FCC-ee

Physics opportunities

M. Koratzinos

On behalf of the FCC study

Massachusetts Institute of Technology

http://cern.ch/fcc

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photo: J. Wenninger

Acknowledgements

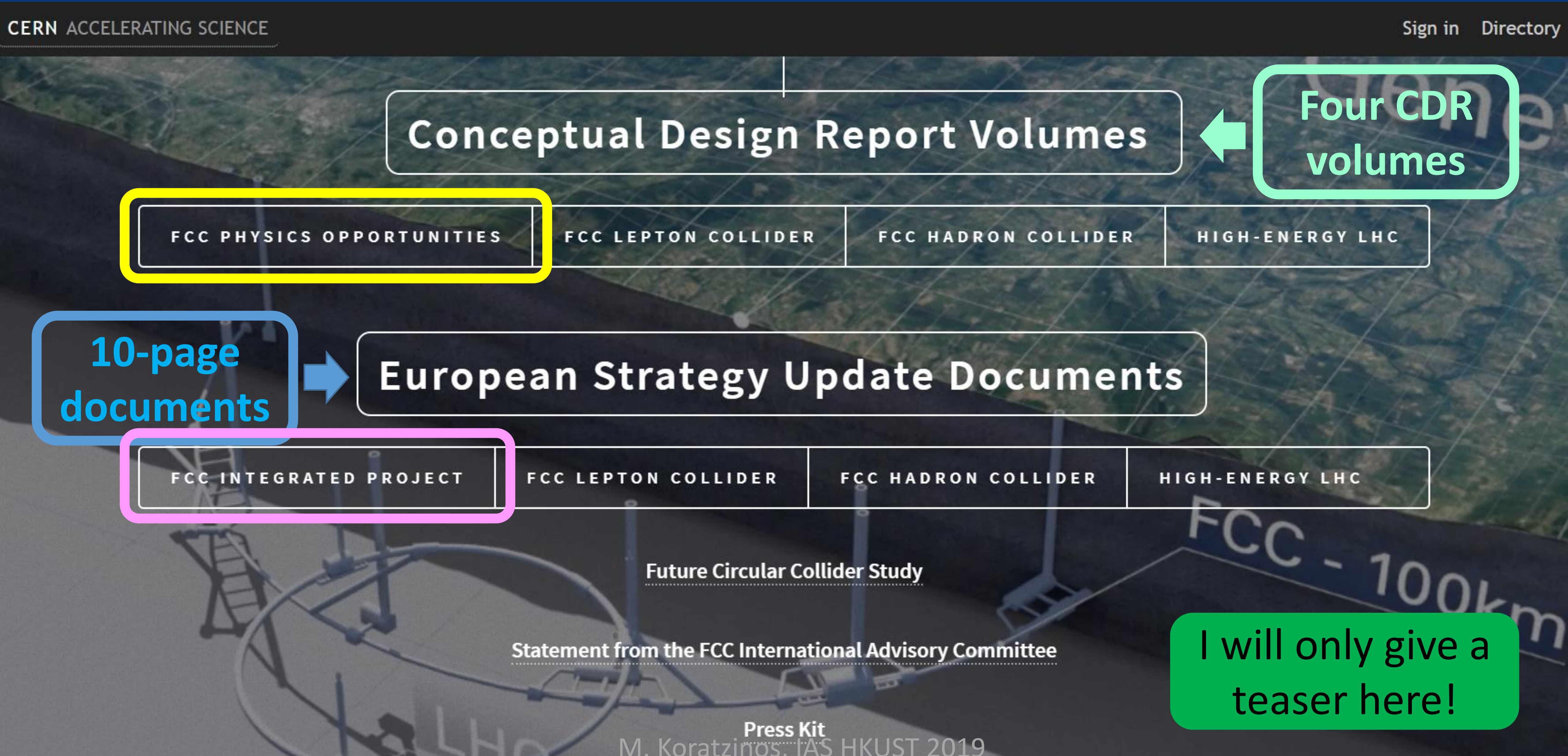
We should not forget the pioneers of the modern circular Higgs factory idea: **Roy Aleksan, Alain Blondel, John Ellis, Patrick Janot, Frank Zimmermann**, that promoted the idea when it was not fashionable

A. Blondel F. Zimmermann M. Koratzinos J. Ellis P. Janot R. Aleksan

I have taken material liberally from the CDR and from various talks, notably from Patrick Janot

FCC in this conference:
- John Ellis: Back to the future, 17/4/2019
- Emmanuel Tsesmelis: the FCC, 18/5/2019
- Mike Koratzinos: FCC-ee physics opportunities

FCC study: CDR released on 15 January 2019



CERN ACCELERATING SCIENCE

Conceptual Design Report Volumes

FCC PHYSICS OPPORTUNITIES | FCC LEPTON COLLIDER | FCC HADRON COLLIDER | HIGH-ENERGY LHC

European Strategy Update Documents

FCC INTEGRATED PROJECT | FCC LEPTON COLLIDER | FCC HADRON COLLIDER | HIGH-ENERGY LHC

Future Circular Collider Study

Statement from the FCC International Advisory Committee

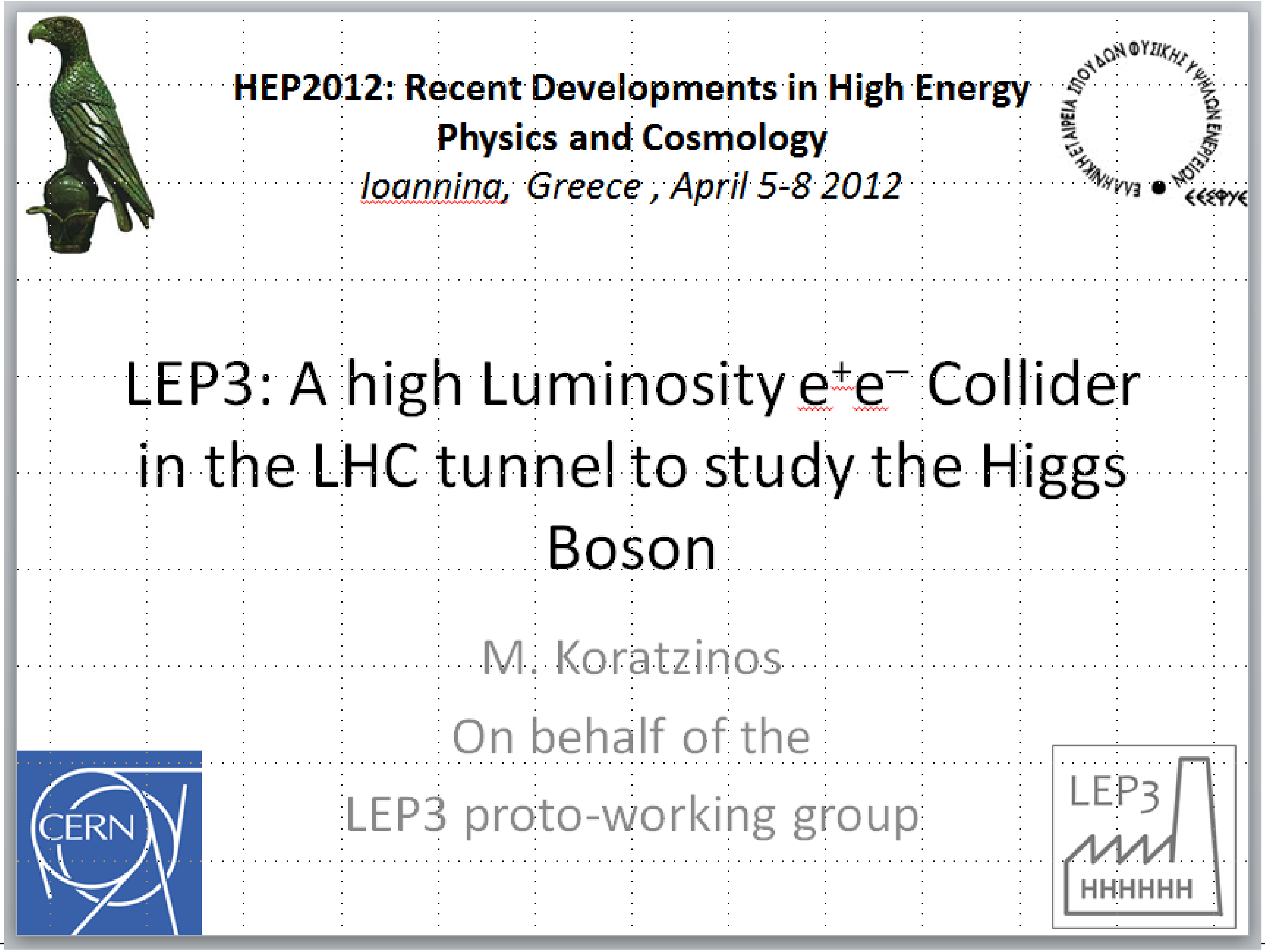
Press Kit

Four CDR volumes

10-page documents

I will only give a teaser here!

You have heard it here first!

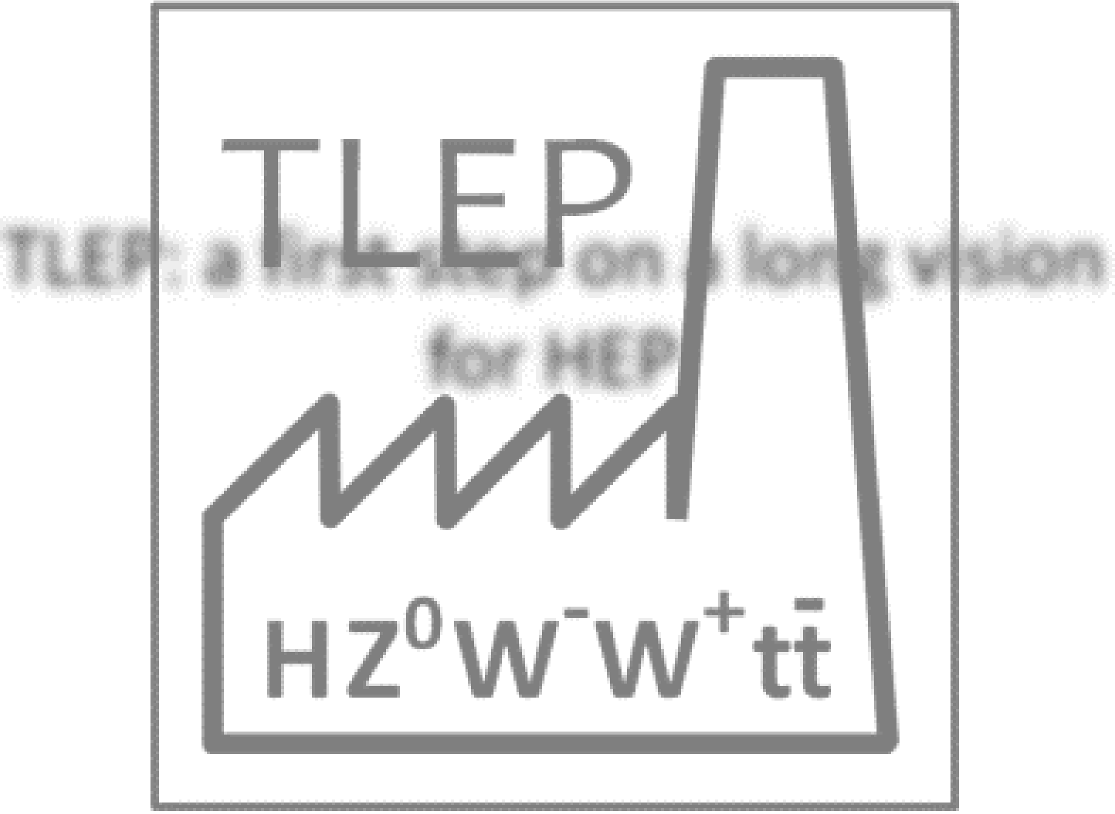


HEP2012: Recent Developments in High Energy Physics and Cosmology
Ioannina, Greece , April 5-8 2012

LEP3: A high Luminosity e^+e^- Collider in the LHC tunnel to study the Higgs Boson

M. Koratzinos
On behalf of the
LEP3 proto-working group

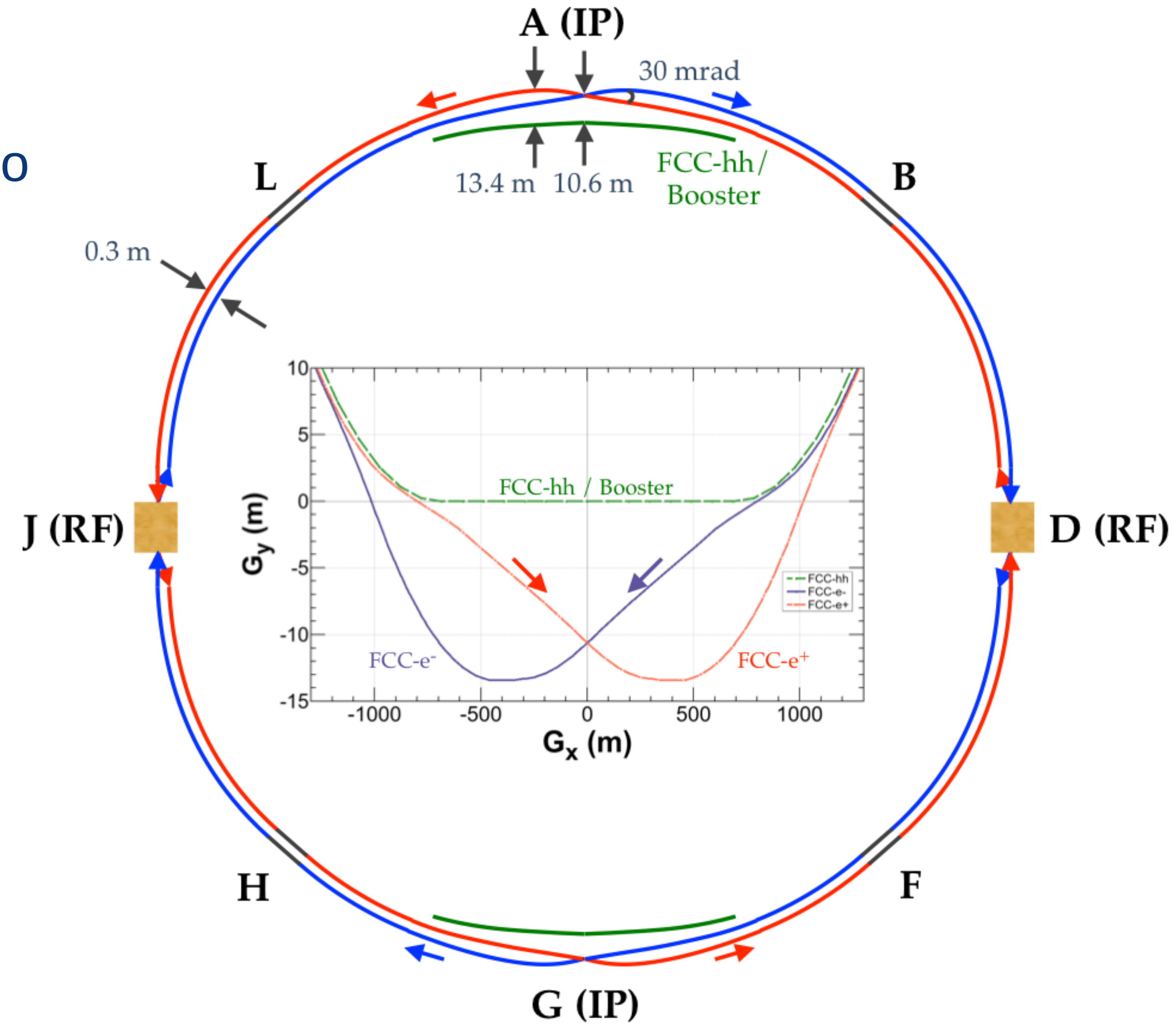
…and you have heard it again in Chios in 2013



TLEP: a first step on a long vision for HEP

FCC-ee basic design choices

- **Double ring** e+ e- collider ~100 km
- **Asymmetric “moustashe” IR layout and optics** to limit synchrotron radiation towards the detector
- **2 IPs, large** horizontal crossing angle **30 mrad, crab-waist optics**
- **Synchrotron radiation power 50 MW/beam** at all beam energies
- **Top-up injection** scheme for high luminosity
- Requires **booster synchrotron in collider tunnel**
- **The design can be modified to a 4-IP layout if needed**



The FCC-ee accelerator – interesting facts

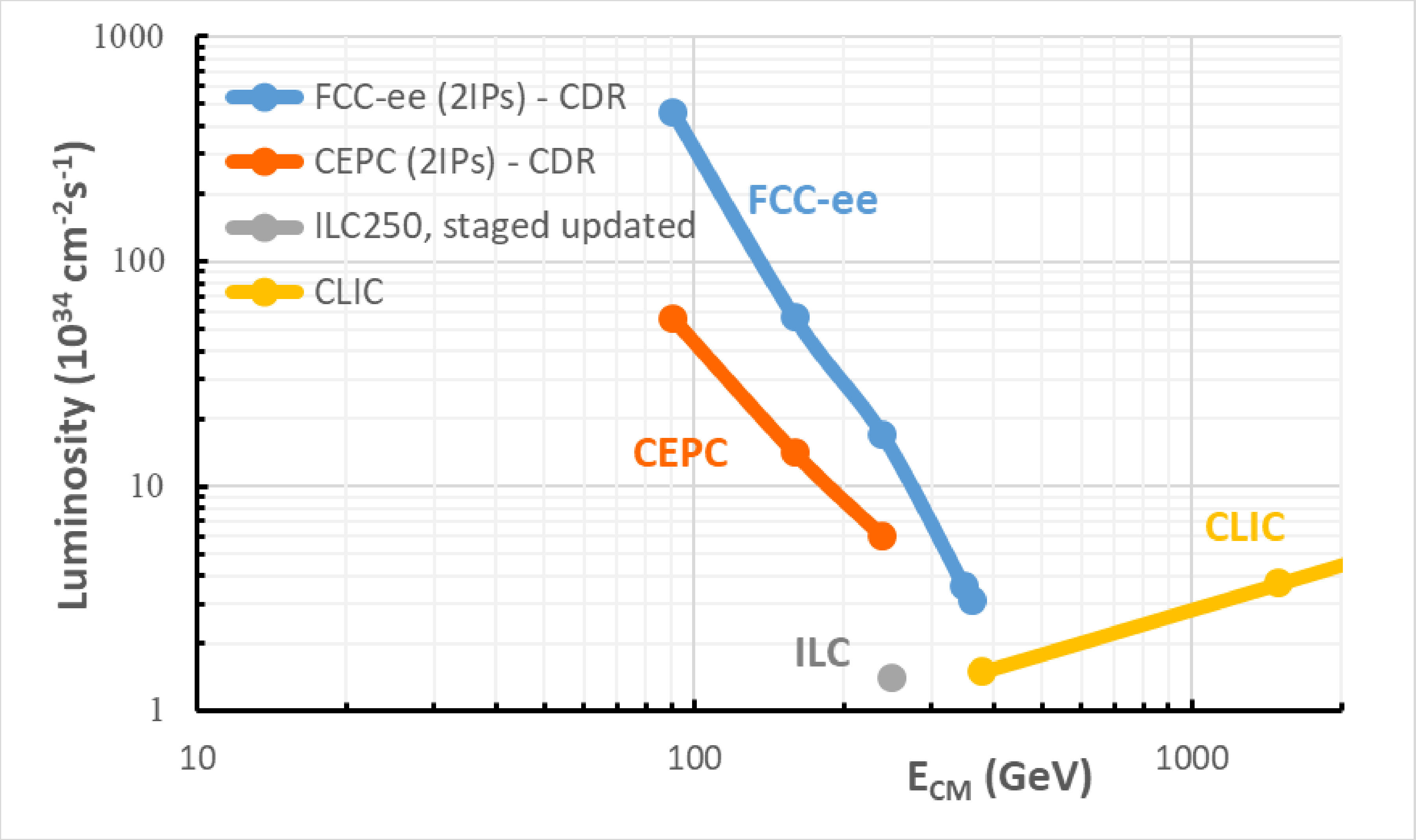
The FCC-ee accelerator is not simply a bigger LEP! It is a modern synchrotron that pushes the design envelope to the maximum.

- The luminosity is so high that the beams burn up very quickly (beam lifetime 12 minutes at the ZH). Mandatory to use a full-size booster – the injector is the same size as the main ring and injects at top energy)
- Full LEP physics dataset every 2 minutes!
- Beam energy will be known to 100keV, whereas the (gravitational) effect of the moon passing overhead gives an energy change of 100MeV, one thousand times bigger.
- The performance quoted in the CDR is not a paper exercise, it is fully backed by simulations, leading to stringent requirements: Colliding bunches must have the same charge to within 10%
- Emittance blow up in the region ±2m from the IPs is equal to the emittance of the rest of the 100 kilometers – the area around the IP is very tricky and complex

FCC-ee collider parameters

parameter	FCC-ee				LEP2
energy/beam [GeV]	**45**	**80**	**120**	**182.5**	105
bunches/beam	16640	2000	328	48	4
beam current [mA]	1390	147	29	5.4	3
luminosity/IP x 10^{34} cm^{-2}s^{-1}	**230**	**28**	**8.5**	**1.5**	0.0012
energy loss/turn [GeV]	0.036	0.34	1.72	9.2	3.34
total synchrotron power [MW]	100				22
RF voltage [GV]	0.1	0.75	2.0	4+6.9	3.5
rms bunch length (SR,+BS) [mm]	3.5, 12	3.0, 6.0	3.2, 5.3	2.0, 2.5	12, 12
rms emittance $e_{x,y}$ [nm, pm]	0.3, 1.0	0.84, 1.7	0.6, 1.3	1.5, 2.9	22, 250
Horiz.,vertical beta* [mm]	150, 0.8	200, 1	300, 1	1000, 1.6	
longit. damping time [turns]	1273	236	70	20	31
crossing angle [mrad]	30				0
beam lifetime (rad.B+BS) [min]	68	59	12	12	434

Lepton collider luminosities

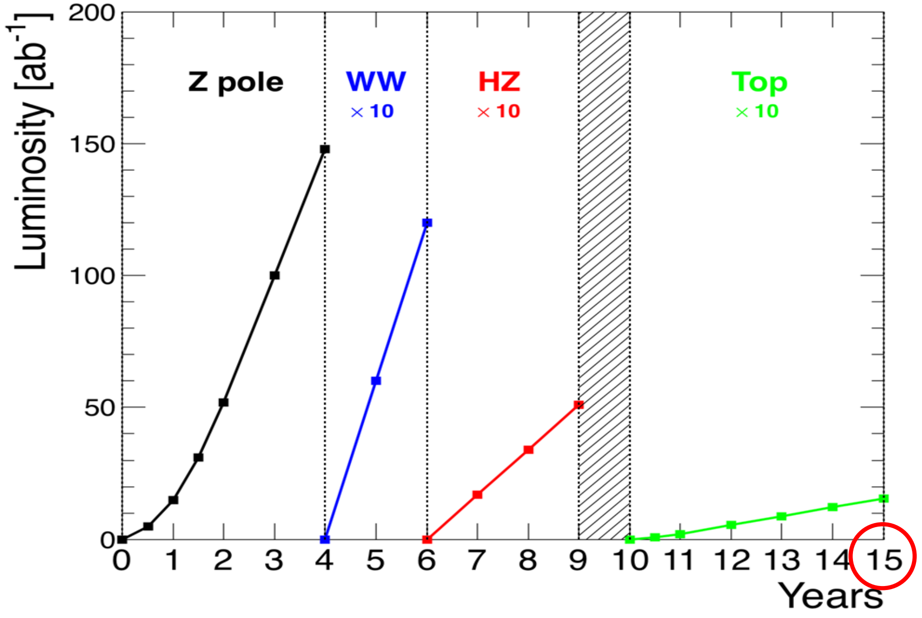


M. Koratzinos, HEP2019, 18 April 2019.

The FCC-ee operation model and statistics

- 185 physics days / year, 75% efficiency, 10% margin on luminosity

Working point	Z, years 1-2	Z, later	WW	HZ	tt threshold…	… and above
√s (GeV)	88, 91, 94		157, 163	240	340 – 350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	100	200	25	7	0.8	1.4
Lumi/year (2 IP)	24 ab^{-1}	48 ab^{-1}	6 ab^{-1}	1.7 ab^{-1}	0.2 ab^{-1}	0.34 ab^{-1}
Physics goal	150 ab^{-1}		10 ab^{-1}	5 ab^{-1}	0.2 ab^{-1}	1.5 ab^{-1}
Run time (year)	2	2	2	3	1	4



Total : 15 years

Event statistics

5×10^{12} $e^+e^- \to Z$
10^8 $e^+e^- \to W^+W^-$
10^6 $e^+e^- \to HZ$
10^6 $e^+e^- \to t\bar{t}$

√s precision

100 keV
300 keV
1 MeV
2 MeV

FCC-ee physics opportunities

FCC-ee will create vast physics opportunities due to its huge statistics and the centre-of-mass energy range it can cover (from 88 to 365GeV):

- EW precision observable (EWPO) measurements sensitive to the 10-70TeV scale

20 to 50 times improved precision on ALL electroweak observables
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 …

- Model-independent Higgs coupling measurements

~10 times more precise and model-independent Higgs couplings measurements

- Precise tests of flavour conservation/universality
- Possible direct observation of very weakly coupled particles
- Possible discovery of dark matter in invisible H or Z decays
- …

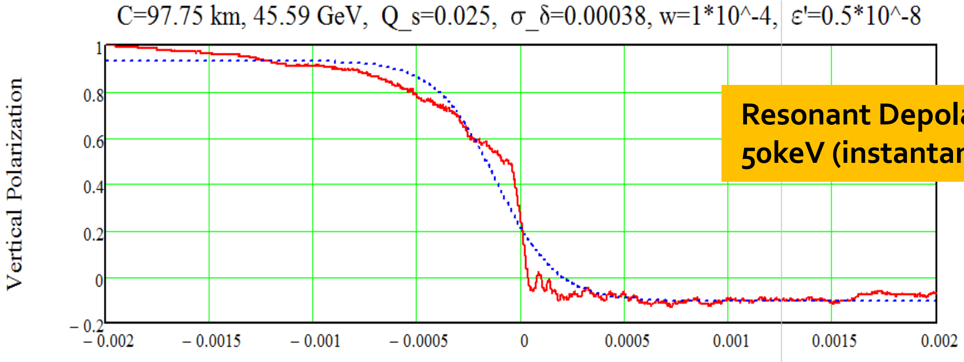
FCC-ee is not only a Higgs factory! It is also a Z, W, and t factory

Important features for precision – EWPO regime

- **Statistics**
  - Very high statistics at the Z pole (70 kHz of visible Z decays) – we are systematics dominated at the Z!
  - Beam-induced backgrounds are mild compared to linear colliders, but not negligible
    - Readout must be able to cope with both
- **Luminosity measurement**
  - Aim at 0.01% from small angle Bhabhas
    - Requires μm precision for LumiCal
    - Requires calculation/measurement of outgoing $e^{\pm}$ deflection from the opposite bunch
  - Need to study $e^+e^- \rightarrow \gamma\gamma$ to possibly reach 0.001%
- **$\sqrt{s}$ calibration and measurement of $\sqrt{s}$ spread**
  - 50 keV "continuous" E_{BEAM} measurement with resonant depolarization
  - Powerful cross checks from di-muon acollinearity and polarimeter/spectrometer
    - Requires muon angle measurement to better than 100 μrad
- **Flavour tagging**
  - Beam pipe radius (15 mm) smaller than at linear collider (vertex detector 1st layer). 10 mm radius is currently investigated!
    - New CEPC studies claim Purity × Efficiency ~ 97% for $H \rightarrow bb$. And at FCC-ee ?

Beam Polarization and Energy Calibration

- **Simulations show adequate transverse polarization at the Z and WW energies**
  - **Energy calibration by resonant depolarization every 10 mins on pilot bunches**
    - **UNIQUE TO CIRCULAR COLLIDERS**



Resonant Depolarization precision: 50keV (instantaneous)

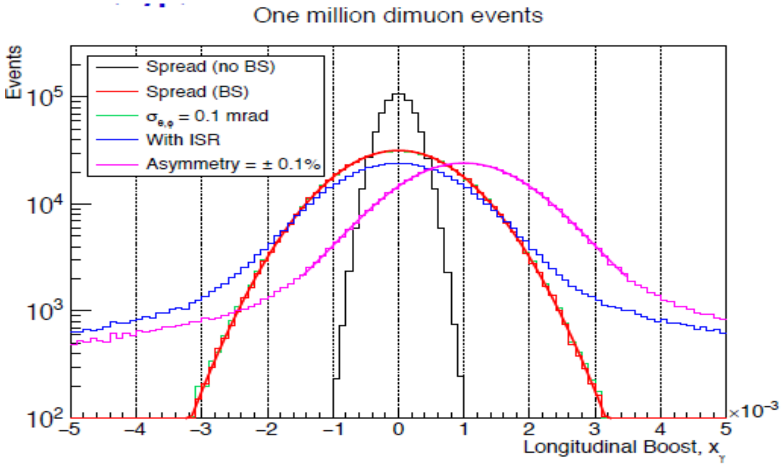
260 seconds sweep of depolarizer frequency

Principle of the resonant depolarization method	
Spin tune (spin prerecession frequency):	$\nu = a\gamma = \frac{aE}{mc^2} = \frac{E[MeV]}{440.6486(1)[MeV]}$

- **Total √s uncertainty of 100 keV @ Z pole, and 300 keV at the WW threshold**

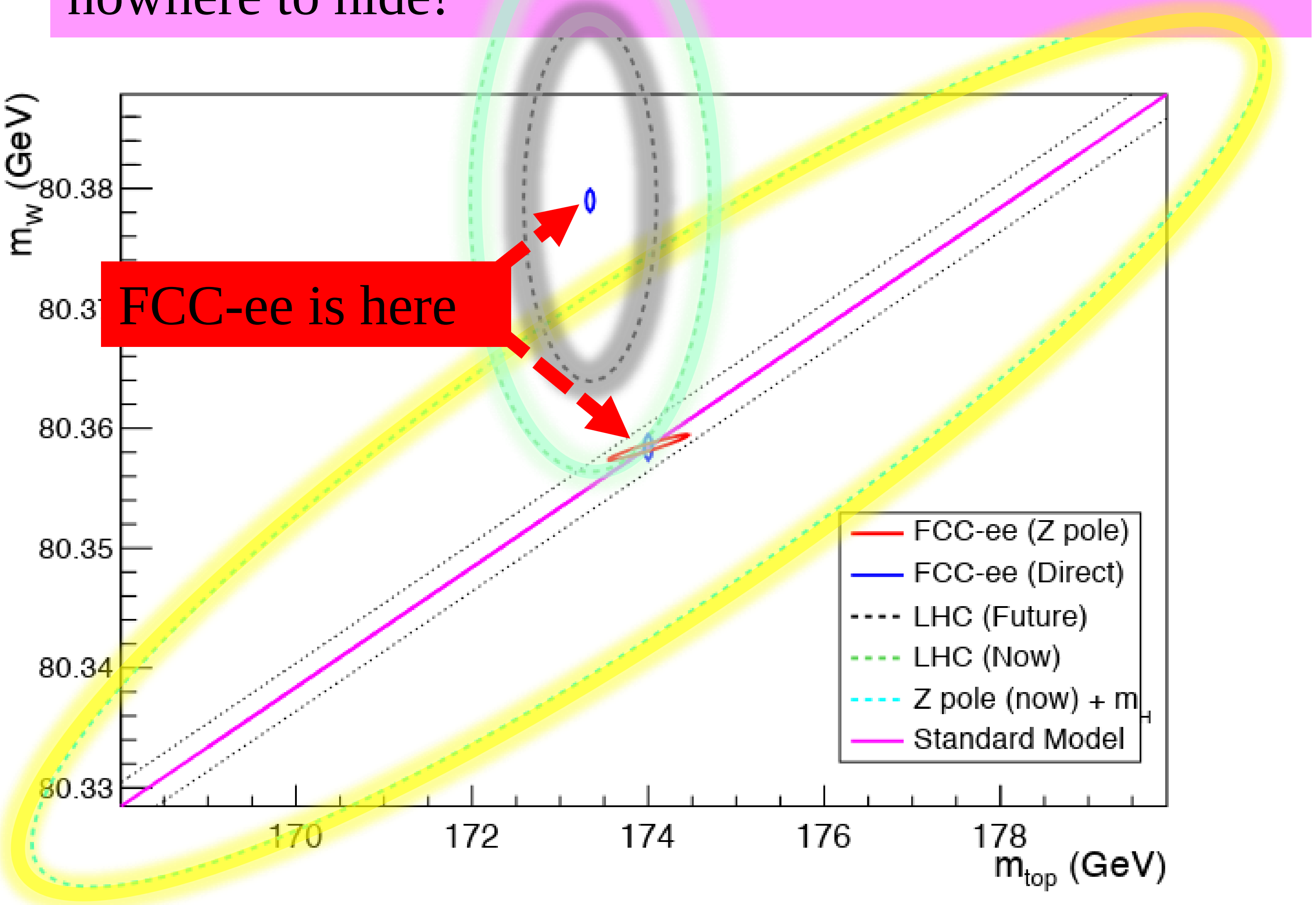
Unique to FCC-ee: a helping hand from dimuon events

- **Energy spread (~100 MeV) will be measured**
  - **From $e^+e^- \to \mu^+\mu^-$ longitudinal boost**
    - **10^6 events every 4 mins @ Z pole**
      - ➔ **Continuous 35 keV precision on δ√s**
    - **Also measures $\Delta E = E^+ - E^-$ to at both IPs**



Combination of all EW measurements

With m_{top}, m_H and m_W known, the standard model has nowhere to hide!



Effect of BSM physics is to modify EW observables through quantum effects (cf top & H @ LEP)

LEP + M_H @LHC

LHC (now)

LHC (future)

Standard model

FCC-ee direct FCC-ee Z-pole

Need to measure all ingredients! Improving theory predictions mandatory.

A note on attainable precision

Example: the W mass

Prediction:

before FCC

After FCC

$$m_W = 80.3593 \pm \boxed{0.0001}(m_{top}) \pm \boxed{0.0001}(m_Z) \pm \boxed{0.0003}(\alpha_{QED}) \pm \boxed{0.0002}(\alpha_S) \pm \boxed{0.0000}(m_H) \pm 0.0040\,(\text{theo.})$$

direct measurement:

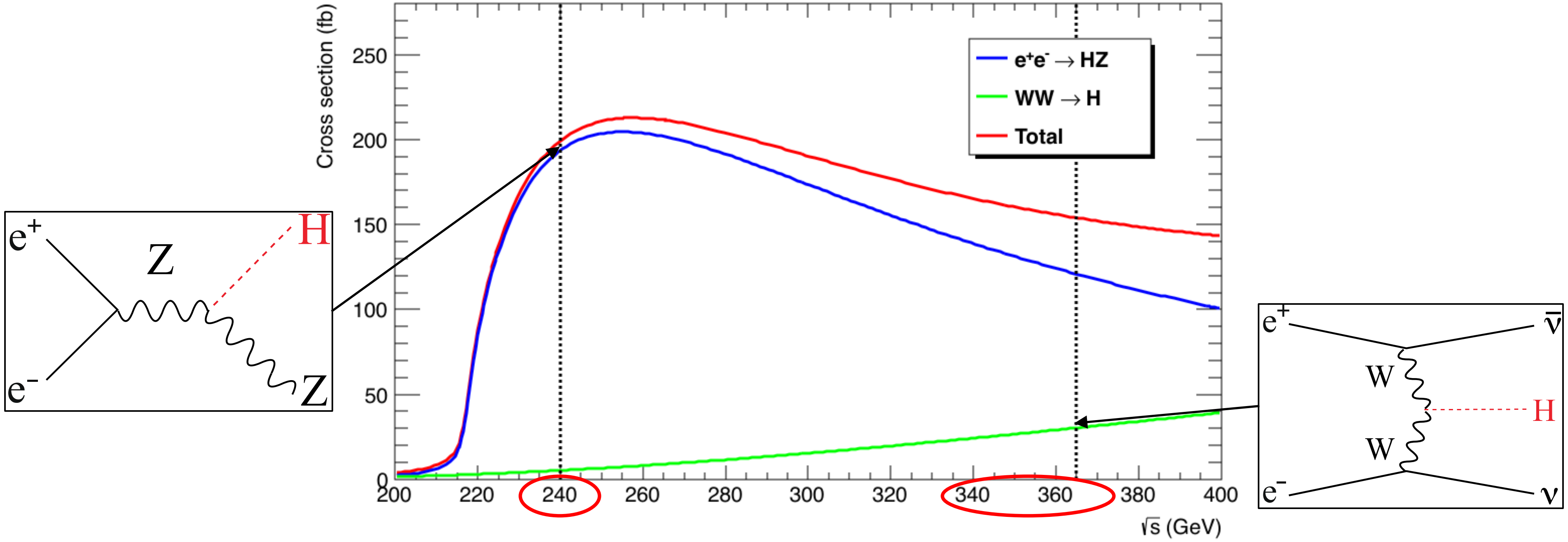
$$m_W = 80.385 \pm \boxed{0.0005}$$

If only one ingredient is missing, the sensitivity to new physics may entirely vanish

Essential to reduce theory error: necessitates calculation up to 3-4 loops. Effort has already started. 2 loop calculations finished – 3 loops started. There is good hope that the theory error can be reduced so that it does not dominate the calculations

The FCC-ee as a Higgs factory

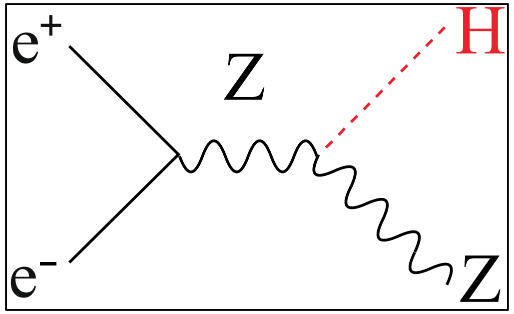
- Higgsstrahlung ($e^+e^- \to ZH$) event rate largest at $\sqrt{s}$ ~ 240 GeV : σ ~200 fb



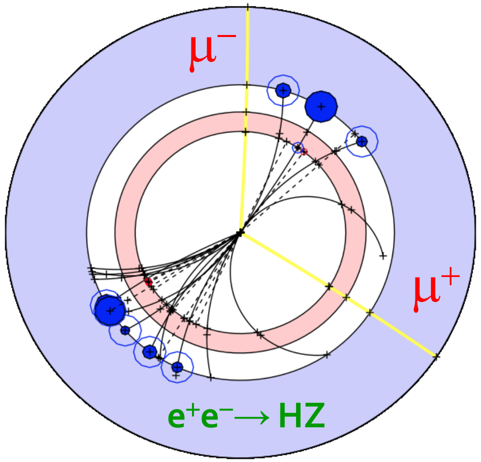
- 10^6 $e^+e^- \to ZH$ events with 5 ab^{-1} – cross section predicted with great accuracy
  - Target : (few) per-mil precision on couplings, statistics-limited.
  - Complemented with 200k events at $\sqrt{s}$ = 350 – 365 GeV
    - ➔ Of which 30% in the WW fusion channel (useful for the Γ_H precision)

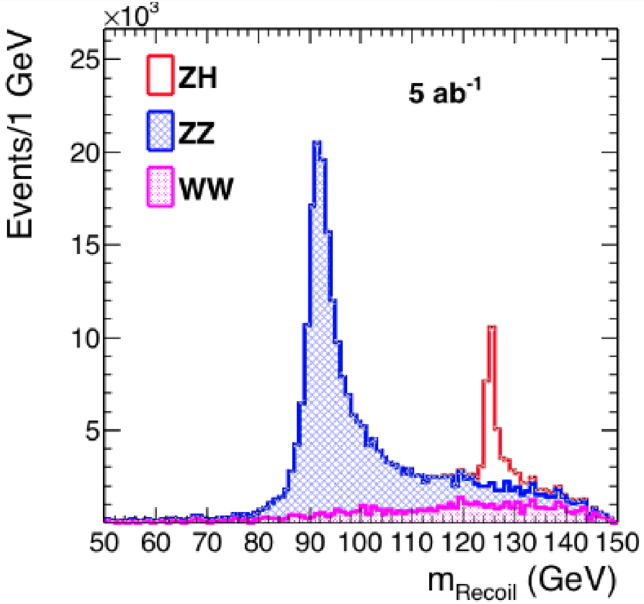
Absolute coupling and width measurement

- Higgs tagged by a Z, Higgs mass from Z recoil



$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$

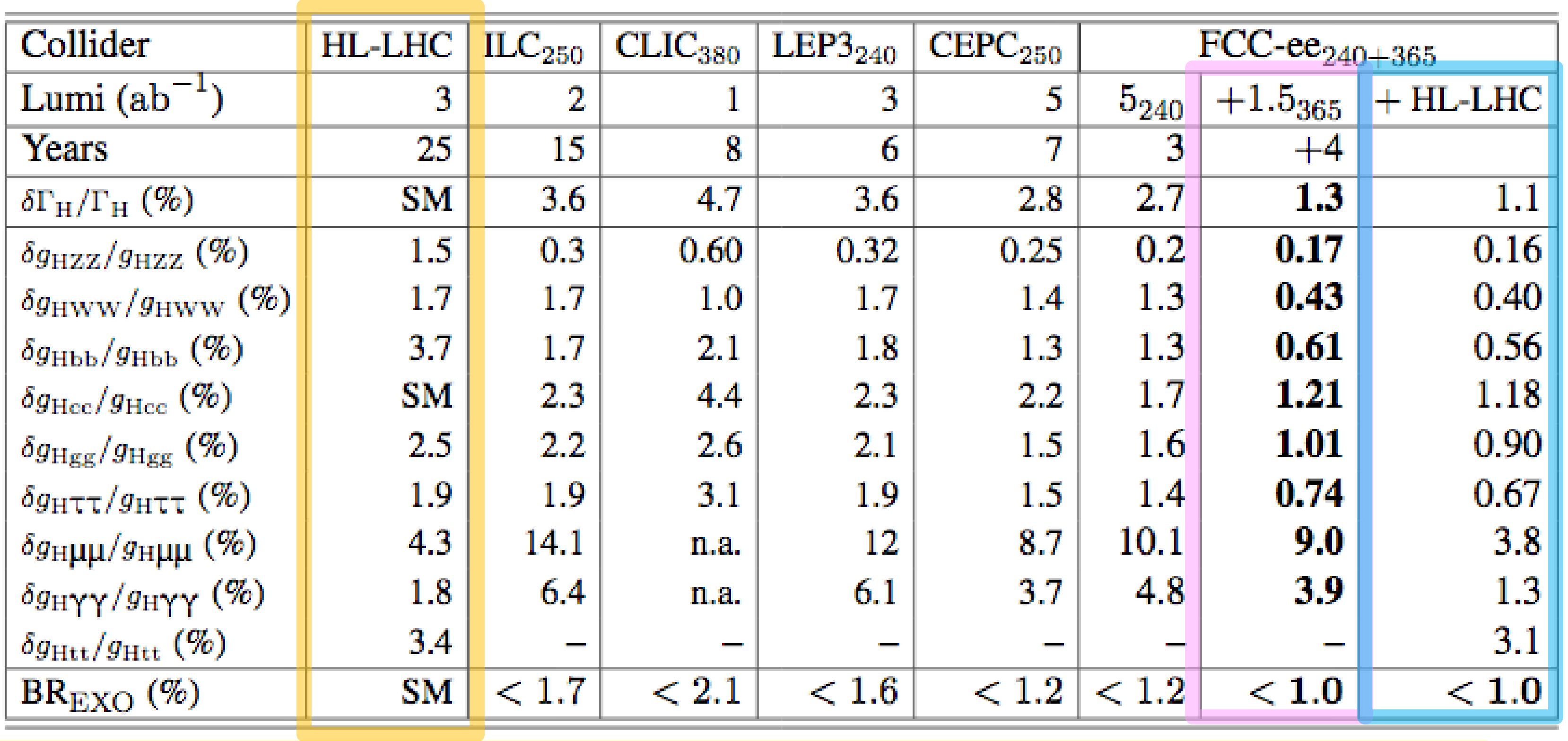




  - Total rate ∝ g_{HZZ}^2 → measure g_{HZZ} to 0.2%
  - ZH → ZZZ final state ∝ g_{HZZ}^4 / Γ_H → measure Γ_H to a couple %
  - ZH → ZXX final state ∝ $g_{HXX}^2\, g_{HZZ}^2 / \Gamma_H$ → measure g_{HXX} to a few per-mil / per-cent
  - Empty recoil = invisible Higgs width; Funny recoil = exotic Higgs decays
- Note: The HL-LHC is a great Higgs factory (10^9 Higgs produced) but …
  - $\sigma_{i\rightarrow f}^{(\mathrm{observed})} \propto \sigma_{\mathrm{prod}}\, (g_{Hi})^2\, (g_{Hf})^2 / \Gamma_H$
    - Difficult to extract the couplings : σ_{prod} is uncertain and Γ_H is largely unknown
      - ➔ Must do physics with ratios or with additional assumptions.

Result of the “kappa” fit

- **Same fit applied to all Higgs factories inputs (for unbiased comparison)**

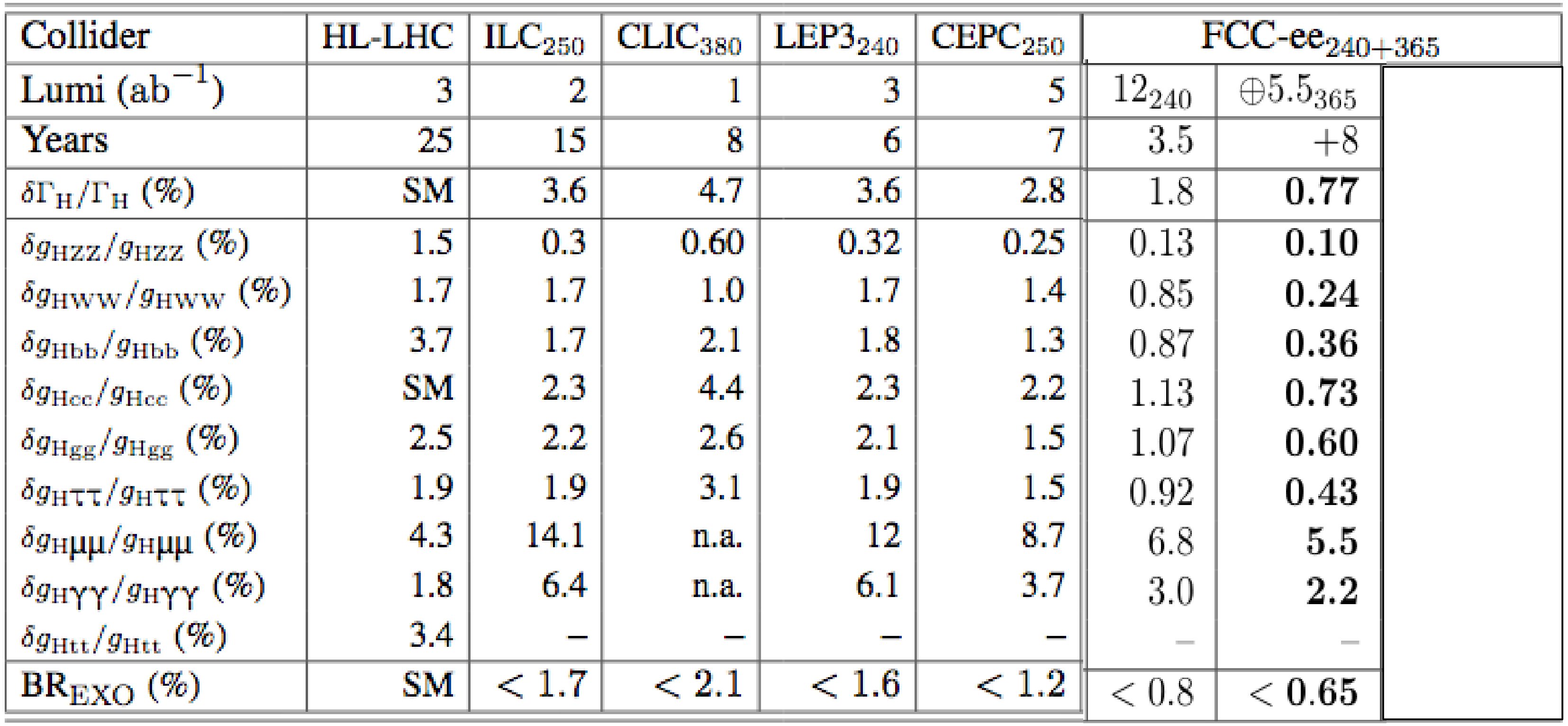


Collider	HL-LHC	ILC_{250}	CLIC_{380}	LEP3_{240}	CEPC_{250}	$\text{FCC-ee}_{240+365}$		
Lumi (ab^{-1})	3	2	1	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	15	8	6	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.7	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.8	1.3	1.3	**0.61**	0.56
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	2.3	2.2	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	2.1	1.5	1.6	**1.01**	0.90
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.9	1.5	1.4	**0.74**	0.67
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	12	8.7	10.1	**9.0**	3.8
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	6.1	3.7	4.8	**3.9**	1.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	–	–	3.1
BR_{EXO} (%)	SM	< 1.7	< 2.1	< 1.6	< 1.2	< 1.2	< 1.0	< 1.0

- **The FCC-ee improves precision of HL-LHC by large factors (copious modes)**
  - With no need for additional assumptions – best on the e^+e^- collider market
- **It is important to have two energy points (240 and 365 GeV)**
  - Combination better by a factor 2 (4) than 240 (365) GeV alone

Result of the "kappa" fit in 4 IP scenario

- **Same fit applied to all Higgs factories inputs (for unbiased comparison)**



Collider	HL-LHC	ILC_{250}	CLIC_{380}	$\mathrm{LEP3}_{240}$	CEPC_{250}	$\text{FCC-ee}_{240+365}$	
Lumi (ab^{-1})	3	2	1	3	5	12_{240}	$\oplus 5.5_{365}$
Years	25	15	8	6	7	3.5	+8
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	1.8	**0.77**
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.13	**0.10**
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.7	1.4	0.85	**0.24**
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.8	1.3	0.87	**0.36**
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	2.3	2.2	1.13	**0.73**
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	2.1	1.5	1.07	**0.60**
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.9	1.5	0.92	**0.43**
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	12	8.7	6.8	**5.5**
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	6.1	3.7	3.0	**2.2**
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	–	–
$\mathrm{BR}_{\mathrm{EXO}}$ (%)	SM	< 1.7	< 2.1	< 1.6	< 1.2	< 0.8	$< \mathbf{0.65}$

- **The FCC-ee improves precision of HL-LHC by large factors (copious modes)**
  - With no need for additional assumptions – best on the e^+e^- collider market
- **It is important to have two energy points (240 and 365 GeV)**
  - Combination better by a factor 2 (4) than 240 (365) GeV alone

Comment about longitudinal polarization

- The FCC-ee e^+ and e^- beams will not be longitudinally polarized
  - Unlike at linear colliders where 80% polarized e^- can be injected and accelerated
    - And, with some difficulty and money, may get 30% polarized e^+ as well.
- Effect of longitudinal polarization at 240/250 GeV for Higgs couplings
  - Polarization causes σ_{HZ} to increase by 1.4 (1.08) in $e^-_L e^+_R$ ($e^-_R e^+_L$) configuration
    - Similar increase for the backgrounds (except for WW : 2.34 and 0.14)
      - ➔ Precision better by 20% with the same luminosity in the κ fits
  - EFT fits benefit from different polarization states to constrain additional operators
    - At circular colliders, constraints come from EW precision measurements
      - ➔ Precision still better by ~20% or less with the same luminosity in the EFT fits
      - ➔ The only coupling for which polarization brings significant gain is $g_{HZ\gamma}$

        Much better measured at hadron collider (e.g., FCC-hh) anyway
- At the FCC-ee, longitudinal polarization is not worth the induced luminosity loss
  - NB. Without polarization, one year at the FCC-ee with 2 (4) IPs at $\sqrt{s}$ = 240 GeV offers the same Higgs coupling precision as 8 (16) years with ILC polarized e^+ and e^+
    - Similar remark holds for EWPO or top EW couplings measurements at other $\sqrt{s}$

J. De Blas

Comment about longitudinal polarization

- The FCC-ee e^+ and e^- beams won't be longitudinally polarized
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    - Similar remark holds fo O or top EW couplings measurements at other √s

Beam polarization brings no information that cannot be obtained otherwise.

There is no obvious need for it.

Is a $\sqrt{s}$ = 500 GeV upgrade required/useful ?

According to the white book of ESU 2013 :

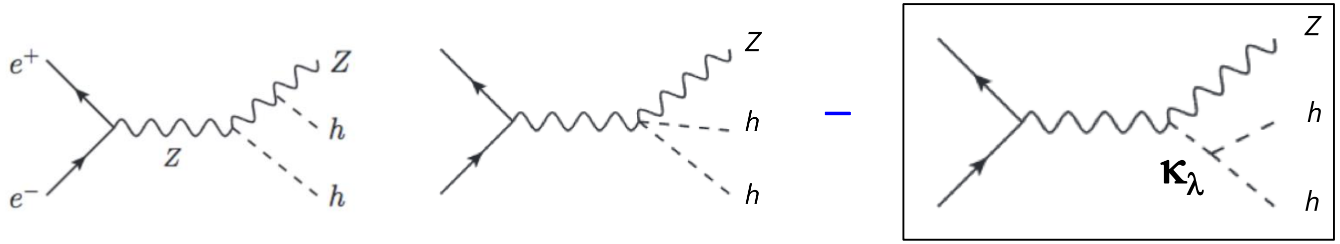
https://cds.cern.ch/record/1567295/

> At energies of 500 GeV or higher, such a machine could explore the Higgs properties further, for example **the coupling to the top quark, the self-coupling, and the total width.**

- The same arguments are used by some documents submitted to ESU 2020!
- So, should we foresee an upgrade of FCC-ee at $\sqrt{s}$ = 500 GeV ?
  - For the total width and the coupling to the top quark : the answer is NO (slide 17) – there is a much better prior measurement (HL-LHC) which becomes model-independent after 7 yers of FCC-ee higgs physics
  - For the Higgs self-coupling (κ_λ):

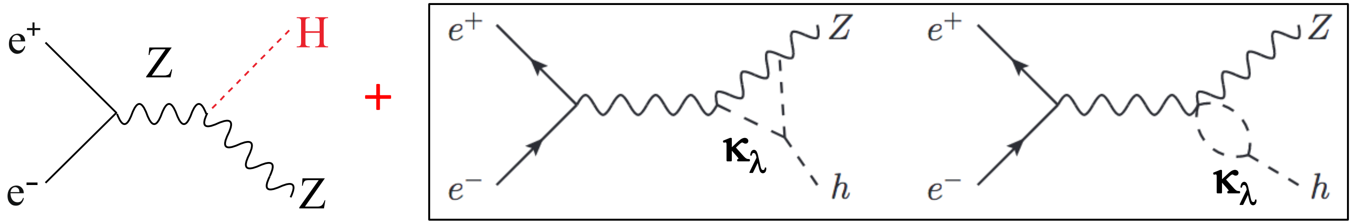
At $\sqrt{s}$ = 500 GeV

Di-Higgs production



At FCC-ee

σ_{HZ}

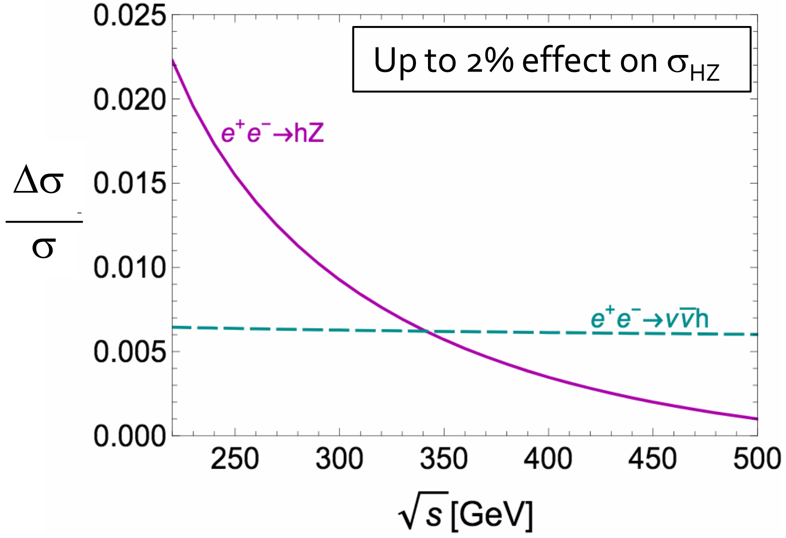


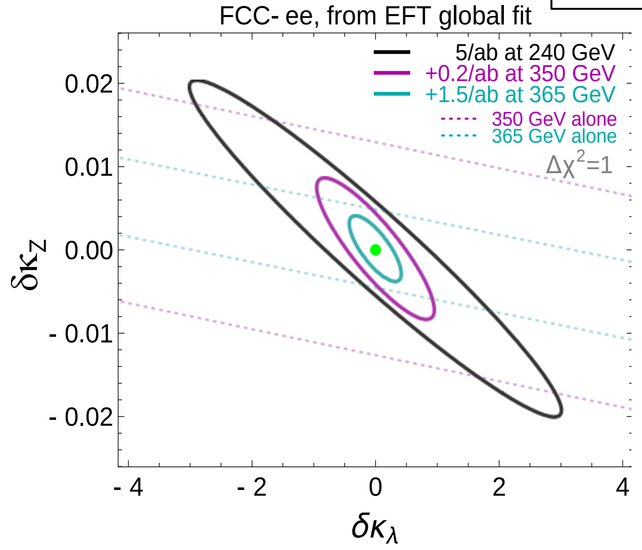
M. McCullough
arXiv:1312.3322

Higgs self-coupling at the FCC-ee

- Effect of Higgs self coupling (κ_λ) on σ_{ZH} and $\sigma_{\nu\nu H}$ depends on √s

C. Grojean et al.
arXiv:1711.03978





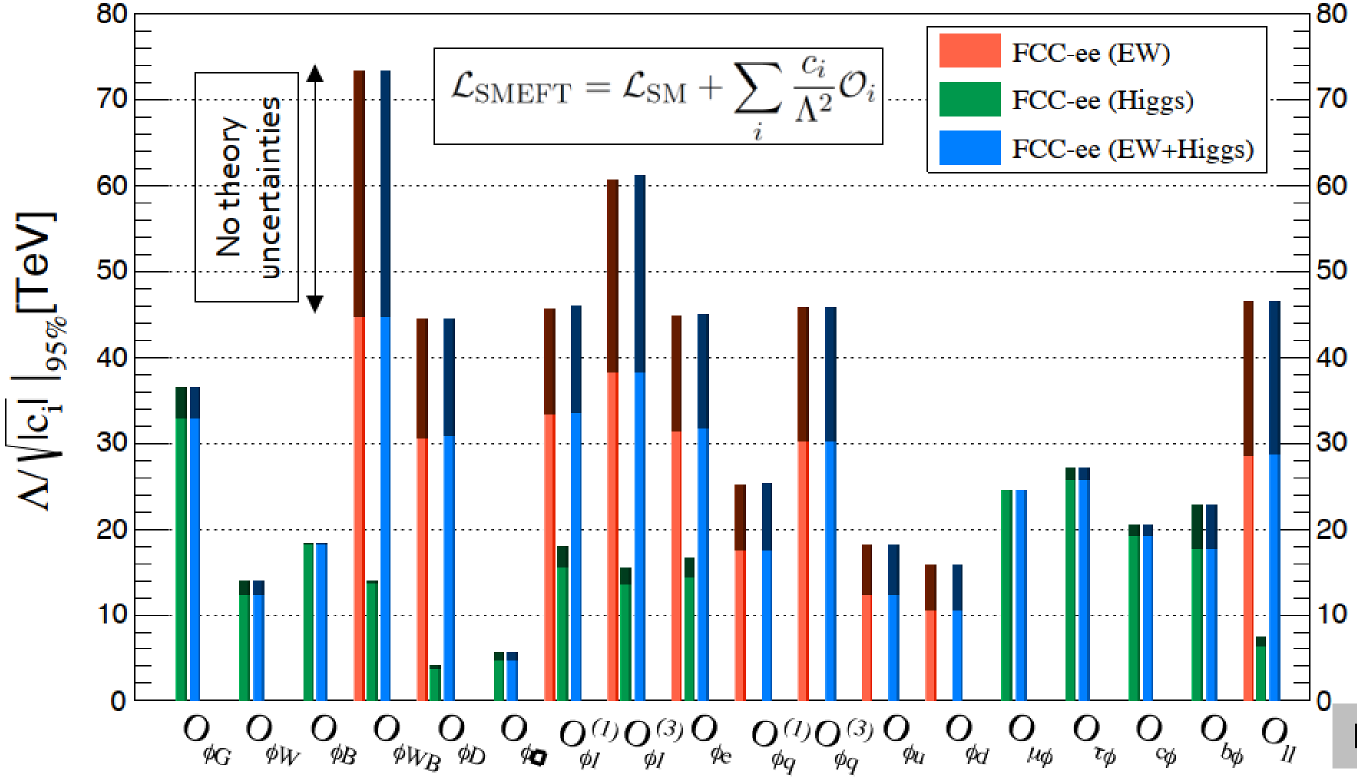
- Two energy points lift off the degeneracy between $\delta\kappa_Z$ and $\delta\kappa_H$
  - Precision on κ_λ with 2 IPs at the end of the FCC-ee (91+160+240+365 GeV)
    - ➔ Global EFT fit (model-independent) : ±34% (3σ); in the SM : ±12%
  - Precision on κ_λ with 4 IPs : ±21% (EFT fit) (5σ); ±9% (SM fit)
    - ➔ ~5σ discovery with 4 IPs instead of 2 – much less costly than 500 GeV upgrade (in time and funds, in view of FCC-hh)

A. Blondel, P. J.
arXiv:1809.10041

- And, most importantly
  - Only FCC-hh, in combination with FCC-ee, can measure κ_{top} and κ_λ to 1% and 5%, respectively.

Precision ⟺ Discovery

Sensitivity to new physics: Combining precision Higgs and EW measurements in SMEFT*



Deviating operators may point to the new physics to be looked for at the FCC-hh

FCC-ee reach for new physics: from typically 20TeV all the way to 70TeV

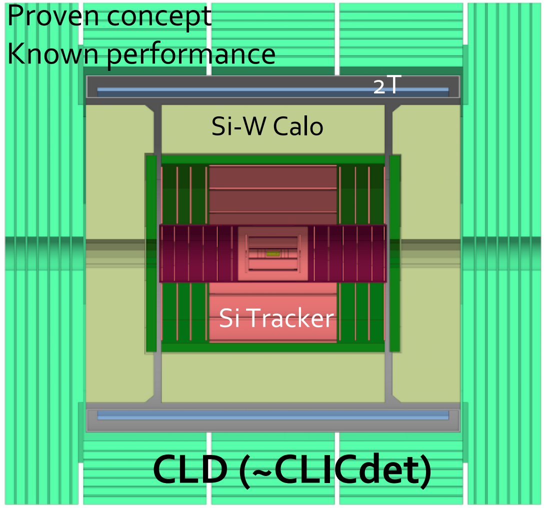
Dark bars: neglecting theory uncertainties

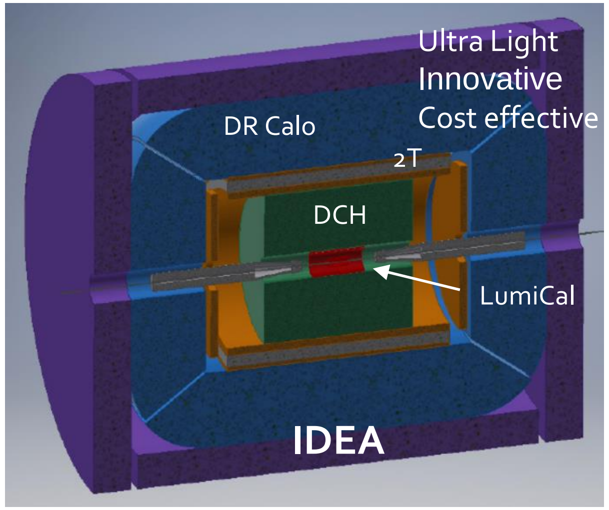
- Higgs and EWPO measurements are well complementary
- EWPO are more sensitive to heavy new physics (up to 50-70 TeV)
- Larger statistics pays off for Higgs measurements (4 IPs ?)
- Further improvement in theory predictions pays off for EWPO measurements

(*)SMEFT The Standard Model effective field theory is a model-independent framework for parameterising deviations from the Standard Model in the absence of light states.

FCC-ee detector design concepts

- Two designs studied so far





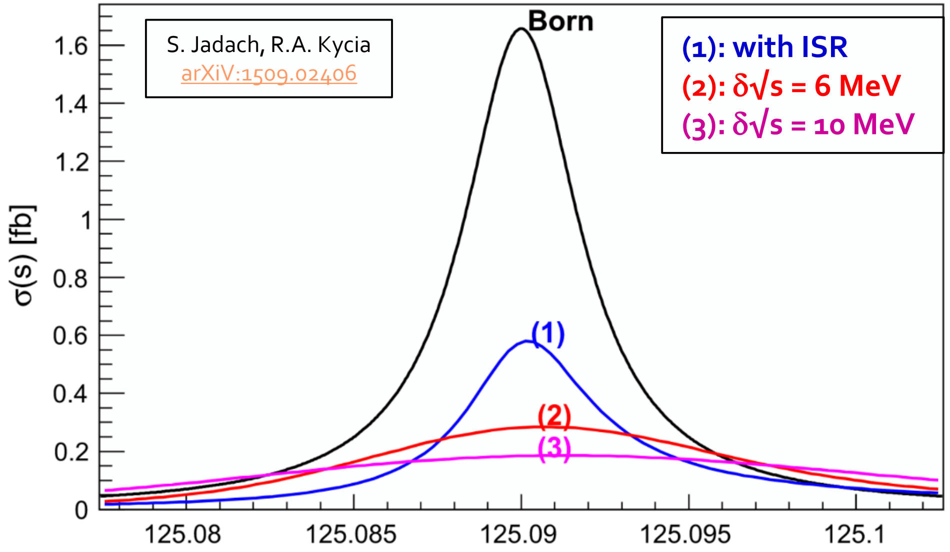
Two different concepts have been demonstrated to work, one a proven concept and the other with a thin solenoid and simple calorimeter (and a factor 2 cheaper)

  - It was demonstrated that detectors satisfying the requirements are feasible
    - Physics performance, invasive MDI, beam backgrounds
- More complete studies, with full simulation, needed
  - Towards at least four detector proposals to be made by ~2026
    - Light, granular, fast, b and c tagging, lepton ID and resolutions, hadron ID
    - Cost effective
    - Satisfy constraints from interaction region layout

We are now open to detector collaborations!

Unique at FCC-ee : First generation couplings

- If schedule allows or calls for a prolongation of FCC-ee, can spend few years at $\sqrt{s} = 125.09$ GeV
  - For s-channel production $e^+e^- \to H$ (a la muon collider, with 10^4 higher lumi)

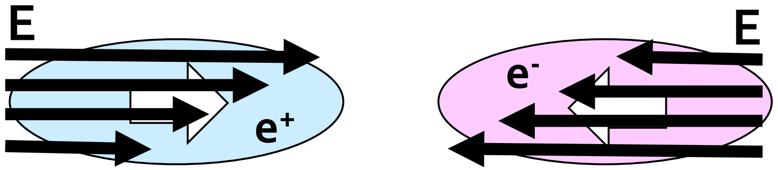


- FCC-ee monochromatization setups
  - Default: $\delta\sqrt{s} = 100$ MeV, 25 ab^{-1} / year
    - No visible resonance
  - Option 1: $\delta\sqrt{s} = 10$ MeV, 7 ab^{-1} / year
    - $\sigma(e^+e^- \to H) \sim 100$ ab
  - Option 2: $\delta\sqrt{s} = 6$ MeV, 2 ab^{-1} / year
    - $\sigma(e^+e^- \to H) \sim 250$ ab
  - Backgrounds much larger than signal
    - $e^+e^- \to q\bar{q}, \tau\tau, WW^*, ZZ^*, \gamma\gamma, \ldots$

- Expected signal significance of ~$0.4\sigma / \sqrt{\text{year}}$ in both option 1 and option 2
  - Set a electron Yukawa coupling upper limit : $\kappa_e < 2.5$ @ 95% C.L.
  - Reaches SM sensitivity after five years (or 2.5 years with 4 IPs)

D. d'Enterria
arXiV:1701.02663

Monochromatization:



- Unique opportunity to constrain first generation Yukawa's

Come and join us!

Future Circular Collider Conference

FCC WEEK 2019

BRUSSELS, BELGIUM
24 - 28 JUNE 2019
Crowne Plaza Brussels
Le Palace

WRITING the FUTURE

http://fccweek2019.web.cern.ch/

Conclusions

- FCC-ee has tremendous physics potential due to its
  - Huge statistics
  - Great precision
- It can improve EWPO by factors of ~20 to 50 compared to the situation today
- It can measure Higgs couplings to sub-percent precision
- It is sensitive to energy scales for new physics of 20-70TeV
- It has excellent upgrade potential: the FCC-hh, an 100TeV-plus hadron collider

Come and join the adventure!

Extra slides

Measuring the beam energy and energy spread

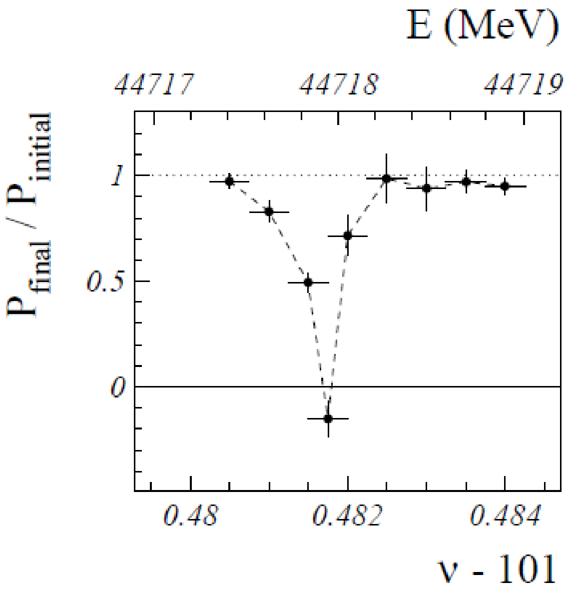
- Measuring the beam energy and energy spread is essential at the Z and W running.
- We aim for errors of ~100keV for ECM. Use the resonant depolarization method (transverse polarization needed)
  - Note that statistical error for the Z mass determination is only 5keV (5.10^{12} Zs!)
  - Also note that the daily variation of the energy due to terrestrial tides would be ~130MeV
  - LEP experience: M_z measured to 2MeV
- A working group has been set up (chaired by A. Blondel) and a workshop was organised at CERN
- Please note that measuring the beam energy necessitates the use of dedicated hardware, so it needs to be designed early.

The resonant depolarization method

$$\nu = a\gamma = \frac{aE}{mc^2} = \frac{E[MeV]}{440.6486(1)[MeV]}$$

- The spin tune of an electron in a storage ring, ν, is proportional to its energy.
- This energy can be measured (instantaneously) to ~100keV per beam!
- Different effects change the beam energy by orders of magnitude larger than that!
- We have the LEP experience to assist us, but still need to do a factor 20 better than that.
- Unique to FCC-ee: the resonant depolarization method can be used not only for the running around the Z, but also for the WW running

Unique to circular colliders



At the Z, polarization times are high (200 hours) – use dedicated wigglers

Transverse polarization of a few % is sufficient for a measurement – every 5 mins / both beams

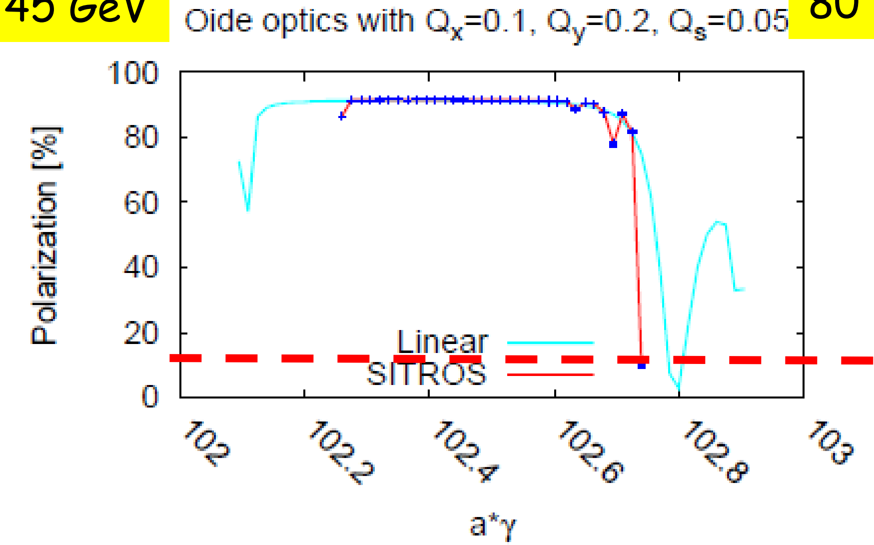
Careful machine preparation + harmonic bump tuning

Achieving polarization

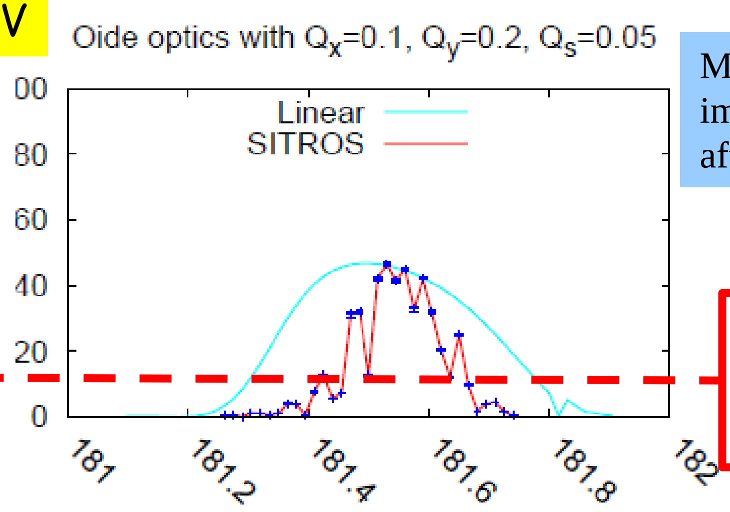
Accurate energy determination is needed for: M_z, Γ_Z, M_W, $sin^2\theta_W$ (from the muon F-B asymmetry at the Z)

- To depolarize you must first have achieved polarization; ~10% polarization sufficient
- A real (imperfect) machine depolarizes fast – need careful corrections to restore polarization levels
- Would this be possible? Simulation code SISTROS says yes both for the Z and for the W. Correcting an imperfect machine (quad misalignments + BPM errors) restores polarization levels.

45 GeV



80 GeV



Machine with imperfections after correction

Minimum polarization level required

Excellent polarization at the Z (but slow)

Energy spread increases $\sigma_{Eb} \propto E_b^2/\rho$ and polarization level decreases.
At the W expectation similar to LEP at Z
→ enough for energy calibration

E. Gianfelice-Wendt

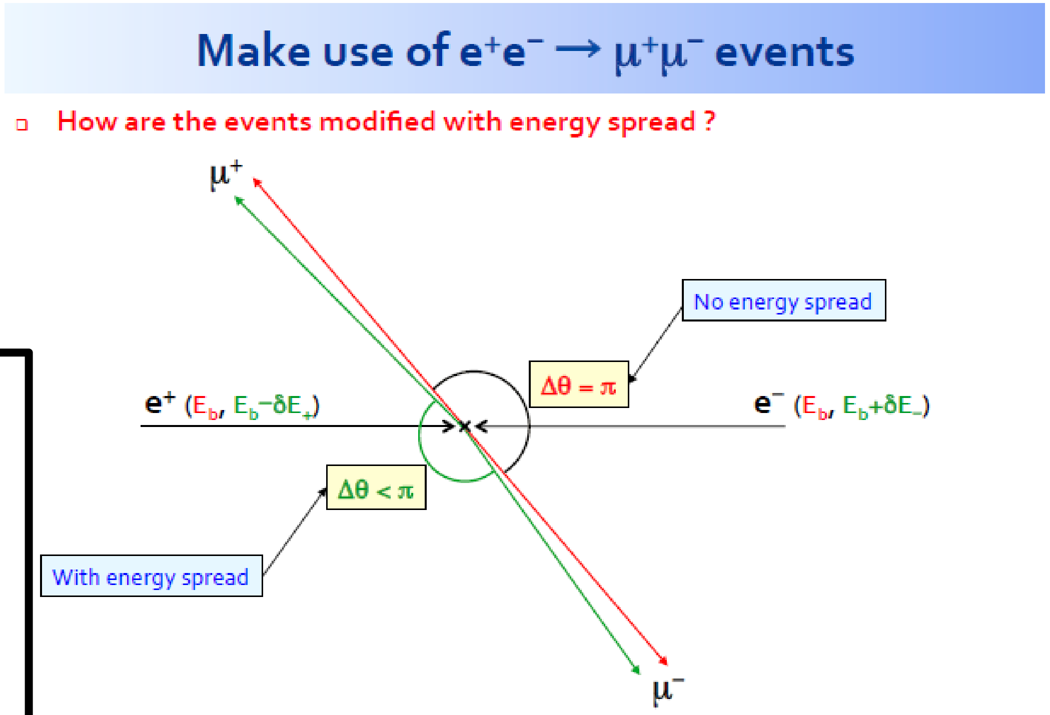
Energy spread determination

At the Z peak we collect 10^6 μμ events every 5 minutes.
Their kinematics is affected by:

- energy spread
- e+ vs e- energy difference.

P. Janot has shown that indeed both can be determined with extremely good precision with these events.

The energy difference is an important ingredient in understanding the RF model

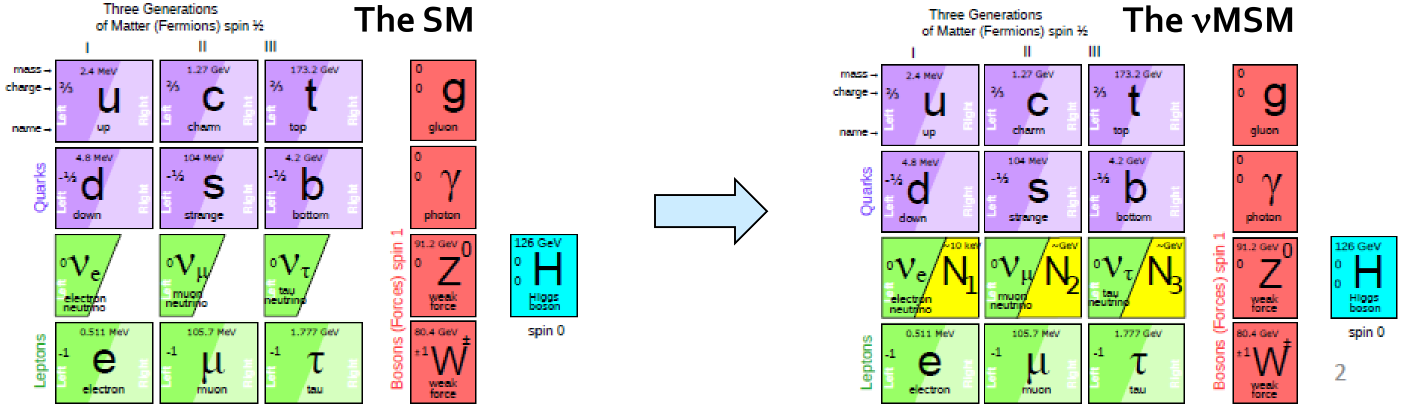


Make use of $e^+e^- \rightarrow \mu^+\mu^-$ events

- How are the events modified with energy spread ?

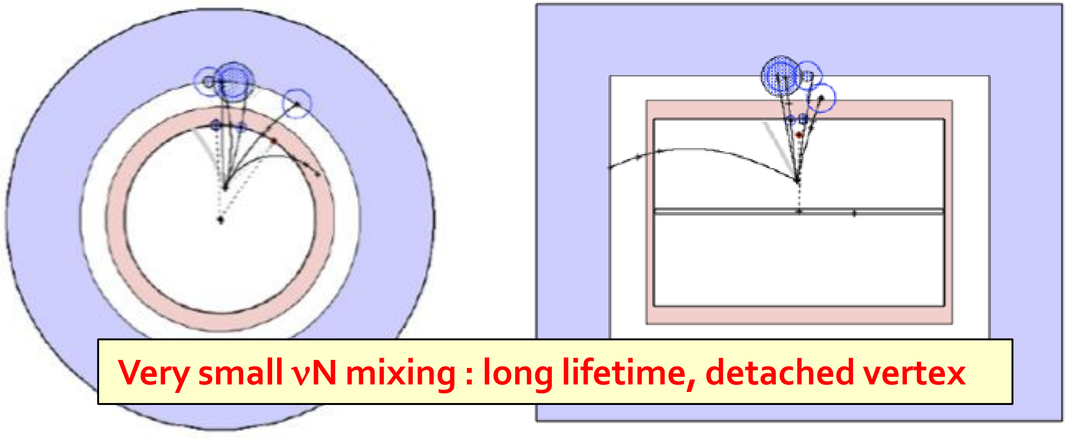
Direct discoveries

- **Discover right-handed neutrinos**
  - νMSM : Complete particle spectrum with the missing three right-handed neutrinos

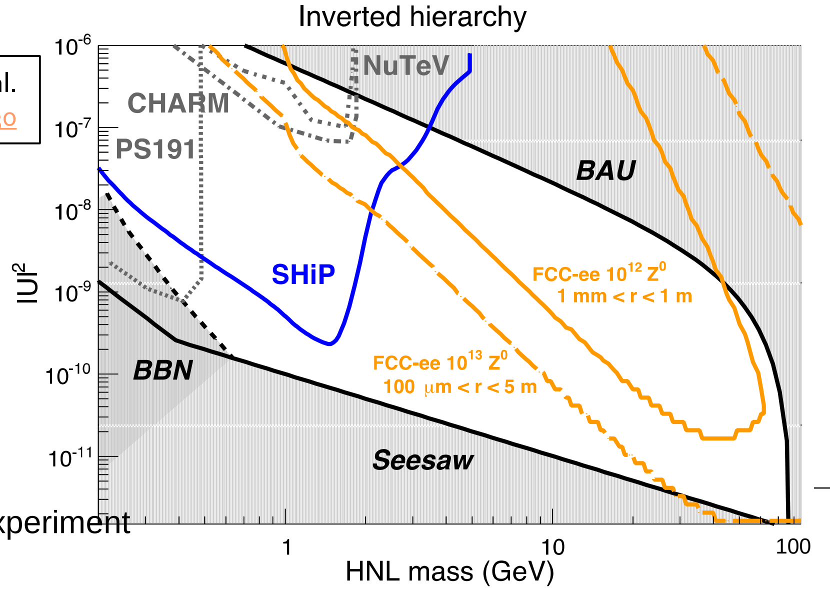


  - Could explain everything: Dark matter (N_1), Baryon asymmetry, Neutrino masses
  - Searched for in very rare $Z \rightarrow \nu N_{2,3}$ decays
    - Followed by $N_{2,3} \rightarrow W^*\ell$ or $Z^*\nu$

A. Blondel et al.
arXiv:1411.5230



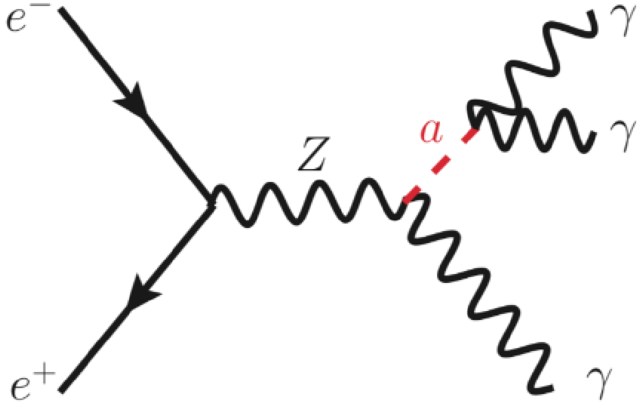
Very small νN mixing : long lifetime, detached vertex



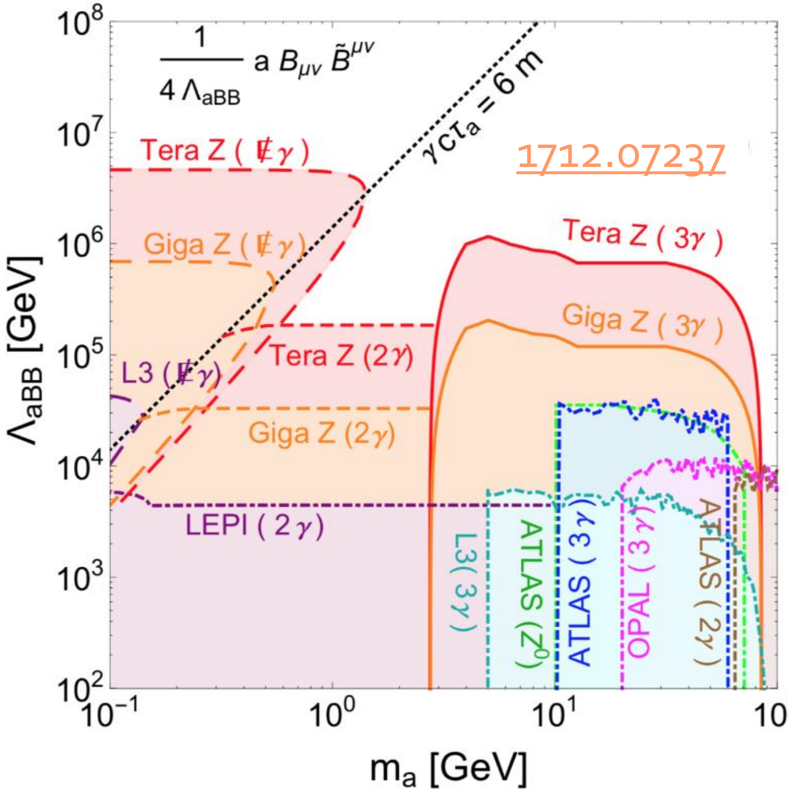
Direct discoveries (cont'd)

Discover the dark sector

- **A very-weakly-coupled window to the dark sector is through light "Axion-Like Particles" (ALPs)**



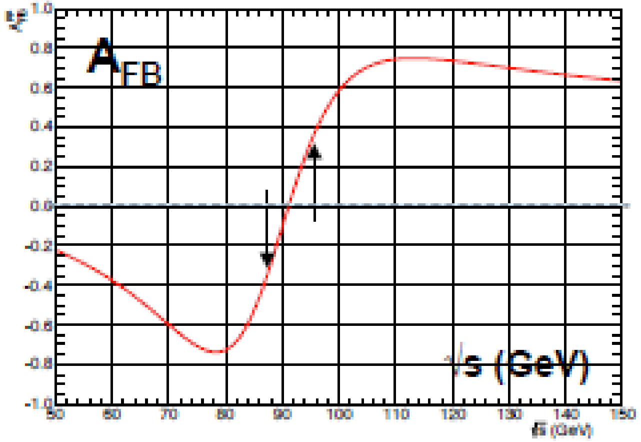
- ➔ $\gamma + E_{MISS}$ for very light a
- ➔ $\gamma\gamma$ for light a
- ➔ $\gamma\gamma\gamma$ for heavier a

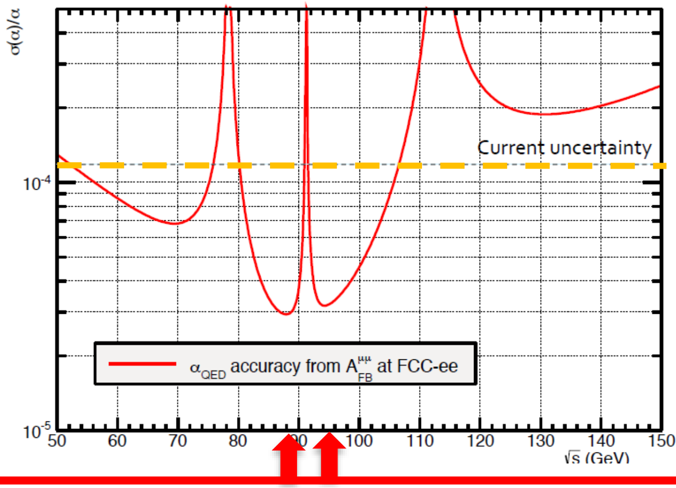


- Orders of magnitude of parameter space accessible at FCC-ee

Statistics needed at/around the Z pole

- Many measurements dominated by systematic uncertainties with 10^{12} Z
  - Baseline FCC-ee parameters give 40 ab^{-1} / year, i.e. 2×10^{12} Z / year at the Z pole
    - Aren't the 0.6 ab^{-1} and 3×10^{10} Z / year at CEPC more than enough ?
- Some crucial measurements / discovery channels need more
  - Example: measurement of $\alpha_{QED}(m_Z)$ from A_{FB} ($\mu\mu$) through γ/Z interference





- With 40 ab^{-1} at 87.9 GeV and 40 ab^{-1} at 94.3 GeV (two years in total)
  - $\Delta\alpha/\alpha$ ~3×10^{-5} (stat) ; Most syst. exp. uncertainties cancel in the combination

    Beam energy calibrat

    A knowledge of the b

This is statistical uncertainty – systematic uncertainty cancels when we measure 2 points

- Similar statistics needed for most asymmetries at / around the Z pole

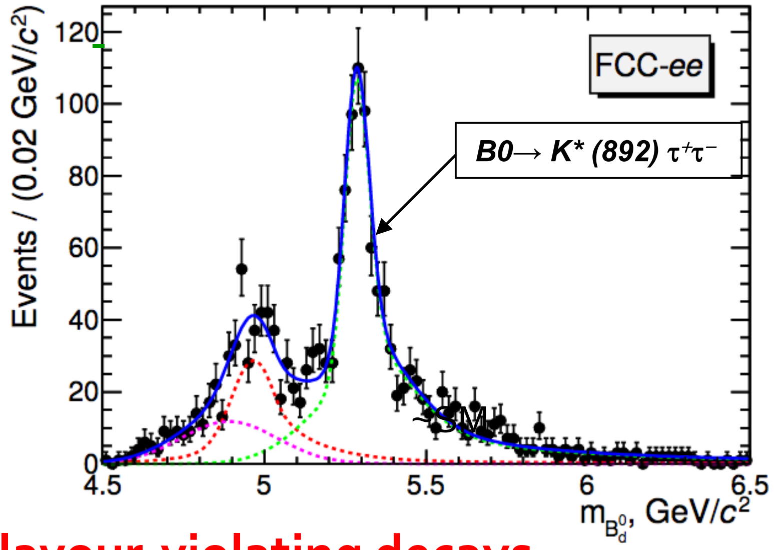
P.Janot, eeFACT2016, Daresbury

Flavours : B anomalies, τ physics, …

- Lepton flavour universality is challenged in b → s $\ell^+\ell^-$ transitions @ LHCb
  - This effect, if real, could be enhanced for $\ell = \tau$, in $B \to K^{(*)} \tau^+\tau^-$
    - Extremely challenging in hadron colliders
    - With 10^{12} Z → bb, FCC-ee is beyond any foreseeable competition
      - ➔ Decay can be fully reconstructed; full angular analysis possible

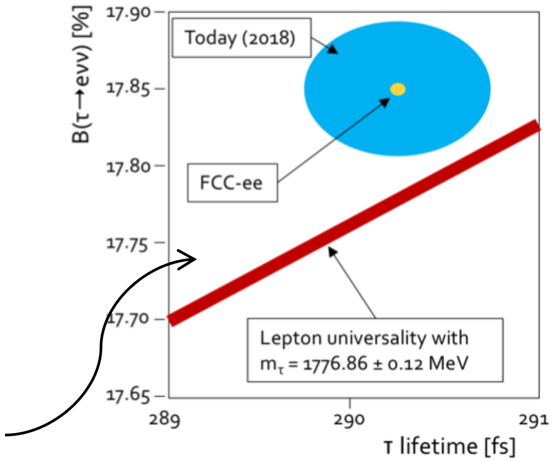
Talk from A. Bondar

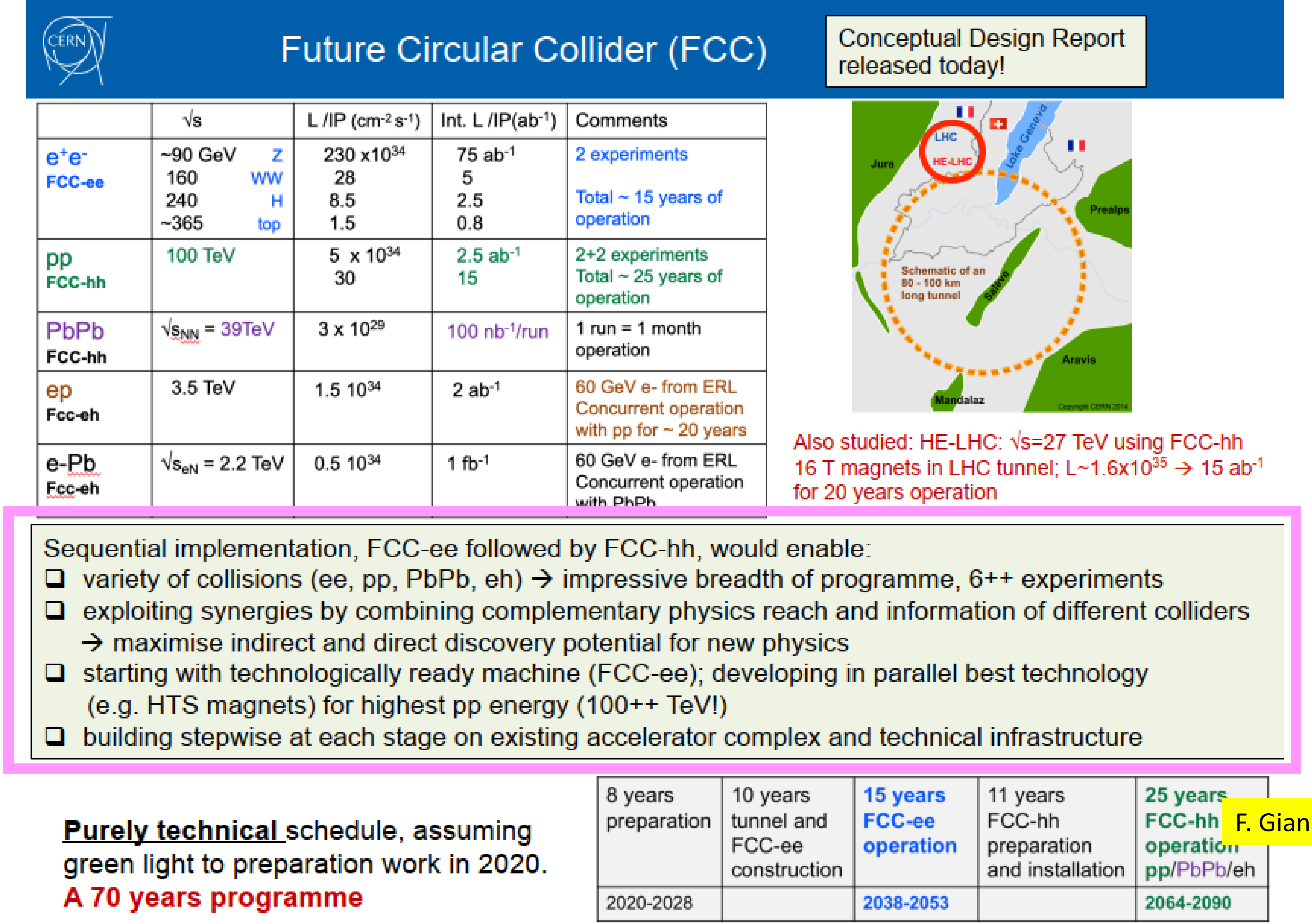
J.F. Kamenik et al.
arXiv:1705.11106



Also 100,000 $B_S \to \tau^+\tau^-$ @ FCC-ee
Reconstruction efficiency under study

- Not mentioning lepton-flavour-violating decays
  - BR(Z → eτ, μτ) down to 10^{-9} (improved by 10^4)
  - BR(τ → μγ, μμμ) down to a few 10^{-10}
  - τ lifetime vs BR($\tau \to e\nu_e\nu_\tau, \mu\nu_\mu\nu_\tau$) : lepton universality tests





Future Circular Collider (FCC)

Conceptual Design Report released today!

	$\sqrt{s}$	L /IP ($cm^{-2} s^{-1}$)	Int. L /IP(ab^{-1})	Comments
e^+e^- **FCC-ee**	~90 GeV Z 160 WW 240 H ~365 top	230 $\times 10^{34}$ 28 8.5 1.5	75 ab^{-1} 5 2.5 0.8	2 experiments Total ~ 15 years of operation
pp **FCC-hh**	100 TeV	5 $\times 10^{34}$ 30	2.5 ab^{-1} 15	2+2 experiments Total ~ 25 years of operation
PbPb **FCC-hh**	$\sqrt{s_{NN}}$ = 39TeV	3 x 10^{29}	100 nb^{-1}/run	1 run = 1 month operation
ep **Fcc-eh**	3.5 TeV	1.5 10^{34}	2 ab^{-1}	60 GeV e- from ERL Concurrent operation with pp for ~ 20 years
e-Pb **Fcc-eh**	$\sqrt{s_{eN}}$ = 2.2 TeV	0.5 10^{34}	1 fb^{-1}	60 GeV e- from ERL Concurrent operation with PbPb

Also studied: HE-LHC: $\sqrt{s}$=27 TeV using FCC-hh 16 T magnets in LHC tunnel; L~1.6×10^{35} → 15 ab^{-1} for 20 years operation

Sequential implementation, FCC-ee followed by FCC-hh, would enable:

- ☐ variety of collisions (ee, pp, PbPb, eh) → impressive breadth of programme, 6++ experiments
- ☐ exploiting synergies by combining complementary physics reach and information of different colliders → maximise indirect and direct discovery potential for new physics
- ☐ starting with technologically ready machine (FCC-ee); developing in parallel best technology (e.g. HTS magnets) for highest pp energy (100++ TeV!)
- ☐ building stepwise at each stage on existing accelerator complex and technical infrastructure

Purely technical schedule, assuming green light to preparation work in 2020.

A 70 years programme

8 years preparation	10 years tunnel and FCC-ee construction	**15 years FCC-ee operation**	11 years FCC-hh preparation and installation	**25 years FCC-hh operation pp/PbPb/eh**
2020-2028		**2038-2053**		**2064-2090**

F. Gianotti 15/1/2019

FCC-ee

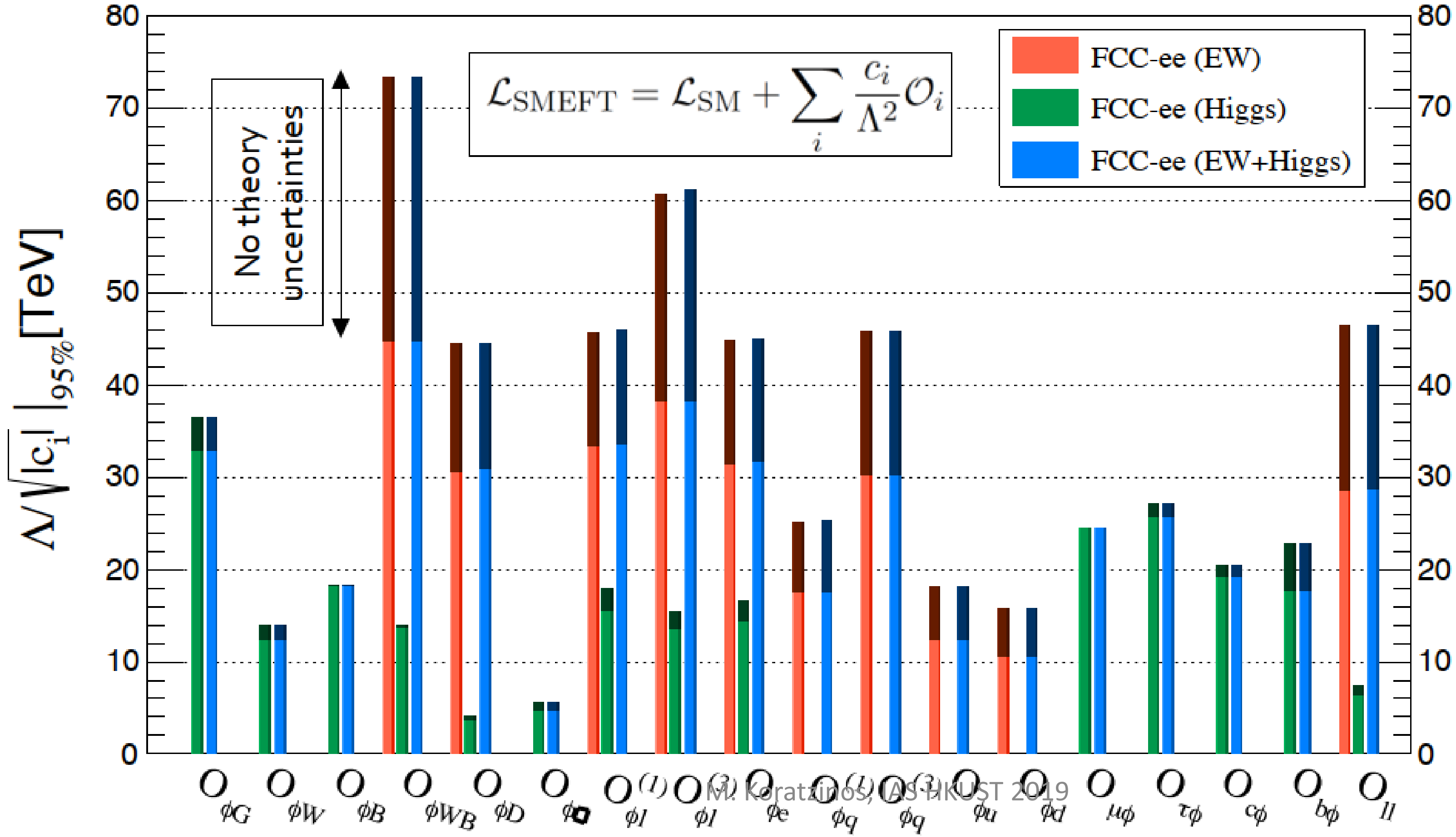
5×10^{12} Z (10^5 x LEP), 10^8 WW (10^3 x LEP), 10^6 H (not yet in e^+e^-), 10^6 tt (not yet in e^+e^-)

☐ Unprecedentedly precise measurements of Higgs couplings (model-independent) and EW parameters with x10-50 improvement on current precision → indirect sensitivity to new physics up to Λ ~ 100 TeV

→ pattern of deviations may indicate specific scenarios for new physics

☐ Searches for ultra-rare/forbidden decays (e.g. Z → τμ) and new particles with very small couplings

Note: need improved theoretical calculations to match experimental precision → strategic investment



previous e^+e^-
st and current

0 GeV),

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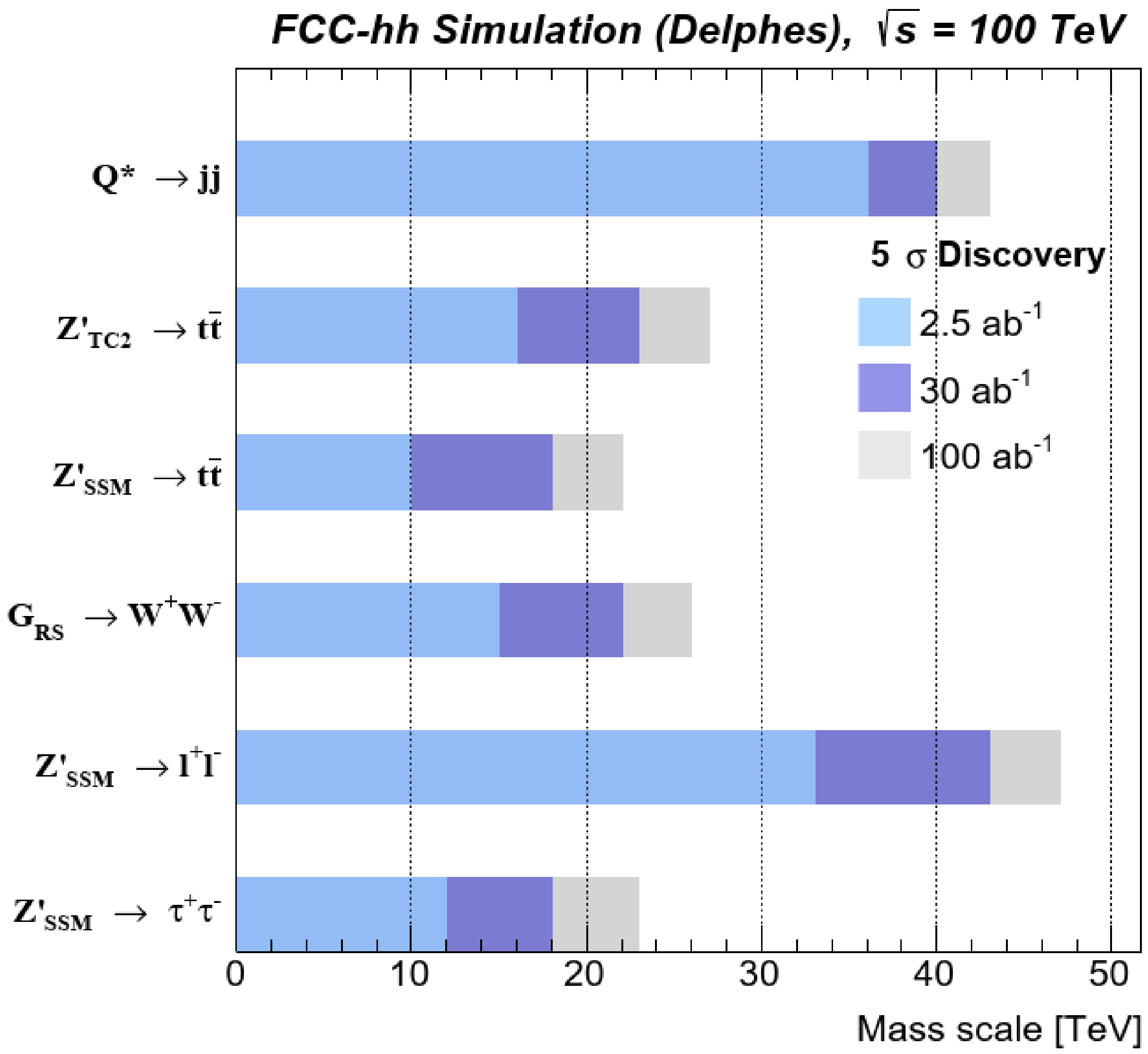
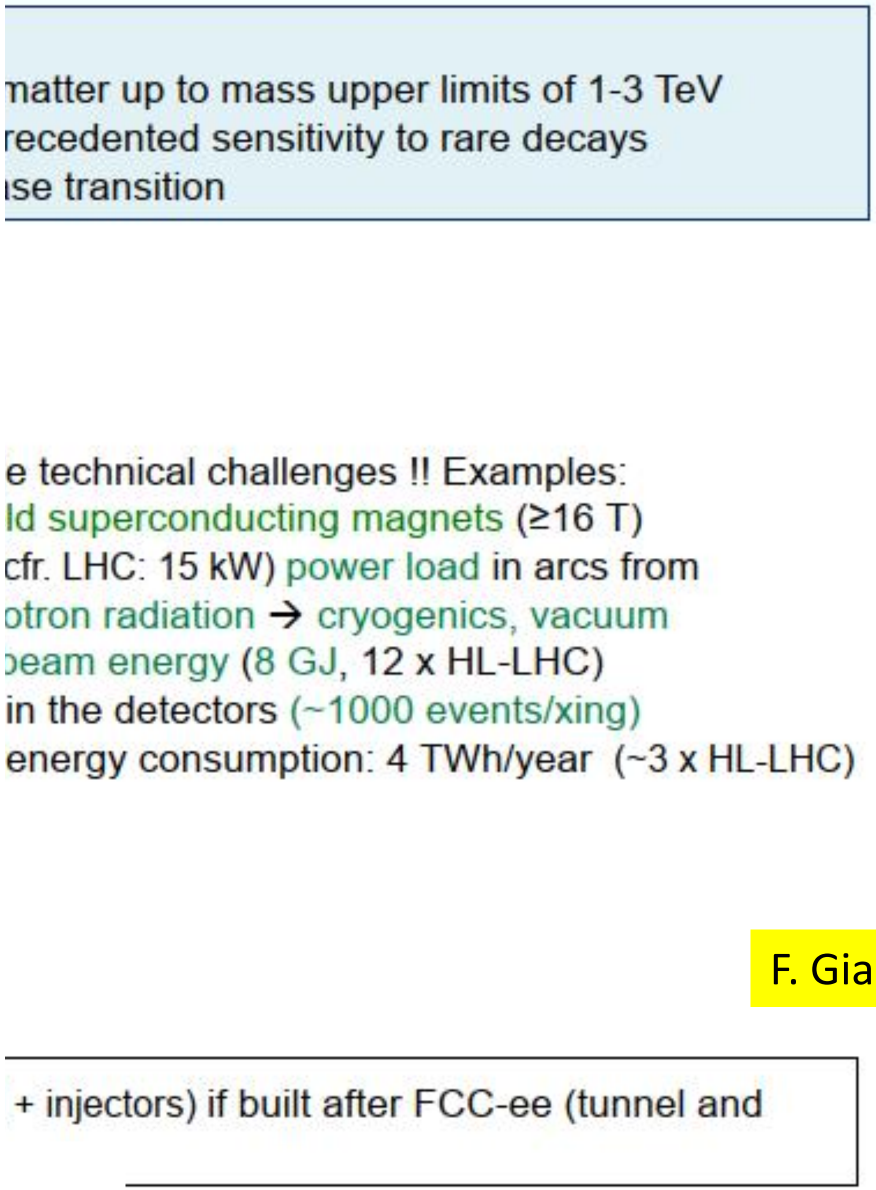
FCC-hh



FCC-hh mass reach for different s-channel resonances



matter up to mass upper limits of 1-3 TeV
recedented sensitivity to rare decays
ise transition

e technical challenges !! Examples:
ld superconducting magnets (≥16 T)
cfr. LHC: 15 kW) power load in arcs from
otron radiation → cryogenics, vacuum
beam energy (8 GJ, 12 x HL-LHC)
in the detectors (~1000 events/xing)
energy consumption: 4 TWh/year (~3 x HL-LHC)

+ injectors) if built after FCC-ee (tunnel and

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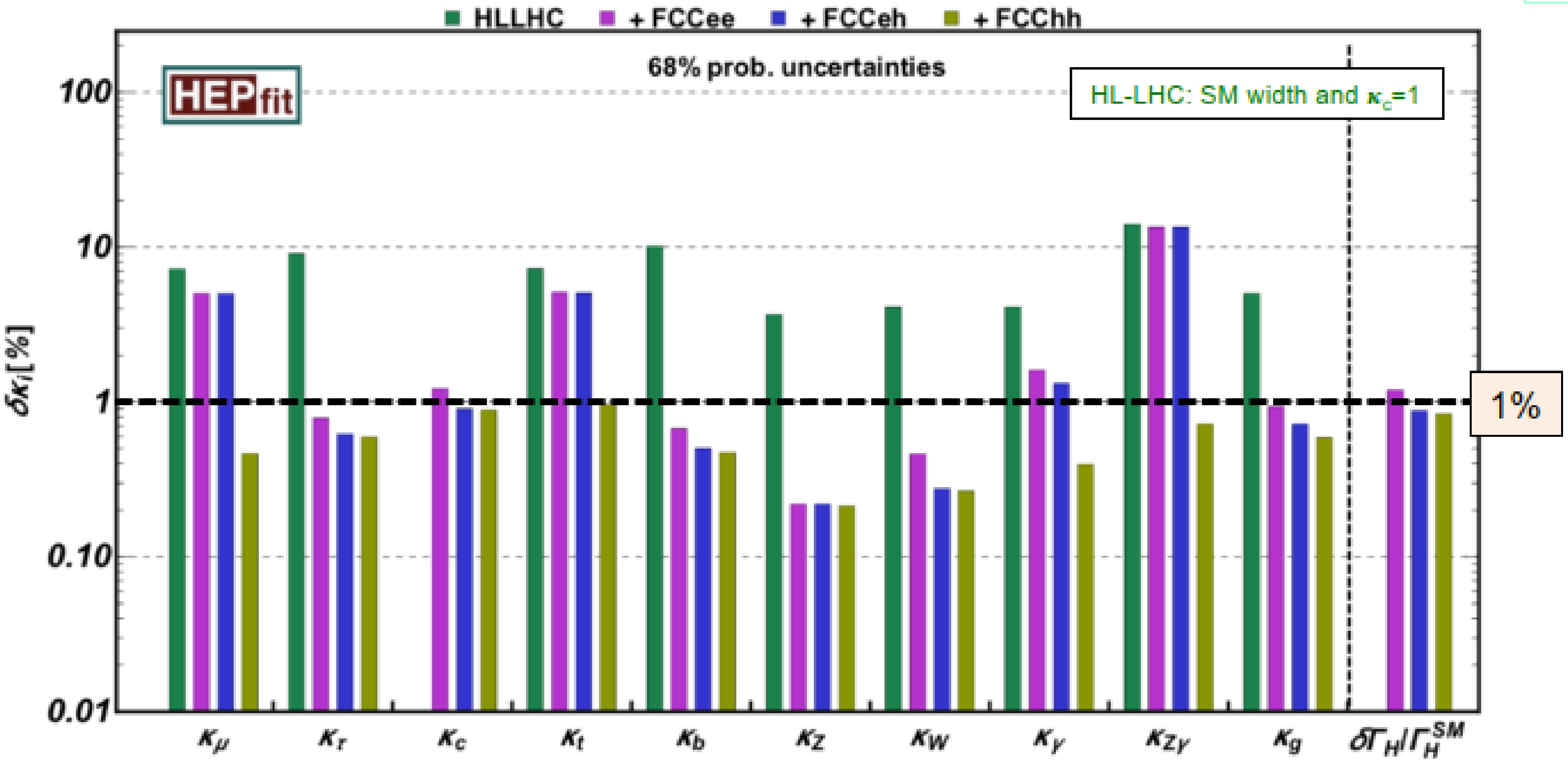
FCC-ee, FCC-ep, FCC-pp together

“Ultimate” precision on the Higgs coupling measurements by combining the results from HL-LHC and each FCC collider sequentially.

Number of Higgs bosons produced:
FCC-ee: 10^6
FCC-eh: $2. 10^6$
FCC-hh: 10^{10}



One-sigma precision reach at the FCC on the different Higgs coupling scaling factors within the κ-framework

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Note: input from FCC-ee (e.g. HZZ coupling) removes model-dependence of several couplings that are best measured at FCC-HH (e.g. ttH, H→μμ, H → Zγ)