The FCC-ee Project

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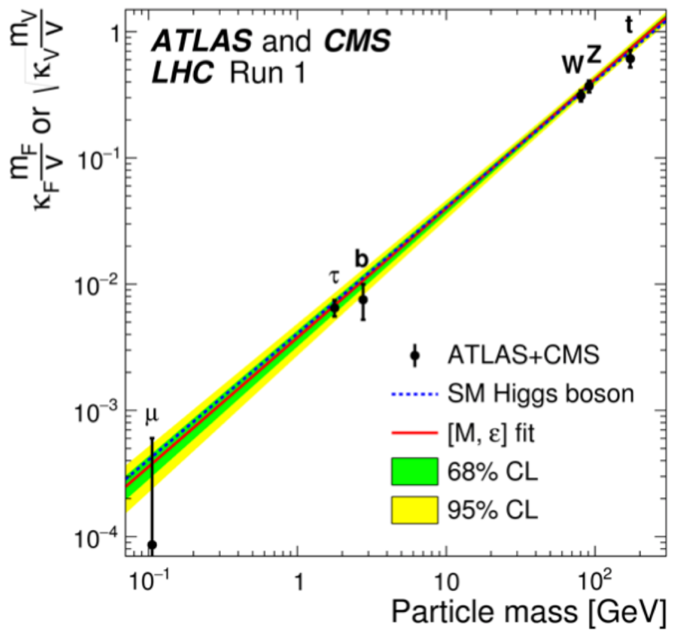
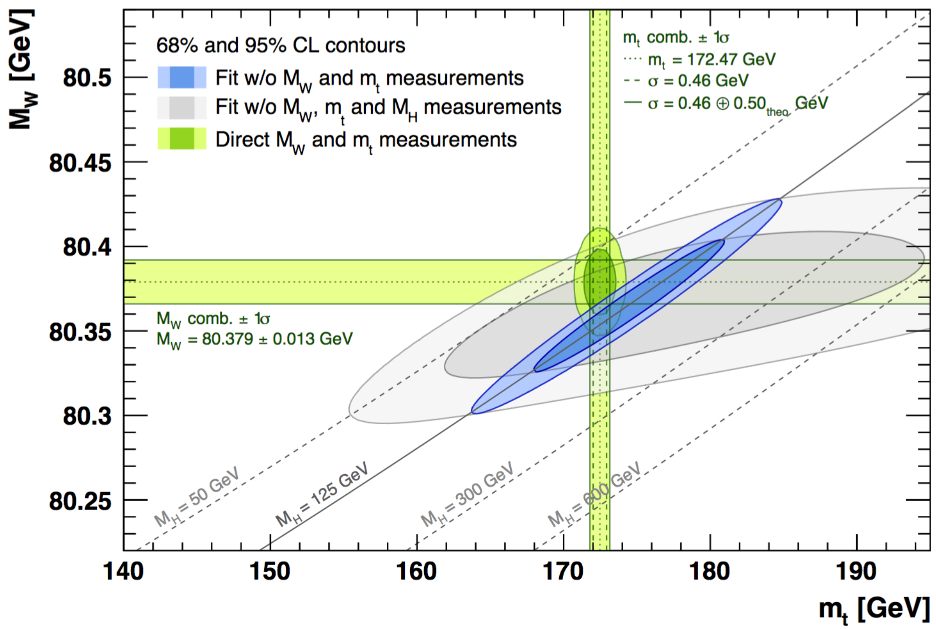
Picture and slide layout, courtesy Jörg Wenninger

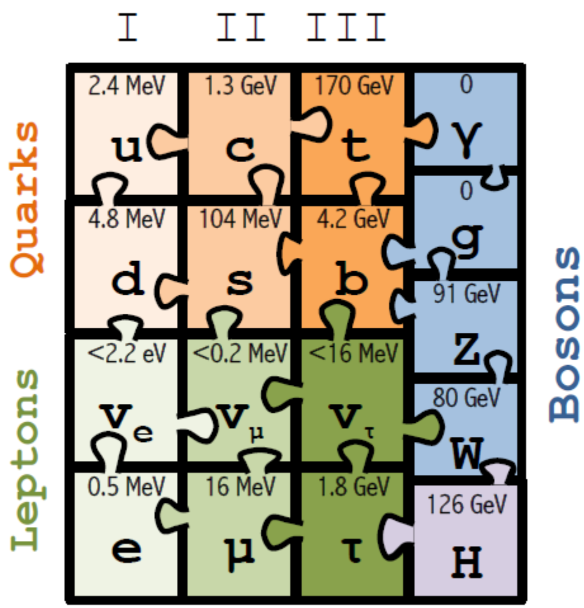
- Seven years with the Higgs boson





- The Higgs boson seems so far to be a rather Standard Model one
- To current precision "everything" looks to be rather Standard Model
- So far, no indications for new BSM physics up to several hundred GeV
    - However: in flavour physics, tensions observed between LHCb data and SM predicitions

Standard Model Complete…



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

- ✓ complete
- ✓ coherent
- ✓ predictive to all energies

Is this the end ?

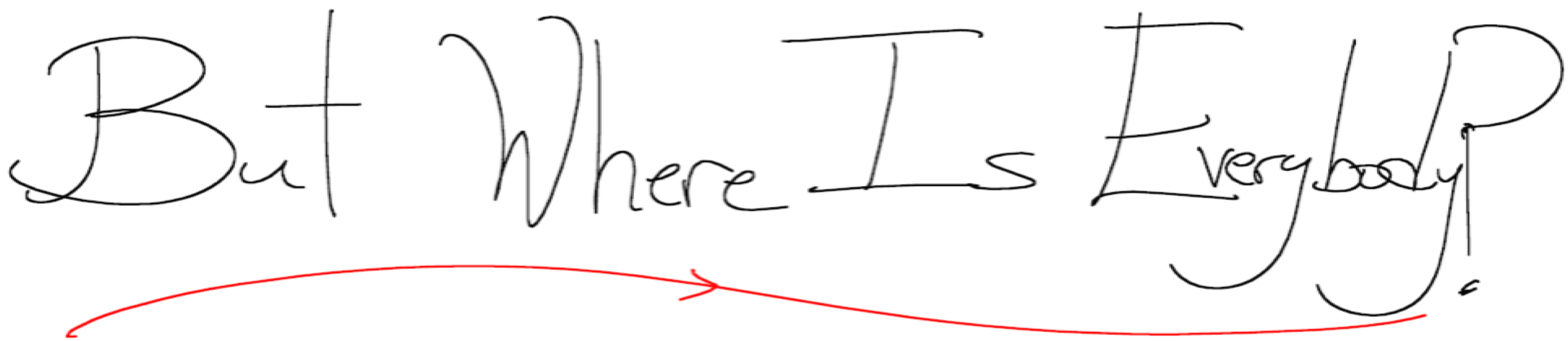
It is most likely not!

Many unanswered questions based on experimental observations?

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

New Physics ?

- Many diverse theoretical ideas to extend Standard Model (with new particles)

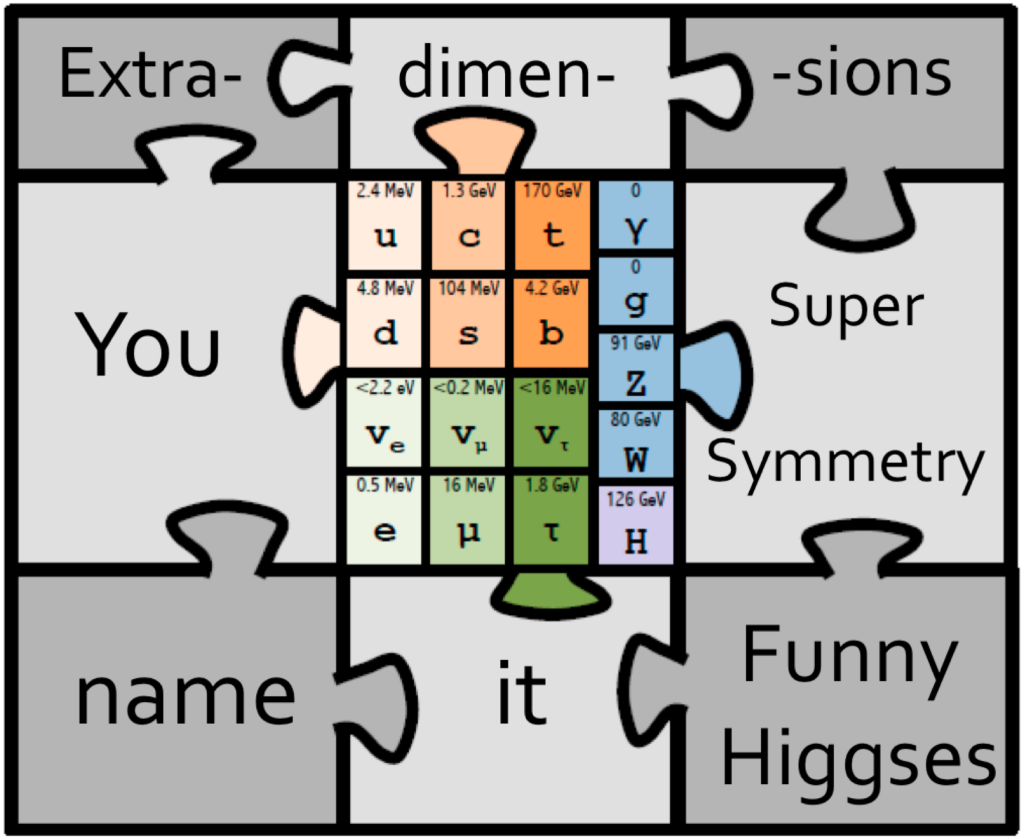


Nima Arkani-Hamed, 2014

- Is new physics at larger masses ? Or at smaller couplings ? Or both ?
  - Only way to find out: ***go look***, following the historical approach:
    - Direct searches for new heavy particles
      - ⇒ Need colliders with *larger energies:* ***Energy frontier***
    - Searches for the imprint of New Physics at lower energies, e.g. on the properties of Z, W, top, and Higgs particles
      - ⇒ Need colliders/measurements with *unprecedented accuracy:* ***Precision frontier***

Energy vs Precision

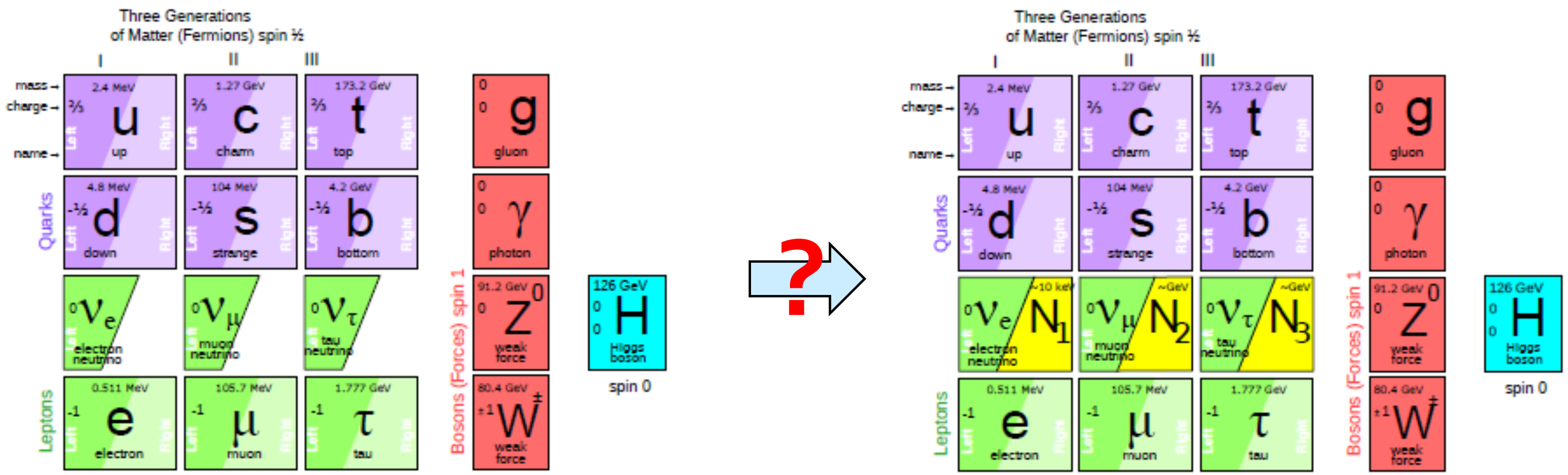
- Many ideas lean towards higher-energy replicas of the standard theory



- Direct searches at larger energies may be the key – but how much larger ?
  - Rare decays and precise measurements may also unveil these extension's imprints

Precision vs. Energy

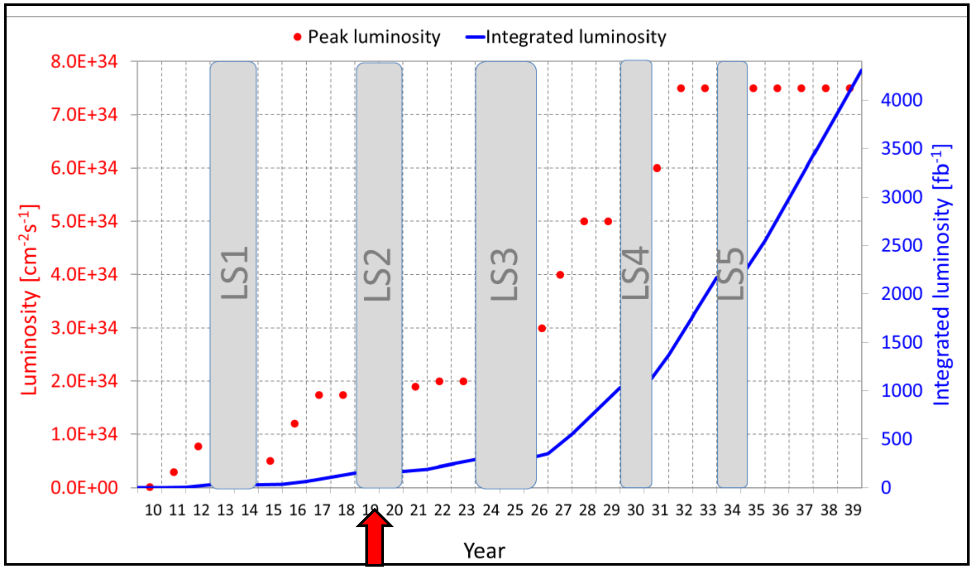
- The Standard Model is complete ? Obviously three pieces missing !



- Three right-handed neutrinos ?
  - Extremely small couplings, nearly impossible to find but could explain "everything" !
    - Small m_ν (see-saw), DM (light N_1), and BAU (leptogenesis)
  - Need very-high-precision experiments to unveil
    - Could cause a slight reduction (increase) in the Z (H) invisible decay width
    - Could open exotic Z and Higgs decays: Z, H → $\nu_i N_i$
      - Possibly measurable / detectable in precision e^+e^- collisions
      - Most likely out of reach for hadron colliders (small couplings)

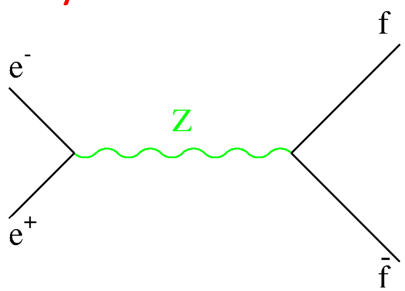
Where we are heading

- The LHC is still pretty much still in its childhood
- Factor ~15 more luminosity to be collected until the end of HL-LHC (~2037 !)
  - Exciting search programme for New Physics
    - Stop: 1.5 TeV; squarks/gluinos: 3 TeV; Z': 7 TeV; etc., etc.
      - Be prepared for the unexpected !
  - Important precision measurement
    - Higgs couplings to 2-5%
    - Top quark mass to 200 MeV
    - W boson to 10 MeV ?
    - Flavour physics measurements
      - Be prepared for surprises !

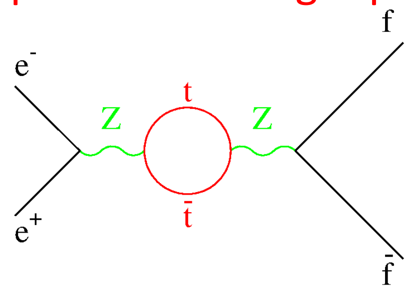


Why precision measurements are interesting

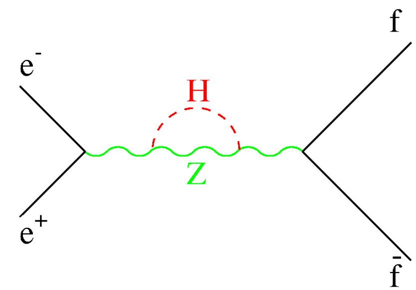
- Electroweak observables can be calculated / predicted with precision
  - They are sensitive to heavier particles through quantum corrections



Tree level



$$0.002 \times \frac{m_t^2}{m_W^2} \simeq 1\%$$



$$-0.0006 \times \left(\ln \frac{m_H^2}{m_W^2} - \frac{5}{6}\right)$$

[small correction]

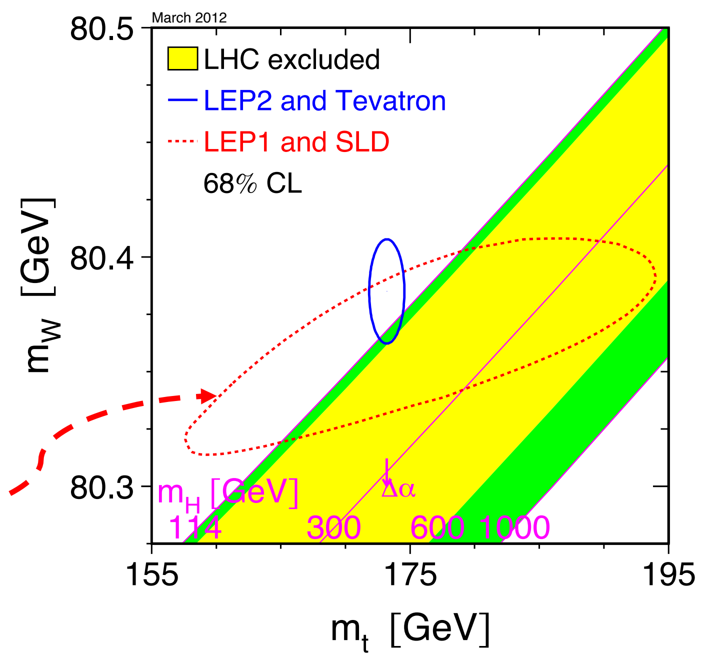
- Example: $\Gamma_Z \rightarrow \Gamma_Z \times (1+\Delta\rho)$

$$\Delta\rho = 0.0020 \times \frac{m_t^2}{m_W^2} - 0.0006 \times \left(\ln \frac{m_H^2}{m_W^2} - \frac{5}{6}\right) + \ldots$$

- Similarly, $m^2_W = m^2_Z \cos^2\theta_W^{eff} (1+\Delta\rho)$

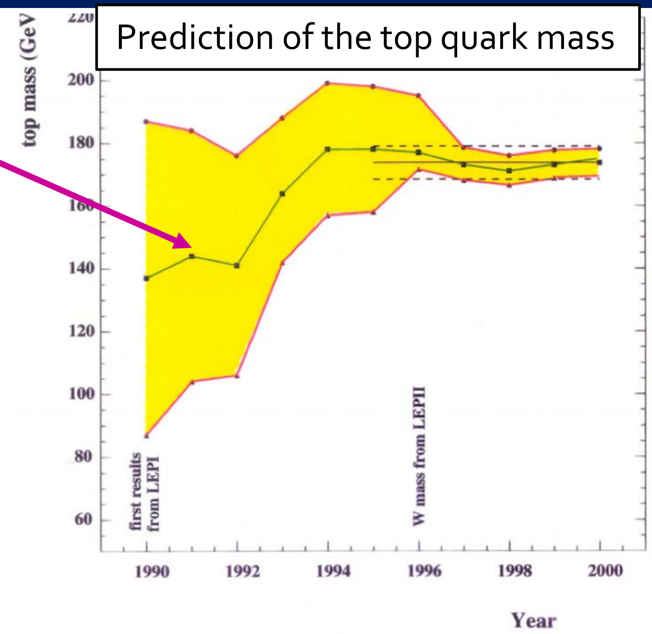
  ($\sin^2\theta_W^{eff}$ from, e.g., asymmetries)

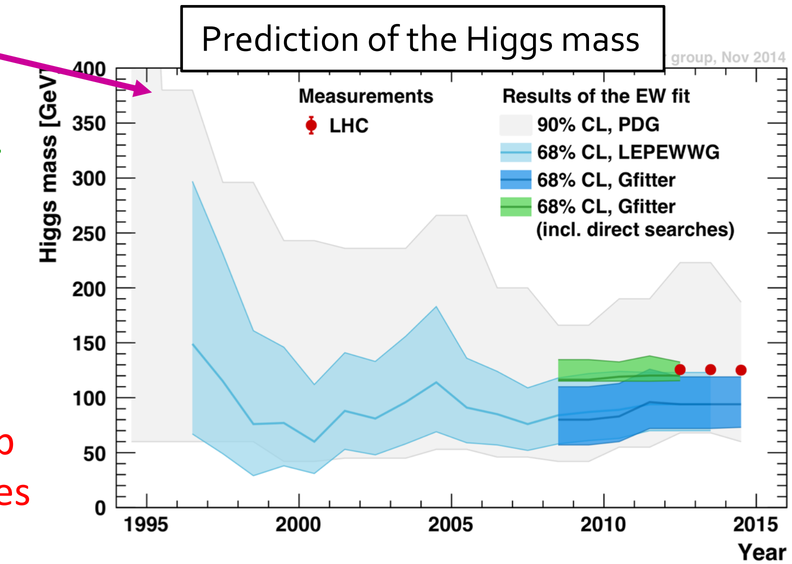
- Precict m_W and m_{top} from Z measurements



Lessons from EW precision measurement

- Top quark
  - 1990-1994: Mass predicted from quantum loops
    - m_{top}(pred.) = 178.0 $\pm$ 10 GeV
  - 1995: Discovered at the Tevatron (DØ, CDF) ✓
    - Today: m_{top}(obs.) = 173.23$\pm$ 0.7 GeV
- W boson
  - 1990-1995: Mass predicted from quantum loops
    - m_{top}(pred.) = 80.362 $\pm$ 0.032 GeV
  - 1996-2018: Direct measurements (LEP2, Tevatron, LHC) ✓
    - Today: m_{top}(obs.) = 80.379 $\pm$ 0.012 GeV
- Higgs boson
  - 1996-2011: Mass predicted from quantum loops
    - m_{Higgs}(pred.) = 98^{+25}_{-21} GeV
  - 2012: Discovery at the LHC (ATLAS, CMS) ✓
    - Today: m_{Higgs}(obs.) = 125.09 $\pm$ 0.24 GeV

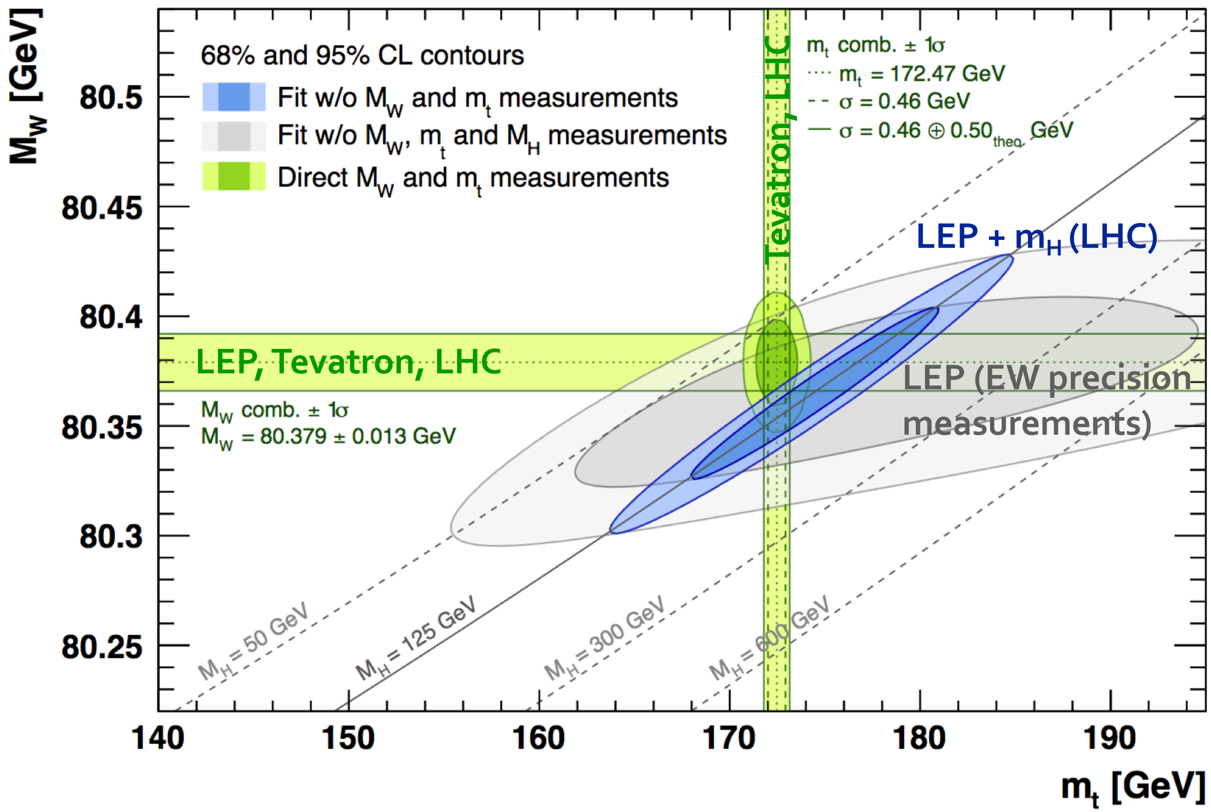




- Lesson:
  - Precision measurements interpreted via quantum loop corrections can give very strong constraints on particles at higher masses than what can be directly probed!

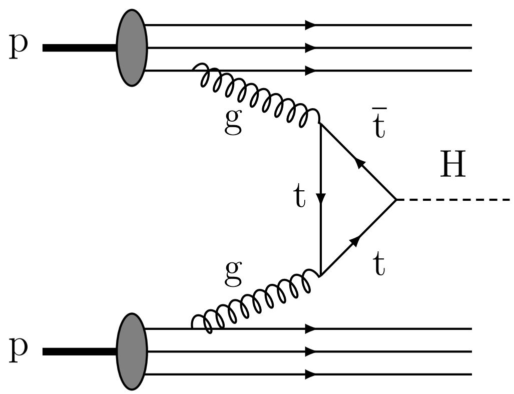
Current status of precison measurements

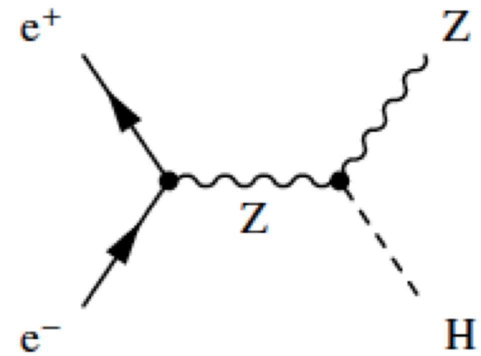
- With m_{top}, m_W and m_H known, the Standard Model has nowhere to go



- Within current precision, direct and indirect constraints are consistent
  - No evidence for the need for BSM physics
  - But what if measurements precisions were improved ?
- Strong incentive to significantly improve the precision of all measurements
  - Towards being sensitive to 100 TeV new physics through quantum corrections

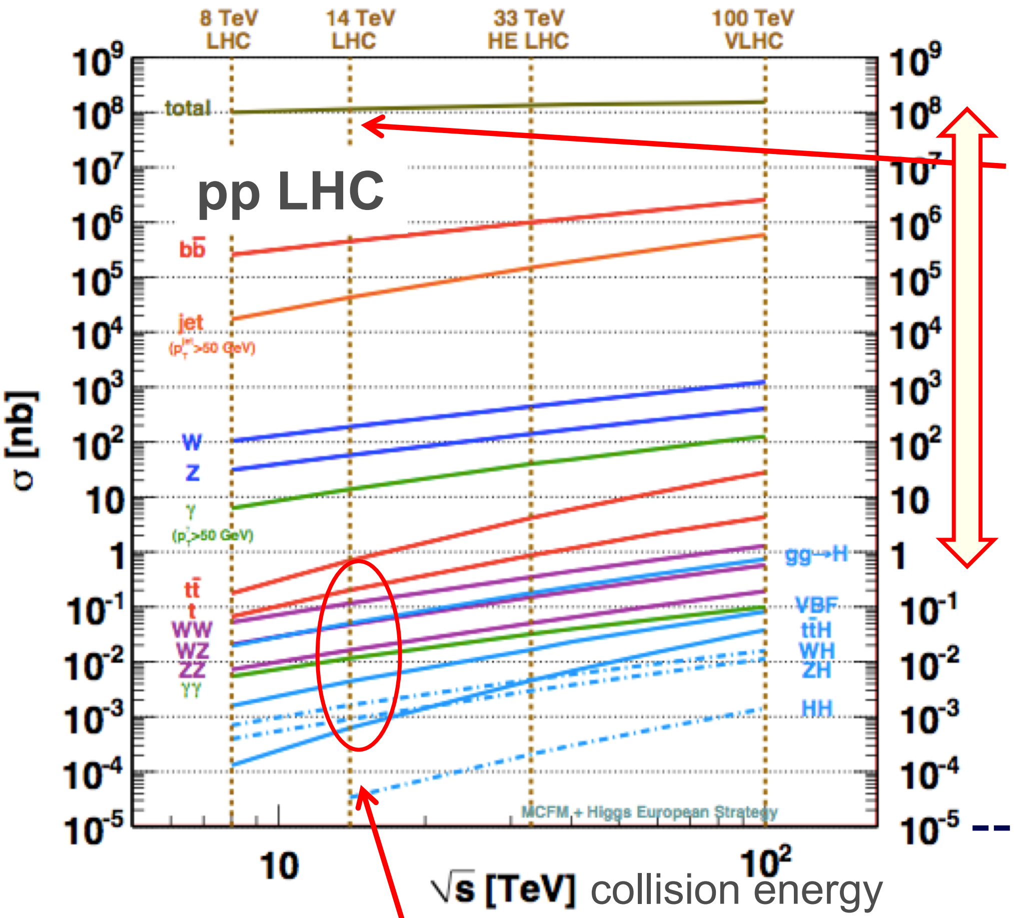
pp collisions vs. e^+e^- collisions (1)





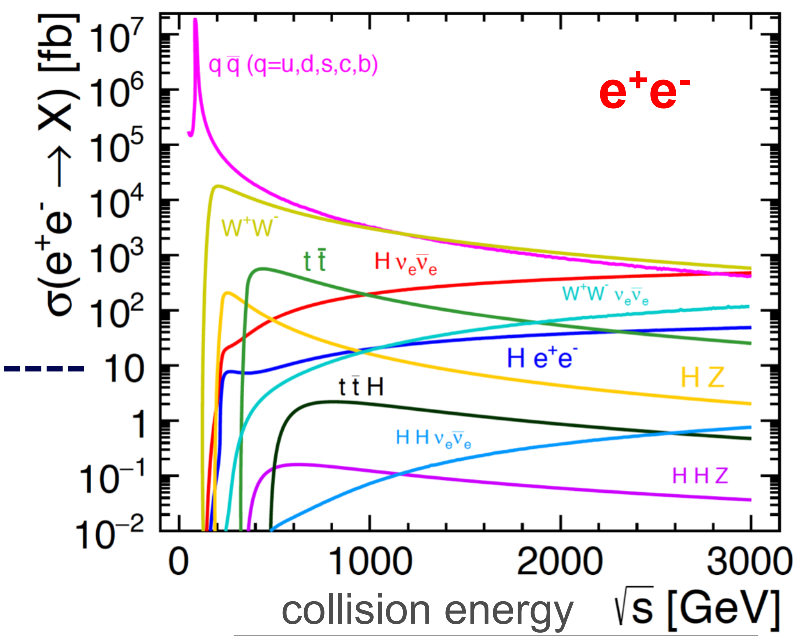
p-p collisions	e^+e^- collisions
Proton is compound object → Initial state not known event-by-event → Limits achievable precision	**e^+/e^- are point-like** → Initial state well defined (E, $\boldsymbol{p}$) → High-precision measurements
High rates of QCD backgrounds → Complex triggering schemes → High levels of radiation	**Clean experimental environment** → Trigger-less readout → Low radiation levels
High cross-sections for **colored-states**	Superior sensitivity for **electro-weak states**
High-energy **circular** pp colliders feasible	- At lower energies ($\lesssim$ 400 GeV) , **circular** e^+e^- colliders can deliver **very large luminosities.** - Higher energy e^+e^- requires **linear** collider.

pp collisions vs. e^+e^- collisions (2)



LHC total cross section factor > 100 million !!

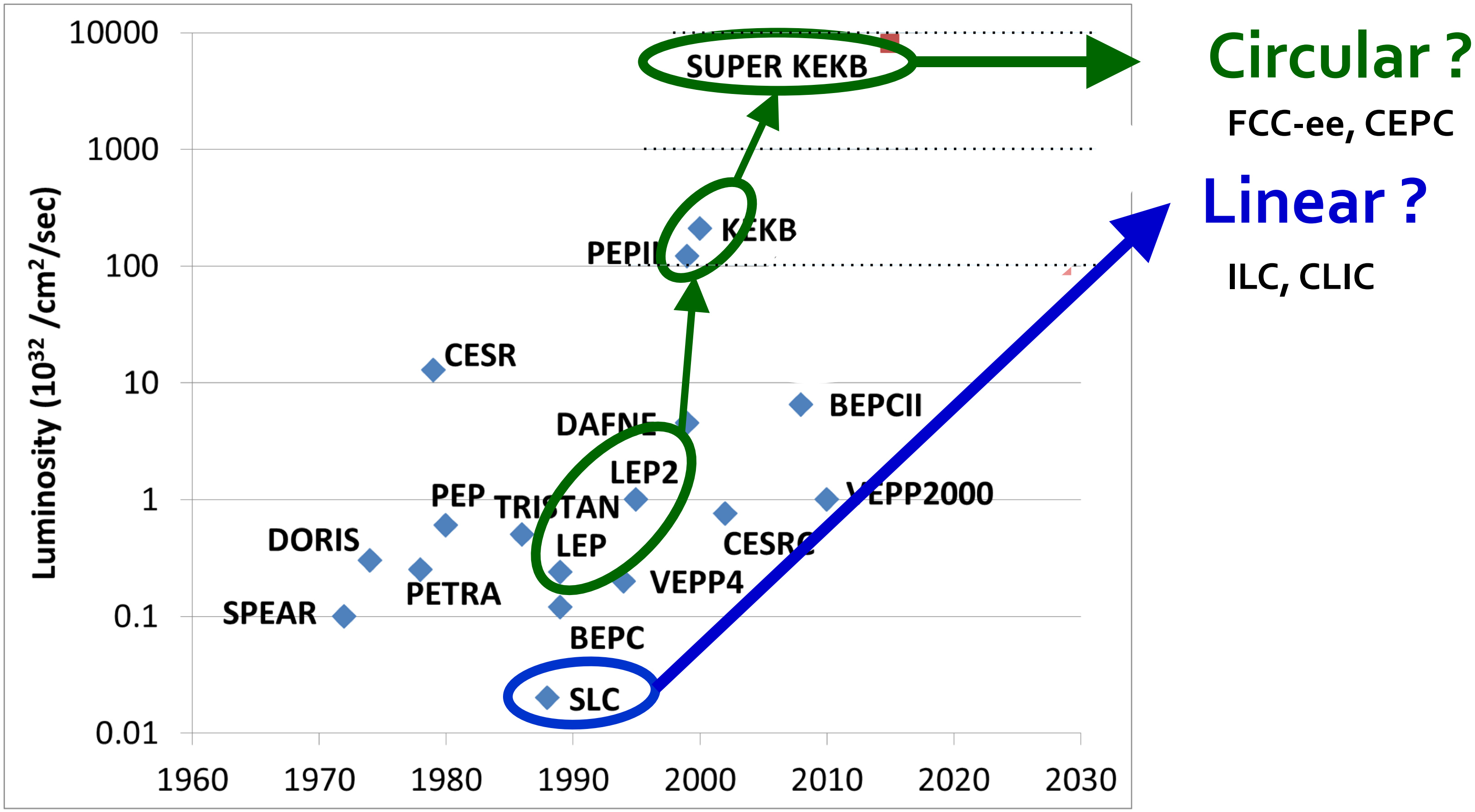
At LHC, much of the interesting physics needs to be found among a huge number of collisions



e^+e^- events are "clean"

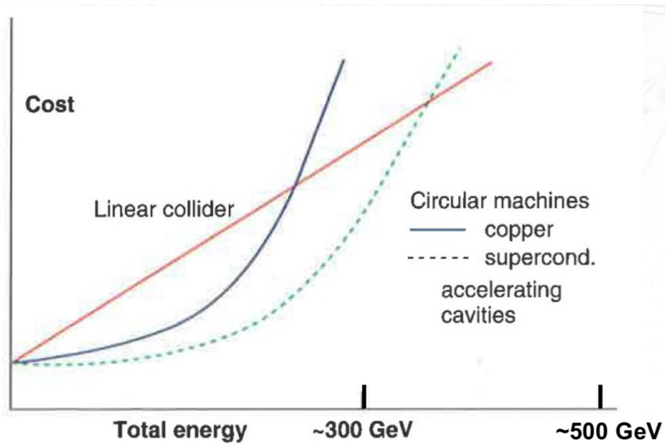
Precision requires luminosity

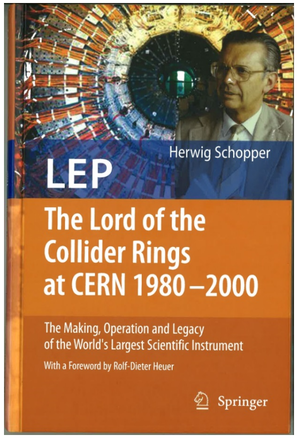
- So far, all e^+e^- colliders except SLC (at SLAC) have been circular
  - Over time there has been a dramatic increase in luminosity
- The next e^+e^- collider will be …



Linear or Circular ?

- For > 20 years, only linear colliders on “the market”: ILC, CLIC
- Why not a 500 GeV circular collider ?
  - Synchrotron radiation in circular machines
    - Energy lost per turn grows like $\boxed{\Delta E \propto \frac{1}{R}\left(\frac{E}{m}\right)^4}$, e.g., 3.5 GeV per turn at LEP2
      - Must compensate with *R* and accelerating cavities ⟶ Cost grows like E^4 too

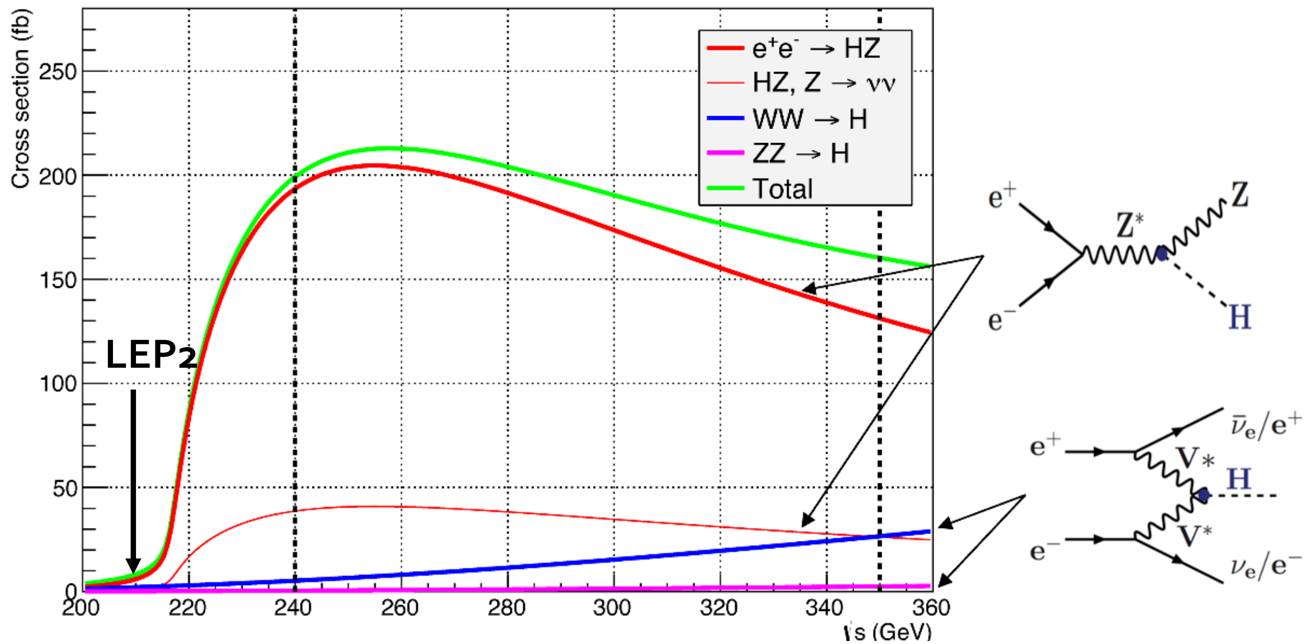




  - “Up to a centre-of-mass energy of 350 GeV at least, a circular collider with superconducting accelerating cavities is the cheapest option”, Herwig Schopper
  - At and above 500 GeV, a e^+e^- collider can only be linear

Revival of Circular e^+e^- Colliders

- Interest for circular collider projects grew up again after first LHC results
  - The Higgs boson is light – LEP2 almost made it: only moderate $\sqrt{s}$ increase needed



  - There seems to be no heavy new physics below 500 GeV
    - The interest of $\sqrt{s}$ = 500 GeV (and even 1 TeV) is now very much debated
  - Way out: study with unprecedented precision the Z, W, H bosons and the top quark
    - Need to go up to the top-pair threshold (350+ GeV) anyway to study the top quark
    - Highest possible luminosities at 91, 160, 240 and 350+ GeV are needed

International FCC collaboration to study (since 2014)

- **~100 km tunnel infrastructure** in Geneva area, linked to CERN
- **Ultimate goal: ≥ 100 TeV pp-collider (FCC-hh)**

≥16 T magnets

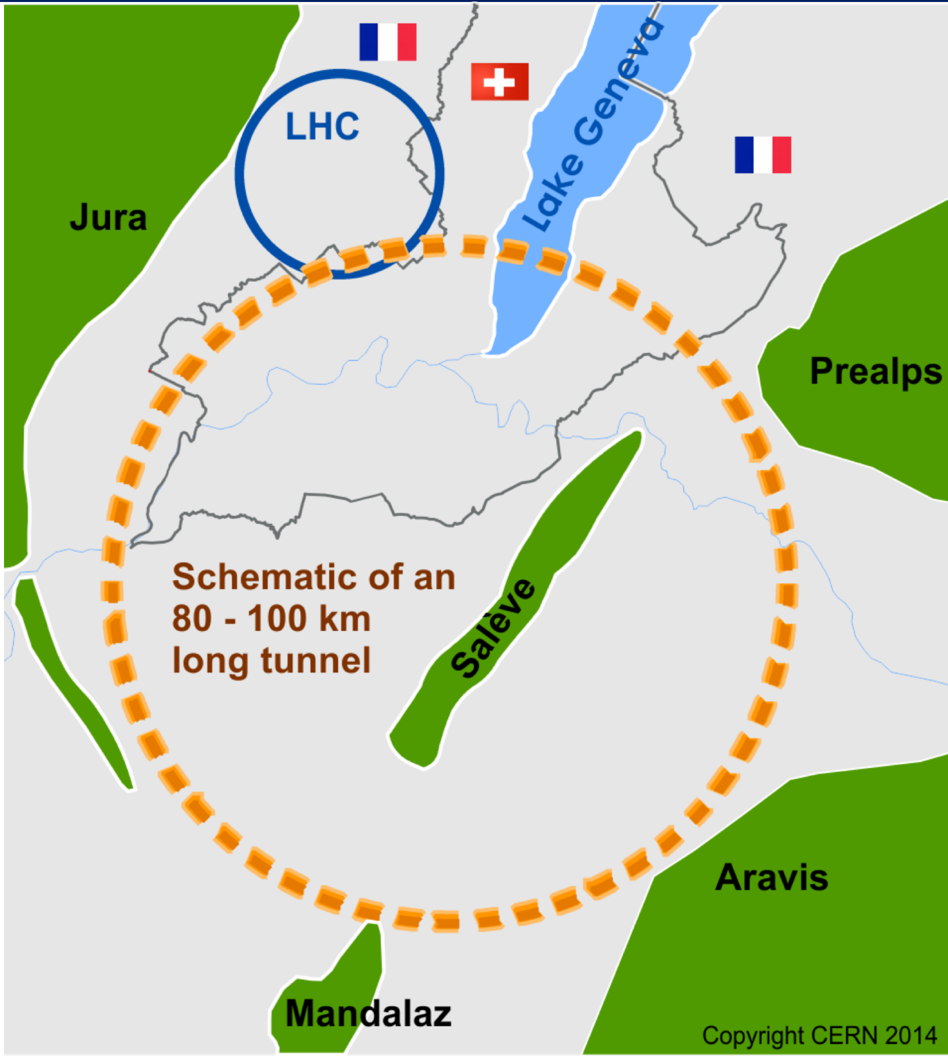
→ defining infrastructure requirements

Two possible first steps:

- e^+e^- collider (FCC-ee)
  High Lumi, E_{CM} = 90-400 GeV
- *HE-LHC:* 16 T ⇒ 27 TeV
  in LEP/LHC tunnel

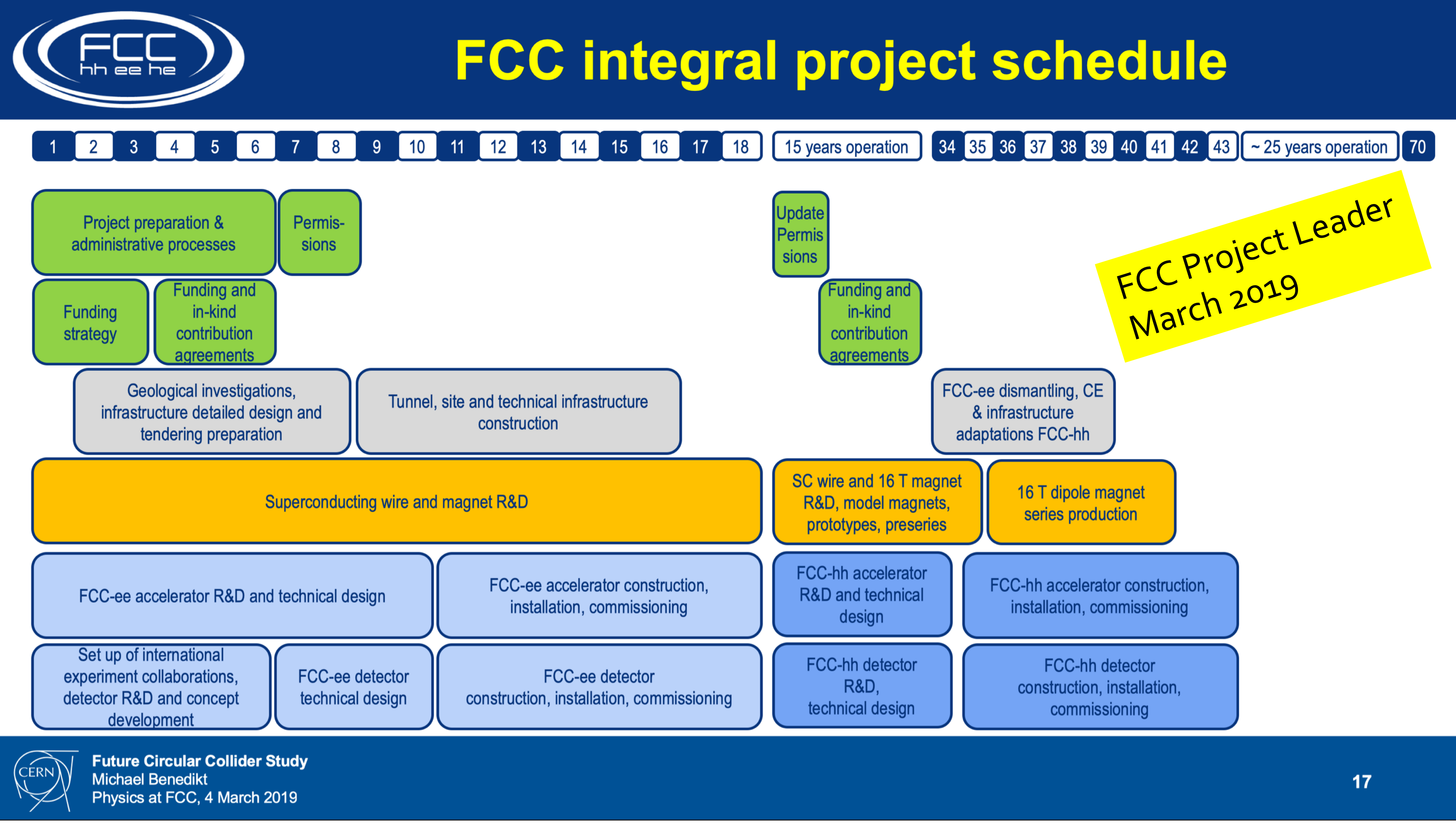
Possible addition

- p-e (FCC-he)



FCC CDRs available at

http://fcc-cdr.web.cern.ch/



A little FCC-ee history:

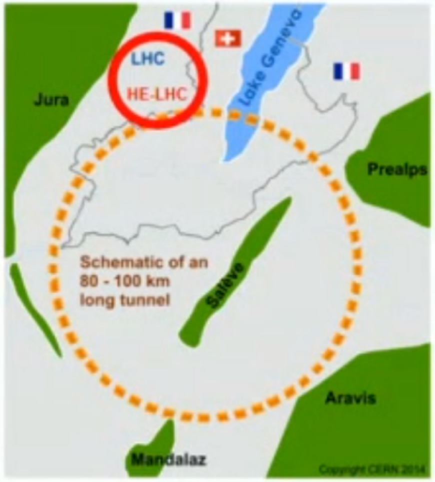
- 2012-1013: From LEP3 to TLEP "standalone" project
- Since 2014: Official part of FCC project. In the beginning: "potential intermediate step"
- 2019: Phase 1 of "FCC Integral Project"

Fabiola Gianotti
Jan. 15, 2019

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	230×10^{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	5×10^{34} 30	2.5 ab^{-1} 15	2+2 experiments Total ~ 25 years of operation
PbPb FCC-hh	$\sqrt{s_{NN}}$ = 39TeV	3×10^{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

FCC Home


A
B
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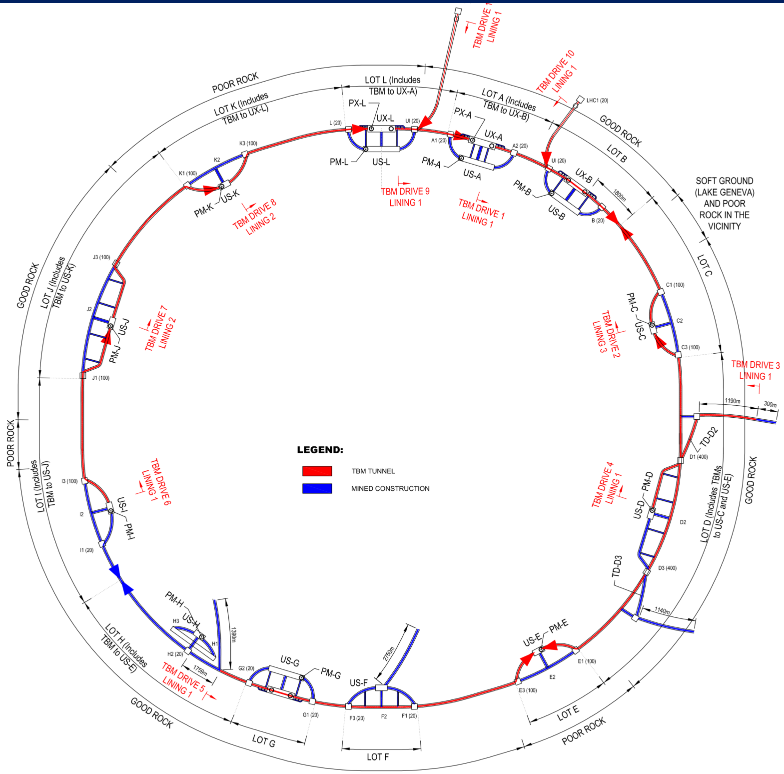
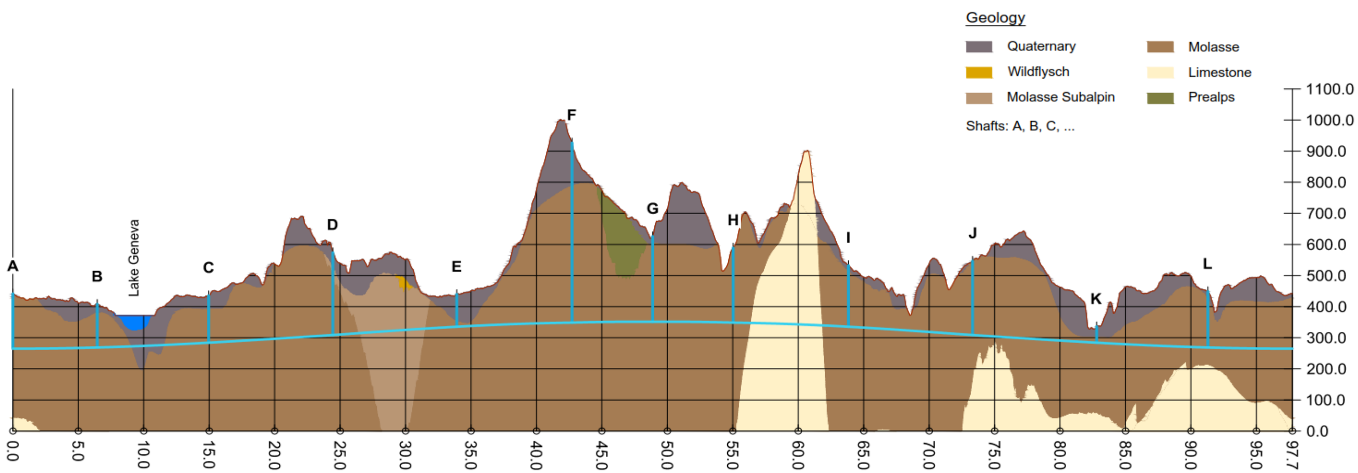
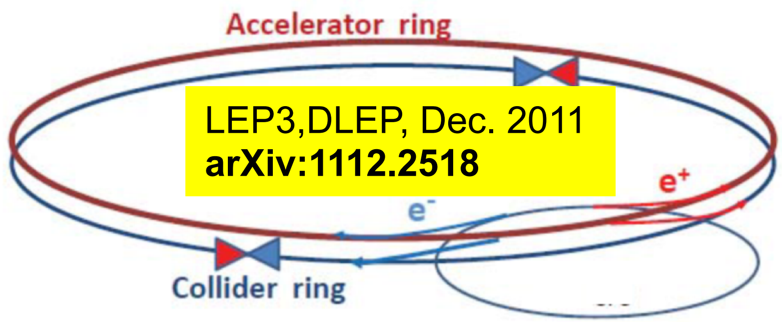

LEGEND:
TBM TUNNEL
MINED CONSTRUCTION
POOR ROCK
GOOD ROCK
SOFT GROUND (LAKE GENEVA) AND POOR ROCK IN THE VICINITY


Geology
Quaternary
Wildflysch
Molasse Subalpin
Molasse
Limestone
Prealps
Shafts: A, B, C, ...
Lake Geneva

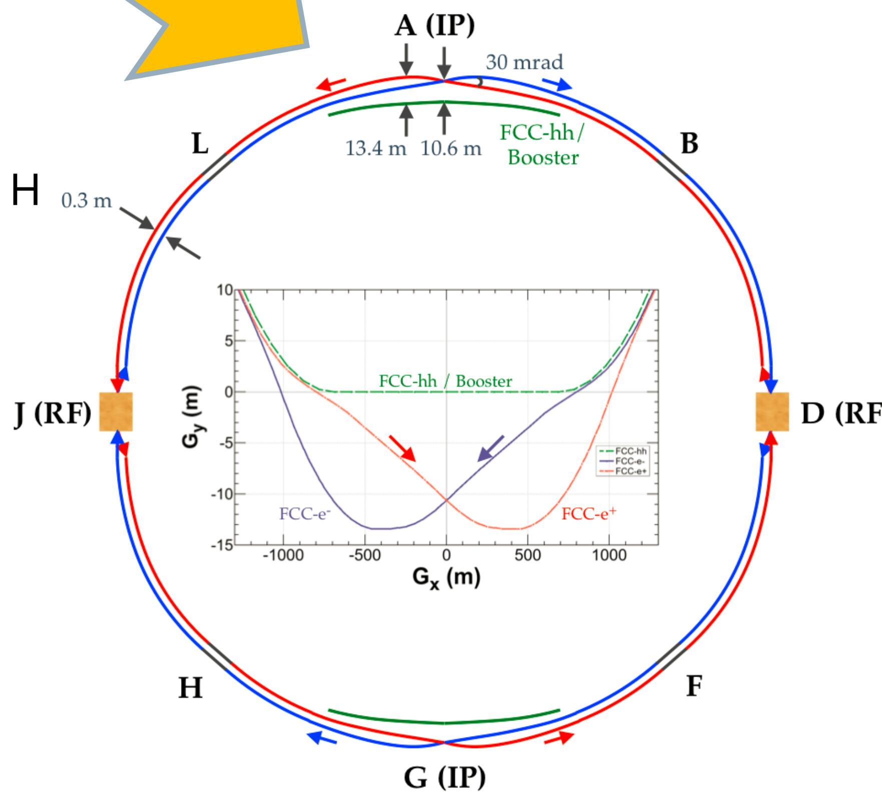
FCC-ee baseline design choices



Design Study

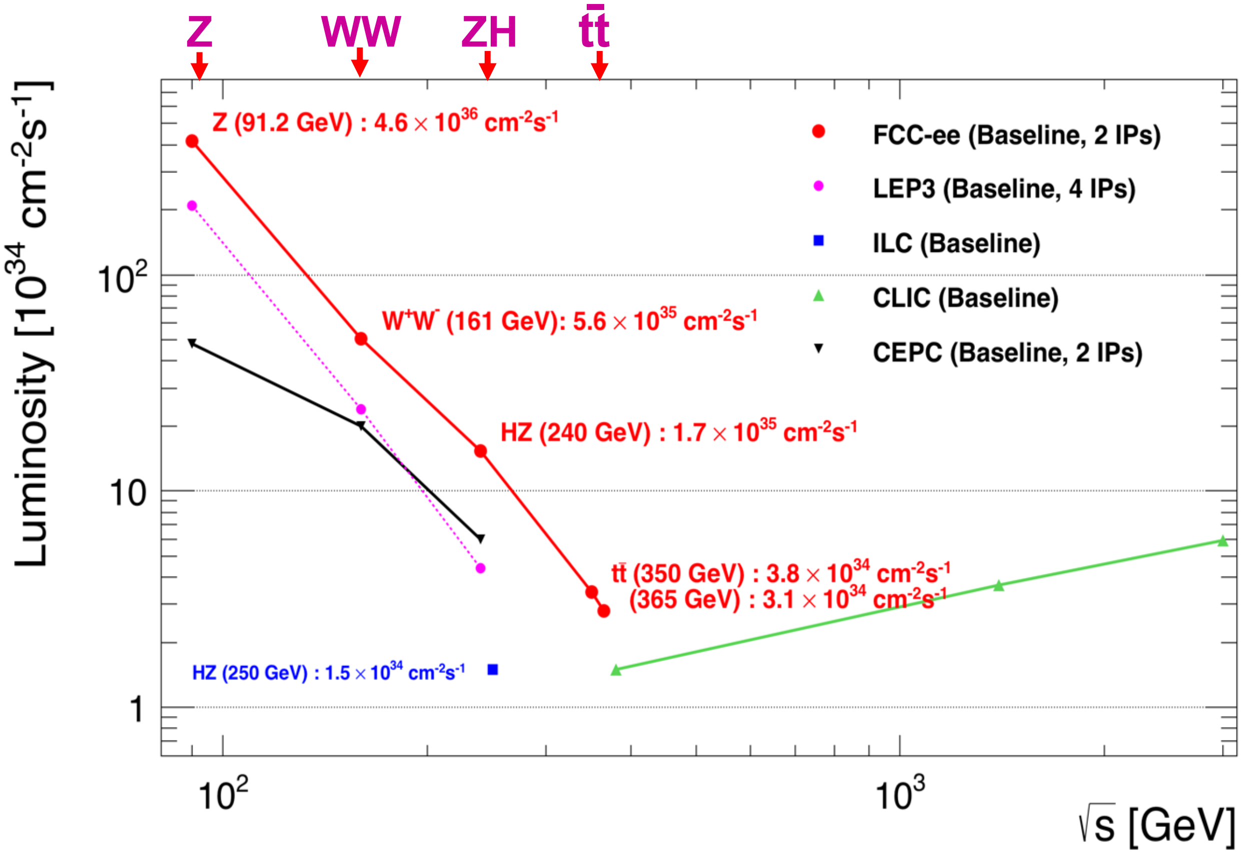
TLEP: arXiv:1208.0504
TLEP physics case: arXiv:1308.6176

- **Follows footprint of FCC-hh, except around IPs**
- **~100 km to reach $t\bar{t}$ production**
- **Double ring (e+, e-) collider, multi-bunch**
- **Top-up injection for high efficiency**
  → high-energy injector in collider tunnel
- **Crab-waist optics** to maximize luminosity @Z, W, H
  30 mrad crossing angle
- **Asymmetric interaction region layout and optics**
  Limit synchrotron radiation in the detector
- **Two interaction points (IP) in A and G**
  4 IPs to be studied -- significant layout changes
- **50 MW/beam Synchrotron Radiation power:**
  at all energies
- **Continuous E_{CM} calibration at Z and W (100 keV)**
  based on resonant transverse depolarization
  polarimeter, wigglers, RF kicker



EW factories: Energies and luminosities

The FCC-ee offers the largest luminosities in the 88 → 365 GeV √s range



Ultimate statistics/precision:

- 100 000 Z / second
  - 1 Z / second at LEP
- 10 000 W / hour
  - 20 000 W total at LEP2
- 1 500 Higgs bosons / day
  - 10 times ILC
- 1 500 top quarks / day

  in each detector

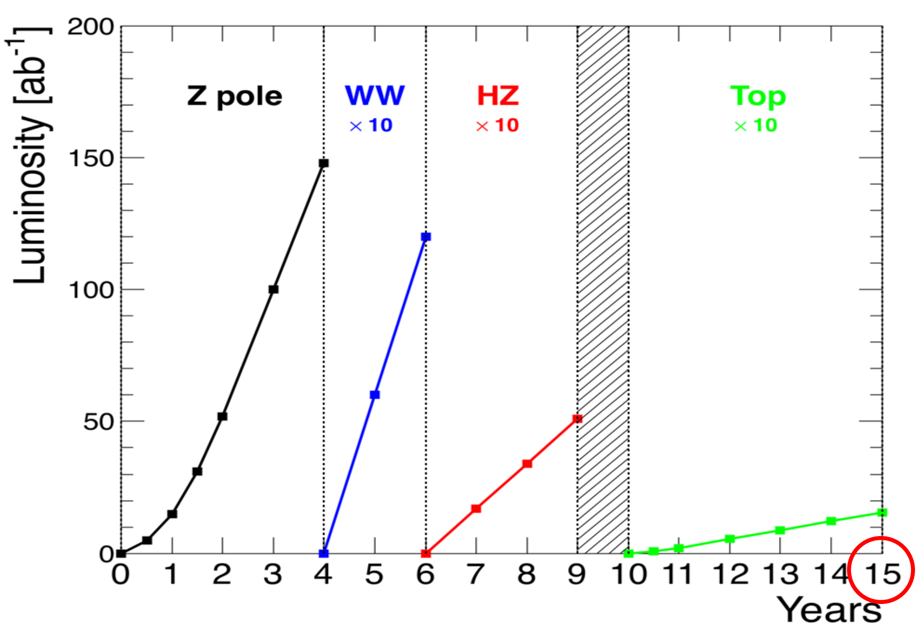
PRECISION and SENSITIVITY
to rare or elusive phenomena

Design with 4 IPs now being investigated
- Luminosity per IP down my 10% only
- Approaching a doubling of total luminosity !

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
$\sqrt{s}$ (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

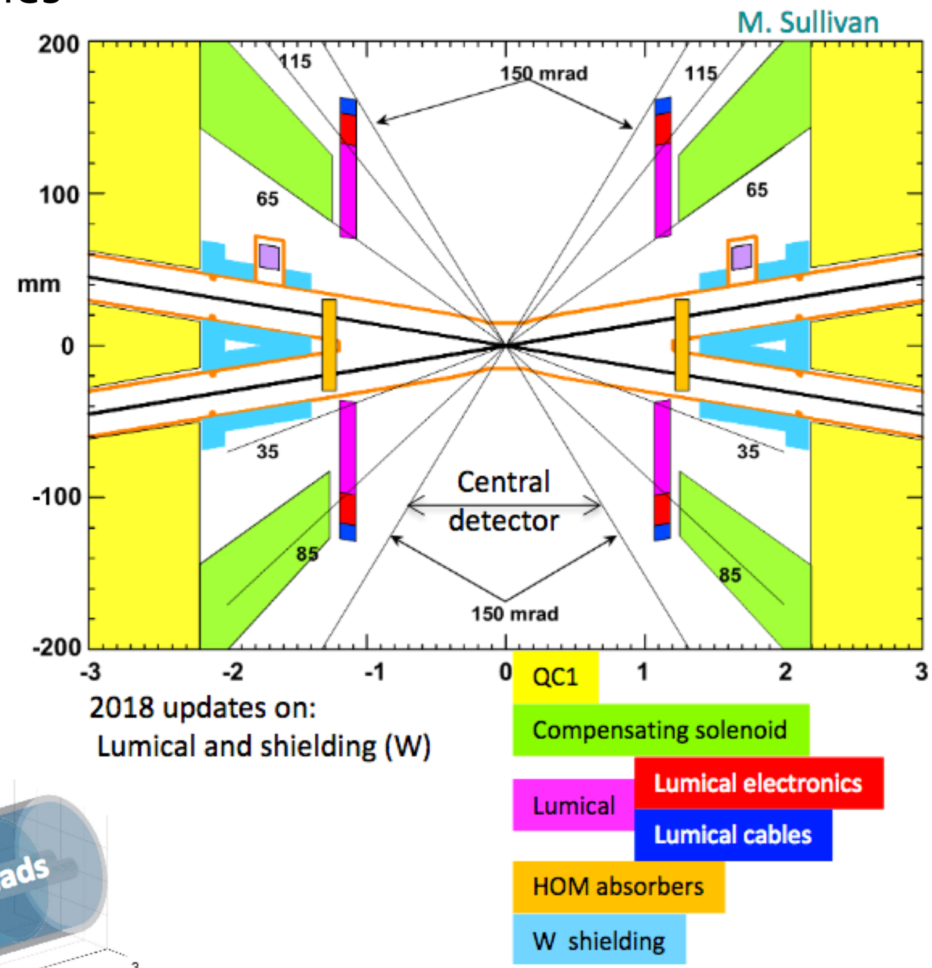
Event statistics	$\sqrt{s}$ precision
5×10^{12} $e^+e^- \rightarrow Z$	100 keV
10^8 $e^+e^- \rightarrow W^+W^-$	300 keV
10^6 $e^+e^- \rightarrow HZ$	1 MeV
10^6 $e^+e^- \rightarrow t\bar{t}$	2 MeV

Important features for precision measurements

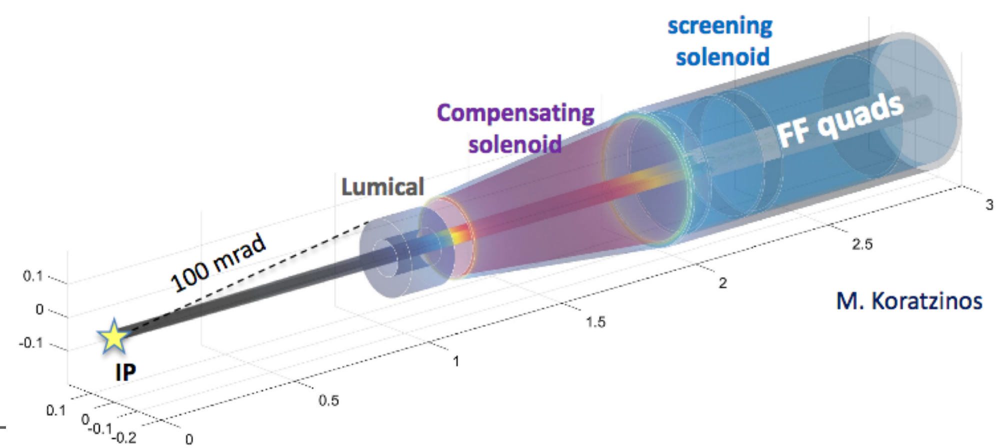
- Statistics
  - Very high statistics at the Z pole (70 kHz of visible Z decays)
  - Beam-induced background are mild compared to linear colliders, but not negligible
    - Readout must be able to cope with both
    - CW running imposes constraints on detector cooling
- Luminosity measurement
  - Aim at 0.01% from small angle Bhabhas
    - Requires μm precision for LumiCal
    - Requires measurement of outgoing $e^{\pm}$ deflection from the opposite bunch
  - Need to study $e^+e^- \rightarrow \gamma\gamma$ to possibly approach 0.001%
- √s calibration and measurement of √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
  - Small beam pipe radius: Vertex detector 1st layer at 17 mm.
    - Impact parameter resolution: 3-5 μm ($c\tau$ = 89 μm for τ and more for Bs)
    - New CEPC studies claim Purity × Efficiency ~ 97% for H → bb. Ongoing studies for FCC-ee

Interaction Region Layout (MDI)

- Unique and flexible design at all energies
  - $L^* = 2.2$ m
    - Acceptance: 100 mrad
  - Solenoid compensation scheme
    - Reduce ε_y blow-up $\Rightarrow B_{Detector} \leq 2$T
  - Beam pipe
    - Warm, liquid cooled (~SuperKEKB)
    - Be in central region, then Cu
    - R = 15 mm in central region
      - 1st vertex detector layer 17 mm from IP
    - SR masks, W shielding
  - Mechanical design and assembly concept
    - Under engineering study



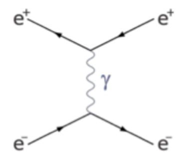
2018 updates on:
Lumical and shielding (W)



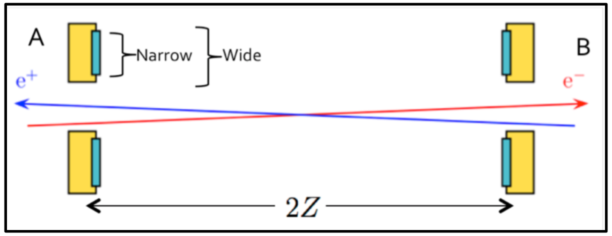
Luminosity Measurement

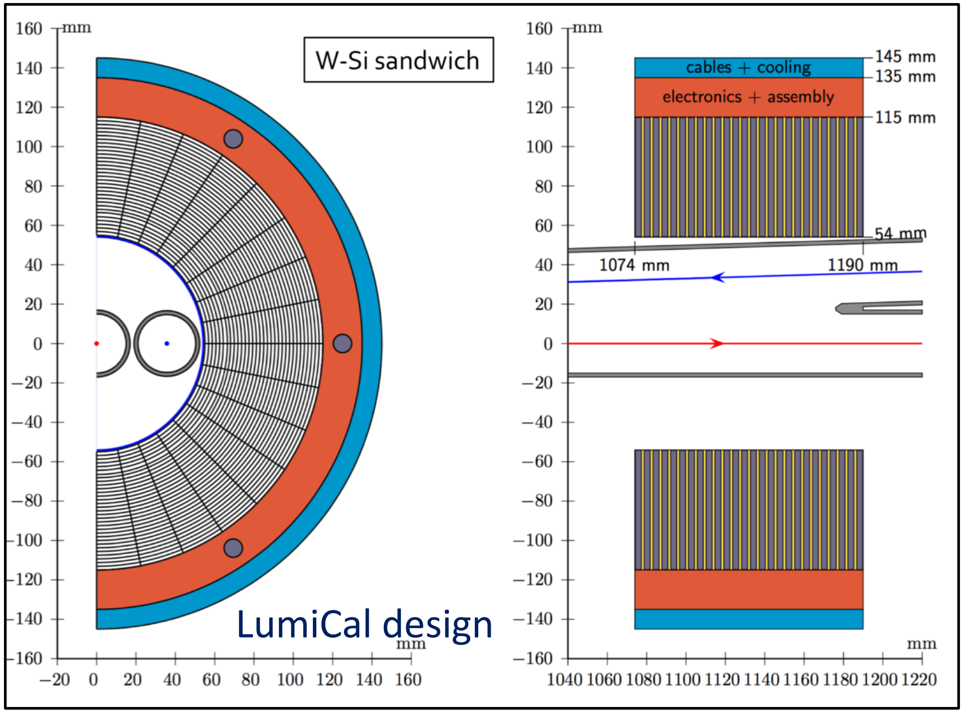
Ambitious goal:
- Absolute to 10^{-4}
- Relative (energy-to-energy point) to 10^{-5}

Small angle Bhabha scattering.
Very strongly forward peaked



Monitors centered around outgoing beam line
-- micron level precision needed



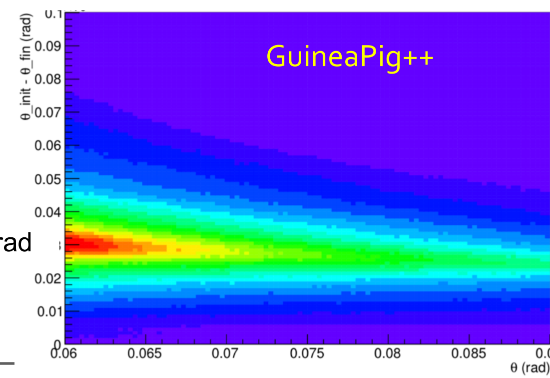


- **Theory:** Now at 3.8×10^{-4}; theory friends foresees that 1×10^{-4} will happen

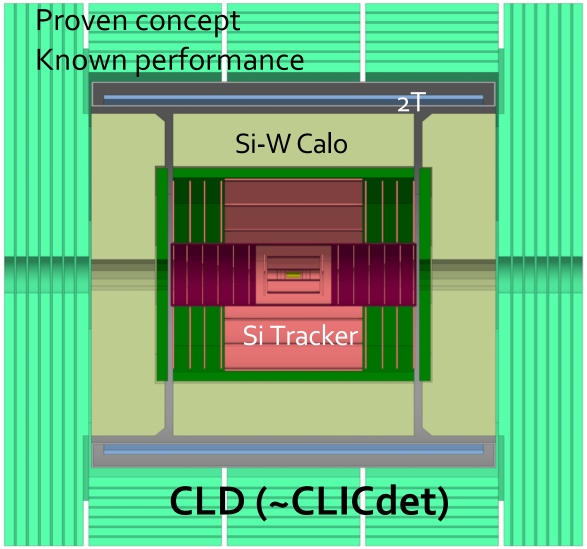
arXiv:1812.01004]

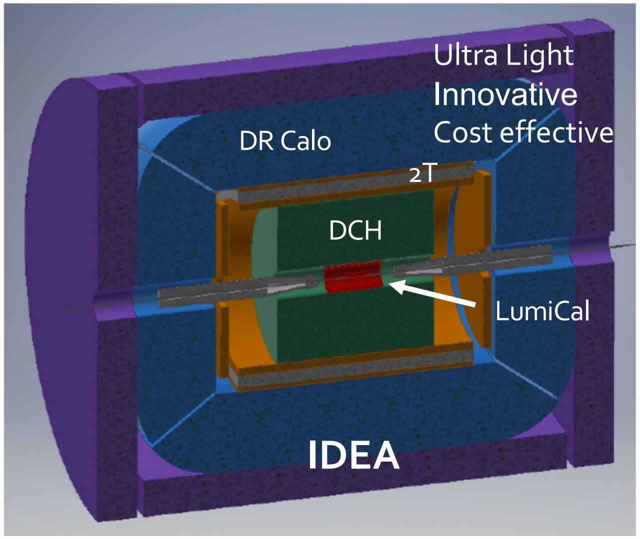
- **Backgrounds:** have been studied and seem to be under control
  - Only "incoherent pair production" starts to pop up at $t\bar{t}$ energies
- **Electromagnetic focussing of Bhabhas** (similar to "pinch effect")
  - average focussing of 30 μrad: 15×10^{-4} effect on acceptance
  - under study…

30 μrad



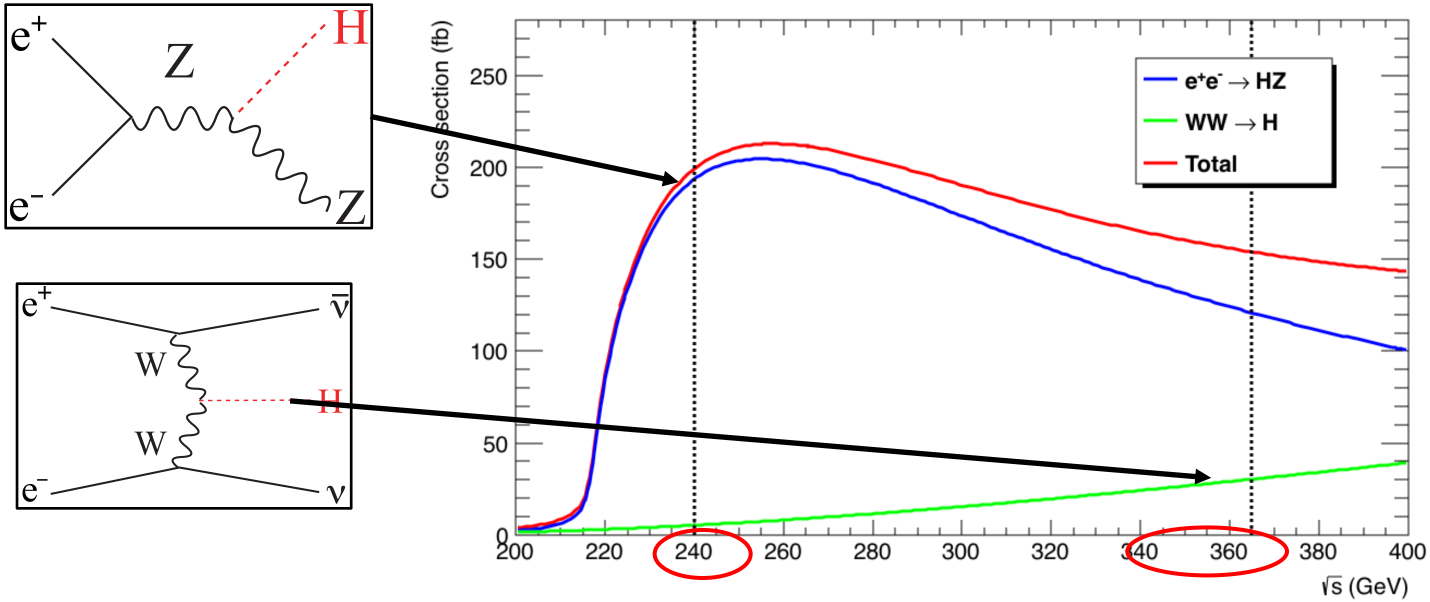
FCC-ee Detector Design Concepts





- Two designs studied so far
  - Has been demonstrated that detectors satisfying the requirements are feasible
    - Physics performance, invasive MDI, beam backgrounds
- Next: more complete studies, with full simulation
  - Towards 4 detector proposals by ~2026
    - Light, granular, fast, b and c tagging, lepton ID and resolutions, hadron ID
    - Cost effective
    - Satisfy constraints from interaction region layout

FCC-ee as a Higgs factory



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

- Higgsstrahlung ($e^+e^- \rightarrow ZH$) event rate largest at $\sqrt{s}$ ~ 240 GeV : σ ~ 200 fb
  - 10^6 $e^+e^- \rightarrow ZH$ events with 5 ab^{-1} ; cross section predicted with great accuracy
    - Target : (few) per-mille precision, statistics-limited
- Complemented with 200k events at $\sqrt{s}$ = 350 – 365 GeV
  - Of which 30% in the WW fusion channel (important for the Γ_H precision)

Precision Higgs physics – Which precison ?

- Higgs couplings will be measured at the few percent level at the the end of HL-LHC

Collider	HL-LHC
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.3
$\delta g_{HWW}/g_{HWW}$ (%)	1.4
$\delta g_{Hbb}/g_{Hbb}$ (%)	2.9
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM
$\delta g_{Hgg}/g_{Hgg}$ (%)	1.8
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.7
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.4
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.6
$\delta g_{Htt}/g_{Htt}$ (%)	2.5

- Is this precision good enough to make a "discovery" ?

- Higgs couplings sensitive to New Physics (NP)
  - Expected deviations from SM coupling strengths depend on NP scale.

$$\boxed{\frac{g_{HXX}}{g_{HXX}^{SM}} \approx 1 + \delta \times \left(\frac{1\ \text{TeV}}{\Lambda_{NP}}\right)^2}$$

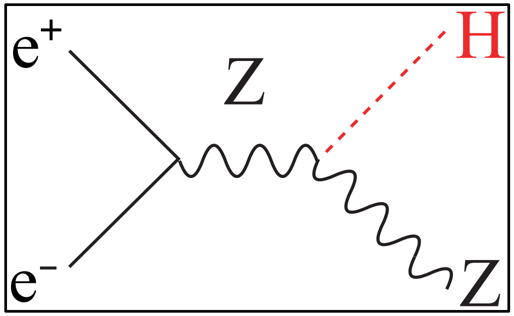
with $\boldsymbol{\delta}$ =

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

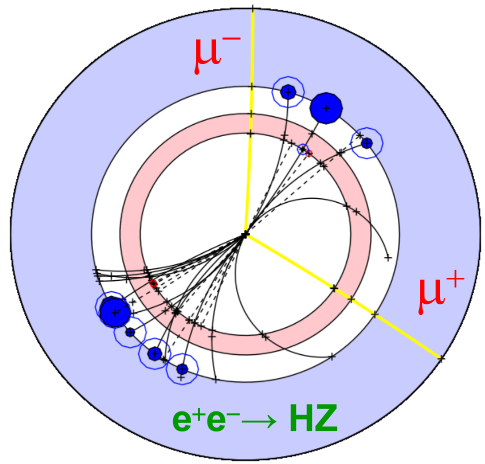
- Need a <u>minimum</u> of ~1% precision on couplings for a 5σ discovery if Λ_{NP} = 1 TeV
  - And better for heavier New Physics

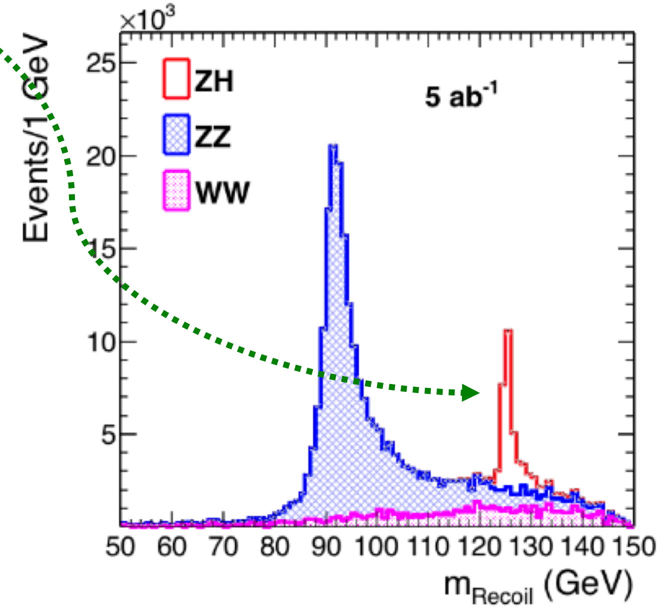
Higgs: Absolute couplings and width

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



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





- Total rate $\propto g_{HZZ}^2$ → measure g_{HZZ} to 0.2%
- ZH → ZZZ final state $\propto g_{HZZ}^4 / \Gamma_H$ → measure Γ_H to a couple %
- ZH → ZXX final state $\propto g_{HXX}^2\, g_{HZZ}^2 / \Gamma_H$ → 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 …
  - $\sigma_{i\to f}^{(observed)} \propto \sigma_{prod}\,(g_{Hi})^2\,(g_{Hf})^2 / \Gamma_H$
    - 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

- Relative precisions for HL-LHC and the FCC-ee

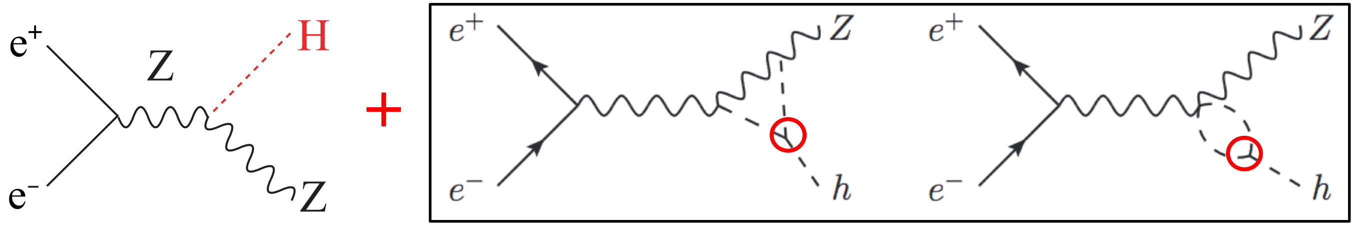
Collider	HL-LHC	FCC-ee		
Luminosity (ab^{-1})	3	5 @ 240GeV	+1.5 @ 365GeV	+HL-LHC
Years	25	3	**+4**	-
$\delta\Gamma_H/\Gamma_H$ (%)	SM	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.3	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	2.9	1.3	**0.61**	0.55
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	1.8	1.6	**1.01**	0.83
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.7	1.4	**0.74**	0.64
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.4	10.1	**9.0**	3.9
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.6	4.8	**3.9**	1.1
$\delta g_{Htt}/g_{Htt}$ (%)	2.5	–	**–**	2.4
BR$_{EXO}$ (%)	SM (0.0)	<1.2	**<1.0**	<1.0

Model-independent

- FCC-ee precision better than HL-LHC by sizable factors (copious modes)
  - With no need for additional assumptions
- It is important to have two energy points (240 and 365 GeV)
  - Combination better by a factor 2 (4) than 240 (365) GeV alone
- (HL-)LHC measures the σ_{ttH} , but requires assumptions for the g_{Htt}
  - Absolute g_{Htt} measurement in a combination with FCC-ee (precision: 2.4%)

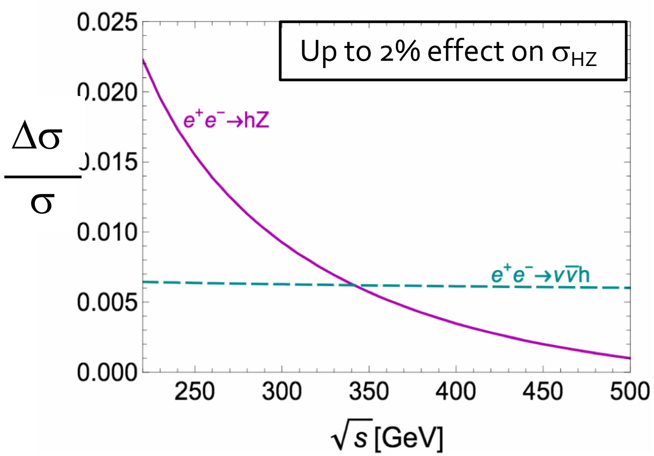
Higgs self-coupling at FCC-ee

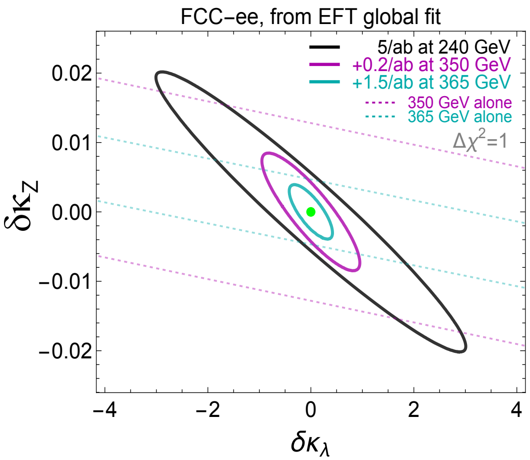
- FCC-ee does not produce Higgs pairs, from which self coupling can be extracted
- But, loops including Higgs self coupling contribute to Higgs production



M. McCullough
arXiv:1312.3322

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





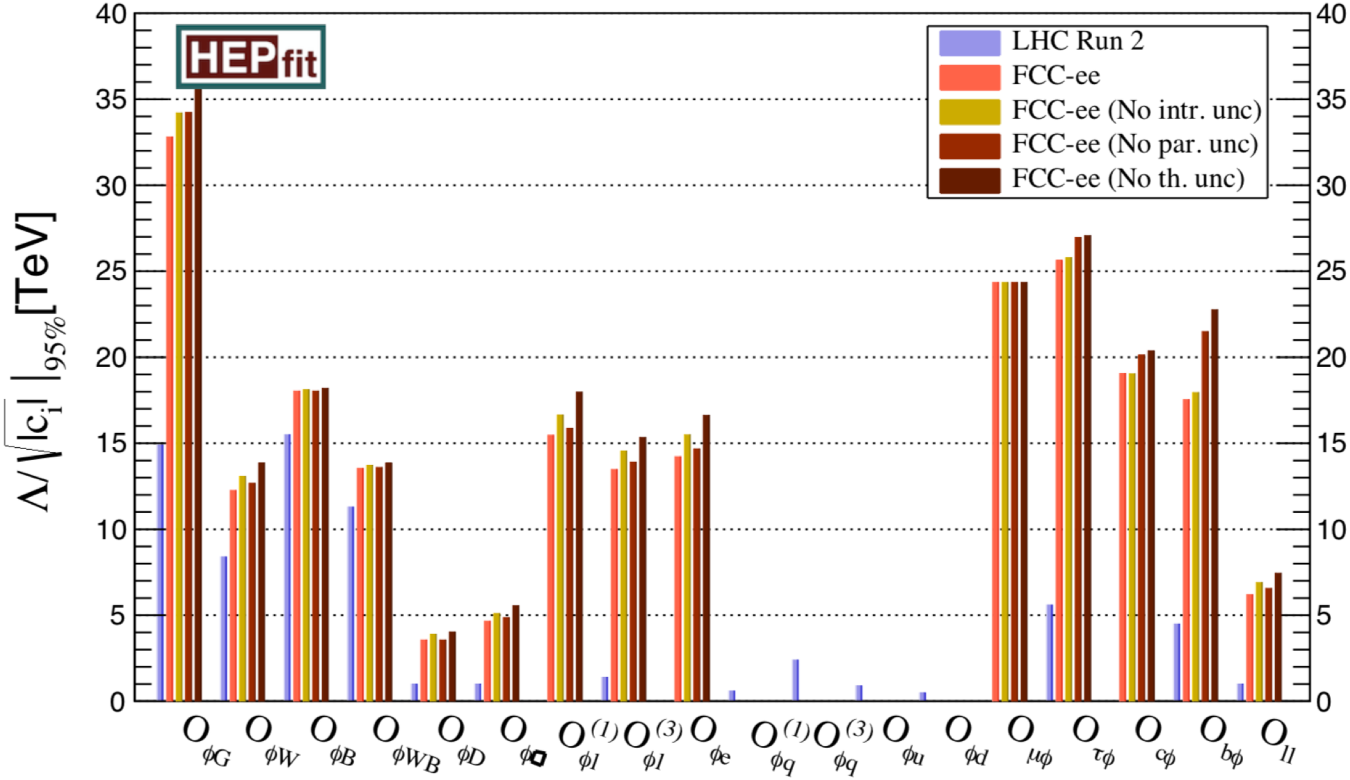
C. Grojean et al.
arXiv:1711.03978

- Two energy points (240 and 365 GeV) lift off the degeneracy between $\delta\kappa_Z$ and $\delta\kappa_\lambda$
  - 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)

A. Blondel, P. Janot
arXiv:1809.10041

Higgs Measurements – Discovery Potential

- Evaluate discovery potential for New Physics via a Standard Model Effective Field Theory (SMEFT) fit
  - Expressed in terms of coefficients of dim-6 operators: *"interaction scale"*



Precision electroweak physics

- Reminder: The FCC-ee goals in numbers

√s (GeV)	90 (Z)	160 (WW)	240 (HZ)	350 (tt)	365 (WW→H)
# years	4	2	3	5	
Events@FCCee	5×10^{12}	10^8	10^6	10^6	45,000

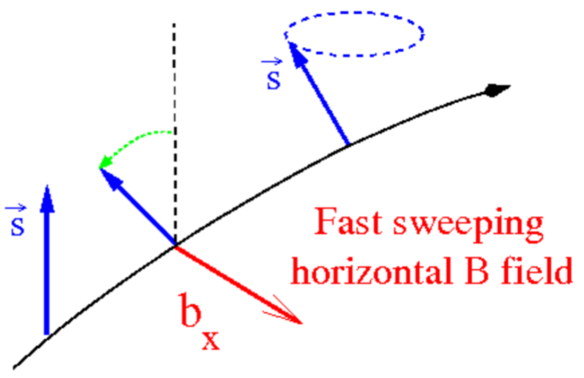
- FCC-ee is the **ultimate Z, W, Higgs and top factory**
  - 10^5 times more Zs and 10^3 times more Ws than LEP1 and LEP2
    - Potential statistical accuracies are mind-boggling !

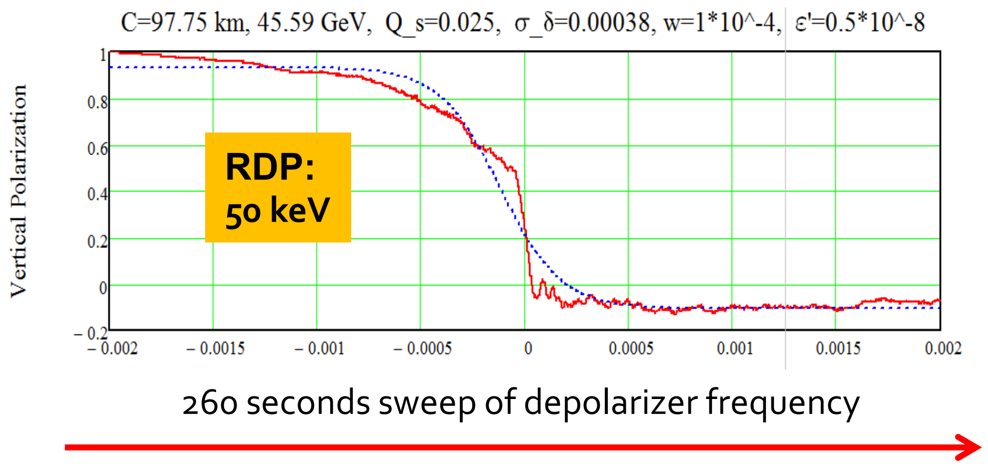
- With 200 times smaller statistical precision than at LEP, it is hard to predict accuracies
  - For now, conservatively, use LEP experience for systematics

- Example: The uncertainty on E_{BEAM} (2 MeV) was the dominant uncertainty on m_Z, Γ_Z
  - Can we do significantly better at FCC-ee ?

Beam Polarization and Energy Calibration

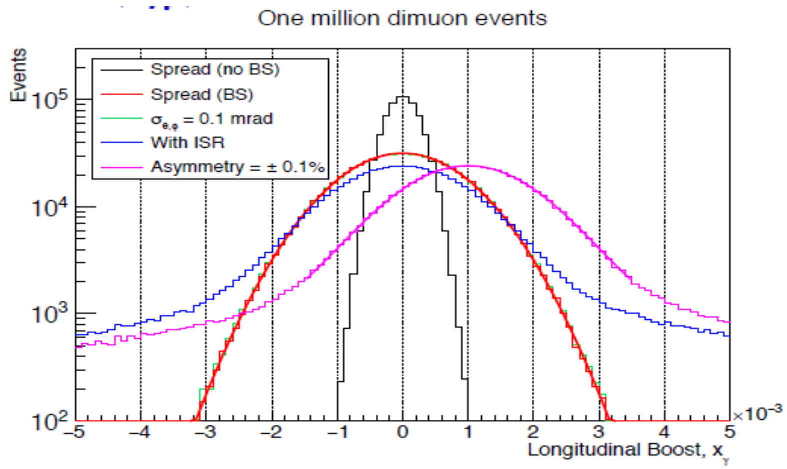
- Simulation show transverse polarization at the Z (wigglers) and WW energies
  - Energy calibration by resonant depolarization every 10 mins on pilot bunches
    - UNIQUE TO CIRCULAR COLLIDERS





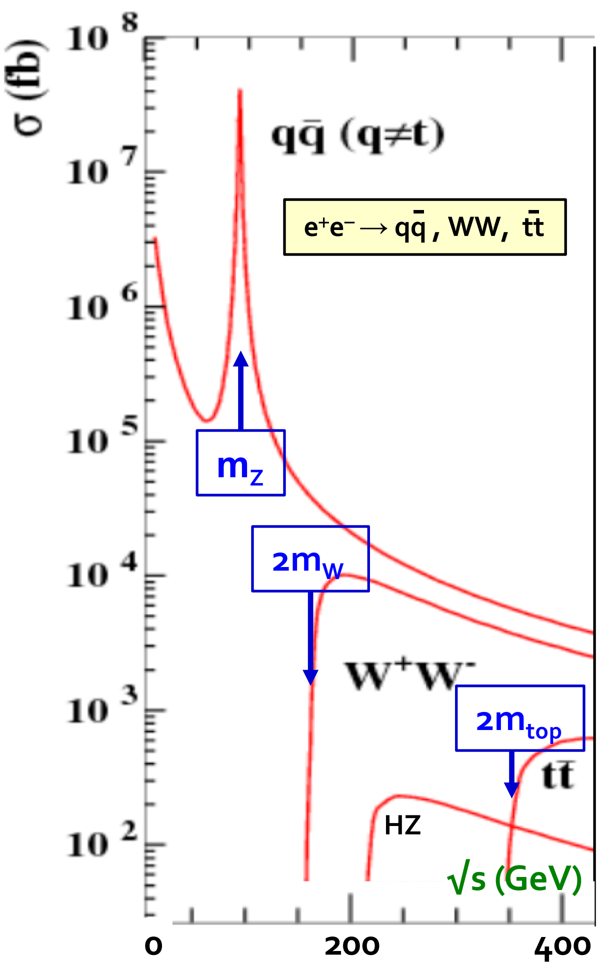
- Total √s uncertainty of **100 keV** @ Z pole, and **300 keV** at the WW threshold

- Energy spread (~100 MeV) will be measured
  - From $e^+e^- \rightarrow \mu^+\mu^-$ longitudinal boost
    - 10^6 events every 4 mins @ Z pole
      - Continuous 35 keV precision on $\delta\sqrt{s}$
    - Also measures $\Delta E = E^+ - E^-$ to similar precision

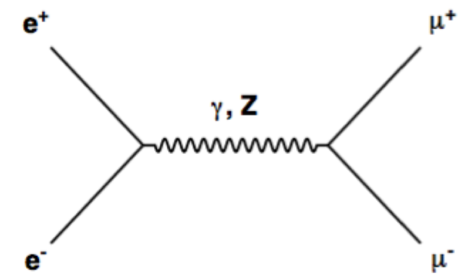


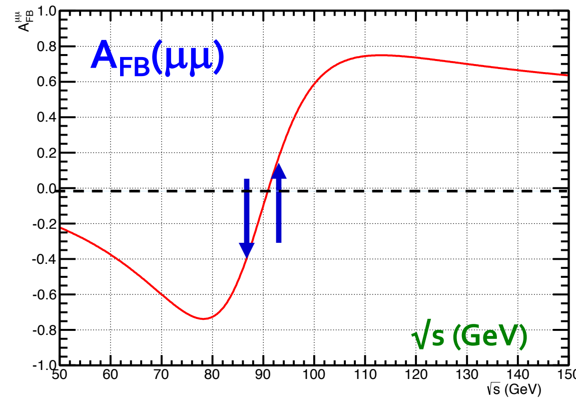
Precision Electroweak Measurements (i)

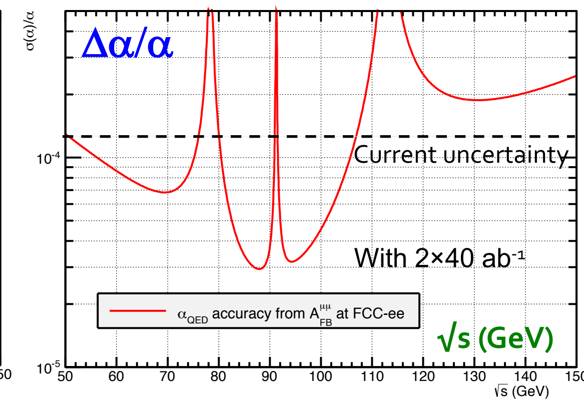
- Boils down to measuring cross sections and asymmetries



$e^+e^- \to \mu^+\mu^-$







$$A_{FB}^{\mu\mu} = \frac{N_F^{\mu+} - N_B^{\mu+}}{N_F^{\mu+} + N_B^{\mu+}} \approx f(\sin^2 \vartheta_W^{eff}) + \alpha_{QED}(s) \frac{s - m_Z^2}{2s} g(\sin^2 \vartheta_W^{eff})$$

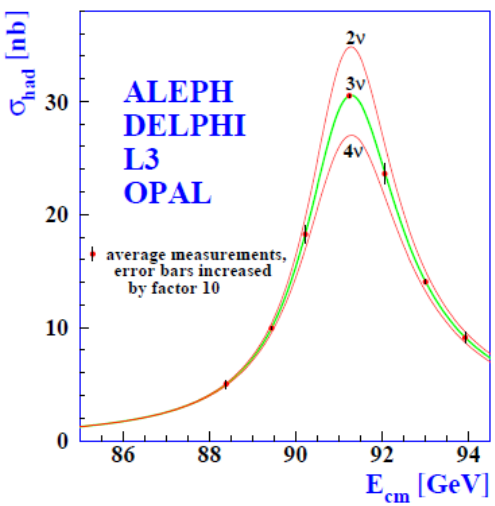
- Measure $\sin^2\theta_W$ with A_{FB} at $\sqrt{s} = m_Z$
- Measure $\alpha_{QED}(m_Z)$ with A_{FB} at $\sqrt{s}$ = 87.9 and 94.3 GeV
  - $\sqrt{s}$-points also for the Z resonance scan (m_Z, Γ_Z)

- The dominant experimental uncertainties (still) come from the beam energy knowledge

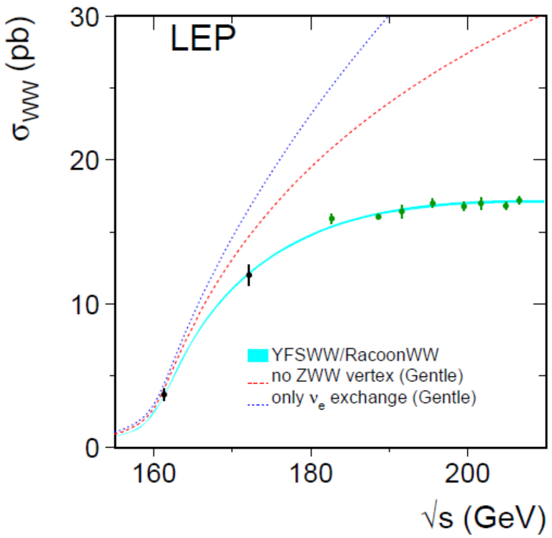
Precision Electroweak Measurements (ii)

- EW precision measurements at FCC-ee (see arXiv:1308.6176 and CDR)

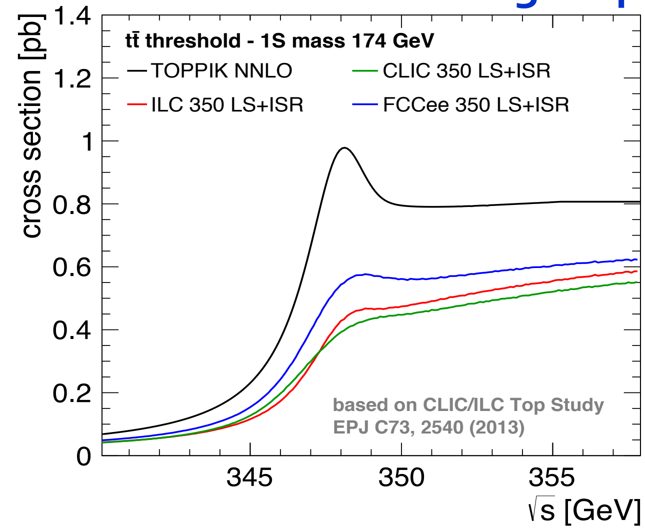
Z reconance: TeraZ



WW threshold scan: OkuW



tt threshold scan: MegaTop



Lineshape

- Exquisite E_{beam} (unique!)
- m_{Z}, Γ_Z to < 100 keV (2.2 MeV)

Asymmetries

- $\sin^2\theta_W$ to 6×10^{-6} (1.6×10^{-4})
- $\alpha_{QED}(m_Z)$ to 3×10^{-5} (1.5×10^{-4})

Branching ratios R_l, R_b

- $\alpha_S(m_Z)$ to 0.0002 (0.002)

Threshold scan

- m_W to 0.5 MeV (12 MeV)

Branching ratios R_l, R_b

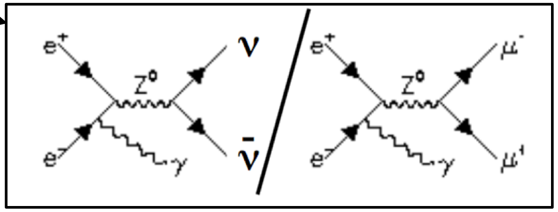
- $\alpha_S(m_Z)$ to 0.0002

Radiative return $e^+e^- \rightarrow Z\gamma$

- N_ν to 0.0004 (0.008)

Threshold scan

- m_{top} to 10 MeV (500 MeV)
- λ_{top} to 10%
- EW couplings to 1%



Sample of EW observables, experimental precisions

Z pole

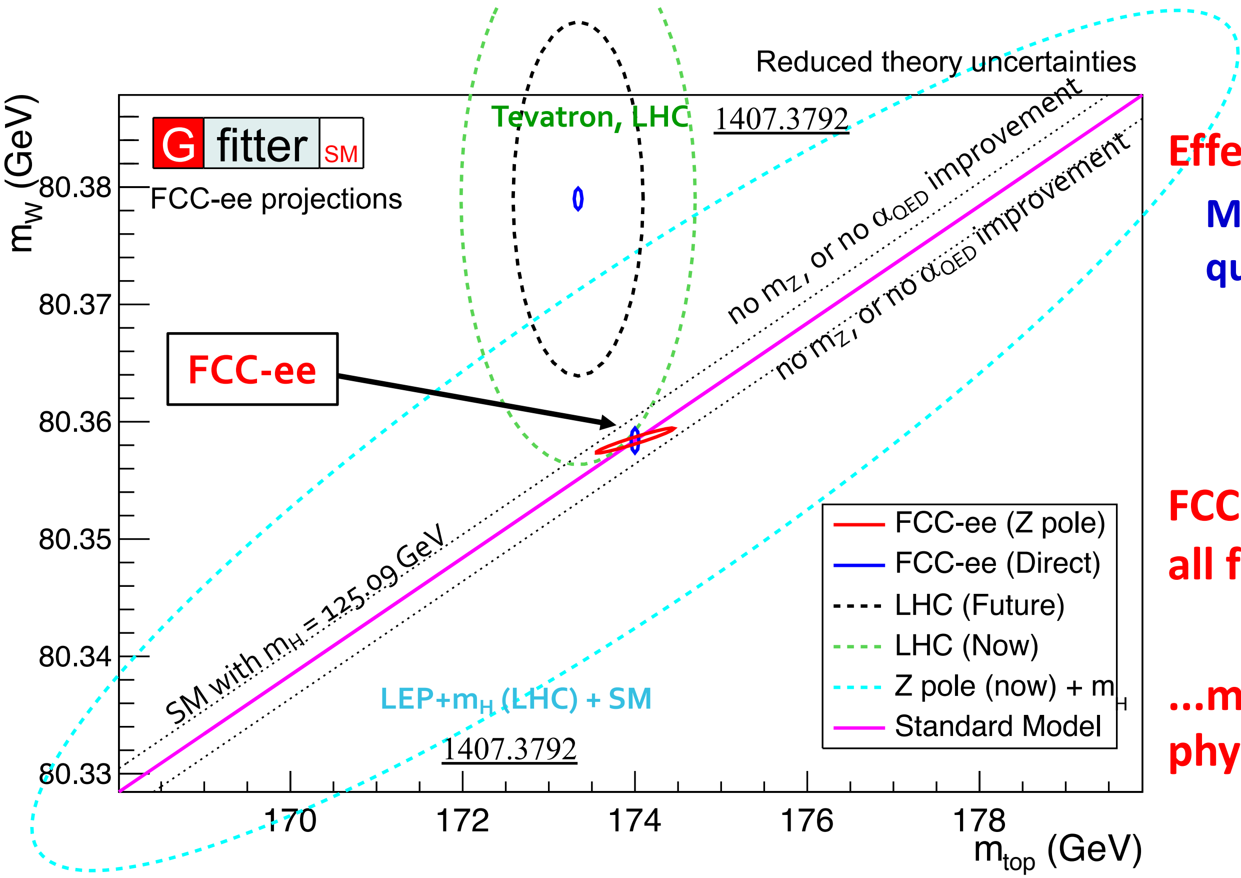
WW thresh.

$t\bar{t}$ thresh.

Observable	Measurement	Current precision	FCC-ee **stat.**	FCC-ee **syst.**	Dominant exp. error
m_Z (keV)	Z Lineshape	91187500 ± 2100	5	< 100	Beam energy
Γ_Z (MeV)	Z Lineshape	2495200 ± 2300	8	< 100	Beam energy
R_l ($\times 10^3$)	Z Peak ($\Gamma_{had}/\Gamma_{lep}$)	20767 ± 25	0.06	0.2 – 1	Detector acceptance
R_b ($\times 10^6$)	Z Peak (Γ_{bb}/Γ_{had})	216290 ± 660	0.3	< 60	$g \rightarrow bb$
N_ν ($\times 10^3$)	Z Peak (σ_{had})	2984 ± 8	0.005	1	Lumi measurement
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	$A_{FB}^{\mu\mu}$ (peak)	231480 ± 160	3	2 – 5	Beam energy
$1/\alpha_{QED}(m_Z)$ ($\times 10^3$)	$A_{FB}^{\mu\mu}$ (off-peak)	128952 ± 14	4	< 1	Beam energy
$\alpha_s(m_Z)$ ($\times 10^4$)	R_l	1196 ± 30	0.1	0.4 – 1.6	Same as R_l
m_W (MeV)	WW Threshold scan	80385 ± 15	0.6	0.3	Beam energy
Γ_W (MeV)	WW Threshold scan	2085 ± 42	1.5	0.3	Beam energy
N_ν ($\times 10^3$)	$e^+e^- \rightarrow \gamma Z$, $Z \rightarrow \nu\nu$, ll	2920 ± 50	0.8	small	?
$\alpha_s(m_W)$ ($\times 10^4$)	$B_l = (\Gamma_{had}/\Gamma_{lep})_W$	1170 ± 420	2	small	CKM Matrix
m_{top} (MeV)	Top Threshold scan	173340 ± 760 ± 500	17	< 40	QCD corr.
Γ_{top} (MeV)	Top Threshold scan	?	45	< 40	QCD corr.
λ_{top}	Top Threshold scan	μ = 1.28 ± 0.25	0.10	< 0.05	QCD corr.
ttZ couplings	$\sqrt{s}$ = 365 GeV	± 30%	0.5 – 1.5%	< 2%	QCD corr

Combination of EW measurements

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



Effect of BSM physics

Modify EW observables through quantum effects (*cf* top & H @ LEP)

Blue (direct) & red (Z pole) ellipses may or may not overlap

Standard Model may or may not fit

FCC-ee provides improvement from all fronts…

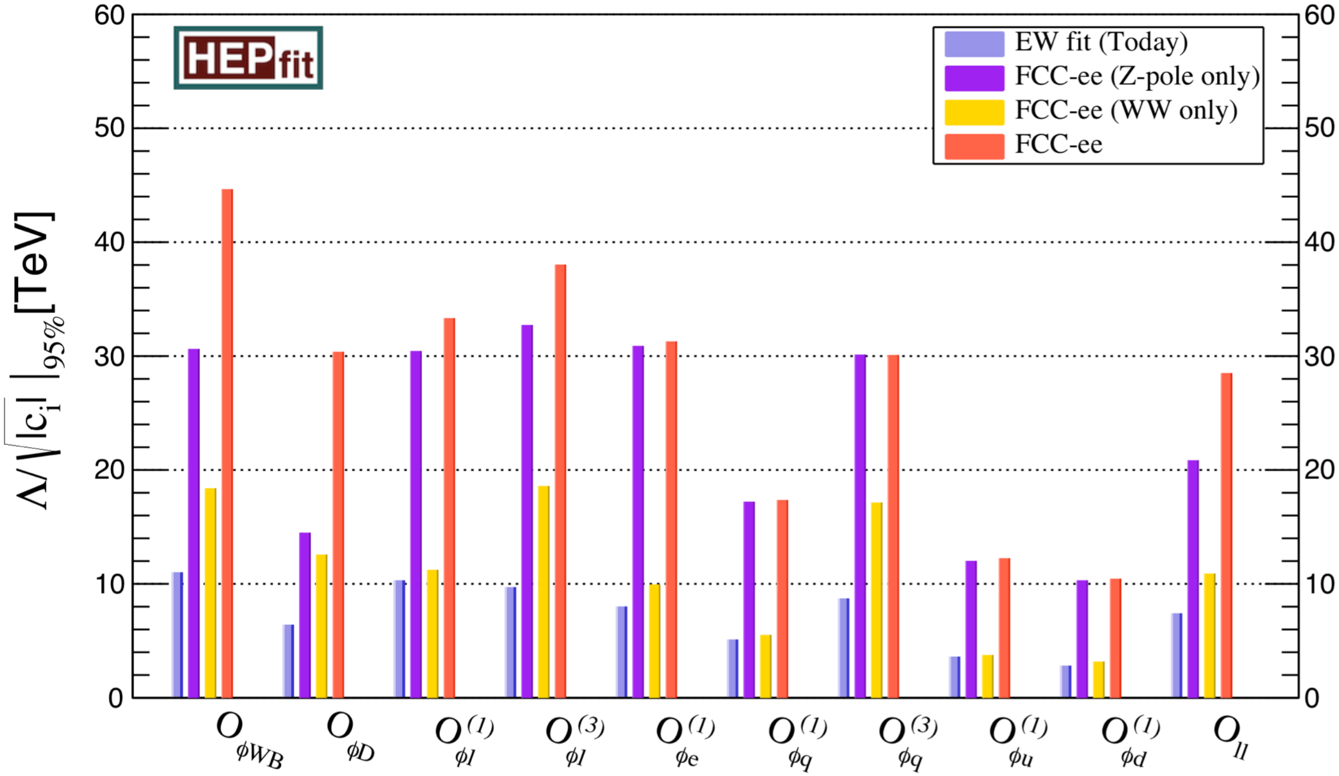
e.g. m_Z, α_{QED}, m_{top}, …

…maximizing sensitivity to BSM physics

- Precision of theory predictions needs to improve for full sensitivity to new physics
  - higher order calculations needed

EW Measurements – Discovery Potential

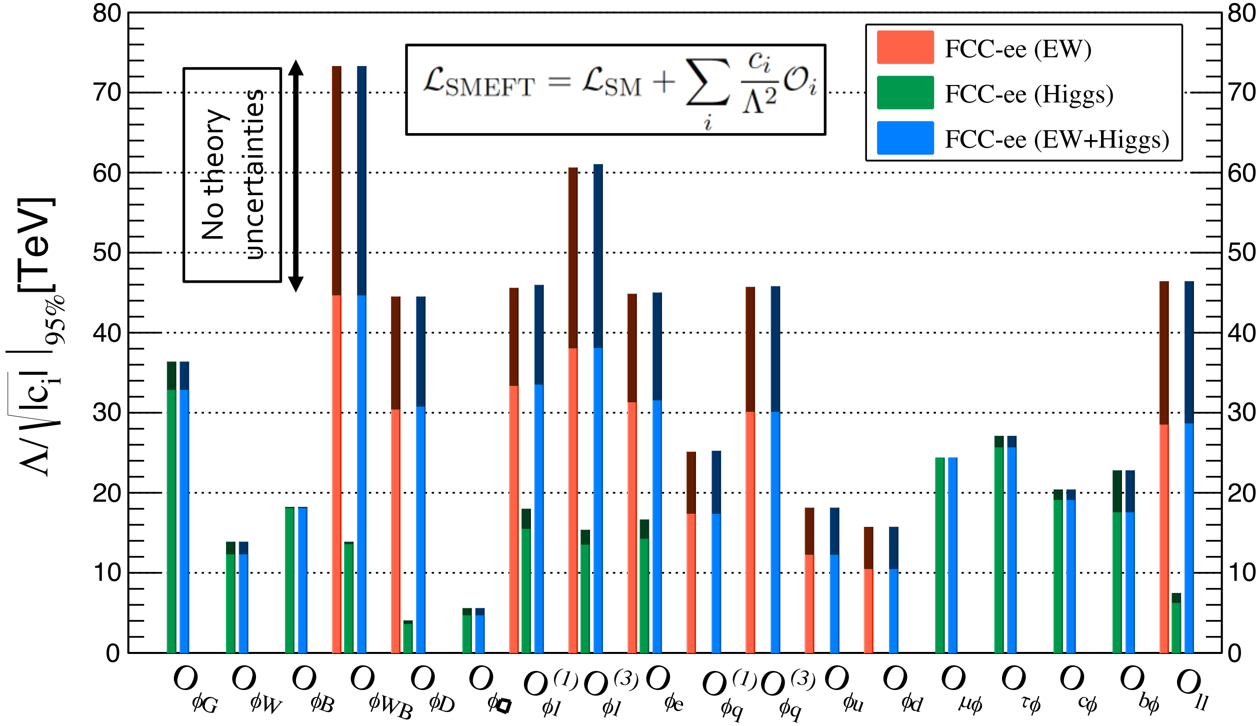
- Evaluate discovery potential for New Physics via Standard Model Effective Field Theory (SMEFT) fit
  - Expressed in terms of coefficients (*interaction scale*) in front of dim-6 operators



- Here, no improvements in theory uncertainties assumed (see next page)

Precision ⇔ Discovery ?

- Combining precision Higgs and EW measurements in SMEFT



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

- Higgs and EWPO measurements are well complementary (b,c,τ PO to be added)
- EWPO are more sensitive to heavy new physics (up to 50-70 TeV)
  - Sensitivity was at the level of up to ~5 TeV at LEP
- Larger statistics pays off for Higgs measurements (4 IPs ?)
- *Further improvement in theory predictions pays off for EWPO measurements*

Precision of theory predictions

- Improving the precision of EW and QCD calculations for the FCC-ee
  - Is a great challenge (exponentially growing number of diagrams with # loops)
  - Has discovery potential (see previous slide)
  - Is therefore recognized as strategic
    - *Included in the FCC-ee CDR volume as a target for "Strategic R&D"*

- First workshop on "Methods and tools" in January 2018
  - 33 participants
  - Produced a 250+ pages proceedings !
  - Conclusion of the workshop
    - ***We cannot promise, but yes, we can do it !***
    - Requires ~500 person-year over the next 20 years

Standard Model theory for the FCC-ee (2018)
J. Gluza et al., https://arxiv.org/abs/1809.01830

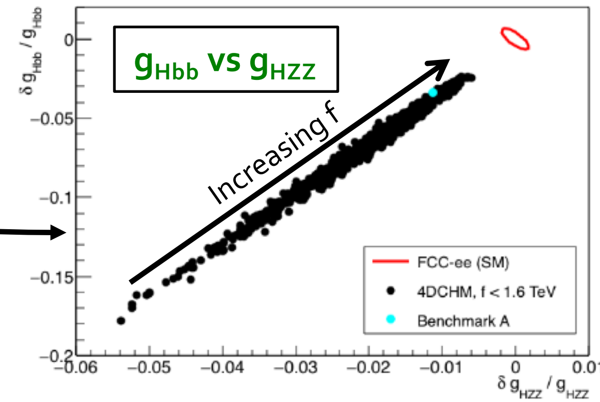
- Workshop series continued in January 2019
  - Topics covered the whole FCC-ee programme, 106 registered participants
    - Z, W, Higgs, top, b, c, QED, Monte Carlo, software, and detector technologies

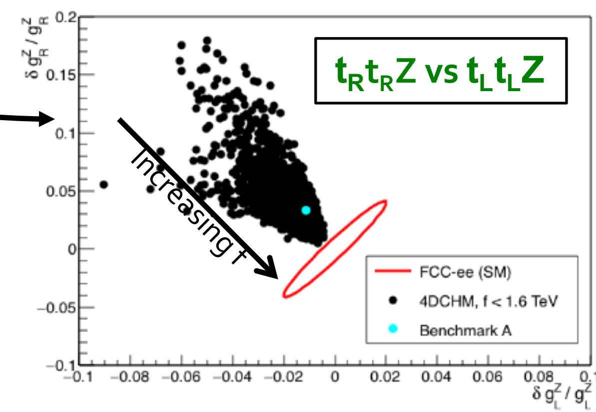
Composite Higgs ?

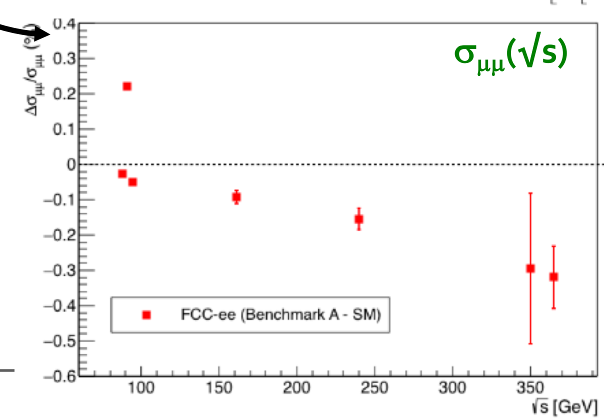
- Deviations may point to specific BSM physics
  - E.g, 4D Composite Higgs Model
    - Deviations in Higgs couplings
      - √s = 240, 350, 365 GeV
    - Deviations in EW top couplings
      - "top polarization measurement"
      - √s = 365 GeV optimal
        - No need for beam polarisation
    - Deviations in EW lepton couplings
      - All energies
- Pattern of deviations may become significant
  - Correlations between observations
    - Allow first characterization of the model
  - For example, gauge sector parameters in benchmark A
    - f = 1.6 TeV, g*=1.78, $m_{Z'}$ ~ 3 TeV, $\Gamma_{Z'}$ ~ 600 GeV
    - With the FCC-ee precision
      - Z' mass predicted with 2% precision
      - Compositeness scale f, coupling g* predicted with 8% precision

S. de Curtis et al.
arXiv:1110.1613

P. Janot
arXiv:1503.01325



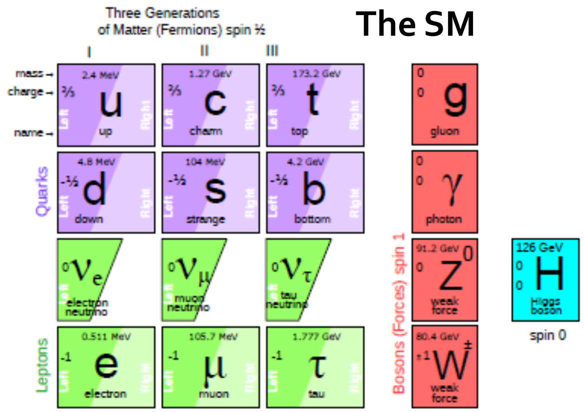




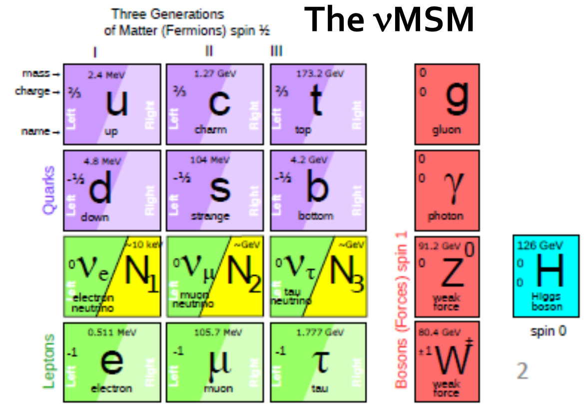
Direct discoveries

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

The SM

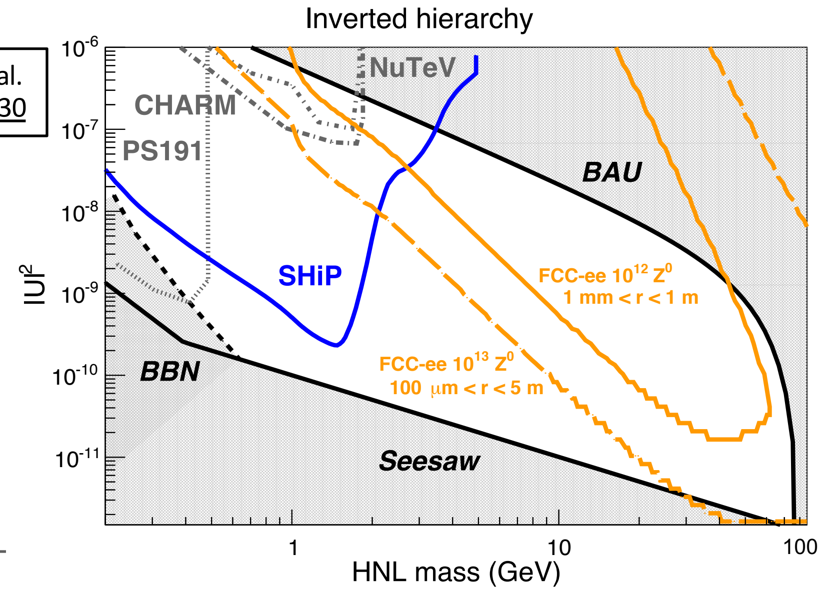


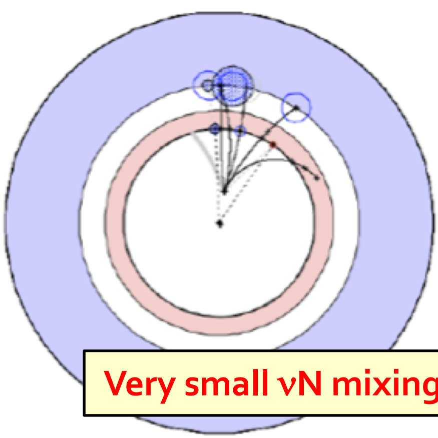
The νMSM

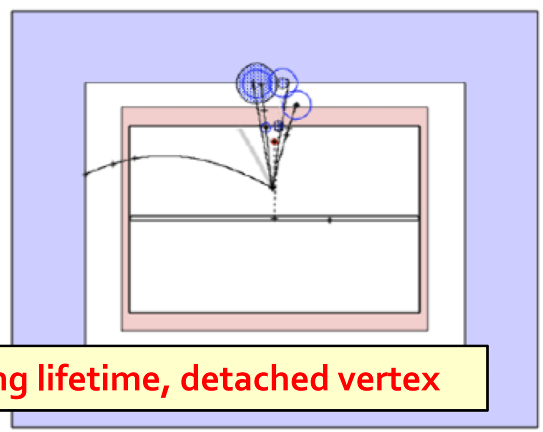


- Could explain everything: Dark matter (N_1), Baryon asymmetry, Neutrino masses
  - Searched for in very rare $Z \to nN_{2,3}$ decays
  - Followed by $N_{2,3} \to W^*\ell$ or Z^*n

A. Blondel et al.
arXiv:1411.5230



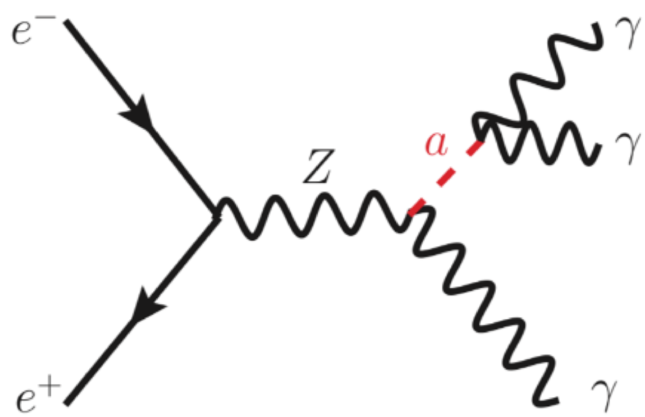


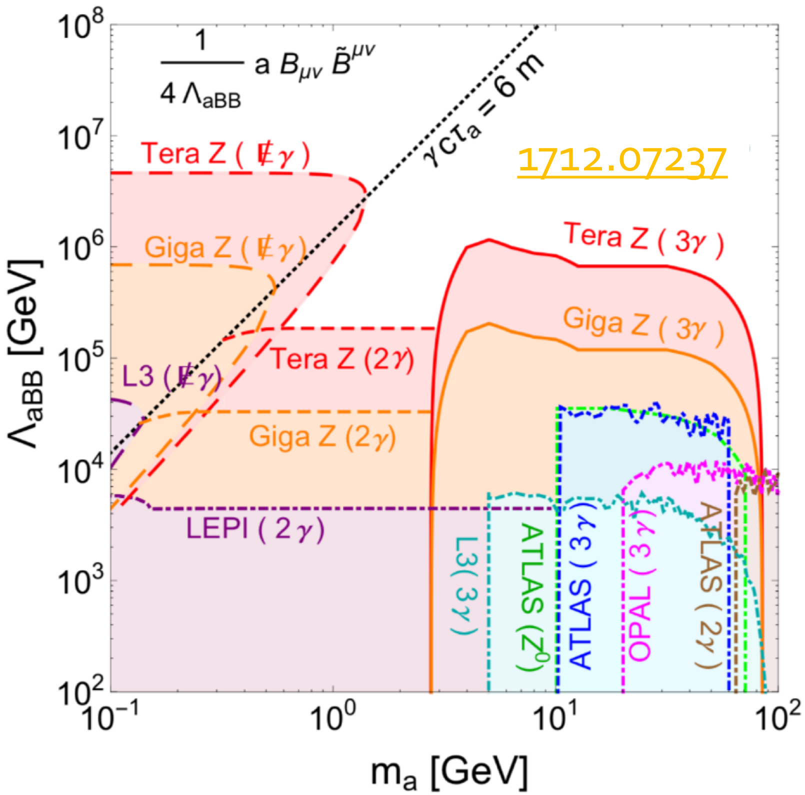


Very small νN mixing : long lifetime, detached vertex

Direct discoveries (cont'd)

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





- $\gamma\gamma$ for light a
- $\gamma\gamma\gamma$ for heavier a

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

Heavy Flavour

- Z run ➪ 10^{12} bb events, 1.7×10^{11} $\tau^+\tau^-$ events (significantly more than BelleII)
  - Higher energy, higher boost ➪ better $e/\mu/\pi$ separation
  - lifetime, branching fractions, rare decays, test of Universality

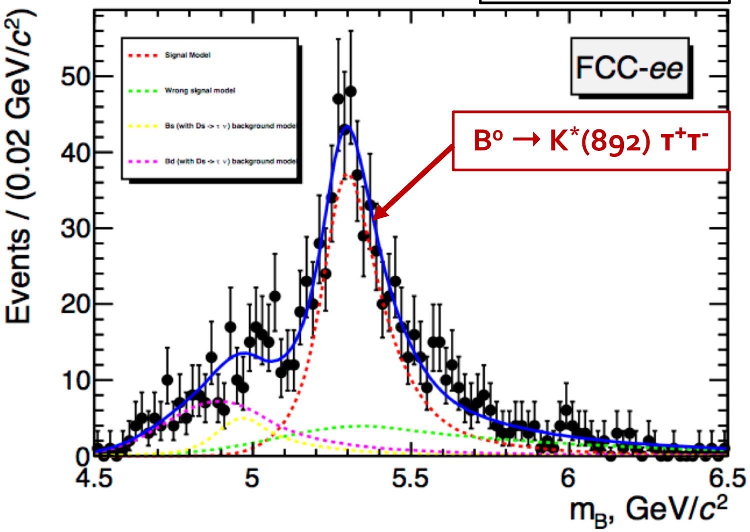
Table 7.1: Expected production yields of heavy-flavoured particles at Belle II (50 ab^{-1}) and FCC-ee.

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\overline{c}$	$\tau^+\tau^-$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	1000	1000	250	250	550	170

J.F. Kamenik et al.
arXiv:1705.11106

- Study of B decays and test of flavour universality

Decay mode	$B^0 \to K^*(892)e^+e^-$	$B^0 \to K^*(892)\tau^+\tau^-$	$B_s(B^0) \to \mu^+\mu^-$
Belle II	∼ 2 000	∼ 10	n/a (5)
LHCb Run I	150	-	∼ 15 (–)
LHCb Upgrade	∼ 5000	-	∼ 500 (50)
FCC-ee	∼ 200000	∼ 1000	∼1000 (100)



τ physics

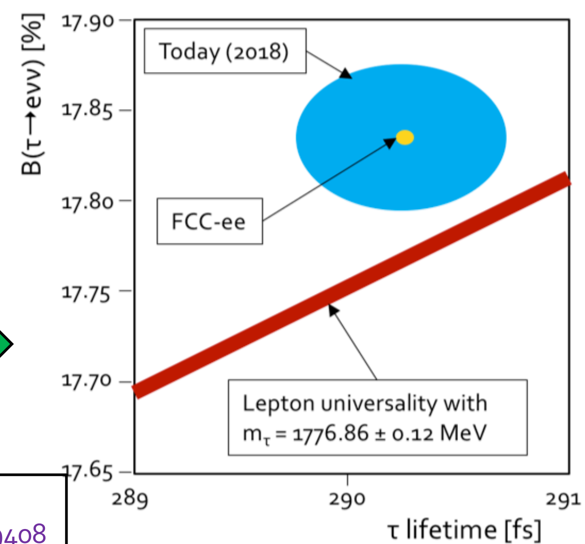
τ properties and Universality

- τ branching fractions and lifetime provide strong test of Universality of the α - ν_α CC coupling, α = e, μ, τ
  - Sensitive to light-heavy neutrino mixing
  - Need also (more) precise mass measurement

Visible Z decays	3 x 10^{12}
$Z \to \tau^+\tau^-$	1.3 x 10^{11}
1 vs. 3 prongs	3.2 x 10^{10}
3 vs. 3 prong	2.8x 10^{9}
1 vs. 5 prong	2.1 x 10^{8}
1 vs. 7 prong	< 67,000
1 vs 9 prong	?

Observable	Current precision	FCC-ee **stat.**	**Possible syst.**
m_τ [MeV]	1776.86 **± 0.12**	**0.004**	**0.1**
τ_τ [fs]	290.3 **± 0.5 fs**	**0.001**	**0.04**
B($\tau\to e\nu\nu$) [%]	17.82 **± 0.05**	**0.0001**	**0.003**
B($\tau\to\mu\nu\nu$) [%]	17.39 **± 0.05**		

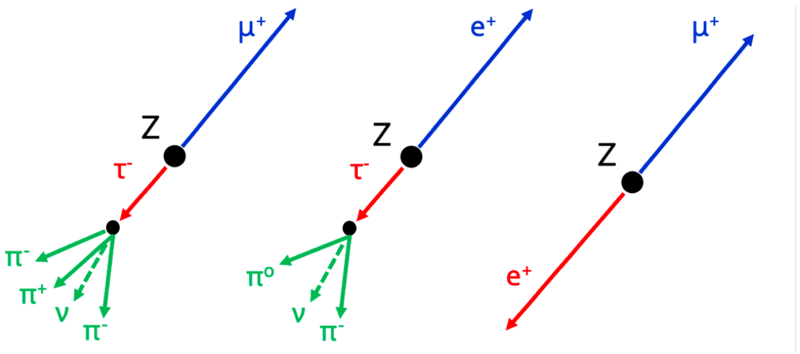
Quantity	Measurement	Current precision	FCC-ee precision
$\lvert g_\mu/g_e\rvert$	$\Gamma_{\tau\to\mu}$ / $\Gamma_{\tau\to e}$	1.0018 **± 0.0014**	**Improvement by a factor 10 or more**
$\lvert g_\tau/g_\mu\rvert$	$\Gamma_{\tau\to e}$ / $\Gamma_{\mu\to e}$	1.0030 **± 0.0015**	



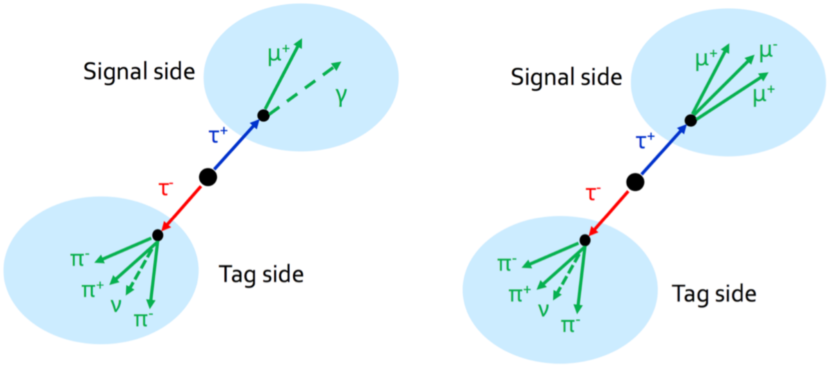
M.Dam
arXiv:1811.09408

τ physics

- Improve sensitivity of lepton flavour violation Z decays by **4 orders of magnitude**



- Improve sensitivity of lepton flavour violation τ decays by 1-2 orders of magnitude



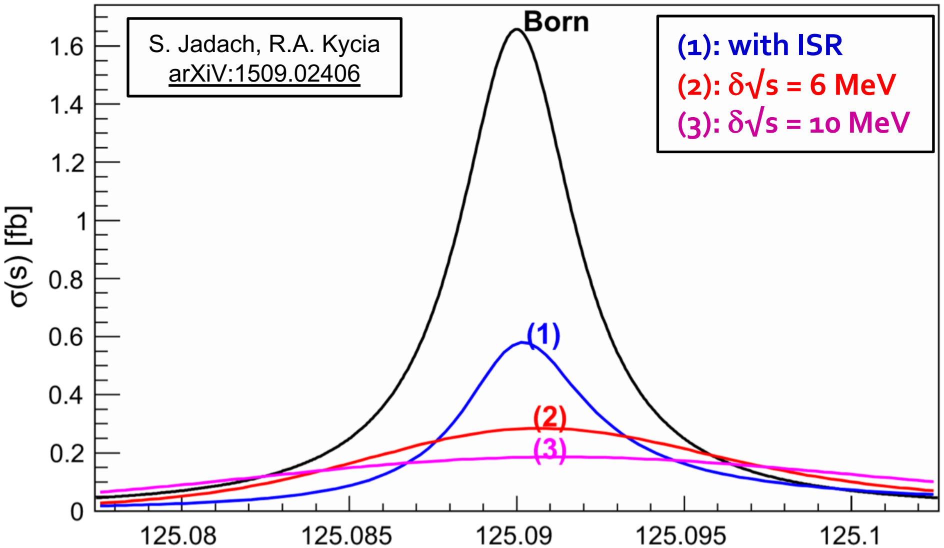
Decay	Present bound	FCC-ee sensitivity
$Z \to \mu e$	0.75×10^{-6}	10^{-10}–10^{-8}
$Z \to \tau\mu$	12×10^{-6}	10^{-9}
$Z \to \tau e$	9.8×10^{-6}	10^{-9}
$\tau \to \mu\gamma$	4.4×10^{-8}	2×10^{-9}
$\tau \to 3\mu$	2.1×10^{-8}	10^{-10}

M.Dam
arXiv:1811.09408

FCC-ee is not only a Z, WW, Higgs and tt factory. But also a factory of heavy flavour: b, τ,…

And if there is time …

- Spend few years at $\sqrt{s}$ = 125.09 GeV with high luminosity
  - For s-channel production $e^+e^- \rightarrow H$ (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
    - $\sigma(e^+e^- \rightarrow H) \sim 100$ ab
  - Option 2: $\delta\sqrt{s}$ = 6 MeV, 2 ab^{-1} / year
    - $\sigma(e^+e^- \rightarrow H) \sim 250$ ab
  - Backgrounds much larger than signal
    - $e^+e^- \rightarrow q\bar{q}, \tau\tau, WW^*, ZZ^*, \gamma\gamma, \ldots$

- Expected signal significance of ~0.4σ / √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

- Unique opportunity to constrain first generation Yukawa's

Summary: FCC-ee physics potential (excerpt)

- EXPLORE the 10-100 TeV energy scale
  - With precision measurements of the properties of the Z, W, Higgs, and top particles
    - Up to 20-50-fold improved precision on ALL electroweak observables (EWPO)
      - m_Z, m_W, m_{top}, Γ_Z, $\sin^2\theta_w^{eff}$, R_b, $\alpha_{QED}(m_z)$, $\alpha_s(m_z, m_W, m_\tau)$, top EW couplings …
    - Up to 10-fold more precise and model-independent Higgs couplings measurements

arXiv:1512.05544
arXiv:1603.06501
arXiv:1503.01325

- DISCOVER that the Standard Model does not fit
  - NEW PHYSICS ! Pattern of deviations may point to the source.
- DISCOVER a violation of flavour conservation / universality
  - Examples: $Z \to \tau\mu$ in 5×10^{12} Z decays; or $\tau \to \mu\gamma$ / $\tau \to e\gamma$ in 2×10^{11} τ decays; …
  - Also $B^0 \to K^{*0}\tau^+\tau^-$ or $B_S \to \tau^+\tau^-$ in 10^{12} bb events
- DISCOVER dark matter as invisible decays of Higgs or Z
  - Precise invisible width measurements
- DIRECT DISCOVERY of very-weakly-coupled particles
  - in the 5-100 GeV mass range, such as right-handed neutrinos, dark photons, ALPs, …
    - Motivated by all measurements / searches at colliders (SM and "nothing else")

All 4 phases of the FCC-ee programme, Z, WW, H, and $t\bar{t}$, are important for the physics potential

Conclusions

The FCC CDR, released on 15/01/2019, demonstrates that:

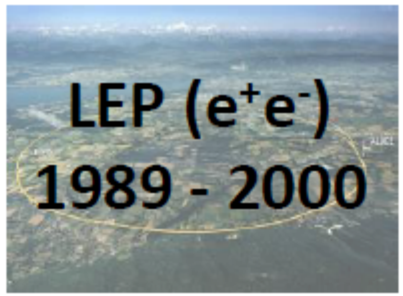
- The FCC-ee design is robust and mature
  - accelerator with record luminosity performance at all four energy points (Z, WW, H, $t\bar{t}$) and with moderate background levels
  - MDI including luminosity monitors
  - two detector designs (to be extended to four)
- With its 4 energy points, FCC-ee has an outstanding physics reach
  - as summarized on the previous slide
- FCC-ee and FCC-hh are highly synenergetic and complementary
  - The sequential implementation : FCC-ee → FCC-hh maximises the physics reach
  - FCC can serve High-Energy Physics in a cost effective manner throughout this century

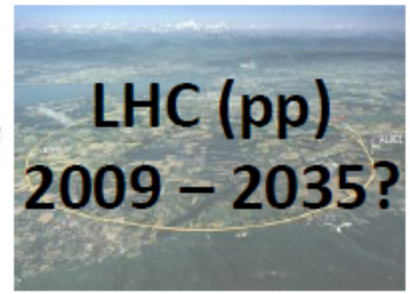
<u>FCC-ee can start seamlessly at the end of HL-LHC</u>

The FCC integrated programme

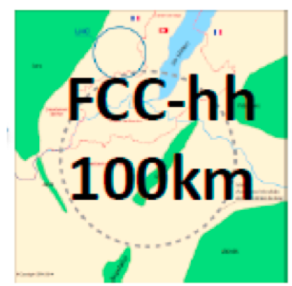
Base the next generation of colliders on a proven model

- 27 km tunnel





- The next step: 100 km tunnel



1 | 2 | 3 | 4 ~ 17 | 18 | 15 years operation | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | ~ 25 years operation | 70

Extra Slides

The FCC CDR

First ideas in 2010-11. Study kicked off in 2014

CDR published on 15/01/2019 at http://fcc-cdr.web.cern.ch/ (>1000 authors)

Vol.1 : Physics Opportunities

Vol.2 : The lepton collider (FCC-ee)

Vol.3 : The hadron collider (FCC-hh) (includes e-h option)

Vol.4: HE-LHC

Common ~100 km infrastructure @ CERN

Civil engineering, electricity, cooling, ventilation, cryogenics

R&D for SC magnets (up to highest affordable field)

Staged approach for collider and physics

1st step: high-luminosity and precision e+e- collider **(FCC-ee)**

Phase A: 88 → 240 GeV (Z, W, Higgs)

Phase B: 345 → 365 GeV (Higgs, top) (significant RF upgrade)

2nd step: high-energy pp collider (**FCC-hh**, 100-150 TeV?) e-p option (FCC-eh)

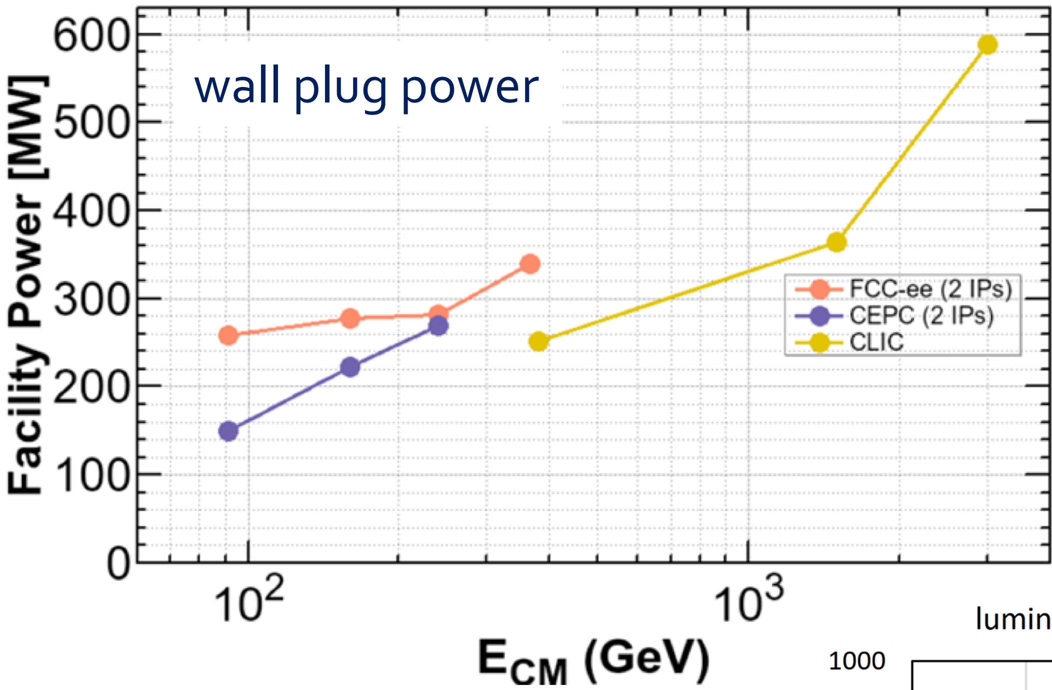
At least 60 years of the most sensitive and versatile search for solutions to the mysteries of Universe (BAU, Dark matter, Neutrino masses, Flavour etc.)

Baseline parameters

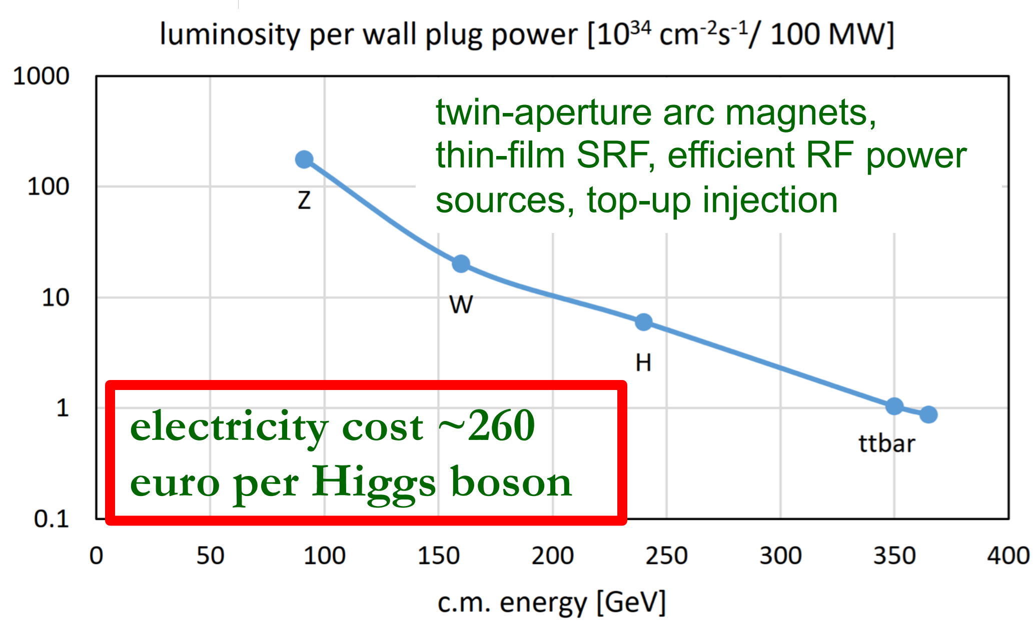
parameter	FCC-ee				LEP2
energy/beam [GeV]	**45**	**80**	**120**	**182.5**	105
bunches/beam	16640	2000	328	48	4
beam current [mA]	1390	147	29	5.4	3
luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	**230**	**28**	**8.5**	**1.5**	0.0012
energy loss/turn [GeV]	0.036	0.34	1.72	9.2	3.34
total synchrotron power [MW]	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 $\varepsilon_{x,y}$ [nm, pm]	0.3, 1.0	0.8, 1.7	0.6, 1.3	1.5, 2.9	22, 250
longit. damping time [turns]	1273	236	70	20	31
crossing angle [mrad]	30				0
beam lifetime (rad.B+BS) [min]	68	48	12	12	434

FCC-ee: 2 separate rings LEP: Single beam pipe

Power consumption



"green accelerator": Very high luminosity per input power unit



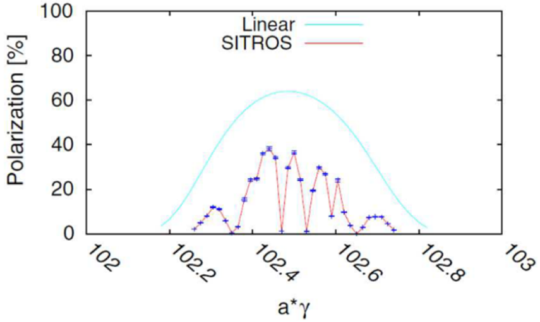
electricity cost ~260 euro per Higgs boson

Polarisation and energy calibration

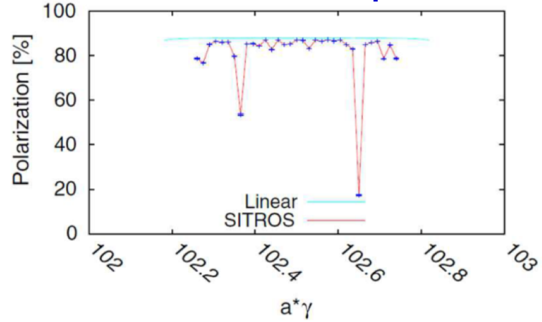
Z pole with polarisation wigglers

E. Gianfelice-Wendt

orbit correction

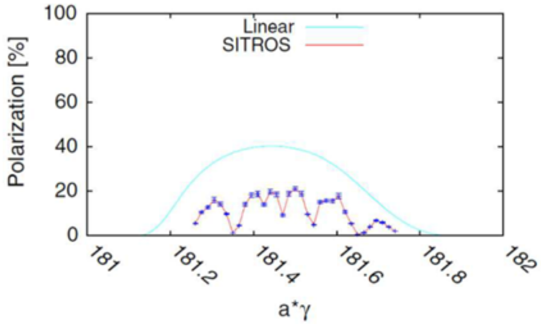


+ harmonic bumps

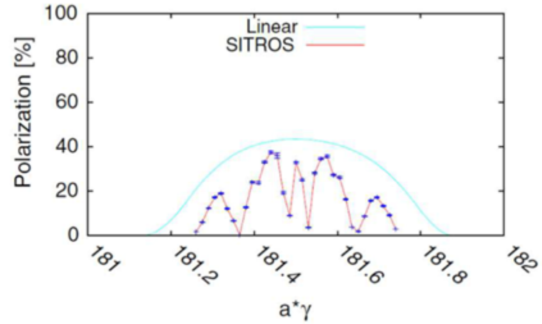


WW threshold

orbit correction



+ harmonic bumps

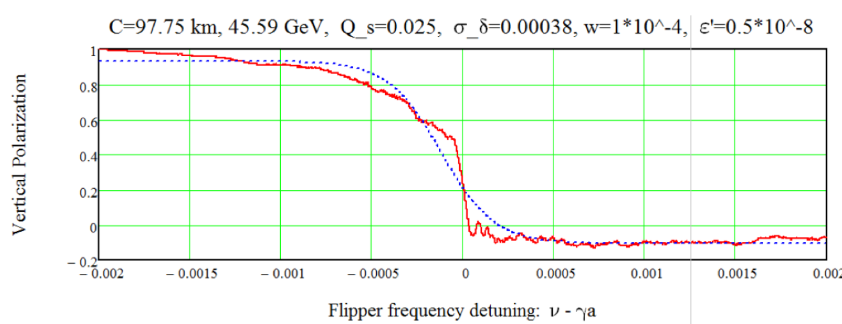


luminosity-averaged centre-of-mass uncertainties:

~100 keV around the Z pole

~300 keV at the W pair threshold

simulated frequency sweep with depolariser



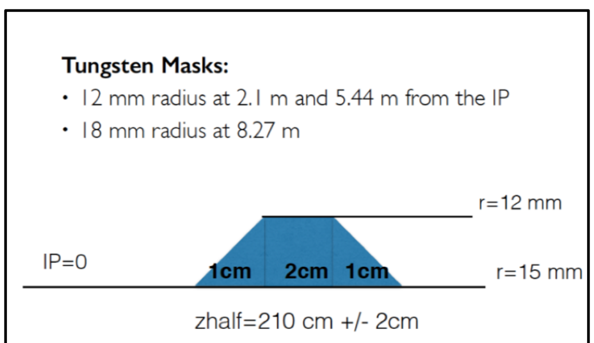
technique used at LEP

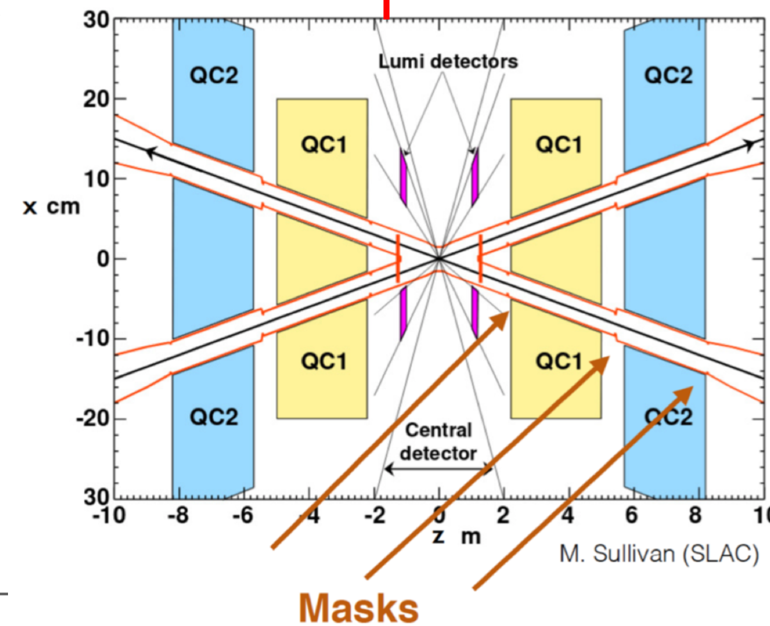
Efficient masking against synchrotron radiation

	Energy (GeV)	Critical energy (keV)	number of bunches	Current (mA)	Incident γ/xing (500μm from tip)	Incoming on central pipe/xing	γ rate on central pipe (Hz)
tt+	**182.5**	113.4	33	5.41	3.32E+09	1195	1.18E+08
tt	**175**	100	40	6.4	3.06E+09	1040	1.25E+08
h	**125**	36.4	328	29	1.05E+09	10.3	1.01E+07
W	**80**	9.56	1300	147	6.11E+08	0.18	7.02E+05
Z	**45.6**	1.77	16640	1390	9.62E+07	1.92E-04	9.58E+03

rate of photons that strike the central pipe that come from the mask tip

- No SR from dipoles or from quads hits directly the central beam pipe (cylinder +/- 12.5 cm long, 1.5 cm radius)
- Non-Gaussian beam tails, considered out to +/-20 σ_x and +/-60σ_y
- On-axis beam
- Quadrupole radiation that may strike mask surfaces included

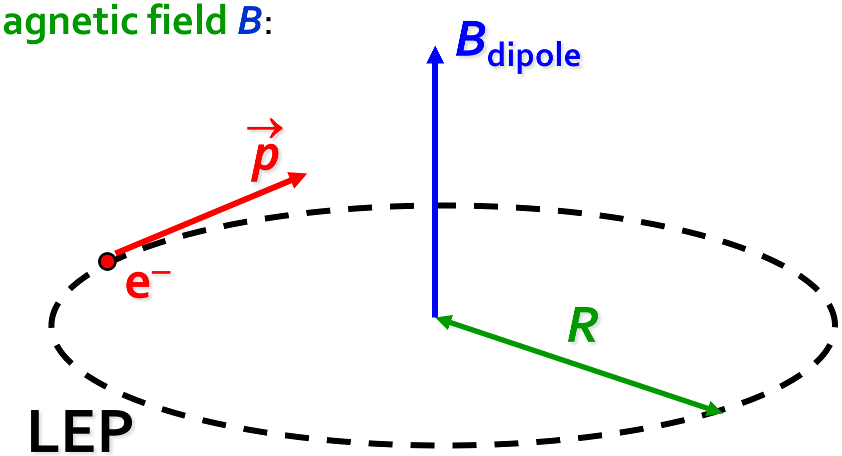




Precision electroweak physics at FCC-ee (2)

- Measurement of the beam energy at LEP
  - Ultra-precise measurement unique to circular colliders (crucial for m_Z, Γ_Z)

Electron with momentum *p* in a uniform vertical magnetic field *B*:



L = 2πR = 27km

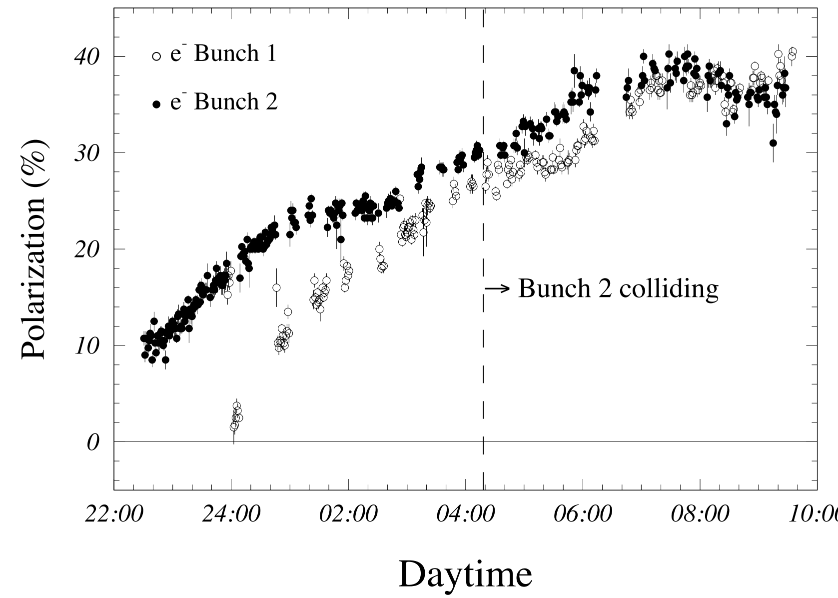
$$E \sim p = e\,B\,R = (e/2\pi)\,B\,L$$

In real life, *B* non uniform, LEP ring not circular

$$\boxed{E = \frac{e}{2\pi}\oint_{\mathrm{LEP}} B\,\mathrm{d}l}$$

To be measured

The electrons get transversally polarized (i.e., their spin tends to align with *B*)

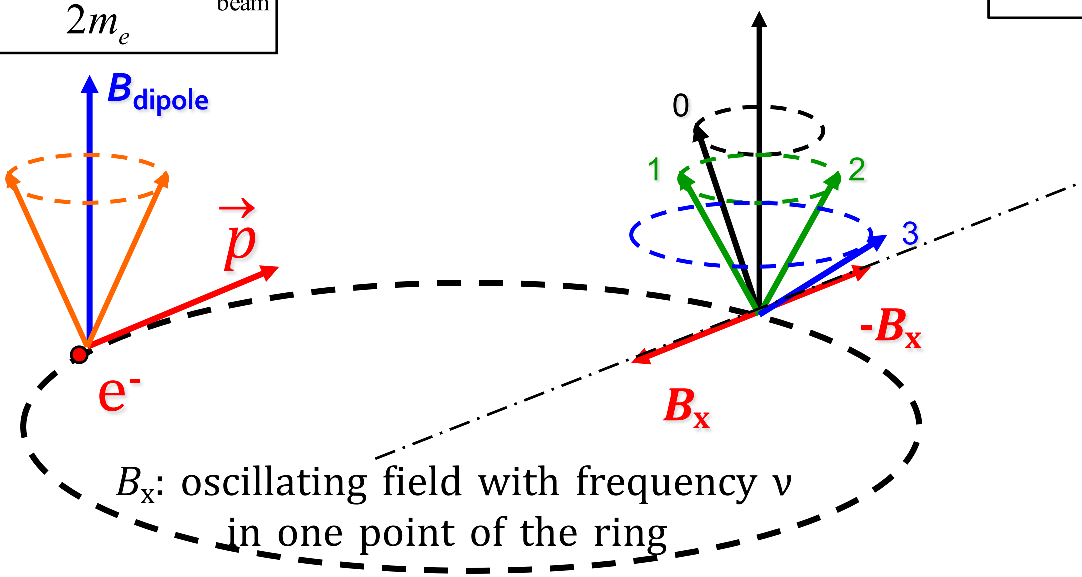


Slow process (~ 1 hour to get 10% polarization)

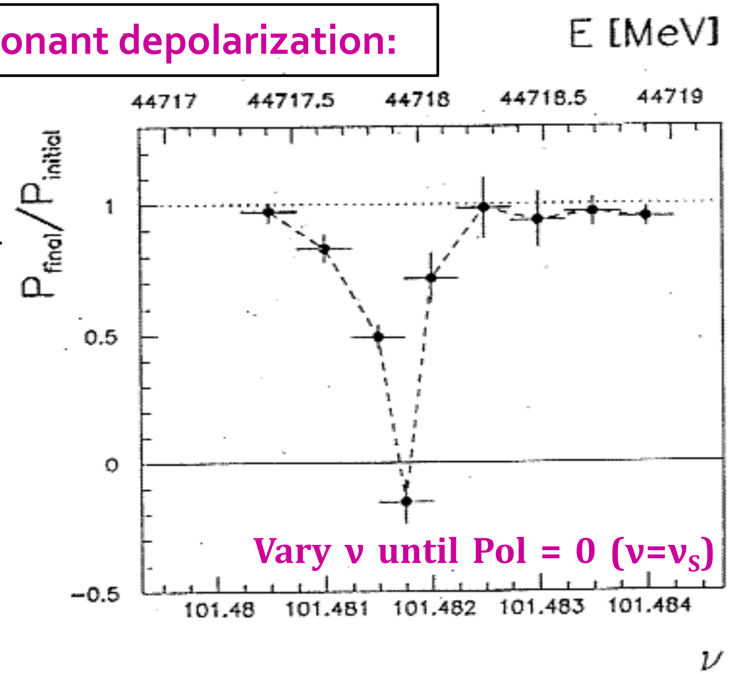
NB. Polarization can be kept in collision (was attempted only once at LEP).

- Measurement of the beam energy at LEP (cont'd)
  - The spin precesses around *B* with a frequency proportional to *B* (Larmor precession)
    - Hence, the number of revolutions ν_S for each LEP turn is proportional to $\int B dl$

$$\nu_s = \frac{g_e - 2}{2m_e} \times E_{\mathrm{beam}}$$



Resonant depolarization:



- LEP was colliding 4 bunches of e^+ and e^-; FCC-ee will have 1,000's of bunches
  - Use ~10 "single" bunches to measure E_{BEAM} with resonant depolarization
    - Each measurement gives 100 keV precision, with no extrapolation uncertainty

Precision electroweak physics at FCC-ee (12)

- The predictions of m_{top}, m_W, m_H, $\sin^2\theta_W$ have theoretical uncertainties
  - Which may cancel the sensitivity to new physics
- For m_W and $\sin^2\theta_W$ today, these uncertainties are as follows

$$\begin{aligned} m_W = \quad & 80.3584 \quad \pm 0.0055_{m_{top}} \pm 0.0025_{m_Z} \pm 0.0018_{\alpha_{QED}} \\ & \qquad\qquad \pm 0.0020_{\alpha_S} \pm 0.0001_{m_H} \pm 0.0040_{theory} \text{ GeV} \\ = \quad & 80.358 \quad \pm 0.008_{total} \text{ GeV}, \end{aligned}$$

Exp: 0.012 GeV

$$\begin{aligned} \sin^2\theta_W^{eff} = \quad & 0.231488 \quad \pm 0.000029_{m_{top}} \pm 0.000015_{m_Z} \pm 0.000035_{\alpha_{QED}} \\ & \qquad\qquad \pm 0.000010_{\alpha_S} \pm 0.000001_{m_H} \pm 0.000047_{theory} \\ = \quad & 0.23149 \quad \pm 0.00007_{total}, \end{aligned}$$

Exp: 0.00016

- Parametric uncertainties and missing higher orders in theoretical calculations:
  - Are of the same order
  - Smaller than experimental uncertainties

Precision electroweak physics at FCC-ee (13)

- Most of the parametric uncertainties will reduce at the FCC-ee
  - New generation of theoretical calculations is necessary to gain a factor 10 in precison
    - To match the precision of the direct FCC-ee measuremetns

$$
\begin{aligned}
m_W = \quad & 80.3584 \quad \pm 0.0001_{m_{top}} \pm 0.0001_{m_Z} \pm 0.0003_{\alpha_{QED}} \\
& \qquad\qquad \pm 0.0002_{\alpha_S} \pm 0.0000_{m_H} \pm 0.0040_{theory} \text{ GeV} \\
= \quad & 80.358 \quad \pm 0.005_{total} \text{ GeV},
\end{aligned}
$$

Exp: 0.0005

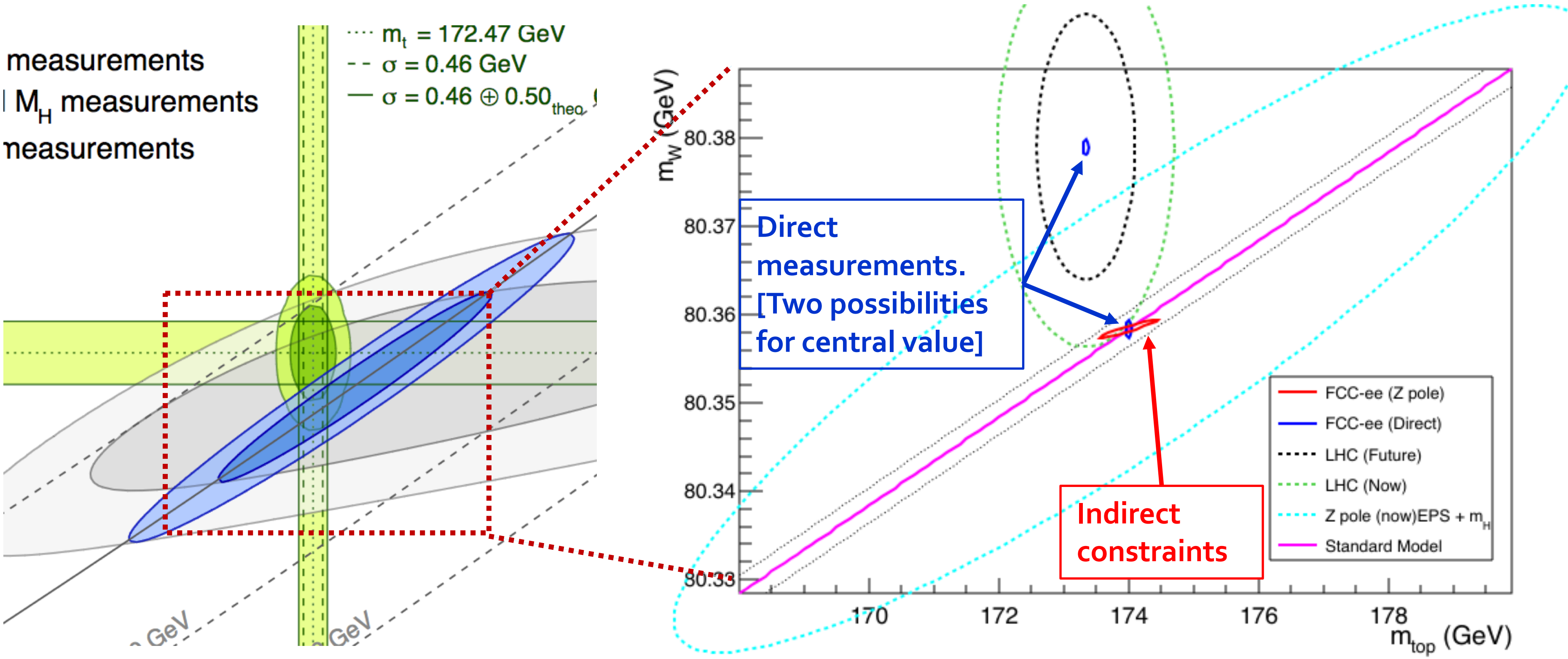
$$
\begin{aligned}
\sin^2\theta_W^{eff} = \quad & 0.231488 \quad \pm 0.000001_{m_{top}} \pm 0.000001_{m_Z} \pm 0.000008_{\alpha_{QED}} \\
& \qquad\qquad \pm 0.000001_{\alpha_S} \pm 0.000000_{m_H} \pm 0.000047_{theory} \\
= \quad & 0.23149 \quad \pm 0.00006_{total},
\end{aligned}
$$

Exp: 0.000006

- Will require calculations up to three or four loops to gain an order of magnitude
  - Might need a new paradigm in the actual computing methods
    - Lots of interesting work for future generations of theorists (you?)

Precision electroweak physics at FCC-ee (8)

- Combination of all precision electroweak measurements
  - FCC-ee precision allows m_{top}, m_W, $\sin^2\theta_W$ to be predicted within the SM
    - … and to be compared to the direct measurements

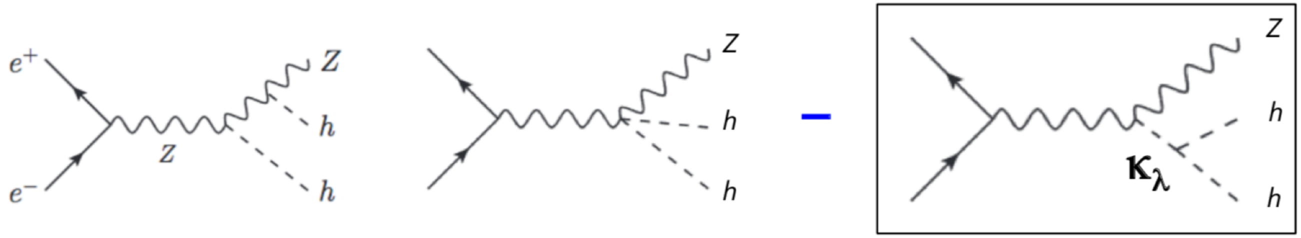


- New Physics ?
  - Direct measts (blue ellipse) and indirect constraints (red ellipse) may or may not overlap

The trilinear Higgs self-coupling κ_λ [1]

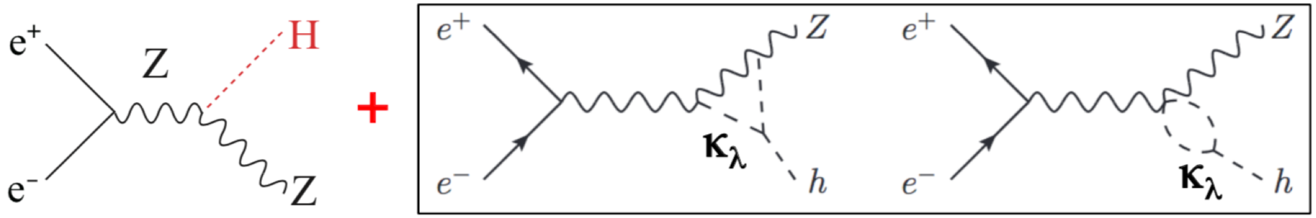
- Traditionally κ_λ is measured with a c.o.m. energy of at least 500 GeV.

Double Higgs production

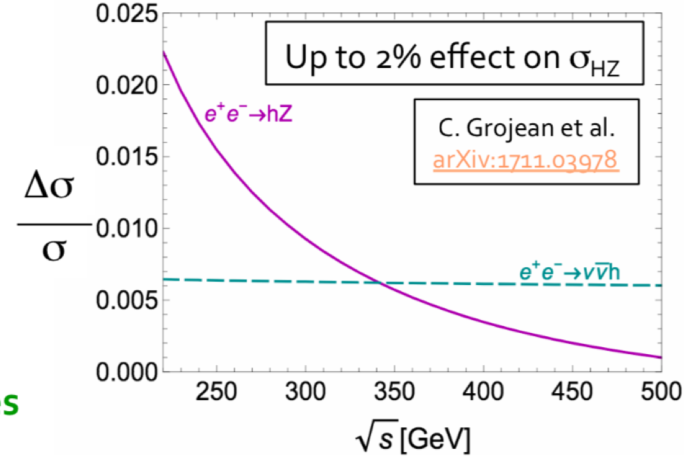


  - At the FCC-ee, a different method can be used with single Higgs production

σ_{HZ}



M. McCullough
arXiv:1312.3322



- Effect on σ_{HZ} is large at the FCC-ee
  - With respect to exp'tal precision on σ_{HZ}
- ~12% exclusive precision on κ_λ with 2 IPs
  - Reduced to 9% with a 4 IP scenario
    - If all other couplings are fixed to their SM values