FUTURE CIRCULAR COLLIDERS

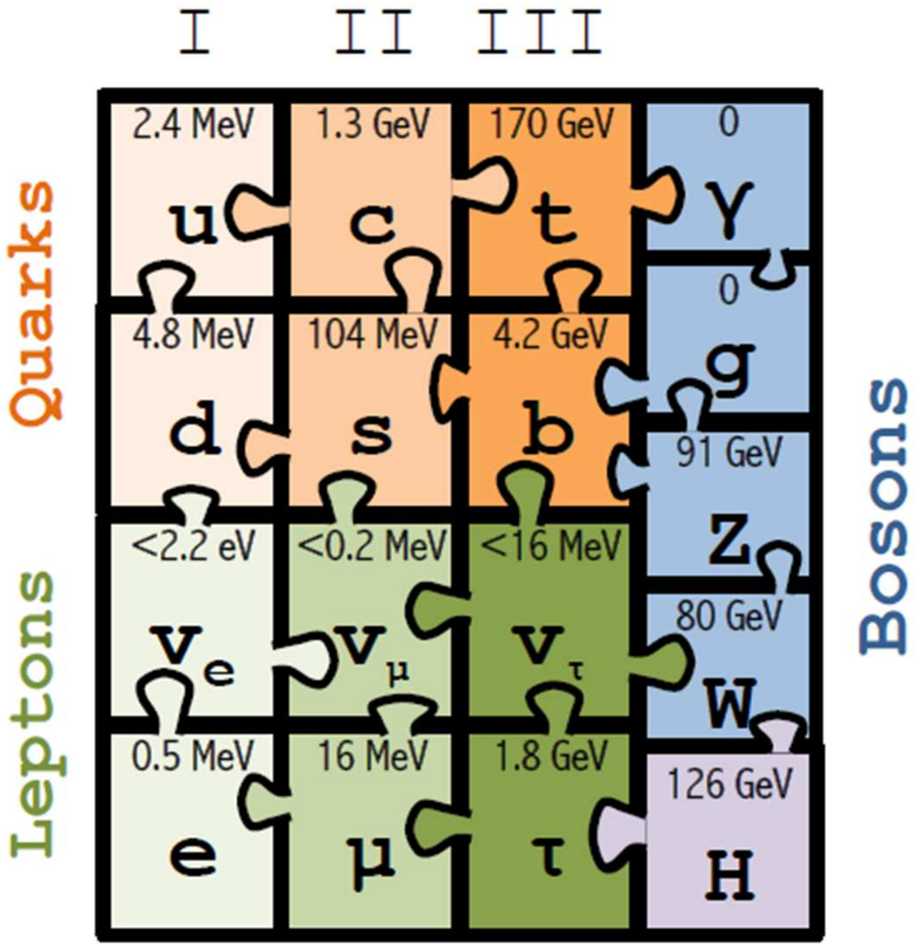
join us! http:cern.ch/fcc-ee

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

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

Higgs Boson discovered (LHC)

Englert and Higgs get Nobel Prize



(c) Sfyrla

Asymptotic safety of gravity and the Higgs boson mass

Mikhail Shaposhnikov

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

Christof Wetterich

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

12 January 2010

Abstract

There are indications that gravity is asymptotically safe. The Standard Model (SM) plus gravity could be valid up to arbitrarily high energies. Supposing that this is indeed the case and assuming that there are no intermediate energy scales between the Fermi and Planck scales we address the question of whether the mass of the Higgs boson m_H can be predicted. For a positive gravity induced anomalous dimension $A_\lambda > 0$ the running of the quartic scalar self interaction λ at scales beyond the Planck mass is determined by a fixed point at zero. This results in $m_H = m_{\rm min} = 126$ GeV, with only a few GeV uncertainty. This prediction is independent of the details of the short distance running and holds for a wide class of extensions of the SM as well. For $A_\lambda < 0$ one finds m_H in the interval $m_{\rm min} < m_H < m_{\rm max} \simeq 174$ GeV, now sensitive to A_λ and other properties of the short distance running. The case $A_\lambda > 0$ is favored by explicit computations existing in the literature.

Key words:
Asymptotic safety, gravity, Higgs field, Standard Model
PACS: 04.60.-m 11.10.Hi 14.80.Bn

Detecting the Higgs scalar with mass around 126 GeV at the LHC could give a strong hint for the absence of new physics influencing the running of the SM couplings between the Fermi and Planck/unification scales.

Is it the end?

-- Dark matter

-- Baryon Asymmetry in Universe

-- Neutrino masses

-- and... why are the charges of e and p identical to 21 significant digits?

are *experimental* proofs that there is more to understand.

We must continue our quest

«We can extrapolate to the Planck scale»

and

«There MUST be new physics at TeV scale»

mutually exclusive?

There is one way to find out: go look!

FCC

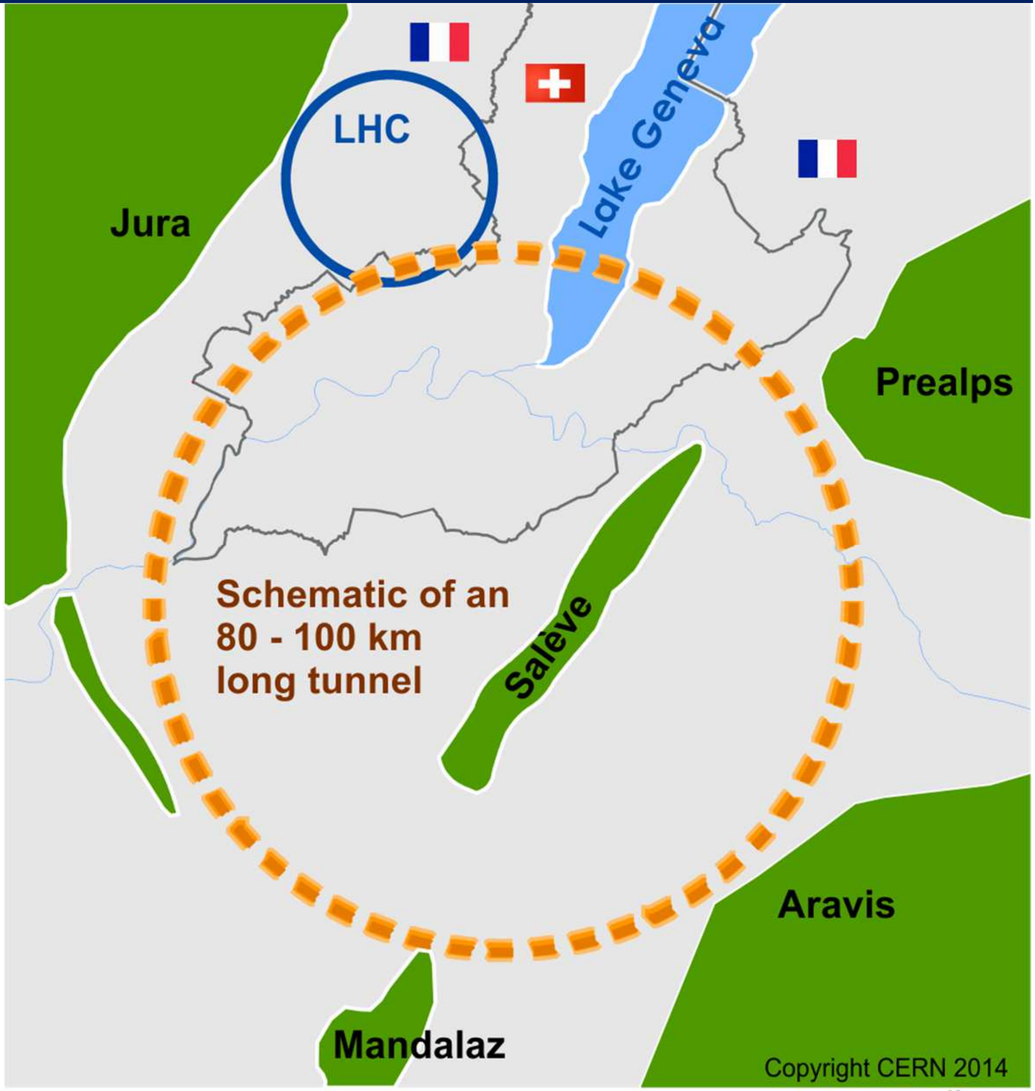
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

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

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

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



Future Circular Collider Study - FCC

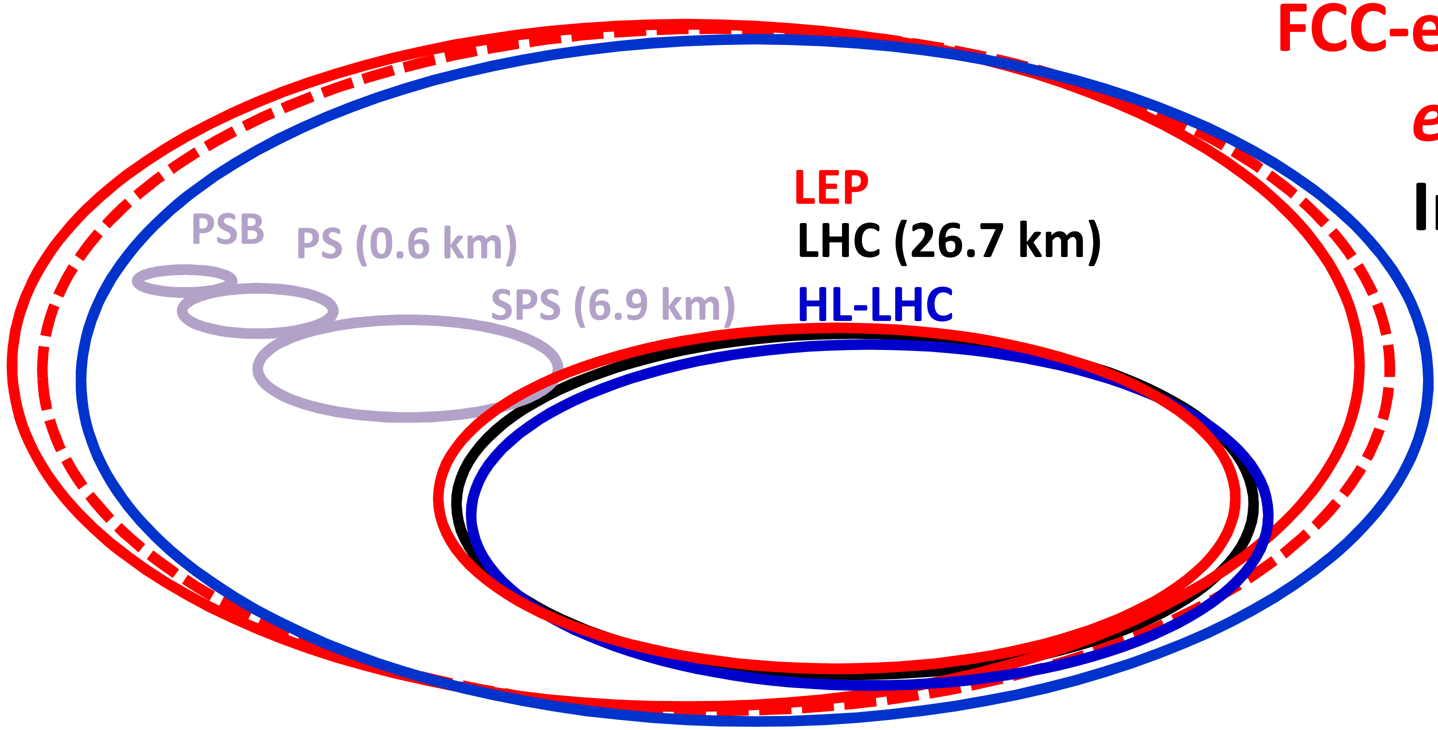
Mandate

Scope

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

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

possible long-term strategy



FCC-ee (80-100 km,
***e⁺e⁻*, 90-400 GeV**
Interm. step

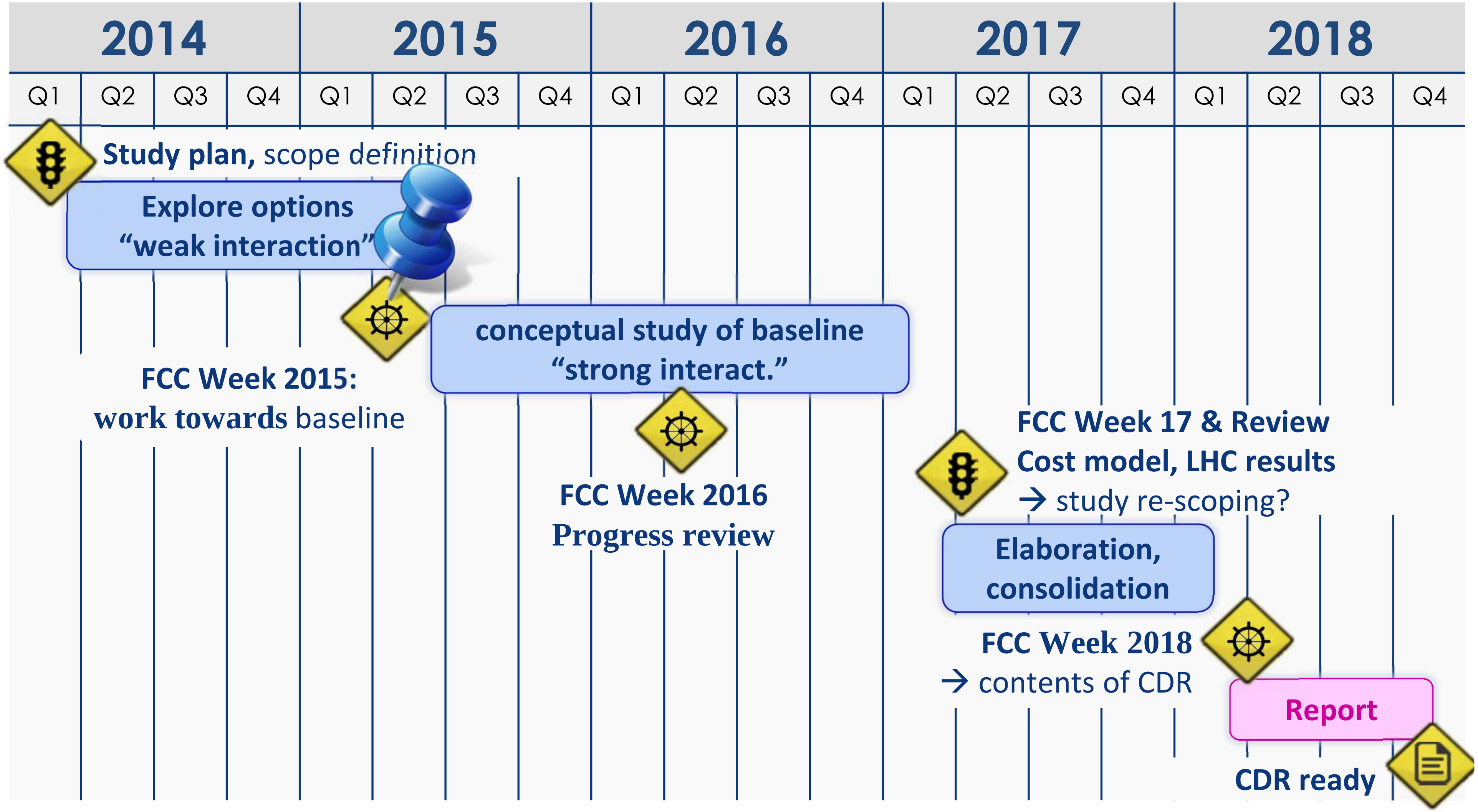
FCC-hh
(*pp*, up to
100 TeV c.m.)

Ultimate goal

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

≥60 years of *e$^+$e$^-$*, *pp*, *ep/A* physics at highest energies

Study time line towards CDR



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

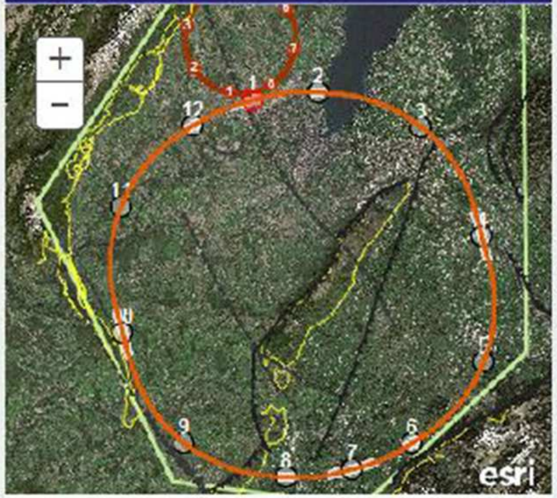
CALCULATE

Alignment centre

X: 2498923 Y: 1106695

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

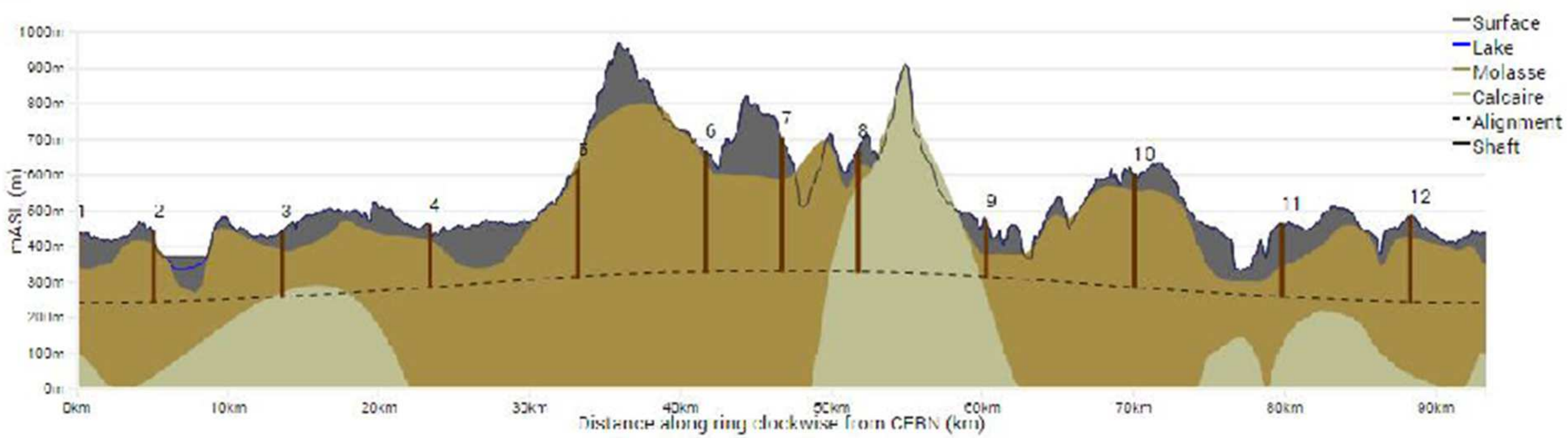
Alignment Location



Geology Intersected by Shafts | **Shaft Depths**

	Shaft Depth (m)				Geology (m)		
Shaft	Actual	Min	Mean	Max	Moraine	Molasse	Calcaire
1	200	195	197	200	92	108	0
2	196	143	181	211	34	162	0
3	183	176	184	194	53	121	9
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	237
9	155	131	145	157	94	61	0
10	315	305	320	336	46	269	0
11	203	199	202	204	122	81	0
12	239	229	238	243	58	181	0
Total	3014	2801	3001	3211	711	2052	247

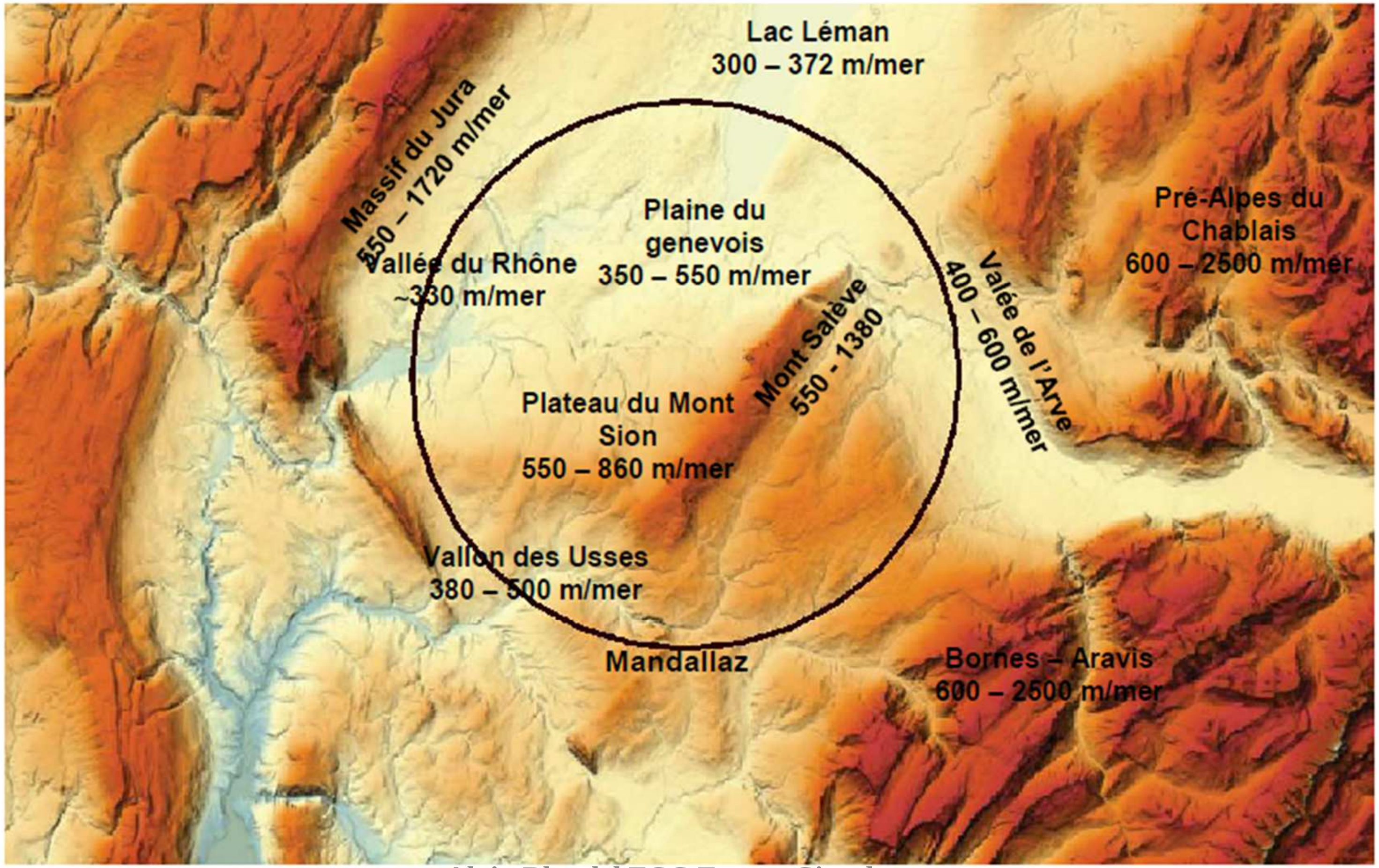
Alignment Profile



J. Osborne & C. Cook

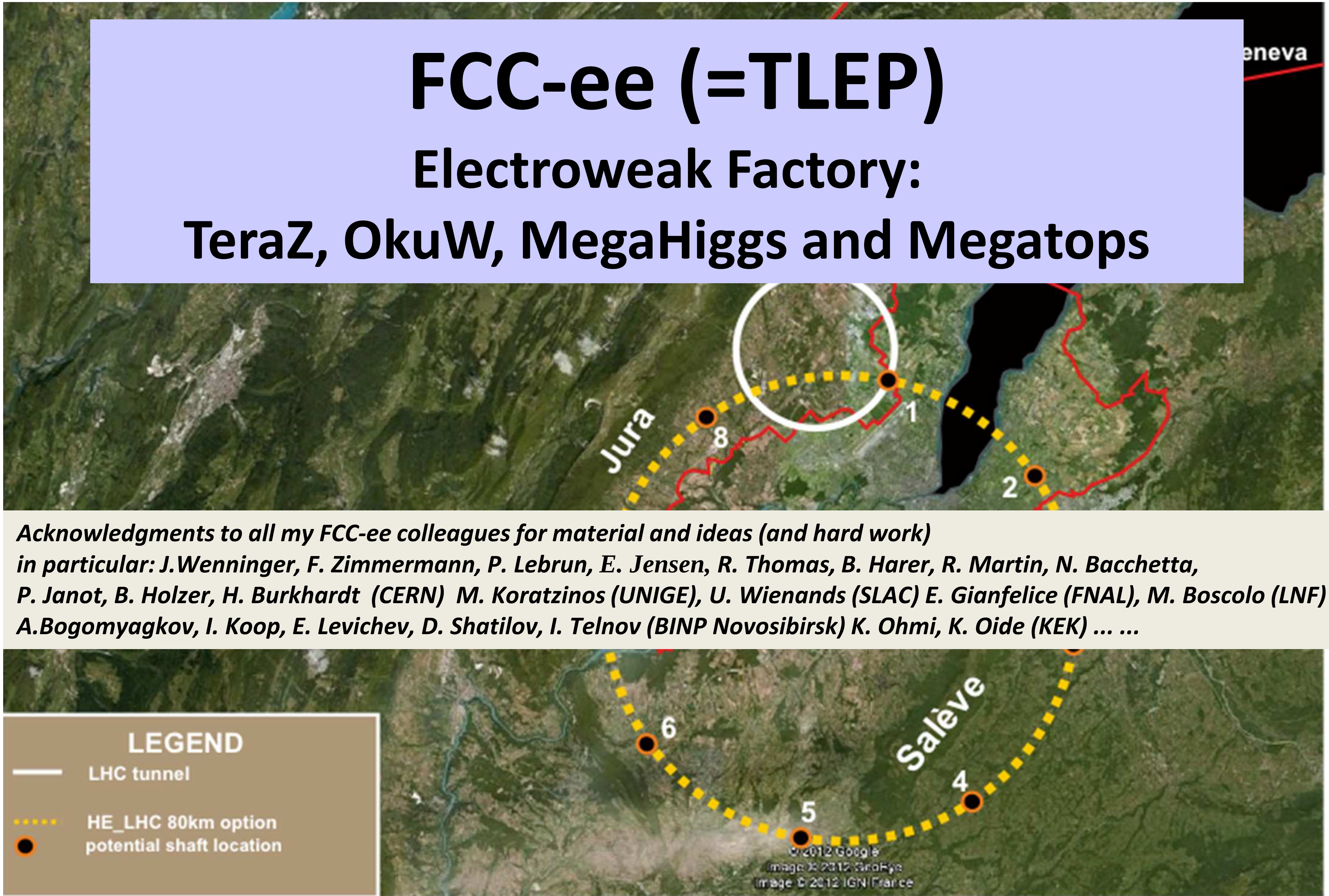
Tunnel location: topography [1/3]

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



FCC-ee (=TLEP)

Electroweak Factory:
TeraZ, OkuW, MegaHiggs and Megatops



Acknowledgments to all my FCC-ee colleagues for material and ideas (and hard work)
in particular: J.Wenninger, F. Zimmermann, P. Lebrun, E. Jensen, R. Thomas, B. Harer, R. Martin, N. Bacchetta,
P. Janot, B. Holzer, H. Burkhardt (CERN) M. Koratzinos (UNIGE), U. Wienands (SLAC) E. Gianfelice (FNAL), M. Boscolo (LNF)
A.Bogomyagkov, I. Koop, E. Levichev, D. Shatilov, I. Telnov (BINP Novosibirsk) K. Ohmi, K. Oide (KEK) ... ...

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

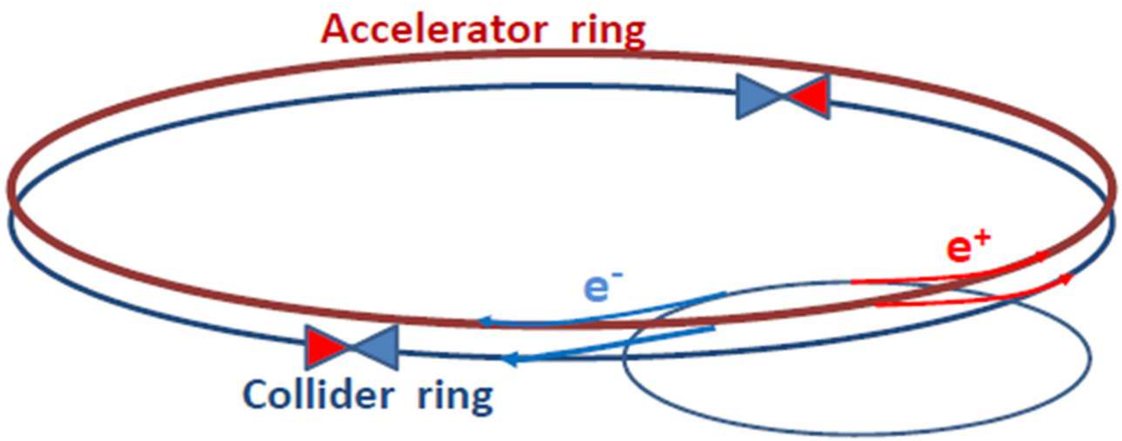
➔ Discovery of New Physics in rare phenomena or precision measurements

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

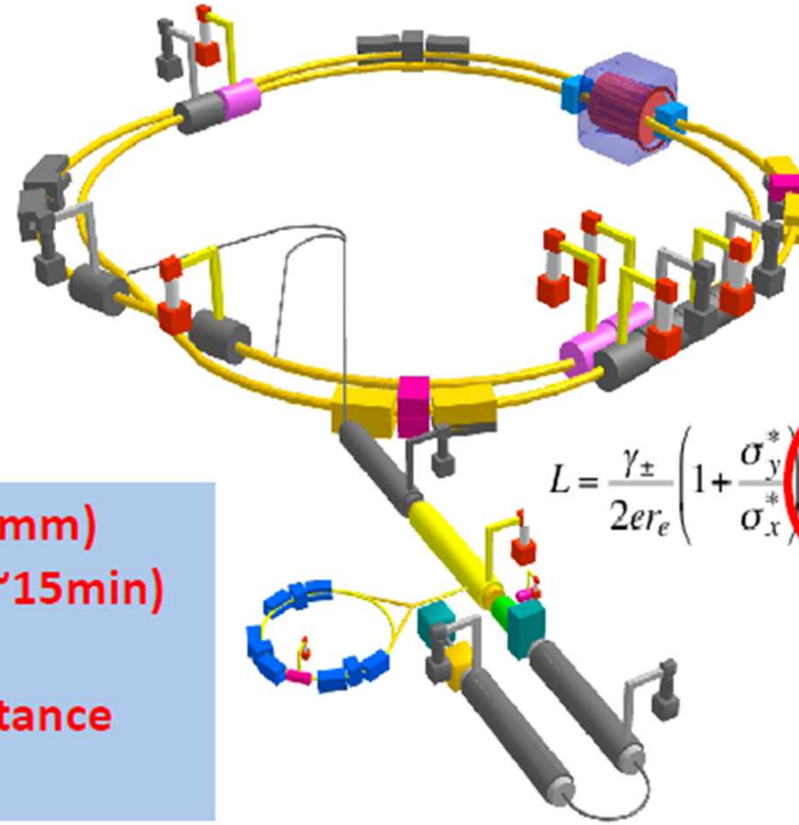
1000

at ZH threshold
in LEP/LHC tunnel
X 4 in FCC tunnel
X 4 interaction points
EXCITING!



SuperKEKB – TLEP demonstrator!

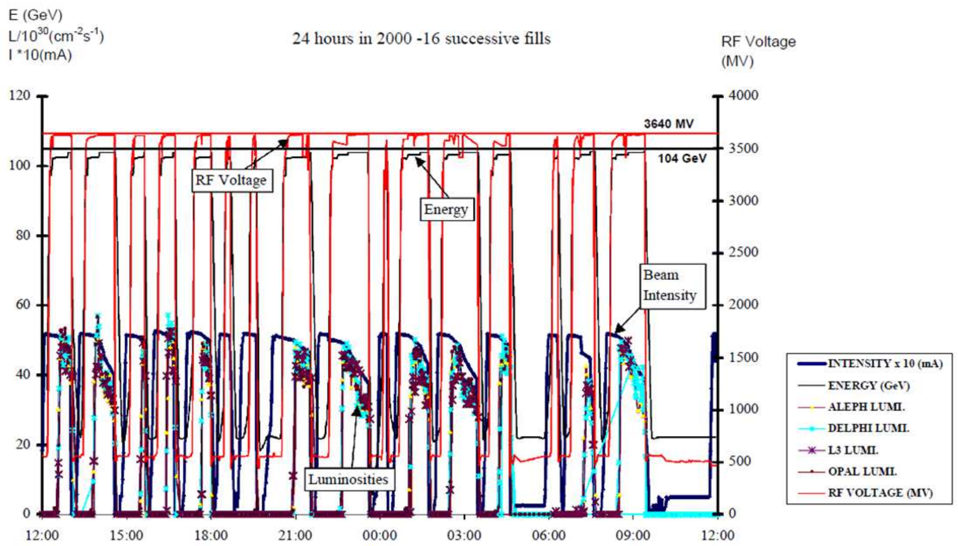
beam commissioning will start in early 2015

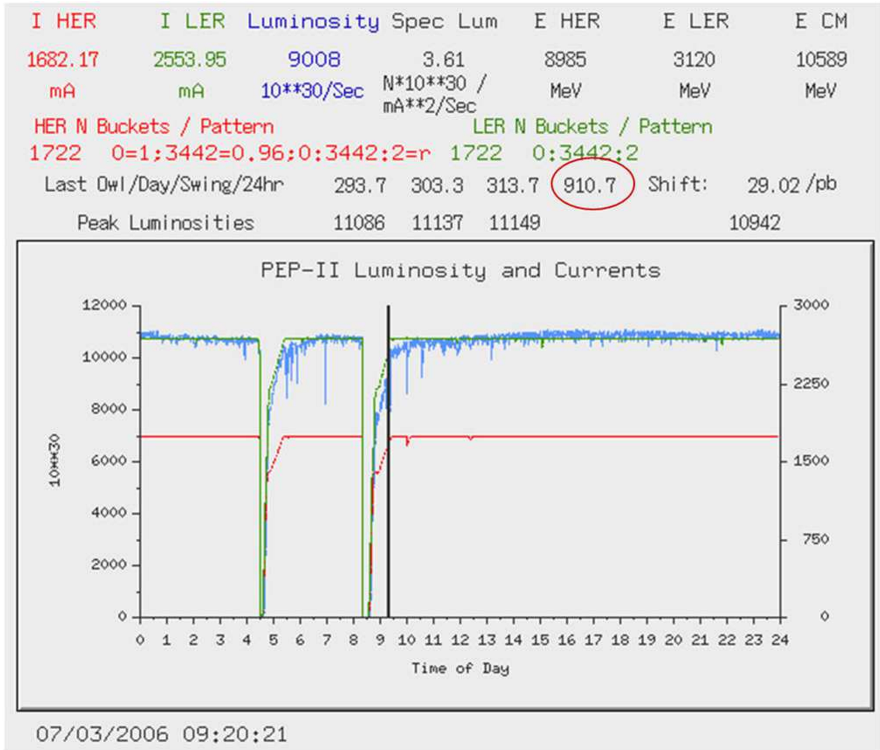


$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

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

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

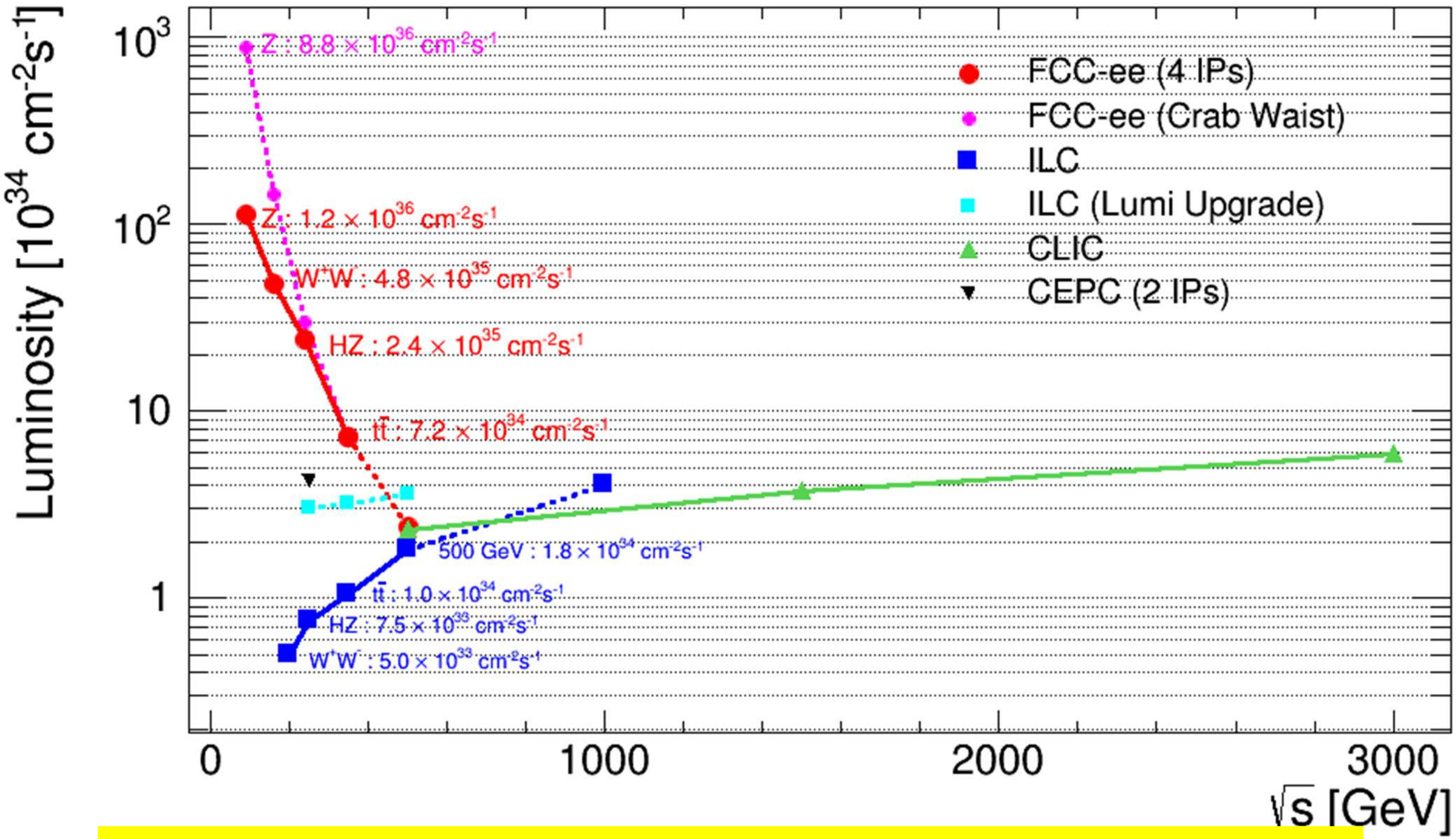




LEP2 in 2000 (12th year!):
fastest possible turnaround but
average luminosity ~ 0.2 peak luminosity

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

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



Overlapp in Higgs/top region, but differences and complementarities between linear and circular machines

TLEP: PARAMETERS & STATISTICS

(e^+e^- -> ZH, $e^+e^- \rightarrow W^+W^-$, $e^+e^- \rightarrow$ Z,[$e^+e^- \rightarrow t\bar{t}$])

	TLEP-4 IP, per IP	statistics
circumference	80 km	
max beam energy	175 GeV	
no. of IPs	4	
Luminosity/IP at 350 GeV c.m.	1.3×10^{34} $cm^{-2}s^{-1}$	10^6 $\bar{tt}$ pairs
Luminosity/IP at 240 GeV c.m.	6.0×10^{34} $cm^{-2}s^{-1}$	2 10^6 ZH evts
Luminosity/IP at 160 GeV c.m.	1.6×10^{35} $cm^{-2}s^{-1}$	10^8 WW pairs
Luminosity/IP at 90 GeV c.m.	2. $10^{35/36}$ $cm^{-2}s^{-1}$	$10^{12/13}$ Z decays

at the *Z* pole repeat the LEP physics programme in a few minutes…

PUBLISHED

JHEP

Published for SISSA by Springer

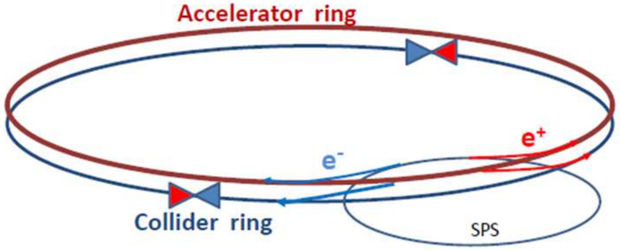
Received: *September 23, 2013*
Accepted: *December 25, 2013*
Published: *January 29, 2014*

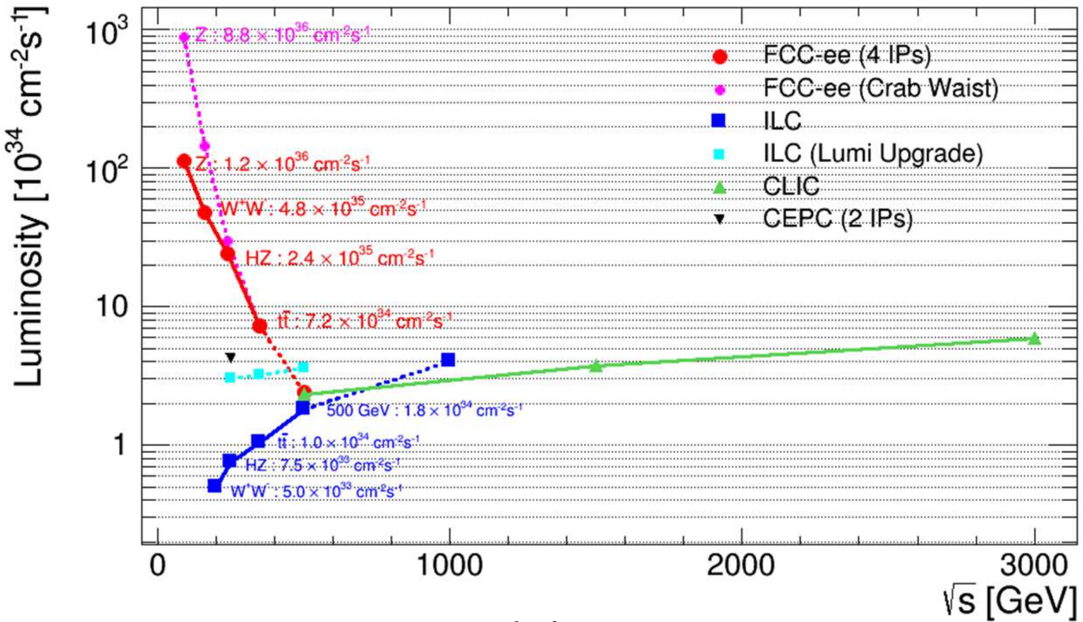
First look at the physics case of TLEP

The TLEP Design Study Working Group

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

JHEP01(2014)164





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

-- Model independent Higgs couplings and invisible width

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

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

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

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

Snapshot of novelties appeared in recent workshops

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

➔ sensitivity to right handed (sterile) neutrinos

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

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

➔ discovery potential for very small couplings

➔ precision event generators (Jadach et al)

http://cern.ch/FCC-ee

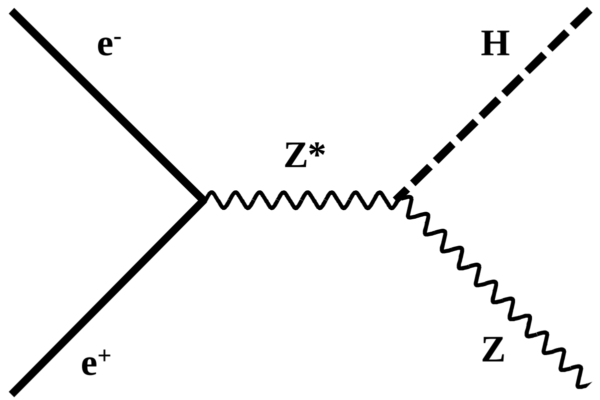
Higgs production mechanism

“higgstrahlung” process close to threshold

Production xsection has a maximum at near threshold ~200 fb

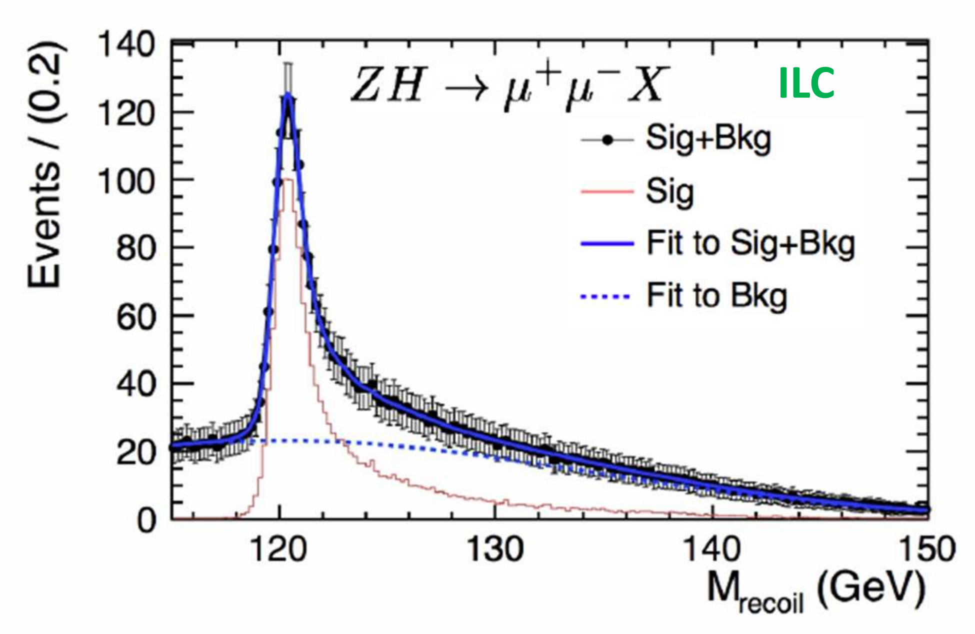
10^{34}/cm^2/s ➔ 20’000 HZ events per year. (~ ILC, muon collider)

FCC-ee → 400’000 HZ events a 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 $\propto g_{HZZ}^2$

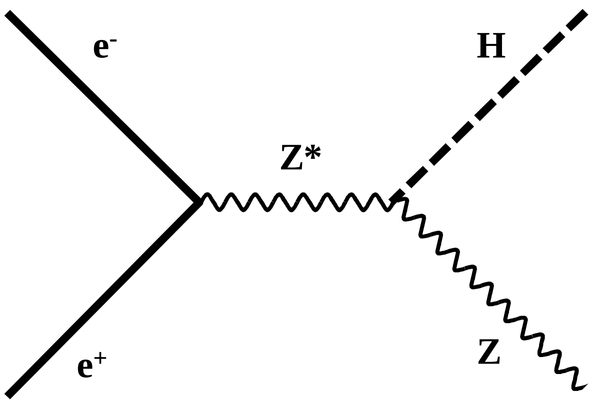
ZZZ final state $\propto g_{HZZ}^4 / \Gamma_H$

➔ measure total width Γ_H

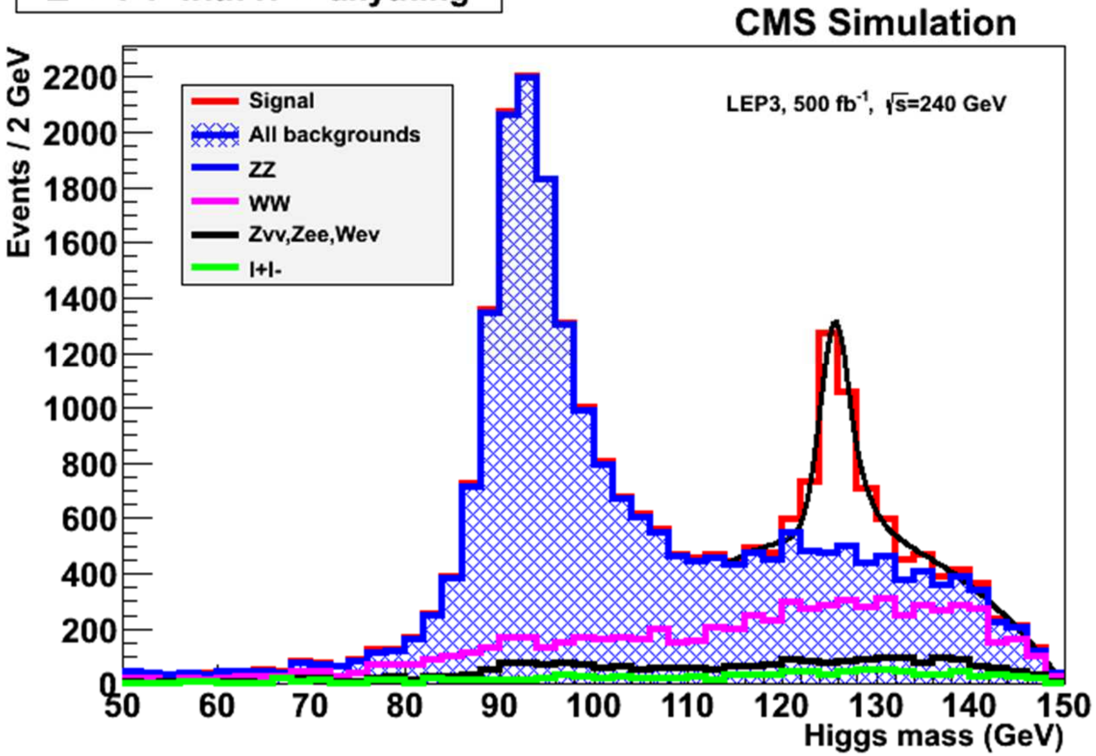
empty recoil = invisible width

'funny recoil' = exotic Higgs decay

easy control below theshold



Z -> l+l- with H -> anything



Higgs factory

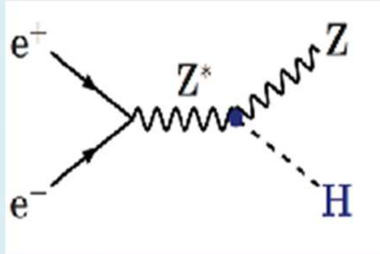
(constrained fit including 'exotic')

	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

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



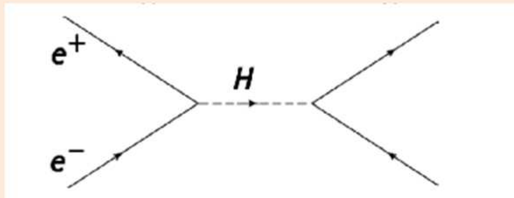
$2\ 10^6$ ZH events in 5 years

«A tagged Higgs beam».

sensitive to new physics in loops

incl. invisible = (dark matter?)

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



10^4 events per year.
Very difficult because huge background and beam energy spread ~ 10 x Γ_H
limits or signal? monochromators?
Aleksan, D'Enterria, Woijcik

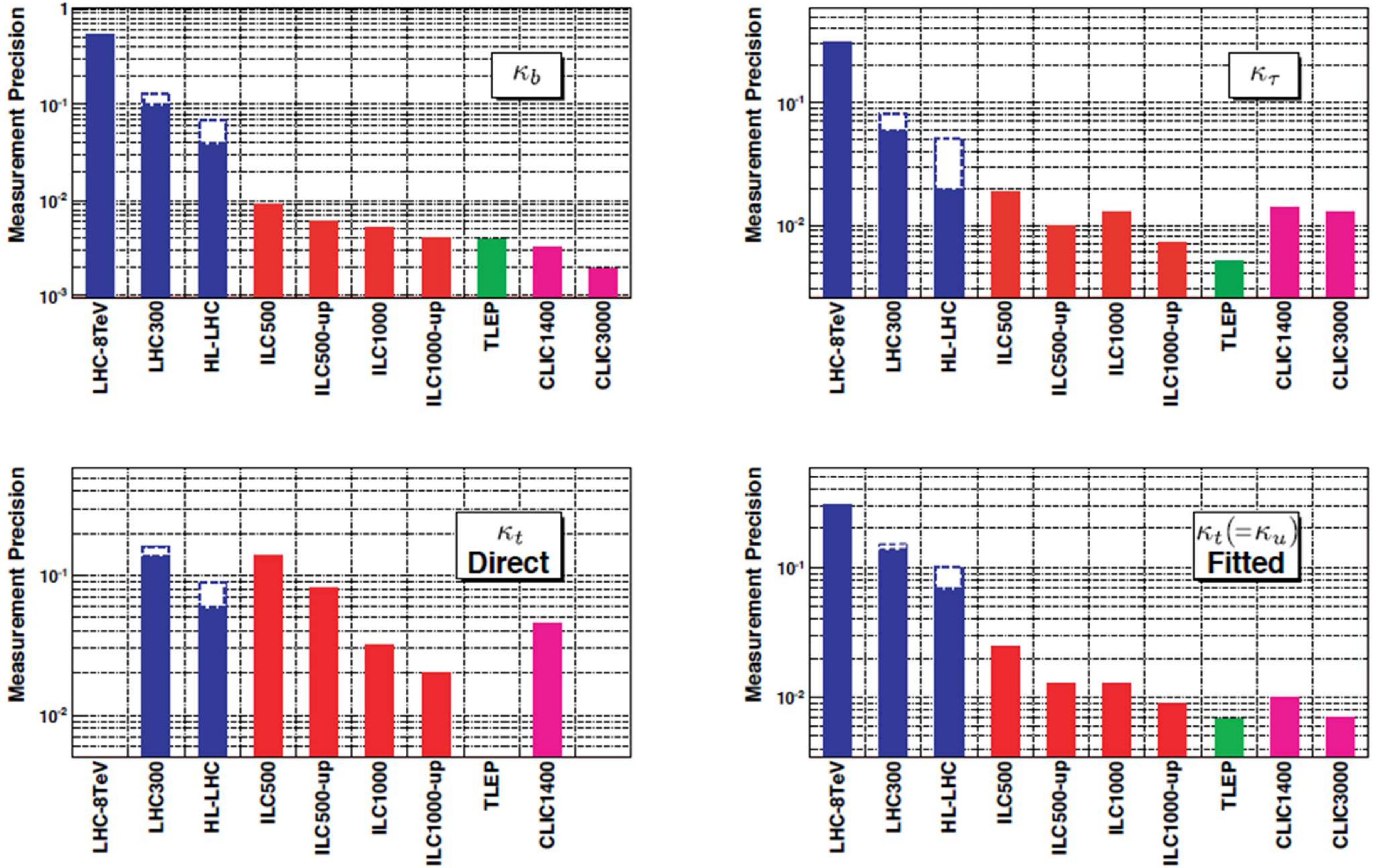


Figure 1-4. *Measurement precision on κ_b, κ_τ, and κ_t measured both directly via $t\bar{t}H$ and through global fits at different facilities.*

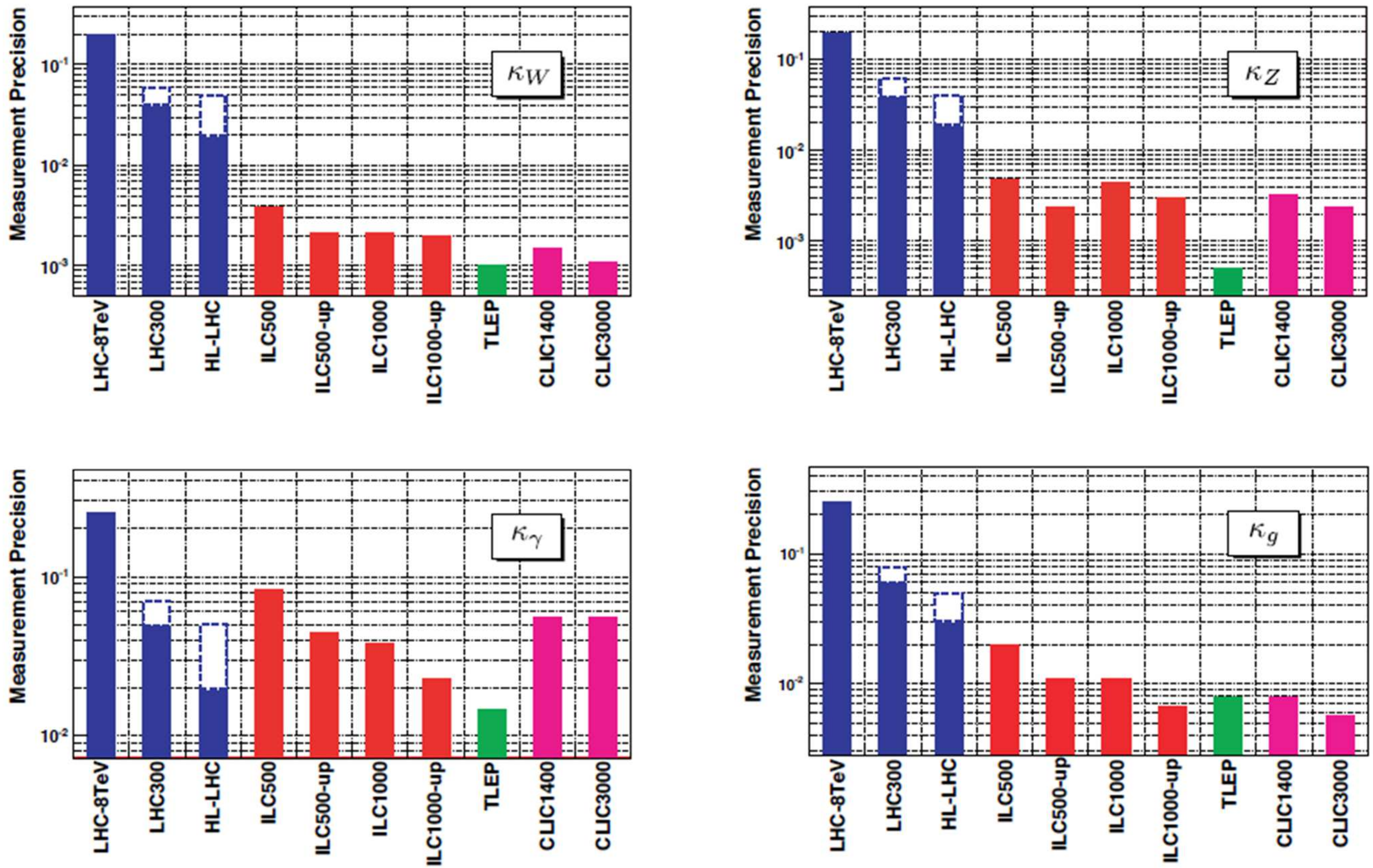
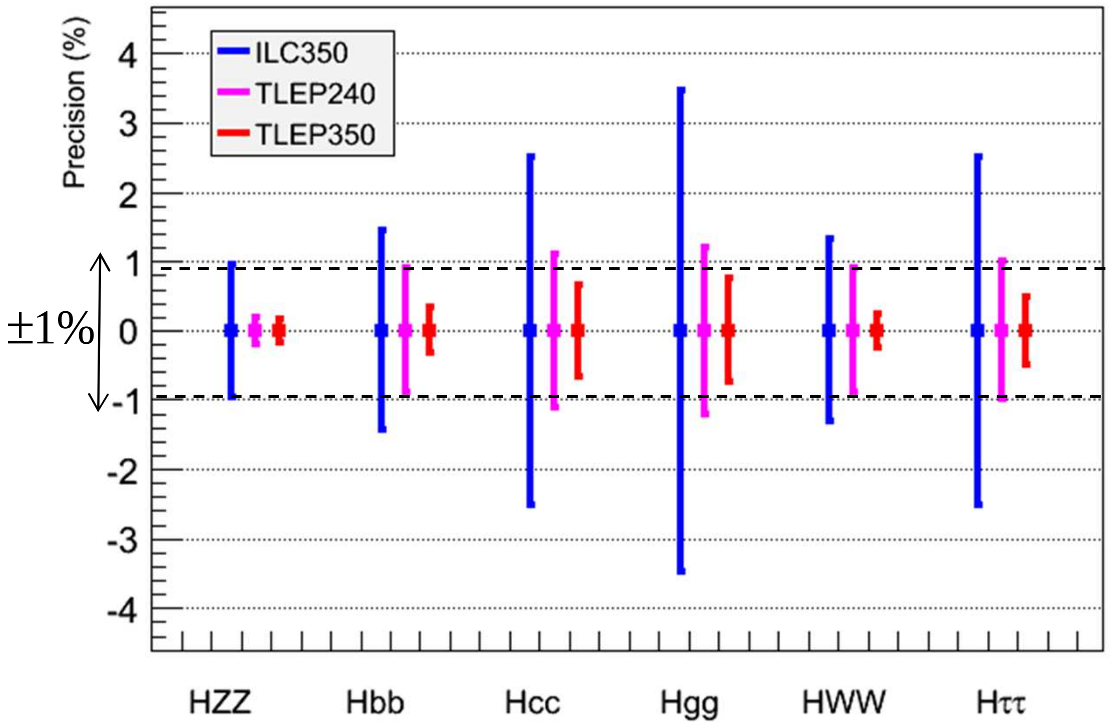


Figure 1-3. *Measurement precision on κ_W, κ_Z, κ_γ, and κ_g at different facilities.*

Performance Comparison

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

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

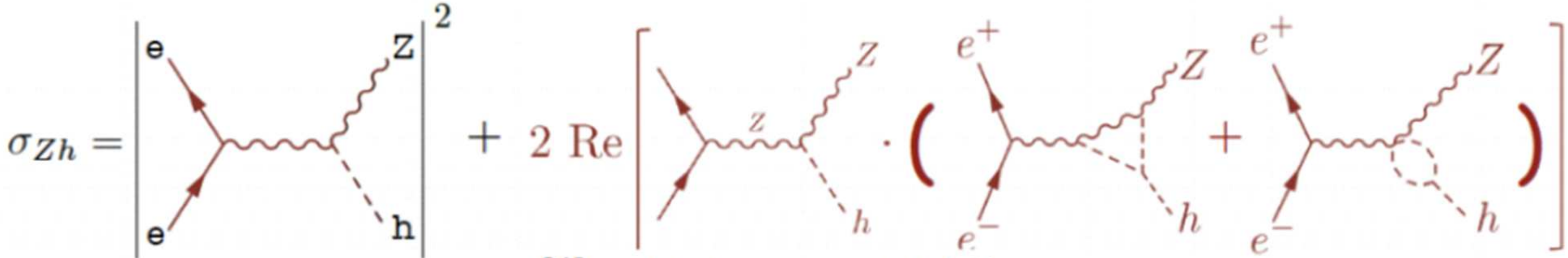


Expected precision on the total width

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

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

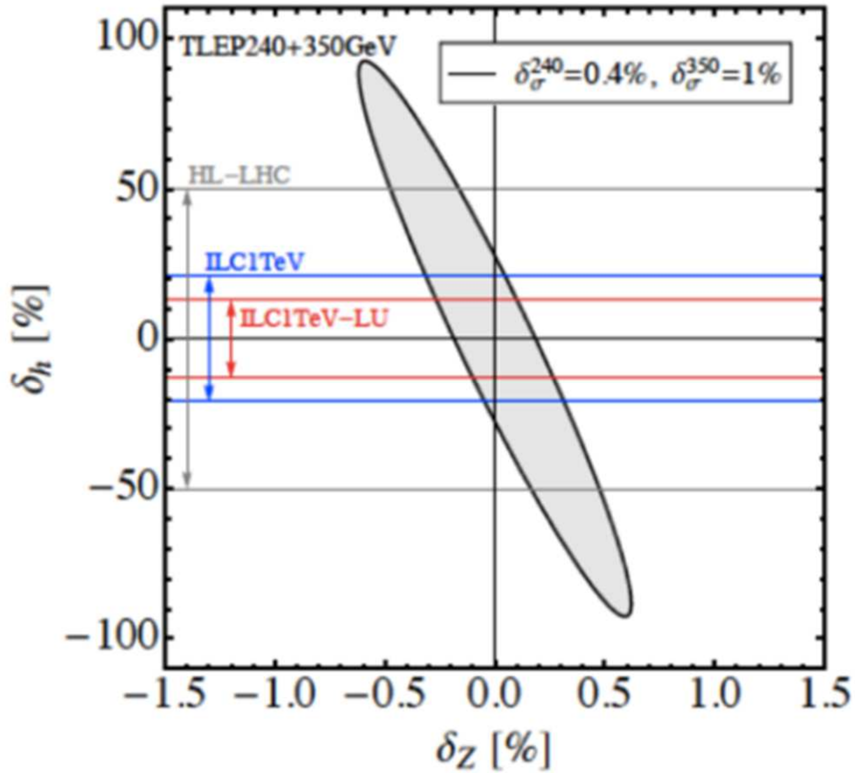
very accurate precision on threshold cross-section sensitive to loop corrections



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

arxiv:1312.3322

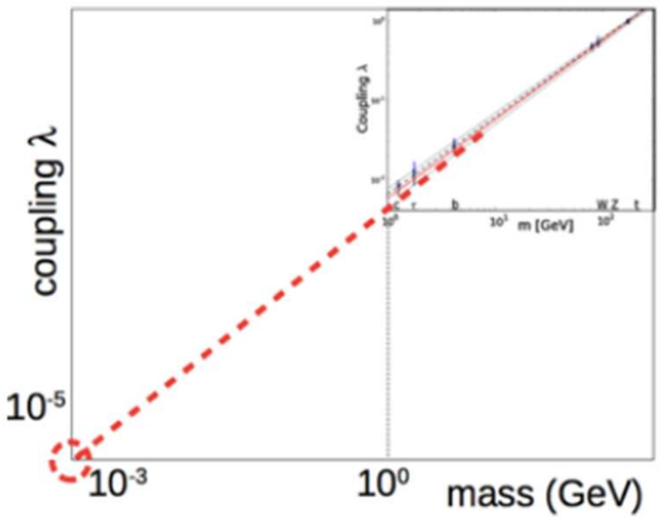
- ➡ Very large datasets at high energy allow extreme precision g_{ZH} measurements
- ➡ Indirect and model-dependent probe of Higgs self-coupling
- ➡ Note, the time axis is missing from the plot

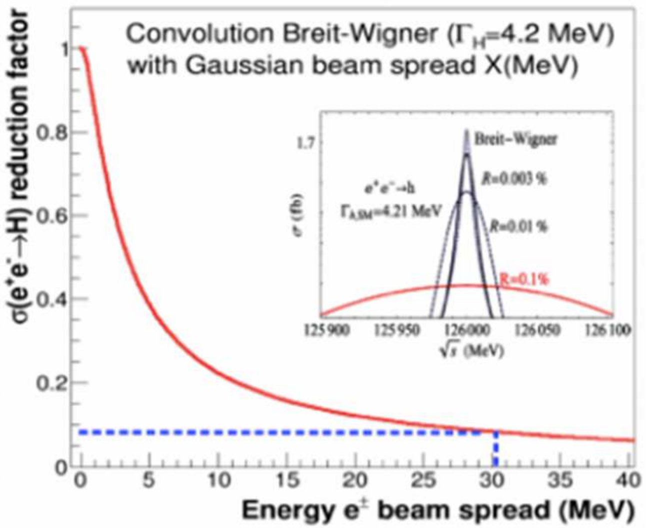


First generation couplings

➡ **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}

$\kappa_e < 2.2$ at 3σ

➡ **Work in progress**

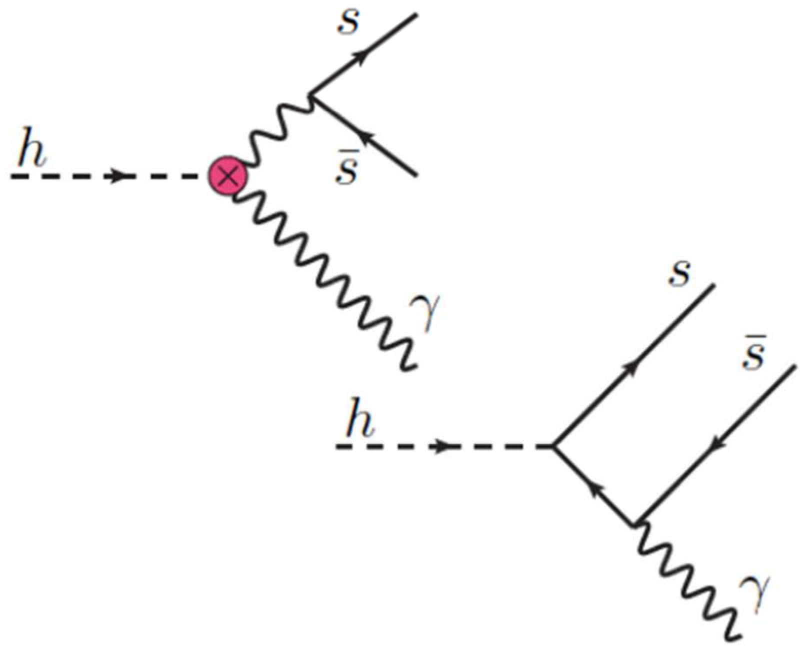
- How large are loop induced corrections? How large are BSM effects?
- Do we need an energy scan to find the Higgs?
- How much luminosity will be available for this measurement? By how much is the luminosity reduced by monochromators?

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

$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.9\pm0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d\right]}{0.57\bar{\kappa}_b^2}\times 10^{-5}$$

- 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

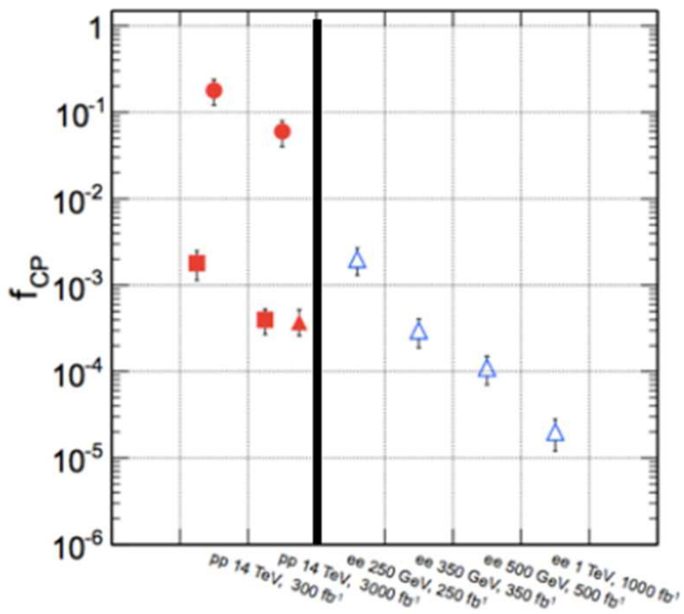
H → **ρ** γ

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

for HVV couplings



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

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°

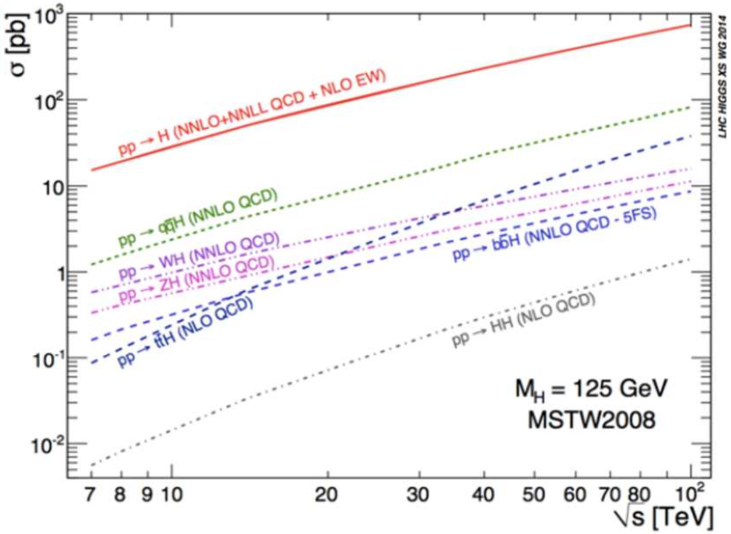
Rare and Exotics Higgs Bosons

- 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

$h \to \not{E}_T$
$h \to 4b$
$h \to 2b2\tau$
$h \to 2b2\mu$
$h \to 4\tau, 2\tau2\mu$
$h \to 4j$
$h \to 2\gamma2j$
$h \to 4\gamma$
$h \to ZZ_D, Za \to 4\ell$
$h \to Z_DZ_D \to 4\ell$
$h \to \gamma + \not{E}_T$
$h \to 2\gamma + \not{E}_T$
$h \to$ 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
$h \to b\bar{b} + \not{E}_T$
$h \to \tau^+\tau^- + \not{E}_T$

HIGGS AT FCC-pp

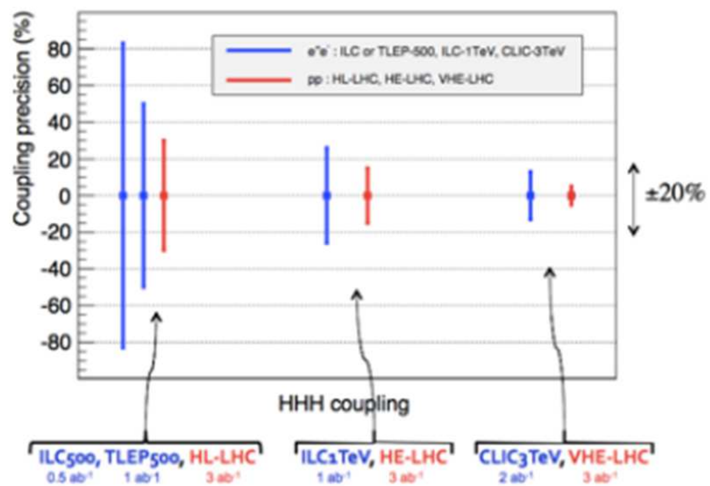
Process	8 TeV	14 TeV	100 TeV
gF	0.38	1	14.7
VBF	0.38	1	18.6
WH	0.43	1	9.7
ZH	0.47	1	12.5
ttH	0.21	1	61
bbH	0.34	1	15
gF to HH	0.24	1	42



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

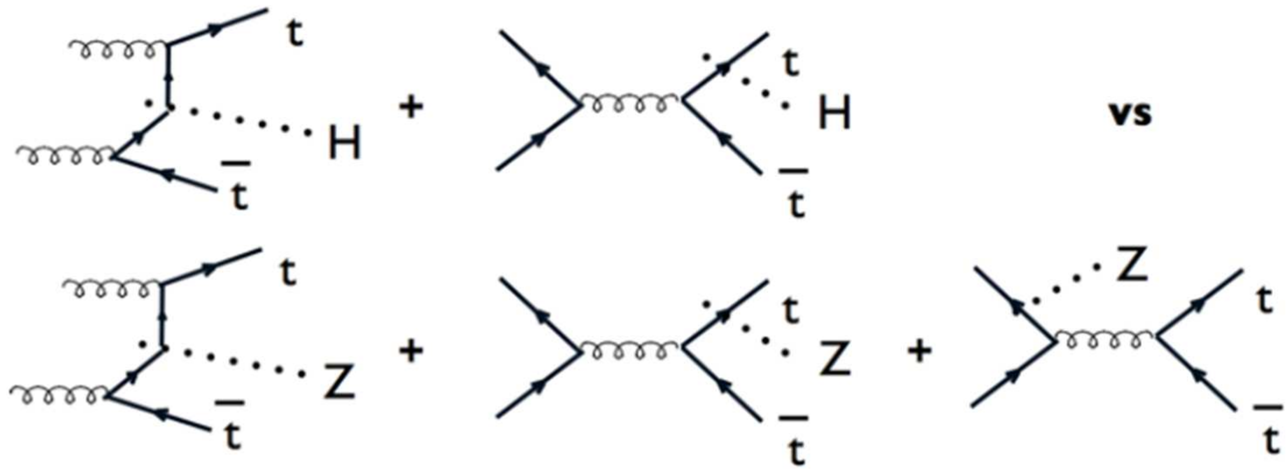
	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L}dt$ (fb^{-1})	3000	3000	3000
$\sigma \cdot BR(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

arXiv:1310.8361



➡ … 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.**

Table from D. Curtin FCC workshop, Washington, 23-27 March 2015)

- Both lepton and 100 TeV pp colliders are vital for this effort!

Observables at Current + Future Colliders	100 TeV	ILC/TLEP
• producing extra higgs states (incl. superpartners)	✓	
• Exotic Higgs Decays	✓	✓
• Electroweak Precision Observables		✓
• Higgs coupling measurements	✓	✓
• Higgs portal direct production of new states	✓	
• Higgs self coupling measurements	✓	✓
• Zh cross section measurements		✓

Higgs invisible decays

Right handed Neutrinos
etc.. etc..

because of Luminosity FCC-ee (in combination with HL-LHC and/or FCC-hh) is a very powerful Higgs Factory, but....

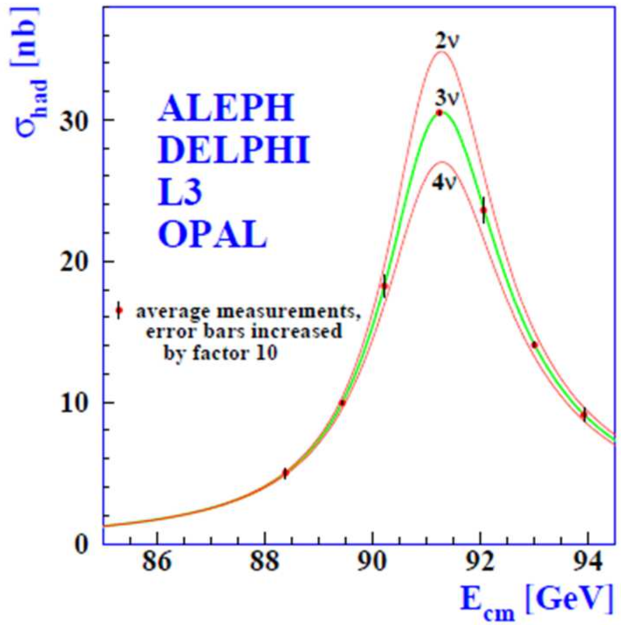
FCC-ee is MUCH more than a Higgs Factory!

TERA-Z, Oku-W, Megatops

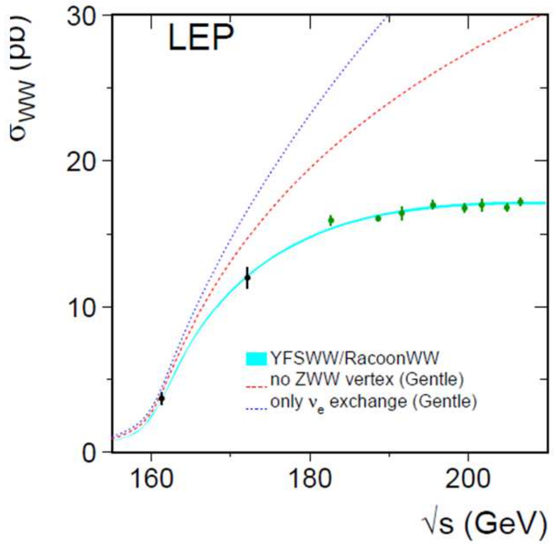
Precision tests of the closure of the Standard Model

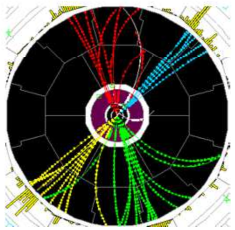
Precision tests of EWSB

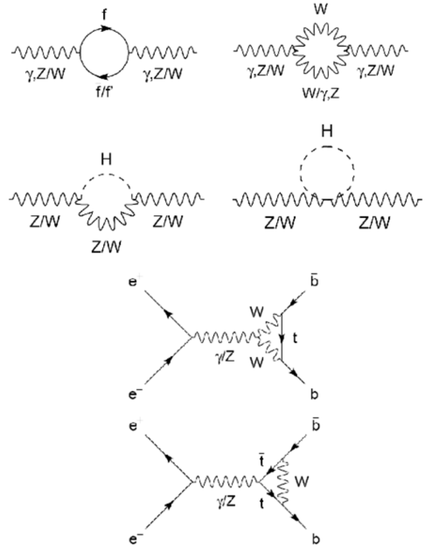
Z pole ssymmetries, lineshape



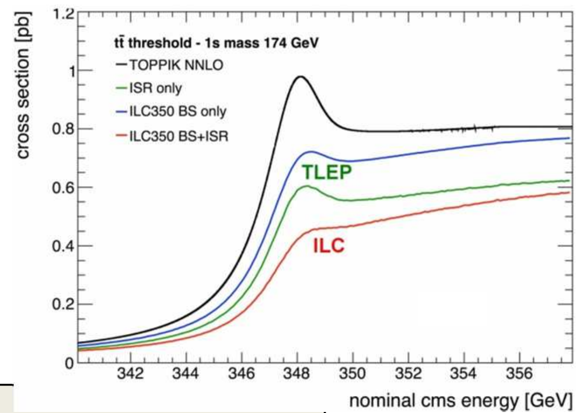
WW threshold scan







tt threshold scan



Frank Simon

TLEP : Repeat the LEP1 physics programme every 15 mn

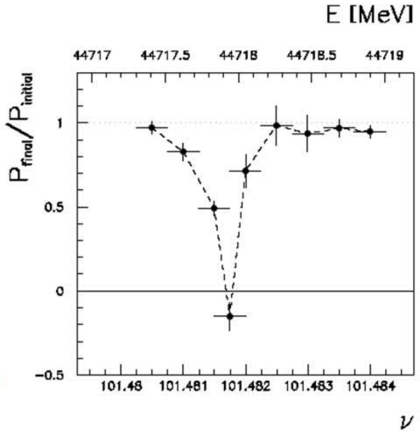
Transverse polarization up to the WW threshold

- **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…**

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

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

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

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

Similarly:

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

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

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

target precisions

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

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

Design study to establish possibility of corresponding precision theoretical calculations.

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

Asset: -- high luminosity (10^{12} Z decays + 10^{8} Wpairs + … 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 $\sin^2\theta^{\rm eff}_{\rm W}$, 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 from	…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
… 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?

Input from Physics to the accelerator design

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

1. Do we need polarized beams?

-1- transverse polarization:

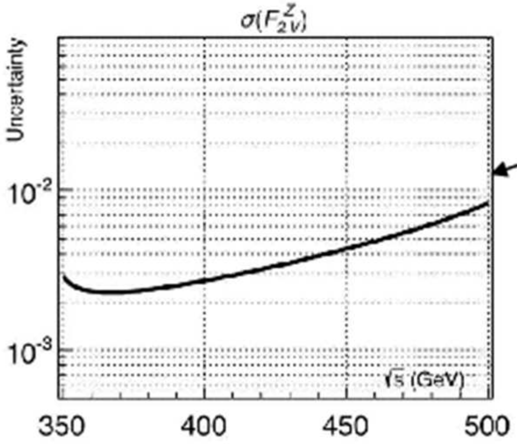
continuous beam Energy calibration with resonant depolarization
central to the precision measurements of m_Z , m_W , Γ_Z
requires 'single bunches'
a priori doable up to W energies -- workarounds exist above (e.g. γZ events)
large ring with small emittance offers *a priori* excellent prospects
need wigglers; simulations ongoing (E. Gianfelice, M. Koratzinos)

-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, Azzi)
-- 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?

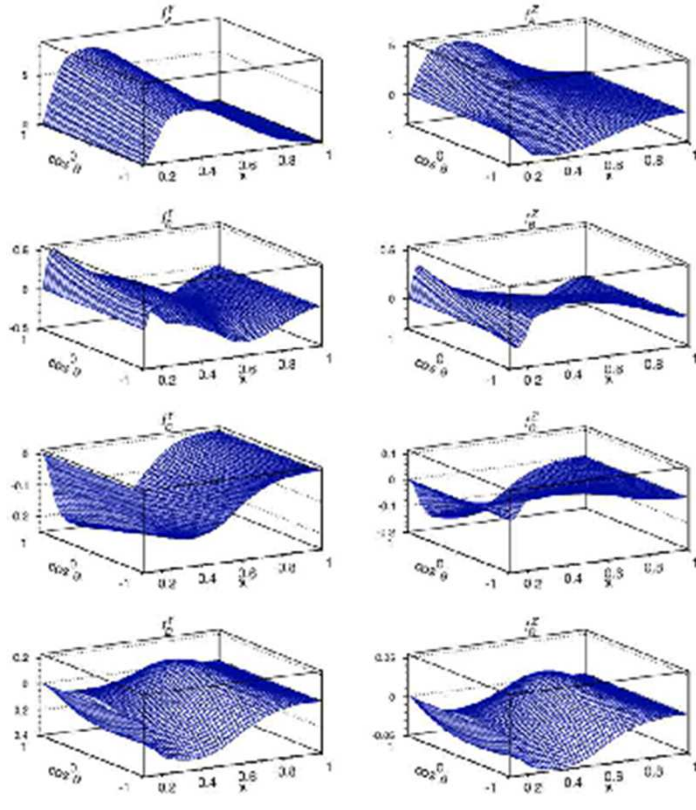
-- in addition to Z, W, H and top listed the following are being considered
-- e+e- → H(125.2) (requires monochromatization A. Faus) (under study)
-- e+e- at ~70 GeV (Z-γ interference)
-- e+e- at top threshold + <~20 GeV for top couplings (E_max up to 180 -185 GeV)
-- no obvious case for going to 500 GeV

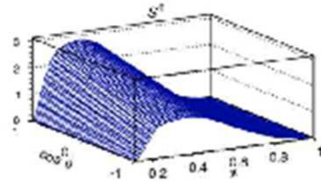
Determination of top-quark EW couplings via measurement of top-quark polarization.
In semileptonic decays, fit to lepton momentum vs scattering angle

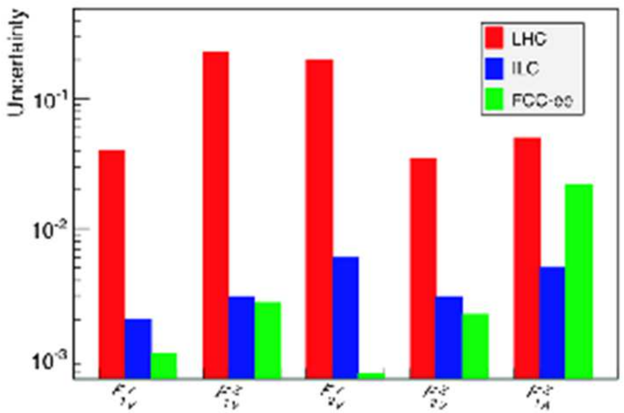


Typically best sensitivity just above production threshold

Momenta up to: 175 GeV







Patrizia Azzi:
Top physics at FCC-ee

Patrick Janot
arXiv:1503.01325v2

Next plans for FCC-ee

-- quality of FCC-ee experiments is intimately related to accelerator performance
- -- available energy points
- -- Luminosities
- -- beam polarization and energy calibration
- -- knowledge of other beam parameters (e.g. energy spread vs Z width)

reinforce work hand-in-hand

-- we can (mostly out of LEP experience) project fairly well the experimental precisions
-- sometimes they are vertiginously small
$\Delta \sin^2\theta_W^{eff} = 5\ 10^{-6}$, Δm_Z= 0.1 MeV $\Delta\Gamma_Z$= 0.1 MeV Δm_W = 0.5 MeV $\Delta\sigma_{ZH} / \sigma_{ZH} \sim 10^{-3}$ etc...
careful revisiting will be necessary.

-- full use of precision measurements requires a considerable improvement in the theory calculations
- -- for the measurements themselves (e.g. Full two loops exponentiated for the QED ISR)
- -- for the interpretation; full three loop calculations for EWRCs and on inputs ($\Delta\alpha$_QED(m_Z)) *Was, Gluza, Heynemeyer, Kuhn, Frietas, Jadach, Ward..*

Rare decays

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

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

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

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

-- flavour physics...

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

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

But Where Is Everybody?

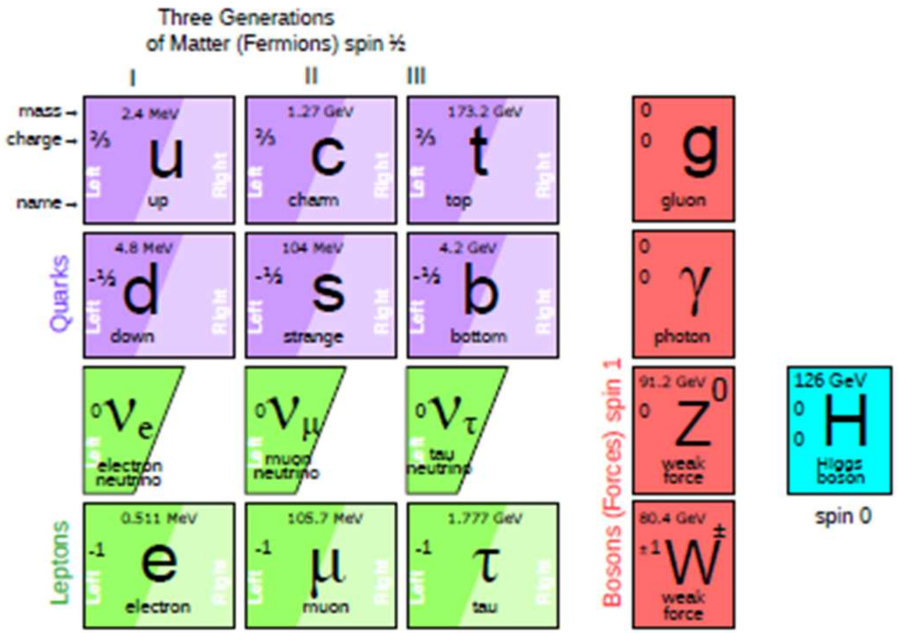
Nima

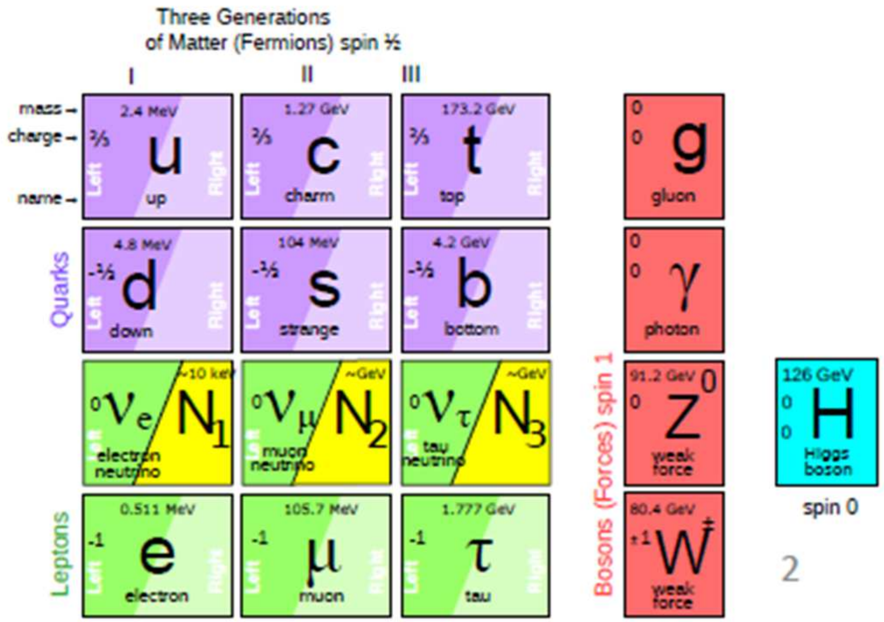
Nima

At higher masses -- or at smaller couplings?

THE STANDARD MODEL IS COMPLETE .....

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





2

neutrinos have mass...

and this very probably implies new degrees of freedom

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

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

Electroweak eigenstates

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

Mass eigenstates

See-saw in a general way :

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

$M_R \neq 0$
$m_D \neq 0$
<u>Dirac + Majorana mass terms</u>

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

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

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

general formula — if $m_D \ll M_R$

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

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)

$M_R \neq 0$
$m_D = 0$
<u>Majorana only</u>

m ↑

	ν_L	$\bar{\nu}_R$
I_{weak}=	½	½

2 states of equal masses

All have I=1/2 (active)

---

see-saw

$M_R \neq 0$
$m_D \neq 0$
<u>Dirac + Majorana</u>

m ↑

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

4 states , 2 mass levels

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

There even exists a scenario that explains everything: the νMSM

Shaposhnikov et al

TeV

GeV

MeV

keV

eV

meV

ν_3

ν_2

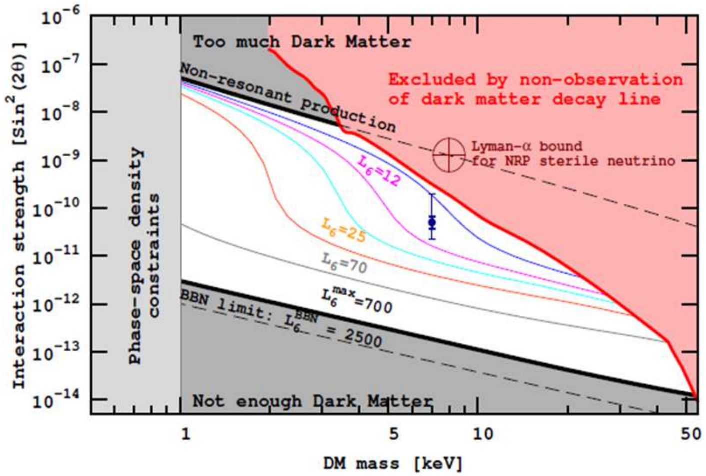
ν_1

N_2, N_3

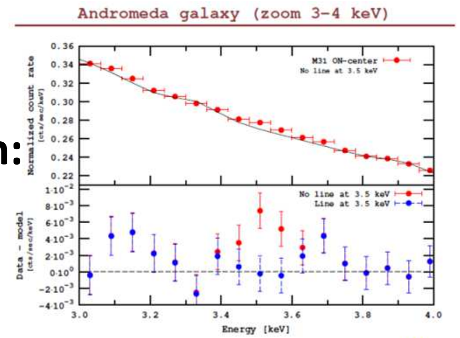
can generate Baryon Asymmetry of Universe
if $m_{N2,N3}$ > 140 MeV

N_1

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



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



(or not)

Manifestations of right handed neutrinos

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

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

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

what is produced in W, Z decays is:

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

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

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

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

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

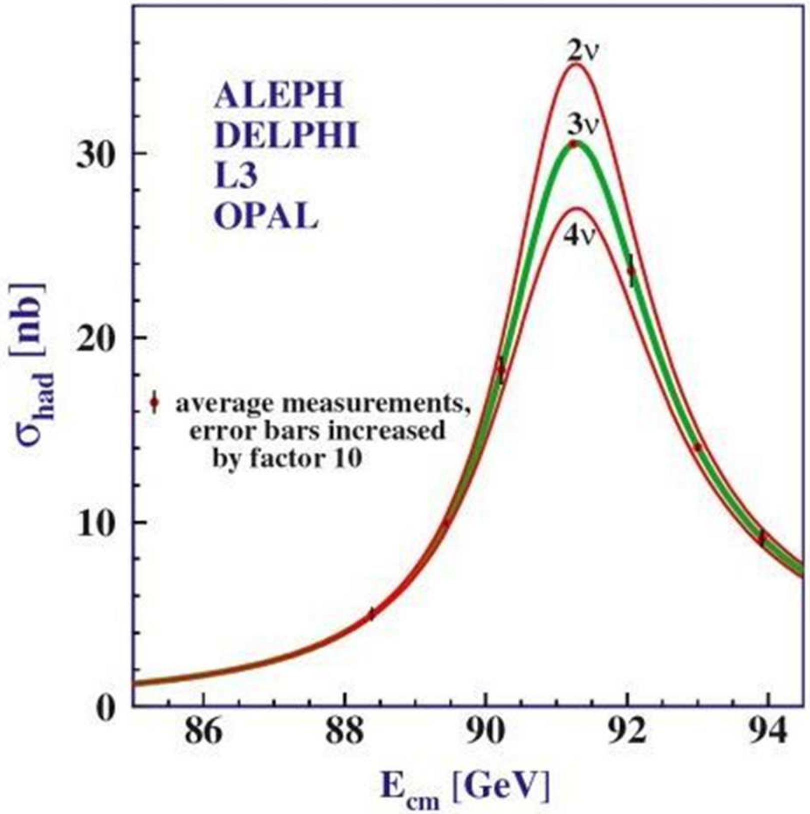
see recent work arXiv:1411.5230 arXiv:1412.6322v1

At the end of LEP:

Phys.Rept.427:257-454,2006

$N_\nu = 2.984 \pm 0.008$

- 2 σ :^) !!



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

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

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

Neutrino counting at TLEP

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

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

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

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

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

161 GeV (10^7 s) running at $1.6\times10^{35}/cm^2/s$ 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

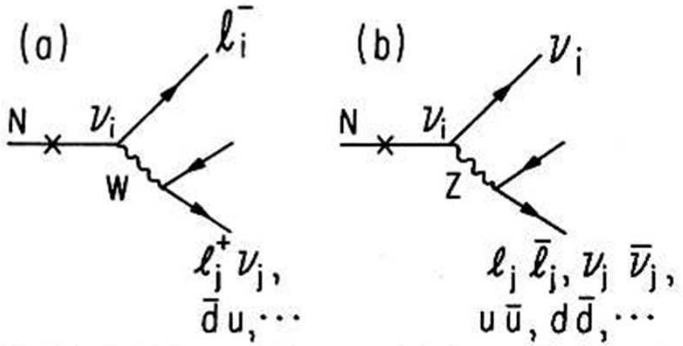


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

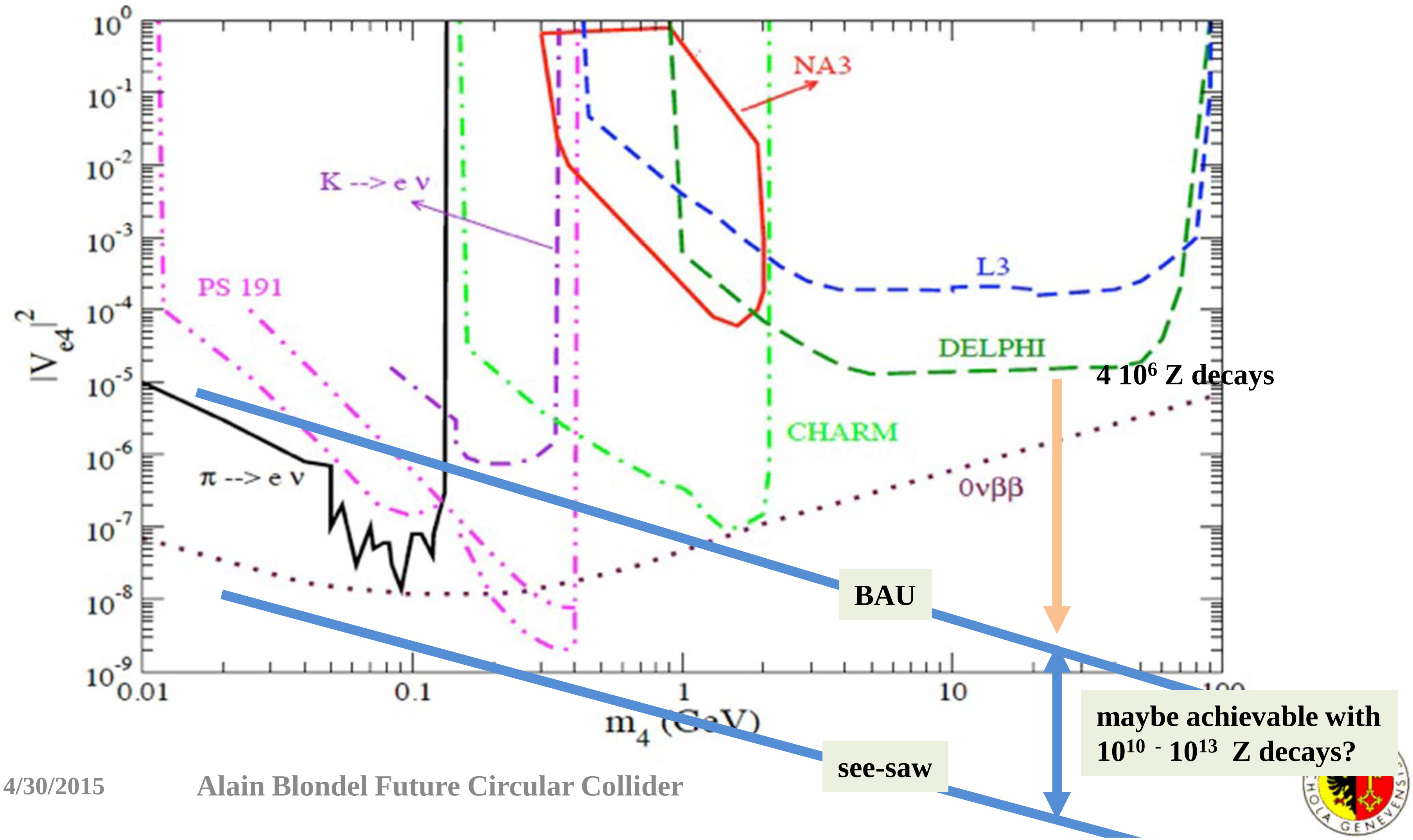
Decay length:

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

NB CC decay always leads to ≥ 2 charged tracks

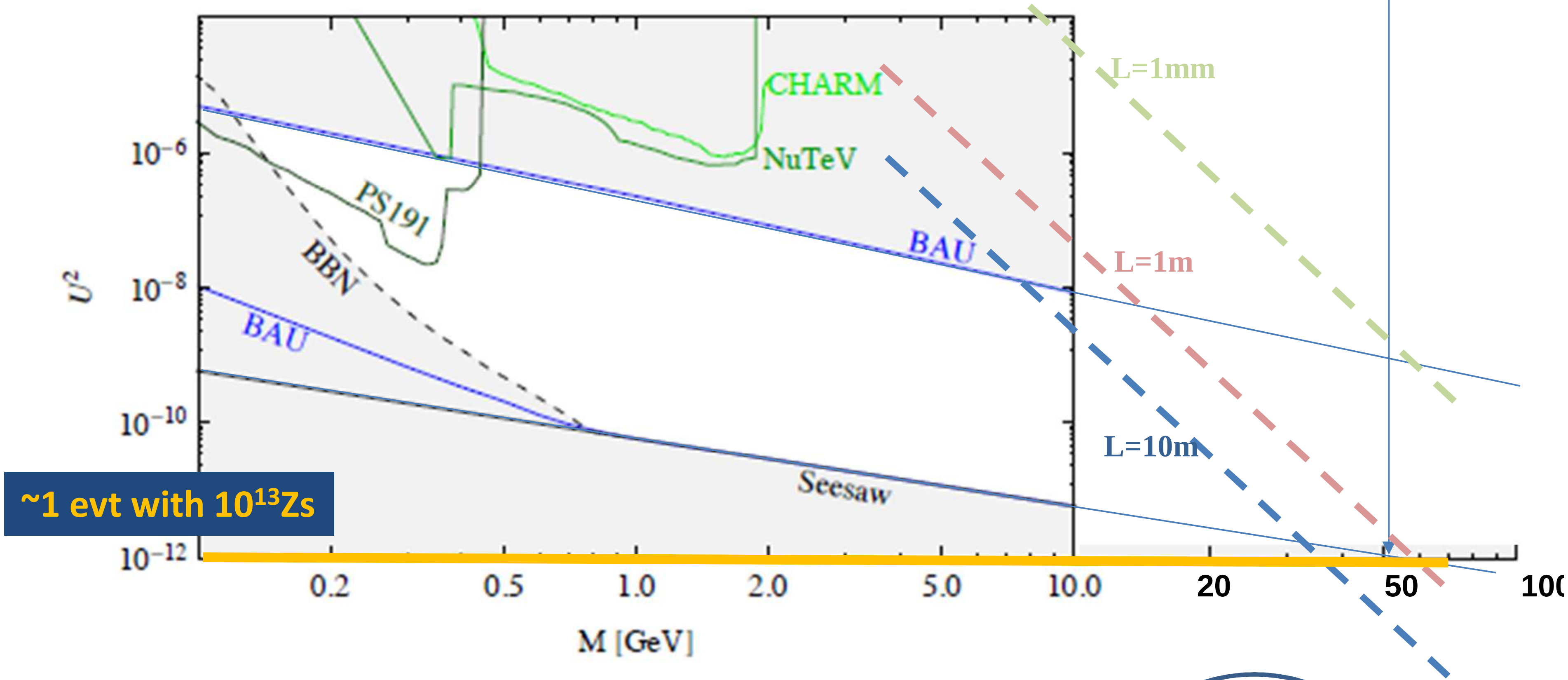
Backgrounds : four fermion: e+e- → W*+ W*- e+e- → Z*(νν) + (Z/γ)*

Order-of-magnitude extrapolation of existing limits



Decay length

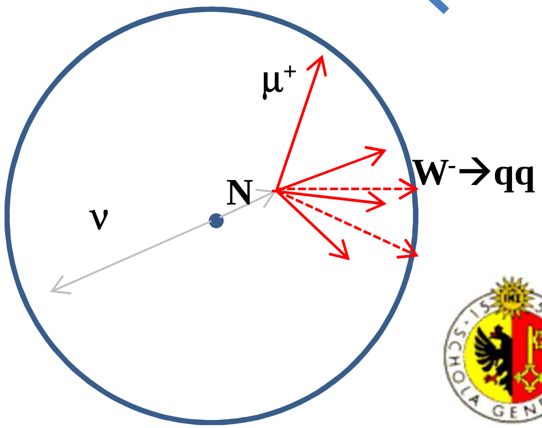
Interesting region
$|U|^2 \sim 10^{-9}$ to 10^{-12} @ 50 GeV



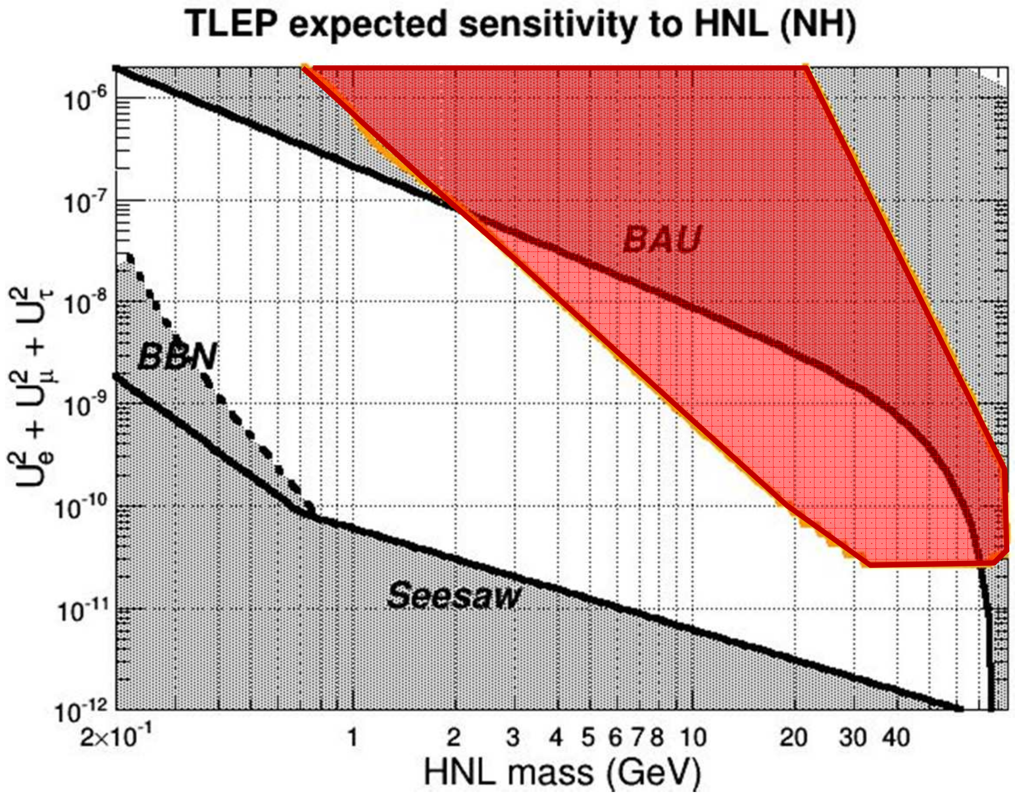
heavy neutrino mass ~ M

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

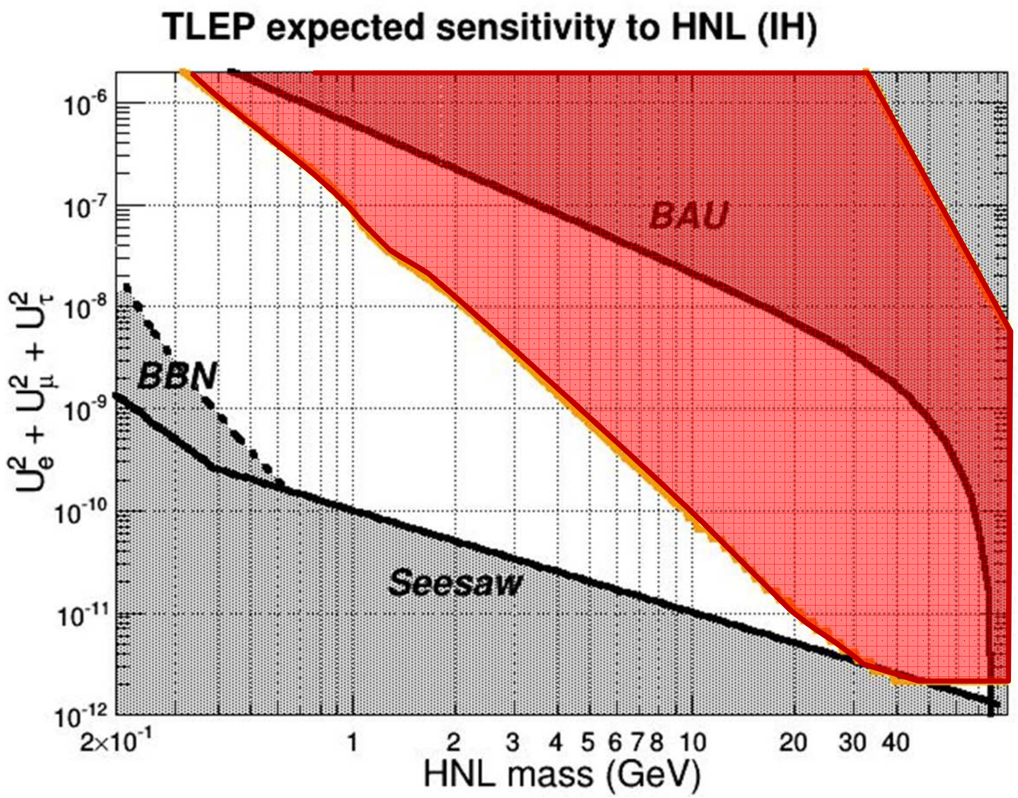


$N_Z = 10^{12}$ 1mm<L<1m

region of interest

FCC-ee sensitivity

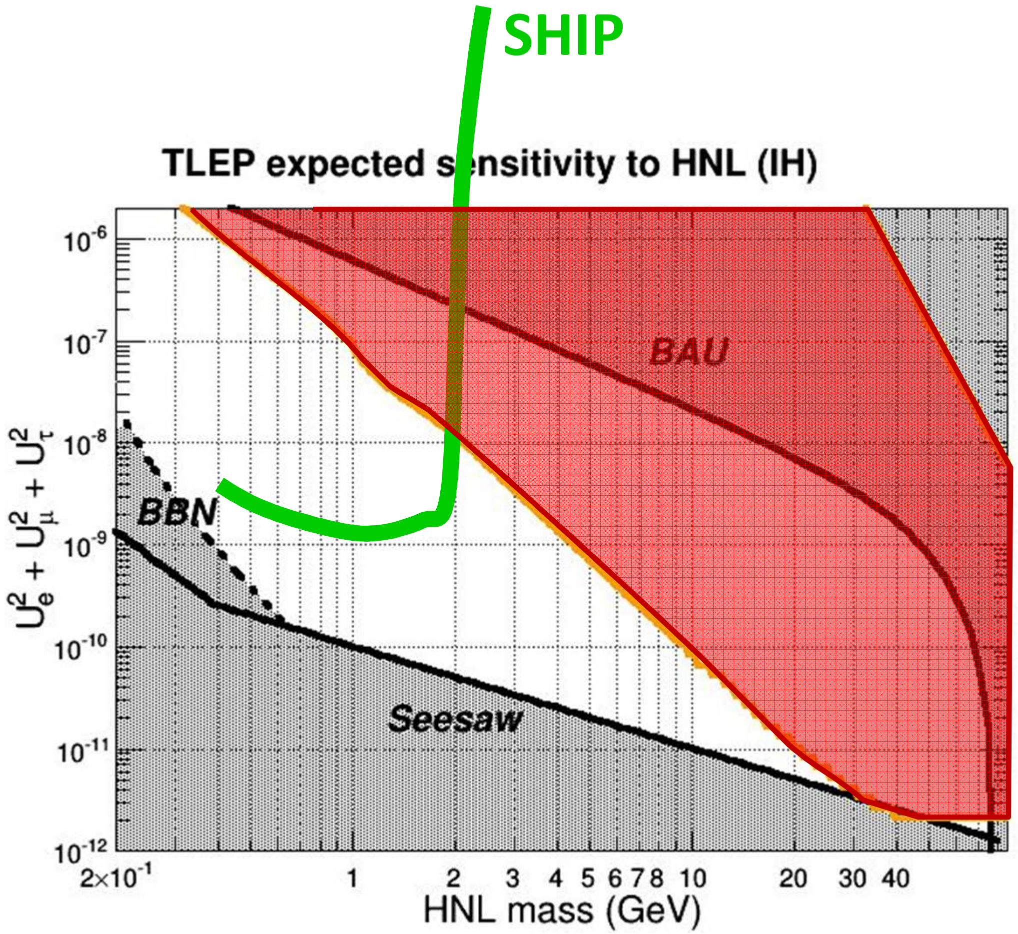
A.B, Elena Graverini, Nicola Serra, Misha Shaposhnikov



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

region of interest

FCC-ee sensitivity



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

region of interest

FCC-ee sensitivity

see recent work arXiv:1411.5230

FCC-ee is a wonderful first step towards the Ultimate goal of a 100 TeV hadron collider and this is one of the reasons it is attracive.

But...
FCC-ee is MUCH more than a launching pad!

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

CONCLUSIONS

330 registered participants

Experimental Studies: Conveners

- Coordinators A. Blondel, P. Janot
  - Study the properties of the Higgs and other particles with unprecedented precision

EW Physics (Z pole)
R. Tenchini
F. Piccinini

Diboson physics, m_W
?
R. Tenchini

H(126) Properties
M. Klute
K. Peters

Top Quark Physics
?
P. Azzi

QCD and $\gamma\gamma$ Physics
D. d'Enterria
P. Skands

Flavour Physics
S. Monteil
J. Kamenik

New Physics
M. Pierini
C. Rogan

- Develop the necessary tools

Understand the experimental conditions

Physics Software
C. Bernet
B. Hegner

Synergy with FCC-hh,,
LHC, Linear Colliders

Online & Trigger
!?!
C. Leonidopoulos

Exp'tal Environment
?
N. Bacchetta

Synergy with FCC-hh
and Linear Colliders

- Set constraints on the possible detector designs to match statistical precision

Detector Designs
A. Cattai
G. Rolandi

Synergy with Linear Collider detectors and others

Phenomenological Studies: Conveners

- **Coordinators: J. Ellis, C. Grojean**
  - Set up a long-term programme to match theory predictions to experimental precisions

QCD and $\gamma\gamma$ Physics
(Joint exp/th)
P. Skands

Precision EW calculations
S. Heinemeyer

Flavour Physics
(Joint exp/th)
J. Kamenik

  - Understand how new physics would show up in precision measurements, and in searches for rare decays (Z, W, t, H, b, c, τ, …) and rare processes

Model Building and New Physics
A. Weiler

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

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

Global Analysis, Combination, Complementarity
J. Ellis

some REFERENCES for right handed neutrino searches

PHYSICAL REVIEW D VOLUME 29, NUMBER 11 1 JUNE 1984

Extending limits on neutral heavy leptons

Michael Gronau*

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

theories of the electroweak strong interactions. At presen
and mixings with ordinary neutrinos of these leptons are v

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

arxiv:1208.3654

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

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

JHEP Published for SISSA by Springer

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

First look at the physics case of TLEP

arxiv:1308.6176

FCC TLEP

The TLEP Design Study Working Group

M. Bicer,[a] H. Duran Yildiz,[b] I. Yildiz,[c] G. Coignet,[d] M. Delmastro,[d] T. Alexopoulos,[e] C. Grojean,[f] S. Antusch,[g] T. Sen,[h] H.-J. He,[i] K. Potamianos,[j] S. Haug,[k] A. Moreno,[l] A. Heister,[m] V. Sanz,[n] G. Gomez-Ceballos,[o] M. Klute,[o] M. Zanetti,[o] L.-T. Wang,[p] M. Dam,[q] C. Boehm,[r] N. Glover,[r] F. Krauss,[r] A. Lenz,[r] M. Syphers,[s]

CERN–PPE/96–195

18 December 1996

Search for Neutral Heavy Leptons Produced in Z Decays

DELPHI Collaboration

The Role of Sterile Neutrinos in Cosmology and Astrophysics

Alexey Boyarsky*†, Oleg Ruchayskiy‡ and Mikhail Shaposhni

The νMSM, Dark Matter and Neutrino Masses

Takehiko Asaka, Steve Blanchet, and Mikhail Shaposhnikov

Institut de Théorie des Phénomènes Physiques,
CH-1015 Lausanne, Switzerland
2005)

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

FCC design study and FCC-ee http://cern.ch/fcc-ee
and presentations at *FCC-ee physics workshop*
http://indico.cern.ch/event/313708/
and arXiv:1411.5230v2 [hep-ex] 6 Dec 2014

The Search for Heavy Majorana Neutrinos

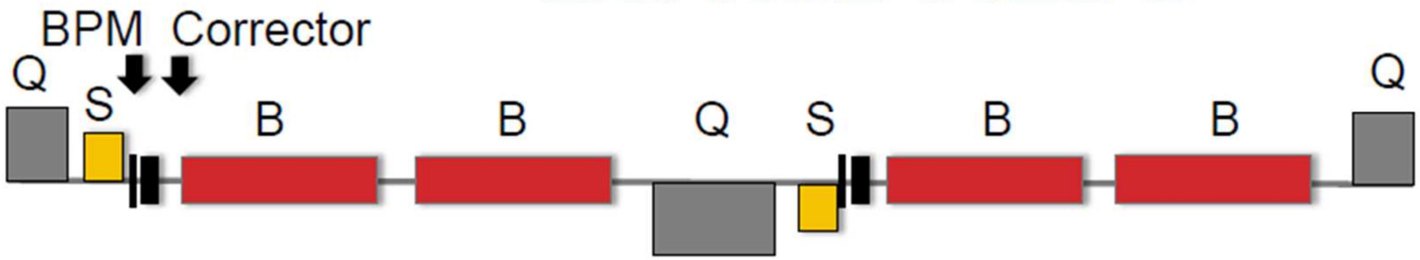
Anupama Atre[1,2], Tao Han[2,3,4], Silvia Pascoli[5], Bin Zhang[4*]

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

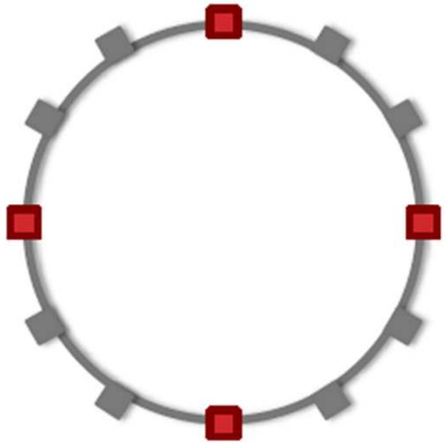
Arc lattice (circular machine)

LATTICE V12B-S

arc cell layout



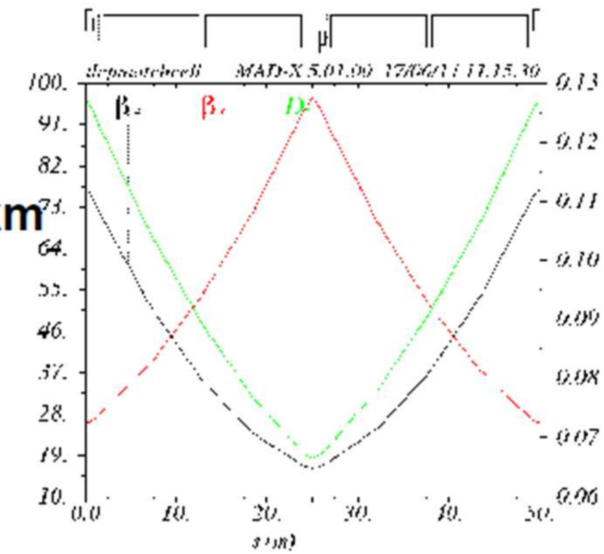
B = bending magnet, Q = quadrupole, S = sextupole

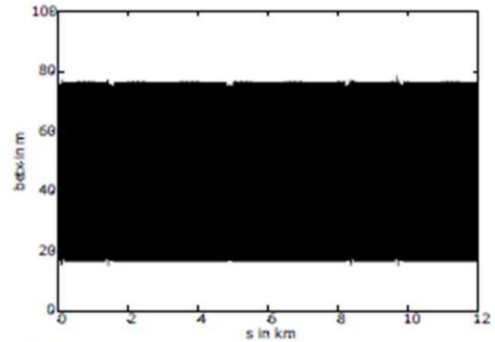


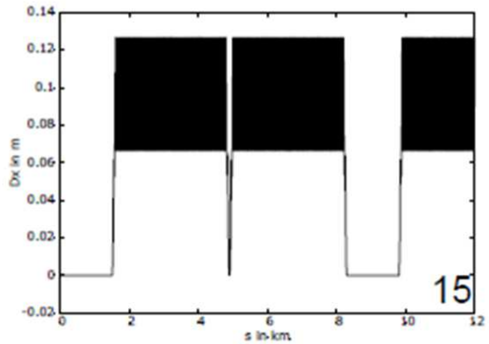
Circumference: 100 km
Arc length: 2 × 3.4 km
Straight section: 1.5 km

B. Harer, B. Holzer

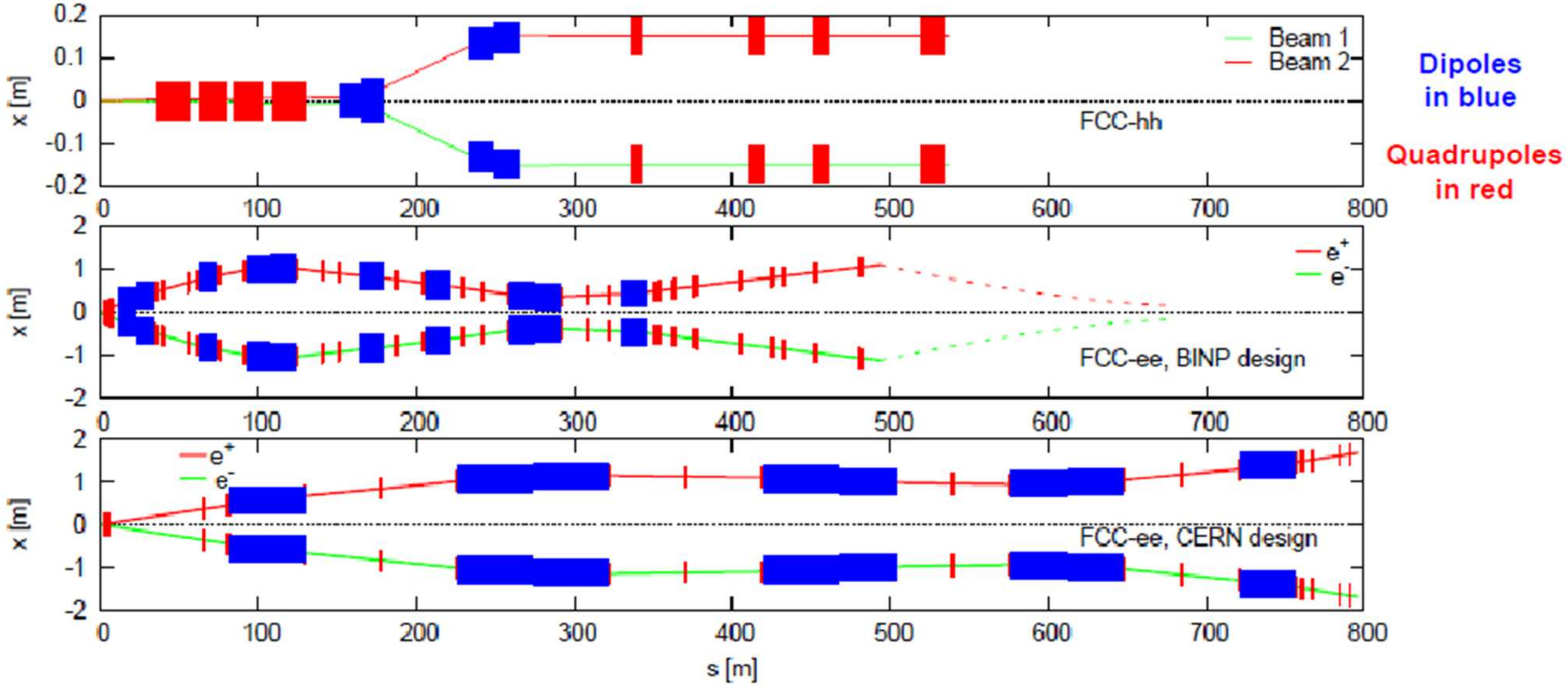
FODO cell optics
cell length 50 m





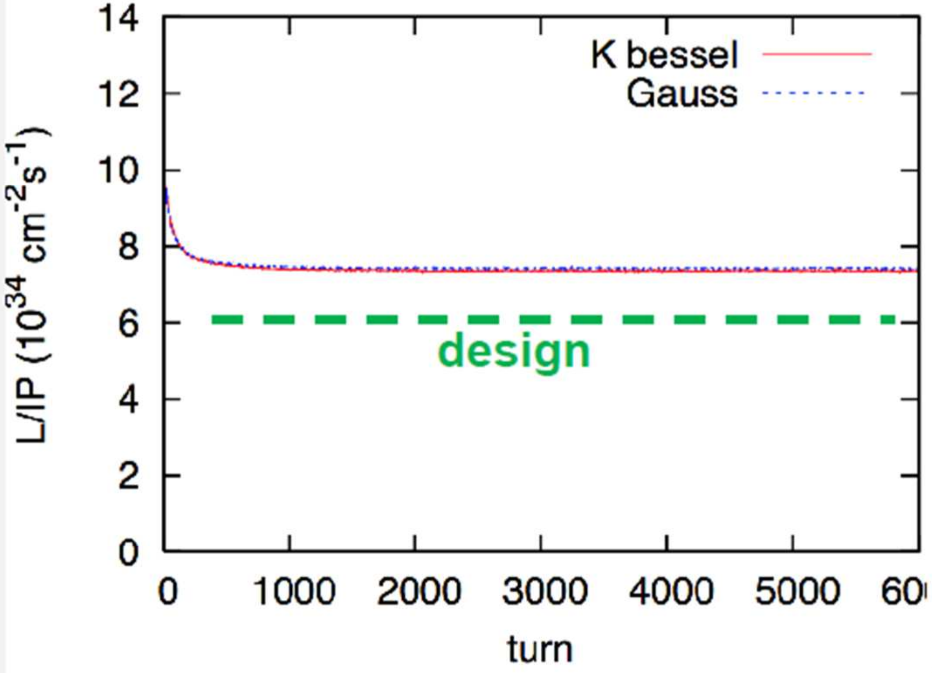


IR layouts



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

Beam-beam simulations



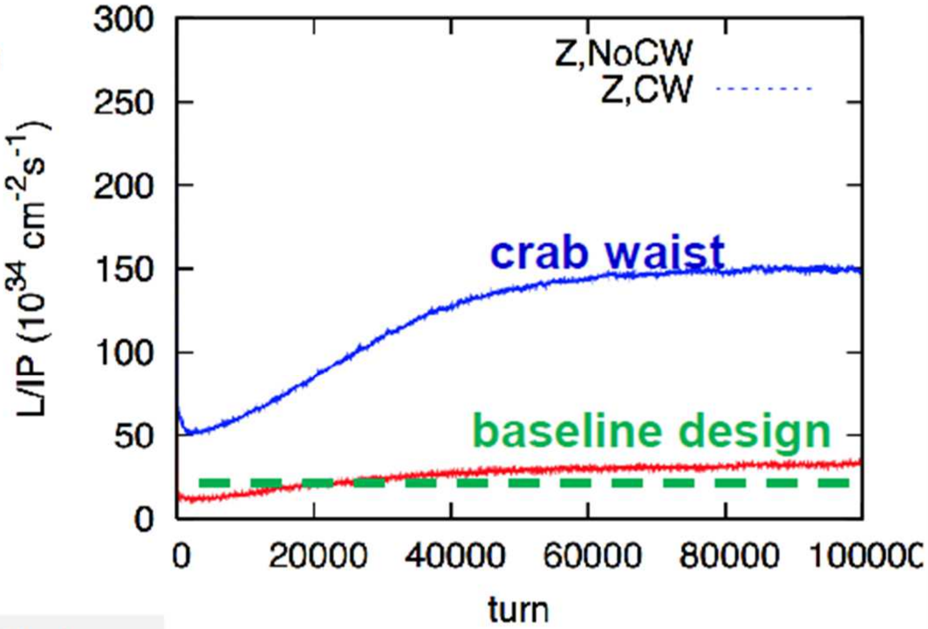
BBSS strong-strong simulation with beamstrahlung

FCC-ee at 120 GeV:

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

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

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



Tracking confirms assumptions!

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

Key Parameters FCC-hh

Parameter	FCC-hh	LHC
Energy [TeV]	100 c.m.	14 c.m.
Dipole field [T]	16	8.33
# IP	2 main, +2	4
Luminosity/IP$_{main}$ [cm^{-2}s^{-1}]	5 - 25 x 10^{34}	1 x 10^{34}
Stored energy/beam [GJ]	8.4	0.39
Synchrotron rad. [W/m/aperture]	28.4	0.17
Bunch spacing [ns]	25 (5)	25

FCC-hh: some design challenges

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

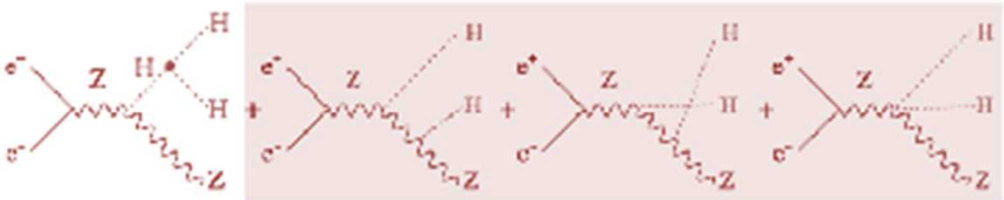
- **Collimation, beam loss control, radiation effects: very important**
- **Injection/dumping/beam transfer: very critical operations**
- **Magnet/machine protection: to be considered from early phase**

H^3 @ TLEP

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

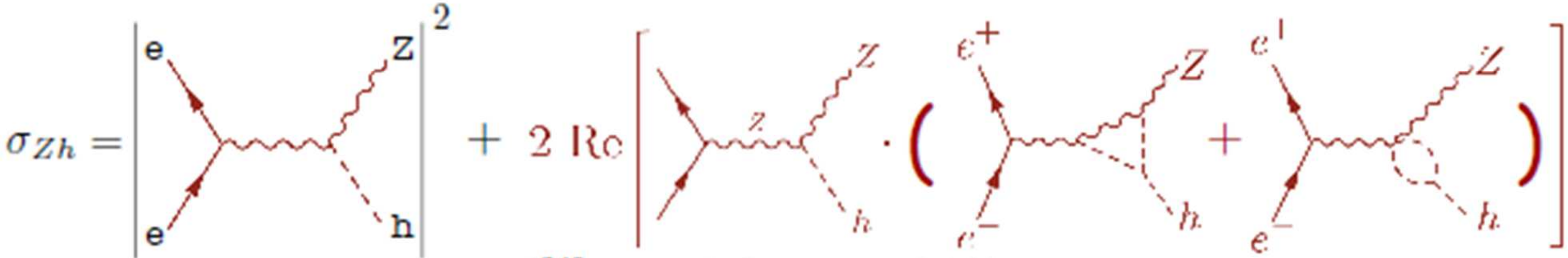
Dolan, Englert, Spannowsky

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



J. Tian, K. Fujii

- At TLEP 240 GeV: M. McCullough '14



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

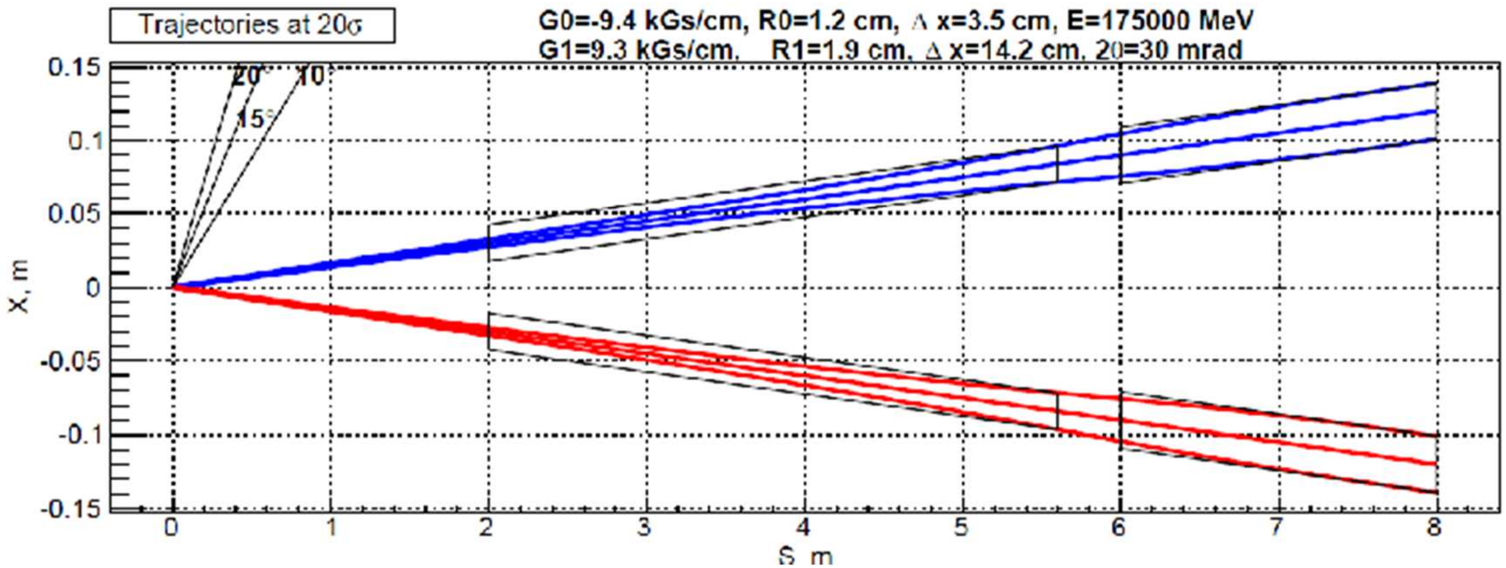
tiny effect but visible thanks to the extraordinary TLEP sensitivity on Zh **(0.05%)**

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

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

the 10B$ ILC

Trajectories L*=2m

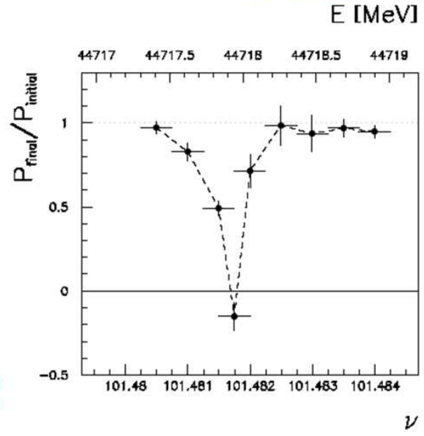


Mogens Dam

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

Beam polarization and E-calibration @ TLEP

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



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

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

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

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

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

Asymptotic safety of gravity and the Higgs boson mass

Mikhail Shaposhnikov

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

Christof Wetterich

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

12 January 2010

Abstract

There are indications that gravity is asymptotically safe. The Standard Model (SM) plus gravity could be valid up to arbitrarily high energies. Supposing that this is indeed the case and assuming that there are no intermediate energy scales between the Fermi and Planck scales we address the question of whether the mass of the Higgs boson m_H can be predicted. For a positive gravity induced anomalous dimension $A_\lambda > 0$ the running of the quartic scalar self interaction λ at scales beyond the Planck mass is determined by a fixed point at zero. This results in $m_H = m_{\min} = 126$ GeV, with only a few GeV uncertainty. This prediction is independent of the details of the short distance running and holds for a wide class of extensions of the SM as well. For $A_\lambda < 0$ one finds m_H in the interval $m_{\min} < m_H < m_{\max} \simeq 174$ GeV, now sensitive to A_λ and other properties of the short distance running. The case $A_\lambda > 0$ is favored by explicit computations existing in the literature.

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

FCC Work and Organisation (i)

Work/meeting structures established based on INDICO, see:

- **FCC Study: https://indico.cern.ch/category/5153/**
- **http://cern.ch/FCC-ee (more developed, for FCC-ee)**

In particular:

- **FCC-hh Hadron Collider Physics and Experiments VIDYO meetings**
  - **https://indico.cern.ch/category/5258/**
  - **Contacts: michelangelo.mangano@cern.ch, fabiola.gianotti@cern.ch, austin.ball@cern.ch**

- **FCC-ee Lepton Collider (TLEP) Physics and Experiments VIDYO meetings**
  - **https://indico.cern.ch/category/5259/**
  - **Contacts: alain.blondel@cern.ch, patrick.janot@cern.ch**

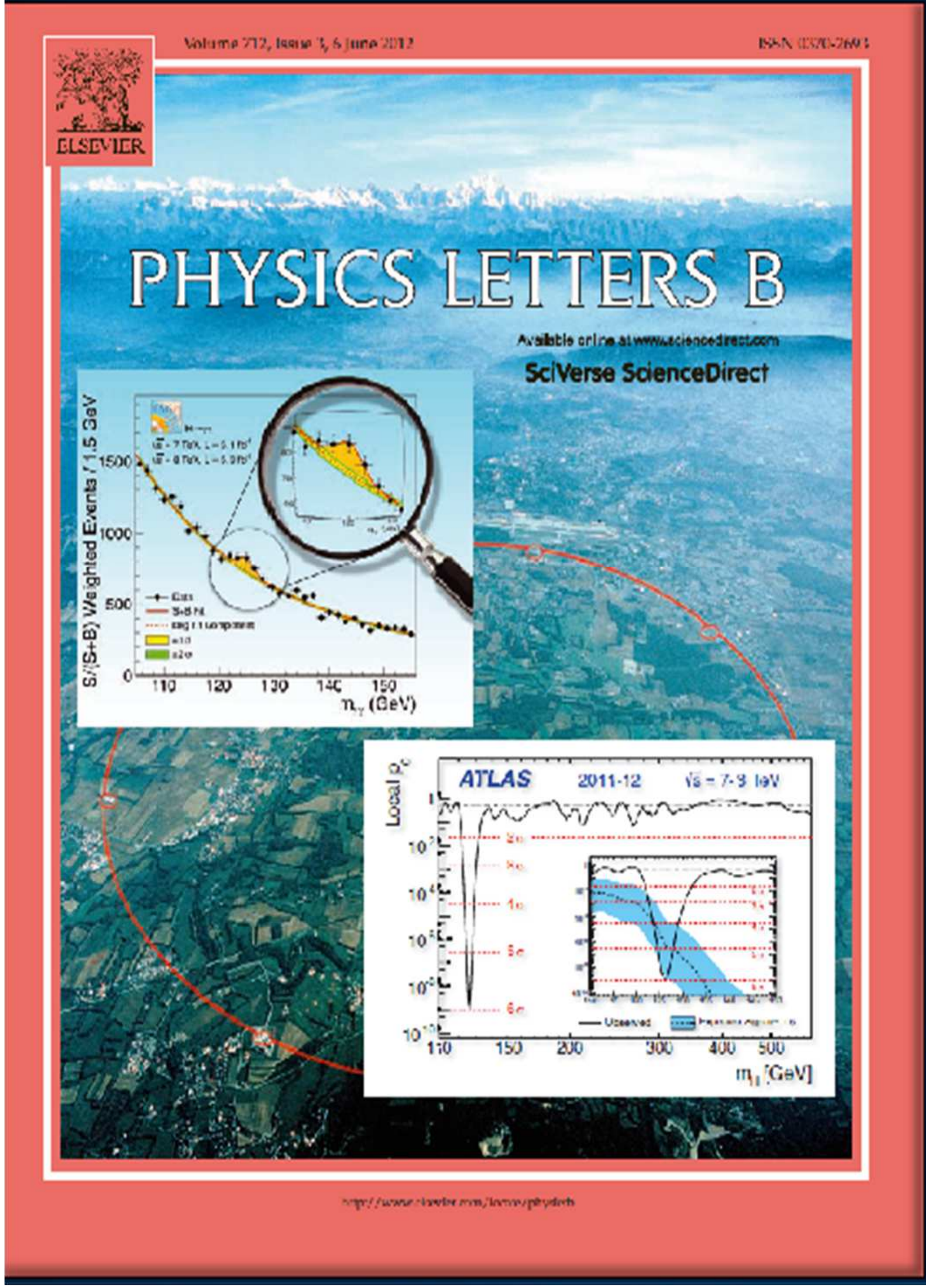
FCC Work and Organisation (ii)

- **FCC-hh Hadron Collider VIDYO meetings**
  - https://indico.cern.ch/category/5263/
  - **Contacts:** daniel.schulte@cern.ch

- **FCC-hadron injector meetings**
  - https://indico.cern.ch/category/5262/
  - **Contacts:** brennan.goddard@cern.ch

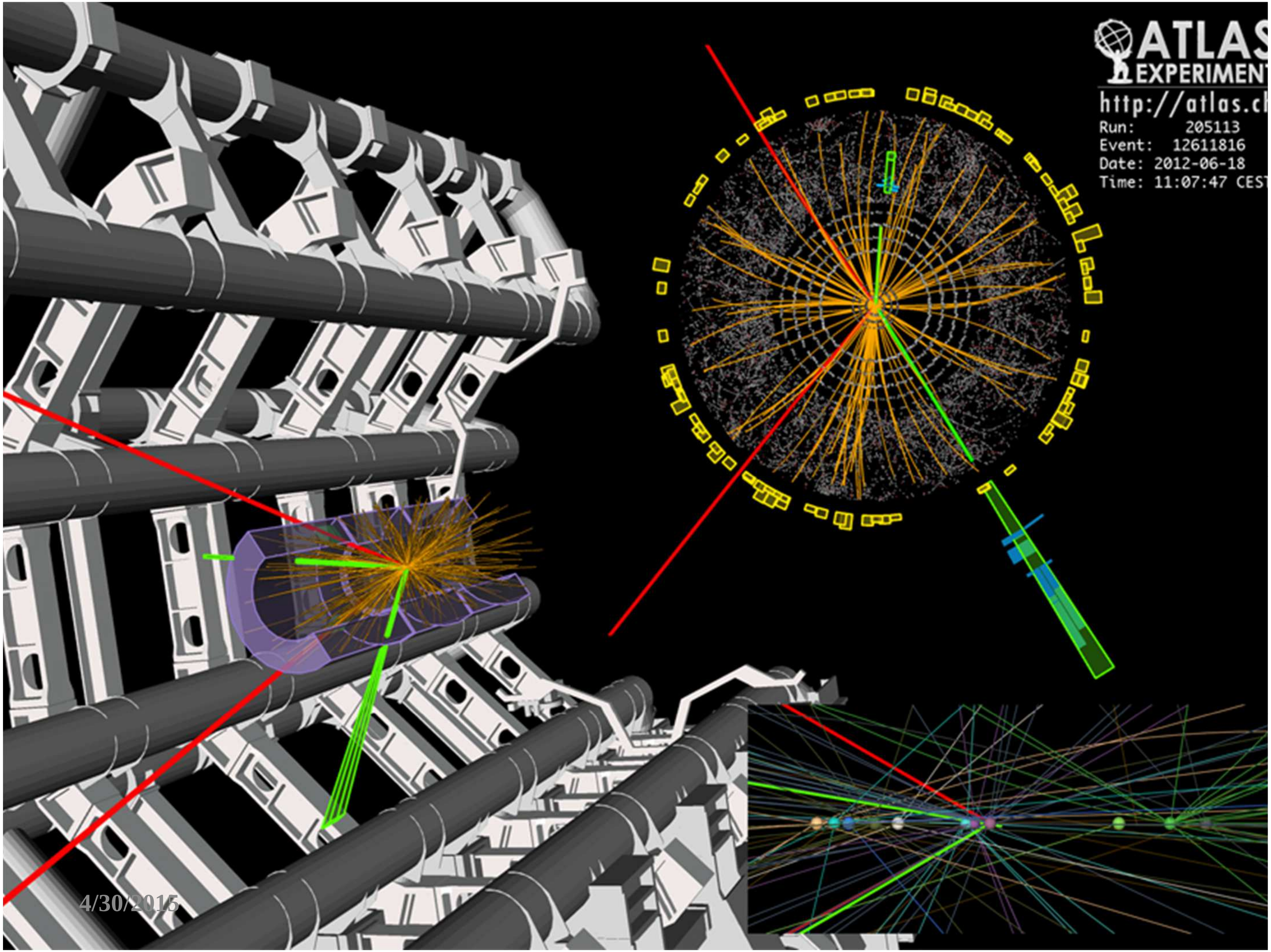
- **FCC-ee (TLEP) Lepton Collider VIDYO meetings**
  - https://indico.cern.ch/category/5264/
  - **Contacts:** jorg.wenninger@cern.ch,

- **FCC infrastructure meetings**
  - https://indico.cern.ch/category/5253/
  - **Contacts:** philippe.lebrun@cern.ch, peter.sollander@cern.ch



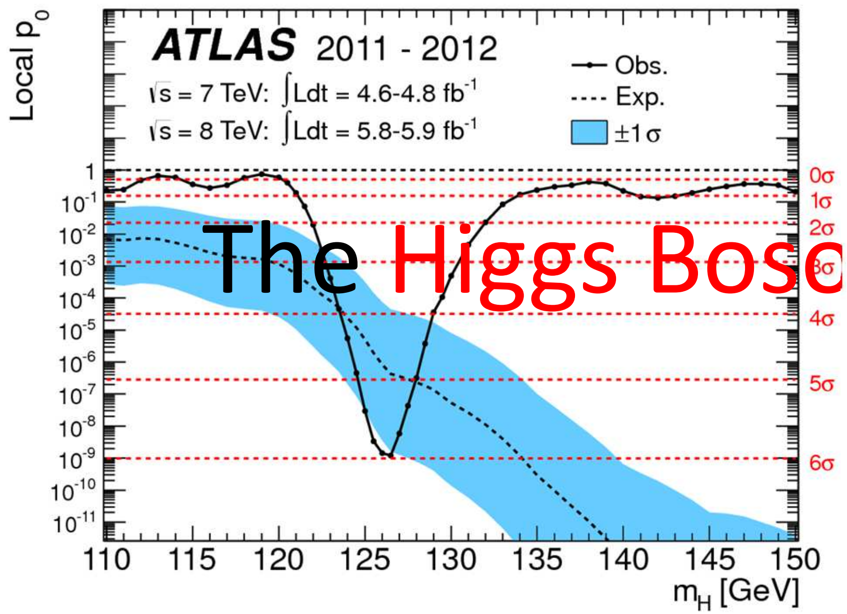
ELSEVIER
Volume 712, Issue 3, 6 June 2012
PHYSICS LETTERS B
Available online at www.sciencedirect.com
SciVerse ScienceDirect
S/(S+B) Weighted Events / 1.5 GeV
$m_{\gamma\gamma}$ (GeV)
ATLAS
2011-12
Local p_0
m_H [GeV]

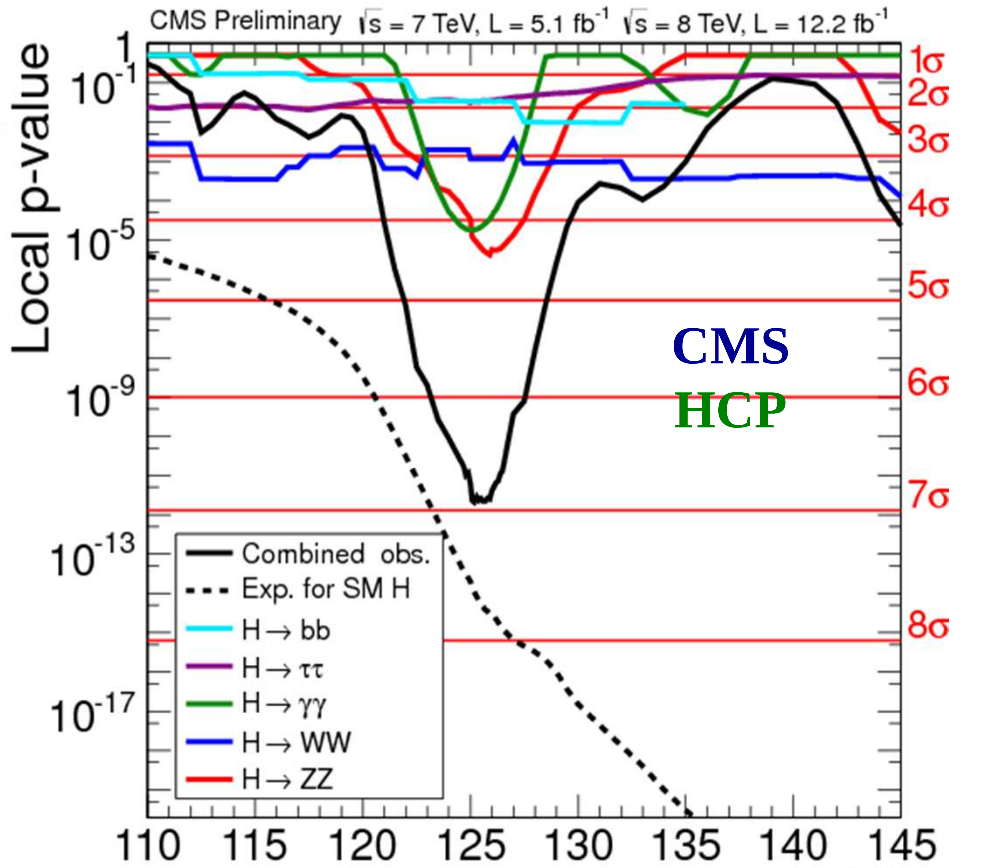
The Economist
JULY 7TH–13TH 2012
Economist.com
In praise of charter schools
Britain's banking scandal spreads
Volkswagen overtakes the rest
A power struggle at the Vatican
When Lonesome George met Nora
A giant leap for science
Finding the Higgs boson


ATLAS
EXPERIMENT
http://atlas.ch
Run: 205113
Event: 12611816
Date: 2012-06-18
Time: 11:07:47 CEST

The Higgs Boson

4



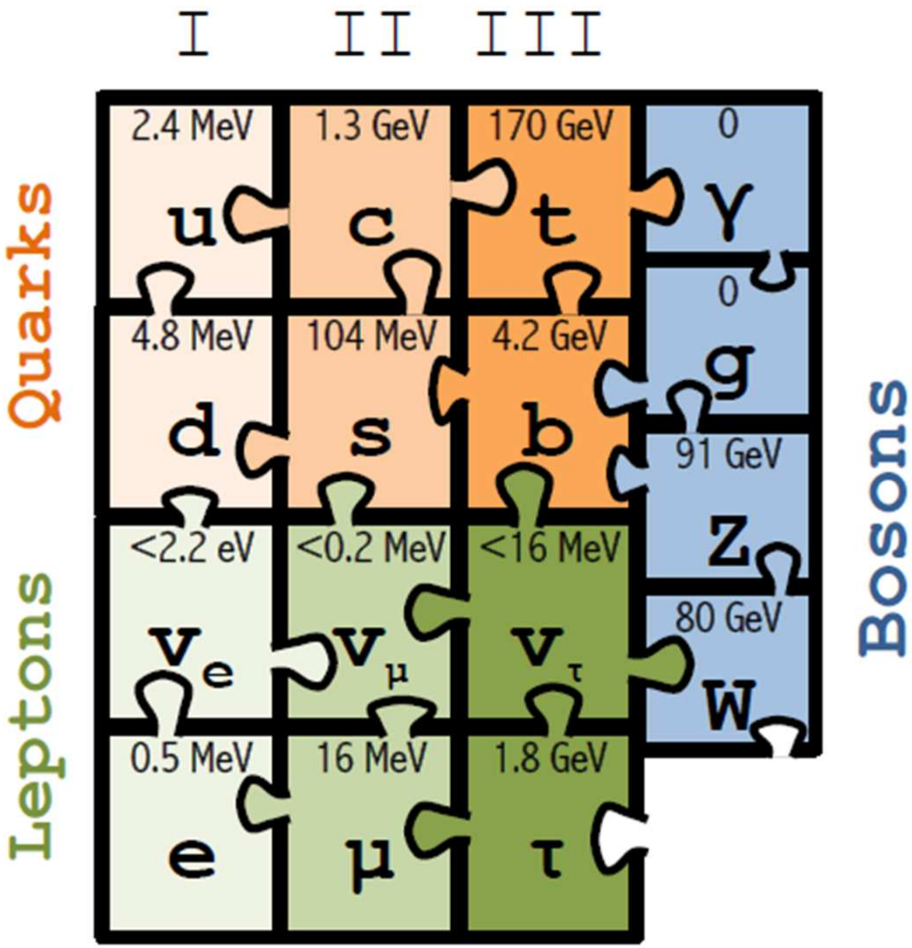


observed: 6.9; expected: 7.8

Discovered Higgs-like Boson: Clear mass peak in γγ and ZZ*→4l

Is this the SM one ? From searches to measurements

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

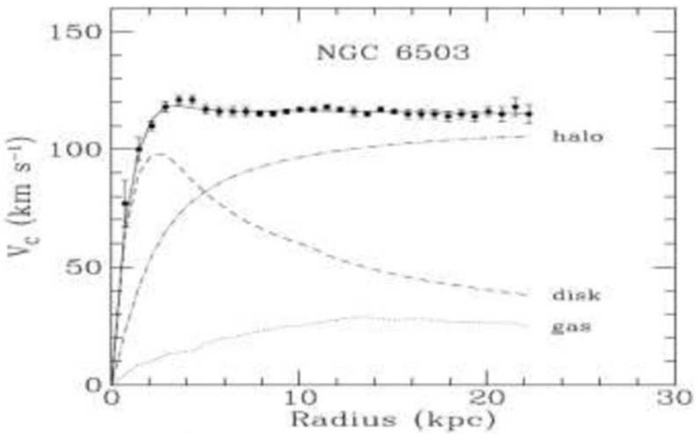


(c) Sfyrla

We cannot explain:

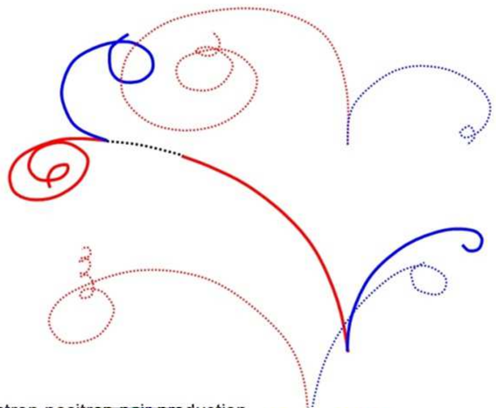
Dark matter

Standard Model particles constitute only 5% of the energy in the Universe



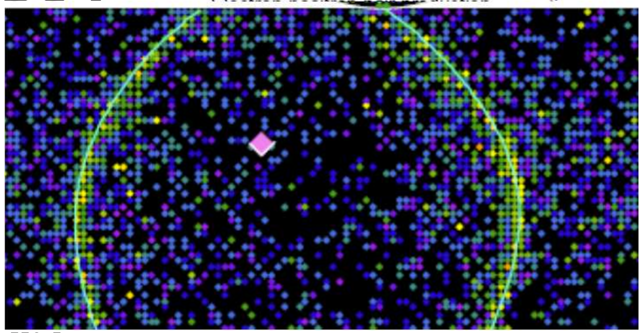
Rotation curve for Galaxy

Were is antimatter gone?



What makes neutrino masses?

Not a unique solution in the SM --
Dirac masses (why so small?)
Majorana masses (why not Dirac?)
Both (the preferred scenarios, see-saw...)
➔ heavy right handed neutrinos?



we cannot explain:

charge of proton = - charge of electron

$$|q_p + q_e|/e \quad < 1 \times 10^{-21}$$

we have no explanation for this, except ...

that it is necessary for the stability of

1. the universe

2. the Standard Model calculations

PARAMETERS FOR CRAB WAIST OPERATION

	Z	W	H	tt
Energy [GeV]	45	80	120	175
Perimeter [km]	100			
Crossing angle [mrad]	30			
Particles per bunch [10^{11}]	1	4	4.7	4
Number of bunches	29791	739	127	33
Energy spread [10^{-3}]	1.1	2.1	2.4	2.6
Emittance hor. [nm]	0.14	0.44	1	2.1
Emittance ver. [pm]	1	2	2	4.3
β_x^* / β_y^* [m]	0.5 / 0.001			
Luminosity / IP [$10^{34}\ cm^{-2}s^{-1}$] **Nominal :**	**28**	**12**	**6.0**	**1.8**
	212	36	9	1.3
Energy loss / turn [GeV]	0.03	0.3	1.7	7.7

Important scope for improvement in luminosity.

Luminosity optimisation

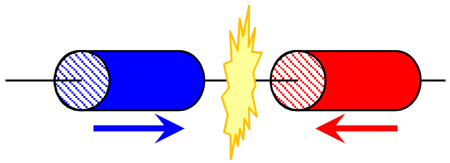
Ideal situation is that beam lifetime is driven by particle-particle interactions
-- dominated by radiative Bhabha scattering e+e- → e+e-γ (typically 150 mb)
with $e^{+/-}$ out of energy acceptance (improved with larger acceptance)

At high luminosity considered in FCC-ee, Beamstrahlung (particle-opp. beam interaction) becomes important.
-- requires very flat beams and +- 2% energy acceptance
-- reduces beam lifetime
-- increases energy spread and bunch length
This is the case in FCC-tt

At lower energy the beams are blowing eachother (beam-beam interaction)
-- this can be fought with 'crab waist' crossing
This is the case at all lower energies operating points

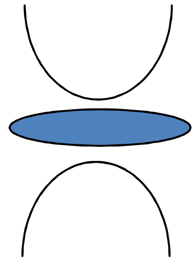
Numbers in main parameter list include beamstrahlung treatment, but have not considered crab waist operation.

Luminosity



$$e\,f\,k\,N = \text{beam current} \propto \frac{1}{E^4}$$

$$L = \frac{f\,k\,N^2}{4\pi\sigma_x\sigma_y} F\,H$$

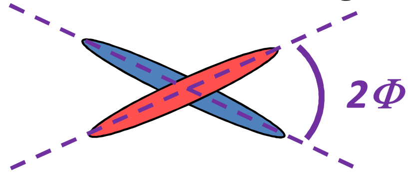


H ≤ 1

Hour-glass

F ≤ 1

Crossing angle



$$\xi_y \propto \frac{\beta_y^* N}{E\sigma_x\sigma_y} \leq \xi_y^{\max}(E)$$

Beam-beam parameter

$$L \propto \frac{P_{SR}}{E^3}\frac{\xi_y}{\beta_y^*}$$

σ = beam size

k = no. bunches

f = rev. frequency

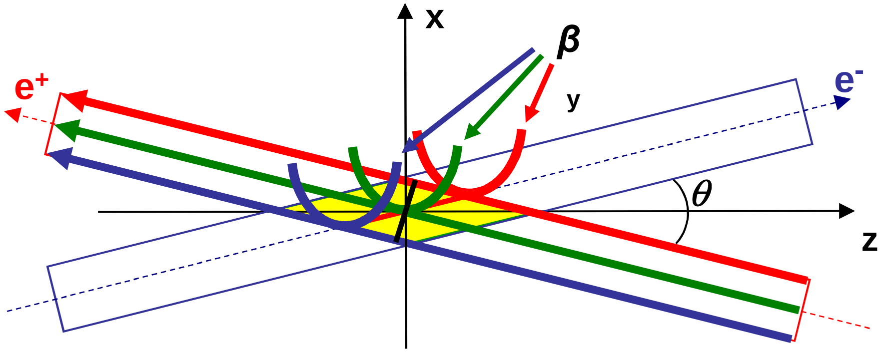
N = bunch population

P_{SR} = synch. rad. power

β^* = betatron fct at IP (beam envelope)

Crab Waist Scheme

P. Raimondi, 2006



$$\phi = \frac{\sigma_z}{\sigma_x} tg\left(\frac{\theta}{2}\right)$$ **– Piwinski angle**

1) Large Piwinski angle: ϕ >> 1

2) **β_y approx. equals to overlapping area: $\beta_y \sim \sigma_z / \phi$**

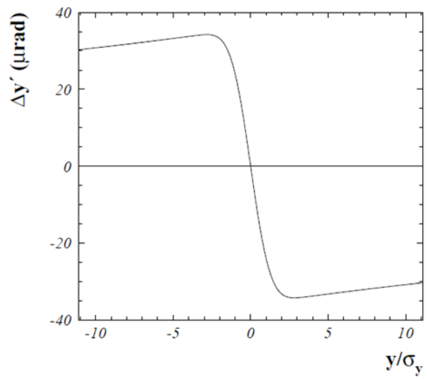
3) Crab Waist: minimum of β_y along the axis of the opposite beam

Advantages:

- ✓ **Impact of hour-glass is small and does not depend on bunch lengthening**
- ✓ **Suppression of betatron coupling resonances allows to achieve $\xi_y \sim 0.2$**
- ✓ **As a result, luminosity can be significantly increased especially at Z, otherwise $\xi_y \sim 0.03$**

Beam-beam parameter

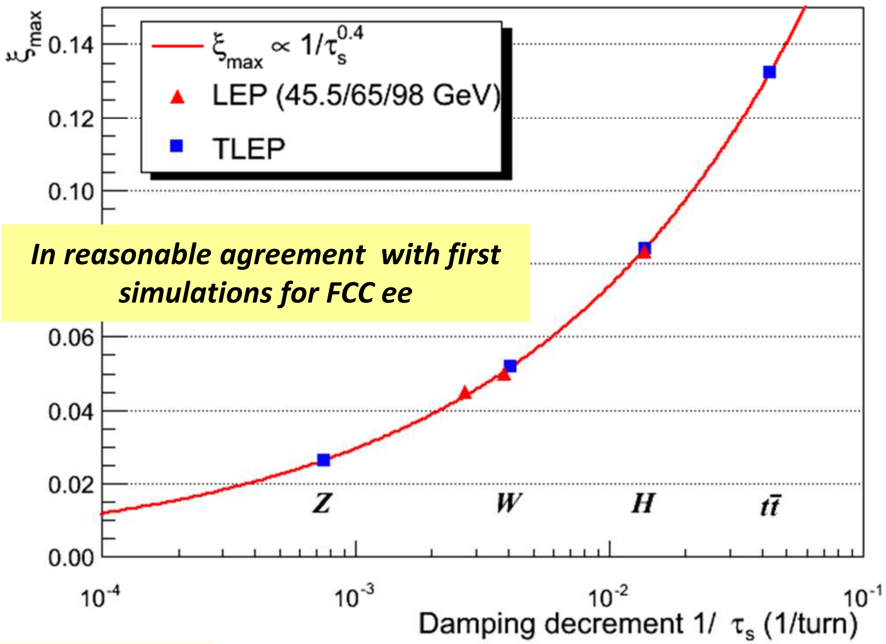
- The beam-beam parameter ξ measures the strength of the field sensed by the particles due to the counter-rotating bunch.
- Beam-beam parameter limits are empirically scaled from LEP data (also 4 IPs).



$$\xi_y \propto \frac{\beta_y^* N}{E \sigma_x \sigma_y} \leq \xi_y^{\max}(E)$$

$$\xi_y^{\max}(E) \propto \frac{1}{\tau_s^{0.4}} \propto E^{1.2}$$

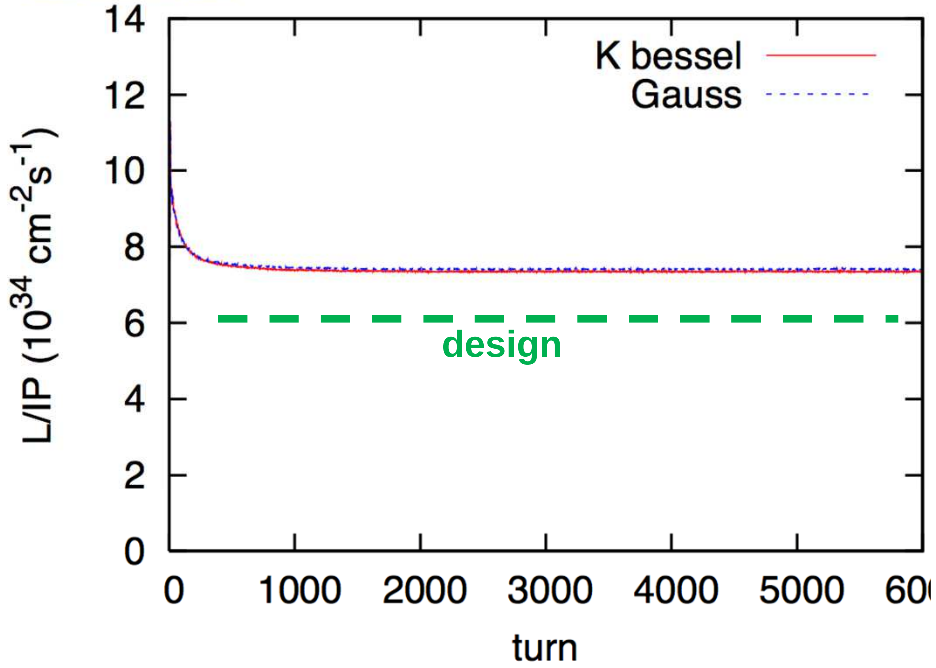
$$L \propto \frac{P_{SR}}{E^{1.8}} \frac{1}{\beta_y^*}$$



In reasonable agreement with first simulations for FCC ee

ξ_y and L may be raised significantly (x 4) with Crab-Waist schemes !

Beam-beam simulations



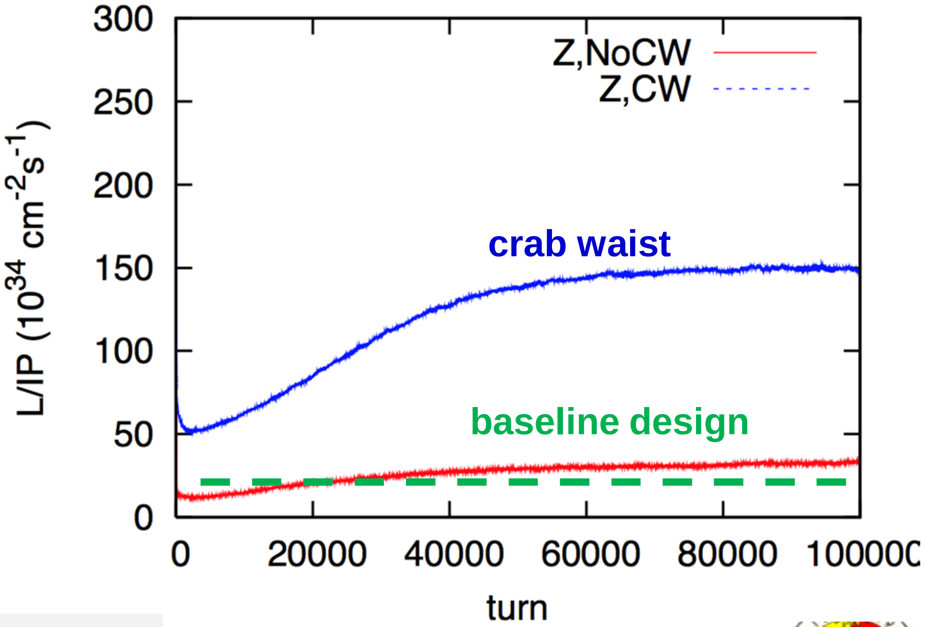
BBSS strong-strong simulation with beamstrahlung

FCC-ee **at 120 GeV:**

***L*≈7.5x10^{34} cm^{-2}s^{-1} per IP**

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

***L*≈1.5x10^{36} cm^{-2}s^{-1} per IP**



Tracking confirms assumptions!

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

Beamstrahlung

- Hard photon emission at the IPs, '*Beamstrahlung*', can become a lifetime / performance limit for large bunch populations (N), small hor. beam size (σ_x) and short bunches (σ_s) .

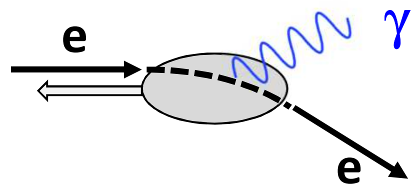
$$\tau_{bs} \propto \frac{\rho^{3/2}\sqrt{\eta}}{\sigma_s} \exp(A\eta\rho)$$

η : ring energy acceptance

Lifetime expression by V. Telnov

$$\frac{1}{\rho} \approx \frac{N r_e}{\gamma \sigma_x \sigma_s}$$

$$L = \frac{f k N^2}{4\pi\sigma_x\sigma_y} F\, H$$

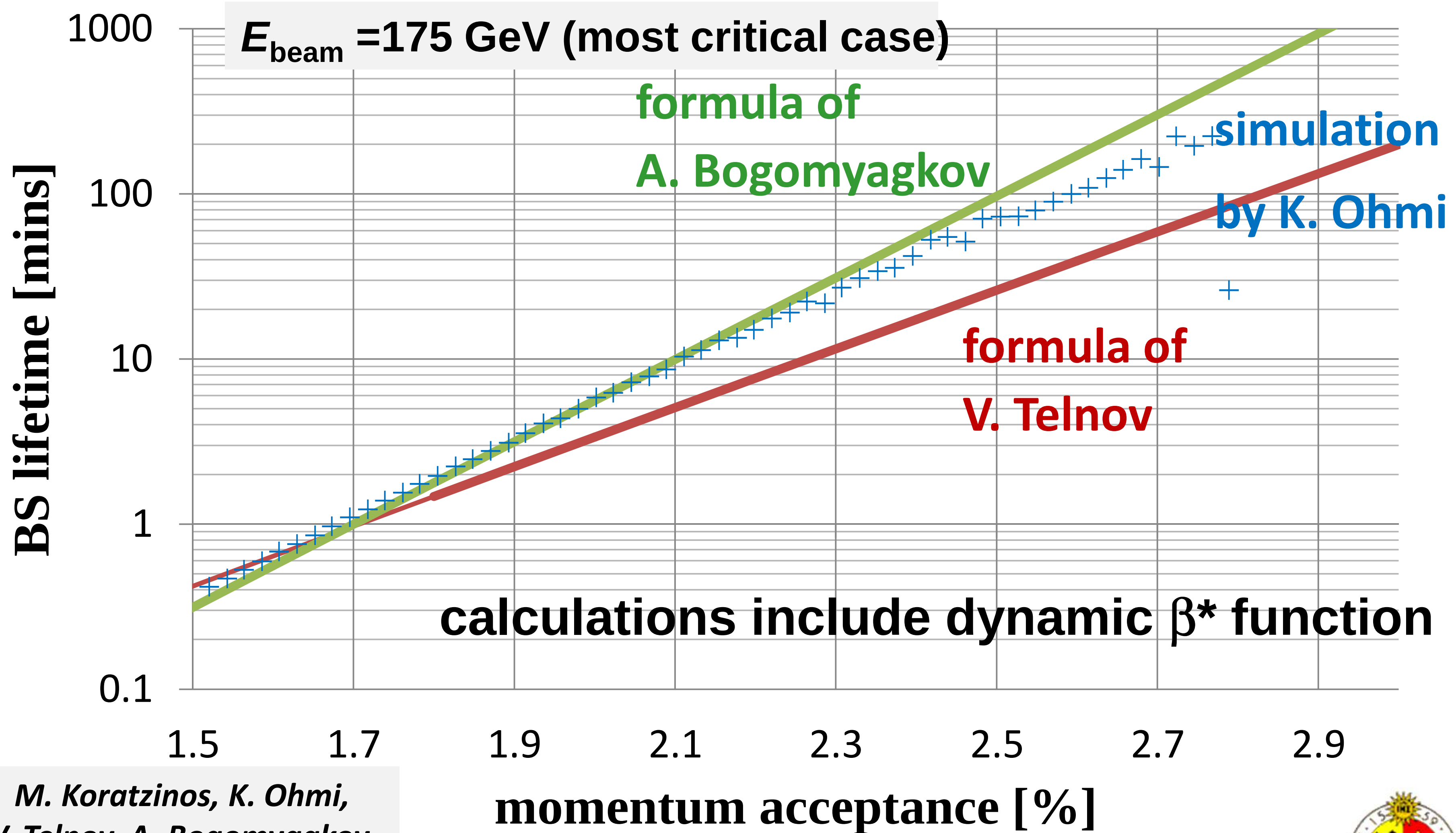


ρ : mean bending radius at the IP (in the field of the opposing bunch)

- To ensure an acceptable lifetime, $\rho \times \eta$ must be sufficiently large.
  - Flat beams : large σ_x and small σ_y !
  - Bunch length !
  - Large momentum acceptance of the lattice: 1.5 – 2% required.
    - LEP had < 1% acceptance, SuperKEKB ~ 1-1.5%.

Beamstrahlung lifetime

Reasonable agreement between tracking and analytical estimates.



M. Koratzinos, K. Ohmi, V. Telnov, A. Bogomyagkov, E. Levichev, D. Shatilov

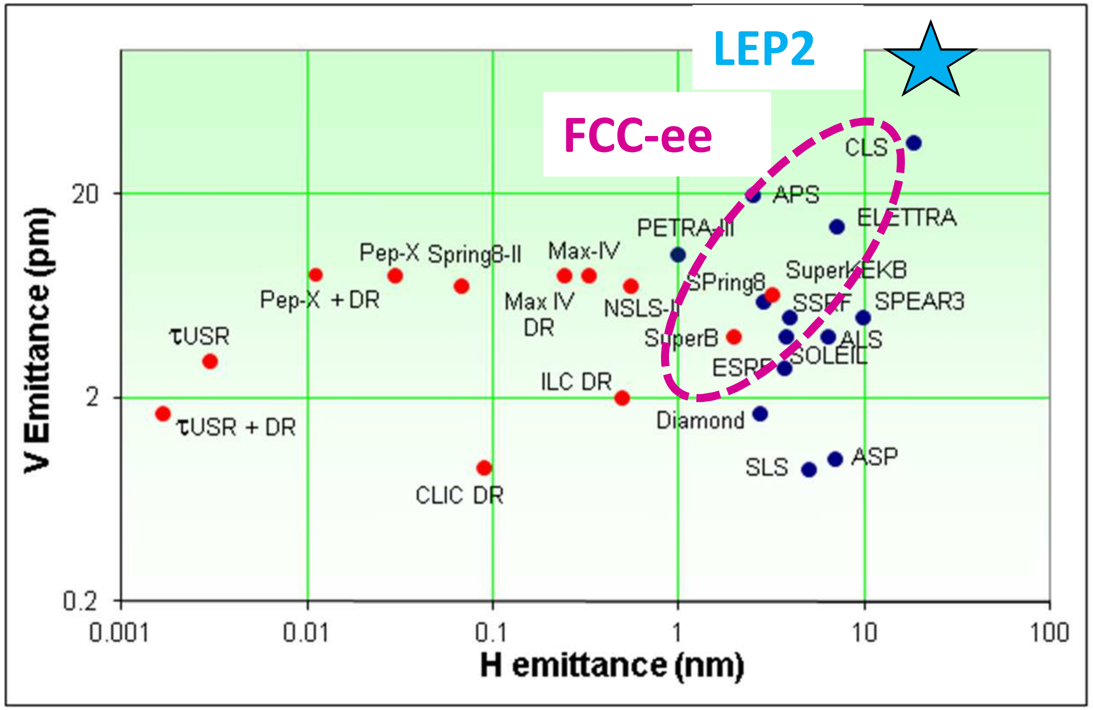
Emittances

- FCC-ee is a very large machine, scaling of achievable emittances (mainly vertical) is not straightforward.
  - Coupling, spurious vertical dispersion.
- Low emittances tend to be more difficult to achieve in colliders as compared to light sources or damping rings – beam-beam !
- FCC-ee parameters:
  - $\varepsilon_y/\varepsilon_x \geq 0.001$,
  - $\varepsilon_y \geq \approx 2$ pm

with a ring ~50-100 larger than a typical light source.

- Very challenging target for a ring of that size!
- LEP2 achived routinely 0.004

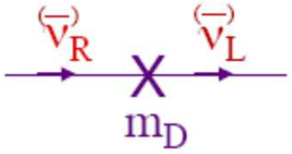
beam corrections are much better now.



R. Bartolini, DIAMOND

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

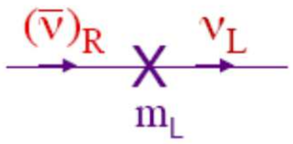
$$m_D \nu_L \overline{\nu_R}. \qquad m_D \overline{\nu_L}\, \nu_R$$



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'