What after the LHC?

To a Higgs Factory and beyond

A. Faus-Golfe on behalf the IN2P3
Present and Future Large Accelerator projects

International Large Scale Projects

Medium Term Plan

- EPPSU

Long Term Plan

- EPPSU

Year of start Physics

- LHC
- DAPHNE SC linac
- ESS
- HL-LHC 11T Nb3Tn
- CepC. High current Z-pole
- CCC Cool Copper
- ILC 1.3GHz SC nano-beam/stabilization
- FCCee High current Z-pole
- FCCeh ERL
- CLIC 12 GHz nano-beam/stabilization
- SppC
- FCChh (FCCee) 16T Nb3Tn/NbTn

In operation
In construction
Under study
Present and Future Large Accelerator projects

An uncompleted view ...

International Large Scale Projects

- FAIR
- CepC
- High current Z-pole
- LHC
- DAPHNE
- Super KEKB...
- HL-LHC 11T Nb
- ...3
- FCCee
- High current Z-pole
- LBNF
- EI C
- CLIC 12 GHz
- nano-beam/stabilization
- An uncompleted view ...

Year of start Physics

A complex choice
Outline

- Future Collider Projects
  ESSP & Snowmass context
  State of the Art and Scientific Issues
- IN2P3 contribution
  R&D and Projects (2021-2025)
- Future Perspectives

- Higgs Factories
  - Linear: ILC/CLIC
  - Circular: FCC-ee
20 strategy statements have been unanimously adopted by the European Strategy Group (ESG) in January 2020:

**High-priority future initiative:** Prepare a **Higgs factory**, followed by a future **hadron collider** with sensitivity to energy scales an order of magnitude higher than those of the LHC, while addressing the associated environmental and technical challenges.
Context: The LDG process

CERN and the national laboratories in Europe (LDG) are charged by Council to define a Roadmap for Accelerator R&D

Topics:
- High-field magnets
- High-gradient accelerations (plasma, SCRF)
- Muon beams
- Energy recovery linacs
- Education and training

Panel chairs:

<table>
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<tr>
<th>Chair</th>
<th>High Field Magnets Low Temp &amp; H-TS</th>
<th>High Gradient Acceleration (plasma)</th>
<th>Muon Collider</th>
<th>ERL</th>
<th>High Gradient Accelerating Structures (sc &amp; nc)</th>
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<tbody>
<tr>
<td>Pierre Vedrine</td>
<td>IFU</td>
<td>Ralph Assmann, DESY &amp; INFN</td>
<td>Daniel Schulthe, CERN</td>
<td>Max Klein, Liverpool</td>
<td>Sebastien Bousson, UCLab</td>
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<td>Co-chair</td>
<td>Luis Garcia-Tabarca, CIEFAT</td>
<td>Edda Gschwendter, CERN</td>
<td>Nadia Pastrone, INFN</td>
<td>Andrew Hutton, JLAB</td>
<td>Hans Weise, DESY</td>
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IN2P3 Panel Members:
- Kevin Cassou, IJCLab
- Angeles Faus-Golfe, IJCLab
- Walid Kaabi, IJCLab

LDG Report (2022)
Context: Snowmass’21 process

Energy Frontier (Message)
- Compared to Snowmass 2013, the physics landscape has significantly changed
  - The program of measuring the Higgs boson properties is well underway at the LHC with growing precision
  - A broad range of searches have explored multiple BSM scenarios without convincing evidence of new physics
  - The HL-LHC is an approved project
- Without a robust support for the HL-LHC and a clearly defined path towards a Higgs factory, we leave critically important physics unchecked and crucial questions unanswered
- The EF community should be prepared to explore a broad range of BSM phenomena at the 10 TeV mass scale

The Energy Frontier community voices a strong support for
1. HL-LHC operations and 3 ab⁻¹ physics program, including auxiliary experiments
2. The fastest path towards an e⁺e⁻ Higgs factory (linear or circular) in a global partnership
3. A vigorous R&D program for a multi-TeV collider (hadron or muon collider)

The Energy Frontier is >50% of the US HEP community, therefore the potential impact on CEF (governmental advocacy, workforce training, diversity, and inclusion) are critical to the progress of HEP...

...and the public praising of EF by Michael Peskin for enabling a vigorous discussion on future multi-TeV colliders

Neutrino Frontier
- We need to finish DUNE, and its broad physics program.
  - Both Phase I and Phase II are required to complete the original DUNE design.
- We are excited about long-term, broader possibilities that make use of our investment in the facility and could expand the DUNE scope beyond that originally envisioned.
- A healthy program of projects of different sizes and time scales, with wide-ranging connections is highly desired and very much needed.

Neutrinos are tools for astrophysics and cosmology. Astrophysics and cosmology provide insight into NF physics.

What surprised us? Great technical progress on the detectors!
Well, that was not totally a surprise— but it was even more impressive than expected!

Accelerator Frontier
- The accelerator community has technology and expertise to address the next generation accelerator.
- By the time of next Snowmass/PS a National Future Colliders R&D program (new initiative!) should consider international and US based options and carry out technical and design studies sufficient to make informed decision on future directions toward
  - Higgs/EW factories
  - 10 TeV/Top quark colliders.

Intersections: Progress in accelerators will critically impact all future particle physics endeavors (neutrinos, colliders, DM) and therefore R&D should be prioritized by P5 inclusively accelerators need to be part of the P5 charge.
Full utilization of the unique proton power capability of the upcoming PIP-II accelerator should be developed by the HEP community (use remaining 98% of full beam power).

Surprising Thing this week at Snowmass:
We seem to be clever enough to be seriously taken by the Theory Frontier (they even did argue with us)
Context: HEP FC new Timelines

- Timelines technologically limited
- Uncertainties to be sorted out
  - Find a contact lab(s)
  - Successful R&D and feasibility demonstration for CCC and Muon Collider
  - Evaluate CCC progress in the international context, and consider proposing an ILC/CCC [ie CCC used as an upgrade of ILC] or a CCC only option in the US.
  - International Cost Sharing
- Consider proposing hosting ILC in the US.
## Future Colliders Maturity

<table>
<thead>
<tr>
<th>Collider</th>
<th>Design Maturity</th>
<th>R&amp;D Maturity</th>
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<td>ILC-250</td>
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<td>XCC γγ</td>
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<td>HE&amp;HL γγ</td>
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### Design Maturity
- **Score:** Total points out of 10 (10=Advanced Design Concept)
- **Criteria:**
  1. No end-to-end design concept documented.
  2. End-to-end preliminary design concept documented.
  3. End-to-end design concept available.
  4. End-to-end integrated design concept available.
  5. End-to-end integrated design concept available. Enables end-to-end performance evaluation.
  6. End-to-end performance evaluation complete. Reference (pre-CUR) design report under development.
  7. Reference design available. Sub-system parameters and high potential alternatives documented.

### R&D Maturity
- **Score:** Total points out of 10 (10=Complete R&D Program)
- **Criteria:**
  1. No systematic design requirements and/or parameters available.
  2. Concept proposed, proof-of-concept R&D underway.
  4. Preliminary design concepts with operating parameters established for all sub-systems. Sub-system design R&D underway.
  5. Sub-system design R&D underway.
  7. Sub-system detailed design and performance R&D for higher risk sub-systems underway.
  8. Sub-system specifications with validated operating parameters established. High risk sub-systems underway.

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### HEP FC Key Technologies

#### HEP Large Accelerator Projects Key Technologies

<table>
<thead>
<tr>
<th>Components</th>
<th>RF cavities</th>
<th>Magnets</th>
<th>Others</th>
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<tr>
<td></td>
<td>SCRF</td>
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<td>Techniques</td>
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<td>FCC</td>
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<td>CRYO</td>
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<td>CLIC</td>
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**e^+e^- Higgs factory technology is ready**

- **FCC-hh**
- **FCC-ee**
- **ILC**
- **CLIC**

**Techniques**
- **Design**
- **HG/HQ**
- **CRYO**
- **CRAB**
- **HE-Klys**
- **Nb3Tn**
- **CRYO**

**Projects**
- **FCC**
- **ILC**
- **CLIC**

**Others**
- **Integr.**
- **Alig./Pos**
A rich R&D program is driving the developing and building of these new facilities. A strong cooperation between national institutes, CERN and others global laboratories or collaborations is vital for the progress of the field and also for preserving the expertise.

In this context the main goal of the FCC-NPC IN2P3 project is to ensure an appropriate contribution to this vibrant and diverse R&D program focusing in where we have already demonstrated our know-how and expertise:

- Nanobeams handling
- Nanobeam stabilization and positioning techniques
- Luminosity and backgrounds
- High-intensity e+ sources
- e+e- polarimetry
- Dynamics vacuum and material studies
- SRF multipacting and materials
Scientific issues: Nanobeam size handling

Very high peak luminosity needs nanometre transverse IP beam sizes (FCC-ee 30-70 nm, ILC 3-8 nm, CLIC 1-3 nm).

To demagnify the beams, complex IR and FFS are designed.

ILC/CLIC scaled FFS: ATF2-3

ATF/ATF2 FFS has verified the minimal technical feasibility of ILC/CLIC-FFS, to maximize the luminosity potential of ILC/CLIC a further investigation and complementary experimental program on:

- Intensity dependence effects on the IP size
- Optical aberrations specially with smaller $\beta_x^*$, design optics ($\beta_x^* \times \beta_y^*$)
- Smaller sizes ultra-low $\beta^*$ (CLIC) will be pursued in a follow-on upgraded facility “ATF3” (ILC-IDT framed).
Scientific issues: Nanobeam size handling

Very high peak luminosity needs nanometre transverse IP beam sizes
(FCC-ee 30-70 nm, ILC 3-8 nm, CLIC 1-3 nm).
To demagnify the beams, complex IR and FFS are designed.

FCC-ee IR studies:

In some “special” IR configurations as monochomatization the energy spread could be reduced to maximize the sensitivity of certain physics channels. Further studies on:
- Parameters including Beamsstrahlung (BS) (increased $\varepsilon_x \sigma_b$) and crossing angle (Crab Cavities-CC)
- Optics design to generate antisymmetric $D_x^*$ are needed to probe the feasibility of this kind of IR schemes.

Realistic IR simulations: Synchrotron Radiation (SR) and Solenoidal detector fields impacts in MADIX code.
Scientific issues: Nanobeam stabilization and Positioning

Vibration mitigation and misalignments control are crucial to obtain high luminosity (CLIC FFS magnet specification displacements 0.2 nm at 4Hz).

With thousand of magnets, dynamic positioning approach by girder is the most effective approach.

Nanobeam stabilization

Ground Motion (GM), structural vibrations effects and elements position inaccuracies has an impact on beam brightness and position stability at the IP. R&D to mitigate this effect on:

• Beam dynamics studies to evaluate vibrations impacts
• Modelling (finite elements simulation) of mechanical dynamics behavior and prototyping
• Coherence motion, reducing the relative motions between the elements (main experiments strategy-low cost)
• Active control to reduce the absolute motion (high-cost) and beam control trajectory
• Vibration monitoring to evaluate the seismic and cultural noise (luminosity correlation...)
Scientific issues: Nanobeam stabilization and Positioning

Vibration mitigation and misalignments control are crucial to obtain high luminosity (CLIC FFS magnet specification displacements 0.2 nm at 4Hz). With thousand of magnets, dynamic positioning approach by girder is the most effective approach.

Positioning systems and vibration sensors and actuators

FCC-ee positioning strategy based on the management of the girder position, with elements already aligned, is in the state of the art (ESRF, SLS, CepC). R&D to extend the application is needed:

- **Actuators** (cam movers on components, control systems, nano-positioning systems)
- **Sensors**: Hydrostatic Leveling System (HLS), Wire Positioning Systems, differential sensors and vibrations sensors.
Scientific issues: Luminosity and Backgrounds

High luminosity implies the continuous correction of residual beam offsets or aberrations, fast luminosity measurement are an essential tool. Backgrounds mitigation are increasingly difficult with ultra-low $\beta^*$ and very high currents.

Fast luminosity measurements

Fast Luminometers (1% precision at 1 kHz) designed by IJCLab are deployed at SuperKEKB with large dynamic range, bunch-by-bunch and serving also as beam loss monitors. Their measurements are the input for:

- Feedback systems which stabilize the colliding beams and minimise their residual horizontal and vertical offsets.
- Aberration correction tuning procedure
- Luminosity optimization, including mechanical vibration near the detector area

Backgrounds

Simulation and experimental studies on beam loss backgrounds from continuous top-up injection system

Power Spectral Density component at 12.5 Hz reconstructed during 3 minute scan: injections are visible lasting 10 seconds every 20 seconds!
Scientific issues: High-Intensity e\(^+\) sources

High-beam intensity and low emittance e\(^+\) are necessary to achieve high-luminosity (ILC/CLIC 10\(^{16}\) e\(^+\)/s, 3.5\times10^{10} e\(^+\)/bunch or ~10\(^{13}\)e\(^+\)/s)

- **Novel types of e\(^+\) sources**
  - R&D beyond existing lepton injector technology:
    - Novel types of e\(^+\) source based on the hybrid scheme (channeling in crystals) with new granular targets.
    - e\(^+\) capture system based on SC solenoid as the matching device for the capture system
    - Use of the Artificial Intelligence (AI) for global optimisation of the e\(^+\) injector parameters
    - PoP e\(^+\) experiment in PSI (P3).

Capture system

Crystal-based target Hybrid scheme

PoP experiment for novel positron source (P3)

\[ L = \frac{N_e^2}{4\pi \sqrt{x_0 y_0 e_0 y_0}} \]
Scientific issues: \(e^+e^-\) Polarimetry

To optimize the collision of polarized beams, rapid measurements of polarization are a key ingredient. (ILC per-mil level precision)

- **Compton polarimetry**

R&D on:
- Design of the laser systems in terms of the real time monitoring of the laser-beam polarization that enters as an unavoidable systematic uncertainty on longitudinal polarization
- Feasibility study of per-mil level precision
- Beam energy measurement by resonant depolarization at FCC-ee.

**ILC Compton polarimeter + Spin tracking + \(e^+e^-\) collision data**

**Laser beam injection line**

**Upstream** Laser design: 30\(\mu\)J/pulse in red for continuous ellipsometry at 1.8 MHz, 100W in red 50W in green

**Downstream** Laser design: 100mJ at 2KHz

**HERA** polarization cavity

July 2023
One of the main potential limitation in all future colliders is the dynamic pressure. Specifications of vacuum systems and vacuum studies, including materials are of paramount importance.

- Dynamics Vacuum and Materials studies

  Experimental and Simulation studies on:
  - Measurement of the Secondary Emission Yield (SEY) (multipacting)
  - Surface analysis of materials
  - In situ measurements of pressure and development of the Dynamic pressure simulation (DYVACS)
  - Ion Stimulated Desorption (ISD) experimental studies at yields of production for the conditioning surfaces of FCC-ee

E=182 Gev
Energie critique ~ 1.2Mev !!!
SRF Cryogenics and materials

Understanding the physics of SRF regime to **optimize** the **performance** of **Nb** or other **new materials** in terms of accelerating gradient and quality factor (cost) is crucial for the performance improvement of SCRF cavities.

Further studies on:
- **Improvement of SCRF** with **innovative surface treatments and processing** (plasma cleaning)
- **Heat Treatments**: N$_2$ infusion and doping of Nb surfaces (low-frequency and low-beta).
- **Thin films** SC materials (multipactor mitigation)
- **Multipacting modelling** (FCC-ee SRF SWELL) and benchmarking with experiments
- **SEY measurements** (FCC-ee SWELL cavity surface samples)

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**SRF materials**

Plasma cleaning set-up

ALD deposition in Nb

Preliminary studies of multipacting location

SEY measurement set-up at cryogenic temperature @ IJCLab (2024)
Beyond Higgs factories…

- Boosting the performances of Higgs factories
- ERLs for FCCee and ILC
- Plasma Injectors
- Muon colliders
- Advance Linear Collider e+e-: HEP Energies in PWA
- Dreamt colliders…

Linear colliders based on laser-plasma accelerators

**PERLE synergies**

Twin SC LC with ERL

**ERL based FCC-ee upgrade**

C=100 km

4-pass ERL

CEPC Injector Alternative: Plasma Accelerator up to 45GeV (single stage)~120GeV (cascade)

**Muon Collider Concept**

1) Dense neutrino flux mitigated by mover system and site selection

2) Beam-induced background

3) Cost and power consumption limit energy reach. e.g. 35 km accelerator for 10 TeV, 10 km collider ring also impacts beam quality

4) Drives the beam quality MAP put much effort in design optimise as much as possible
# Projects and R&D Future Perspectives

## Projects and R&D Future Perspectives

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<th>PROJECTS R&amp;D</th>
<th>Present</th>
<th>MT Future</th>
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<td></td>
<td>B Factories</td>
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<td>SRF Cryo &amp; Materials</td>
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## Timeline
- **Medium Term Plan**
  - 2020
  - 2021
  - 2022
  - 2023
  - 2024
  - 2025
  - 2026
  - 2027
- **Long Term Plan**
  - 2028
  - 2029
  - 2030
  - 2031
The MT objective is to integrate, harmonize and synergize the IN2P3 R&D accelerator activities related with current and future colliders

- Consolidate the R&D areas
- Identify the approaches with greatest potential.

All of this in alignment with the IN2P3 strategy and having in view the next EPPSU strategy update.
There is no favorable wind if we don’t know where we are going...
Thanks for your attention