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THE CASE FOR FCC-EE

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Gratefully acknowledging the contributions of the FCC Coordination Group

Mandate for this presentation

- **Original invitation**

> The SPC feels that it would be important to have a presentation about the **FCC-ee physics case**, linked to the implications for installation and schedule (including the plan for order and duration of the different runs at different energy thresholds), at the next SPC meeting

First part

- **Additional questions asked**
  - **Are there ways to improve energy consumption and carbon footprint?**
  - **Is there anything mandatory that would be missed with five times less luminosity?**
    - **Subsidiary question: is there anything for which 5 times more lumi would be a game changer?**
      - ➔ **With, e.g., more detectors, smaller β^*_y, …**
  - **Can the detectors operate with 100 MW synchrotron radiation?**

The “official” case: a powerful long-term vision

- Case made by the European Strategy, updated by CERN Council in 2020

> ***An electron-positron Higgs factory** is 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**.*

https://cds.cern.ch/record/2721370/

- That’s the exact description of FCC
  - FCC-ee is an electron-positron Higgs factory
  - FCC-hh is a proton-proton collider at the highest achievable energy
- The ee → hh sequence (FCC-INT) optimizes the overall investment and its science value
  - Synergistic infrastructure (and related carbon footprint) and advantageous funding profile
  - Time flexibility for R&D towards affordable 16-20T dipole magnet technology
  - Best route towards a 100 TeV hadron collider (see https://arxiv.org/abs/1906.02693)
  - Fundamental physics complementarity/synergy

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 electroweak 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.

Feasibility Study approved by the Council in June 2021: https://cds.cern.ch/record/2774006

The alignment of stars towards FCC-ee

- Discovery of a light Higgs boson – m_H = 125 GeV, just above LEP limit
  - Higgs boson can be produced at e^+e^- centre-of-mass energies accessible at circular colliders

- Progress in e^+e^- circular collider technology (B factories)
  - Makes it possible to exceed 10^{35} $cm^{-2}s^{-1}$ at the $e^+e^- \rightarrow ZH_{125}$ cross section max. (~240 GeV)

- No BSM physics found (yet) in the TeV range at LHC (+ ttH/HH sensitivity at HL-LHC)
  - Greatly limits the physics potential of TeV-class e^+e^- linear colliders
  - Forces to think differently about BSM physics to explain the big open questions
    - Dark matter, Neutrinos, BAU, Flavour, Hierarchy problem, …
  - Solutions to these open questions can be at even higher energy
    - Higgs compositeness is among the most popular avenues
  - But often include light and very-weakly-coupled structures
    - Axion-like particles, dark photons, heavy neutral leptons, long-lifetime particles

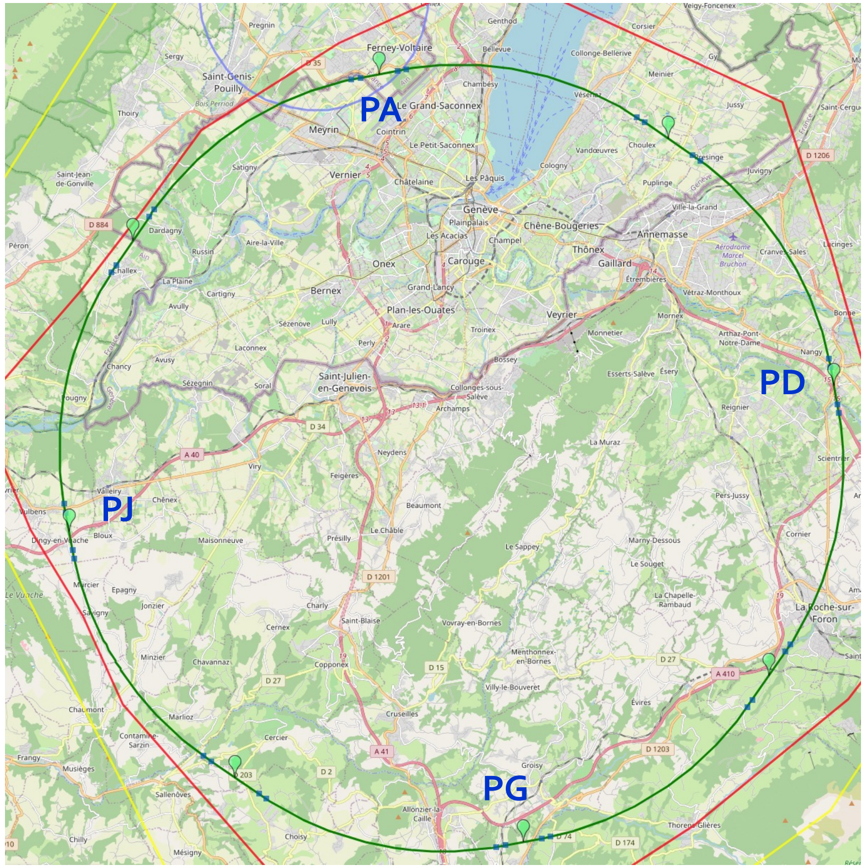
The alignment of stars towards FCC-ee (cont'd)

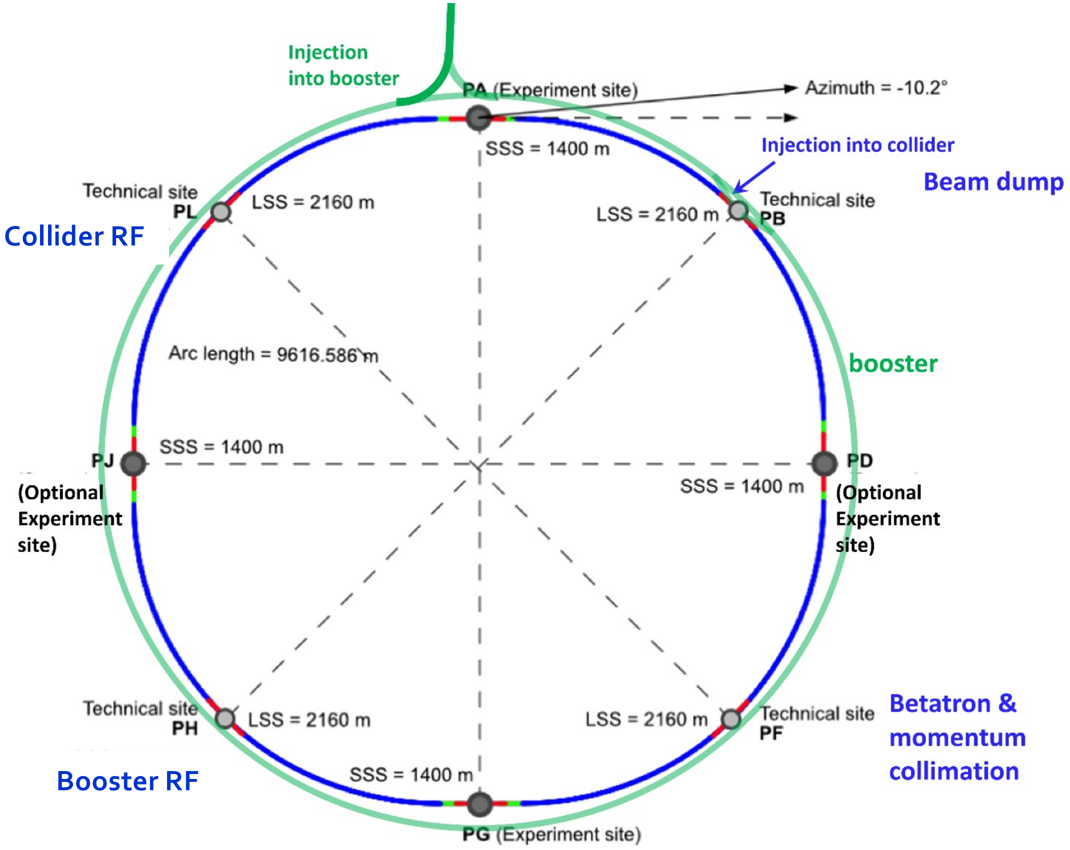
- Without additional theoretical guidance, it calls for a broad and versatile programme
  - To experimentally push the frontiers of the unknown as far as possible
    - At the intensity frontier, to possibly reveal light and very weakly coupled particles
    - At the energy frontier, to possibly reveal new heavy particles
    - At both frontiers, to sharpen our knowledge of already existing physics
      - ➔ EW, QCD, Flavour & Tau, Higgs, Top measurements, with indirect sensitivity to heavy new physics
  - FCC-ee and FCC-hh combine synergistically all these different aspects
    - The intensity frontier gives FCC-ee a compelling case on its own.

- A new 80-100 km ring opens the possibility of 100 TeV pp collisions (ESU'12)
  - It is geographically optimal for the Geneva basin
  - Happy coincidence: a 80-100 km ring is also what is needed for an e^+e^- collider
    - To reach and exceed the top pair threshold (Higgs, top, EW)
    - To enable $\sqrt{s}$ measurement with resonant depolarization (RDP) up to the WW threshold (EW)
    - To offer a luminosity that allows breakthroughs to be made at the intensity frontier (All)
  - Optimal to fulfil the powerful long-term vision for CERN elaborated after ESU'20

Optimized placement and new layout: ~91 km

- New four-fold periodicity and increased FCC-ee / FCC-hh synergies





- Opens the possibility of four experiment sites at FCC-ee
  - Same experimental areas and positions for FCC-ee and FCC-hh interaction points

The uniqueness of FCC-ee

With respect to linear collider's 1st stage

Optimal energy range for SM particles

Sharpen and challenge our knowledge of already existing physics

LEP1 statistics in a few minutes

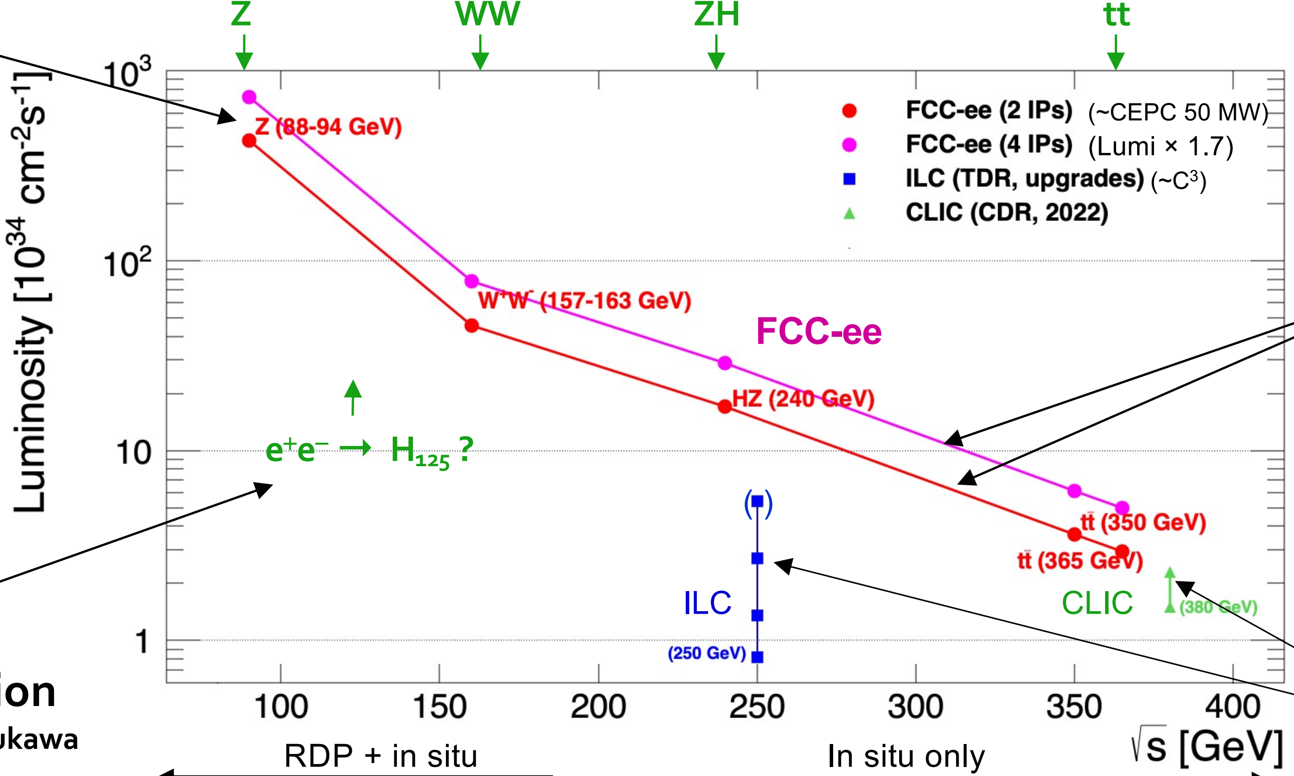
Detector calibration/alignment at all √s

Highest luminosities

Less running time for a given physics outcome

Better physics outcome for a given running time

Increase discovery potential



RDP + in situ

In situ only

Serve up to 4 interaction points

Net overall gain in MW/ab^{-1} or CO2-eq/ab^{-1}

Essential redundancy for precision measurements

May satisfy all detector requirements

Increase discovery potential

Enhance the community (FCC/CERN clients)

√s Monochromatisation

Unique opportunity for electron Yukawa

Motivates the competition

Luminosity is the name of the game

Precise and continuous √s, √s spread, boost determination

Both with resonant depolarisation (RDP) and with collision events in up to four detectors

Essential for precision measurements

Baseline scenario with 2IPs (from CDR)

- Numbers of events in 15 years, tuned to maximise the physics outcome

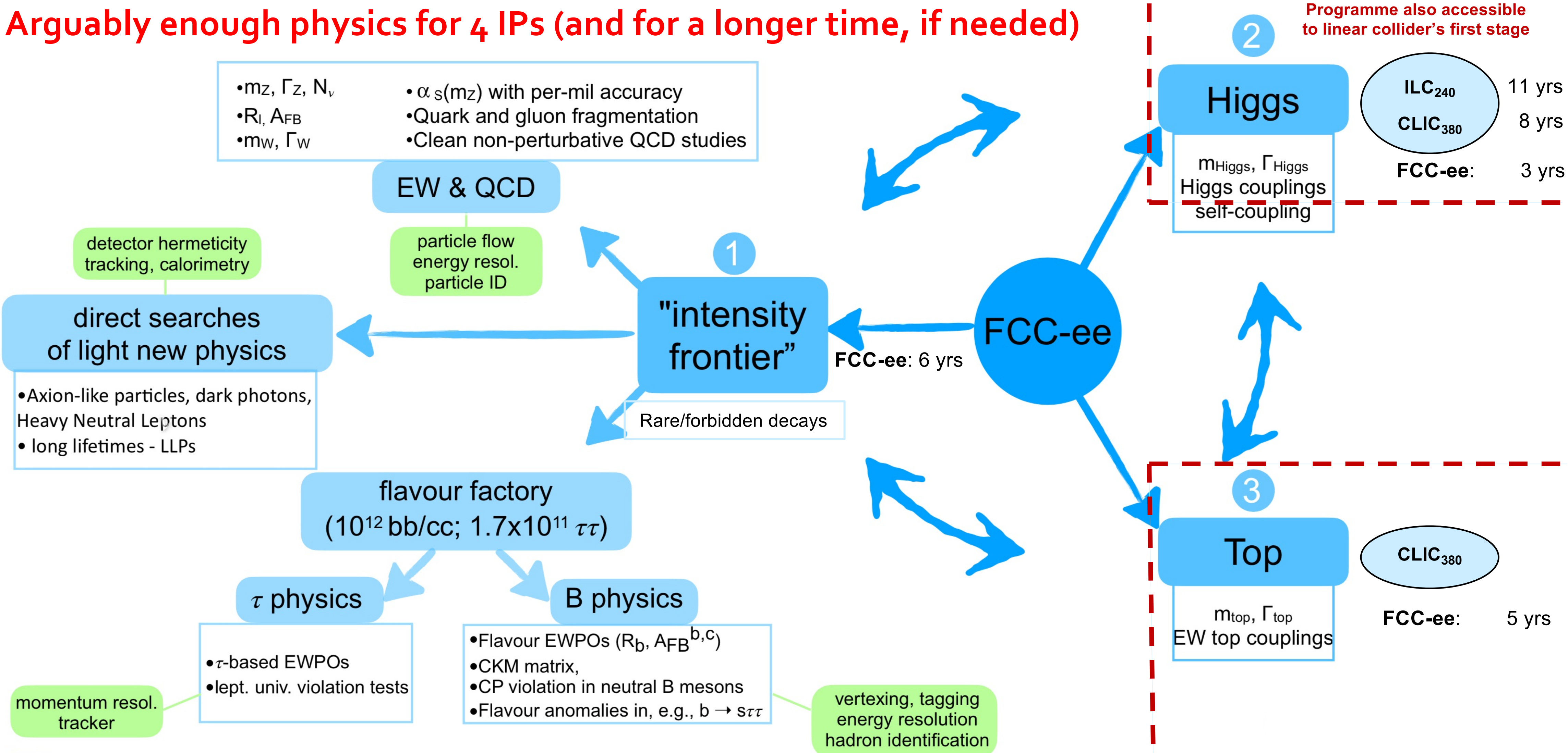
						√s uncertainty
ZH maximum	$\sqrt{s} \sim 240$ GeV	3 years	10^6	$e^+e^- \rightarrow ZH$	Never done	2 MeV
$t\bar{t}$ threshold	$\sqrt{s} \sim 365$ GeV	5 years	10^6	$e^+e^- \rightarrow t\bar{t}$	Never done	5 MeV
Z peak	$\sqrt{s} \sim 91$ GeV	4 years	5×10^{12}	$e^+e^- \rightarrow Z$	LEP x 10^5	< 50 keV
WW threshold+	$\sqrt{s} \geq 161$ GeV	2 years	$> 10^8$	$e^+e^- \rightarrow W^+W^-$	LEP x 10^3	< 200 keV
[s-channel H	$\sqrt{s} = 125$ GeV	5? years	~5000	$e^+e^- \rightarrow H_{125}$]	Never done	< 100 keV

- Exact durations depend on a number of factors (to be studied by the FCCC in 2048-2063)
  - Overall duration: Are the FCC-hh magnets ready ? New physics in FCC-ee data ?
  - Step duration: What is the actual luminosity at each √s? How many IPs? Alternative physics optimization?

- Exact sequence of events is a multi-faceted issue (which can also be decided later)
  - RF installation defines the easiest technical and funding profiles (lowest √s → highest √s)
  - The overall physics outcome, however, is independent of the exact sequence
    - ➔ Higgs and top final precisions need EW and QCD measurements at the Z pole and the WW threshold;
    - ➔ Global electroweak EFT fit requires precise top mass and Higgs couplings
  - Only two serious constraints
    - ➔ Top must come last (RF system significant modification, which cannot be easily undone);
    - ➔ s-channel H cannot come before ZH (m_H) and Z (RDP and monochromatisation must be run routinely)

FCC-ee Physics Programme with 2 IPs and 15 years

- ❑ **Arguably enough physics for 4 IPs (and for a longer time, if needed)**



Programme also accessible to linear collider's first stage

- m_Z, Γ_Z, N_ν
- R_l, A_{FB}
- m_W, Γ_W
- $\alpha_S(m_Z)$ with per-mil accuracy
- Quark and gluon fragmentation
- Clean non-perturbative QCD studies

EW & QCD

particle flow
energy resol.
particle ID

detector hermeticity
tracking, calorimetry

direct searches of light new physics

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

① "intensity frontier"

FCC-ee: 6 yrs

Rare/forbidden decays

FCC-ee

② Higgs

m_{Higgs}, Γ_{Higgs}
Higgs couplings
self-coupling

ILC$_{240}$	11 yrs
CLIC$_{380}$	8 yrs
FCC-ee:	3 yrs

flavour factory (10^{12} bb/cc; $1.7\text{x}10^{11}$ $\tau\tau$)

τ physics

- τ-based EWPOs
- lept. univ. violation tests

momentum resol.
tracker

B physics

- Flavour EWPOs (R_b, $A_{FB}{}^{b,c}$)
- CKM matrix,
- CP violation in neutral B mesons
- Flavour anomalies in, e.g., $b \to s\tau\tau$

vertexing, tagging
energy resolution
hadron identification

③ Top

m_{top}, Γ_{top}
EW top couplings

CLIC$_{380}$	
FCC-ee:	5 yrs

🟩 detector req.

Programme optimally done with circular collider's first stage

Programme also accessible to linear collider's first stage

Slide from C. Grojean @ FCC Week'22

In words: FCC-ee discovery potential (excerpt)

- **EXPLORE the 10-100 TeV energy scale** with precision measurements
  - From the correlated properties of the Z (+ b, c, τ) , W, Higgs, and top particles
    - Up to 20-50-fold improved precision on ALL electroweak observables (EWPO)
      - ➔ m_Z , m_W , m_{top} , Γ_Z , $\sin^2 \theta_W^{eff}$, R_b , $\alpha_{QED}(m_z)$, $\alpha_s(m_z\ m_W\ m_\tau)$, top EW couplings …
    - Up to 10 × more precise and model-independent Higgs couplings (width, mass) measurements
      - ➔ Access the Higgs potential and infer the vacuum structure of the Universe
      - ➔ Reveals the dynamics of the EW phase transition and infer the fate of the EW vacuum
- **DISCOVER** that the Standard Model does not fit
  - NEW PHYSICS ! Pattern of deviations may point to the source.

The whole FCC-ee run plan is needed
The run at the Z pole is special

- **DISCOVER** a violation of flavour conservation / universality
  - $Z \rightarrow \tau\mu$ in 5×10^{12} Z decays; $\tau \rightarrow \mu\nu$ / $\tau \rightarrow e\nu$ in 2×10^{11} τ decays; $B^0 \rightarrow K^{*0}\tau^+\tau^-$ or $B_S \rightarrow \tau^+\tau^-$ in 10^{12} bb events
- **DISCOVER** dark matter, e.g., as invisible decays of Higgs or Z
- **DISCOVER DIRECTLY** feebly-coupled particles
  - in the 5-100 GeV mass range, such as right-handed neutrinos, dark photons, ALPs, …

The power of precision

Inspired by T. You & M. Mangano

- We are often told to "sharpen our physics case", and that "just higher precision is not enough"
  - A factor 50 in precision corresponds to a factor 7 in energy scale (same step as LHC → FCC-hh)
    - And who knows how important a measurement will become to assess the validity of a future theory ?
- A historical lesson
  - From classical mechanics and classical electromagnetism …

1900: Almost all date agree spectacularly with the fundamental theory, without any reason to doubt its universal applicability or completeness

  - … to general relativity and quantum mechanics

1920: A combination of **precision measurements** (Mercury), **aesthetic arguments** (relativity) supported by **null experimental results** (Michelson Morley) and **theoretical inconsistencies** (Rayleigh-Jeans UV catastrophe) led to an overhaul of the fundamental pictures **at smaller scales and higher energies** after pushing the theory and technology frontiers into new regimes

  - Who knows if pushing the intensity and energy frontiers at FCC will lead to a similar revolution ?

(+ cosmology & astroparticle physics)

- We will learn a lot, regardless of the outcome
  - BSM theories will be very much constrained even with a null result of FCC-ee
    - The day some BSM signal is found somewhere, the precision measurements, whether they agree or deviate from the SM, will be precious to establish the nature of the signal.

Mandate for this presentation

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Second part

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  - Is there anything mandatory that would be missed with five times less luminosity?
    - Subsidiary question: is there anything for which 5 times more lumi would be a game changer?
      - ➔ With, e.g., more detectors, smaller β^*_y, …
  - Can the detectors operate with 100 MW synchrotron radiation?

Energy consumption and carbon footprint @ 240 GeV

FCC-ee total instantaneous power demand at each centre-of-mass energies

J.-P. Burnet, FCC Week'22

		Z	W	H	TT
Beam energy (GeV)		45.6	80	120	182.5
Magnet current		25%	44%	66%	100%
Power ratio		6%	19%	43%	100%
PRF EL (MW)	Storage	146	146	146	146
PRFb EL (MW)	Booster	2	2	2	2
Pcryo (MW)	all	1,3	12,6	15,8	47,5
Pcv (MW)	all	33	34	36	40.2
PEL magnets (MW)	Stroage	6	17	39	89
PEL magnets (MW)	Booster	1	3	5	11
Experiments (MW)	Pt A & G	8	8	8	8
Data centers (MW)	Pt A & G	4	4	4	4
General services (MW)		36	36	36	36
Power during beam operation (MW)		237	262	291	384

Ongoing R&D

Ongoing R&D

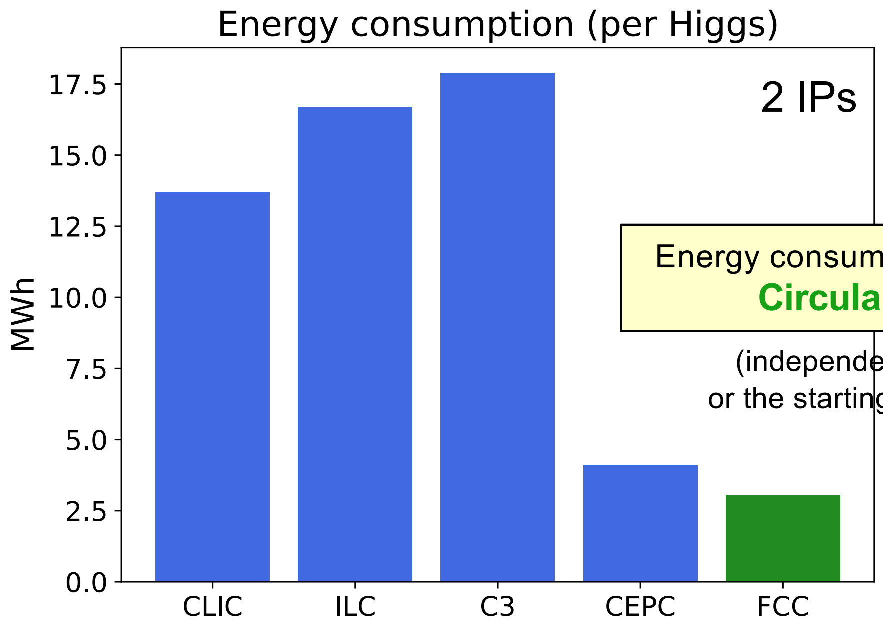
Potential energy savings

- At 240 GeV, the instantaneous power of FCC-ee amounts to 291 MW
  - As a comparison, P(ILC$_{250}$)=140 MW, P(CLIC$_{380}$)=110 MW : less power hungry than FCC-ee?
    - ➔ Unclear: Run 3 to 6 times longer as Higgs factory, but produce 2 to 4 times less Higgs bosons in total

Energy consumption and carbon footprint @ 240 GeV

- Our first responsibility (as particle physicists) is to do the maximum of science
  - With the minimum energy consumption and the minimum environmental impact for our planet
    - Should become one of our top-level decision criteria for design, choice and optimization of a collider

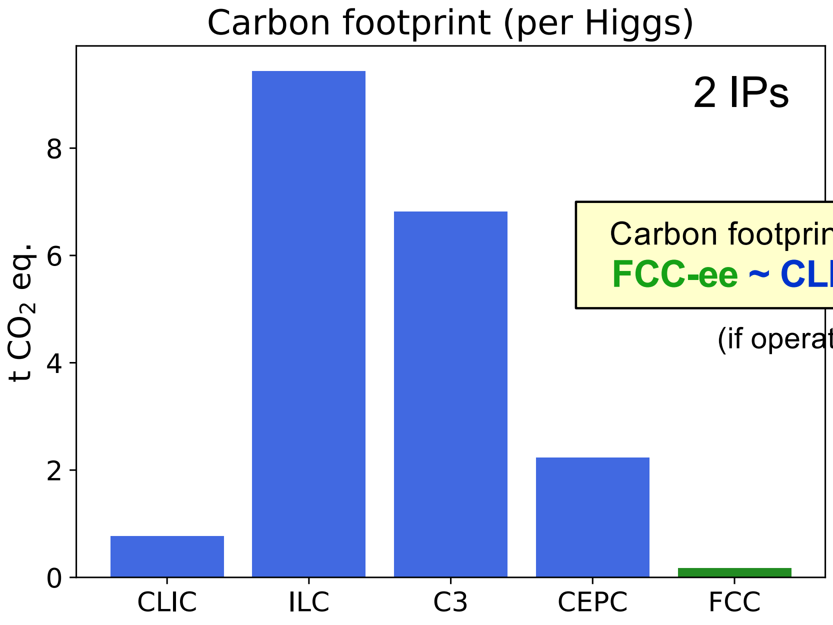
- All Higgs factories have a "similar" physics outcome (ESU'20 and Snowmass'21)
  - Natural question: what is their energy consumption or carbon footprint for the same physics outcome?
    - Circular colliders have a much larger instantaneous luminosity and operate several detectors
    - FCC-ee is at CERN, where electricity is already almost carbon-free (and will be even more so in 2048)



arXiv:2208.10466

Energy consumption / Higgs with 2IP
Circular ~ Linear / 5

(independently of the location
or the starting time of the collider)



Carbon footprint / Higgs with 2IP
FCC-ee ~ CLIC / 5 ~ ILC / 50

(if operating today)

Energy consumption and carbon footprint @ 240 GeV

- **We still want to (and must) improve and optimize these figures for FCC-ee**
  - Operate four detectors instead of two (unique to circular colliders)

    Energy consumption / Higgs with 4IP
    Circular ~ Linear / 10

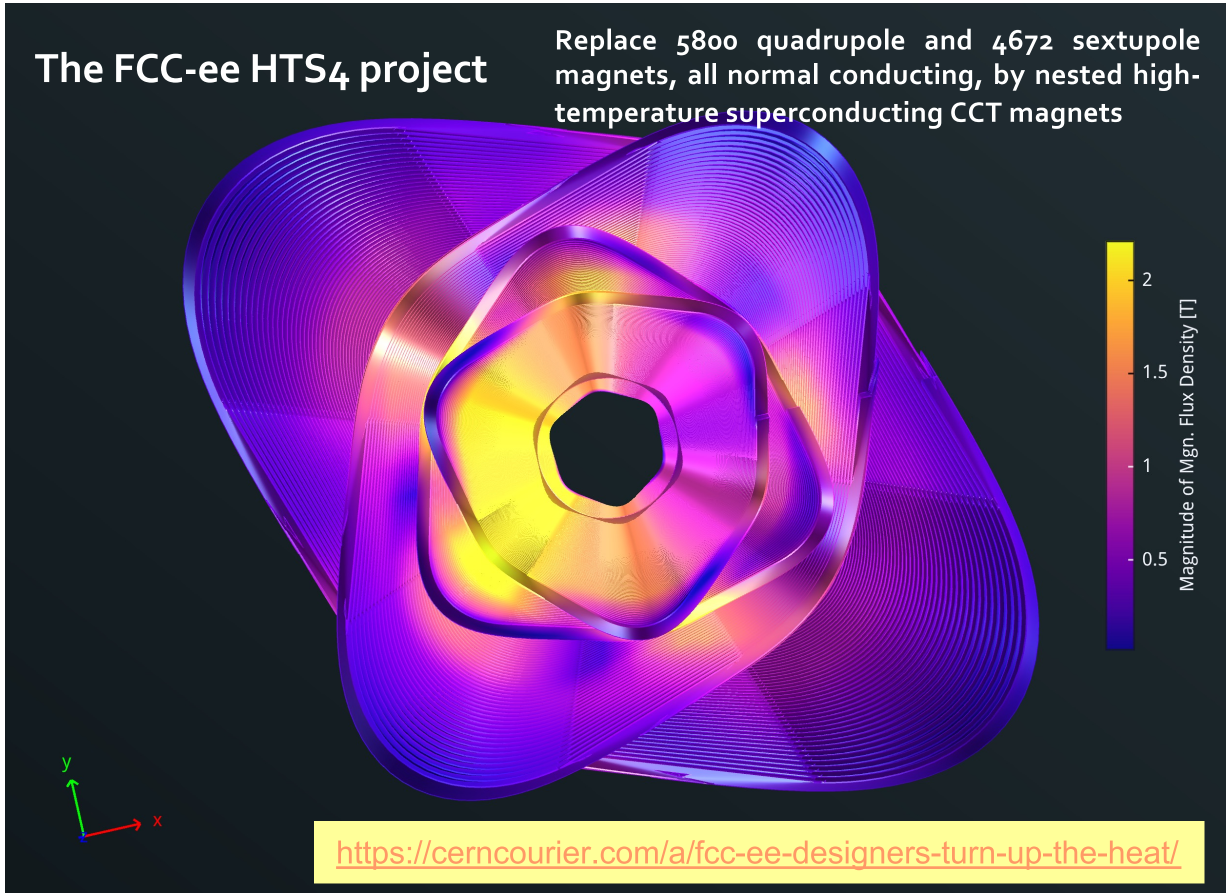
    Carbon footprint / Higgs with 4IP
    FCC-ee ~ CLIC / 10 ~ ILC / 100

    - Would also maximise the science value for the investment (Part III of this presentation)
  - Further improve the specific luminosity (e.g., by decreasing β^*_y)
  - Decrease the power demand for a given current (ongoing R&D)
    - e.g., High-Q cavities; HTS quadrupoles and sextupoles; Higher efficiency klystrons
  - Operate the collider only when carbon-free energy is available
  - Generalise heat recovery for neighbouring domestic heating
  - Decreasing the current (i.e., the luminosity) by decreasing the RF power by a factor 5?
    - Not a very good idea: Energy consumption & carbon footprint / Higgs increases by a factor 3
  - …

Energy consumption and carbon footprint @ 240 GeV

- **The efforts and improvements are highly incentive of innovative developments**
  - **Will benefit to the society at large - for example:**

High-temperature superconductor development



The FCC-ee HTS4 project

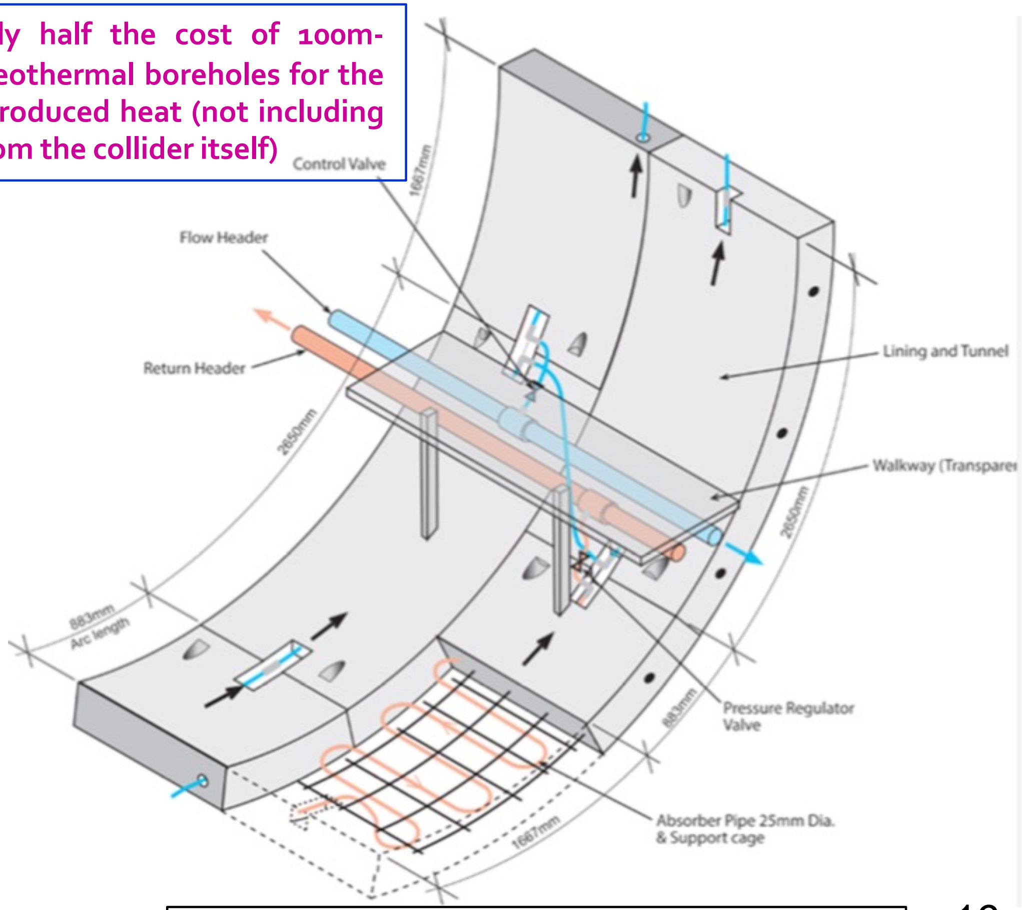
Replace 5800 quadrupole and 4672 sextupole magnets, all normal conducting, by nested high-temperature superconducting CCT magnets

https://cerncourier.com/a/fcc-ee-designers-turn-up-the-heat/

Credit M. Koratzinos

Tunnel geothermal heat

Typically half the cost of 100m-deep geothermal boreholes for the same produced heat (not including heat from the collider itself)



Study performed for CLIC tunnel, Credit ARUP

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      - ➔ With, e.g., more detectors, smaller β^*_y, …

Third part

  - Can the detectors operate with 100 MW synchrotron radiation?

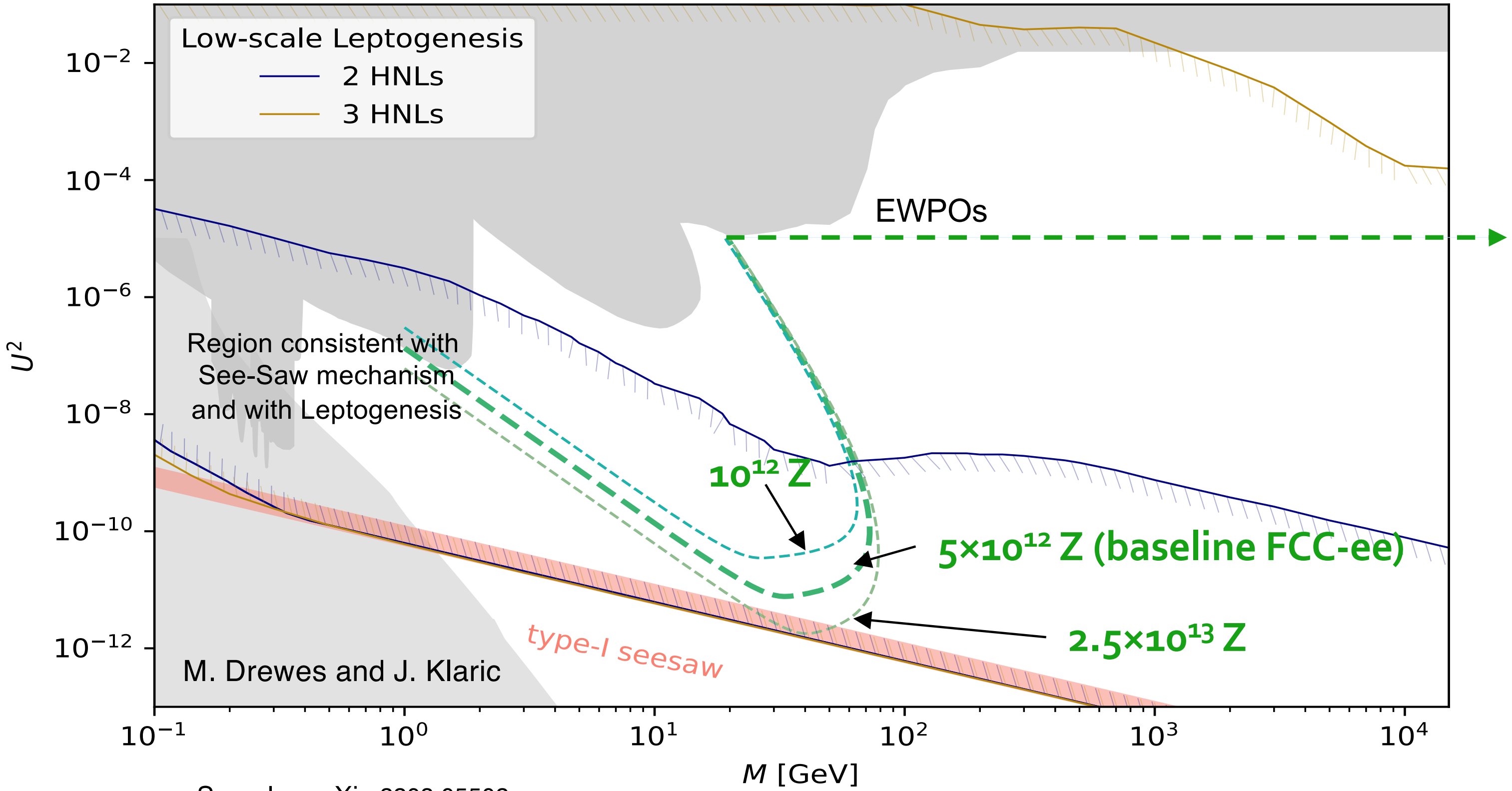
Direct discovery potential: The Dark Sector

- **Light, feebly-coupled particles, provide elegant dark sector solutions to SM puzzles**
  - Rare Z decays have sensitivity to couplings/mixings proportional to 1 / L (if background free)

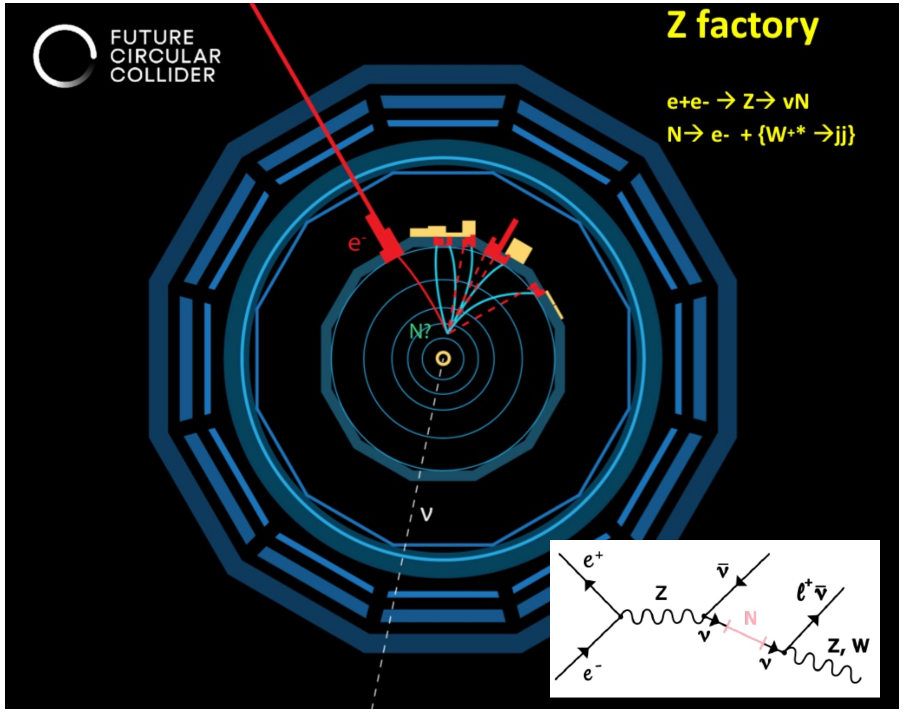
Any increase of luminosity is welcome !

(Also to measure the properties of the discovered particles)

  - Poster child of a generic type of dark sector search in Z decays: heavy right-handed (~sterile) neutrinos



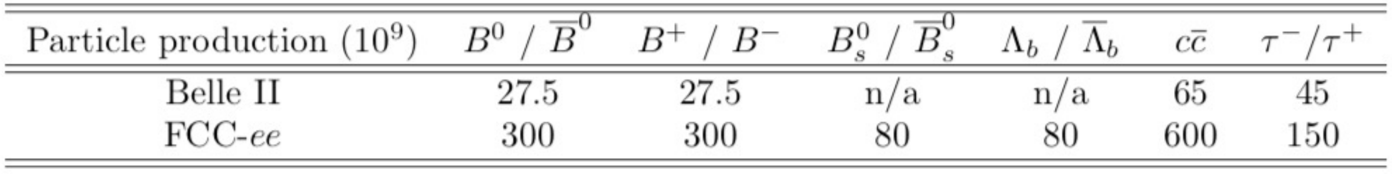
See also arXiv:2203.05502



Flavour: a great mystery for HEP

See talk from S. Monteil '22

- ❑ **With 5×10^{12} Z, FCC-ee is of special relevance for b, c and τ physics** (unique among Higgs factories)
  - ◆ **Production rate@Z pole typically an order of magnitude more than the anticipated Belle II statistics**



Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\overline{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	300	300	80	80	600	150

All highly boosted

- ● **"At least 5×10^{12} Z is desirable, more is better"** **(Granada'19)**

- ◆ **Overperforms LHCb upgrade 2 in many aspects, e.g.,**
  - ● **Everywhere for CKM (γ, β, ϕ_s, V_{ub}, …) @ Z pole, and V_{cb} and V_{cs} above the WW threshold**
  - ● **On all missing energy modes and almost all τ decays (trigger, background)**
    - ➔ **e.g., $B^0 \to K^{*0}\tau^+\tau^-$, $B_s \to \tau^+\tau^-$, b → sνν, $B_c \to \tau\nu$, τ → 7 or 9 prongs. LFV: $B_s \to K^{*0}\tau\ell$, τ → μγ, τ → μμμ, etc.**

- ◆ **Many analyses are statistics limited; All rare decays will also benefit from an increase of statistics**

- ◆ **The flavour community is a natural client for FCC-ee (and CERN)**
  - ● **It is both numerous (>2000 members in Belle II and LHCb), and with high expectations**
  - ● **It will almost certainly need a different detector concept (PID, EM resol.) to explore the full physics programme**

An opportunity not to miss

Precision EW measurements

- We often hear that more Z pole statistics is useless, because they are systematics-limited
  - This is a passive attitude, which leads to pessimistic expectations and wrong conclusions/planning
    - Experience shows that a careful experimental systematic analysis boils down to a statistical problem
    - If well prepared, theory will go as far as deemed useful : this preparation starts today (and needs SUPPORT)
    - We are working in the spirit of matching systematic errors to expected statistics for all precision measurements
  - Take the Z lineshape

FCC-ee special

$\alpha_{QED}(m_Z)$: Stat. 3×10^{-5}

Obtained at FCC-ee from off-peak asymmetries (87.9 & 94.3 GeV): for the first time, it is a direct measurement of this quantity (game changer)

- Enters as a limiting parametric uncertainties in the new physics interpretation many past and future measurements.
- Is statistics limited and will directly benefit from more luminosity
- No useful impact on $\alpha_{QED}(m_Z)$ with five times less luminosity

$\sin^2\theta_W^{eff}$ and Γ_Z (also m_W vs m_Z) : Stat. 2×10^{-6} and 4 keV

Error dominated by point-to-point energy uncertainties.

Based on in-situ comparisons between √s (e.g. with muon pairs), with measurements made every few minutes (100's times per day)

Boils down to

- statistics (the more data the better, scales down as 1/√L)
- detector systematics (uncorrelated between experiments, scales down a $1/\sqrt{N_{experiments}}$)

Z (and W) mass: Stat. 4 keV (250 keV)

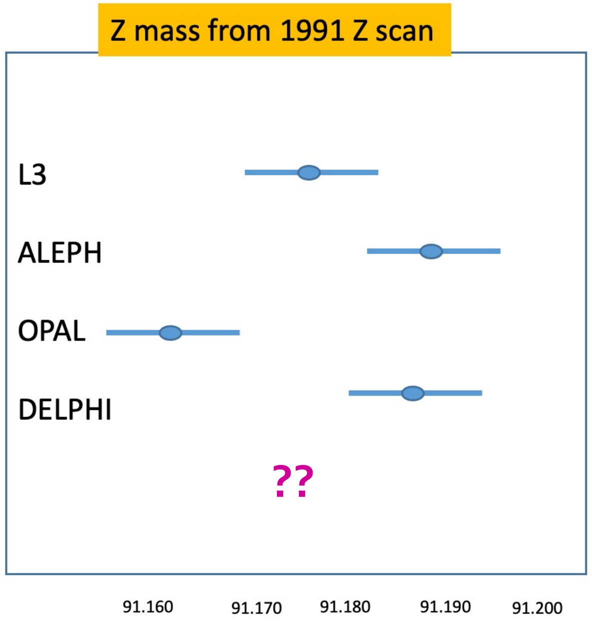
Error dominated by √s determination with resonant depolarization.

As more understanding is gained, progress are made at a constant pace, and this error approaches regularly the statistical limit

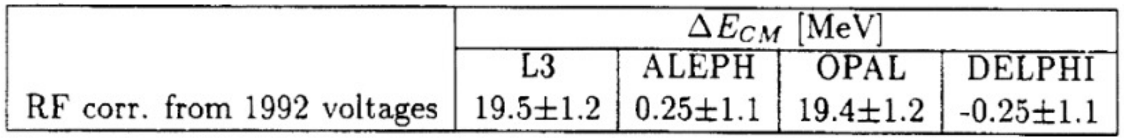
- Most of the work is (will be) on systematics
  - But huge statistics will turn into better precision
    - ➔ A real chance for discovery

Precision EW measurements

- Precision is also about redundancy
  - Measuring the same quantity in several experiments can reveal overlooked sources of errors

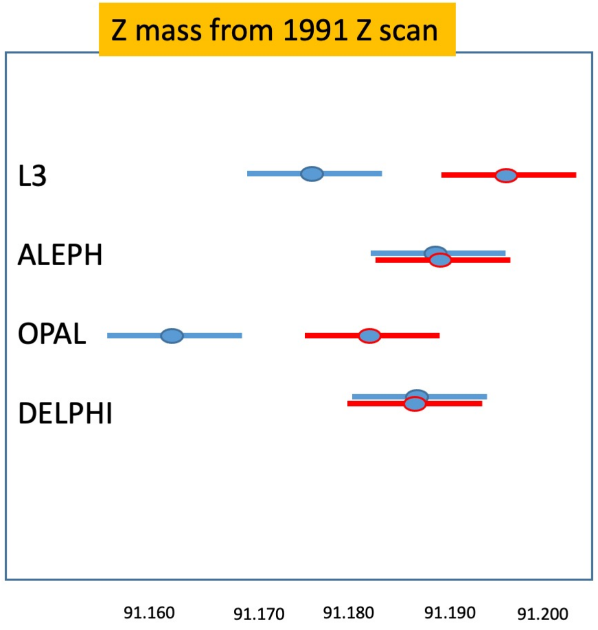


Effect of RF phases and voltages discovered after the fact



	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

Could have remained unnoticed
with ALEPH and DELPHI only, or with L3 and OPAL only

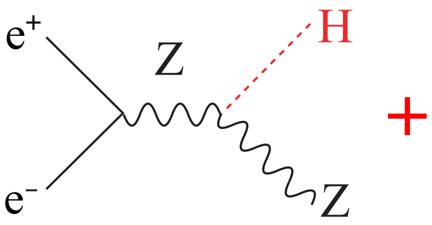


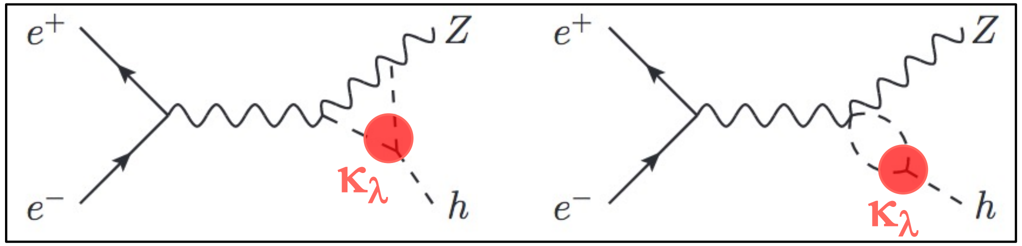
- In this context, a given luminosity is better used in four detectors than in one or two
  - A single experiment is vulnerable to unforeseen effects
  - Consistency between 2 experiments can happen by chance: comparison is a poor measurement of systematics
  - Such bad luck is much less likely in the case of four experiments

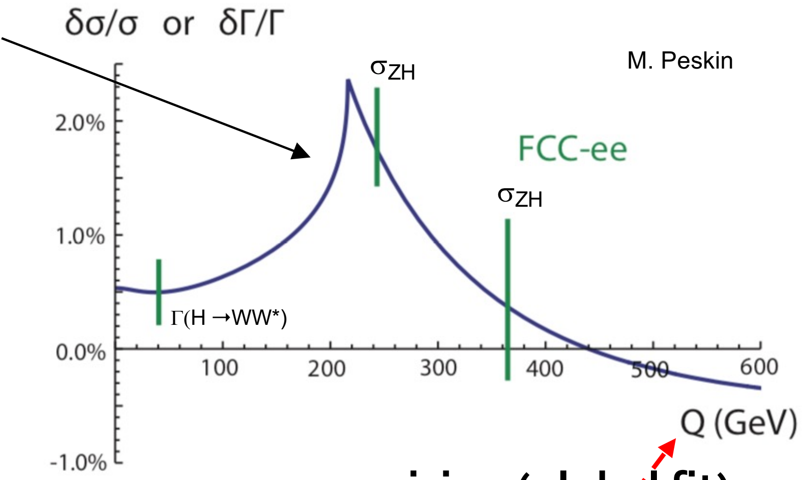
➔ Needless to say, it is even better if more experiments means more statistics

Higgs self-coupling

- **Statistics-limited sensitivity comes from $\sigma_{ee\to ZH}$ measurements at 240 and 365 GeV**
  - Thanks to the relative change with centre-of-mass energy





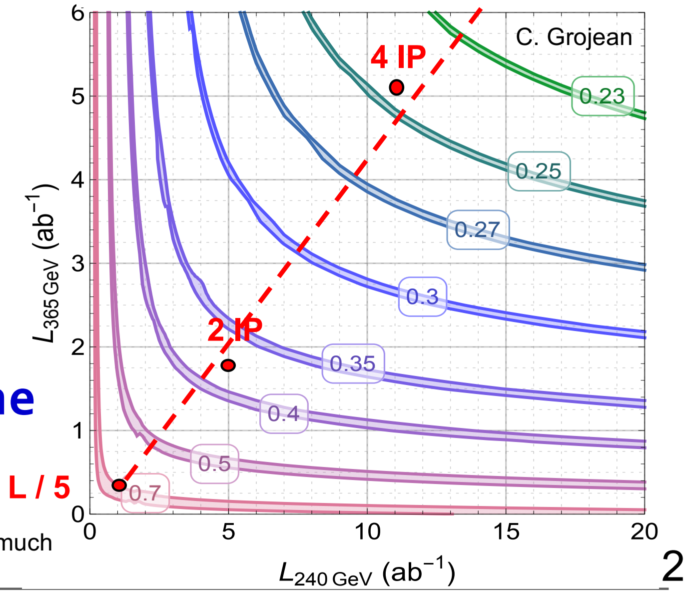


- **Estimate with present run plan and 2 IPs: ≥ 2σ from $\kappa_\lambda = 0$**
  - Analyses will improve, but no hope with 5 times less luminosity

(Discovery)

- **With 4 IPs and optimization of run plan: target ≥ 5σ, $\delta\kappa_\lambda \sim 20\%$**
  - Increase duration at 240 and 365 GeV (to 4 and 7 years)
    - Reduce Z and WW run duration @ constant statistics
  - Or better: increase specific luminosity and/or overall running time
    - If it is worth doing, it is worth doing well

κ_λ precision (global fit)

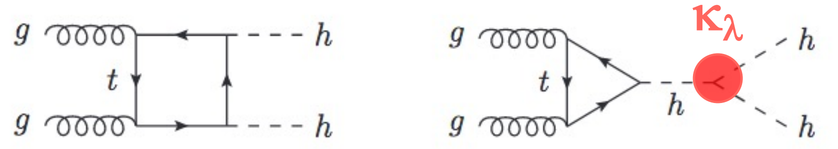


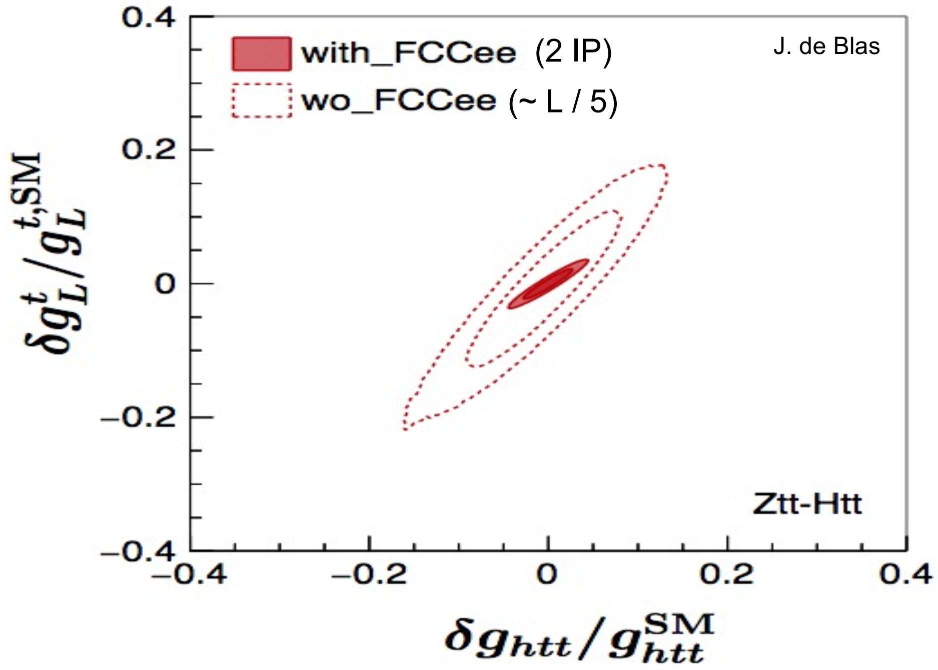
HL-LHC alone cannot do much
in a global EFT fit …

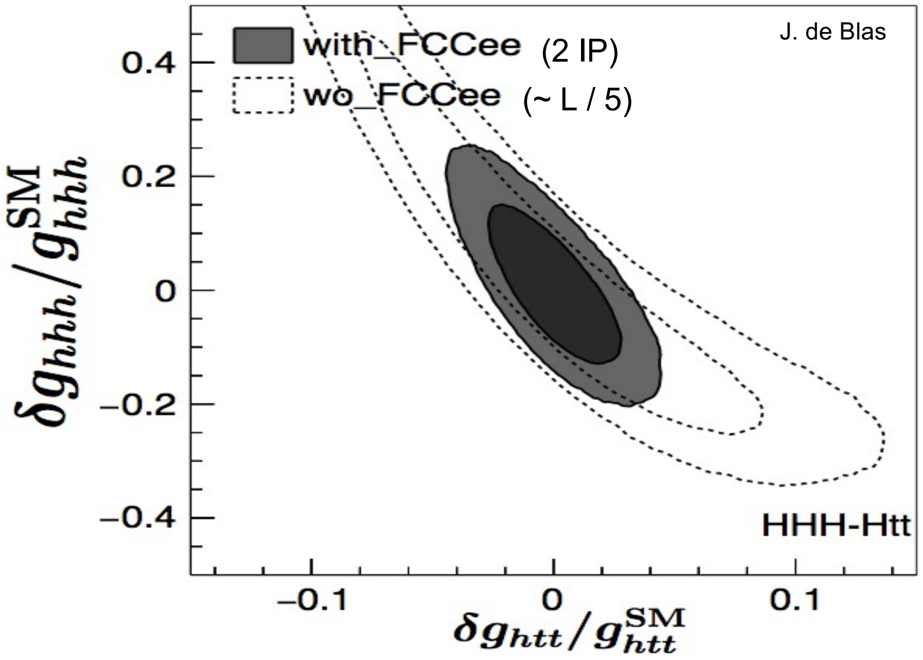
Top Yukawa and Higgs self-coupling @ FCC-hh

- Top Yukawa coupling from σ(ttH) / σ(ttZ) measurement at FCC-hh
  - Most theory uncertainties cancel in the ratio: <1% precision possible
    - ttZ couplings come $e^+e^- \to t\bar{t}$ at 365 GeV ⇒ Expected precision with 2IPs on $\sigma(ttZ)_{\text{FCC-hh}}$: ~1.5%,
    - Statistics limited, more lumi at 365 Gev (e.g., with 4IP) helps
      - ➔ Five times less luminosity cancel all hopes for an improvement with this method

- Higgs self-coupling from double Higgs production at FCC-hh
  - Precise top Yukawa coupling needed to predict σ(gg → HH)



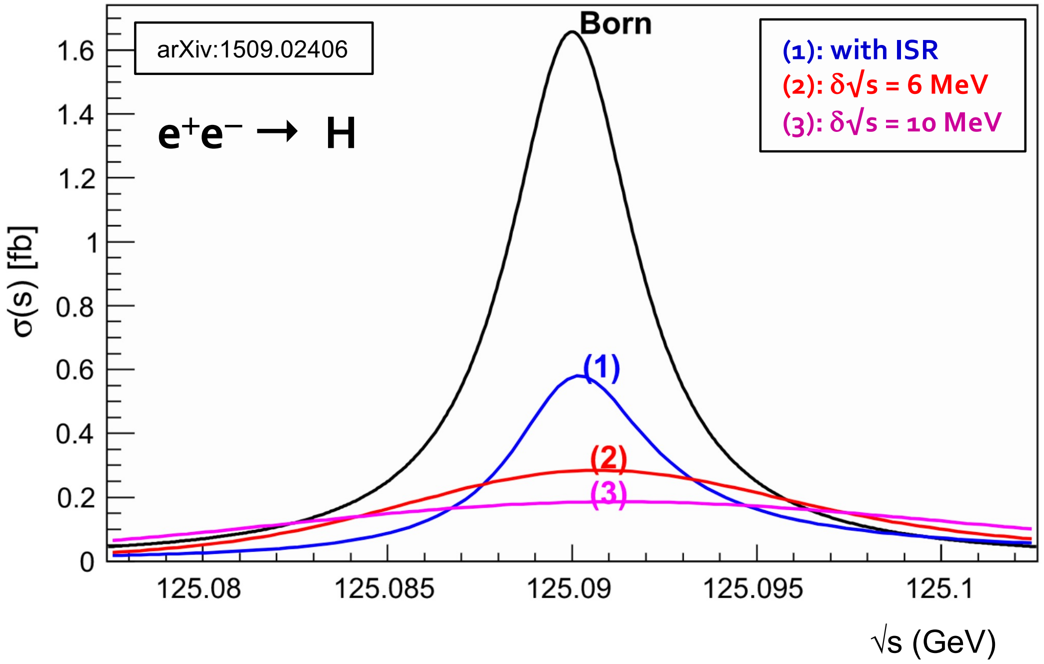


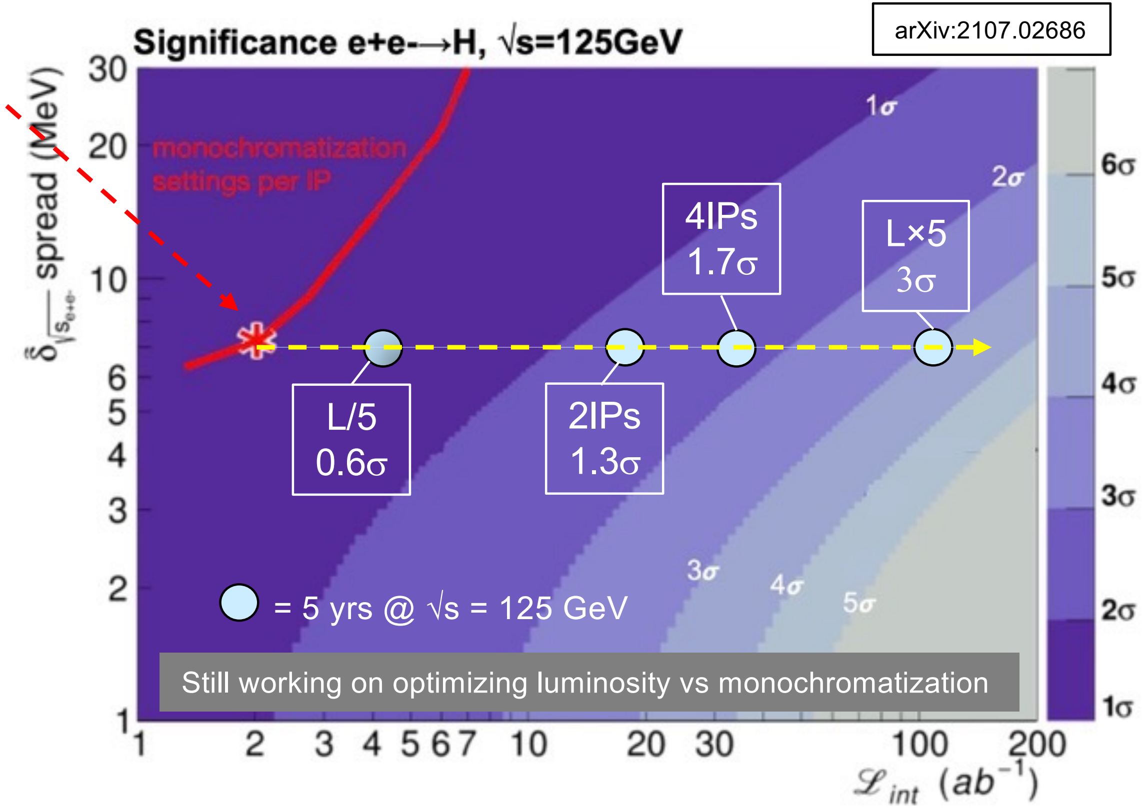


Electron Yukawa coupling: Unique @ FCC-ee

(not yet in the baseline)

- One of the toughest challenges, which requires in particular, at $\sqrt{s}$ = 125 GeV
  - Higgs boson mass prior knowledge to a couple MeV, requires at least the design lumi at $\sqrt{s}$ = 240 GeV
  - Huge luminosity, achievable with with several years of running and possibly 4 IPs
  - $\sqrt{s}$ monochromatisation : Γ_H (4.2 MeV) ≪ natural beam energy spread (~100 MeV)
- First studies indicate a significance of 0.4σ with one detector in one year





● = 5 yrs @ √s = 125 GeV

Still working on optimizing luminosity vs monochromatization

Mandate for this presentation

- **Original invitation**

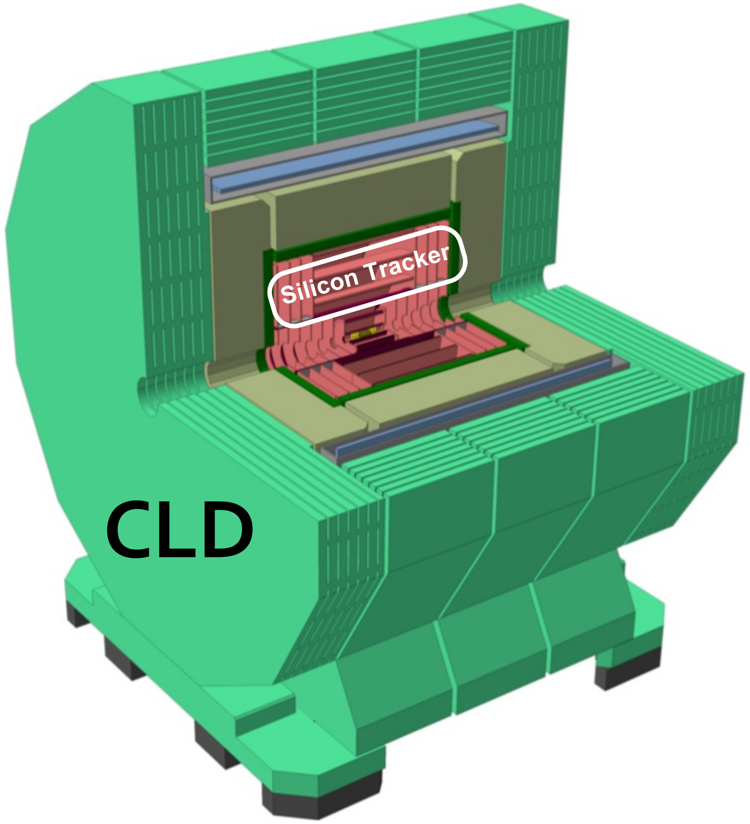
  The SPC feels that it would be important to have a presentation about the **FCC-ee physics case**, linked to the implications for installation and schedule (including the plan for order and duration of the different runs at different energy thresholds), at the next SPC meeting

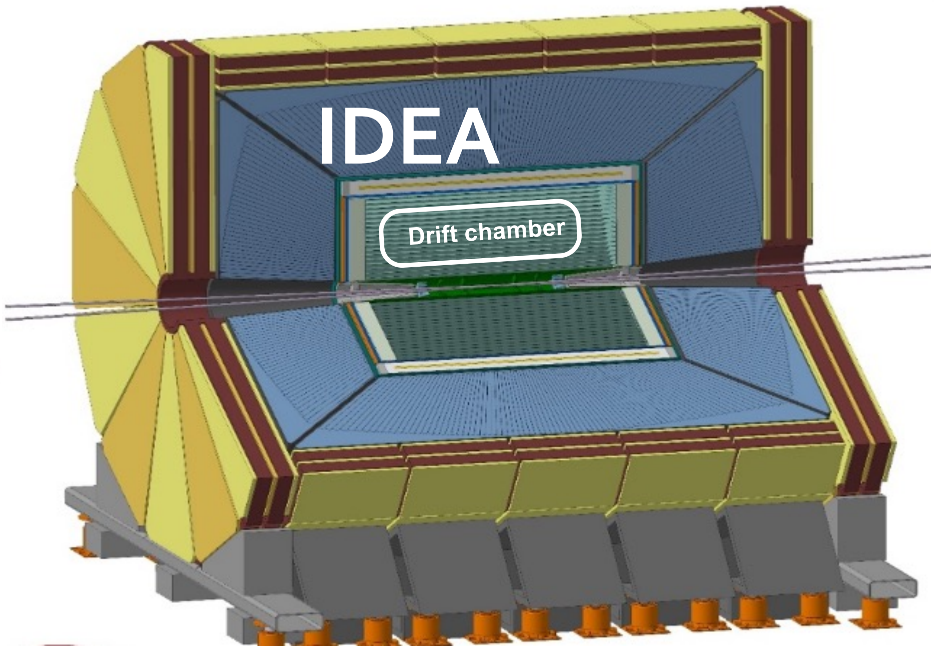
- **Additional questions asked**
  - Are there ways to improve energy consumption and carbon footprint?
  - Is there anything mandatory that would be missed with five times less luminosity?
    - Subsidiary question: is there anything for which 5 times more lumi would be a game changer?
      - ➔ With, e.g., more detectors, smaller β^*_y, …
  - Can the detectors operate with 100 MW synchrotron radiation?

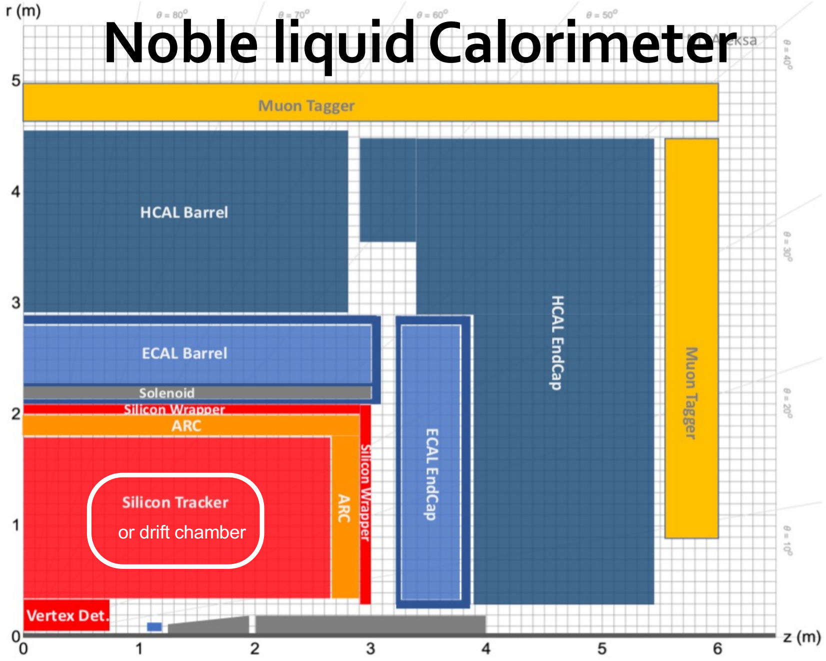
Fourth part

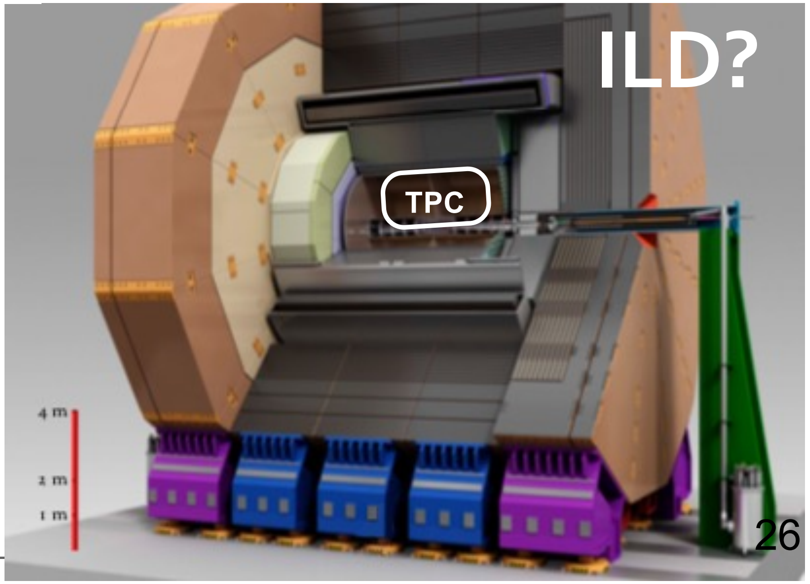
Requires full simulation of all detectors and of the interaction region
Final results might not be fully available for all tracker concepts by the mid-term review

Proto-detectors: A basis towards detector concepts





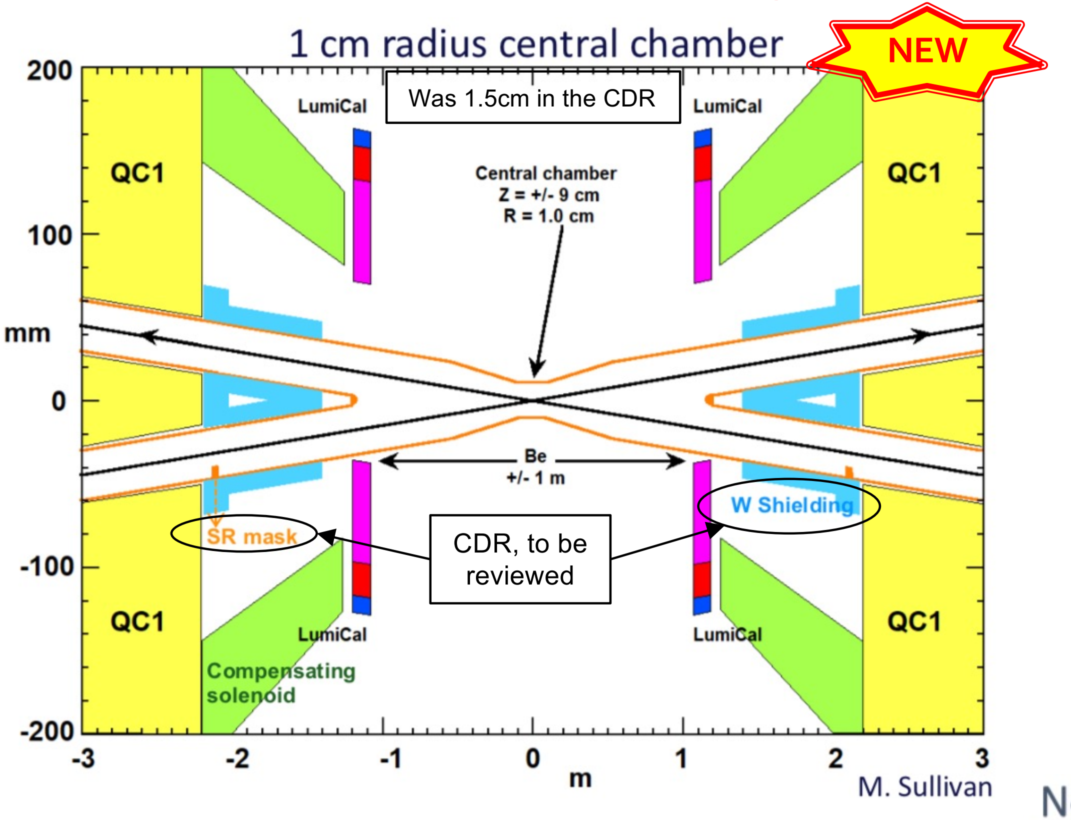

Noble liquid Calorimeter



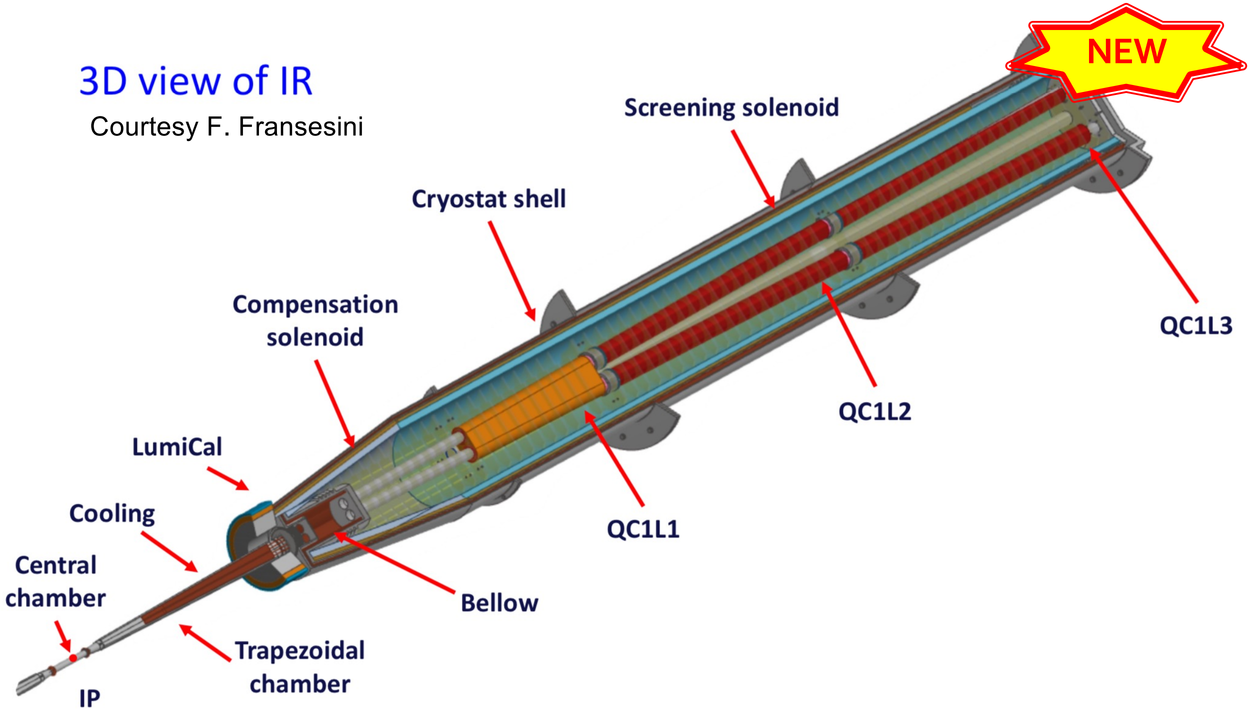
- ❑ Three tracker concepts to test for synchrotron radiation
  - ◆ Si Tracker, Drift Chamber, Time Projection Chamber
    - Only existing simulation so far : CLD Si Tracker
      - ➔ IDEA Drift Chamber will follow soon

The interaction region

- Critical for detector background studies, currently under engineering development

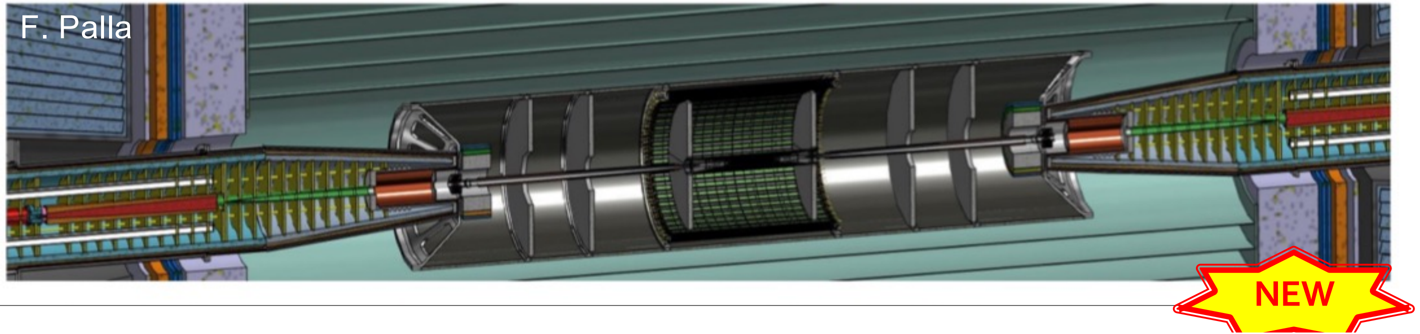

1 cm radius central chamber

M. Sullivan


3D view of IR

Courtesy F. Fransesini

Novel outer support tube for central beam pipe and vertex detector

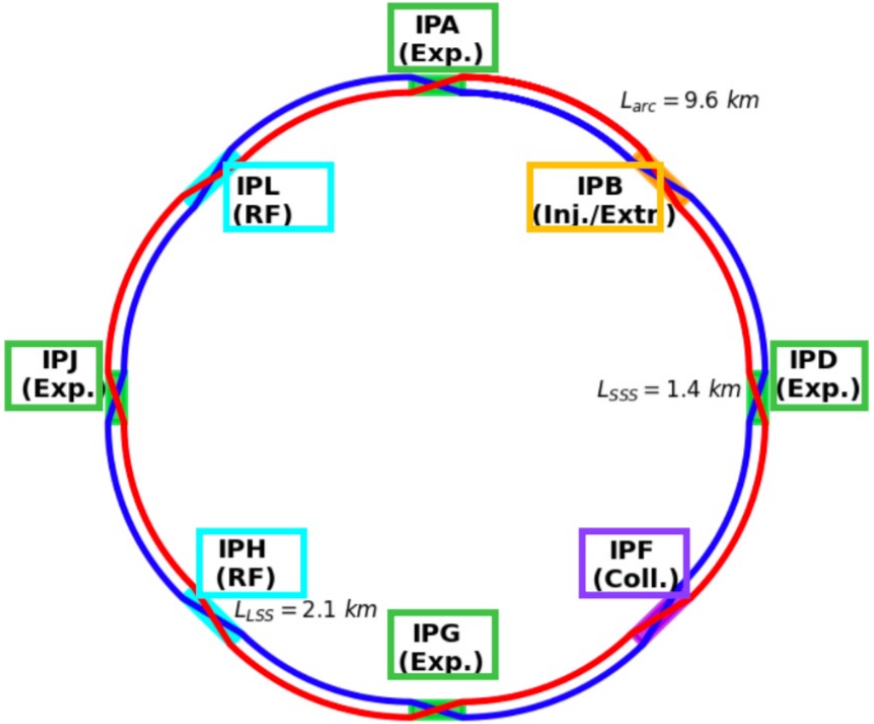

F. Palla

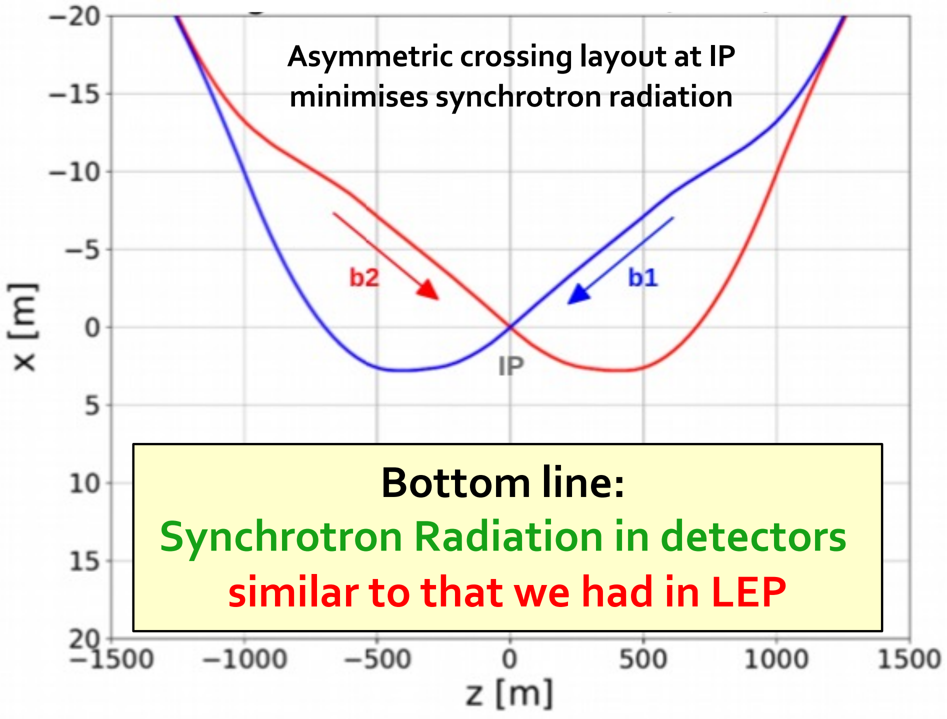
- Full simulation in development
  - Background studies next

(Additional resources would be highly welcome)

Synchrotron radiation (as in the CDR)

- Of course, the 100 MW from synchrotron radiation mostly go in the arcs





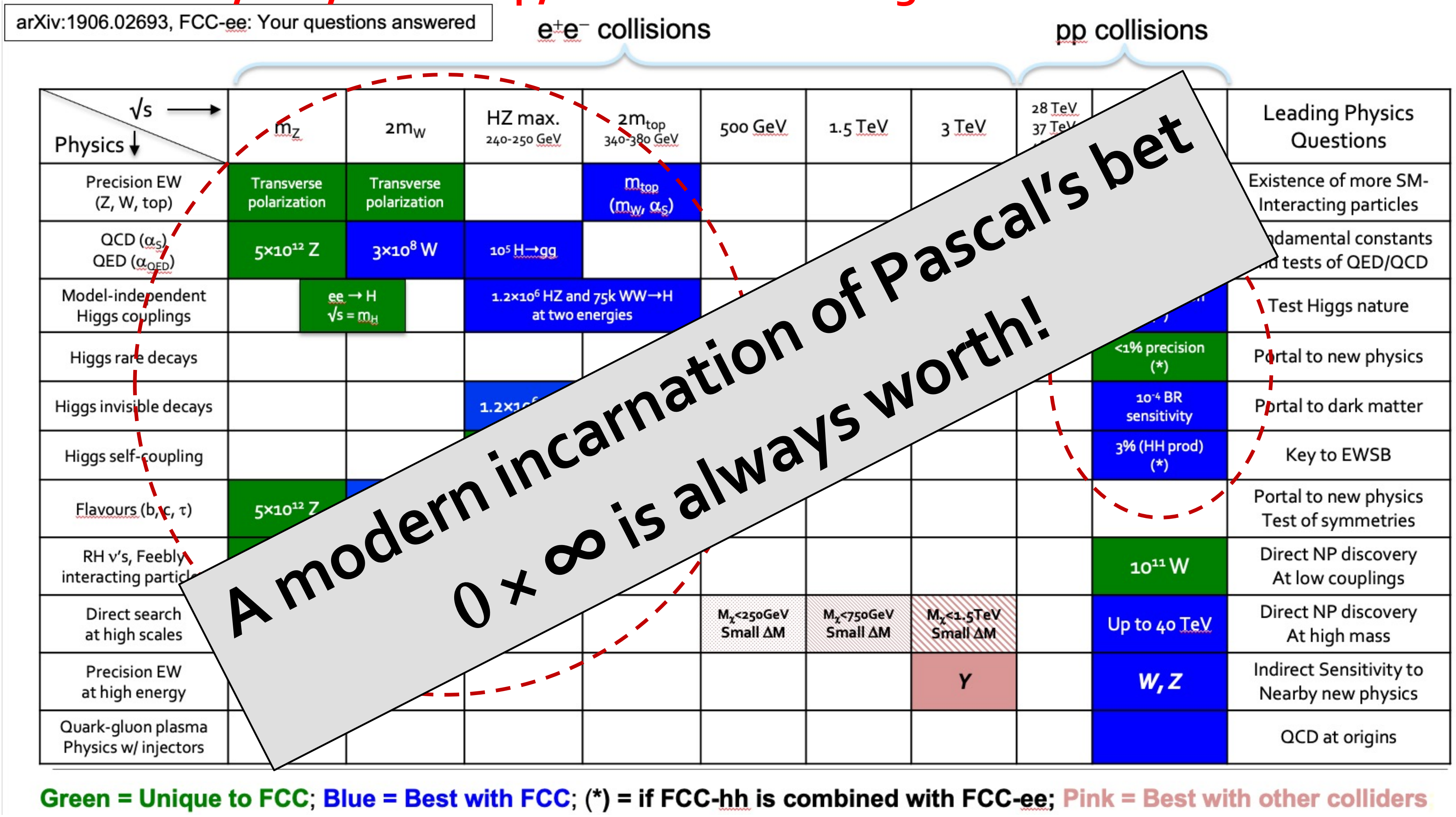
Asymmetric crossing layout at IP minimises synchrotron radiation

Bottom line:
Synchrotron Radiation in detectors similar to that we had in LEP

- SR photons from the last bend followed through the interaction region and the CLD tracker
  - Full GEANT4 simulation predicts no hits in the detector from SR all the way to √s = 240 GeV
    - At √s = 365 GeV, hits in the central tracker suppressed by additional shielding. VTX 1st layer occupancy ~ 10^{-4}
      - ➔ Being revisited as we speak (including the need for shielding) with the old and new IR designs
      - ➔ Effect of synchrotron radiation in the IDEA drift chamber will follow

The case for FCC-ee: Summary (I)

- The FCC-ee case is clear, rich, and sharp, both on its own right and in combination with FCC-hh



arXiv:1906.02693, FCC-ee: Your questions answered

$\sqrt{s}$ → Physics ↓	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		Leading Physics Questions
Precision EW (Z, W, top)	Transverse polarization	Transverse polarization		m_{top} (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							ndamental constants nd 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							Test Higgs nature
Higgs rare decays									<1% precision (*)	Portal to new physics
Higgs invisible decays			1.2×1						10^{-4} BR sensitivity	Portal to dark matter
Higgs self-coupling									3% (HH prod) (*)	Key to EWSB
Flavours (b, c, τ)	5×10^{12} Z									Portal to new physics Test of symmetries
RH ν's, Feebly interacting partic									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

A modern incarnation of Pascal's bet

$0 \times \infty$ is always worth!

- The ultimate "multi-messenger" collider, with a unique capability to search on many different fronts
  - And with a small, albeit finite, probability for a discovery in each of the searches and measurements

The case for FCC-ee: Summary (II)

- The proposed FCC-INT is large, expensive, and therefore must be ambitious
  - The tunnel circumference is optimal at both the intensity and the energy frontiers
    - Provide the necessary luminosity and energies for studying all particles of the Standard Model in FCC-ee
    - Guarantees a significant jump in energy reach for the hadron collider FCC-hh

  - Other proposed (linear) Higgs factories
    - Are considerably less broad in physics ability, while environmentally considerably less friendly
    - Not much cheaper, and actually significantly more expensive when the route to 100 TeV is considered

  - The ratio "science value / investment" can be maximised, as the ring is compatible with 4 detectors
    - Provide an overall net gain both in ab^{-1} and in kg CO_2-eq (or MWh) per ab^{-1}
    - Allow for a range of detector solutions to cover all physics opportunities
    - Increase the interest of the community for FCC
    - Strengthen robustness of systematic uncertainty estimates and of discovery claims
    - Improve the many measurements / potential discoveries that are statistically limited
    - Open several key physics targets that are tantalizingly close (but missed) with the current setup
      - ➔ Instead, a reduction of the RF power significantly would reduce the science-value-to-investment ratio

  - FCC-ee offers precious time flexibility for high-field magnet R&D and for budget profile optimization
    - There is enough valuable, and often unique, physics to do for as long as needed, even with 4IPs.

Outlook

See M. Benedikt's presentation

- The FCC-ee is becoming a very concrete collider project
  - With the steady progress of the technical feasibility study
    - And the in-depth contacts with the representatives of the local population

- The FCC-ee arguably offers the best science value for the (long-term) investment
  - With the smallest energy consumption and carbon footprint per physics outcome
  - With the most ambitious scientific prospects for the many decades to come
  - Will be driving computational change forward (quantum computing, AI, ≈ the Web @ LEP)

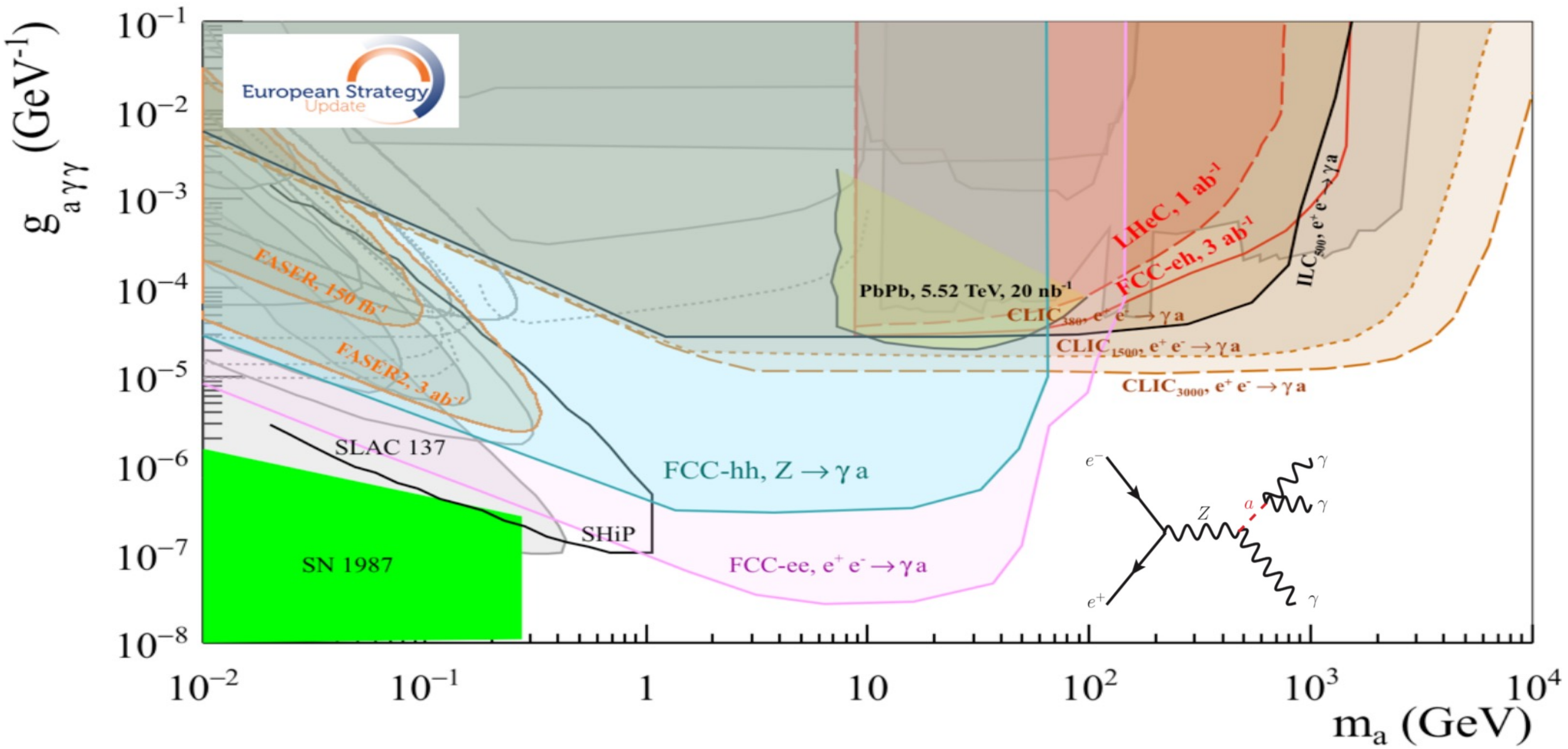
- Being provocative: It is time to unify the particle physicist community around FCC-ee
  - The artificially maintained competition in Europe between Higgs factories is confusing
    - … and may even be dangerous for Europe and CERN (with, e.g., CEPC in China)
  - The funding agencies will support at most one project
    - Meanwhile, the resources are far too scarce for physics and experiments studies in all of them
  - The young generation is expecting a clear signal before actually committing

- CERN Council can tremendously help in this perspective

Additional material

Direct discovery potential: The Dark Sector

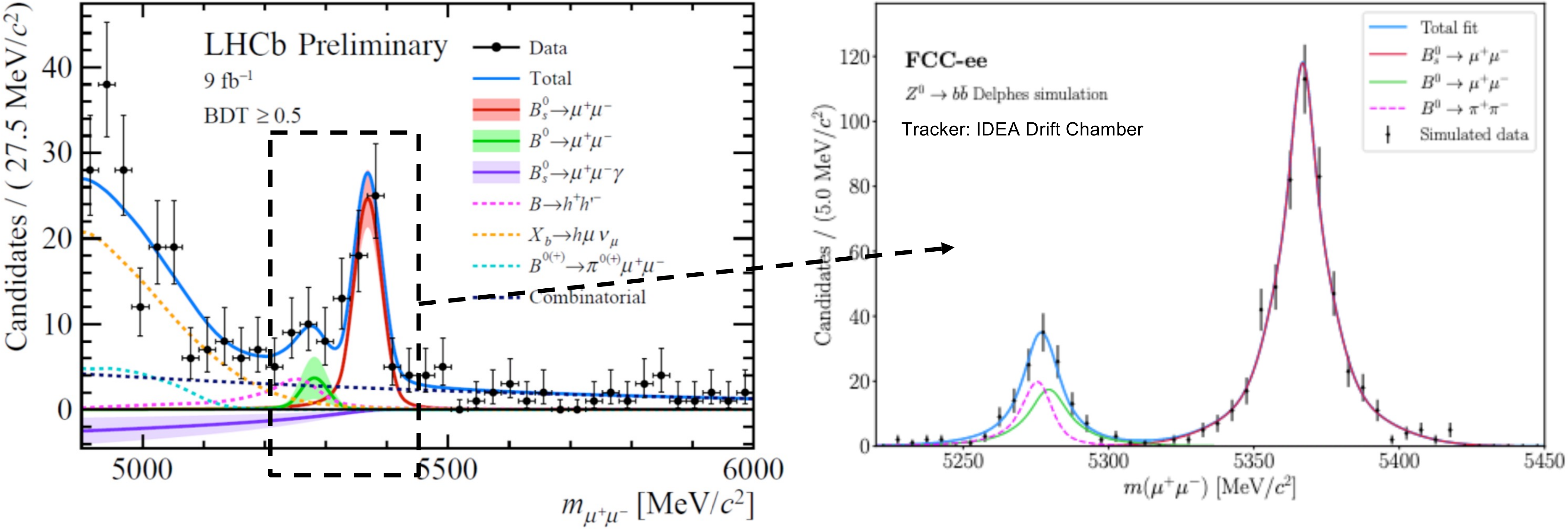
- Similar situation for Axion-Like Particles (ALPS): Luminosity is key to the game



- FCC-ee also has sensitivity to dark photons sensitivity, e.g., through $\bar{\gamma} \to a\gamma$, $a \to \gamma\bar{\gamma}$

Flavour: a great mystery for HEP

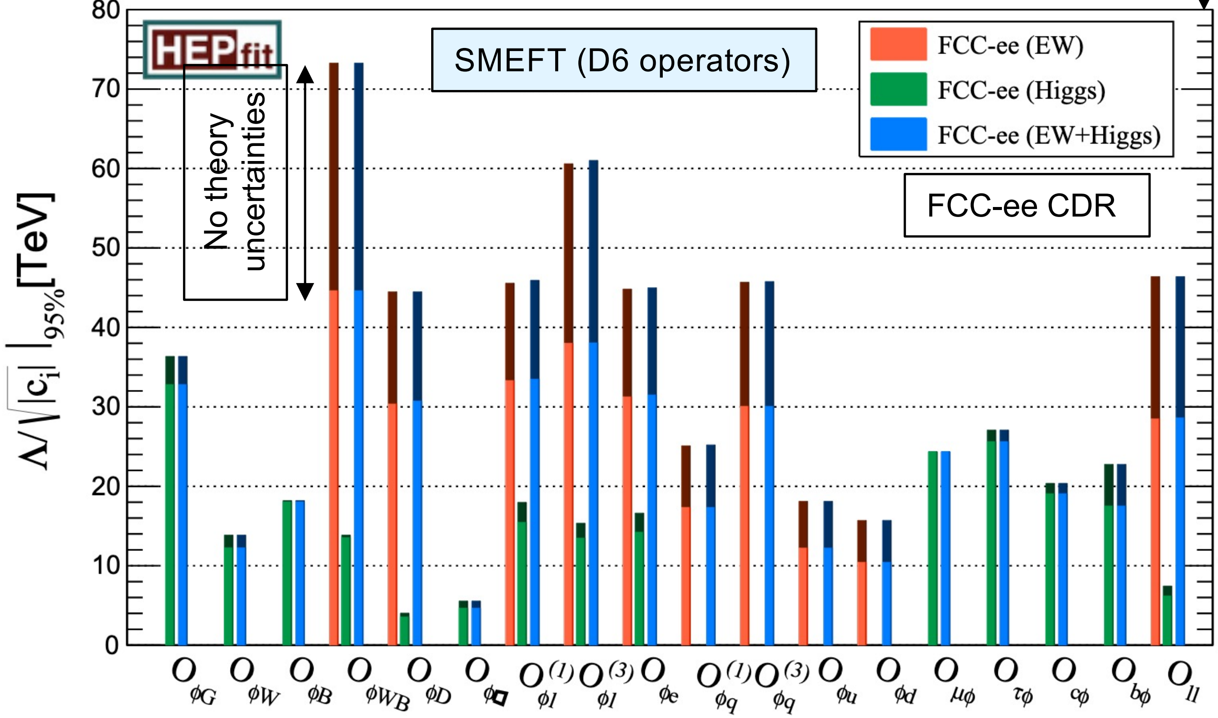
- With 4 IPs, and five years at √s = 91.2 GeV (or with 3 times larger specific luminosity)
  - Even the $B_{s,d} \rightarrow \mu\mu$ sample would be of the same size as that of LHCb Upgrade 2
    - But much better resolved (tracking performance) : more sensitivity to New Physics.

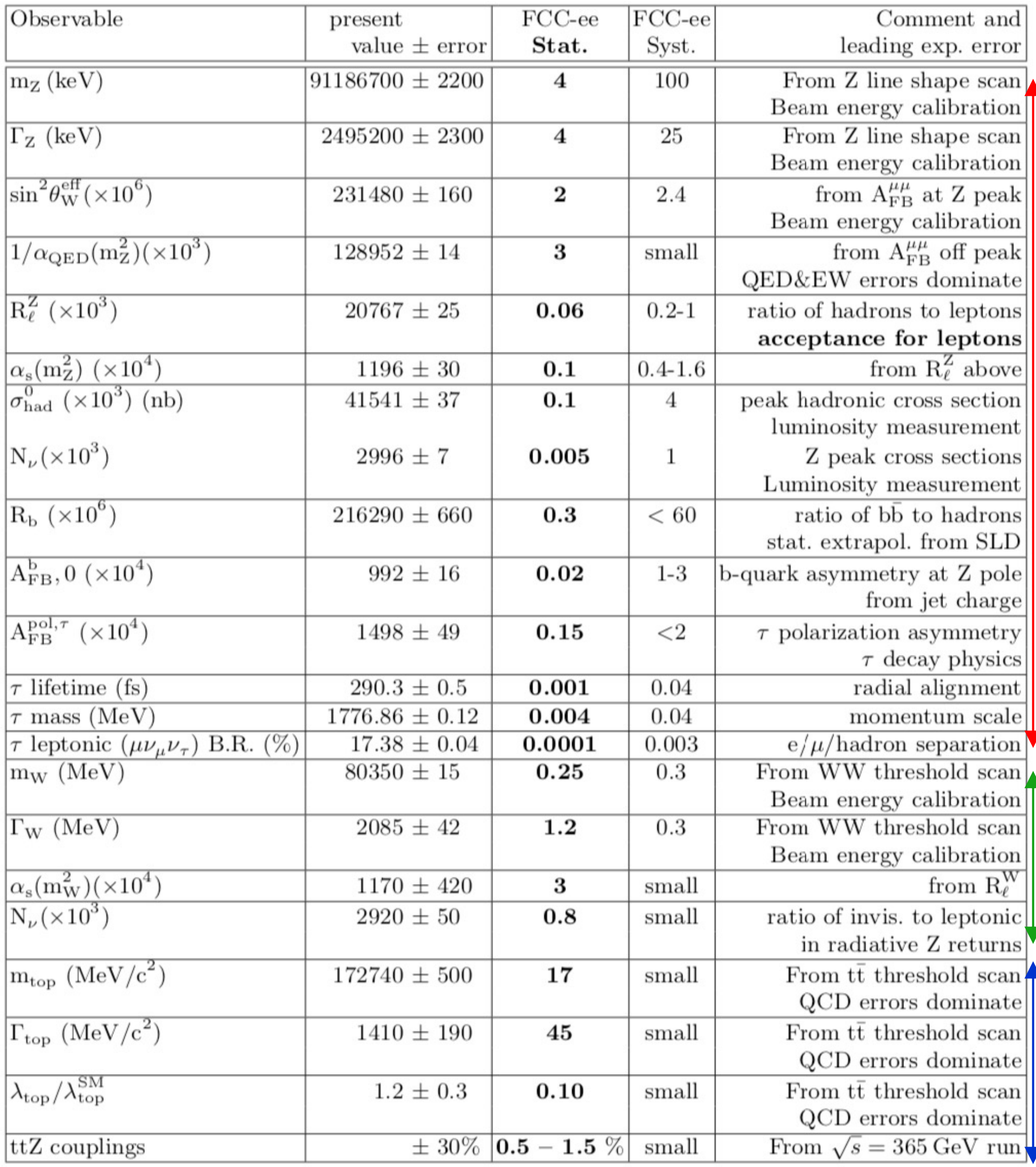


Precision EW measurements

arXiv:2106.13885

- **Many interconnected measurements**
  - The whole FCC-ee run plan is essential (Z,W,top)
  - Complementary to Higgs for New Physics
  - Huge statistics → precision
    - Real chance of discovery
  - Most of the work is (will be) on systematics
    - Experimental and theoretical





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
$\sin^2\theta_W^{\rm eff}(\times 10^6)$	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
$\sigma^0_{\rm had}$ $(\times 10^3)$ (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
$A_{FB}^{{\rm pol},\tau}$ $(\times 10^4)$	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
$m_{\rm top}$ (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\Gamma_{\rm top}$ (MeV/c^2)	1410 ± 190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{\rm top}/\lambda_{\rm top}^{\rm SM}$	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

Z

W

top

Higgs performance as a function of luminosity

- ❑ **Most of the Higgs properties measured at FCC-ee are statistics-limited**
  - ◆ Higgs couplings to fermions and bosons, normalized to σ_{ZH}
    - Fixed candle to past and future pp colliders (g_{HZZ})

      [Also g_{Hgg}]
  - ◆ Other Higgs properties
    - Higgs width, Higgs mass, CP violation, …
  - ◆ Changing the luminosity by a factor 5 …
    - … would change their precision by a factor 2.2
    - … challenges increment from HL-LHC to FCC-INT
    - … affects new physics sensitivity scale by a factor 1.5

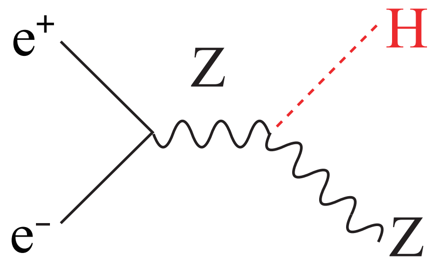
Collider	HL-LHC	FCC-ee$_{240\to365}$	FCC-INT	
Lumi (ab^{-1})	3	5 + 0.2 + 1.5	30	
Years	10	3 + 1 + 4	25	
g_{HZZ} (%)	1.5	0.18 / 0.17	0.17/0.16	ee
g_{HWW} (%)	1.7	0.44 / 0.41	0.20/0.19*	
g_{Hbb} (%)	5.1	0.69 / 0.64	0.48/0.48	
g_{Hcc} (%)	SM	1.3 / 1.3	0.96/0.96	
g_{Hgg} (%)	2.5	1.0 / 0.89	0.52/0.5	
$g_{H\tau\tau}$ (%)	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

- ❑ **Some are close to discovery level at FCC-ee**
  - ◆ Higgs self coupling (1-5σ ?): a fundamental question!
    - Via loop diagrams @ FCC-ee: complementary to HH production @ FCC-hh
  - ◆ Electron Yukawa coupling with s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s}$ = 125 GeV
    - Highly demanding in integrated luminosity, and requires very accurate m_H knowledge (~ 2 MeV)
- ❑ **Some FCC-hh measurements (top Yukawa, Higgs self-coupling) depend on FCC-ee**

Higgs self-coupling @ HL-LHC and FCC-ee

- **Sensitivity of the fit obtained fixing the HZZ coupling to its SM value**



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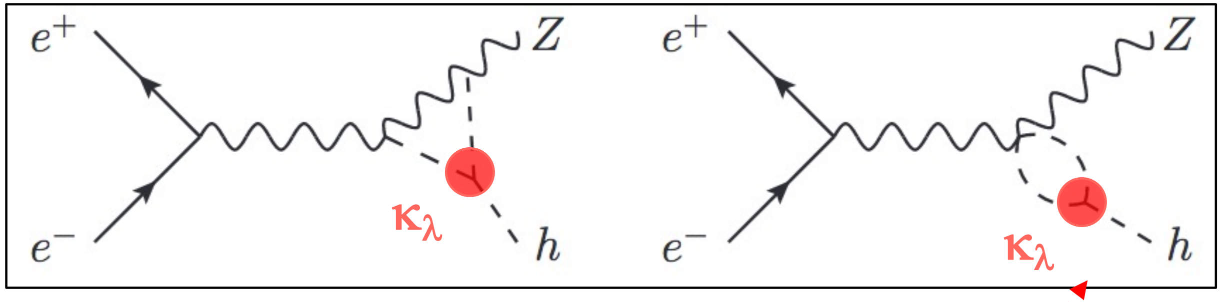
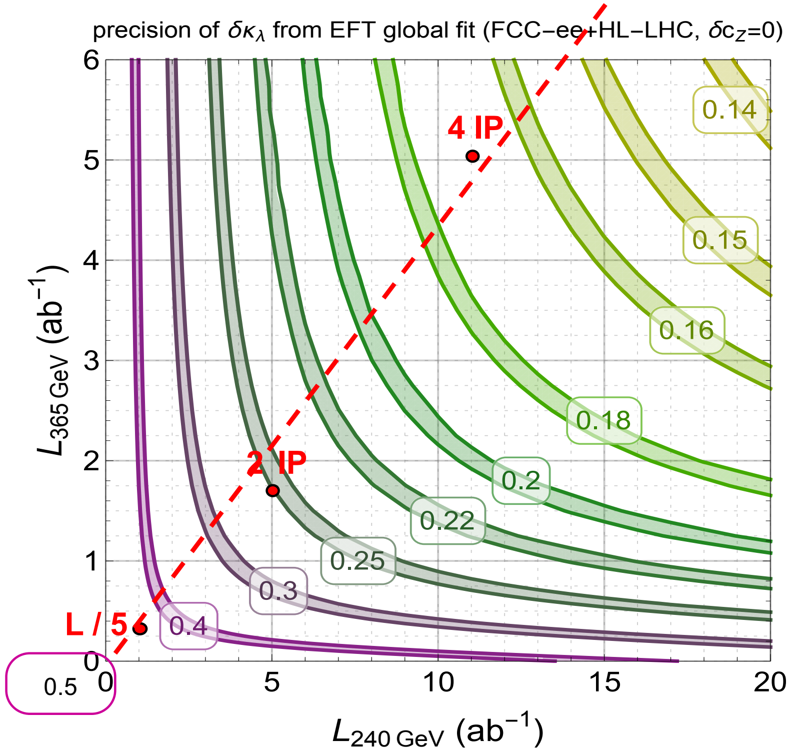
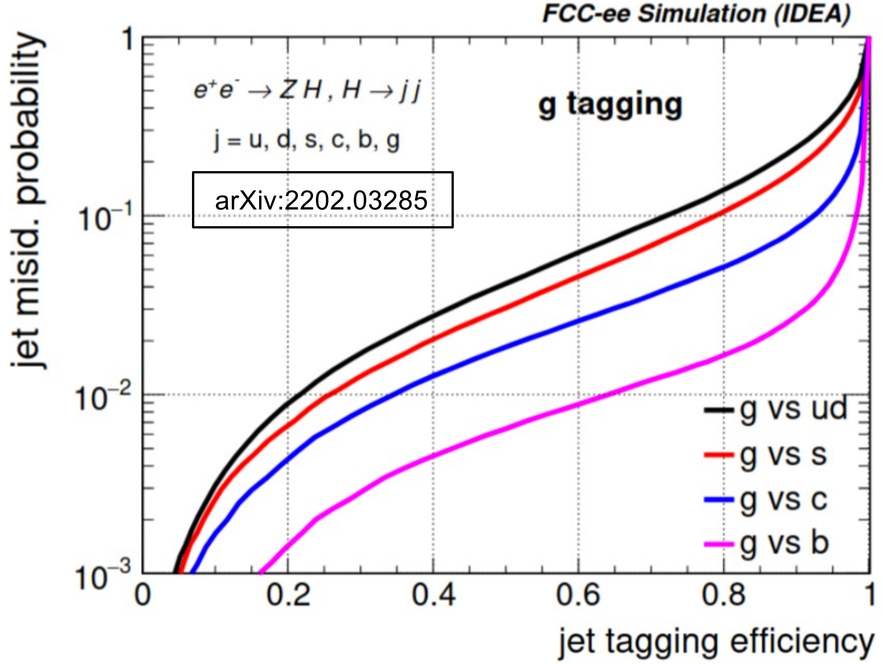


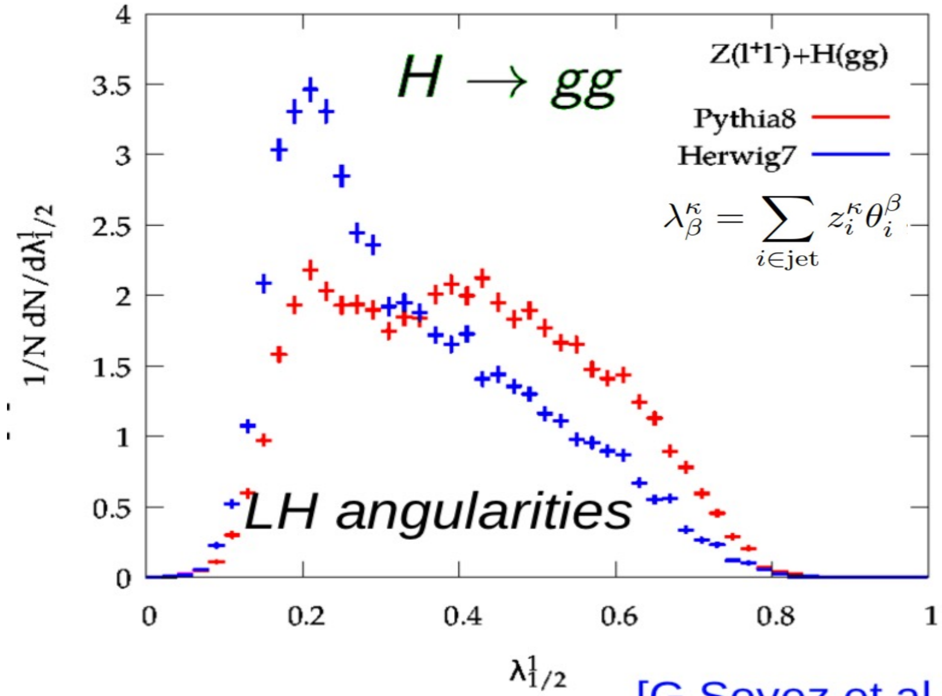
- Fit shown in slide 18: global EFT fit
  - HL-LHC data cannot constrain all parameters
- Fit shown here similar to that with HL-LHC data
  - Only self coupling is allowed to vary
    - ➔ 50% precision with HL-LHC only
  - With L/5 : no improvement wrt to HL-LHC
  - With 2 IPs : 4σ from $\kappa_\lambda = 0$
  - With 4 IPs : 6σ from $\kappa_\lambda = 0$



QCD studies with H → gg

- Quark-gluon discrimination is an essential tool to enhance hadronic (B)SM signals (*)
  - Several handles exist (e.g., ML approaches), but not clear how they can be trusted





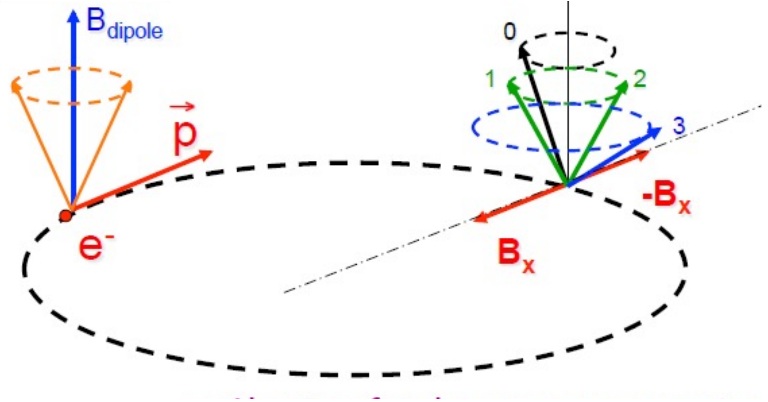
[G.Soyez et al.]

- Exploit FCC-ee as "pure gluon" factory with 10^5 H → gg events
  - To understand better gluon radiation, showering, and hadronization
    - And tune the Monte Carlo programmes towards a trustworthy q/g discrimination evaluation
- Statistics is of the essence

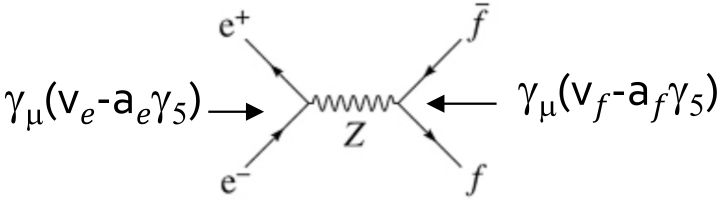
(*) Even at FCC-hh

Transverse and Longitudinal Polarisation

- At the Z pole (and WW thresh.), beam transverse polarisation = √s determination
  - Precession frequency $\nu_0 = E_{beam}/0.4406486$
  - Kicker with freq. ν_0 provokes sharp depolarization
    - Reach ppm precision on √s (100 keV → 10 keV?)
  - All EWPOs depends critically on √s
    - Lineshape parameters, of course, but also asymmetries



- At the Z pole, beam longitudinal polarisation = full statistical power for asymmetry parameters



$a_f = \pm 1/2$

$v_f = a_f(1 - 4|Q_f|\sin^2\theta^\ell_{eff})$

Asymmetry parameter

$$\boxed{A_f = \frac{2a_f v_f}{v_f^2 + a_f^2}}$$

$$\boxed{A_{LR} = \frac{\sigma_{tot}(P) - \sigma_{tot}(-P)}{\sigma_{tot}(P) + \sigma_{tot}(-P)} = PA_e}$$

$$\boxed{A_{FB}^{polf} = \frac{\sigma_{Ff}(P) - \sigma_{Ff}(-P) - [\sigma_{Bf}(P) - \sigma_{Bf}(-P)]}{\sigma_{totf}(P) + \sigma_{totf}(-P)} = \frac{3}{4}PA_f}$$

Polarisation parameter

$$P = \frac{P_{e^-} - P_{e^+}}{(1 - P_{e^-}P_{e^+})}$$

- Longitudinally Unpolarized beams still produce longitudinally polarised fermions (Z couplings)
  - Longitudinal polarization of the τ's obtained from the decay particle spectrum (π, ρ, etc.)

$$\boxed{\langle P_\tau \rangle = \frac{\sigma_{R\tau} - \sigma_{L\tau}}{\sigma_{R\tau} + \sigma_{L\tau}} = -A_\tau}$$

$$\boxed{A_{FB}^{pol\tau} = \frac{\sigma_{RF\tau} - \sigma_{LF\tau} - [\sigma_{RB\tau} - \sigma_{LB\tau}]}{\sigma_{R\tau} + \sigma_{L\tau}} = -\frac{3}{4}A_e}$$

$$\boxed{A_{FB}^{f} = \frac{\sigma_{Ff} - \sigma_{Bf}}{\sigma_{Ff} + \sigma_{Bf}} = \frac{3}{4}A_e\,A_f}$$

Transverse and Longitudinal Polarisation

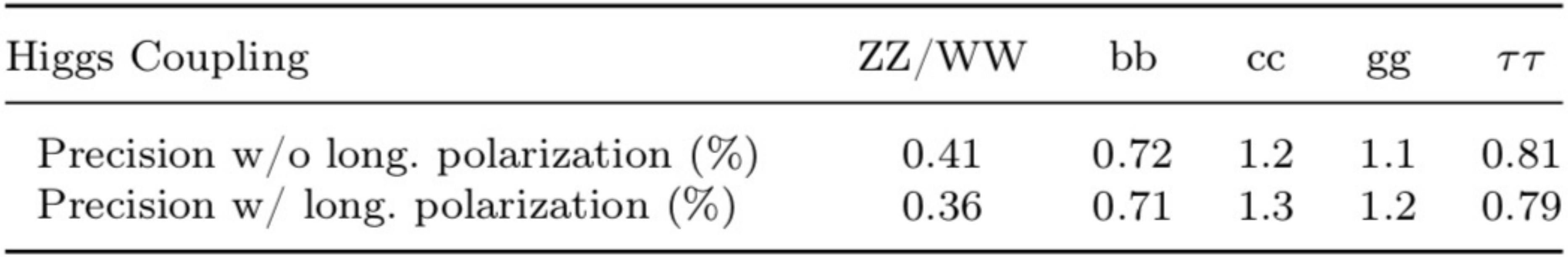
- Longitudinal polarisation brings no information that cannot be obtained with more statistics

Observables	Present value ($\times10^4$)	TeraZ / GigaZ stat.	TeraZ / GigaZ current syst.	Theory input (not exhaustive)
A_e from P_τ (FCC-ee)	1514 ± 19	0.07	0.20	SM relation to measured quantities
A_e from A_{LR} (ILC)		0.15	0.80	
A_μ from A_{FB} (FCC-ee)	1456 ± 91	0.23	0.22	Accurate QED (ISR, IFI, FSR)
A_μ from A_{FB}^{pol} (ILC)		0.30	0.80	
A_τ from P_τ (FCC-ee)	1449 ± 40	0.05	2.00	Prediction for non-τ backgrounds
A_τ from A_{FB} (FCC-ee)		0.23	1.30	
A_τ from A_{FB}^{pol} (ILC)		0.30	0.80	
A_b from A_{FB} (FCC-ee)	8990 ± 130	0.24	2.10	QCD calculations
A_b from A_{FB}^{pol} (ILC)		0.90	5.00	
A_c from A_{FB} (FCC-ee)	65400 ± 210	2.00	1.50	
A_c from A_{FB}^{pol} (ILC)		2.00	3.70	

◆ But transverse polarisation and statistics bring lots of information unavailable otherwise

Transverse and Longitudinal Polarisation

- **Higgs coupling uncertainties with one million Higgs bosons produced**
  - At √s = 250 GeV, from a global EFT fit
    - With and without longitudinal polarisation



Higgs Coupling	ZZ/WW	bb	cc	gg	$\tau\tau$
Precision w/o long. polarization (%)	0.41	0.72	1.2	1.1	0.81
Precision w/ long. polarization (%)	0.36	0.71	1.3	1.2	0.79

Extrapolated from arXiv:1903.01629

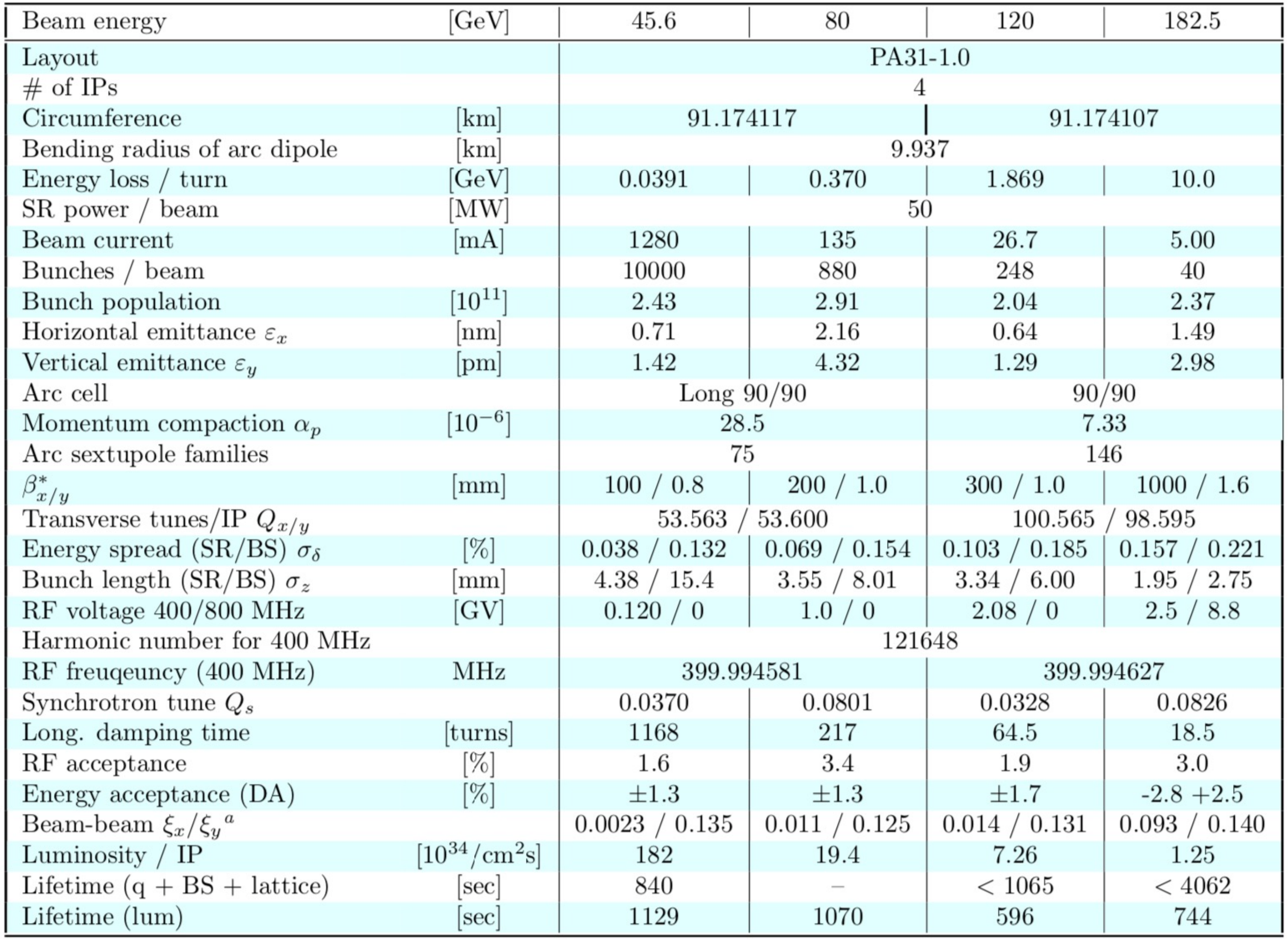
Carbon footprint of the FCC tunnel construction ?

- ❑ Carbon footprint of an electric vehicle
  - ◆ In France, it takes 30,000 km to compensate for CO2 emissions from its production
    - It pays off after three years
    - Batteries are fully recyclable

- ❑ Carbon footprint of solar panels
  - ◆ In France, it takes three years to compensate for CO2 emissions from their production
    - They pay off after three years
    - Most recent models are 99% recyclable

- ❑ Carbon footprint of FCC tunnel, based on the carbon footprint of existing tunnels
  - ◆ The FCC tunnel footprint corresponds to ~ 3 years of FCC-ee operation at $\sqrt{s} = 240$ GeV
    - It pays off after three years
    - It is fully recyclable
      - ➔ Can be entirely re-used, e.g., for FCC-hh
  - ◆ The FCC tunnel footprint is dominated by concrete production
    - An industrial process to reduce concrete production footprint has just been launched in France

FCC-ee parameters



Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-1.0			
# of IPs		4			
Circumference	[km]	91.174117		91.174107	
Bending radius of arc dipole	[km]	9.937			
Energy loss / turn	[GeV]	0.0391	0.370	1.869	10.0
SR power / beam	[MW]	50			
Beam current	[mA]	1280	135	26.7	5.00
Bunches / beam		10000	880	248	40
Bunch population	[10^{11}]	2.43	2.91	2.04	2.37
Horizontal emittance ε_x	[nm]	0.71	2.16	0.64	1.49
Vertical emittance ε_y	[pm]	1.42	4.32	1.29	2.98
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.5		7.33	
Arc sextupole families		75		146	
$\beta^*_{x/y}$	[mm]	100 / 0.8	200 / 1.0	300 / 1.0	1000 / 1.6
Transverse tunes/IP $Q_{x/y}$		53.563 / 53.600		100.565 / 98.595	
Energy spread (SR/BS) σ_δ	[%]	0.038 / 0.132	0.069 / 0.154	0.103 / 0.185	0.157 / 0.221
Bunch length (SR/BS) σ_z	[mm]	4.38 / 15.4	3.55 / 8.01	3.34 / 6.00	1.95 / 2.75
RF voltage 400/800 MHz	[GV]	0.120 / 0	1.0 / 0	2.08 / 0	2.5 / 8.8
Harmonic number for 400 MHz		121648			
RF freuqeuncy (400 MHz)	MHz	399.994581		399.994627	
Synchrotron tune Q_s		0.0370	0.0801	0.0328	0.0826
Long. damping time	[turns]	1168	217	64.5	18.5
RF acceptance	[%]	1.6	3.4	1.9	3.0
Energy acceptance (DA)	[%]	±1.3	±1.3	±1.7	-2.8 +2.5
Beam-beam $\xi_x/\xi_y{}^a$		0.0023 / 0.135	0.011 / 0.125	0.014 / 0.131	0.093 / 0.140
Luminosity / IP	[10^{34}/cm^{2}s]	182	19.4	7.26	1.25
Lifetime (q + BS + lattice)	[sec]	840	–	< 1065	< 4062
Lifetime (lum)	[sec]	1129	1070	596	744

SuperKEKB performance in 2022

- Compared to KEKB and SuperKEKB initial design

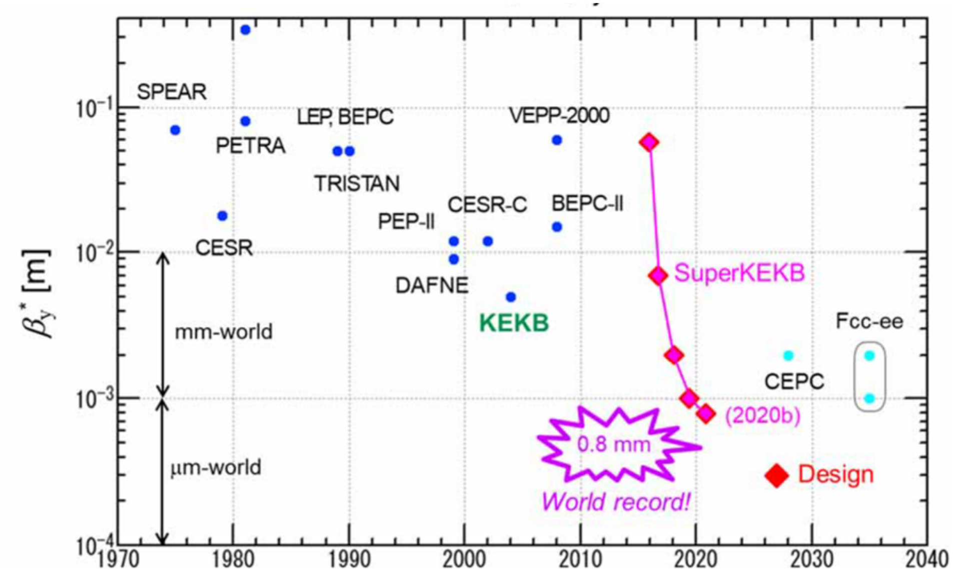
parameter	KEKB w Belle		SuperKEKB 2022 w Belle II		SuperKEKB Design	
			β_y^* = 1.0 mm CW			
	LER	HER	LER	HER	LER	HER
E [GeV]	3.5	8	4	7	4	7
β_x^* (mm)	1200	1200	**80**	**60**	**32**	**25**
β_y^* (mm)	5.9	5.9	**1.0**	**1.0**	**0.27**	**0.30**
ε_x (nm)	18	24	**4.0**	**4.6**	3.2	4.6
ε_y (pm)	150	150	**~45**	**~45**	**8.6**	**12.9**
I (mA)	**1640**	**1190**	**1321**	**1099**	**3600**	**2600**
n_b	1584		**2249**		2500	
I_b (mA)	1.04	0.75	**0.587**	**0.489**	1.44	1.04
ξ_y *	**0.098**	**0.059**	**0.041**	**0.028**	0.069	0.060
L_{sp} (10^{30}cm^{-2}s^{-1} mA^{-2})	17.1		**72.1**		214	
L (10^{34}cm^{-2}s^{-1})	2.11		4.65		80	

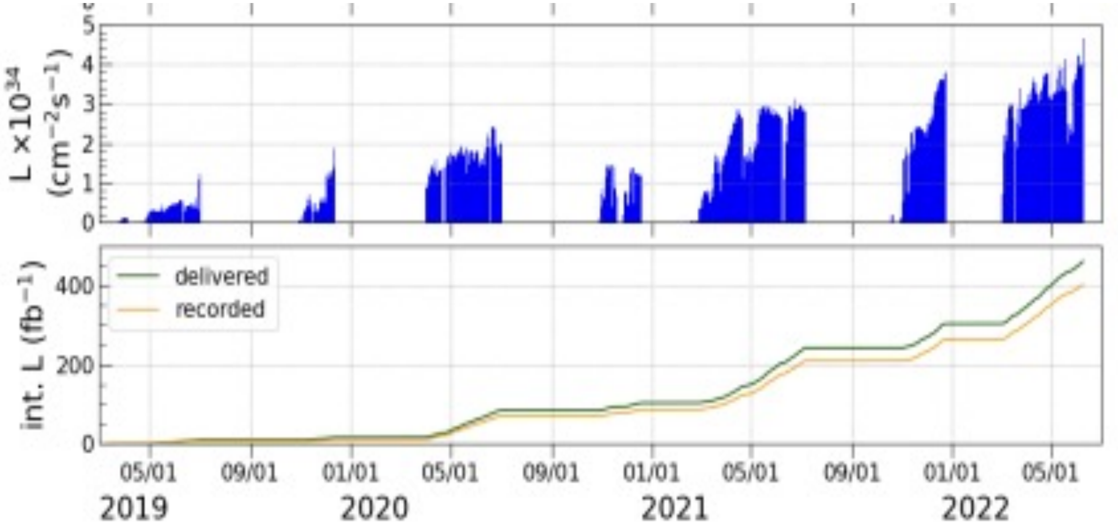
SuperKEKB as a FCC-ee demonstrator

- Tested successfully FCC-ee-type "virtual crab waist collisions

K. Oide, Phys. Rev. Accel. Beams 19, 111005)

- Run routinely with smallest β_y^* ever considered for FCC-ee: 1mm and 0.8mm





- World-record luminosity of 4.71×10^{34} cm^{-2}s^{-1} , and counting.

- e^+ production rate similar to FCC-ee: feasibility shown
  - Top-up injection with short beam lifetime (< 10 mins) demonstrated

SuperKEKB challenges

- Design luminosity was too optimistic
  - Twice larger than simulated for ideal case w/o impedance and w/o errors
    - By contrast, FCC-ee luminosity projections are not guessed. They are simulated, with impedance and errors

- Sudden beam losses, presently avoided by bunch currents significantly lower than design
  - Such losses did not occur in previous machines (PEP-II and KEKB), even at much higher currents
    - Reason not yet identified, but seems specific to SuperKEKB (Feedback noise? Dust? …?)

- Overlap of solenoid field and final focus quadrupole field
  - Aberration tentatively corrected (maybe not successfully?) by skew sextupoles
    - By contrast, FCC-ee design perfectly separates the solenoid and final quads

- Big emittance blow-up in the injection line (by factors 10-100 from Linac to collider)
  - This transport line is inherited from TRISTAN and KEKB, which did not require low emittance
    - By contrast, FCC-ee will have a new transport line, with new magnets, and w/o sharp bends

- Vertical emittance still 3-5 times too large and β_y^* still 3-4 times larger than design
  - Progress are slown down by the limited IR aperture and the large emittance of the injected beam
    - Lessons learnt towards FCC-ee

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International Task Force formed in 2021 to address these challenges

FCC-ee experts contributing