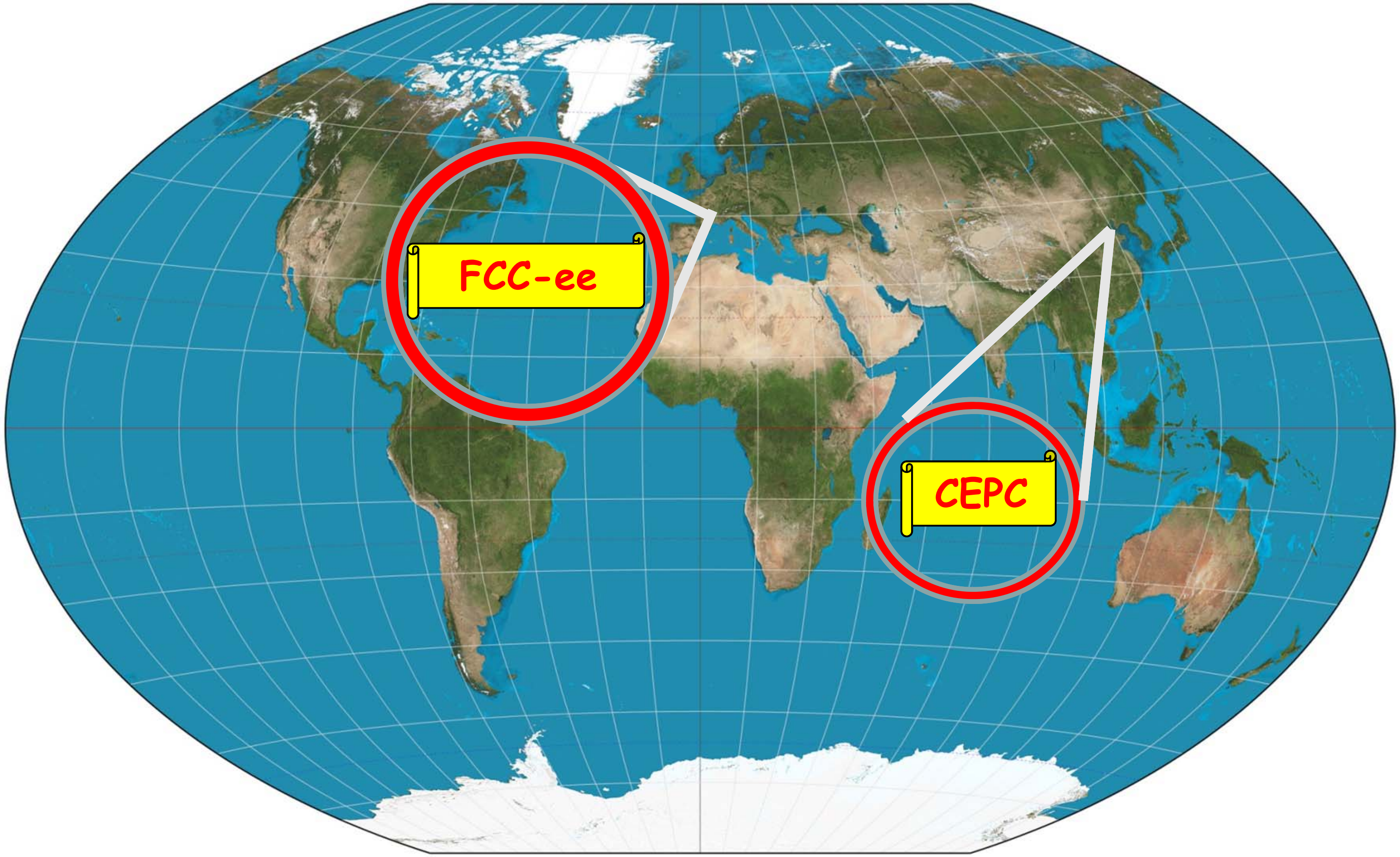
New Circular e^+e^- Accelerators at the Energy Frontier



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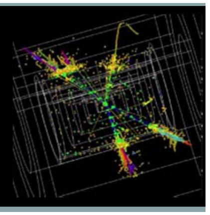
Leitmotif and Outline



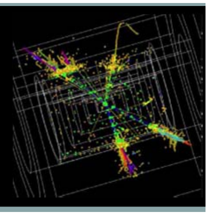
The discovery of the Higgs particle WITH LOW MASS
calls naturally for

a HIGGS FACTORY
- a circular e^+e^- collider of 240 GeV
(only 15% higher than the 209 GeV at LEP2).

The new, big accelerator tunnel will be ideal to host a future *pp* collider.

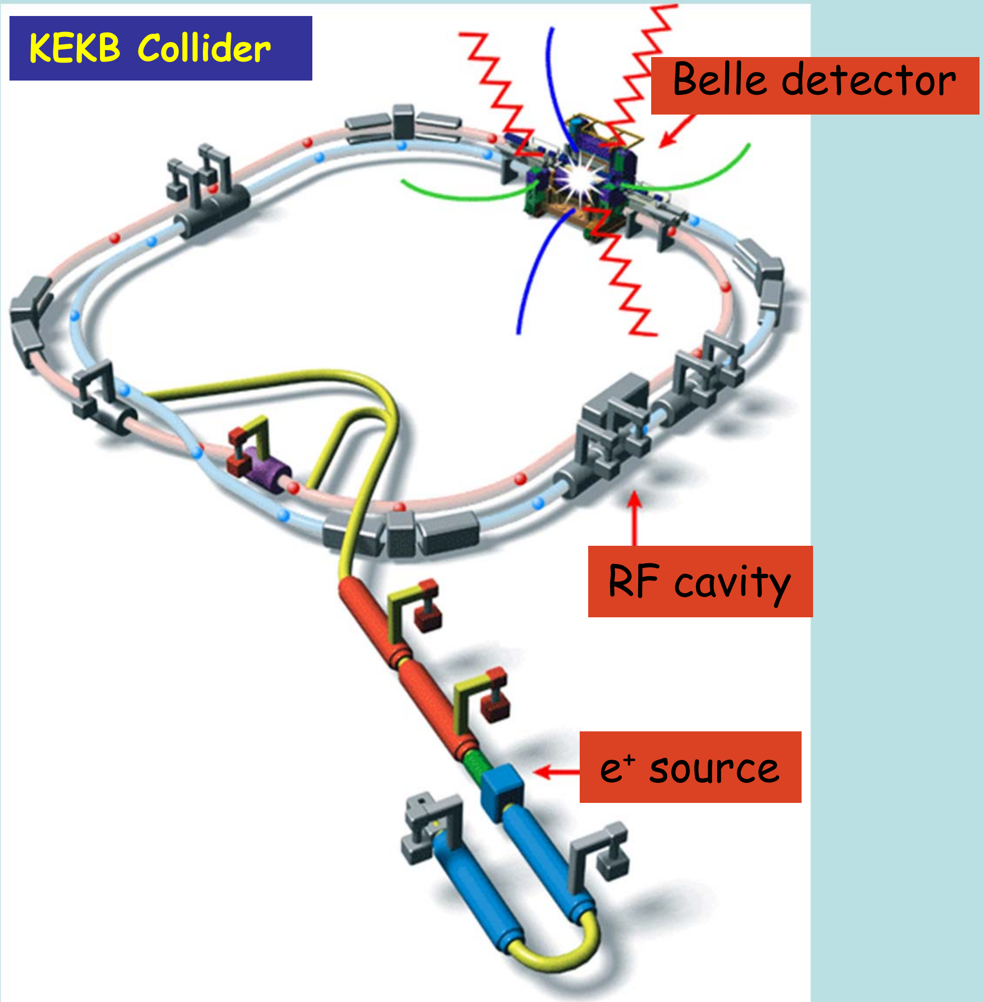
1. **Future Circular Collider (FCC-ee) at CERN**
2. **Circular (Chinese) Electron Positron Collider (CEPC)**
3. **Physics at future circular colliders (with selected topics, studied in Kraków)**

Key Physics Explorations for Future e^+e^- Colliders



- ✓ **Precise measurements of the Higgs(-es) properties (mass, width, spin, couplings, CP violation...).**
- ✓ Precise determination of the Top properties (studies at threshold).
- ✓ W and Z physics (vector boson pair production, TGCs).
- ✓ Precise studies of electroweak observables.
- ✓ Studies of two-fermion processes (Z', quark and lepton compositness, extra dimensions…) and four-fermion final states.
- ✓ Searches for new particles.
- ✓ …

Future Circular e^+e^- Colliders



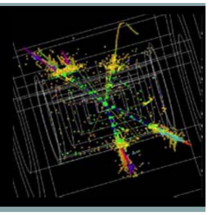
FCC – ee

Future Circular Collider, CERN, Switzerland

CEPC

Circular (Chinese) Electron Positron Collider, Qinghuada, China

Circular Colliders strike back



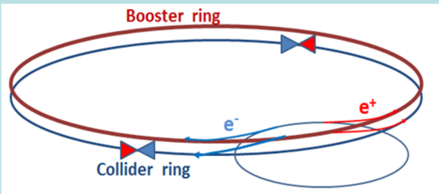
- To meet the need of Higgs/top studies and NP searches
- one should increase over LEP2 luminosity by a factor 1000.
- **How can one do that without exploding the power bill?**

$$\boxed{L \propto R \frac{P_{\mathrm{SR}}}{\beta_y^*}}$$

R – radius
P_{SR} – beam power; SR – synchrotron radiation

The answer is in the B-factory design: a low vertical emittance ring with higher intrinsic luminosity, and small β^*_y (1mm vs 5cm at LEP) $\boxed{\times 50}$

Electrons and positrons have a much higher chance of interacting (high density & Bhabha scattering): ➔ much shorter lifetime (few minutes)
➔ top up continuous injection booster $\boxed{\times 5}$



increase operation efficiency
increase SR beam power P_{SR} to 50MW/beam $\boxed{\times 4}$

$\boxed{\sum : \quad \times 1000}$

at ZH threshold in LEP/LHC tunnel

Additional $\boxed{\times 4}$ at the 100 km tunnel $\boxed{\times 4}$ (interaction points)

Energy loss per turn: up to 7.55 GeV at E_{beam} = 175 GeV (FCC tunnel; top-threshold)

FCC
– Future Circular Collider

- **FCC – international collaboration aiming at the study of:**

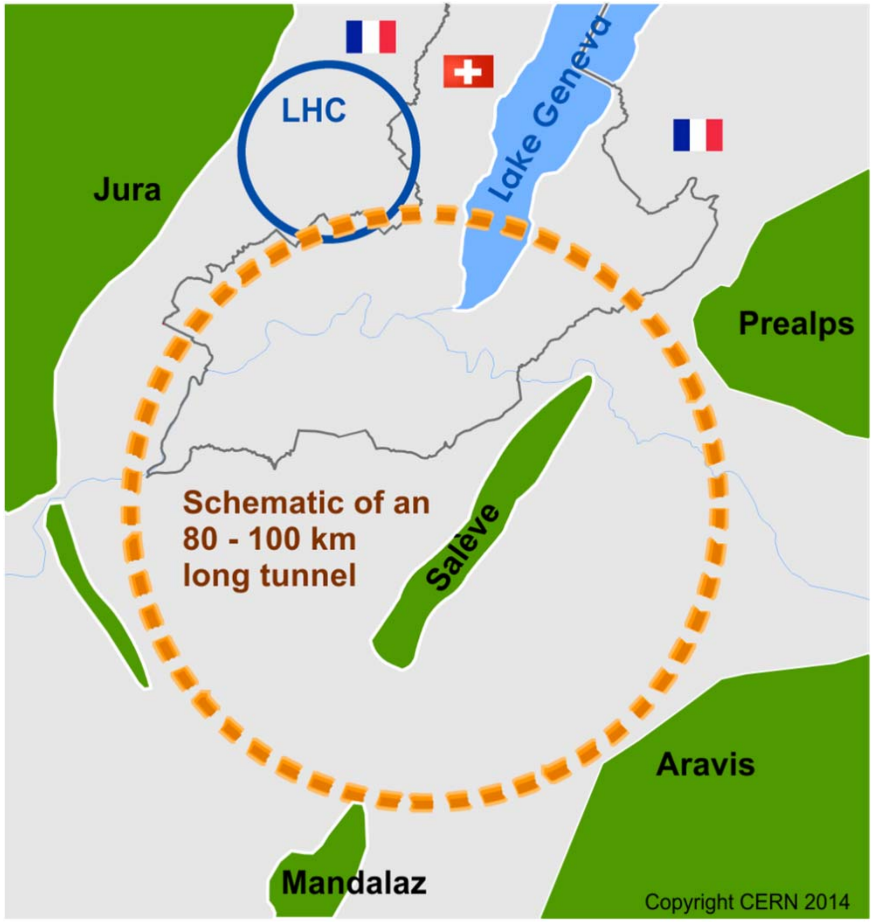
✓ **p-p collider:** FCC-hh – flagship

✓ **e^--e^+ collider:** FCC-ee – intermediate step, preceding the FCC-pp

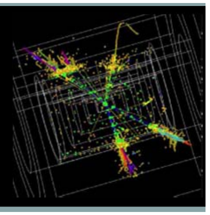
✓ **e-p collider:** FCC-he – additional option

- **80-100 km infrastructure** in Geneva area

- **Goal: CDR and cost review by 2018**



FCC-ee
- Future Circular Collider



$\Delta M_Z = 100\ \mathrm{keV}$ $\Delta M_W = 500\ \mathrm{keV}$ (LEP: $\Delta M_Z = 2\ \mathrm{MeV}$ $\Delta M_W = 50\ \mathrm{MeV}$)

Two rings; four interaction points; flat beams; non-zero crossing angle

Five working points: $\sqrt{s} = M_Z$ $\sqrt{s} = M(WW)$ $\sqrt{s} = M(ZH)$ $\sqrt{s} = M(t\bar{t})$ $\sqrt{s} = 400$ GeV

Parameter	FCC-Z	FCC-WW	FCC-ZH	FCC-tt	LEP2
E (GeV)	**45**	**80**	**120**	**175**	**104**
I (mA)	1400	152	30	7	4
No. bunches	16 700	4 490	1 330	98	4
Energy loss/turn [GeV]	0.03		1.67	7.55	3.34
Synchrotron power [MW]	100	100	100	100	22
RF Voltage [GV]	0.3-2.5		3.6-5.5	11	3.5
$\beta^*_{x/y}$ (mm)	500 / 1	500 / 1	500 / 1	1000 / 1	1500 / 50
ε_x (nm)	29	3.3	1	2	30-50
ε_y (pm)	60	7	2	2	~250
ξ_y	0.03	0.06	0.09	0.09	0.07
L (10^{34} cm^{-2}s^{-1})/IP	28	12	**6.0**	1.8	0.012
Statistics (4 expts)	10^{12} Z / 2yrs	10^8 WW / 1yr	2 10^6 ZH/5yrs	10^6 $t\bar{t}$ / 5yrs	

LEP1 : $2.1 \times 10^{31}\ \mathrm{cm^{-2}s^{-1}}$

FCC Collaboration

fcc.web.cern.ch

- 60 Institutes, 23 Countries;   EuroCirCol H2020 project

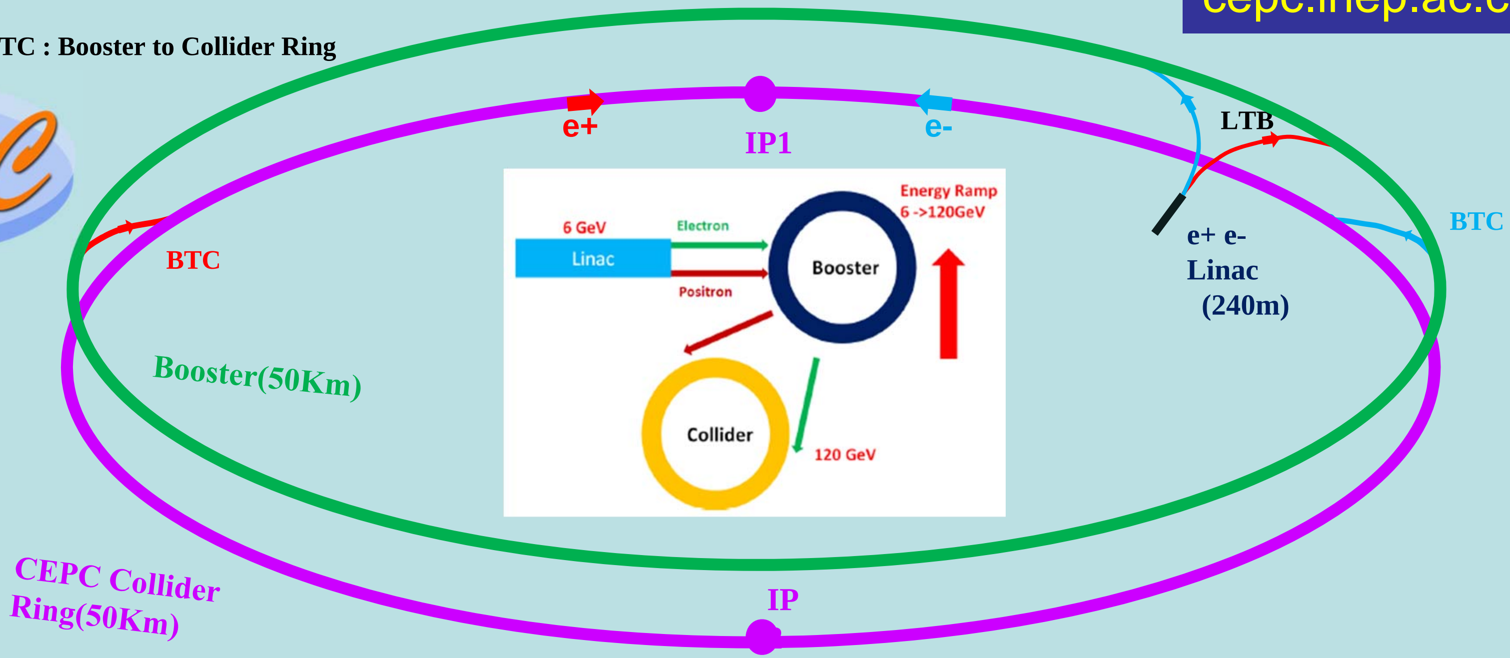
- Polish Institutions:
  - ✓ Silesia University, Katowice
  - ✓ Wroclaw University of Technology
  - ✓ Institute of Nuclear Physics PAN, Kraków
  - ✓ Cracow University of Technology

CEPC
– Circular Electron-Positron Collider

LTB : Linac to Booster

BTC : Booster to Collider Ring

cepc.ihep.ac.cn

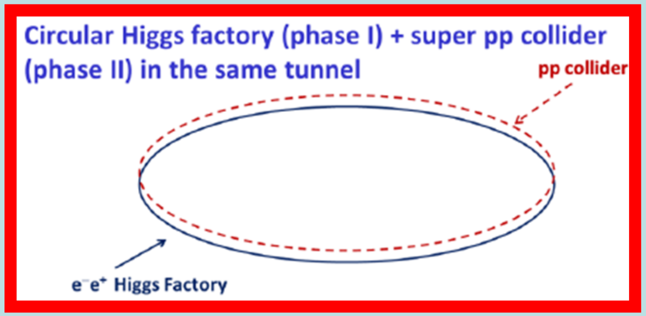


Two Interaction Points

Two working points in beam energy:

$\sqrt{s} = 240\ \text{GeV}$ $L \approx 2 \times 10^{34}\ \text{cm}^{-2}s^{-1}$

$\sqrt{s} = M_Z$



Major characteristics of CEPC

54.4.km circumference

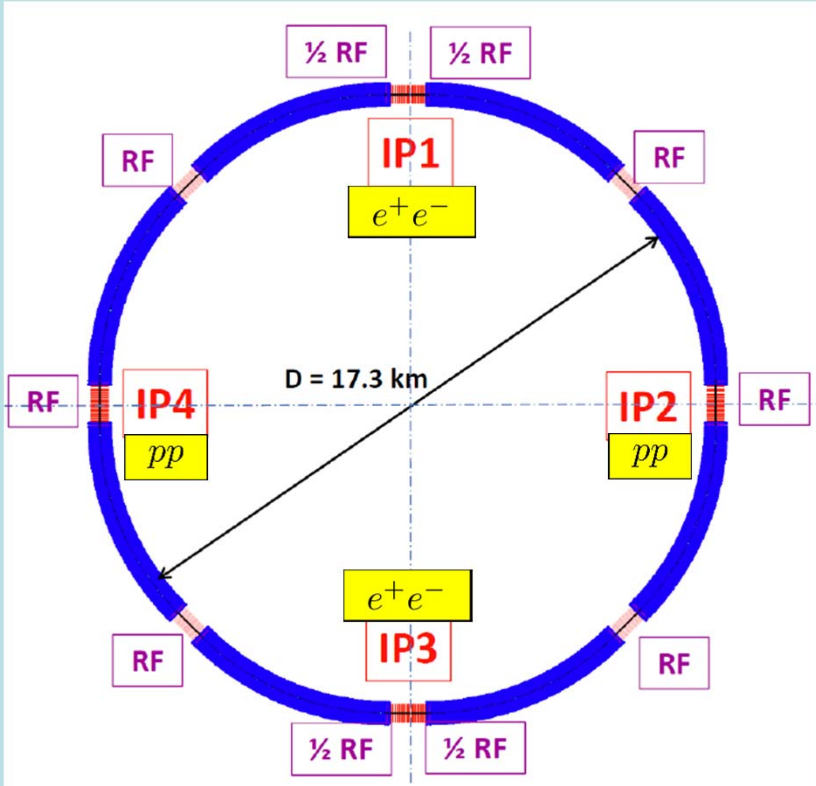
250 fb^{-1} /IP/year
➔ 5 ab^{-1} (10 years of operation)
➔ at least 10^6 Higgs particles from each IP after 10 years of running

Single beam pipe (parasiting crossings, orbit instabilities…)
→ total number of bunches maks. 50

Energy loss: 3 GeV/turn at 120 GeV

Beam current 16.6 mA/beam

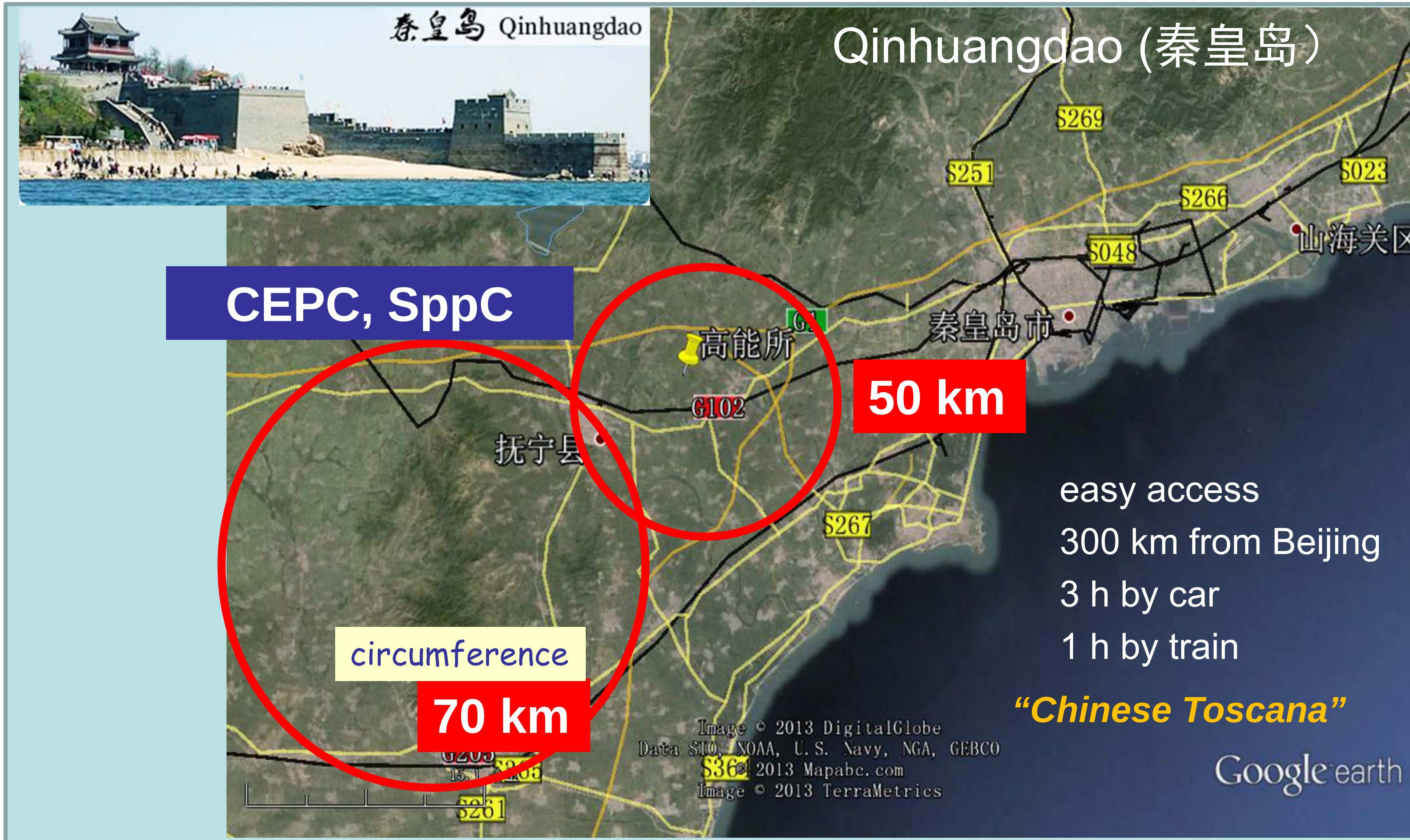
$L^* = 1.5$m $\beta^*_y = 1.2$ mm



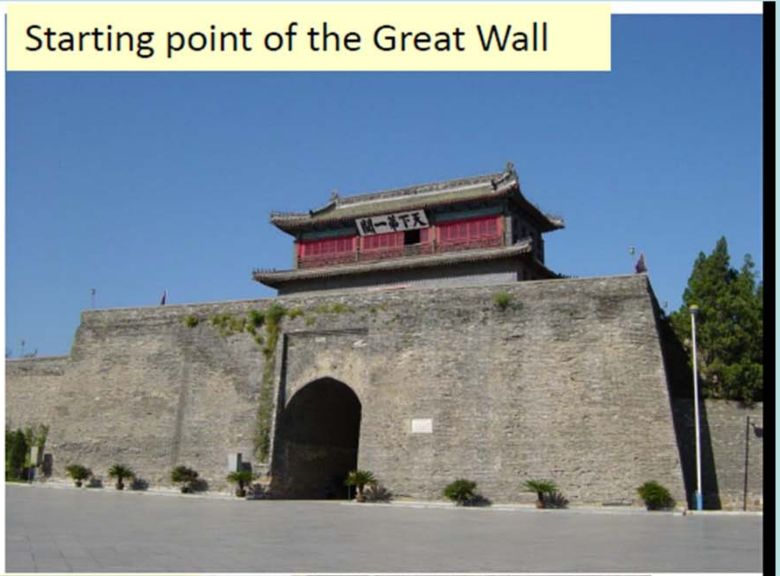
8 arcs and 8 straight sections

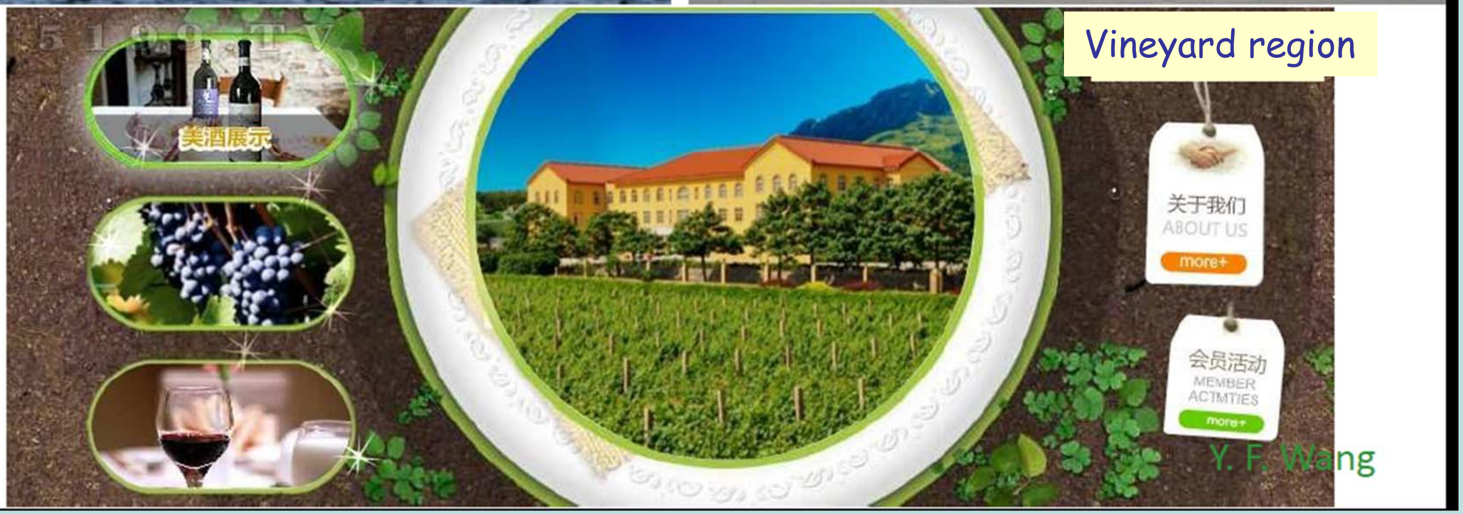
Tunnel's diameter 6m (LHC 3.6m)

CEPC
– Circular Electron-Positron Collider

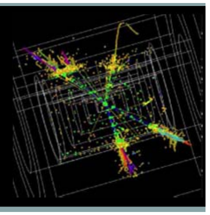


CEPC
– Circular Electron-Positron Collider

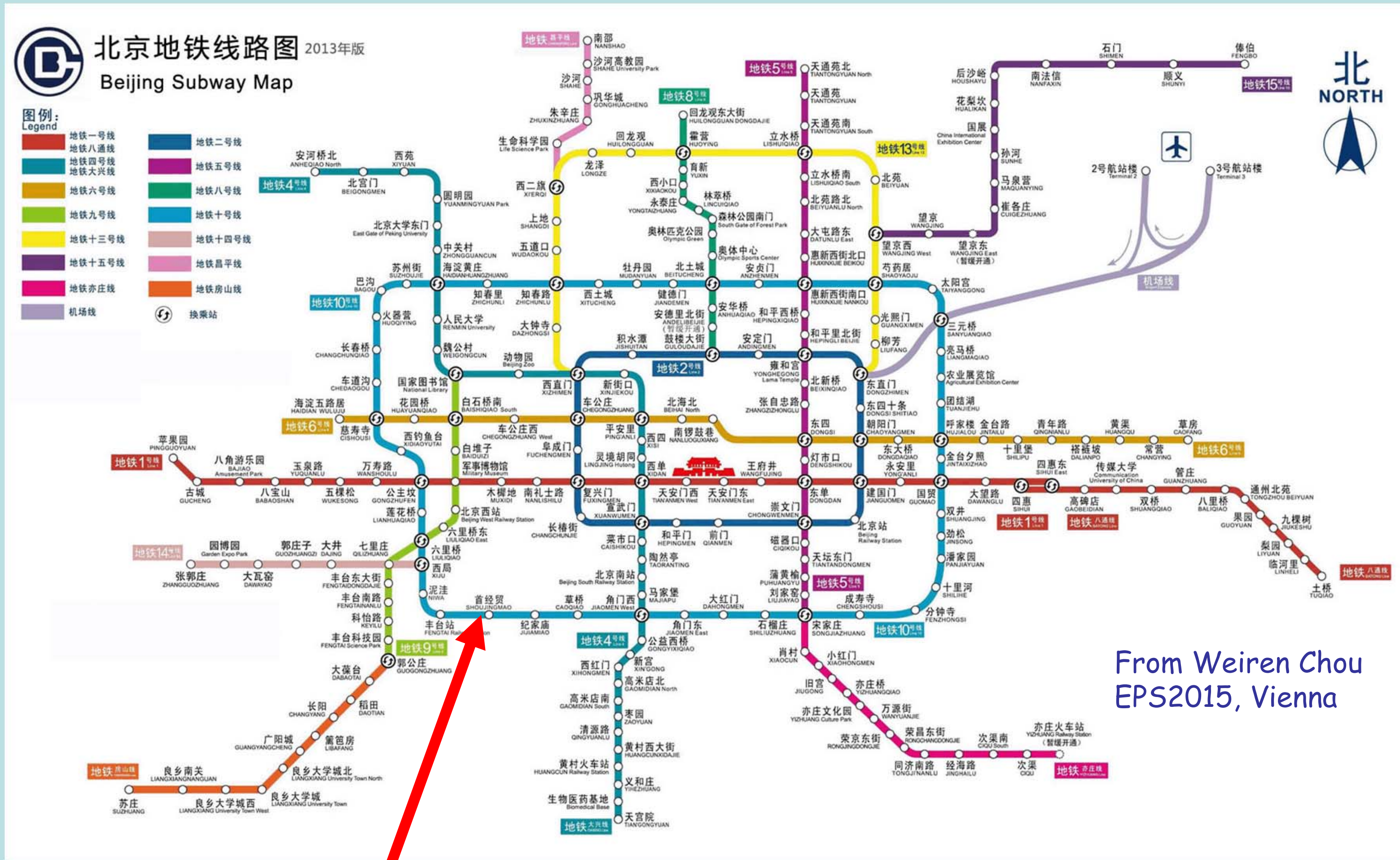




CEPC
– Circular Electron-Positron Collider



Beijing subway:

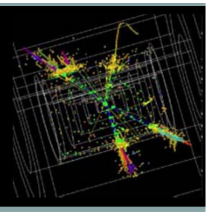


From Weiren Chou
EPS2015, Vienna

Subway line #10: 57 km
Construction: 2003-2008

Warsaw: the 1st line of 23km
Construction: 1925-2008

CEPC – Circular Electron-Positron Collider



IHEP-CEPC-DR-2015-01
IHEP-EP-2015-01
IHEP-TH-2015-01

CEPC-SPPC

Preliminary Conceptual Design Report

Volume I - Physics & Detector

403 pages, 480 authors

The CEPC-SPPC Study Group

March 2015

March 2015

IHEP-CEPC-DR-2015-01
IHEP-AC-2015-01

CEPC-SPPC

Preliminary Conceptual Design Report

Volume II - Accelerator

328 pages, 300 authors

The CEPC-SPPC Study Group

March 2015

Parameters: FCC-ee & CEPC

Parameter	LEP(2)	FCC-Z	FCC-WW	FCC-ZH	FCC-tt	CEPC
E (GeV)	104	45	80	120	175	120
I (mA)	4	1400	152	30	7	16.6
No. bunches	4	16’700	4’490	1’330	98	50
$\beta^*_{x/y}$ (mm)	1500/ 50	500 / 1	500 / 1	500 / 1	1000 / 1	800 / 1.2
ε_x (nm)	30-50	29	3.3	1	2	6.8
ε_y (pm)	250	60	7	2	2	20
P_{SR} [MW]	22	100	100	100	100	100
L (10^{34} $cm^{-2}s^{-1}$)/IP	0.012	28	12	6.0	1.8	1.8

Timeline: FCC-ee & CEPC

Phase	FCC	CEPC
Pre-studies; engineering design; R&D	2014-2022	2014-2021
Preparatory phase	2022-2027	
Construction	2027-2037	2021-2027
Data taking	2037-2045	2028-2036

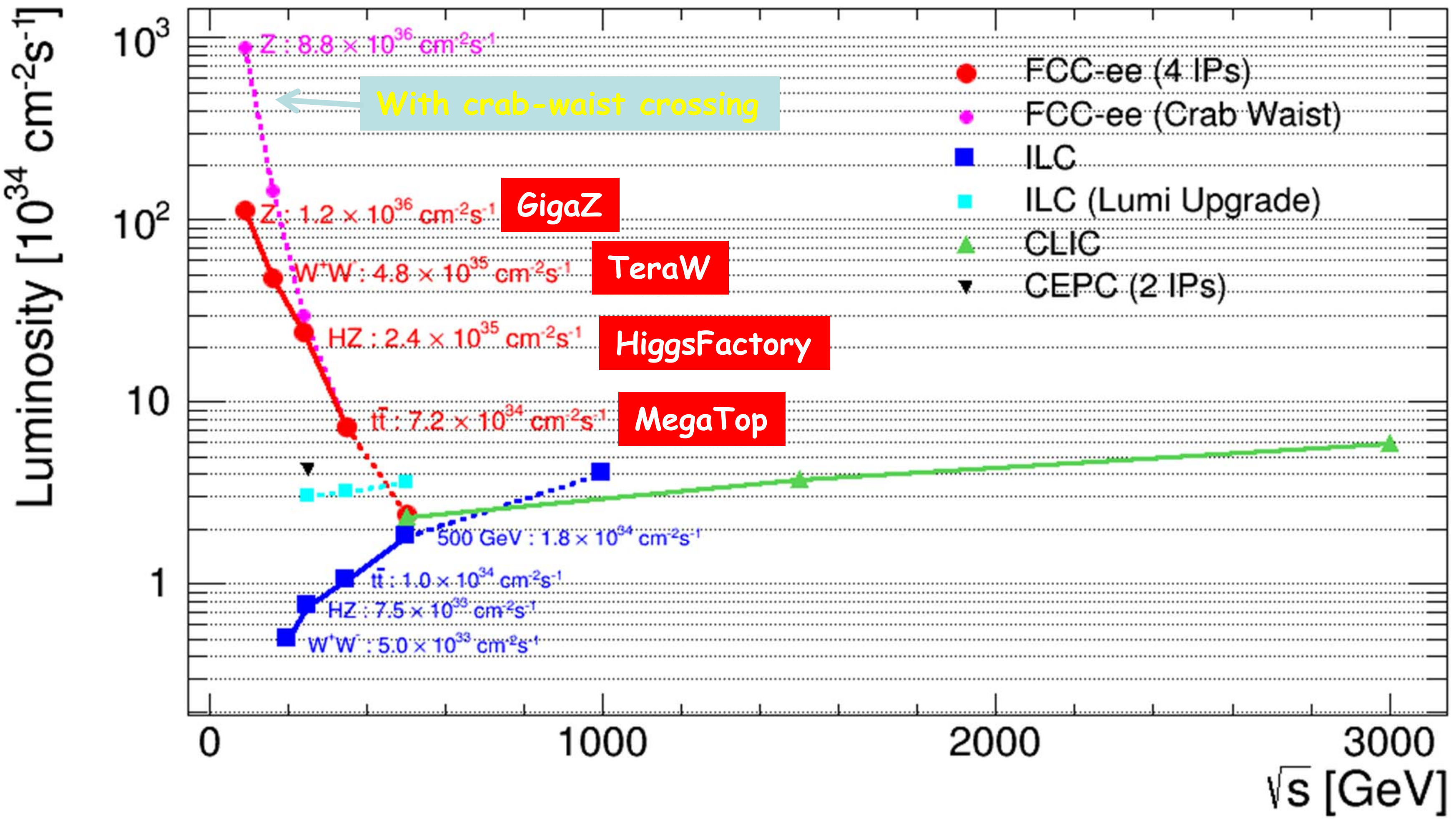
Important milestones:

FCC: The first annual meeting: Washington D.C. 23-27. March 2015
http://indico.cern.ch/event/340703/

preparation of Conceptual Design Report (CDR) **for 2018**
(update of European Strategy of High Energy Physics).

CEPC: Accelerator pre-CDR issued in **March 2015;**
Physics pre-CDR appeared in **April 2015;**
R&D funding request passed to Chinese Government (5-year plan 2016-20)

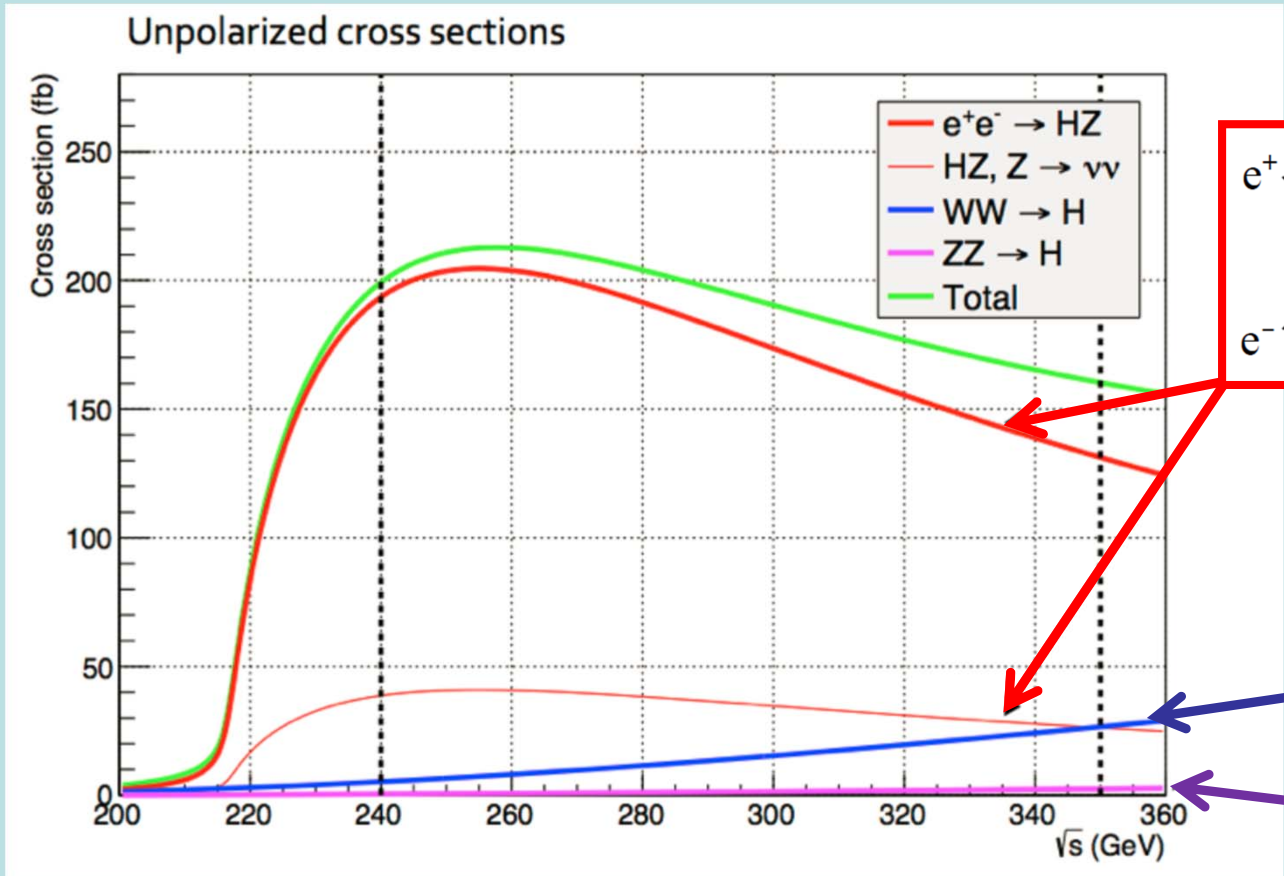
Proposals of New e^+e^- Colliders: Instead of Summary



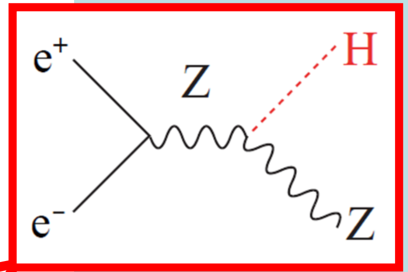
Physics at Future Circular Colliders

Higgs Physics

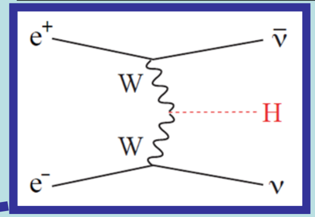
Three major Higgs production processes at the e⁺e⁻ circular collider:



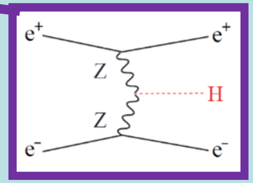
$e^+e^- \to ZH$



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



$e^+e^- \to e^+e^-H$

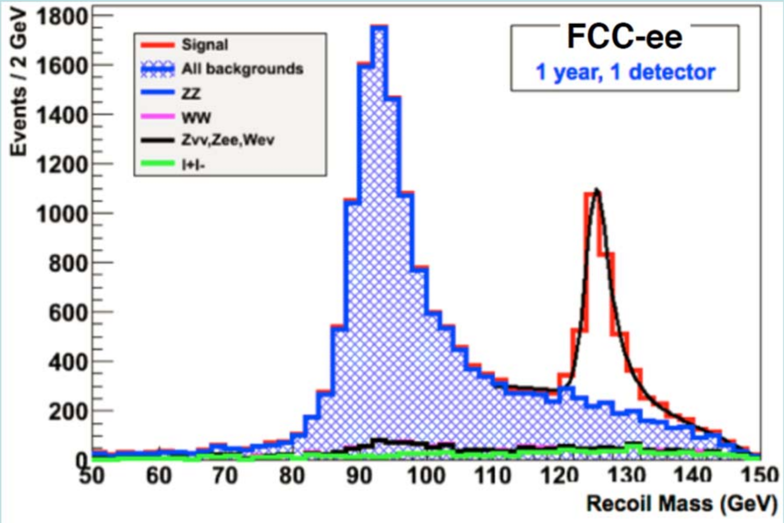


Higgs Mass and Width

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

$$\boxed{m^2_{\mathrm{recoil}} = (\sqrt{s} - E_{ll})^2 - |\vec{p}_{ll}|^2}$$

- Preferably with $Z \to \mu^+\mu^-$ or $Z \to e^+e^-$
- ZH events are tagged independently of Higgs decay mode (invisible decays included).
- Precise measurement of the g_{HZZ}: $\boxed{\sigma(HZ) \propto g^2_{HZZ}}$



	ILC500 lumiUp	FCC – ee	CEPC
ZH statistics $[10^6]$	1	2	1
Δm_H[MeV]	15	8(?)	5.9(?)
$\Delta\Gamma_H/\Gamma_H$[%]	3	1.0	2.8

Higgs Couplings

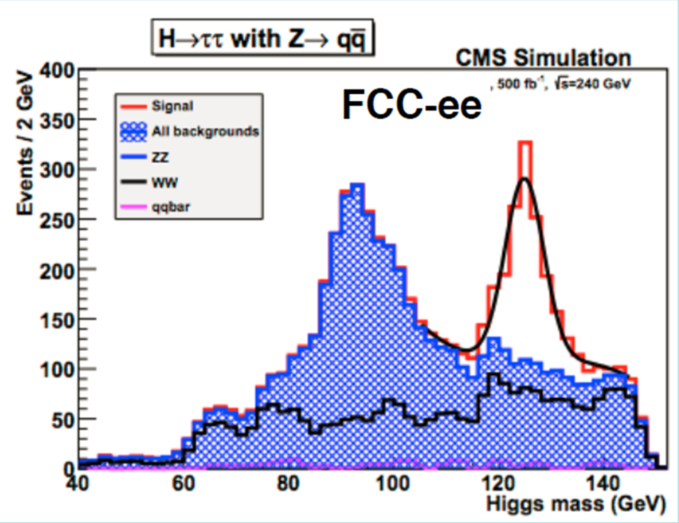
- Higgs couplings to WW, ZZ, bb,cc, gg, ττ, γγ etc can be determined through the tagging of the respective Higgs decay final states.

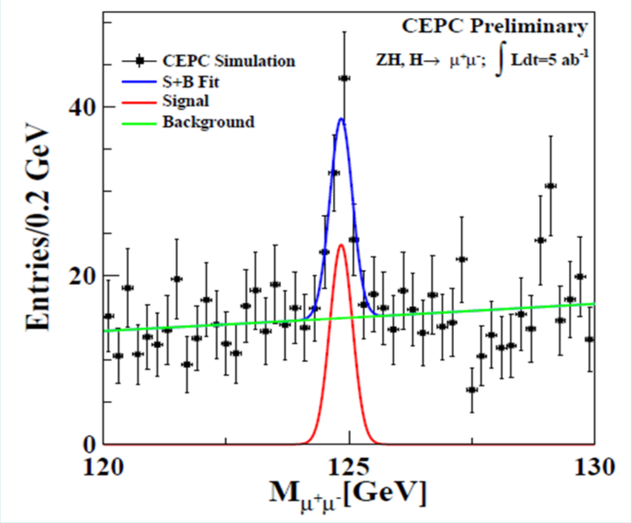
- Observables:

$$\boxed{\sigma(e^+e^- \to ZH) \times \mathrm{BR}(H \to X)}$$

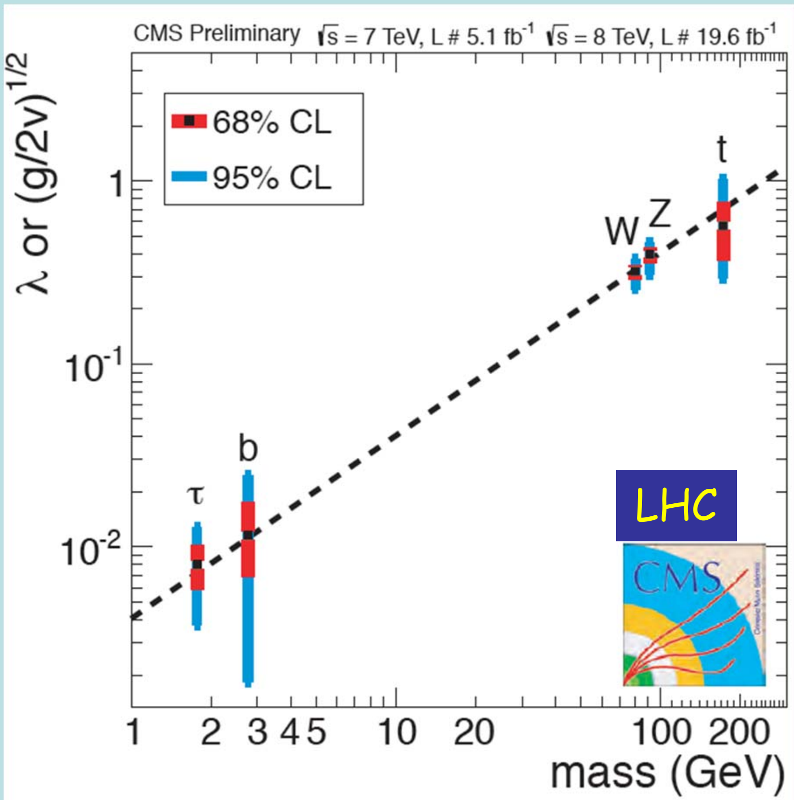
$$\left(\boxed{\sigma(e^+e^- \to \nu\bar{\nu}H) \times \mathrm{BR}(H \to X)} \right)$$

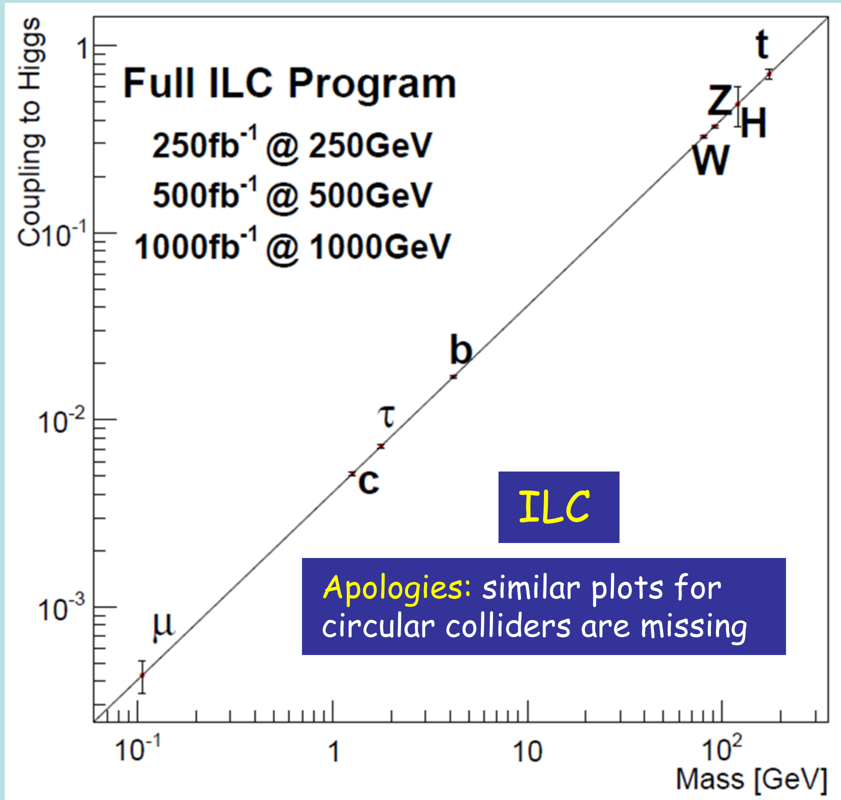
all uncertainties are in %	FCC – ee 240 GeV	CEPC 250 GeV
$\sigma(ZH)$	0.40	0.51
$\sigma(ZH) \times \mathrm{BR}(H \to b\bar{b})$	0.20	0.28
$\sigma(ZH) \times \mathrm{BR}(H \to c\bar{c})$	1.2	2.2
$\sigma(ZH) \times \mathrm{BR}(H \to \tau^+\tau^-)$	0.7	1.2
$\sigma(ZH) \times \mathrm{BR}(H \to \mu^+\mu^-)$	13	17.0
$\sigma(ZH) \times \mathrm{BR}(H \to gg)$	1.4	1.6
$\sigma(ZH) \times \mathrm{BR}(H \to WW)$	0.9	1.5
$\sigma(ZH) \times \mathrm{BR}(H \to ZZ)$	3.1	4.3
$\sigma(ZH) \times \mathrm{BR}(H \to \gamma\gamma)$	3.0	9.0





Higgs Couplings: Mission Accomplished





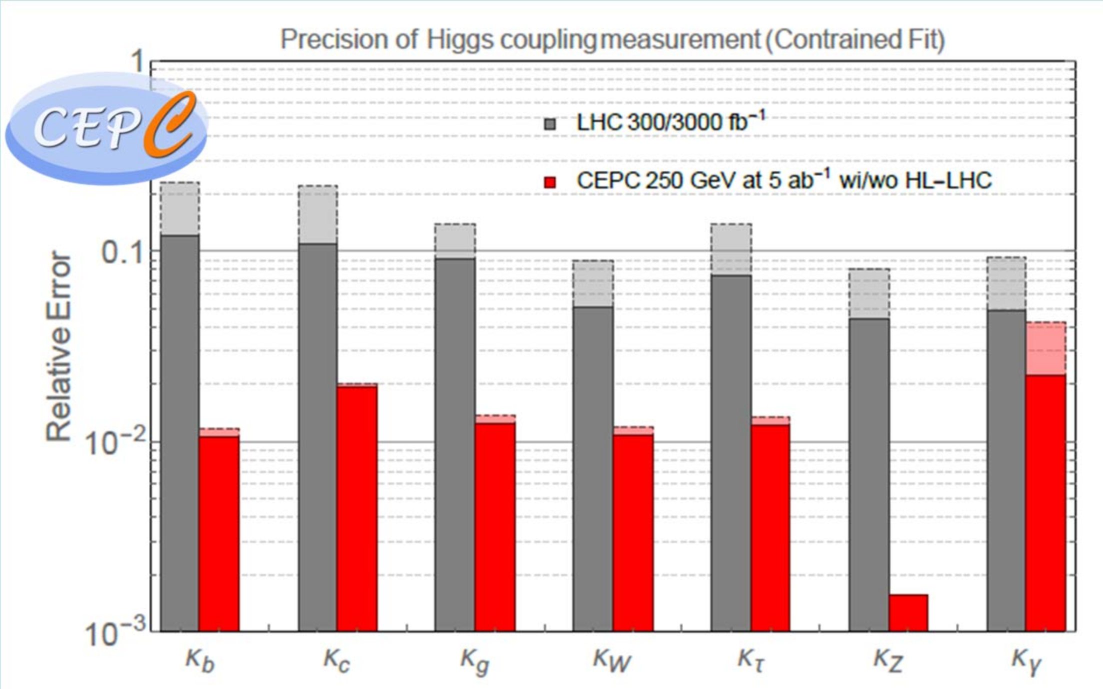
$\Delta \sim 15\%$ → $\Delta \sim 1\%$

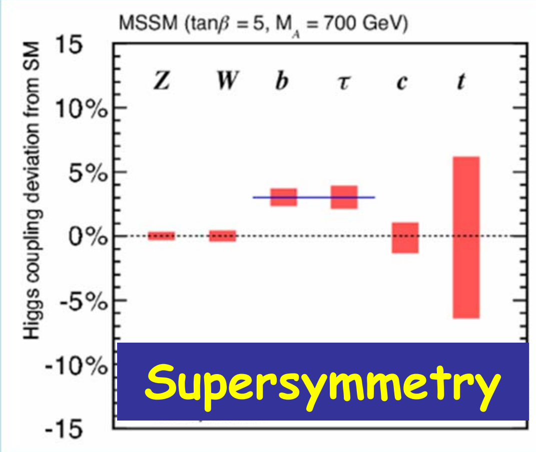
Normalized Higgs Couplings

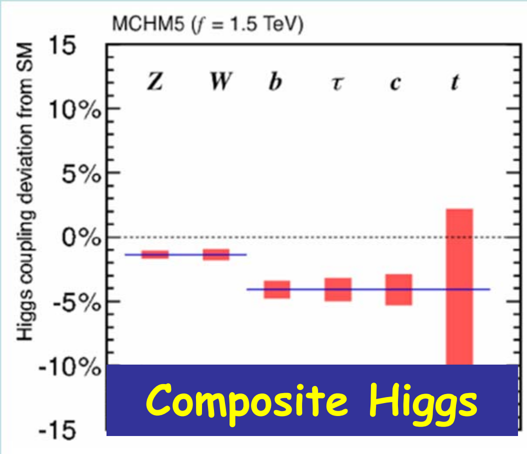
- Higgs couplings normalized to the Standard Model predictions:

$$k_f = \frac{g_{Hff}}{g_{Hff}^{SM}}, \; f = b, c, \tau = \mu$$

$$k_V = \frac{g_{HVV}}{g_{HVV}^{SM}}, \; V = W, Z, \gamma, g$$

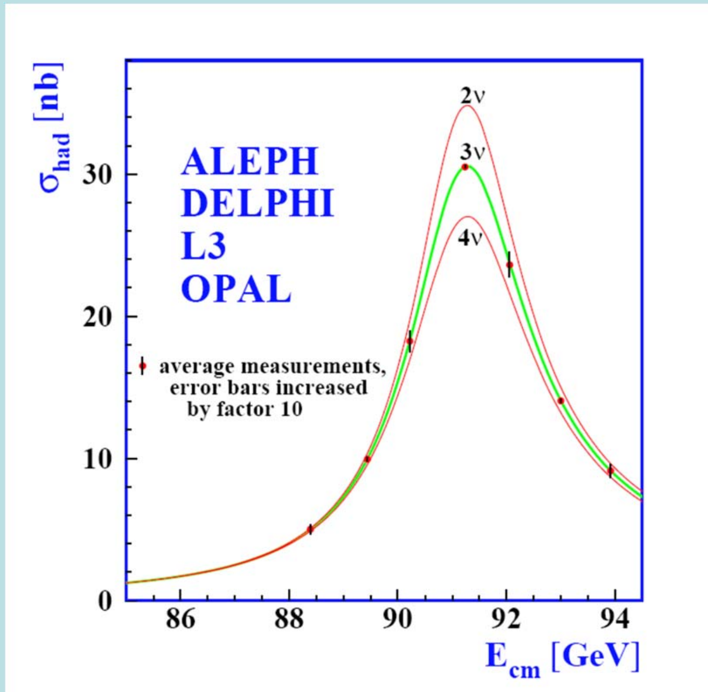






- Run around $\sqrt{s} = M_Z$ (energy scan)

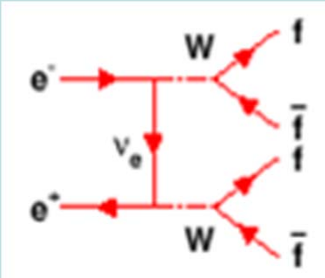
	Current Stat./Precision	FCC – ee stat (syst)	CEPC stat only
N_Z	2×10^7	10^{12}	2×10^9
M_Z [MeV]	91187.6 ± 2.1	$0.005\ (< \pm 0.1)$	0.1
Γ_Z [MeV]	2495.2 ± 2.3	$0.008\ (< \pm 0.1)$	0.2
R_l	20.767 ± 0.025	$0.0001\ \left(^{0.002}_{0.0002}\right)$	0.001
R_b	0.21629 ± 0.00066	$0.000003\ (< \pm 0.00004)$	0.00018
A_{FB}^b	0.923 ± 0.020	$--$	0.002
N_ν	2.984 ± 0.008	$0.00008 (< \pm 0.004)$	0.003

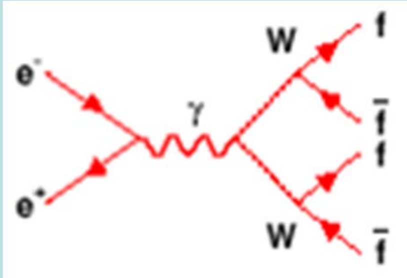


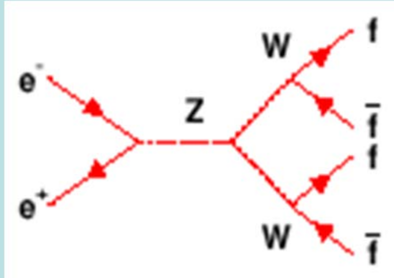
- Potential to reach precision of 100 keV on Z mass and width.

- Critical progress in R_b , R_l, asymmetry measurements, $\sin\Theta_W$, …

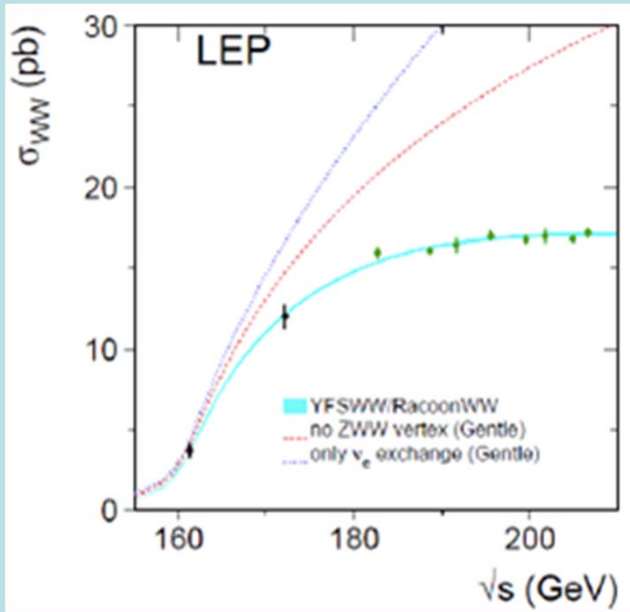
OkuW: WW Threshold Scan







- Final states: $W^+W^- \to q_1\bar{q}_2q_3\bar{q}_4$ $W^+W^- \to q_1\bar{q}_2l\bar{\nu}_l$ $W^+W^- \to l_1\bar{\nu}_{l_1}l_2\bar{\nu}_{l_2}$



	Current Stat./Prec.	FCC – ee stat (syst)	CEPC stat (syst)
N_{WW} (LEP2)	4×10^3	10^8	10^7
M_W [MeV] (LEP2)	$80376 \pm 33 \pm 4$	$0.3\ (< \pm 1)$	$3(1)$

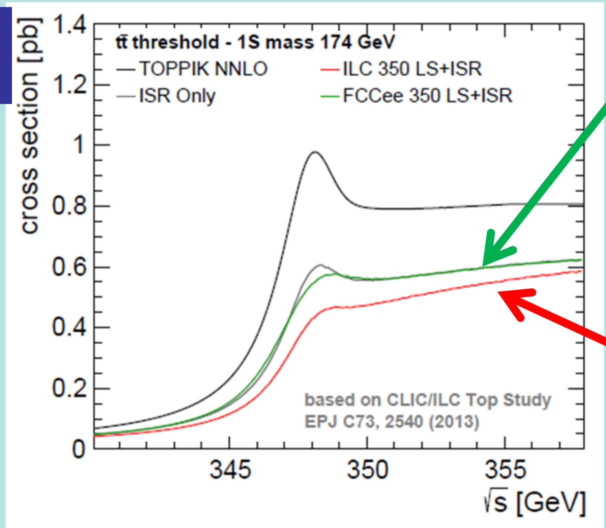
- Precision of **1 MeV** on the W mass

MegaTop: $t\bar{t}$ Threshold Scan

- For the 1st time the top quark to be studied using a precisely defined leptonic state.
- The beam energy is known and readily variable.

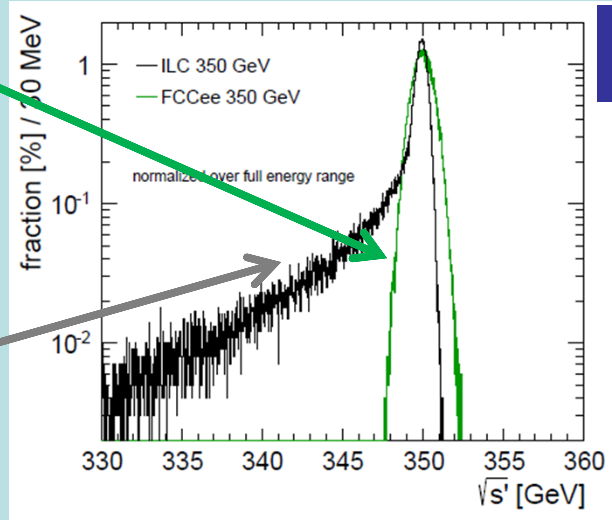
- It is possible to tune the initial spin state, giving additional options for precision threshold measurements.
- The dependence of the t quark cross-section shape on the t quark mass and interactions is **computable to high precision** (depends on m_t, Γ_t, α_s, g_{Htt}, ISR, luminosity spectrum).

Cross-section



FCC

ILC



Lumi spectrum

PDG: $m_t = (173.21 \pm 0.51 \pm 0.71)$ GeV ⇒ FCC-ee: $\sigma(m_t) \geq 10$ MeV

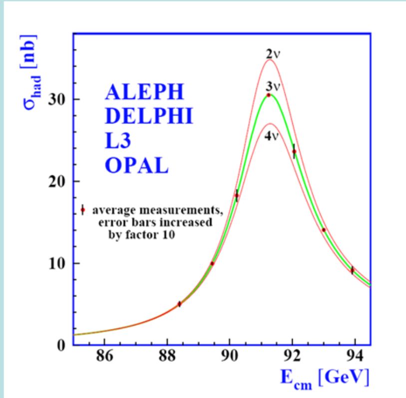
Number of light neutrino species (N_ν)

„Direct method”: N_ν determined at LEP1 from the Z line-shape scan:

$$\Gamma_{tot} = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \sum_{i=1}^{5} \Gamma_{qq} + N_\nu \Gamma_{\nu\nu}$$

$$N_\nu = 2.984 \pm 0.008$$

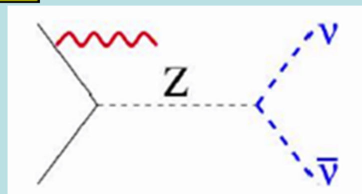
(2σ below 3)



- A hint of non-unitarity of the PMNS matrix?
- Only small room for improvements: precision limited by the theoretical uncertainty on normalization, i.e. on small angle Bhabha cross section (0.0046 at LEP1).

Alternative **„indirect method”:** $e^+e^- \to \nu\bar{\nu}\gamma$

$$N_\nu \equiv \left(\frac{e^+e^- \to \gamma Z_{inv}}{e^+e^- \to \gamma Z_{lept}}\right)^{meas} / \left(\frac{\Gamma_{\bar{\nu}\nu}}{\Gamma_{lept}}\right)^{SM}$$



- Not feasible at LEP1 (statistics too scarse).
- Relatively small theoretical uncertainties.

IFJ PAN & CUT

- Photon selection common for both final states ➔ cancellations of systematics.
- N_ν can be measured vs sqrt(s) ➔ sensitivity to NP at high energy scales.

Number of light neutrino species (N_ν)

Both methods are independent and complementary: data sets, systematics, theoretical input…

CEPC

direct: $\Delta N_\nu = 0.003$ (stat & syst)

indirect: $\sqrt{s} = 240$ GeV — $\Delta N_\nu = 0.003$ (stat & syst)

FCC ee

direct: $\Delta N_\nu = 0.00008(\text{stat}) \pm 0.004(\text{syst})$

indirect:

$\sqrt{s} = 161$ GeV	1 year of running : 3×10^7 $\gamma Z(\text{inv})$ evts	$\Delta N_\nu = 0.0011$
$\sqrt{s} = 240$ and 350 GeV	5 years of running	$\Delta N_\nu = 0.0008$
$\sqrt{s} = 125$ GeV	1 year of running	$\Delta N_\nu = 0.0004$

(Opportunity to measure directly $e^+e^- \to H$)

(stat)

Heavy Neutrino Searches (FCCee)

$I = \frac{1}{2}$

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$$

$I = 0$

$$(e)_R \quad (\mu)_R \quad (\tau)_R$$

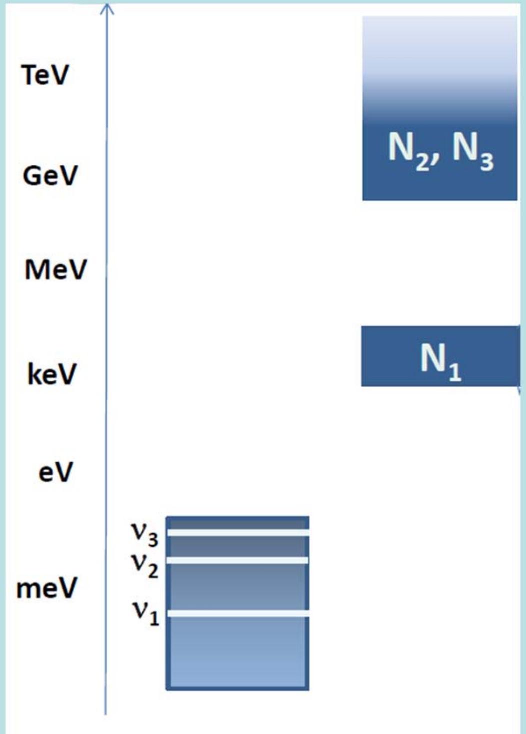
$$(\nu_e)_R \equiv N_1 \quad (\nu_\mu)_R \equiv N_2 \quad (\nu_\tau)_R \equiv N_3$$

$I = -1$

$I = 0$

„sterile”, HNL – Heavy Neutral Leptons

L.Canetti, M.Drewes, T.Frosard, M.Shaposhnikov „Dark Matter, Baryogenesis and Neutrino Oscillations from Right Handed Neutrinos” Phys. Rev. D87 (9) (2013) 093006



N_2, N_3 can generate Baryon Asymmetry of the Universe if $m_{N_2,N_3} > 140$ MeV

N_1 - DM candidate

Search for: $N_1 \to \nu\gamma$

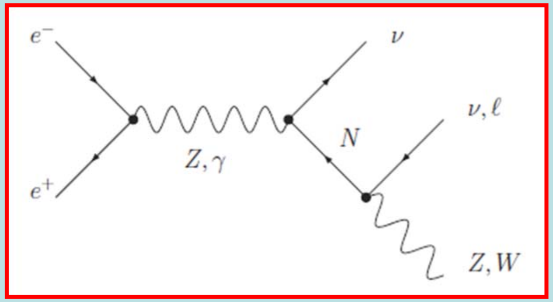
A left-handed neutrino produced e.g. in the Z^0 decay is actually a mixture of the light and heavy state

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

with the mixing angle $\theta \approx m_\nu / m_N$

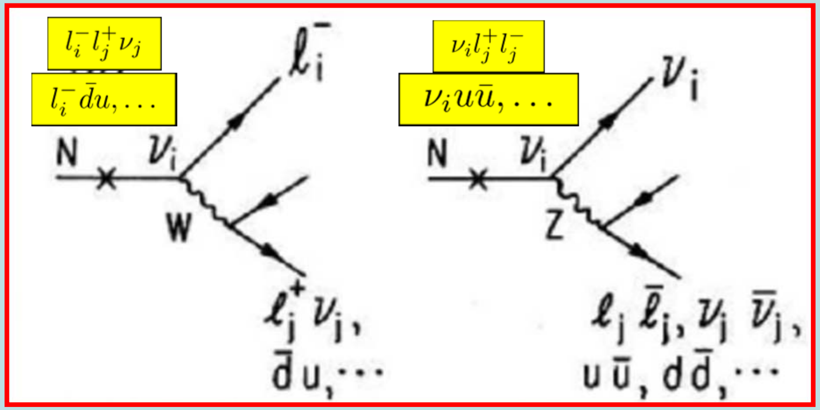
Constraints: $m_{N_1} \in (1 - 50)$ keV $\quad \theta \in (10^{-7} - 10^{-13})$ $\quad \tau_{N_1} > \tau_{\text{Universe}}$

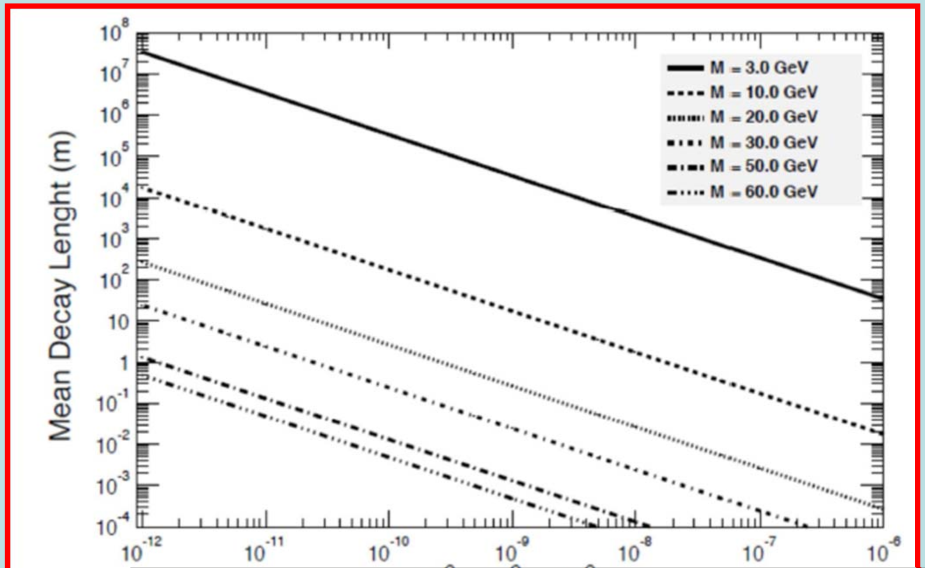
Heavy Neutrino Searches (FCCee) HNL production and decay



$Z^0 \to N + \nu$

$N \to l^+W^-,\ \nu Z$





$|U|^2 = |U_e|^2 + |U_\mu|^2 + |U_\tau|^2$ ($N - \nu$ couplings)

The average decay length of N:

$$L \sim \frac{3\ [\mathrm{cm}]}{|U|^2 \cdot (m_N[\mathrm{GeV}])^6}$$

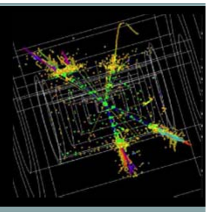
$m_N \approx 50$ GeV

$m_\nu \approx 0.05$ GeV

$|U|^2 \sim 10^{-12}$

Decay length ~1 m

Studies of charged Lepton Flavour Violation (cLFV)



Evidence for neutrino oscillations:

→ neutrinos are massive fermions AND

→ (neutral) lepton flavour is not conserved

So far there is no experimental evidence for **charged** Lepton Flavour Violation…

1. Search for cLFV in the decays of Z bosons $Z \to ll',\ l \neq l',\ l, l' = e, \mu, \tau$

IFJ PAN & CUT

SM: $\mathrm{BR}(Z \to e^{\pm}\mu^{\mp}) \sim \mathrm{BR}(Z \to e^{\pm}\tau^{\mp}) \sim \mathrm{BR}(Z \to \mu^{\pm}\tau^{\mp}) \leq 10^{-40}$

BSM: $BR(Z \to ll') \sim (10^{-12} - 10^{-10})$ (Particularly for models with new sterile fermions)

Expt: $\mathrm{BR}(Z \to e^{\pm}\mu^{\mp}) < 7.5 \times 10^{-7}$ (ATLAS)

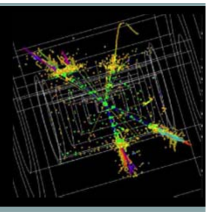
$\mathrm{BR}(Z \to e^{\pm}\tau^{\mp}) \leq 9.8 \times 10^{-6}$ (LEP)

$\mathrm{BR}(Z \to \mu^{\pm}\tau^{\mp}) \leq 1.2 \times 10^{-5}$ (LEP)

FCC ee

Sensitivity up to 10^{-12}

Studies of charged Lepton Flavour Violation (cLFV)

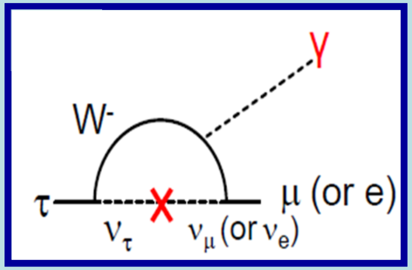


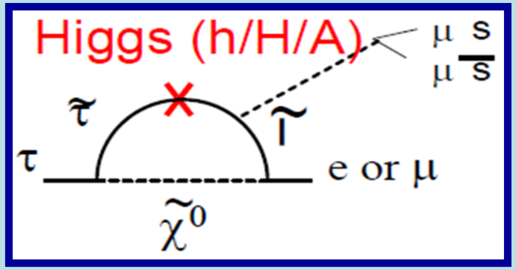
2. Search for cLFV in the decays of τ leptons

$\tau^- \to \mu^- \mu^+ \mu^-$ $\tau^- \to \mu^- \gamma$

SM: $\mathrm{BR}(\tau \to \mu\gamma) \le 10^{-40}$

$$\mathrm{BR}(\tau \to \mu\mu\mu) = \frac{3\alpha_{em}}{32\pi} \left| \sum_{i=1}^{3} U^*_{\tau i} U_{\mu i} \frac{\Delta m^2_{i2}}{m^2_W} \right| \le 10^{-40}$$





BSM: $BR(\tau \to \mu\mu\mu) < 10^{-9}$ (Particularly SUSY, Little Higgs, 4gen…)

IFJ PAN

Expt:

$\mathrm{Belle:}\ \ BR(\tau \to \mu\mu\mu) < 2.1 \times 10^{-8}$

$\mathrm{BaBar:}\ BR(\tau \to \mu\mu\mu) < 3.3 \times 10^{-8}$

$\mathrm{LHCb:}\ \ BR(\tau \to \mu\mu\mu) < 4.6 \times 10^{-8}$

M.Chrzaszcz, T.Lesiak, A Lusiani „ Search for Charged Lepton Flavour Violation at LHCb Experiment" book ISBN 978-3-639-70636-9 (2015)

- New Physics effects can be parametrized in a general way using the Effective Field Theory approach including beyond the Standard Model operators with different chirality structures (as in the LHCb analysis).

- This approach is being integrated with the TAUOLA package (Z.Was, S Jadach).

Summary

- *The circular colliders at the energy frontiers are back on the market (contrary to the death sentence received after LEP).*
- *Two ambitious projects (FCC-ee and CEPC) are being pursued.*
- *The circular colliders offer the potential for biggest data sets up to ttbar threshold and thus provide a vast physics program, in particular:*
  - ✓ *Higgs studies*
  - ✓ *Electroweak precise measurements (neutrino counting)*
  - ✓ *Top quark parameters*
  - ✓ *W mass*
  - ✓ *Flavour physics (charged lepton flavour violation)*
  - ✓ *…*

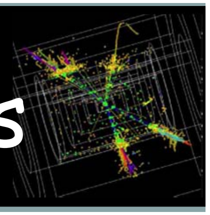
BACKUP

Physics reach of linear colliders

arXiv:1504.01726v1 [hep-ph]

$\sqrt{s}$/GeV:	92,160	240	350	500	1000	3000	threshold scans required
Higgs							
m_H	–	x	x	x	x	x	x
Γ_{tot}	–	–	x	x			
$g_{c,b}$	–	x	x	x		x	
g_{ttH}	–	–	–	x	x		
g_{HHH}	–	–	–	x	x	x	
$m_{H,A}^{SUSY}$	–	–	–	x	x	x	x
Top							
m_t^{th}	–	–	x				x
m_t^{cont}	–	–	–	x	(x)	(x)	
A_{FB}^t	–	–	x	x			
$g_{Z,\gamma}$	–	–	–	x			
g_{FCNC}	–	–	–	x	x	(?)	
Electroweak Precision Observables							
$\sin^2\theta_{\mathrm{eff}}$(Z-pole)	x					(x)	
m_W^{th}	x						x
m_W^{cont}		x	x	x	(x)	(x)	
Γ_Z	x						x
A_{LR}	x						
A_{FB}	x						

Physics reach of linear colliders



arXiv:1504.01726v1 [hep-ph]

$\sqrt{s}$/GeV:	92,160	240	350	500	1000	3000	threshold scans required
SUSY							
indirect search	x	x	x				
direct search	–	–	x	x	x	x	x
light higgsinos	–	–	x	x			x
parameter determination	–	–	x	x	x		x
quantum numbers	–	–	x	x	x		x
extrapolations	–	–	–	x	x	x	x
ν mixing							
θ_{23}^2	–	–	x	x			
Dark Matter							
effective-field-theory	–	–	–	x	x	x	
non-relativistic	–	–	x	x	x	x	
Extra gauge bosons							
indirect search $m_{Z'}$	x	–	–	x	x	x	
v'_f, a'_f	–	–	–	x	x	(x)	
$m_{W'}$	x	–	–	x	x	x	
direct search	–	–	–	–	–	x	x

FCC-hh baseline parameters

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

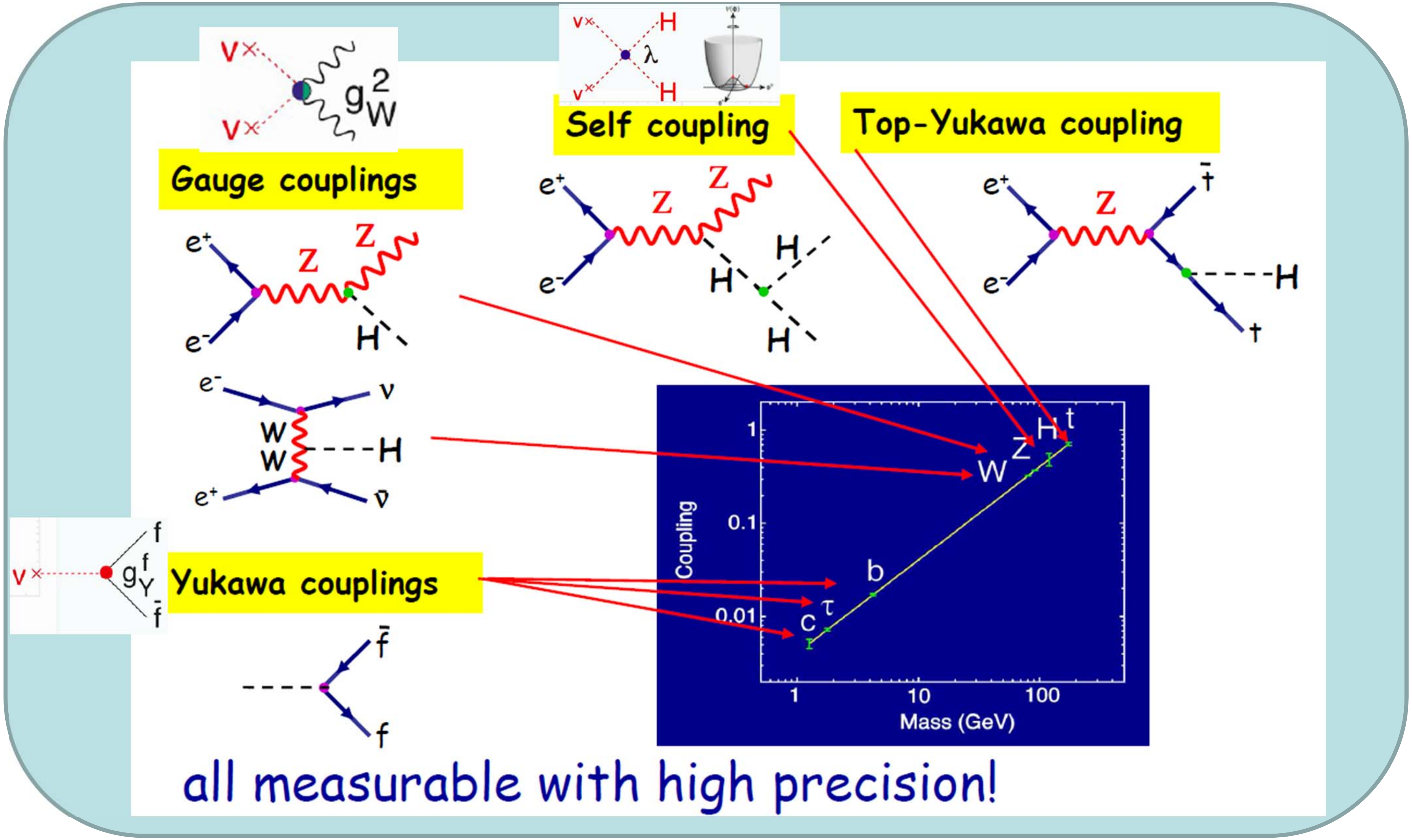
- Cross-sections for most interesting processes grow significantly from 14 TeV to 100 TeV
- With the luminosity of 30 ab^{-1} @ 100 TeV most measurements will be limited by systematic uncertainties

FCC-hh issues

- Stored beam energy: 8 GJ/beam (0.4 GJ LHC) = 16 GJ total = 2 tons of TNT
  ➔ equivalent to an Airbus A380 (560 t) at full speed (850 km/h).

- Task: develop Nb_3Sn-based 16 T dipole magnet technology.
- Goal: 16T short dipole models by 2018/19 (America, Asia, Europe).
- Non negligible synchrotron radiation (the first time in proton-proton).

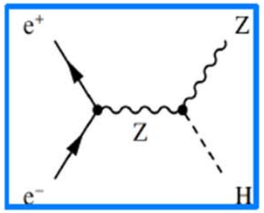
Higgs Couplings



Higgs Couplings

★ **Higgs-strahlung**

Total HZ cross section
(recoil mass)

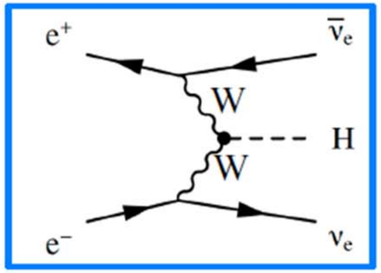


$$\sigma(\mathrm{HZ}) \propto \boxed{g^2_{\mathrm{HZZ}}}$$

+exclusive cross sections

$$\sigma(\mathrm{HZ}) \times BR(\mathrm{H} \to XX) \propto \boxed{g^2_{\mathrm{HZZ}} \cdot \frac{g^2_{\mathrm{HXX}}}{\Gamma_{\mathrm{H}}}}$$

★ Total Higgs width determined from WW fusion process



e.g.
$$\frac{\sigma(\mathrm{HZ}) \times BR(\mathrm{H} \to \mathrm{b\overline{b}})}{\sigma(\mathrm{H}\nu_e\overline{\nu}_e) \times BR(\mathrm{H} \to \mathrm{b\overline{b}})} \propto \boxed{\frac{g^2_{\mathrm{HZZ}}}{g^2_{\mathrm{HWW}}}}$$

⇒ $\boxed{g_{\mathrm{HWW}}}$

and

$$\sigma(\mathrm{H}\nu_e\overline{\nu}_e) \times BR(\mathrm{H} \to \mathrm{WW}^*) \propto \boxed{\frac{g^4_{\mathrm{HWW}}}{\Gamma_{\mathrm{H}}}}$$

Credit:
Mark
Thomson

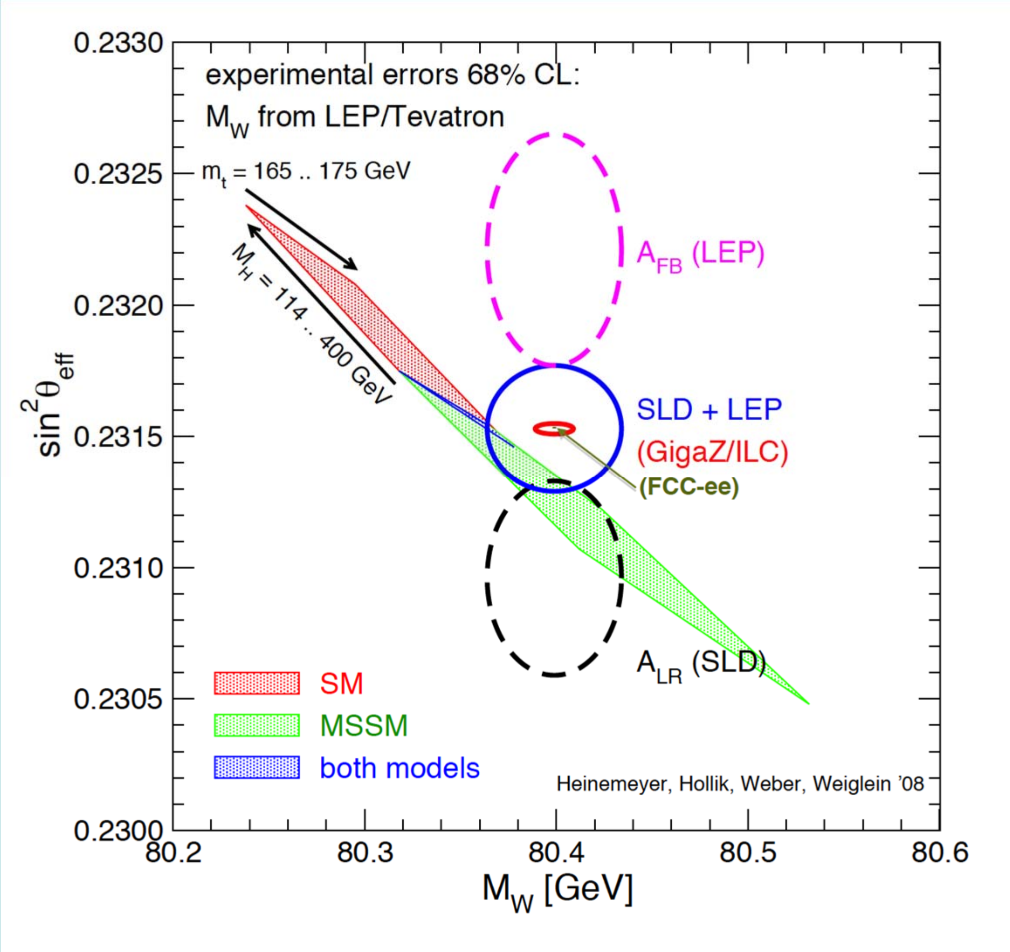
$\Gamma_H = 4.07$ GeV
for $m_H = 125$ GeV

⇒ $\boxed{\Gamma_{\mathrm{H}}}$

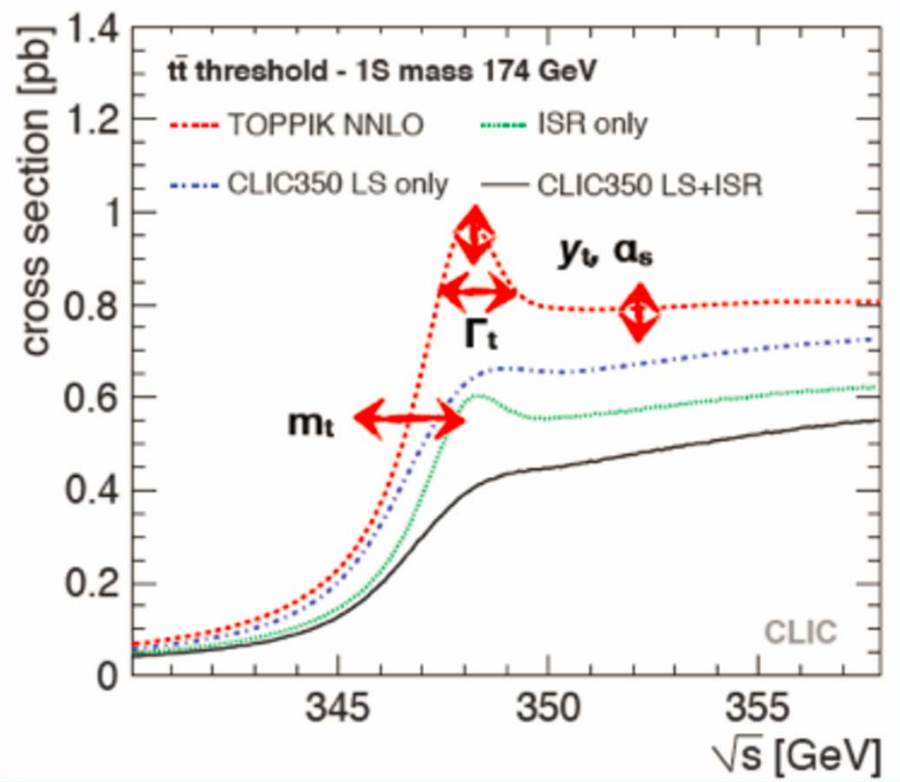
everything else follows…. all fully M.I.

Precision measurements and New Physics

- With the Higgs discovery the SM has nowhere to go!
- Any deviation is now 'new physics' , 5σ is discovery.
- Indirect but inclusive information on new physics with ~weak couplings.
- Precise knowledge of both m_H and m_{top} is essential.

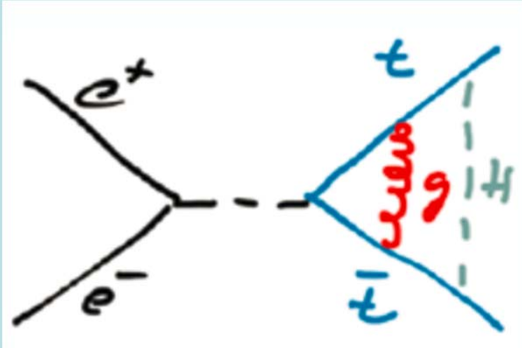


Top threshold scan



The cross-section around the threshold is affected by several properties of the top quark and by QCD

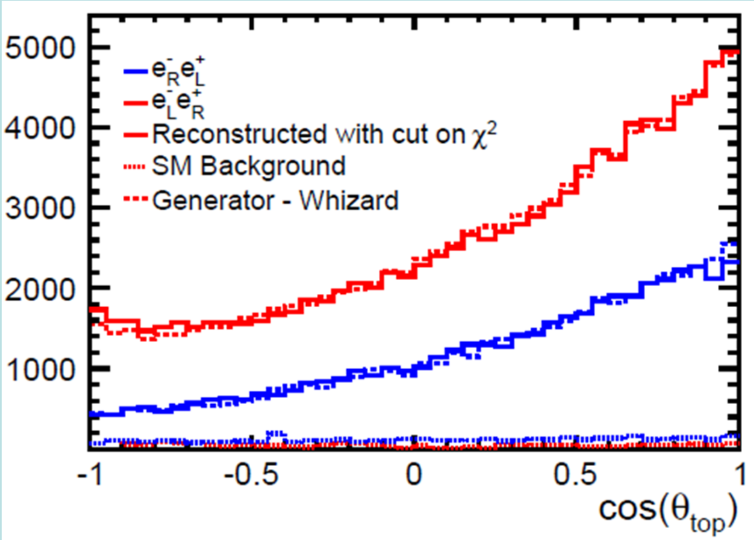
- Top mass, width, Yukawa coupling
- Strong coupling constant



- Effects of some parameters are correlated; dependence on Yukawa coupling rather weak - precise external α_s helps

Top Physics above threshold – tool in search for NP

- ✓ Precise measurements of the electroweak couplings of the top (here beam polarization plays a crucial role).
- ✓ In particular, for the forward-backward asymmetry:



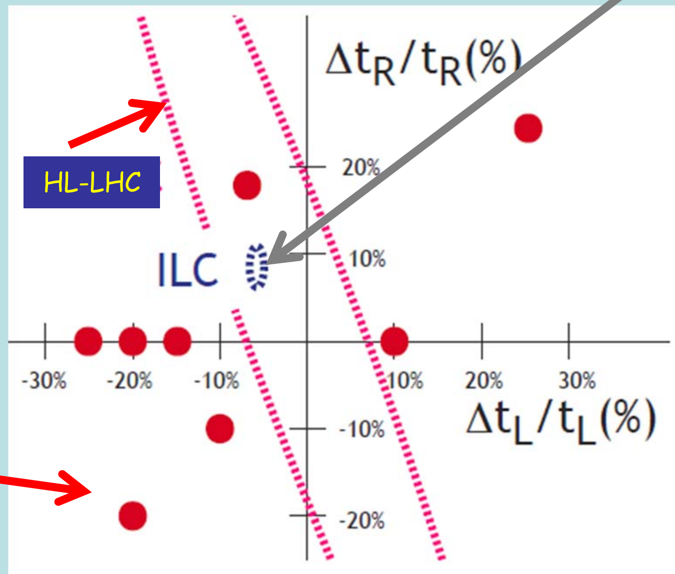
ILD, full simulation

$\sqrt{s} = 500$ GeV, $\mathcal{L} = 500$ fb^{-1}

$P(e^+, e^-) = (+30\%, -80\%)$

$\Delta A_{FB} \approx 2\%$

$\frac{\Delta t_L}{t_L} \approx 0.7\%$ $\frac{\Delta t_R}{t_R} \approx 1.8\%$



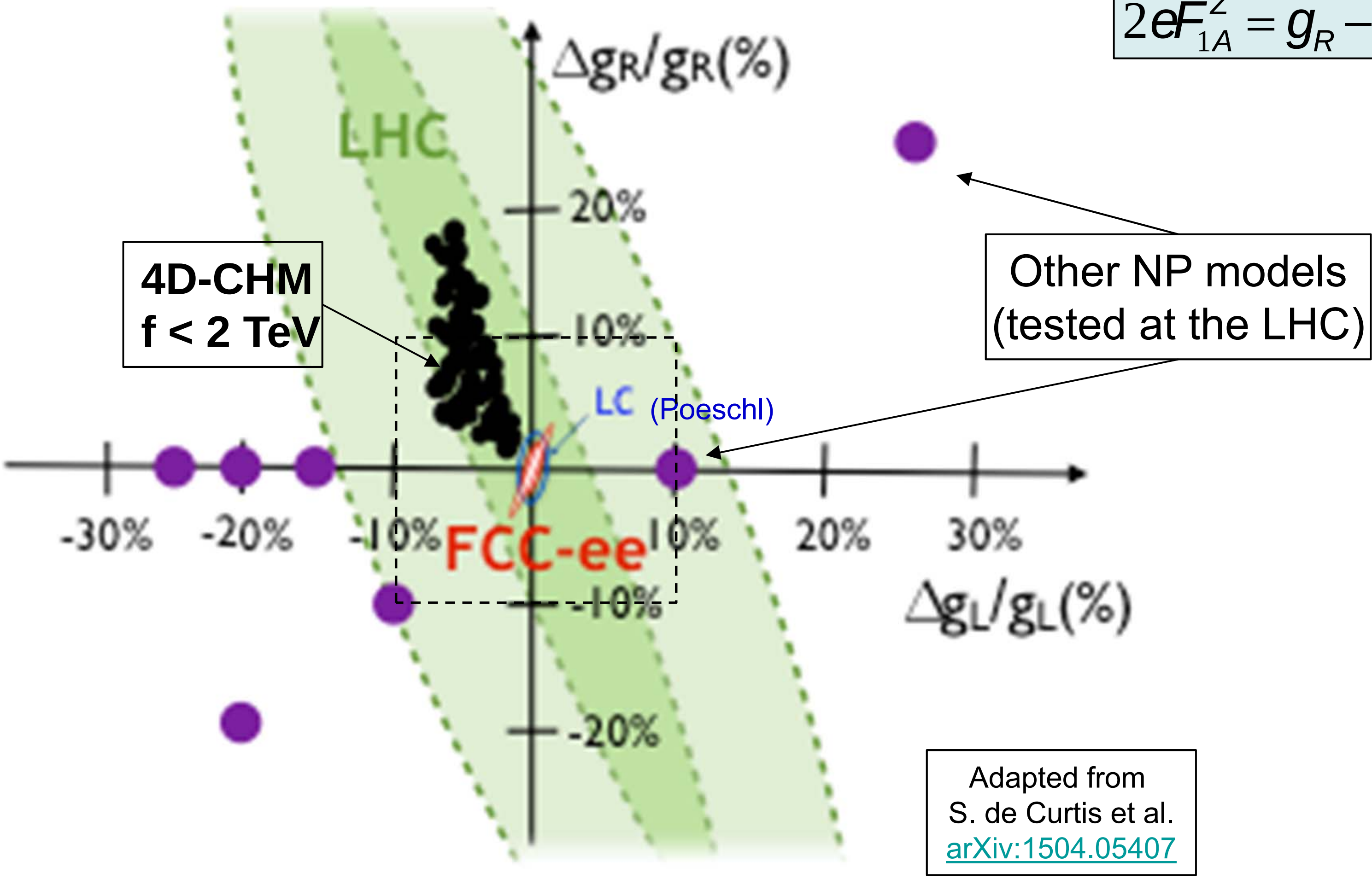
Predictions of a variety of models with composite Higgs bosons

Note: LHC comparisons not recent (Snowmass 2005)

Top Anomalous Couplings

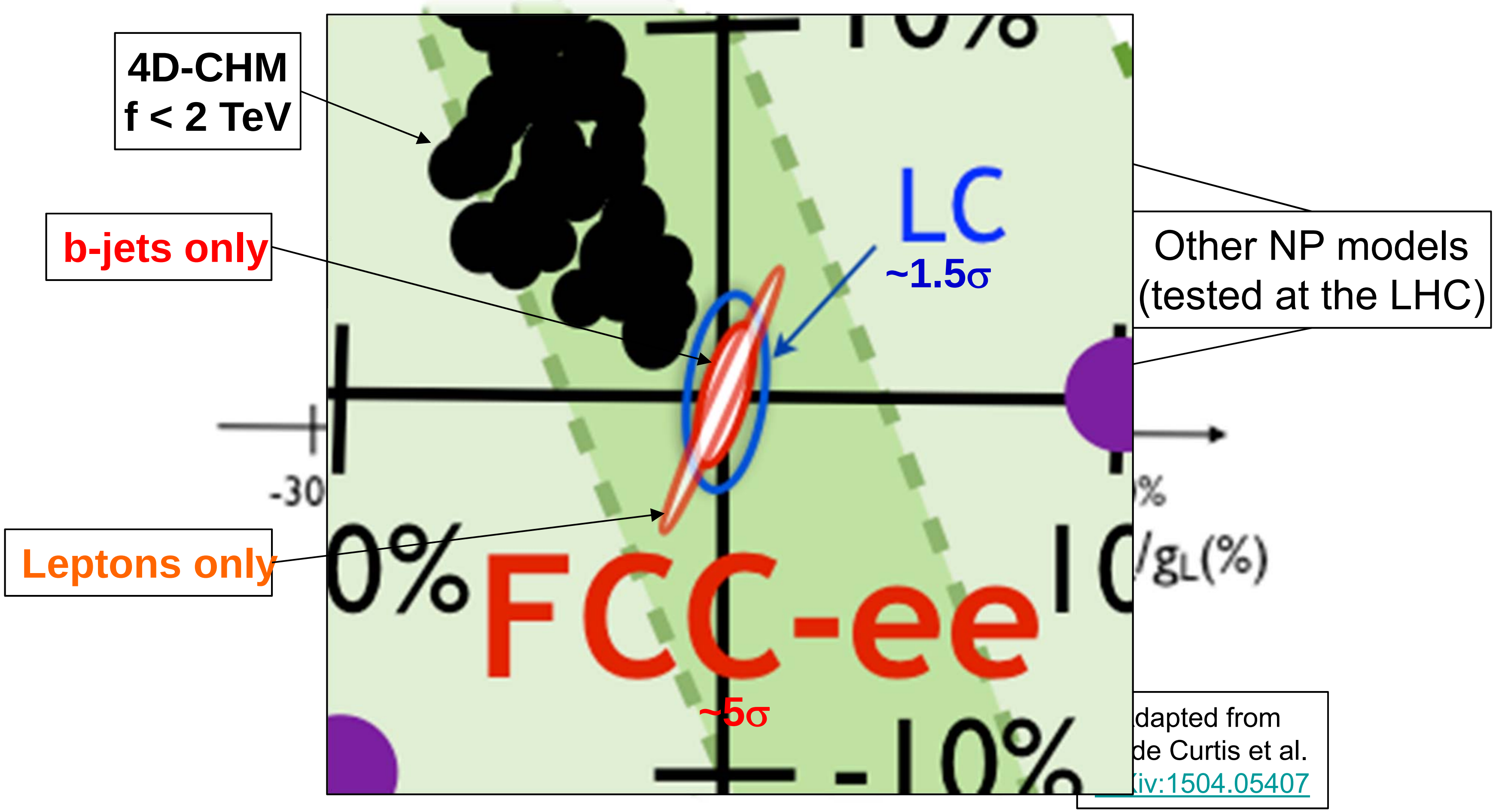
- Example: $t_L t_L Z$ and $t_R t_R Z$ couplings, g_L and g_R
  - Couplings most sensitive to composite Higgs models

$$2eF_{1V}^{Z} = g_R + g_L$$
$$2eF_{1A}^{Z} = g_R - g_L$$



Adapted from
S. de Curtis et al.
arXiv:1504.05407

Top Anomalous Couplings



Heavy Neutrino Searches (FCC-ee)

Fermions get mass via the Yukawa couplings

$$-\mathcal{L}_{\text{Yukawa}} = Y^d_{ij}\overline{Q_{Li}}\phi D_{Rj} + Y^u_{ij}\overline{Q_{Li}}\tilde{\phi}U_{Rj} + Y^\ell_{ij}\overline{L_{Li}}\phi E_{Rj} + \text{h.c.}$$

If we want the same coupling for neutrinos, we need right-handed (sterile) neutrinos… the most generic lagrangian is

$$\mathcal{L}_N = i\overline{N}_i\partial_\mu\gamma^\mu N_i - \frac{1}{2}M_{ij}\overline{N^c}_i N_j - Y^\nu_{ij}\overline{L_{Li}}\tilde{\phi}N_j$$

Kinetic term

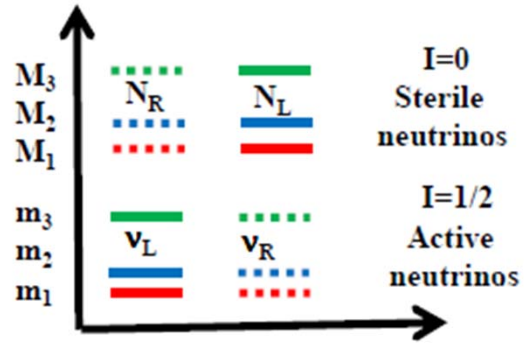
Majorana mass term

Yukawa coupling

(carries no gauge charge)

Neutrinos : the New Physics there is… and a lot of it!

forgive the confusion between fields and particle notations

SM	Dirac mass term only ≡ «Yukawa»	Majorana mass term only	Dirac AND Majorana mass terms
ν_L I= ½ $\bar{\nu}_R$ ½	ν_L ½ ν_R 0 $\bar{\nu}_R$ ½ $\bar{\nu}_L$ 0	ν_L ½ ‘ $\bar{\nu}_R$ ‘ ½	
X 3 Families	X 3 Families	X 3 Families	
6 massless states **wrong**	3 masses 12 states 3 active neutrinos 3 active antinu’s **6 sterile neutrinos…** 3 mixing angles 1 CP violating phase **0νββ = 0**	3 masses 6 active states **No steriles** 3 mixing angles 3 CP violating phases **0νββ ≠ 0**	6 masses (Majorana) 12 states 6 active states **6 sterile neutrinos…** More mixing angles and CPV phases **0νββ ≠ 0** (different than pure Majorana case if m_N<100 MeV) **➔ Leptogenesis and Dark matter**

Mass hierarchies are all unknown except $m_1 < m_2$

Preferred scenario has both Dirac and Majorana terms …

… many physics possibilities and experimental challenges *one* family see-saw :

$\theta \approx (m_D/M)$

$m_\nu \approx \frac{m_D{}^2}{M}$

$m_N \approx M$

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

Manifestations of right handed neutrinos

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

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

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

what is produced in W, Z decays is:

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

-- 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 (Serguei)

➔ Higgs and Z visible exotic decays $H \rightarrow \nu_i \bar{N}_i$ and $Z \rightarrow \nu_i \bar{N}_i$ also $W \rightarrow l_i \bar{N}_i$

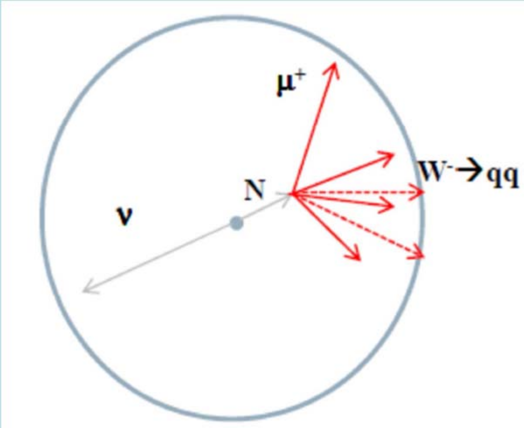
➔ violation of unitarity and lepton universality in Z, W or τ decays

-- 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)

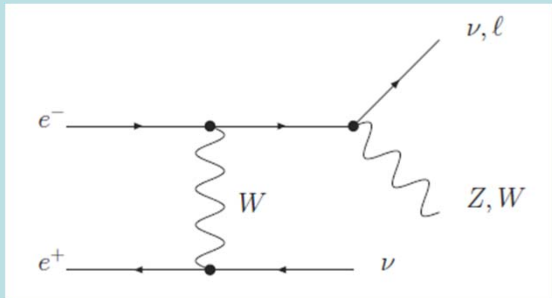
Heavy Neutrino Searches (FCCee)
Direct Search for HNL in Z decays

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



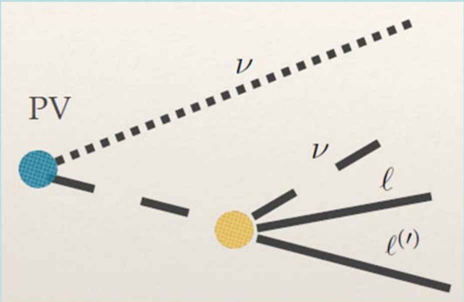
Background (4f):

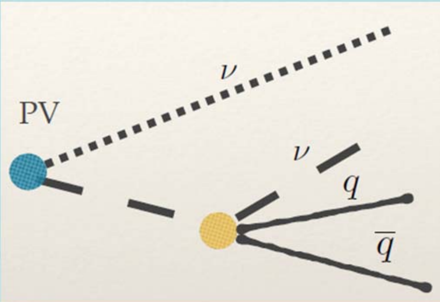
$e^+e^- \to Z \to W^*W \to l\nu\, q\bar{q}'$

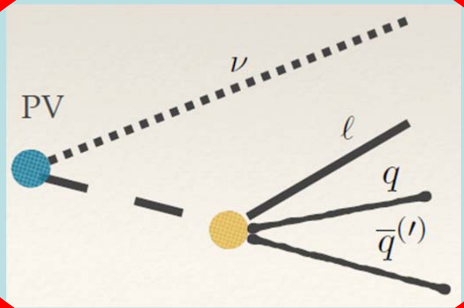


No problem if N decays after L ~ 1m away of the interaction point (expected for m_N ~ (20-80) GeV)

Experimental signatures:







The EFT approach

CLFV processes resulting from BSM theories can be described in a model independent way in terms of new operators. If new physics exists at a mass scale Λ, it can manifest itself at an electroweak scale in the form of higher order operators which, however, do not spoil the $SU(2)_L \times U(1)_Y$ symmetry. As mentioned in Sect. 2.2.3, the left-handed leptons from isospin doublets cf. Eq. 2.9 and the right-handed partners belong to isospin singlets. In the EFT approach the right-handed singlets are written as the following isospin doublets [53]:

$$R_e = \frac{1-\gamma_5}{2}\begin{pmatrix} 0 \\ \psi_e \end{pmatrix},\ R_\mu = \frac{1-\gamma_5}{2}\begin{pmatrix} 0 \\ \psi_\mu \end{pmatrix},\ R_\tau = \frac{1-\gamma_5}{2}\begin{pmatrix} 0 \\ \psi_\tau \end{pmatrix}. \tag{2.40}$$

Taking into account Eq. 2.9 and 2.40 and the matrix of Higgs fields from [53], one can derive the following relevant dimension six operators:

$$O_1 = (\bar{L}\gamma_\mu L)(\bar{L}\gamma^\mu L), \tag{2.41}$$
$$O_2 = (\bar{L}\tau^a\gamma_\mu L)(\bar{L}\tau^a\gamma^\mu L), \tag{2.42}$$
$$O_3 = (\bar{R}\gamma_\mu R)(\bar{R}\gamma^\mu R), \tag{2.43}$$
$$O_4 = (\bar{R}\gamma_\mu R)(\bar{L}\gamma^\mu L), \tag{2.44}$$
$$R_1 = g'(\bar{L}H\sigma_{\mu\nu}R)B^{\mu\nu}, \tag{2.45}$$
$$R_2 = g(\bar{L}\tau^a H\sigma_{\mu\nu}R)W^{\mu\nu}, \tag{2.46}$$

The EFT approach

as defined above, $B_{\mu\nu}$ and $W_{\mu\nu,a}$ are the electroweak gauge fields, g and g' are the coupling constants of $SU(2)_L$ and $U(1)_Y$, H denotes the matrix of Higgs fields, $L(R)$ are the left(right)-handed fields and $\sigma^{\mu\nu} = \frac{i}{4}[\gamma^\mu, \gamma^\nu]$. According to S. Turczyk et. al. [54], higher order operators are suppressed by small lepton Yukawa couplings, so we will not consider them in this thesis. In the effective field theory the most general Hamiltonian that describes the discussed process is formed as the sum of the operators from Eq. 2.41 - 2.46. For the studied process $\tau^- \to \mu^-\mu^+\mu^-$ the operators O_1 and O_2 are identical after projecting them on charged leptons. The O_3 corresponds to a purelly right-handed current and is completely analogous to O_1. For radiative operators R_1 and R_2 the latter is suppressed by small Yukawa coupling of τ, so only the photonic operator R_1 is relevant.

The analysis performed in this dissertation was also interpreted in terms of the BSM operators, as described in Sect. 4.10. The respective decay widths can be presented in the form of Dalitz distributions [55], which were derived in the following five cases, corresponding to different lepton chirality structures:

The EFT approach

- Four left-handed leptons (O_1 operator):

$$\frac{d^2\Gamma_V^{(LL)(LL)}}{d^2m_{23}d^2m_{12}} = \frac{\left|g_V^{(L_\mu L^\tau)(L_\mu L^\mu)}\right|^2}{\Lambda^4} \frac{(m_\tau^2 - m_\mu^2)^2 - (2m_{12}^2 - m_\tau^2 - 3m_\mu^2)^2}{256\pi^3 m_\tau^3}. \tag{2.47}$$

- Two left-handed, two right-handed leptons (O_4 operator):

$$\frac{d^2\Gamma_V^{(LL)(RR)}}{d^2m_{23}d^2m_{12}} = \frac{\left|g_V^{(L_\mu L^\tau)(L_\mu L^\mu)}\right|^2}{\Lambda^4} \left[\frac{(m_\tau^2 - m_\mu^2)^2 - 4m_\mu^2(m_\tau^2 + m_\mu^2 - m_{12}^2)}{512\pi^3 m_\tau^3} - \frac{(2m_{12}^2 - m_\tau^2 - 3m_\mu^2)^2 + (2m_{23}^2 - m_\tau^2 - 3m_\mu^2)^2}{1024\pi^3 m_\tau^3}\right]. \tag{2.48}$$

$$\frac{d^2\Gamma_{rad}^{(LR)}}{d^2m_{23}d^2m_{12}} = \alpha_{em}^2 \frac{\left|g_{rad}^{(L_\mu R^\tau)}\right|^2 \nu^2}{\Lambda^4} \left[\frac{4m_\mu^2(m_\tau^2 + m_\mu^2 - m_{12}^2)}{128\pi^3 m_\tau^3}\left(\frac{1}{m_{13}^4} + \frac{1}{m_{23}^4}\right) + \frac{m_\mu(m_\tau^4(-3m_\tau^2 m_\mu^2 + 2m_\mu^2)}{128\pi^3 m_\tau^3 m_{23}^2 m_{12}^2} + \frac{2m_{12}^2 - 3m_\mu^2}{128\pi^3 m_\tau^3} + \frac{(m_{13}^2 + m_{23}^2)(m_{12}^4 + m_{13}^4 + m_{23}^4 - 6m_\mu^2(m_\mu^2 + m_\tau^2))}{256\pi^3 m_\tau^3 m_{23}^2 m_{12}^2}\right]. \tag{2.49}$$

- Interference between O_1 and R_1:

$$\frac{d^2\Gamma_{mix}^{(LL)(RR)}}{d^2m_{23}d^2m_{12}} = \alpha_{em}^2 \frac{2\nu Re\left[g_V^{(L_\mu L^\tau)(L_\mu L^\mu)} g_{rad}^{*LR}\right]}{\Lambda^4} \left[\frac{m_{12}^2 - 3m_\mu^2}{64\pi^3 m_\tau^2} + \frac{m_\mu^2(m_\tau^2 - m_\mu)^2(m_{13}^2 + m_{23}^2)}{128\pi^3 m_\tau^3 m_{23}^2 m_{12}^2}\right]. \tag{2.50}$$

- Interference between O_4 and R_1:

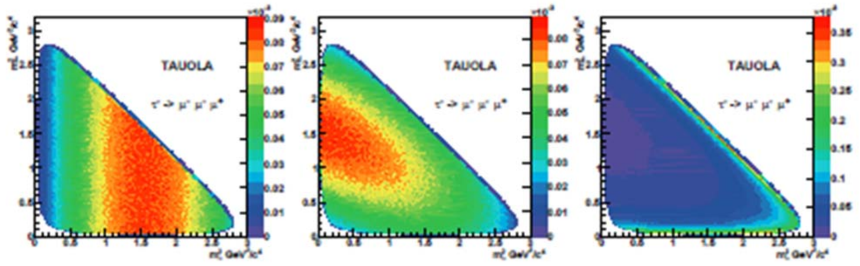
$$\frac{d^2\Gamma_{rad}^{(LL)(RR)}}{d^2m_{23}d^2m_{12}} = \alpha_{em} \frac{2\nu Re\left[g_V^{(L_\mu L^\tau)(R_\mu R^\mu)} g_{rad}^{*LR}\right]}{\Lambda^4} \left[\frac{m_\tau^2 - m_{12}^2 - 3m_\mu^2}{256\pi^3 m_\tau^3} + \frac{m_\mu(m_\tau^2 - m_\mu^2)(m_{13}^2 + m_{23}^2)}{256\pi^3 m_\tau^3 m_{23}^2 m_{12}^2}\right]. \tag{2.51}$$

The EFT approach

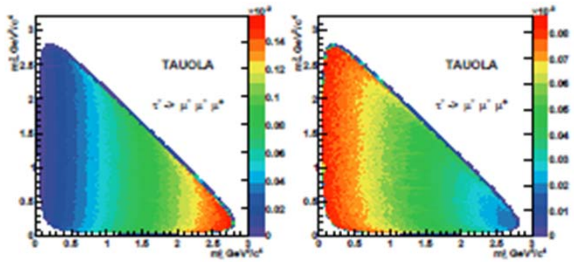
In the Eq. 2.47 - 2.51 the following dimuon masses are defined:

$$m^2_{--} = m_{12} = (p_{\mu^-} + p'_{\mu^-})^2, \qquad m^2_{+-} = m_{23} = (p_{\mu^-} + p_{\mu^+})^2, \qquad (2.52)$$

and m_ℓ are the masses of corresponding leptons, g_V are the coupling constants and ν is the element from the Higgs matrix. All the above models and several others were implemented by the author in the TAUOLA library [56] of Monte Carlo programs dedicated to τ physics. The Dalitz distributions corresponding to the simulation of each of the above mentioned models can be found in Fig. 2.5.



(a) Simulated distribution for Eq. 2.47. (b) Simulated distribution for Eq. 2.48. (c) Simulated distribution for Eq. 2.49.



(d) Simulated distribution for Eq. 2.50. (e) Simulated distribution for Eq. 2.51.

Figure 2.5: Dalitz distributions simulated in the effective field approach for the five different BSM operators corresponding to different lepton chirality structures [53]. The distributions were implemented in the TAUOLA package and normalized to unit area.