FCC

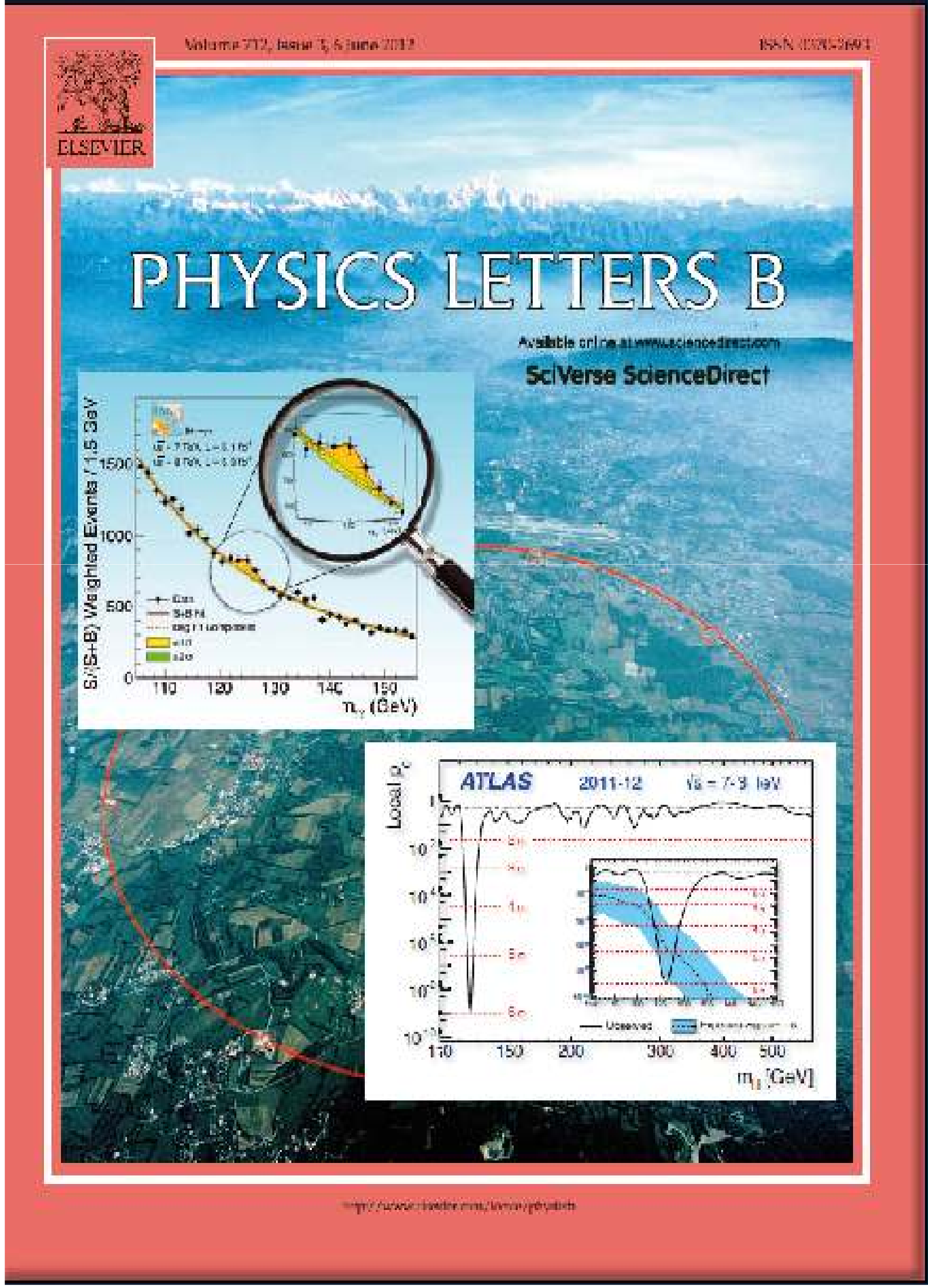
hh ee he

Physics at FCC-ee

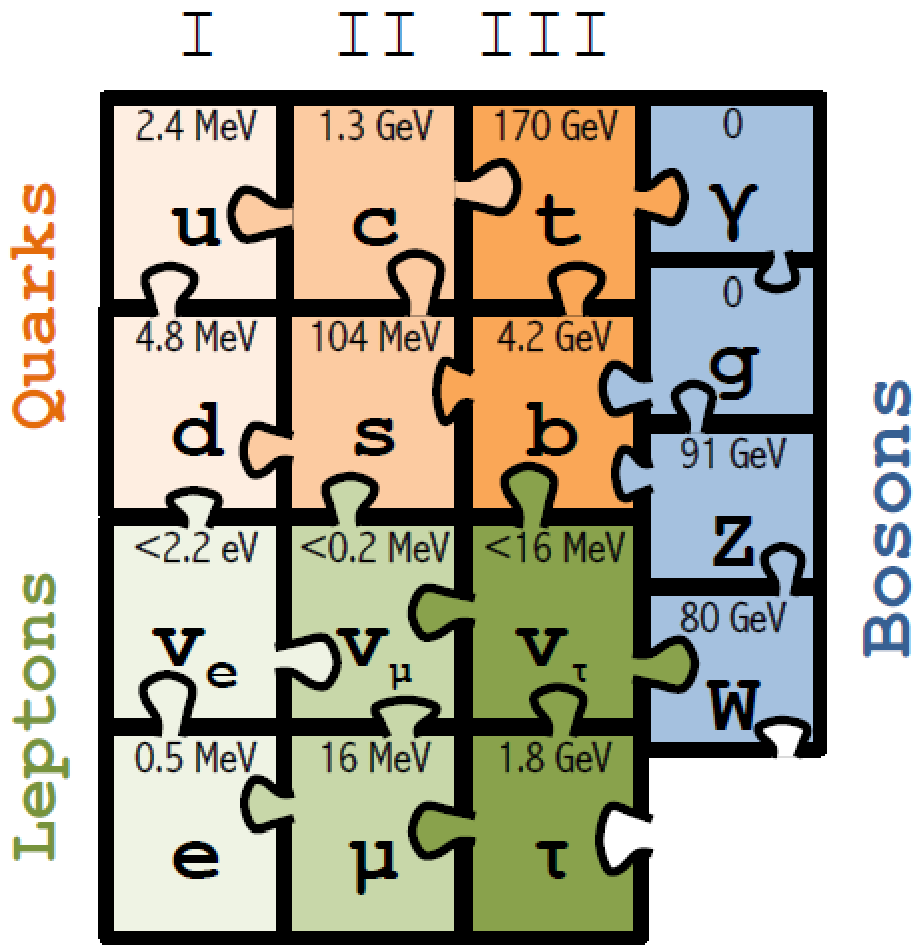
A. Blondel

see presentations and contributions by M. Dam, M. Klute, P. Janot, S. Monteil, M. Koratzinos, A. Blondel at HEP-EPS 2015 in Vienna.

THREE YEARS AGO ALREADY



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

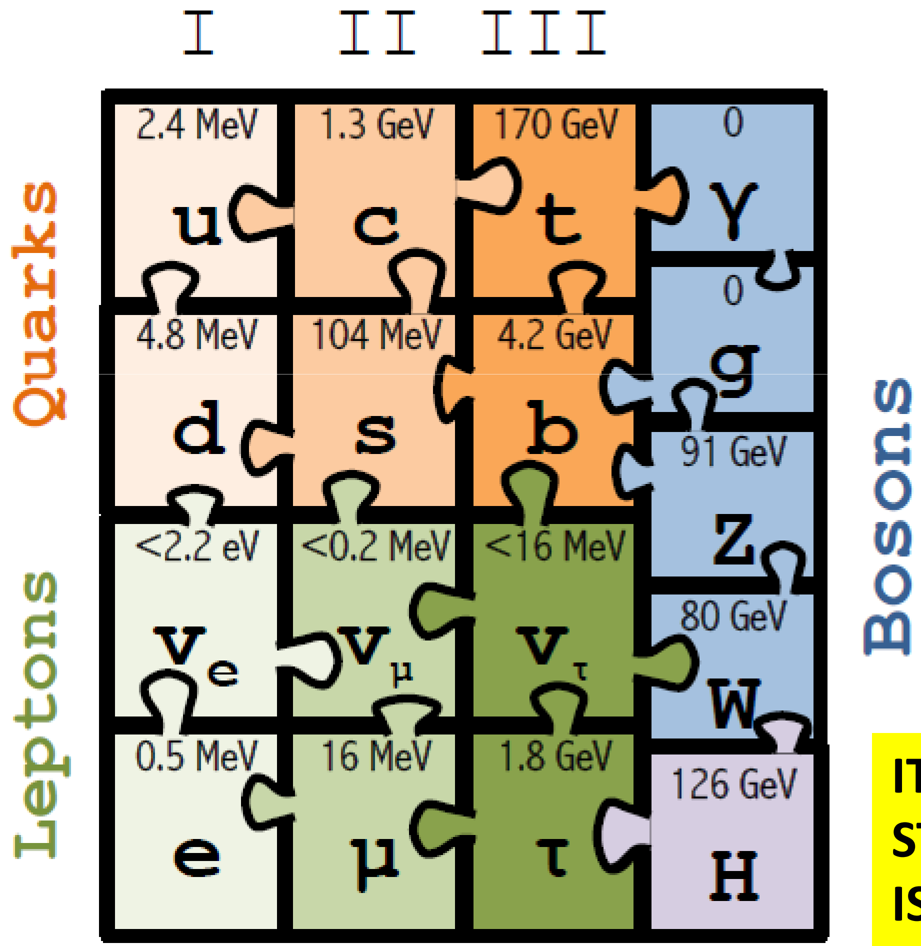


(c) Sfyrla

1997-2013 **Higgs boson mass cornered** (LEP H, M_Z etc +Tevatron m_t , M_W)

Higgs Boson discovered (LHC)

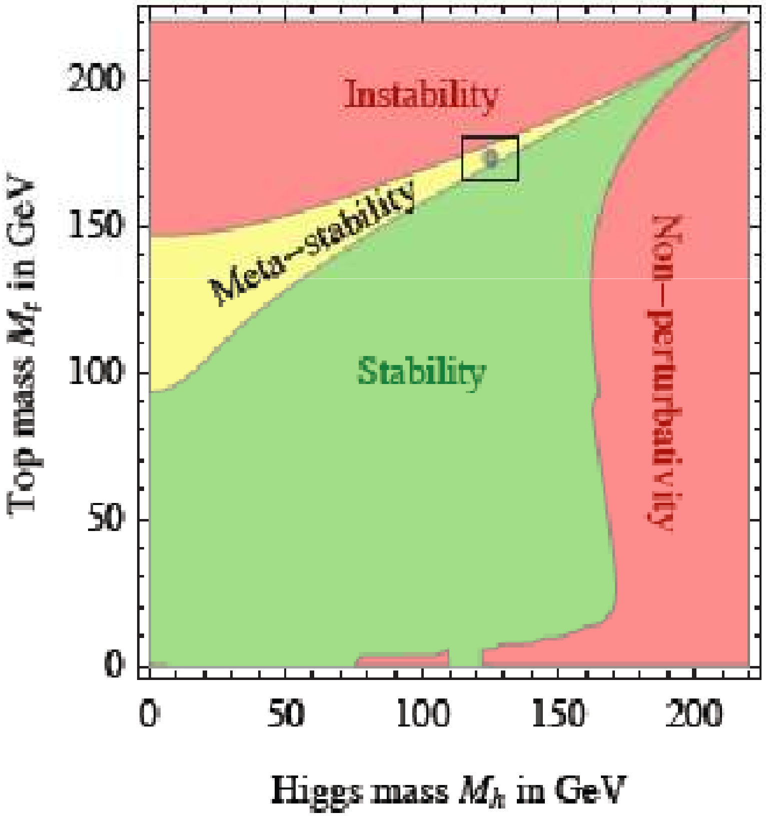
Englert and Higgs get Nobel Prize



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

(c) Sfyrla

Is it the end?



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

Is it the end?

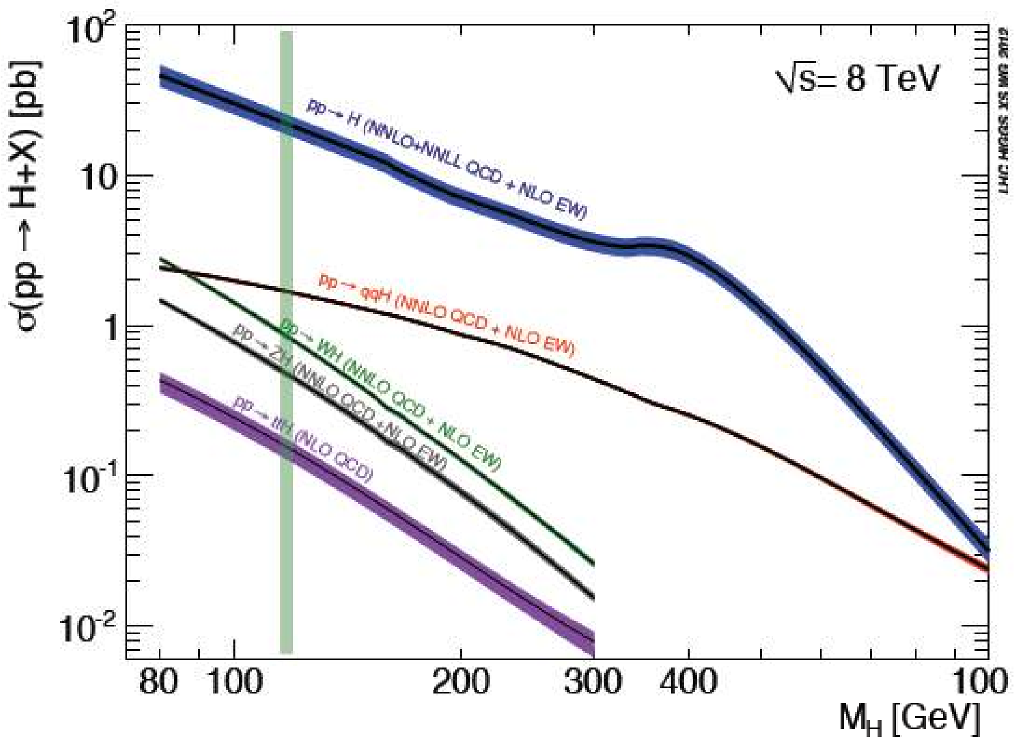
Certainly not!
-- Dark matter
-- Baryon Asymmetry in Universe
-- Neutrino masses

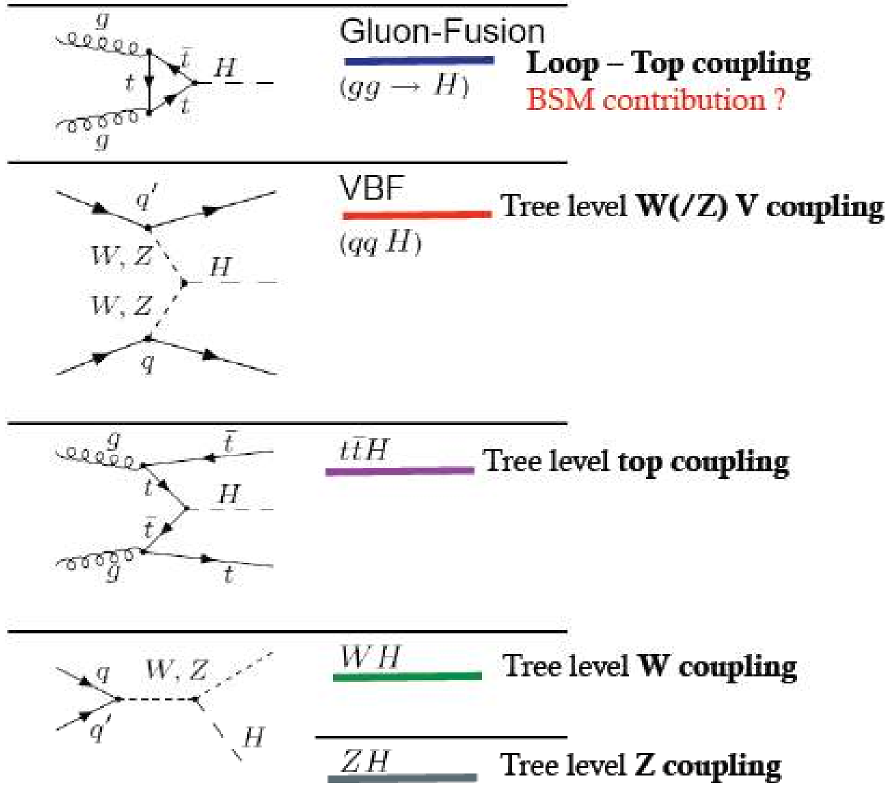
are experimental proofs that there is more to understand.

We must continue our quest

HOW?

Detection through direct observation or deviations from precise predictions **(ref. Uranus to Neptune)**





THE LHC is a Higgs Factory

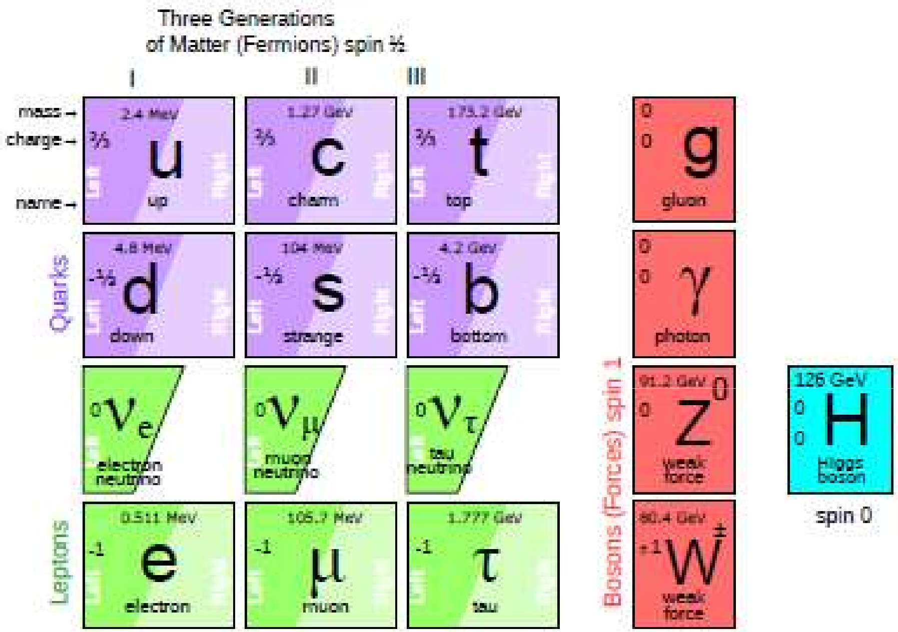
several Million Higgs already produced – more than most Higgs factory projects.
15 Higgs bosons / minute – and more to come (gain factor 3-6 going to 13 TeV)

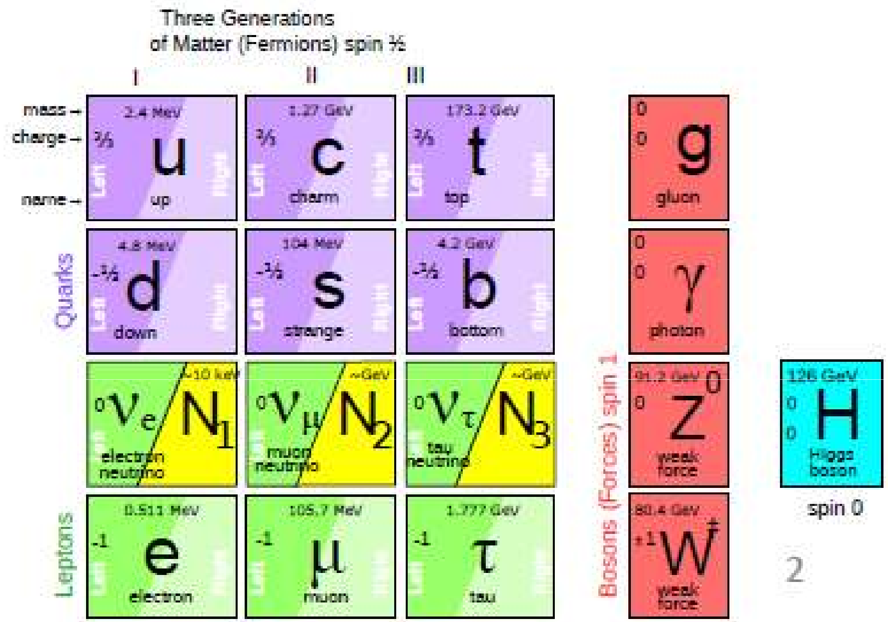
Difficulties: several production mechanisms to disentangle and significant systematics in the production cross-sections σ_{prod} .

Challenge will be to reduce systematics by measuring related processes.

$\sigma_{i\to f}^{\ observed} \propto \sigma_{prod} \dfrac{(g_{Hi})^2 (g_{Hf})^2}{\Gamma_H}$ → couplings to initial and final state, modulo total width.

at least 3 pieces are still missing





Since 1998 it is established that neutrinos have mass
and this very probably implies new degrees of freedom
➔ «sterile», very small coupling to known particles
completely unknown masses (eV to ZeV), nearly impossile to find.
.... but could perhaps explain all: DM, BAU,ν-masses

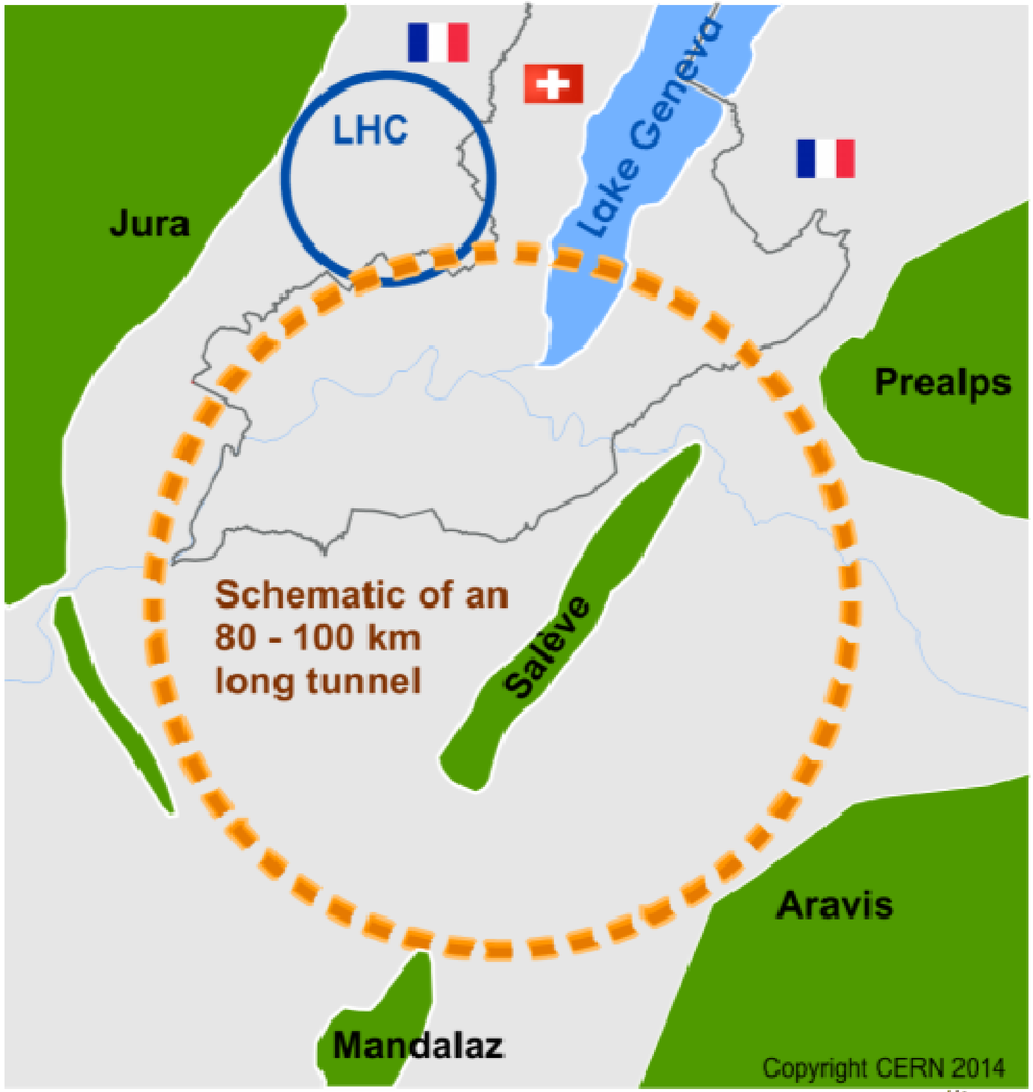
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

international design study:

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

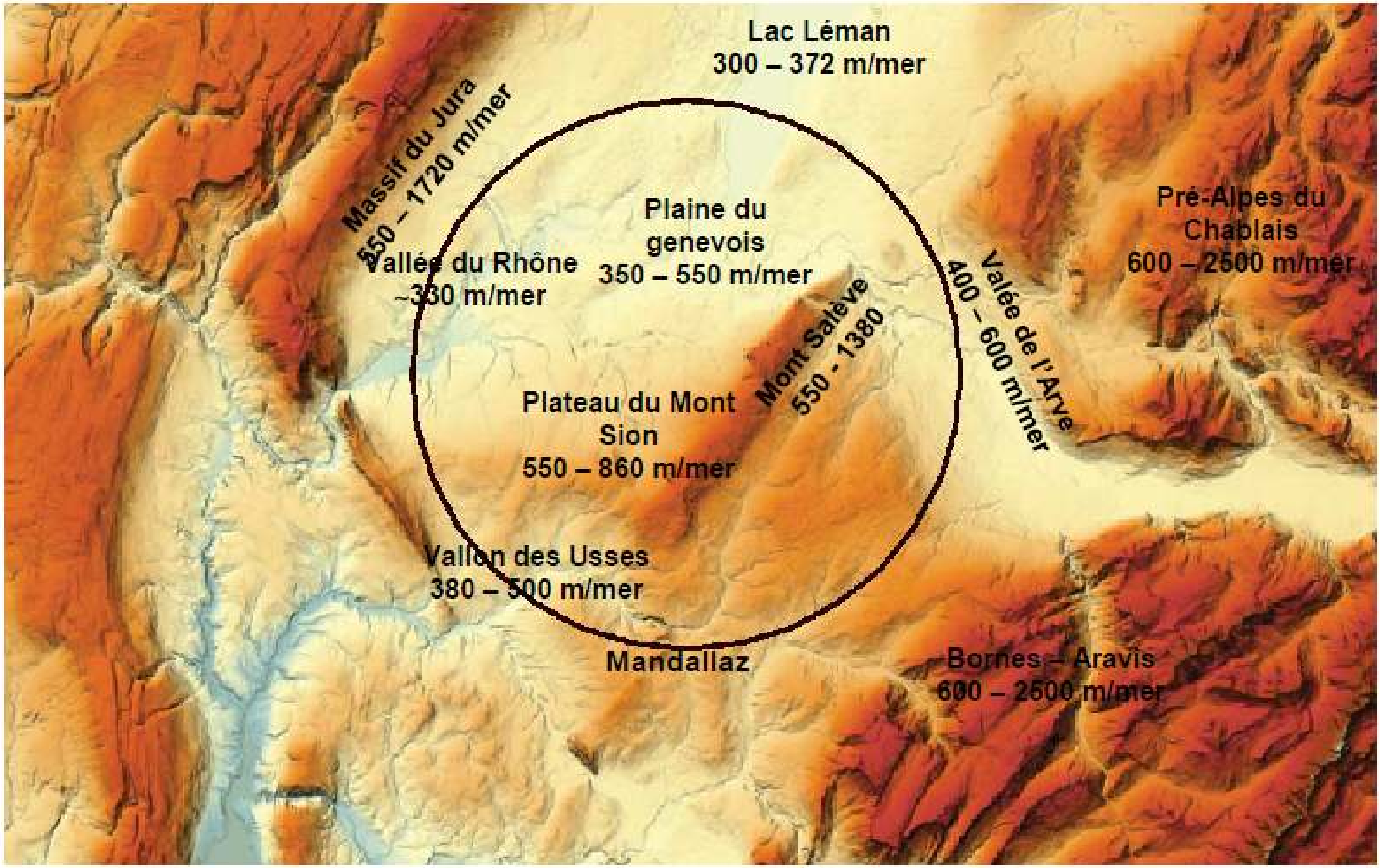
~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- e^+e^- collider (*FCC-ee*) as potential intermediate *(i.e. first)* step ECM=90-400 GeV
- *p-e* (*FCC-he*) option
- 80-100 km infrastructure in Geneva area



Tunnel location: topography [1/3]

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



93km "optimised" racetrack

PRELIMINARY

Alignment | **Shaft Tools**

Choose alignment option

93km quasi-circular ▼

Tunnel depth at centre: 206mASL

Gradient Parameters

Azimuth (°):	-15
Slope Angle x-x(%):	3
Slope Angle y-y(%):	0

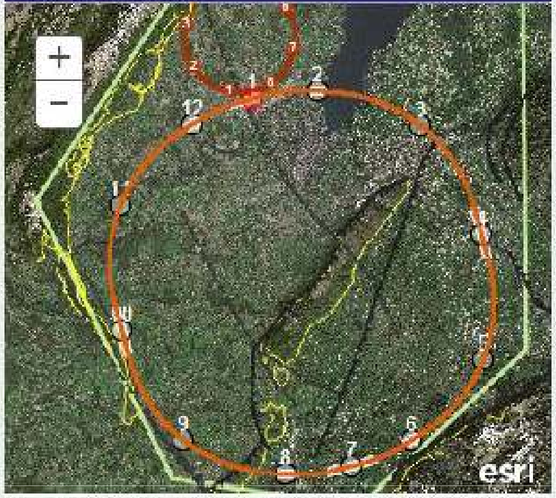
CALCULATE

Alignment centre

X: 2493923 Y: 1106695

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

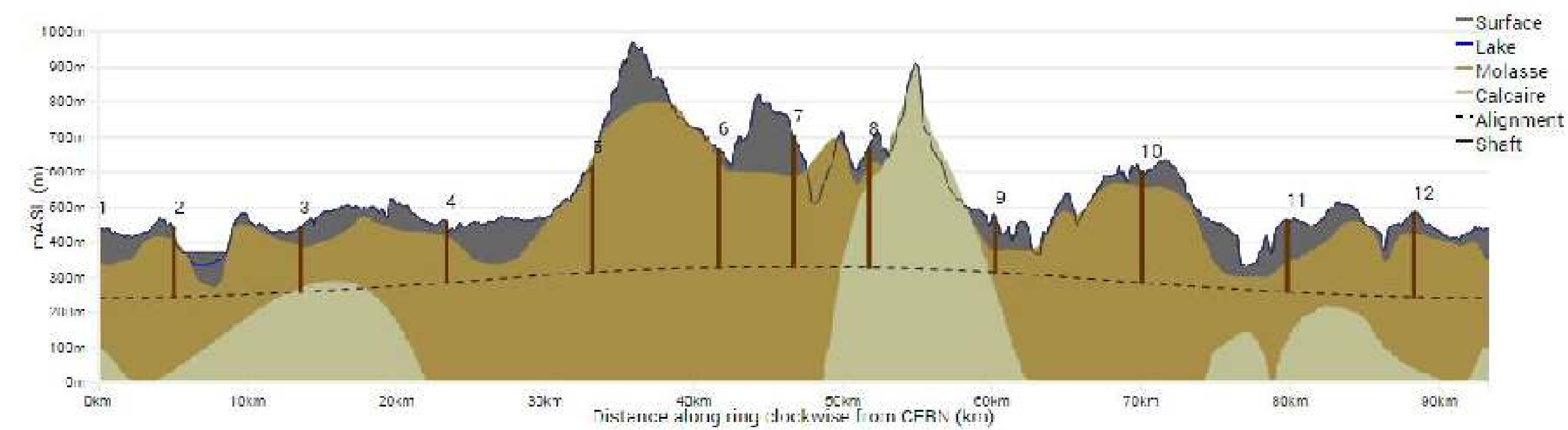
Alignment Location



Geology Intersected by Shafts | **Shaft Depths**

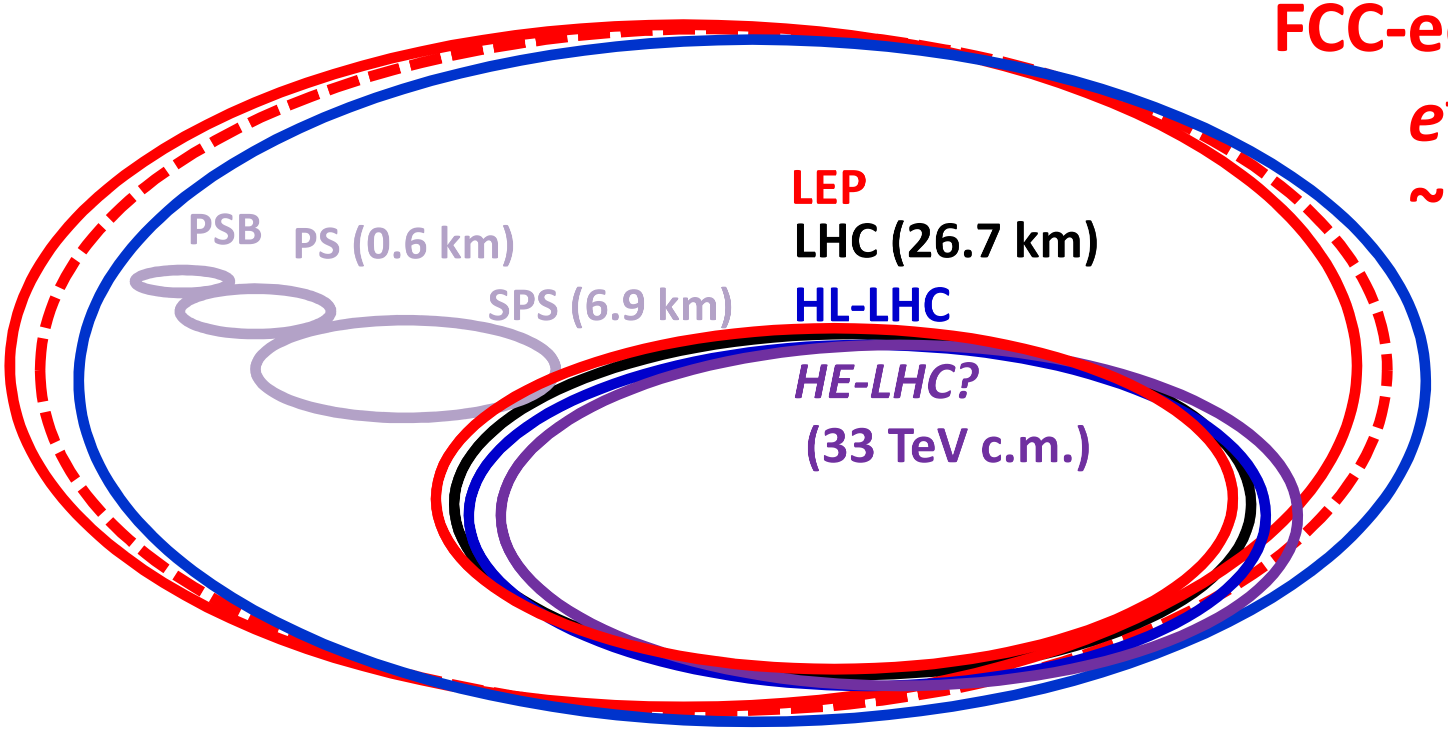
Shaft	Shaft Depth (m) Actual	Min	Mean	Max	Geology (m) Moraine	Molasse	Calcaire
1	200	195	197	200	92	108	0
2	196	143	181	211	34	167	0
3	183	175	184	194	62	121	5
4	174	146	166	178	44	130	0
5	299	286	311	350	0	325	0
6	336	325	339	350	35	302	0
7	374	349	377	412	119	256	0
8	337	318	341	356	44	56	257
9	156	131	145	157	94	61	0
10	315	305	320	336	46	269	0
11	233	199	202	234	122	81	0
12	239	229	238	243	58	181	0
Total	3014	2801	3001	3211	741	2062	247

Alignment Profile



J. Osborne & C. Cook

possible long-term strategy



FCC-ee (80-100 km, e^+e^-, up to ~350 GeV c.m.)

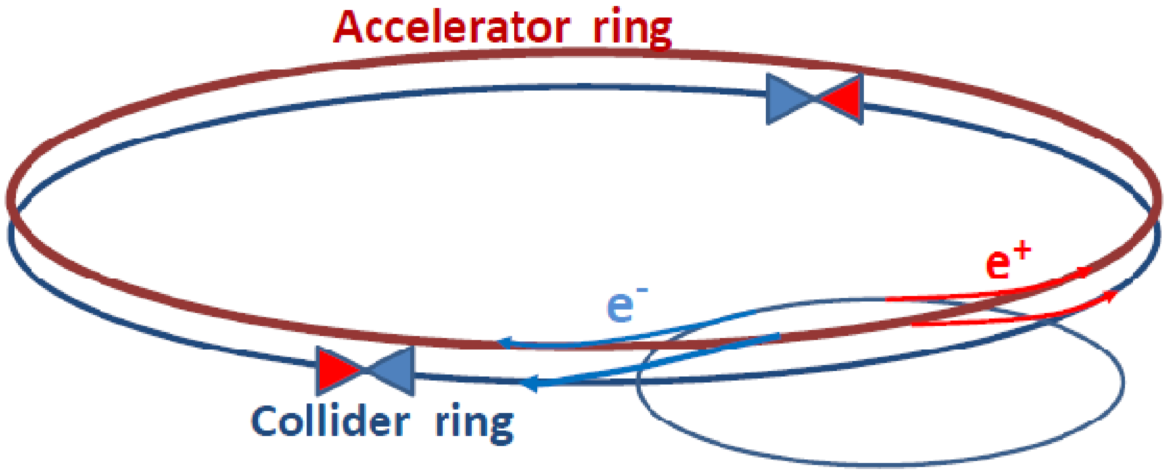
FCC-hh (*pp*, up to 100 TeV c.m.)

60 years of e^+e^- *pp AA* ep physics @ highest energies

NB if there is an electron ring it will be before the hadron machine !

LEP3, CEPC and TLEP/FCC-ee

Circular e+e- colliders designed to study the Higgs boson
but also: Z, W and top factories



AB, F. Zimmermann
Dec. 13 2011

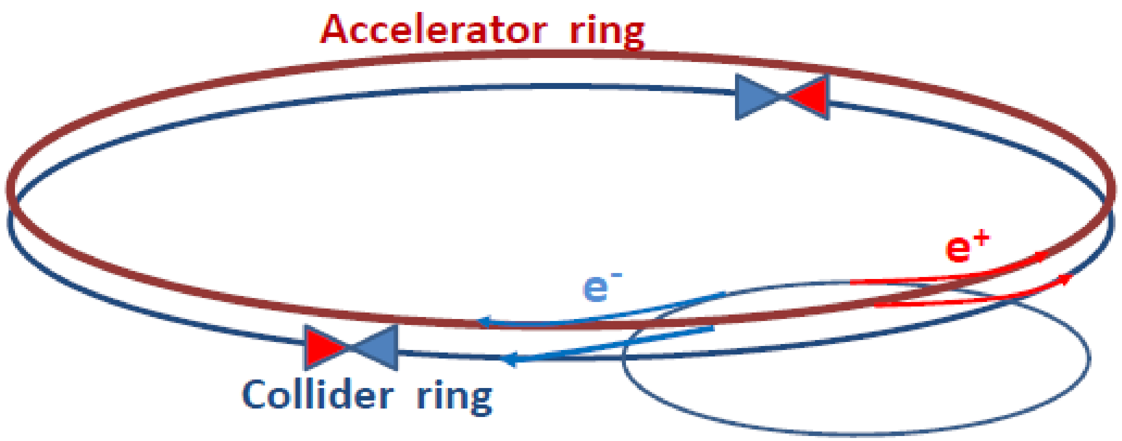
Original motivation (end 2011): now that m_H and m_top are known, explore EW region with a high precision, affordable, high luminosity machine

➔ Discovery of New Physics in rare phenomena or precision measurements

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

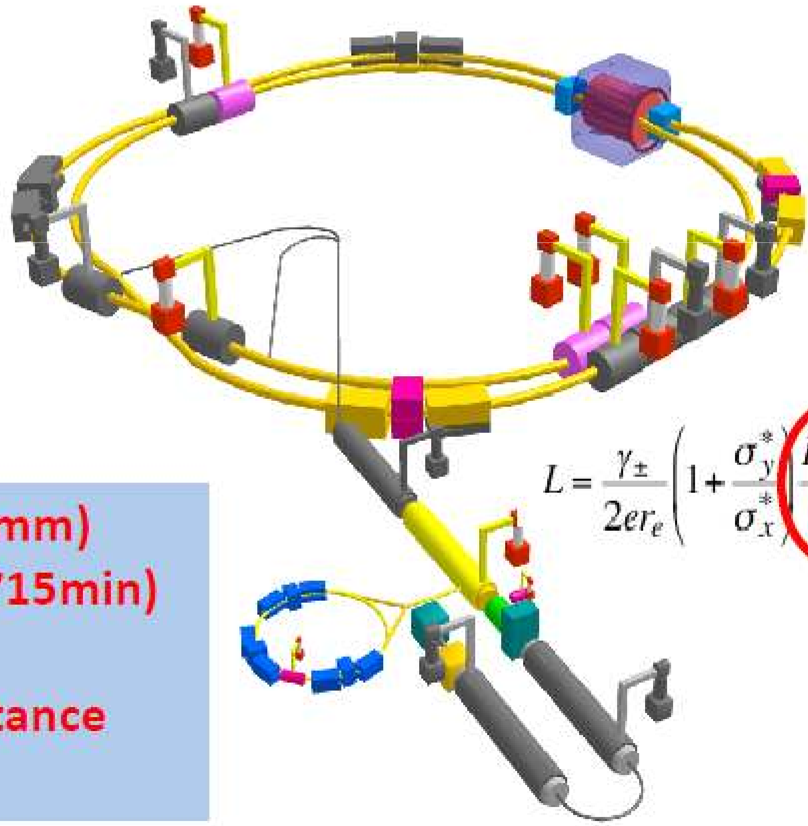
Answer is in the B-factory design: a low vertical emittance ring with higher intrinsic luminosity, and small β^*_y (1mm vs 5cm at LEP) 50
Electrons and positrons have a much higher chance of interacting
➔ much shorter lifetime (few minutes)
➔ top up continuously with booster ==> increase operation efficiency 5
Increase SR beam power to 50MW/beam 4

1000
at ZH threshold
in LEP/LHC tunnel
X 4 in FCC tunnel
X 4 interaction points
ah-ah!



SuperKEKB – TLEP demonstrator!

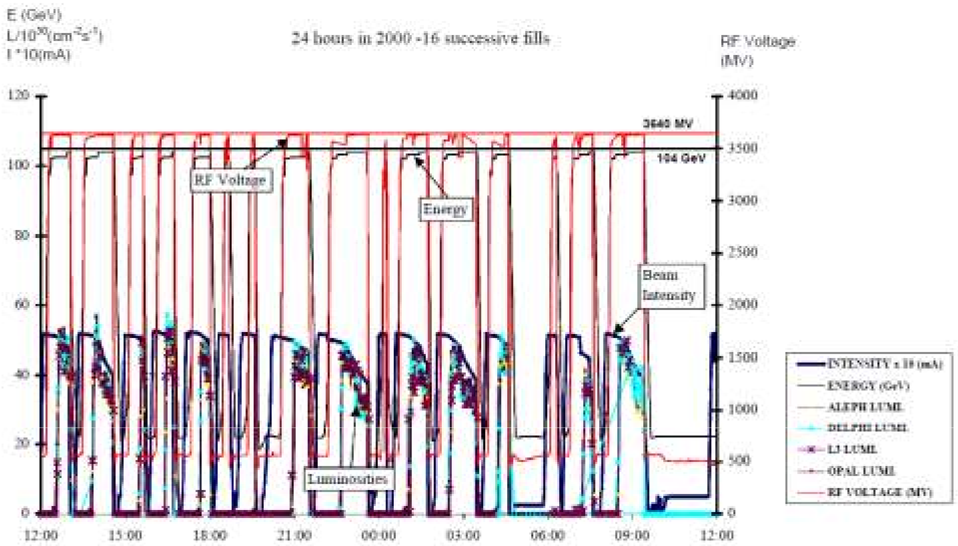
beam commissioning will start in **2016**



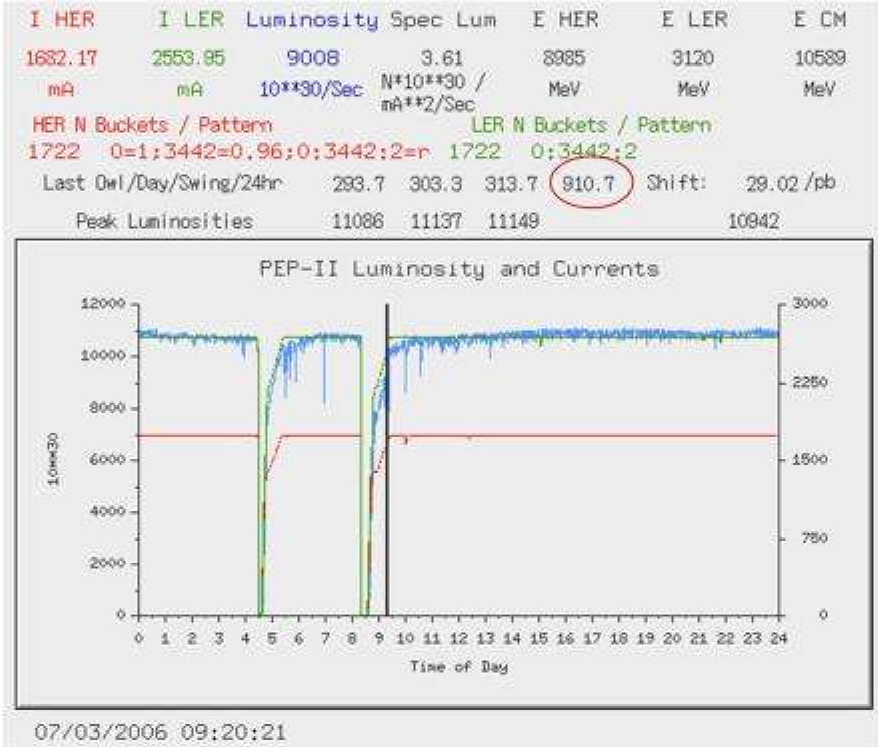
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

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

Toping up ensures constant current, settings, etc... and greater reproducibility of system



LEP2 in 2000 (12th year!):
fastest possible turnaround but
average luminosity ~ 0.2 peak luminosity



B factory in 2006 with toping up
average luminosity ≈ peak luminosity

The Higgs at a e+e- Collider has been studied for many years (Tesla, ILC, CLIC)

At a given Ecm and Luminosity, the physics has marginally to do with the fact that the collider is *linear or circular*

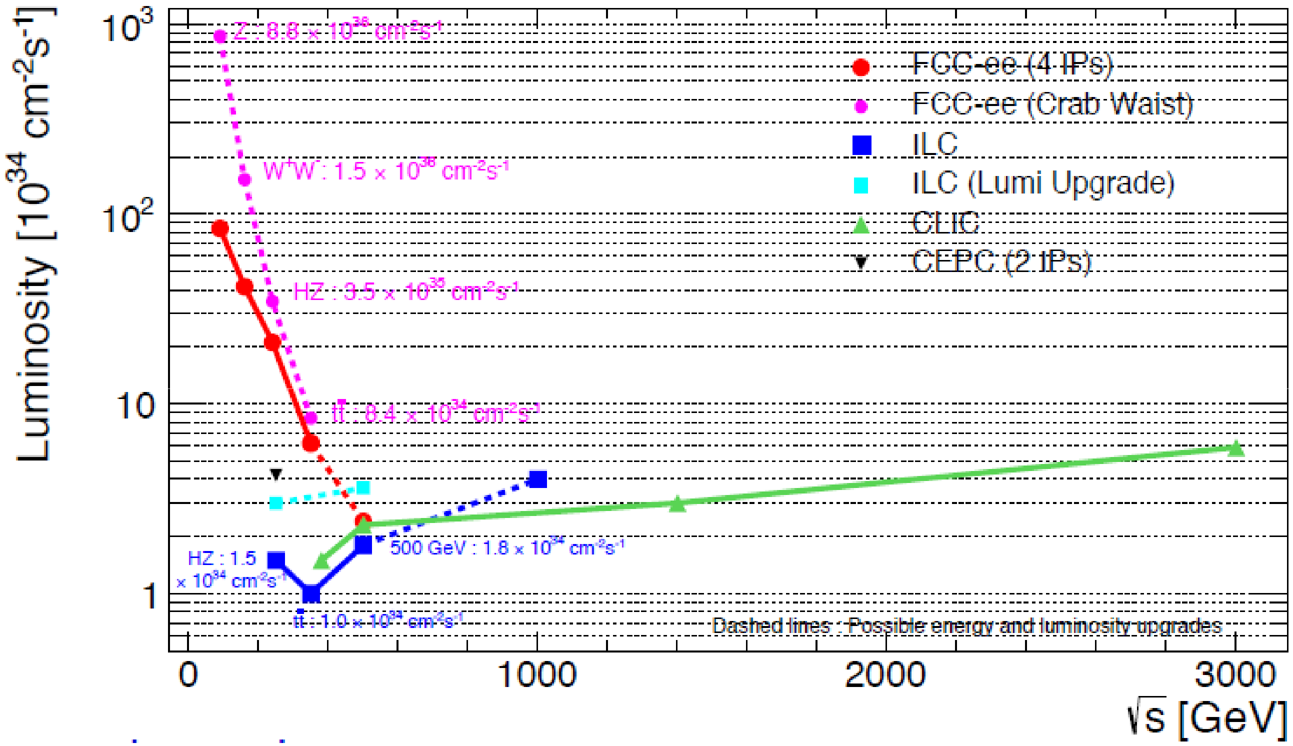
--specifics:

-- e- polarization is easy at the source in LC, (not critical for Higgs)
-- EM backgrounds from beam disruption at LC
-- knowledge and definition of beam energy at CC
-- one IP (LC) vs several IPs (CC)
-- Dependence of Luminosity on Center-of-mass energy →

-- detectors are likely to share many qualities.

Provide highest possible luminosity from Z to tt by exploiting b-factory technologies:

- **separate e- and e+ storage rings**
- **very strong focussing: β*y = 1mm**
- **top-up injection**
- **crab-waist crossing**



Overlap in Higgs/top region, but differences and complementarities between linear and circular machines:
Circ: High luminosity, experimental environment (up to 4 IP), E_{CM} calibration
Linear: higher energy reach, longitudinal beam polarization

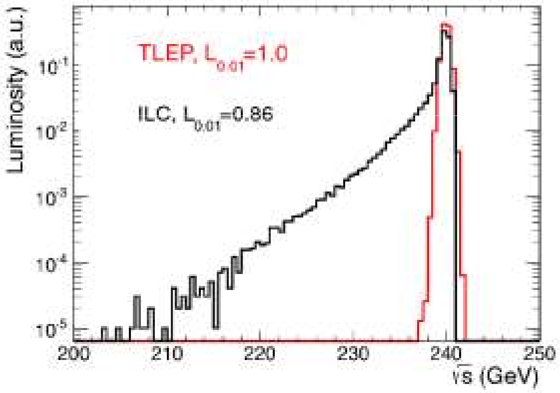
Experimental conditions

-- 2-4 IPs L^*~2m

-- bunch crossing spacing from 2-5 ns (Z) up to 3μs (top)

-- no pile-up (<0.001 at FCC-Z/CrabWaist)

-- beamstrahlung is mild for experiments



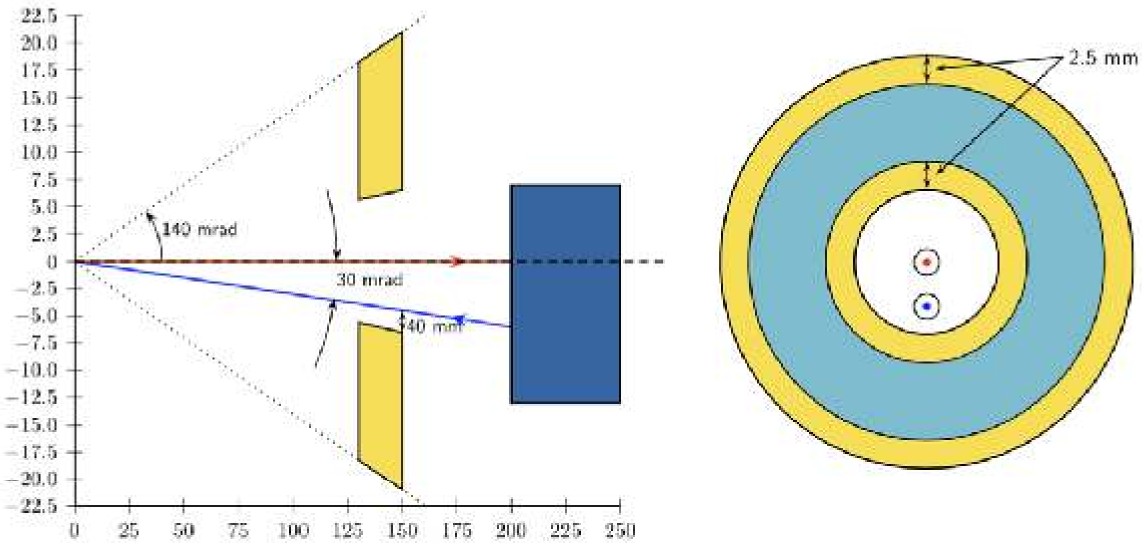
	FCCZ	FCCZ, c.w	CEPC	FCC ZH	ILC500
Npairs / BX	200	9900	3260	640	165000
Leading process	96% LL	65% LL	80% LL	90% LL	60% BH
Epairs / BX (GeV)	86	2940	2600	570	400000
Leading process	100% LL	100% LL	98% LL	96% LL	70% BH

-- Beam energy calibration for Z and W running

-- IR design with crossing angle is not trivial

➔ a challenging magnet design issue.

Of particular importance: luminosity monitors



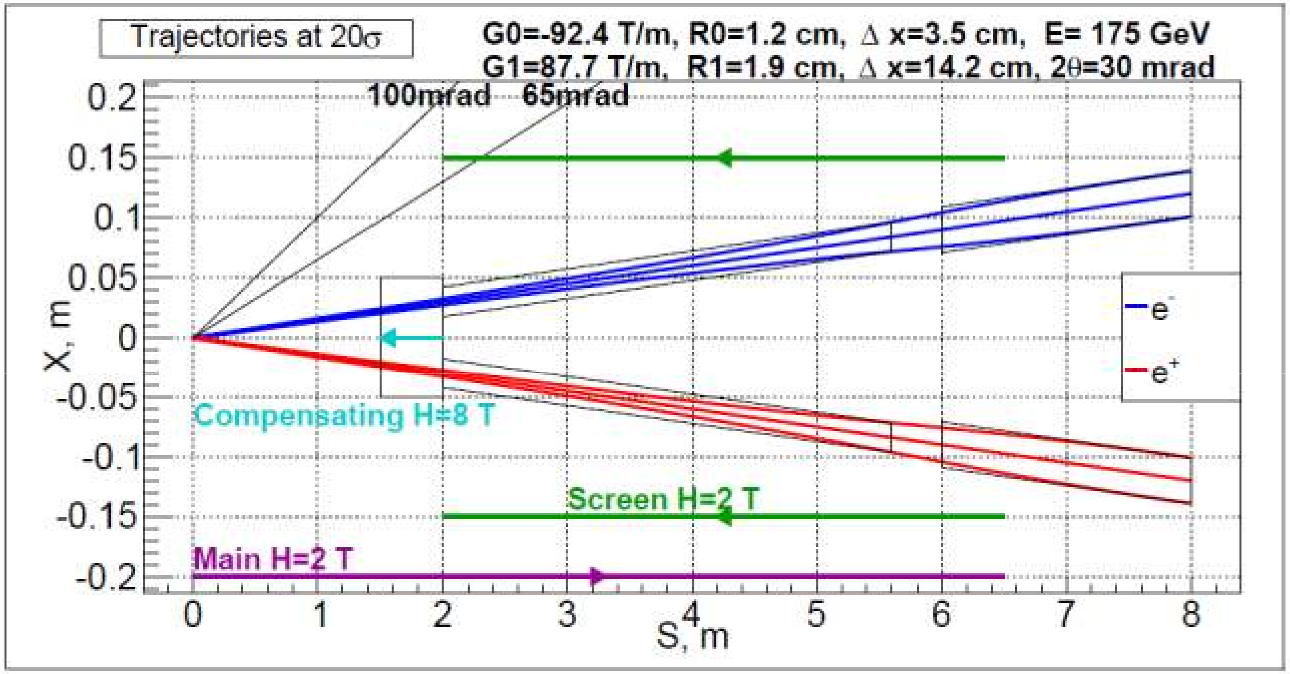
M. Dam

Requirements dominated by Z line shape and peak cross-section measurements

Shift in parameter for a shift of +10^{-4} in acceptance

z_{front} [mm]	r_{min} [mm]	r_{max} [mm]	θ_{min} [mrad]	θ_{max} [mrad]	σ [nb]	δz_{front} [μm]	δr_{min} [μm]	δr_{max} [μm]
1000	80	115	80	115	10	50	−2.1	6.1
1300	89	157	68	121	18	65	−3.0	17
1500	95	185	63	123	23	75	−3.5	26

Final Focus layout: sketch of solenoids



Solenoid compensation and integration (similar to superKEKB)
integration of luminosity monitors
Synchrotron radiation

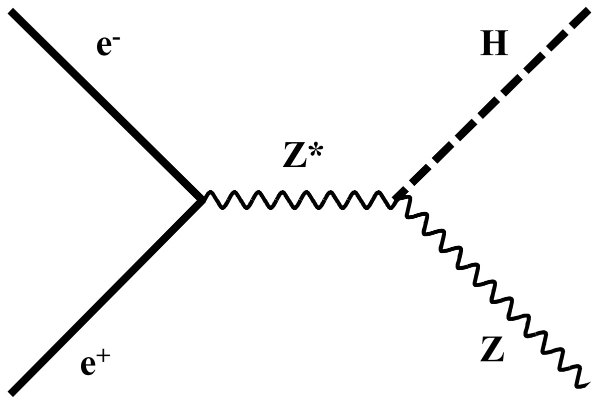
➔ **creation of dedicated MDI group.**

Higgs production mechanism

"higgstrahlung" process close to threshold

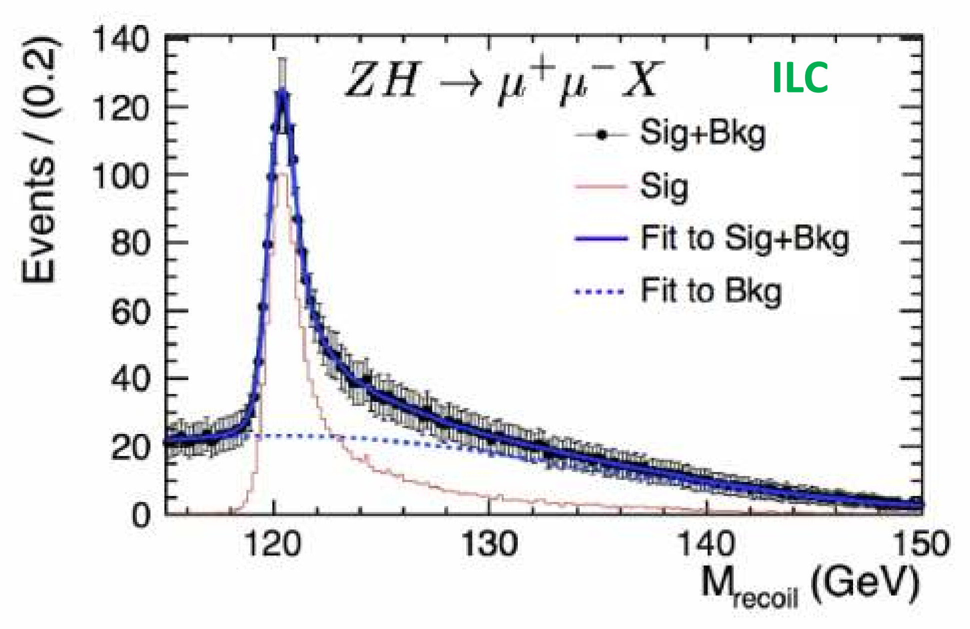
Production xsection has a maximum at near threshold ~200 fb

$10^{34}/cm^2/s$ ➔ 20'000 HZ events per year.



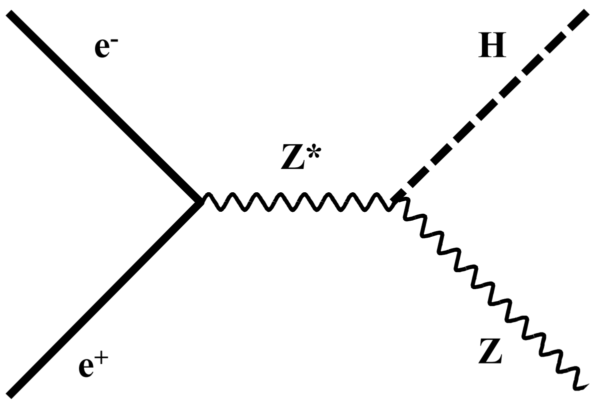
Z – tagging
by missing mass

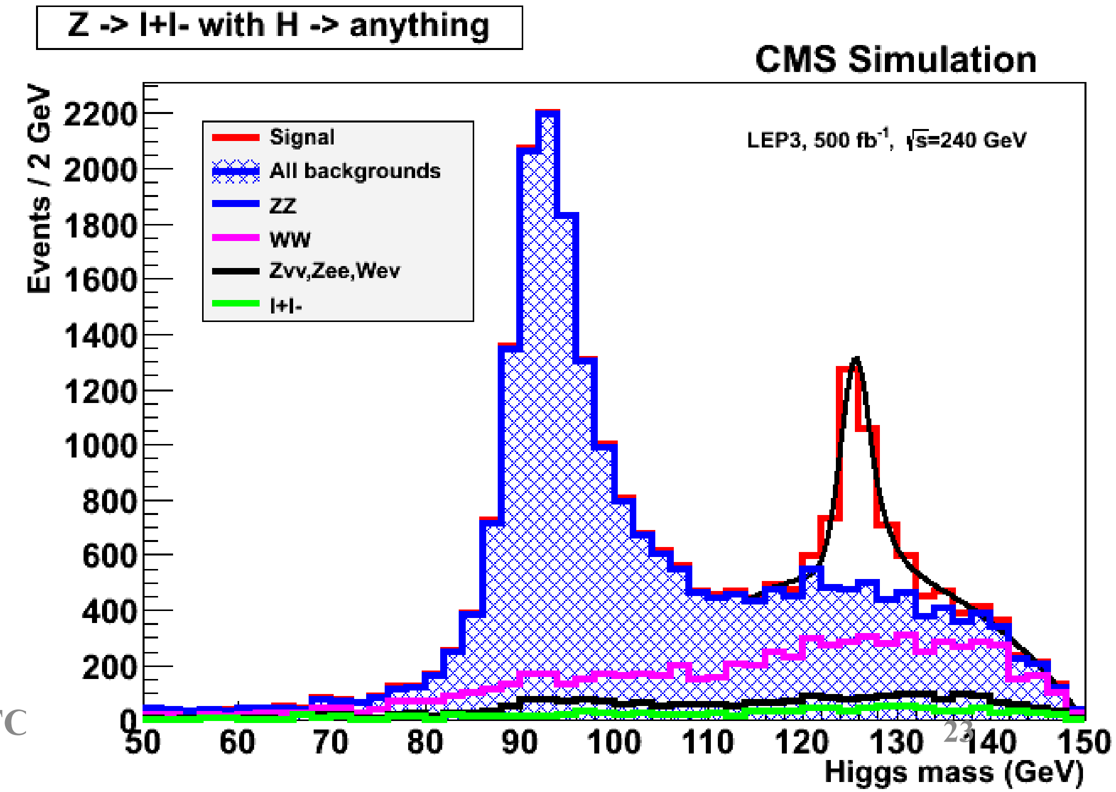
For a Higgs of 125GeV, a centre of mass energy of 240GeV is sufficient
➔ kinematical constraint near threshold for high precision in mass, width, selection purity



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





FCC-ee as Higgs factory

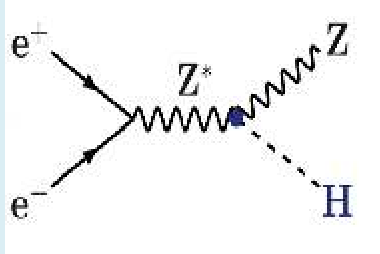
(constrained fit including ‘exotic’)

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

➔ total width ***<1%***

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

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



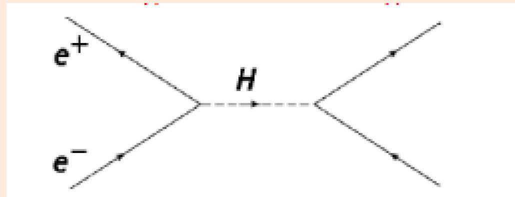
2 10^6 ZH events in 5 years

«A tagged Higgs beam».

sensitive to new physics in loops

incl. invisible = (dark matter?)
NB leptonic tag only.
Will improve with Hadronic Z tag

A big challenge, but unique:
Higgs s-channel production at $\sqrt{s} = m_H$



10^4 events per year. limits or signal?
monochromators?
Aleksan, D’Enterria, Woijcik

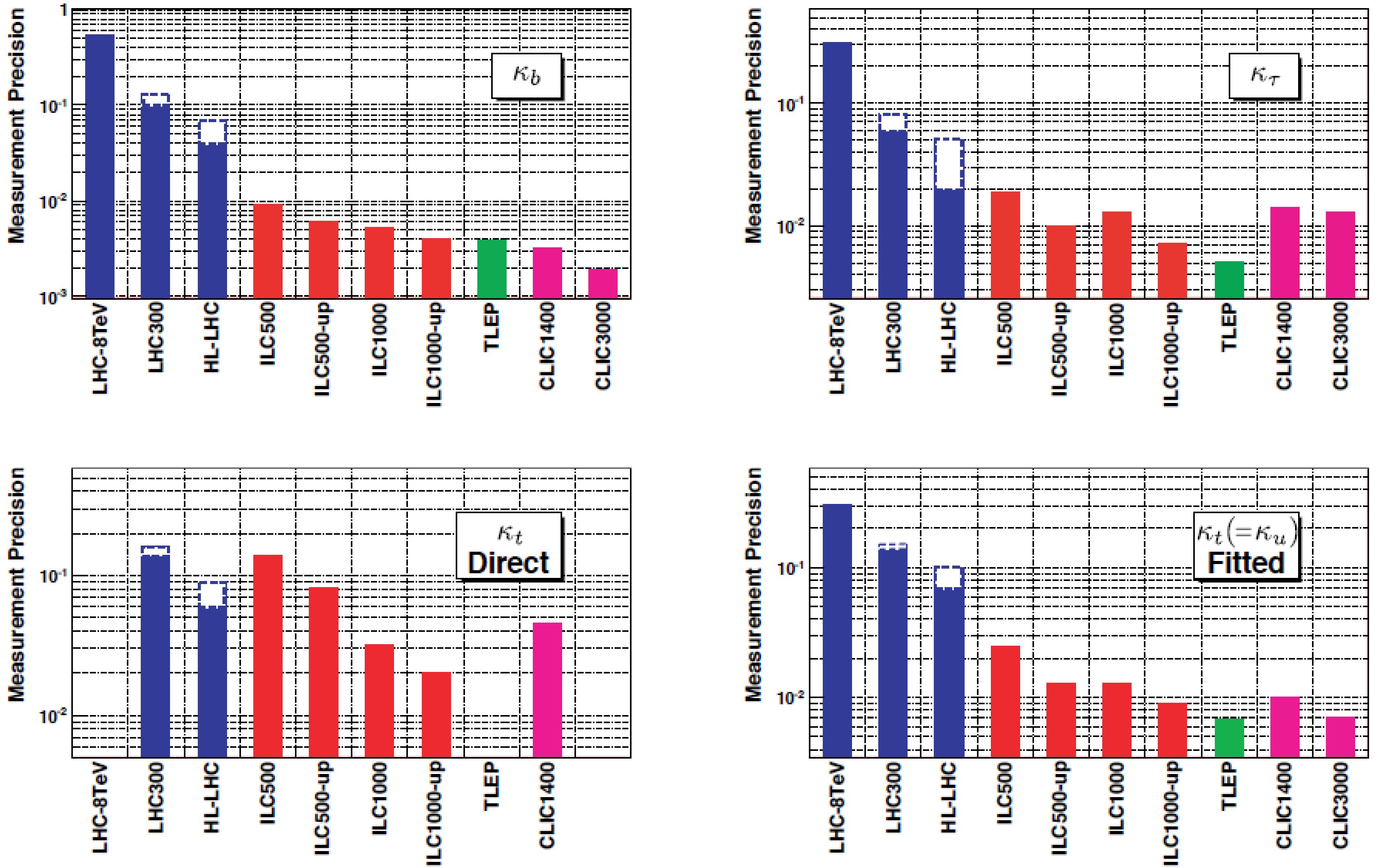


Figure 1-4. *Measurement precision on κ_b, κ_τ, and κ_t measured both directly via $t\bar{t}H$ and through global fits at different facilities.*

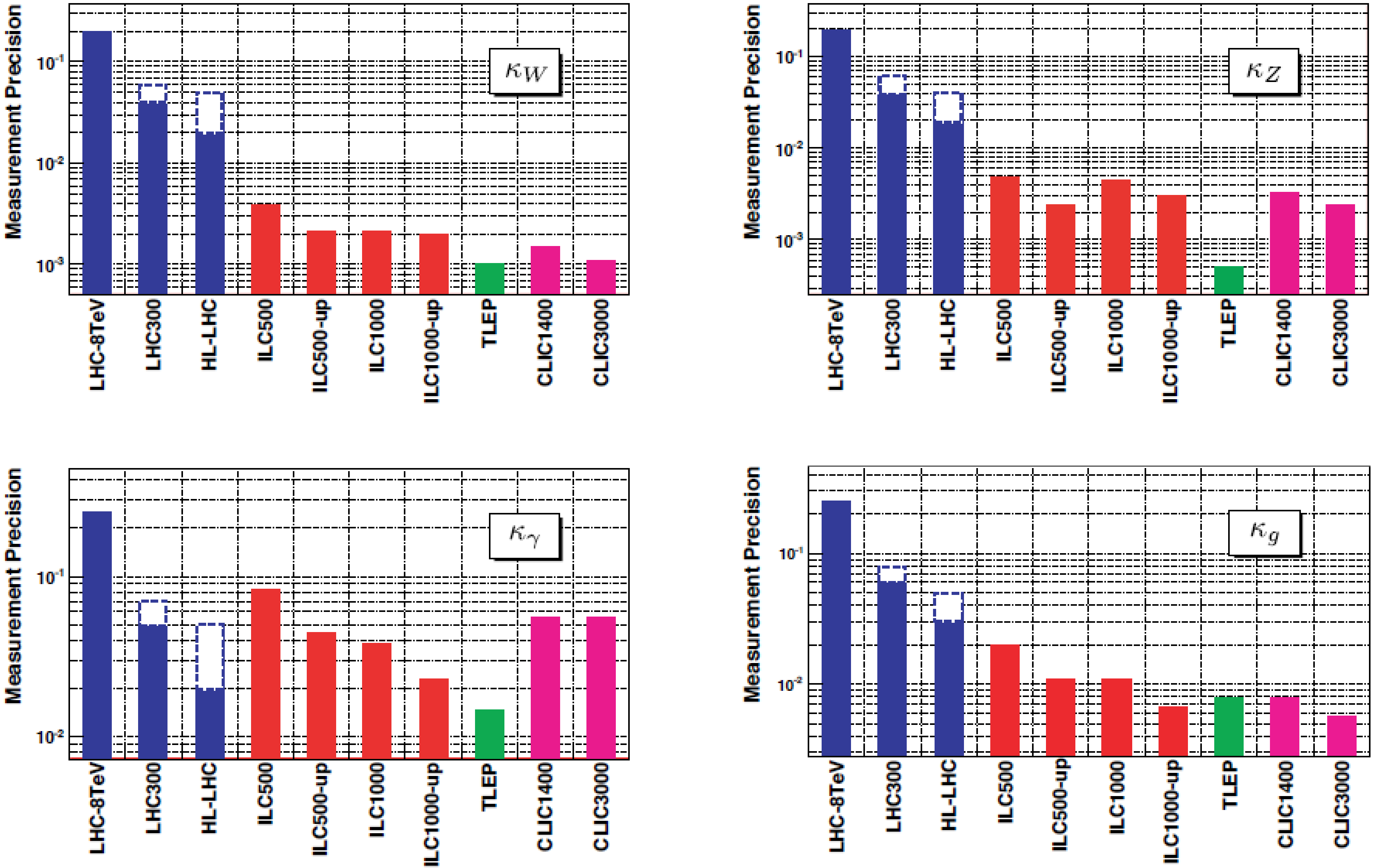
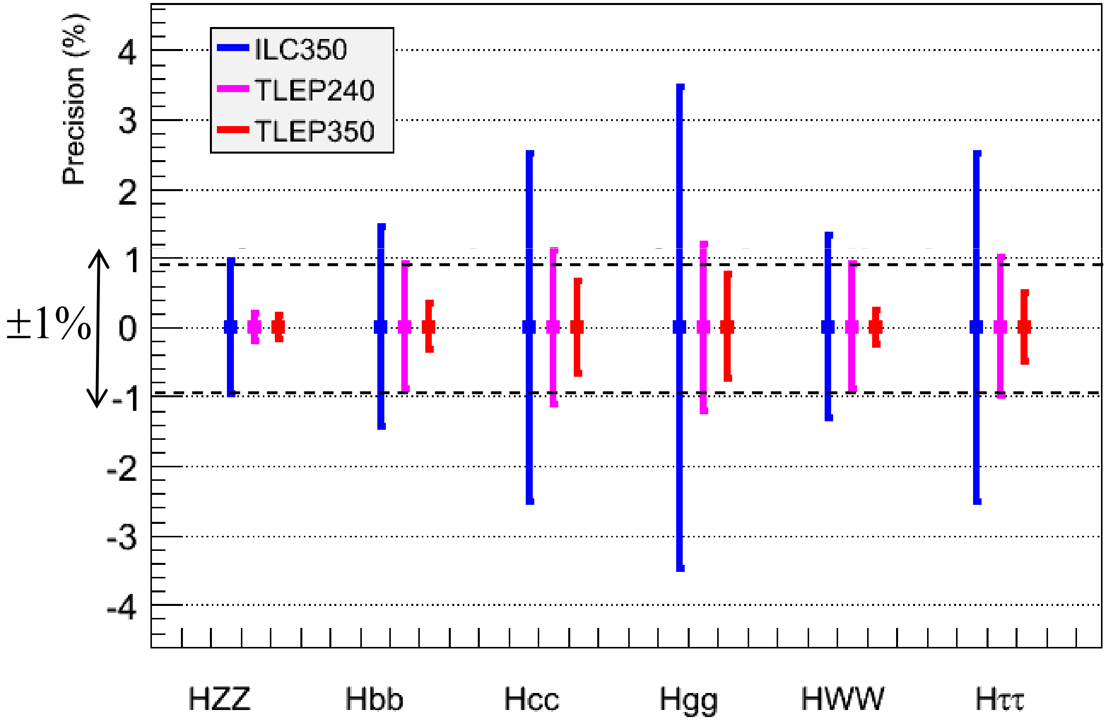


Figure 1-3. *Measurement precision on κ_W, κ_Z, κ_γ, and κ_g at different facilities.*

Performance Comparison

$$\sigma_{HZ} \propto g^2_{HZZ}, \text{ and } \sigma_{HZ,WW\to H} \square \mathrm{BR}(H \to XX) \propto g^2_{HZZ,HWW} g^2_{HXX} / \Gamma_H$$

- Same conclusion when Γ_H is a free parameter in the fit

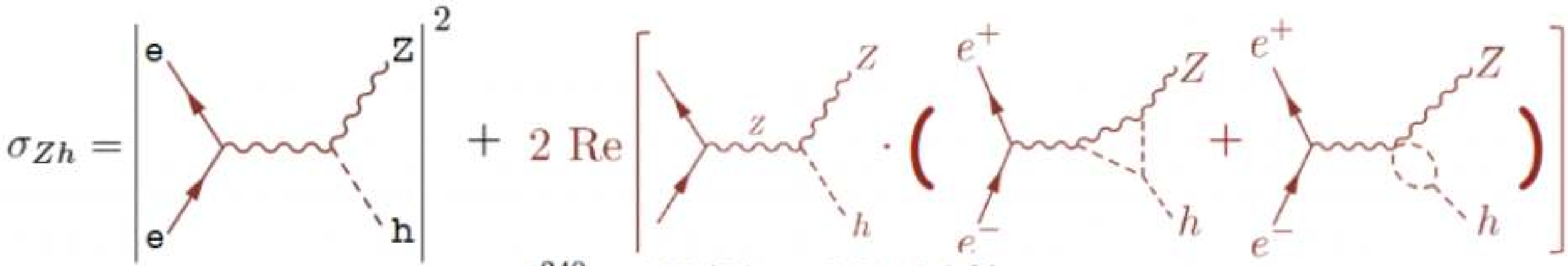


Expected precision on the total width

$\mu^+\mu^-$	ILC350	ILC1000	TLEP240	TLEP350
5%	5%	3%	2%	1%

TLEP : sub-percent precision, BSM Physics sensitivity beyond several TeV

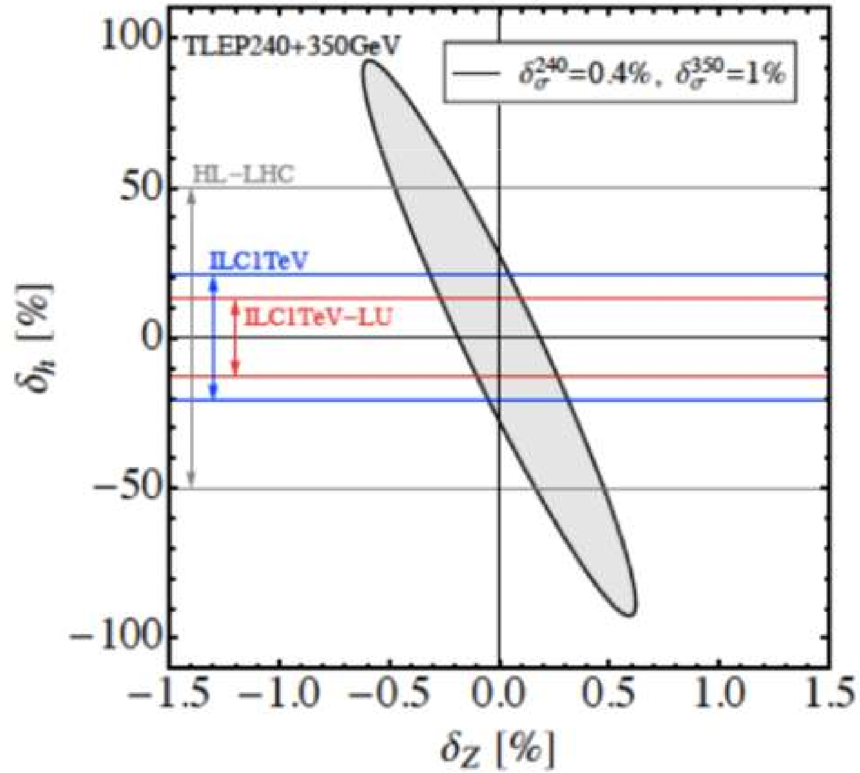
very accurate precision on threshold cross-section sensitive to loop corrections



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

arxiv:1312.3322

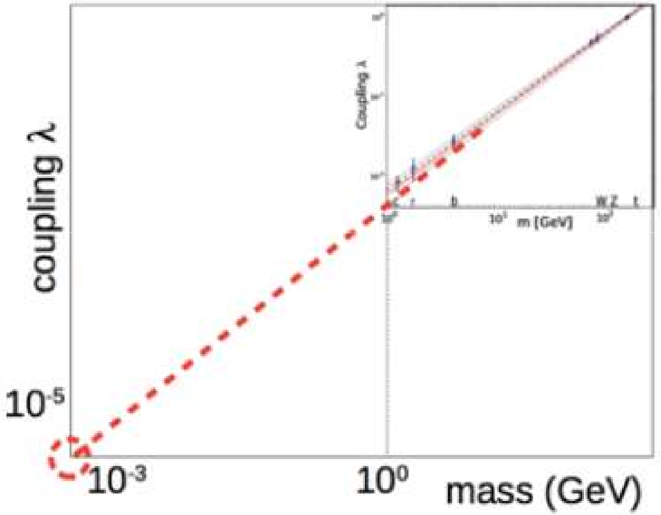
- ➡ Very large datasets at high energy allow extreme precision g_{ZH} measurements
- ➡ Indirect and model-dependent probe of Higgs self-coupling
- ➡ Note, the time axis is missing from the plot

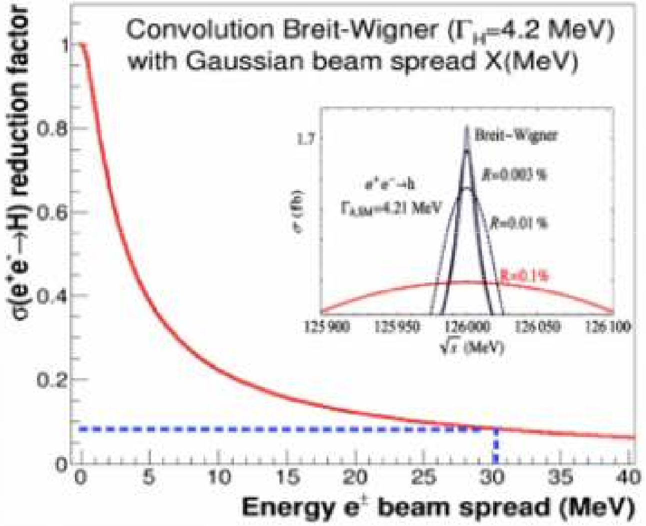


First generation couplings

➡ **s-channel Higgs production**

- Unique opportunity for measurement close to SM sensitivity
- Highly challenging; σ(ee→H) = 1.6fb; 7 Higgs decay channels studied





Preliminary Results

L = 10 ab^{-1}

κ_e < 2.2 at 3σ

➡ **Work in progress**

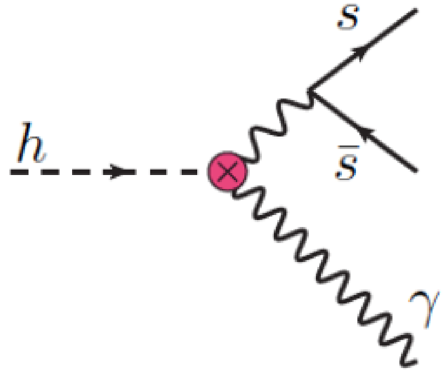
- How large are loop induced corrections? How large are BSM effects?
- Do we need an energy scan to find the Higgs?
- How much luminosity will be available for this measurement? By how much is the luminosity reduced by monochromators?

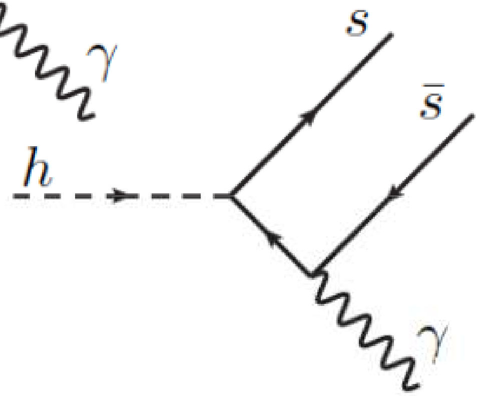
Exclusive Higgs boson decays

- First and second generation couplings accessible
  - Study of **ργ** channel most promising; expect ~50 evts.
  - Sensitivity to u/d quark Yukawa coupling
  - Sensitivity due to interference

$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\,[(1.9\pm0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d]}{0.57\bar{\kappa}_b^2}\times10^{-5}$$

- Also interesting to FCC-hh program
- Alternative H→MV decays should be studied (V= γ, W, and Z)





H → J/Ψ γ → y_c

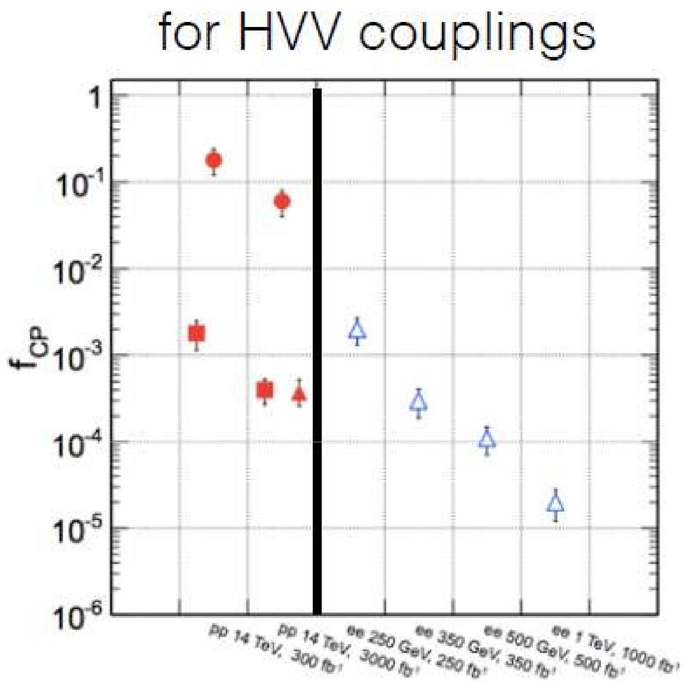
H → **ϕ** γ → y_s

H → **ρ** γ
H → ω γ → y_u, y_d

CP Measurements

- ➡ CP violation can be studied by searching for CP-odd contributions; CP-even already established
- ➡ Snowmass Higgs paper http://arxiv.org/abs/1310.8361
- ➡ Higgs to Tau decays of interest
- ➡ More detailed presentation by Felix Yu

http://arxiv.org/abs/1308.1094



$$\mathcal{L}_{hff} \propto h\bar{f}(\cos\Delta + i\gamma_5 \sin\Delta)f$$

Colliders	LHC	HL-LHC	FCCee (1 ab^{-1})	FCCee (5 ab^{-1})	FCCee (10 ab^{-1})
Accuracy(1σ)	25°	8.0°	5.5°	2.5°	1.7°

Rare and Exotics Higgs Bosons

- ➡ 2,000,000 ZH events allow for detailed studies of rare and exotic decays
  - ◉ requires hadronic and invisible Z decays
  - ◉ set requirements for FCC-ee detector
- ➡ Coupling measurements have sensitivity to BSM decays
- ➡ Dedicated studies using specific final states improve sensitivity
- ➡ Example: Higgs to invisible, flavor violating Higgs, and many more
- ➡ Potential at the LHC (and HL-LHC) currently not fully explored
- ➡ Modes with of limited LHC sensitivity are of particular importance to FCC-ee program
  - ◉ currently under study
- ➡ FCC-ee might allow precision measurement of exotic Higgs decays
- ➡ Detailed discussion of exotic Higgs decays at Phys. Rev. D 90, 075004 (2014) More from David Curtin

$h \to \not\!\!E_T$

$h \to 4b$

$h \to 2b2\tau$

$h \to 2b2\mu$

$h \to 4\tau, 2\tau2\mu$

$h \to 4j$

$h \to 2\gamma 2j$

$h \to 4\gamma$

$h \to ZZ_D, Za \to 4\ell$

$h \to Z_D Z_D \to 4\ell$

$h \to \gamma + \not\!\!E_T$

$h \to 2\gamma + \not\!\!E_T$

$h \to$ 4 ISOLATED LEPTONS $+ \not\!\!E_T$

$h \to 2\ell + \not\!\!E_T$

$h \to$ ONE LEPTON-JET $+ X$

$h \to$ TWO LEPTON-JETS $+ X$

$h \to b\bar{b} + \not\!\!E_T$

$h \to \tau^+\tau^- + \not\!\!E_T$

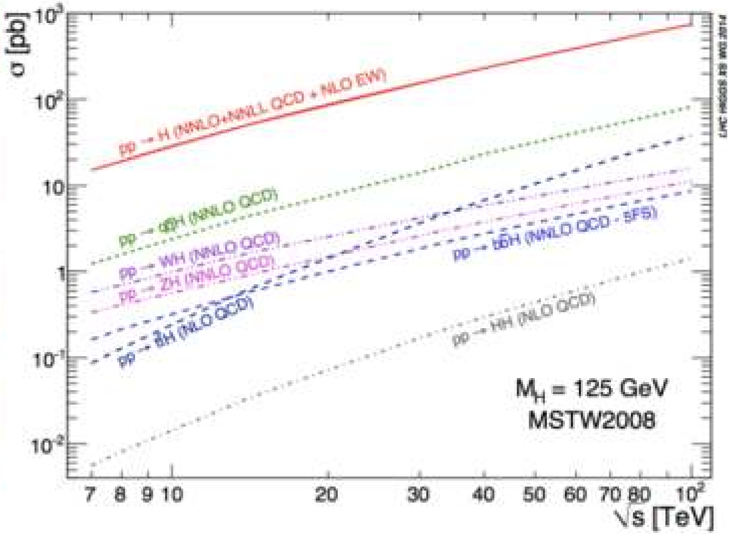
FCC-hh parameters

parameter	FCC-hh		LHC	HL LHC
energy cms [TeV]	100		14	
dipole field [T]	16		8.3	
# IP	2 main & 2		2 main & 2	
bunch intensity $[10^{11}]$	1	1 (0.2)	1.1	2.2
bunch spacing [ns]	25	25 (5)	25	25
luminosity/Ip $[10^{34}\ cm^{-2}s^{-1}]$	5	20	1	5
events/bx	170	680 (136)	27	135
stored energy/beam [GJ]	8.4		0.36	0.7
synchr. rad. [W/m/apert.]	30		0.2	0.35

$2.5\ 10^{35} cm^{-2}s^{-1}$ is the goal luminosity of FCC-hh

HIGGS AT FCC-pp

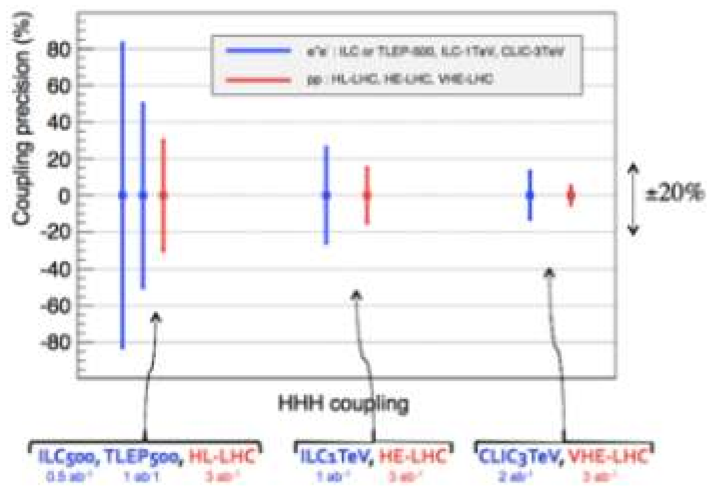
Process	8 TeV	14 TeV	100 TeV
gF	0.38	1	14.7
VBF	0.38	1	18.6
WH	0.43	1	9.7
ZH	0.47	1	12.5
ttH	0.21	1	61
bbH	0.34	1	15
gF to HH	0.24	1	42



Proton-proton Higgs datasets | **LHC Run I** → x300-600 → **HL LHC** → x10-400 → **FCC pp**

	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L}dt$ (fb^{-1})	3000	3000	3000
$\sigma \cdot \mathrm{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

arXiv:1310.8361



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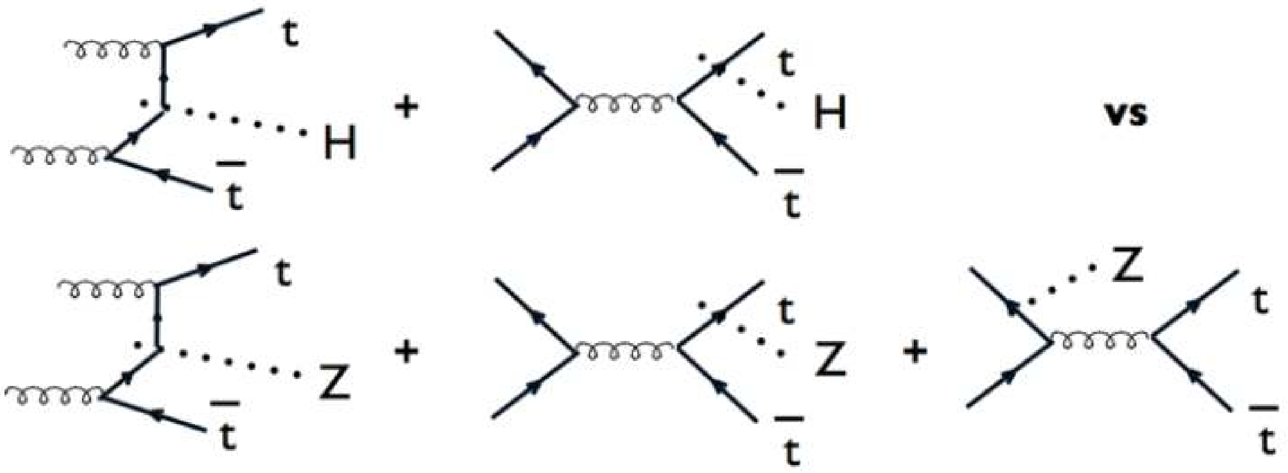
➡ … but also new measurements not possible at the LHC/HL-LHC

ttH / ttZ



➡ Theoretical uncertainties cancel mostly

- PDF (CTEQ 6.6) ± 0.5%
- Missing higher orders ± 1.2%

➡ One can not conclude that one can measure the cross section ratio with ~2% ($\delta\lambda_{top} \cong$ 1%) precision. **More detailed studies are ongoing.**

➔ Lots of statistics and ideas for small systematics

FCC Higgs physics program

g_{HXY}	ZZ	WW	γγ	Zγ	tt	bb	ττ	cc	ss	μμ	uu,dd	ee	Γ_H	HH	BR_{exo}
FCC-ee	0.15	0.19	1.5			0.42	0.54	0.71	H→Vγ	6.2	H→Vγ	ee→H	0.9		0.45
FCC-hh			< 1?	1 ?	1 ?					2 ?				5 ?	$<10^{-6}$?

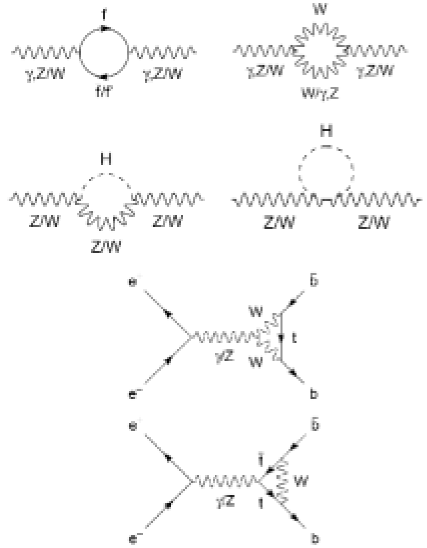
➡ Summary of FCC-ee studies and "guesses" for FCC-hh performance. Uncertainty in %.

➡ Almost perfect complementarity between FCC-ee and FCC-hh program

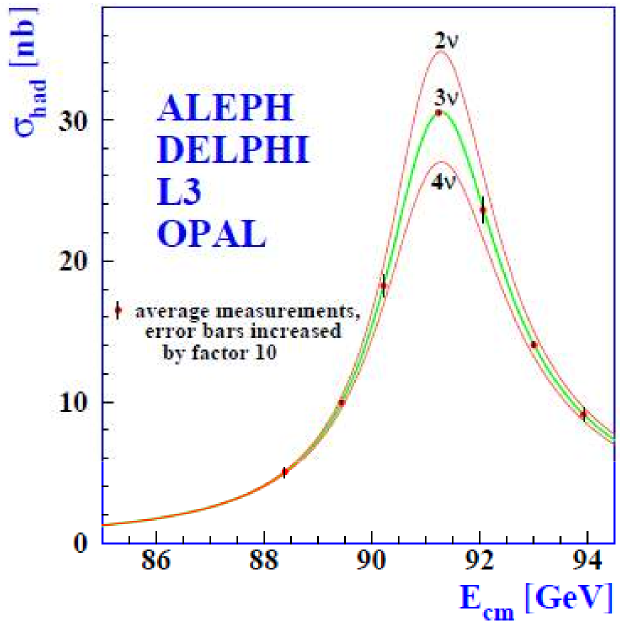
TERA-Z, Oku-W, Megatops

Precision tests of the closure of the Standard Model

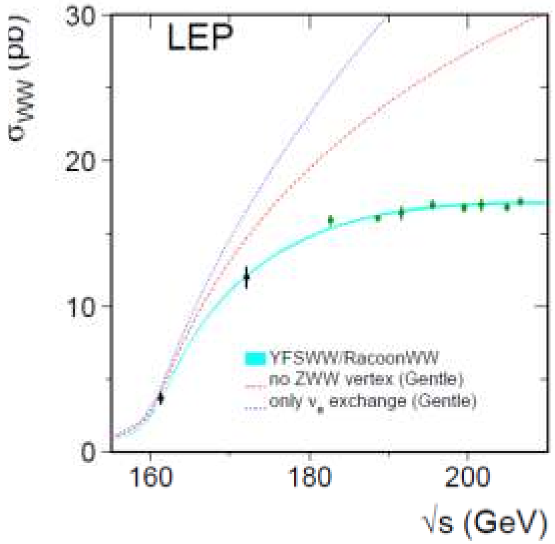
Precision tests of EWSB

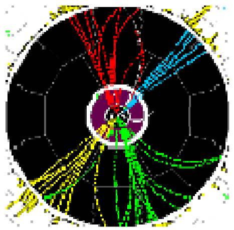


Z pole ssymmetries, lineshape

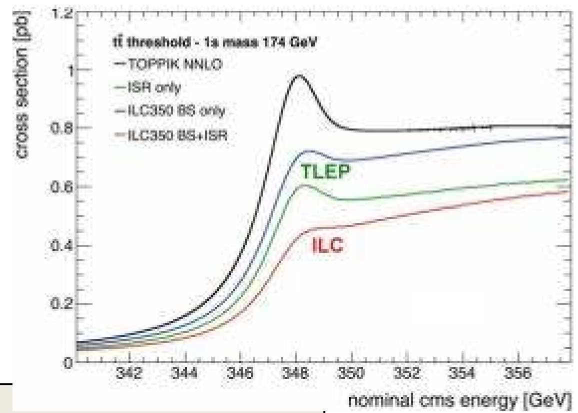


WW threshold scan





tt threshold scan



TLEP : Repeat the LEP1 physics programme every 15 mn

Transverse polarization up to the WW threshold

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

Longitudinal polarization at the Z pole

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

Frank Simon

EWRCs

Input G_F m_Z α_{QED}

Radiative corrections affect the relationship between the input quantities and the others.

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

$\Delta\rho$: $\equiv \varepsilon_1$

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

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}

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

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

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

obtained from asymmetries at the Z.

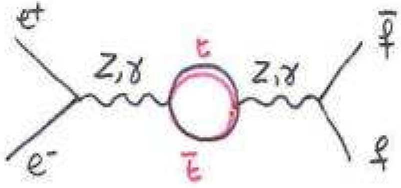
also

Δr

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

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

Examples of LOOPS

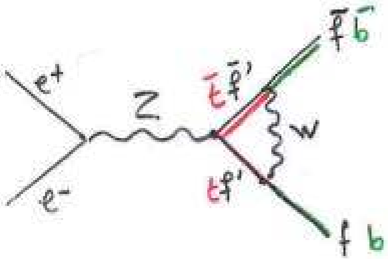


Z propagator

→ Z width, asymmetries

universal

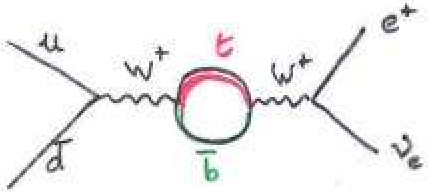
$\Delta\rho$, ε_3



VERTEX CORRECTIONS

non-universal

δ_v^b

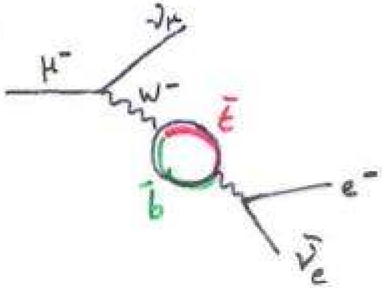


W propagator

→ W mass

ε_2

and also



W propagator

at low q^2

corrections to G_F .

Example (from Erler &Freytas **PDG 2014**)

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

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

$\Delta\rho$ today = 0. 00040 +– 0.00024

-- is consistent with 0 at 1.7σ

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

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

-- does not decouple!

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

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

Present measurement implies

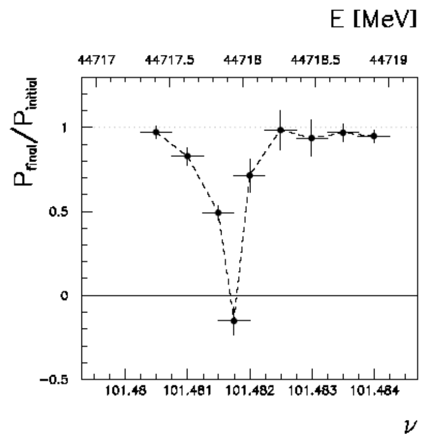
$$\sum_i \frac{C_i}{3}\,\Delta m_i^2 \leq (52\ \mathrm{GeV})^2.$$

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

Today, the larger possible mass splitting of an SU(2) doublet is 50 GeV

no matter what its mass is.

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 much 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…
but saw-toothing must be well understood! **require Wigglers to speed up pol. time**

<< 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

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

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

target precisions

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

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

Design study to establish possibility of corresponding precision theoretical calculations.

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

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

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

Quantity	Present precision	Measured fro...	...ity	Systematic uncertainty
m_Z (keV)	91187500 ± 2100	Z Li...	...(6) keV	< 100 keV
Γ_Z (keV)	2495200 ± 2300		8 (10) keV	< 100 keV
R_ℓ	20.767 ± 0.025		0.00010 (12)	< 0.001
N_ν	2.984 ± 0.0...		0.00008 (10)	< 0.004
N_ν	2.92 ...	...61 GeV	0.0010 (12)	< 0.001
R_b	0.21...	Z Peak	0.000003 (4)	< 0.000060
A_{LR}		Z peak, polarized	0.000015 (18)	< 0.000015
m_W (MeV)		WW threshold scan	0.3 (0.4)MeV	< 0.5 MeV
m_{top} ...	... 900	$t\bar{t}$ threshold scan	10 (12) MeV	< 10 MeV

...from W and Z hadronic widths

...of magnitude on FCNCs and rare decays etc. etc.

...study to establish possibility of corresponding precision theoretical calculations.

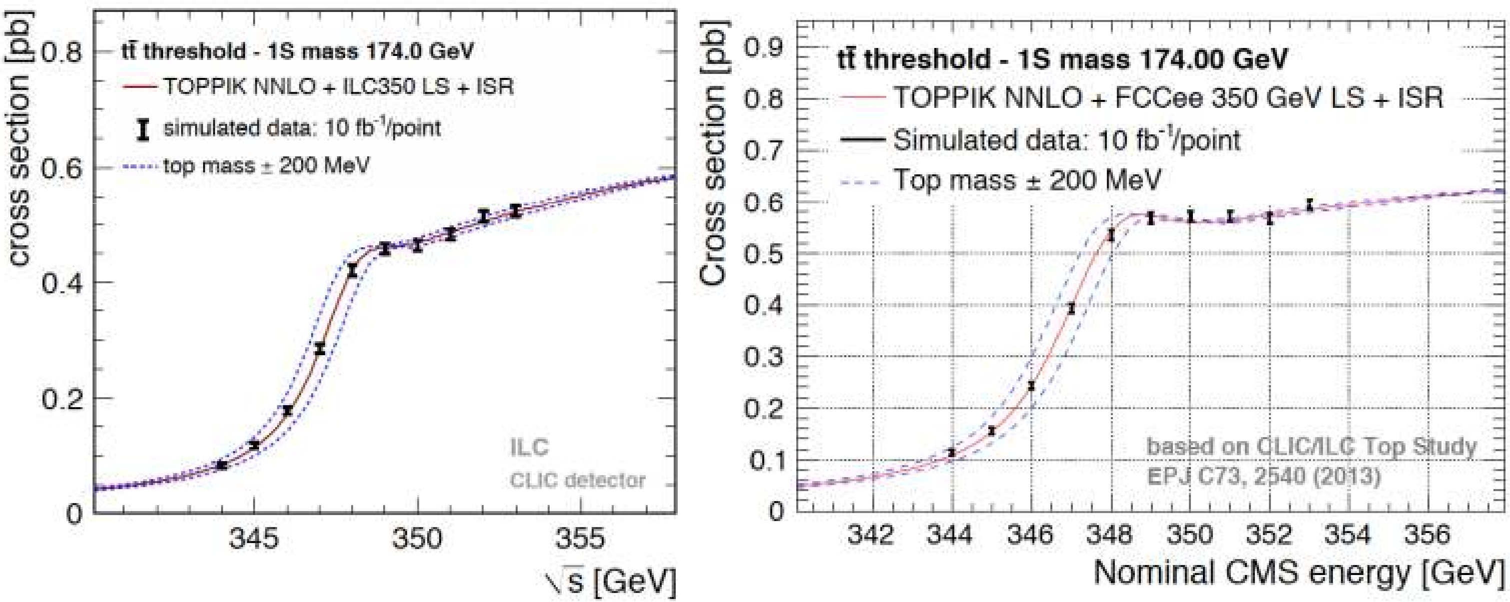
A Sample of Essential Quantities:

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** **0.0004-0.001**	->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 in circular machines**
- **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

Potential of $\alpha_{QED}(m_Z)$ measurement (1)

For exploitation of precision EW measurements, need precise knowledge of $\alpha_{QED}(m_Z)$

- Standard method involves extrapolation from $\alpha_{QED}(0)$ to $\alpha_{QED}(m_Z)$
  - Dispersion integral over hadronic cross section – low energy resonances: **$\delta\alpha/\alpha = 1.1 \times 10^{-4}$**

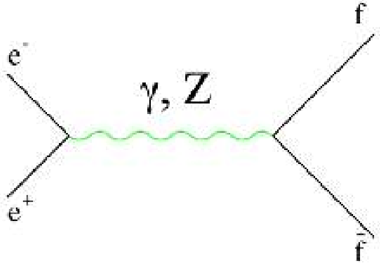
$$\boxed{\alpha_{QED}^{-1}(m_Z) = 128.952 \pm 0.014}$$

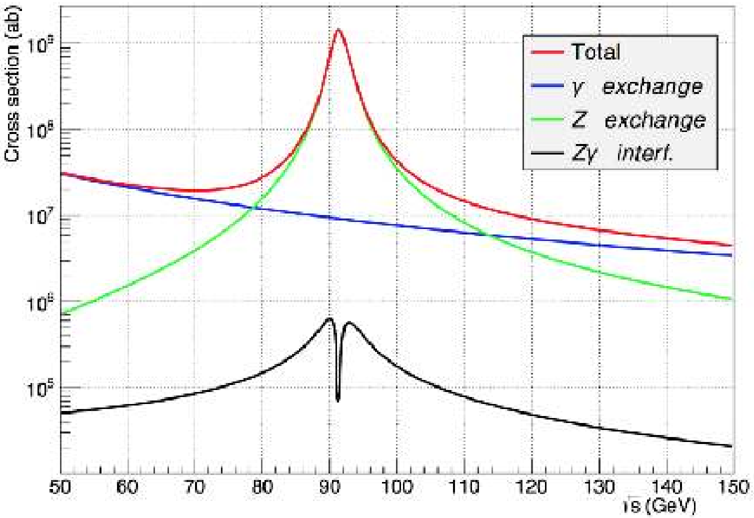
New idea: exploit large statistics of FCC-ee to measure $\alpha_{QED}(m_Z)$ directly **close to m_Z**

- Extrapolation error becomes negligible!

Two methods considered: Meast. of cross section, $\sigma(e^+e^- \to \mu^+\mu^-)$, and asymmetry, $A_{FB}^{\mu\mu}$

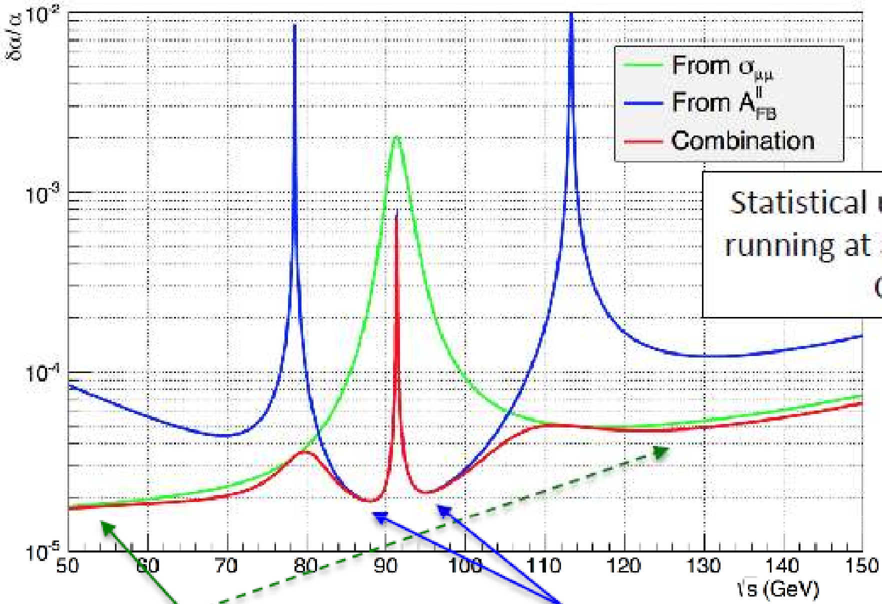
- γ exchange proportional to $\alpha^2_{QED}(\sqrt{s})$
- Z exchange independent of $\alpha_{QED}(\sqrt{s})$
- γZ interference proportional to $\alpha_{QED}(\sqrt{s})$





P. Janot: FCC-ee Physics Vidyo Meeting, June 29th 2015

Potential of $\alpha_{QED}(m_Z)$ measurement (2)



Statistical uncertainty for one year of running at any centre-of-mass energy. Crab-waiste, 4 IP.

From $\sigma_{\mu\mu}$ measurement

- Sensitivity best "far" away from Z peak, particularly at the low side
- Systematics (normalisation) probably a killer

From $A_{FB}^{\mu\mu}$ measurement

- Sensitivity best at 88 and 95 GeV
- Experimental systs. looks controlable; further studies needed
- Theoretical systs. to large degree cancel by "averaging" over 88 and 95 GeV point

By running six months at each of 88 and 95 GeV points:

➢ Could potentially reach a precision of : $\delta\alpha/\alpha = 2 \times 10^{-5}$

Strong coupling constant, $\alpha_s(m_Z)$

At LEP, a precise $\alpha_s(m_Z)$ measurement was derived from the Z decay ratio $R_l = \Gamma_{had}/\Gamma_l$.
Reinterpreting this measurement in light of: i) new N_3LO calculations; ii) improved m_{top}; and iii) knowledge of the m_{Higgs}, the uncertainty is now something like:

$$\boxed{\delta\,(\alpha_s(m_Z)\,)_{LEP} = \pm\,0.0038\ (\text{exp.}) \pm 0.0002\ (\text{others})}$$

R_l measurement was statistics dominated: Foresee a factor ≥25 improvement at FCC-ee.
From the Z-pole, therefore a resonable experimental target is

$$\boxed{\delta\,(\alpha_s(m_Z)\,)_{FCC\text{-}ee} = \pm\,0.00015}$$

Similarly, from the WW threshold, $\alpha_s(m_W)$ can be derived from the high stats measurement of $B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$

$$\boxed{\delta\,(\alpha_s(m_W)\,)_{FCC\text{-}ee} = \pm\,0.00015}$$

Combining the two above, a realistic target precision would be

$$\boxed{\delta\,(\alpha_s(m_Z)\,)_{FCC\text{-}ee} = \pm\,0.0001}$$

Theoretical limitations

FCC-ee

SM predictions (using other input)

M_W = 80.3593 ± **0.0002** 6_{m_t} ± **0.0001** $_{M_Z}$ ± **0.0002?** $\Delta\alpha_{\rm had}$

0.0003

± **0.00025?** $_{\alpha_S}$ ± **0.0000** 2_{M_H} ± $0.0040_{\rm theo}$

$$= 80.359 \pm 0.011_{\rm tot}$$

$\sin^2\theta^\ell_{\rm eff}$ = 0.231496 ± **0.0000015** $_{m_t}$ ± **0.000001** 5_{M_Z} ± **0.000007?** $\Delta\alpha_{\rm had}$

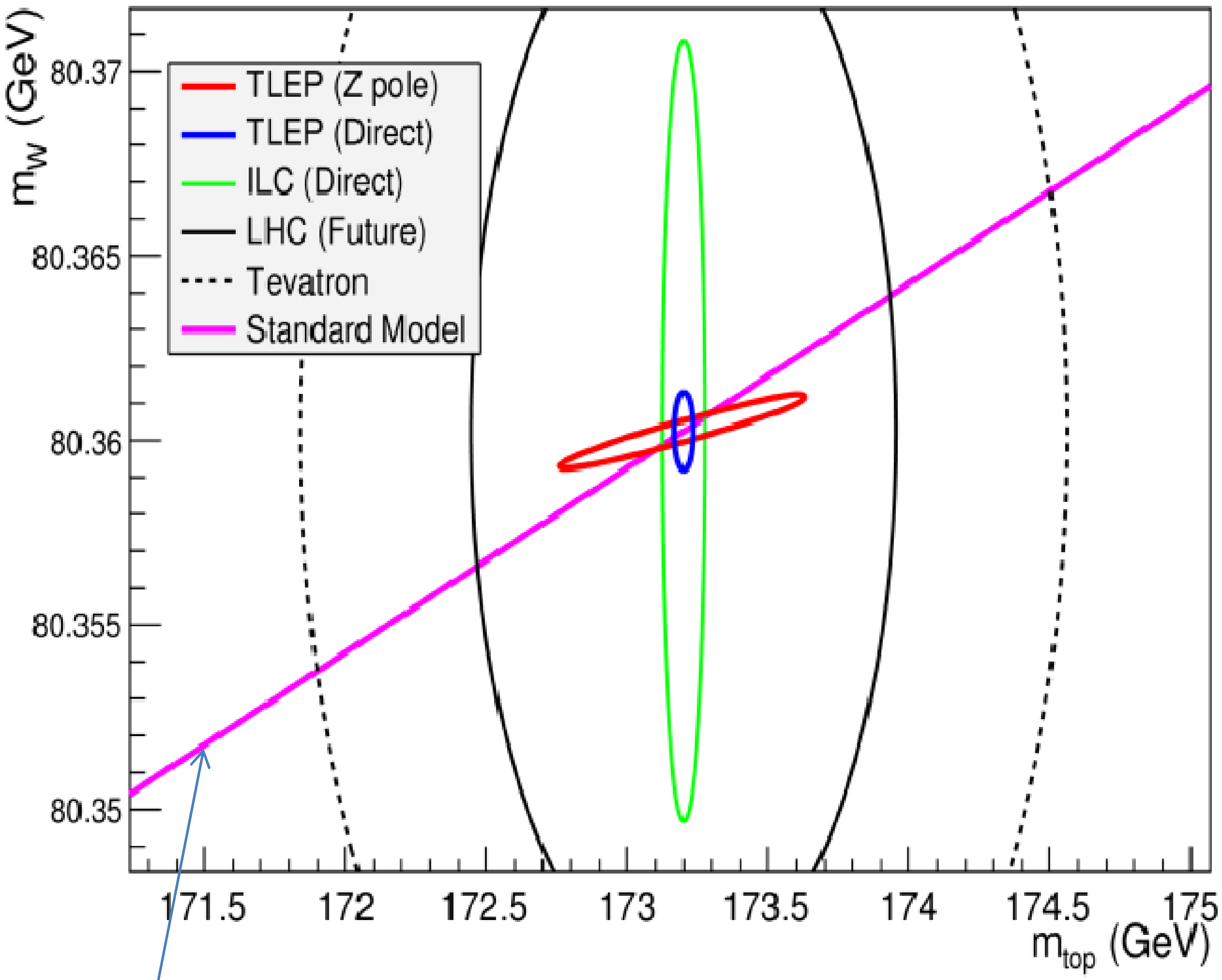
0.000001

± **0.0000014?** $_{\alpha_S}$ ± **0.000000** 2_{M_H} ± $0.000047_{\rm theo}$

$$= 0.23150 \pm 0.00010_{\rm tot}$$

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 theory errors
Will require significant theoretical effort and additional measurements!

Radiative correction workshop 13-14 July 2015 stressed the need for 3 loop calculations for the future!
Suggest including manpower for theoretical calculations in the project cost.

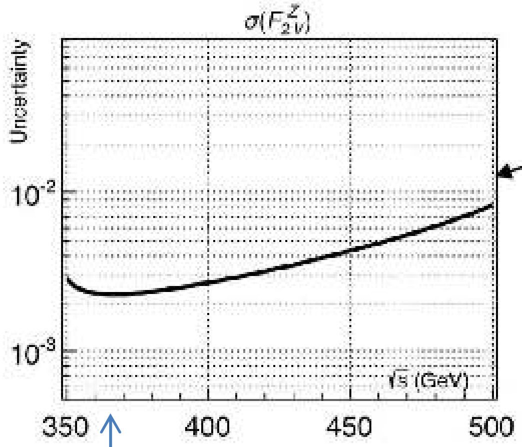


NB width of this line : Z mass error. Without FCC-ee its 2.2 MeV!

in other words .... $\Delta(\Delta\rho) = \pm\, 10^{-5}$ + several tests of same precision

NEW

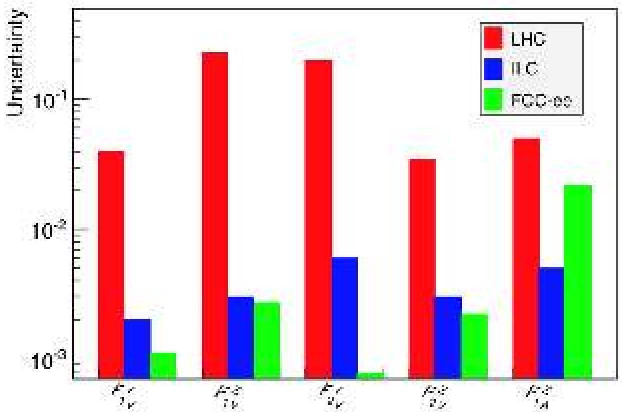
Determination of top-quark EW couplings via measurement of top-quark polarization.
In semileptonic decays, fit to lepton momentum vs scattering angle

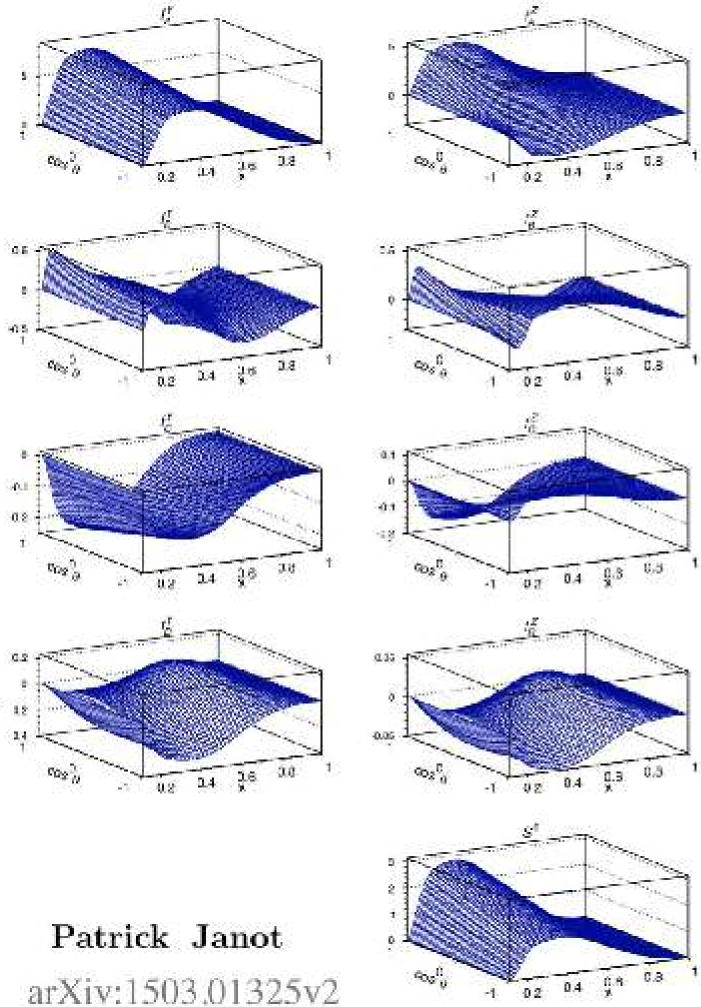


Typically best sensitivity just above production threshold

Momenta up to: 175 GeV

no need for High Energy or beam polarization!

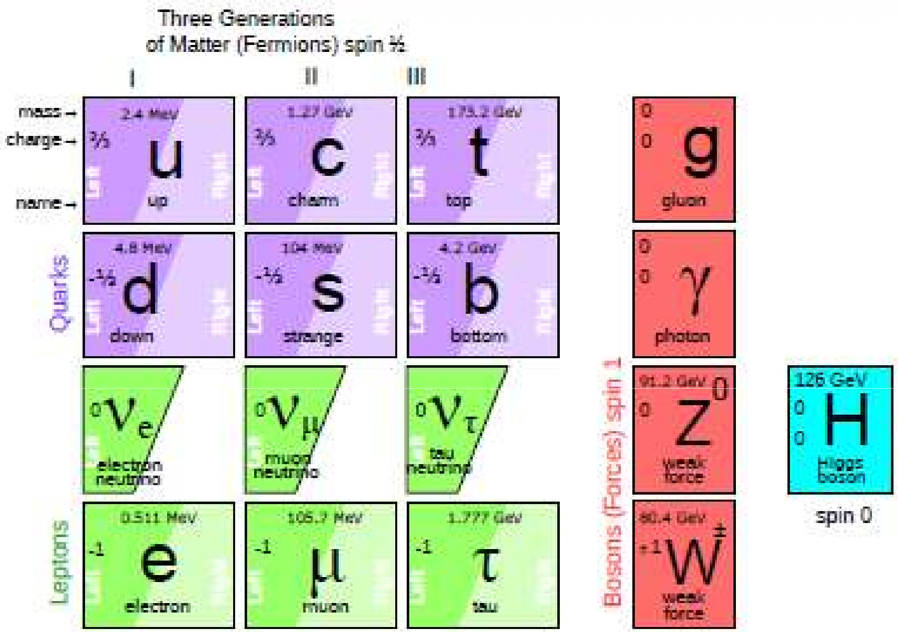


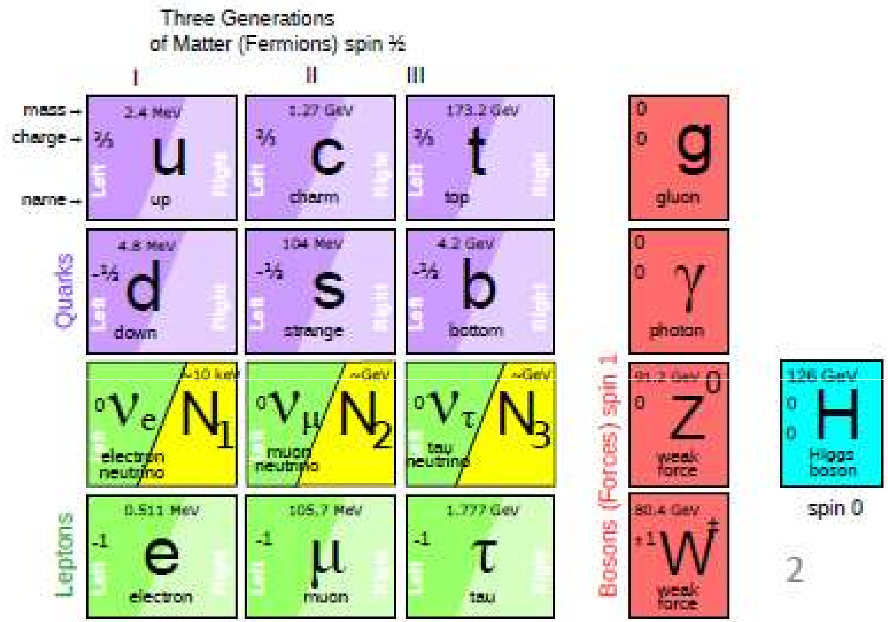


Patrick Janot
arXiv:1503.01325v2

THE STANDARD MODEL IS COMPLETE .....

But at least 3 pieces are still missing





neutrinos have mass...

and this very probably implies new degrees of freedom

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

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

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

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arxiv:1208.3654

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

C. Garcia Cely[a)], A. Iba

theories of the el

and mixings with

JHEP

First look at the physics case of TLEP

arxiv:1308.6176

The TLEP Design Study Working Group

Search for Heavy Right Handed Neutrinos at the FCC-ee

A. Blondel (presenter)[a], E. Graverini[b], N. Serra[b], M. Shaposhnikov[c]

[a]DPNC, University of Geneva, Quai Ansermet 24, CH-1205 Geneva, Switzerland
[b]Physik Institut, Universitat of Zurich, CH-8057 Zurich, Switzerland
[c]ITPP, EPFL, CH-1015 Lausanne, Switzerland

CERN–PPE/96–195

18 December 1996

Neutral Heavy Leptons
uced in Z Decays

DELPHI Collaboration

The Role of Sterile Ne
Astrophysics

Alexey Boyarsky*†, Oleg Ruchayskiy‡ and Mikhail Shaposhn

FCC design study and FCC-ee http://cern.ch/fcc-ee
and presentations at *FCC-ee physics workshops*
http://indico.cern.ch/category/5684/

The νMSM, Dark Matter and Neutrino Masses

Takehiko Asaka, Steve Blanchet, and Mikhail Shaposhnikov

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

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

Preprint typeset in JHEP style - HYPER VERSION

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The Search for Heavy Majorana Neutrinos

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

Electroweak eigenstates

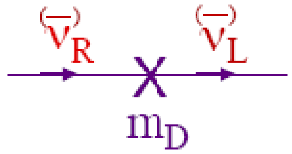
$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L$ $\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L$ $\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$(e)_R$ $(\mu)_R$ $(\tau)_R$	Q= -1
	$(\nu_e)_R$ $(\nu_\mu)_R$ $(\nu_\tau)_R$	Q= 0
I = 1/2	I = 0	

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

can't produce them
can't detect them
-- so why bother? --

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

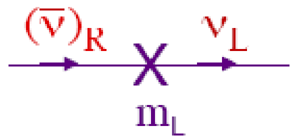
$$m_D \nu_L \overline{\nu}_R \qquad m_D \overline{\nu}_L \nu_R$$



implies adding a right-handed neutrino (new particle)

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

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



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

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

B. Kayser, the physics of massive neutrinos (1989)

Mass eigenstates

See-saw in a general way :

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

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

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

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

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

general formula   if $m_D \ll M_R$

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

m ↑

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

4 states of equal masses

Some have I=1/2 (active)

Some have I=0 (sterile)

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

m ↑

	ν_L	$\bar{\nu}_R$
I_{weak}=	½	½

2 states of equal masses

All have I=1/2 (active)

$M_R > m_D \neq 0$ **see-saw**

Dirac + Majorana

m ↑

dominantly:

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

4 states , 2 mass levels

m_1 have ~I=1/2 (~active)

m_2 have ~I=0 (~sterile)

Manifestations of right handed neutrinos

one family see-saw :
$\theta \approx (m_D/M)$
$m_\nu \approx \frac{m_D^2}{M}$
$m_N \approx M$
$|U|^2 \propto \theta^2 \approx m_\nu / m_N$
can be larger with 3 families

$$\nu = \nu_L \cos\theta - N^c_R \sin\theta$$

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

ν = light mass eigenstate
N = heavy mass eigenstate
$\neq \nu_L$, active neutrino
which couples to weak inter.
and $\neq N_R$, 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 (short baseline)

-- 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, W, Z exotic decays H→ $\nu_i \bar{N}_i$ and Z→ $\nu_i \bar{N}_i$, W-> $l_i \bar{N}_i$

→ also in charm and b decays via W^*-> $l_i \bar{N}_i$

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

-- etc... etc...

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

Indirect effects

-- neutrino Majorana mass term can lead to lepton number violating processes by virtual neutrino exchange and to flavour violation

-- neutrinoless double beta decay (the most powerful one)
-- FCNC ($\mu \rightarrow e\gamma$) etc...

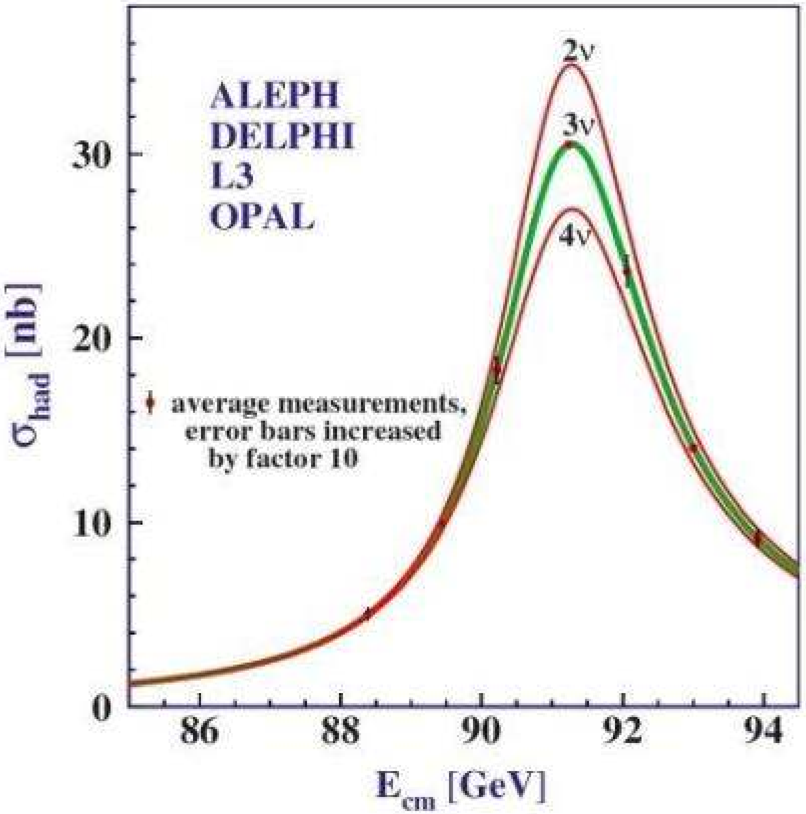
-- at a Z factory : Z→ $\tau\mu$ Z→ τe Z-> $\tau\tau$, τ → $\mu\gamma$ τ → $e\gamma$ etc...

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!

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NEUTRINO COUNTING AT THE Z-PEAK AND RIGHT-HANDED NEUTRINOS

C. JARLSKOG
CERN, CH-1211 Geneva 23, Switzerland
and Department of Physics, University of Stockholm, S-113 46 Stockholm, Sweden

Received 20 February 1990

We consider the implications of extending the minimal standard model, with n families of quarks and leptons, by introducing an arbitrary number of right-handed neutrinos, for neutrino-counting via the "invisible width" of the Z. It is shown that the effective number of neutrinos, $\langle n \rangle$, satisfies the inequality $\langle n \rangle \leqslant n$, where $\langle n \rangle$ is defined by $\Gamma(\mathrm{Z} \to \text{neutrinos}) \equiv \langle n \rangle \Gamma_0$ and Γ_0 is the standard width for one massless neutrino. Thus, in the case of three families, the neutrino-counting can give a result which is less than three, if there are right-handed neutrinos.

Theorem.

In the standard model, with n left-handed lepton doublets and $N-n$ right-handed neutrinos, the effective number of neutrinos, $\langle n \rangle$, defined by

$$\Gamma(\mathrm{Z} \to \text{neutrinos}) \equiv \langle n \rangle \Gamma_0 ,$$

where Γ_0 is the standard width for one massless neutrino, satisfies the inequality

$$\langle n \rangle \leqslant n . \tag{15}$$

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

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

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

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

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

161 GeV (10^7 s) running at $1.6\times10^{35}/cm^2/s$ x 4 exp ➔ 3×10^7 γ Z(inv) evts, $\Delta N_\nu=0.0011$
adding 5 yrs data at 240 and 350 GeV .... $\Delta N_\nu=0.0008$

A better point may be 105 GeV (20pb and higher luminosity) may allow $\Delta N_\nu=0.0004$?

RHASnu'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

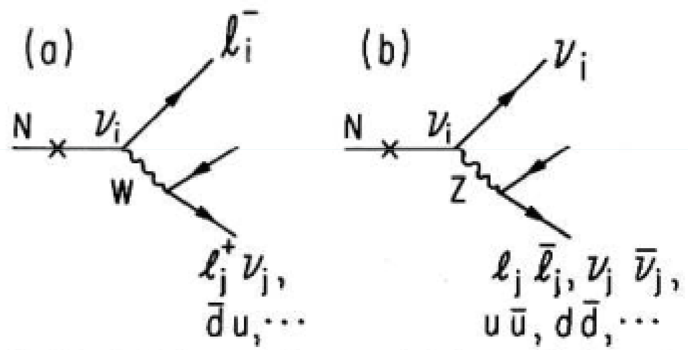


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

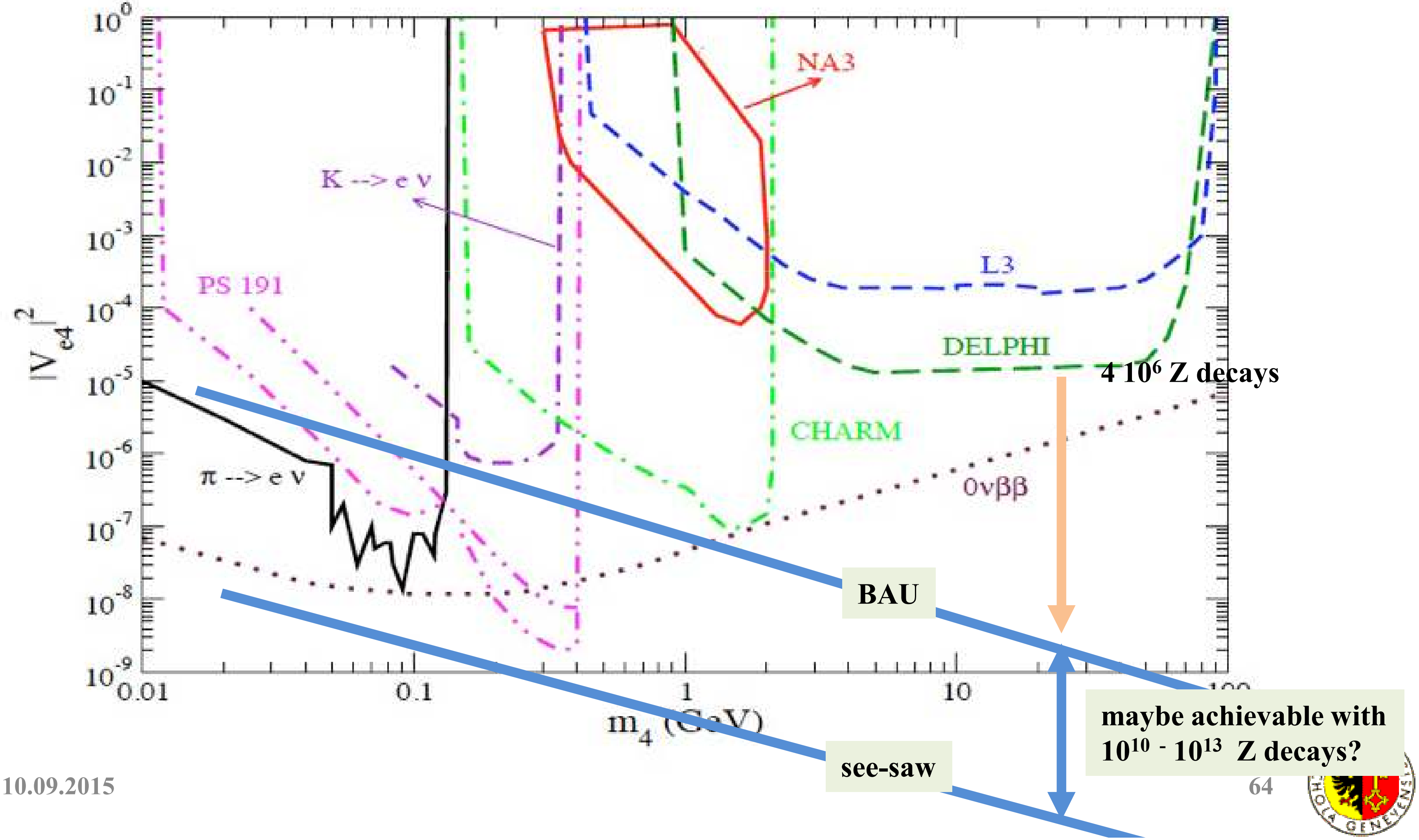
Decay length:

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

NB CC decay always leads to $\geq$ 2 charged tracks

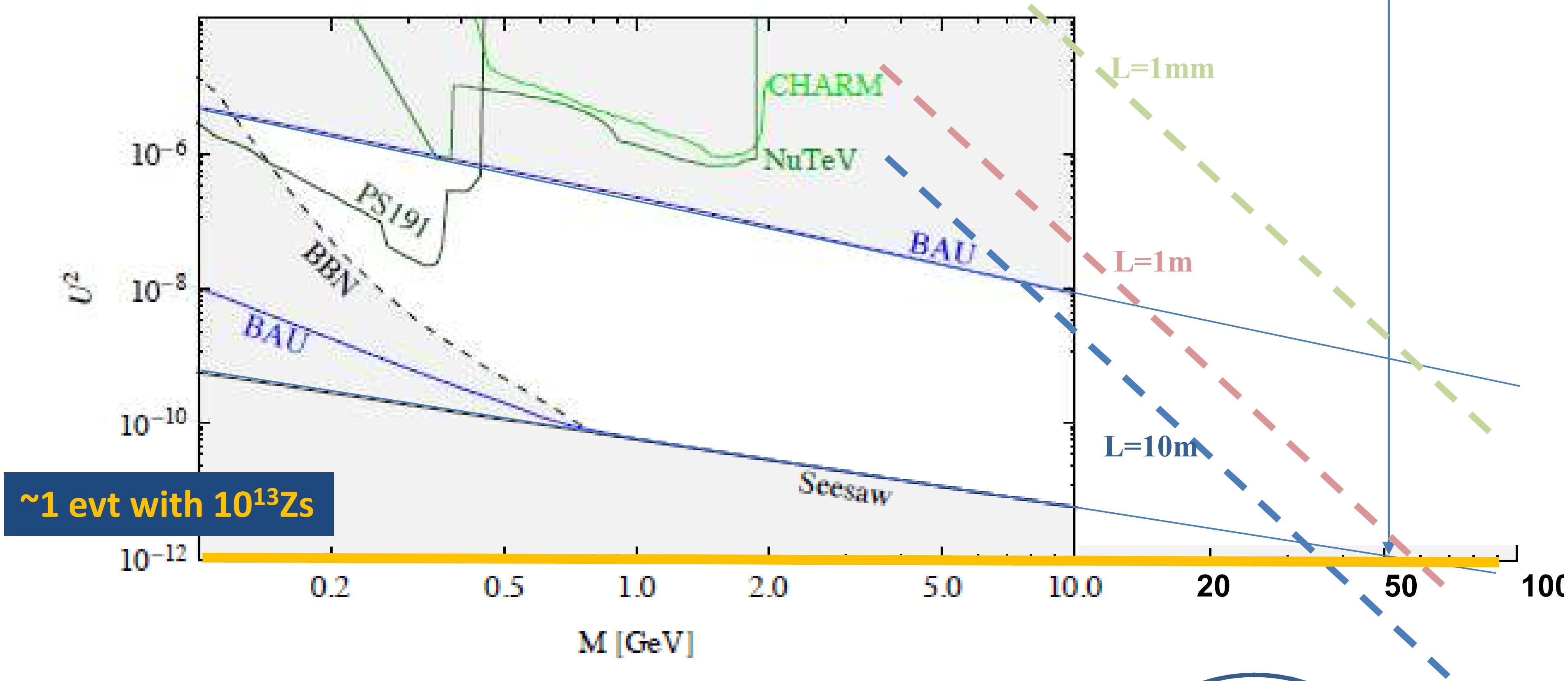
Backgrounds : four fermion: e+e- → $W^{*+} W^{*-}$ e+e- → Z*(vv) + (Z/γ)*

Order-of-magnitude extrapolation of existing limits



Decay length

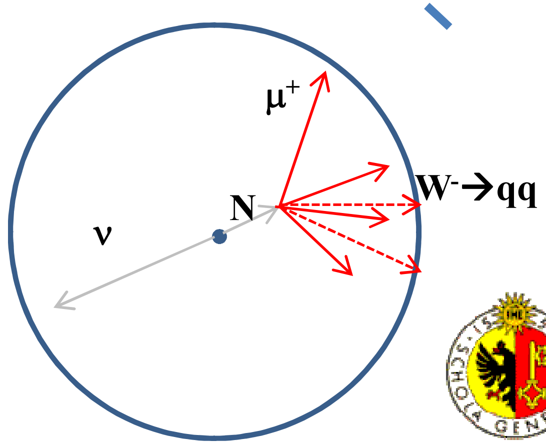
Interesting region
$|U|^2 \sim 10^{-9}$ to 10^{-12} @ 50 GeV



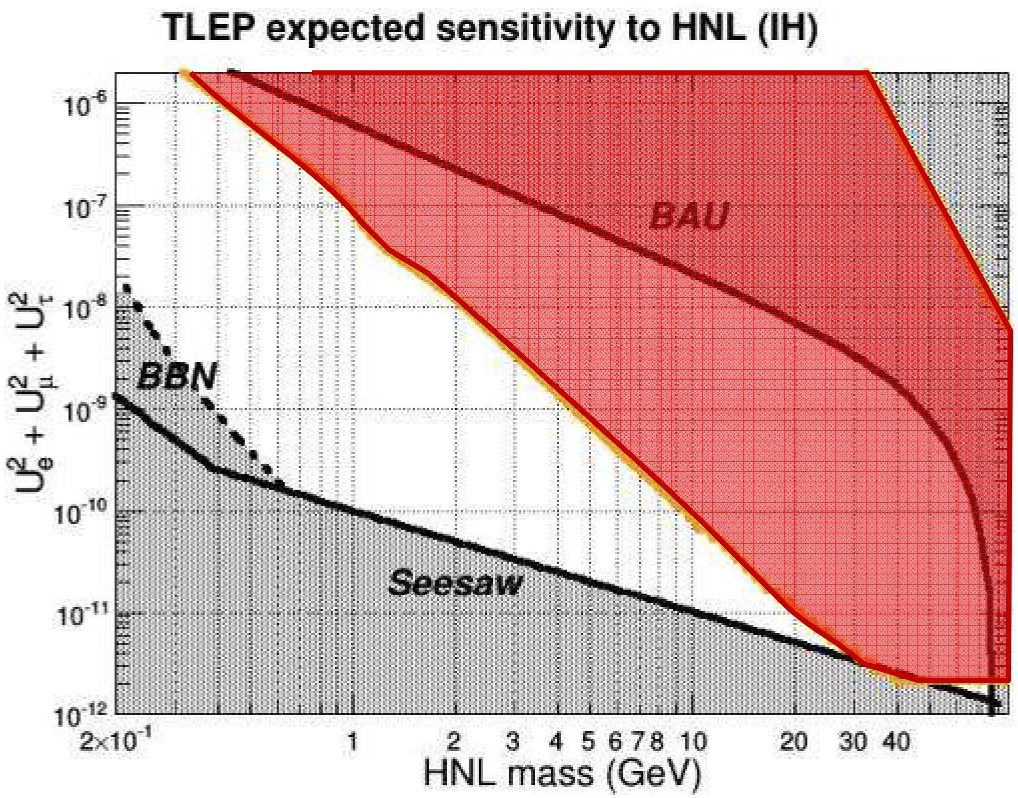
heavy neutrino mass ~ M

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

... → very strong reduction of background!



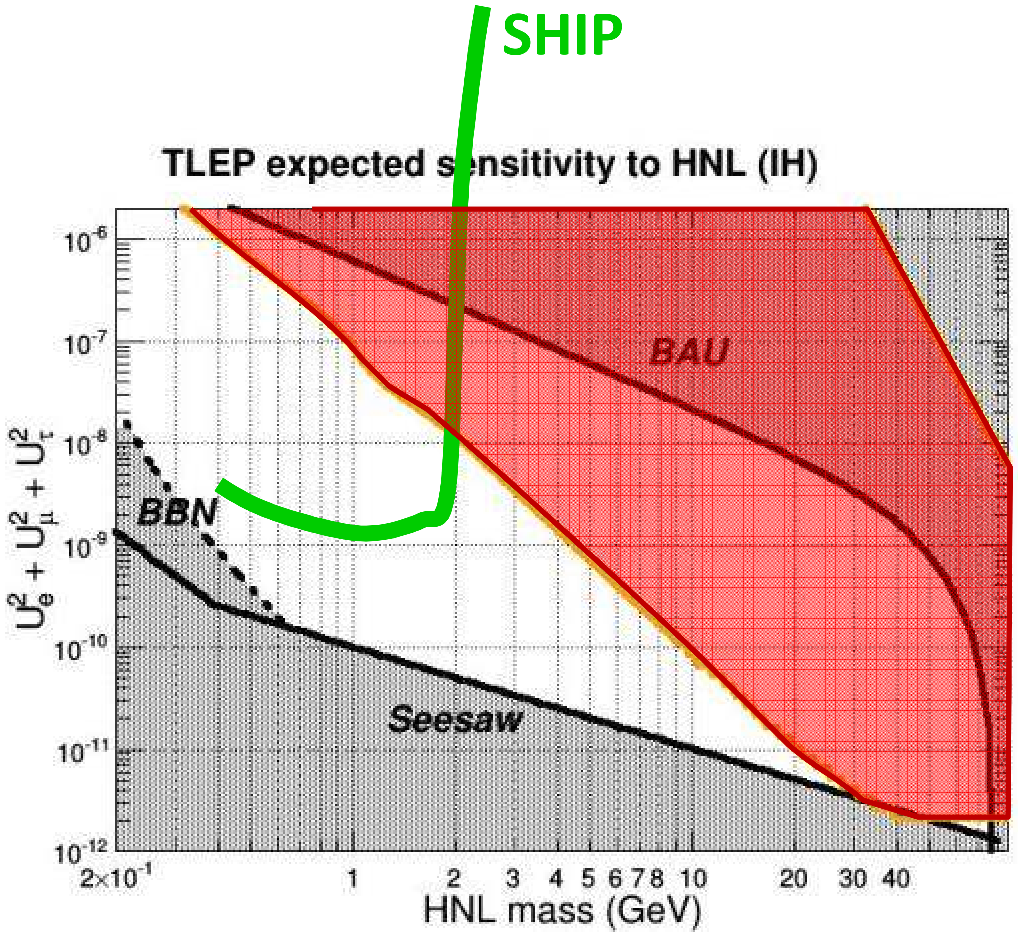
Exact reach domain will depend on detector size and details of displaced vertex efficiency & background



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

region of interest

FCC-ee sensitivity



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

region of interest

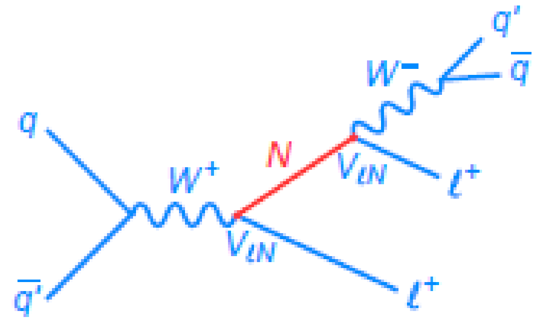
FCC-ee sensitivity

NB very large detector caverns for FCC-hh may allow very large FCC-ee detector (R=15m?) leading to improved reach at lower masses.

Comment/Outlook for FCC-hh

We have seen that the Z factory offers a clean method for detection of Heavy Right-Handed neutrinos

At the 100 TeV hadron machine the W is the dominant particle.



There is a lot of /pile-up/backgrounds/lifetime/trigger issues which need to be investigated.
BUT.... in the regime of long lived HNLs the simultaneous presence of
-- the initial lepton from W decays
-- the detached vertex with kinematically constrained decay
allows for a significant background reduction and *may* allow search reach in the $10^{-x?}$ region

But it allows also a characterization both in flavour and charge of the produced neutrino, thus information of the flavour sensitive mixing angles and a test of the fermion violating nature of the intermediate (Majorana) particle.

VERY interesting...

Input from Physics to the accelerator design

0. Nobody complains that the luminosity is too high (the more you get, the more you want)

no pile up, even at the Z: at most 1ev /300bx

1. Do we need polarized beams?

-1- transverse polarization:

continuous beam Energy calibration with resonant depolarization

central to the precision measurements of m_Z , m_W , Γ_Z

requires 'single bunches' and calibration of both e+ and e-

a priori doable up to W energies -- workarounds exist above (e.g. γZ events)

large ring with small emittance excellent. Saw-tooth smaller than LEP for Z

<u>need wigglers</u> (or else inject polarized e- and e+) to polarize 'singles';

simulations ongoing (E. Gianfelice, M. Koratzinos, I.Kopp)

-2- longitudinal polarization requires spin rotators and is very difficult at high energies

-- We recently found that it is not necessary to extract top couplings (Janot)

-- improves Z peak measurements *if loss in luminosity is not too strong*

but brings no information that is not otherwise accessible

2. What energies are necessary?

-- in addition to Z, W, H and top listed the following are being considered

-- e+e- → H(125.2) (requires monochromatization A. Faus) (under study)

-- e+e- at top threshold ~20 GeV for top couplings (E_max up to 180 -185 GeV)

-- no obvious case for going to 500 GeV

FCC-ee activities

Working groups conveners appointed and regular VIDYO meetings for physics, accelerator and joined, as well as WG.

mini-workshops

-- detector mini-workshop (C. Leonidopoulos, E. Perez, M. Dam) 17-18 June 2015
-- precision calculations mini-workshop 13-14 July 2015 (Heinemeyer, Ellis, Grojean)
-- Higgs mini-workshop 24-25 September 2015 (Klute, Peters)
-- alpha_s workshop 12-13 October 2015 (D'Enterria)

FCC-ee workshop 9-11 November in London (Ellis et al)

General FCC week in Rome 11-18 April 2016

What we believe now and work 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

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

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