Prospects and challenges for future ee and ep colliders

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Outline

⇛ Future e^+e^- colliders.

- ILC
- CLIC
- FCCee,eh

⇛ Detector

⇛ Physics program:

- Higgs program.
- Z pole program.
- *WW* program.
- $t\bar{t}$ program.
- Neutrino program.

Quo Vadis HEP?

What has LHC found...

$\Rrightarrow$ A Higgs boson.

$$m_H = 125\ \mathrm{GeV}$$
$$\Gamma_H = 4.1\ \mathrm{MeV}$$

... and what is still missing.

$\Rrightarrow$ Dark matter/energy?

$\Rrightarrow$ Neutrino masses?

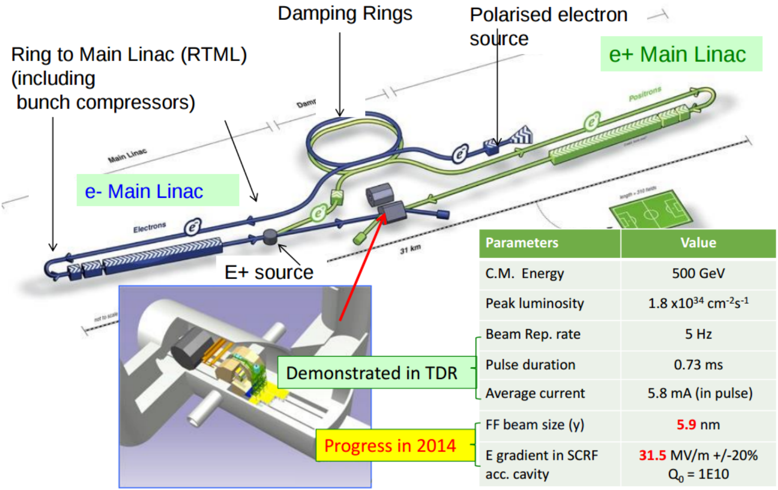
$\Rrightarrow$ Matter/antimatter asymmetry?

$\Rrightarrow$ LHC has ongoing physics program...

- Run 2 +3: 300 by 2023
- HL-HLC: 3000 by 2035

$\Rrightarrow$ But what for post-LHC area? Need to plan now!

International Linear Collider (ILC)



Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} cm^{-2}s^{-1}
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
FF beam size (y)	5.9 nm
E gradient in SCRF acc. cavity	31.5 MV/m +/-20% Q_0 = 1E10

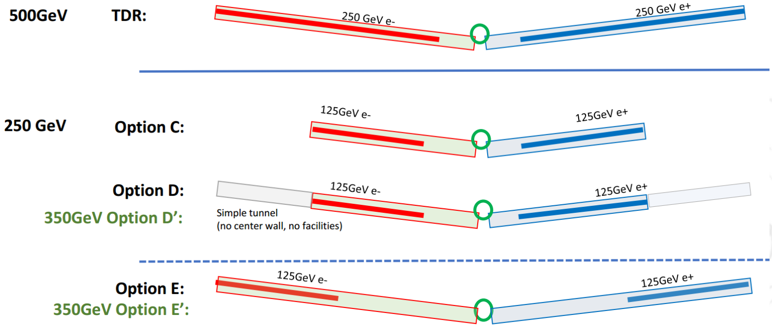
International Linear Collider (ILC)

⇛ The ILC concept was reviewed by the Japanese government.

Feedbacks (domestic only)

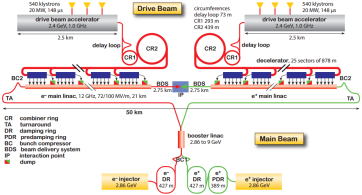
⇛ Academia in general: reserved/hostile
⇛ Funding authorities: reserved/critical
⇛ Political allies (Local/Central): enthusiastic/cautious

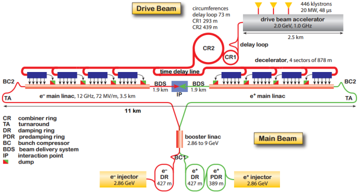
⇛ "Given the fact that the energy scale of new physics is currently unknown, the physics reach of precision Higgs and other SM probes of ILC250 are comparable to that of ILC500", Hiroaki Aihara



Compact Linear Collider (CLIC)

⇛ CLIC also wants a staged approach:





Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	$10^{34}\ \text{cm}^{-2}\text{s}^{-1}$	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	$10^{34}\ \text{cm}^{-2}\text{s}^{-1}$	0.9	1.4	2
Main tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	N	10^9	5.2	3.7	3.7

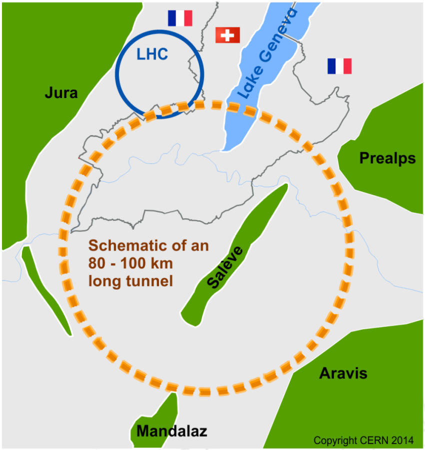
Future Circular Collider (FCC)

FCC - study:

$\Rightarrow$ pp collider: the ultimate goal.
$\Rightarrow$ ee collider: first step.
$\Rightarrow$ ep collider: additional option.

○ $98\ \mathrm{km}$ infrastructure in Geneva area

$\Rightarrow$ The Goal: CDR and cost review by the end of 2018!



12 CDR Volumes (9 + 3 Annex)

__Preliminary__ layout of CDR (work in progress)

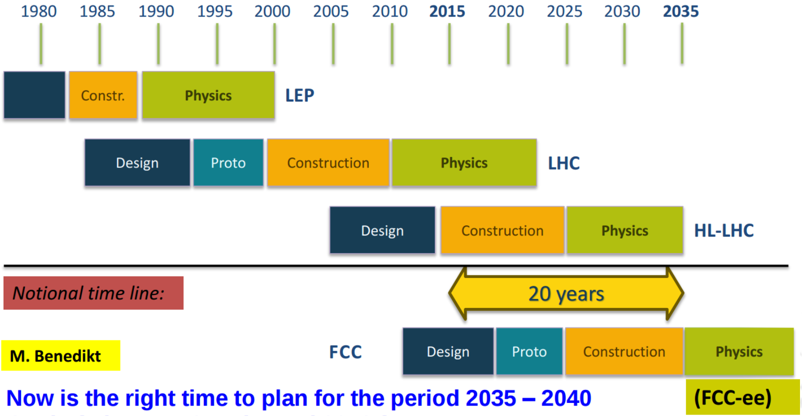
all to be printer-ready by end 2018!

FCC overview

Overview of the project.
The big physics questions and how FCC will address them.
ee,hh, AA, eh,HE physics capabilities and complementarities

M. Benedikt

Time line of FCC



Now is the right time to plan for the period 2035 – 2040
Goal of phase 1: CDR by end 2018 for next update of European Strategy

Why circular collider?

⇛ To achieve interesting physics program one would have to obtain a factor of 10^3 of LEP luminosity.
⇛ The Luminosity scales:

$$L \sim R \frac{P_{SR}}{\beta^*}$$

⇛ So how can one increase the luminosity without the electric energy cost?
⇛ The answer is inside the B-factory design!
⇛ One has to lower the beam emittance: β^*.

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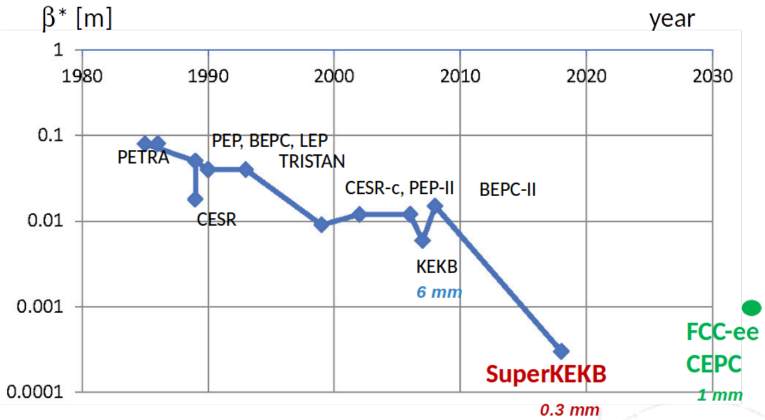
β^* over last 40 years



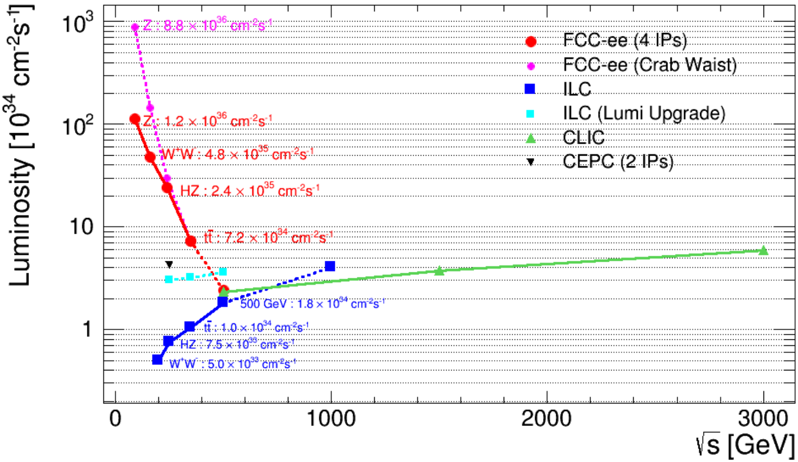
- ⇛ The β^* will be increased to $1\mathrm{mm}$ compared to $5\ \mathrm{cm}$ at LEP.
- ⇛ SuperKEKB will pave the way towards $\beta^* < 1\ \mathrm{mm}$.
- ⇛ Additional improvements to reach the 10^3 factor in lumi are:
  - Continues injection
  - More bunches

Beam parameters

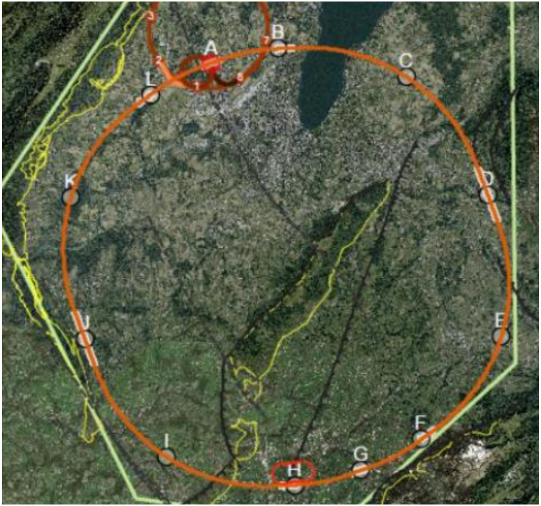
parameter	FCC-ee (400 MHz)					LEP2
Physics working point	Z		WW	ZH	$t\bar{t}$ (tt_{bar})	
energy/beam [GeV]	45.6		80	120	175	105
bunches/beam	30180	91500	5260	780	81	4
bunch spacing [ns]	7.5	2.5	50	400	4000	22000
bunch population [10^{11}]	1.0	0.33	0.6	0.8	1.7	4.2
beam current [mA]	1450	1450	152	30	6.6	3
luminosity/IP x $10^{34}cm^{-2}s^{-1}$	210	90	19	5.1	1.3	0.0012
energy loss/turn [GeV]	0.03	0.03	0.33	1.67	7.55	3.34
synchrotron power [MW]	100					22
RF voltage [GV]	0.4	0.2	0.8	3.0	10	3.5

- ⇛ Identical beam optics for all energies.
- ⇛ FCC would have two separate rings
- ⇛ Detectors similar to the ILC and CLIC.

Comparison of e^+e^- colliders



FCCep

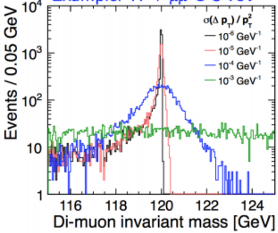


⇛ Requires additional ERL

⇛ Would be needed anyway for FCChh.

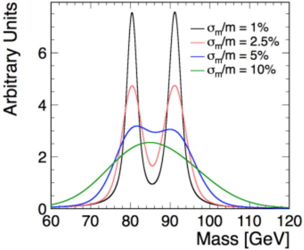
- **momentum resolution**
  - Higgs recoil mass, Higgs coupling to muons, BSM (smuon and neutralino masses)
  - for high p_T tracks

$$\boxed{\sigma_{p_T}/p_T^2 \simeq 2\times 10^{-5} GeV^{-1}}$$



- **jet energy resolution**
  - W/Z di-jet mass separation
  - jet energy up to 1 TeV

$$\boxed{\sigma_E/E \simeq 3.5\%}$$



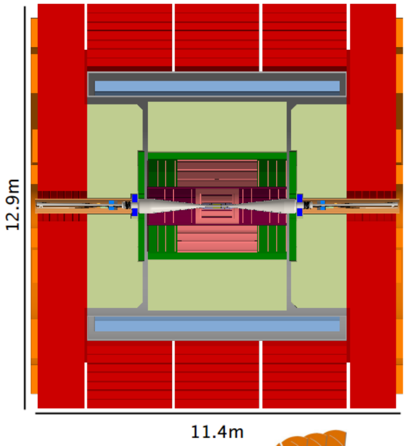
- **impact parameter resolution**
  - c/b tagging, Higgs BR

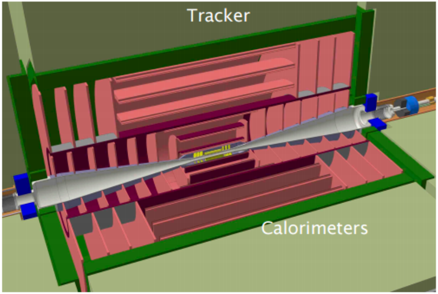
$$\boxed{\sigma_{d_0}^2 = a^2 + \frac{b^2}{p^2\sin^3\theta} \qquad a \lesssim 5\mu m \quad b \lesssim 15\mu m GeV}$$

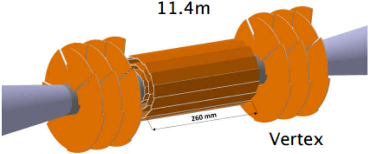
- **lepton ID efficiency** $\boxed{> 95\ \%}$
  - over full energy range

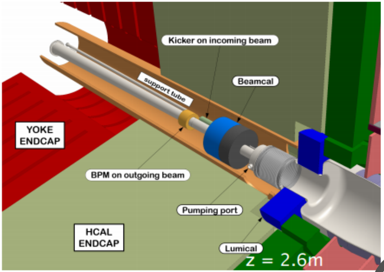
- **forward coverage**
  - electron and photon tagging (e.g. dark matter studies)

CLIC detector



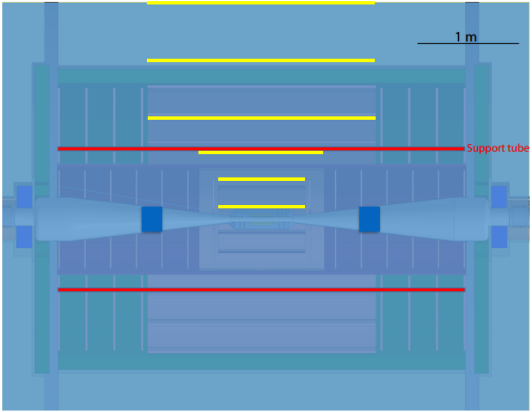






E.Leogrande

- OUTER BARREL RADIUS to be increased to 2.14 m
- to compensate for the lower B



Scale all the barrel layers*

layer radius [mm]	CLIC	FCC
ITB1	127	127
ITB2	340	400
ITB3	554	670
OTB1	819	1000
OTB2	1153	1568
OTB3	1486	2136

*layer thickness may need to be increased to accommodate more water cooling

Support tube*

radius [mm]	CLIC	FCC
inner	575	675
outer	600	700

*to be checked for mechanical stability

IDEA detector

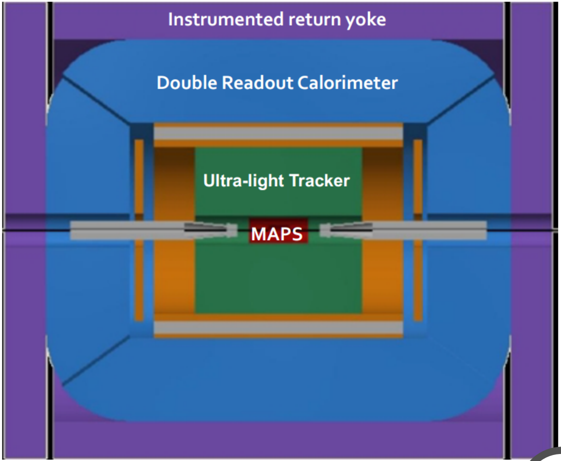
M.Dam

IDEA detector concept based on present state-of-the-art technologies:

- Vertex detector, MAPS
- Ultra-light drift chamber with PID
- Pre-shower counter
- Double read-out calorimetry
- 2 T solenoidal magnetic field
- Possibly instrumented return yoke

- Or possibly surrounded by large tracking volume (R ≃ 8m) for very weakly coupled (long-lived) particles

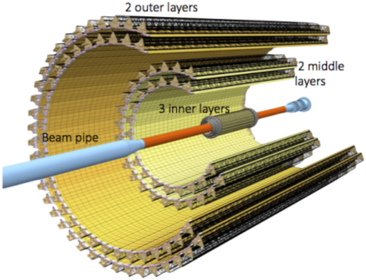
Two Options: Coil inside or outside calorimetry



Tracker

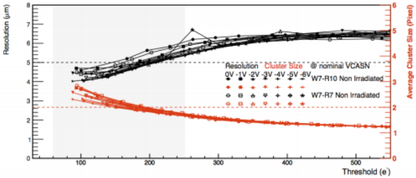
Inspired by new ALICE ITS based on MAPS technology
- Pixels 30 × 30 μm²

- Light
  - Inner layers: 0.3% of X_0 / layer
  - Outer layers: 1% of X_0 / layer
- Performance:
  - Point resolution of 5 μm (or better)
  - Efficiency of ~100%
  - Extremely low fake rate hit rate

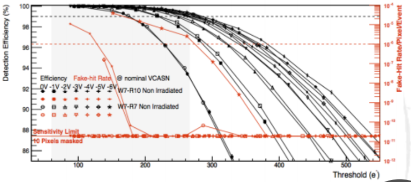


Courtesy J.W. van Hoorne

Position resolution and cluster size



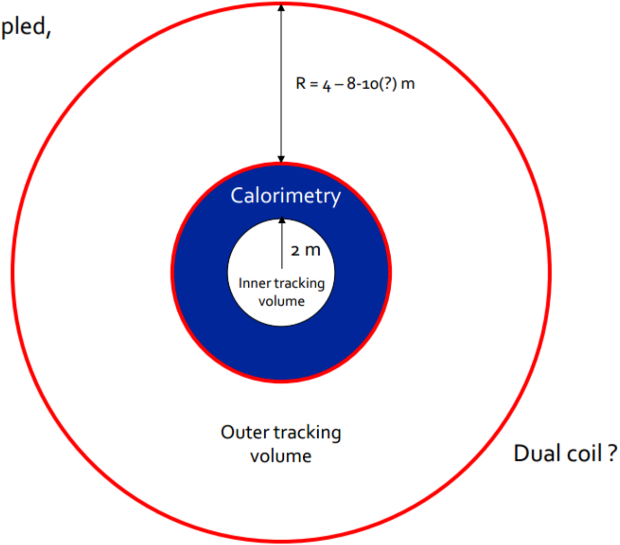
Detection efficiency and fake-hit rate



Tracker (for) the idea ;)

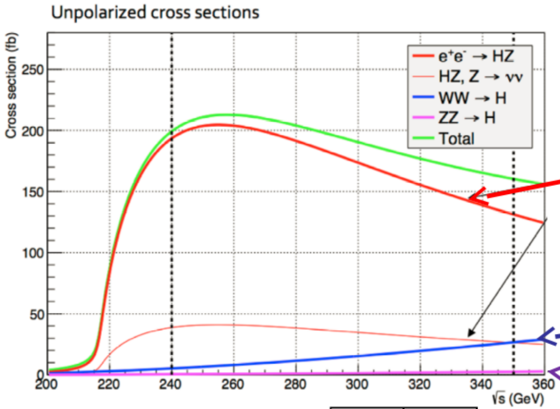
M.Dam

For weakly coupled, very long-lived particles

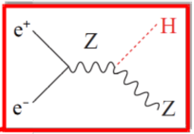


Physics program

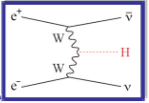
Higgs production

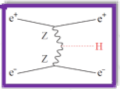


$e^+e^- \to ZH$



$e^+e^- \to \nu\bar{\nu}H$





	FCC-ee 240 GeV	FCC-ee 350 GeV
Total Integrated Luminosity (ab-1)	5	1.5
Number of Higgs bosons from $e^+e^- \to HZ$	1,000,000	200,000
Number of Higgs bosons form fusion process	25,000	40,000

Higgs Mass

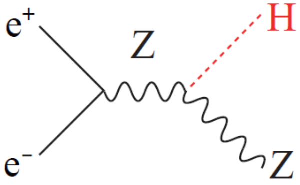
⇛ A very clean Higgs mass determination in $e^+e^- \to ZH$ and using a recoil technique (unique for lepton colliders):

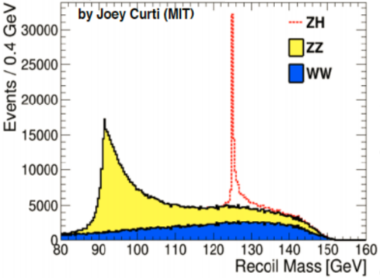
$$m_{\text{recoil}} = (\sqrt{s} - E_\mu)^2 - |p_\mu|^2$$

⇛ With $Z \to \mu\mu$ and $Z \to ee$

⇛ *ZH* decays are tagged independently of the Higgs decay mode.

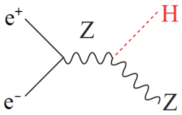
⇛ Precise measurement of g_{HZZ}:





Higgs Width

⇛ Higgs-strahlung.



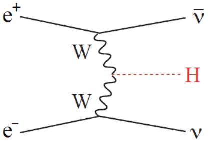
⇛ Total HZ crossection:

$\sigma(HZ) \propto g_{HZZ}^2$

⇛ Exclusive cross section:

$\sigma(HZ) \times Br(H \to XX) \propto g_{HZZ}^2 \frac{g_{HXX}^2}{\Gamma_H}$

⇛ Total Higgs width from *WW* process:



$$\frac{\sigma(HZ) \times Br(H \to b\bar{b})}{\sigma(H\nu\nu) \times Br(H \to b\bar{b})} \propto \frac{g_{HZZ}^2}{g_{HWW}^2}$$

⇛ And finally:

$$\sigma(H\nu\nu) \times Br(H \to WW^*) \propto \frac{g_{HWW}^4}{\Delta_H}$$

○ From this: Δ_H.

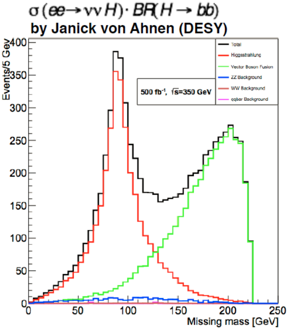
Higgs Couplings

⇛ The Higgs couplings to WW, ZZ, $c\bar{c}$, gg, $\tau^-\tau^+$, $\gamma\gamma$ can be determined via tagging the respective Higgs decay final states

⇛ Observables:

$$\sigma(e^+e^- \rightarrow ZH) \times Br(H \rightarrow X)$$

$$\sigma(e^+e^- \rightarrow H\nu\nu) \times Br(H \rightarrow X)$$



in %	HL-LHC	FCC-ee
g_{HZ}	2-4	0.21
g_{HW}	2-5	0.43
g_{Hb}	5-7	0.64
g_{Hc}	-	1.04
g_{Hg}	3-5	1.18
$g_{H\tau}$	5-8	0.81
$g_{H\mu}$	5	8.79
$g_{H\gamma}$	2-5	2.12
Γ_H	5-8%	1.55

arXiv:1307.7135 arXiv:1308.6176

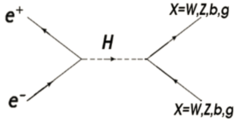
Higgs Production in S-channel

⇛ Potentially possibility to measure the Hee Yukawa coupling!

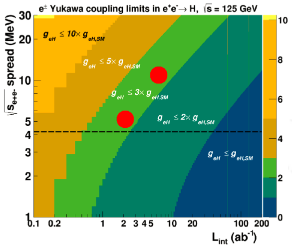
⇛ Several final states can be studied.

⇛ It requires running:

$$\sqrt{s} = M_H = 125 \text{ GeV}$$



⇛ Since $\Gamma_H = 4.2$ MeV, it requires monochromatization (increasing the energy resolution in the CMS energies for $e^- e^+$ interaction without reducing the inherent energy spread of the colliding beams)



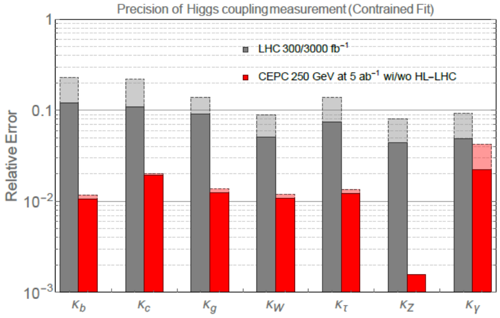
CMS energy Spread [MeV]	L [ab-1]
6	2
2	7

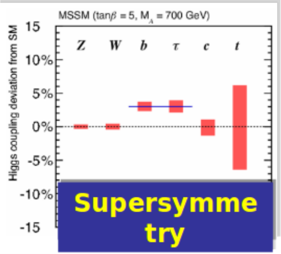
- Limits 3.5 times the SM predictions in both cases.

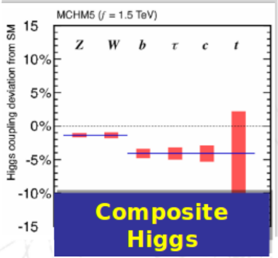
Normalized Higgs Couplings

⇛ Higgs couplings normalized to the SM predictions:

$$k_x = \frac{g_{Hxx}}{g_{Hxx}^{SM}}$$



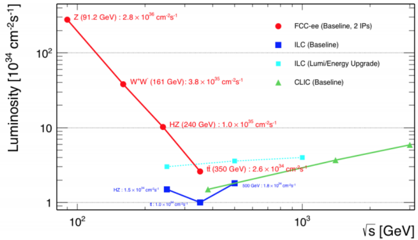


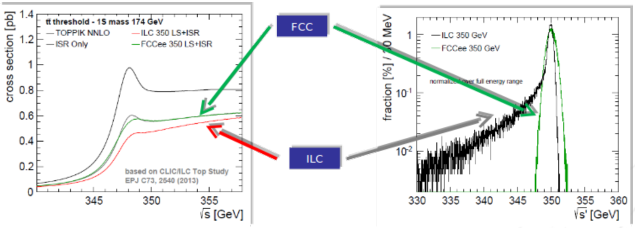


MegaTop: $t\bar{t}$ threshold scan

$\Rrightarrow$ For the first time the the top quark to be studied using a precisely defined leptonic state.

$\Rrightarrow$ The dependence of the t quark cross-section shape on the t quark mass and interactions is computable to high precision (depends on m_t, Γ_t, α_s, $g_H tt$, ISR, luminosity spectrum).





$\Rrightarrow$ PRD:

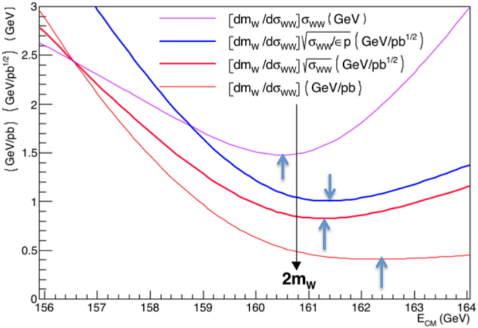
$$m_{=}(173.21 \pm 0.51 \pm 0.71)$$

$\Rrightarrow$ FCCee:

$$\sigma(m_t) < 10 \text{ MeV}$$

Physics program WW

⇛ Measurement of m_W from σ_{WW}



Max statistical sensitivity at
$\sqrt{s} = 2m_W + 0.6$ GeV

Stat. precision

- with
$L = 11\ \mathrm{pb}^{-1} \to\ 350$ MeV
- with
$L = 8\ \mathrm{ab}^{-1} \to\ 0.4$ MeV

⇛

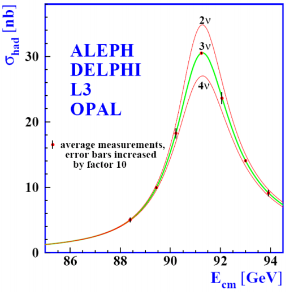
Sys. precision needed:

- $\Delta E(\mathrm{beam}) < 0.4$ MeV
- $\Delta\epsilon/\epsilon < 10^{-4}$
- $\Delta\sigma_B < 0.7$ fb

$$\Delta m_W^{FCC} = 500\ \mathrm{keV} \qquad \Delta \mathrm{m}_\mathrm{W}^\mathrm{LEP} = 50\ \mathrm{MeV}$$

Physics program at the Z pole

- $\Rrightarrow$ $L = 3 \times 10^{36} \rightarrow 4 \times 10^{12}$ Z decays.
- $\Rrightarrow$ Z mass and width wit precision of $10\ \mathrm{keV}$ (stat) $+100\ \mathrm{keV}$ (sys).



- $\Rrightarrow$ Radiation function calculated to $\mathcal{O}(\alpha_s^3) \sim 10^{-4}$
- $\Rrightarrow$ Relative precisions (JHEP01(2014)164):
  - $R_\ell = \frac{\Gamma_\ell}{\Gamma_{\mathrm{had}}} \sim 5 \times 10^{-5}$
  - $R_b = \frac{\Gamma_{b\bar{b}}}{\Gamma_{\mathrm{had}}} \sim 2 - 5 \times 10^{-5}$
  - $N_\nu \sim 10^{-3}$

$$\Delta_{\mathrm{rel}}\alpha_s(m_Z^2) \sim 2 \times 10^{-3} \qquad \Delta_{\mathrm{QED}}\alpha_s(m_Z^2) \sim 3 \times 10^{-3}$$

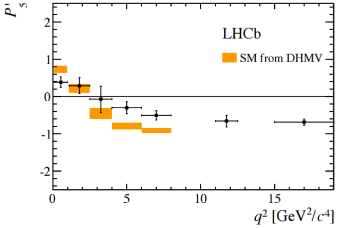
Z pole summary

From A.Blondel

X	Physics	Present precision		TLEP stat Syst Precision	TLEP key	Challenge
M_Z MeV	**Input**	91187.5 ±2.1	Z Line shape scan	**0.005 MeV** **<±0.1 MeV**	E_{CM}	QED corrections
Γ_Z MeV	**$\Delta\rho$ (T)** **(no $\Delta\alpha$!)**	2495.2 ±2.3	Z Line shape scan	**0.008 MeV** **<±0.1 MeV**	E_{CM}	QED corrections
R_l	**α_s , δ_b**	20.767 ± 0.025	Z Peak	**0.0001** **± 0.002**	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 Statistics	**QED Bhabha corrections**
R_b	**δ_b**	0.21629 ±0.00066	Z Peak	**0.000003** **±0.000020 - 60**	Statistics, small IP	Hemisphere correlations
A_{FB}	**$\Delta\rho$, ε_3 ,$\Delta\alpha$ (T, S)**	0.0171 ±0.0010	Z peak	**0.000003** **±0.00001**		

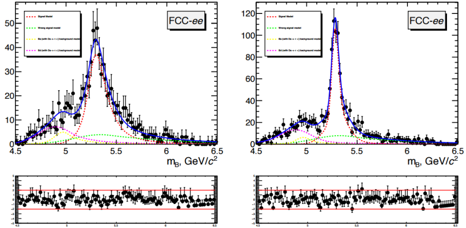
Flavour Physics

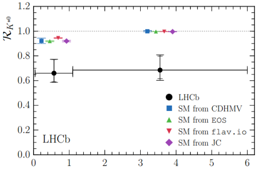
$\Rrightarrow$ Flavour Physics is an very active topic:

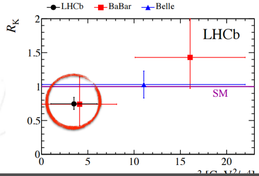


$\Rrightarrow$ LHCb will dominate in the decays where the muon are in final state.

$\Rrightarrow$ However τs are very challenging for them!





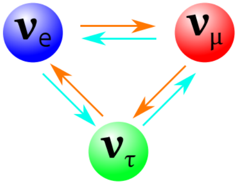


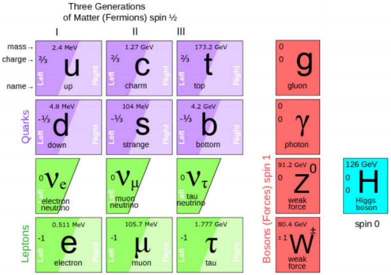
$\Rrightarrow$ Overall $\mathcal{O}(10^3)$ events!

$\Rrightarrow$ Angular analysis possible.

$\Rrightarrow$ Similar beeing studied for $B_s^0 \to \tau\tau$.

Right-handed neutrinos





Shaposhnikov *et al.*

⇛ Neutrino oscillations: at least two massive light neutrinos. ⇛ No renormalisable way in the SM therefore → evidence for new physics.

⇛ Sterile neutrinos for type I seesaw mechanism.

Neutrino mass eigenstates

⇛ See-saw mechanism:

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

$$\mathrm{tg}\, 2\theta = \frac{2m_D}{M_R}, \quad m_\nu = \frac{1}{2}\left[M_R - \sqrt{M_R^2 + 4m_D^2}\right]$$

$$M = \frac{1}{2}\left[M_R + \sqrt{M_R^2 + 4m_D^2}\right]$$

Dirac only

$M_R = 0, m_D \neq 0$

⇛ 4 states of equal masses.

⇛ $I = 1/2$ active neutrinos.

⇛ $I = 0$ sterile neutrinos.

Majorana only

$M_R \neq 0, m_D = 0$

⇛ 4 states of equal masses.

⇛ $I = 1/2$ active neutrinos.

⇛ $I = 0$ sterile neutrinos.

Dirac + Majorana

$M_R \neq 0, m_D \neq 0$

⇛ 4 states of diff. masses.

⇛ $I = 1/2$ active neutrinos.

⇛ $I = 0$ ALMOST sterile neutrinos.

Right handed neutrinos

$$\nu = \nu_L \cos\theta - N_R^c \sin\theta$$

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

ν_L - light mass eigenstate
N - heavy mass eigenstate
ν_L - active neutrino
N_R - “sterile” neutrino

$\Rrightarrow$ In the EW interaction the ν_L are produced:

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

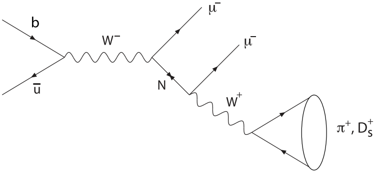
$\Rrightarrow$ Many consequences:

- Effect on neutrino oscillations (eV mass)
- Dark matter (keV mass regime)
- *Z* invisible width.
- Exotic particle decays: $H\nu N$ and $Z\nu N$.
- Heavy Flavour physics: strange, charm, beauty flavoured mesons via W^*.
- Violation on lepton flavour/universality.

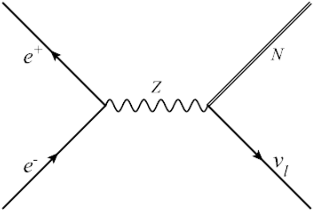
Collider experiments

arxiv::1503.05491

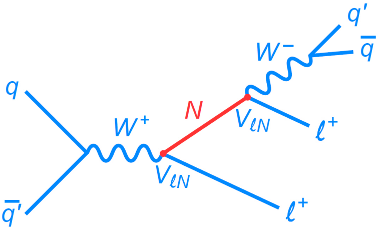
⇛ B-factories:



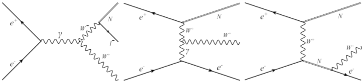
⇛ Z factory:



⇛ pp colliders:



⇛ ee colliders:



and many many more...

Production in Z decays

⇛ Production:

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

⇛ Decay length:

$$L \approx \frac{3\mathrm{cm}}{|U|^2 (m_\nu^2)^6}$$

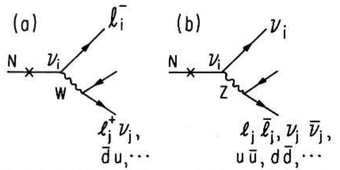
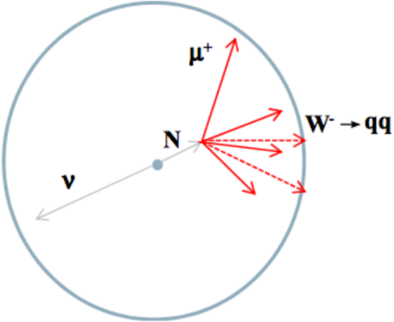


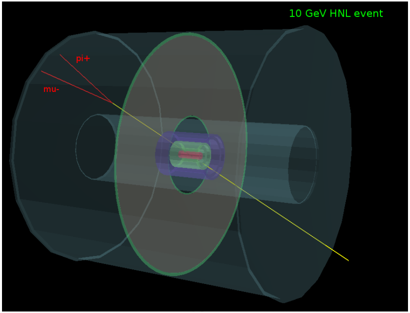
FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

⇛ Background: four fermion: $e^-e^+ \to W^*W^*$, $e^-e^+ \to Z^*(\nu\nu) + Z/\gamma$

⇛ Long lifetime of N helps rejecting the background!

Detection at a hadron collider

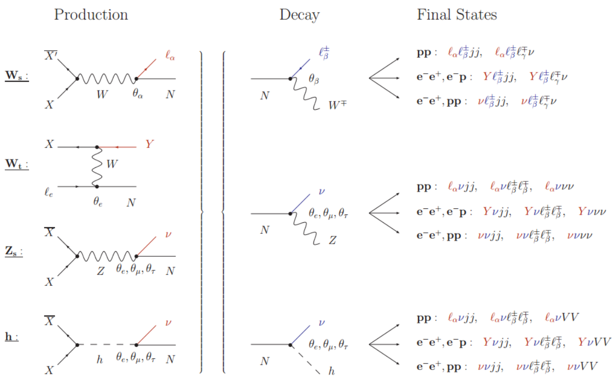




⇛ Super easy to detect topology!

⇛ At least two charged tracks produced.

arxiv::1612.02728



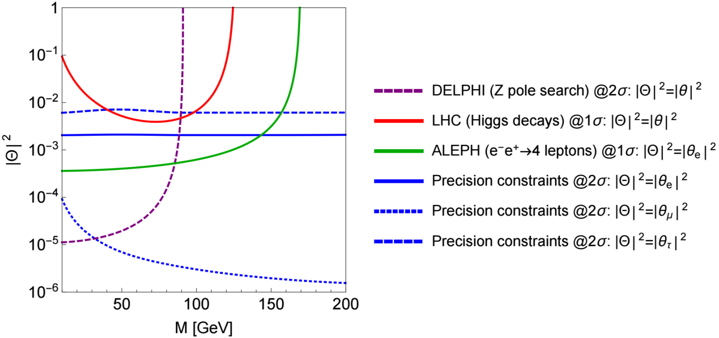
⇛ FCCee:

- Displaced vertices (Z-pole).
- Electroweak precision measurements (mostly Z-pole).
- Higgs boson production and decay modes.

⇛ FCC-hh/e: LFV, LNV, displeased vertex.

Current picture

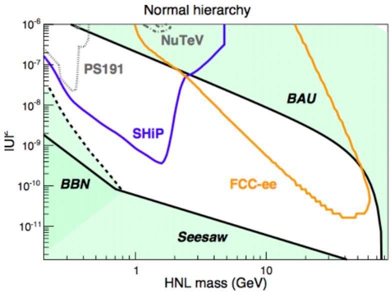
JHEP 1505 (2015) 053



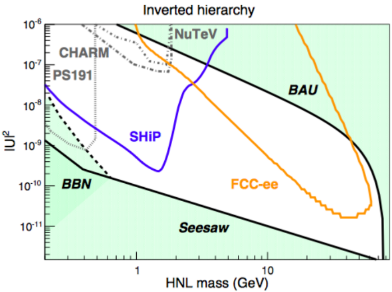
- $\Rrightarrow$ Present limits are dominated by LEP.
- $\Rrightarrow$ Higgs decays: Best constraints from $H \to \gamma\gamma$

Sensitivity

⇛ Preliminary studies show excellent potential!
⇛ Confirmation needed, based on accurate detector simulation
⇛ Complementarity with other CERN projects (e.g., SHiP, see N.Serra talk tmr.)



(a) Decay length 10-100 cm, 10^{12} Z^0



(a) Decay length 10-100 cm, 10^{12} Z^0

Synergy between FCC-xy

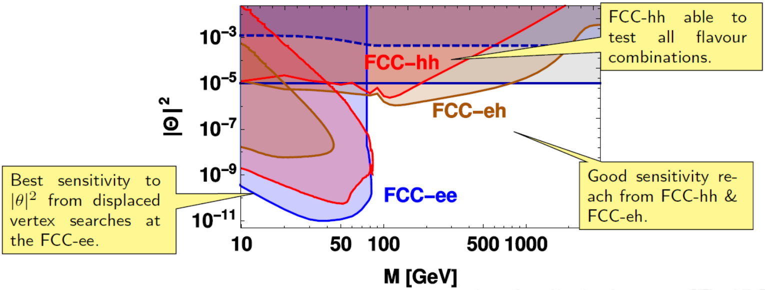
O.Fischer

⇛ Systematics assessment of heavy neutrino signatures at colliders.

⇛ First looks FCC-hh and FCC-he sensitivities.

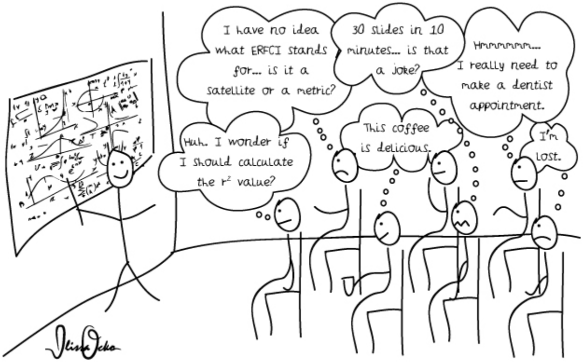
⇛ Golden channels:

- FCC-hh: LFV signatures and displeased vertexes.
- FCC-he LFV signatures and displeased vertexes.
- FCC-hh: EWPO and displeased vertexes.



Summary

- ⇛ The FCC program is constantly growing.
- ⇛ CDR in 2018!
- ⇛ One of the core program of FCC are HNL!
- ⇛ future colliders will exclude large part of parameter space!



Backup