

The LHC as a Photon Collider & Cosmic-ray Lab

Particle Physics Seminar

Brookhaven National Laboratory

May 28, 2026

Jesse Liu

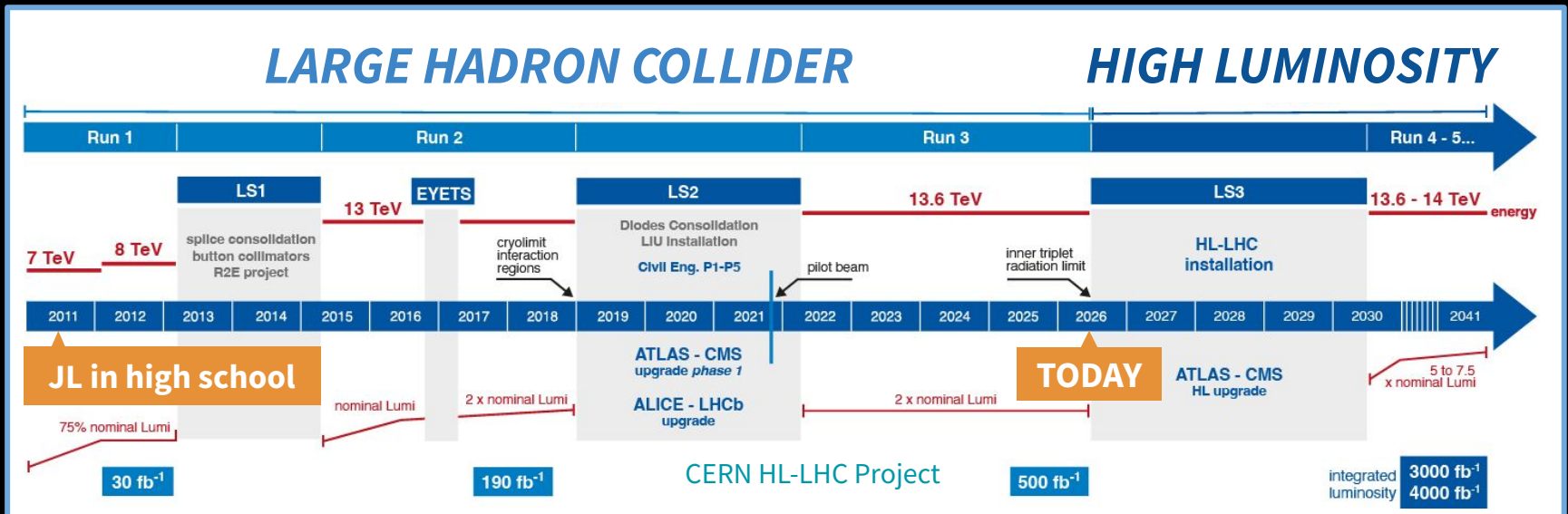
New York University



NYU

LANDSCAPE

Highest energy collider for another 30+ years



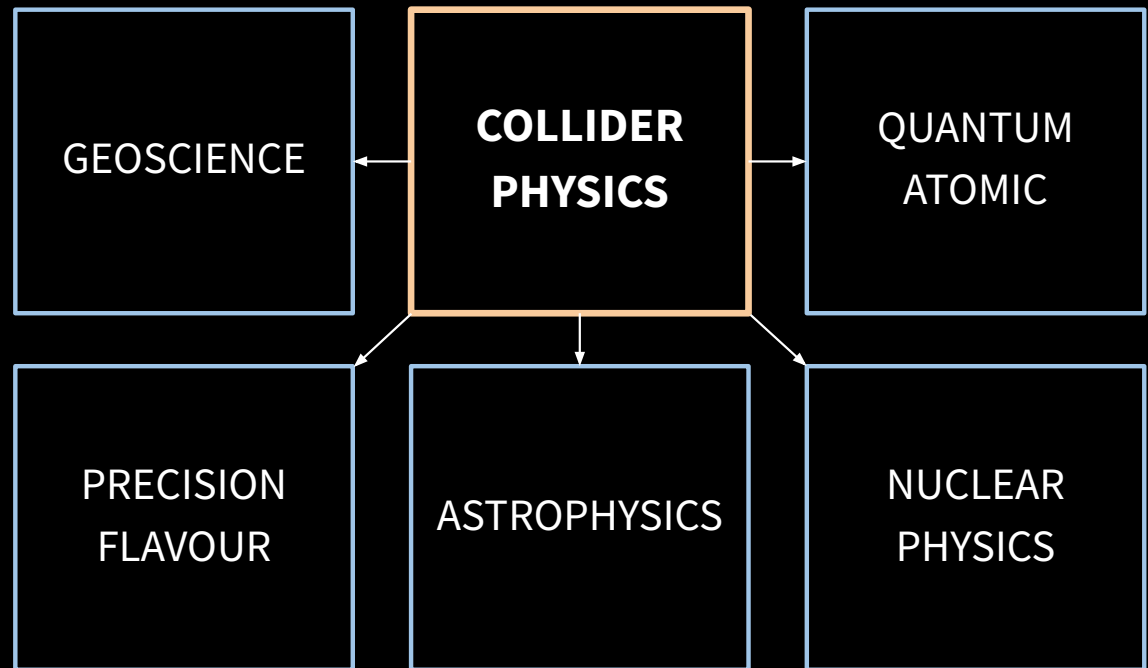
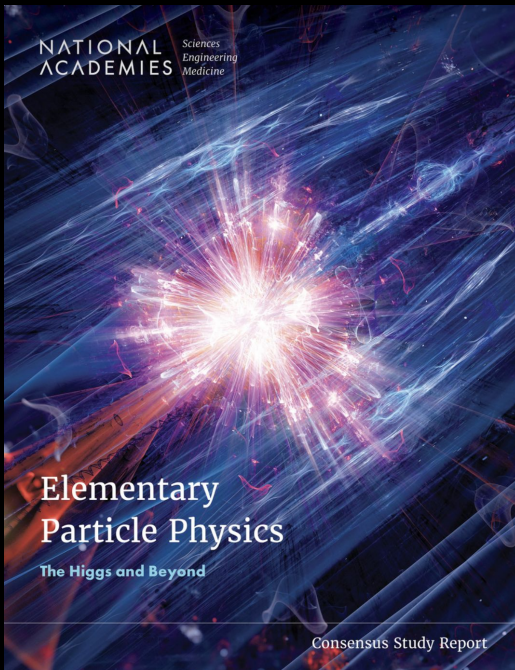
Last decade: 1.96 → 13 TeV
My PhD: simple ATLAS searches

Today: 13 → 13.6 TeV
Seek new ideas & science goals

Renaissance of creativity enabling exciting science

THINK OUTSIDE THE BOX

*“Recommendation 4: The United States should explore new synergistic **partnerships across traditional science disciplines and funding boundaries**”*

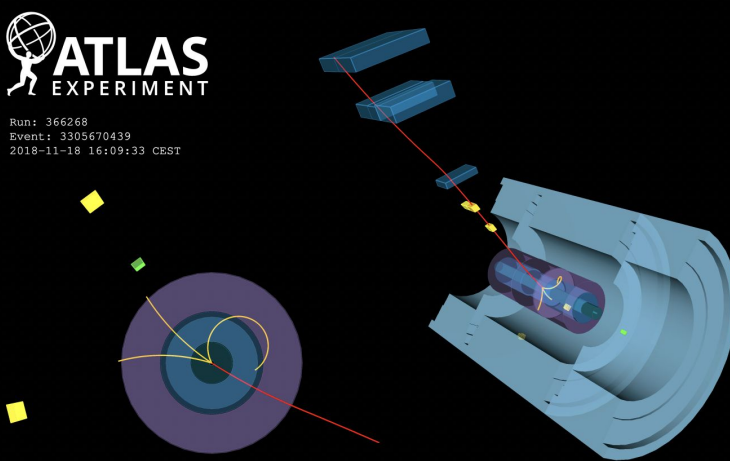


*“Cross-disciplinary work often leads to **innovation and breakthroughs but can be challenging** both for the scientists involved and for those who fund it”*

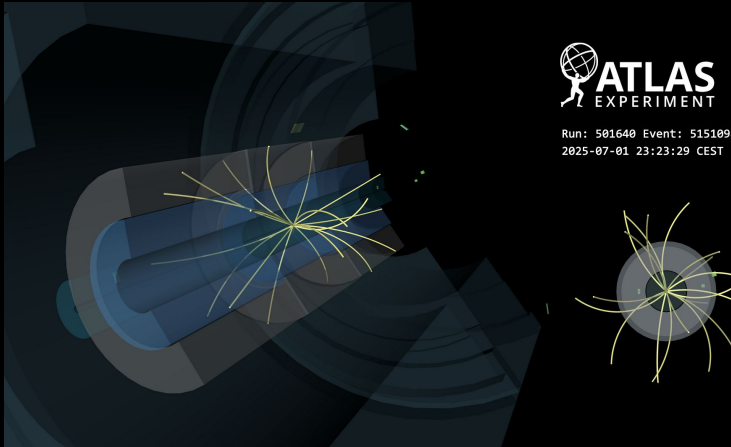
— National Academy of Sciences | Elementary Particle Physics Report 2025

OUTLINE

Broaden collider science across disciplinary boundaries



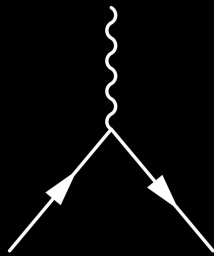
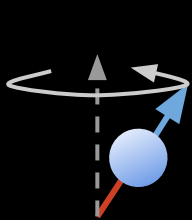
LHC as Photon Collider
Quantum dipole physics
Tau $g - 2$ via $\gamma\gamma \rightarrow \tau\tau$
QUANTUM + NUCLEAR + FLAVOUR



LHC as Cosmic-ray Lab
PeV astroparticle physics
Proton-oxygen collisions
PRECISION + NUCLEAR + ASTROPHYSICS

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

RELATIVISTIC QM
Antimatter exists



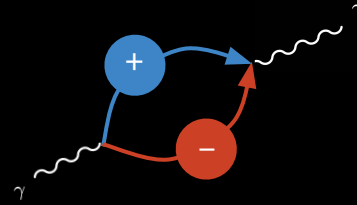
$g =$

2

Dirac 1928



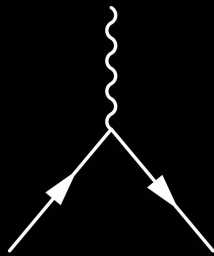
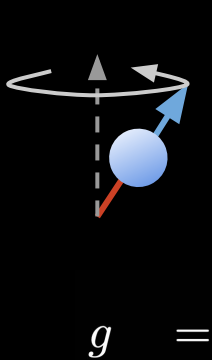
$$\boldsymbol{\mu}_f \cdot \mathbf{B} = \frac{g_f e}{2m_f} \mathbf{S} \cdot \mathbf{B}$$



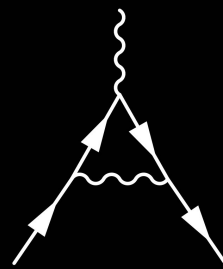
RELATIVISTIC QM
Antimatter exists



QUANTUM FIELDS
Dynamical vacuum



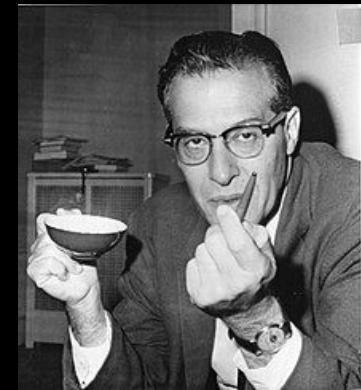
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+

Dirac 1928

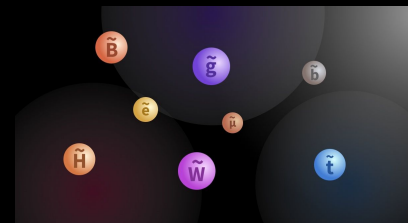
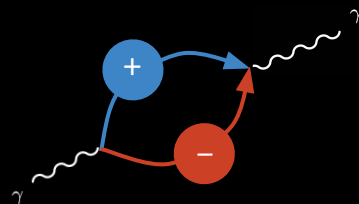
Schwinger 1948



QED: QUANTUM ELECTRODYNAMICS

$$a = (g - 2)/2 \approx \alpha/2\pi \approx 0.00116$$

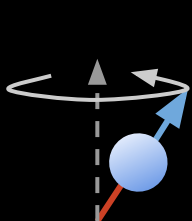
$$\mu_f \cdot \mathbf{B} = \frac{gfe}{2m_f} \mathbf{S} \cdot \mathbf{B}$$



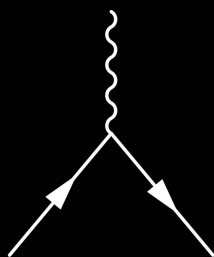
RELATIVISTIC QM
Antimatter exists

QUANTUM FIELDS
Dynamical vacuum

NEW PARADIGMS?
Dark matter?



$g =$

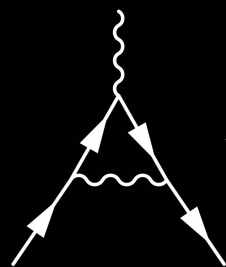


2

Dirac 1928

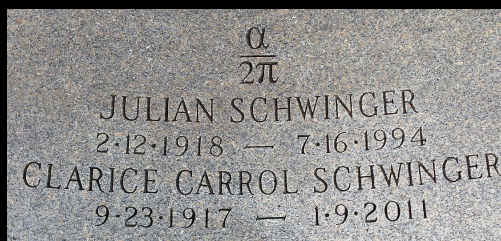


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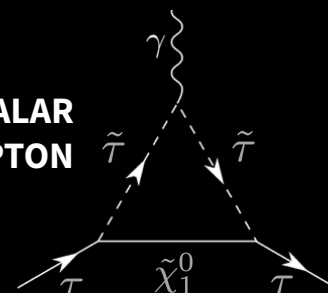
$\frac{\alpha}{\pi}$

Schwinger 1948



+

SCALAR LEPTON



DARK MATTER

New physics?

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

Electron $g - 2$ first measured in 1948

“Why measure next decimal place when theory predicts nothing?”

The Magnetic Moment of the Electron†

P. KUSCH AND H. M. FOLEY

Department of Physics, Columbia University, New York, New York

(Received April 19, 1948)

[Phys. Rev. 74 \(1948\) 250](#)

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

Discovery of quantum field theory

Vacuum neither static nor empty!

Electron $g - 2$: 13 decimal places

CORNERSTONE OF ATOMIC PHYSICS

“TRIUMPH OF MODERN SCIENCE!”

$$a_e^{\text{exp}}(\text{cyclotron}) = 0.001\,159\,652\,180\,59(13) \quad \leftarrow \text{Northwestern: Fan et al PRL 130 (2023) 071801}$$

↓ Paris: Morel et al Nature 588 (2022) 61

$$a_e^{\text{theory}}(\alpha_{\text{EM}}^{\text{Rb}}) = 0.001\,159\,652\,182\,037(720) \quad \alpha_{\text{EM}}^{\text{Rb}}(11)\text{theory}(12)\text{hadron}$$

$$a_e^{\text{theory}}(\alpha_{\text{EM}}^{\text{Cs}}) = 0.001\,159\,652\,181\,606(229) \quad \alpha_{\text{EM}}^{\text{Cs}}(11)\text{theory}(12)\text{hadron}$$

Berkeley ↑: Parker et al
Science 360 (2018) 191

↑ Theory: 10th order QED
Aoyama et al PRL 109 (2012) 111807

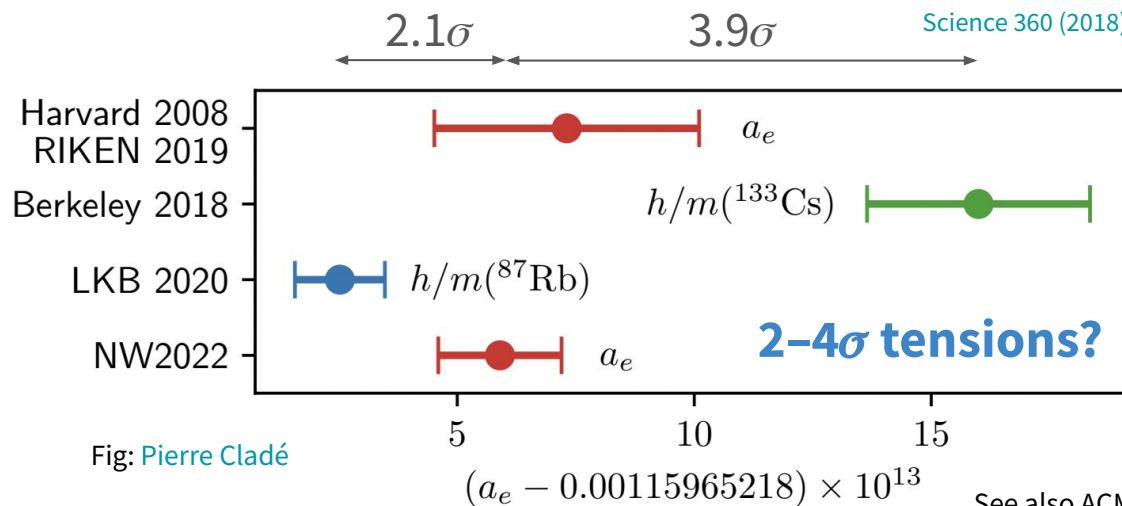
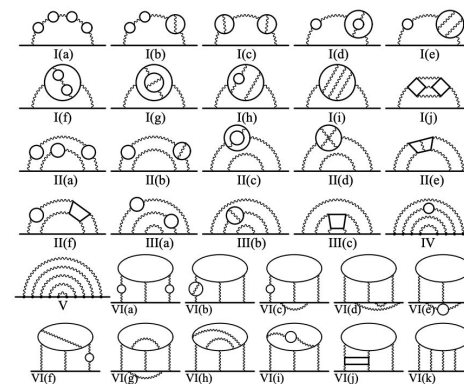
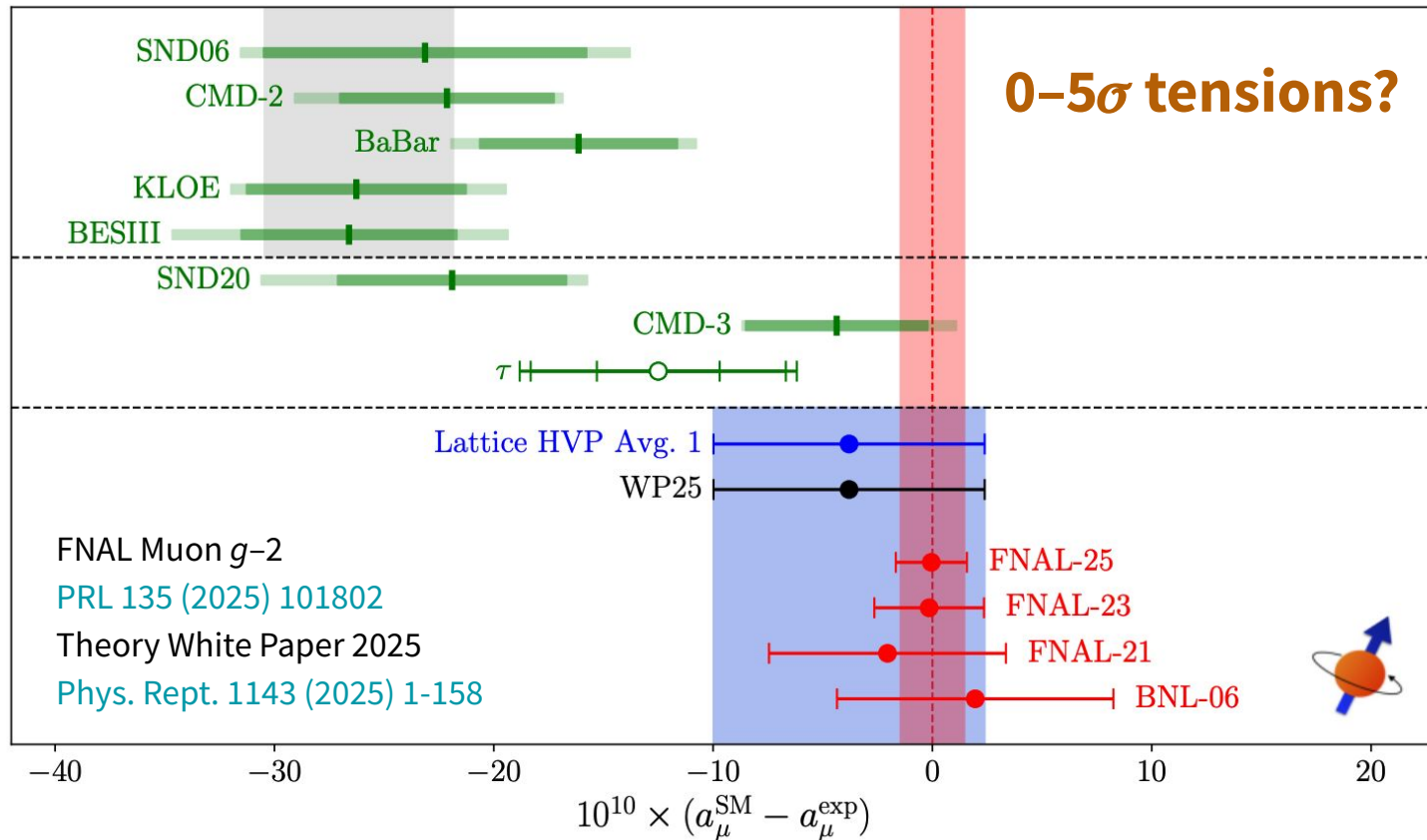


Fig: Pierre Cladé



See also ACME electric dipole search Nature 562 (2018) 7727

Muon $g - 2$: testing 10 decimal places



“NEW PHYSICS OR HADRONIC IGNORANCE?”

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

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

What about tau $g - 2$?

SHOCKING EXPERIMENTAL IGNORANCE!

Overlooked problem: PDG value from 2004

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

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

DELPHI EPJC 35 (2004) 159, Eidelman & Passera MPLA 22 (2007) 159

Not even testing 78 year old 1-loop QED 🤯

Phys. Rev. 73 (1948) 416

On Quantum-Electrodynamics and the Magnetic Moment of the Electron

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

corresponds to an additional magnetic moment associated with the electron spin, of magnitude $\delta\mu/\mu = (\frac{1}{2}\pi)e^2/\hbar c = 0.001162$. It is indeed gratifying that recently acquired experimental data confirm this prediction. Measurements on the hyperfine splitting of the ground states of atomic hydrogen and deuterium¹ have yielded values that are definitely larger than those to be expected from the directly

Hide new physics larger than QED term?


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

Martin & Wells PRD 64 (2001) 035003

Stalled progress motivates “crazy ideas”

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

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Open Access Access by Cambridge

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

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

PHYSICAL REVIEW LETTERS

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EDITORS' SUGGESTION



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

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

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

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

Propose new idea



Pioneer in ATLAS & CMS

Creativity revives interest

Beresford & JL [PRD 102 \(2020\) 113008](#)

First tau $g - 2$ results in 2 decades

ATLAS (JL Editor) & CMS [PRL 131 \(2023\) 151802](#) & [03](#)

Tau $g - 2$ measurable without lepton collider

Foundational (B)SM tests hidden in LHC data

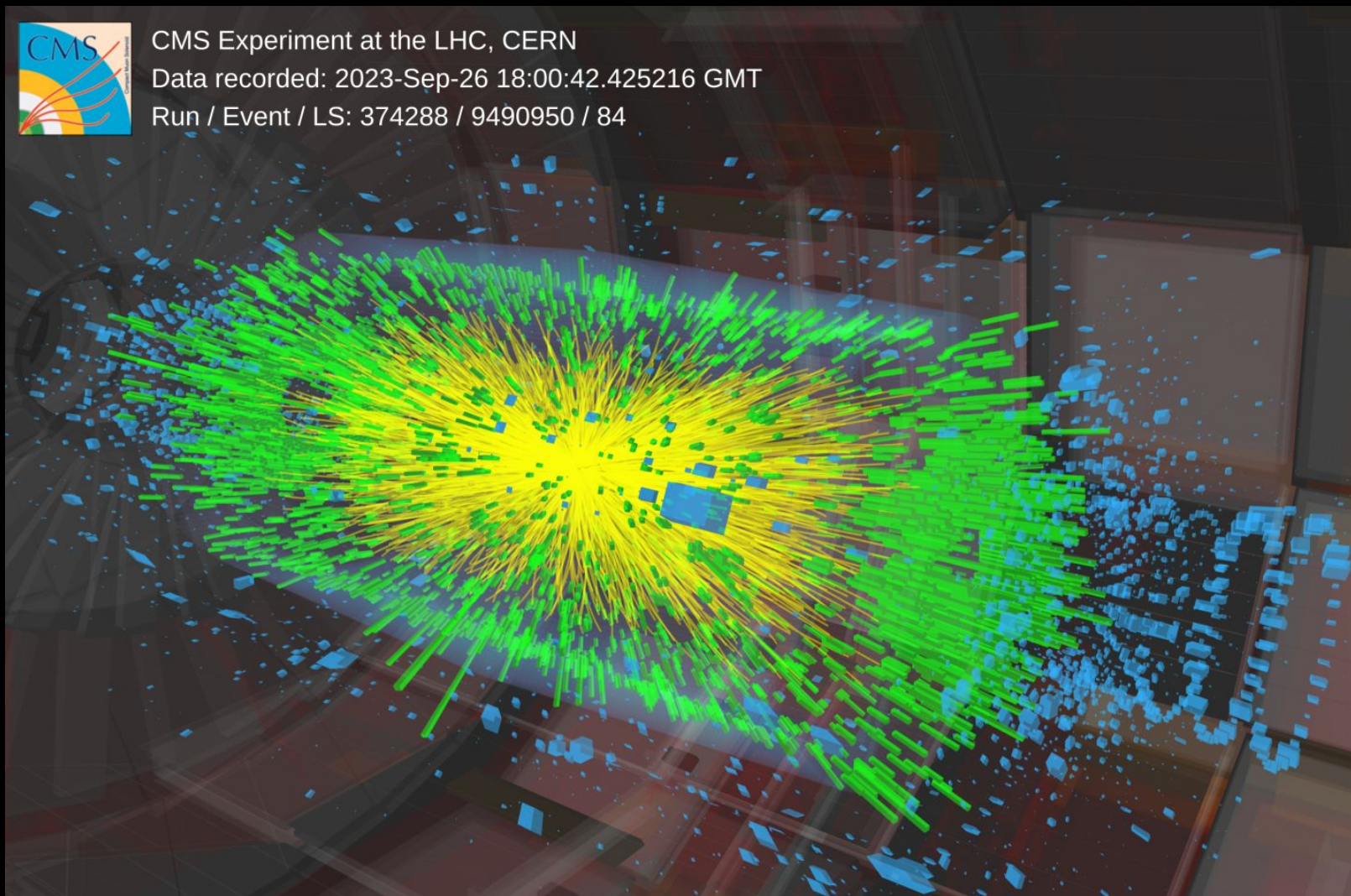
Heavy-ion collisions: what usually comes to mind



CMS Experiment at the LHC, CERN

Data recorded: 2023-Sep-26 18:00:42.425216 GMT

Run / Event / LS: 374288 / 9490950 / 84

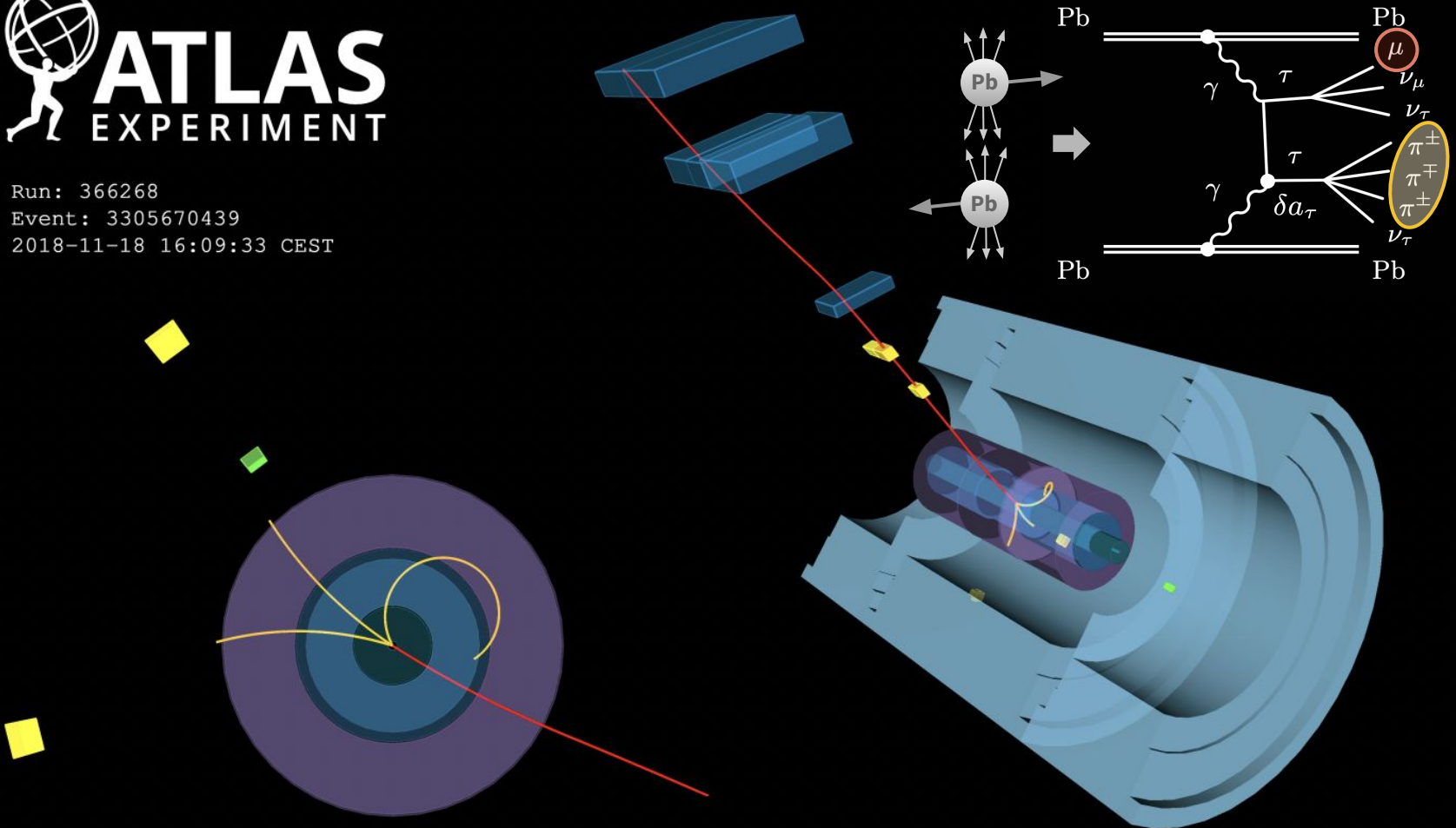


CMS PHO-EVENTS-2023-024

Heavy-ion collisions: sometimes it's all quiet



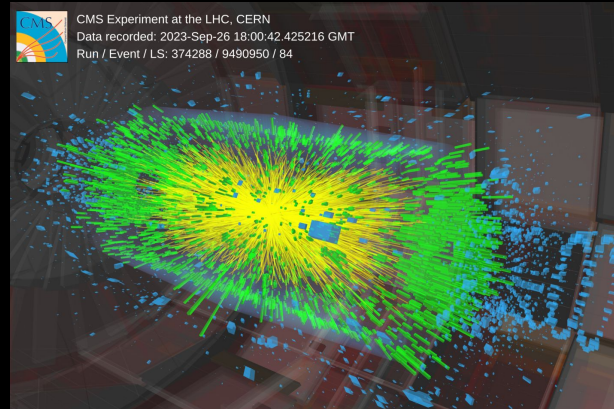
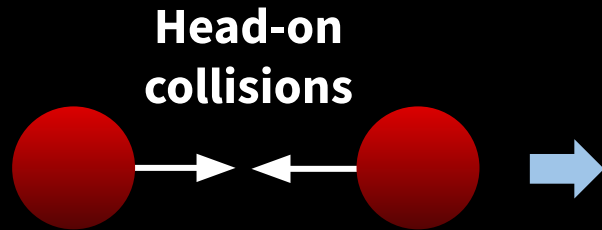
Run: 366268
Event: 3305670439
2018-11-18 16:09:33 CEST



↑ “All charged-particle tracks above 100 MeV are shown”

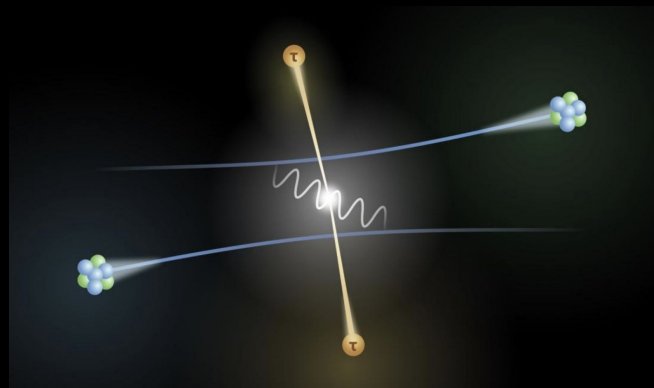
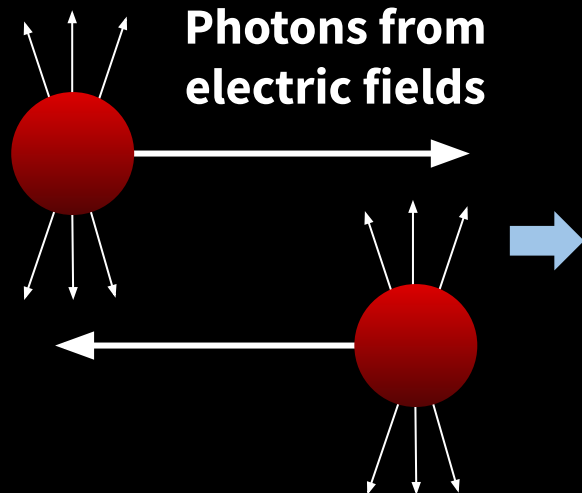
ATLAS (JL Editor) PRL 131 (2023)151802

Think different: turn LHC into photon collider



**CONVENTIONAL
WISDOM**

*“Heavy-ion data
irrelevant for
particle physics”*



**NEARLY MISS LOW
HANGING FRUIT**

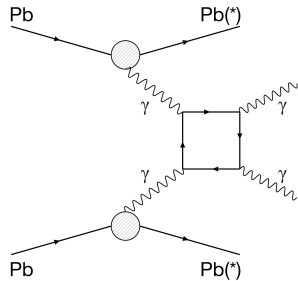
*“I never thought
heavy ions may
hide new physics”*

Beresford & JL PRD 102 (2020) 113008

LHC 2020 breakthroughs overlook $\gamma\gamma \rightarrow \tau\tau$

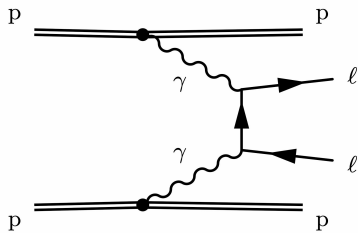
NYU 92 years ago! Collision of Two Light Quanta [Phys. Rev. 46 \(1934\) 1087](#)

G. BREIT* AND JOHN A. WHEELER,** *Department of Physics, New York University*
(Received October 23, 1934)



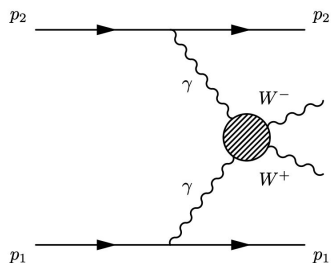
Observation of light-by-light scattering in ultraperipheral Pb+Pb collisions with the ATLAS detector
Photon self-coupling & axion-like particles

ATLAS [PRL 123 \(2019\) 052001](#)



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

ATLAS (JL Editor) [PRL 125 \(2020\) 261801](#)

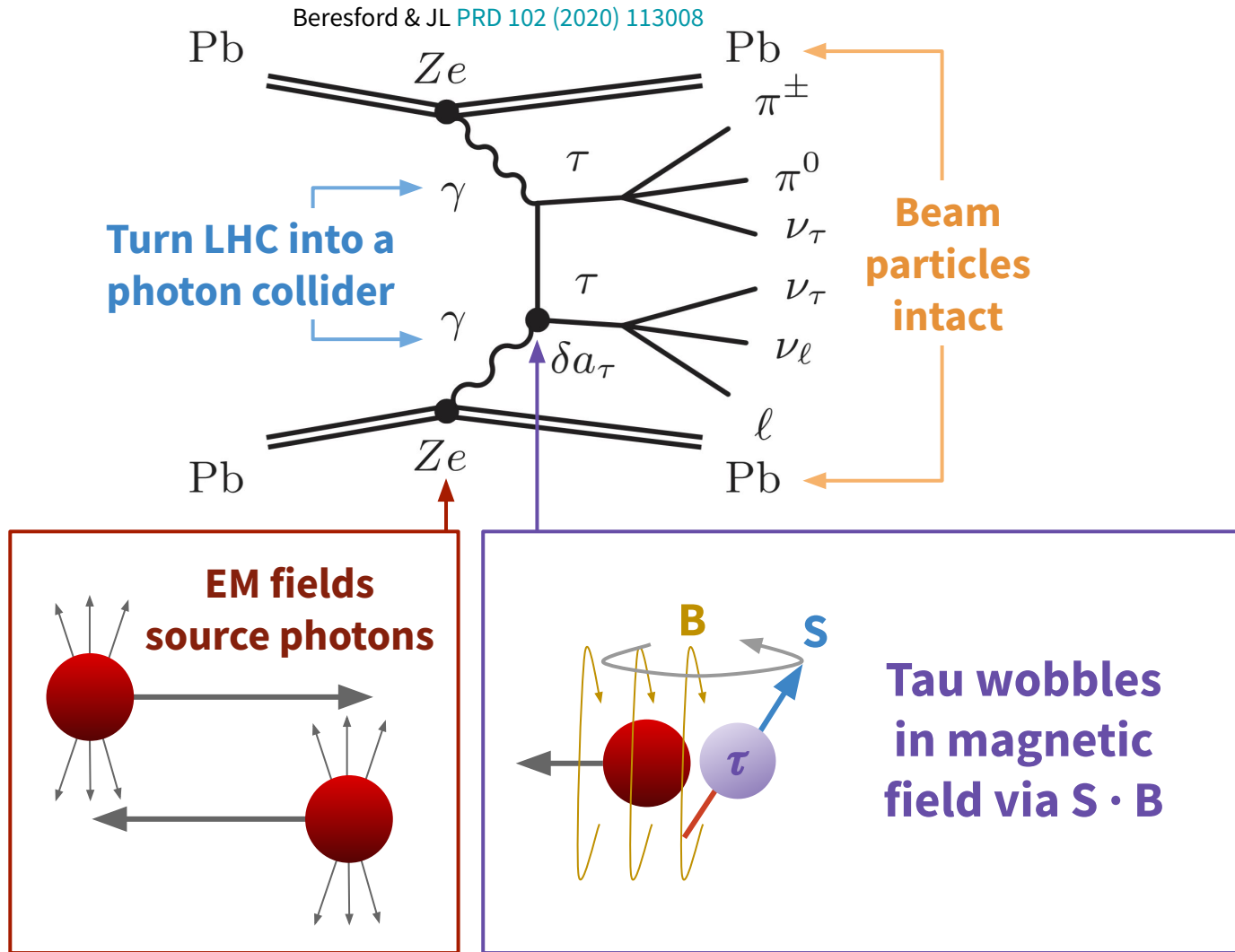


Observation of photon-induced W^+W^- production in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector

Create electroweak mass states

ATLAS [PLB 816 \(2021\) 136190](#)

Collide light to measure tau $g - 2$

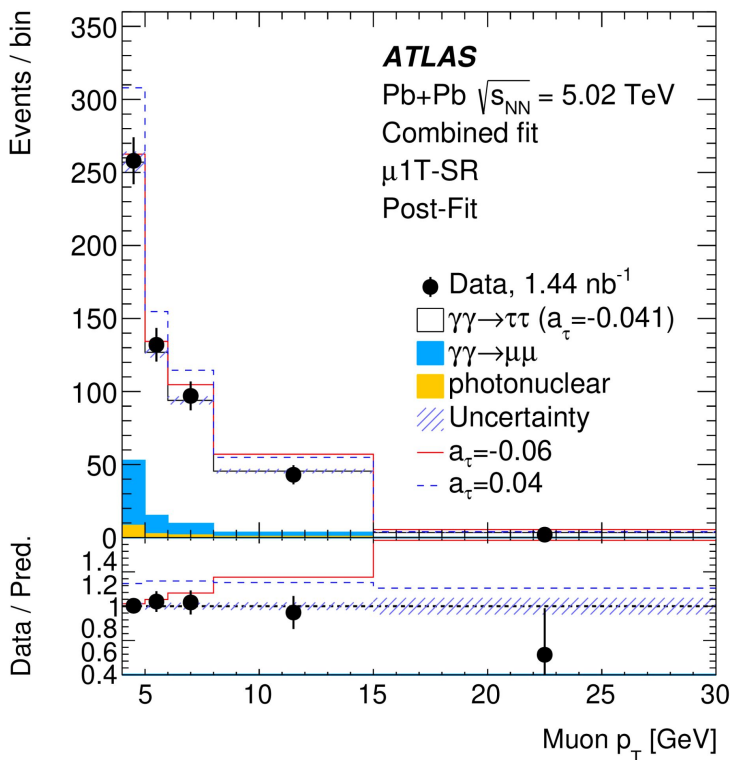


$$\sigma \sim Z^4 \sim 500\,000 \text{ nb} \quad (Z_{\text{Pb}} = 82) \Rightarrow 1 \text{ million events per month}$$

Pathbreaking results competitive with LEP

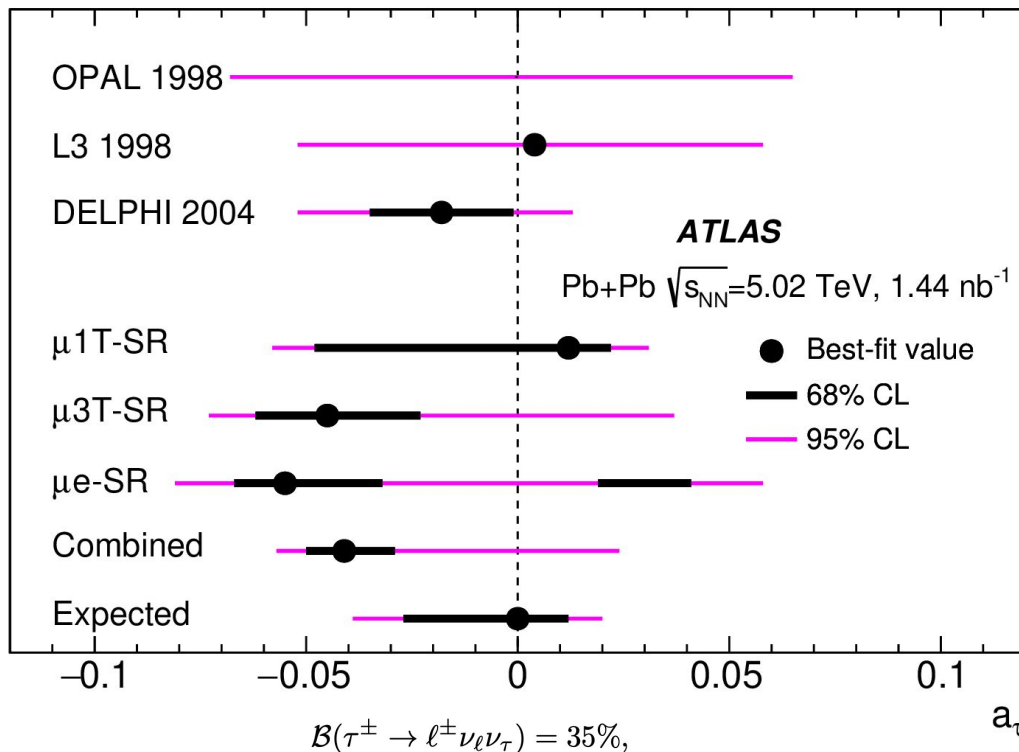
Missed signal in existing data as **we were not looking!**

>10 σ $\gamma\gamma \rightarrow \tau\tau$ signal



$p_T(\mu) > 4$ GeV trigger, 2015+18 data

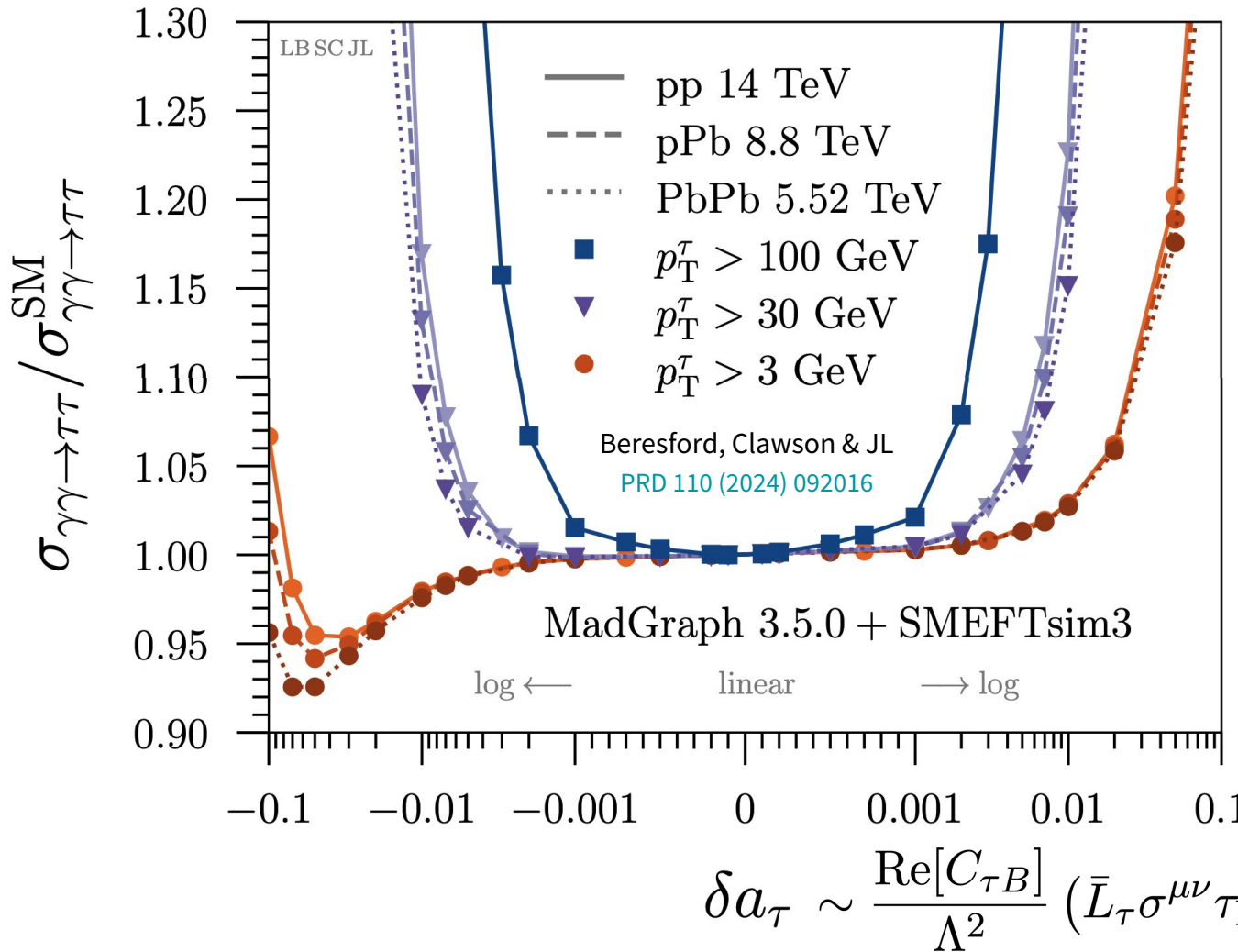
First hadron collider tau $g - 2$ result



ATLAS (JL Editor)

[PRL 131 \(2023\)151802](https://arxiv.org/abs/2305.15180)

LHC as precision quantum microscope



Theory progress

gamma-UPC fluxes: Shao & d'Enterria *JHEP* 09 (2022) 248

Superchic soft survival: Harland-Lang *EPJC* 84 (2024) 12

NLO EW corrections: Shao & d'Enterria *JHEP* 02 (2025) 023

Shao & Simon *JHEP* 07 (2025) 020
 Dittmaier et al *JHEP* 08 (2025) 051

Effective theory
 of new physics
 imprinted in
 quantum dipole

Per-mille dipole shifts \Rightarrow percent cross-section shifts

Next target: high-mass $\gamma\gamma \rightarrow \tau\tau$ in pp

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

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

Lydia Beresford^{1,*}, Savannah Clawson^{1,†} and Jesse Liu^{2,‡}

¹Deutsches Elektronen-Synchrotron DESY, Notkestrasse 85, 22607 Hamburg, Germany
²Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, United Kingdom

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

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

DOI: 10.1103/PhysRevD.110.092016

PRD 110 (2024) 092016

I. INTRODUCTION

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

The most precise single-experiment a_τ constraint is a $-0.052 < a_\tau^{\text{obs}} < 0.013$ 95% confidence level (CL) limit by DELPHI [22] at the Large Electron Positron Collider (LEP), with similar precision by L3 and OPAL [23,24]. ATLAS and Compact Muon Solenoid (CMS) recently pioneered Large Hadron Collider (LHC) probes of a_τ using photon fusion production of tau-leptons ($\gamma\gamma \rightarrow \tau\tau$) in lead-lead (PbPb) data [25,26]; the ATLAS 95% CL limit

is $-0.057 < a_\tau^{\text{obs}} < 0.024$. Such large experimental uncertainties relative to the SM prediction $a_{\tau,\text{SM}}^{\text{pred}} = 0.00117721(5)$ [27] could conceal BSM dynamics, for example, those motivated by lepton sector tensions [28–44]. Specific models predict quadratic scaling $\delta a_\tau \propto m_\tau^2$ with lepton mass m_τ [45–47], implying $(m_\tau/m_\mu)^2 \simeq 280$ times larger effects for a_τ than a_μ . New physics can also violate charge-parity (CP) symmetry, inducing an electric dipole d_τ . Standard LHC proton-proton (pp) collisions reach higher $\mathcal{O}(\text{TeV})$ masses, enhancing BSM dipole sensitivity over $\mathcal{O}(100 \text{ GeV})$ in PbPb [48–53]. Despite this key benefit, cross section yielding over 30 million events to date, and major photon-fusion advances [54–88], $\gamma\gamma \rightarrow \tau\tau$ remarkably evades observation in pp data.

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

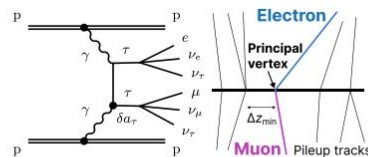


FIG. 1. Tau-leptons produced from photon fusion in proton beams with electron-muon $\tau\tau \rightarrow e\mu\mu e$ decays as a Feynman diagram (left) and detector signature illustrating the vertex isolation technique for the electron-muon vs pileup tracks (right). New physics can modify the magnetic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

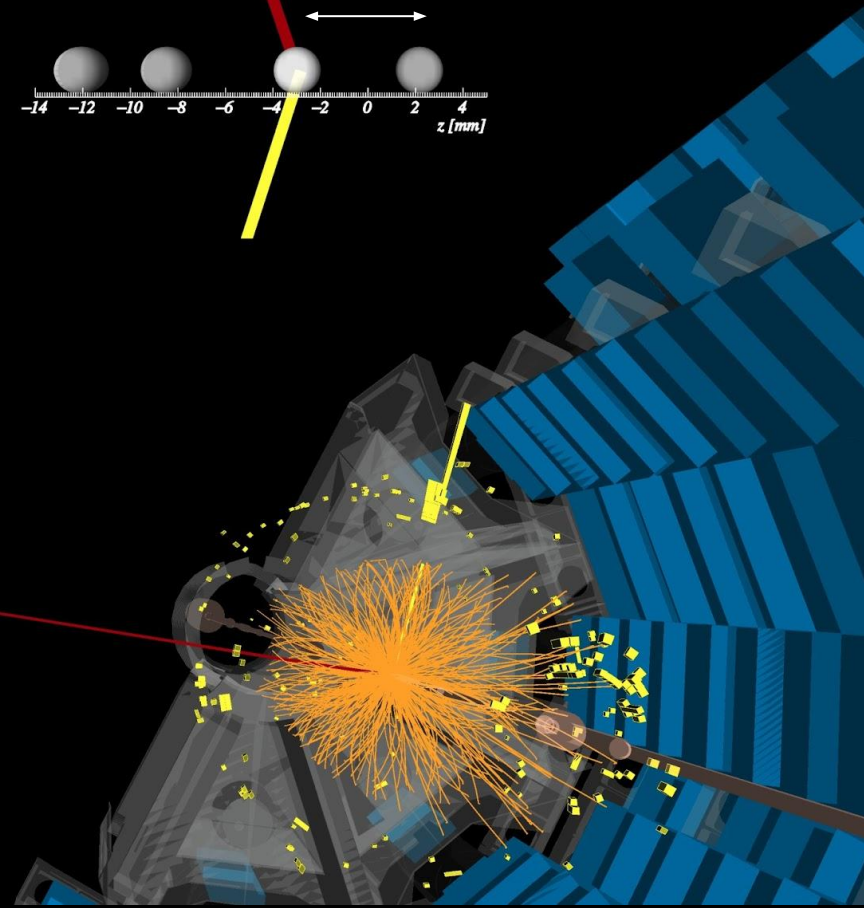
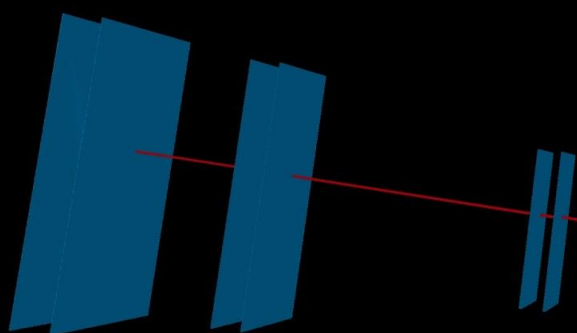
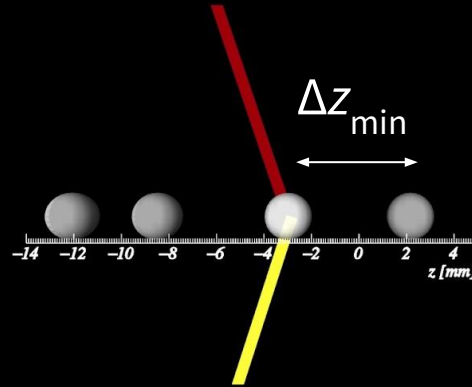
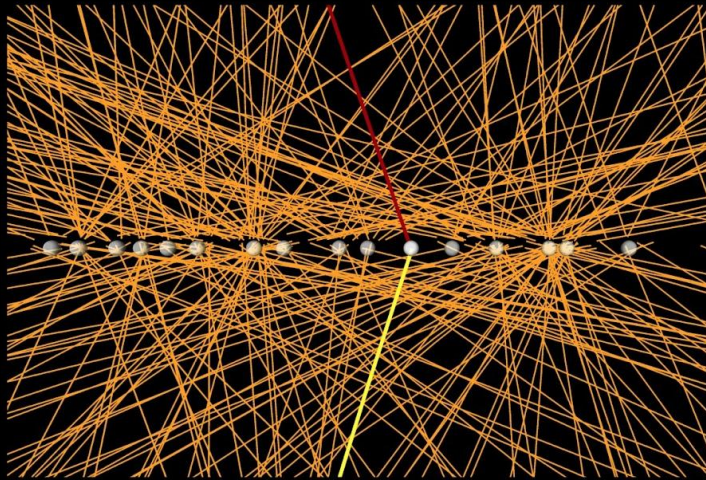
*Contact author: lydia.beresford@desy.de
[†]Contact author: savannah.clawson@desy.de
[‡]Contact author: jesseliu@hep.phy.cam.ac.uk

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↑ Savannah Clawson / JL / Lydia Beresford

Unconventional signature: no proton breakup



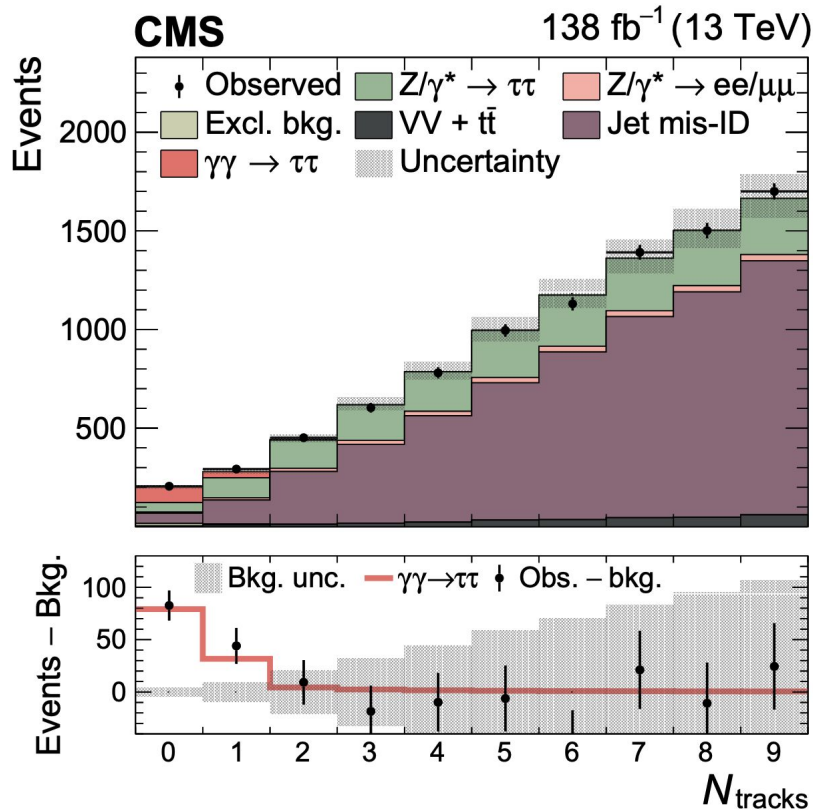
$$2 \times \mathcal{B}(\tau \rightarrow e\nu\nu) \times \mathcal{B}(\tau \rightarrow \mu\nu\nu) \simeq 6\%$$


ATLAS Run: 357620
 EXPERIMENT Event: 653219636
 2018-08-06 01:08:33 CEST

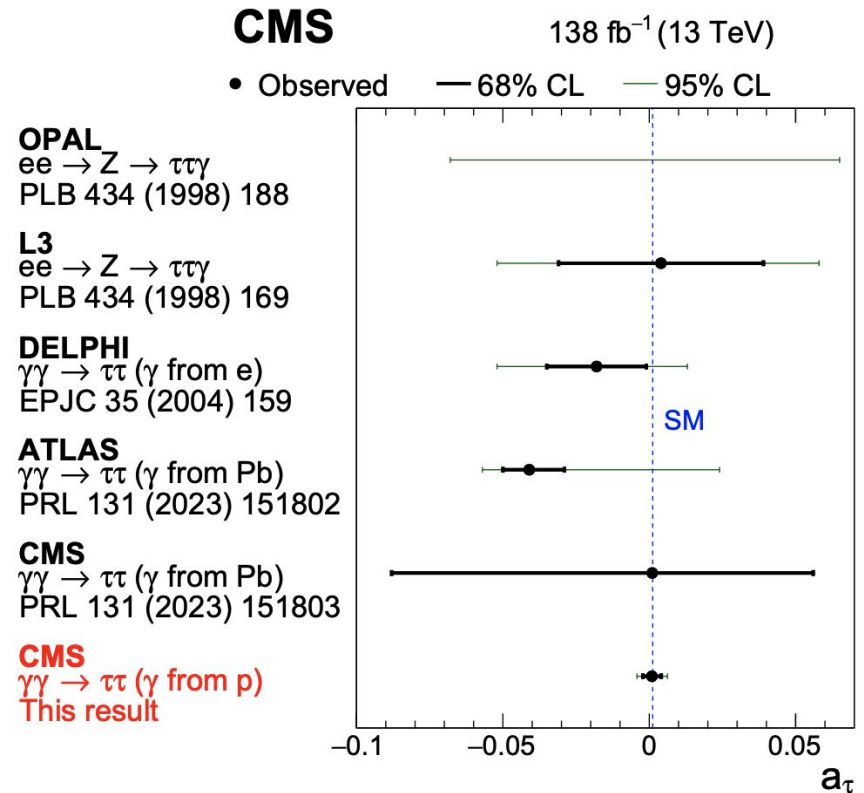
Soft tracks $p_T > 500 \text{ MeV}$ to extract $\gamma\gamma \rightarrow \tau\tau \rightarrow e\nu\mu\nu$

CMS observation of $\gamma\gamma \rightarrow \tau\tau$ in Run 2 pp

Observation of $\gamma\gamma \rightarrow \tau\tau$ in proton-proton collisions and limits on the anomalous electromagnetic moments of the τ lepton RPP (2024) 87 107801



$\gamma\gamma \rightarrow \tau\tau$ in pp: 5.3 σ (6.5) obs (exp)



Tau g - 2: 5x improvement vs LEP

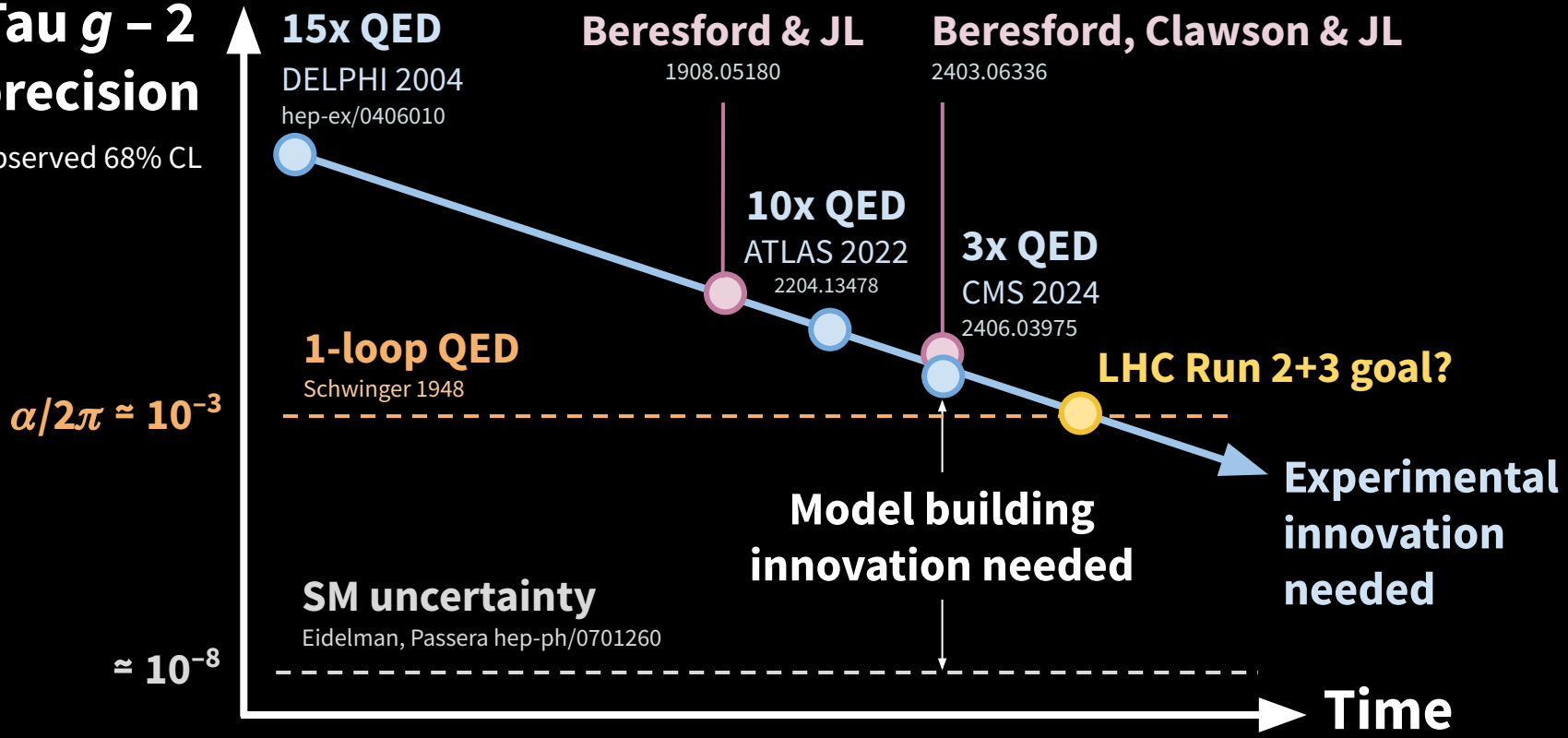
Nearing per-mille & stats limited: $a_\tau = 0.0009^{+0.0016}_{-0.0015}(\text{syst})^{+0.0028}_{-0.0027}(\text{stat})$

Dominated by soft QCD modelling \uparrow

ROADMAP

Tau $g - 2$ precision

Observed 68% CL



2004–22: tau $g - 2$ ‘winter’ **2022+: LHC renaissance**

*“It would be very nice to measure μ_τ with enough precision to check [the Schwinger term]...
At present such precision is a dream” — Martin Perl hep-ph/9812400*

HISTORY

Neutron magnetic moment

DIRAC THEORY 1928

$$g_n = 0$$

Neutral & pointlike

EXPERIMENT 1930s

$$g_n = -3.8$$

Large & negative?!

Completely confounded expectation!

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

TRANSFORMATIVE

Neutron magnetic moment

DIRAC THEORY 1928

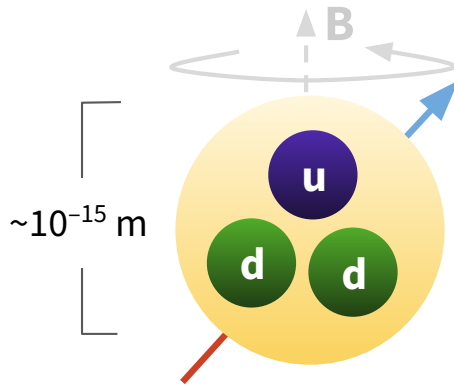
$$g_n = 0$$

Neutral & pointlike

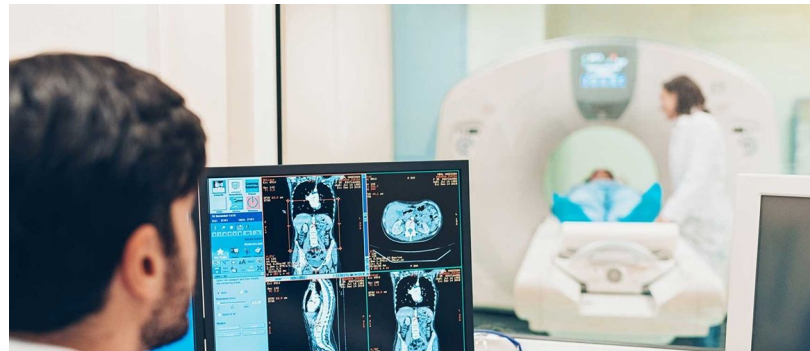
EXPERIMENTS 1930s

$$g_n = -3.8$$

Large & negative?!



STRONG FORCE
Quarks & gluons

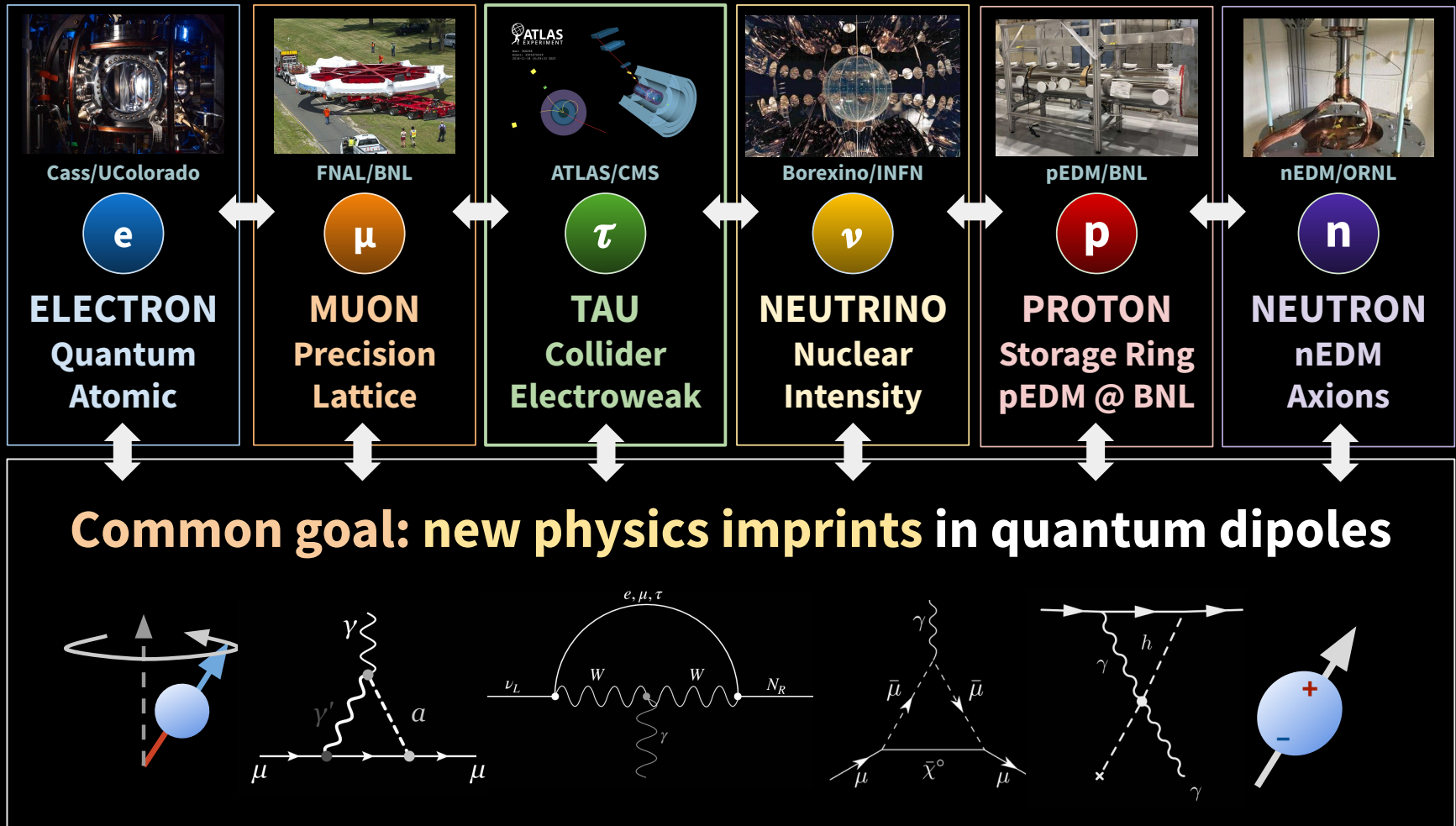


MEDICAL PHYSICS
Nuclear magnetic moments save lives

hopkinsmedicine.org, Nobel prize in Medicine 2003

Vision: “Quantum Dipoles for Discovery” Program?

Active community but must cross **atomic** ↔ **nuclear** ↔ **particle** silos

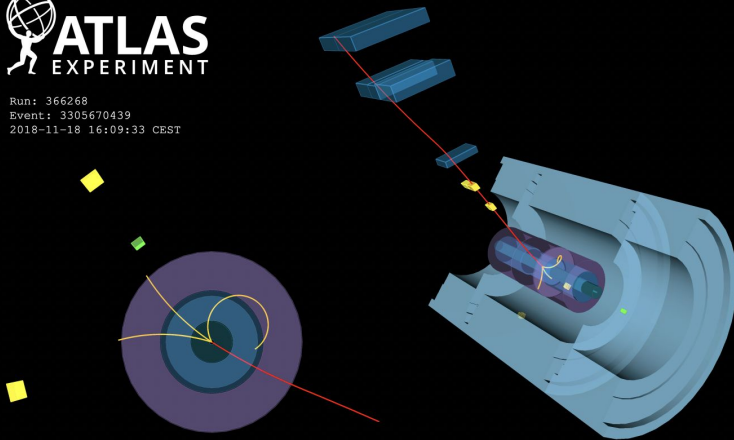


OUTLINE

Broaden collider science across disciplinary boundaries



Run: 366268
Event: 3305670439
2018-11-18 16:09:33 CEST



LHC as Photon Collider

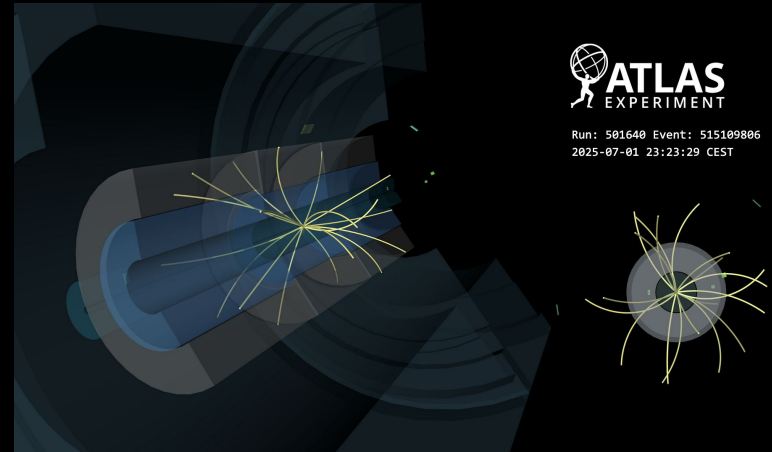
Quantum dipole physics

$\text{Tau } g - 2 \text{ via } \gamma\gamma \rightarrow \tau\tau$

QUANTUM + NUCLEAR + FLAVOUR



Run: 501640 Event: 515109806
2025-07-01 23:23:29 CEST

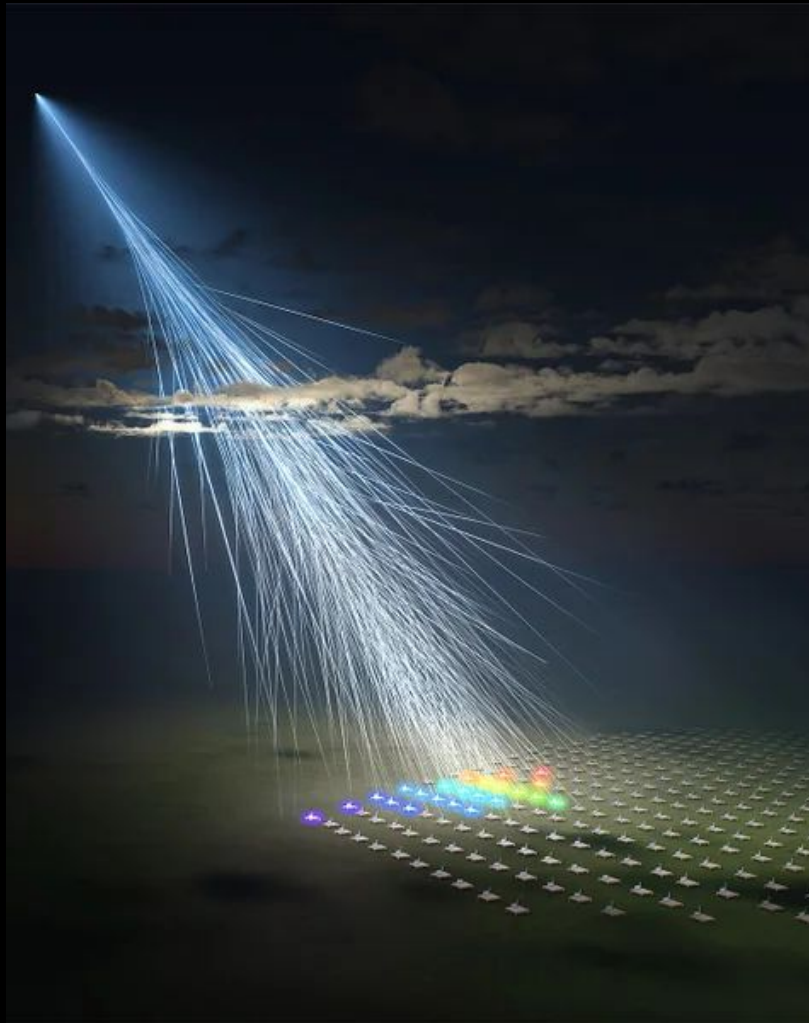


LHC as Cosmic-ray Lab

PeV astroparticle physics

Proton-oxygen collisions

PRECISION + NUCLEAR + ASTROPHYSICS



COSMIC RAYS

Highest energy particles
ORIGINS ENDURING ENIGMA

Where do they come from?
What is their composition?
How do they reach 10^{20} eV?
Plays role in origins of life?

Historic e^+ , μ^\pm , π^\pm , K^\pm discovery
Share heritage with particle physics

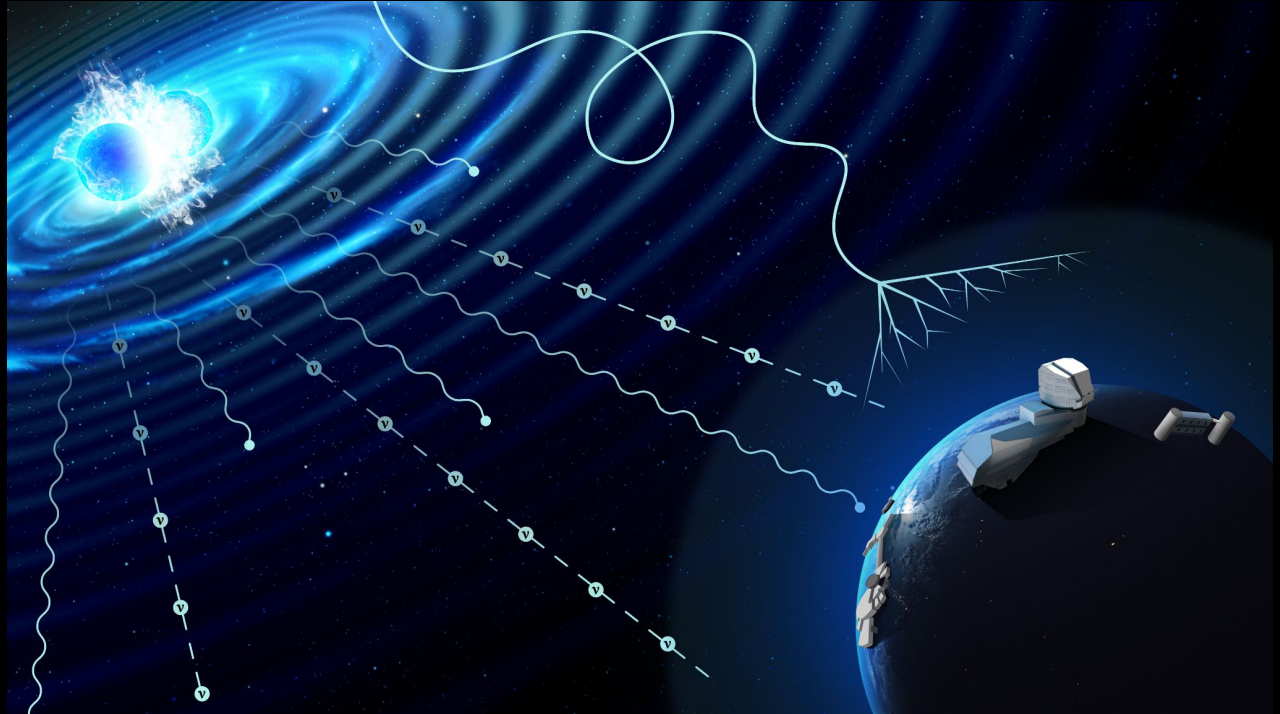
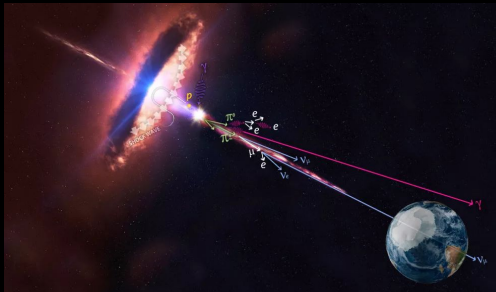
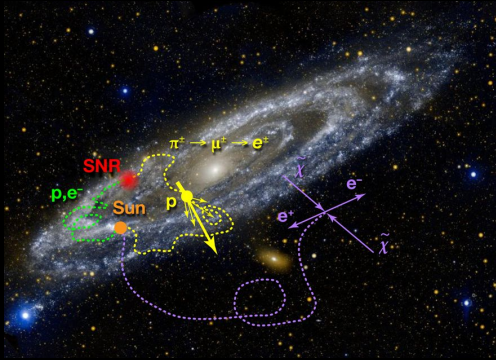
Telescope Array in Utah Science 382 (2023) 903

Osaka Metropolitan University/L-INSIGHT, Kyoto University/Ryuunosuke Takeshige

Unraveling origins of cosmic messengers

Supernova remnants? Dark matter?

Binary neutron-star mergers?



Blazars & quasars: supermassive black holes?

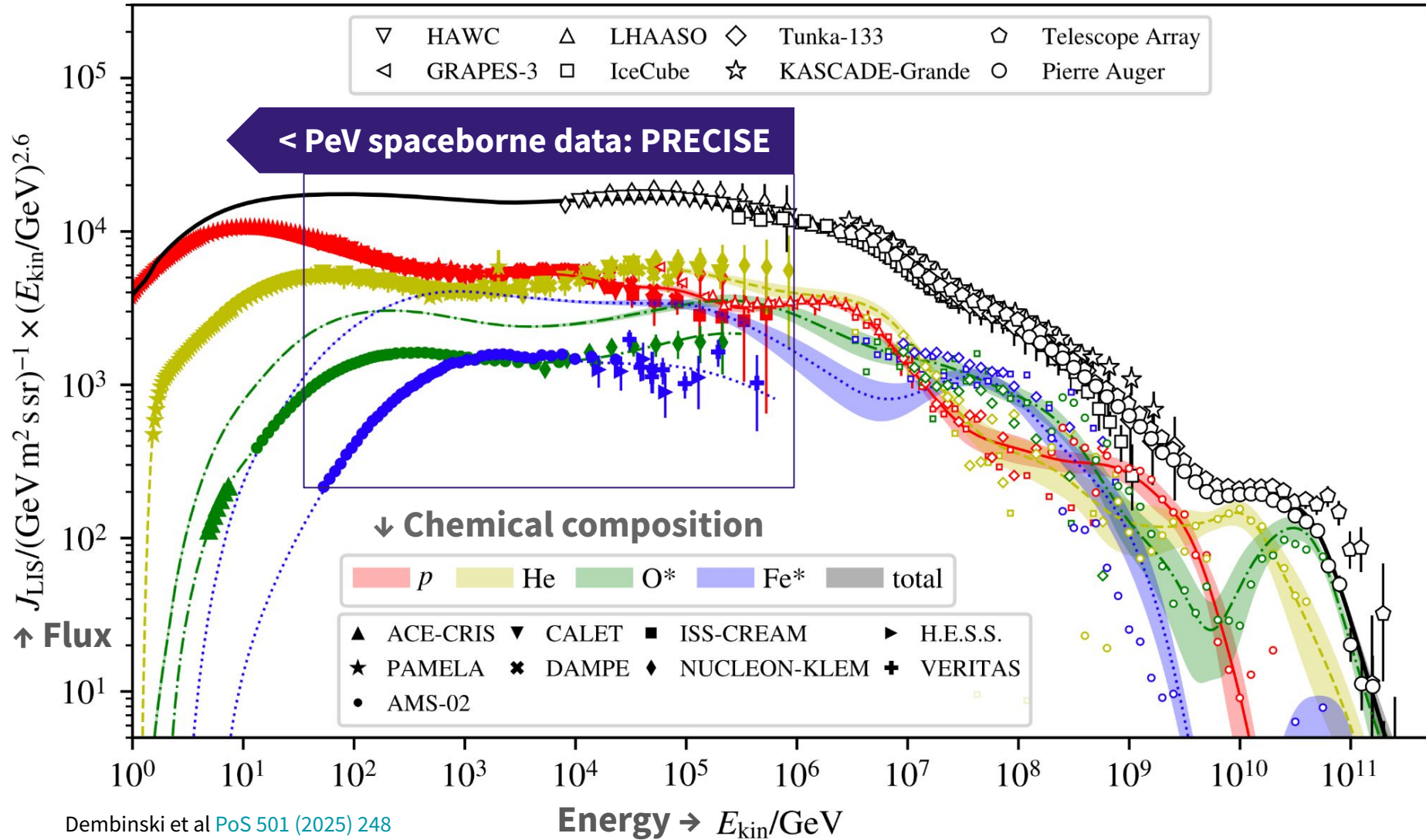
Figs: APS, IceCube/NASA, NOIRLAB

“Synergies between particle and astroparticle physics should be strengthened”

— European Strategy Update 2020

Extreme physics of cosmic-ray spectrum

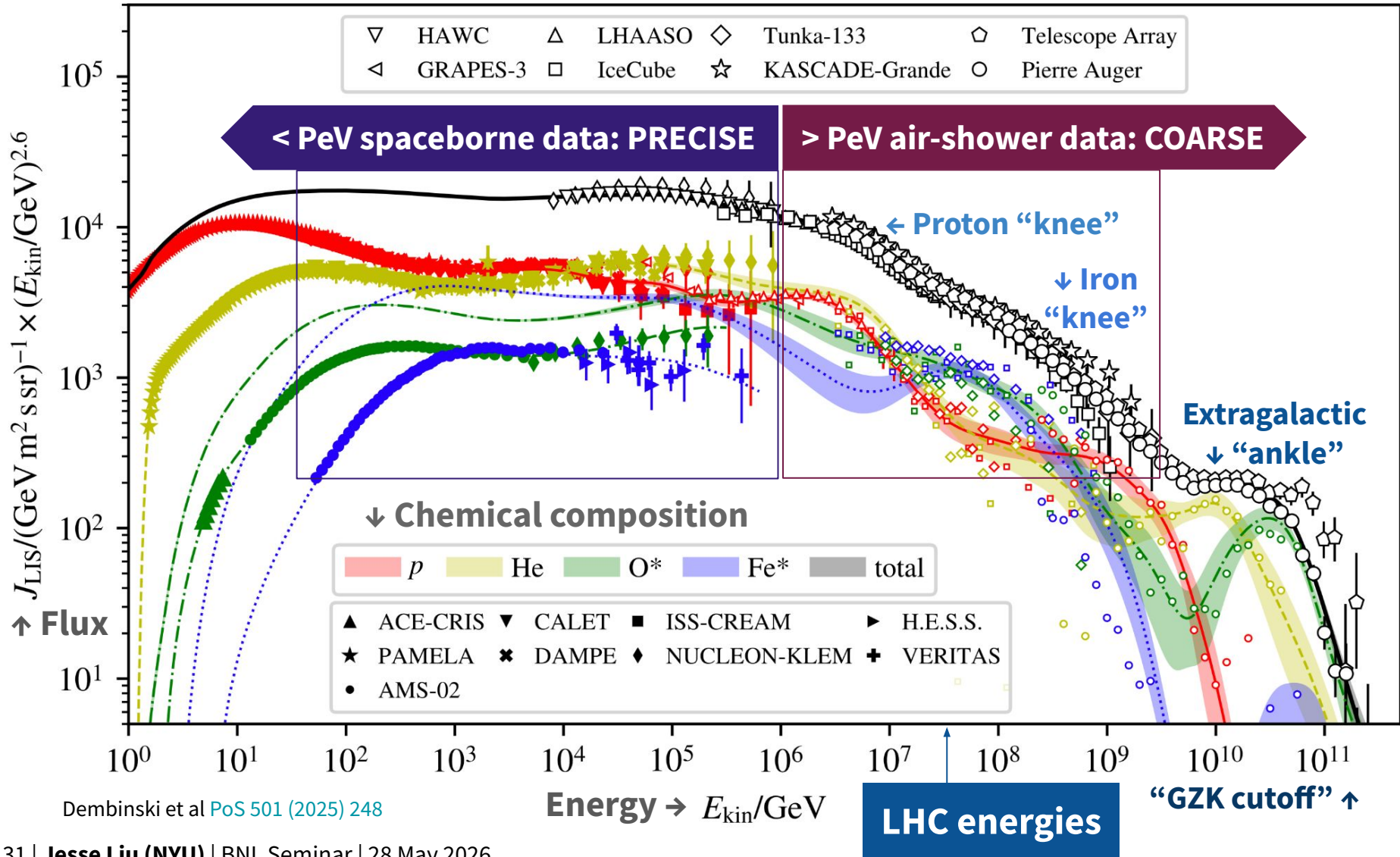
Galactic supernova remnants ←



Dembinski et al PoS 501 (2025) 248

Extreme physics of cosmic-ray spectrum

Galactic supernova remnants ← → Extragalactic black holes



Cosmic-ray primary

What we *want* to measure...

... to unravel their **astrophysics**

Origins: where do they come from?

Composition: what are they made of?

Acceleration: how are they so fast?

Air shower

Soft QCD
"SO MESSY!"
"RUN AWAY!"
"NOT IN P5!"

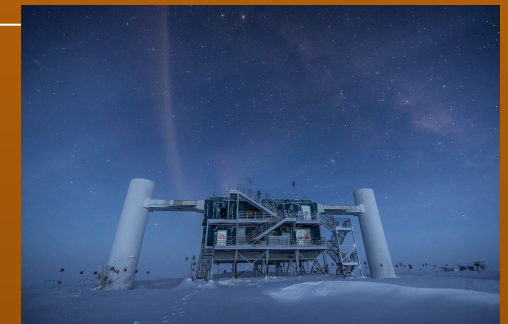
Auger Observatory

Mendoza, Argentina



Brainchild of James Cronin & Alan Watson

Fig: A. Chantelauze, S. Staffi, L. Bret



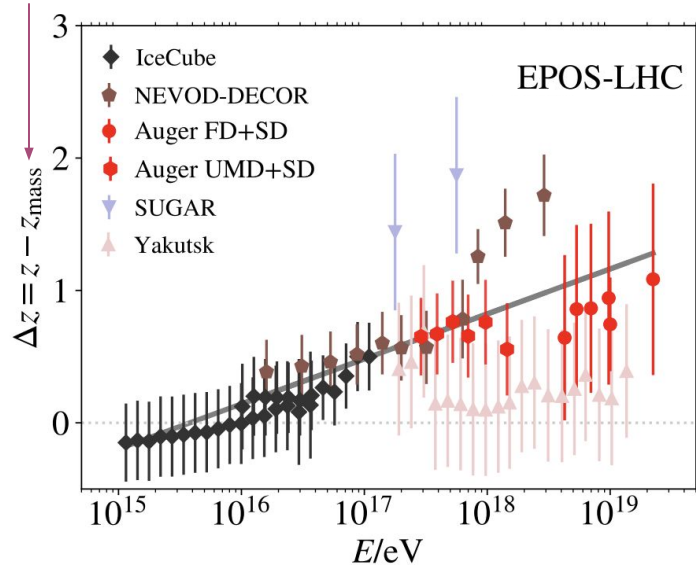
IceCube Observatory

South Pole, Antarctica

Hadronic ignorance obstructs astroparticle precision

The Muon Puzzle in cosmic-ray induced air showers and its connection to the Large Hadron Collider Albrecht et al *Astrophys. Space Sci.* 367 (2022) 27

“Residual of muon vs non-muon data”

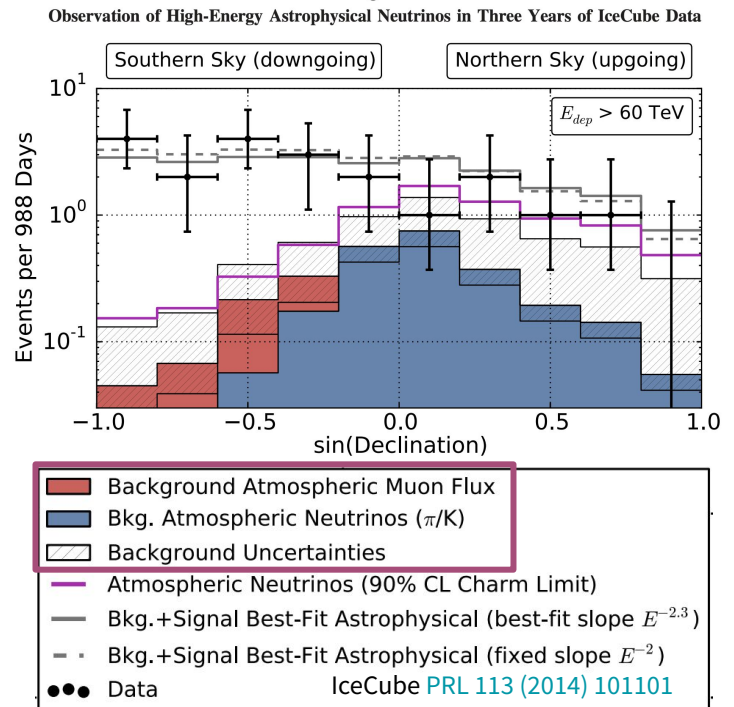


“For the models EPOS-LHC and QGSJet-II.04, the slope is found **significant at 8 sigma**”

MUON PUZZLE

“Atmosphere as calorimeter”
vs muon data discrepancies

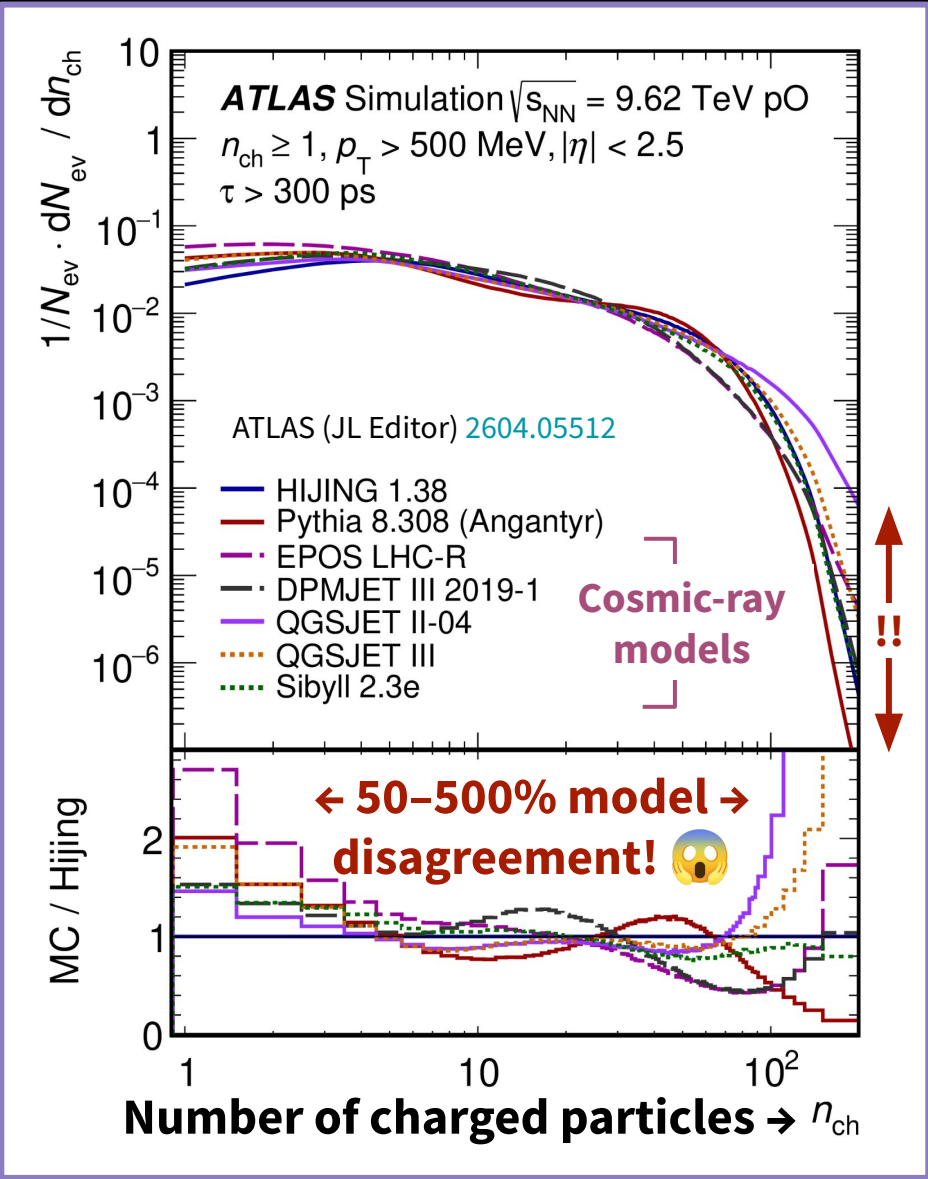
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS week ending 5 SEPTEMBER 2014



- Background Atmospheric Muon Flux
 - Bkg. Atmospheric Neutrinos (π/K)
 - Background Uncertainties
 - Atmospheric Neutrinos (90% CL Charm Limit)
 - Bkg. + Signal Best-Fit Astrophysical (best-fit slope $E^{-2.3}$)
 - Bkg. + Signal Best-Fit Astrophysical (fixed slope E^{-2})
 - Data
- IceCube PRL 113 (2014) 101101

ICECUBE UNCERTAINTIES

50–500% uncertainties in muon
& neutrino background flux



HEART OF PROBLEM

Models tuned to pp & p+Pb data terrible for pO!

Predictivity breaks down for soft QCD

1 July 2025: first proton-oxygen collisions



CERN

ABOUT NEWS

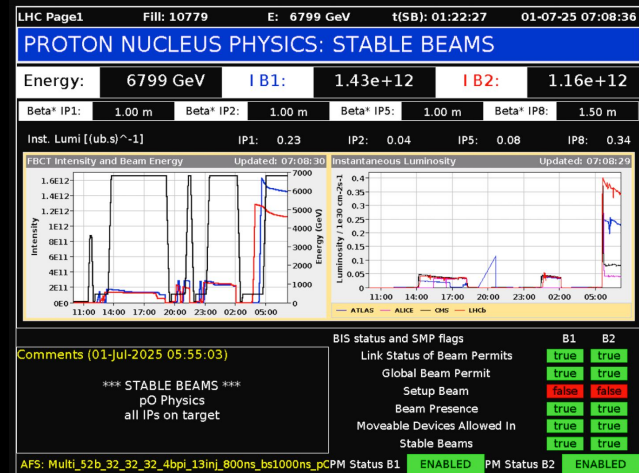
News > News > Topic: Accelerators

CERN News

Voir en français

First-ever collisions of oxygen at the LHC

The Large Hadron Collider gets a breath of fresh air as it collides beams of protons and oxygen ions for the very first time. Oxygen-oxygen and neon-neon collisions are also on the menu of the next few days



Unique opportunity: last TeV hadron collider in a lifetime

JL organised sessions on pO case for cosmic rays at ATLAS SM 2023 & LPPC Forward Physics 2024 Workshops

Landmark results: beams to paper in 9 months! 🎉

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)



Submitted to: Phys. Rev. Lett.



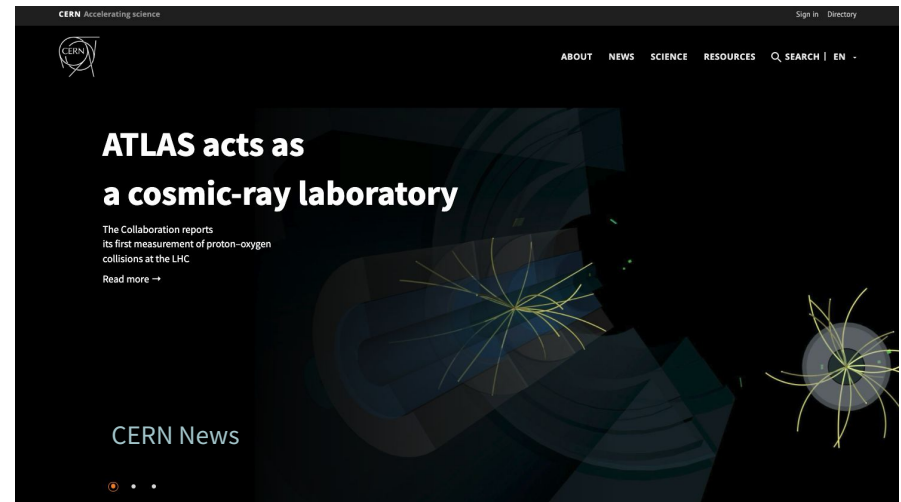
CERN-EP-2026-106
April 8, 2026

Measurement of charged-particle production in $\sqrt{s_{NN}} = 9.62$ TeV proton-oxygen collisions as a probe of cosmic-ray air showers with the ATLAS detector

The ATLAS Collaboration

This Letter presents a measurement of prompt charged-particle production in proton-oxygen interactions at $\sqrt{s_{NN}} = 9.62$ TeV center-of-mass energy with the ATLAS detector, corresponding to $634 \mu\text{b}^{-1}$ of integrated luminosity. A total of 246 million selected events have at least one track with transverse momentum $p_T > 500$ MeV and pseudorapidity $|\eta| < 2.5$. The measured fiducial proton-oxygen cross section is $\sigma_{\text{fid}}^{pO} = 396 \pm 6$ (exp.) ± 9 (lumi.) mb and the extrapolated inelastic proton-air cross section is $\sigma_{\text{incl}}^{p\text{air}} = 406 \pm 6$ (exp.) ± 9 (lumi.) ± 28 (th.) mb. Measurements of charged-particle multiplicity, p_T , and η distributions are an order-of-magnitude more precise than differences between hadronic-interaction models. These results enable improved modeling of cosmic-ray air showers, which is important for astroparticle physics.

ATLAS (JL Editor) [2604.05512](tel:2604.05512)



↑ Top of CERN Homepage 23rd April!



Lydia
Beresford
(DESY)



Savannah
Clawson
(DESY → CERN)



Ynyr
Harris
(Bonn)



Clara
Leitgeb
(Humboldt)

JL lead analyzer in core team

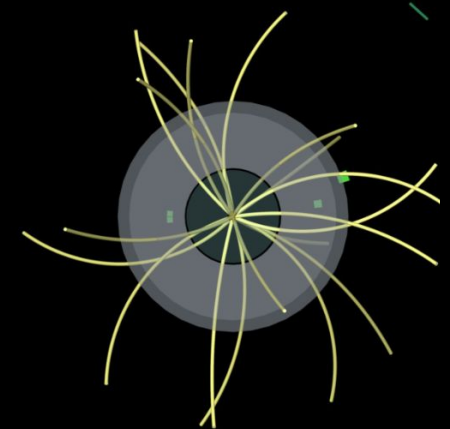
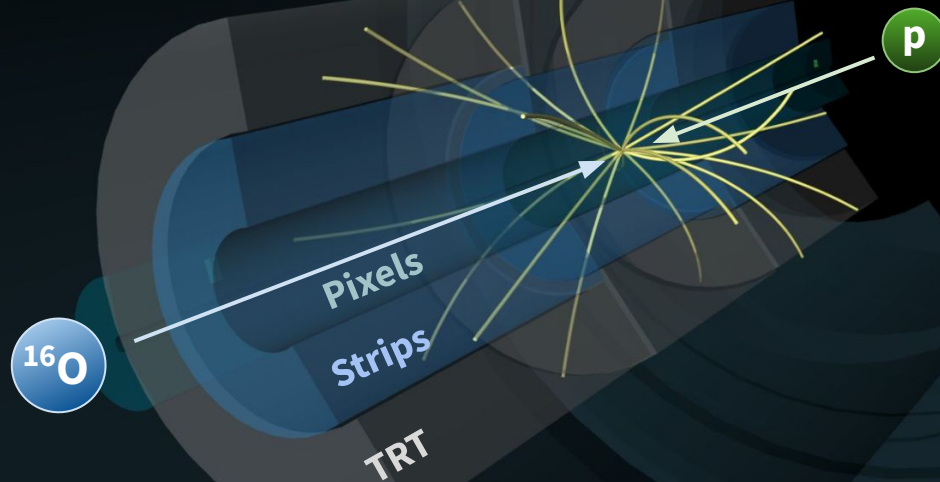
Turn ATLAS into cosmic-ray laboratory

634 μb^{-1} luminosity | 0.025 pileup | transition radiation tracker trigger

246 million events: 5.1 billion prompt tracks $p_{\text{T}} > 500$ MeV, $|\eta| < 2.5$



Run: 501640 Event: 515109806
2025-07-01 23:23:29 CEST

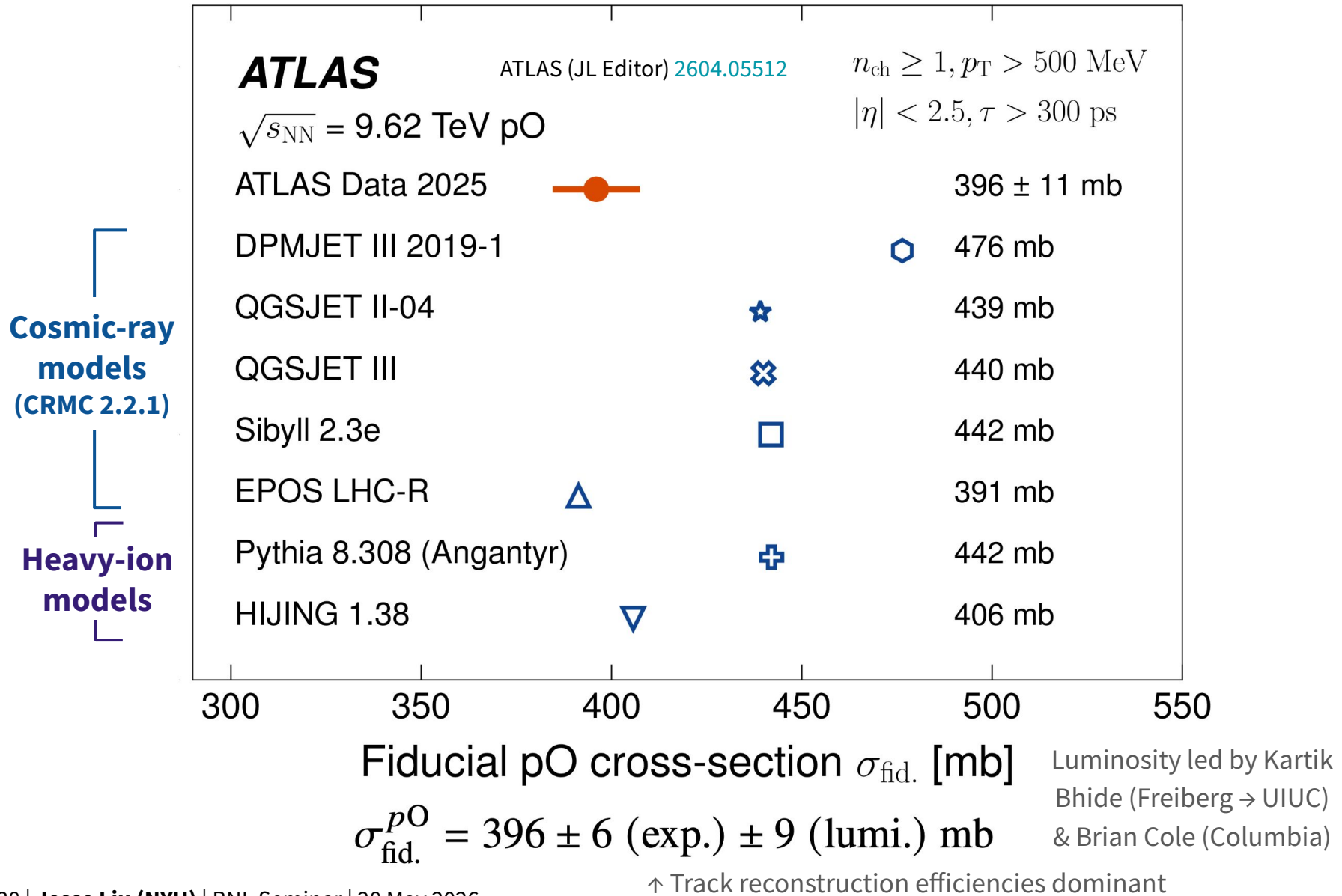


ATLAS (JL Editor) 2604.05512

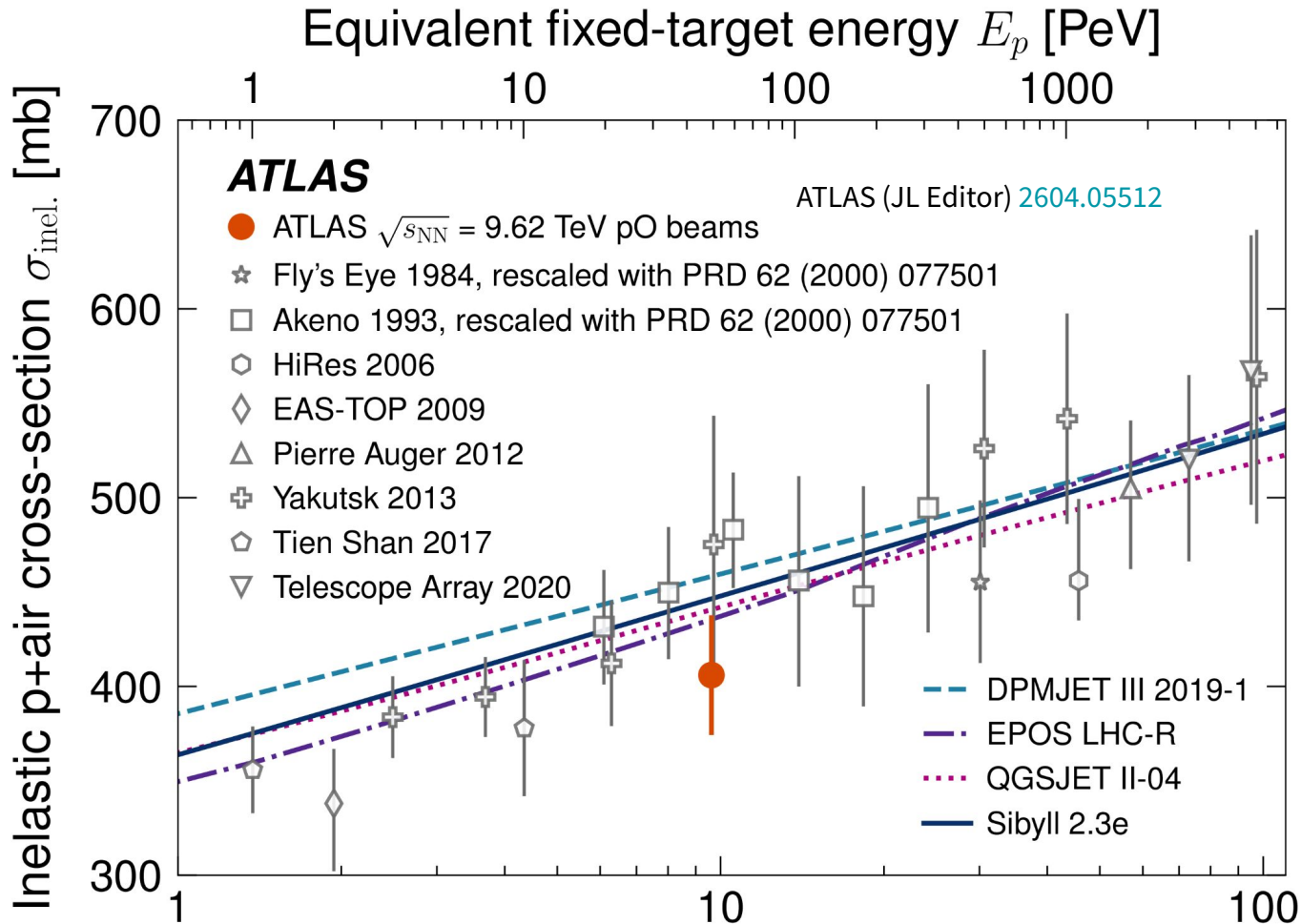
Proven pp methods: track efficiencies & $\sim 2\%$ non-prompt backgrounds via Geant4

Details for experts in backup: mean p_{T} & η results, track modeling, backgrounds, systematics

First terascale p0 cross-section measurement



Renew links across energy & cosmic frontiers



Assume air = 78% ^{14}N + 22% ^{16}O

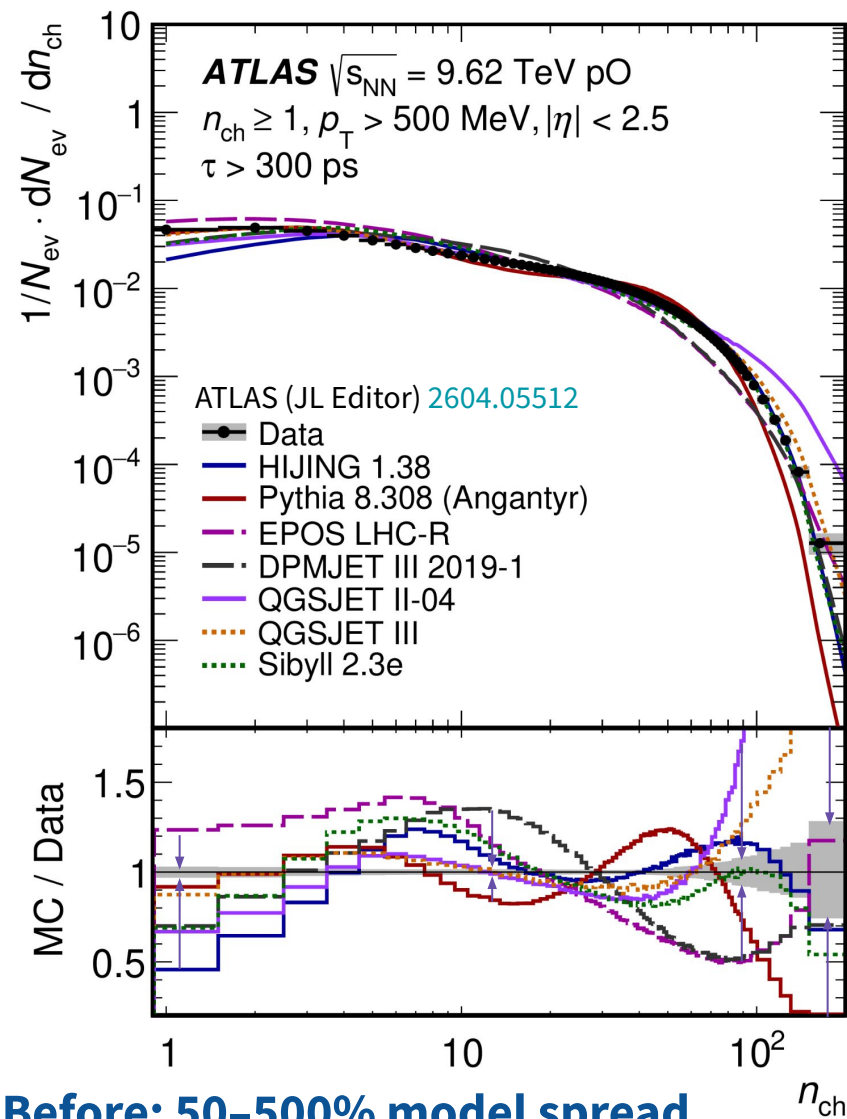
$$\sigma_{p+\text{air}} = f_{\text{air}} \sigma_{p\text{O}}, \sigma_{p\text{N}} / \sigma_{p\text{O}} \sim (14/16)^{2/3} \sim 0.9$$

$$f_{\text{air}} = 0.78 \cdot (\sigma_{\text{MC}}^{p\text{N}} / \sigma_{\text{MC}}^{p\text{O}}) + 0.22$$

Center-of-mass energy $\sqrt{s_{\text{NN}}}$ [TeV]

↓ Models to compute acceptance
 $\sigma_{\text{inel}} = \sigma_{\text{fid}} / A_{\text{MC}}, A_{\text{MC}} = (90 \pm 6)\%$

$$\sigma_{\text{inel}}^{p+\text{air}} = 406 \pm 6 \text{ (exp.)} \pm 9 \text{ (lumi.)} \pm 28 \text{ (th.) mb}$$

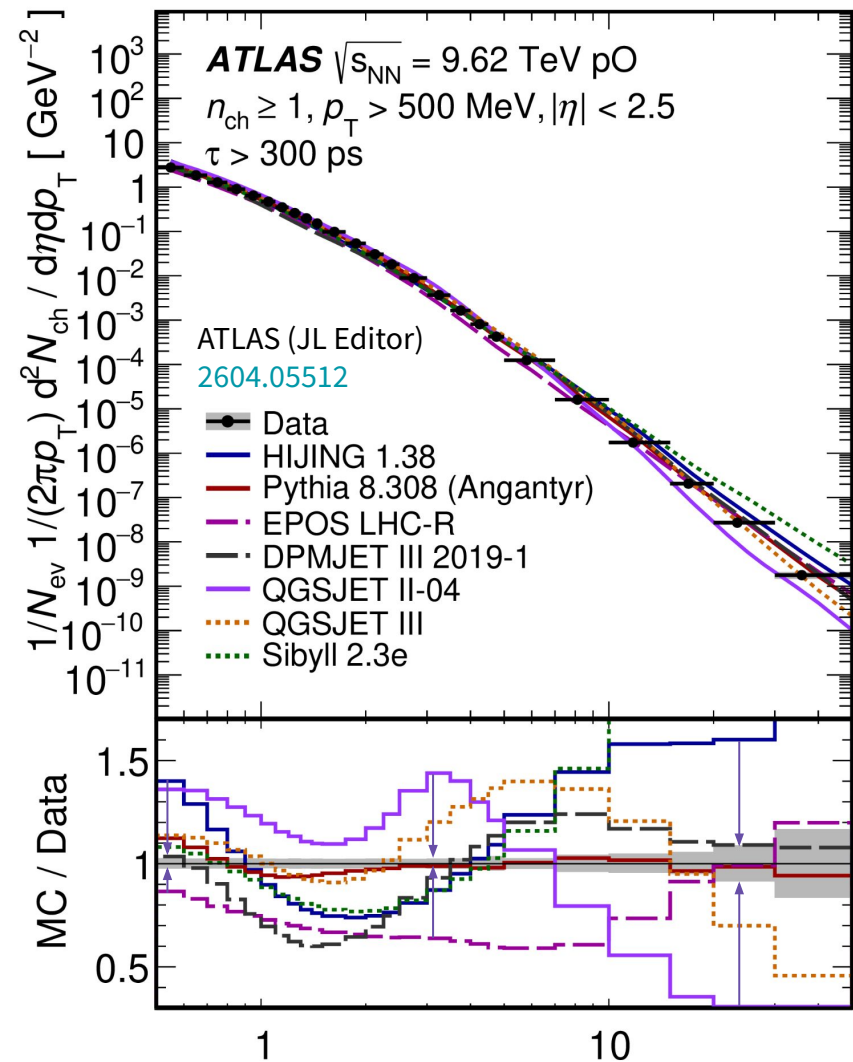


Charged particle multiplicity

ORDER OF MAGNITUDE better knowledge of cosmic-ray showers!

Before: 50–500% model spread

After: 1.5%–28% precision data



Before: 50–500% model spread

After: 2.5%–17% precision data

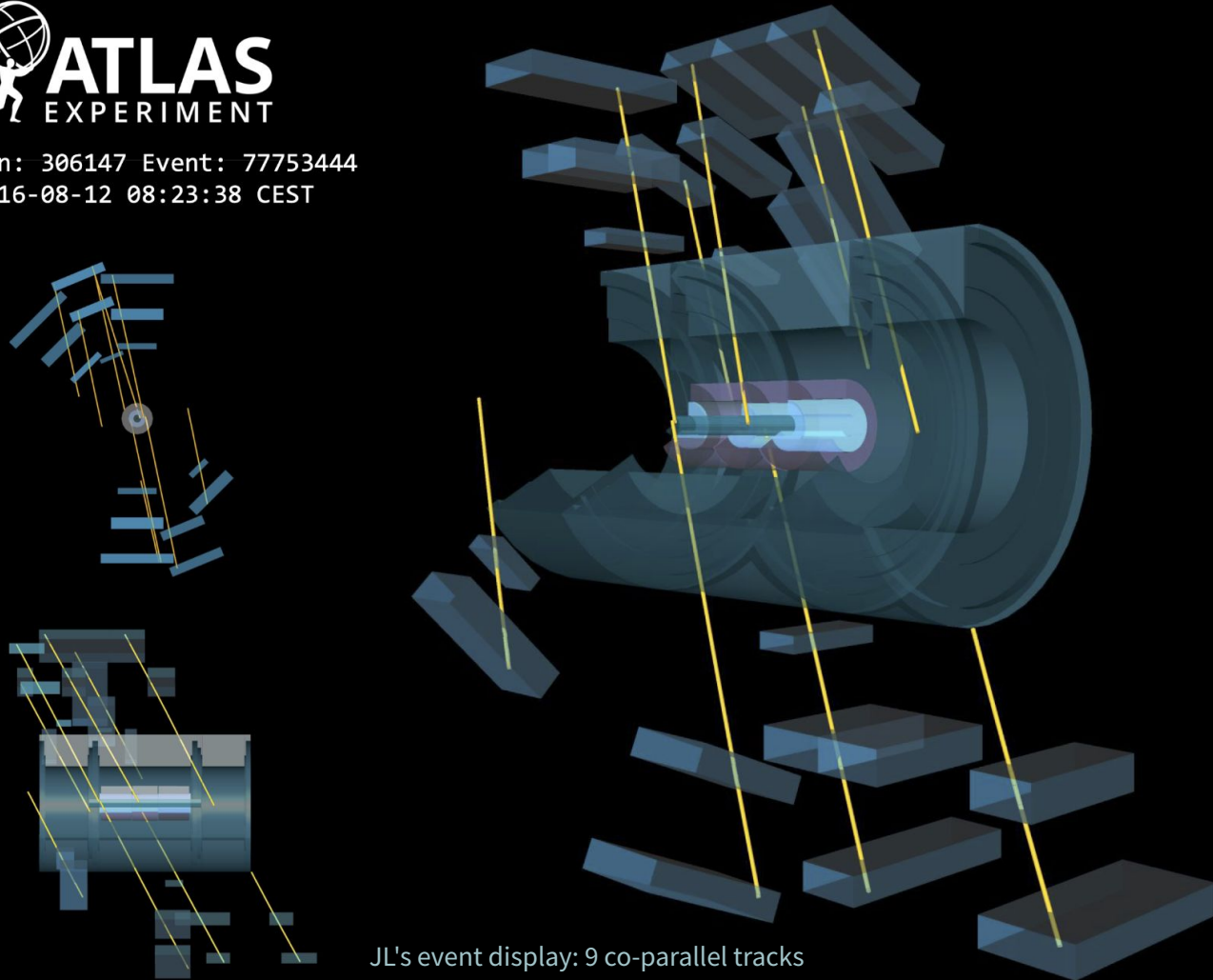
**Charged
particle
momenta**

**ORDER OF MAGNITUDE
better knowledge of
cosmic-ray showers!**

Adaptive Toroidal Laboratory for Astroparticle Science



Run: 306147 Event: 77753444
2016-08-12 08:23:38 CEST



JL's event display: 9 co-parallel tracks

ATLAS as telescope directly probing 10^{17} eV cosmic rays

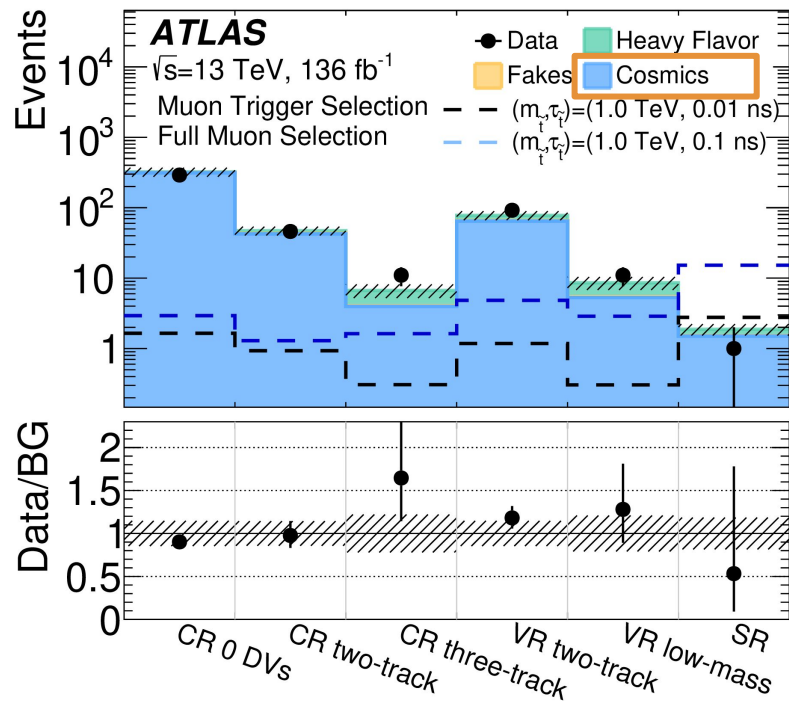
Collider detectors *already* cosmic observatories

Long-lived particle searches

“Your background is my signal!”

Count muons for astrophysics

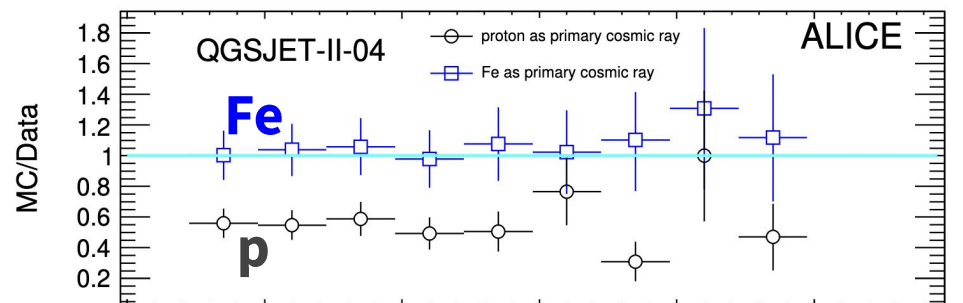
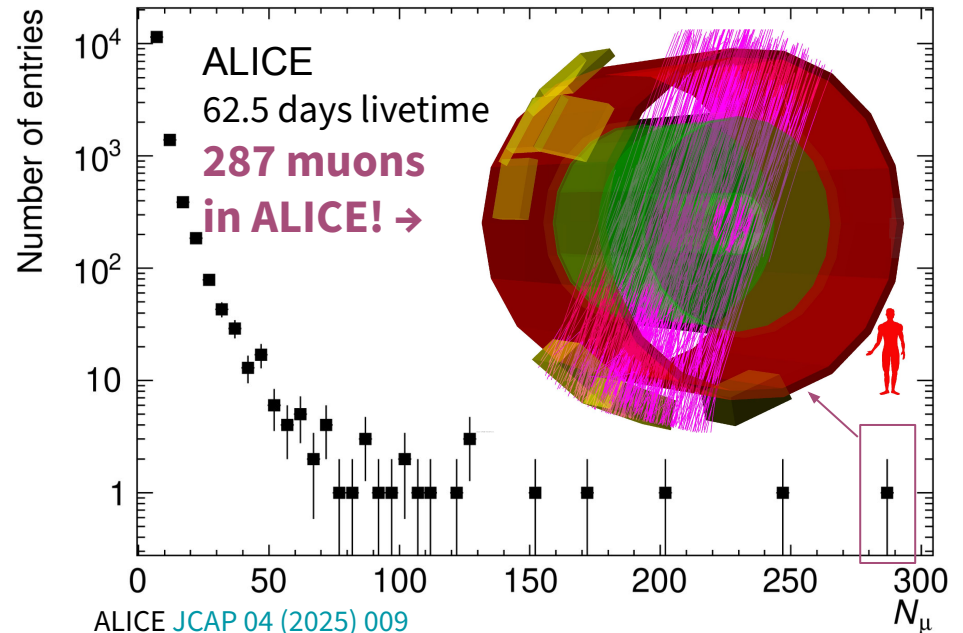
“Beam-off data is exciting science!”



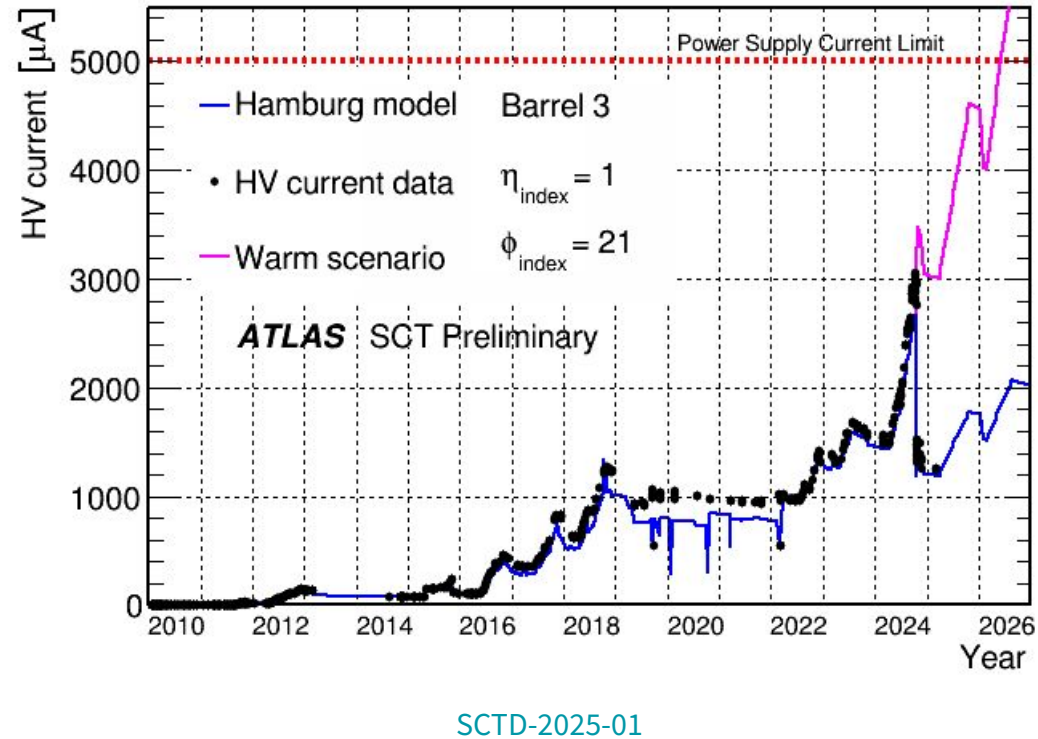
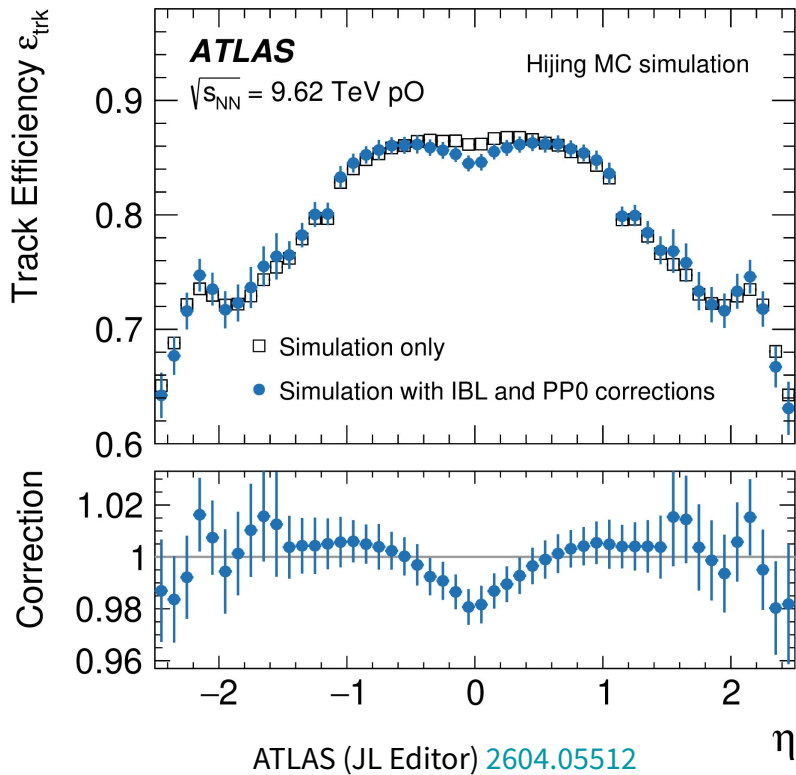
ATLAS PRD 102 (2020) 032006

See also ALICE JCAP 01 (2016) 032

DELPHI *Astropart. Phys.* 28 (2007) 273, L3+C PLB 598 (2004) 15



Current tracker confronts radiation damage



Tracking performs well in 2025

JL derived corrections for % precision

Mitigation: raise voltage & cool sensors

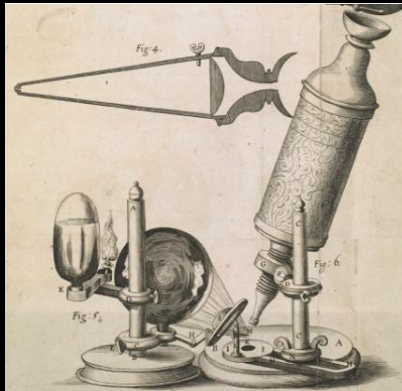
Hit power supply & cooling ceiling

Upgrades: new instruments drive new discoveries

MICROSCOPE

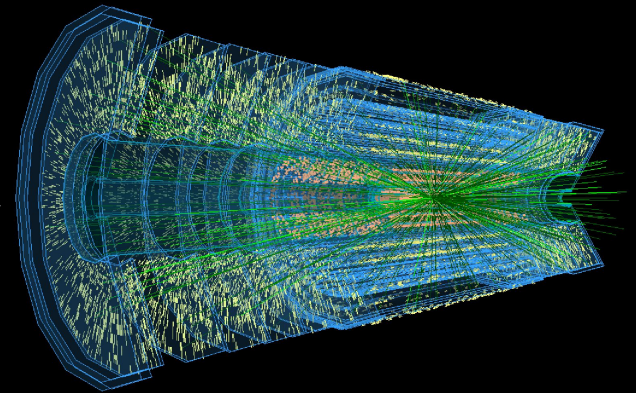
Microbiology revolution

Drebbel 1621, Hooke 1665
van Leeuwenhoek 1678

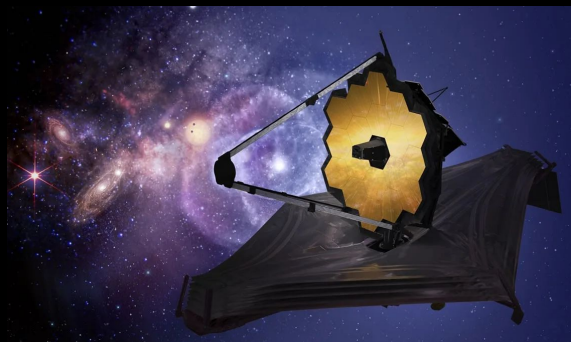


10x sharper & 100x faster for 10x fainter physics

6 → 60 million channels 10 kHz → 1 MHz readout 400 → 4000/fb luminosity



Inner Tracker (ITk) for ATLAS II



TELESCOPE

Copernican revolution

Lippershey 1604, Galileo 1610, Newton 1668

Today

2030s

Pics: Micrographia British Library, Royal Society, CERN LHC, NASA JWST, ESO ELT

ITk: build new precision camera for ATLAS II



JL glueing 🧑‍🔬



Modules x10796

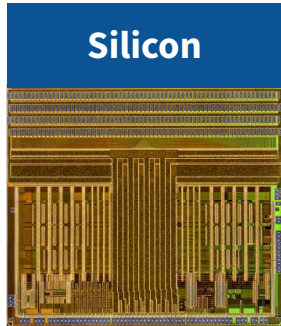


Staves x392



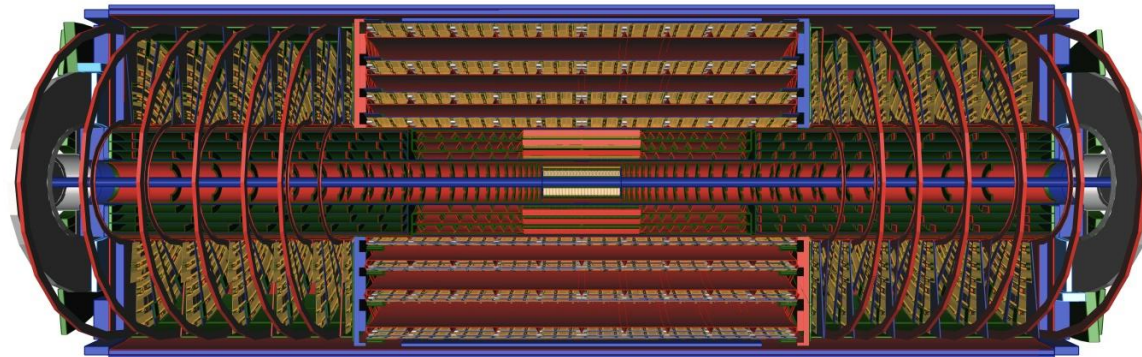
↑ Sebastian Colmenares Rutherford (NYU postdoc)

↑ With Anna Mullin (Cam PhD)



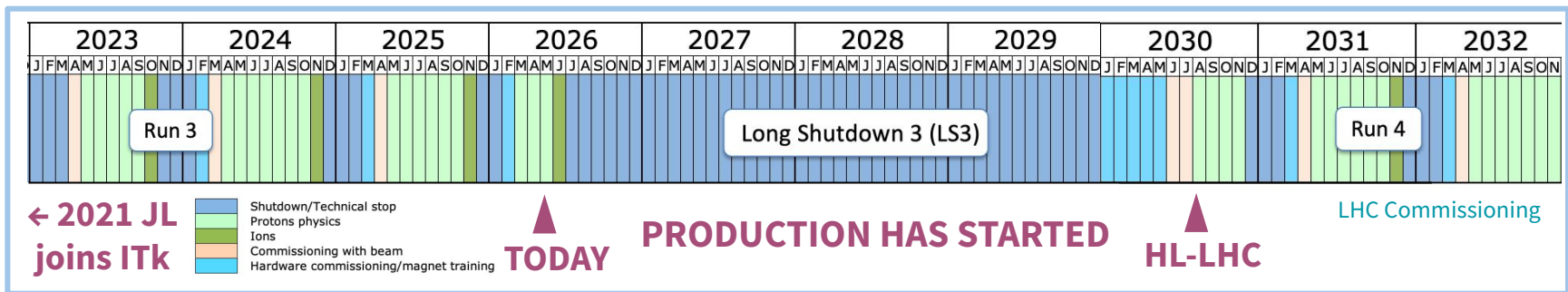
Silicon

ITk Strips TDR
PHYS-PUB-2021-024



┌ Strips
└
← Pixels
┌ Strips
└

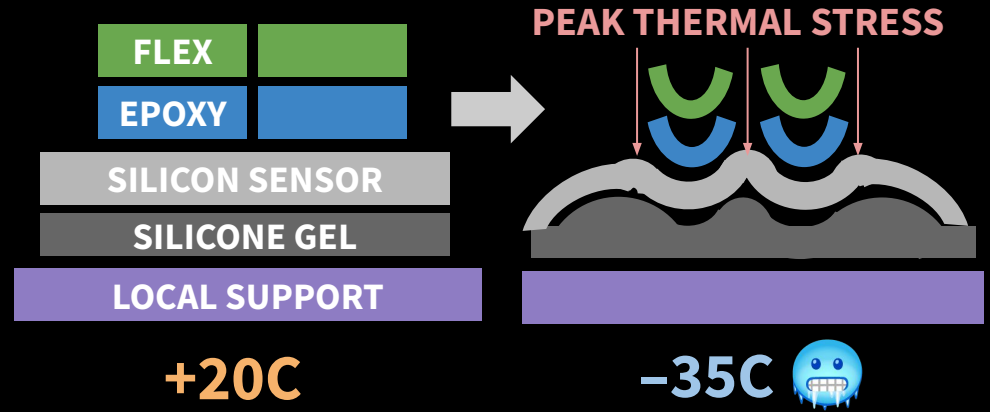
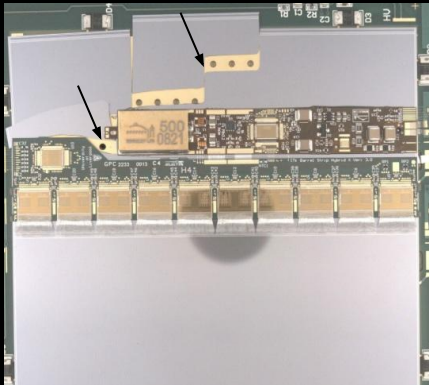
Endcap A Barrel (US+UK) Endcap C



Disaster strikes 2023: sensor fracturing

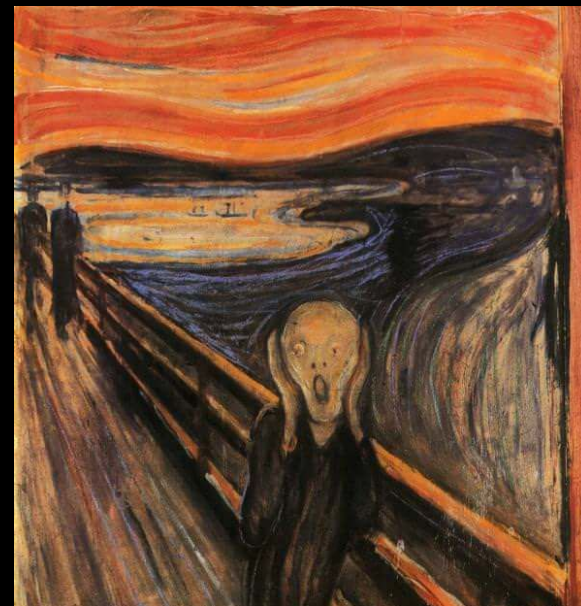
Cambridge

BNL staves



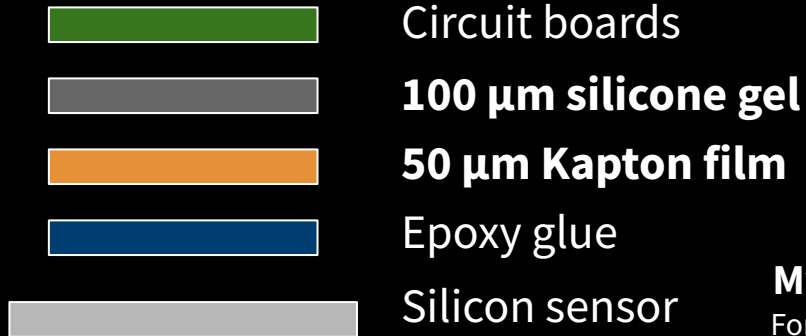
Material	Modulus (GPa)	CTE ($10^{-6}/K$)
Silicon	160	2.6
Copper	120	16.7
Kapton	2.5	20
Epoxy	3.1	60
Silicone	0.001	-

Overlooked in original design
Delays production by 1.5 years



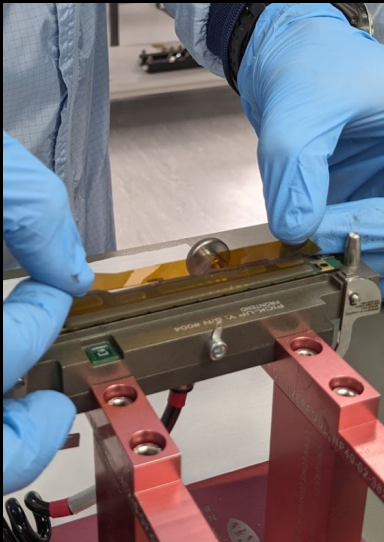
Edvard Munch *The Scream*

Solution: stress mitigating interposer



**New: soft silicone
decouples thermal stress**

My contribution: 1st working interposer module
Fomin, Hommels, Ivison, Kariyapperuma, JL JINST 20 (2025) P09036



Jinst

PUBLISHED BY IOP PUBLISHING FOR SISSA MEDIALAB

RECEIVED: July 18, 2025
REVISED: September 2, 2025
ACCEPTED: September 8, 2025
PUBLISHED: September 23, 2025

**Extended thermal cycling of ATLAS ITk strip modules
with and without stress mitigating interposers**

Nikolai Fomin,^a Bart Hommels,^a Thomas Ivison,^a Kosala Kariyapperuma^a
and Jesse Liu^{a,b,*}

^aCavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, U.K.

^bDepartment of Physics, New York University, New York City, NY 10003, U.S.A.

E-mail: jesse.liu2@nyu.edu

First stave results towards mitigating sensor fracturing with
interposers in the ATLAS ITk strips barrel JINST 20 (2025) P09025

G. D'Amen, D. Dewhurst, E. Dibley, J. Dopke, E. Duden, G. Hawker, B. Gallop, N. Ghorbanian,
P. Jacobson, M. Kurth, A. Li, D. Lynn, A. Petersen, P. Phillips, D. Russell, C. Sawyer, C. Solaz,
W. Sorger, S. Stucci, A. Tishelman-Charny, A. Tricoli and G. van Nieuwenhuizen [Hide full author list](#)

“We have interposer parts: let’s cut and stick with art roller!”

— Bart Hommels & JL, Cambridge Coffee Break 22 Mar 2024

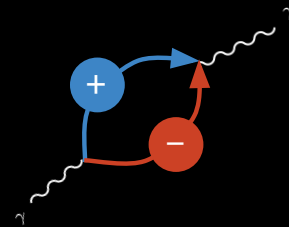
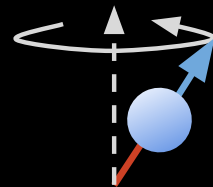
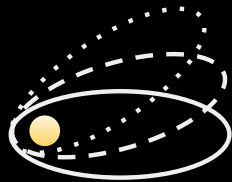
EPILOGUE

Precise measurements open paradigm shifts

General Relativity: SPACETIME IS DYNAMICAL

“Mercury known since antiquity: no new planets”

*But precise perihelion precession **upends gravity***



Quantum Field Theory: VACUUM IS DYNAMICAL

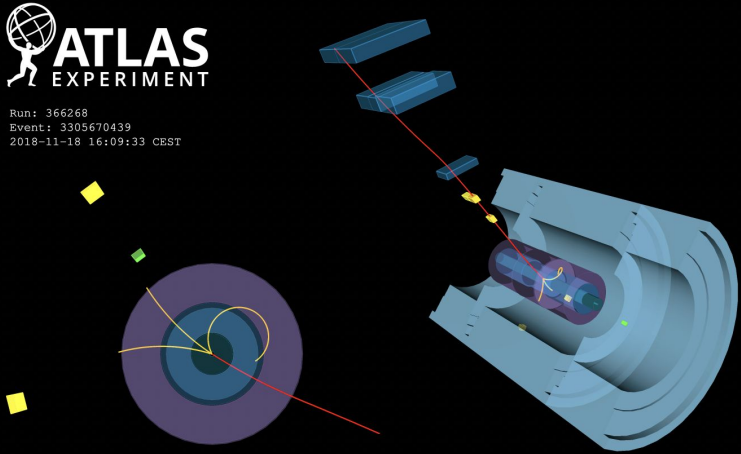
“Why probe next decimal place: no new particles”

*But per-mille electron precession **upends vacuum***

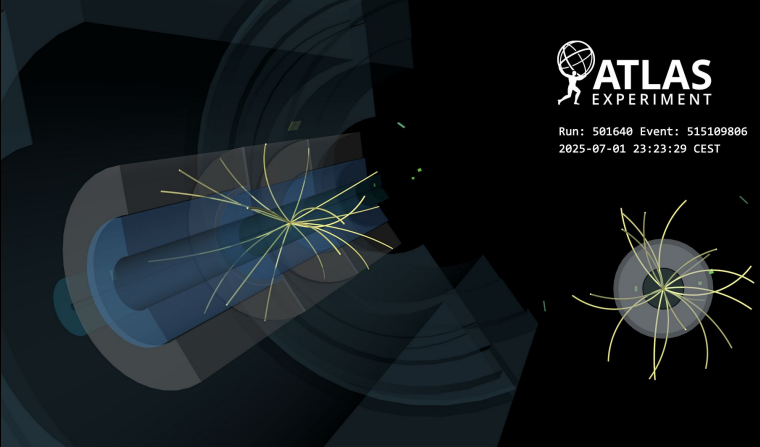
Ordinary harboured extraordinary surprises

SUMMARY

Broaden collider science across disciplinary boundaries



LHC as Photon Collider
Quantum dipole physics
 $\text{Tau } g - 2 \text{ via } \gamma\gamma \rightarrow \tau\tau$
QUANTUM + NUCLEAR + FLAVOUR



LHC as Cosmic-ray Lab
PeV astroparticle physics
Proton-oxygen collisions
PRECISION + NUCLEAR + ASTROPHYSICS