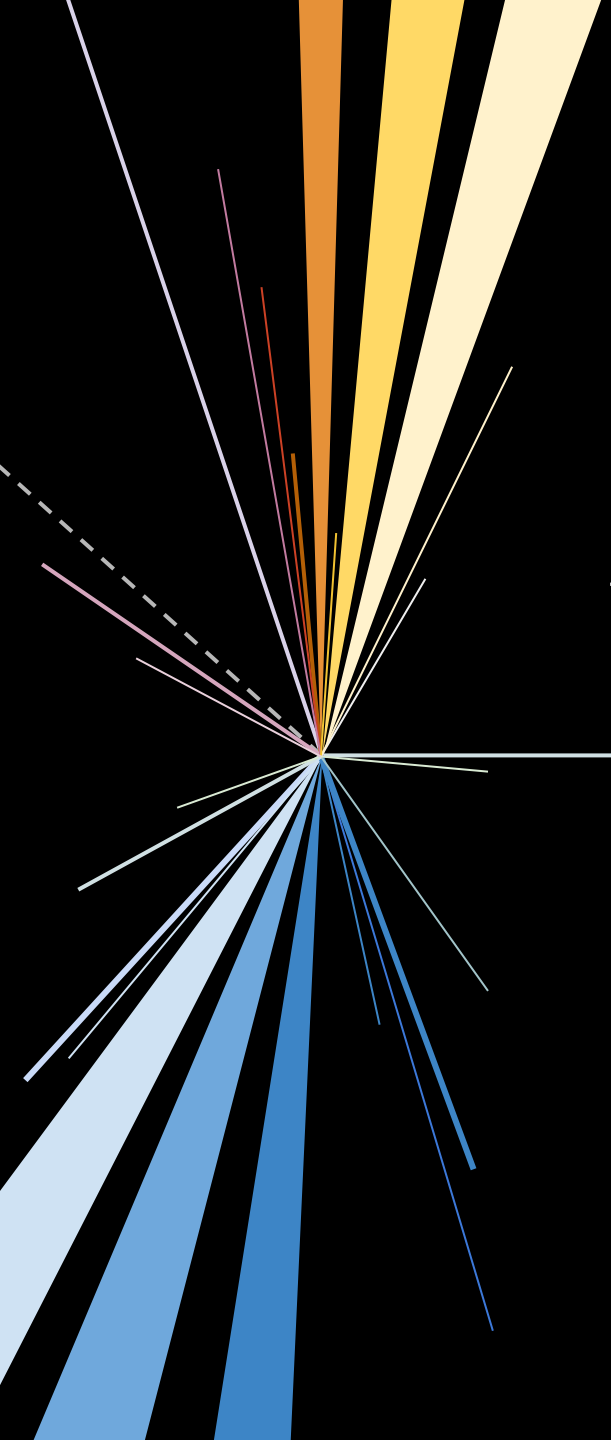


COLLIDING LIGHT

To search for BSM phenomena

Snowmass Energy Frontier

EF09 BSM General Explorations

4 September 2020

Jesse Liu
University of Chicago
In collaboration with Lydia Beresford (University of Oxford)

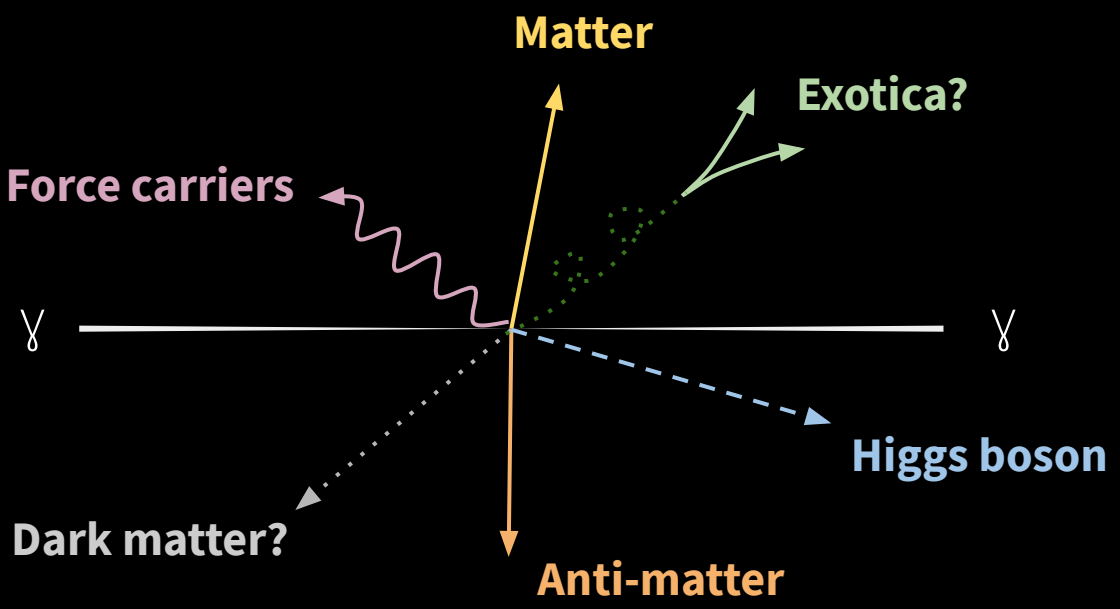
THE UNIVERSITY OF CHICAGO

What happens when we collide light
at the most extreme laboratory energies?

What happens when we **collide light** at extreme energies?

Sounds more exotic than a muon collider?

E.g. LUXE (Laser Und XFEL Experiment) [1909.00860], CERN γγ Higgs factory [Snowmass EF/AF 1 Jul]

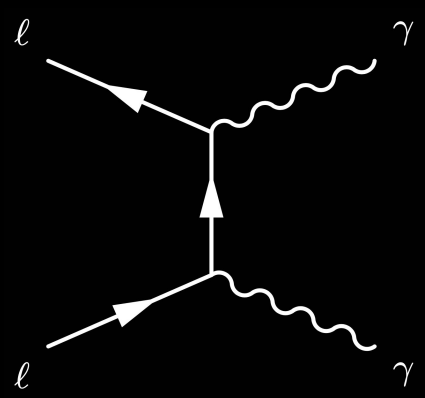


Actually already reality: **LHC is an energy frontier photon collider**

Renaissance renewed by groundbreaking experimental results

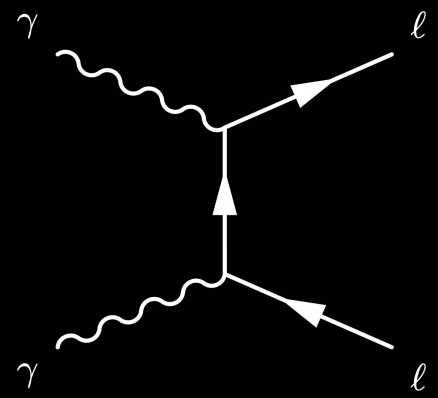
Fermi (1925) [hep-th/0205086], Weizsäcker (1934), Williams (1934), Breit & Wheeler (1934), Schwinger (1952)
See also Baltz et al [0706.3356], de Favereau de Jeneret et al [0908.2020], Bruce et al [1812.07688]

Foundational tests of quantum electrodynamics



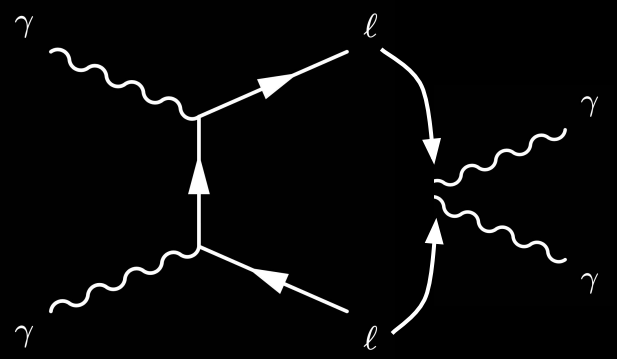
Matter turns into light

Positron–electron tomography



Light turns into matter

Extragalactic light cosmic rays

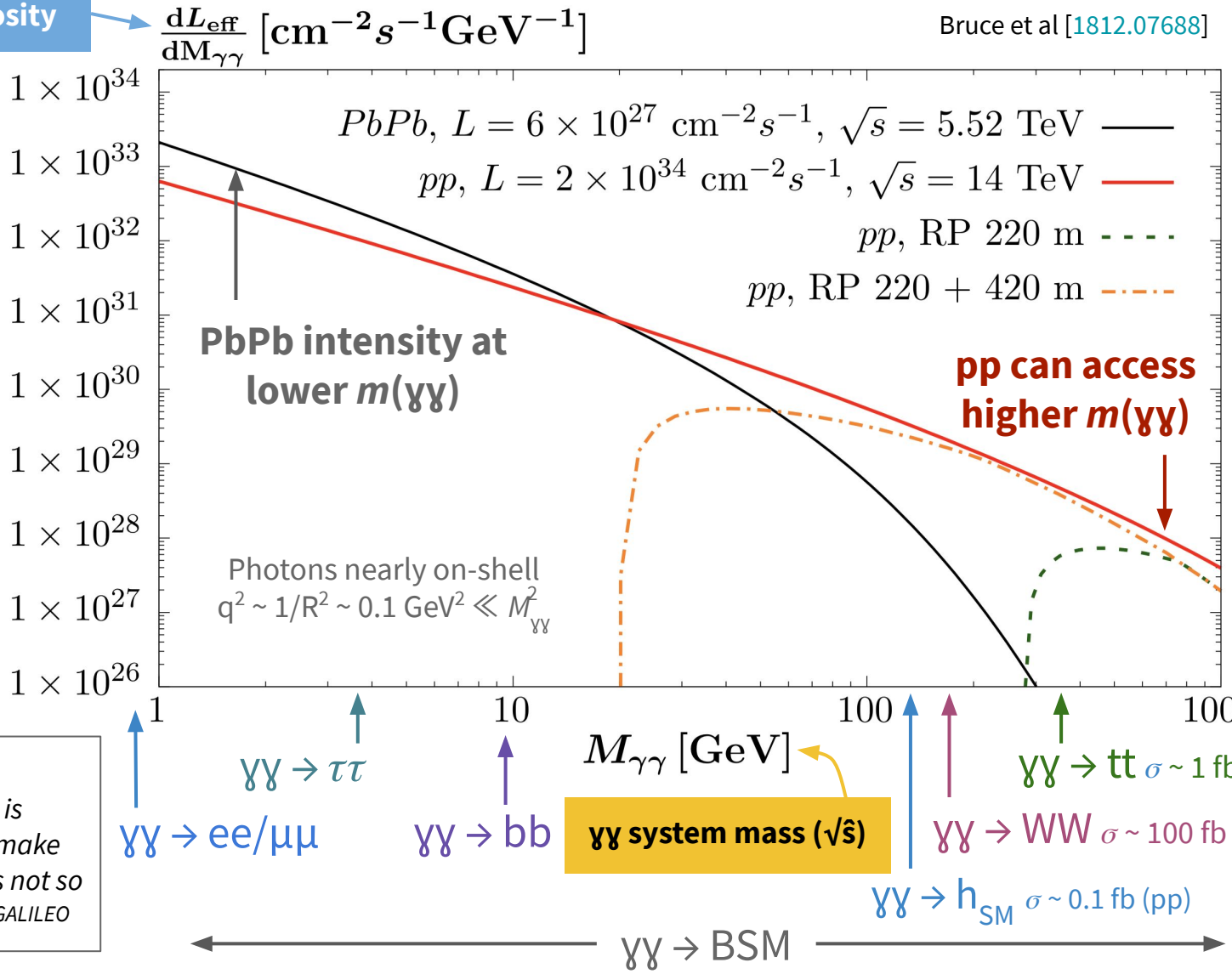


Light scatters off light

Axion-like particle searches

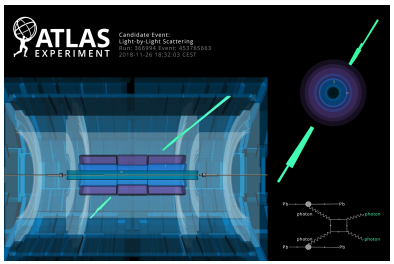
Colliding γγ spectrum: LHC uniquely probes above EW scale

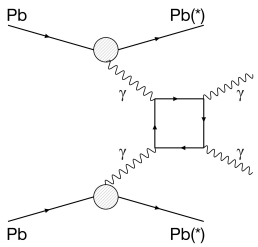
Photon luminosity



> *"Measure what is measurable and make measurable what is not so*
> *– attrib. GALILEO*

Recent landmark results using LHC as a photon collider

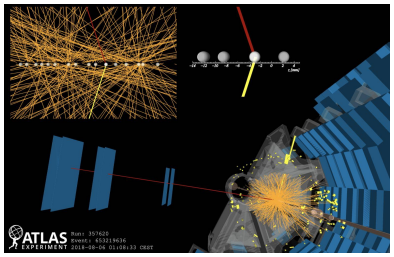


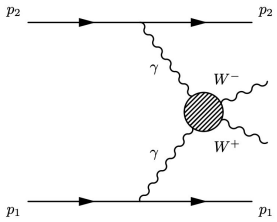


Observation of light-by-light scattering in ultraperipheral Pb+Pb collisions with the ATLAS detector

[CERN Press Statement, ATLAS Briefing, 1904.03536 (PRL)]

Test 1-loop self-coupling of light

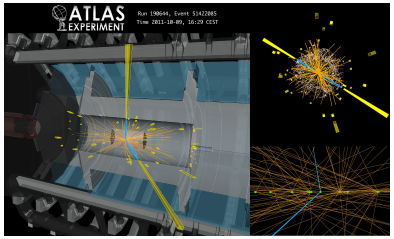


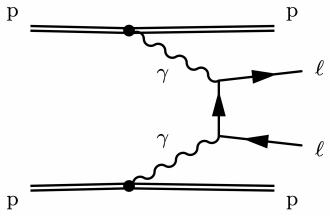


Observation of photon-induced W^+W^- production in pp collisions at $\sqrt{s}$ = 13 TeV using the ATLAS detector

[CERN Press Statement, ATLAS Briefing, ATLAS-CONF-2020-038]

See light turning into particles with weak scale masses





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

[CERN Courier feature, ATLAS Briefing, ATLAS-CONF-2020-041]

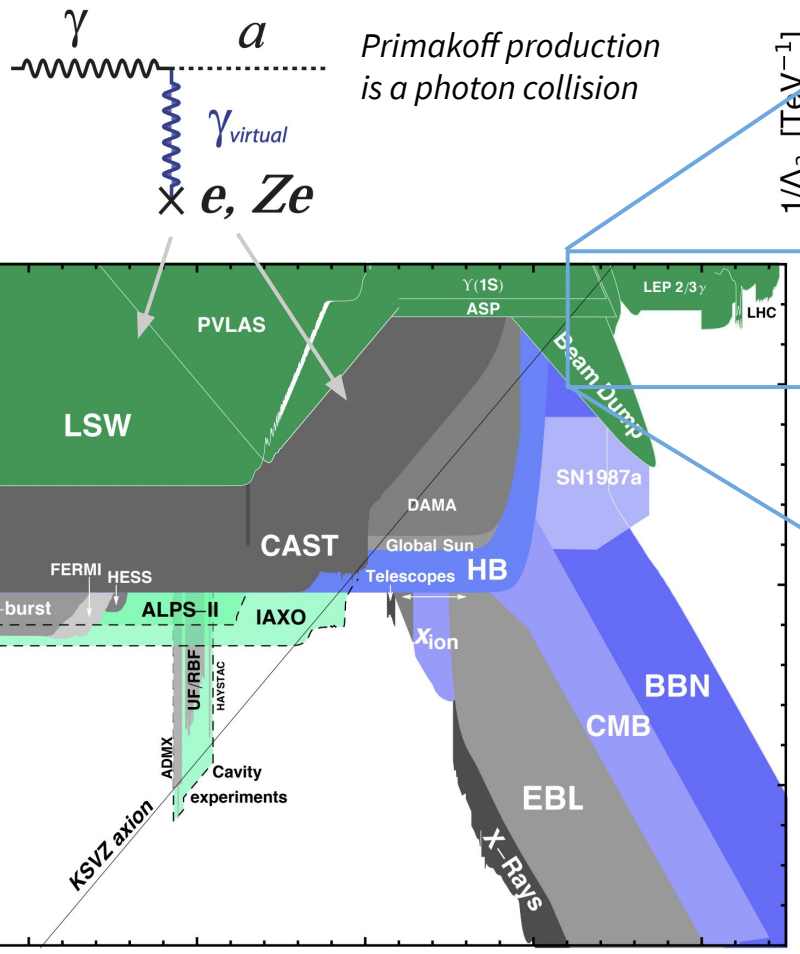
First high-μ physics using AFP detectors (Beresford & JL Editors)

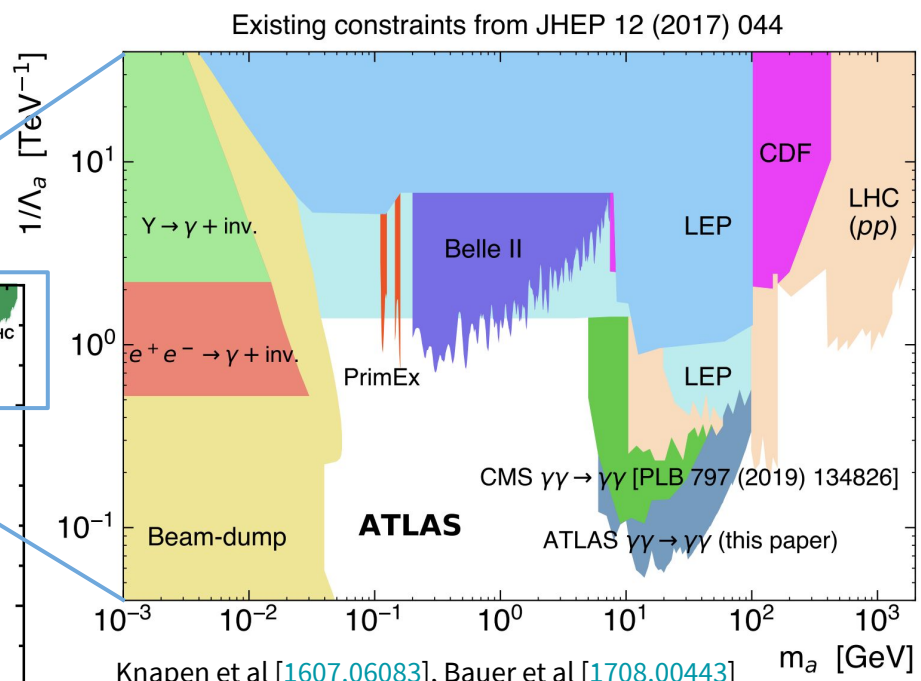
We are looking at nature in ways we have never done before

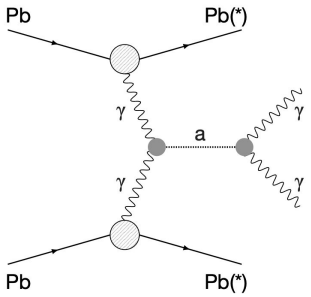
Extraordinary probes of microcosm in extreme QED regimes

See also STAR [1910.12400], CMS–TOTEM [1803.04496], LHCb [CONF-2018-003], CMS [1604.04464], ALICE [1406.7819], PHENIX [0903.2041]

Example BSM application: γγ → γγ for axion-like particles







Photon self-coupling could be resonantly enhanced ⇒ bumphunt

Probe uncharted regimes of QED: could be modified by motivated BSM physics

New opportunities for important & interesting BSM targets

We already have special LHC datasets & detectors 100+ m away
Let's use them for BSM physics!

Hot topic
Flagship science, has $$$$

↓

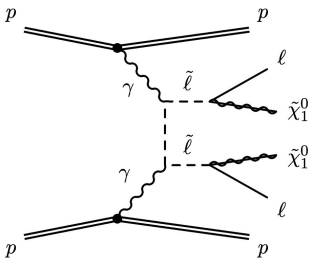
Critical problem
Dismissed as hopeless $

↓

Creative solution
From overlooked areas $

↓

Breakthrough
New field, attract $$$$



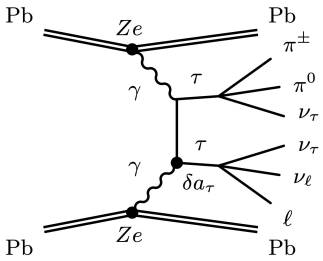
What is dark matter?

p_{miss} 4-vector immeasurable

***Collide light* to tag protons using AFP**

Direct dark matter mass measurement

Beresford & JL [1811.06465, (PRL)]
Harland-Lang et al [1812.04886]



Muon *g* – 2 tension?

Tau *g* – 2 immeasurable

***Collide light* with heavy ions & use ZDC**

Test 70 year old QED 1-loop prediction

Beresford & JL [1908.05180]
Dyndal et al [2002.05503]

***See also backup or our Snowmass EF05/06/07 talk* [8 July 2020]**

Vibrant Snowmass EF LoIs on laboratory photon collisions

New Phenomena Searches in Heavy Ion Collisions

Snowmass 2021 Energy-Frontier – Letter of Interest

Liliana Apolinário[1], Lydia Beresford[2], Nora Brambilla[3], Émilien Chapon[4], Yang-Ting Chien[5], David d'Enterria[6], Albert De Roeck[6], Marco Drewes[7], Mateusz Dyndal[6], Hesham El Faham[7], Glennys R. Farrar[8], Sylvain Fichet[9], Andrea Giammanco[7], Victor P. Goncalves[10], Oliver Gould[11], Jan Hajer[7], Lucian Harland-Lang[12], Sonia Kabana[13], Simon Knapen[6], Vladimir Kovalenko[14], Georgios K. Krintiras[15], Jesse Liu[16], Steven Lowette[17], Michele Lucente[7], Daniel E. Martins[18], Guilherme Milhano[1,19], Matthew Nguyen[20], Vitalii A. Okorokov[21], James Pinfold[22], Arttu Rajantie[23], Patricia Rebello Teles[24], Federico Leo Redi[25], Ingo Schienbein[26], Matthias Schott[27], Gustavo Gil da Silveira[28], Rajeev Singh[29], Michael Spannowsky[30], Jiayin Sun[31], Ralf Ulrich[32], Merijn van de Klundert[33], and Michael Winn[34]

[1]LIP, Av. Professor Gama Pinto 2, 1649-003 Lisboa, Portugal
[2]Department of Physics, University of Oxford, Oxford OX1 3RH, UK
[3]Physik Department, Technische Universität München, München
[4]Institute of High Energy Physics, Beijing, China
[5]C.N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, NY 11794, USA
[6]CERN, 1211 Geneva, Switzerland
[7]Centre for Cosmology, Particle Physics and Phenomenology, Université catholique de Louvain, Louvain-la-Neuve B-1348, Belgium
[8]Centre for Cosmology and Particle Physics, New York University, NY, NY 10003, USA
[9]ICTP South American Institute for Fundamental Research & IFT-UNESP, Sao Paulo, Brazil
[10]Universidade Federal de Pelotas, Pelotas - RS, Brazil
[11]Helsinki Institute of Physics, University of Helsinki, FI-00014, Finland
[12]University of Oxford, England
[13]Instituto de Alta Investigación, Universidad de Tarapacá, Arica, 1000000, Chile
[14]Saint Petersburg State University, Russia
[15]Department of Physics and Astronomy, 1082 Malott, 1251 Wescoe Hall Dr. Lawrence, KS 66045
[16]Department of Physics, University of Chicago, Chicago IL 60637, USA
[17]Department of Physics, Vrije Universiteit Brussel, Brussels, Belgium
[18]Universidade Federal do Rio de Janeiro (UFRJ), Brazil
[19]Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1609-001, Lisboa, Portugal
[20]Laboratoire Leprince-Ringuet - École Polytechnique, 91120 Palaiseau, France
[21]National Research Nuclear University MEPhI, 115409 Moscow, Russia
[22]Centre for Particle Physics, University of Alberta, Edmonton, Alberta, Canada
[23]Department of Physics, Imperial College London, London SW7 2AZ, United Kingdom
[24]Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
[25]École polytechnique fédérale de Lausanne - EPFL, Lausanne, Switzerland
[26]Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3,53 Avenue des Martyrs, 38026 Grenoble, France
[27]Johannes Gutenberg University Mainz, Germany

EF07/08 [link]

Short-Bunch Paradigm Laserless $\gamma\gamma$ Collider LoI to Energy Frontier

Phil H. Bucksbaum, Gerald V. Dunne, Frederico Fiuza, Sebastian Meuren, Michael E. Peskin[a)], David A. Reis, Greger Torgrimsson, Glen White[b)], and Vitaly Yakimenko

Abstract. We propose to investigate a new paradigm for a $\gamma\gamma$ collider based on an e^-e^- collider with extremely short, cylindrical bunches and strong beam-beam interaction. In this regime, the beams emit beamstrahlung in the extreme quantum limit, producing a hard photon spectrum that, in principle, can be useful for physics. We plan to investigate this idea for applications to low-energy $\gamma\gamma$ collisions, a $\gamma\gamma$ Higgs factory, and a 30 TeV $\gamma\gamma$ frontier collider.

EF01/AF1 [link]

First measurement of the $\gamma\gamma \to \tau^+\tau^-$ process and τ lepton electromagnetic moments at LHC

Georgios K Krintiras,[1,*] Michael Murray,[1,†] Muhammad Alibordi,[2,‡] Yuta Takahashi,[3,§] Stefanos Leontsinis,[3,¶] and Ben Kilminster[3,**]
[1]*Department of Physics and Astronomy 1082 Malott, 1251 Wescoe Hall Dr. Lawrence, KS 66045*
[2]*Indian Institute Of Technology Madras, Chennai, India*
[3]*University of Zurich, Switzerland*

(Dated: August 31, 2020)

EF06/07 [link]

Production of Charged BSM Particles at Future Heavy-Ion Colliders Via Photon-Photon Fusion

Laura Jeanty and Jenna Kishinevsky
*University of Oregon**

Lawrence Lee
Harvard University†

(Dated: August 25, 2020)

EF07/08 [link]

Probing anomalous quartic gauge couplings with proton tagging at the CERN Large Hadron Collider

C. Baldenegro[1], S. Fichet[2], G. von Gersdorff[3], T. Isidori[1], C. Royon[1], and J. Williams[1]

[1]University of Kansas, Lawrence, US
[3]ICTP-SAIFR, Sao Paulo, Brazil
[4]Pontificia Universidade Catolica, Rio de Janeiro, Brazil

EF06 [link]

EF07: Ultra-Peripheral Collisions in Heavy-Ion Physics

Jaroslav Adam[2], Carlos Bertulani[12], James D. Brandenburg[2], Frank Geurts[7], Victor P. Goncalves[5], Yoshitaka Hatta[2], Yongsun Kim[13], Spencer R. Klein[4], Cong Li[3], Wei Li[7], Michael Murray[6], Joakim Nystrand[9], Mariusz Przybycien[1,*], John P. Ralston[6], Christophe Royon[6], Lijuan Ruan[2], Bjoern Schenke[2], Janet Seger[10], Peter Steinberg[2], Daniel Tapia Takaki[6], Zebo Tang[11], Zhoudunming Tu[2], Ralf Ulrich[14], Ramona Vogt[4], Bowen Xiao[8], Zhangbu Xu[2,*], Shuai Yang[7], Wangmei Zha[11], Jian Zhou[3,*], and Ya-jin Zhou[3]

[1]AGH University of Science and Technology, Cracow, 30-059, Poland
[2]Physics Deparment, Brookhaven National Laboratory, Upton, NY 11973, USA
[3]Key Laboratory of Particle Physics and Particle Irradiation (MOE), Institute of Frontier and Interdisciplinary Science, Shandong University (QingDao), Shandong 266237, China
[4]Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley CA 94720 USA
[5]Universidade Federal de Pelotas, Pelotas - RS, 96010-900, Brazil
[6]Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA
[7]T.W. Bonner Nuclear Laboratory, Rice University, Houston, TX 77005, USA
[8]Physics Department, Central China Normal University, Wuhan, Hubei 430079, China
[9]Department of Physics and Technology, University of Bergen, Bergen, Norway
[10]Physics Department, Creighton University, Omaha 68178, NE, USA
[11]Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui, China
[12]Department of Physics and Astronomy, Texas AM University-Commerce, Commerce, TX
[13]Physics department Sejong University, Seoul, South Korea
[14]KIT, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany
*Coordinators for this LOI

EF06/07 [link]

Survey progress & define science vision for 2020s

Our LoI [SNOWMASS21-EF9-019] EF09 as home + EF06–10 cross-topic; RF03, RF06, CF07, IF03, TF07, AF3 cross-frontier links

Strategic vision for energy frontier photon collider science

Lydia Beresford[1,*] and Jesse Liu[2,†]

[1] *Department of Physics, University of Oxford, Oxford OX1 3RH, UK*
[2] *Department of Physics, University of Chicago, Chicago IL 60637, USA*

(Dated: June 30, 2020)

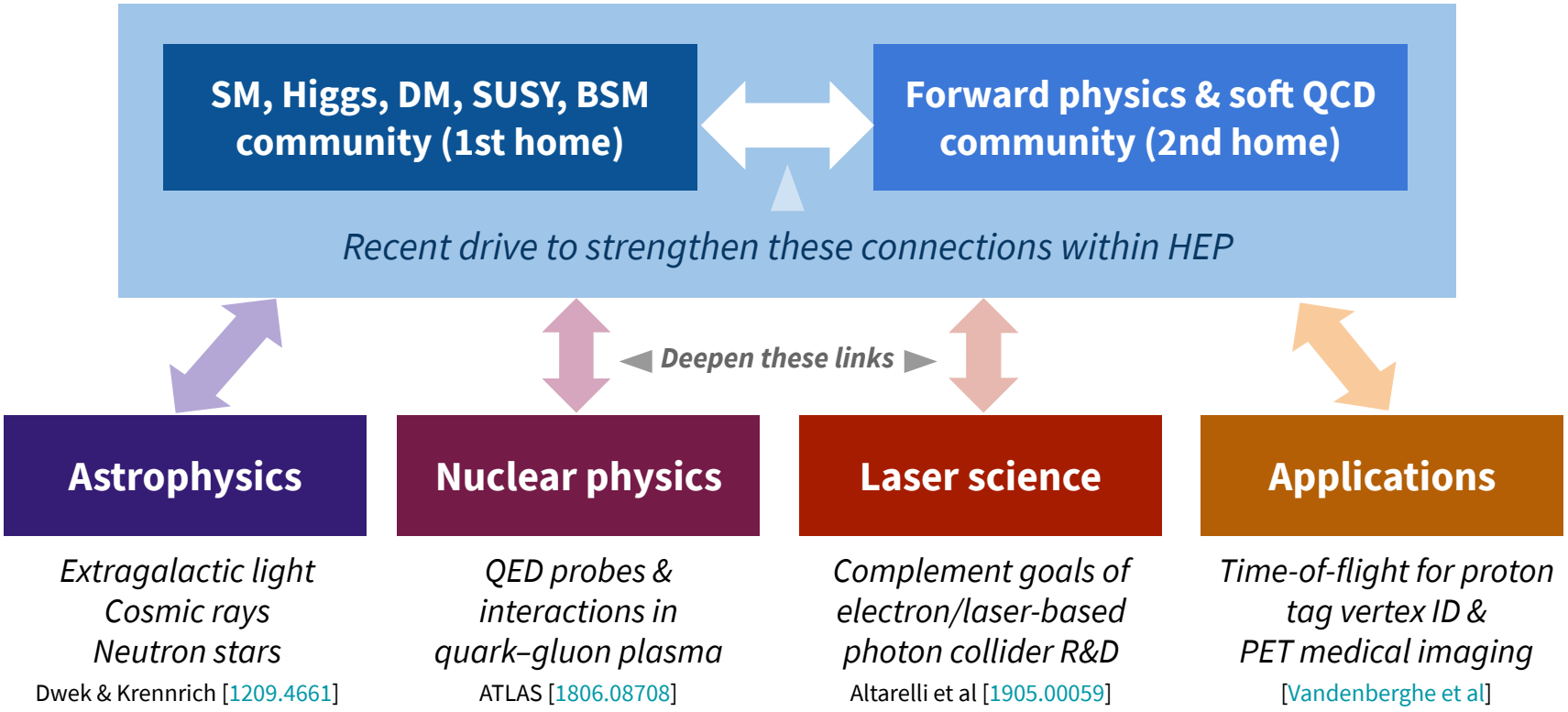
Recent landmark results are renewing interest in using the LHC as a photon–photon $\gamma\gamma$ collider. We initiate our strategic vision to transform QED production at the LHC and beyond into a flagship programme with a thriving community this decade. This defines the science drivers for precision measurements and new physics searches such as electromagnetic dipole moments and dark sectors. We identify opportunities to invest in technology and theory, interdisciplinary synergies with laser science and astrophysics, and community outreach to expand this exciting programme.

Science drivers & big questions	**Physics targets, probes, benchmarks**	**Facilities, instrumentation, software**	**Interdisciplinary synergies**	**Outreach, education, applications**
Why must we research & fund laboratory tests of extreme QED?	*What is the roadmap for discoveries & exploring model space?*	*Which techniques & technological enablers must we invest in?*	*Where can we share expertise & goals with neighbours of HEP?*	*How do we attract, train & uplift this diverse community?*

Interest & community exists but **sociological HEP/Nuclear/Accelerator split** due to historical/funding divisions
Snowmass is science-driven: bring together communities with little sociological but large science overlap
Desired Snowmass & P5 outcome: make easier to **attract funding to do better science collaboratively**

Expand horizons for new cross-cutting opportunities

PHOTON COLLIDER SCIENCE



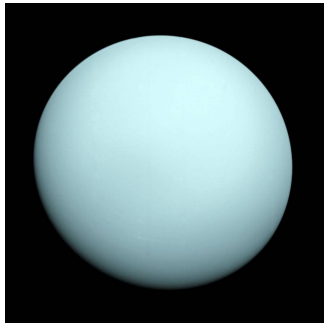
Discoveries transforming our understanding of nature often occur at the interface of established communities

EXTRAS

HISTORY

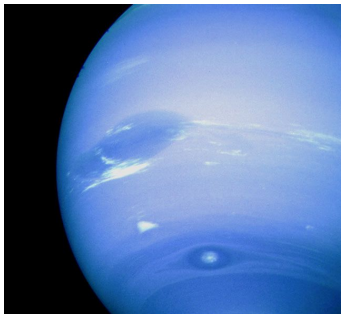
*"Haven't we precisely tested **Kepler–Newtonian dynamics** already?"*
*"What more is there to learn about **Mercury's orbit – a planet known since antiquity**?"*

Self-consistency tests	Spectacular predictive power	Transformative precision



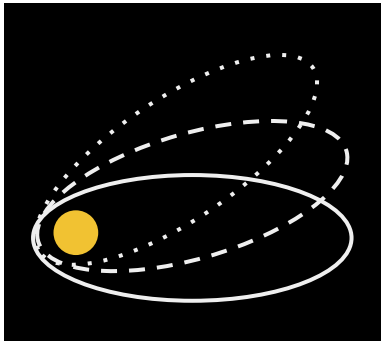
Credits: NASA/JPL-Caltech

Uranus
Herschel 1781
Planet never seen before
65 years of measuring
Like precision electroweak tests



Credits: NASA/JPL-Caltech

Neptune
Le Verrier/Galle 1846
Discover on same night
within 1° of prediction
Like 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

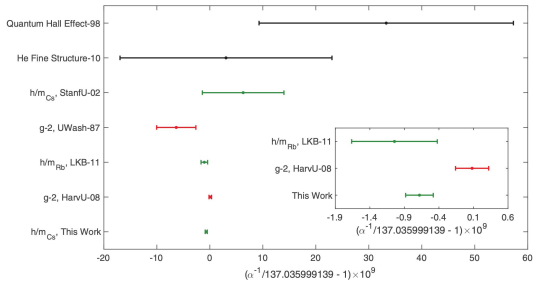
Discovering new planets amazing but did not upturn laws of nature
But precisely measuring known planet transformative: geometry = gravity

Per mille measurement of electron precession did not discover new particles
But conceptually revolutionary: virtual loops are physical

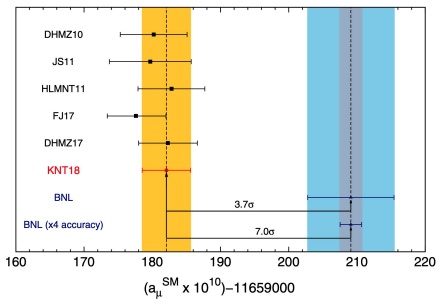
Such stories embody the fundamental spirit of empirical enquiry that we as a community must keep celebrating and championing

Persistent widespread indirect evidence for new physics

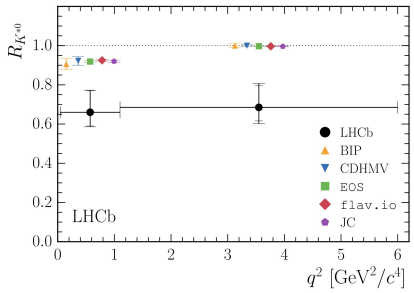
Electron $g-2$
[Science (2018)]



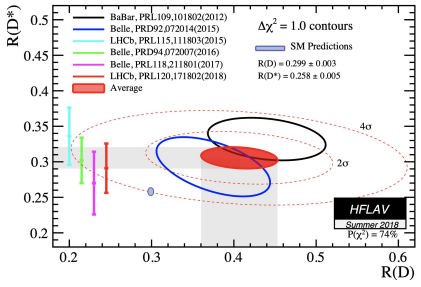
Muon $g-2$
[PRD (2018)]



$B \to K\ell\ell$
[JHEP (2017)]



$B \to D\tau\nu$
[HFLAV (2018)]

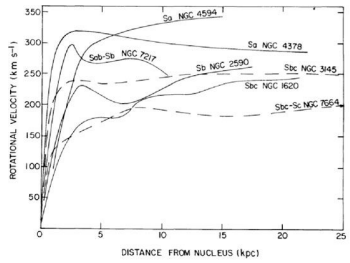


Lepton anomalies

Involves e/μ/τ across different labs
Indirect evidence of new particles (in loops)
(Also neutrino anomalies but beyond today's scope)

Dark matter

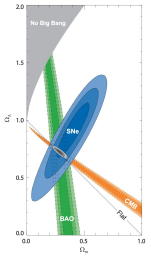
Sub-galactic to cosmological scales
Indirect evidence for particle nature
(Also dark energy but beyond my pay grade)



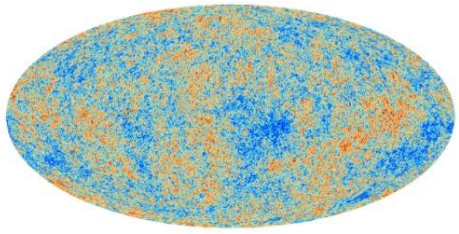
Galaxy rotation
[ApJ (1978)]

Lensing
[ESA/Hubble & NASA]

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



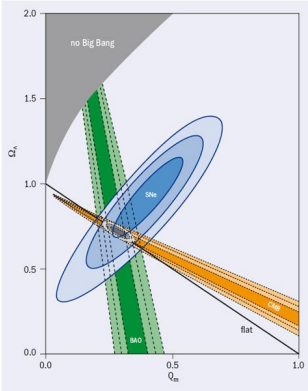
BAO
[ApJ (2008)]



CMB
[ESA/Planck]

Early days Zwicky, Rubin et al were just measuring stars & galaxies precisely: DM a surprise

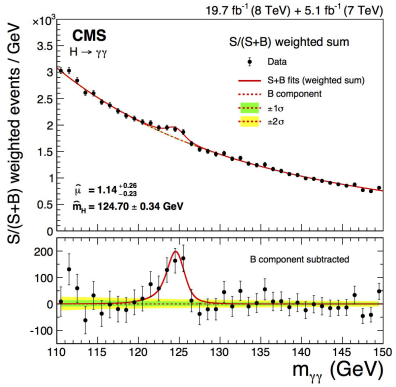
Precisely controlling light still transforming science



Dark energy

Nobel Prize in Physics 2011

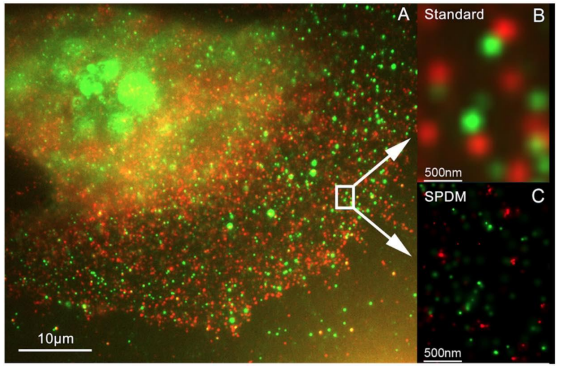
Supernovae redshift



Higgs boson

Nobel Prize in Physics 2013

Seeing origin of mass



Super-resolution microscopy

Nobel Prize in Chemistry 2014

Overcome diffraction limit

Gravitational waves

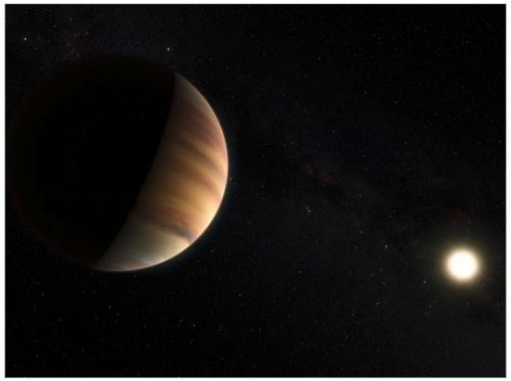
Nobel Prize in Physics 2017

Lasers + interferometry

Optical tweezers

Nobel Prize in Physics 2018

Manipulate nanoparticles



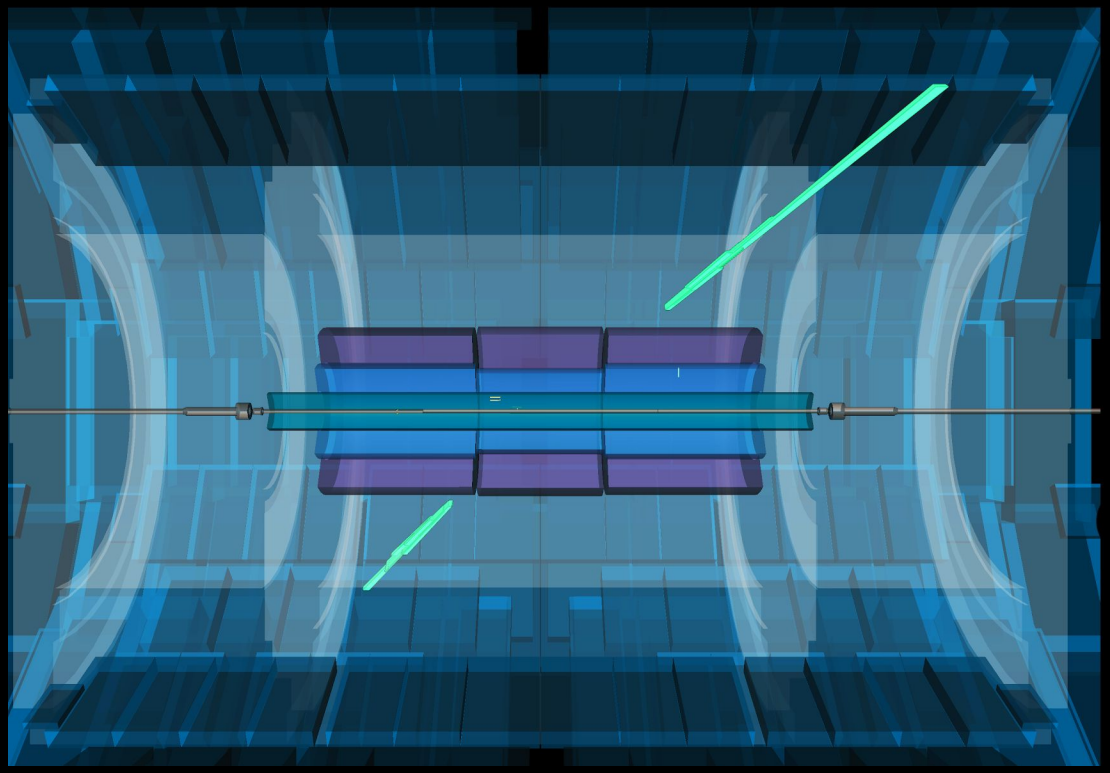
Extrasolar planets

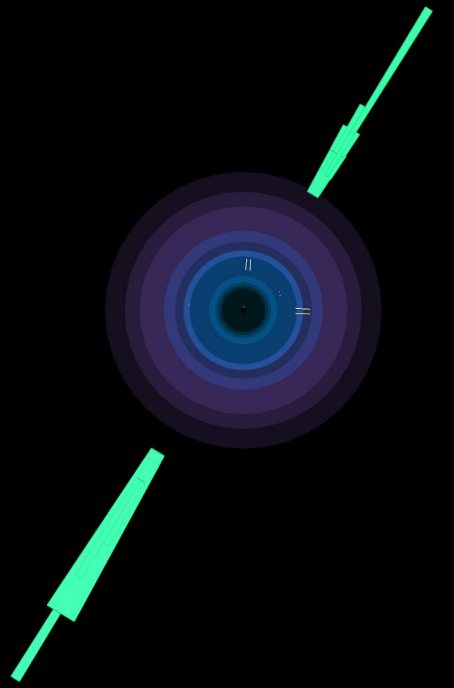
Nobel Prize in Physics 2019

See new worlds

ATLAS EXPERIMENT

Candidate Event:
Light-by-Light Scattering
Run: 366994 Event: 453765663
2018-11-26 18:32:03 CEST





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

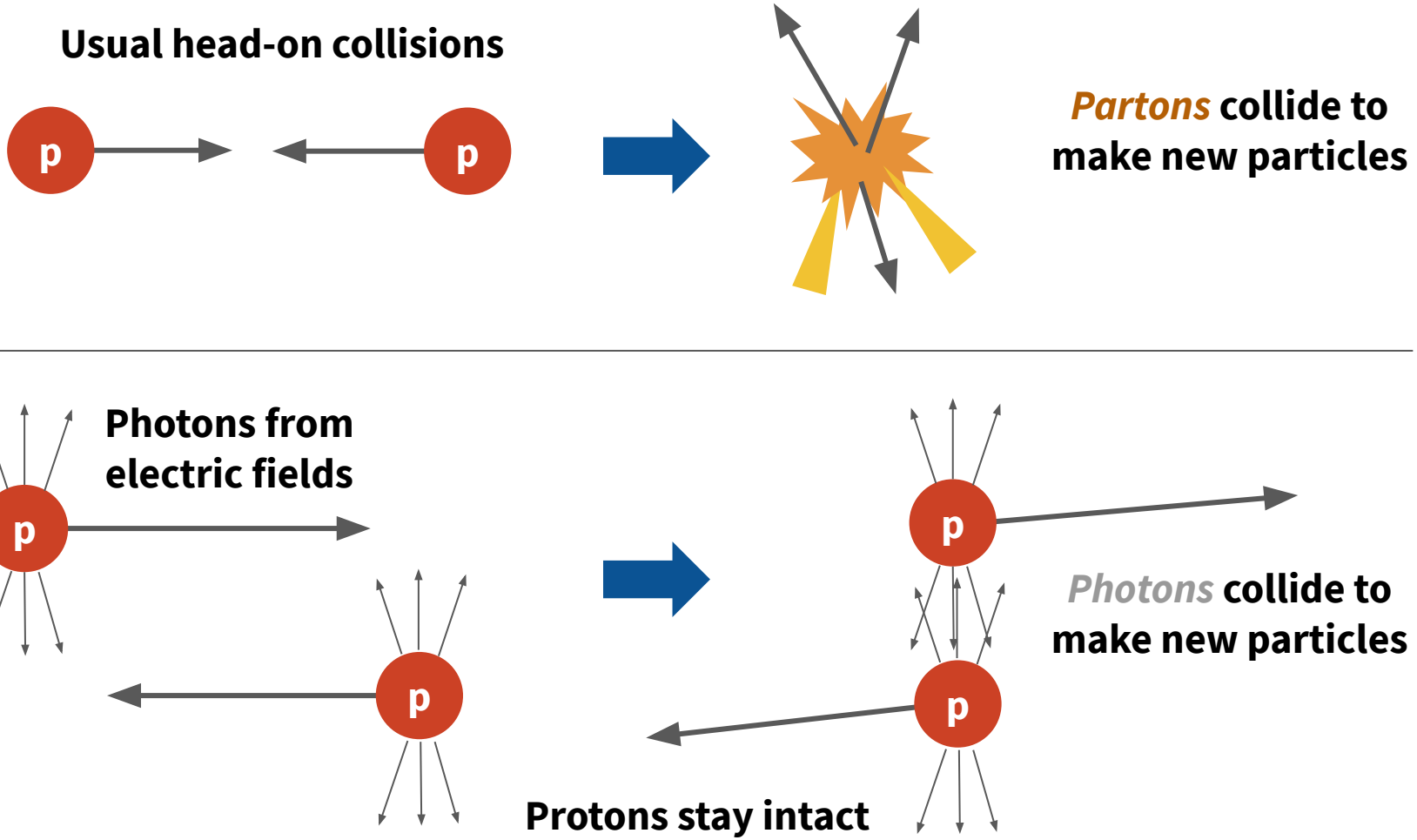
BREAKTHROUGH 1

Observation of light-by-light scattering γγ → γγ

Significance: 8.2σ (6.2σ) obs (exp) [1904.03536 (PRL); see also 1702.01625 (Nat Phys) , 2008.05355]

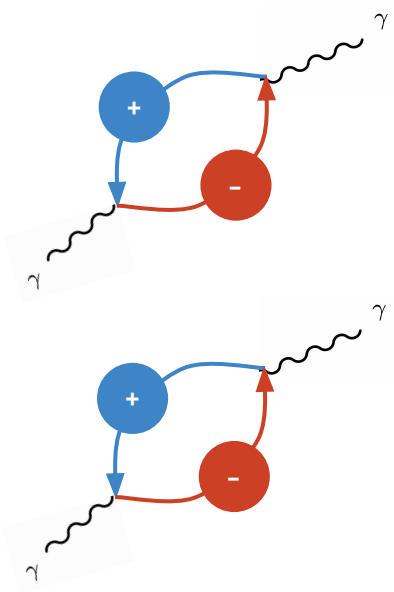
$$\sigma_{\text{meas.}} = 78 \pm 13\ (\text{stat.}) \pm 7\ (\text{syst.}) \pm 3\ (\text{lumi.})\ \text{nb}$$

Colliding light @ LHC



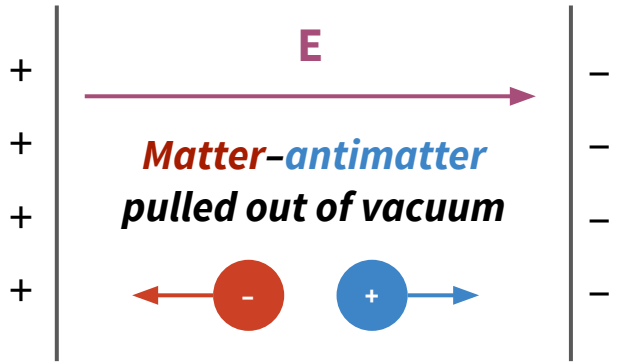
Fermi (1925) [hep-th/0205086], Weizsäcker (1934), Williams (1934), Schwinger (1952)
Brodsky, Kinoshita, Terazaw (1971), Budnev, Ginzburg, Meledin, Serbo (1975)
d'Enterria and da Silveira [1305.7142], ATLAS [1702.01625, 1904.03536], CMS [1810.04602], Bruce et al [1812.07688]

Colliders are laboratory tests of extreme QED



Uncertainty principle
$\Delta E \Delta t \sim \hbar/2 \Rightarrow$ virtual loops polarise vacuum

Quantum vacuum



Work done by E field on pair of charges in Compton wavelength*

Threshold for pair production

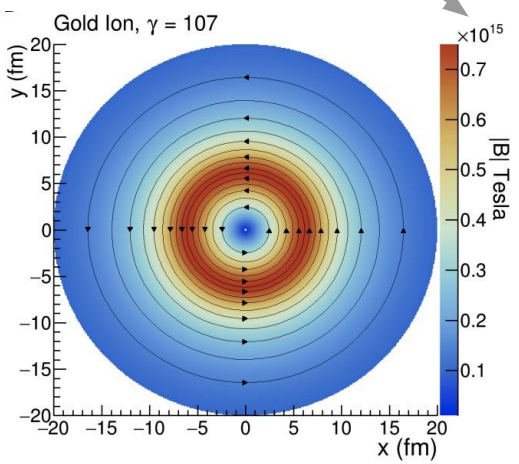
$$eE_{\text{crit}}\left(2\frac{\hbar}{m_e c}\right) \sim 2m_e c^2$$

$$\Rightarrow E_{\text{crit}} = \frac{m_e^2 c^3}{e\hbar} \sim 10^{18}\ \text{V m}^{-1}$$

$$B_{\text{crit}} = \frac{m_e^2 c^2}{e\hbar} \sim 10^{9}\ \text{T}$$

Schwinger limit

B ~ 10^{15} T @ colliders exceed Schwinger limit



STAR Collaboration (RHIC) [1910.12400]

In nature: magnetar neutron stars B ~ 10^{10} T

Kaspi & Beloborodov [1703.00068]

Extreme QED in lab

*Semiclassical intuition: full field-theoretic calculation requires non-perturbative QED [Schwinger 1952]

In popular press: “rip apart empty space”

New Scientist (2019)
Science Magazine News (2018)
The Telegraph (2011)

NEWSLETTERS
Sign up to read our regular email newsletters

NewScientist

News Podcasts Video Technology Space Physics Health More Shop Tours Events

What's inside nothing? This laser will rip it up to find out

Far from being empty, the vacuum of space could be brimming with mysterious virtual particles. We now have a machine powerful enough to tear it apart and see

PHYSICS 23 January 2019

AAAS Become a Member

Science Contents News Careers Journals

SHARE 431 923

A laser in Shanghai, China, has set power records yet fits on tabletops. KAN ZHAN

Physicists are planning to build lasers so powerful they could rip apart empty space

By Edwin Cartlidge | Jan. 24, 2018 , 9:00 AM

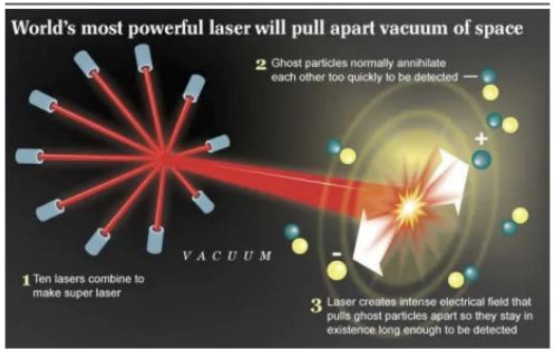
The Telegraph

Home Video News World Sport Business Money Comment Culture Travel Life W
Politics Investigations Obits Education Science Earth Weather Health Royal Celebr
Science News Dinosaurs Space Night Sky Evolution Picture Galleries Science Video

HOME » NEWS » SCIENCE » SCIENCE NEWS

World's most powerful laser to tear apart the vacuum of space

A laser powerful enough to tear apart the fabric of space could be built in Britain as part major new scientific project that aims to answer some of the most fundamental questions about our universe.

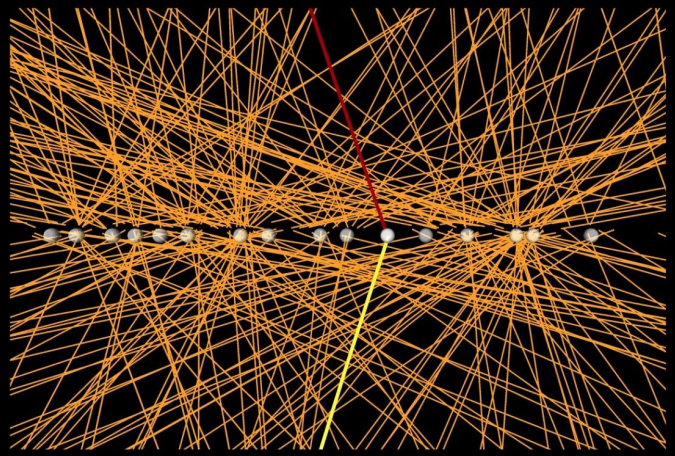


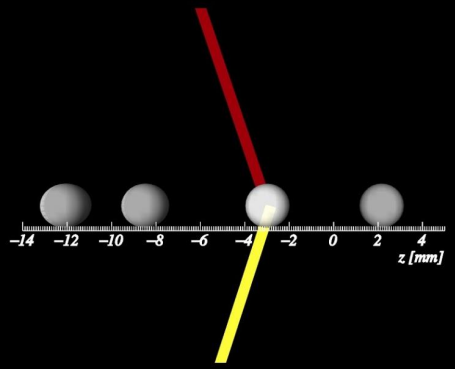
Print this article

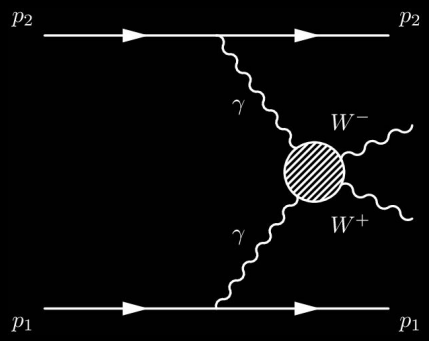
Science News
News » Europe »
UK News » Science »
Richard Gray »

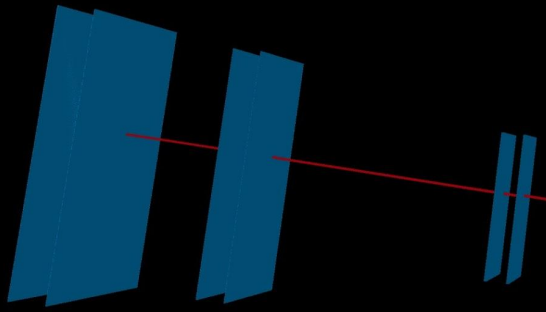
In Science News

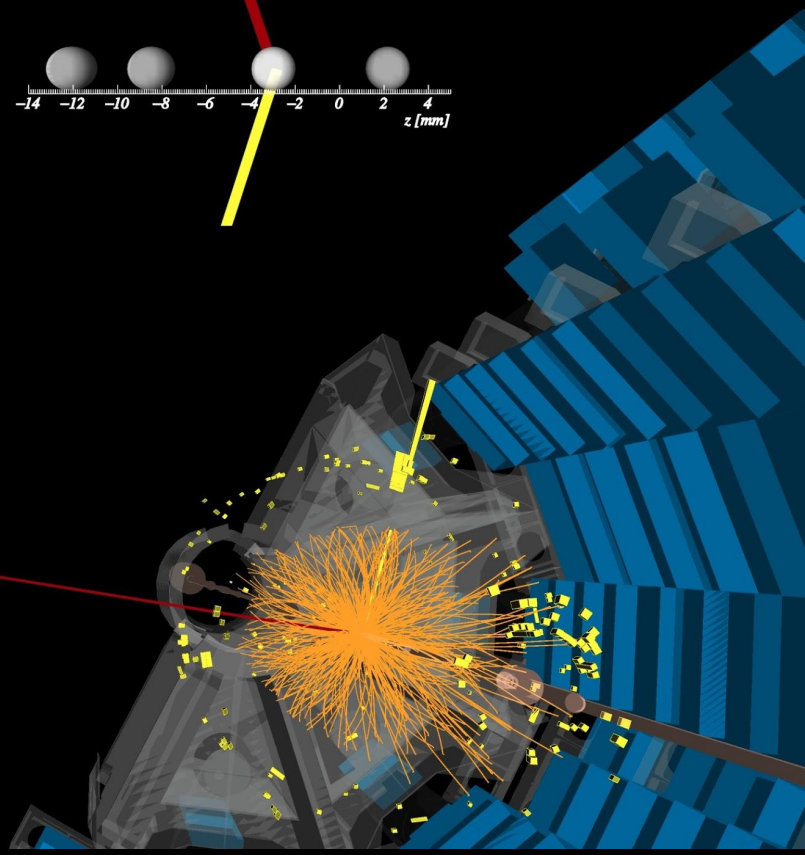
Total eclipse, in pictures











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

BREAKTHROUGH 2

Observation of γγ → WW

Hot-off-the-press: announced at ICHEP

Previously unobserved in nature or laboratory

[ATLAS-CONF-2020-038, Press Statement, Physics Briefing]

Rare phenomenon observed by ATLAS features the LHC as a high-energy photon collider

The ATLAS experiment reports the observation of photon collisions producing weak-force carriers and provides further insights into their interactions.

5 AUGUST, 2020

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

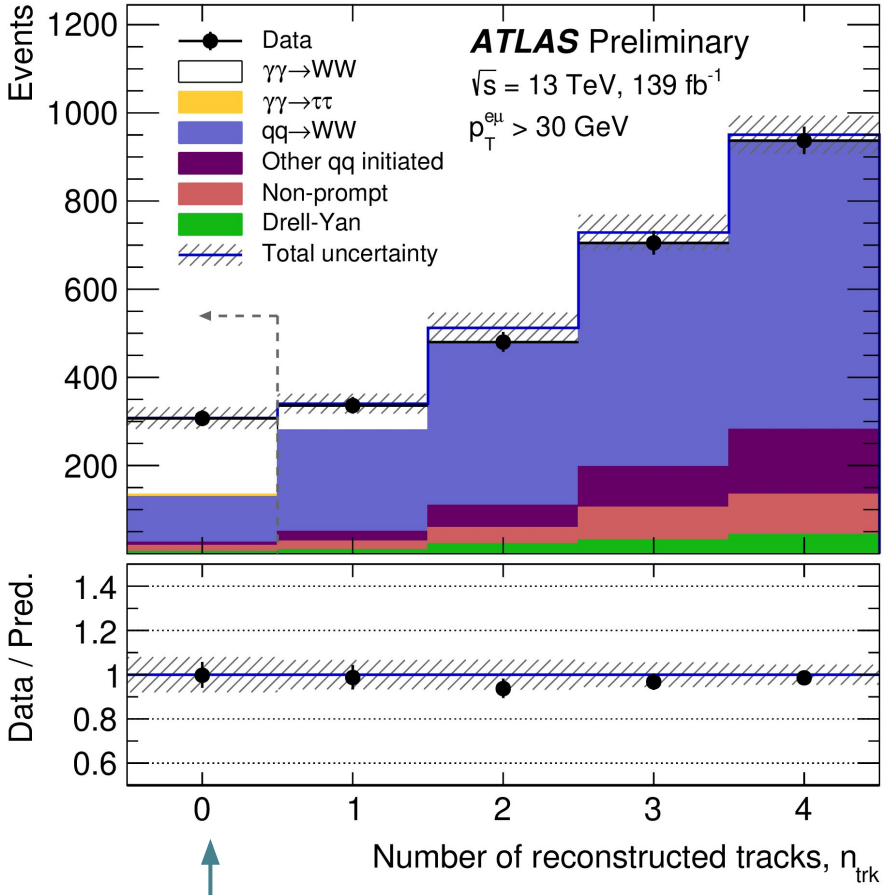
ATLAS-CONF-2020-038

29 July 2020

Significance: 8.4σ (6.6σ) obs (exp)

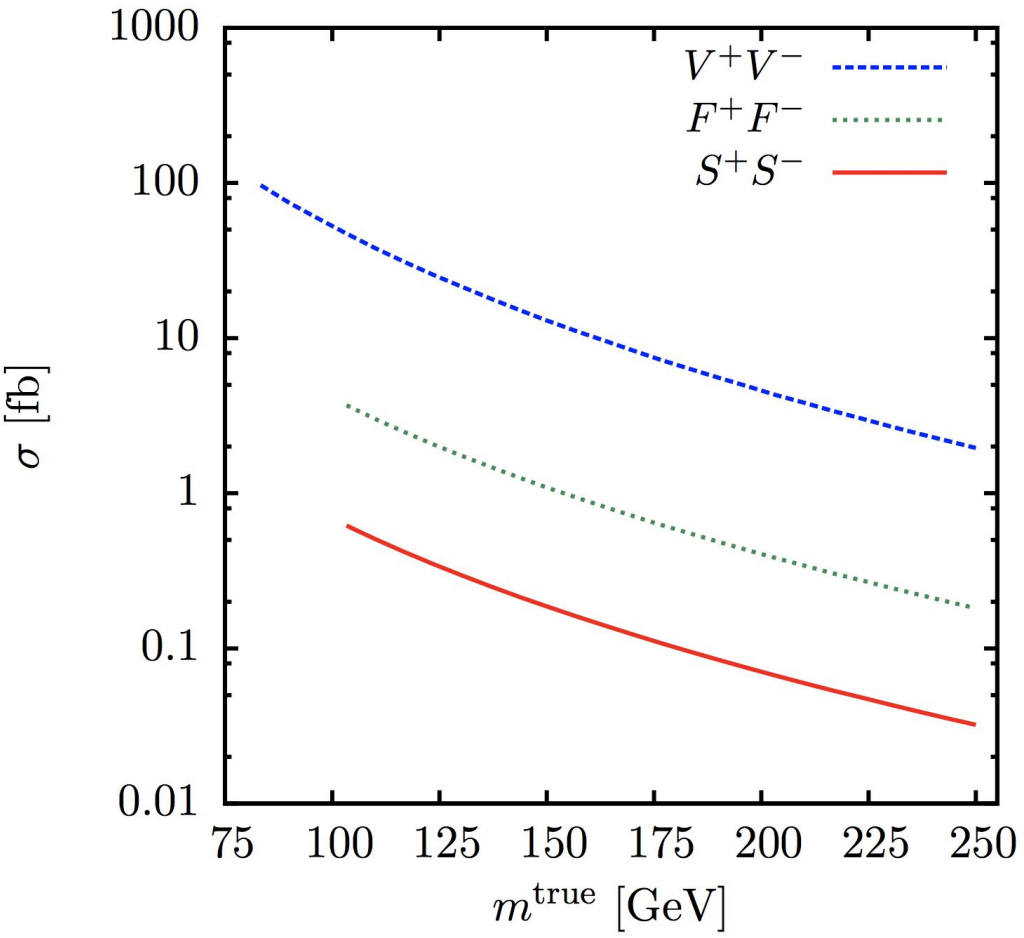
Direct laboratory evidence of light transforming into particles with weak scale masses

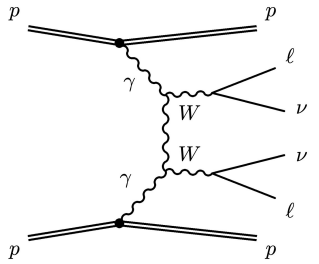
$\sigma_{meas} = 3.13 \pm 0.31\,(stat.) \pm 0.28\,(syst.)$ fb



Main discriminant: photon collisions leave no additional tracks near eμ vertex

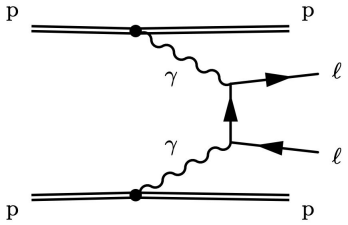
Cross-sections: QED pair production





γγ → WW

CMS 1604.04464
ATLAS 1607.03745
ATLAS CONF-2020-038



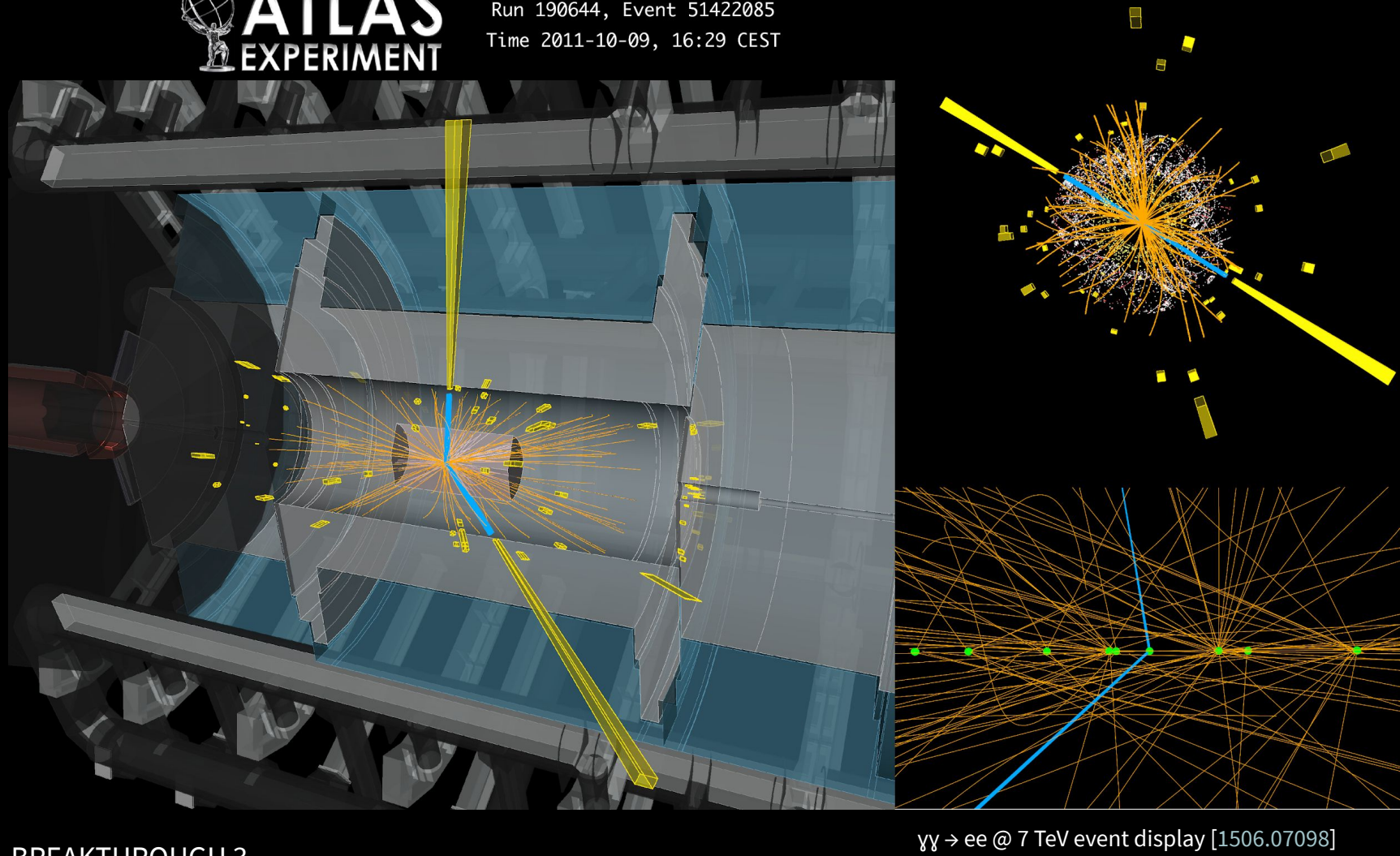
γγ→ ee/μμ

CMS 1209.1666
ATLAS 1506.07098
ATLAS 1708.04053
ATLAS CONF-2016-025
ATLAS CONF-2020-041

14 TeV pp → p (γγ → XX) p

QED production fixed by mass & spin

Harland-Lang, Kom, Sakurai, Stirling [1110.4320]



γγ → ee @ 7 TeV event display [1506.07098]

BREAKTHROUGH 3

Observation of proton scattering in pp → p + (γγ → ee/μμ) + p

New: see scattered protons stay intact

Without proton-tagging can only see this

Also hot-off-the-press: just announced at ICHEP!

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

ATLAS-CONF-2020-041

29 July 2020

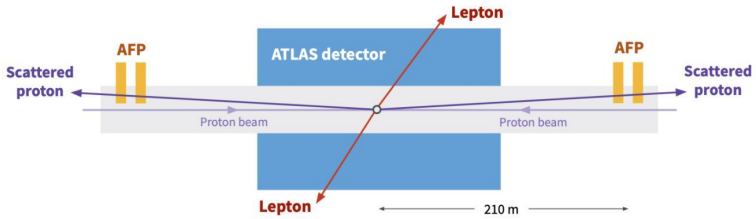
Physics Briefing

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.



$$\sigma^{\text{fid.}}_{ee+p} = 11.0 \pm 2.6\,(\text{stat.}) \pm 1.2\,(\text{syst.}) \pm 0.3\,(\text{lumi.})\ \text{fb},$$
$$\sigma^{\text{fid.}}_{\mu\mu+p} = 7.2 \pm 1.6\,(\text{stat.}) \pm 0.9\,(\text{syst.}) \pm 0.2\,(\text{lumi.})\ \text{fb}.$$

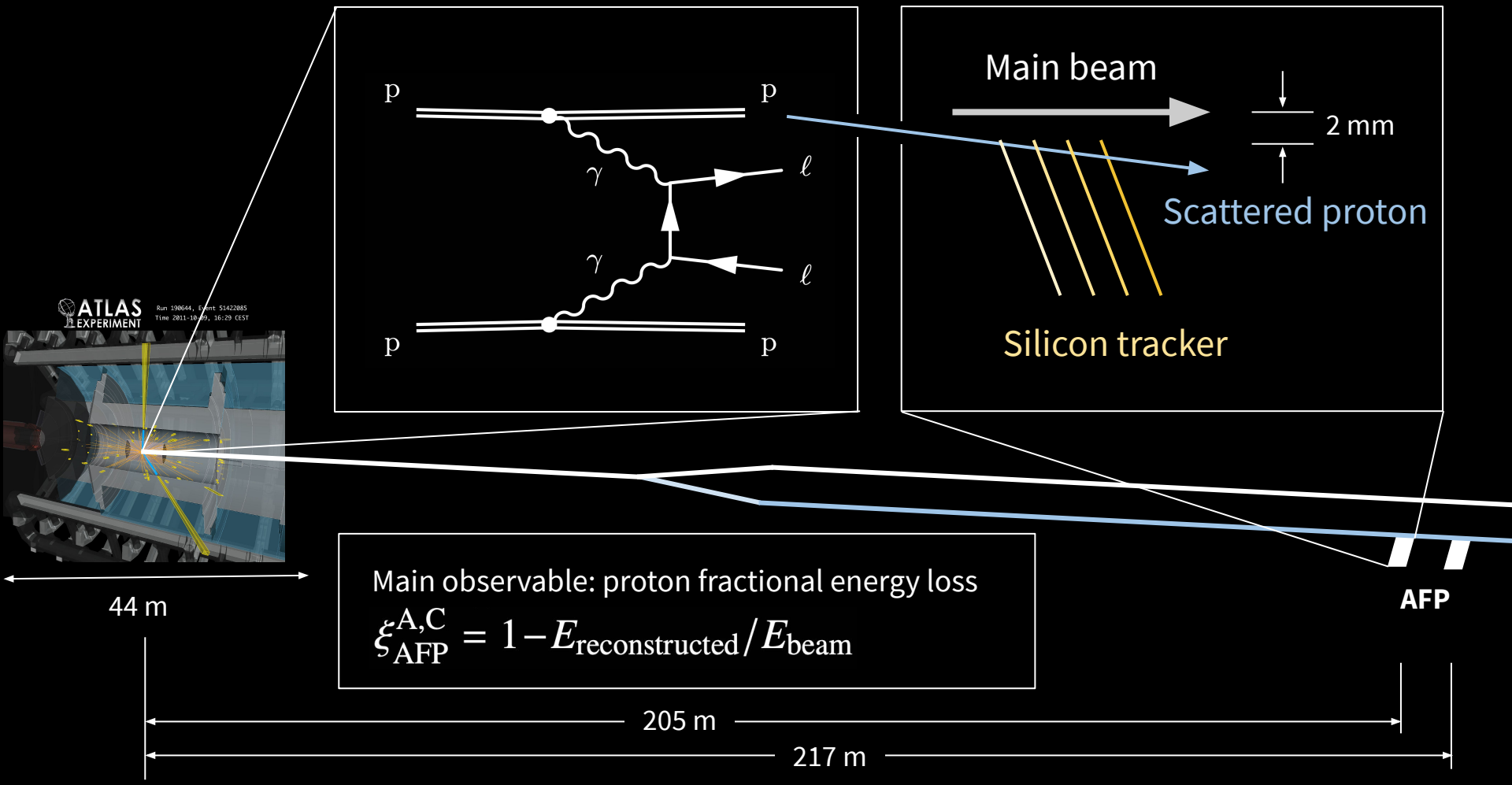
First cross-section measurement of (γγ → ℓℓ)+p at LHC

New analysis with new detector & new reconstruction

Main project I co-led for past year [ATLAS-CONF-2020-041, ATLAS Physics Briefing]

ATLAS Forward Proton

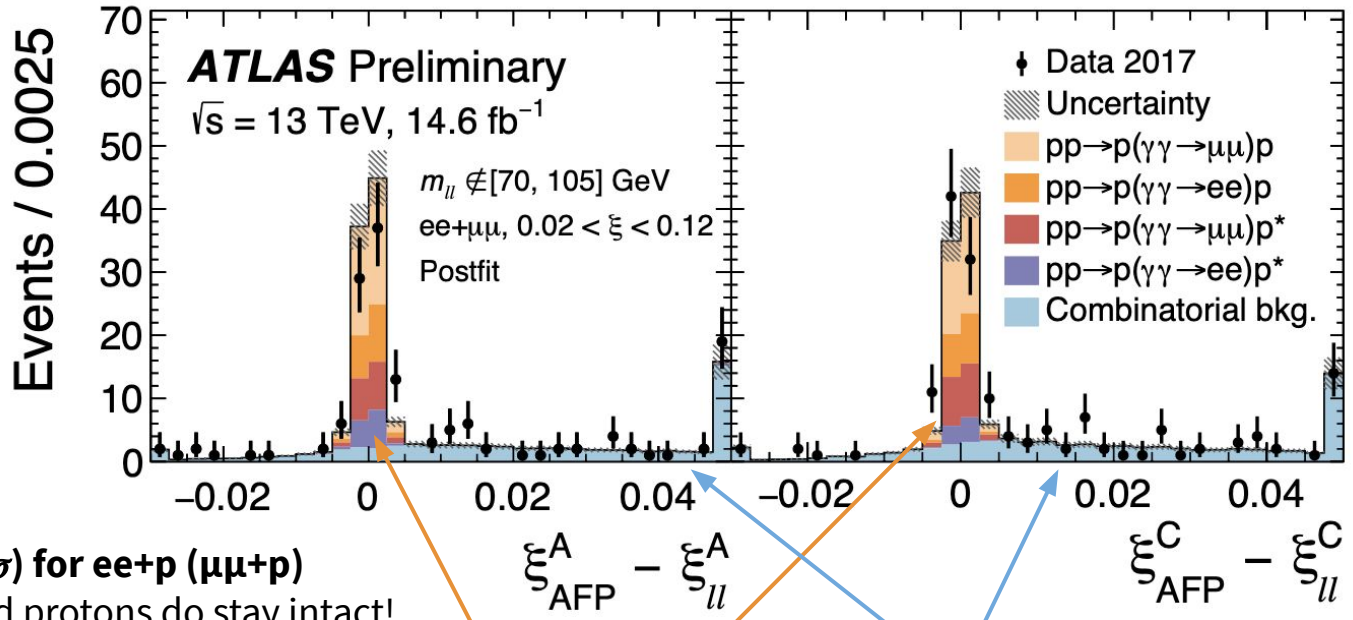
Both arms installed in 2017 for standard high-luminosity LHC data-taking
New analysis object opening exciting program of photon collision physics



Main observable: proton fractional energy loss

$$\xi_{\mathrm{AFP}}^{\mathrm{A,C}} = 1 - E_{\mathrm{reconstructed}} / E_{\mathrm{beam}}$$

First physics results using ATLAS Forward Proton

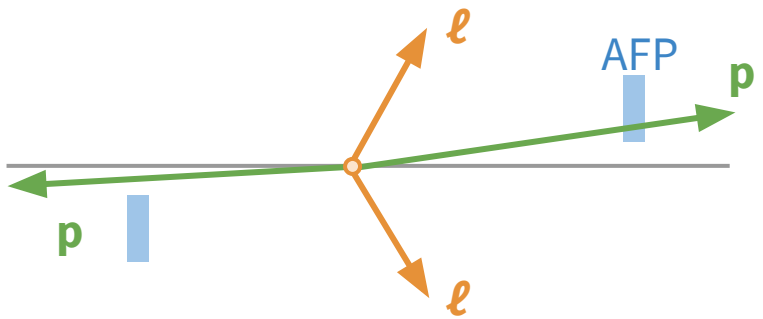


Expected energy loss

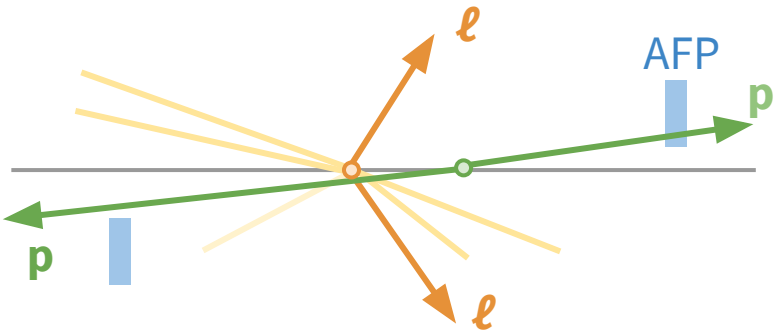
$$\xi^{\pm}_{\ell\ell} = \frac{m_{\ell\ell}}{\sqrt{s}} e^{\pm y_{\ell\ell}}$$

> 9σ (13σ) for ee+p (μμ+p)
Scattered protons do stay intact!

Signal: ξ_{AFP} & $\xi_{\ell\ell}$ kinematically correlated

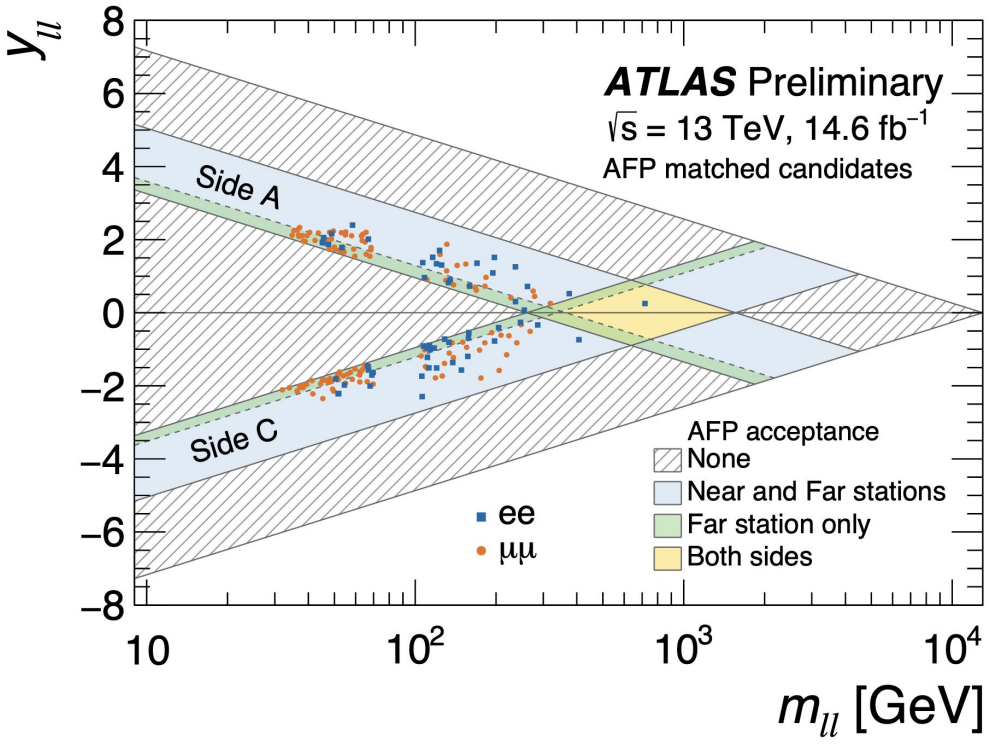


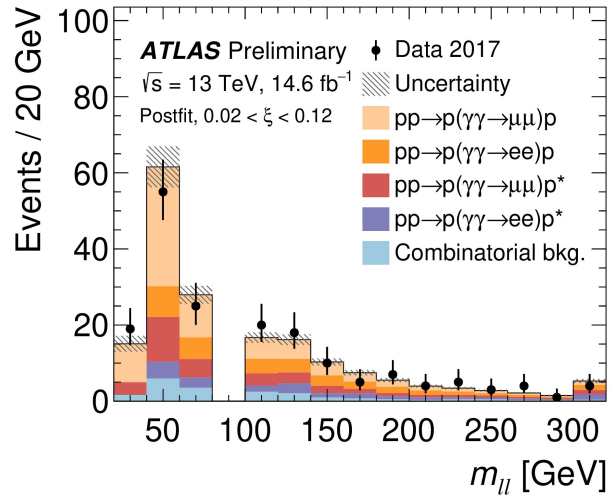
Background: no correlation (mixed data)

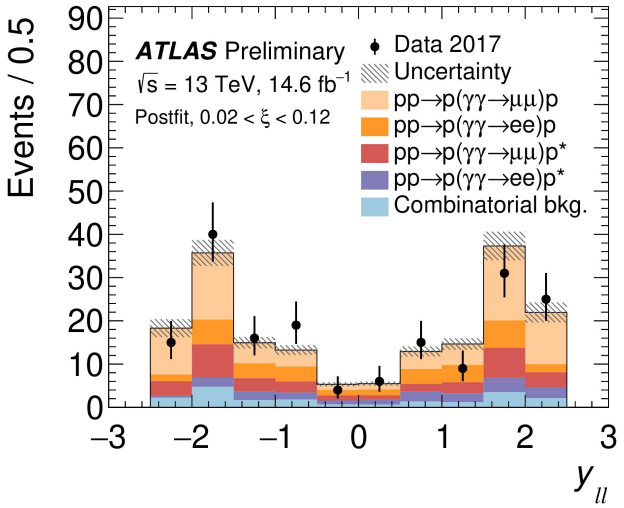


CMS–TOTEM: 2.6σ (4.3σ) for ee+p (μμ+p) [1803.04496]

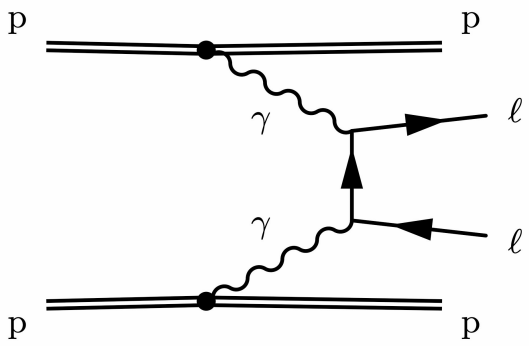
Proton tagged dilepton kinematics

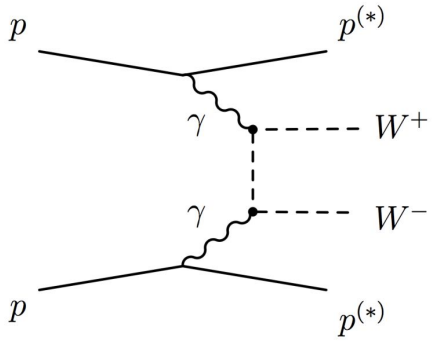


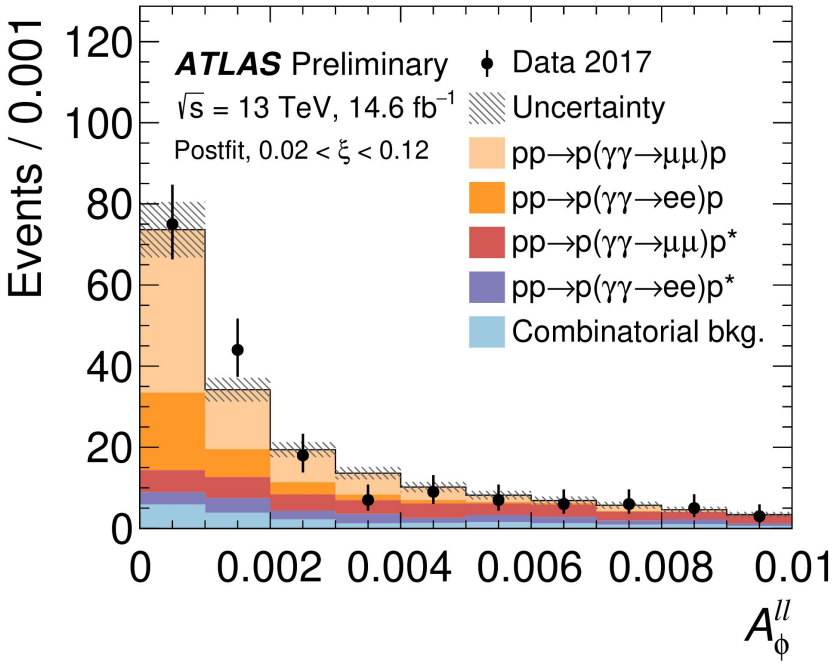


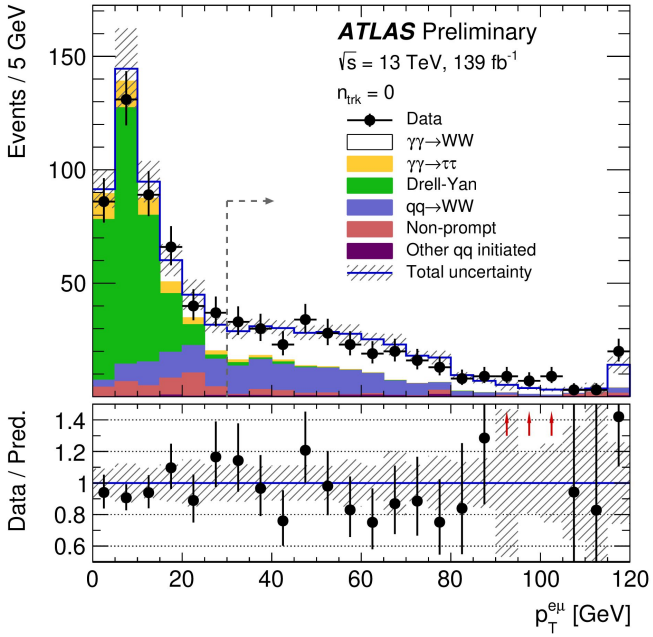


Colliding light using LHC pp beams

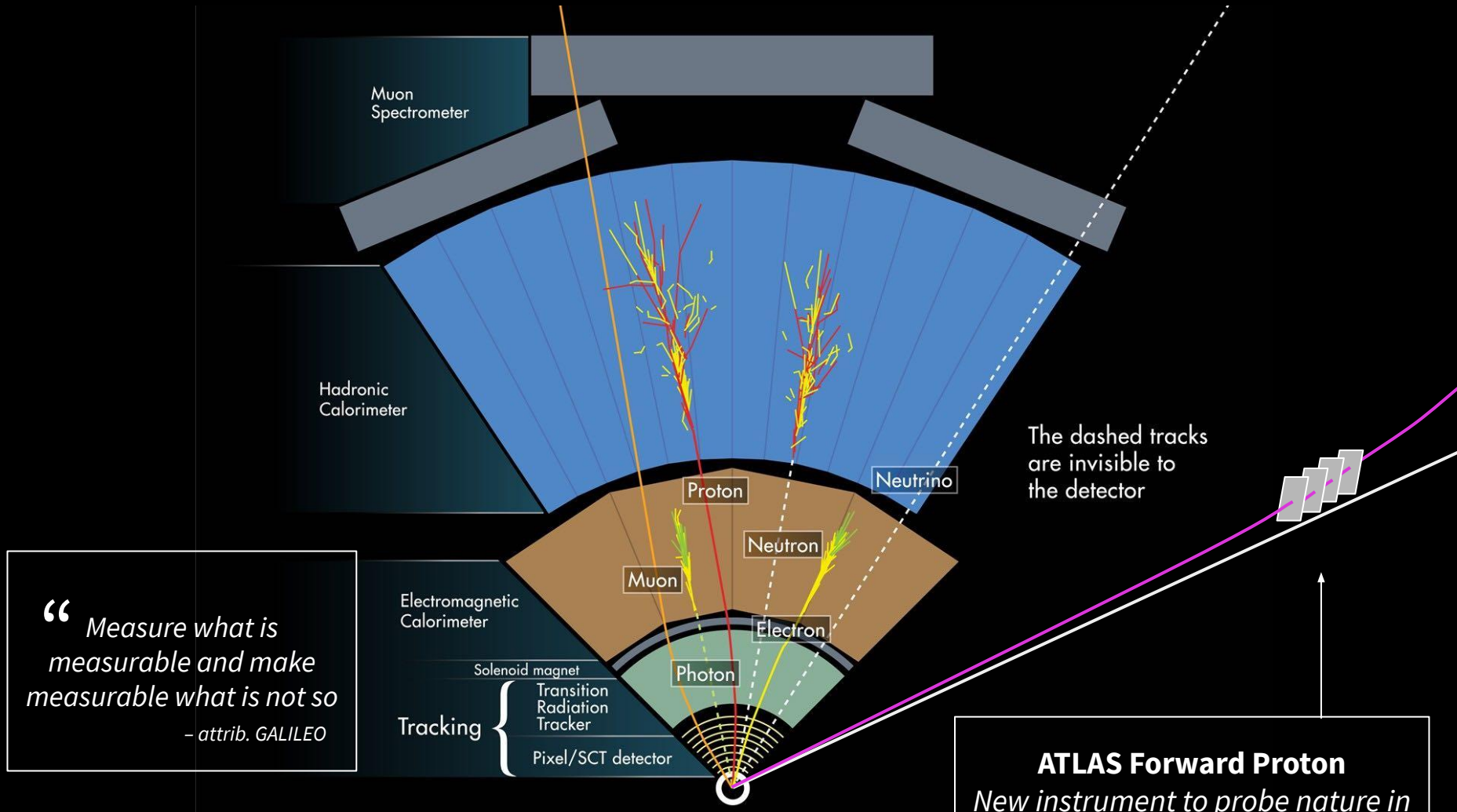








AFP expands our repertoire to probe the microcosm



> *"Measure what is measurable and make measurable what is not so*
>
> *– attrib. GALILEO*

ATLAS Forward Proton

New instrument to probe nature in ways we have never done before

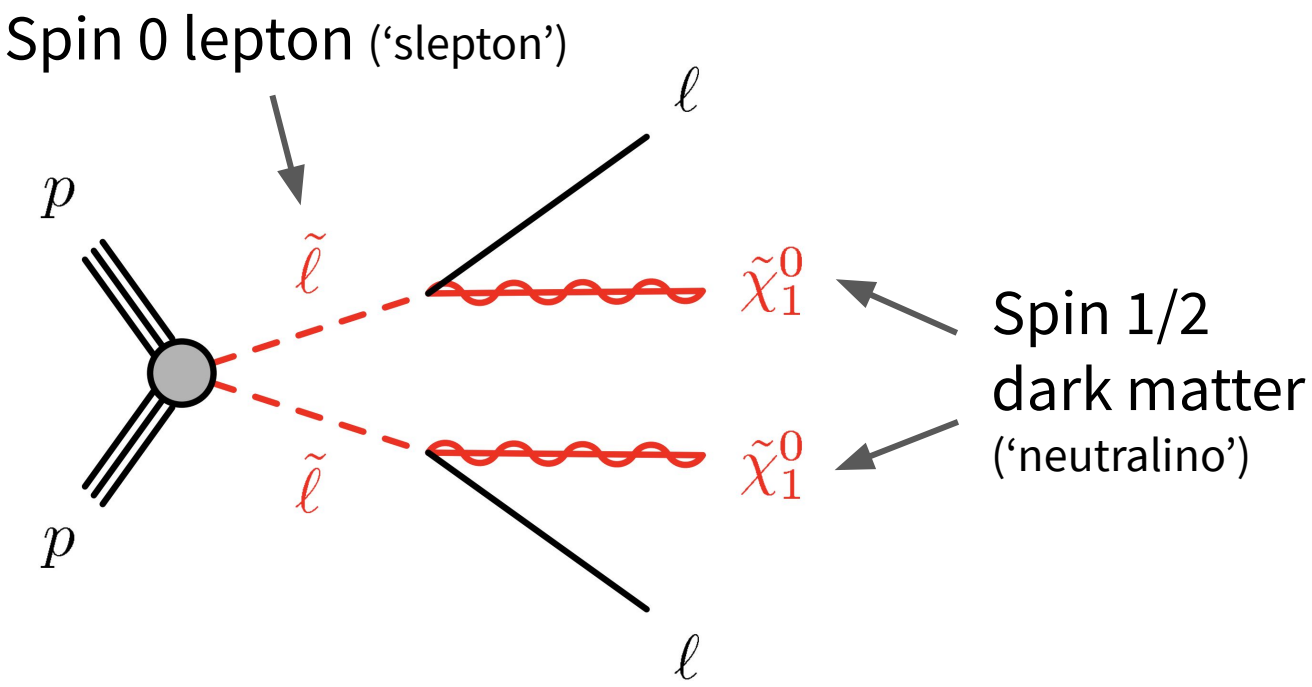
CERN [https://cds.cern.ch/record/1505342]

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

Case study: simple extension to Standard Model

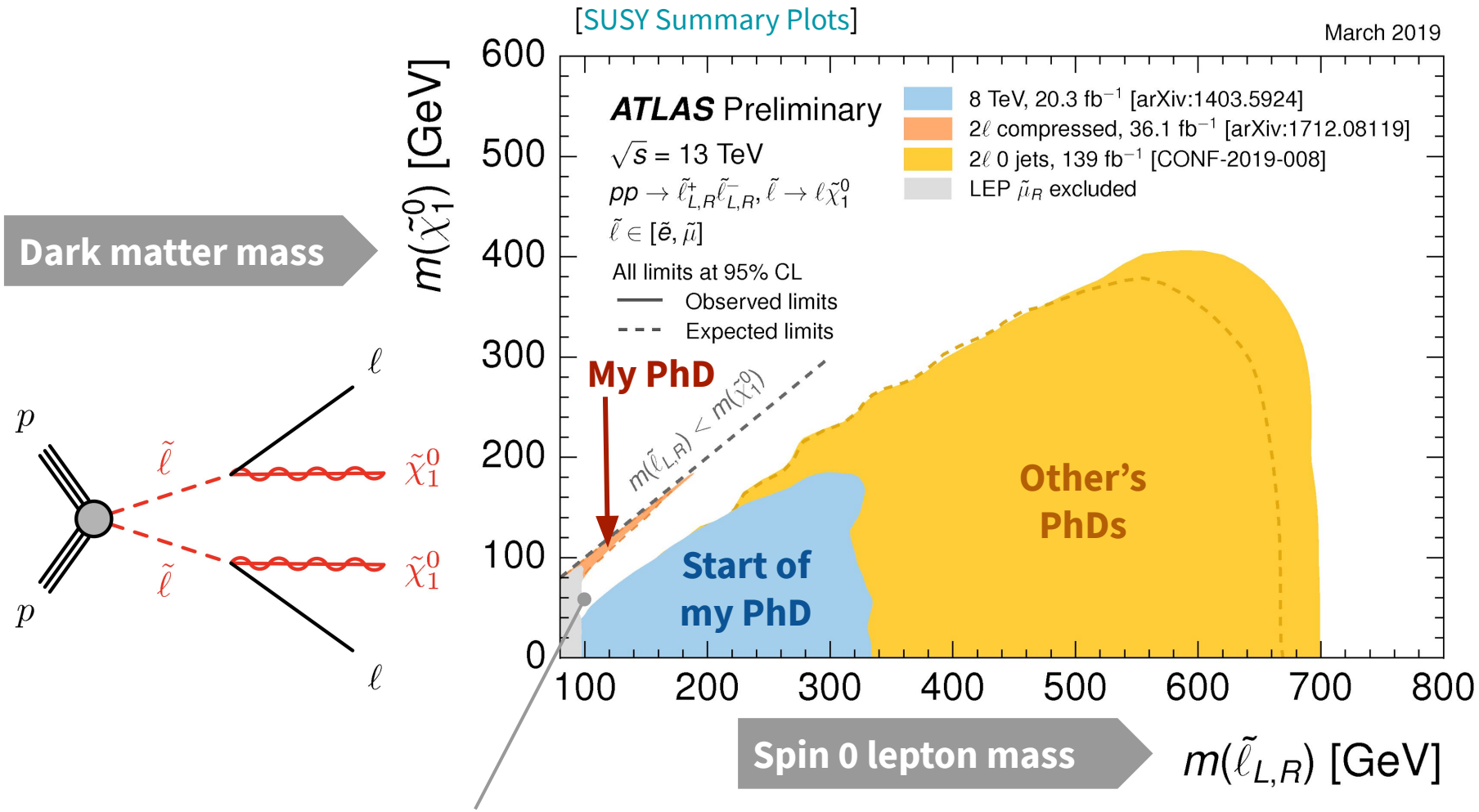


PHYSICALLY MOTIVATED
Explain dark matter, $(g-2)_\mu$

THEORETICALLY SIMPLE
2 free parameters

EXPERIMENTALLY CLEAN
2 leptons + missing E_T

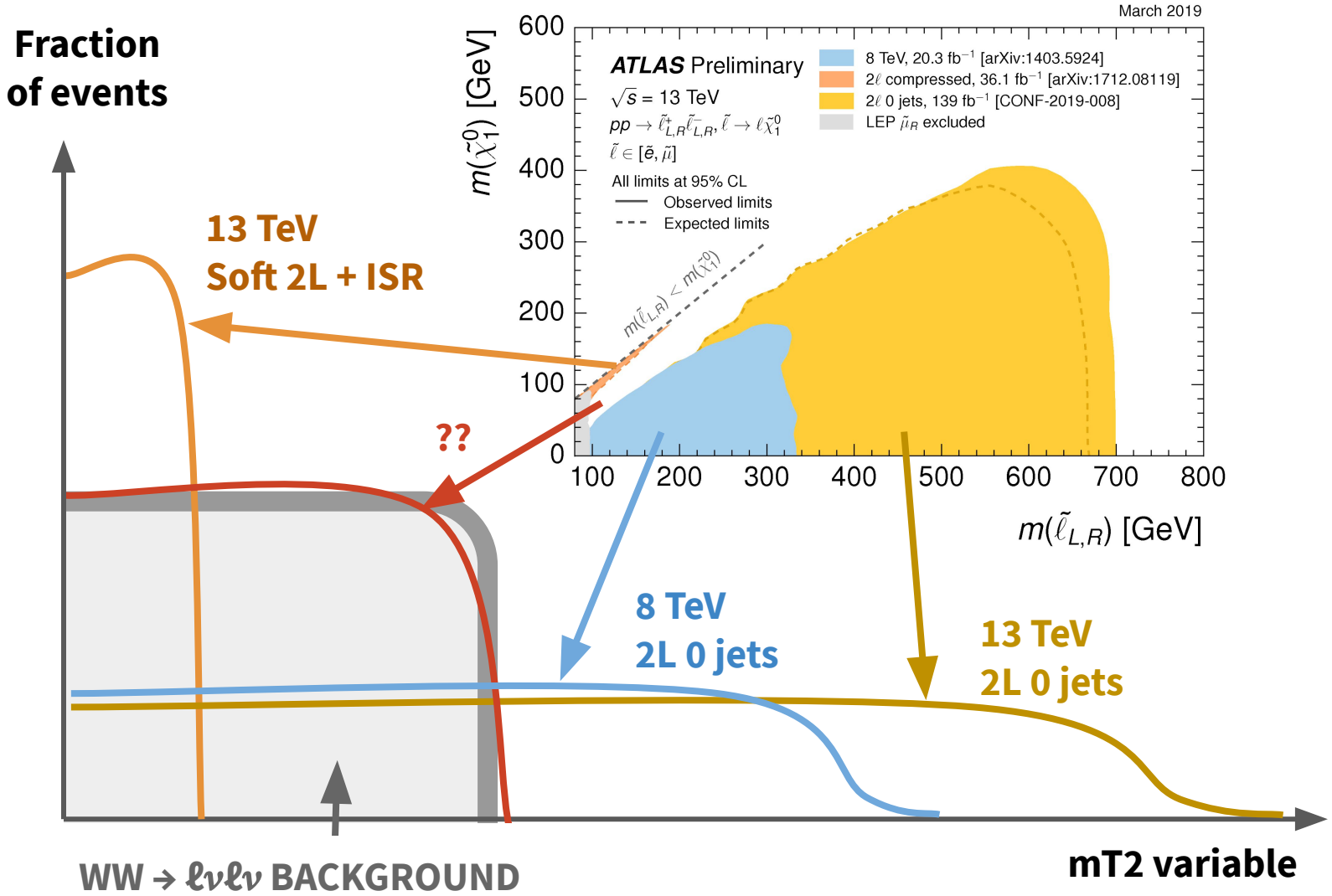
Striking blind spot remains at low masses



As scientists our job is to see, but here we are blind

$m(\tilde{\ell}) \sim 100$ GeV: $\sigma(pp \to \tilde{\ell}\tilde{\ell}) \times \mathcal{L} \sim 730$ fb $\times$ 140 fb^{-1} $\sim$ 100 000 events

Why can't we see?

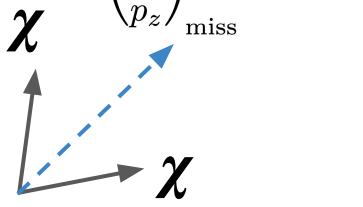


Lester, Summers [hep-ph/9906349]
Barr, Lester Stephens [hep-ph/0304226]

Heart of problem generic to all hadron colliders

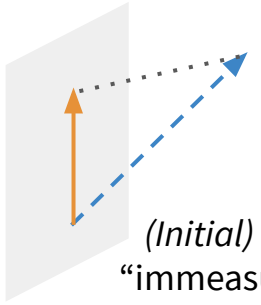
Dream

$$\begin{pmatrix} E \\ p_x \\ p_y \\ p_z \end{pmatrix}_{\text{miss}} \Rightarrow (2m_\chi)^2$$



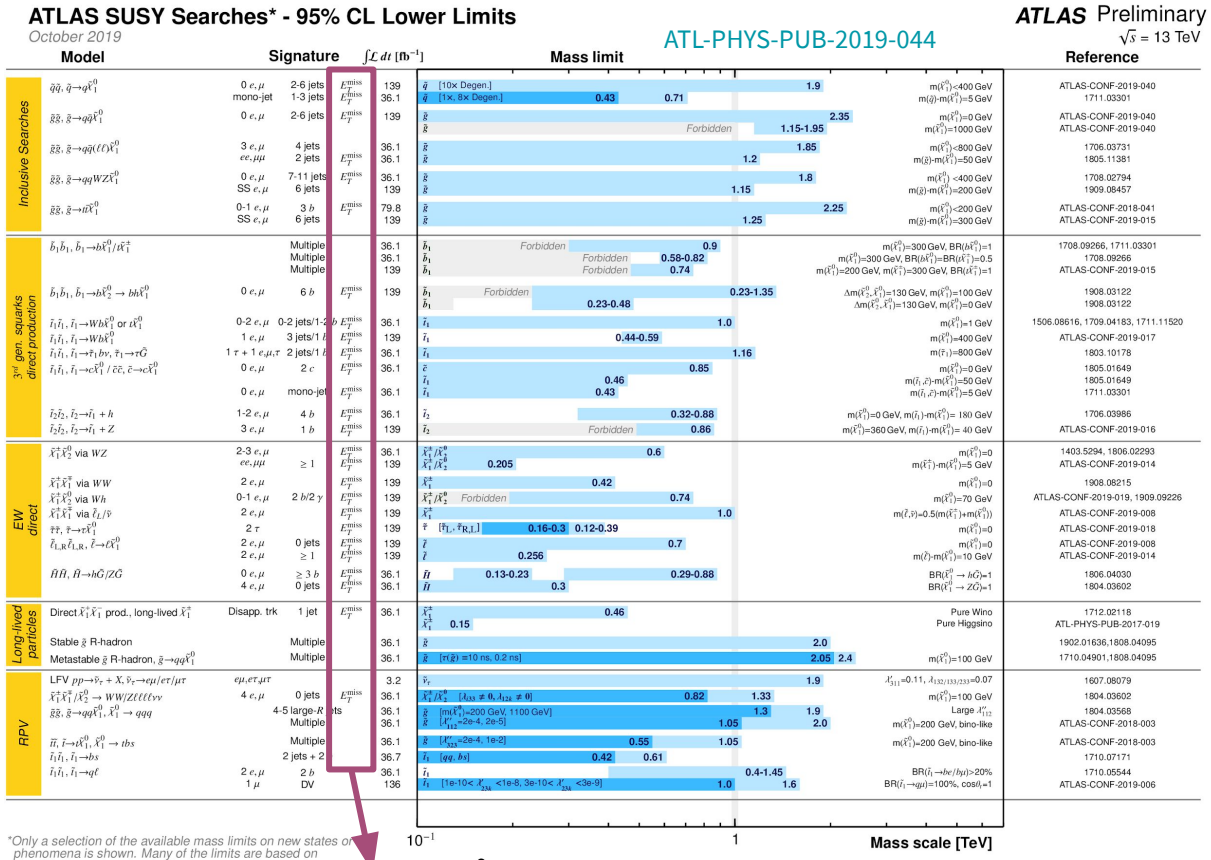
Reality

$$\begin{pmatrix} p_x \\ p_y \end{pmatrix}_{\text{miss}}$$ 2-vector



(Initial) E & p_z
"immeasurable"

Consequence: at least 2 degrees of freedom lost

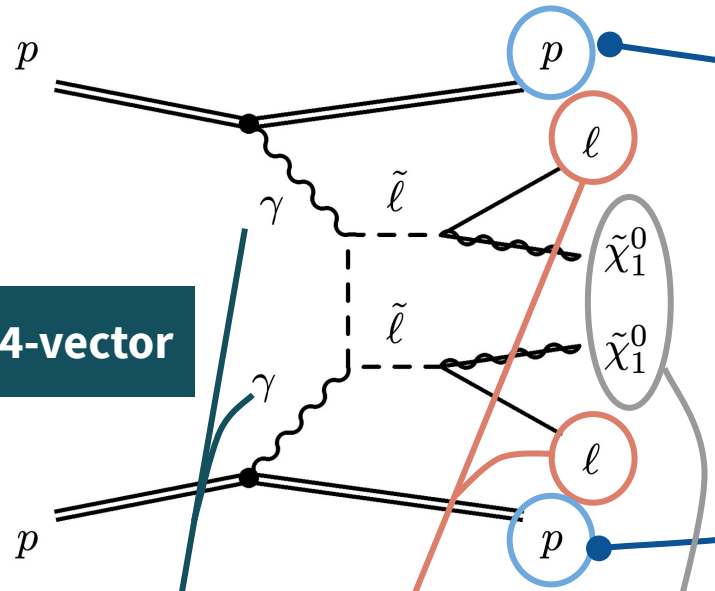


*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

E_T^{miss}

Only transverse measured but really
desire *missing momentum 4-vector*

Solution: collide light and tag protons



1

Measure intact protons

Using AFP

2

Compute photon 4-vector

$$p_{\text{miss}} = \sum_{\text{initial}} p_i - \sum_{\text{final}} p_f^{\text{visible}} \quad \Rightarrow \quad m^2_{\text{miss}} = p^2_{\text{miss}}$$

3

"Impossible @ hadron colliders" ***no more***

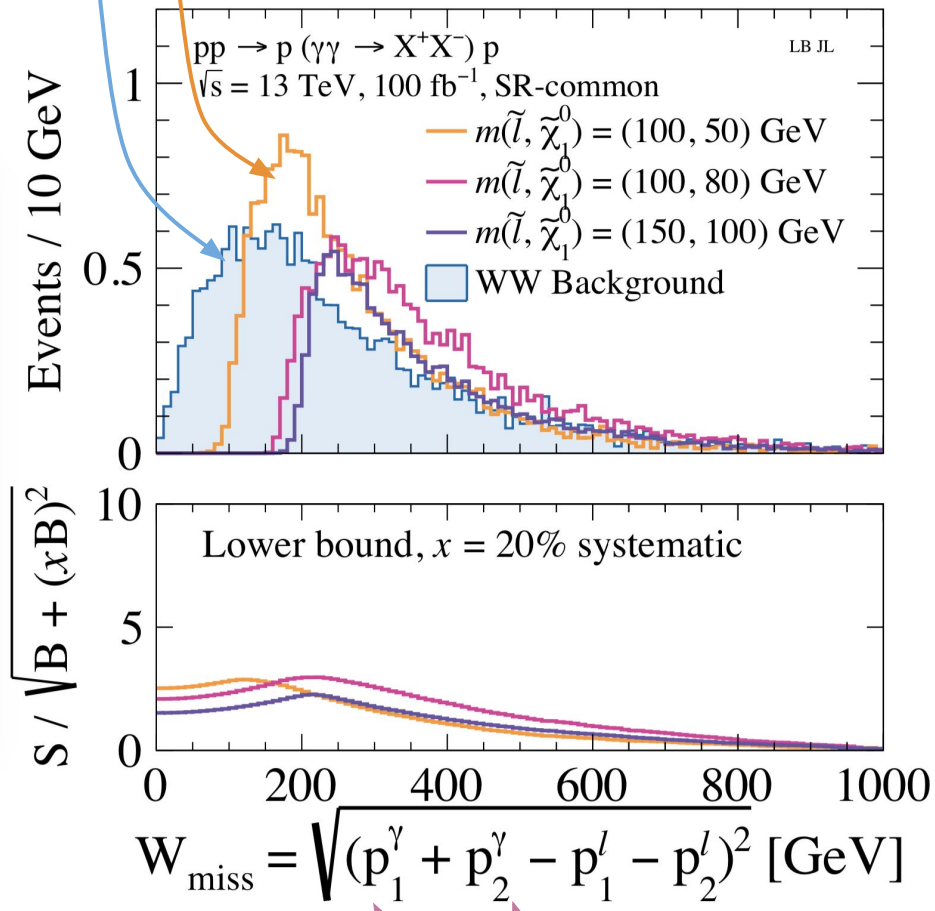
Square 4-vector to measure dark matter mass!

Beresford & JL 1811.06465, Harland-Lang, Khoze, Ryskin & Tasevsky 1812.04886

From "MET + X" to "p_{miss} + X" searches

γγ → WW irreducible background *just observed last month*

Sharp threshold at $2 \times m_{DM}$ ⇒ direct DM mass measurement



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

ATLAS-CONF-2020-038

29 July 2020

We are *two* steps closer to this dream

Join the two ideas together to open new class of dark matter search!

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

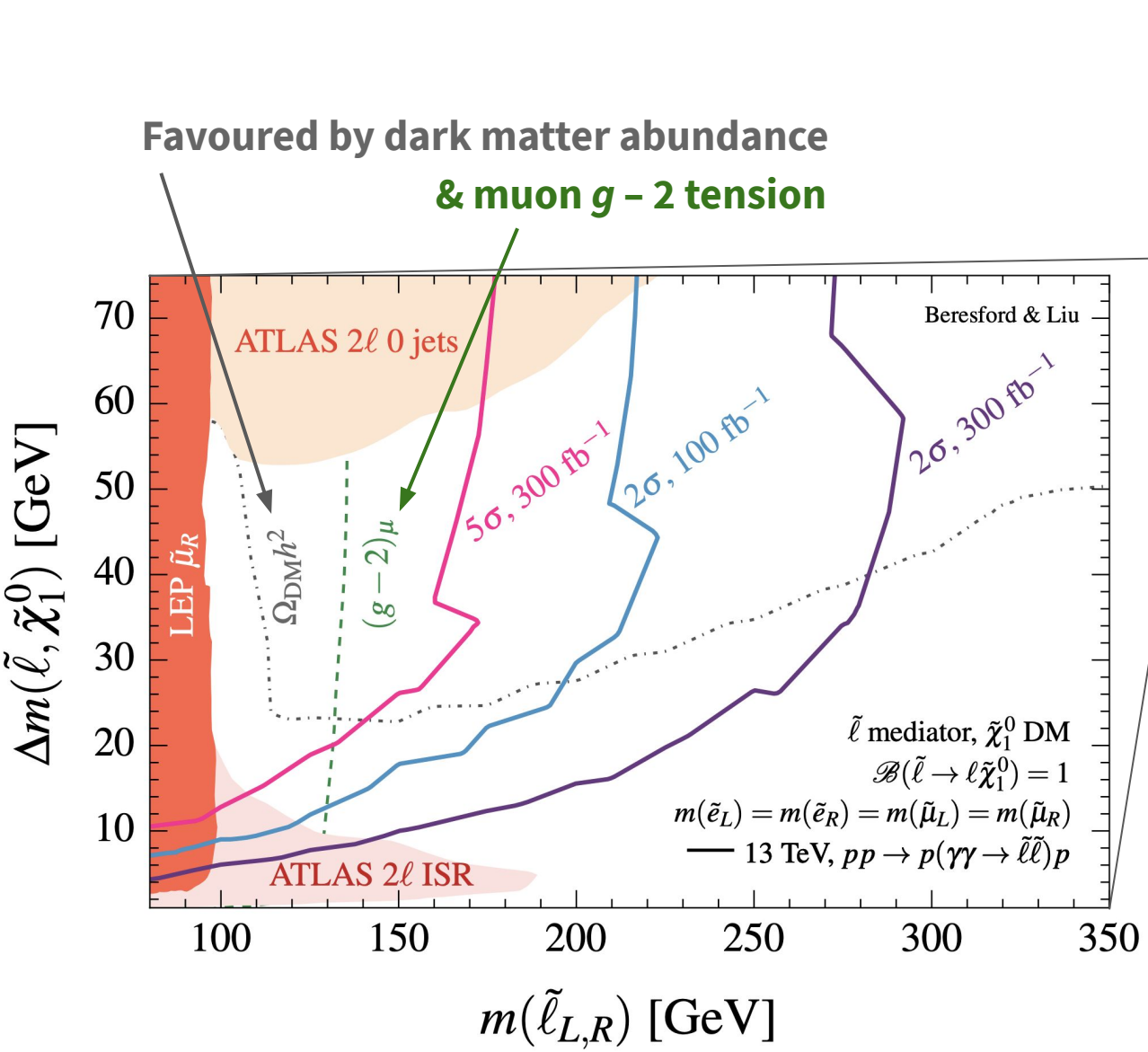
ATLAS-CONF-2020-041

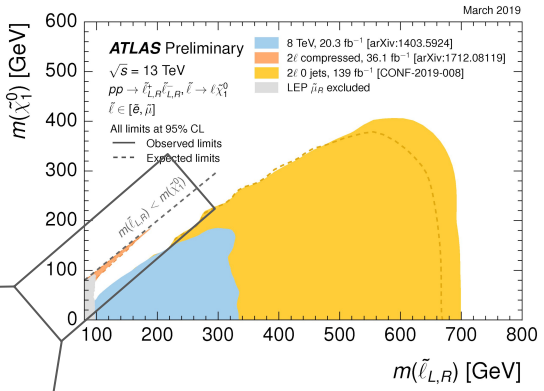
29 July 2020

Missing momentum 4-vector

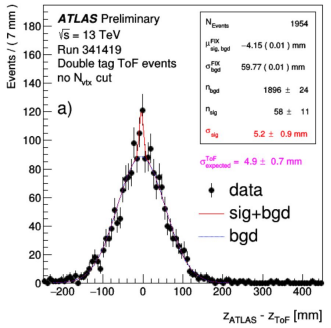
Demonstrate AFP delivers physics

Impact: turn light into dark matter this decade?



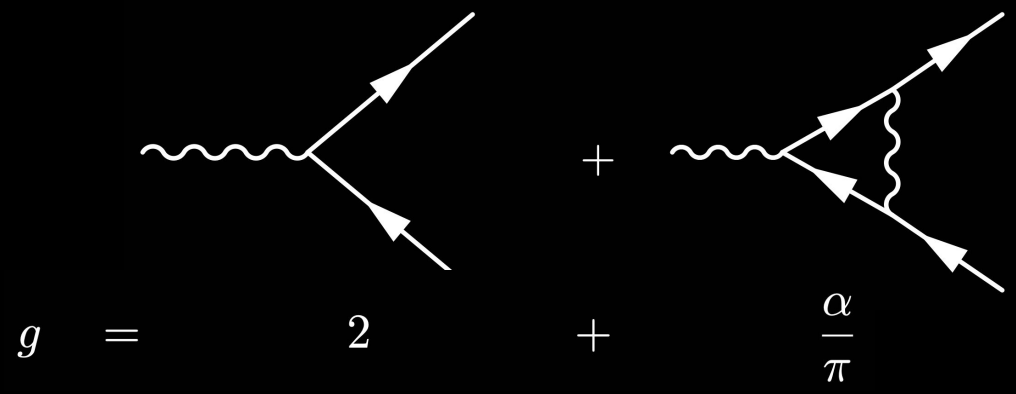


Opportunity: AFP time-of-flight vertex identification



g – 2: foundational test of QED

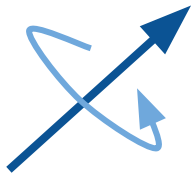
"How does light interact with matter?"



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

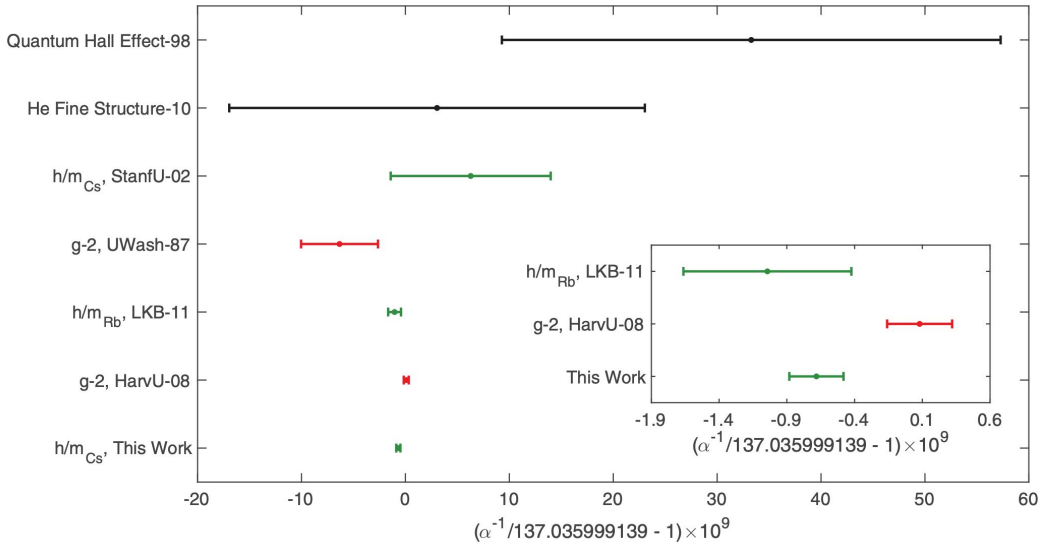
Dirac (1928) **Schwinger (1948)**

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



Directly measure via spin–magnetic precession

State-of-the-art: cracks at the heart of Standard Model?

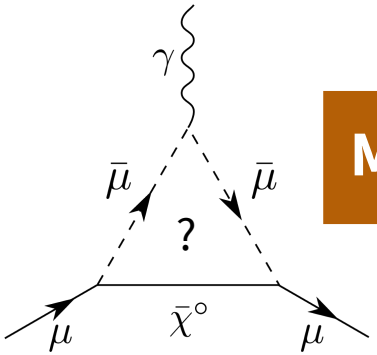


Electron g – 2 (–2.5σ)

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"

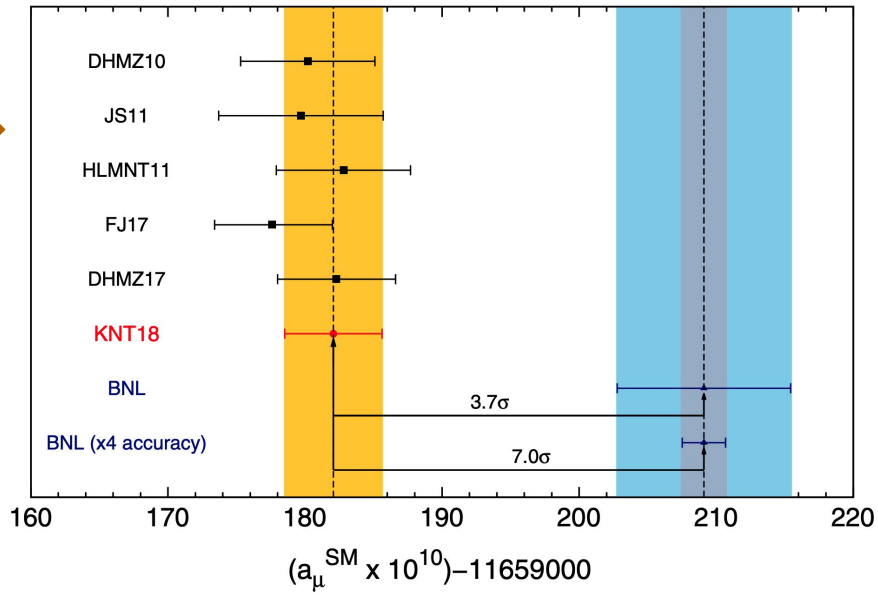


Muon g – 2 (+3.7σ)

BNL E821 [hep-ex/0602035]
Fermilab E989 [1501.06858]
J-PARC [1901.03047]
Keshavarzi, Nomura, Teubner [1802.02995]
Davier, Hoecker, Malaescu, Zhang [1908.00921]

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

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

DELPHI [hep-ex/0406010]

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

Eidelman, Passera [hep-ph/0701260]

Pressing problem: no measurement!

Not even testing 70 year old 1-loop QED!

$\alpha/2\pi$ = 0.001162

Schwinger (1948)

Pressing *& interesting* open problem

Huge uncertainty
⇒ huge room for new physics

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

280× more sensitive
to new physics
than muon *g* – 2

No model shortage for e & μ *g* – 2:

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]
…

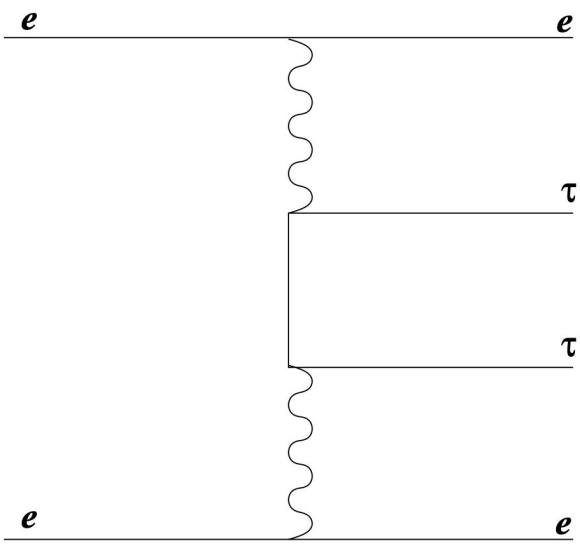
But how can we measure tau *g* – 2?

Belle-II/CLIC/ILC/FCC-ee:
Eidelman, Epifanov, Fael, Mercolli, Passera [1601.07987]
Chen, Wu [1803.00501]
Koksal, Billur, Gutierrez-Rodriguez, Hernandez-Ruiz [1804.02373]
Howard, Rajaraman, Riley, Tait [1810.09570]
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]

"Measure what is measurable and make measurable what is not" *– attrib. Galileo*

Potential low hanging fruit: bring LEP success to LHC?

PDG constraint of tau *g*– 2



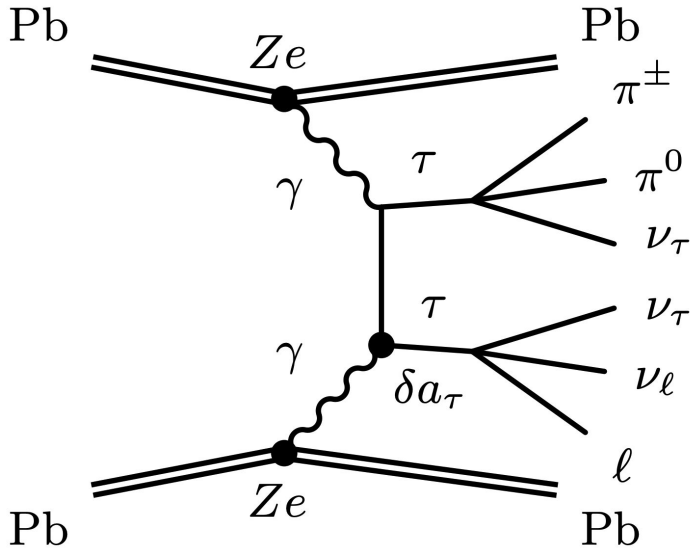
LEP photon collisions

σ ~ 400 pb

⇒ 200k events all years

DELPHI [EPJC (2004)]

Proceed analogously @ LHC?



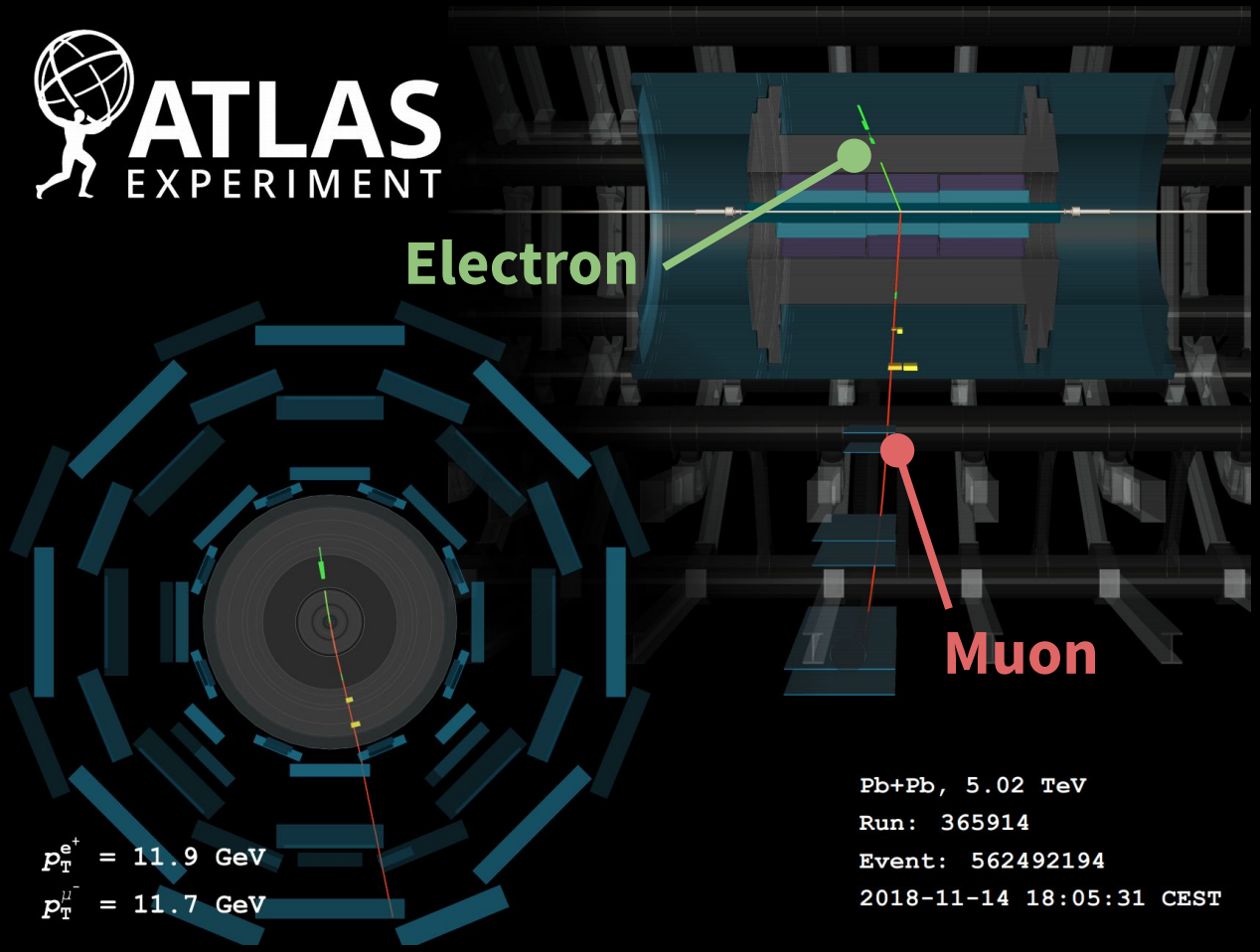
Never been seen at LHC

σ ~ Z^4 ~ 500 000 nb (Z_{Pb} = 82)

⇒ 1 million events *already*

del Aguila, Cornet, Illana (PLB 1991)
Beresford, JL [1908.05180]

Stunning events already recorded by ATLAS/CMS

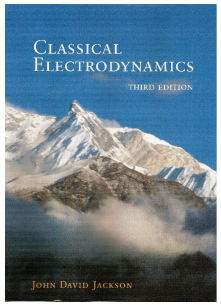


1 month to collect dataset | No pileup μ ~ 0.001 | Ultra loose triggers

"All calorimeter cells with a transverse energy above 500 MeV are shown."

[ATLAS Event Displays]

Photon collisions using MadGraph & SMEFTsim



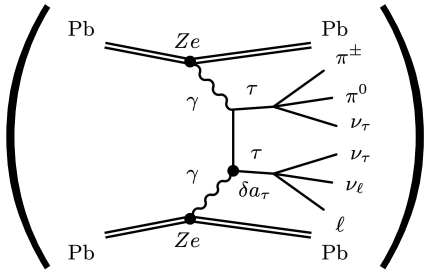
Photon flux: classical field theory

Look up Chapter 15 §4, put in MadGraph 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

$$\sigma^{(\mathrm{PbPb})}_{\gamma\gamma\to XX}$$

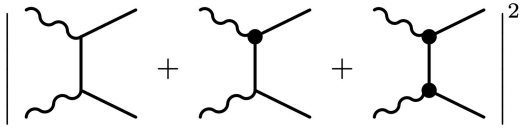


$$= \int \mathrm{d}x_1 \mathrm{d}x_2\, n(x_1)n(x_2)\, \sigma_{\gamma\gamma\to XX}$$

SMEFTsim: implement dim-6 in Feynrules

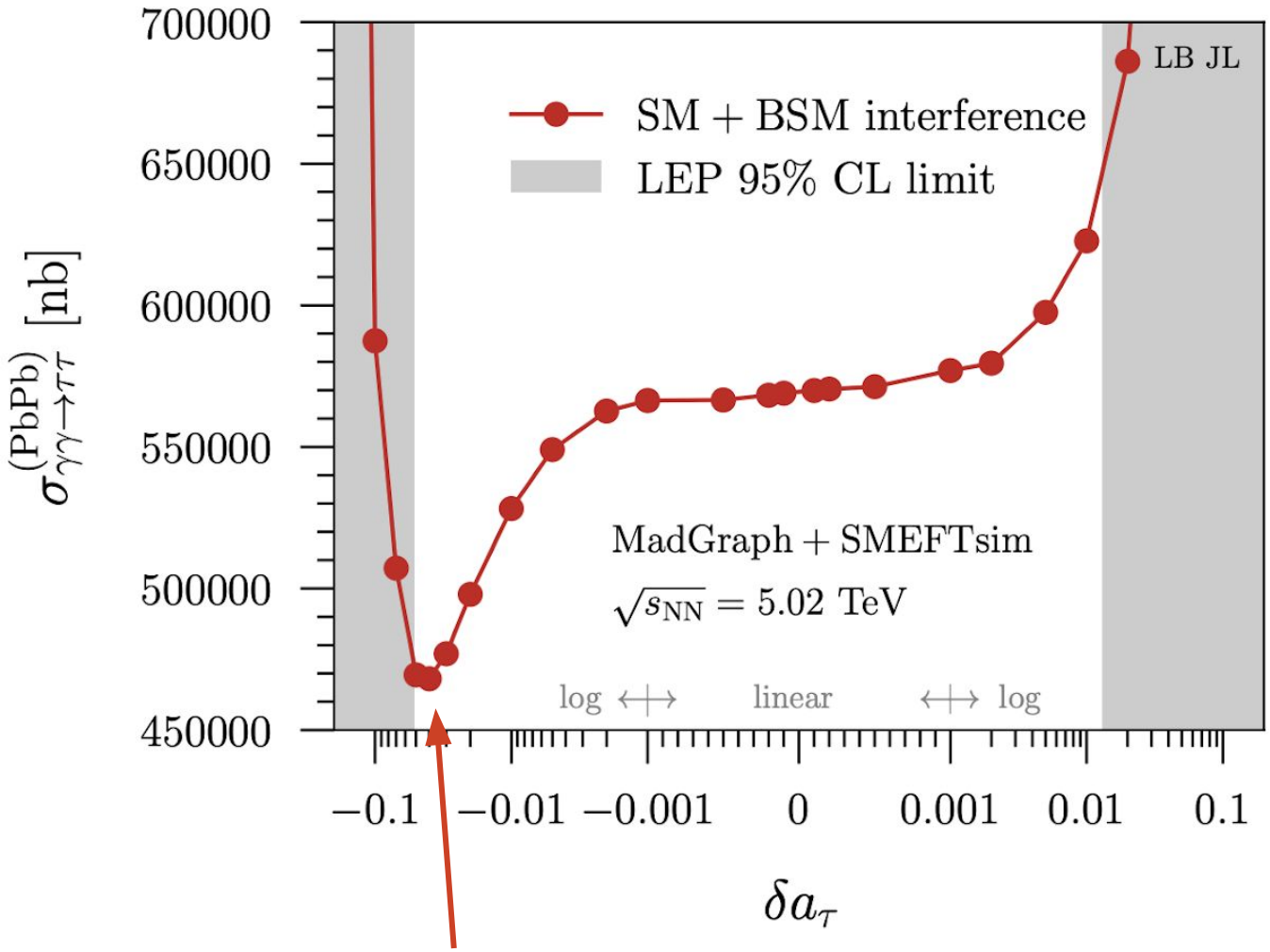
Grzadkowski, Iskrzyński,M. Misiak, Rosiek [1008.4884]
Alloul, Christensen, Degrande, Duhr, Fuks [1310.1921]
Brivio, Jiang, Trott [1709.06492]

Include interference up to 2 BSM couplings



MadGraph factorised prescription
d'Enterria, Lansberg [0909.3047]
Superchic 3
Harland-Lang, Khoze, Ryskin [1810.06567]

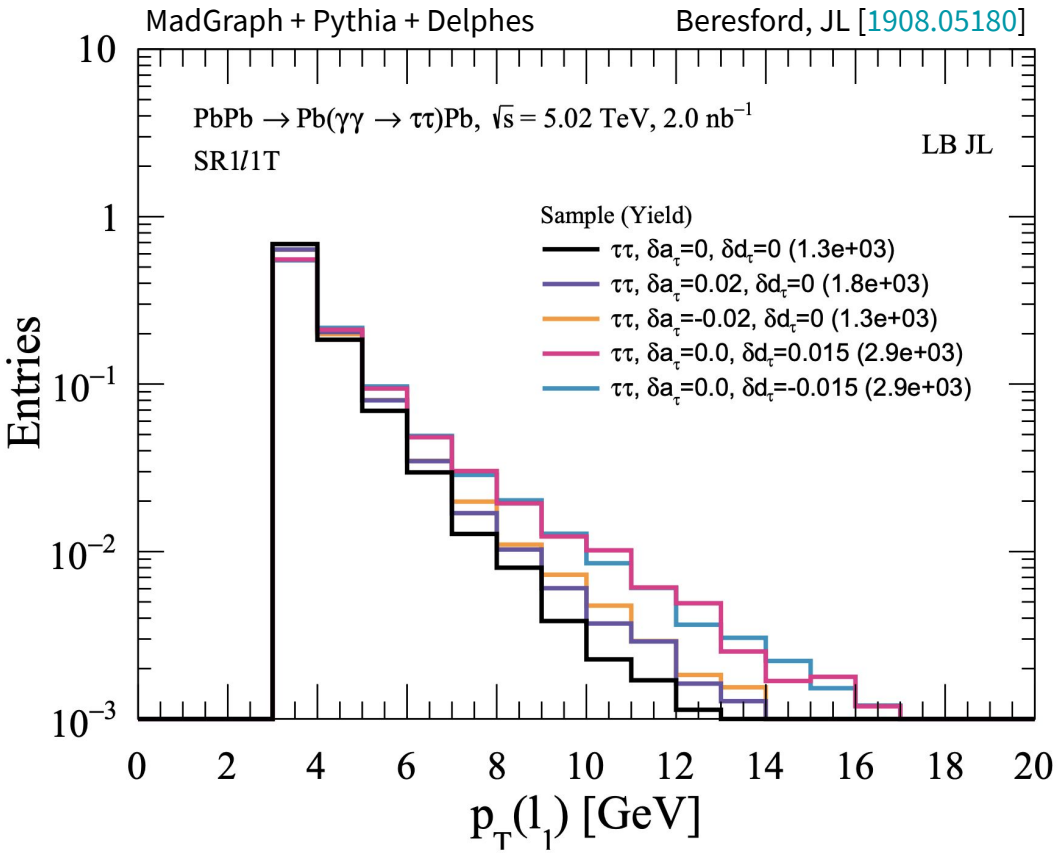
Cross-sections as function of g – 2 deviations (PbPb)



Beresford, JL [1908.05180]

Maximal destructive interference

Groundbreaking soft leptons in ATLAS/CMS crucial



Soft lepton ID

$p_T(e/\mu) > 4.5/3$ GeV suppresses hadronic backgrounds

1 lepton + 1 track

Target 2ℓ or $1\ell+1\pi$ decays

28% of ditau events

1 lepton + 2/3 tracks

Target 3π decays

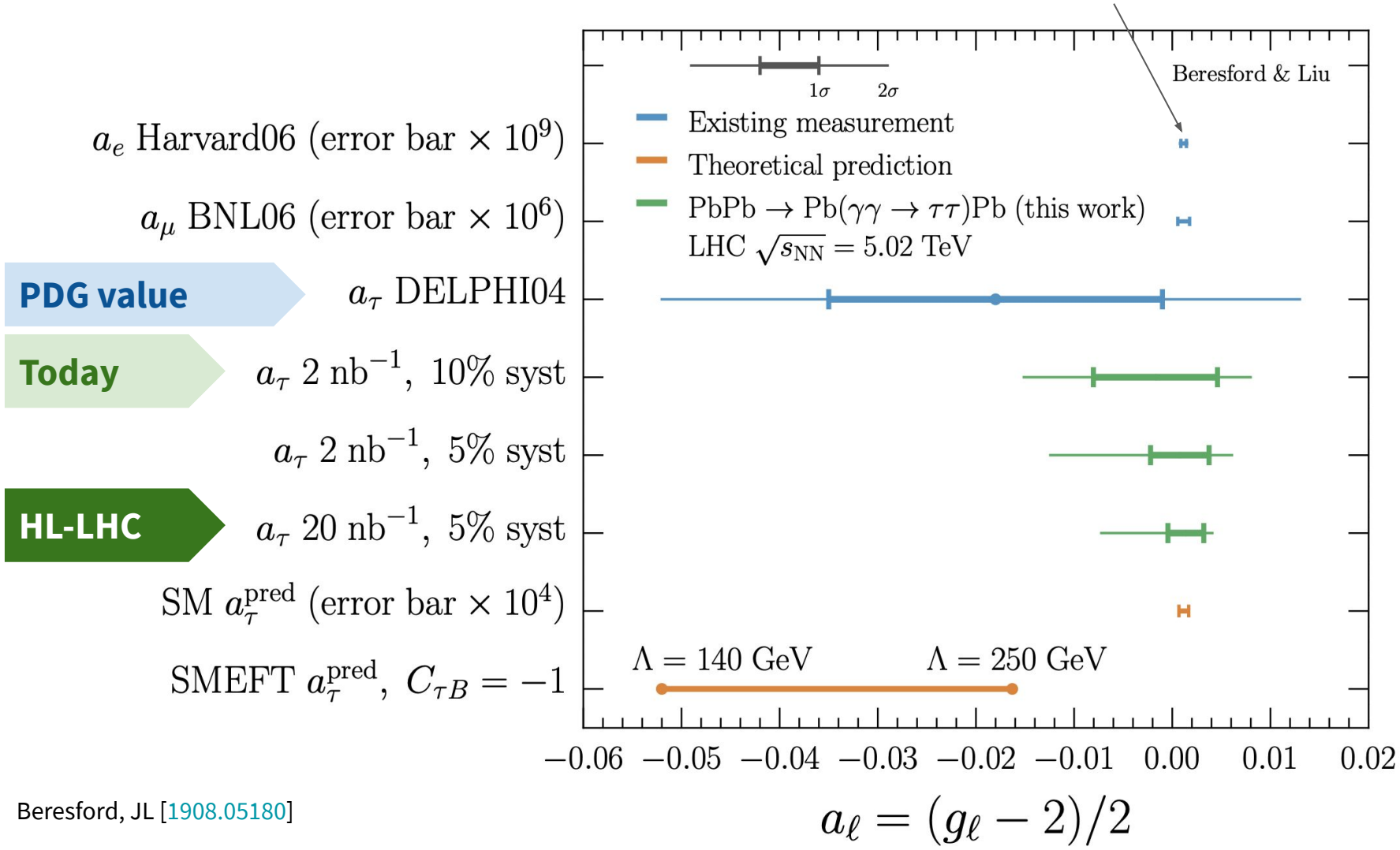
7% of ditau events

$p_T(\ell)$ sensitive to different dipole moments

Soft leptons in ATLAS [1712.08119, CONF-2019-014] & CMS [1801.01846]
Tracks pT > 100 MeV, E_T > 1 GeV EM cluster trigger [1904.03536], p_T > 0 GeV muon trigger [CONF-2016-025]

Prospects: surpass 15 year old LEP precision

If to scale, error bar would be **width of atom** on this screen



Beresford, JL [1908.05180]