# FASTER, SMALLER, CHEAPER

### **DISCOVERING THE UNIVERSE ON A SHOESTRING BUDGET**



### Pagels Public Lecture, Aspen Center for Physics

Jonathan Feng, University of California, Irvine

9 August 2018

### OUTLINE

### 1. Discovering the Universe

### 2. Traditional Experiments: Big Science

3. New Experiments: Faster, Smaller, Cheaper

## PART 1

### 1. Discovering the Universe

### 2. Traditional Experiments: Big Science

### 3. New Experiments: Faster, Smaller, Cheaper

## **DISCOVERING THE UNIVERSE**

If you lived in early times, how would you begin to map out the Universe?



# THE VISIBLE UNIVERSE



## THE INVISIBLE UNIVERSE

### Left is what we expect

### Right is what we see

 Stars on the outskirts rotate faster than expected given the visible matter; something else is pulling them toward the center and preventing them from flying off to infinity

### **DARK MATTER**



- With this and other evidence, it is apparent now that the stars we see are just islands in an ocean of invisible "dark matter."
- In fact, the surprising result is that there is actually 5 times more dark matter than normal matter. And it is not "out there": lots of it is currently passing through your body and this room!

# THE UNIVERSE TODAY



- We now have an overall picture of the Universe
- We know a lot about a little: the normal matter (5%)
- But we know little about a lot: dark matter / dark energy (95%).
  Most of the universe is still to be discovered and understood.

## **AN HISTORICAL PRECEDENT**

If you lived in early times, how would you begin to map out the Earth?



## A MORE GLOBAL VIEW

• Eratosthenes measured the size of the Earth in 200 B.C.



Sun

 His answer was thought to be unbelievably large for a long time, but we now know that it was accurate to about 10%.

# THE AGE OF EXPLORATION

 Eratosthenes' result gave an overall picture of the Earth, but it was hardly a complete understanding; this required an age of exploration.



For the Universe, we are now starting on our own age of exploration.
 9 Aug 2018

### PART 2

### 1. Discovering the Universe

2. Traditional Experiments: Big Science

3. New Experiments: Faster, Smaller, Cheaper

### **TRADITIONAL EXPERIMENTS: BIG SCIENCE**

- So there is a lot of the Universe left to discover. How do we go about it?
- In the case of the Earth we needed to prepare ships that could take us into the unknown.
- For the Universe, we need to prepare experiments that can find the unknown. But if it is unknown, how do we prepare experiments to find it?
- The answer can be traced back to two giants of physics and has led to what we now call "big science."

## ALBERT EINSTEIN



 In 1905, Einstein discovered E = mc<sup>2</sup>: mass can be converted to energy and vice versa.



- Energy is the "universal translator": we can take known particles (protons p) and collide them to form energy, which then turns back into new particles (X).
- We can therefore discover new particles, even if we don't know much about them beforehand.

## **ERNEST O. LAWRENCE**





- In the 1930's Lawrence made a cyclotron, which accelerated particles to higher velocities and energies.
- The first cyclotron was small, but soon, bigger accelerators led to higher energies, which allowed heavier particles to be produced and discovered.
- This has led to "big science" and the discovery of many new particles.

# THE KNOWN PARTICLES



- We now know that normal matter is made of 3 kinds of particles: u and d quarks, which bind together to form protons and neutrons, and electrons.
- Many more particles have been discovered at particle colliders (and elsewhere). The latest was the Higgs particle in 2012.
- But none of these can be dark matter. There must be more particles and the search goes on at bigger and bigger machines.

## THE LARGE HADRON COLLIDER

### The biggest realization of Lawrence's vision today: the LHC in Geneva



## THE ATLAS DETECTOR

One of several giant detectors that observe particle collisions at the LHC



### HOW BIG IS BIG SCIENCE?

- Size: Big.
- Timescale: The LHC was conceived in the 1980's. It was constructed from 1998-2008, and has been running since 2008, with periodic shutdowns to upgrade and fix equipment.
- Budget: The cost of constructing the LHC and the various experiments was roughly \$10 billion. The annual operations budget of CERN, the host laboratory, is about \$1 billion/year, or roughly 1 coffee per year per EU citizen.
- People: The number of physicists working on each experiment is *large*.

### **A RECENT CMS AUTHOR LIST**

### 17 Δ The CMS Collaboration Yerevan Physics Institute, Yerevan, Armenia A.M. Sirunyan, A. Tumasyan Institut für Hochenergiephysik, Wien, Austria W. Adam, F. Ambrogi, E. Asilar, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth<sup>1</sup>, V.M. Ghete, J. Hrubec, M. Jeitler<sup>1</sup>, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck<sup>1</sup>, R. Schöfbeck, M. Spanring, D. Spitzbart, A. Taurok, W. Waltenberger, J. Wittmann, C.-E. Wulz<sup>1</sup>, M. Zarucki Institute for Nuclear Problems, Minsk, Belarus V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez Universiteit Antwerpen, Antwerpen, Belgium EA. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, M. Pieters, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel Vrije Universiteit Brussel, Brussel, Belgium S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs Université Libre de Bruxelles, Bruxelles, Belgium D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, A.K. Kalsi, T. Lenzi, J. Luetic, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, Q. Wang Ghent University, Ghent, Belgium T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov<sup>2</sup>, D. Poyraz, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis Université Catholique de Louvain, Louvain-la-Neuve, Belgium H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, P. David, C. Delaeze, M. Delcourt, A. Giammanco, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrzkowski, A. Saggio, M. Vidal Marono, S. Wertz, J. Zobec Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

EL Alves, G.A. Alves, M. Correa Martins Junior, G. Correia Silva, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

### Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

E Belchior Batista Das Chagas, W Carvalho, J. Chinellato<sup>3</sup>, E. Coelho, E.M. Da Costa, G.G. Da Silveira<sup>4</sup>, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote<sup>3</sup>, E. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista ", Universidade Federal do ABC <sup>b</sup>, São Paulo, Brazil S. Ahuja", C.A. Bernardes", L. Calligaris", T.R. Fernandez Perez Tomei", E.M. Gregores<sup>b</sup>, P.G. Mercadante<sup>b</sup>, S.E. Novaes<sup>a</sup>, SandraS. Padula<sup>a</sup>

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia,

### 18

### Bulgaria

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China W. Fang<sup>5</sup>, X. Gao<sup>5</sup>, L. Yuan

### Institute of High Energy Physics, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo, S.M. Shaheen<sup>6</sup>, A. Spiezia, J. Yao, Z. Wang, E. Yazgan, H. Zhang, S. Zhang<sup>6</sup>, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Z. Xu

Tsinghua University, Beijing, China Y. Wang

Universidad de Los Andes, Bogota, Colombia C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. Gorzález Hernández, M.A. Segura Delgado

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia B. Courbon, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Science, Split, Croatia Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov<sup>7</sup>, T. Susa

University of Cyprus, Nicosia, Cyprus M.W. Ather, A. Attikis, M. Kolosova, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

Charles University, Prague, Czech Republic M. Finger<sup>8</sup>, M. Finger Jr.<sup>8</sup>

Escuela Politecnica Nacional, Quito, Ecuador E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt H. Abdalla<sup>9</sup>, A.A. Abdelalim<sup>10,11</sup>, E. Salama<sup>12,13</sup>

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken Department of Physics, University of Helsinki, Helsinki, Finland P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

### Helsinki Institute of Physics, Helsinki, Finland

J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.O. Sahin, M. Titov

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France

A. Abdulsalam<sup>14</sup>, C. Amendola, I. Antropov, F. Beaudette, P. Busson, C. Charlot, R. Granier de Cassagnac, I. Kucher, A. Lobanov, J. Martin Blanco, C. Martin Perez, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, A. Zabi, A. Zghiche

### Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

J.-L. Agram<sup>15</sup>, J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, V. Cherepanov, C. Collard, E. Conte<sup>15</sup>, J.-C. Fontaine<sup>15</sup>, D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

S. Beauceron, C. Bernet, G. Boudoul, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, S. Perries, A. Popov<sup>16</sup>, V. Sordini, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia A. Khvedelidze<sup>8</sup>

Tbilisi State University, Tbilisi, Georgia

Z. Tsamalaidze<sup>8</sup>

### RWTH Aachen University, L Physikalisches Institut, Aachen, Germany

C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer

### RWTH Aachen University, IIL Physikalisches Institut A, Aachen, Germany

A. Albert, D. Duchardt, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, S. Ghosh, A. Güth,

T. Hebbeker, C. Heidemann, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer,

A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, A. Schmidt,

D. Teyssier, S. Thüer

19

### 20

### RWTH Aachen University, III, Physikalisches Institut B, Aachen, Germany

G. Flügge, O. Hlushchenko, T. Kæss, A. Künsken, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl

### Deutsches Elektronen-Synchrotron, Hamburg, Germany

M Aldava Martin T Arndt C Asawatangtrakuldee I Babounikau K Beernaert O Behnke U. Behrens, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras<sup>18</sup>, V. Botta, Campbell, P. Connor, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranchis, Diez Pardos, D. Domínguez Damiani, G. Eckerlin, T. Eichhorn, A. Elwood, E. Eren, E Gallo<sup>19</sup>, A. Geiser, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, J. Hauk, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, W. Lohmann<sup>20</sup>, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, V. Myronenko, S.K. Pflitsch, D. Pitzl, A. Raspereza, M. Savitskyi, P. Saxena, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, H. Tholen, O. Turkot, A. Vagnerini, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O Zenaiev

### University of Hamburg, Hamburg, Germany

R. Aggleton, S. Bein, L. Benato, A. Benecke, V. Blobel, T. Dreyer, A. Ebrahimi, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, D. Marconi, J. Multhaup, M. Niedziela, C.E.N. Niemeyer, D. Nowatschin, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, A. Vanhoefer, B. Vormwald, I. Zoi

### Karlsruher Institut fuer Technology

M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, B. Freund, M. Giffels, M.A. Harrendorf, F. Hartmann<sup>17</sup>, S.M. Heindl, U. Husemann, F. Kassel<sup>17</sup>, I. Katkov<sup>16</sup>, S. Kudella, S. Mitra, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C Wöhrmann R Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

G. Anagnostou, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki, I. Topsis-Giotis

National and Kapodistrian University of Athens, Athens, Greece B. Francois, G. Karathanasis, S. Kesisoglou, P. Kontaxakis, A. Panagiotou, I. Papavergou, N Saculidou E Triaferi K Vellidis

National Technical University of Athens, Athens, Greece K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis, D. Tsitsonis

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

M. Bartók<sup>21</sup>, M. Csanad, N. Filipovic, P. Major, M.I. Nagy, G. Pasztor, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath<sup>22</sup>, Á. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi<sup>†</sup>

Institute of Nuclear Research ATOMKI, Debrecen, Hungary N. Beni, S. Czellar, J. Karancsi<sup>23</sup>, A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary P. Raics, Z.L. Trocsanvi, B. Uivari

Indian Institute of Science (IISc), Bangalore, India S. Choudhury, J.R. Komaragiri, P.C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India S. Bahinipati<sup>24</sup>, C. Kar, P. Mal, K. Mandal, A. Nayak<sup>25</sup>, D.K. Sahoo<sup>24</sup>, S.K. Swain

### Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, M. Kaur, S. Kaur, R. Kumar, P. Kumari, M. Lohan, A. Mehta, K. Sandeep, S. Sharma, J.B. Singh, A K Virdi G Walia

### University of Delhi, Delhi, India

A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, Ashok Kumar, S. Malhotra, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

R. Bhardwaj<sup>26</sup>, M. Bharti<sup>26</sup>, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep<sup>26</sup>, D. Bhowmik, S. Dey, S. Dutt<sup>26</sup>, S. Dutta, S. Ghosh, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, S. Roy Chowdhury, G. Saha, S. Sarkar, M. Sharan, B. Singh<sup>26</sup>, S. Thakur<sup>26</sup>

Indian Institute of Technology Madras, Madras, India PK Behera

Bhabha Atomic Research Centre, Mumbai, India R. Chudasama, D. Dutta, V. Iba, V. Kumar, P.K. Netrakanti, I. M. Pant, P. Shukla

Tata Institute of Fundamental Research-A. Mumbai, India T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, B. Sutar, RavindraKumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Karmakar, S. Kumar, M. Maity<sup>27</sup>, G. Majumder, K. Mazumdar, N. Sahoo, T. Sarkar<sup>2</sup>

Indian Institute of Science Education and Research (IISER), Pune, India S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran S. Chenarani<sup>28</sup>, E. Eskandari Tadavani, S.M. Etesami<sup>28</sup>, M. Khakzad, M. Mohammadi Na iafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh<sup>29</sup>, M. Zeinali

University College Dublin, Dublin, Ireland M Belcini M Grupewald

INFN Sezione di Bari <sup>a</sup>, Università di Bari <sup>b</sup>, Politecnico di Bari <sup>c</sup>, Bari, Italy M. Abbrescia<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, L. Cristella<sup>a,b</sup>, N. De Filippis<sup>a,c</sup>, M. De Palma<sup>4,5</sup>, A. Di Florio<sup>4,5</sup>, E. Errico<sup>4,4</sup>, L. Fiore<sup>4</sup>, A. Gelmi<sup>4,5</sup>, G. Isselli<sup>4,4</sup>, M. Ine<sup>4,5</sup>, S. Izzki<sup>4,5</sup>, G. Maggi<sup>4,4</sup>, M. Maggi<sup>4</sup>, G. Miniello<sup>4,5</sup>, S. My<sup>4,5</sup>, S. Nuzzo<sup>4,5</sup>, A. Pompili<sup>4,5</sup>,



22

G. Pugliese<sup>a,c</sup>, R. Radogna<sup>a</sup>, A. Ranieri<sup>a</sup>, G. Selvaggi<sup>a,b</sup>, A. Sharma<sup>a</sup>, L. Silvestris<sup>a</sup>, R. Venditti<sup>a</sup>, P. Verwilligen\*, G. Zito\*

### INFN Sezione di Bologna ", Università di Bologna b, Bologna, Italy

G Abbiendi<sup>\*</sup>, C. Battilans<sup>a,b</sup>, D. Bonacorsi<sup>\*,b</sup> I. Borgonovi<sup>\*,b</sup>, S. Braibant-Giacornelli<sup>\*,b</sup>, R. Campanini<sup>\*,b</sup>, P. Capiluppi<sup>\*,b</sup>, A. Castro<sup>\*,b</sup>, F.R. Cavallo<sup>\*</sup>, S.S. Chhibra<sup>\*,b</sup>, C. Ciocca<sup>\*</sup> G. Codispotin, M. Cuffianin, G.M. Dallavalle, F. Fabbrin, A. Fanfanin, E. Fontanesi, P. Giacomelli", C. Grandi", I. Guiducci", S. Lo Meo", S. Marcellini", G. Masetti", A. Montanari", F.I. Navarria", A. Perrotta", F. Primavera", <sup>4</sup>, <sup>17</sup>, A.M. Rossi", <sup>b</sup>, <sup>1</sup>, Rovelli", <sup>b</sup> C D Similar N Youis

INFN Sezione di Catania <sup>a</sup>, Università di Catania <sup>b</sup>, Catania, Italy S. Albergo<sup>a,b</sup>, A. Di Mattia<sup>a</sup>, R. Poterza<sup>a,b</sup>, A. Tricomi<sup>a,b</sup>, C. Tuve<sup>a</sup>

### INFN Sezione di Firenze<sup>4</sup>, Università di Firenze<sup>b</sup>, Firenze, Italy

G. Barbagli<sup>a</sup>, K. Chatteriee<sup>a,b</sup>, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, E. Focardi<sup>a,b</sup> G. Latino, P. Lenzi<sup>\*,b</sup>, M. Meschini<sup>\*</sup>, S. Paoletti<sup>\*</sup>, L. Russo<sup>\*,30</sup>, G. Sguazzoni<sup>\*</sup>, D. Strom<sup>\*</sup>, L. Viliani<sup>4</sup>

INFN Laboratori Nazionali di Frascati, Frascati, Italy L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

INFN Sezione di Genova ", Università di Genova <sup>b</sup>, Genova, Italy E Ferro<sup>a</sup>, L. Panizzi<sup>a,b</sup>, F. Ravera<sup>a,b</sup>, E. Robutti<sup>a</sup>, S. Tosi<sup>a,b</sup>

### INFN Sezione di Milano-Bicocca<sup>4</sup>, Università di Milano-Bicocca<sup>4</sup>, Milano, Italy

A. Benaglia<sup>a</sup>, A. Beschi<sup>b</sup>, F. Brivio<sup>a,b</sup>, V. Ciriolo<sup>a,b,17</sup>, S. Di Guida<sup>a,d,17</sup>, M.E. Dinardo<sup>a,b</sup> Fiorendi<sup>a,b</sup>, S. Gennai<sup>a</sup>, A. Ghezzi<sup>a,b</sup>, P. Govoni<sup>a,b</sup>, M. Malberti<sup>a,b</sup>, S. Malvezzi<sup>a</sup> A. Massironi", b. Menasce", F. Monti, L. Moroni", M. Paganoni", b. D. Pedrini", S. Ragazzi", b. T. Tabarelli de Fatis<sup>a, b</sup>, D. Zuolo<sup>a, b</sup>

INFN Sezione di Napoli", Università di Napoli'Federico II'<sup>b</sup>, Napoli, Italy, Università della Basilicata <sup>c</sup>, Potenza, Italy, Università G. Marconi <sup>d</sup>, Roma, Italy

S. Buontempo", N. Cavallo", A. De Iorio", A. Di Crescenzo", B. Fabozzi", F. Fienga", G. Galati", A.O.M. Iorio", b, W.A. Khan", L. Lista", S. Meola", d.W. P. Paolucci", D. C. Sciacca", b. E Voevodina<sup>®</sup>

### INFN Sezione di Padova ", Università di Padova <sup>b</sup>, Padova, Italy, Università di Trento <sup>c</sup>, Trento, Italy

R. Azzi<sup>\*</sup>, N. Bacchetta<sup>\*</sup>, D. Bisello<sup>\*,b</sup>, A. Boletti<sup>\*,b</sup>, A. Bragagnolo, R. Carlin<sup>\*,b</sup>, P. Checchia<sup>\*</sup>, M. Dall'Osso<sup>\*,b</sup>, P. De Castro Manzano<sup>\*</sup>, T. Dorigo<sup>\*</sup>, F. Gasparini<sup>\*,b</sup>, U. Gasparini<sup>\*,b</sup> A. Gozzelino", S.Y. Hoh, S. Lacaprara", P. Lujan, M. Margoni", A.T. Meneguzzo", b. F. Montecassiano", J. Pazzini", h. N. Pozzobon", h. Ronchese", h. R. Rossin", h. E. Simonetto", h. A. Tiko, E. Torassa", M. Zanetti", G. Zumerle", b

### INFN Sezione di Pavia ", Università di Pavia <sup>b</sup>, Pavia, Italy

A. Braghieri", A. Magnani", P. Montagna", S.P. Rattin, V. Re", M. Ressegottin, b. C. Riccardi", b. P. Salvini<sup>a</sup>, I. Vai<sup>a,b</sup>, P. Vitulo<sup>a,b</sup>

INFN Sezione di Perugia<sup>\*</sup>, Università di Perugia<sup>b</sup>, Perugia, Italy M. Biasini<sup>a,b</sup>, G.M. Bilei<sup>\*</sup>, C. Cecchi<sup>\*,b</sup>, D. Ciangottini<sup>\*,b</sup>, L. Fanà<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, R. Leonardi<sup>\*,b</sup>, E. Manoni<sup>a</sup>, G. Mantovani<sup>a,b</sup>, V. Mariani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, A. Rossi<sup>a,b</sup>, A. Santocchia<sup>a,b</sup>, D. Spiga\*

### 23

INFN Sezione di Pisa \*, Università di Pisa <sup>b</sup>, Scuola Normale Superiore di Pisa \*, Pisa, Italy K. Androsov\*, P. Azzurri, G. Bagliari, L. Bianchini\*, T. Boccalir, L. Bornelo, R. Castaldi\*, M. Cicocci\* R. BOUl'Ono\*, G. Facifi, F. Ront\*, I. Casnini\*, A. Castaldi\*, M. Grieppo; F. Elgabare\*, E. Manca\*\*, G. Mandorli\*, A. Measine-o\*, F. Palta\*, A. Razte\*, E. Spagnolo\*, R. Tenchini, G. Tonelli\*, A. Vennitt, P.G. Verdini\*

INFN Sezione di Roma<sup>+</sup>, Sapienza Università di Roma<sup>+</sup>, Rome, Italy L. Barone<sup>+,4</sup>, E. Cavallari<sup>+</sup>, M. Cipriani<sup>+,5</sup>, D. Del Re<sup>+,6</sup>, E. Di Marco<sup>+,4</sup>, M. Diemoz<sup>+</sup>, S. Gelli<sup>+,5</sup>, E. Longo<sup>+,4</sup>, B. Mazzochi<sup>+,6</sup>, F. Meridiani<sup>+</sup>, G. Organini<sup>+,6</sup>, F. Pandolfi<sup>+</sup>, R. Paramatti<sup>+,6</sup>, F Prejato<sup>#,b</sup>, S. Rahatlou<sup>#,b</sup>, C. Rovelli<sup>#</sup>, F. Santanastasio<sup>#</sup>

### INFN Sezione di Torino <sup>a</sup>, Università di Torino <sup>b</sup>, Torino, Italy, Università del Pier

Orientale<sup>\*</sup>, Novara, Italy N. Arnapane<sup>+\*</sup>, R. Arcidiacono<sup>6,e</sup>, S. Argiro<sup>6,a</sup>, M. Arneodo<sup>6,e</sup>, N. Bartosik<sup>a</sup>, R. Bellan<sup>e,b</sup>, C. Bino<sup>4</sup>, N. Cartiglia<sup>\*</sup>, E. Cenna<sup>6,b</sup>, S. Cornetti<sup>\*</sup>, M. Costa<sup>\*,b</sup>, R. Covarelli<sup>\*,b</sup>, N. Demaria<sup>\*</sup>, B. Kiani<sup>4,b</sup>, C. Mariotti<sup>4</sup>, S. Maselli<sup>4</sup>, E. Migliore<sup>4,b</sup>, V. Monaco<sup>4,b</sup>, E. Monteil<sup>4,b</sup>, M. Monteno M.M. Obertino<sup>4,b</sup>, L. Pacher<sup>4,b</sup>, N. Pastrone<sup>4</sup>, M. Pelliccioni<sup>4</sup>, G.L. Pinna Angioni<sup>4,1</sup> A. Romero<sup>a,b</sup>, M. Ruspa<sup>a,c</sup>, R. Sacchi<sup>a,b</sup>, K. Shchelina<sup>a,b</sup>, V. Sola<sup>a</sup>, A. Solano<sup>a,b</sup>, D. Soldi<sup>a,b</sup> Staiance

INFN Sezione di Trieste<sup>4</sup>, Università di Trieste<sup>4</sup>, Trieste, Italy S. Belforte<sup>4</sup>, V. Candelise<sup>4,4</sup>, M. Casarsa<sup>4</sup>, F. Cossutti<sup>4</sup>, A. Da Rold<sup>4,4</sup>, G. Della Ricca<sup>4,4</sup> F. Vazzoler", b, A. Zanetti"

### Kyungpook National University Numppoor National Chaversity D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, S. Sekmen, D.C. Son, Y.C. Yang

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

H. Kim, D.H. Moon, G. Oh

Hanyang University, Seoul, Korea I. Goh<sup>31</sup>, T.I. Kim

Korea University, Seoul, Korea S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Sejong University, Seoul, Korea H.S. Kim

eoul National University, Seoul, Korea J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

University of Secul. Secul. Kore D. Jeon, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

Sungkyunkwan University, Suwon, Korea Y. Choi, C. Hwang, J. Lee, I. Yu Vilnius University, Vilnius, Lithuania V. Dudenas, A. Juodagalvis, I. Vaitkus

### National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysi

Ahmed, Z.A. Ibrahim, M.A.B. Md Ali<sup>32</sup>, F. Mohamad Idris<sup>33</sup>, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico F Benitez, A. Castaneda Hernandez, I.A. Murillo Ouijad

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico H. Castilla-Valdez, E. De La Cruz-Burelo, M.C. Duran-Osuna, I. Heredia-De La Cruz<sup>14</sup>, R. Lopez-Pernadez, J. Mejia Guisao, R.I. Rabadara-Trejo, M. Ramirez-Garcia, G. Ramirezanchez, R Reves-Almanza, A. Sanchez-Hernandez

ided Ib cana. Mexico City. Mexic 5 Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

emerita Universidad Autonoma de Puebla, Puebla, Mexic J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico A Morelos Pineda

University of Auckland, Auckland, New Zealand Kenfeback

University of Canterbury, Christchurch, New Zealand S Rhonnette PH Butler

National Centre for Physics, Quaid-1-Azam University, Islamabad, Pakistan A. Ahmad, M. Ahmad, M.I. Asehar, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah. M. Shoaib, M. Wagas

National Centre for Nuclear Research, Swierk, Poland L Białkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, M. Szleper, P. Traczyk P. Zalewski

nstitute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland 5. Bunkowski, A. Byszuk<sup>36</sup>, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portuga M. Araujo, P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, M.V. Nemallapudi, J. Seixas, G. Strong, O. Yoldaiev, D. Vadruccio, I. Varela

### Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Goltwin, I. Gorbunov, A. Kamenev, V. Karjavine A. Lanev, A. Malakhov, V. Matveev<sup>34, 37</sup>, P. Moiserz, V. Palichik, V. Perelygin, S. Shmatov S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia V. Golovisov, Y. Ivanov, V. Kim<sup>38</sup>, E. Kuznetsova<sup>39</sup>, P. Levchenko, V. Murzin, V. Oreshkin, nov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobye

Institute for Nuclear Research, Moscow, Russia Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov A. Pashenkov, D. Tlisov, A. Toropin

25

etical and Experimental Physics, Moscow, Rus . Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, Spiridonov, A. Stepennov, V. Stolin, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia & Chistov<sup>40</sup>, M. Danilov<sup>40</sup>, P. Parygin, D. Philippov, S. Polikarpov<sup>40</sup>, E. Tarkovskii

RN. Lebedev Physical Institute, Moscow, Russia V. Andreev, M. Azarkin, I. Dremin<sup>97</sup>, M. Kirakosyan, S.V. Rusakov, A. Yerkulov

Skoheltsyn Institute of Nuclear Physics, Lomonosov Moscow State University Moscow

Aussia A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin<sup>41</sup>, L. Dudko, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, M. Perfilov, S. Petrushanko, / Savrin

Novosibirsk State University (NSU), Novosibirsk, Russia A. Barnyakov<sup>42</sup>, V. Blinov<sup>42</sup>, T. Dimova<sup>42</sup>, L. Kardapoltsev<sup>42</sup>, Y. Skovpen<sup>42</sup>

State Research Center of Russian Federation, Institute for High Energy Physics of NRC Kurchatov Institute", Protvino, Russia Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, A. Godizov, V. Kachanov, A. Kalinin,

J. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshir J. Yyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia Babaev, S. Baidali, V. Okhotniko

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade

Adzic<sup>43</sup>, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

Madrid, Spain J. Alcaraz Masette, A. Álvane z Fernández, L. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, M. Gerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Ferrandez, Bedoya, J.P. Fernández, Ramos, J. Fitz, M.C. Fouz, O. Goruzkez Lopez, S. Goy Lopez, J.M. Herrandez, M.J. Joss, D. Moran, A. Petrez-Calero Yzquierdo, J. Fuerta Pelayo, I. Redondo, L. Romero, M.S. Soares, A. Triossi

Universidad Autónoma de Madrid, Madrid, Spai C. Albajar, J.E. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

J. Cuevas, C. Erice, J. Fernandez, Menendez, S. Folgueras, I. Gonzalez, Caballero, J.R. González Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz, P. Vischia, M. Vizan Garcia

instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain LJ. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Camporta, Sintanaci, Spanier, J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Camporteros, M. Fernandez, P. Fernández Manteca, A. García Alonso, J. García-Fernero, G. Gomez, A. Lopez Virto,

### University of Ruhuna, Department of Physics, Matara, Sri Lanka Wickramage

ERN, European Organization for Nuclear Research, Geneva, Switzer

D. Abbaneo, H. Alagun, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, E. Brondolin, Y. Camponesi, M. Cepeda, G. Cerminara, F. Chapon, Y. Chen, G. Cucciati, D. d'Enterria, A. Dabrowski, N. Deci, V. Daponte, A. David, De Roeck, N. Deelen, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaen Fallavollita<sup>44</sup>, D. Fasanella, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, M. Mukkers, J. Ngadiuba, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo<sup>17</sup>, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, Reis, G. Rolandi<sup>46</sup>, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, Sharma, P. Silva, P. Sphicas<sup>67</sup>, A. Stakia, J. Steggermann, M. Yosi, D. Treille, A. Tsirou, Veckaln<sup>46</sup>, M. Verzetti, W.D. Zeuner

aul Scherrer Institut, Villigen, Switzerland

Caminada<sup>49</sup>, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski Langenegger, T. Rohe, S.A. Wiederkehr

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland M. Backhaus, L. Bäni, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Dor Donegà . Dorfer, Y.A. Górnez Espinosa, C. Grab, D. Hits, Y. Klijnsma, W. Lustermann, R.A. Maruconi, A. Marionneau, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-ředaldi, J. Pata, F. Pausa, F. Perrin, L. Perrozzi, S. Pigazzini, M. Quittnat, C. Reissel, D. Ruini, D.A. Sarz, Becerra, K. Schönenberger, I. Shchutska, V.R. Yavolaro, K. Yheofilatos, M.I. Vesterbacka Ols R. Walling, D.H. Zhu

UniversitätZürich, Zurich, Switzerland f.K. Aarrestad, C. Amsler<sup>50</sup>, D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, Y. Hreus, B. Kilminster, S. Leontsinis, I. Neutelings, G. Rauco, P. Robman D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

National Central University, Chung-Li, Taiwan Y.H. Chang, K.y. Cheng, T.H. Doan, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Arun Kumar, Y.F. Liu, R.-S. Lu, E. Paganis

Psalli Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand B. Asavapibhop, N. Srimanobhas, N. Suwoniandee

Cukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

Qukurova University, Priyases Lepariment, Science and Art Faculty, Adana, Turkey A. Bale, Boorna, S. Cerell<sup>3</sup>, S. Damaroghu, E. Dole, C. Dozen, I. Dumanoghu, S. Gingi, G. Gokkulut, Y. Gulet, E. Gurpinar, I. Hos<sup>30</sup>, C. Iaik, E.R. Kangall<sup>50</sup>, O. Kara, A. Kayis Topaksu, U. Kiminu, M. Oglakci, G. Onengut, K. Ordemir<sup>64</sup>, S. Ozturk<sup>55</sup>, D. Suara Cerel<sup>3</sup>, B. Tali<sup>31</sup>, U.G. Tok, S. Turkapar, I.S. Zorbakir, C. Zorbilinez.

Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, I. Piedra Gom

Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

### Aiddle East Technical University, Physics Department, Ankara, Turke B. Isildak<sup>56</sup>, G. Karapinar<sup>57</sup>, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya<sup>58</sup>, O. Kaya<sup>59</sup>, S. Ozkorucuklu<sup>60</sup>, S. Tekten, E.A. Yetkin<sup>6</sup> stanbul Technical University, Istanbul, Turkey

M.N. Agaras, A. Cakir, K. Cankocak, Y. Komurcu, S. Sen<sup>6</sup>

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine

B. Gryny on

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukrain Levchul

### University of Bristol, Bristol, United King

University of Bristel, Bristel, United Kingdom B Ball, L. Beck, JJ. Brooke, D. Burns, E. Clement, D. Cussans, O. Davigson, H. Flacher, Goldwirt, C.P.Flesht, H.F. Hesht, L.Koreko, D.M. New-bold<sup>61</sup>, S. Paramewaran, B. Penning, K. L. Berns, M. Clane, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, accessio, O.R. Long, M. Oltmedo Negrete, M.L. Paneva, W. Si, L. Wang, H. Wei, accession, O.R. Long, M. Oltmedo Negrete, M.L. Paneva, W. Si, L. Wang, H. Wei, accession, O.R. Long, M. Oltmedo Negrete, M.L. Paneva, W. Si, L. Wang, H. Wei, accession, C.R. Long, M. Oltmedo Negrete, M.L. Paneva, W. Si, L. Wang, H. Wei, accession, C.R. Long, M. Oltmedo Negrete, M.L. Paneva, W. Si, L. Wang, H. Wei, accession, C.R. Long, M. Oltmedo Negrete, M.L. Paneva, W. Si, L. Wang, H. Wei, accession, C.R. Long, M. Oltmedo Negrete, M.L. Paneva, W. Si, L. Wang, H. Wei, accession, C.R. Long, M. Oltmedo Negrete, M.L. Paneva, W. Si, L. Wang, H. Wei, accession, C.R. Long, M. Oltmedo, Negrete, M.L. Paneva, W. Si, L. Wang, H. Wei, accession, C.R. Long, M. Oltmedo, Negrete, M.L. Paneva, W. Si, M. Wei, accession, C.R. Long, M. Oltmedo, Negrete, M.L. Paneva, W. Si, L. Wang, H. Wei, accession, C.R. Long, M. Oltmedo, Negrete, M.L. Paneva, W. Si, L. Wang, H. Wei, accession, C.R. Long, M. Oltmedo, Negrete, M.L. Paneva, W. Si, L. Wang, H. Wei, accession, C.R. Long, M. Oltmedo, Negrete, M.L. Paneva, W. Si, L. Wang, H. Wei, accession, C.R. Long, M. Oltmedo, Negrete, M.L. Paneva, W. Si, L. Wang, H. Wei, accession, C.R. Long, M. Chine, M. Chine, M. Chine, M. Sing, M. S

### Rutherford Appleton Laboratory, Didcot, United Kings D. Barducci, K.W. Bell, A. Belyaev<sup>64</sup>, C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill,

A. Coughlan, K. Harder, S. Harper, I. Linacre, S. Moretti, E. Olaiva, D. Petvt, C.H. Shepherd- ? Chang, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, ous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womensler perial College, London, United Kingdom

R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, D. Colling, P. Daunory, J. Yagil, G. Zevi Della Porta G. Davies, M. Della Negra, R. Di Maria, Y. Haddad, G. Hall, G. Hes, Y. James, M. Komm, alifornia, Santa Barbara- Department of Physics, Santa Barbara, USA C. Laree, L. Lyore, A. Magara, S. Maili, A. Martieli, J. Masié, A. Nikirika/Y. P. Pallation, and et al. Readmile-Fold C. Camosarout M. Chron, A. Dichawe, V. D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, Ia, L. Gouskos, R. Heller, J. Incandela, A. Ovcharova, H. Qu, J. Richman, Singh, M. Stoye, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee<sup>10</sup>, N. Wardle, nz, S. Wang, J. Yoc bottom, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingd J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, A. Morton, I.D. Reid, L. Teodor a Zahid

Baylor University, Waco, USA K. Call, J. Dittmann, K. Hatakeyama, H. Liu, C. Madrid, B. Mcmaster, N. Pastika, C. Smith Catholic University of America, Washington DC, USA R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, USA

A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West Boston University, Boston, USA

D. Arcaro, T. Bose, D. Gastler, D. Pinna, D. Rankin, C. Richardson, I. Rohlf, L. Sulak, D. Zou

rown University, Providence, USA 3 Benelli, X. Coubez, D. Cutts, M. Hadley, I. Hakala, U. Heintz, I.M. Hogan<sup>66</sup>, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Sagir<sup>67</sup>, R. Syarif, E. Usai, D. Yu University of California, Davis, Davis, USA

R. Band, C. Brainerd, R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok,

anway, P.Y. Cox, R. Erbacher, C. Flores, G. Funk, W. Ko, O. Kukral, R. Lander, Pellett, J. Pilot, S. Shalhout, M. Shi, D. Stolp, D. Taylor, K. Tos, M. Tripathi

alifornia, Los Angeles, USA ravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, altzberg, C. Schnaible, V. Valuev

27

alifornia, San Diego, La Jolla, USA

Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciove Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovechio, D. Olivito, S. Padhi, ni, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech<sup>68</sup>, I. Wood, Yagil, G. Zevi Della Porta

andari, J. Bradmiller-Feld, C. Campagnari, M. Citron, A. Dishaw, V. Dutta,

tute of Technology, Pasadena, USA A. Bornheim, J.M. Lawhorn, H.B. Newman, Y.Q. Nguyen, M. Spiropulu, <sup>11,</sup> Wilkinson, S. Xie, Z. Zhang, R.Y. Zhu

n University, Pittsburgh, USA f. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

olorado Boulder, Boulder, USA 1. Ford, F. Jensen, A. Johnson, M. Krohn, E. MacDonald, T. Mulholland, R. Patel,

mson, K.A. Ulmer, S.R. Wagner ity. Ithaca, USA

aves, Y. Cheng, J. Chu, A. Datta, K. Mcdermott, N. Mirman, J.R. Patt inkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, antek

### Acœlerator Laboratory, Batavia, USA

Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, A. Beretvas, J. Berryhill, P.C. Bhat, K. Burkett, I.N. Butler, A. Canepa, V.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Fr tschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris,

Hinschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, C. Pena, O. Prokofyev, G. Rakness, L. Ristori, A. Savoy-Navarro<sup>69</sup>, B. Schneider, E Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Ykaczyk, N.V. Yran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

29 very P Bortignon, D Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes

urry, R.D. Field, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, K.H. Lo, hev. H. Mei, G. Mitselmakher, D. Rosenzweig, K. Shi, D. Sperka, J. Wang,

tional University, Miami, USA aiversity Tallahassee, USA

orida, Gainesville, USA

Askew V. Hagopian, K.E. Johnson, T. Kolbe Perry, H. Prosper, A. Saha, C. Schiber, R. Yohay

e of Technology, Melbourne, USA 1. V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, M. Rahmani

linois at Chicago (UIC), Chicago, USA Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, C. Mills, srezalez, M.B. Tonjes, H. Trauger, N. Varelas, H. Wang, X. Wang, Z. Wu, J. Zhang

of Iowa, Iowa City, USA Hilki<sup>20</sup>, W. Clarida, K. Dilsiz<sup>21</sup>, S. Durgut, R.P. Gandrajula, M. Haytmyradov, Freet, A. Hortiangtham, D.M. [-P. Merlo, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul<sup>22</sup>, Y. Onel, Wang, A. Wisscarver, D. Wood Bilki<sup>20</sup>, W. Clarida, K. Dilsiz<sup>21</sup>, S. Durgut, R.P. Gandrajula, M. Haytm zo, C. Snyder, E. Tiras, I. Wetze University, Baltimore, USA

A Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, W.T. Hung, I. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

of Kansas, Lawrence, USA P. Baringer, A. Bean, S. Boren, J. Bowen, A. Bylinkin, J. Castle, S. Khalil, D. Main i, Q. Wang

versity Ma nov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, , L.K. Saini, N. Skhirtladze

more National Laboratory, Livermore, USA

laryland, College Park, USA ron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, Kunkle, A.C. Mignerey, S. Nabili, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar,

Wright

K. Sur

Masachanestis Institute of Schnology, Cambridge USA D. Aberronbek, B. Aller, V. Aronini, A. Shiy, G. Buez, R. S. Strandt, W. Buez, I.A. Cait, Karnes, S. Das, I. Congr., M. Jones, A.W. Jang, A. Khatiwada, B. Mahakud, M. D'Alfonan, Z. Demiragli, G. Gomez Ceballos, M. Gorcharov, P. Harris, D. Hau, M. Hu, J. Laurensite, C.C. Peng, S. Piperov, H. Qin, J.B. Schulte, J. Sun, F. Wang, R. Xan, T.A. Laurensite Fatte Scaleg, Gis-uar-Verte, France . Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, Meginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, G.S.F. Stephans,

orok, K. Yatar, D. Velicanu, J. Wang, Y.W. Wang, B. Wyslouch, S. Zhaozhong

### ata, Minneapolis, USA

R.M. Chatteriee, A. Evans, P. Hansen, J. Hiltbrand, Sh. Jain, S. Kalafut ko, J. Mans, N. Ruckstuhl, R. Rusack, M.A. Wadud ississippi, Oxford, USA

sbraska-Lincoln, Lincoln, USA Koom, D.R. Class, C. Fangmeier, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, Monroy, J.E. Siado, G.R. Snow, B. Stieger

of New York at Buffalo, Buffalo, USA Harrington, I. Jashvili, A. Kharchilava, C. Mclean, D. Nguyen, A. Parker,

iversity, Boston, USA D.M. Morse, T. Orimoto, R. Teixeira De Lima,

iversity Evanaton USA

O. Charaf, K.A. Hahn, N. Mucia, N. Odell, M.H. Schmitt, K. Sung, M. Trovato,

stre Dame, Notre Dame, USA M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, i, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko<sup>36</sup>, M. Planer, mder, W. Mcbrayer, M. Murray, C. Rogan, S. Sanders, E. Schmitz, Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf,

> University, Columbus, USA atonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, BL Winer

rsity, Princeton, USA P. Elmer, J. Hardenbrook, S. Higginbotham, A. Kalogeropoulos, D. Lange,

Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeldland, C. Tully

n, N. Parashar

e for Theoretical and Experimental Physics, Moscow, Russia erome tor Nuclear Research, Dubra, Russia Iniversity of Rochester, USA A. Boeke, P. de Barbaro, R. Denins, Y. Luba, J.L. Dukemba, C. Fallon, Y. Ferbel, M. Galarri, il Gior Sócano and Hörology Zewail, Egypt A. Garcia-Bellido, J. Han, O. Hindricha, A. Khukhunaishvill, P. Tan, R. Taus stitute for Nuclear Research, Dubna, Russia

4: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia : Also at Université de Haute Alsace, Mulhouse, France 6: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State Unive Moscow, Russia

sidade Estadual de Campinas, Campinas, Brazil University of Rio Grande do Sul, Porto Alegre, Brazil

7: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland 18: Also at KWTH Aachen University, III, Physikalisches Institut A, Aachen, Gern

te University of New Jersey, Piscataway, USA

nessee, Knoxville, USA

rensity, College Station, USA

rsity, Lubbock, USA

ersity, Nashville, USA

Y. Wang, E. Wolfe, F. Xia

versity, Detroit, USA

inia Charlotterville USA

hin N Pourlyal I Shurthy P Thana S Zalaski

sconsin - Madison, Madison, WI, USA

sité Libre de Bruxelles, Bruxelles, Belgium sity of Chinese Academy of Sciences, Beijing, China

na, N. Smith, W.H. Smith, N. Woods

Heideman, G. Riley, S. Spanier

Chou, Y. Gershtein, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan

Chou, L. Gesnieut, E. Handadaka, M. Fiennai, E. Hagnes, J. Kapan, Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, Zer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Diklick, R. Eusebi, uang, T. Kamor<sup>75</sup>, S. Luo, R. Mueller, D. Overton, L. Perniè, D. Rathjens,

Damgov, E. De Guio, P.R. Dudero, S. Kunori, K. Lamichhane, S.W. Lee, thumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

urrola, R. Janjam, W. Johns, C. Maguize, A. Melo, H. Ni, K. Padeken, P. Sheldon, S. Yuo, J. Velkovska, M. Verweij, Q. Xu

chanan, C. Caillol, D. Carlsmith, S. Dasu, L. Dodd, B. Gomber, M. Grothe,

Hervé, U. Hussain, P. Klabbers, A. Lanaro, K. Long, R. Loveless, Y. Ruggles,

nria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu

### About 4000 physicists from 200 institutions in 43 countries

31

erto Rico, Mayaguez, USA

ity Northwest, Hammond, USA

Rice University, Houston, USA Z. Cher, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, W. Li, B.P. Padley, R. Redjimi,



## **ICECUBE IN ANTARCTICA**

There are many other extraordinary examples of big science.





IceCube looks for neutrinos, which can be produced, for example, when dark matter particles collide with each other in our galaxy.

### **DARK MATTER DETECTORS**



These experiments are looking for evidence that a dark matter particle collides with a normal nucleus, causing it to recoil. They are currently sensitive to 1 collision per ton per year.

## TRADITIONAL EXPERIMENTS: STATUS

- Each of these experiments is a testament to human ingenuity and what can happen when large groups of people from many countries and backgrounds work together. They continue to gather data and any one could announce a groundbreaking discovery at almost any time – very exciting!
- But so far, none has discovered evidence for new particles. In the absence of discovery, what other approaches are possible?
- "If you plan to make a voyage of discovery, choose a ship of small draught." Captain James Cook, when rejecting the giant ships offered to him for his Pacific voyages.
- A few small groups of physicists are now taking Captain Cook's advice to heart.

### PART 3

### 1. Discovering the Universe

### 2. Traditional Experiments: Big Science

3. New Experiments: Faster, Smaller, Cheaper

### THE LAMPPOST LANDSCAPE



## LIGHT PARTICLES IN NUCLEAR EXPERIMENTS

- If new particles are light, we don't need giant colliders to produce them. We can look for them by re-doing 1960's era physics experiments in a more precise way.
- For example, we can make lots of excited Beryllium-8 nuclei and see if they produce new particles when they decay.



# THE ATOMKI <sup>8</sup>BE EXPERIMENT



# THE ATOMKI ANOMALY

- In 2016, the ATOMKI group reported evidence that <sup>8</sup>Be nuclei are indeed decaying to new particles X, which then further decay to electron-positron pairs. The new particle is only 1/50 the mass of a proton.
- The probability that it is background: 5.6 x 10<sup>-12</sup> (6.8σ).
- This is either the first sign of a new particle or an experimental error; follow-up experiments are underway.

Observation of Anomalous Internal Pair Creation in  $^8\mathrm{Be}$  A Possible Indication of a Light, Neutral Boson

A. J. Krasznahorkay, M. Csatlós, L. Csige, Z. Gácsi, J. Gulyás, M. Hunyadi, I. Kuti, B. M. Nyakó, L. Stuhl, J. Timár, T. G. Tornyi, Zs. Vajta, T. J. Ketel, and A. Krasznahorkay Phys. Rev. Lett. **116**, 042501 – Published 26 January 2016



### LIGHT PARTICLES IN DARK MATTER DETECTORS

- If the dark matter particle is very light, traditional detectors looking for nuclear recoils are ineffective.
- Better to look for electron recoils.
- Current bounds are very poor for light dark matter, and so even very small electron recoil detectors can discover dark matter.







## THE SENSEI EXPERIMENT

- In 2018 with 0.019 gram-days of data (not ton-years!), the SENSEI experiment achieved world-leading sensitivity to light dark matter.
- Cost: \$1M supported by the Heising-Simons Foundation and Fermilab.
- Time from funding to result: ~ 1 year.

### SENSEI: First Direct-Detection Constraints on sub-GeV Dark Matter from a Surface Run

The SENSEI Collaboration: Michael Crisler,<sup>1,</sup> <sup>[\*]</sup> Rouven Essig,<sup>2,</sup> <sup>[†</sup> Juan Estrada,<sup>1, |‡</sup> Guillermo Fernandez,<sup>1, |§</sup> Javier Tiffenberg,<sup>1, |¶</sup> Miguel Sofo Haro,<sup>1, 3, <sup>[\*\*]</sup></sup> Tomer Volansky,<sup>4, 5, |††</sup> and Tien-Tien Yu<sup>6, 7, |‡‡</sup>



## LIGHT PARTICLE SEARCHES AT THE LHC

- We can also look in new ways for light particles at existing colliders. If they are very light, they may have escaped traditional searches.
- An example: at the LHC, light particles are dominantly produced parallel to the beam, not perpendicular to it. Unfortunately, this is exactly where the detectors have holes in them to let the proton beams in, and so these light particles would escape undetected.



### FASER: ForwArd Search ExpeRiment

- To take advantage of this, a few of us have joined together to propose a new detector for the LHC, called FASER.
- "The acronym recalls another marvelous instrument that harnessed highly collimated particles and was used to explore strange new worlds."

### FASER FORWARD SEARCH EXPERIMENT AT THE LHC

Akitaki Ariga,<sup>1</sup> Tomoko Ariga,<sup>1,2</sup> Jamie Boyd,<sup>3,\*</sup> David W. Casper,<sup>4</sup> Jonathan L. Feng,<sup>4,†</sup> Iftah Galon,<sup>5</sup> Shih-Chieh Hsu,<sup>6</sup> Felix Kling,<sup>4</sup> Hidetoshi Otono,<sup>2</sup> Brian Petersen,<sup>3</sup> Osamu Sato,<sup>7</sup> Aaron M. Soffa,<sup>4</sup> Jeffrey R. Swaney,<sup>4</sup> and Sebastian Trojanowski<sup>8</sup>



## FASER

• To avoid blocking the proton beams, FASER is placed 480 m downstream. At that location, the proton beams curve away, but the light new particles will travel straight into FASER.



• The entire detector is under 5m long and fits in an existing, unused tunnel.





## FASER

- FASER is small, cheap, and fast, but there are many more hurdles to pass.
- Fortunately, the most famous living physicists are already on board.



### SUMMARY

- 95% of the Universe is still completely unexplored we live in a new age of exploration.
- Large experiments are underway and have exciting prospects for discovering new kinds of particles and identifying dark matter.
- There are also now promising experiments that are relatively fast, small, and cheap: ~years, ~10 collaborators, and ~\$1-10M. These were made possible by "big science," just like the internet, MRIs, shrink wrap, etc., but probe different ideas and possibilities.
- Lots of interesting results to come!