Synergies of the long-baseline neutrino and collider programs

Joe Lykken
Fermilab
CERN Neutrino Platform Week

My qualifications for giving this talk:

According to my 3 minutes of careful research, the only people who are on the author list of both DUNE && (ATLAS || CMS) are me, David Lissauer, Albert De Roeck, and Milos Lokajicek

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

The CMS Collaboration

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albert, M. Albrow, J. Anderson, G. Apollinari, M. Atac†, W. Badgett, D. Bailleux, 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. Klima, S. Kunori, S. Kwan, K. Larson, C. Leonidopoulos[62], 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, S.J. Murray, Y. Musienko[63], S. Muzaffar, C. Newman-Holmes, V. O'Dell, I. Osborne, J. Pivarski, S. Popescu[28], 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

The DUNE Collaboration

B. Abi[105], R. Acciarri[45], M. A. Acero[7], M. Adamowski[45], C. Adams[149], D. L. Adams[12], P. Adamson[45], M. Adinolfi[11], Z. Ahmad[139], C. H. Albright[45], T. Alion[131], J. Anderson[5], K. Anderson[45], C. Andreopoulos[81,121], M. P. Andrews[45], R. A. Andrews[45], J. dos Anjos[14], A. Ankowski[141], J. Anthony[23], M. Antonello[47], A. Aranda Fernandez[30], A. Ariga[9], T. Ariga[9], E. Arrieta Diaz[129], J. Asaadi[135], M. Ascencio[115], D. M. Asner[106], M. S. Athar[2], M. Auger[9], A. Aurisano[28], V. Aushev[77], D. Autiero[66], F. Azfar[105], J. J. Back[144], H. O. Back[106], C. Backhouse[22], X. Bai[126], M. Baird[141], A. B. Balantekin[147], S. Balasubramanian[149], B. Baller[45], P. Ballett[39], B. Bambah[54], H. Band[149], M. Bansal[109], S. Bansal[109], G. J. Barker[144], G. Barr[105], J. Barranco Monarca[49], N. Barros[112], A. Bashyal[104], M. Bass[105], F. Bay[137], J. L. Bazo[115], J. F. Beacom[103], B. R. Behera[109], G. Bellettini[113], V. Bellini[24], O. Beltramello[16], N. Benekos[16], P. A. Benetti[110], A. Bercellie[119], E. Berman[45], H. Berns[19], R. Bernstein[45], S. Bertolucci[16], V. Bhatnagar[109], B. Bhuyan[59], J. Bian[20], K. Biery[45], M. Bishai[12], A. Bitadze[87], T. Blackburn[131], A. Blake[79], F. d. M. Blaszczyk[10], E. Blaufuss[88], G. C. Blazey[95], M. Blennow[73], E. Blucher[26], V. Bocean[45], F. Boffelli[110], J. Boissevain[83], S. Bolognesi[15], T. Bolton[74], M. Bonesini[61], T. Boone[32], C. Booth[122], S. Bordoni[16,16], P. Bour[35], B. Bourguille[55], S. B. Boyd[144], D. Boyden[95], D. Brailsford[79], A. Brandt[135], J. Bremer[16], S. J. Brice[45], C. Bromberg[91], G. Brooijmans[33], G. Brown[135], G. Brunetti[45,108], N. Buchanan[32], H. Budd[119], P. Calafiura[80], A. Calatayud[115], E. Calligarich[110], E. Calvo[17], L. Camilleri[33], M. Campanelli[82], C. Cantini[40], B. Carls[45], M. Cascella[82], E. Catano-Mur[68], M. Cavaili-Sforza[55], F. Cavanna[45,149], S. Centro[108], A. 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Gandhi[50], S. Gao[12], D. Garcia-Gamez[87], S. Gardiner[19], D. Gastler[10], A. Gendotti[40], D. Gibin[108], I. Gil-Botella[17], R. Gill[12], A. K. Giri[60], D. Goeldi[9], M. Gold[98], S. Gollapinni[133], R. A. Gomes[46], J. J. Gomez Cadenas[56], M. C. Goodman[5], D. Gorbunov[67], S. Goswami[107], N. Graf[114], N. Graf[120], M. Graham[120], E. Gramelini[149], R. Gran[93], C. Grant[10], N. Grant[144], V. Greco[24], H. Greenlee[45], L. Greenler[147], M. Groh[65,28], K. Grzelak[142], E. Guardincerri[83], V. Guarino[5], G. P. Guedes[44], R. Guenette[105], A. Guglielmi[108], K. K. Guthikonda[76], M. M. Guzzo[41], A. T. Habig[93], A. Hackenburg[149], R. W. Hackenburg[12], H. Hadavand[135], R. Haenni[9], A. Hahn[45], M. D. Haigh[144], T. Haines[83], T. Hamernik[45], P. Hamilton[132], T. Handler[133], S. Hans[12], D. Harris[45], J. Hartnell[131], T. Hasegawa[72], R. Hatcher[45], A. Hatzikoutelis[133], S. Hays[45], E. Hazen[10], M. Headley[127], A. Heavey[45], K. M. Heeger[149], J. 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Kocaman[137], L.W. Koerner[52], S. Kohn[18,80], G. Koizumi[45], A. Kopylov[67], M. Kordosky[146], L. Kormos[79], U. Kose[16,9], V. A. Kostelecký[65], M. Kramer[18,80], I. Kreslo[9], K. Kriesel[147], W. Kropp[20], Y. Kudenko[67], V. A. Kudryavtsev[122], S. Kulagin[67], A. Kumar[109], J. Kumar[51], L. Kumar[109], V. Kus[35], T. Kutter[84], K. Lande[112], C. Lane[37], K. Lang[136], T. Langford[149], F. Lanni[12], A. Laundrie[147], T. Le[138], J. Learned[51], P. Lebrun[45], D. Lee[83], W. M. Lee[45], M. A. Leigui de Oliveira[43], Q. Z. Li[45], S. Li[12], S. W. Li[103], X. Li[130], Y. Li[12], Z. Li[38], C. S. Lin[80], S. Lin[32], R. Linehan[120], J. Link[141], Z. Liptak[31], D. Lissauer[12], M. Lokajicek[13], L. LoMonaco[24], K. Long[64], K. Loo[71], J. P. Lopez[31], D. Lorca[9], J. M. LoSecco[102], W. Louis[83], M. Luethi[9], K. B. Luk[18,80], T. Lundin[45], X. Luo[149], T. Lux[55], J. Lykken[45], J. Maalampi[71], A. A. Machado[43], C. T. Macias[65], J. R. Macier[45], R. 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Rebel[45], C. Regenfus[40], J. Reichenbacher[126], S. D. Reitzner[45], A. Remoto[78], A. Renshaw[52], S. Rescia[12], L. Rice[95], K. Rielage[83], K. Riesselmann[45], D. Rivera[112], M. Robinson[122], L. Rochester[120], O. B. Rodrigues[46], P. Rodrigues[119], B. Roe[90], R. M. Roser[45], M. Ross-Lonergan[39], M. Rossella[110], J. Rout[70], S. Roy[50], A. Rubbia[40], C. Rubbia[48], R. Rucinski[45], C. Rudolph von Rohr[9], B. Russell[149], D. Ruterbories[119], R. Saakyan[82], K. Sachdev[45], N. Sahu[60], P. Sala[92,16], N. Samios[12], F. Sanchez[55], M.C. Sanchez[68], W.R. Sands[116], S. Santana[117], R. Santorelli[17], L. M. Santos[41], G. Santucci[130], N. Saoulidou[6], G. Savage[45], A. Scaramelli[110], A. Scarpelli[1], T. Schaffer[93], H. Schellman[104], P. Schlabach[45], D. Schmitz[26], J. Schneps[138], K. Scholberg[38], A. Schukraft[45], E. Segreto[41], S. Sehrawat[50], J. A. Sepulveda-Quiroz[68], F. Sergiampietri[40], K. Sexton[12], L. Sexton-Kennedy[45], M. H. Shaevitz[33], J. Shahi[109], S. Shahsavarani[135], P. Shanahan[45], R. Sharma[12], R. K. Sharma[118], T. Shaw[45], D. Shooltz[91], R. Shrock[130], N. Simos[12], J. Sinclair[9], G. Sinev[38], I. Singh[109], J. Singh[109], J. Singh[85], V. Singh[8], F. W. Sippach[33], K. Siyeon[27], A. Smith[23], P. Smith[65], J. Smolik[35], M. Smy[20], E. Snider[45], P. Snopok[57], J. Sobczyk[148], H. Sobel[20], M. Soderberg[132], N. Solomey[145], W. Sondheim[83], M. Sorel[56], A. Sousa[28], K. Soustruznik[25], M. Spanu[110], J. Spitz[90], N. J. C. Spooner[122], M. Stancari[45], D. Stefan[16,97], A. Stefanik[45], H. M. Steiner[80,18], J. Stewart[12], J. Stock[126], S. Stoica[53], J. Stone[10], J. Strait[45], M. Strait[94], T. Strauss[45], S. Striganov[45], R. Sulej[97], G. Sullivan[88], Y. Sun[51], L. Suter[45], C. M. Sutera[24], R. Svoboda[19], B. Szczerbinska[134], A. M. Szelc[87], S. Söldner-Rembold[87], R. Talaga[5], S. Tariq[45], E. Tatar[63], R. Tayloe[65], K. Terao[33], M. Thiesse[122], L. F. Thompson[122], M. Thomson[23], C. Thorn[12],

Outline of this talk

- Synergies between Higgs flavor physics and neutrinos
- Leptogenesis versus electroweak baryogenesis
- Composite Higgs and neutrinos
- Naturalness, vacuum stability, scales, and unification
- Synergies with operating large international collaborations and large detectors
- Synergies with using AI for reconstruction, triggering, simulation, …

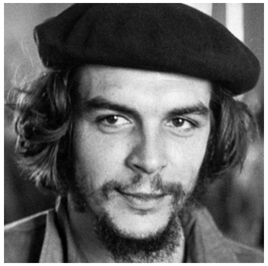
I will **not** discuss LHC direct production of heavy neutrinos, since this is covered in another talk

Summary of the current status of particle theory on one slide:

"The revolution is not an apple that falls when it is ripe.
You have to make it fall" -- Ernesto Guevara de la Serna

- To cast off the tyranny of the Standard Model, it will not be sufficient just to discover new physics - this we already have (neutrino masses, dark matter, dark energy, inflation, baryogenesis, and quantum gravity are all BSM)
- It is also not sufficient to build BSM frameworks – we already have a lot of these too
- We seem to be missing some key clues that will propel us into new ways of thinking and new connections

So we need to keep shaking the tree…

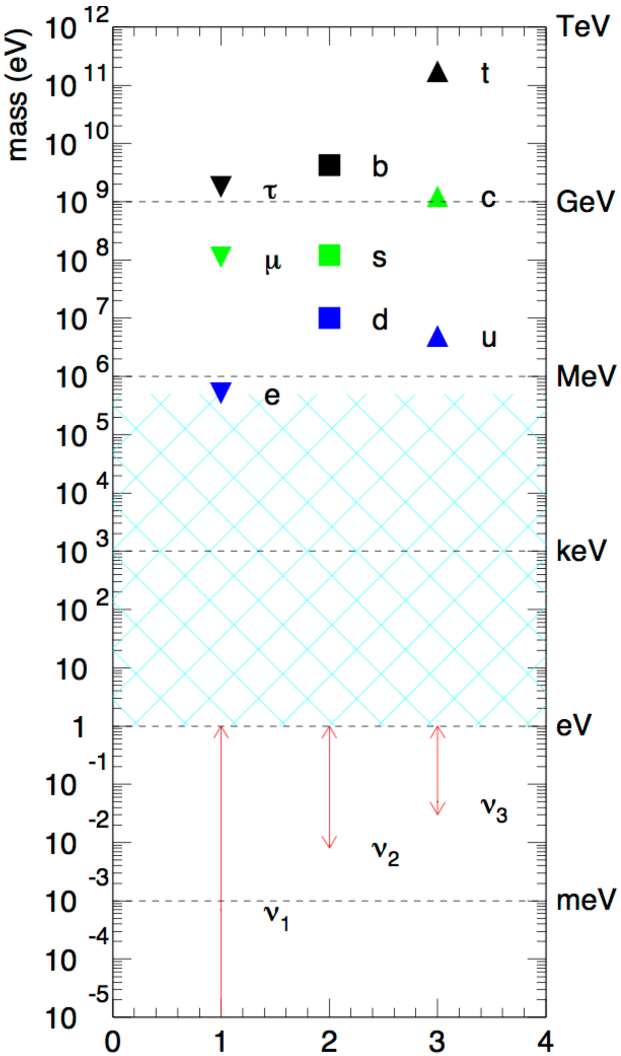


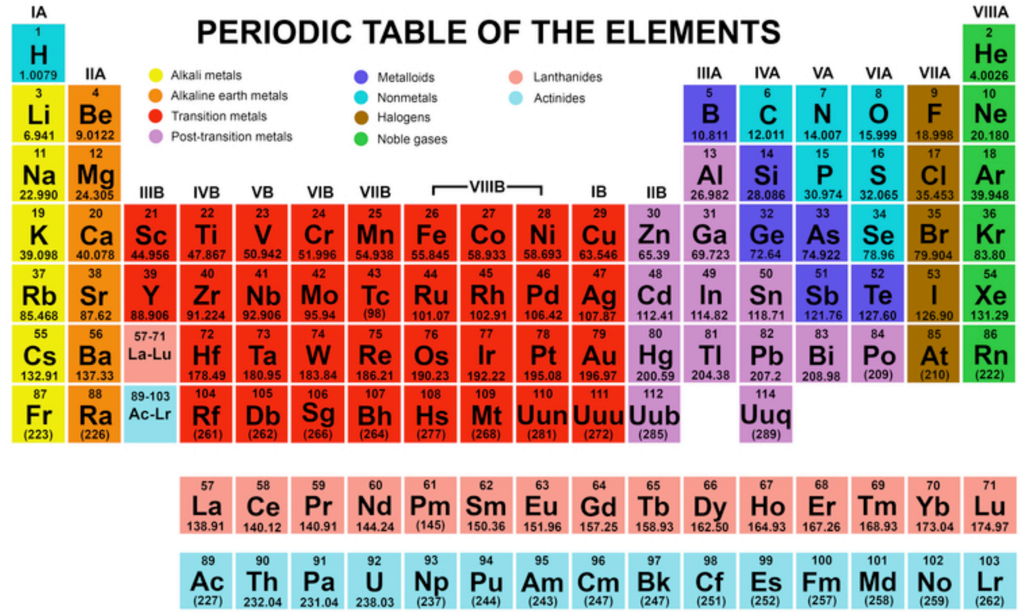
Shaking the tree

There are lots of ways to do this:

- Looking for new phenomena at LHC and lower energy accelerator-based experiments
- Shaking the tree of standard cosmology
- Dark matter/ dark sector direct and indirect detection
- Quantum simulations
- **Pushing on the two particles that we can produce but know the least about, namely:**
    - **The Higgs boson**
    - **Neutrinos**

What is the underlying dynamics of flavor?





Saying that the Standard Model with the Higgs mechanism is a successful theory of fermion masses is like saying that the Periodic Table is a successful theory of atoms

Neutrinos are especially strange – understanding them better may be a clue to this whole puzzle

Synergies between Higgs flavor physics and neutrinos

Flavor surprises in the Higgs sector would be exciting, and could have pretty direct connections to neutrinos

- A major effort of the LHC program going forward is to probe flavor via the Higgs boson
- Of course in the SM the Yukawa couplings (of unknown origin) directly relate the Higgs to flavor. But is there more to this picture?
- This complements neutrino expts, where we try to probe the origins of flavor by studying neutrinos
- How do LHC collider Higgs studies probe flavor?

Flavor and Higgs decays

In the SM the Higgs boson Yukawa couplings to the fermions are proportional to their masses:

$$\mathcal{L}_Y = -m_i \bar{f}_L^i f_R^i - Y_{ij}(\bar{f}_L^i f_R^j)h + h.c. + \cdots$$

$$Y_{ij} = \frac{m_i}{v}\delta_{ij}$$

But this may not be the case if the Higgs sector is more complicated

e.g. G. Blankenburg, J. Ellis, G. Isidori, arXiv:1202.5704
R. Harnik, J. Kopp, J. Zupan, arXiv:1209.1397
R. Harnik, A. Martin, T. Okui, R. Primulando, F. Yu, arXiv:1308.1094
J. Brod, U. Haisch, J. Zupan, arXiv:1310.1385

Flavor and Higgs decays

The effective action may contain higher dimension operators coupling the Higgs doublet field to the fermions in a flavor dependent way, e.g.

$$\mathcal{L} = \lambda_f H \bar{f} f + \frac{(H^\dagger H) H \bar{f} f}{\Lambda^2}$$

$$Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$$

The resulting Yukawa couplings are in general flavor off-diagonal and could even violate CP

Flavor and Higgs decays

For off-diagonal quark flavor we have already strong experimental constraints from meson mixing data:

Technique	Coupling	Constraint
D^0 oscillations [48]	$\|Y_{uc}\|^2$, $\|Y_{cu}\|^2$	$< 5.0 \times 10^{-9}$
	$\|Y_{uc} Y_{cu}\|$	$< 7.5 \times 10^{-10}$
B_d^0 oscillations [48]	$\|Y_{db}\|^2$, $\|Y_{bd}\|^2$	$< 2.3 \times 10^{-8}$
	$\|Y_{db} Y_{bd}\|$	$< 3.3 \times 10^{-9}$
B_s^0 oscillations [48]	$\|Y_{sb}\|^2$, $\|Y_{bs}\|^2$	$< 1.8 \times 10^{-6}$
	$\|Y_{sb} Y_{bs}\|$	$< 2.5 \times 10^{-7}$
K^0 oscillations [48]	$\mathrm{Re}(Y_{ds}^2)$, $\mathrm{Re}(Y_{sd}^2)$	$[-5.9 \ldots 5.6] \times 10^{-10}$
	$\mathrm{Im}(Y_{ds}^2)$, $\mathrm{Im}(Y_{sd}^2)$	$[-2.9 \ldots 1.6] \times 10^{-12}$
	$\mathrm{Re}(Y_{ds}^* Y_{sd})$	$[-5.6 \ldots 5.6] \times 10^{-11}$
	$\mathrm{Im}(Y_{ds}^* Y_{sd})$	$[-1.4 \ldots 2.8] \times 10^{-13}$

So this idea is really much more interesting when applied to lepton flavor

Flavor and Higgs decays

$$\mathcal{L}_Y \supset -Y_{e\mu}\bar{e}_L\mu_R h - Y_{\mu e}\bar{\mu}_L e_R h - Y_{e\tau}\bar{e}_L\tau_R h - Y_{\tau e}\bar{\tau}_L e_R h - Y_{\mu\tau}\bar{\mu}_L\tau_R h - Y_{\tau\mu}\bar{\tau}_L\mu_R h + h.c.$$

There are many constraints from data, but they are much weaker than for quarks:

Channel	Coupling	Bound
$\mu \to e\gamma$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 3.6 \times 10^{-6}$
$\mu \to 3e$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	< 0.31
electron $g-2$	$\mathrm{Re}(Y_{e\mu}Y_{\mu e})$	$-0.019 \ldots 0.026$
electron EDM	$\lvert\mathrm{Im}(Y_{e\mu}Y_{\mu e})\rvert$	$< 9.8 \times 10^{-8}$
$\mu \to e$ conversion	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 4.6 \times 10^{-5}$
M-$\bar{M}$ oscillations	$\lvert Y_{\mu e} + Y_{e\mu}^*\rvert$	< 0.079
$\tau \to e\gamma$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	< 0.014
$\tau \to e\mu\mu$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	< 0.66
electron $g-2$	$\mathrm{Re}(Y_{e\tau}Y_{\tau e})$	$[-2.1 \ldots 2.9] \times 10^{-3}$
electron EDM	$\lvert\mathrm{Im}(Y_{e\tau}Y_{\tau e})\rvert$	$< 1.1 \times 10^{-8}$
$\tau \to \mu\gamma$	$\sqrt{\lvert Y_{\tau\mu}\rvert^2 + \lvert Y_{\mu\tau}\rvert^2}$	$< 1.6 \times 10^{-2}$
$\tau \to 3\mu$	$\sqrt{\lvert Y_{\tau\mu}^2 + \lvert Y_{\mu\tau}\rvert^2}$	< 0.52
muon $g-2$	$\mathrm{Re}(Y_{\mu\tau}Y_{\tau\mu})$	$(2.7 \pm 0.75) \times 10^{-3}$
muon EDM	$\mathrm{Im}(Y_{\mu\tau}Y_{\tau\mu})$	$-0.8 \ldots 1.0$
$\mu \to e\gamma$	$\left(\lvert Y_{\tau\mu}Y_{\tau e}\rvert^2 + \lvert Y_{\mu\tau}Y_{e\tau}\rvert^2\right)^{1/4}$	$< 3.4 \times 10^{-4}$

R. Harnik, J. Kopp, J. Zupan, arXiv:1209.1397

Flavor and Higgs decays

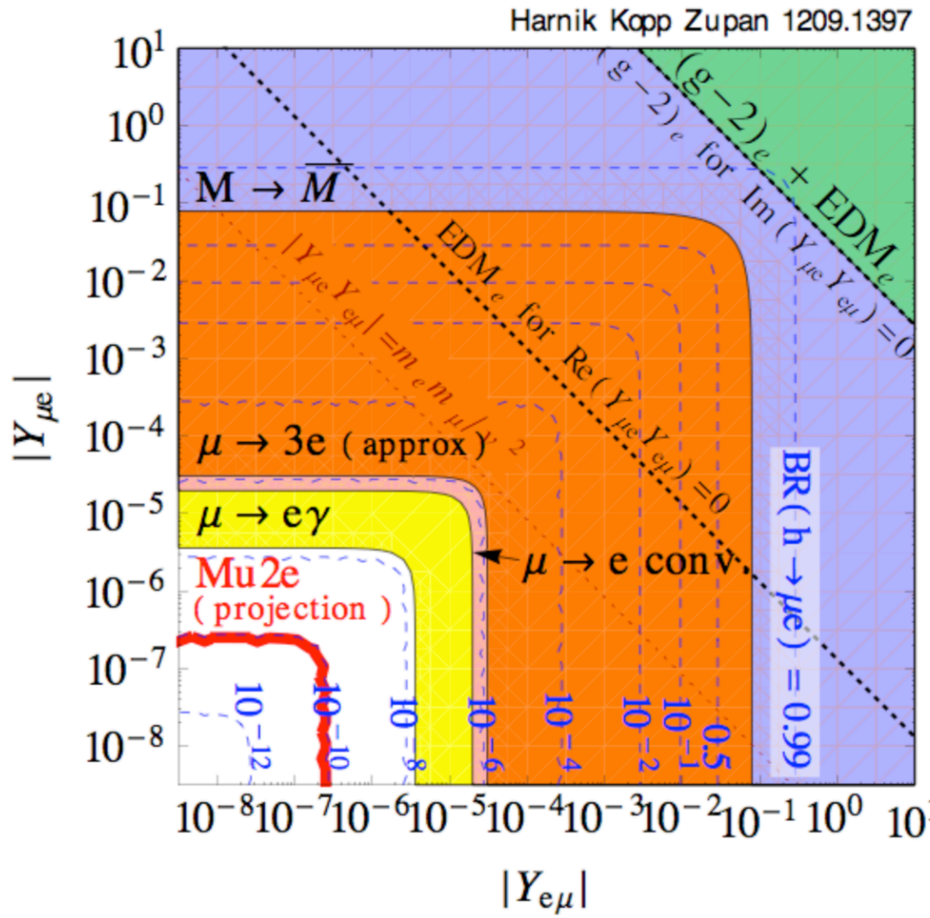
Still, for the case of Higgs boson decays $h \to \mu e$, LHC sensitivity cannot compete with the corresponding sensitivity of present and near future charged lepton flavor violation experiments like MEG or Mu2e

Thus it is more interesting to focus on LHC searches for

$h \to \tau\mu$

and

$h \to \tau e$



R. Harnik, J. Kopp, J. Zupan, arXiv:1209.1397

Two Higgs Doublets and flavor

- We do not actually know yet if the 125 GeV Higgs boson has Yukawa couplings to 1st or 2nd generation fermions
- If it does not, this has profound implications, including for neutrino mass generation
- A simple way to realize this possibility is a Two-Higgs-Doublet Model, where the lighter Higgs has Yukawas only with 3rd generation fermions. Thus for the leptons you have textures like:

$$-\mathcal{L}_Y = \sum_{i,i} \Big(\lambda^u_{ij} (\bar{q}_i u_j) \tilde{\Phi} + \lambda'^u_{ij} (\bar{q}_i u_j) \tilde{\Phi}' + \lambda^d_{ij} (\bar{q}_i d_j) \Phi + \lambda'^d_{ij} (\bar{q}_i d_j) \Phi' + \lambda^e_{ij} (\bar{\ell}_i e_j) \Phi + \lambda'^\ell_{ij} (\bar{\ell}_i e_j) \Phi' \Big) + \text{h.c.}$$

$$\lambda^\ell \sim \frac{\sqrt{2}}{v} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix} \qquad \lambda'^\ell \sim \frac{\sqrt{2}}{v'} \begin{pmatrix} m_e & m_e & m_e \\ m_e & m_\mu & m_\mu \\ m_e & m_\mu & m_\mu \end{pmatrix}$$

W. Altmannshofer, J. Eby, S. Gori, M. Lotito, M. Martone, D. Tuckler, arXiv:1610.02398

Two Higgs Doublets and flavor

- The light Higgs couples to the 1st and 2nd generation fermions through mixing
- Eventually LHC expts can find the heavier neutral Higgs and charged Higgs
- This model makes predictions for flavor-violating decays of the 125 GeV Higgs:

$$\mathrm{BR}(h \to \tau\mu) \sim \mathrm{BR}(h \to \mu^+\mu^-) \sim \frac{m_\mu^2}{3m_b^2} \sim 10^{-3}$$

$$\mathrm{BR}(h \to \tau e) \sim \frac{m_e^2}{m^2} \times \mathrm{BR}(h \to \tau\mu) \sim 10^{-7} \,.$$

$$\mathrm{BR}(h \to \mu e) \sim \frac{m_e^2}{m_\tau^2} \times \mathrm{BR}(h \to \tau\mu) \sim 10^{-10}$$

How does this compare with the latest LHC data?

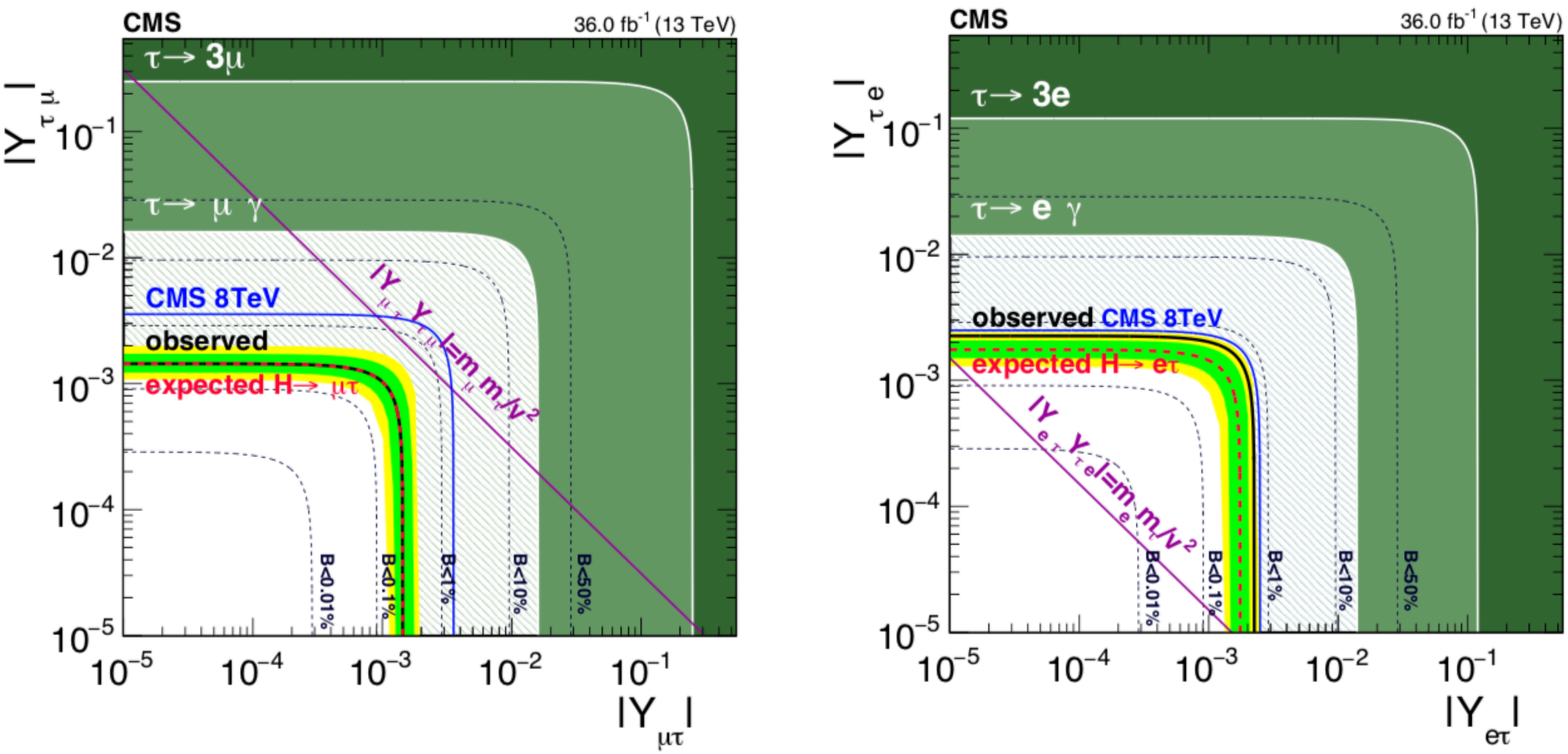
W. Altmannshofer, J. Eby, S. Gori, M. Lotito, M. Martone, D. Tuckler, arXiv:1610.02398

Status of flavor-violating Higgs decays

New! Strong CMS constraints on the Higgs flavor-violating decays with taus

CMS collaboration, arXiv:171207173

B($h \to \tau\mu$) < 0.0025, B($h \to \tau e$) < 0.0061, 95% CL



Flavor-violating Higgs decays and neutrinos

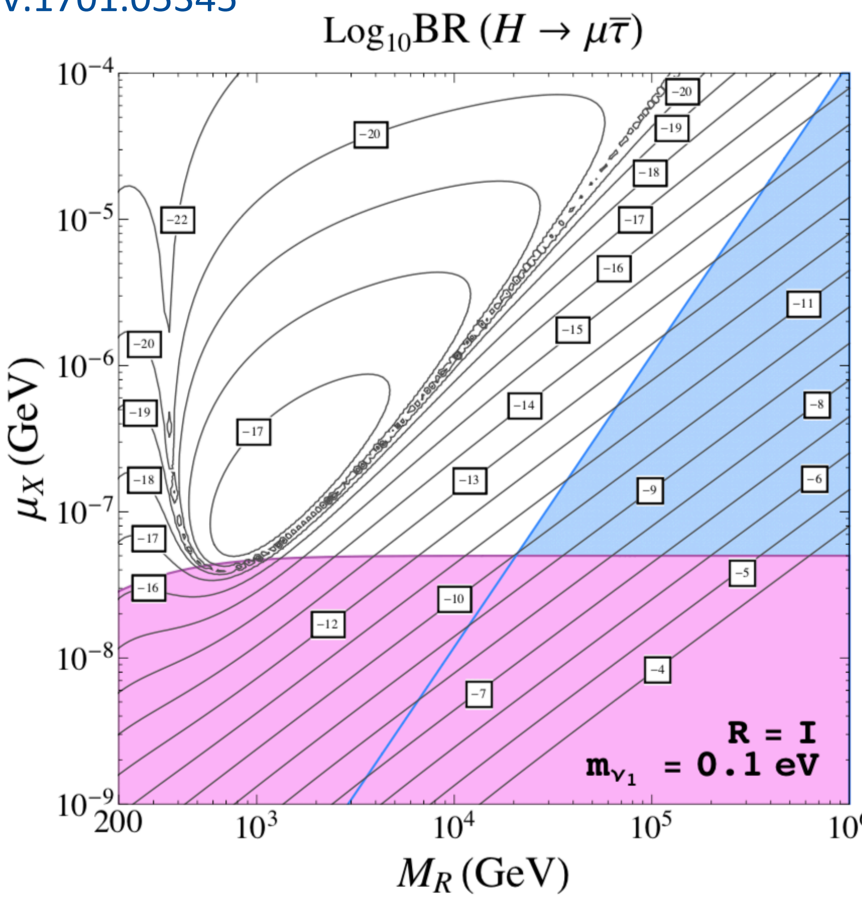
Does one predict **observable** rates of flavor-violating Higgs decays in any specific neutrino mass models?

J. Herrero-Garcia, N. Rius, A. Santamaria, arXiv:1605.06091

J. Herrero-Garcia, T. Ohlsson, S. Riad, J. Wiren, arXiv:1701.05345

The answer generically is no, because the flavor-violating Higgs decays are generated at loop level and the resulting branching fraction for $h \to \tau\mu$ is at most 10^{-4}

For example, inverse see-saw models give at most 10^{-4}, which becomes 10^{-10} when you impose constraints from $\mu \to e\gamma$



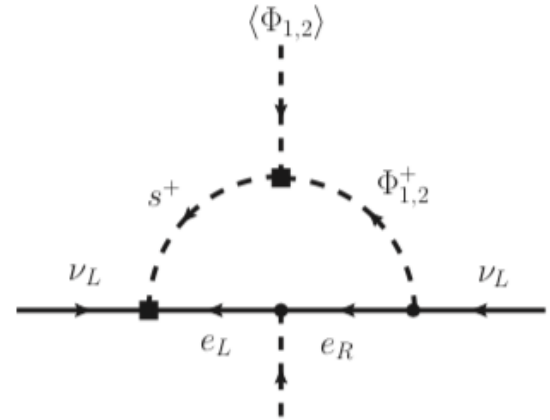
E. Arganda, M. Herrero, X. Marcano, C. Weiland, arXiv:1405.4300

Flavor-violating Higgs decays and neutrinos

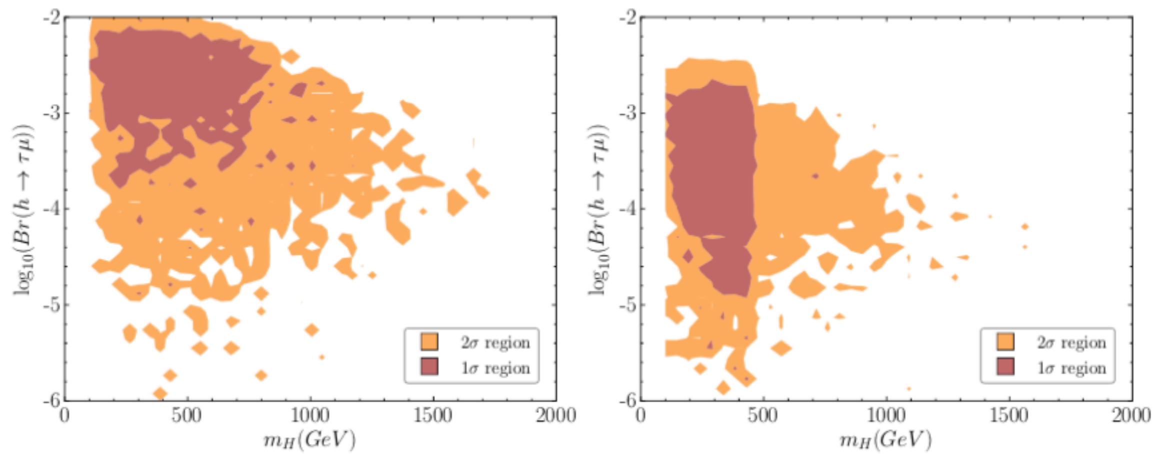
A. Zee, Phys. Lett. B93 (1980) 389

However there is at least one exception:

The Zee model is a Two-Higgs-Doublet Model where both doublets have Yukawa couplings to all three generations of leptons. There is also a singlet scalar s^+



In this case the LHC experiments may be close to discovering $h \to \tau\mu$



(a) NO (b) IO

J. Herrero-Garcia, N. Rius, A. Santamaria, arXiv:1605.06091

J. Herrero-Garcia, T. Ohlsson, S. Riad, J. Wiren, arXiv:1701.05345

Electroweak Baryogenesis

Leptogenesis is a very attractive scenario and a strong motivation for a long-baseline neutrino program that can establish the existence of CPV in neutrino oscillations and measure the phase

At the same time, electroweak baryogenesis (EWBG) is also an attractive scenario, which can be probed at the LHC and future colliders

Successful EWBG requires new physics beyond the SM, to accomplish two things:

- Produce a sufficiently strongly first-order electroweak phase transition
- Provide sufficient CPV at the expanding bubble walls of the transition

See e.g. D. Morrissey and M. Ramsey-Musolf, arXiv:1206.2942

Electroweak Baryogenesis

Producing a sufficiently strongly first-order electroweak phase transition is a statement about the Higgs effective potential

Even though the Higgs boson has been discovered and so far appears consistent with the SM, we actually know almost nothing about the shape of the Higgs effective potential, or what dynamics may be contributing to that shape

For example, if the Higgs sector is extended by some ~TeV mass scalars, the Higgs potential after integrating these out could look like

$$-\mathcal{L} \supset -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{\Lambda_N^2}|H|^6 + \ldots$$

The sextic term can be enough to drive a first-order phase transition for $\Lambda_N \lesssim 800\ \mathrm{GeV}$

C. Grojean, G. Servant, J. Wells, hep-ph/0407019

Can we rule out Electroweak Baryogenesis?

Since the extra particles needed to modify the Higgs potential (to get a first order phase transition) cannot be too heavy, one could imagine ruling out all possibilities by a combination of direct searches and precision measurements at colliders

LHC by itself is not good enough to establish such a no-lose theorem, unless you make extra assumptions (e.g. the MSSM)

One concrete approach is to try to write down the worst-case “nightmare” scenario from the point of view of collider tests, then show what can be done even in this case

It has been argued that this worst case is a SM-singlet real scalar coupled directly to the Higgs, but with a Z_2 symmetry to suppress mixing of the Higgs and the singlet

D. Curtin, P. Meade, C-T Yu, arXiv:1409.0005

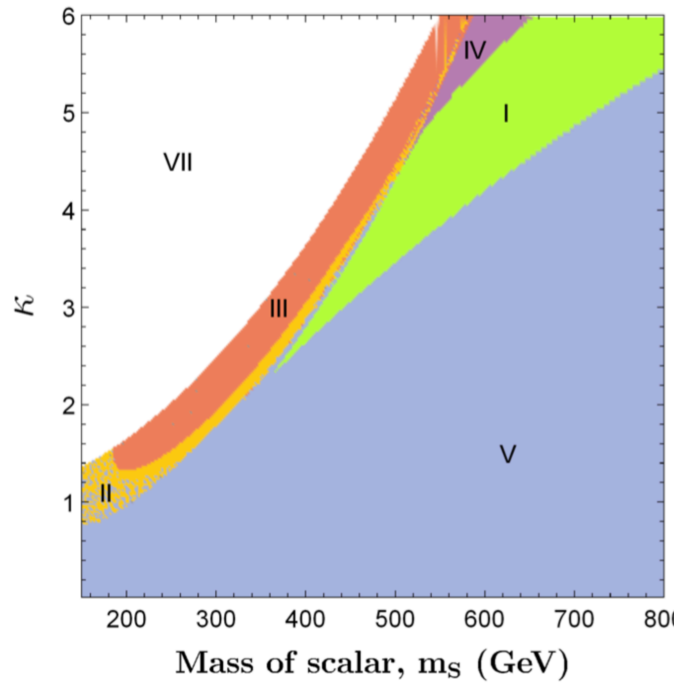
Can we rule out EWBG from a real singlet scalar?

The combined tree level scalar potential is:

$$V(H;S) = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}m_0^2S^2 + \frac{\eta}{4}S^4 + \kappa S^2|H|^2,$$

G. Kurup, M. Perelstein, arXiv:1704.03381

A suitable phase transition for EWBG occurs in the green and yellow regions only



If the Z_2 symmetry is exact or nearly exact, then collider production of S is via pair production from an off-shell Higgs. The two best channels are associated production with W/Z, or VBF:

$$q\bar{q} \to VSS$$

$$qq \to SSqq$$

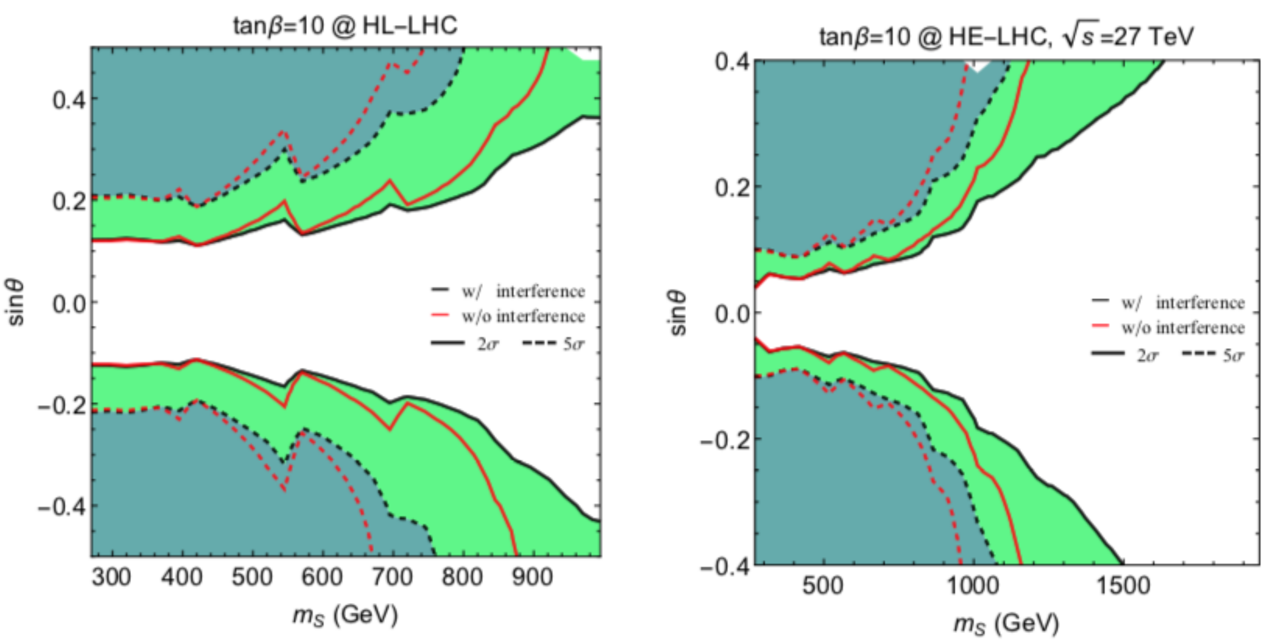
D. Curtin, P. Meade, C-T Yu, arXiv:1409.0005

To see or exclude this requires a ~100 TeV pp collider

Can we rule out EWBG from a real singlet scalar?

- If the Z_2 is broken, then the singlet will mix with the Higgs, my some amount $\sin\theta$
- LHC Higgs signal strength data already require $\sin\theta < 0.35$,
- LHC searches and EW precision observables slightly stricter over part of the possible range of singlet mass T. Huang et al, arXiv:1701.04442

Then compute the exclusion and discovery reach of HL-LHC and HE-LHC:



This is from looking for resonant di-Higgs production, in final state $b\bar{b}\gamma\gamma$

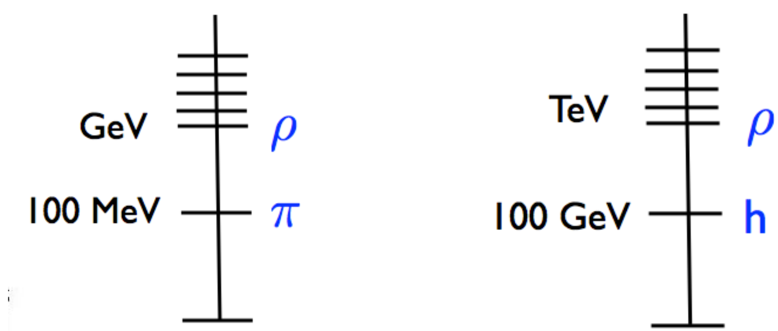
M. Carena, Z. Liu, M. Riembau, arXiv:1801.00794

Minimal Composite Higgs Models

e.g. K. Agashe, R. Contino, A. Pomarol, hep-ph/0412089

Is the Higgs boson an elementary scalar, or is it more like the pion, i.e. a pseudo-Nambu-Goldstone boson resulting from spontaneous breaking of global symmetries connected to some new strong interactions?

If we let $\mathbf{f}$ denote the analog of the pion decay constant, then we expect new resonances associated with the new strong interaction physics to start appearing at a scale around $\mathbf{4\pi f}$, the analog of the rho meson mass.



There will also be vector and fermionic resonances

Minimal Composite Higgs Models

The minimal global symmetry breaking that produces the equivalent of a Higgs doublet and unbroken custodial symmetry is $\mathbf{SO(5) \rightarrow SO(4)}$

Higgs mass and EWSB generated at one loop by SM couplings that explicitly break the global symmetry

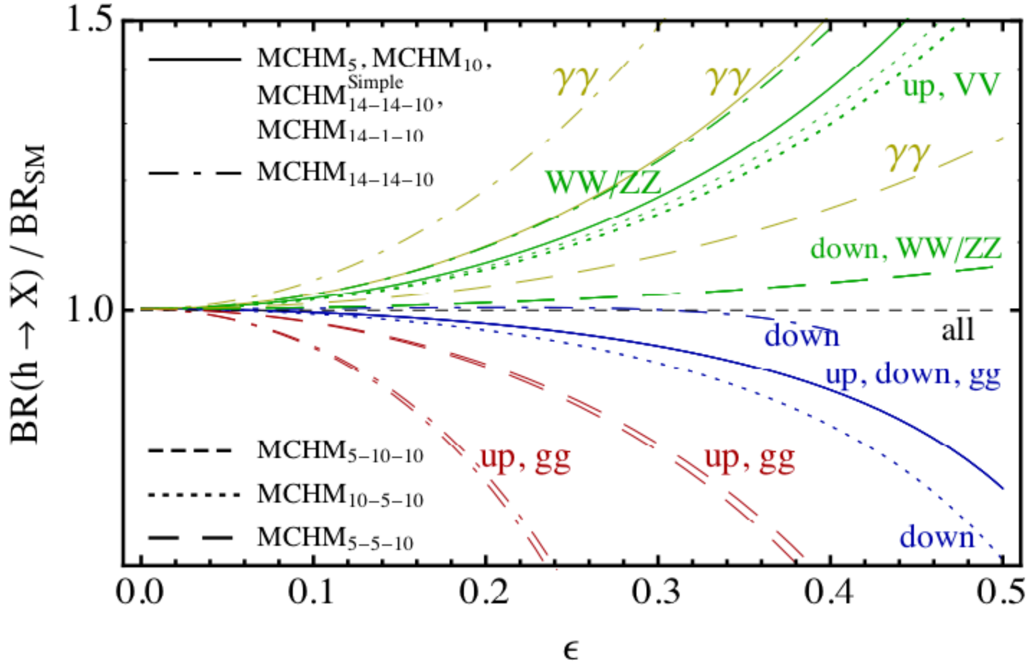
The model parameter epsilon describes the relation between the EWSB scale and $\mathbf{f}$: $\epsilon = \mathbf{sin(v/f)}$

Even in the minimal case, there are many possible ways to embed the SM fermions into representations of $\mathbf{SO(5)}$; the Higgs potential and other details depend on these choices

Minimal Composite Higgs Models

Such models predict deviations from the SM predictions for Higgs decay branching fractions

The overall scale of the deviations is set by epsilon, or equivalently **f**



M Carena, L. Da Rold, E. Ponton, arXiv:1402.2987

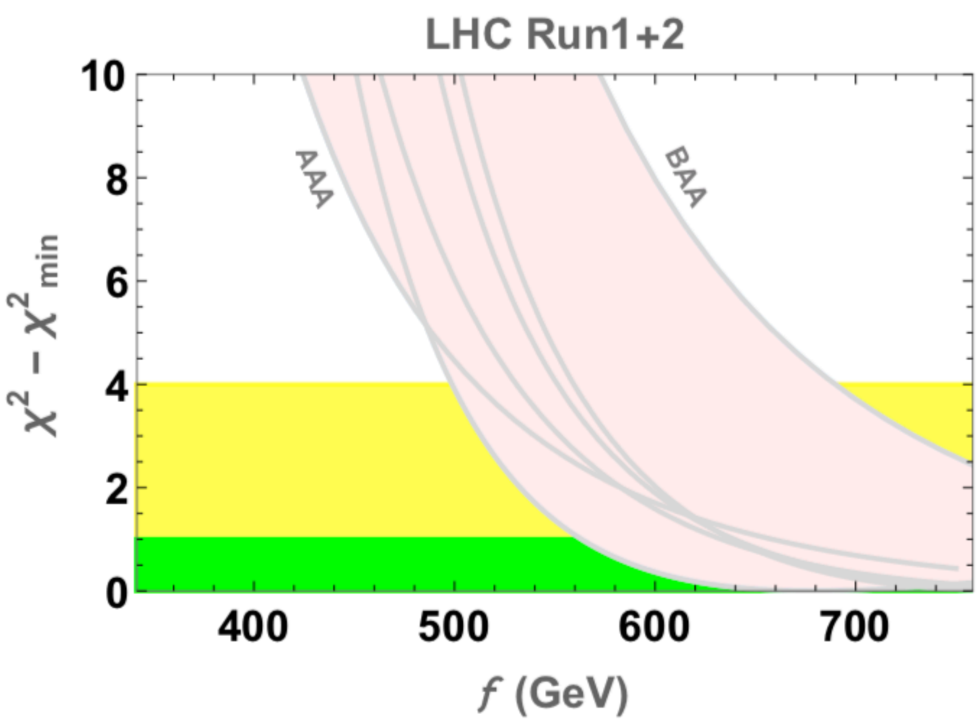
The detailed predictions depend on how the SM fermions are embedded

The SM fermions in general are mixtures of elementary fermions and fermionic resonances, i.e. they are "partially composite"

These mixings of course map into SM flavor

Minimal Composite Higgs Models

So far the lower bounds on the scale $\mathbf{f}$ derived from ATLAS + CMS Higgs measurements are not very strict: $\mathbf{f} > \mathbf{500}$ GeV



V. Sanz and J. Setford, arXiv:1703.10190

This corresponds to new heavy vector resonances, W' and Z', at the multi-TeV scale, which could also be directly accessible to LHC searches

Typically these models also have "top partners" with mass < 1 TeV; this is already in tension with LHC direct search limits…

Leptons in Minimal Composite Higgs Models

A. Carmona and F. Goertz, arXiv:1410.8555, arXiv:1510.07658, arXiv:1712.02536
C. Hagedorn and M. Serone, arXiv:1106.4021

One simple way to embed the SM leptons (including RH neutrinos) is to put each generation in a $\mathbf{5_L} + \mathbf{14_R}$ of the global SO(5).

Remarkably, this produces the following three correlated features:

- The partially composite leptons eliminate the need for dangerously light top partners (mass < 1 TeV)
- There is a simple type-III see-saw mechanism for neutrino masses
- There is a prediction of potentially large lepton-flavor-universality violating effects

The third feature may sound like a bad thing, until one recalls the LHCb anomalies…

Leptons in Minimal Composite Higgs Models

LHCb sees two indications of lepton flavor non-universality in two ratios, with combined significance of about 4 sigma

$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}, \qquad R_{K^*} \equiv \frac{\mathcal{B}(B^0 \to K^*\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^*e^+e^-)},$$

$$R_K^{[1,6]\,\mathrm{exp}} \equiv R_K\big|^{\mathrm{exp}}_{q^2\in[1,6]\,\mathrm{GeV}^2} = 0.745^{+0.090}_{-0.074} \pm 0.036\,.$$

$$R_{K^*}^{[1.1,6]\mathrm{exp}} = 0.69^{+0.11}_{-0.07} \pm 0.05\,,$$

$$R_{K^*}^{[0.045,1.1]\mathrm{exp}} = 0.66^{+0.11}_{-0.07} \pm 0.03\,,$$

Here $\mathbf{q^2}$ is the dilepton invariant mass squared

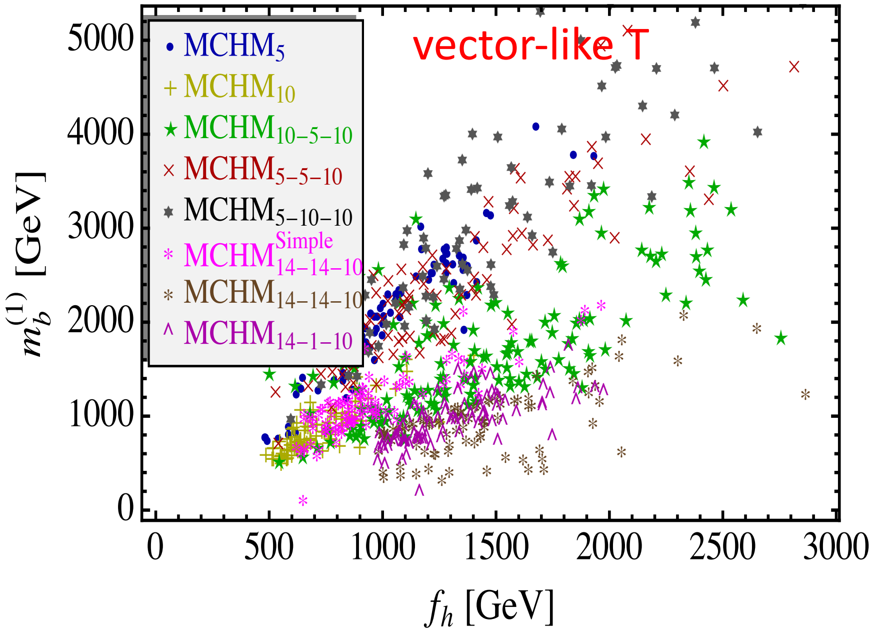
LHCb collaboration, arXiv:1406.6482, arXiv:1705.05802

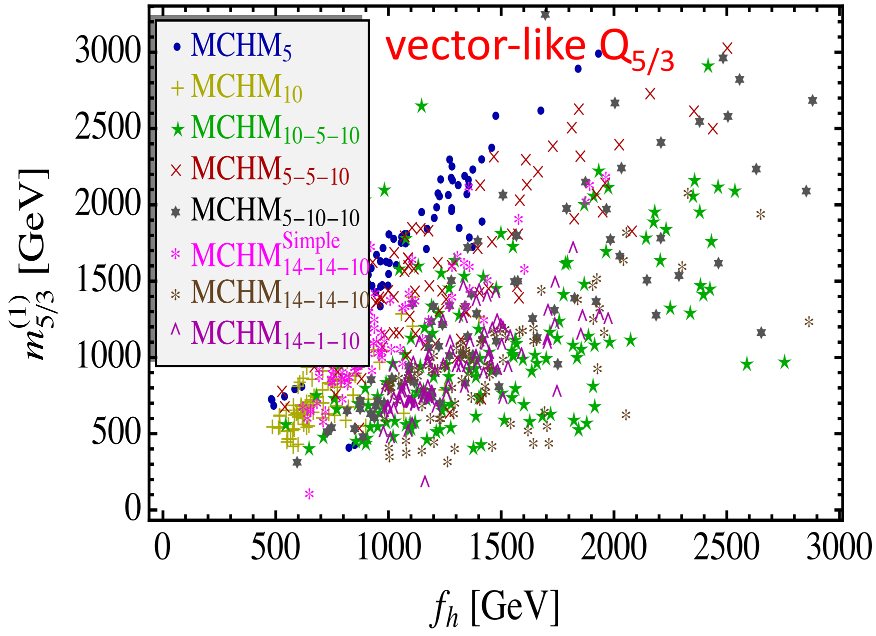
Other explanations have also been proposed to explain the LHCb results, but this is a beautiful example of how collider results could tie together fundamental properties of Higgs and neutrinos

New heavy fermions at LHC

If any of this picture is correct, heavy top partners, other exotic heavy quarks, and possibly heavy leptons, should eventually show up in direct LHC or HE-LHC searches

M Carena, L. Da Rold, E. Ponton, arXiv:1402.2987





The neutrino mass mechanism: Which see-saw? What scale?

Smallness of neutrino mass can be "explained" by:

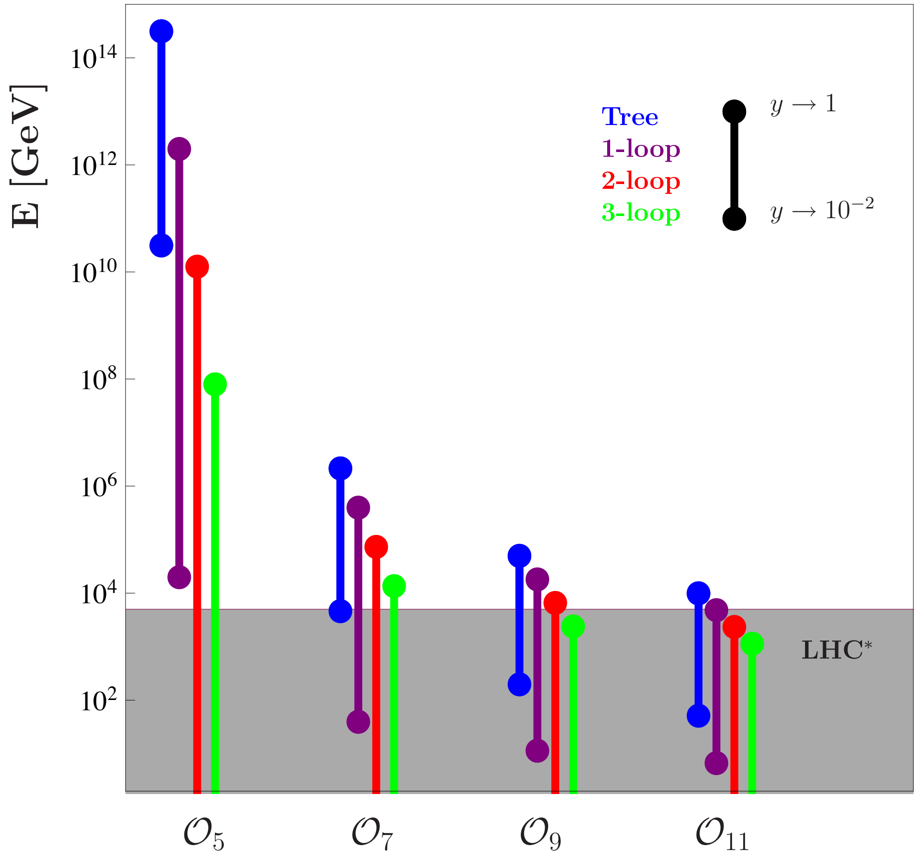
$\Rightarrow$ High scale: Large Λ
"classical" seesaw

$\Rightarrow$ Loop factor: $n \geq 1$
+ "smallish" $Y \sim \mathcal{O}(10^{-3} - 10^{-1})$

$\Rightarrow$ Higher order: $d = 7, 9, 11$

$\Rightarrow$ Nearly conserved L,
i.e. small ϵ ("inverse seesaw")

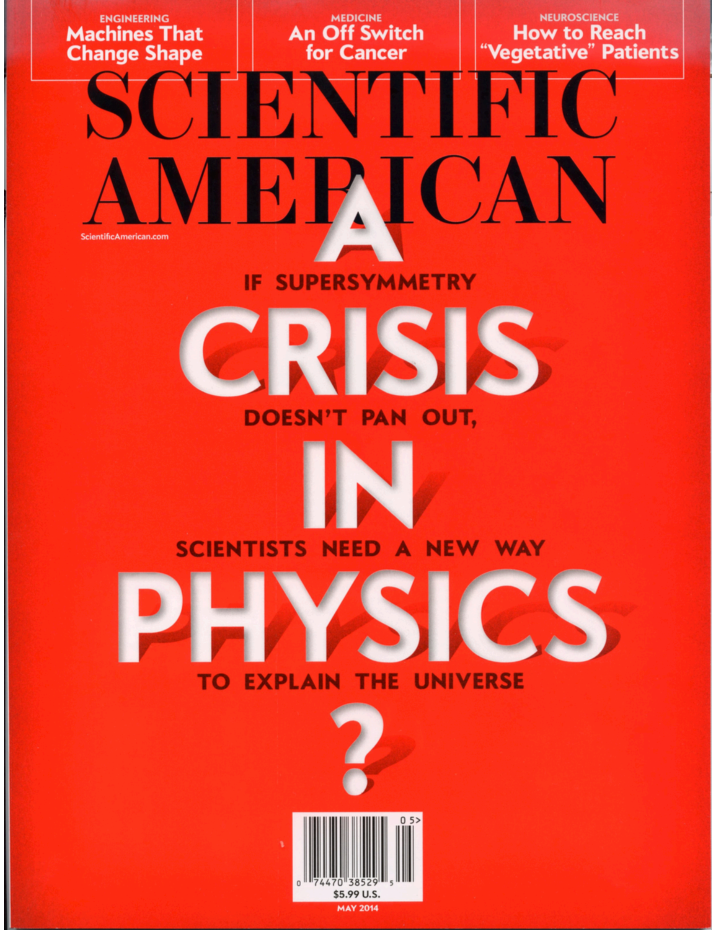
$\cdots$ or combination thereof



M. Hirsch, WIN2015

Scales of new physics: The naturalness crisis at LHC

- LHC searches so far have not seen any strong signals of supersymmetry or other mechanisms motivated by naturalness
- This has led to something of a mini-crisis in the collider community



- But of course in science a crisis usually means we are on the verge of some kind of breakthrough in our understanding
- And indeed there has been a lot of new ideas and new approaches recently related to naturalness and scales of new physics

Neutrinos and naturalness

F. Visani, hep-ph/9709409

M. Fabbrichesi and A. Urbano, arXiv:1504.05403

- Of course the Standard Model by itself does not have a naturalness problem, since it does not predict either the Higgs mass or the scale of EWSB

- But unless you believe in purely Dirac neutrinos with teenie-tiny Yukawas, you need to posit some kind of neutrino mass mechanism; generically this is already enough to raise questions of naturalness

- For the popular Type I see-saw, for example, this already raises the issue of naturalness, since the RH neutrino mass scale M generates a radiative correction to the Higgs mass

$$\delta m_H^2 \simeq \frac{y_\nu^2}{16\pi^2} M^2$$

where the Yukawa couplings are: $y_\nu^2 = M m_\nu / v^2$

Neutrinos and naturalness

$$\delta m_H^2 \simeq \frac{y_\nu^2}{16\pi^2} M^2 \qquad y_\nu^2 = M m_\nu / v^2$$

- So naturalness sets an upper bound on the scale M:

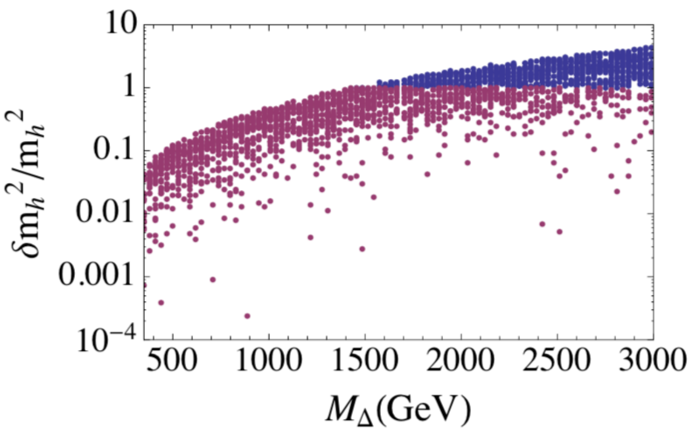
$$M \lesssim 10^7 – 10^8 \text{ GeV}$$

- This corresponds to $y_\nu \sim 10^{-4}$, which is not so bad

- However vanilla leptogenesis requires $M \gtrsim 10^9$ GeV, so a bit of model engineering is required to make things work

P. Di Bari, arXiv:1206.3168
J. Clarke, R. Foot, R. Volkas, arXiv:1502.01352

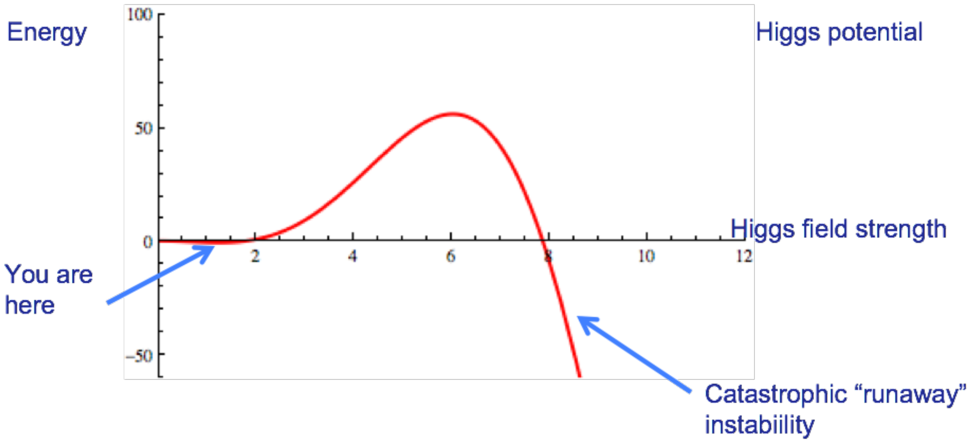
One can do a similar analysis for Type II see-saw models, which have a scalar triplet with a small vev and a large mass; the naturalness constraint is not very strict here

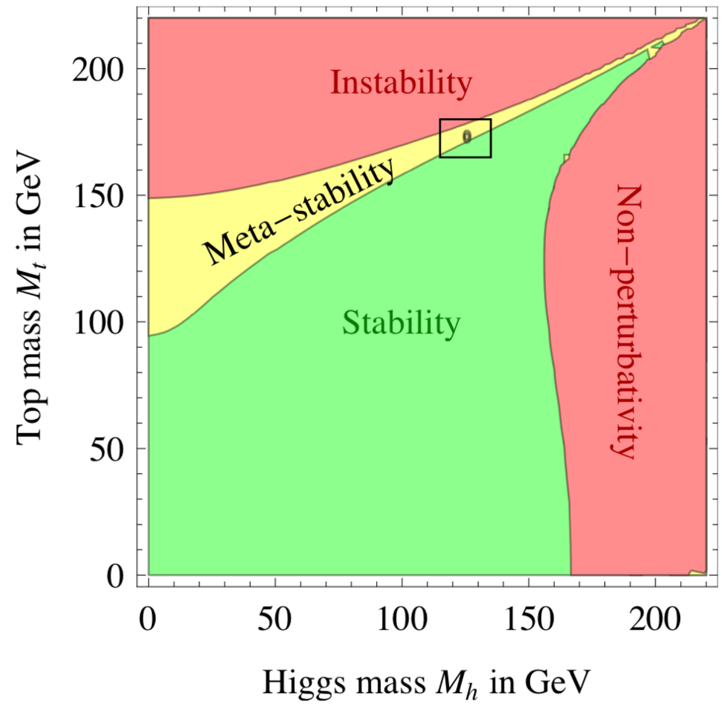


P. Bhupal Dev, C. Miralles Vila, W. Rodejohann, arXiv:1703.00828

Higgs vacuum stability

See e.g. G. Degrassi et al, arXiv:1205.6497



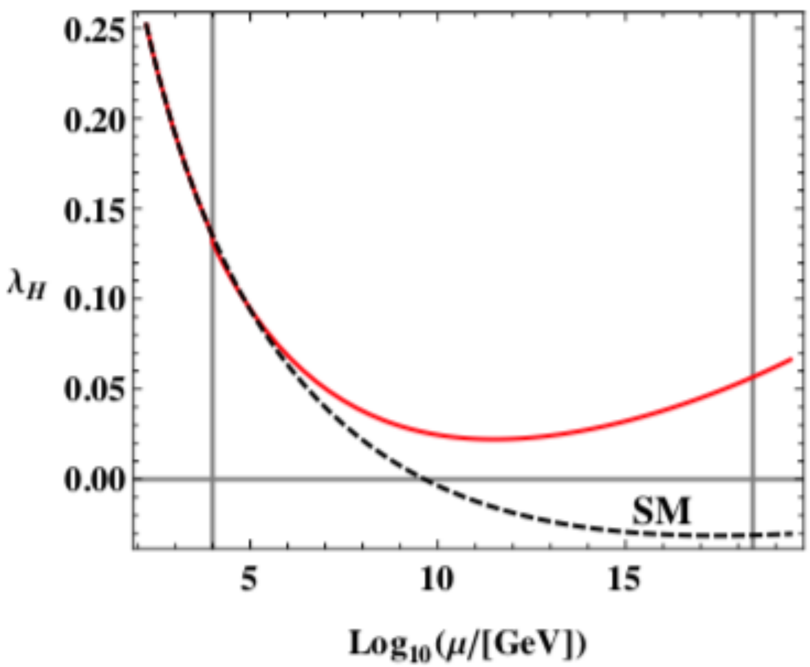


It is a striking and unexplained fact that the Standard Model EWSB vacuum is only meta-stable

Neutrinos and Higgs vacuum stability

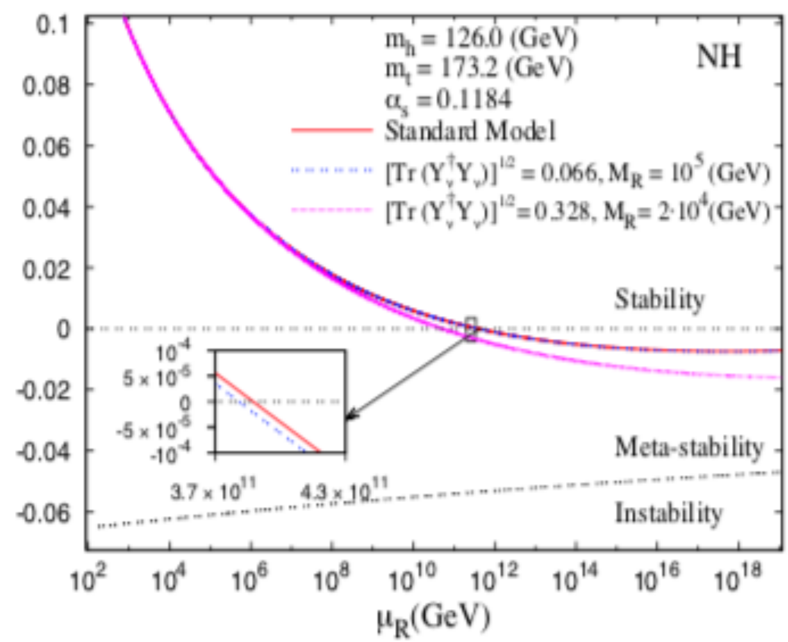
Adding your favorite neutrino mass mechanism generically has an effect on the Higgs potential and thus the calculation of vacuum stability

Type II see-saw:
stability restored



N. Haba, H. Ishida, N. Okada,
Y. Yamaguchi arXiv:1601.05217

Minimal Type I see-saw:
instability gets slightly worse…



G. Bambhaniya, P. Bhupal Dev, S. Goswami,
S. Kahn, W. Rodejohann arXiv:1611.03827

Does neutrino mass generation also generate EWSB radiatively?

I. Brivio and M. Trott, arXiv:1703.10924

Instead of assuming a SM Higgs potential and adding a Type I see-saw at a much higher scale to generate neutrino masses, why not start with high-scale theory and try to generate EWSB radiatively?

For simplicity, discuss in terms of two parameters: m_p is the RH neutrino mass scale, and ω represents the high-scale Yukawa couplings

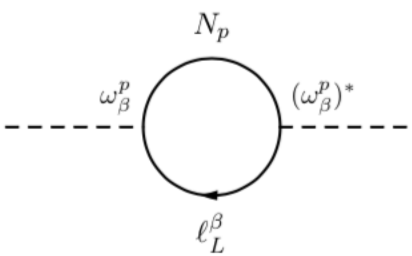
Assume the Higgs mass-squared parameter is zero at the high scale, i.e. the only dimensionful parameter in the high-scale Lagrangian is m_p

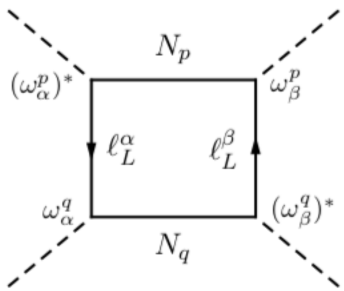
Of course one may still have a naturalness problem connecting this high-scale Lagrangian to, e.g. Planck scale or unification scale physics, but that is a another story

Does neutrino mass generation also generate EWSB radiatively?

I. Brivio and M. Trott, arXiv:1703.10924

Integrate out the heavy neutrinos; this already starts to generate a SM-like Higgs potential from the diagrams:





$$V_c(H^\dagger H) = -\frac{m^2}{2}(H^\dagger H) + \lambda (H^\dagger H)^2,$$

$$m^2(m_p) = \frac{n|\omega|^2}{8\pi^2} m_p^2$$

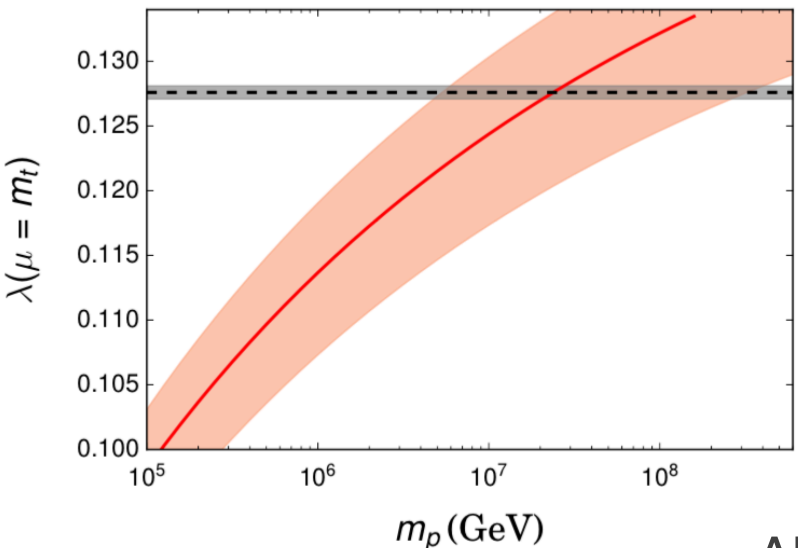
$$\lambda(m_p) = -n^2 \frac{5}{64\pi^2} |\omega|^4$$

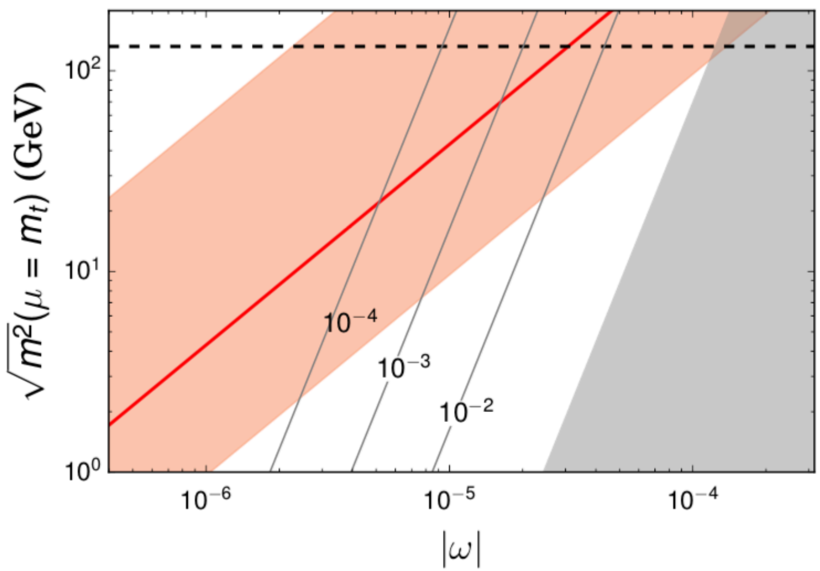
Then use the RG equations to run the effective theory down to lower energy scales

Does neutrino mass generation also generate EWSB radiatively?

I. Brivio and M. Trott, arXiv:1703.10924

Using the measured values of EWSB, the Higgs mass, and the top mass, we get a consistent solution if $m_p \sim 10^7$ GeV

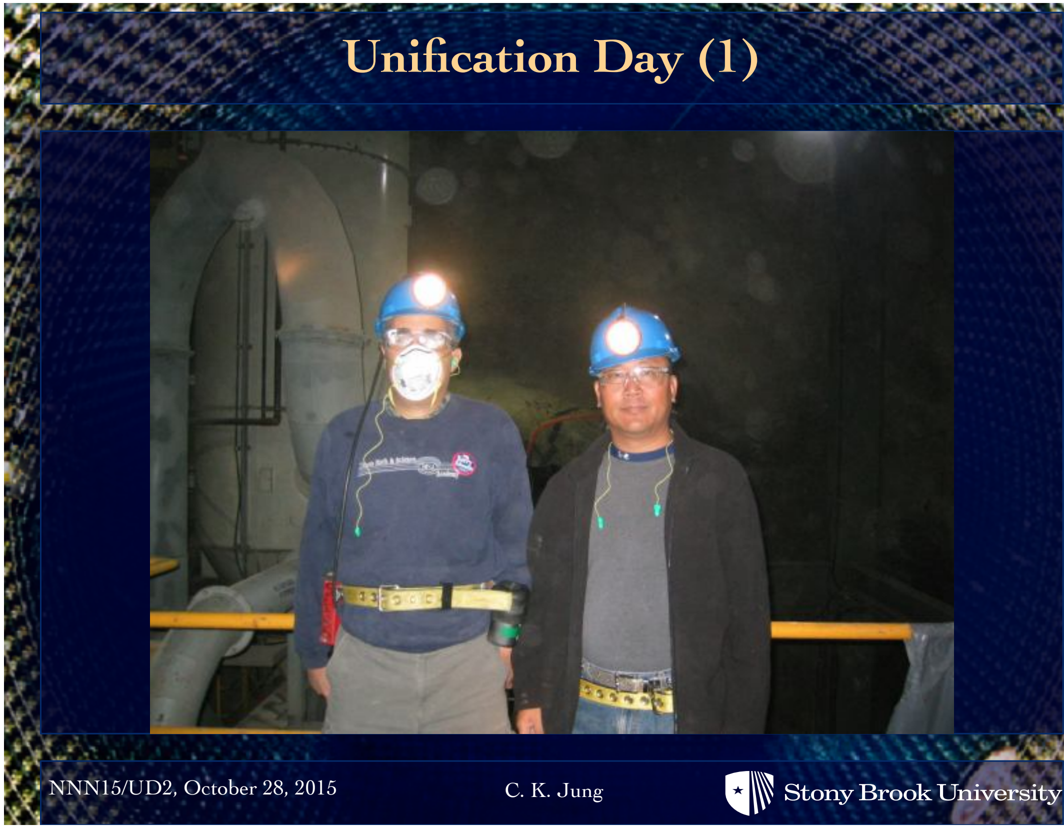




Allowing a 2 sigma uncertainty spread in the top mass, the light neutrino mass scale can vary from 10^{-4}–10^{-2} eV

Synergies with trying to understand Unification

- The idea of unification is at the heart of particle physics
- Pulls together our seemingly very different communities studying neutrinos, Higgs, dark matter, string theory, etc



string theorist neutrino experimenter

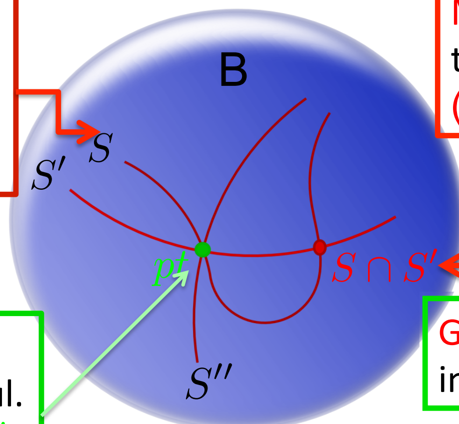
The challenge of top-down unification

F-theory: basic ingredients

- Total space of torus-fibration: singular elliptic Calabi-Yau manifold X
  D=4, N=1 vacua: fourfold X_4
- Singularities encode complicated set-up of intersecting D-branes:

Non-Abelian gauge symmetry in codimension-one singul. in B (divisors wrapped by branes)

Matter in codimension-two singul. in B (intersecting branes)



G_4-flux at intersection induces chiral 4D matter

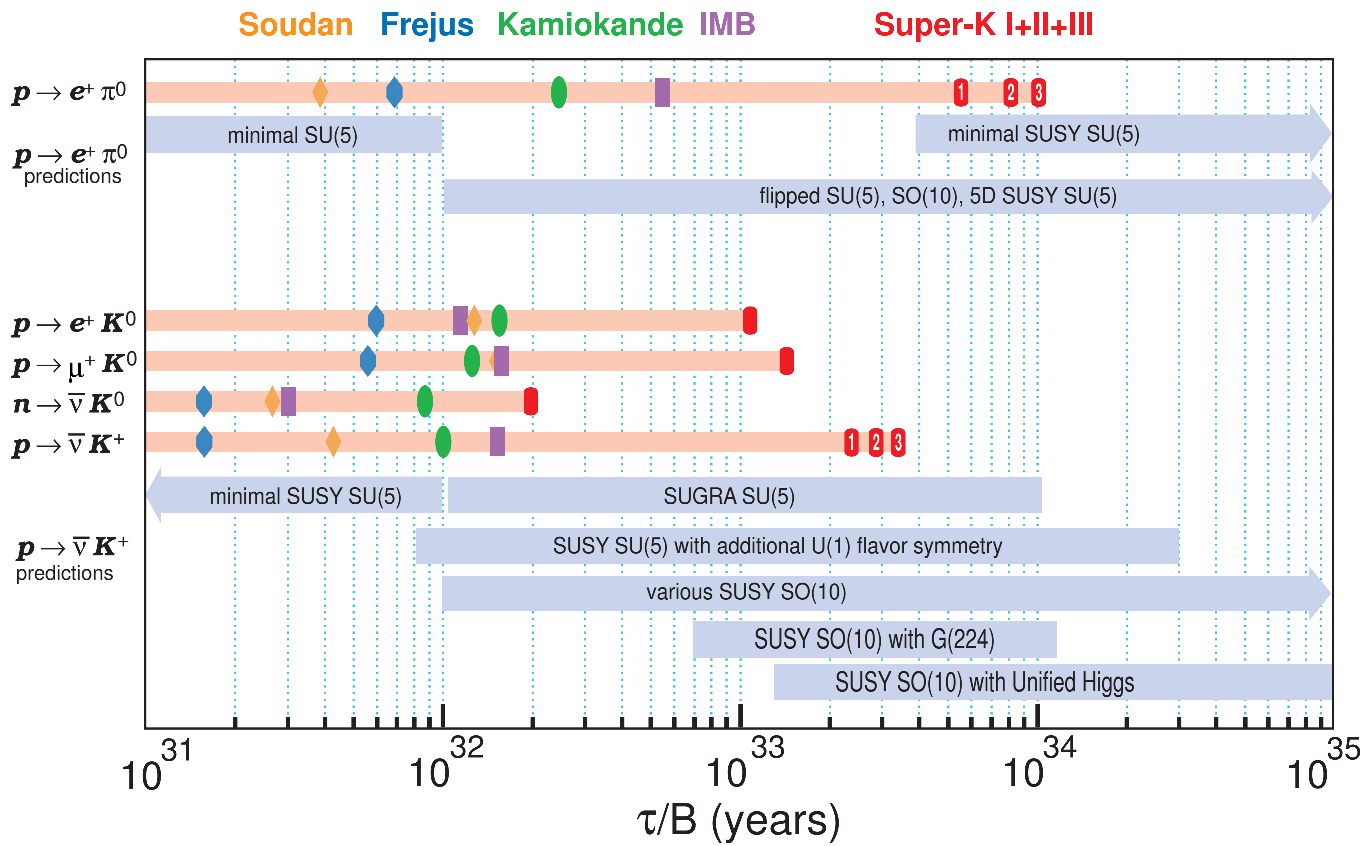
Yukawa couplings in codimension-three singul. in B $pt = S \cap S' \cap S''$

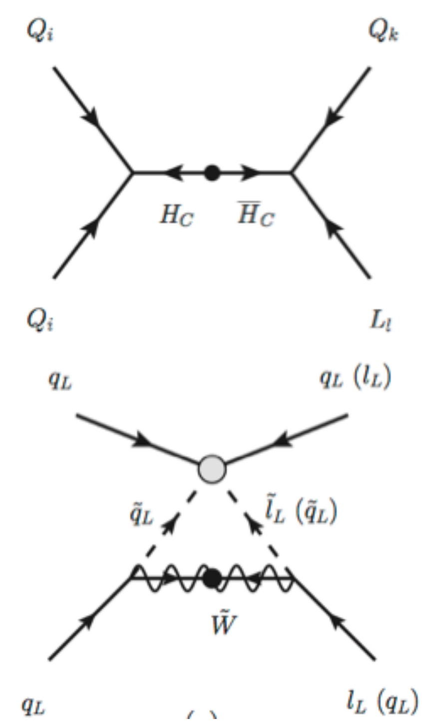
M. Cvetic,Unification Day 2

- Don’t know what is the right framework to start with
- Difficult to connect to observables
- We need more clues – some of these may come from neutrinos

Proton decay: problem or feature?

- Supersymmetric Grand Unified Theories have exotic particles related to the Higgs that induce proton decay even with R-parity
- Long known to be trouble for minimal models: experimental lower limits on the proton lifetime are very strong!

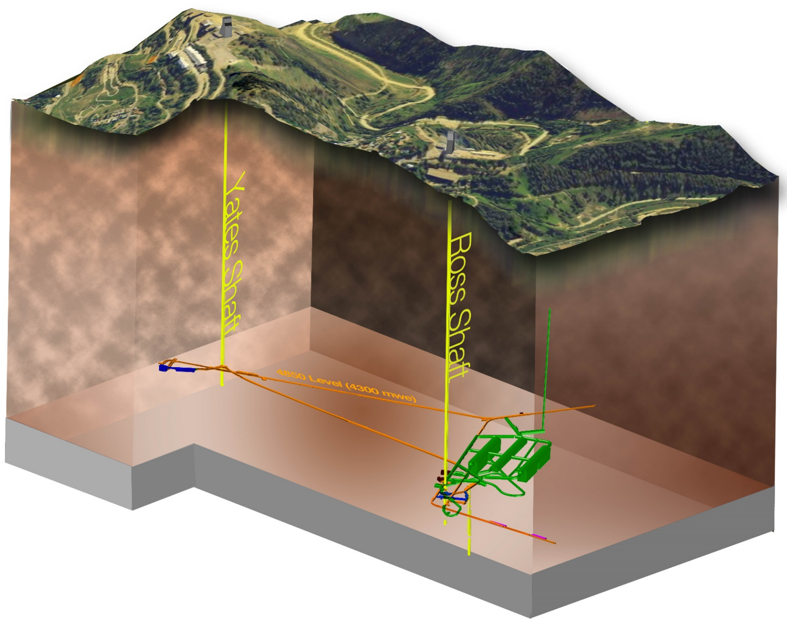


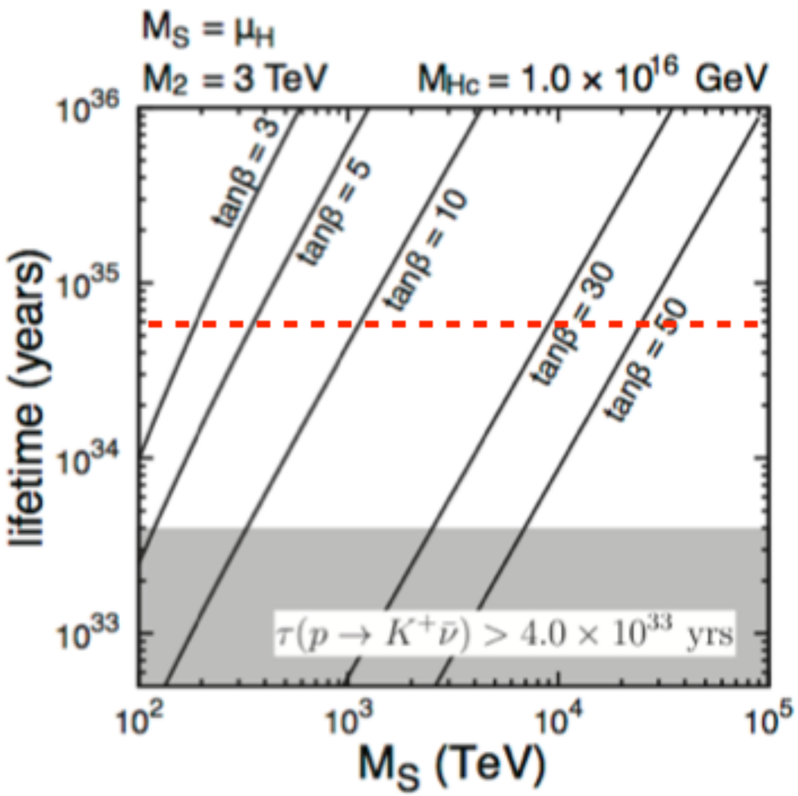


Proton decay: problem or feature?

- Lifting some superpartner masses to ~100 TeV gives an extra suppression of proton decay that revives minimal supersymmetric GUT models
- In this case next generation experiments may observe proton decay

Dashed line shows sensitivity of next generation experiments DUNE and HyperK





Large international collaborations

The global neutrino community is now entering a new era of LHC-scale international collaboration

MiniBooNE collaboration, 2007:
77 people from 2 countries

Collaborator #1000

DUNE collaboration, 2017:
1,061 people from 31 countries

Large international collaborations

The impressive speed at which DUNE has grown into a global mega-experiment (the first collaboration meeting was April 2015!) would not have been possible if we did not already have the successful model of LHC, especially ATLAS, CMS, and the international oversight mechanisms developed by CERN

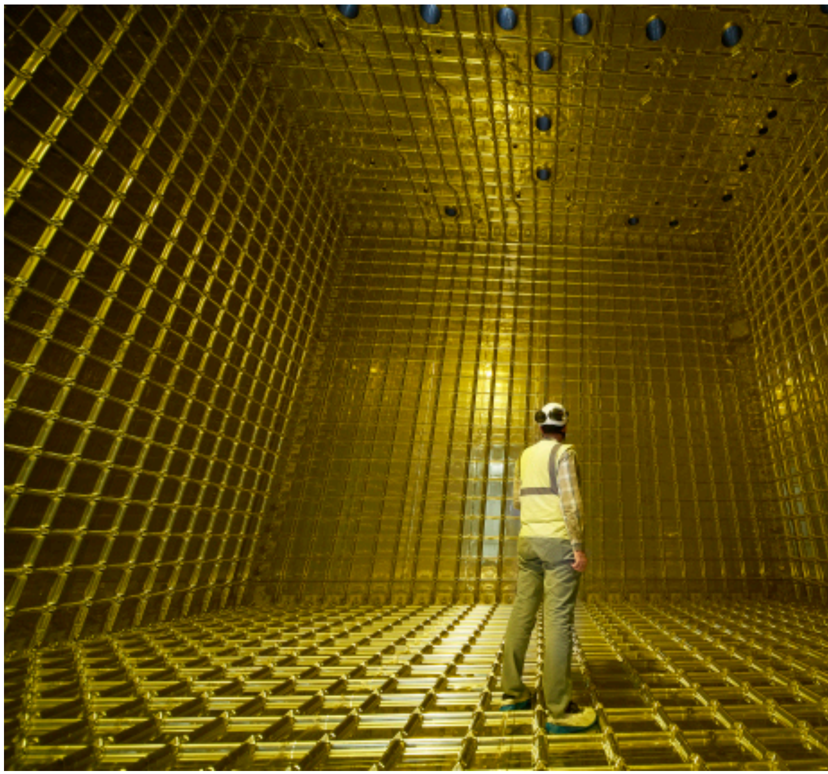
Don’t re-invent the wheel – just adapt it

- Host lab: CERN
- ATLAS/CMS Collaboration Boards
- ATLAS/CMS Technical and Resource Coordinators
- LHCC
- CERN LHC RRB
- LHC Upgrade Cost Group
- CERN Latin America mobility programs

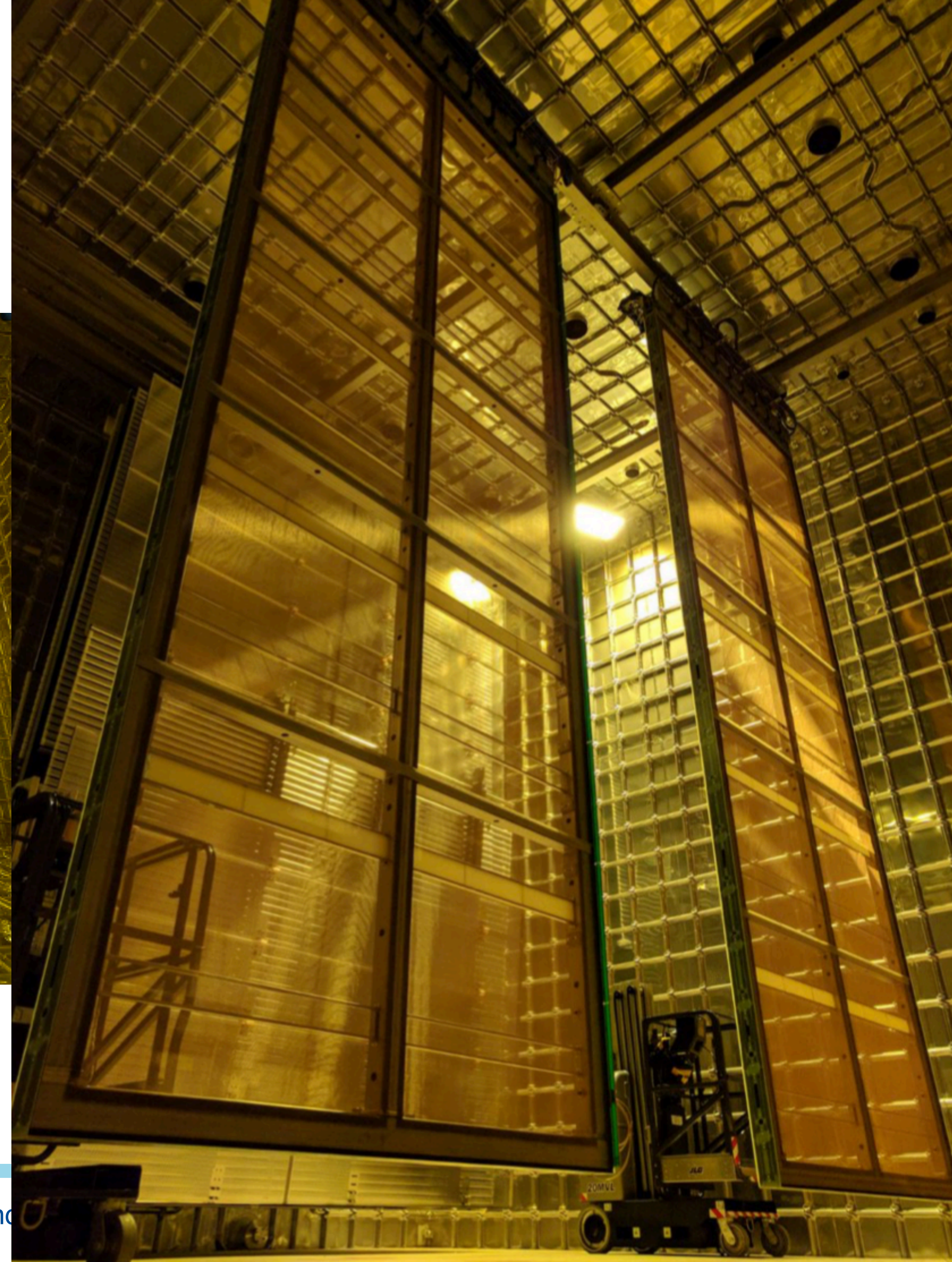
- Host lab: Fermilab
- DUNE Institutional Board
- DUNE Technical and Resource Coordinators
- LBNC
- Fermilab DUNE/LBNF RRB
- DUNE Cost Group
- Fermilab Latin America mobility programs

Building and operating large detectors

The DUNE detectors will be huge complicated ambitious devices

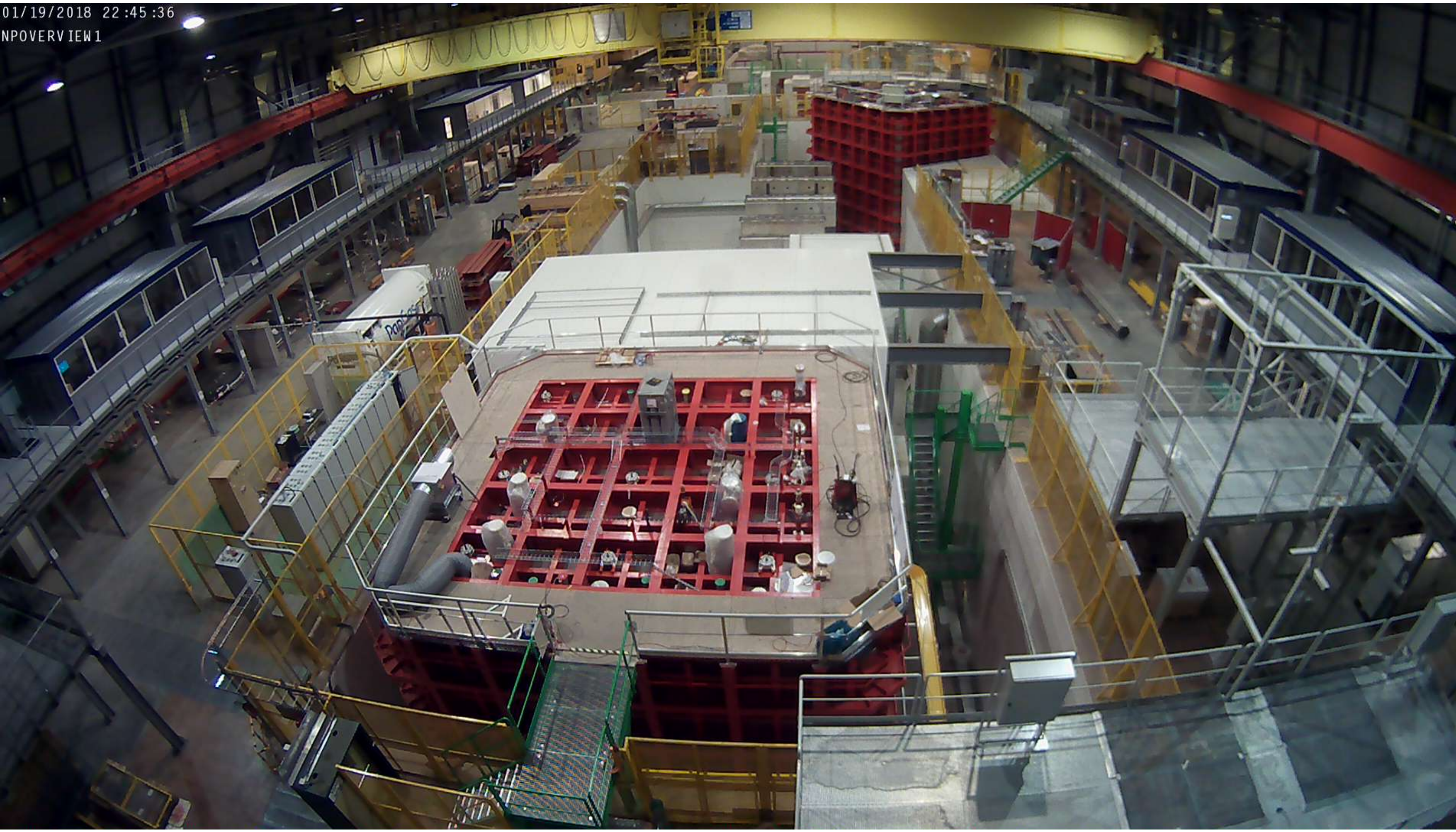


The massive ProtoDUNES are 1/25 the scale of the actual DUNE detectors



Building and operating large detectors

Without the CERN Neutrino Platform and Marzio Nessi, it is hard to imagine how DUNE would be on track to baseline as a project in 2019



Artificial Intelligence is here

Mastering Chess and Shogi by Self-Play with a General Reinforcement Learning Algorithm

David Silver,[1*] Thomas Hubert,[1*] Julian Schrittwieser,[1*]
Ioannis Antonoglou,[1] Matthew Lai,[1] Arthur Guez,[1] Marc Lanctot,[1]
Laurent Sifre,[1] Dharshan Kumaran,[1] Thore Graepel,[1]
Timothy Lillicrap,[1] Karen Simonyan,[1] Demis Hassabis[1]

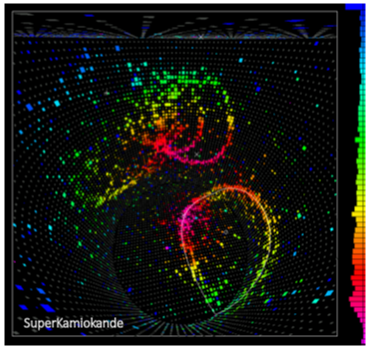
[1]DeepMind, 6 Pancras Square, London N1C 4AG.
[*]These authors contributed equally to this work.

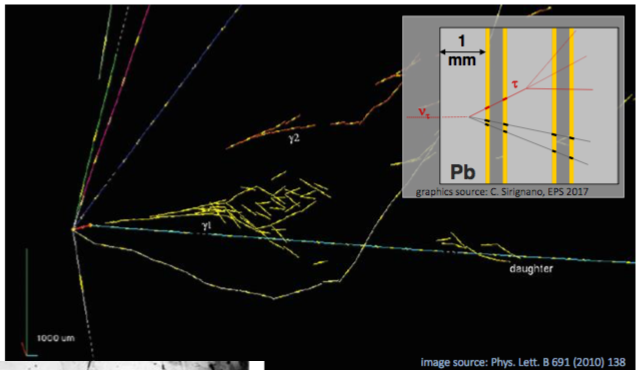
Abstract

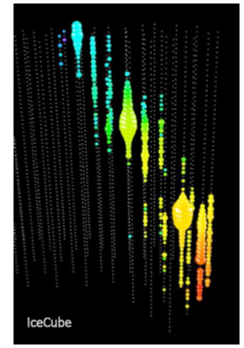
The game of chess is the most widely-studied domain in the history of artificial intelligence. The strongest programs are based on a combination of sophisticated search techniques, domain-specific adaptations, and handcrafted evaluation functions that have been refined by human experts over several decades. In contrast, the *AlphaGo Zero* program recently achieved superhuman performance in the game of Go, by *tabula rasa* reinforcement learning from games of self-play. In this paper, we generalise this approach into a single *AlphaZero* algorithm that can achieve, *tabula rasa*, superhuman performance in many challenging domains. Starting from random play, and given no domain knowledge except the game rules, *AlphaZero* achieved within 24 hours a superhuman level of play in the games of chess and shogi (Japanese chess) as well as Go, and convincingly defeated a world-champion program in each case.

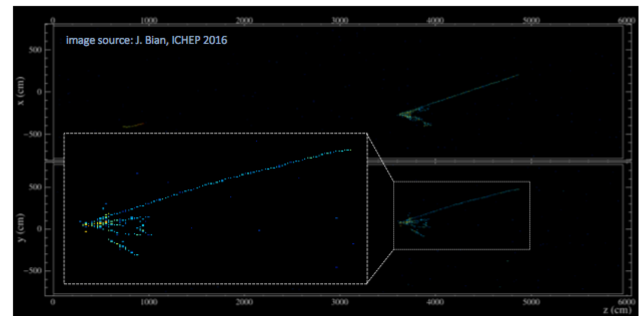
Artificial Intelligence and HEP

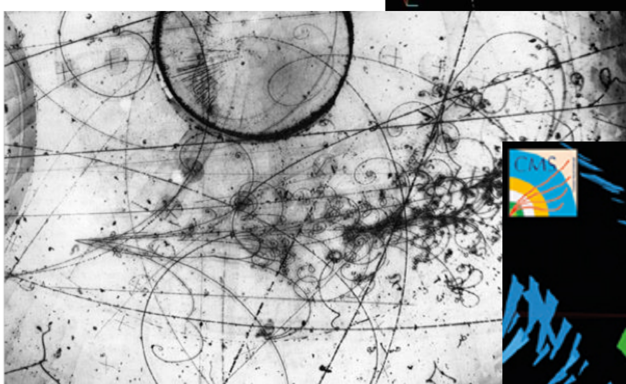
HEP events are images

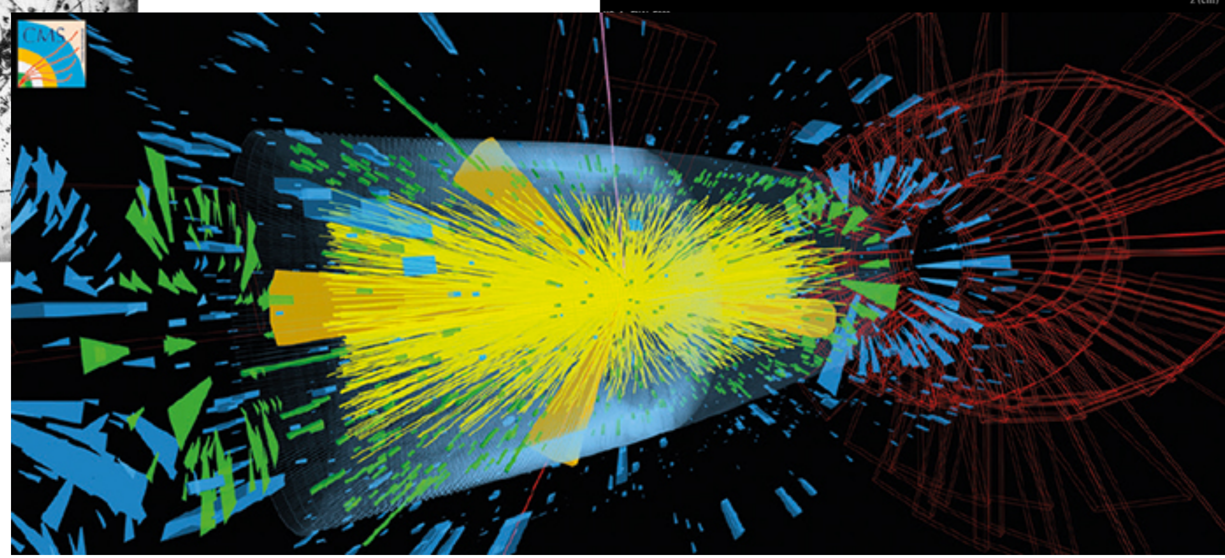










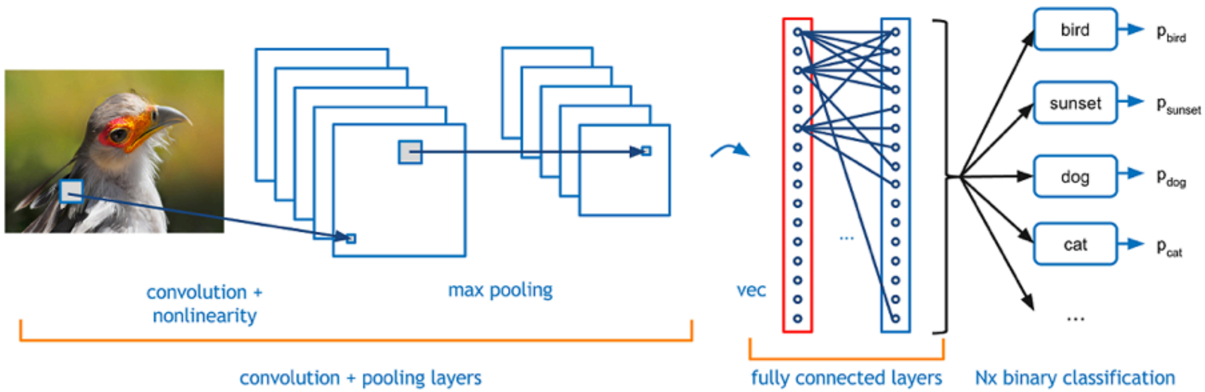


Maurizio Pierini, talk at
Princeton LAr workshop

Artificial Intelligence and HEP

Deep Learning & Image Detection

- *Image detection is the quintessence of Deep Learning*
  - *Special architectures (Convolutional Neural Networks) designed to accomplish the tsk by scanning portions of the images*
  - *Loosely inspired by how human eye capture images in patches and how human brain put patches together*
- *Approach proven successful on datasets that are not so different than our*



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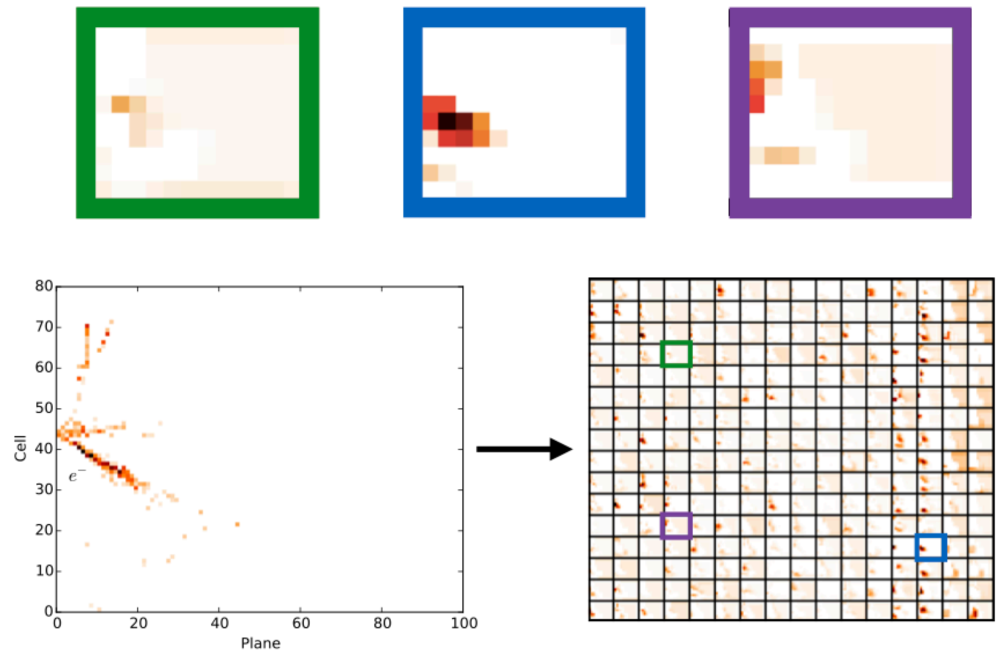
Maurizio Pierini, talk at Princeton LAr workshop

Artificial Intelligence and HEP: NOvA's big success

11 P. Vahle, Neutrino 2016

- This analysis features a new event selection technique based on ideas from computer vision and deep learning

- Calibrated hit maps are inputs to Convolutional Visual Network (CVN)
- Series of image processing transformations applied to extract abstract features
- Extracted features used as inputs to a conventional neural network to classify the event

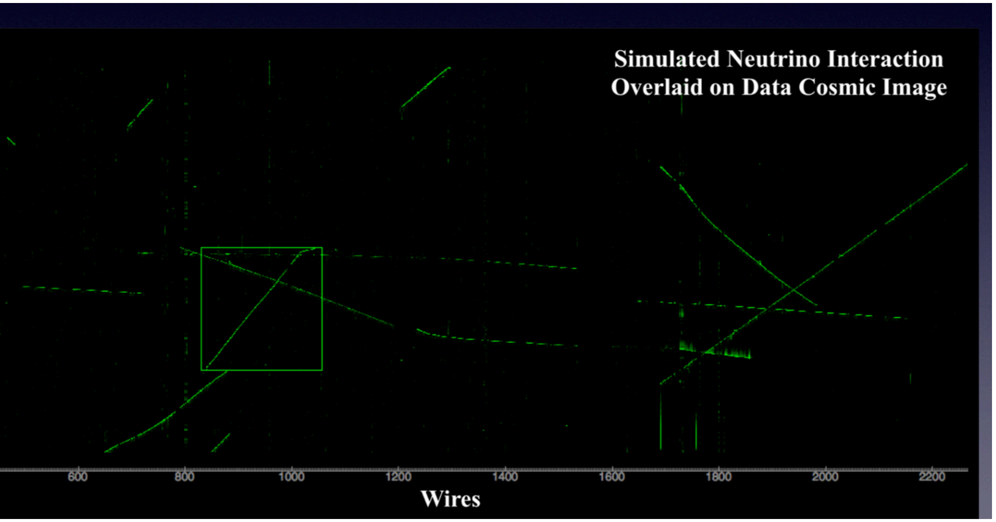


Improvement in sensitivity from CVN equivalent to 30% more exposure

Like adding 4,000 extra tons of detector mass!

Artificial Intelligence and HEP: MicroBooNE

Event classification and particle ID in Liquid Argon TPCs are very promising applications of Deep Learning techniques



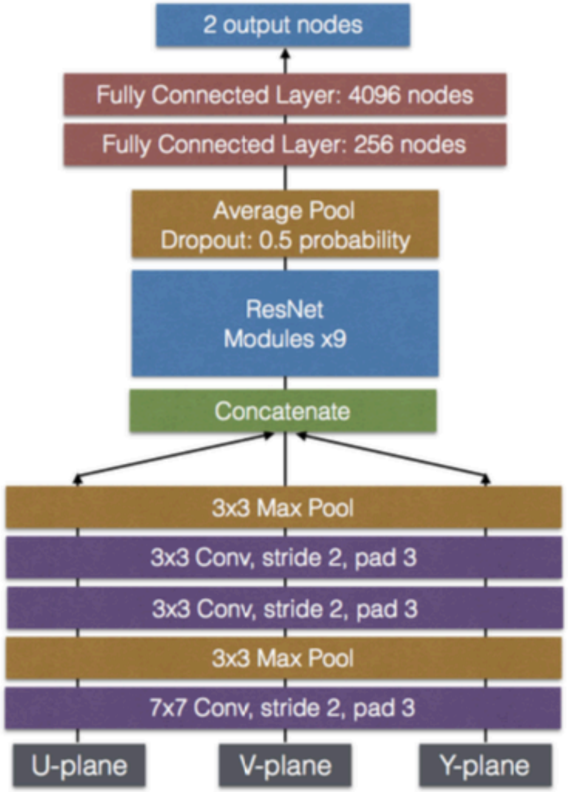


Figure 24. Neutrino ID Network. The data input layer is at the bottom and takes three wire plane views separately. The process flows from the bottom to the top where the final decision of a neutrino or cosmic event is made.

MicroBooNE collaboration, arXiv:1611.05531

Artificial Intelligence and HEP: CMS and ATLAS

Plans in CMS

- *CMS is planning to use Virtex-7 Xlinx FPGAs for the L1 trigger, where heavy data processing will not be possible in any case (25 ns latency from LHC collision frequency)*
- *We want to try to train DL to “model” the outcome of more CPU-consuming software*
- *In this context, a group at CERN/FNAL is developing a customised library to load NNs into the FPGA firmware*
- *We are planning to explore this possibility for LHC Phase II*

Maurizio Pierini, talk at Princeton LAr workshop

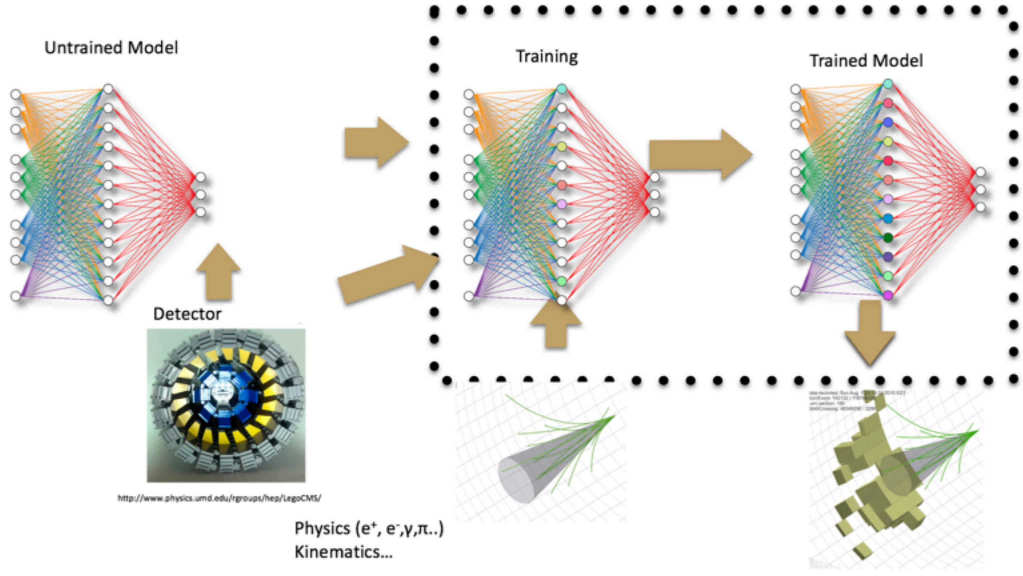
Artificial Intelligence and HEP: faster simulation

6

A DL ENGINE FOR FAST SIMULATION

INTEL PCC in 2017

- Focus on time consuming detectors
  - Reproduce particle showers in calorimeters
- Train on full simulation
  - Test training on real data
- Test different models
  - Generative Adversarial Networks, Recurrent Networks
- Embed inference (and training) step in GEANTV
  - Provide a configurable interface



Sofia Vallecorsa, talk at CERN openlab technical workshop

Any questions?