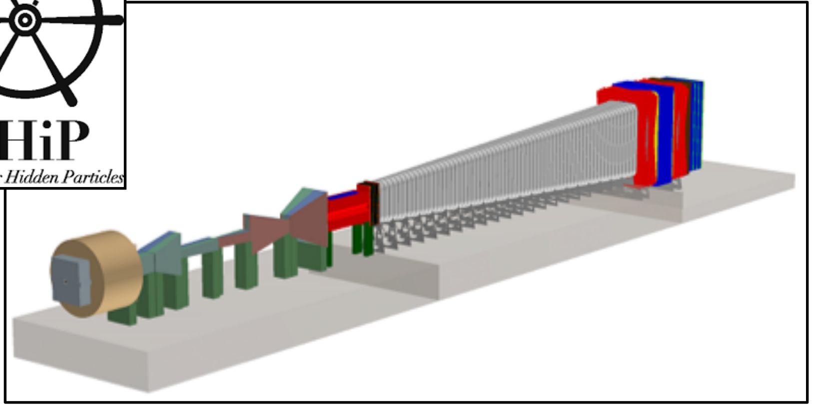
Future Facilities

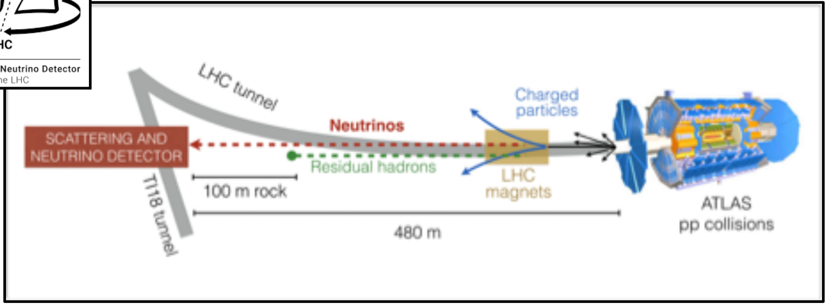
Mogens Dam, NBI

Danish PANP Meeting
Odense, 21th April, 2022

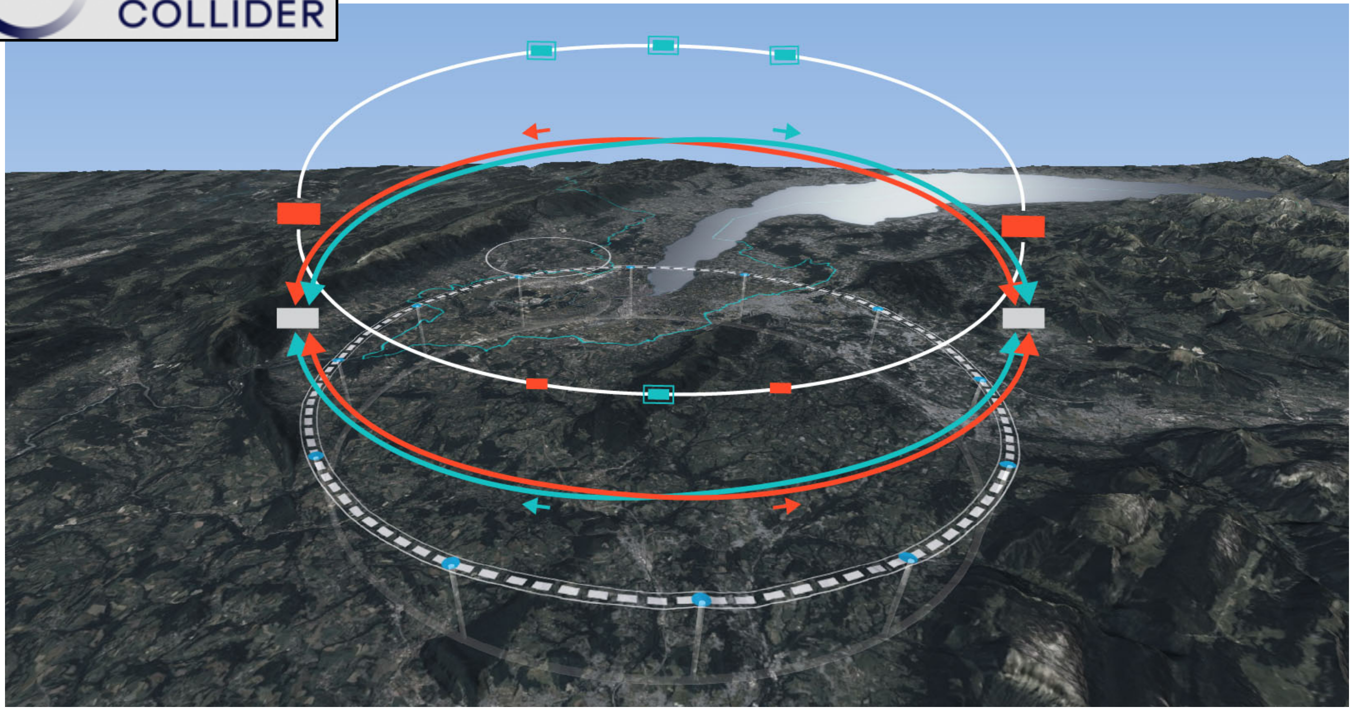
SHiP
Search for Hidden Particles



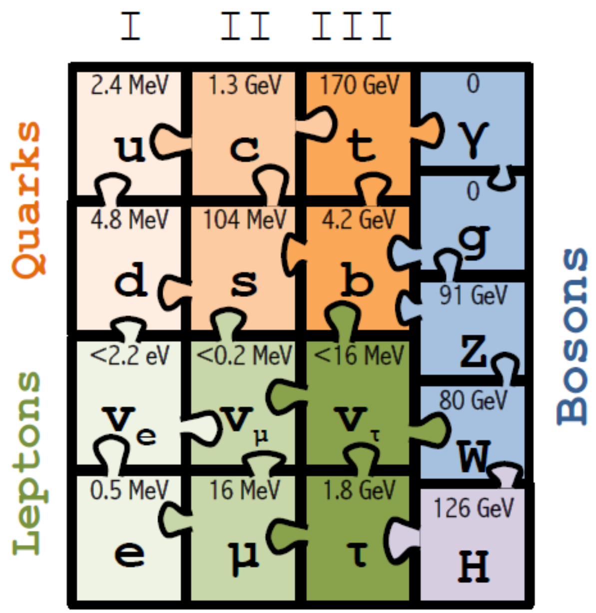
LHC
Scattering and Neutrino Detector at the LHC



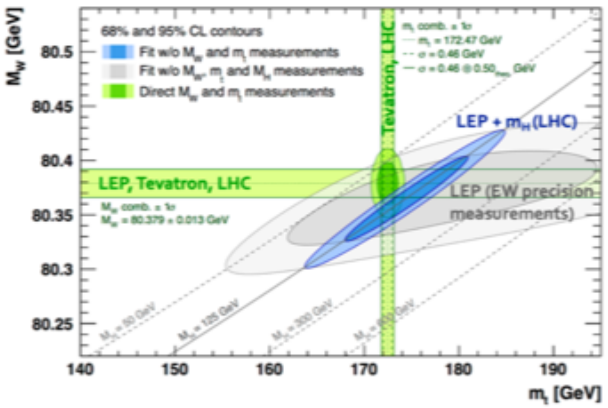
FUTURE CIRCULAR COLLIDER



Status of the Standard Model (until April 7th)



complete



coherent

With the Higgs boson, the Standard Model as a theory of particles and their interactions is now

- ✓ complete
- ✓ coherent (will return to this)
- ✓ predictive to all energies

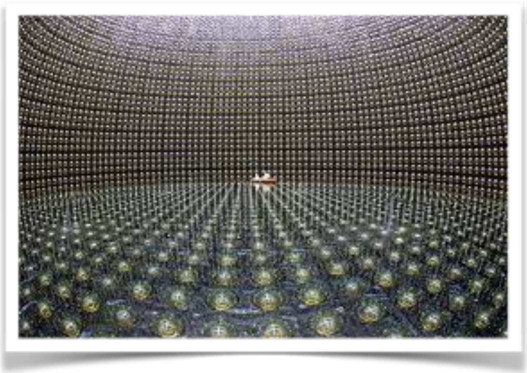
Is this the end ?

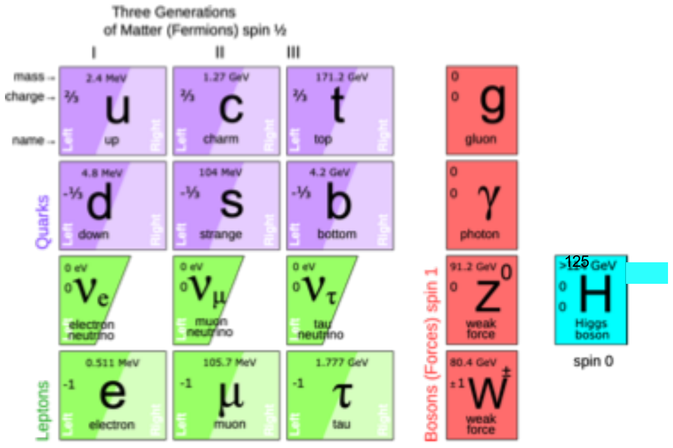
…most likely not… !?

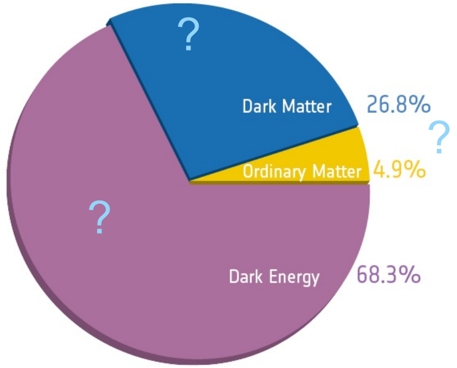
Many unanswered questions based on experimental observations?

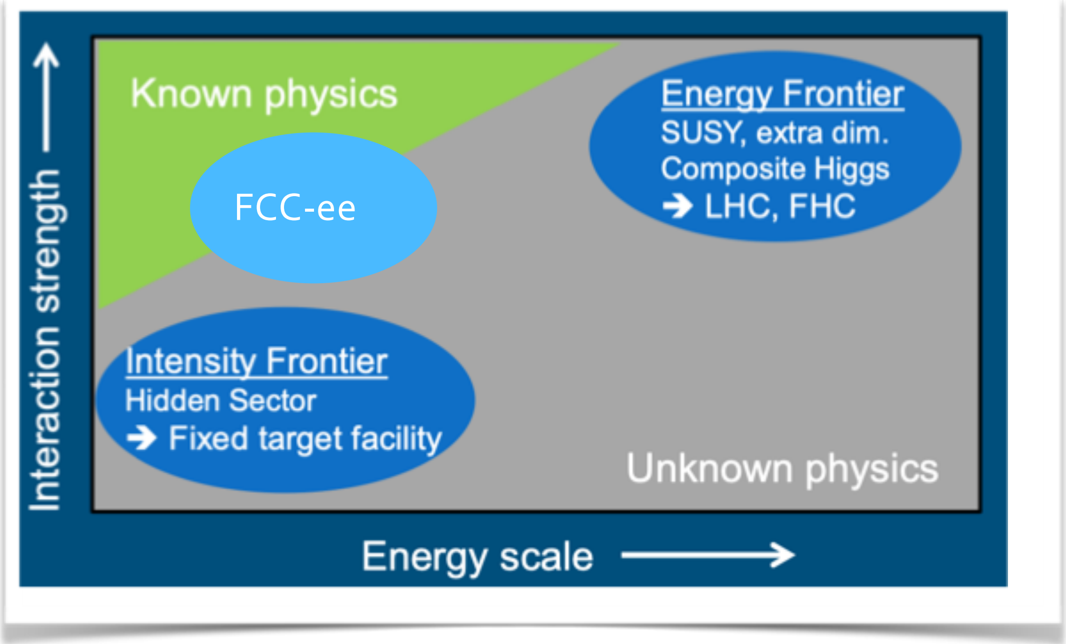
- Why 3 generations of fermions ?
- What is the origin of neutrino masses and oscillations ?
- What is the composition of dark matter ?
- What is the origin of the matter-antimatter asymmetry in the Universe [BAU] ?
- Why is gravity so weak ?
- Why is the Higgs boson so light ?
  - so-called "naturalness" or "hierarchy" problem
- What is the origin of the Universe's accelerated expansion ?

Beyond the Standard Model physics and where NBI is going to find it





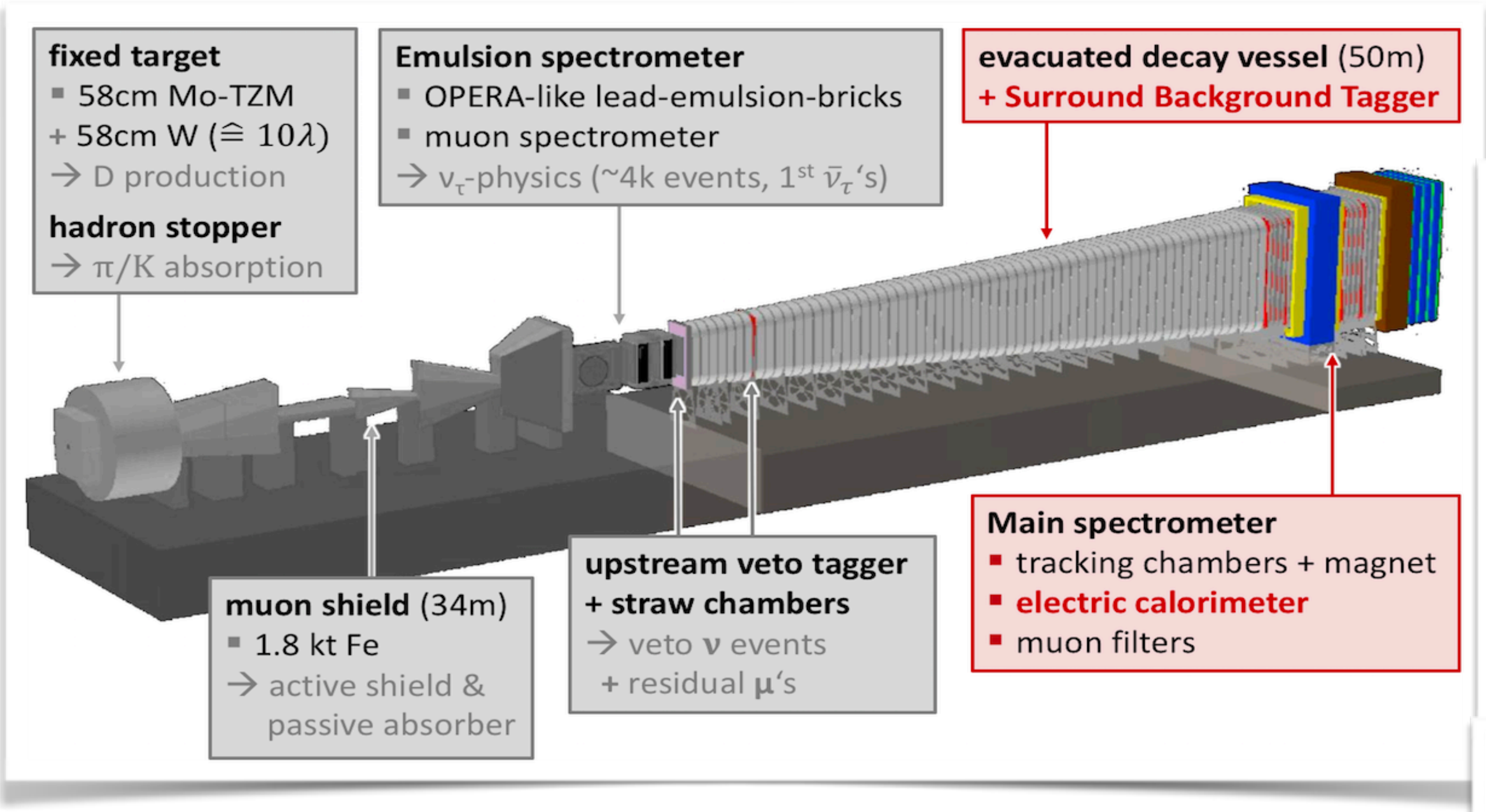




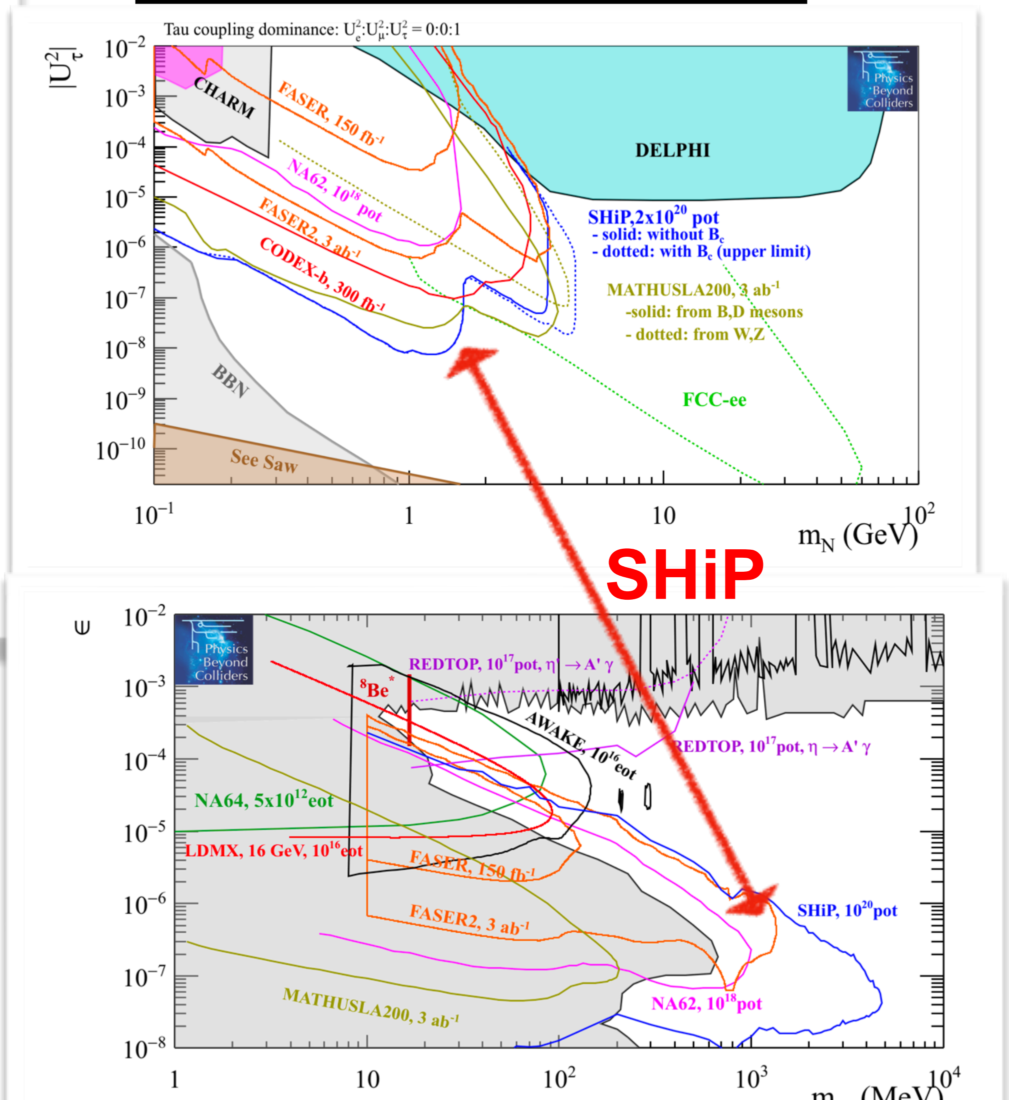
Did not yet find new particles because they are:

1) Too heavy **(energy frontier)**
2) Interact too weakly **(intensity frontier)**

SHiP — Search for Hidden Particles



For particles below O(10) GeV SHiP provides unmatched sensitivity



European Strategy Updage 2020:

… dedicated Physics Beyond Colliders study … Beam Dump Facility at the SPS … one of the frontrunners. However, such a project would be difficult to resource within the CERN budget, considering the other recommendations of this Strategy.

SND @ LHC

- Stand-alone experiment to probe neutrino production at the LHC in the forward direction
  - Sensitivity also to FIPs (Feebly Interacting Particles) including Light Dark Matter
- Approved by the CERN Research Board March, 2021
  - Under construction, data taking now in upcoming Run 3
- Comprises 24 institutes from 13 countries

LHC
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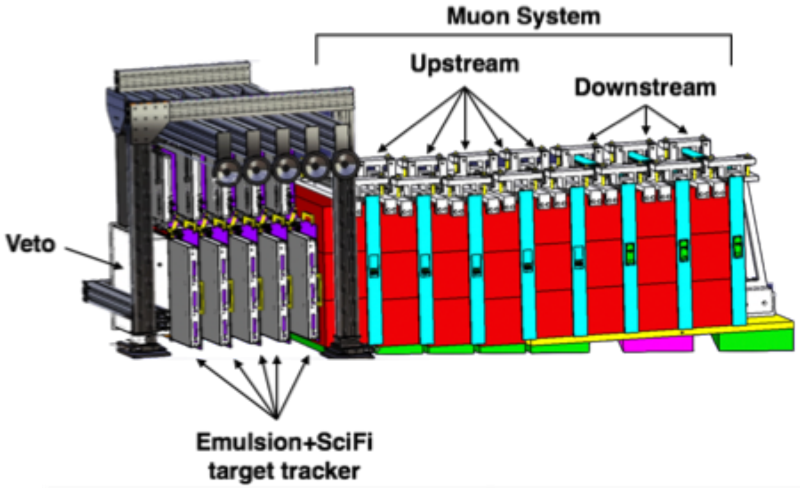
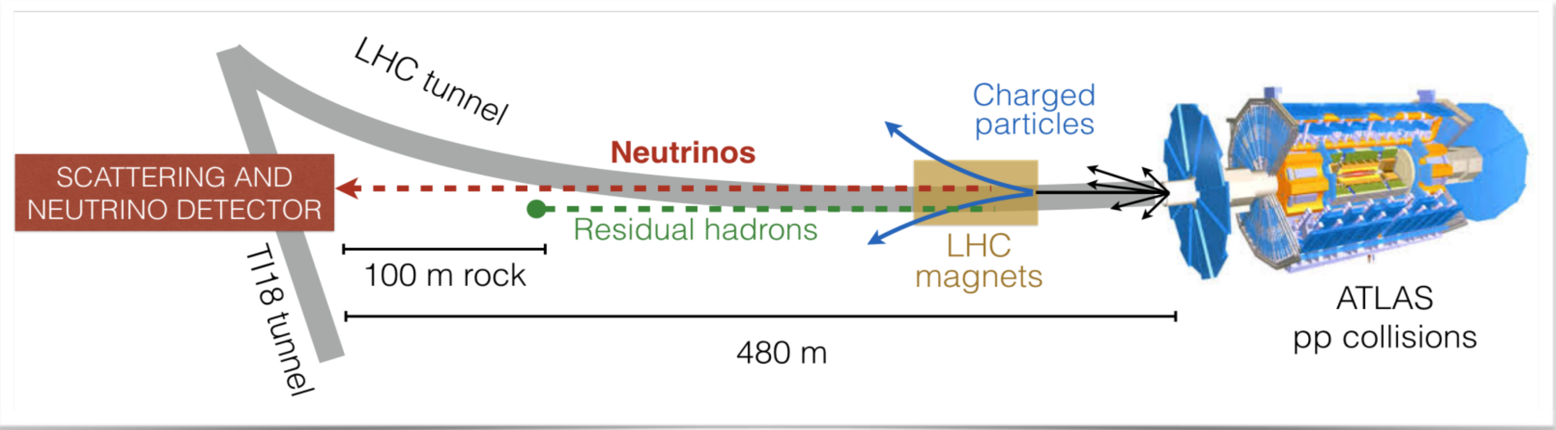
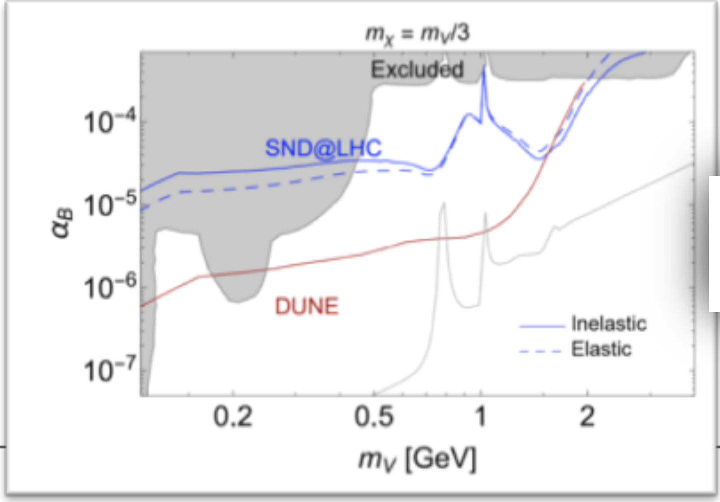


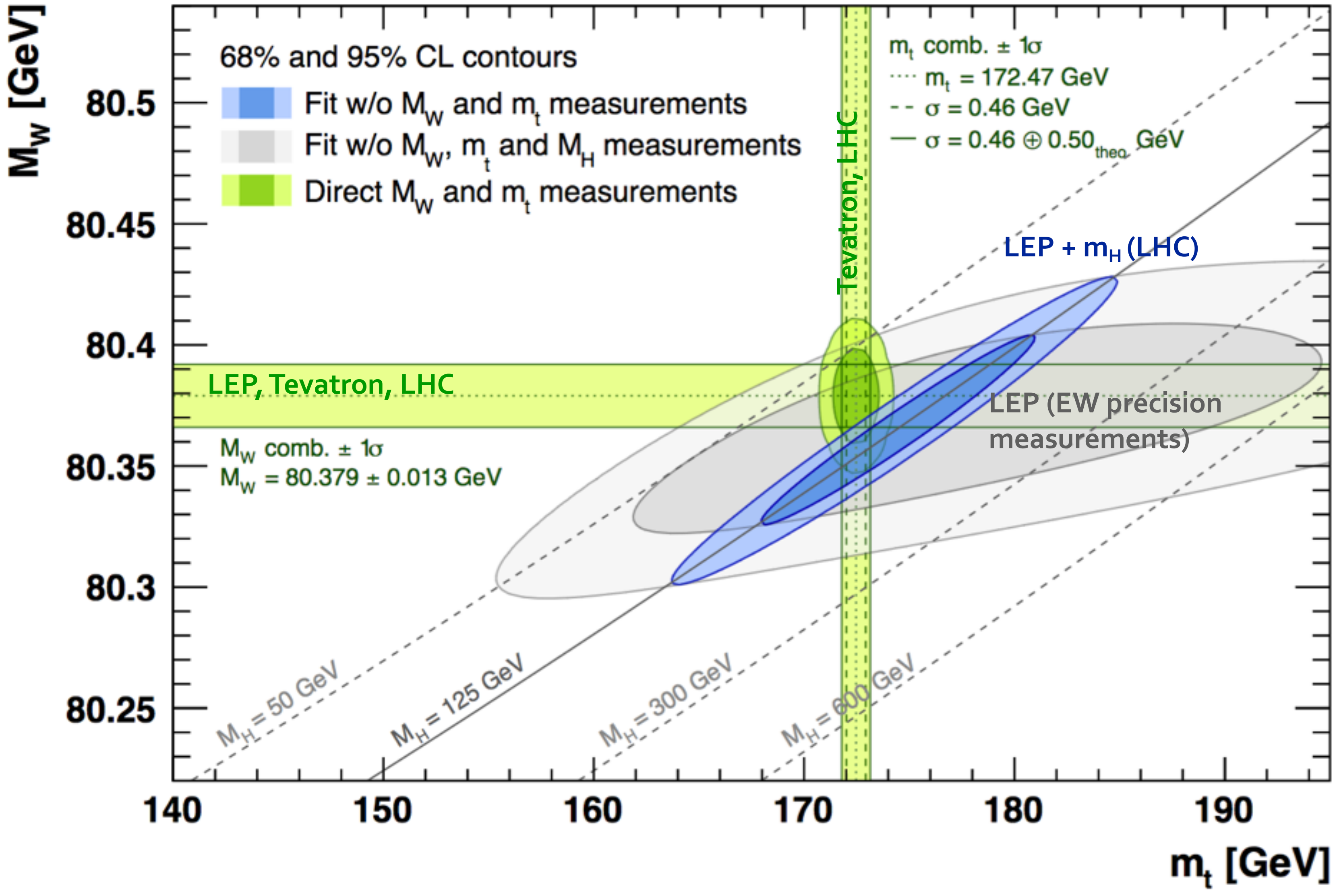


Measurement	Uncertainty Stat.	Sys.
$pp \to \nu_e X$ cross-section	5%	15%
Charmed hadron yield	5%	35%
ν_e/ν_τ ratio for LFU test	30%	20%
ν_e/ν_μ ratio for LFU test	10%	10%
Measurement of NC/CC ratio	5%	10%

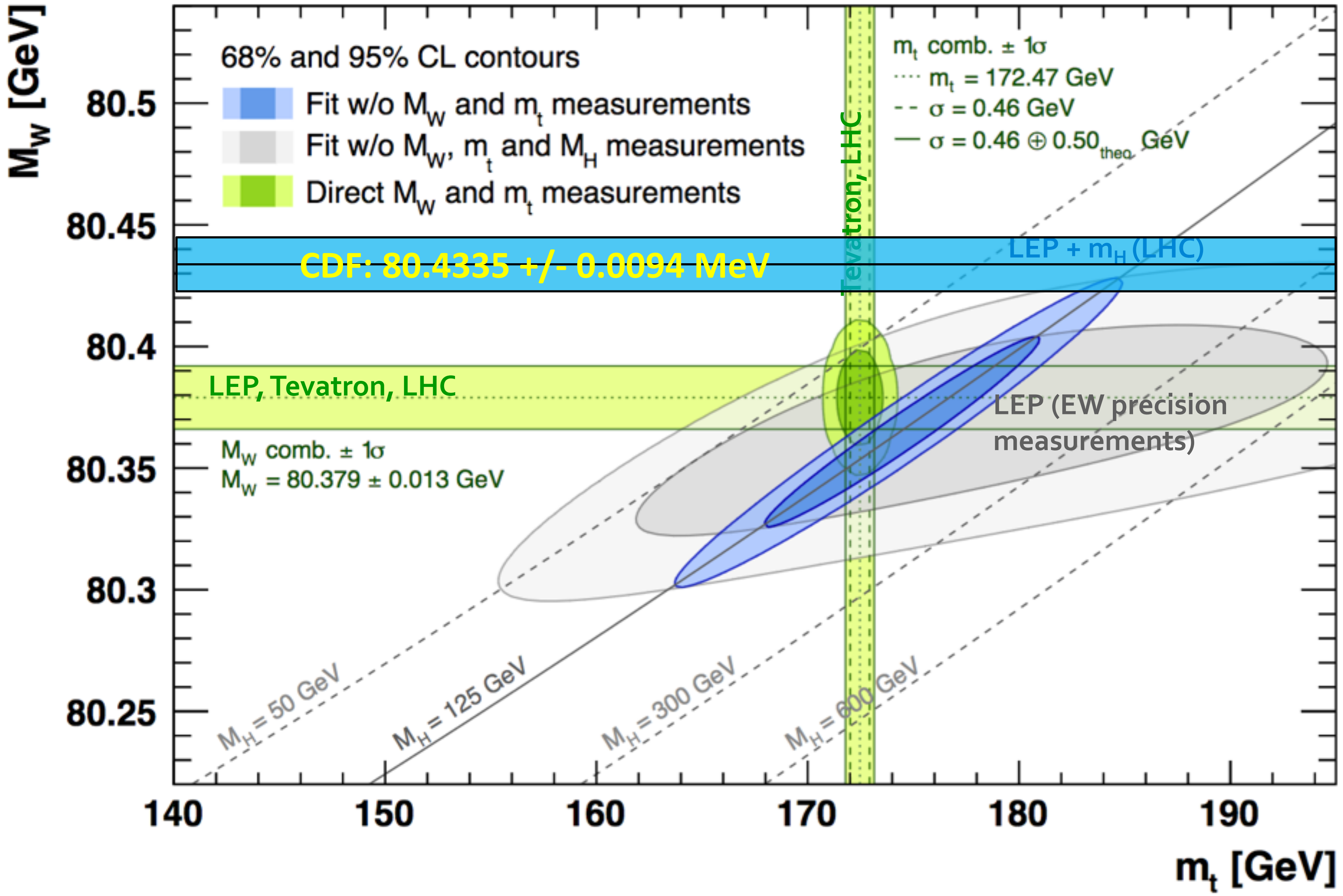


Light Dark Matter

SM coherence before April 7th



SM coherence after April 7th

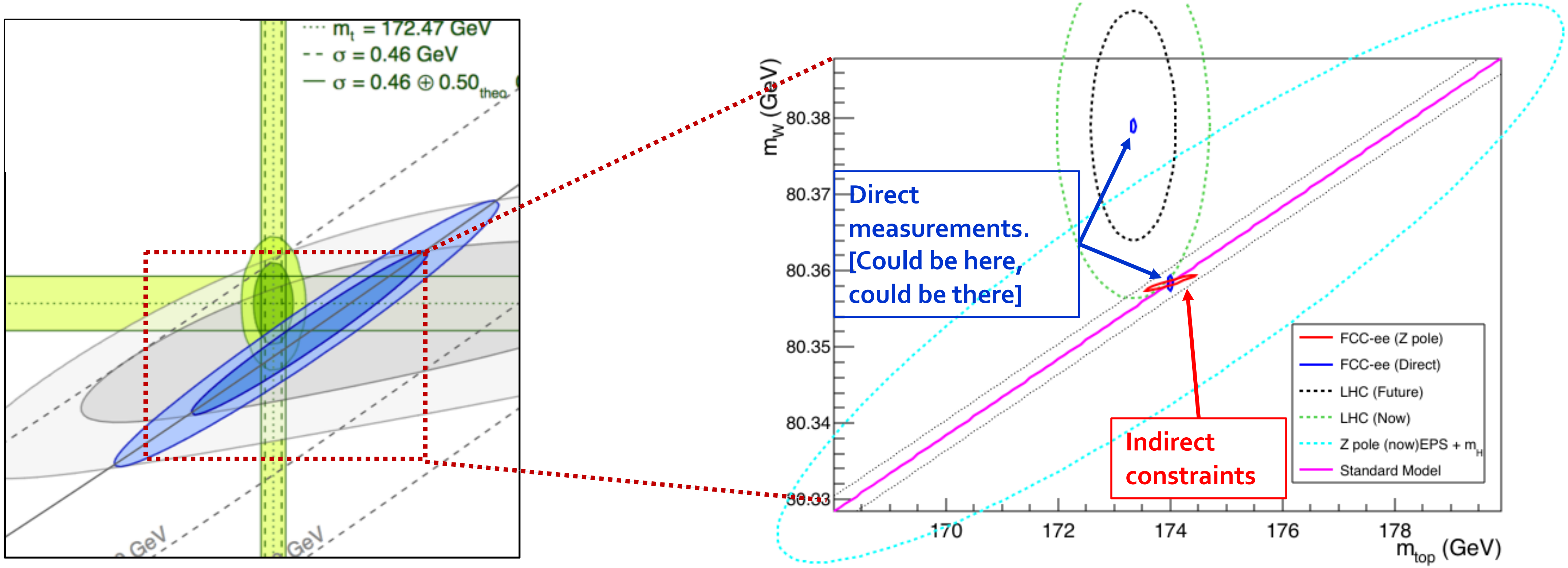


CDF:
"A comparison with the SM expectation of M_W= 80,357±6 MeV, … yields a difference with a significance of **7.0σ** and suggests the possibility of improvements to the SM calculation or of extensions to the SM."

Exciting….

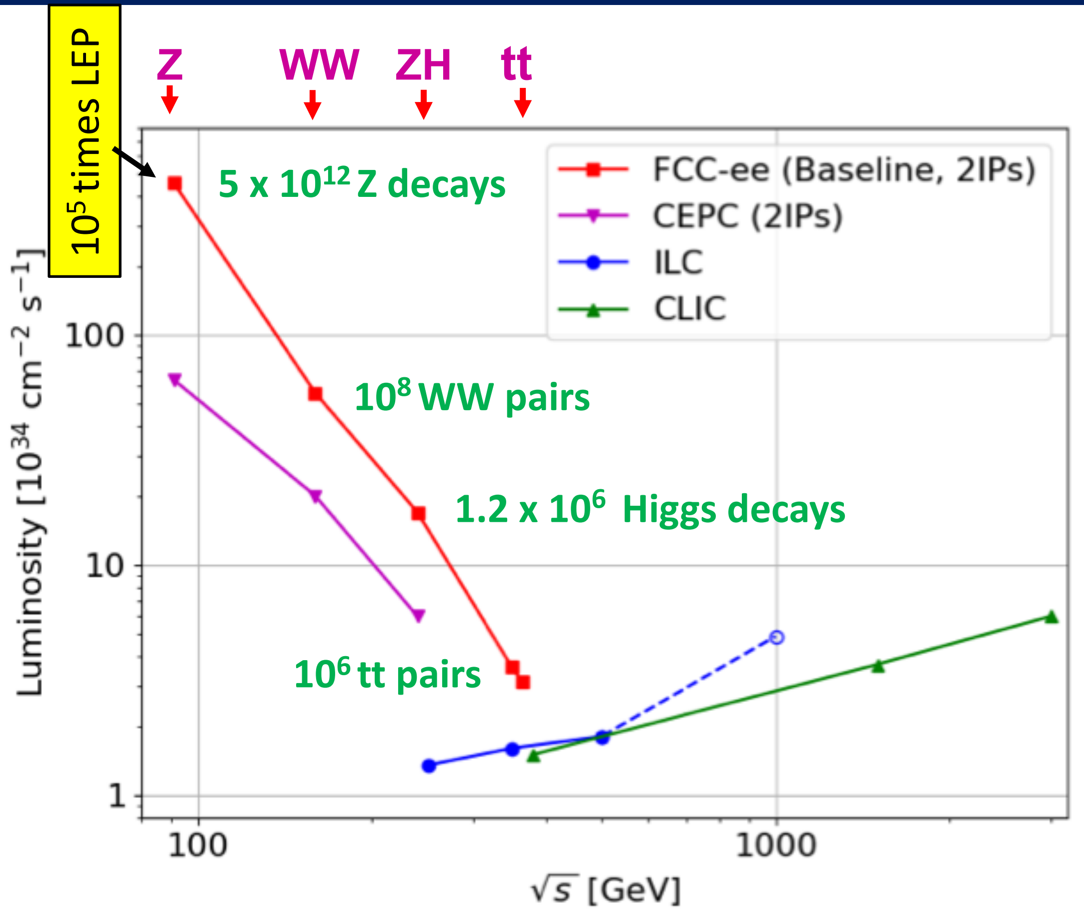
… and what if we improve precision further?

What if we improved all measurements by 1-2 orders ??



"Today" → "2055"

FCC-ee ; precision via luminosity



Statistics is immense:

- Ultimate factory for Z, W, Higgs, top, and heavy flavour, c, b, tau
- Uncertainties will be systematics limited

⇒ Detector Design is essential ⇐

	Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
Z	m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Z	Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
Z	$\sin^2\theta_W^{eff}(\times10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
Z	$1/\alpha_{QED}(m_Z^2)(\times10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
Z	R_ℓ^Z $(\times10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
Z	$\alpha_s(m_Z^2)$ $(\times10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
Z	σ_{had}^0 $(\times10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
Z	$N_\nu(\times10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
Z	R_b $(\times10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
Z	$A_{FB}^b, 0$ $(\times10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
Z	$A_{FB}^{pol,\tau}$ $(\times10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
Z	τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
Z	τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
Z	τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
WW	m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
WW	Γ_W (MeV)	2085 ± 42	**1.2**	0.3	From WW threshold scan Beam energy calibration
WW	$\alpha_s(m_W^2)(\times10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
WW	$N_\nu(\times10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
tt	m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
tt	Γ_{top} (MeV/c^2)	1410 ± 190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
tt	$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
tt	ttZ couplings	± 30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run

FCC and the 2020 European Particle Physcics Strategy Update

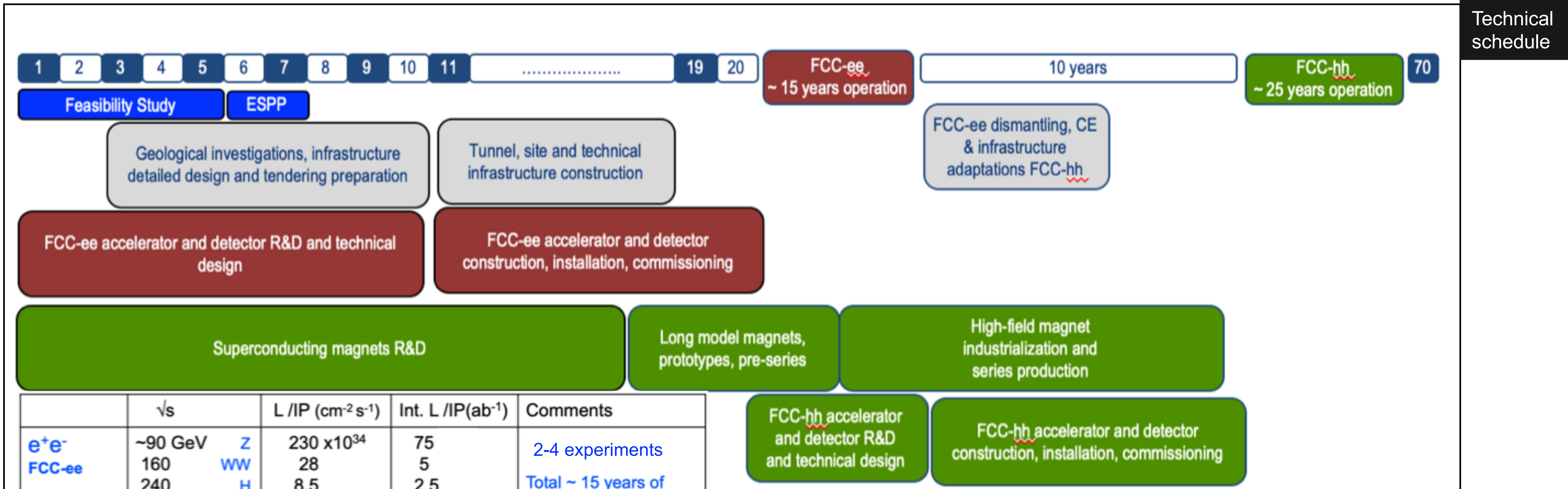
From the strategy document:

- *An **electron-positron Higgs factory is the highest-priority next collider**. For the longer term, the European particle physics community has the ambition to operate a **proton-proton collider at the highest achievable energy**.*

- *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.***

⇒ In June 2020, Future Circular Collider Feasibility Study was launched by CERN Council

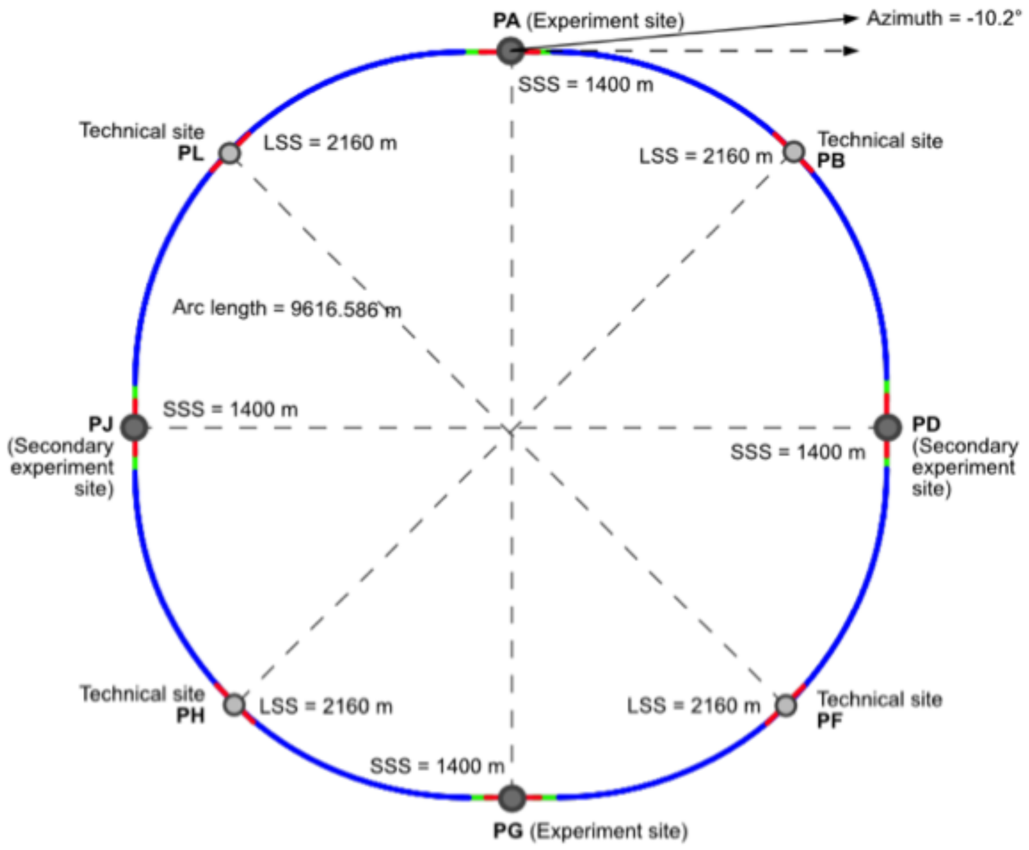
Timeline for FCC Integrated programme

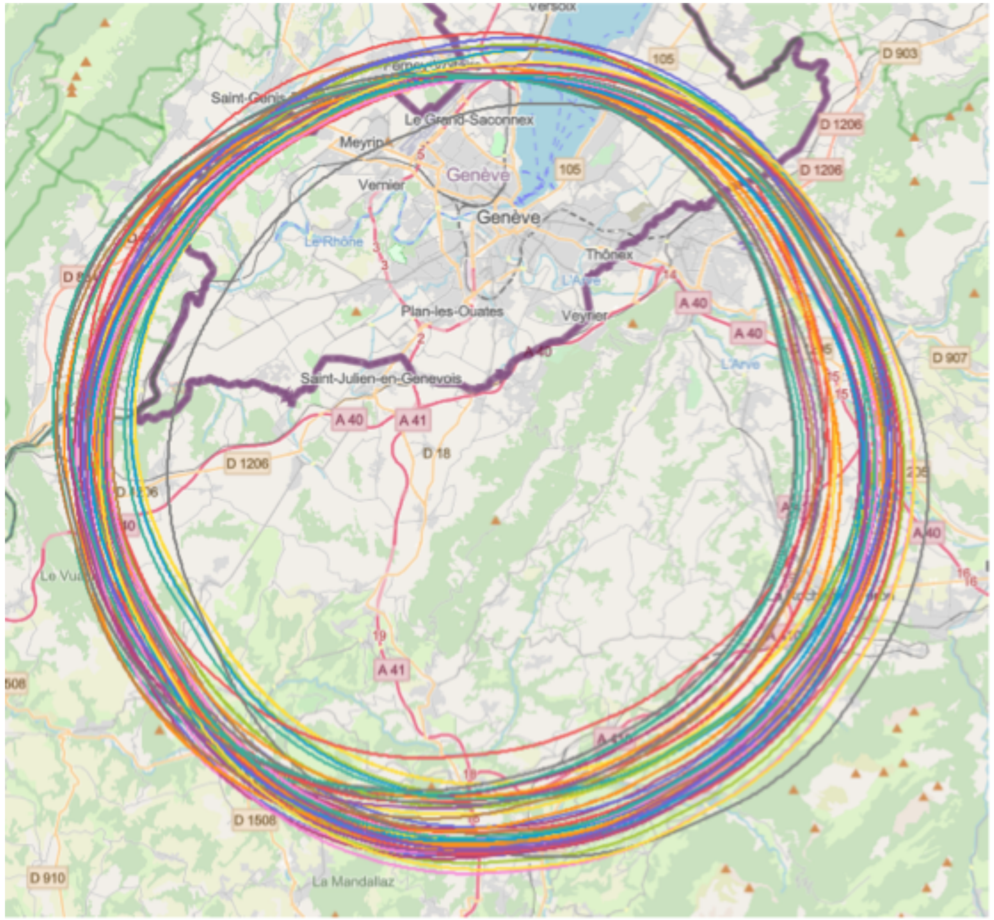


	√s	L /IP ($cm^{-2} s^{-1}$)	Int. L /IP(ab^{-1})	Comments
e^+e^- FCC-ee	~90 GeV Z 160 WW 240 H ~365 top	230 $\times 10^{34}$ 28 8.5 1.5	75 5 2.5 0.8	2-4 experiments Total ~ 15 years of operation
pp FCC-hh	100 TeV	5 x 10^{34} 30	20-30	2+2 experiments Total ~ 25 years of operation
PbPb FCC-hh	$\sqrt{s_{NN}}$ = 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

- ❑ Feasibility Study: 2021-2025
- ❑ If project approved before end of decade → construction can start beginning 2030s
- ❑ FCC-ee operation ~2045-2060
- ❑ FCC-hh operation 2070-2090++

Geometry and Placement





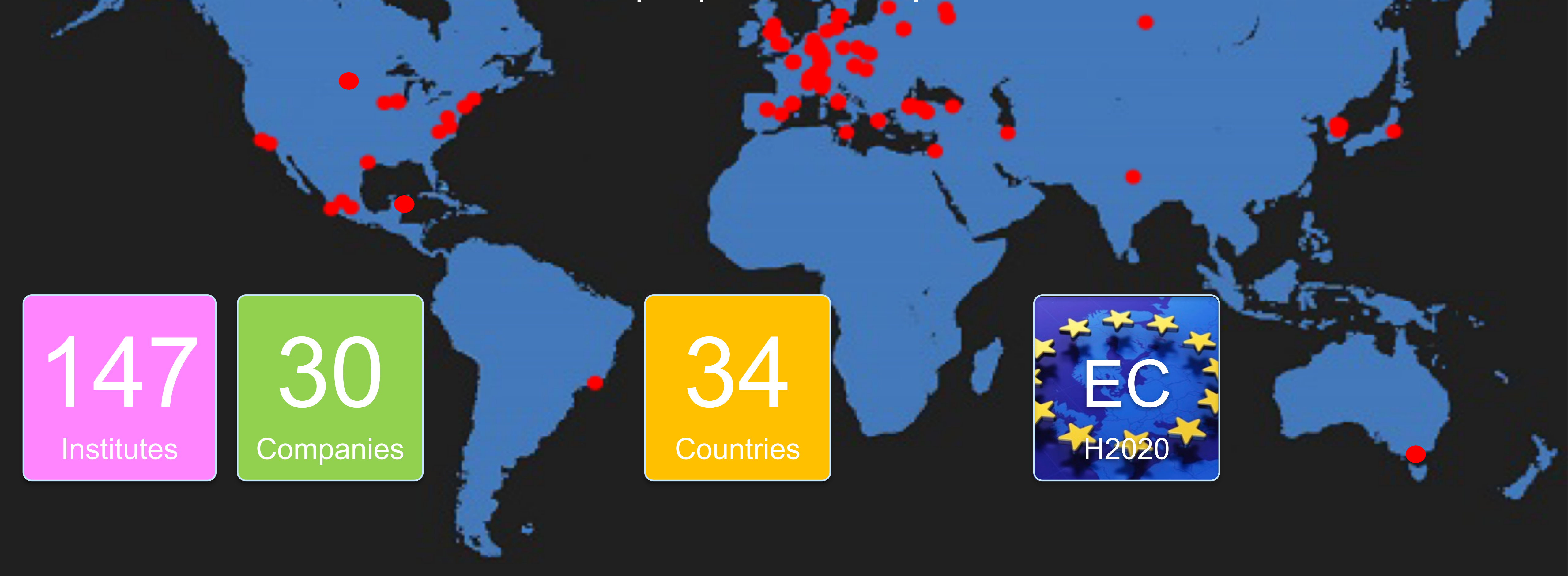
- 8-fold symmetry: allows for 2 or 4 interaction points
- Circumference 91.19 km [Z factory ;-)]

- Placement studies

Status of Global FCC Collabortion

Increasing international collaboration as a prerequisite for success:

links with science, research & development and **high-tech industry** will be essential to further advance and prepare the implementation of FCC



FCC Feasibility Study – Coordination Team

EU Projects
NN

Collaboration building
Emmanuel Tsesmelis

Communications
Panagiotis Charitos, James Gillies

Study Support and Coordination
Study Leader: Michael Benedikt
Deputy Study Leader: Frank Zimmermann

Study Support Unit
IT: Sylvain Girod
Procurement: Adam Horridge
Quality control: NN
Resources: Sylvie Prodon
Scheduling, quality mangement: NN
Secretariat: Julie Hadre

Physics, Experiments and Detectors
Patrick Janot
Christophe Grojean

- **Physics programme** – Matthew McCullough, Frank Simon
- **Detector concept** – Mogens Dam
- **Physics performance** – Patrizia Azzi, Emmanuel Perez
- **Software and computing** – Gerardo Ganis, Clément Helsens

Accelerators
Tor Raubenheimer
Frank Zimmermann

- **FCC-ee collider design** – Katsunobu Oide
- **FCC-hh design** – Massimo Giovannozzi
- **Technology R&D** – Roberto Losito
- **FCC-ee booster design** – Antoine Chancé
- **FCC-ee injector** – Paolo Craievich, Alexej Grudiev
- **FCC-ee energy calibration polarization** – Alain Blondel, Jorg Wenninger
- **FCC-ee MDI** – Manuela Boscolo, Mike Sullivan

Technical Infrastructures
Klaus Hanke

- **Integration** – Jean-Pierre Corso
- **Geodesy & survey** – Hélène Mainaud Durand
- **Electricity and energy management** – Jean-Paul Burnet
- **Cooling and ventilation** – Guillermo Peon
- **Cryogenics systems** – Laurent Delprat
- **Computing and controls infrastructure, communication and network** – Dirk Duellmann
- **Safety** – Thomas Otto
- **Operation, maintenance, availability, reliability** – Jesper Nielsen
- **Transport, installation concepts** – Cristiana Colloca

Host State processes and civil engineering
Timothy Watson

- **Administrative processes** – Friedemann Eder
- **Placement studies** – Johannes Gutleber, Volker Mertens
- **Environmental evaluation** – Johannes Gutleber
- **Tunnel, subsurface design** – John Osborne
- **Surface sites layout, access and building design**

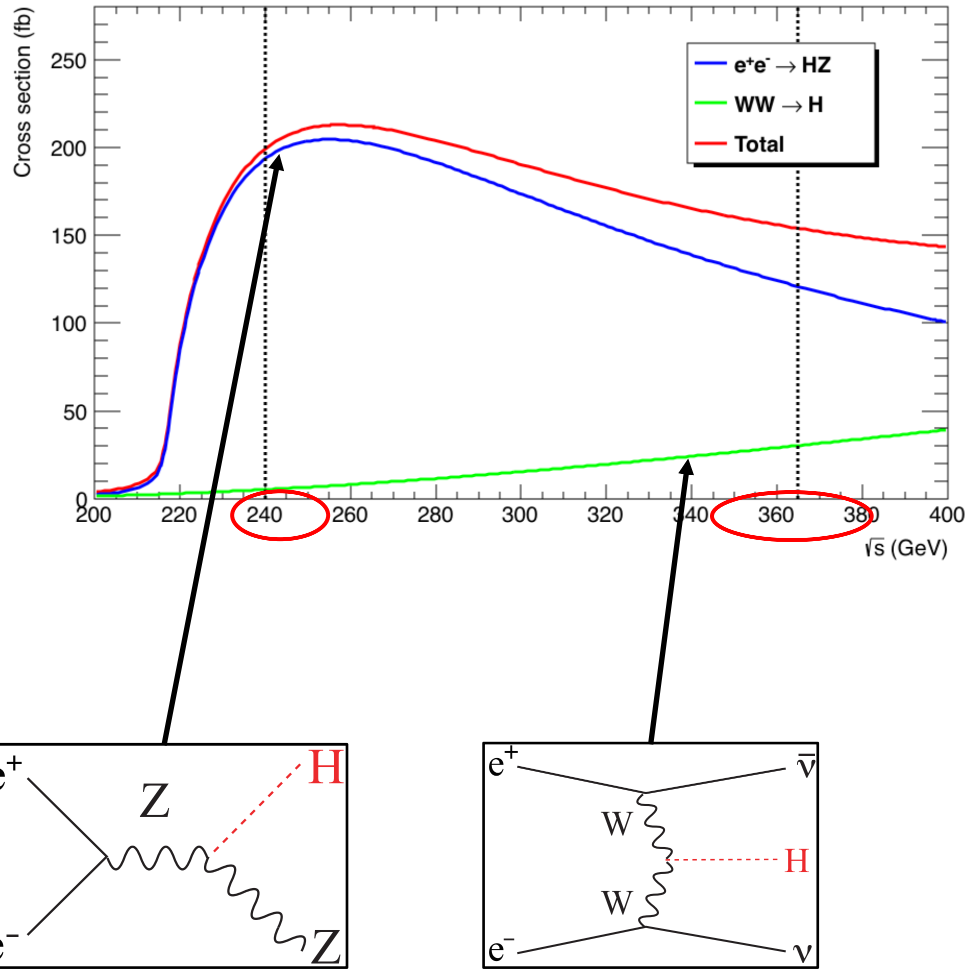
Organisation and financing models
Paul Collier (interim)

- **Project organisation model**
- **Financing model** – Florian Sonnemann
- **Procurement strategy and rules**
- **In-kind contributions**
- **Operation model** – Paul Collier, Jorg Wenninger

Luckily recently joined by
- Felix Sefkow, DESY
- Philipp Roloff, CERN

Status February 2022

FCC-ee Higgs Factory



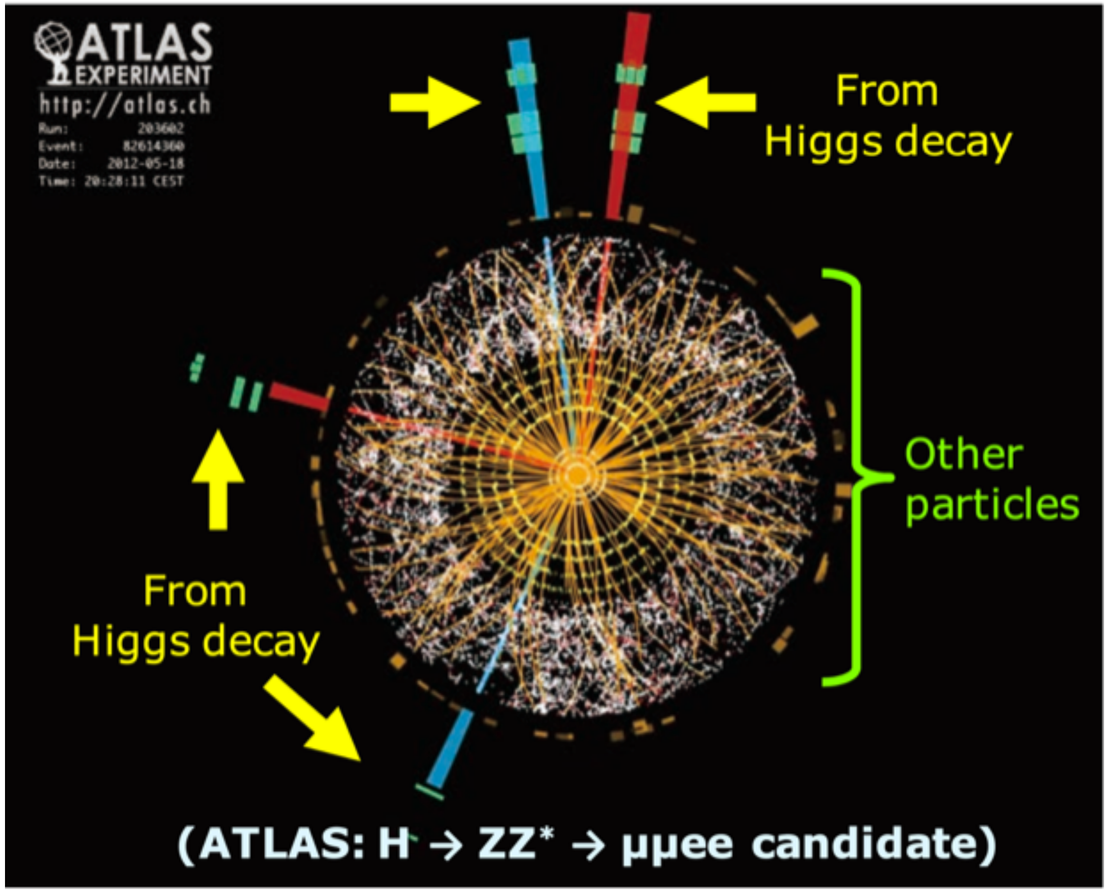
- 10^6 Higgsstrahlung event at √s ~ 240 GeV
- Complemented with 200k events at √s = 350 – 365 GeV
  - Of which 30% in the WW fusion channel (important for the Γ_H precision)

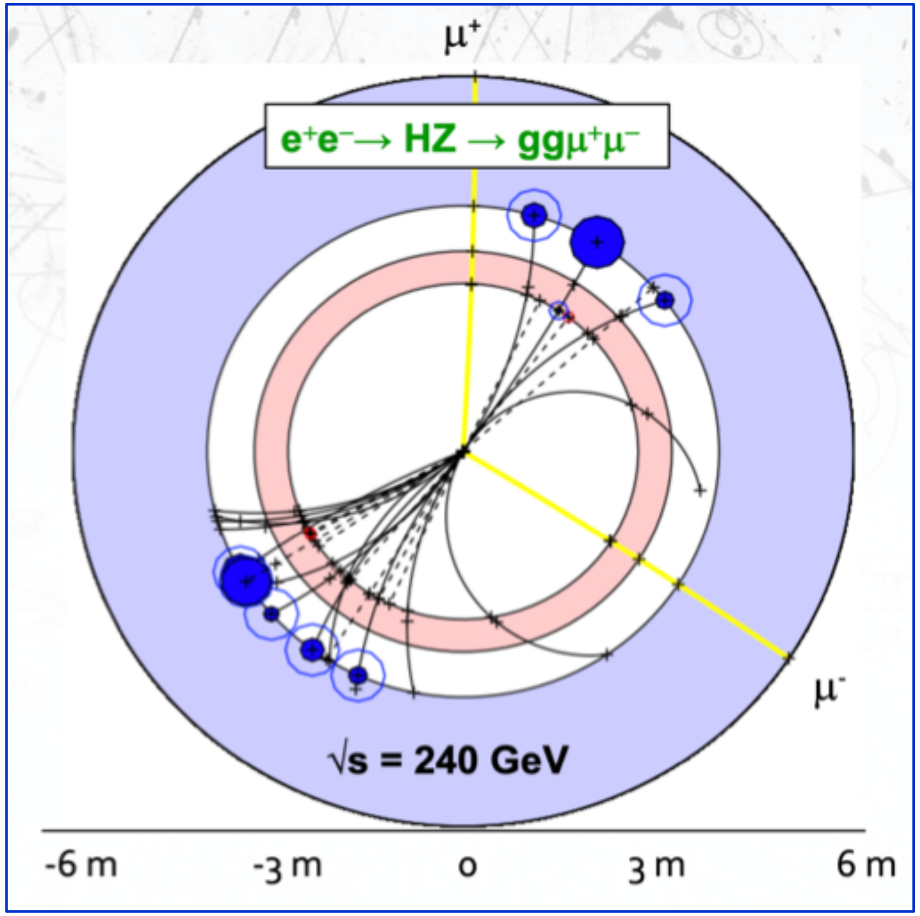
m_H = 125 GeV	
Decay	BR [%]
bb	57.7
ττ	6.32
cc	2.91
μμ	0.022
WW	21.5
gg	8.57
ZZ	2.64
γγ	0.23
Zγ	0.15
ΓH [MeV]	4.07

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.	44./33. **2IP** 27./24. **4IP**	3-4
Γ_H (%)	SM	1.1	0.91
BR_{inv} (%)	1.9	0.19	0.024
BR_{EXO} (%)	SM (0.0)	1.1	1

w/wo HL-LHC

Reminder: Higgs event in pp and e^+e^-





Proton-proton: look for striking signal in large background

Already ~3 M Higgs bosons produced per LHC experiment

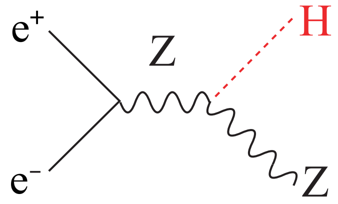
$e+e^-$: detect everything; measure precisely

A "beam" of Higgs'es tagged by the invariant mass and recoil mass of the Z decay products

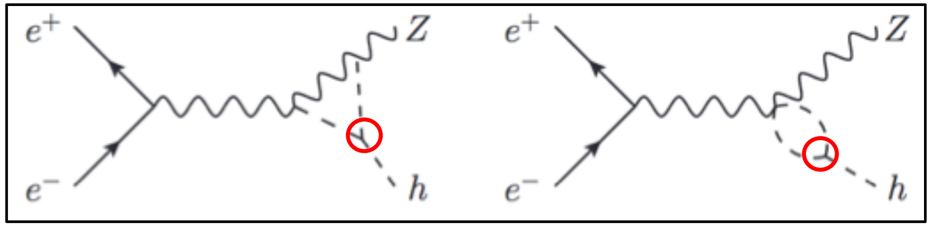
Higgs Self Coupling

- FCC-ee does not produce Higgs pairs, from which self coupling can be extracted (insufficient energy)
- But, loops including Higgs self coupling contribute to Higgs production

M. McCullough
arXiv:1312.3322

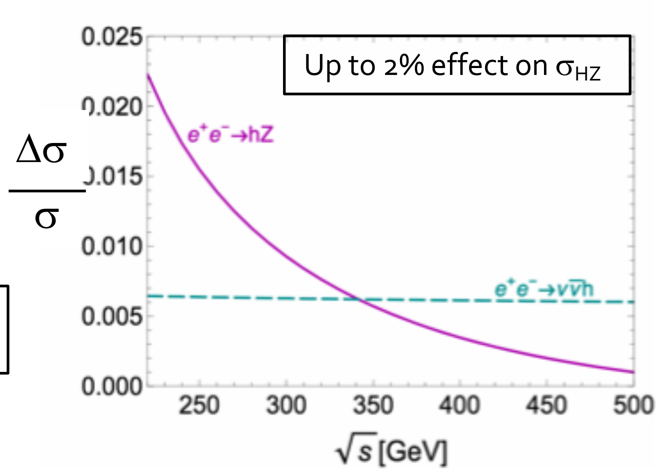


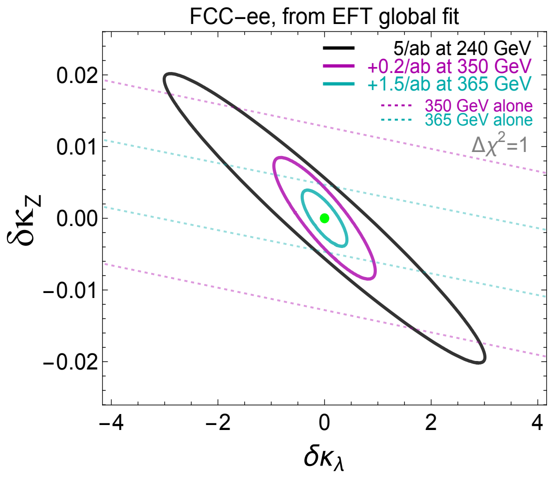
+



- 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

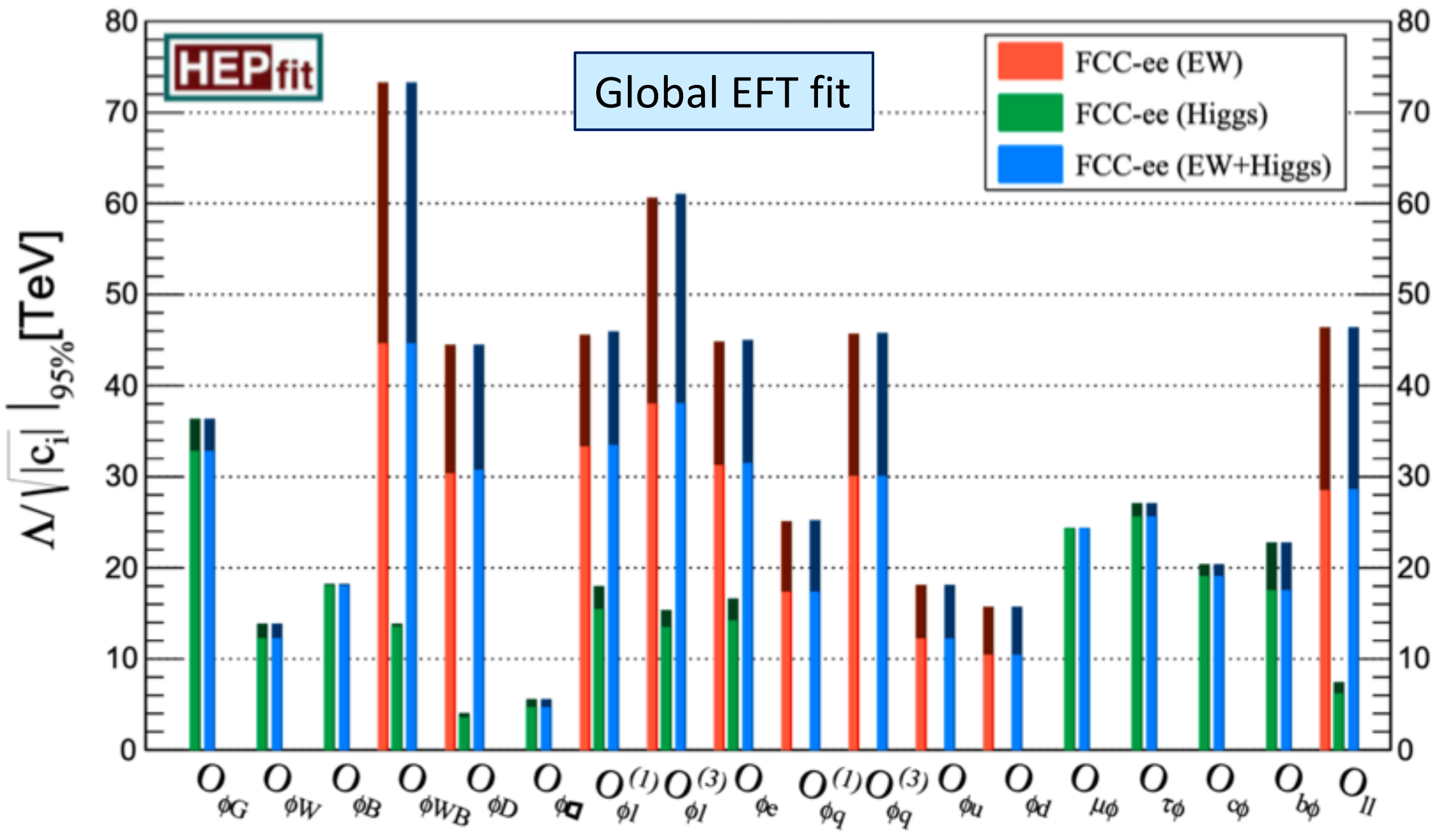




3-4 σ evidence in baseline programme.
Run few more years, 5σ discovery

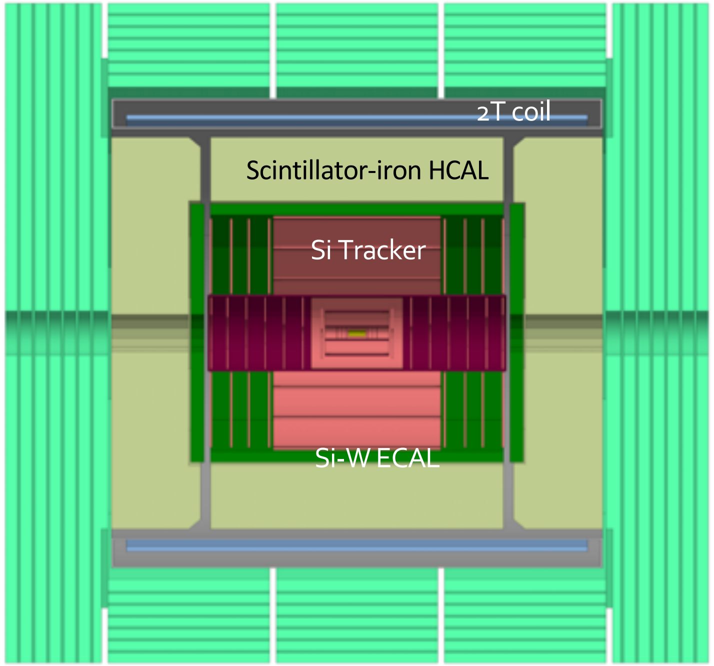
- Two energy points (240 and 365 GeV) lift the degeneracy between $\delta\kappa_Z$ and $\delta\kappa$!

Precision Physics sensitivity to New Physics

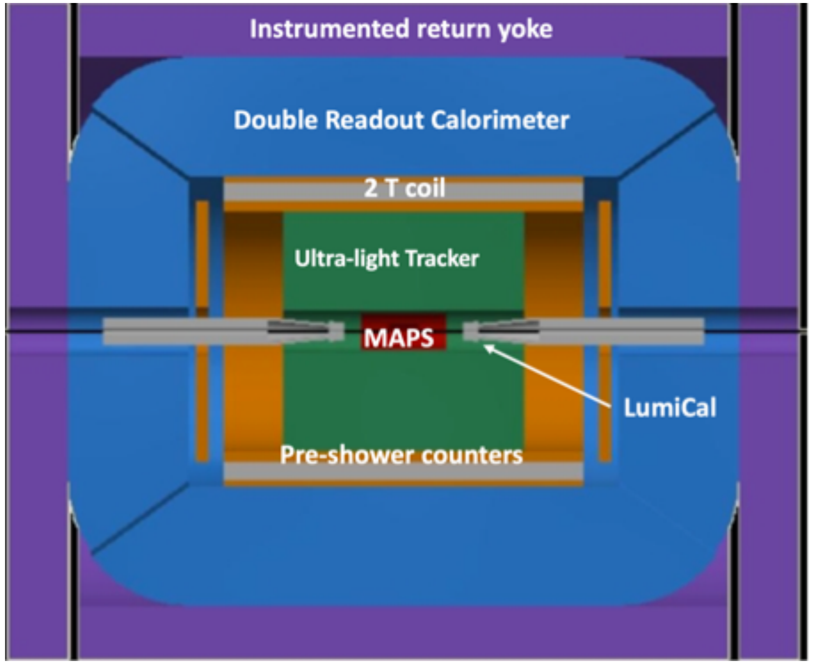


- Higgs and EW programmes are largely complementary
- Generally highest reach via EW programme
  - Much higher statistics; Higgs programme statistics limited
- Sensitivity to new physics up to 70 TeV

Detector Concepts: At least three Complementary Designs



Here show only two



CLD

- Consolidated option based on the detector design developed for CLIC
  - All silicon vertex detector and tracker
  - 3D-imaging highly-granular calorimeter system
  - Coil *outside* calorimeter system
- Proven concept, understood performance

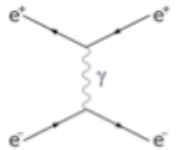
IDEA

- New, innovative, possibly more cost-effective design
  - Silicon vertex detector
  - Short-drift, ultra-light wire chamber (fantastic PID)
  - Dual-readout calorimeter
    - Possibly (hopefully!) agumented with crystal ECAL
  - Thin and light solenoid coil *inside* calorimeter system

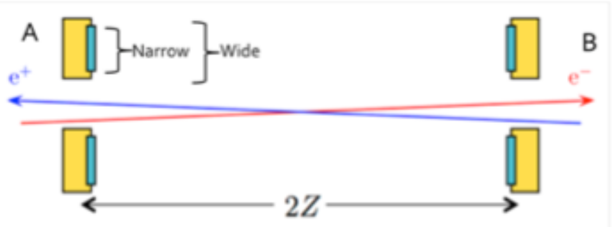
Precision Challenge: Luminosity Measurement

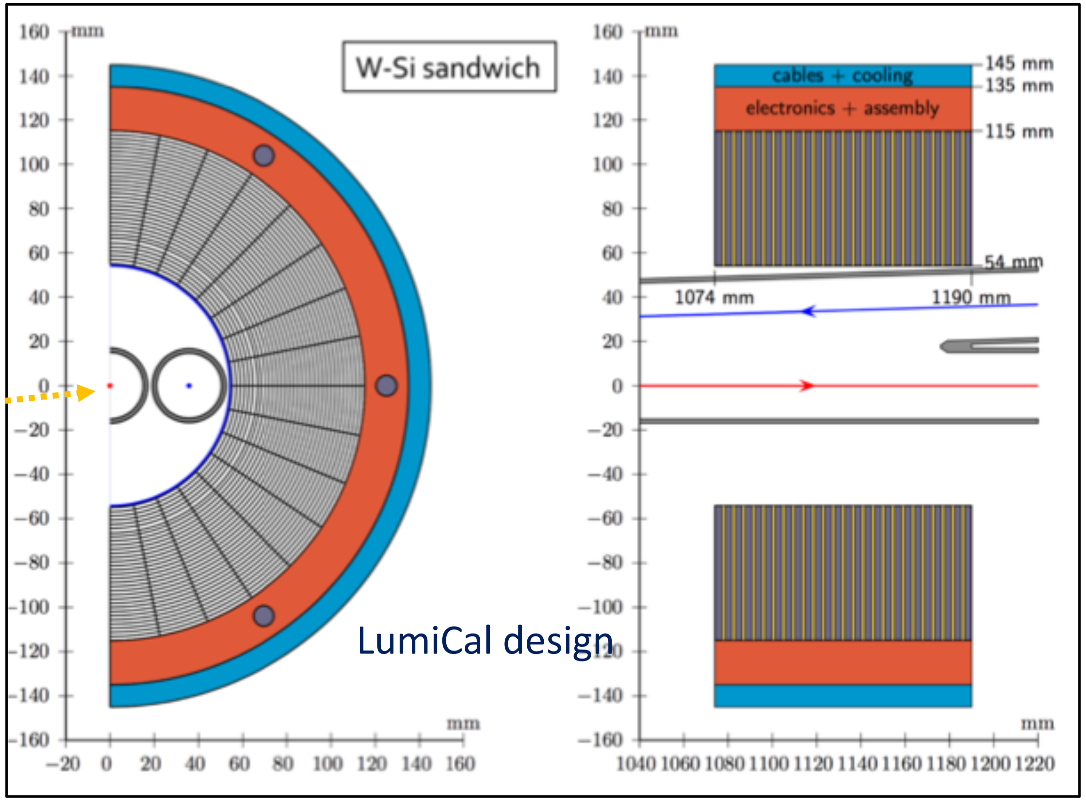
Ambitious goal:
- Absolute to 10^{-4}
- Relative (energy-to-energy point) to 10^{-5}

Small angle Bhabha scattering (QED).
Very strongly forward peaked



Monitors **centered around outgoing beam lines**
-- micron level precision needed on monitor dimensions (inner radius)





- **Theory**: Now at 3.8 × 10^{-4}; theory friends foresee that 1 × 10^{-4} will happen
- **Backgrounds:** have been studied and seem to be under control

Many (interesting!) R&D/engineering challenges
- Precision on acceptance boundaries to $\mathcal{O}$(1 μm) !
- Mechanical assembly, metrology, alignment
- Physics rate of $\mathcal{O}$(100 kHz)
- Readout at 50 MHz BX rate ?
- Power management / cooling
- Support / integration in crowded and complex MDI area

Example of precision challenge: Universality of Fermi constant

Andreas Crivellin and John Ellis.

EXOTIC FLAVOURS AT THE FCC

CERN COURIER
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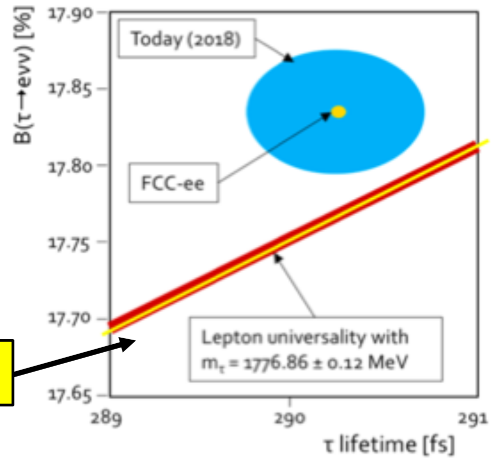
Here, a new-physics effect at a relative sub-per-mille level compared to the SM would suffice to explain the anomaly. This could be achieved by a heavy new lepton or a massive gauge boson affecting the determination of the Fermi constant that parametrises the strength of the weak interactions. As the Fermi constant can also be determined from the global electroweak fit, for which Z decays are crucial inputs, FCC-ee would again be the perfect machine to investigate this anomaly, as it could improve the precision by a large factor (see "High precision" figure). Indeed, the Fermi constant may be determined directly to one part in 10^5 from the enormous sample (>10^{11}) of Z decays to tau leptons.

M. Dam, SciPostPhys.Proc.1,041(2019)

Property	Current WA	FCC-ee stat	FCC-ee syst
Mass [MeV]	1776.86 +/- 0.12	0.004	0.1
Electron BF [%]	17.82 +/- 0.05	0.0001	0.003
Muon BF	17.39 +/- 0.05	0.0001	0.003
Lifetime [fs]	290.3 +/- 0.5	0.005	0.04



Shown in yellow: first *guestimates* on FCC-ee precisions

The Fermi constant is measured in μ decays and defined by

$$\left(G_F^\mu\right)^2 = 192\pi^3 \frac{\tau_\mu}{m_\mu^5}$$ (known to 0.5 ppm)

Similarly can define Fermi constant measured in τ decays by

$$\left(G_F^\tau\right)^2 = 192\pi^3 \frac{\tau_\tau}{m_\tau^5} \cdot \frac{1}{\mathscr{B}(\tau \to e\nu\nu)}$$ (known to 1700 ppm)

$$\frac{\delta G_F^\tau}{G_F^\tau} = \frac{5}{2}\frac{\delta m_\tau}{m_\tau} \oplus \frac{1}{2}\frac{\delta \tau_\tau}{\tau_\tau} \oplus \frac{1}{2}\frac{\delta \mathscr{B}}{\mathscr{B}}$$

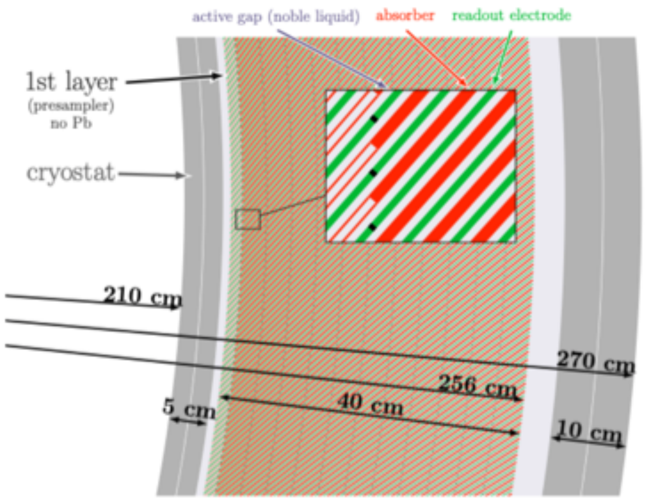
Today: 67 ppm BES; 1700 ppm Belle; 1700 ppm LEP

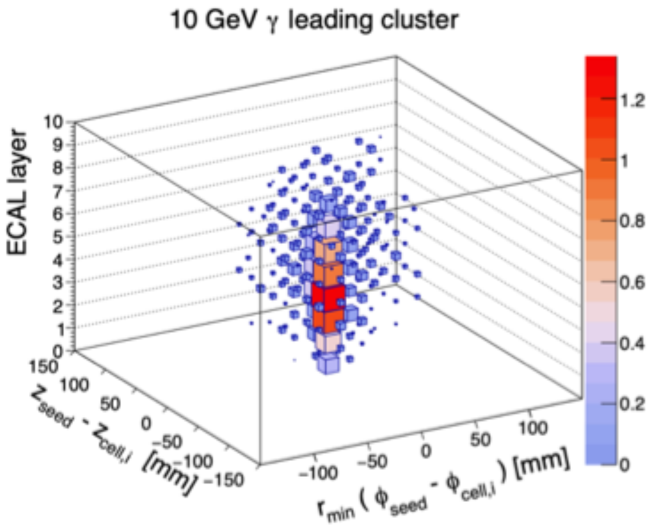
FCC-ee: Will see 3x10^{11} τ decays
Statistical uncertainties at the 10 ppm level
How well can we control systematics?

m_τ	Use J/ψ mass as reference (known to 2 ppm)	tracking
τ_τ	Laboratory flight distance of 2.2 mm ⇒ 10 ppm corresponds to 22 nm (!!)	vertex detector
$\mathscr{B}$	No improvement since LEP (statistics limited) Depends primarily e^-/π^- (& e^-/ρ^-) separation	ECAL dE/dx

FCC at NBI

- Together, Jørgen Beck Hansen and MD have adviced five FCC MSc projects
  - Sissel: *Study of FCC-ee sensitivity to Heavy Neutral Leptons*
    - PhD student at DTU
  - Molly: *Study of tau decay performance of Dual Readout Calorimeter*
    - job in ministry immediately
  - Kunal: *B-tagging methods at FCC-ee*
    - PhD student at CP3, Brussels
  - Julie: *Study of SM-EFT anomalous contributions in $t\bar{t}$ production*
    - PhD student at DESY, Hamburg
  - Katinka: *Tau Decay Mode Identification in a Liquid Argon Electromagnetic Calorimeter at the FCC-ee*
    - *?*





Outlook

- Standard Model is extremely succesful in parametrizing Nature as we observe it in our laboratories
- Leaves, however, unanswered the deepest questions about Nature
- Exciting future ahead
  - LHC + HL-LHC:
    - Searches:
      - Be prepared for the unexpected
      - Both in general purpose experiments and in dedicated, small, ”parasitic” experiments
    - Precision measurements:
      - top quark and W boson masses (we really should try to beat CDF’s 9.4 MeV precision)
      - Higgs couplings to few %-level; Higgs triple selfcoupling (λ_3) to 50%
  - High intensity beam dump experiments (SHiP) ?
    - Priority in next ESPP?
  - Future Circular Collider
    - Ongoing Feasibility Study for decision on first step (FCC-ee) by next ESPP (~2026)
    - Possible long term future for CERN
      - FCC-IS: FCC-ee followed by FCC-hh
      - Unchallenged precision tests of Standard Model including Higgs sector (λ_3 to few %)
      - Unprecedented sensitivity to New Physics both indirectly (**precision measurements**) and directly at **intensity** as well as at **energy frontier**