The CMS experiment at the Large Hadron Collider

Ted Kolberg (Florida State University)

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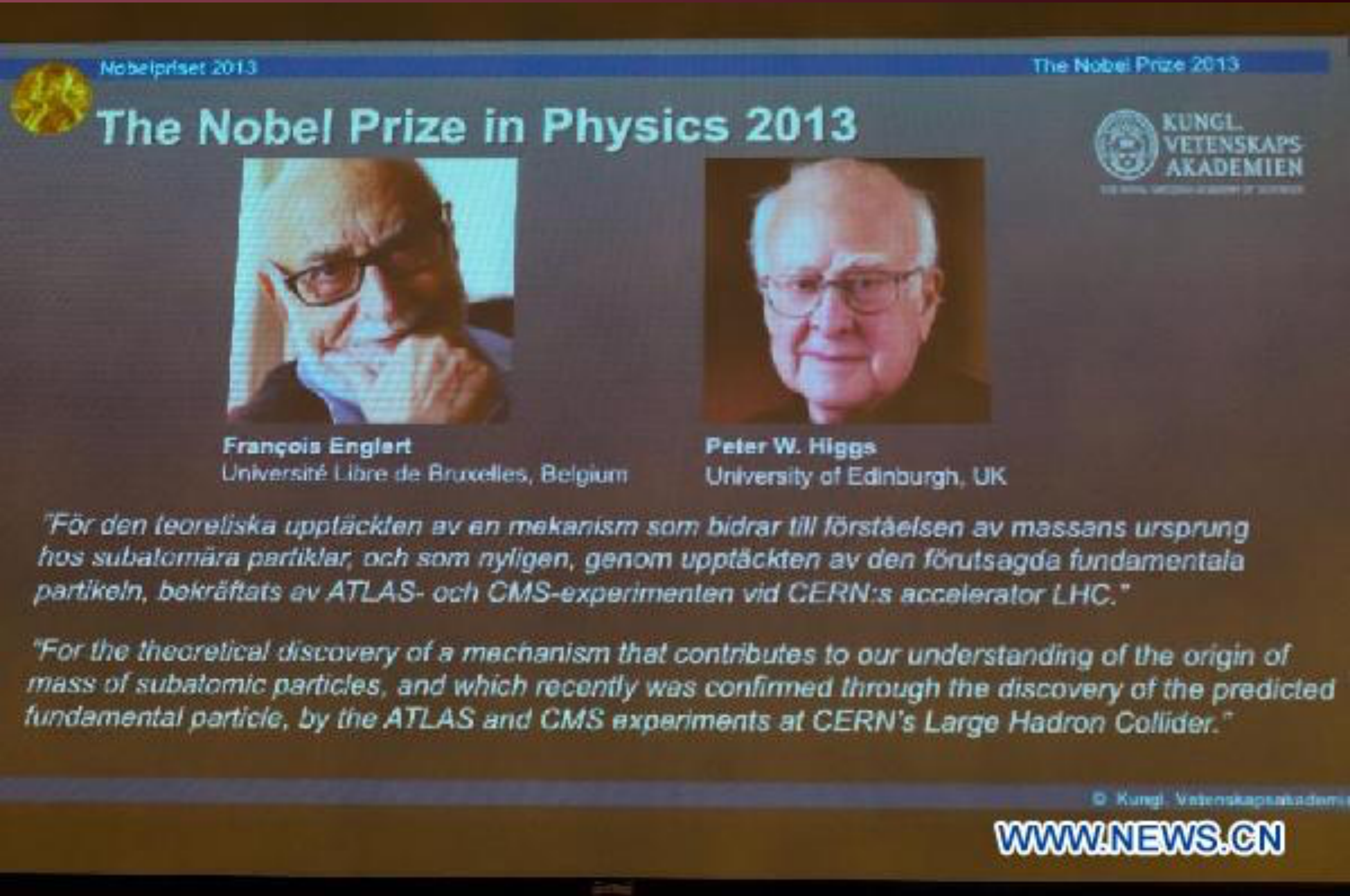

The paper (one of two!)

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

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Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

The CMS Collaboration

Abstract

Results are presented from searches for the standard model Higgs boson in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of up to $5.1\,\mathrm{fb}^{-1}$ at 7 TeV and $5.3\,\mathrm{fb}^{-1}$ at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, $\mathrm{W}^+\mathrm{W}^-$, $\tau^+\tau^-$, and $\mathrm{b\bar{b}}$. An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of $125.3 \pm 0.4\,(\mathrm{stat.}) \pm 0.5\,(\mathrm{syst.})$ GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

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Authors

CMS Collaboration

S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, E. Aguilo, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan [1], M. Friedl, R. Frühwirth [1], V.M. Ghete, J. Hammer, M. Hoch, N. Hörmann, J. Hrubec, M. Jeitler [1], W. Kiesenhofer, V. Knünz, M. Krammer [1], I. Krätschmer, D. Liko, W. Majerotto, I. Mikulec, M. Pernicka [†], B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, F. Szoncsó, A. Taurok, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz [1]

Institut für Hochenergiephysik der OeAW, Wien, Austria

V. Chekhovsky, I. Emeliantchik, A. Litomin, V. Makarenko, V. Mossolov, N. Shumeiko, A. Solin, R. Stefanovitch, J. Suarez Gonzalez

National Centre for Particle and High Energy Physics, Minsk, Belarus

A. Fedorov, M. Korzhik, O. Missevitch, R. Zuyeuski

Research Institute for Nuclear Problems, Minsk, Belarus

M. Bansal, S. Bansal, W. Beaumont, T. Cornelis, E.A. De Wolf, D. Druzhkin, X. Janssen, S. Luyckx, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, Z. Staykova, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Universiteit Antwerpen, Antwerpen, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, O. Devroede, R. Gonzalez Suarez, R. Goorens, A. Kalogeropoulos, M. Maes, A. Olbrechts, S. Tavernier, W. Van Doninck, L. Van Lancker, P. Van Mulders, G.P. Van Onsem, I. Villella

Vrije Universiteit Brussel, Brussel, Belgium

Authors

CMS Collaboration

S. Chatrchyan, V. Kha

Yerevan Physics Institute, Yerevan, Ar

W. Adam, E. Aguilo, T ... M. Ghete,
J. Hammer, M. Hoch, ... mer[1],
I. Krätschmer, D. Lik ... Rohringer,
R. Schöfbeck, J. Strau ... z[1]

Institut für Hochenergiephysik der Oe

V. Chekhovsky, I. Em ... n,
R. Stefanovitch, J. Sua

National Centre for Particle and High

A. Fedorov, M. Korzh

Research Institute for Nuclear Problem

M. Bansal, S. Bansal, ... kx,
L. Mucibello, S. Oche ... ,
P. Van Mechelen, N. V

Universiteit Antwerpen, Antwerpen, B

F. Blekman, S. Blywe ... poulos,
M. Maes, A. Olbrecht ... n Onsem,
I. Villella

Vrije Universiteit Brussel, Brussel, Bel

D. Boutigny, D. Mercier

Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France, Villeurbanne, France

G. Baulieu, S. Beauceron, N. Beaupere, M. Bedjidian, O. Bondu, G. Boudoul, S. Brochet, J. Chasserat, R. Chierici[5], C. Combaret, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, N. Giraud, M. Gouzevitch, R. Haroutunian, B. Ille, T. Kurca, M. Lethuillier, N. Lumb, H. Mathez, L. Mirabito, S. Perries, L. Sgandurra, V. Sordini, Y. Tschudi, M. Vander Donckt, P. Verdier, S. Viret

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

V. Roinishvili, L. Rurua

E. Andronikashvili Institute of Physics, Academy of Science, Tbilisi, Georgia

N. Amaglobeli, I. Bagaturia, B. Chiladze, R. Kvatadze, D. Lomidze, R. Shanidze, Z. Tsamalaidze[15]

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia

R. Adolphi, G. Anagnostou, C. Autermann, S. Beranek, K. Brauer, W. Braunschweig, B. Calpas, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, W. Karpinski, K. Klein, K. Lübelsmeyer, J. Merz, A. Ostapchuk, D. Pandoulas, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Schmitz, A. Schultz von Dratzig, R. Siedling, D. Sprenger, H. Weber, B. Wittmer, M. Wlochal, V. Zhukov[16]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

M. Ata, P. Biallass, J. Caudron, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, G. Hilgers, K. Hoepfner, C. Hof, T. Klimkovich, D. Klingebiel, P. Kreuzer, C. Magass, M. Merschmeyer, A. Meyer, M. Olschewski, P. Papacz, B. Philipps, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, M. Sowa, J. Steggemann, D. Teyssier, M. Weber

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

M. Bontenackels, V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, J. Lingemann[5], A. Nowack, L. Perchalla, O. Pooth, P. Sauerland, A. Stahl, M.H. Zoeller

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

M. Aldaya Martin, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz[17], A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, E. Castro, F. Costanza, D. Dammann, C. Diez Pardos, G. Eckerlin, D. Eckstein, A. Flossdorf, G. Flucke, A. Geiser, I. Glushkov, P. Goettlicher, A. Grebenyuk, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, H. Jung, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, B. Lewendel, W. Lohmann[17], B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, C. Muhl, A. Mussgiller, S. Naumann-Emme, O. Novgorodova, J. Olzem, A. Parenti, H. Perrey, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, E. Ron, C. Rosemann, M. Rosin, J. Salfeld-Nebgen, R. Schmidt[17], T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, J. Tomaszewska, D. Volyanskyy, R. Walsh, C. Wissing, C. Youngman

Deutsches Elektronen-Synchrotron, Hamburg, Germany

V. Blobel, J. Draeger, H. Enderle, J. Erfle, U. Gebbert, M. Görner, T. Hermanns, R.S. Höing, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, B. Mura, F. Nowak, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, J. Sibille[18], V. Sola, H. Stadie, G. Steinbrück, J. Thomsen, L. Vanelderen

University of Hamburg, Hamburg, Germany

C. Barth, J. Bauer, J. Berger, P. Blüm, C. Böser, V. Buege, Z.Y. Chen, S. Chowdhury, T. Chwalek, D. Daeuwel, W. De Boer, A. Descroix, A. Dierlamm, G. Dirkes, M. Fahrer, M. Feindt, U. Felzmann, M. Frey, A. Furgeri,

Authors

CMS Collaboration

N. Godinovic, D. Lelas, R. Plestina [6], D. Polic, I. Puljak [5]

Technical University of Split, Split, Croatia

Z. Antunovic, M. Kovac

University of Split, Split, Croatia

V. Brigljevic, S. Duric, K. Kadija, J. Luetic, S. Morovic

Institute Rudjer Boskovic, Zagreb, Croatia

A. Attikis, M. Galanti, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

University of Cyprus, Nicosia, Cyprus

M. Finger, M. Finger Jr.

Charles University, Prague, Czech Republic

A. Aly, Y. Assran [7], A. Awad, S. Elgammal [8], A. Ellithi Kamel [9], S. Khalil [8], M.A. Mahmoud [10], A. Mahrous, A. Radi [11,12]

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

A. Hektor, M. Kadastik, K. Kannike, M. Müntel, M. Raidal, L. Rebane, A. Strumia, A. Tiko

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, G. Fedi, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

E. Anttila, J. Härkönen, A. Heikkinen, V. Karimäki, H.M. Katajisto, R. Kinnunen, M.J. Kortelainen, M. Kotamäki, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, T.P. Vanhala, L. Wendland

Helsinki Institute of Physics, Helsinki, Finland

K. Banzuzi, A. Karjalainen, A. Korpela, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Anfreville, M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, F.X. Gentit, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Kircher, M.C. Lemaire, E. Locci, J. Malcles, I. Mandjavidze, A. Nayak, J.P. Pansart, J. Rander, J.M. Reymond, A. Rosowsky, I. Shreyber, M. Titov, P. Verrecchia

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

J. Badier, S. Baffioni, F. Beaudette, E. Becheva, L. Benhabib, L. Bianchini, M. Bluj [13], C. Broutin, P. Busson, M. Cerutti, D. Chamont, C. Charlot, N. Daci, T. Dahms, M. Dalchenko, L. Dobrzynski, Y. Geerebaert, R. Granier de Cassagnac, M. Haguenauer, P. Hennion, G. Millerer, P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, T. Romanteau, D. Sabes, R. Salerno, A. Sartirana, Y. Sirois, C. Thiebaux, C. Veelken, A. Zabi

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

J.-L. Agram [14], J. Andrea, A. Besson, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte [14], F. Drouhin [14], C. Ferro, J.-C. Fontaine [14], D. Gelé, U. Goerlach, C. Goetzmann, L. Gross, D. Huss, P. Juillot, E. Kieffer, A.-C. Le Bihan, J. Pansanel, Y. Patois, P. Van Hove

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

Authors

CMS Collaboration

S. Chatrchyan, V. Kha

Yerevan Physics Institute, Yerevan, Ar

W. Adam, E. Aguilo, T
J. Hammer, M. Hoch,
I. Krätschmer, D. Lik
R. Schöfbeck, J. Strau

Institut für Hochenergiephysik der Oe

V. Chekhovsky, I. Em
R. Stefanovitch, J. Su

National Centre for Particle and High

A. Fedorov, M. Korzh

Research Institute for Nuclear Problem

M. Bansal, S. Bansal,
L. Mucibello, S. Oche
P. Van Mechelen, N.

Universiteit Antwerpen, Antwerpen, B

F. Blekman, S. Blywe
M. Maes, A. Olbrecht
I. Villella

Vrije Universiteit Brussel, Brussel, Bel

B. Betchart, A. Bodek, H. Budd, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, A. Garcia-Bellido, G. Ginther, P. Goldenzweig, Y. Gotra, J. Han, A. Harel, S. Korjenevski, D.C. Miner, D. Orbaker, W. Sakumoto, P. Slattery, D. Vishnevskiy, M. Zielinski

University of Rochester, Rochester, USA

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, S. Malik, C. Mesropian

The Rockefeller University, New York, USA

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, A. Lath, S. Panwalkar, M. Park, R. Patel, V. Rekovic, J. Robles, K. Rose, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas

Rutgers, the State University of New Jersey, Piscataway, USA

G. Cerizza, M. Hollingsworth, G. Ragghianti, S. Spanier, Z.C. Yang, A. York

University of Tennessee, Knoxville, USA

O. Bouhali, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon [58], V. Khotilovich, R. Montalvo, C.N. Nguyen, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

Texas A&M University, College Station, USA

N. Akchurin, J. Damgov, C. Dragoiu, P.R. Dudero, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, Y. Roh, A. Sill, I. Volobouev, R. Wigmans

Texas Tech University, Lubbock, USA

E. Appelt, A.G. Delannoy, D. Engh, C. Florez, W. Gabella, S. Greene, A. Gurrola, W. Johns, P. Kurt, C. Maguire, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

Vanderbilt University, Nashville, USA

D. Andelin, M.W. Arenton, M. Balazs, S. Boutle, S. Conetti, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, D. Phillips II, J. Wood

University of Virginia, Charlottesville, USA

S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, M. Mattson, C. Milstène, A. Sakharov

Wayne State University, Detroit, USA

M. Anderson, D. Belknap, J.N. Bellinger, L. Borrello, D. Bradley, D. Carlsmith, M. Cepeda, I. Crotty [5], S. Dasu, F. Feyzi, E. Friis, T. Gorski, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, J. Lackey, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, S. Lusin [5], M. Magrans de Abril, W. Maier, A. Mohapatra, I. Ojalvo, F. Palmonari, G.A. Pierro, D. Reeder, I. Ross, A. Savin, W.H. Smith, J. Swanson, D. Wenman

University of Wisconsin, Madison, USA

Authors

L.M. Cremaldi, R. Kroeger, L. Perera, R. Rahmat, J. Reidy, D.A. Sanders, D. Summers

University of Mississippi, University, USA

G. Attebury, E. Avdeeva, K. Bloom, B. Bockelman, S. Bose, D.R. Claes, A. Dominguez, M. Eads, J. Keller, I. Kravchenko, J. Lazo-Flores, C. Lundstedt, H. Malbouisson, S. Malik, R. Snihur, G.R. Snow, D. Swanson

University of Nebraska-Lincoln, Lincoln, USA

U. Baur, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S.P. Shipkowski, K. Smith

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, J. Moromisato, D. Nash, J. Swain, D. Trocino, E. Von Goeler, D. Wood, J. Zhang

Northeastern University, Boston, USA

A. Anastassov, B. Gobbi, A. Kubik, L. Lusito, N. Odell, R.A. Ofierzynski, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

Northwestern University, Evanston, USA

L. Antonelli, B. Baumbaugh, D. Berry, A. Brinkerhoff, K.M. Chan, A.H. Heering, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, J. Kolb, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, M. Planer, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

B. Bylsma, L.S. Durkin, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, C.J. Rush, V. Sehgal, C. Vuosalo, G. Williams, B.L. Winer

The Ohio State University, Columbus, USA

N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, P. Jindal, D. Lopes Pegna, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval, H. Saka, D. Stickland, C. Tully, J.S. Werner, T. Wildish, Z. Xie, S.C. Zenz, A. Zuranski

Princeton University, Princeton, USA

J.G. Acosta, M. Bonnett Del Alamo, E. Brownson, X.T. Huang, A. Lopez, H. Mendez, S. Oliveros, J.E. Ramirez Vargas, A. Zatserklyaniy

University of Puerto Rico, Mayaguez, USA

E. Alagoz, K. Arndt, V.E. Barnes, D. Benedetti, G. Bolla, D. Bortoletto, A. Bujak, M. De Mattia, A. Everett, L. Gutay, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, J. Lee, N. Leonardo, C. Liu, V. Maroussov, P. Merkel, D.H. Miller, J. Miyamoto, N. Neumeister, C. Rott, A. Roy, I. Shipsey, D. Silvers, A. Svyatkovskiy, M. Vidal Marono, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University, West Lafayette, USA

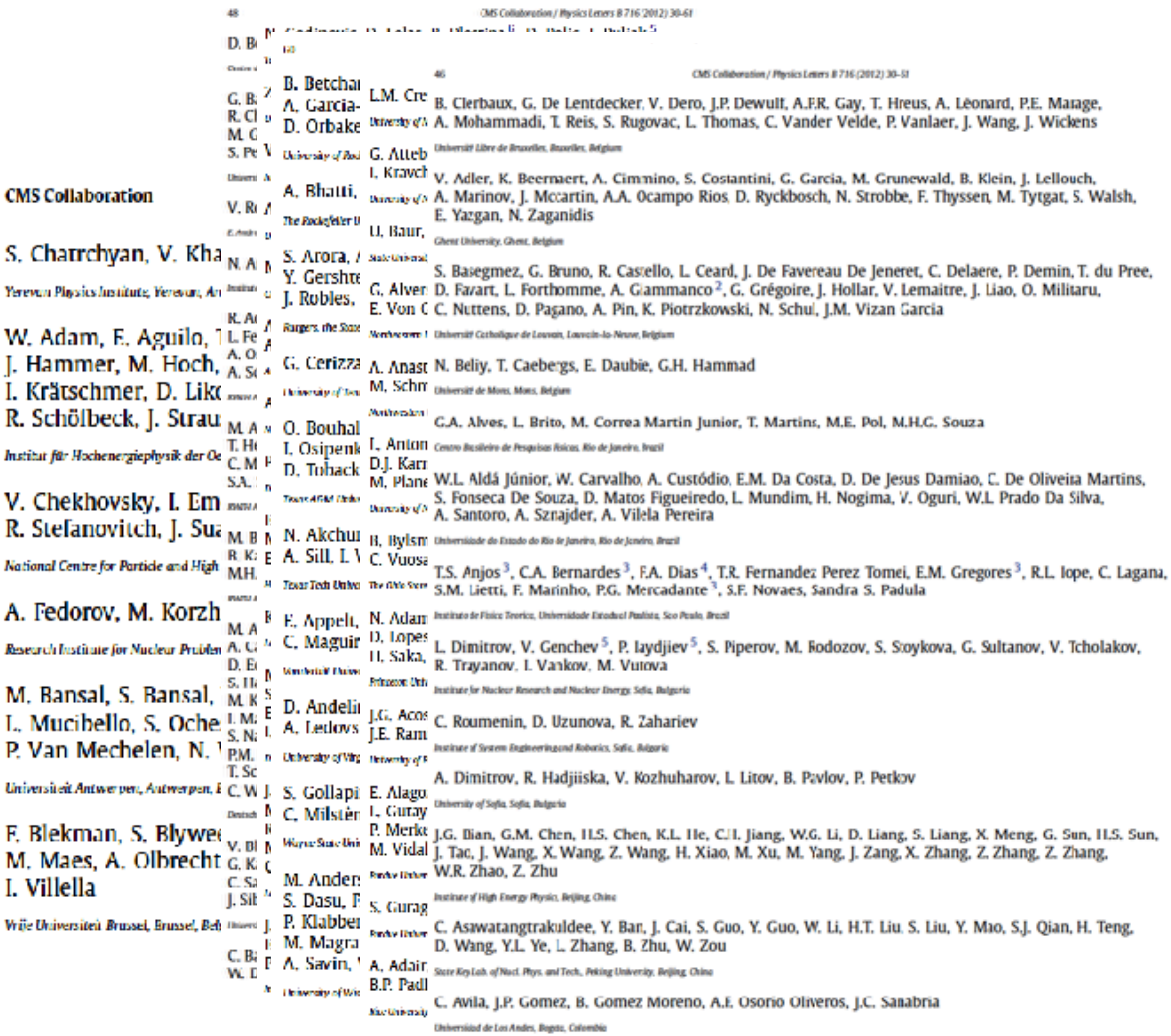
S. Guragain, N. Parashar

Purdue University Calumet, Hammond, USA

A. Adair, C. Boulahouache, V. Cuplov, K.M. Ecklund, F.J.M. Geurts, S.J. Lee, W. Li, J.H. Liu, M. Matveev, B.P. Padley, R. Redjimi, J. Roberts, A. Tumanov, P. Yepes, J. Zabel

Rice University, Houston, USA

Authors



B. Clerbaux, G. De Lentdecker, V. Dero, J.P. Dewulf, A.P.R. Gay, T. Hreus, A. Léonard, P.E. Marage, A. Mohammadi, T. Reis, S. Rugovac, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang, J. Wickens

Université Libre de Bruxelles, Bruxelles, Belgium

V. Adler, K. Beernaert, A. Cimmino, S. Costantini, G. Garcia, M. Grunewald, B. Klein, J. Lellouch, A. Marinov, J. Mccartin, A.A. Ocampo Rios, D. Ryckbosch, N. Strobbe, F. Thyssen, M. Tytgat, S. Walsh, E. Yazgan, N. Zaganidis

Ghent University, Ghent, Belgium

S. Basegmez, G. Bruno, R. Castello, L. Ceard, J. De Favereau De Jeneret, C. Delaere, P. Demin, T. du Pree, D. Favart, L. Forthomme, A. Giammanco[2], G. Grégoire, J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrzkowski, N. Schul, J.M. Vizan Garcia

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

N. Beliy, T. Caebergs, E. Daubie, G.H. Hammad

Université de Mons, Mons, Belgium

G.A. Alves, L. Brito, M. Correa Martins Junior, T. Martins, M.E. Pol, M.H.G. Souza

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, W. Carvalho, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, D. Matos Figueiredo, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, A. Sznajder, A. Vilela Pereira

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

T.S. Anjos[3], C.A. Bernardes[3], F.A. Dias[4], T.R. Fernandez Perez Tomei, E.M. Gregores[3], R.L. Iope, C. Lagana, S.M. Lietti, F. Marinho, P.G. Mercadante[3], S.F. Novaes, Sandra S. Padula

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil

L. Dimitrov, V. Genchev[5], P. Iaydjiev[5], S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, I. Vankov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

C. Roumenin, D. Uzunova, R. Zahariev

Institute of System Engineering and Robotics, Sofia, Bulgaria

A. Dimitrov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

J.G. Bian, G.M. Chen, H.S. Chen, K.L. He, C.H. Jiang, W.G. Li, D. Liang, S. Liang, X. Meng, G. Sun, H.S. Sun, J. Tao, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, M. Yang, J. Zang, X. Zhang, Z. Zhang, Z. Zhang, W.R. Zhao, Z. Zhu

Institute of High Energy Physics, Beijing, China

C. Asawatangtrakuldee, Y. Ban, J. Cai, S. Guo, Y. Guo, W. Li, H.T. Liu, S. Liu, Y. Mao, S.J. Qian, H. Teng, D. Wang, Y.L. Ye, L. Zhang, B. Zhu, W. Zou

State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China

C. Avila, J.P. Gomez, B. Gomez Moreno, A.F. Osorio Oliveros, J.C. Sanabria

Universidad de Los Andes, Bogota, Colombia

Authors

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T. Adams, A. Askew, M. Bertoldi, J. Bochenek, J. Chen, W.G.D. Dharmaratna, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, H. Prosper, S. Tentindo, V. Veeraraghavan, M. Weinberg

Florida State University, Tallahassee, USA

M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, R. Ralich, I. Vodopiyanov, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, I. Bucinskaite, J. Callner, R. Cavanaugh, M.H. Chung, O. Evdokimov, E.J. Garcia-Solis, L. Gauthier, C.E. Gerber, D.J. Hofman, R. Hollis, A. Iordanova, S. Khalatyan, G.J. Kunde[63], F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, C. Silvestre, A. Smoron, D. Strom, P. Turner, N. Varelas

University of Illinois at Chicago (UIC), Chicago, USA

U. Akgun, E.A. Albayrak, A.S. Ayan, B. Bilki[64], W. Clarida, P. Debbins, F. Duru, F.D. Ingram, E. McCliment, J.-P. Merlo, H. Mermerkaya[65], A. Mestvirishvili, M.J. Miller, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, J. Olson, Y. Onel, F. Ozok[66], I. Schmidt, S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

The University of Iowa, Iowa City, USA

B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, G. Giurgiu, A.V. Gritsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, A. Whitbeck

Johns Hopkins University, Baltimore, USA

P. Baringer, A. Bean, G. Benelli, D. Coppage, O. Grachov, R.P. Kenny Iii, M. Murray, D. Noonan, V. Radicci, S. Sanders, R. Stringer, G. Tinti, J.S. Wood, V. Zhukova

The University of Kansas, Lawrence, USA

A.F. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze

Kansas State University, Manhattan, USA

J. Gronberg, D. Lange, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

A. Baden, R. Bard, M. Boutemeur, B. Calvert, S.C. Eno, J.A. Gomez, T. Grassi, N.J. Hadley, R.G. Kellogg, M. Kirn, T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, K. Pedro, A. Peterman, K. Rossato, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, T. Toole, E. Twedt

University of Maryland, College Park, USA

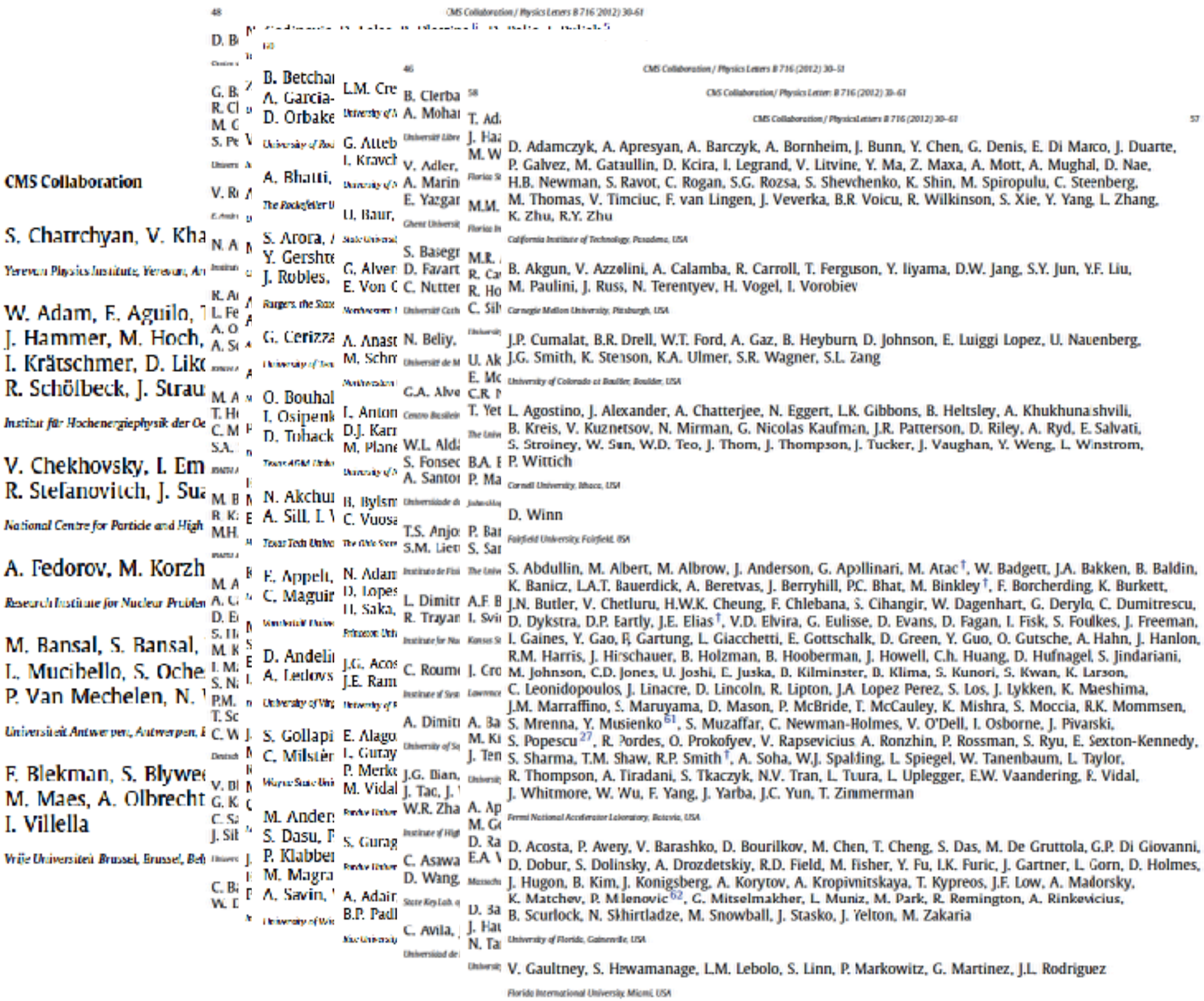
A. Apyan, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, Y. Kim, M. Klute, K. Krajczar[67], A. Levin, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, E.A. Wenger, R. Wolf, B. Wyslouch, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

Massachusetts Institute of Technology, Cambridge, USA

D. Bailleux, S.I. Cooper, P. Cushman, B. Dahmes, A. De Benedetti, R. Egeland, G. Franzoni, A. Gude, J. Haupt, A. Inyakin, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, R. Rusack, A. Singovsky, N. Tambe, J. Turkewitz

University of Minnesota, Minneapolis, USA

Authors



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D. Adamczyk, A. Apresyan, A. Barczyk, A. Bornheim, J. Bunn, Y. Chen, G. Denis, E. Di Marco, J. Duarte, P. Galvez, M. Gataullin, D. Kcira, I. Legrand, V. Litvine, Y. Ma, Z. Maxa, A. Mott, A. Mughal, D. Nae, H.B. Newman, S. Ravot, C. Rogan, S.G. Rozsa, S. Shevchenko, K. Shin, M. Spiropulu, C. Steenberg, M. Thomas, V. Timciuc, F. van Lingen, J. Veverka, B.R. Voicu, R. Wilkinson, S. Xie, Y. Yang, L. Zhang, K. Zhu, R.Y. Zhu

California Institute of Technology, Pasadena, USA

B. Akgun, V. Azzolini, A. Calamba, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, S.Y. Jun, Y.F. Liu, M. Paulini, J. Russ, N. Terentyev, H. Vogel, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, B.R. Drell, W.T. Ford, A. Gaz, B. Heyburn, D. Johnson, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner, S.L. Zang

University of Colorado at Boulder, Boulder, USA

L. Agostino, J. Alexander, A. Chatterjee, N. Eggert, L.K. Gibbons, B. Heltsley, A. Khukhunaishvili, B. Kreis, V. Kuznetsov, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, D. Riley, A. Ryd, E. Salvati, S. Stroiney, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Tucker, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Cornell University, Ithaca, USA

D. Winn

Fairfield University, Fairfield, USA

S. Abdullin, M. Albert, M. Albrow, J. Anderson, G. Apollinari, M. Atac[†], W. Badgett, J.A. Bakken, B. Baldin, K. Banicz, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, M. Binkley[†], F. Borcherding, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, S. Cihangir, W. Dagenhart, G. Derylo, C. Dumitrescu, D. Dykstra, D.P. Eartly, J.E. Elias[†], V.D. Elvira, G. Eulisse, D. Evans, D. Fagan, I. Fisk, S. Foulkes, J. Freeman, I. Gaines, Y. Gao, P. Gartung, L. Giacchetti, E. Gottschalk, D. Green, Y. Guo, O. Gutsche, A. Hahn, J. Hanlon, R.M. Harris, J. Hirschauer, B. Holzman, B. Hooberman, J. Howell, C.h. Huang, D. Hufnagel, S. Jindariani, M. Johnson, C.D. Jones, U. Joshi, E. Juska, B. Kilminster, B. Klima, S. Kunori, S. Kwan, K. Larson, C. Leonidopoulos, J. Linacre, D. Lincoln, R. Lipton, J.A. Lopez Perez, S. Los, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, T. McCauley, K. Mishra, S. Moccia, R.K. Mommsen, S. Mrenna, Y. Musienko[61], S. Muzaffar, C. Newman-Holmes, V. O'Dell, I. Osborne, J. Pivarski, S. Popescu[27], R. Pordes, O. Prokofyev, V. Rapsevicius, A. Ronzhin, P. Rossman, S. Ryu, E. Sexton-Kennedy, S. Sharma, T.M. Shaw, R.P. Smith[†], A. Soha, W.J. Spalding, L. Spiegel, W. Tanenbaum, L. Taylor, R. Thompson, A. Tiradani, S. Tkaczyk, N.V. Tran, L. Tuura, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, J. Yarba, J.C. Yun, T. Zimmerman

Fermi National Accelerator Laboratory, Batavia, USA

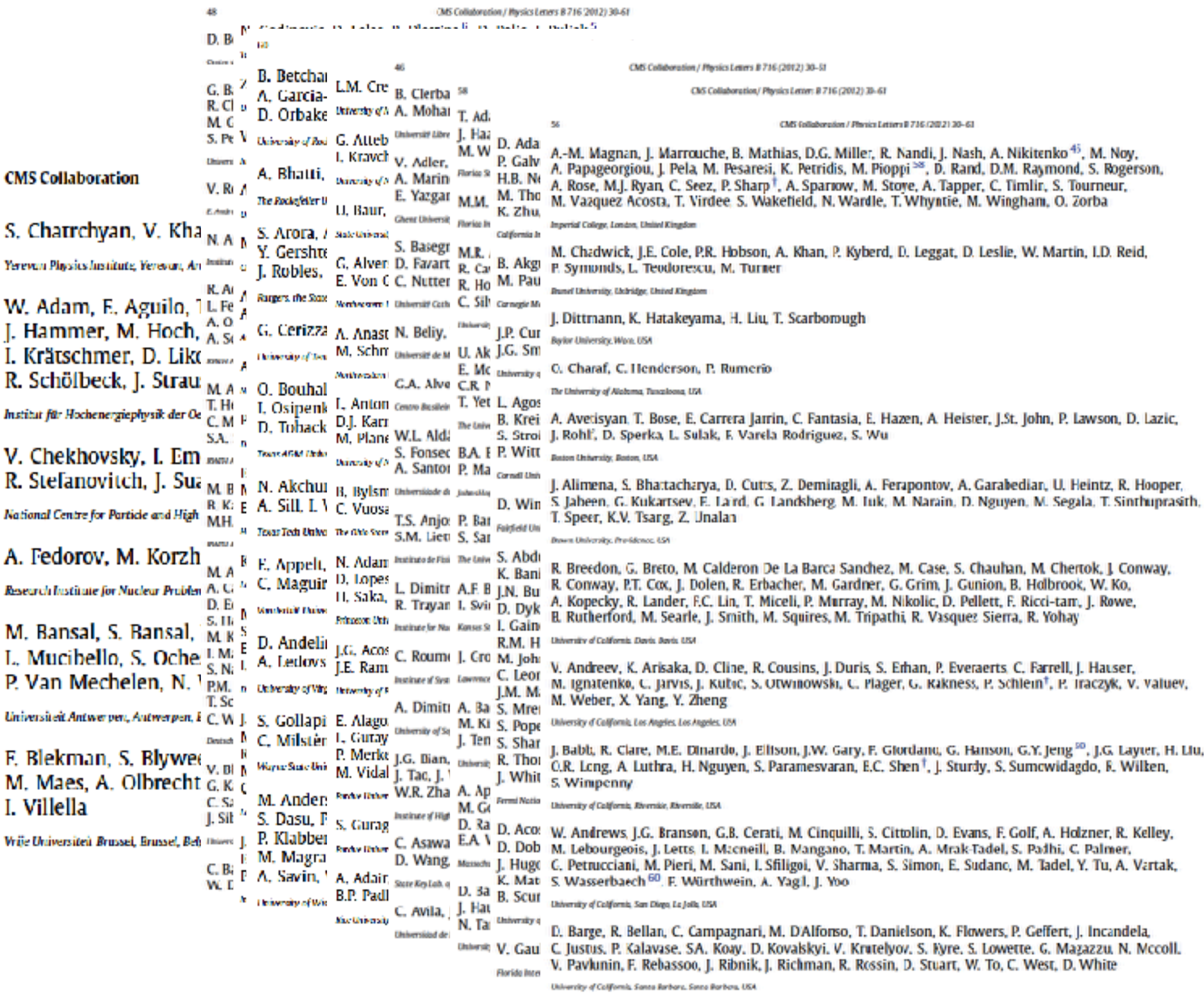
D. Acosta, P. Avery, V. Barashko, D. Bourilkov, M. Chen, T. Cheng, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, S. Dolinsky, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, L. Gorn, D. Holmes, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, A. Madorsky, K. Matchev, P. Milenovic[62], G. Mitselmakher, L. Muniz, M. Park, R. Remington, A. Rinkevicius, B. Scurlock, N. Skhirtladze, M. Snowball, J. Stasko, J. Yelton, M. Zakaria

University of Florida, Gainesville, USA

V. Gaultney, S. Hewamanage, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida International University, Miami, USA

Authors



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A.-M. Magnan, J. Marrouche, B. Mathias, D.G. Miller, R. Nandi, J. Nash, A. Nikitenko [45], M. Noy, A. Papageorgiou, J. Pela, M. Pesaresi, K. Petridis, M. Pioppi [58], D. Rand, D.M. Raymond, S. Rogerson, A. Rose, M.J. Ryan, C. Seez, P. Sharp †, A. Sparrow, M. Stoye, A. Tapper, C. Timlin, S. Tourneur, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie, M. Wingham, O. Zorba

Imperial College, London, United Kingdom

M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, W. Martin, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Brunel University, Uxbridge, United Kingdom

J. Dittmann, K. Hatakeyama, H. Liu, T. Scarborough

Baylor University, Waco, USA

O. Charaf, C. Henderson, P. Rumerio

The University of Alabama, Tuscaloosa, USA

A. Avetisyan, T. Bose, E. Carrera Jarrin, C. Fantasia, E. Hazen, A. Heister, J.St. John, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, L. Sulak, F. Varela Rodriguez, S. Wu

Boston University, Boston, USA

J. Alimena, S. Bhattacharya, D. Cutts, Z. Demiragli, A. Ferapontov, A. Garabedian, U. Heintz, R. Hooper, S. Jabeen, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, D. Nguyen, M. Segala, T. Sinthuprasith, T. Speer, K.V. Tsang, Z. Unalan

Brown University, Providence, USA

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, M. Case, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, J. Dolen, R. Erbacher, M. Gardner, G. Grim, J. Gunion, B. Holbrook, W. Ko, A. Kopecky, R. Lander, F.C. Lin, T. Miceli, P. Murray, M. Nikolic, D. Pellett, F. Ricci-tam, J. Rowe, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra, R. Yohay

University of California, Davis, Davis, USA

V. Andreev, K. Arisaka, D. Cline, R. Cousins, J. Duris, S. Erhan, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, J. Kubic, S. Otwinowski, C. Plager, G. Rakness, P. Schlein †, P. Traczyk, V. Valuev, M. Weber, X. Yang, Y. Zheng

University of California, Los Angeles, Los Angeles, USA

J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng [59], J.G. Layter, H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, E.C. Shen †, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, Riverside, Riverside, USA

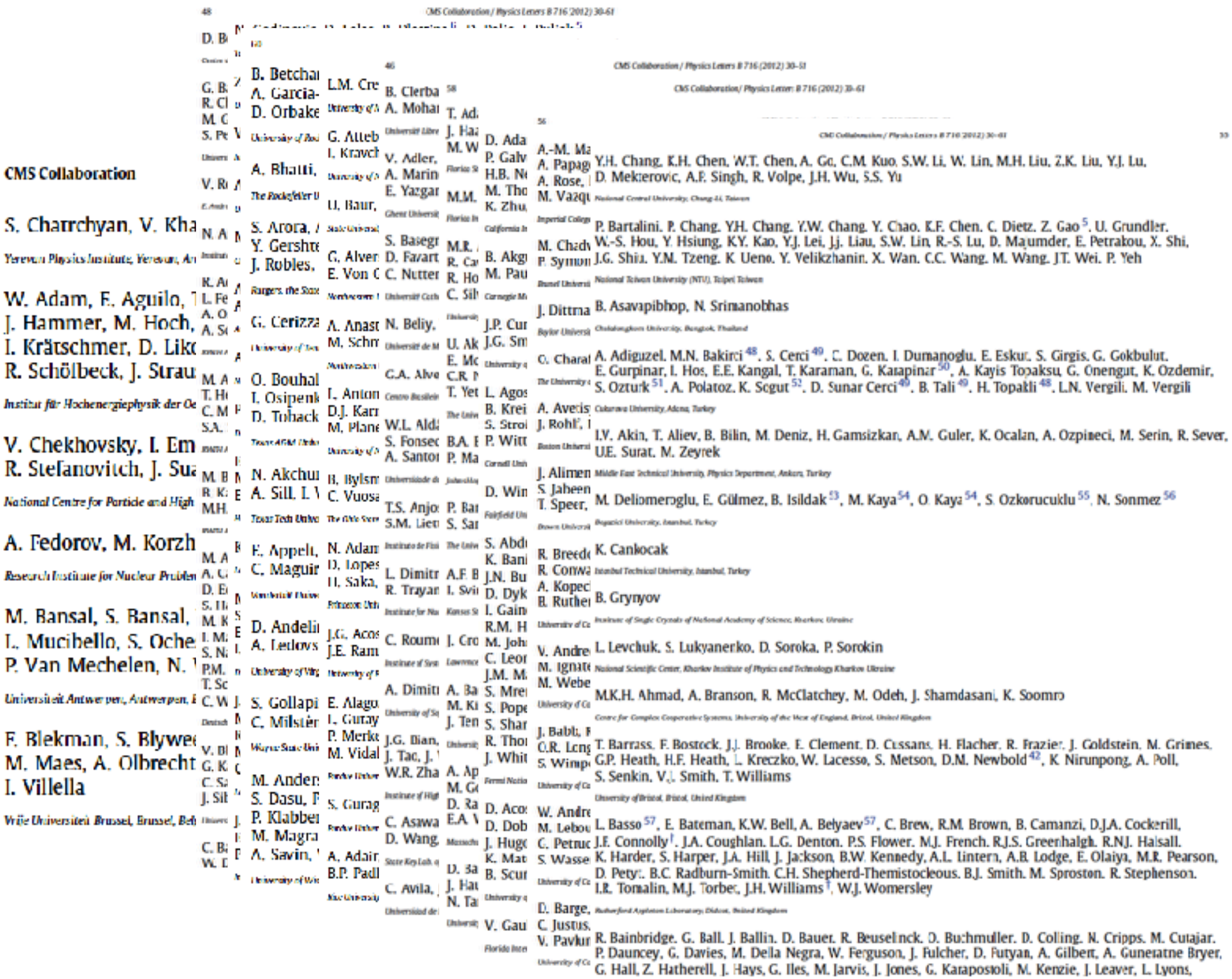
W. Andrews, J.G. Branson, G.B. Cerati, M. Cinquilli, S. Cittolin, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, T. Martin, A. Mrak-Tadel, S. Padhi, C. Palmer, C. Petrucciani, M. Pieri, M. Sani, I. Sfiligoi, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech [60], F. Würthwein, A. Yagil, J. Yoo

University of California, San Diego, La Jolla, USA

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, S. Kyre, S. Lowette, G. Magazzu, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, C. West, D. White

University of California, Santa Barbara, Santa Barbara, USA

Authors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Y.H. Chang, K.H. Chen, W.T. Chen, A. Go, C.M. Kuo, S.W. Li, W. Lin, M.H. Liu, Z.K. Liu, Y.J. Lu, D. Mekterovic, A.P. Singh, R. Volpe, J.H. Wu, S.S. Yu

National Central University, Chung-Li, Taiwan

P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, C. Dietz, Z. Gao[5], U. Grundler, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, J.J. Liau, S.W. Lin, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, J.G. Shiu, Y.M. Tzeng, K. Ueno, Y. Velikzhanin, X. Wan, C.C. Wang, M. Wang, J.T. Wei, P. Yeh

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, N. Srimanobhas

Chulalongkorn University, Bangkok, Thailand

A. Adiguzel, M.N. Bakirci[48], S. Cerci[49], C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, G. Karapinar[50], A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk[51], A. Polatoz, K. Sogut[52], D. Sunar Cerci[49], B. Tali[49], H. Topakli[48], L.N. Vergili, M. Vergili

Cukurova University, Adana, Turkey

I.V. Akin, T. Aliev, B. Bilin, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

M. Deliomeroglu, E. Gülmez, B. Isildak[53], M. Kaya[54], O. Kaya[54], S. Ozkorucuklu[55], N. Sonmez[56]

Bogazici University, Istanbul, Turkey

K. Cankocak

Istanbul Technical University, Istanbul, Turkey

B. Grynyov

Institute of Single Crystals of National Academy of Science, Kharkov, Ukraine

L. Levchuk, S. Lukyanenko, D. Soroka, P. Sorokin

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

M.K.H. Ahmad, A. Branson, R. McClatchey, M. Odeh, J. Shamdasani, K. Soomro

Centre for Complex Cooperative Systems, University of the West of England, Bristol, United Kingdom

T. Barrass, F. Bostock, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, W. Lacesso, S. Metson, D.M. Newbold[42], K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

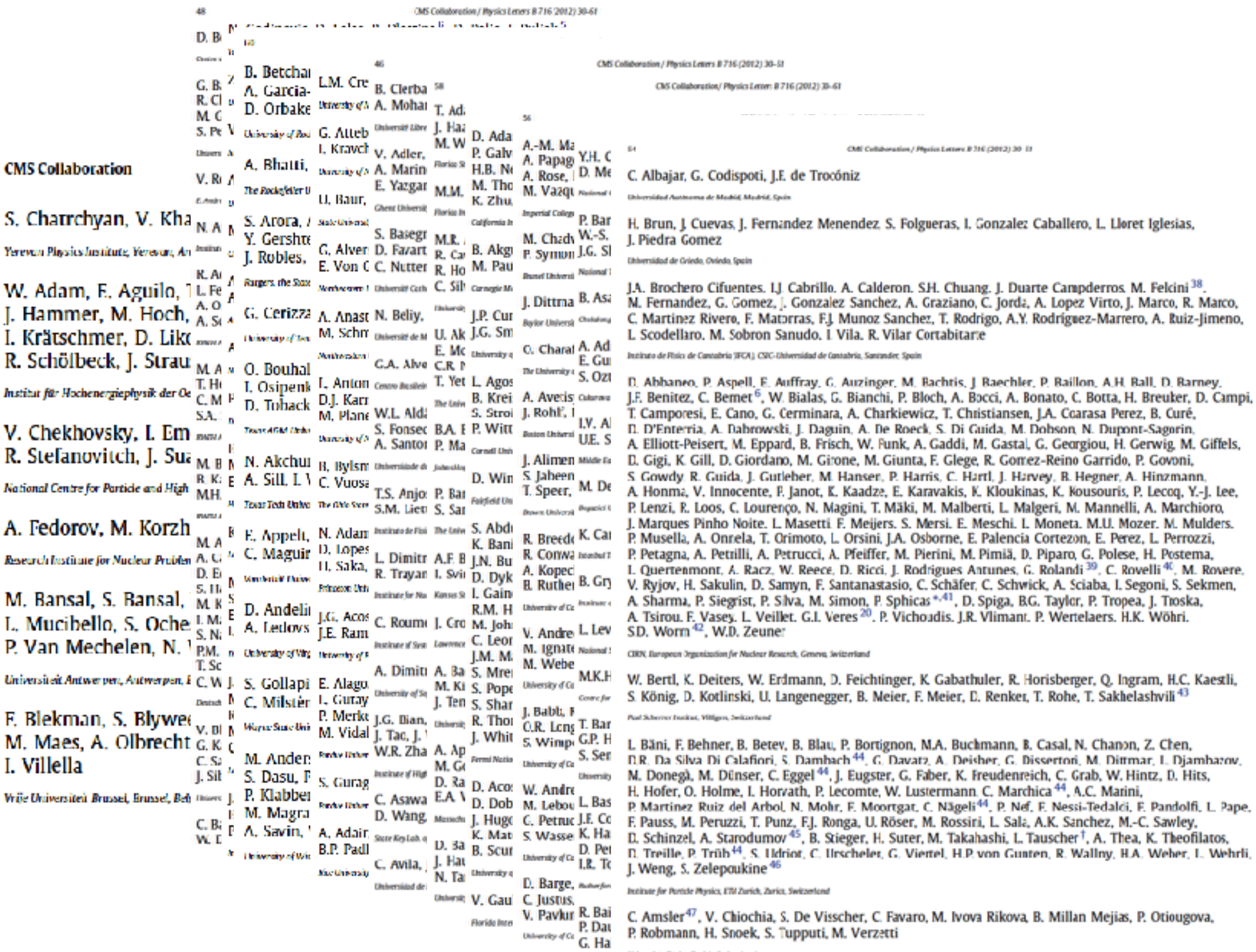
University of Bristol, Bristol, United Kingdom

L. Basso[57], K. Bateman, K.W. Bell, A. Belyaev[57], C. Brew, R.M. Brown, D.J.A. Cockerill, J.F. Connolly†, J.A. Coughlan, L.G. Denton, P.S. Flower, M.J. French, R.J.S. Greenhalgh, R.N.J. Halsall, K. Harder, S. Harper, J.A. Hill, J. Jackson, B.W. Kennedy, A.L. Lintern, A.B. Lodge, E. Olaiya, M.R. Pearson, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, B.J. Smith, M. Sproston, R. Stephenson, I.R. Tomalin, M.J. Torbet, J.H. Williams†, W.J. Womersley

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, G. Ball, J. Ballin, D. Bauer, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, J. Jones, G. Karapostoli, M. Kenzie, J. Leaver, L. Lyons,

Authors



CMS Collaboration / Physics Letters B 716 (2012) 30–61

C. Albajar, G. Codispoti, J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J. Piedra Gomez

Universidad de Oviedo, Oviedo, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini[38], M. Fernandez, G. Gomez, J. Gonzalez Sanchez, A. Graziano, C. Jorda, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

D. Abbaneo, P. Aspell, E. Auffray, G. Auzinger, M. Bachtis, J. Baechler, P. Baillon, A.H. Ball, D. Barney, J.F. Benitez, C. Bernet[6], W. Bialas, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, D. Campi, T. Camporesi, E. Cano, G. Cerminara, A. Charkiewicz, T. Christiansen, J.A. Coarasa Perez, B. Curé, D. D'Enterria, A. Dabrowski, J. Daguin, A. De Roeck, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, M. Eppard, B. Frisch, W. Funk, A. Gaddi, M. Gastal, G. Georgiou, H. Gerwig, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Girone, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, J. Gutleber, M. Hansen, P. Harris, C. Hartl, J. Harvey, B. Hegner, A. Hinzmann, A. Honma, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, K. Kloukinas, K. Kousouris, P. Lecoq, Y.-J. Lee, P. Lenzi, R. Loos, C. Lourenço, N. Magini, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, A. Marchioro, J. Marques Pinho Noite, L. Masetti, F. Meijers, S. Mersi, E. Meschi, L. Moneta, M.U. Mozer, M. Mulders, P. Musella, A. Onnela, T. Orimoto, L. Orsini, J.A. Osborne, E. Palencia Cortezon, E. Perez, L. Perrozzi, P. Petagna, A. Petrilli, A. Petrucci, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, H. Postema, L. Quertenmont, A. Racz, W. Reece, D. Ricci, J. Rodrigues Antunes, G. Rolandi[39], C. Rovelli[40], M. Rovere, V. Ryjov, H. Sakulin, D. Samyn, F. Santanastasio, C. Schäfer, C. Schwick, A. Sciaba, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas[*,41], D. Spiga, B.G. Taylor, P. Tropea, J. Troska, A. Tsirou, F. Vasey, L. Veillet, G.I. Veres[20], P. Vichoudis, J.R. Vlimant, P. Wertelaers, H.K. Wöhri, S.D. Worm[42], W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

W. Bertl, K. Deiters, W. Erdmann, D. Feichtinger, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, B. Meier, F. Meier, D. Renker, T. Rohe, T. Sakhelashvili[43]

Paul Scherrer Institut, Villigen, Switzerland

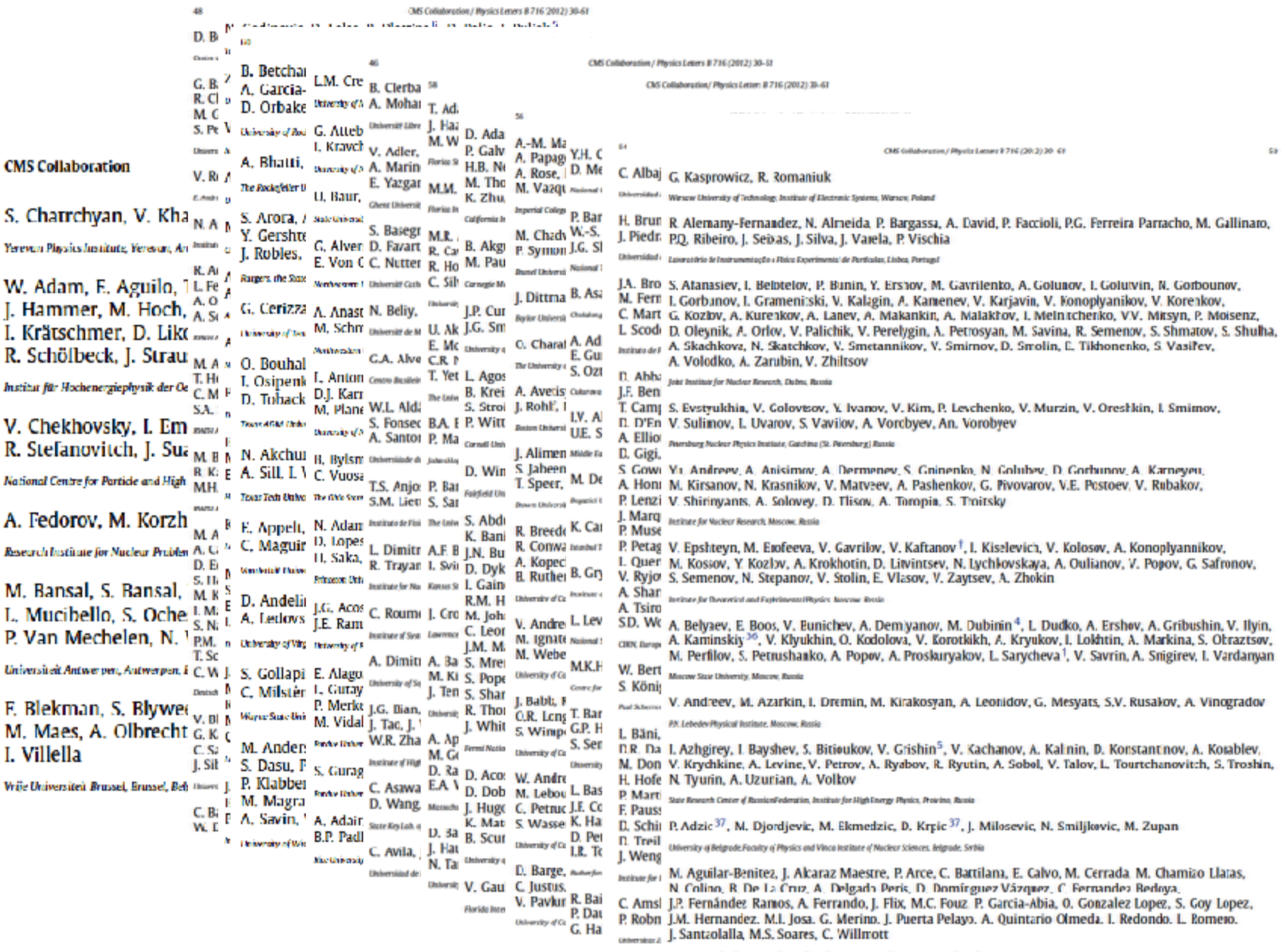
L. Bäni, F. Behner, B. Betev, B. Blau, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, Z. Chen, D.R. Da Silva Di Calafiori, S. Dambach[44], G. Davatz, A. Deisher, G. Dissertori, M. Dittmar, L. Djambazov, M. Donegà, M. Dünser, C. Eggel[44], J. Eugster, G. Faber, K. Freudenreich, C. Grab, W. Hintz, D. Hits, H. Hofer, O. Holme, I. Horvath, P. Lecomte, W. Lustermann, C. Marchica[44], A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli[44], P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, T. Punz, F.J. Ronga, U. Röser, M. Rossini, L. Sala, A.K. Sanchez, M.-C. Sawley, D. Schinzel, A. Starodumov[45], B. Stieger, H. Suter, M. Takahashi, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, P. Trüb[44], S. Udriot, C. Urscheler, G. Viertel, H.P. von Gunten, R. Wallny, H.A. Weber, L. Wehrli, J. Weng, S. Zelepoukine[46]

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

C. Amsler[47], V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Tupputi, M. Verzetti

Universität Zürich, Zurich, Switzerland

Authors



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G. Kasprowicz, R. Romaniuk

Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland

R. Alemany-Fernandez, N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, P.Q. Ribeiro, J. Seixas, J. Silva, J. Varela, P. Vischia

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

S. Afanasiev, I. Belotelov, P. Bunin, Y. Ershov, M. Gavrilenko, A. Golunov, I. Golutvin, N. Gorbounov, I. Gorbunov, I. Gramenitski, V. Kalagin, A. Kamenev, V. Karjavin, V. Konoplyanikov, V. Korenkov, G. Kozlov, A. Kurenkov, A. Lanev, A. Makankin, A. Malakhov, I. Melnitchenko, V.V. Mitsyn, P. Moisenz, D. Oleynik, A. Orlov, V. Palichik, V. Perelygin, A. Petrosyan, M. Savina, R. Semenov, S. Shmatov, S. Shulha, A. Skachkova, N. Skatchkov, V. Smetannikov, V. Smirnov, D. Smolin, E. Tikhonenko, S. Vasil'ev, A. Volodko, A. Zarubin, V. Zhiltsov

Joint Institute for Nuclear Research, Dubna, Russia

S. Evstyukhin, V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

Yu. Andreev, A. Anisimov, A. Dermenev, S. Gninenko, N. Golubev, D. Gorbunov, A. Karneyeu, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, G. Pivovarov, V.E. Postoev, V. Rubakov, V. Shirinyants, A. Solovey, D. Tlisov, A. Toropin, S. Troitsky

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, M. Erofeeva, V. Gavrilov, V. Kaftanov[†], I. Kiselevich, V. Kolosov, A. Konoplyannikov, M. Kossov, Y. Kozlov, A. Krokhotin, D. Litvintsev, N. Lychkovskaya, A. Oulianov, V. Popov, G. Safronov, S. Semenov, N. Stepanov, V. Stolin, E. Vlasov, V. Zaytsev, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

A. Belyaev, E. Boos, V. Bunichev, A. Demiyanov, M. Dubinin[4], L. Dudko, A. Ershov, A. Gribushin, V. Ilyin, A. Kaminskiy[36], V. Klyukhin, O. Kodolova, V. Korotkikh, A. Kryukov, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, A. Popov, L. Proskuryakov, L. Sarycheva[†], V. Savrin, I. Snigirev, I. Vardanyan

Moscow State University, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov

P.N. Lebedev Physical Institute, Moscow, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin[5], V. Kachanov, A. Kalinin, D. Konstantinov, A. Korablev, V. Krychkine, A. Levine, V. Petrov, A. Ryabov, R. Ryutin, A. Sobol, V. Talov, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

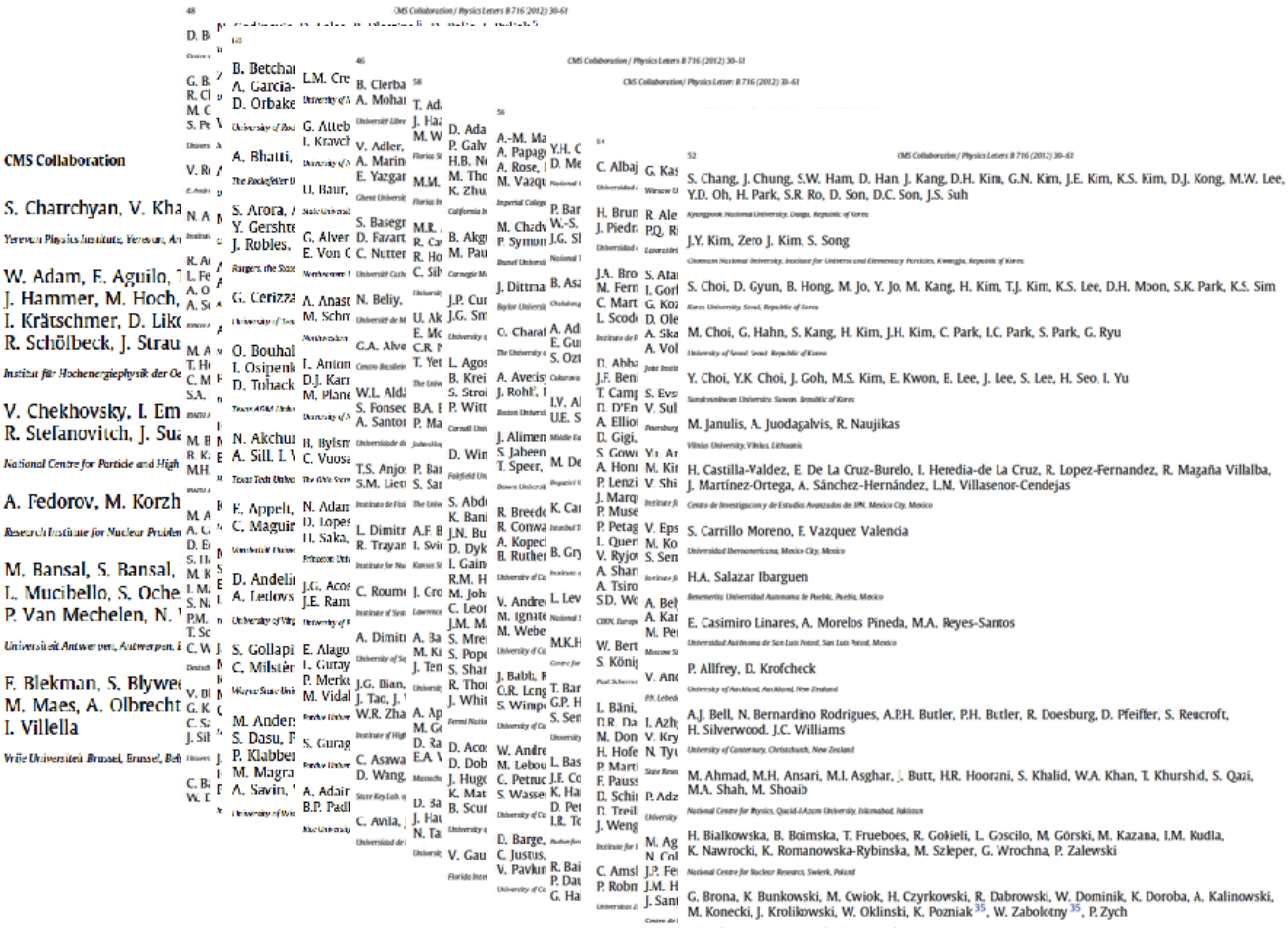
P. Adzic[37], M. Djordjevic, M. Ekmedzic, D. Krpic[37], J. Milosevic, N. Smiljkovic, M. Zupan

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

M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

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

Authors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S. Chang, J. Chung, S.W. Ham, D. Han, J. Kang, D.H. Kim, G.N. Kim, J.E. Kim, K.S. Kim, D.J. Kong, M.W. Lee, Y.D. Oh, H. Park, S.R. Ro, D. Son, D.C. Son, J.S. Suh

Kyungpook National University, Daegu, Republic of Korea

J.Y. Kim, Zero J. Kim, S. Song

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

S. Choi, D. Gyun, B. Hong, M. Jo, Y. Jo, M. Kang, H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park, K.S. Sim

Korea University, Seoul, Republic of Korea

M. Choi, G. Hahn, S. Kang, H. Kim, J.H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

University of Seoul, Seoul, Republic of Korea

Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, E. Kwon, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

M. Janulis, A. Juodagalvis, R. Naujikas

Vilnius University, Vilnius, Lithuania

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, R. Lopez-Fernandez, R. Magaña Villalba, J. Martínez-Ortega, A. Sánchez-Hernández, L.M. Villasenor-Cendejas

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

H.A. Salazar Ibarguen

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

P. Allfrey, D. Krofcheck

University of Auckland, Auckland, New Zealand

A.J. Bell, N. Bernardino Rodrigues, A.P.H. Butler, P.H. Butler, R. Doesburg, D. Pfeiffer, S. Reucroft, H. Silverwood, J.C. Williams

University of Canterbury, Christchurch, New Zealand

M. Ahmad, M.H. Ansari, M.I. Asghar, J. Butt, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoaib

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

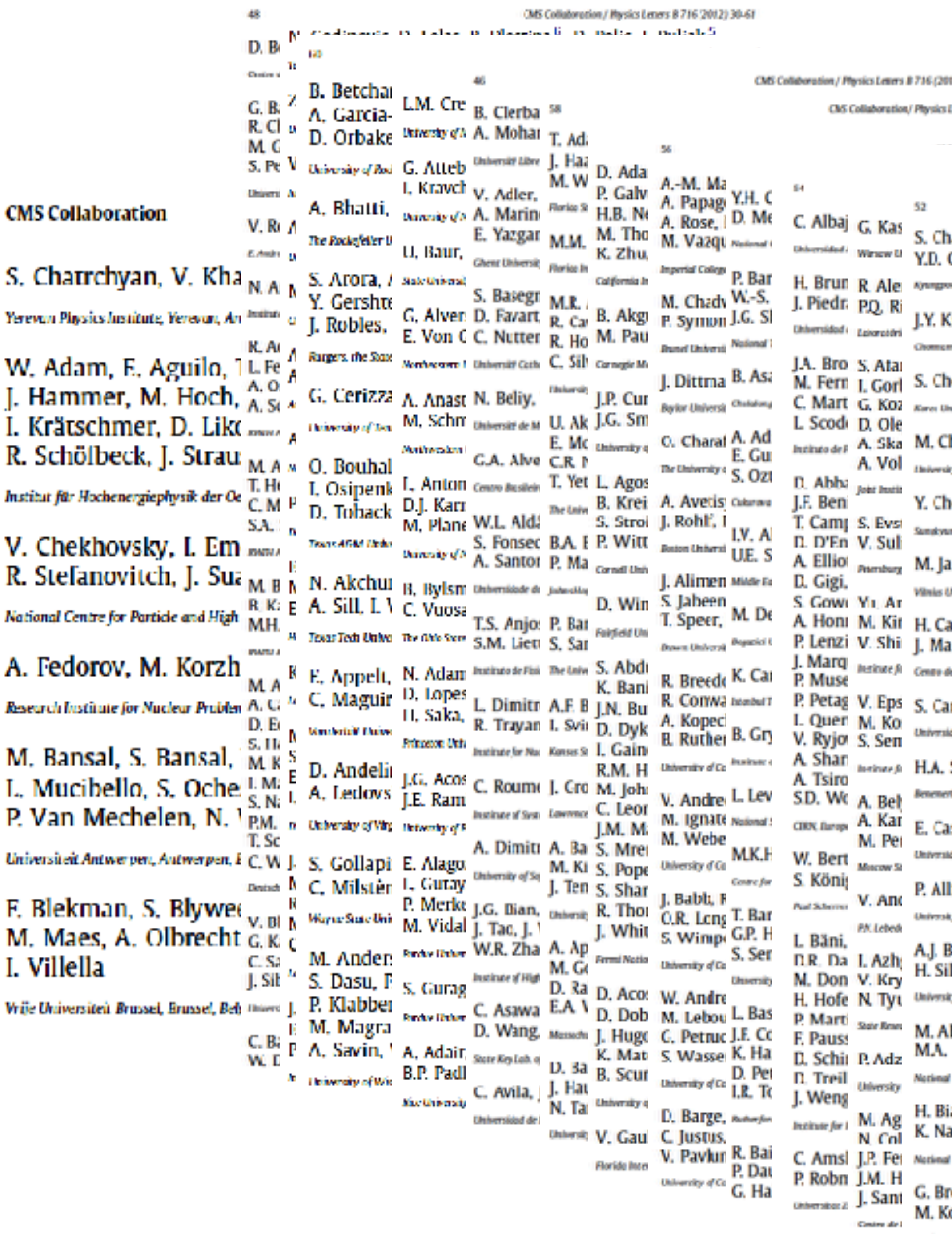
H. Bialkowska, B. Boimska, T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

G. Brona, K. Bunkowski, M. Cwiok, H. Czyrkowski, R. Dabrowski, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, W. Oklinski, K. Pozniak[35], W. Zabolotny[35], P. Zych

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

Authors



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P. Azzi[a], N. Bacchetta[a,5], M. Bellato[a], M. Benettoni[a], M. Biasotto[a,31], D. Bisello[a,b], A. Branca[a,5], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a], U. Dosselli[a], F. Fanzago[a], F. Gasparini[a,b], U. Gasparini[a,b], P. Giubilato[a,b], F. Gonella[a], A. Gozzelino[a], M. Gulmini[a,31], K. Kanishchev[a,c], S. Lacaprara[a], I. Lazzizzera[a,c], M. Loreti[a], M. Margoni[a,b], G. Maron[a,31], M. Mazzucato[a], A.T. Meneguzzo[a,b], F. Montecassiano[a], M. Passaseo[a], J. Pazzini[a,b], M. Pegoraro[a], N. Pozzobon[a,b], P. Ronchese[a,b], F. Simonetto[a,b], E. Torassa[a], M. Tosi[a,b], S. Vanini[a,b], S. Ventura[a], P. Zotto[a,b], G. Zumerle[a,b]

[a] INFN Sezione di Padova, Padova, Italy
[b] Università di Padova, Padova, Italy
[c] Università di Trento (Trento), Padova, Italy

U. Berzano[a], M. Gabusi[a,b], S.P. Ratti[a,b], C. Riccardi[a,b], P. Torre[a,b], P. Vitulo[a,b]

[a] INFN Sezione di Pavia, Pavia, Italy
[b] Università di Pavia, Pavia, Italy

M. Biasini[a,b], G.M. Bilei[a], L. Fanò[a,b], P. Lariccia[a,b], A. Lucaroni[a,b,5], G. Mantovani[a,b], M. Menichelli[a], A. Nappi[a,b,†], D. Passeri[a,b], P. Placidi[a,b], F. Romeo[a,b], A. Saha[a], A. Santocchia[a,b], L. Servoli[a], A. Spiezia[a,b], S. Taroni[a,b], M. Valdata[a,b]

[a] INFN Sezione di Perugia, Perugia, Italy
[b] Università di Perugia, Perugia, Italy

F. Angelini[a], S. Arezzini[a], P. Azzurri[a,c], G. Bagliesi[a], A. Basti[a], R. Bellazzini[a], J. Bernardini[a], T. Boccali[a], F. Bosi[a], A. Brez[a], G. Broccolo[a,c], F. Calzolari[a], A. Carboni[a], R. Castaldi[a], C. Cerri[a], A. Ciampa[a], R.T. D'Agnolo[a,c,5], R. Dell'Orso[a], F. Fiori[a,b,5], L. Foà[a,c], A. Giassi[a], S. Giusti[a], A. Kraan[a], L. Latronico[a], F. Ligabue[a,c], S. Linari[a], T. Lomtadze[a], L. Martini[a,32], M. Massa[a], M.M. Massai[a], E. Mazzoni[a], A. Messineo[a,b], A. Moggi[a], F. Palla[a], F. Raffaelli[a], A. Rizzi[a,b], G. Sanguinetti[a], G. Segneri[a], A.T. Serban[a,33], P. Spagnolo[a], G. Spandre[a], P. Squillacioti[a,5], R. Tenchini[a], G. Tonelli[a,b], A. Venturi[a], P.G. Verdini[a]

[a] INFN Sezione di Pisa, Pisa, Italy
[b] Università di Pisa, Pisa, Italy
[c] Scuola Normale Superiore di Pisa, Pisa, Italy

S. Baccaro[a,34], L. Barone[a,b], A. Bartoloni[a], F. Cavallari[a], I. Dafinei[a], D. Del Re[a,b], M. Diemoz[a], C. Fanelli, M. Grassi[a,b,5], E. Longo[a,b], P. Meridiani[a,5], F. Micheli[a,b], S. Nourbakhsh[a,b], G. Organtini[a,b], R. Paramatti[a], S. Rahatlou[a,b], M. Sigamani[a], L. Soffi[a,b], I.G. Talamo[a]

[a] INFN Sezione di Roma, Roma, Italy
[b] Università di Roma "La Sapienza", Roma, Italy

N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], C. Biino[a], N. Cartiglia[a], M. Costa[a,b], N. Demaria[a], C. Mariotti[a,5], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], M. Musich[a,5], M.M. Obertino[a,c], N. Pastrone[a], M. Pelliccioni[a], C. Peroni[a,b], A. Potenza[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], A. Solano[a,b], A. Staiano[a]

[a] INFN Sezione di Torino, Torino, Italy
[b] Università di Torino, Torino, Italy
[c] Università del Piemonte Orientale (Novara), Torino, Italy

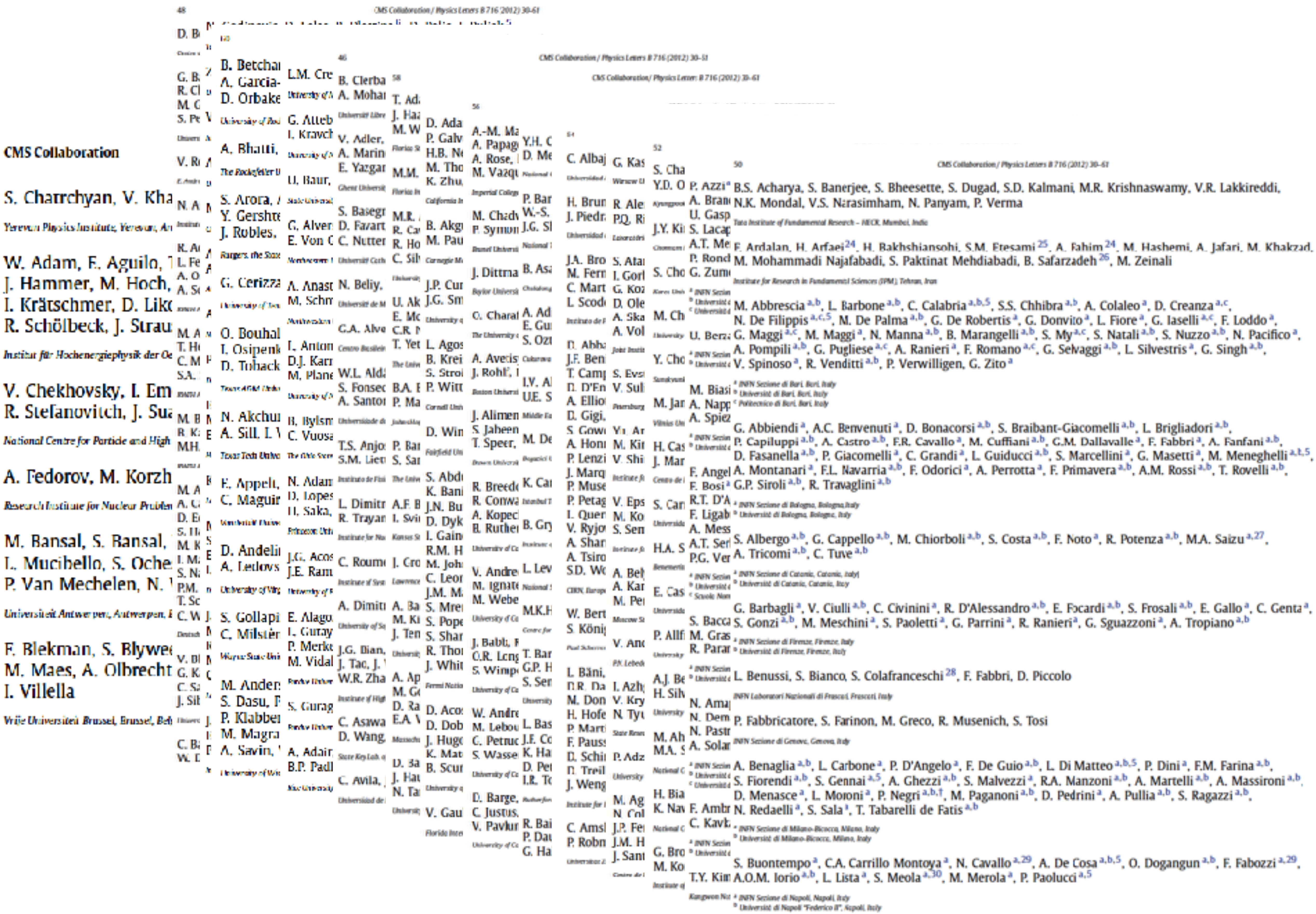
F. Ambroglini[a,b], S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], G. Della Ricca[a,b], B. Gobbo[a], C. Kavka[a], M. Marone[a,b,5], D. Montanino[a,b,5], A. Penzo[a], A. Schizzi[a,b]

[a] INFN Sezione di Trieste, Trieste, Italy
[b] Università di Trieste, Trieste, Italy

T.Y. Kim, S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

Authors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B.S. Acharya, S. Banerjee, S. Bheesette, S. Dugad, S.D. Kalmani, M.R. Krishnaswamy, V.R. Lakkireddi, N.K. Mondal, V.S. Narasimham, N. Panyam, P. Verma

Tata Institute of Fundamental Research – HECR, Mumbai, India

F. Ardalan, H. Arfaei[24], H. Bakhshiansohi, S.M. Etesami[25], A. Fahim[24], M. Hashemi, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh[26], M. Zeinali

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

M. Abbrescia[a,b], L. Barbone[a,b], C. Calabria[a,b,5], S.S. Chhibra[a,b], A. Colaleo[a], D. Creanza[a,c], N. De Filippis[a,c,5], M. De Palma[a,b], G. De Robertis[a], G. Donvito[a], L. Fiore[a], G. Iaselli[a,c], F. Loddo[a], G. Maggi[a,c], M. Maggi[a], N. Manna[a,b], B. Marangelli[a,b], S. My[a,c], S. Natali[a,b], S. Nuzzo[a,b], N. Pacifico[a], A. Pompili[a,b], G. Pugliese[a,c], A. Ranieri[a], F. Romano[a,c], G. Selvaggi[a,b], L. Silvestris[a], G. Singh[a,b], V. Spinoso[a], R. Venditti[a,b], P. Verwilligen, G. Zito[a]

[a] INFN Sezione di Bari, Bari, Italy
[b] Università di Bari, Bari, Italy
[c] Politecnico di Bari, Bari, Italy

G. Abbiendi[a], A.C. Benvenuti[a], D. Bonacorsi[a,b], S. Braibant-Giacomelli[a,b], L. Brigliadori[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a,b], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], S. Marcellini[a], G. Masetti[a], M. Meneghelli[a,b,5], A. Montanari[a], F.L. Navarria[a,b], F. Odorici[a], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b], R. Travaglini[a,b]

[a] INFN Sezione di Bologna, Bologna, Italy
[b] Università di Bologna, Bologna, Italy

S. Albergo[a,b], G. Cappello[a,b], M. Chiorboli[a,b], S. Costa[a,b], F. Noto[a], R. Potenza[a,b], M.A. Saizu[a,27], A. Tricomi[a,b], C. Tuve[a,b]

[a] INFN Sezione di Catania, Catania, Italy
[b] Università di Catania, Catania, Italy

G. Barbagli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], S. Frosali[a,b], E. Gallo[a], C. Genta[a], S. Gonzi[a,b], M. Meschini[a], S. Paoletti[a], G. Parrini[a], R. Ranieri[a], G. Sguazzoni[a], A. Tropiano[a,b]

[a] INFN Sezione di Firenze, Firenze, Italy
[b] Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, S. Colafranceschi[28], F. Fabbri, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

P. Fabbricatore, S. Farinon, M. Greco, R. Musenich, S. Tosi

INFN Sezione di Genova, Genova, Italy

A. Benaglia[a,b], L. Carbone[a], P. D'Angelo[a], F. De Guio[a,b], L. Di Matteo[a,b,5], P. Dini[a], F.M. Farina[a,b], S. Fiorendi[a,b], S. Gennai[a,5], A. Ghezzi[a,b], S. Malvezzi[a], R.A. Manzoni[a,b], A. Martelli[a,b], A. Massironi[a,b], D. Menasce[a], L. Moroni[a], P. Negri[a,b,†], M. Paganoni[a,b], D. Pedrini[a], A. Pullia[a,b], S. Ragazzi[a,b], N. Redaelli[a], S. Sala[a], T. Tabarelli de Fatis[a,b]

[a] INFN Sezione di Milano-Bicocca, Milano, Italy
[b] Università di Milano-Bicocca, Milano, Italy

S. Buontempo[a], C.A. Carrillo Montoya[a], N. Cavallo[a,29], A. De Cosa[a,b,5], O. Dogangun[a,b], F. Fabozzi[a,29], A.O.M. Iorio[a,b], L. Lista[a], S. Meola[a,30], M. Merola[a], P. Paolucci[a,5]

[a] INFN Sezione di Napoli, Napoli, Italy
[b] Università di Napoli "Federico II", Napoli, Italy

Authors

CMS Collaboration / Physics Letters B 716 (2012) 30–61 49

I. Gebauer, A. Gessler, J. Gruschke, M. Guthoff[5], C. Hackstein, F. Hartmann, F. Hauler, T. Hauth[5], S. Heier, S.M. Heindl, M. Heinrich, A. Heiss, H. Held, K.H. Hoffmann, S. Honc, U. Husemann, M. Imhof, C. Jung, S. Junghans, I. Katkov[16], U. Kerzel, D. Knoblauch, J.R. Komaragiri, M. Kräber, T. Kuhr, T. Liamsawan, P. Lobelle Pardo, D. Martschei, A. Menchikov, X. Mol, D. Mörmann, S. Mueller, Th. Müller, D. Neuberger, M.B. Neuland, M. Niegel, A. Nürnberg, O. Oberst, A. Oehler, T. Ortega Gomez, J. Ott, C. Piasecki, A. Poschlad, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, M. Renz, S. Röcker, F. Roederer, A. Sabellek, C. Saout, A. Scheurer, D. Schieferdecker, P. Schieferdecker, F.-P. Schilling, M. Schmanau, G. Schott, W. Schwerdtfeger, H.J. Simonis, A. Skiba, F.M. Stober, A. Theel, W.H. Thümmel, D. Troendle, A. Trunov, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, M. Zeise, E.B. Ziebarth, M. Zvada

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari

Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece

L. Gouskos, A. Panagiotou, N. Saoulidou

University of Athens, Athens, Greece

I. Evangelou, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras, F.A. Triantis

University of Ioánnina, Ioánnina, Greece

G. Bencze, C. Hajdu, P. Hidas, D. Horvath[19], F. Sikler, V. Veszpremi, G. Vesztergombi[20], P. Zalan

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

N. Beni, S. Czellar, A. Fenyvesi, J. Molnar, J. Palinkas, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

J. Karancsi, P. Raics, Z.L. Trocsanyi, B. Ujvari, G. Zilizi

University of Debrecen, Debrecen, Hungary

S.B. Beri, V. Bhandari, V. Bhatnagar, N. Dhingra, R. Gupta, M. Kaur, J.M. Kohli, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, J.B. Singh

Panjab University, Chandigarh, India

Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, S. Chatterji, B.C. Choudhary, P. Gupta, S. Malhotra, M. Naimuddin, K. Ranjan, R.K. Shivpuri

University of Delhi, Delhi, India

S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, S. Sarkar, M. Sharan

Saha Institute of Nuclear Physics, Kolkata, India

A. Abdulsalam, R.K. Choudhury, D. Dutta, M. Ghodgaonkar, S. Kailas, S.K. Kataria, V. Kumar, P. Mehta, A.K. Mohanty[5], L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Chendvankar, P.V. Deshpande, S.N. Ganguli, S. Ganguly, M. Guchait[21], A. Gurtu[22], M. Maity[23], K. Mazumdar, G.B. Mohanty, B. Parida, M.R. Patil, R. Raghavan, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research – EHEP, Mumbai, India

S. Buontempo[a], C.A. Carrillo Montoya[a], N. Cavallo[a,29], A. De Cosa[a,b,5], O. Dogangun[a,b], F. Fabozzi[a,29], A.O.M. Iorio[a,b], L. Lista[a], S. Meola[a,30], M. Merola[a], P. Paolucci[a,5]

~3000 authors × 2 experiments!

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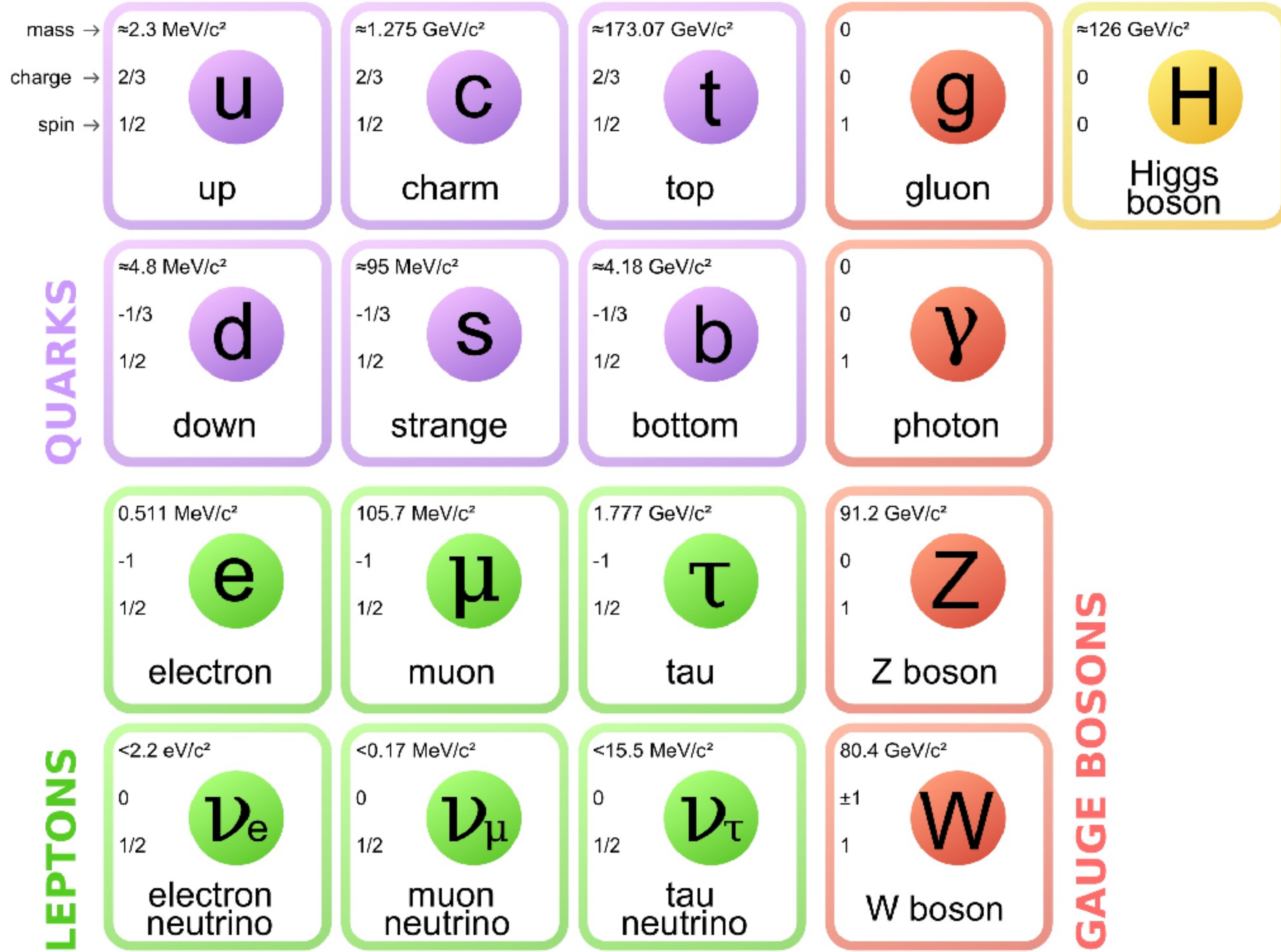
Overview

What do all these people do?

- How to make a new particle
- Building a particle detector
- Operating a detector
- Understanding the detector
- Analyzing the data & making a discovery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charge →
spin →
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2/3
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1/2
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charm
≈173.07 GeV/c²
2/3
1/2
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top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
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-1/3
1/2
d
down
≈95 MeV/c²
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1/2
s
strange
≈4.18 GeV/c²
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1/2
b
bottom
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0
1
γ
photon
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-1
1/2
e
electron
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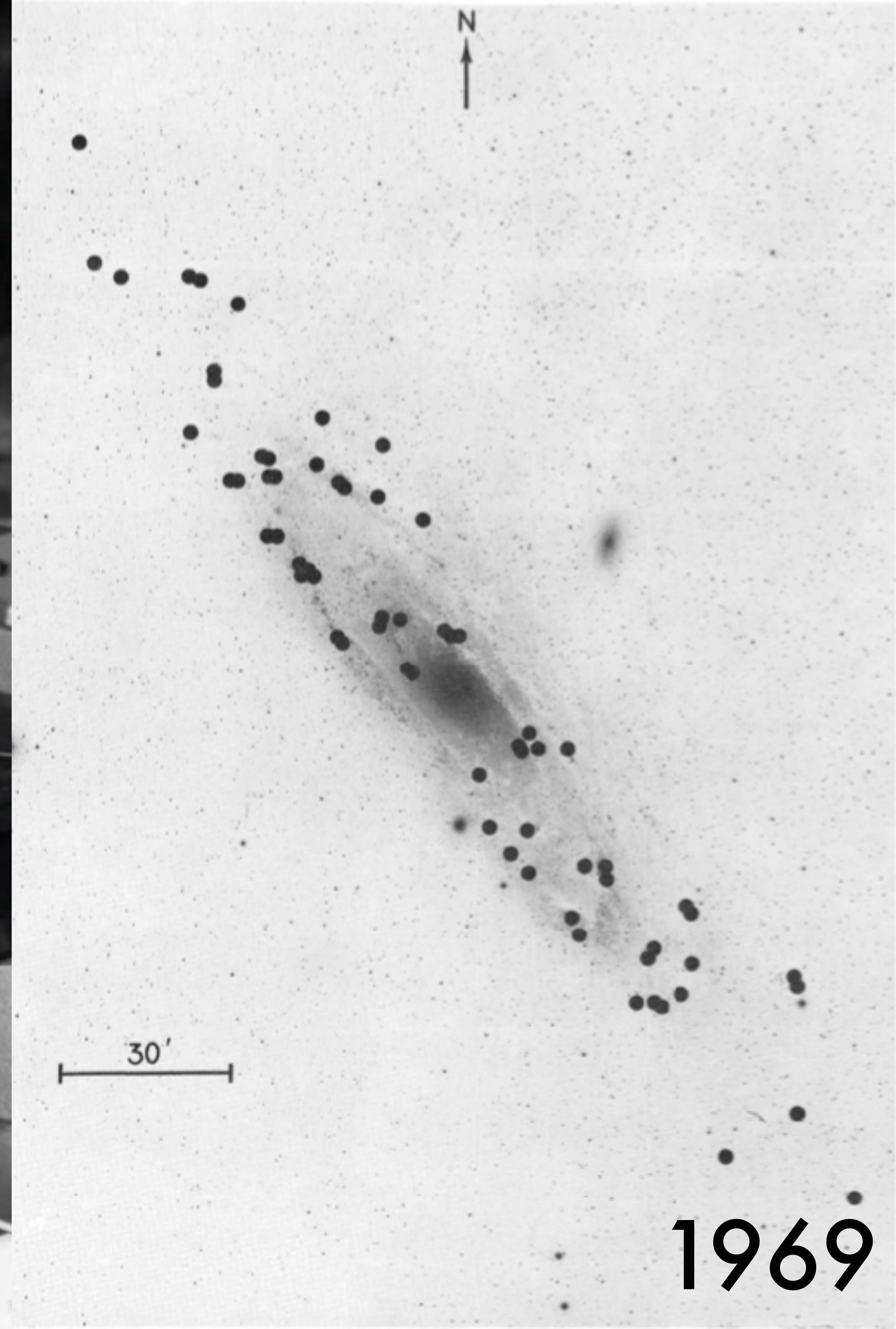
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS

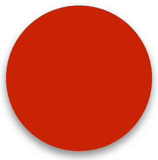


1969

2015

How to make a new particle

$$E = mc^2$$



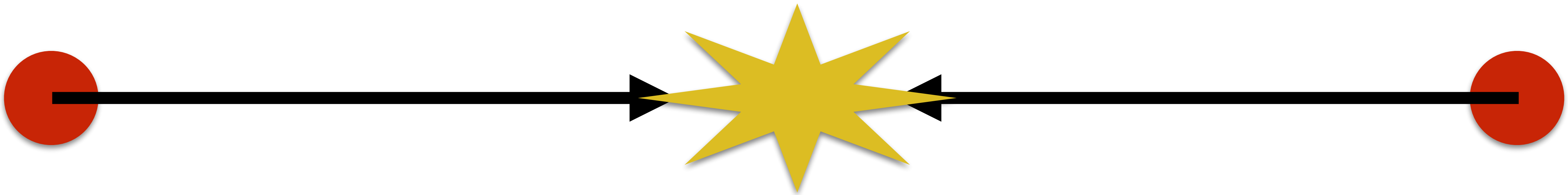
How to make a new particle

$$E = \gamma mc^2$$

How to make a new particle

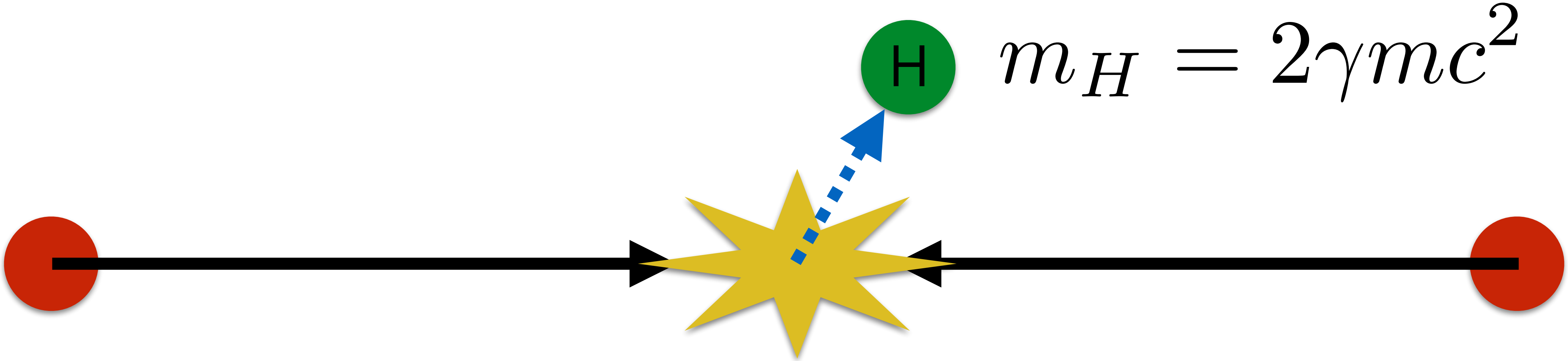
$$E = \gamma mc^2 \qquad\qquad E = \gamma mc^2$$

How to make a new particle



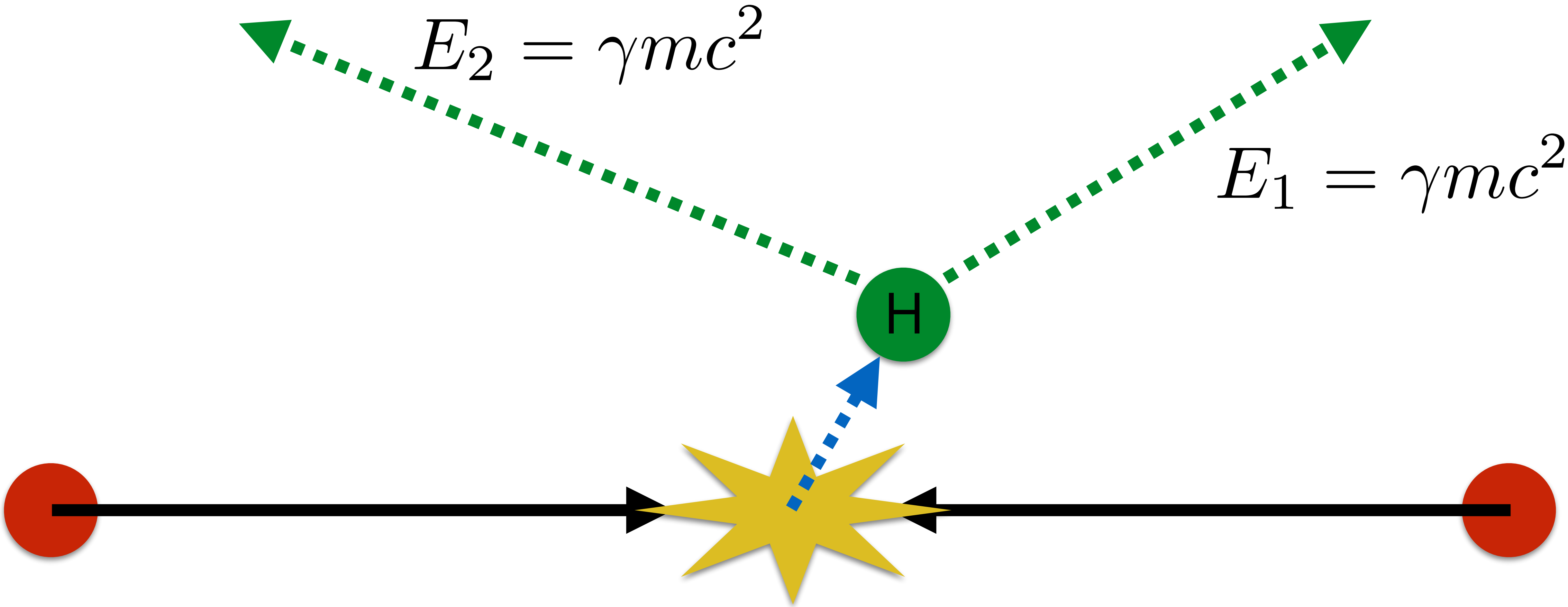
$$E = 2\gamma mc^2$$

How to make a new particle



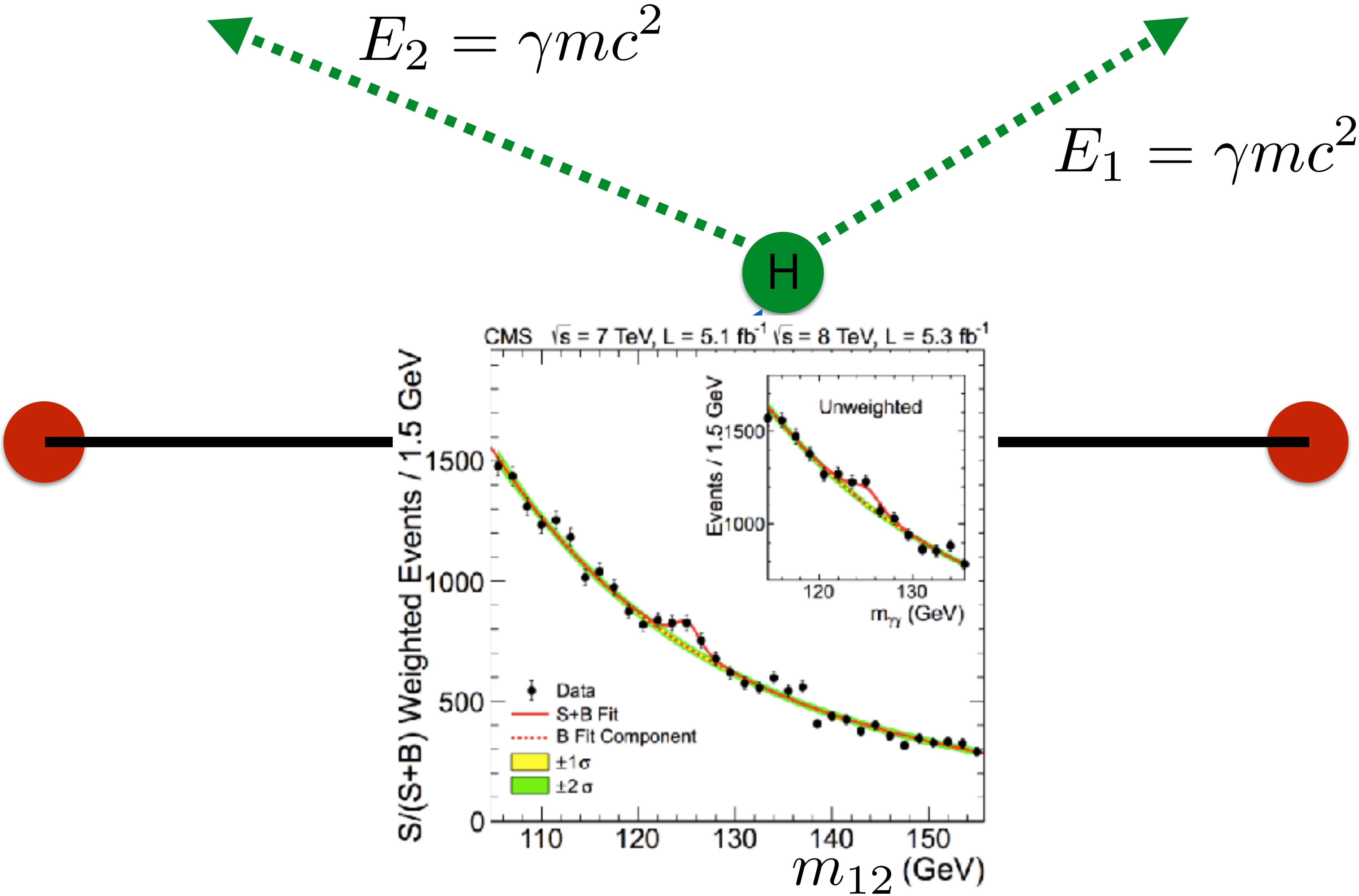
$$m_H = 2\gamma mc^2$$

How to make a new particle

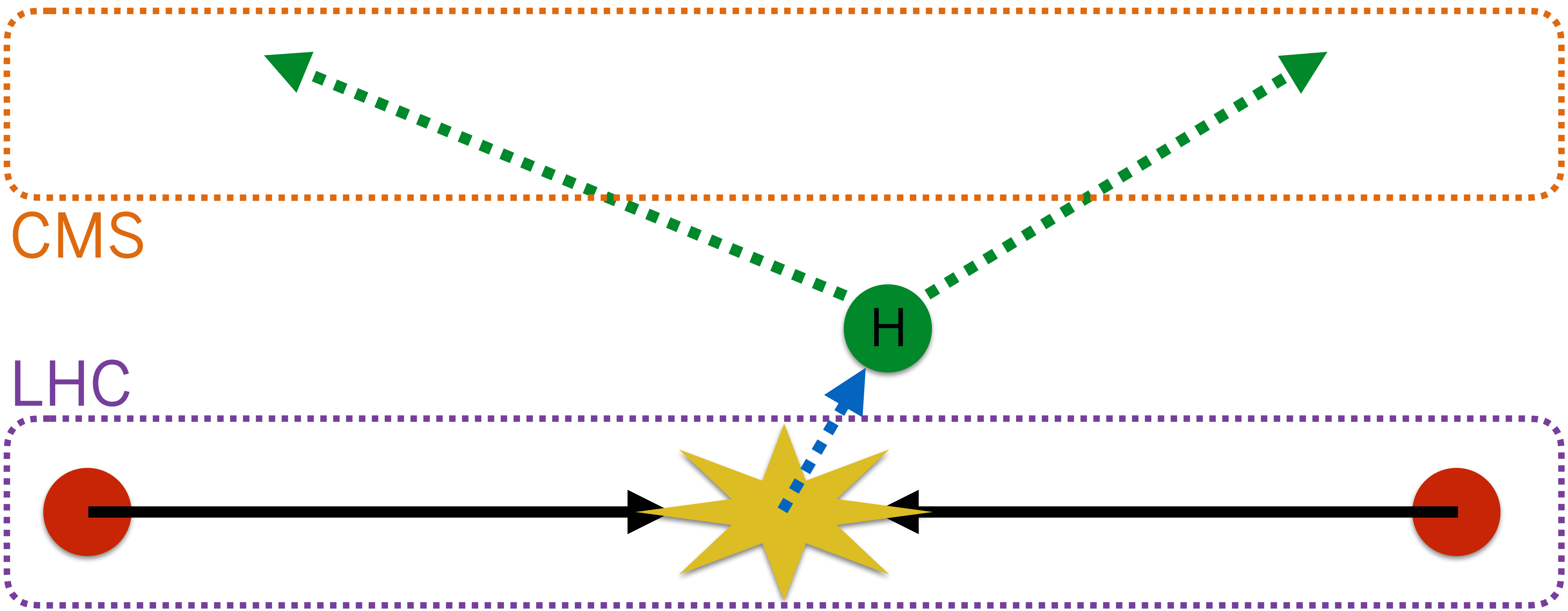


m_{12}

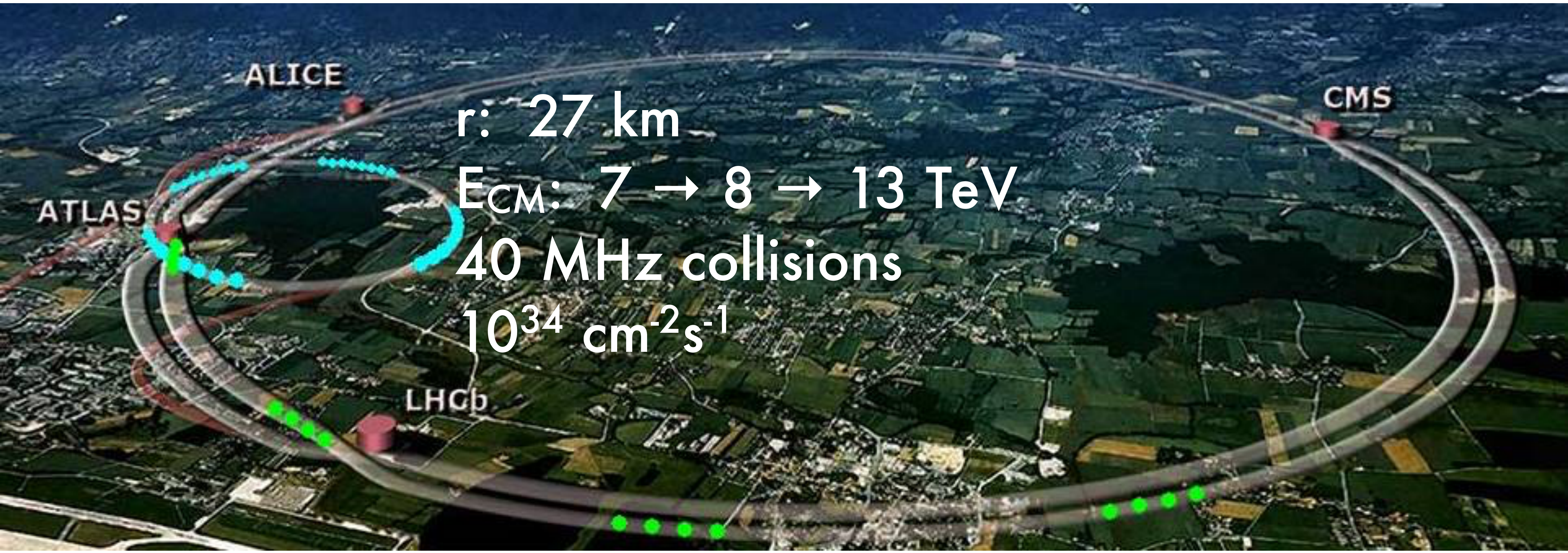
How to make a new particle



How to make a new particle



The LHC



r: 27 km

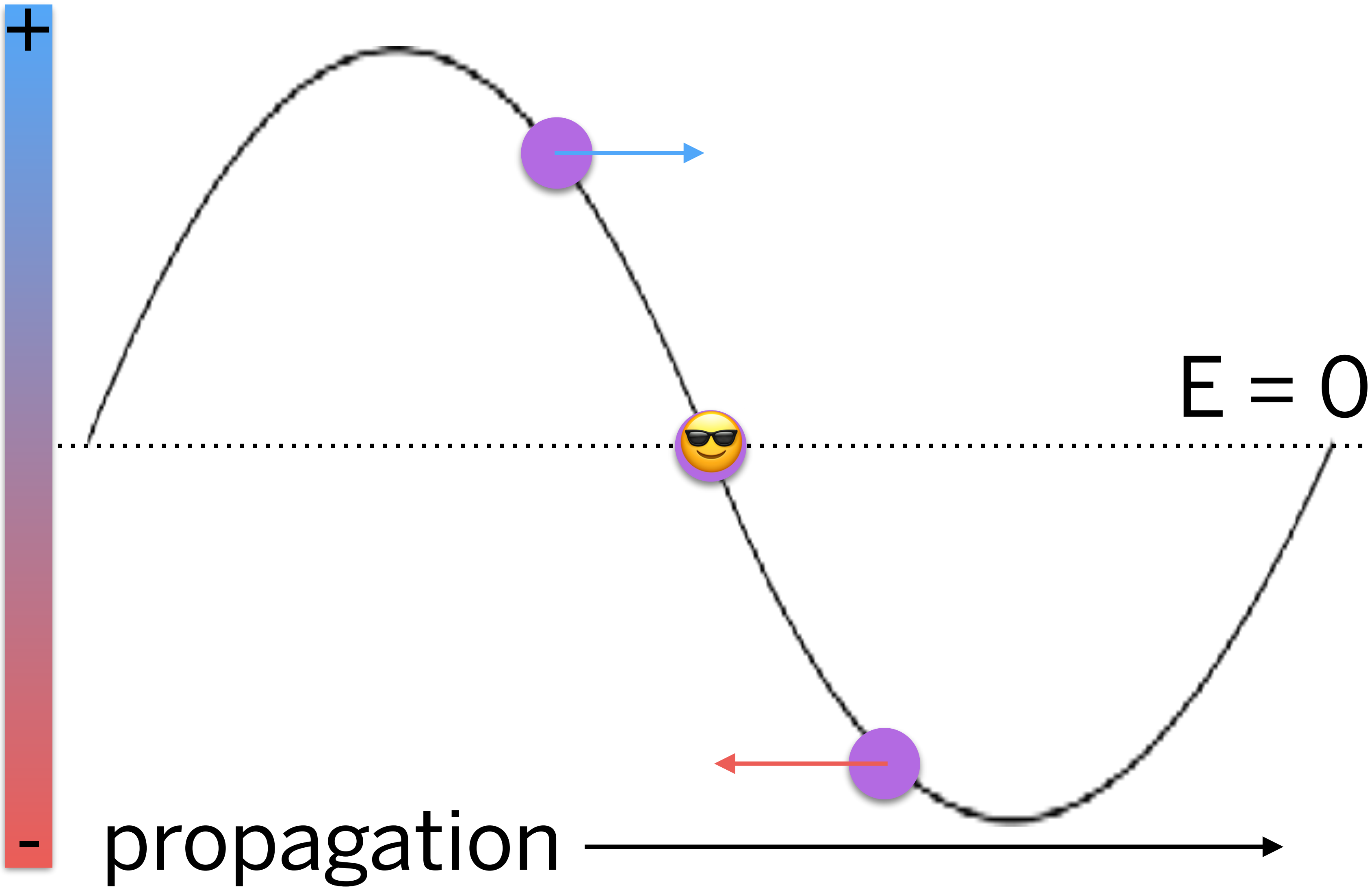
E_{CM}: 7 → 8 → 13 TeV

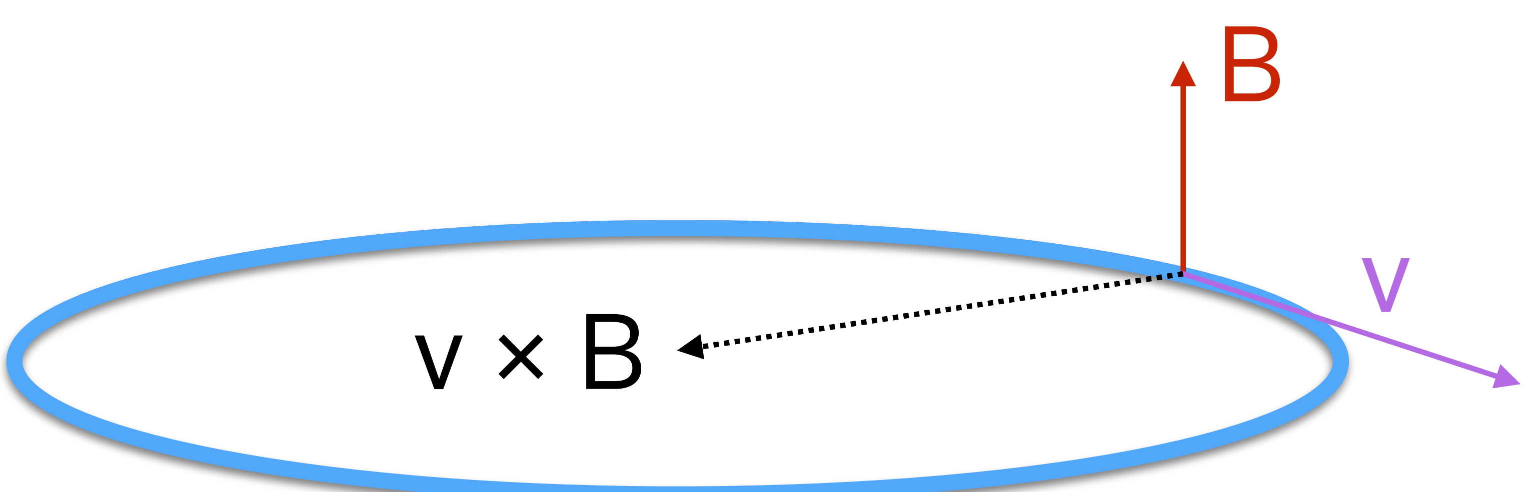
40 MHz collisions

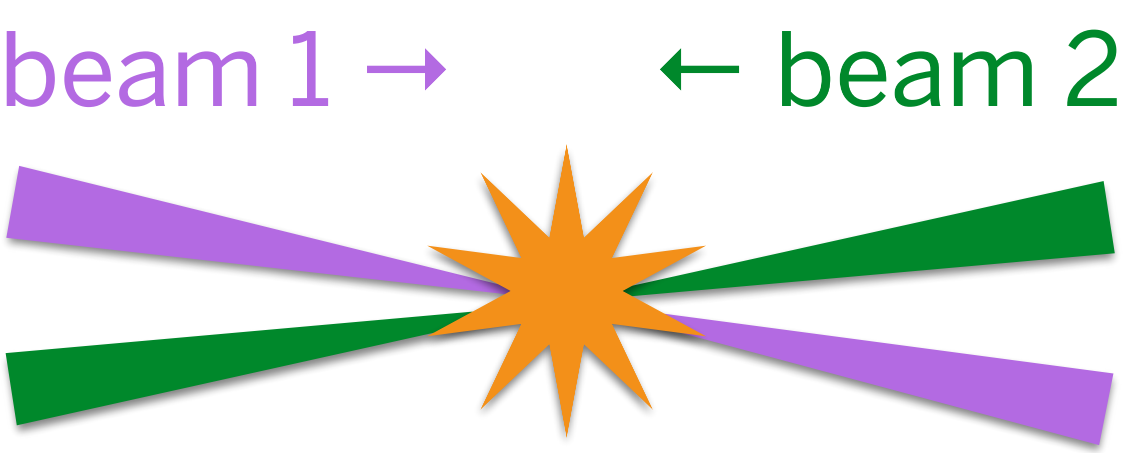
10^{34} cm^{-2}s^{-1}

Tools of the trade

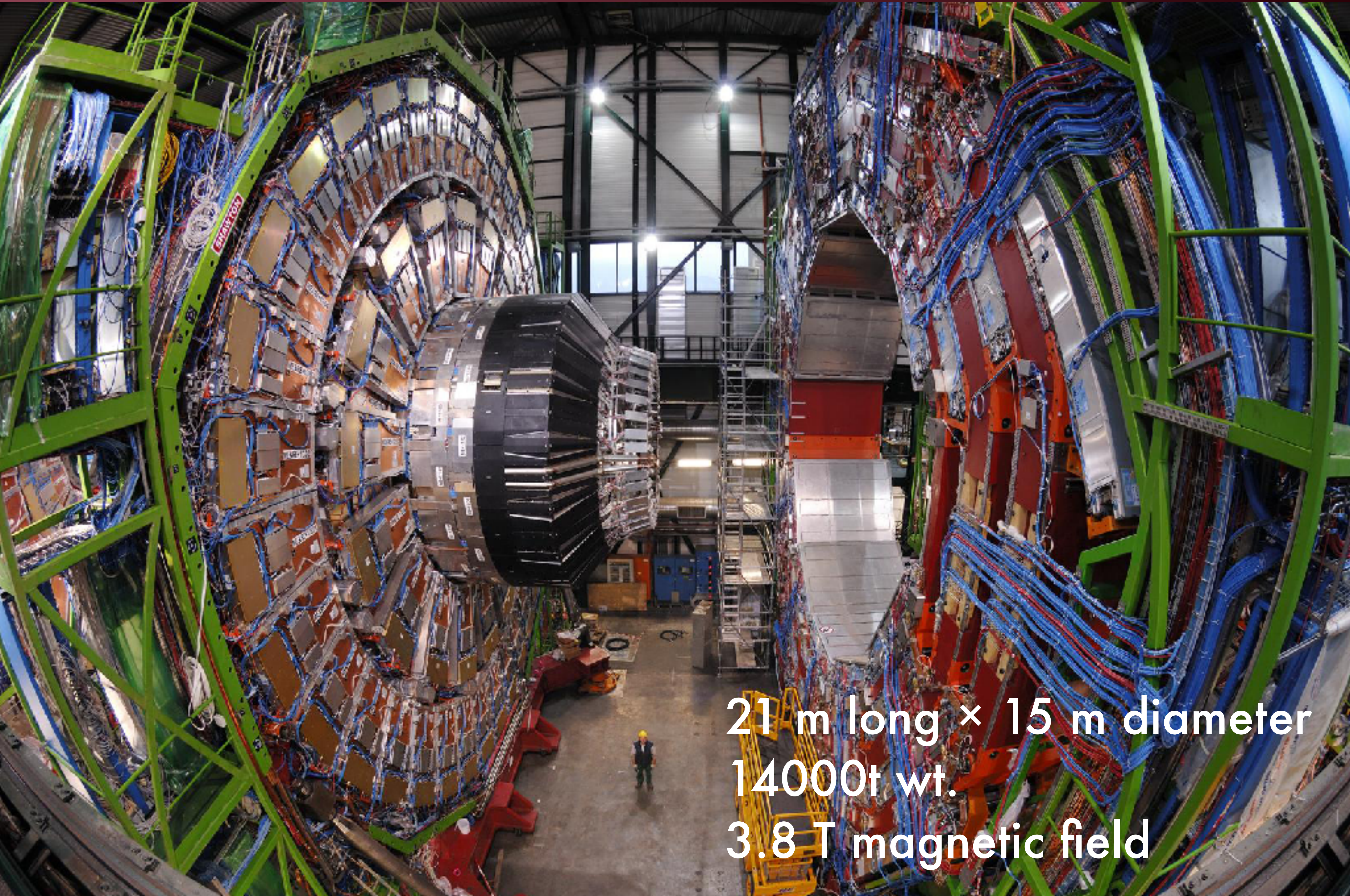
Particle accelerators/colliders







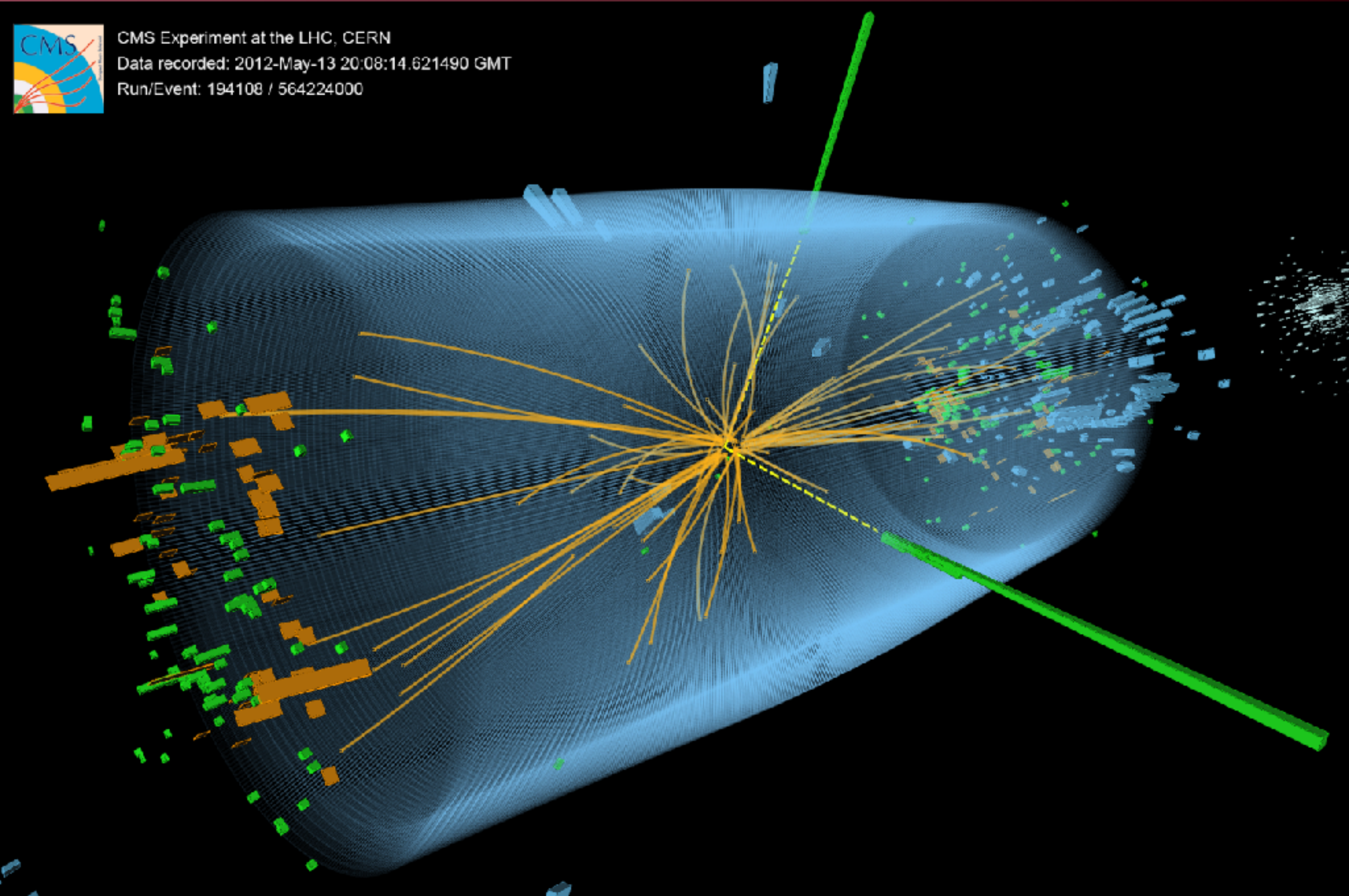
CMS



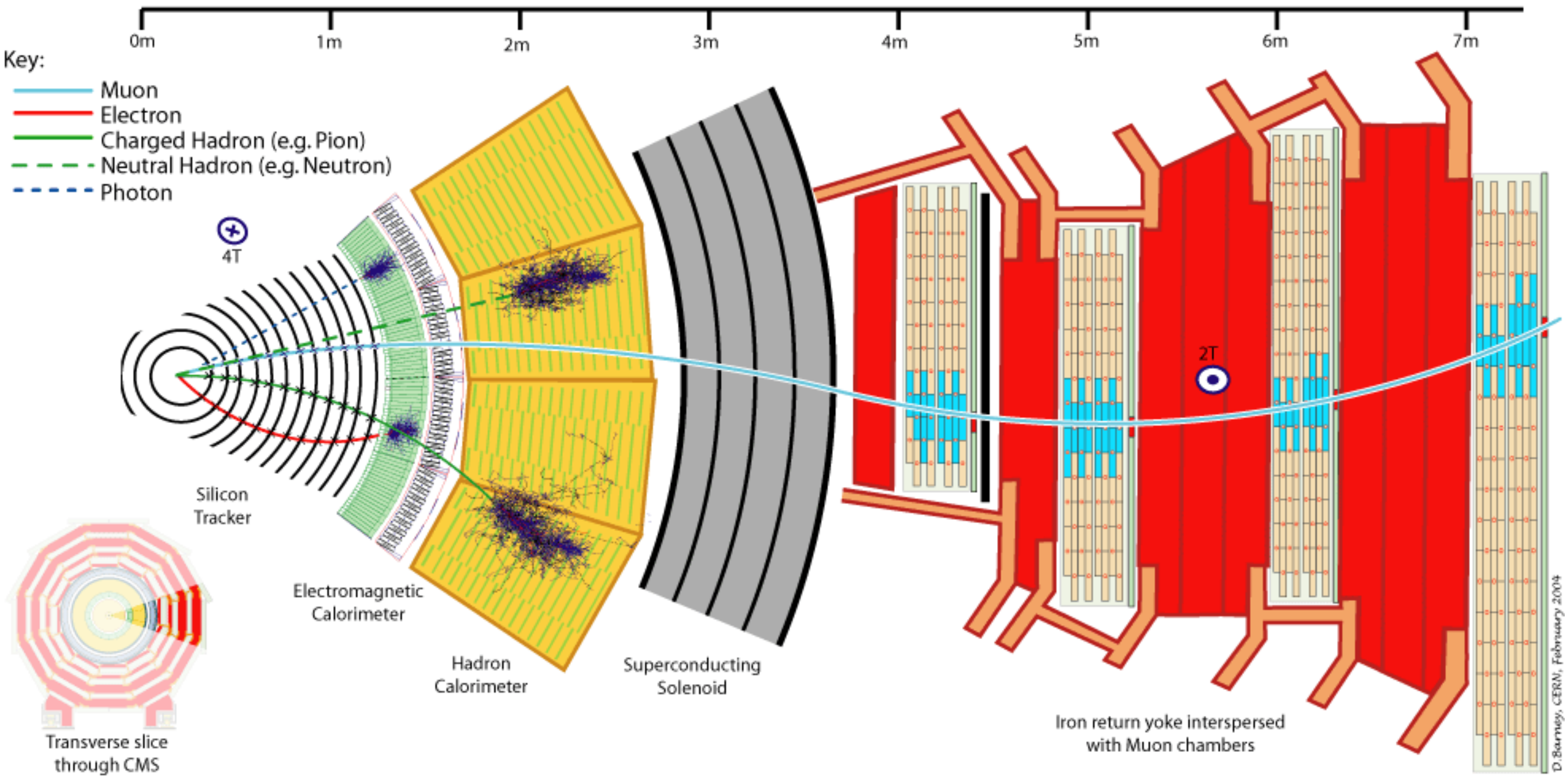
Our detector — CMS

[A. Askew]

An LHC event


CMS
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

CMS detector components



How detectors work

Semiconductor

1. dope Si (or Ge) to create a diode

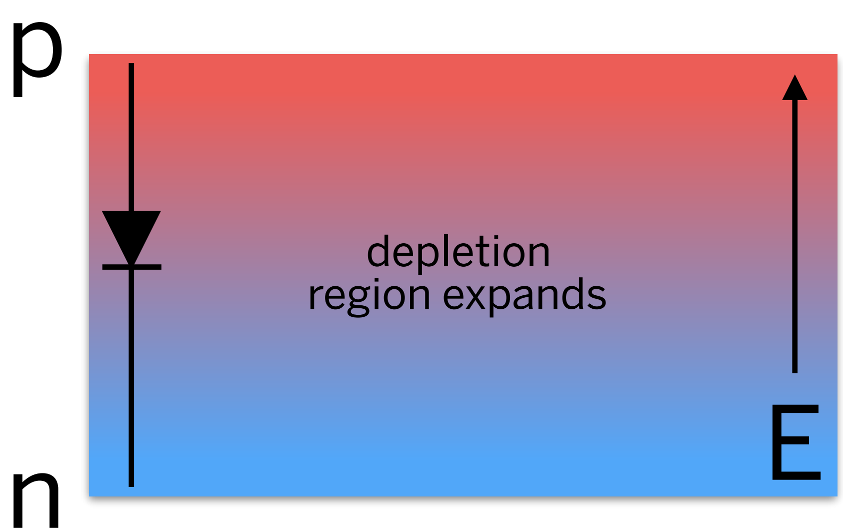
Scintillator

Cherenkov

Readout

How detectors work

Semiconductor



1. dope Si (or Ge) to create a diode

2. apply reverse bias; no current flows

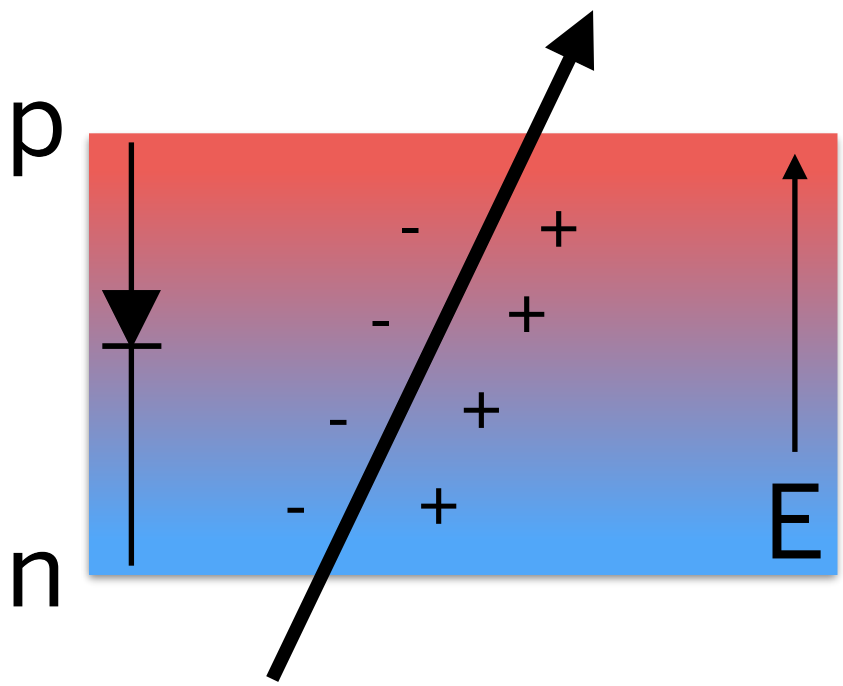
Scintillator

Cherenkov

Readout

How detectors work

Semiconductor



1. dope Si (or Ge) to create a diode
2. apply reverse bias; no current flows
3. charged particle passes through; creates e/h pairs

Scintillator

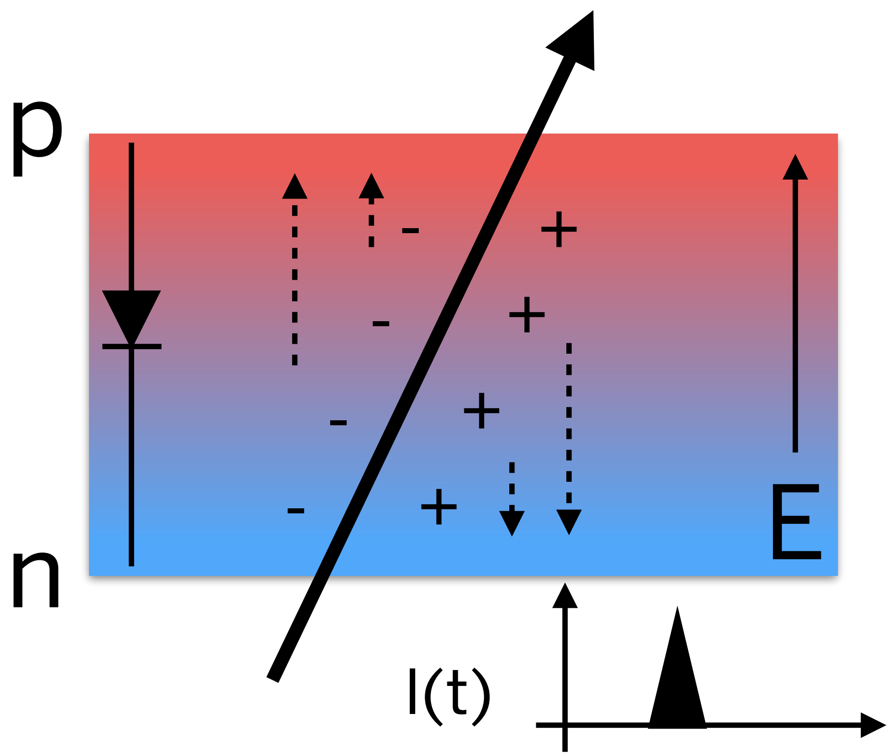
Cherenkov

Readout

How detectors work

Semiconductor

Scintillator



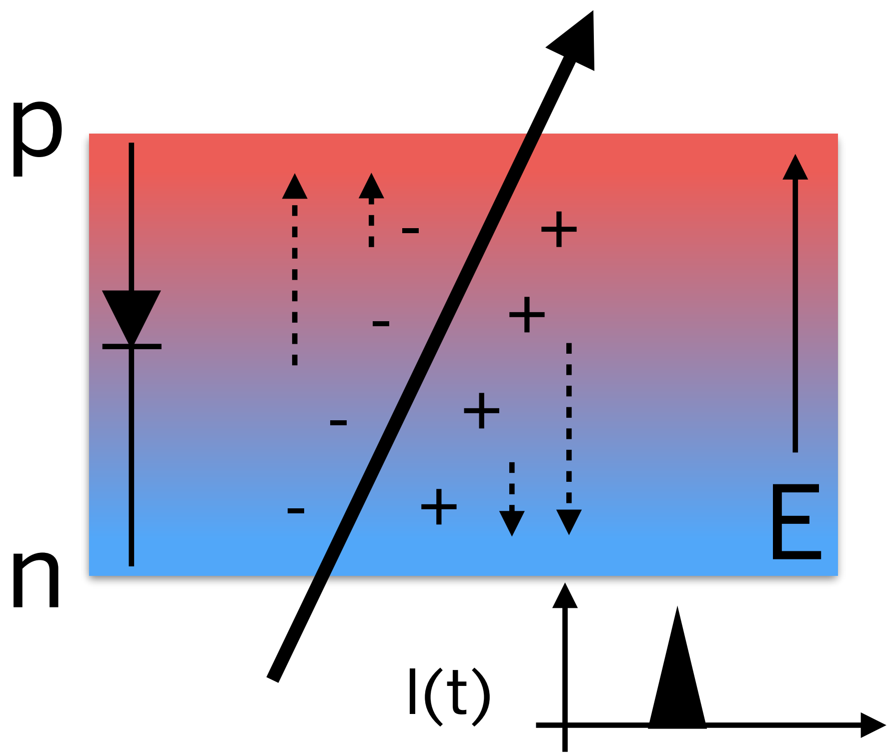
1. dope Si (or Ge) to create a diode
2. apply reverse bias; no current flows
3. charged particle passes through; creates e/h pairs
4. current pulse is produced

Cherenkov

Readout

How detectors work

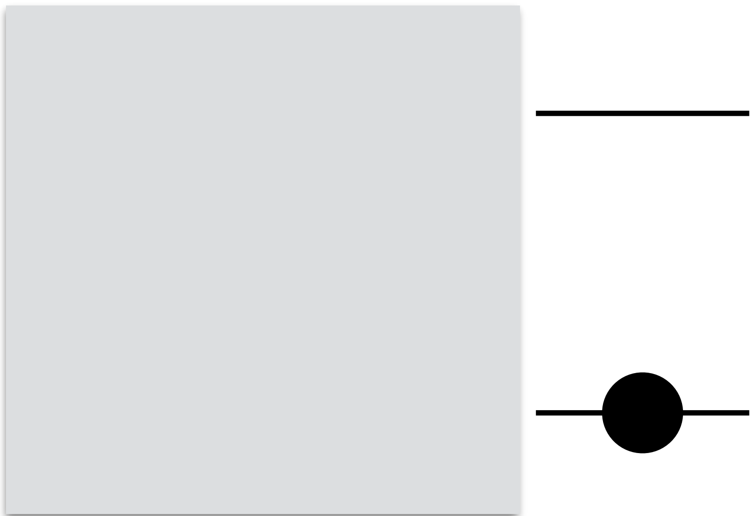
Semiconductor



Cherenkov

Scintillator

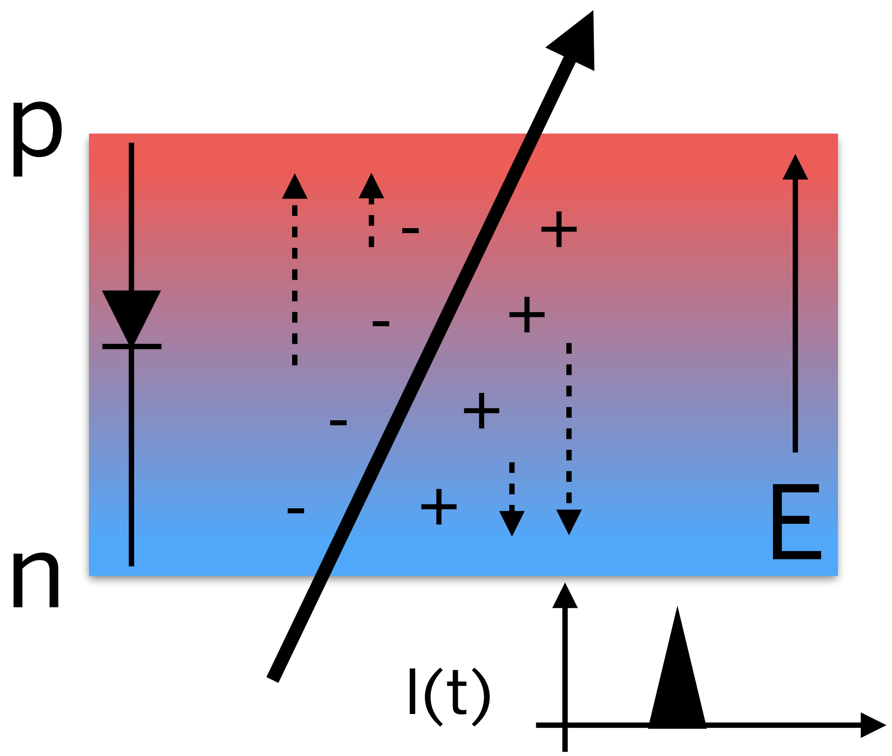
1. choose a material with energy levels separated by visible wavelength



Readout

How detectors work

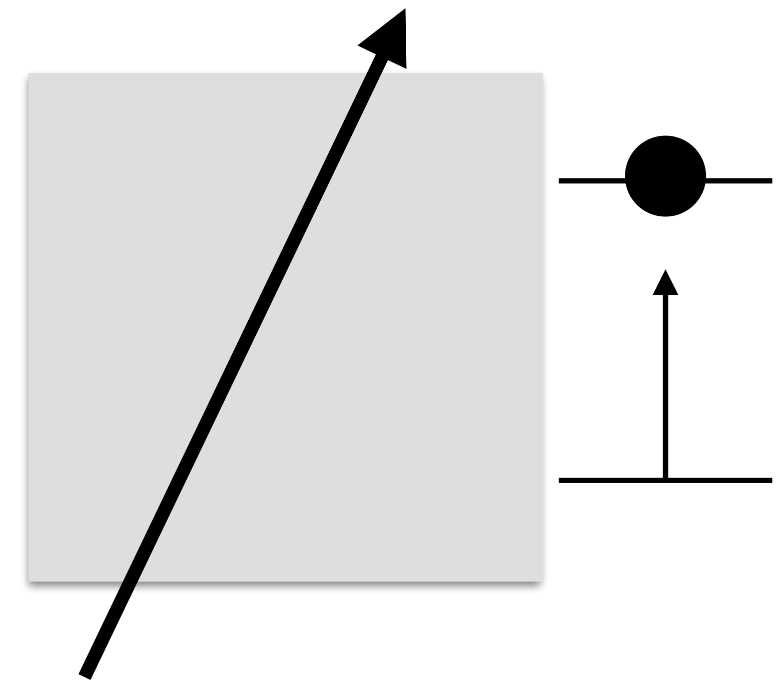
Semiconductor



Cherenkov

1. choose a material with energy levels separated by visible wavelength
2. charged particle passes through; transfers energy to atoms in material

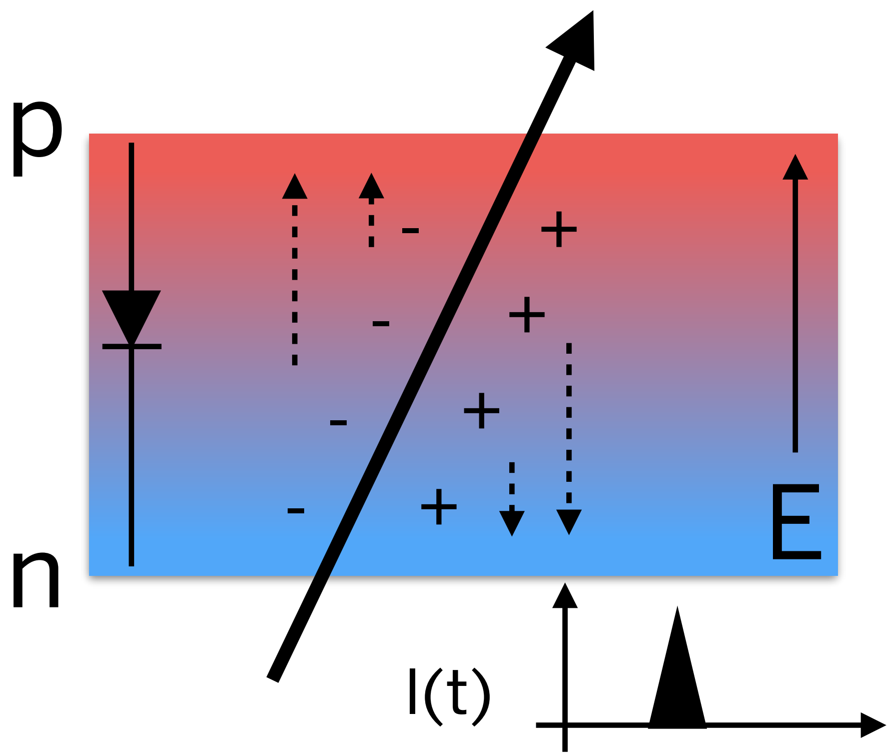
Scintillator



Readout

How detectors work

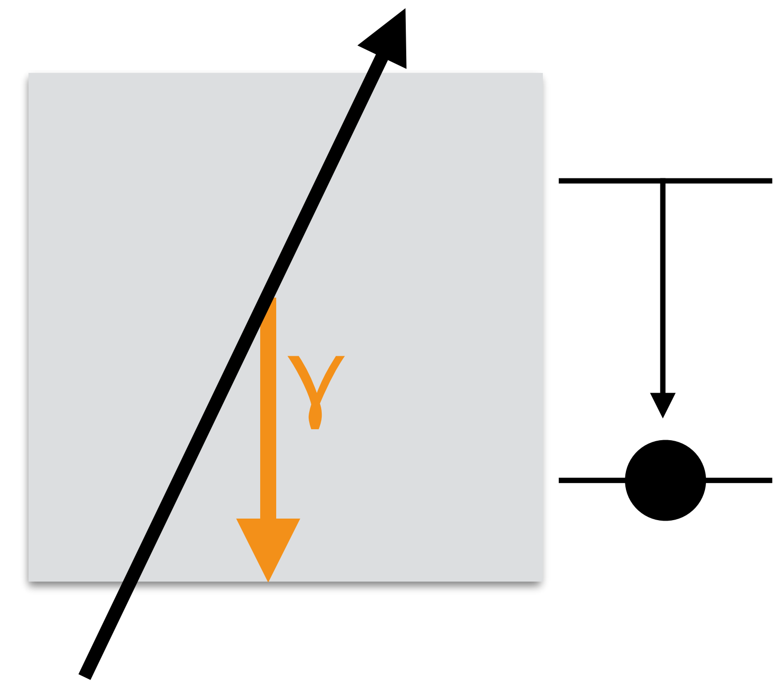
Semiconductor



Cherenkov

1. choose a material with energy levels separated by visible wavelength
2. charged particle passes through; transfers energy to atoms in material
3. excited atom decays; emits a photon

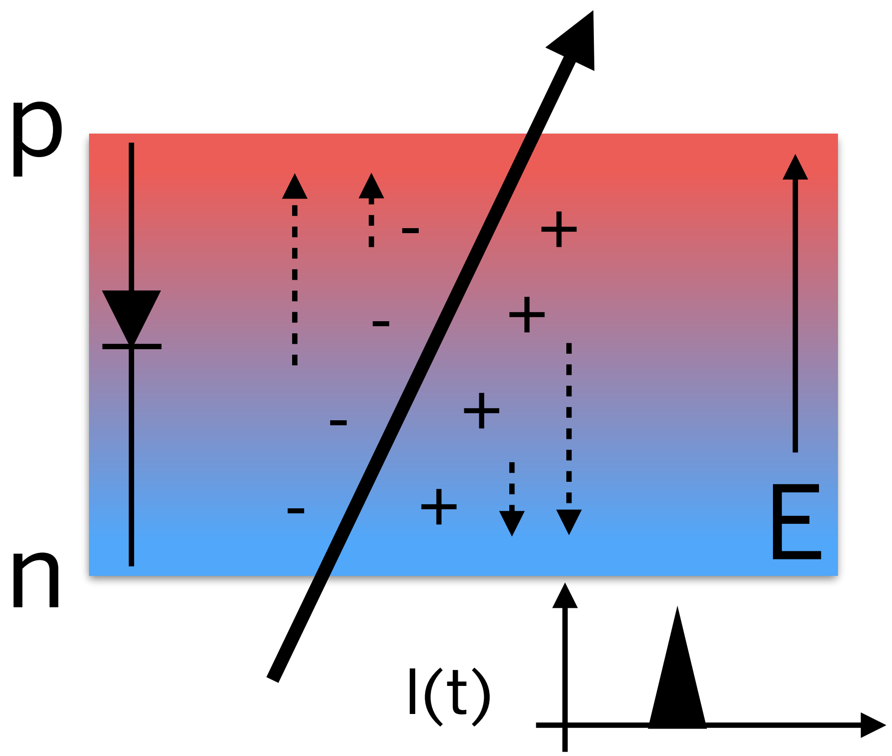
Scintillator



Readout

How detectors work

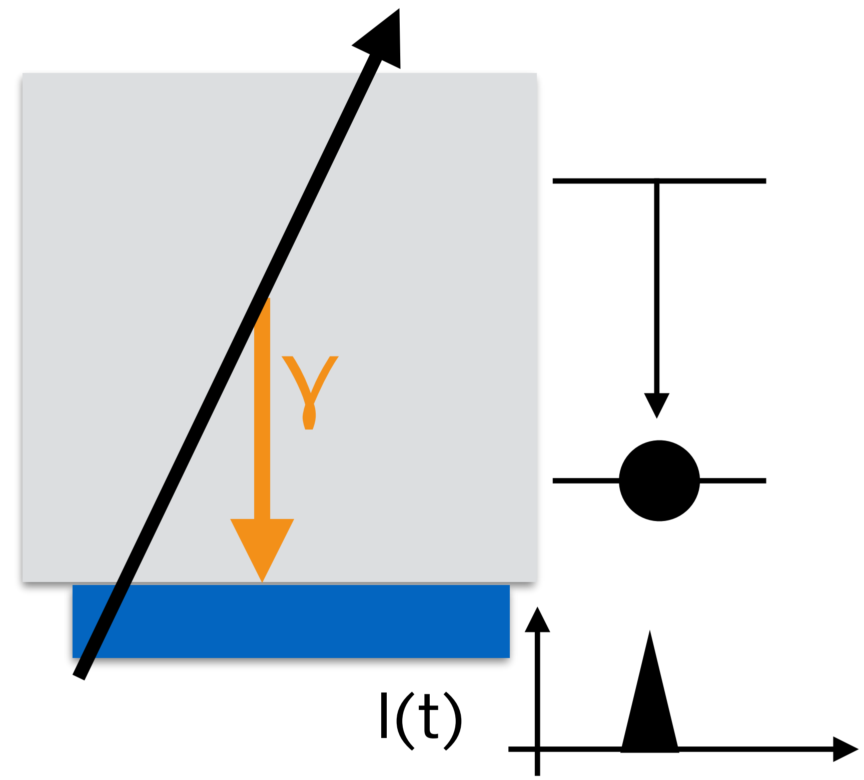
Semiconductor



Cherenkov

1. choose a material with energy levels separated by visible wavelength
2. charged particle passes through; transfers energy to atoms in material
3. excited atom decays; emits a photon
4. photodetector measures the photon and produces a current

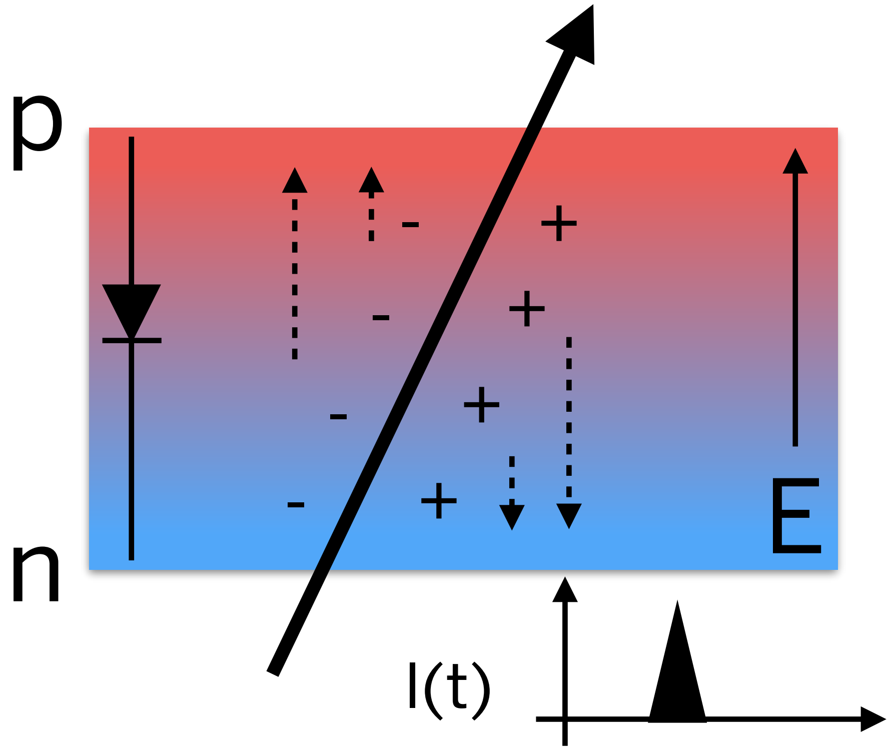
Scintillator



Readout

How detectors work

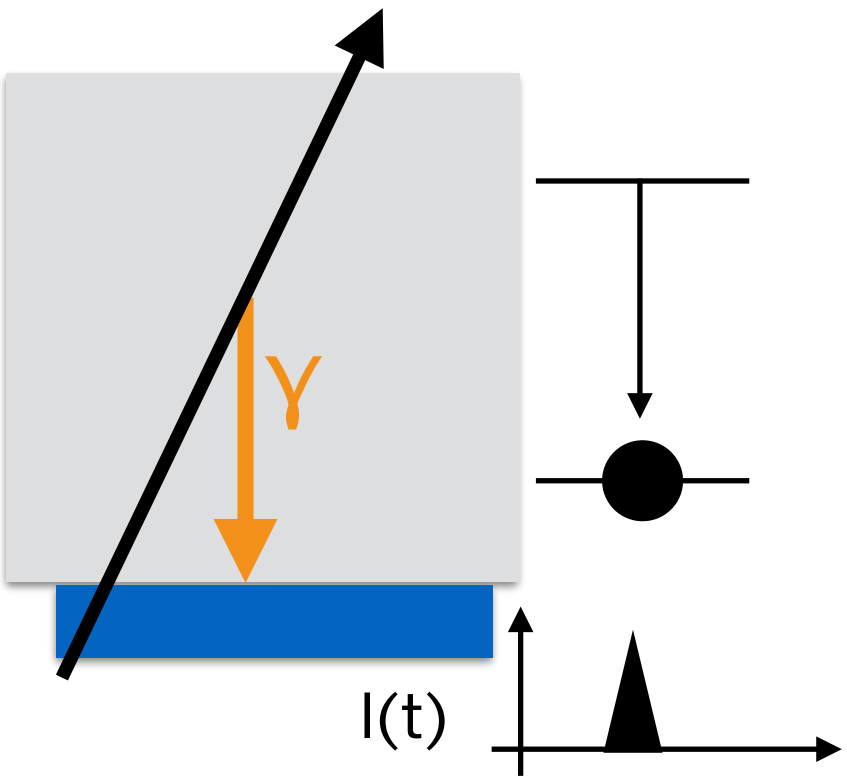
Semiconductor



Cherenkov

1. choose an optically clear material with a known index of refraction

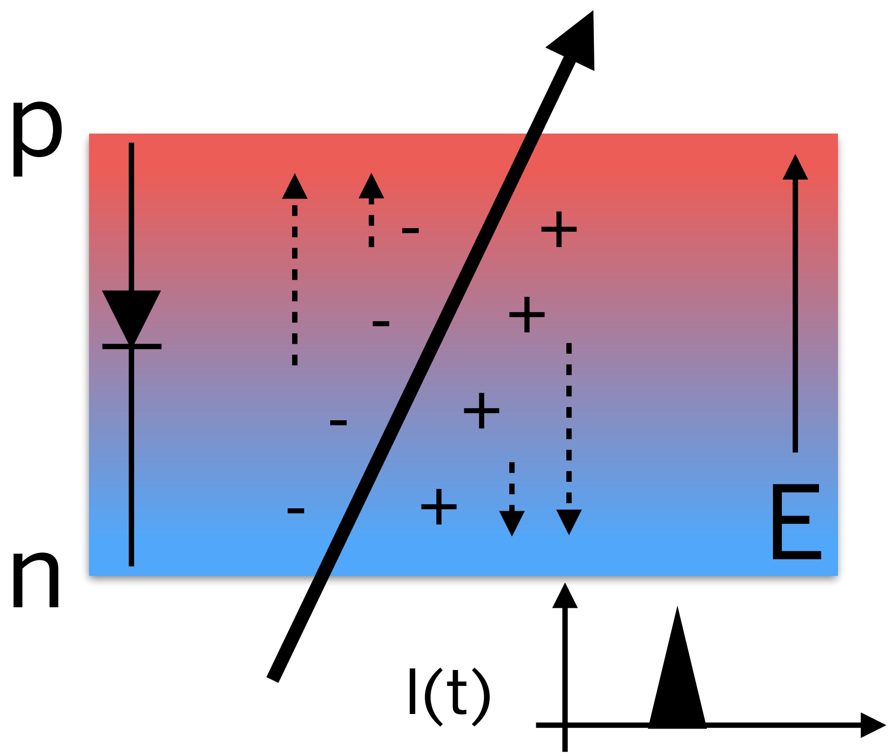
Scintillator



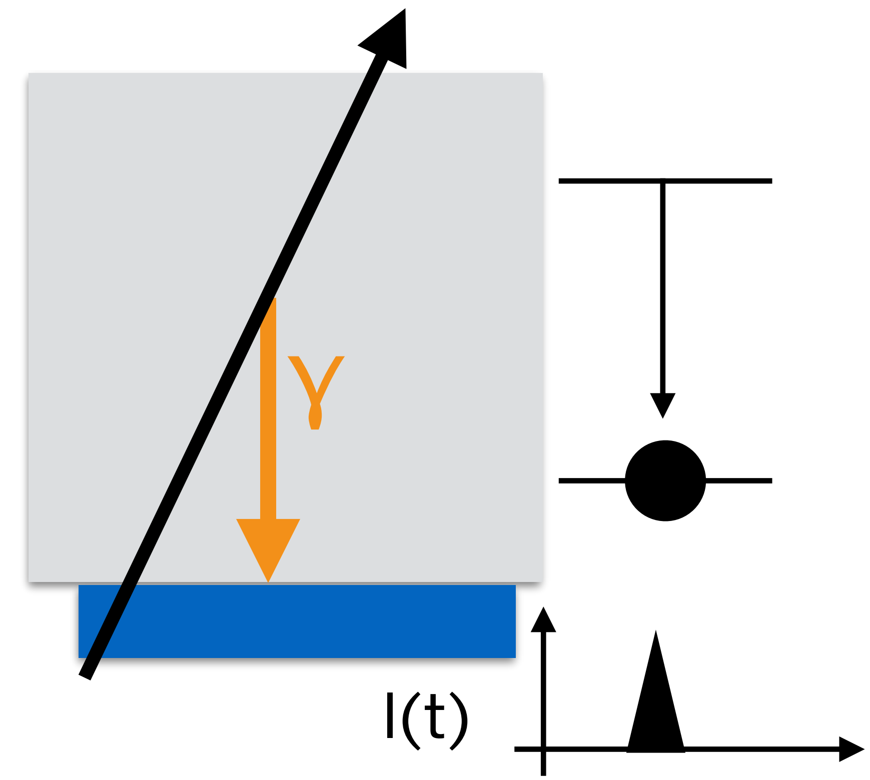
Readout

How detectors work

Semiconductor

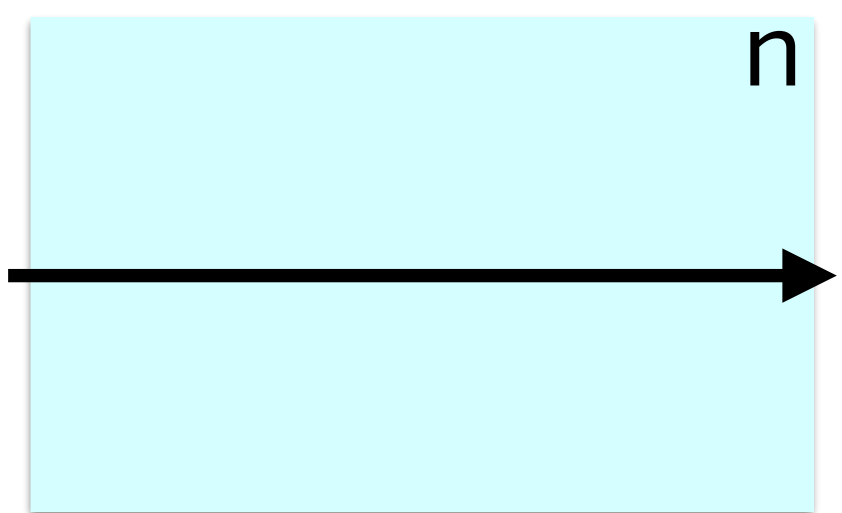


Scintillator



Readout

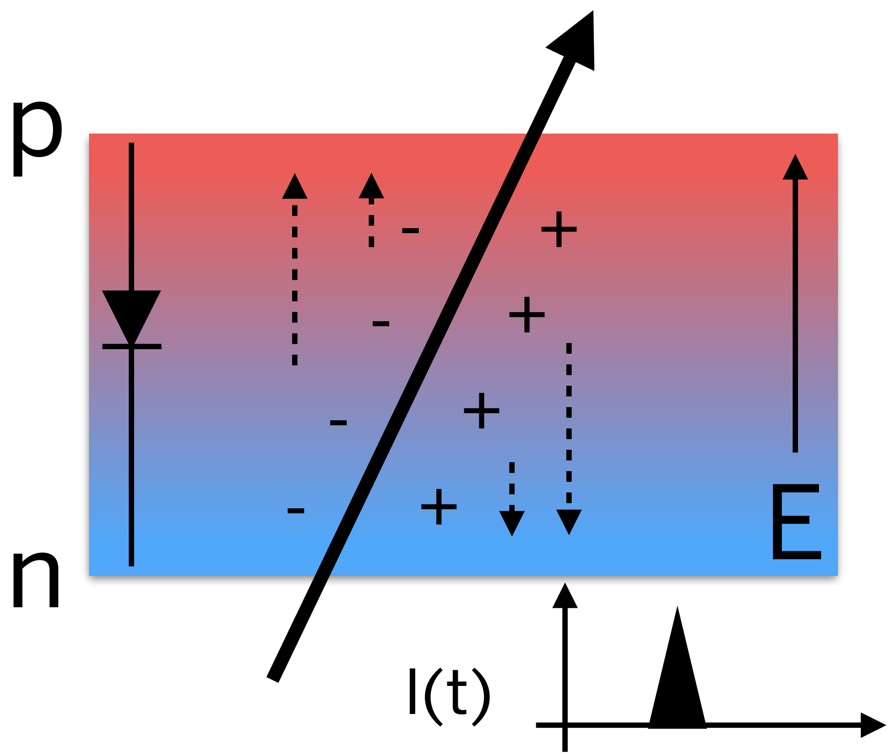
Cherenkov



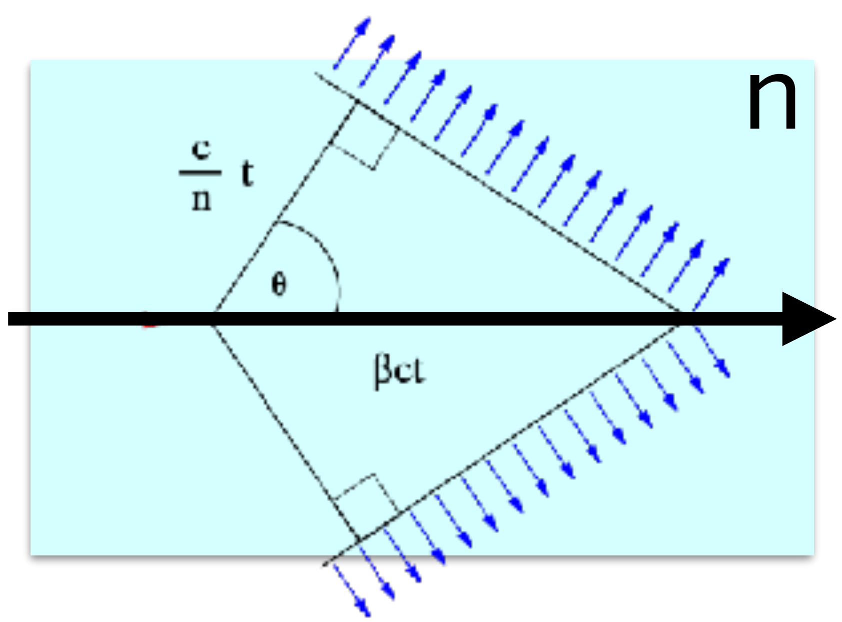
1. choose an optically clear material with a known index of refraction
2. relativistic particle travels through with speed c/n < v < c

How detectors work

Semiconductor

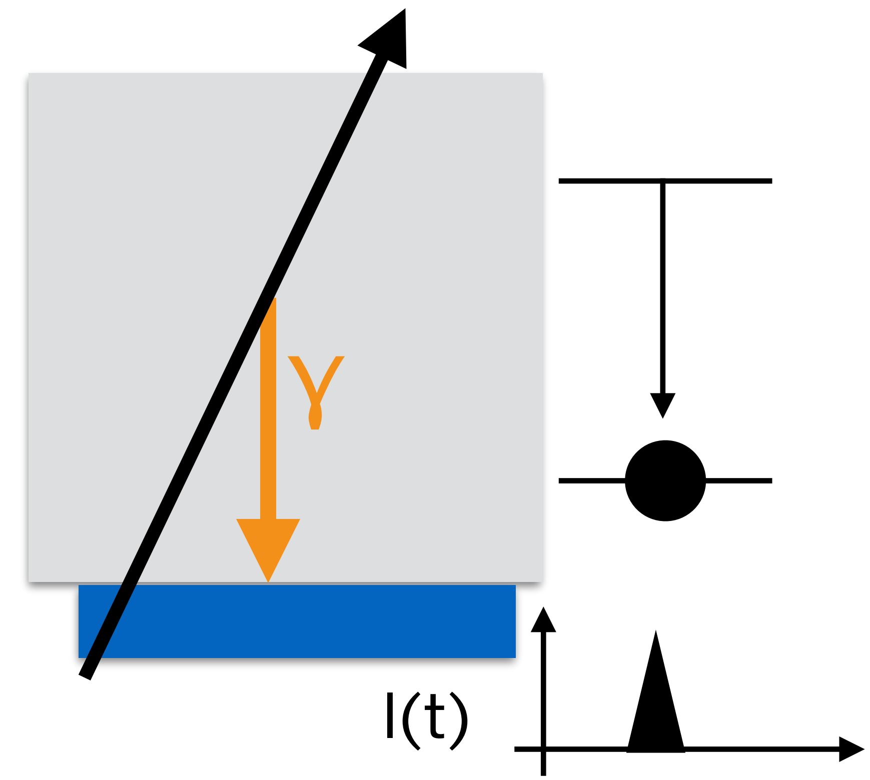


Cherenkov



1. choose an optically clear material with a known index of refraction
2. relativistic particle travels through with speed $c/n < v < c$
3. Cherenkov radiation is produced with characteristic cone angle relative to speed of particle

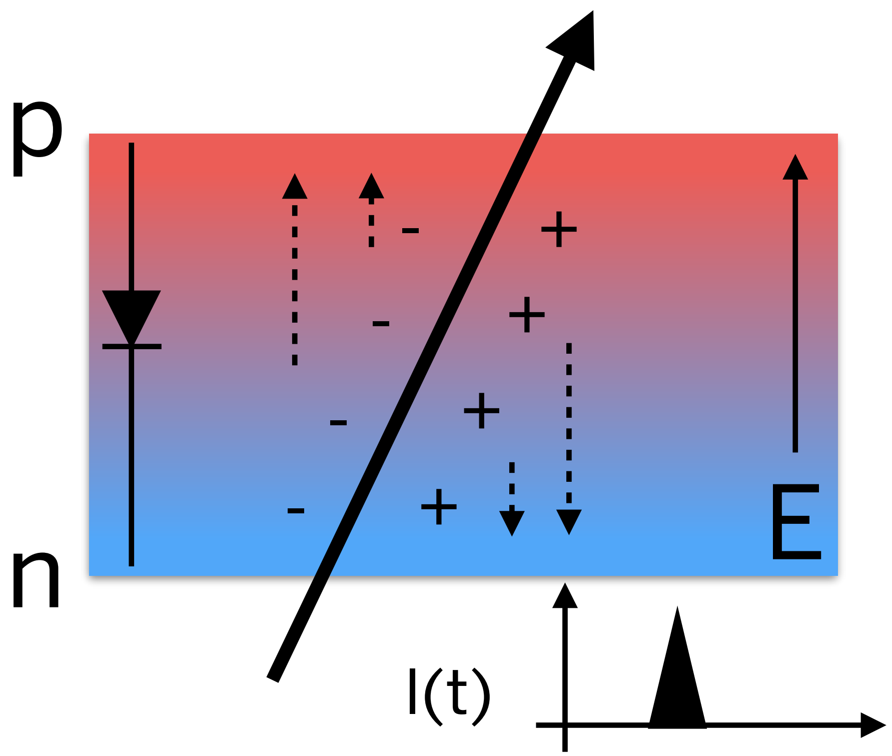
Scintillator



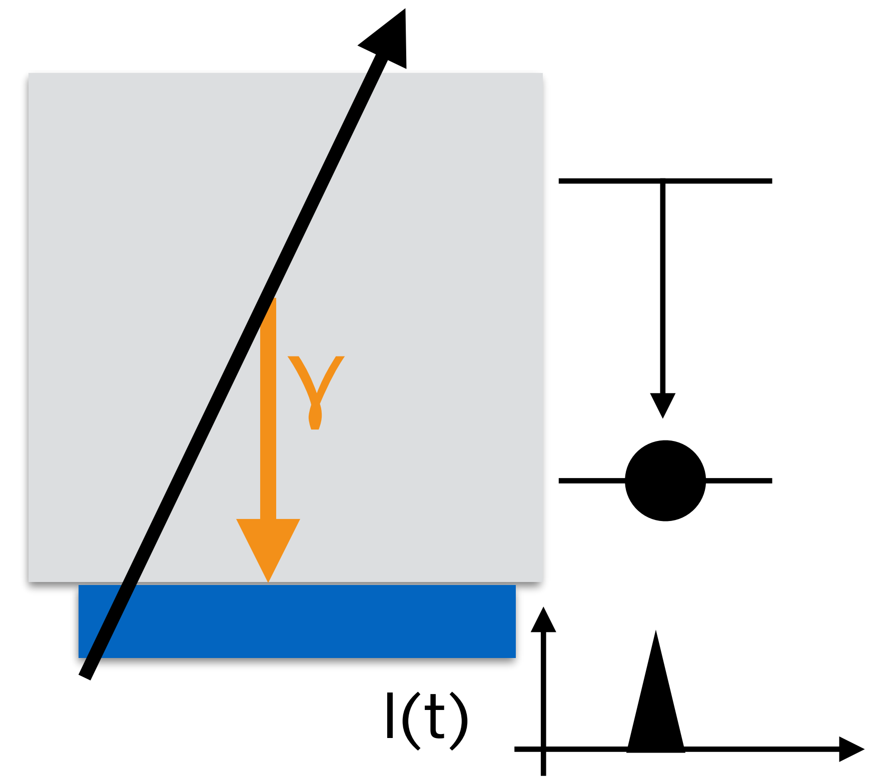
Readout

How detectors work

Semiconductor

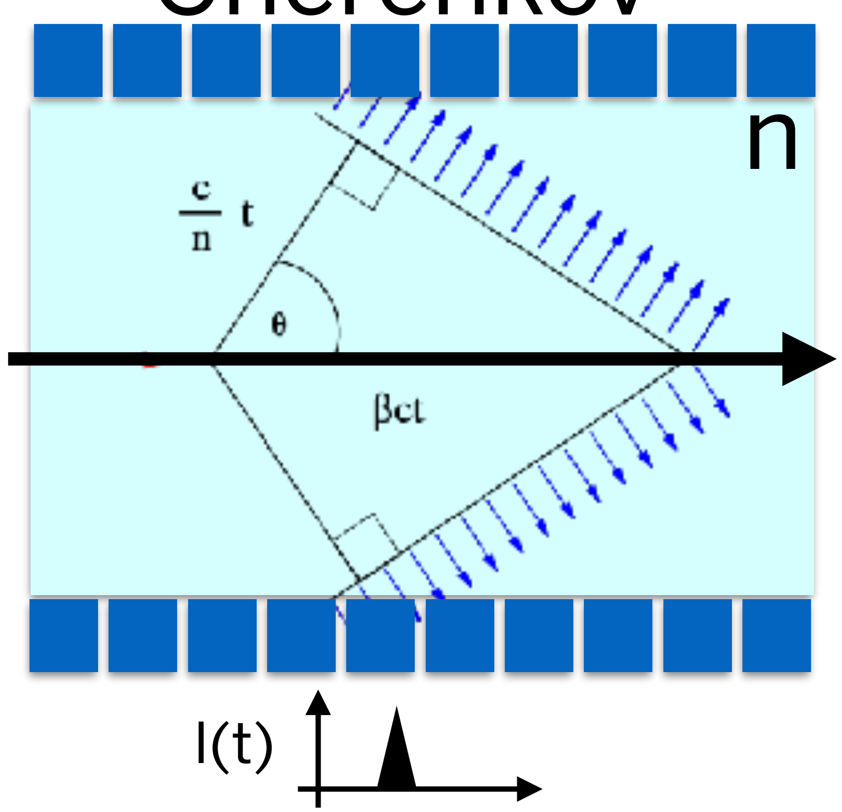


Scintillator



Readout

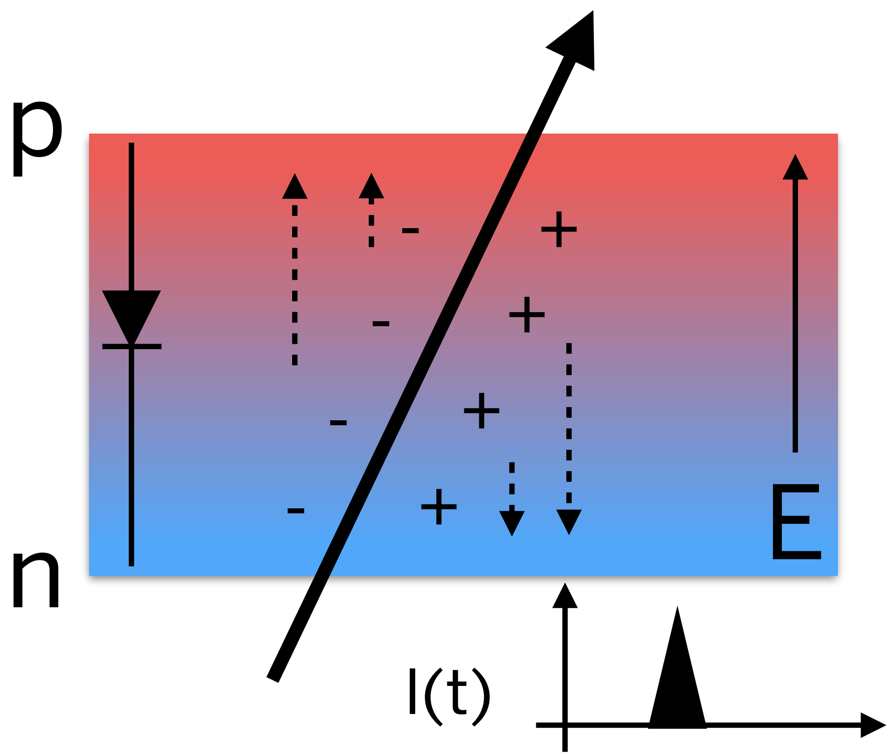
Cherenkov



1. choose an optically clear material with a known index of refraction
2. relativistic particle travels through with speed c/n < v < c
3. Cherenkov radiation is produced with characteristic cone angle relative to speed of particle
4. photodetectors around edges image this cone

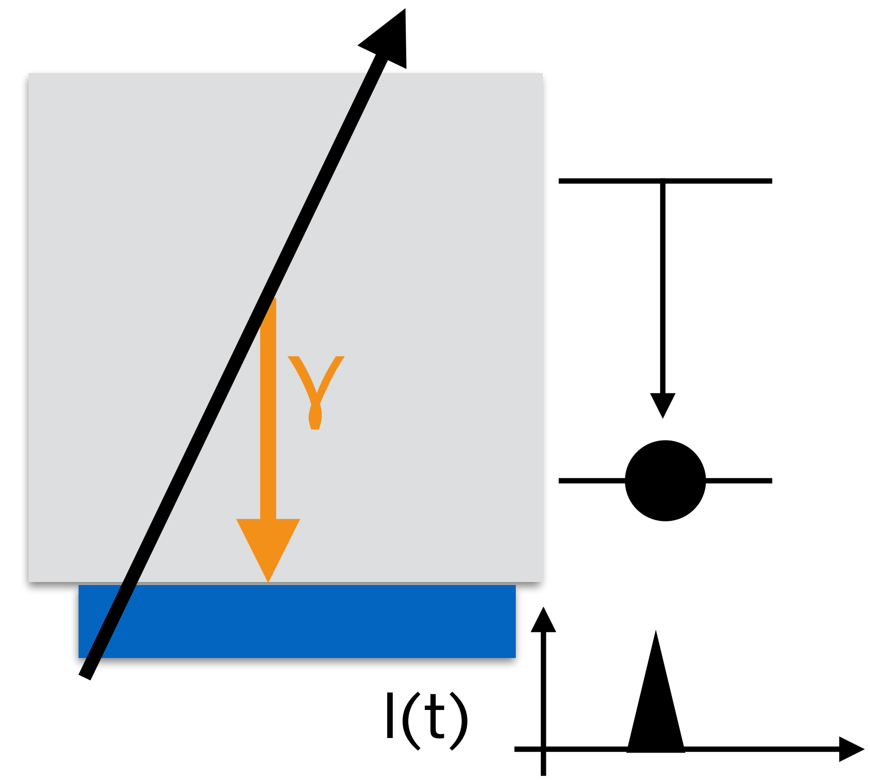
How detectors work

Semiconductor

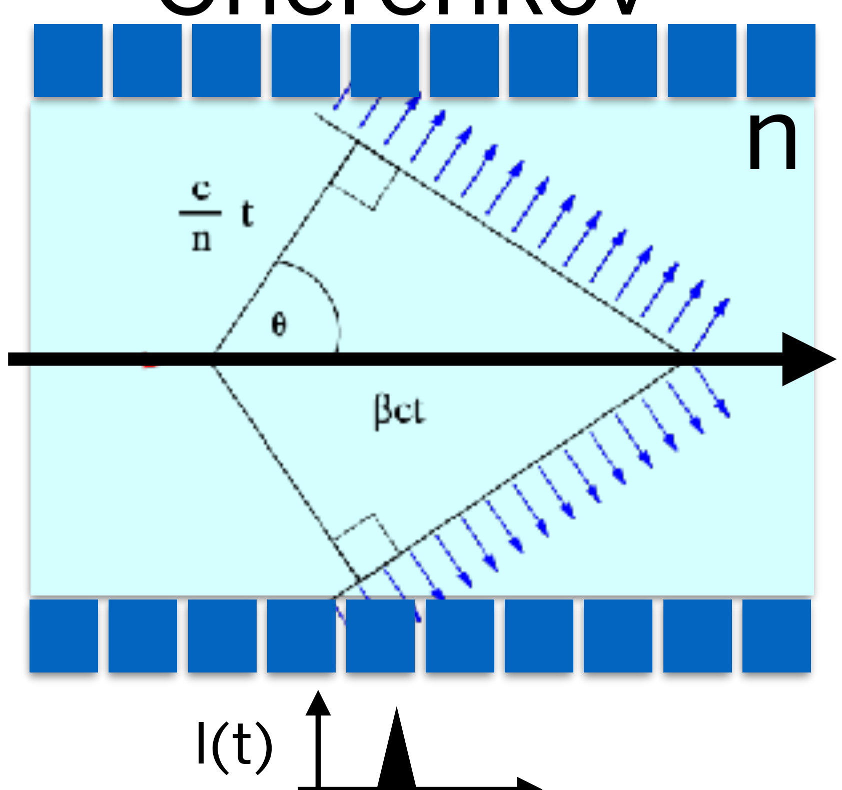


1. detectors produce a small amount of current

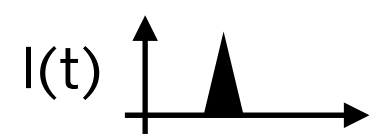
Scintillator



Cherenkov

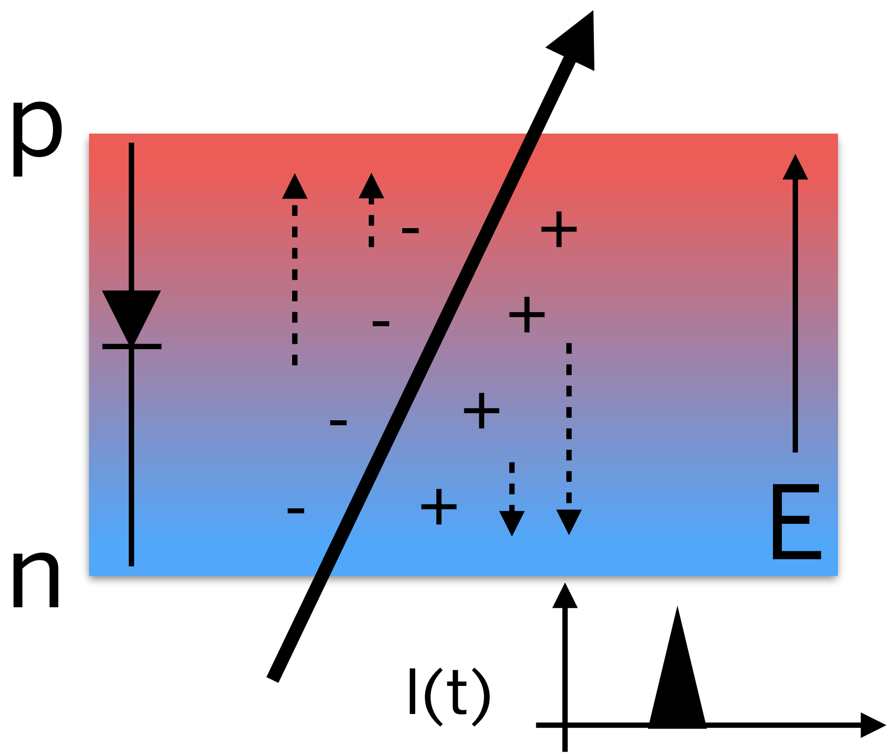


Readout

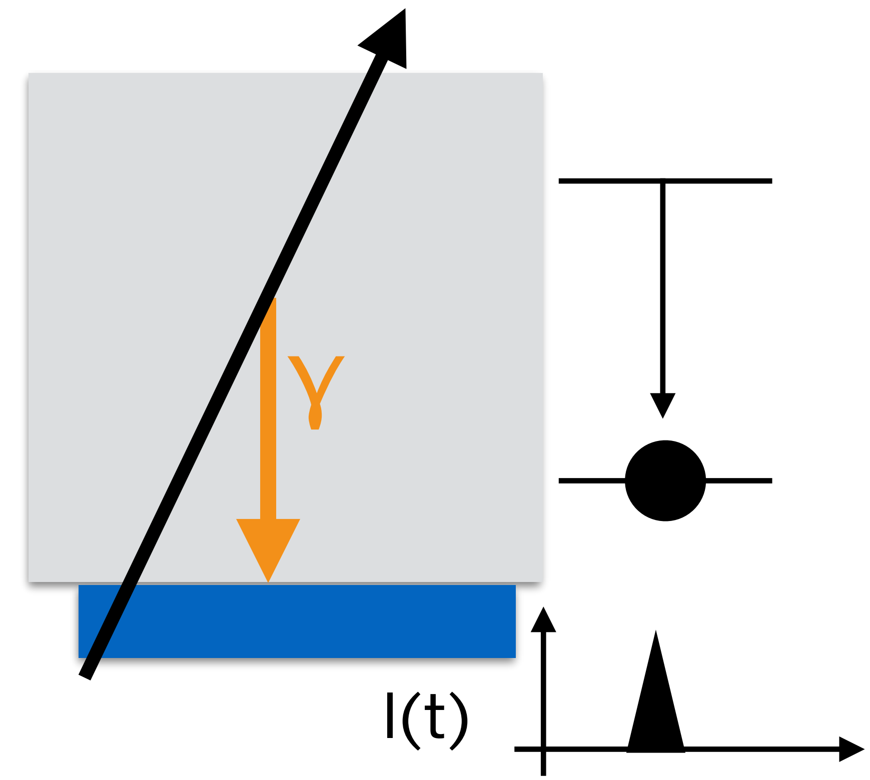


How detectors work

Semiconductor



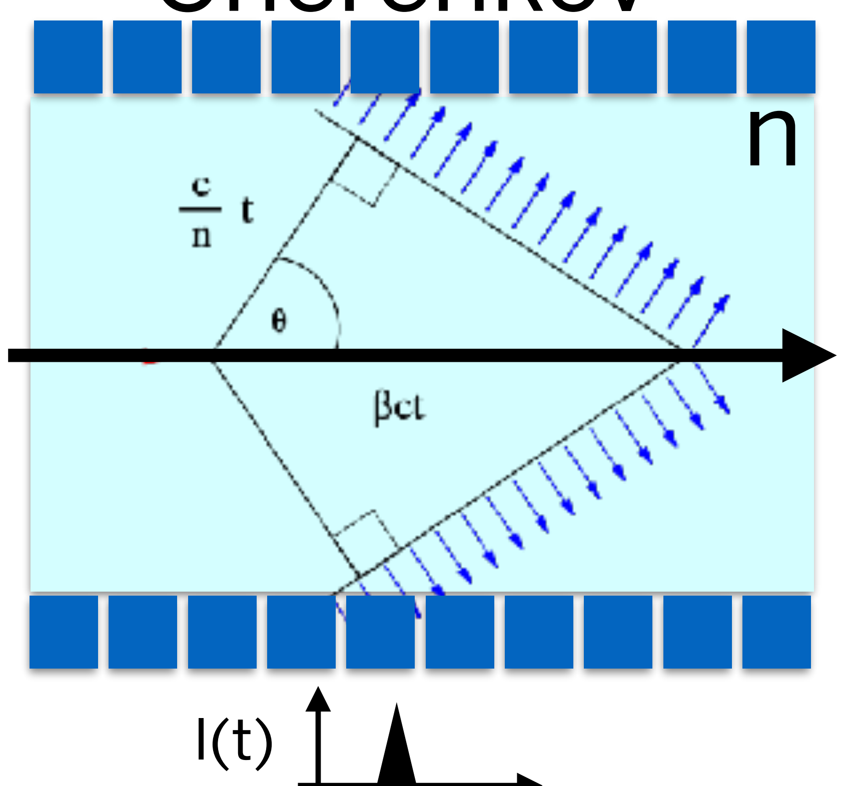
Scintillator



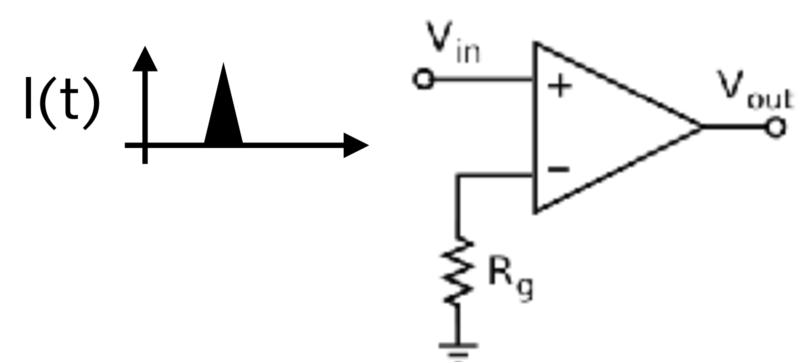
1. detectors produce a small amount of current

2. pass it through an amplifier to make it measurable

Cherenkov

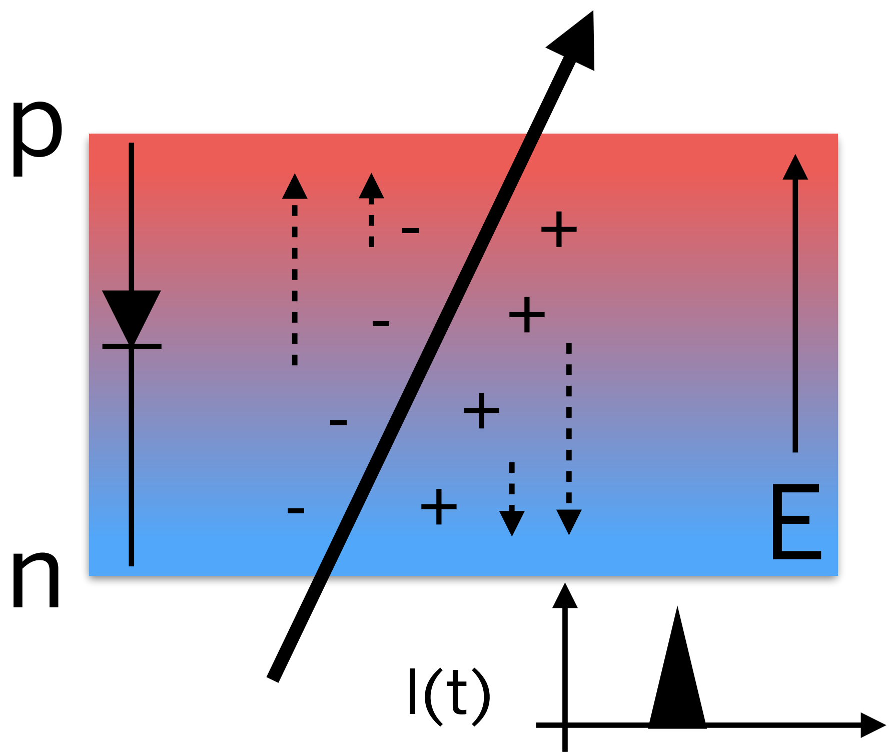


Readout

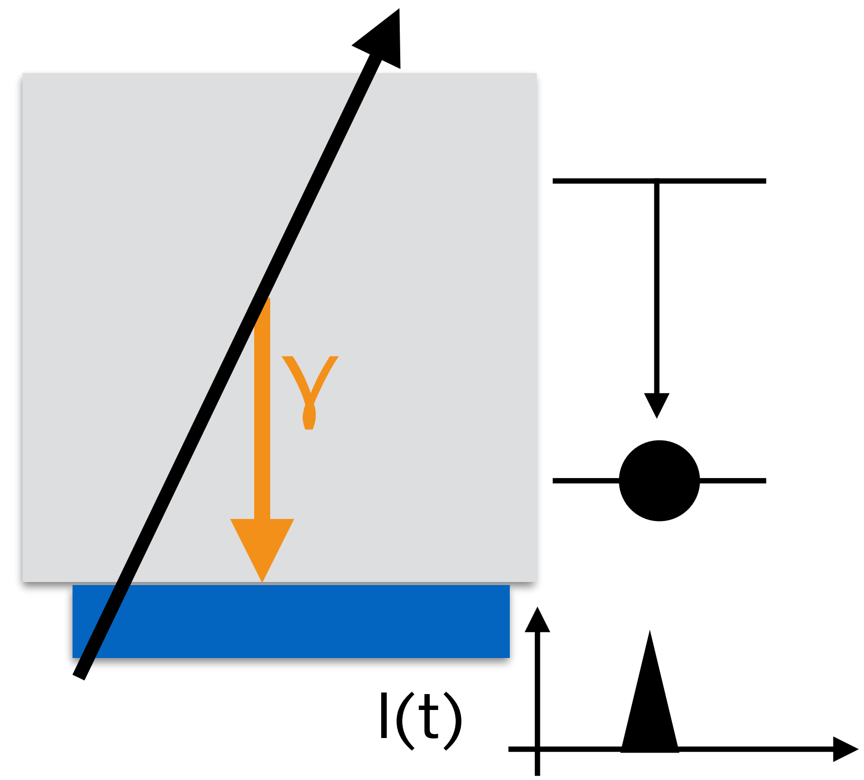


How detectors work

Semiconductor

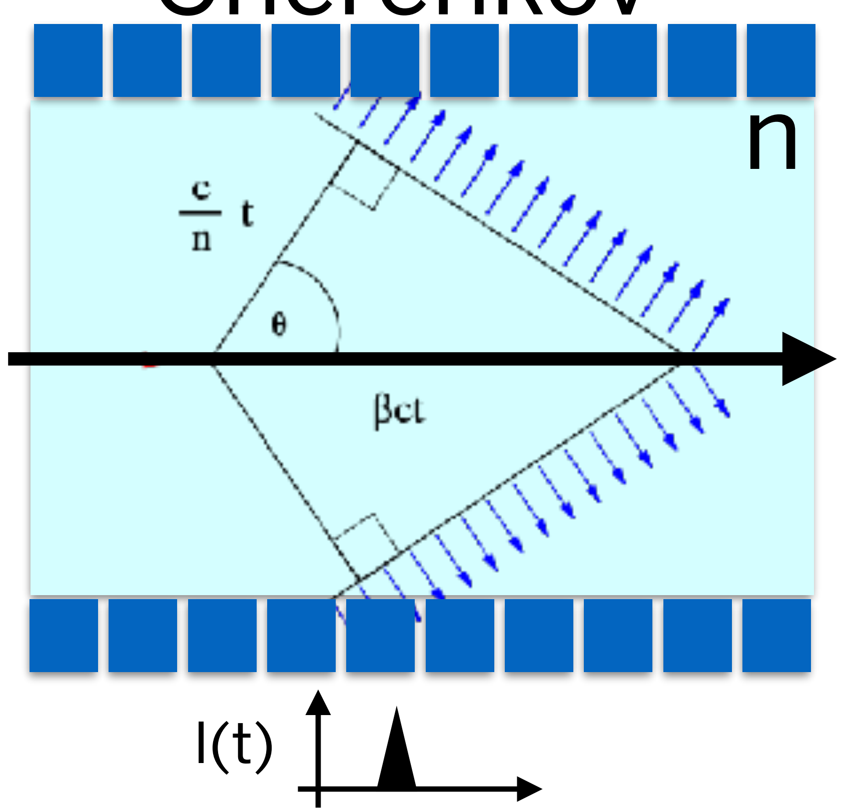


Scintillator

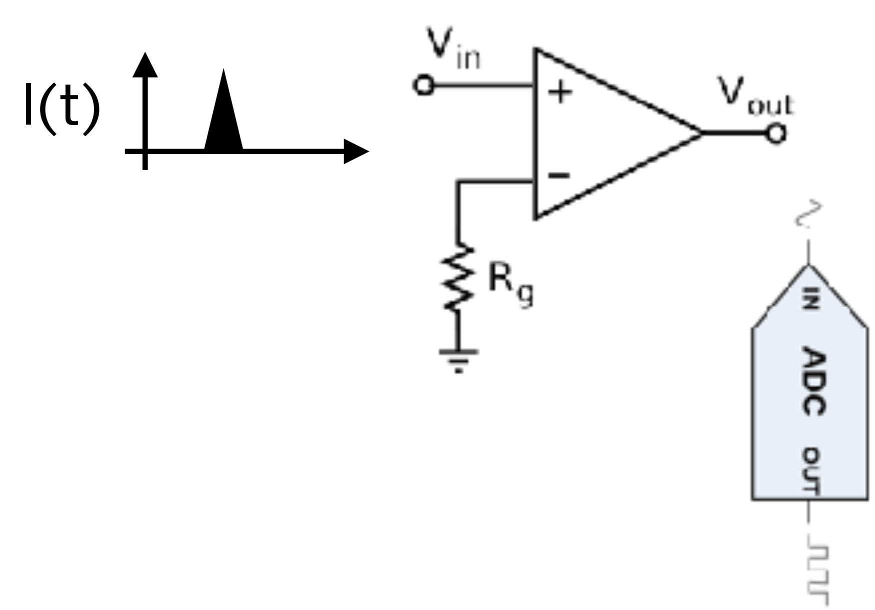


1. detectors produce a small amount of current
2. pass it through an amplifier to make it measurable
3. amplifier output is passed to an ADC which converts to digital data

Cherenkov

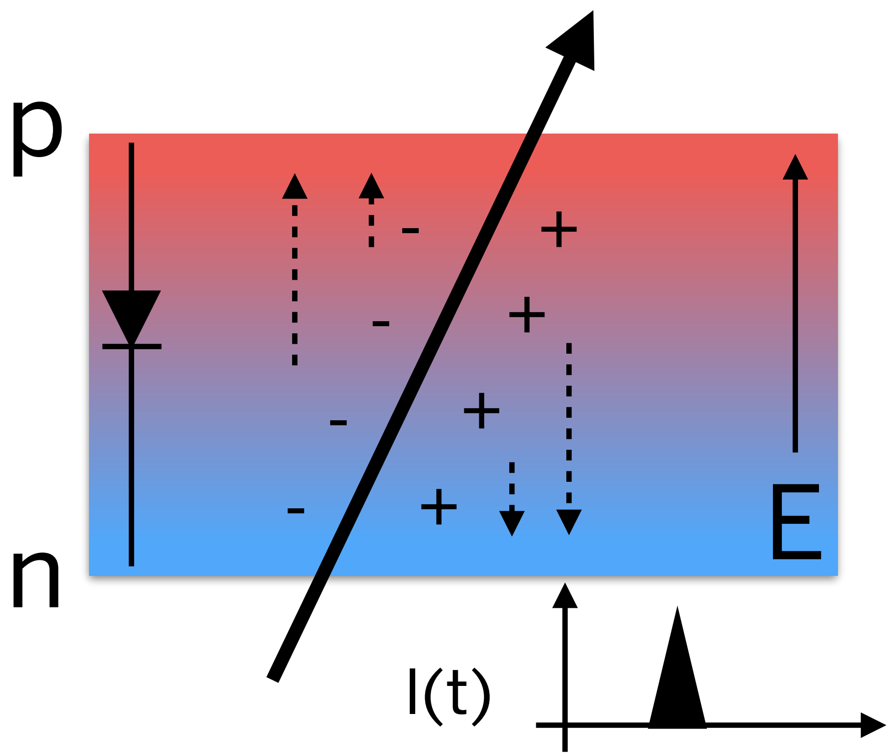


Readout

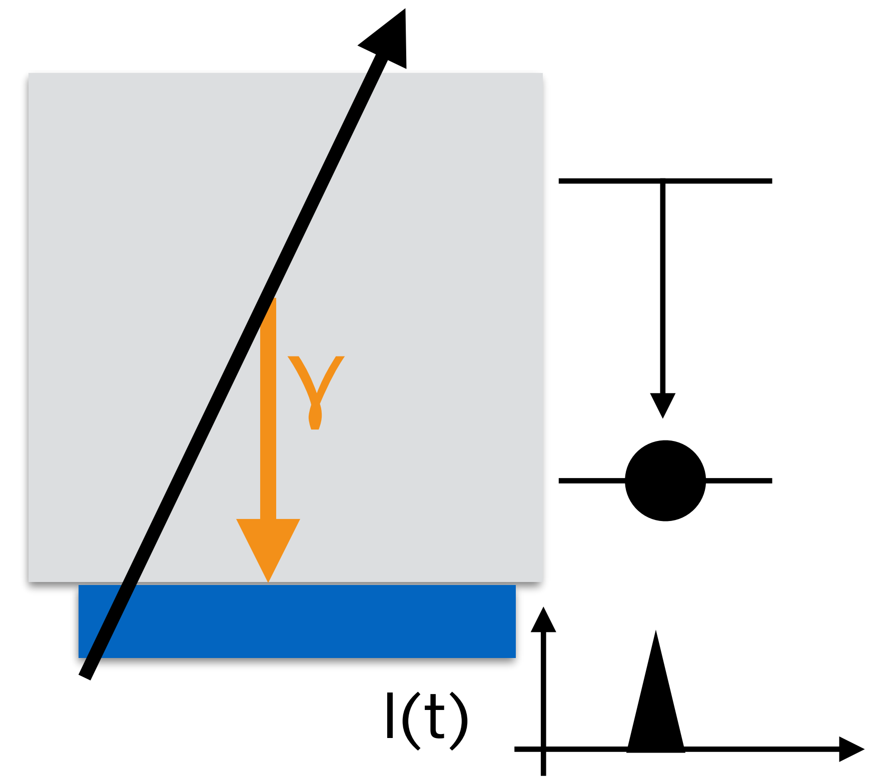


How detectors work

Semiconductor

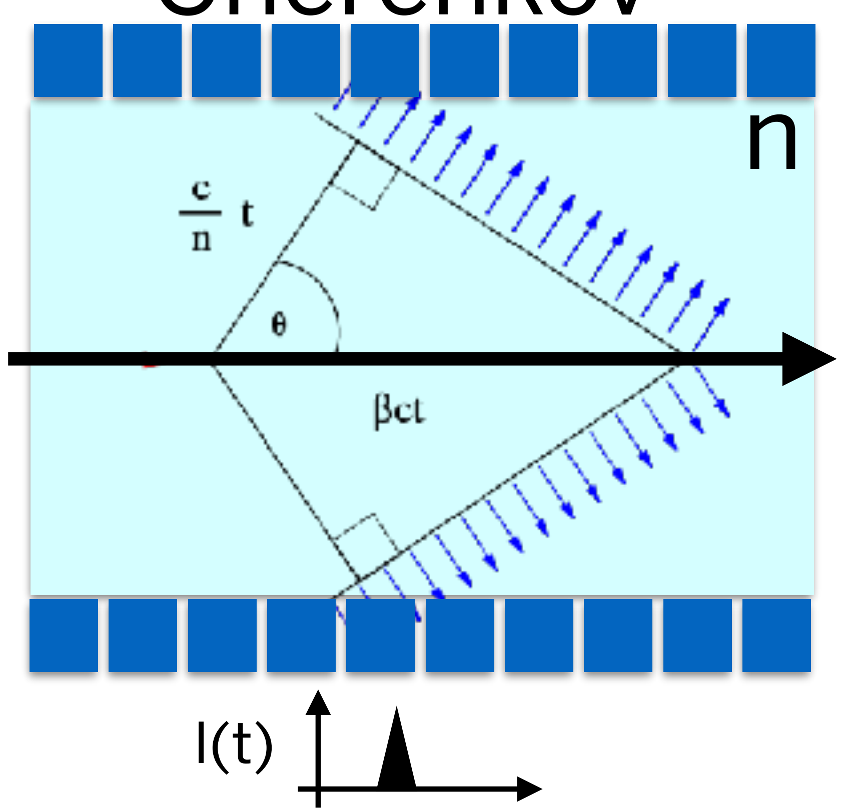


Scintillator

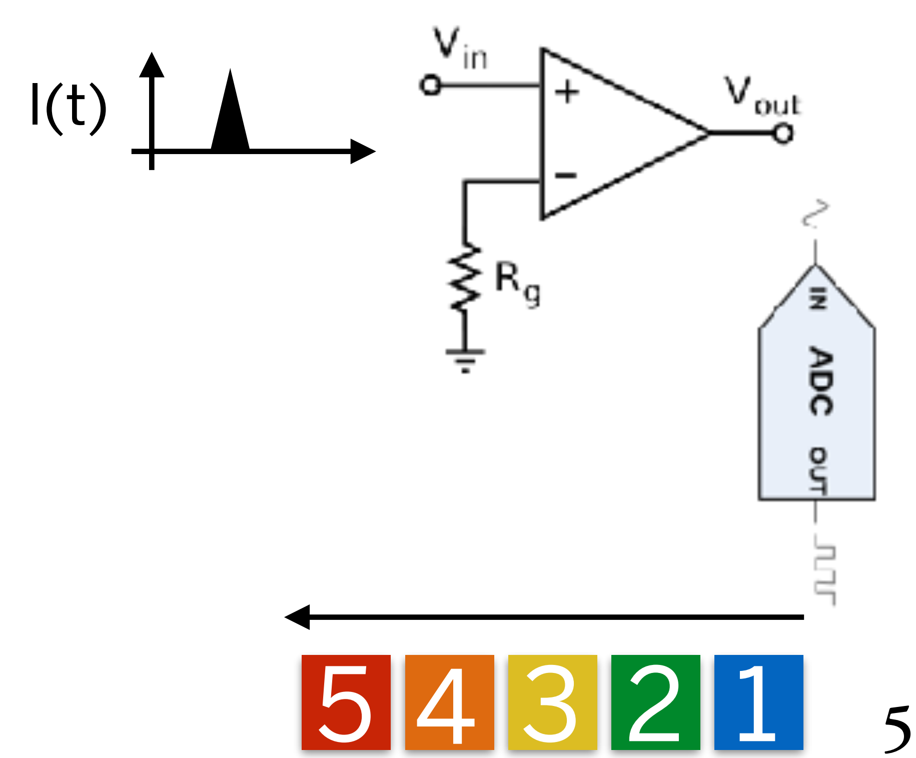


1. detectors produce a small amount of current
2. pass it through an amplifier to make it measurable
3. amplifier output is passed to an ADC which converts to digital data
4. store events in FIFO and wait for readout decision

Cherenkov

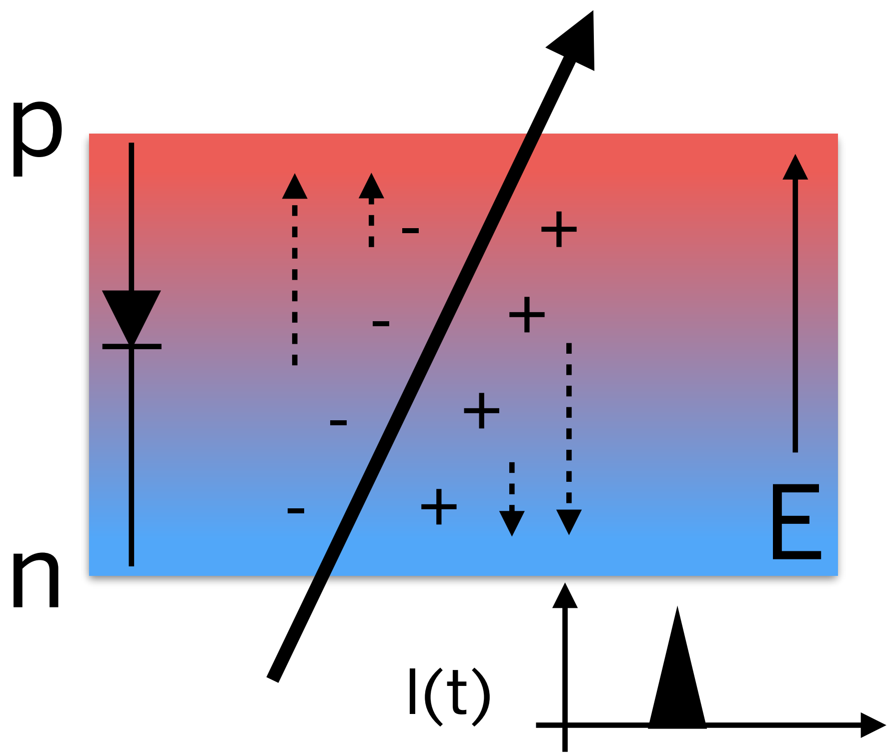


Readout

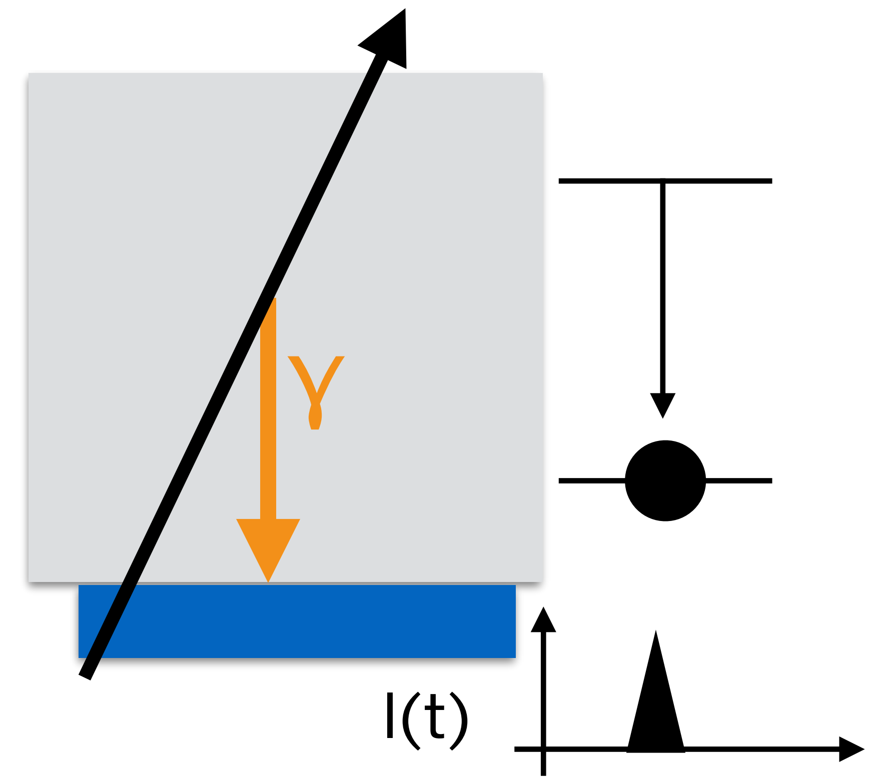


How detectors work

Semiconductor

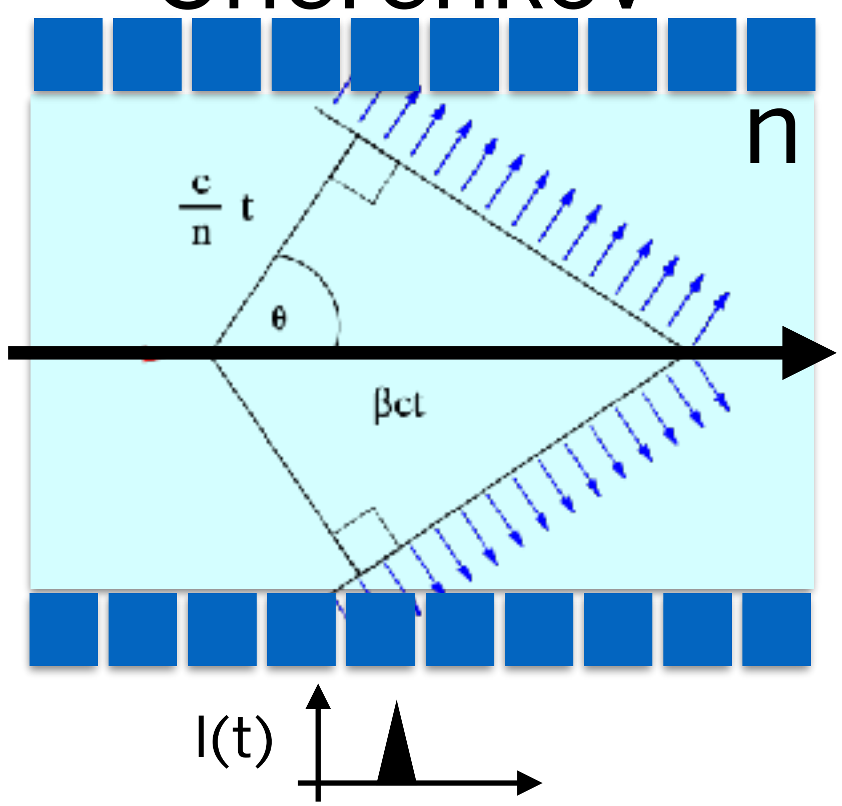


Scintillator

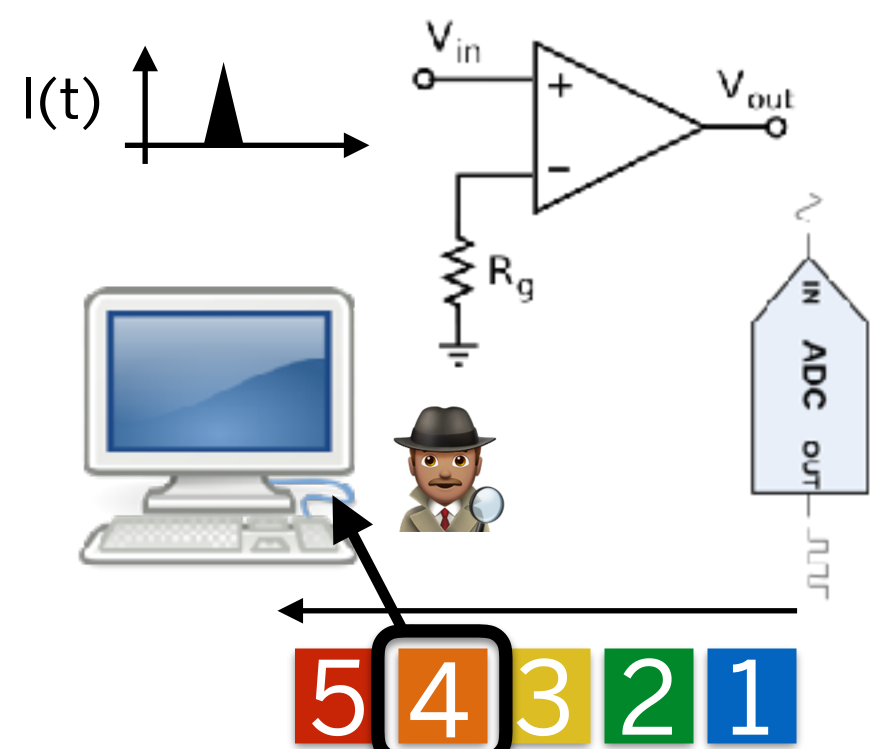


1. detectors produce a small amount of current
2. pass it through an amplifier to make it measurable
3. amplifier output is passed to an ADC which converts to digital data
4. store events in FIFO and wait for readout decision
5. save for analysis!

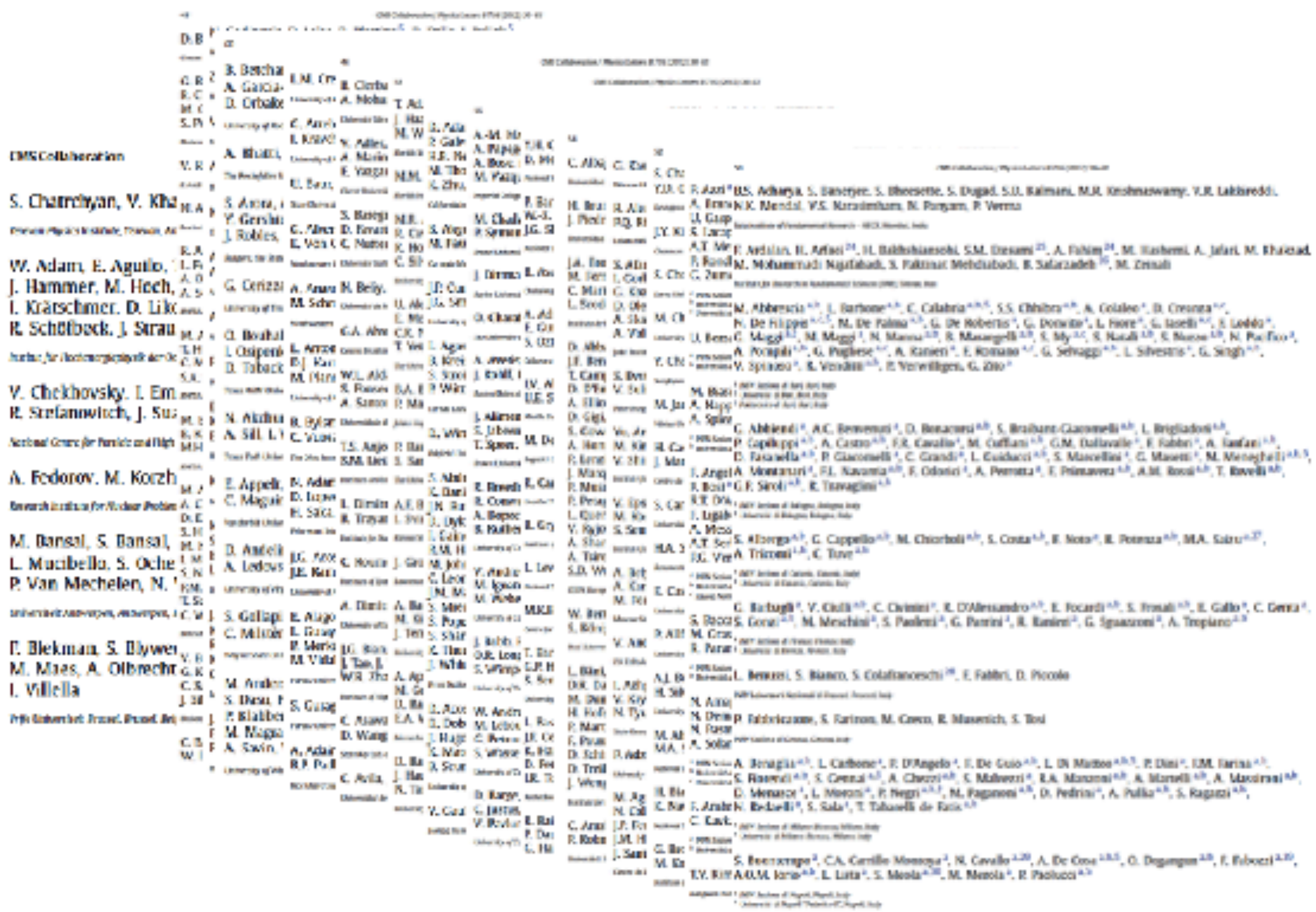
Cherenkov



Readout



So what does everyone do?



- Remember the 3000 authors on the Higgs discovery paper.
- What does everyone do?
- Use FSU as an example…

FSU CMS group

FSU author list

A. Ackert, T. Adams, A. Askew, V. Hagopian, S. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, A. Santra, R. Yohay

Academic faculty — at any given time, some of the faculty are retired, or working part or all of their time on other things (teaching, university administration, ...)

PhD scientists and postdocs — most are working full time on CMS

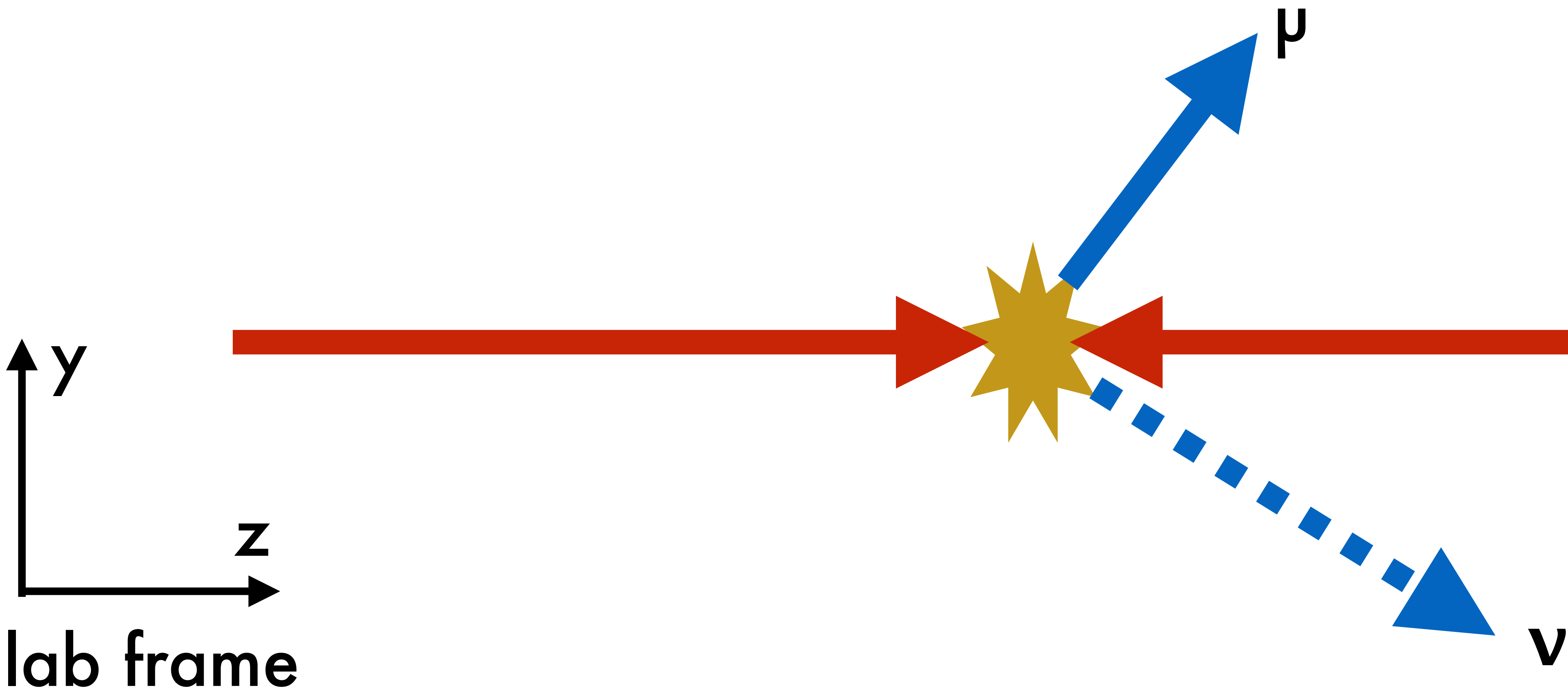
PhD students — some are working part time while taking classes, writing their doctoral thesis, etc.

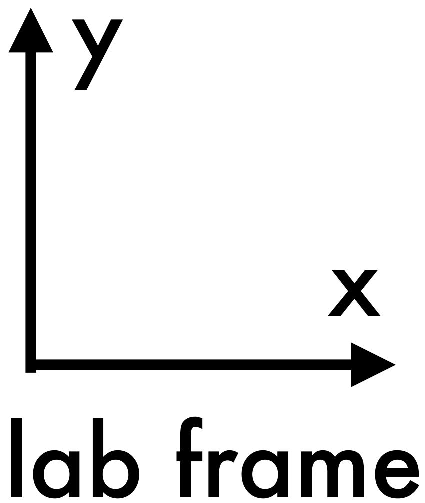
To be an author, you have to work on the experiment for at least a year, and help pay into a common fund which keeps the lights on, etc. As a very rough rule of thumb, about half of the authors might be actively working on CMS at any given moment.

Only a few of us worked 'directly' on the Higgs discovery. What is everyone else doing?

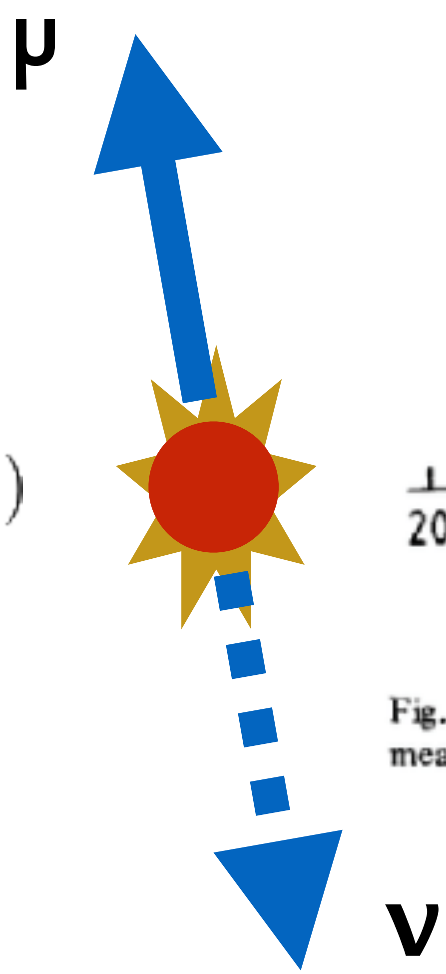
Understanding the detector

- Discovering a particle like the Higgs requires a very good understanding of how the detector responds to different kinds of events.
- At any given time, CMS physicists are constantly updating and refining many performance studies which quantify how well the detector is working.
- These numbers change as the experimental conditions evolve, the software algorithms used to analyze the data are improved, and the detector hardware ages and is upgraded. So it is a constant struggle to stay up to date.
- The next few slides illustrate an example of a performance measurement…





$$M_T^2 \rightarrow 2E_{T,1}E_{T,2}\,(1-\cos\phi)$$



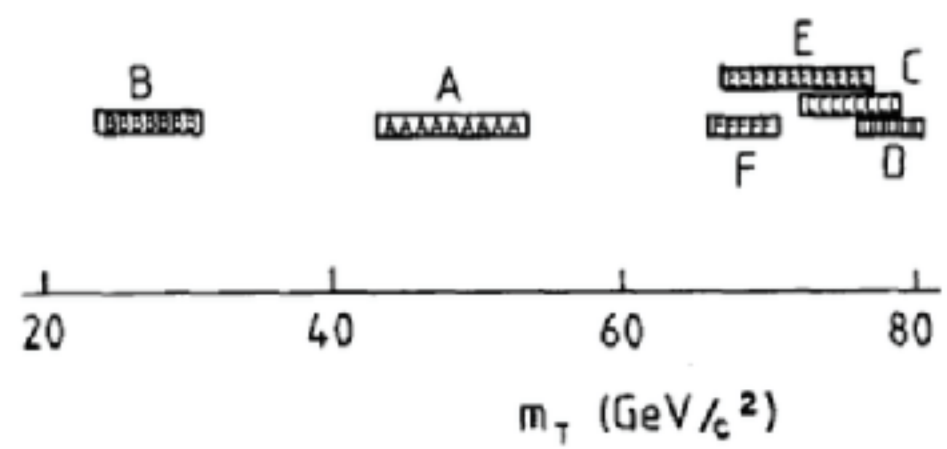
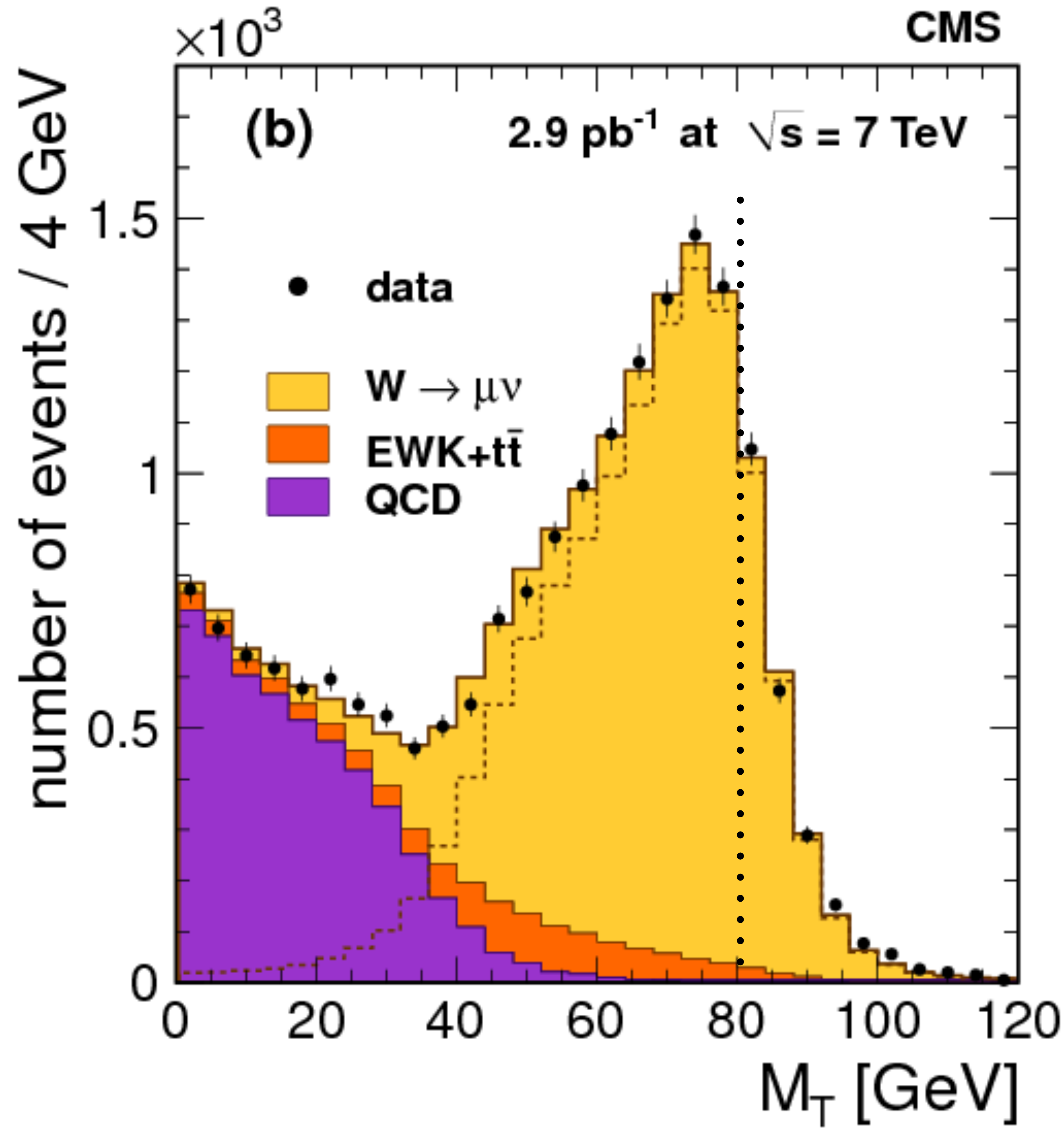
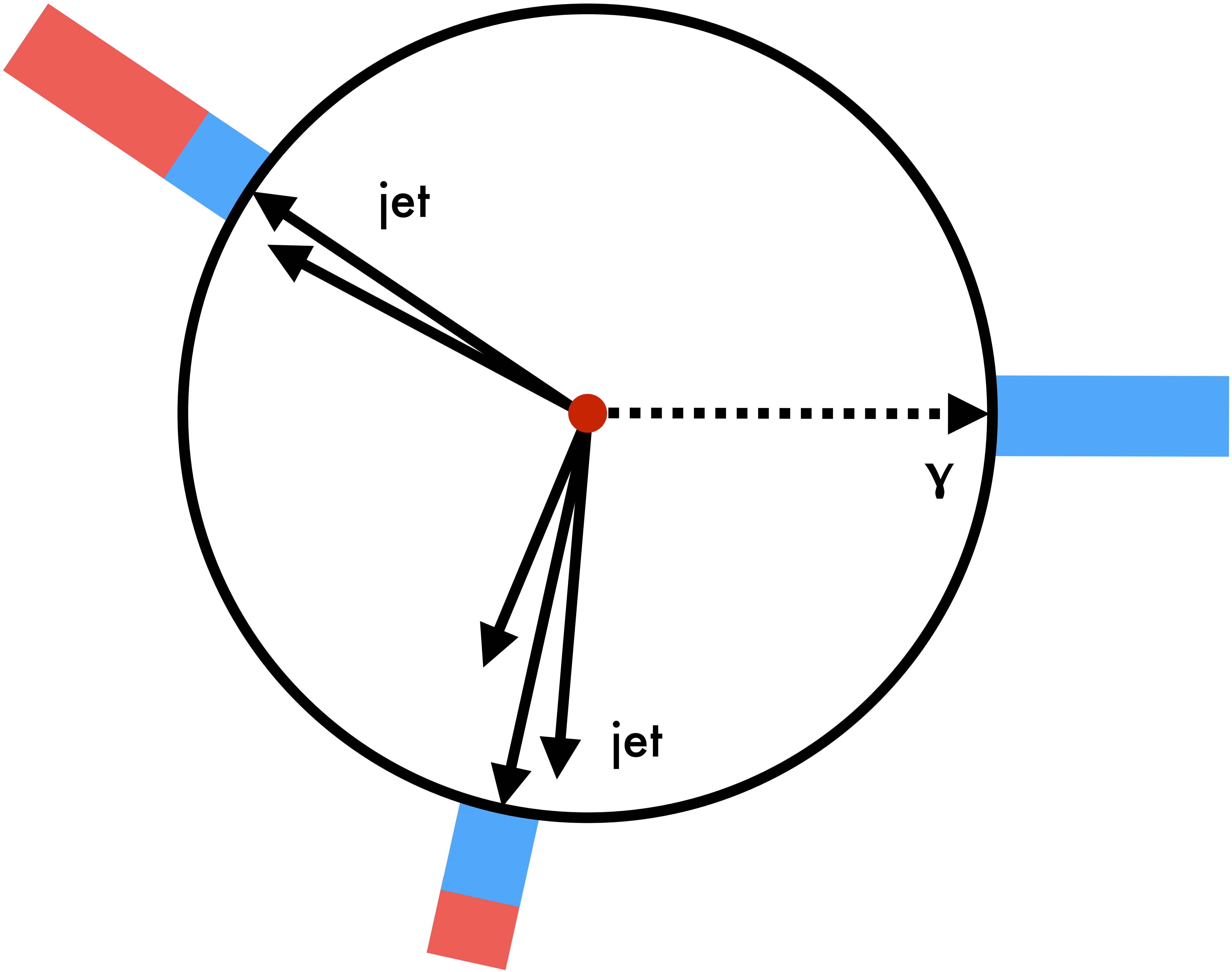


Fig. 9. The distribution of the transverse mass derived from the measured electron and neutrino vectors of the six electron events.

Transverse mass of W events




jet
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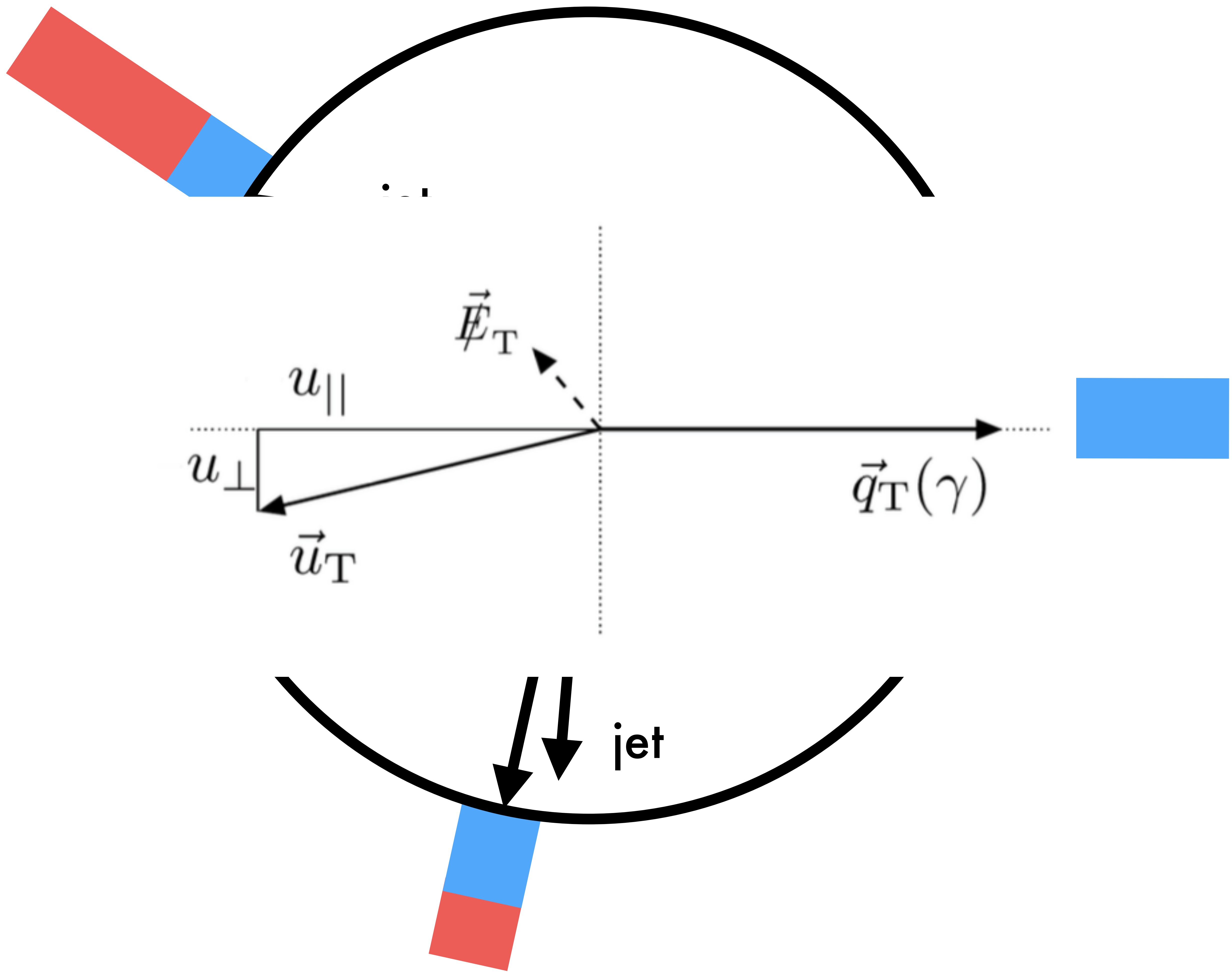
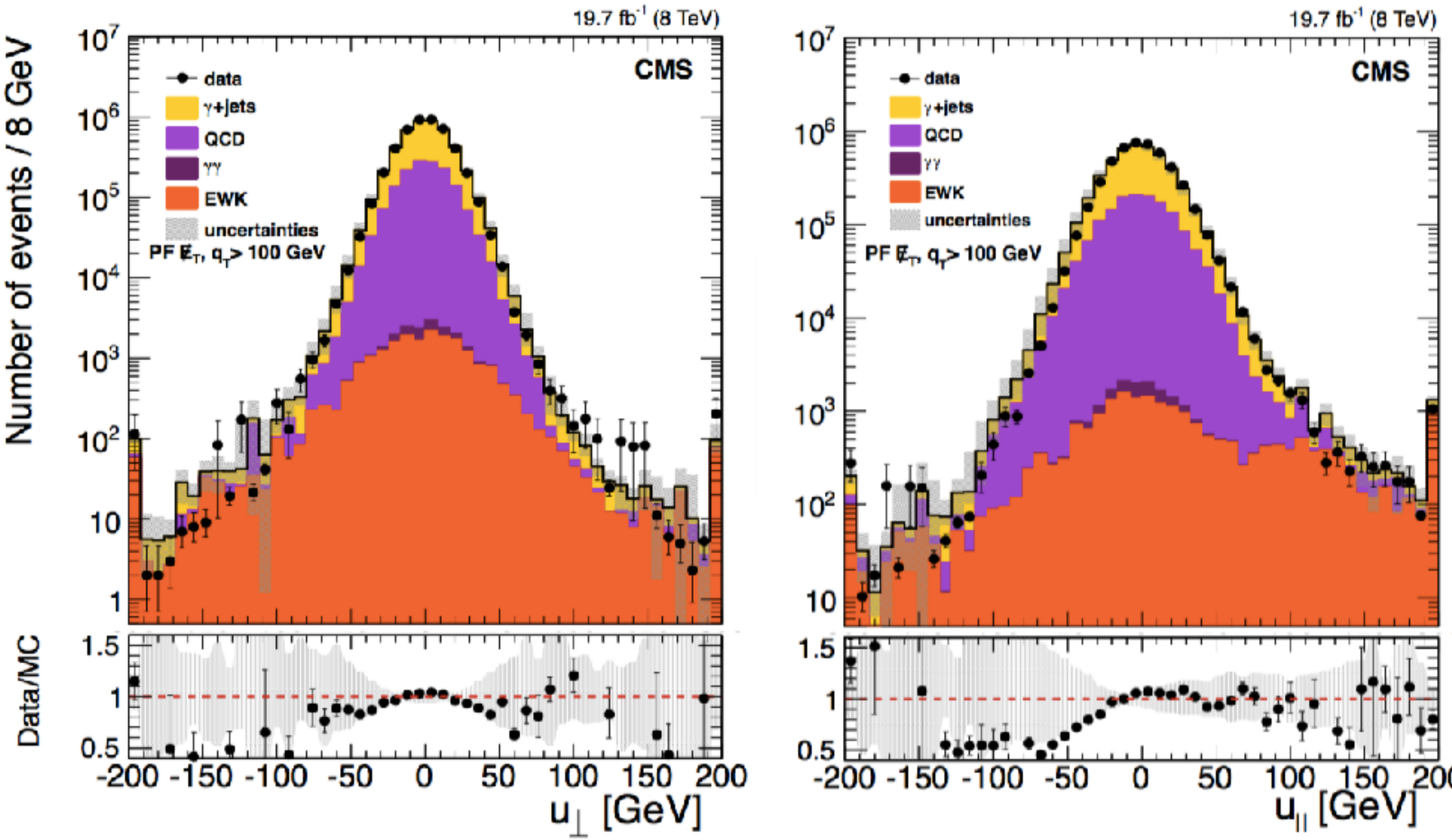

$\vec{\not{E}}_T$
$u_{||}$
$u_\perp$
$\vec{q}_T(\gamma)$
$\vec{u}_T$
jet

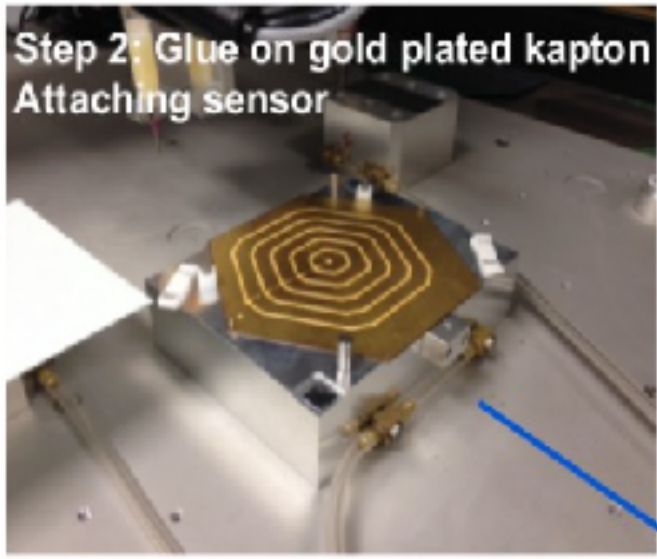


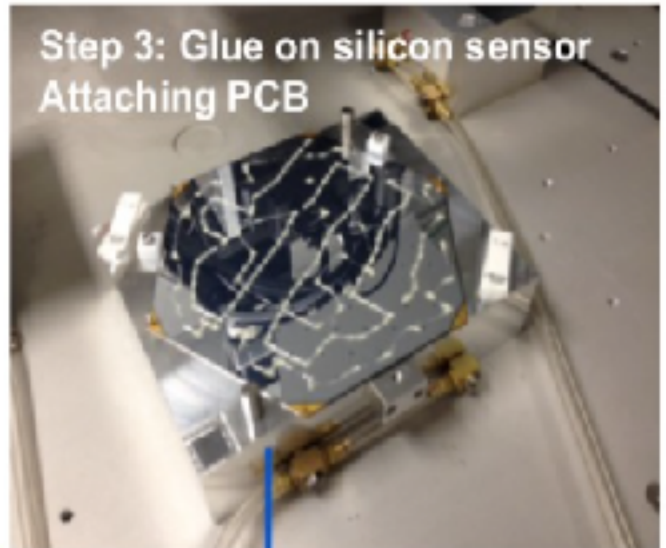
[JINST 10 (02) 2015 P02006]

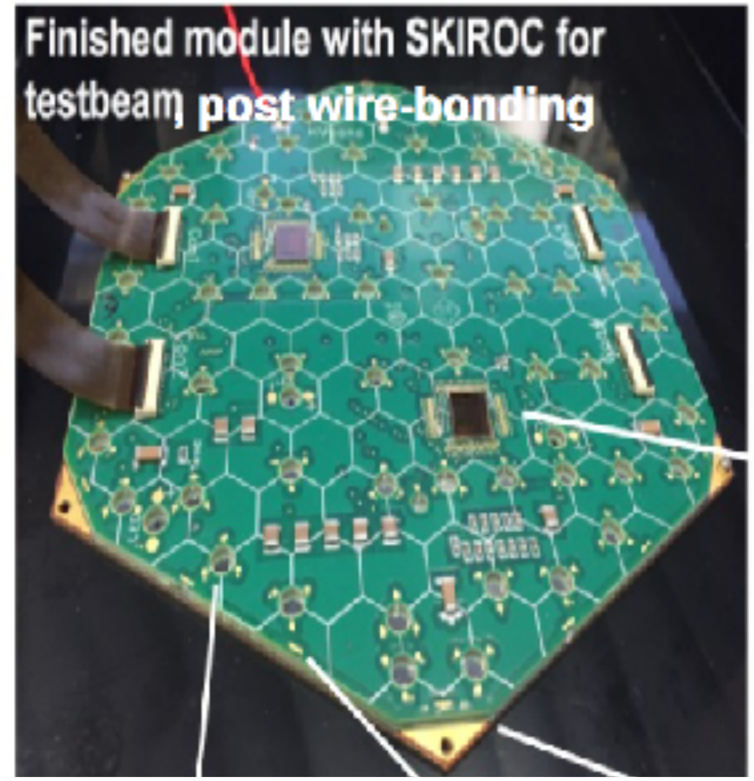
Other activities…

- Building detectors
- Developing electronic systems for readout
- Working on the physical plant of the experiment and taking shifts
- Distributed computing and writing software

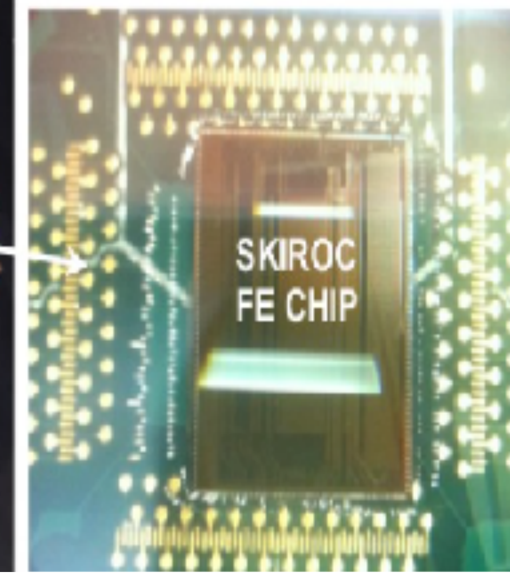
Detector development

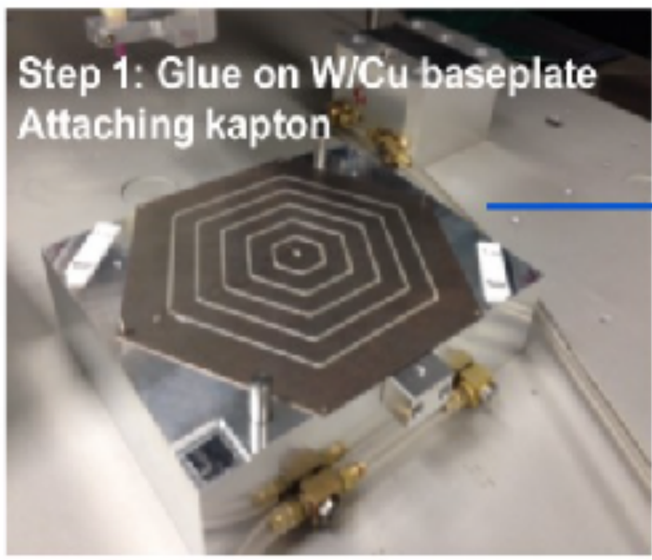


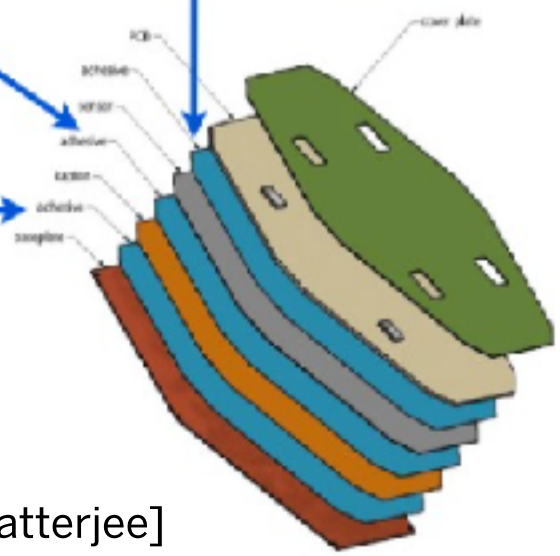




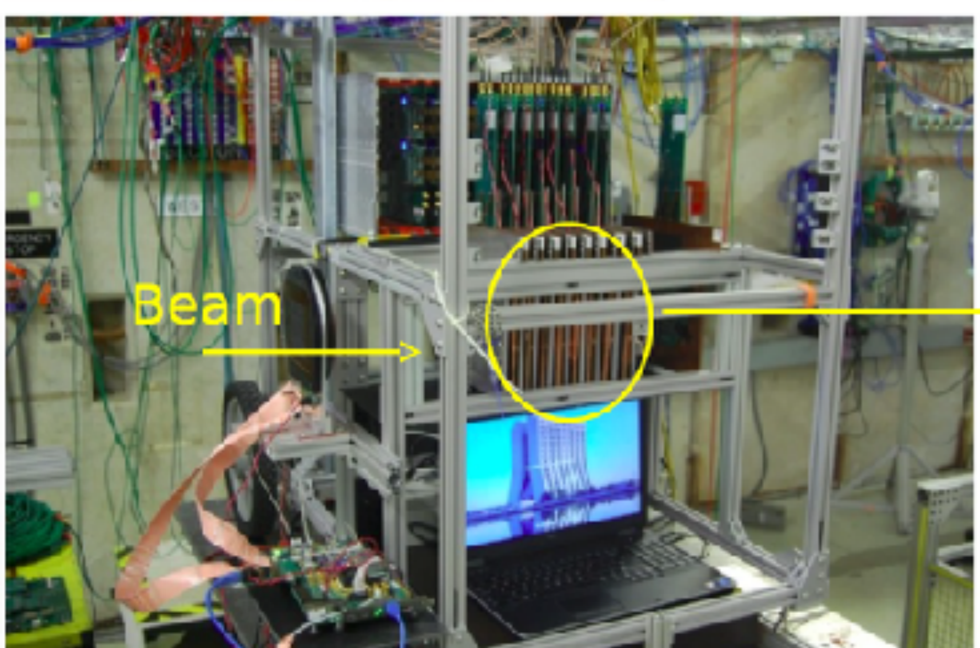
- ~ 700 wire bonds on a single module!

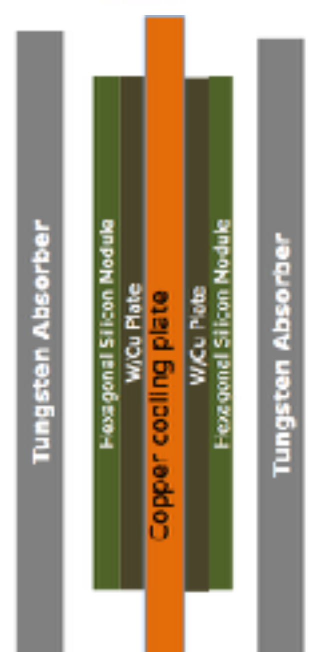


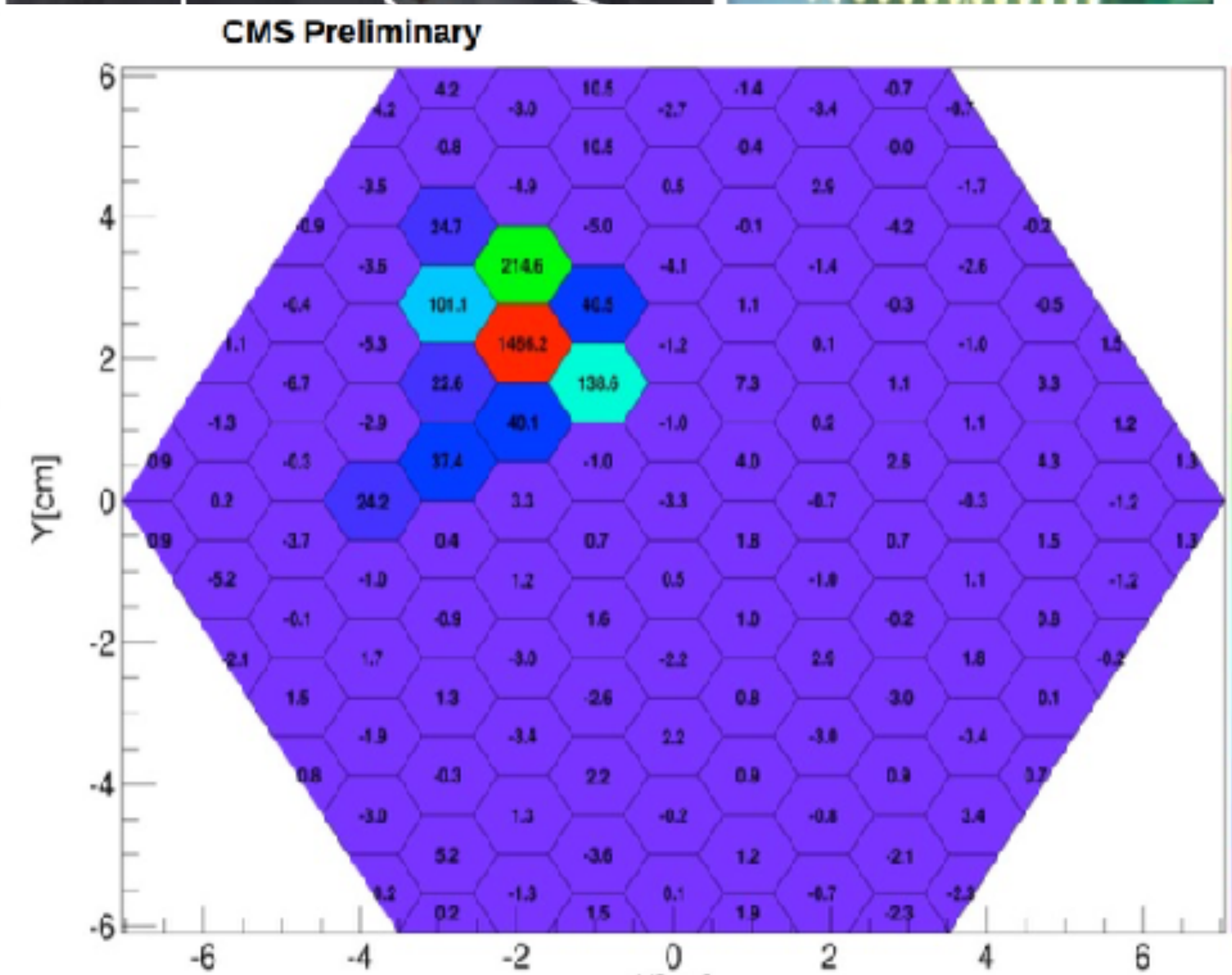




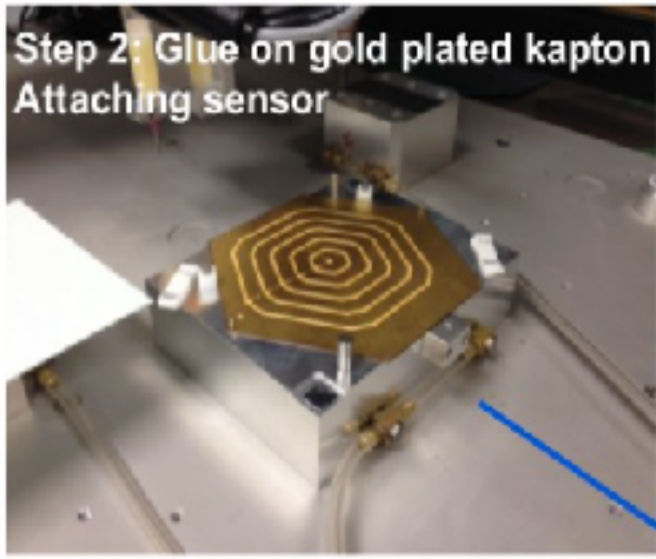
[R. Chatterjee]

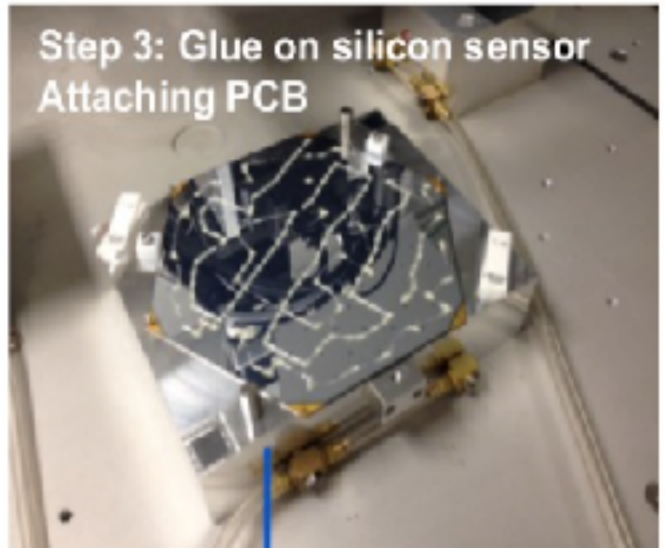


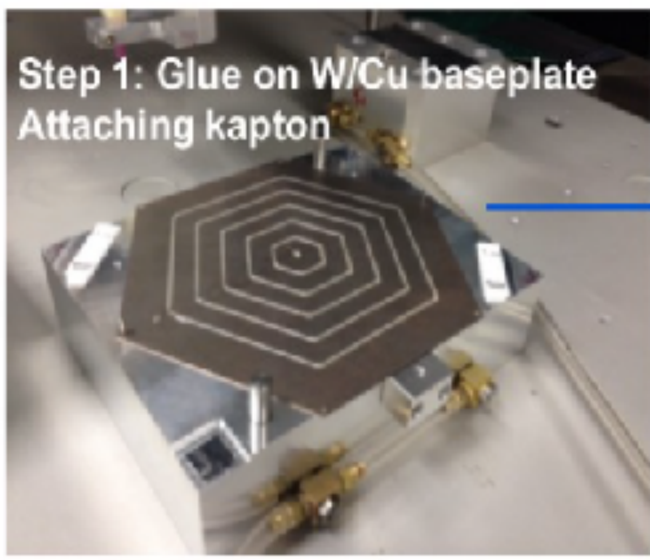


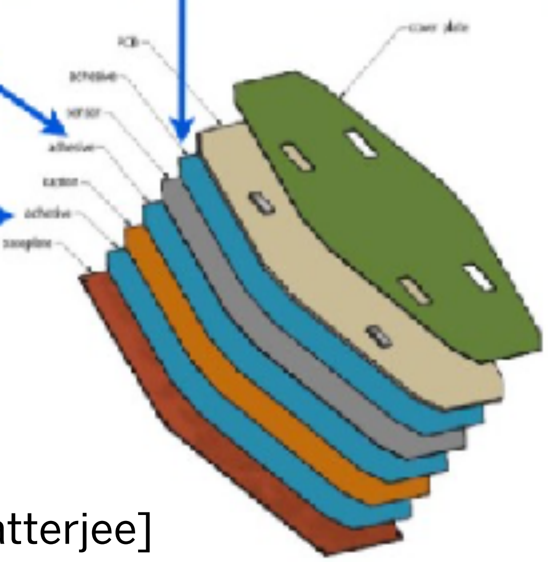


Detector development

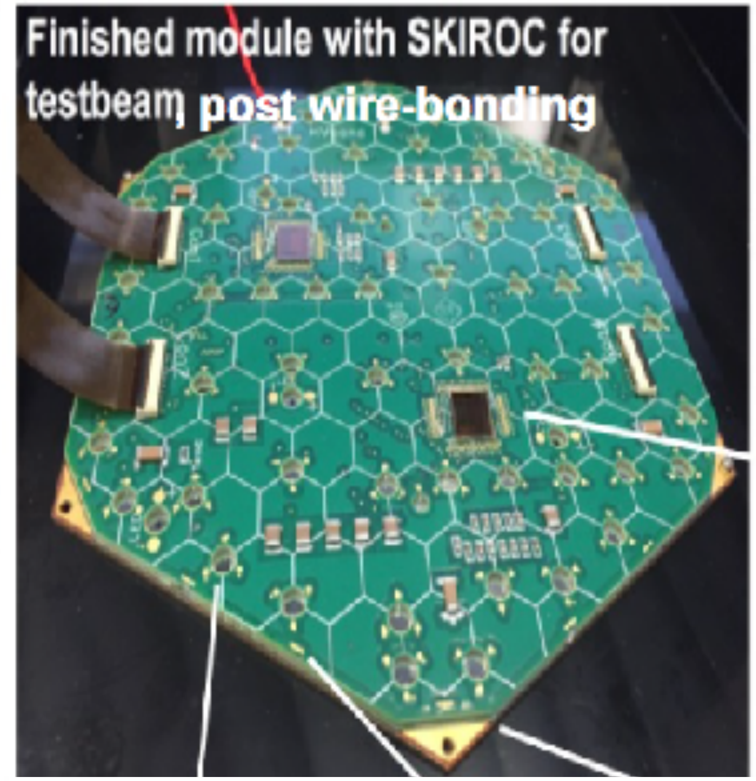




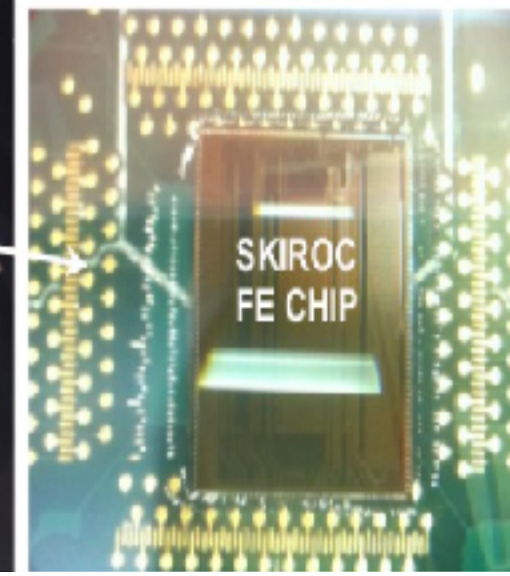


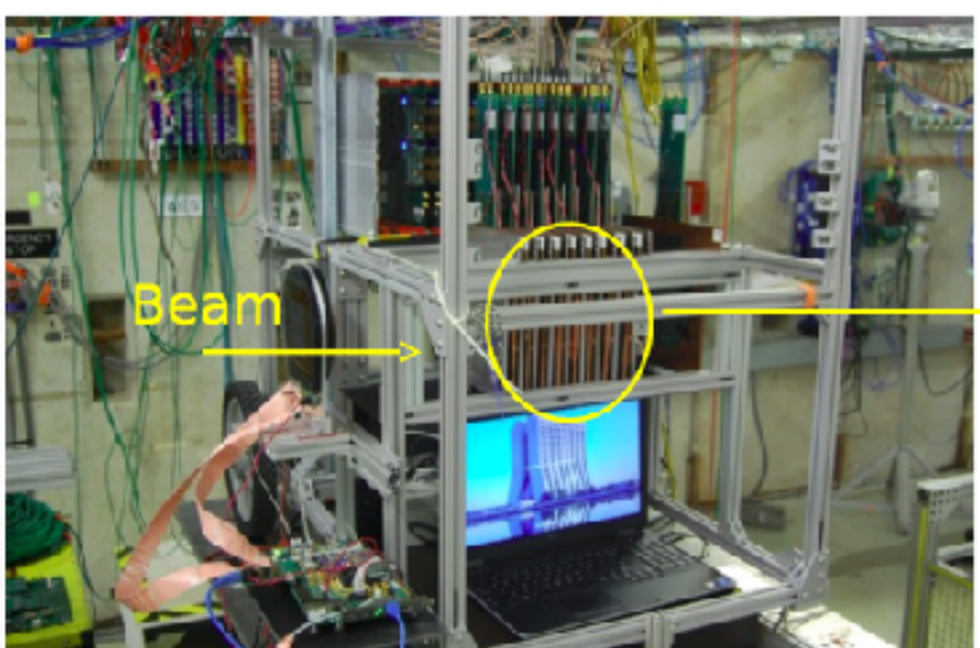


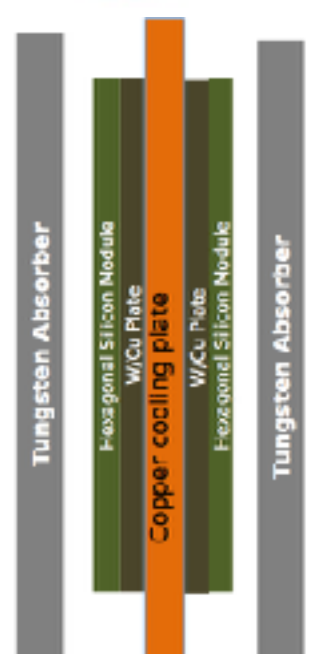
[R. Chatterjee]

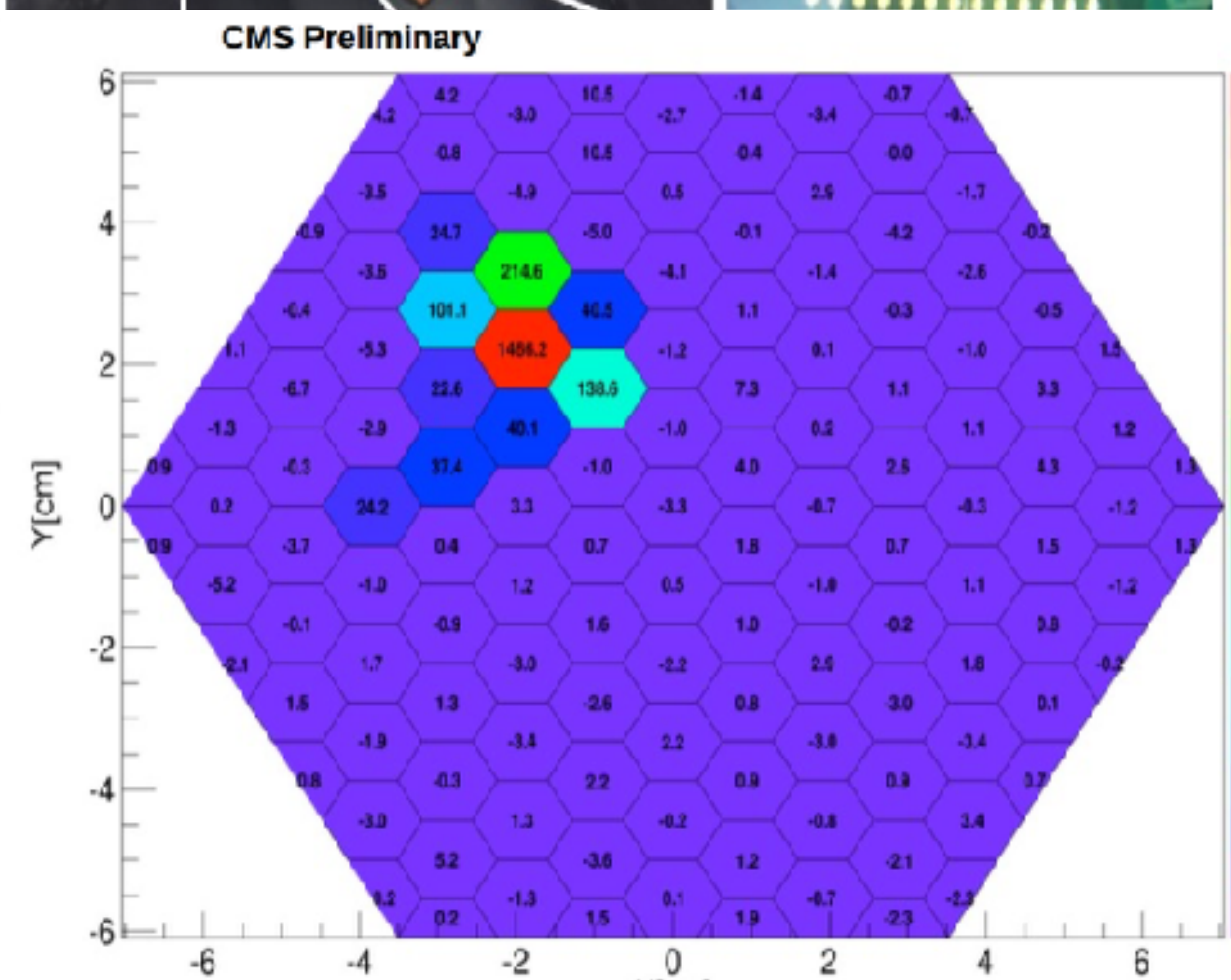


• ~ 700 wire bonds on a single module!

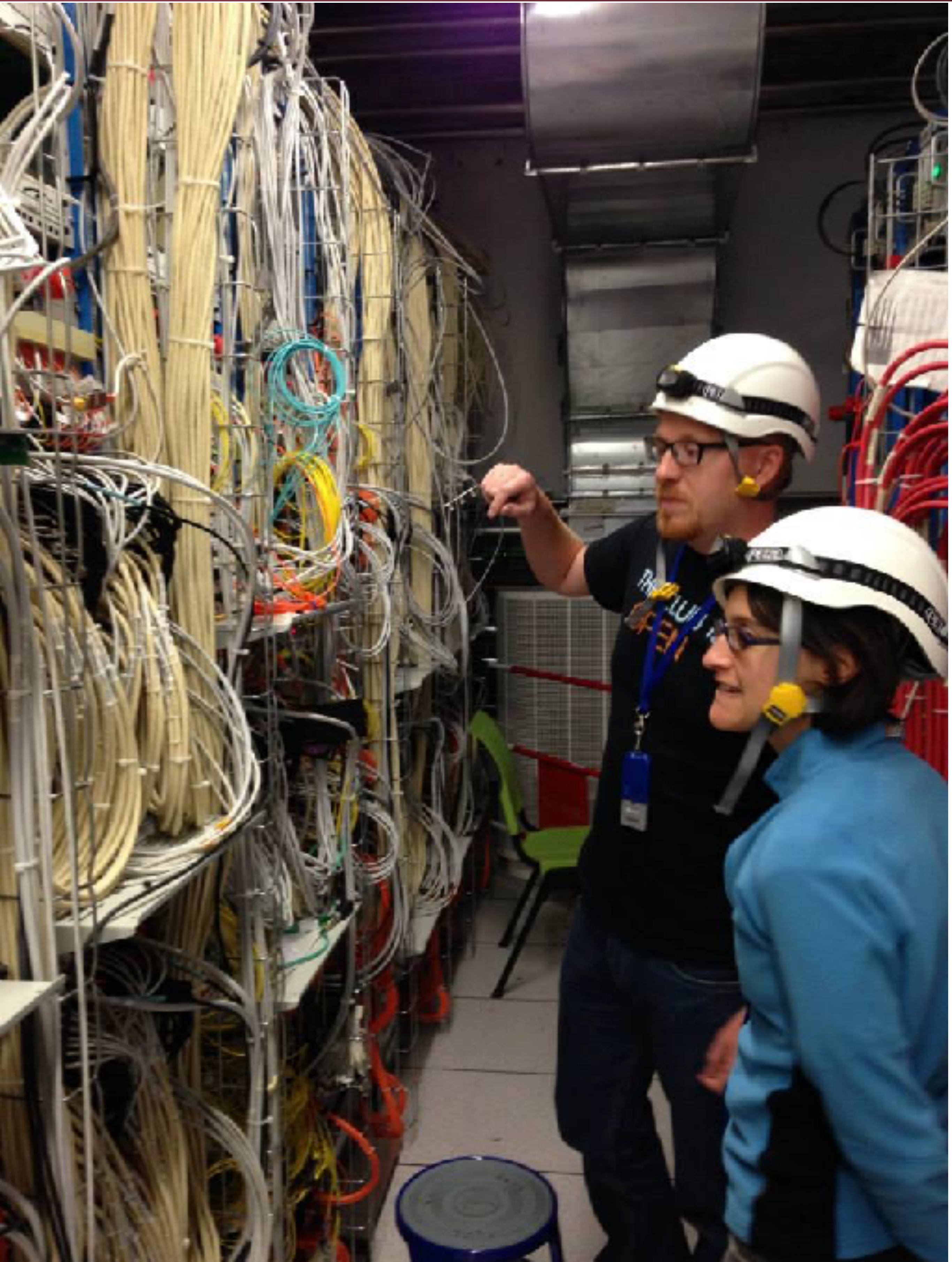


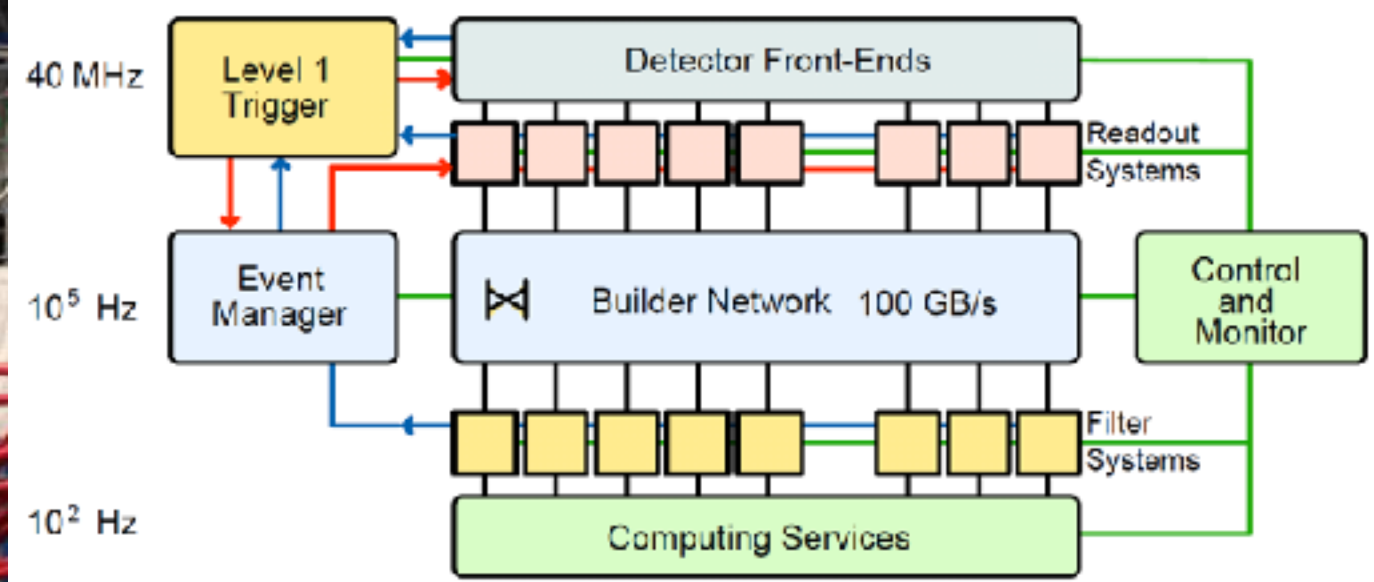


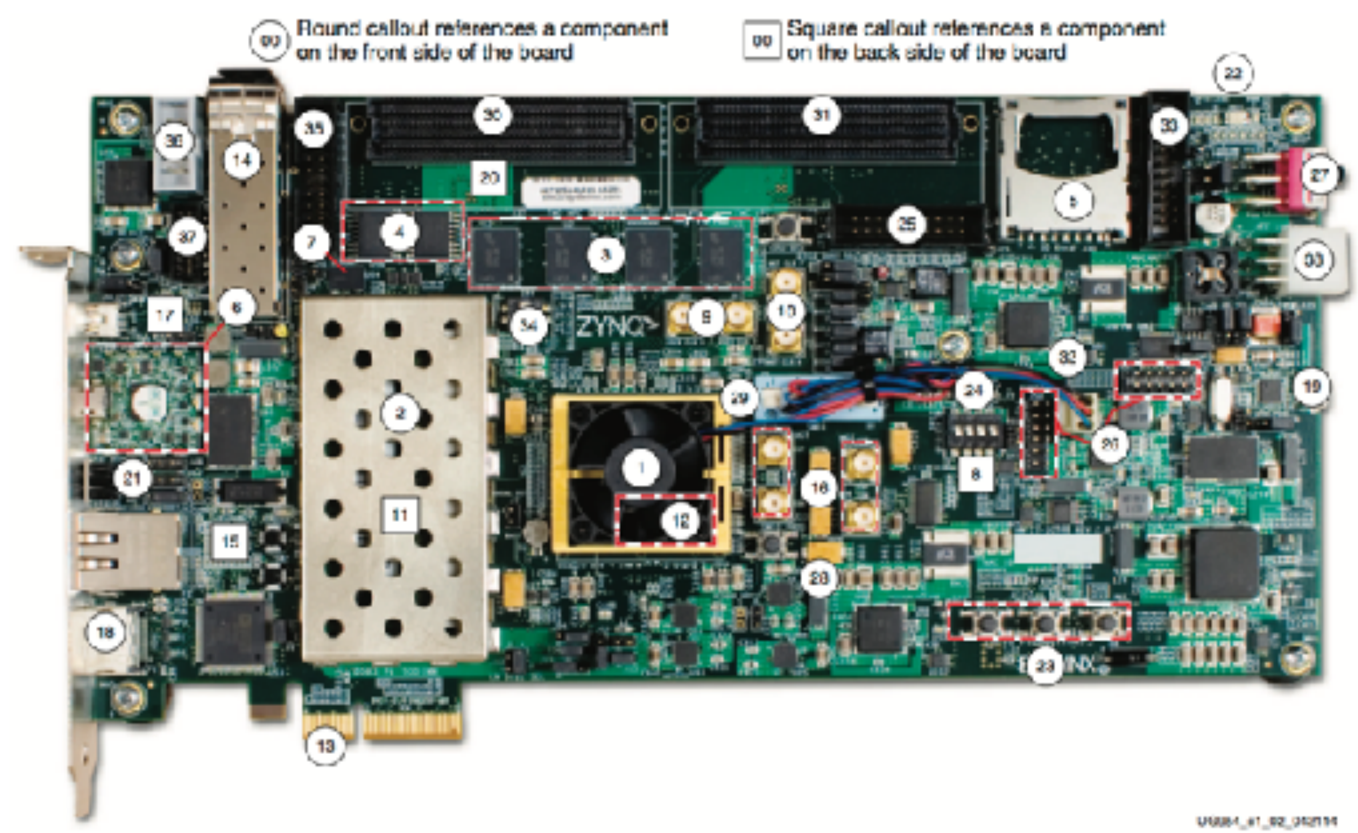




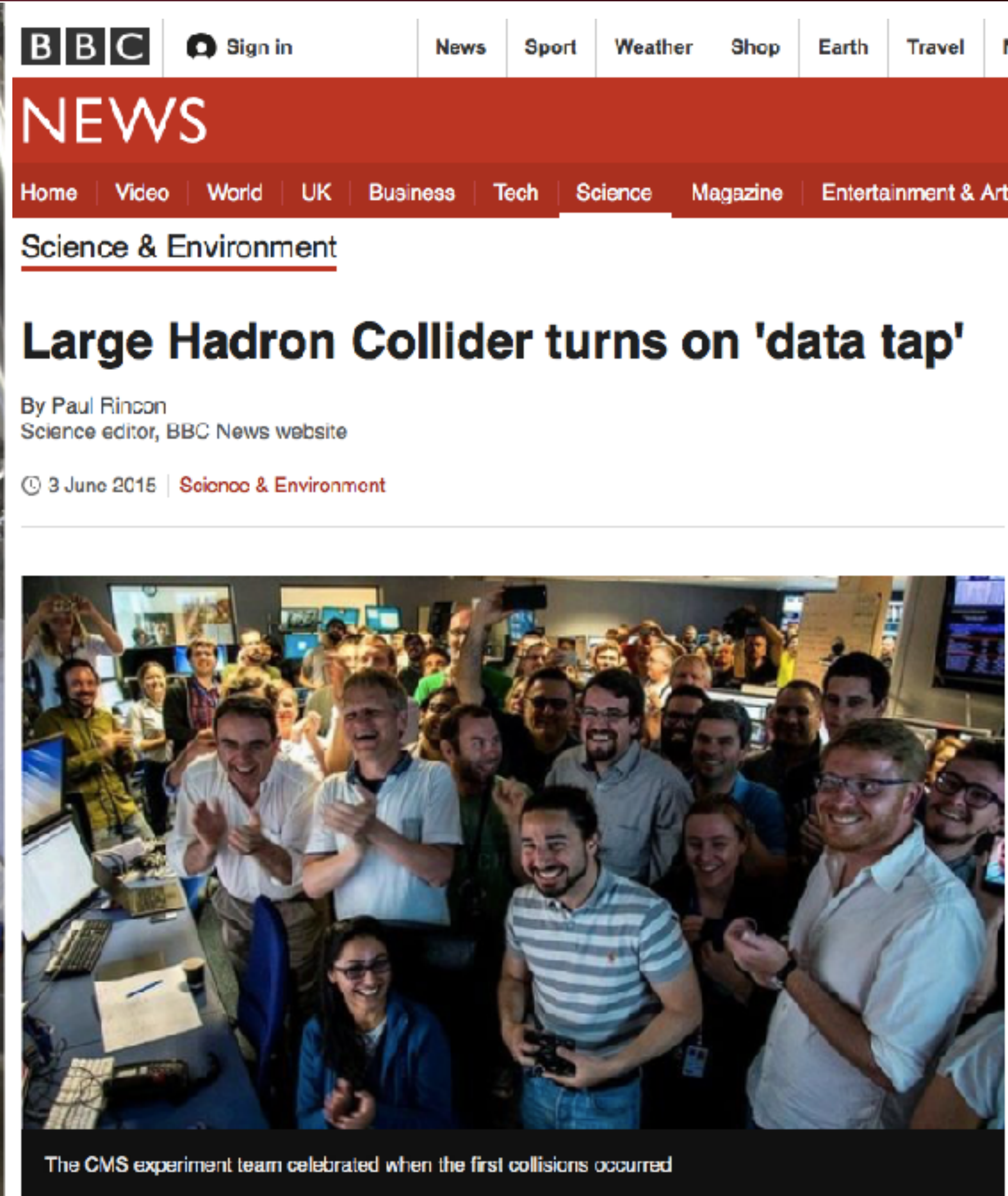
Electronics development







Installation & operations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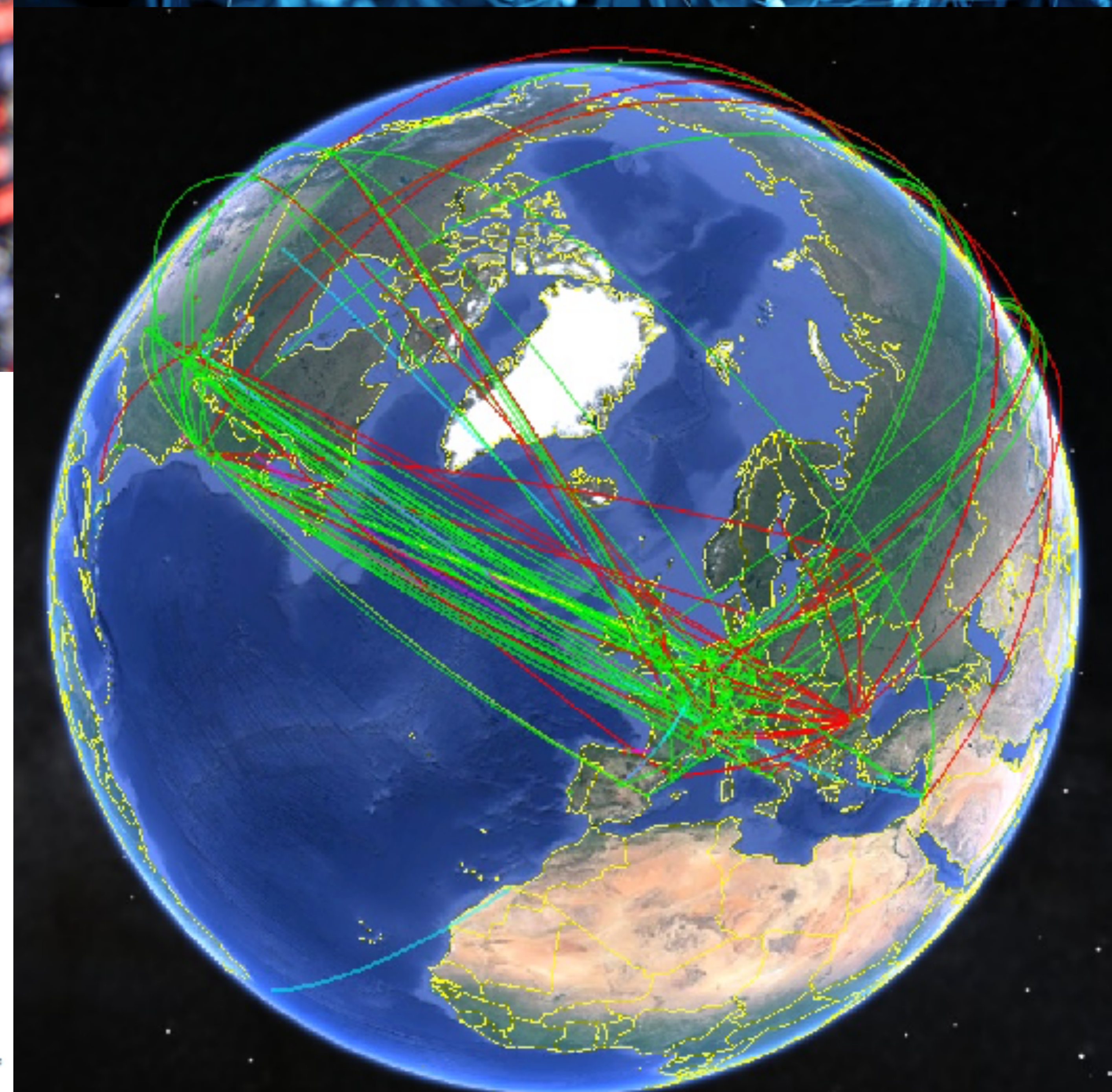
Large Hadron Collider turns on 'data tap'

By Paul Rincon
Science editor, BBC News website

3 June 2015 | Science & Environment

The CMS experiment team celebrated when the first collisions occurred

Marketable skills



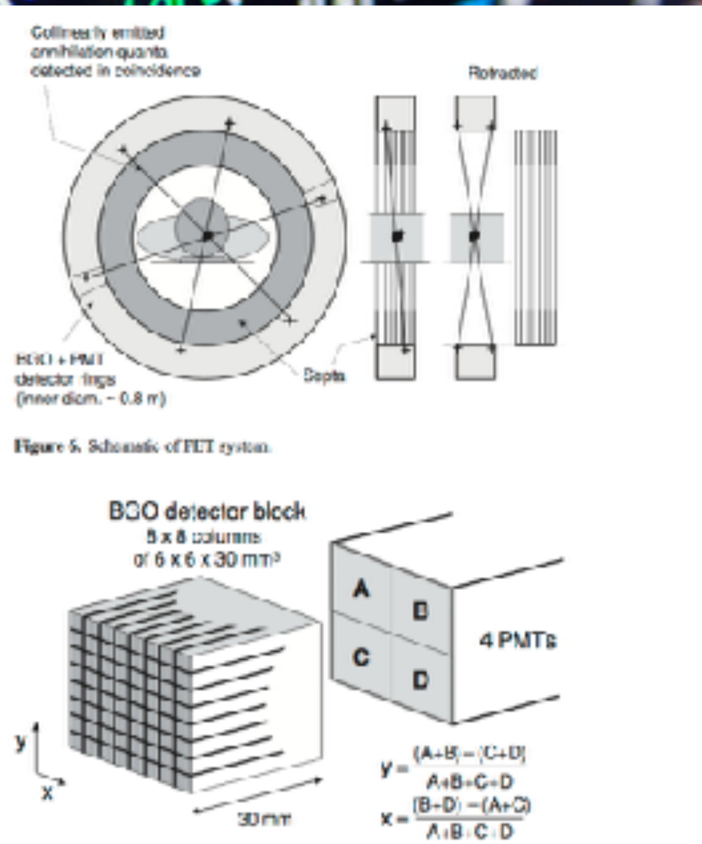


Figure 5. Schematic of PET system.

Figure 7. Schematic of BGO detector block showing saw cuts of 8 × 8 columns (left), to be coupled to four PMTs for position sensitive light detection (right).

Summary

- Adding together all the activities needed to discover a particle like the Higgs, the huge size of the collaboration starts to look rather small!
- We could do more if we had more resources…
- CMS experiment at the LHC is an exciting place and time to do physics.