FCC-ee Physics Potential (and PED organisation)

FCC

P. Janot

FCC France (Annecy)
30 Nov 2021

The alignment of stars towards FCC

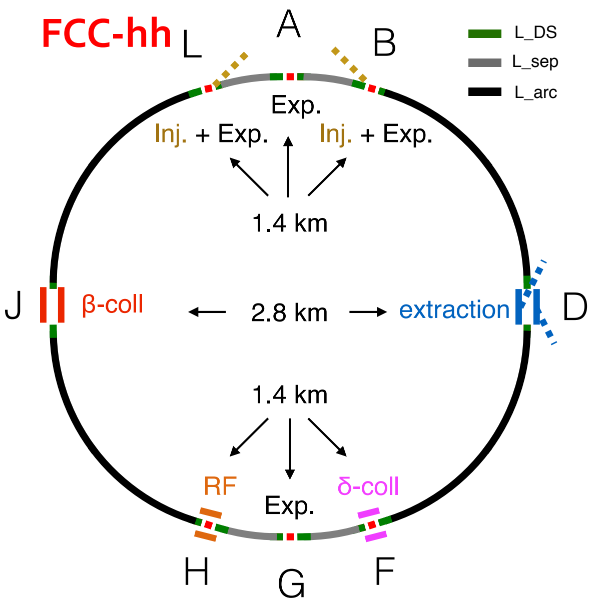
- Discovery of the Higgs boson (2011-12) at 125 GeV – just above LEP limit
  - Possibility to (re)build an e^+e^- collider in the LEP/LHC tunnel to produce and study H_{125} ?

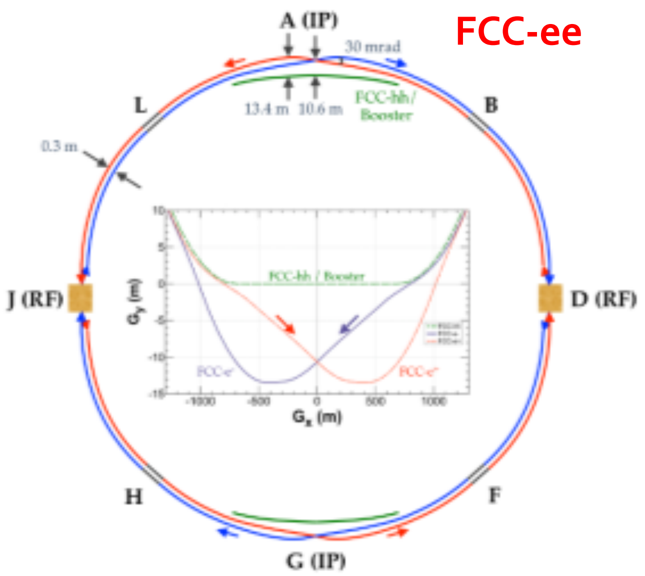
arXiv:1112.2518

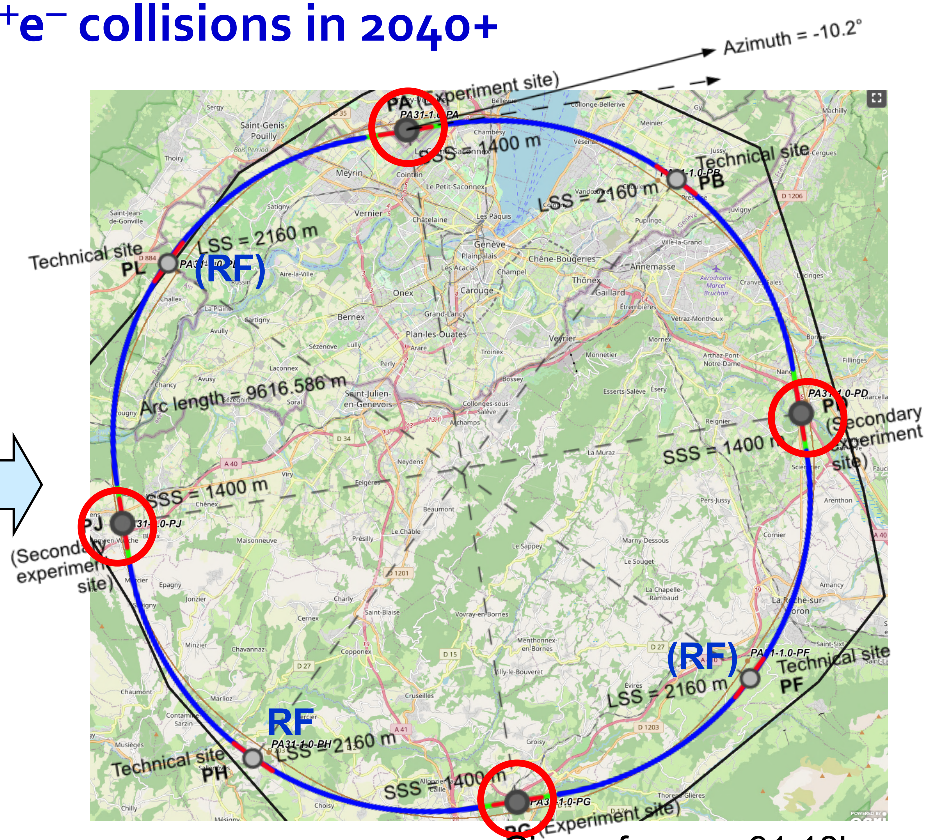
- Progress in circular collider technology (Super B, SuperKEKB)
  - Made it possible to exceed 10^{34} $cm^{-2}s^{-1}$ at the $e^+e^- \to ZH_{125}$ cross section max. (~240 GeV)
- Discussions about a new ring of 80-100 km circumference (ESPPU'12)
  - To increase the hadron collider energy to 100 TeV with 16-20 T magnets
    - Geographically optimal for the Geneva basin
- Happy coincidence !
  - 80-100 km is also required to reach the top-pair threshold in e^+e^- collisions (~350 GeV)
    - Enabling precise top-quark measurements essential to the EW precision physics programme
      - ➔ Just the right energy range to study all heavy particles of the Standard Model (Z, W, Higgs, top)
      - ➔ Fantastic springboard to a 100 TeV pp collider, with great physics complementarity and synergies

Feasibility study launched in July 2021

- **More details in FCC Week 2021: https://indico.cern.ch/event/995850/**
  - **Intermediate review mid 2023 – FSR end 2025 – First e^+e^- collisions in 2040+**
- **Work has started on placement in Geneva area**





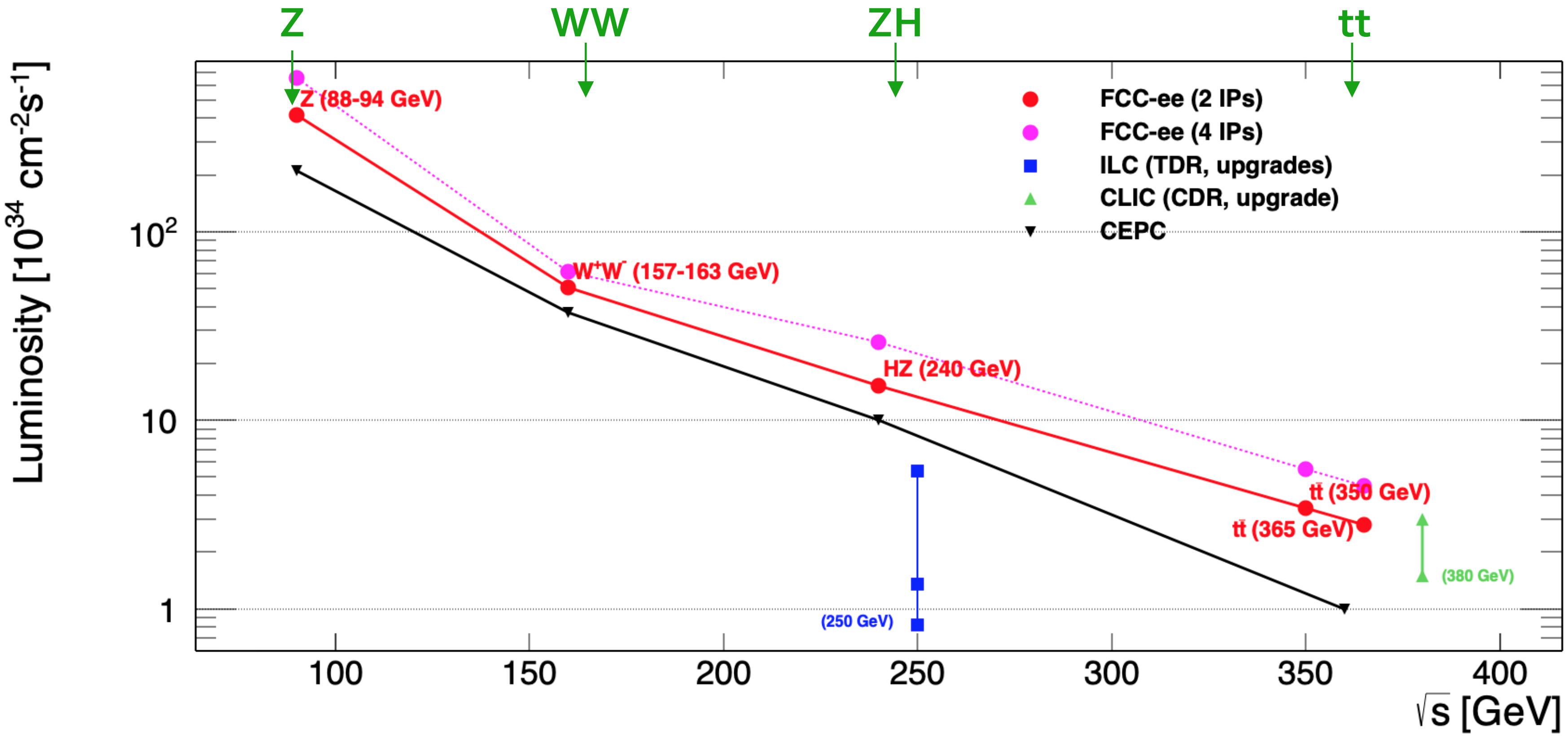


Circumference 91.18km
LAPP 5 km south from PG

- **Number of surface points reduced to 8, with fourfold super-periodicity**
  - **This new layout is consistent with later choice of 2 or 4 Interaction Points (IP) for FCC-ee**

Physics at FCC-ee - New opportunities for discovery

- Great energy range for SM heavy particles <u>AND</u> highest luminosities <u>AND</u> √s precision

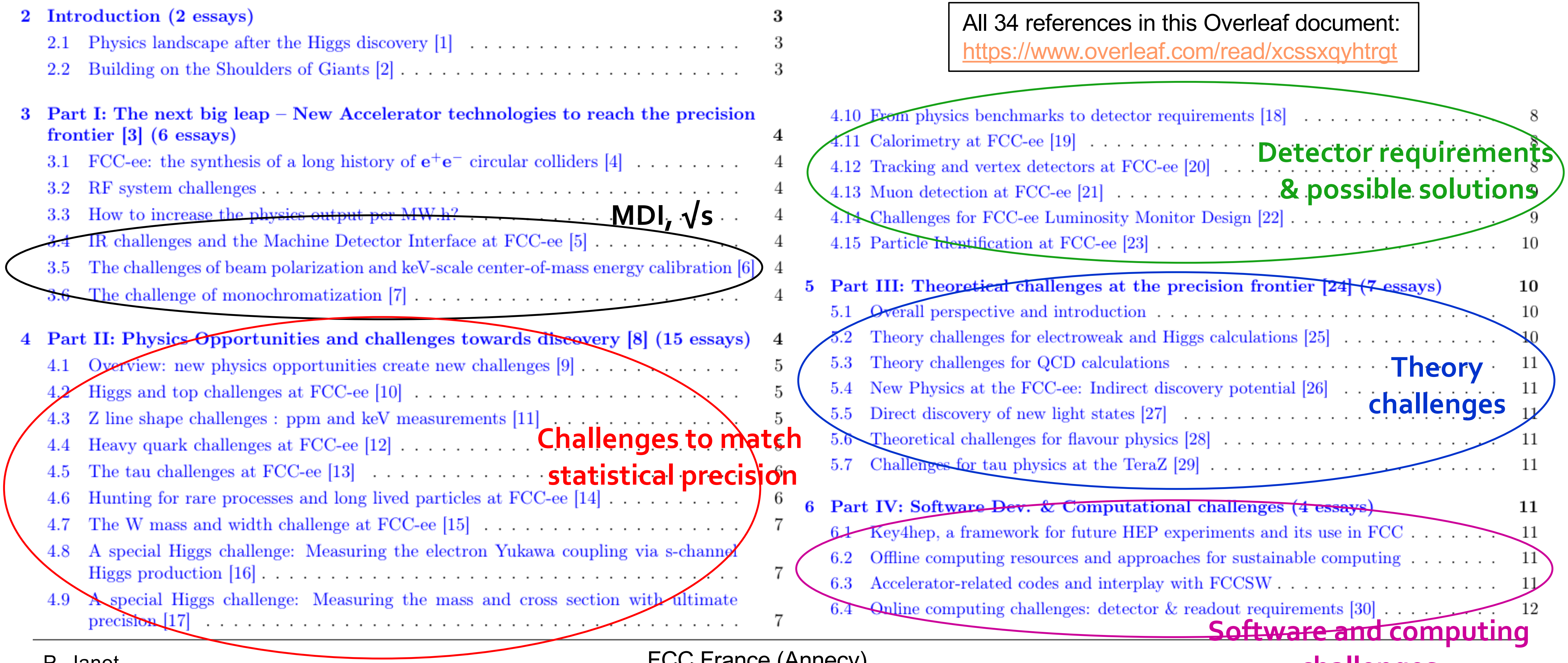


						√s errors
ZH maximum	√s ~ 240 GeV	3 years	10^6	$e^+e^- \to ZH$	Never done	2 MeV
$t\bar{t}$ threshold	√s ~ 350 GeV	5 years	10^6	$e^+e^- \to t\bar{t}$	Never done	5 MeV
Z peak	√s ~ 91 GeV	4 years	5×10^{12}	$e^+e^- \to Z$	LEP x 10^5	< 100 keV
WW threshold+	√s ≥ 161 GeV	2 years	> 10^8	$e^+e^- \to W^+W^-$	LEP x 10^3	< 300 keV
s-channel H	√s = 125 GeV	? Years	~5000	$e^+e^- \to H$	Never done	< 200 keV

New opportunities create new challenges

- **EPJ+ special issue "A future Higgs and EW Factory: Challenges towards discovery"**

All 34 references in this Overleaf document:
https://www.overleaf.com/read/xcssxqyhtrgt



MDI, √s

Challenges to match statistical precision

Detector requirements & possible solutions

Theory challenges

Software and computing challenges

FCC-ee as a Higgs factory: Original motivation

- Past linear-collider studies have set the scene with great details
  - FCC-ee delivers twice more Higgs bosons five times quicker (10^6 H in 3 years @ 240 GeV w/ 2IP)
    - Can produce many more Higgs boson per MW (or CHF) spent arXiv:1906.02693
    - Alternatively, allows much more physics to be done with the same amount of MW
      - ➔ Greener collider !
  - Detector performance requirements not drastically different, but may need adapting to
    - More gentle beam conditions, but CW operations (no electronics power-pulsing)
    - Smaller beam-pipe radius (10 mm), smaller maximum operating energy
    - Need of an accurate Higgs-boson mass value prior to s-channel run
      - ➔ 2-3 MeV possible with drift chamber, down to 2 MeV with B = 3T

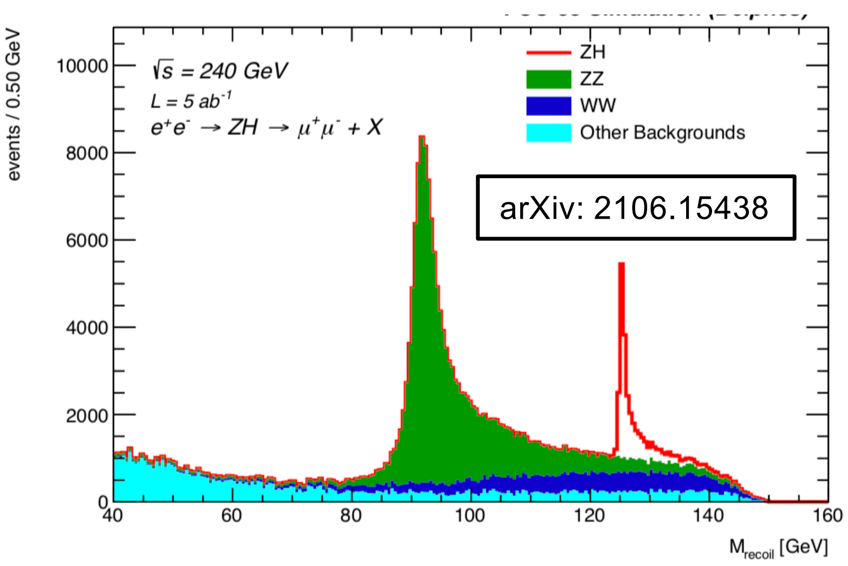
        Clear difference between drift chamber and Si Tracker
    - Need of a more accurate cross-section measurement
      - ➔ To enable a precise measurement of the Higgs self-coupling

        25% precision on κ_λ envisioned with 4 IP
  - Relevance of a dedicated run at $\sqrt{s}$ = 217 GeV (ZH threshold) ?

FCC-ee as a Higgs factory: Case studies

Higgs mass and inclusive cross section measurement

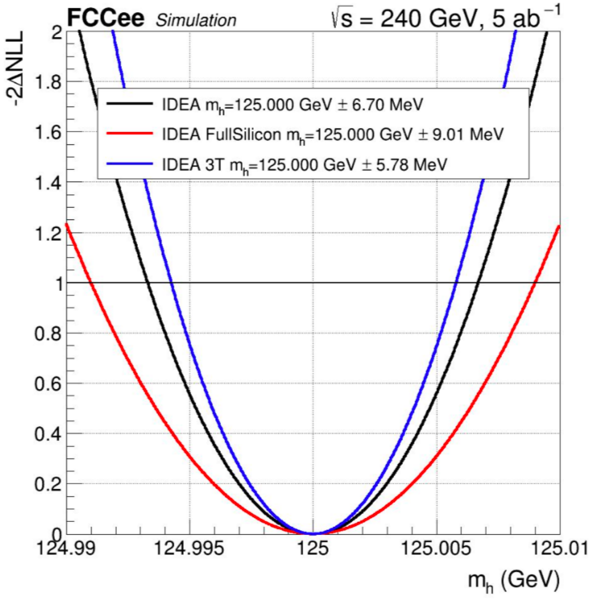
Recoil mass fit in $e^+e^- \rightarrow ZH$ with $Z \rightarrow \mu^+\mu^-$



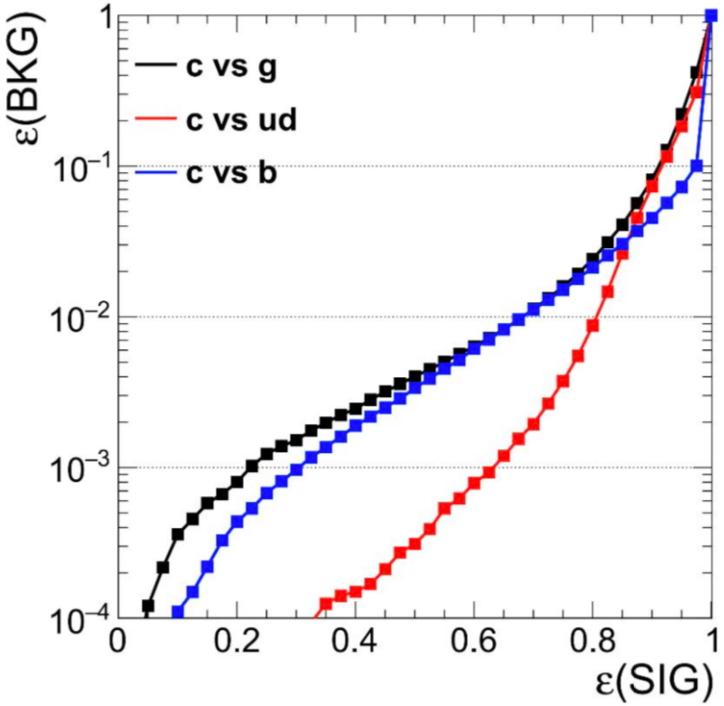
arXiv: 2106.15438

Gentle beamstrahlung
→ limited mass tail

Light tracker much better
Mag. Field of 3T helps a bit



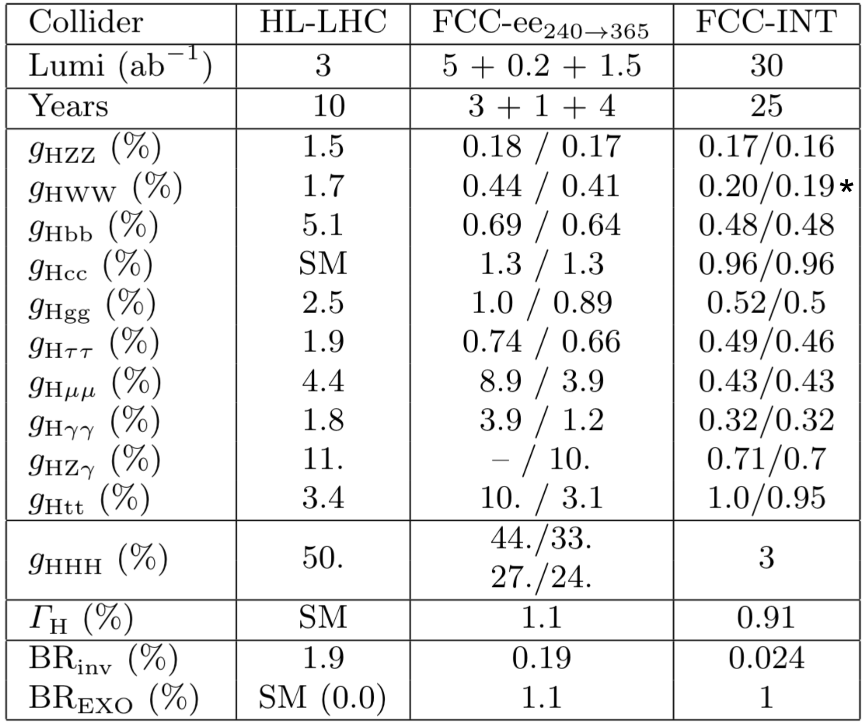
Flavour tagging



- Advanced flavour-tagging algorithm based on a Dynamic Graph Convolutional Neural Network.
- Very promising c-tagging
- Innovative developments on s-tagging too

FCC-ee as a Higgs factory and beyond

- Higgs provides a very good reason why we need both e^+e^- AND pp colliders
  - FCC-ee measures g_{HZZ} to 0.2% (absolute, model-independent, standard candle) from σ_{ZH}
    - Γ_H, g_{Hbb}, g_{Hcc}, $g_{H\tau\tau}$, g_{HWW} follow
    - Standard candle fixes all HL-LHC / FCC-hh couplings
  - FCC-hh produces over 10^{10} Higgs bosons
    - (1st standard candle →) $g_{H\mu\mu}$, $g_{H\gamma\gamma}$, $g_{HZ\gamma}$, Br_{inv}
  - FCC-ee measures top EW couplings ($e^+e^- \rightarrow t\bar{t}$)
    - Another standard candle
  - FCC-hh produces 10^8 ttH and 2. 10^7 HH pairs
    - (2nd standard candle →) g_{Htt} and g_{HHH}



Collider	HL-LHC	FCC-ee$_{240\rightarrow365}$	FCC-INT	
Lumi (ab^{-1})	3	5 + 0.2 + 1.5	30	
Years	10	3 + 1 + 4	25	
g_{HZZ} (%)	1.5	0.18 / 0.17	0.17/0.16	ee
g_{HWW} (%)	1.7	0.44 / 0.41	0.20/0.19*	
g_{Hbb} (%)	5.1	0.69 / 0.64	0.48/0.48	
g_{Hcc} (%)	SM	1.3 / 1.3	0.96/0.96	
g_{Hgg} (%)	2.5	1.0 / 0.89	0.52/0.5	
$g_{H\tau\tau}$ (%)	1.9	0.74 / 0.66	0.49/0.46	
$g_{H\mu\mu}$ (%)	4.4	8.9 / 3.9	0.43/0.43	pp
$g_{H\gamma\gamma}$ (%)	1.8	3.9 / 1.2	0.32/0.32	
$g_{HZ\gamma}$ (%)	11.	– / 10.	0.71/0.7	
g_{Htt} (%)	3.4	10. / 3.1	1.0/0.95	
g_{HHH} (%)	50.	44./33. 27./24.	3	
Γ_H (%)	SM	1.1	0.91	ee
BR$_{inv}$ (%)	1.9	0.19	0.024	pp
BR$_{EXO}$ (%)	SM (0.0)	1.1	1	ee

* g_{HWW} includes also ep

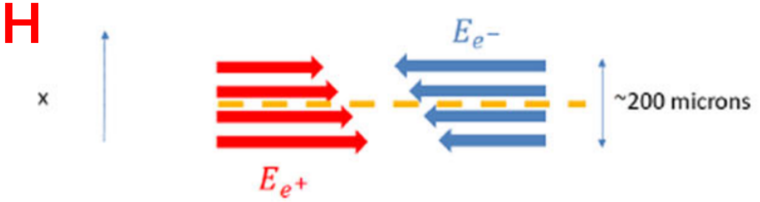
- FCC-ee / FCC-hh complementarity is outstanding
  - Unreachable by high-energy lepton colliders
- FCC-ee is also the most pragmatic, safest, and most effective way toward FCC-hh
  - In particular, FCC-ee can start physics seamlessly after the end of HL-LHC

Refs for the table: arXiv:1905.03764, arXiv:2004.03505

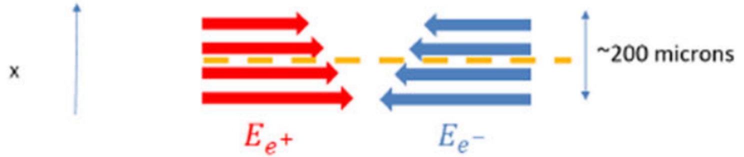
Centre-of-mass energy (mono)chromatisation

- ❑ Something unique: electron Yukawa coupling from $e^+e^- \rightarrow H$
  - ◆ One of the toughest challenges, which requires
    - (Mono)chromatisation: Γ_H (4.2 MeV) ≪ beam energy spread (100 MeV)
    - Higgs boson mass prior knowledge to a couple MeV
    - Huge luminosity (i.e., several years with possibly 4 IPs)
    - Continuous monitoring and adjustment of $\sqrt{s}$
    - Different e^+ and e^- energies (to avoid integer spin tune)
    - Extremely sensitive event selection against SM backgrounds
      - ➔ For all Higgs decay channels

A. Blondel's talk



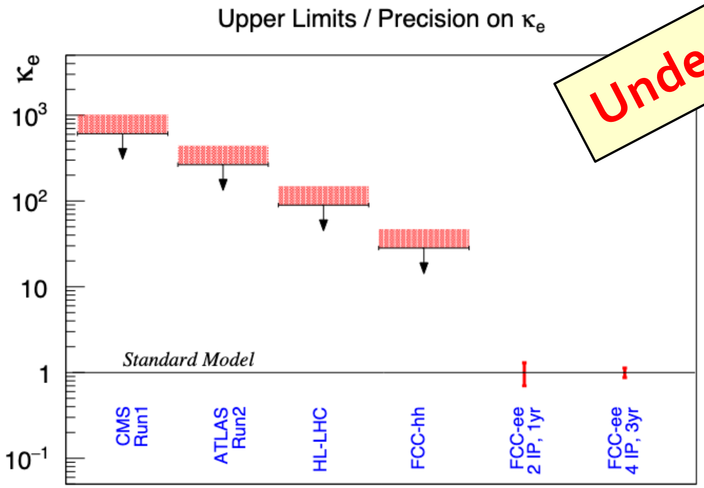
A. Monochromatization

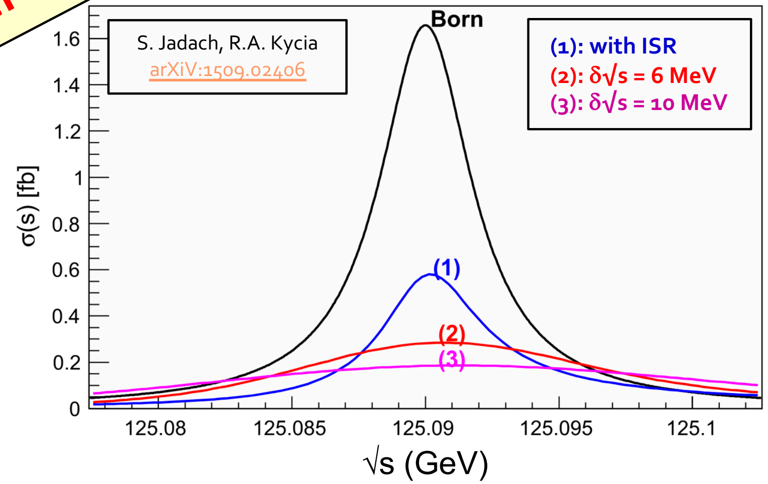


B. Chromatization

arXiv:2107.02686

Under Study





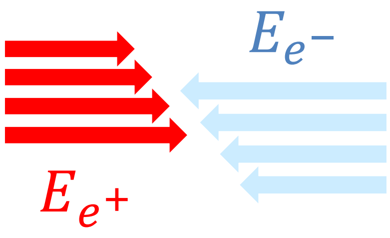
First studies indicate an uncertainty at the SM level

Indicates whether the Higgs boson (also) gives mass to ordinary matter.

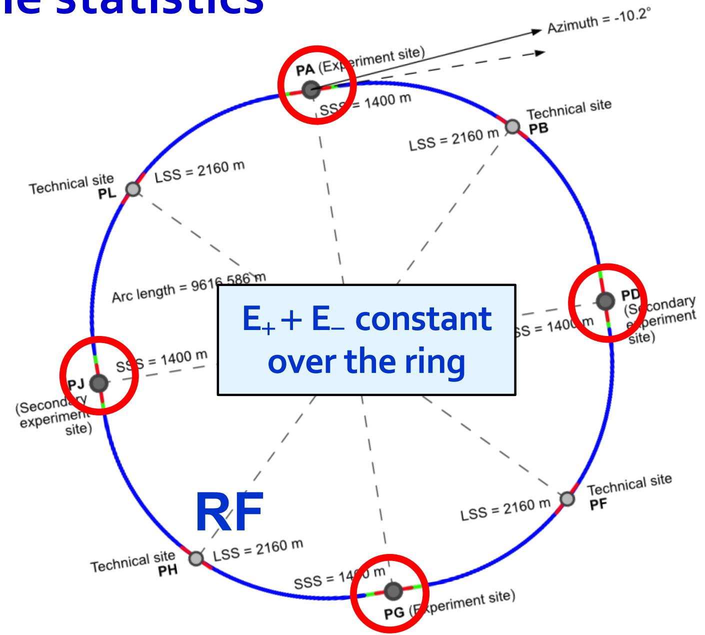
Centre-of-mass energy ppm calibration

- A cornerstone of the FCC-ee physics programme at the Z pole and the WW threshold
  - Motivation: measurement of m_Z, Γ_Z (stat. 4 keV), A_{FB} (stat. ~ 10^{-5}) and m_W (stat. 300 keV)
  - Opportunities:
    - ppm $\langle E_{beam} \rangle$ measurement with resonant depolarisation: 100 keV (LEP, Z) or 6 keV (VEPP4, J/ψ)
      - ➔ Unique to circular colliders – use a small fraction of non-colliding e^+ and e^- bunches
    - Per-mil beam energy spread measurement (for Γ_Z, A_{FB}) from huge dimuon statistics at the Z pole
  - A few serious challenges to be solved to match achievable statistics
    - Get beams polarized enough (→ wigglers)
    - Ground motion (tides)
    - IP dispersion and IP offsets
    - Relate $\langle E_{beam} \rangle$ to $\sqrt{s_{IP}}$
      - ➔ Single RF system essential
    - Ring imperfections
    - Point-to-point errors (for Γ_Z, A_{FB})
    - How well can we check that $P_{IP} = 0$?
    - How do we operate it all ?

A. Blondel's talk



arXiv:1909.12245



$E_+ + E_-$ constant over the ring

FCC-ee as an Electroweak Factory

- With highest luminosities at 91, 160 and 350 GeV
  - Complete set of EW observables can be measured
    - Precision (10^{-3} today) down to few 10^{-6}

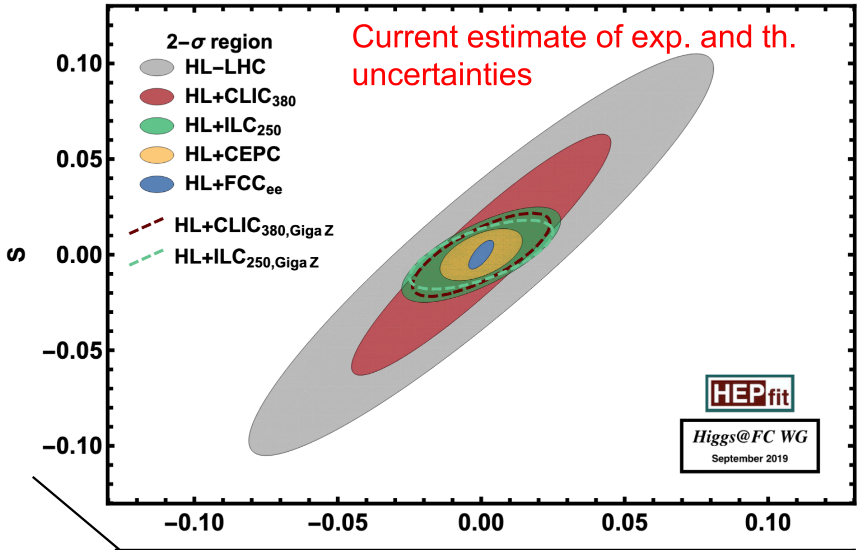
e.g., m_Z (100 keV), Γ_Z (25 keV), $\alpha_{QED}(m_Z)$ (3.10^{-5}), $\sin^2\theta_W$ ($3.\ 10^{-6}$), m_W (<500 keV), m_{top} (20 MeV)

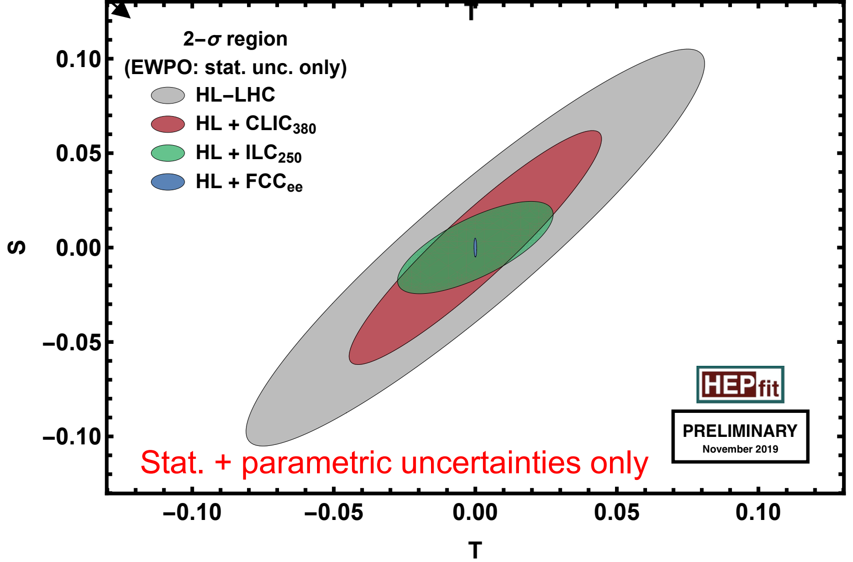
Benefiting from √s calibration with resonant depolarisation at 91 and 160 GeV

- Precision unique to FCC-ee, with smallest parametric errors
  - Challenge: match syst. uncertainties to the stat. precision
    - A lot more potential to exploit with good detector design than the present treatment suggests
    - Theory work is critical and initiated

S ↘ ↙ T

- Precision = discovery potential (e.g., NP in Z/W propagators)
  - Generic discovery potential: Show that SM does not suffice
  - Challenge: test specific models with ALL information
    - Clarify the need for precision from a theoretical perspective
    - Explain how FCC-ee go towards answering big questions in fundamental physics

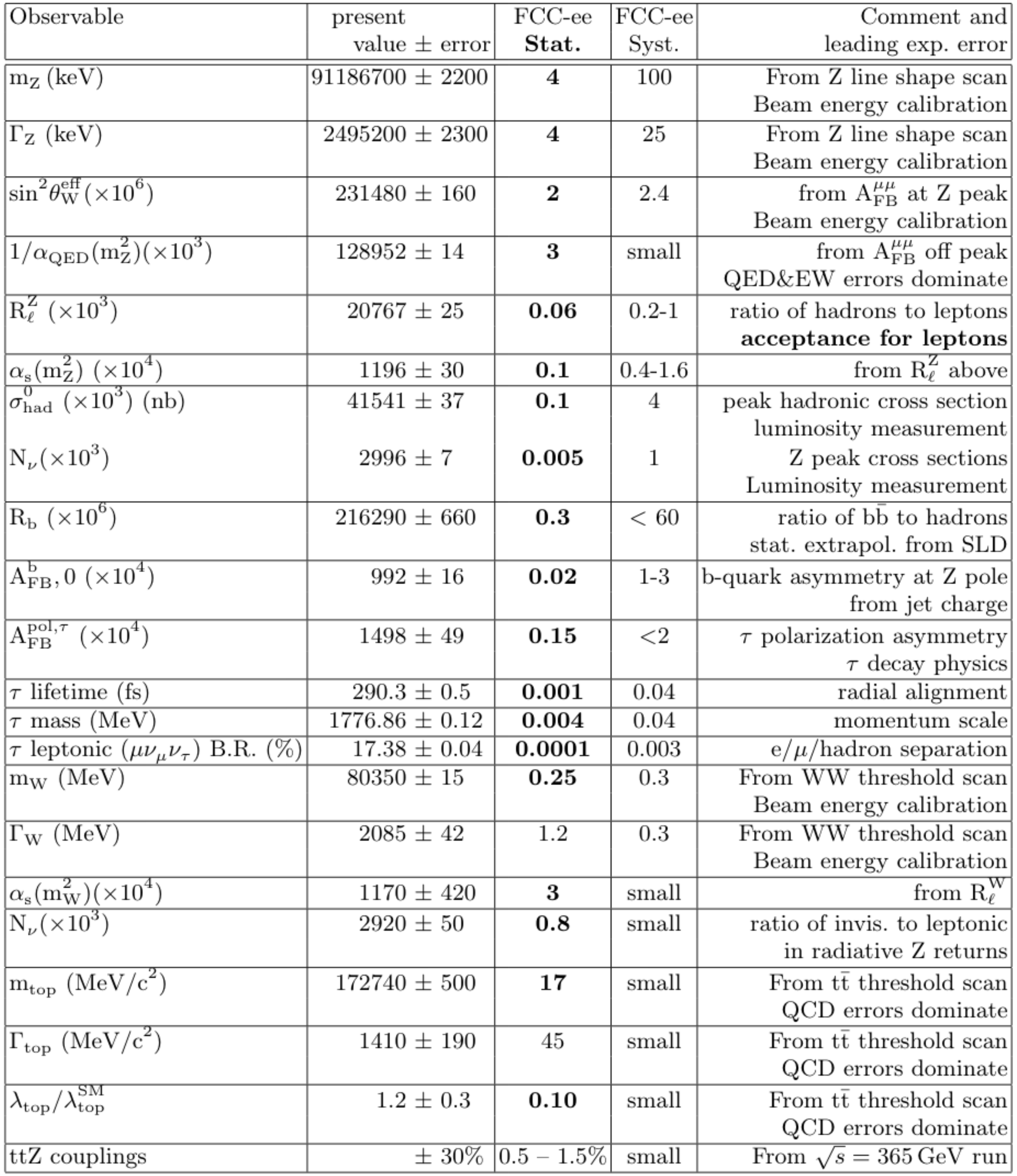




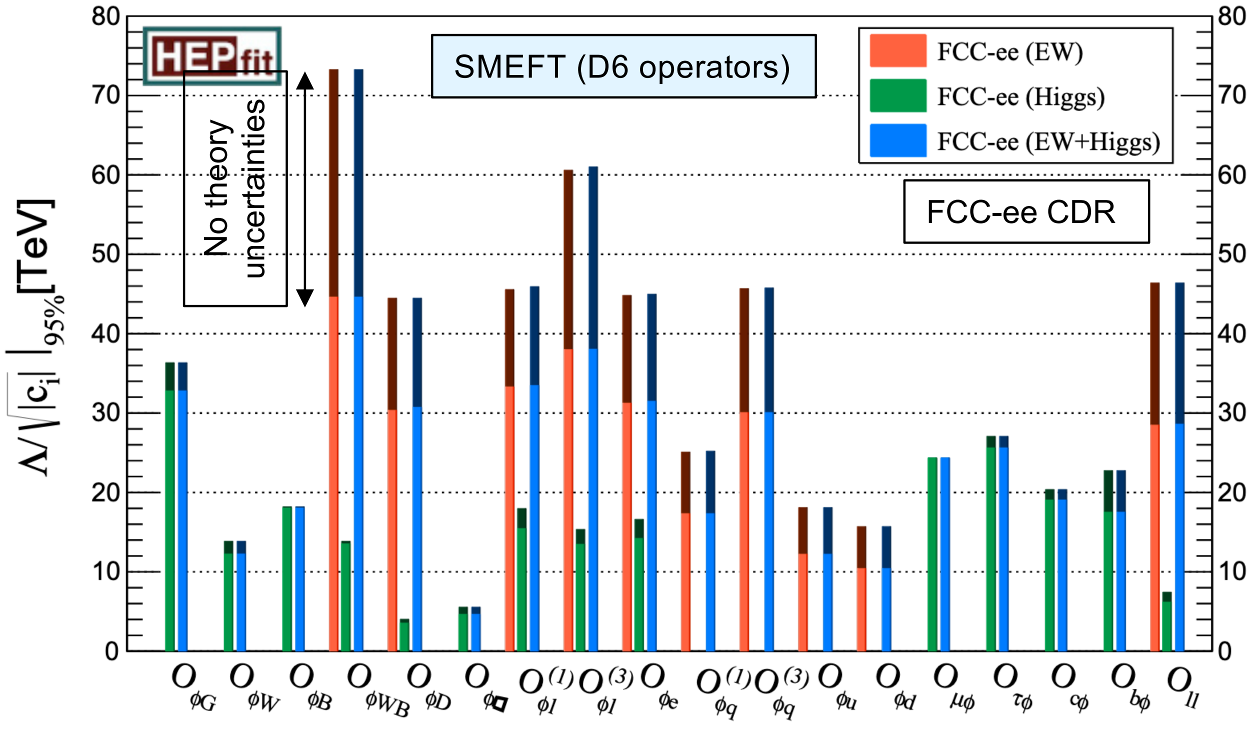
FCC-ee as an Electroweak Factory

- Physics requirements probably set mostly by the TeraZ run (5. 10^{12} Z)
  - High luminosity, large event rate (100 kHz), simulated data
    - Considerable challenges for data taking, storage and processing
  - Z lineshape determination based on cross-section measurements as a function of $\sqrt{s}$
    - Extremely accurate mechanical construction of the luminometers
    - Precise knowledge of the central detector (tracker & calorimeters) acceptance
    - Point-to-point $\sqrt{s}$ uncertainties sets stringent constraint on μ momentum resolution stability
  - Theoretical predictions should match (statistical) experimental uncertainties
    - Identification of (ratio of) pseudo-observables for which uncertainties can be reduced
    - Calculation of these pseudo-observables in the SM with the precision required
    - Calculation of QED (EW, QCD) corrections to convert measurements into pseudo-observables
    - Delivery of appropriately accurate event generators
    - Investigation of the sensitivity to new physics in a number of specific scenarios

Must be tackled at an early stage as it may affects detector concepts and run plan



Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
σ_{had}^0 $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu(\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	45	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	0.5 – 1.5%	small	From $\sqrt{s} = 365$ GeV run



- **Multiple new-physics sensitivity**
  - **Higgs and EWPO are complementary**
  - **Top quark mass and couplings are essential**
  - **Theory work is critical and has discovery potential**
  - **More observables to be studied/added (flavours, etc.)**
  - **Pattern may point to the source of new physics**
- **Reach for new physics depends on the new physics**
  - **1/Λ² new physics (SMEFT) → 30 – 70 TeV**
  - **Heavy neutrino mixing → 500 – 1000 TeV**
  - **Specific models → to be studied case by case**

FCC-ee at the intensity frontier

- **TeraZ offers four additional pillars to the FCC-ee physics programme**

Flavour physics programme

- Enormous statistics 10^{12} bb, cc
- Clean environment, favourable kinematics (boost)
- Small beam pipe radius (vertexing)

1. Flavour EWPOs (R_b, $A_{FB}^{b,c}$) : large improvements wrt LEP
2. CKM matrix, CP violation in neutral B mesons
3. Flavour anomalies in, e.g., $b \rightarrow s\tau\tau$

QCD programme

- Enormous statistics with $Z \rightarrow \ell\ell$, qq(g)
- Complemented by 100,000 $H \rightarrow gg$

1. $\alpha_S(m_Z)$ with per-mil accuracy
2. Quark and gluon fragmentation studies
3. Clean non-perturbative QCD studies

Often statistics-limited
$5 \cdot 10^{12}$ Z is a minimum

Tau physics programme

- Enormous statistics: $1.7\ 10^{11}$ $\tau\tau$ events
- Clean environment, boost, vertexing
- Much improved measurement of mass, lifetime, BR's

1. τ-based EWPOs (R_τ, A_{FB}^{pol}, P_τ)
2. Lepton universality violation tests
3. PMNS matrix unitarity
4. Light-heavy neutrino mixing

Rare/BSM processes, e.g. Feebly Coupled Particles

Intensity frontier offers the opportunity to directly observe new feebly interacting particles below m_Z

- Signature: long lifetimes (LLP's)
- Other ultra-rare Z (and W) decays

1. Axion-like particles
2. Dark photons
3. Heavy Neutral Leptons

FCC-ee at the intensity frontier

- … which in turn provide specific detector requirements

Flavour physics programme

- Formidable vertexing ability; b, c, s tagging
- Superb electromagnetic energy resolution
- Hadron identification covering the momentum range expected at the Z resonance

QCD + EW programme

- Particle-Flow reconstruction
- Lepton and jet angular and energy resolution ; Lepton ID

More case studies will lead to more detector requirements

Tau physics programme

- Momentum resolution
  - Mass measurement, LFV search
- Precise knowledge of vertex detector dimensions
  - Lifetime measurement
- Tracker and ECAL granularity and $e/\mu/\pi$ separation
  - BR measurements, EWPOs, spectral functions

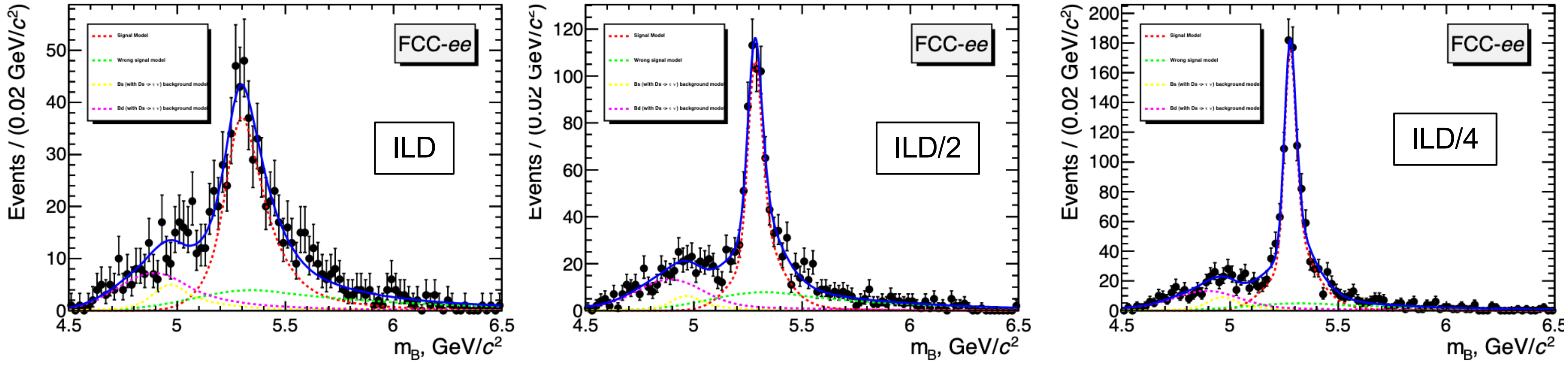
Rare/BSM processes, e.g. Feebly Coupled Particles

- Sensitivity to far-detached vertices (mm → m)
  1. Tracking: more layers, continuous tracking
  2. Calorimetry: granularity, tracking capability
- Larger decay lengths ⇒ extended detector volume
- Full acceptance ⇒ Detector hermeticity

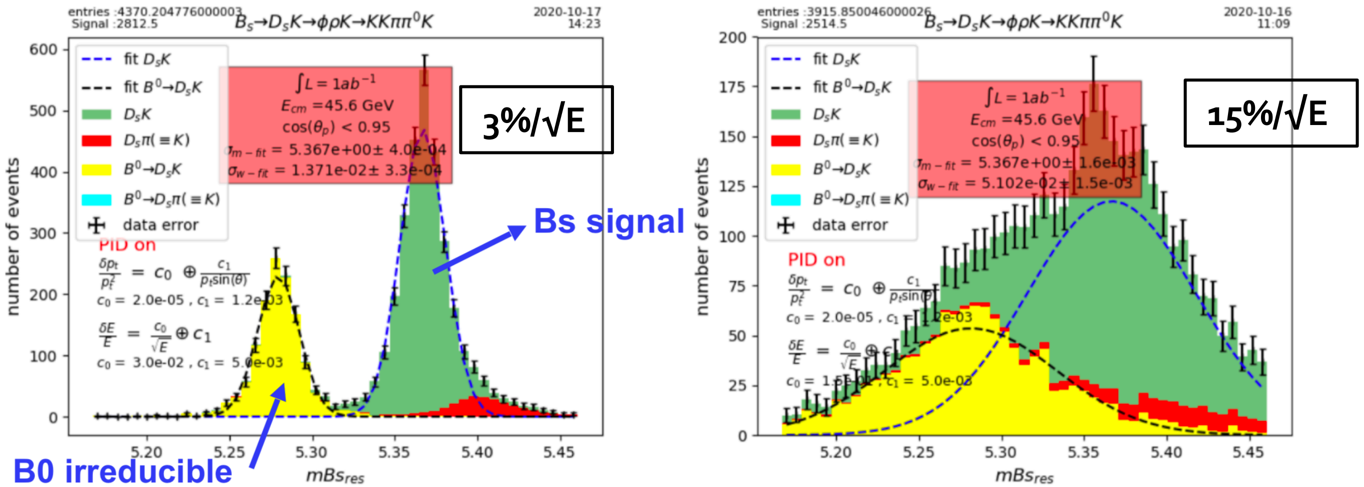
If all these constraints are met, Higgs and top programme probably OK (tbc)

FCC-ee at the intensity frontier: Case studies

- **$B^0 \to K^{*0}\tau^+\tau^-$: Vertexing**



- **$B_s \to D_s K$, modes with neutrals : ECAL energy resolution**



3%/√E

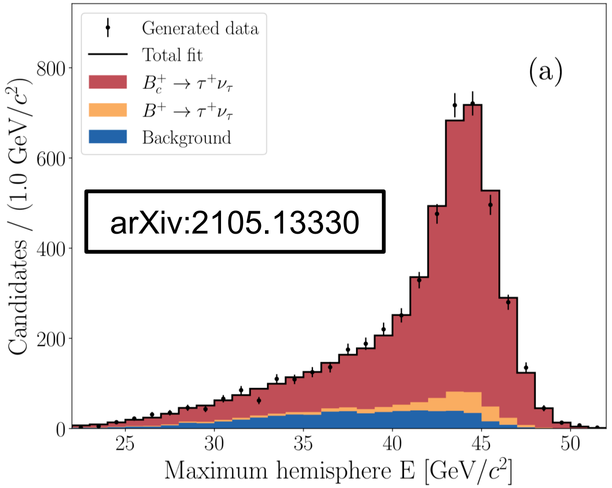
15%/√E

Bs signal

B0 irreducible bckgd

State-of-the-art Xtal-type to HGCal-type : $\sigma(D_s^\pm(\phi\rho^\pm)K^\mp) \approx 14MeV \to 51MeV$

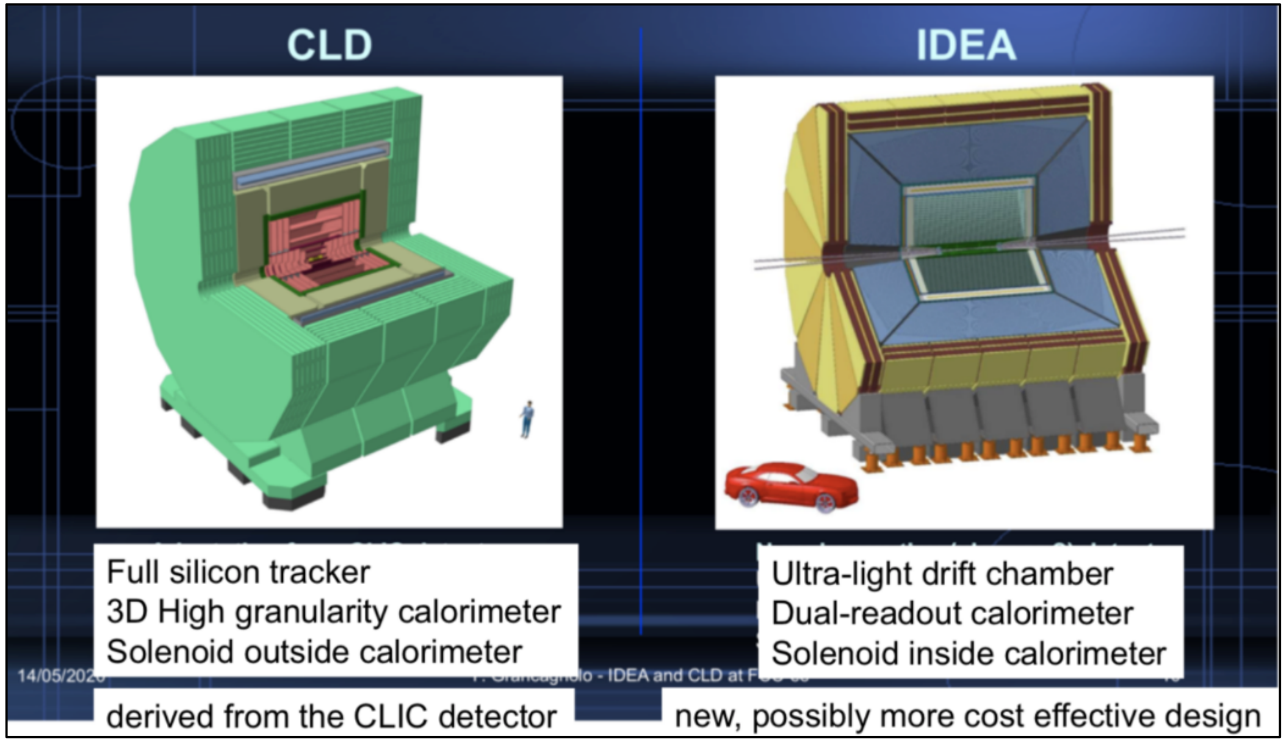
- **$B_c \to \tau\nu$: Prospects**



arXiv:2105.13330

FCC-ee detectors: an attractive challenge

- FCC-ee can serve up to four interaction points: allows for a range of detector solutions
  - Specific detector challenges arise from the richness of the FCC-ee programme
    - Match the experimental systematic uncertainties to the statistical precision
    - Match the detector configuration(s) with the variety of channels and discovery cases
  - Requires a systematic program of case studies of physics benchmark processes



Full silicon tracker
3D High granularity calorimeter
Solenoid outside calorimeter

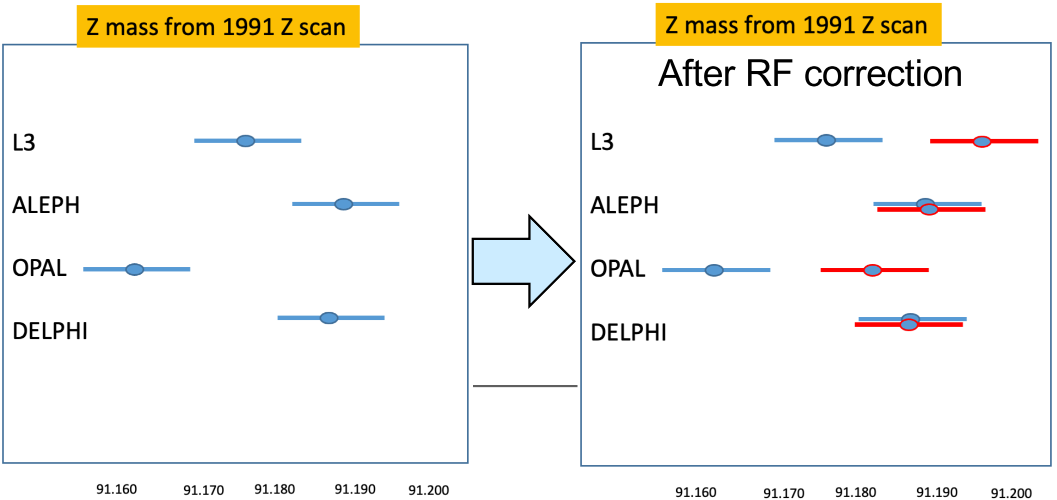
derived from the CLIC detector

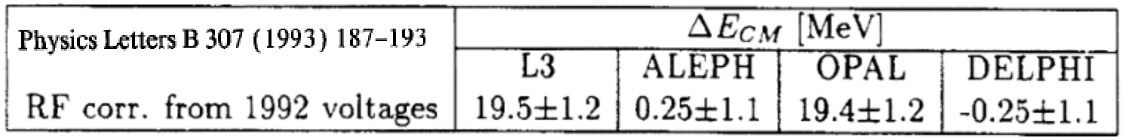
Ultra-light drift chamber
Dual-readout calorimeter
Solenoid inside calorimeter

new, possibly more cost effective design

The case for four interaction points

- One of the many advantages of circular colliders: can serve several IP
  - Overall gain in luminosity and in luminosity/MW (greener collider)
    - Many measurements are statistics limited – some are tantalizingly close with only 2 IP
      - ➔ E.g., Higgs self-coupling ; Search for HNL; Flavour anomalies; etc.
  - Variety of detector requirements may not be satisfied by one or even two detectors
    - E.g., High precision, high granularity, high stability, geometric accuracy, PID, cost constraints
      - ➔ Having four IP allows for a range of detector solutions to cover all FCC-ee opportunities
  - Four IP provide an attractive challenge for all skills in the field of particle physics
  - Redundancy is invaluable in uncovering hidden systematic biases or conspiracy of errors
    - E.g., m_Z discrepancy at LEP in 1991
      - ➔ Found to be an effect of RF phases and voltages
    - Could have remained unnoticed for ever
      - ➔ With only ALEPH and DELPHI
      - ➔ Or with only L3 and OPAL





Physics Letters B 307 (1993) 187–193	ΔE_{CM} [MeV]			
	L3	ALEPH	OPAL	DELPHI
RF corr. from 1992 voltages	19.5 ± 1.2	0.25 ± 1.1	19.4 ± 1.2	-0.25 ± 1.1

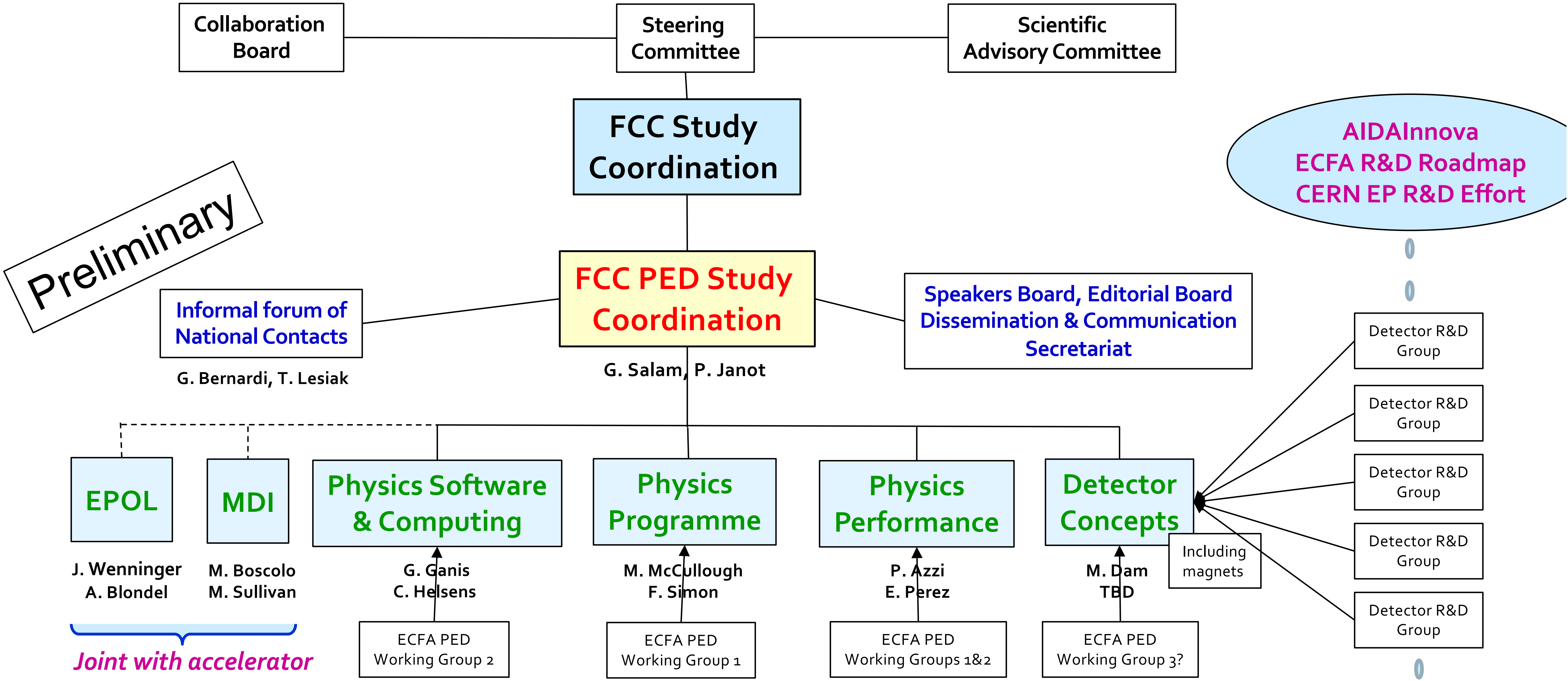
The PED feasibility study work is clearly cut out

- Design the experimental setup and prepare the theoretical tools
  - To be able, demonstrably, to fully exploit (and communicate) the FCC-ee capabilities
  - To prepare the ground towards detector operation and data analysis in 2040+

- A proactive preparation is necessary from all sides
  - Consolidate the physics case for both colliders of FCC
  - Develop the necessary theoretical calculations
  - Tune the accelerator design and running mode to optimize the physics case
  - Develop a common software infrastructure
  - Provide coherent sets of detector requirements and physics analysis tools & methods
  - Benchmark several detector concepts for FCC-ee (up to four) to match these requirements
  - Evaluate computing requirements

- Last but not least
  - Build an international community of particle physicists around the project

PED pillar organisation to tackle these challenges



Preliminary

Collaboration Board

Steering Committee

Scientific Advisory Committee

FCC Study Coordination

AIDAInnova
ECFA R&D Roadmap
CERN EP R&D Effort

Informal forum of National Contacts
G. Bernardi, T. Lesiak

FCC PED Study Coordination
G. Salam, P. Janot

Speakers Board, Editorial Board
Dissemination & Communication
Secretariat

EPOL	MDI	Physics Software & Computing	Physics Programme	Physics Performance	Detector Concepts
J. Wenninger A. Blondel	M. Boscolo M. Sullivan	G. Ganis C. Helsens	M. McCullough F. Simon	P. Azzi E. Perez	M. Dam TBD
		ECFA PED Working Group 2	ECFA PED Working Group 1	ECFA PED Working Groups 1&2	ECFA PED Working Group 3?

Joint with accelerator

Including magnets

Detector R&D Group

Detector R&D Group

Detector R&D Group

Detector R&D Group

Detector R&D Group

FCC PED in France: Possible contributions

- Contributions from France are most welcome everywhere
  - Physics Programme
    - Higgs, EW, QCD, Top, Flavours, BSM, …
  - Physics Performance
    - From physics benchmark measurements to detector requirements
      - ➔ Development of analysis and tools
  - Detector Concepts
    - From detector R&D to meet detector requirements
  - Software
    - Framework now common with linear colliders
  - Polarisation and monochromatisation
    - Centre-of-mass energy precise calibration and Electron Yukawa coupling measurement
  - Machine-Detector Interface
    - How to fit and optimize a detector in a busy interaction region

Now is a good time to join the FCC feasibility study

- **PED Kick-off workshop in Liverpool, 7-11 Feb 2022**

5th FCC PHYSICS WORKSHOP

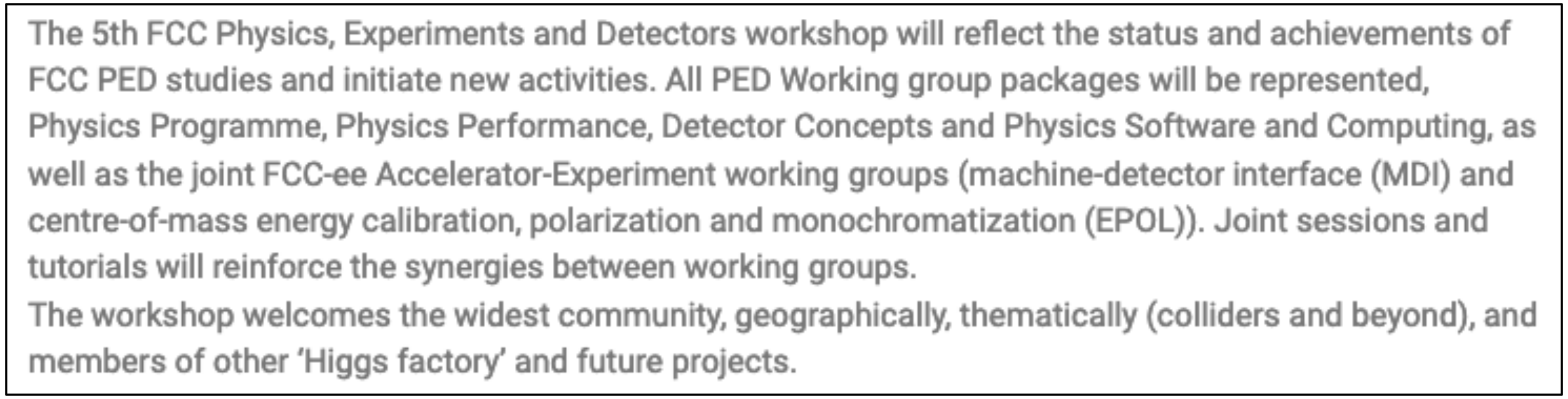
LIVERPOOL
07 – 11 February 2022

In-person meeting for the first limited number of registering attendees

www.cern.ch/FCCPhysics2022

FUTURE CIRCULAR COLLIDER

FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.



The 5th FCC Physics, Experiments and Detectors workshop will reflect the status and achievements of FCC PED studies and initiate new activities. All PED Working group packages will be represented, Physics Programme, Physics Performance, Detector Concepts and Physics Software and Computing, as well as the joint FCC-ee Accelerator-Experiment working groups (machine-detector interface (MDI) and centre-of-mass energy calibration, polarization and monochromatization (EPOL)). Joint sessions and tutorials will reinforce the synergies between working groups.

The workshop welcomes the widest community, geographically, thematically (colliders and beyond), and members of other 'Higgs factory' and future projects.

Registration: https://cern.ch/FCCPhysics2022