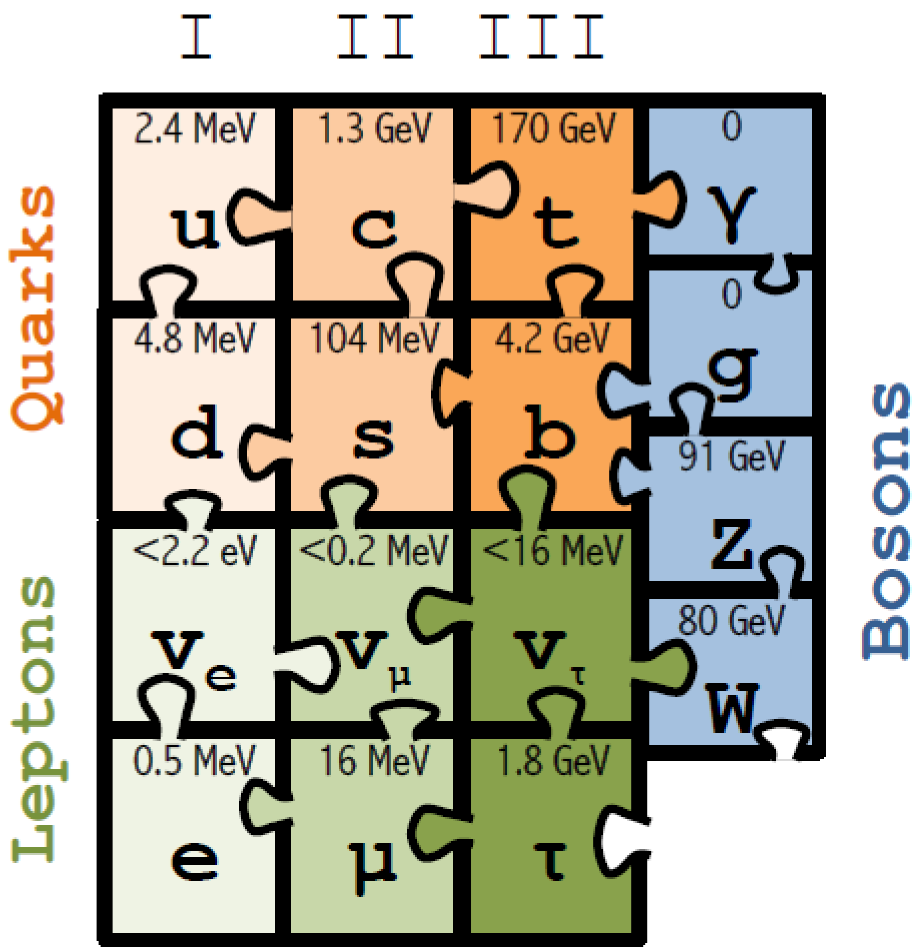
OUTLOOK

Alain BLONDEL
University of Geneva and CERN

With many thanks to all in the FCC collaboration!

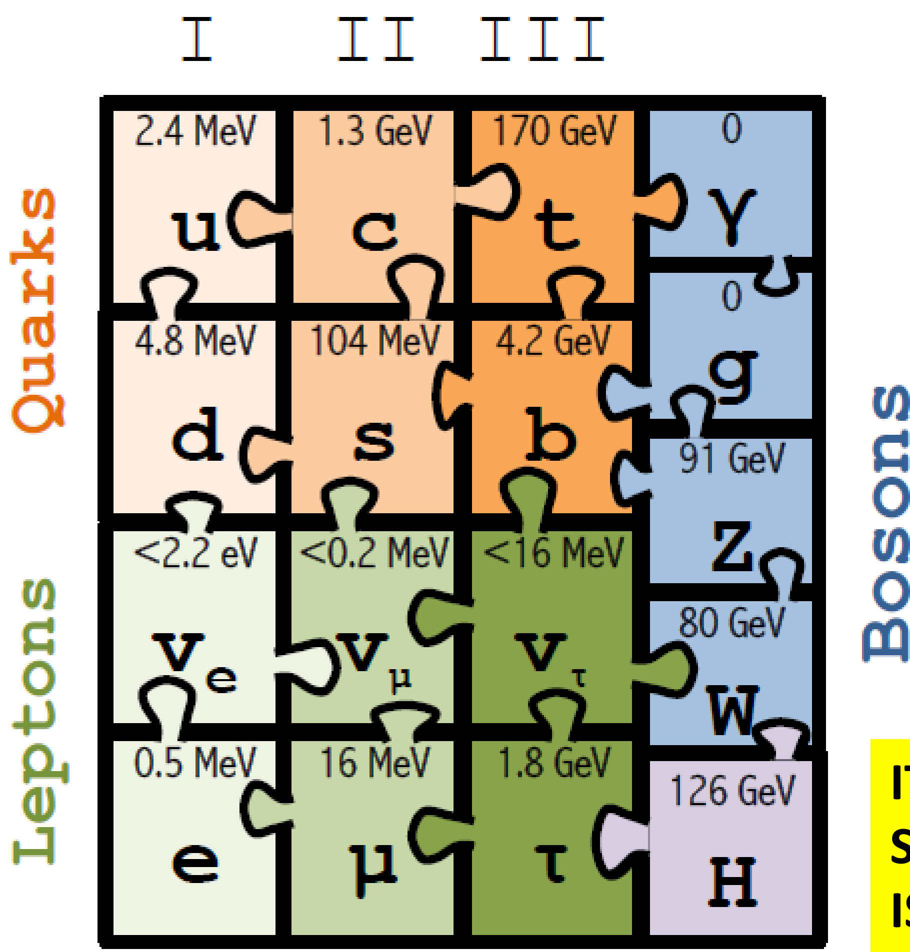
Particle physics has arrived at an important moment of its history

1989-1999: top mass predicted (LEP, mostly Z mass&width)
top quark discovered (Tevatron)
t'Hooft and Veltman get Nobel Prize 1999



(c) Sfyrla

1997-2013 Higgs boson mass cornered (LEP H, M_Z etc +Tevatron m_t , M_W)
Higgs Boson discovered (LHC)
Englert and Higgs get Nobel Prize 2013



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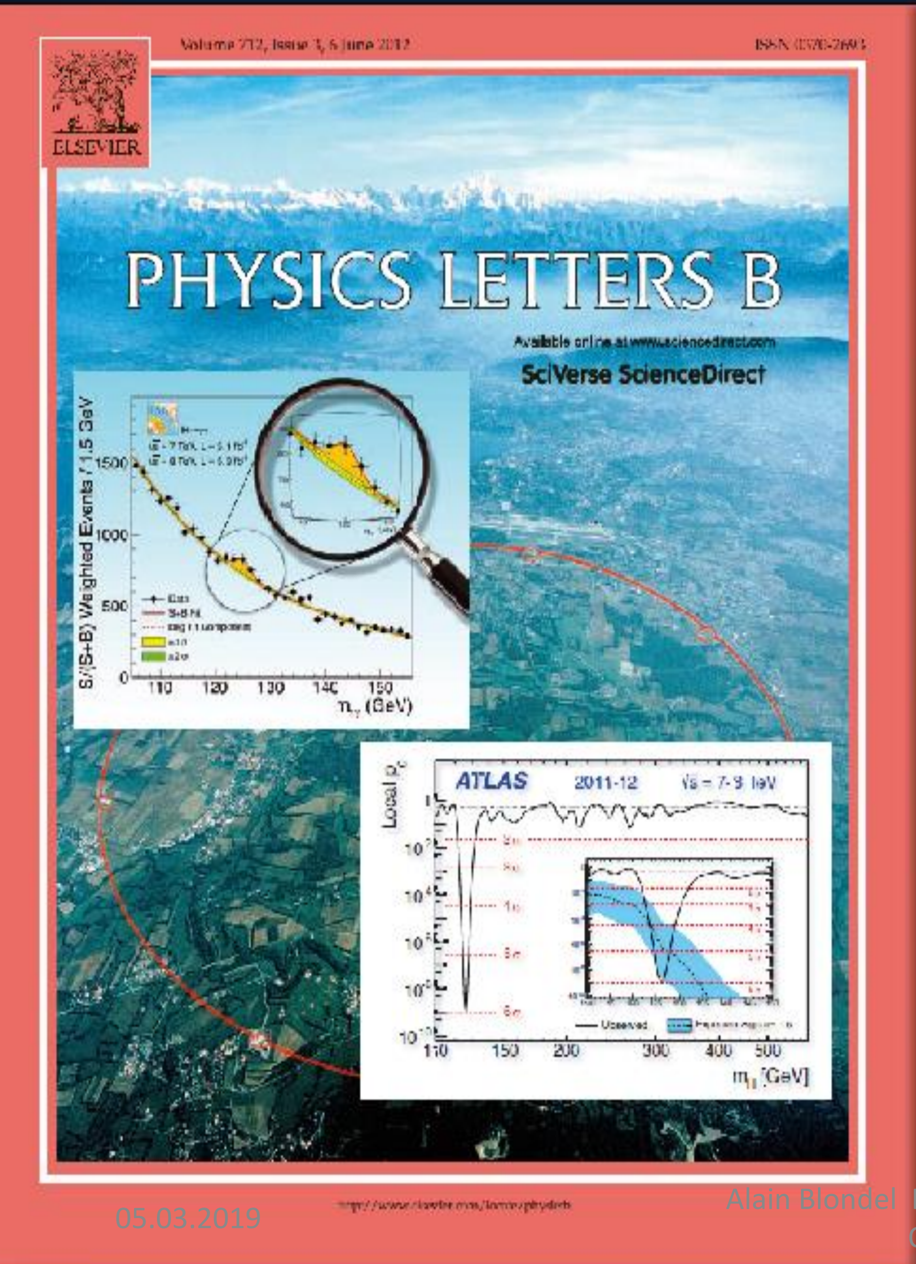
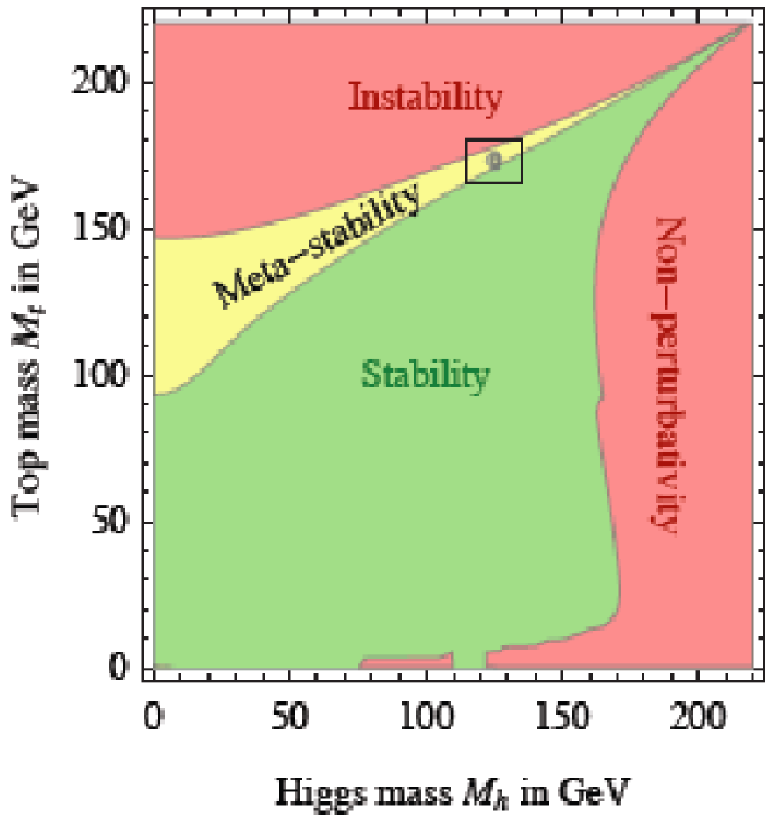
IT LOOKS LIKE THE STANDARD MODEL IS COMPLETE.....

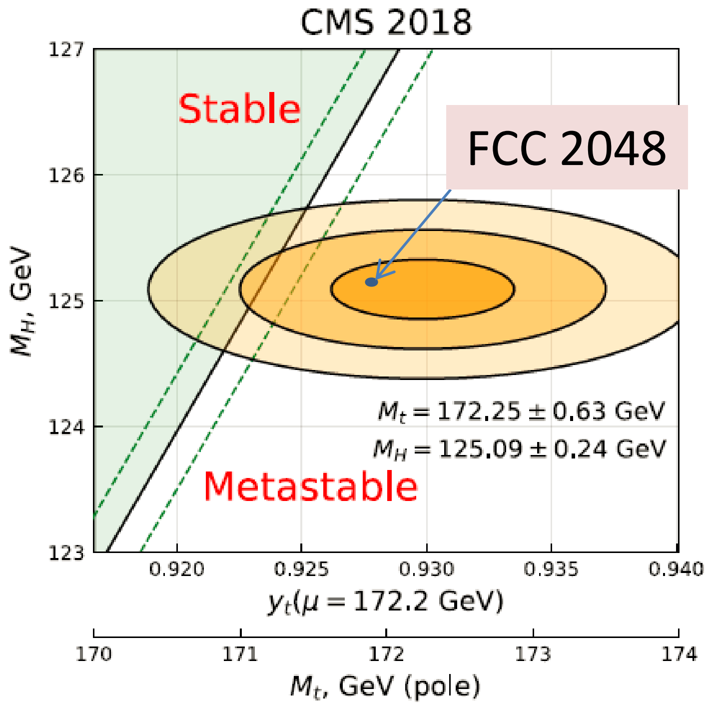
NB in fact we know from oscillations and cosmology that all 3 neutrino masses are less than ~0.1 eV

SEVEN YEARS AGO ALREADY



The Standard Model is a very consistent and complete theory.
It explains all known collider phenomena and almost all particle physics (except ν's)
– this was beautifully verified at LEP, SLC, Tevatron and the LHC.
-- the EWPO radiative corrections predicted top and Higgs masses
assuming SM *and nothing else*
we can even extrapolate the Standard Model all the way to the the Plank scale :





v:0912.0208v2 [hep-th] 12 Jan 2010

Asymptotic safety of gravity and the Higgs boson mass

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12 January 2010

Abstract

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

Key words:
Asymptotic s…
PACS: 04.60.…

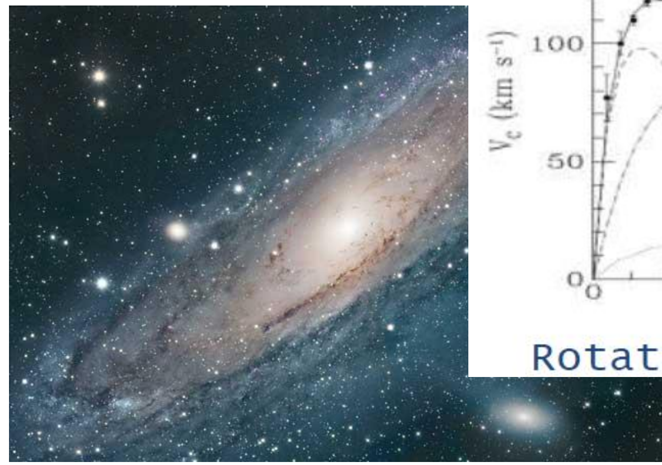
Detecting the Higgs scalar with mass around 126 GeV at the LHC could give a strong hint for the absence of new physics influencing the running of the SM couplings between the Fermi and Planck/unification scales.

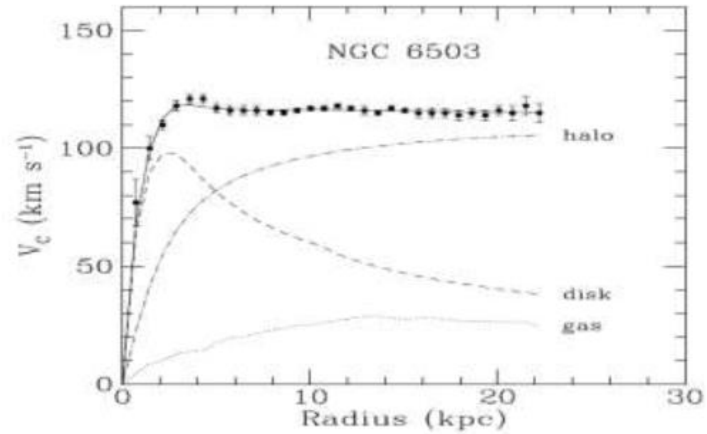
Is it the end?

We cannot explain:

Dark matter

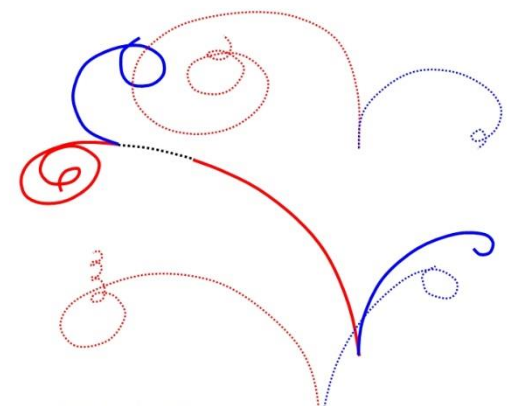
Standard Model particles constitute only 5% of the energy in the Universe





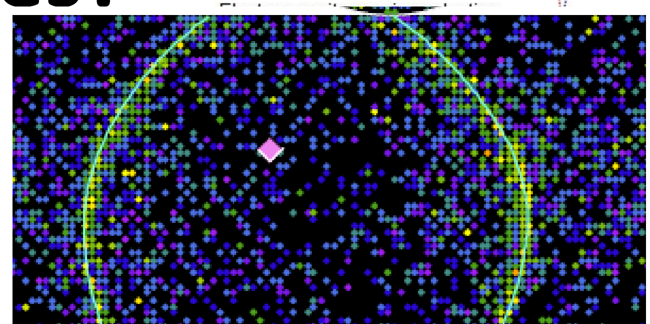
Rotation curve for Galaxy

Were is antimatter gone?



What makes neutrino masses?

Not a unique solution in the SM --
Dirac masses (why so small?)
Majorana masses (why not Dirac?)
Both (the preferred scenarios, see-saw…) ?
➔ heavy right handed neutrinos?



Is it the end?

Certainly not!

-- Dark matter

-- Baryon Asymmetry in Universe

-- Neutrino masses

these facts require particle physics explanations.

To which, one can add many theoretical questions on the SM

are experimental proofs that there is more to understand.

We must continue our quest, but HOW?

Direct observation of new particles (but not only!)

New phenomena (ex: Neutral currents, neutrino oscillations, CP violation..)

Deviations from precise predictions

(ref. Uranus to Neptune, Mercury's perihelion,
top and Higgs predictions from LEP/SLC/Tevatron/B factories, g-2, etc…)

The Physics Landscape

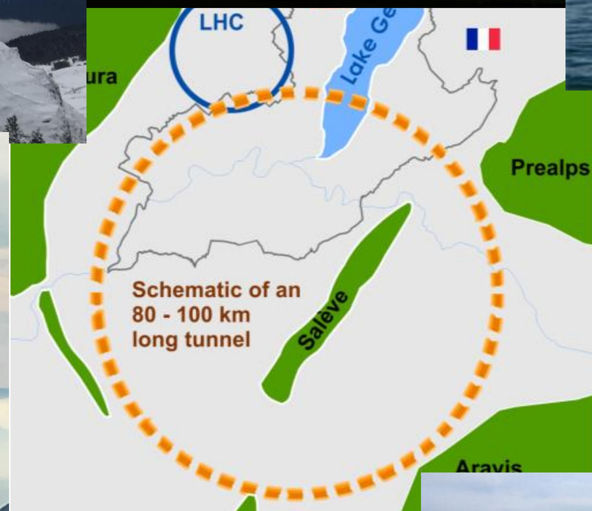
We are in a fascinating situation: where to look and what will we find?

For the first time since Fermi theory, WE HAVE NO SCALE

The next facility must be versatile with as broad and powerful reach as possible, as there is no precise target

➔ more Sensitivity, more Precision, more Energy

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


LHC
Lake Ge
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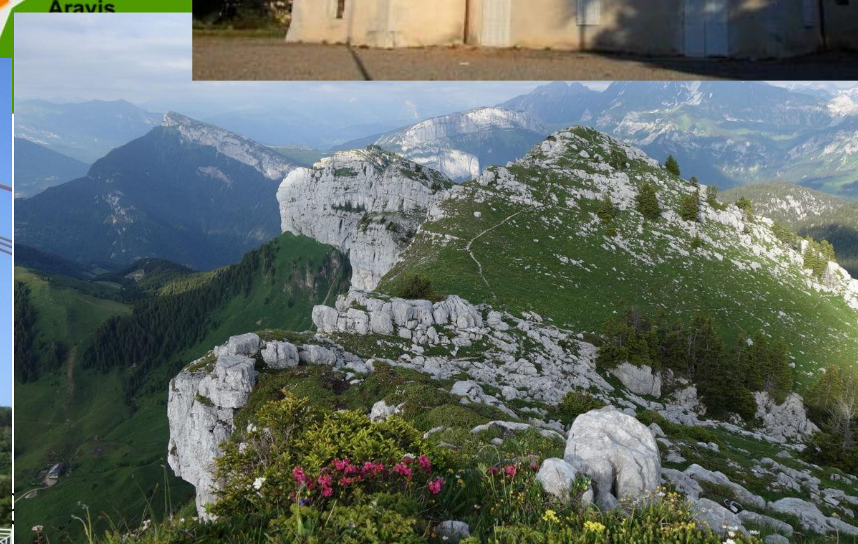
Prealps
Schematic of an
80 - 100 km
long tunnel
Salève
Aravis


PONT DE

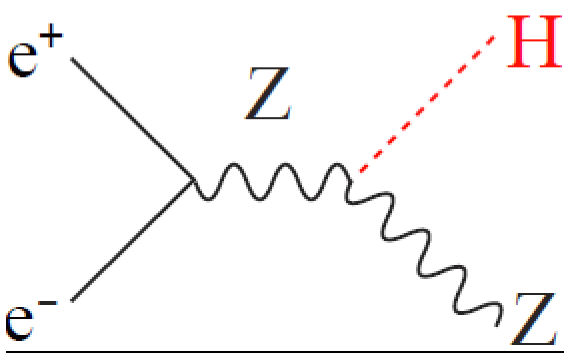


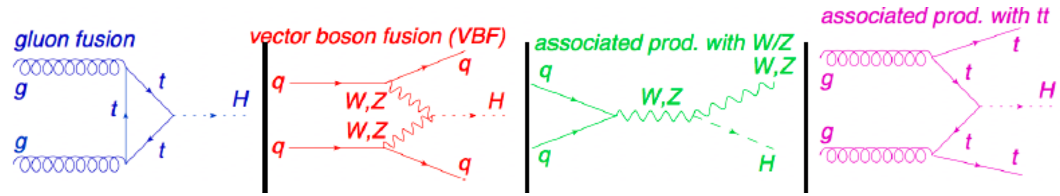
physicsworld MENU C

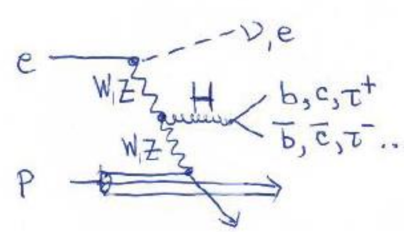
Hadron Collider

“Discoveries make the front pages of the newspapers, while precise measurements of known particle don’t, but scientifically they are just as important."

The FCC integrated program FCC (ee and hh, ep) by way of
synergy and complementarity
will provide the most complete and model-independent studies of the Higgs boson







ee provides 10^6 ZH + 10^5 Hvv evts
-- Model-Independent Γ_H determination
-- g_{HZZ} Higgs coupling to Z at 0.17%
→fixed candle for all measurements
(WW, bb, $\tau\tau$, cc, gg etc… <% level)
→ even possibly Hee coupling!
also first 40% effect of g_{HHH} from loop effect
(22% with 4 IPs)

pp provides 2.10^{10} Higgs !
(Using **ee** 'candle') will provide
-- model-independent ttH coupling to <1%
-- rare decays ($\mu\mu$, $\gamma\gamma$, $Z\gamma$ …)
-- invisible width to 5 10^{-4} BR
-- Higgs self coupling g_{HHH} to 5%

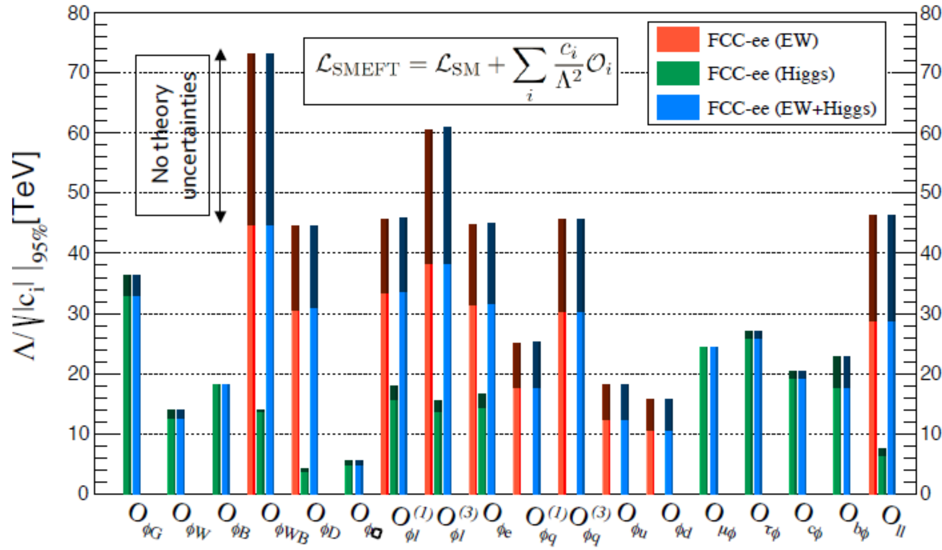
ep will produce 2.5 10^6 Higgs
(using **ee** 'candle') **further improves**
on several measurements esp. g_{HWW} coupling

Superb complementarity!

Table 3.1: Measurement of selected electroweak quantities at the FCC-ee, compared with the present precisions.

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV/c^2)	91186700 ± 2200	5	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	8	100	From Z line shape scan Beam energy calibration
R^Z_ℓ ($\times 10^3$)	20767 ± 25	0.06	0.2-1	ratio of hadrons to leptons acceptance for leptons
$\alpha_s(m_Z)$ ($\times 10^4$)	1196 ± 30	0.1	0.4-1.6	from R^Z_ℓ above [29]
R_b ($\times 10^6$)	216290 ± 660	0.3	<60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD [30]
σ^0_{had} ($\times 10^3$) (nb)	41541 ± 37	0.1	4	peak hadronic cross-section luminosity measurement
N_ν($\times 10^3$)	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement
$\sin^2\theta^{eff}_W$($\times 10^6$)	231480 ± 160	3	2 - 5	from $A^{\mu\mu}_{FB}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z)$($\times 10^3$)	128952 ± 14	4	small	from $A^{\mu\mu}_{FB}$ off peak [20]
$A^b_{FB}, 0$ ($\times 10^4$)	992 ± 16	0.02	1-3	b-quark asymmetry at Z pole from jet charge
$A^{pol,\tau}_{FB}$ ($\times 10^4$)	1498 ± 49	0.15	<2	τ polarisation and charge asymmetry τ decay physics
m_W (keV/c^2)	80350000 ± 15000	600	300	From WW threshold scan Beam energy calibration
Γ_W (keV)	2085000 ± 42000	1500	300	From WW threshold scan Beam energy calibration
$\alpha_s(m_W)$($\times 10^4$)	1170 ± 420	3	small	from R^W_ℓ [31]
N_ν($\times 10^3$)	2920 ± 50	0.8	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	20	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	40	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda^{SM}_{top}$	1.2 ± 0.3	0.08	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	<2%	small	From E_{CM} = 365GeV run

Pecision EW measurements: is the SM complete?



-^- EFT D6 operators (some assumptions)

-^- Higgs and EWPOs are complementary

-^- top quark mass and couplings essential!
(the 100km circumference is optimal for this)

<-- many systematics are preliminary
and should improve with more work.
<-- tau b and c observables still to be added
<-- complemented by high energy FCC-hh

Theory work is critical and initiated

ɔR presentation
ɔk

Theoretical challenges

FCC proposes a HUGE step in statistical precision w.r.t. LEP/SLC/Tevatron/LHC
(up to factor sqrt(N)~400 improvement)
Also rare processes at the level of <**10^{-12}** of Z decays (10^{-8} for W, 10^{-6} for H and top)
→ need to know rare SM processes at that kind of level!

Experiment (i.e. accelerator physics + experimental physics) will work hard to make sure that this is matched by experimental systematics and experimental backgrounds

This is a huge challenge for the theoretical community!

QED
QCD (incl. quark masses)
EW
Multi-loop calculations and exponentiation

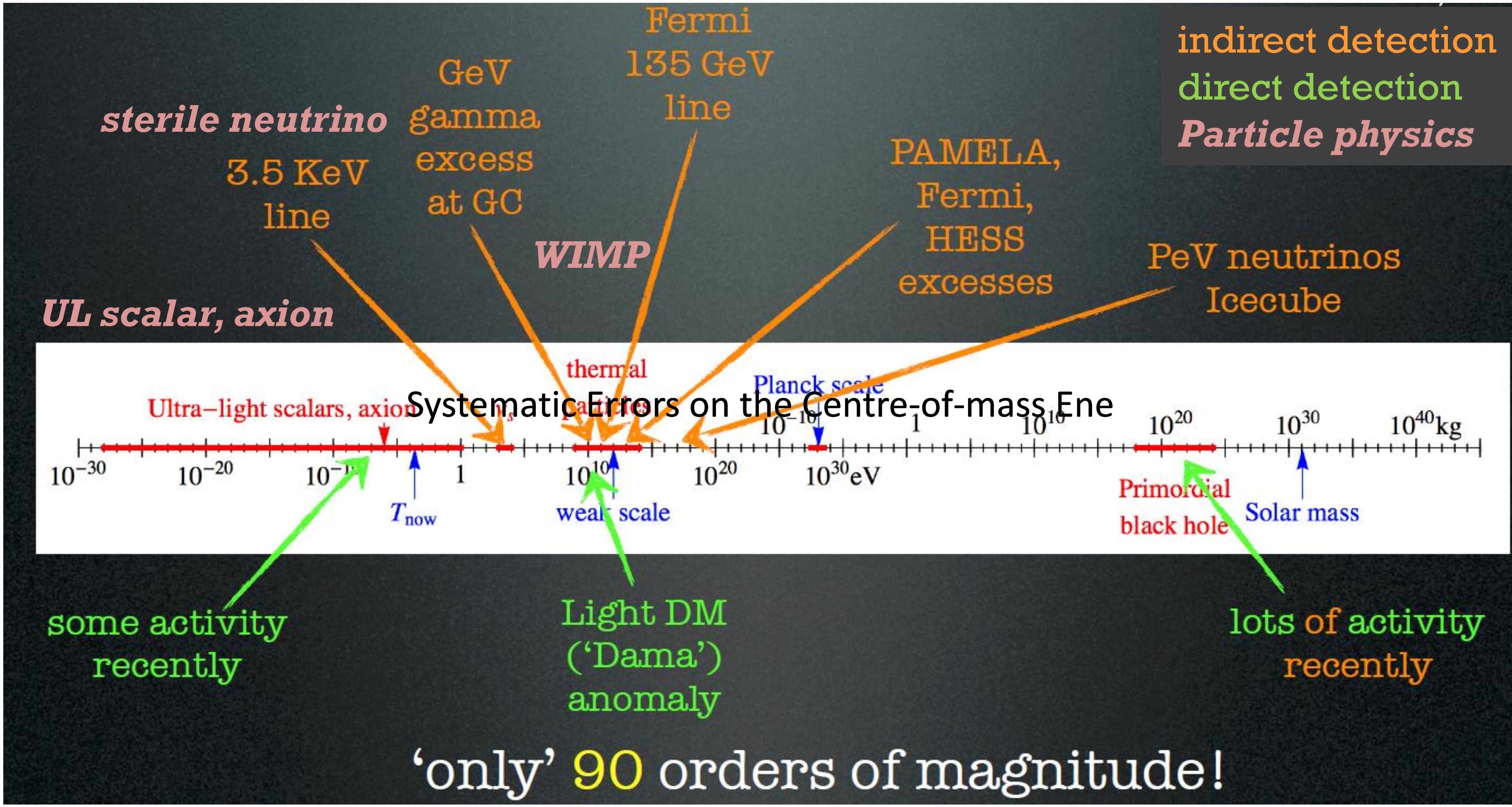
THIS IS EXPLICITELY INSCRIBED IN THE ESPP SUBMISSIONS AS CRITICAL CHALLENGE

Insufficient level of theoretical precision and accuracy.	Full exploitation of machine's capabilities depends on accurate theoretical predictions of SM phenomena at levels where higher-order contributions become significant.	Set up an international collaboration, leveraging existing world-wide HEP computing infrastructures, to develop the tools and to carry out the necessary computations. This effort is assumed to require substantial committed engagement of personnel by the collaborating institutes during the design, construction and operation phases.


But Where Is Everybody?
Nima
At higher masses -- or at smaller couplings?

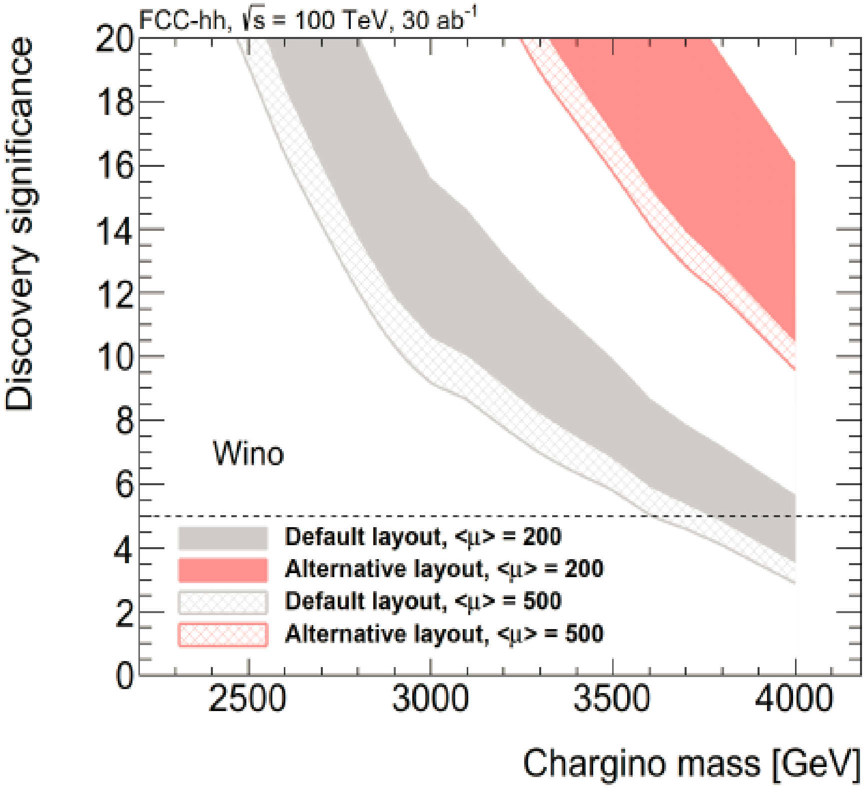
Dark Matter exists. It is made of very long lived neutral particle(s).

Plausible candidates:

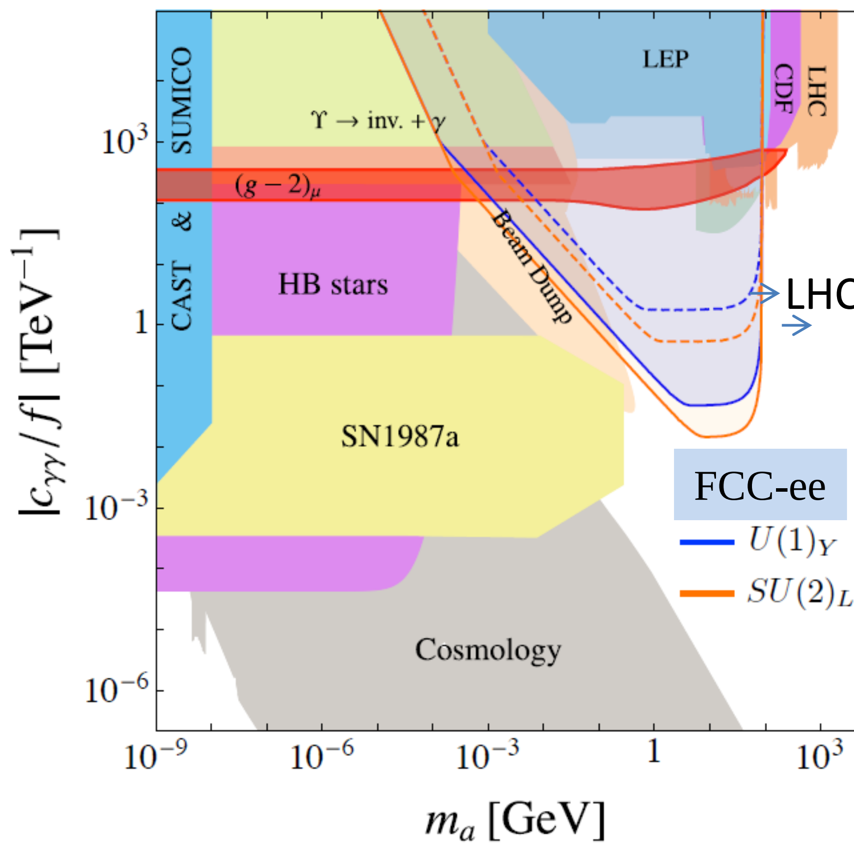


Cirelli

DM neutralino search at the FCC-hh



FCC-ee Z Axion-like particle

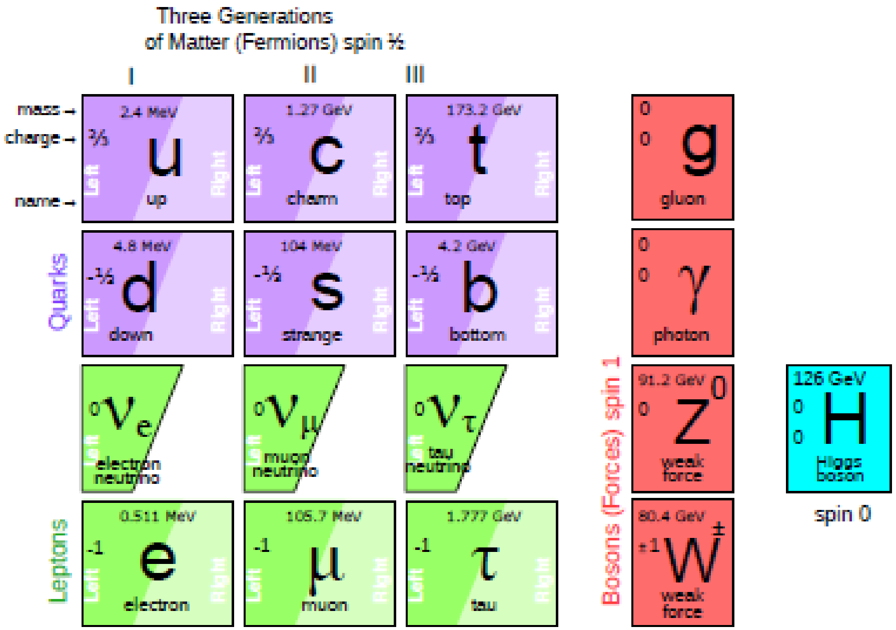


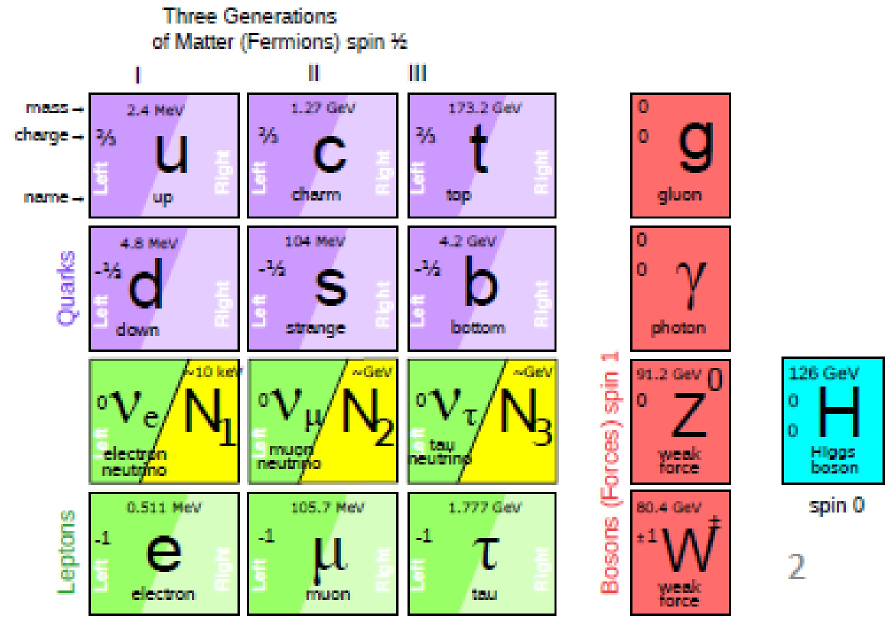
"FCC-hh covers the full mass range for the discovery of these WIMP Dark Matter candidates"

Z→ γa with a→γγ
FCC-ee (solid lines)
Run-2 of the LHC with 300 fb^{-1} (dashed)

«The Z run of FCC-ee is particularly fertile for discovery of particles with very small couplings»

at least 3 pieces are still missing



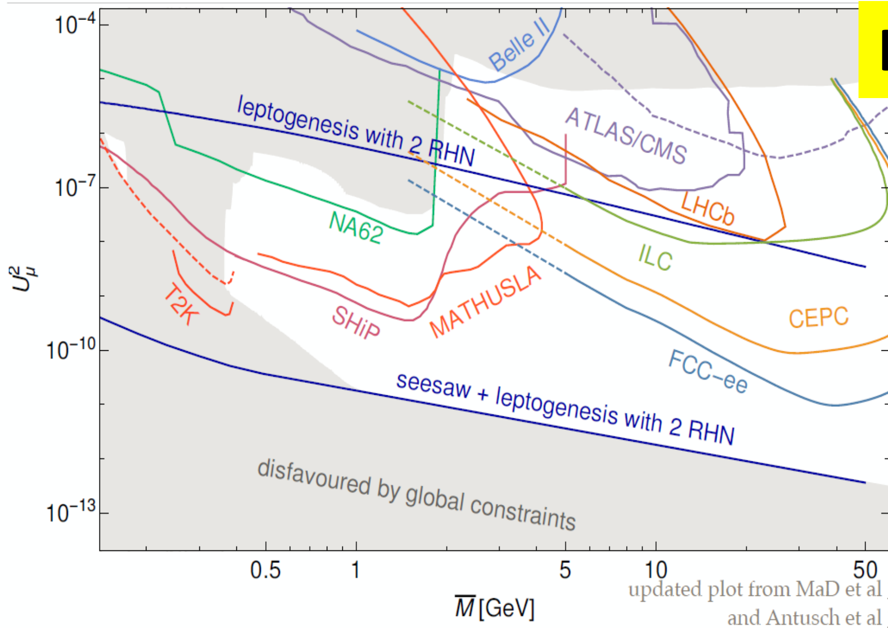


Since 1998 it is established that neutrinos have mass (oscillations)
and this very probably implies new degrees of freedom

➔ «sterile», very small coupling to known particles
completely unknown masses (eV to ZeV), nearly impossile to find.

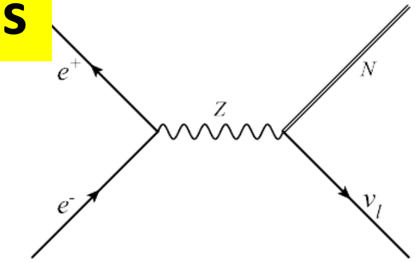
.... but could perhaps explain all: DM, BAU, ν-masses

Heavy neutrinos

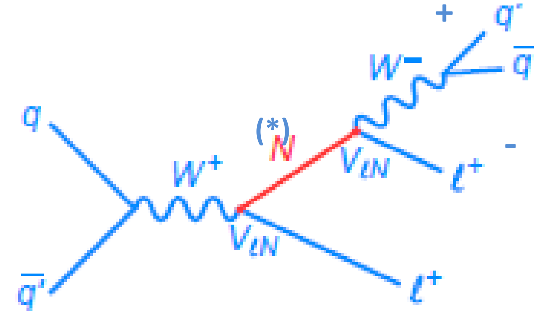


updated plot from MaD et al 1609.09069
and Antusch et al 1710.03744
cf. also Cai et al 1711.02180

FCC-ee Z



FCC-hh



or $l^\pm\nu$

FCC-ee

-- EWPO : sensitivity 10^{-5} up to very high masses

-- high sensitivity to single N($\rightarrow l_2^{\pm}$W) in Z decay

FCC-hh

-- production in W-> $l_1^{\pm}$ + N($\rightarrow l_2^{\pm}$W)

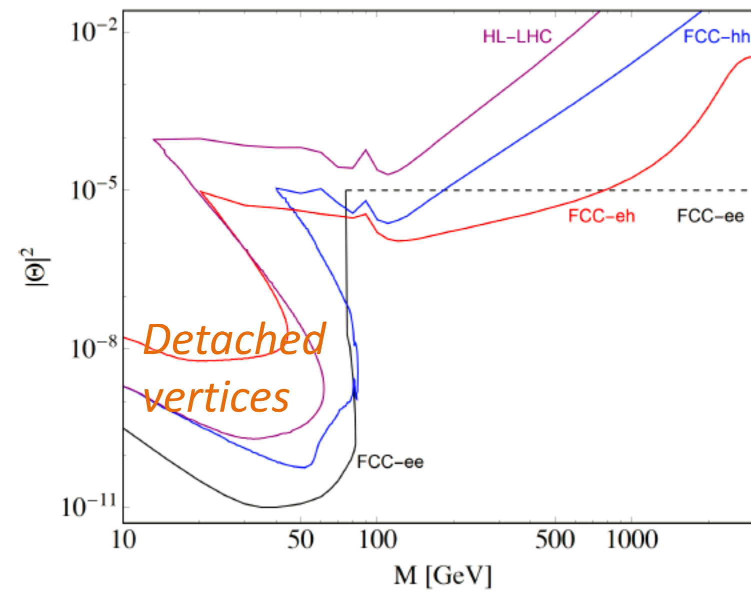
with initial and final lepton charge and flavour

FCC e-p

-- production in CC e$^{\pm}$ p $\rightarrow$ X N($\rightarrow l^{\pm}$W) high mass

<u>Complementarity:</u>

discovery + studies of FNV and LFV!



The capability to probe massive neutrino mechanisms for generating the matter-antimatter asymmetry in the Universe should be a central consideration in the selection and design of future colliders. (from the neutrino town meeting report to the ESPP)

FCC-ee discovery potential and Highlights

Today we do not know how nature will surprise us. A few things that FCC-ee could discover :

EXPLORE 10-100 TeV energy scale (and beyond) with Precision Measurements

-- ~20-100 fold improved precision on many EW quantities (equiv. to factor 5-10 in mass)

$m_{Z,}$ m_W, m_{top} , $\sin^2\theta_w^{eff}$, R_b , $\alpha_{QED}(m_z)$ $\alpha_s(m_z\, m_W\, m_\tau)$, Higgs and top quark couplings

model independent «fixed candle» for Higgs measurements

DISCOVER a violation of flavour conservation or universality and unitarity of PMNS @10^{-5}

-- ex FCNC ($Z \to \mu\tau$, $e\tau$) in 5 10^{12} Z decays and τ BR in 2 10^{11} $Z\to \tau\tau$

+ flavour physics (10^{12} bb events) ($B\to s\,\tau\,\tau$ etc..)

DISCOVER dark matter as «invisible decay» of H or Z (or in LHC loopholes)

DISCOVER very weakly coupled particle in 5-100 GeV energy scale

such as: Right-Handed neutrinos, Dark Photons, ALPS, etc…

+ and many opportunities in – e.g. QCD (α_s @ 10^{-4}, fragementations, $H\to gg$) etc….

NB Not only a «Higgs Factory»! «Z factory» and «top» are important for 'discovery potential'

FCC-hh discovery potential and Highlights

FCC-hh is a HUGE discovery machine (if nature …), but not only.

FCC-hh physics is dominated by three features:

-- Highest center of mass energy –> a big step in high mass reach!
ex: strongly coupled new particle up to >30 TeV
Excited quarks, Z', W', up to ~tens of TeV
Give the final word on natural Supersymmetry, and WIMPS
extra Higgs etc.. reach up to 5-20 TeV
Sensitivity to high energy phenomena in e.g. WW scattering

-- HUGE production rates for single and multiple production of SM bosons (H,W,Z) and quarks
- **Higgs precision tests using ratios to e.g. $\gamma\gamma/\mu\mu/\tau\tau/ZZ$, ttH/ttZ @<% level**
- **Precise determination of triple Higgs coupling (~3% level) and quartic Higgs coupling**
- **detection of rare decays $H \rightarrow V\gamma$ ($V = \rho, \varphi, J/\psi, \Upsilon, Z$ …)**
- **search for invisibles (DM searches, RH neutrinos in W decays)**
- **renewed interest for long lived (very weakly coupled) particles.**
- **rich top and HF physics program**

-- Cleaner signals for high Pt physics
- **allows clean signals for channels presently difficult at LHC (e.g. $H \rightarrow bb$)**

FCC-eh Discovery Potential and Highlights

FCC-ep explores hitherto untouched domain of (x,q2) DIS plane and provides production of high mass SM particles (H, top) in cleaner conditions than pp.

-- extremely precise structure function work
important input on structure functions for FCC-hh
complete resolution of the partonic contents of the proton, for the first time
high precision α_s O(10^{-4}) similar to FCC-ee from totally different source

-- 2 10^6 Higgs produced from from W & Z to deliver precise H couplings complementary to ee -- esp (g_{HWW})

-- Searches for new physics (Leptoquarks, RH neutrinos, etc...) in new domain of mass and couplings

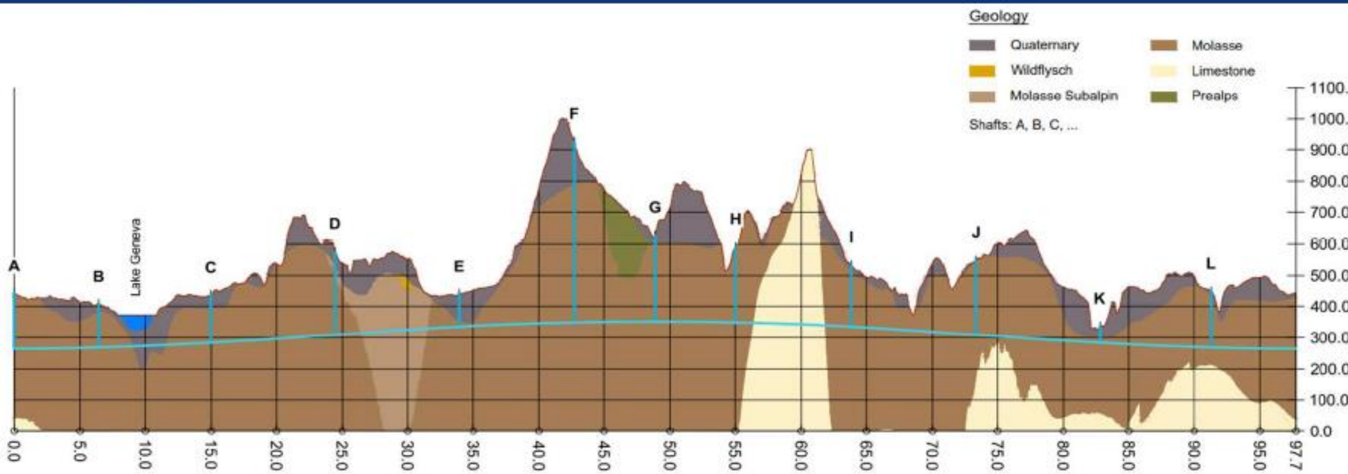
-- rich top (Vtb @% level, FCNC) and HF physics program

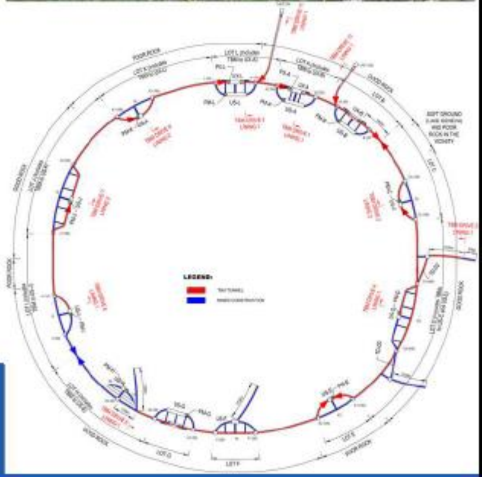
-- Discovery in QCD: non-linear parton evolutions, instantons?, ..

-- Unique electron-ion physics related to QGP physics

SYNERGY

FCC implementation - footprint baseline





Present baseline position was established considering:

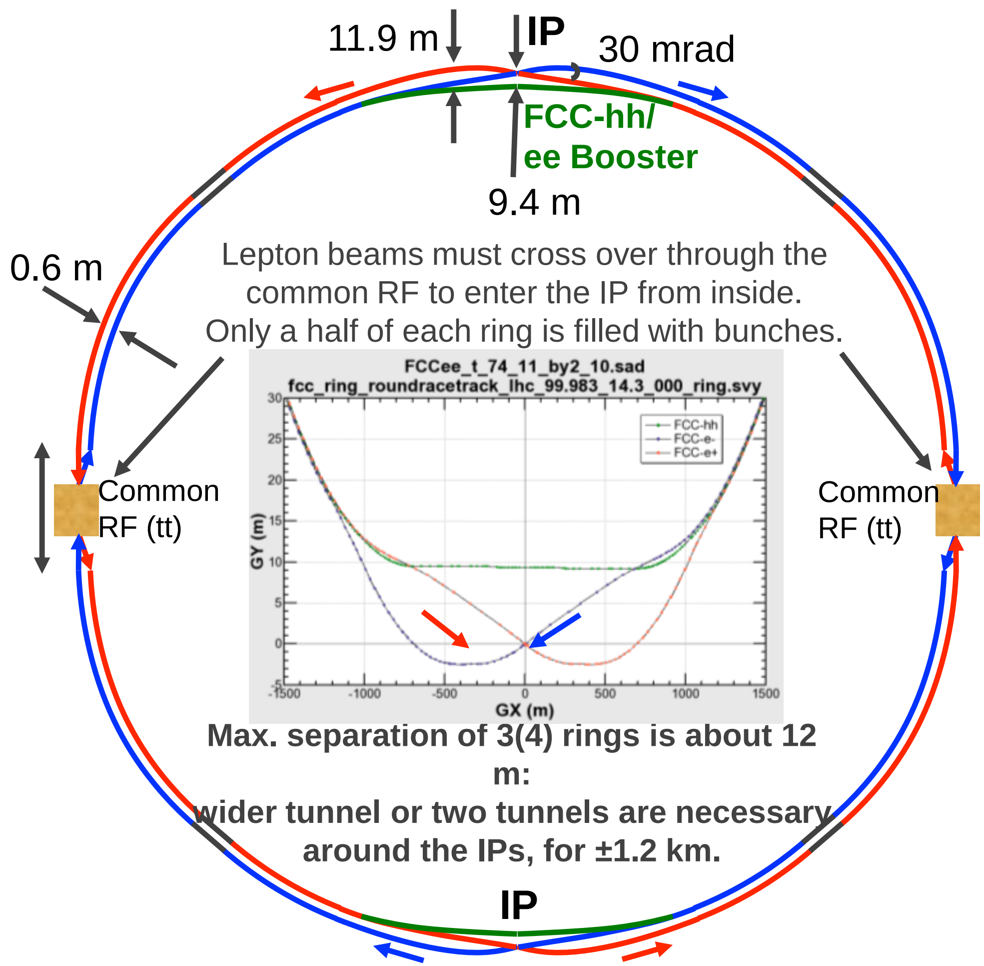
- lowest risk for construction
- fastest and cheapest construction
- feasible positions for large span caverns (most challenging structures)

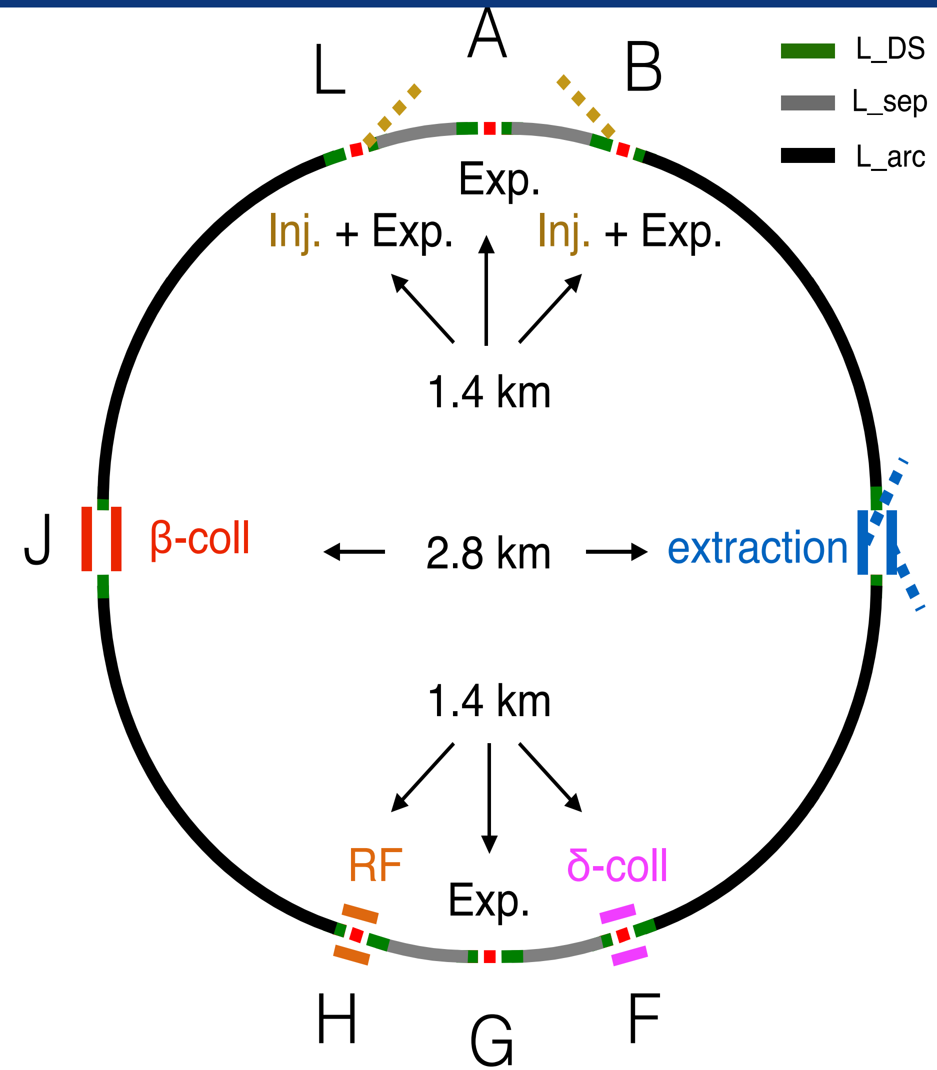
next step: review of surface site locations and machine layout

Future Circular Collider Study
Michael Benedikt
9th IPAC Vancouver, 3 May 2018

Sharing the same tunnel

common layouts for hh & ee





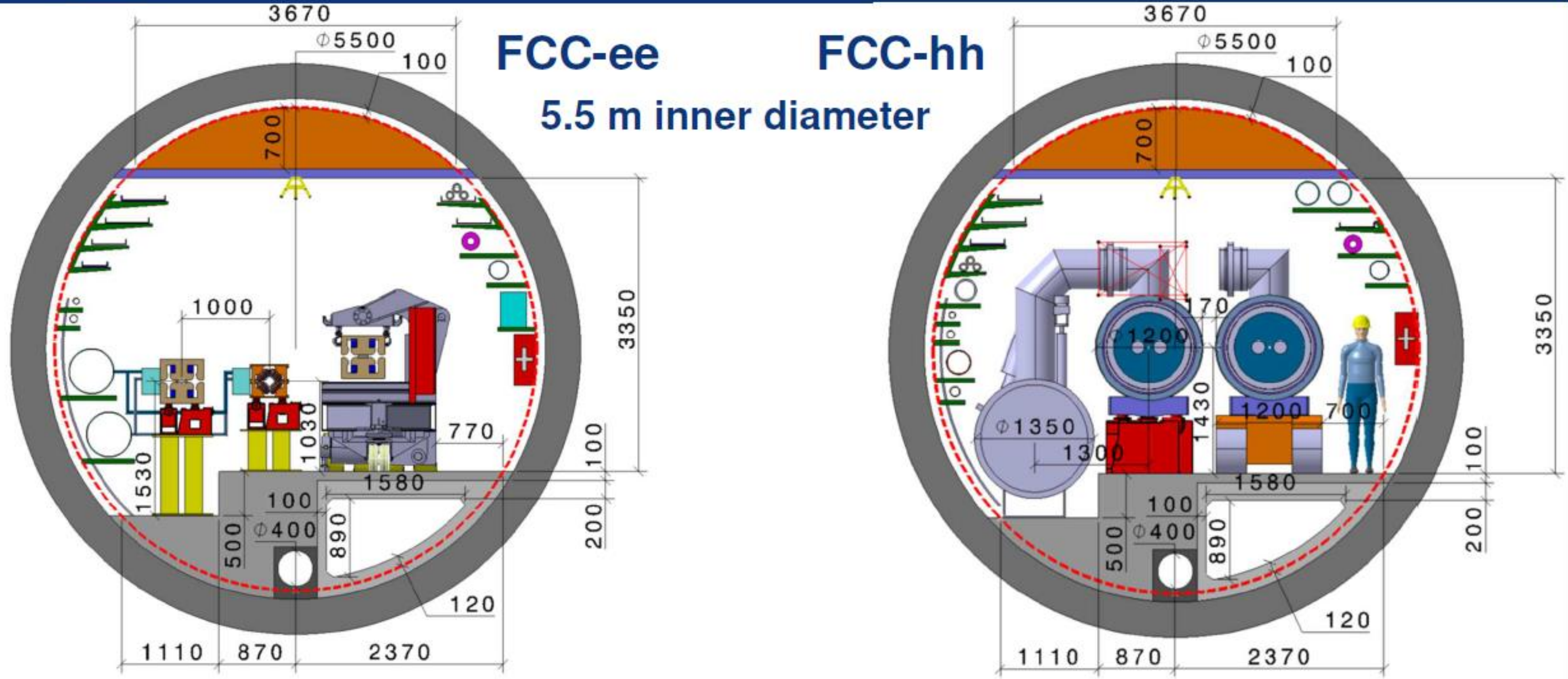
FCC-ee 1, FCC-ee 2,

FCC-ee booster (FCC-hh footprint)

Asymmetric IR for ee, limits SR to expt

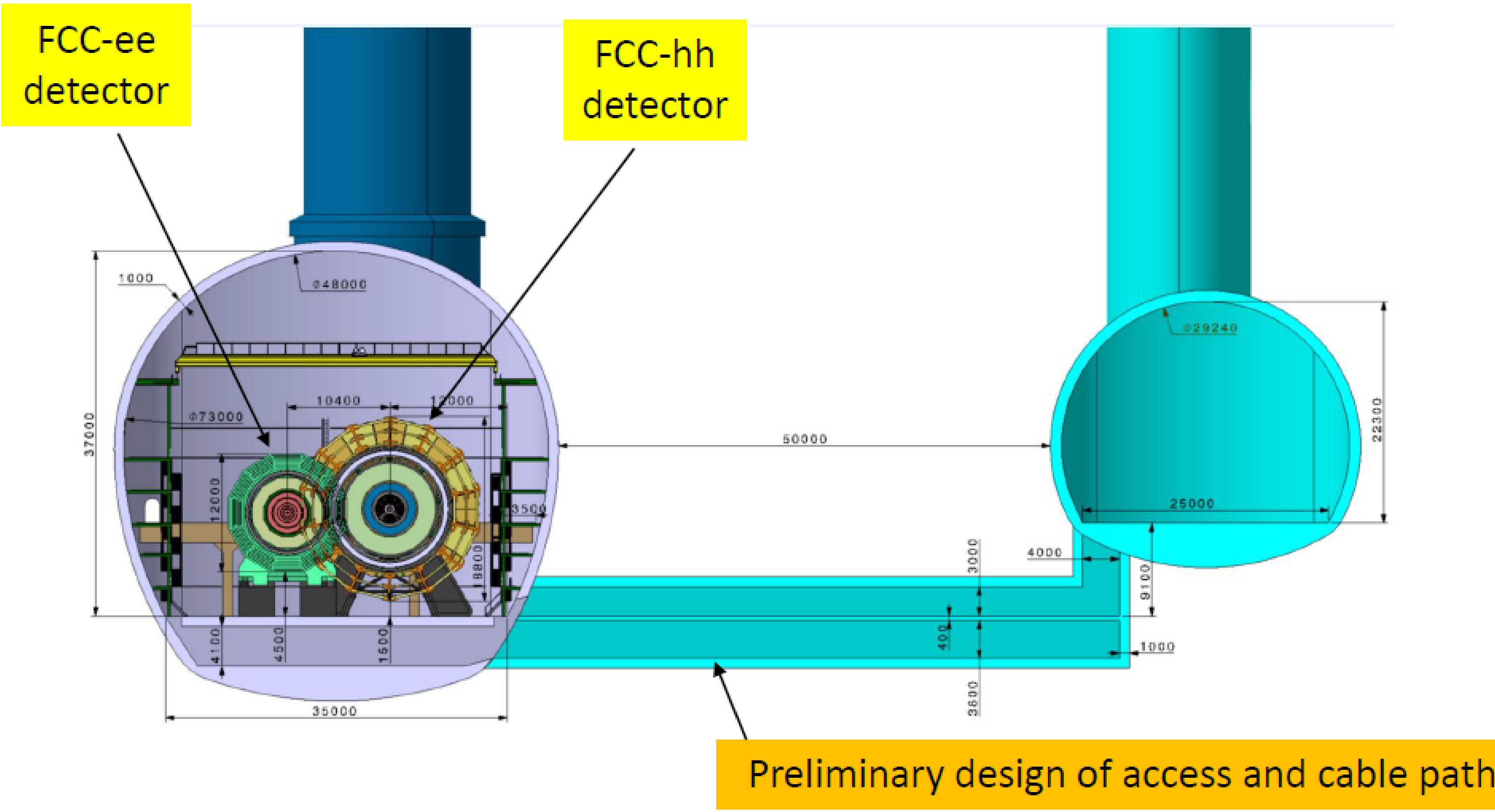
2 main IPs in A, G for both machines

FCC – tunnel integration in arcs

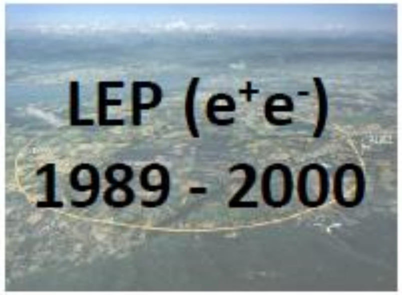


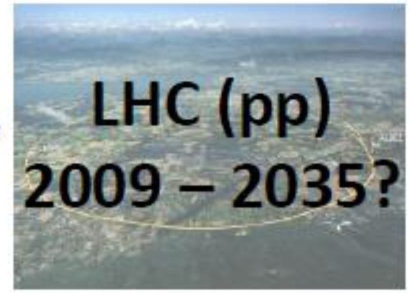
The same caverns

Distance between detector cavern and service cavern 50 m.



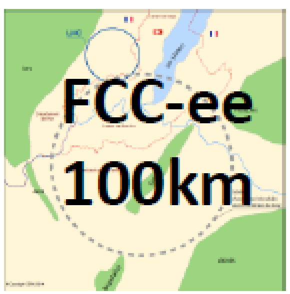
- **27km tunnel**

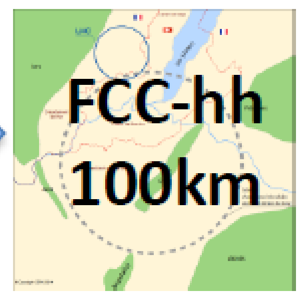




M. Aleksa

- **The next step: 100km tunnel**





a 10-20 TeV muon collider using the 45 GeV stored e+ as LEMMA SOURCE?

FCC data taking starts at the end of HL-LHC

We have gone a long way!

2010-11-12 : ideas, wishes, basic concepts, (VHE-LHC, LEP3, TLEP), Higgs discovery

2013 ESPP2013 wants «ambitious post-LHC accelerator projcet »

2014 Kick-off meeting

2018 ESPP contributions and CDR submitted

<u>FCC can be done!</u>

Starting with the e+ e- collider.

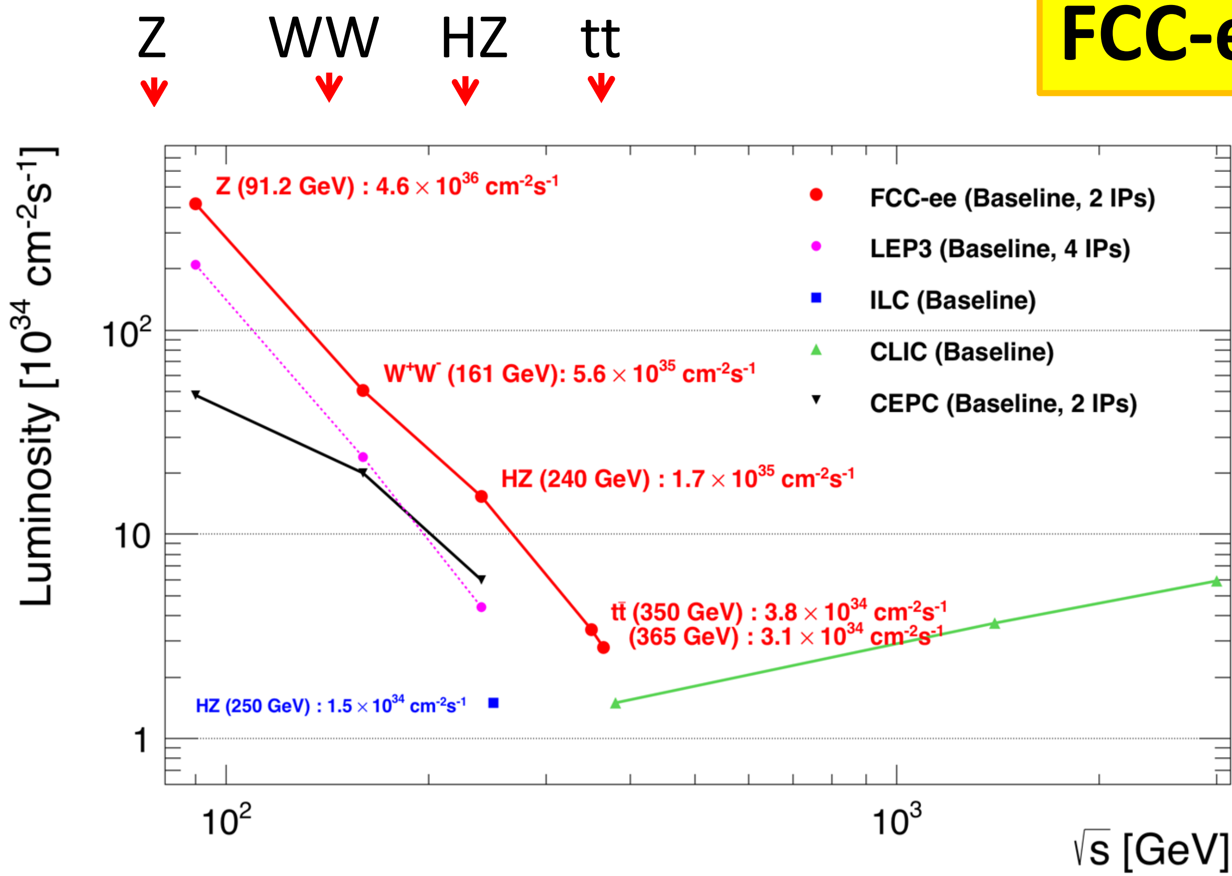
2019→ Start of a new era towards realization

2019 (15 January) CERN directorate New Year Presentation
https://indico.cern.ch/event/779524/
Press release on FCC CDR release
FCC CDR physics presentation 4-5 March at CERN;
Plenary Meeting (ESPP) Granada 13-17 May
FCC General meeting in 24-28 June in Brussels https://indico.cern.ch/event/727555

FCC Kick-off Meeting

341 registered participants

FCC-ee



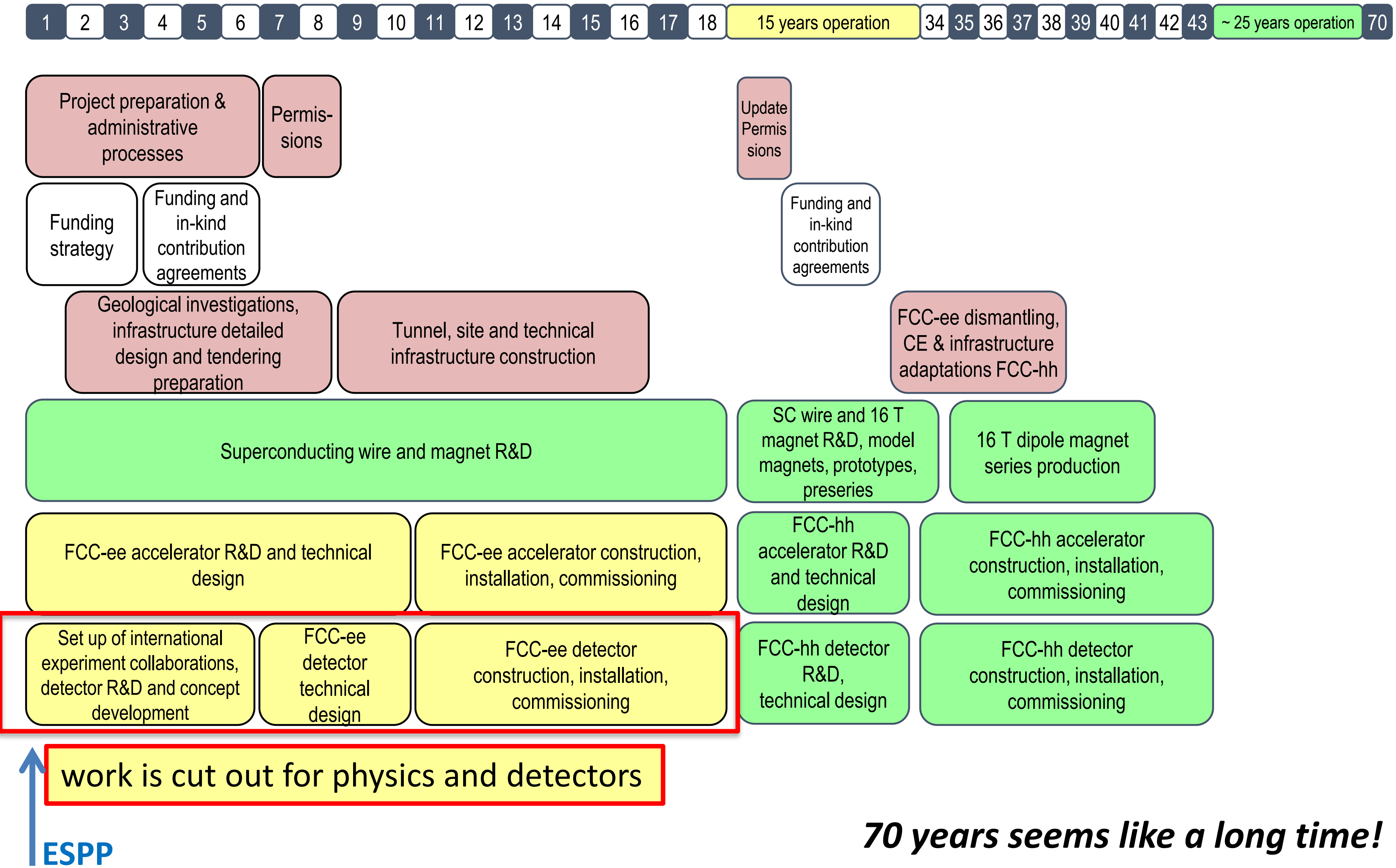
Event statistics :

E_{CM} errors:

				E_{CM} errors
Z peak	**E_{cm} : 91 GeV**	**$5\ 10^{12}$ e+e- → Z**	**LEP x 10^5**	100 keV
WW threshold	**E_{cm} : 161 GeV**	**10^8 e+e- → WW**	**LEP x 2.10^3**	300 keV
ZH threshold	**E_{cm} : 240 GeV**	**10^6 e+e- → ZH**	**Never done**	2 MeV
$\bar{t}t$ threshold	**E_{cm} : 350 GeV**	**10^6 e+e- → $\bar{t}t$**	**Never done**	5 MeV

Great energy range for the heavy particles of the Standard Model.

FCC integrated project technical timeline



70 years seems like a long time!

PHYSICS WITH VERY HIGH ENERGY
e^+e^- COLLIDING BEAMS

CERN 76-18
8 November 1976

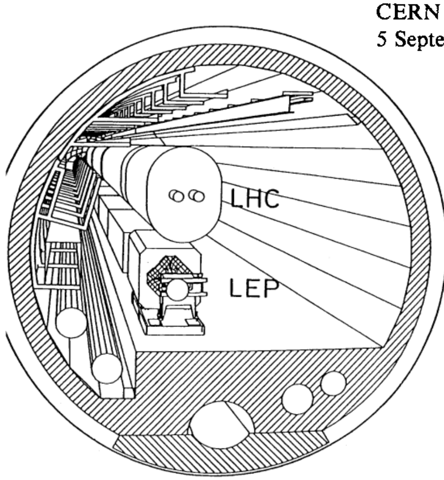
L. Camilleri, D. Cundy, P. Darriulat, J. Ellis, J. Field,
H. Fischer, E. Gabathuler, M.K. Gaillard, H. Hoffmann,
K. Johnsen, E. Keil, F. Palmonari, G. Preparata, B. Richter,
C. Rubbia, J. Steinberger, B. Wiik, W. Willis and K. Winter

ABSTRACT

This report consists of a collection of documents produced by a Study Group on Large Electron-Positron Storage Rings (LEP). The reactions of

Did these people know that we would be running HL-LHC in that tunnel >**60 years later?**

ECFA 84/85
CERN 84-10
5 September 1984



LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

Let’s not be SHY!

CONCLUSIONS

-- The FCC design study has established the feasibility -- or the path to feasibility -- of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology. **FCC can be done!**

-- FCC-ee and FCC-hh have outstanding physics cases
- -- each in their own right
- -- the sequential implementation of FCC-ee, FCC-hh with eh option offers the broadest physics reach proposed today

big jumps in **Sensitivity, Precision, Energy**

-- An attractive scenario of staging and implementation cover 70 years of exploratory physics, taking full advantage of the **synergies and complementarities**.

FCC (ee) can start seamlessly at the end of HL-LHC

FINAL WORDS

The proposed integrated FCC is a large, ambitious, expensive facility

The size is optimal for studying the heavy particles of the Standard Model with an e+e- collider , and guarantees a big jump in energy reach for the hadron collider.

Alternative facilities that are proposed to provide e.g. the same table of Higgs properties are 1) less precise 2) not much cheaper and 3) considerably less broad in physics ability.

The other routes to 100 TeV are less precise, less complete, and more expensive.

CERN is the best place for such a challenging enterprise, given its demonstrated extraordinary competence, its international membership, and the CERN existing infrastructure: accelerator complex, including the injectors, cryogenics, etc.
(Building FCC in a green field would be much more challenging and risky)

We have of course made the point that CERN has many by-products and spin-offs that benefit society, even at short time-scale:
-- the web, fast electronics, particle accelerator & detector technology and know-how, leading to beneficial effects in communications, medicine, health, other sciences etc…

FINAL WORDS (II)

The **SCIENCE** we do today, hand in hand with cosmology, astrophysics and many other fields:
'How the Universe was born and how it works'
addresses questions that have fascinated humanity, and raised passions, for a very long time.

The existence of a large community of scientists from all continents, gender, culture and religion, working together to come closer to these fundamental questions, with explanations based on **facts,** in a language that is **universal** …

… is a tremendous hope for education, harmony and peace.

Progress in knowledge has no price