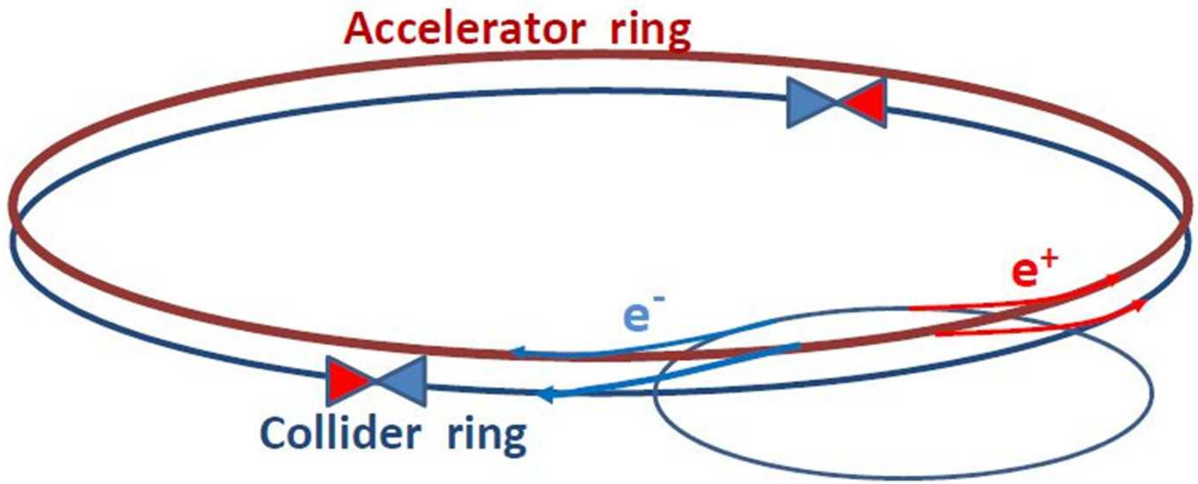
Higgs Factory Workshop
Fermilab, 14-16 2012

Higgs Factory

ICHEP’14:
“ICFA supports studies of energy frontier circular colliders and encourages global coordination“

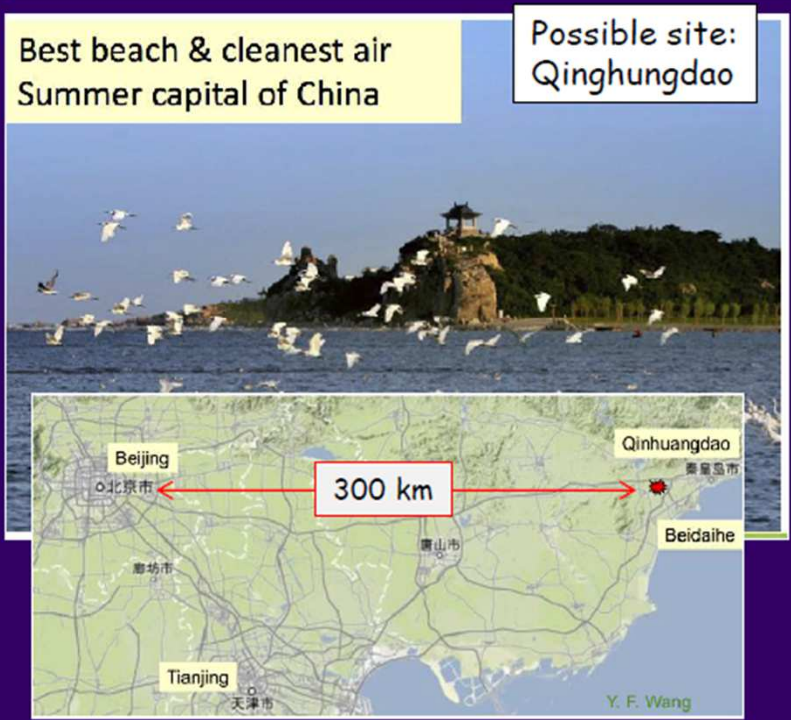
Dec. 2011:



Future high-energy circular colliders

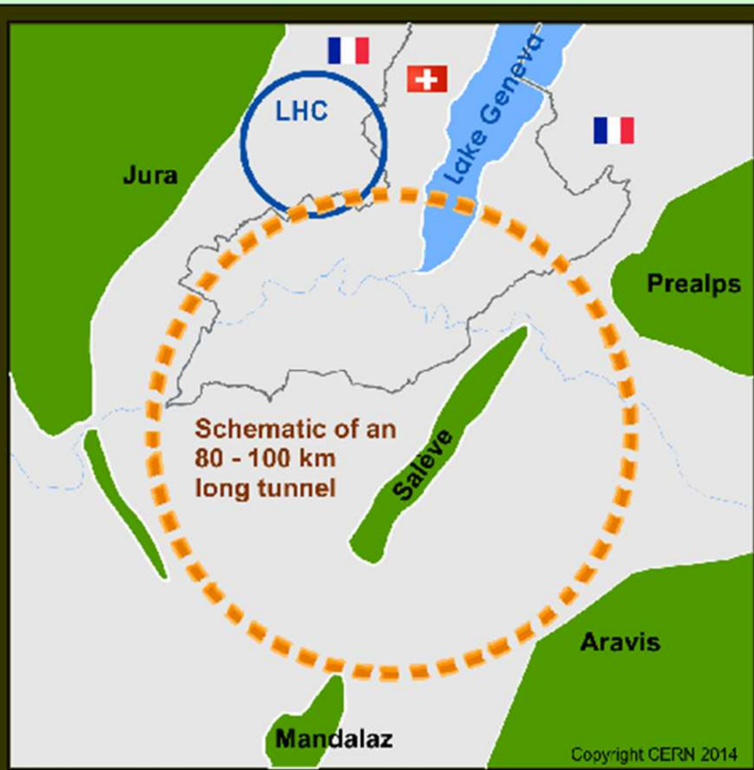
http://cern.ch/fcc and
http://cern.ch/fcc-ee

China: 50-70 km e^+e^- $\sqrt{s}$=240 GeV (CepC) followed by 50-90 TeV pp collider (SppC) in same tunnel
50 km e^+e^- machine + 2 experiments:
- pre-CDR: end 2014
- construction: 2021-2027
- data-taking: 2028-2035
- cost (material): ~3 B$



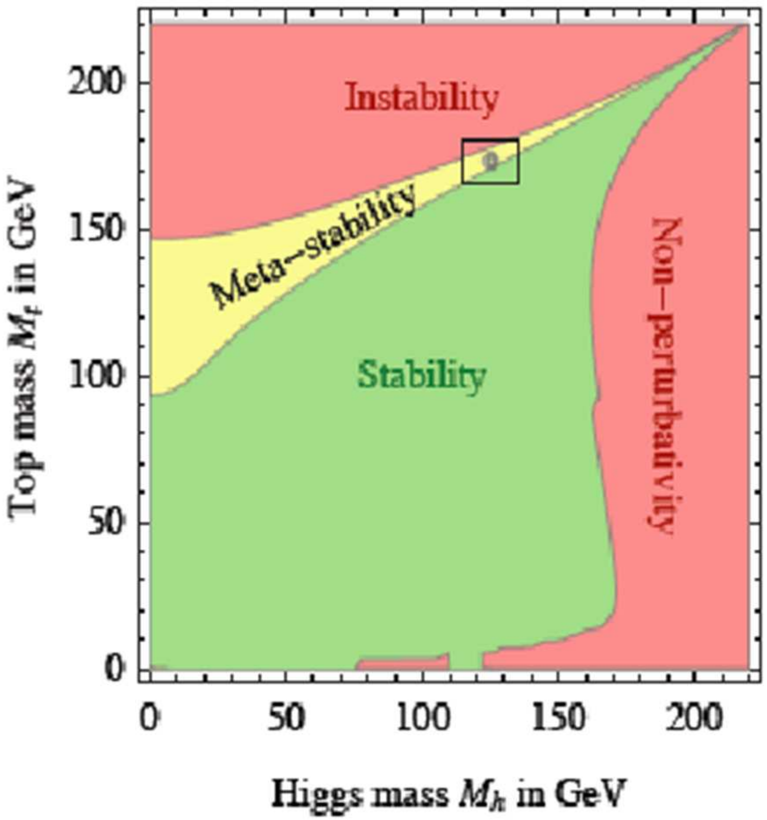
CERN FCC: international design study for Future Circular Colliders in 80-100 km ring:
- 100 TeV pp: ultimate goal (FCC-hh)
- 90-350 GeV e^+e^-: possible first step (FCC-ee)
- $\sqrt{s}$= 3.5-6 TeV ep: option (FCC-eh)

Goal of the study: CDR in ~2018.



NB (AB): time scale for FCC-ee similar to CLIC (2030++)

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
0
50
100
150
200

Is it the end?

Certainly not!

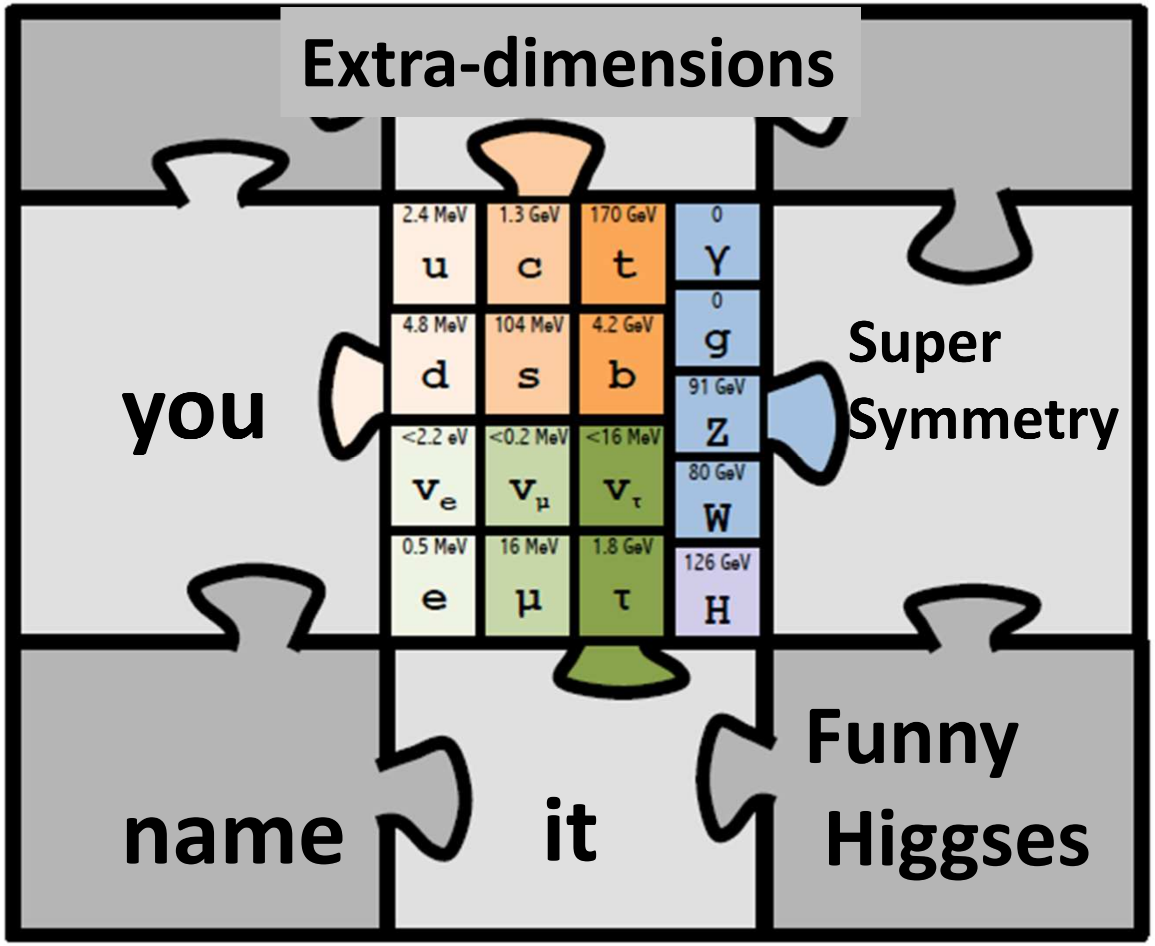
-- Dark matter

-- Baryon Asymmetry in Universe

-- Neutrino masses

are experimental proofs that there is more to understand.

perhaps new world(s) of SM replicas?



or perhaps only right handed 'sterile' neutrinos.....

But Where Is Everybody?

Nima

But Where Is Everybody?

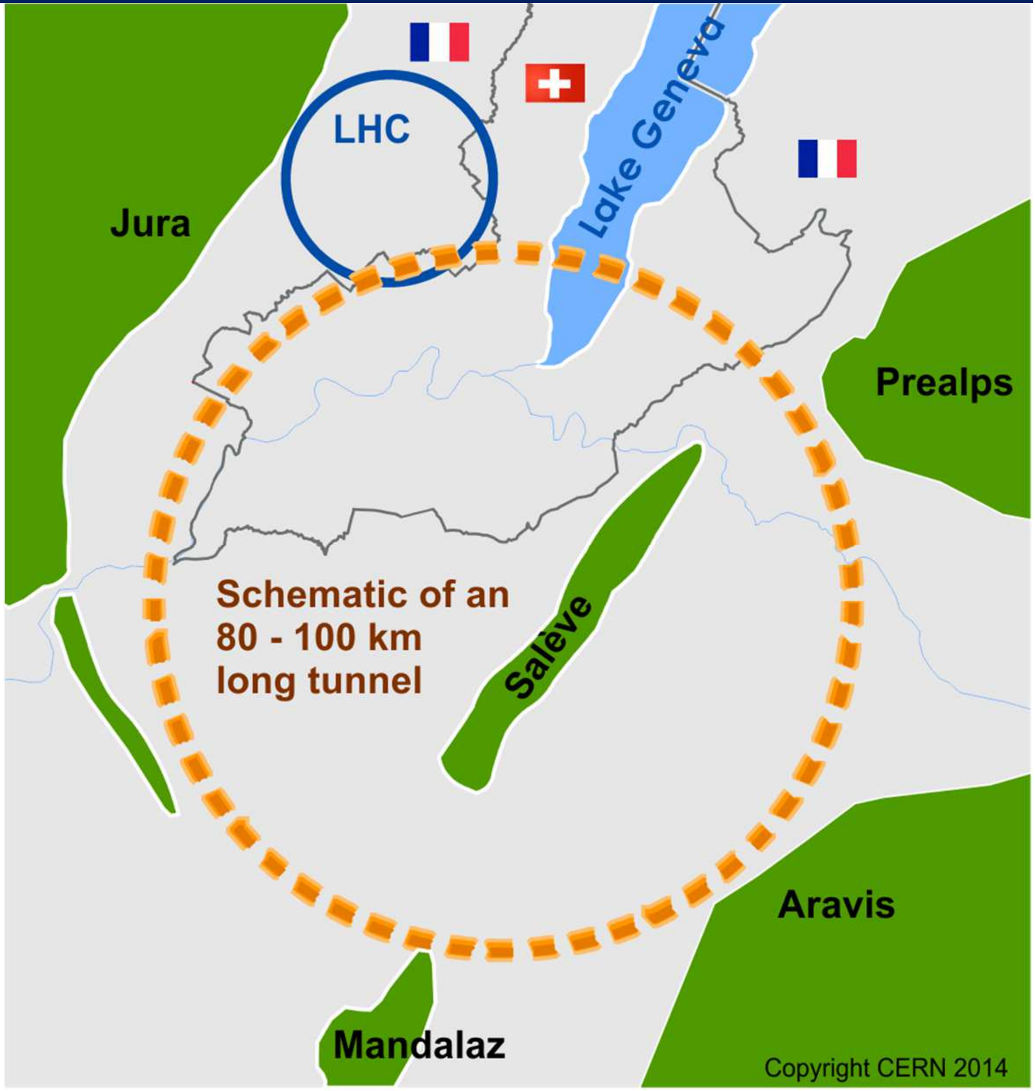
Nima

At higher masses -- or at smaller couplings?

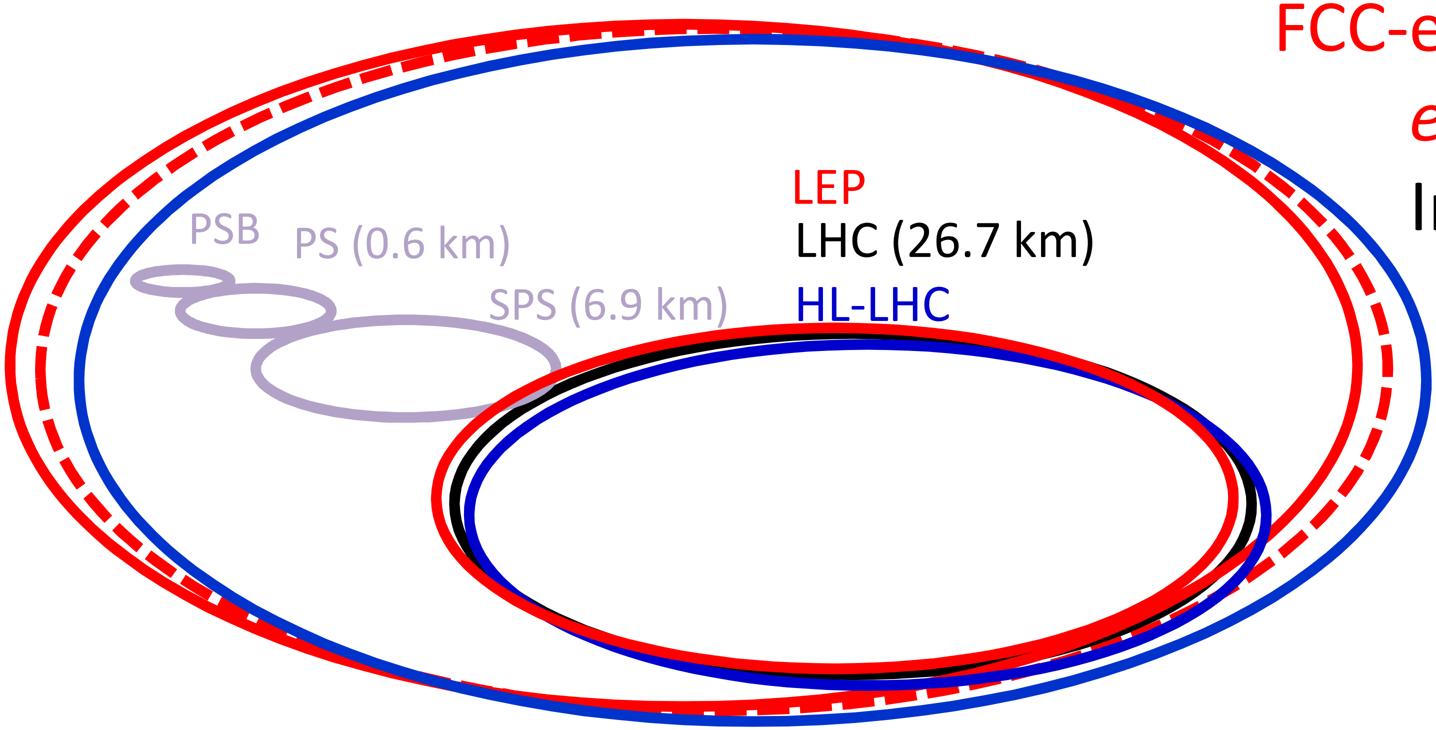
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements
- ***ultimate goal: 100 TeV pp collisions***
- ***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

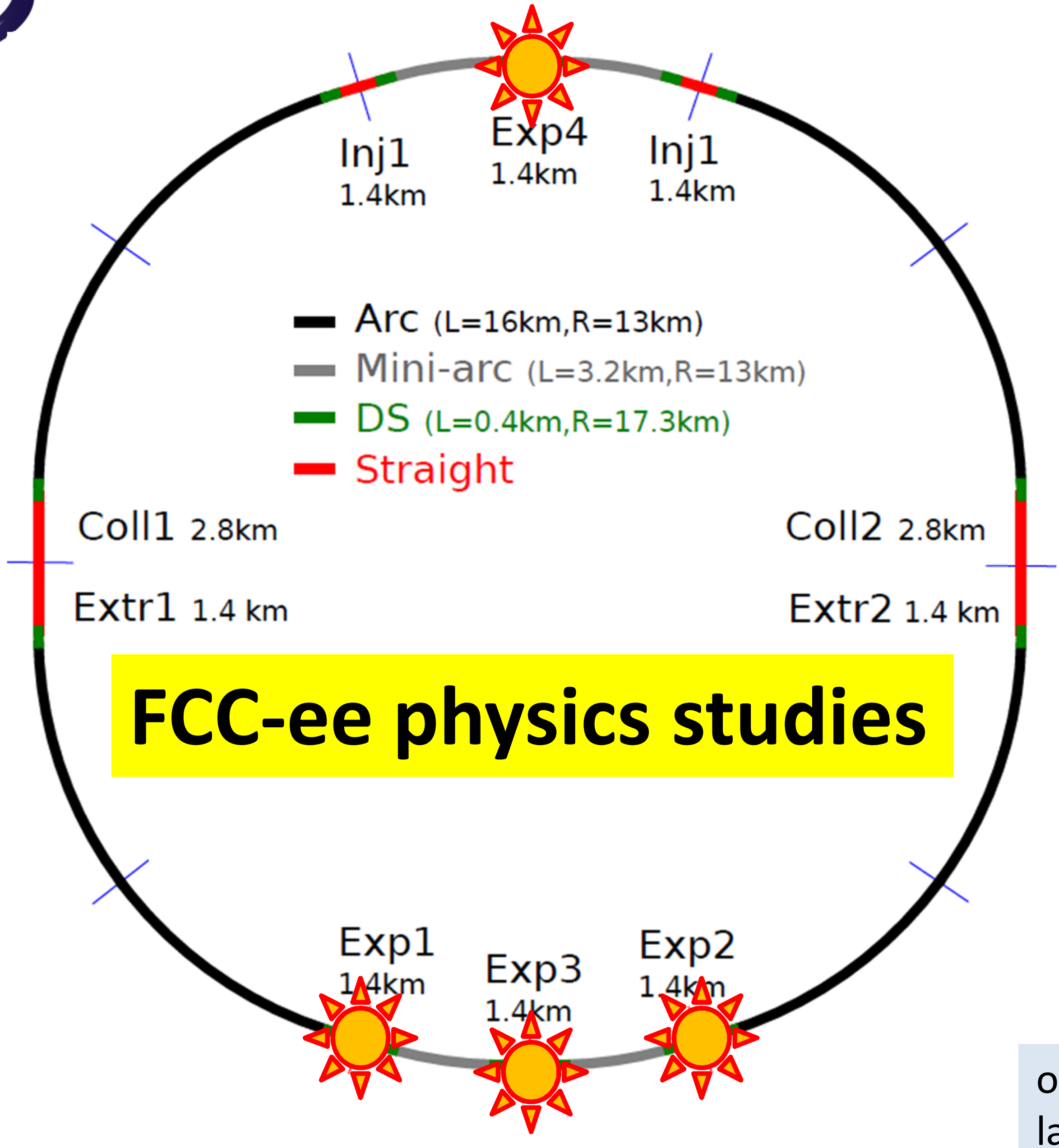
FCC-hh (*pp*, up to 100 TeV c.m.)

Ultimate goal

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

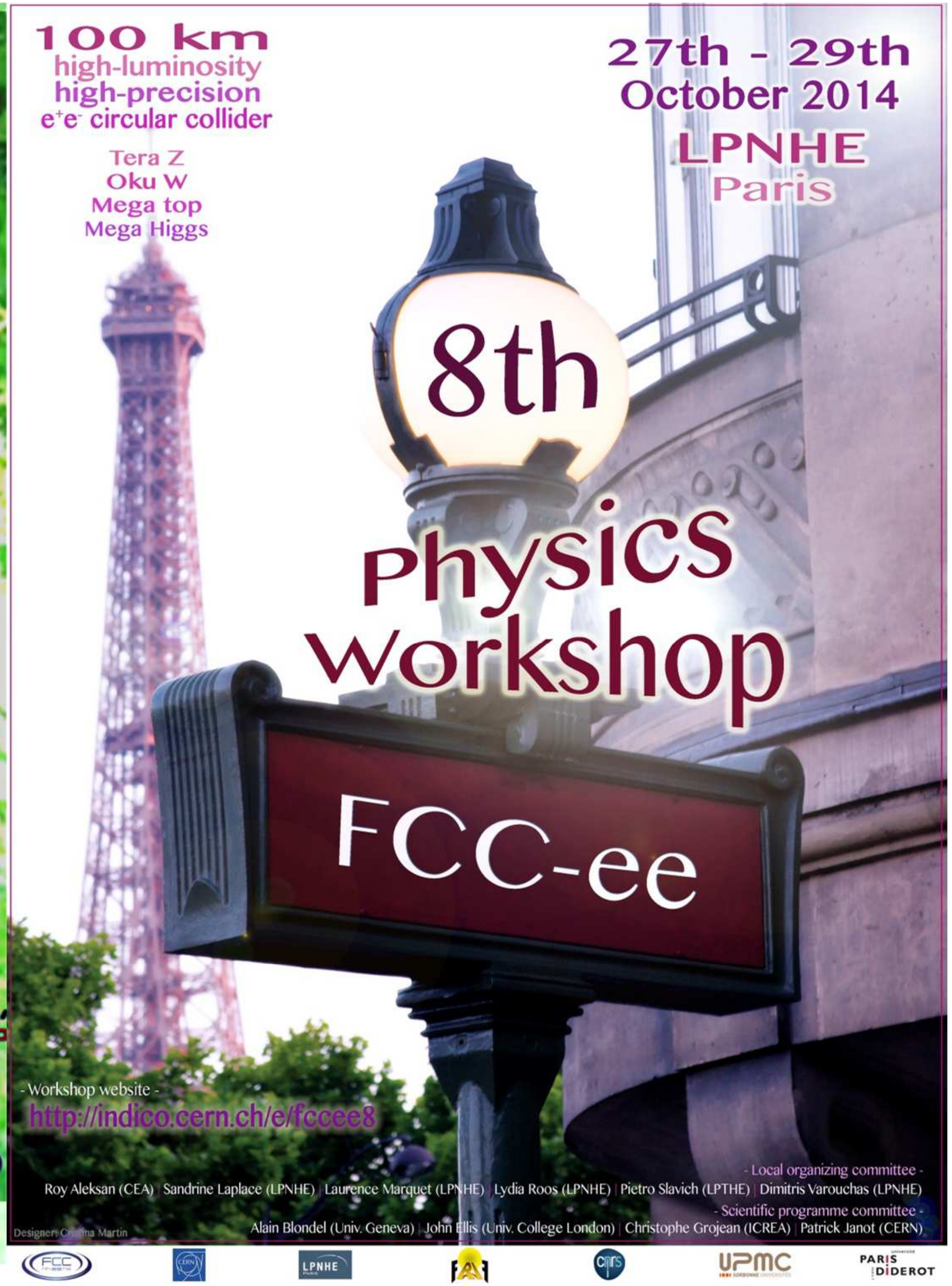
≥50 years of e^+e^-, *pp*, *ep/A* physics at highest energies

FCC-ee physics studies



one of the possible layouts of the FCC with 4 IPs.


The 7th FCC-ee
Physics Workshop
A 100 km Tunnel for Luminosity, Energy and Precision
19 - 21 June 2014
TH Auditorium (CERN)
Register at
indico.cern.ch/event/313708/
Organizing committee
Alain Blondel - U. Geneva
John Ellis - U. College London
Christophe Grojean - ICREA
Patrick Janot - CERN
Designer:
Cristina Martin Perez
International Design Study
of Future Circular Colliders
European Organization
for Nuclear Research


100 km
high-luminosity
high-precision
e+e- circular collider
Tera Z
Oku W
Mega top
Mega Higgs
27th - 29th
October 2014
LPNHE
Paris
8th
Physics
Workshop
FCC-ee
- Workshop website -
http://indico.cern.ch/e/fccee8
- Local organizing committee -
Roy Aleksan (CEA) | Sandrine Laplace (LPNHE) | Laurence Marquet (LPNHE) | Lydia Roos (LPNHE) | Pietro Slavich (LPTHE) | Dimitris Varouchas (LPNHE)
- Scientific programme committee -
Alain Blondel (Univ. Geneva) | John Ellis (Univ. College London) | Christophe Grojean (ICREA) | Patrick Janot (CERN)
Designer: Cristina Martin
LPNHE
UPMC
PARIS DIDEROT

Successes of 7th FCC-ee Physics workshop

-1- All top level conveners are nominated and engaged!

congratulations to Patrick Janot and to the conveners!

-2- Software effort is underway

big thanks to Benedikt Hegner et al! (joined since by Colin Bernet)

-3- Nice participation by e+e- Linear collider colleagues

part of FCC-ee mandate. We all agree that the next machine should be an e+e- collider.

(Thanks to Simon, Wilson, Sailer, Mele, Heinemeyer, Grojean, Brient, Haddad, etc...)

We re-invented the wheel (circle) but we do not need to re-invent the electron!

-4- Complementarity with hadron machine is not just words

ttH coupling is a good example

-5- Reaching out to dark matter, BAU and neutrinos

invisible widths, direct search for rare Z,H, W ... decays

-6- We are discovering the immense potential offered by the high luminosity e+e- Z,W,H,t factory

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

A lot is published in JHEP:
I will insist on new things

The TLEP Design Study Working Group

M. Bicer,[a] H. Duran Yildiz,[b] I. Yildiz,[c] G. Coignet,[d] M. Delmastro,[d] T. Alexopoulos,[e] C. Grojean,[f] S. Antusch,[g] T. Sen,[h] H.-J. He,[i] K. Potamianos,[j] S. Haug,[k] A. Moreno,[l] A. Heister,[m] V. Sanz,[n] G. Gomez-Ceballos,[o] M. Klute,[o] M. Zanetti,[o] L.-T. Wang,[p] M. Dam,[q] C. Boehm,[r] N. Glover,[r] F. Krauss,[r] A. Lenz,[r] M. Syphers,[s] C. Leonidopoulos,[t] V. Ciulli,[u] P. Lenzi,[u] G. Sguazzoni,[u] M. Antonelli,[v] M. Boscolo,[v] U. Dosselli,[v] O. Frasciello,[v] C. Milardi,[v] G. Venanzoni,[v] M. Zobov,[v] J. van der Bij,[w] M. de Gruttola,[x] D.-W. Kim,[y] M. Bachtis,[z] A. Butterworth,[z] C. Bernet,[z] C. Botta,[z] F. Carminati,[z] A. David,[z] L. Deniau,[z] D. d'Enterria,[z] G. Ganis,[z] B. Goddard,[z] G. Giudice,[z] P. Janot,[z] J. M. Jowett,[z] C. Lourenço,[z] L. Malgeri,[z] E. Meschi,[z] F. Moortgat,[z] P. Musella,[z] J. A. Osborne,[z] L. Perrozzi,[z] M. Pierini,[z] L. Rinolfi,[z] A. de Roeck,[z] J. Rojo,[z] G. Roy,[z] A. Sciabà,[z] A. Valassi,[z] C.S. Waaijer,[z] J. Wenninger,[z] H. Woehri,[z] F. Zimmermann,[z] A. Blondel,[aa] M. Koratzinos,[aa] P. Mermod,[aa] Y. Onel,[ab] R. Talman,[ac] E. Castaneda Miranda,[ad] E. Bulyak,[ae] D. Porsuk,[af] D. Kovalskyi,[ag] S. Padhi,[ag] P. Faccioli,[ah] J. R. Ellis,[ai] M. Campanelli,[aj] Y. Bai,[ak] M. Chamizo,[al] R.B. Appleby,[am] H. Owen,[am] H. Maury Cuna,[an] C. Gracios,[ao] G. A. Munoz-Hernandez,[ao] L. Trentadue,[ap] E. Torrente-Lujan,[aq] S. Wang,[ar] D. Bertsche,[as] A. Gramolin,[at] V. Telnov,[at] M. Kado,[au] P. Petroff,[au] P. Azzi,[av] O. Nicrosini,[aw] F. Piccinini,[aw] G. Montagna,[ax] F. Kapusta,[ay] S. Laplace,[ay] W. da Silva,[ay] N. Gizani,[az] N. Craig,[ba] T. Han,[bb] C. Luci,[bc] B. Mele,[bc] L. Silvestrini,[bc] M. Ciuchini,[bd] R. Cakir,[be] R. Aleksan,[bf] F. Couderc,[bf] S. Ganjour,[bf] E. Lançon,[bf] E. Locci,[bf] P. Schwemling,[bf] M. Spiro,[bf] C. Tanguy,[bf] J. Zinn-Justin,[bf] S. Moretti,[bg] M. Kikuchi,[bh] H. Koiso,[bh] K. Ohmi,[bh] K. Oide,[bh] G. Pauletta,[bi] R. Ruiz de Austri,[bj] M. Gouzevitch[bk] and S. Chattopadhyay[bl]

JHEP01(2014)164

First phase until March 2015:

SCOPING the physics panorama and the main technical issues

Establish collaboration and reach out to interested groups

Get things started.

FCC-ee experiments

Experimental Studies: A. Blondel, P. Janot

- Discovery through precision measurements, rare, or invisible processes.

Electroweak Physics at the Z pole R. Tenchini F. Piccinini	Di-boson Physics m_W measurement R. Tenchini	H(126) Properties M. Klute K. Peters	Top Quark Physics P. Azzi
QCD and $\gamma\gamma$ Physics D. d'Enterria P. Skands	Flavour Physics S. Monteil J. Kamenic	New Physics M. Pierini C. Rogan	

- Develop the necessary tools

Understand the experimental conditions

Offline Software
B. Hegner
C. Bernet
common across FCC

Online Software
C. Leonidopoulos

Experimental Environment
N. Bacchetta

- Set constraints (specifications) on possible detector designs to match statistical precision

Detector Designs
A. Cattai
G. Rolandi

Synergy with linear collider detectors:
ILD proposed as benchmark, SID (CERN group)
both require L^* modifications!
Several detectors possible:
lots of space for new ideas!

NB Conveners have mission for one year to assemble group and find co-conveners

FCC-ee Phenomenology Studies

Phenomenology Studies: J. Ellis, C. Grojean

- Match theory predictions to FCC-ee experimental precisions

QCD and $\gamma\gamma$ Physics (Joint exp/th) **P. Skands**	Precision EW calculations **S. Heinemeyer**	Flavour Physics (Joint exp/th) **Jernej Kamenik**

- How to discover new physics in precision measurements, in rare decays (Z, W, t, H, b, c, τ, ...) in rare or invisible processes (Right Handed neutrinos etc..)

:

Model Building and New Physics
Andreas Weiler

Synergy with
FCC-hh physics
Linear collider physics,
LEP physics
HF physics

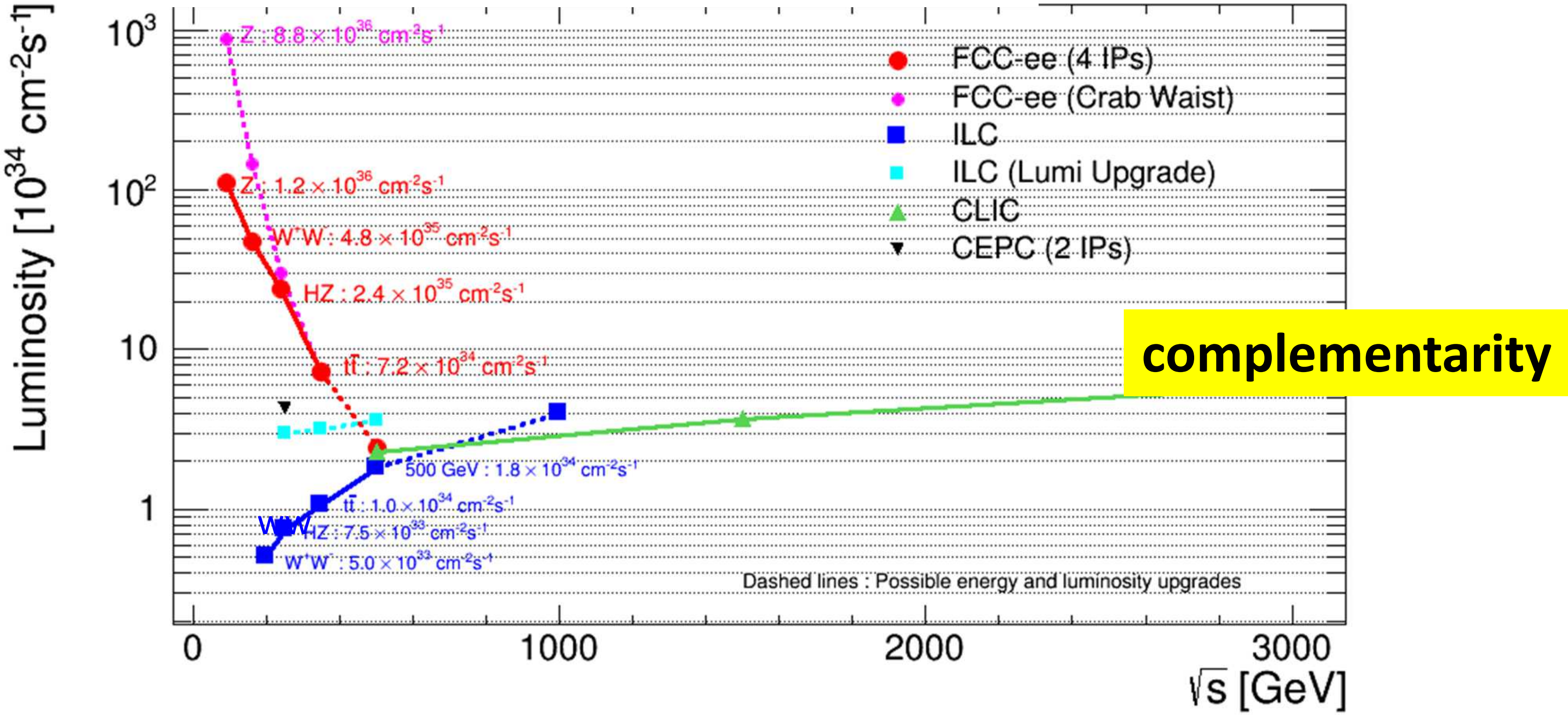
- Set up the framework for global fits and understand the complementarity with other colliders (LHC, FCC-hh, in particular)

Global Analysis, Combination, Complementarity
John Ellis

This tells the story:

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

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



NB: ideas for lumi upgrades:

-- ILC arxiv:1308.3726 (not in TDR). Upgrade at 250GeV by reconfiguration after 500 GeV running

-- FCC-ee (crab waist) see Zimmermann's talk

1 Precision measurements

-- EW observables Z, W, top

-- Higgs boson

2. Search for rare processes

-- neutrinos

1. ELECTROWEAK PRECISION TESTS (EWPT)

Due to the non-abelian Gauge theory, Electroweak observables offer sensitivity to electroweakly coupled new particles ...

-- if they are nearby in Energy scale
or
-- if they violate symmetries of the Standard Model (in which case, no «decoupling»)

Higgs boson and top-bottom mass splitting constitute such symmetry violations

2. TESTS OF ELECTROWEAK SYMMETRY BREAKING (EWSB)

Is the H(125) a Higgs boson?
→ couplings proportional to mass?
if not: could be more complicated EWSB e.g. more Higgses

→ Higgs supposed to cancel WW scattering anomalies at TeV scale: does this work?

$\Delta\rho : \equiv \varepsilon_1$ $$\Gamma_\ell = (1+\Delta\rho)\frac{G_F\, M_Z^3}{24\pi\sqrt{2}}\left(1+\left(\frac{g_{V\ell}}{g_{A\ell}}\right)^2\right)\left(1+\frac{3}{4}\frac{\alpha}{\pi}\right)$$

ε_3 $$\sin^2\theta_W^{eff}\cos^2\theta_W^{eff} = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}\, G_F\, m_Z^2}\frac{1}{1+\Delta\rho}\frac{1}{1-\frac{\varepsilon_3}{\cos^2\theta_W}}$$

δ_{vb} $$\Gamma_b = (1+\delta_{vb})\,\Gamma_d\left(1-\underset{\alpha\, m_b^2/M_Z^2}{\text{mass corrections}}\right)$$

ε_2 $$M_W^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}\, G_F \sin^2\theta_W^{eff.}}\cdot\frac{1}{(1-\varepsilon_3+\varepsilon_2)}$$

$\sin^2\theta_W^{eff}$ is defined from

$$\sin^2\theta_W^{eff} = \frac{1}{4}\Big(1-\underbrace{\frac{g_{V\ell}}{g_{A\ell}}}\Big) = \sin^2\theta_W{}^{eff}_{lept}$$

obtained from asymmetries at the Z.

also

Δr $$m_W^2 = \frac{\pi\alpha}{\sqrt{2}\, G_F}\cdot\frac{1}{\left(1-\frac{M_W^2}{M_Z^2}\right)}\frac{1}{(1-\Delta r)}$$

$$\Delta r = \Delta\alpha - \frac{\cos^2\theta_W}{\sin^2\theta_W}\Delta\rho + 2\frac{\cos^2\theta_W}{\sin^2\theta_W}\varepsilon_3 + \frac{c^2-s^2}{s^2}\varepsilon_2$$

EWRCs

relations to the well measured

G_F m_Z α_{QED}

at first order:

$\Delta\rho = \alpha/\pi\ (m_{top}/m_Z)^2$

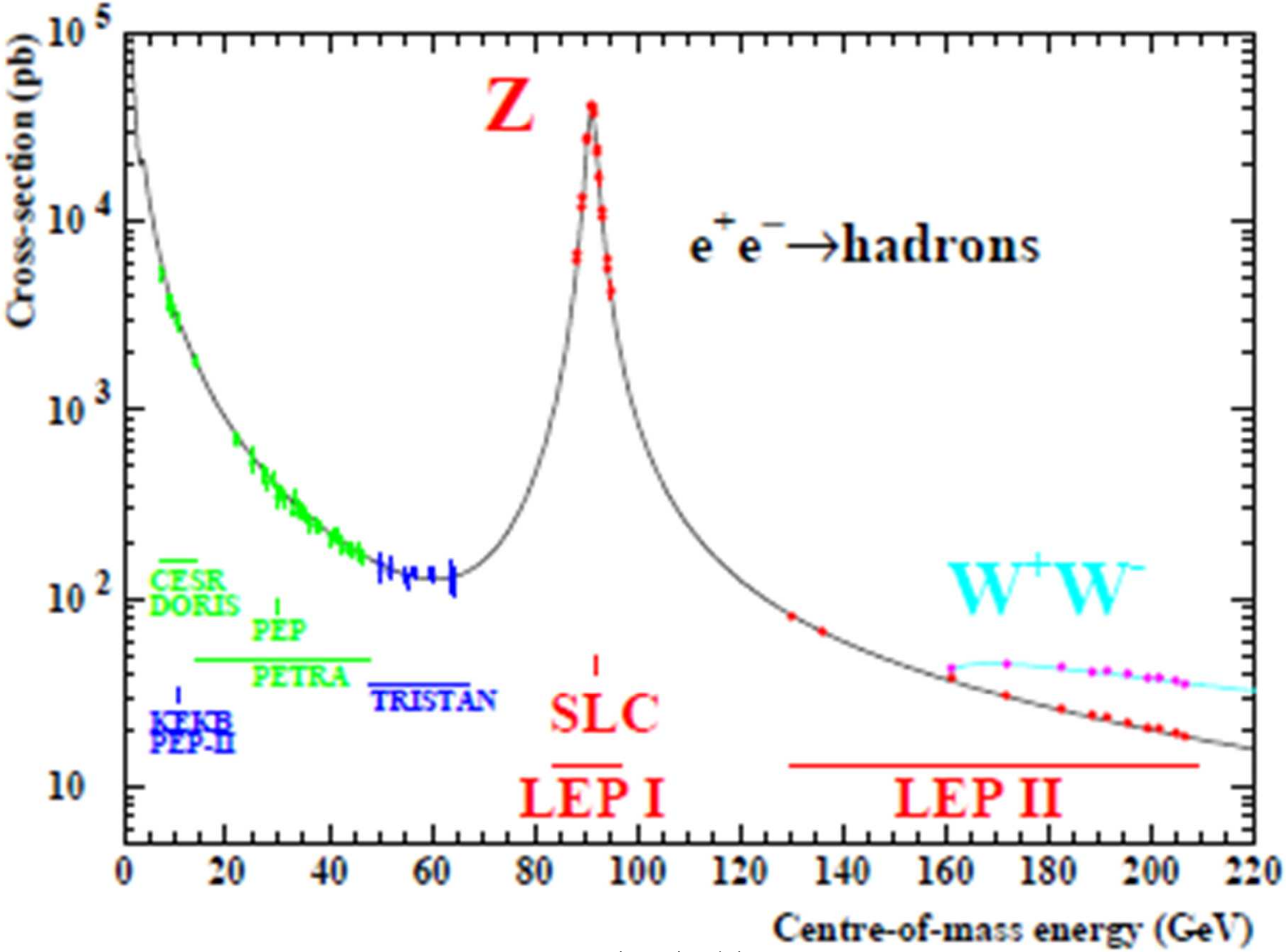
$-\ \alpha/4\pi\ \log\ (m_h/m_Z)^2$

$\varepsilon_3 = \cos^2\theta_w\ \alpha/9\pi\ \log\ (m_h/m_Z)^2$

$\delta_{vb} = 20/13\ \alpha/\pi\ (m_{top}/m_Z)^2$

complete formulae at 2d order
including strong corrections
are available in fitting codes

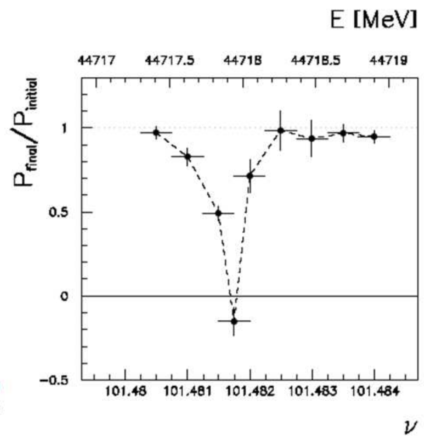
e.g. ZFITTER , GFITTER



Cross-section (pb)
10^5
10^4
10^3
10^2
10
Z
e+e- →hadrons
W+W-
CESR
DORIS
PEP
PETRA
TRISTAN
KEKB
PEP-II
SLC
LEP I
LEP II
0 20 40 60 80 100 120 140 160 180 200 220
Centre-of-mass energy (GeV)

Beam polarization and E-calibration @ FCC-ee

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 FCC-ee transverse polarization up to at least 80 GeV
to go to higher energies requires spin rotators and siberian snake

FCC-ee: 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

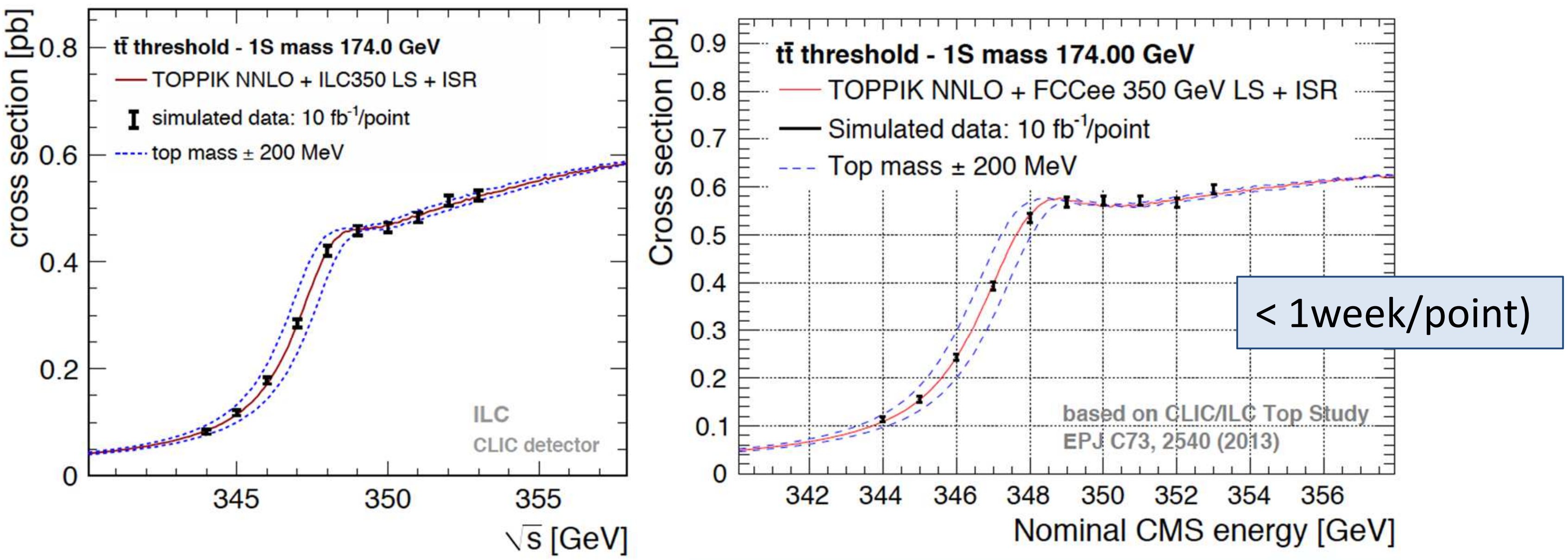
A Sample of Essential Quantities:

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	$\Delta\rho$ (T) (no $\Delta\alpha$!)	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}	$\Delta\rho$, ε_3 ,$\Delta\alpha$ (T, S)	0.1514 ±0.0022	Z peak, polarized	±0.000015	4 bunch scheme	Design experiment
M_W MeV/c2	$\Delta\rho$, ε_3 ,ε_2, $\Delta\alpha$ (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?

350 GeV: the top mass

- Advantage of a very low level of beamstrahlung
- **Could potentially reach 10 MeV uncertainty (stat) on m_{top}**

- Comparing ILC and FCCee - assuming identical detector performance



Simulated data points - same integrated luminosity

NB: Assuming unpolarized beams - LC beams can be polarized, increasing cross-sections / reducing backgrounds

From Frank Simon, presented at 7th TLEP-FCC-ee workshop, CERN, June 2014

The Higgs

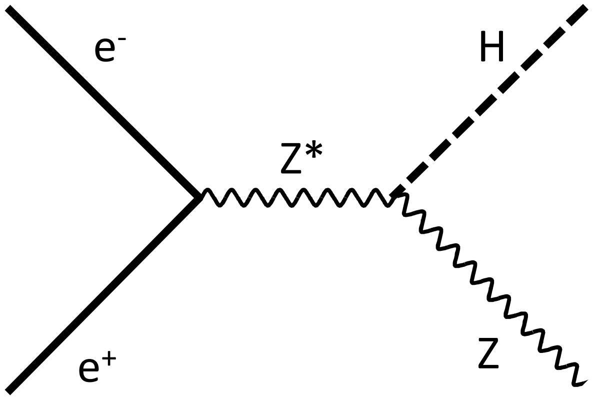
Higgs Production Mechanism in e+ e- collisions

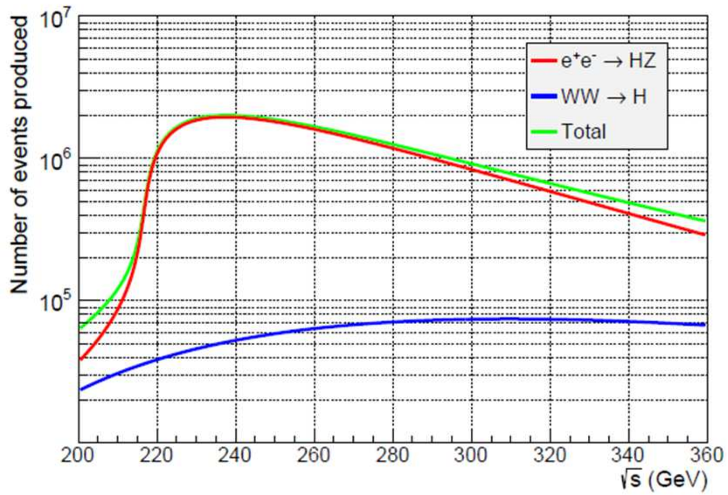
Light Higgs is produced by "Higgstrahlung" process close to threshold

Production xsection has a maximum of ~200 fb

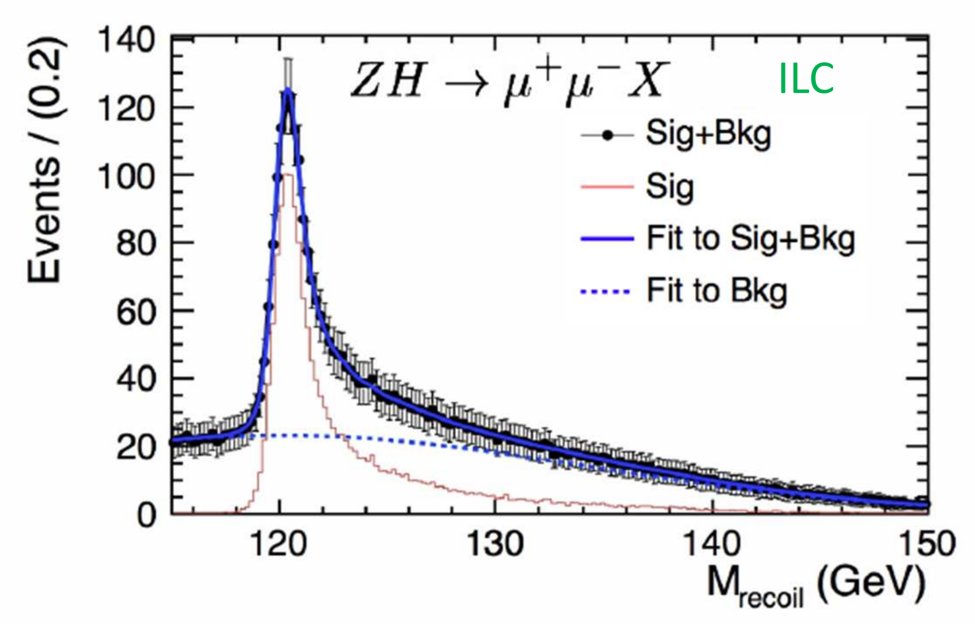
TLEP: 2. 10^{35}/cm^2/s ➔ 400'000 HZ events per year (2 million Higgses in 5 years)

Z – tagging by missing mass



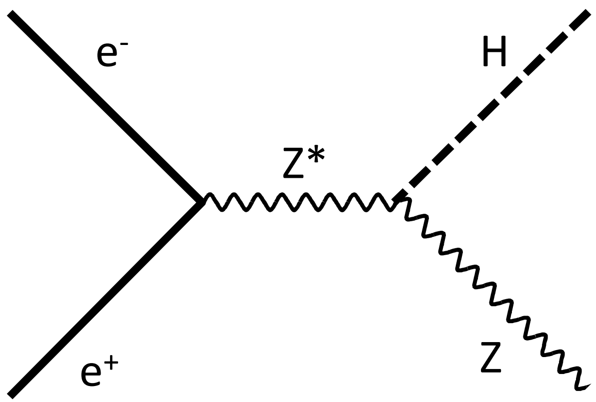


For a Higgs of 125GeV, a centre of mass energy of 240GeV is sufficient
➔ kinematical constraint near threshold for high precision in mass, width, selection purity



Z – tagging by missing mass

total rate $\propto g_{HZZ}^2$
ZZZ final state $\propto g_{HZZ}^4 / \Gamma_H$
➔ measure total width Γ_H
empty recoil = invisible width
'funny recoil' = exotic Higgs decay
easy control below theshold



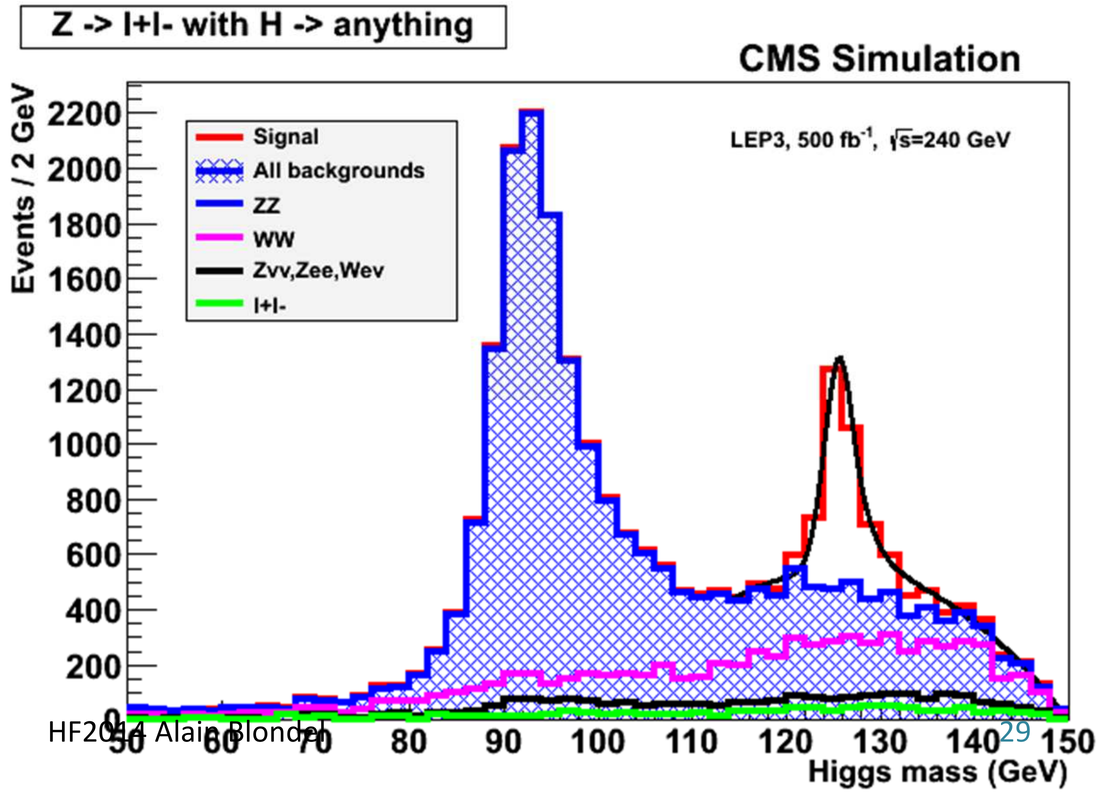


Table 1-20. *Expected precisions on the Higgs couplings and total width from a constrained 7-parameter fit assuming no non-SM production or decay modes. The fit assumes generation universality ($\kappa_u \equiv \kappa_t = \kappa_c$, $\kappa_d \equiv \kappa_b = \kappa_s$, and $\kappa_\ell \equiv \kappa_\tau = \kappa_\mu$). The ranges shown for LHC and HL-LHC represent the conservative and optimistic scenarios for systematic and theory uncertainties. ILC numbers assume (e^-, e^+) polarizations of $(-0.8, 0.3)$ at 250 and 500 GeV and $(-0.8, 0.2)$ at 1000 GeV. CLIC numbers assume polarizations of $(-0.8, 0)$ for energies above 1 TeV. TLEP numbers assume unpolarized beams.*

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%	3.8%	2.3%	$-/5.5/<5.5\%$	1.45%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%	1.3%	0.72%	$3.5/1.4/<1.3\%$	0.51%
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

many comparisons in Snowmass report.

bottom line: FCC-ee + FCC-hh (for ttH, ttZ and HHH) cover couplings very well!

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%	$< 0.19\%$			

baseline ILC

Invisible width is unique feature of lepton collider at 240 GeV
HIGH LUMINOSITY + PRECISE KNOWLEDGE OF SPECTRUM

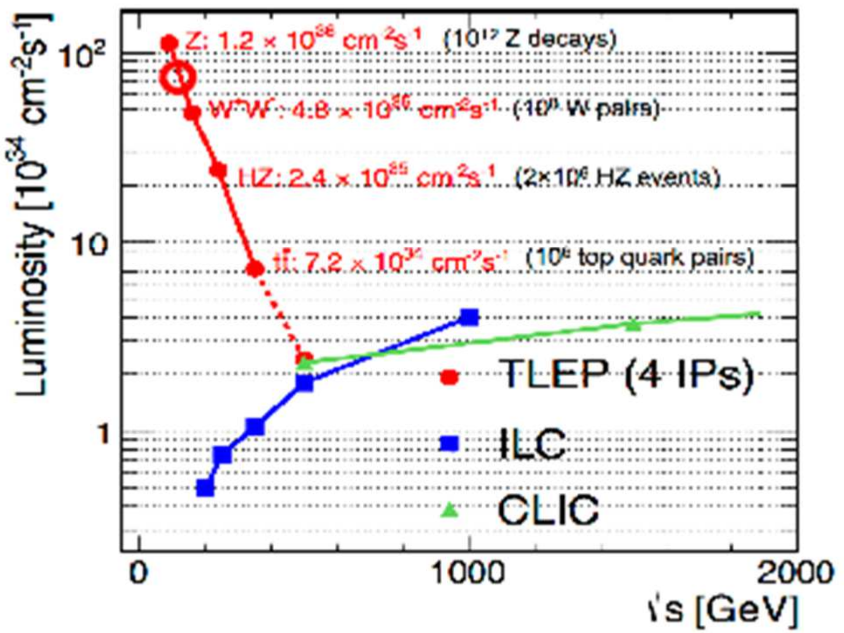
For those who like challenges:
Higgs s-channel production at $\sqrt{s} = m_H$

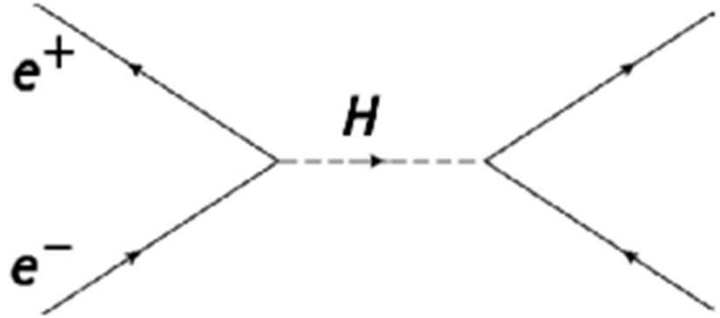
- Resonant Higgs production considered so far only for muon collider:
  $\sigma(\mu\mu \to H) \sim 70$ pb. Tiny g_{Hee} Yukawa coupling $\Rightarrow$ Tiny $\sigma(ee \to H)$

$$\frac{g_{H\mu\mu}}{g_{Hee}} \propto \frac{m_\mu^2}{m_e^2} = 4.28 \times 10^4$$

BR($H \to e^+e^-$)~$5.3 \cdot 10^{-9}$ (decay unobservable)

$$\sigma(e^- e^- \to H) = \frac{4\pi\Gamma_H^2 Br(H \to e^+e^-)}{(\hat{s} - M_H^2)^2 + \Gamma_H^2 M_H^2} \sim 1.64 \text{ fb } (m_H = 125 \text{ GeV}, \Gamma_H = 4.2 \text{ MeV})$$

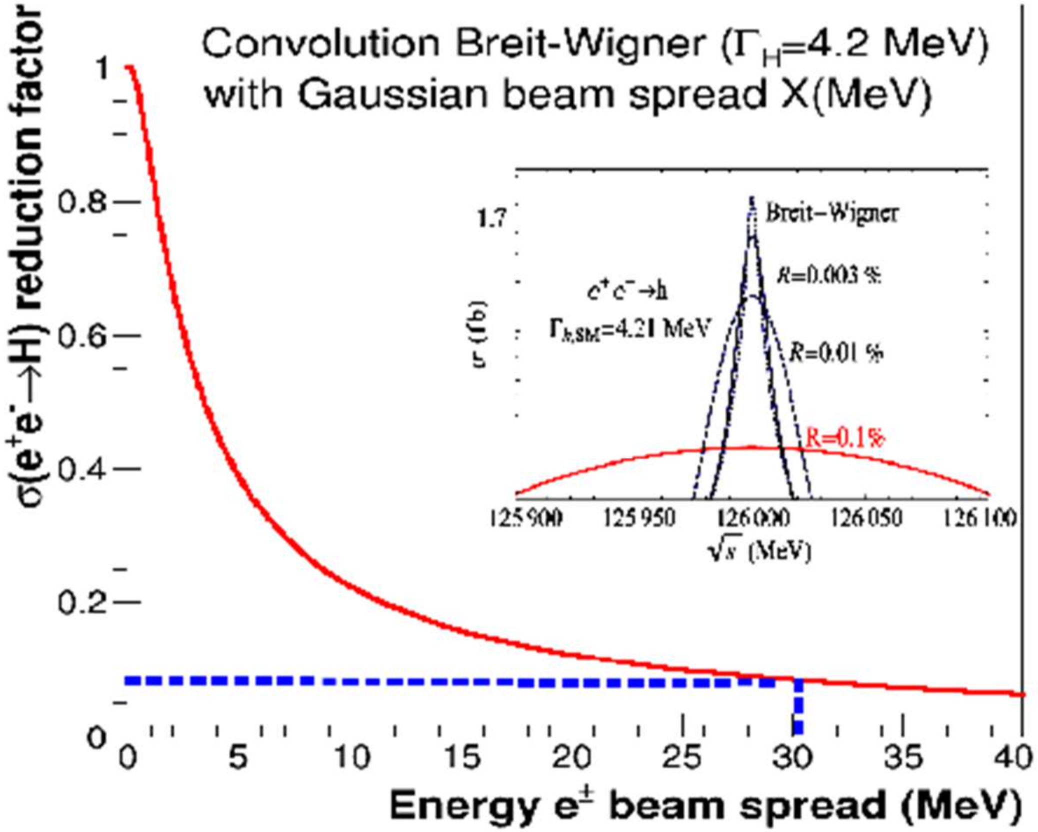




In theory, with L_{int}~6 ab-1 (4 exps./year)
FCC-ee running at H pole mass
➔ 10^4 events per year.
Very difficult because huge background
and beam energy spread ~ 10 x Γ_H
limits or signal? monochromators?
Aleksan, D'Enterria, Woijcik

$e^+e^- \to H$ x-section: Beam energy spread

- $\sigma(e^+e^- \to H)$ considered so far is for B.-W. with natural 4.2 MeV width...
- Convolution of increasing Gaussian energy spread of each $e^\pm$ beam with Higgs B.W. results on a (Voigtian) effective cross-section decrease:



$E_{spread} \sim \Gamma_H \sim$ 4.2 MeV:
Reduction factor: 45%

Current FCC-ee nominal ($\Delta E_{beam}/E_{beam} \sim 0.05\%$):
$E_{spread} \sim$ 30 MeV:
Reduction factor: 8%

need to gain a factor of ~8
➔ monochromator?

Search for Rare Processes

the example of right-handed neutrinos

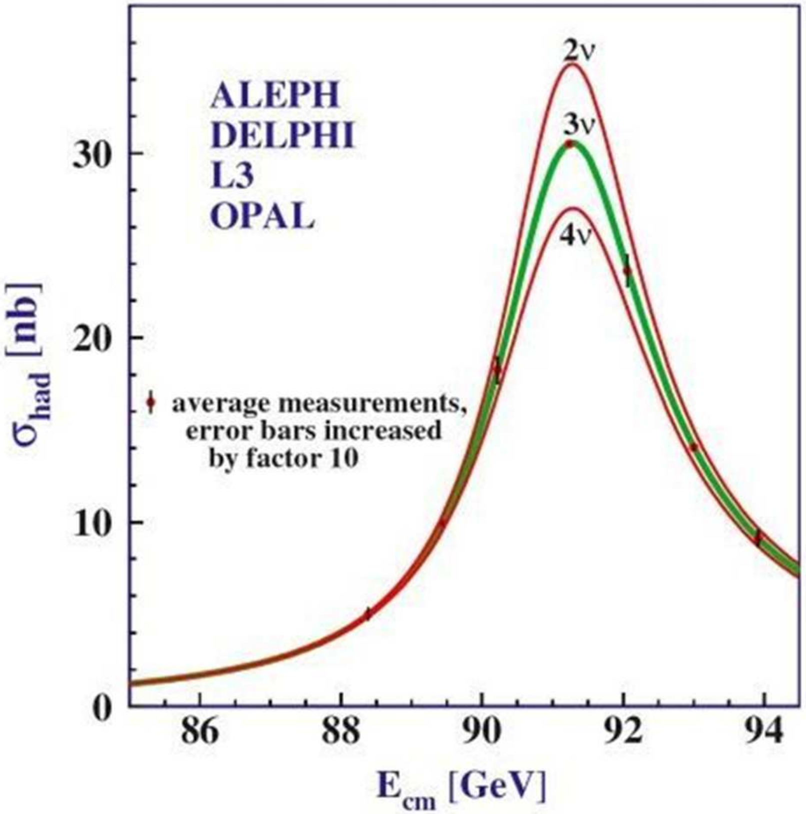
At the end of LEP:

Phys.Rept.427:257-454,2006

N_ν = 2.984 ±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!

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

above Z peak
(105-160 GeV Ecm)

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

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.

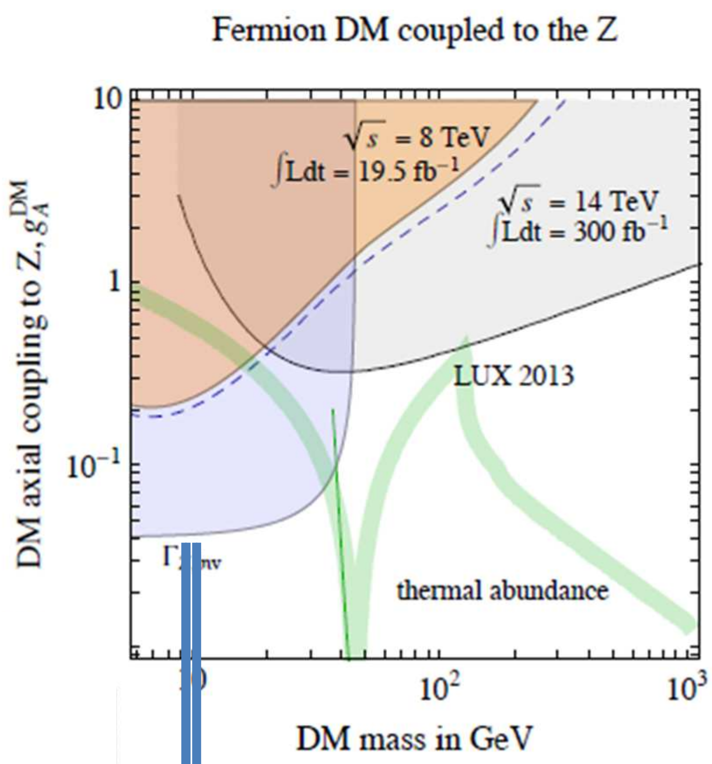
A good measurement can be made from the data accumulated at the WW threshold where σ (γ Z(inv)) ~4 pb for $|\cos\theta_\gamma| < 0.95$

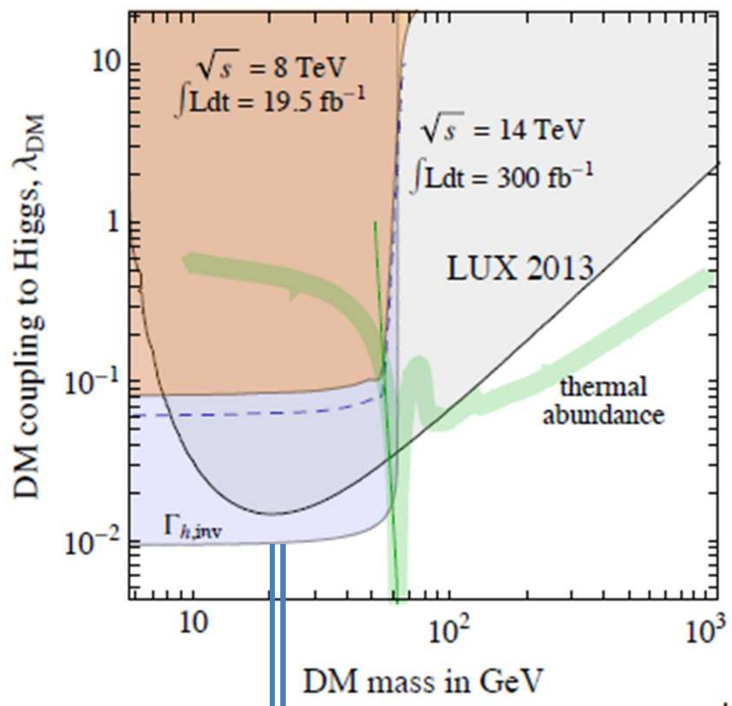
161 GeV (10^7 s) running at 1.6×10^{35}/cm^2/s x 4 exp → 3×10^7 γ Z(inv) evts, ΔN_ν=0.0011
adding 5 yrs data at 240 and 350 GeV .... ΔN_ν=0.0008

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

Γ_Z and Γ_h invisible are the most efficient way to explore SM-mediated DM at colliders

(Giudice)





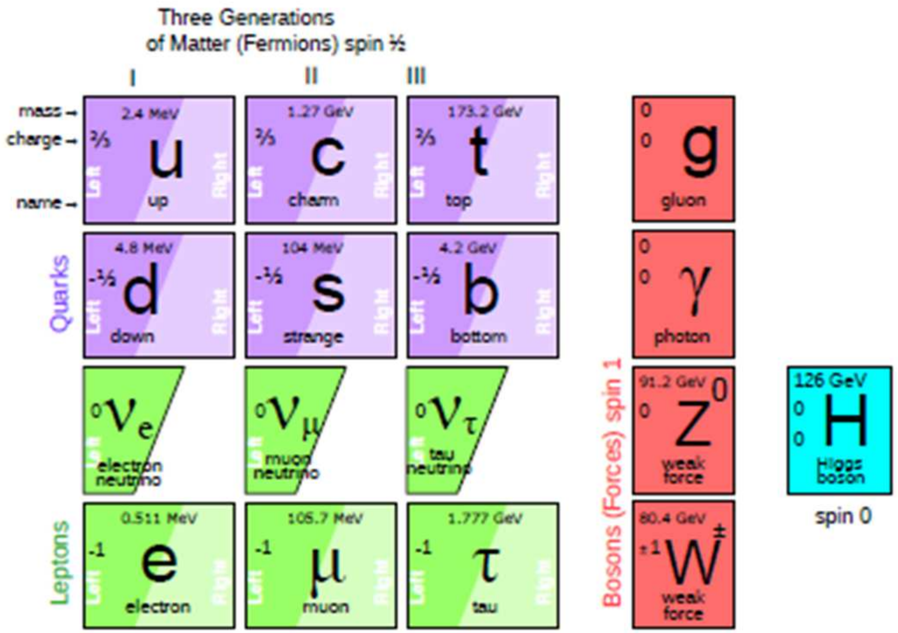
Will improve these by large factors!

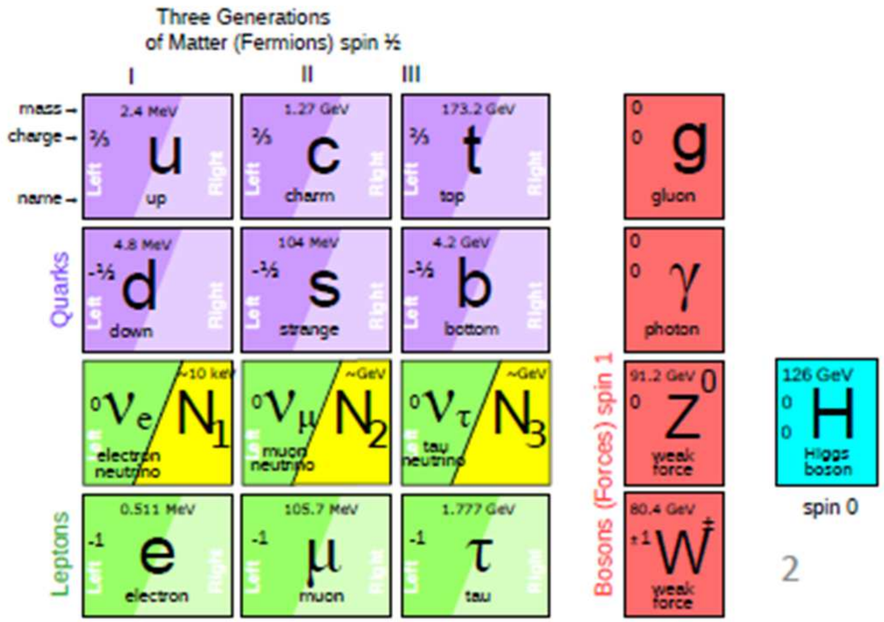
ΔN_ν = 0.0004? from e+e-→Zγ

$\Delta\Gamma_{h,inv}/\Gamma_{tot}$ <0.19%

SM is NOT complete!

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

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

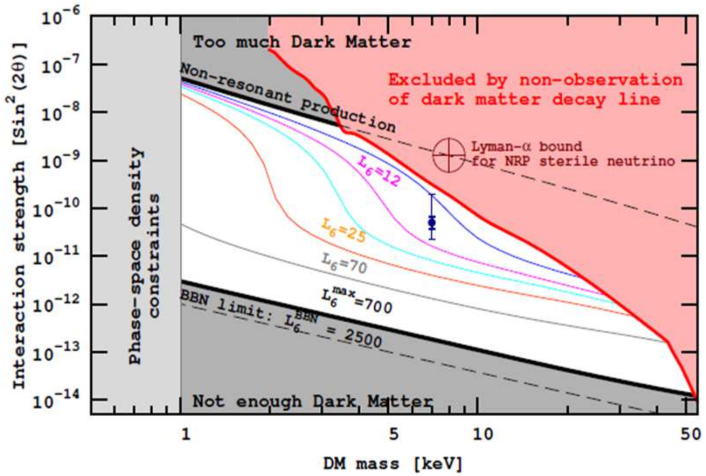
N_2, N_3

N_1

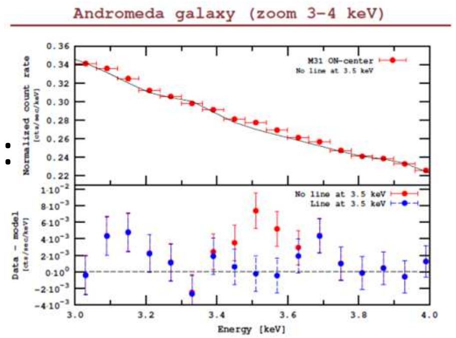
ν_3
ν_2
ν_1

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

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



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 $H \rightarrow \nu_i \bar{N}_i$ and $Z \rightarrow \nu_i \bar{N}_i$, $W \rightarrow l_i \bar{N}_i$
- ➔ also in charm and b decays via $W^* \rightarrow l_i \bar{N}_i$
- ➔ 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)

Direct RH nu's production in Z decays

Production:

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

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

Decay

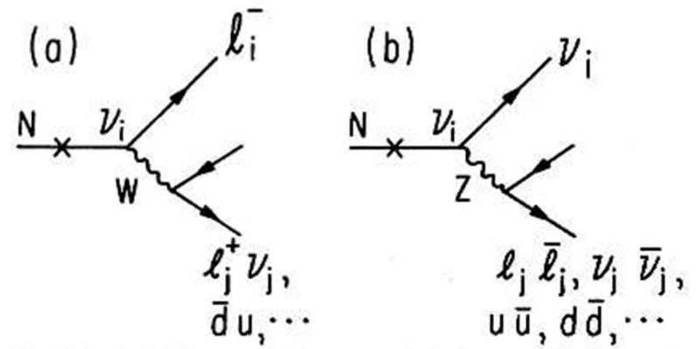


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

Decay length:

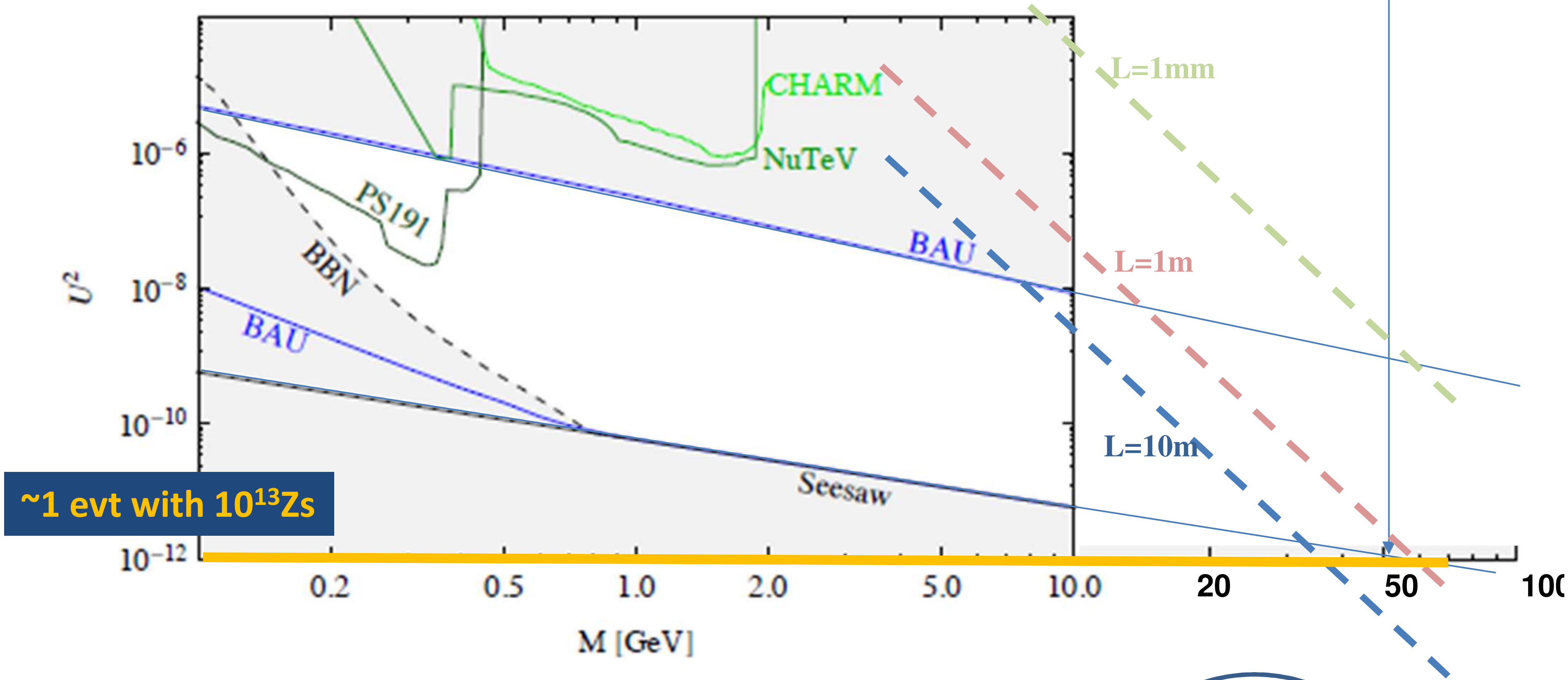
$$L \approx \frac{3 \text{ cm}}{|U|^2 \left(m_{\nu_m}(\mathrm{GeV}/c^2)\right)^6}$$

NB CC decay always leads to ≥ 2 charged tracks

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

Decay length

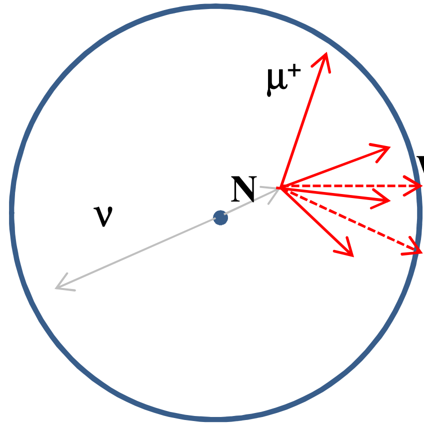
Interesting region
$|U|^2 \sim 10^{-9}$ to 10^{-12} @ 50 GeV



heavy neutrino mass ~ M

a large part of the interesting region will lead to detached vertices

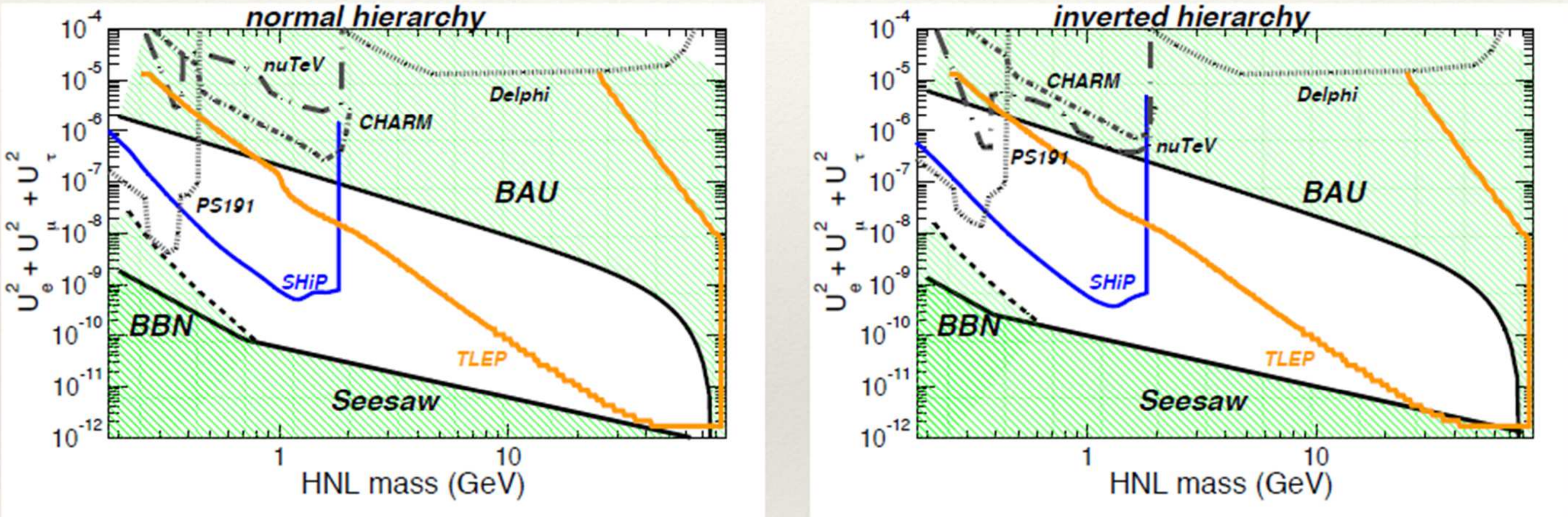
… → very strong reduction of background!



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

Sensitivity assuming zero background

Let's start with the most optimistic scenario, i.e. the maximum region we can probe



This should be considered the maximum sensitivity managing to go to zero background in the region 100um and 5m with 10^{13} Z^0

Complementarity

Proposed physics topics to be used in the study of **synergy/complementarity** among experiments **at FCC-hh/ee/eh**

Subject		ee	hh	he
Higgs Physics	precision studies higher dimension operators composite Higgs rare and exotic decays multiple Higgs production extra Higgs bosons			
Interface with Cosmology	Dark matter baryogenesis right-handed/(almost) sterile neutrinos			
Electroweak Sym. Breaking	WW scattering supersymmetry extra dimensions composite models			
Flavour Changing	rare H,Z,W,top decays lepton flavor violation			
Extensions of the SM	extra vector-like fermions $SU(2)_R$ models leptoquarks			
QCD	Perturbation theory, structure functions Modelling final states			
EW/SM precision issues	precision measts ($m_Z, m_W, m_t, \alpha, \alpha_s(m_Z), \sin^2\theta_W, R_b$... higher-order EW corrections W,Z triple and quadruple couplings top (anomalous) couplings charm/bottom flavor studies			

What we **believe** now and hope to **demonstrate** in a few years:

The combination of the FCC machines offers outstanding discovery potential by exploration of new domains of
-- precision
and
-- direct search, both at high energy and at very small couplings

CONCLUSIONS

-- FCC-ee physics studies are in construction phase
for software, event generators, etc.. no results yet.
-- contacts with linear collider groups positive

-- high luminosity FCC-ee offers real opportunities for discovery

-- precision measurements
-- rare processes (FCNCs, LFV, heavy neutrinos, etc..)

-- Circular Collider complex (ee, hh, eh) is a fantastic
story in the making!

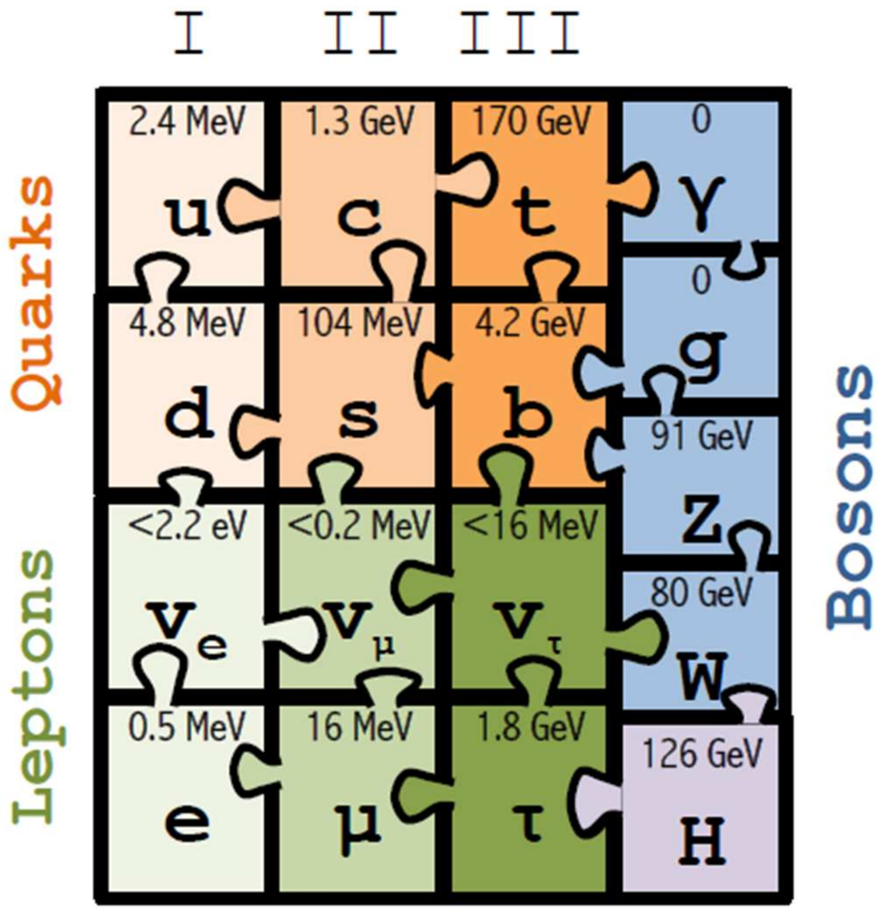
Let’s go for it!

1964-2013 Higgs boson predicted,

mass cornered (LEP direct, indirect M_Z etc +Tevatron m_t , M_W)

Higgs Boson discovered (LHC)

Englert and Higgs get Nobel Prize



(c) Sfyrla

FCC Kick-off Meeting

341 registered participants

FCC Coordination Team

Future Circular Colliders - Conceptual Design Study
Study coordination, M. Benedikt, F. Zimmermann

Hadron collider	Hadron injectors	e+ e- collider and injectors	Infrastructure, cost estimates	Technology	Physics and experiments
D. Schulte	**B. Goddard**	**J. Wenninger**	**P. Lebrun**	High Field Magnets **L. Bottura**	Hadrons **A. Ball, F. Gianotti, M. Mangano**
				Supercon-ducting RF **E. Jensen**	e+ e- **A. Blondel J. Ellis, P. Janot**
e- p option Integration aspects **O. Brüning**				Cryogenics **L. Tavian**	
Operation aspects, energy efficiency, safety, environment **P. Collier**				Specific Technologies **JM. Jimenez**	e- p **M. Klein**

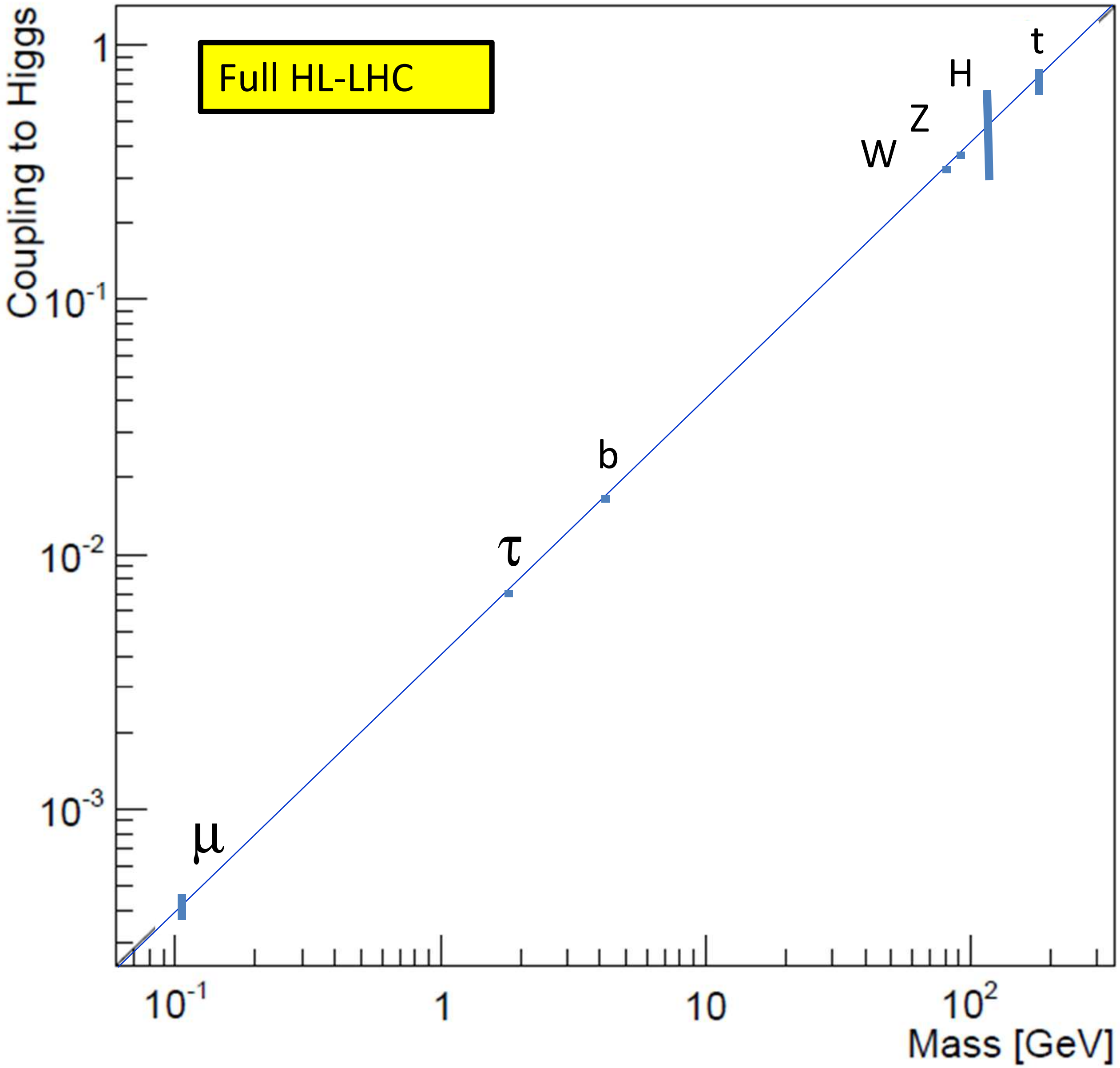
Planning (Implementation roadmap, financial planning, reporting)
F. Sonnemann, J. Gutleber

FCC-PHYSics-COordination-group

FCC-ee
Alain Blondel
John Ellis
Christophe Grojean
Patrick Janot

FCC-hh
Austin Ball
Fabiola Gianotti
Michelangelo Mangano

FCC-he
Max Klein
Monica d'Onofrio


Full HL-LHC
Coupling to Higgs
1
10^{-1}
10^{-2}
10^{-3}
t
H
Z
W
b
τ
μ
10^{-1}
1
10
10^{2}
Mass [GeV]

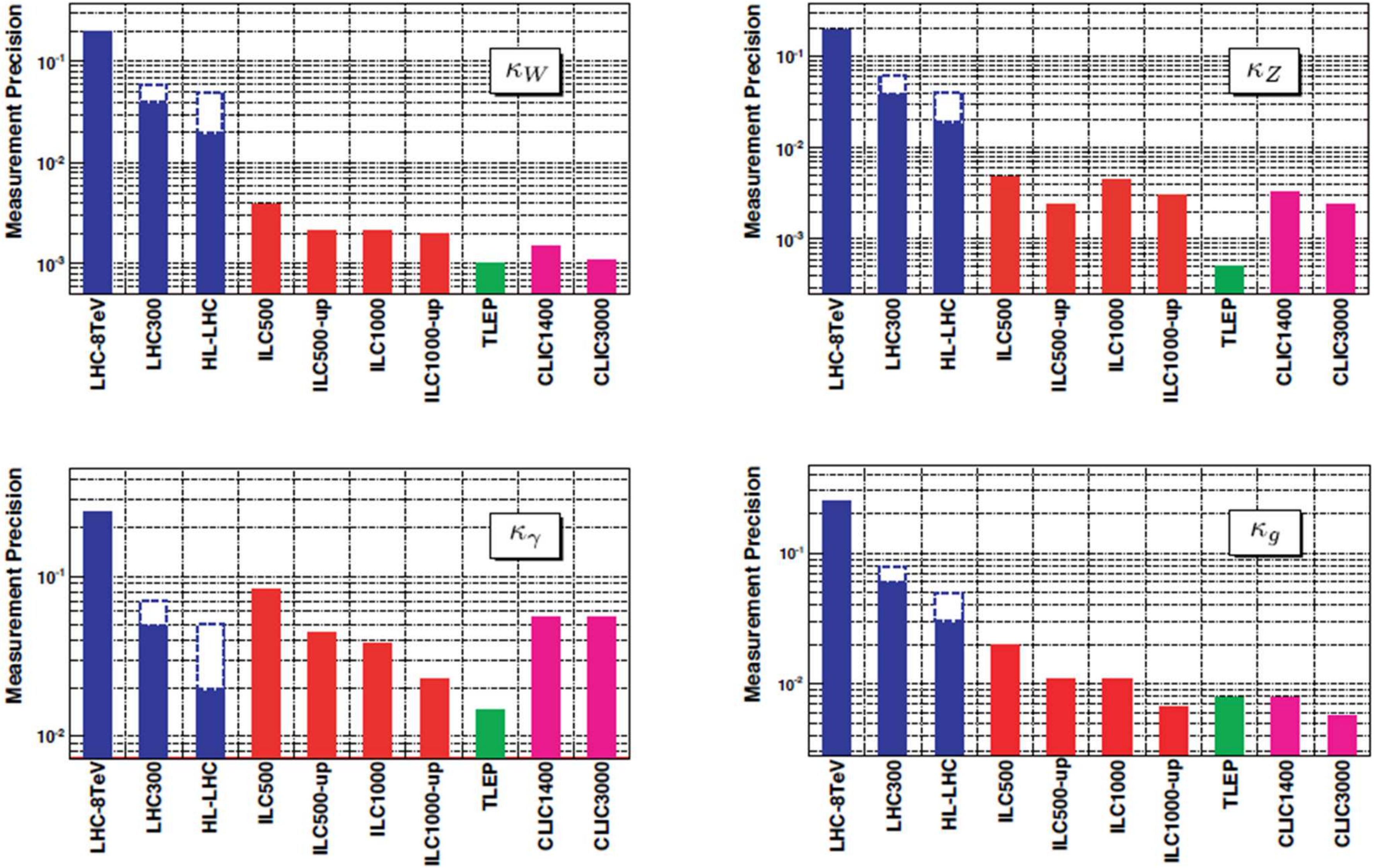


Figure 1-3. *Measurement precision on κ_W, κ_Z, κ_γ, and κ_g at different facilities.*

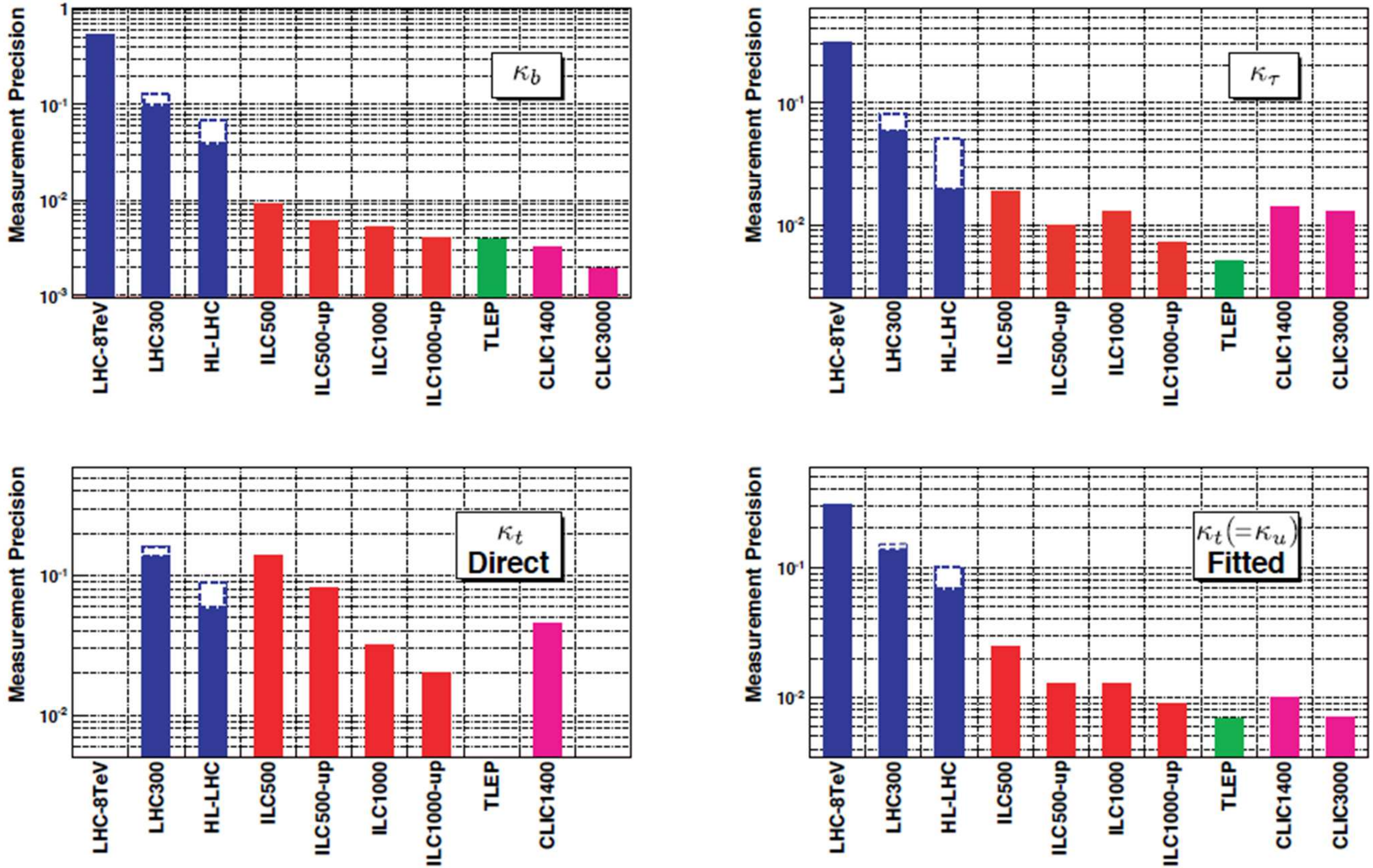
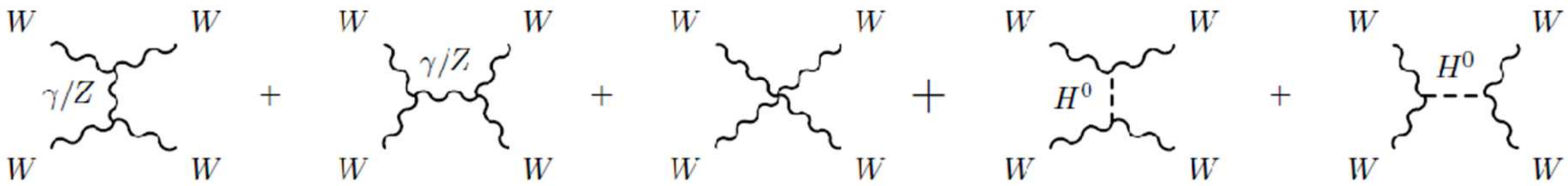


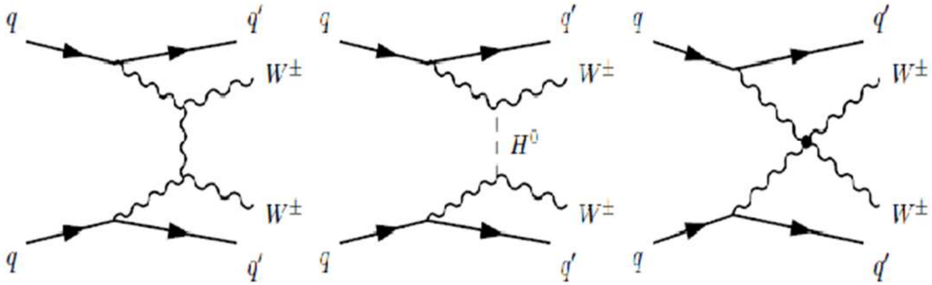
Figure 1-4. *Measurement precision on κ_b, κ_τ, and κ_t measured both directly via $t\bar{t}H$ and through global fits at different facilities.*

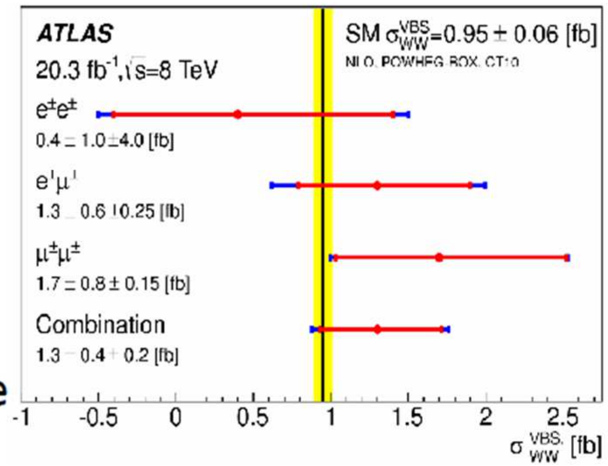
Vector boson scattering (VBS) WW → WW

SM electroweak symmetry breaking with Higgs essential to preserve VBS cross section unitarity



Same-sign WW VBS production provides attractive S/B at LHC





3.6σ significance

Experimental Highlights, Young-Kee Kim, University of Chicago — ICHEP 2014, Valencia, July 2-9, 2014

This will remain the reserved domain of the hadron colliders with HL-LHC and FCC-hh!

The main players

Inputs:

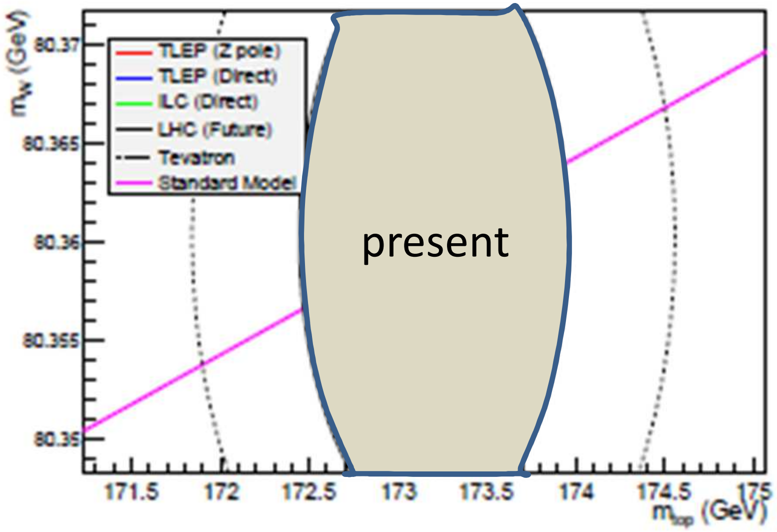
$G_F = 1.1663787(6) \times 10^{-5}$ /GeV^2	from muon life time	**$6\ 10^{-7}$**
$M_Z = 91.1876 \pm 0.0021$ GeV	Z line shape	**$2\ 10^{-5}$**
$\alpha = 1/137.035999074(44)$	electron g-2	**$3\ 10^{-10}$**

EW observables sensitive to new physics:

$M_W = 80.385 \pm 0.015$	LEP, Tevatron	**$2\ 10^{-4}$**
$\sin^2\theta_W^{eff} = 0.23153 \pm 0.00016$	WA Z pole asymmetries	**$7\ 10^{-4}$**

Nuisance parameters:

$\alpha\ (M_Z) = 1/127.944(14)$	**hadronic corrections** to running alpha	**$1.1\ 10^{-4}$**
$\alpha_S\ (M_Z) = 0.1187(7)$	strong coupling constant	**$7\ 10^{-3}$**
m_{top} $= 173.34 \pm 0.76$ GeV	from LHC+Tevatron combination	**$4\ 10^{-3}$**
m_H = ATLAS 125.36 ± 0.37 (stat) ± 0.18 (syst) GeV; CMS 125.03 ± 0.26 (stat) ± 0.14 (syst) GeV	***125.17 ± 0.25***	**$2\ 10^{-3}$**



Precision measurements as tests of existence of weakly coupled new physics

🡐 'classical' precision measurements
+ flavour physics + Higgs precision measts

Thickness of SM line
is given by error on m_Z:
precise measurements of m_Z
and m_W

➔ Energy calibration by resonnant depolarization

- Higher-dimensional operators as relic of new physics ?
  - Possible corrections to the standard model

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

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

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

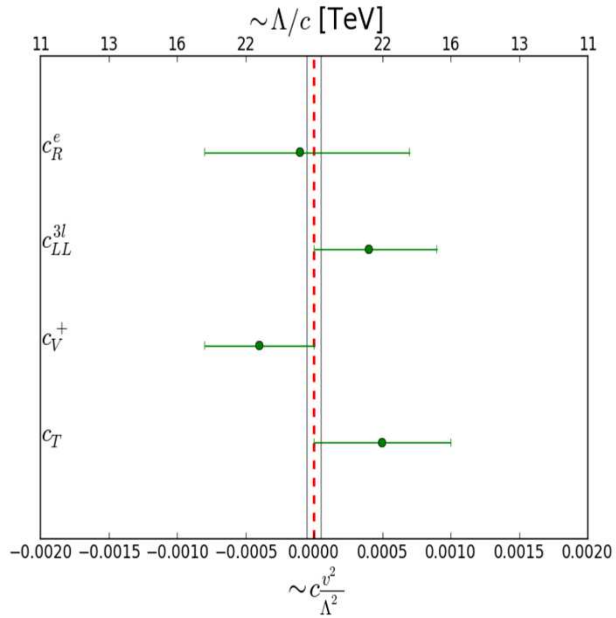
$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$

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

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

LEP constraints: $\Lambda_{NP} > 10$ TeV

After FCC-ee: $\Lambda_{NP} > 100$ TeV ?



Sensitivity to Weakly coupled NP

Theoretical limitations

FCC-ee

R. Kogler, Moriond EW 2013

SM predictions (using other input)

$$M_W = 80.3593 \pm 0.0005_{m_t} \pm 0.0001_{M_Z} \pm 0.0005?_{\Delta\alpha_{\rm had}}$$
$$\pm 0.0005?_{\alpha_S} \pm 0.0000_{M_H} \pm 0.0040_{\rm theo}$$
$$= 80.359 \pm 0.011_{\rm tot}$$

0.0005
- 0.001

$$\sin^2\theta^{\ell}_{\rm eff} = 0.231496 \pm 0.000003_{m_t} \pm 0.000001_{M_Z} \pm 0.000003?_{\Delta\alpha_{\rm had}}$$
$$\pm 0.000001?_{\alpha_S} \pm 0.000000_{M_H} \pm 0.000047_{\rm theo}$$
$$= 0.23150 \pm 0.00010_{\rm tot}$$

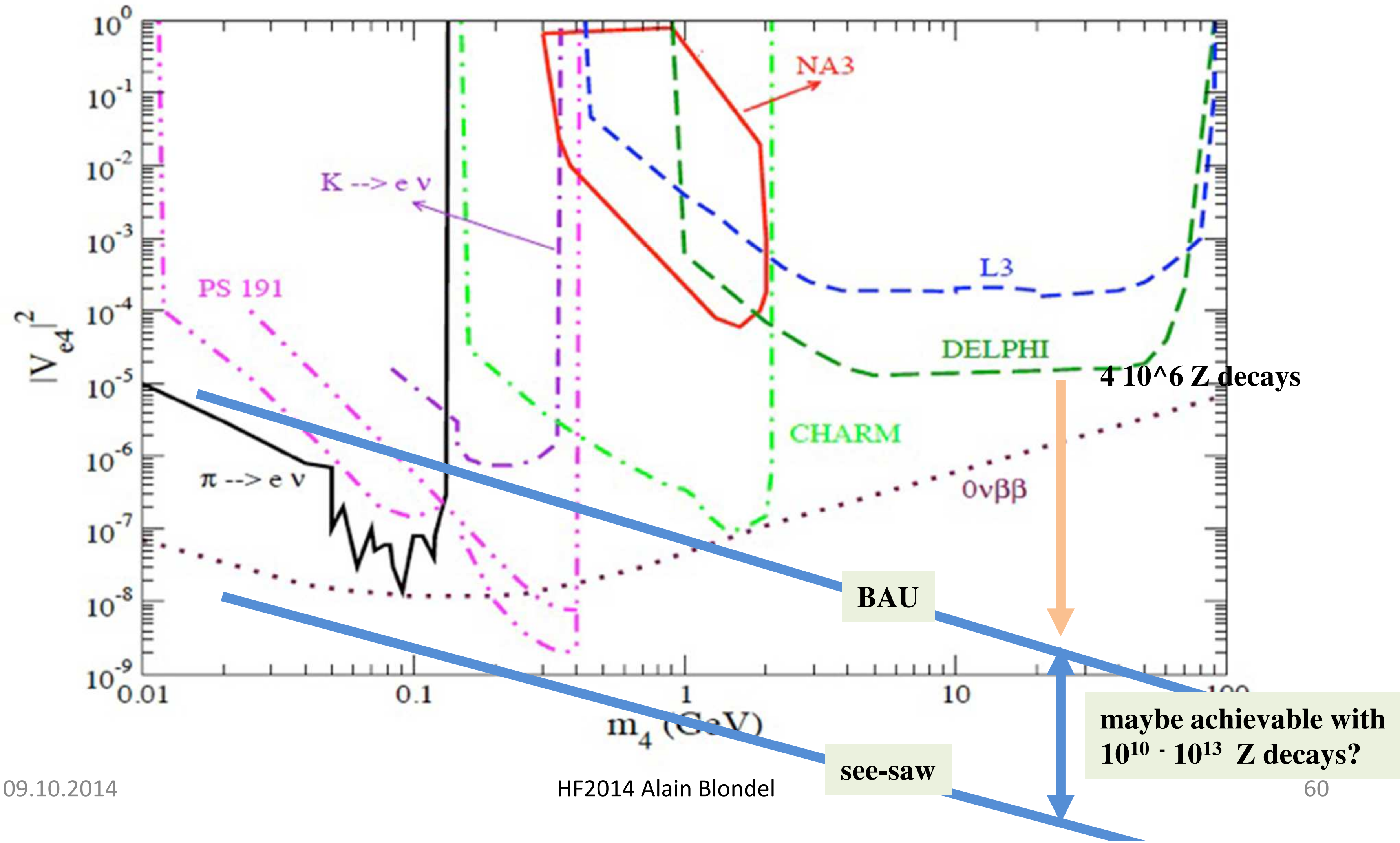
0.000002

Experimental errors at FCC-ee will be 20-100 times smaller than the present errors.

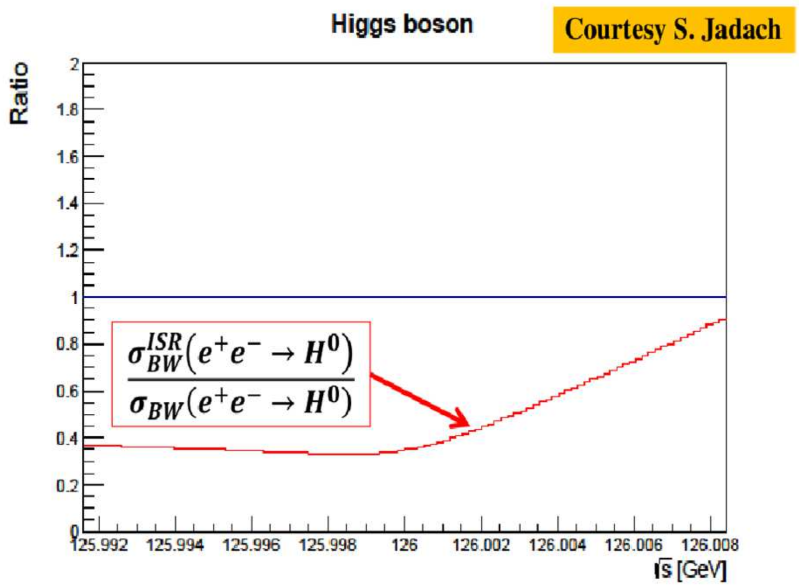
BUT can be typically 10 -30 times smaller than present level of <u>theory errors</u>

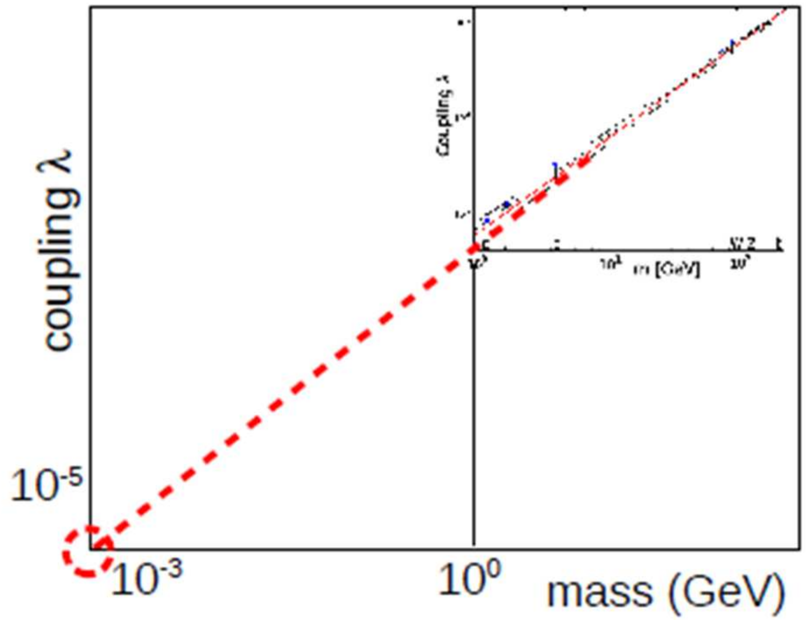
<u>Will require significant theoretical effort and additional measurements!</u>

Order-of-magnitude extrapolation of existing limits



- Extra ~40% reduction in $\sigma(e^+e^-\to H)$ due to initial state radiation:





- **Thanks to high FCC-ee luminosity at low energies:**
- **Preliminary event selections lead to sensitivity at ~ x SM cross-section**
- **linearity test of H→ ff couplings extended by doubling the orders of magnitude**
- **study on-going: monochromators, better selections, etc...**

Search for heavy neutral leptons

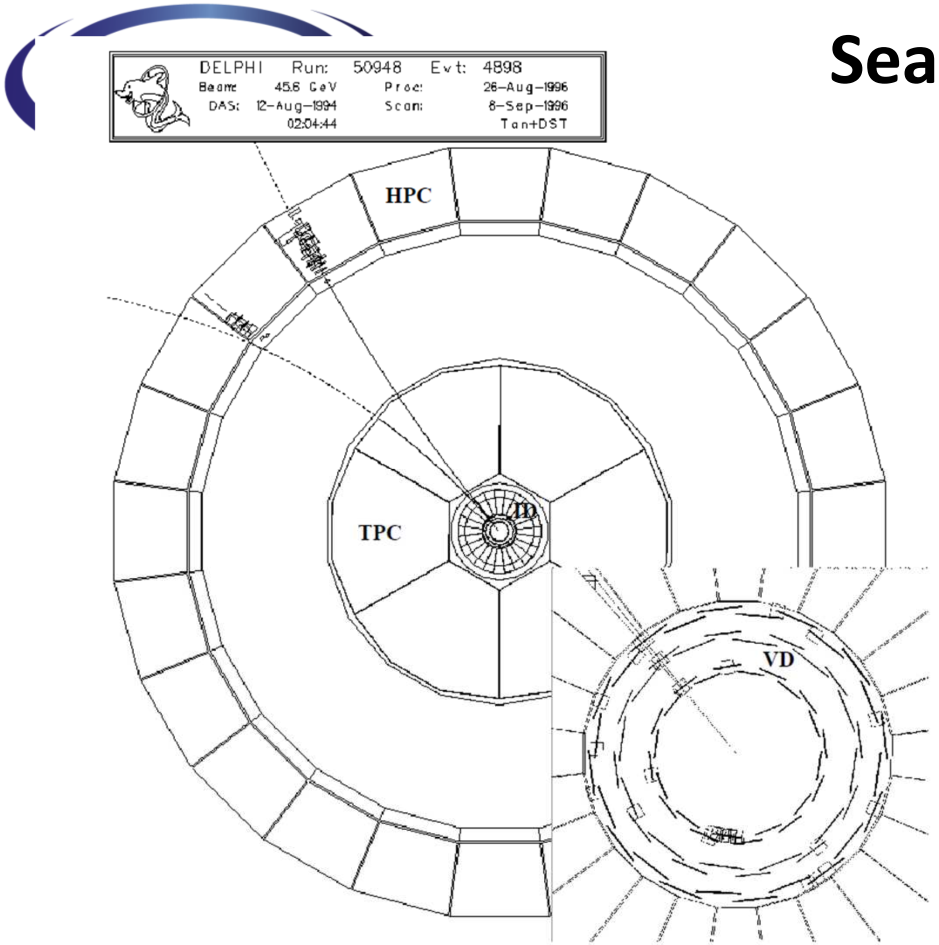


Fig. 3. Surviving event in the monojet search. It has an invariant mass of 300 MeV/c^2 and a missing p_t of 6 GeV/c and is probably an $e^+e^- \to e^+e^-\nu\bar{\nu}$ interaction

search $e^+ e^- \to \nu$ N

N $\to \nu(\gamma/Z)^* \to$ monojet

Find: one event in 4×10^6Z:

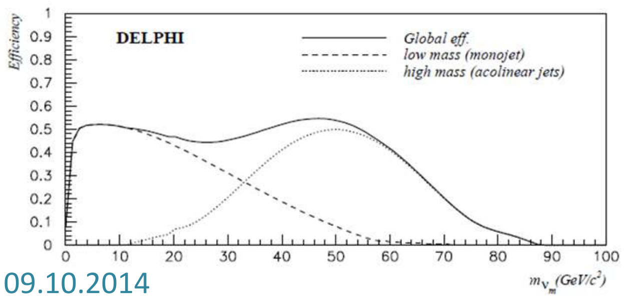
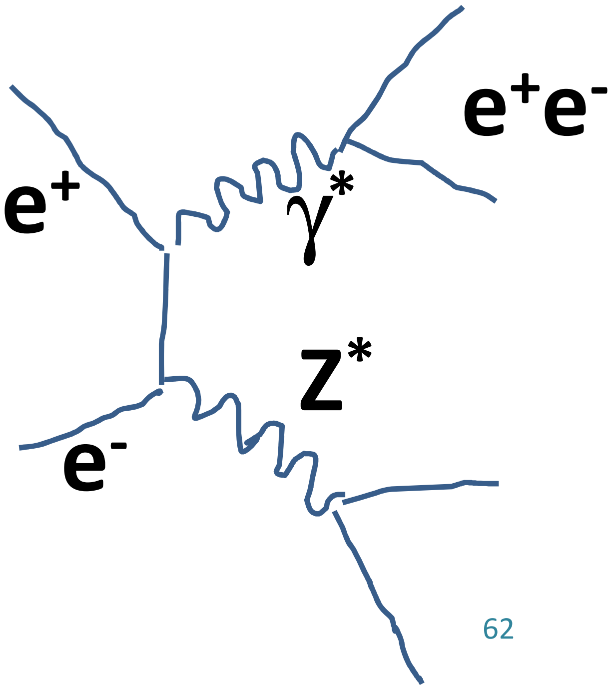


Fig. 4. Efficiency of the monojet search (Sect. 3) and the acolinear jets search (Sect. 4). The full curve shows the efficiency of the two searches combined



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

theories of the electroweak strong interactions. At presen

and mixings with ordinary neutrinos of these leptons are v

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]

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

M. Bicer, H. Duran Yildiz, I. Yildiz, G. Coignet, M. Delmastro, T. Alexopoulos, C. Grojean, S. Antusch, T. Sen, H.-J. He, K. Potamianos, S. Haug, A. Moreno, A. Heister, V. Sanz, G. Gomez-Ceballos, M. Klute, M. Zanetti, L.-T. Wang, M. Dam, C. Boehm, N. Glover, F. Krauss, A. Lenz, M. Syphers,

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 Shaposhni

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,

Lausanne, Switzerland

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

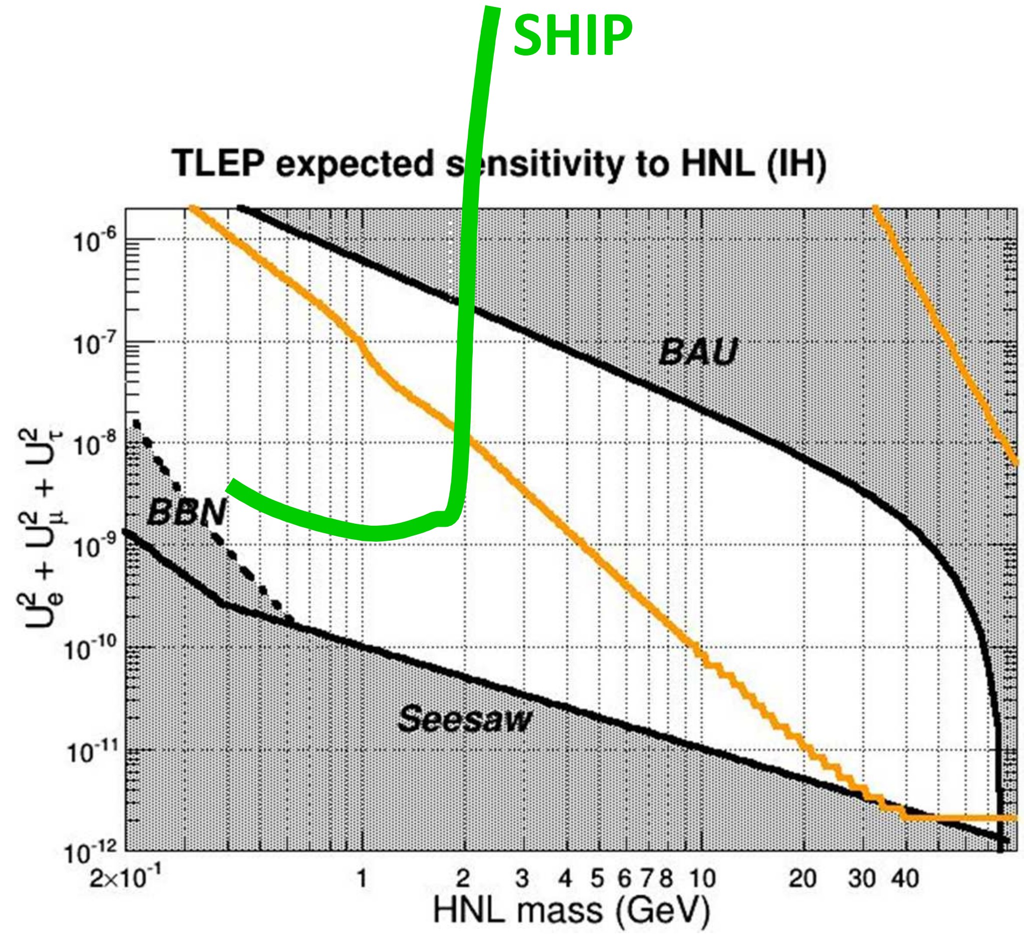
Preprint typeset in JHEP style - HYPER VERSION

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



$N_Z = 10^{13}$ 100μm <L<5m

Elena Graverini, Nicola Serra