The FCC-ee Project: Plans and Physics Potential

IPA 2022, Vienna

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Valentin Volkl, for the FCC collaboration
CERN

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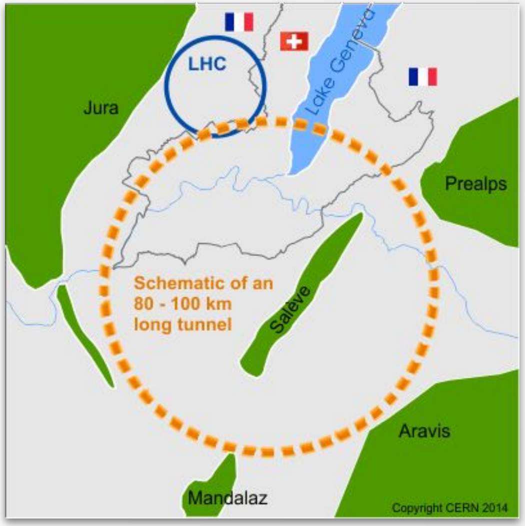
The Future Circular Collider Design Study

The FCC Design Study explores the potential and feasibility of a large (~100 km) collider ring in the Geneva area as successor to the LHC.

- A hadron collider (FCC-hh) could reach $\sqrt{s}$ = 100 TeV with 16 T magnets.
- A lepton collider (FCC-ee) could reach record luminosities up to $\sqrt{s}$ = 365 GeV
- A hadron-electron collider (FCC-eh) is possible as well

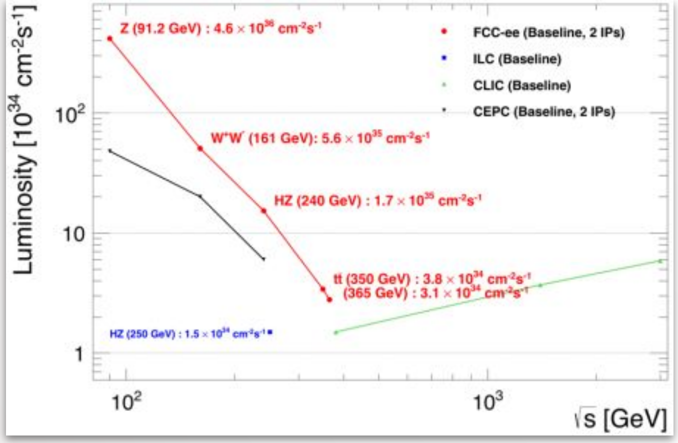
These options are highly complementary and an **integrated FCC program** is the optimal solution!

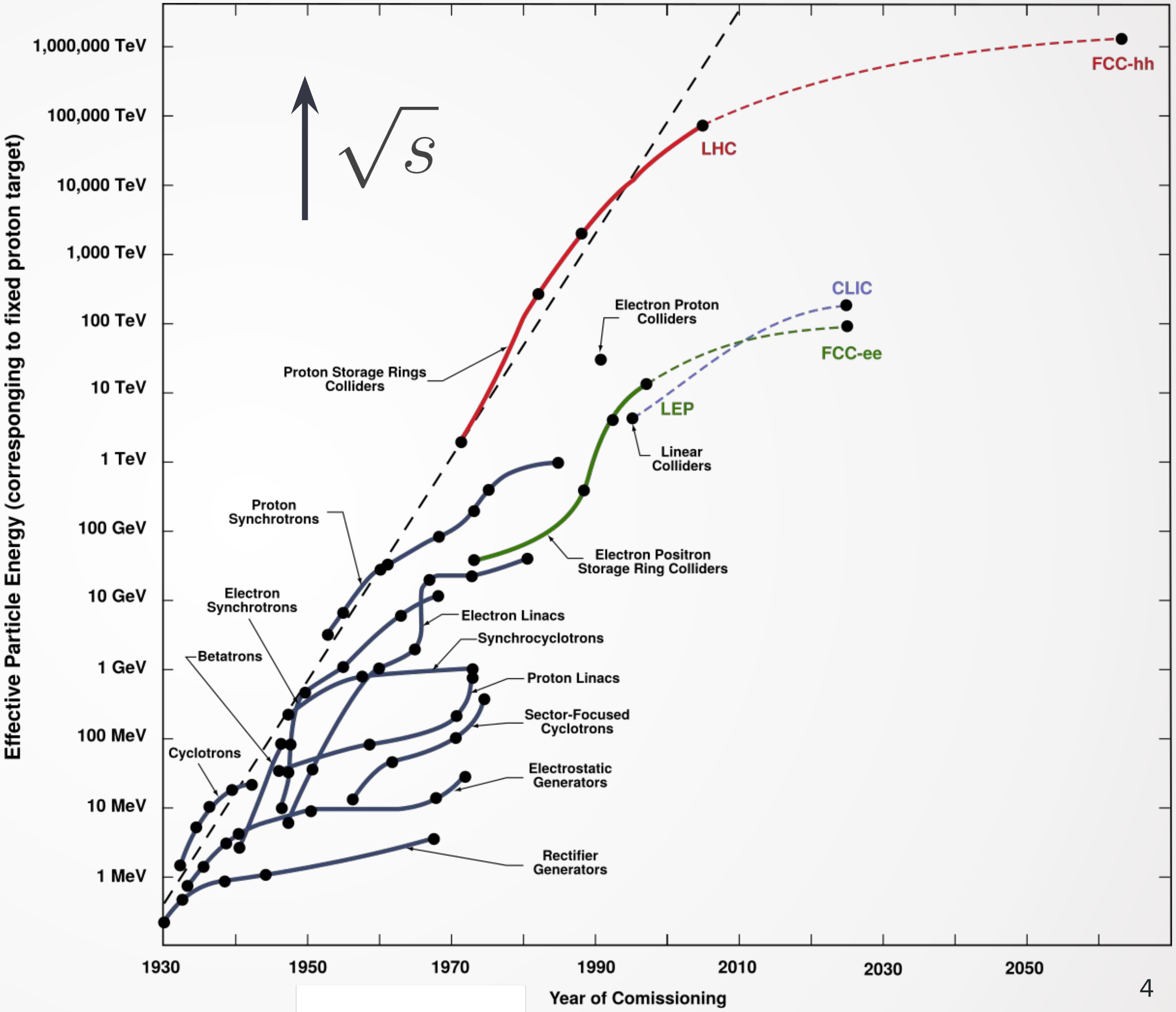



LHC
PS
SPS
FCC
photo: J. Wenninger

Energy and intensity frontier

- The historical exponential growth of collider energies is already tapering off
- The FCC-ee is not at the energy-, but at the intensity frontier, sensitive to higher energies via precision measurements!

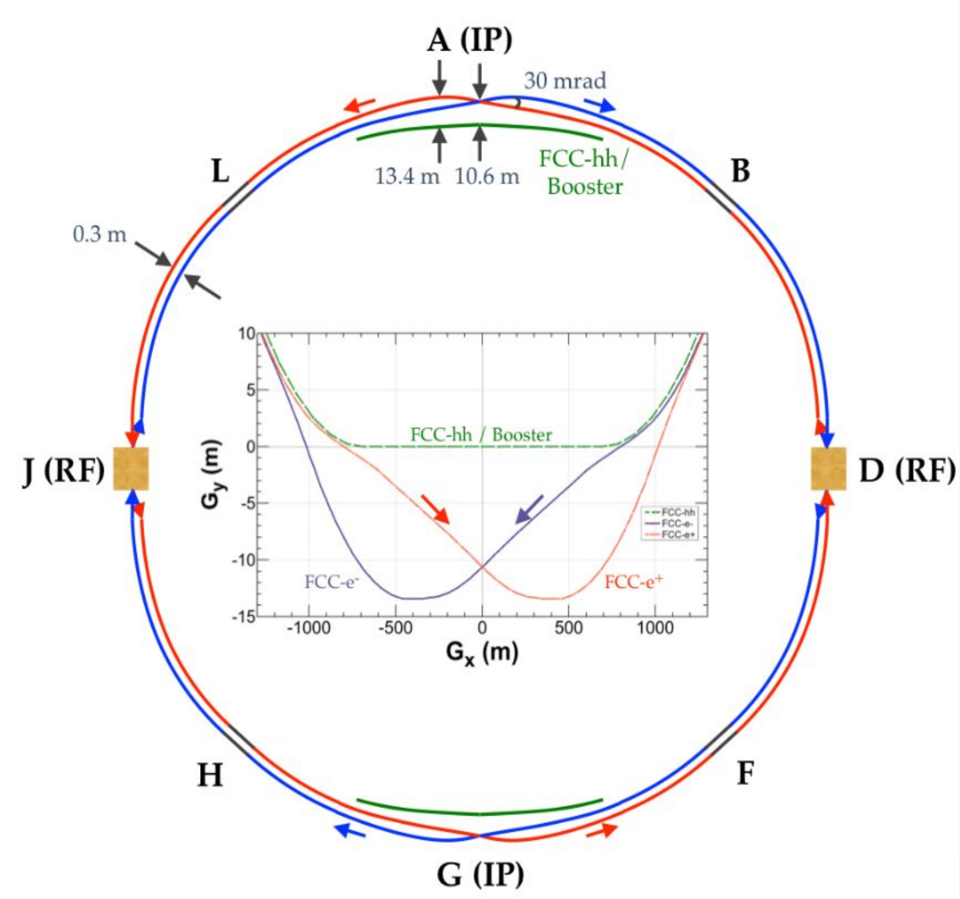




FCC-ee basic design choices

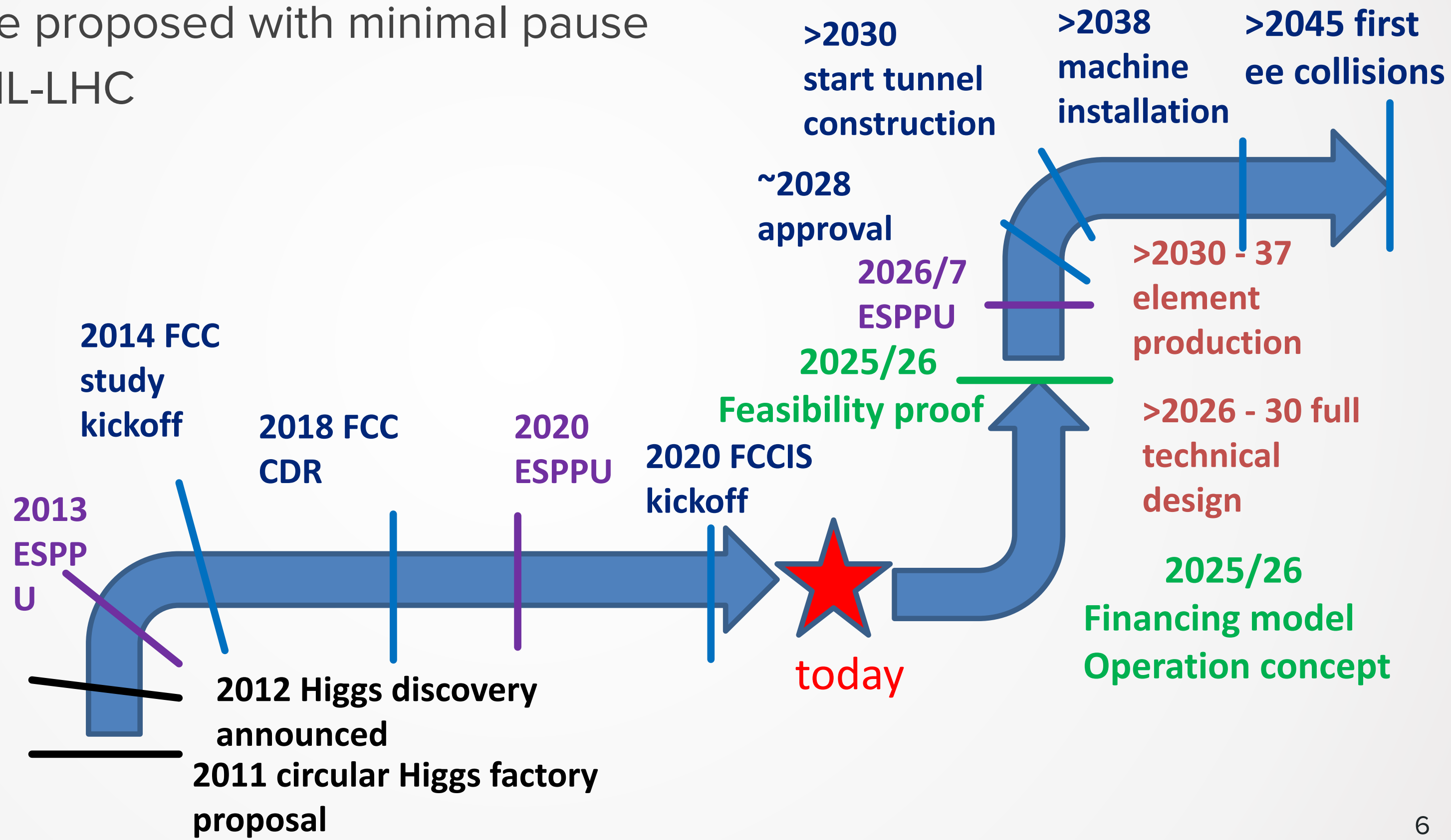
- Double ring e+e- collider + injector
  - ~100 km
- follows footprint of FCC-hh
  - except around IPs
- Asymmetric IR layout & optics to limit synchrotron radiation towards the detector - also separates detector from injector
- Presently 2 IPs (alternative layout with 4 IPs under study), large horizontal x-ing angle 30mrad
- crab-waist optics
- synchrotron radiation power 50 MW/beam at all beam energies; tapering of arc magnet strengths to match local energy
- common RF for running

top-up injection requires
booster synchrotron in collider tunnel
Beam Polarization and energy calibration, wigglers, polarimeters, depolarization kicker for Z and WW operation.



Timeline

Feasible schedule proposed with minimal pause of physics after HL-LHC



The FCC-ee Physics Landscape

Mogens Dam

"Higgs Factory" Program

- At two energies, 240 and 365 GeV, collect in total
  - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production: $e^+e^- \to H,\ \sqrt{s} = 125\,\mathrm{GeV}$

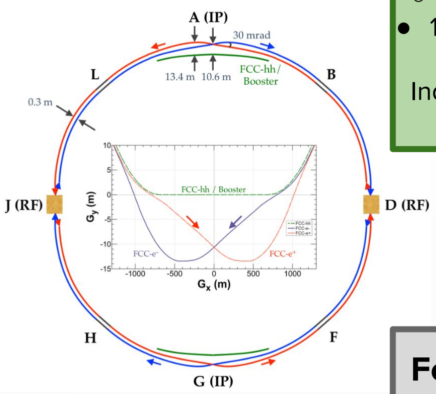
Ultra Precise EW Program

Measurement of EW parameters with factor ~300

Improvement in *statistical* precision wrt. current WA

- 5x10^12 Z and 10^8 WW
  - $m_Z,\ \Gamma_Z,\ \Gamma_{\mathrm{inv}},\ \sin^2\theta_W^{\mathrm{eff}},\ R_\ell^Z,\ \alpha_s,\ m_W,\ \Gamma_W, \ldots$
- 10^6 tt
  $m_{\mathrm{top}},\ \Gamma_{\mathrm{top}},\ \mathrm{EW\ couplings}$

Indirect sensitivity to new phys. up to Λ=70 TeV scale



Heavy Flavour Program

- Enormous statistics: 10^12 bb, cc; 1.7x10^11 ττ
- Extremely clean environment, favourable kinematic conditions (boost) from Z decays
- CKM matrix, CP measurements, "flavour anomaly" studies, e.g. b →sττ, rare decays, cLFV searches, lepton universality, PNMS matrix unitarity

Feebly Coupled Particles - LLPs

Intensity frontier: Opportunity to directly observe new feebly interacting particles with masses below m_Z :

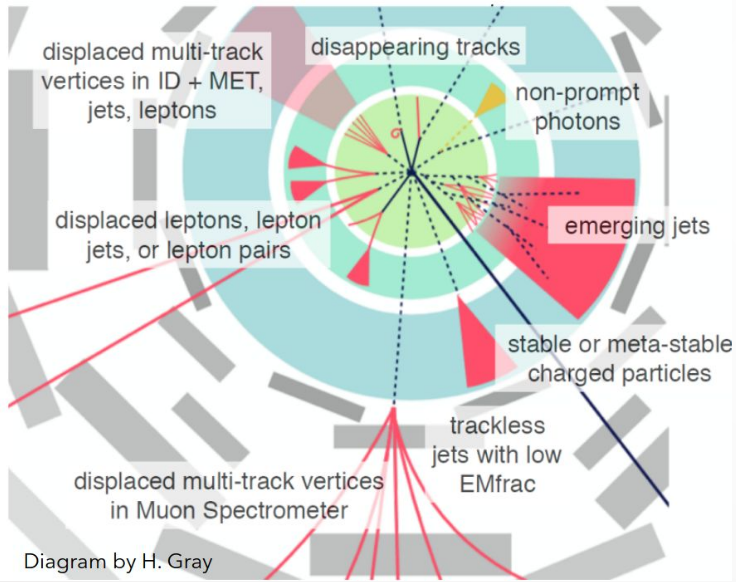
- Axion-like particles, dark photons, Heavy Neutral Leptons
- Signatures: long lifetimes - LLPs

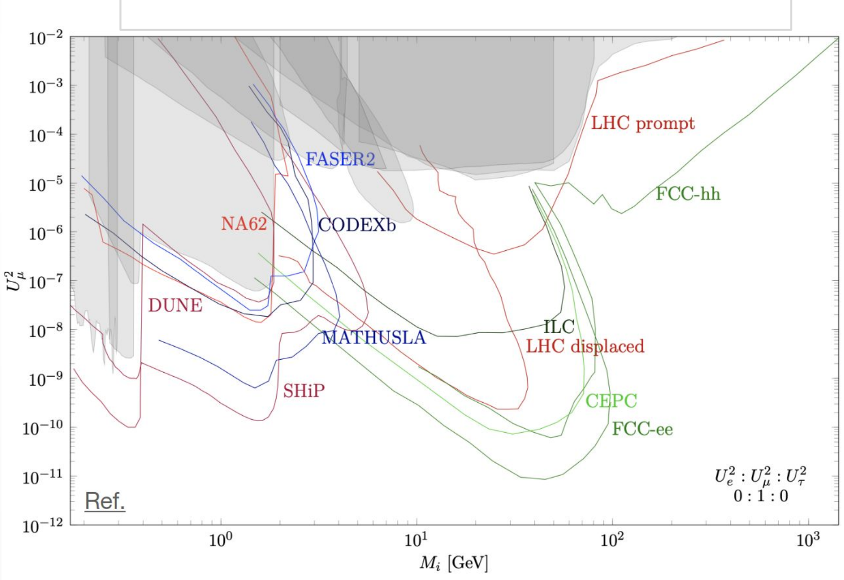
Long Lived Particles

Suchita Kulkarni,
Rebecca Gonzalez Suarez

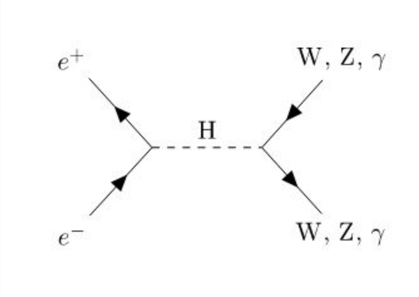
Interesting in many BSM and dark matter contexts, but challenging reconstruction

bounds on the mixing between Heavy Neutral Leptons and the active neutrinos



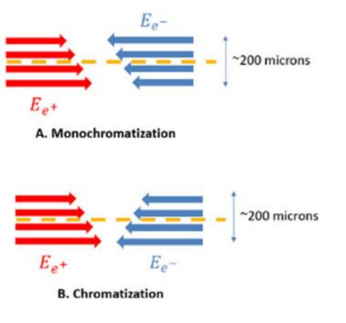


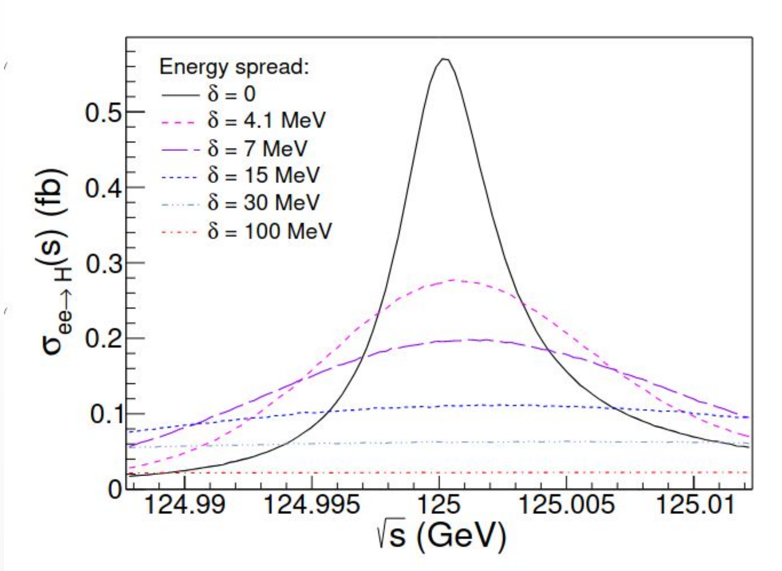
Electron Yukawa coupling



Unique possibility at FCC-ee, but formidable experimental challenge, 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 √s
- Different e^+ and e^- energies (to avoid integer spin tune)
- Extremely sensitive event selection against SM backgrounds
  - For all Higgs decay channels





Complimentarity

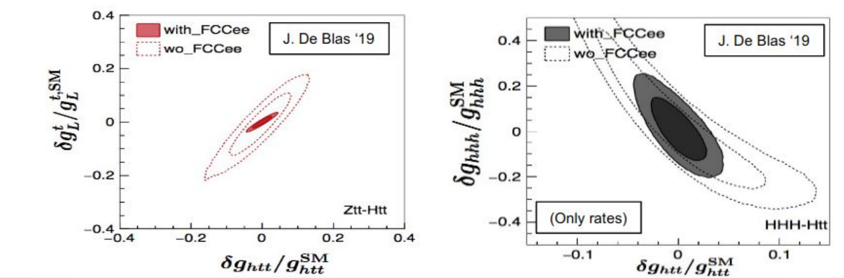
Patrik Janot

Higgs measurements will profit from both e+e- and pp collider

- FCC-ee measures g_{HZZ} to 0.2% (absolute, model-independent, standard candle) from σ_{ZH}
  - Fixes all other couplings (HL-LHC/FCC-hh/FCC-ee)
- FCC-hh produces over 10^{10} Higgs bosons
  - (1^{st} standard candle) $g_{H\mu\mu}$, $g_{H\gamma\gamma}$, $g_{HZ\gamma}$, Br_{inv}
- FCC-ee measures ttZ couplings ($e^+e^- \to$ tt)
  - Another standard candle
- FCC-hh produces 10^8 ttH and 2×10^7 HH pairs
  - (2^{nd} standard candle) g_{Htt} and g_{HHH}

Collider	HL-LHC	FCC-ee$_{240\to365}$	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	
g_{HWW} (%)	1.7	0.44 / 0.41	0.20/0.19*	
g_{Hbb} (%)	5.1	0.69 / 0.64	0.48/0.48	ee
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	
$g_{H\gamma\gamma}$ (%)	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	pp
g_{HHH} (%)	50.	44./33. 27./24.	3-5	
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



Summary of physics potential

FCC-ee note, 1906.02693

√s → / Physics ↓	e+e− collisions							pp collisions		
	m_Z	$2m_W$	HZ max. 240-250 GeV	$2m_{top}$ 340-380 GeV	500 GeV	1.5 TeV	3 TeV	28 TeV 37 TeV 48 TeV	100 TeV	Leading Physics Questions
Precision EW (Z, W, top)	Transverse polarization	Transverse polarization		m_W, α_S						Existence of more SM-Interacting particles
QCD (α_S) QED (α_{QED})	5×10^{12} Z	3×10^{8} W	10^5 H→gg							Fundamental constants and tests of QED/QCD
Model-independent Higgs couplings	ee → H $\sqrt{s} = m_H$		1.2×10^6 HZ and 75k WW→H at two energies						<1% precision (*)	Test Higgs nature
Higgs rare decays									<1% precision (*)	Portal to new physics
Higgs invisible decays									10^{-4} BR sensitivity	Portal to dark matter
Higgs self-coupling			3 to 5σ from loop corrections to Higgs cross sections						5% (HH prod) (*)	Key to EWSB
Flavours (b, τ)	5×10^{12} Z									Portal to new physics Test of symmetries
RH ν's, Feebly interacting particles	5×10^{12} Z								10^{11} W	Direct NP discovery At low couplings
Direct search at high scales					M_χ<250GeV Small ΔM	M_χ<750GeV Small ΔM	M_χ<1.5TeV Small ΔM		Up to 40 TeV	Direct NP discovery At high mass
Precision EW at high energy							Y		*W, Z*	Indirect Sensitivity to Nearby new physics
Quark-gluon plasma Physics w/ injectors										QCD at origins

Green = Unique to FCC; Blue = Best with FCC; (*) = if FCC-hh is combined with FCC-ee; Pink = Best with other colliders

EPJ+ special issue “A future Higgs and EW Factory: Challenges towards discovery”

MDI, √s

Challenges to match statistical precision;
Detector requirements and possible solutions

Theory Challenges

Software and computing challenges

Recap: The FCC-ee Physics Landscape

Mogens Dam 🔗

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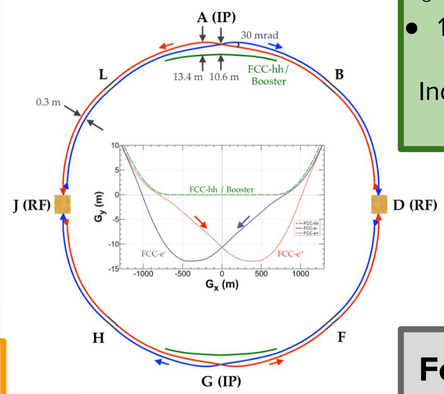

Ultra Precise EW Program

Measurement of EW parameters with factor ~300
Improvement in *statistical* precision wrt. current WA

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Feebly Coupled Particles - LLPs

Intensity frontier: Opportunity to directly observe new feebly interacting particles with masses below m_Z :

- Axion-like particles, dark photons, Heavy Neutral Leptons
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Detector Requirements

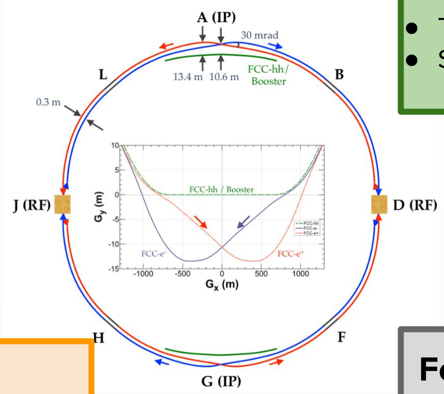
Mogens Dam

"Higgs Factory" Program

- Momentum resolution of $\sigma_{pT} / p_T^2 \cong 2 \times 10^{-5} GeV^{-1}$ commensurate with $O(10^{-3})$ beam energy spread
- Jet energy resolution of 30% / √E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Program

- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had} / \Gamma_{lep}$) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability fof B-field to 10^{-6} : stability of √s measts.



Heavy Flavour Program

- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measurements
- ECAL resolution at the few %/ √E level for inv. Mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and tau physics

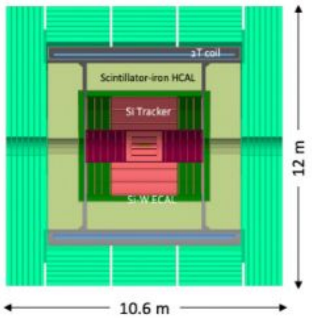
Feebly Coupled Particles - LLPs

Benchmark signature Z → νN with N decaying late

- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continuous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths → extended detector volume
- Hermeticity

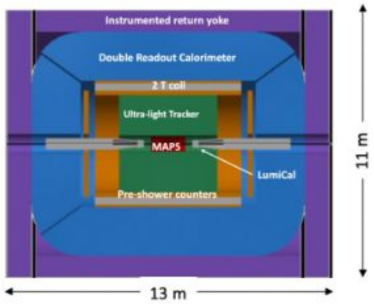
Overview over detector concepts

A. Sailer — CLD



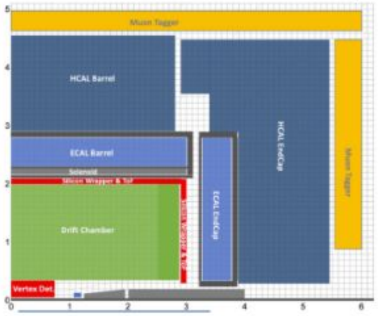
- Well established design
  - ILC -> CLIC detector -> CLD
- Engineering needed to make able to operate with continous beam (no pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations?
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?
  - …
- Robust software stack
  - Now ported (wrapped) to FCCSW

P. Giacomelli — IDEA



- Less established design
  - But still ~15y history: 4th Concept
- Developed by very active community
  - Prototype construction / test beam compains
  - Italy, Korea,…
- Is IDEA really two concepts? Or will it be?
  - w, w/o crystals : EM resolution
    long. segmentation
    Maybe even GRAiNITA ?
- Software under active development
  - Being ported to FCCSW

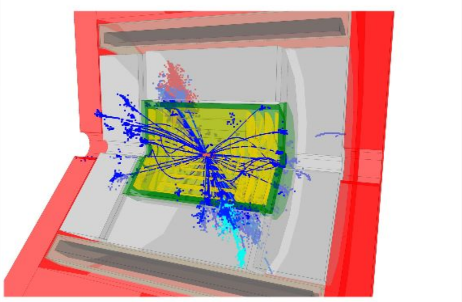
Noble Liquid ECAL based — M. Aleksa

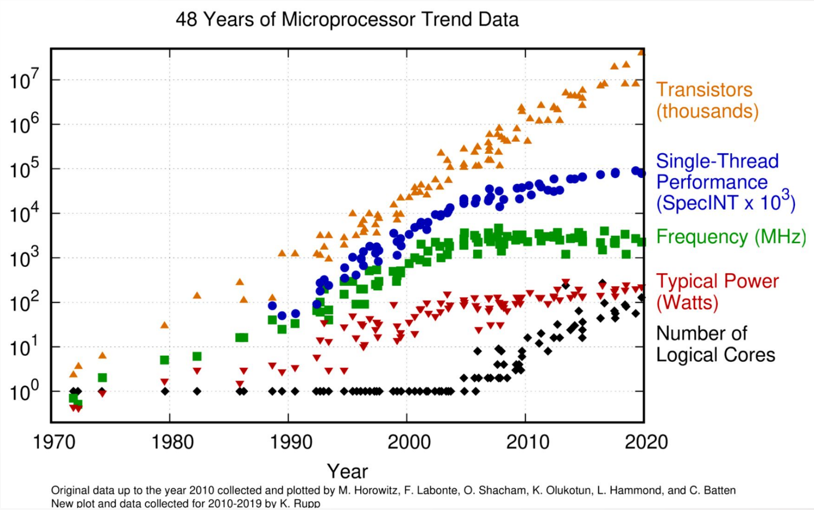


- A design in its infancy
- High granul Noble Liquid ECAL is the core
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies
- Full simulation of ECAL available in FCCSW

Software Challenges for (Future) Detector Developments

- Complex workflows
  - MC Simulations: Event Generation, Particle Propagation; Backgrounds, Digitization, Reconstruction, Analyses ...
- Performance
  - Need distributed computing infrastructure
  - And parallel programming to use evolving hardware efficiently
- Advantage: No “real-world” problems like Alignment and Conditions
  - ... but need to design for it!

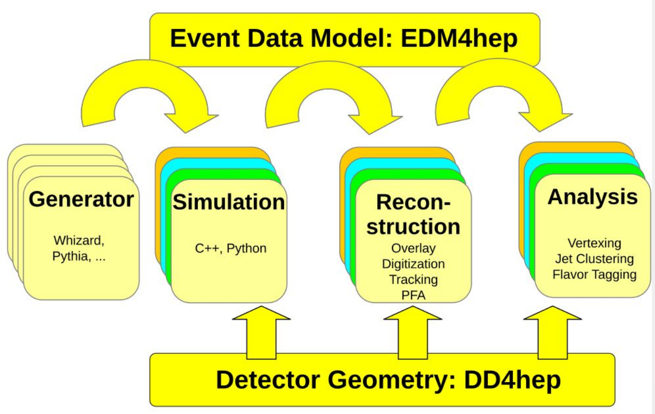




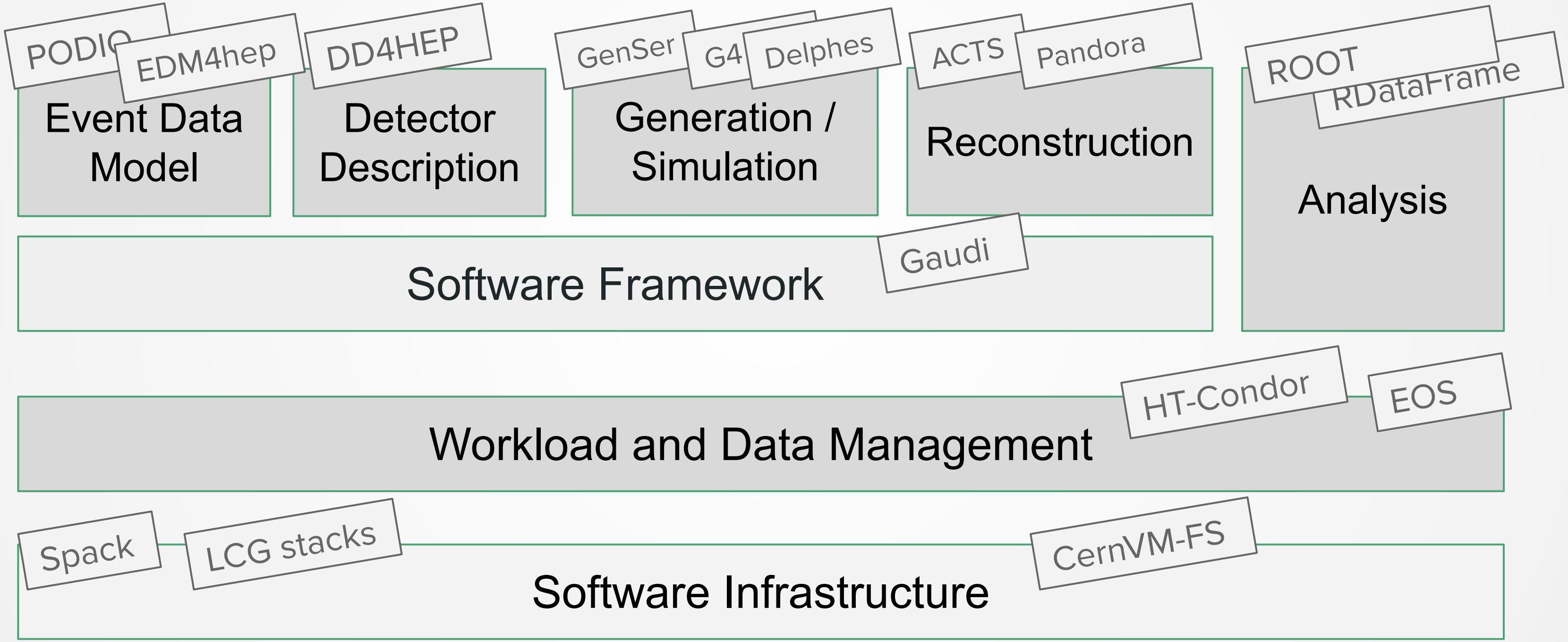
Common software tools for future colliders - a.k.a. Key4hep

Software stack that connects and extends packages to provide a complete data processing framework, comprising fast and full simulation, reconstruction, and analysis.

- Contributions from different Future Collider communities
  - FCC, CLIC, ILC, CEPC, EIC, ...
- Consistent choice of technologies for interoperability
  - EDM4hep: data model
  - Gaudi: framework
  - DD4hep: geometry description
  - Spack: package manager
- Ease of use for librarians, developers and users
- Provide examples, documentation, templates and comm
  practices



Software: Fostering a common ecosystem



ACTS A Common Tracking Software

Project to preserve and enhance LHC track reconstruction software for future **detectors**

A flexible, **open source R&D testbed**:

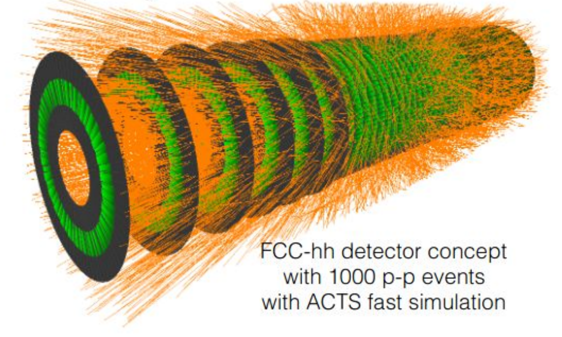
- Facilitate collaboration across experiments and external contributors, e.g. machine learning experts
- Allow for novel algorithms and detector components (e.g. timing, tracklets)

A high-performant toolbox for track reconstruction based on LHC experience

- Modern code and software concepts to allow for concurrent computing
- Support high luminosity and high precision tracking algorithms

Very active ongoing efforts:

- Updating geometry loading for seamless use with FCC detector models
- Include existing EIC framework components

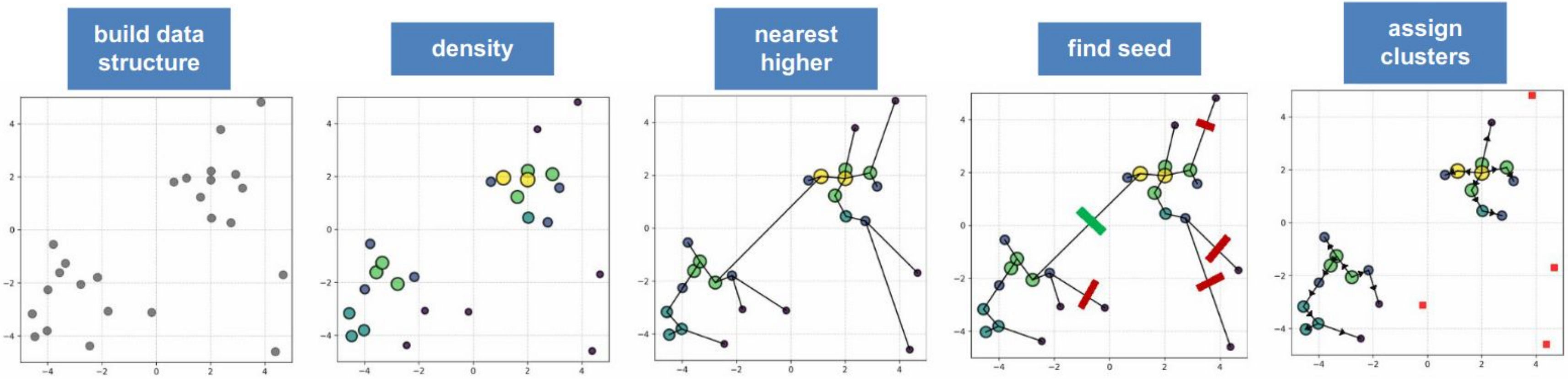


FCC-hh detector concept
with 1000 p-p events
with ACTS fast simulation

k4Acts: Andreas Salzburger, Paul Gessinger, Andreas Steffl

2D Clusters with CLUE

- CLUE (**CLUstering by Energy**) is an algorithm inspired by “Clustering by fast search and find of density peaks” (Ref.)
- Main characteristic:
  - *Energy density* - rather than individual cell energy - used to define ranking, seeding threshold, etc…
- GPU-friendly, i.e. suitable for the upcoming era of heterogeneous computing in HEP



Conclusions

FCC-ee could explore, observe, and discover:

- **Explore** the 10-100 TeV energy scale (and beyond) with precision measurements
- 20- 100 fold improved precision on many EW quantities (equivalent to factor 5-10 in mass)
- m_z,m_W, $\sin^2 \theta_W^{eff}$, R_b, α_{QED}, α_S , Higgs and top quark couplings
- And provide model independent Higgs measurements which can be propagated to LHC and FCC-hh
- **Observe** at the > 3 σ level, the Higgs couplings to the 1st generation, the Higgs self-coupling
- **Discover** a violation of flavour conservation or universality and unitarity of PMNS @ 10^{-5}
- FCNC ($Z \to \mu\tau, e\tau$) in $5\text{x}10^{12}$ Z decays and τ BR in $2\text{x}10^{11}$ $Z \to \tau\tau$
- + flavour physics (10^{12} bb events) ($B \to s\,\tau\,\tau$ etc.)
- **Discover** dark matter as “invisible decay” of H or Z (or in LHC loopholes)
- **Discover** very weakly coupled particles in the 5 to 100 GeV energy scale
    - Such as: Right-handed neutrinos, Dark photons, ALPS, etc, …
- Many other opportunities in e.g. QCD (α_S @ 10^{-4}, fragmentations, $H \to gg$) etc, …

➔ Not only a Higgs Factory: Z, Heavy Flavor, and top are also important for ‘discovery potential’