FCCs: Future Circular Colliders

Une vision à long terme pour la physique des particules

Séminaire @ LLR Palaiseau
27 avril 2015

Join us ! http://cern.ch/fcc-ee/
http://cern.ch/fcc/

Outline

- The FCC Design Study
  - A few facts of life
    - Genesis, goal, scope, implementation, timeline, organization
- Open issues
  - A few selected items
    - FCC-hh: parameters, geology, magnets, power, detectors
    - FCC-ee: parameters, RF, power, SR, MDI, detectors
- Physics opportunities
  - A few synergies between FCC-hh and FCC-ee
    - Complete exploration of the Higgs boson and its dynamics
    - Significant extension of the search range for BSM physics
- Conclusions

The FCC Design Study

A few facts of life

FCCs: European Strategy implementation

After careful analysis of many possible large-scale scientific activities requiring significant re
sizeable collaborations and sustained commitment, the following four activities have been id
as carrying the highest priority.

LHC and HL-LH

c) The discovery of the Higgs boson is the start of a major programme of work to meas particle's properties with the highest possible precision for testing the validity of the Standar and to search for further new physics at the energy frontier. The LHC is in a unique position t this programme. *Europe's top priority should be the exploitation of the full potential of th including the high-luminosity upgrade of the machine and detectors with a view to collecting t more data than in the initial design, by around 2030. This upgrade programme will also further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

pp and ee HE fro

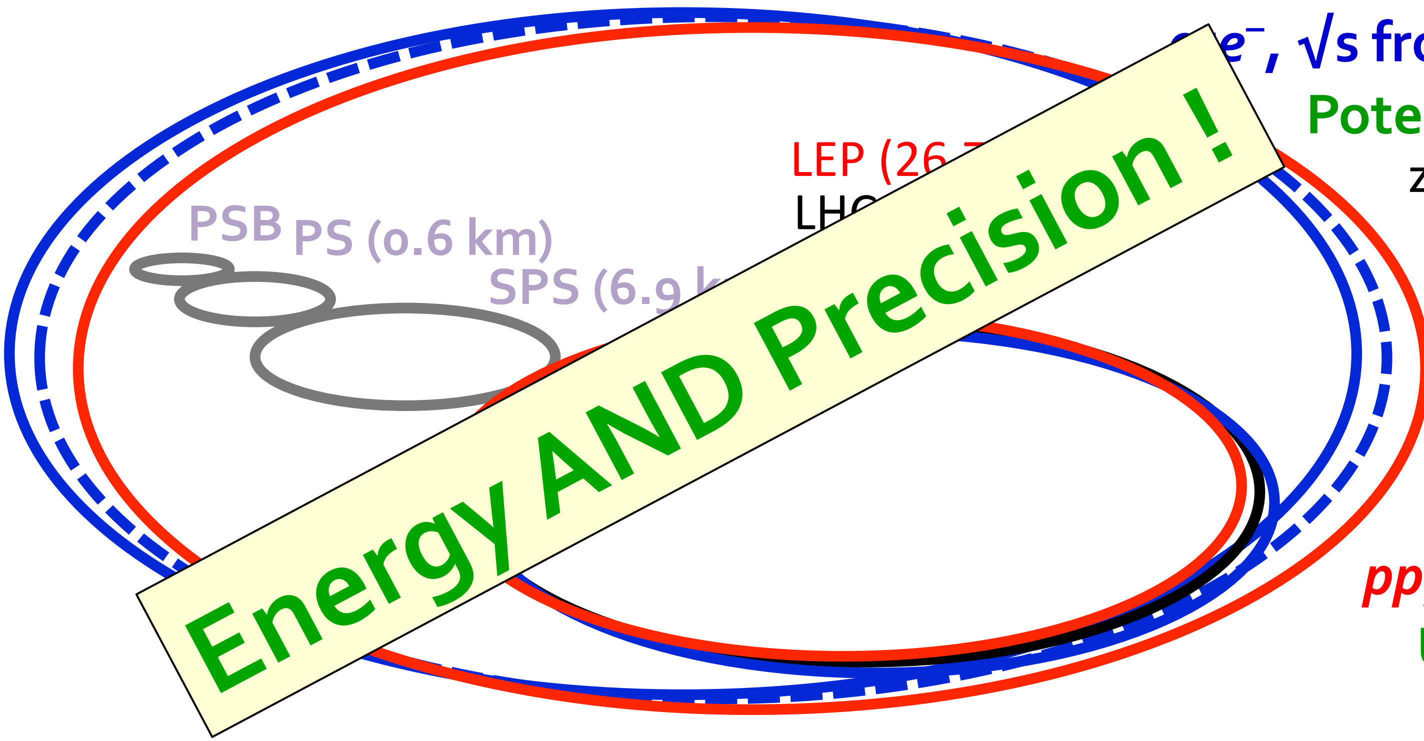
d) To stay at the forefront of particle physics, Europe needs to be in a position to pro ambitious post-LHC accelerator project at CERN by the time of the next Strategy updat physics results from the LHC running at 14 TeV will be available. *CERN should undertak studies for accelerator projects in a global context, with emphasis on proton-proton and e positron high-energy frontier machines. These design studies should be coupled to a v accelerator R&D programme, including high-field magnets and high-gradient acce structures, in collaboration with national institutes, laboratories and universities worldwide.*

Precision e+e

e) There is a strong scientific case for an electron-positron collider, complementary to the LI can study the properties of the Higgs boson and other particles with unprecedented precis whose energy can be upgraded. The Technical Design Report of the International Linear (ILC) has been completed, with large European participation. The initiative from the Japanese physics community to host the ILC in Japan is most welcome, and European groups are participate. *Europe looks forward to a proposal from Japan to discuss a possible participation*

FCCs: Implementation at CERN (1)

- **A long-term vision towards highest precision and energy frontiers**
  - Repeat past successful circular strategy in a 80-100 km tunnel



FCC-ee

e^+e^-, $\sqrt{s}$ from ~60 to ~400 GeV

Potential first step

Z, W, H, top studies
Precision Frontier
Rare decays
Small couplings

FCC-hh

pp, up to 100 TeV.

Ultimate goal

ttH, HHH couplings
Energy Frontier
Rare decays

& ***e***$^\pm$ **(50-175 GeV) – *p* (50 TeV)** collisions (*FCC-he*)

≥ 50 years of e^+e^-, pp and ep collisions at highest energies

FCCs: Implementation at CERN (2)

- Goal of the Study (from http://cern.ch/fcc)

Future Circular Collider Study

FCC ▾ Physics ▾ Accelerators ▾ Opportunities ▾ Society ▾ Recent ▾

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Our Goal

CERN is undertaking an integral design study for post-LHC particle accelerator options in a global context. The Future Circular Collider (FCC) study has an emphasis on proton-proton and electron-positron (lepton) high-energy frontier machines. It is exploring the potential of hadron and lepton circular colliders, performing an in-depth analysis of infrastructure and operation concepts and considering the technology research and development programs that would be required to build a future circular collider. A conceptual design report will be delivered before the end of 2018, in time for the next update of the European Strategy for Particle Physics.

News and Events

Press Releases

- CERN prepares its long-term future
- ARUP develops BIM tool for design of future particle accelerator

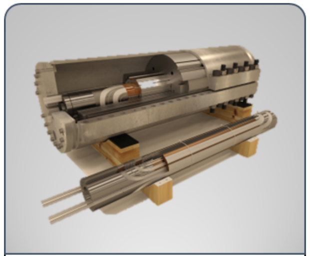
FCCs: Implementation at CERN (3)

- **Scope of the project: Accelerator and infrastructure**

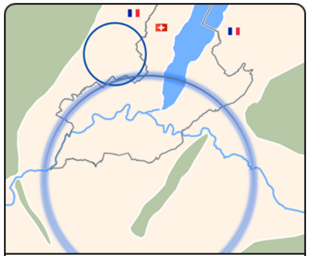
  - FCC-hh: Long-term goal. Defines the infrastructure needs
  - FCC-ee: Potential first step. Defines corrections to the infrastructure
  - FCC-eh: Synergy with ee and hh. Integration aspects studied

Collider Designs

  - Push key technologies in dedicated R&D programmes, e.g.,
    - 16T magnets for 100 TeV pp collisions in 100 km
    - High-gradient superconducting RF in CW mode
    - Efficient RF power sources

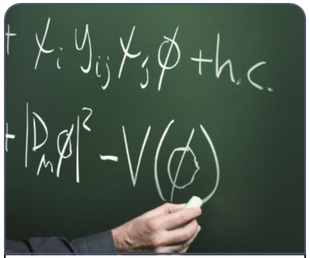

R&D Programs

  - Tunnel infrastructure in Geneva area
    - Links to existing CERN accelerator complex
    - Site specific, as requested by European Strategy


Infrastructures

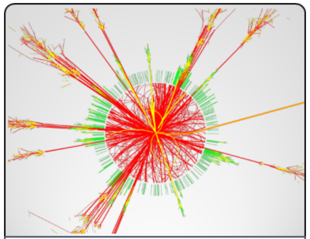
FCCs: Implementation at CERN (4)

- **Scope of the project: Physics and Experiments**
  - Elaborate and document
    - Physics opportunities and discovery potential
    - Complementaries/synergies of the three colliders



Physics Cases

  - Propose detector concepts for hh, ee, and eh
  - Study and optimize machine-detector interface
  - Conceive worldwide data services



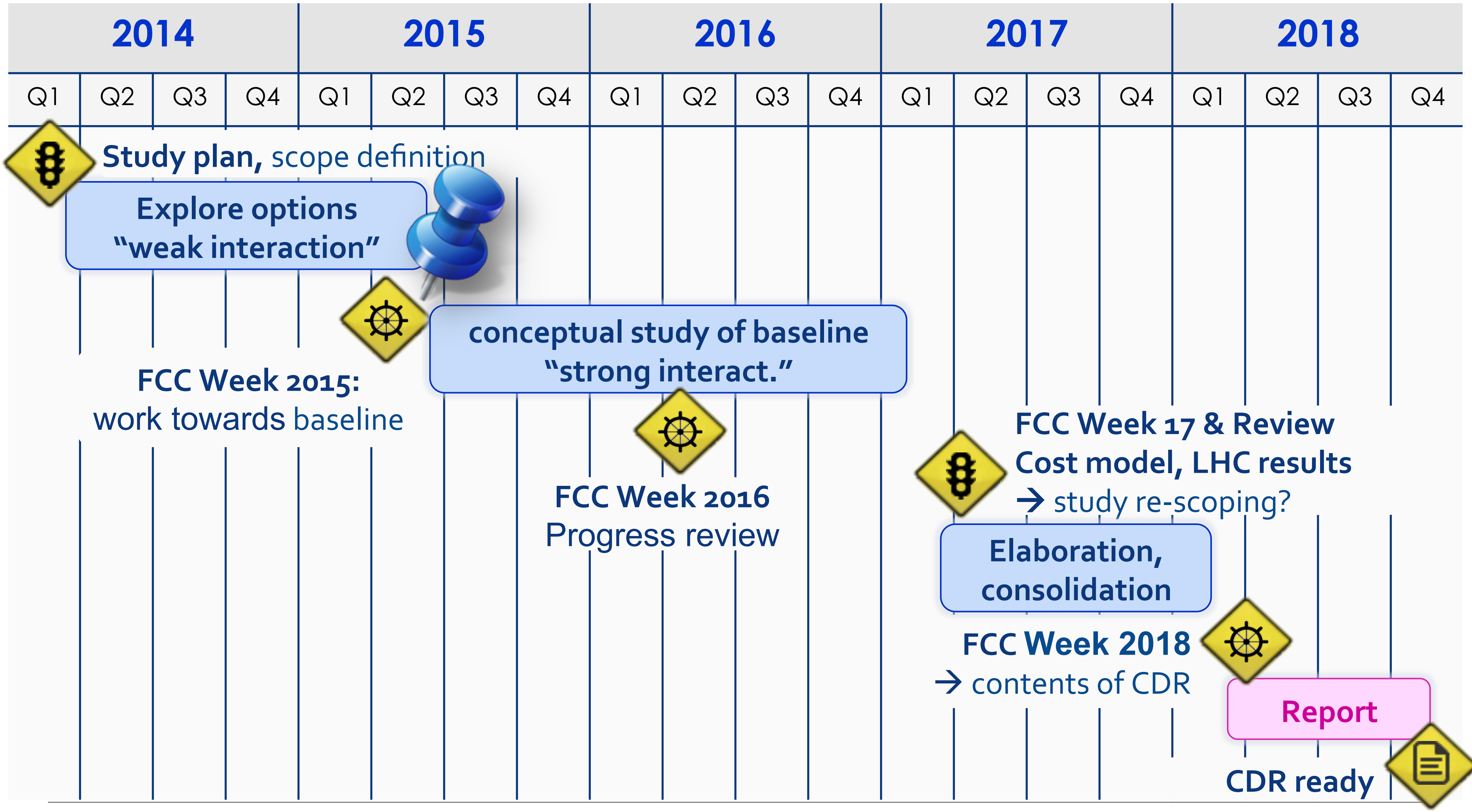
Experiments

- **Scope of the project: Cost**
  - Overall cost model
    - Cost scenarios for collider options
    - Including infrastructure and injectors
    - Implementation and governance models

Cost Estimates

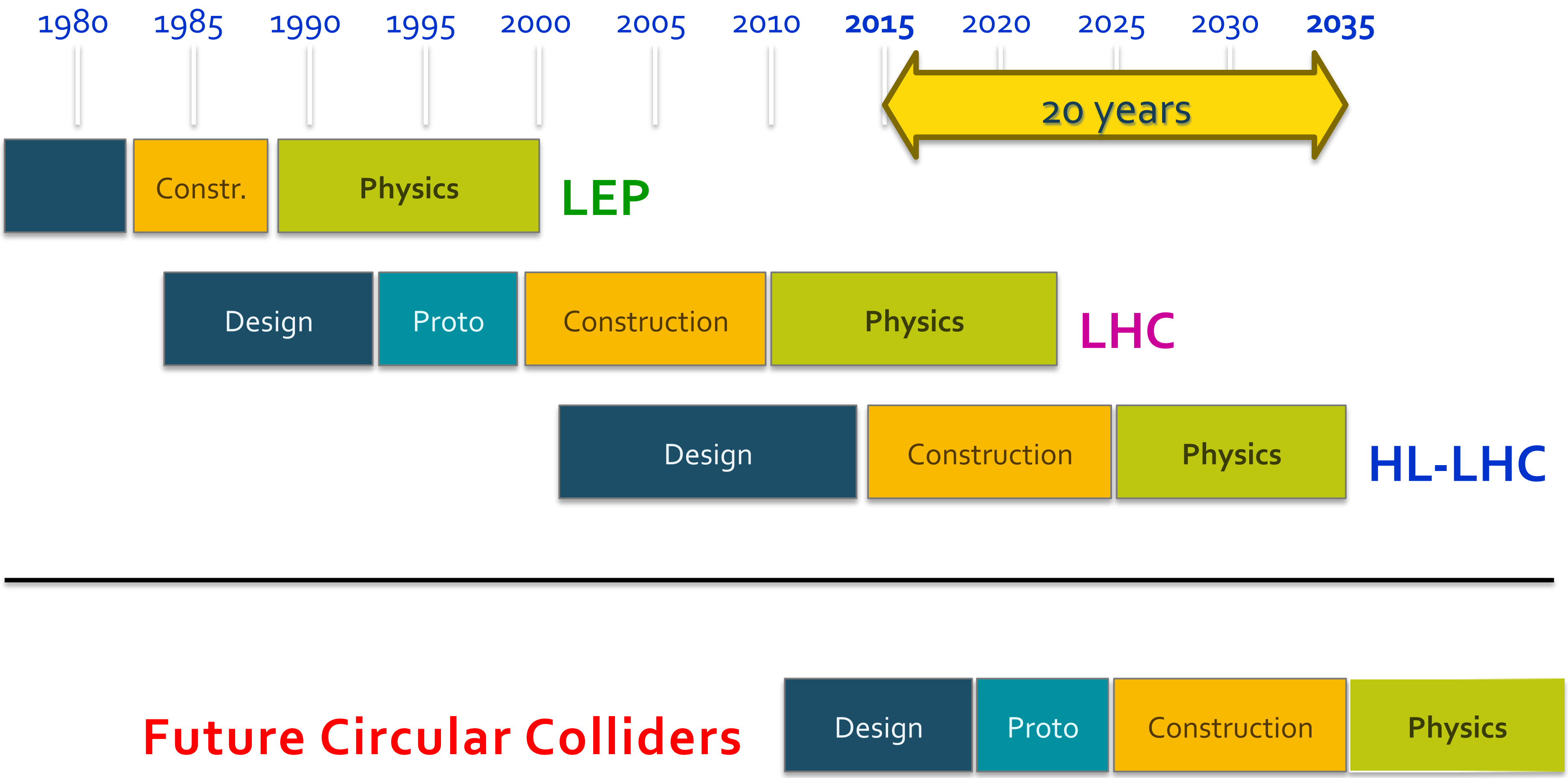
FCCs: Implementation at CERN (5)

- Study timeline towards CDR



FCCs: Implementation at CERN (6)

- **Long-term timeline: Circular colliders at CERN**



The FCC Collaboration (1)

- **51 institutes, 19 countries, EC participation (EuroCircol H2020)**

- A consortium of of partners based on a Memorandum of Understanding (MoU)
  - IN2P3 is among the signatories of the MoU (signed on 02/10/14 by J. Martino)
  - Each institute can now sign the agreement addendum with specific contributions
    - ➨ https://cern.ch/fcc-ee/content/sign-mou
    - ➨ I am the CERN contact for physics and experiments

The FCC Collaboration (2)

- **International support and already large participation**
  - **E.g., at the 1st FCC week in Washington (21-27 March 2015)**
    - **More than 340 participants**
      - **Of which many lab directors (CERN, FNAL, …)**

The FCC Collaboration (3)

Coordination group of the FCC study

Study Lead	M. Benedikt, F. Zimmermann
Hadron Collider **Physics** & **Experiments**	A. Ball, W. Riegler, M. Mangano
Lepton Collider **Physics** & **Experiments**	A. Blondel, J. Ellis, C. Grojean, P. Janot
ep **Physics, Experiment**, IP Integration	M. Klein, O. Bruning
Hadron **Injectors**	B. Goddard
Hadron Collider	D. Schulte, M. Syphers
Lepton **Injectors**	Y. Papaphilippou
Lepton Collider	F. Zimmermann, J. Wenninger, U. Wienands
Accelerator Technologies **R&D**	L. Bottura, E. Jensen, L. Tavian
Special Technologies	JM. Jimenez
Infrastructures & **Operation**	P. Lebrun, P. Collier
Costing & **Planning**	P. Lebrun, F. Sonnemann

The FCC Collaboration (4)

- **Experimental studies – Coordinators A. Blondel, P. Janot**
  - Precision measurements of the Z, W, H, t properties - Rare decays – BSM physics

EW Physics (Z pole)	Diboson physics, m_W	H(126) Properties	Top Quark Physics
R. Tenchini F. Piccinini	R. Tenchini F. Piccinini	M. Klute K. Peters	P. Azzi

QCD and $\gamma\gamma$ Physics	Flavour Physics	New Physics
D. d'Enterria P. Skands	S. Monteil J. Kamenik	M. Pierini C. Rogan

  - Develop the necessary tools

Understand the experimental conditions

Physics Software	Online & Trigger	Exp'tal Environment
C. Bernet B. Hegner	E. Perez C. Leonidopoulos	N. Bacchetta

Common across FCC
Synergies with LCs

Synergy with FCC-hh
and Linear Colliders

  - Set constraints on the possible detector designs to match statistical precision

Detector Designs
A. Cattai
G. Rolandi

Synergy with linear collider detectors:
Collaboration with CLIC detector (CERN group)
Several detectors possible
lots of space for new ideas!

Open issues

A few selected items for FCC-hh and FCC-ee

FCC-hh : Preliminary parameters

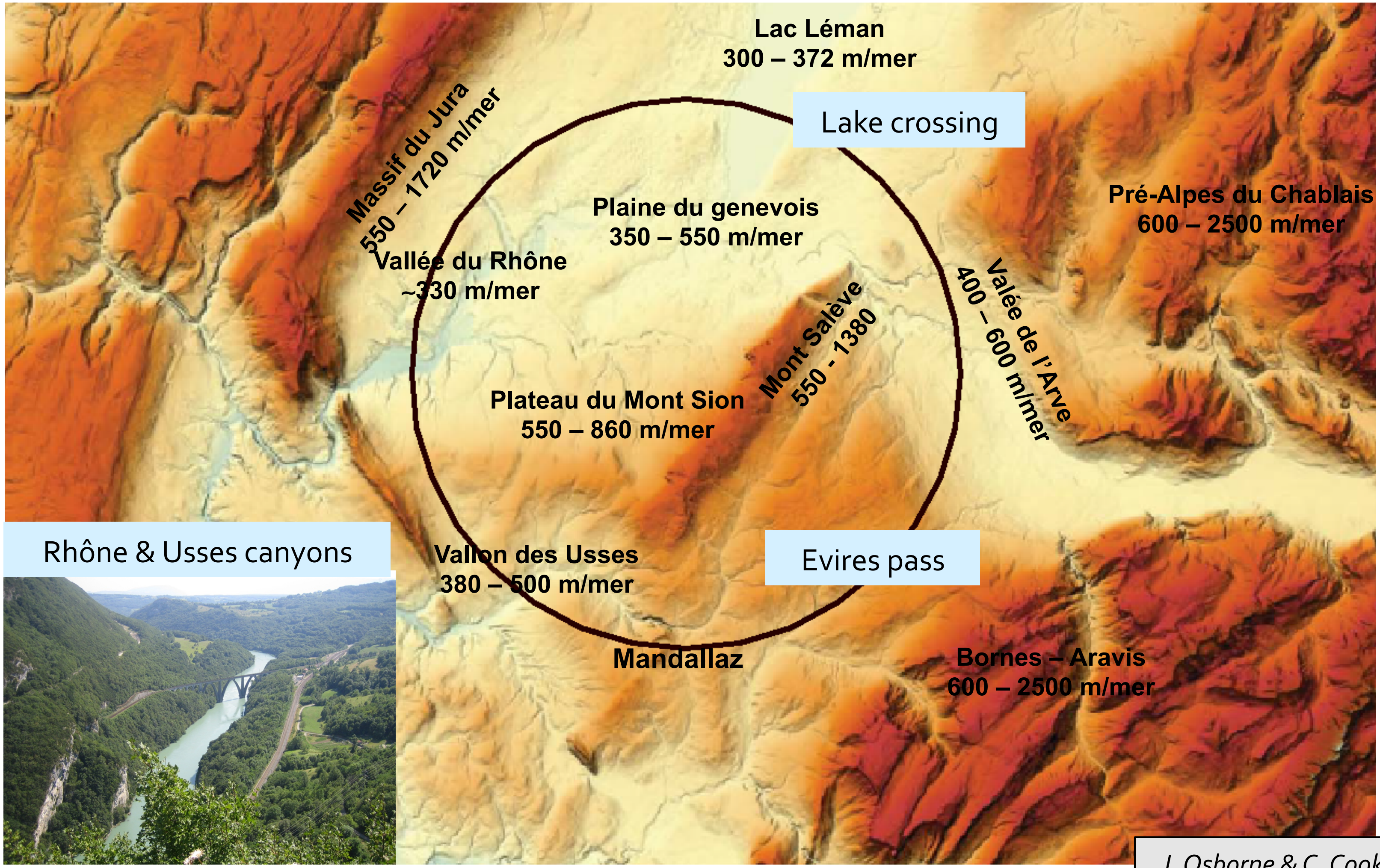
- Challenges are well beyond HL-LHC

Parameter	LHC	HL-LHC	FCC-hh
√s (TeV)	14		**100**
Circumference (km)	26.7		**100 (80)**
Dipole field (T)	8.3		**16 (20)**
Luminosity (10^{34} $cm^{-2}s^{-1}$)	1	5	5 [→ **30**]
Integrated Lumi (ab^{-1})	0.3	3	3 [→ **30**]
Bunch spacing (ns)	25		25 {**5**}
Events / bunch crossing	35	140	170 {34} [→ **1020** {**204**}]
Total SR Power (MW)	0.007	0.015	**5** [→ **30**]

- **A few selected open issues**
  - **Geology and civil engineering**
  - **High-field dipoles**
  - **Power consumption (cryogenics)**
  - **Cost**
  - **Detectors (studied with the ultimate parameters)**

FCC-hh : Geology and civil engineering (1)

- Geneva basin seems to be tailored for a 90-100 km circular tunnel



J. Osborne & C. Cook

FCC-hh : Geology and civil engineering (2)

- 93-km optimized racetrack: preliminary tunnel shape and location

Alignment | **Shaft Tools**

Choose alignment option

93km quasi-circular ▼

Tunnel depth at centre: 286mASL

Gradient Parameters

Azimuth (°): -15

Slope Angle x-x(%): .3

Slope Angle y-y(%): 0

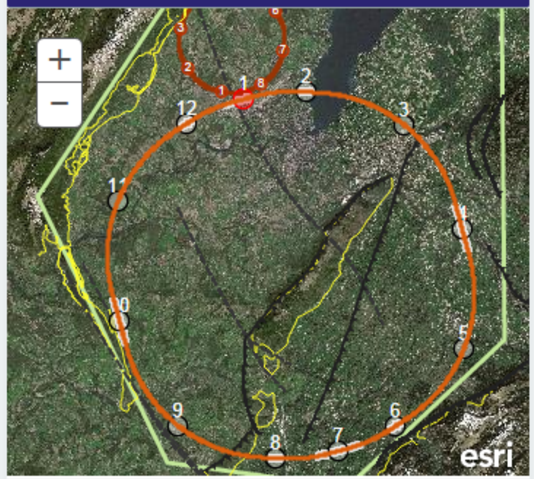
CALCULATE

Alignment centre

X: 2498923 Y: 1106695

LHC Intersection	IP 1	IP 2
Angle	1°	-1°
Depth	542m	542m

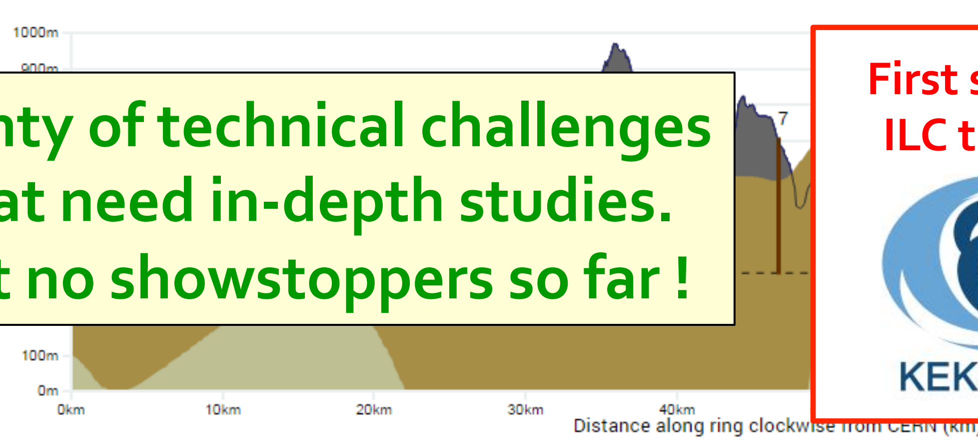
Alignment Location



Geology Intersected by Shafts | **Shaft Depths**

	Shaft Depth (m)				Geology (m)		
Shaft	Actual	Min	Mean	Max	Moraine	Molasse	Calcaire
1	200	195	197	200	92	108	0
2	196	143	181	211	34	162	0
3	183	175	184	194	53	121	9
4	174	146	166	178	44	130	0
5	299	286	311	350	0	325	0
6	336	325	339	350	35	302	0
7	374	349	377	412	119	256	0
8	337	318	341	366	44	56	237
9	155	131	145	167	94	61	0
10	315	305	320	336	46	269	0
11	203	199	202	204	122	81	0
12	239	229	238	243	58	181	0
Total	3014	2801	3001	3211	741	2052	247

Alignment Profile



Plenty of technical challenges that need in-depth studies. But no showstoppers so far !

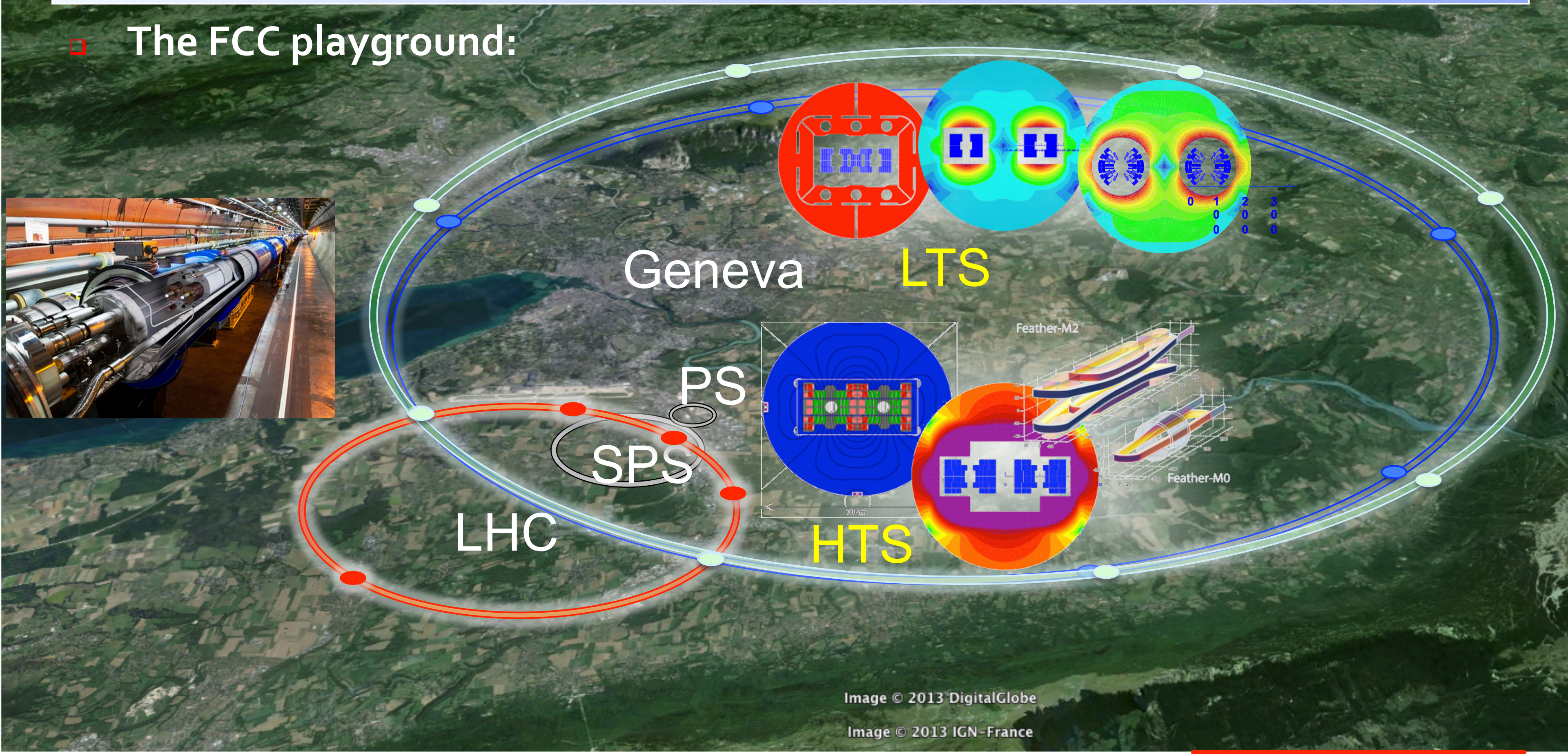
First spin-off: tool will be used for ILC tunnel optimization in Japan

KEK-JAPAN

J. Osborne & C. Cook

FCC-hh : High-Field Dipoles (1)

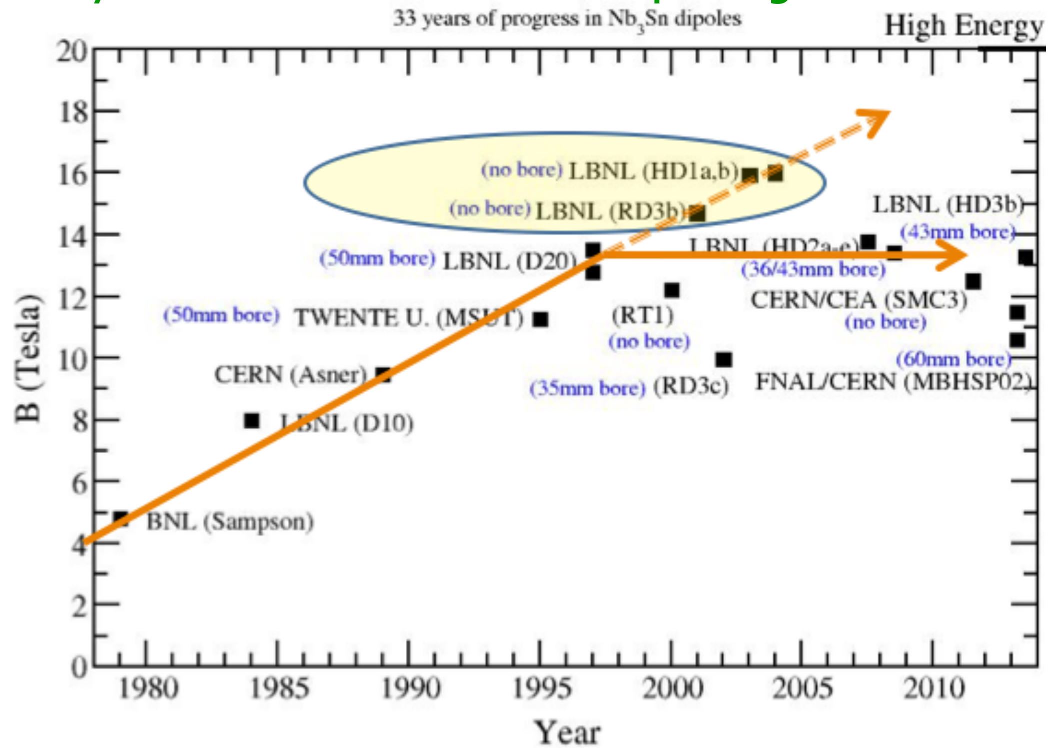
- The FCC playground:



LHC, 27 km 8.33 T, 14 TeV 1300 tons NbTi	HE-LHC, 27 km **20 T,** 33 TeV 3000 tons LTS 700 tons HTS	FCC-hh, 80 km **20 T,** 100 TeV 9000 tons LTS 2000 tons HTS	FCC-hh, 100 km **16 T,** 100 TeV 6000 tons Nb_3Sn 3000 tons Nb-Ti

FCC-hh : High-Field Dipoles (2)

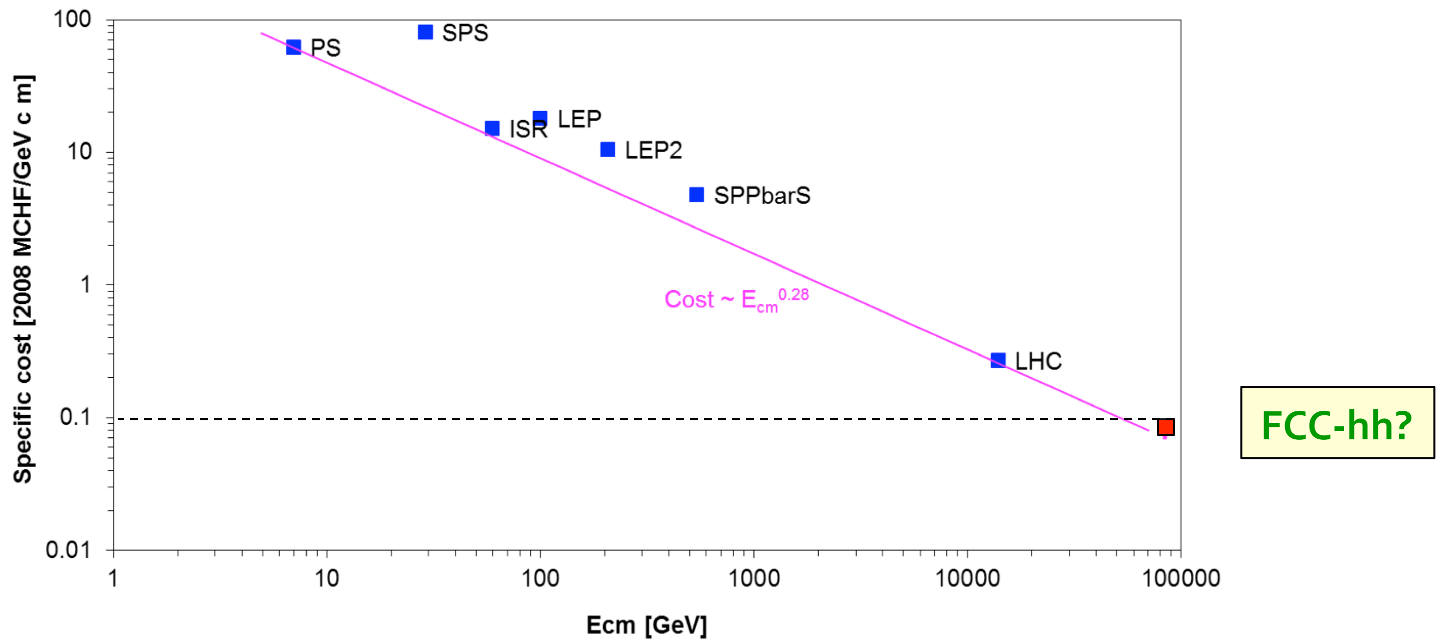
- **Dipoles: increasing magnetic field is not easy**
  - Fields above 16T have been reached at LBNL in three prototypes with Nb_3Sn
  - But a wall at 11-13T is hit with realistic bores are incorporated – no progress in 20 years
    - Probably mechanical limitations: New paradigm needed



  - Going to 20T will probably requires high-temperature superconducting (HTS) magnets
- **Decades of R&D ahead, with America, Asia, Europe (EuroCirCol)**

FCC-hh : Cost reduction

- **Cost: any estimate would be purely speculative**
  - It is a project in its infancy (about one year old) and a 5-years study is just starting
    - Can learn from past experience: cost/GeV steadily decreases



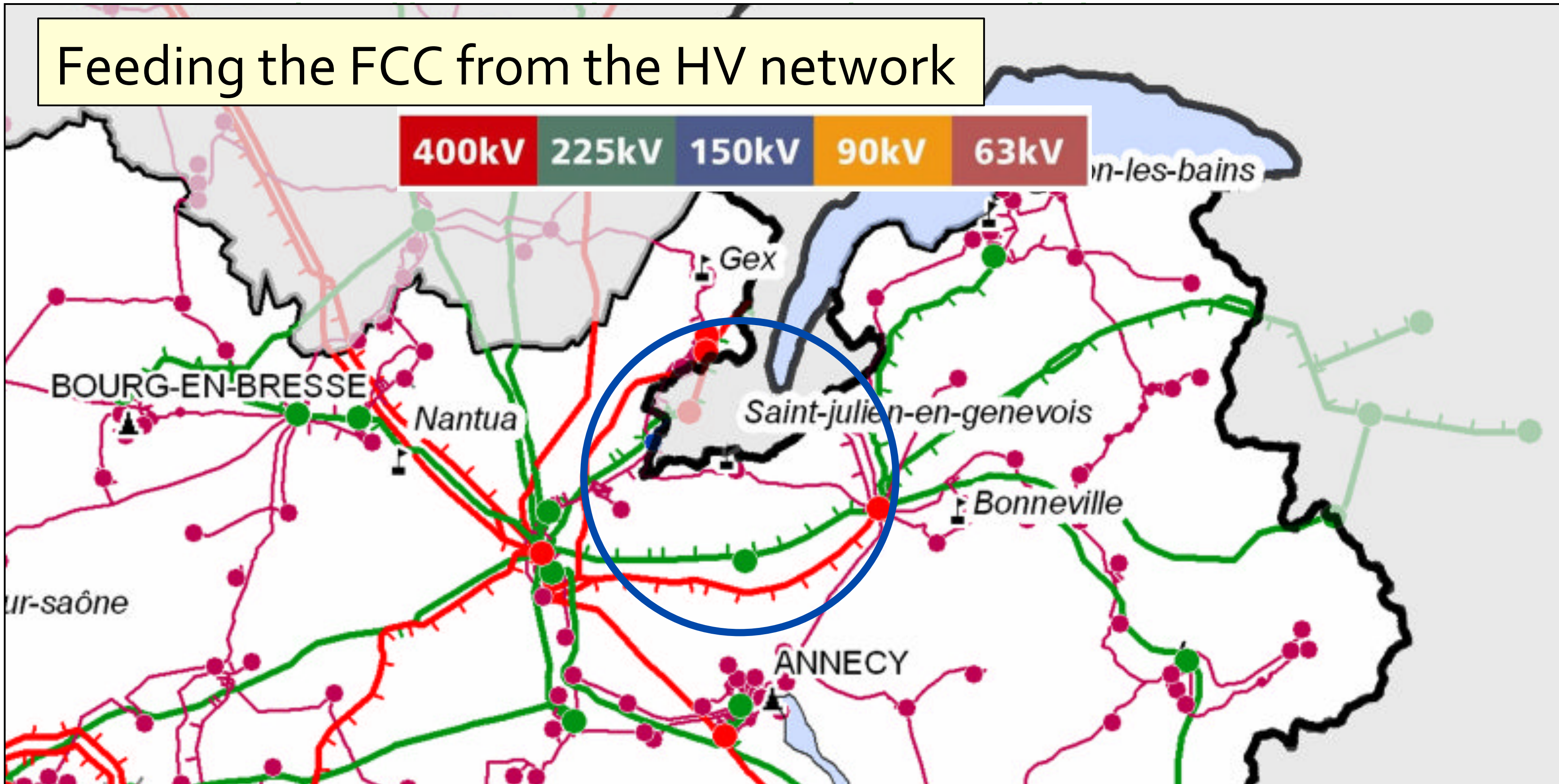
  - To be affordable, the cost needs to be reduced by a factor 3 (100 kCHF/GeV)
    - Cost of the 6000 tons of Nb_3Sn must decrease to below 1000 CHF / kg
    - While increasing the dipole field by a factor two or more !

That's 10 BCHF for 100 TeV

- **Time will be needed before FCC-hh becomes affordable**

FCC-hh : Power consumption and cryogenics

- **Power: the FCC-hh will be greedy**
  - **FCC-hh power consumption will be mostly LHC × 4 is nothing specific is done**



    - Cryogenic system design and cold mass optimization
  - **The overall energy consumption can be optimized, e.g., by waste heat recovery**

FCC-hh : Detectors (1)

- **Detectors: a formidable challenge, beyond HL-LHC**
  - Up to 1000 in-time pile-up events with 25 ns bunch spacing, bunch length 5 cm
    - High-granularity calorimetry, tracking and vertexing required
  - Reduced to 200 in-time pile-up events with 5 ns bunch spacing
    - Ultra fast detectors required (out-of time pile-up)

  - Large longitudinal event boost
    - Enhanced coverage at large rapidity required (with tracking and calorimetry)
      - ➨ Also need for forward-jet tagging in boson fusion production
  - Zs, Ws, Higgses, tops, will also be boosted
    - Again, high-granularity detectors needed

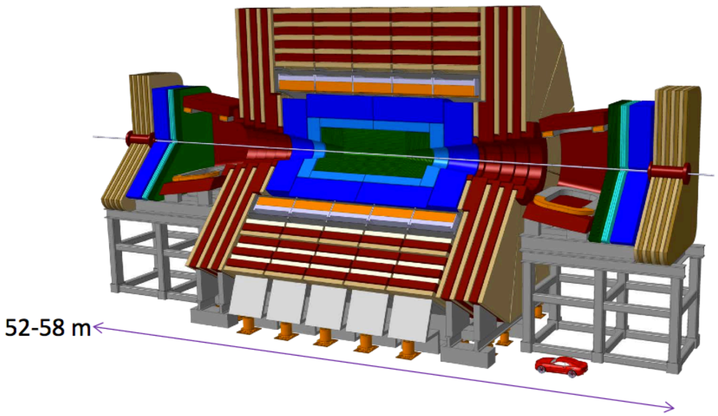
  - Very energetic charged particles
    - Precise momentum measurement up to 10 TeV: strong B field (6T) and large tracker
  - Very energetic jets
    - Energy containment require thicker calorimeter

Bigger, thicker, faster, stronger, clever detectors

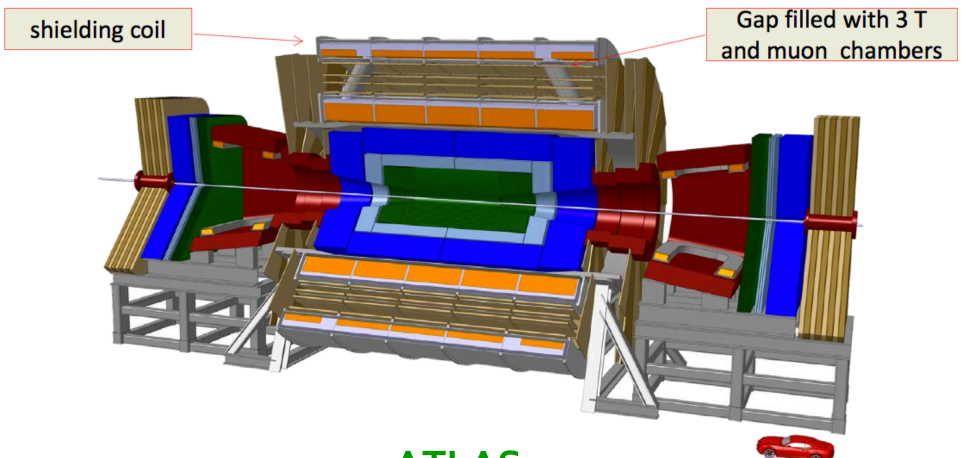
FCC-hh : Detectors (2)

- **Several options contemplated**

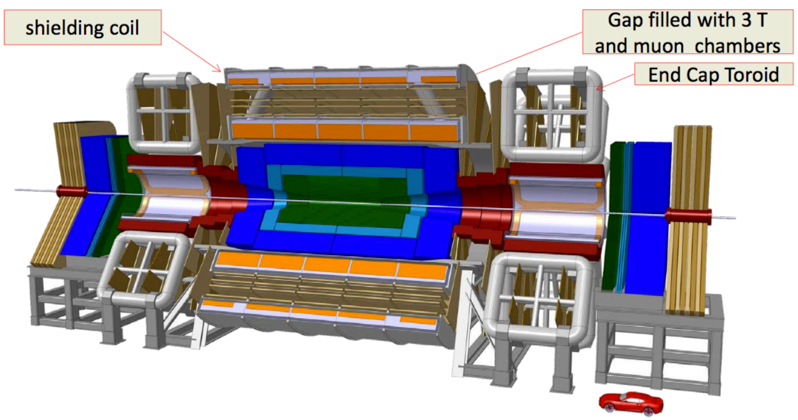
CMS+ (solenoid+yoke+dipoles)



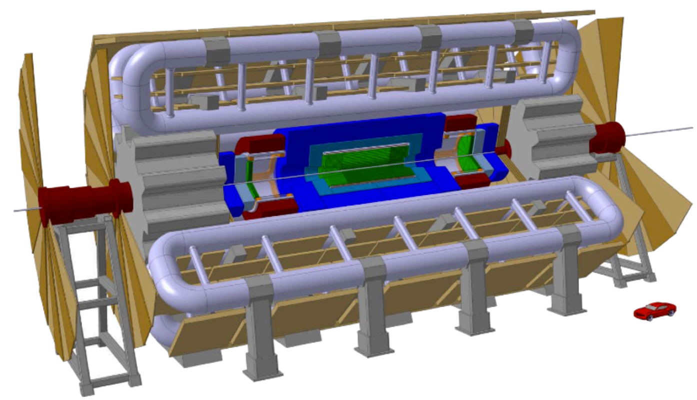
+ shield coil (3T) to avoid 120 kt yoke !



CMS/ATLAS hybrid



ATLAS+



FCC-hh detector strategy meeting (29 Apr): http://indico.cern.ch/event/388119/

FCC-hh open issues : Bottom line

- **It will take time before FCC-hh can be realized**
  - Loads of R&D ahead for high-field dipoles magnets
  - Power consumption is a challenge
  - Beyond-the-state-of-the-art detectors must be conceived
  - Huge construction costs must be reduced to make it affordable
  - CERN budget is what it is…

- **The next machine after the LHC will probably be an e^+e^- collider**
  - Be it only to measure precisely the properties of the newly-discovered Higgs boson
    - The FCC-ee can actually do much more (see later)

- **"We would be crazy not to study the ee option in the FCC ring"**
  - Quote from Rolf Heuer in front of the CERN council (December 2014)

FCC-ee : Preliminary parameters (1)

- **Four different machines from below the Z pole to above the top threshold**

parameter	**FCC-ee**	LEP2
Energy/beam	45 – **175** GeV	105 GeV
Energy loss / turn	0.03 – **7.55** GeV	3.34 GeV
Synchrotron radiation power	**100 MW (Design choice)**	23 MW
RF voltage	2.5 – **11 GV**	3.5 GV
Bunches / beam	**60000 – 50**	4
Beam current	**1450** – 6.6 mA	3 mA
Hor. emittance	**~2 nm**	~22 nm
Emittance ratio $\varepsilon_y/\varepsilon_y$	**0.2 – 0.1%**	1%
Vert. IP beta function β_y^*	**1 mm**	50 mm
Luminosity / IP	**280 – 1.5** x 10^{34} $cm^{-2}s^{-1}$	0.0012 x 10^{34} $cm^{-2}s^{-1}$

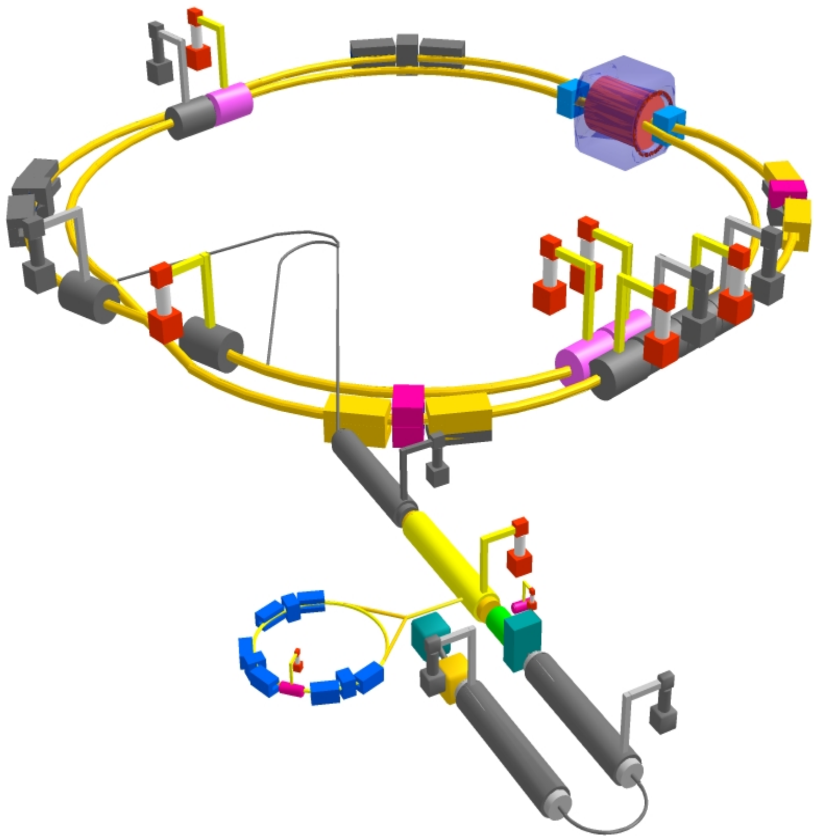
ILC-like optics

- **Large number of bunches at the lower energies requires two separated collider rings**
  - **But high RF voltage at the top threshold calls for sharing the RF system**
- **High luminosity means short beam lifetime (few mins, Bhabha scattering)**
  - **Requires continuous top-up beam injection with a third accelerator ring**

(possibly not going through detectors!)

FCC-ee : Preliminary parameters (2)

- **Challenging, but … SuperKEK-B will be a FCC-ee demonstrator**
  - **Most of the challenging FCC-ee parameters will be commissioned starting this year**



To be commissioned in 2015

Some SuperKEKB parameters :

β^*_y : 300 µm
FCC-ee (H) : 1 mm

σ_y : 50 nm
FCC-ee (H) : 50 nm

$\varepsilon_y/\varepsilon_x$: 0.25%
FCC-ee (H) : 0.2% to 0.1%

e^+ production rate : 2.5×10^{12} / s
FCC-ee (H) : $< 1 \times 10^{11}$ / s

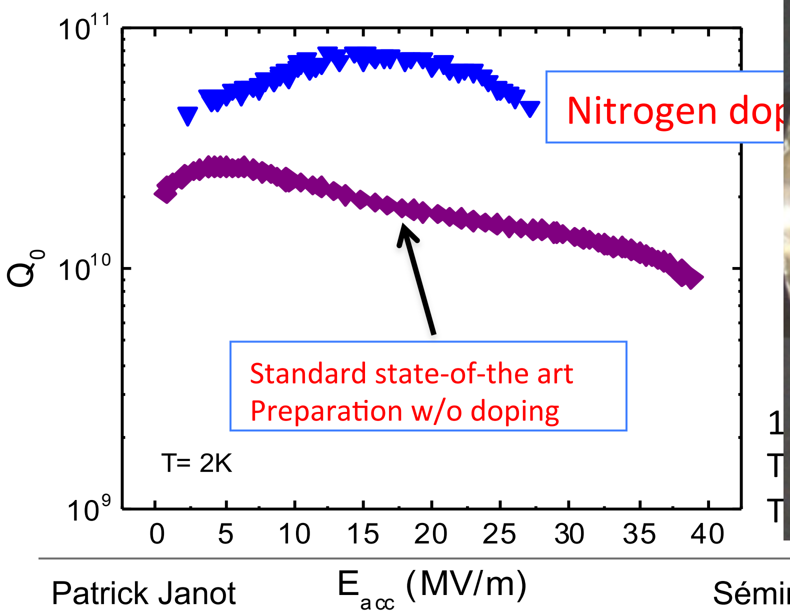
Off-momentum acceptance at IP : ±1.5%
FCC-ee (H) : ±2.0% to ±2.5%

Beam Lifetime : 5 minutes
FCC-ee (H) : 20 minutes

Centre-of-mass energy: ~10 GeV
FCC-ee (H) : 240 GeV

FCC-ee : SCRF and Power Sources

- **Main characteristics and areas for R&D**
  - 100 MW from synchrotron radiation, to be continuously compensated by RF power
    - Requires highly efficient RF power generation from klystron (LEP2: 55%)
      - ➨ 2014 breakthrough in klystron theory: promises efficiency > 90% (simulation)
  - Up to 11 GV of RF voltage at the top threshold
    - Requires high-gradient cavities to reduce the RF system length (LEP2: 7 MV/m)
    - Requires optimal use of the cryogenic system
      - ➨ 2013 breakthrough in
  - Up to 1.4 A beam current : Requ



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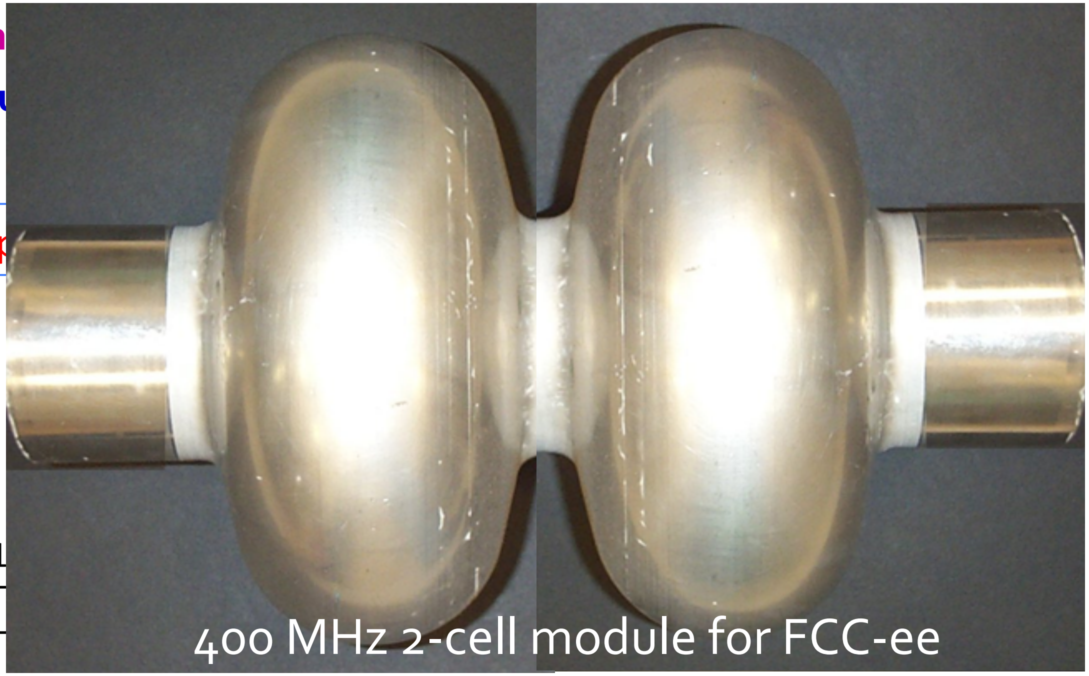
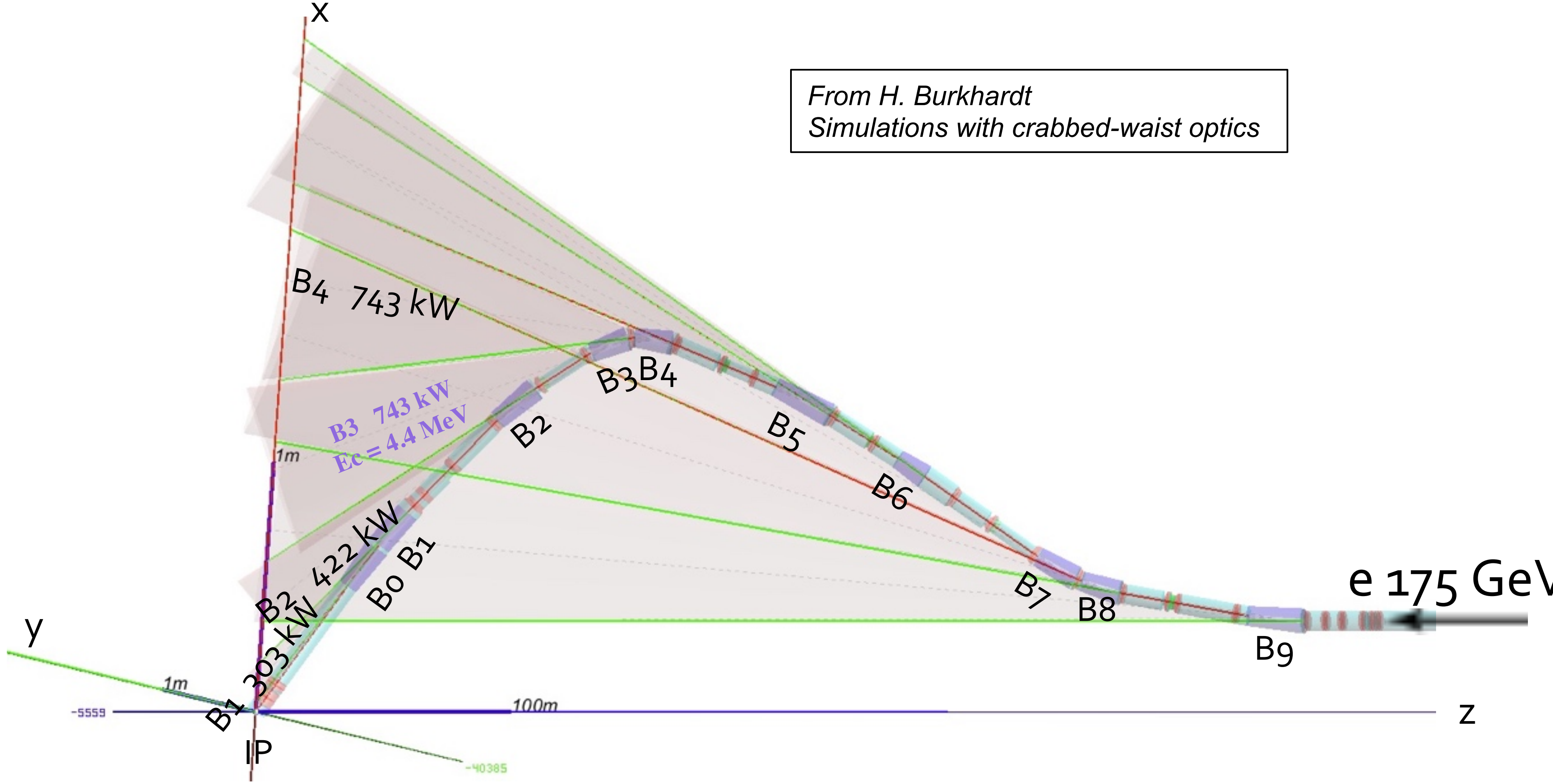


FCC-ee : Synchrotron radiation

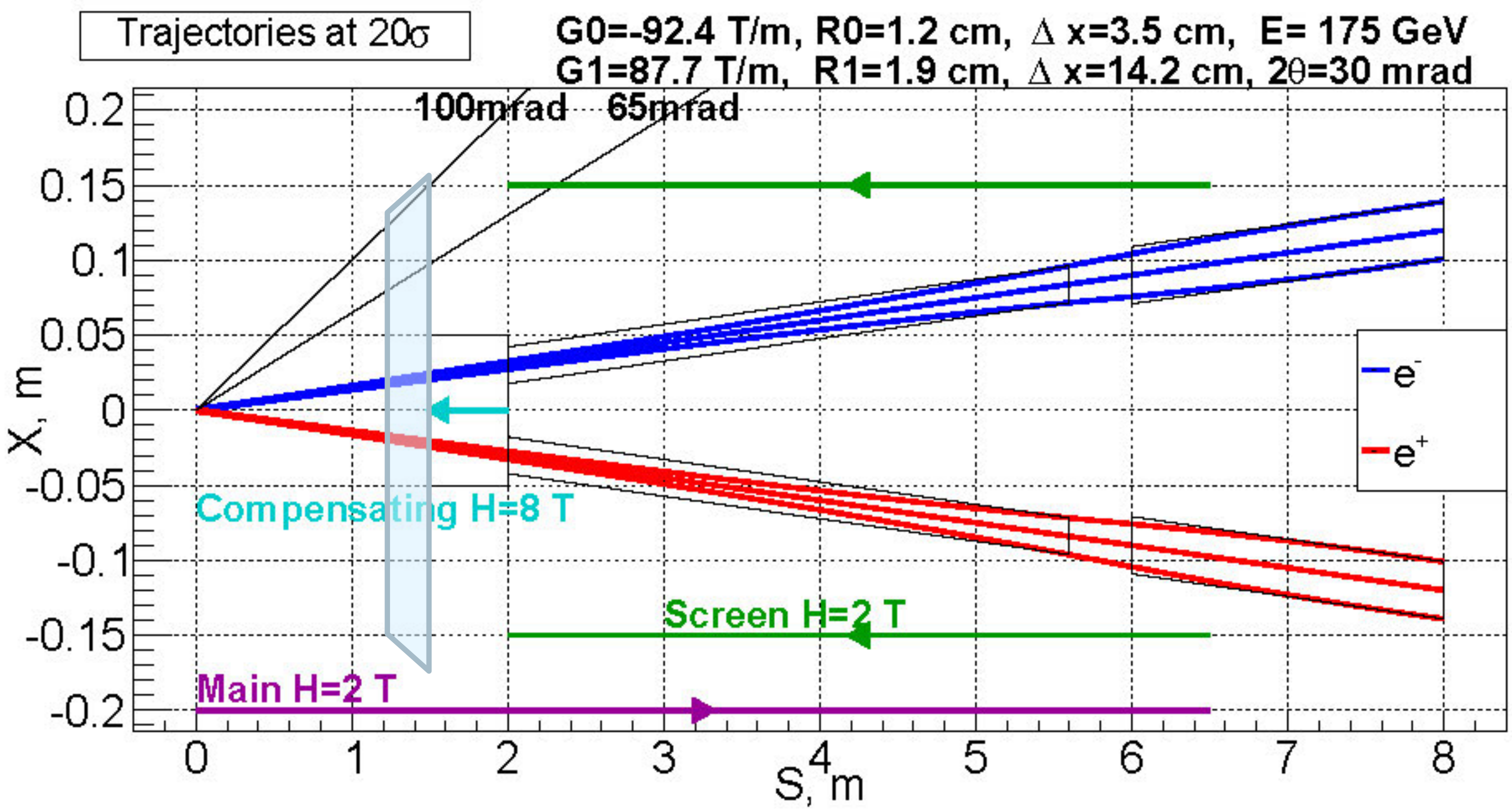
- A major challenge in the interaction regions



- Current simulations : up to 2.3 MW of MeV photons in the detector !
  - Lots of optimization needed.

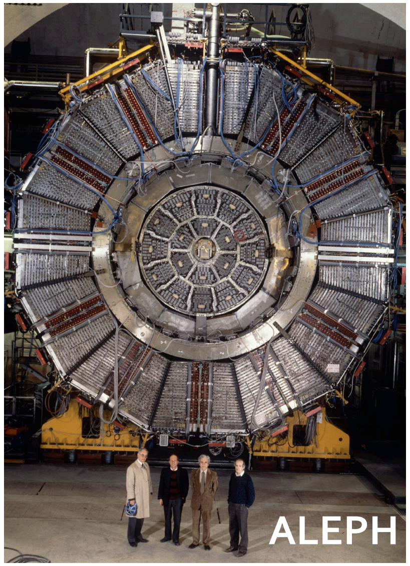
FCC-ee : Machine-detector interface

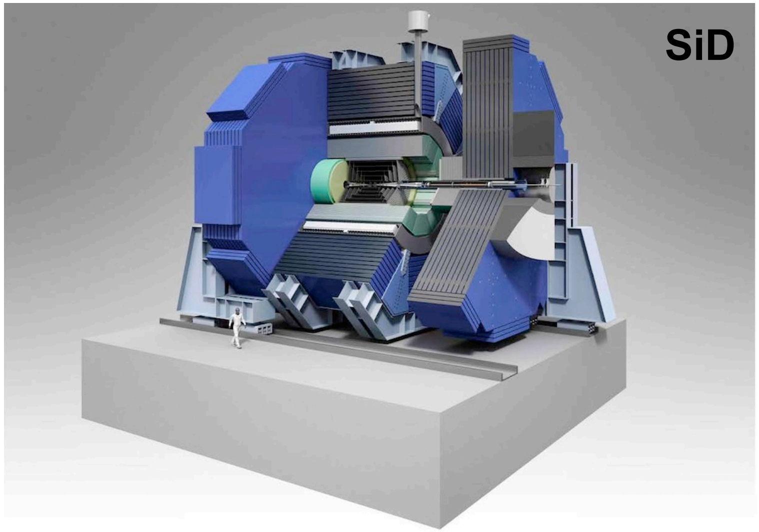
- **Crossing angle ~ 30 mrad, L* ~ 2m**
  - Last quadrupoles inside the detector
  - Experimental solenoid field must be compensated to preserve vertical emittance
  - Little space for luminosity monitor



FCC-ee : Detectors

- **We know today how to build a detector for e^+e^- precision physics**
  - Experience with LEP detectors and 20-years R&D with ILC/CLIC detectors
    - The challenge is to build four detectors for an affordable price
      - ➨ Something between ALEPH (price) and SiD (performance) would be suitable





Detectors must also have the ability to collect 100 kHz of Z decays, with 100% efficiency

… and be able to repeat the whole LEP1 programme in about two minutes.

Inspiration should come from LHC detector upgrades and DAQ systems (ALICE, LHCb, CMS)

- Lots of synergies with the work already done for linear colliders
  - Collaboration has already started with the CERN CLIC group
    - ➨ Detector mini-workshop at CERN in June 2015 (check at http://cern.ch/fcc-ee)

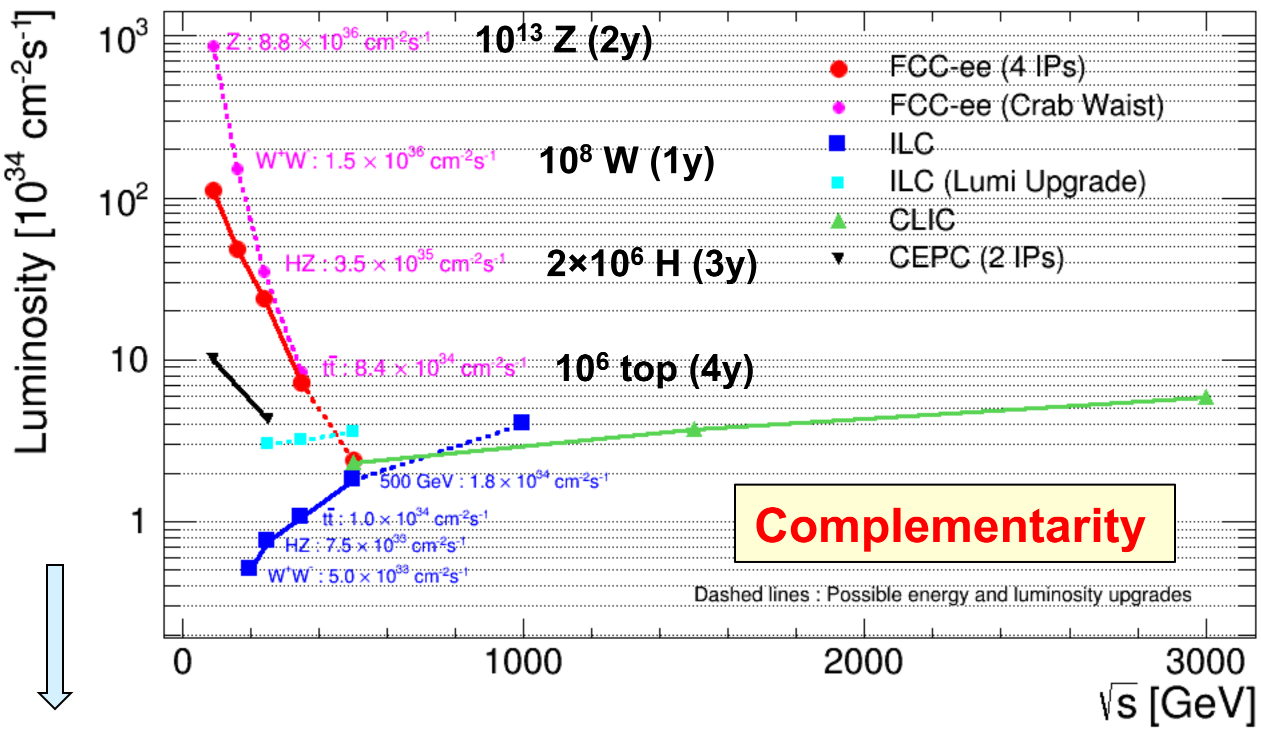
FCC-ee open issues : Bottom line

- A rich R&D programme for the next few years
  - Largely anticipated by
    - At least 50 years of experience with circular e^+e^- colliders
    - The commissioning of SuperKEKB starting at the end of this year
    - Similar R&D work for linear colliders
- Probably the most effective step towards FCC-hh a.s.a.p.
  - With unprecedented, unequalled, luminosities

Circular Colliders
- Larger luminosity
- Up to four detectors
- √s precise calibration
- Followed by high-√s pp

Linear Colliders
- Higher √s reach in e^+e^-
- Longitudinal polarization

LEP: 0.001 – 0.01, SLC: 0.001



Physics opportunities

Synergies between FCC-hh and FCC-ee

Key goals of the FCC

- **Not much theoretical guidance after the Higgs boson discovery**
  - **Many experimental for BSM physics: DM, BAU, ν masses, … at what scale ??**
    - **Next breakthrough will probably come from experimental observation**

- **Complete exploration of the Higgs boson and its dynamics**
  - **Precise measurement of all its properties (ee/hh)**

- **Significant extension of the search for BSM physics**
  - **Direct production of heavy particles (hh) and/or very weakly coupled particles (ee)**
  - **Precise measurement of EW observables (ee/hh)**
  - **Observation of rare / forbidden decays (hh/ee)**

- **Fulfilling these goals will also require**
  - **Order-of-magnitude improvement of theoretical calculations for precision physics**
  - **A reduction of theoretical systematic uncertainties**
  - **Data to improve precision on fundamental inputs** [$\alpha_S(m_Z)$, $\alpha_{QED}(m_Z)$, m_Z **(ee),** PDFs **(eh)**]
    - **Radiative correction mini-workshop at CERN on 13-14 July** (check http://cern.ch/fcc-ee)

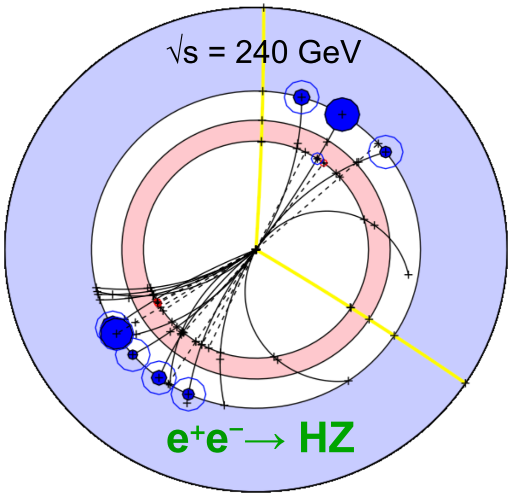
Complete exploration of the Higgs boson (1)

- **@ FCC-ee: $\sigma(e^+e^- \to HZ) \sim 200$ fb at $\sqrt{s} \sim 240$-260 GeV**

bosons produced is maximal, as displayed in figure 8. The nun
has a broad maximum for centre-of-mass energies between 280 a
convenient to couple the analysis of the WW fusion with the sc
$\sqrt{s}$ around 350 GeV, where the background from the Higgs-stra
and most separated from the WW fusion signal.

– 14 –

2×10^6 Higgs bosons in 10 ab^{-1} (in about 3 years)



- **Model-independent (absolute) measurements of the couplings from Higgs decays**
  - **Measure total cross section at $\sqrt{s} = 240$ GeV**
  - **Measure exclusive cross sections**
  - **Measure ZZZ cross section**

Mark Thomson

Mark Thomson

Mark Thomson

Mark Thomson ZZ

Mar

Mark Thomson

Complete exploration of the Higgs boson (2)

Expected precisions for e^+e^- colliders

Table 1.16. *Uncertainties on coupling scaling factors as determined in a completely model-independent fit for differe Precisions reported in a given column include in the fit all measurements at lower energies at the same facility, and no independence requires the measurement of the recoil HZ process at lower energies. ‡ILC luminosity upgrade assumes an period on top of the low luminosity program and cannot be directly compared to TLEP and CLIC numbers without a additional running period. ILC numbers include a 0.5% theory uncertainty. For invisible decays of the Higgs, the num 95% confidence upper limit on the branching ratio.*

Facility	ILC			ILC(LumiUp)	TLEP (4 IP)		
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%

The 10B$ ILC
1-10% precision

FCC-ee
0.1-1% precision

- **New-physics deviations of the order of or smaller than a few % / Λ^2_{NP} (Λ_{NP} in TeV)**
  - **FCC-ee can test the multi-TeV new physics scales (for NP that couples to H)**
- **Probe dark matter through invisible width: e.g., sterile neutrinos with $H \rightarrow \nu N$?**

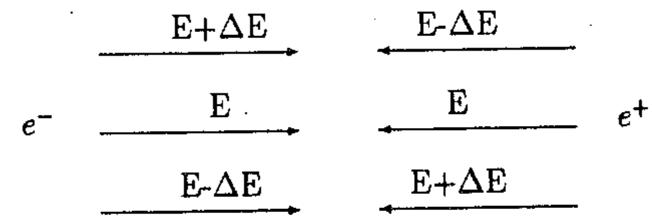
Complete exploration of the Higgs boson (3)

- **Unique to FCC-ee: couplings to the first generation of fermions**
  - Resonant production in the s channel : measure the electron Yukawa coupling

HHH (best a
Htt (best at

$\sqrt{s}$ = 125 GeV

D. d'Enterria



R&D and use of monochromators ?
Never tested … will reduce luminosity

- FCC-ee: 10^4 events / year at the peak, but …
  - ➨ Huge background from Z, γ
  - ➨ $\Delta E_{beam} \sim 10\ \Gamma_H$
- Set upper limit on κ_e to ~2 × SM value

- **Measurement of CP phase, e.g., $g_{H\tau\tau} = |g_\tau|$ x $(\cos\Delta + i\gamma_5 \sin\Delta)$**
  - Modify energy and angular distributions of the τ decay products in $H \rightarrow \tau\tau$
    - Expected accuracy on Δ

Collider	LHC	HL-LHC	ILC250	FCC-ee
σ_Δ	25°	8°	11°	1.7°

F. Yu

Complete exploration of the Higgs boson (4)

- @ FCC-hh : Large √s = larger cross section for the rarest processes
  - For example, ttH production and double Higgs production

Process	14 TeV	100 TeV
$gg \to ttH$	0.62 pb	37.8 pb × 61 (~10^9 evts)
+ $p_T(H) > 100$ GeV		× 250 (~10^8 evts)
$gg \to HH$	33.8 fb	1.41 pb × 42 (~5.10^7 evts)

  - Other rare Higgs decays which will benefit from huge statistics
    - e.g., $\sigma(gg \to H \to \mu\mu)$: ~ % precision
  - Absolute couplings fixed by ratios at FCC-hh and absolute measurements from e^+e^-

Complete exploration of the Higgs boson (5)

- **ttH coupling @ FCC-hh**
  - Measurement of λ_t with $\sigma(ttH) / \sigma(ttZ)$
    - Very similar production mechanism, gg production dominant

- Identical production dynamics:

o correlated QCD corrections, correlated scale dependenc
o correlated α_S systematics

- $m_Z \sim m_H \Rightarrow$ almost identical kinematic boundaries:

o correlated PDF systematics
o correlated m_{top} systematics

For a given y_{top}, we expect σ
to be predicted with great p

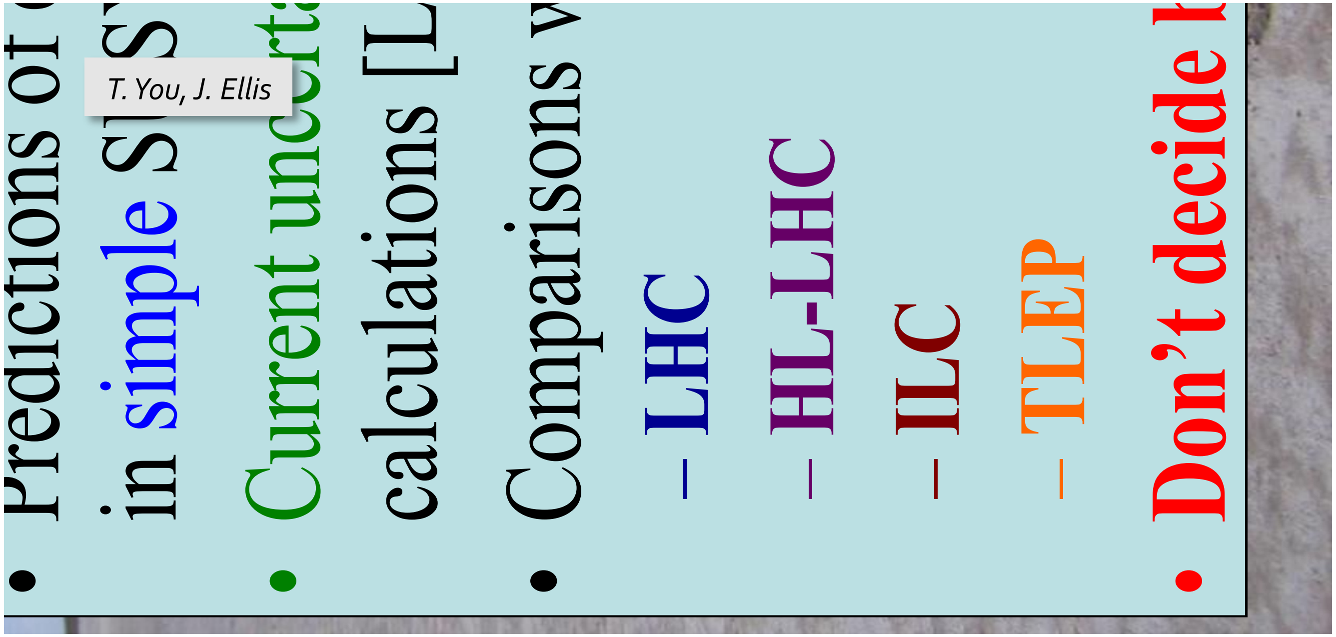
    - Most theory uncertainties cancel: < 1% precision possible on $\sigma(ttH) / \sigma(ttZ)$
      - ➨ $\sigma(ttZ)$ and H BR's given by FCC-ee

- **Higgs self-coupling @ FCC-hh with gg → HH → bbγγ**

Collider	HL-LHC	ILC500	ILC1TeV-up	CLIC3TeV	FCC-hh
λ_τ	4%	14%	2%	<4%	**<1%**
λ_H	50%	83%	13%	10%	**5%**

Complete exploration of the Higgs boson (5)

- **Interpretation of Higgs measurements: Much work ahead !**
  - Experimental systematic uncertainties @ FCC-ee under control at the level of few 10^{-4}
    - As was achieved at LEP1: exploit high-statistics calibration runs at $\sqrt{s} = m_Z$
      - ➨ Sufficient for per-mil or sub-per-mil precision measurements
  - Theoretical uncertainties on SM BR's are, as of today, much larger than the per-mil

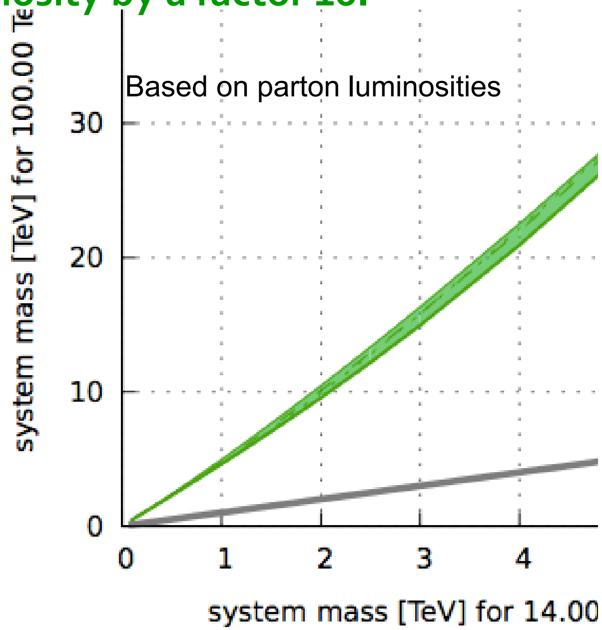


    - Mainly due to QCD uncertainty of 7.5% on $\Gamma(H \rightarrow bb)$
      - ➨ An uncertainty of 0.3% on Γ_{bb} (SM) is possible in the future

H. Kuehn

Direct production of heavy particles

- **Potential for new particle discovery @ FCC-hh: Rules of thumb**
  - A factor ~5 in mass reach from LHC (14 TeV, 300 fb^{-1}) to FCC-hh (100 TeV, 3 ab^{-1})
    - Then add ~1 to this factor for each increase of luminosity by a factor 10.



Examples

Particle	LHC, 300 fb^{-1}	FCC-hh, 3 ab^{-1}
Gluino	2 TeV	11 TeV
Stop	1.2 TeV	6 TeV
Z′, W′	5 – 6 TeV	30 – 35 TeV

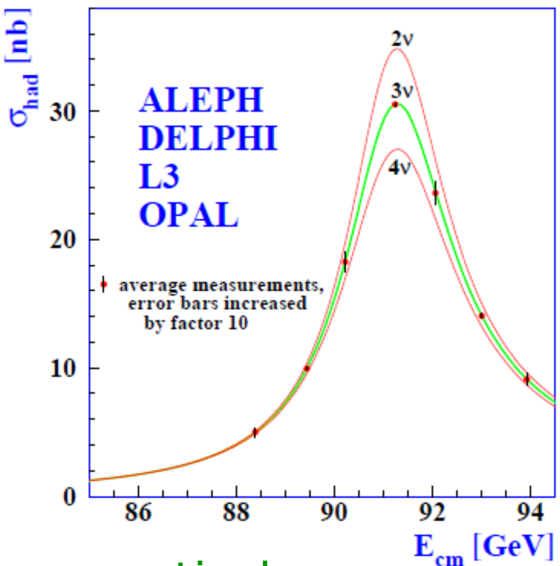
  - Comparison with CLIC-3TeV (Z′)
    - Direct: ~1.5 TeV
    - Indirect: ~15 TeV

Rule of thumb: at fixed Lumin
=> x 5 from 14 to 100 TeV

Precision EW physics (1)

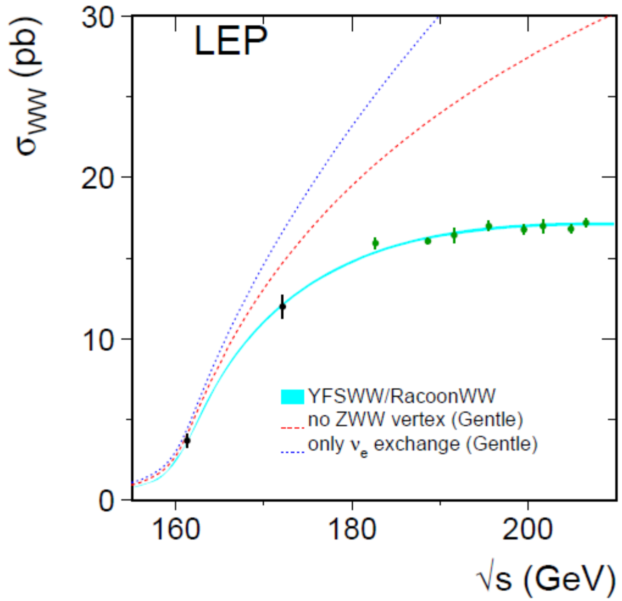
- **Exquisite precision at FCC-ee (large lumi, √s precise calibration)**

Z resonance: TeraZ



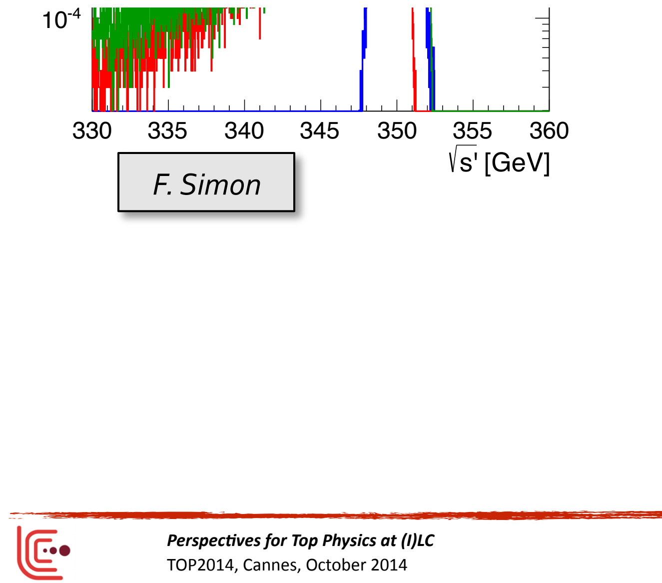
- Lineshape
  - Exquisite E_{beam}
  - m_Z, Γ_Z to <100 keV
- Asymmetries
  - $\sin^2\theta_W$ to 2×10^{-6}
- Branching ratios, R_l, R_b
  - $\alpha_S(m_Z)$ to 0.0002
- Predict m_{top}, m_W in SM

WW threshold scan: OkuW



- Threshold scan
  - m_W to 500 keV
- Branching ratios R_l, R_{had}
  - $\alpha_S(m_W)$ to 0.0002
- Radiative returns $e^+e^-\rightarrow\gamma Z$ $(Z\rightarrow\nu\nu, \mu^+\mu^-)$
  - N_ν to 0.0008

tt threshold scan: MegaTops



- Threshold scan + 2D fit
  - m_{top} to 10 MeV
  - Γ_{top} to 12 MeV

(λ_{top} from FCC-hh)

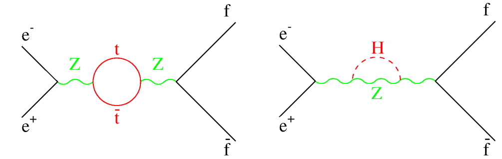
Precision EW physics (2)

- **Experimental uncertainties mostly of systematic origin**
  - **Conservatively based on LEP experience so far – it is just a start. Much work ahead.**

Observable	Measurement	Current precision	TLEP stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1	QED corr.
R_l	Peak	20.767 ± 0.025	0.0001	< 0.001	Statistics
R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	$g \to bb$
N_ν	Peak	2.984 ± 0.008	0.00004	< 0.004	Lumi meast
$\alpha_s(m_Z)$	R_l	0.1190 ± 0.0025	0.00001	0.0002	New Physics
m_W (MeV)	Threshold scan	80385 ± 15	0.3	< 0.5	QED Corr.
N_ν	Radiative returns $e^+e^- \to \gamma Z, Z \to \nu\nu, ll$	2.92 ± 0.05 2.984 ± 0.008	0.001	< 0.001	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 ± 0.27	0.00018	< 0.0001	CKM Matrix
m_{top} (MeV)	Threshold scan	173200 ± 900	10	10	QCD (~40 MeV)
Γ_{top} (MeV)	Threshold scan	?	12	?	$\alpha_s(m_Z)$

Precision EW physics (3)

- **Sensitivity to heavy new physics (with EW couplings)**
  - e.g., LEP was able to predict m_{top} and m_H
    - Now that m_{top} and m_H are known, the standard model has nowhere to go



physics:

– discovery can be better prepared if we know where to look

– once a new state is discovered need a framework to build the full picture (e.g. test the New Standard Model, give indications where other states could be)

SM
after FCC-ee

before LHC

  - Any deviation now is "new physics"
    - 5σ is new physics discovery
    - Indirect, but inclusive information on new physics with ~weak couplings
  - Precision on SM "inputs" crucial
    - m_Z , m_{top}
      - e.g., SM prediction on m_W would have a 2.2 MeV width without m_Z @ FCC-ee ($\sqrt{s}$ calibration)
    - $\alpha_{QED}(m_Z)$, $\alpha_S(m_Z)$

Precision EW physics (4)

- **Parameterize the relics of new physics in dimension-6 operators**
  - Possible corrections to the standard model lagrangian

$$L_{\text{eff}} = \sum_n \frac{c_n v^2}{\Lambda^2} O_n$$

$$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$$

$$\mathcal{O}_{LL}^{(3)\,l} = (\bar{L}_L \sigma^a \gamma^\mu L_L)\,(\bar{L}_L \sigma^a \gamma_\mu L_L)$$

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$$

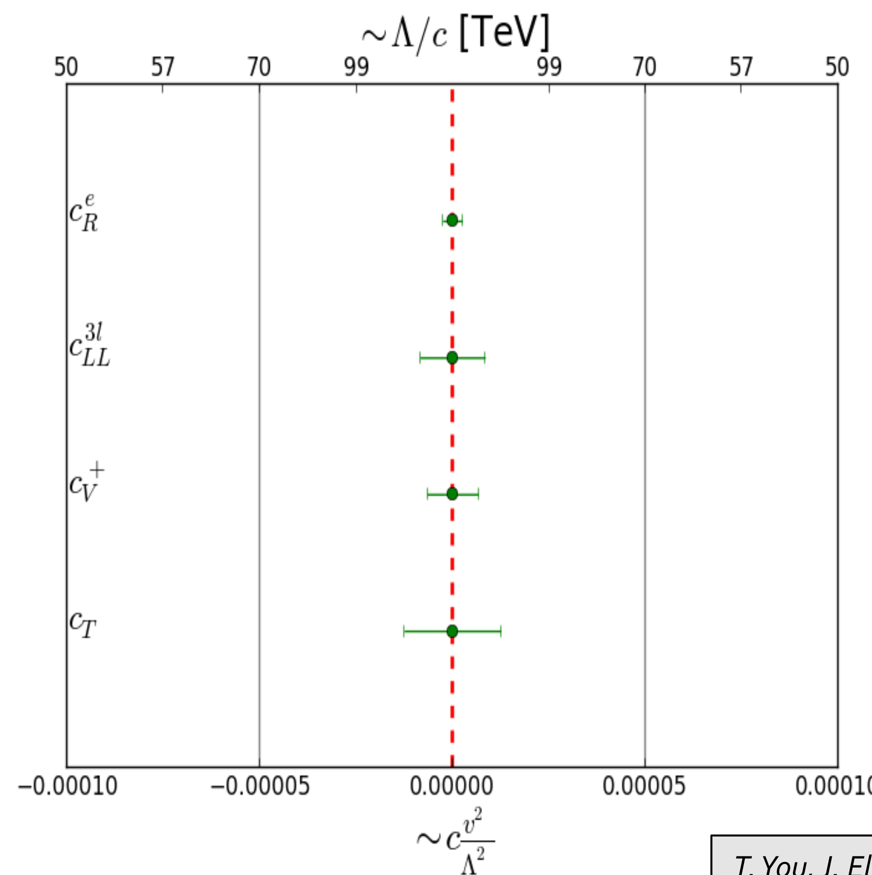
$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$

LEP constraints: Λ_{NP} > 10 TeV

After FCC-ee: Λ_{NP} > 100 TeV ?

Sensitivity to Weakly-coupled NP



T. You, J. Ellis

Precision EW physics (5)

- **Traditional QED coupling constant $\alpha_{QED}(m_Z)$ determination**
  - Evaluate hadronic loop corrections to α_{QED} (0) from low-energy e^+e^- data

$$3\pi \int_{4m_\pi^2} \frac{}{s'(s'-s)}$$

Are there other ways ?

e^+e^- data.

• Precision should be factor 3 to profit of F

$$\alpha(s) = \frac{\alpha}{1-\Delta\alpha_l(s) - \Delta\alpha}$$

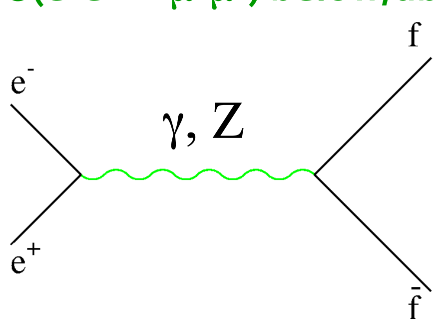
$$\Delta\alpha^{(5)}_{had}(s) = -\frac{\alpha s}{3\pi}\int_{4m_\pi^2}^{\infty}\frac{R_h}{s'(}$$

$$\alpha^{-1}_{QED}(m_Z) = 128.952 \pm 0.014$$

(Precision ~ 10^{-4})

Are there othe

  - Would need another factor 3-5 in precision
    - With $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ below/above m_Z @ FCC-ee?



Precision EW physics (6)

- **m_Z determination: $\sqrt{s}$ calibration is the key**
  - Resonant depolarization
    - Natural transverse polarization in circular colliders
      - ➨ Precession frequency $\nu_p \sim \sqrt{s}$
    - Apply sweeping horizontal B field with frequency n
      - ➨ Depolarization occurs when $\nu = \nu_p$
  - Depolarizing resonance very narrow at LEP (~100 keV)
    - Systematic uncertainties ~ 2 MeV
      - ➨ Extrapolation from polarization runs to physics runs affect by many external parameters
  - At FCC-ee, perform “in situ” and continuous calibration
    - With ~100 dedicated single e^+ and e^- bunches
      - ➨ Out of the 60,000 colliding bunches

dedicate

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• At FCC
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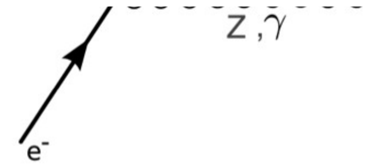
Precision EW physics (7)

❑ Top electroweak couplings



ALCW15, KEK, Tsukuba, April 2015 Marcel Vos (marcel.vos@ific.uv.es)

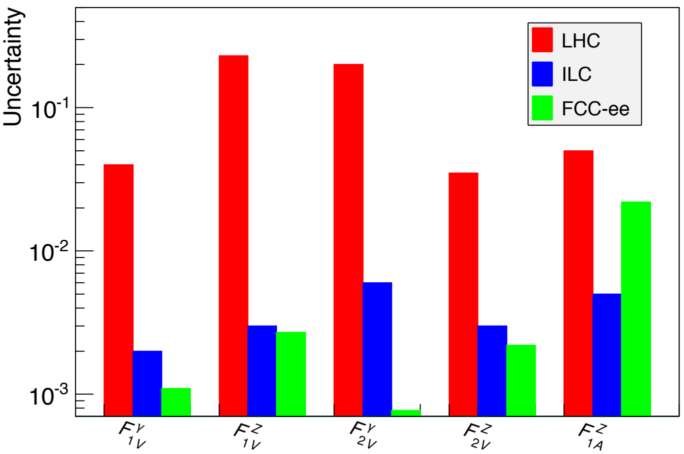
- **From lepton momentum/angular distributions @ FCC-ee:**

ALCW15, KEK, Tsukub

quark electroweak for

bottom: F_{1V}^{γ}, F_{1V}^{Z}, an

The first striking



P. J.

- Per-mil level precision
- No need of beam polarization
- Optimum at √s ~ 365-370 GeV

- **Interpretation in composite Higgs models @ FCC-ee ?**
  - **Need a full analysis of the Z, W, H, and top data**
    - ➨ **With sole top data, sensitivity similar to ILC**

S. de Curtis

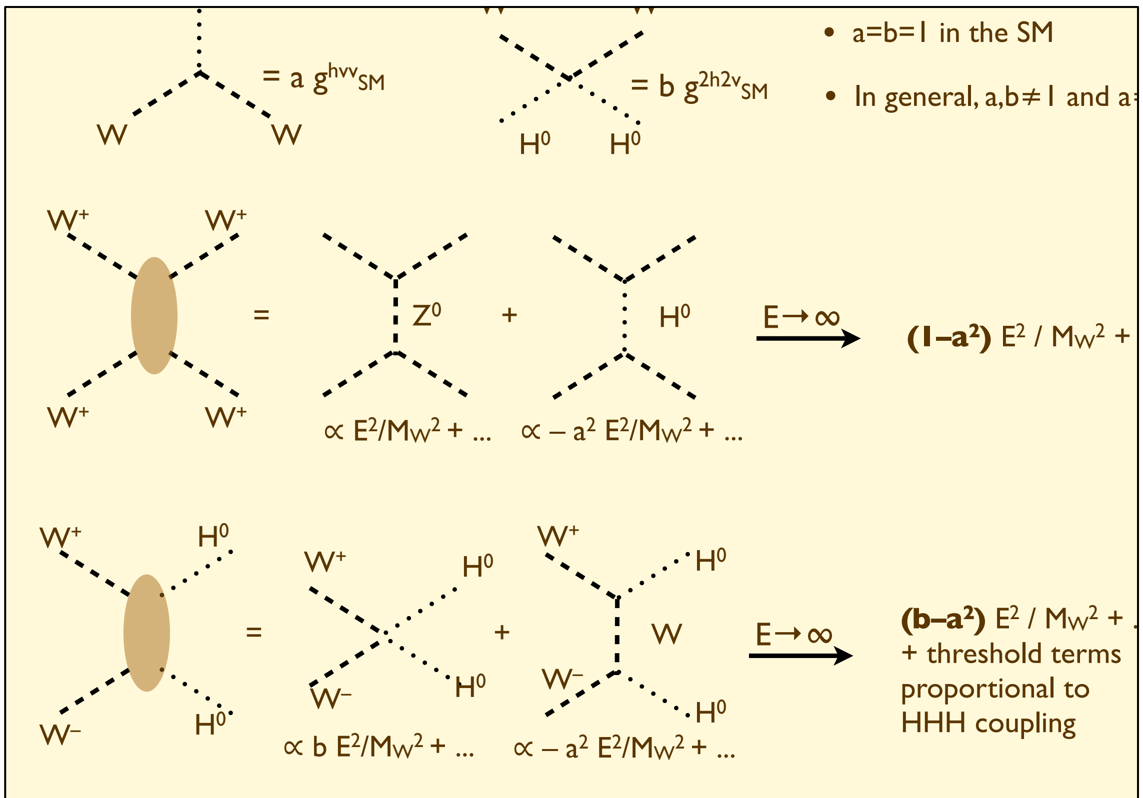
Precision EW physics (8)

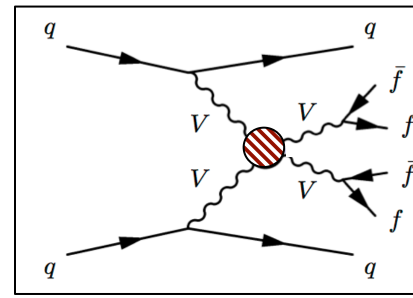
- Both lepton and 100 TeV pp colliders are vital for this effort!

Observables at Current + Future Colliders	100 TeV (FCC-hh)	ILC/TLEP (FCC-ee)
producing extra higgs states (incl. superpartners)	✓	
Exotic Higgs Decays		✓
Electroweak Precision Observables		✓
Higgs coupling measurements	(✓)	✓
Higgs portal direct production of new states	✓	
Higgs self coupling measurements	✓	(✓)
Zh cross section measurements		✓

Precision EW physics (9)

- **WW scattering (and Higgs pair production) @ FCC-hh**
  - In the SM, Z and H exchange diagrams diverge, but exactly cancel each other
    - Anomalous HWW couplings, as relics of new physics, would have dramatic effects
      - Total WW scattering / Higgs pair cross section diverge with $m^4_{WW,HH}$





Precision on a and b

~30% at HL-LHC

~30% with CLIC 3 TeV

~1% with FCC-hh 100 TeV

NB. "a" can be measured with 0.1% (1%) precision with FCC-ee (ILC) from H → WW

Rare decays (1)

- At FCC-hh, 10 ab^{-1} at 100 TeV imply
  - 10^{10} Higgs bosons = 10^4 today's statistics, 10^4 FCC-ee statistics
    - More precision measurements
    - Rare decays, FCNC probes, e.g., $H \to e\mu$ …
  - 10^{12} top quarks = 5×10^4 today's statistics, 10^6 FCC-ee statistics
    - Rare decays, FCNC probes, e.g., $t \to cZ$, cH
    - CP violation
    - 10^{12} W and 10^{12} b from top decays
    - 10^{11} τ from $t \to W \to \tau$
      - Rare decays, e.g., $\tau \to 3\mu$, $\mu\gamma$, CP violation …
    - BSM decays : any interesting channels to consider ?
      - Example: Majorana neutrino search in top decays

o BSM decays
-- Example

Majorana neutrinos and lepton-number-violating signals in top-quark and W-boson rare decays

Shaouly Bar-Shalom[a,*] Nilendra G. Deshpande[b,†] Gad Eilam[a,‡] Jing Jiang[b,§] and Amarjit Soni[c,¶]

Majorana neutri

Shaouly Bar-Sha

Rare decays (2)

- **At FCC-ee, may be the fastest way to heaven (beyond FCC-hh)**
  - How far can one go with 10^{13} Z, 10^{8} W and several millions Higgs and top ?
    - Lepton-flavour violating Z decays: opportunities with $Z \rightarrow \tau\mu$, τe below 10^{-9}
    - Lepton-flavour violating H decays: $H \rightarrow \tau\mu$, τe could be as high as 10%
    - Flavour changing neutral current, e.g., $e^+e^- \rightarrow tq$ @ 240 GeV
    - Flavour physics with 10^{12} b and c's, 10^{11} τ's
      - 200,000 $B_s \rightarrow \tau^+\tau^-$, 1000 $B_s \rightarrow \mu^+\mu^-$
    - Invisible Higgs decays
    - Z invisible width: neutrino couting
      - Today: $N_\nu = 2.984 \pm 0.008$
        (Note the 2σ deficit)
    - Direct search for heavy neutrinos
      - $Z \rightarrow \nu N$
  - We have just started to scratch the surface !

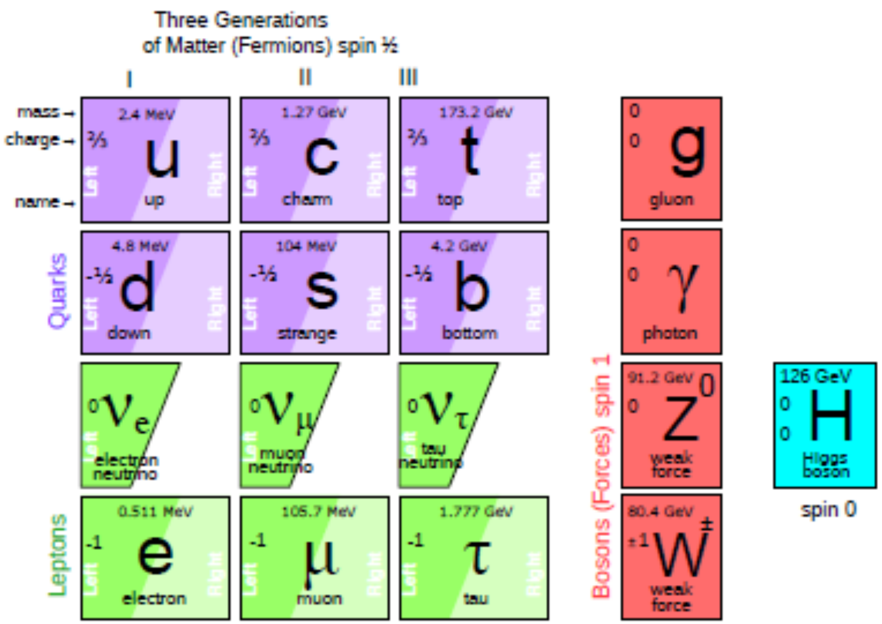
very preliminary results (IPM
group) cross checks in progr
also hadronic channel being
studied (Rome)

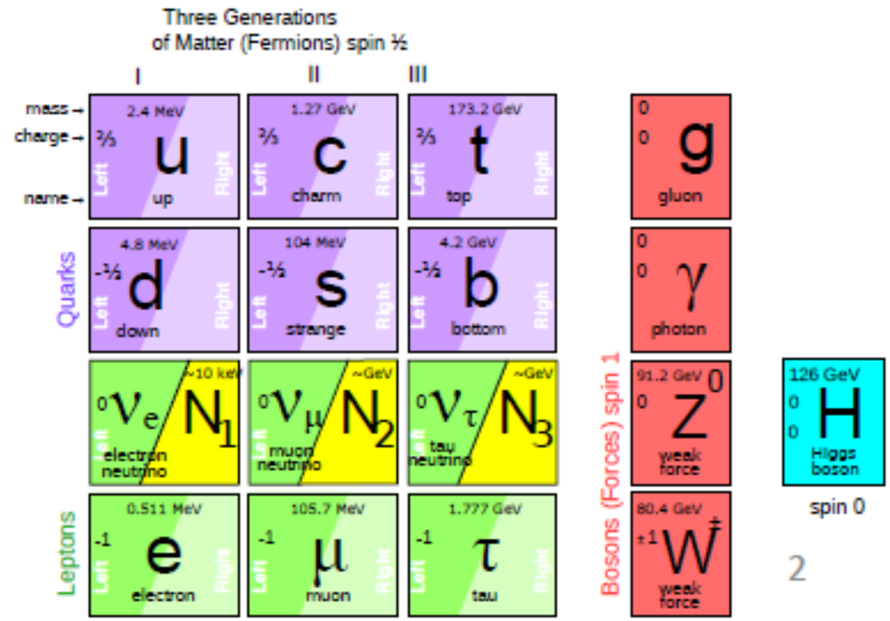
- Plan from the pheno-side to use
- Plan from the exp-side: use a Del
potential for the Ztc case and to

Patrizia Azzi - 29/10/

Very small couplings: An example (1)

- **New physics might not be heavy – only couplings may be very small**
  - **Example : three sterile right-handed neutrinos to complete SM**





M. Shaposhnikov

  - **Nearly impossible to find, but could perhaps explain it all !**
    - **Small m_ν (see-saw), DM (light N_1), and B.A.U. (leptogenesis)**
    - **Small deficit in Z invisible width (νN mixing), reactor anti-neutrino anomaly, …**

$$(Z \rightarrow \nu_L \bar{\nu}_R \text{ with } \nu_L = \nu \cos\theta + N \sin\theta)$$

Very small couplings: An example (2)

- **Sensitivity with 10^{13} Z**
  - Direct search for $Z \rightarrow \nu N$, with detached decay $N \rightarrow \nu Z^*$ or lW^* (small mixing)
    - Start eating deeply in the region of interest : <u>10^{13} Z is the key</u>

This work would not have be

We thank A. Blondel for use

$|U|^2 = \sin^2\theta \approx m_\nu/m_N$

-

N. Serra

Conclusions (1)

- **The FCC-ee is a very powerful e^+e^- collider**
  - **A beautiful Higgs factory – and much more**
  - **Complete set of EW precision measurements including the top quark**
  - **Real potential for discovery in rare processes and precision measurements**
    - **Up to and exceeding the FCC-hh energy scales for weakly-coupled particles**
  - **Much more than an "intermediate step"**
  - **Many ideas keep coming up**
    - **So far, no obvious case for longitudinal polarization or for $\sqrt{s}$ = 500 GeV**

European Strategy for Particle Physics:
"There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded."

P5 report for DOE:
An e^+e^- collider can provide the next outstanding opportunity [after LHC/HL-LHC] to investigate the properties of the Higgs in detail. […] the physics case is extremely strong.

(Admittedly, these sentences were initially alluding to the ILC – I'll come to that in a minute)

Conclusions (2)

- Exquisite complementarity of FCC-ee with (HL-LHC and) FCC-hh

Subject		ee	hh	eh
Higgs Physics	precision studies higher dimension operators composite Higgs			
Interface w				
EW Symme				
Flavour Ch				
Extensions				
QCD				
EW/SM precision issues	precision meas ts (m_Z, m_W, m_t, α, $\alpha_s(m_Z)$, $\sin^2\theta_W$, R_b... higher-order EW corrections W,Z triple and quadruple couplings			

effectiveness, the best precisi
and the best search reach of a
options presently on the mark

First look at The Physics Case of TLEP
arXiv:1308.6176v2 [hep-ex] 22 Sep 2013

Alain Blondel FCC Future Circular Colliders

JHEP 01 (2014) 164

"The FCC exploring power will be invincible"

From a referree of the Swiss National Science Foundation

Conclusions (3)

- Question from F. Gianotti at the FCC week in Washington:
  - How long will the FCC-ee physics programme take ? Will it delay FCC-hh ?

- This is an important question (especially with respect to ILC)
  - With the ultimate target luminosities presented in slide 31,
  - and with the goal to provide precision/discovery reach that matches the FCC-hh range,
    - About 10 years are necessary – let's say 20 years to be on the safe side.

  - However, if the goal is a physics programme equivalent to that of the ILC (the physics case of which is "extremely strong")
    - One year of measurement would be more than enough (after one year of commissioning)

  - On the question of the "delay", it is not stupid to think that the best and safest way to get to 100 TeV a.s.a.p. is to start FCC-ee a.s.a.p. (example: LEP and LHC)
    - It is also the method that gets most physics per Giga€ !
    - There is no such thing as "lepton" or "hadron" physicists. The combination of the two machines is very attractive and will give the best chances to find the funding.

FCC Week 2016

- Rome, 11-15 April 2016

  - See you in Rome next year !