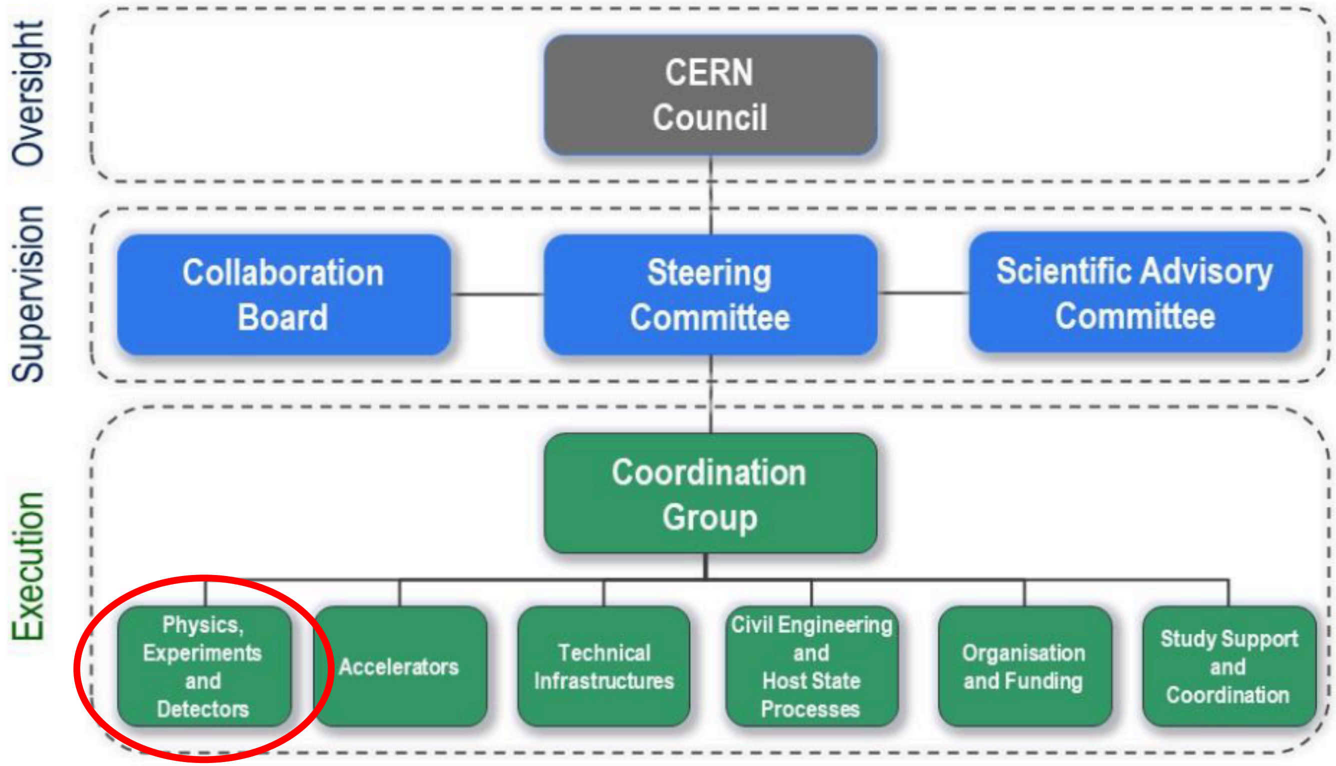
Structure and Objectives (2021-2025)

- **Outline**
  - Introduction: where we are today
    - The conceptual design study
    - The European strategy update
    - The FCC feasibility study
  - PED objectives and structure
  - Work package deliverables
  - Community building
  - Conclusion and outlook



Conceptual Design Study (2014-2018)

- **The FCC infrastructure offers the most comprehensive & cost-effective programme**
  - Building on and reusing CERN's existing infrastructure
  - Maximising the opportunities to tackle and explain yet unsolved physics issues
    - Origin of electroweak symmetry breaking
    - Origin of dark matter
    - Origin of matter dominance over anti-matter
    - Origin of neutrino (and other fermion) masses

    All these phenomena are observed, but are not explained in the Standard Model
  - Delivering the needed statistics, precision, and energy in a staged approach
    - Stage 1: FCC-ee (Z, WW, ZH, tt)
      - ➔ as 1st generation EW/top/Higgs factory with highest luminosities
    - Stage 2: FCC-hh (100 TeV) with eh and heavy-ion options
      - ➔ as natural continuation at the energy and intensity frontier

See presentations from
M. Reece : Why ?
G. Wilkinson : How ?

Conceptual Design Study (2014-2018)

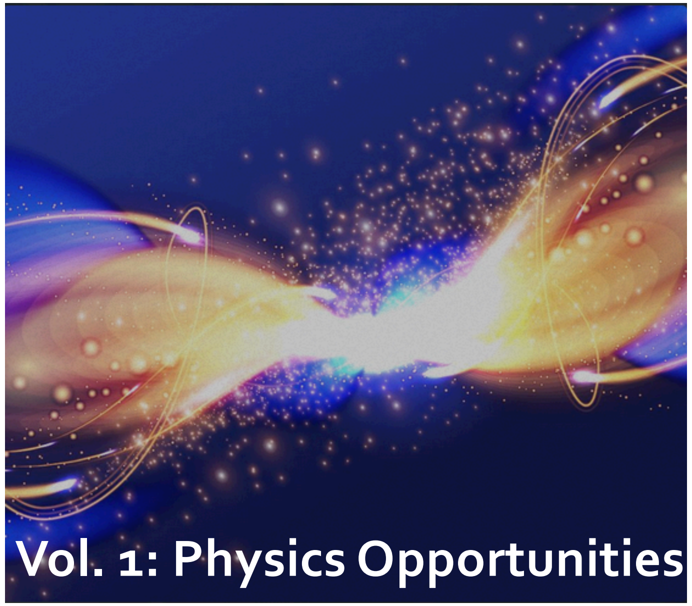
The FCC discovery potential in a nutshell

- **Stage 1: FCC-ee, as 1st generation EW/top/Higgs factory with highest e^+e^- luminosities**
  - Comprehensive EW/flavour/top/Higgs precision measurements
    - → Up to 10-to-100-fold precision improvement on all observables
    - → Sensitive to SM-coupled new physics in the 10-100 TeV range
    - → Discover that SM is indeed not sufficient; Pattern of deviations may point to the source of new physics.
  - Huge statistics to directly produce new particles and/or new phenomena
    - → Discover light feebly-coupled particles, dark matter in invisible H and Z decays, flavour violation, …
  - These fundamental discoveries would point to a more fundamental theory at low or high scale

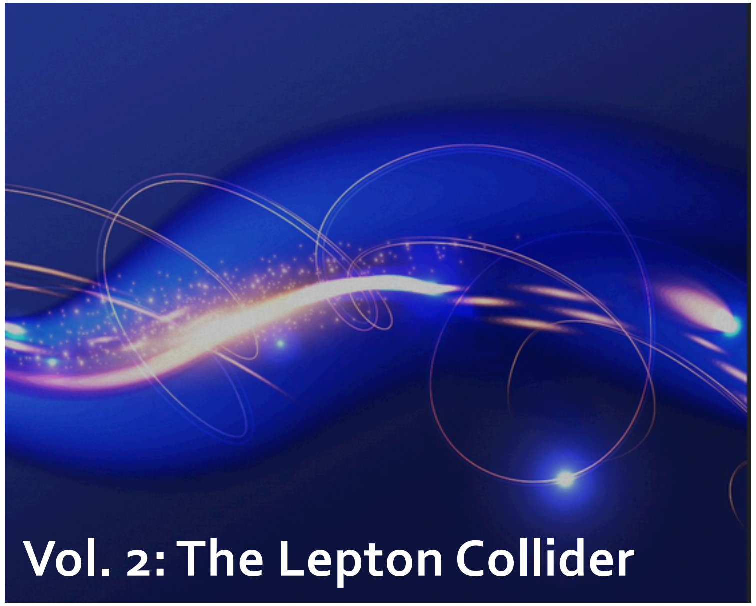
- **Stage 2: FCC-hh, as natural continuation at the energy and intensity frontier in pp collisions**
  - More precision measurements, making use of FCC-ee absolute "standard candles"
    - → With huge production Higgs, top, and W's; Expands the sensitivity to SM- / feebly-coupled new physics
  - Large collision energy allows the production & discovery of new heavy particles up to 30-40 TeV
  - Complementarities / synergies with FCC-ee will help understanding the underlying new physics
  - Additional opportunities with FCC-eh, heavy ions, and dedicated experiments

Conceptual Design Reports (2018-2019)

- See https://fcc-cdr.web.cern.ch



Vol. 1: Physics Opportunities



Vol. 2: The Lepton Collider

Vol. 3: The Hadron collider

- Other useful documentation to extend and deepen knowledge
  - FCC-ee: Your questions answered – https://arxiv.org/abs/1906.02693
  - Circular vs Linear colliders: another story of complementarity – https://arxiv.org/abs/1912.11871
  - Theory calculations for FCC-ee – https://arxiv.org/abs/1809.01830 & https://arxiv.org/abs/1905.05078

European Strategy Update (2019-2020)

- **Confirms Conceptual Design Study conclusions with its new high priority initiatives**

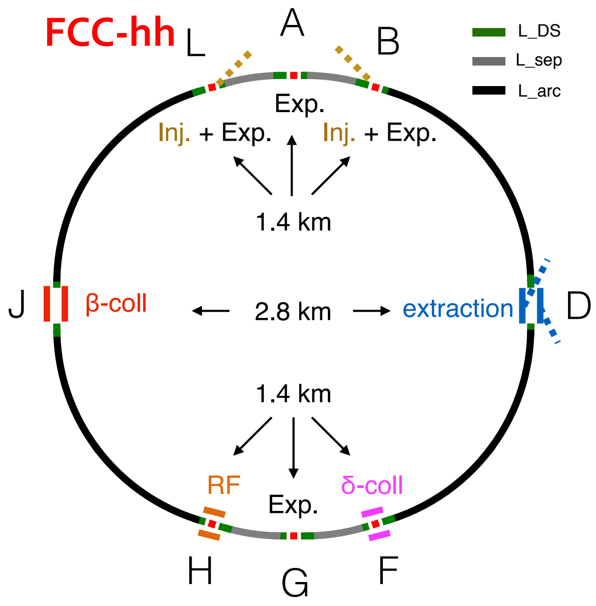
  An electron-positron Higgs factory in the highest priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.

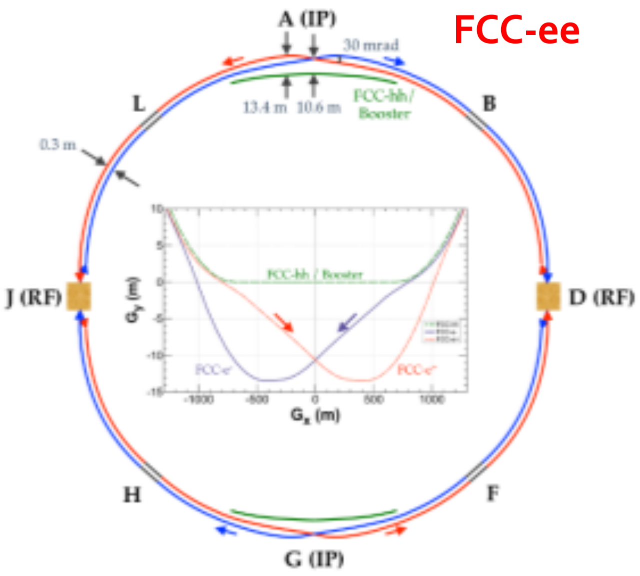
  Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron positron Higgs and EW factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.

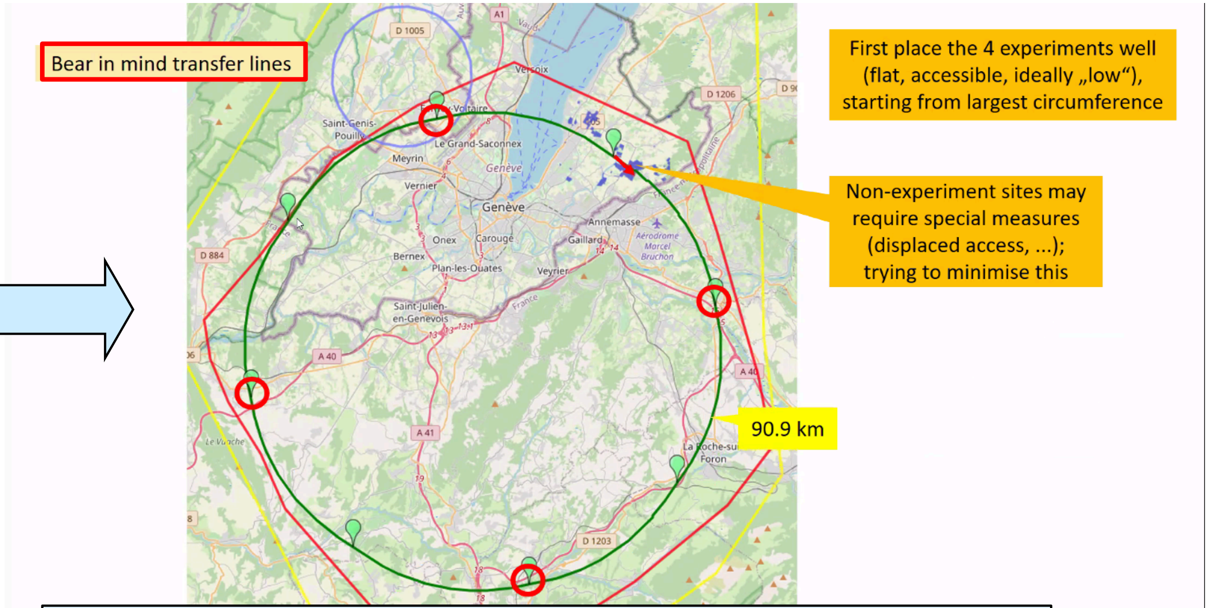
- **"A possible first stage": is FCC-ee optional?**
  - **There is no feasibility study in Europe or elsewhere without FCC-ee as the 1st stage of FCC**
    - Common infrastructure, staged budget, time for high-field magnet R&D, complementary physics
  - **Going directly to FCC-hh seems technically, financially (and politically?) not feasible**
    - FCC-ee first provides control of technical & financial risks + Seamless continuation of HEP:
      - → "Such a timeline is realistic for FCC-ee, more difficult for FCC-hh"

      See presentation from F. Gianotti
  - **Incidentally, FCC-ee fits particularly well the highest-priority next collider of the ESU**

- **Increased emphasis is internally placed on the common infrastructure and on FCC-ee**
  - H2020 Innovation Study (FCC-IS) is focussed on FCC-ee and partially financed by Europe
  - The High-field magnet R&D effort proceeds independently of the Feasibility Study
  - Priority shifted from FCC-hh to FCC-ee when it comes to the common collider footprint
    - From Conceptual Design Study .... To Feasibility Study







Priority on hh led to race-track choice and 2IP only for FCC-ee

But FCC-hh can certainly live with 4-fold symmetry.

FCC Feasibility Study (2021-2025)

- Meanwhile, the CERN Council has been informed of the FCC-FS milestones
  - E.g., about the financial feasibility assessment

FUTURE CIRCULAR COLLIDER FEASIBILITY STUDY:

MAIN DELIVERABLES AND MILESTONES

CERN/SPC/1161
CERN/3588
Original: English
21 June 2021

RESTRICTED COUNCIL
203rd Session
17 June 2021

- a committee including external experts will be established to review the cost of the first-stage project (the tunnel and the FCC-ee collider) by mid-2023; a second cost review will take place at the end of the Feasibility Study in 2025;

- "A possible first stage" ? (Here, possible means optional)
  - The FCC-ee is not only a "possible" first stage
    - FCC-ee is probably the *only* "possible" first stage on the path to a 100 TeV collider (Here, possible means feasible)

The PED Pillar Objectives in 2025

- **Mostly defined by the general (tight) timeline of the FCC project**

Infrastructure and accelerator | **Physics, Experiments, and Detectors**

Milestone / activity	Target date	Possible timeline
First e^+e^- collisions in FCC-ee	Early 2040's	FCC-ee detector commissioning
Start machine installation	2037	Start FCC-ee detector installation
Tunnel completion	2035/36	
Start tunnel construction	2030	Start FCC-ee detector construction
Project approval	2028/29	FCC-ee Detector TDR's and approvals
Next European Strategy Update	2026/27	Next European Strategy Update (ESU)
Key prototypes (feasibility proof)	2026	FCC-ee Proto-collaborations and EoI's
FSR(*) (feasibility proof)	End 2025	PED FSR, includes enough common material and knowledge for FCC-ee proto-collaborations

(*) FSR = Feasibility Study Report

Adapted from schedule in M. Benedikt's presentation

The PED Pillar Objectives in 2025

- **Towards the FCC Feasibility Study report**
  - Expand the physics vision beyond the 2018 CDR first pass
  - Establish the requirements on
    - Detector design and performance
    - Theory precision
    - Accelerator performance, operation, accuracy
    - Analysis tools and Computing environment
      - ➔ With detailed performance studies that implement in practice the physics vision

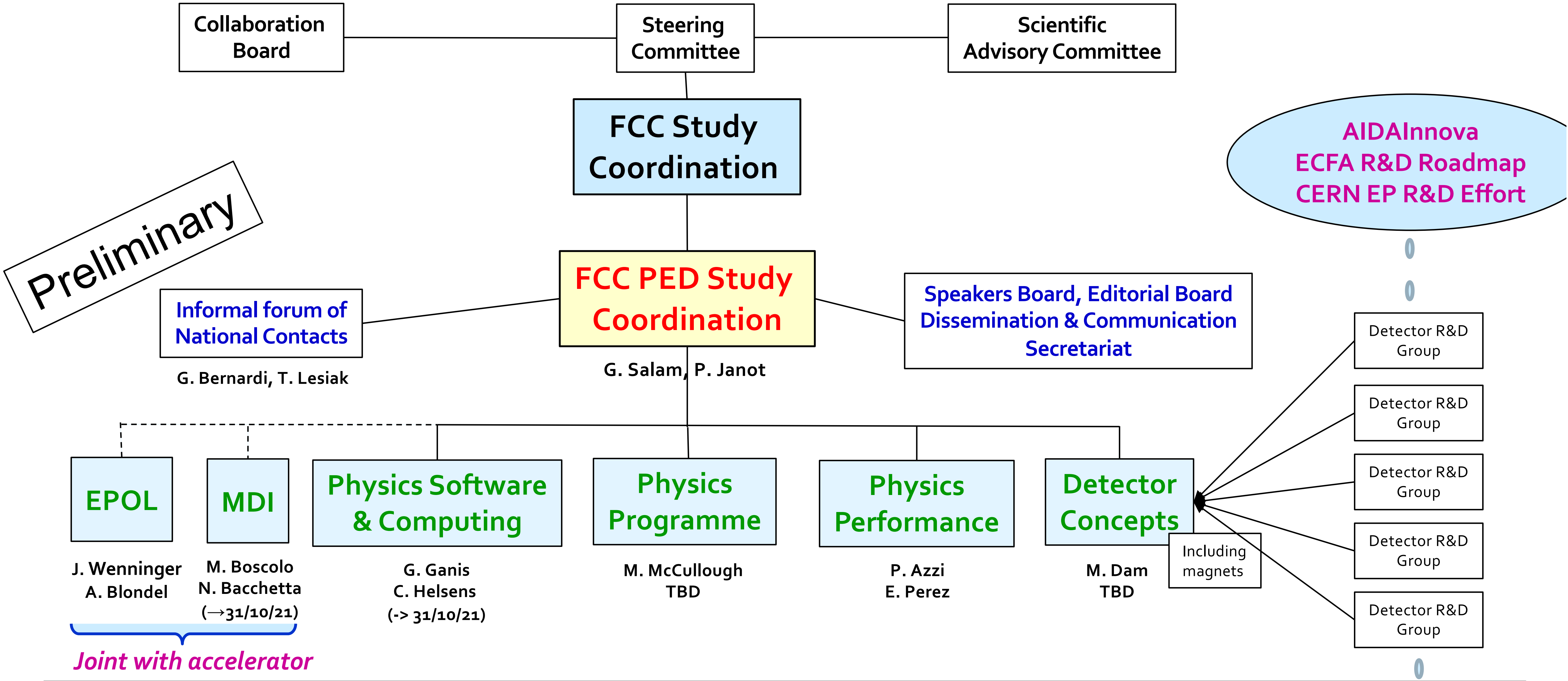
  to make experimental and theory uncertainties match the huge available statistics
  - Develop & evaluate detector concepts
    - Capable of delivering the requirements set by physics studies
    - Compatible with operation conditions
    - Integrated in an optimized machine-detector interface
  - Support all of the above with a common and modern software framework
  - Propose solutions for computing, storage, and bookkeeping infrastructure

The PED Pillar Objectives in 2025

- These objectives cover the FCC integrated program (ee, then hh)
  - It is essential for the community of particle physicists, funding agencies, committees, etc.
    - To realize that FCC-ee and hh come together as one project and that FCC-ee is not optional
- Some emphasis will be placed on the first stage, but…
  - The physics vision relies on complementarities and synergies between ee and hh
    - The exploration of the FCC-hh physics reach will be continued
    - The cross-talk between ee and pp/LHC/eh/heavy ions communities will be encouraged
      - ➔ There is no such thing as ee or hh physicists – we are all particle physicists !
  - The software framework (FCCSW) has always been common to ee and hh
  - The FCC-hh detector concept is already thoroughly documented
    - Will be revisited in the light of the physics landscape evolution and HL-LHC upgrade experience
    - Detector possibilities for experiments beyond the multi-purpose detectors will be explored
  - Performance studies to compare FCC-hh reach with "Plan B's" (*) will likely be needed
    - Specific analysis tools (to deal, e.g., with boosted objects and 1000 PU) will be necessary

(*) High-energy lepton colliders: CLIC, muon collider

The PED Pillar Structure



Physics Programme

- Six working groups (with at least one experimentalist and one theorist conveners, tbd)
  - Focus on the phenomenological aspects of the integrated FCC programme
    1. Precision Electroweak Physics
       - ➔ Z peak and WW threshold (ee)
       - ➔ High-energy diboson and difermion (hh)
    2. Higgs physics
    3. Flavour (c, b, τ) physics
    4. BSM Physics
       - ➔ Indirect sensitivity from precision measurements (ee and hh)
       - ➔ Direct BSM searches at the smallest couplings (ee and hh) and highest masses (hh)
    5. QCD
    6. Top physics
  - To be considered in addition
    - Physics at FCC-hh with dedicated experiments

Physics Programme: Key deliverables

- **Within the domain of expertise of each working group**
  - Bring together theorists and experimentalists
  - Report on recent results in the literature and develop new ideas
    - New models to probe; new experimental tests to implement; new observables to test
    - Examine different operation models (L vs $\sqrt{s}$: values and time ordering)
    - Propose ancillary (in situ) measurements of key accelerator/detector parameters
  - Propose physics benchmark measurements
    - Which may lead to new detector performance requirements or theory precision requirements
  - Plan for precision theory calculation development, to match experimental uncertainties
    - A strategic priority for FCC-ee – Such developments have focussed on LHC in the past 20 years.
  - Review existing MC generators
    - And plan for upgrade to include most recent theoretical progress
  - Deliver and test global fitting code and formulae
    - For standard model, specific BSM models, and generic Effective-Field-Theory (EFT) approach
  - Organize public documentation for the results of the working group

Physics Programme: Literature

- **A number of essays have been written and are under review (to be published in EPJ+)**
  - **Pave the way for the Physics Programme Work Package**

A future Higgs and Electroweak Factory (FCC): Challenges towards discovery

Scope:

- Physics Landscape after the Higgs discovery (M. Reece)

Theoretical challenges at the precision frontier:

- Overall perspective and introduction (C. Grojean)
- Theory challenges for EW and Higgs calculations (S. Heinemeyer, S. Jadach, J.Reuter)
- Theory challenges for QCD calculations (P. Monni, G. Zanderighi)
- Indirect discovery of physics beyond the Standard Model (J. de Blas)
- Direct discovery of new light states (S. Knapen, A. Thamm)
- Theoretical challenges for flavour physics (Y. Grossman, Z. Ligeti)
- Theoretical challenges for tau physics (T. Pich)

Physics opportunities and challenges

- FCC-ee overview: New opportunities create new challenges (A. Blondel, P. Janot)

Links will be added in this slide when available

Physics Performance

See presentation from P. Azzi

- This work package makes the link between
  - Physics Benchmark Measurements (proposed by "Physics Programme")
  - Detector Requirements (used by "Detector Concepts")

By means of concrete "Physics Case Studies"

- For each physics benchmark measurement
  - Identify and implement one or several Case Studies to optimize the ultimate statistical sensitivity
  - Identify and evaluate the limiting systematic uncertainties
  - Establish detector requirements to match systematic uncertainties with statistical precision
- Key deliverables
  - Physics tools and analysis code, re-usable by others (in contact with "Physics Software")
  - Coherent formulation of detector requirements (e.g., resolutions, alignment, stability …)
  - Public documentation (web, technical notes, conference presentations, preprints, papers, …)

Physics Performance

- This work package makes the link between
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By means of concrete "P...

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    - Identify and ev... ...rtainties
    - Establis... ...systematic uncertainties with statistical precision
  - ...
    - ...lysis code, re-usable by others (in contact with "Physics Software")
    - ...ulation of detector requirements (e.g., resolutions, alignment, stability …)
    - ...ocumentation (web, technical notes, conference presentations, preprints, papers, …)

Ideal entry point for youngsters to learn about and work on (e+e-) Physics, Analysis, and Detector aspects in small and motivated teams, with help from experts

Physics Performance: Literature

- **A preliminary list of concrete physics studies**

  See presentation from P. Azzi

  https://www.overleaf.com/read/dyjpdszrqxhz and https://indico.cern.ch/event/951830/

- **EPJ+ essays (under review) paving the way for the Physics Performance Work Package**

Higgs and Electroweak Factory (FCC): Challenges towards discovery

Links will be added in this slide when available

Physics opportunities and challenges

- FCC-ee overview: New opportunities create new challenges (A. Blondel, P. Janot)
- From physics benchmark to detector requirements (P. Azzi, E Perez)
- Higgs and top challenges (P. Azzi, L. Gouskos, M. Selvaggi, F. Simon)
- Z line shape challenges: ppm and keV (J. Alcaraz, A. Blondel, M. Dam, P. Janot)
- Heavy-quark opportunities and challenges (S. Monteil, G. Wilkinson)
- The tau challenges (M. Dam)
- Hunt for rare processes and long-lived particles (R. Gonzales-Suarez, M. Chrzaszcz, S. Monteil)
- The W mass challenge (P. Azzurri)
- A special Higgs challenge: Measuring the electron Yukawa coupling (D. d'Enterria)
- A special Higgs challenge: The mass and cross-section measurements with ultimate precision (P. Azzurri, G. Bernardi, S. Braibant, D. d'Enterria, P. Janot, A. Li, E. Perez)

Detector Concepts

See presentation from P. Giacomelli

- The work-package mandate exists, structure is being prepared
  - Key deliverable: FCC-ee Detector Concept proposals, evaluation, and documentation
    - Compatible the Detector Performance Requirements from "Physics Performance"
    - Compatible with MDI layout and with timing and background conditions
      - ➔ A "Detector Concept" includes the assembly of sub-detectors (geometrical description, simulation, local reconstruction); the magnet system; an overview of services, power consumption, ecological impact; an evaluation of construction and operation costs
    - For up to four interaction points
      - ➔ Allow for a range of complementary detector solutions to cover all FCC-ee physics opportunities
  - Selection of other key tasks
    - Establish links with a broad range of R&D groups
      - ➔ Includes ECFA R&D Roadmap; AIDAInnova; CERN EP R&D effort
    - Follow technological developments that could lead to new physics opportunities
    - Identify and encourage R&D work in the direction of the FCC-ee requirements
    - Promote the use of the common FCCSW platform and tools for performance simulation
    - Maintain and update FCC-hh detector concept + study FCC-hh dedicated experiments

Detector Concepts: Literature

- **EPJ+ essays (under review) paving the way for the Detector Concepts Work Package**

Higgs and Electroweak Factory (FCC): Challenges towards discovery
Physics opportunities and challenges

- From physics benchmark to detector requirements (P. Azzi, E. Perez)
- Tracking and vertex detectors at FCC-ee (N. Bacchetta, P. Collins, P. Riedler)
- Calorimetry at FCC-ee (M. Aleksa, F. Bedeschi, R. Ferrari, F. Sefkow, C. Tully)
- Muon detection at FCC-ee (S. Braibant, P. Giacomelli)
- Particle Identification at FCC-ee (G. Wilkinson)
- Luminosity measurement at FCC-ee (M. Dam)

Links will be added in this slide when available

- **CDR for the FCC-hh baseline detector**
  - **Main editor: W. Riegler - currently under proofreading review.**

Software and Computing

See presentation from G. Ganis

Key deliverables for FCC Software (FCCSW)

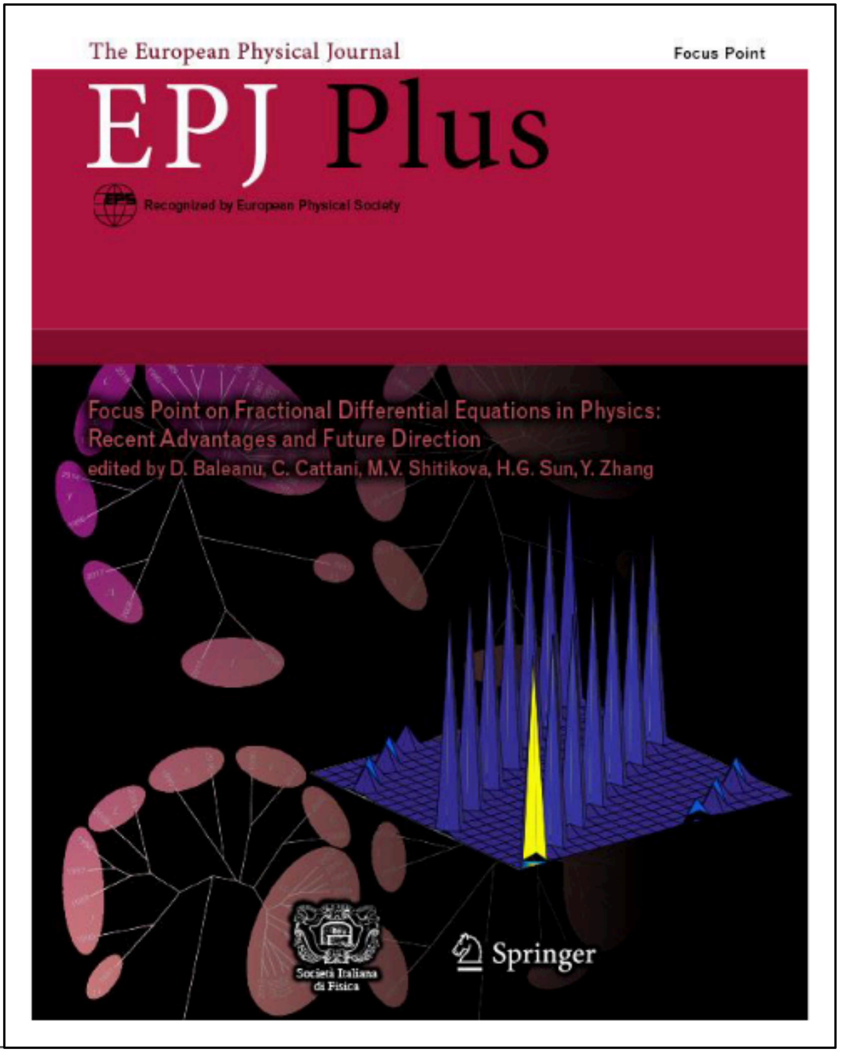
- Appropriate sets of Monte Carlo generators (with input from "Physics Programme")
- Framework for fast and full simulation (with input from "Detector Concepts")
  - Maximally flexible for detector optimization in the specific FCC environement
- Framework for event reconstruction (with input from "Physics Performance")
- User-friendly analysis framework for case studies and phenomenological studies
- Library of common tools (with input from all)
- Event display(s)
- Framework for machine-induced background simulation (with input from "MDI")
- Tutorial for users

Key deliverables for computing

- Evaluation of the computing, storage, bookkeeping infrastructure for the FCC data
- Enable use of distributed resources

Software and Computing: Literature

- EPJ+ essays (under review) paving the way for "Software and Computing" WP



Software Developments an Computational Challenges

- Key4hep, a framework for future HEP experiments and its use in FCC
  (G. Ganis, C. Helsens, V. Volkl)
- Accelerator-related codes and interplay with FCCSW
  (M. Boscolo, H. Burkhardt , G. Ganis, C. Helsens)
- Online computing challenges: detector and readout requirements
  (R. Brenner, C. Leonidopoulos)
- Offline computing resources and approaches for sustainable computing
- (G. Ganis, C. Helsens)

Links will be added in this slide when available

PED / Accelerator Design: Joint WP's

- FCC-ee Machine-detector interface (MDI)

See presentation from G. Wilkinson

Parallel session on Thursday, 9am

  - Key deliverables (limited here to detector-related aspects)
    - Simulation, evaluation, and mitigation of machine-related backgrounds in the detector
      - ➔ Implementation in FCCSW (with help from "Software and Computing")
    - Conceptual design of the supporting structure for beam pipe, vertex detector, lumi monitors…
    - Follow-up, evaluation, and possibly implementation of requirements from Physics
      - ➔ e.g., smaller beam pipe, larger magnetic field, …

- FCC-ee Energy calibration, polarisation, monochromatisation (EPOL)

See presentation from G. Wilkinson

  - Key deliverables (limited here to detector-related aspects)
    - Design and evaluation of methods for in-situ measurements (with $e^+e^- \to \ell^+\ell^-$)
      - ➔ $\sqrt{s}$ value and spread, longitudinal boost, collision angle, horizontal and longitudinal dispersion
      - ➔ Correlations with position, time, and longitudinal boost of the collision
      - ➔ For $\sqrt{s}$ value, understand and control experimental and theory biases

        e.g., experiment magnetic field calibration and stability, impact of QED effects (ISR, FSR, IFI), …
    - Demonstration and monitoring of the monochromatisation scheme (from the above studies)
    - Tracking of $\sqrt{s}$ calibration results; evaluation of impact on the FCC-ee precision measurements

First WP meeting
7 Oct 21, 4:30pm

Key for success: Community building

- A tremendous amount of exciting challenges to work out and solve <u>in practice</u>!
  - Will be a lot of fun for creative enthusiasts
  - Will be very educational and source of "few authors" papers for Early Career Researchers
    - With possibly real data as well (from LEP) in FCCSW

See G. Ganis' talk @ https://indico.cern.ch/event/1043155

- Might be mission impossible w/o increased participation from worldwide community
  - Strategic importance recognized in FCC-ee document @ ESPP

"The greatest remaining challenge is the creation of a world-wide consortium of scientific contributors, who reliably commit resources to the development of the FCC-ee science project from 2020 onwards."

  - Now part and parcel of the mandate of the FCC-IS WP5

Parallel sessions on Tuesday and Wednesday

"<u>WP5: Leverage and Engage</u>
Engage stakeholders in the preparation of a new research infrastructure. Communicate the project rationale, objectives, and progress. Create lasting impact by building theoretical and experimental physics communities, creating awareness of the technical feasibility and financial sustainability, forging a project preparation plan with the Host States (France, Switzerland).

Key for success: Community building

- **Started to explore several avenues in the past year**
  - Creation of an Informal Forum of National Contacts

    See presentation from G. Bernardi

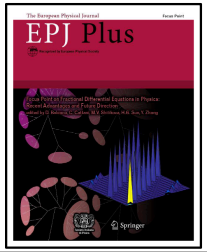
    - Informal entry point for new members and communication with the PED pillar effort
      - ➔ Participation to PED study does not necessarily imply signing a MoU (unlike CB representation)
  - Creation of an informal PED Programme Advisory Committee
    - Give suggestions, e.g., on speakers at FCC workshops or group conveners in the PED pillar
  - Creation of an official "FCC Global Collaboration" (FGC) group

    See presentation from E. Tsesmelis

    - Towards a top-down connection with the worldwide particle physics institutes
  - Reshuffling and expanding the FCC PED organizational chart

    See *this* presentation

    - Towards a broad, international, active participation in the various leadership positions
      - ➔ With the high-priority task of attracting and training new people in the various groups
  - Publication of a large number of essays on challenges and opportunities towards discovery
    - Has encouraged many (new) authors to embrace the project
    - Serves as a reference document for the exciting work that needs to be done
    - Will ease the integration of newcomers



Key for success: Community building

- **Started to explore several avenues in the past year (cont'd)**
  - Initiated a common effort across all e^+e^- projects for the physics software framework
    - Aim 1: share experience on analysis / simulation / event reconstruction more easily
    - Aim 2: gather physicists (and work) from other e^+e^- communities

See presentation from G. Ganis

  - Kicked-off the ECFA series of PED common workshops

https://indico.cern.ch/event/1033941/

    - Aim at gathering all e^+e^- physicists to work on common or synergistic topics
  - Enhanced interactions with ECFA detector R&D roadmap

See presentation from K. Jakobs

    - To increase awareness about specific (and challenging) FCC-ee detector requirements
  - Submitted a number of LoI's to the US Snowmass effort

https://indico.cern.ch/event/951830/

    - To increase awareness about FCC project (ee, then hh) in the US
      - ➔ On hold until the end of summer 2021

See presentation from T. Raubenheimer

  - Plan and organize annual FCC PED workshops
    - First workshop in Liverpool, 7-11 February 2022 (preferably in person)
      - ➔ Local organizing committee at work; Chairs of the programme committee nominated.
    - Second workshop in Krakow (Winter 2023); Third workshop in Annecy (Winter 2024)

Conclusion / Outlook

- **A lot of trailblazing work has been done during the Conceptual Design Study**
  - Developed, understood, and widely advertised the FCC (ee, then hh) physics case
    - By a few motivated and creative enthusiasts, on top of their LHC/T2K/ILC/ … commitments
      - ➔ A. Blondel, M. Mangano, W. Riegler must be praised for their visionary leadership in this enterprise
  - FCC-ee and FCC-hh offer complementary and synergistic physics programs
    - FCC-ee provides ideal conditions for the study of the four heaviest SM particles
      - ➔ With a flurry of opportunities for discoveries
    - FCC-ee is also the perfect springboard for a 100 TeV hadron collider
      - ➔ With which it shares a great part of the infrastructure
    - The integrated FCC offer a uniquely powerful long-term programme for CERN and Europe
  - This work led in 2020 to the visionary ESPP update endorsing the FCC feasibility study
    - As the top priority for CERN and its international partners

Conclusion / Outlook

- The work for particle physicists in the feasibility study is clearly cut out
  - Design the experimental setup and prepare the theoretical tools for FCC-ee
    - To be able, demonstrably, to fully exploit the FCC-ee capabilities
    - To prepare the ground towards detector operation and data analysis in 2040
  - Maintain and update the FCC-hh detector concept and physics case
    - According to the scientific landscape evolution, and the HL-LHC upgrade experience

- The FCC-ee challenges arise from the richness of the program
  - Match the experimental and theoretical accuracy to the statistical precision
  - Match the detector configuration with the variety of channels and discovery cases
  - Match the computing infrastructure to the incredible statistics expected at the Z pole
  - Match the common physics software to the needs of up to four experiments

Conclusion / Outlook

- There is a lot to do in five years!
  - The current "best-effort" delivery strategy might no longer suffice

- Community building is the necessary backbone of the whole enterprise, including
  - Worldwide participation in the efforts towards the Feasibility Study Report
  - Local support at CERN, with financial and human resources for FCC PED activities
  - Support from large funding agencies
  - Individual funding requests by young professors and researchers (e.g., ITN's)
  - Continuous recruiting and training of young physicists by the working group conveners

You'll be the leaders of the (4?) FCC collaborations in about two decades. The project needs you now.