FASTER, SMALLER, CHEAPER

FORWARD SEARCH EXPERIMENT AT THE LHC

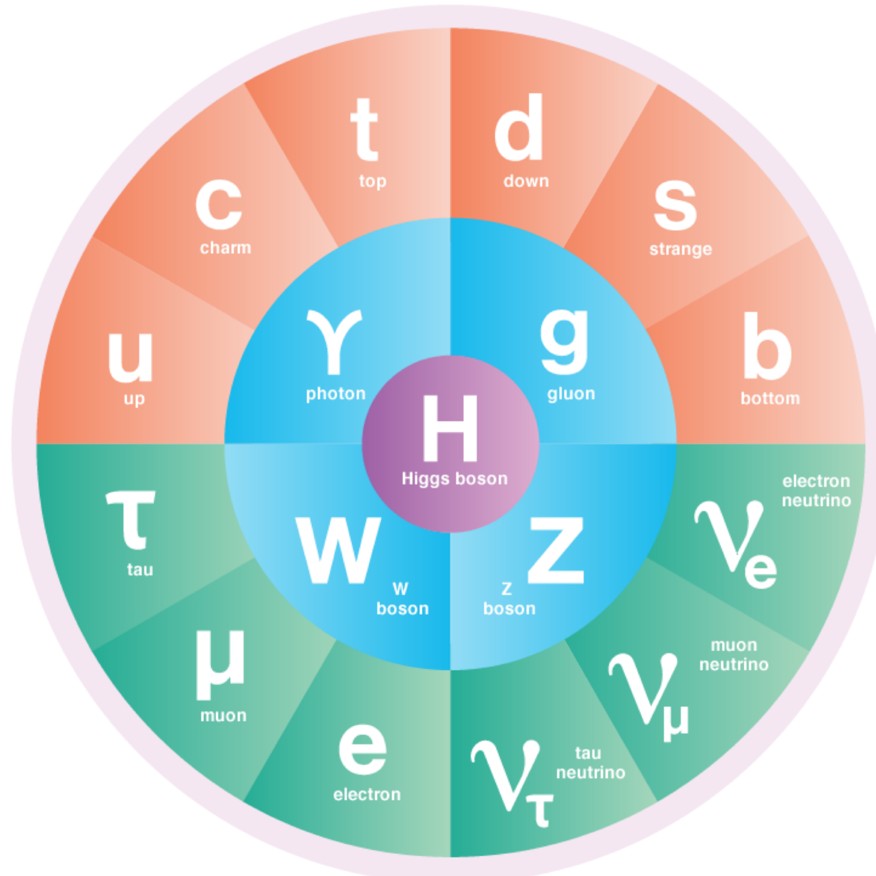
Department Colloquium, New York University

Jonathan Feng, UC Irvine, 5 September 2019

PARTICLE PHYSICS NOW

A BRIEF HISTORY OF PARTICLE PHYSICS

- In the last century, we have been tremendously successful in discovering new particles and deepening our understanding of the laws of nature and the contents of the Universe.



- The workhorse tools leading to much of this progress have been particle accelerators and colliders.

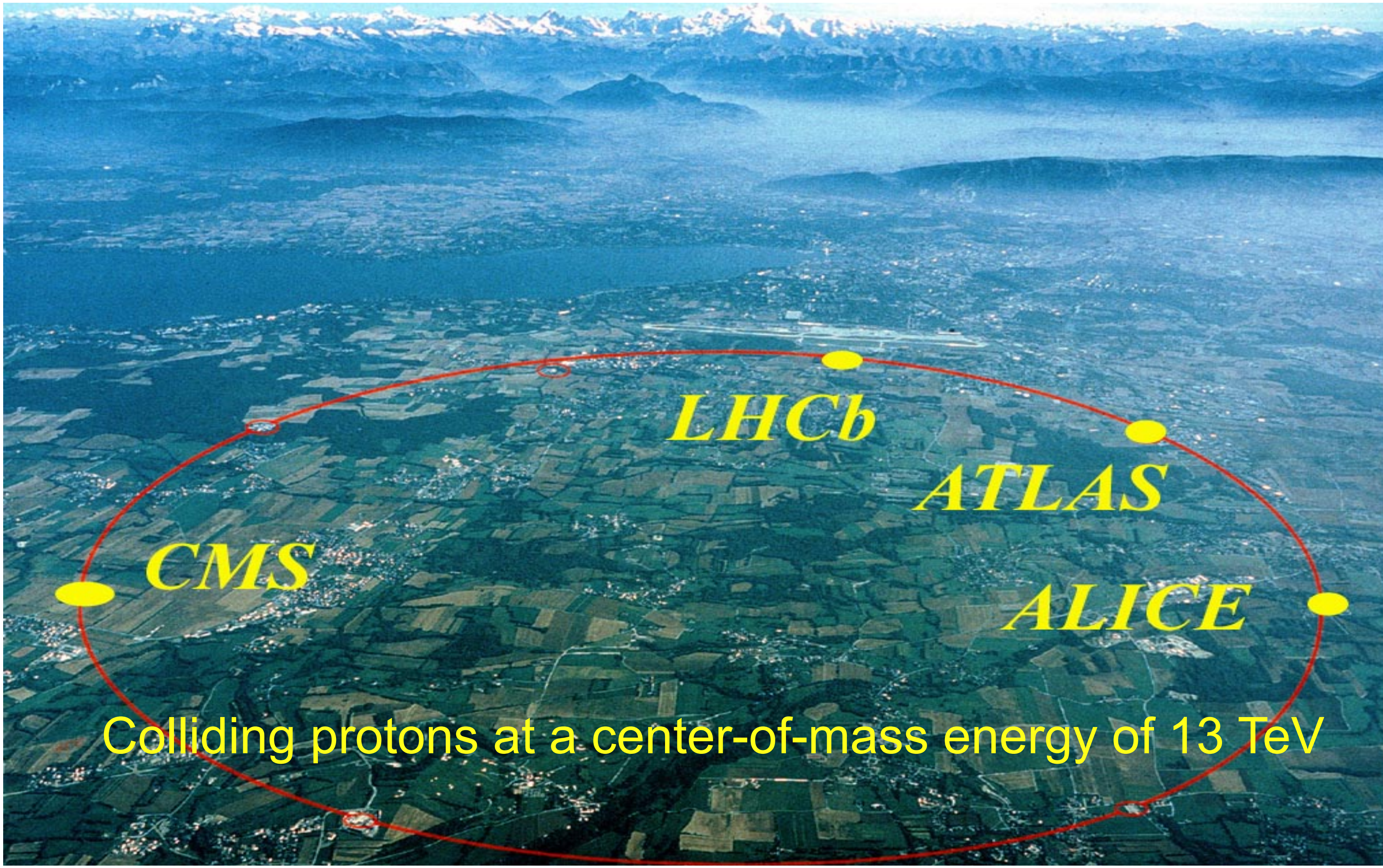
PARTICLE ACCELERATORS AND COLLIDERS

- In the 1930's, E. O. 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.

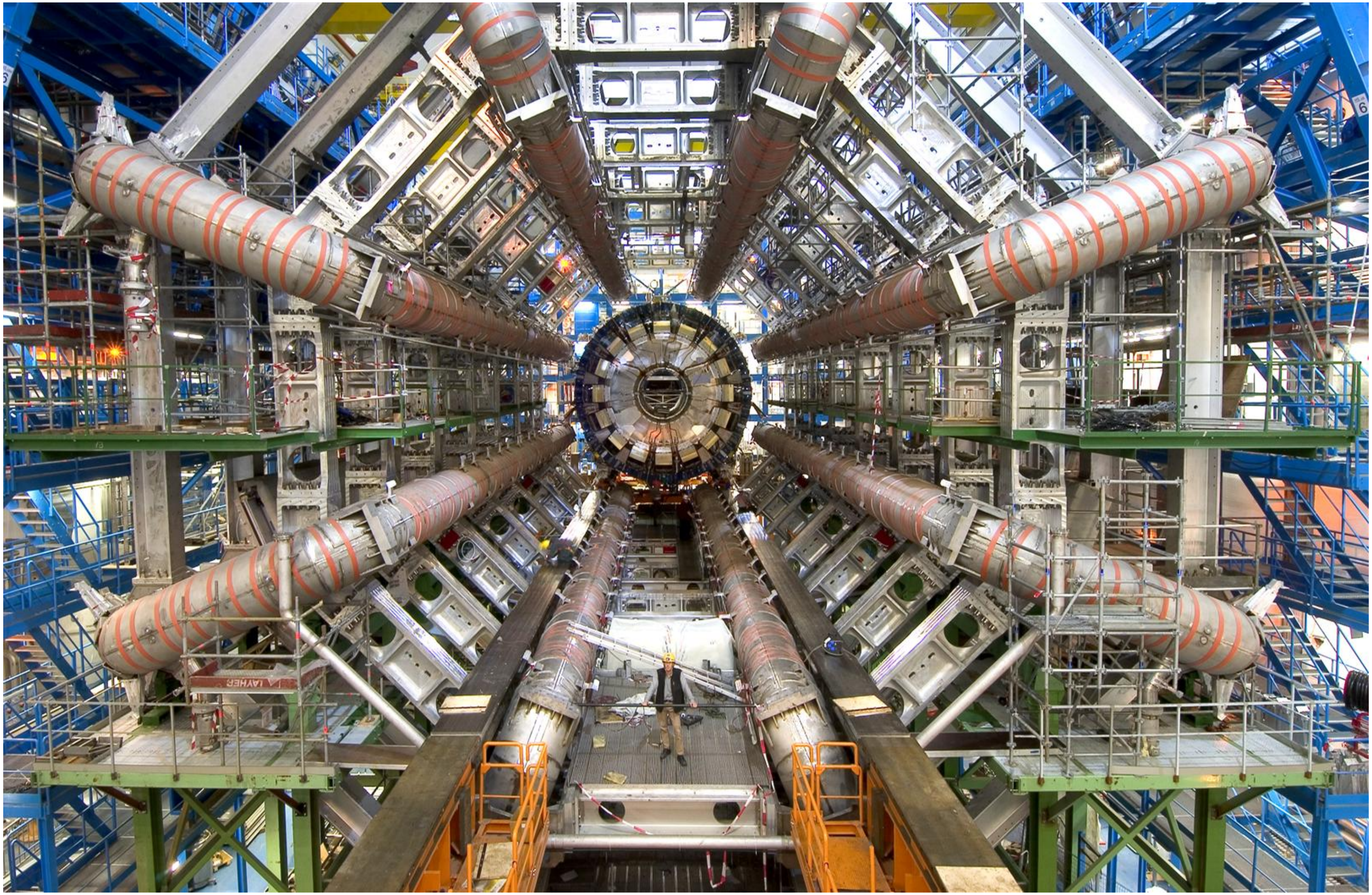
THE LARGE HADRON COLLIDER

The latest realization of Lawrence's vision: 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. Colliders the size of cities, detectors the size of buildings.

- Timescale: Long. 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: Expensive. 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: Many.

A RECENT CMS AUTHOR LIST

D 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[1], V.M. Ghete, J. Hrubec, M. Jeitler[1], N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck[1], R. Schöfbeck, M. Spanring, D. Spitzbart, W. Waltenberger, J. Wittmann, C.-E. Wulz[1], M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus
V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, A. Lelek, M. Pieters, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium
F. Blekman, J. D'Hondt, 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, A. Grebenyuk, A.K. Kalsi, J. Luetic, A. Popov[2], 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[3], C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
O. Bondu, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, G. Krintiras, V. Lemaitre, A. Magitteri, K. Piotrzkowski, A. Saggio, M. Vidal Marono, P. Vischia, J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
F.L. Alves, G.A. Alves, 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[4], E. Coelho, E.M. Da Costa, G.G. Da Silveira[5], D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, 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[4], F. Torres Da Silva De Araujo, A. Vilela Pereira

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

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

A RECENT CMS AUTHOR LIST (CONTINUED)

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

Beihang University, Beijing, China
W. Fang[6], X. Gao[6], 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, S.M. Shaheen[7], A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang[7], 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

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. González Hernández, M.A. Segura Delgado

Universidad de Antioquia, Medellin, Colombia
J.D. Ruiz Alvarez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
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, M. Roguljic, A. Starodumov[8], 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[9], M. Finger Jr.[9]

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[10], M.A. Mahmoud[11,12], A. Mohamed[13]

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, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[14], M. Titov

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France
C. Amendola, F. Beaudette, P. Busson, C. Charlot, B. Diab, R. Granier de Cassagnac, I. Kucher, A. Lobanov, J. Martin Blanco, C. Martin Perez, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, 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[15], J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, V. Cherepanov, C. Collard, E. Conte[15], J.-C. Fontaine[15], 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, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia
A. Khvedelidze[9]

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[9]

RWTH Aachen University, I. 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, III. Physikalisches Institut A, Aachen, Germany
A. Albert, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, S. Ghosh, T. Hebbeker, C. Heidemann, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, A. Novak, T. Pook, A. Pozdnyakov, M. Radziej, H. Reithler, M. Rieger, A. Schmidt, A. Sharma, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
G. Flügge, O. Hlushchenko, T. Kress, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl[16]

A RECENT CMS AUTHOR LIST (CONTINUED)

98

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, I. Babounikau, H. Bakhshiansohi, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras[17], V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, T. Eichhorn, A. Elwood, E. Eren, E. Gallo[18], A. Geiser, J.M. Grados Luyando, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, N.Z. Jomhari, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Leonard, K. Lipka, W. Lohmann[19], 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, A. Saibel, M. Savitskyi, P. Saxena, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, H. Tholen, O. Turkot, A. Vagnerini, M. Van De Klundert, 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, B. Vormwald, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
M. Akbiyik, C. Barth, M. Baselga, S. Baur, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, M. Giffels, M.A. Harrendorf, F. Hartmann[16], U. Husemann, I. Katkov[2], S. Kudella, S. Mitra, M.U. Mozer, Th. Müller, M. Musich, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Weber, 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

National and Kapodistrian University of Athens, Athens, Greece
A. Agapitos, G. Karathanasis, P. Kontaxakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Vellidis

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

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, K. Manitara, 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[20], M. Csanad, N. Filipovic, P. Major, K. Mandal, A. Mehta, M.I. Nagy, G. Pasztor, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath[21], Á. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi[†]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi[20], A. Makovec, J. Molnar, Z. Szillasi

99

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, Z.L. Trocsanyi, B. Ujvari

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[23], C. Kar, P. Mal, A. Nayak[24], S. Roy Chowdhury, D.K. Sahoo[23], 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, P. Kumari, M. Lohan, M. Meena, 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[25], M. Bharti[25], R. Bhattacharya, S. Bhattacharya, U. Bhawandeep[25], D. Bhowmik, S. Dey, S. Dutt[25], S. Dutta, S. Ghosh, M. Maity[26], K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, G. Saha, S. Sarkar, T. Sarkar[26], M. Sharan, B. Singh[25], S. Thakur[25]

Indian Institute of Technology Madras, Madras, India
P.K. Behera, A. Muhammad

Bhabha Atomic Research Centre, Mumbai, India
R. Chudasama, D. Dutta, V. Jha, V. Kumar, D.K. Mishra, P.K. Netrakanti, L.M. Pant, P. Shukla, P. Suggisetti

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, 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, G. Majumder, K. Mazumdar, N. Sahoo

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

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[27], E. Eskandari Tadavani, S.M. Etesami[27], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh[28], M. Zeinali

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], C. Calabria[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], F. Errico[a,b], L. Fiore[a], A. Gelmi[a,b], G. Iaselli[a,c], M. Ince[a,b], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], G. Miniello[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a], R. Venditti[a], P. Verwilligen[a]

100

INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a,b], S. Braibant-Giacomelli[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], S.S. Chhibra[a,b], G. Codispoti[a,b], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], E. Fontanesi, P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], F. Iemmi[a,b], S. Lo Meo[a,29], S. Marcellini[a], G. Masetti[a], A. Montanari[a], F.L. Navarria[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b], N. Tosi[a]

INFN Sezione di Catania [a], Università di Catania [b], Catania, Italy
S. Albergo[a,b,30], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,30], C. Tuve[a,b]

INFN Sezione di Firenze [a], Università di Firenze [b], Firenze, Italy
G. Barbagli[a], K. Chatterjee[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], G. Latino, P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], L. Russo[a,31], G. Sguazzoni[a], D. Strom[a], L. Viliani[a]

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

INFN Sezione di Genova [a], Università di Genova [b], Genova, Italy
F. Ferro[a], R. Mulargia[a,b], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
A. Benaglia[a], A. Beschi[b], F. Brivio[a,b], V. Ciriolo[a,b,16], S. Di Guida[a,b,16], M.E. Dinardo[a,b], S. Fiorendi[a,b], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], M. Malberti[a,b], S. Malvezzi[a], D. Menasce[a], F. Monti, L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b], D. Zuolo[a,b]

INFN Sezione di Napoli [a], Università di Napoli 'Federico II' [b], Napoli, Italy, Università della Basilicata [c], Potenza, Italy, Università G. Marconi [d], Roma, Italy
S. Buontempo[a], N. Cavallo[a,c], A. De Iorio[a,b], A. Di Crescenzo[a,b], F. Fabozzi[a,c], F. Fienga[a], G. Galati[a], A.O.M. Iorio[a,b], L. Lista[a], S. Meola[a,d,16], P. Paolucci[a,16], C. Sciacca[a,b], E. Voevodina[a,b]

INFN Sezione di Padova [a], Università di Padova [b], Padova, Italy, Università di Trento [c], Trento, Italy
P. Azzi[a], N. Bacchetta[a], D. Bisello[a,b], A. Boletti[a,b], A. Bragagnolo, R. Carlin[a,b], P. Checchia[a], M. Dall'Osso[a,b], P. De Castro Manzano[a], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], S.Y. Hoh, S. Lacaprara[a], P. Lujan, M. Margoni[a,b], A.T. Meneguzzo[a,b], J. Pazzini[a,b], M. Presilla[b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], A. Tiko, E. Torassa[a], M. Tosi[a,b], M. Zanetti[a,b], P. Zotto[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
A. Braghieri[a], A. Magnani[a], P. Montagna[a,b], S.P. Ratti[a,b], V. Re[a], M. Ressegotti[a,b], C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy
M. Biasini[a,b], G.M. Bilei[a], C. Cecchi[a,b], D. Ciangottini[a,b], L. Fanò[a,b], P. Lariccia[a,b], R. Leonardi[a,b], E. Manoni[a], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a]

INFN Sezione di Pisa [a], Università di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa, Italy
K. Androsov[a], P. Azzurri[a], G. Bagliesi[a], L. Bianchini[a], T. Boccali[a], L. Borrello, R. Castaldi[a], M.A. Ciocci[a,b], R. Dell'Orso[a], G. Fedi[a], F. Fiori[a,c], L. Giannini[a,c], A. Giassi[a], M.T. Grippo[a], F. Ligabue[a,c], E. Manca[a,c], G. Mandorli[a,c], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], G. Rolandi[32], A. Scribano[a], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], A. Venturi[a], P.G. Verdini[a]

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101

INFN Sezione di Roma [a], Sapienza Università di Roma [b], Rome, Italy
L. Barone[a,b], F. Cavallari[a], M. Cipriani[a,b], D. Del Re[a,b], E. Di Marco[a,b], M. Diemoz[a], S. Gelli[a,b], E. Longo[a,b], B. Marzocchi[a,b], P. Meridiani[a], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], F. Preiato[a,b], C. Quaranta[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b]

INFN Sezione di Torino [a], Università di Torino [b], Torino, Italy, Università del Piemonte Orientale [c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], C. Biino[a], A. Cappati[a,b], N. Cartiglia[a], F. Cenna[a,b], S. Cometti[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], B. Kiani[a,b], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], E. Monteil[a,b], M. Monteno[a], M.M. Obertino[a,b], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G.L. Pinna Angioni[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], R. Salvatico[a,b], K. Shchelina[a,b], V. Sola[a], A. Solano[a,b], D. Soldi[a,b], A. Staiano[a]

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], A. Da Rold[a,b], G. Della Ricca[a,b], F. Vazzoler[a,b], A. Zanetti[a]

Kyungpook National University, Daegu, Korea
D.H. Kim, G.N. Kim, M.S. Kim, J. 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

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B. Francois, J. Goh[33], T.J. Kim

Korea University, Seoul, Korea
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Y. Choi, C. Hwang, J. Lee, I. Yu

Riga Technical University, Riga, Latvia
V. Veckalns[34]

Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
Z.A. Ibrahim, M.A.B. Md Ali[35], F. Mohamad Idris[36], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

102

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

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[37], R. Lopez-Fernandez, J. Mejia Guisao, R.I. Rabadan-Trejo, G. Ramirez-Sanchez, R. Reyes-Almanza, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
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Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
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 Montenegro, Podgorica, Montenegro
N. Raicevic

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
S. Bheesette, P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, M.I. Asghar, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

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

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk[38], 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, Portugal
M. Araujo, P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, J. Seixas, G. Strong, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev[39,40], P. Moisenz, 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. Golovtsov, Y. Ivanov, V. Kim[41], E. Kuznetsova[42], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

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

103

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

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
R. Chistov[43], M. Danilov[43], D. Philippov, E. Tarkovskii

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin[40], M. Kirakosyan, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin[44], L. Dudko, A. Ershov, V. Klyukhin, I. Lokhtin, S. Obraztsov, M. Perfilov, V. Savrin, P. Volkov

Novosibirsk State University (NSU), Novosibirsk, Russia
A. Barnyakov[45], V. Blinov[45], T. Dimova[45], L. Kardapoltsev[45], Y. Skovpen[45]

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia
A. Babaev, S. Baidali, A. Iuzhakov, V. Okhotnikov

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences
P. Adzic[46], P. Cirkovic, D. Devetak, M. Dordevic, P. Milenovic[47], J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, A. Triossi

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. 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, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

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University of Ruhuna, Department of Physics, Matara, Sri Lanka
N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, E. Brondolin, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, G. Cucciati, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, A. De Roeck, N. Deelen, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, F. Fallavollita[48], D. Fasanella, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, M. Gruchala, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, Y. Iiyama, V. Innocente, G.M. Innocenti, A. Jafari, P. Janot, O. Karacheban[19], J. Kieseler, A. Kornmayer, M. Krammer[1], C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo[16], L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas[49], A. Stakia, J. Steggemann, D. Treille, A. Tsirou, A. Vartak, M. Verzetti, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
L. Caminada[50], K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
M. Backhaus, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T.A. Gómez Espinosa, C. Grab, D. Hits, T. Klijnsma, W. Lustermann, R.A. Manzoni, M. Marionneau, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, M. Reichmann, C. Reissel, T. Reitenspiess, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland
T.K. Aarrestad, C. Amsler[51], D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, S. Leontsinis, V.M. Mikuni, I. Neutelings, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, S. Wertz, A. Zucchetta

National Central University, Chung-Li, Taiwan
T.H. Doan, C.M. Kuo, W. Lin, S.S. Yu

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

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

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
A. Bat, F. Boran, S. Cerci[52], S. Damarseckin[53], Z.S. Demiroglu, F. Dolek, C. Dozen, I. Dumanoglu, G. Gokbulut, EmineGurpinar Guler[54], Y. Guler, I. Hos[55], C. Isik, E.E. Kangal[56], O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir[57], S. Ozturk[58], D. Sunar Cerci[52], B. Tali[52], U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
B. Isildak[59], G. Karapinar[60], M. Yalvac, M. Zeyrek

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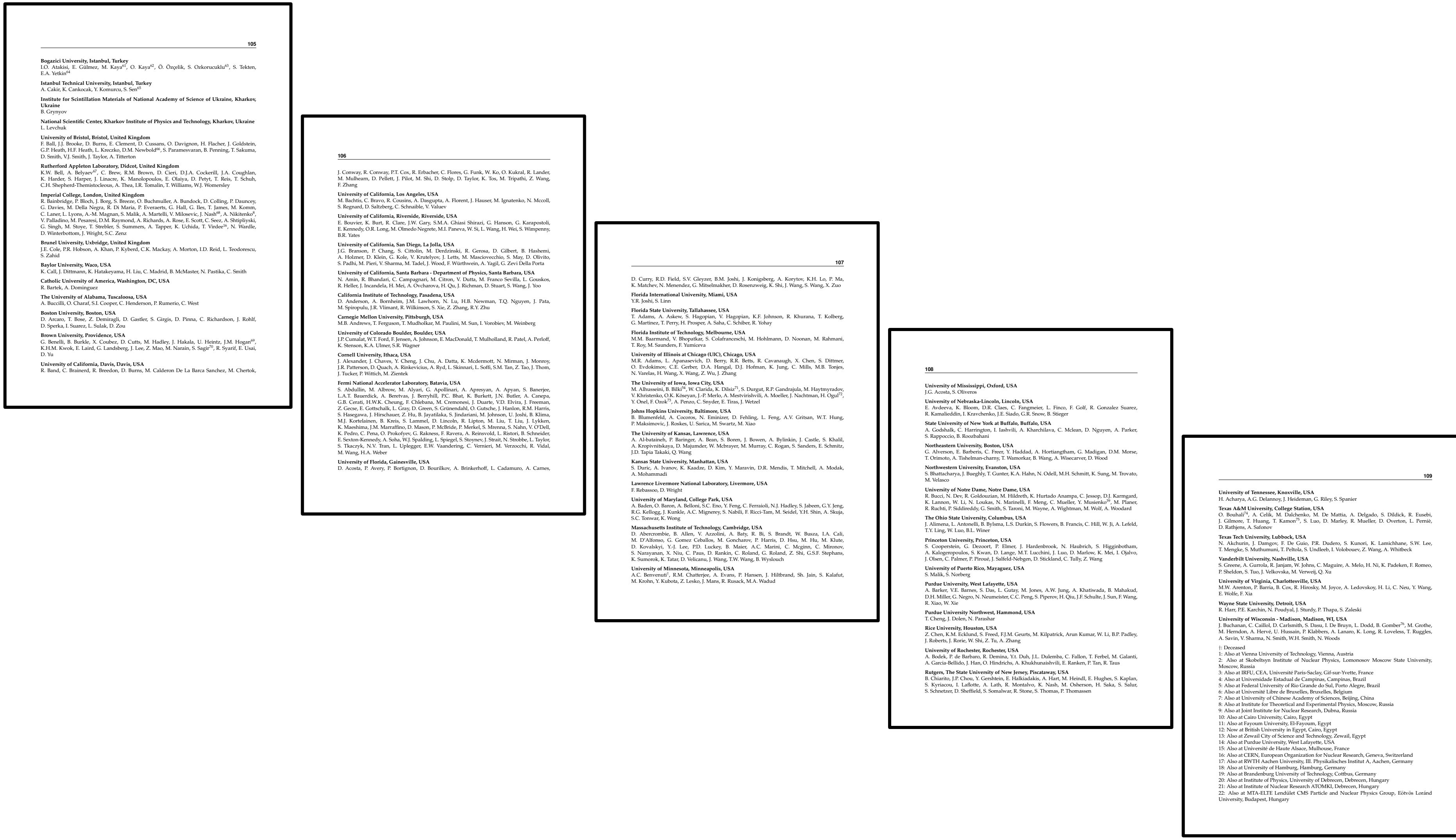
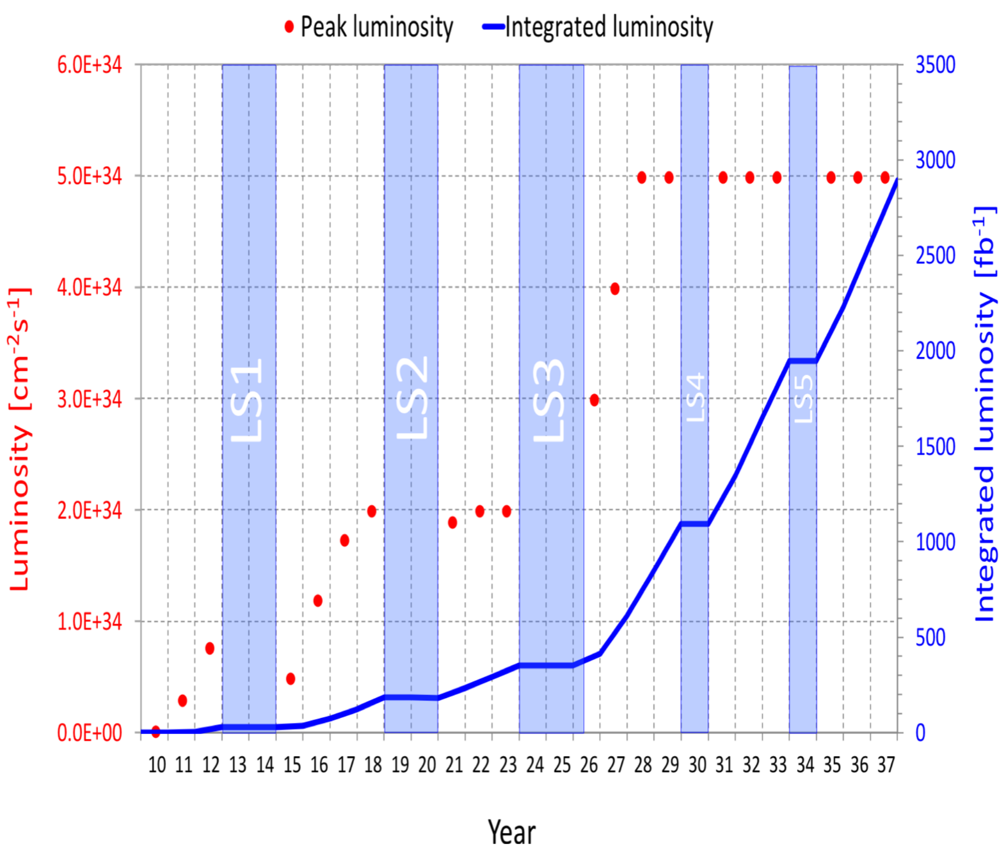


4000 collaborators from 230 institutions in 51 countries

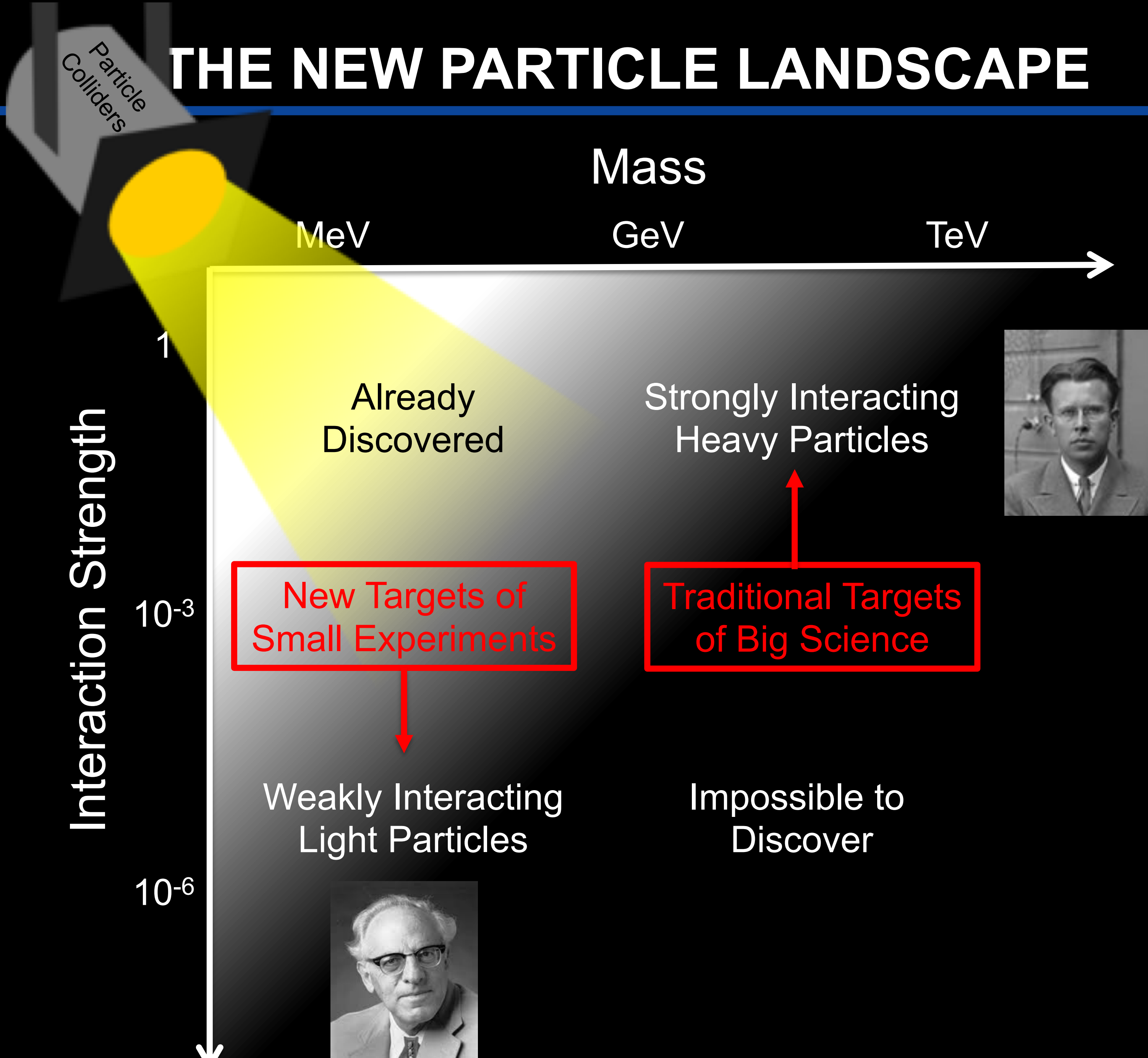
LHC: CURRENT STATUS

- The discovery of the Higgs boson in 2012 completed the standard model of particle physics, an amazing achievement.
- So far there has been no other evidence for new particles.
- The LHC is currently in Long Shutdown 2, but will start up again in 2021 and run till ~2037. Will we find new particles through conventional searches?
- What other approaches can enhance the prospects for discovering new particles?

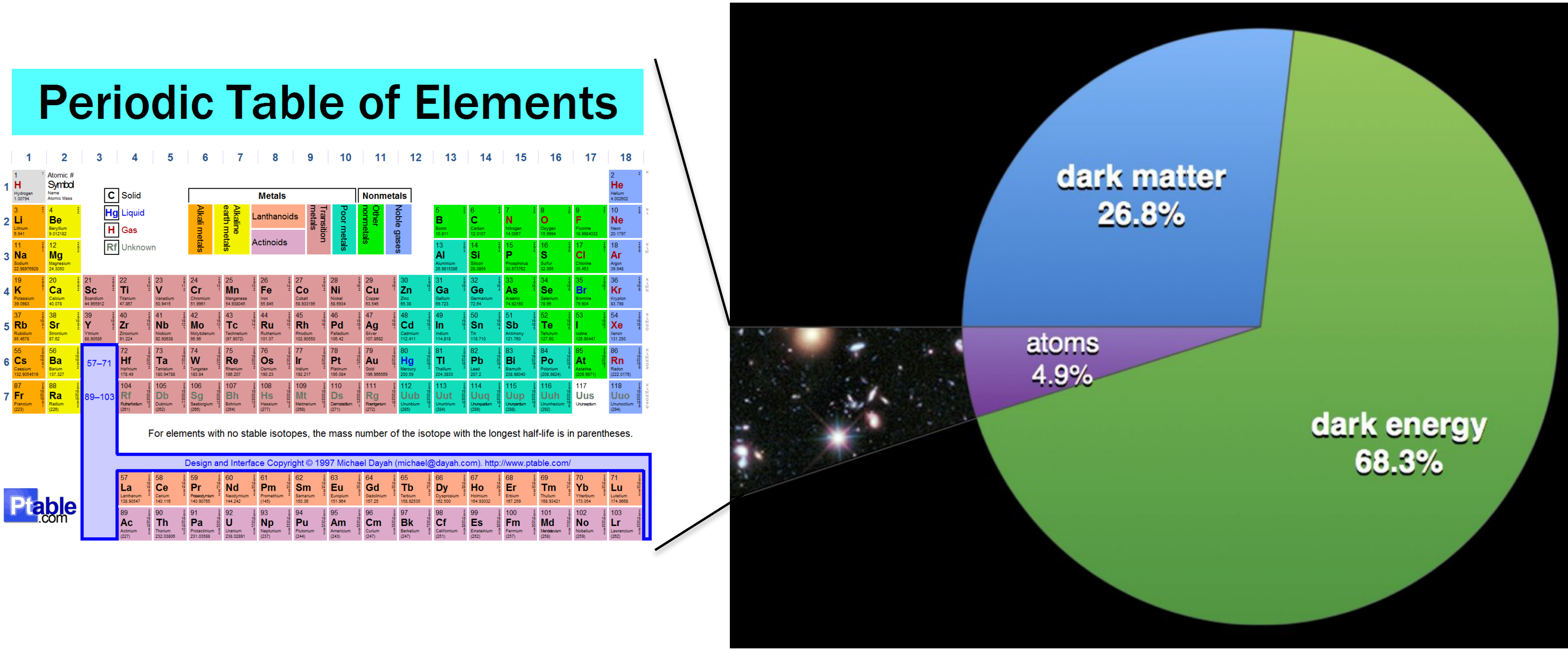


THE LIFETIME FRONTIER

THE NEW PARTICLE LANDSCAPE



THE UNIVERSE TODAY



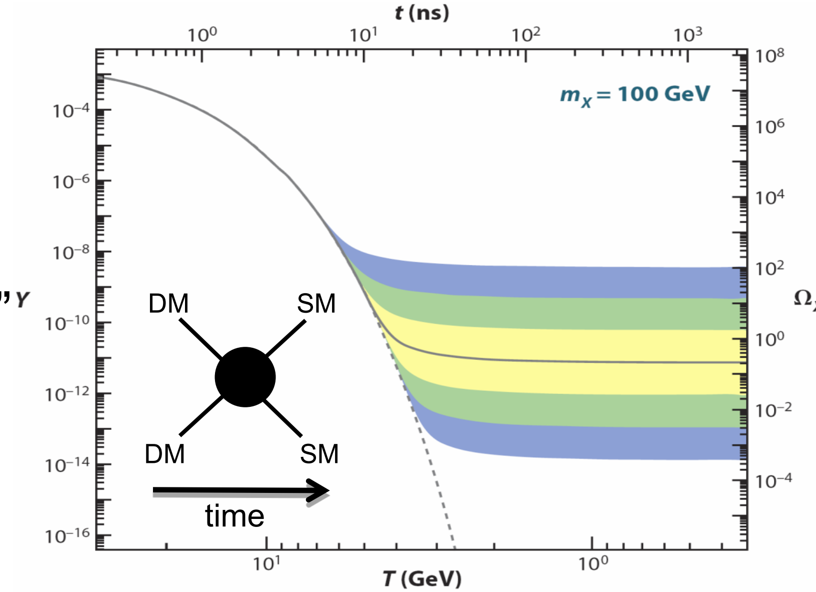
- We now have an overall picture of the Universe
- We know a lot about a little: the normal matter (5%)
- But we know little about a lot: dark matter / dark energy (95%). Most of the universe is still to be discovered and understood.

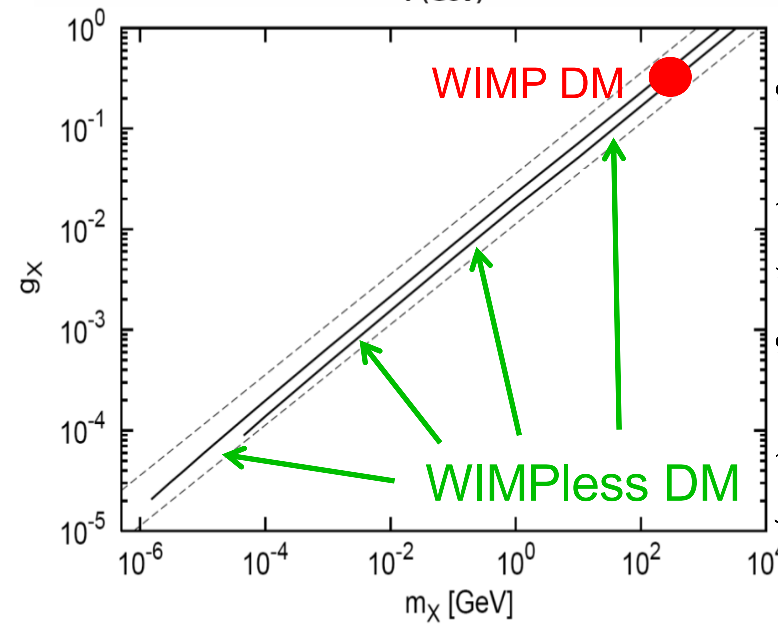
DARK MATTER

- What properties should DM have?
- A simple mechanism for generating DM: DM particles exist in the early universe, then pair annihilate until they "freeze out."
- The weaker their interactions, the more dark matter survives to the present day:

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

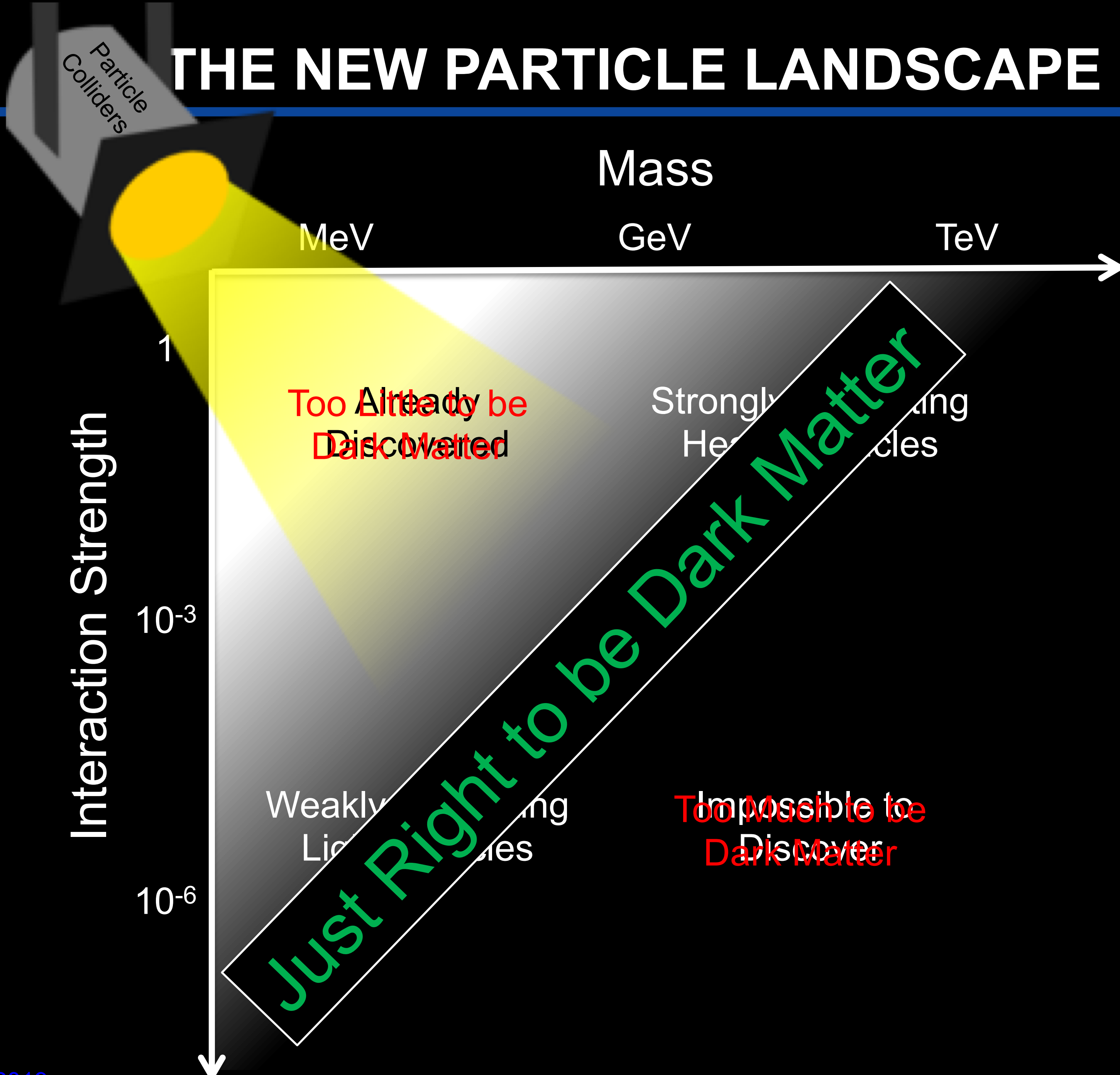
- WIMP Miracle: ~100 GeV to 1 TeV masses, strong couplings → right abundance
- WIMPless Miracle: lighter particles, weaker interactions → right abundance





Feng, Kumar (2008); Feng, Tu, Yu (2010)

THE NEW PARTICLE LANDSCAPE



THE LIFETIME FRONTIER

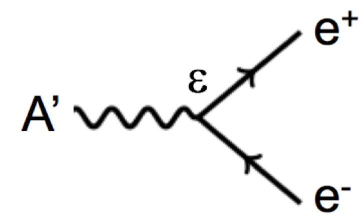
- What are the basic properties of light and weakly interacting particles? Consider a neutral particle with energy E ~ TeV, and
  - mass between electron (0.5 MeV) and proton (1 GeV): take $m \sim 100$ MeV
  - coupling between milli-charged and micro-charged: take $\varepsilon \sim 10^{-5}$

- They pass through matter essentially without interacting: radiation length is (10 cm) $\varepsilon^{-2} \sim 10^9$ m. The distance to the moon!

- They go straight; unaffected by E and B fields.

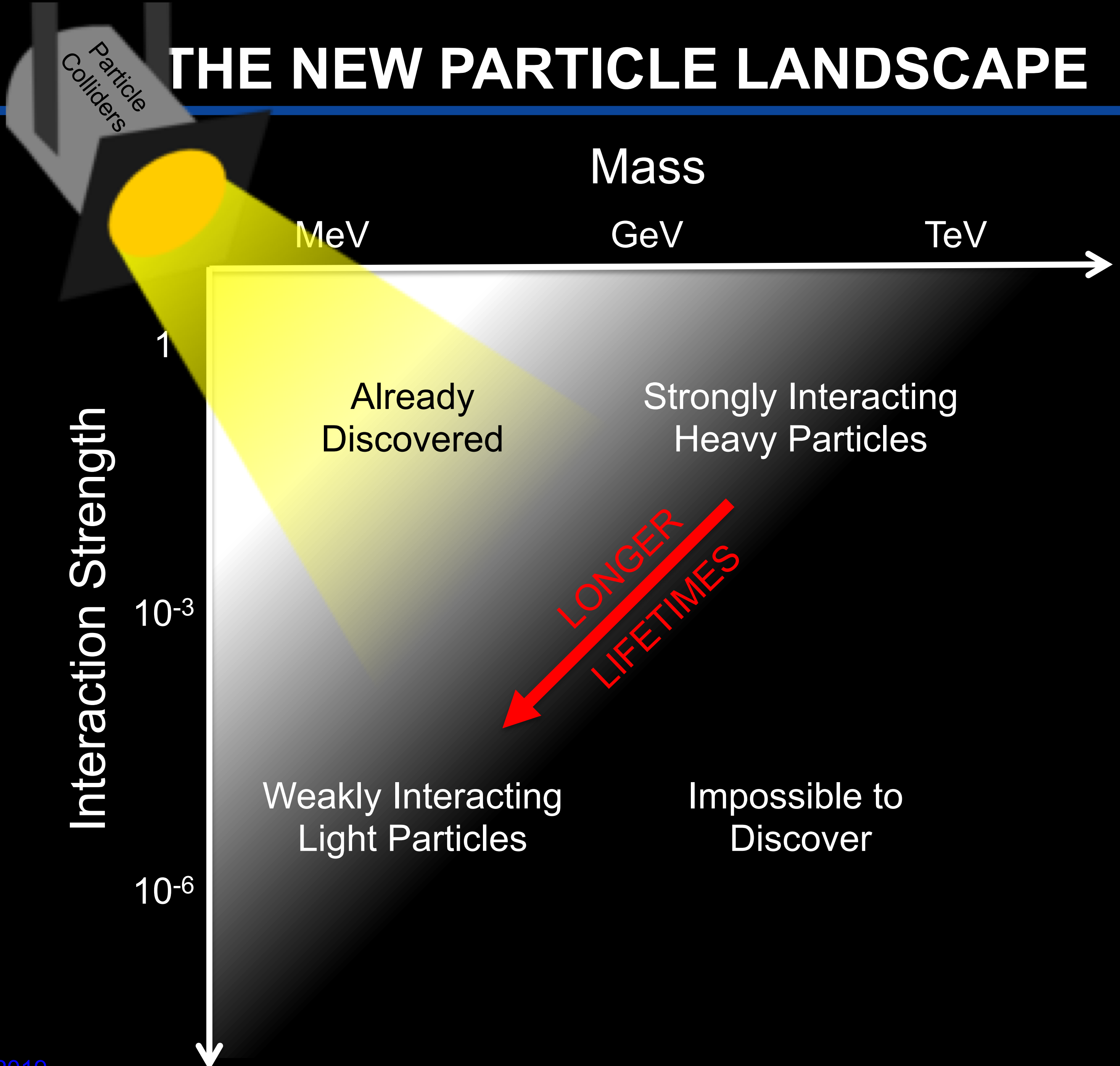
- They may decay to visible particles, but only after a long time:

$$L = v\tau\gamma \sim (100\ \text{m}) \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{100\ \text{MeV}}{m}\right]^2 \left[\frac{E}{\text{TeV}}\right]$$



- Strong dependence on m and ε, but these are long-lived particles and decay lengths may be meters or kilometers: human length scales!

THE NEW PARTICLE LANDSCAPE



LOTS OF ACTIVITY

Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider

1903.04497

March 6, 2019

Particles beyond the Standard Model (SM) can generically have lifetimes that are long compared to SM particles at the weak scale. When produced at experiments such as the Large Hadron Collider (LHC) at CERN, these long-lived particles (LLPs) can decay far from the interaction vertex of the primary proton-proton collision. Such LLP signatures are distinct from those of promptly decaying particles that are targeted by the majority of searches for new physics at the LHC, often requiring customized techniques to identify, for example, significantly displaced decay vertices, tracks with atypical properties, and short track segments. Given their non-standard nature, a comprehensive overview of LLP signatures at the LHC is beneficial to ensure that possible avenues of the discovery of new physics are not overlooked. Here we report on the joint work of a community of theorists and experimentalists with the ATLAS, CMS, and LHCb experiments — as well as those working on dedicated experiments such as MoEDAL, milliQan, MATHUSLA, CODEX-b, and FASER — to survey the current state of LLP searches at the LHC, and to chart a path for the development of LLP searches into the future, both in the upcoming Run 3 and at the High-Luminosity LHC. The work is organized around the current and future potential capabilities of LHC experiments to generally discover new LLPs, and takes a signature-based approach to surveying classes of models that give rise to LLPs rather than emphasizing any particular theory motivation. We develop a set of simplified models; assess the coverage of current searches; document known, often unexpected backgrounds; explore the capabilities of proposed detector upgrades; provide recommendations for the presentation of search results; and look towards the newest frontiers, namely high-multiplicity "dark showers", highlighting opportunities for expanding the LHC reach for these signals.

Editors:
Juliette Alimena[1] (Experimental Coverage, Backgrounds, Upgrades), James Beacham[2] (Document Editor, Simplified Models), Martino Borsato[3] (Backgrounds, Upgrades), Yangyang Cheng[4] (Upgrades), Xabier Cid Vidal[5] (Experimental Coverage), Giovanna Cottin[6] (Simplified Models, Reinterpretations), Albert De Roeck[7] (Experimental Coverage), Nishita Desai[8] (Reinterpretations), David Curtin[9] (Simplified Models), Jared A. Evans[10] (Simplified Models, Experimental Coverage), Simon Knapen[11] (Dark Showers), Sabine Kraml[12] (Reinterpretations), Andre Lessa[13] (Reinterpretations), Zhen Liu[14] (Simplified Models, Backgrounds, Reinterpretations), Sascha Mehlhase[15] (Backgrounds), Michael J. Ramsey-Musolf[16,126] (Simplified Models), Heather Russell[17] (Experimental Coverage), Jessie Shelton[18] (Simplified Models, Dark Showers), Brian Shuve[19,20] (Document Editor, Simplified Models, Simplified Models Library), Monica Verducci[21] (Upgrades), Jose Zurita[22,23] (Experimental Coverage)

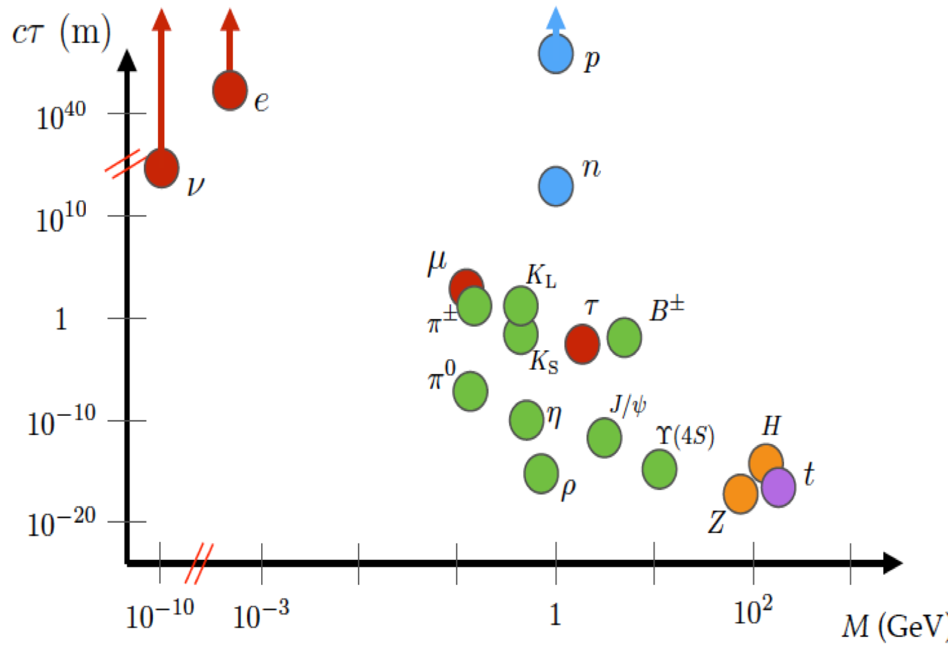
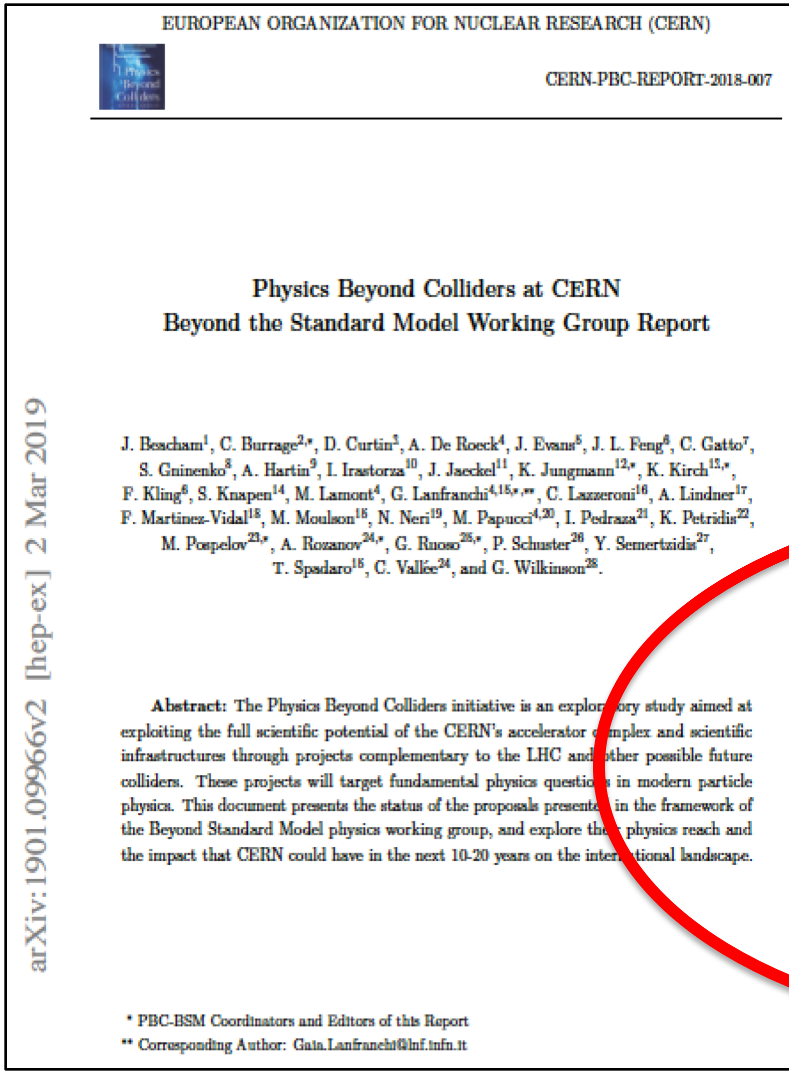


Figure 1.1: Particle lifetime $c\tau$, expressed in meters, as a function of particle mass, expressed in GeV, for a variety of particles in the Standard Model [1].

LOTS OF ACTIVITY



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PBC-REPORT-2018-007

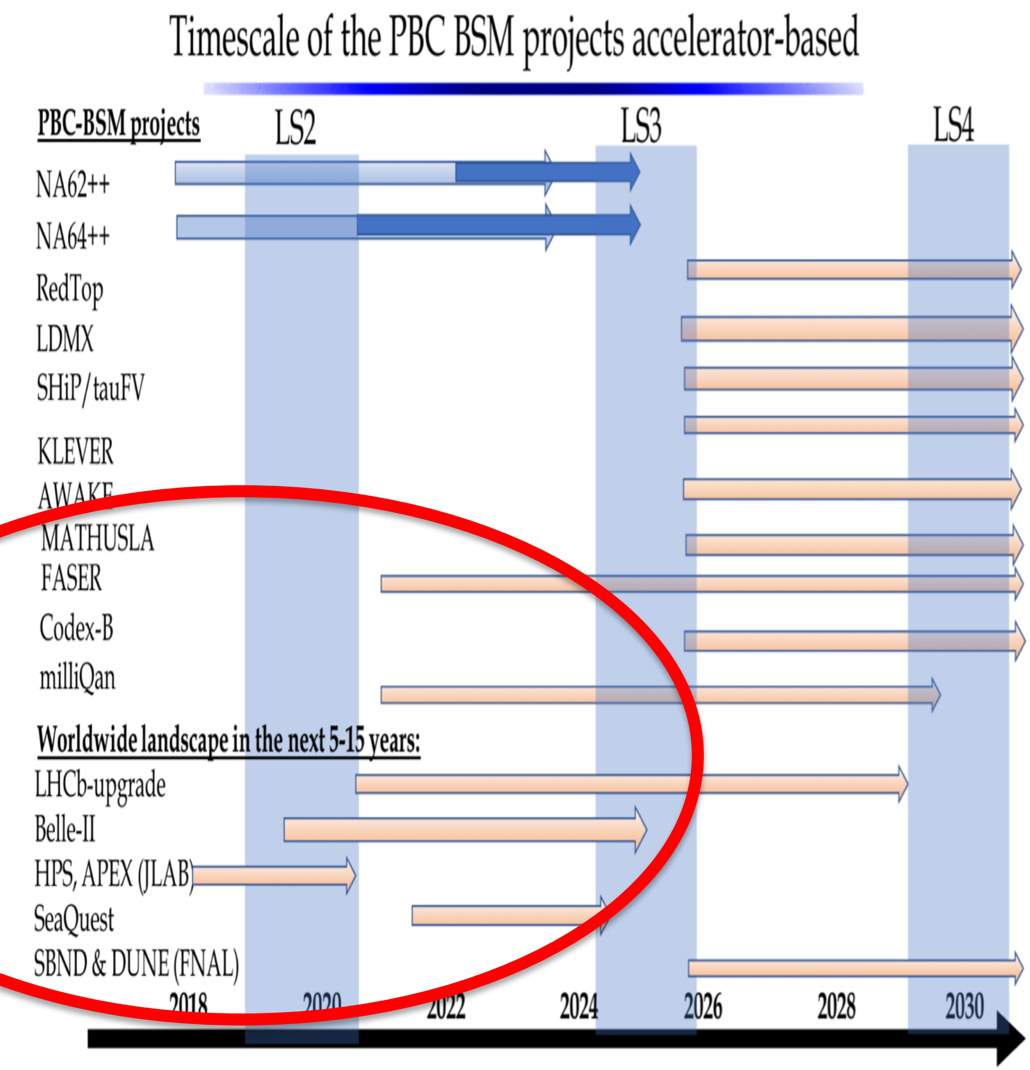
Physics Beyond Colliders at CERN
Beyond the Standard Model Working Group Report

J. Beacham[1], C. Burrage[2,*], D. Curtin[3], A. De Roeck[4], J. Evans[5], J. L. Feng[6], C. Gatto[7], S. Gninenko[8], A. Hartin[9], I. Irastorza[10], J. Jaeckel[11], K. Jungmann[12,*], K. Kirch[13,*], F. Kling[6], S. Knapen[14], M. Lamont[4], G. Lanfranchi[4,15,*,**], C. Lazzeroni[16], A. Lindner[17], F. Martinez-Vidal[18], M. Moulson[15], N. Neri[19], M. Papucci[4,20], I. Pedraza[21], K. Petridis[22], M. Pospelov[23,*], A. Rozanov[24,*], G. Ruoso[25,*], P. Schuster[26], Y. Semertzidis[27], T. Spadaro[15], C. Vallée[24], and G. Wilkinson[28].

Abstract: The Physics Beyond Colliders initiative is an exploratory study aimed at exploiting the full scientific potential of the CERN's accelerator complex and scientific infrastructures through projects complementary to the LHC and other possible future colliders. These projects will target fundamental physics questions in modern particle physics. This document presents the status of the proposals presented in the framework of the Beyond Standard Model physics working group, and explore their physics reach and the impact that CERN could have in the next 10-20 years on the international landscape.

arXiv:1901.09966v2 [hep-ex] 2 Mar 2019

* PBC-BSM Coordinators and Editors of this Report
** Corresponding Author: Gaia.Lanfranchi@lnf.infn.it



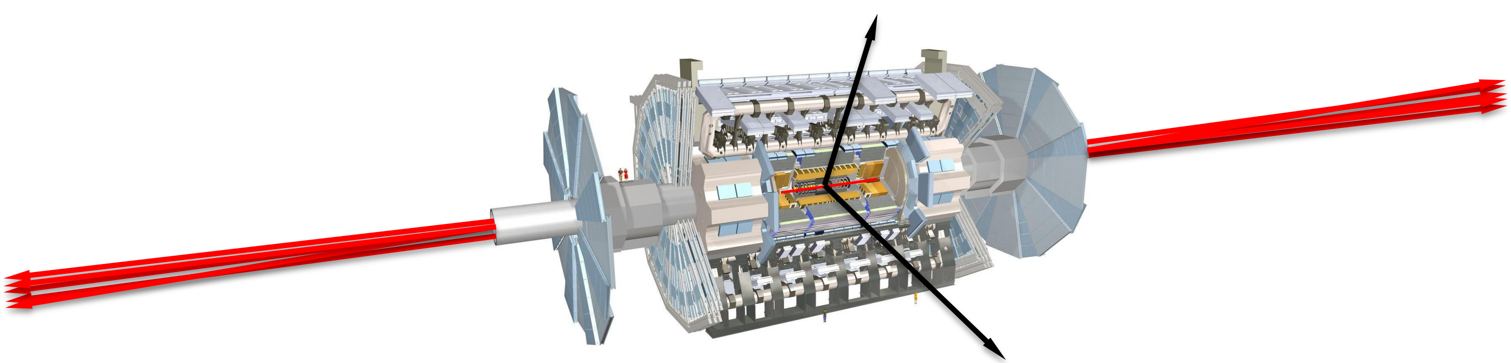
- Many experiments, including some on short timescales

FASER

THE BASIC IDEA

- If new particles are light and weakly interacting, they can also be produced in the decays of light particles.
  - Light → they may be produced in π, *K*, *D*, *B* decays…
  - Weakly-interacting → …but extremely rarely in π, *K*, *D*, *B* decays

- More promising to go where the π, *K*, *D*, *B* particles are: along the beamline.
  - For example, the LHC produces ~10^{16} pions per year
  - But for E > 10 GeV, 10% of these (and most of the high energy ones) are produced within 2 mrad of the beamline.



THE BASIC IDEA

- 2 mrad is very small (η > 7)
  - Moon diameter is 9 mrad.
  - Moreover, the ATLAS and CMS detectors have holes here to let the proton beams in and so are completely blind to these particles.

- Can we cover this “blind spot”? A detector on the beamline would block the proton beams. However, our target particles do not interact and travel straight for a long time. We can therefore place the detector on the “line of sight,” a few 100 m away, after the beam curves.

- (100 m) (mrad) = 10 cm → particles are still highly collimated.

- These considerations motivate a small, inexpensive experiment placed in the very forward region of ATLAS/CMS, a few 100m downstream.

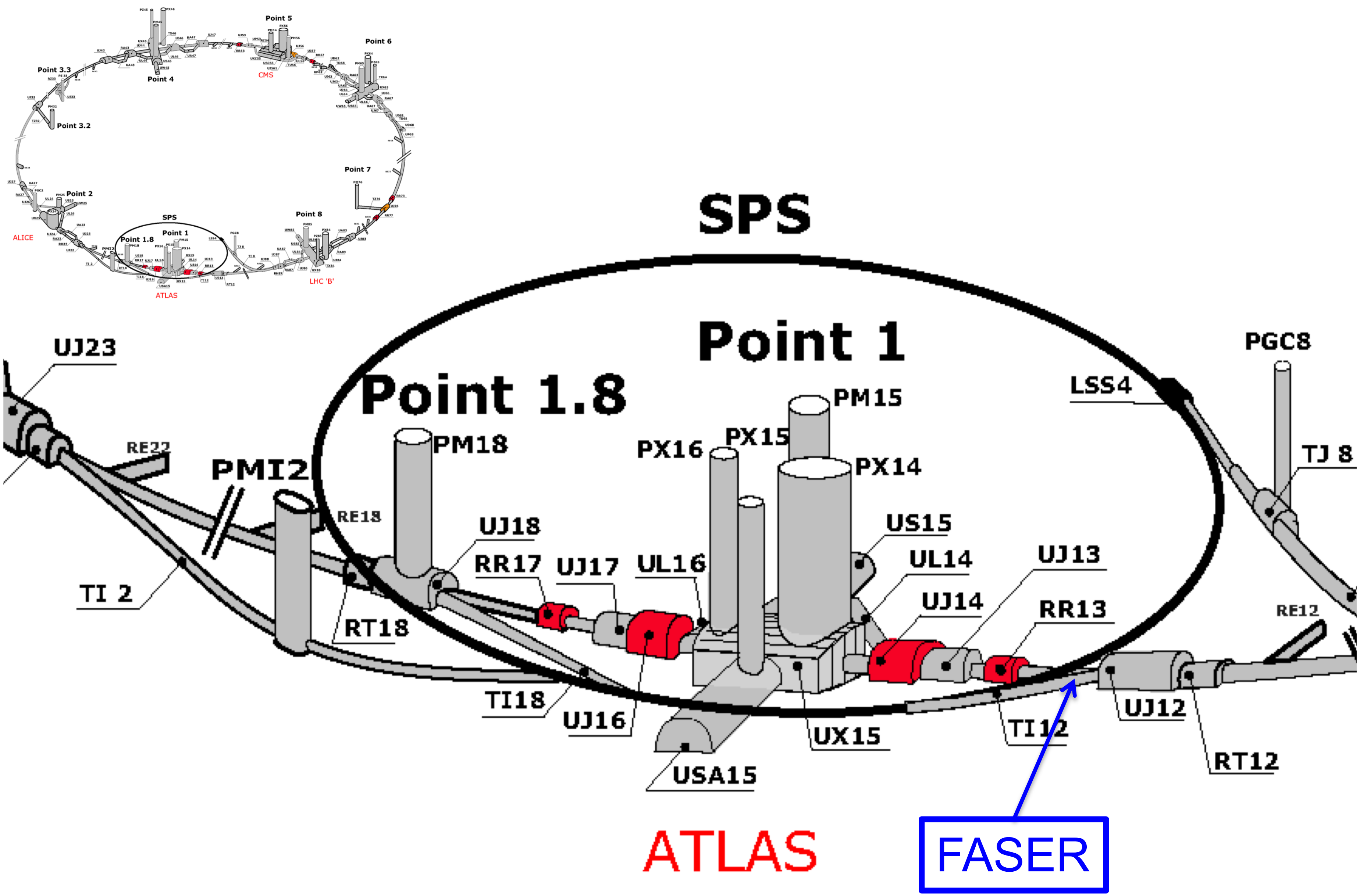
FORWARD SEARCH EXPERIMENT

FASER

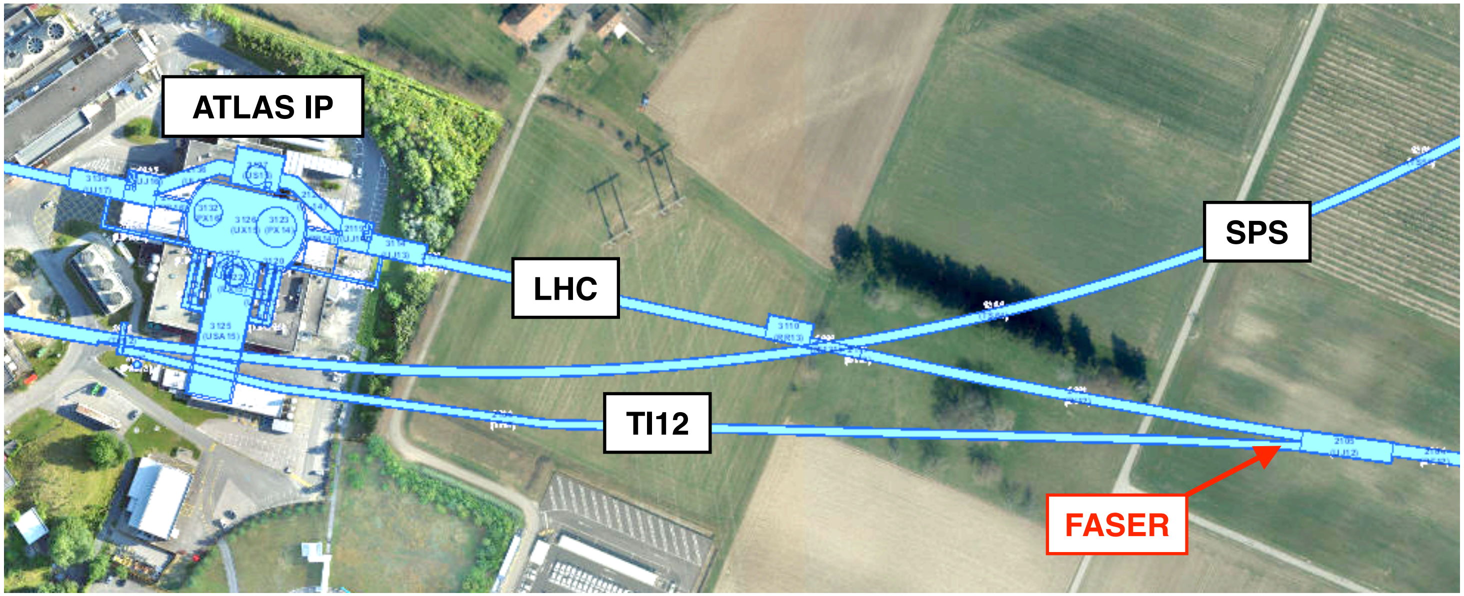
- "The acronym recalls another marvelous instrument that harnessed highly collimated particles and was used to explore strange new worlds."

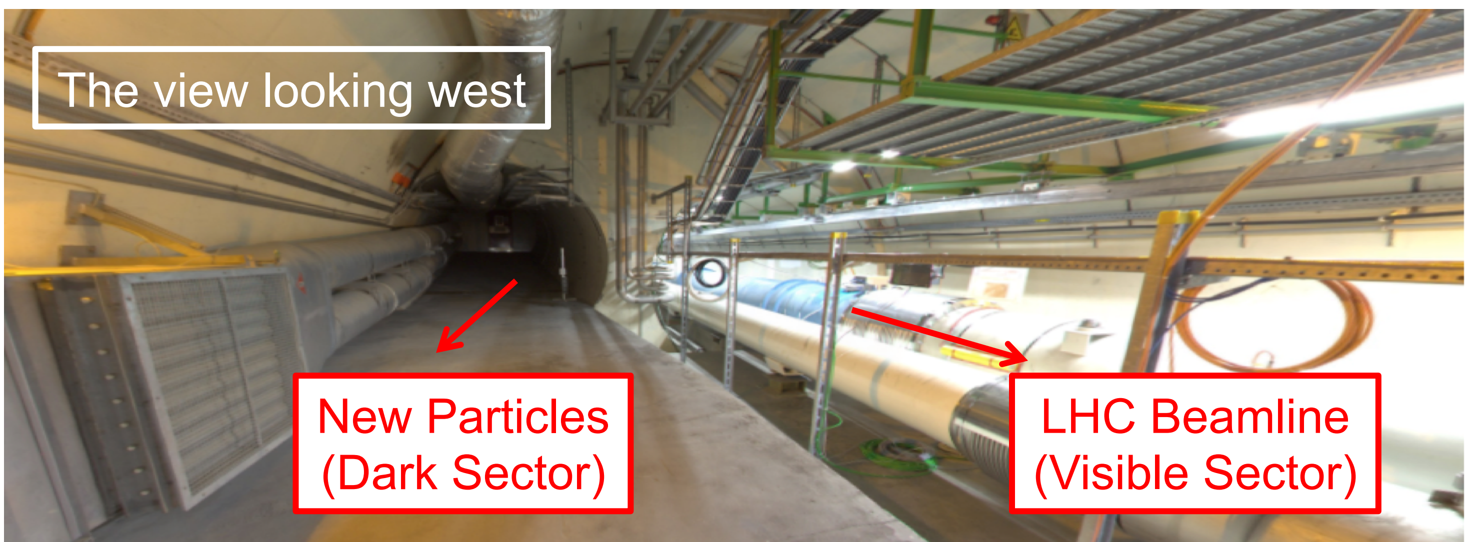
  Feng, Galon, Kling, Trojanowski (2017)

LOCATION, LOCATION, LOCATION



LOCATION, LOCATION, LOCATION



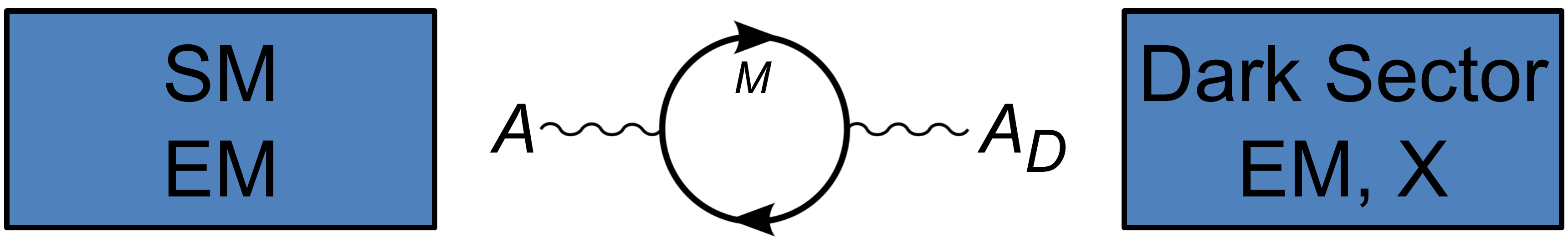


PARTICLE PATH FROM ATLAS TO FASER

FASER SEARCH EXAMPLE: DARK PHOTONS

- Suppose there is a dark sector that contains dark matter X and also a dark force: dark electromagnetism.

- Generically, the force carriers of the SM and dark EMs will mix



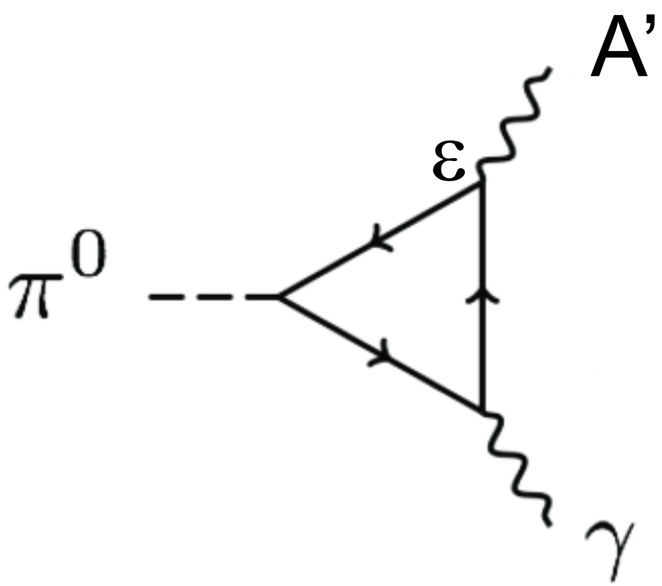
- The resulting theory contains a new gauge boson, the dark photon A', with mass $m_{A'}$ and εQ_f couplings to SM fermions f, where ε is loop-induced and so expected to be small.

Okun (1982), Galison, Manohar (1984), Holdom (1986)

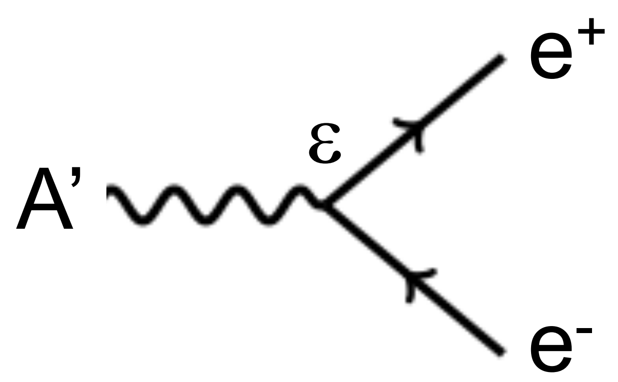
DARK PHOTON PROPERTIES

- The dark photon is like the standard photon, but
  - It is massive, with a mass $m_{A'}$
  - Its coupling to SM particles is suppressed by a small coupling ε

- It can be produced, for example, in pion decay:

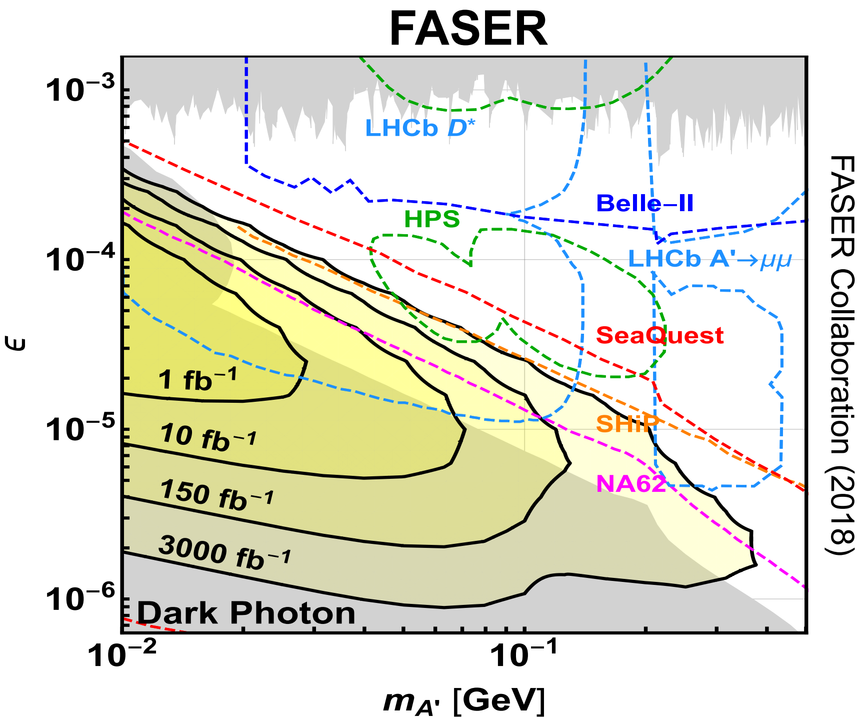


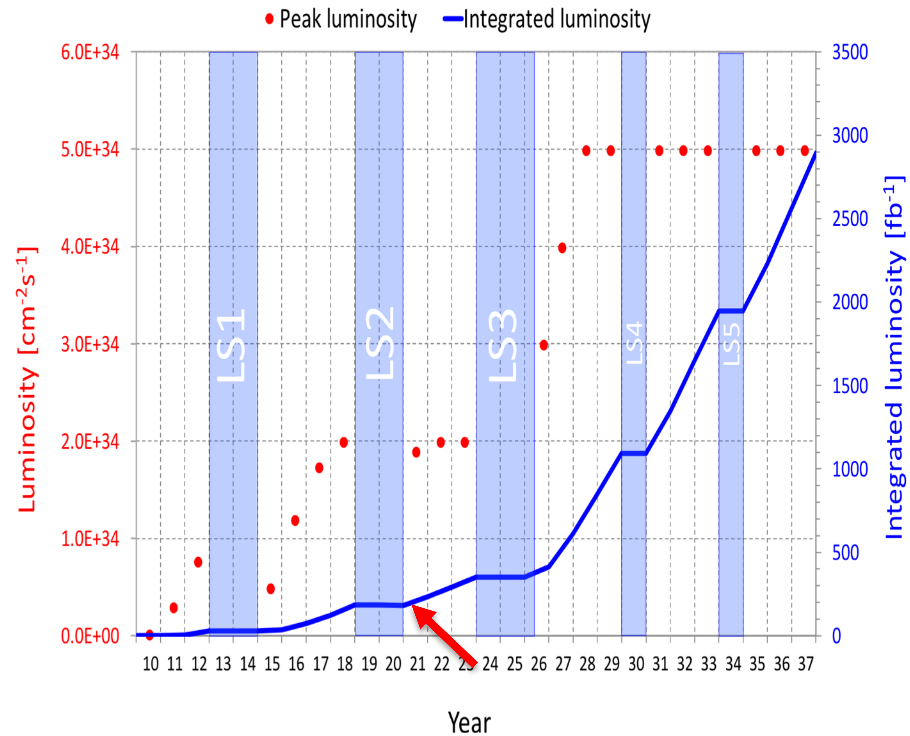
- It can decay to particle/anti-particle pairs:



DARK PHOTON SENSITIVITY REACH

- Consider two cylindrical detectors
  - FASER: R = 10 cm, L = 1.5 m, tabletop experiment!
  - FASER 2: R = 1 m, L = 5 m, a possible upgrade





- FASER probes new parameter space with just 1 fb^{-1} starting in 2021

- Without upgrade, HL-LHC extends (L*Volume) by factor of 3000; with possible upgrade to FASER 2, HL-LHC extends (L*Volume) by ~10^6

PHYSICS SUMMARY

- Many other studies: FASER has discover prospects for all candidates with renormalizable couplings (dark photon, dark Higgs, HNL); ALPs with all types of couplings (γ, f, g); and many other examples; see 1811.12522.

Benchmark Model	FASER	FASER 2	References
V1/BC1: Dark Photon	√	√	Feng, Galon, Kling, Trojanowski, 1708.09389
V2/BC1': $U(1)_{B-L}$ Gauge Boson	√	√	Bauer, Foldenauer, Jaeckel, 1803.05466 FASER Collaboration, 1811.12522
BC2: Invisible Dark Photon	–	–	–
BC3: Milli-Charged Particle	–	–	–
S1/BC4: Dark Higgs Boson	–	√	Feng, Galon, Kling, Trojanowski, 1710.09387 Batell, Freitas, Ismail, McKeen, 1712.10022
S2/BC5: Dark Higgs with hSS	–	√	Feng, Galon, Kling, Trojanowski, 1710.09387
F1/BC6: HNL with e	–	√	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
F2/BC7: HNL with μ	–	√	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
F3/BC8: HNL with τ	√	√	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
A1/BC9: ALP with photon	√	√	Feng, Galon, Kling, Trojanowski, 1806.02348
A2/BC10: ALP with fermion	√	√	FASER Collaboration, 1811.12522
A3/BC11: ALP with gluon	√	√	FASER Collaboration, 1811.12522

FASER STATUS

FASER TIMELINE

- September 2017: First theory paper
- November 2017: Support from the two most famous living physicists
- July 2018: Submitted LOI to CERN LHCC
- October 2018: Approval from ATLAS SCT and LHCb Collaborations for use of spare detector modules
- November 2018: Submitted Technical Proposal to LHCC
- November 2018 – January 2019: Experiment funded by $1M grants from the Heising-Simons and Simons Foundations
- March 2019: FASER fully approved by CERN LHCC and Research Board along with support for infrastructure costs
- April 2019: 1st FASER Collaboration Meeting
- May 2020: Install FASER in tunnel before cool down in Long Shutdown 2, begin commissioning detector
- April 2021: Start collecting data in Run 3

FASER ON BIG BANG THEORY

Season 11, Episode 9, "The Bitcoin Entanglement" (November 2017)

FIRST FASER COLLABORATION MEETING

FASER COLLABORATION TODAY

- 46 collaborators, 18 institutions, 8 countries

Henso Abreu (Technion), Claire Antel (Geneva), Akitaka Ariga (Bern), Tomoko Ariga (Kyushu/Bern), Jamie Boyd (CERN), Dave Casper (UC Irvine), Franck Cadoux (Geneva), Xin Chen (Tsinghua), Andrea Coccaro (INFN), Candan Dozen (Tsinghua), Yannick Favre (Geneva), Jonathan Feng (UC Irvine), Didier Ferrere (Geneva), Iftah Galon (Rutgers), Stephen Gibson (Royal Holloway), Sergio Gonzalez-Sevilla (Geneva), Shih-Chieh Hsu (Washington), Zhen Hu (Tsinghua), Peppe Iacobucci (Geneva), Sune Jakobsen (CERN), Roland Jansky (Geneva), Enrique Kajomovitz (Technion), Felix Kling (SLAC), Susanne Kuehn (CERN), Lorne Levinson (Weizmann), Congqiao Li (Washington), Josh McFayden (CERN), Sam Meehan (CERN), Friedemann Neuhaus (Mainz), Hidetoshi Otono (Kyushu), Brian Petersen (CERN), Helena Pikhartova (Royal Holloway), Michaela Queitsch-Maitland (CERN), Jakob Salfeld-Nebgen (CERN), Osamu Sato (Nagoya), Kristof Schmieden (CERN), Matthias Schott (Mainz), Anna Sfyrla (Geneva), Savannah Shively (UC Irvine), Jordan Smolinsky (UC Irvine), Aaron Soffa (UC Irvine), Yosuke Takubo (KEK), Eric Torrence (Oregon), Sebastian Trojanowski (Sheffield), Dengfeng Zhang (Tsinghua), Gang Zhang (Tsinghua)

HELP FROM MANY OTHERS

The FASER Collaboration has received essential support from the Heising-Simons and Simons Foundations, CERN, the ATLAS SCT and LHCb Collaborations, and also many others at CERN and elsewhere

We are grateful to the ATLAS SCT project and the LHCb Calorimeter project for letting us use spare modules as part of the FASER experiment. In addition, FASER acknowledges the invaluable assistance from the CERN Physics Beyond Colliders study group; the LHC Tunnel Region Experiment (TREX) working group; the LHC Machine Committee; the LS2 Committee and the LHCC. FASER gratefully acknowledges the contributions from:

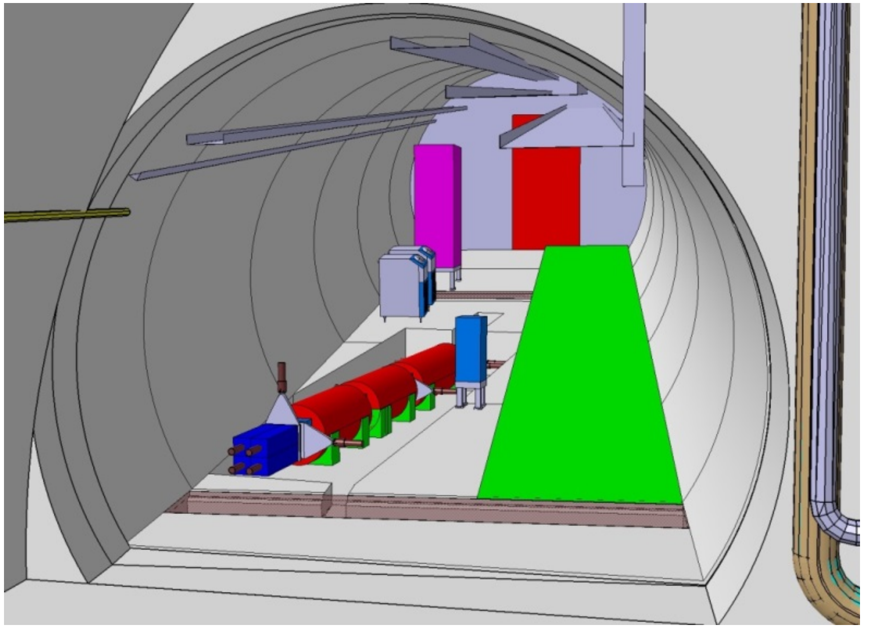
- Jonathan Gall, John Osborne (civil engineering);
- Liam Dougherty, Francisco Galan (integration);
- Pierre Thonet (magnets);
- Francesco Cerutti, Marta Sabate Gilarte (FLUKA simulation and background characterization);
- Salvatore Danzeca, Serge Chalaye (radiation measurements);
- James Storey, Swann Levasseur (beam instrumentation);
- Pierre Valentin, Tobias Dobers (survey);
- Caterina Bertone, Serge Pelletier, Frederic Delsaux (transport);
- Gael Girardot, Olivier Crespo-Lopez, Yann Maurer, Maria Papamichali (LS2 works);
- Marzia Bernardini, Anne-Laure Perrot, Katy Foraz, Markus Brugger (LHC access and schedule);
- Marco Andreini, Olga Beltramello, Thomas Otto (safety);
- Dave Robinson (ATLAS SCT), Yuri Guz (LHCb calorimeters);
- Stephen Wotton, Floris Keizer (SCT QA system and SCT readout);
- Burkhard Schmitt, Raphael Dumps, Sune Jacobsen, Giovanna Lehmann (CERN-DT contributions);
- Mike Lamont, Andreas Hoecker, Ludovico Pontecorvo, Christoph Rembser (useful discussions).

Thanks also to the CERN management for their support!

FASER IN TUNNEL TI12

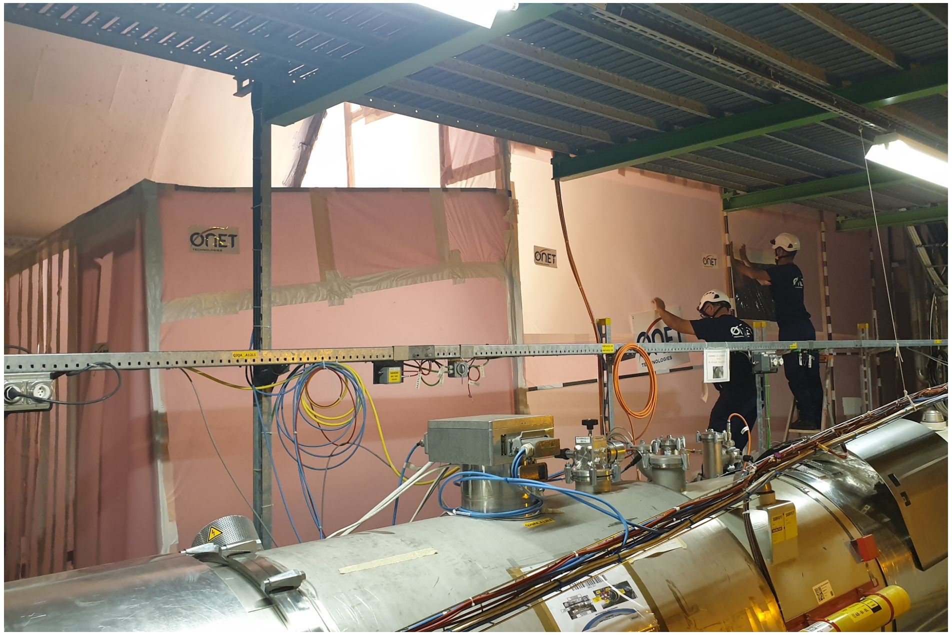
- The beam collision axis has been located to mm accuracy by the CERN survey department. To place FASER on this axis, a trench is required to lower the floor by 46 cm.

- The goal is to convert before (left) to after (right).



FASER LOCATION NOW

- A hoist and stairs have been installed to move equipment over the LHC.
- The FASER work zone has been surrounded by a plastic barrier to contain dust, prepare for trench digging.

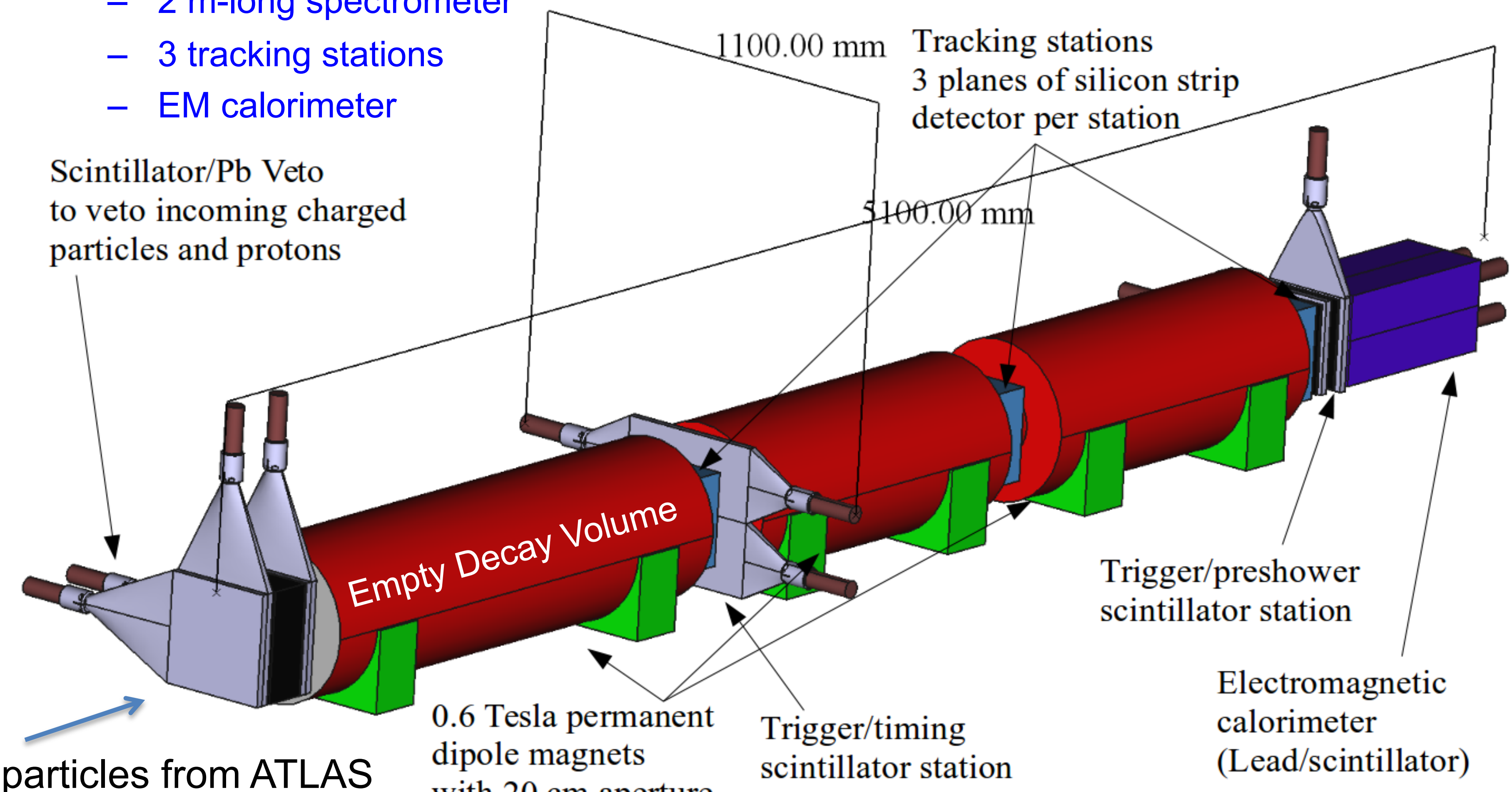


FASER LOCATION NOW

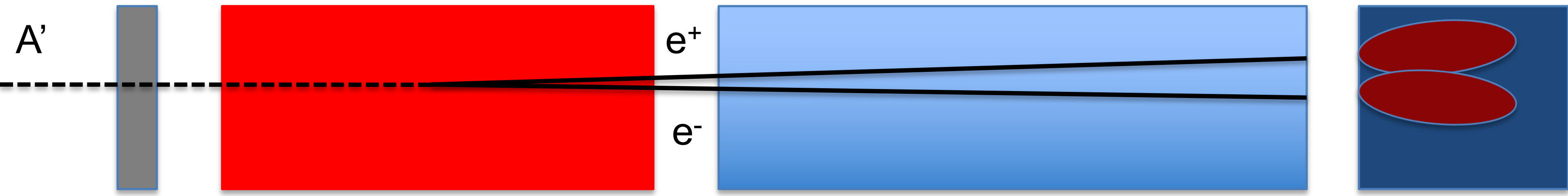
- In TI12, unused ventilation ducts, cables, etc. have been removed to prepare for FASER trench excavation and installation.

THE FASER DETECTOR

- The detector consists of
  - Scintillator veto
  - 1.5 m-long decay volume
  - 2 m-long spectrometer
  - 3 tracking stations
  - EM calorimeter



THE SIGNAL

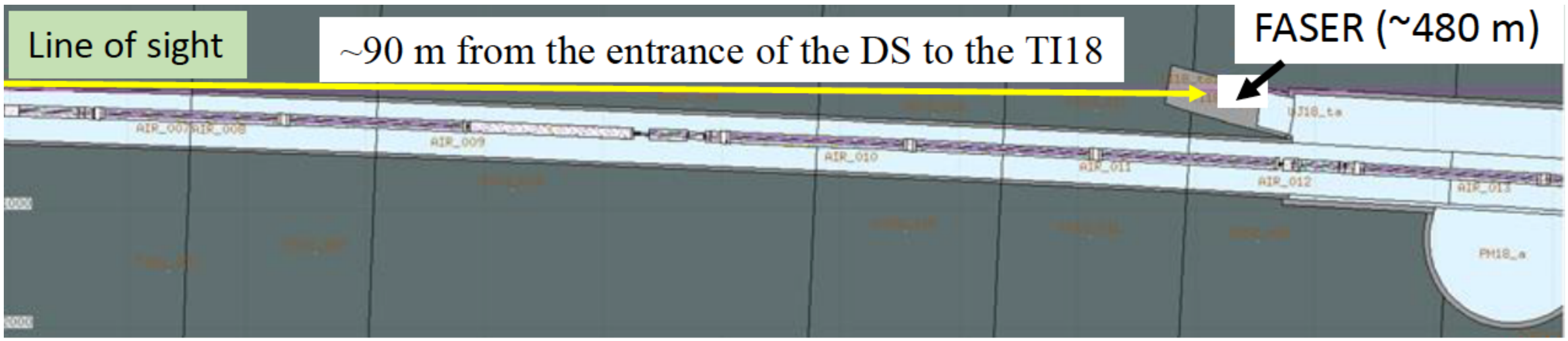


- The signal is spectacular: 2 ~TeV-energy, oppositely-charged tracks originating from a common vertex in the decay volume and with a combined momentum pointing back to the IP
- No signal in the veto scintillator
- For e^+e^- signature, also a large EM deposit in the calorimeter
- Magnets separate the 2 charged tracks sufficiently to resolve them in the tracker

$$h_B \approx \frac{ec\ell^2}{E} B = 3\ \mathrm{mm}\ \left[\frac{1\ \mathrm{TeV}}{E}\right] \left[\frac{\ell}{10\ \mathrm{m}}\right]^2 \left[\frac{B}{0.1\ \mathrm{T}}\right]$$

BACKGROUNDS

- FASER's location is very quiet – 100 m of rock and concrete between IP and FASER. The only SM particles that get through from the IP are muons and neutrinos.



- A high-energy muon that radiates a photon or an EM or hadronic jet is a leading background if the incoming muon is not vetoed, but this is under control with 4 layers of scintillator veto.

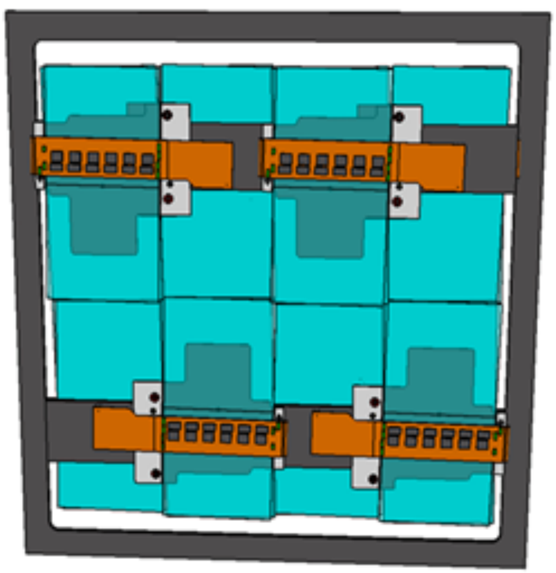
- Backgrounds have also been studied with FLUKA simulation, which finds that beam-gas background (from "beam 2" traveling in the other direction) is also negligible.

- The FLUKA results have been validated with *in situ* measurements taken with emulsion detectors installed and removed in Technical Stops in 2018.

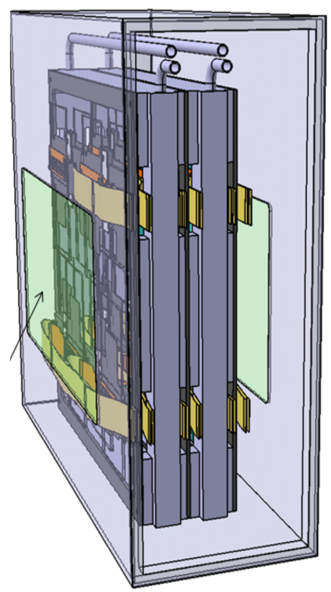
TRACKER

- The FASER tracker is composed of spare SCT modules from ATLAS. About 350 spares were prepared. They were not needed, and the ATLAS SCT collaboration has allowed us to use 80 of them. QA now completed.

- 8 SCT modules make up a 24cm x 24cm tracking layer, 3 layers make up a tracking station, and FASER has 3 tracking stations. Tests of prototype tracking layer have started.



Tracking layer

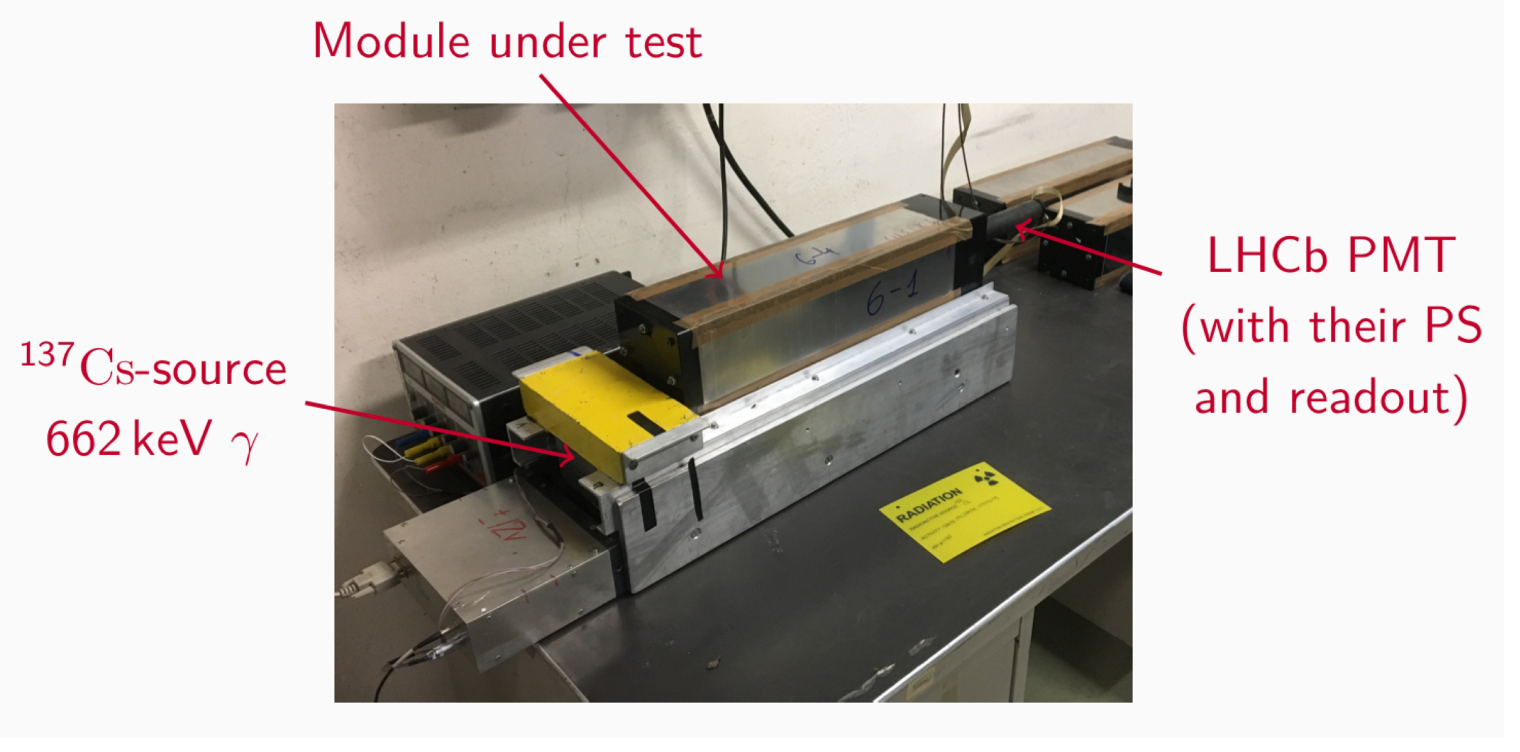


Tracking station

Prototype tracking layer

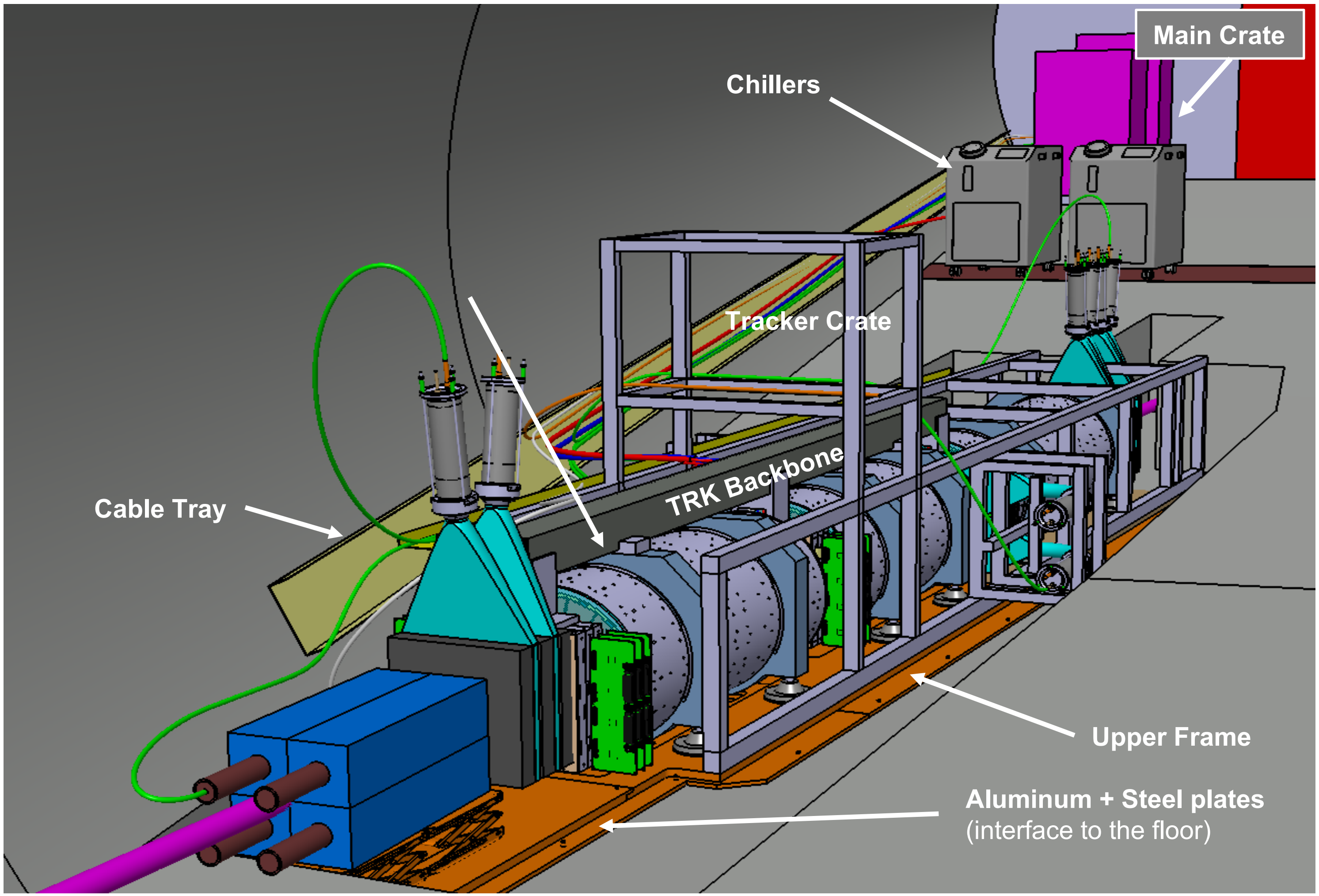
CALORIMETERS

- The FASER ECAL consists of spare LHCb outer ECAL modules, which the LHCb Collaboration has allowed us to use. Provide ~1% energy resolution for 1 TeV electrons.
- All modules passed QA, ready for assembly.

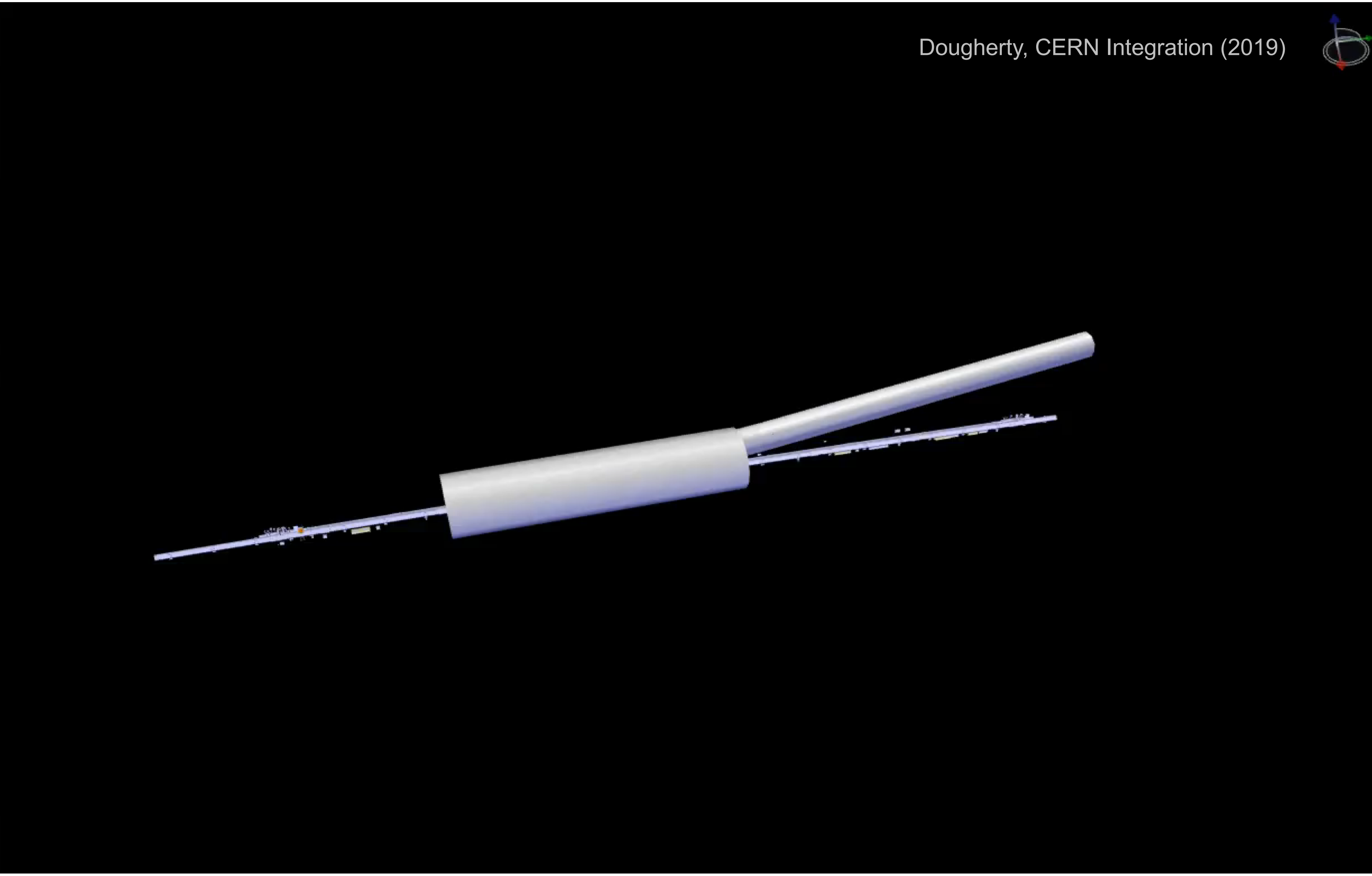


OTHER COMPONENTS

- On-schedule progress on magnets, base plates, chillers, cabling, electronics crates, power supplies, TDAQ, computing



FASER INSTALLATION



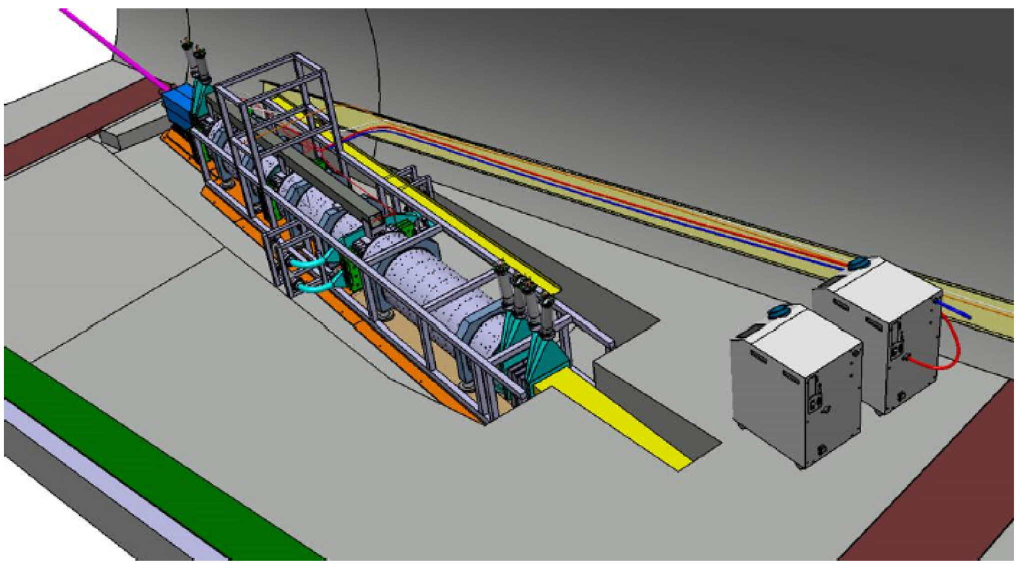
FASERν

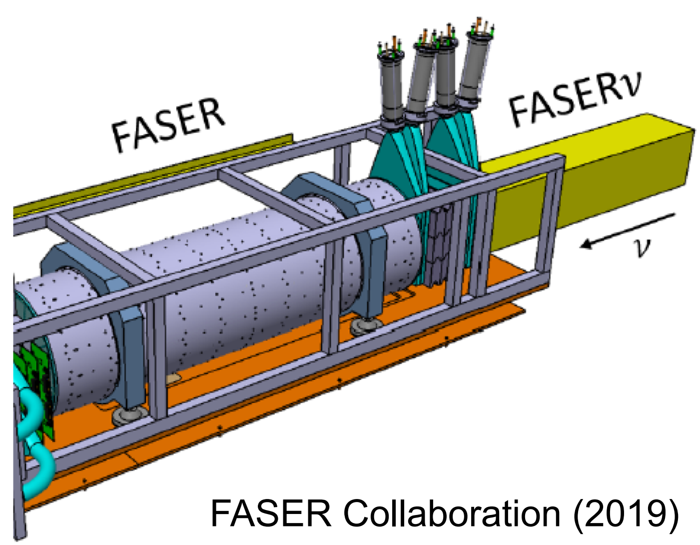
COLLIDER NEUTRINOS

- FASER will search for light, weakly-interacting new particles.
- But we already know of some light, weakly-interacting particles: neutrinos!
- Neutrinos have been detected from a variety of sources: nuclear reactors, beam dump experiments, cosmic ray interactions in the atmosphere, the Sun, the Earth, supernovae, and other astrophysical bodies outside our galaxy, with interesting implications for particle physics, nuclear physics, and cosmology.
- But so far, no collider neutrino has ever been directly detected
  - Probability to interact in a meter of water: $P \sim 4 \times 10^{-13} \, (E_\nu/\mathrm{GeV})$
  - The largest flux of high-energy neutrinos travels down the beamline and have escaped all collider detectors so far.

FASERν EMULSION DETECTOR

- FASER is ideally located to detect collider neutrinos.
- FASERν is a proposed 25cm x 25cm x 1.35m emulsion detector consisting of 1000 emulsion layers interleaved with 1mm-thick tungsten plates. FASERν is at the front of FASER, required trench is in the plans.
- In Run 3, ~10^{13} neutrinos and anti-neutrinos will pass through FASERν, and we expect 1300 ν_e, 20,000 ν_μ, and 20 ν_τ to interact.

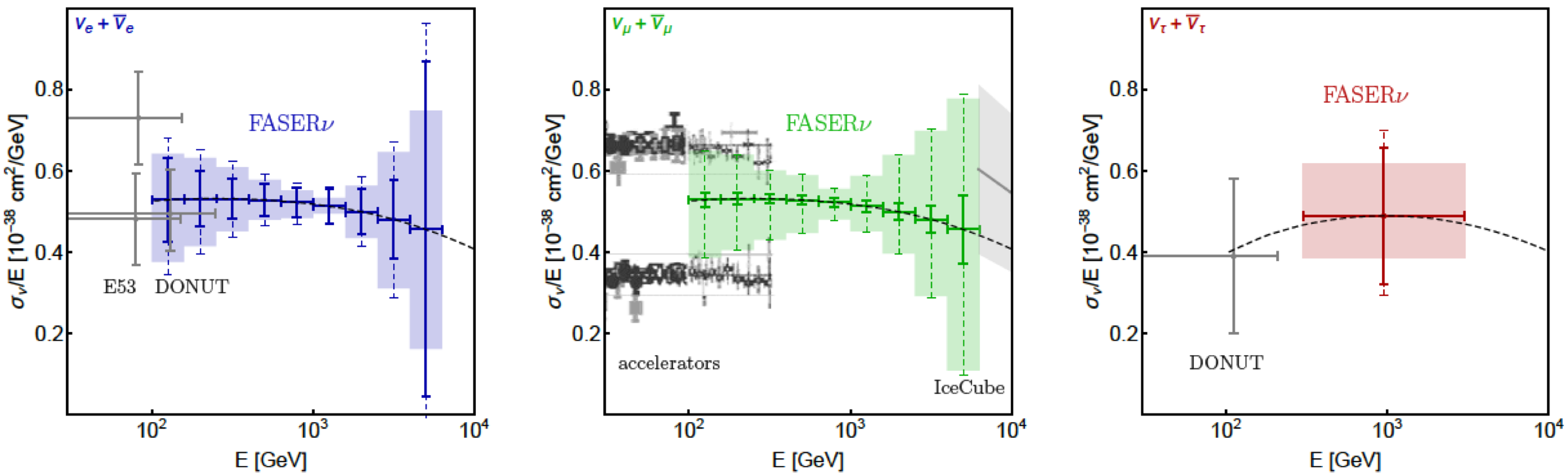




FASER Collaboration (2019)

FASERν PHYSICS GOALS

- 1^{st} direct detection of a collider neutrino
- Reconstruct ~20 ν_τ (doubling current world's sample)
- Measure neutrino cross sections at E_ν ~ TeV, the highest energies ever for electron and tau neutrinos, and a new energy range for muon neutrinos
- Constrain forward particle production



FASER Collaboration 1908.02310 (2019)

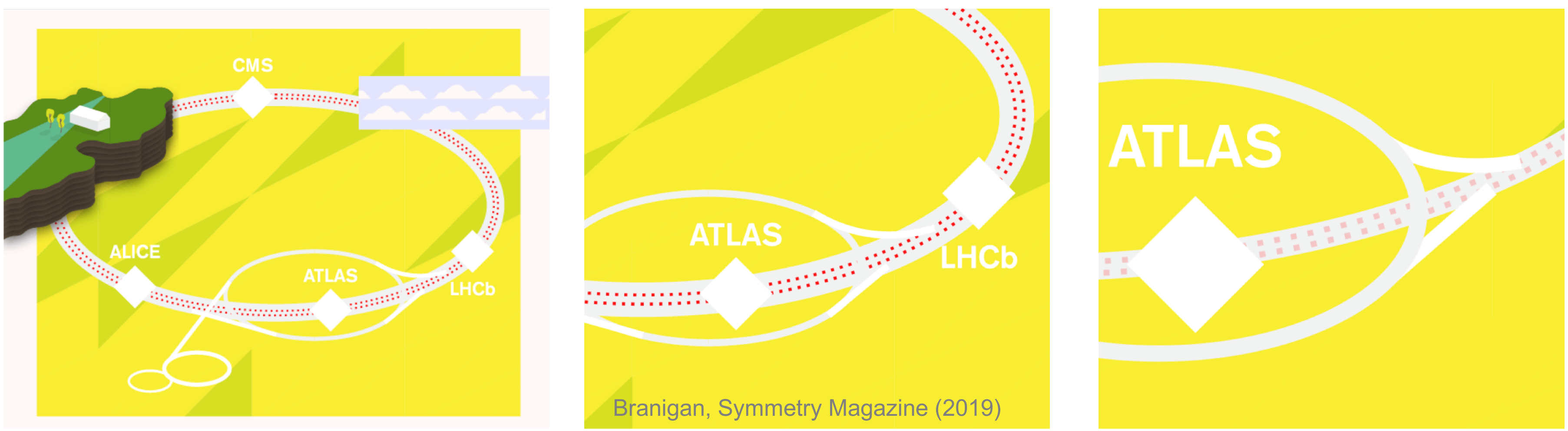
FASERν is guaranteed to provide interesting neutrino measurements and will complement FASER's searches for new particles.

SUMMARY AND OUTLOOK

- A new target for particle physics experiments: light and weakly-interacting particles at the lifetime frontier.

- Fast, small, cheap experiments can provide world-leading sensitivities.

- FASER: 18 months from theory paper to beginning of construction, fits on a tabletop, ~$2M. Data-taking begins 2021 with new neutrino measurements and discovery prospects for a host of proposed new particles.



Branigan, Symmetry Magazine (2019)

- More info: https://twiki.cern.ch/twiki/bin/viewauth/FASER/WebHome.