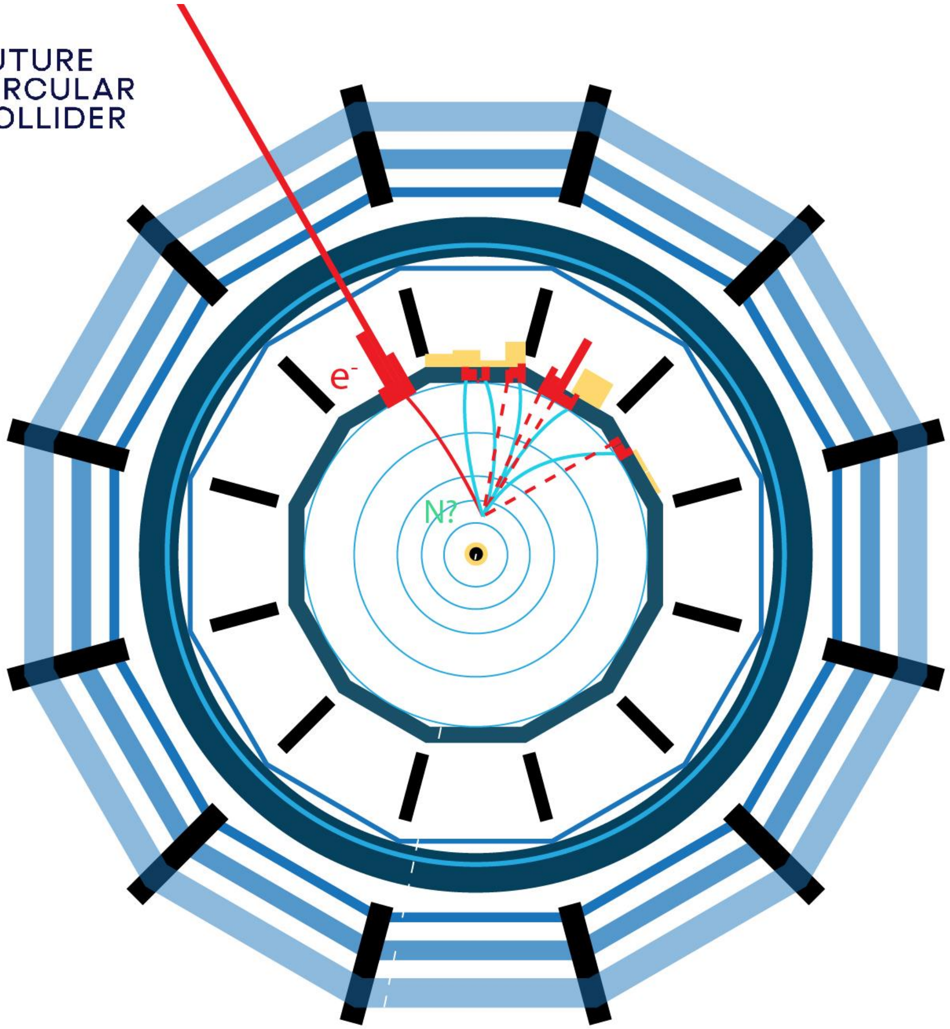
FCC Physics



Emphasis here on FCC-ee:
A great `Higgs Factory' and MUCH MORE!

Many thanks to the FCC collaboration members
for the great efforts and ideas
joining Theory, Experiment and Accelerator Physics
And congratulations/thanks to
Florencia Canelli, Anna Sfyrla, ahmin Ilg and all organizers
of this second FCC-CHIPP physics meeting

Particle physics after the discovery of the Higgs boson

Two facets:

The Higgs boson is very special

It generates (couples to) mass. Alone?

-- W,Z masses ⇔ Higgs coupling to WW, ZZ? FCC-ee

-- (all) fermion masses ⇔ Higgs couplings? FCC-ee

FCC-hh(+ee) decays ($\gamma\gamma$, gg, Zγ) ⇔ SM particle content?

-- are all elementary particles given mass this way?

FCC-ee(?) even electrons? and even the neutrinos?

Yukawa (→ ν_R , sterile)

+ Majorana ($\nu \leftrightarrow \bar{\nu}$) → HNL? FCC-ee

It couples to itself!

-- Spontaneous Symmetry Breaking

-- What is the value of the self coupling?

-- impact on σ_{HZ} near threshold FCC-ee

-- HH production FCC-hh

FCC-hh, high energy lepton colliders

The SM is « complete »

-- Higgs and top masses predicted from EWPOs

assuming no new SM coupled particles exist

-- SM extrapolates to the Plank scale

assuming no new SM coupled particles exist

-- SM works wonderfully... **So why continue?**

-- But SM does not explain everything

Baryon Asymmetry of the Universe

Dark Matter

and more.... → require new particles!

mass scale is unknown

FCC-ee: EWPO Flavour

Are there any further SM-coupled particles?

-- no guarantee or solid indication that there are

-- but many BSM solutions include them.. FCC-hh

-- DARK SECTOR → possibly light, sterile particles

FCC-ee: LLP EWPO Flavour

After the discovery of the Higgs boson we enter a new era of exploration

We absolutely need a next accelerator but the next facility must be versatile (and feasible!) with as broad and powerful reach as possible, as there is no precise target

➔ more Sensitivity, more Precision, more Energy

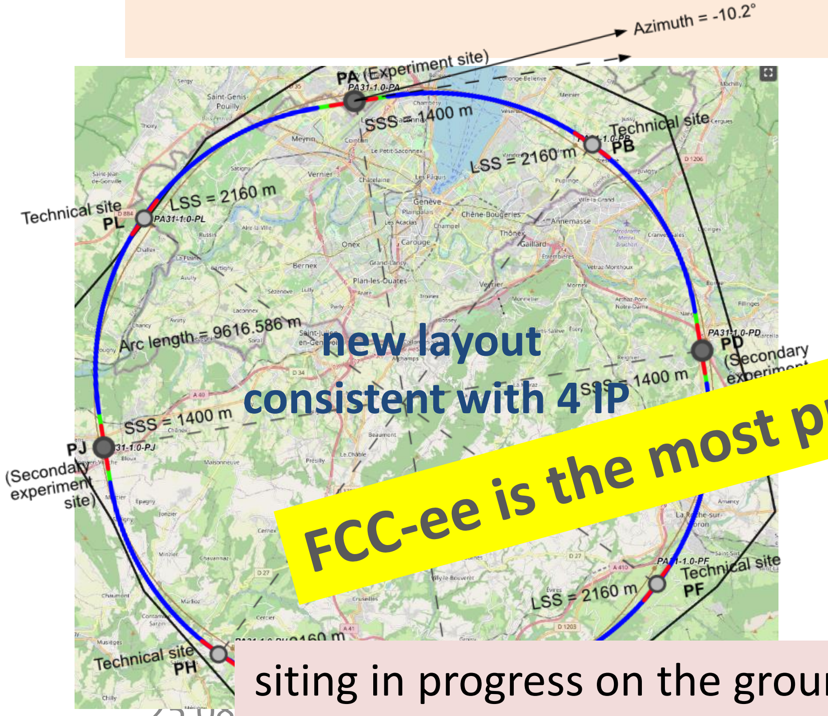
FCC, thanks to synergies and complementarities, offers the most versatile and adapted response to today's physics landscape

Synergy: The FCC integrated program at CERN

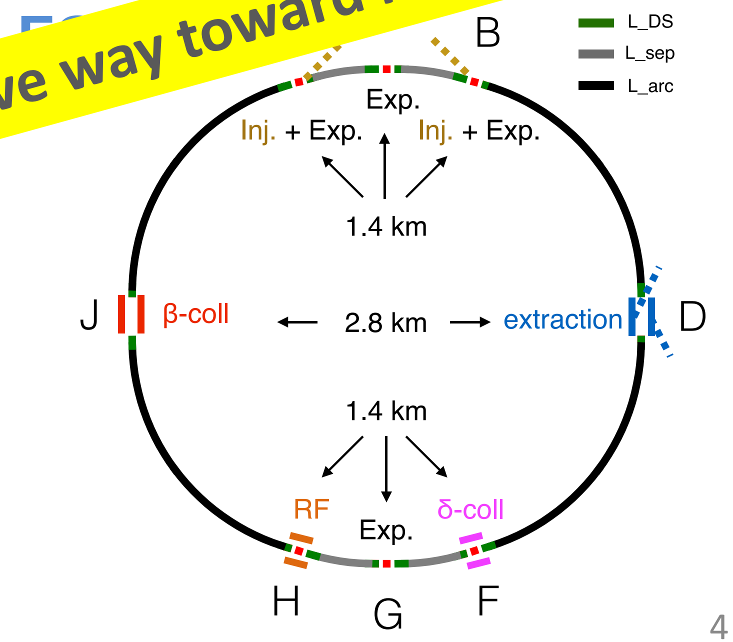
Comprehensive cost-effective program inspired by successful LEP – LHC success story

- **Stage 1: FCC-ee (Z, W, H, tt) as first generation Higgs EW and top factory at highest luminosities.**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options.**
- **Maximizes physics output with strong complementarity**
- Integrating an ambitious high-field magnet R&D program
- Common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure.
- **Start construction early 2030's, start data taking shortly after HL-LHC completion**
- **FCC-INT project plan is fully integrated with HL-LHC exploitation ➔ seamless continuation of HEP**
- **Feasibility study approved and funded at CERN (100MCHF/5yrs) + magnet R&D (120 MCHF/6yrs)**

***** GLOBAL COLLABORATION *****



FCC-ee

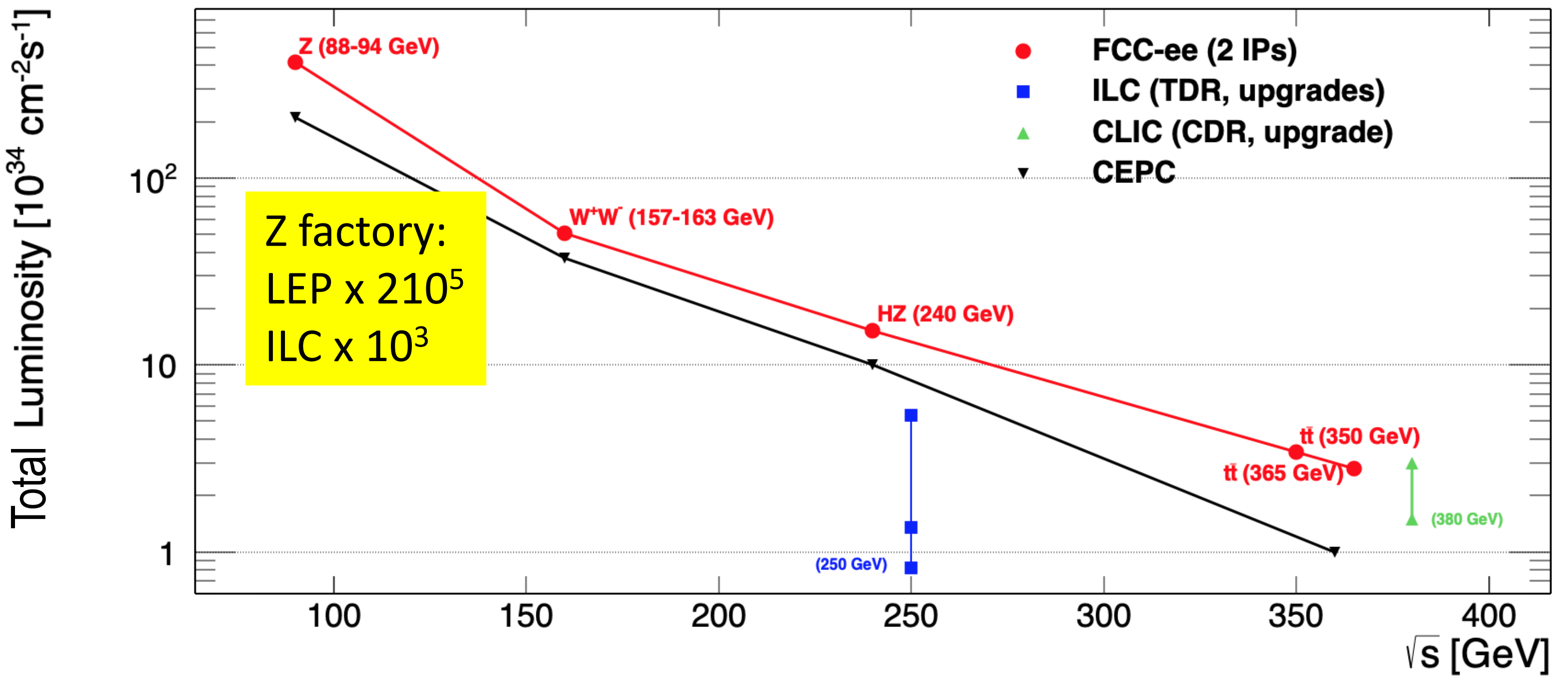


FCC-ee is the most pragmatic, safest, and most effective way toward FCC-hh

siting in progress on the ground.
It.is.happening!

FCC-ee

Great energy range for the heavy particles of the Standard Model



notes:

-- 4IP increases Total Lumi by 1.7

-- 2IP assumed in all numbers below

-- order and duration of Z/WW/ZH can be decided at a later stage

-- ee→ H must be after both Z and ZH and before tt

see back-ups for facility comparisons

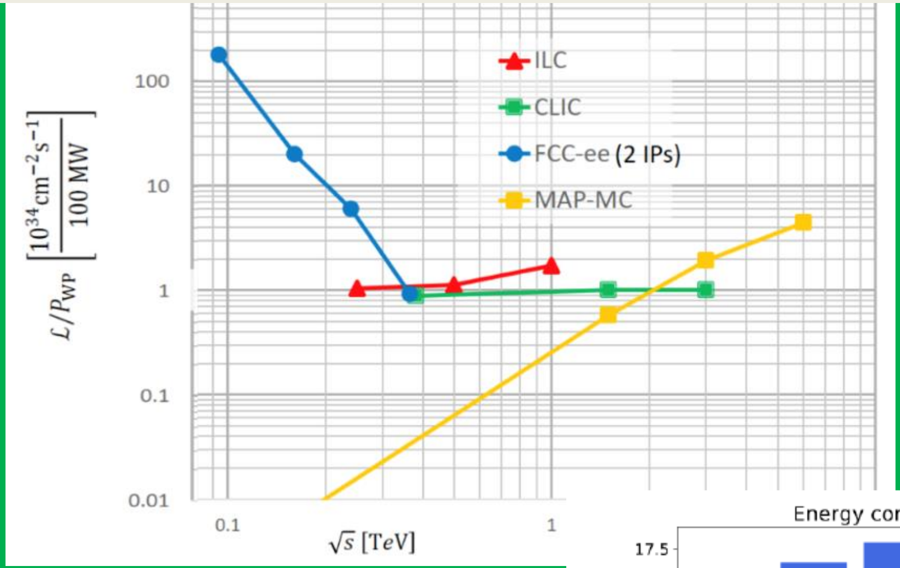
Event statistics (2IP) for typical run plan:

					E_{CM} errors:
Z peak	E_{cm} : 91 GeV	4yrs	5 10^{12} e+e- → Z	LEP x 2.10^5	<100 keV
WW threshold	E_{cm} ≥ 161 GeV	2yrs	>10^8 e+e- → WW	LEP x 2.10^3	<300 keV
ZH maximum	E_{cm} : 240 GeV	3yrs	> 10^6 e+e- → ZH	Never done	1 MeV
s-channel H	*E_{cm} : m_H*	*(3yrs?)*	*O(5000) e+e- → H*	*Never done*	*<< 1 MeV*
$t\bar{t}$	E_{cm} : ≥ 340 GeV	5yrs	10^6 e+e- → $t\bar{t}$	Never done	2 MeV

The Greenest

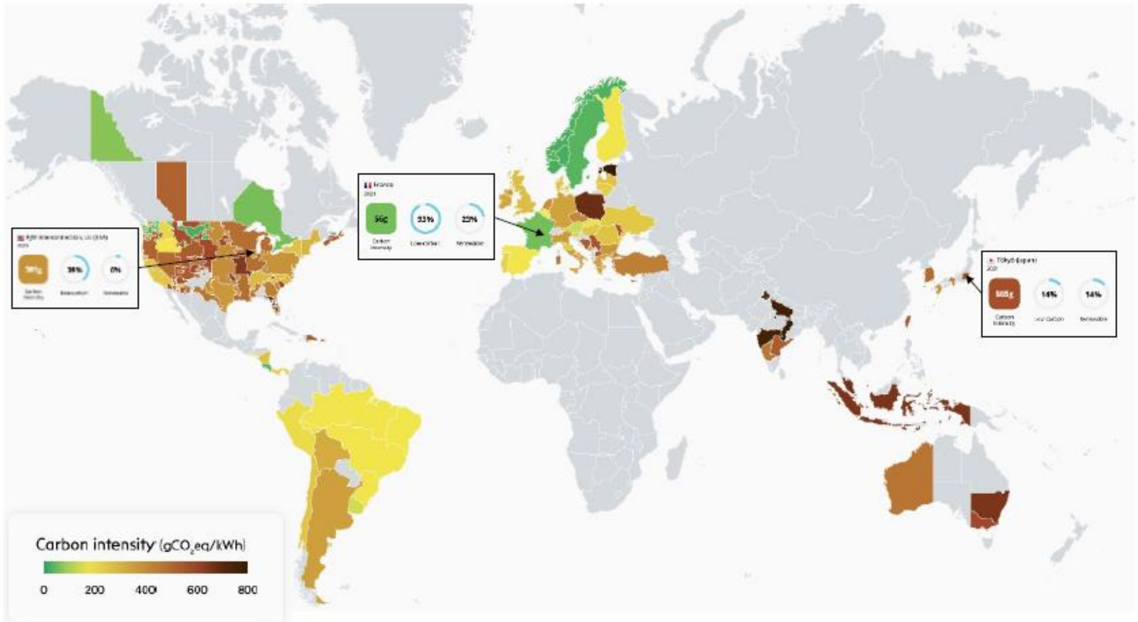
Luminosity/Power → Energy efficiency

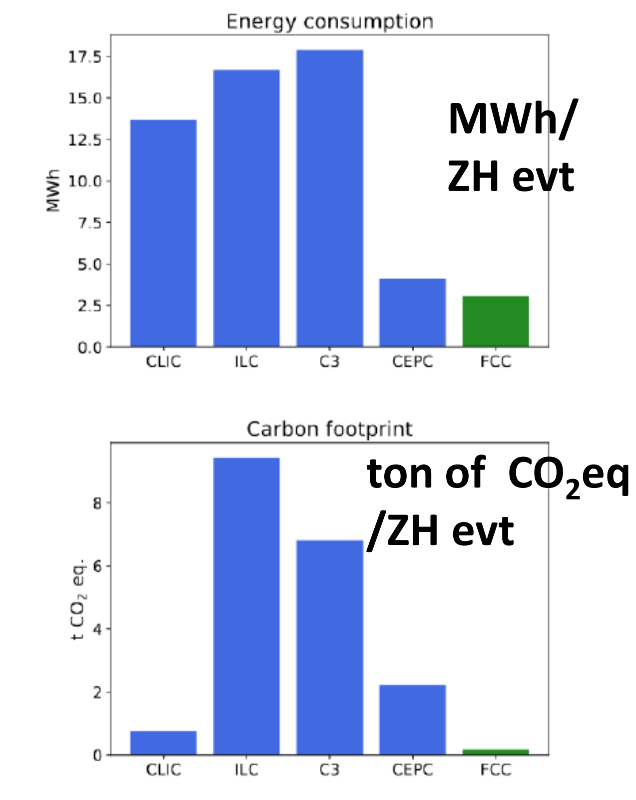
plot fromESPP Briefing Book



Compounding the higher energy efficiency at the ZH point (and below!) the FCC benefits from clean energy as France and Switzerland rely largely on low carbon footprint energy sources: nuclear, hydro, solar and wind

Fig. 1: Carbon intensity of electricity production around the world in 2021, in kgCO_2 equivalent / MWh, obtained from Ref. [22]. The carbon footprints of the energy produced in Illinois, Japan, and France, and used respectively at FNAL, KEK, and CERN, are highlighted.

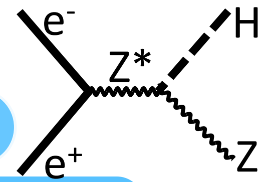


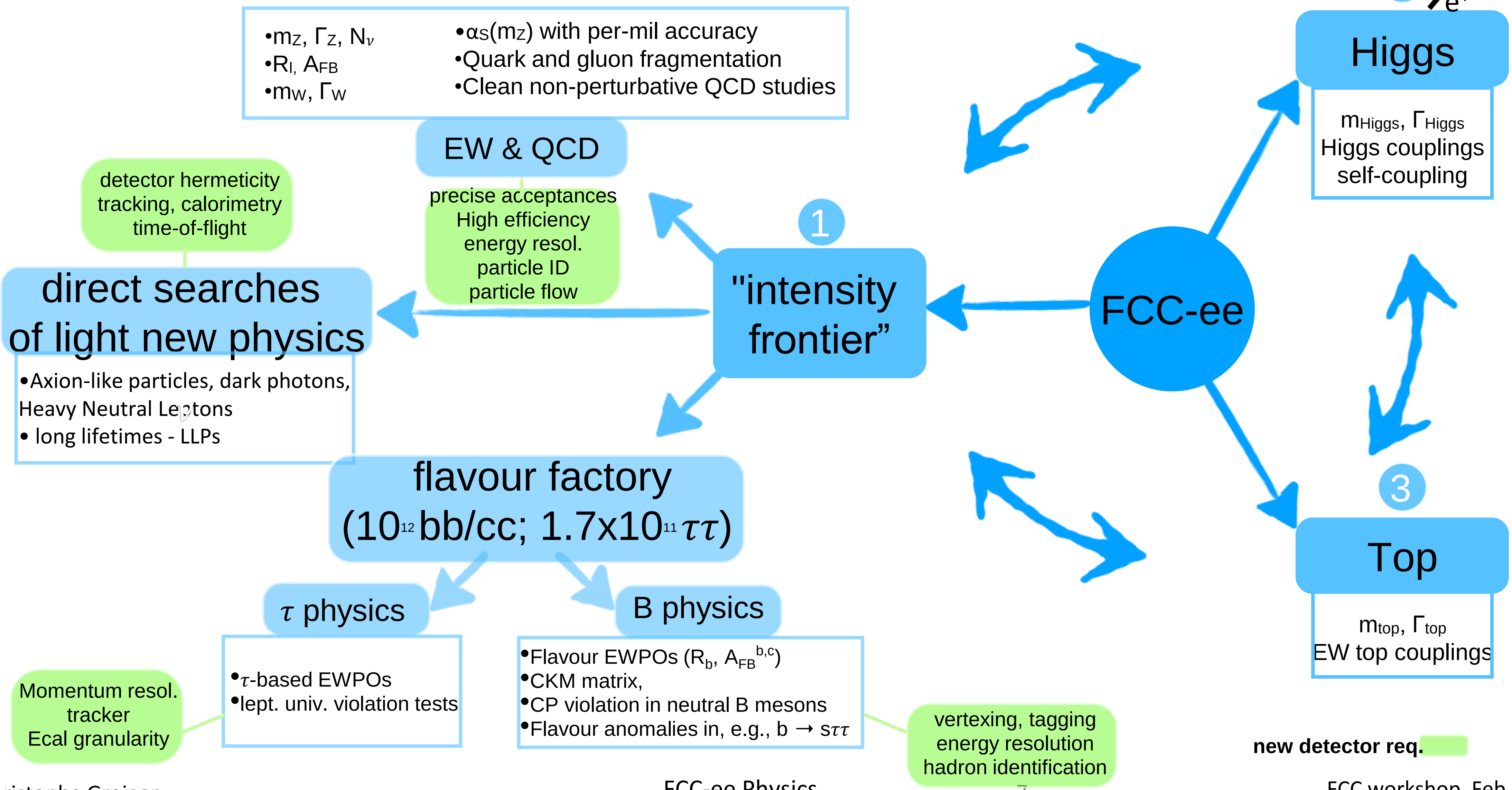


The carbon footprint of a Higgs boson is much much smaller for FCC-ee @CERN

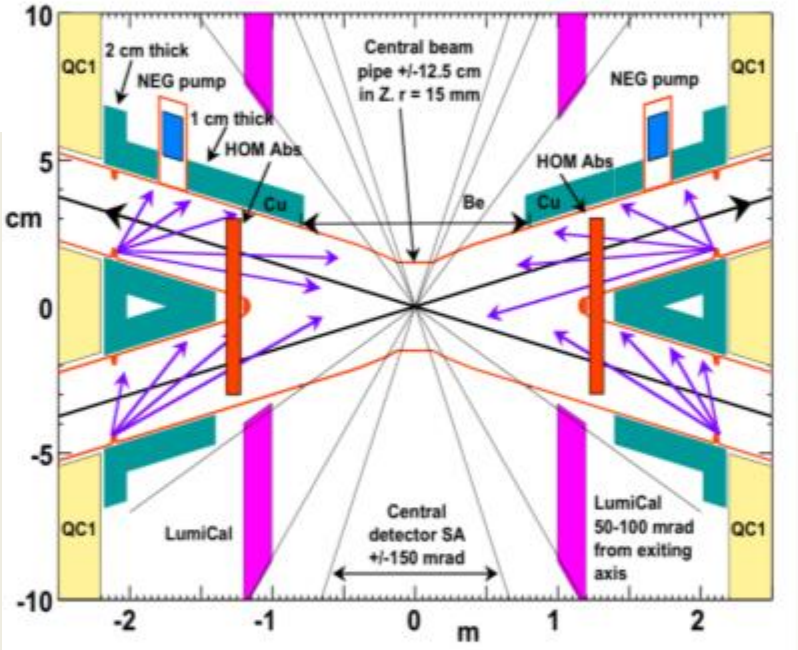
Janot, AB 2208.10466

FCC-ee Physics Programme





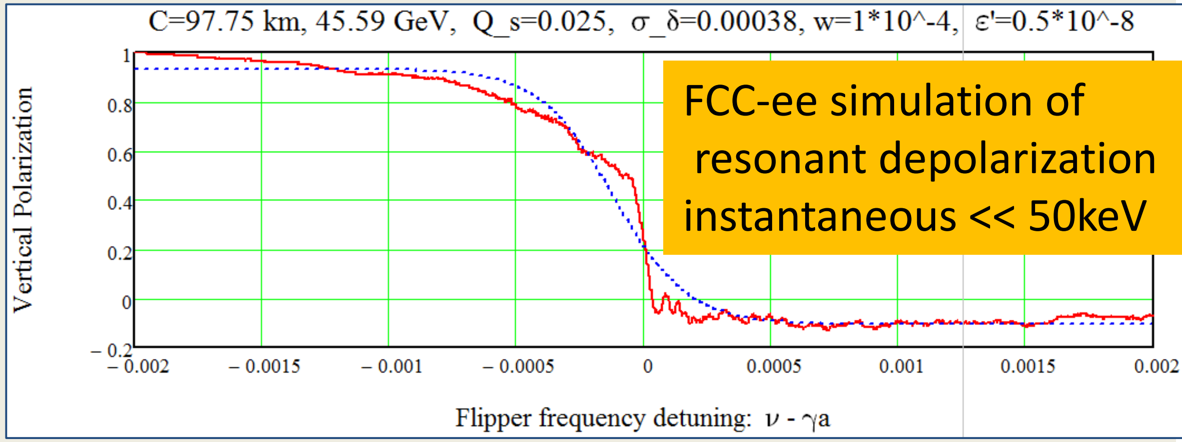
FCC-ee experimental conditions



1. By design of the accelerator, low background conditions in the experiments, ~1cm radius beam pipe

2. High luminosity → high DAQ rate, 100kHz @Z
   Low pile-up : $O(0.001)$
   No trigger necessary (important for LLP searches)

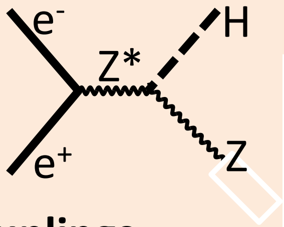
3. High precision E_{CM} calibration O(100 keV)
   --@ Z (+WW unlike LEP) resonant depolarization:
   -- at higher energies relies on ee→ Zγ , WW



4. Moderate beamstrahlung
   →measurable, ~Gaussian energy spread

5. New design compatible with 4 IP for FCC-ee → improve total Luminosity (and physics/MW) to match the multiple detector requirements

ee-hh complementarity: Higgs Physics at FCC



FCC-ee → g_{HZZ} to <±0.2% from σ_{ZH}
(model-independent)
and Γ_H, g_{Hbb} , g_{Hcc} , $g_{H\tau\tau}$, g_{HWW}
→normalizes all HL-LHC / FCC-hh couplings

also measure m_H with 2-3 MeV precision

FCC-hh produces over 10^{10} Higgs bosons
use g_{HZZ} from FCC_{ee} will give $g_{H\mu\mu}$, $g_{H\gamma\gamma}$, $g_{HZ\gamma}$, Br_{inv}

FCC-ee also measures top EW couplings ($e^+e^- \rightarrow tt$)

FCC-hh produces 10^8 ttH and 2. 10^7 HH pairs
→ g_{Htt} and g_{HHH}, model-independent & precise!

HL-LHC/FCC-ee/FCC-hh complementarity !

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	ee
g_{Hbb} (%)	5.1	0.69 / 0.64	0.48/0.48	ee
g_{Hcc} (%)	SM	1.3 / 1.3	0.96/0.96	ee
g_{Hgg} (%)	2.5	1.0 / 0.89	0.52/0.5	ee
$g_{H\tau\tau}$ (%)	1.9	0.74 / 0.66	0.49/0.46	ee
$g_{H\mu\mu}$ (%)	4.4	8.9 / 3.9	0.43/0.43	hh
$g_{H\gamma\gamma}$ (%)	1.8	3.9 / 1.2	0.32/0.32	hh
$g_{HZ\gamma}$ (%)	11.	– / 10.	0.71/0.7	hh
g_{Htt} (%)	3.4	10. / 3.1	1.0/0.95	hh
g_{HHH} (%)	50.	2 IP: 44./33. 4 IP: 27./24.	3-4	hh
Γ_H (%)	SM	1.1	0.91	ee
m_H (MeV)	30-50	3	3	hh
BR_{inv} (%)	1.9	0.19	0.024	hh
BR_{EXO} (%)	SM (0.0)	1.1	1	ee

ee only

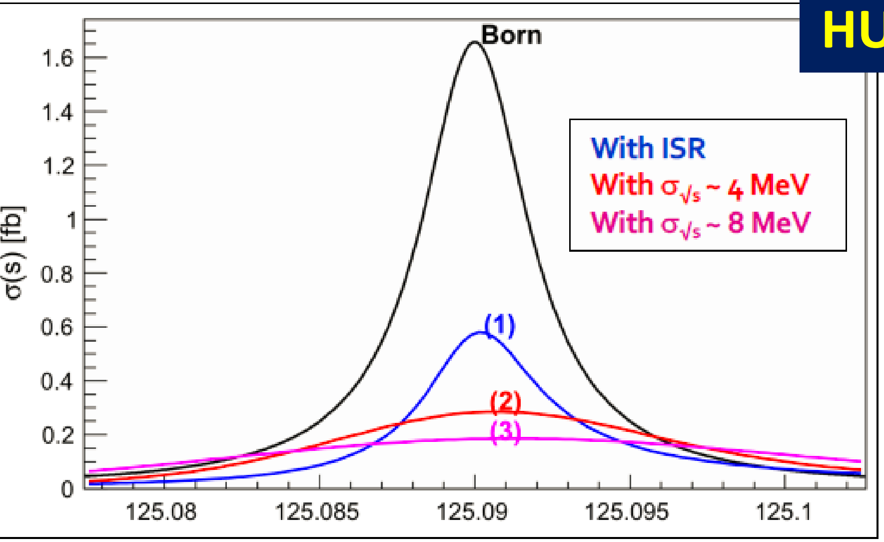
LHC +ee

FCC-ee+hh+ep
ep → WW mostly

Comparison with other e+e- colliders in spare slides

Unique: electron Yukawa @FCC-ee

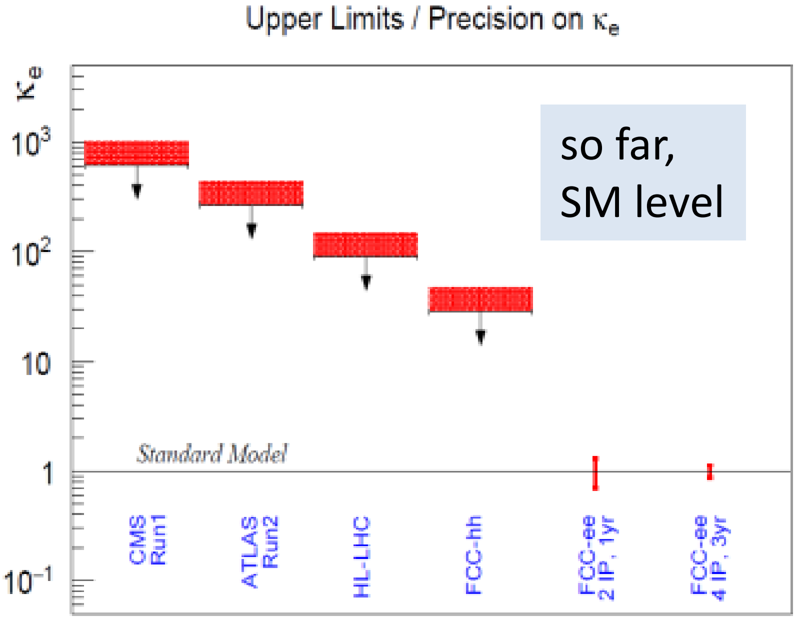
HUGE CHALLENGE



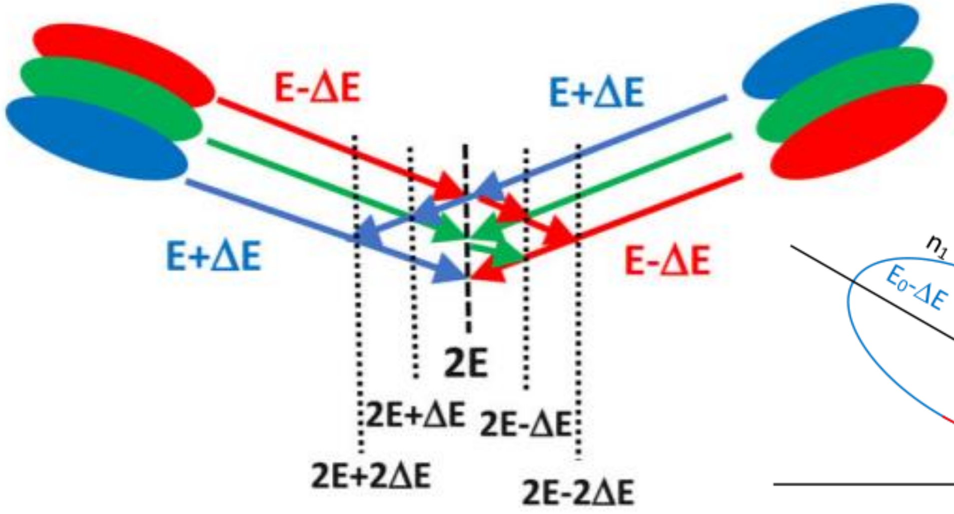
Measure e+e- → H @ 125.xxx GeV
requires

-- Higgs mass to be known to <<5 MeV (OK, 3 MeV)
-- **Huge luminosity** (several years)
-- **monochromatization** to reduce σ_{ECM}
-- **continuous adjustment of E_{CM}** (transv. Polar.)
-- an extremely sensitive event selection

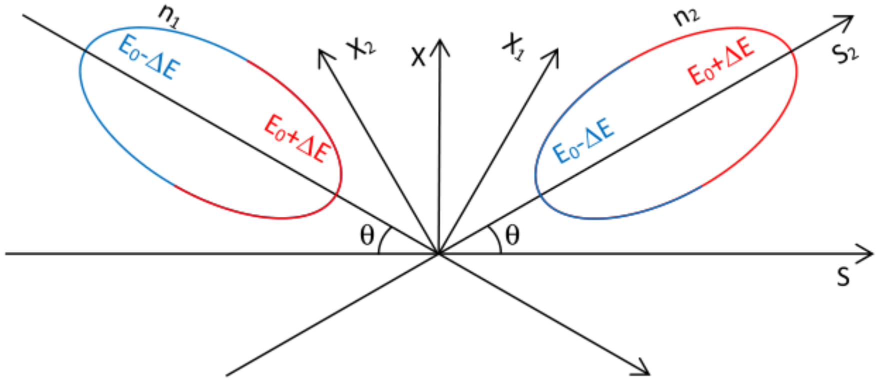
Monochromatization: **UNDER STUDY**
taking advantage of the separate e+ and e- rings, one can distribute in opposite way high and low energies in the beam (in x, z time)



so far,
SM level



combine?



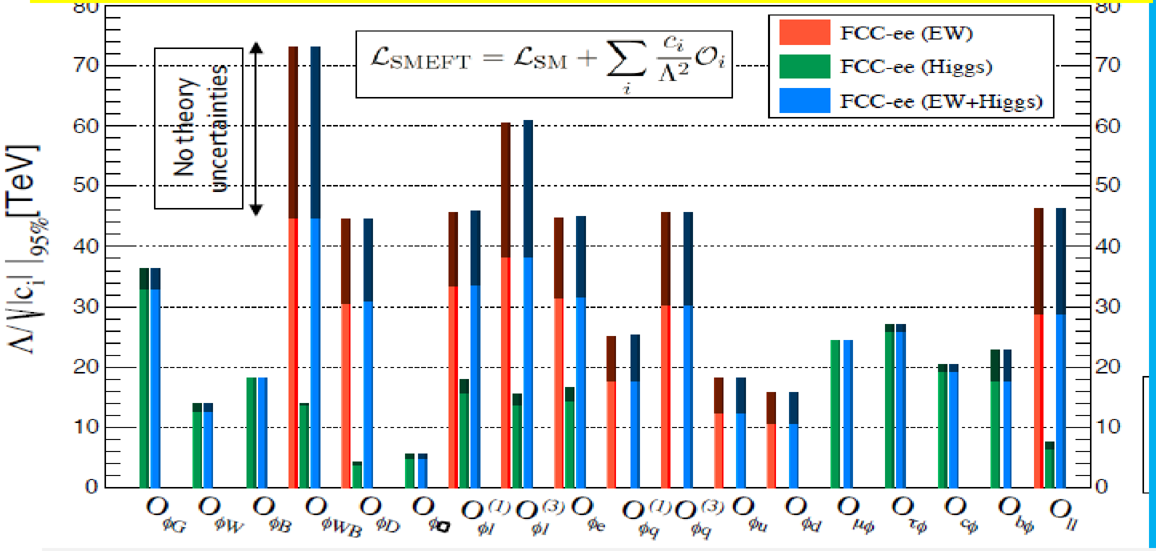
opposite sign horizontal dispersion

Alain Blondel motivational talk

opposite difference in arrival time within 30 ps

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

Precision EW measurements: is the SM complete?



NP Sensitivity by oblique/vertex loops or mixing

- ***Higgs + EWPO (+ flavours) are complementary***
- top quark mass and couplings essential!

(the 91km circumference is optimal for this)

- preliminary systematics!

aim at reducing to the level of statistics

- many observables still to be added (flavours)
- complemented by high energy FCC-hh
- ***Theory work is critical and initiated*** *1809.01830*
- *see also recent physics workshop session.*

Precision Natural SUSY at CEPC, FCC-ee, and ILC, JJ Fan, M. Rees and Liantao Wang

arXiv:1412.3107v2 figure 5 (top row)

«Higgs and EWPOs are complementary»

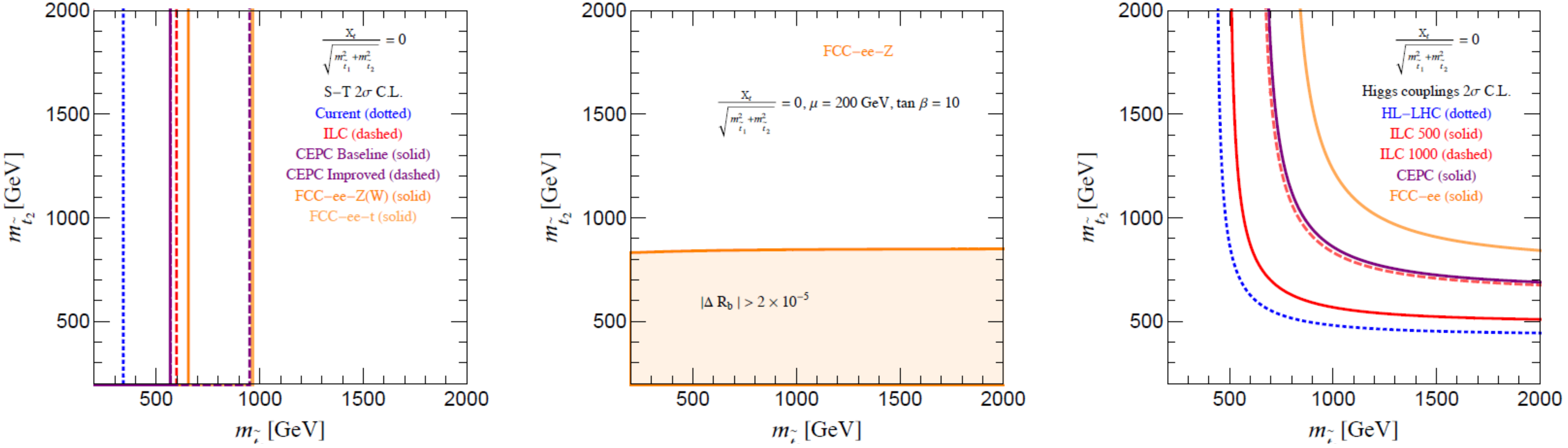


Figure 5. Regions in the stop physical mass plane that are/will be excluded at 2σ by EWPT with oblique corrections (left column), R_b at FCC-ee (mid column) and Higgs couplings (right column) for different choices of $X_t/\sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2}$: 0 (first row), 0.6 (2nd row), 1.0 (3rd row) and 1.4 (last row). We chose the mass eigenstate with $m_{\tilde{t}_1}$ to be mostly left-handed while the mass eigenstate with $m_{\tilde{t}_2}$ to be mostly right-handed. For non-zero choices of X_t, there are regions along the diagonal line which cannot be attained by diagonalizing a Hermitian mass matrix [32]. Also notice that the vacuum instability bound constrains $X_t/\sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2} \lesssim \sqrt{3}$ [76].

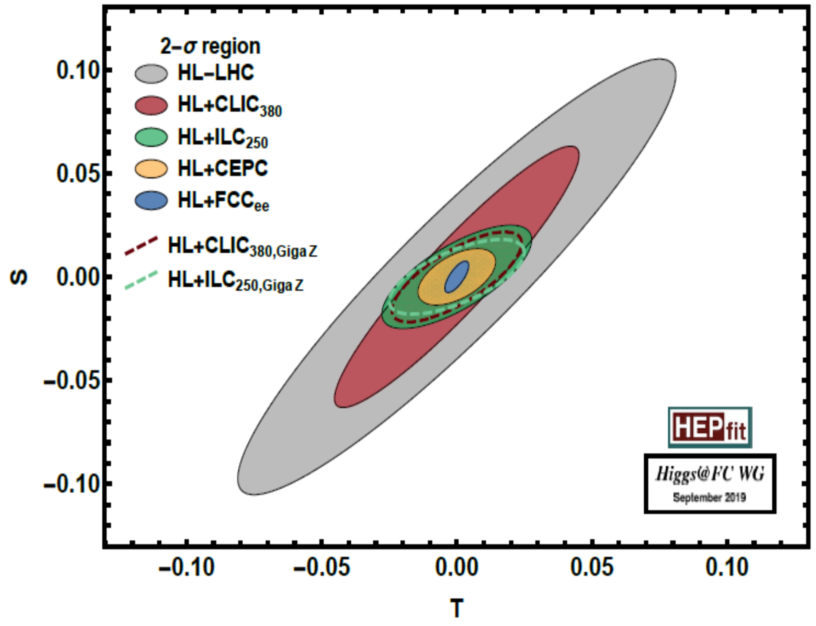
" also, b→ sγ could be useful"

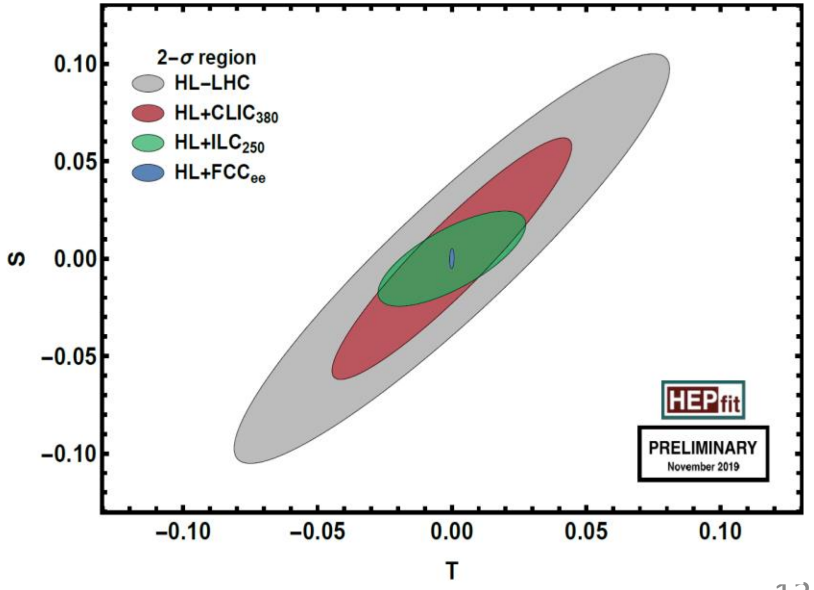
Electroweak Physics

Z factory + WW + top The realm of FCC-ee

Highest luminosities at 91, 160 and 350 GeV
Transverse pol. at 91 and 160 GeV → Ecm calibration
m_Z (100 keV) Γ_Z (25 keV), m_W (<500 keV), $\alpha_{QED}(m_Z)$ (3.10^{-5})
and $\sin^2\theta_W$ at 310^{-6}

Complete set of EW observables can be measured
Precision unique to FCC-ee + new physics sensitivity
→ a lot more potential to exploit with good detector design than present treatment suggests

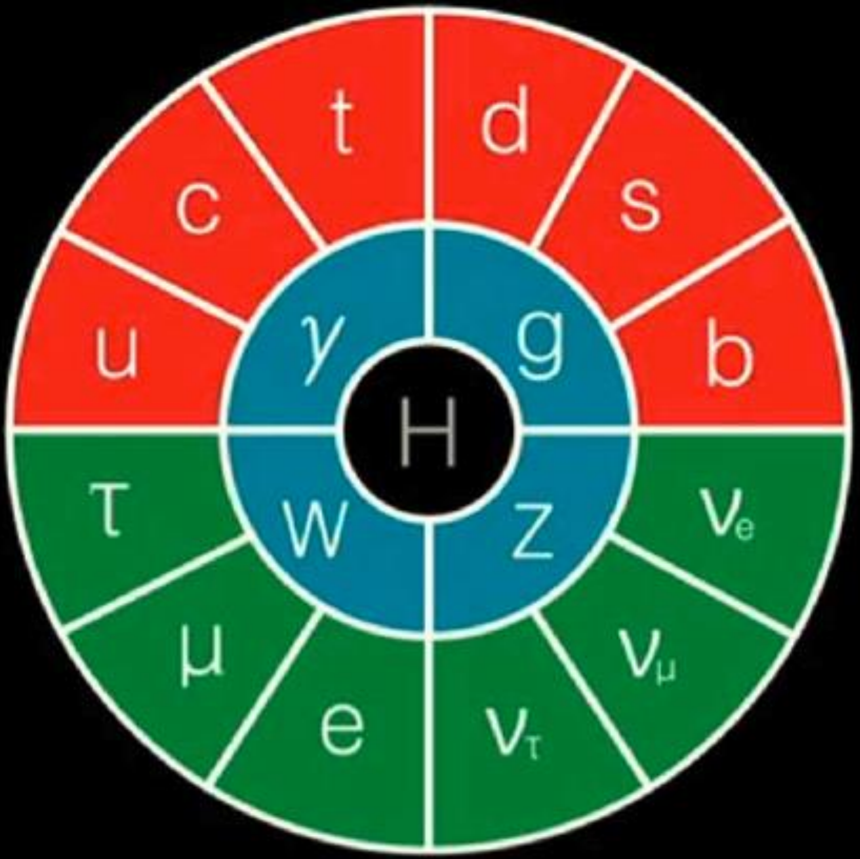




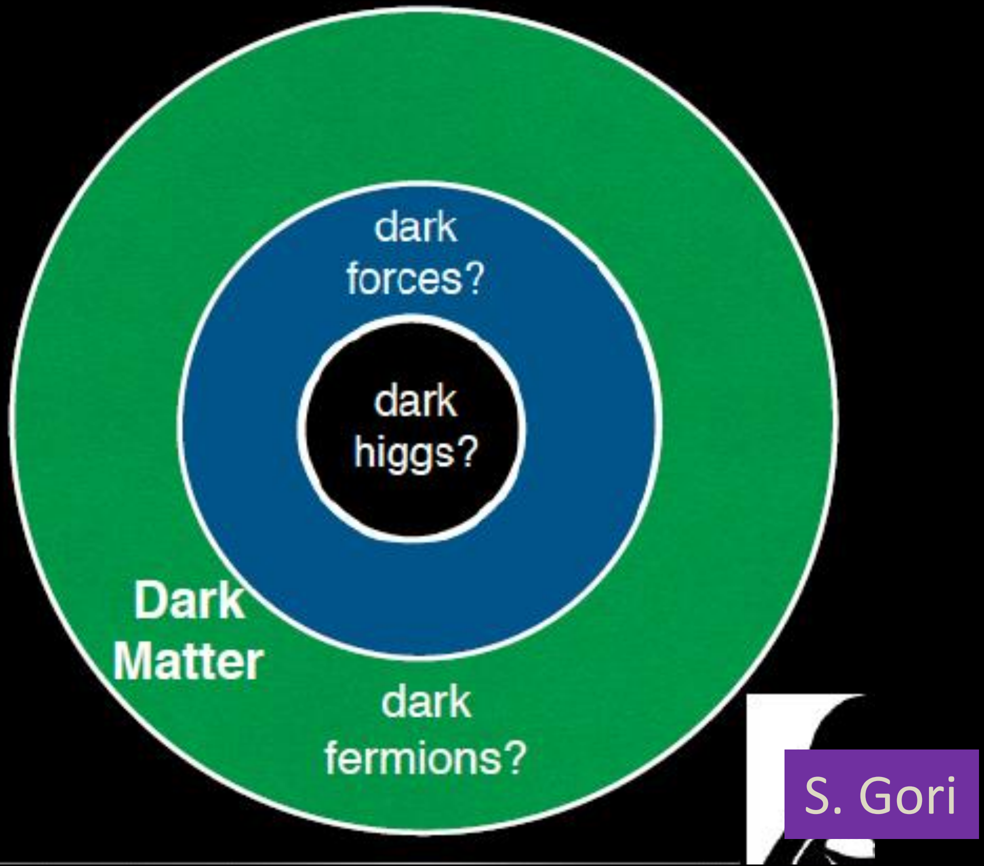
The reach for new physics depends on which new physics:
-- $1/\Lambda^2$ new physics → 30-70 TeV
-- Heavy Neutrino → 500-1000 TeV
-- new non-degenerate doublet should not have mass splitting greater than ~5 GeV

Dark Sector at Z factory

With the Higgs discovery SM works perfectly, yet we need new physics to explain the baryon asymmetry of the Universe, the dark matter etc… without interfering with SM rad. corr.



mediator
or
mixing



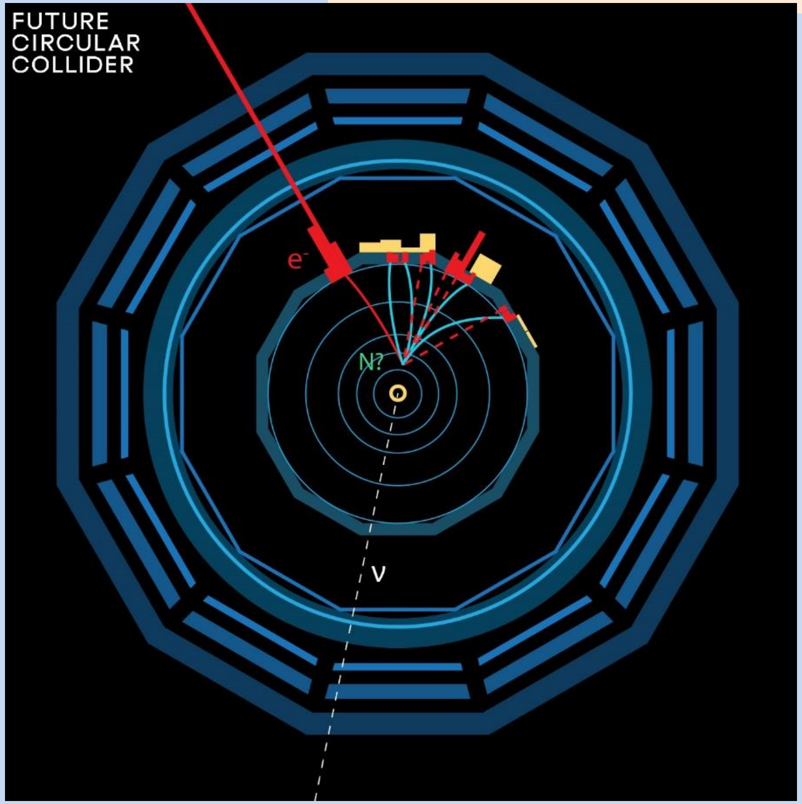
Dark photons, axion like particles, sterile neutrinos, all *feebly coupled* to SM particles

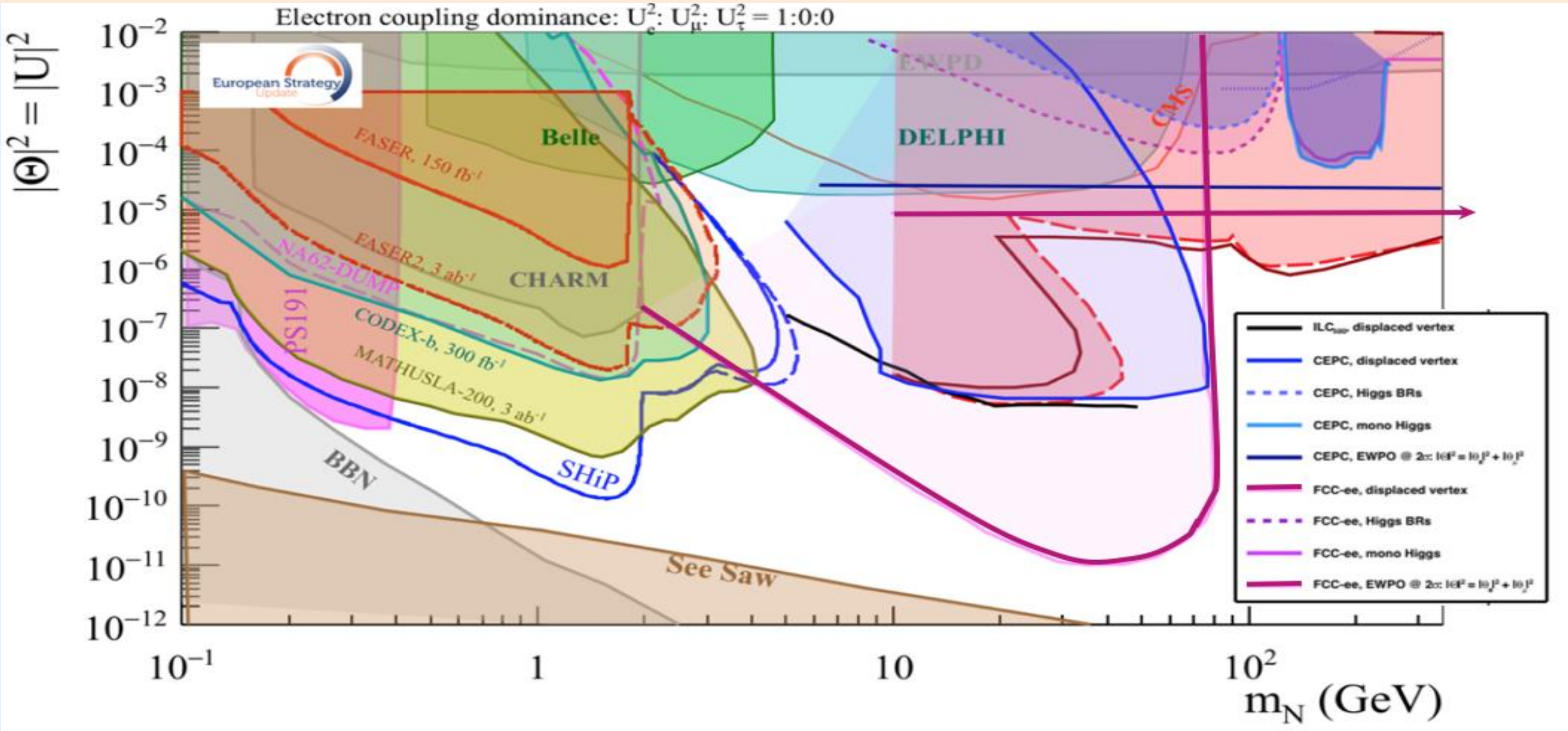
Heavy Right-Handed 'sterile' neutrinos (see-saw type I) **Higgs couplings to neutrinos!**

Straighforward SM extension for massive neutrinos with Dirac *and* Majorana mass terms

FCC-ee (Z) compared to the other machines shows the power of the TeraZ running.

Both «direct» and «indirect» observation. How close can we get to the 'see-saw limit'?





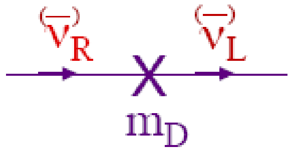
-- the purple line shows the 95% CL limit if no HNL is observed. (here for 10^{12} Z)

-- the horizontal line represents the sensitivity to **mixing of neutrinos** to the dark sector, using EWPOs (G_F vs $\sin^2\theta_W^{eff}$ and m_Z, m_W + tau decays) which extends sensitivity to 10^{-5} mixing all the way to very high energies (500-1000 TeV at least). arxiv:2011.04725

Neutrino masses occur via processes which are intimately related to the Higgs boson
This aspect is quite relevant for a « Higgs factory »!

Adding masses to the Standard model neutrino 'simply' by adding a Dirac mass term

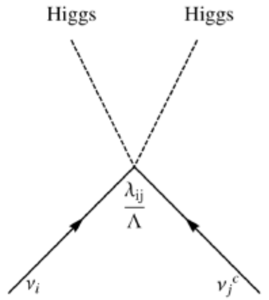
$$m_D \overline{\nu_L} \nu_R$$



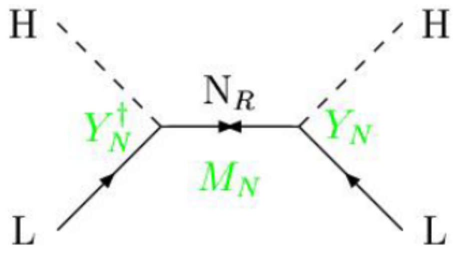
m_D is the **Yukawa coupling** (like everybody else). Then the right handed neutrinos are perfectly sterile.

Things become more interesting when a Majorana mass term arises. So-called **Weinberg Operator** (only Dim5 operator in EFT) and involves the Higgs boson and the neutrino Yukawa coupling

Origin of neutrino mass:



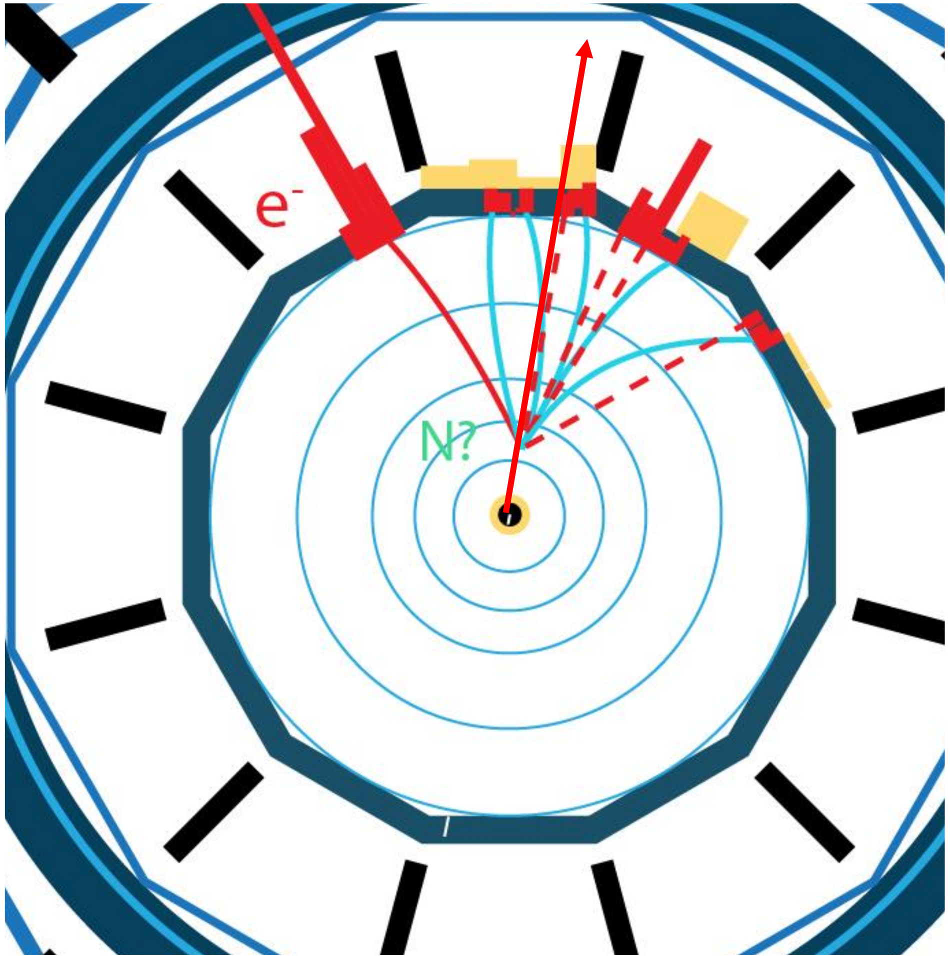
Pilar Hernandez, Granada 2019-05



Majorana mass term is extremely interesting as this is the **particle-to-antiparticle transition** that we want in order to explain **the Baryon asymmetry of the Universe** (+ CP violation in neutrinos)

This implies a decay H→ νN that would be worthwhile investigating -- can we see such a thing with 10^{10} Higgs decays @FCC-hh?
<u>**“Direct” observation of Yukaya coupling of neutrinos at FCC-hh**</u>

A little bit on timing studies



A. In an event like this, there is considerable amount of information for reconstruction.
-- primary vertex and secondary vertex give 3D direction of HNL and decay length
-- the final state reconstruction has therefore many constraints for a kinematic fit
--ECM and PCM
-- v_N and energy at secondary

B However if precision timing is available,
mass and velocity can be reconstructed for any visible decay on the basis only of
-- time-of-flight
-- and decay length

time of flight = E/M . τ
Decay length = P/M . $c\tau$
knowning the two and applying the 2-body constraint at production $P^2 = (m^2_Z - m^2_N)/2m_Z$, $E^2 = (m^2_Z + m^2_N)/2m_Z$
will give the required information. This means that **long lived particle mass can be reconstructed by timing**

FCC

The Flavour Factory

More on TeraZ

Progress in flavour physics wrt SuperKEKb/BELLEII requires > 10^{11} b pair events,

FCC-ee(Z): will provide ~10^{12} bb pairs. "**Want at least 5 10^{12} Z…"**

- precision of CKM matrix elements
- Push forward searches for FCNC, CP violation and mixing
- Study rare penguin EW transitions such as b →s $\tau^+\tau^-$, spectroscopy (produce b-baryons, B_s …)
- **Test lepton universality with 10^{11} τ decays (with τ lifetime, mass, BRs) at 10^{-5} level, LFV to 10^{-10}**

-- all very important to constrain / (provide hints of) new BSM physics.

need special detectors (PID, lifetime); a story to be written!

The 3.5 × 10^{12} hadronic Z decay also provide precious input for QCD studies

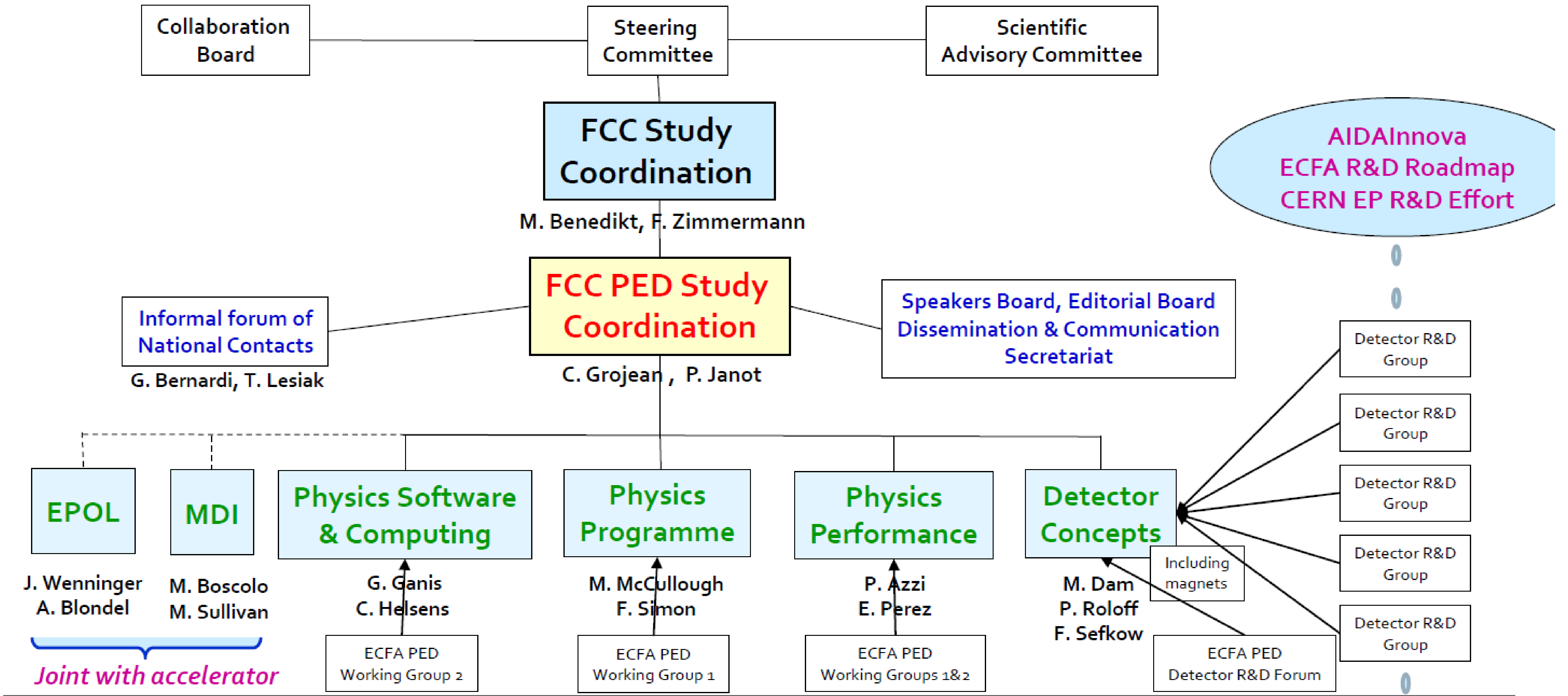
High-precision measurement of $\alpha_s(m_Z)$ with R_ℓ in Z and W decay, jet rates, τ decays, etc. : 10^{-3} →10^{-4}

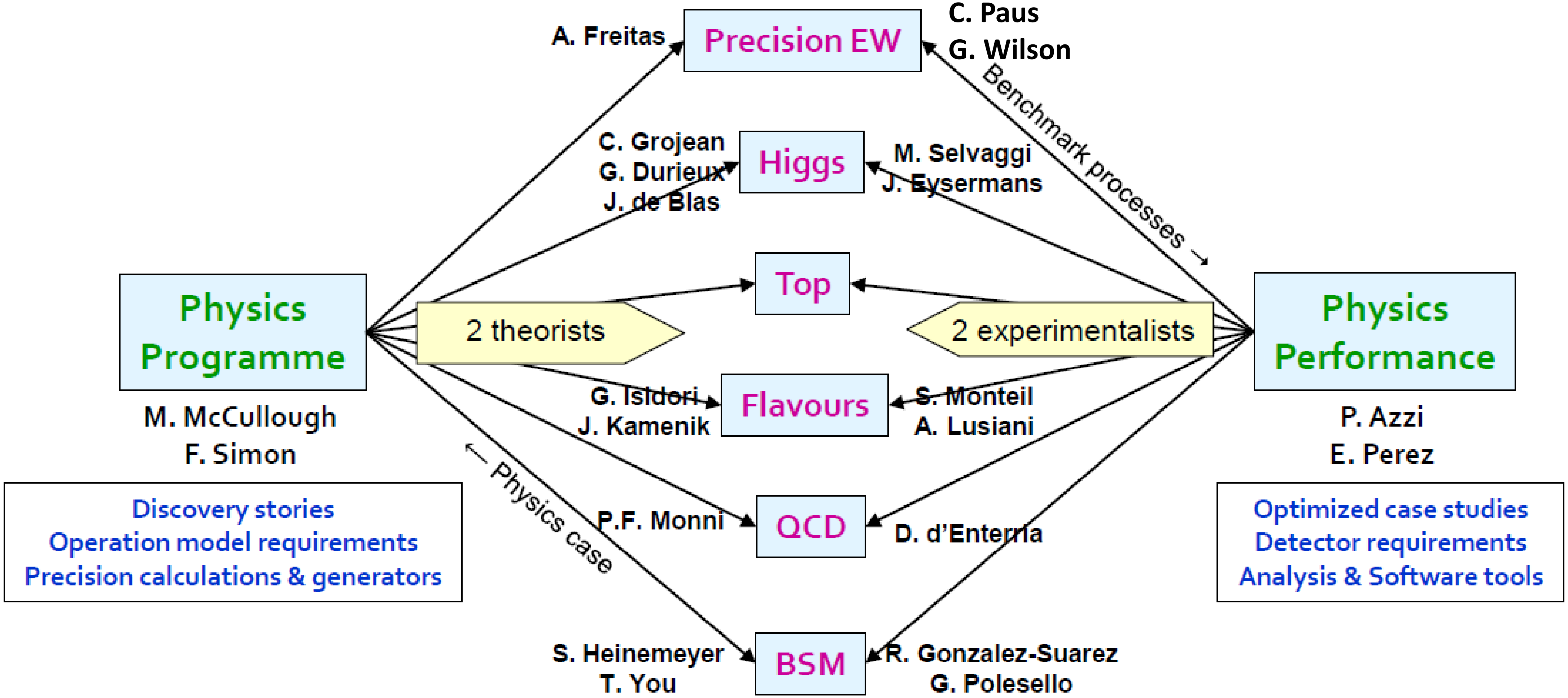
huge √s lever-arm between 30 GeV and 365 GeV, fragmentation, baryon production ….

Testing running of α_s to excellent precision with hadron production from low energy (γ*/Z* +γ) to 365 GeV

And… H→gg is a pure gluon factory (100'000 events)

Organigram of the PED pillar of the FCC feasibility study





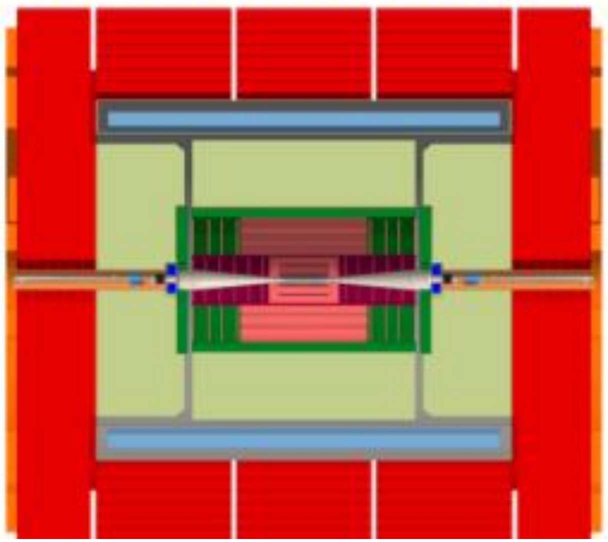
Physics groups define benchmark measurements
to be picked up by case studies ...
leading to performance evaluation and detector requirements

FCC-ee Detectors

Detectors can be done and work for the FCC-ee, but physics optimization remains to be done.

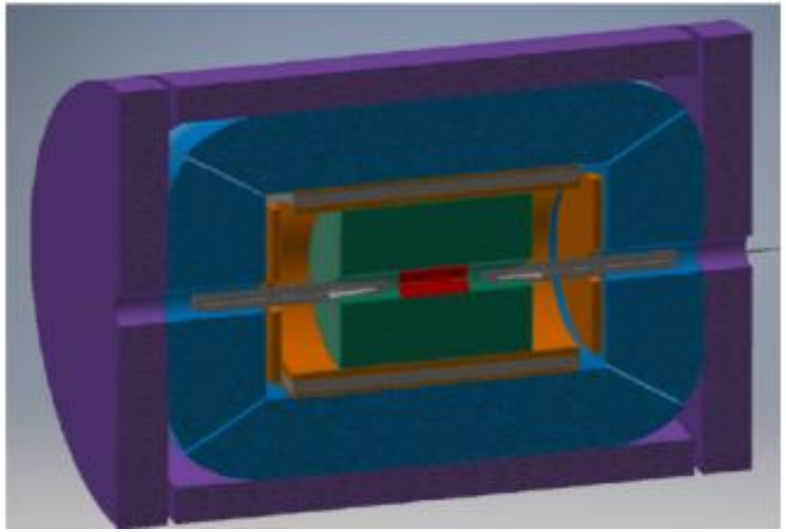
Two integration, performance and cost estimates:
- -- Linear Collider Detector group at CERN has undertaken the adaption of CLIC-SID detector for FCC-ee
- -- IDEA, detector specifically designed for FCC-ee (and CEPC)

"CLIC-detector revisited"



SiD at ILC, CLD at FCC-ee

"IDEA"



- Vertex detector: ALICE **MAPS**
- Tracking: MEG2
- Si Preshower
- Ultra-thin solenoid (2T)
- Calorimeter: DREAM
- Equipped return yoke

IDEA at FCC-ee & CEPC

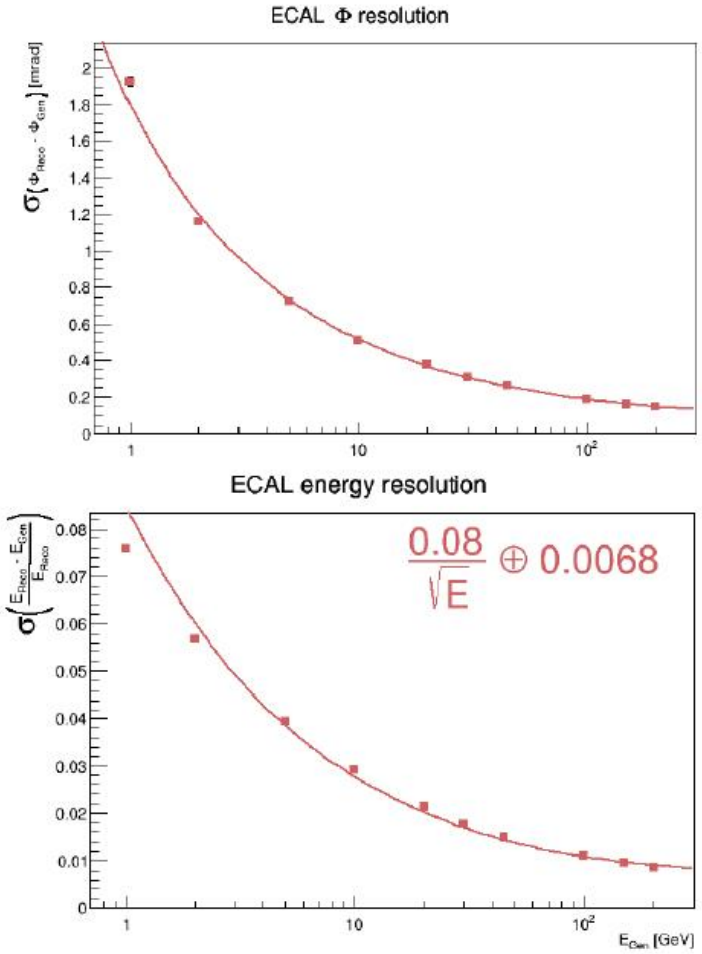
Many challenges to come, mainly because of the Z run.

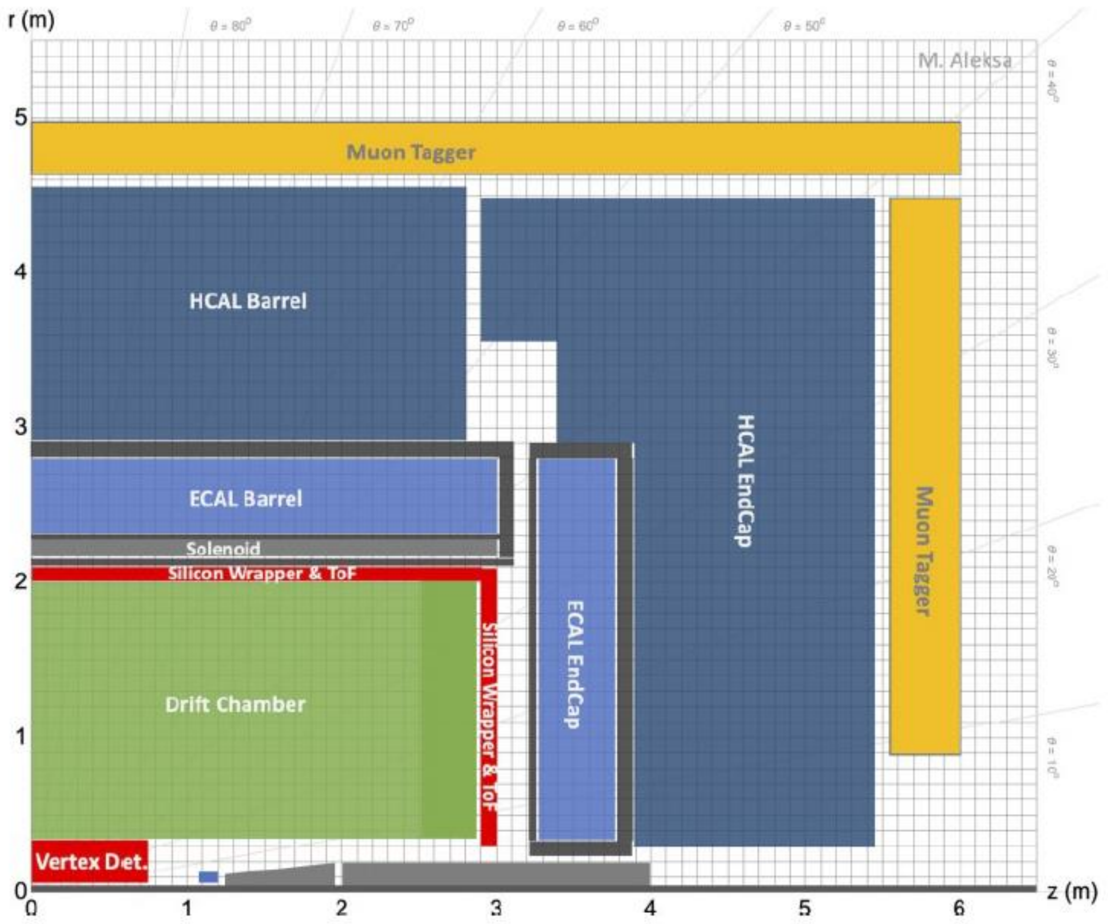
New at the FCC 'Liverpool' physics workshop

implementation of Noble Liquid Calorimeter in FCCSW

→ intention to develop an entire detector concept around this key element.

Brieuc François, Weds + Fri





Remember: Detector Concepts must pay attention to *full range* of FCC-ee physics !

The PED ultimate objectives until the next ESU

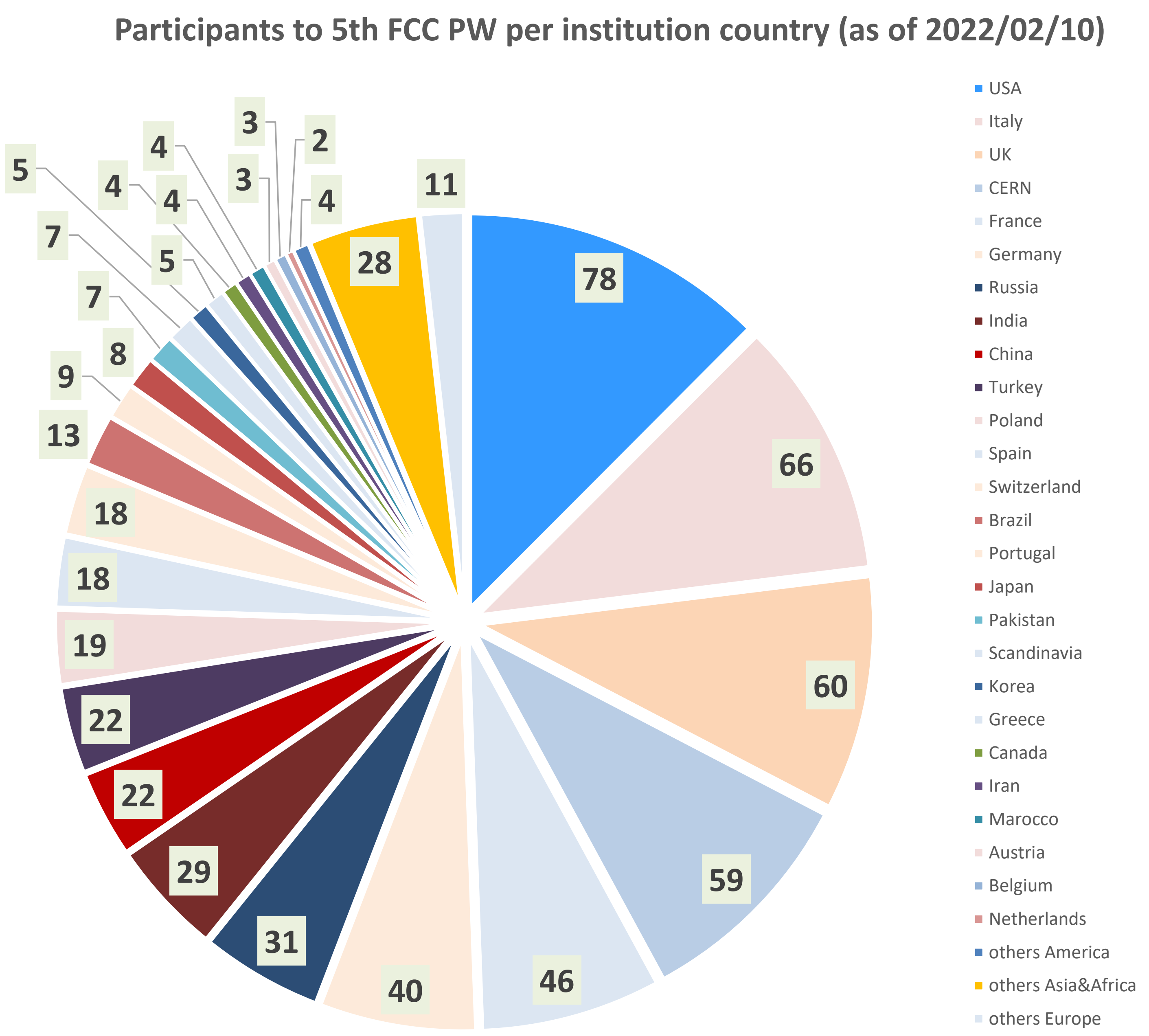
- Match detectors with the physics opportunities offered by the facility
  - Establish a coherent set of detector requirements from physics studies → Physics Programme
    - To fully benefit from statistics, variety of channels, new physics sensitivity → Physics Performance
  - Provide a coherent set of detector solutions (or path to solutions) → Detector Concepts
    - To maximally exploit the new collider layout compatibility with four interaction points
    - To deliver preliminary infrastructure requirements and cost estimates

- This ought to happen in time for (proto)collaborations to
  - Pick up the wealth of knowledge acquired and common tools developed on the way → Software & Computing
  - Present EoI's to the next strategy, and
  - Run away with the project once approved

- Best would be that at least four (proto)collaborations propose a detector
  - Serious funding will arise at this point
  - More precise costs and demands on infrastructure will be elaborated

USA	78
Italy	66
UK	60
CERN	59
France	46
Germany	40
Russia	31
India	29
China	22
Turkey	22
Poland	19
Spain	18
Switzerland	18
Brazil	13
Portugal	9
Japan	8
Pakistan	7
Scandinavia	7
Korea	5
Greece	5
Canada	4
Iran	4
Marocco	4
Austria	3
Belgium	3
Netherlands	2
others America	4
others Asia&Africa	28
others Europe	11
unidentified	17
sum	625
grand total 642	642

other Europe:
Ireland 1
Israel 1
Slovenia 1
Czech 2
Estonia 1
Croatia 1
Serbia 1
Bulgaria 1
Belarus 1
Romania 1



Conclusions and what to do

The FCC-integrated programme, FCC-ee then hh with ep and heavy ion options, thanks to synergies and complementarities, offers the most versatile and adapted response to today's physics landscape.

FCC-ee is the best low energy Higgs Factory, and MUCH more. It offers a unique physics programme and discovery potential (Precision EW and Flavour, high sensitivity LLP searches, QCD) thanks to an outstanding high luminosity and E_{cm} calibration.

FCC-ee presents numerous novel challenges in detector design and experimentation!

FCC-ee matches well the European strategy vision and recommandations, and is well supported by CERN council!

The FCC is a global project and the participation of the CERN international partners is both essential and welcome

PED goal is to deliver input for the FCC FS CDR+ in 2025, assemble community, promote detector concepts towards next ESPP

It is a great project, where there is much to learn

The FCC PED effort will strive from the contributions of its members
we rejoy to see enthusiasm from the Swiss particle community!

SPARES

Particle physics after the discovery of the Higgs boson

Two facets:

The Higgs boson is very special

It generates (couples to) mass. Alone?

-- W,Z masses ⇔ Higgs coupling to WW, ZZ? FCC-ee

-- (all) fermion masses ⇔ Higgs couplings? FCC-ee

FCC-hh(+ee) decays ($\gamma\gamma$, gg, $Z\gamma$) ⇔ SM particle content?

-- are all elementary particles given mass this way?

FCC-ee(?) even electrons? and even the neutrinos?

Yukawa (→ ν_R , sterile)

+ Majorana ($\nu \leftrightarrow \bar{\nu}$) → HNL? FCC-ee

It couples to itself!

-- Spontaneous Symmetry Breaking

-- What is the value of the self coupling?

-- impact on σ_{HZ} near threshold FCC-ee

-- HH production FCC-hh

FCC-hh, high energy lepton colliders

The SM is « complete »

-- Higgs and top masses predicted from EWPOs

assuming no new SM coupled particles exist

-- SM extrapolates to the Plank scale

assuming no new SM coupled particles exist

-- SM works wonderfully... **So why continue?**

-- But SM does not explain everything

Baryon Asymmetry of the Universe

Dark Matter

and more.... ➔ require new particles!

mass scale is unknown

FCC-ee: EWPO Flavour

Are there any further SM-coupled particles?

-- no guarantee or solid indication that there are

-- but many BSM solutions include them.. FCC-hh

-- DARK SECTOR → possibly light, sterile particles

FCC-ee: LLP EWPO Flavour

After the discovery of the Higgs boson we enter a new era of exploration

We absolutely need a next accelerator but the next facility must be versatile (and feasible!) with as broad and powerful reach as possible, as there is no precise target

➔ more Sensitivity, more Precision, more Energy

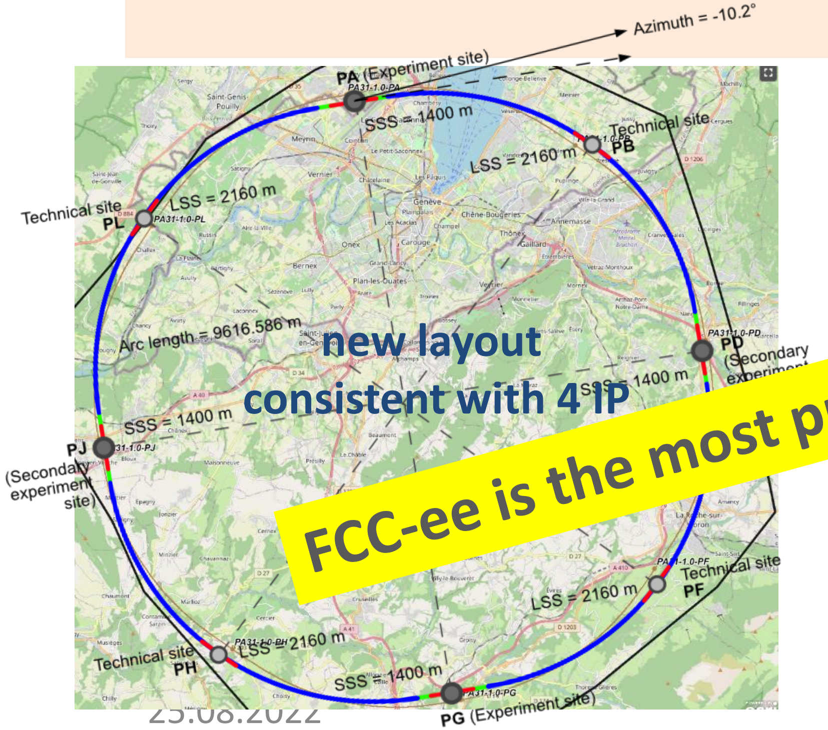
FCC, thanks to synergies and complementarities, offers the most versatile and adapted response to today's physics landscape

Synergy: The FCC integrated program at CERN

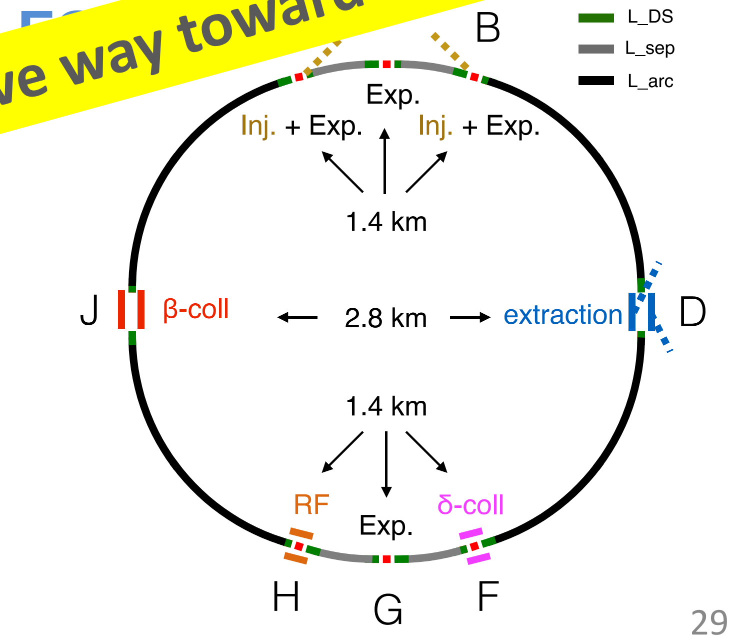
Comprehensive cost-effective program inspired by successful LEP – LHC success story

- **Stage 1: FCC-ee (Z, W, H, tt) as first generation Higgs EW and top factory at highest luminosities.**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options.**
- **Maximizes physics output with strong complementarity**
- Integrating an ambitious high-field magnet R&D program
- Common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure.
- **Start construction early 2030's, start data taking shortly after HL-LHC completion**
- **FCC-INT project plan is fully integrated with HL-LHC exploitation ➔ seamless continuation of HEP**
- **Feasibility study approved and funded at CERN (100MCHF/5yrs) + magnet R&D (120 MCHF/6yrs)**

***** GLOBAL COLLABORATION *****



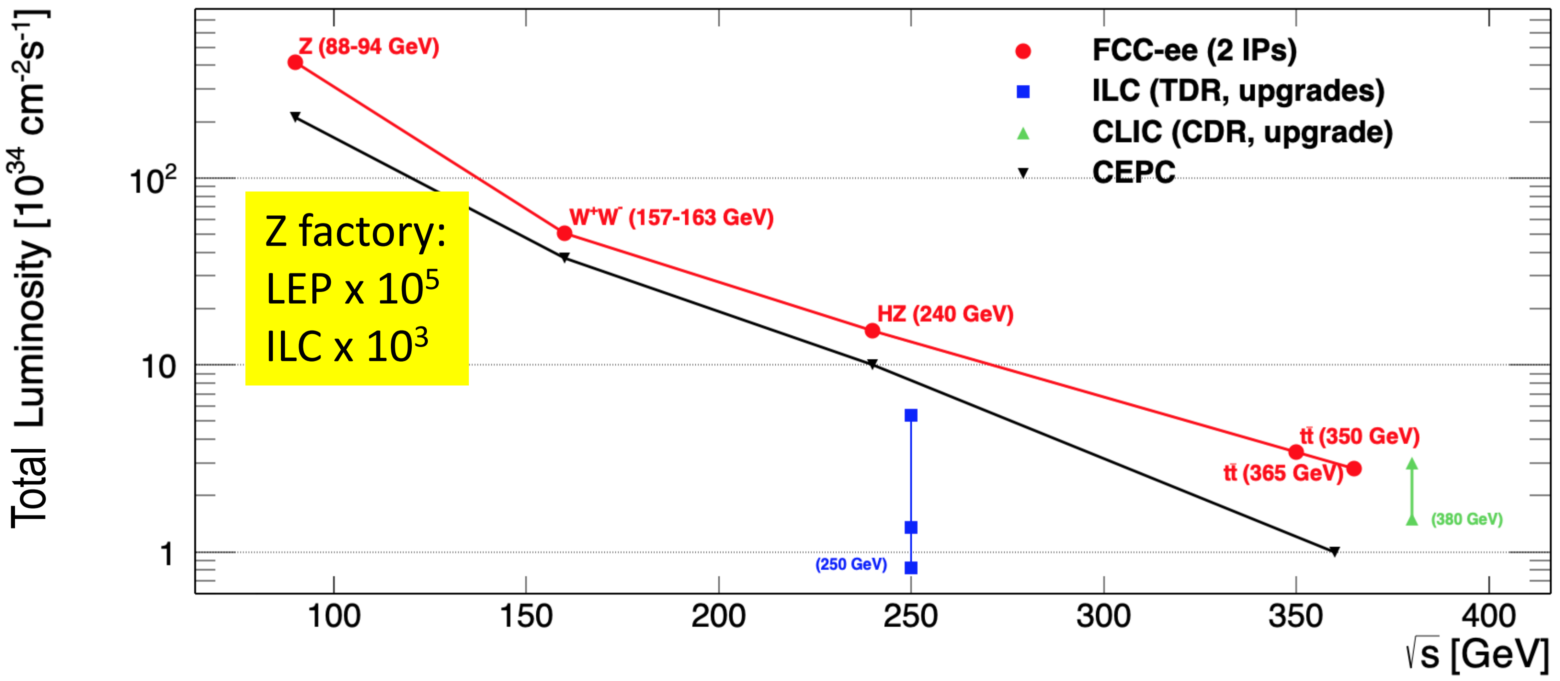
FCC-ee



FCC-ee is the most pragmatic, safest, and most effective way toward FCC-hh

FCC-ee

Great energy range for the heavy particles of the Standard Model



notes:
-- 4IP increases Total Lumi by 1.7
-- 2IP assumed in all numbers below
-- order and duration of Z/WW/ZH can be decided at a later stage
-- ee→ H must be after both Z and ZH and before tt

see back-ups for facility comparisons

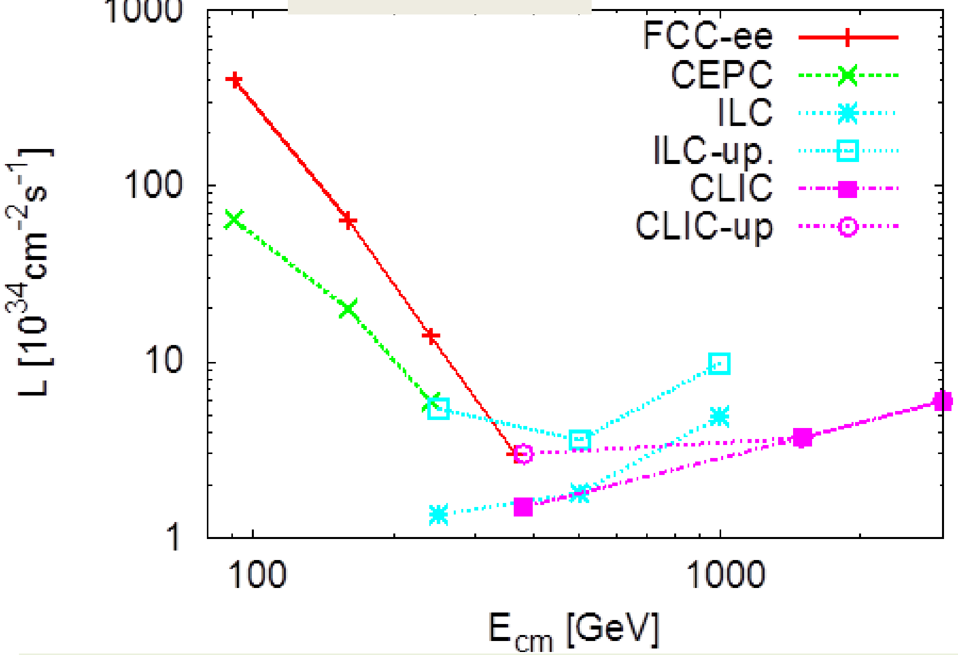
Event statistics (2IP)

					E_{CM} errors:
Z peak	E_{cm} : 91 GeV	4yrs	$5\ 10^{12}$ e+e- → Z	LEP x 10^5	<100 keV
WW threshold	$E_{cm} \geq 161$ GeV	2yrs	$>10^8$ e+e- → WW	LEP x 2.10^3	<300 keV
ZH maximum	E_{cm} : 240 GeV	3yrs	$> 10^6$ e+e- → ZH	Never done	1 MeV
s-channel H	E_{cm} : m_H	*(3yrs?)*	*O(5000) e+e- → H*	*Never done*	<< 1 MeV
$t\bar{t}$	E_{cm} : ≥ 350 GeV	5yrs	10^6 e+e- → $t\bar{t}$	Never done	2 MeV

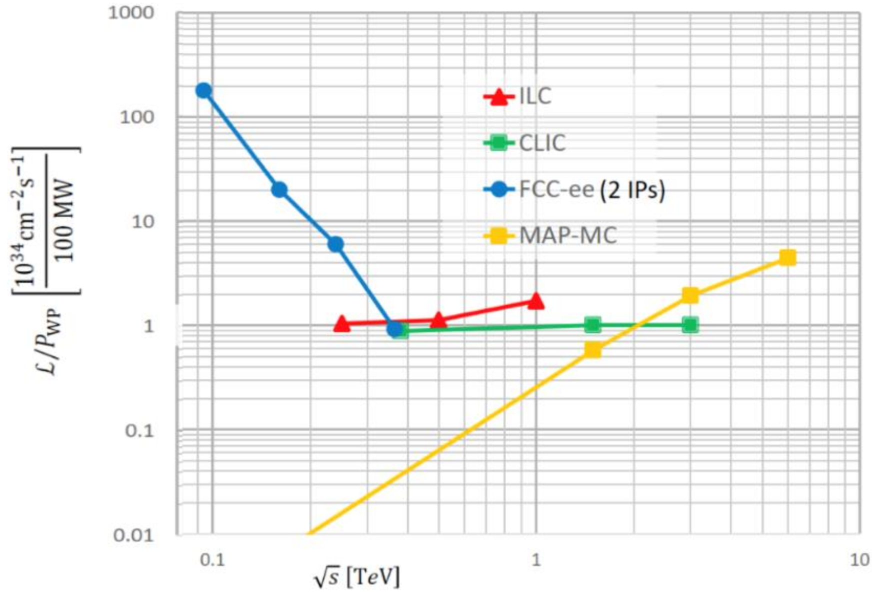
«Higgs Factories»

plots from Briefing Book

Luminosity



Luminosity/Power → Energy efficiency



Luminosity vs Energy circular below 350 GeV linear above 250 GeV

Efficiency : 9 (5) GJ/Higgs at FCC-ee with 2(4)IP vs 50GJ/Higgs for ILC250 (first 15 years)

Beam polarization: circular: transverse → ppm beam energy calibration

linear: longitudinal : e- ±80% easy, (e+ ±30% difficult → additional d.o.f

Long term energy upgrade circular: pp collider linear: High energy lepton collisions

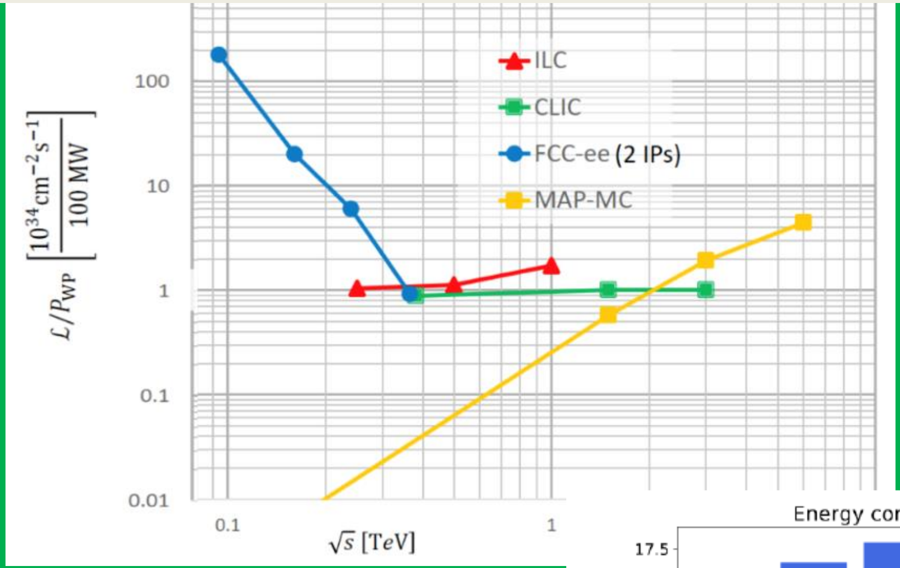
Interaction points circular: 2-4 linear: 1

Run limited in time by arrival of hadron collider Run is open ended

The Greenest

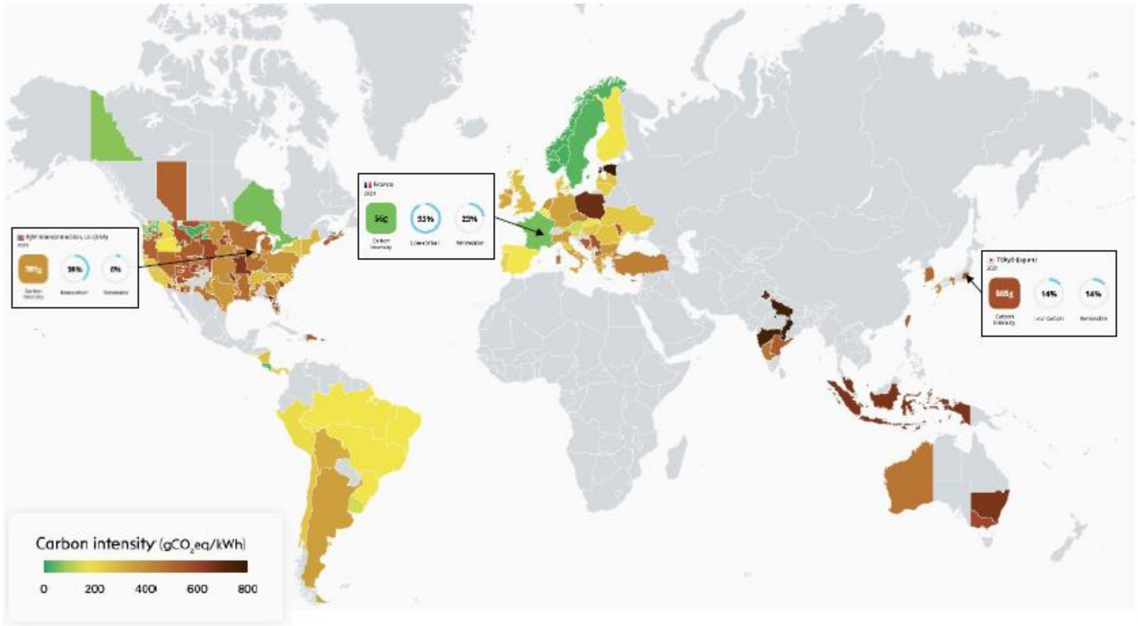
plot fromESPP Briefing Book

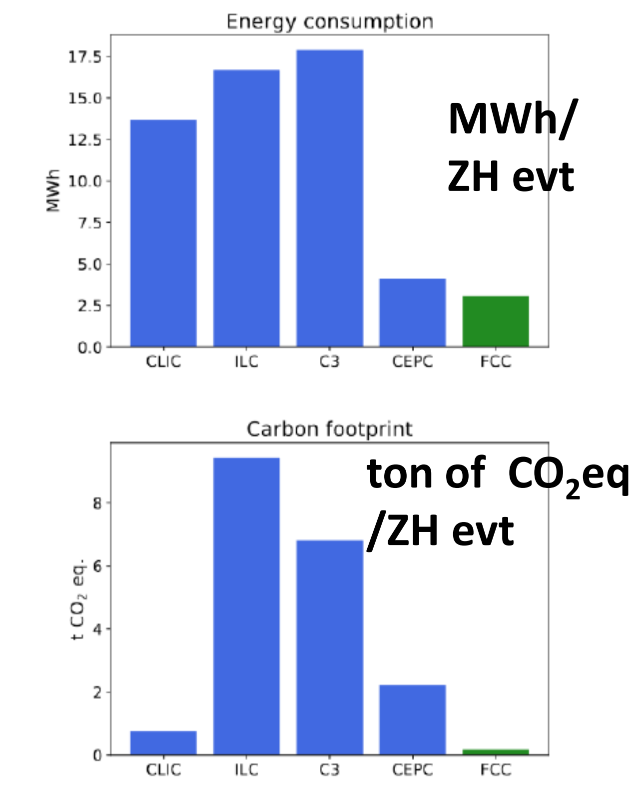
Luminosity/Power → Energy efficiency



Compounding the higher energy efficiency at the ZH point (and below!) the FCC benefits from clean energy as France and Switzerland rely largly on low carbon footprint energies: nuclear, hydro, solar and wind energies

Fig. 1: Carbon intensity of electricity production around the world in 2021, in kgCO_2 equivalent / MWh, obtained from Ref. [22]. The carbon footprints of the energy produced in Illinois, Japan, and France, and used respectively at FNAL, KEK, and CERN, are highlighted.





Janot, AB 2208.10466

The carbon footprint of a Higgs boson is much much smaller for FCC-ee @CERN

Physics at FCC-ee

1. **HIGGS FACTORY**

Higgs provides a very good reason why we need e+e- (or $\mu\mu$) collider

2. **ELECTROWEAK PRECISION (10^{-3} today → 10^{-5})**

Z + WW + top required!

Test of the completeness of the SM

3. **Z FACTORY**

(5 10^{12} Z i.e. 1.5 10^{11} ee, $\mu\mu$, $\tau\tau$; ~0.7 10^{12} uu,dd,ss,cc,bb ; 10^{12} $\nu\nu$)

High statistics for Heavy Flavours, QCD

Search for Feebly Coupled Particles

The place for 'direct discovery'

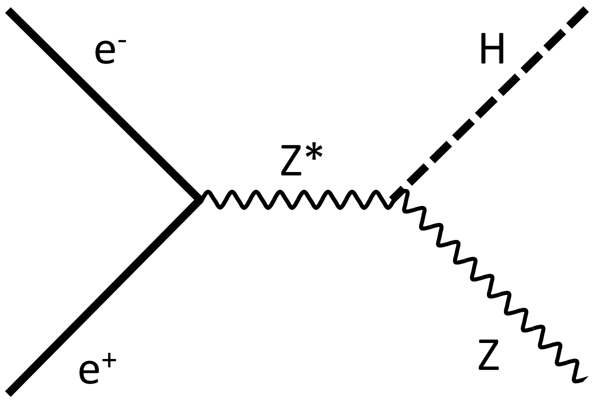
+ comments on the synergy and complementarity of FCC-ee hh and eh

e+e- : Z – tagging by missing mass

THE LHC is a Higgs Factory…BUT

$$\sigma_{i\to f}^{\text{observed}} \propto \sigma_{prod} \frac{(g_{Hi})^2(g_{Hf})^2}{\Gamma_H} \,?$$

→ must do physics with ratios



total rate $\propto g_{HZZ}^2$

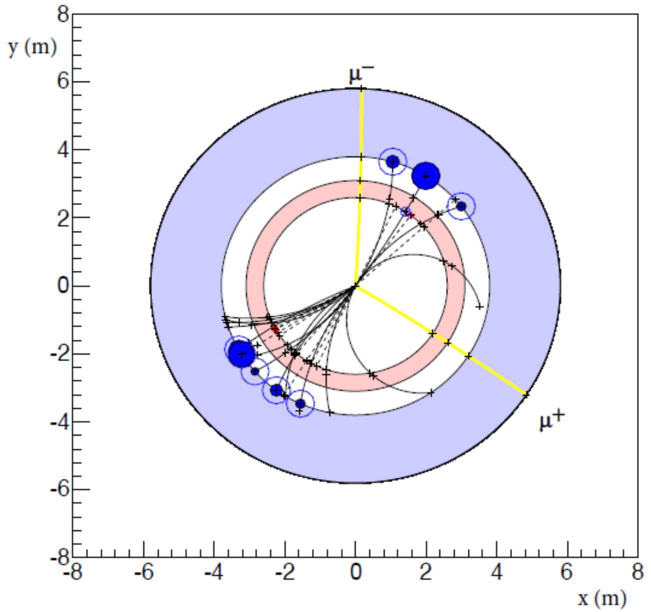
ZZZ final state $\propto g_{HZZ}^4/\Gamma_H$

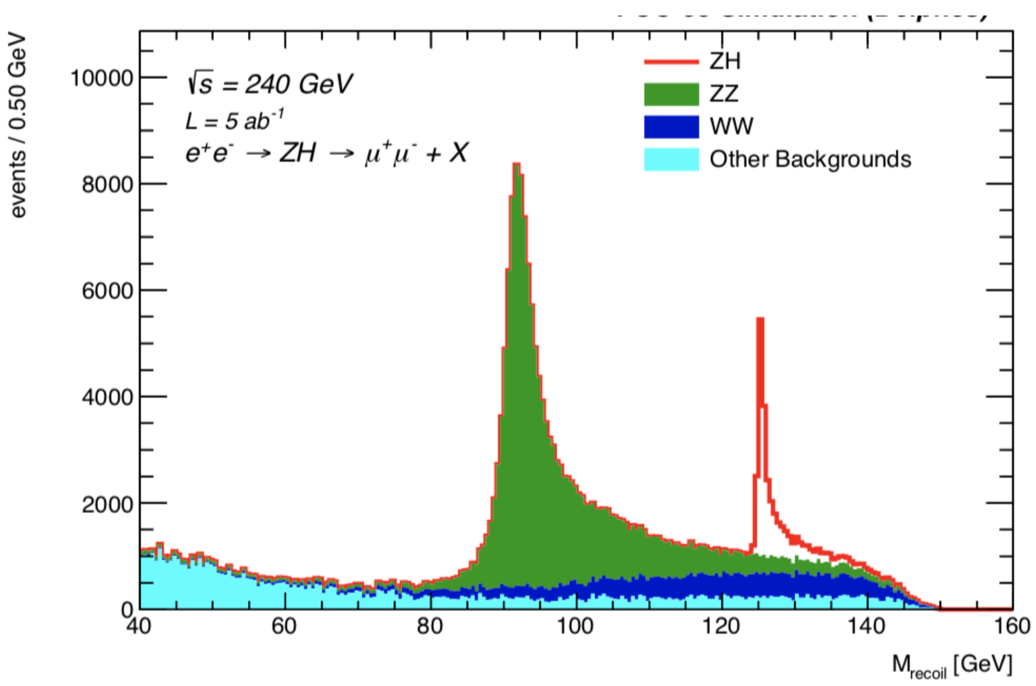
➔ measure total width Γ_H

g_{HZZ} to ±0.2%

empty recoil = invisible width

'funny recoil' = exotic Higgs decay





FCC

Complementarity: Higgs Physics at FCC

FCC-ee → g_{HZZ} **to <±0.2% from** σ_{ZH}
(model-independent standard candle)
and Γ_H, g_{Hbb}, g_{Hcc}, $g_{H\tau\tau}$, g_{HWW}

→fixes all HL-LHC / FCC-hh couplings

FCC-hh produces over 10^{10} Higgs bosons
use g_{HZZ} from FCC_{ee} will give $g_{H\mu\mu}$, $g_{H\gamma\gamma}$, $g_{HZ\gamma}$, Br_{inv}

FCC-ee also measures top EW couplings ($e^+e^- \rightarrow tt$)

FCC-hh produces 10^8 ttH and 2. 10^7 HH pairs
→ g_{Htt} and g_{HHH}, model-independent & precise!

HL-LHC/FCC-ee/FCC-hh complementarity outstanding

Comparison with other e+e- colliders in spares

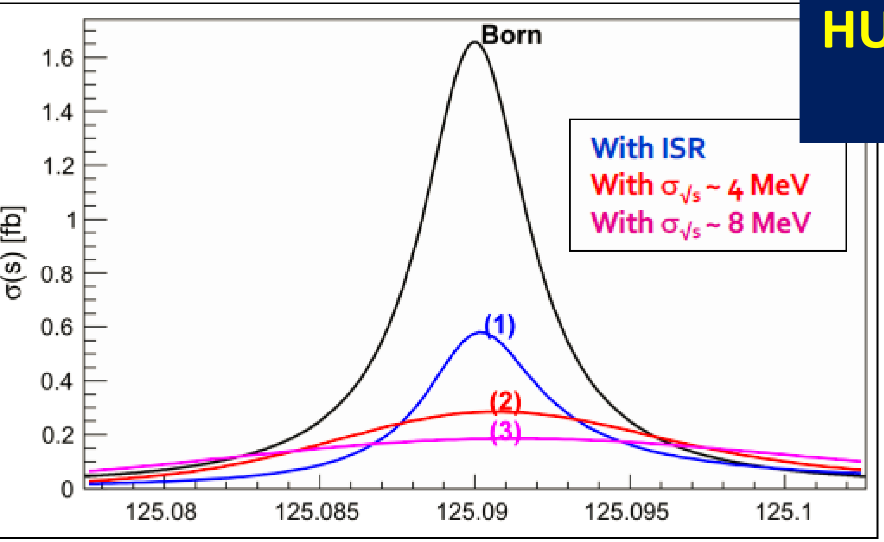
Collider	HL-LHC	FCC-ee$_{240\rightarrow365}$	FCC-INT	
Lumi (ab^{-1})	3	5 + 0.2 + 1.5	30	
Years	10	3 + 1 + 4	25	
g_{HZZ} (%)	1.5	0.18 / 0.17	0.17/0.16	ee
g_{HWW} (%)	1.7	0.44 / 0.41	0.20/0.19	ee
g_{Hbb} (%)	5.1	0.69 / 0.64	0.48/0.48	ee
g_{Hcc} (%)	SM	1.3 / 1.3	0.96/0.96	ee
g_{Hgg} (%)	2.5	1.0 / 0.89	0.52/0.5	ee
$g_{H\tau\tau}$ (%)	1.9	0.74 / 0.66	0.49/0.46	ee
$g_{H\mu\mu}$ (%)	4.4	8.9 / 3.9	0.43/0.43	hh
$g_{H\gamma\gamma}$ (%)	1.8	3.9 / 1.2	0.32/0.32	hh
$g_{HZ\gamma}$ (%)	11.	– / 10.	0.71/0.7	hh
g_{Htt} (%)	3.4	10. / 3.1	1.0/0.95	hh
g_{HHH} (%)	50.	2 IP: 44./33. 4 IP: 27./24.	3-4	hh
Γ_H (%)	SM	1.1	0.91	ee
m_H (MeV)	30-50	3	3	hh
BR_{inv} (%)	1.9	0.19	0.024	ee
BR_{EXO} (%)	SM (0.0)	1.1	1	

ee only

LHC +ee

FCC-ee+hh+ep
ep → WW mostly

Unique: electron Yukawa coupling



HUGE CHALLENGE under study

Measure e+e- → H @ 125.xxx GeV

requires

-- Higgs mass to be known to <<5 MeV (OK, 3 MeV)

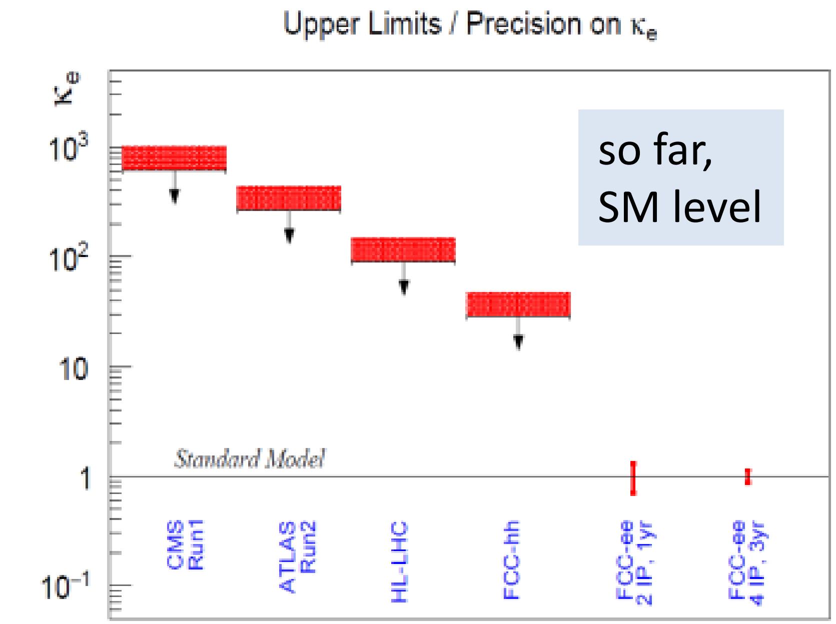
-- **Huge luminosity** (several years)

-- **monochromatization** to reduce σ_{ECM}

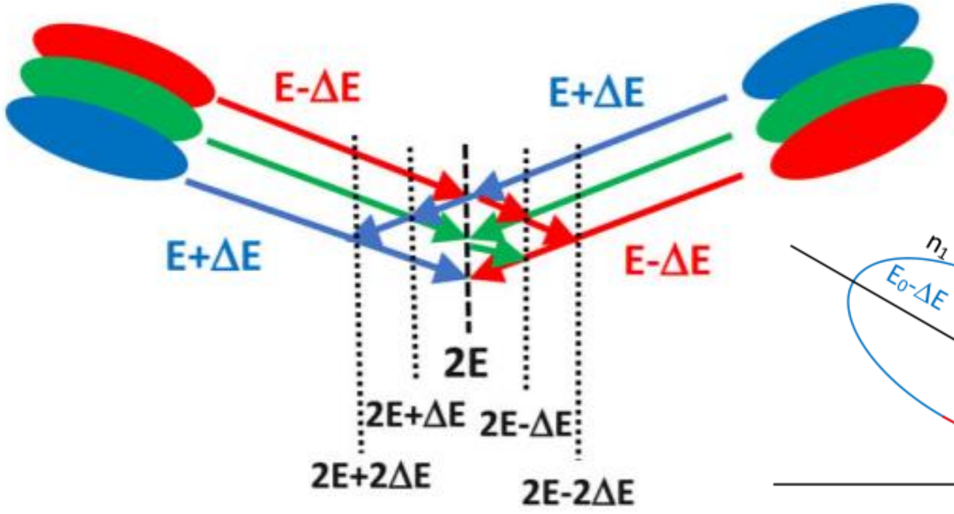
-- **continuous adjustment of E_{CM}** (transv. Polar.)

-- an extremely sensitive event selection

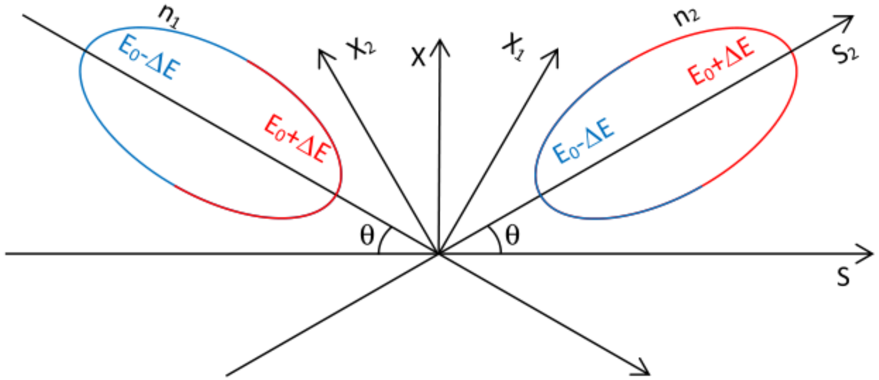
Monochromatization: **UNDER STUDY**
taking advantage of the separate e+ and e- rings, one can distribute in opposite way high and low energies in the beam (in x, z time)



so far,
SM level



combine?



opposite sign horizontal dispersion

opposite difference in time within 30ps luminosity

Centre of mass Energy Calibration: the cornerstone of the precision programme

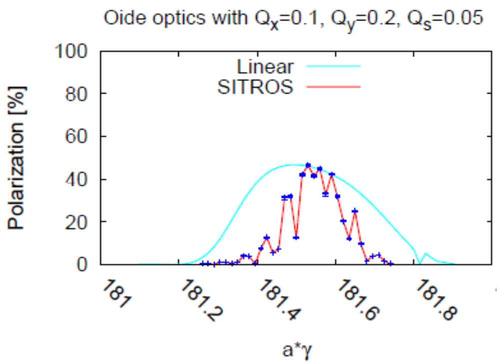
E. Gianfelice

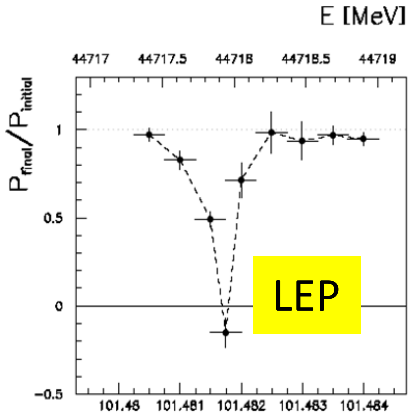
Large ring → transverse polarization of $e^{\pm}$ up to $E_{beam} > 80$ GeV $\quad \sigma_E \propto E^2/\sqrt{\rho}$

Resonant depolarization provides high precision E_{beam} $\nu_s = \frac{g-2}{2}\frac{E_b}{m_e} = \frac{E_b}{0.4406486(1)}$

Unique to circular machines (ee and μμ)

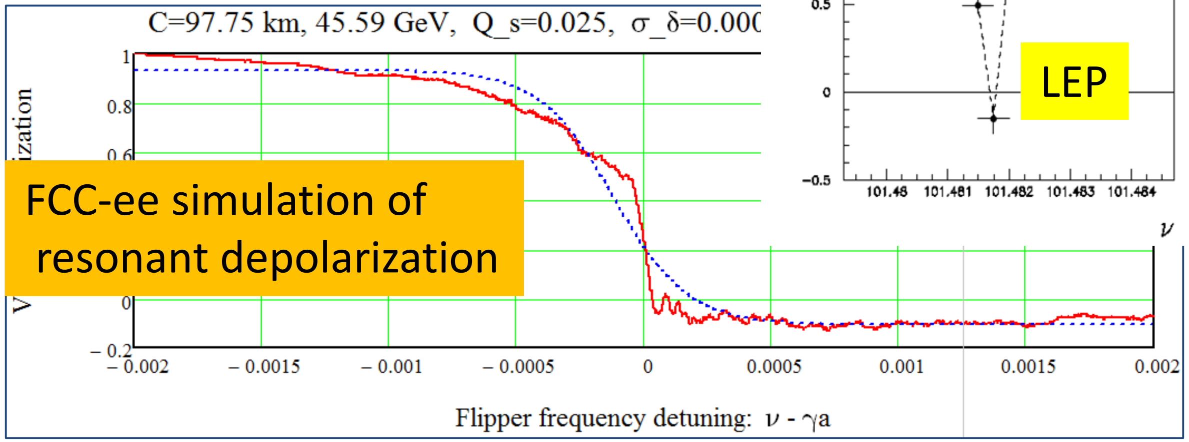
Improve over LEP by using pilot bunches + e- and e+ polarimeter





Relationship between ν_s and E_{CM}

- ➔ **CM boost, σ_{ECM}, α_{coll} determined from 10^6 μμ /5min**
- ➔ **Beamstahlung monitor under study etc...**

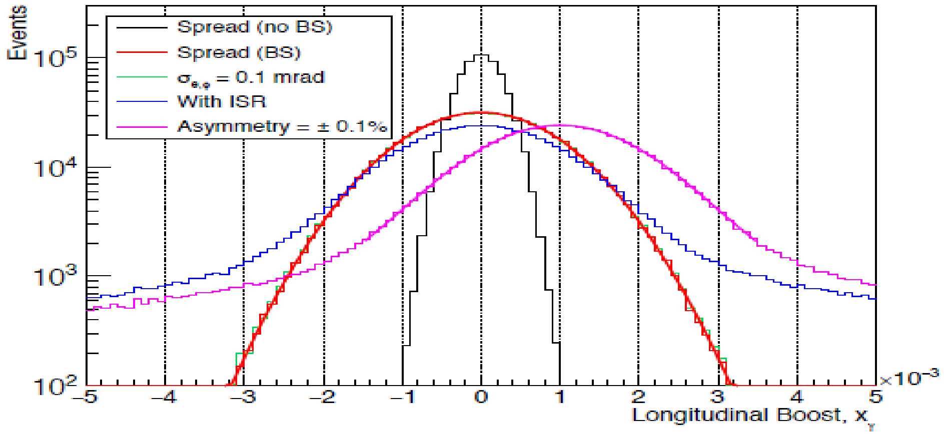


First round of studies (arxiv 1909.12245)

m_Z, Γ_Z, $\sin^2\theta_W^{eff}$, $\alpha_{QED}(m_Z)$, m_W

next target: bring syst. closer to stat. errors.

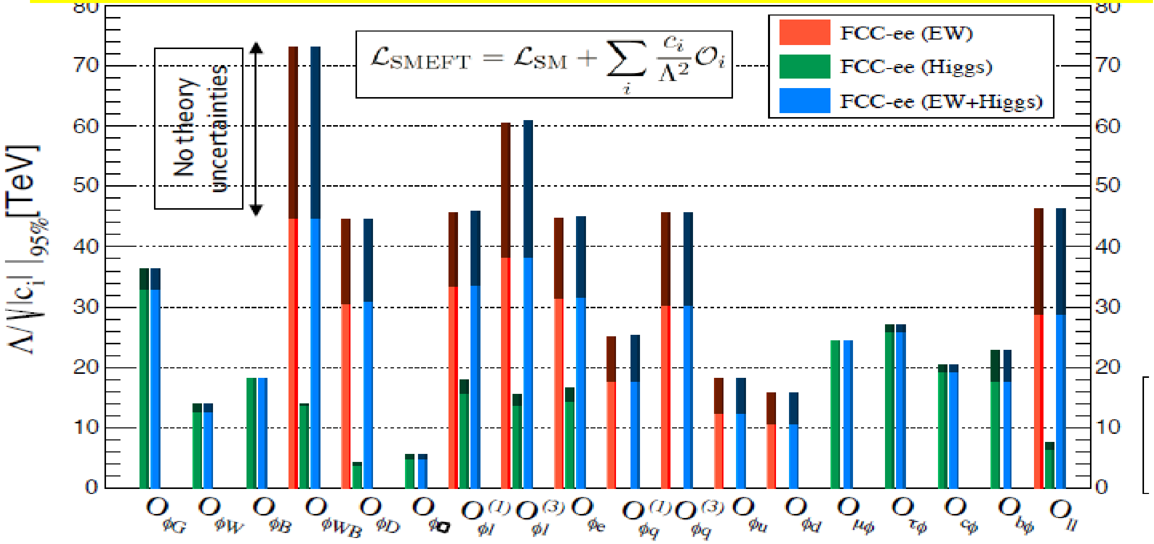
Quantity	statistics	ΔE_{CMabs} 100 keV	$\Delta E_{CMSyst-ptp}$ **40 keV**	calib. stats. $200\ keV/\sqrt{(N^i)}$	σE_{CM} (84) ± **0.05** MeV
m_Z (keV)	4	100	**28**	1	–
Γ_Z (keV)	7	2.5	**22**	1	**10**
$sin^2\theta_W^{eff} \times 10^6$ from $A_{FB}^{\mu\mu}$	2	–	**2.4**	0.1	–
$\frac{\Delta\alpha_{QED}(M_Z)}{\alpha_{QED}(M_Z)} \times 10^5$	3	0.1	**0.9**	–	**0.05**



At our luminosity level, longitudinal polarization brings nothing that cannot be done otherwise.

Precision EW measurements: is the SM complete?

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



- ***Higgs and EWPOs are complementary***
- top quark mass and couplings essential!

(the 100km circumference is optimal for this)

- preliminary systematics!

aim at reducing to the level of systematics

- many observables still to be added (flavours)
- complemented by high energy FCC-hh
- ***Theory work is critical and initiated*** *1809.01830*

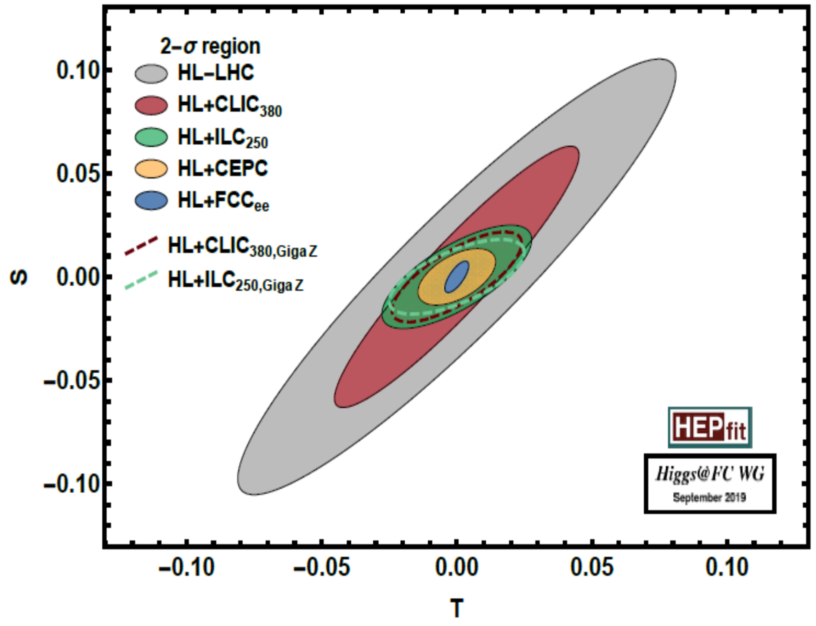
Electroweak Physics

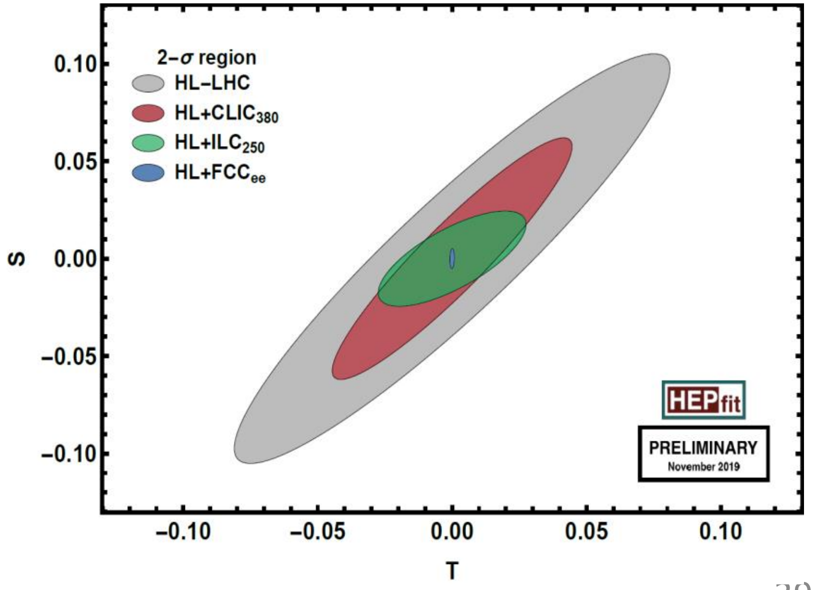
Z factory + WW + top The realm of FCC-ee

Highest luminosities at 91, 160 and 350 GeV
Transverse pol. at 91 and 160 GeV→Ecm calibration
m_Z (100 keV) Γ_Z (25 keV), m_W (<500 keV), $\alpha_{QED}(m_Z)$ (3.10^{-5})
and $\sin^2\theta_W$ at 310^{-6}

Complete set of EW observables can be measured
Precision unique to FCC-ee + new physics sensitivity
→ a lot more potential to exploit with good detector design than present treatment suggests

The reach for new physics depends on which new physics:
-- $1/\Lambda^2$ new physics → 30-70 TeV
-- Heavy Neutrino → 500-1000 TeV
-- new non-degenerate doublet should not have mass splitting greater than ~5 GeV





FCC

The Flavour Factory

More on TeraZ

Progress in flavour physics wrt SuperKEKb/BELLEII requires > 10^{11} b pair events,

FCC-ee(Z): will provide ~10^{12} bb pairs. "**Want at least 5 10^{12} Z…"**

- precision of CKM matrix elements
- Push forward searches for FCNC, CP violation and mixing
- Study rare penguin EW transitions such as $b \rightarrow s\ \tau^+ \tau^-$, spectroscopy (produce b-baryons, B_s …)
- **Test lepton universality with 10^{11} τ decays (with τ lifetime, mass, BRs) at 10^{-5} level, LFV to 10^{-10}**

-- all very important to constrain / (provide hints of) new BSM physics.

need special detectors (PID); a story to be written!

The 3.5 × 10^{12} hadronic Z decay also provide precious input for QCD studies

High-precision measurement of $\alpha_s(m_Z)$ with R_ℓ in Z and W decay, jet rates, τ decays, etc. : $10^{-3} \rightarrow 10^{-4}$

huge √s lever-arm between 30 GeV and 365 GeV, fragmentation, baryon production ….

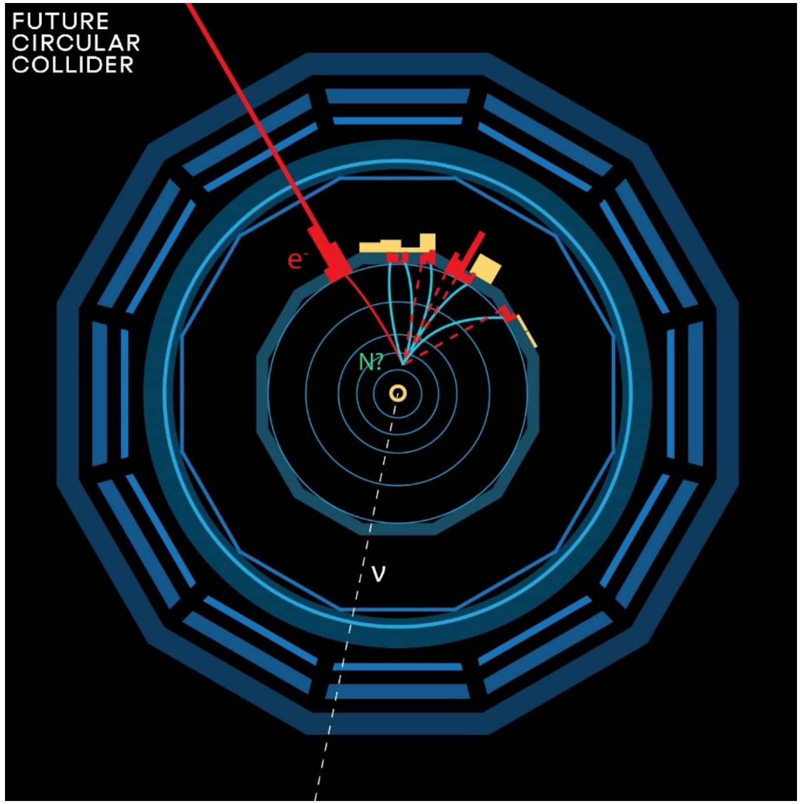
Testing running of α_s to excellent precision with hadron production from low energy ($\gamma^*/Z^* +\gamma$) to 365 GeV

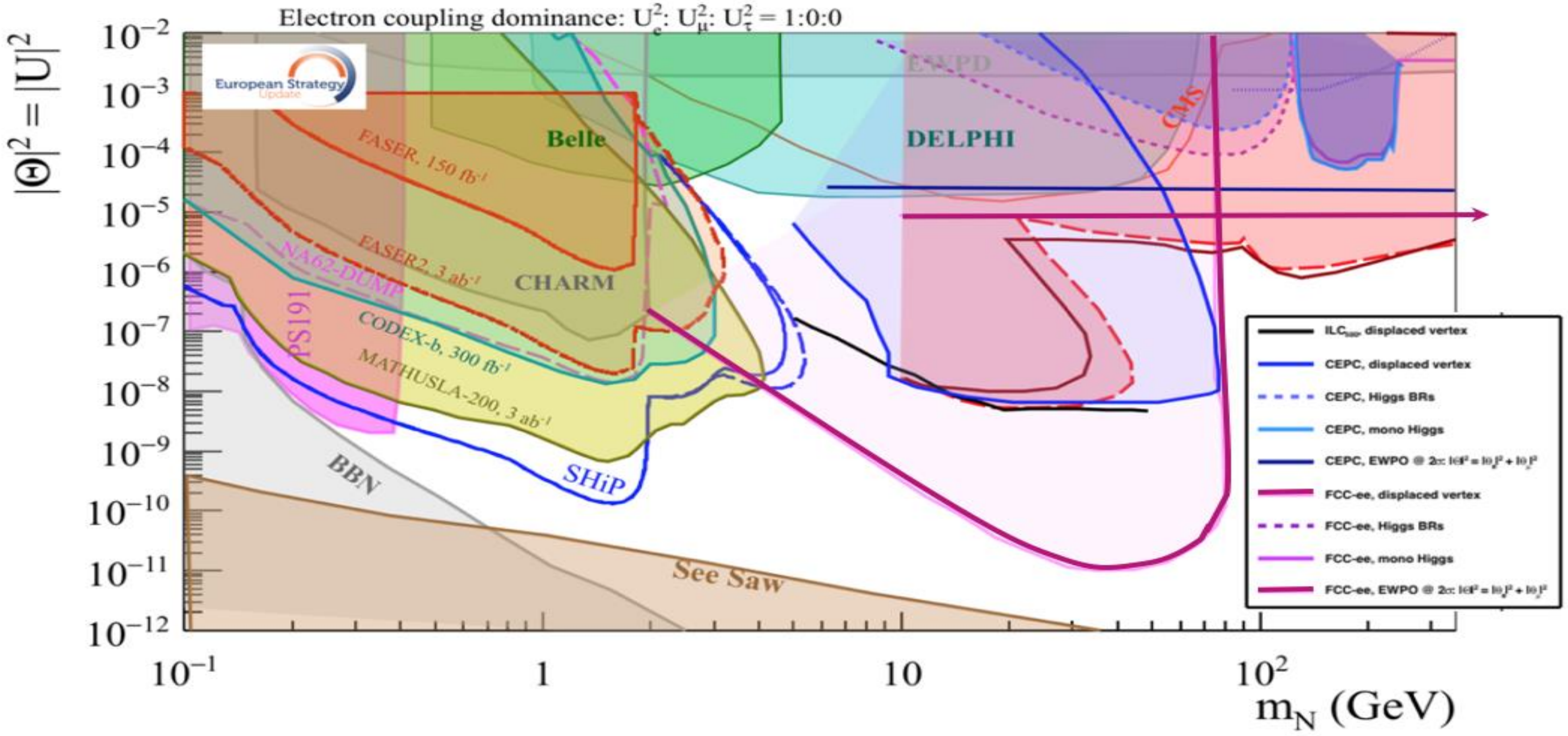
And… H→gg is a pure gluon factory (100’000 events)

FCC This picture is relevant to Neutrino, Dark sectors and High Energy Frontiers.

FCC-ee (Z) compared to the other machines for right-handed (sterile) neutrinos

How close can we get to the 'see-saw limit'?

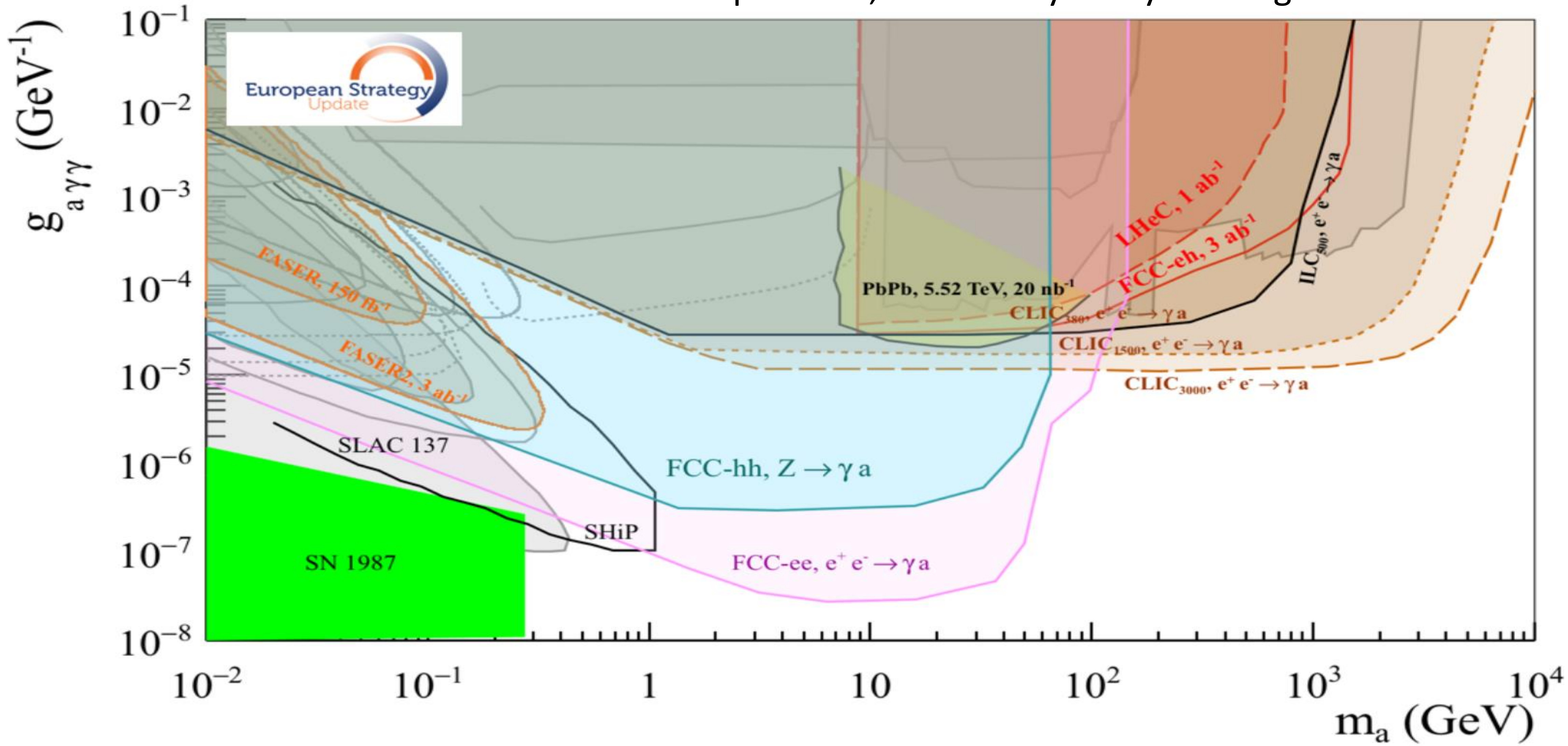




-- the purple line shows the 95% CL limit if no HNL is observed. (here for 10^{12} Z),

-- the horizontal line represents the sensitivity to **mixing of neutrinos** to the dark sector, using EWPOs (G_F vs $\sin^2\theta_W^{eff}$ and m_Z, m_W, tau decays) which extends sensitivity to 10^{-5} mixing all the way to very high energies (500-1000 TeV at least). arxiv:2011.04725

Similar situation for Axion-like-particles; Luminosity is key to the game



Complementarity with High energy lepton collider,

Much more left to explore at FCC-ee-Z and FCC-hh!

Conclusions

The FCC-integrated programme, FCC-ee then hh with ep and heavy ion options, thanks to synergies and complementarities, offers the most versatile and adapted response to today's physics landscape.

FCC-ee is the best low energy Higgs Factory, and MUCH more. It offers a unique physics programme and discovery potential (Precision EW and Flavour, high sensitivity LLP searches, QCD) thanks to an outstanding high luminosity and E_{cm} calibration.

FCC-ee presents numerous novel challenges in detector design and experimentation!

FCC-ee matches well the European strategy vision and recommandations, and is well supported by CERN council!
The FCC financial and technical feasibility study has now started (with focus on the tunnel and FCC-ee implementation).
Significant funding (100MCHF/5years) at CERN together with the High Field Magnet R&D (120MCHF/6years).
Start of construction target: soon after completion of the HL-LHC construction and commissionning (2030).

The FCC is a global project and the participation of the CERN international partners is both essential and welcome

It is a great project, where there is much to learn, join us!

5th Physics workshop 7-11 Feb 2022 Registration: https://cern.ch/FCCPhysics2022

FCC-Conceptual Design Reports and other resources

- **Vol 1 – Physics**
  Vol 2 – FCC-ee,
  Vol 3 – FCC-hh,
  Vol 4 – HE-LHC
  1338 authors

A public presentation of the CDR was given on 4-5 March 2019 at CERN https://indico.cern.ch/event/789349/

FCC Phys workshop Nov 9-13 2020 https://indico.cern.ch/event/932973/
FCC week 28/06-02/07/2021 https://indico.cern.ch/event/995850/
ECFA plenary 20/11/2021 https://indico.cern.ch/event/1085137/
FCC Physics Workshop Feb 7-11 2022 https://cern.ch/FCCPhysics2022

- Preprints since 15 January 2019 on http://fcc-cdr.web.cern.ch/ and INSPIRE
- **CDRs published in European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**
- **ESPP summaries: FCC-integral, FCC-ee, FCC-hh, HE-LHC** http://fcc-cdr.web.cern.ch/
- FCC-ee «Your questions answered» https://arxiv.org/abs/1906.02693v1
  “Circular vs linear, another story of complementarity” arXiv:1912.11871v2
  FCC-ee Energy Calibration paper https://arxiv.org/abs/1909.12245
- LOIs to Snowmass, **challenges**: https://indico.cern.ch/event/951830/

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

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Mogens.Dam@nbi.dk philipp.roloff@cern.ch felix.sefkow@cern.ch (Detector Concepts)

1. register to the study (both)

https://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=fcc-experiments-lepton

https://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=fcc-experiments-hadron

2. Prepare MOU with Addendum that can evolve with increased participation

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Physics at FCC-ee

1. HIGGS FACTORY

Higgs provides a very good reason why we need e+e- (or $\mu\mu$) collider

2. ELECTROWEAK PRECISION (10^{-3} today → 10^{-5})

Z + WW + top required!

Test of the completeness of the SM

3. Z FACTORY

($5\ 10^{12}$ Z i.e. $1.5\ 10^{11}$ ee, $\mu\mu$, $\tau\tau$; ~$0.7\ 10^{12}$ uu,dd,ss,cc,bb ; 10^{12} $\nu\nu$)

High statistics for Heavy Flavours, QCD

Search for Feebly Coupled Particles

The place for 'direct discovery'

+ comments on the synergy and complementarity of FCC-ee hh and eh

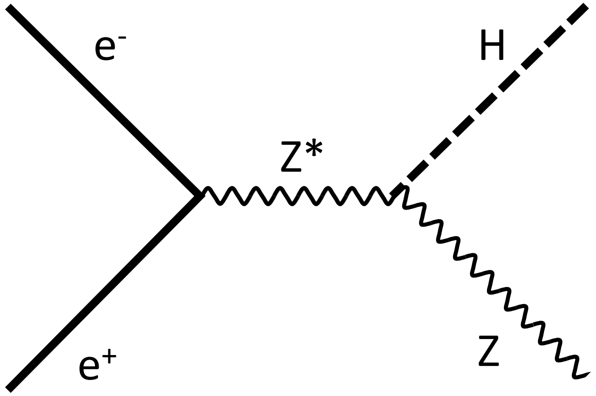
Higgs Physics

e+e- : Z – tagging by missing mass

THE LHC is a Higgs Factory…BUT

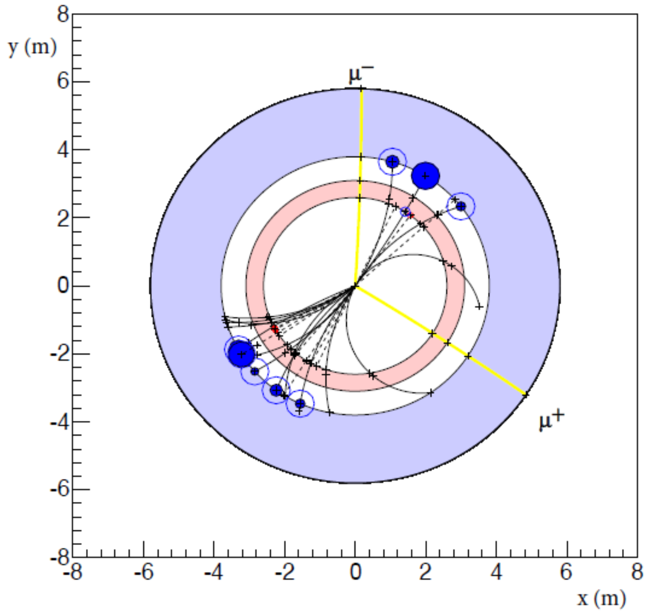
$$\sigma_{i\to f}^{\ \ observed} \propto \sigma_{prod} \frac{(g_{Hi})^2(g_{Hf})^2}{\Gamma_H} \ \textbf{?}$$

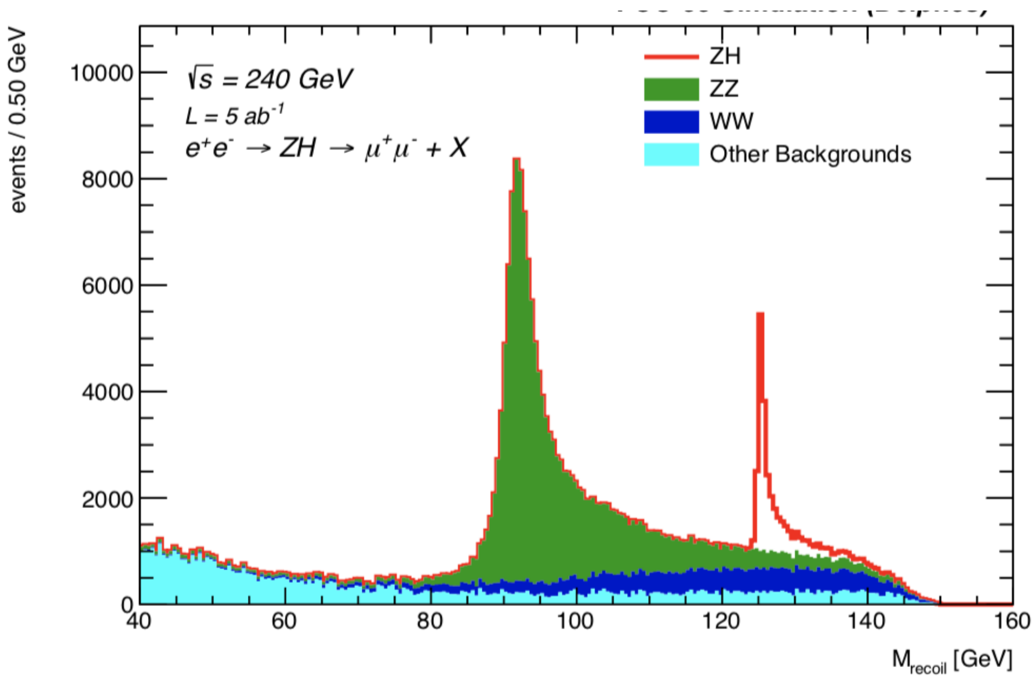
→ must do physics with ratios



total rate $\propto g_{HZZ}^{\ 2}$
ZZZ final state $\propto g_{HZZ}^{\ 4}/\Gamma_H$
➔ **measure total width** Γ_H

g_{HZZ} to ±0.2%
empty recoil = invisible width
'funny recoil' = exotic Higgs decay





FCC

Complementarity: Higgs Physics at FCC

FCC-ee → g_{HZZ} to <±0.2% from σ_{ZH}
(model-independent standard candle)
and Γ_H, g_{Hbb}, g_{Hcc}, $g_{H\tau\tau}$, g_{HWW}

→fixes all HL-LHC / FCC-hh couplings

FCC-hh produces over 10^{10} Higgs bosons
use g_{HZZ} from FCC_{ee} will give $g_{H\mu\mu}$, $g_{H\gamma\gamma}$, $g_{HZ\gamma}$, Br_{inv}

FCC-ee also measures top EW couplings ($e^+e^- \to tt$)

FCC-hh produces 10^8 ttH and 2. 10^7 HH pairs
→ g_{Htt} and g_{HHH}, model-independent & precise!

HL-LHC/FCC-ee/FCC-hh complementarity outstanding

Comparison with other e+e- colliders in spares

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
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
g_{HHH} (%)	50.	2 IP: 44./33. 4 IP: 27./24.	3-4
Γ_H (%)	SM	1.1	0.91
m_H (MeV)	30-50	3	3
BR_{inv} (%)	1.9	0.19	0.024
BR_{EXO} (%)	SM (0.0)	1.1	1

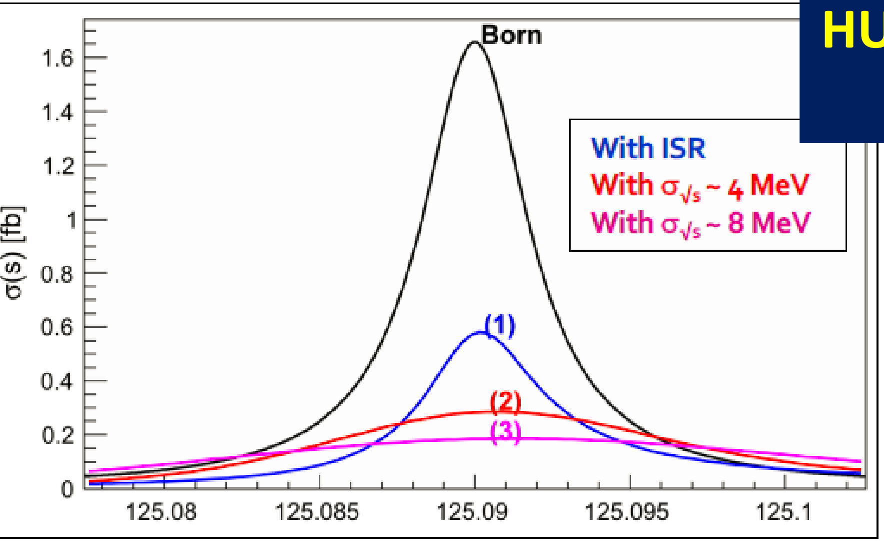
ee
hh
ee
hh
ee

ee only | LHC +ee

FCC-ee+hh+ep
ep → WW mostly

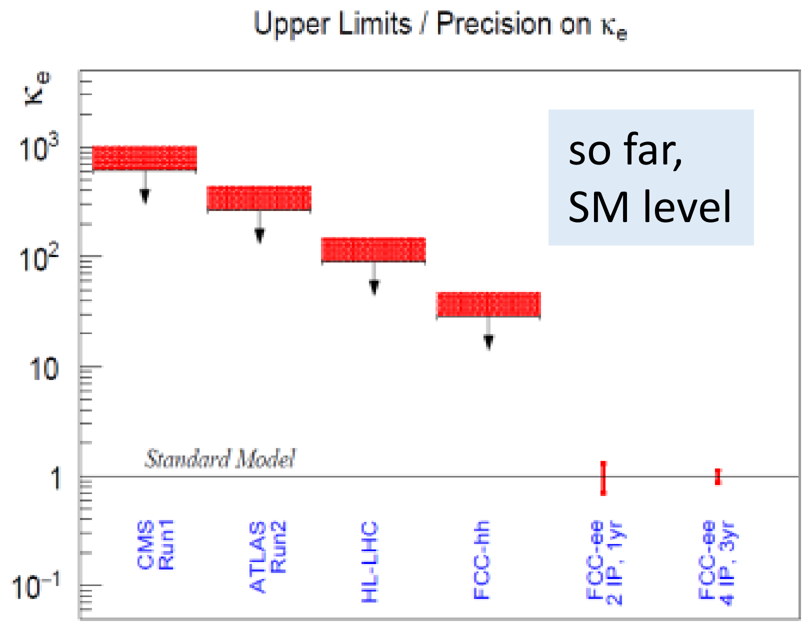
Unique: electron Yukawa coupling

Measure e+e- → H @ 125.xxx GeV
requires
-- Higgs mass to be known to <<5 MeV (OK, 3 MeV)
-- **Huge luminosity** (several years)
-- **monochromatization** to reduce σ_{ECM}
-- **continuous adjustment of E_{CM}** (transv. Polar.)
-- an extremely sensitive event selection

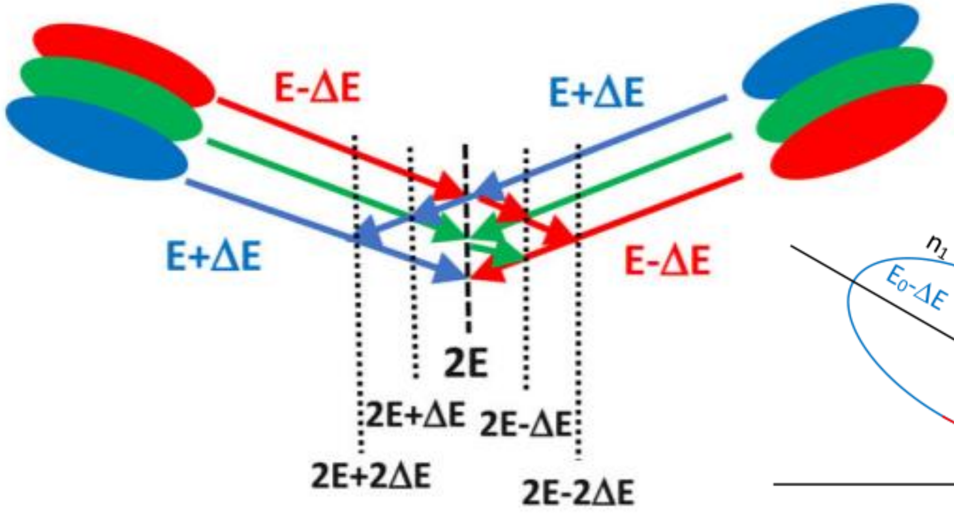


HUGE CHALLENGE under study

Monochromatization: **UNDER STUDY**
taking advantage of the separate e+ and e- rings, one can distribute in opposite way high and low energies in the beam (in x, z time)

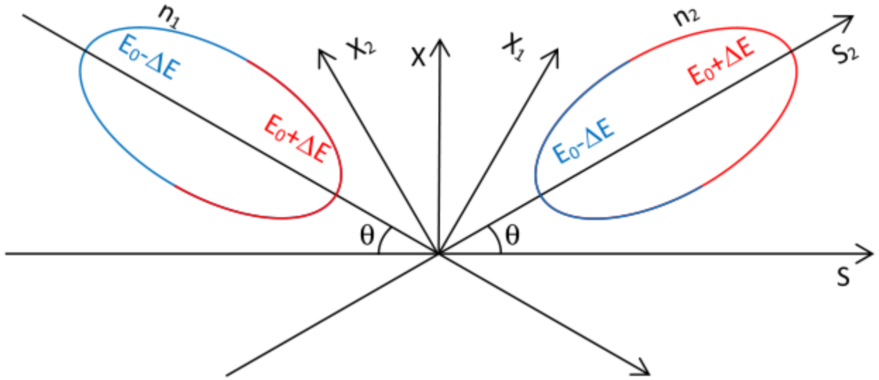


so far, SM level



opposite sign horizontal dispersion

combine?



opposite difference in time within 30ps luminosity

Centre of mass Energy Calibration: the cornerstone of the precision programme

FCC

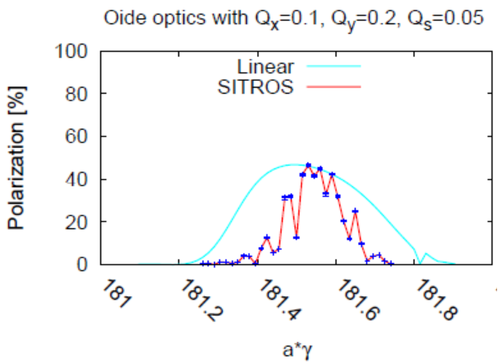
Large ring→transverse polarization of $e^{\pm}$ up to $E_{beam} > 80$ GeV $\sigma_E \propto E^2/\sqrt{\rho}$

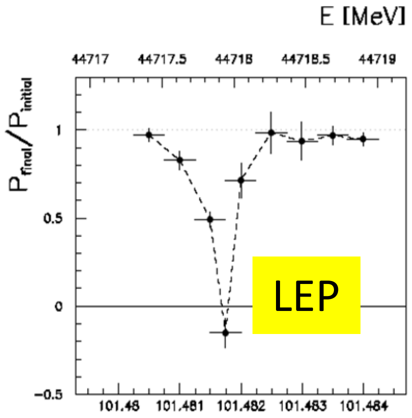
Resonant depolarization provides high precision E_{beam} $\nu_s = \frac{g-2}{2}\frac{E_b}{m_e} = \frac{E_b}{0.4406486(1)}$

Unique to circular machines (ee and μμ)

Improve over LEP by using pilot bunches + e- and e+ polarimeter

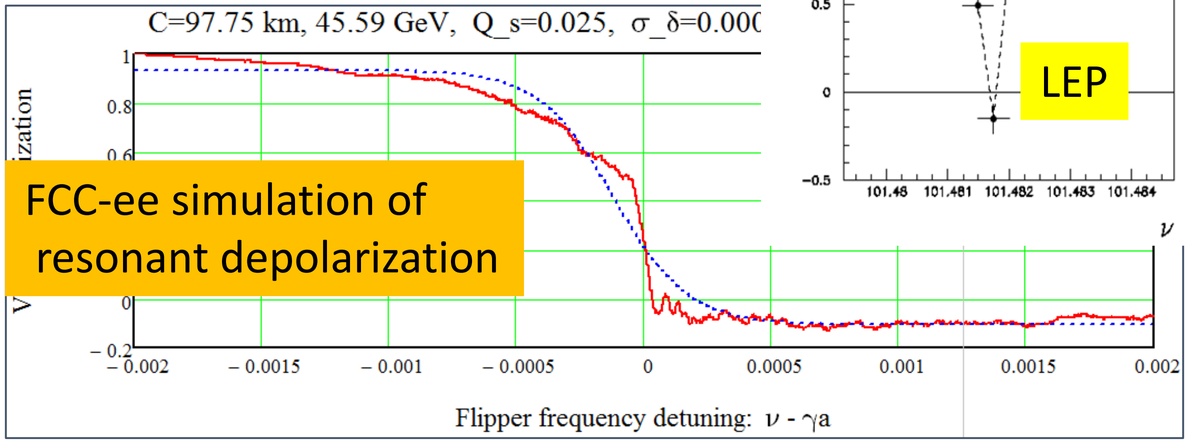
E. Gianfelice





Relationship between ν_s and E_{CM}

- ➔ **CM boost, σ_{ECM}, α_{coll} determined from 10^6 μμ /5min**
- ➔ **Beamstahlung monitor under study etc...**

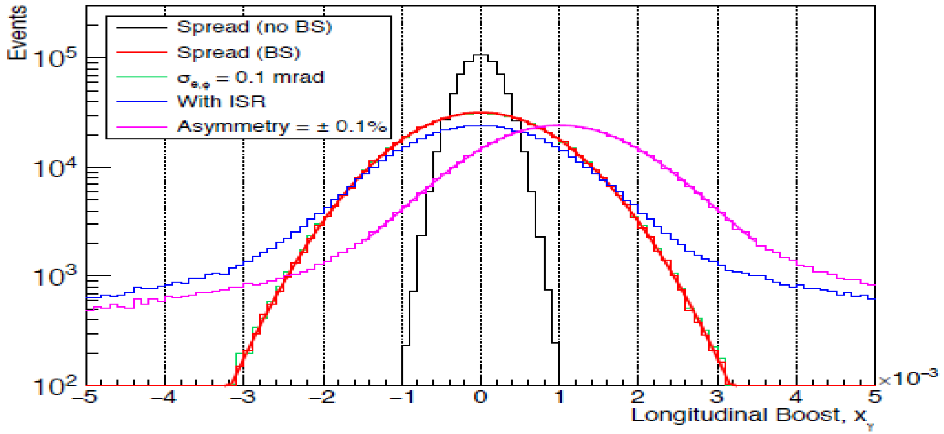


First round of studies (arxiv 1909.12245)

m_Z, Γ_Z, $\sin^2\theta_W^{eff}$, $\alpha_{QED}(m_Z)$, m_W

next target: bring syst. closer to stat. errors.

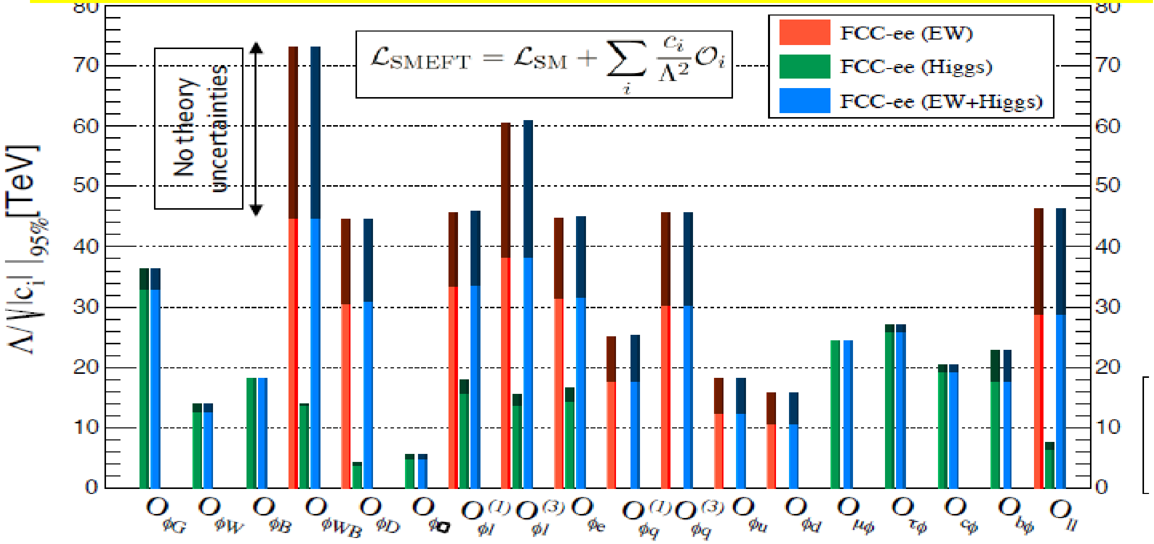
Quantity	statistics	ΔE_{CMabs} 100 keV	$\Delta E_{CMSyst-ptp}$ **40 keV**	calib. stats. $200\ keV/\sqrt{(N^i)}$	σE_{CM} (84) ± **0.05** MeV
m_Z (keV)	4	100	**28**	1	–
Γ_Z (keV)	7	2.5	**22**	1	**10**
$sin^2\theta_W^{eff} \times 10^6$ from $A_{FB}^{\mu\mu}$	2	–	**2.4**	0.1	–
$\frac{\Delta\alpha_{QED}(M_Z)}{\alpha_{QED}(M_Z)} \times 10^5$	3	0.1	**0.9**	–	**0.05**



At our luminosity level, longitudinal polarization brings nothing that cannot be done otherwise.

Precision EW measurements: is the SM complete?

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



- ***Higgs and EWPOs are complementary***
- top quark mass and couplings essential!

(the 100km circumference is optimal for this)

- preliminary systematics!

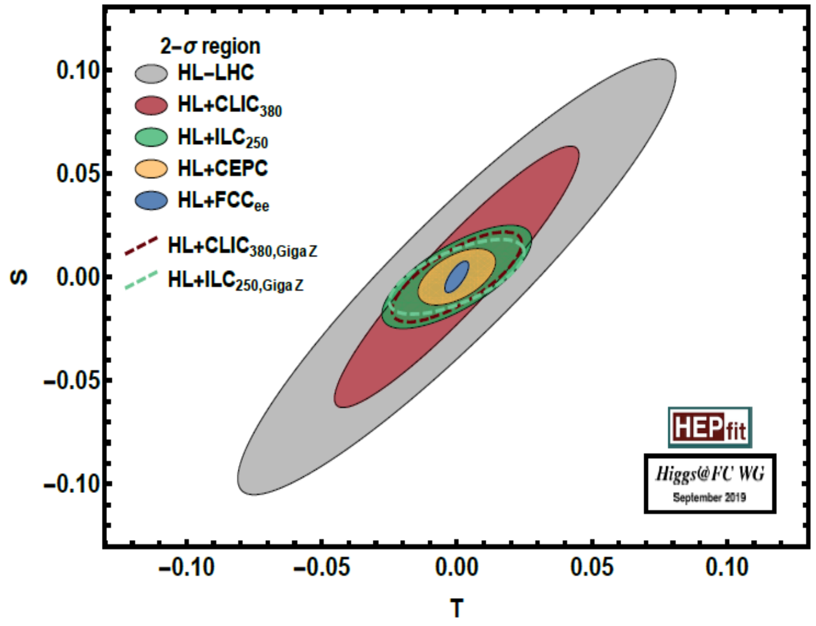
aim at reducing to the level of systematics

- many observables still to be added (flavours)
- complemented by high energy FCC-hh
- ***Theory work is critical and initiated*** *1809.01830*

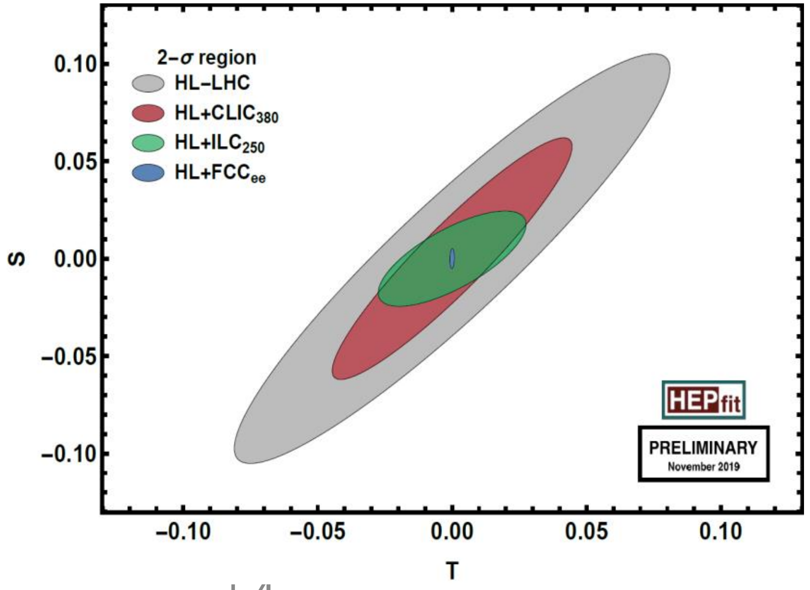
Electroweak Physics

Z factory + WW + top The realm of FCC-ee

Highest luminosities at 91, 160 and 350 GeV
Transverse pol. at 91 and 160 GeV→Ecm calibration
m_Z (100 keV) Γ_Z (25 keV), m_W (<500 keV), $\alpha_{QED}(m_Z)$ (3.10^{-5})
and $\sin^2\theta_w$ at 310^{-6}



Complete set of EW observables can be measured
Precision unique to FCC-ee + new physics sensitivity
→ a lot more potential to exploit with good detector design than present treatment suggests



The reach for new physics depends on which new physics:
-- $1/\Lambda^2$ new physics → 30-70 TeV
-- Heavy Neutrino → 500-1000 TeV
-- new non-degenerate doublet should not have mass splitting greater than ~5 GeV

FCC

More on TeraZ

The Flavour Factory

Progress in flavour physics wrt SuperKEKb/BELLEII requires > 10^{11} b pair events,

FCC-ee(Z): will provide ~10^{12} bb pairs. "**Want at least 5 10^{12} Z…"**

- precision of CKM matrix elements
- Push forward searches for FCNC, CP violation and mixing
- Study rare penguin EW transitions such as $b \to s\, \tau^+ \tau^-$, spectroscopy (produce b-baryons, B_s …)
- **Test lepton universality with 10^{11} τ decays (with τ lifetime, mass, BRs) at 10^{-5} level, LFV to 10^{-10}**

-- all very important to constrain / (provide hints of) new BSM physics.

need special detectors (PID); a story to be written!

The 3.5 × 10^{12} hadronic Z decay also provide precious input for QCD studies

High-precision measurement of $\alpha_s(m_Z)$ with R_ℓ in Z and W decay, jet rates, τ decays, etc. : $10^{-3} \to 10^{-4}$

huge √s lever-arm between 30 GeV and 365 GeV, fragmentation, baryon production ….

Testing running of α_s to excellent precision with hadron production from low energy ($\gamma^*/Z^* + \gamma$) to 365 GeV

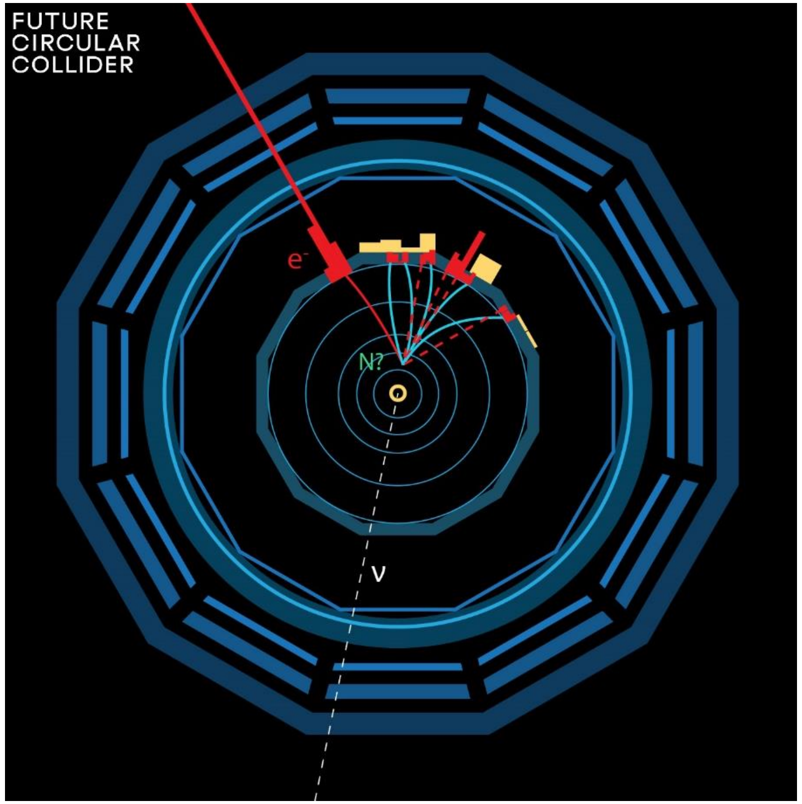
And… H→gg is a pure gluon factory (100'000 events)

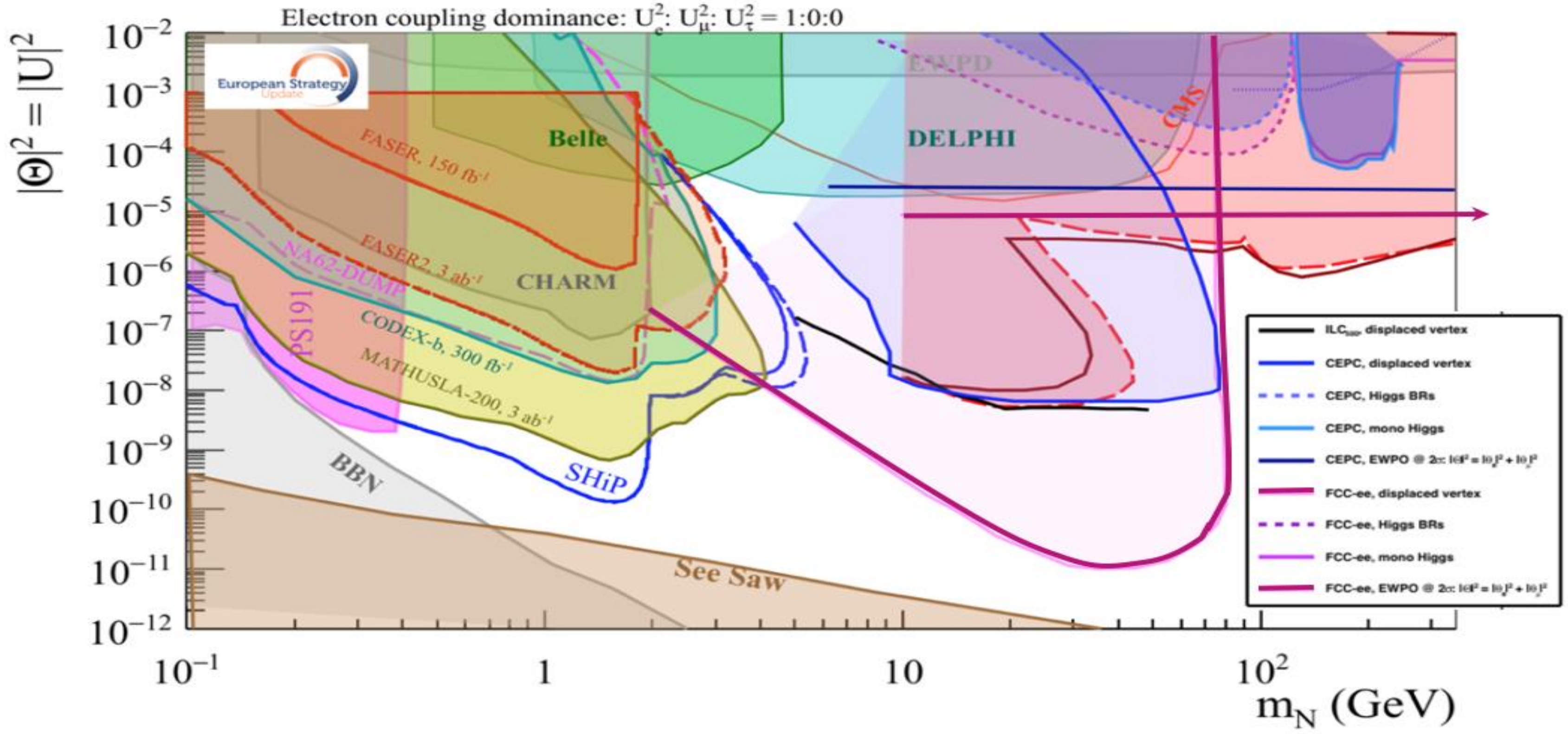
FCC

This picture is relevant to Neutrino, Dark sectors and High Energy Frontiers.

FCC-ee (Z) compared to the other machines for right-handed (sterile) neutrinos

How close can we get to the 'see-saw limit'?

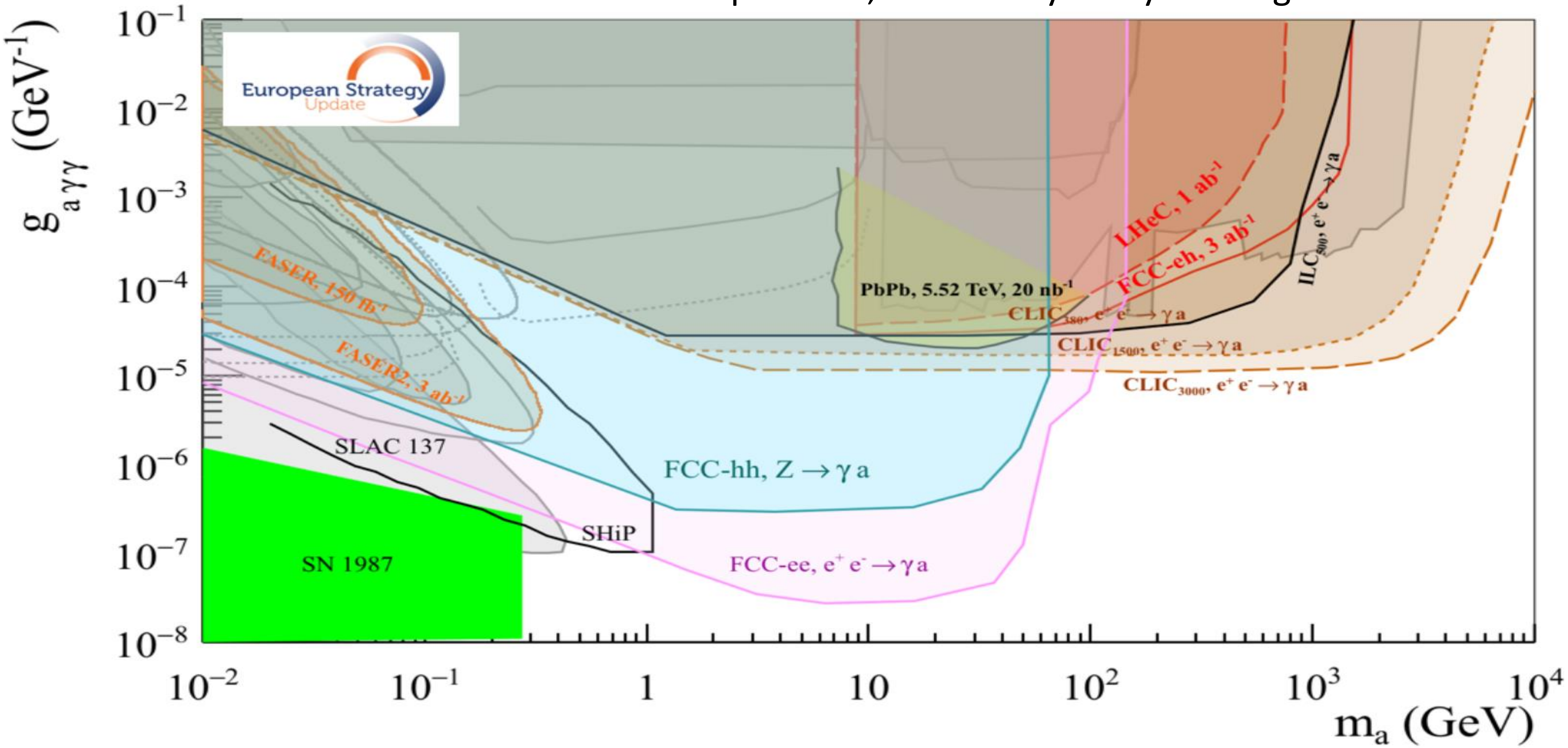




-- the purple line shows the 95% CL limit if no HNL is observed. (here for 10^{12} Z),

-- the horizontal line represents the sensitivity to **mixing of neutrinos** to the dark sector, using EWPOs (G_F vs $\sin^2\theta_W^{eff}$ and m_Z, m_W, tau decays) which extends sensitivity to 10^{-5} mixing all the way to very high energies (500-1000 TeV at least). arxiv:2011.04725

Similar situation for Axion-like-particles; Luminosity is key to the game



Complementarity with High energy lepton collider,

Much more left to explore at FCC-ee-Z and FCC-hh!

Conclusions

The FCC-integrated programme, FCC-ee then hh with ep and heavy ion options, thanks to synergies and complementarities, offers the most versatile and adapted response to today's physics landscape.

FCC-ee is the best low energy Higgs Factory, and MUCH more. It offers a unique physics programme and discovery potential (Precision EW and Flavour, high sensitivity LLP searches, QCD) thanks to an outstanding high luminosity and E_{cm} calibration.

FCC-ee presents numerous novel challenges in detector design and experimentation!

FCC-ee matches well the European strategy vision and recommandations, and is well supported by CERN council!
The FCC financial and technical feasibility study has now started (with focus on the tunnel and FCC-ee implementation).
Significant funding (100MCHF/5years) at CERN together with the High Field Magnet R&D (120MCHF/6years).
Start of construction target: soon after completion of the HL-LHC construction and commissionning (2030).

The FCC is a global project and the participation of the CERN international partners is both essential and welcome

It is a great project, where there is much to learn, join us!

5th Physics workshop 7-11 Feb 2022 Registration: https://cern.ch/FCCPhysics2022

Our marching orders from ESPP 2020:

“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 of the colliders (ee and hh) and related infrastructure.
→ **FCC is the highest priority after HL-LHC for Europe and its international partners (Plan A)**

Physics at FCC-ee

1. **HIGGS FACTORY**

Higgs provides a very good reason why we need e+e- collider

2. ELECTROWEAK PRECISION (10^{-3} today → 10^{-5})

Z + WW + top required!

Test of the completeness of the SM

Are there further particles with SM couplings?

3. Z FACTORY

($5\ 10^{12}$ Z i.e. $1.5\ 10^{11}$ ee, $\mu\mu$, $\tau\tau$; ~$0.7\ 10^{12}$ uu,dd,ss,cc,bb ; 10^{12} $\nu\nu$)

High statistics for Heavy Flavours, QCD

Search for Feebly Coupled Particles

The place for 'direct discovery'

+ comments on the synergy and complementarity of FCC-ee hh and eh

Status of FCC

-- June 2021 The FCC Feasibility Study (2021-2025) organization was proposed to CERN council, approved unanimously

MTP: 100MCHF/5yrs

-- Council documents :

- Organisational structure of the FCC feasibility study
http://cds.cern.ch/record/2774006/files/English.pdf
- Main deliverables and timeline of the FCC feasibility study
http://cds.cern.ch/record/2774007/files/English.pdf

-- Financial study: “ The focus will be on the tunnel and the first-stage collider (FCC-ee)”
-- Design of FCC-ee and FCC-hh, and their injectors, key technologies, technical infrastructure
-- MDI and Ecm calibration for FCC-ee
-- The physics case and detector concepts will be consolidated for both colliders (FCC-ee and FCC-hh).
-- intermediate review mid 2023, delivery of Feasibility Study Report (FSR) end 2025, (first collisions >2040)
-- Stress the importance of communication towards
scientific community, governments and funding agencies, industries and general public
-- work has started on placement in Geneva area (France and Switzerland)
→ reduce number of surface points to 8
→ layout consistent with later choice of 2 or 4IP for the e+e- collider
-- in parallel, high field magnet R&D for FCC-hh will be carried out with high priority

+120MCHF/6yrs

These events bring both FCC-ee and FCC-hh one step closer to reality

FCC

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huge √s lever-arm between 30 GeV and 365 GeV, fragmentation, baryon production ….

Testing running of α_s to excellent precision with hadron production from low energy (γ^*/Z^* +γ) to 365 GeV

And… H→gg is a pure gluon factory (100'000 events)

Centre of mass Energy Calibration: the cornerstone of the precision programme

Large ring→transverse polarization of $e^{\pm}$ up to $E_{beam} > 80$ GeV $\quad \sigma_E \propto E^2/\sqrt{\rho}$

Resonant depolarization provides high precision E_{beam} $\nu_s = \frac{g-2}{2}\frac{E_b}{m_e} = \frac{E_b}{0.4406486(1)}$

Unique to circular machines (ee and μμ)

Improve over LEP by using pilot bunches + e- and e+ polarimeter

Relationship between ν_s and E_{CM}

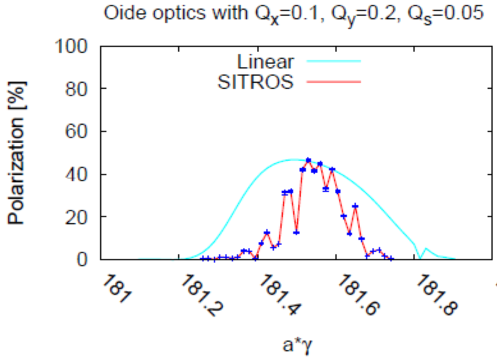
- ➔ **CM boost, σ_{ECM}, α_{coll} determined from 10^6 μμ /5min**
- ➔ **Beamstahlung monitor under study etc...**

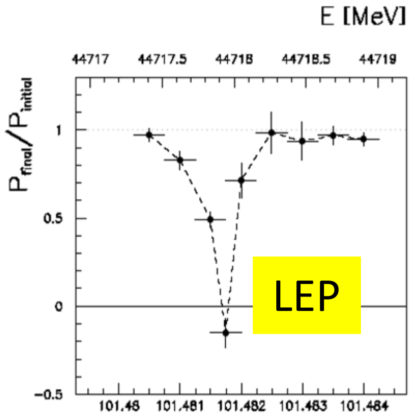
First round of studies (arxiv 1909.12245)

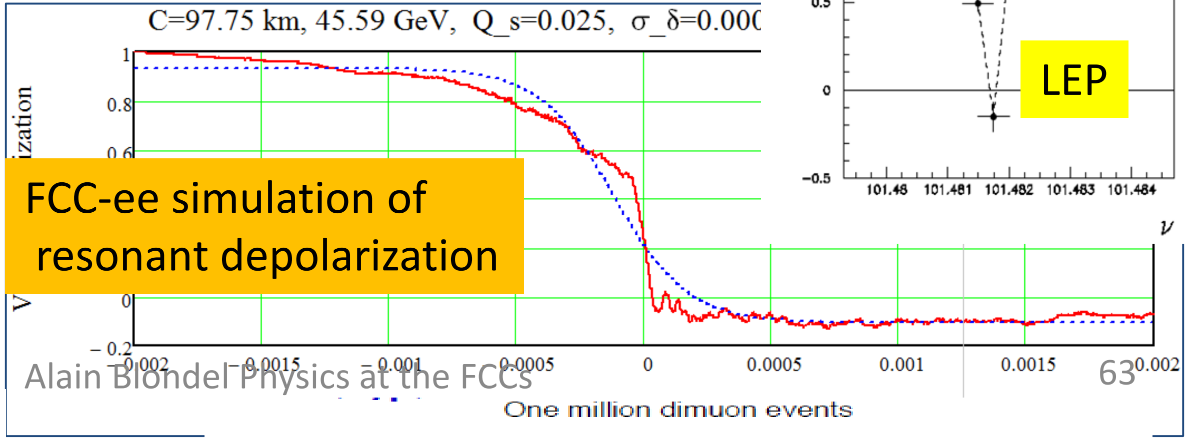
m_Z, Γ_Z, $\sin^2\theta_W^{eff}$, $\alpha_{QED}(m_Z)$, m_W

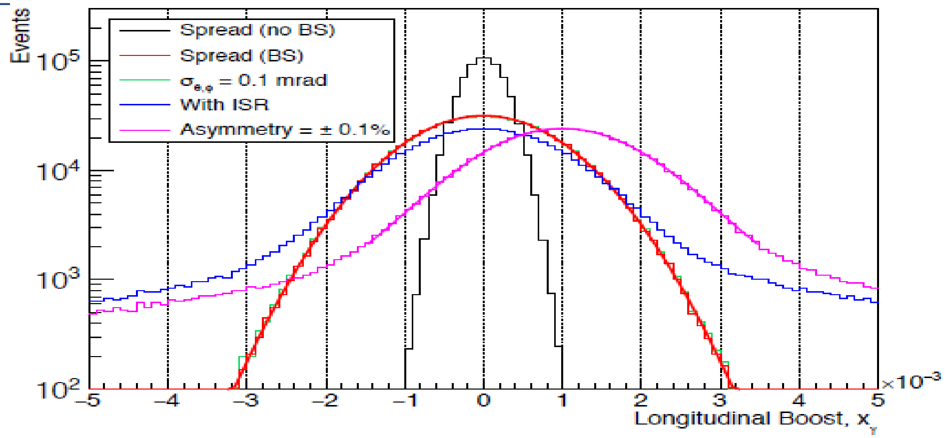
next target: bring syst. closer to stat. errors.

E. Gianfelice









Quantity	statistics	ΔE_{CMabs} 100 keV	$\Delta E_{CMSyst-ptp}$ **40 keV**	calib. stats. $200\ \mathrm{keV}/\sqrt{(N^i)}$	σE_{CM} (84) ± **0.05** MeV
m_Z (keV)	4	100	**28**	1	–
Γ_Z (keV)	7	2.5	**22**	1	**10**
$\sin^2\theta_W^{eff} \times 10^6$ from $A_{FB}^{\mu\mu}$	2	–	**2.4**	0.1	–
$\frac{\Delta\alpha_{QED}(M_Z)}{\alpha_{QED}(M_Z)} \times 10^5$	3	0.1	**0.9**	–	**0.05**

At our luminosity level, longitudinal polarization brings nothing that cannot be done otherwise.

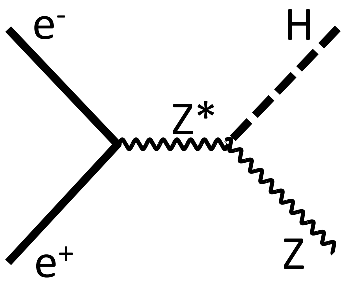
Higgs Physics

e+e- : Z – tagging by missing mass

THE LHC is a Higgs Factory…BUT

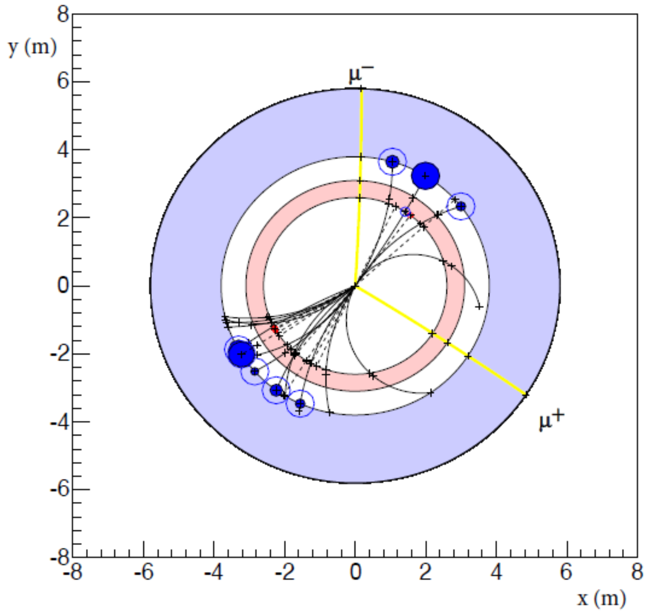
$$\sigma_{i\to f}^{\text{observed}} \propto \sigma_{prod}\,\frac{(g_{Hi})^2(g_{Hf})^2}{\Gamma_H}\ ?$$

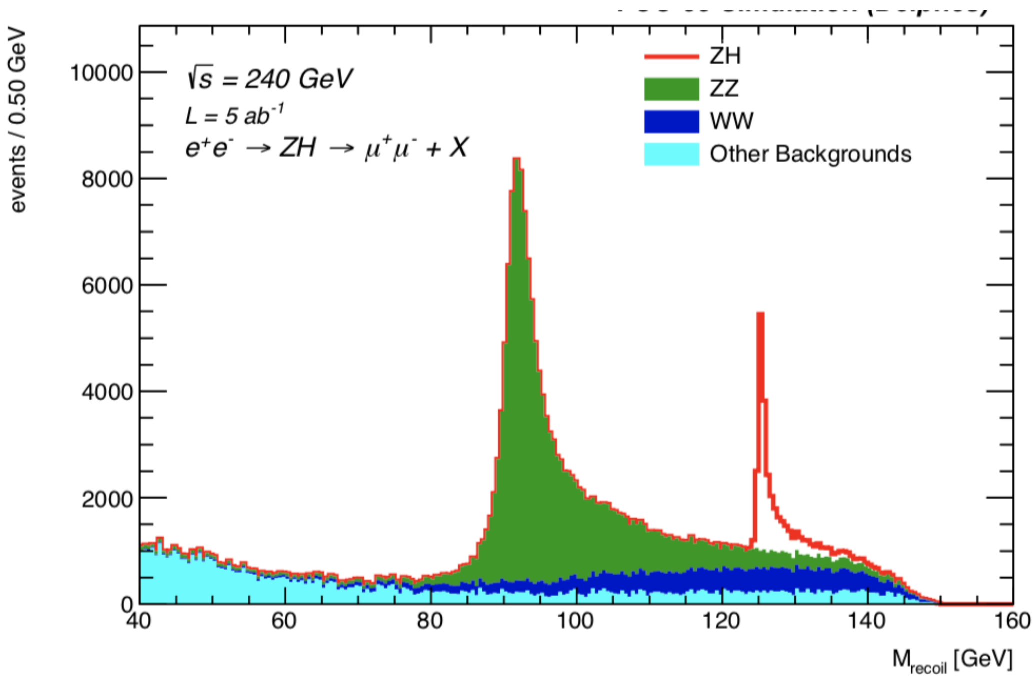
→ must do physics with ratios



total rate $\propto g_{HZZ}^2$
ZZZ final state $\propto g_{HZZ}^4/\Gamma_H$
➔ measure total width Γ_H

g_{HZZ} to ±0.2%
empty recoil = invisible width
'funny recoil' = exotic Higgs decay

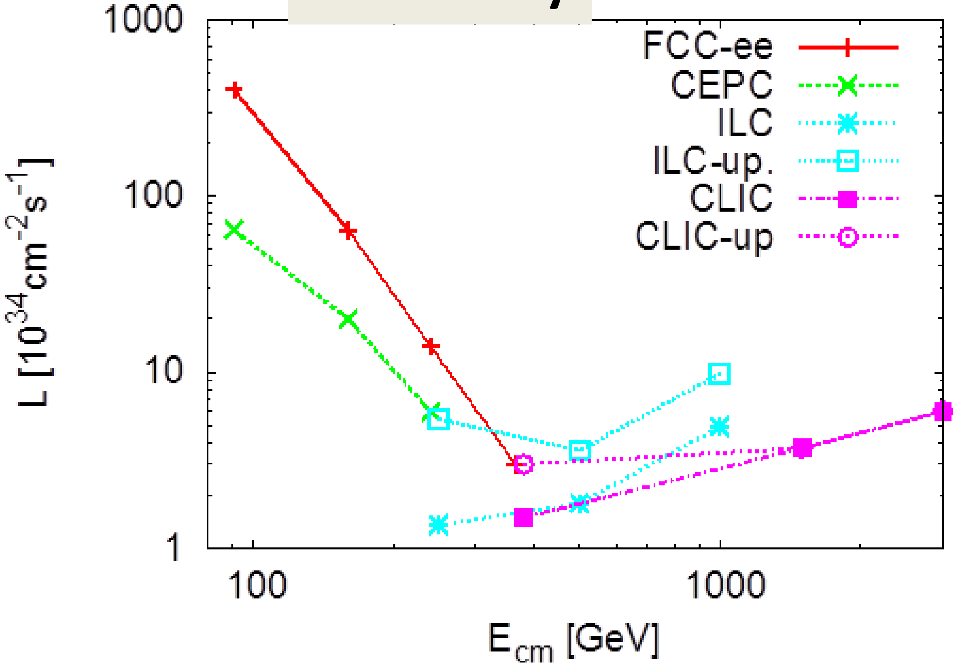




Circular vs linear complementarity

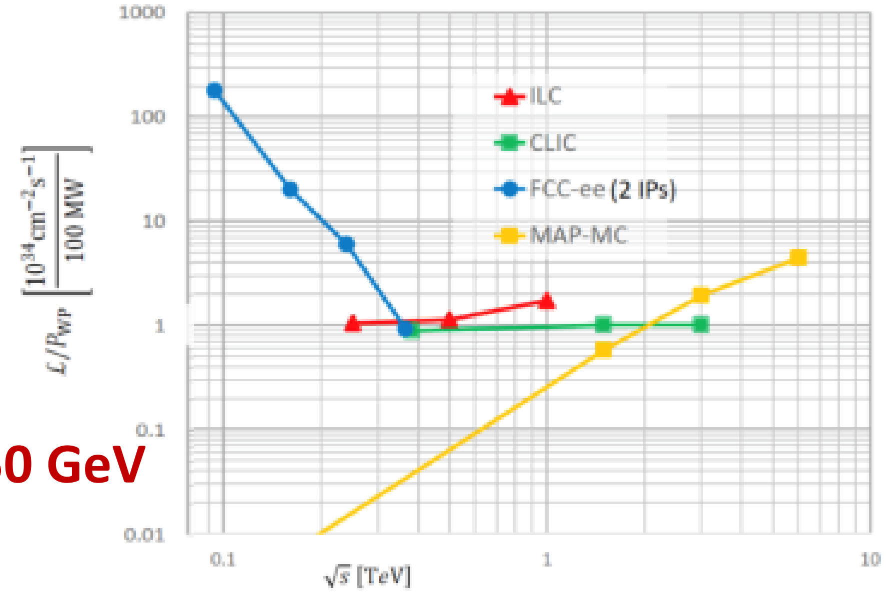
plots from Briefing Book

Luminosity



cross-over ~350 GeV

Luminosity/Power → Energy efficiency



Luminosity vs Energy circular below 365GeV linear above 365 GeV

Efficiency : 9 (5) GJ/Higgs at FCC-ee with 2(4)IP 50GJ/Higgs for ILC250 (first 15 years)

Beam polarization: circular: transverse → ppm beam energy calibration

linear: longitudinal : e- ±80% easy, (e+ ±30% difficult) → additional d.o.f

Monochromatization for e+e- → H (125 GeV)

Long term energy upgrade circular: pp, AA, e-h linear: High energy lepton collisions

Interaction points circular: 2-4 linear: 1 IP (at a time)

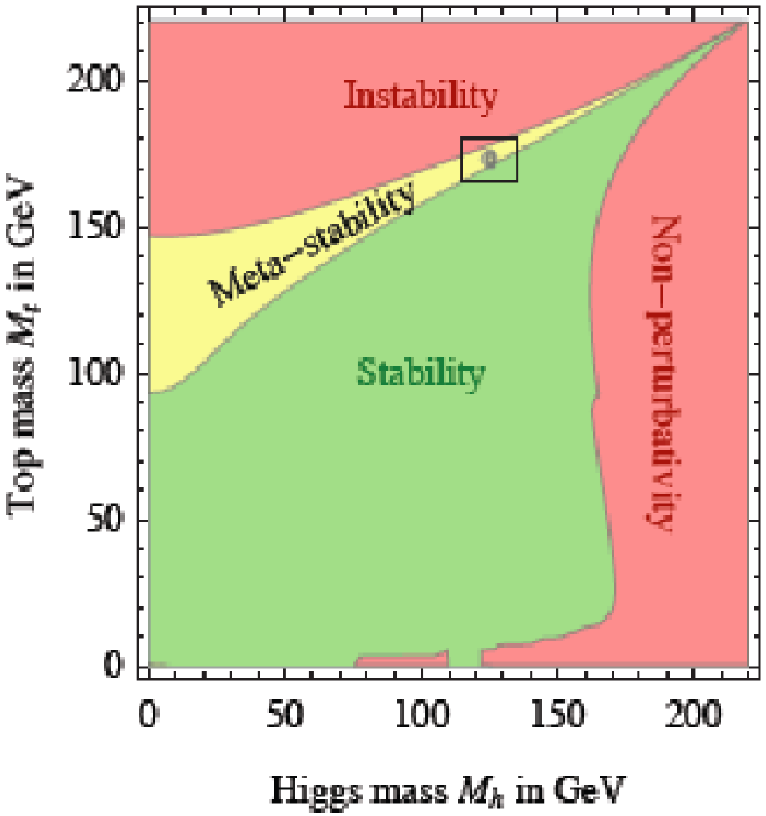
Run limited in time by arrival of hadron collider Run is open ended

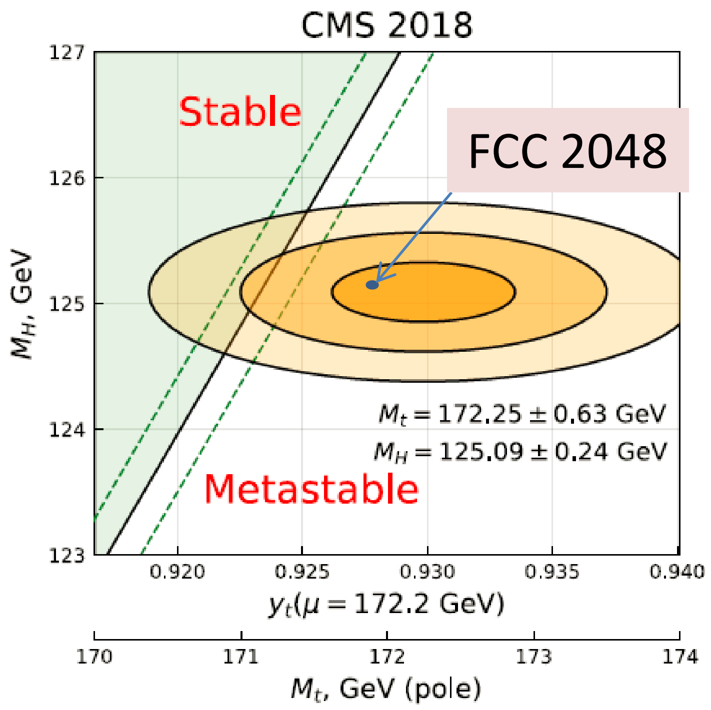
The Standard Model is a very consistent and complete theory.
It explains all known collider phenomena and almost all particle physics (except ν's)

– this was beautifully verified at LEP, SLC, Tevatron and the LHC.

-- the EWPO radiative corrections predicted top and Higgs masses
assuming SM *and nothing else*

we can even extrapolate the Standard Model all the way to the the Plank scale :





Asymptotic safety of gravity and the Higgs boson mass

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12 January 2010

Abstract

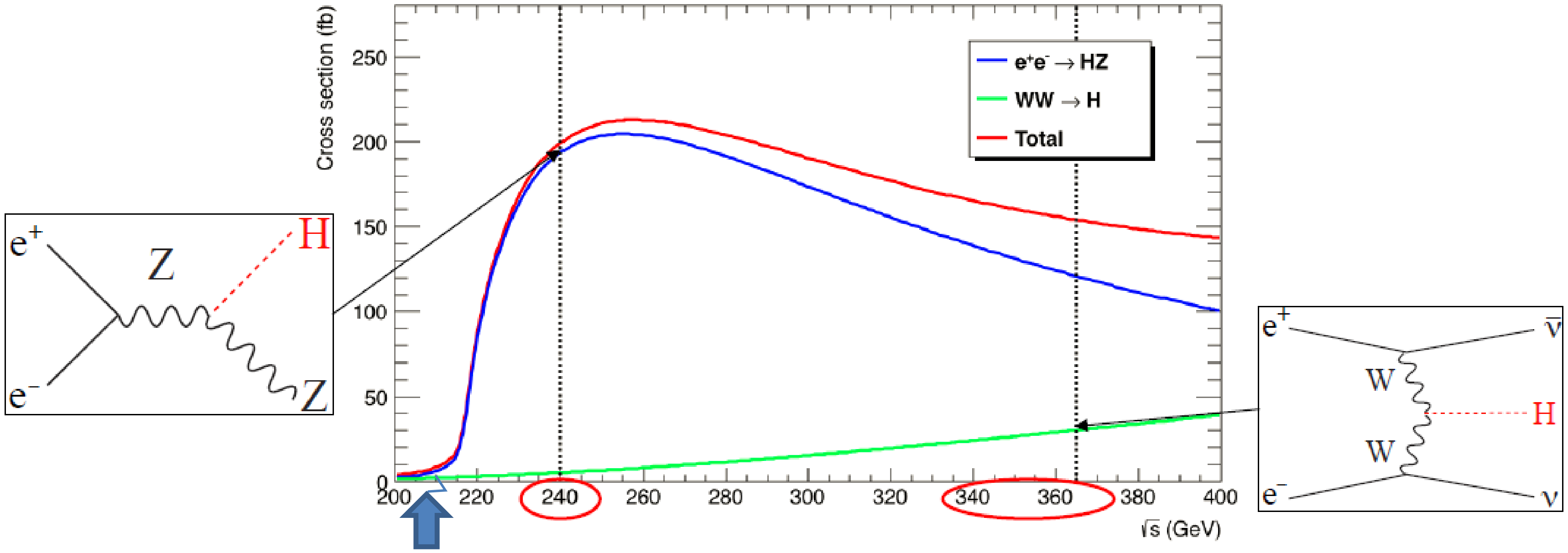
There are indications that gravity is asymptotically safe. The Standard Model (SM) plus gravity could be valid up to arbitrarily high energies. Supposing that this is indeed the case and assuming that there are no intermediate energy scales between the Fermi and Planck scales we address the question of whether the mass of the Higgs boson m_H can be predicted. For a positive gravity induced anomalous dimension $A_\lambda > 0$ the running of the quartic scalar self interaction λ at scales beyond the Planck mass is determined by a fixed point at zero. This results in $m_H = m_{\text{min}} = 126$ GeV, with only a few GeV uncertainty. This prediction is independent of the details of the short distance running and holds for a wide class of extensions of the SM as well. For $A_\lambda < 0$ one finds m_H in the interval $m_{\text{min}} < m_H < m_{\text{max}} \simeq 174$ GeV, now sensitive to A_λ and other properties of the short distance running. The case $A_\lambda > 0$ is favored by explicit computations existing in the literature.

Key words:
Asymptotic s
PACS: 04.60.

Detecting the Higgs scalar with mass around 126 GeV at the LHC could give a strong hint for the absence of new physics influencing the running of the SM couplings between the Fermi and Planck/unification scales.

Is it the end?

Higgs Production



LEP

10^6 e+e- → ZH events with 5 ab-1

- **Target : few per-mil precision, statistics-limited.**
- **Complemented with 200k events at √s = 350 – 365 GeV**

Of which 30% in the WW fusion channel (useful for the Γ_H precision)

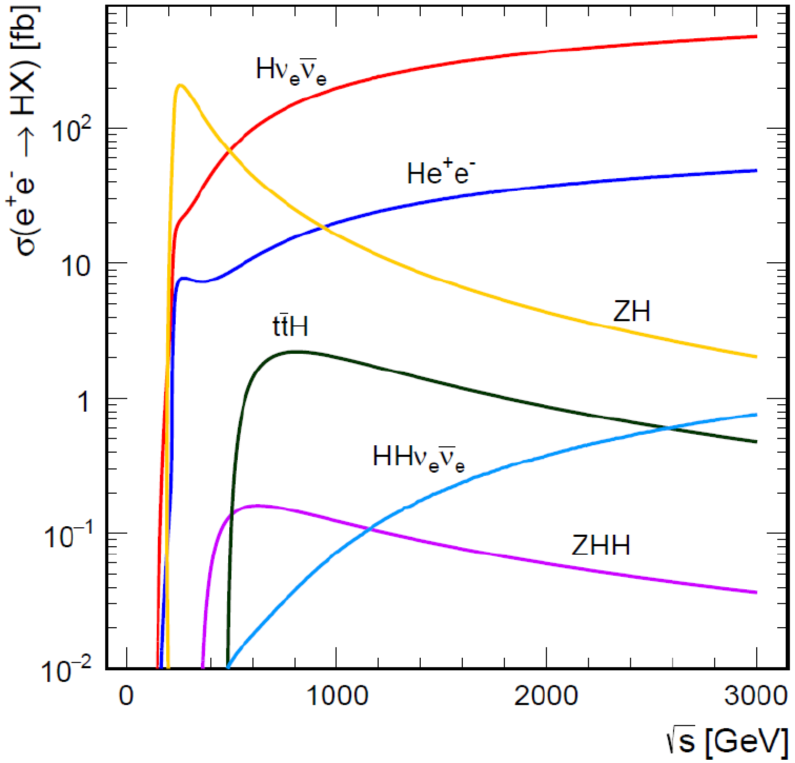
Table 1: Precision on the Higgs boson couplings, from Ref. [12], in the κ framework without (first numbers) and with (right numbers) a combination with HL-LHC projections [13], for the five low-energy Higgs factories (ILC_{250}, $CLIC_{380}$, $CEPC_{240}$, and $FCC\text{-}ee_{240\to365}$ with 2 IPs). For g_{HHH}, the result of a global EFT fit is shown with 2 IPs (top) and 4 IPs (bottom). All numbers are in % and indicate 68% C.L. sensitivities. Also indicated are the standalone precision on the total decay width and the 95% C.L. sensitivity on the "invisible" and "exotic" branching fractions, the latter accounting for final states that cannot be tagged as SM decays. All numbers include current projected parametric uncertainties. The HL-LHC result is obtained by fixing the total Higgs boson width and the $H \to c\bar{c}$ branching fraction to their Standard Model values, and by assuming no BSM decays. The CEPC team has shown that a significant result for the $HZ\gamma$ coupling can be achieved from the large sample of Higgs bosons accessible at circular e^+e^- colliders. The $HZ\gamma$ coupling is otherwise obtained solely from HL-LHC projections. A result similar to that obtained with CEPC can be expected from FCC-ee.

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$CEPC_{240}$	$FCC\text{-}ee_{240\to365}$
Lumi (ab^{-1})	3	2	1	5.6	5 + 0.2 + 1.5
Years	10	11.5	8	7	3 + 1 + 4
g_{HZZ} (%)	1.5	0.30 / 0.29	0.50 / 0.44	0.19 / 0.18	0.18 / 0.17
g_{HWW} (%)	1.7	1.8 / 1.0	0.86 / 0.73	1.3 / 0.88	0.44 / 0.41
g_{Hbb} (%)	5.1	1.8 / 1.1	1.9 / 1.2	1.3 / 0.92	0.69 / 0.64
g_{Hcc} (%)	SM	2.5 / 2.0	4.4 / 4.1	2.2 / 2.0	1.3 / 1.3
g_{Hgg} (%)	2.5	2.3 / 1.4	2.5 / 1.5	1.5 / 1.0	1.0 / 0.89
$g_{H\tau\tau}$ (%)	1.9	1.9 / 1.1	3.1 / 1.4	1.4 / 0.91	0.74 / 0.66
$g_{H\mu\mu}$ (%)	4.4	15. / 4.2	– / 4.4	9.0 / 3.9	8.9 / 3.9
$g_{H\gamma\gamma}$ (%)	1.8	6.8 / 1.3	– / 1.5	3.7 / 1.2	3.9 / 1.2
$g_{HZ\gamma}$ (%)	11.	– / 10.	– / 10.	8.2 / 6.3	– / 10.
g_{Htt} (%)	3.4	– / 3.1	– / 3.2	– / 3.1	10. / 3.1
g_{HHH} (%)	50.	– / 49.	– / 50.	– / 50.	44./33. 27./24.
Γ_H (%)	SM	2.2	2.5	1.7	1.1
BR_{inv} (%)	1.9	0.26	0.65	0.28	0.19
BR_{EXO} (%)	SM (0.0)	1.8	2.7	1.1	1.1

table from ESPP briefing book

High energy Higgs factories: ILC500, CLIC3000, FCC-hh.

FCC-ee + FCC-hh is very competitive



Collider	ILC_{500}	ILC_{1000}	CLIC	FCC-INT	
g_{HZZ} (%)	0.24 / 0.23	0.24 / 0.23	0.39 / 0.39	0.17 / 0.16	ee
g_{HWW} (%)	0.31 / 0.29	0.26 / 0.24	0.38 / 0.38	0.20 / 0.19	ee
g_{Hbb} (%)	0.60 / 0.56	0.50 / 0.47	0.53 / 0.53	0.48 / 0.48	ee
g_{Hcc} (%)	1.3 / 1.2	0.91 / 0.90	1.4 / 1.4	0.96 / 0.96	ee
g_{Hgg} (%)	0.98 / 0.85	0.67 / 0.63	0.96 / 0.86	0.52 / 0.50	ee
$g_{H\tau\tau}$ (%)	0.72 / 0.64	0.58 / 0.54	0.95 / 0.82	0.49 / 0.46	ee
$g_{H\mu\mu}$ (%)	9.4 / 3.9	6.3 / 3.6	5.9 / 3.5	0.43 / 0.43	hh
$g_{H\gamma\gamma}$ (%)	3.5 / 1.2	1.9 / 1.1	2.3 / 1.1	0.32 / 0.32	hh
$g_{HZ\gamma}$ (%)	– / 10.	– / 10.	7. / 5.7	0.71 / 0.70	hh
g_{Htt} (%)	6.9 / 2.8	1.6 / 1.4	2.7 / 2.1	1.0 / 0.95	hh
g_{HHH} (%)	27.	10.	9.	±3(stat)±~1.4(syst)	hh
Γ_H (%)	1.1	1.0	1.6	0.91	ee
BR_{inv} (%)	0.23	0.22	0.61	0.024	hh
BR_{EXO} (%)	1.4	1.4	2.4	1.0	ee

FCC-hh > 10^{10} H produced, +
FCC-ee measurement of g_{HZZ}
→ g_{HHH} , $g_{H\gamma\gamma}$, $g_{HZ\gamma}$, $g_{H\mu\mu}$, BR_{inv}

(*)see M. Selvaggi, 3d FCC physics workshop,
9% precision in 3 years of FCC-hh running, 2004.03505v1

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., $b \to s\tau\tau$

QCD programme

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

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)

Precision Natural SUSY at CEPC, FCC-ee, and ILC, JJ Fan, M. Rees and Liantao Wang

arXiv:1412.3107v2 figure 5 (top row)

«Higgs and EWPOs are complementary»

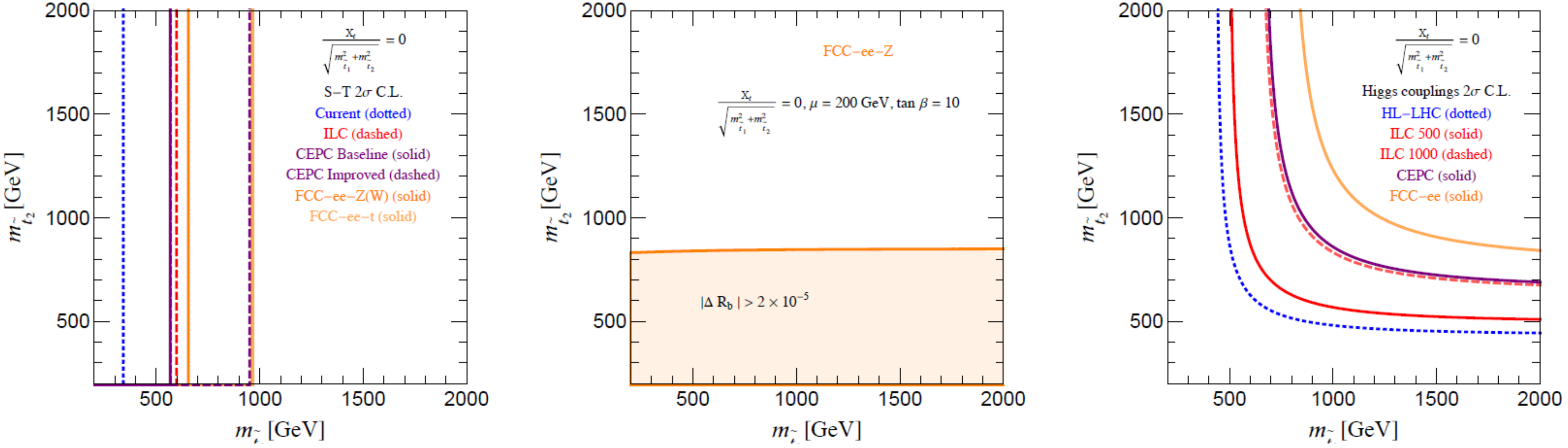


Figure 5. Regions in the stop physical mass plane that are/will be excluded at 2σ by EWPT with oblique corrections (left column), R_b at FCC-ee (mid column) and Higgs couplings (right column) for different choices of $X_t/\sqrt{m^2_{\tilde{t}_1}+m^2_{\tilde{t}_2}}$: 0 (first row), 0.6 (2nd row), 1.0 (3rd row) and 1.4 (last row). We chose the mass eigenstate with $m_{\tilde{t}_1}$ to be mostly left-handed while the mass eigenstate with $m_{\tilde{t}_2}$ to be mostly right-handed. For non-zero choices of X_t, there are regions along the diagonal line which cannot be attained by diagonalizing a Hermitian mass matrix [32]. Also notice that the vacuum instability bound constrains $X_t/\sqrt{m^2_{\tilde{t}_1}+m^2_{\tilde{t}_2}} \lesssim \sqrt{3}$ [76].

" also, $b \to s\gamma$ could be useful"