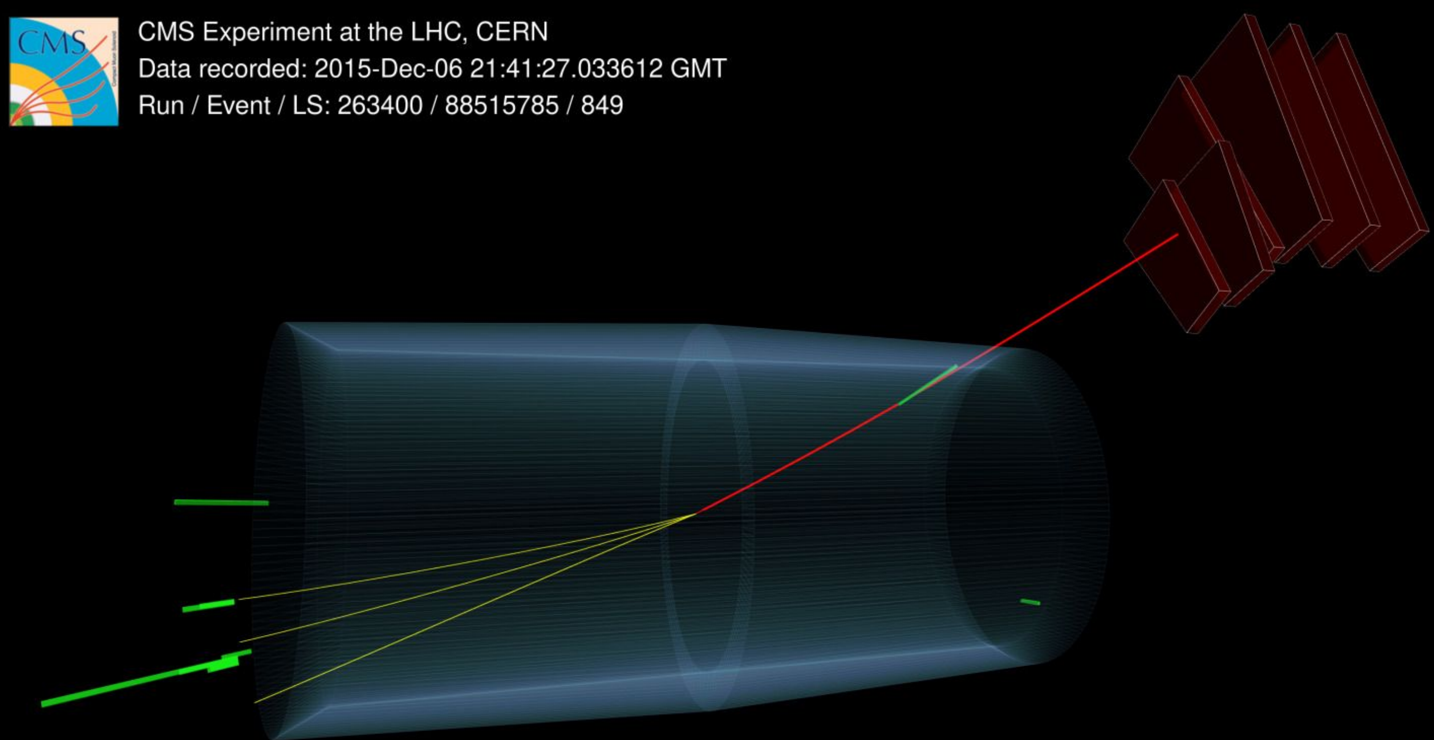
STUNNING TRIDENT EVENT

PbPb → Pb ($\gamma\gamma \to \tau\tau$) Pb

1 month to collect ~ few nb^{-1}

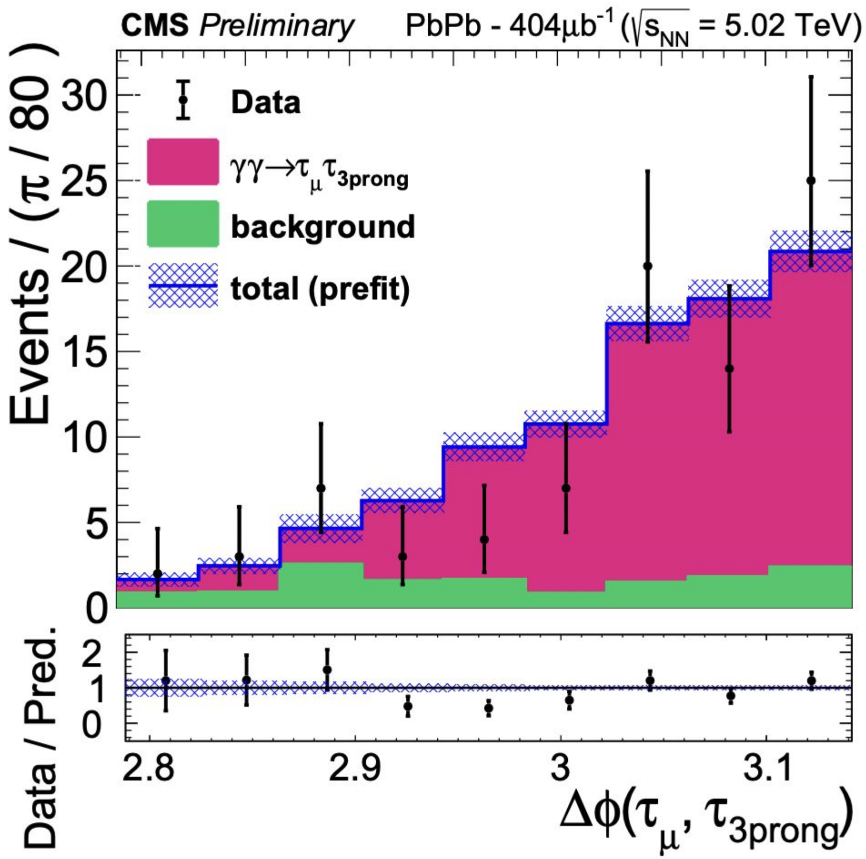
Negligible pileup μ ~ per mille

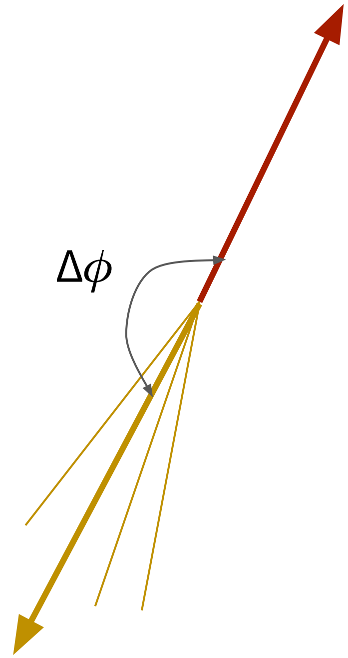
Loose triggers pT ~ few GeV



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

CMS successfully follows our 1μ + 3-track proposal





2015 PbPb data [PAS-HIN-21-009]

Signal yield: N_{sig} = 77 ± 12

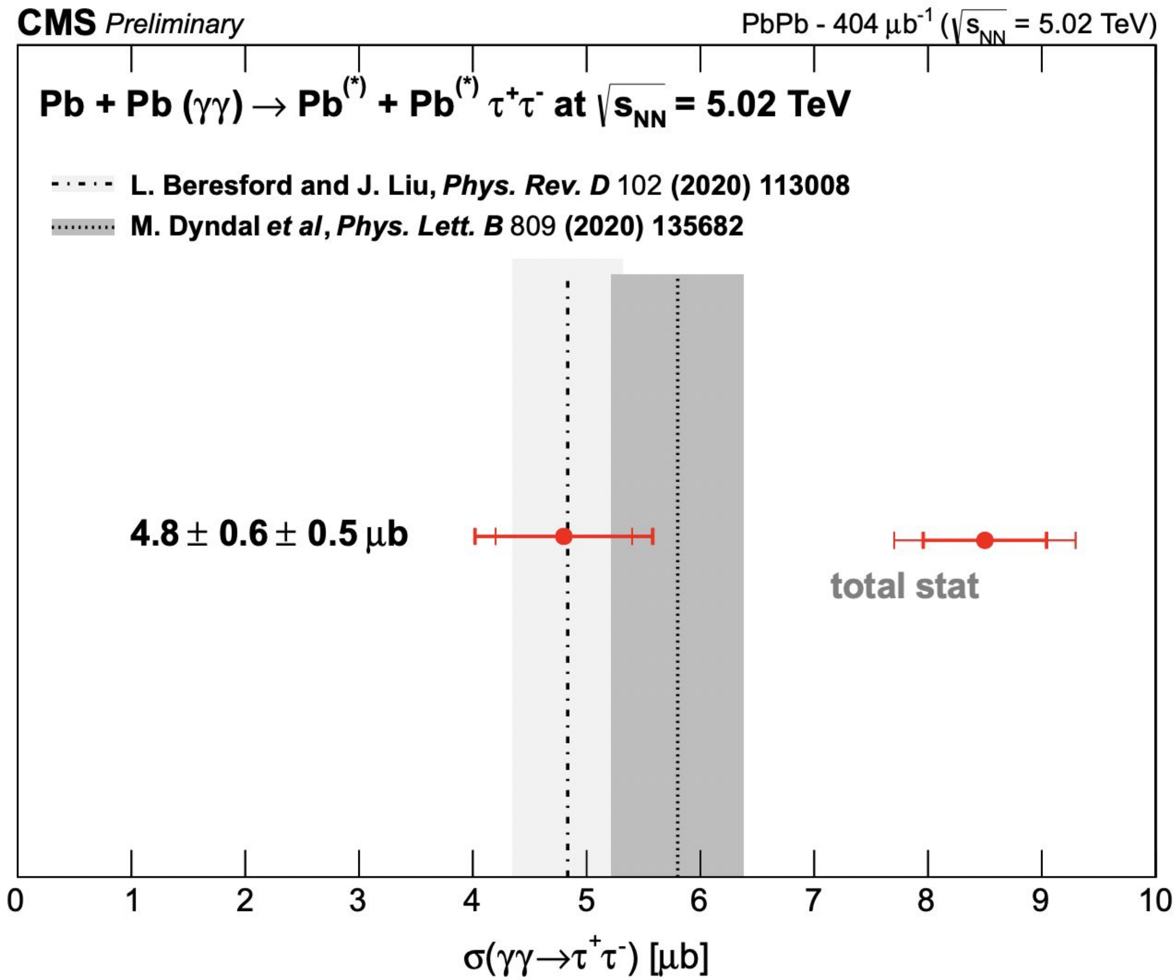
→ Event selection & fiducial definition

For the μ	$p_T > 3.5\,\text{GeV}$ for $\lvert\eta\rvert < 1.2$ $p_T > 2.5\,\text{GeV}$ for $1.2 < \lvert\eta\rvert < 2.4$
For the pions	$p_T^{\text{leading}} > 0.5\,\text{GeV}$ & $p_T^{\text{subleading}} > 0.3\,\text{GeV}$ for the (sub-)subleading $\lvert\eta\rvert < 2.5$
For the $\tau_{3\text{prong}}$	$p_T^{\text{vis}} > 2\,\text{GeV}$ and $0.2 < m_\tau^{\text{vis}} < 1.5\,\text{GeV}$

First PbPb → Pb(γγ → $\tau\tau$)Pb cross-section measurement

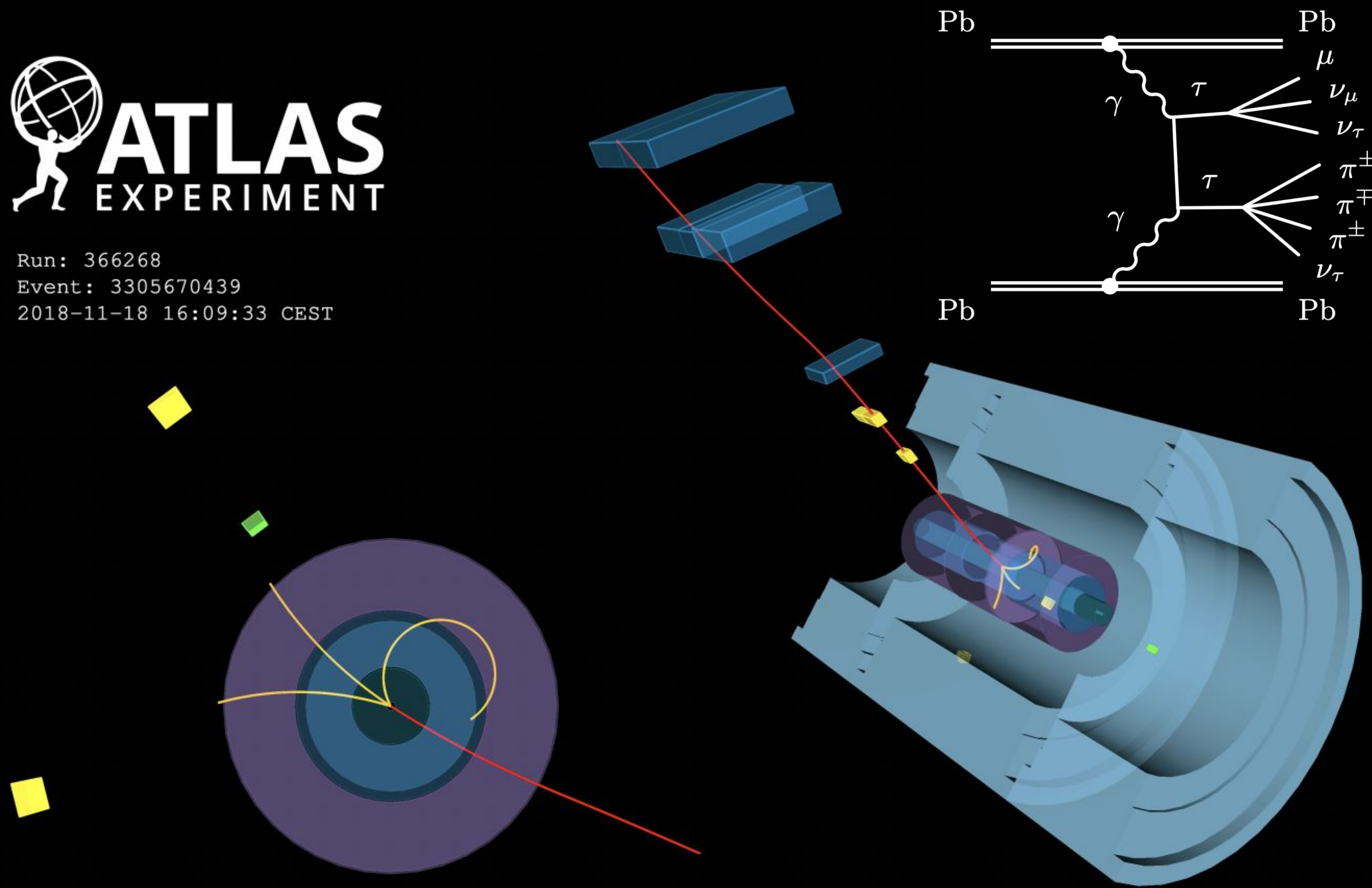
Jackson Electrodynamics works! 😅 →

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



Remarkable result 🤩 …and just getting started!

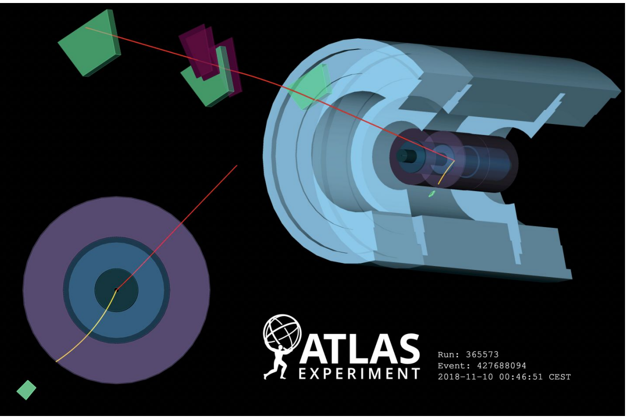
Dominant systematics: muon scale factors (5%), luminosity (5%), pion scale factor (4%)

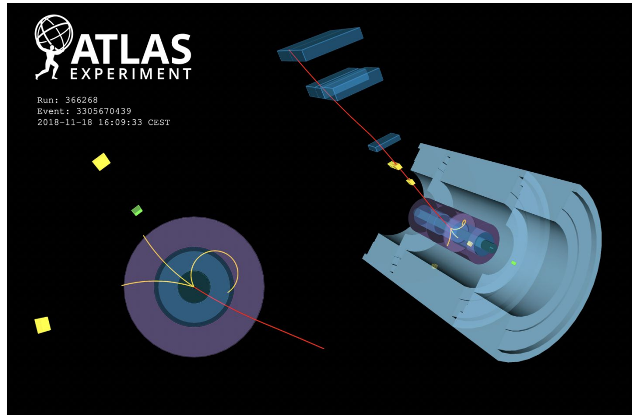


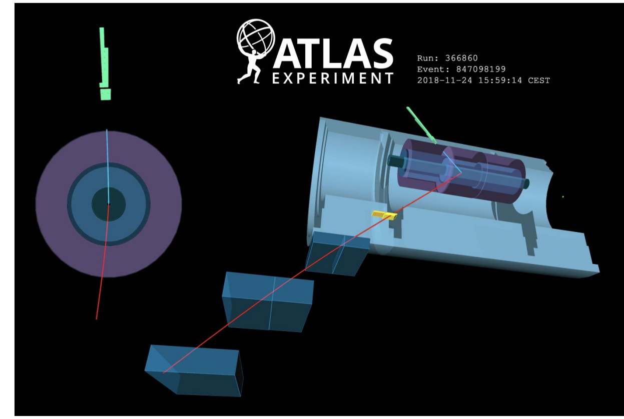
↑ *All charged-particle tracks above 100 MeV are shown; muon trigger pT > 4 GeV*

ATLAS (JL Editor) 2204.13478

ATLAS analyses 2018 data in our 3 proposed channels



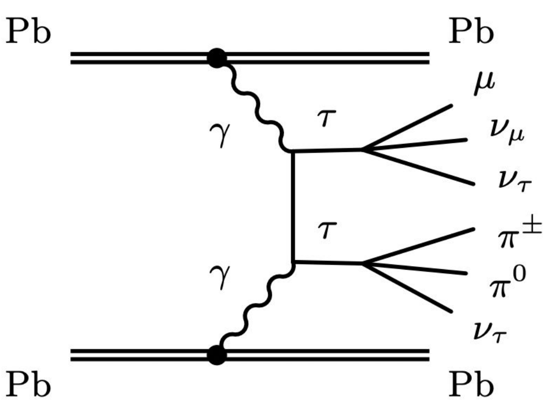


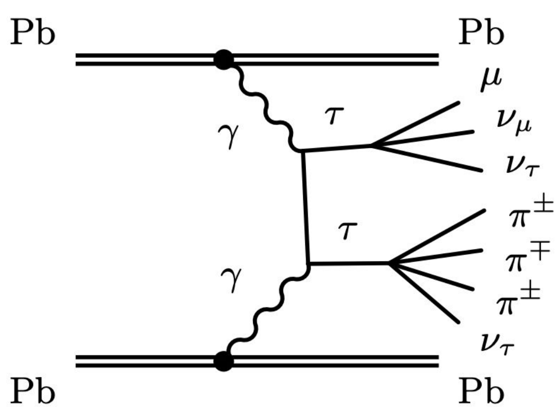


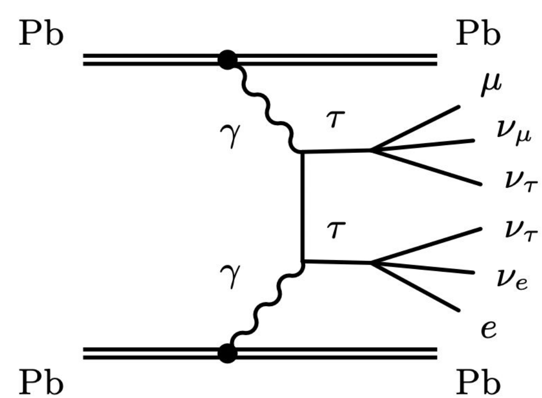
1 muon + 1 track (μ1T-SR)

1 muon + 3 tracks (μ3T-SR)

1 muon + 1 electron (μe-SR)







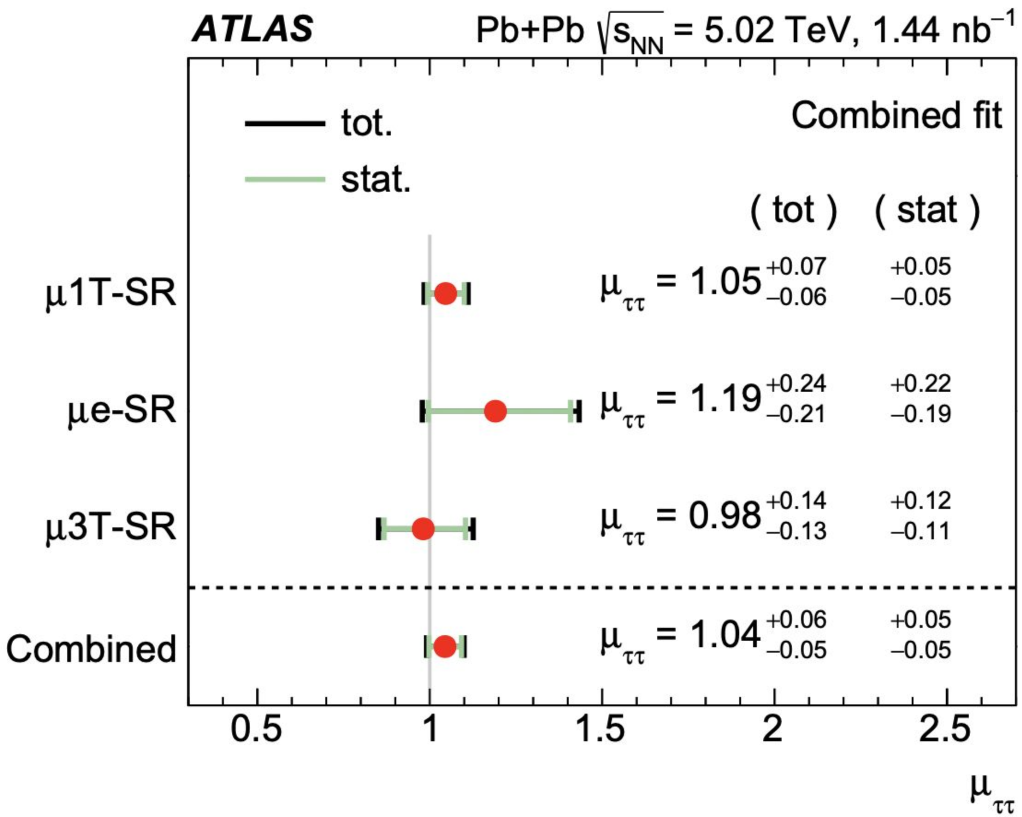
$N_{obs} = 532$, $N_{bkg} = 84 \pm 19$

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

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

ATLAS (JL Editor) 2204.13478

Precision currently limited by data sample size

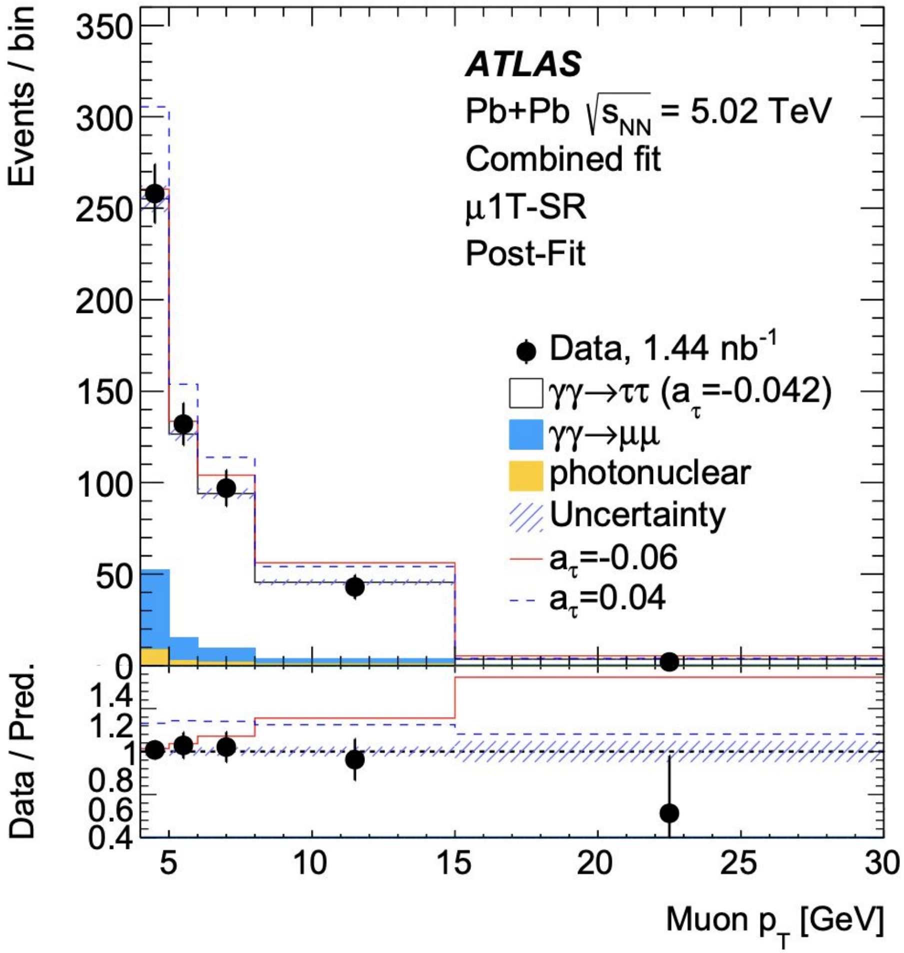


Signal strength $\mu_{\tau\tau}$ = observed rate / expected SM rate

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

ATLAS (JL Editor) 2204.13478

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

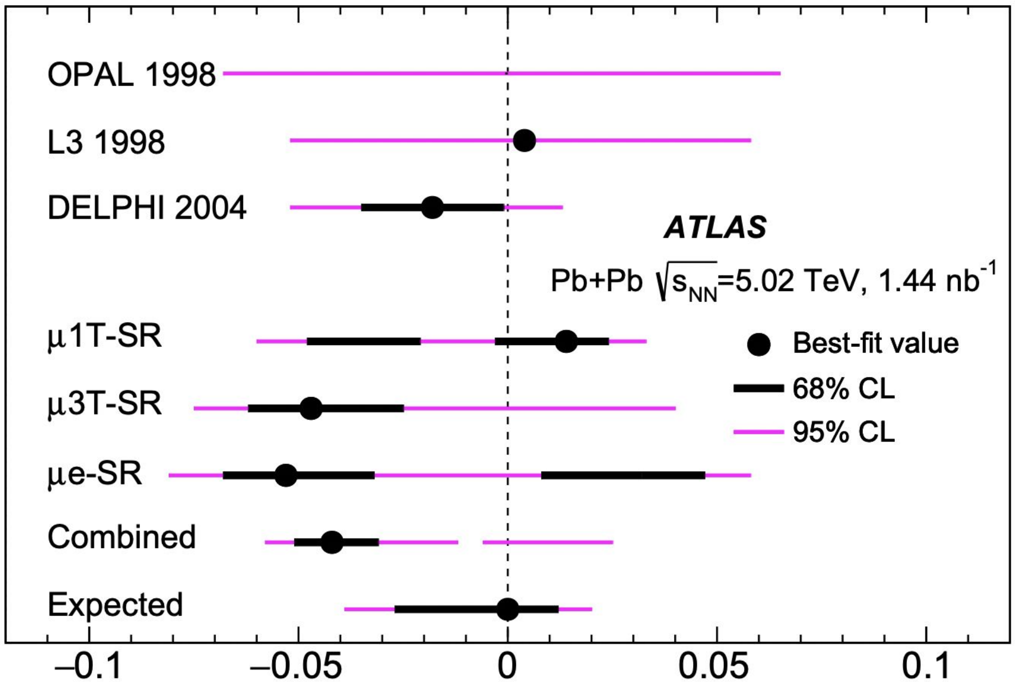
ATLAS (JL Editor) 2204.13478

Groundbreaking results competitive with LEP

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

First time taus analysed in heavy ion collisions

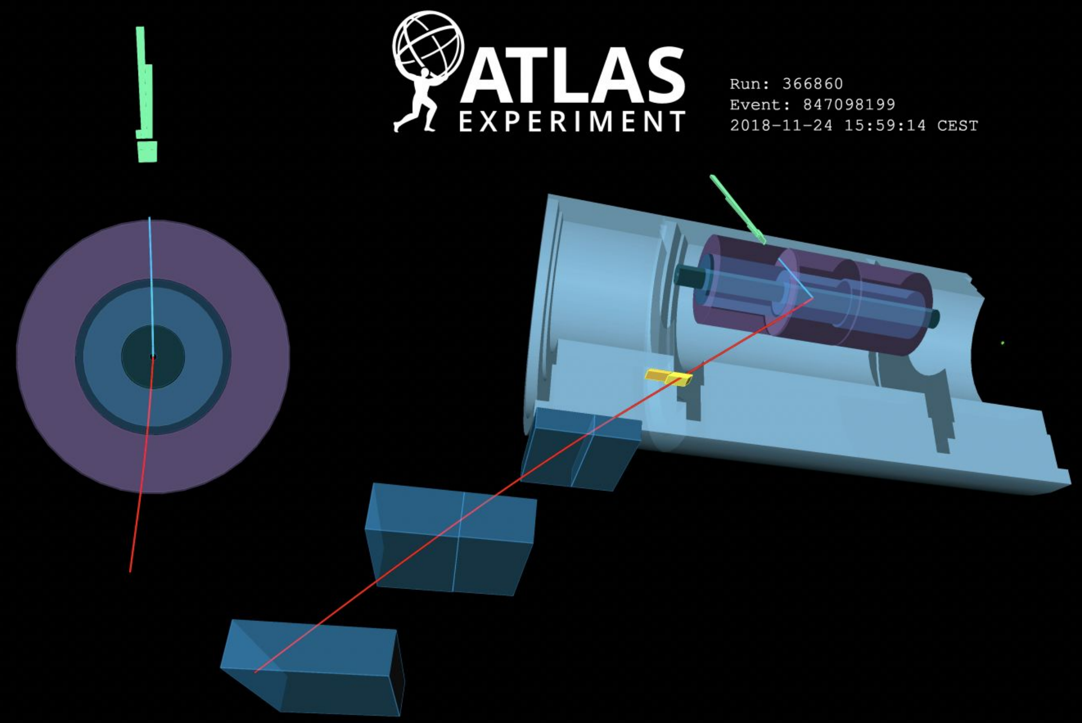
Heavy ions enabled 5% measurement of QED g_τ



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

ATLAS (JL Editor) 2204.13478

LET'S REFLECT FOR A MOMENT



Foundational O(mb) cross-section SM process

was not observed at the LHC until last month

Consider severe implication for BSM searches…

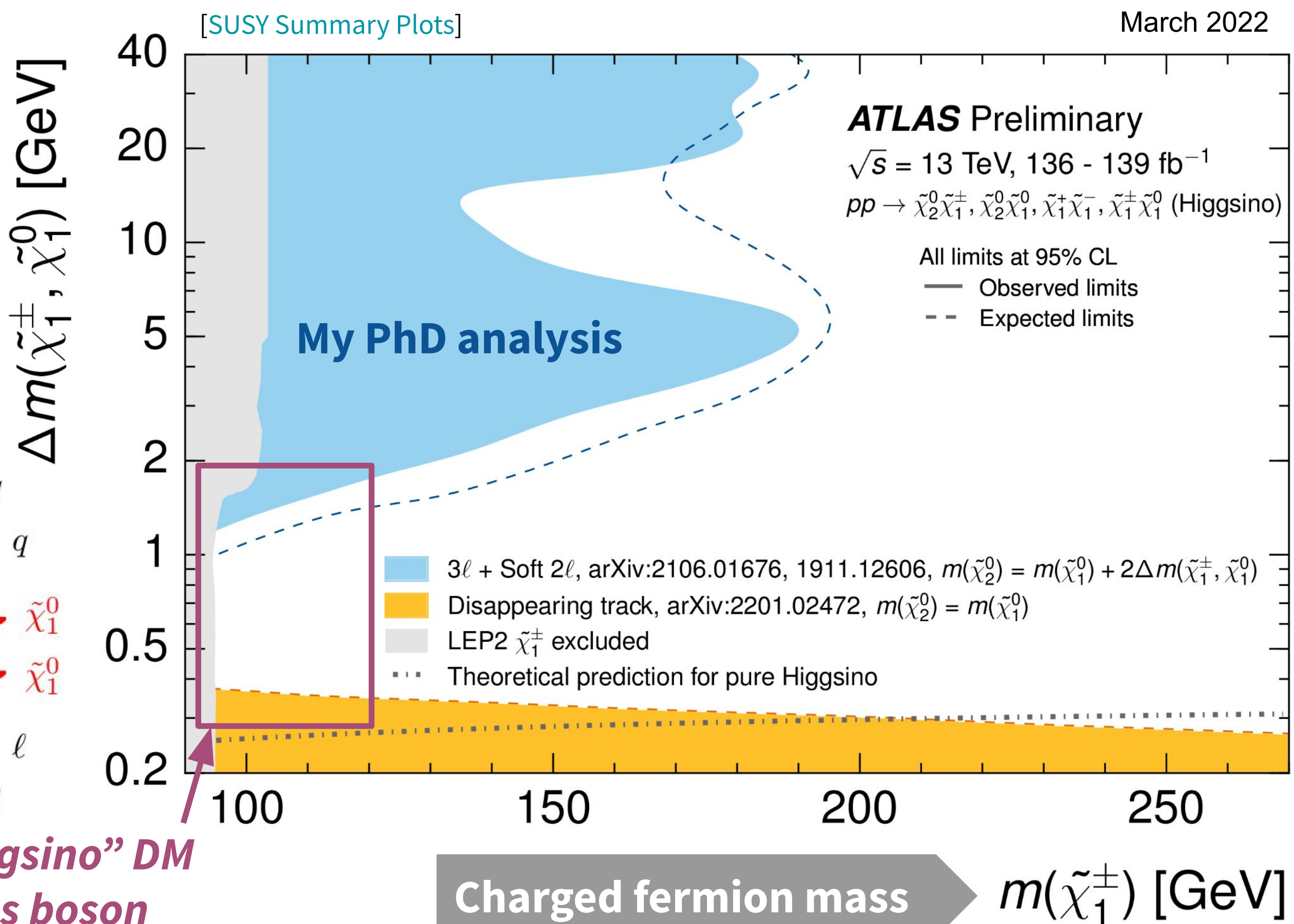
DEEPEST SCIENTIFIC TRAGEDY

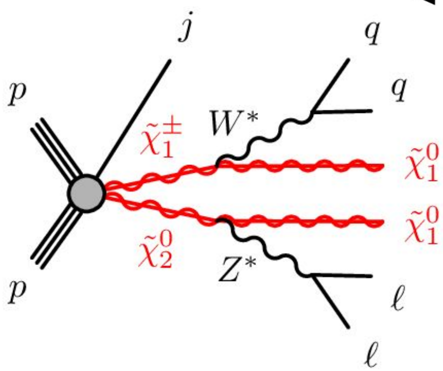
is not if new physics were absent at the weak scale

It's if we were **capable of making** new physics
but **incapable of seeing** it

LHC could be Higgsino DM factory & we'd have no idea!

Charged–DM mass splitting





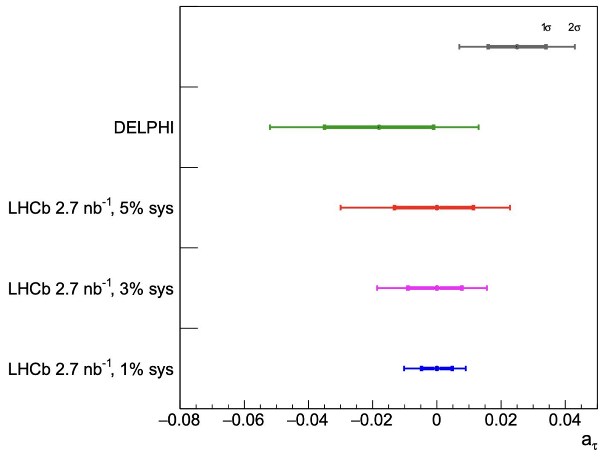
Higgs fermion "Higgsino" DM lighter than Higgs boson STILL experimentally viable

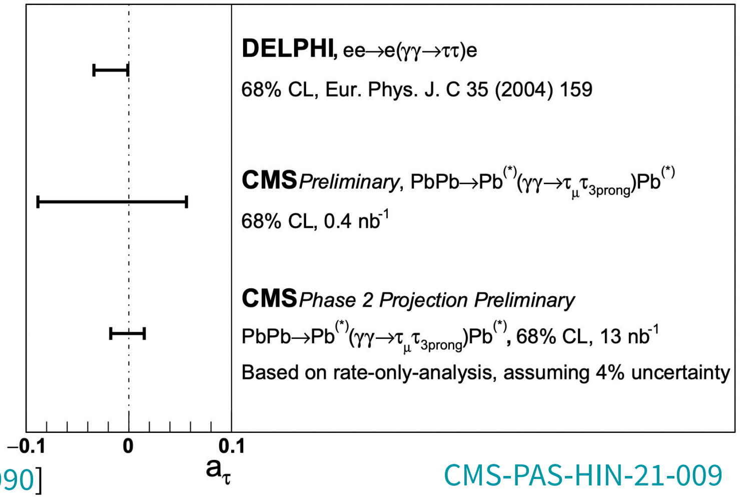
Charged fermion mass

$m(\chi)$ ~ 100 GeV: $\sigma(pp \to \chi\chi) \times \mathcal{L}$ ~ 16800 fb × 140 fb^{-1} ~ 2.4 million events

Fuks et al [1304.0790, LHC SUSY cross-sections], Thomas & Wells [hep-ph/9804359]

Every innovative idea strengthens HL-LHC science



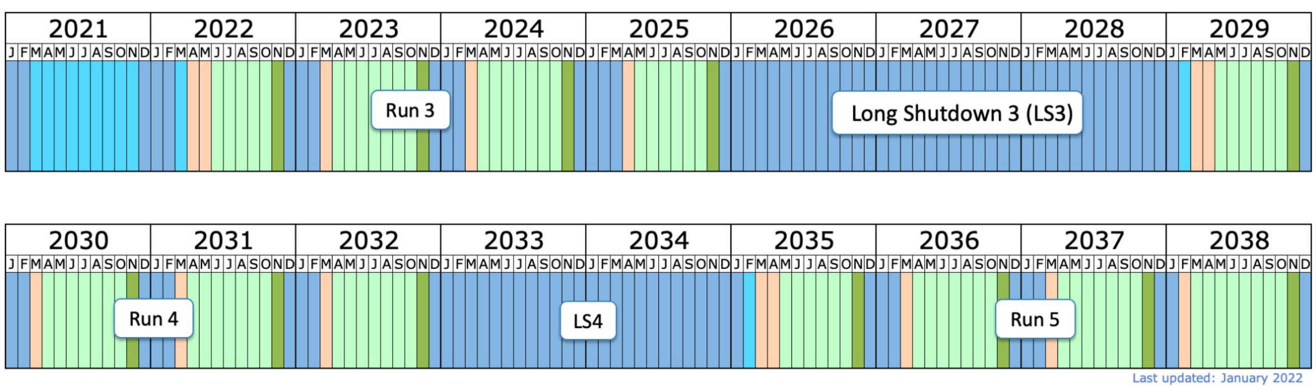


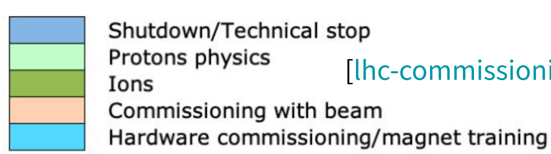
LHCb+ALICE too! Burmasov et al [2203.00990]

CMS-PAS-HIN-21-009

d'Enterria et al [2203.05939]

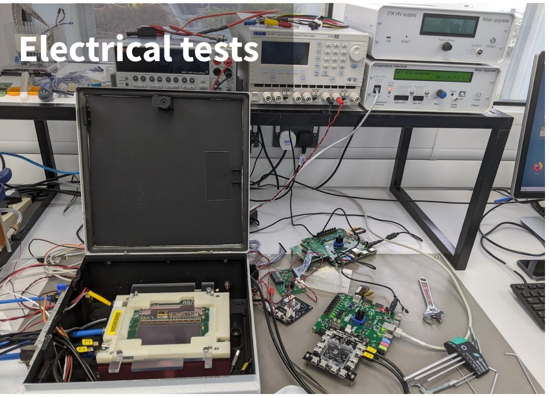
Pb-Pb	runtime	ATLAS/CMS	ALICE	LHCb
	1 month	2.1–2.5 nb^{-1}	2.5–2.8 nb^{-1}	$<$ 0.5 nb^{-1}
	5 months	10.5–12.5 nb^{-1}	12.5–14.0 nb^{-1}	$<$ 2.5 nb^{-1}

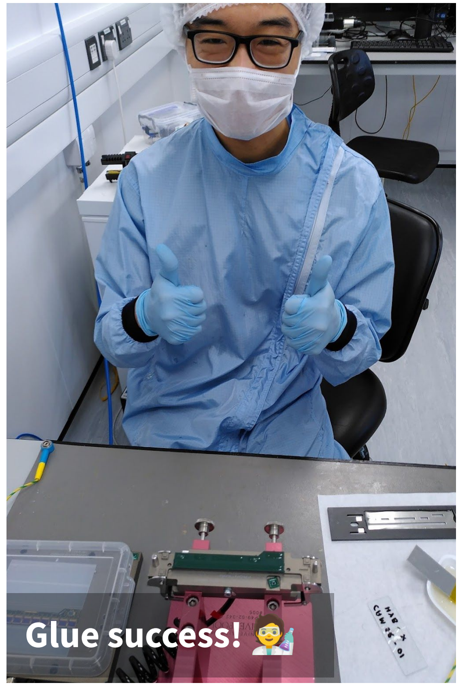


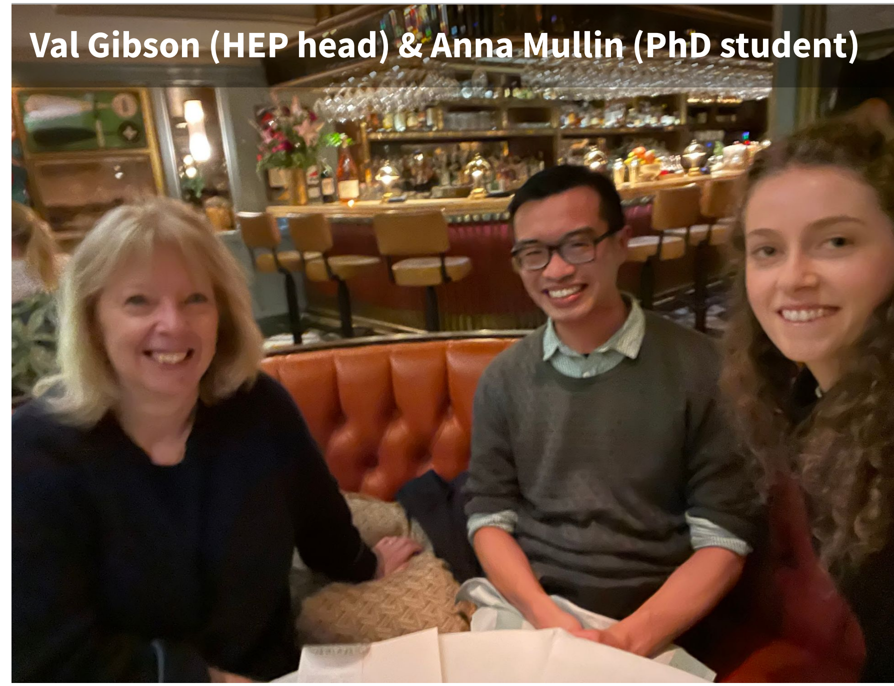


[lhc-commissioning.web.cern.ch]

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







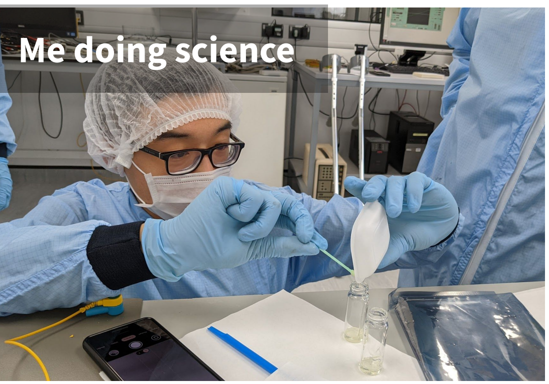
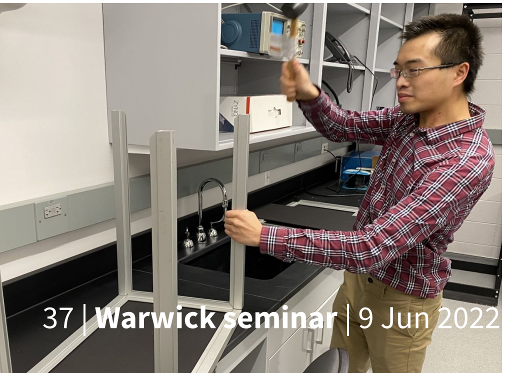


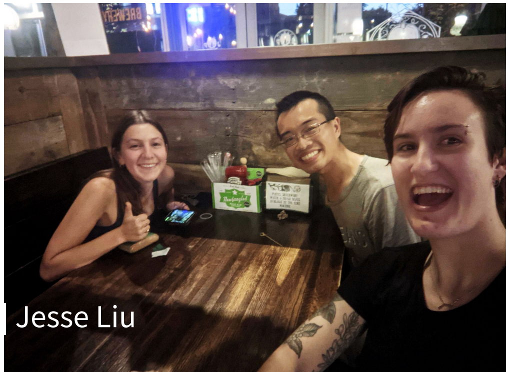
Photo credits: Bart Hommels, Val Gibson, Will Fawcett

PART 2

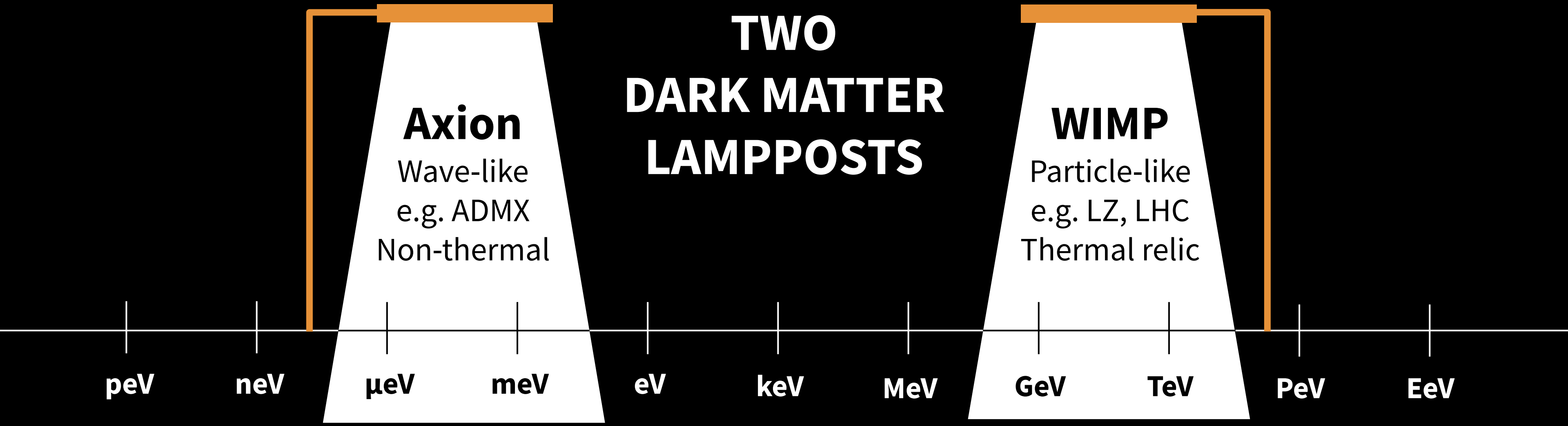
BABY STEPS TOWARDS BREAD

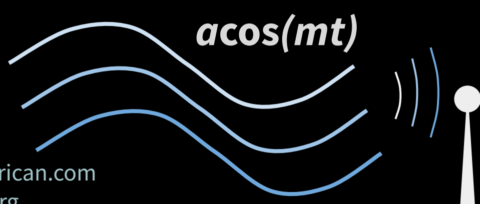
POSTDOC YEARS @ UCHICAGO (2019–21)

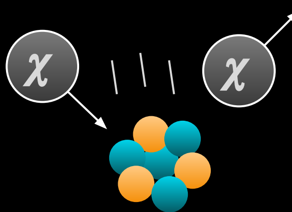




TWO DARK MATTER LAMPPOSTS

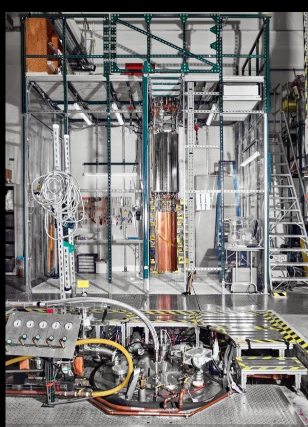


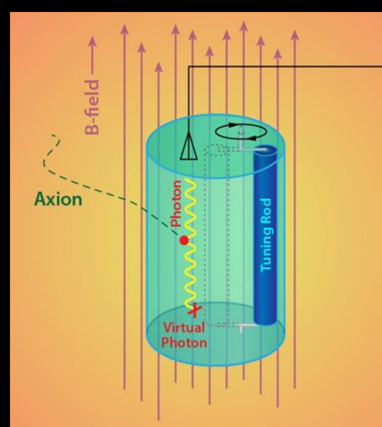


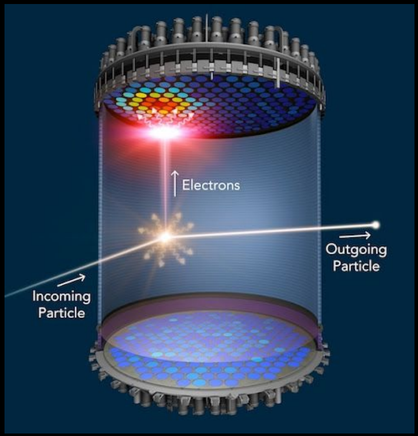


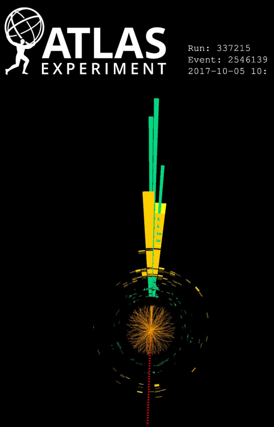
scientificamerican.com
physics.aps.org

lz.ac.uk
2102.10874

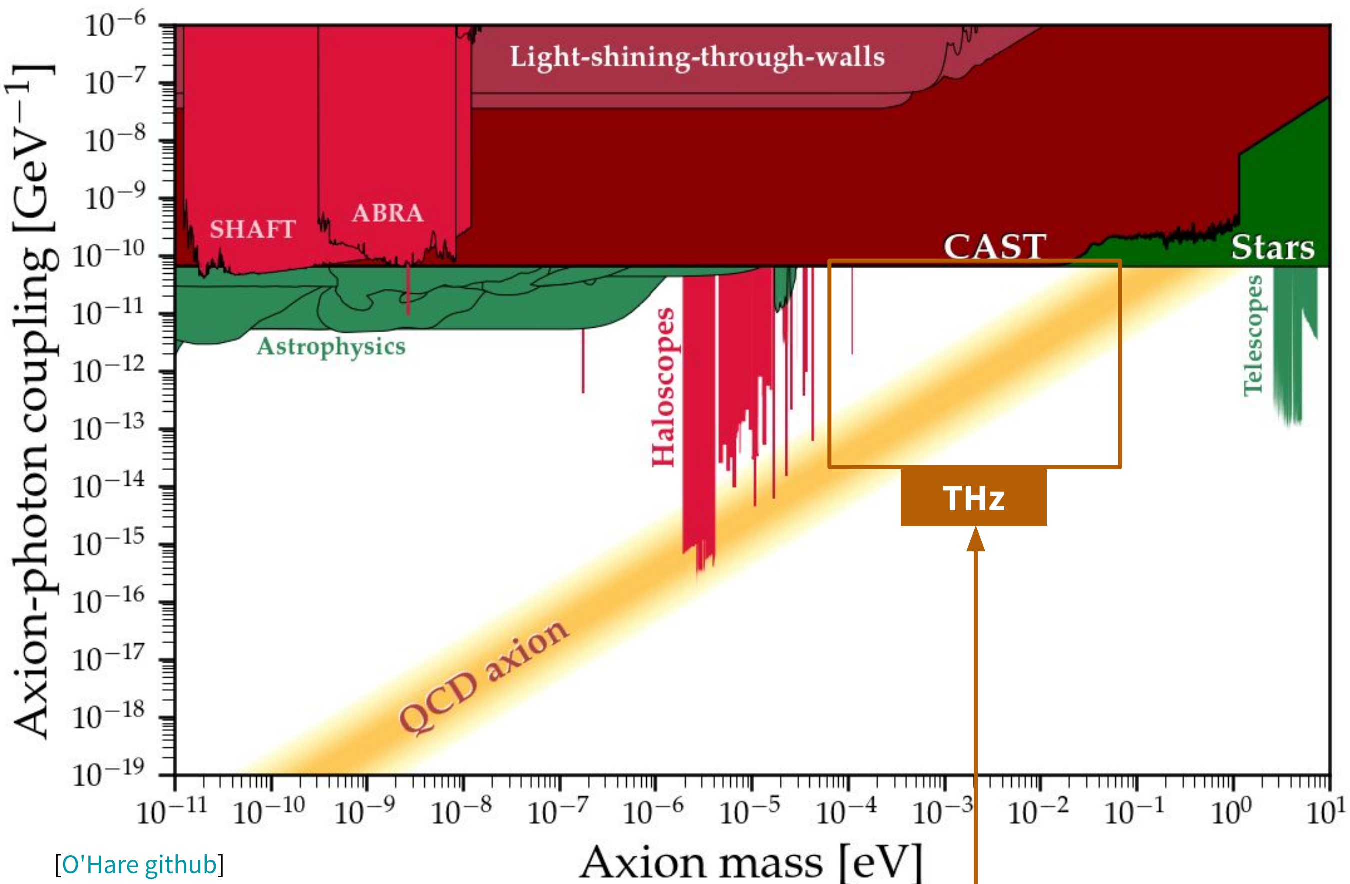








The milli-eV/terahertz axion search problem



[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

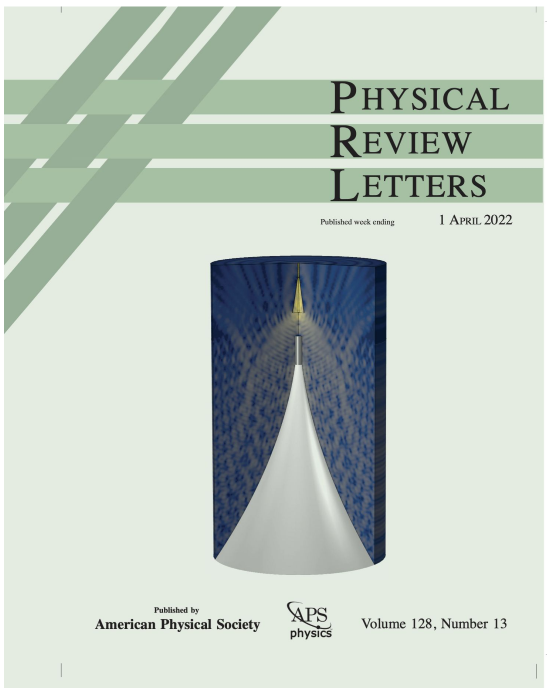
Simulation of the full electric field inside the conceptual design of the Broadband Reflector Experiment for Axion Detection (BREAD). Selected for an Editors' Suggestion.

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)



BREAD roadmap to flagship next-gen axion experiment

BREAD	Pilot	Stage 1	Stage 2a	Stage 2b
Axion a	—	✓	✓	✓
Dark photon A'	✓	✓	✓	✓
Experimental parameters				
A_{dish} [m^2]	0.7	10	10	10
B_{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)				
$\lvert g_{a\gamma\gamma}/g_{a\gamma\gamma}^{\text{KSVZ}}\rvert$	—	280	9.0	0.90
$\lvert g_{a\gamma\gamma}/g_{a\gamma\gamma}^{\text{DFSZ}}\rvert$	—	740	23	2.3
$\kappa/10^{-14}$	8400	22	0.7	0.07

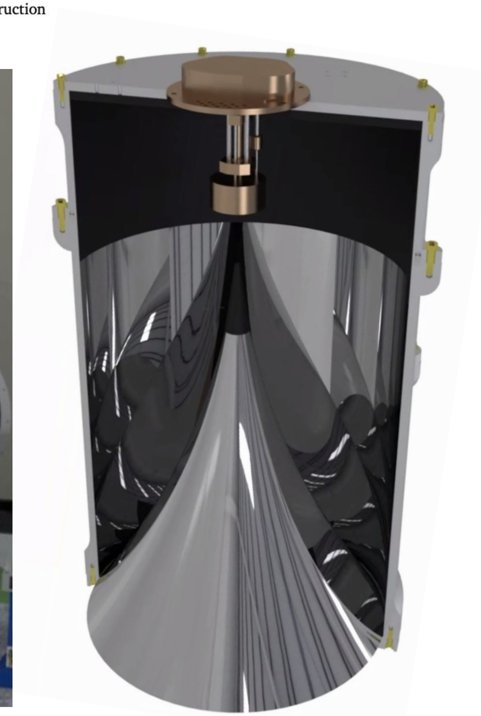
Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

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

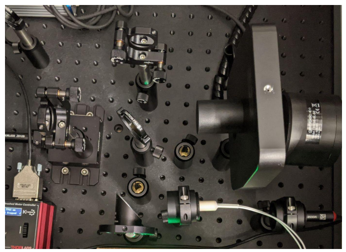
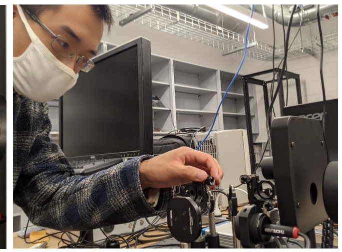
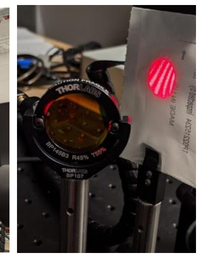
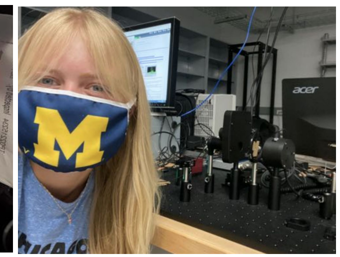


Hands on 1: build spectrometer to characterize optics

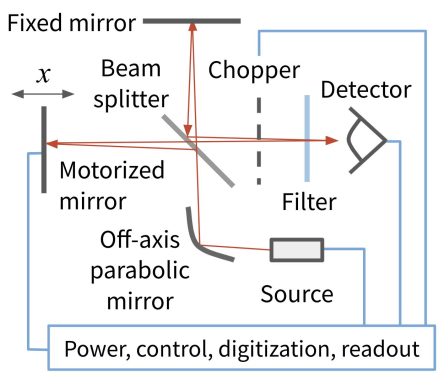
JANUARY 2020
Hardware arrival & assembly

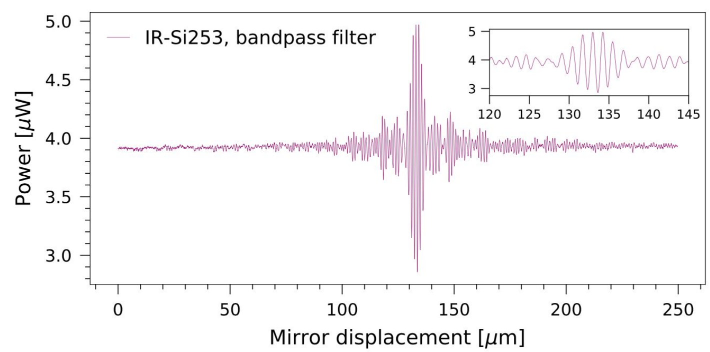


AUGUST
Laser alignment

OCTOBER
Begin measurements





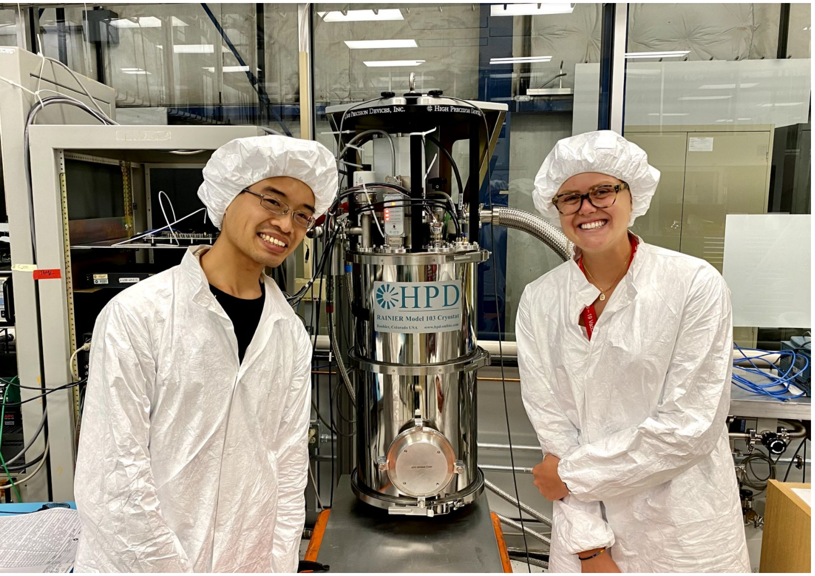
APRIL 2021
Write up
2104.07157
Accepted by JINST (2022)

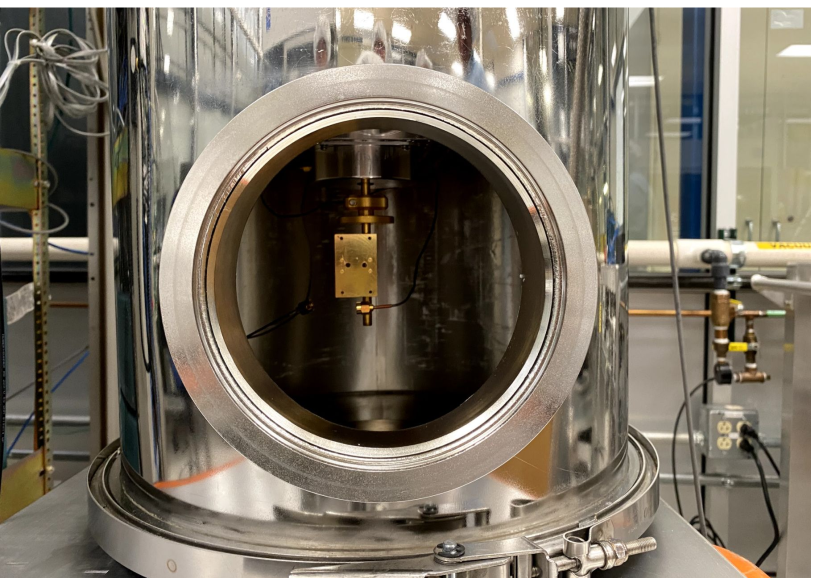
Design and performance of a multi-terahertz Fourier transform spectrometer for axion dark matter experiments

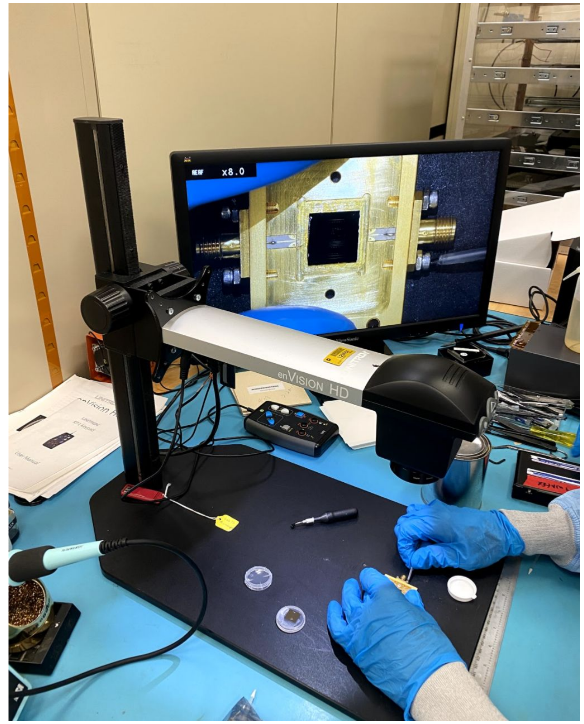
Kristin Dona,[1,*] Jesse Liu,[1,†] Noah Kurinsky,[2,3,‡] David Miller,[1,§]
Pete Barry,[2,4] Clarence Chang,[2,4] and Andrew Sonnenschein[3,¶]
[1]Department of Physics, University of Chicago, Chicago IL 60637, USA
[2]Kavli Institute for Cosmological Physics, University of Chicago, Chicago IL 60637, USA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

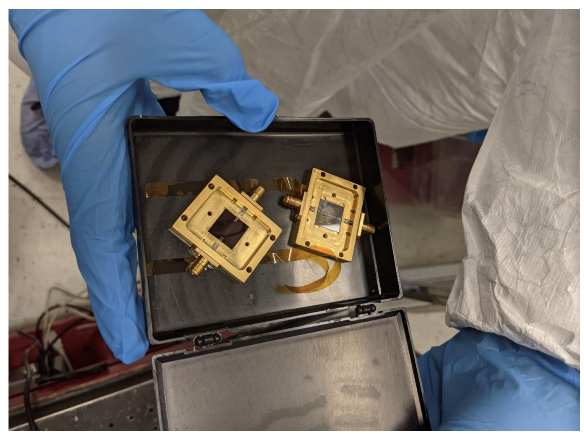
Funded by DOE HEP-QIS QuantISED grant with FNAL and Argonne collaborators

Hands on 2: sensor testing for BREAD pilot @ FNAL





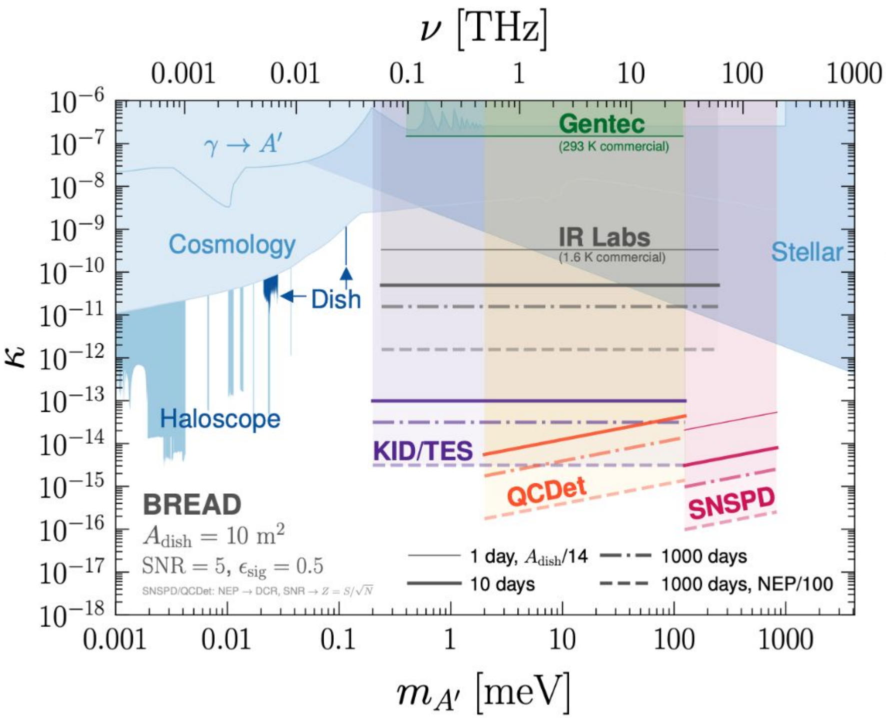


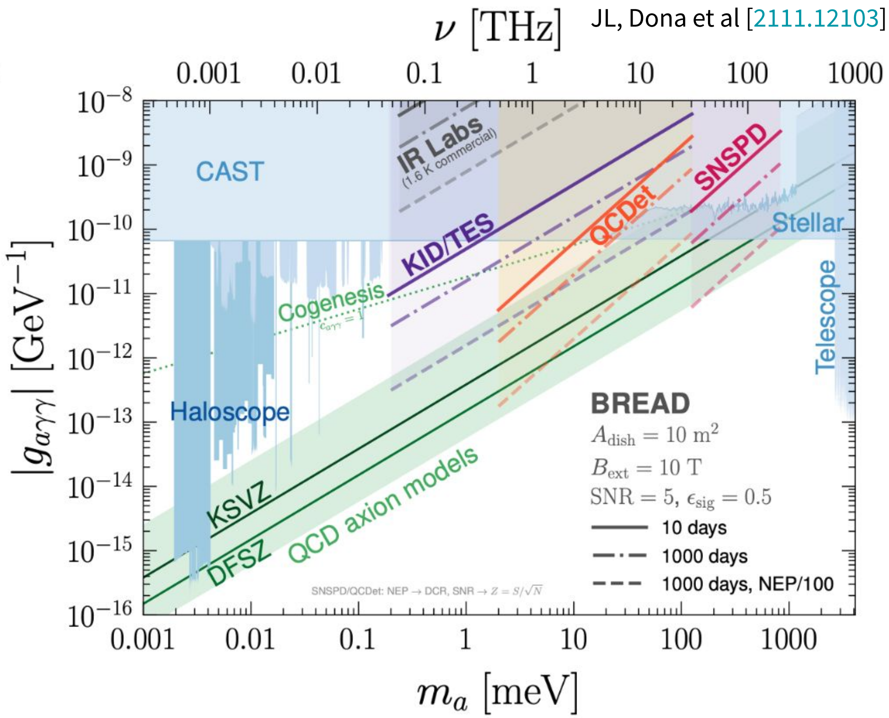


Kristin Dona, Stefan Knirck, JL, Andrew Sonnenschein pictured;
thanks to Israel Hernandez, David Miller, Tony Zhou et al

Sensitivity: concept → pilot → full science program

JL, Dona et al [2111.12103]





DARK PHOTON (VECTOR)

Preparing "sourdough starter" pilot

Near term ~3 years proof of principle

AXION (PSEUDOSCALAR)

Need high-field magnet & sensor R&D

Longer term ~5-10 year timescale

BREAD
COLLABORATION

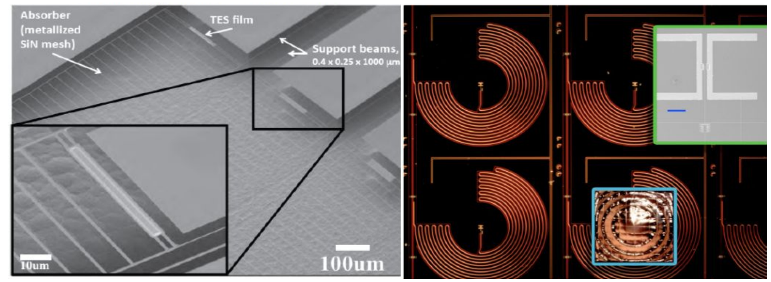
$$\left\{\begin{array}{c}\left(\frac{g_{a\gamma\gamma}}{10^{-12}}\right)^2\\ \left(\frac{\kappa}{10^{-15}}\right)^2\end{array}\right\} = \left\{\begin{array}{c}\frac{3.0}{\mathrm{GeV}^2}\left(\frac{m_a}{\mathrm{meV}}\right)^3\left(\frac{10\,\mathrm{T}}{B_\mathrm{ext}}\right)^2 \\ 11.9\,\frac{2/3}{\alpha_\mathrm{pol}^2}\,\frac{m_{A'}}{\mathrm{meV}}\end{array}\rig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

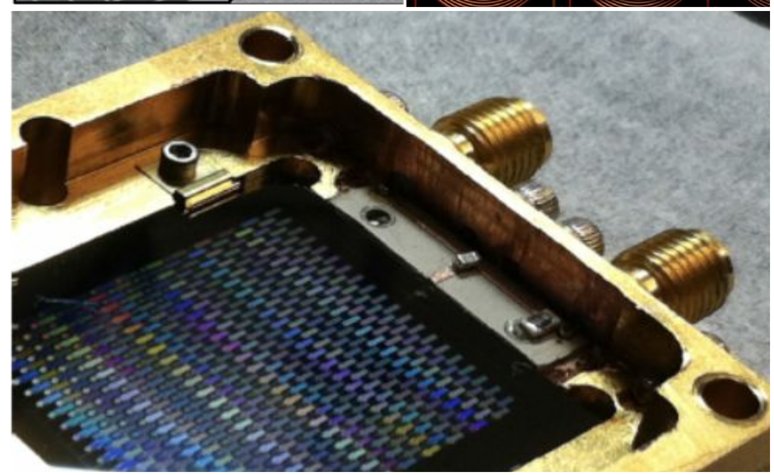
Innovation at interdisciplinary interfaces

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

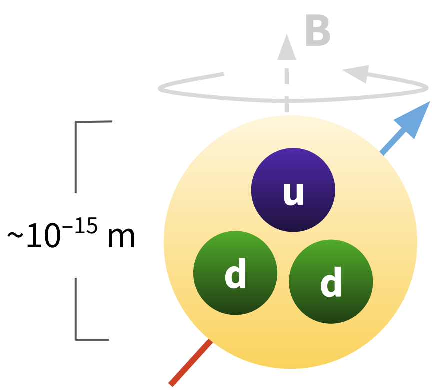
Neutron magnetic moment

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

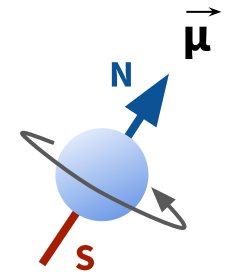
However, solution for neutron MDM **opens new problem with EDM**

MAGNETIC DIPOLE MOMENT (MDM)

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

Reality: huge & negative! :O

Solved: new physics → QCD ✔

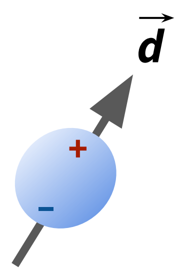


ELECTRIC DIPOLE MOMENT (EDM)

Expectation: large (strong CP violation)

Reality: 0 to 1 part per billion! :O

Solution: new physics → axions…?



THANK YOU

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