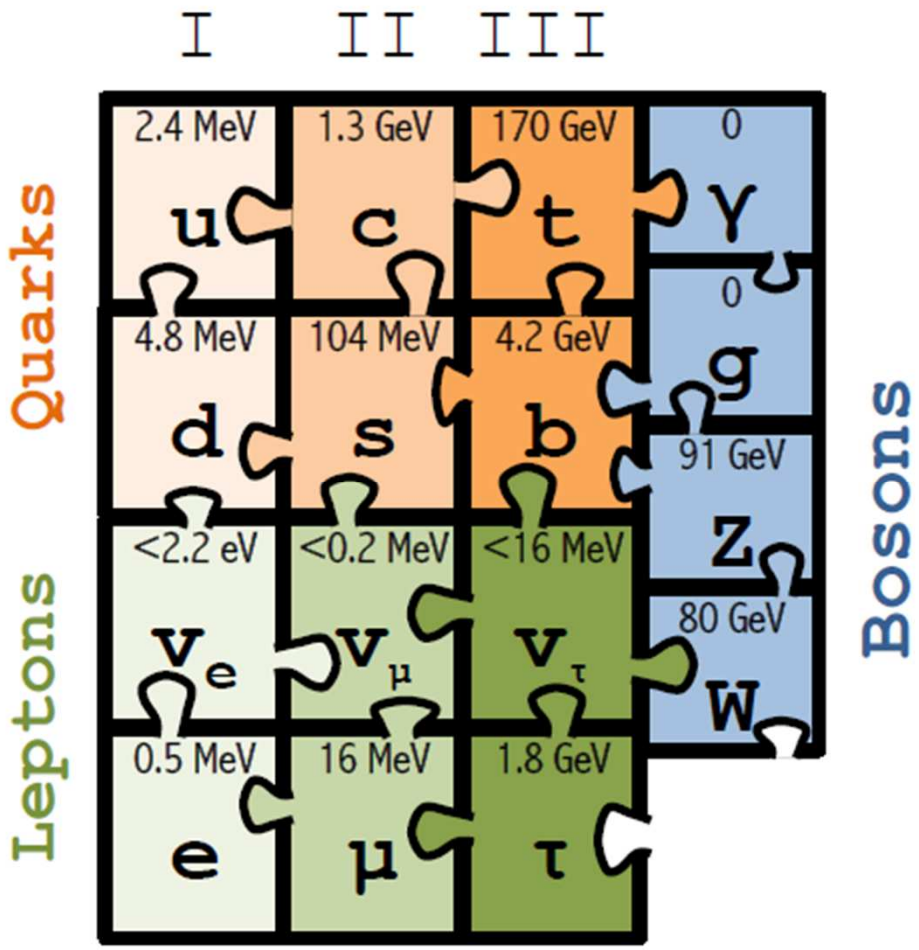
FUTURE CIRCULAR COLLIDERS

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

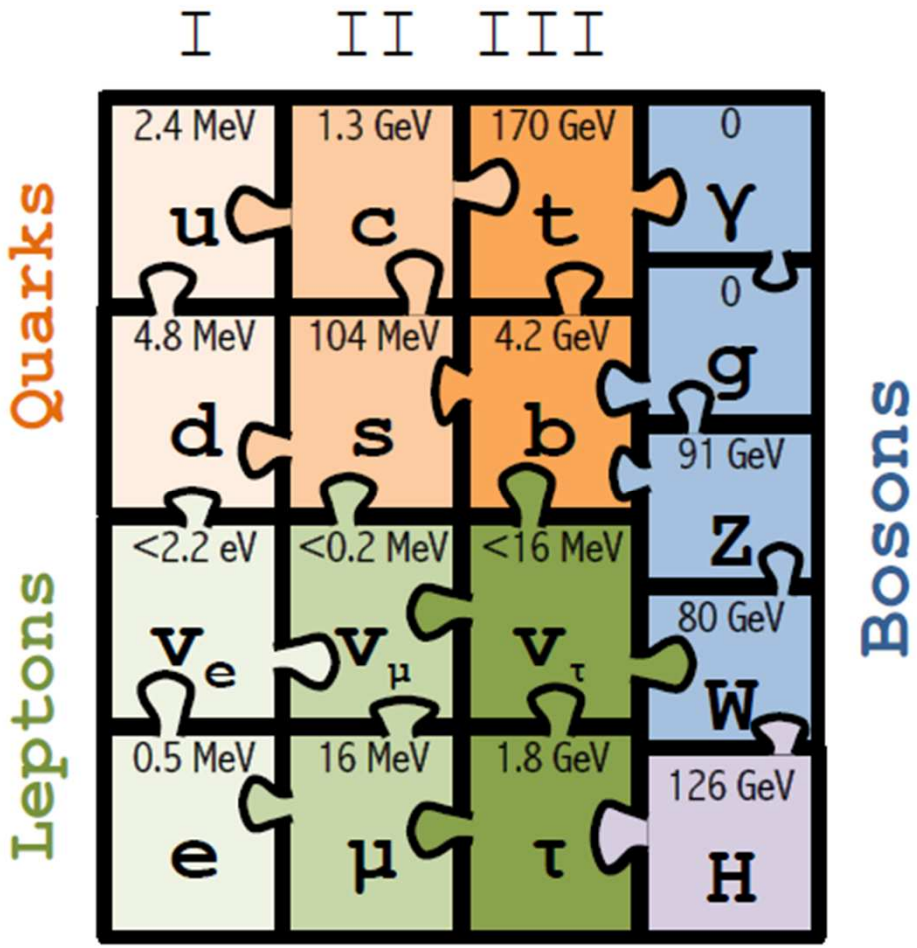
http://espace2013.cern.ch/fcc/Pages/Science.aspx

1994-1999: top mass predicted (LEP, mostly Z mass&width)
top quark discovered (Tevatron)
t'Hooft and Veltman get Nobel Prize



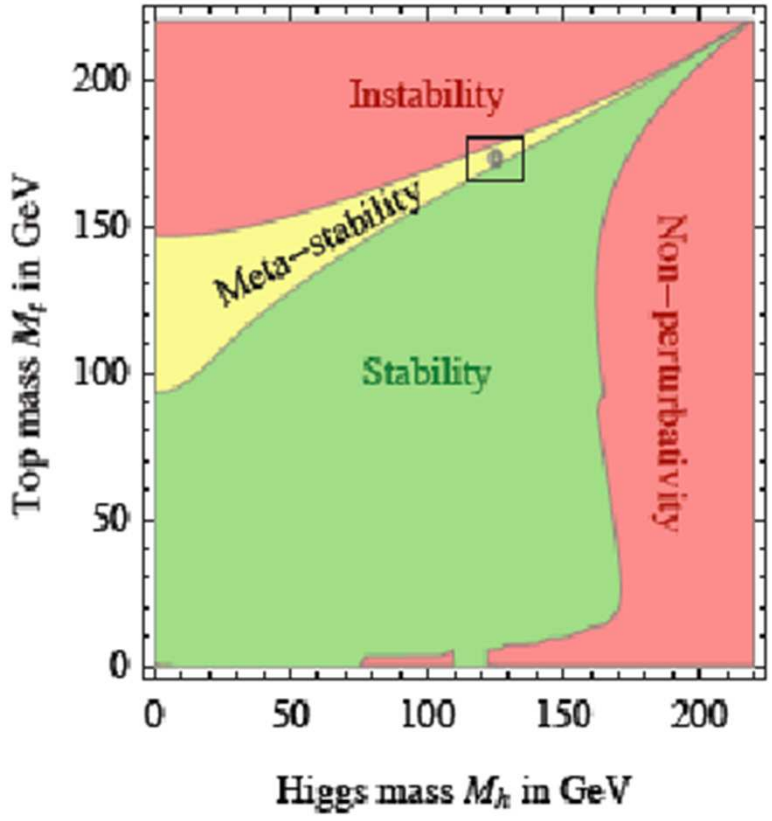
(c) Sfyrla

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



(c) Sfyrla

Is it the end?


Instability
Meta−stability
Stability
Non−perturbativity
Top mass M_t in GeV
Higgs mass M_h in GeV
0
50
100
150
200

Asymptotic safety of gravity and the Higgs boson mass

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Institut de Théorie des Phénomènes Physiques, École Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland

Christof Wetterich

Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, D-69120 Heidelberg, Germany

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.

in 2010 Shaposhnikov and Wetterich predict m_H=126 GeV if there is no intermediate energy scale between the Fermi and Planck scales...

Is it the end?

Certainly not!

-- Dark matter

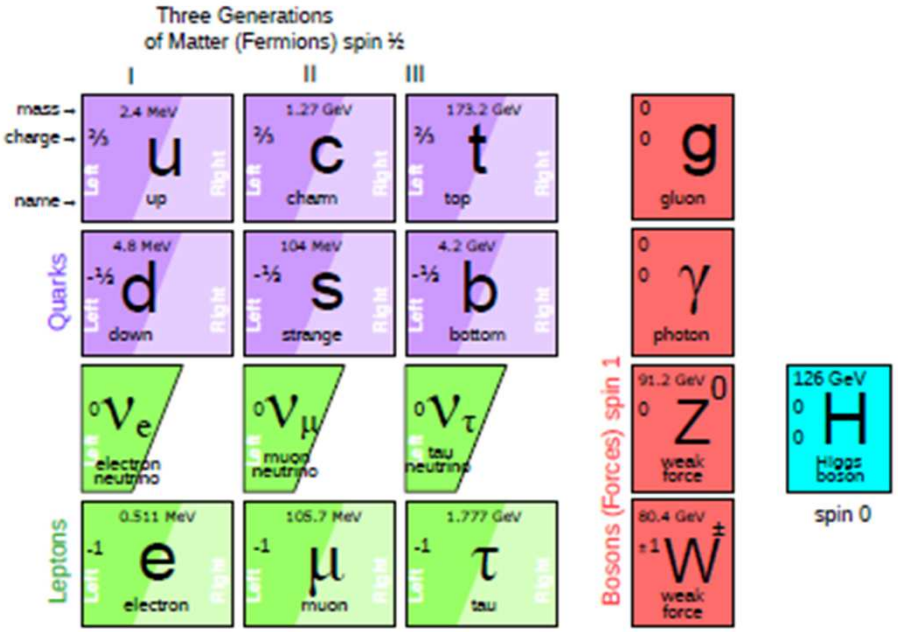
-- Baryon Asymmetry in Universe

-- Neutrino masses

are experimental proofs that there is more to understand.

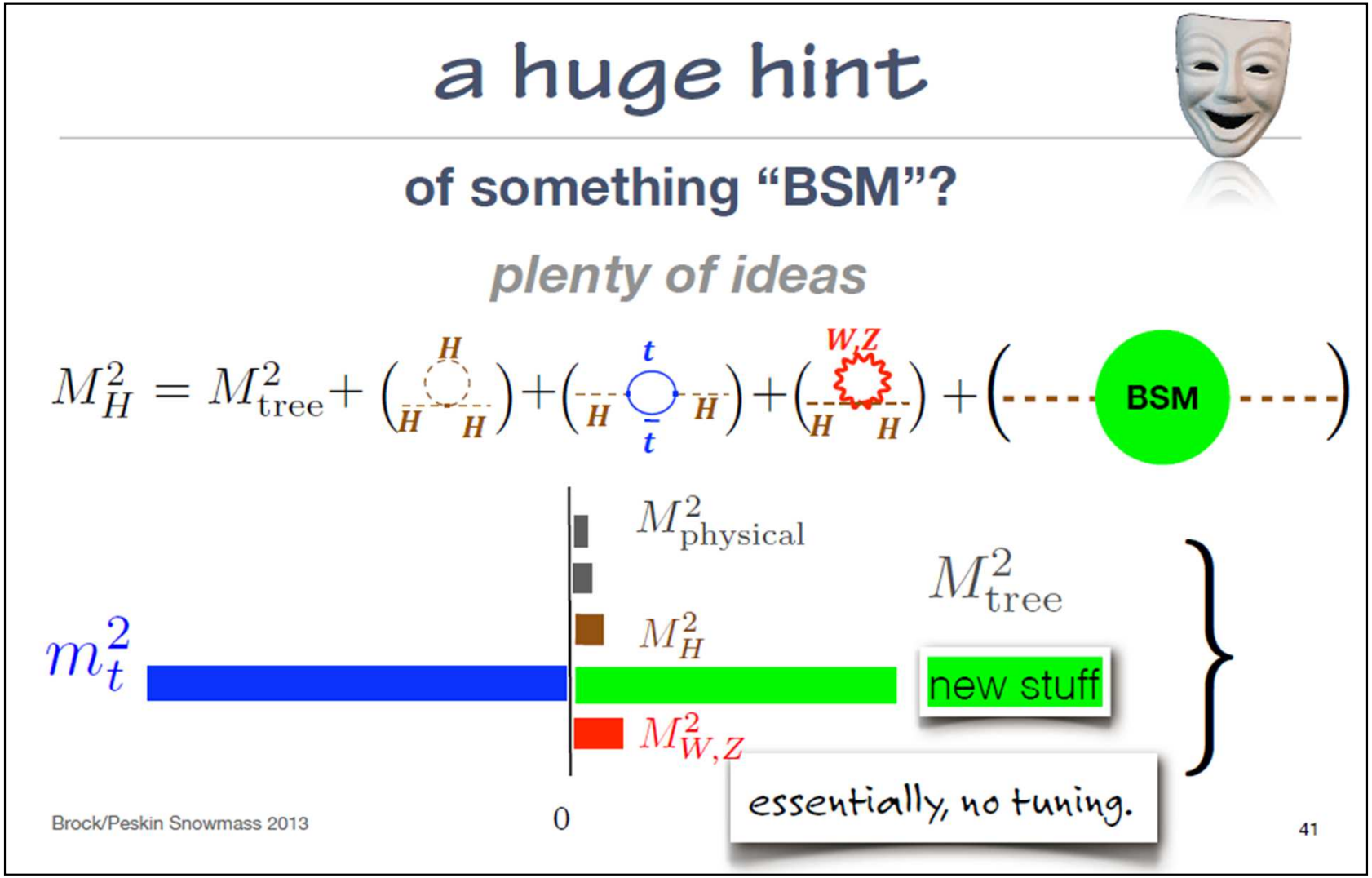
We must continue our quest

at least 3 pieces are still missing



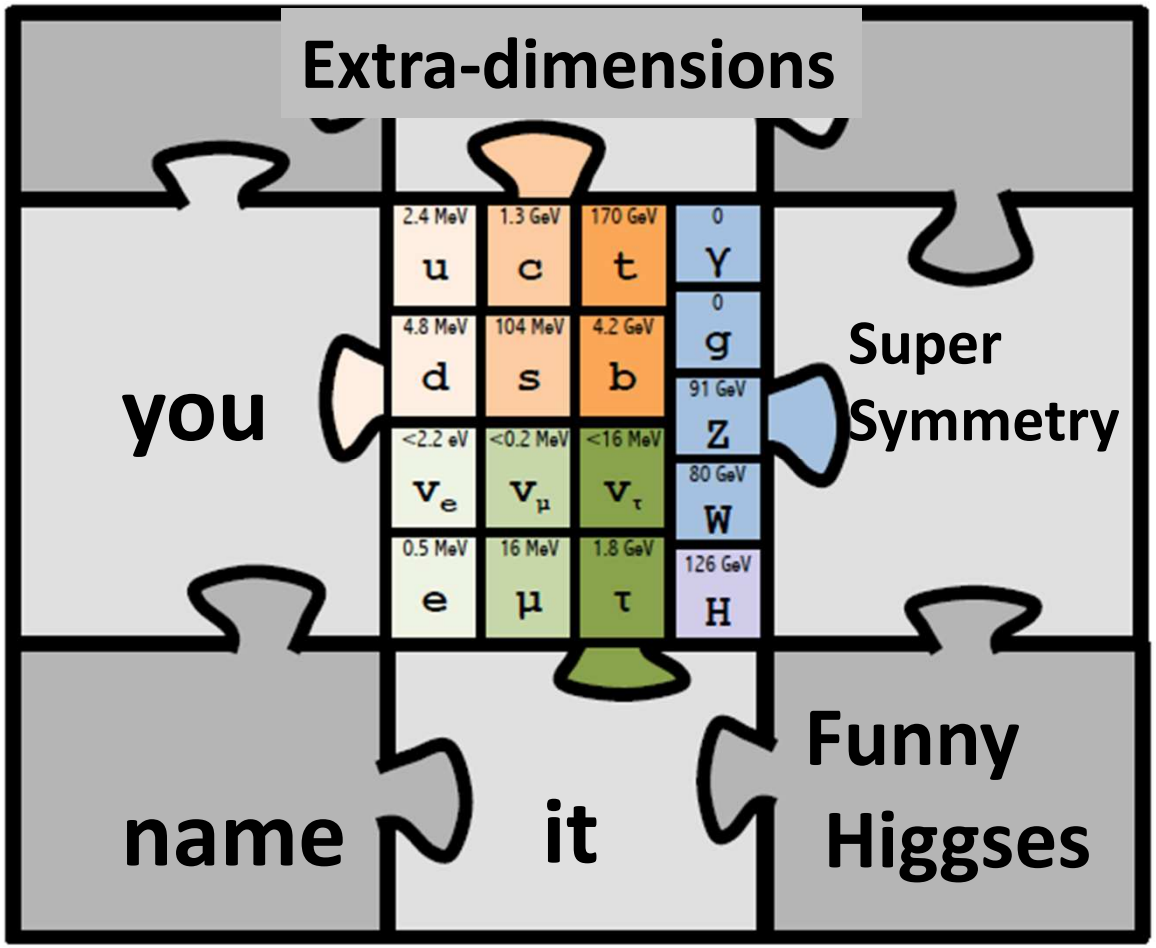
Since 1998 it is established that neutrinos have mass and this very probably implies new degrees of freedom

And some say there MUST be new physics at TeV scale



AB: or is it just that the SM scalar self energy can't make sense perturbatively?

perhaps new world(s) of SM replicas?



«We can extrapolate to the Planck scale»

and

«There MUST be new physics at TeV scale»

are mutually exclusive.

There is one way to find out: go look!

Nima

Nima

At higher masses -- or at smaller couplings?

26 March 2013

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE

CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

White paper

Update of the European Strategy for Particle Physics

by the European Strategy Group for Particle Physics

Final version agreed by consensus at the 15th European Strategy Session of the Council on 22 March 2013 and which will be submitted for formal adoption to the Special European Strategy Session of the Council in Brussels on 30 May 2013.

High-priority large-scale scientific activities

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

LHC and HL-LHC

c) The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme. *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

pp and ee HE frontier

d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. *CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating 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 LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. *Europe looks forward to a proposal from Japan to discuss a possible participation.*

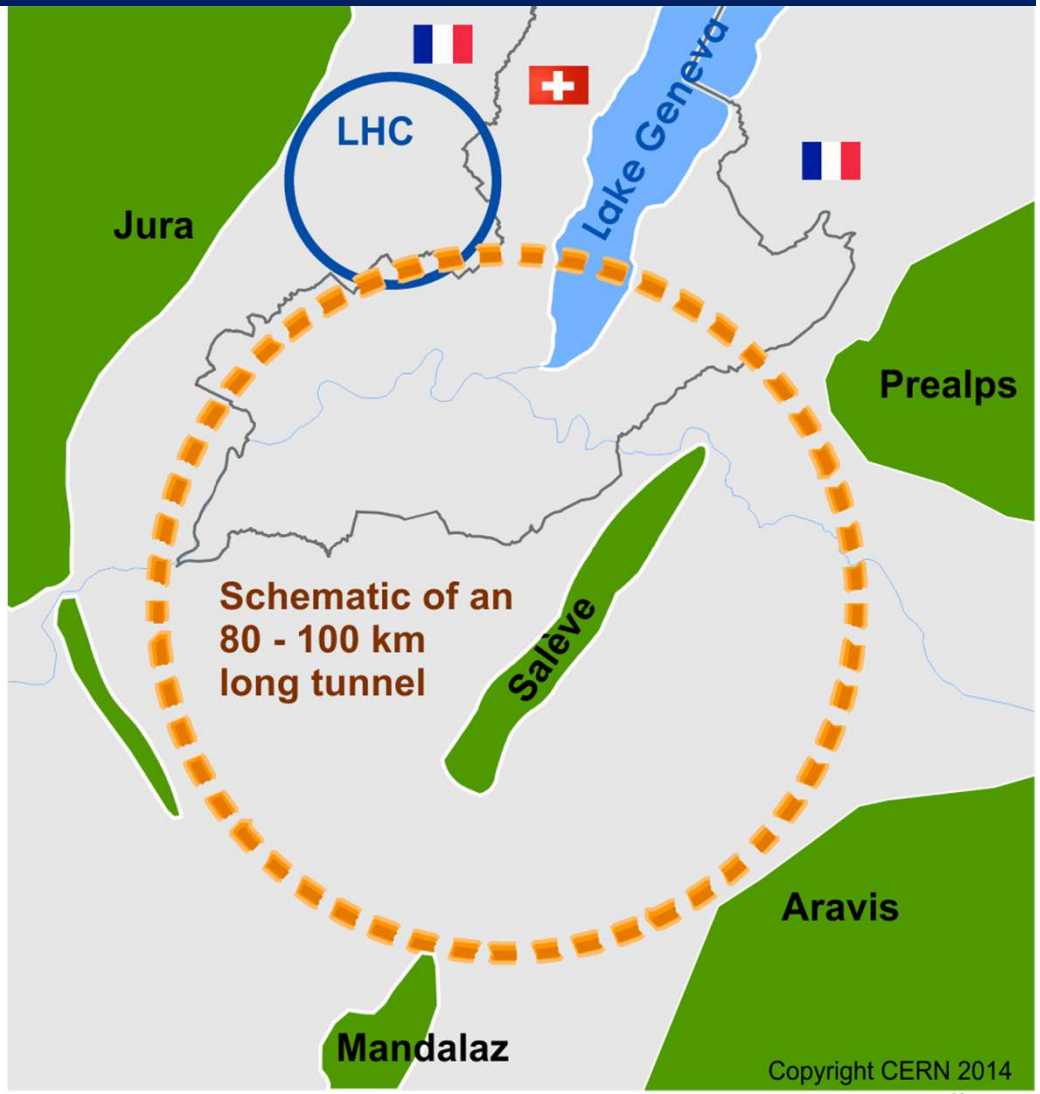
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

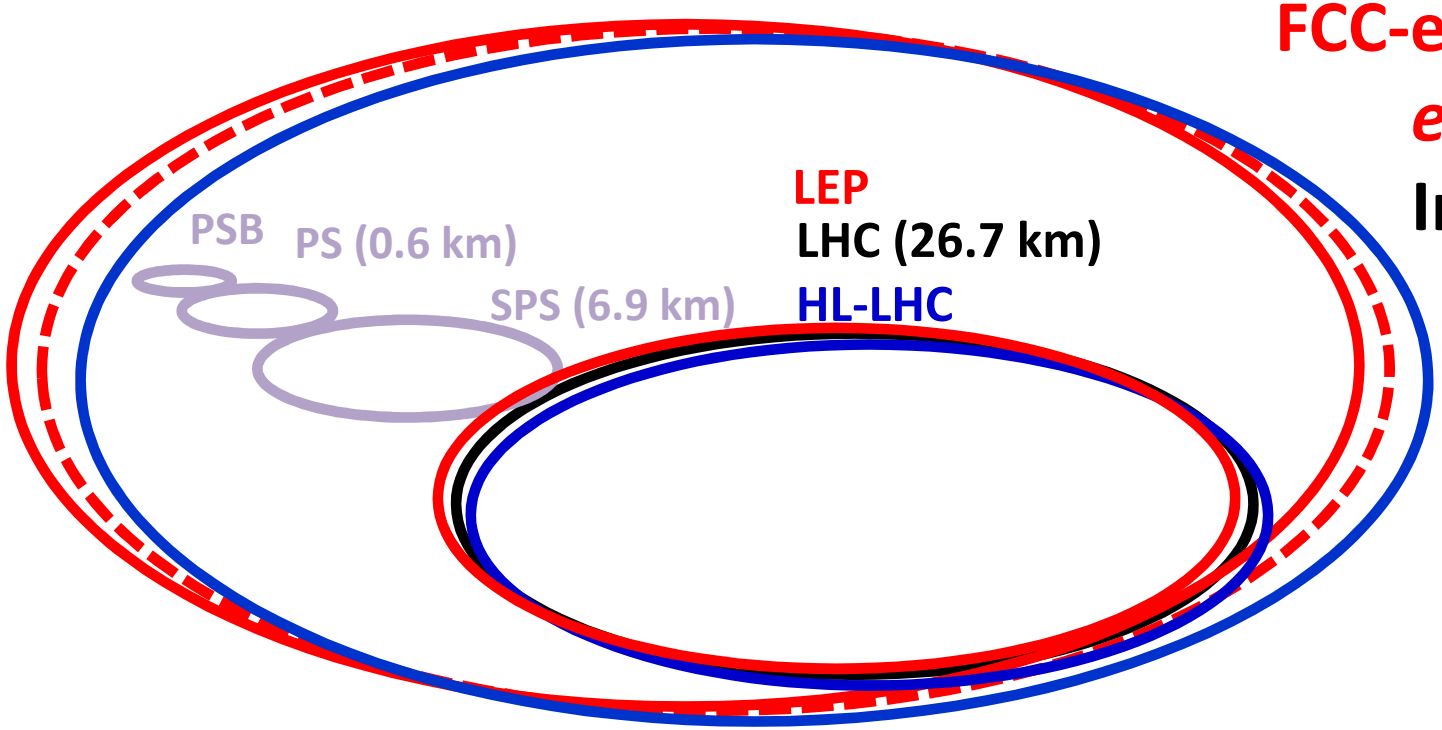
- ***pp*-collider (*FCC-hh*) → defining infrastructure**

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- **e^+e^- collider (*FCC-ee*) as potential intermediate step**
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure in Geneva area**



possible long-term strategy



FCC-ee (80-100 km, e^+e^-, 90-350 GeV

Interm. step

FCC-hh (*pp*, up to 100 TeV c.m.)

Ultimate goal

& $e^{\pm}$ **(120 GeV)–*p* (7, 16 & 50 TeV)** collisions FCC-eh)

≥50 years of e^+e^-, *pp*, *ep/A* physics at highest energies

-- On CERN's 60th birthday --

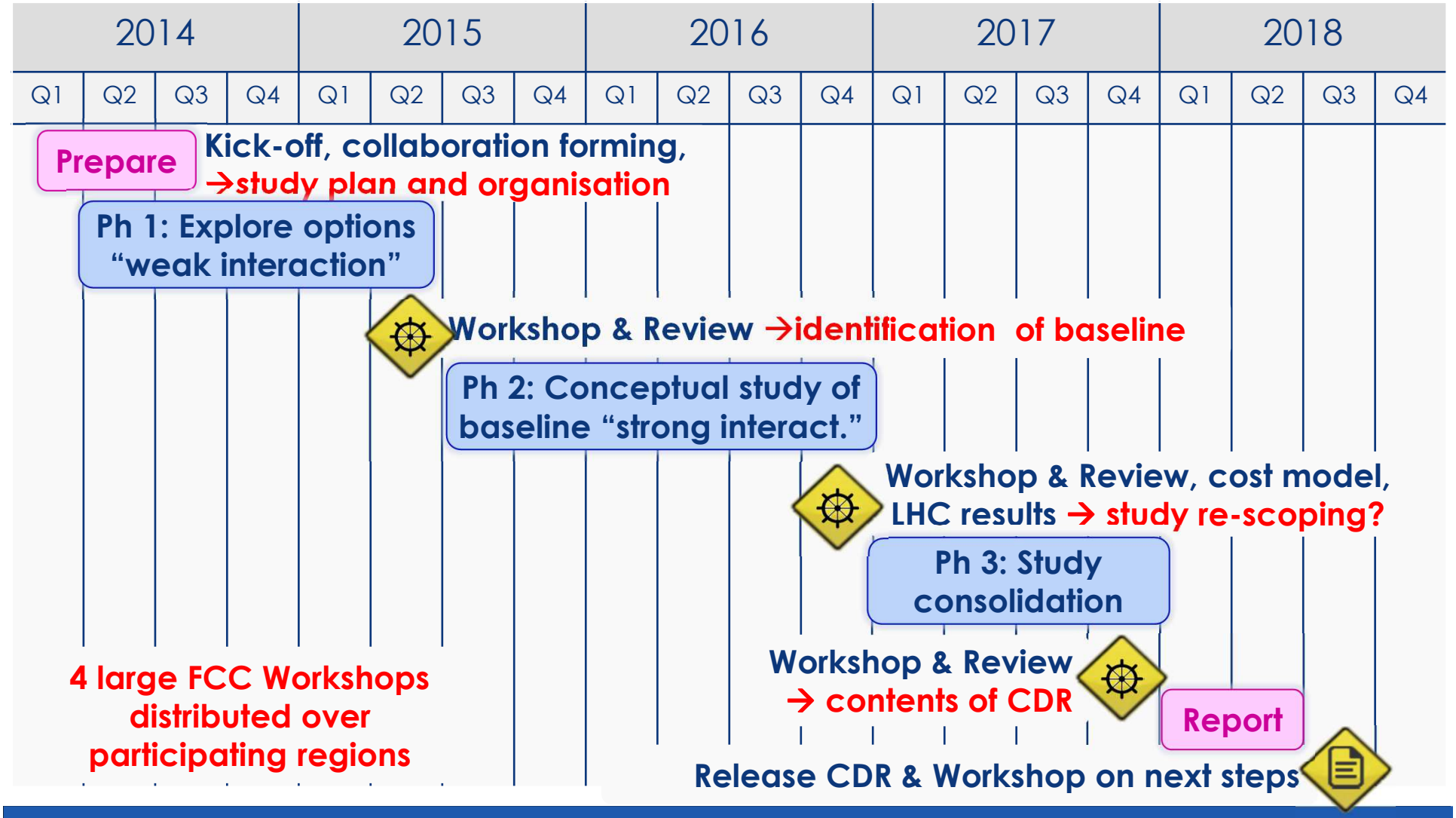
Future Circular Collider Study Kickoff Meeting

FCC Study Coordination Group

Study Coordination	M. Benedikt, F. Zimmermann
Hadron Collider Physics and Experiments	F. Gianotti, A. Ball, M. Mangano
Lepton Collider Physics and Experiments	A. Blondel, J. Ellis, P. Janot
e-p Physics, Experiments, IP Integration	M. Klein, O. Bruning
Hadron Injectors	B. Goddard
Hadron Collider	D. Schulte, M. Syphers, J.M. Jimenez
Lepton Injectors	Y. Papaphilippou (tbc)
Lepton Collider	J. Wenninger, U. Wienands, J.M. Jimenez
Accelerator R & D Technologies	M. Benedikt, F. Zimmermann
Infrastructures and Operation	P. Lebrun, P. Collier
Costing Planning	F. Sonnemann, P. Lebrun

M. Benedikt

Proposal for FCC Study Time Line



FCC-hh parameters – starting point

Energy	**100 TeV c.m.**
Dipole field	**~ 16 T (Nb_3Sn), [20 T option HTS]**
Circumference	**~ 100 km**
#IPs	**2 main (tune shift) + 2**
Luminosity/IP_{main}	**$5x10^{34}$ $cm^{-2}s^{-1}$**
Stored beam energy	**8.2 GJ/beam**
Synchrotron radiation	**26 W/m/aperture** (filling fact. ~78% in arc)
Long. emit damping time	**0.5 h**
Bunch spacing	**25 ns [5 ns option]**
Bunch population (25 ns)	$1x10^{11}$ p
Transverse emittance	2.2 micron normalized
#bunches	10500
Beam-beam tune shift	0.01 (total)
β*	1.1 m (HL-LHC: 0.15 m)

} already available from SPS for 25 ns

Ongoing discussion : should we go to $10^{36}cm^{-2}s^{-1}$?

parameter	LHC	HL-LHC	FCC-hh
c.m. energy [TeV]	14		100
dipole magnet field [T]	8.33		16 (20)
circumference [km]	26.7		100 (83)
luminosity [10^{34} cm^{-2}s^{-1}]	1	5	5 [→20?]
bunch spacing [ns]	25		25 {5}
events / bunch crossing	27	**135**	**170 {34}**
bunch population [10^{11}]	1.15	2.2	1 {0.2}
norm. transverse emitt. [μm]	3.75	2.5	2.2 {0.44}
IP beta-function [m]	0.55	0.15	1.1
IP beam size [μm]	16.7	7.1	6.8 {3}
synchrotron rad. [W/m/aperture]	0.17	0.33	28 (44)
critical energy [keV]	0.044		4.3 (5.5)
total syn.rad. power [MW]	**0.0072**	**0.0146**	**4.8 (5.8)**
longitudinal damping time [h]	**12.9**		**0.54 (0.32)**

FCC-hh baseline parameters
defined in EDMS No. 1342402,
FCC-ACC-SPC-0001
- preliminary -

93km “optimised” racetrack

PRELIMINARY

Alignment | **Shaft Tools**

Choose alignment option

90km quasi-circular

Tunnel depth at centre: 236mASL

Gradient Parameters

Azimuth (°): -15

Slope Angle x-x(%): 3

Slope Angle y-y(%): 0

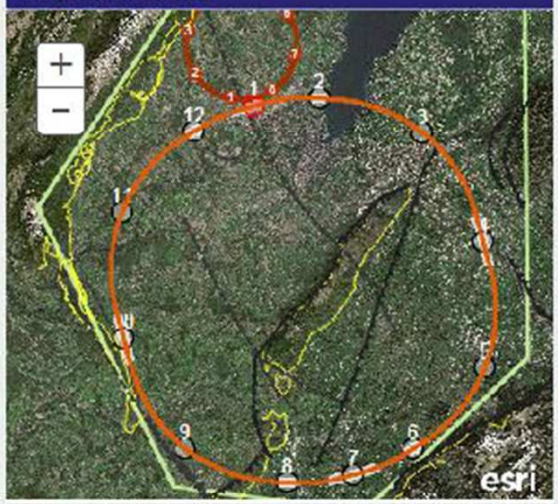
CALCULATE

Alignment centre

X: 2493923 Y: 1105695

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

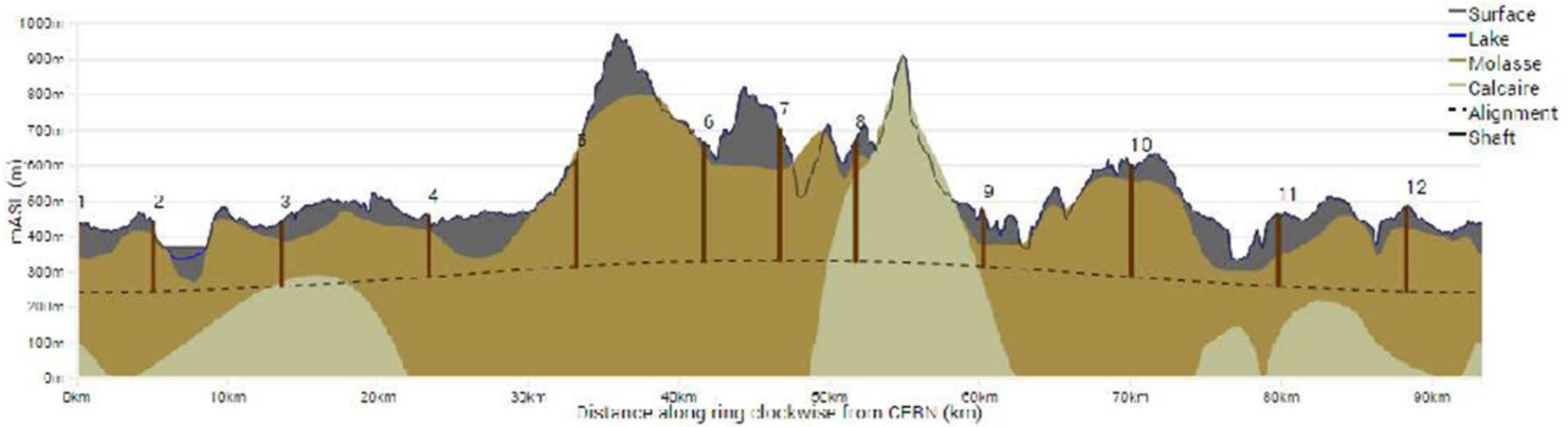
Alignment Location



Geology Intersected by Shafts | **Shaft Depths**

Shaft	Shaft Depth (m) Actual	Min	Mean	Max	Geology (m) Moraine	Molasse	Calcaire
1	200	195	197	200	92	108	0
2	196	143	181	211	34	167	0
3	183	175	184	194	63	121	9
4	174	146	166	178	44	130	0
5	299	286	311	350	0	325	0
6	396	325	339	350	55	307	0
7	374	349	377	412	119	256	0
8	397	318	341	356	44	56	297
9	156	131	145	157	94	61	0
10	315	305	320	336	46	269	0
11	203	199	202	234	122	81	0
12	239	229	238	243	58	181	0
Total	3014	2801	3001	3211	741	2062	247

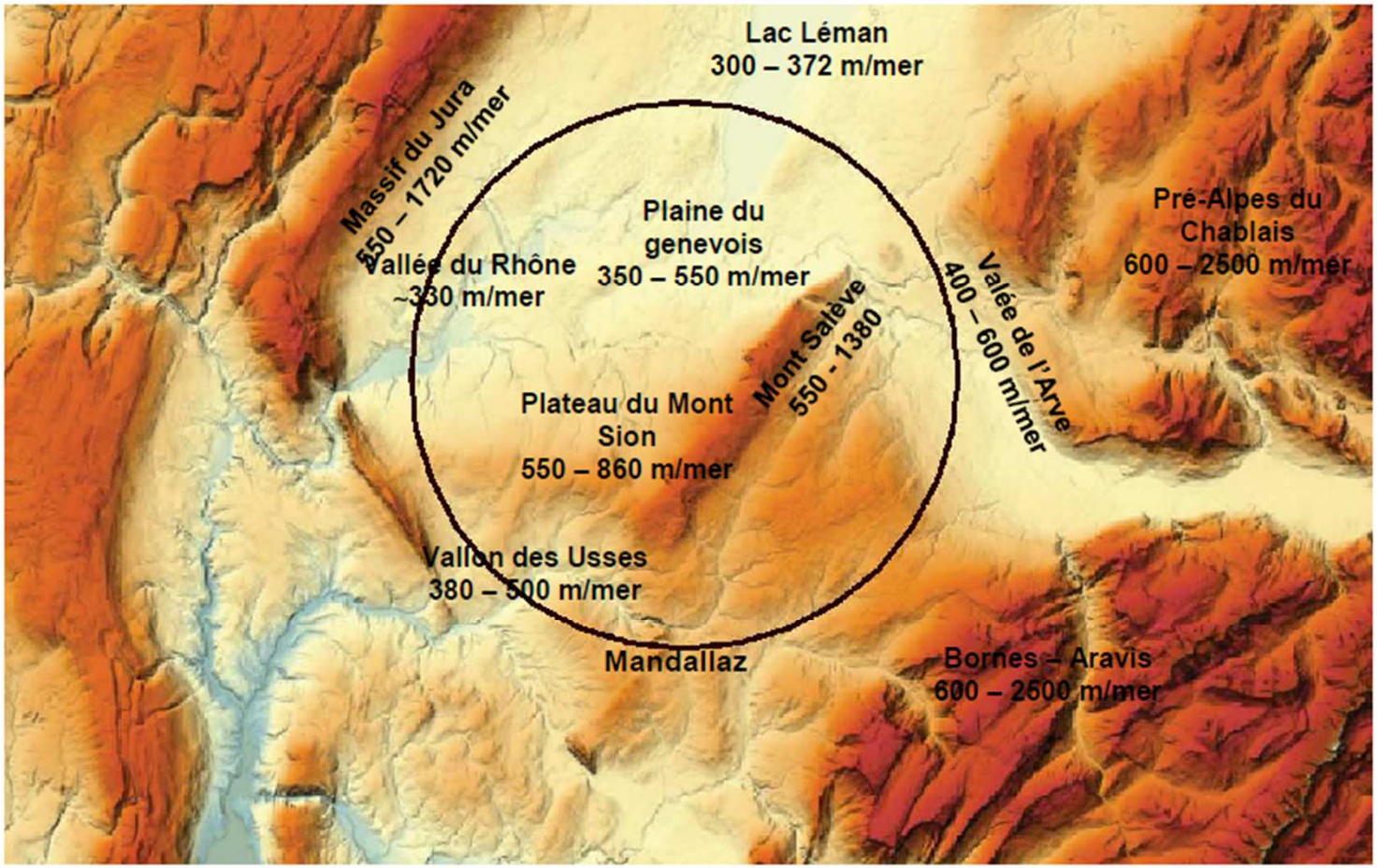
Alignment Profile



J. Osborne & C. Cook

Tunnel location: topography [1/3]

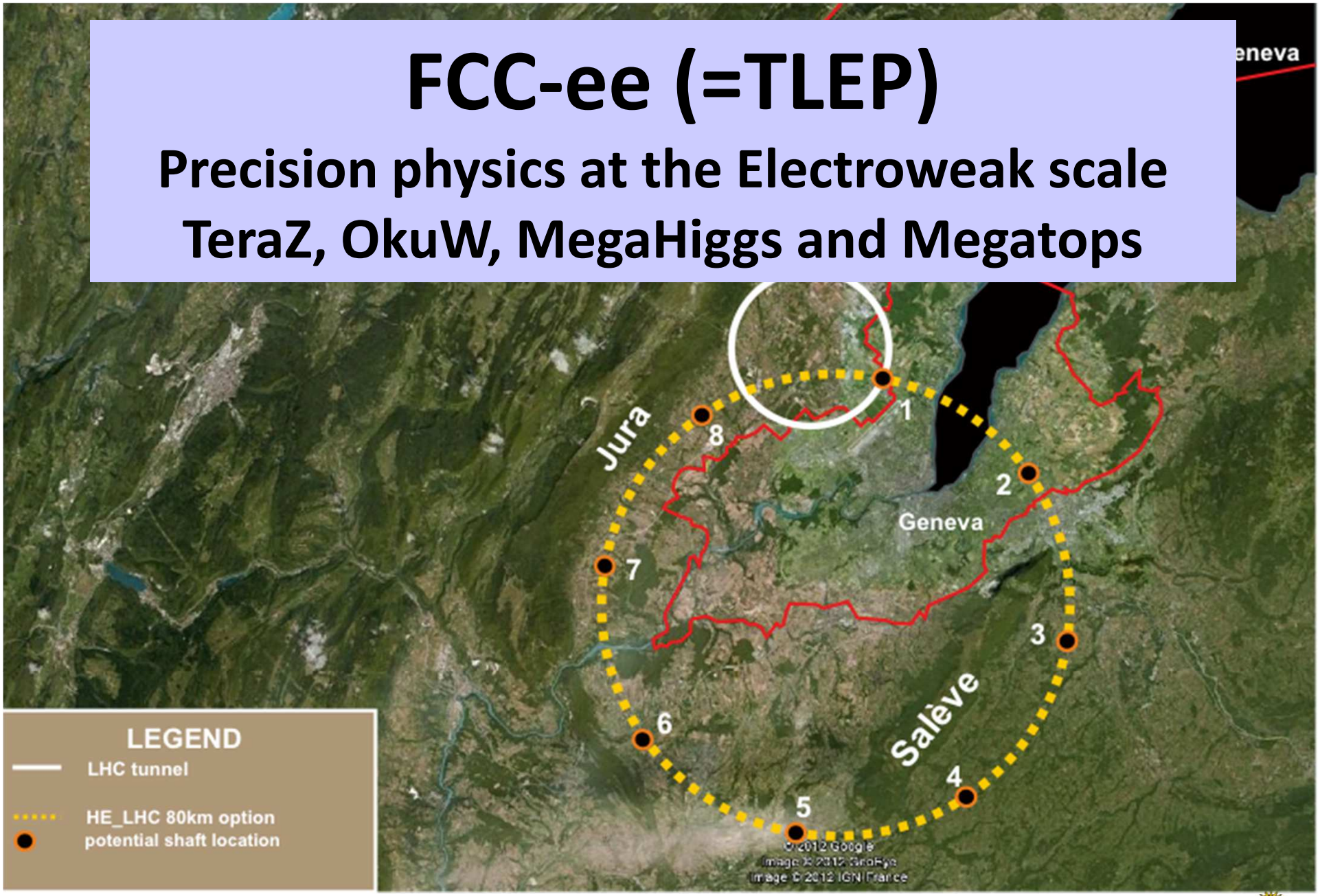
- Minimize ground coverage
  - Hydrostatic pressure for TBM tunnelling
  - Shaft depth/cost



FCC-ee (=TLEP)

Precision physics at the Electroweak scale

TeraZ, OkuW, MegaHiggs and Megatops



Future Circular Collider Study - FCC

Mandate

Scope

The main emphasis of the conceptual design study shall be the long-term goal of a hadron collider with a centre-of-mass energy of the order of 100 TeV (currently referred to as VHE-LHC) in a new tunnel of 80-100 km circumference for the purposes of studying physics at the highest energies. The hadron collider and its detectors shall determine the basic requirements for the tunnel, surface and technical infrastructures. The corresponding hadron injector chain shall be included in the study, taking into account the existing CERN accelerator infrastructure and long-term accelerator operation plans. The performance and cost of the hadron collider shall be compared to a high-energy LHC based on the same high-field magnet technology and housed in the LHC tunnel.

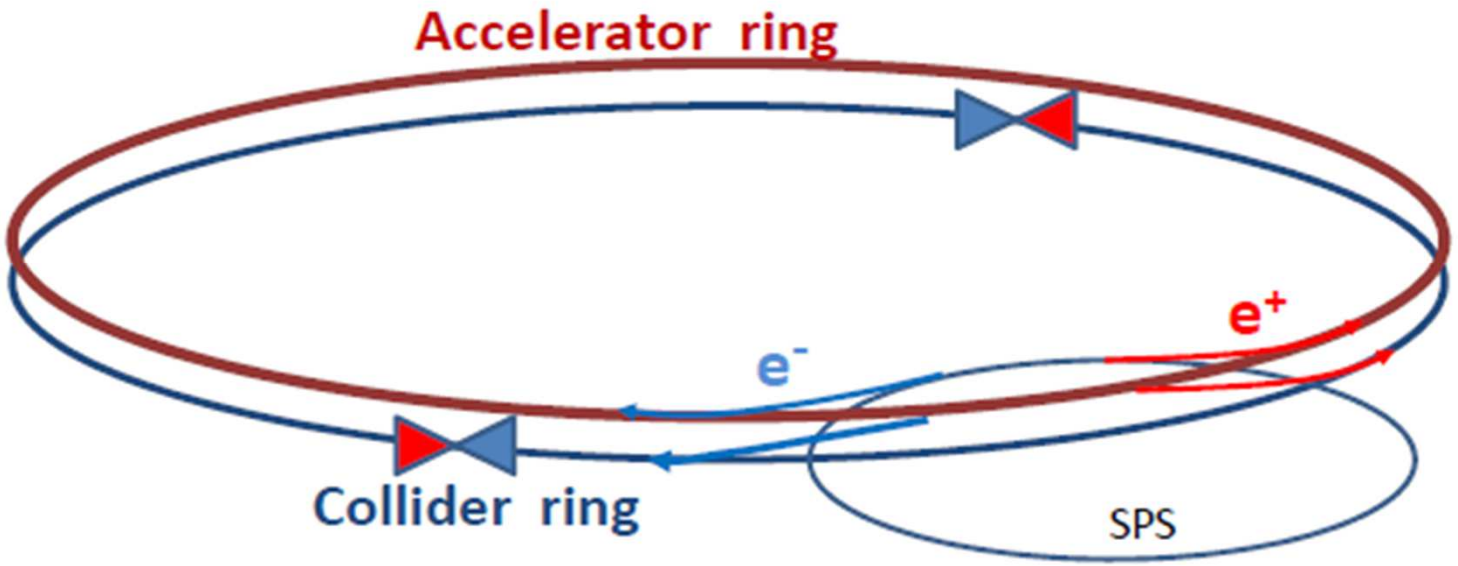
The conceptual design study shall also include a lepton collider and its detectors (currently referred to as TLEP), as a potential intermediate step towards realization of the hadron facility. The design of the lepton collider complex shall be based on the hadron collider infrastructure and any substantial incompatibilities with respect to the hadron collider infrastructure requirements shall be analysed and quantified. Potential synergies with linear collider detector designs should be considered.

Original motivation: now that m_H and m_top are known, explore EW region with high precision with High Luminosity machine

Discovery of New Physics in rare phenomena or precision measurements

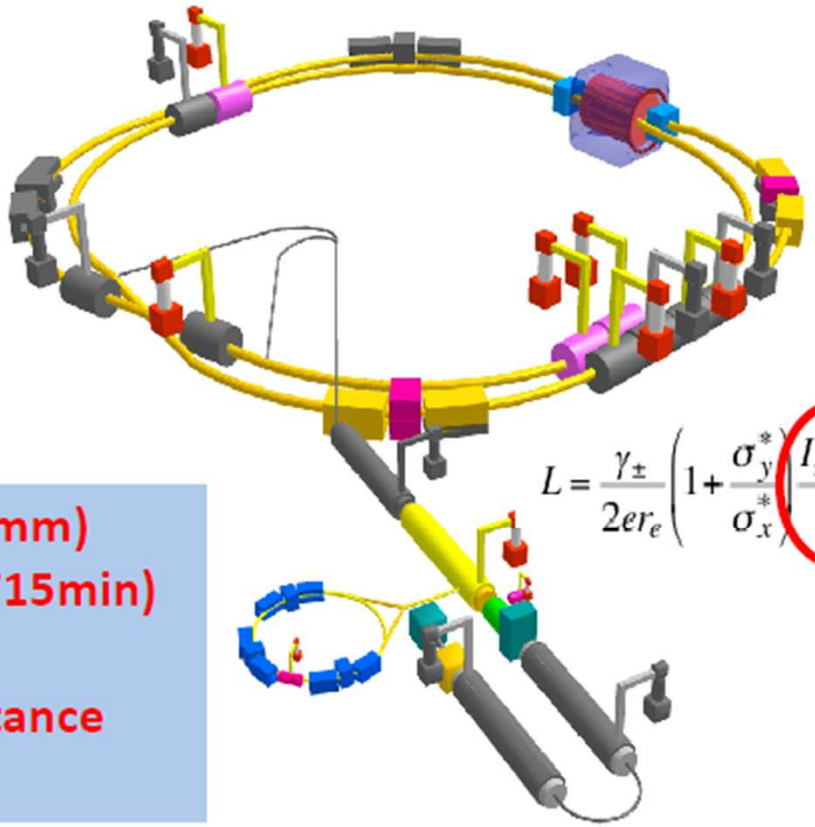
ILC studies → need increase over LEP 2 (average) luminosity by a factor 1000
How can one do that without exploding the power bill?

Answer is in the B-factory design: a very low vertical emittance ring with higher intrinsic luminosity . electrons and positrons have a much higher chance of interacting ➔ much shorter lifetime (few minutes)
➔ feed beam continuously with a ancillary accelerator



SuperKEKB – TLEP demonstrator!

beam
commissioning will
start in early 2015



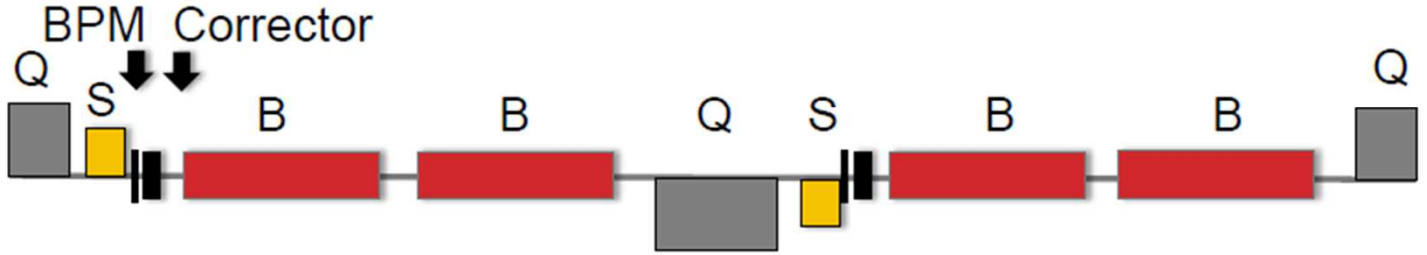
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

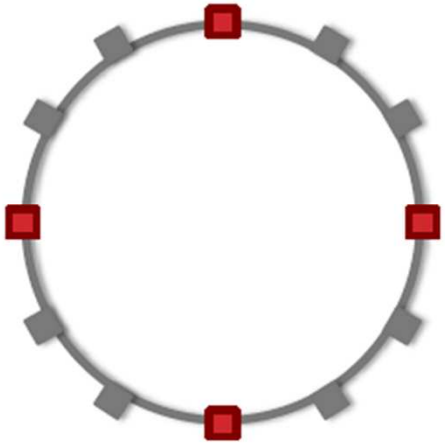
- β_y*=300 μm (TLEP: 1 mm)
- lifetime 5 min (TLEP: ~15min)
- $\varepsilon_y/\varepsilon_x$=0.25% (~TLEP)
- off momentum acceptance
- e^+ production rate

Arc lattice (circular machine)

LATTICE V12B-S

arc cell layout

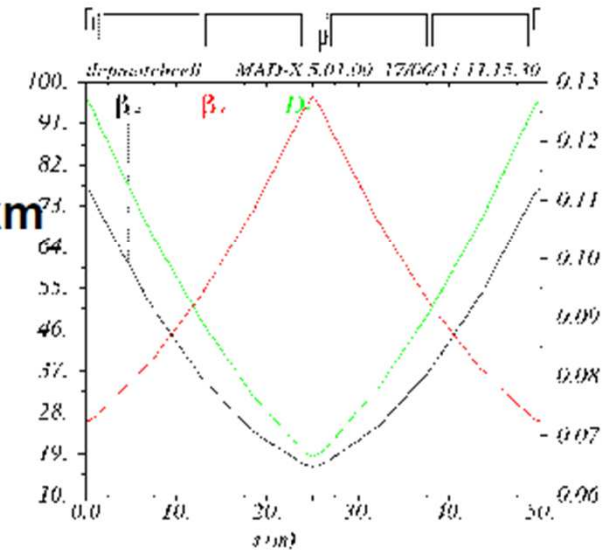


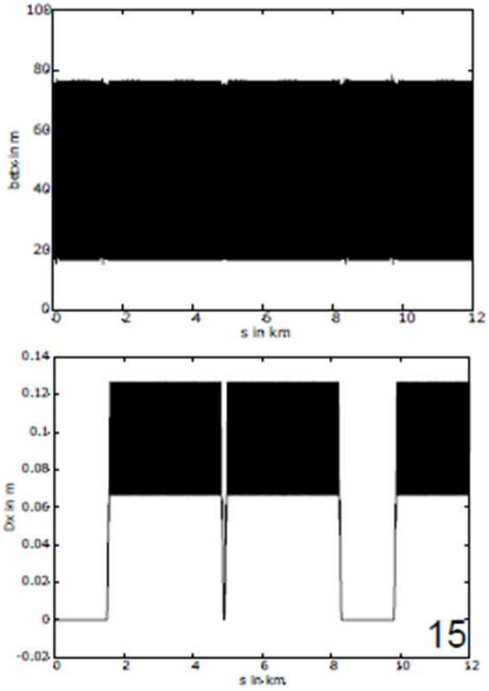


B = bending magnet, Q = quadrupole, S = sextupole

Circumference: 100 km
Arc length: 2 × 3.4 km
Straight section: 1.5 km

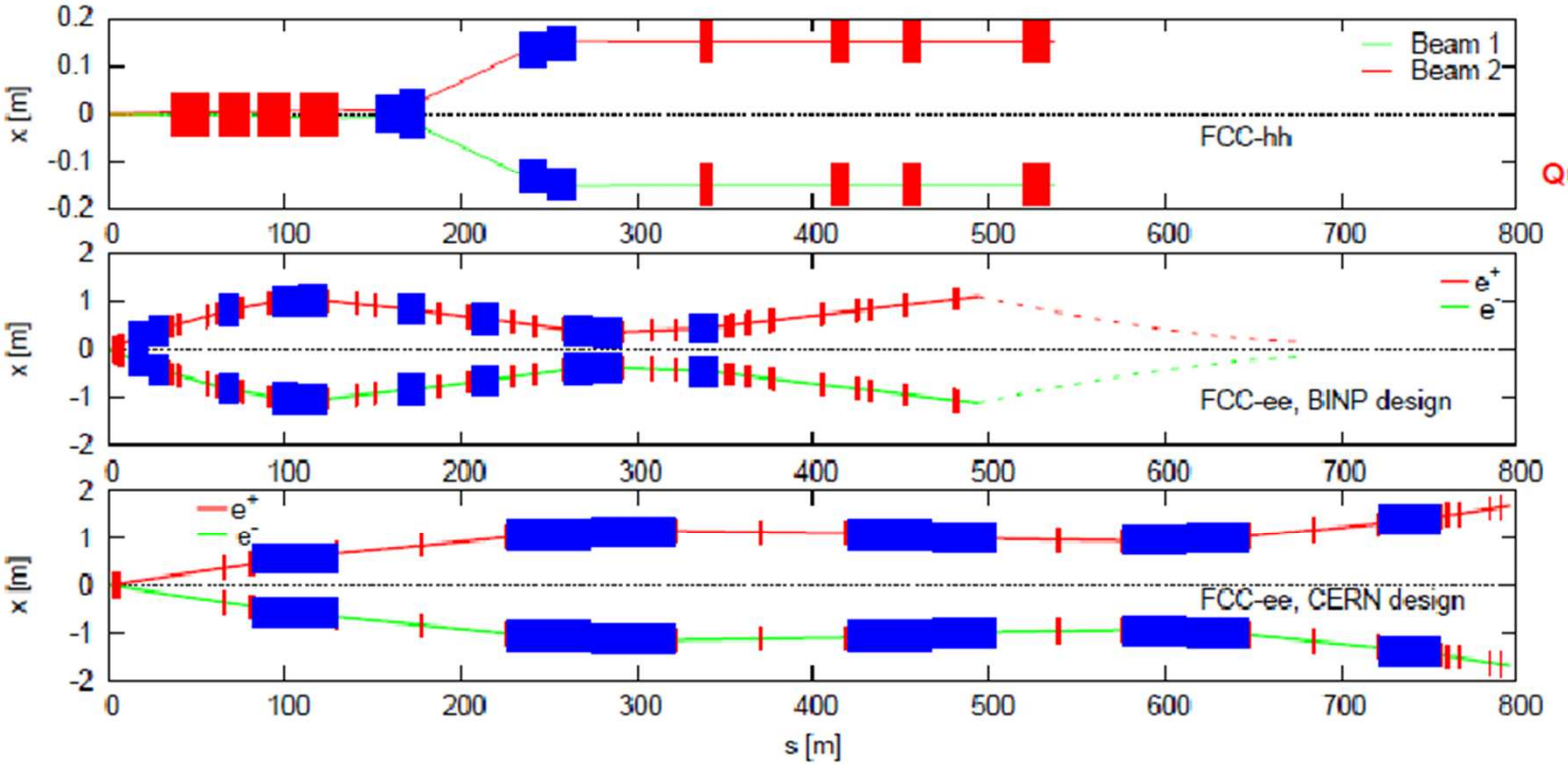
FODO cell optics
cell length 50 m





B. Harer, B. Holzer

IR layouts

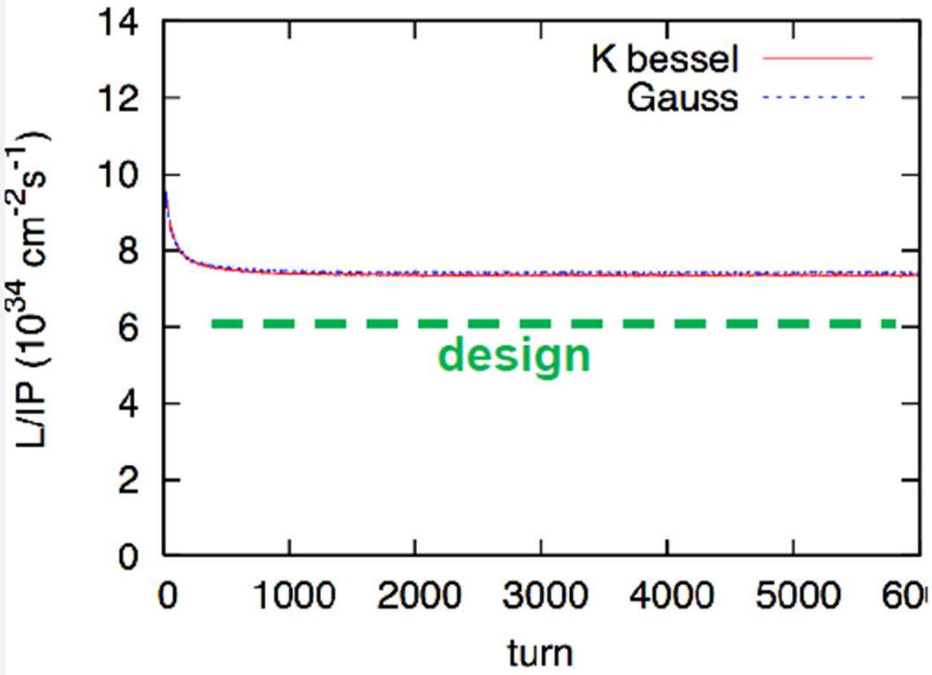


Dipoles in blue

Quadrupoles in red

- Tunnel transverse width of both FCC-ee designs ~3-4 m.
- Additional length is required to bend beams back, plus room for RF.
- Synchrotron rad. power per IP: CERN 140 kW, BINP 1400 kW.
  - *Optimum between length and power loss to be identified !*
  - *93 km racetrack IR straights of 1400 m may be too short for ee !*

Beam-beam simulations



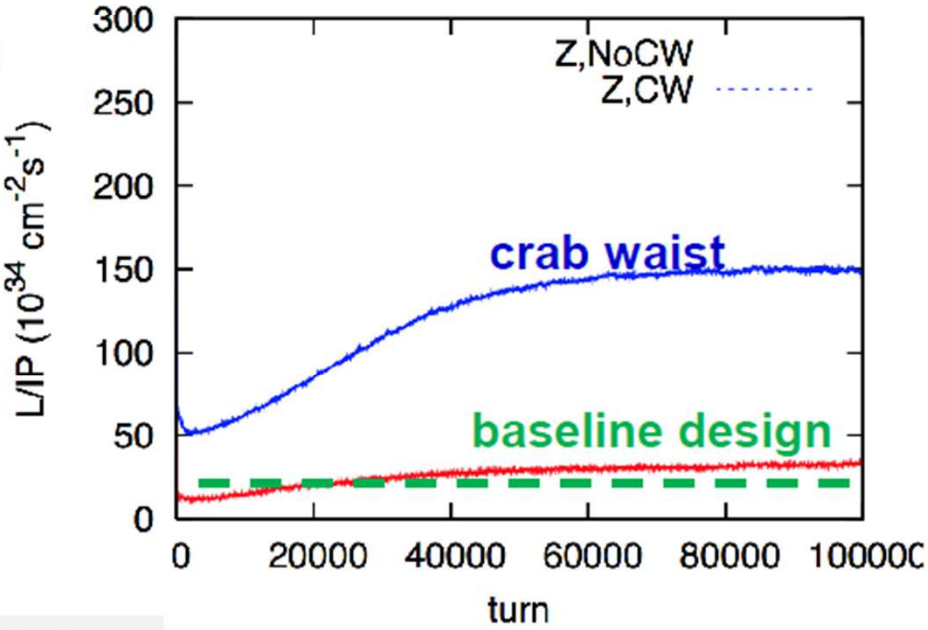
BBSS strong-strong simulation with beamstrahlung

FCC-ee at 120 GeV:

$L \approx 7.5 \times 10^{34}$ cm^{-2}s^{-1} per IP

FCC-ee in crab-waist mode at the Z pole (45.5 GeV):

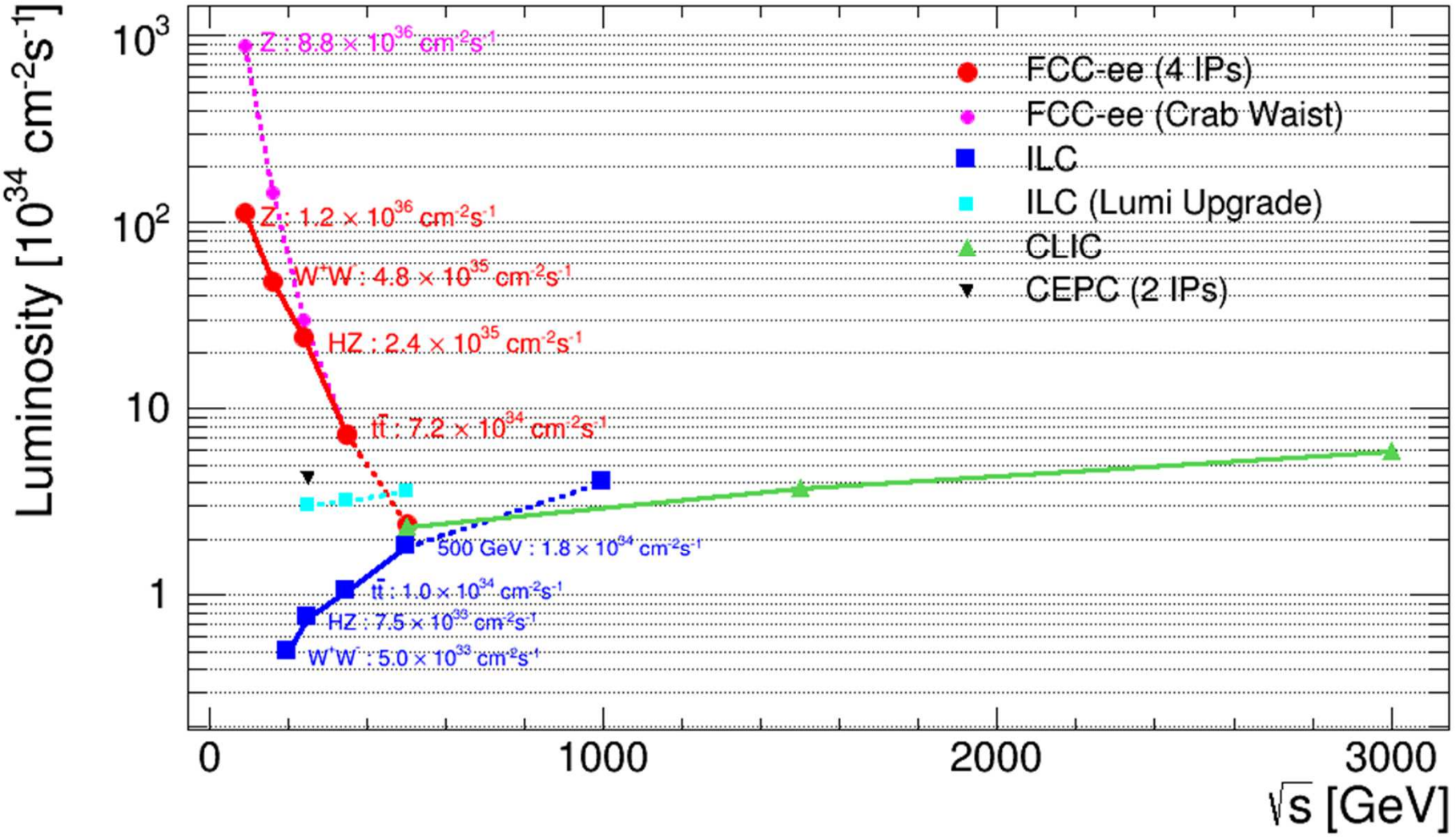
$L \approx 1.5 \times 10^{36}$ cm^{-2}s^{-1} per IP



Tracking confirms assumptions!

K. Ohmi, A. Bogomyagkov, E. Levichev, P. Piminov

parameter	LEP2	FCC-ee				
		Z	Z (c.w.)	W	H	t
E_{beam} [GeV]	104	45	45	80	120	175
beam-beam par. ξ_y/IP	0.06	0.03	0.175	0.06	0.093	0.092
current [mA]	3.0	1450	1431	152	30	6.6
$P_{SR,tot}$ [MW]	22	100	100	100	100	100
no. bunches	4	16700	29791	4490	1360	98
N_b [10^{11}]	4.2	1.8	1.0	0.7	0.46	1.4
ε_x [nm]	22	29	0.14	3.3	0.94	2
ε_y [pm]	250	60	1	1	2	2
β^*_x [m]	1.2	0.5	0.5	0.5	0.5	1.0
β^*_y [mm]	50	1	1	1	1	1
σ^*_y [nm]	3500	250	32	84	44	45
$\sigma_{z,SR}$ [mm]	11.5	1.64	2.7	1.01	0.81	1.16
$\sigma_{z,tot}$ [mm] (w beamstr.)	11.5	2.56	5.9	1.49	1.17	1.49
hourglass factor F_{hg}	0.99	0.64	0.94	0.79	0.80	0.73
L/IP [10^{34} cm^{-2}s^{-1}]	0.01	28	212	12	6	1.7
τ_{beam} [min]	434	298	39	73	29	21


Luminosity [10^34 cm^-2s^-1]
10^3
10^2
10
1
0
1000
2000
3000
√s [GeV]
FCC-ee (4 IPs)
FCC-ee (Crab Waist)
ILC
ILC (Lumi Upgrade)
CLIC
CEPC (2 IPs)
Z : 8.8 × 10^36 cm^-2s^-1
Z : 1.2 × 10^36 cm^-2s^-1
W+W- : 4.8 × 10^35 cm^-2s^-1
HZ : 2.4 × 10^35 cm^-2s^-1
tt̄ : 7.2 × 10^34 cm^-2s^-1
500 GeV : 1.8 × 10^34 cm^-2s^-1
tt̄ : 1.0 × 10^34 cm^-2s^-1
HZ : 7.5 × 10^33 cm^-2s^-1
W+W- : 5.0 × 10^33 cm^-2s^-1

Published for SISSA by Springer

Received: *September 23, 2013*
Accepted: *December 25, 2013*
Published: *January 29, 2014*

First look at the physics case of TLEP

PUBLISHED

The TLEP Design Study Working Group

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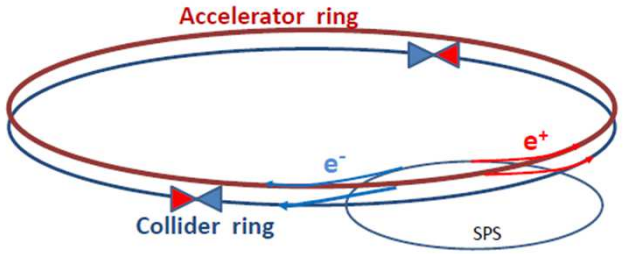
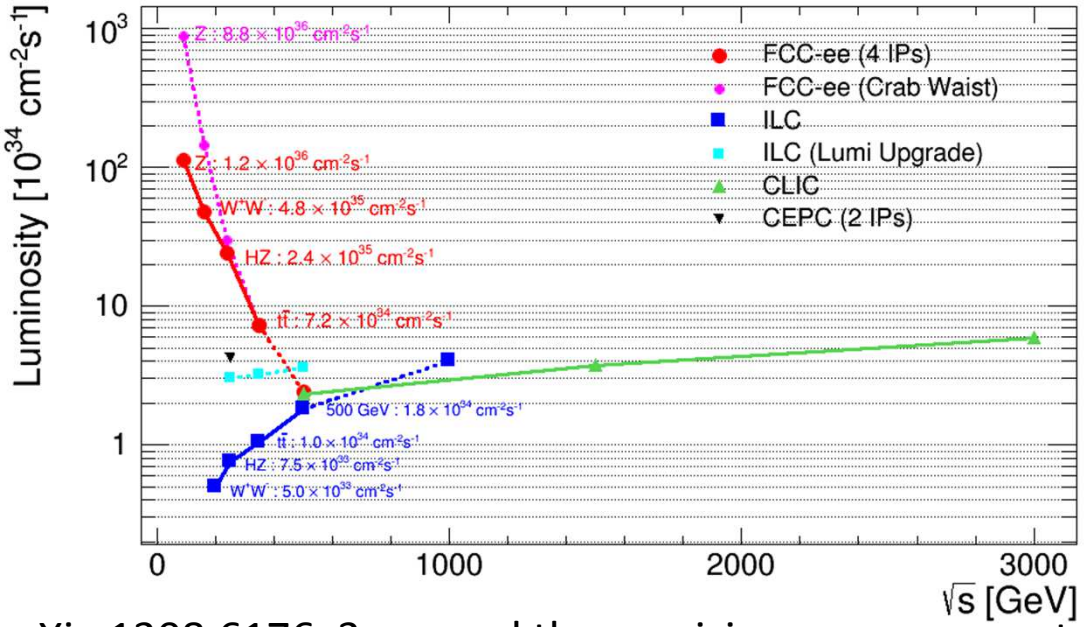
JHEP01(2014)164





First look at the physics case of TLEP, arXiv:1308.6176v3 scoped the precision measurements:

-- Model independent Higgs couplings and invisible width

-- Z mass (0.1 MeV), W mass (0.5 MeV) top mass (~10 MeV), $\sin^2{}_W^{\text{eff}}$, R_b, N_ν etc...

➔ powerful exploration of new physics with EW couplings up to very high masses

➔ importance of luminosity and E_{beam} calibration by beam depolarization up to W pair

So far: simulations with CMS detector (Higgs) -- or «just» paper studies.

Snapshot of novelties appeared in recent workshops

Higher luminosity prospects at W, Z with **crab-waist**

➔ sensitivity to right handed (sterile) neutrinos

➔ s-channel e+e- → H(125.2) production almost possible (➔ monochromators?)

➔ rare Higgs Z W and top decays, FCNCs etc...

➔ discovery potential for very small couplings

➔ precision event generators (Jadach et al)

http://cern.ch/FCC-ee

FCC hh ee he

Higgs factory

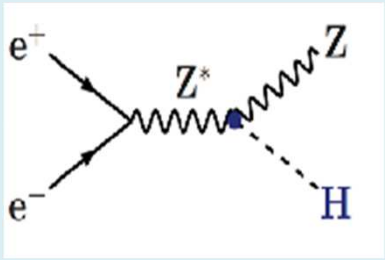
(constrained fit including 'exotic')

	4 IPs TLEP	(2 IPs)
g_{HZZ}	0.05%	(0.06%)
g_{HWW}	0.09%	(0.11%)
g_{Hbb}	0.19%	(0.23%)
g_{Hcc}	0.68%	(0.84%)
g_{Hgg}	0.79%	(0.97%)
$g_{H\tau\tau}$	0.49%	(0.60%)
$g_{H\mu\mu}$	6.2%	(7.6%)
$g_{H\gamma\gamma}$	1.4%	(1.7%)
BR_{exo}	0.16%	(0.20%)

→ *total width* <1%

HHH (best at FCC-hh) 28% → from HZ thresh

Htt (best at FCC-hh) 13% → from tt thresh



2 10^6 ZH events in 5 years

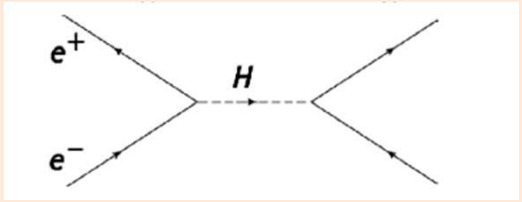
«A tagged Higgs beam».

sensitive to new physics in loops

incl. invisible = (dark matter?)

A big challenge, but unique:

Higgs s-channel production at $\sqrt{s} = m_H$



10^4 events per year.

Very difficult because huge background and beam energy spread ~ 10 x Γ_H

limits or signal? monochromators?

Aleksan, D'Enterria, Woijcik

Table 1-16. *Uncertainties on coupling scaling factors as determined in a completely model-independent fit for different e^+e^- facilities. Precisions reported in a given column include in the fit all measurements at lower energies at the same facility, and note that the model independence requires the measurement of the recoil HZ process at lower energies. ‡ILC luminosity upgrade assumes an extended running period on top of the low luminosity program and cannot be directly compared to TLEP and CLIC numbers without accounting for the additional running period. ILC numbers include a 0.5% theory uncertainty. For invisible decays of the Higgs, the number quoted is the 95% confidence upper limit on the branching ratio.*

Facility		ILC		ILC(LumiUp)	TLEP (4 IP)			CLIC	
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%
BR_{inv}	0.9%	< 0.9%	< 0.9%	0.4%	0.19%	< 0.19%			

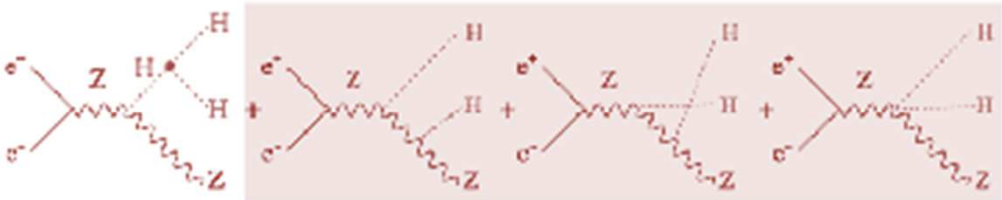
the 10B$ ILC

H^3 @ TLEP

- At LHC (Requires $E_{CM} > 2\ m_h$):

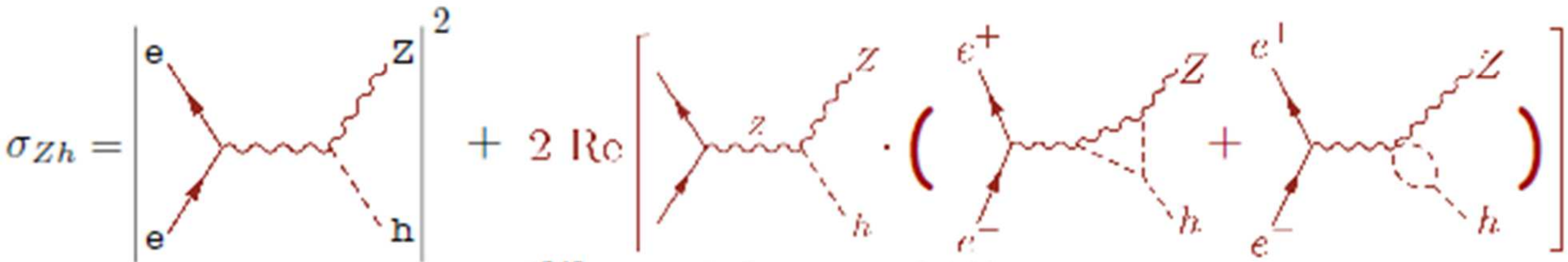
Dolan, Englert, Spannowsky

- At ILC (Requires $E_{CM} > 2\ m_h + m_Z$):



J. Tian, K. Fujii

- At TLEP 240 GeV: M. McCullough '14



$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

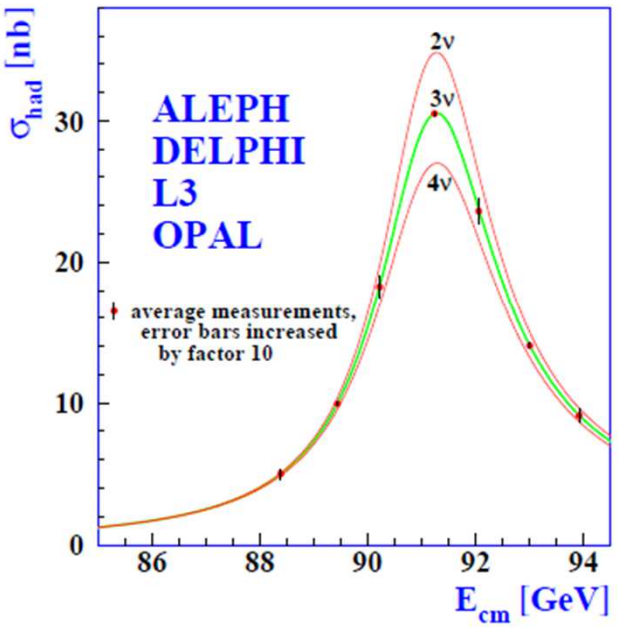
tiny effect but visible thanks to the extraordinary TLEP sensitivity on Zh **(0.05%)**

TERA-Z, Oku-W, Megatops

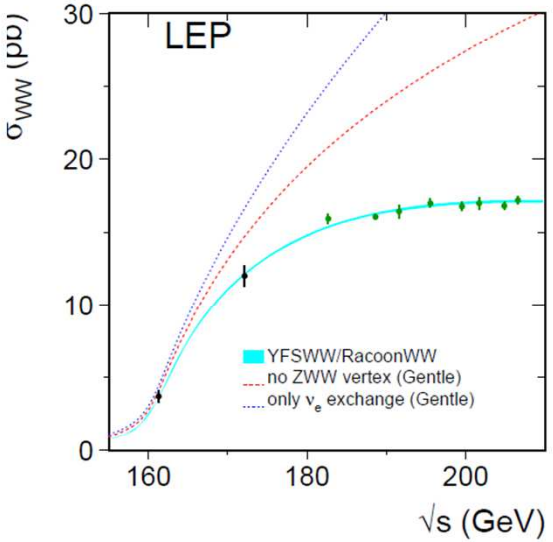
Precision tests of the closure of the Standard Model

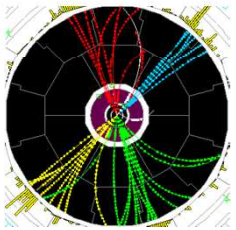
Precision tests of EWSB

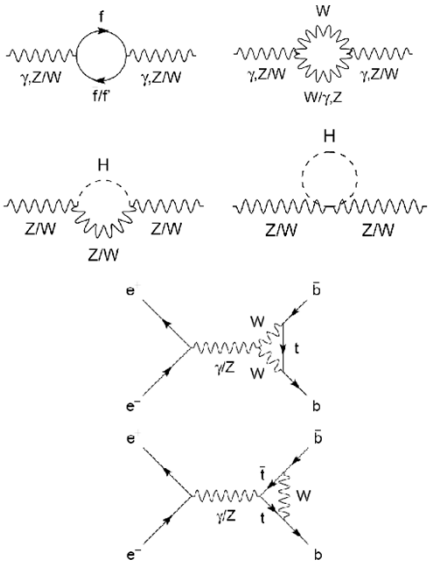
Z pole ssymmetries, lineshape



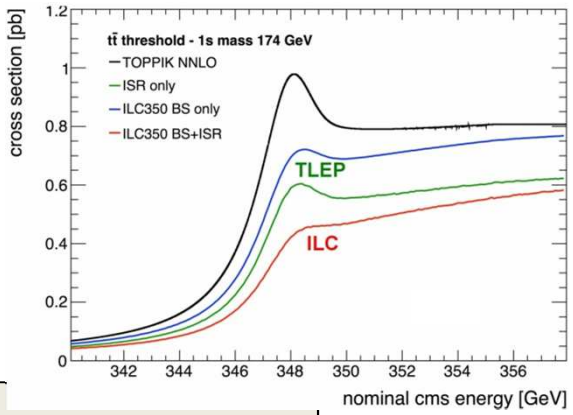
WW threshold scan







tt threshold scan



TLEP : Repeat the LEP1 physics programme every 15 mn

Transverse polarization up to the WW threshold

- **Exquisite beam energy determination (10 keV)**

Longitudinal polarization at the Z pole

- **Measure $\sin^2\theta_W$ to 2.10^{-6} from A_{LR}**
- **Statistics, statistics: 10^{10} tau pairs, 10^{11} bb pairs, QCD and QED studies etc…**

Frank Simon

Example (from Langacker& Erler **PDG 2011**)

$\Delta\rho = \varepsilon_1 = \alpha(M_Z)\ .\ T$

$\varepsilon_3 = 4\ \sin^2\theta_W\ \alpha(M_Z)\ .\ S$

$\Delta\rho$ today = 0. 0004+0.0003−0.0004

-- is consistent with 0 at 1σ

-- is sensitive to non-conventional Higgs bosons (e.g. in SU(2) triplet with 'funny v.e.v.s)

-- is sensitive to Isospin violation such as $m_t \neq m_b$ or **ibid for stop-sbottom**

$$\rho_0 = 1 + \frac{3\,G_F}{8\sqrt{2}\pi^2} \sum_i \frac{C_i}{3} \Delta m_i^2 \ , \qquad (10.63)$$

where the sum includes fourth-family quark or lepton doublets, $\binom{t'}{b'}$ or $\binom{E^0}{E^-}$, right-handed (mirror) doublets, non-degenerate vector-like fermion doublets (with an extra factor of 2), and scalar doublets such as $\binom{\tilde{t}}{\tilde{b}}$ in Supersymmetry (in the absence of L–R mixing).

Present measurement implies $\sum_i \frac{C_i}{3} \Delta m_i^2 \leq (52\ \mathrm{GeV})^2.$

Most e.g. SUSYmodels have these symmetries embedded from the start

Similarly: $S = \frac{C}{3\pi} \sum_i \left(t_{3L}(i) - t_{3R}(i) \right)^2 ,$

best-of ee-FCC/TLEP #2: Precision EW measts

Asset: -- high luminosity (10^{12} Z decays + 10^8 Wpairs + 10^6 top pairs)
-- exquiste energy calibration up and above WW threshold

target precisions

Quantity	Present precision	Measured from	Statistical uncertainty	Systematic uncertainty
m_Z (keV)	91187500 ± 2100	Z Line shape scan	5 (6) keV	< 100 keV
Γ_Z (keV)	2495200 ± 2300	Z Line shape scan	8 (10) keV	< 100 keV
R_ℓ	20.767 ± 0.025	Z Peak	0.00010 (12)	< 0.001
N_ν	2.984 ± 0.008	Z Peak	0.00008 (10)	< 0.004
N_ν	2.92 ± 0.05	$Z\gamma$, 161 GeV	0.0010 (12)	< 0.001
R_b	0.21629 ± 0.00066	Z Peak	0.000003 (4)	< 0.000060
A_{LR}	0.1514 ± 0.0022	Z peak, polarized	0.000015 (18)	< 0.000015
m_W (MeV)	80385 ± 15	WW threshold scan	0.3 (0.4)MeV	< 0.5 MeV
m_{top} (MeV)	173200 ± 900	$t\bar{t}$ threshold scan	10 (12) MeV	< 10 MeV

Also -- $\Delta \sin^2 \theta_W \approx 10^{-6}$
-- $\Delta \alpha_S = 0.0001$ from W and Z hadronic widths
-- orders of magnitude on FCNCs and rare decays etc. etc.

Design study to establish possibility of corresponding precision theoretical calculations.

best-of ee-FCC/TLEP #2: Precision EW measts

Asset: -- high luminosity (10^{12} Z decays + 10^{8} Wpairs + [illegible] pairs)
-- exquiste energy calibration up and abov[illegible]hold

Quantity	Present precision	Measured fro[illegible]	[illegible]ity	Systematic uncertainty
m_Z (keV)	91187500 ± 2100	Z Li[illegible]	(6) keV	< 100 keV
Γ_Z (keV)	2495200 ± 2300	[illegible]	8 (10) keV	< 100 keV
R_ℓ	20.767 ± 0.025	[illegible]	0.00010 (12)	< 0.001
N_ν	2.984 ± 0.0[illegible]	[illegible]	0.00008 (10)	< 0.004
N_ν	2.92[illegible]	[illegible]o1 GeV	0.0010 (12)	< 0.001
R_b	0.21[illegible]	Z Peak	0.000003 (4)	< 0.000060
A_{LR}	[illegible]	Z peak, polarized	0.000015 (18)	< 0.000015
m_W (MeV)	[illegible]	WW threshold scan	0.3 (0.4)MeV	< 0.5 MeV
m_{top} [illegible]	[illegible] 900	tt̄ threshold scan	10 (12) MeV	< 10 MeV

As another example of the importance of precision measurements, the LEP determination of $\alpha_s(m_Z)$ was already able, in association with $\sin^2\theta_W^{eff}$, to distinguish between supersymmetric and non-supersymmetric models of grand unification [55–58]. The prospective TLEP accuracies on these quantities would take this confrontation between theory and experiments to a completely new level.

[illegible]rom W and Z hadronic widths
[illegible] magnitude on FCNCs and rare decays etc. etc.

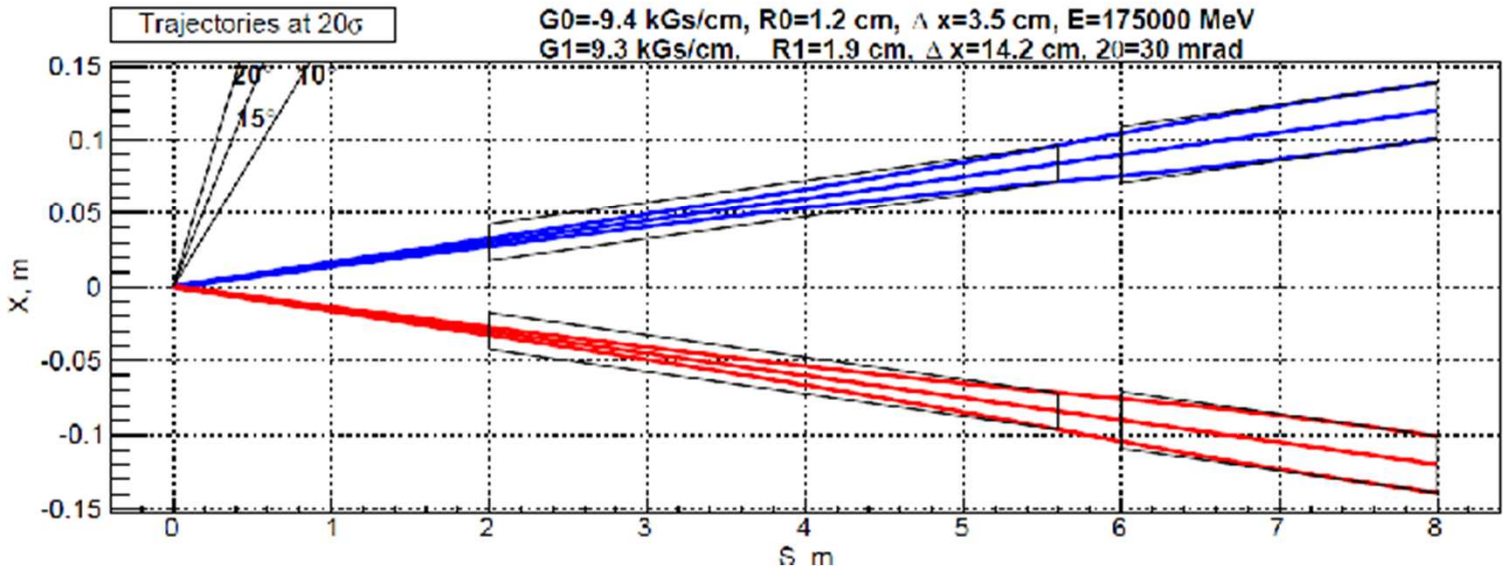
[illegible] study to establish possibility of corresponding precision theoretical calculations.

TLEP

A Sample of Essential Quantities:

X	Physics	Present precision		TLEP stat Syst Precision	TLEP key	Challenge
M_Z MeV/c2	Input	91187.5 ±2.1	Z Line shape scan	0.005 MeV <±0.1 MeV	E_cal	QED corrections
Γ_Z MeV/c2	Δρ (T) (no Δα!)	2495.2 ±2.3	Z Line shape scan	0.008 MeV <±0.1 MeV	E_cal	QED corrections
R_ℓ	α_s , δ_b	20.767 ± 0.025	Z Peak	0.0001 ± 0.002 - 0.0002	Statistics	QED corrections
N_ν	Unitarity of PMNS, sterile ν's	2.984 ±0.008	Z Peak Z+γ(161 GeV)	0.00008 ±0.004 0.001	->lumi meast Statistics	QED corrections to Bhabha scat.
R_b	δ_b	0.21629 ±0.00066	Z Peak	0.000003 ±0.000020 - 60	Statistics, small IP	Hemisphere correlations
A_{LR}	Δρ, ε_3 ,Δα (T, S)	0.1514 ±0.0022	Z peak, polarized	±0.000015	4 bunch scheme	Design experiment
M_W MeV/c2	Δρ, ε_3 , ε_2, Δα (T, S, U)	80385 ± 15	Threshold (161 GeV)	0.3 MeV <1 MeV	E_cal & Statistics	QED corections
m_{top} MeV/c2	Input	173200 ± 900	Threshold scan	10 MeV	E_cal & Statistics	Theory limit at 100 MeV?

Trajectories L*=2m

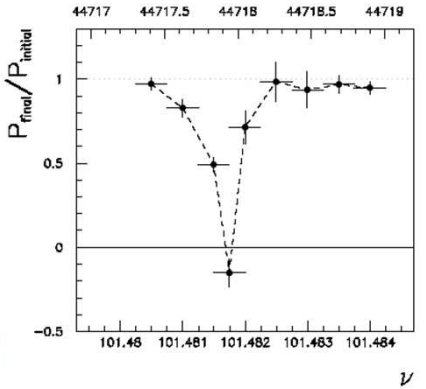


Mogens Dam

example of challenge: crab crossing to increase further luminosity? (Novosibirsk) emittance and polarization compensation, etc

Beam polarization and E-calibration @ TLEP

Precise meast of E_{beam} by resonant depolarization
~100 keV each time the meast is made



At LEP transverse polarization was achieved routinely at Z peak.
instrumental in 10^{-3} measurement of the Z width in 1993
led to prediction of top quark mass (179+- 20 GeV) in March 1994

Polarization in collisions was observed *(40% at BBTS = 0.04)*

At LEP beam energy spread destroyed polarization above 60 GeV
$\sigma_E \propto E^2/\sqrt{\rho}$ ➔ At TLEP transverse polarization up to at least 80 GeV
to go to higher energies requires spin rotators and siberian snake

TLEP: use 'single' bunches to measure the beam energy continuously
no interpolation errors due to tides, ground motion or trains etc…

<< 100 keV beam energy calibration around Z peak and W pair threshold.
Δm_Z ~0.1 MeV, $\Delta\Gamma_Z$ ~0.1 MeV, Δm_W ~ 0.5 MeV

Rare decays

-- FCNC: $Z \rightarrow e + \tau$ $Z \rightarrow \mu + \tau$

-- Heavy neutrinos (they *must* be somewhere!)

neutrino counting and search for explicit $Z \rightarrow \nu$-N
(with N-> vX or eX' and possibly displayed vertices)

-- other final states with single or double photons and jets

-- flavour physics...

-- and many others ($Z \rightarrow \gamma\gamma\gamma$ etc)

-- How far can one go with 10^{12} or 10^{13} Z decays?

Nima

Nima

At higher masses -- or at smaller couplings?

some REFERENCES

PHYSICAL REVIEW D VOLUME 29, NUMBER 11 1 JUNE 1984

Extending limits on neutral heavy leptons

Michael Gronau*

Department of Physics, Syracuse University, Syracuse, New York 132

JHEP Published for SISSA by Springer

Received: September 23, 2013
Accepted: December 25, 2013
Published: January 29, 2014

First look at the physics case of TLEP

arxiv:1308.6176

The TLEP Design Study Working Group

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FLAVOUR(267104)-ERC-23 TUM-HEP 850/12 SISSA 25/2012/EP CFTP/12-013

arxiv:1208.3654

Higgs Decays in the Low Scale Type I See-Saw Model

C. Garcia Cely[a)], A. Ibarra[a)], E. Molinaro[b)] and S. T. Petcov[c,d)] [1]

CERN–PPE/96–195

18 December 1996

Search for Neutral Heavy Leptons Produced in Z Decays

DELPHI Collaboration

The Role of Sterile Neutrinos in Cosmology and Astrophysics

Alexey Boyarsky*†, Oleg Ruchayskiy‡ and Mikhail Shaposhn

FCC design study and FCC-ee http://cern.ch/fcc-ee and presentations at *FCC-ee physics workshop* http://indico.cern.ch/event/313708/

The νMSM, Dark Matter and Neutrino Masses

Takehiko Asaka, Steve Blanchet, and Mikhail Shaposhnikov

Institut de Théorie des Phénomènes Physiques, CH-1015 Lausanne, Switzerland

Phys.Lett.B631:151-156,2005
arXiv:hep-ph/0503065

Preprint typeset in JHEP style - HYPER VERSION

FERMILAB-PUB-08-086-T, NSF-KITP-08-54, MADPH–06–1466, DCPT/07/198, IPPP/07/99

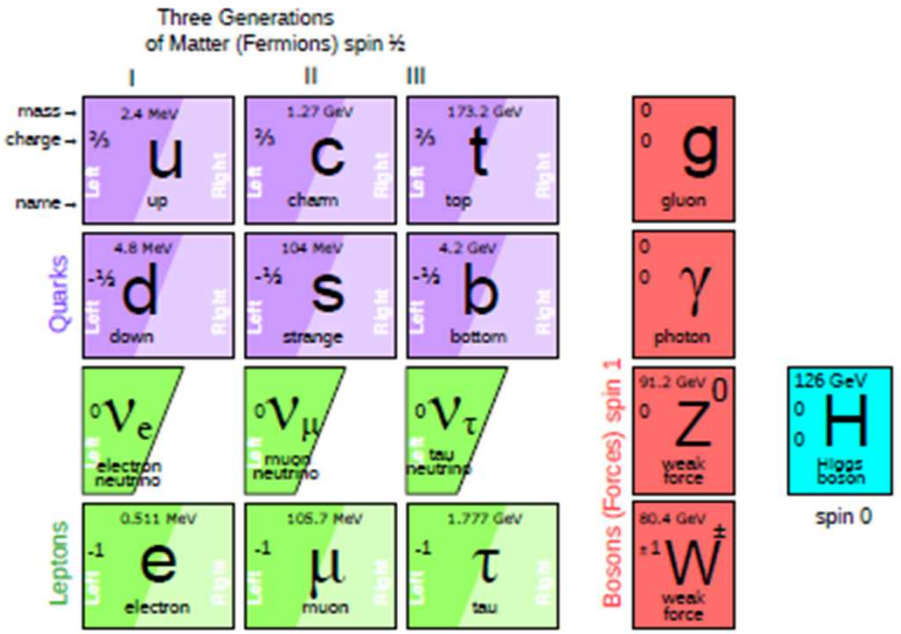
The Search for Heavy Majorana Neutrinos

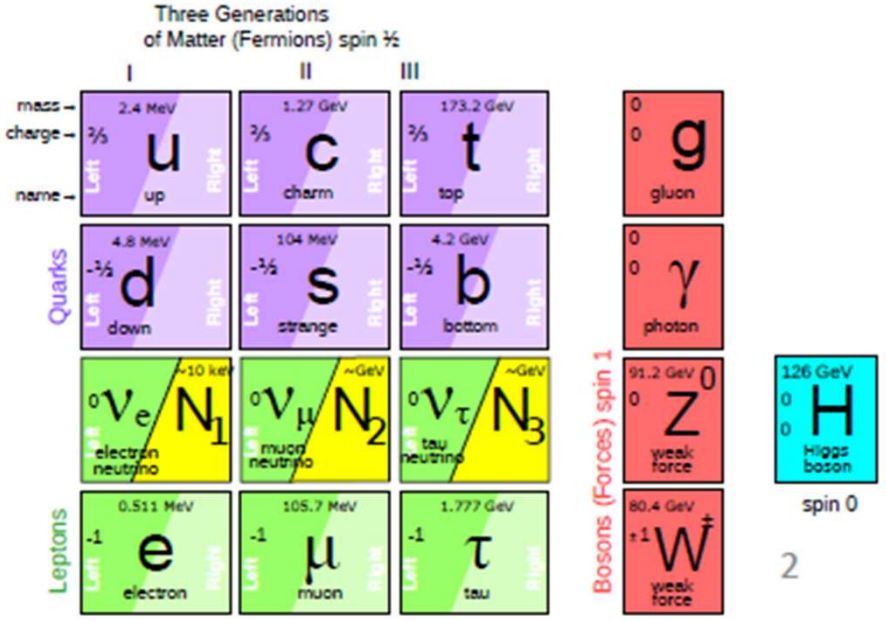
Anupama Atre[1,2], Tao Han[2,3,4], Silvia Pascoli[5], Bin Zhang[4*]

talks by Maurizio Pierini (BSM), Manqi Ruan (Higgs) Roberto Tenchini (Top & Precision) tomorrow, posters tonight at Future accelerator session

THE STANDARD MODEL IS COMPLETE .....

but... at least 3 pieces are still missing!





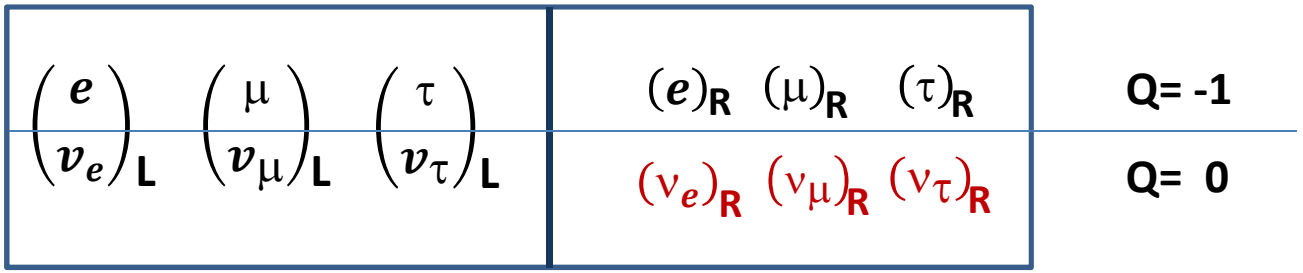
neutrinos have mass...

and this very probably implies new degrees of freedom

➔ Right-Handed, Almost «Sterile» (*very* small couplings) Neutrinos completely unknown masses (meV to ZeV), nearly impossile to find.

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

Electroweak eigenstates

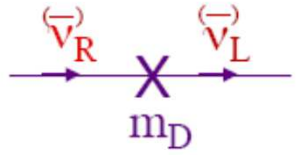


Right handed neutrinos
are singlets
no weak interaction
no EM interaction
no strong interaction

can't produce them
can't detect them
-- so what? --

Adding masses to the Standard model neutrino 'simply' by adding a Dirac mass term (Yukawa coupling)

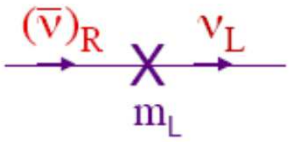
$$m_D \nu_L \overline{\nu}_R \qquad m_D \overline{\nu_L}\, \nu_R$$



implies adding a right-handed neutrino (new particle)

<u>No SM symmetry</u> prevents adding then a term like

$$m_M \overline{\nu_R{}^c}\, \nu_R$$



and this simply means that a neutrino turns into a antineutrino
(the charge conjugate of a right handed antineutrino is a left handed neutrino!)

It is perfectly conceivable ('natural'?) that both terms are present ➔ 'see-saw'

Mass eigenstates

See-saw in a general way :

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L,\ \bar{N}_R^c) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

$M_R \neq 0$
$m_D \neq 0$
Dirac + Majorana mass terms

$$\tan 2\theta = \frac{2\,m_D}{M_R - 0} \qquad \ll 1$$

$$m_\nu = \tfrac{1}{2}\left[(0 + M_R) - \sqrt{(0 - M_R)^2 + 4\,m_D^2}\right] \qquad \simeq -m_D^2/M_R$$

$$M = \tfrac{1}{2}\left[(0 + M_R) + \sqrt{(0 - M_R)^2 + 4\,m_D^2}\right] \qquad \simeq M_R$$

general formula — if $m_D \ll M_R$

$M_R = 0$
$m_D \neq 0$
Dirac only, (like e- vs e+):

m ↑

	ν_L	ν_R	$\bar{\nu}_R$	$\bar{\nu}_L$
I_{weak} =	½	0	½	0

4 states of equal masses

Some have I=1/2 (active)
Some have I=0 (sterile)

$M_R \neq 0$
$m_D = 0$
Majorana only

m ↑

	ν_L	$\bar{\nu}_R$
I_{weak} =	½	½

2 states of equal masses

All have I=1/2 (active)

see-saw

$M_R \neq 0$
$m_D \neq 0$
Dirac + Majorana

m ↑

	ν_L	N_R	$\bar{\nu}_R$	$\bar{N}_L$
I_{weak} =	½	0	½	0

4 states , 2 mass levels

m1 have I=1/2 (~active)
m2 have I=0 (~sterile)

There even exists a scenario that explains everything: the νMSM

Shaposhnikov et al

TeV

GeV

MeV

keV

eV

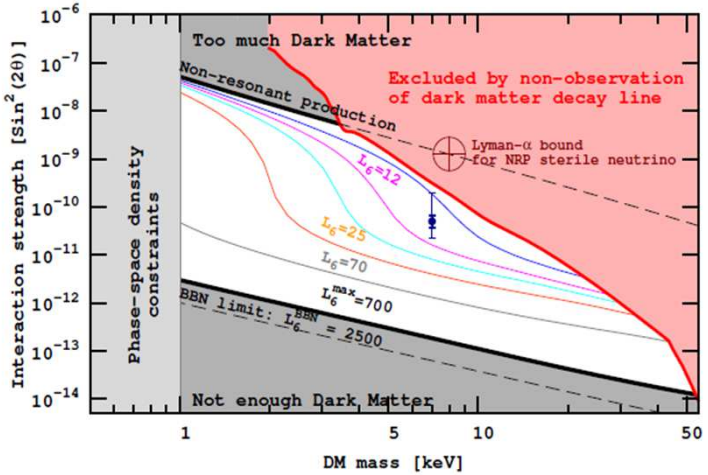
meV

N_2, N_3

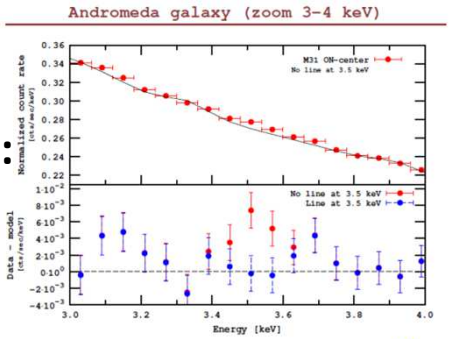
can generate Baryon Asymmetry of Universe
if $m_{N2,N3} > 140$ MeV

N_1

constrained:
mass: 1-50 keV
mixing :
10^{-7} to 10^{-13}
decay time:
$\tau_{N1} > \tau_{Universe}$



$N_1 \rightarrow \nu\gamma$
may have been seen:
arxiv:1402:2301
arxiv:1402.4119



ν_3
ν_2
ν_1

Manifestations of right handed neutrinos

one family see-saw :
$\theta \approx (m_D/M)$
$m_\nu \approx \frac{m_D^2}{M}$
$m_N \approx M$
$|U|^2 \propto \theta^2 \approx m_\nu / m_N$

$$\nu = \nu L \cos\theta - N^c{}_R \sin\theta$$

$$N = N_R \cos\theta + \nu_L{}^c \sin\theta$$

what is produced in W, Z decays is:

$$\nu_L = \nu \cos\theta + N \sin\theta$$

ν = light mass eigenstate
N = heavy mass eigenstate
$\neq \nu_L$, active neutrino
which couples to weak inter.
and $\neq N_R$, which does'nt.

-- mixing with active neutrinos leads to various observable consequences
-- if very light (eV) , possible effect on neutrino oscillations
-- if in keV region (dark matter), monochromatic photons from galaxies with $E=m_N/2$

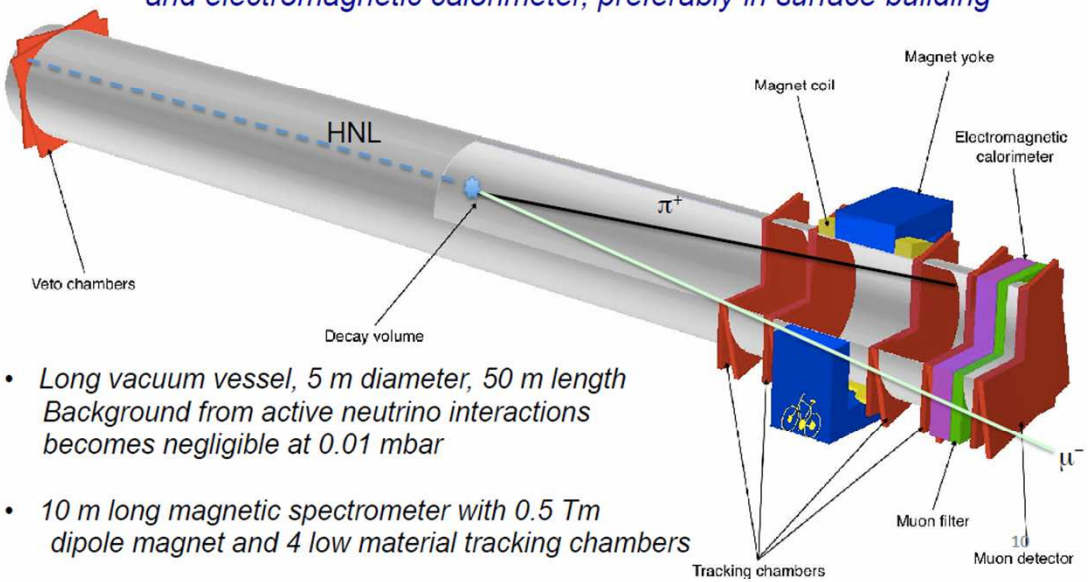
-- possibly measurable effects at High Energy
If N is heavy it will decay in the detector (not invisible)
➔ PMNS matrix unitarity violation and deficit in Z «invisible» width
➔ Higgs and Z visible exotic decays H→ $\nu_i \bar{N}_i$ and Z→ $\nu_i \bar{N}_i$, W-> $l_i \bar{N}_i$
➔ also in charm and b decays via W^*-> $l_i \bar{N}_i$
➔ violation of unitarity and lepton universality in Z, W or τ decays
-- etc... etc...

-- Couplings are small (m_ν / m_N) *(but who knows?)* and generally out of reach of hadron colliders (but this deserves to be revisited for detached vertices @LHC, HL-LHC, FCC-hh)

Detector concept
(based on existing technologies)

- *Reconstruction of the HNL decays in the final states: $\mu^-\pi^+$, $\mu^-\rho^+$ & $e^-\pi^+$*

  → *Requires long decay volume, magnetic spectrometer, muon detector and electromagnetic calorimeter, preferably in surface building*

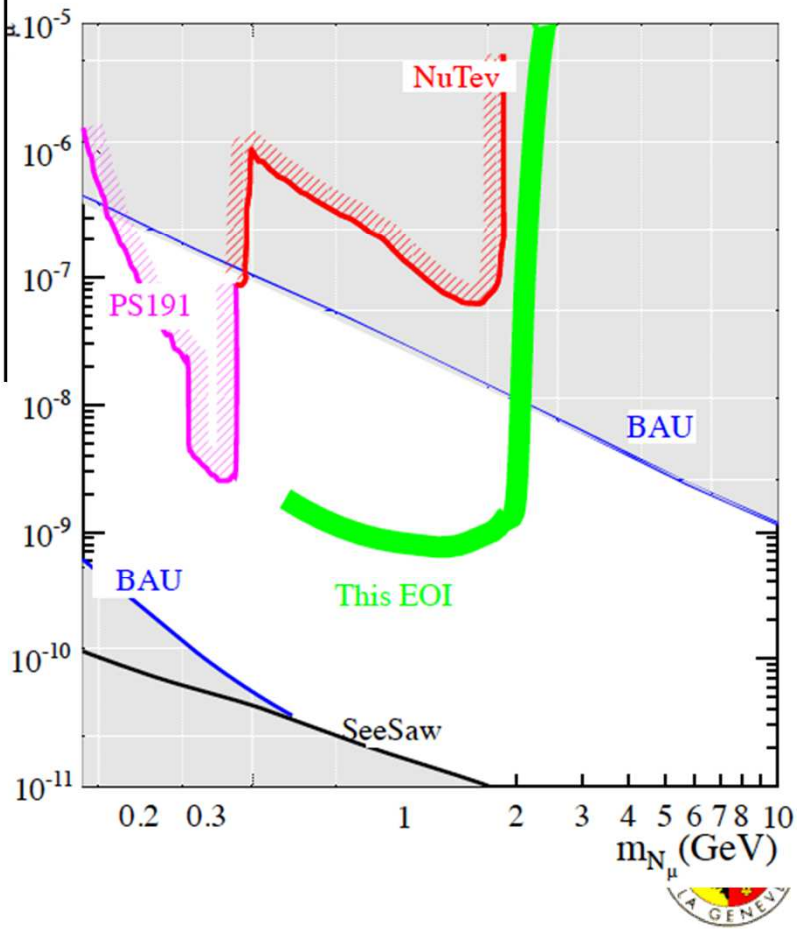


- *Long vacuum vessel, 5 m diameter, 50 m length Background from active neutrino interactions becomes negligible at 0.01 mbar*
- *10 m long magnetic spectrometer with 0.5 Tm dipole magnet and 4 low material tracking chambers*

Proposal to search for Heavy Neutral Leptons at the SPS

(CERN-SPSC-2013-024 / SPSC-EOI-010)

Disclaimer: It is not a classical neutrino physics experiment



On behalf of:

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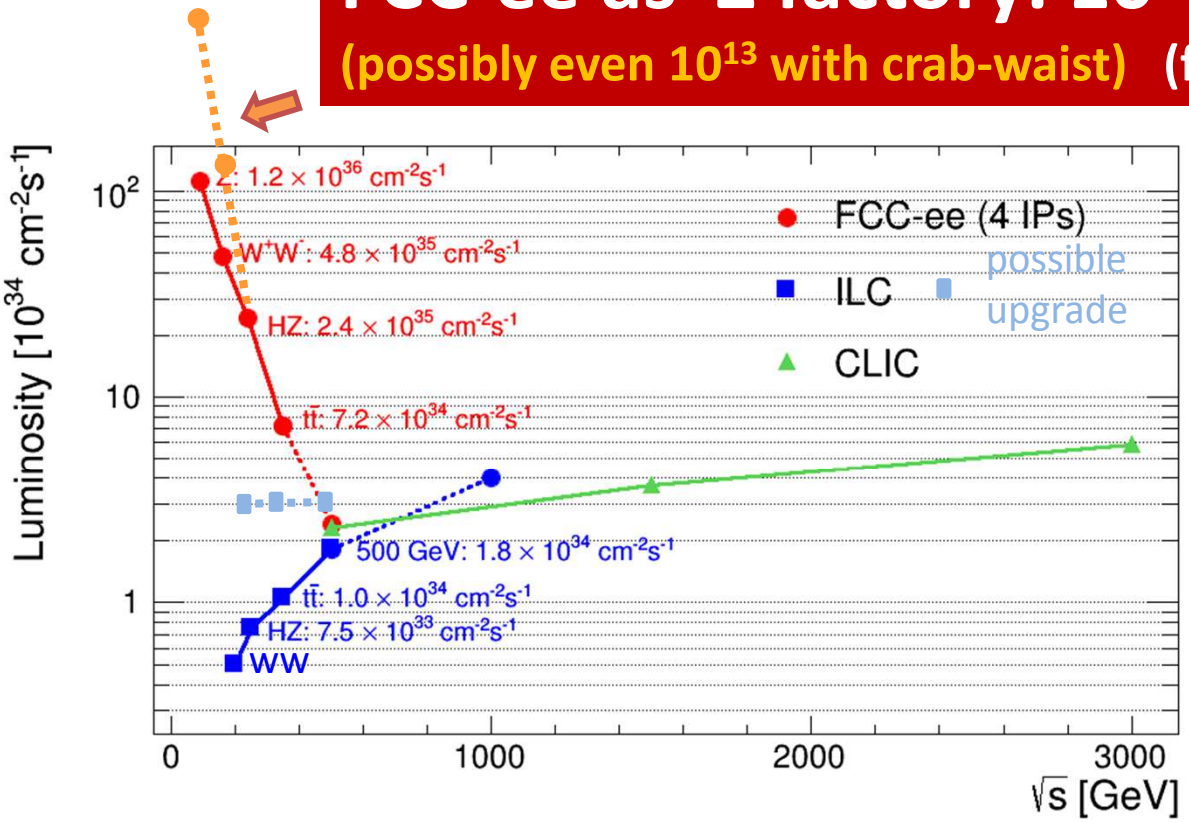
[(‡)] *retired*

Goal performance of e+ e- colliders

FCC-ee as Z factory: 10^{12} Z

(possibly even 10^{13} with crab-waist) (few years)



complementarity

NB: ideas for lumi upgrades:
ILC arxiv:1308.3726 (not in TDR. Upgrade at 250GeV by reconfiguration after 500 GeV running; under discussion)
FCC-ee (crab waist)

At the end of LEP:

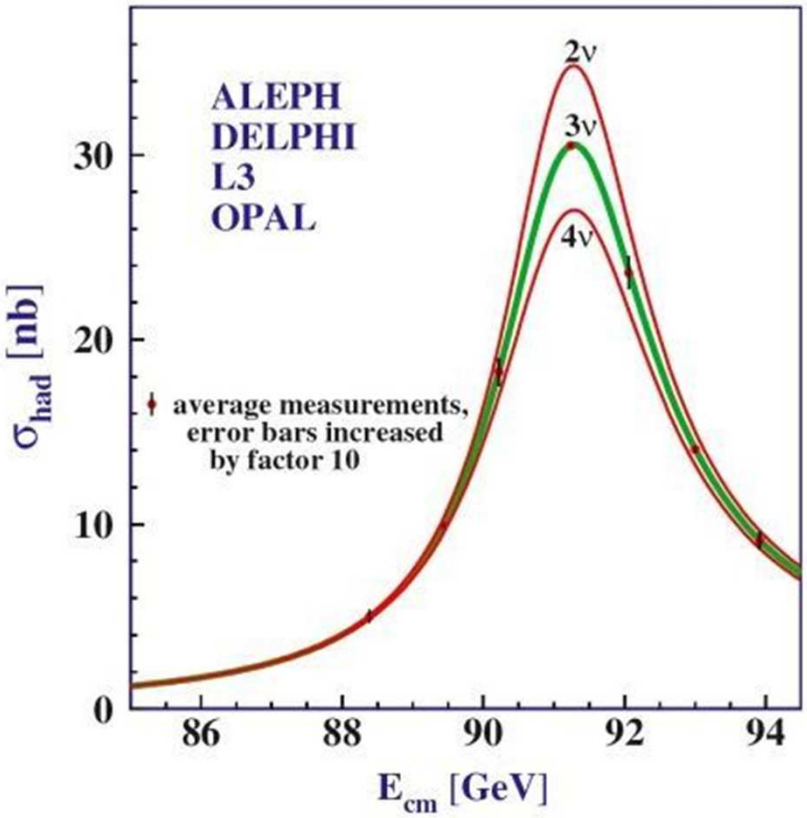
Phys.Rept.427:257-454,2006

$N_\nu = 2.984 \pm 0.008$

- 2 σ :^) !!

This is determined from the Z line shape scan and dominated by the measurement of the hadronic cross-section at the Z peak maximum ➔

The dominant systematic error is the theoretical uncertainty on the Bhabha cross-section (0.06%) which represents an error of ±0.0046 on N_ν



Improving on N_ν by more than a factor 2 would require a large effort to improve on the Bhabha cross-section calculation!

Neutrino counting at TLEP

given the very high luminosity, the following measurement can be performed

$$N_\nu = \frac{\gamma Z(inv)}{\gamma Z \to ee, \mu\mu} \Big/ \frac{\Gamma_\nu}{\Gamma e, \mu}\,(SM)$$

The common γ tag allows cancellation of systematics due to photon selection, luminosity etc. The others are extremely well known due to the availability of O(10^{12}) Z decays.

The full sensitivity to the number of neutrinos is restored , and the theory uncertainty on $\frac{\Gamma_\nu}{\Gamma e}\,(SM)$ is very very small.

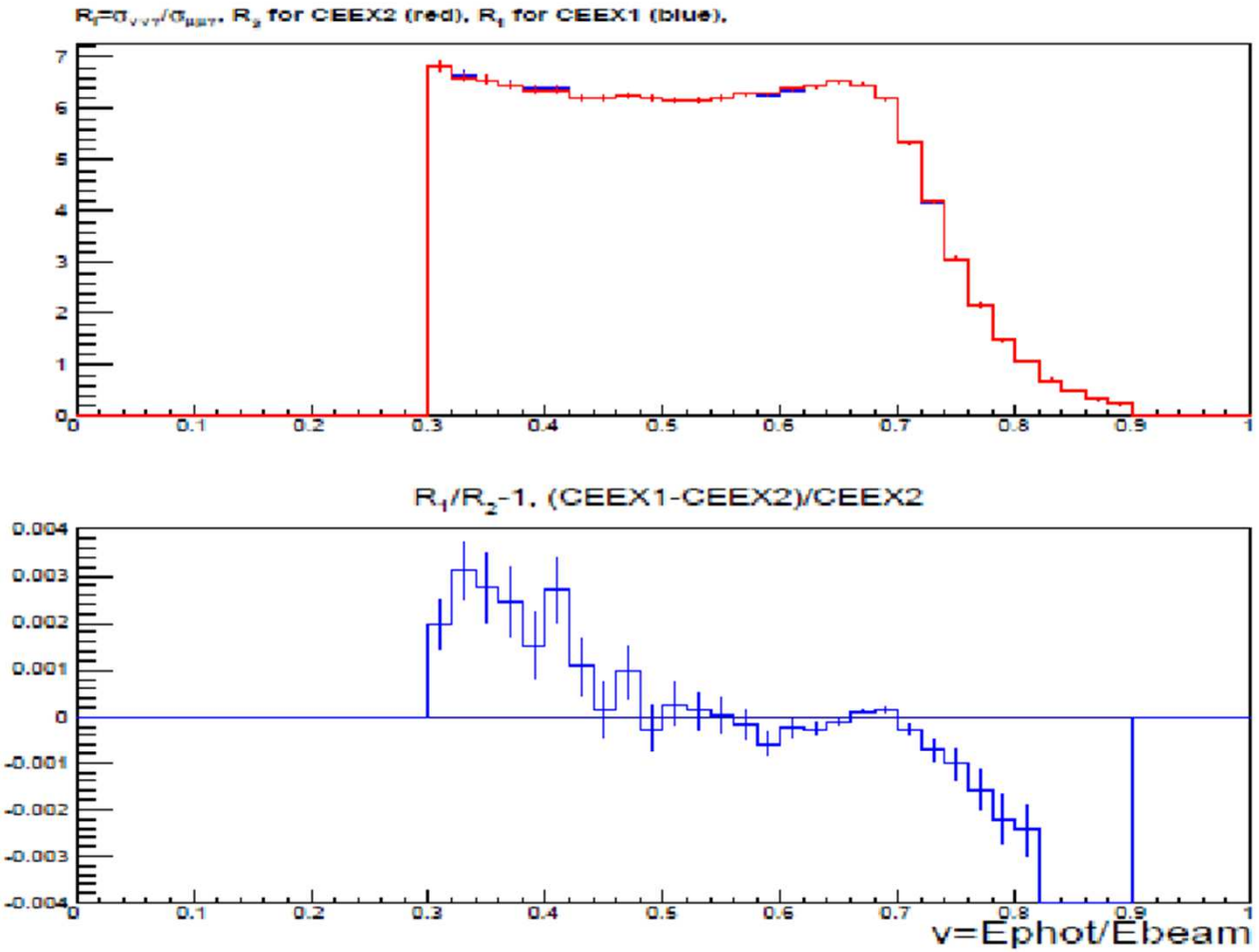
A good measurement can be made from the data accumulated at the WW threshold where σ (γ Z(inv)) ~4 pb for $|\cos\theta_\gamma| < 0.95$

161 GeV (10^7 s) running at 1.6x10^{35}/cm^2/s x 4 exp ➔ 3x10^7 γ Z(inv) evts, ΔN_ν=0.0011
adding 5 yrs data at 240 and 350 GeV ..... ΔN_ν=0.0008

A better point may be 105 GeV (20pb and higher luminosity) may allow ΔN_ν=0.0004?

Jadach, Ward, Was, FCC-ee VC March 2014

QED corr. estimate in $\sigma(\nu\bar{\nu}\gamma)/\sigma(\mu^-\mu^+\gamma)$



QED corrections seems to cancell dramaticaly in the ratio $\sigma(\nu\bar{\nu}\gamma)/\sigma(\mu^-\mu^+\gamma)$. They drop to $\sim$ 0.03% !!!.
This is PRELIMINARY result requiring further tests.

RHASnu's production in Z decays

Production:

$$BR\,(Z^0 \to \nu_m \overline{\nu}) = BR\,(Z^0 \to \nu\bar{\nu})\,|U|^2 \left(1 - \frac{m^2_{\nu_m}}{m_{Z^0}{}^2}\right)^2 \left(1 + \frac{1}{2}\frac{m^2_{\nu_m}}{m_{Z^0}{}^2}\right)$$

multiply by 2 for anti neutrino and add contributions of 3 neutrino species (with different $|U|^2$)

Decay

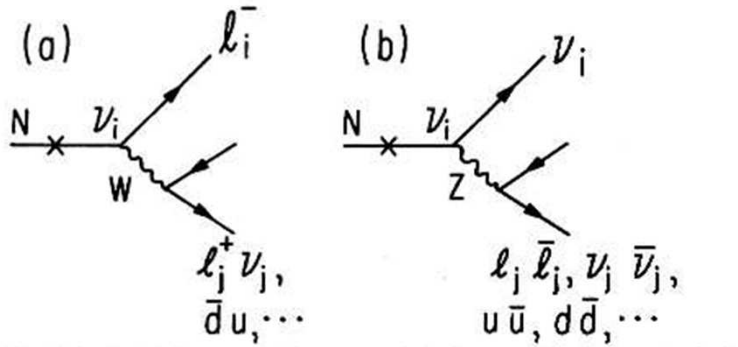


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

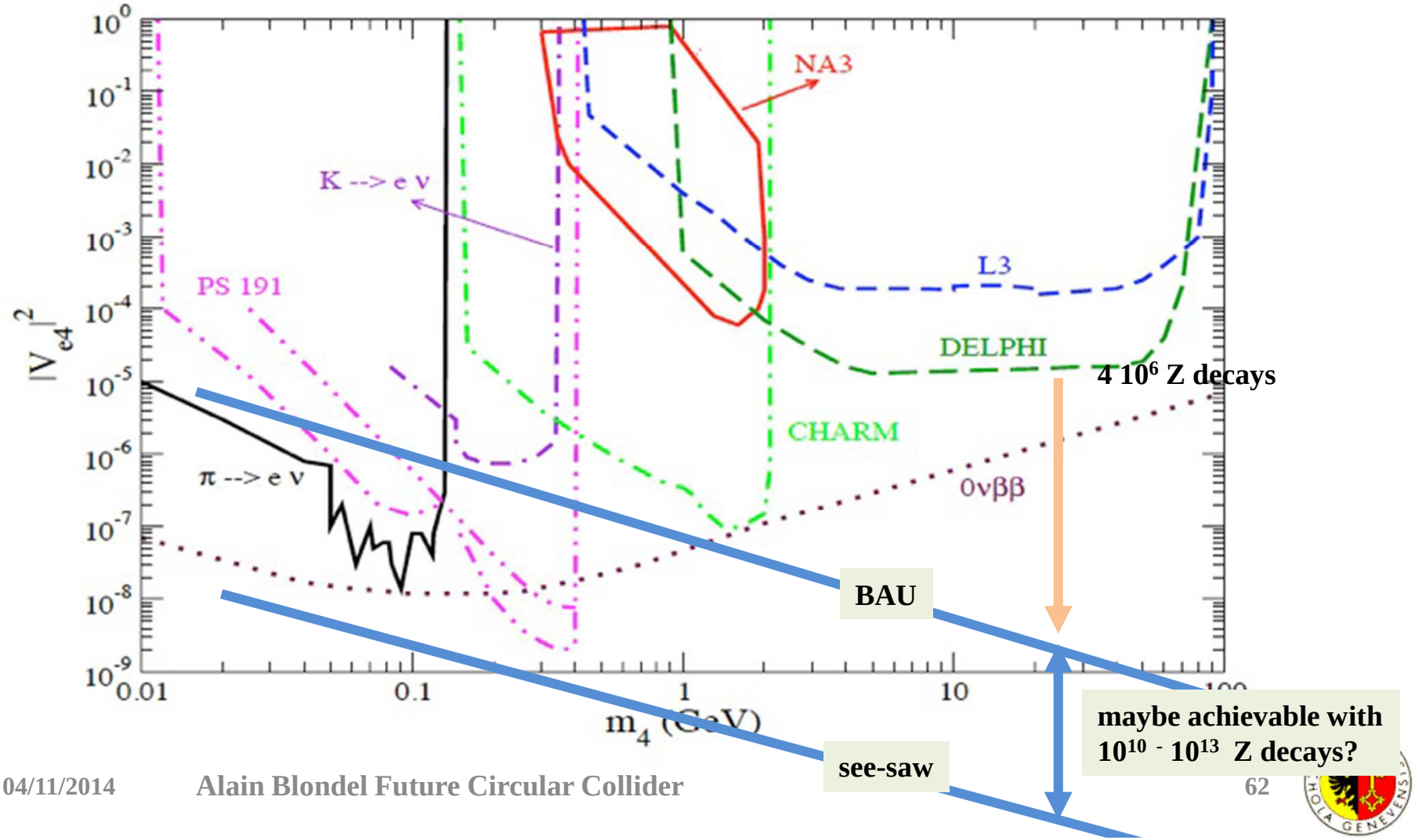
Decay length:

$$L \approx \frac{3 \text{ cm}}{|U|^2\,(m_{\nu_m}(\mathrm{GeV}/c^2))^6}$$

NB CC decay always leads to ≥ 2 charged tracks

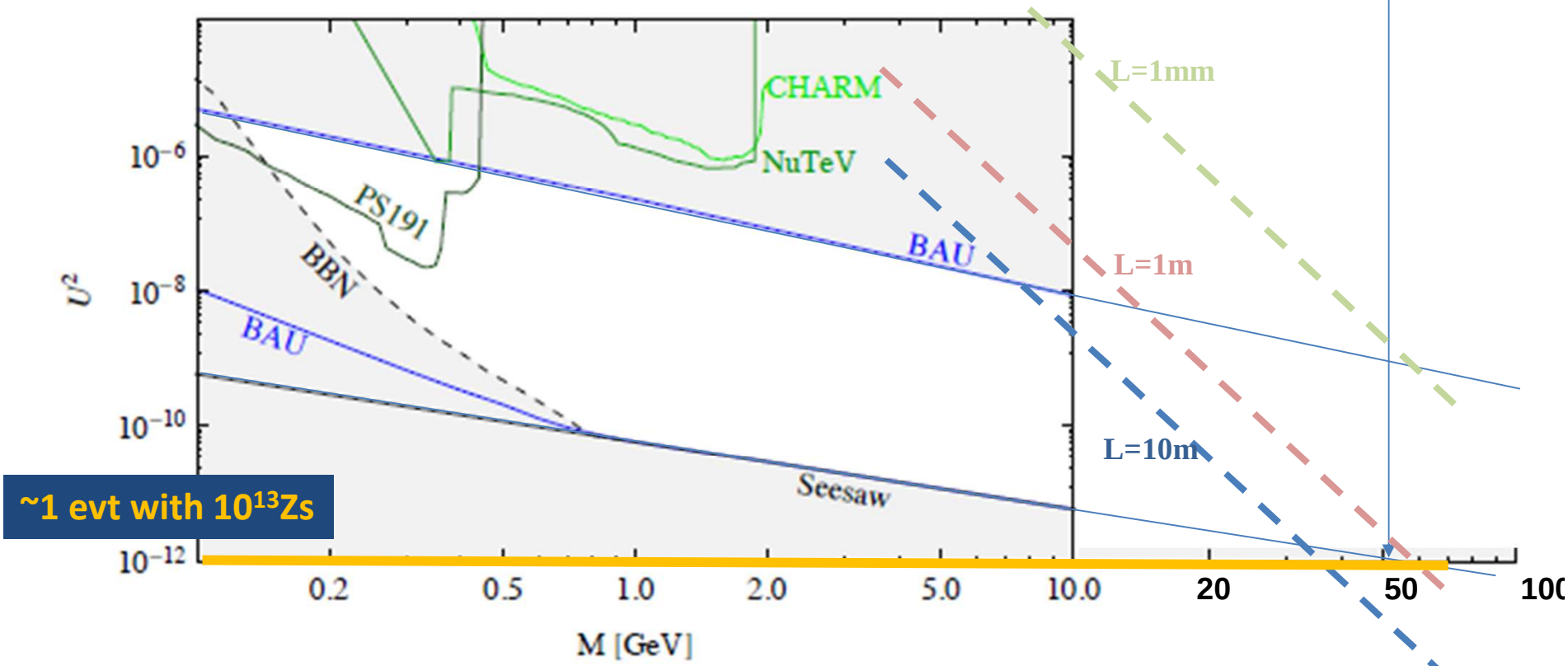
Backgrounds : four fermion: e+e- → W*+ W*- e+e- → Z*(νν) + (Z/γ)*

Order-of-magnitude extrapolation of existing limits



Decay length

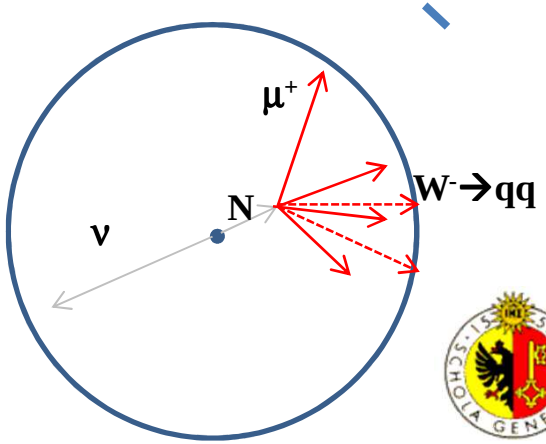
Interesting region
$|U|^2$ ~ 10^{-9} to 10^{-12} @ 50 GeV



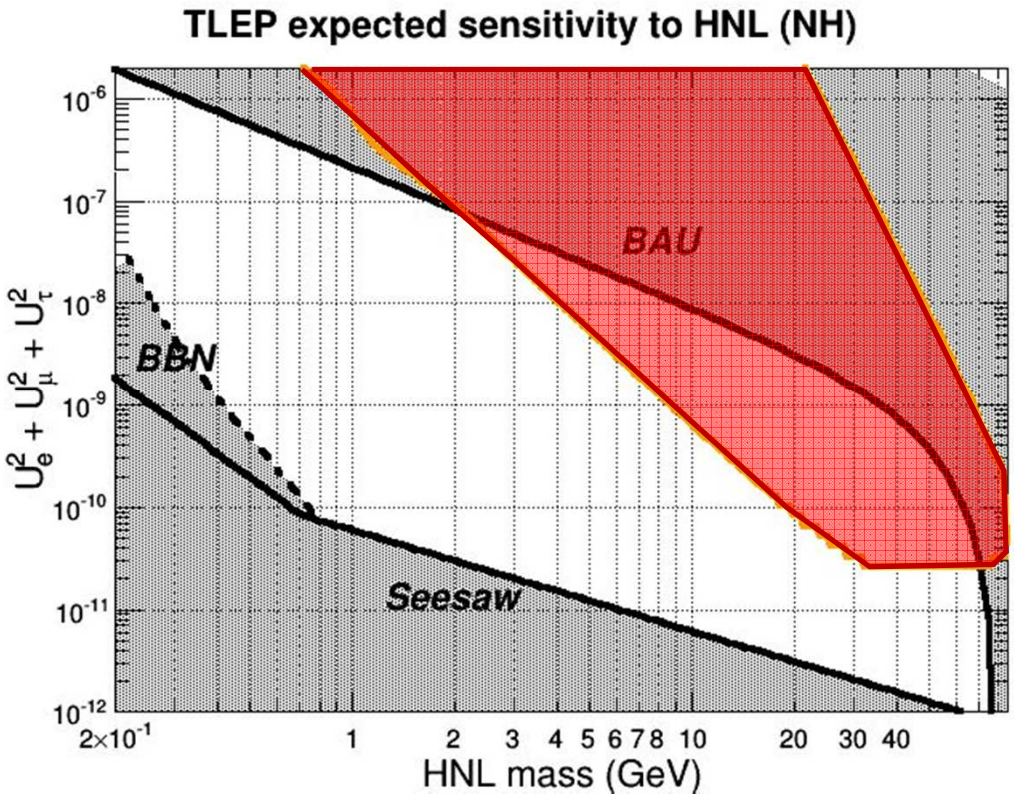
~1 evt with 10^{13}Zs

heavy neutrino mass ~ M

a large part of the interesting region will lead to detached vertices
... ➔very strong reduction of background!



Exact reach domain will depend on detector size and details of displaced vertex efficiency & background

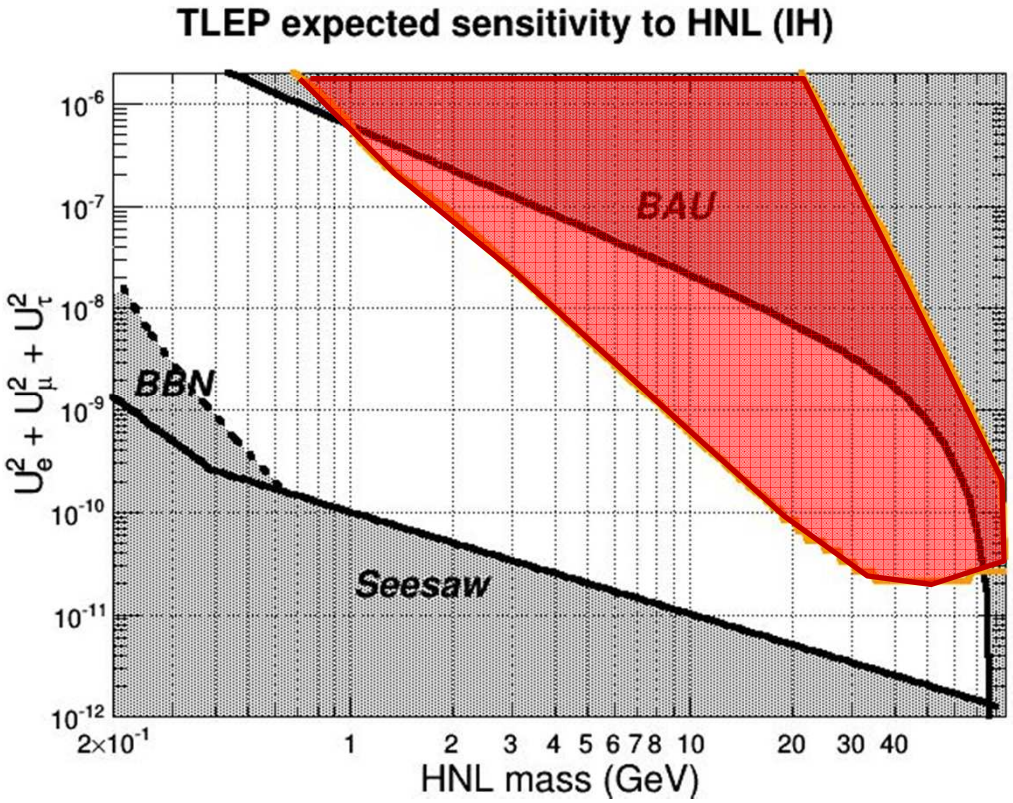


$N_Z = 10^{12}$ 1mm<L<1m

region of interest

FCC-ee sensitivity

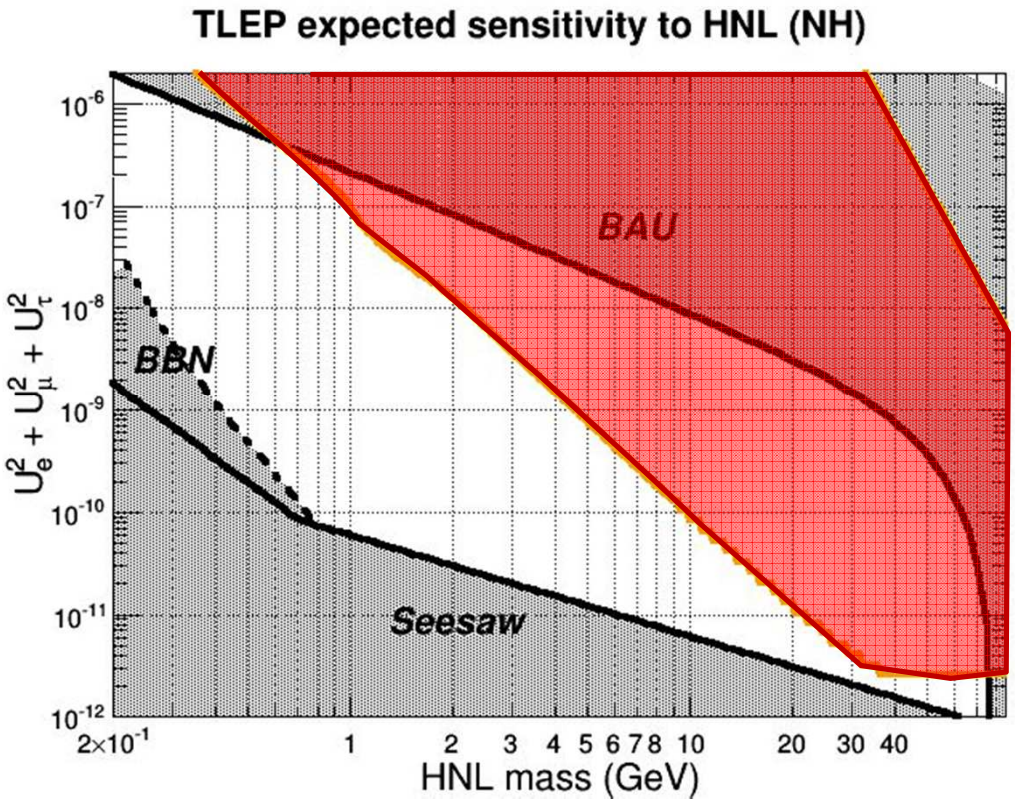
A.B, Elena Graverini, Nicola Serra, Misha Shaposhnikov



$N_Z = 10^{12}$ 1mm<L<1m

region of interest

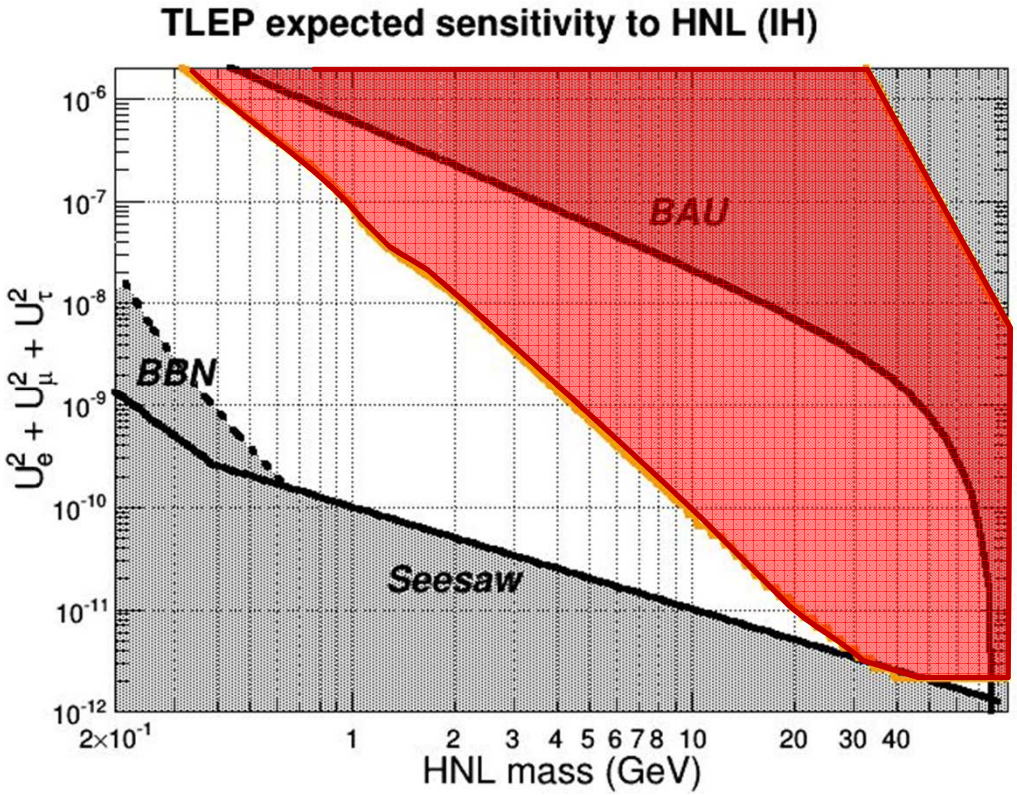
FCC-ee sensitivity



$N_Z = 10^{13}$ $100\mu m$ <L<5m

region of interest

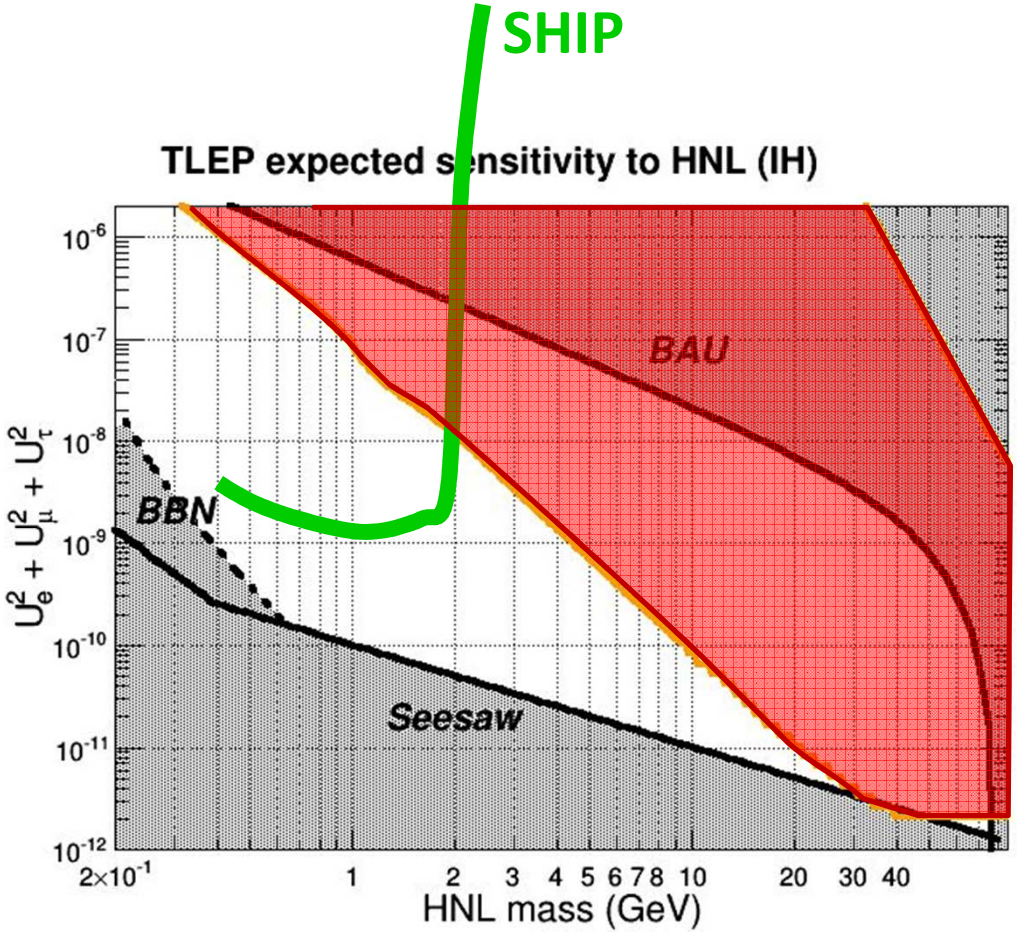
FCC-ee sensitivity



$N_Z = 10^{13}$ $100\mu m$ <L<5m

region of interest

FCC-ee sensitivity



$N_Z = 10^{13}$ $100\mu m$ <L<5m

region of interest

FCC-ee sensitivity

330 registered participants

Meanwhile N. Lockyer was speaking at the ICFA seminar in Beijing

Higgs discovery has dramatically changed the landscape…

- Higgs discovery motivates a precision Higgs factory…not going to make three….what is the right direction?

- China wants to build a Higgs factory
- Europe wants to build a Higgs factory

- ILC higher energy (500 GeV), both beams polarized, mature design & machine ready to go technically e.g., Euro-XFEL~500 cavities built…together 3 regions can build ILC
  - (significant energy increase possible with further R&D on Nb3Sn)
- Strategy for FCC and CECP is however attractive
- Neither FCC or CECP as high energy as Linear Collider(s) but have an attractive growth path just as LEP grew into LHC.

Note that this is not based on physics comparisons but values FCC-ee as launching pad for FCC-hh

I hope to have convinced you that
FCC-ee is the best Higgs Factory, but....

FCC-ee is MUCH more than a Higgs Factory!

The combination of FCC-ee and the FCC-hh offers, for a great cost effectiveness, the best precision and the best search reach of all options presently on the market.

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