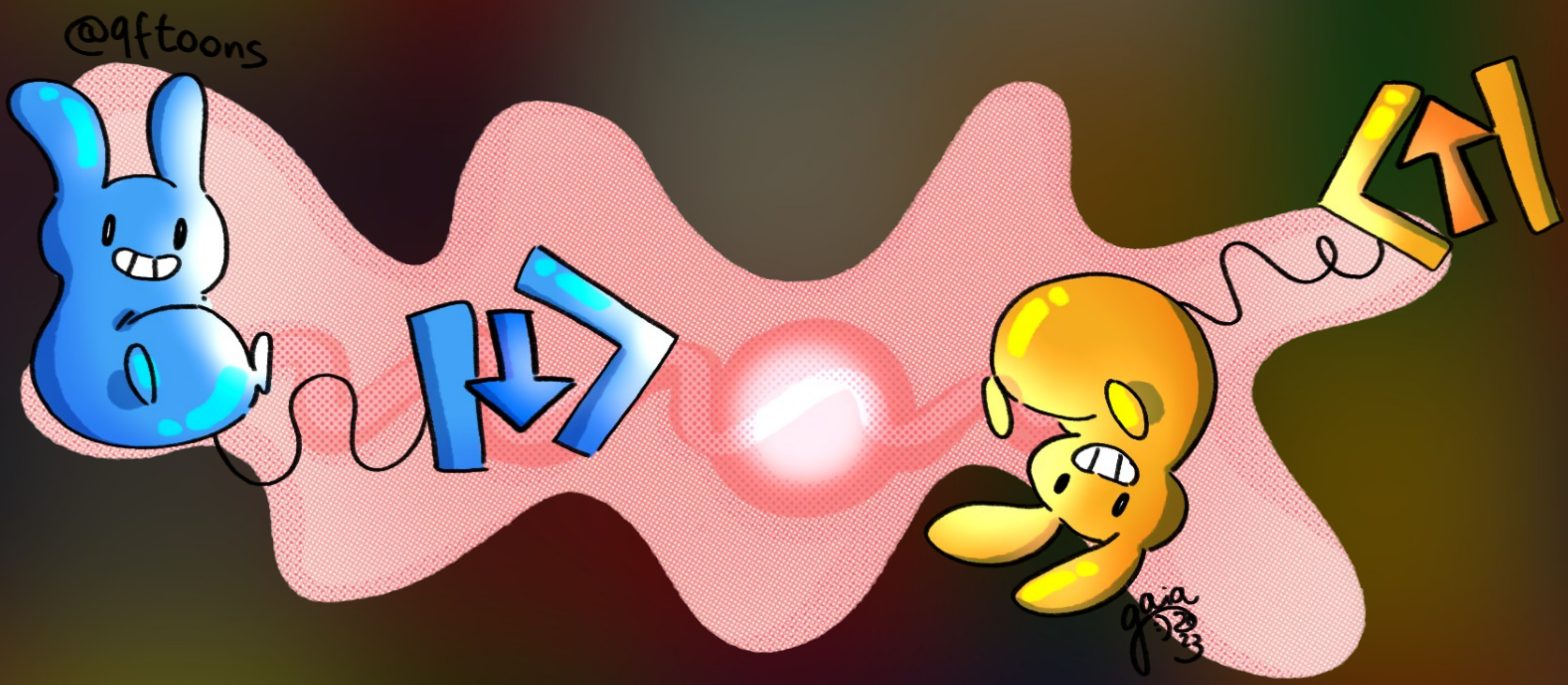
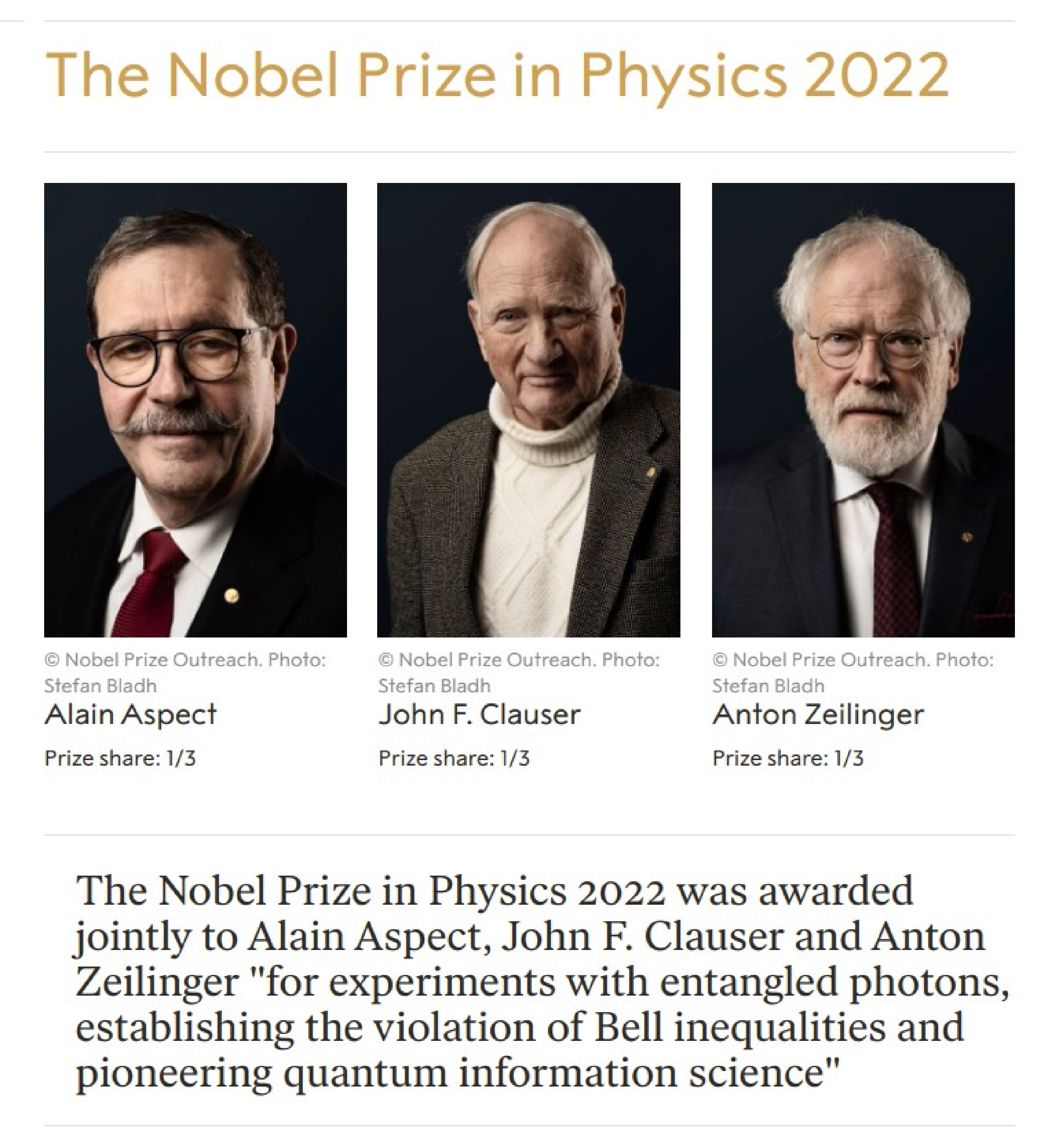
Entanglement in high energy physics

a brief introduction



Drawings by Gaia Fontana
Some slides by Yoav Afik, Fabio Maltoni, Marcel Vos



The Nobel Prize in Physics 2022

© Nobel Prize Outreach. Photo: Stefan Bladh

Alain Aspect

Prize share: 1/3

© Nobel Prize Outreach. Photo: Stefan Bladh

John F. Clauser

Prize share: 1/3

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Anton Zeilinger

Prize share: 1/3

The Nobel Prize in Physics 2022 was awarded jointly to Alain Aspect, John F. Clauser and Anton Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"

The Standard Model is a QFT:

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- Special Relativity
- Quantum Mechanics

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SPECIAL RELATIVITY

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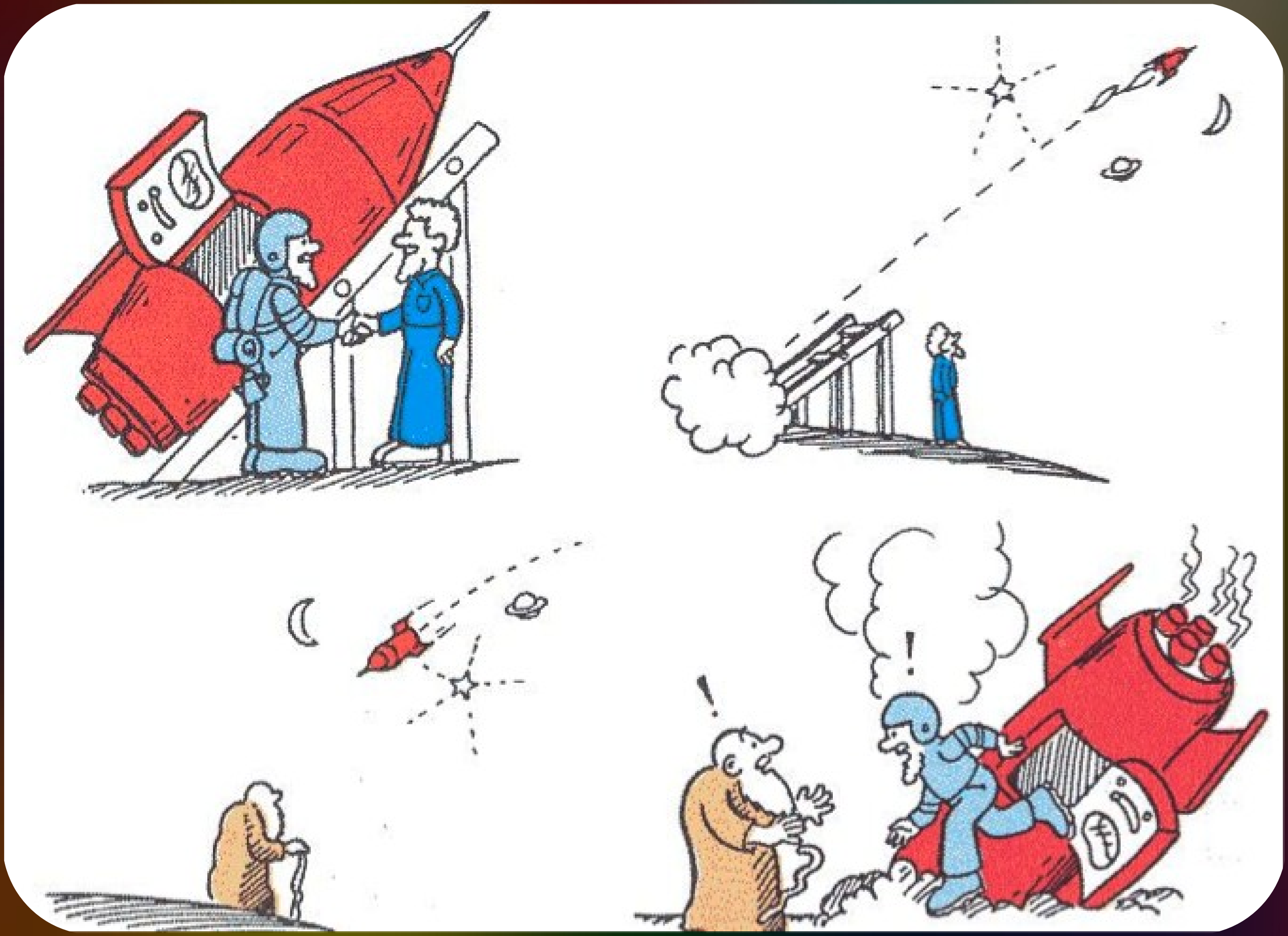

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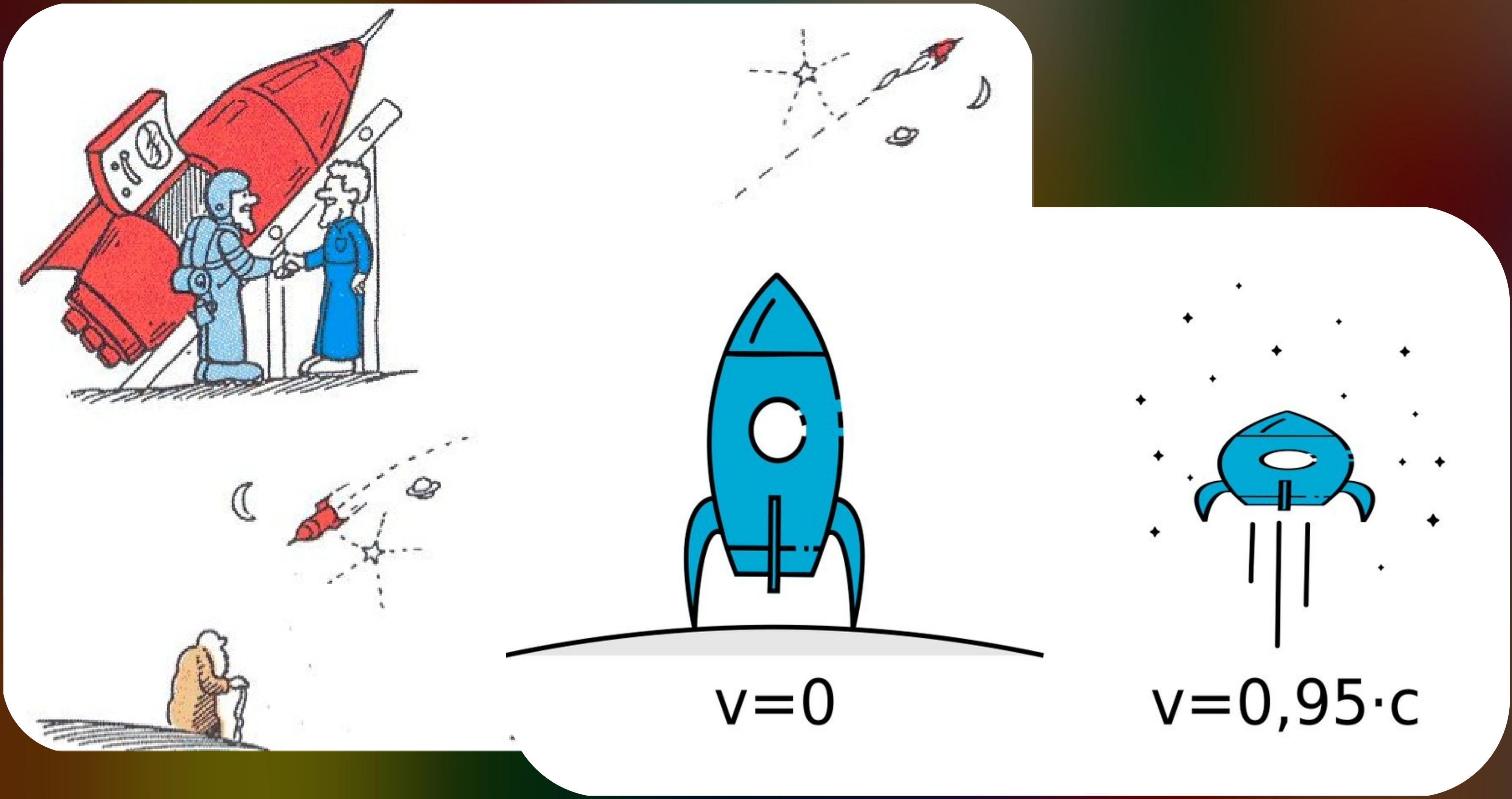

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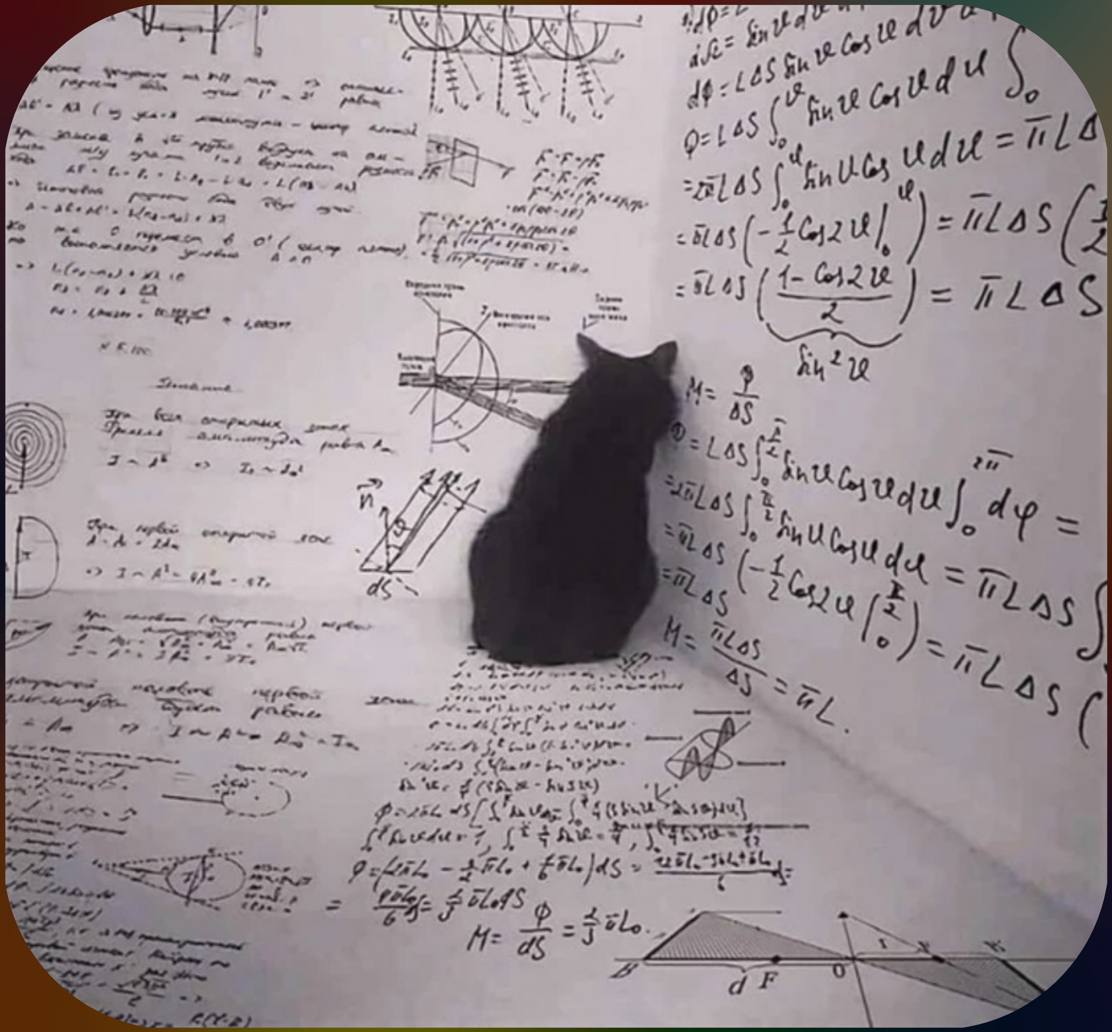

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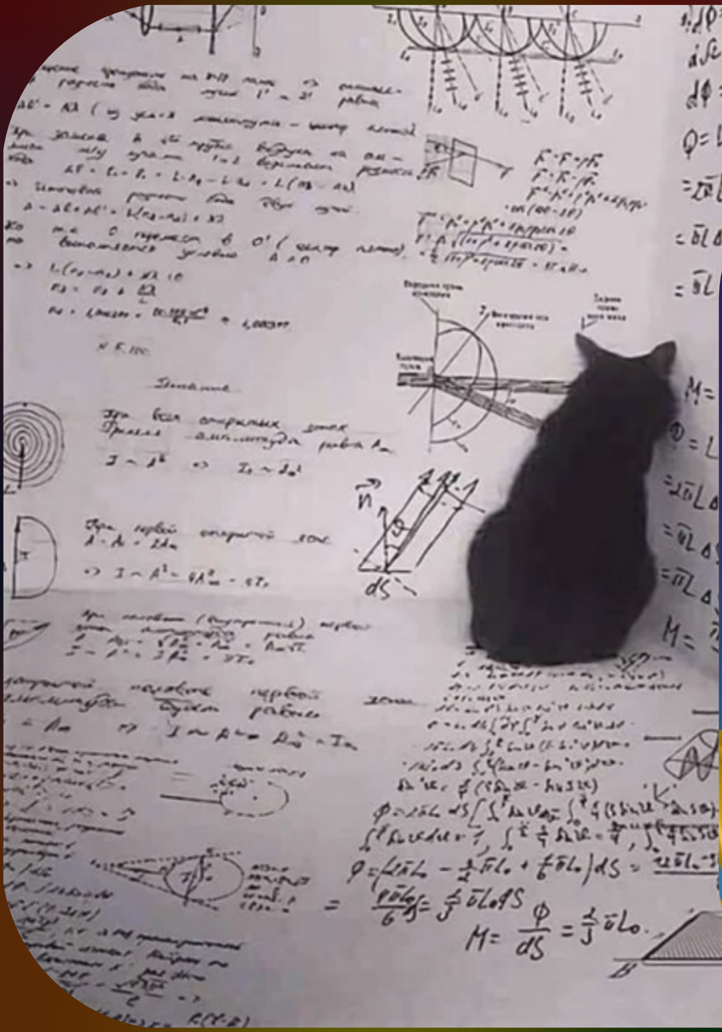

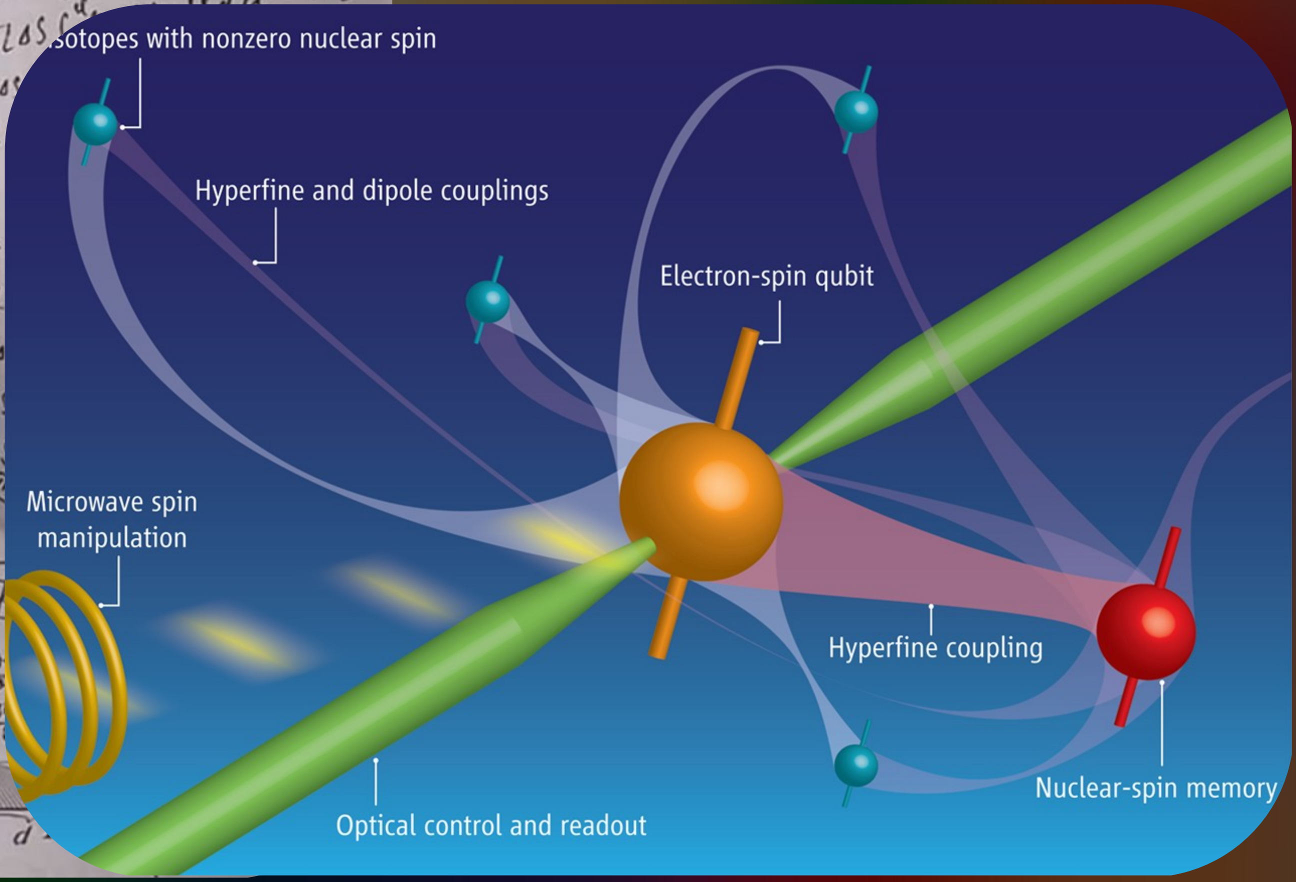

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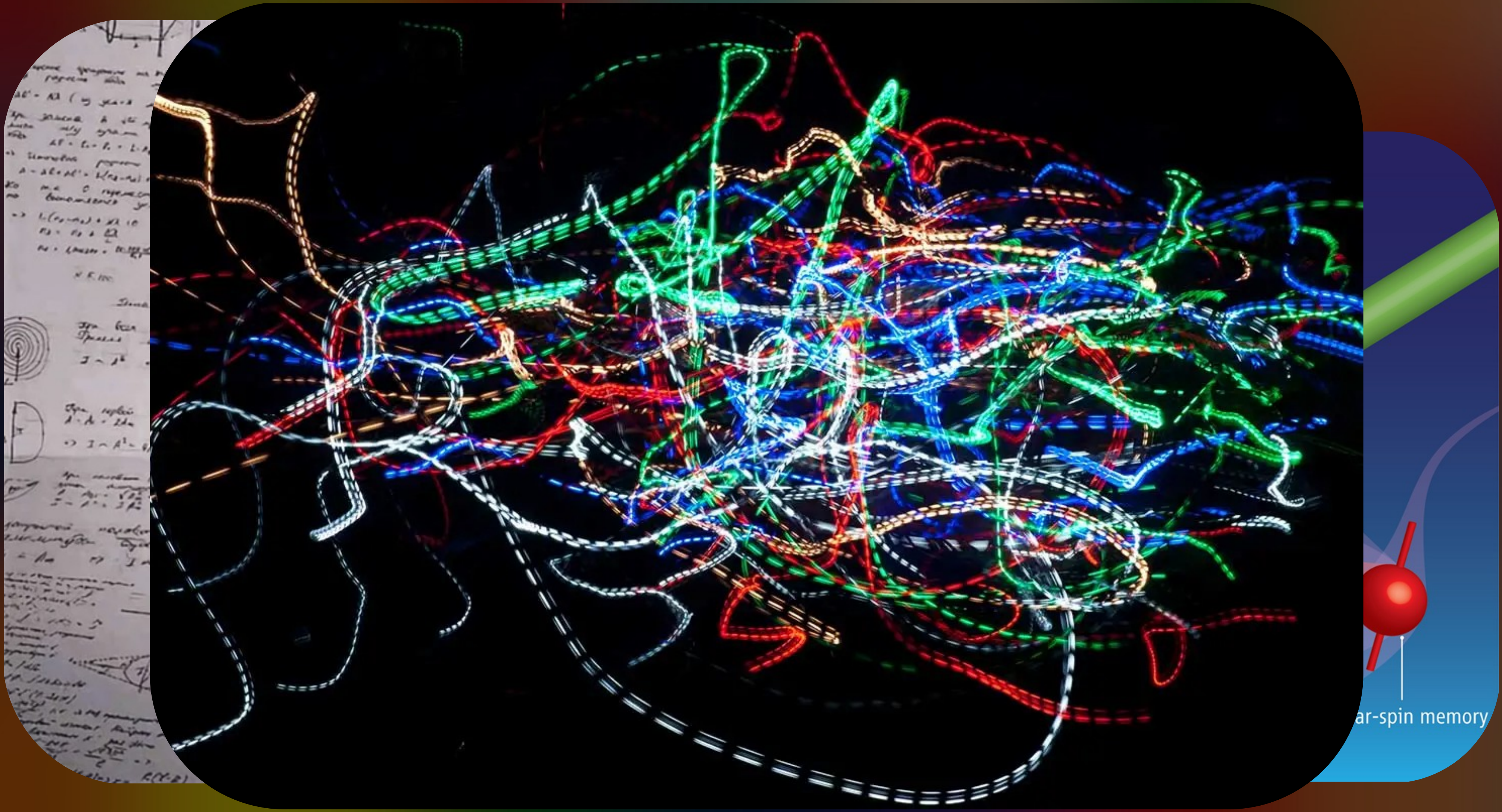

Is there anything genuinely quantum to test in HEP experiments?

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1. Wavefunction evolution, collapse & decoherence

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2. “Quantum” correlations so strong they can not be explained by a classical model

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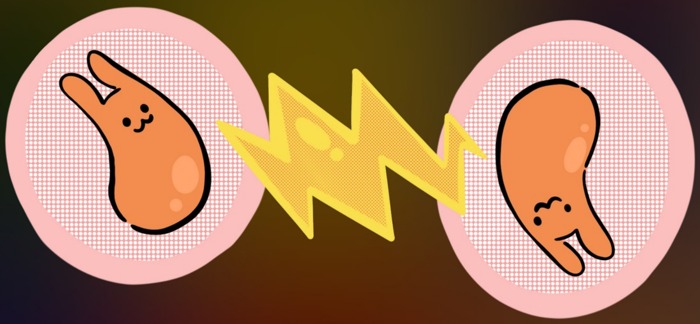

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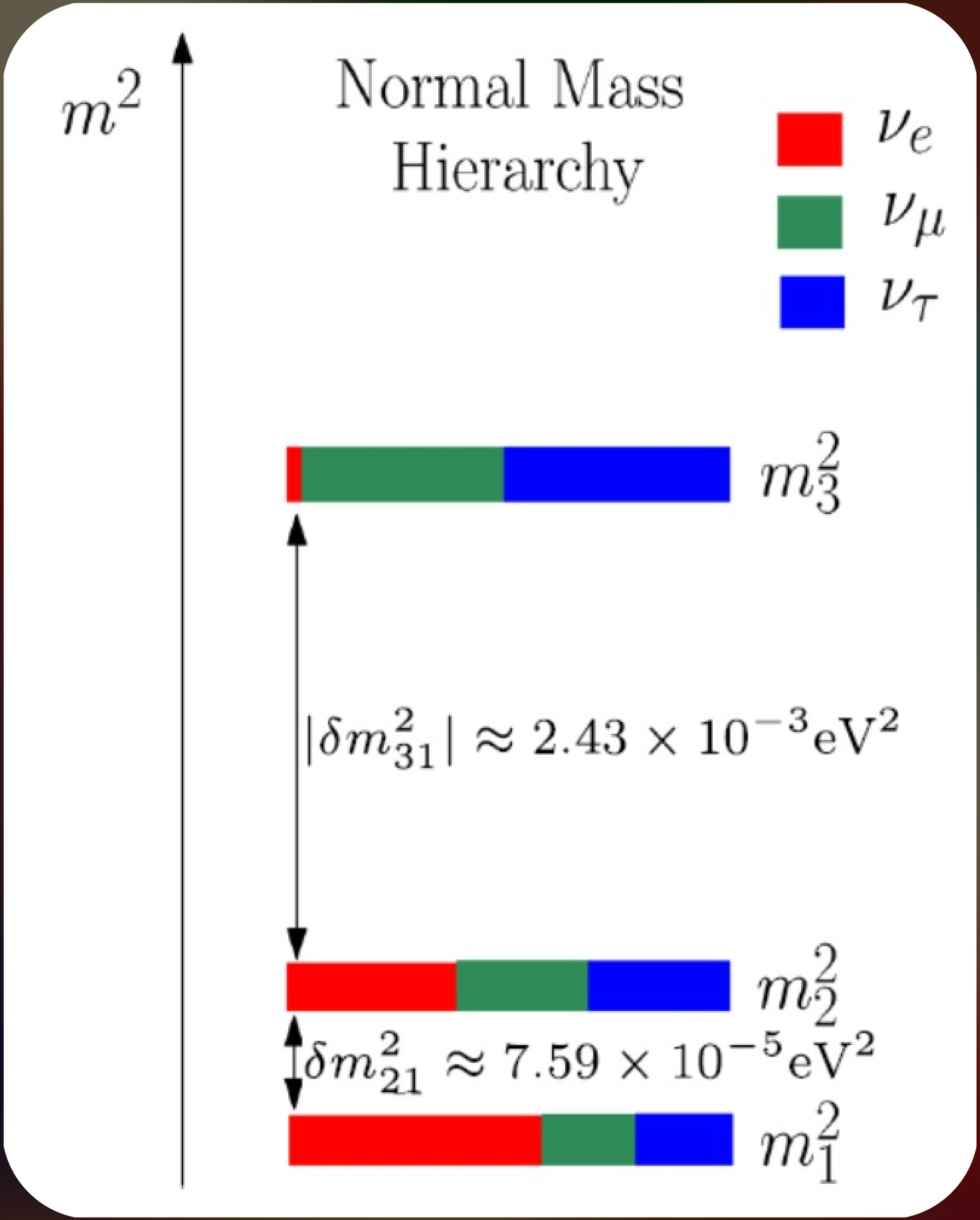
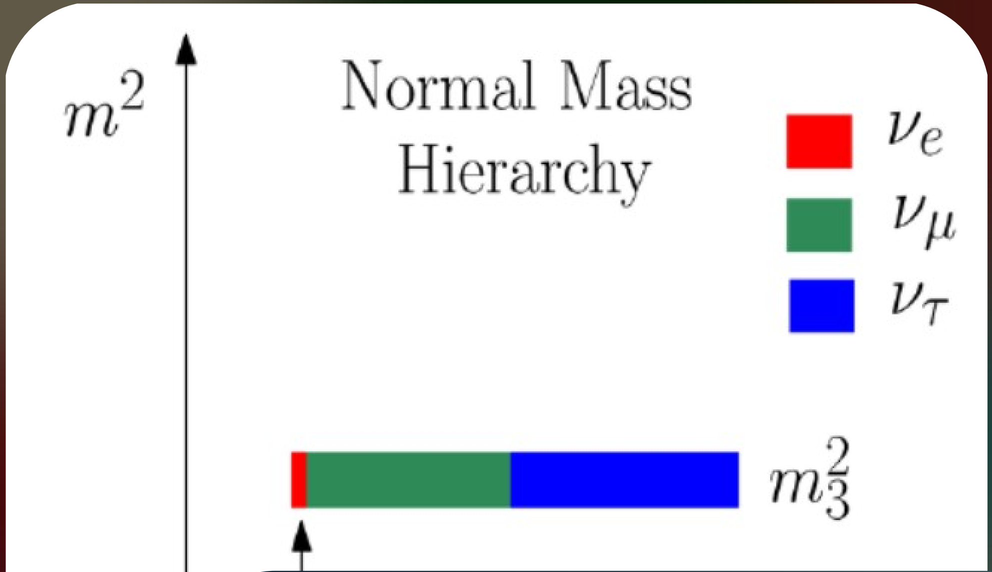
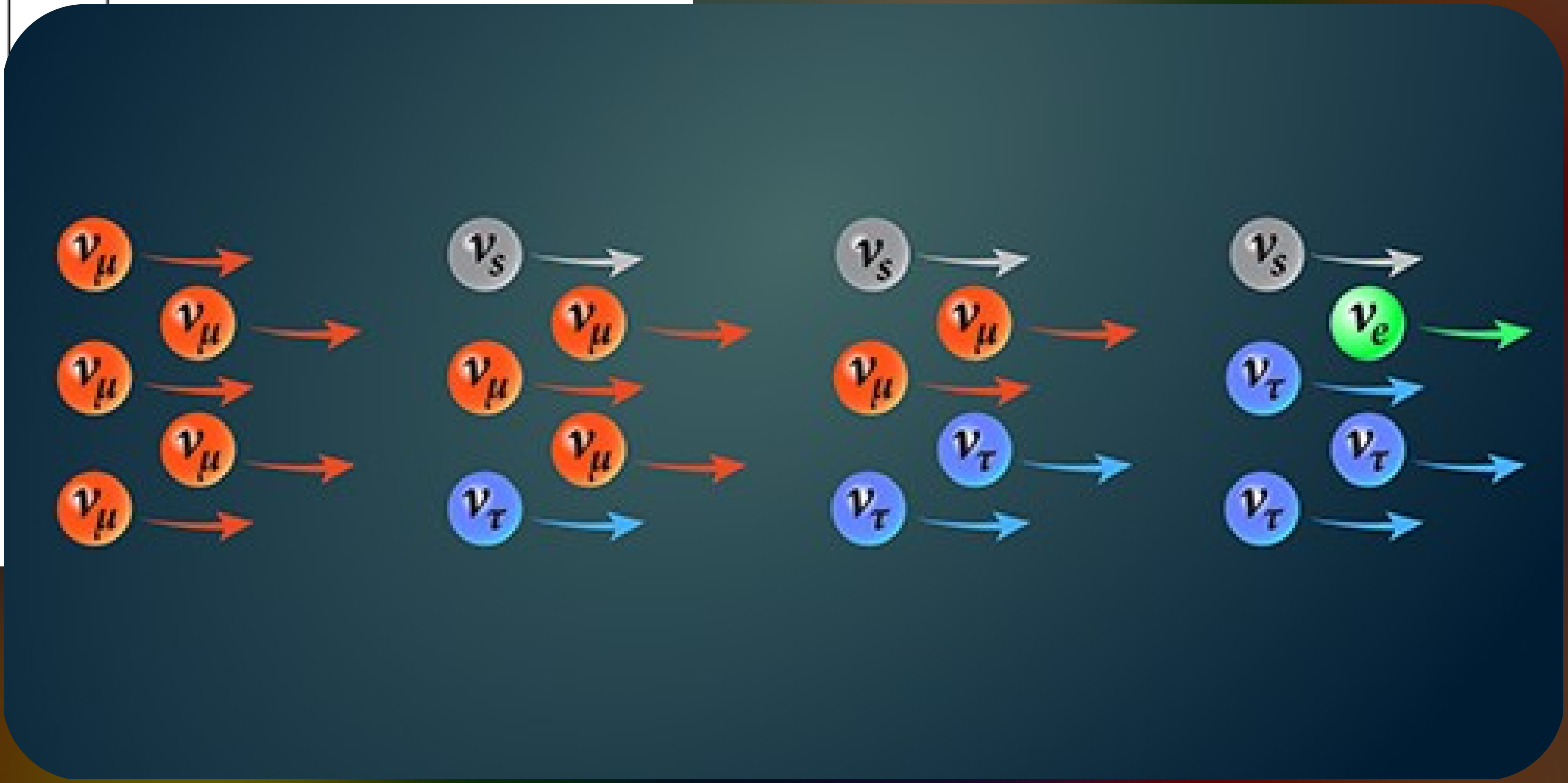
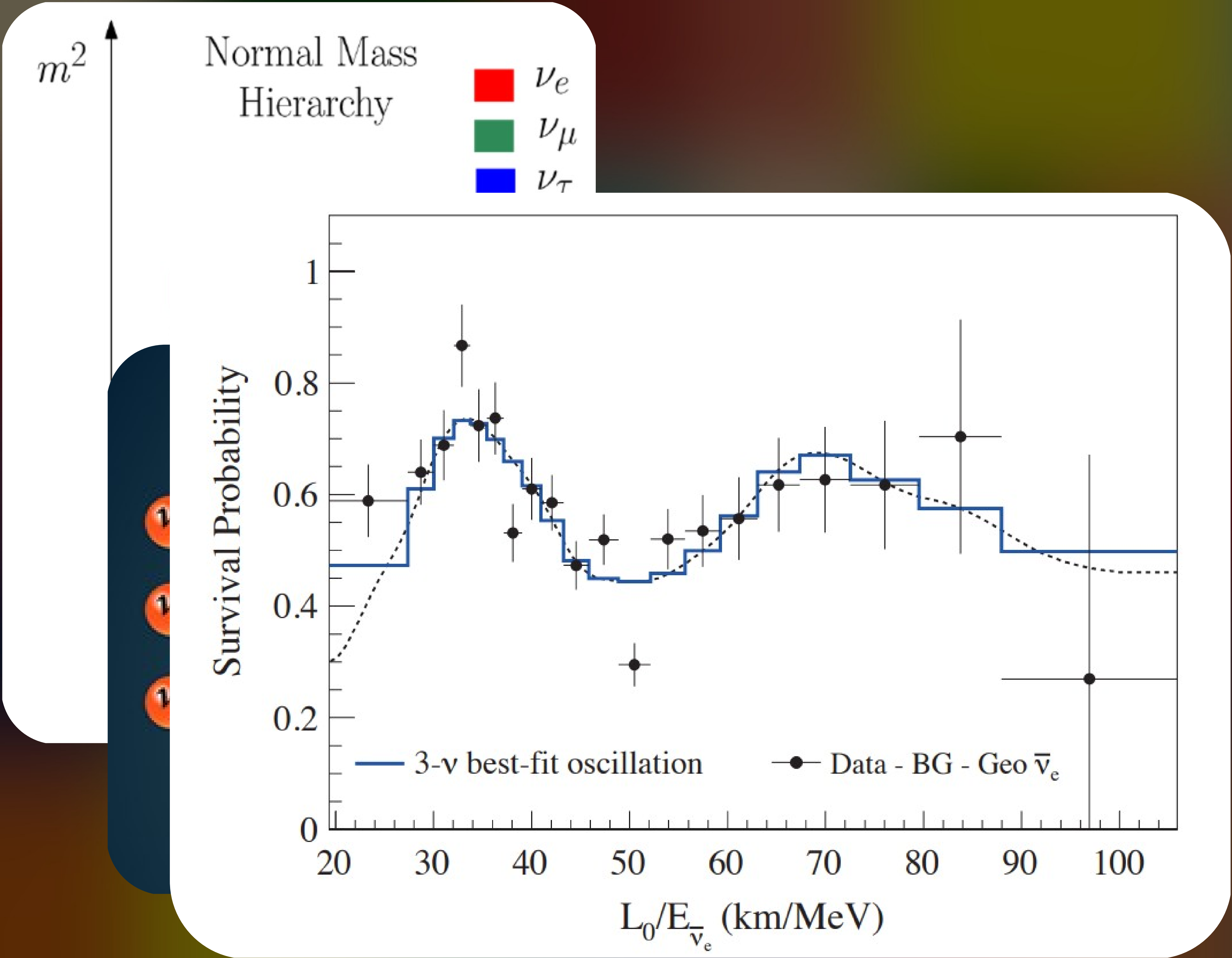
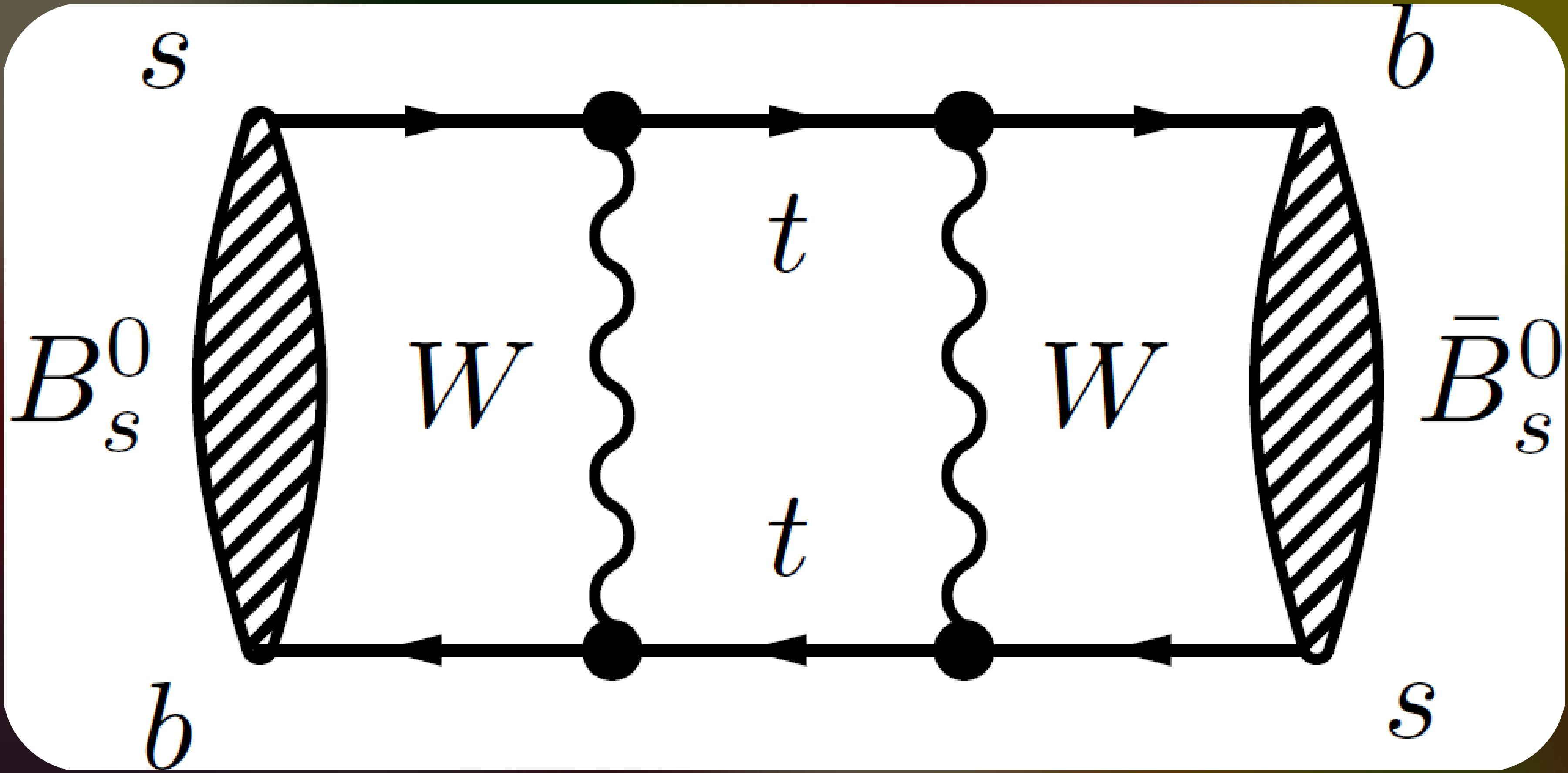

m^2
Normal Mass Hierarchy
ν_e
ν_μ
ν_τ
m_3^2
$|\delta m_{31}^2| \approx 2.43 \times 10^{-3} \mathrm{eV}^2$
m_2^2
$\delta m_{21}^2 \approx 7.59 \times 10^{-5} \mathrm{eV}^2$
m_1^2

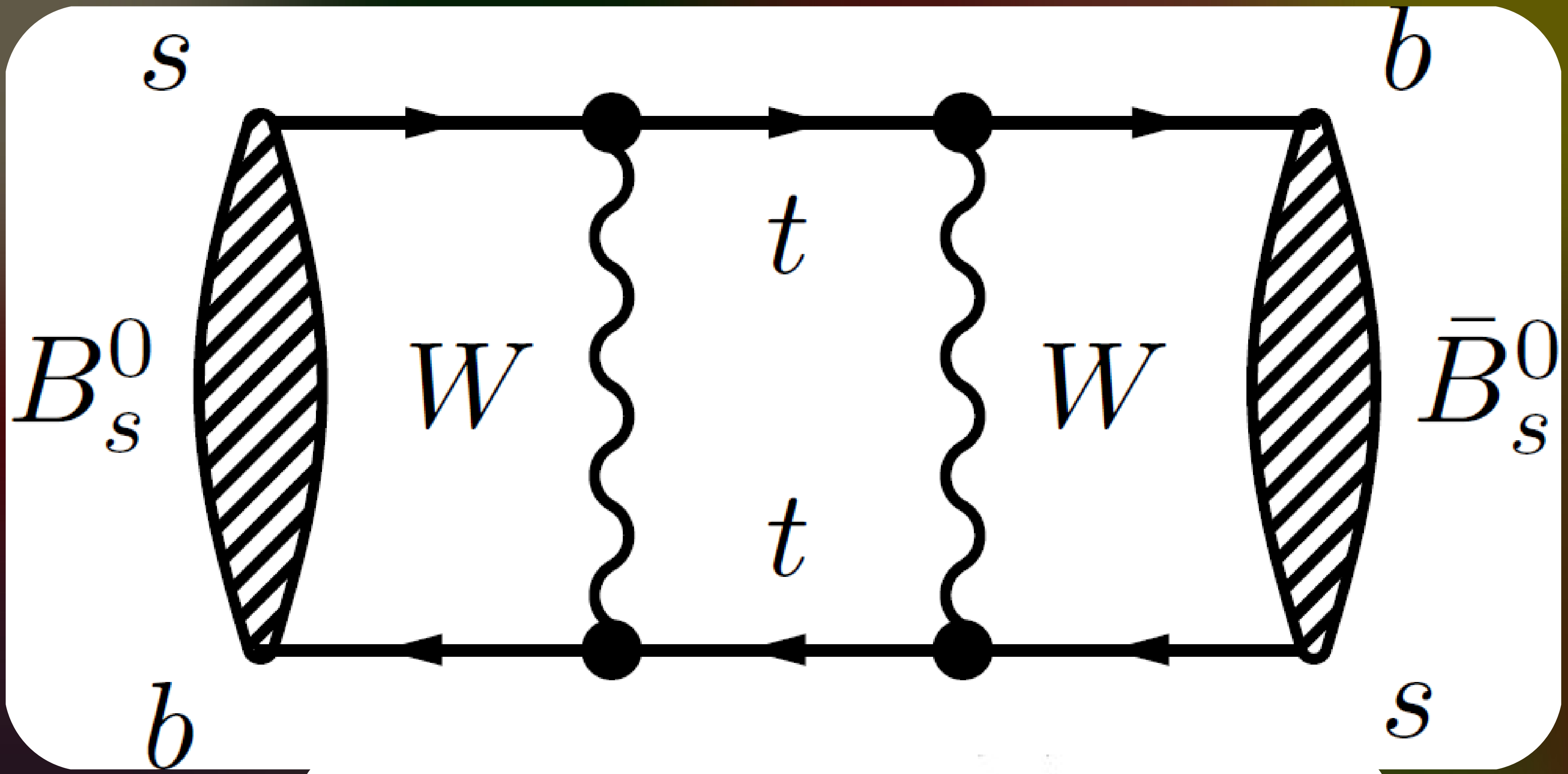

m^2
Normal Mass Hierarchy
🟥 ν_e
🟩 ν_μ
🟦 ν_τ
m_3^2


ν_μ
ν_s
ν_τ
ν_e

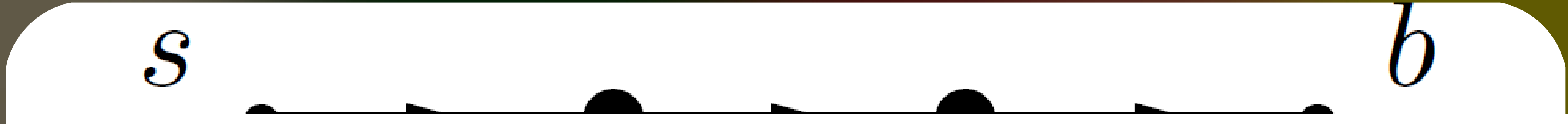


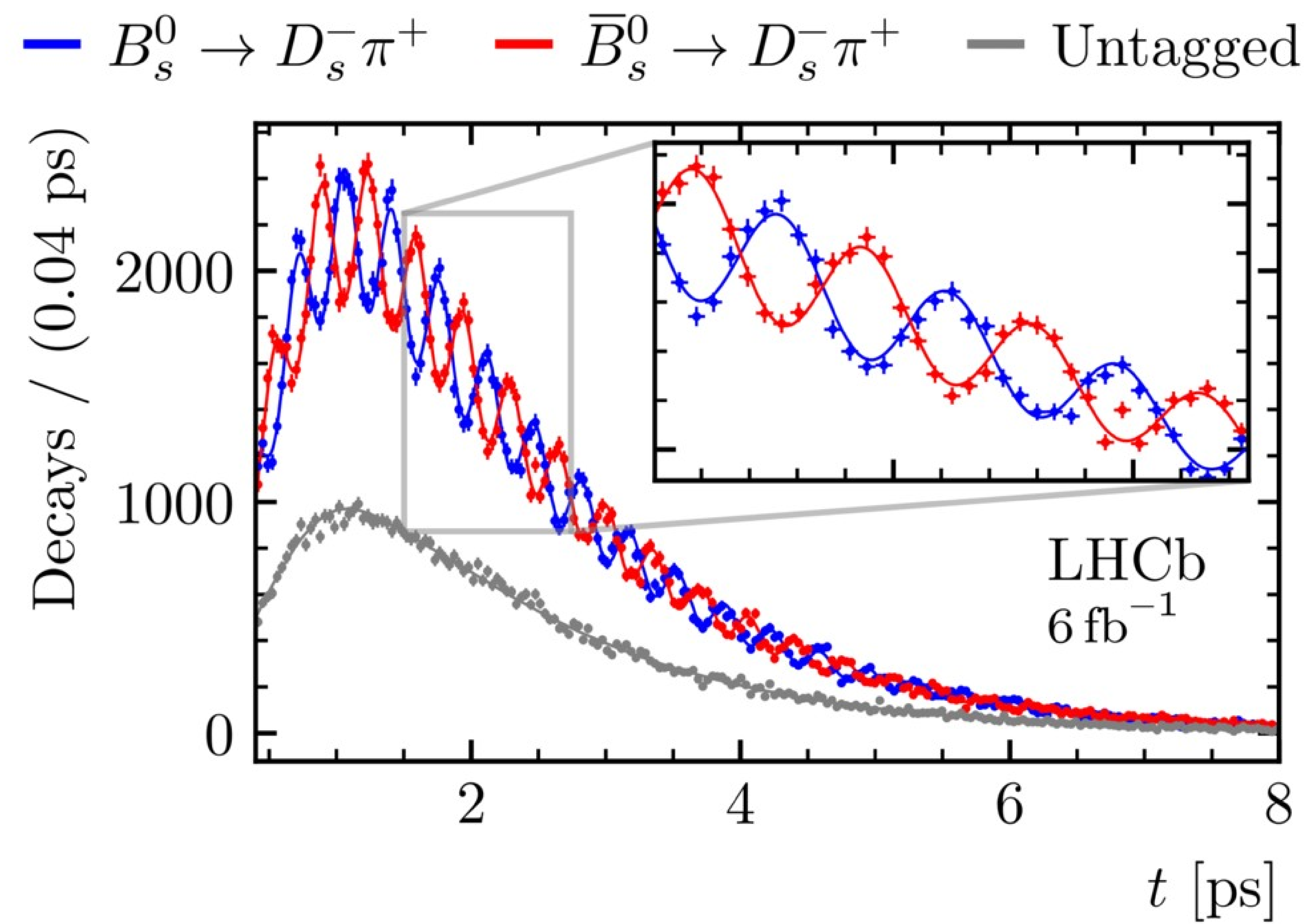
m^2
Normal Mass Hierarchy
🟥 ν_e
🟩 ν_μ
🟦 ν_τ
Survival Probability
0
0.2
0.4
0.6
0.8
1
20
30
40
50
60
70
80
90
100
$L_0/E_{\bar{\nu}_e}$ (km/MeV)
3-ν best-fit oscillation
Data - BG - Geo $\bar{\nu}_e$

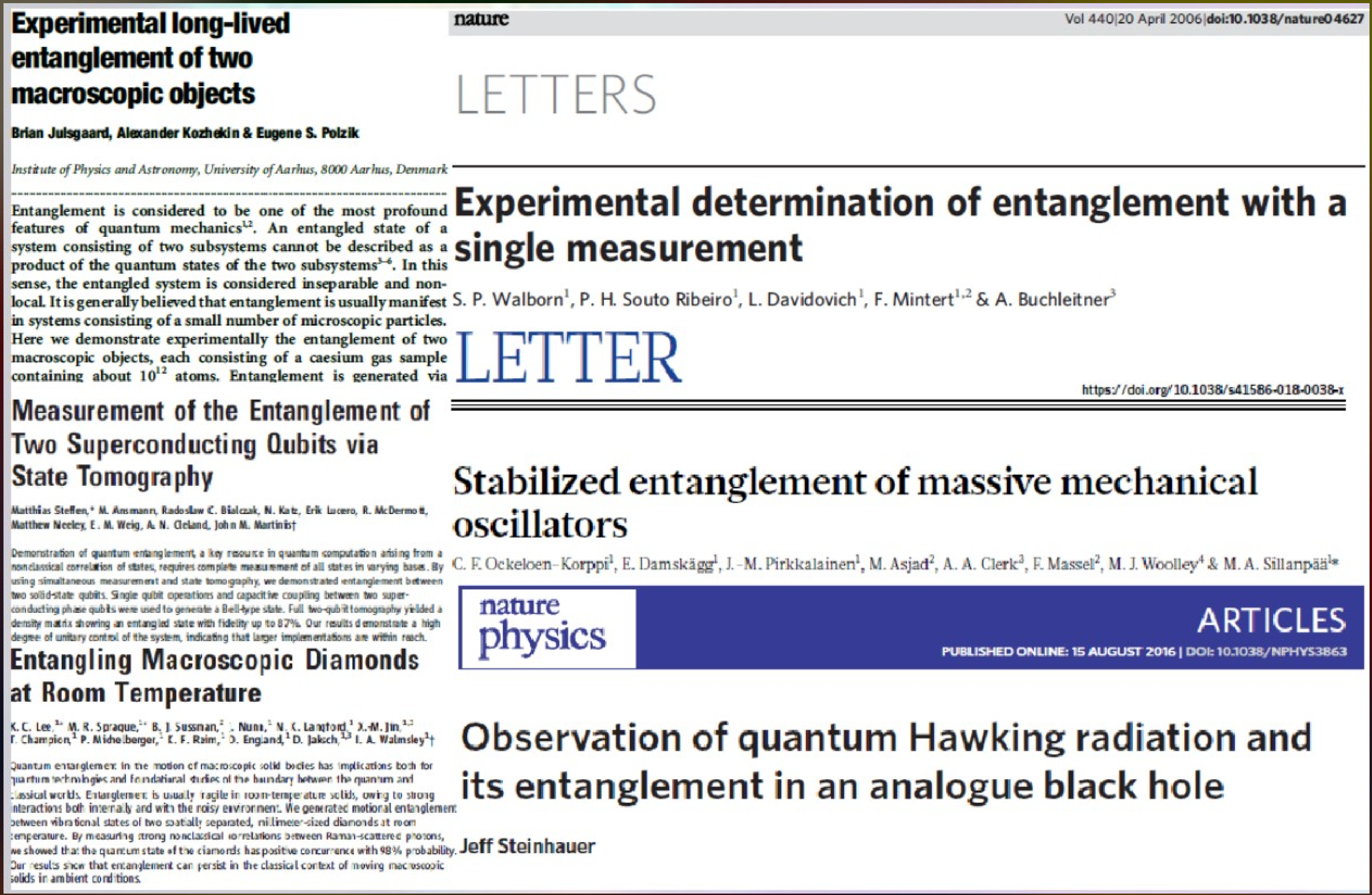

s
b
B_s^0
W
t
t
W
$\bar{B}_s^0$
b
s



$$|B_{\mathrm{L,H}}\rangle = p|B_q^0\rangle \pm q|\overline{B}_q^0\rangle,$$


s
b


$B_s^0 \to D_s^- \pi^+$
$\overline{B}_s^0 \to D_s^- \pi^+$
Untagged
Decays / (0.04 ps)
2000
1000
0
2
4
6
8
t [ps]
LHCb
6 fb^{-1}



Experimental long-lived entanglement of two macroscopic objects

Brian Julsgaard, Alexander Kozhekin & Eugene S. Polzik

Institute of Physics and Astronomy, University of Aarhus, 8000 Aarhus, Denmark

Entanglement is considered to be one of the most profound features of quantum mechanics[1,2]. An entangled state of a system consisting of two subsystems cannot be described as a product of the quantum states of the two subsystems[3–6]. In this sense, the entangled system is considered inseparable and nonlocal. It is generally believed that entanglement is usually manifest in systems consisting of a small number of microscopic particles. Here we demonstrate experimentally the entanglement of two macroscopic objects, each consisting of a caesium gas sample containing about 10^{12} atoms. Entanglement is generated via

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Measurement of the Entanglement of Two Superconducting Qubits via State Tomography

Matthias Steffen,* M. Ansmann, Radoslaw C. Bialczak, N. Katz, Erik Lucero, R. McDermott, Matthew Neeley, E. M. Weig, A. N. Cleland, John M. Martinis†

Demonstration of quantum entanglement, a key resource in quantum computation arising from a nonclassical correlation of states, requires complete measurement of all states in varying bases. By using simultaneous measurement and state tomography, we demonstrated entanglement between two solid-state qubits. Single qubit operations and capacitive coupling between two superconducting phase qubits were used to generate a Bell-type state. Full two-qubit tomography yielded a density matrix showing an entangled state with fidelity up to 87%. Our results demonstrate a high degree of unitary control of the system, indicating that larger implementations are within reach.

Entangling Macroscopic Diamonds at Room Temperature

K. C. Lee,[1*] M. R. Sprague,[1*] B. J. Sussman,[2] J. Nunn,[1] N. K. Langford,[1] X.-M. Jin,[1,3] T. Champion,[1] P. Michelberger,[1] K. F. Reim,[1] D. England,[1] D. Jaksch,[1,3] I. A. Walmsley[1]†

Quantum entanglement in the motion of macroscopic solid bodies has implications both for quantum technologies and foundational studies of the boundary between the quantum and classical worlds. Entanglement is usually fragile in room-temperature solids, owing to strong interactions both internally and with the noisy environment. We generated motional entanglement between vibrational states of two spatially separated, millimeter-sized diamonds at room temperature. By measuring strong nonclassical correlations between Raman-scattered photons, we showed that the quantum state of the diamonds has positive concurrence with 98% probability. Our results show that entanglement can persist in the classical context of moving macroscopic solids in ambient conditions.

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nature Vol 440|20 April 2006|**doi:10.1038/nature04627**

LETTERS

Experimental determination of entanglement with a single measurement

S. P. Walborn[1], P. H. Souto Ribeiro[1], L. Davidovich[1], F. Mintert[1,2] & A. Buchleitner[3]

LETTER

https://doi.org/10.1038/s41586-018-0038-x

Stabilized entanglement of massive mechanical oscillators

C. F. Ockeloen-Korppi[1], E. Damskägg[1], J.-M. Pirkkalainen[1], M. Asjad[2], A. A. Clerk[3], F. Massel[2], M. J. Woolley[4] & M. A. Sillanpää[1]*

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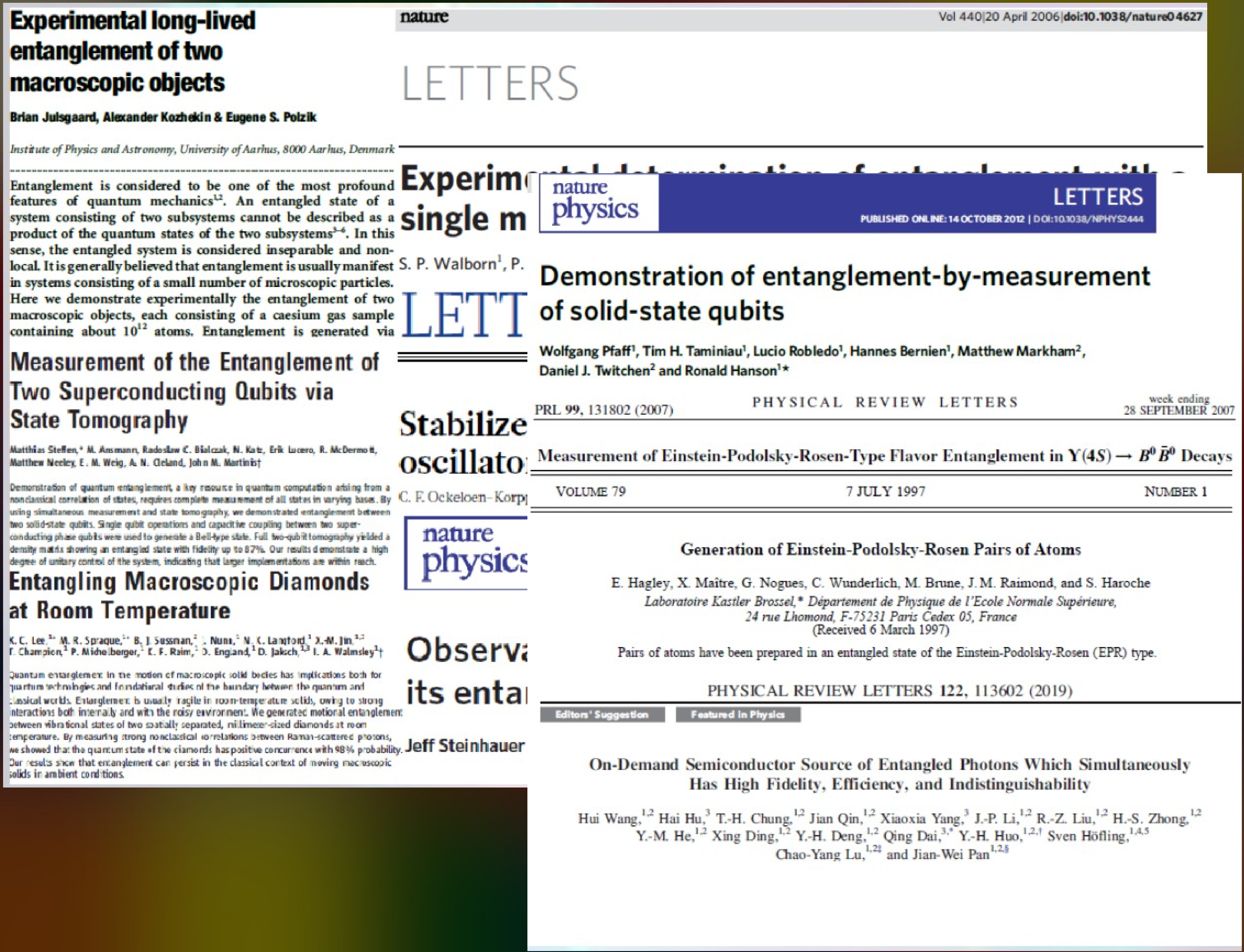
nature physics

ARTICLES

PUBLISHED ONLINE: 15 AUGUST 2016 | DOI: 10.1038/NPHYS3863

Observation of quantum Hawking radiation and its entanglement in an analogue black hole

Jeff Steinhauer



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nature physics LETTERS

PUBLISHED ONLINE: 14 OCTOBER 2012 | DOI:10.1038/NPHYS2444

Demonstration of entanglement-by-measurement of solid-state qubits

Wolfgang Pfaff[1], Tim H. Taminiau[1], Lucio Robledo[1], Hannes Bernien[1], Matthew Markham[2], Daniel J. Twitchen[2] and Ronald Hanson[1]*

PRL 99, 131802 (2007) PHYSICAL REVIEW LETTERS week ending 28 SEPTEMBER 2007

Measurement of Einstein-Podolsky-Rosen-Type Flavor Entanglement in $\Upsilon(4S) \to B^0 \bar{B}^0$ Decays

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VOLUME 79 7 JULY 1997 NUMBER 1

Generation of Einstein-Podolsky-Rosen Pairs of Atoms

E. Hagley, X. Maître, G. Nogues, C. Wunderlich, M. Brune, J. M. Raimond, and S. Haroche

Laboratoire Kastler Brossel, Département de Physique de l'Ecole Normale Supérieure,*
24 rue Lhomond, F-75231 Paris Cedex 05, France
(Received 6 March 1997)

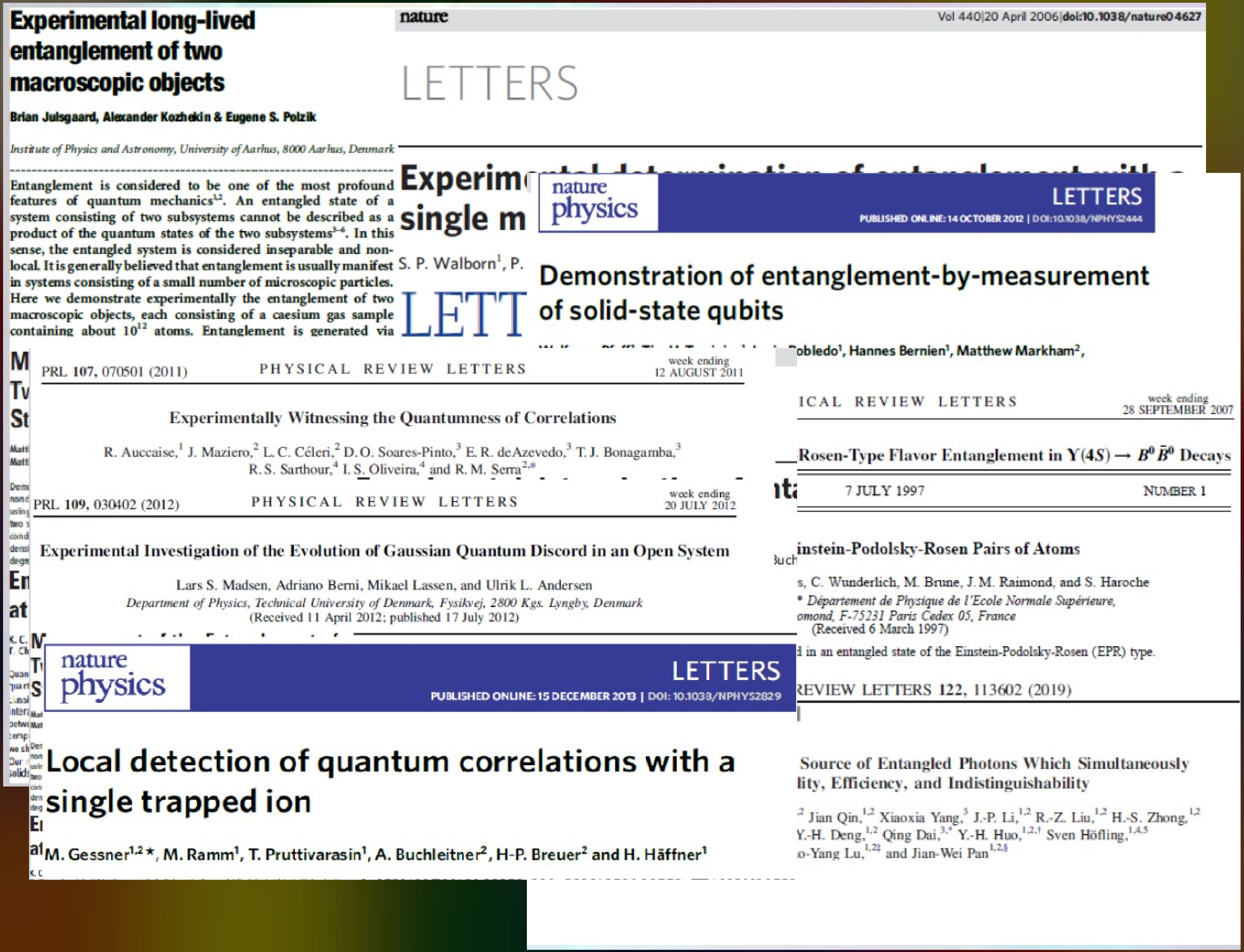
Pairs of atoms have been prepared in an entangled state of the Einstein-Podolsky-Rosen (EPR) type.

PHYSICAL REVIEW LETTERS 122, 113602 (2019)

Editors' Suggestion Featured in Physics

On-Demand Semiconductor Source of Entangled Photons Which Simultaneously Has High Fidelity, Efficiency, and Indistinguishability

Hui Wang,[1,2] Hai Hu,[3] T.-H. Chung,[1,2] Jian Qin,[1,2] Xiaoxia Yang,[3] J.-P. Li,[1,2] R.-Z. Liu,[1,2] H.-S. Zhong,[1,2] Y.-M. He,[1,2] Xing Ding,[1,2] Y.-H. Deng,[1,2] Qing Dai,[3,*] Y.-H. Huo,[1,2,†] Sven Höfling,[1,4,5] Chao-Yang Lu,[1,2‡] and Jian-Wei Pan[1,2,§]



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PRL 107, 070501 (2011) PHYSICAL REVIEW LETTERS week ending 12 AUGUST 2011

Experimentally Witnessing the Quantumness of Correlations

R. Auccaise,[1] J. Maziero,[2] L. C. Céleri,[2] D. O. Soares-Pinto,[3] E. R. deAzevedo,[3] T. J. Bonagamba,[3]
R. S. Sarthour,[4] I. S. Oliveira,[4] and R. M. Serra[2,*]

PRL 109, 030402 (2012) PHYSICAL REVIEW LETTERS week ending 20 JULY 2012

Experimental Investigation of the Evolution of Gaussian Quantum Discord in an Open System

Lars S. Madsen, Adriano Berni, Mikael Lassen, and Ulrik L. Andersen
Department of Physics, Technical University of Denmark, Fysikvej, 2800 Kgs. Lyngby, Denmark
(Received 11 April 2012; published 17 July 2012)

ICAL REVIEW LETTERS week ending 28 SEPTEMBER 2007

Rosen-Type Flavor Entanglement in $\Upsilon(4S) \rightarrow B^0 \bar{B}^0$ Decays

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7 JULY 1997 NUMBER 1

instein-Podolsky-Rosen Pairs of Atoms

s, C. Wunderlich, M. Brune, J. M. Raimond, and S. Haroche
* *Département de Physique de l'Ecole Normale Supérieure,*
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nature physics LETTERS

PUBLISHED ONLINE: 15 DECEMBER 2013 | DOI: 10.1038/NPHYS2829

Local detection of quantum correlations with a single trapped ion

M. Gessner[1,2]*, M. Ramm[1], T. Pruttivarasin[1], A. Buchleitner[2], H-P. Breuer[2] and H. Häffner[1]

REVIEW LETTERS 122, 113602 (2019)

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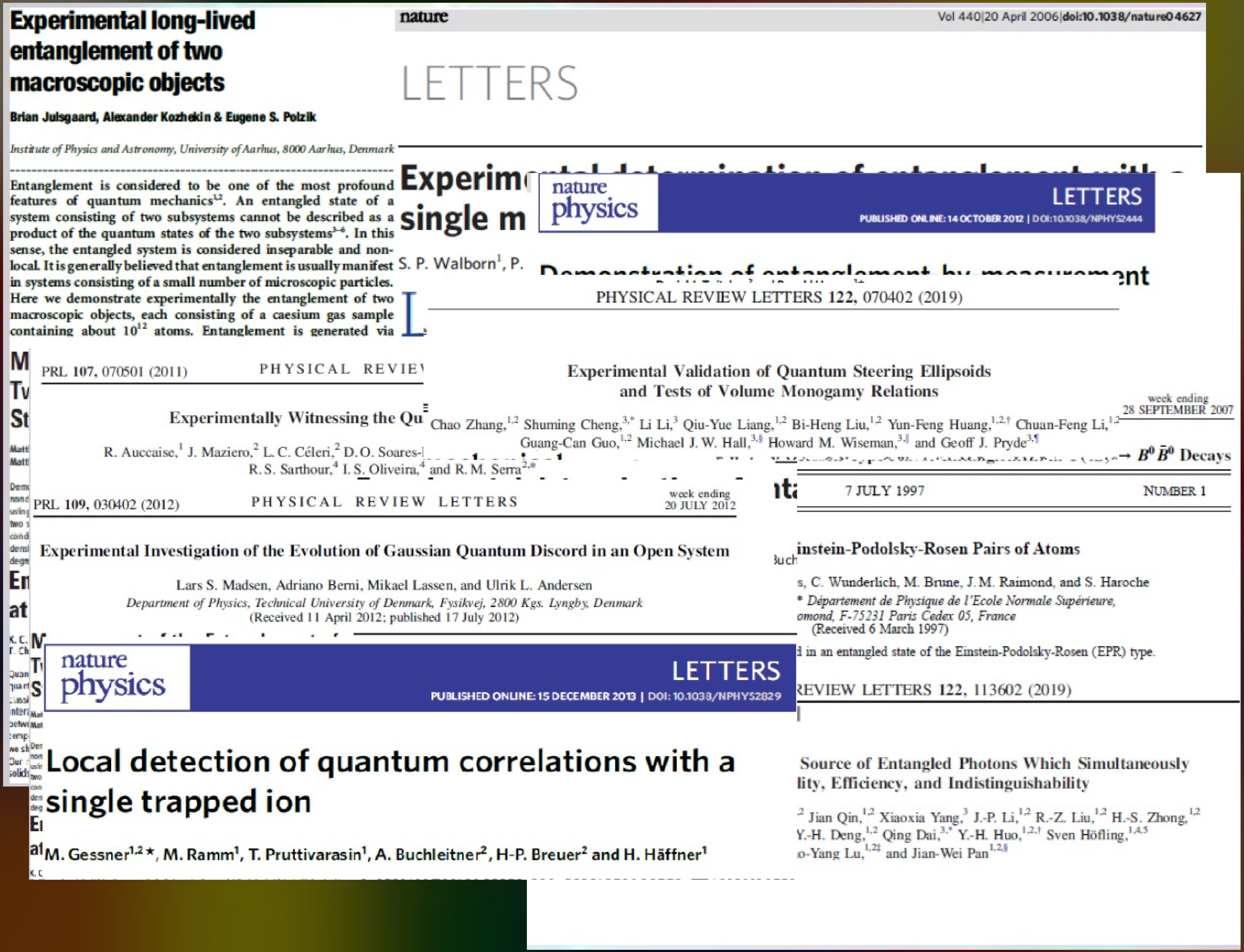

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nature physics LETTERS

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PHYSICAL REVIEW LETTERS 122, 070402 (2019)

Experimental Validation of Quantum Steering Ellipsoids and Tests of Volume Monogamy Relations

Chao Zhang,[1,2] Shuming Cheng,[3,*] Li Li,[3] Qiu-Yue Liang,[1,2] Bi-Heng Liu,[1,2] Yun-Feng Huang,[1,2,†] Chuan-Feng Li,[1,2] Guang-Can Guo,[1,2] Michael J. W. Hall,[3,§] Howard M. Wiseman,[3,∥] and Geoff J. Pryde[3,¶]

PRL 107, 070501 (2011) PHYSICAL REVIE

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week ending 28 SEPTEMBER 2007

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7 JULY 1997 NUMBER 1

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PRL 109, 030402 (2012) PHYSICAL REVIEW LETTERS week ending 20 JULY 2012

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REVIEW LETTERS 122, 113602 (2019)

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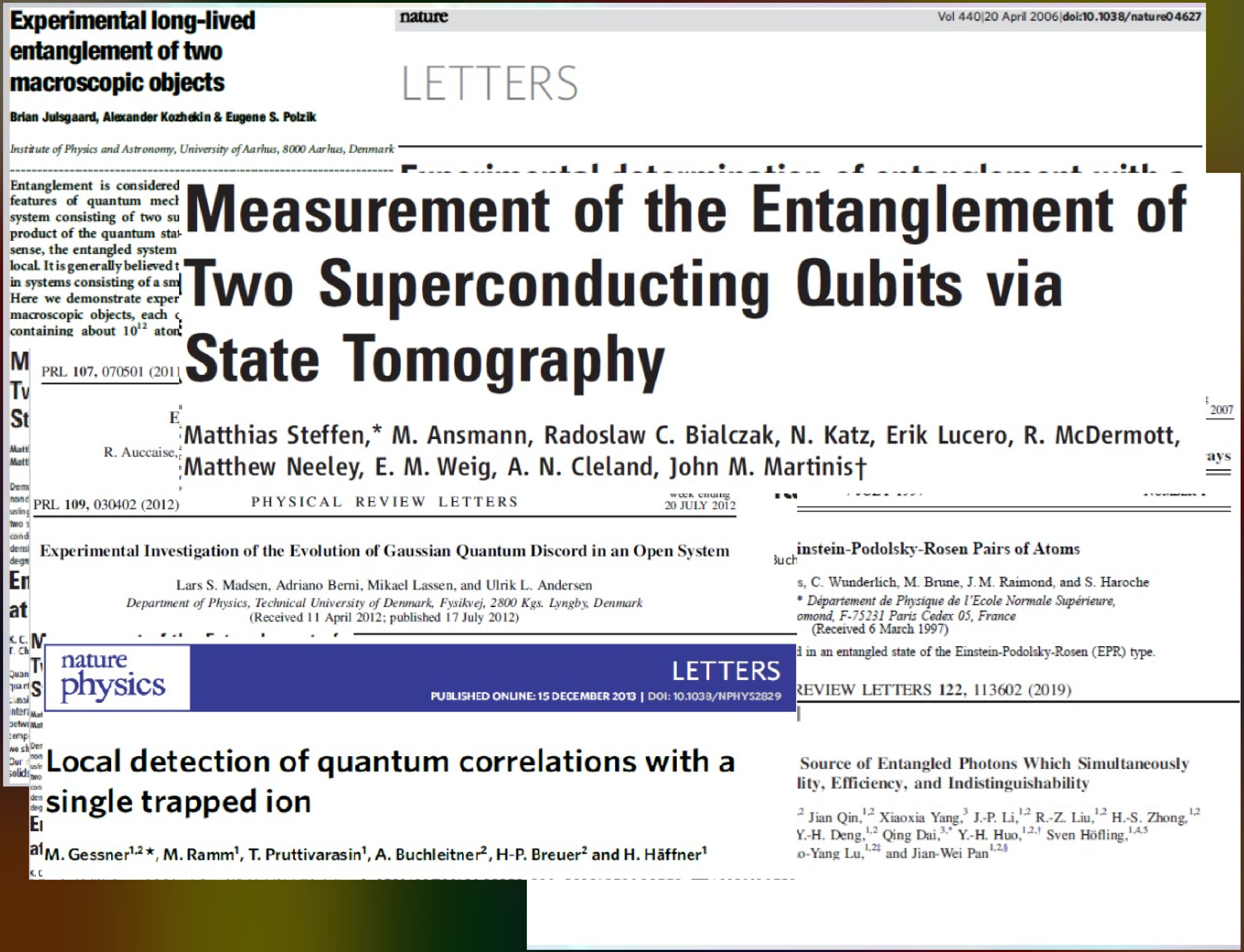

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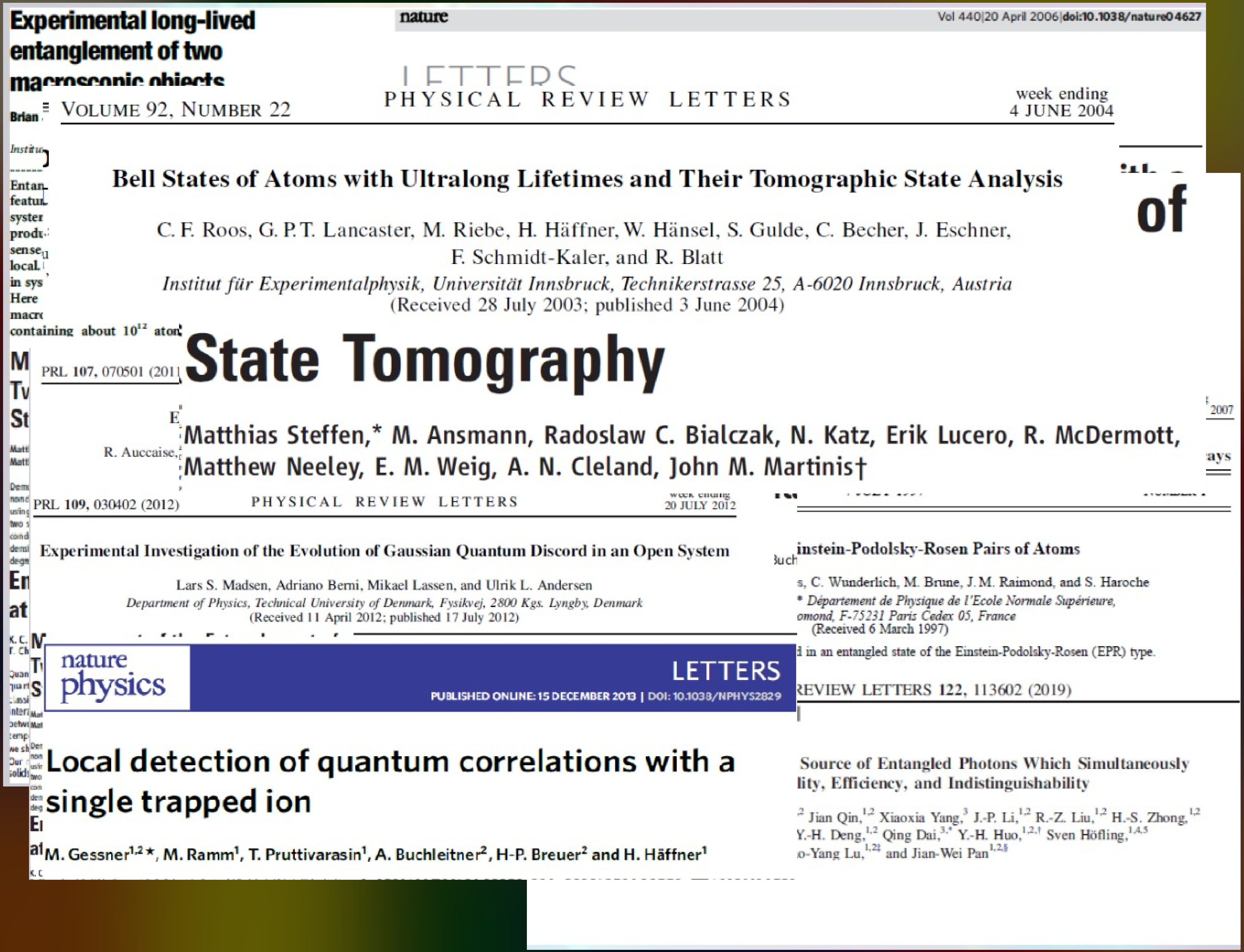
nature physics LETTERS

PUBLISHED ONLINE: 15 DECEMBER 2013 | DOI: 10.1038/NPHYS2829

Local detection of quantum correlations with a single trapped ion

M. Gessner[1,2]*, M. Ramm[1], T. Pruttivarasin[1], A. Buchleitner[2], H-P. Breuer[2] and H. Häffner[1]



Experimental long-lived entanglement of two macroscopic objects

nature Vol 440|20 April 2006|doi:10.1038/nature04627

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PHYSICAL REVIEW LETTERS

VOLUME 92, NUMBER 22

week ending 4 JUNE 2004

Bell States of Atoms with Ultralong Lifetimes and Their Tomographic State Analysis

C. F. Roos, G. P. T. Lancaster, M. Riebe, H. Häffner, W. Hänsel, S. Gulde, C. Becher, J. Eschner, F. Schmidt-Kaler, and R. Blatt

Institut für Experimentalphysik, Universität Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria

(Received 28 July 2003; published 3 June 2004)

containing about 10^{12} atoms

PRL 107, 070501 (2011)

R. Auccaise,

State Tomography

Matthias Steffen,* M. Ansmann, Radoslaw C. Bialczak, N. Katz, Erik Lucero, R. McDermott, Matthew Neeley, E. M. Weig, A. N. Cleland, John M. Martinis†

PRL 109, 030402 (2012) PHYSICAL REVIEW LETTERS week ending 20 JULY 2012

Experimental Investigation of the Evolution of Gaussian Quantum Discord in an Open System

Lars S. Madsen, Adriano Berni, Mikael Lassen, and Ulrik L. Andersen

Department of Physics, Technical University of Denmark, Fysikvej, 2800 Kgs. Lyngby, Denmark

(Received 11 April 2012; published 17 July 2012)

instein-Podolsky-Rosen Pairs of Atoms

s, C. Wunderlich, M. Brune, J. M. Raimond, and S. Haroche

** Département de Physique de l'Ecole Normale Supérieure, omond, F-75231 Paris Cedex 05, France*

(Received 6 March 1997)

d in an entangled state of the Einstein-Podolsky-Rosen (EPR) type.

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REVIEW LETTERS 122, 113602 (2019)

Source of Entangled Photons Which Simultaneously lity, Efficiency, and Indistinguishability

[2] Jian Qin,[1,2] Xiaoxia Yang,[3] J.-P. Li,[1,2] R.-Z. Liu,[1,2] H.-S. Zhong,[1,2] Y.-H. Deng,[1,2] Qing Dai,[3,*] Y.-H. Huo,[1,2,†] Sven Höfling,[1,4,5] o-Yang Lu,[1,2‡] and Jian-Wei Pan[1,2,§]

nature

Letter | Published: 21 October 2015

Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres

B. Hensen, H. Bernien, A. E. Dréau, A. Reiserer, N. Kalb, M. S. Blok, J. Ruitenberg, R. F. L. Vermeulen, R. N. Schouten, C. Abellán, W. Amaya, V. Pruneri, M. W. Mitchell, M. Markham, D. J. Twitchen, D. Elkouss, S. Wehner, T. H. Taminiau & R. Hanson

Nature **526**, 682–686 (2015) | Cite this article

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ril 2006|doi:10.1038/nature04627

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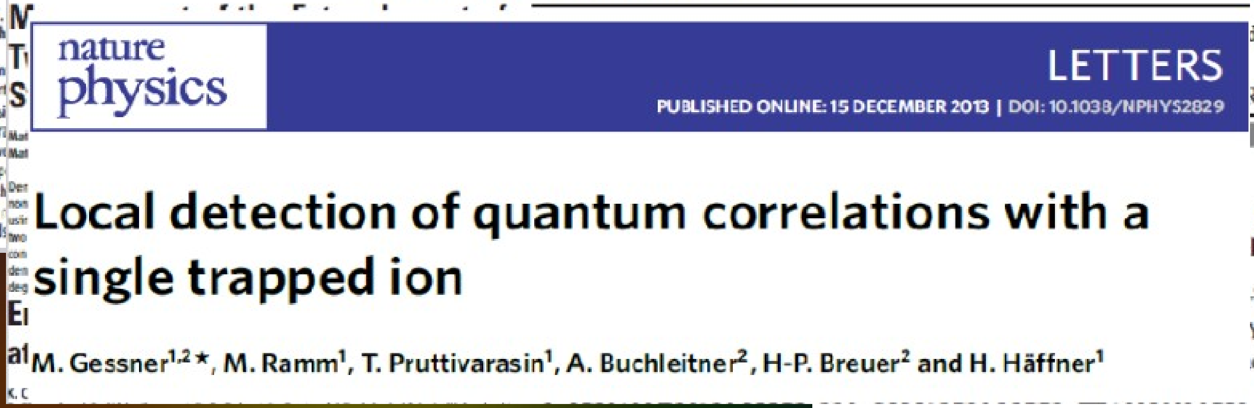

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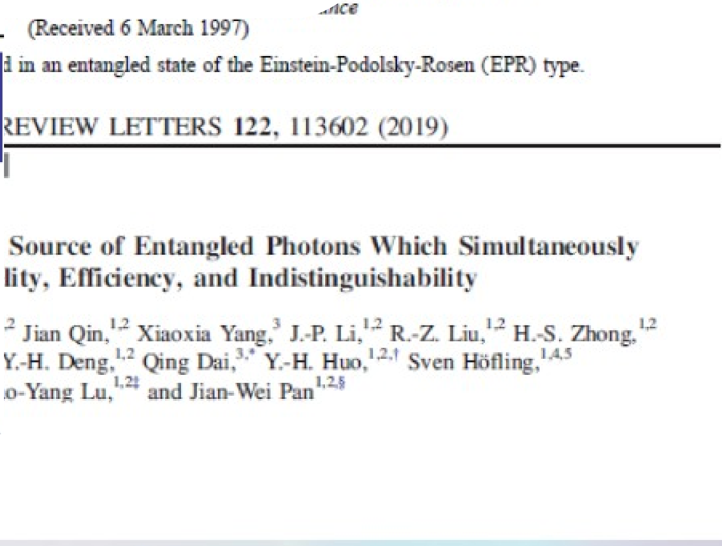

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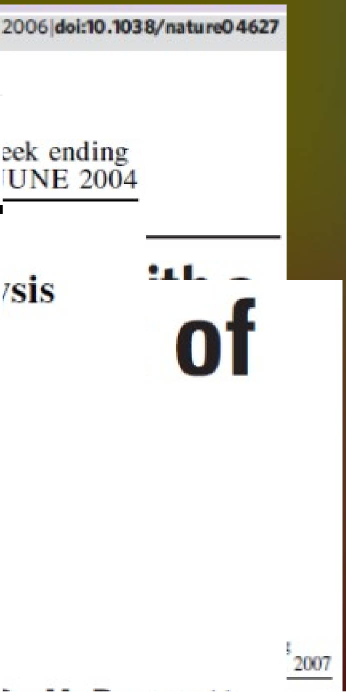

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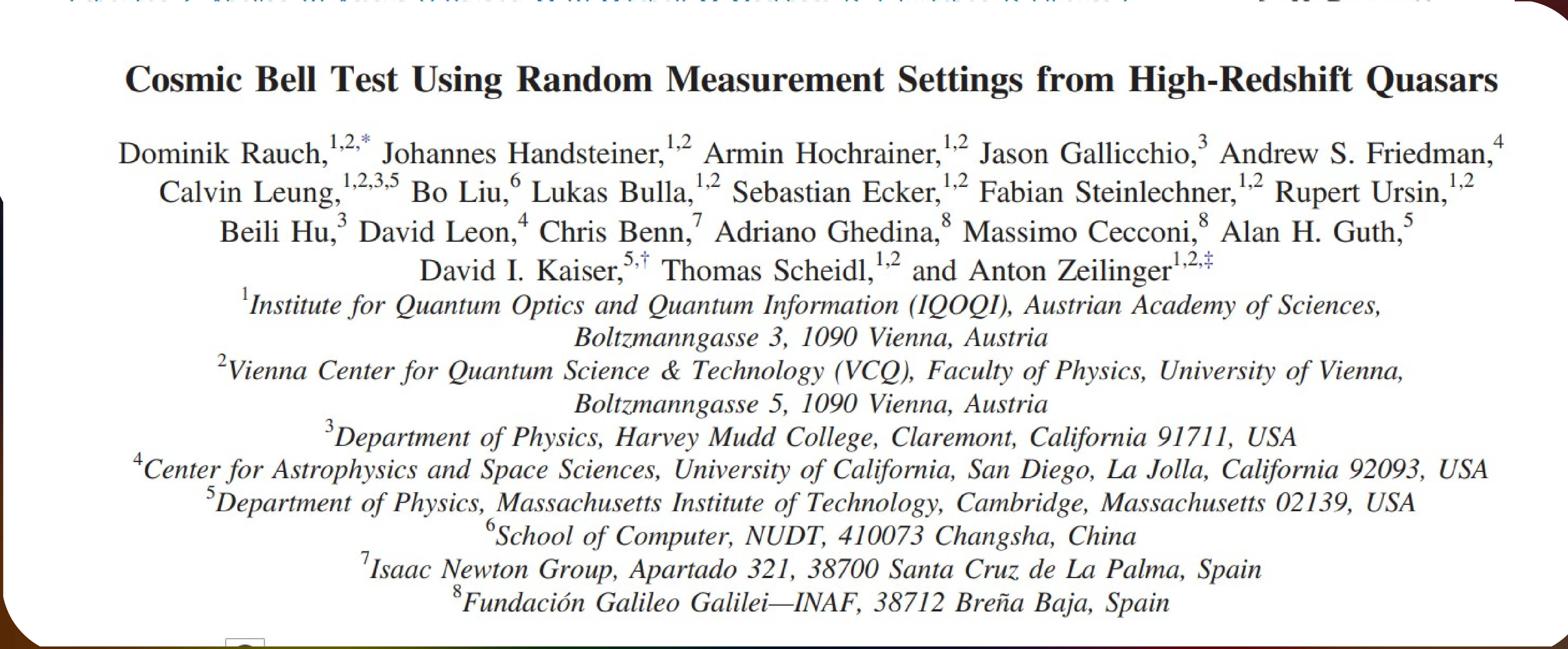

Cosmic Bell Test Using Random Measurement Settings from High-Redshift Quasars

Dominik Rauch,[1,2,*] Johannes Handsteiner,[1,2] Armin Hochrainer,[1,2] Jason Gallicchio,[3] Andrew S. Friedman,[4]
Calvin Leung,[1,2,3,5] Bo Liu,[6] Lukas Bulla,[1,2] Sebastian Ecker,[1,2] Fabian Steinlechner,[1,2] Rupert Ursin,[1,2]
Beili Hu,[3] David Leon,[4] Chris Benn,[7] Adriano Ghedina,[8] Massimo Cecconi,[8] Alan H. Guth,[5]
David I. Kaiser,[5,†] Thomas Scheidl,[1,2] and Anton Zeilinger[1,2,‡]

[1]*Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Sciences,*
Boltzmanngasse 3, 1090 Vienna, Austria
[2]*Vienna Center for Quantum Science & Technology (VCQ), Faculty of Physics, University of Vienna,*
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[3]*Department of Physics, Harvey Mudd College, Claremont, California 91711, USA*
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[5]*Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
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[7]*Isaac Newton Group, Apartado 321, 38700 Santa Cruz de La Palma, Spain*
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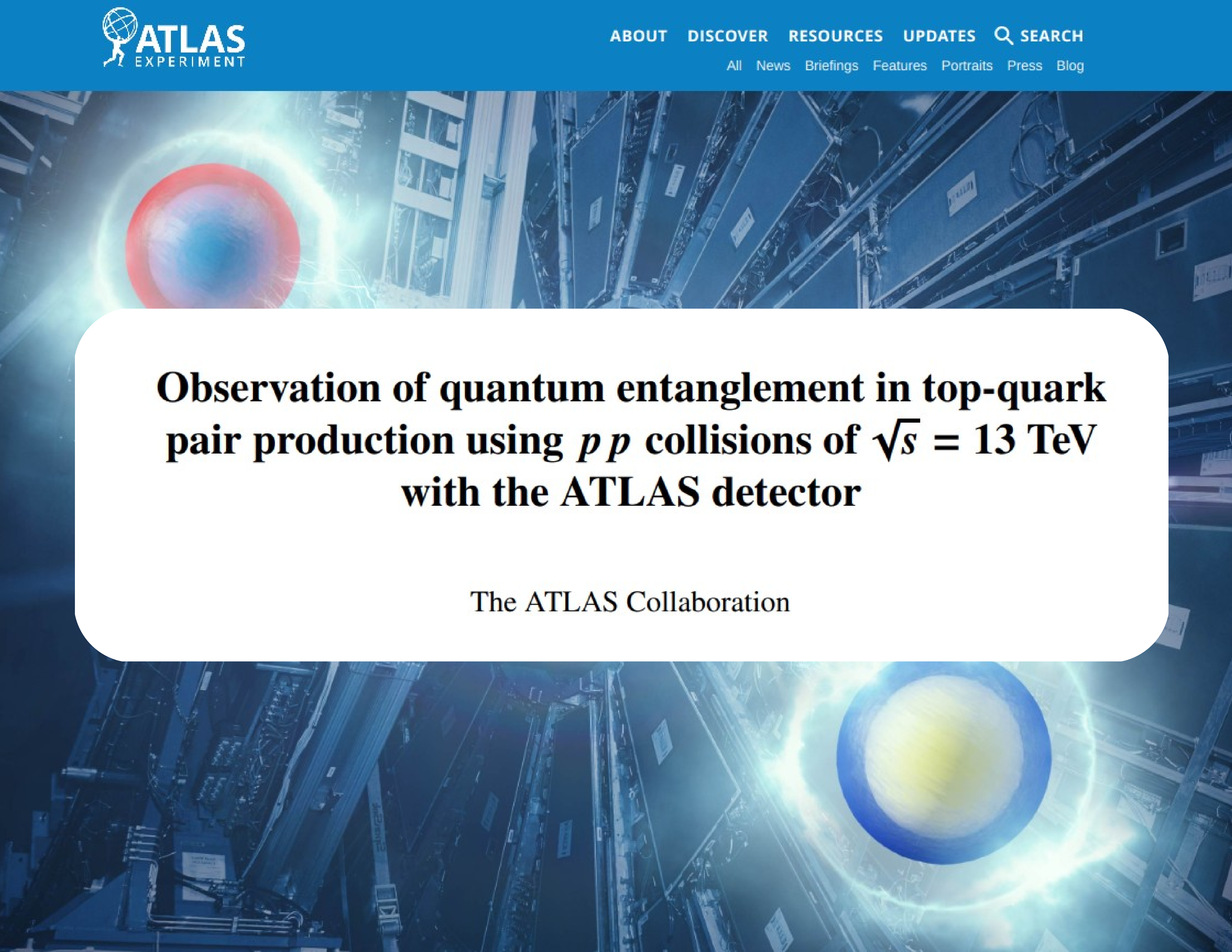
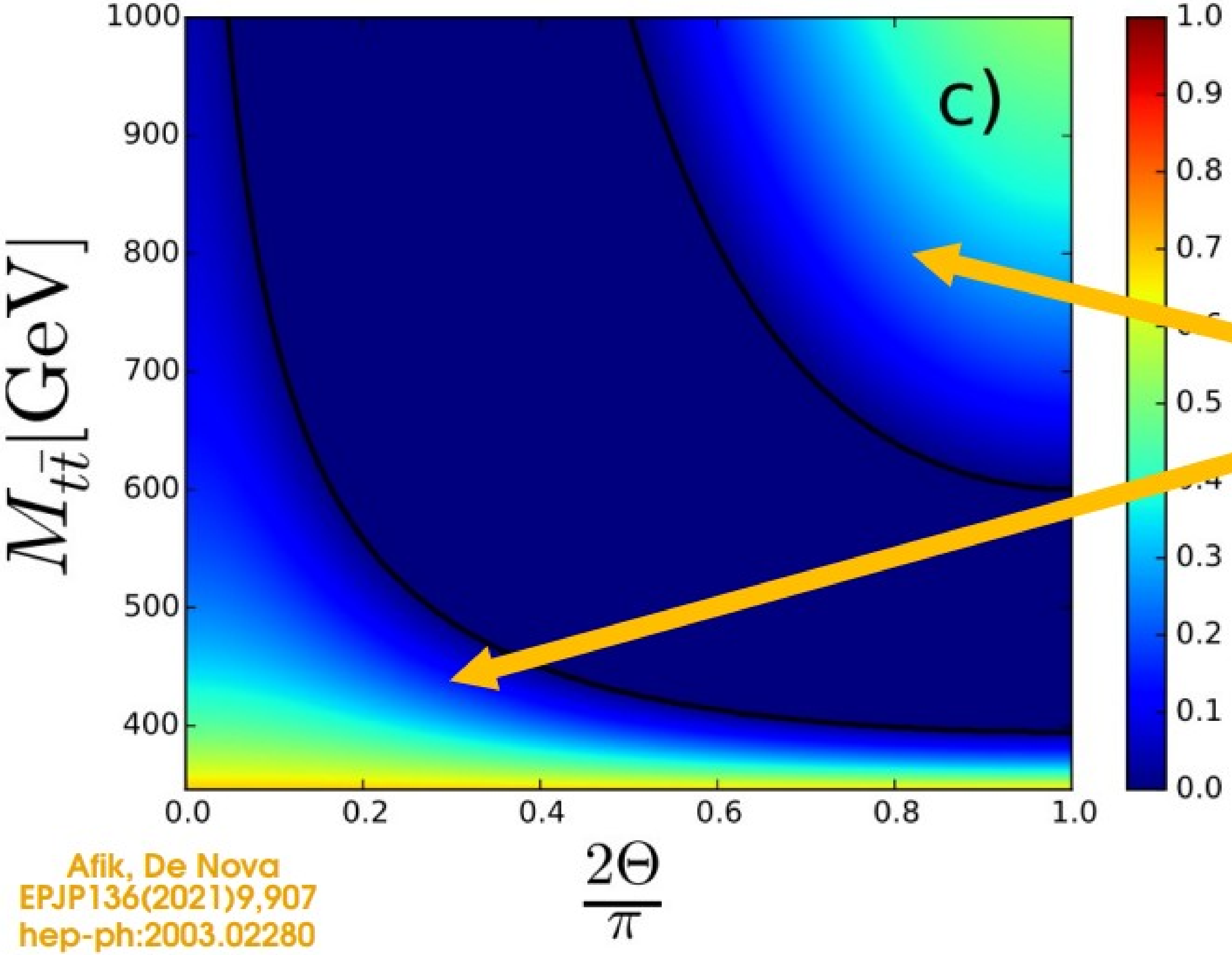


Observation of quantum entanglement in top-quark pair production using pp collisions of $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

The Standard Model produces top pairs with correlated spin. Sometimes spin correlations are so strong they can not be explained classically:



Entangled regions

1. High p_T
2. Threshold & forward (zero p_T)

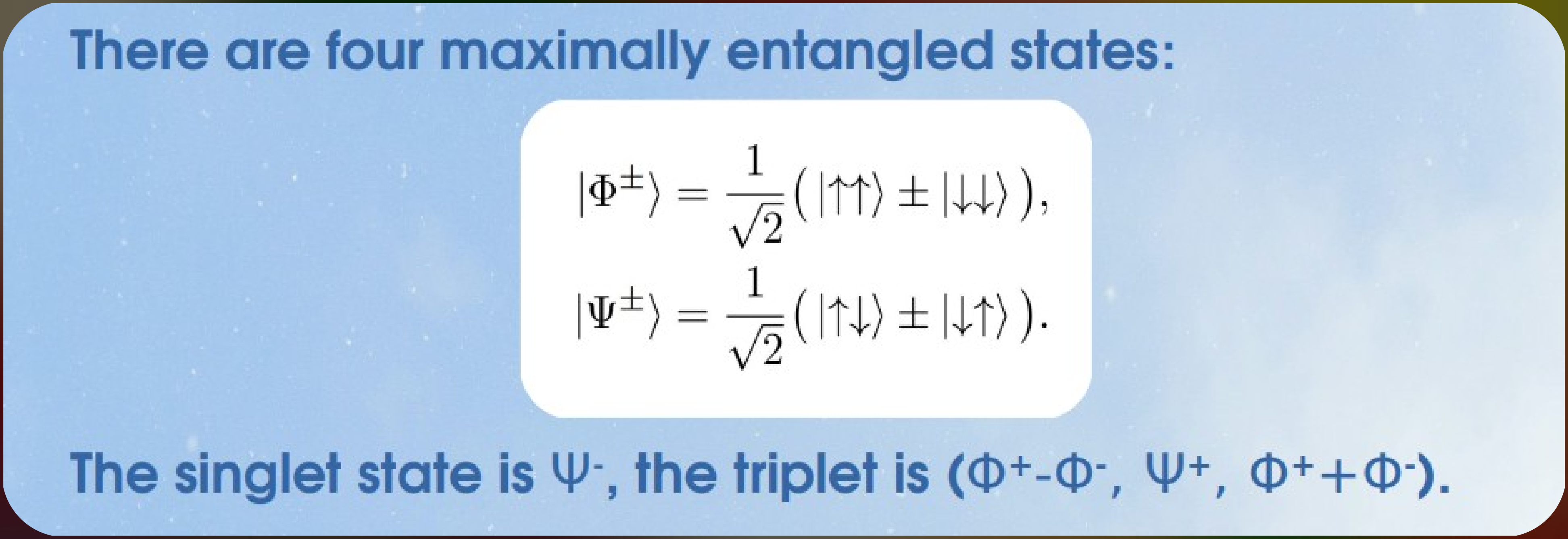
Afik, De Nova
EPJP136(2021)9,907
hep-ph:2003.02280

There are four maximally entangled states:

$$|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}\big(|\uparrow\uparrow\rangle \pm |\downarrow\downarrow\rangle\big),$$

$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}\big(|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle\big).$$

The singlet state is Ψ^{-}, the triplet is $(\Phi^{+}-\Phi^{-}, \Psi^{+}, \Phi^{+}+\Phi^{-})$.



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The singlet state is Ψ^-, the triplet is $(\Phi^+ - \Phi^-,\ \Psi^+,\ \Phi^+ + \Phi^-)$.

For the singlet,

the leptons fly away more aligned
if the original spins were entangled

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For the singlet,

the leptons fly away more aligned if the original spins were entangled

$$D = -3 \cdot \langle \cos\varphi \rangle$$

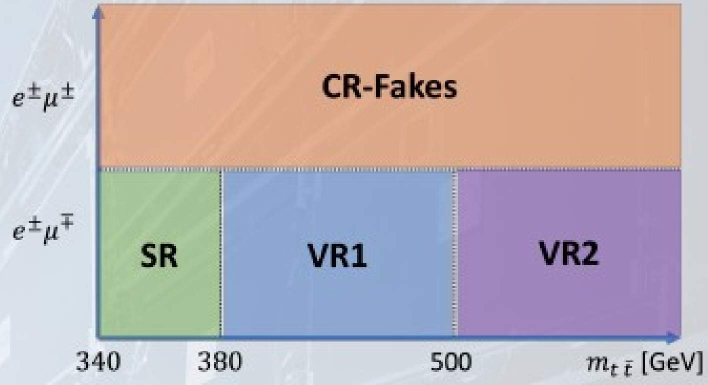
$$D < -1/3.$$

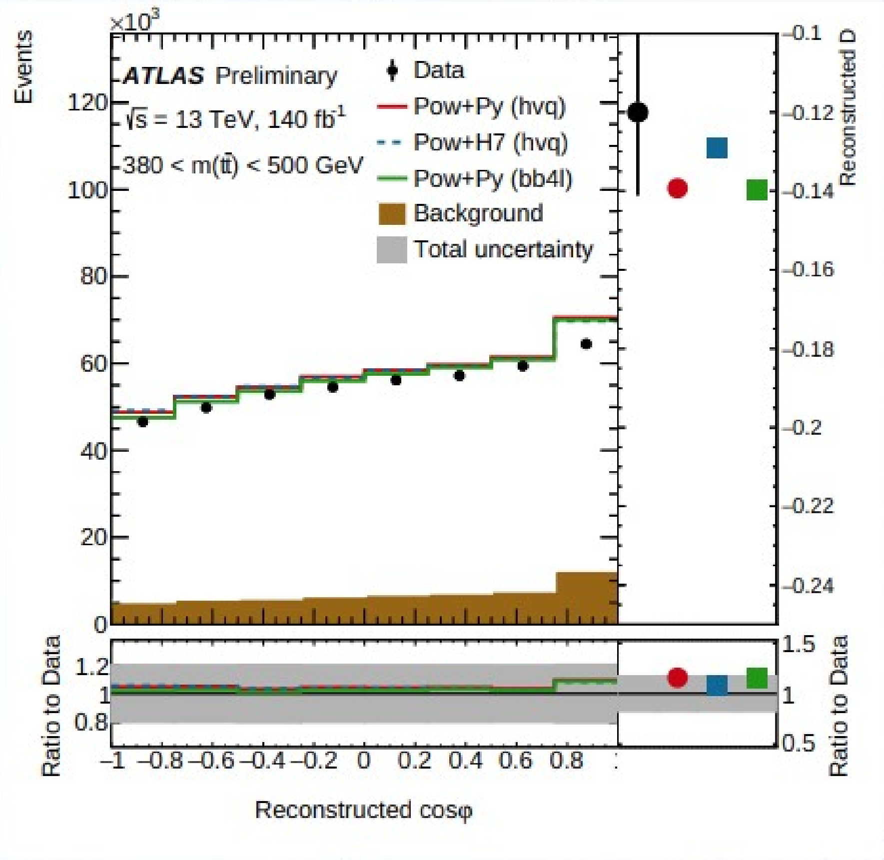
= entanglement

(spin singlet)

Analysis Strategy

- Analysis selection:
  - $1\mu, 1e$ with opposite charges.
  - Single lepton triggers.
  - Lepton $p_{\mathrm{T}} > 25$–28 GeV.
  - $N_b \geq 1$ (85% b-tag efficiency).
- Backgrounds:
  - tW.
  - $t\bar{t} + X (X = H, W, Z)$.
  - $VV (V = W, Z)$.
  - $Z \to \tau^+\tau^-$.
  - Fakes.
- Regions are categorized by $m_{t\bar{t}}$. The $t\bar{t}$ purity is 90% across the signal region (SR) and the validation regions (VR1, VR2).
- **Particle level fiducial regions are defined with similar selections.**





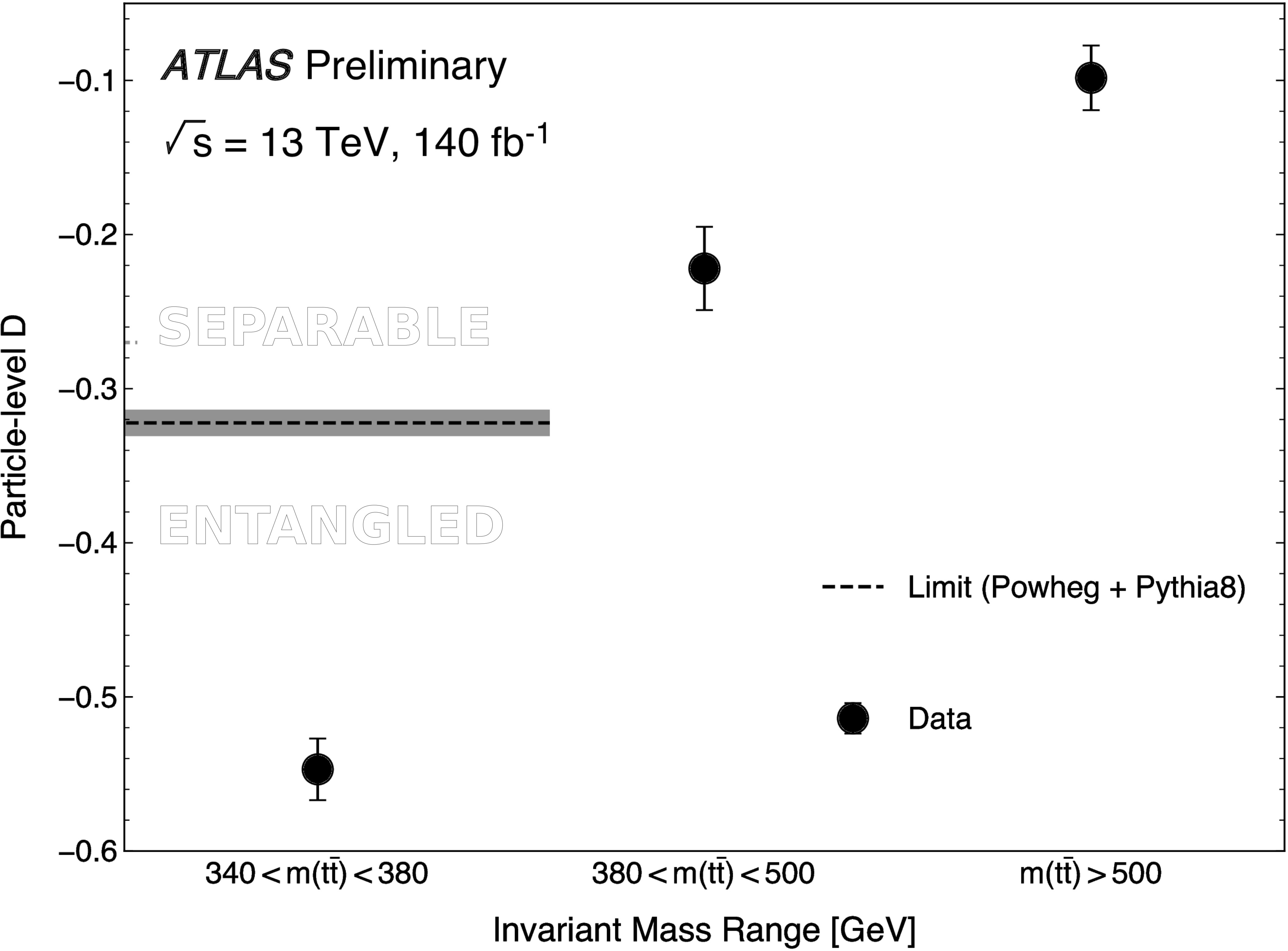
Systematic Uncertainties

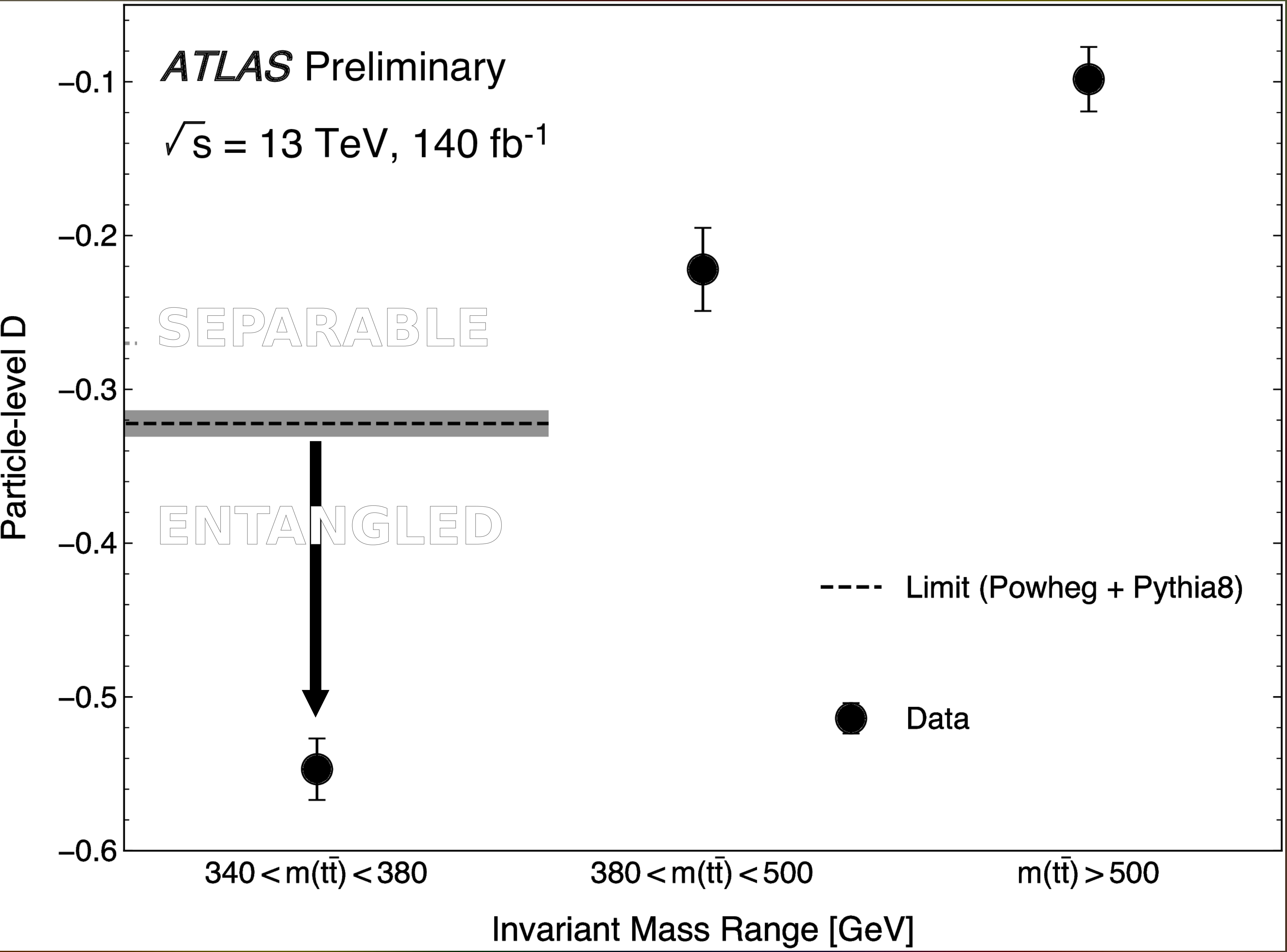
- Three categories:
  - Signal ($t\bar{t}$) modeling.
  - Background modeling.
  - Detector uncertainties.

Systematic source	$\Delta D_{\text{expected}}(D = -0.470)$	ΔD (%)
Signal Modelling	0.015	3.2
Electron	0.002	0.4
Muon	0.001	0.1
Jets	0.004	0.8
b-tagging	0.002	0.4
Pileup	< 0.001	< 0.1
E_T^{miss}	0.002	0.4
Backgrounds	0.009	1.8
Stat.	0.002	0.4
Syst.	0.018	3.9
Total	0.018	3.9

Table: Systematic uncertainties for the **expected** D.

- Signal ($t\bar{t}$) modeling breakdown:
  - Top decay (MADSPIN): 1.6%
  - PDF (PDF4LHC): 1.2%
  - Recoil To Top: 1.1%
  - FSR: 1.1%
  - Scales (μ_R, μ_F): 1.1%
  - NNLO Reweighting: 1.1
  - pThard1 (`pThard = 1`): 0.8%
  - m_t (172.5 ± 0.5 GeV): 0.7%
  - ISR: 0.2%
  - Parton Shower (HERWIG): 0.2%
  - h_{damp}: 0.1%
- Background modeling is dominated by $Z \to \tau^+\tau^-$ uncertainty.
- For each systematic, we extract a curve. The difference w.r.t. the nominal curve is the uncertainty.


ATLAS Preliminary
√s = 13 TeV, 140 fb-1
SEPARABLE
ENTANGLED
Limit (Powheg + Pythia8)
Data
Particle-level D
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6
340 < m(tt̄) < 380
380 < m(tt̄) < 500
m(tt̄) > 500
Invariant Mass Range [GeV]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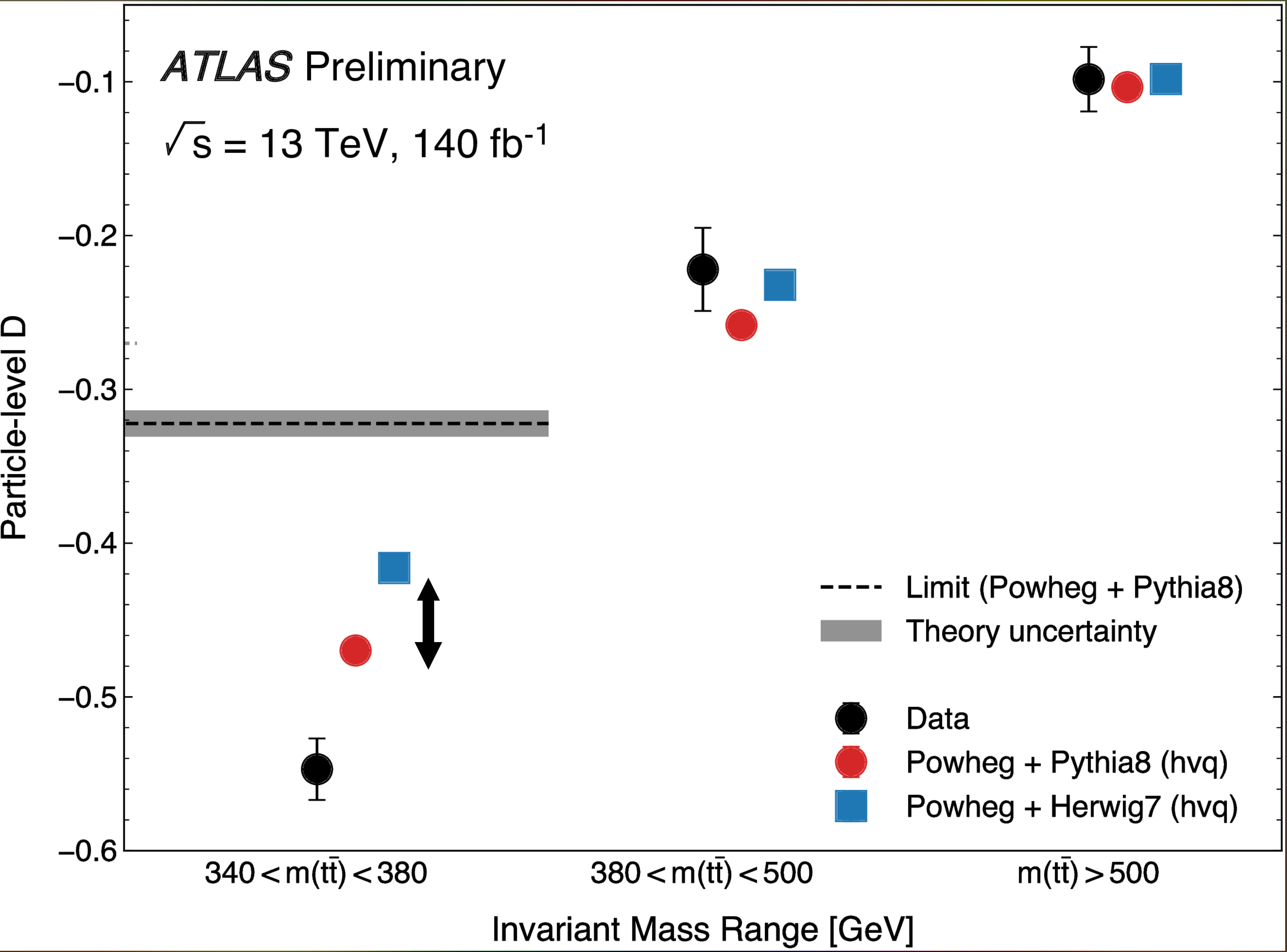

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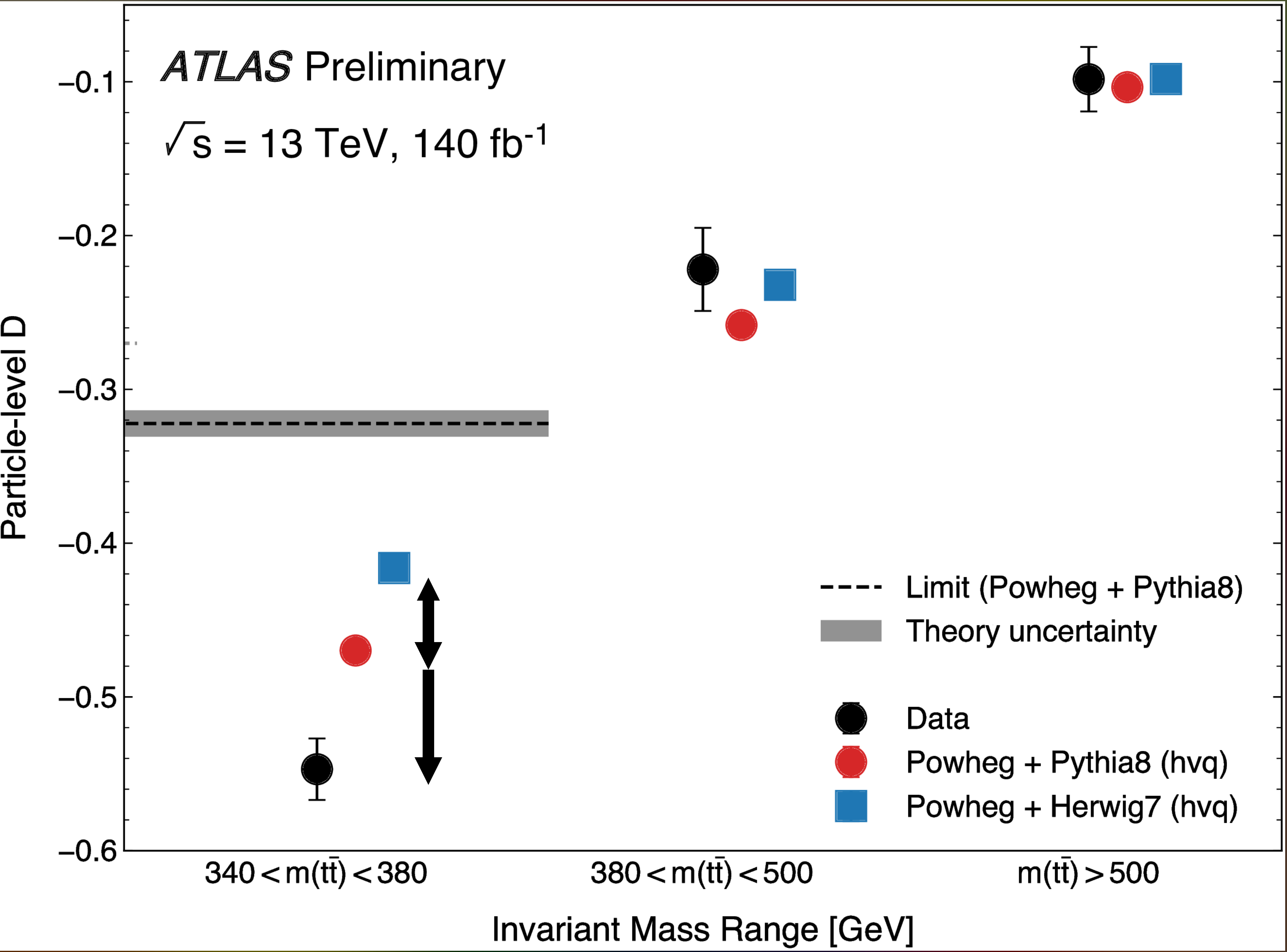
Invariant Mass Range [GeV]
Limit (Powheg + Pythia8)
Theory uncertainty
Data
Powheg + Pythia8 (hvq)
Powheg + Herwig7 (hvq)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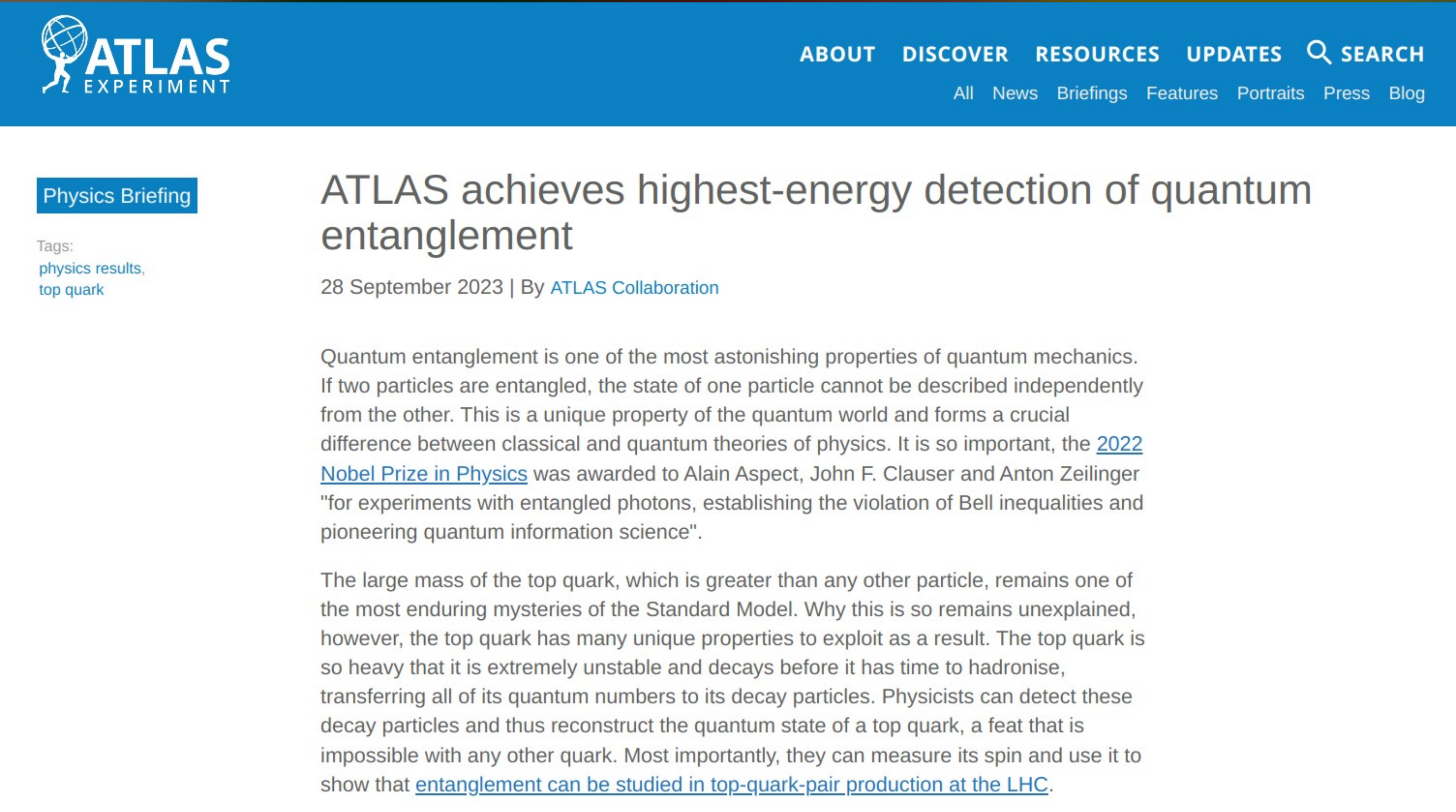
Theory uncertainty
Data
Powheg + Pythia8 (hvq)
Powheg + Herwig7 (hvq)



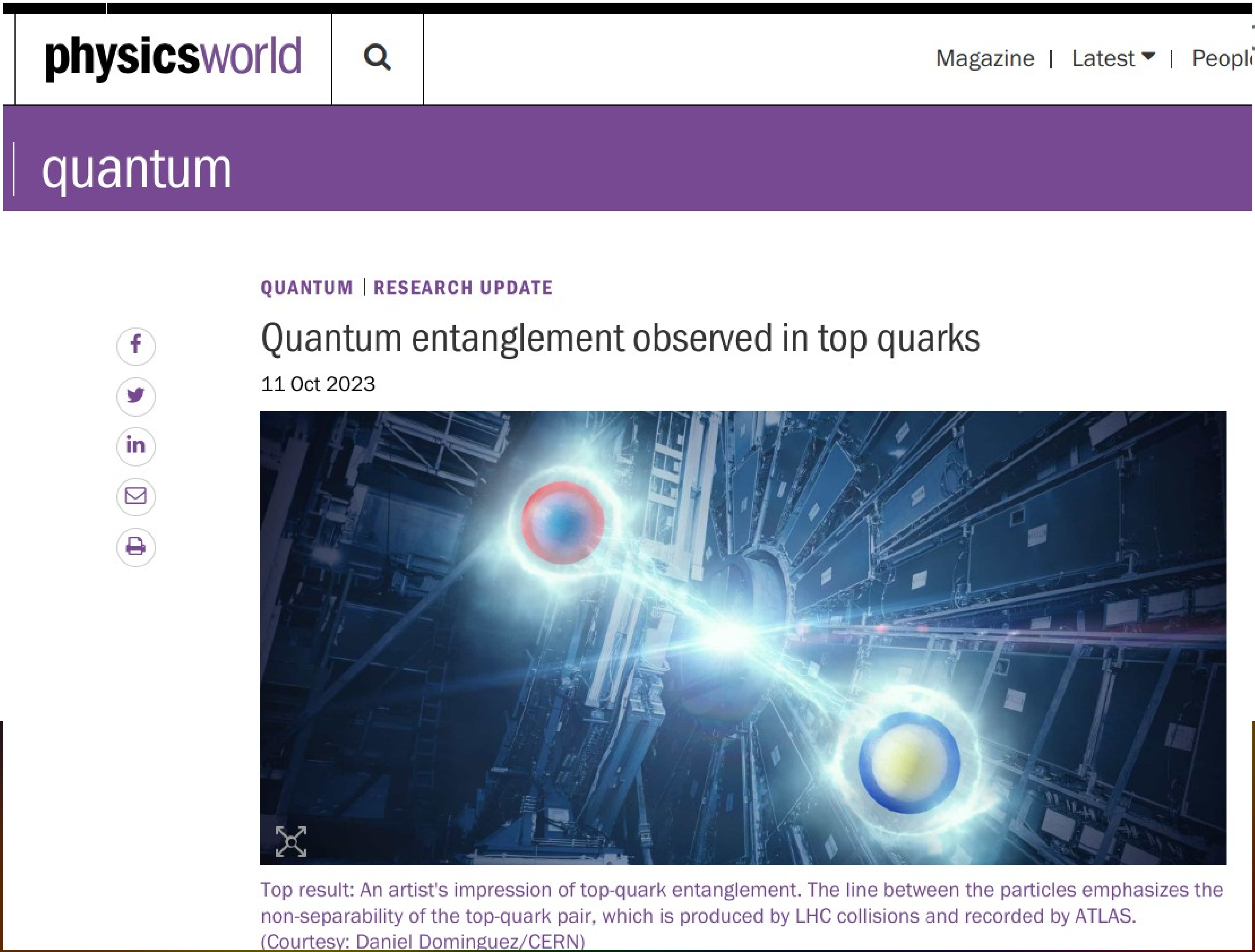
ATLAS achieves highest-energy detection of quantum entanglement

28 September 2023 | By ATLAS Collaboration

Quantum entanglement is one of the most astonishing properties of quantum mechanics. If two particles are entangled, the state of one particle cannot be described independently from the other. This is a unique property of the quantum world and forms a crucial difference between classical and quantum theories of physics. It is so important, the 2022 Nobel Prize in Physics was awarded to Alain Aspect, John F. Clauser and Anton Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science".

The large mass of the top quark, which is greater than any other particle, remains one of the most enduring mysteries of the Standard Model. Why this is so remains unexplained, however, the top quark has many unique properties to exploit as a result. The top quark is so heavy that it is extremely unstable and decays before it has time to hadronise, transferring all of its quantum numbers to its decay particles. Physicists can detect these decay particles and thus reconstruct the quantum state of a top quark, a feat that is impossible with any other quark. Most importantly, they can measure its spin and use it to show that entanglement can be studied in top-quark-pair production at the LHC.

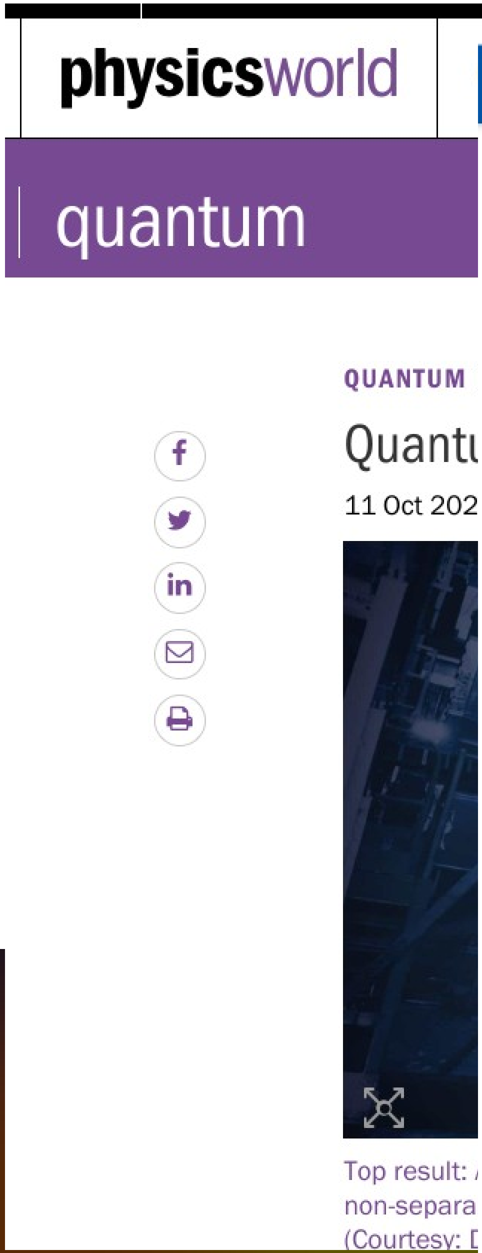
quantum



Quantum entanglement observed in top quarks

11 Oct 2023

Top result: An artist's impression of top-quark entanglement. The line between the particles emphasizes the non-separability of the top-quark pair, which is produced by LHC collisions and recorded by ATLAS. (Courtesy: Daniel Dominguez/CERN)



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Top result: /
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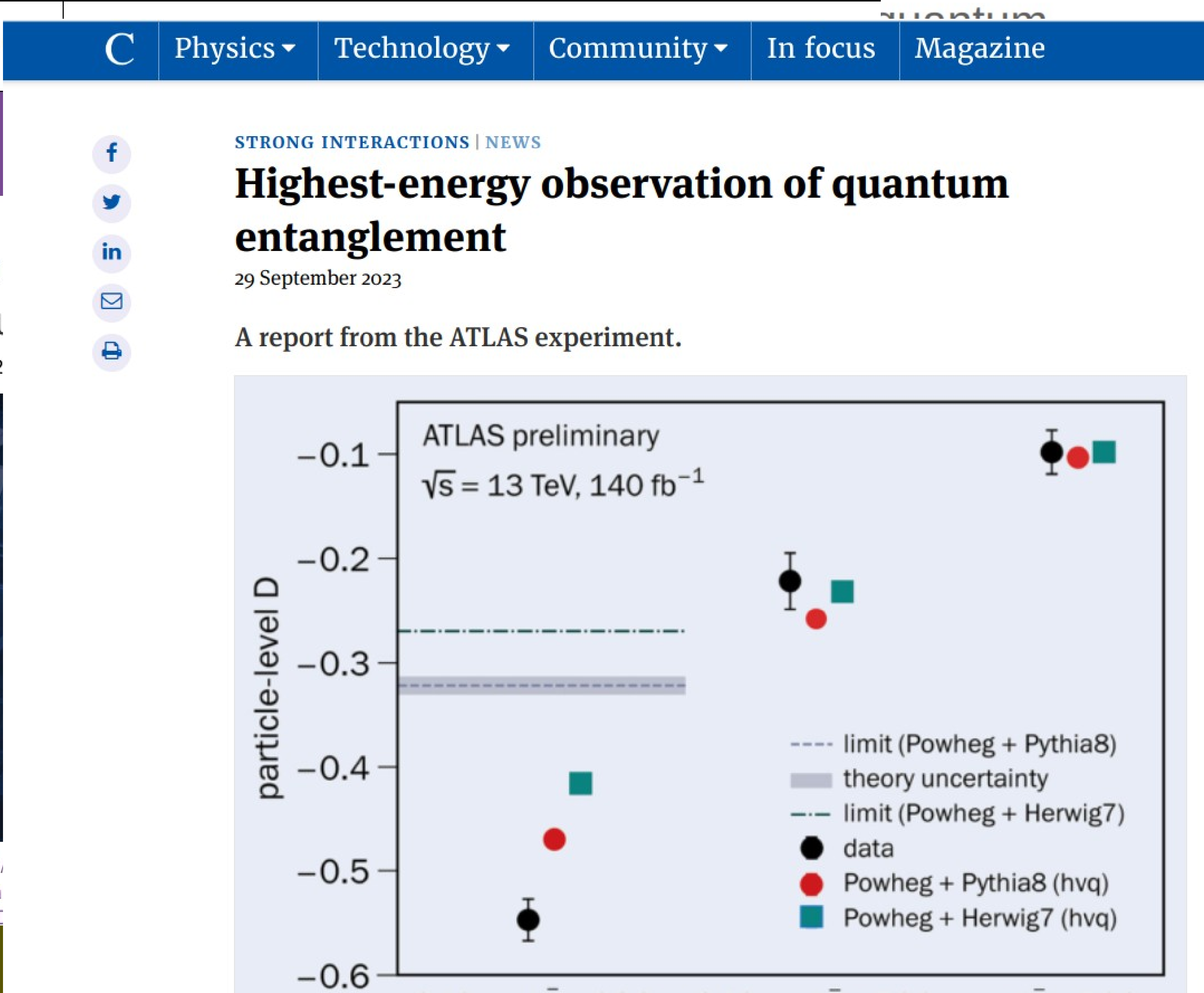
(Courtesy: D

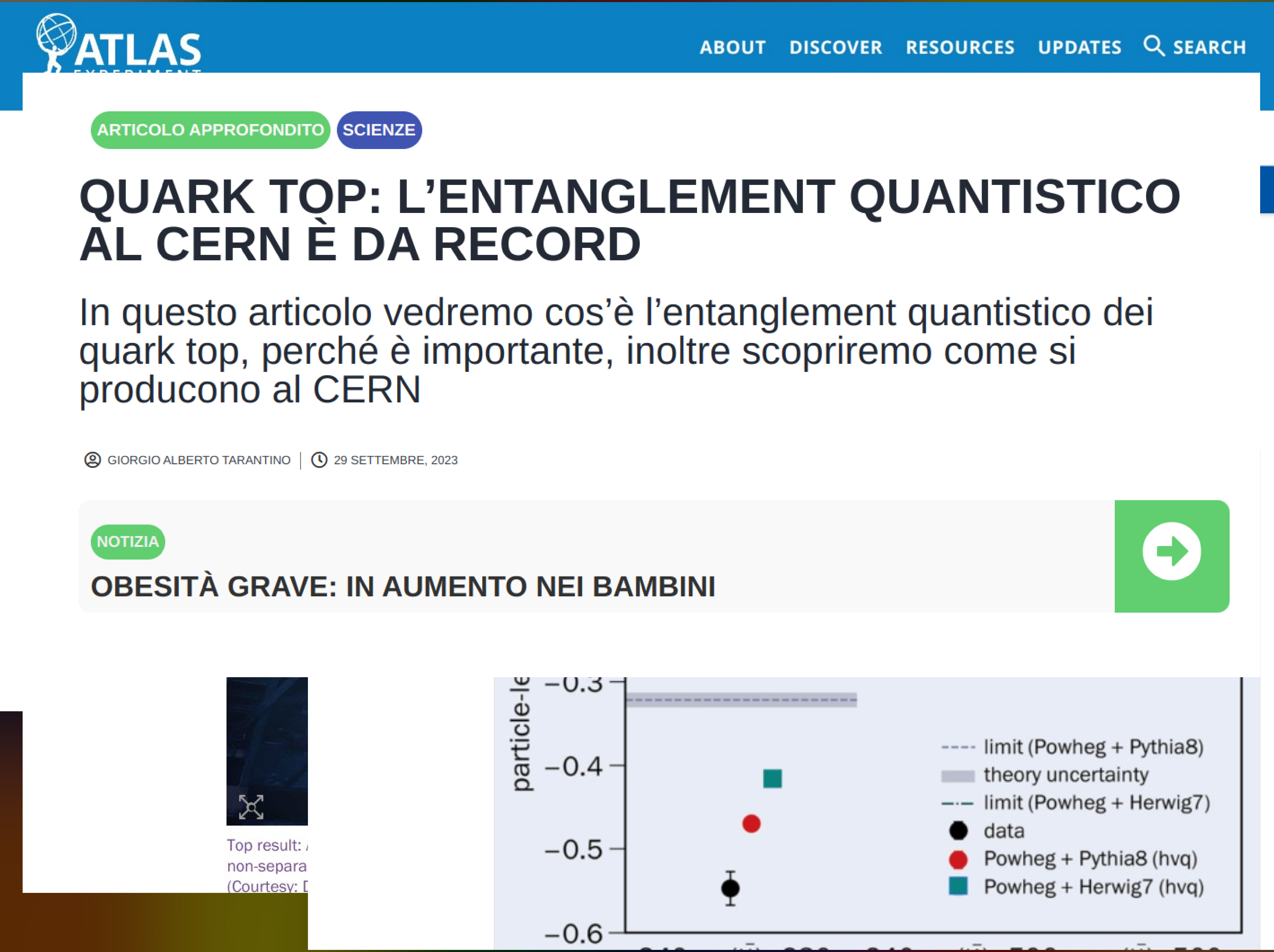


STRONG INTERACTIONS | NEWS

Highest-energy observation of quantum entanglement

29 September 2023

A report from the ATLAS experiment.



ARTICOLO APPROFONDITO SCIENZE

QUARK TOP: L'ENTANGLEMENT QUANTISTICO AL CERN È DA RECORD

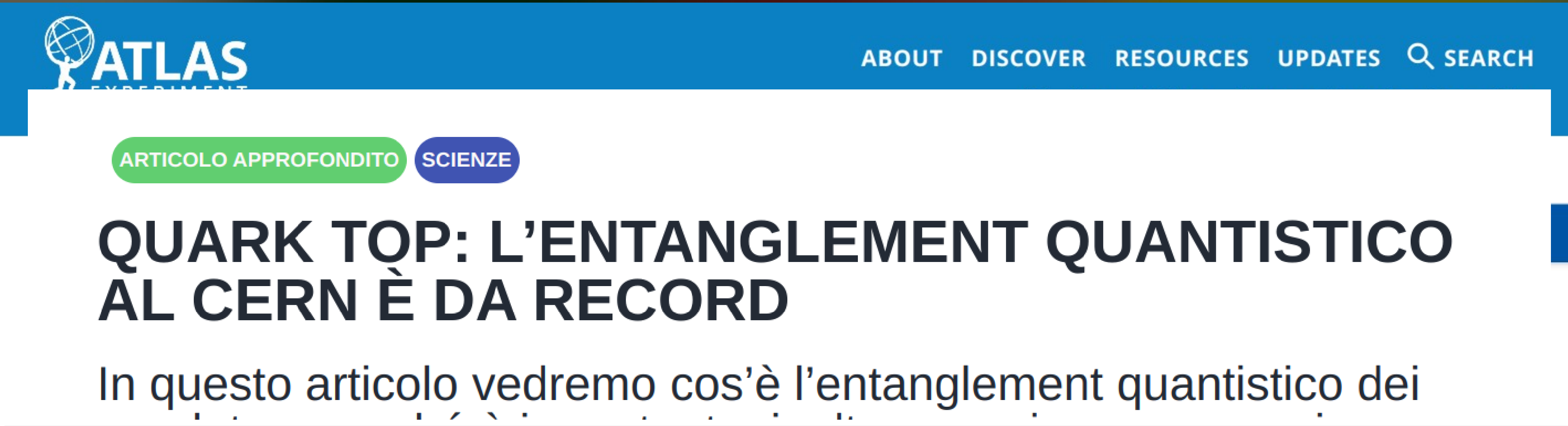
In questo articolo vedremo cos'è l'entanglement quantistico dei quark top, perché è importante, inoltre scopriremo come si producono al CERN

GIORGIO ALBERTO TARANTINO | 29 SETTEMBRE, 2023

NOTIZIA

OBESITÀ GRAVE: IN AUMENTO NEI BAMBINI

Top result:
non-separa
(Courtesy:



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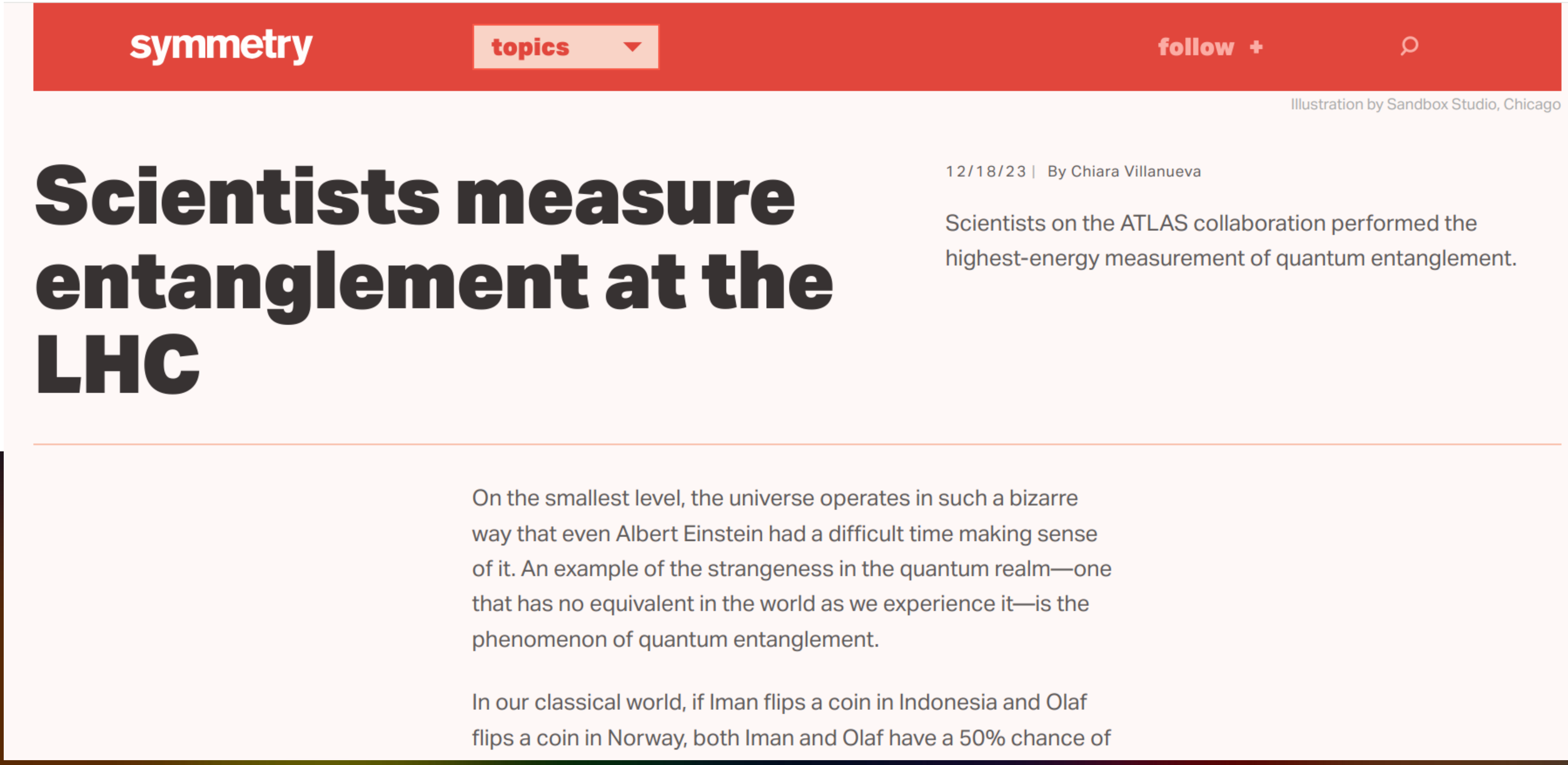

Illustration by Sandbox Studio, Chicago

Scientists measure entanglement at the LHC

12/18/23 | By Chiara Villanueva

Scientists on the ATLAS collaboration performed the highest-energy measurement of quantum entanglement.

On the smallest level, the universe operates in such a bizarre way that even Albert Einstein had a difficult time making sense of it. An example of the strangeness in the quantum realm—one that has no equivalent in the world as we experience it—is the phenomenon of quantum entanglement.

In our classical world, if Iman flips a coin in Indonesia and Olaf flips a coin in Norway, both Iman and Olaf have a 50% chance of

Physics

Large Hadron Collider turned into world's biggest quantum experiment

Physicists have used the famous particle smasher to investigate the strange phenomena of quantum entanglement at far higher energies than ever before

By Alex Wilkins

3 October 2023

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Highest-Energy Detection Of Quantum Entanglement Achieved Yet

The energy scale is a thousand billion times higher than typical laboratory experiments.

DR. ALFREDO CARPINETI

Senior Staff Writer & Space Correspondent

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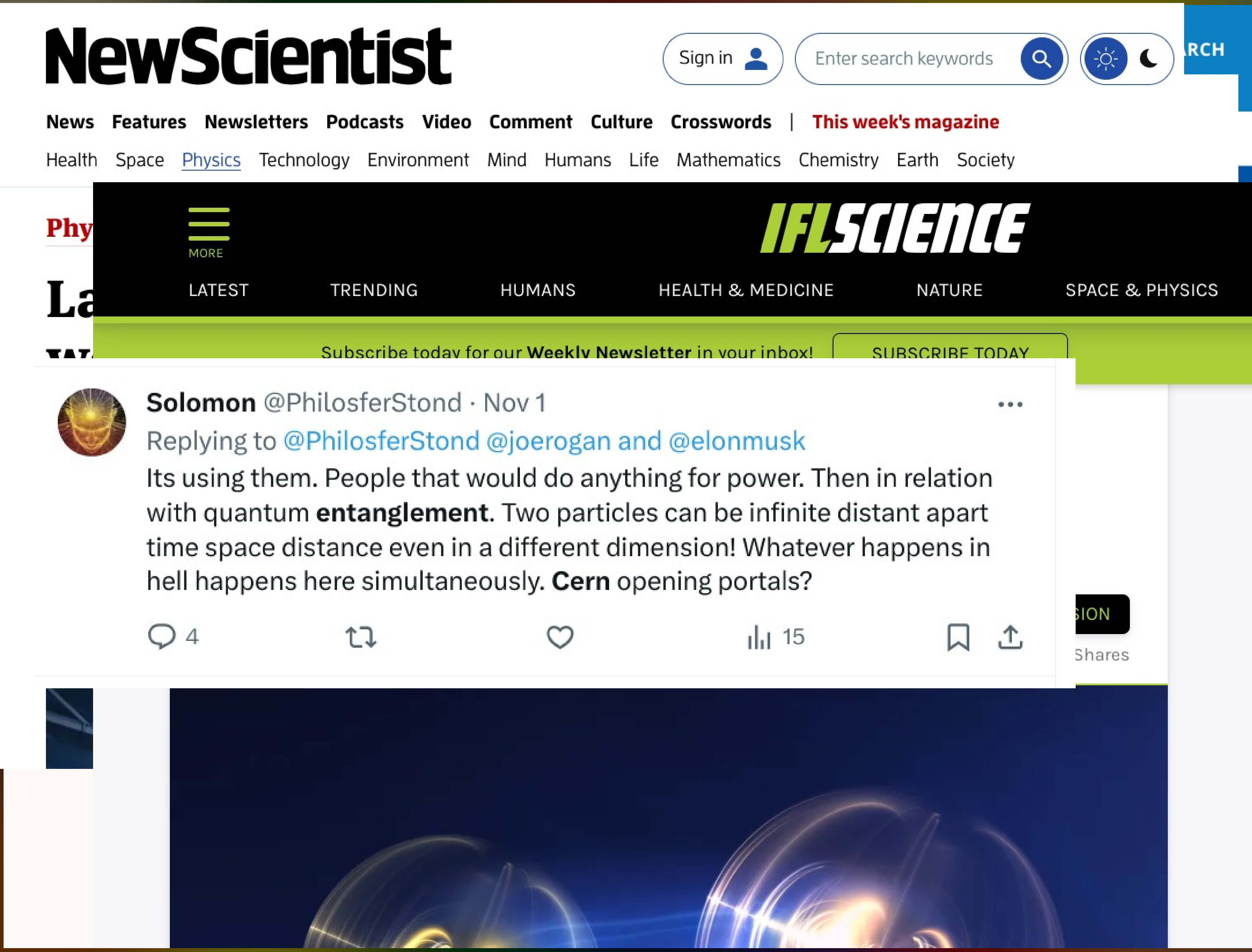

Solomon @PhilosferStond · Nov 1

Replying to @PhilosferStond @joerogan and @elonmusk

Its using them. People that would do anything for power. Then in relation with quantum **entanglement**. Two particles can be infinite distant apart time space distance even in a different dimension! Whatever happens in hell happens here simultaneously. **Cern** opening portals?