# Granada summary: physics capabilities of future colliders

Georg Weiglein, DESY

Hamburg, 06 / 2019

# The next large accelerator project: EW/precision versus energy frontier

Are the relevant questions the ones which could guide a decision, and can we contribute to these answers?

## Higgs / electroweak:

*[B. Heinemann '19]*

# Big Questions

1. **How well can the Higgs boson couplings to fermions, gauge bosons and to itself be probed at current and future colliders?**
2. **How do precision electroweak observables inform us about the Higgs boson properties and/or BSM physics?**
3. **What progress is needed in theoretical developments in QCD and EWK to fully capitalize on the experimental data?**
4. **What is the best path towards measuring the Higgs potential?**

# Higgs / electroweak

*[B. Heinemann ’19]*

# Answers to Big Questions

1. **How well can the Higgs boson couplings to fermions, gauge bosons and to itself be probed at current and future colliders?**
   - **Current colliders: ~1-3% for 3rd gen fermions and gauge bosons, 4% to μ, 50% to itself**
   - **Future colliders: factors of ~2-10 better (!) + $\kappa_c \sim 2\%$ + model-independent $\sigma(ZH)$**
2. **How do precision electroweak observables inform us about the Higgs boson properties and/or BSM physics?**
   - **Important to make sure precision H measurements ($\delta g_Z$) not limited by these**
   - **Themselves probe new physics in interesting and complementary way**
3. **What progress is needed in theoretical developments in QCD and EWK to fully capitalize on the experimental data?**
   - **A lot of progress needed! Plan exists but lots of work/people needed!!**
   - **In some cases, new ideas are needed => and unclear when/if new ideas come**
4. **What is the best path towards measuring the Higgs potential?**
   - **Di-Higgs and single Higgs production are sensitive to derivative $d^3V/d^3\phi$ near minimum**
   - **Seems conceivable to determine it with sufficient precision to test 1st order EWΦT**

*[B. Heinemann '19]*

# # of "largely" improved H couplings (EFT)

| | | Factor ≥2 | Factor ≥5 | Factor ≥10 | Years from $T_0$ |
|---|---|---|---|---|---|
| Initial run | CLIC380 | 9 | 6 | 4 | 7 |
| | FCC-ee240 | 10 | 8 | 3 | 9 |
| | CEPC | 10 | 8 | 3 | 10 |
| | ILC250 | 10 | 7 | 3 | 11 |
| 2nd/3rd Run ee | FCC-ee365 | 10 | 8 | 6 | 15 |
| | CLIC1500 | 10 | 7 | 7 | 17 |
| hh | HE-LHC | 1 | 0 | 0 | 20 |
| | ILC500 | 10 | 8 | 6 | 22 |
| | CLIC3000 | 11 | 7 | 7 | 28 |
| ee,eh & hh | FCC-ee/eh/hh | 12 | 11 | 10 | >50 |

13 quantities in total

NB: number of seconds/year differs: ILC $1.6 \times 10^7$, FCC-ee & CLIC: $1.2 \times 10^7$, CEPC: $1.3 \times 10^7$

# Interpretation of the projections for future facilities

- Report by Higgs@FC Group: charge was to use the inputs as provided by the projects, no scrutinisation of optimism vs. realism and of the level of sophistication of the inputs
- HL-LHC projections are to a large extent systematics-limited; they crucially depend on the level of improvement of the theory uncertainties that can be reached
- This is also a reason for the fact that the Higgs coupling projections for HE-LHC show only relatively small improvements over HL-LHC
- FCC-hh projections, in particular when taken separately, depend on the assumption of a drastic reduction of theory uncertainties
- FCC-ee requires very significant conceptual progress on theory side

ILC and FCC-ee have great potential for high-precision $\mathrm{Z}$, $\mathrm{WW}$, and Higgs physics

Can theory provide the necessary precision? *[S. Dittmaier '19]*

↪ Optimists: "Yes. No show-stoppers seen, great progress can be anticipated."

Sceptics: "Enormous challenge! Conceptual progress difficult to extrapolate."

# Requirements from theory for future facilities

*[B. Heinemann ’19]*

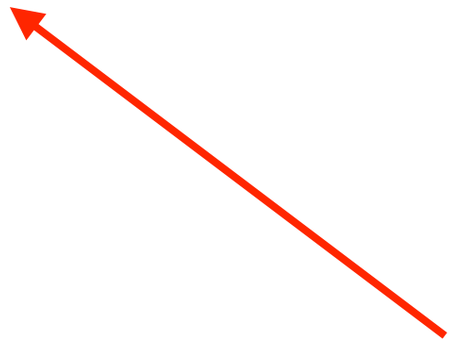
# Theoretical Uncertainties: production

**Production at hadron colliders**

- **For HL-LHC uncertainties expected to be improved by factor 2 w.r.t. current**
- **HE-LHC: another factor of 2**
- **FCC-hh: well below 1%**

**Requires e.g.**

- **Improved PDFs**
- **Higher precision calculations**
- **Improved non-perturbative aspects**
- **…**



Note: this is related to the fact that FCC-hh is assumed to be realised only far in the future!

# Higgs / electroweak

*[B. Heinemann '19]*

1. **Measuring H coupling at the level of few% or better very interesting!!**
   - **Naturalness vs simplicity tested: complementary to LHC direct searches**
   - **Many important questions are related to Higgs boson**
2. **Significant advances in theory needed to exploit data from all (!) colliders**
3. **HL-LHC probes many H couplings to few % level**
   - **Absolute values model dependent, ratios of couplings model-independent**
4. **All ee colliders achieve major (and comparable) improvements in their first stage already in probing Higgs sector compared to HL-LHC:**
   - **At least half of couplings get improved by factor 5 or more**
   - **W/Z effective couplings and $BR(H \rightarrow invisible)$ even probed to ~3x10$^{-3}$**
   - **Model-independent total cross section measurement => access to width, untagged BR**
   - **Clean environment to study H if/when anomalies are seen to understand underlying physics**
5. **Higher energy stages of ee and hadron colliders important**
   - **Excellent sensitivity to high-scale physics, e.g. CLIC3000 and FCC-hh**
   - **FCC-hh/eh improves rare Higgs couplings by large factor compared to FCC-ee**
6. **Electroweak precision measurements important for Higgs programme and NP tests**
   - **Oblique parameters**
     - Circular colliders have naturally an extensive programme on EWPO at Z-pole (also $\Gamma_Z$)
     - CLIC at high energy and FCC-hh excellent reach
   - **Precision top and W programme** important for EFT analysis and theor. Uncertainties
     - Top requires $\sqrt{s} \geq 350$ GeV
   - **Tera-Z programme** at FCC-ee (and potentially CEPC) impressive
     - Giga-Z programme at ILC (incl. polarisation) not part of baseline plan => needs follow-up
7. **Higgs self-coupling sensitivity interesting for electroweak phase transition:**
   - **di-Higgs process probes $\kappa_\lambda$ to 50% at HL-LHC => Improvements from HE-LHC (~15%), ILC$_{500}$ (~27%), CLIC$_{3000}$ (~9%), FCC-hh (~5%)**
   - **Single Higgs production also sensitive through loop effects**
8. **A few other interesting submissions for non-collider/low-energy measurements:**
   - **Not covered here but will include in briefing book**

# Beyond the Standard Model (at colliders)

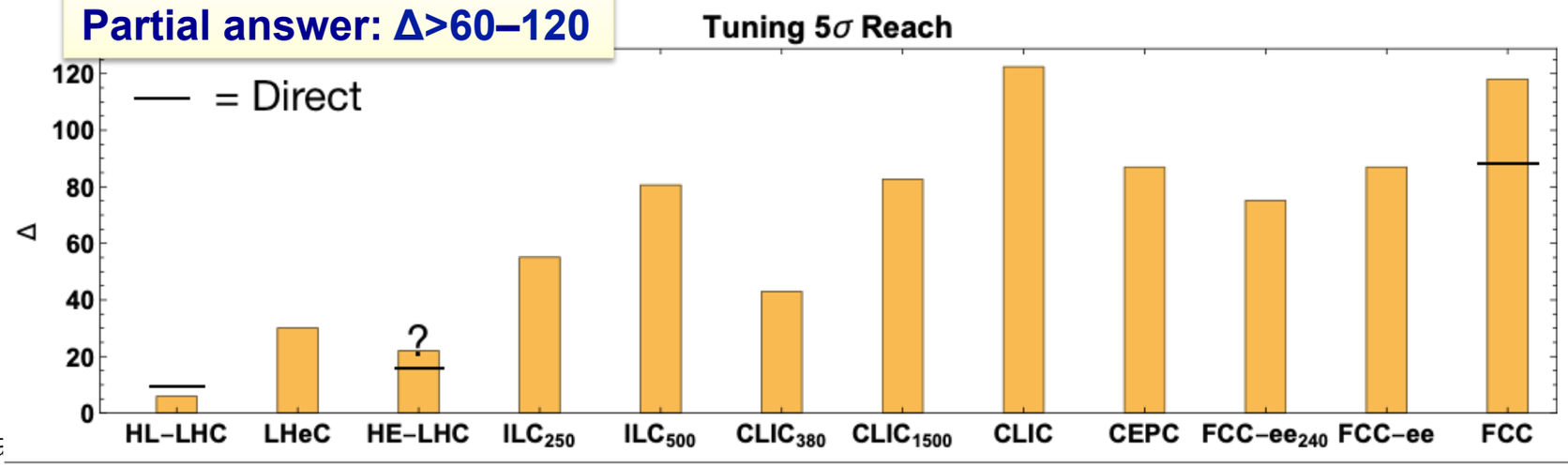
*[P. Sphicas '19]*

## The four big questions for BSM (@colliders):

- **To what extent can we tell whether the Higgs is fundamental or composite?**
- **Are there new interactions or new particles around or above the electroweak scale?**
- **What cases of thermal relic WIMPs are still unprobed and can be fully covered by future collider searches?**
- **To what extent can current or future accelerators probe feebly interacting sectors?**

$$\Delta > \left(\frac{M_{\text{T.P.}}}{500\,\text{GeV}}\right)^2 > \frac{1}{\xi} \qquad \frac{c_\phi}{\Lambda^2} = \frac{g_*^2}{m_*^2} = \frac{\xi}{v^2} \Rightarrow \frac{1}{\xi} = \frac{1}{v^2}\left(\frac{c_\phi}{\Lambda^2}\right)^{-1}$$

**Partial answer: Δ>60–120**



# Beyond the Standard Model (at colliders)

*[P. Sphicas '19]*

## Summary/Outlook

- **We are trying to provide a meaningful comparison between the different machines and experiments**
  - **And to see what we really learn in response to "big questions"**
- **We do learn a lot**
  - **But not everything we would like – answers, unfortunately, are not absolute. As expected, they are expressed in terms of reach in BSM energy/mass scale (and some extra parameters)**
- **Next step: condense detailed reviews into a super-short summary**
  - **And document the (much) longer story behind the Super Short Summary; suggestions welcome.**
- **We are very thankful to all the collaborations**
  - **For the effort put into submissions & accompanying materials**
  - **For answering our questions and for running some extra scenarios [or existing scenarios with different parameters, etc]**
  - **For participating in the discussion sessions and making insightful comments**

# Strong interactions

*[J. D'Hondt '19]*

## "Big Questions" on Open Symposium website

- What are the experimental and theoretical pre-requisites to reach an adequate precision of perturbative and non-perturbative QCD predictions at the highest energies?
- What can be learned from beams-on-target experiments at current and potential future (pre- )accelerators to test strong interactions?
- How to probe the QGP equation of state and to establish whether there is a 1st order phase transition at high baryon density?
- What is known about the make-up of the proton (mass, radius, spin, etc.) and how to extract it?
- What is the role of strong interactions at very low and very high (up to astrophysical) energies?

# Flavour physics

*[A. Zoccoli '19]*

## and in the future ….

### Belle II+1= Belle III

*Just started within Belle II*

Goal: x5 increase in peak luminosity

- ❑ Doable from a machine perspective ?
- ❑ Detectors issues running at 4 $10^{36}$ $cm^{-2}$ $s^{-1}$
- ❑ Physics case

Under study, more before the end of 2019

### $Z^0$ factories

Goal: $10^{11}$ – $10^{12}$ $Z^0$ (CEPC)
5. $10^{12}$ $Z^0$ (FCCee)
BR($Z^0 \rightarrow b\bar{b}$) = 15%

ILD-like detector + charged hadron PID.

FCC-pp a dedicated experiment (à la LHCb)

$e^+e^-$ Super Charm-Tau Factories:
SCT (BINP, Novosibirsk) and STCF/HIEPA (China)
E: 2 to 6 GeV
Peak Luminosity (> 4 GeV) $10^{35}$ $cm^{-2}$ $s^{-1}$

*[M. Zito '19]*

# Neutrino oscillations

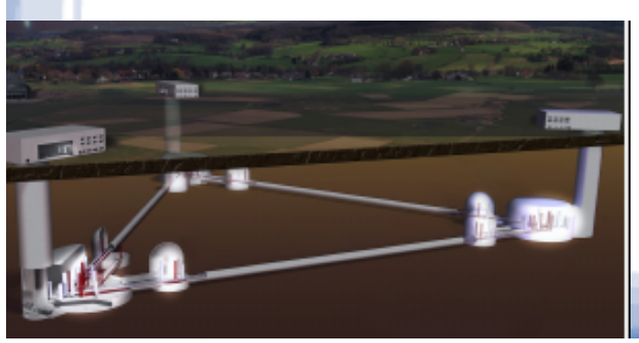
- Vibrant program (DUNE, Hyper-Kamiokande, JUNO, ORCA) to fully measure the PMNS mixing matrix and especially the Mass Ordering and the CP violation phase delta, with strong European contribution. Perceived by the community as a priority.
- Neutrino experiments need cutting-edge detectors and % precision on the flux and cross-sections: leading rôle for Europe (NA61, Neutrino Platform). New facilities currently under study.
- Long term future for high precision LBL measurements with new techniques. Time to prepare for it !

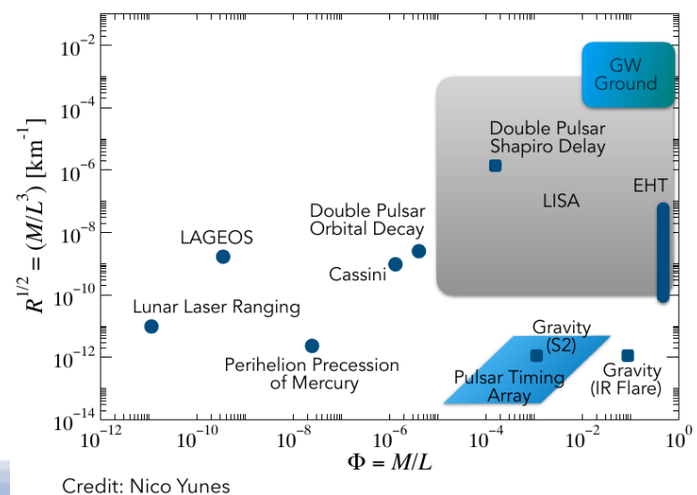
# Neutrino physics

*[M. Zito '19]*

## Gravitational waves

- Gravitational waves open a new field of research
  - Testing General Relativity in extreme conditions
  - Probing Black hole as Dark Matter
  - Equation of state in neutron stars
  - Serendipity : exotic objects, new fields and phenomena
- Einstein Telescope : 3rd generation of interferometers. Ultimate facility to probe the entire universe in the 1-100 Hz frequency range
- ET has put on the table a request for CERN to help with
  - Underground infrastructure, cryogenics
  - Vacuum, material and surface science
  - Electronics and data acquisition, computing






B.S. Sathyaprakash Granada 2019

# Dark Matter / Dark Sector

*[M. Carena '19]*

ean Strategy Update

## Comments from the Discussion Sessions

**Need for better coordination**

- Consensus emerged on the need for more coordination between accelerator based, direct detection and indirect detection dark sector searches, for common interpretation of results.
- This will also be of fundamental importance to validate, through different channels, a possible dark matter discovery.
- To address this issue, it was recommended to make profitable use of the initiative of APPEC on the EuCAPT Astroparticle Theory Centre.
- This offers a strong opportunity to collaborate with working groups such as the LHC DM and Physics Beyond Colliders and the many recognized dark sector experiments using different approaches

See talk by T. Montaruli, EPPSU Granada

# Dark Matter / Dark Sector

*[M. Carena '19]*

## Comments from the Discussion Sessions

**Need for technology support and exchange between communities**

- Technology challenges are shared between and beyond the communities engaged in dark matter searches.
- CERN and other large European National labs has relevant expertise and infrastructure for most/many of the big challenges, including vacuum over large volume, cryogenics, photosensors, liquid argon detectors, design and operation of complex experiments, software and data processing.
- Expanded support for dark matter research at CERN would stimulate knowledge transfer, increase coordination and synergies between experiments, and add guidance and coherence to the overall program.

# Perspective from the Americas

*[Y.-K. Kim '19]*

## Next Collider Options

### ILC

Statement by American Linear Collider Committee (US+Canada)

**ALCC stance vis-a-vis discussions concerning the International Linear Collider in the context of the European Strategy for Particle Physics (2020)** ALCC, March 27, 2019

The Americas Linear Collider Committee supports the ICFA position confirming the international consensus that *"the highest priority for the next global machine is a 'Higgs Factory' capable of precision studies of the Higgs boson."* We remain convinced that the ILC best meets all of the requirements needed to probe detailed properties of the Higgs boson. The ILC has the potential for a future upgrade in energy, can sustain beam polarizations that increase its ability to do precision measurements, and is the most technically mature proposal for an electron-positron collider now available.

The recent statement by MEXT in Japan stated that further consideration by the Science Council of Japan and intergovernmental discussions are necessary before Japan would be in a position to make a bid to host the ILC. Unfortunately, this does not fit naturally into the timetable for finalizing the European Strategy recommendation. On the other hand, it appears that high-level interactions between the U.S. DOE and the Japanese principals, government and DIET, continue to be positive. We understand that the DOE remains interested in discussing with senior Japanese officials about ILC and the possibility of hosting it in Japan.

The ALCC is supportive of any electron-positron project that can distinguish the Standard Model from new physics models through precision measurements of the Higgs production and decay couplings. However, given the strengths of the ILC noted above and the recent progress in obtaining support for it within Japan, we urge that the European Strategy group support the completion of the process underway in Japan to decide on a bid to host the ILC.

### CLIC

- CLIC and normal conducting high-gradient activities
- O(200) signatories for CDR
- Detector design and R&D
- Ongoing studies on physics potential

### FCC-ee, ep, pp

- Deep expertise in accelerator technologies including high field magnets and SCRF
- O(500) engaged; O(100) co-authored European Strategy Documents
- Ongoing studies on physics potential and detector design
- Long and productive cooperation on joint projects in US and at CERN

### CEPC

- Pre-CDR & CDR on arXiv with international contributions
- O(100) participated
- Detector design and R&D

# Perspective from the Americas

*[Y.-K. Kim '19]*

## Conclusions: Towards 2020 ESG

- Support of Americas' current plan
  - Importance of current high-priority projects such as HL-LHC, DUNE, …
- Beyond mid-2020's
  - Scientific drivers of the current plans are still valid
  - More capable facilities and broader programs
  - R&D of enabling technologies for future (accelerator, detector and computing)
- Support of facilities and activities outside of Europe
  - DUNE/LBNF, SNOLAB, CMB-S4, EIC, ….
  - A statement in the ESG document plays a significant role for success of facilities outside of Europe that serves the European / worldwide community
- The American community
  - will continue with its strong partnership with Europe
  - would like to see positive steps toward a new collider: an e+e- collider might be the first one to be realized: O(1000) American community

# Perspective from the Americas

*[Y.-K. Kim '19]*

## Closing Remarks

The worldwide particle physics community can together address the full breadth of the field's most urgent scientific questions

with

each major player hosting a unique world-class facility at home and partnering in high-priority facilities hosted elsewhere.

# Perspective from Asia

*[G. Taylor '19]*

## ILC/CepC Advantage for Europe

- **Allows concentration on proton, high energy future**
  - ***CERN essential for the energy frontier.***
  - ***Proton and high-field magnet expertise***
  - ***The ONLY laboratory capable of attempting very difficult projects, thus should be setting a "high bar"***
- **CERN infrastructure in protons beams outlays the fear of a second 100km tunnel.**
  - ***Possible to see a new proton collider at CERN by mid-2040s (not mid 2060s, but also not 100TeV)***

# Perspective from Asia

*[G. Taylor '19]*

## The Needs of Particle Physics

- **A e+e- collider higgs factory ASAP**
  - ***and, yes, in time, t-tbar, ttH, HH, ..***
- **A new energy frontier facility following HL-LHC**
  - ***even without a specific physics driver, as yet***
  - ***pp, ion-ion and ep all possible***
- **An active field, with multiple activities in parallel:**
  - ***particle physics data taking and analysis***
  - ***accelerator physics, including μμ colliders and plasma acc'n***
  - ***detector development***
  - ***advanced computing techniques***

CoEPP ARC Centre of Excellence for Particle Physics at the Terascale

**Geoffrey Taylor "Perspective on the European Strategy from Asia", EPPSU2019, Granada** 42

# Perspective from Asia

*[G. Taylor '19]*

# Asian (and personal) View

- **Diversity is Critical to thrive in all environments, including HEP.**
  - ***Big and small facilities/experiments, at various stages of development and operation***
- **Push for e+e- colliders, both Linear and Circular, as soon as possible.**
  - ***Linear Collider: ILC***
    - **1 Collision point**
  - ***Circular Collider: CepC***
    - **2 Collision points**
- **Push for FCC tunnel to be ready at completion of HL-LHC**
  - ***Stage the energy frontier with best option magnets available for early 2040's***
  - ***?? Default: ~8T LHC magnets optimised for price***
    - **Minimum energy: >50TeV**
    - **Magnet upgrade foreseen.**
  - ***ep and ion-ion options available***
  - ***4 collision points***
  - ***Upgrade path to higher energy after 20 years operation?***

See A. Yamamoto, S. Rossi, V. Shiltzev talks this symposium

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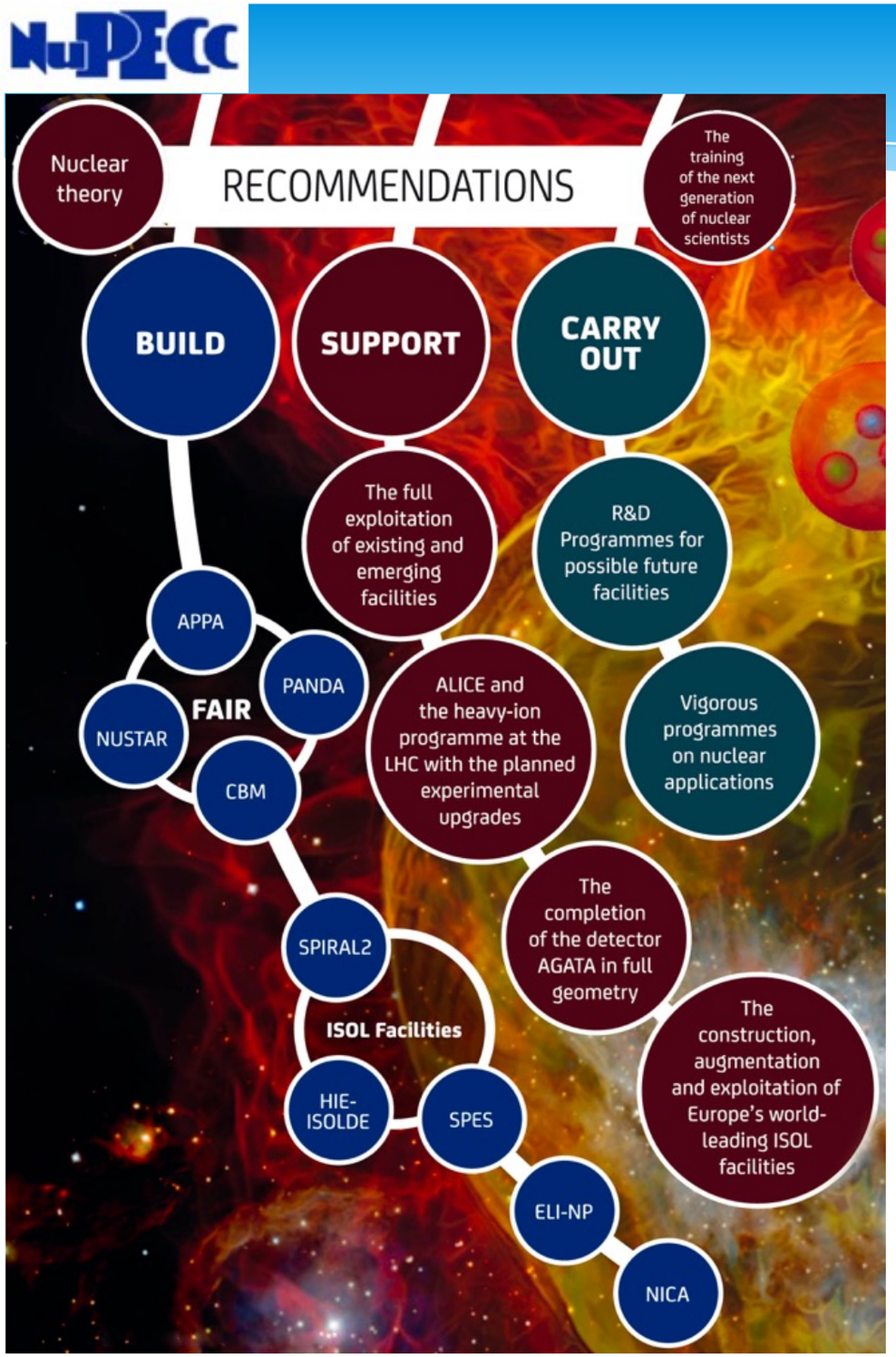
European Strategy Update

# NuPECC Long Range Plan

*[M. Lewitowicz '19]*




## NuPECC LRP

- **The 2017 NuPECC Long Range Plan defined an ambitious strategy for European Nuclear Physics**
- **NuPECC efforts to transform the LR Plan into reality**
- **Development of a global international approach to nuclear science in collaboration with IUPAP, NPD/EPS, ECFA, NSAC (US), ANPhA (Asia), ALAFNA (S. America), CINP (Canada)**

**Joint activities of ECFA, ApPEC & NuPECC**

- **Joint "JENAS" seminar – Oct. 2019**
- **Diversity Charter**
- **…**

# Outcome of the meeting (my interpretation)

- Strong preference for an $e^+e^-$ Higgs factory as the next big project; location and shape to be determined

- The full package of FCC-ee, FCC-eh and FCC-hh looks well in the comparison tables, but this has to be weighted against a timescale of more than 70 years and enormous costs.

There was strong opposition against this sequence of projects. Some arguments:

*[K. Jakobs, G. Taylor, …]*

- Go for a higher-energy proton machine directly
  Do not spend another 30 years on development of 16T magnets, which at the end might turn out to be unaffordable
  Rather use existing magnet technology, cost-optimised; could reach about 50 TeV with 100 km tunnel

# Outcome of the meeting (my interpretation)

- Our field would not survive the long gap between FCC-ee and FCC-hh *[L. Evans, …]*

- An $e^+e^-$ Higgs factory could provide crucial guidance for the future hadron machine. However, this does not work if one has to decide about the size of a circular tunnel as the first step.

# Implications for us at DESY (my interpretation)

- We should not take it for granted that there will be another big collider project, neither at CERN nor elsewhere

- Some people seem to think that the next big CERN project should be the ET

- What we put forward as the outcome of this strategy process has to be very convincing for other scientists, the general public and politicians. Otherwise the future of our field is at risk.

- We need a coherent world-wide programme (see statements by the other areas) and, as a crucial part of it, a forefront collider project at CERN

# Possible contributions to answering the crucial questions

Collider comparison:

- We have the expertise (new forum in this context: *Future Facilities Platform* of the Quantum Universe Cluster) that would allow us to do in-depth comparisons between the capabilities of the different proposed facilities including a judgement about the degree of sophistication and about the optimism / realism of the inputs that were submitted to the strategy process

- Of course, this would require a substantial amount of work.
  Is there an interest / demand of the community to get such a comparison? (and at which time scale?)
  If yes, would there be a mandate (from ICFA?) for such an investigation?

# Possible contributions to answering the crucial questions

Future accelerator concepts:

- We also have the expertise to make an informed statement on when one could realistically expect to have a particle physics collider
  - realised as a muon collider
  - based on plasma acceleration

Beyond colliders:

- DUNE: need to define the possible role of DESY in accordance with the German community