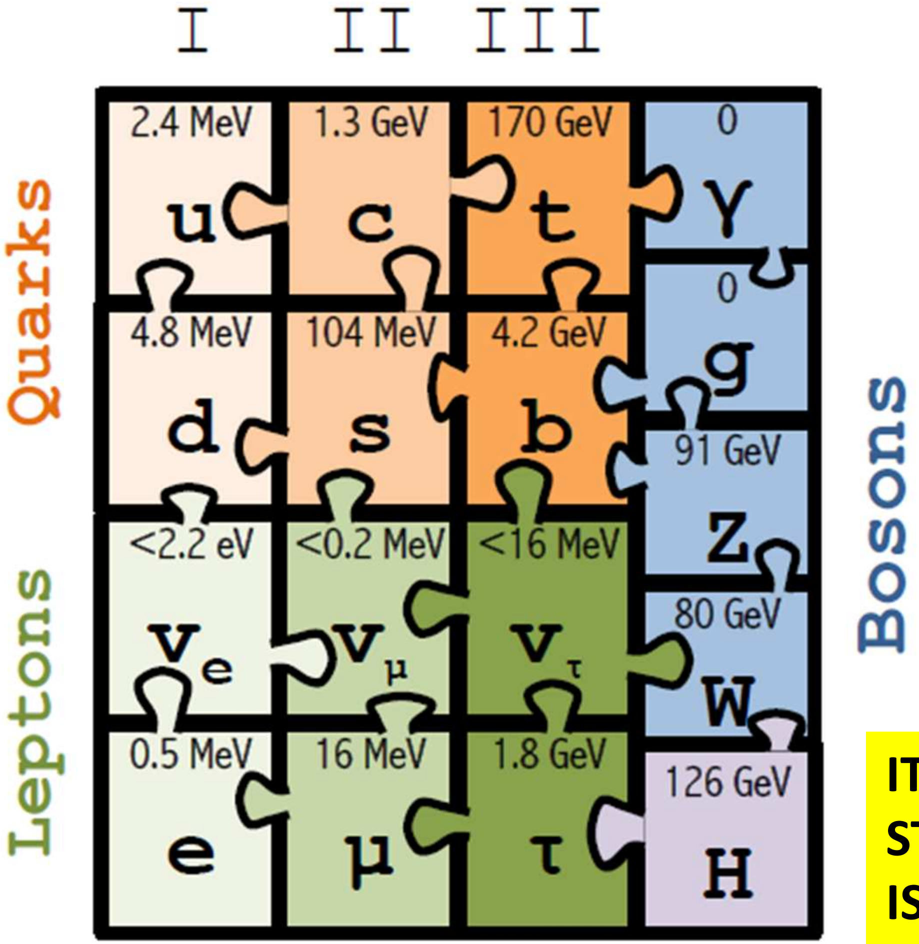
FUTURE CIRCULAR COLLIDERS
FCC-ee

Alain Blondel, University of Geneva, FCC coordination group

see recent metings:
FCC physics workshops I and II
I https://indico.cern.ch/event/550509/
II https://indico.cern.ch/event/618254/
FCC week in Berlin
https://indico.cern.ch/event/556692/

courtesy J. Wenninger

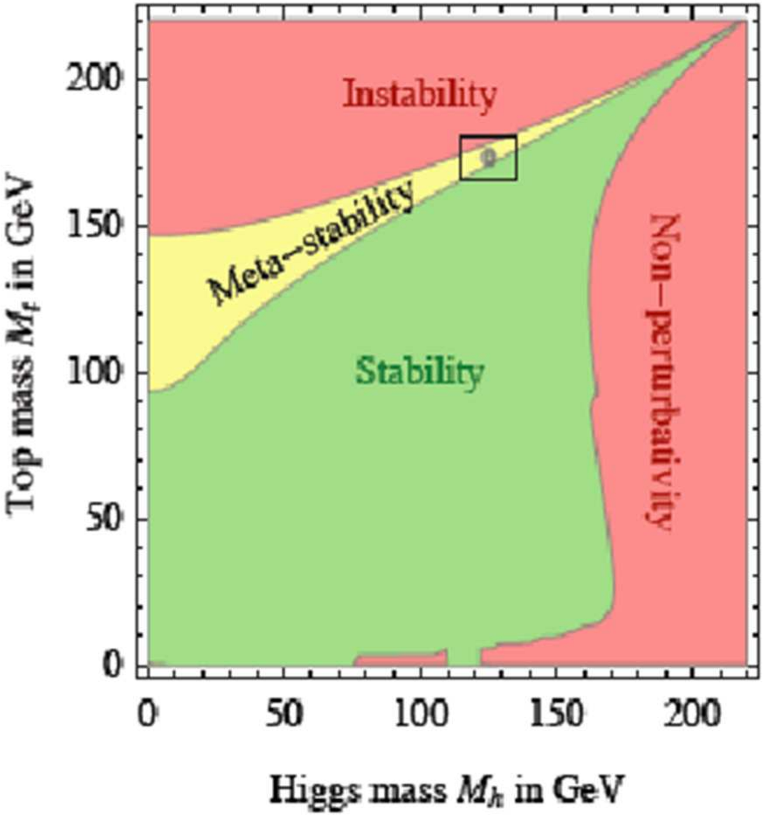
1997-2013 Higgs boson mass cornered (LEP H, M_Z etc +Tevatron m_t , M_W)
Higgs Boson discovered (LHC)
Englert and Higgs get Nobel Prize

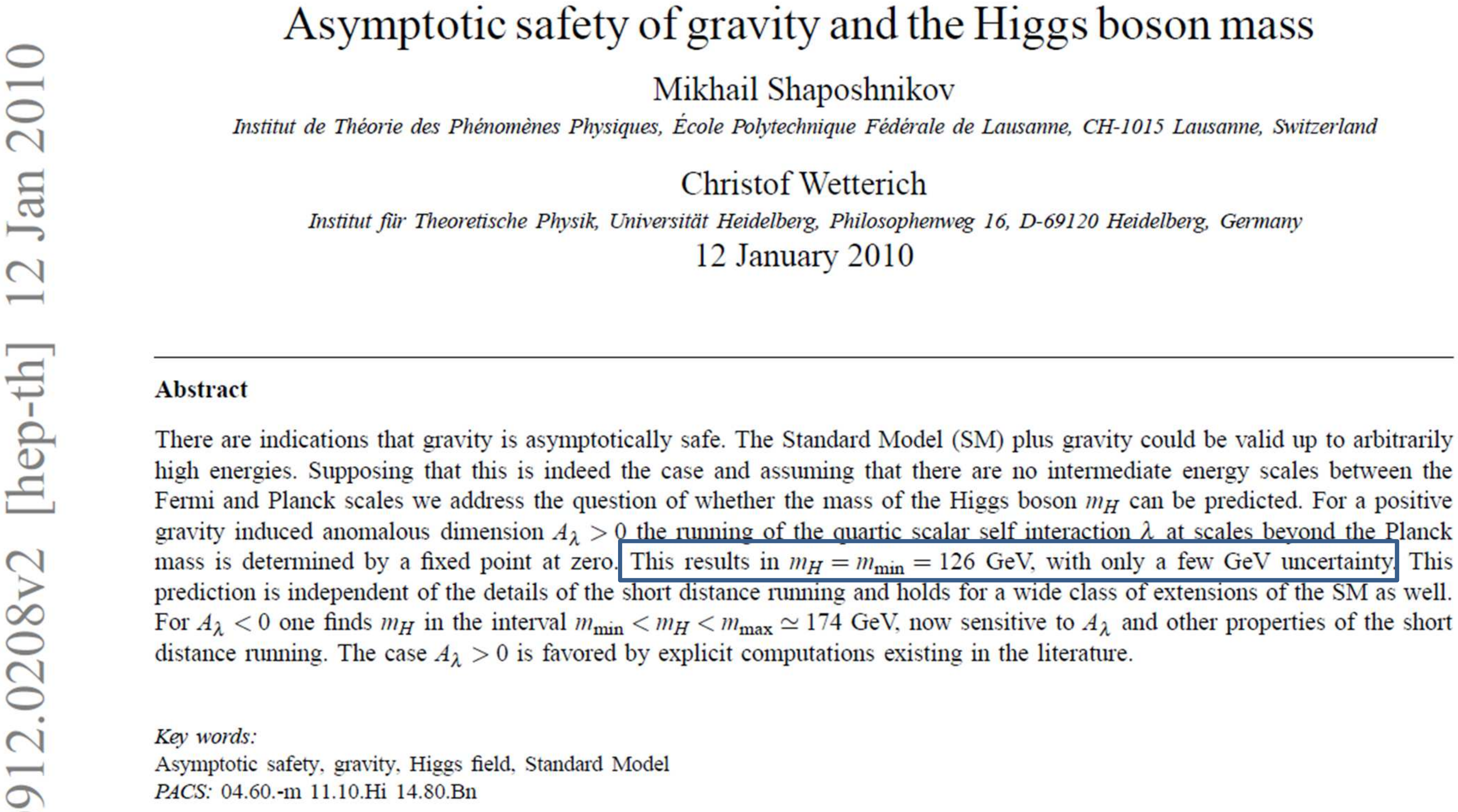


(c) Sfyrla

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

Is it the end?


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



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

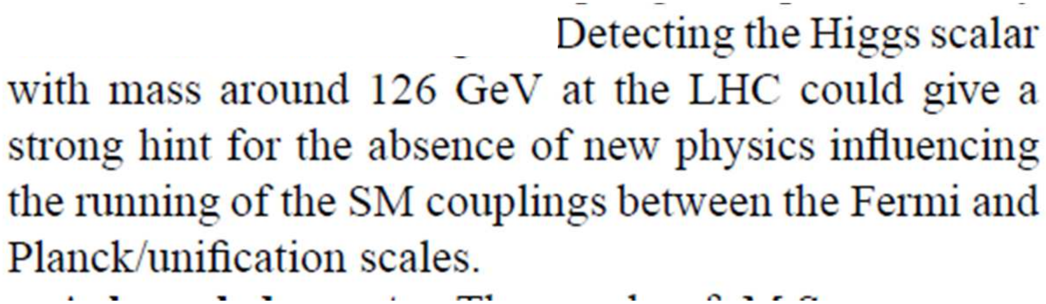
Christof Wetterich
Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, D-69120 Heidelberg, Germany

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.

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?

Certainly not!

- **-- Dark matter**
- **-- Baryon Asymmetry in Universe**
- **-- Neutrino masses -- so small!**

are experimental proofs that there is more to understand.

We must continue our quest

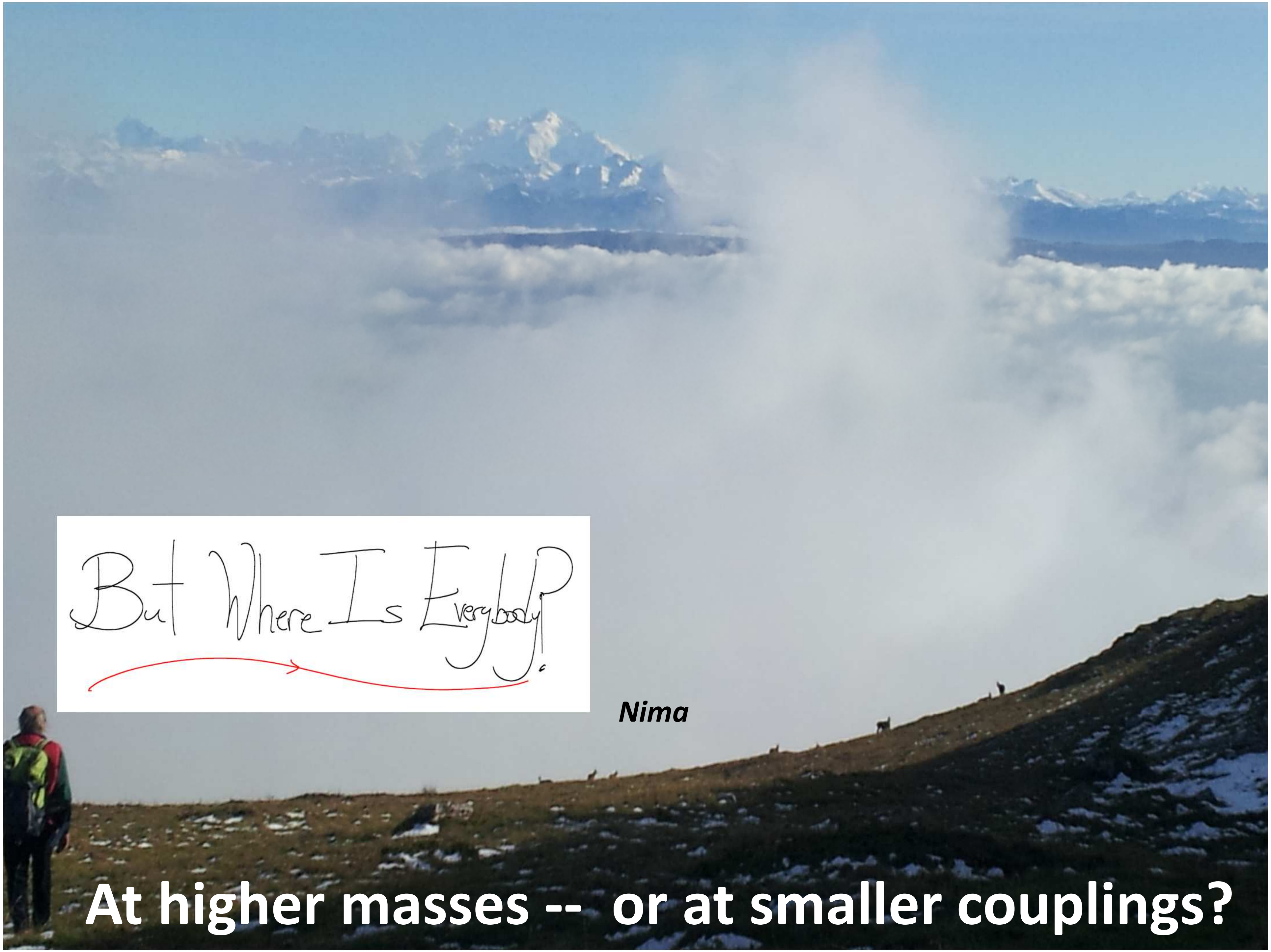
HOW?

Direct observation of new particles (but not only!)

New phenomena (Neutral currents, CP violation, neutrino oscillations…)

Deviations from precise predictions

(ref. Uranus to Neptune, top and Higgs preds from LEP/SLC/Tevatron/B factories, g-2, etc…)



But Where Is Everybody?

Nima

At higher masses -- or at smaller couplings?

FUTURE ACCELERATORS

1. High Luminosity LHC (3000 fb^{-1} @ 14 TeV) → 2035
   An approved program

2. ILC/CLIC as Higgs and top factory and upgrades
   A very ‘mature’ study of a new technique

‘or’

2’. Circular e+e- Z,W,H,top factories (FCC)
   «Young» studies of a very mature technique

3. HE-LHC (FCC)
   apparently straightforward... but

‘or’

4. 100 TeV hadron collider (FCC)
   The ‘ultimate’ energy exploration

4. muon collider (possibly FCC?)
   not so young but still no very mature (will briefly mention H width)

The Physics Landscape

1. we know that new physics beyond the SM is needed for
dark matter,
baryon asymmetry of the universe
neutrino masses
the fact that electron and proton have the same charge to 10^{-22} precision...
and more.

2. The Standard Model without any new particles with couplings .ge. the weak coupling works very well:
-- predicted the top and Higgs masses from m_Z vs m_W vs Γ_z vs $\sin^2\theta^{eff}_W$ etc..
-- and seems to extrapolate smoothly to the Planck scale.

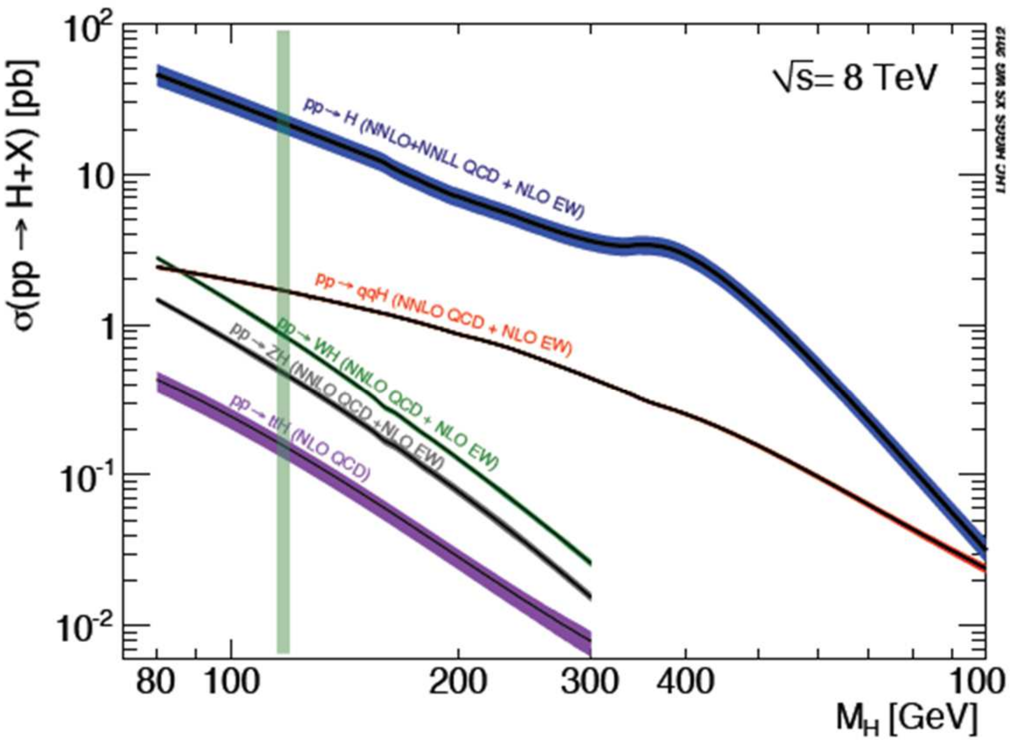
3. Fascinating situation: where to look and what will we find?

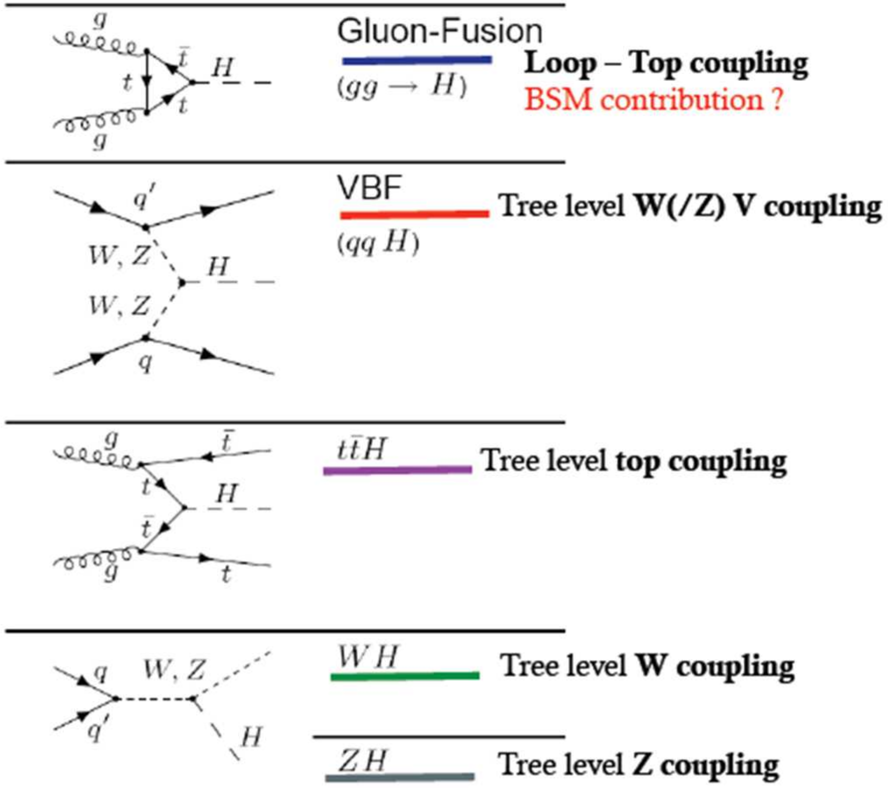
4. search must continue but tools must be as broad and powerful as possible, as there is no precise target.

HIGGS FACTORIES

Higgs provides a very good reason why we need e+e- (or $\mu\mu$) collider

This has been well documented by ILC and Muon collider design studies.





THE LHC is a Higgs Factory

several tens of Million Higgs already produced > than most Higgs factory projects.

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.

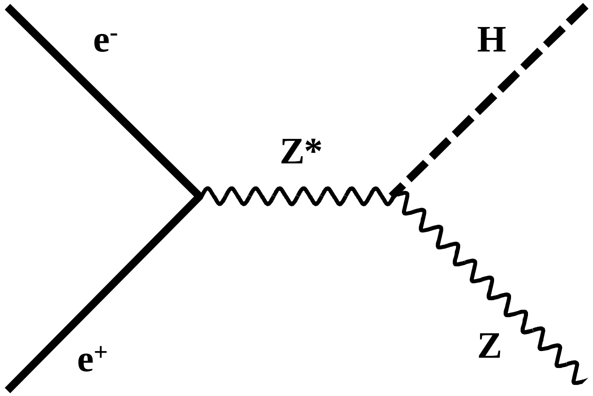
$\sigma_{i\to f}^{\ observed} \propto \sigma_{prod} \frac{(g_{Hi})^2(g_{Hf})^2}{\Gamma_H}$ difficult to extract the couplings because σ_{prod} uncertain and Γ_H is unknown (invisible channels)

Higgs production mechanism

"higgstrahlung" process close to threshold

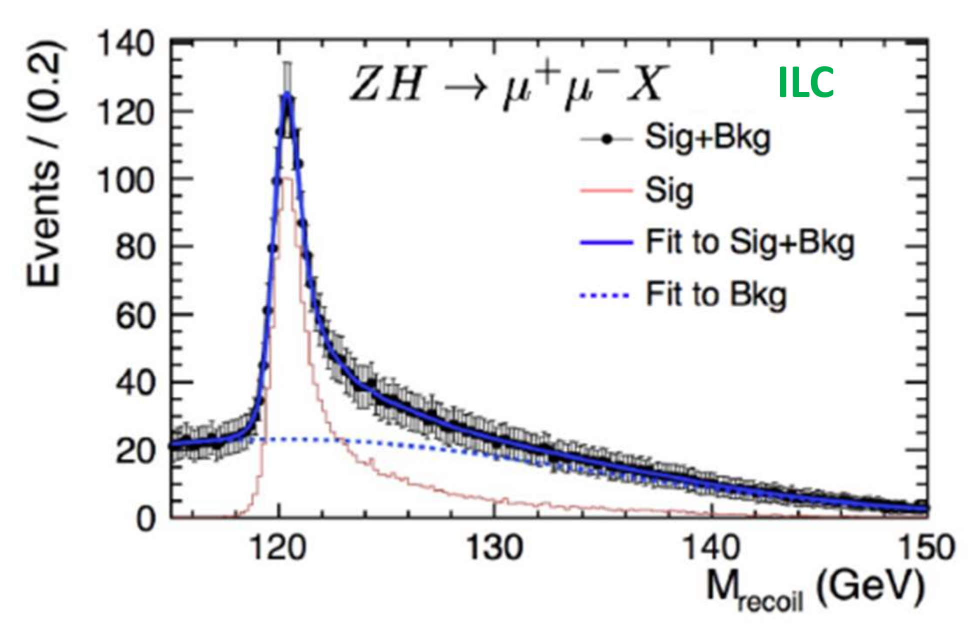
Production xsection has a maximum at near threshold ~200 fb

$10^{34}/cm^2/s$ ➔ 20'000 HZ events per year. or 50 years for 10^6HZ



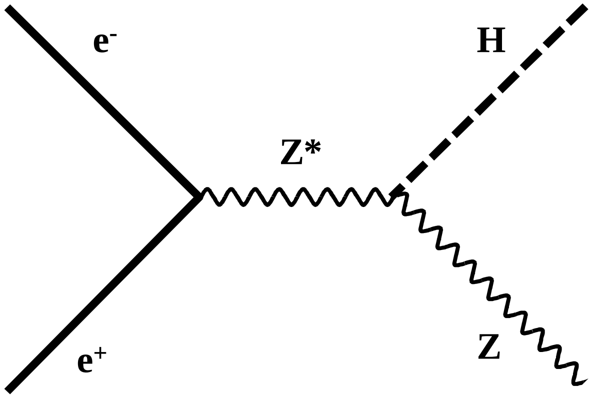
Z – tagging by missing mass

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

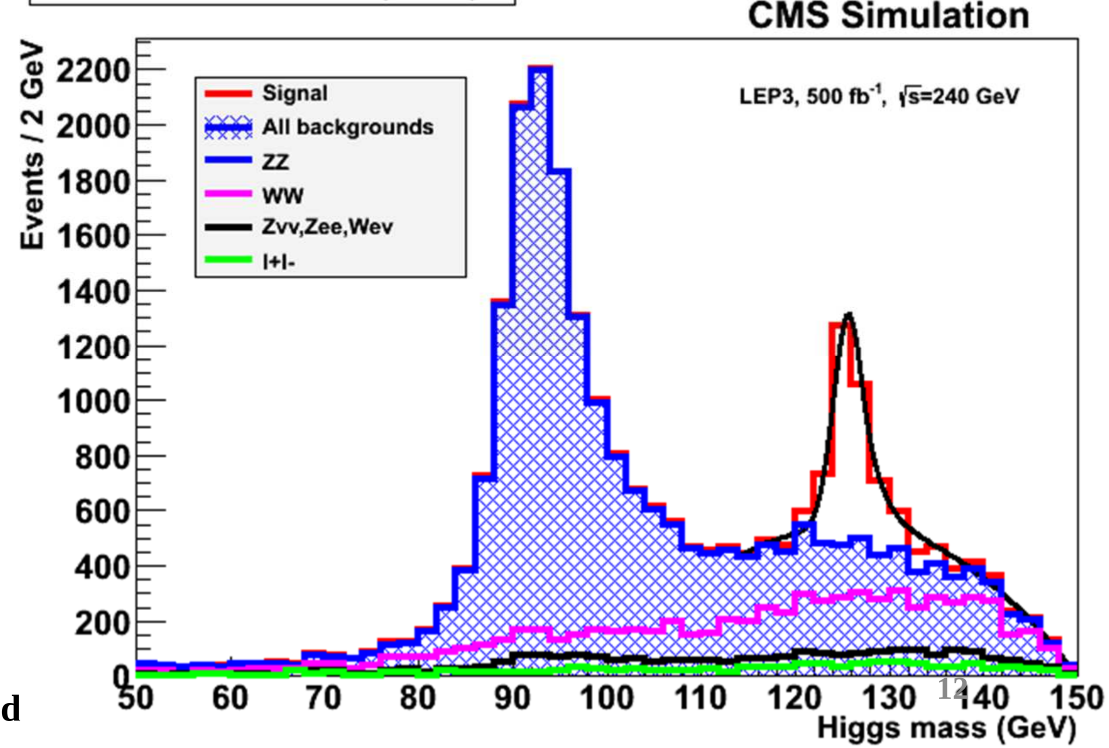


Z – tagging
by missing mass

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



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



$\mu^+\mu^-$ Collider vs e^+e^- Collider ?

- **A $\mu^+\mu^-$ collider can do things that an e^+e^- collider cannot do** [16,17]
  - Direct coupling to H expected to be larger by a factor m_μ/m_e

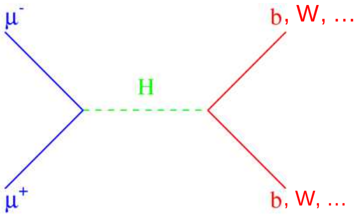
$\sigma(\mu^+\mu^- \to H) \approx 40000 \times \sigma(e^+e^- \to H)$ [σ_{peak} = 70 pb at tree level]

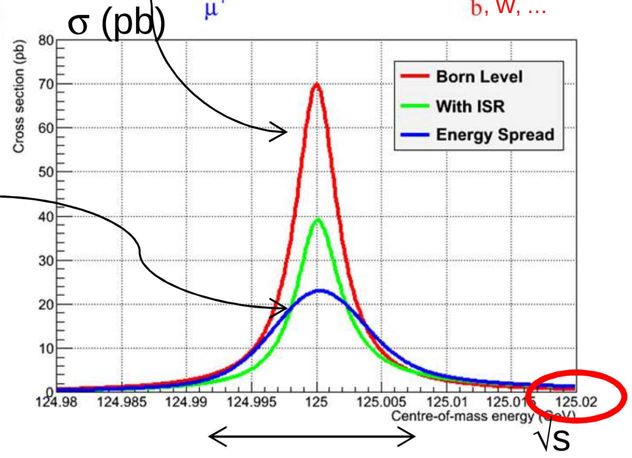
  - Beam energy spread $\delta E/E$ may be reduced to 3×10^{-5}
    - 6D Cooling, no beamstrahlung, ~no bremsstrahlung
    - For $\delta E/E$ = 0.003% (δE ~ 3.6 MeV, Γ_H ~ 4 MeV)
      - ➔ Corresponding luminosity ~ 10^{31} cm^{-2}s^{-1}

Expect 2300 Higgs events in 100 pb^{-1}/ year

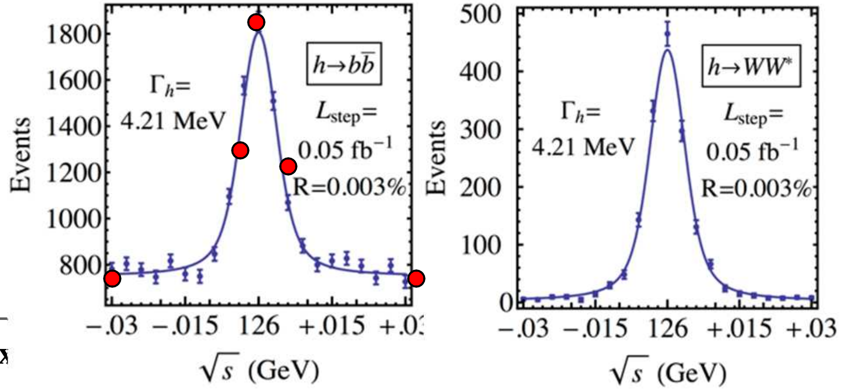
  - Polarization, beam energy and energy spectrum
    - Can be measured with an exquisite precision
      - ➔ From the electrons of the muon decays
  - Then measure the lineshape of the Higgs at $\sqrt{s}$ ~ m_H
    - Five-point scan, 50 + 100 + 200 + 100 + 50 pb^{-1}
      - ➔ Precision from H→bb and WW :

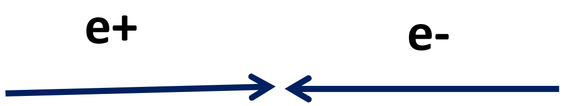
m_H	σ_{Peak}	Γ_H
0.1 MeV	0.6 pb	0.2 MeV
10^{-6}	2.5%	5%





σ(m_H), TLEP





e+ e- colliders have a very rich history of discoveries

examples:

-- charm (1974-76) SPEAR at SLAC (USA)
-- gluon (1978) PETRA at DESY (Germany)
-- B mixing (1985) DORIS at DESY
-- Number of neutrinos is 3 LEP at CERN 1989
-- Prediction of top quark mass LEP 1994
-- Observation of tau neutrinos LEPII at CERN 1996
-- CP violation in the B system 1999 PEPII at SLAC and Belle at KEK (Japan)

and of precision measurements

ex:

tau mass at BEPC, Beijing 1776.99 +0.29−0.26 (1.5 10^{-4})
J/ψ mass at Novosibirsk, 3096.916 ± 0.011 MeV (3.510^{-6})
Z mass and width at LEP 91.1876 ± 0.0021 (2 10^{-5})

The e+e- colliders:

Circular e+e- colliders

Placed in a tunnel of circumference C and bending radius ρ (2π ρ ~0.8 C)

Acceleration occurs in a few RF sections around the ring.

total RF volts needed = energy loss by synchrotron radiation (scales as E^4/ρ)

Main limitation : power and ring size → cost + power + beam energy

Beams collide 10^6 to 10^7 times

Many e+e- storage rings and many successes: c and b factories, LEP

LEP = 27km circumference reached 209 GeV -- long believed to be the last at high energies. Luminosity of b factories has reached unexpected levels

Linear e+ e- colliders

Acceleration takes place once through a large set of RF cavities

total RF volts needed = center-of-mass Energy

e.g. 500 GeV Linear collider requires > 500 GV of RF voltage

Main limitation = cost + power + beam energy

beam polarization is easy for electrons, feasible for positrons

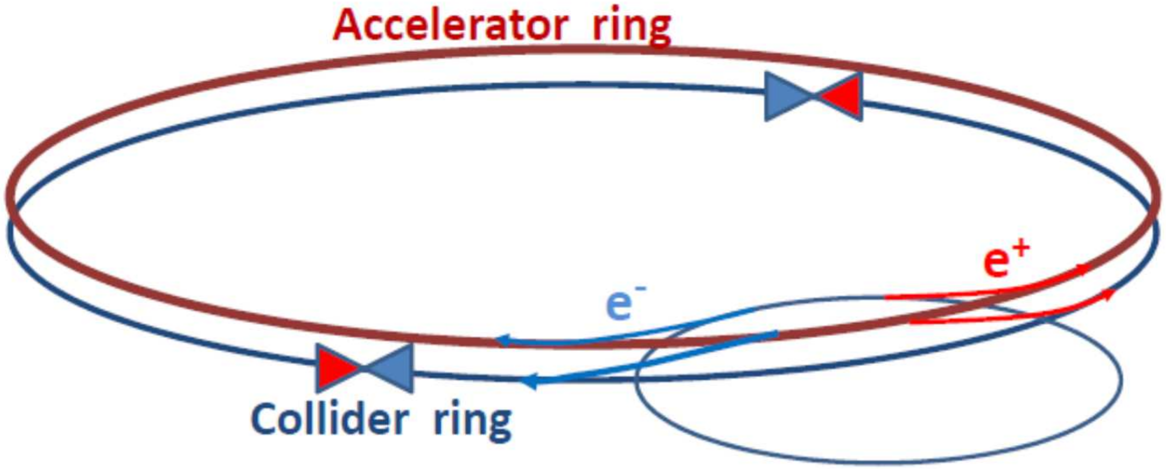
beam energy spread few percent, beam energy calibration $\Delta E/E \sim 10^{-4}$

Beams collide only once

Only one example that worked: SLC at SLAC (1988-1998) -- not easy!

LEP3, CEPC and TLEP/FCC-ee

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

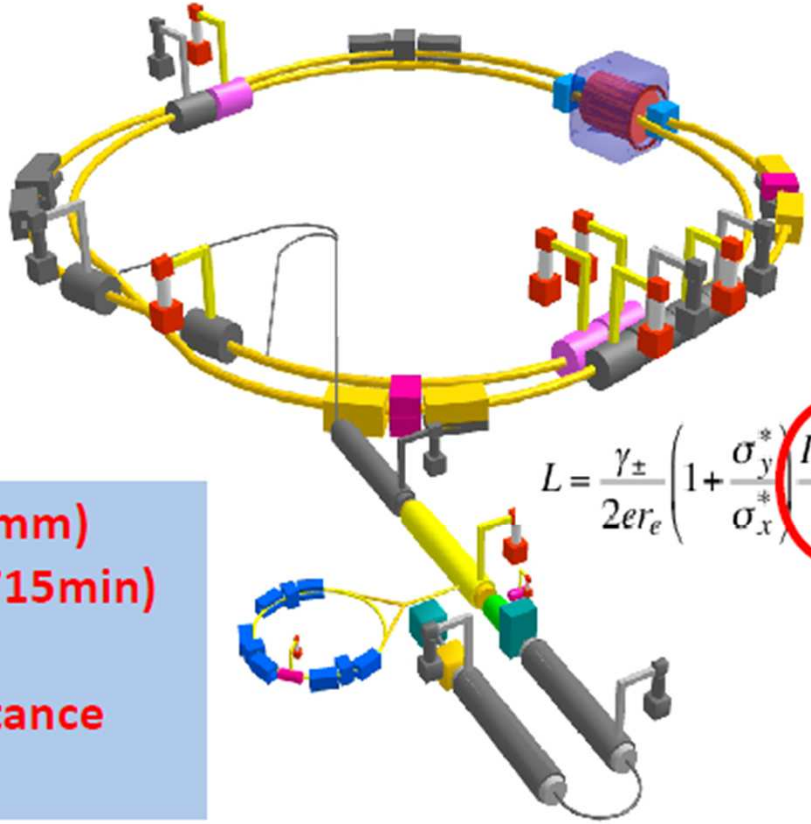


arXiv:1112.2518

AB, F. Zimmermann
Dec. 13 2011

SuperKEKB – TLEP demonstrator!

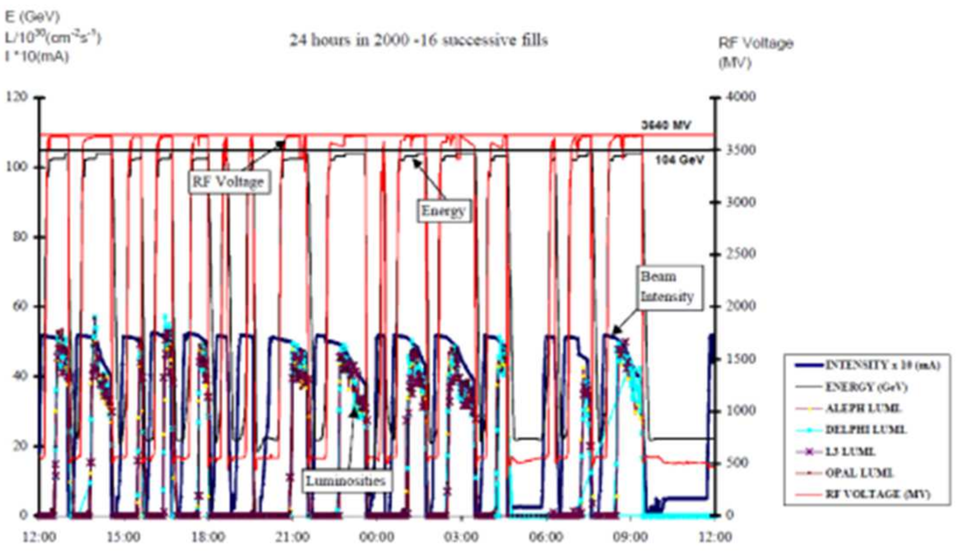
beam
commissioning will
start in **2016**



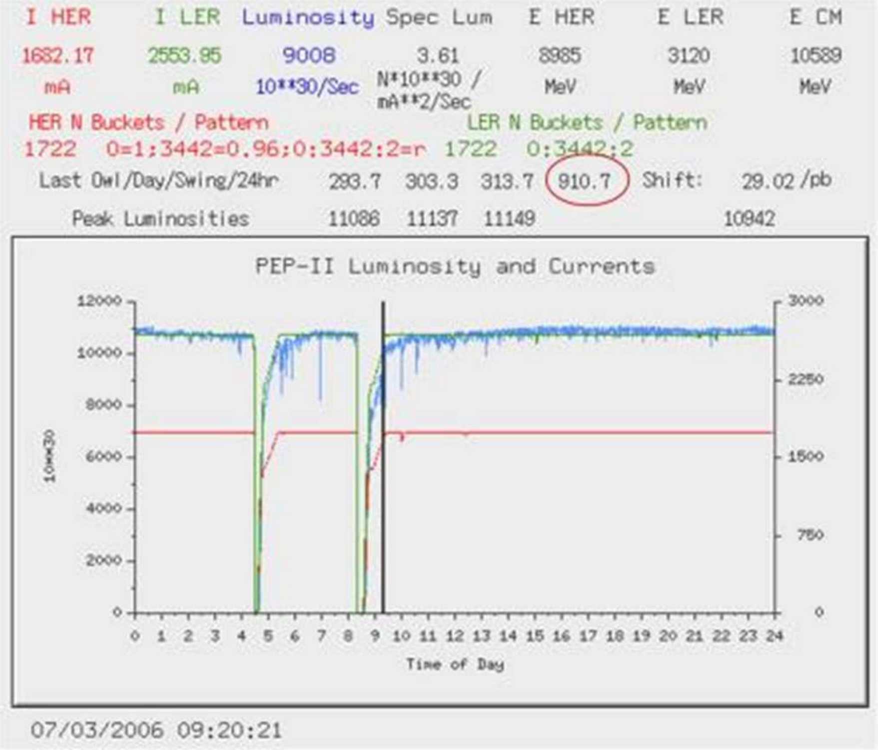
$$L = \frac{\gamma_{\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\boxed{\left(\frac{I_{\pm}\xi_{\pm y}}{\beta_y^*}\right)}\left(\frac{R_L}{R_y}\right)$$

- 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



I HER	I LER	Luminosity	Spec Lum	E HER	E LER	E CM
1682.17	2553.95	9008	3.61	8985	3120	10589
mA	mA	10**30/Sec	N*10**30 / mA**2/Sec	MeV	MeV	MeV

HER N Buckets / Pattern LER N Buckets / Pattern
1722 0=1;3442=0.96;0:3442:2=r 1722 0:3442:2

Last Owl/Day/Swing/24hr 293.7 303.3 313.7 910.7 Shift: 29.02 /pb

Peak Luminosities 11086 11137 11149 10942

07/03/2006 09:20:21

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

The Future Circular Colliders
CDR and cost review for the next ESU (2018)

International collaboration to Study Colliders fitting in a new ~100 km infrastructure, fitting in the *Genevois*

- ***Ultimate goal:* ~16 T magnets**
  ***100 TeV pp*-collider (*FCC-hh*)**

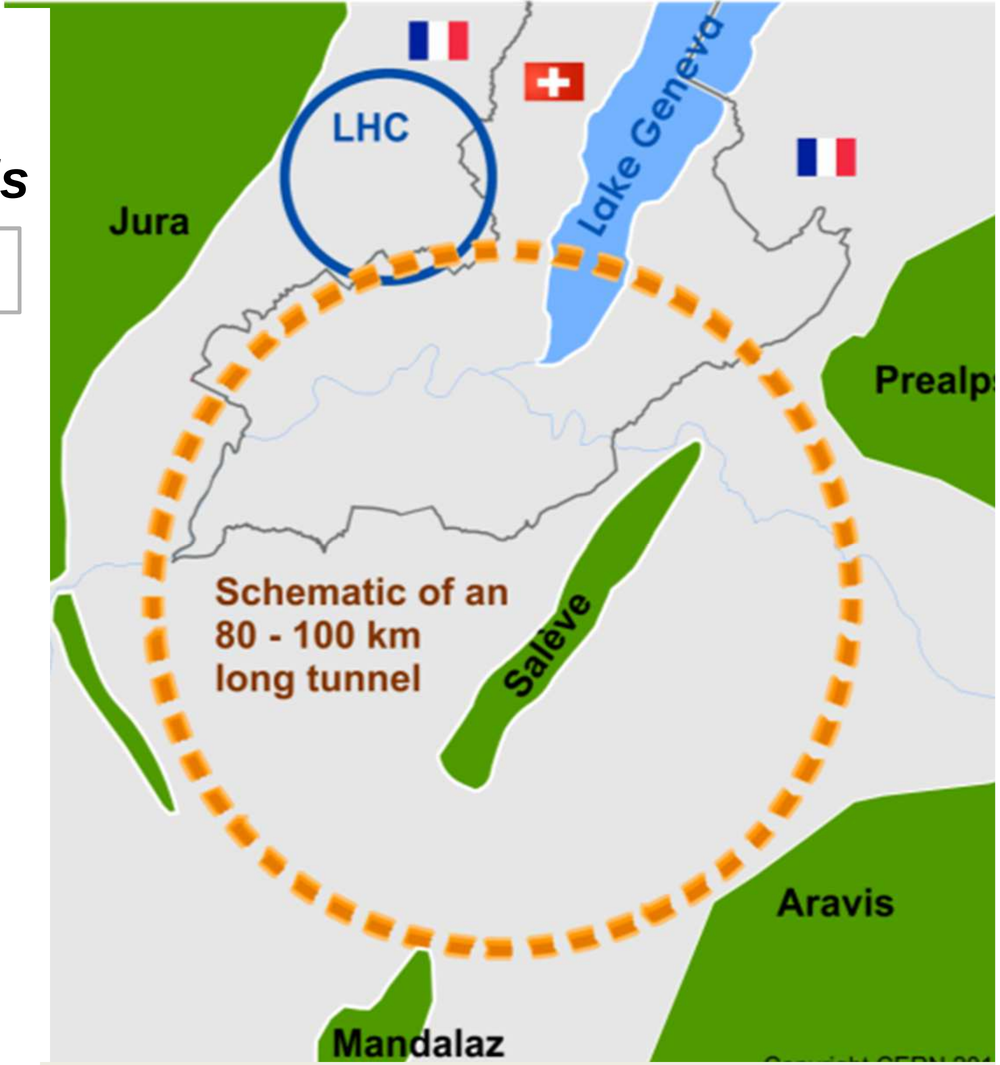
→ defining infrastructure requirements

Possible first steps:

- ***e^+e^-* collider (*FCC-ee*)**
  High Lumi, E_{CM} =90-400 GeV
- ***HE-LHC* 16T ⇒ 27 TeV in LEP/LHC tunnel**

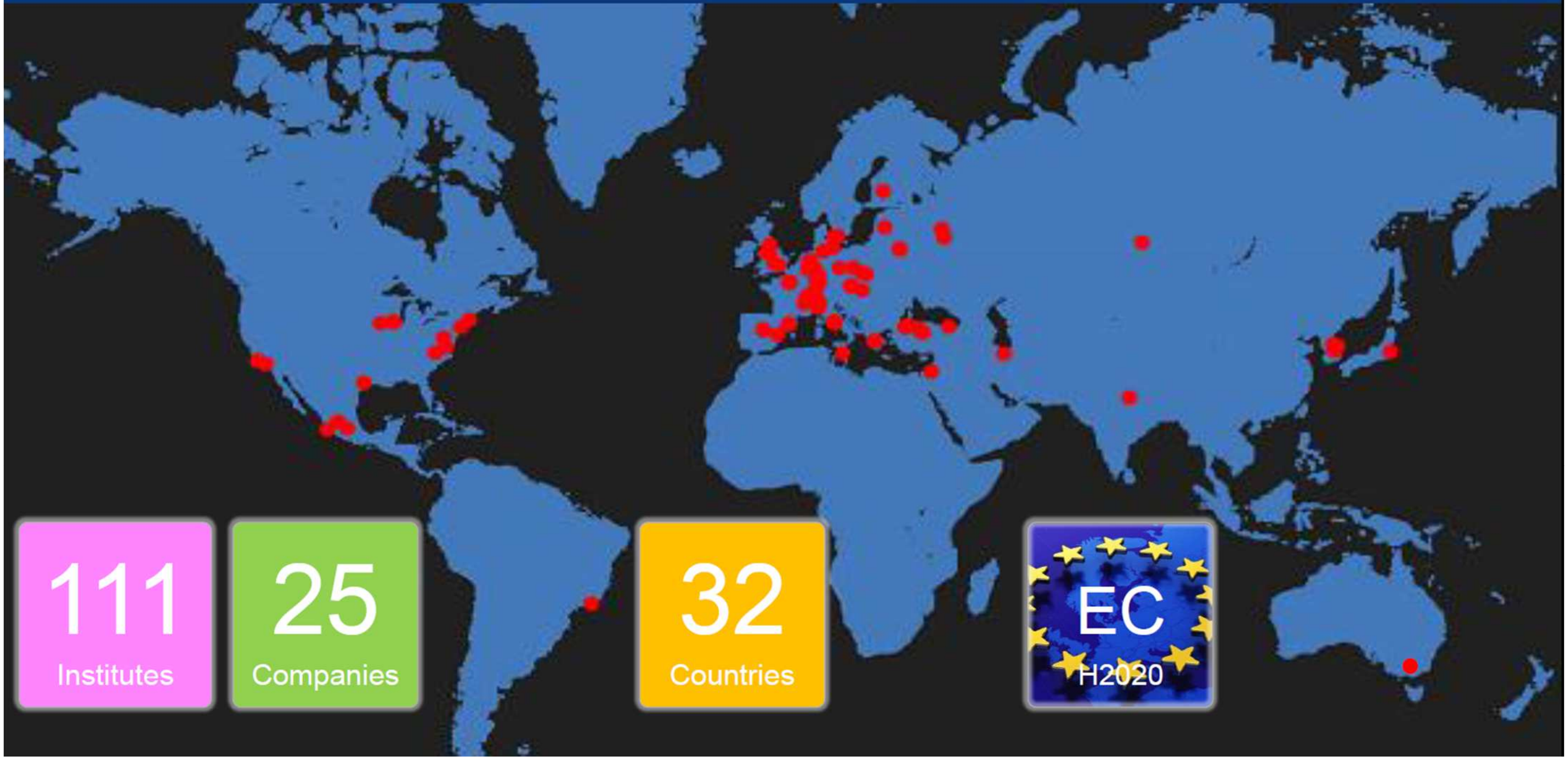
Possible add-on:

- ***p-e* (*FCC-he*) option**



**From European Strategy in 2013:
"ambitious post-LHC accelerator project"
Study kicked-off in Geneva Feb 2014**

Collaboration & Industry Relations

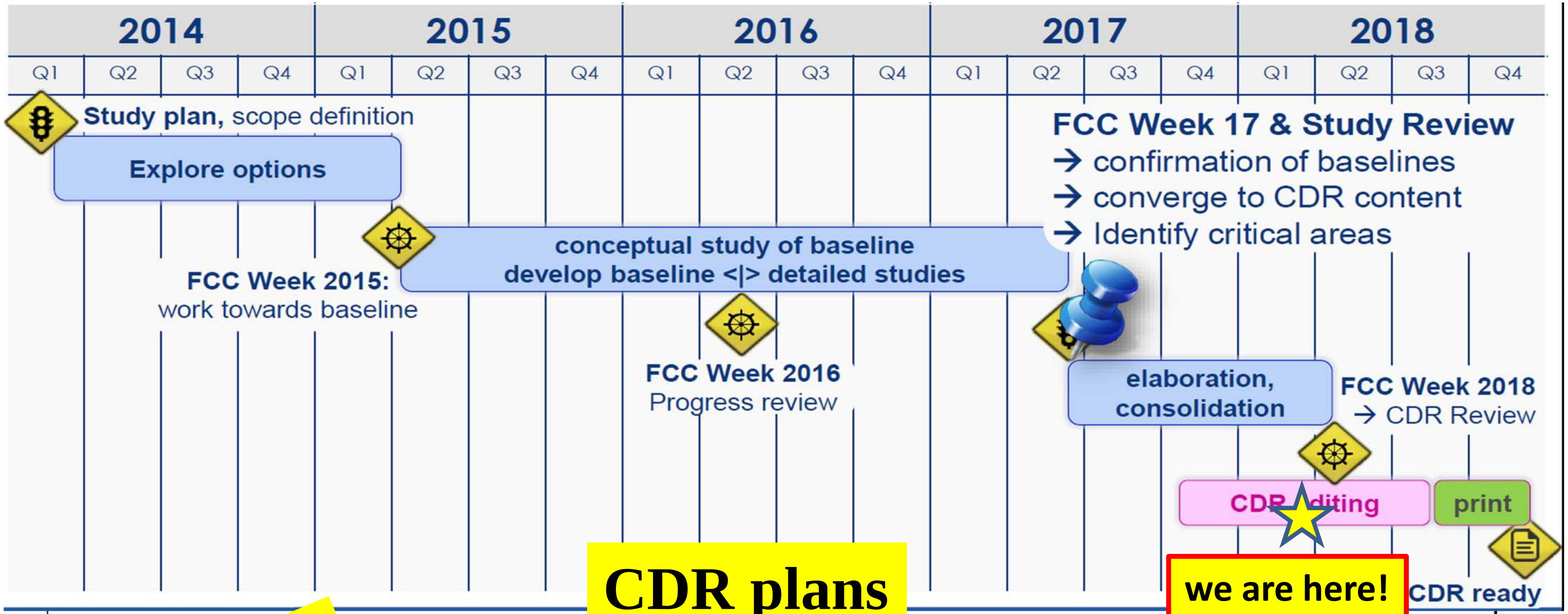


111 Institutes

25 Companies

32 Countries

CDR plans



2014 2015 2016 2017 2018

Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4

Study plan, scope definition

Explore options

FCC Week 2015:
work towards baseline

conceptual study of baseline
develop baseline <|> detailed studies

FCC Week 2016
Progress review

FCC Week 17 & Study Review
→ confirmation of baselines
→ converge to CDR content
→ Identify critical areas

elaboration, consolidation

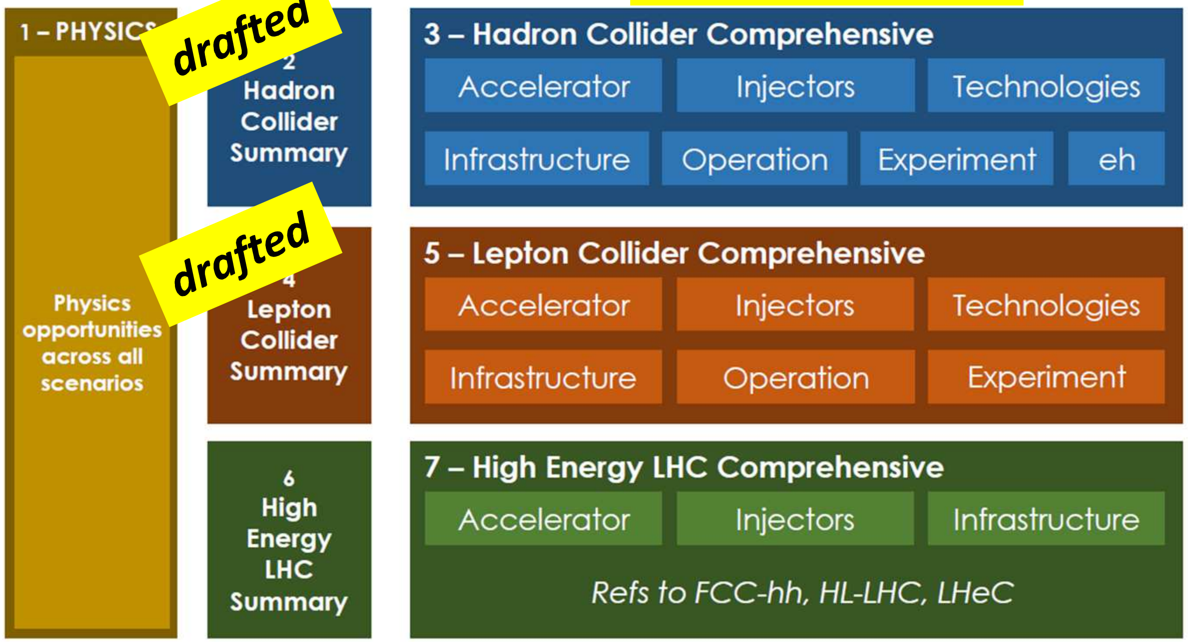
FCC Week 2018
→ CDR Review

CDR editing

print

CDR ready

we are here!



1 – PHYSICS

Physics opportunities across all scenarios

drafted

2
Hadron Collider Summary

drafted

4
Lepton Collider Summary

6
High Energy LHC Summary

3 – Hadron Collider Comprehensive

Accelerator | Injectors | Technologies
Infrastructure | Operation | Experiment | eh

5 – Lepton Collider Comprehensive

Accelerator | Injectors | Technologies
Infrastructure | Operation | Experiment

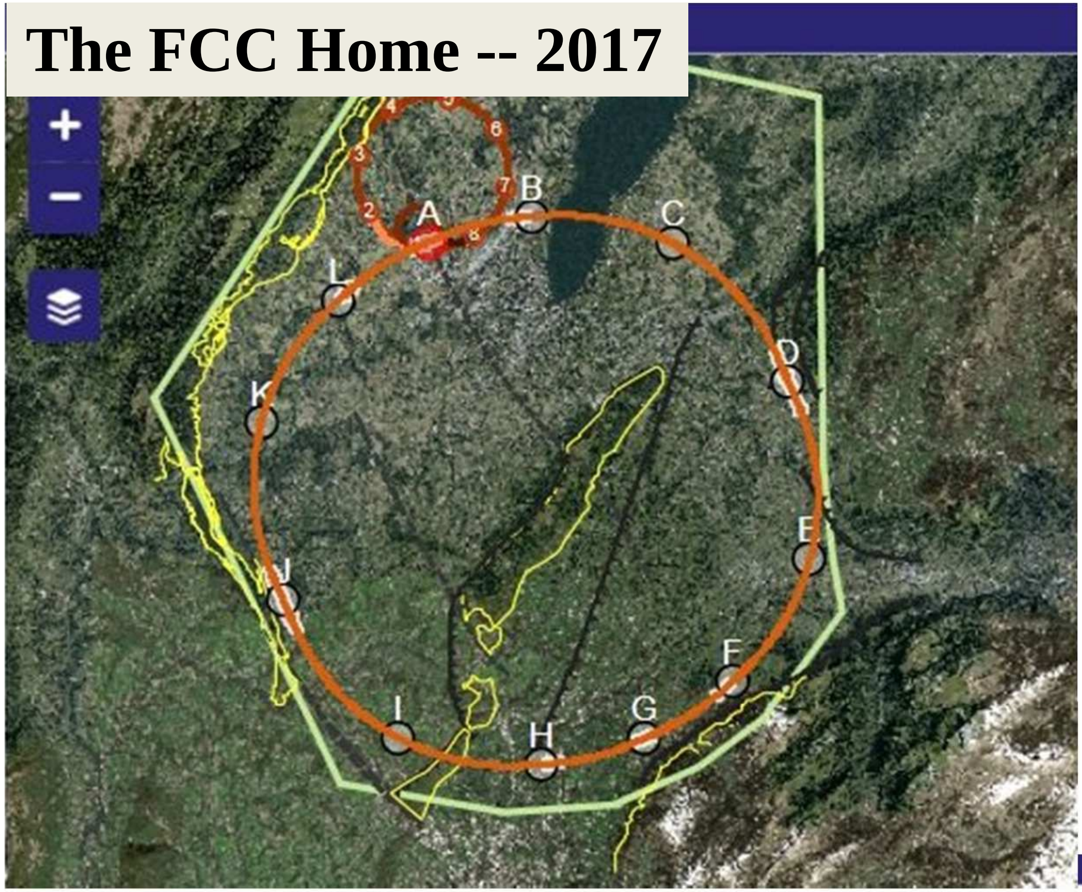
7 – High Energy LHC Comprehensive

Accelerator | Injectors | Infrastructure

Refs to FCC-hh, HL-LHC, LHeC

- **Required for end 2018, as input for European Strategy Update**
- **Common physics summary volume**
- **Three detailed volumes FCChh, FCCee, HE-LHC**
- **Three summary volumes FCChh, FCCee, HE-LHC**

The FCC Home -- 2017



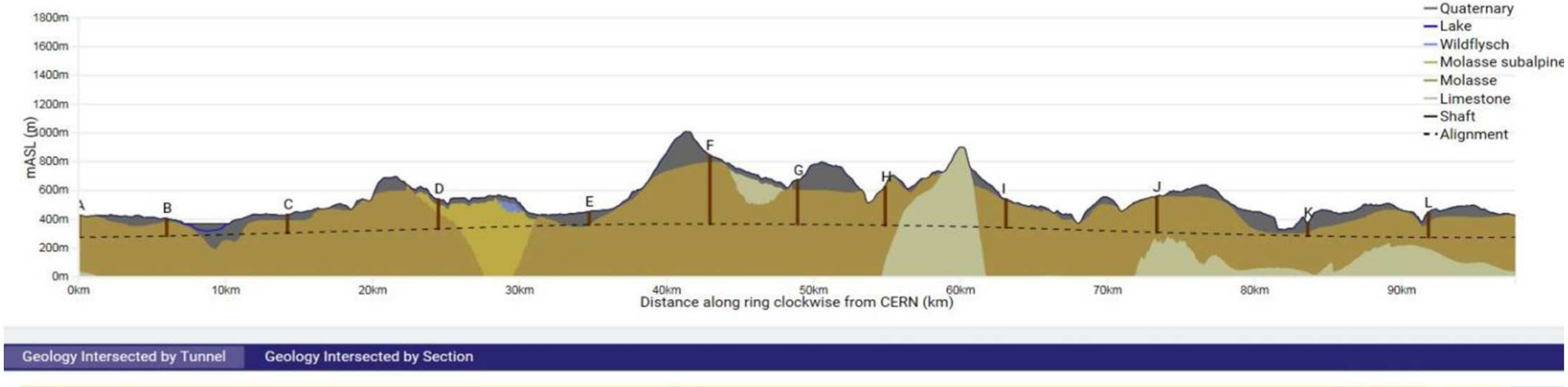
Optimisation in view of accessibility surface points, tunneling rock type, shaft depth, etc. optimum: 97.5 km

Tunneling

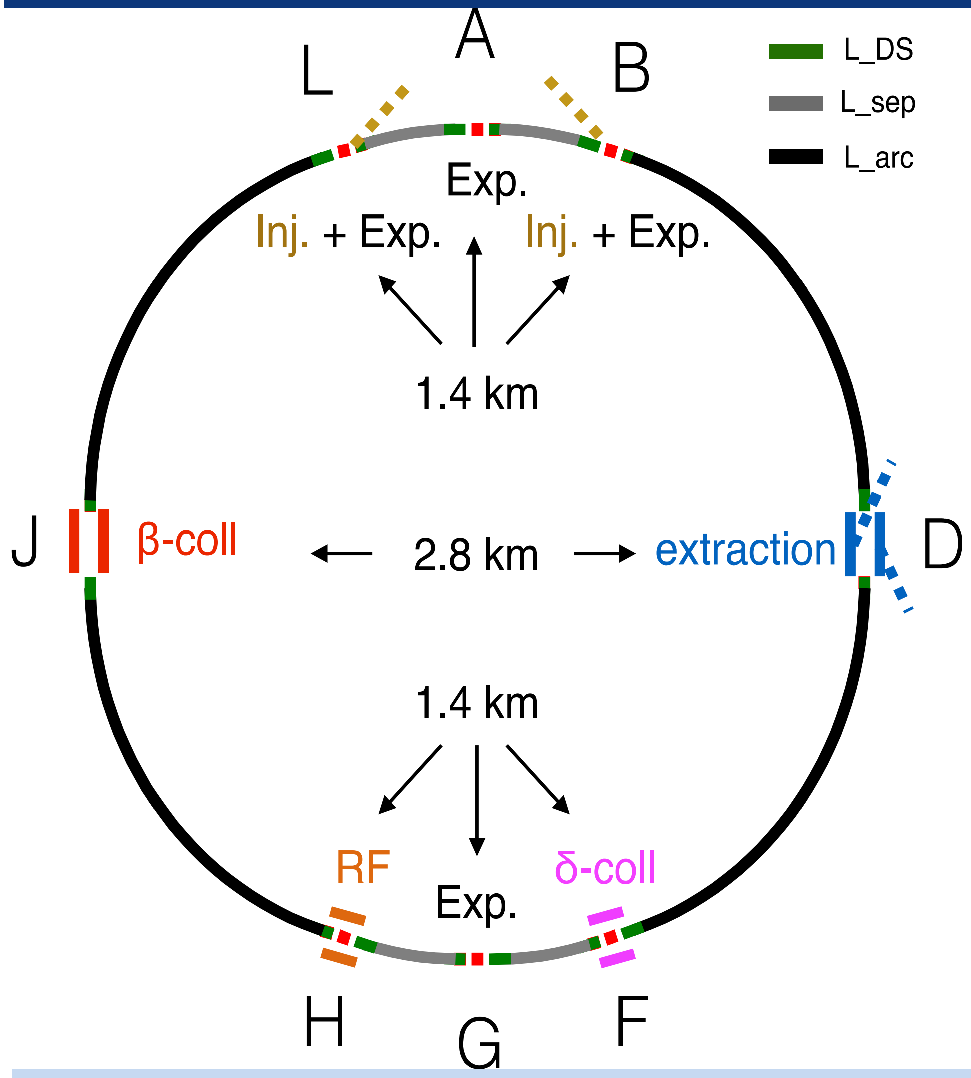
- **Molasse 90% (good rock),**
- **Limestone 5%, Moraines 5% (tough)**

Shallow implementation

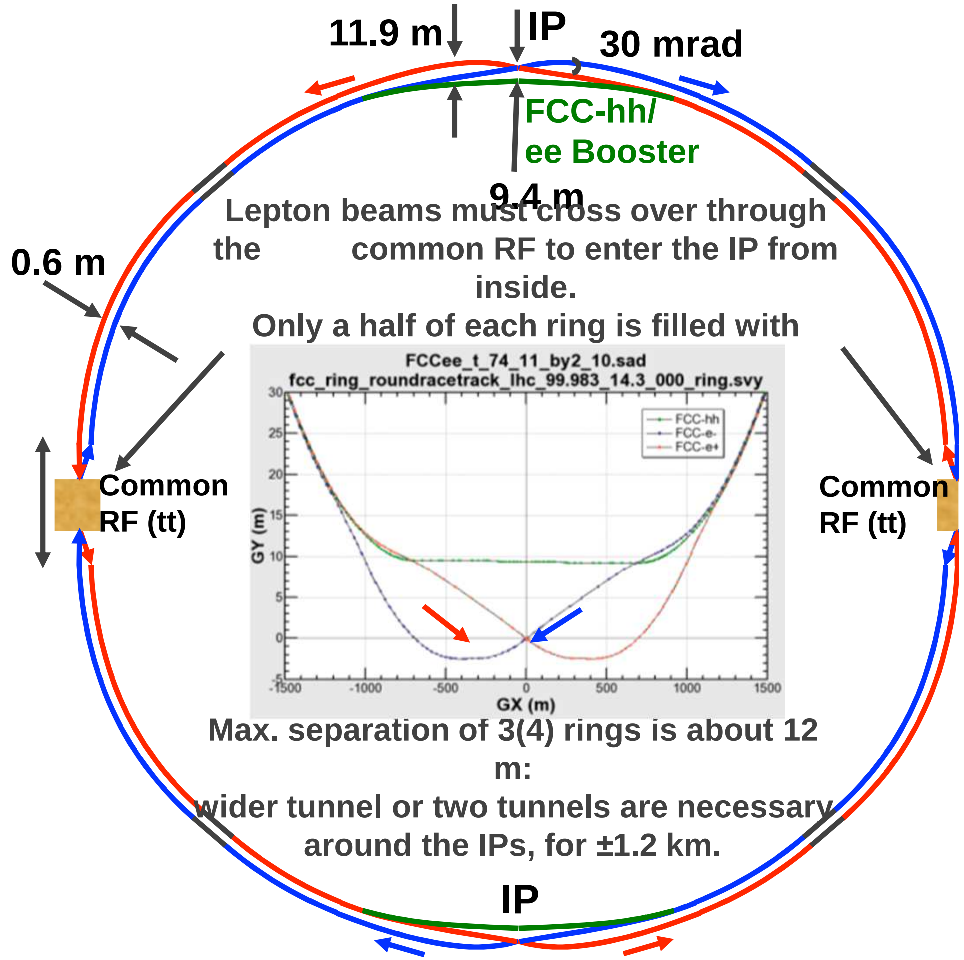
- **~ 30 m below Léman lakebed**
- **Reduction of shaft lengths etc...**
- **One very deep shaft F (476m) (RF or collimation), alternatives being studied, e.g. inclined access**



common layouts for hh & ee



2 main IPs in A, G for both machines



Lepton beams must cross over through the common RF to enter the IP from inside.

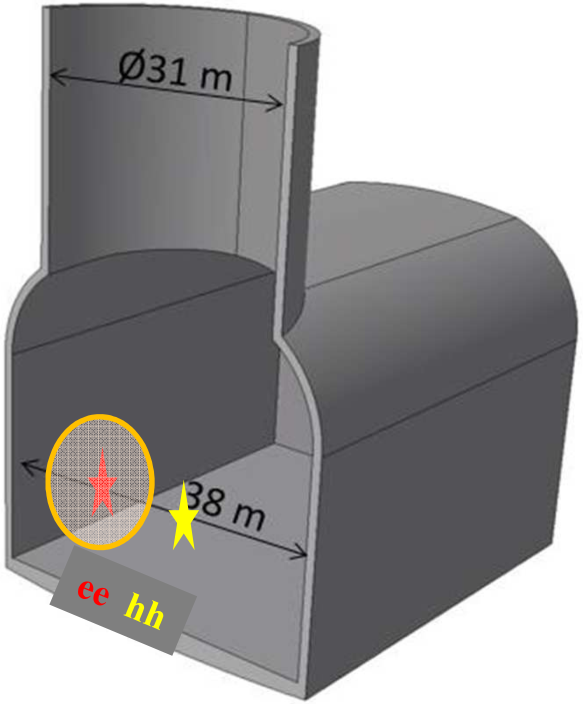
Only a half of each ring is filled with

Max. separation of 3(4) rings is about 12 m:
wider tunnel or two tunnels are necessary around the IPs, for ±1.2 km.

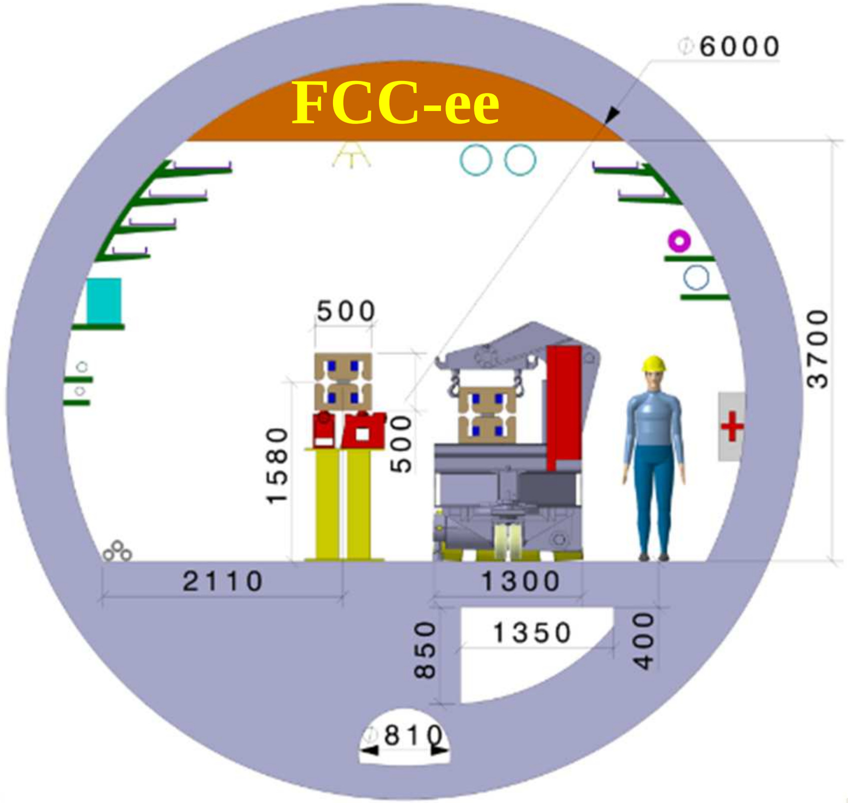
FCC-ee 1, FCC-ee 2,

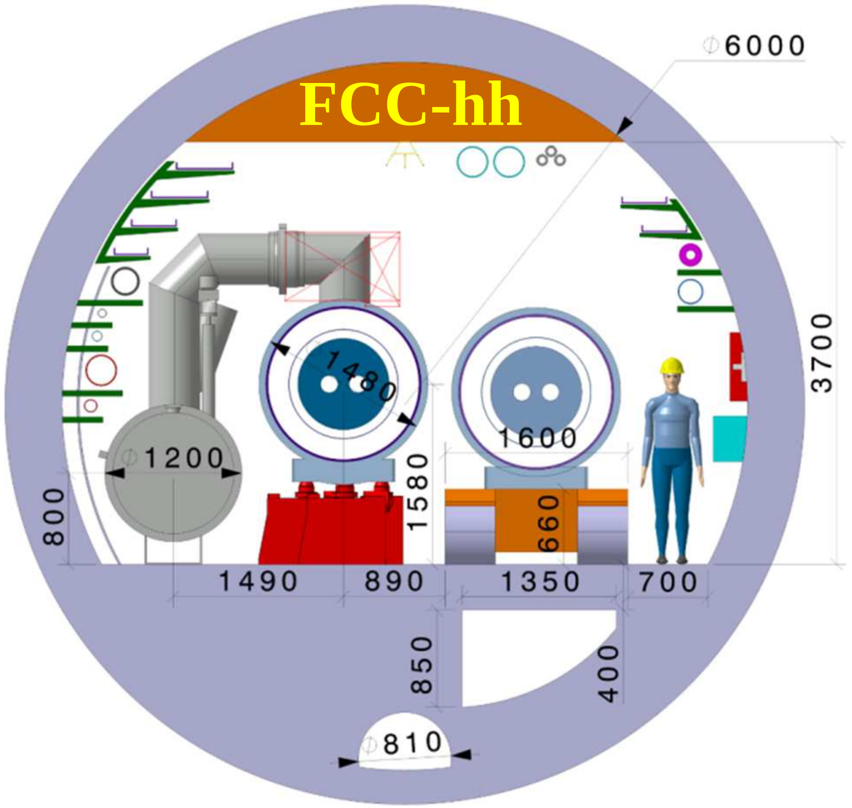
FCC-ee booster (FCC-hh footprint)

Asymmetric IR for ee, limits SR to expt



Sharing the FCC experimental caverns
(Prelim. layout as of FCC-Rome meeting)





HE-LHC :

constraints:

No civil engineering, same beam height as LHC

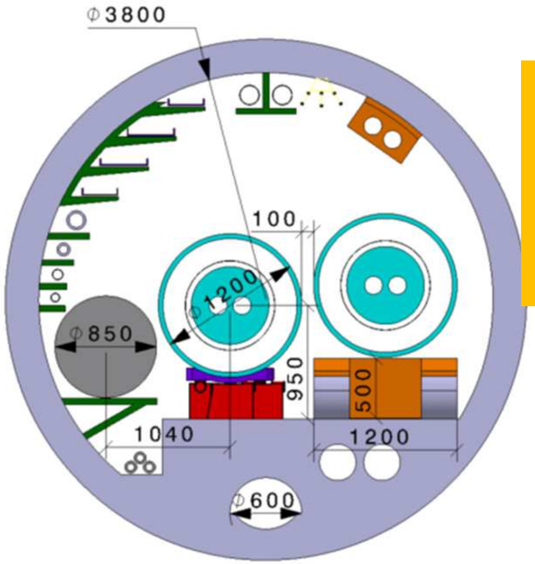
→ Magnets OD ca. 1200 m max

QRL (shorter than FCC) OD ca. 850 mm (all included)

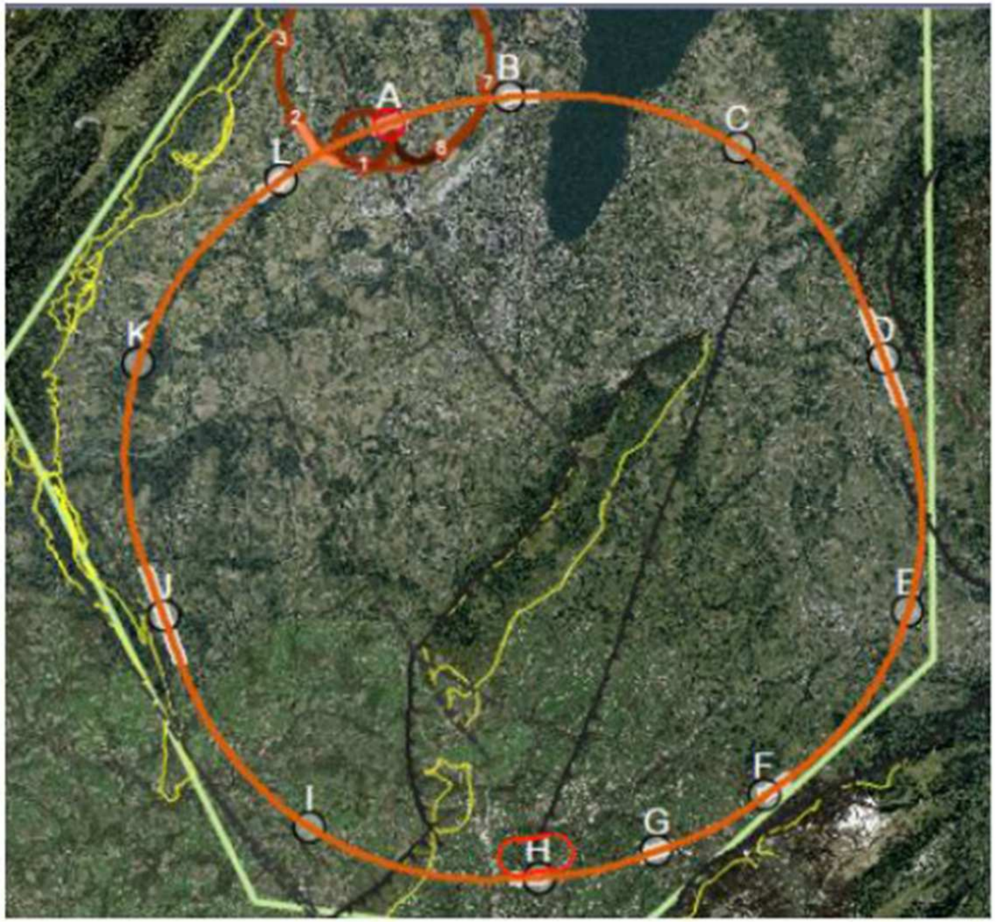
Magnet suspended during „handover“ from transport vehicle to installation transfer table

Compliant 16T magnet design ongoing (challenge)

+ still many items to study!



If HE-LHC can work in 3.8m ∅ ... it will feed-back to FCC tunnel design!



FCC-eh

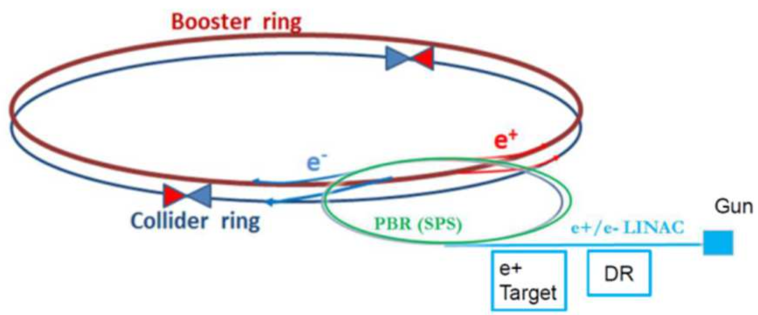
LHeC or FCC-eh function as an add-on to LHC or FCC-hh respectively:
additional 10km cicumference
Electron Reciculating Linac ERL.

The possibility to collide FCC-ee with FCC-hh is not considered in the framework of the study

In the case of FCC-eh it could profit from the -- then existing -- FCC-hh,
and, perhaps, from considerable RF of the -- then dismantled -- FCC-ee

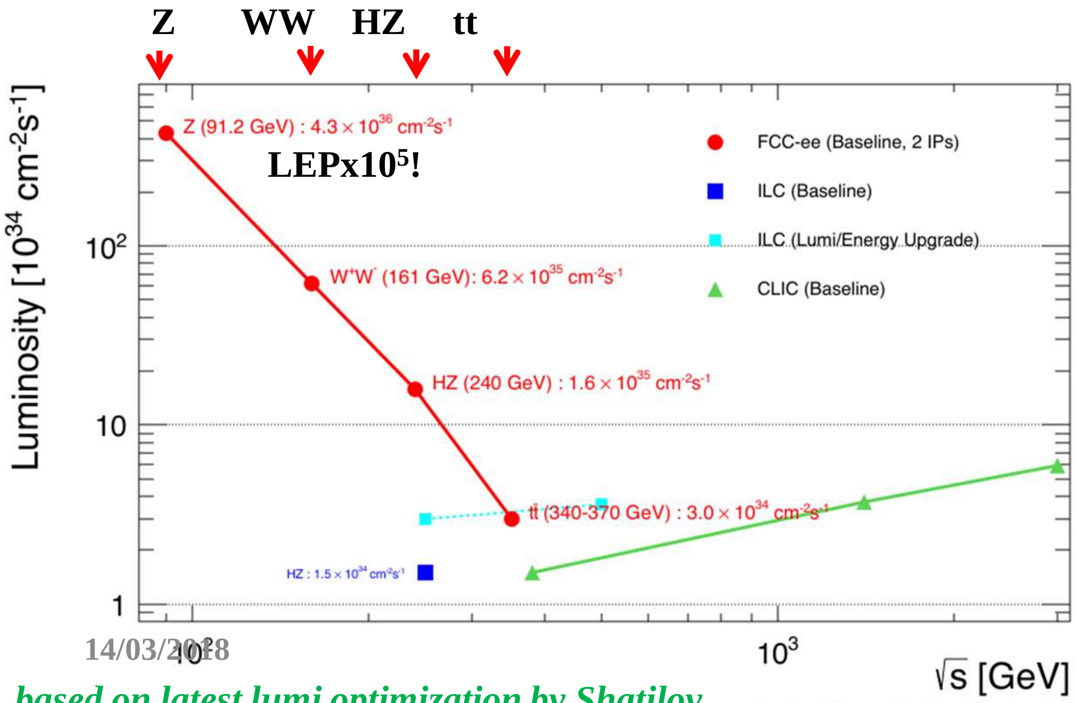
FCC-ee

AB, F. Zimmermann 2011 (LEP3@240 GeV)



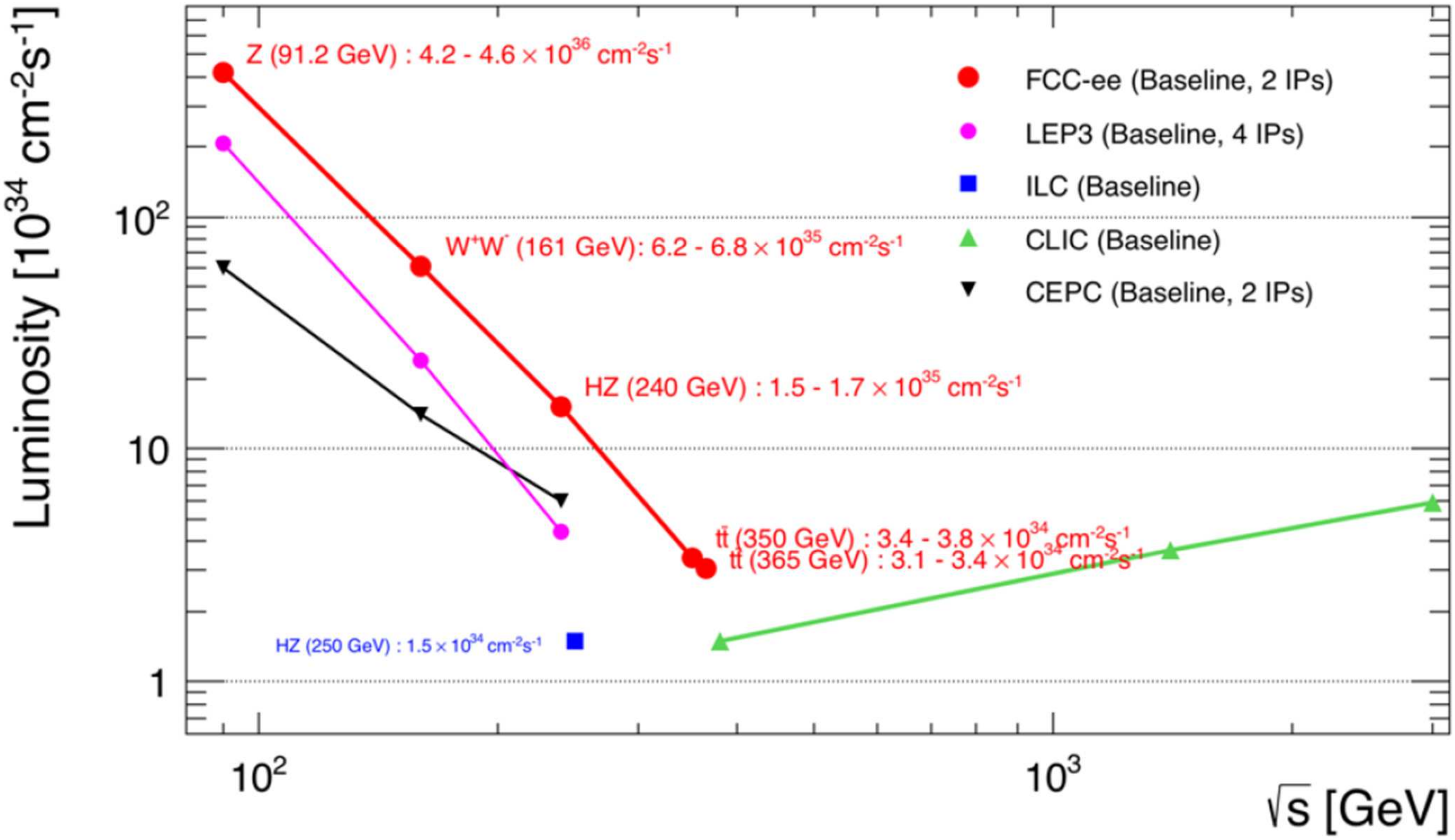
top-up injection for high duty factor
several schemes possible

Q: Why is luminosity so much higher than LEP?
A: inspired by b-factory designs
-- continuous injection (high efficiency)
-- e+ and e- separate (→many bunches)
-- fix 100 MW Synchrotron Radiation at all E
-- low β^*_y , O(1mm)
-- larger ring ($P_{SR} \propto E^4/\rho$)
-- beam cross at angle (30 mrad)
-- crab waist crossing
-- asymmetric IP to avoid SR → LEP levels



Luminosity performance dominated by
-- at Z, WW, H energies:
beam-beam instabilities
→ simulations
-- at top energy: beamstrahlung
depends on value of $\varepsilon_y/\varepsilon_x$
0.2% assumed (0.25%@superKEKB)
0.4% achieved at LEP
-- limit from injector is much higher

based on latest lumi optimization by Shatilov

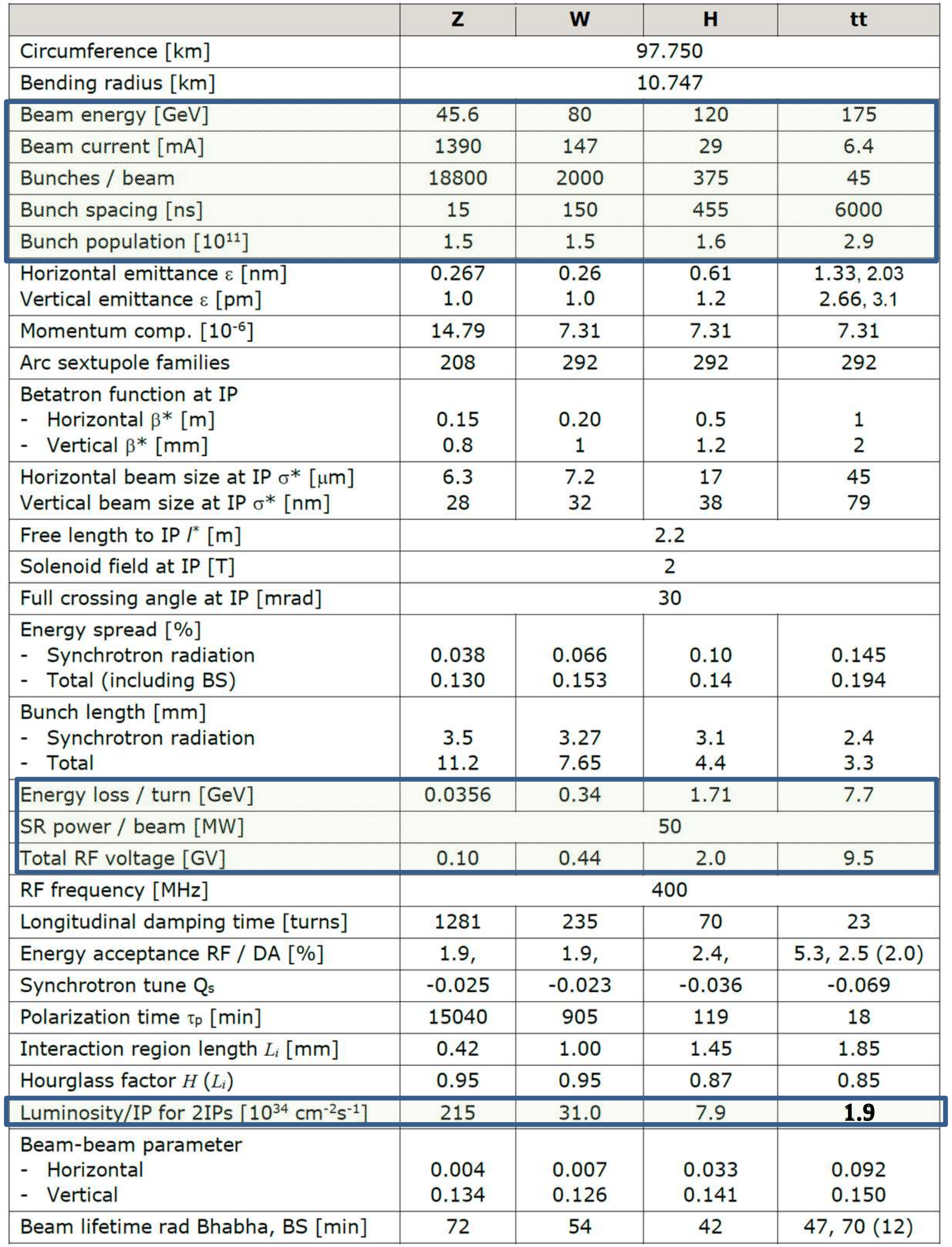


Overlap in Higgs/top region, but differences and complementarities between linear and circular machines:

Circ: High luminosity, experimental environment (2 to 4 IP), E_{CM} calibration

Linear: higher energy reach, longitudinal beam polarization

Recent FCC-ee parameter list

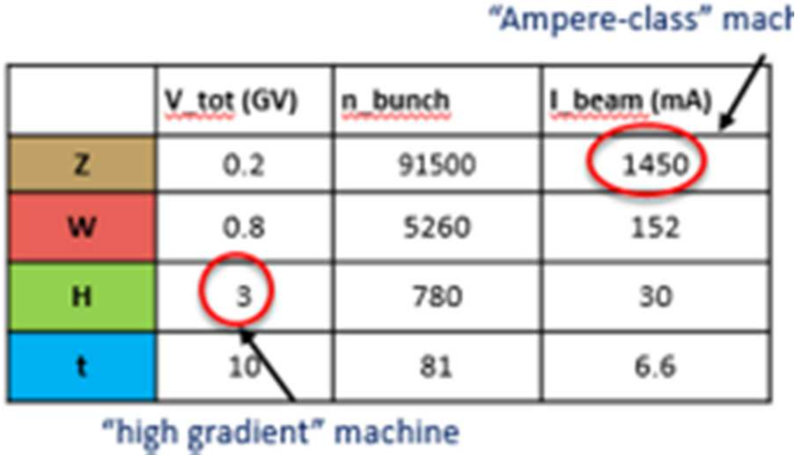


	Z	W	H	tt
Circumference [km]	97.750			
Bending radius [km]	10.747			
Beam energy [GeV]	45.6	80	120	175
Beam current [mA]	1390	147	29	6.4
Bunches / beam	18800	2000	375	45
Bunch spacing [ns]	15	150	455	6000
Bunch population [10^{11}]	1.5	1.5	1.6	2.9
Horizontal emittance ε [nm] Vertical emittance ε [pm]	0.267 1.0	0.26 1.0	0.61 1.2	1.33, 2.03 2.66, 3.1
Momentum comp. [10^{-6}]	14.79	7.31	7.31	7.31
Arc sextupole families	208	292	292	292
Betatron function at IP - Horizontal β^* [m] - Vertical β^* [mm]	0.15 0.8	0.20 1	0.5 1.2	1 2
Horizontal beam size at IP σ^* [μm] Vertical beam size at IP σ^* [nm]	6.3 28	7.2 32	17 38	45 79
Free length to IP l^* [m]	2.2			
Solenoid field at IP [T]	2			
Full crossing angle at IP [mrad]	30			
Energy spread [%] - Synchrotron radiation - Total (including BS)	0.038 0.130	0.066 0.153	0.10 0.14	0.145 0.194
Bunch length [mm] - Synchrotron radiation - Total	3.5 11.2	3.27 7.65	3.1 4.4	2.4 3.3
Energy loss / turn [GeV]	0.0356	0.34	1.71	7.7
SR power / beam [MW]	50			
Total RF voltage [GV]	0.10	0.44	2.0	9.5
RF frequency [MHz]	400			
Longitudinal damping time [turns]	1281	235	70	23
Energy acceptance RF / DA [%]	1.9,	1.9,	2.4,	5.3, 2.5 (2.0)
Synchrotron tune Q_s	-0.025	-0.023	-0.036	-0.069
Polarization time τ_p [min]	15040	905	119	18
Interaction region length L_i [mm]	0.42	1.00	1.45	1.85
Hourglass factor H (L_i)	0.95	0.95	0.87	0.85
Luminosity/IP for 2IPs [10^{34} cm^{-2}s^{-1}]	215	31.0	7.9	**1.9**
Beam-beam parameter - Horizontal - Vertical	0.004 0.134	0.007 0.126	0.033 0.141	0.092 0.150
Beam lifetime rad Bhabha, BS [min]	72	54	42	47, 70 (12)

FCC-ee physics run

- **FCC-ee physics goals (sum of two IPs):**
  - 150 ab^{-1} at and around the Z pole (88, 91, 94 GeV)
  - 10 ab^{-1} at the WW threshold (~161 GeV with a +/- few GeV scan)
  - 5 ab^{-1} at the HZ maximum (~240 GeV)
  - 1.5 ab^{-1} at and above the ttbar threshold (a few 100 fb^{-1} with a scan from 340 to 350 GeV, and the rest at 365-370 GeV)
- **Assumptions:**
  - 200 scheduled physics days per year, i.e. 7 months – 13 days of MD/stops.
  - "Hübner factor" H=0.75 (lower than value achieved with top-up injection at KEKB, ~0.8).
  - Half the design luminosity in the first two years of Z operation, assuming machine starts with Z (similar to LEP-1; LEP-2 start up was much faster)
  - Machine configuration between WPs is changed during winter shutdowns (effective time of about 3 months/year)

IMPLEMENTATION
AND RUN PLAN



"Ampere-class" mach

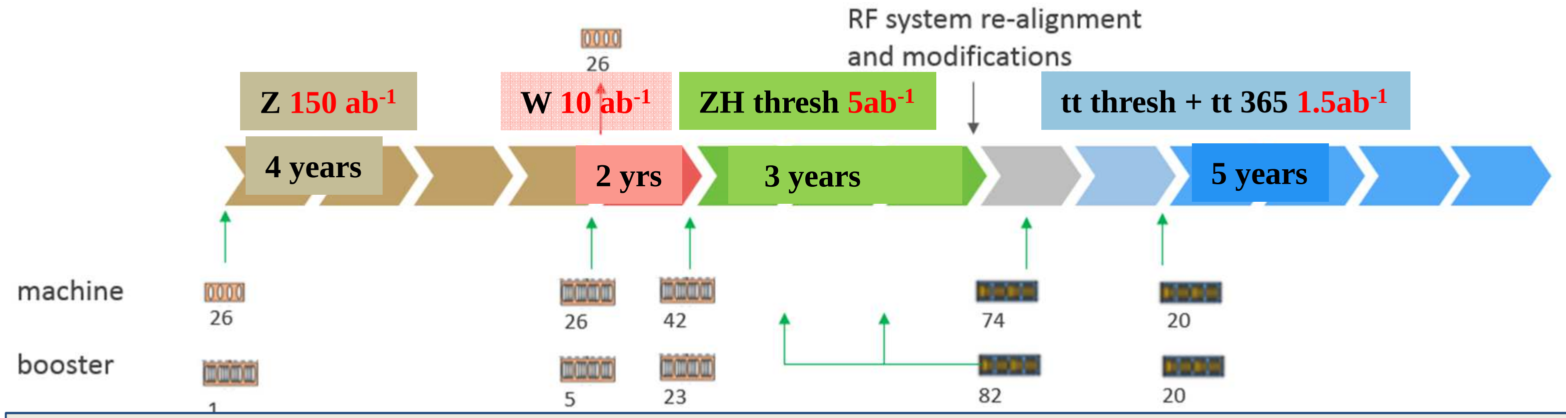
	V_tot (GV)	n_bunch	I_beam (mA)
Z	0.2	91500	1450
W	0.8	5260	152
H	3	780	30
t	10	81	6.6

"high gradient" machine

Three sets of RF cavities for FCCee & Booster:

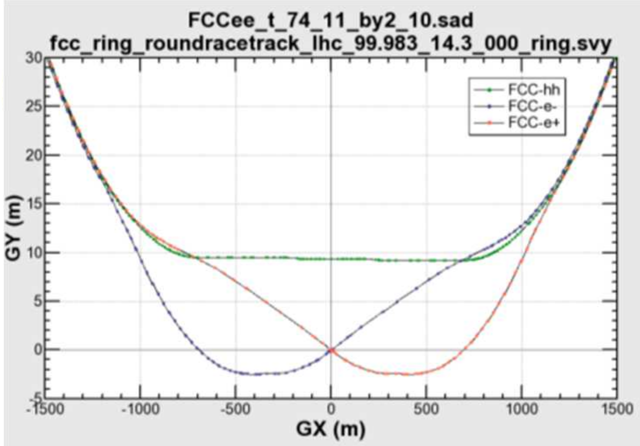
- Installation as LEP (≈30 CM/winter)
- high intensity (Z, FCC-hh): 400 MHz mono-cell cavities, ≈ 1MW source
- high energy (W, H, t): 400 MHz four-cell cavities, also for W machine
- booster and t machine complement: 800 MHz four-cell cavities
- Adaptable 100MW, 400MHz RF power distribution system

➔ Spreads the funding profile

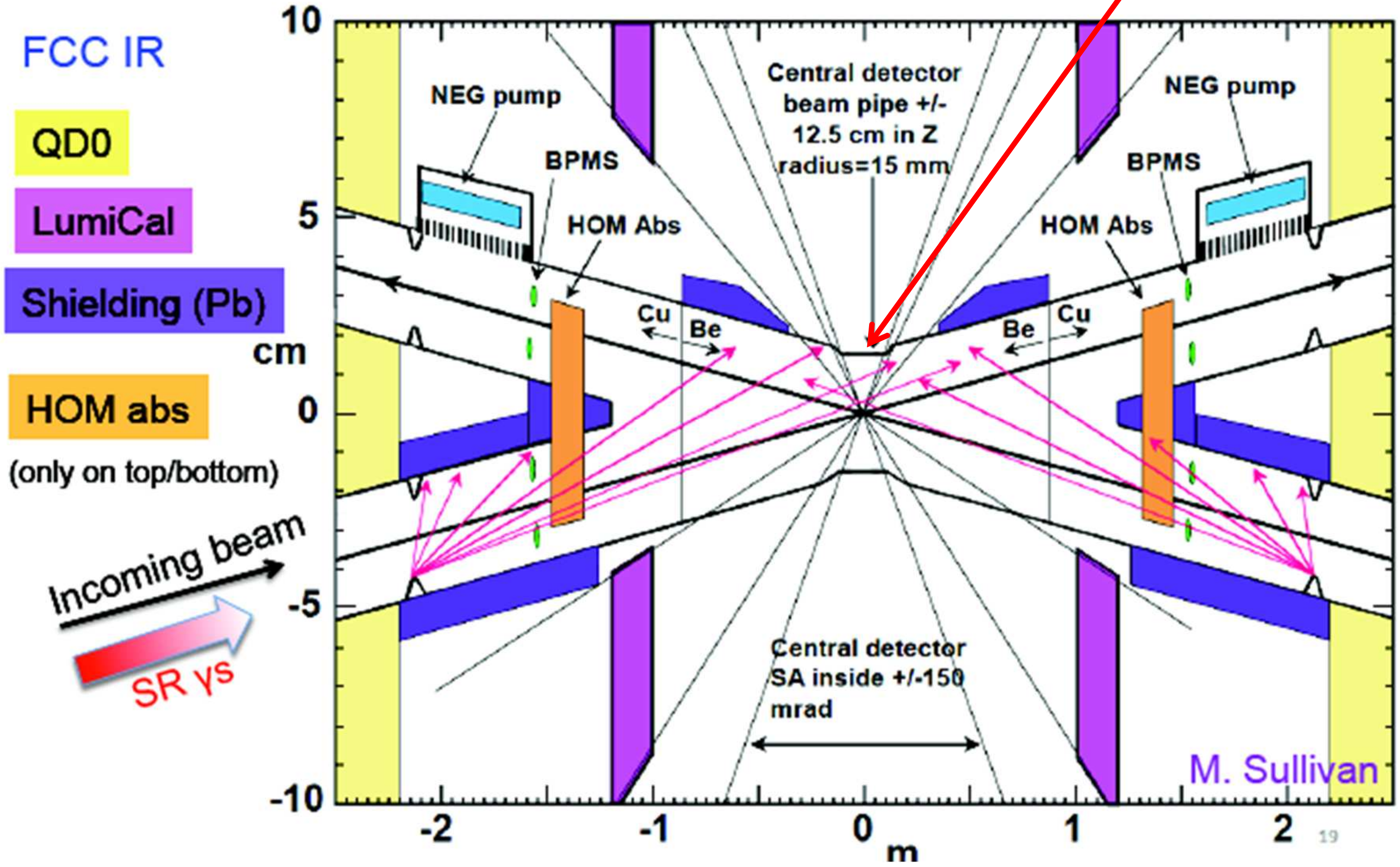


indicative: 2(comm) + 2 2 3 5 **total ~15 years**

Detailed layout of the Interaction Region



Beam pipe radius at IP is 15mm ☺



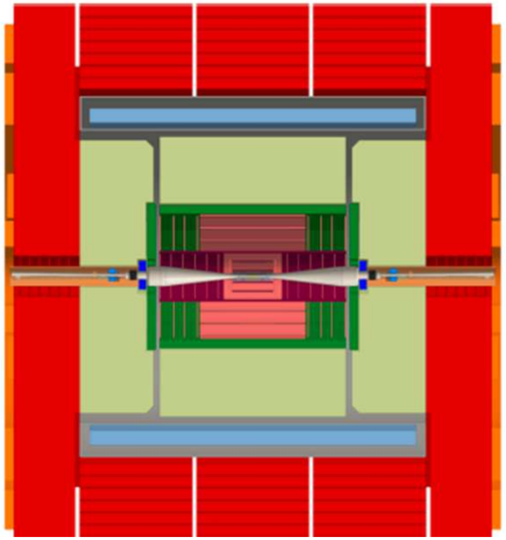
FCC-ee Detectors

Two integration, performance and cost estimates ongoing:

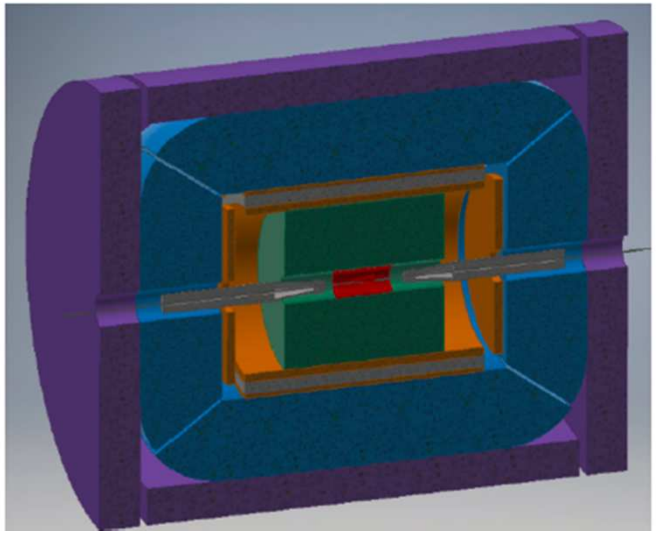
-- Linear Collider Detector group at CERN has undertaken the adaption of CLIC-SID detector for FCC-ee

-- new IDEA, detector specifically designed for FCC-ee (and CEPC)

"CLIC-detector revisited"



"IDEA"

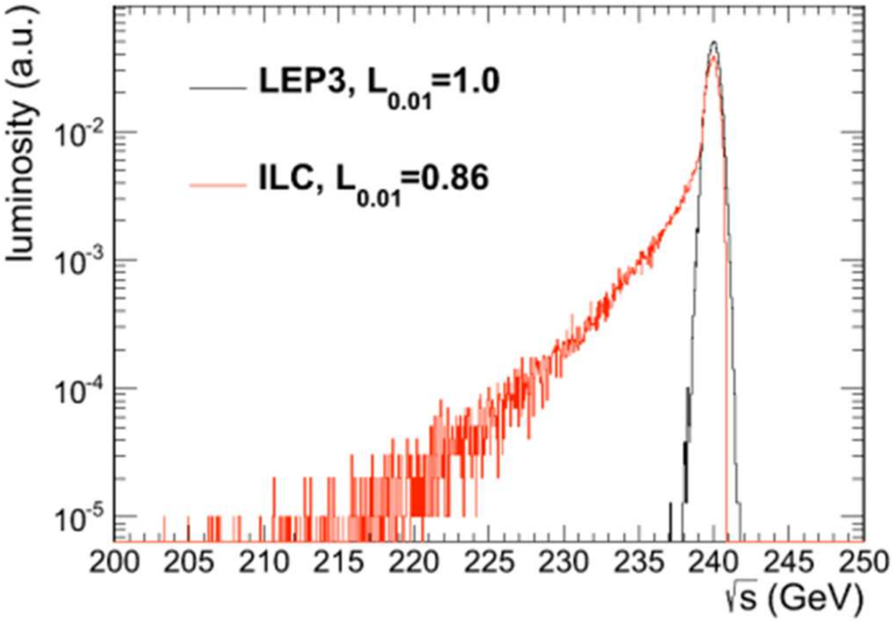


- Vertex detector: ALICE **MAPS**
- Tracking: MEG2
- Si Preshower
- Ultra-thin solenoid (2T)
- Calorimeter: DREAM
- Equipped return yoke

Alain Blondel The FCCs

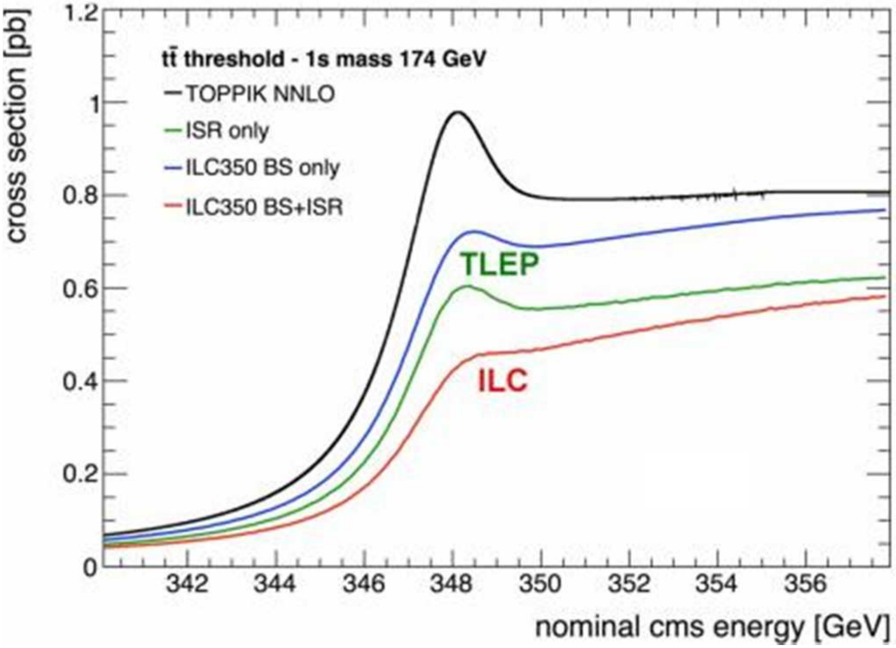
BEAMSTRAHLUNG

Luminosity *E* spectrum



➔

Effect on top threshold



Beamstrahlung @TLEP is benign: particles are either lost or recycled on a synchrotron oscillation

➔ some increase of energy spread
but no change of average energy
Little EM background in the experiment.

FCC-ee discovery potential

Today we do not know how nature will surprise us. A few things that FCC-ee could discover :

EXPLORE 10-100 TeV energy scale (and beyond) with Precision Measurements

-- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass)
$m_{Z,}$ m_W, m_{top} , $\sin^2\theta_w^{eff}$, R_b , α_{QED} (m_z) α_s $(m_z\, m_W\, m_\tau)$, Higgs and top quark couplings

DISCOVER a violation of flavour conservation or universality
-- ex FCNC (Z --> $\mu\tau$, eτ) in 5 10^{12} Z decays.
+ flavour physics (10^{12} bb events) (B→s τ τ etc..)

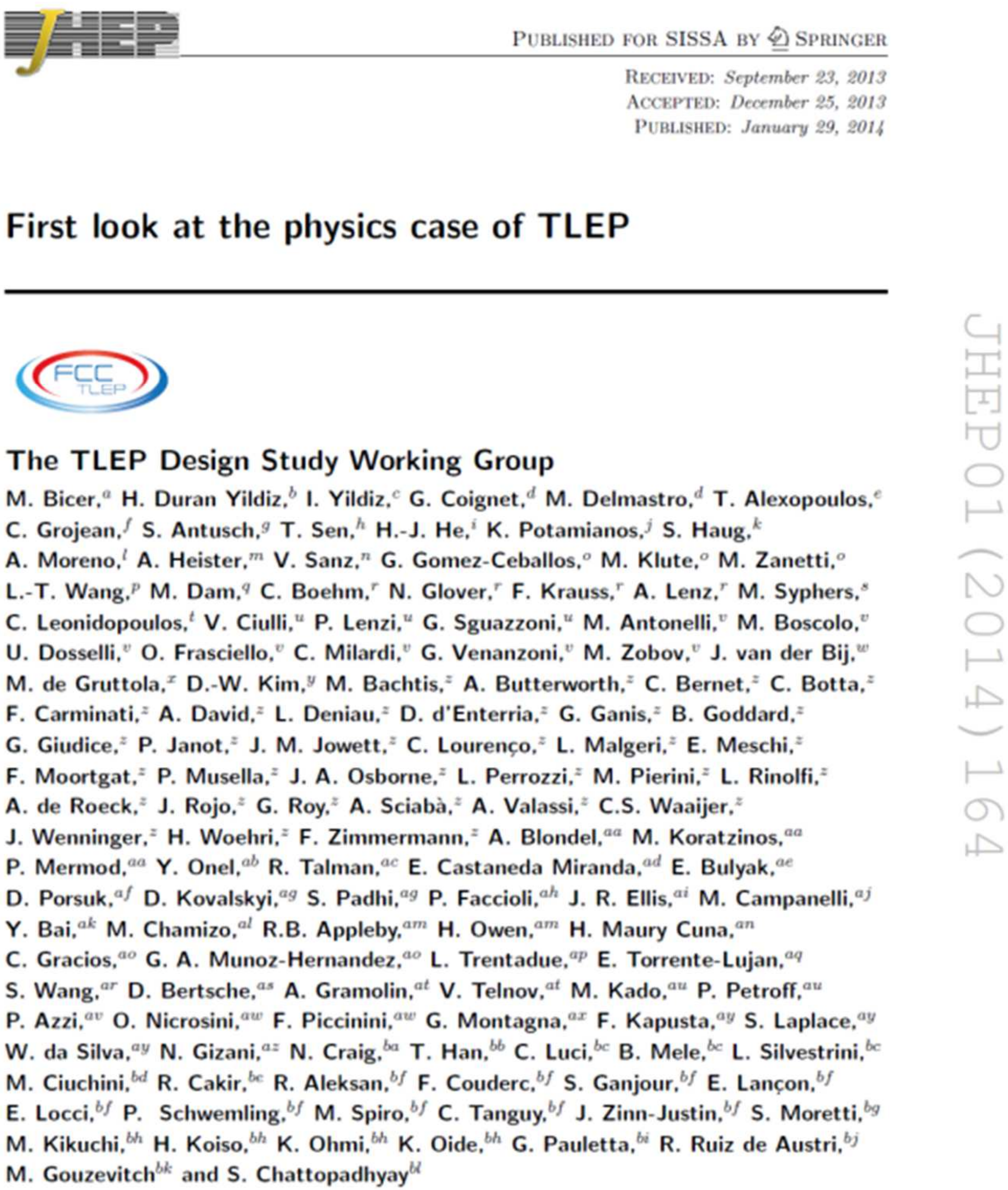
DISCOVER dark matter as «invisible decay» of H or Z or in LHC loopholes.

DISCOVER very weakly coupled particle in 5-100 GeV energy scale
such as: Right-Handed neutrinos, Dark Photons etc…

+ an enormous amount of clean, unambiguous work on QCD etc….

NB the «Z factory» plays an important role in the 'discovery potential'

"First Look at the Physics Case of TLEP", JHEP 1401 (2014) 164,



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

PUBLISHED since 2013
394 citations today

A Sample of Essential Quantities:

X	Physics	Present precision		FCC-ee 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** **± 0.0002**	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** **<0.5 MeV**	E_cal & Statistics	Backgrounds, QED/EW
m_{top} MeV/c2	**Input**	173340 ± 760	Threshold scan	**10 MeV**	E_cal & Statistics	Theory limit at 50 MeV?

Beam Polarization and Energy calibration

Difference between circular and linar machines.

First priority is to achieve transverse polarization for precision energy calibration in a way that allows continuous beam calibration by resonant depolarization (energy measurement every ~10 minutes on 'monitoring' single bunches)

- This is a unique feature of circular e+e- colliders

- baseline running scheme defined with monitoring bunches, wigglers, polarimeter

- the question of the residual systematic error requires further studies of the relationship between spin tune, beam energy at IRs, and center-of-mass energy

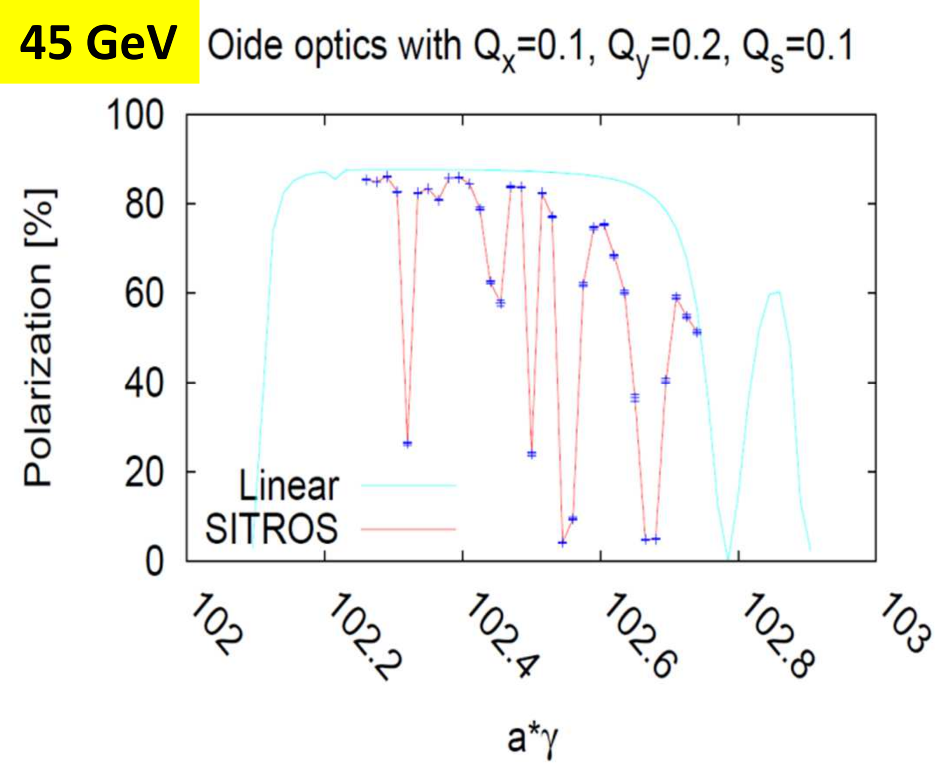
➔ target is O(±100keV) at Z and W pair threshold energies (averaged over data taking)

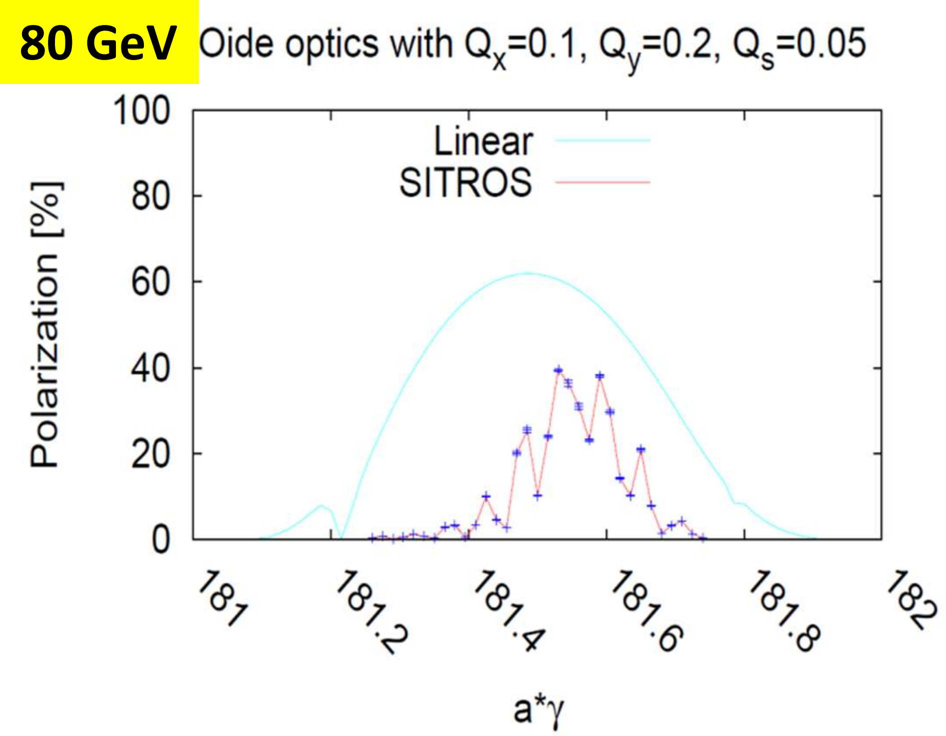
longitudinal polarization?

lower priority

at Z, W, top: no information that we cannot obtain otherwise
from unpolarized A_{FB} asymmetries or final state polarization (top, tau)
+ too much loss of luminosity in present running scheme to provide gain in precision.

Beam Polarization and Energy calibration





At the Z obtain excellent polarization level but too slow for polarization in physics need wigglers for Energy calibration – OK as long as σ_{Eb}< ~55 MeV

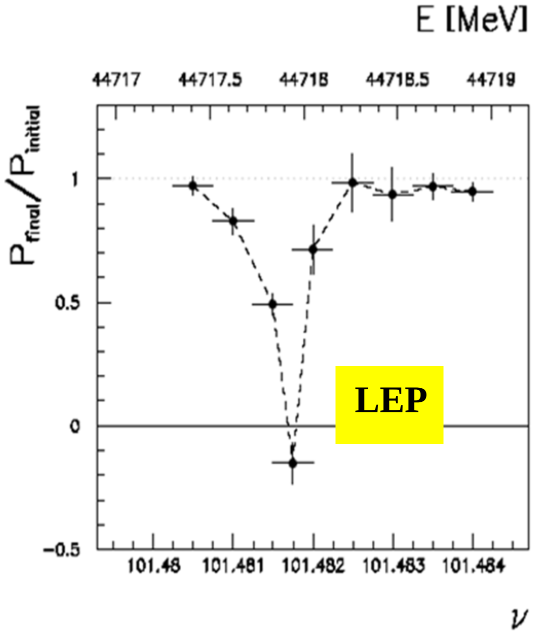
$\sigma_{Eb} \propto E_b^2/\rho$

At the W expectation similar to LEP at Z → enough for energy calibration

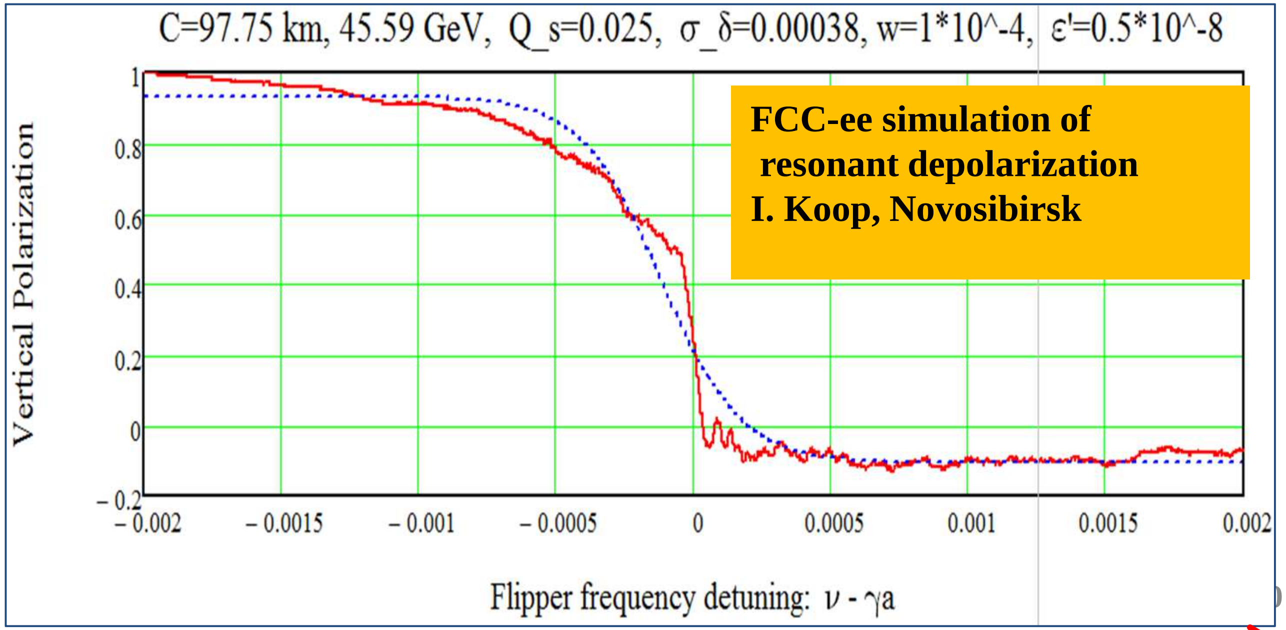
Simulations by Eliana Gianfelice

FCC-ee Beam Polarization and Energy Calibration (I)

1. Priority from Physics : $\Delta E/E \sim O(10^{-6})$ around Z pole and WW threshold → Z,W mass&width
2. Exploit natural transverse beam polarization present at Z and W (E.Gianfelice, S.Aumon)
    - 2.1 This is a unique capability of e+e- circular colliders
    - 2.2 Sufficient level is obtained if machine alignment is good enough for luminosity
    - 2.2 Resonant depolarization has intrinsic stat. precision of ~10^{-6} on spin tune (I.Koop)
    - 2.3 Required hardware (polarimeter, wigglers depolarizer) is defined & integrated (K.Oide)
    - 2.4 Running mode with 1% non-colliding bunches and wigglers defined (Koratzinos)



LEP



FCC-ee simulation of resonant depolarization
I. Koop, Novosibirsk

260 seconds sweep of depolarizer frequency

FCC-ee Beam Polarization and Energy Calibration (II)

3. From spin tune measurement to center-of-mass determination $\nu_s = \frac{g-2}{2}\frac{E_b}{m_e} = \frac{E_b}{0.4406486(1)}$

3.1 Synchrotron Radiation energy loss (9 MeV @Z in 4 ‘arcs’) calculable to < permil accuracy

3.3. Beamstrahlung energy loss (0.62 MeV per beam at Z pole), compensated by RF (Shatilov)

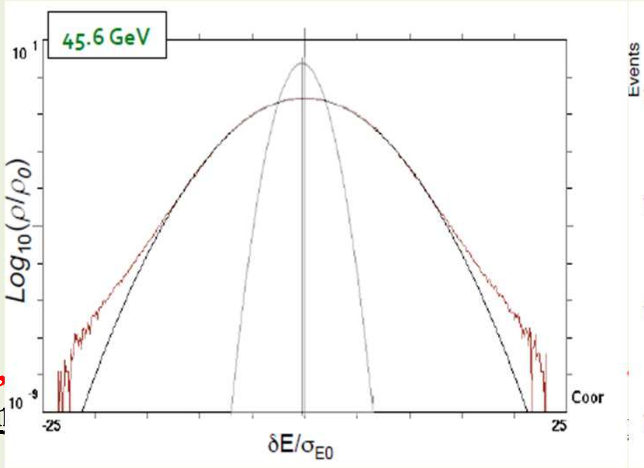
3.4 layout of accelerator with IPs between two arcs well separated from RF

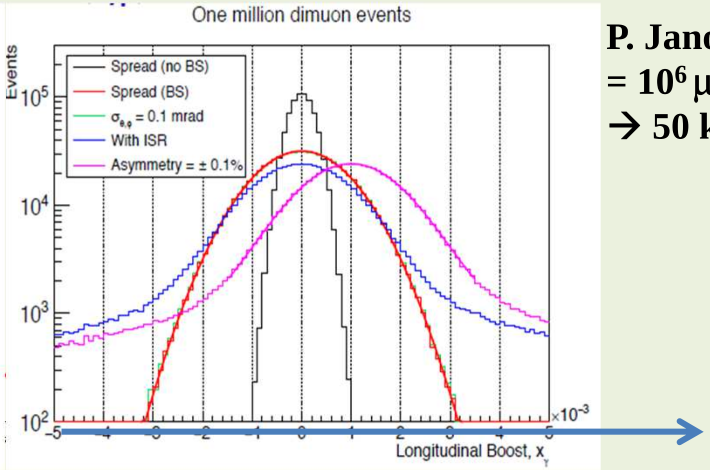
➔ $0.5\,(E_{CM}{}^{A} + E_{CM}{}^{G}) = (E_b{}^{+} + E_b{}^{-})\cos(\alpha_{crossing}/2)$

3.5 $E_b{}^{+}$ **vs** $E_b{}^{-}$ **asymmetries and energy spread can be measured/monitored in expt:**

e+e- → μ+ μ- longitudinal momentum shift and spread (Janot)

D. Shatilov:
beam energy
spectrum
without/with
beamstrahlung





z boost

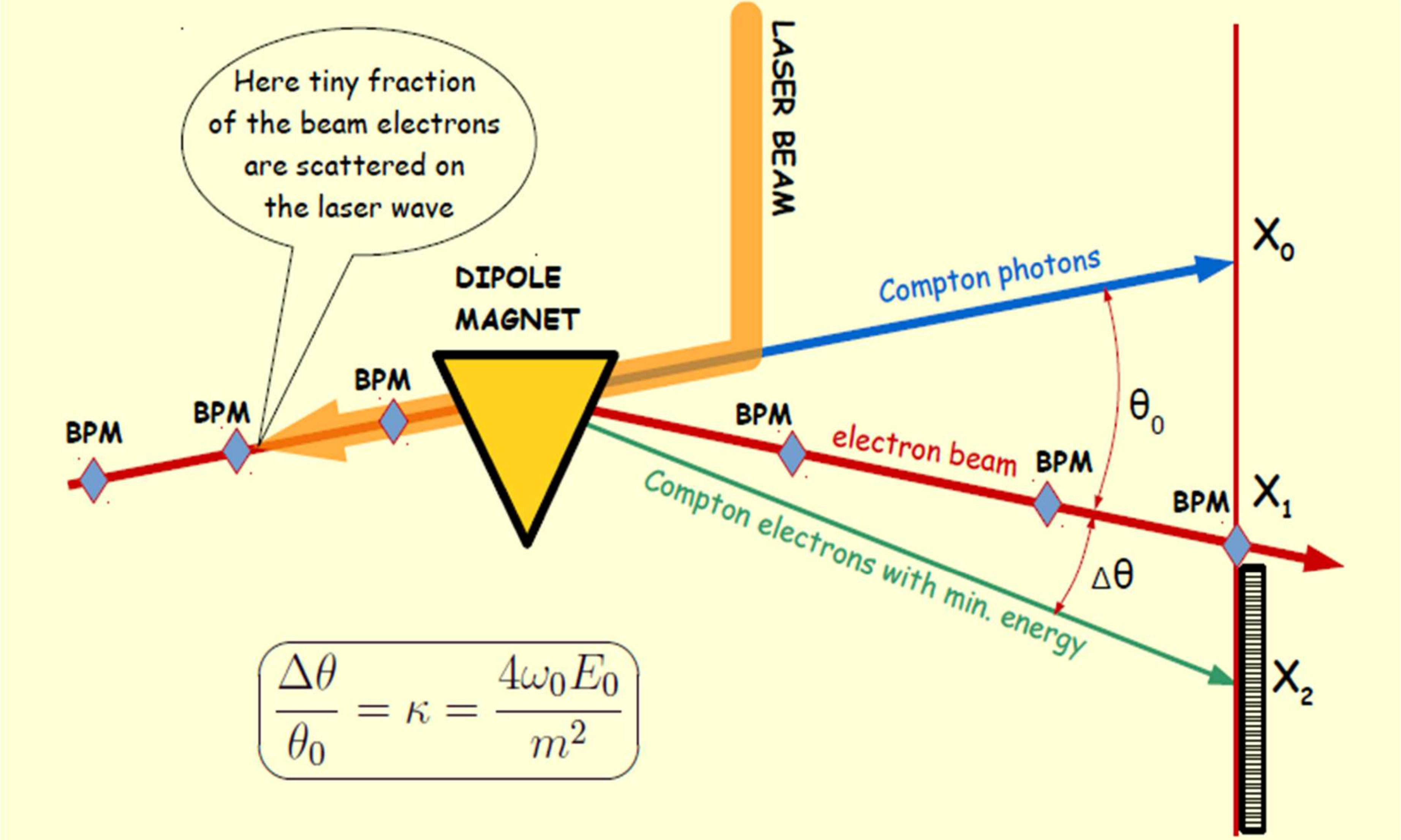
P. Janot: 2 min @Z
= 10^6 μ+ μ- /expt.
➔ 50 keV meast!

4. work in progress:

RF asymmetries,

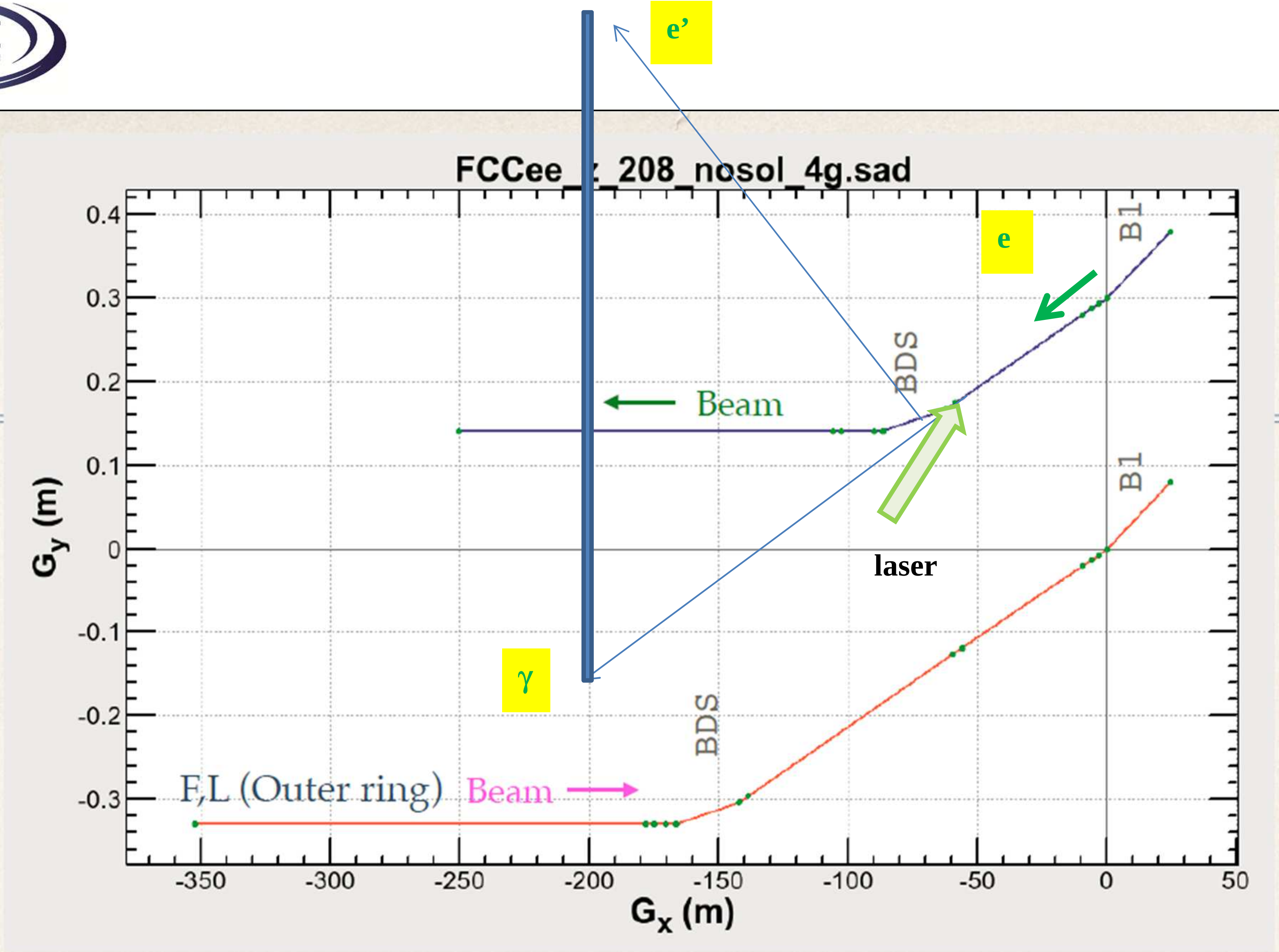
➔ On track to m

Polarimeter



$$\frac{\Delta\theta}{\theta_0} = \kappa = \frac{4\omega_0 E_0}{m^2}$$

N. Muchnoi



The dispersion suppressor dipole (BDS):

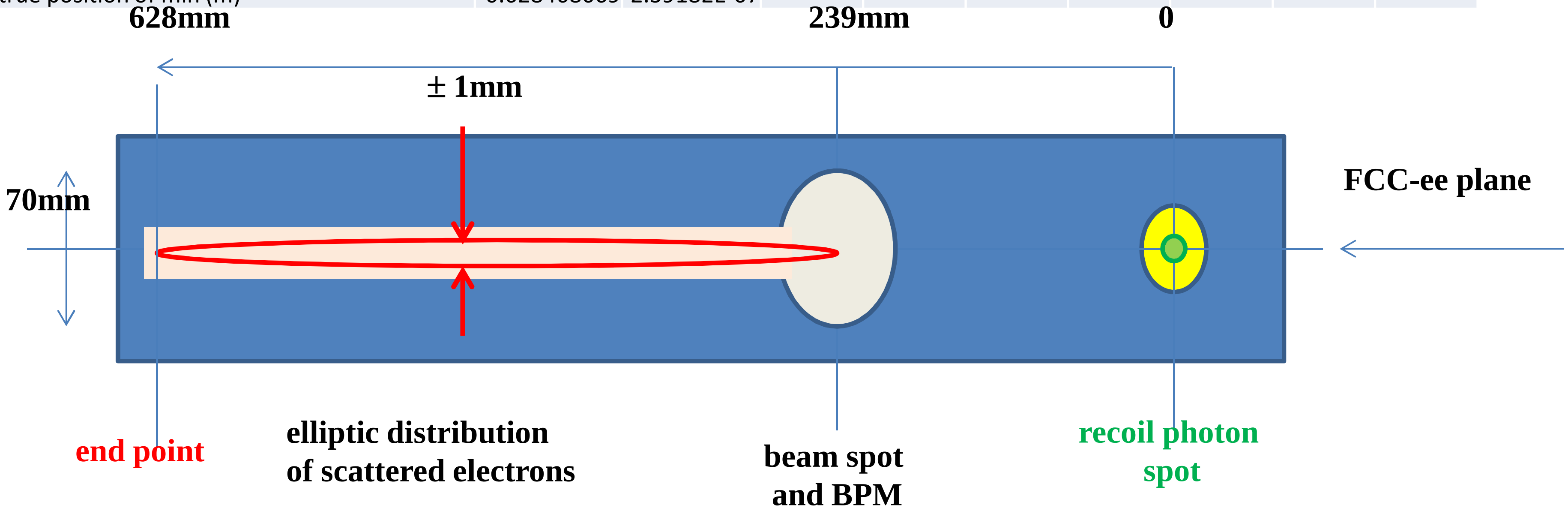
```
;
 BEND    BDS      =(L =24.119925292770883  ANGLE =.002134100603580931    E1 =.5    E2 =.5 )
```

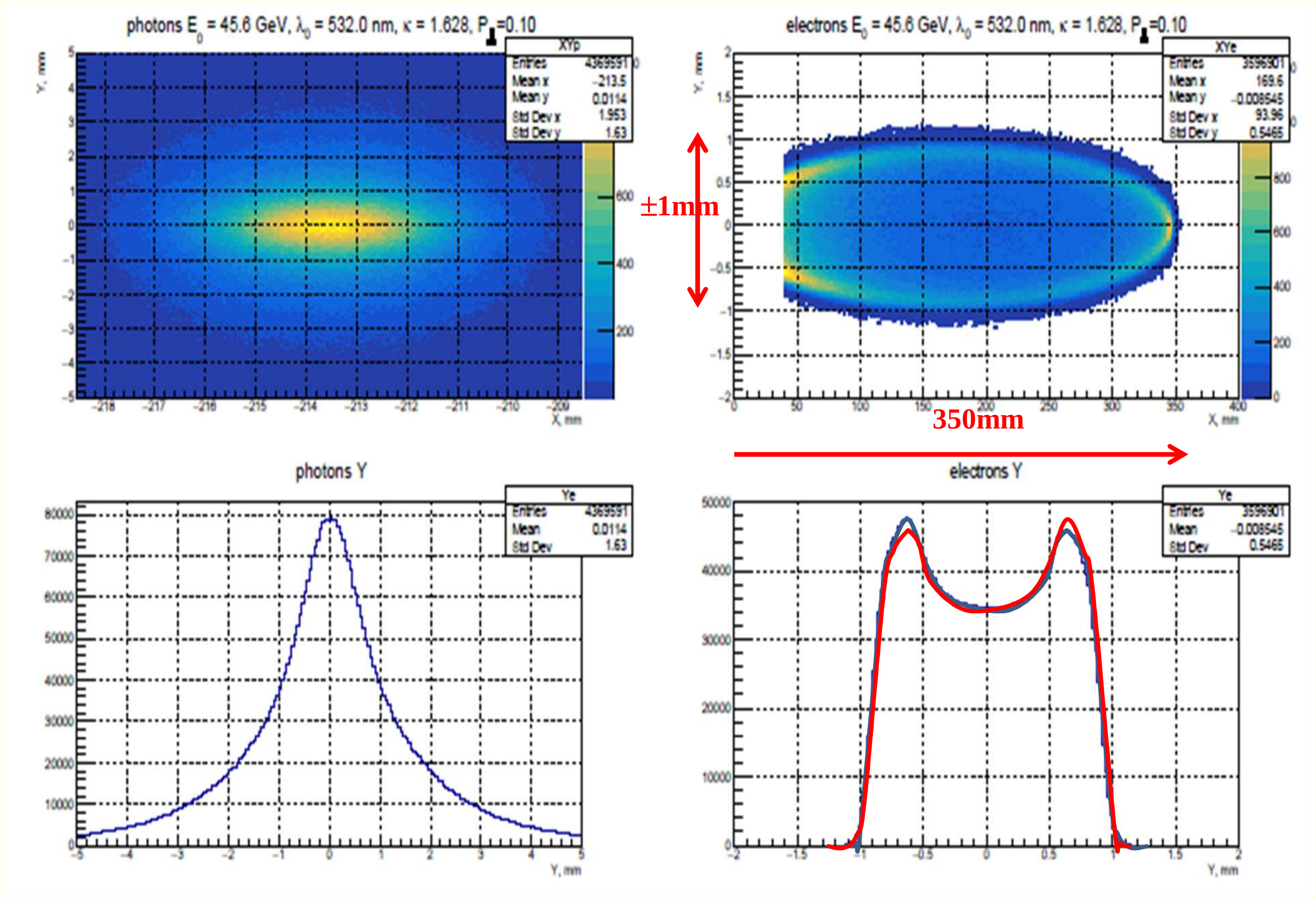
polarimeter-spectrometer situated 100m from end of dipole.

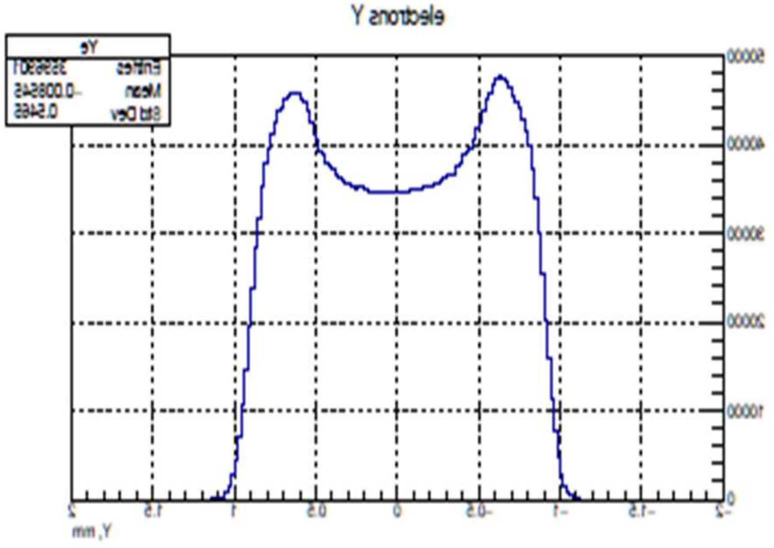
Using the dispersion suppressor dipole with a lever-arm of 100m from the end of the dipole, one finds
-- minimum compton scattering energy at 45.6 GeV is 17.354 GeV
-- distance from photon recoil to Emin electron is 0.628m

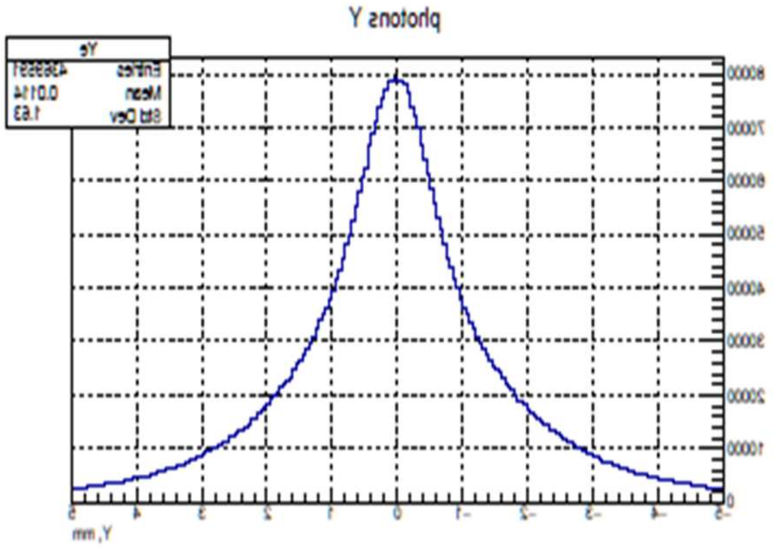
	laser (eV)	beam (GeV)	mc2(MeV)	B field	R	LM	theta	L	true beam
	2.33	45.6	0.511	0.013451	11300	24.119	0.002134	100	45.60005
nominal kappa = 4. E_laser.Ebeam_nom/mc2	1.627567296								
true kappa = 4. E_laser.Ebeam_true/mc2	1.627568924								
nominal Emin	17.35445561								
true Emin	17.35446221								
position of photons	0								
nominal position of beam (m)	0.239182573								
true position of beam (m)	0.239182334	2.39182E-07							
nominal position of min (m)	0.628468308								
true position of min (m)	0.628468069	2.39182E-07							

mouvement of beam and end point are the same:
0.24microns for δEb/Eb=10^{-6} (δEb=45keV)




photons E_0 = 45.6 GeV, λ_0 = 532.0 nm, κ = 1.628, $P_\perp$=0.10
XYp
Entries 4369591
Mean x -213.5
Mean y 0.0114
Std Dev x 1.953
Std Dev y 1.63
Y, mm
X, mm
-218 -217 -216 -215 -214 -213 -212 -211 -210 -209
-5 -4 -3 -2 -1 0 1 2 3 4 5
200 400 600
electrons E_0 = 45.6 GeV, λ_0 = 532.0 nm, κ = 1.628, $P_\perp$=0.10
XYe
Entries 3596901
Mean x 169.6
Mean y -0.008545
Std Dev x 93.96
Std Dev y 0.5465
Y, mm
X, mm
0 50 100 150 200 250 300 350 400
-2 -1.5 -1 -0.5 0 0.5 1 1.5 2
0 200 400 600 800
±1mm
350mm
photons Y
Ye
Entries 4369591
Mean 0.0114
Std Dev 1.63
Y, mm
0 10000 20000 30000 40000 50000 60000 70000 80000
-5 -4 -3 -2 -1 0 1 2 3 4 5
electrons Y
Ye
Entries 3596901
Mean -0.008545
Std Dev 0.5465
Y, mm
0 10000 20000 30000 40000 50000
-2 -1.5 -1 -0.5 0 0.5 1 1.5 2





it is expected that beam polarization can be measured to P ± 1% (absolute)
in a few seconds. (if the level is 5%, this is 5σ). To be verified with improved fitter (Nickolai)

From resonant depolarization to Center-of-mass energy

I. from spin tune to beam energy $\nu_s = \frac{g-2}{2}\frac{E_b}{m_e} = \frac{E_b}{0.4406486(1)}$

The spin tune may not be en exact measurement of the average of the beam energy along the magnetic trajectory of particles. Additional spin rotations may create biases. Anton Bogomyagkov and Eliana Gianfelice made some estimates.

synchrotron oscillations $\Delta E/E$ $-2\ 10^{-14}$

Energy dependent momentum compaction $\Delta E/E$ 10^{-7}

Solenoid compensation $2\ 10^{-11}$

Horizontal betatron oscillations $\Delta E/E$ $2.5\ 10^{-7}$

Vertical betatron oscillations (new, W.I.P. $\Delta E/E$ $2.7\ 10^{-6}\ (\sigma_z\ [\mathrm{mm}])^2$ ➔ $\sigma_z \sim 0.1\mathrm{mm}$

Horizontal correctors $\Delta E/E$ $2.5\ 10^{-6}$

if horizontal orbit change by >0.8mm between calibrations is unnoticed

or if quadrupole stability worse than 5 microns over that time.

Uncertainty in chromaticity correction $O(10^{-6}\ \ \pm 510^{-8}$

invariant mass shift due to beam potential $4\ 10^{-10}$

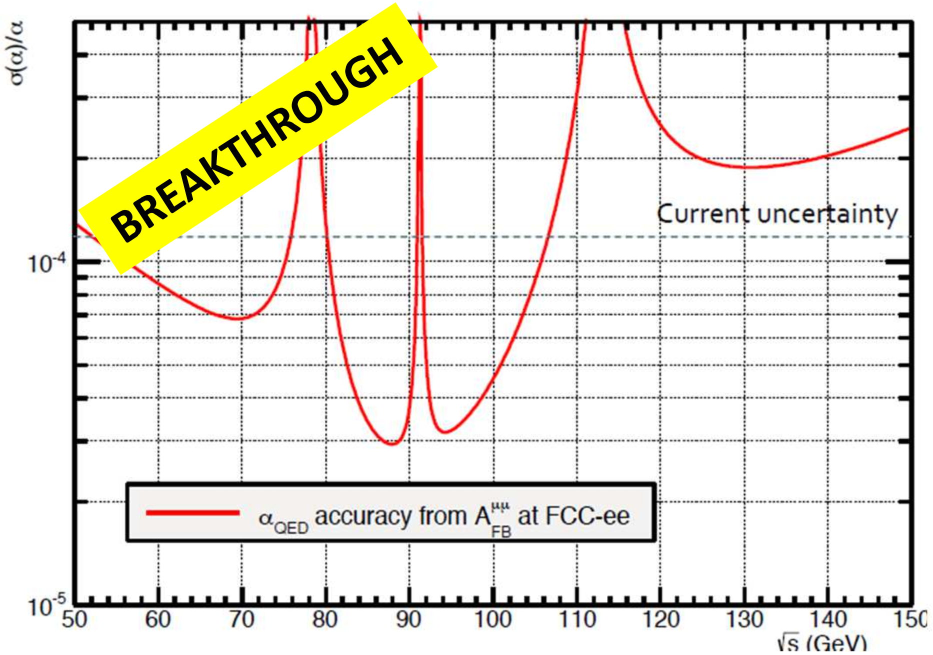
LHC:

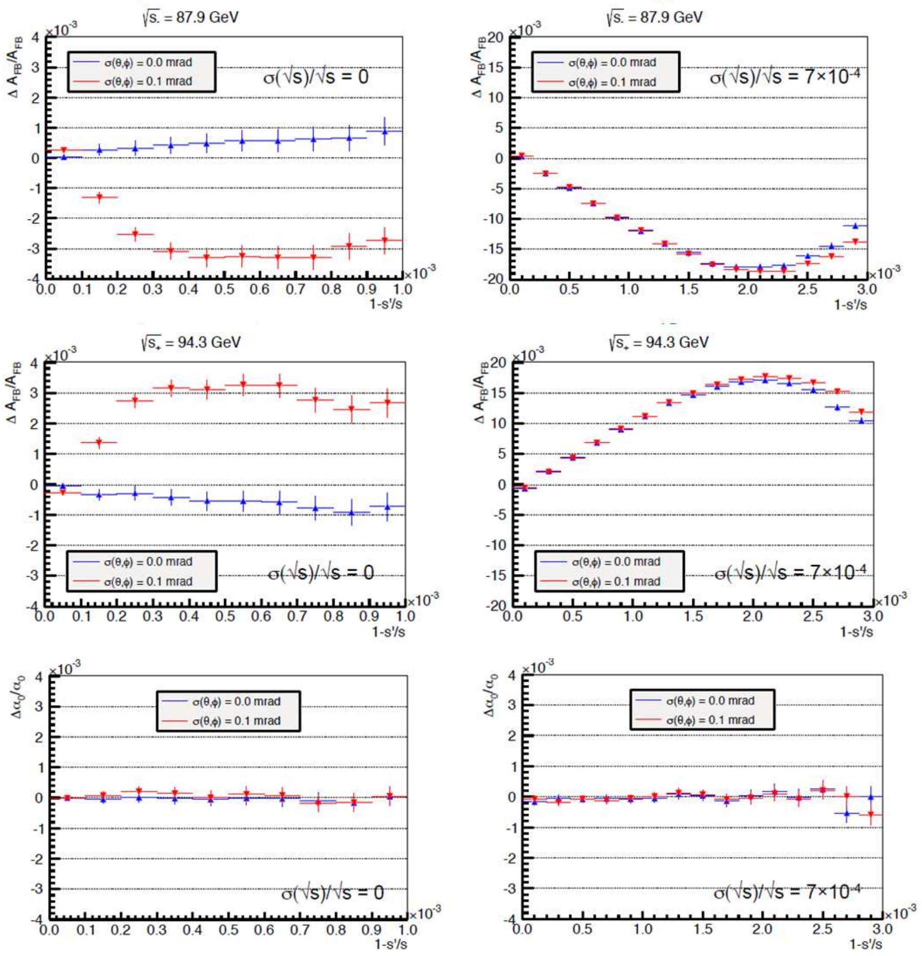
several of these effects are of statistical nature and will cancel with O(100) calibrations per day.

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

Unwanted error

Physics discoveries





- Total bias on $\alpha_{QED}(m_Z^2)$ of the order of 8×10^{-6}

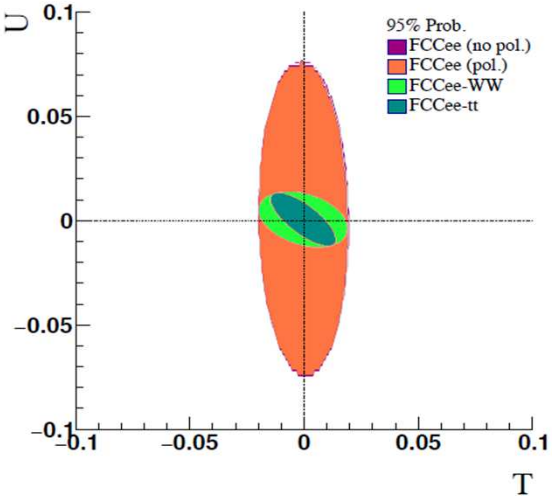
P. Janot discovered that one can measure $\Delta\alpha_{QED}(m_z)$ from measuring $A_{FB}^{\mu\mu}$ at +- 3 GeV from the Z peak. (Nice Z lineshape scan)

Further studies with S. Jadach shows error cancellation of +3 vs -3 points.

DO WE NEED LONGITUDINAL POLARIZATION?

A.Blondel

	$A_{FB}^{\mu\mu}$ @ FCC-ee		A_{LR} @ ILC
visible Z decays	10^{12}	visible Z decays	10^{9}
muon pairs	10^{11}	beam polarization	90%
$\Delta A_{FB}^{\mu\mu}$ (stat)	$3\ 10^{-6}$	ΔA_{LR} (stat)	$4.2\ 10^{-5}$
ΔE_{cm} (MeV)	0.1		2.2
$\Delta A_{FB}^{\mu\mu}$ (E_{CM})	$9.2\ 10^{-6}$	ΔA_{LR} (E_{CM})	$4.1\ 10^{-5}$
$\Delta A_{FB}^{\mu\mu}$	$1.0\ 10^{-5}$	ΔA_{LR}	$5.9\ 10^{-5}$
$\Delta \sin^2\theta^{lept}_W$	$5.9\ 10^{-6}$		$7.5\ 10^{-6}$



J. De Blas

from $A_{FB}^{\mu\mu}$ LEP 2.10^7Z SLC, 5.10^5 Z $\Delta\alpha$= 0.00035 $\Delta\alpha$= 0.00003

$\Delta \sin^2\theta^{lept}_W$ $5.3\ 10^{-4}$ $2.6\ 10^{-4}$ $1.2\ 10^{-4}$ $1.\ 10^{-5}$

W.A. $1.6\ 10^{-4}$

All exceeds the limitation given by $\Delta\alpha(m_Z)$ (310^{-5}) or the needed precision for comparison with m_W (500keV)

But this precision on $\Delta \sin^2\theta^{lept}_W$ can only be exploited at FCC-ee!

At FCC-ee longitudinal polarization is more difficult and implies a significant reduction of luminosity. As far as we can tell today it is not justified

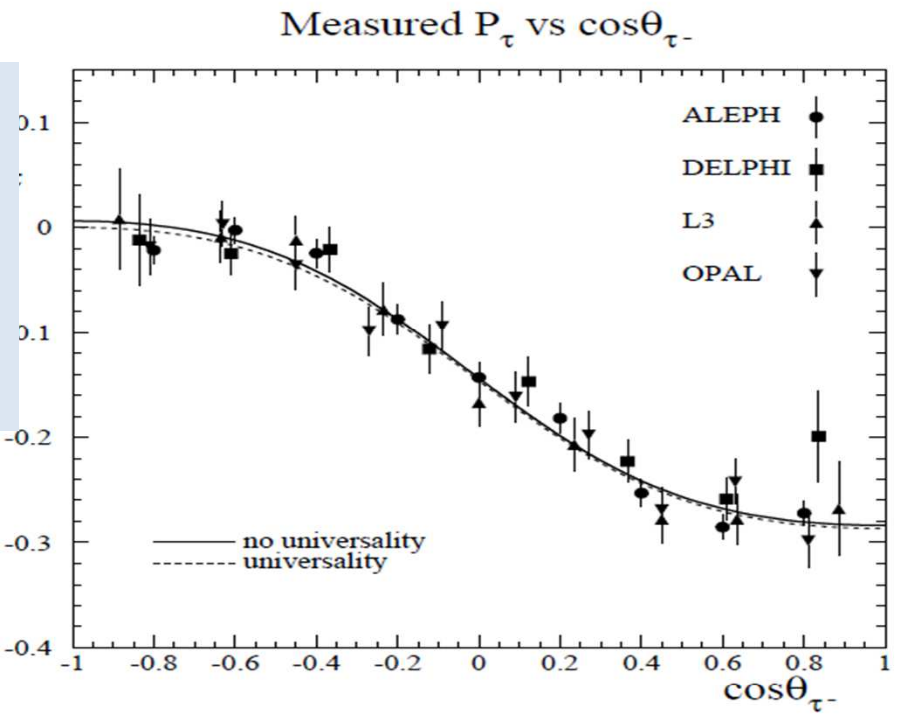
(similar conclusion by J. De Blas in pheno session)

The forward backward tau polarization asymmetry is very clean.
Dependence on E_{CM} same as A_{LR} negl.
At FCC-ee

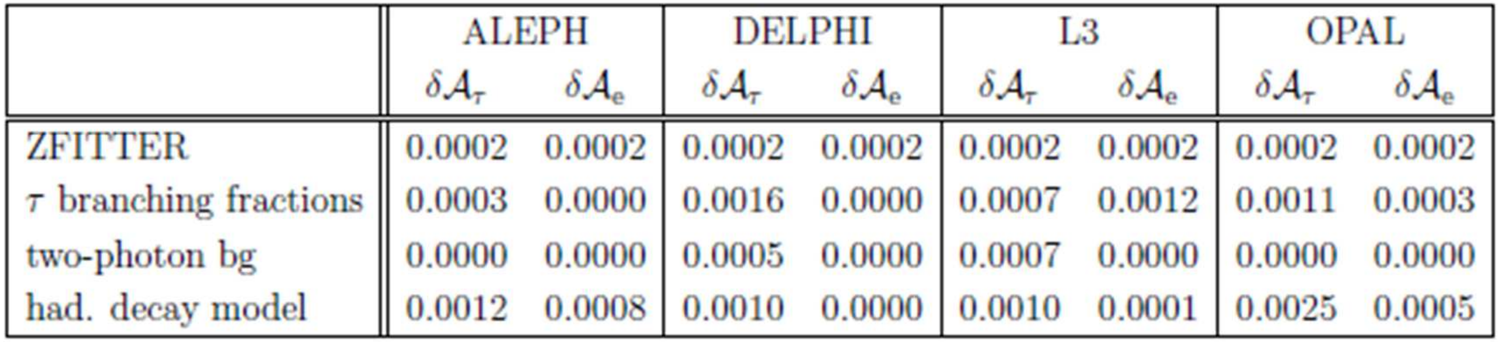
ALEPH data 160 pb^{-1} (80 s @ FCC-ee !)

Already syst. level of 610^{-5}on $\sin^2\theta_W$

much improvement possible
by using dedicated selection
e.g. tau→ π v to avoid had. model



ure 4.7: The values of $\mathcal{P}_\tau$ as a function of $\cos\theta_{\tau^-}$ as measured by each of the LEP experiments. Only the statistical errors are shown. The values are not corrected for radiation, interference or pure photon exchange. The solid curve overlays Equation 4.2 for the LEP values of $\mathcal{A}_\tau$ and $\mathcal{A}_e$. The dashed curve overlays Equation 4.2 under the assumption of lepton universality for the LEP value of $\mathcal{A}_\ell$.



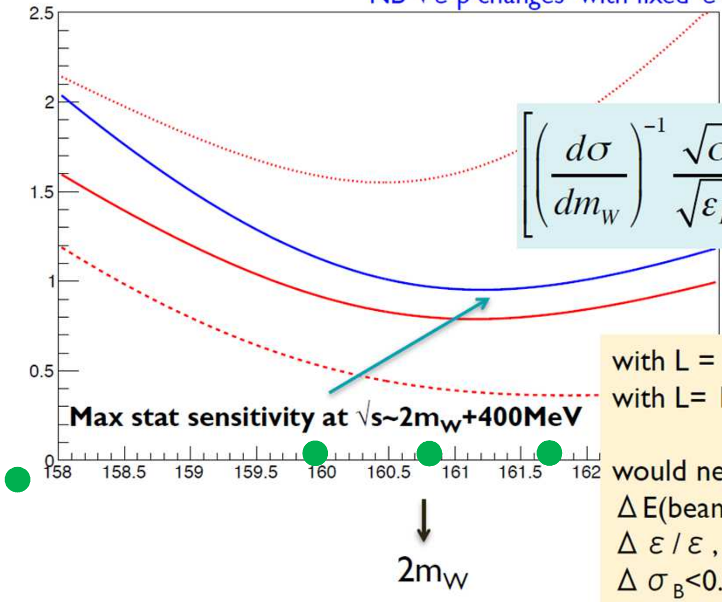
	ALEPH		DELPHI		L3		OPAL	
	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$
ZFITTER	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
τ branching fractions	0.0003	0.0000	0.0016	0.0000	0.0007	0.0012	0.0011	0.0003
two-photon bg	0.0000	0.0000	0.0005	0.0000	0.0007	0.0000	0.0000	0.0000
had. decay model	0.0012	0.0008	0.0010	0.0000	0.0010	0.0001	0.0025	0.0005

Table 4.2: The magnitude of the major common systematic errors on $\mathcal{A}_\tau$ and $\mathcal{A}_e$ by category for each of the LEP experiments.

m_W from σ_{WW}

P. Azzuri started optimizing
The W threshold scan
for measurement of
m_W and Γ_W
Smooth, plenty of points
with half integer spin tunes ●

NB $\sqrt{\varepsilon}$ p changes with fixed ε =0.75 and σ_B=0.3pb



Max stat sensitivity at $\sqrt{s}$~$2m_W$+400MeV

$$\left[\left(\frac{d\sigma}{dm_W}\right)^{-1}\frac{\sqrt{\sigma}}{\sqrt{\varepsilon p}}\right]_{\min}\approx 0.95\frac{GeV}{pb^{1/2}}$$

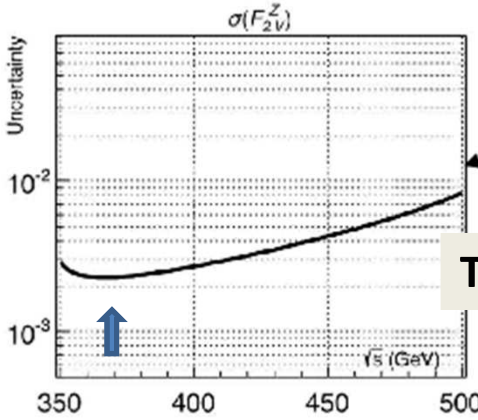
with L = 11/pb ➔ Δ mw≈380MeV
with L= 15/ab ➔ Δ mw≈0.25 MeV

would need
Δ E(beam)<0.25 MeV (3x10-6)
Δ ε / ε , Δ L/L < 10-4
Δ σ_B<0.5 fb (10-3)

Statistical error on m_W will be O(300 keV)
next: background and *signal* cross-sections!

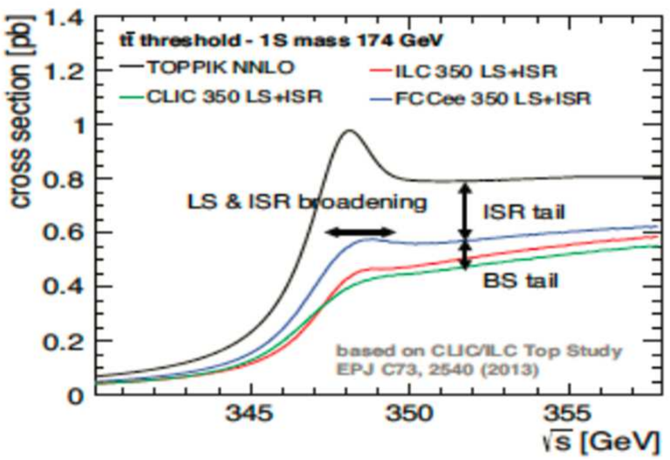
Top physics

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



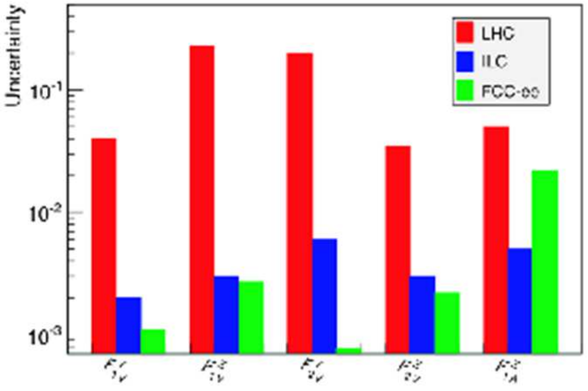
Typically best sensitivity just above production threshold

Top beam energy is 185 GeV



Top mas can be measured to O(10 MeV)
Beam energy calibration from WW, γZ, ZZ
Reduce th. errors due α_S meast @FCC-ee

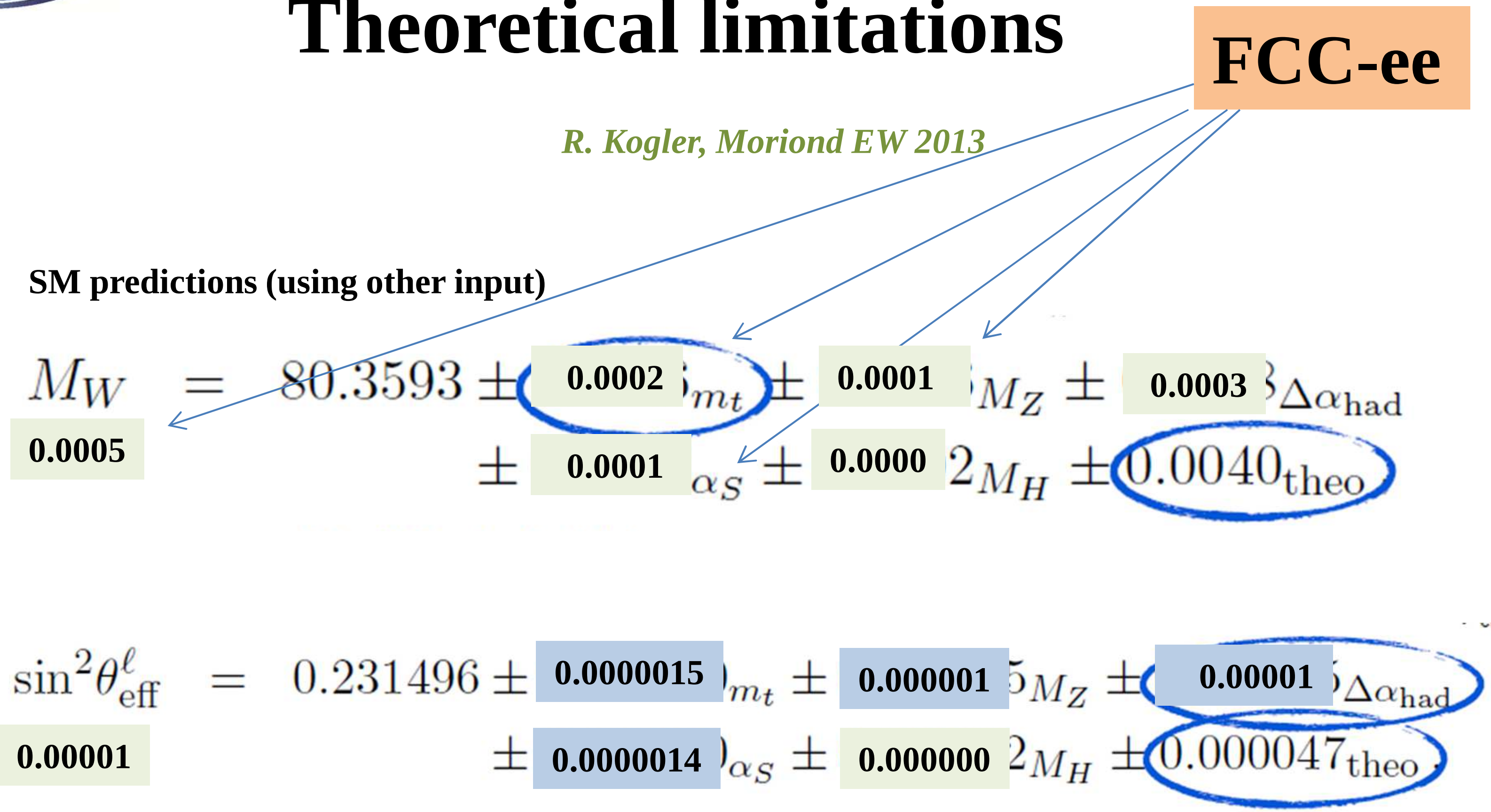
Also:
CKM measurements
FCNC decays down to 10^{-6}
All luminosity can be used!



Patrick Janot
arXiv:1503.01325v2

beam polarization is not necessary here.

Theoretical limitations



FCC-ee

R. Kogler, Moriond EW 2013

SM predictions (using other input)

$$M_W = 80.3593 \pm 0.0002_{m_t} \pm 0.0001_{M_Z} \pm 0.0003_{\Delta\alpha_{\rm had}} \pm 0.0001_{\alpha_S} \pm 0.0000\,2_{M_H} \pm 0.0040_{\rm theo}$$

0.0005

$$\sin^2\theta^{\ell}_{\rm eff} = 0.231496 \pm 0.0000015_{m_t} \pm 0.000001\,5_{M_Z} \pm 0.00001_{\Delta\alpha_{\rm had}} \pm 0.0000014_{\alpha_S} \pm 0.000000\,2_{M_H} \pm 0.000047_{\rm theo}$$

0.00001

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 in 2015 and precision calculation workshop in January 2018 stressed the need for 3 loop calculations for the future!
Will include manpower for theoretical calculations in the project cost.
There is no reason to doubt that the FCC-ee precision will be limited by theoretical calculations.

100 TeV

FCC-hh discovery potential
Highlights

FCC-hh is a HUGE discovery machine (if nature …), but not only.

FCC-hh physics is dominated by three features:

-- Highest center of mass energy –> a big step in high mass reach!

ex: strongly coupled new particle up to 50 TeV

Excited quarks, Z', W', up to ~tens of TeV

Give the final word on natural Supersymmetry, extra Higgs etc.. reach up to 5-20 TeV

Sensitivity to high energy phenomena in e.g. WW scattering

-- HUGE production rates for single and multiple production of SM bosons (H,W,Z) and quarks

- **-- Higgs precision tests using ratios to e.g. $\gamma\gamma/\mu\mu/\tau\tau/ZZ$, ttH/ttZ @% level**
- **-- Precise determination of triple Higgs coupling (~3% level) and quartic Higgs coupling**
- **-- detection of rare decays $H \rightarrow V\gamma$ ($V= \rho,\varphi,J/\psi,\Upsilon,Z\ldots$)**
- **-- search for invisibles (DM searches, RH neutrinos in W decays)**
- **-- renewed interest for long lived (very weakly coupled) particles.**
- **-- rich top and HF physics program**

-- Cleaner signals for high Pt physics

- **-- allows clean signals for channels presently difficult at LHC (e.g. $H \rightarrow bb$)**

PHYSICS COMPLEMENTARITY

Some examples

Higgs Physics -- ee → ZH fixes Higgs width and HZZ coupling , (and many others)
-- FCC-hh gives huge statistics of HH events for Higgs self-coupling

Search for Heavy Physics
-- ee gives precision measurements (m_Z m_W to < 0.5 MeV, m_{top} 10 MeV, etc…)
sensitive to heavy physics up to … 100 TeV
-- FCC-hh gives access to direct observation at unprecedented energies
Also huge statistics of Z,W and top → rare decays

QCD -- ee gives $\alpha_s \pm 0.0002$ (R_{had})
also H→gg events (gluon fragmentation!)
-- ep provides tructure functions and $\alpha_s \pm 0.0002$
-- all this improves the signal and background predictions
for new physics signals at FCC-hh

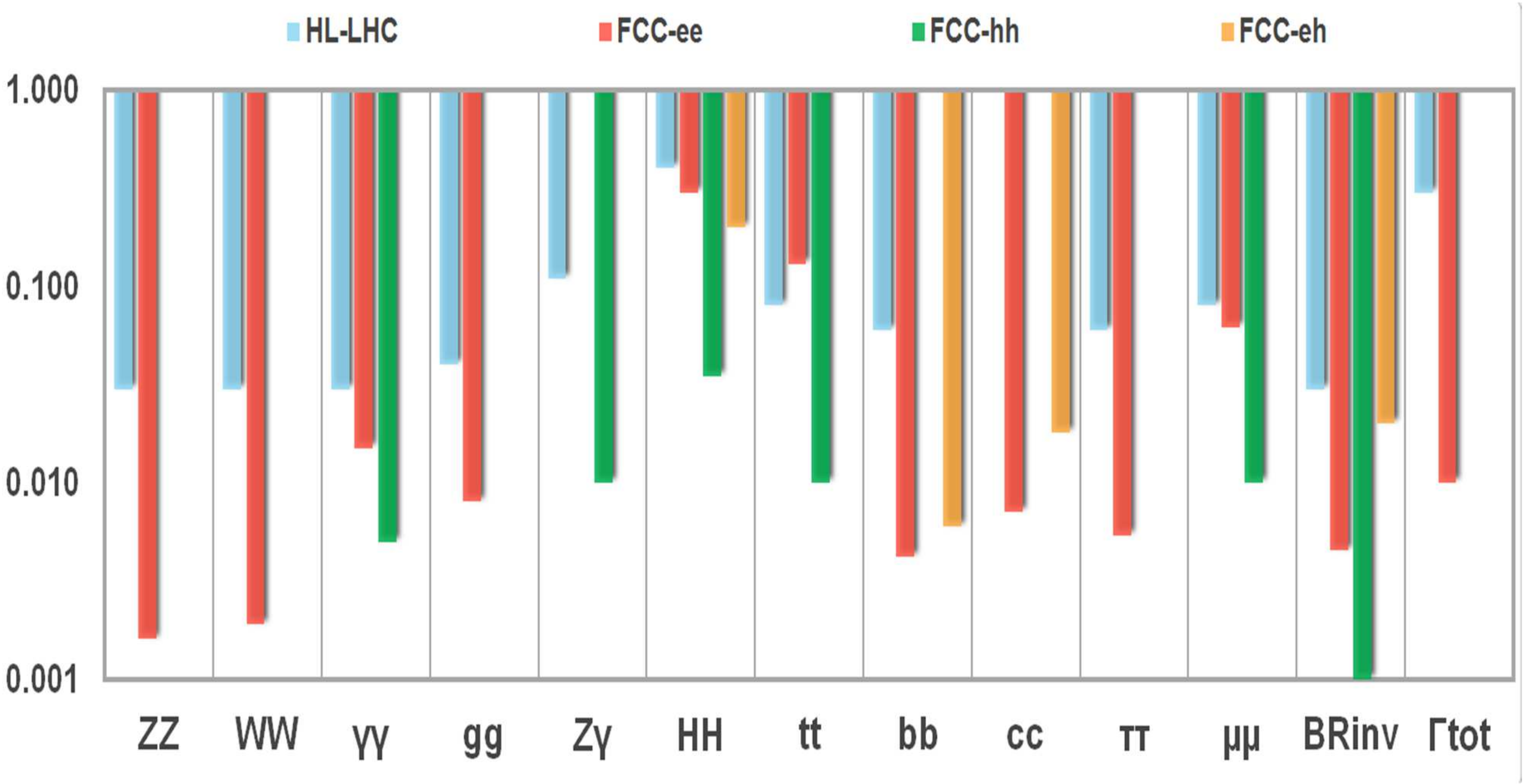
Heavy Neutrinos -- ee: very powerful and clean, but flavour-blind
-- hh and eh more difficult, but potentially flavour sensitive
NB this is very much work in progress!!

HIGGS PHYSICS

Higgs couplings g_{Hxx} precisions

hh, eh precisions assume
SM or ee measurements

g_{Hxx}	FCC-ee	FCC-hh	FCC-eh
ZZ	**0.15 %**		
WW	**0.20%**		
Γ_H	**1%**		
$\gamma\gamma$	1.5%	**<1%**	
$Z\gamma$	--	**1%**	
tt	13%	**1%**	
bb	**0.4%**		0.5%
$\tau\tau$	**0.5%**		
cc	**0.7%**		1.8%
$\mu\mu$	6.2%	**2%**	
uu,dd	H→ $\rho\gamma$?	H→ $\rho\gamma$?	
ss	H→ $\phi\gamma$?	H→ $\phi\gamma$?	
ee	**ee → H**		
HH	30%	**~3%**	20%
inv, exo	<0.45%	**10^{-3}**	5%



NB this is an 'impression plot' not the consistent result of a Higgs coupling fit!

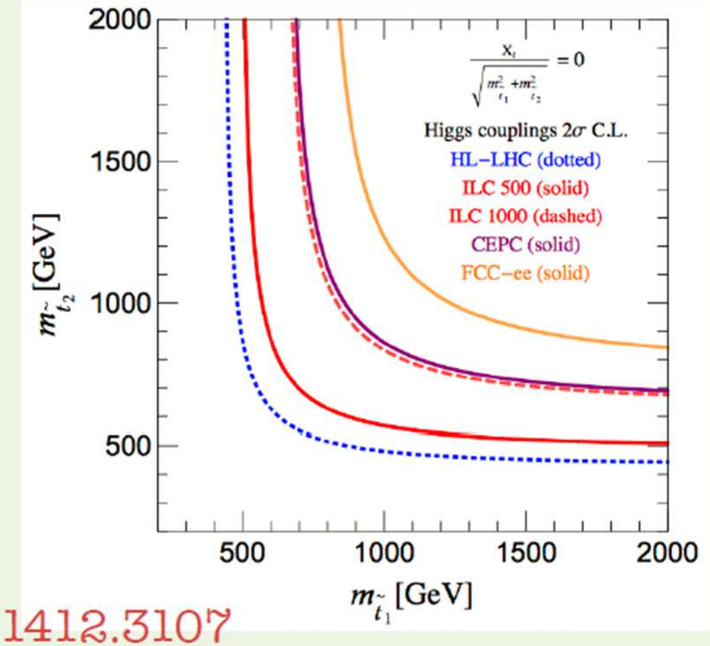
hh, eh precisions assume SM or ee measurements!

Supersymmetry

In supersymmetry top partner is “stop squark”.

FCC-ee

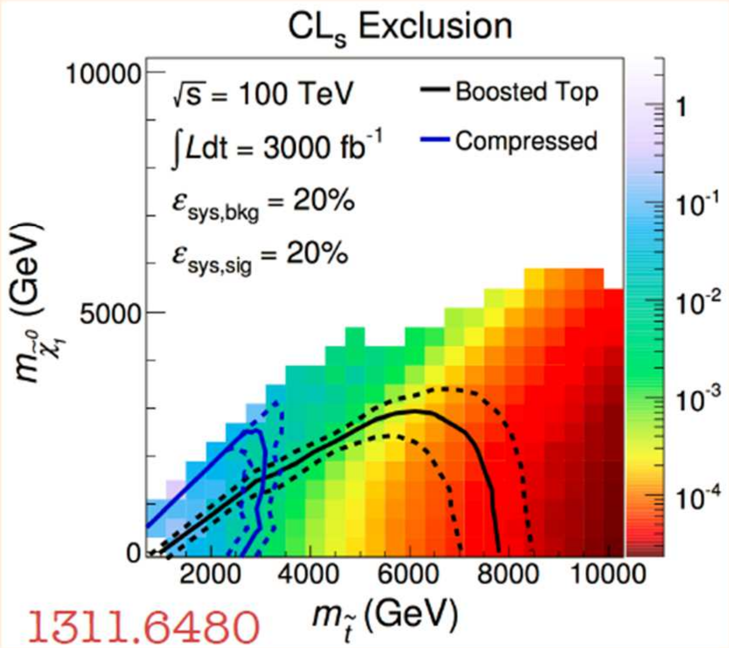
Coloured and charged, stops modify Higgs couplings:



1412.3107

FCC-hh

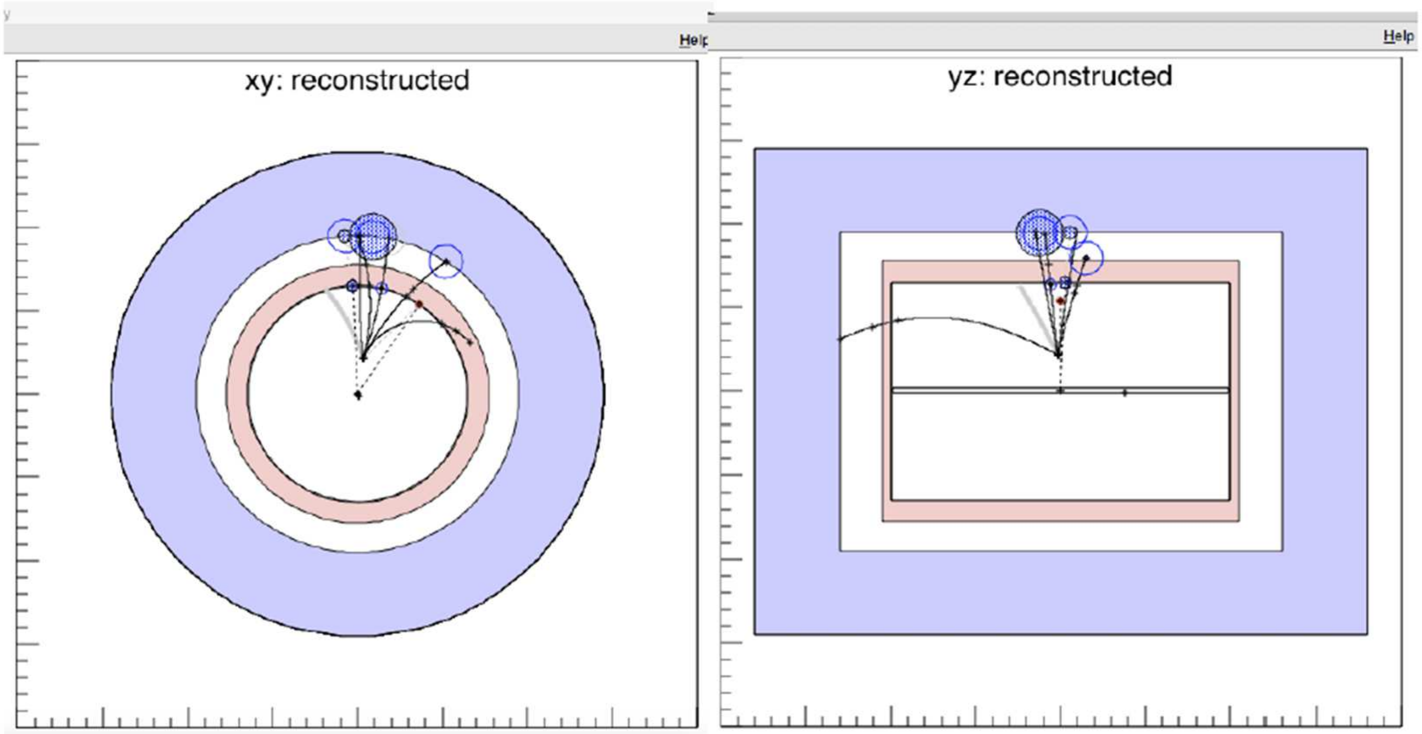
And show up directly at hadron colliders:



1311.6480

FCC-ee: Indirect, but more “spectrum independent”, for a model.
FCC-hh: Direct confirmation, but direct might be hidden.

Simulation of heavy neutrino decay in a FCC-ee detector

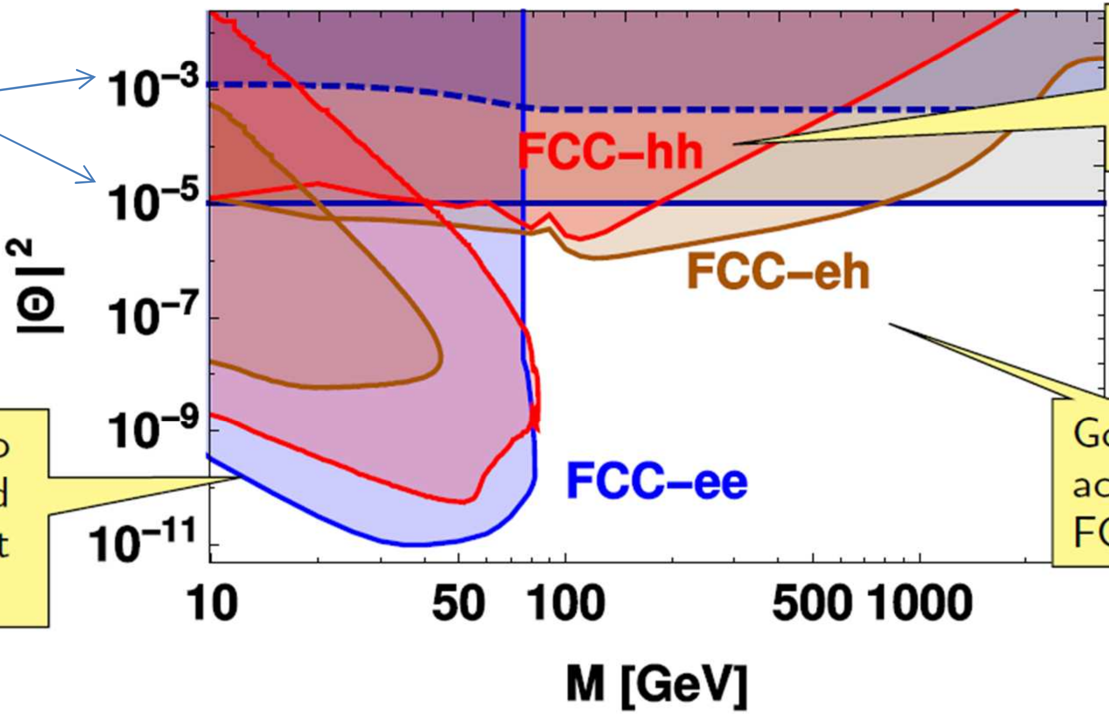


Summary

Another example of Synergy and complementarity
while ee covers a large part of space very cleanly ,
its either ‘white’ in lepton flavour or the result of EWPOs etc
Observation at FCC –hh or eh would test flavour mixing matrix!

- Systematic assessment of heavy neutrino signatures at colliders.
- First looks at FCC-hh and FCC-eh sensitivities.
- Golden channels:
  - **FCC-hh:** LFV signatures and displaced vertex search
  - **FCC-eh:** LFV signatures and displaced vertex search
  - **FCC-ee:** Indirect search via EWPO and displaced vertex search

EWPO sensitivity up to very high mass scales



FCC-hh able to test all flavour combinations.

Best sensitivity to $|\theta|^2$ from displaced vertex searches at the FCC-ee.

Good sensitivity reach from FCC-hh & FCC-eh.

detailed study required for all FCCs – especially FCC-hh to understand feasibility at all

FCC CONCLUSIONS

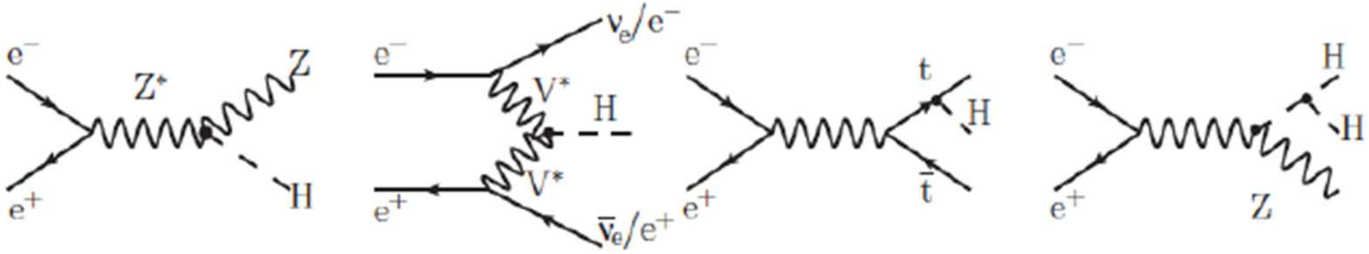
-- The FCC design study is establishing the feasibility or the path to feasibility of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology.

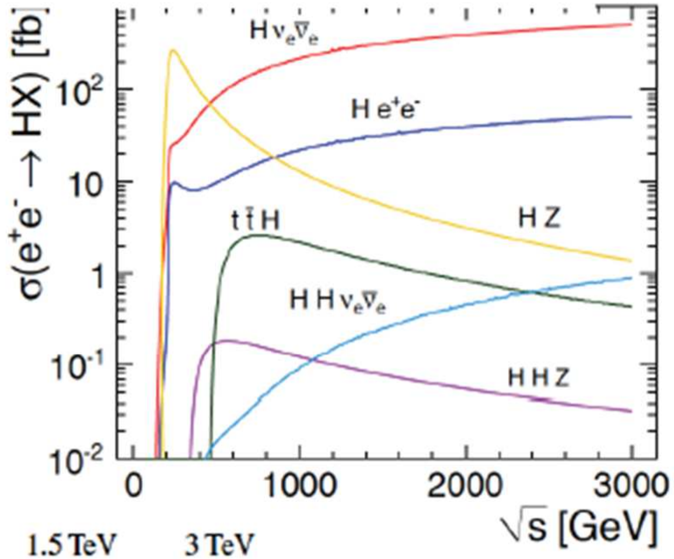
-- Both FCC-ee and FCC-hh have outstanding physics cases
    -- each in their own right
    -- the sequential implementation of FCC-ee, FCC-hh, FCC-eh would maximise the physics reach
    -- it is also the least costly of the roads to 100 TeV

-- Attractive scenarios of staging and implementation (budget!) cover more than 50 years of exploratory physics, taking full advantage of the synergies and complementarities.

-- the FCC are shaping up as the most natural, complete and powerful aspiration of HEP for its long-term future

Higgs in e^+e^-





Many studies performed using full Geant-based MC

Integrated luminosity and numbers of events expected for initial 5 years running at each value of E_{cm}

	250 GeV	350 GeV	500 GeV	1 TeV	1.5 TeV	3 TeV
$\sigma(e^+e^- \to ZH)$	240 fb	129 fb	57 fb	13 fb	6 fb	1 fb
$\sigma(e^+e^- \to H\nu_e\bar{\nu}_e)$	8 fb	30 fb	75 fb	210 fb	309 fb	484 fb
Int. $\mathcal{L}$	250 fb^{-1}	350 fb^{-1}	500 fb^{-1}	1000 fb^{-1}	1500 fb^{-1}	2000 fb^{-1}
# ZH events	60,000	45,500	28,500	13,000	7,500	2,000
# $H\nu_e\bar{\nu}_e$ events	2,000	10,500	37,500	210,000	460,000	970,000

← baseline ILC/CLIC as of ESPP

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 →**

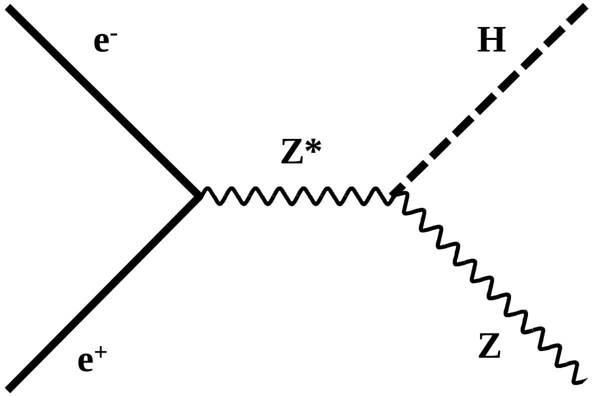
-- detectors are likely to be very similar

Higgs production mechanism

“higgstrahlung” process close to threshold

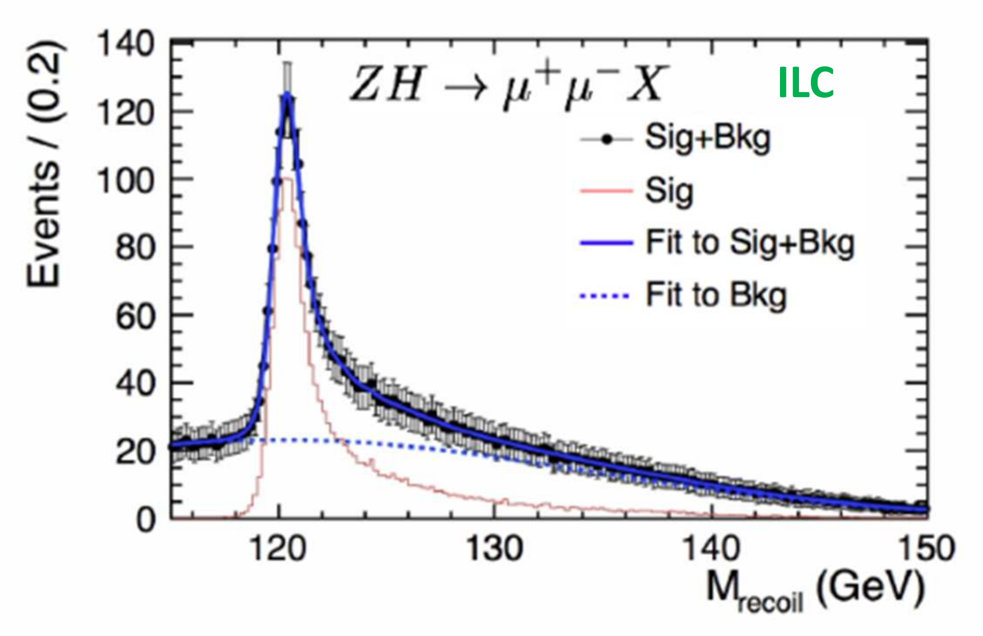
Production xsection has a maximum at near threshold ~200 fb

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



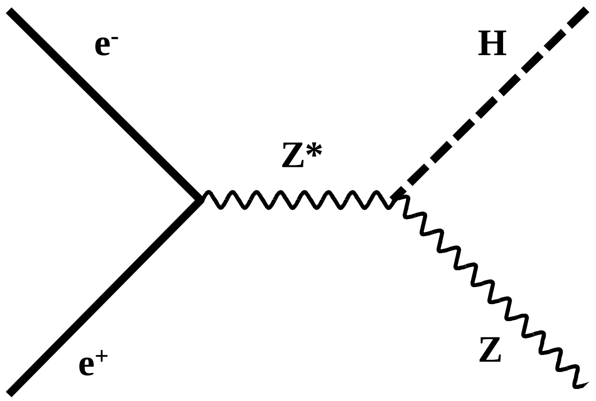
Z – tagging
by missing mass

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

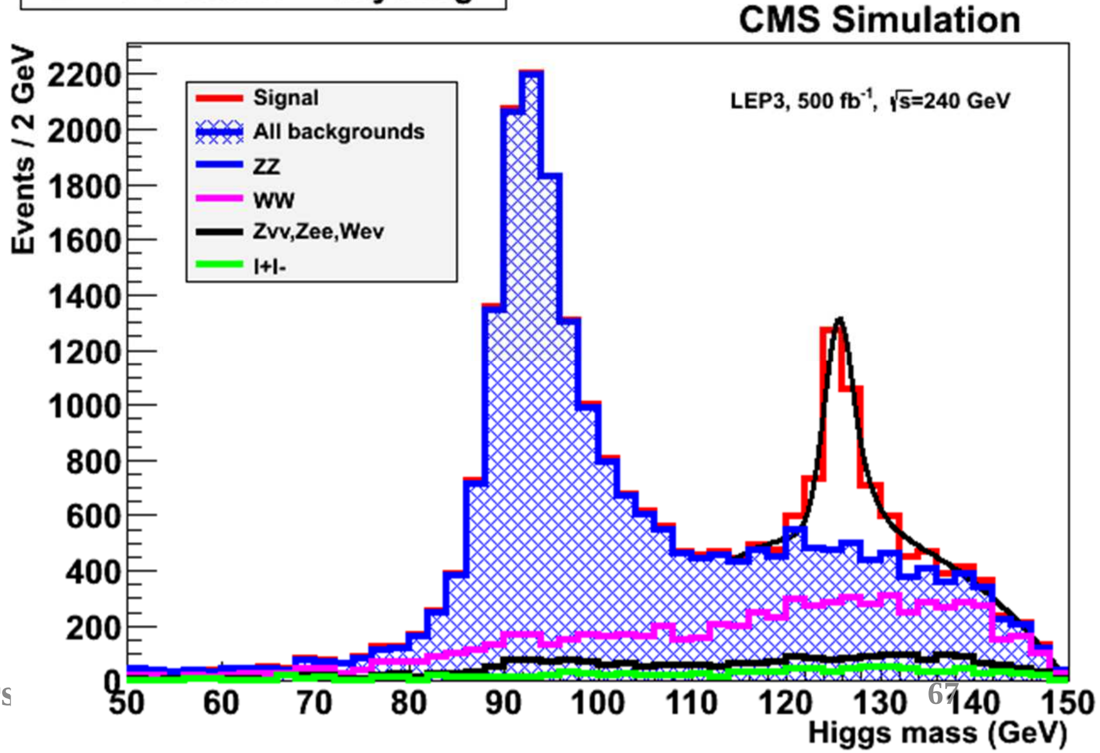


Z – tagging
by missing mass

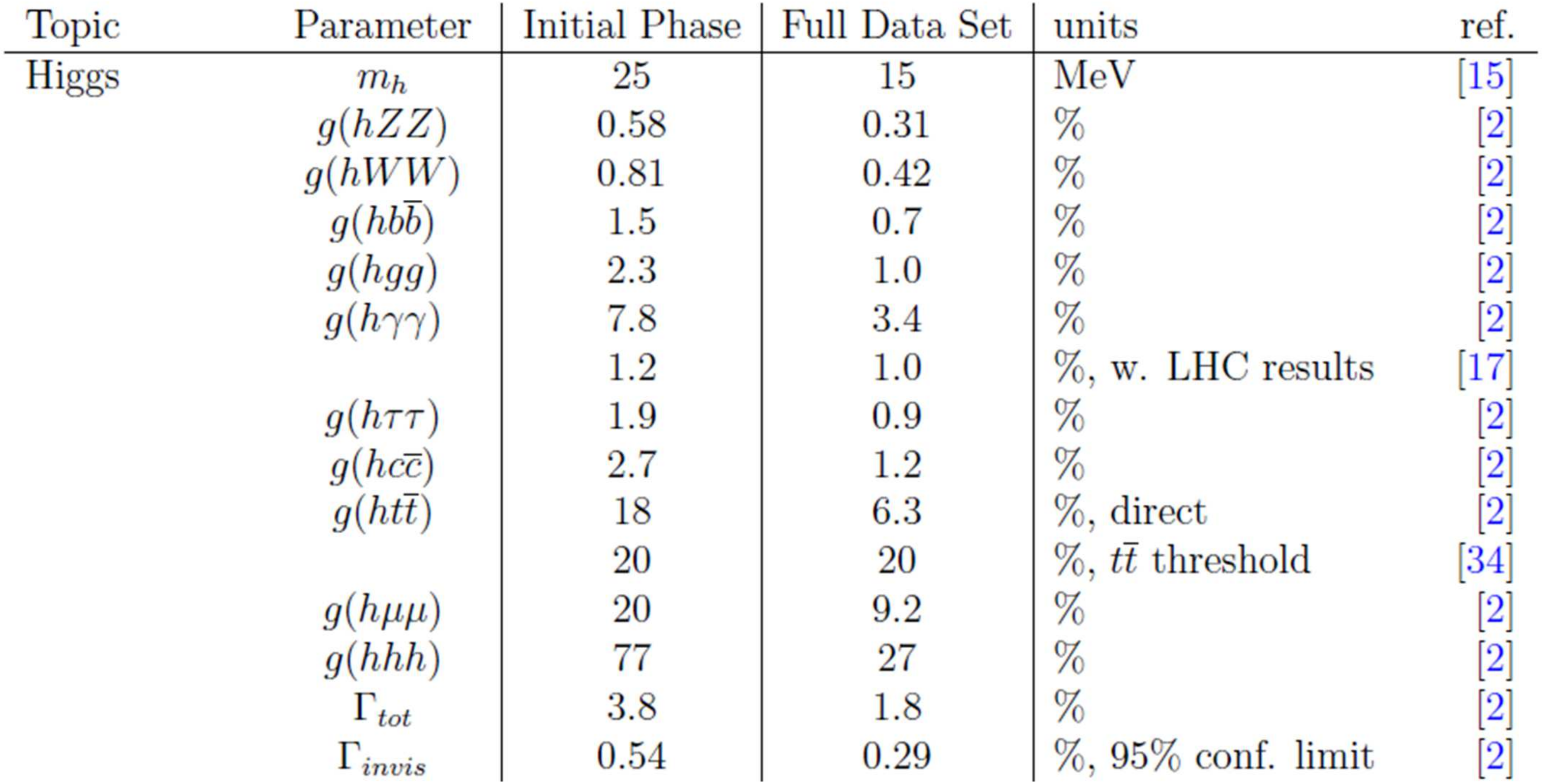
total rate $\propto g_{HZZ}^2$
ZZZ final state $\propto g_{HZZ}^4 / \Gamma_H$
➔ measure total width Γ_H
empty recoil = invisible width
'funny recoil' = exotic Higgs decay
easy control below theshold



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

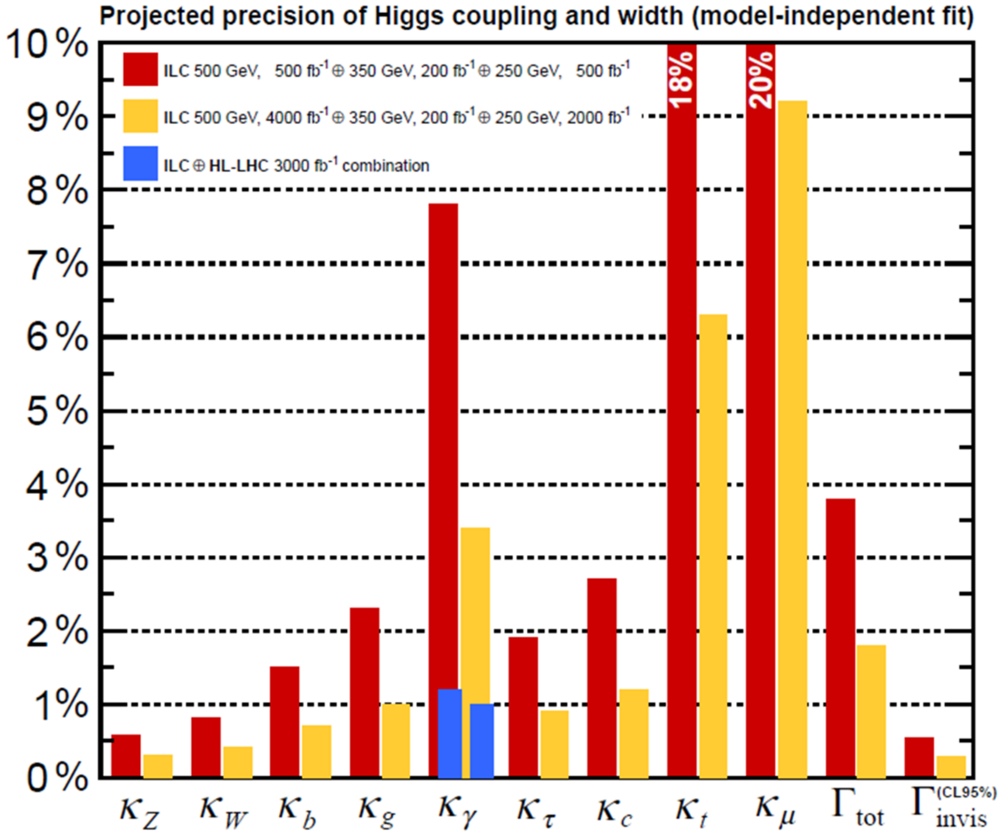


ILC new running scenarios including upgrade of luminosity



Topic	Parameter	Initial Phase	Full Data Set	units	ref.
Higgs	m_h	25	15	MeV	[15]
	$g(hZZ)$	0.58	0.31	%	[2]
	$g(hWW)$	0.81	0.42	%	[2]
	$g(hb\bar{b})$	1.5	0.7	%	[2]
	$g(hgg)$	2.3	1.0	%	[2]
	$g(h\gamma\gamma)$	7.8	3.4	%	[2]
		1.2	1.0	%, w. LHC results	[17]
	$g(h\tau\tau)$	1.9	0.9	%	[2]
	$g(hc\bar{c})$	2.7	1.2	%	[2]
	$g(ht\bar{t})$	18	6.3	%, direct	[2]
		20	20	%, $t\bar{t}$ threshold	[34]
	$g(h\mu\mu)$	20	9.2	%	[2]
	$g(hhh)$	77	27	%	[2]
	Γ_{tot}	3.8	1.8	%	[2]
	Γ_{invis}	0.54	0.29	%, 95% conf. limit	[2]

ILC new running scenarios including upgrade of luminosity



🟥 **10 yrs (1.6 10^7s/yr)**
TDR lumi,
incl. ramp-up

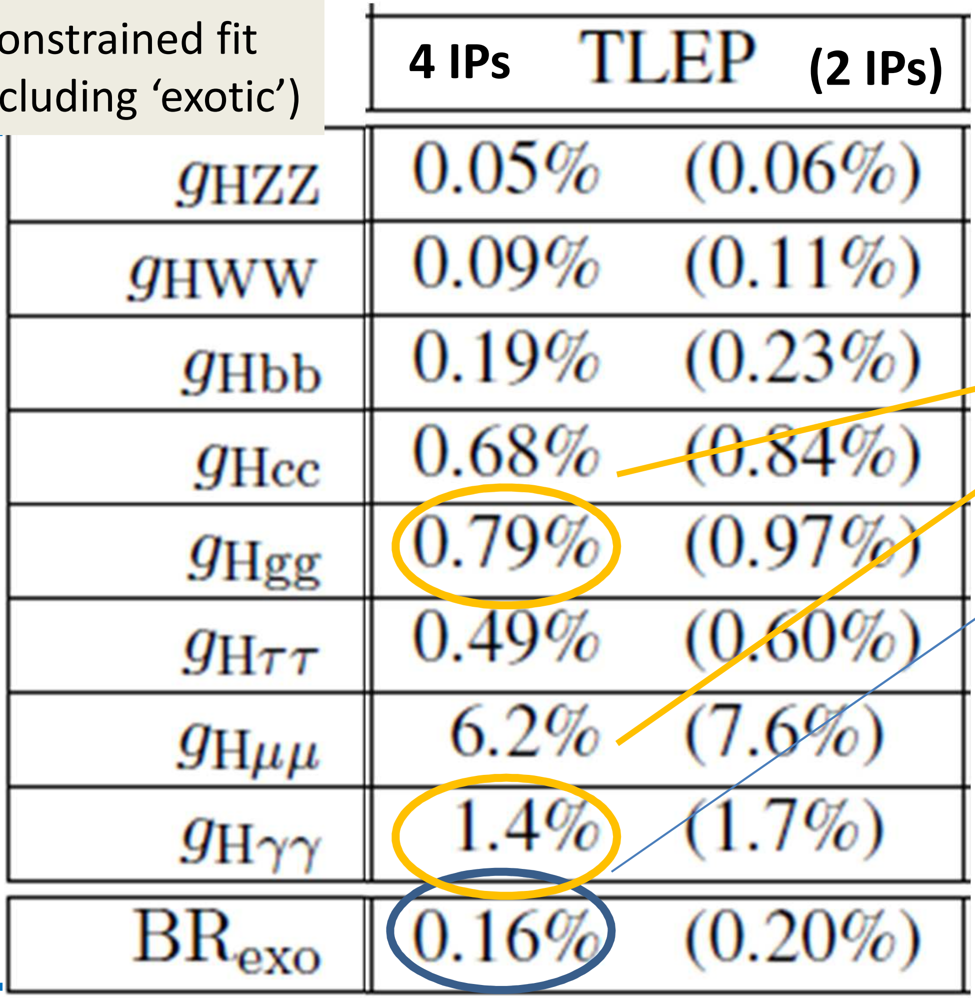
🟨 **20 yrs (1.6 10^7s/yr)**
lumi upgrade
incl. ramp-up

Figure 5: Relative precisions for the various Higgs couplings extracted from a model-independent fit to expected data from the ILC. The notation is as in Fig. 4.

arxiv:1506.07830
arxiv:1506.05992

FCC-ee as Higgs factory

(constrained fit including 'exotic')

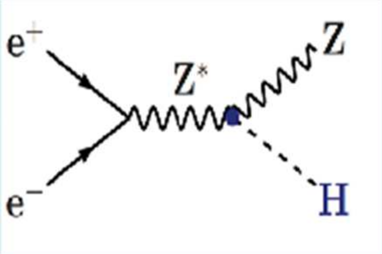


	4 IPs	TLEP (2 IPs)
g_{HZZ}	0.05%	(0.06%)
g_{HWW}	0.09%	(0.11%)
g_{Hbb}	0.19%	(0.23%)
g_{Hcc}	0.68%	(0.84%)
g_{Hgg}	0.79%	(0.97%)
$g_{H\tau\tau}$	0.49%	(0.60%)
$g_{H\mu\mu}$	6.2%	(7.6%)
$g_{H\gamma\gamma}$	1.4%	(1.7%)
BR_{exo}	0.16%	(0.20%)

➔ ***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

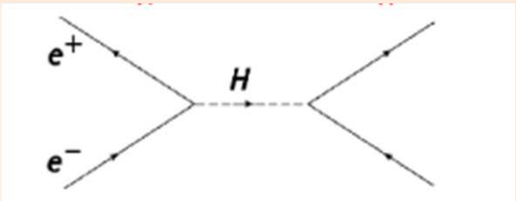
«A tagged Higgs beam».

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

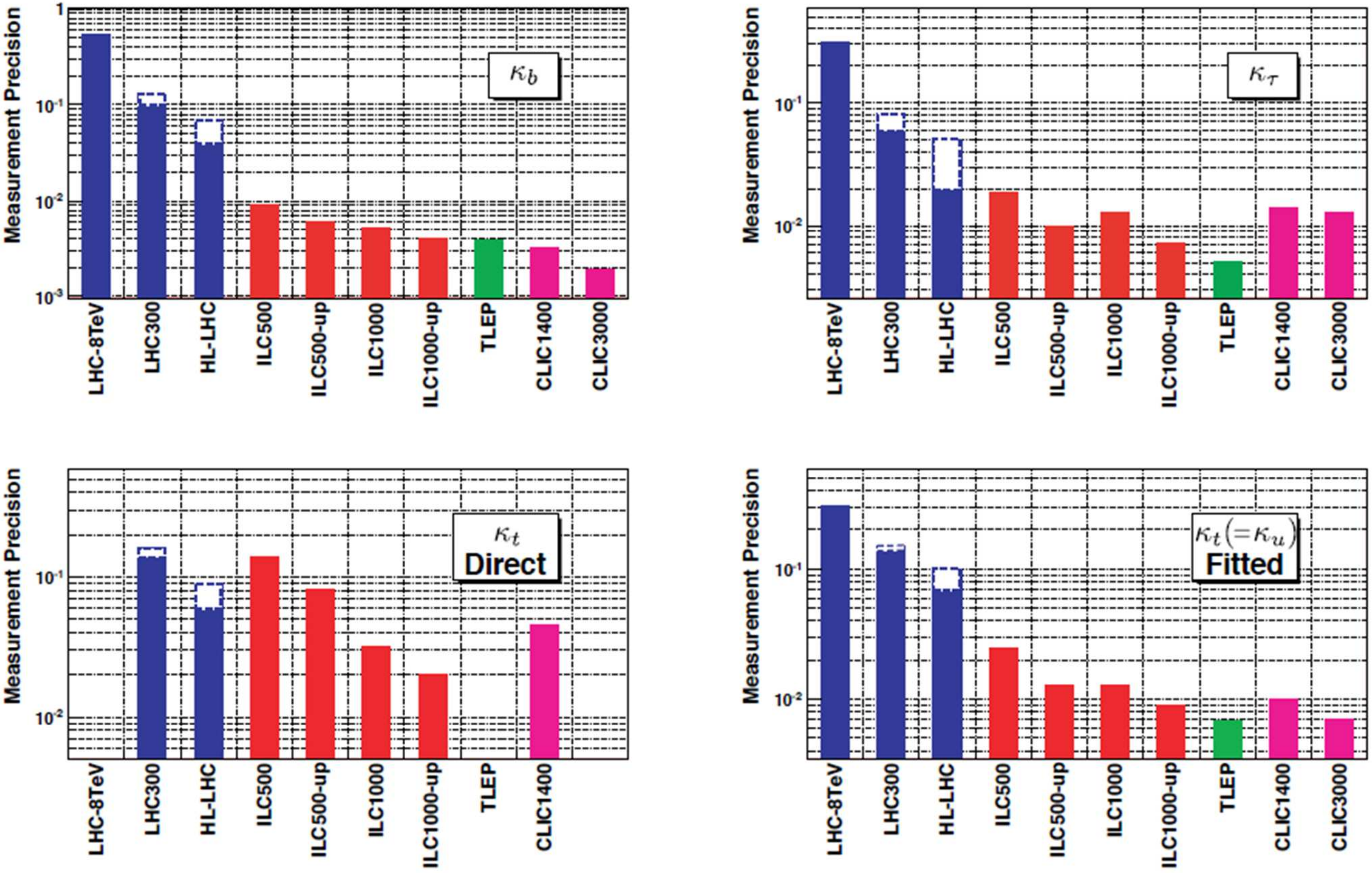


Figure 1-4. *Measurement precision on κ_b, κ_τ, and κ_t measured both directly via $t\bar{t}H$ and through global fits at different facilities.*

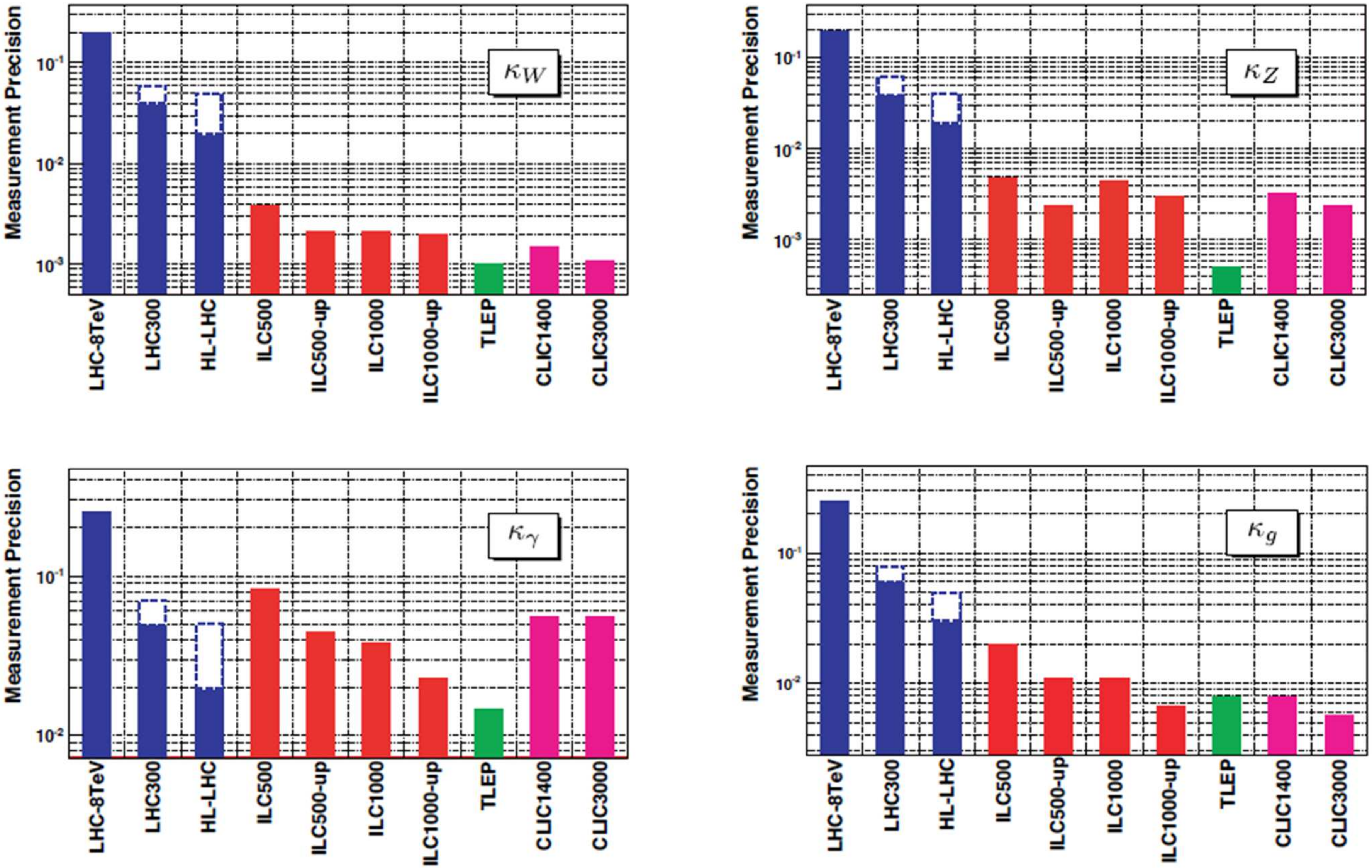
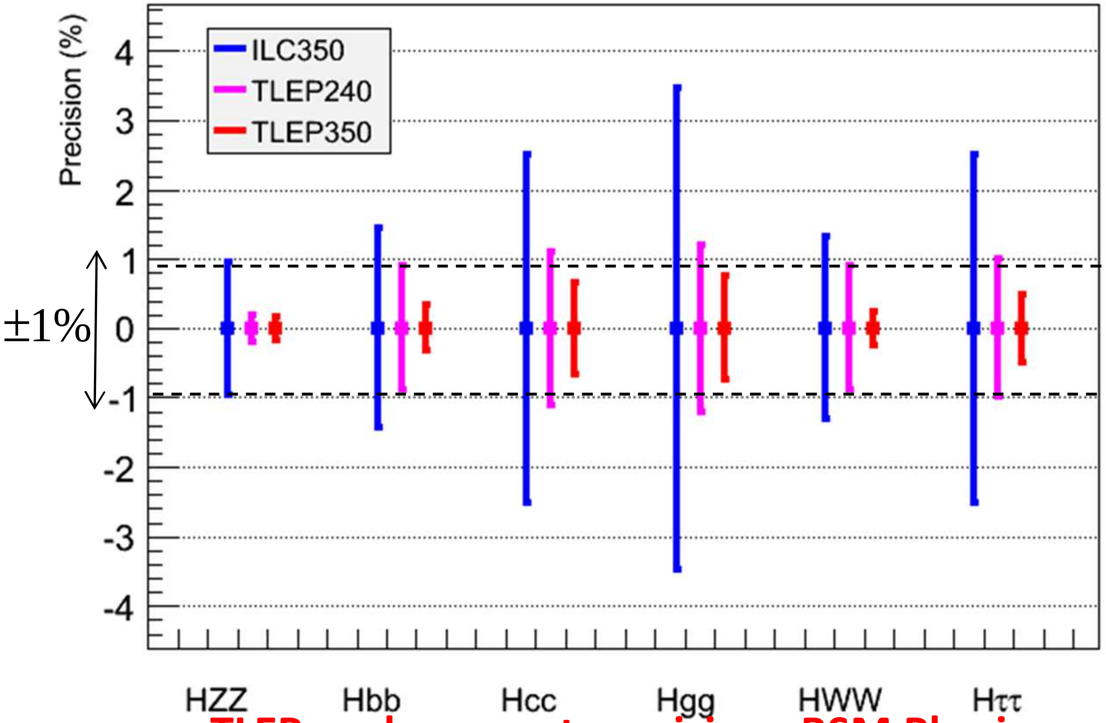


Figure 1-3. *Measurement precision on κ_W, κ_Z, κ_γ, and κ_g at different facilities.*

Performance Comparison

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

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

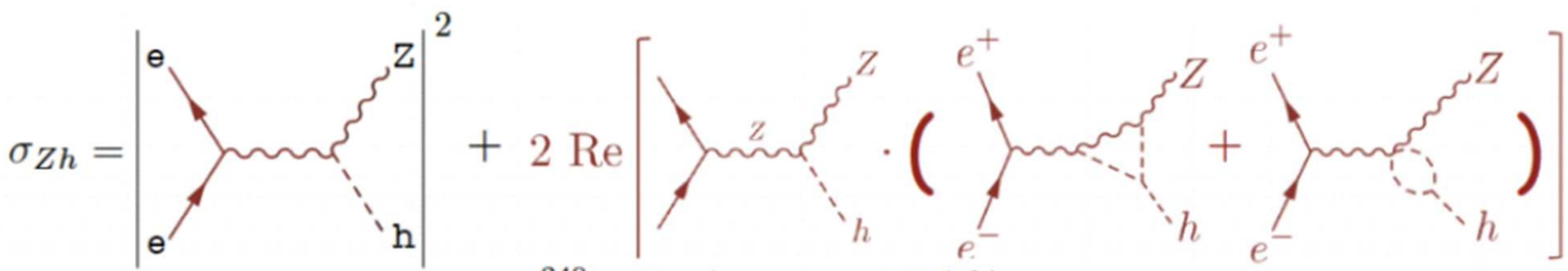


Expected precision on the total width

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

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

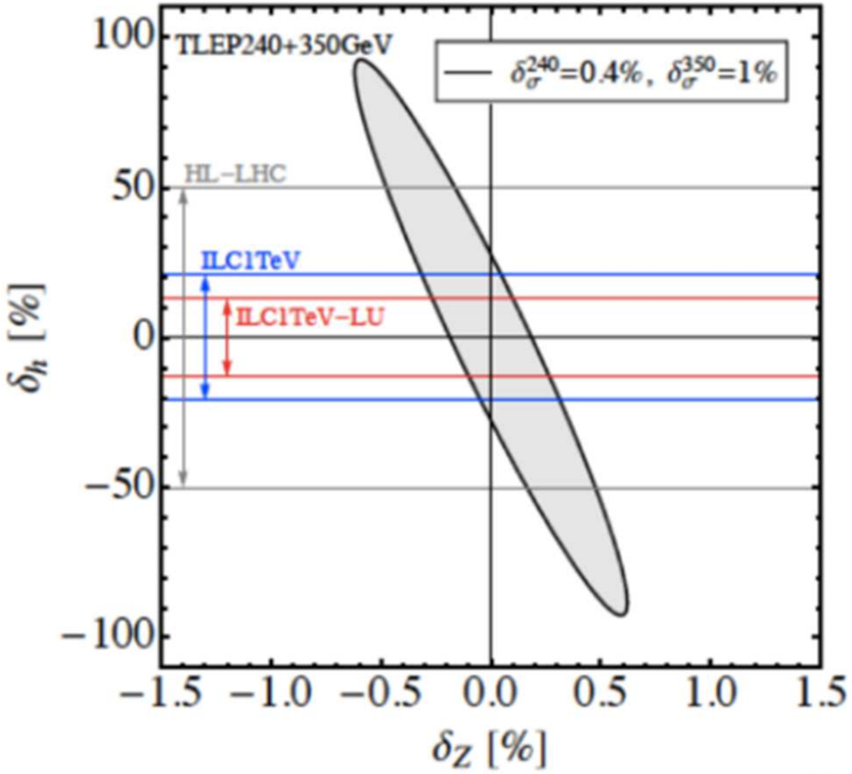
very accurate precision on threshold cross-section sensitive to loop corrections



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

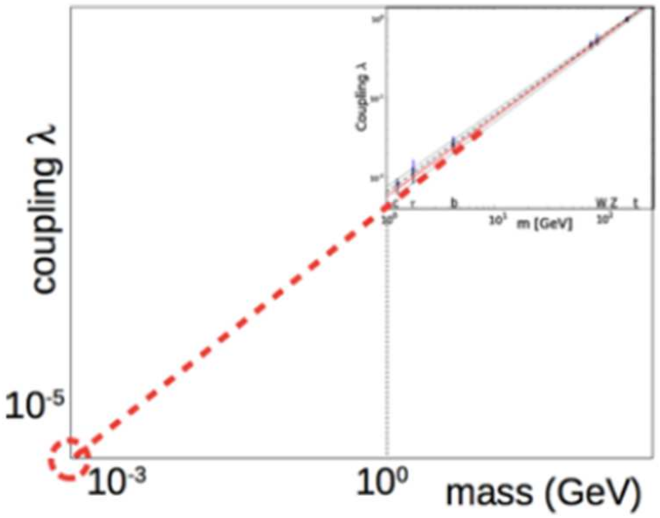
arxiv:1312.3322

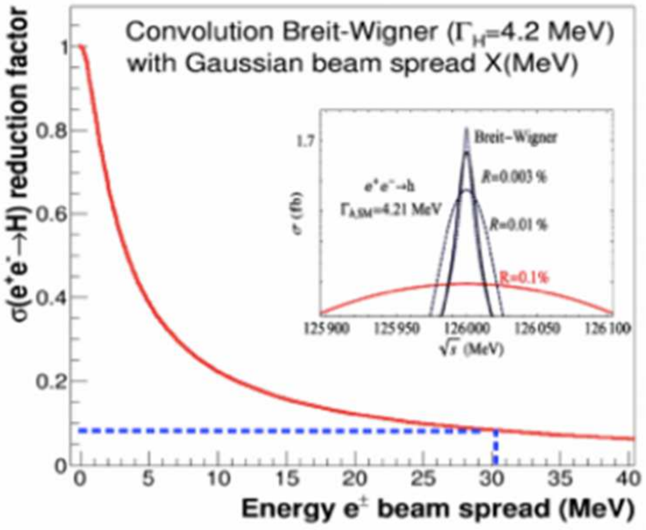
- ➡ Very large datasets at high energy allow extreme precision g_{ZH} measurements
- ➡ Indirect and model-dependent probe of Higgs self-coupling
- ➡ Note, the time axis is missing from the plot



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

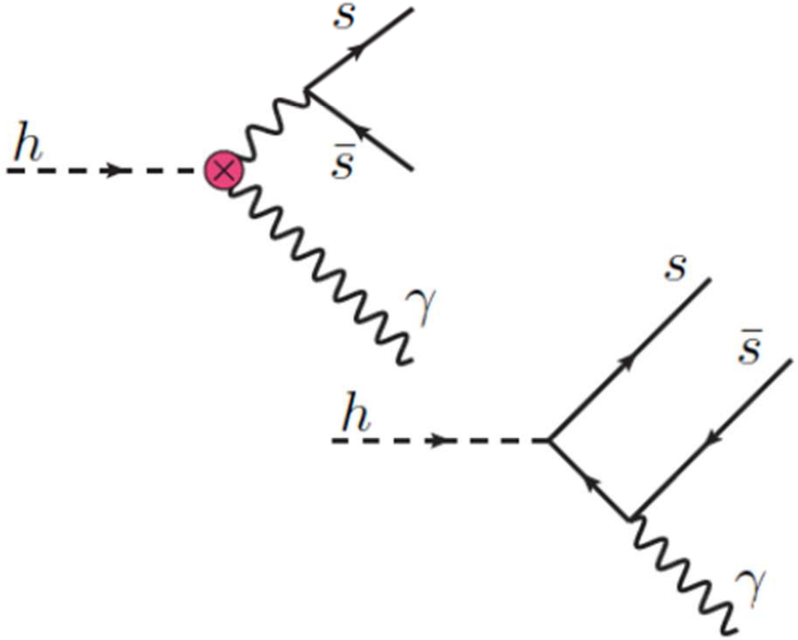
➡ First and second generation couplings accessible

- 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

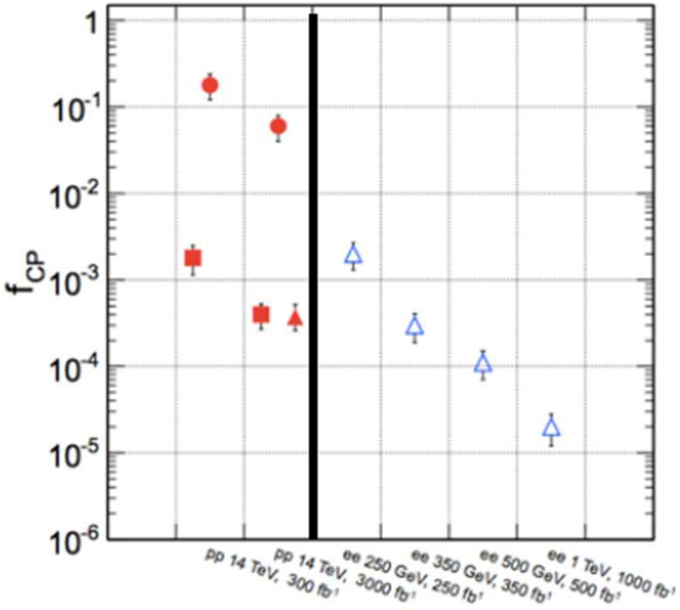
H → **ϕ** γ ➡ y_s

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

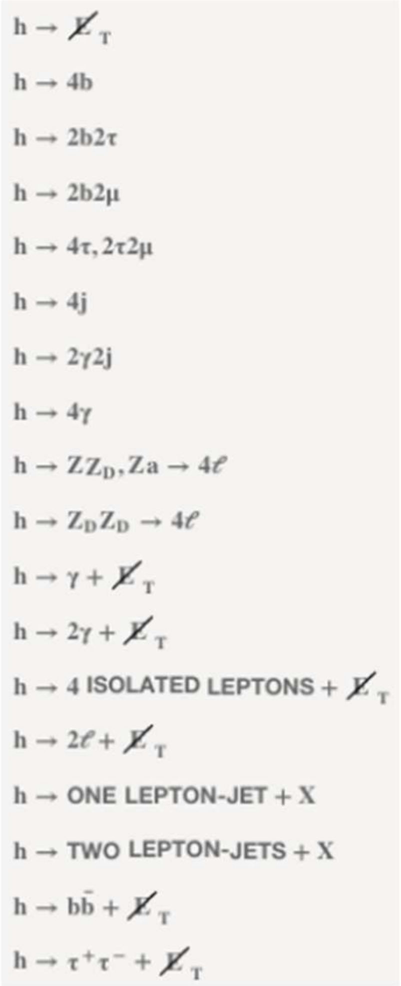

for HVV couplings

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

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



$h \rightarrow \not{E}_T$

$h \rightarrow 4b$

$h \rightarrow 2b2\tau$

$h \rightarrow 2b2\mu$

$h \rightarrow 4\tau, 2\tau 2\mu$

$h \rightarrow 4j$

$h \rightarrow 2\gamma 2j$

$h \rightarrow 4\gamma$

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

$h \rightarrow Z_D Z_D \rightarrow 4\ell$

$h \rightarrow \gamma + \not{E}_T$

$h \rightarrow 2\gamma + \not{E}_T$

$h \rightarrow$ 4 ISOLATED LEPTONS $+ \not{E}_T$

$h \rightarrow 2\ell + \not{E}_T$

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

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

$h \rightarrow b\bar{b} + \not{E}_T$

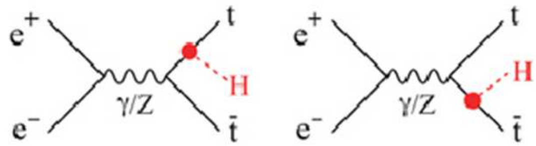
$h \rightarrow \tau^+\tau^- + \not{E}_T$

Top-Yukawa Coupling at 500 GeV

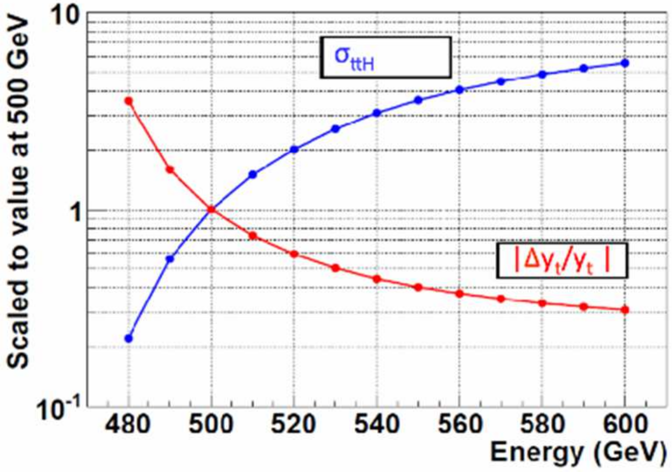
ILC Parameters Joint Working Group, arXiv:1506.07830v1 [hep-ex]

- top quark heaviest particle in SM
  - couples most strongly to Higgs sector
  - g_{Htt} could contain special effects
  - should be measured model-independently
- at ILC directly accessible through

$$e^+e^- \to t\bar{t}H \text{ (with } H \to b\bar{b})$$



- enhanced cross section at $\sqrt{s} = 500$ GeV
  - need full energy → close to production threshold
- at $\sqrt{s} = 550$ GeV better precision on g_{Htt}
  - by factor 4 enhanced cross section
  - main backgrounds decrease



$\Delta g_{Htt}/g_{Htt}$	ILC500	ILC500 LumiUP
500 GeV	18 %	6.3 %
550 GeV	∼ 9 %	∼ 3 %

increasing $\sqrt{s}$ by 10%, precision improves by factor two for same integrated luminosity

NB these are similar precisions as obtained from HL-LHC

Higgs Self-Coupling Measurement at the ILC

- precise measurement of SM Higgs potential via Higgs self-coupling

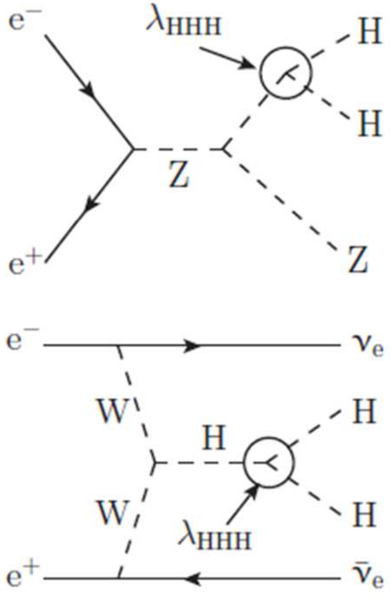
$$V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda v \eta_H^3 + \frac{1}{4} \lambda \eta_H^4$$

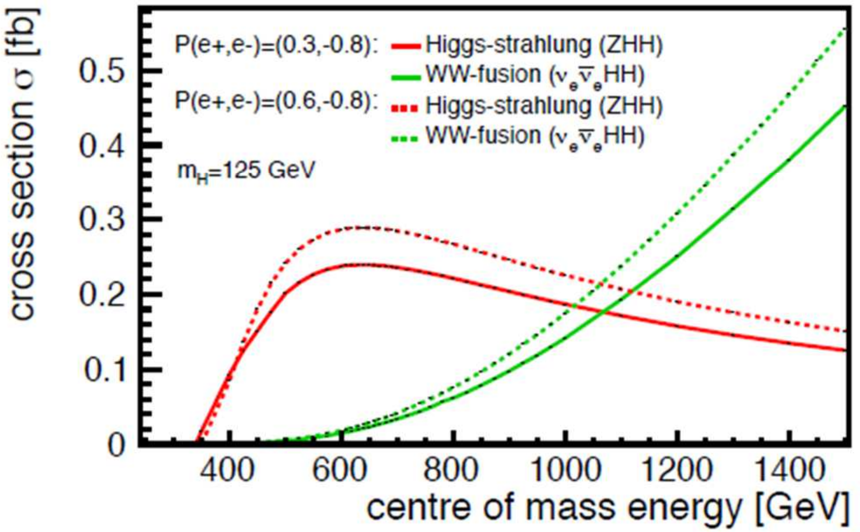
- existence of HHH coupling → direct evidence of vacuum condensation
- one must observe double Higgs production
- very challenging measurement

→ small production cross section, i.e. $\sigma(ZHH) \approx 0.2$fb at 500GeV

→ many jets in final state

→ interference terms due to irreducible diagrams





Claude Fabienne Dürig | Higgs program at the ILC | EPS-HEP Vienna, July 22-29 2015 | 10/13

Higgs Self-Coupling Measurement at the ILC

ILC Parameters Joint Working Group, arXiv:1506.07830v1 [hep-ex]

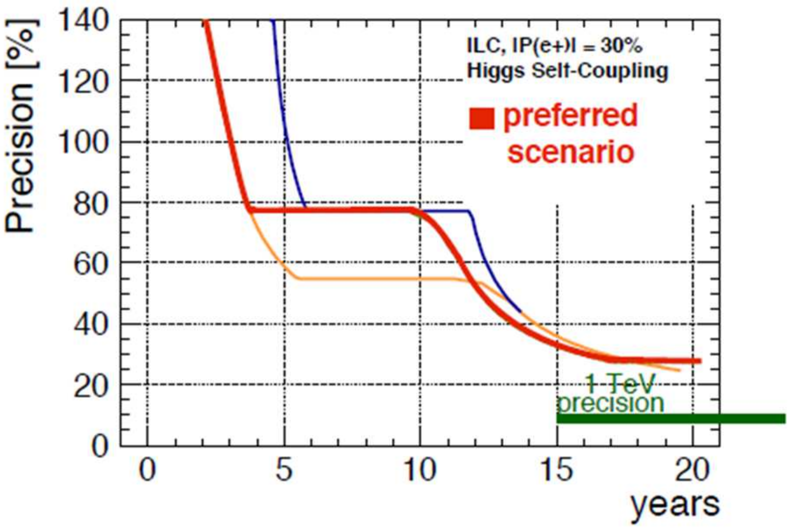
Existing full simulation analyses
for $m_H = 125$ GeV

@ 500 GeV

- ZHH→Z(bb)(bb)
- ZHH→Z(bb)(WW)

@ 1 TeV

- ννHH →νν(bb)(bb)
- ννHH →νν(bb)(WW)



	500 GeV			500 GeV+1 TeV		
Scenario	A	B	C	A	B	C
Baseline	104%	83%	66%	26%	21%	17%
LumiUP	58%	46%	37%	16%	13%	10%

500 GeV: 500 (1600)fb^{-1} P(e$^+$e$^-$)=(0.3,-0.8)
1 TeV: 1000 (2500)fb^{-1} P(e$^+$e$^-$)=(0.2,-0.8)

Scenario A: HH → bbbb ✔

Scenario B: adding HH → bbWW ✔, expect 20% relative improvement

Scenario C: analysis improvement (jet-clustering, kinematic fit, flavor tagging, matrix element method, etc.), expect 20% relative improvement (**ongoing**)

HIGGS SELF COULING VERY DIFFICULT TO MEASURE PRECISELY AT LINEAR COLLIDERS
30% precision after 20 years
needs high energy (another 10-20 years) for 10% precision

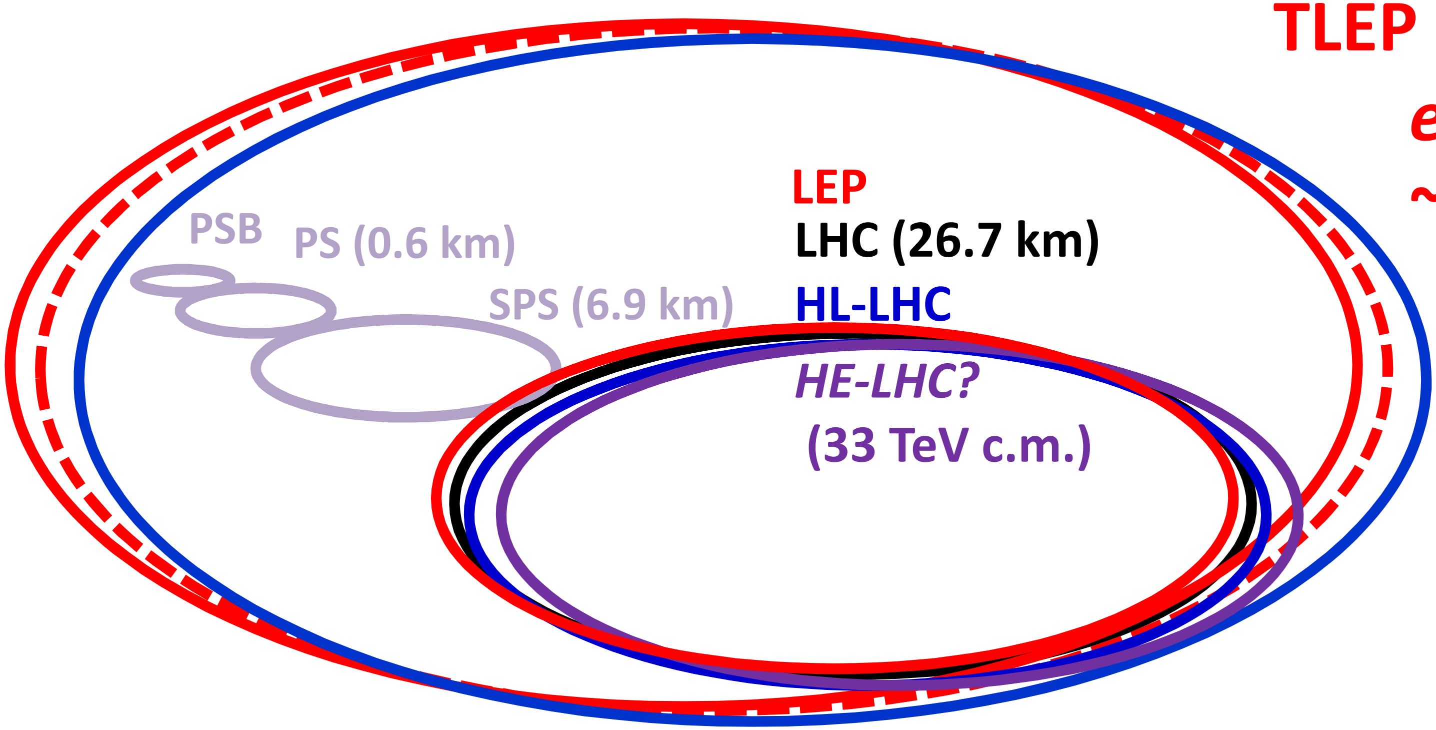
Measurements of most of Higgs physics and couplings, CP violation etc..
are best made with the ZH process at 240-350 GeV

Top quark and Higgs self couplings can be made with a linear collider of energy above 500 GeV (at least 550 GeV for ttH, at least 1 GeV for HHH).

However for ttH and HHH, similar precisions can be achieved by combining the HL-LHC with a 250-350 GeV e+e- machine.

And what about a higher energy pp collider?

possible long-term strategy



TLEP (80-100 km,
***e$^+$e$^-$*, up to**
~350 GeV c.m.)

VHE-LHC
(*pp*, up to
100 TeV c.m.)

"same" detectors!?

& ***e$^\pm$* (120 GeV)–*p* (7, 16 & 50 TeV)** collisions (**[(V)HE-]TLHeC**)

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

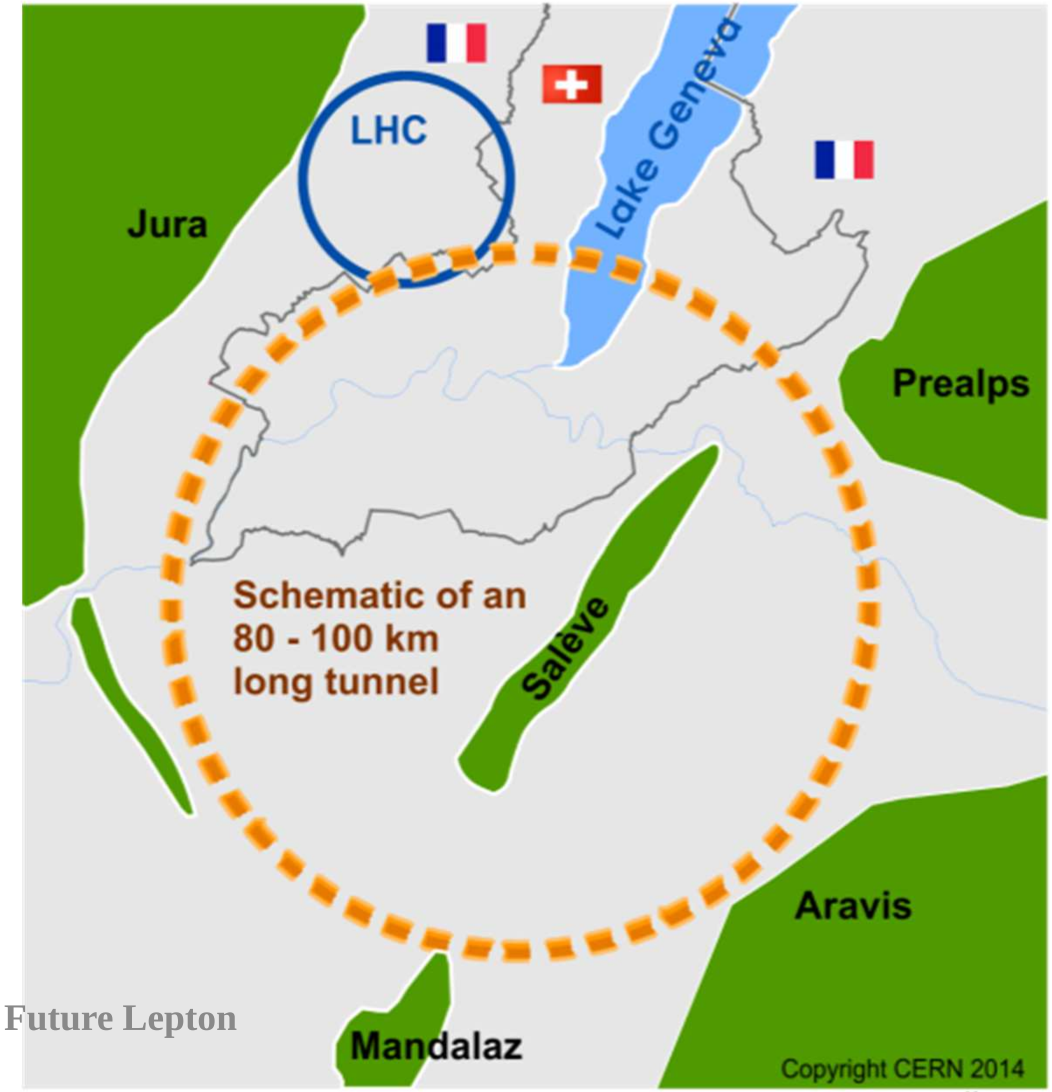
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

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**



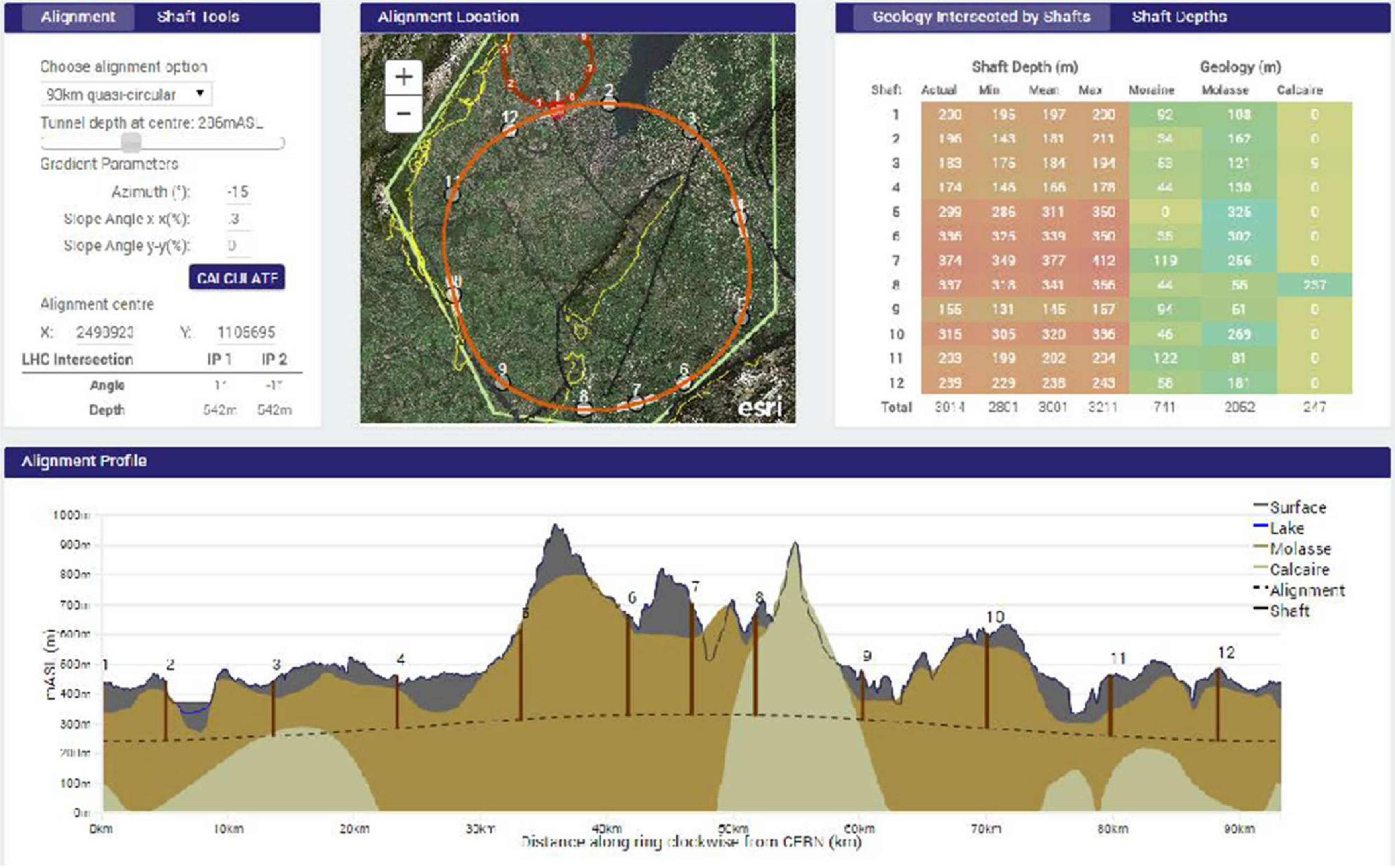
FCC-hh parameters

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

93km “optimised” racetrack

PRELIMINARY



Alignment | **Shaft Tools**

Choose alignment option

90km 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: 2490923 Y: 1106695

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

Alignment Location

Geology Intersected by Shafts | **Shaft Depths**

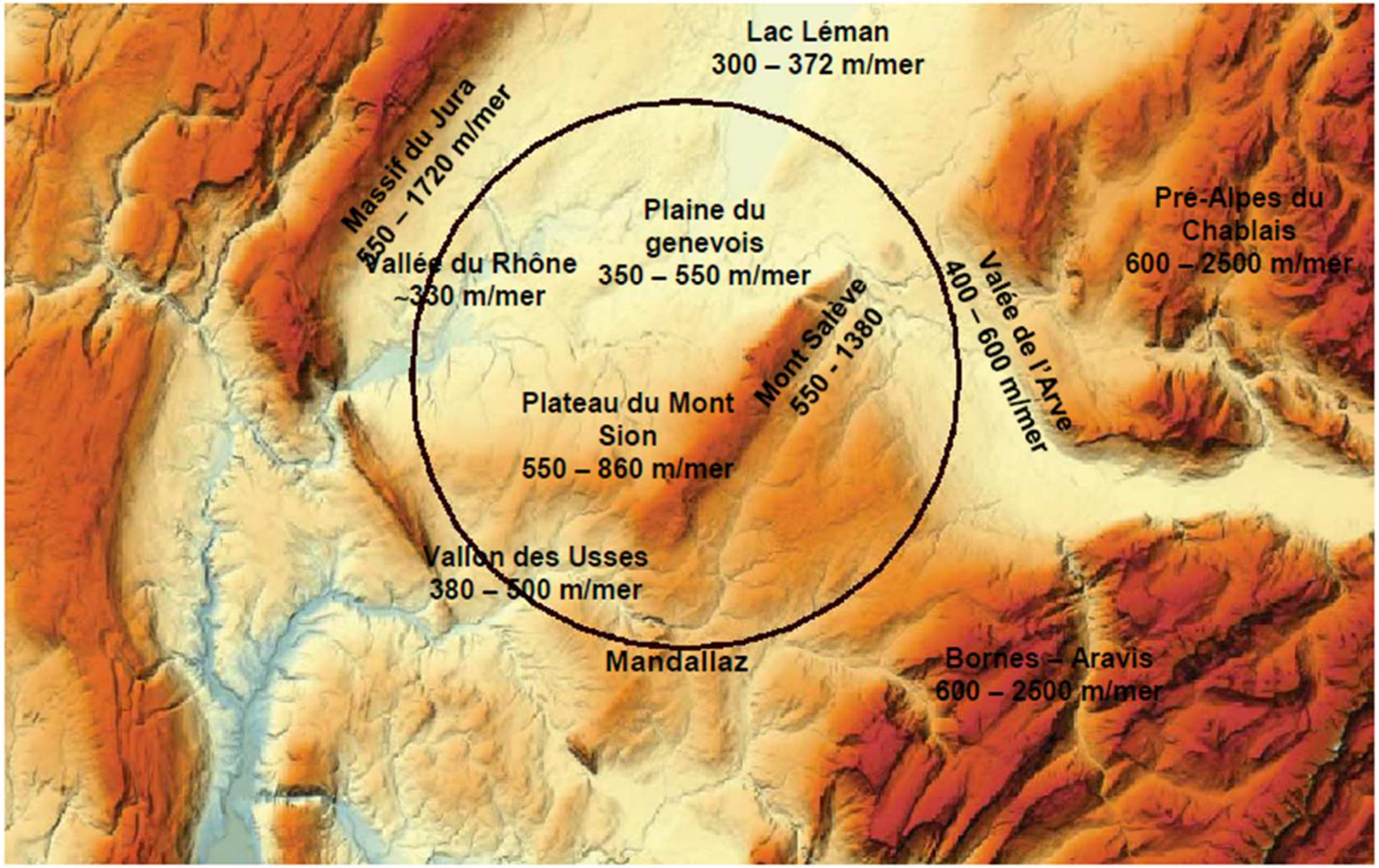
	Shaft Depth (m)				Geology (m)		
Shaft	Actual	Min	Mean	Max	Moraine	Molasse	Calcaire
1	200	195	197	200	92	108	0
2	196	143	181	211	34	162	0
3	183	176	184	194	53	121	9
4	174	145	166	178	44	130	0
5	299	286	311	350	0	325	0
6	336	325	339	350	35	302	0
7	374	349	377	412	119	256	0
8	337	318	341	356	44	56	237
9	155	131	145	157	94	61	0
10	315	305	320	336	46	269	0
11	203	199	202	234	122	81	0
12	239	229	238	243	58	181	0
Total	3014	2801	3001	3211	741	2052	247

Alignment Profile

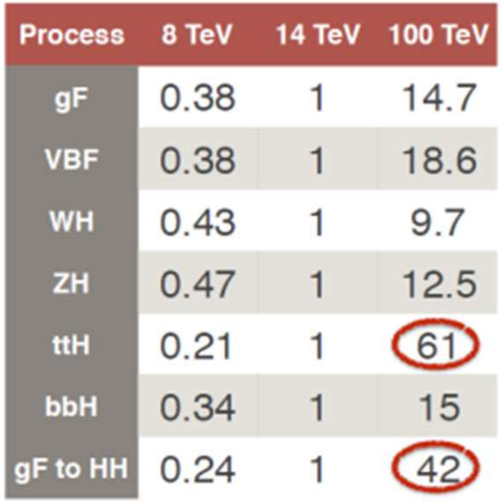
J. Osborne & C. Cook

Tunnel location: topography [1/3]

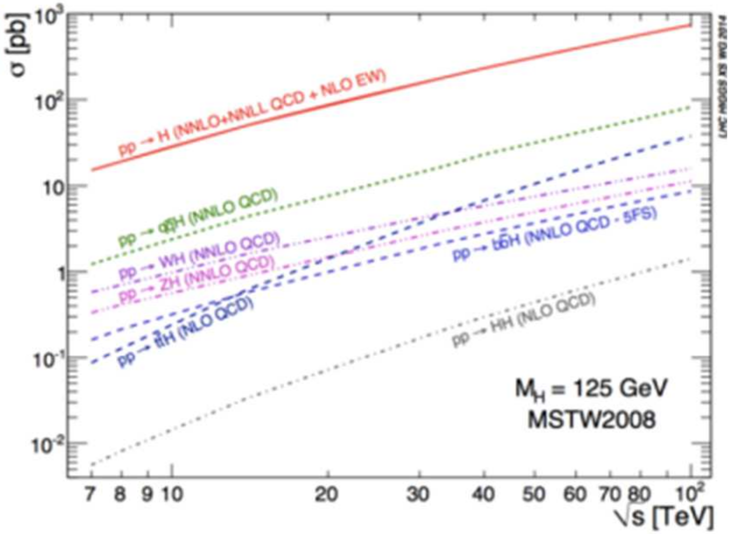
- Minimize ground coverage
  - Hydrostatic pressure for TBM tunnelling
  - Shaft depth/cost

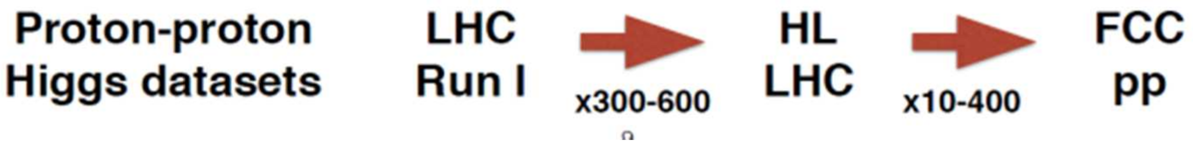


HIGGS AT FCC-pp



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

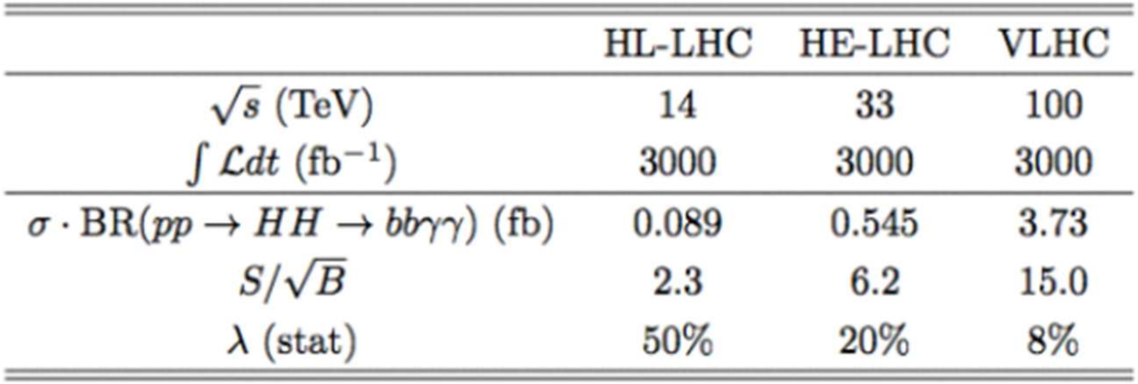
LHC Run I

x300-600

HL LHC

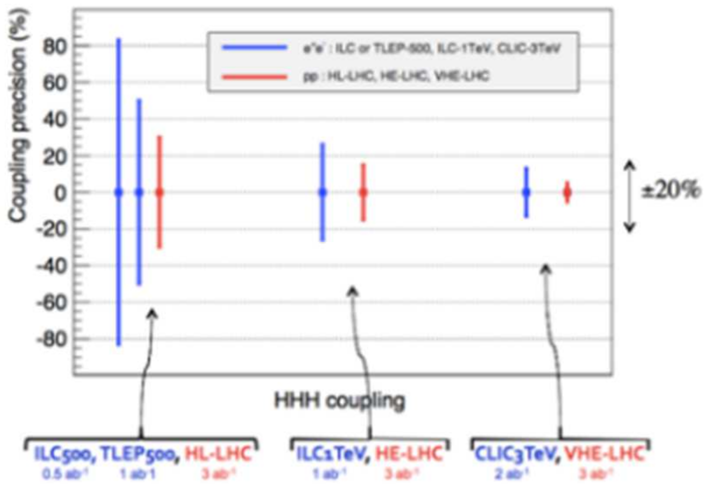
x10-400

FCC pp



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

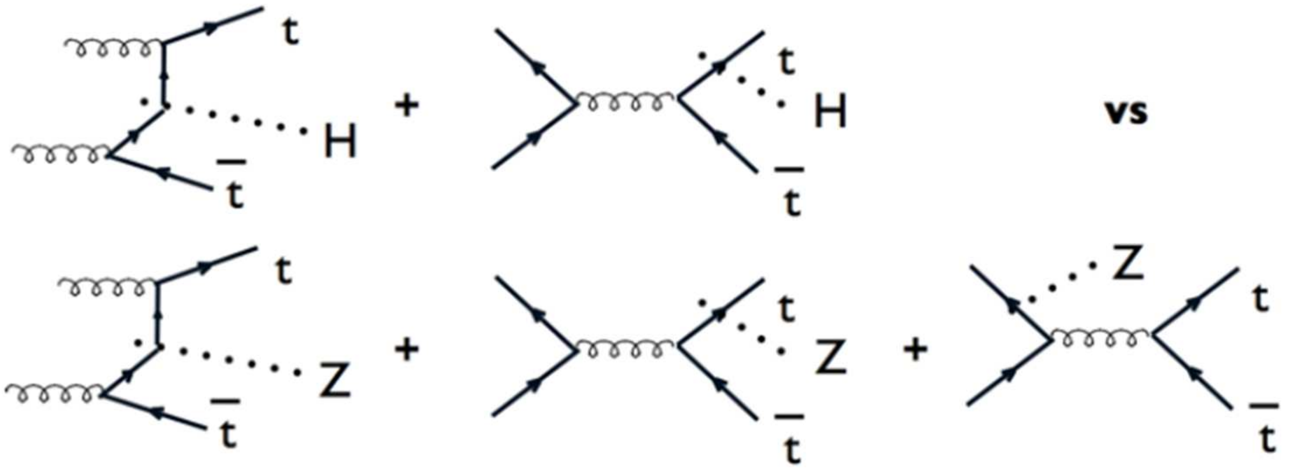
arXiv:1310.8361



10

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

ttH / ttZ



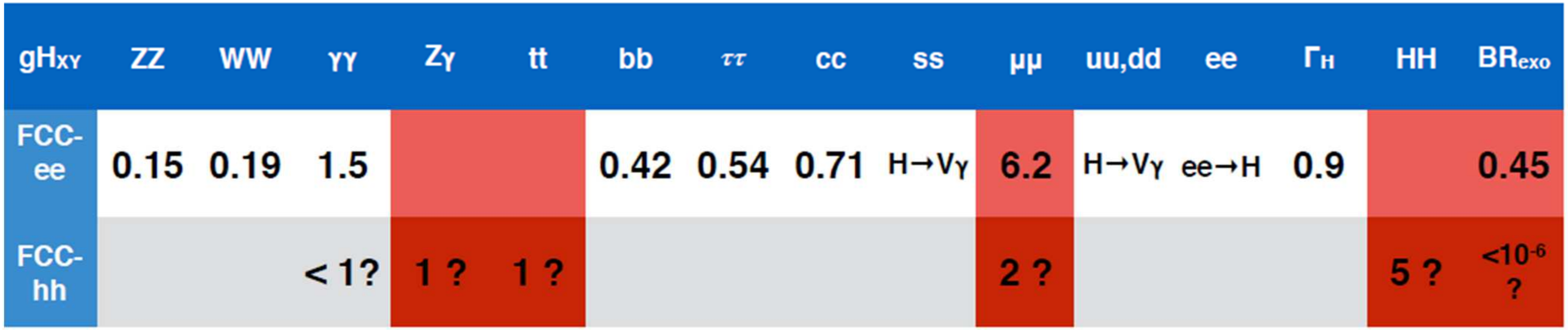
➡ Theoretical uncertainties cancel mostly

- 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



gH_{XY}	ZZ	WW	γγ	Zγ	tt	bb	$\tau\tau$	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

CONCLUSIONS for the HIGGS boson

1. The Higgs boson is the first spin 0 elementary particle ever found.

2. It plays a very particular role in linking a property of the vacuum (Higgs vev) with the masses of the SM particles

(NB what about the neutrinos?)

3. We must study it as well as we can!

4. Many Higgs factories have been discussed.
The best line seems to be the combination of
a High Luminosity, circular e+e- collider in 240-350 GeV region
and a High Energy High Luminosity pp collider (50-100 TeV Ecm)

➔ this is the philosophy of CEPC/SPPS and of the FCC (ee then pp) which, in combination, offer ‘invincible’ potential of investigation of the Higgs physics

FCC
hh ee he

Potentially the first step
in the FCC history

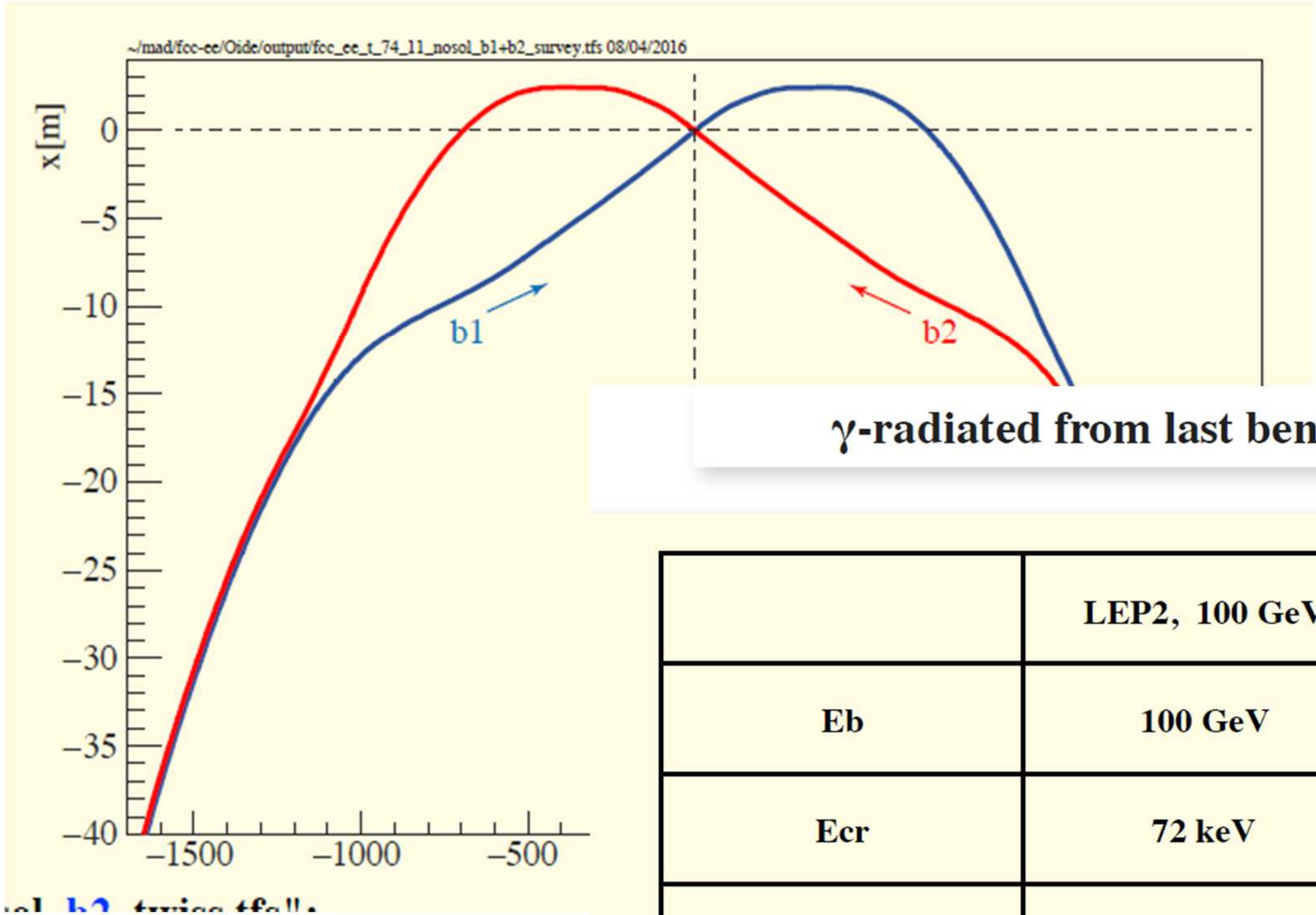
Experiments at FCC-ee

Sessions : -- MDI on Tuesday 8:30
-- FCC-ee experiments on Thursday 13:30-17:00

Some of the main Challenges

M. Boscolo

- Synchrotron Radiation is the main constraint for IR design and it drives the IR optics and layout.
- Feasibility of magnetic system -main detector magnet, final focus elements, compensation magnets- has to be investigated, also with R&D.
- Luminosity measurement, as well as other particle detectors, are part of the IR design, challenge: very close to IP.
- Accelerator and IP Backgrounds: full simulation to check detector sustainability and design proper masking.
- Underground infrastructure is a challenge it itself, of course, together with MDI group compatibility with FCC-hh option has to be assured.



H. Burkhardt

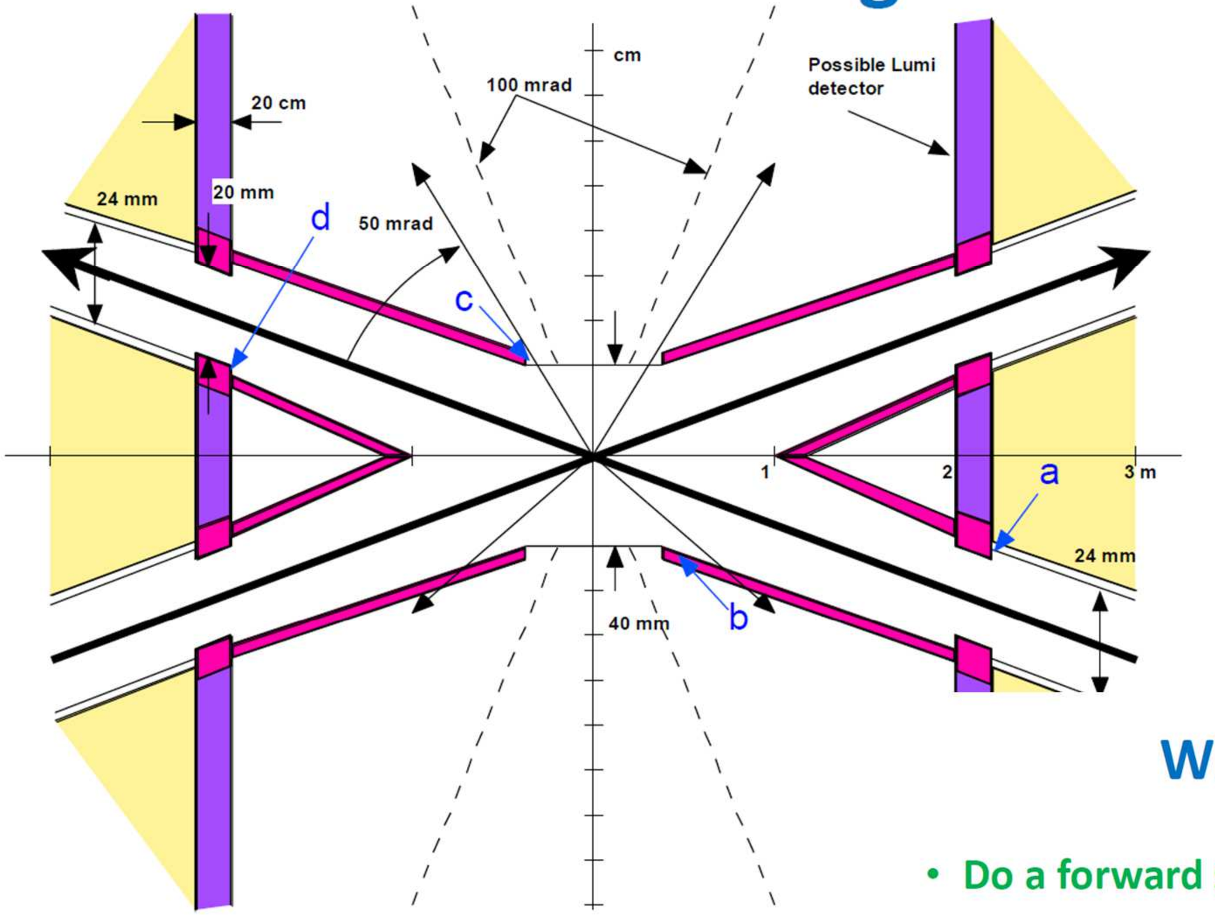
γ-radiated from last bend towards IP

	LEP2, 100 GeV	FCCee_t_74_11 175 GeV
Eb	100 GeV	175 GeV
Ecr	72 keV	100 keV
bunch X freq	45 kHz	180 kHz
γ's / crossing	3E+11	4E+11
γ's Σ energy / crossing	7.e6 GeV	1.2e7 GeV

γ rates and energies from last bend now of same order of magnitude as LEP2

Asymmetric IR design solves
1. The booster bypass
2. The SR problem comes back to LEP levels.
3. can start looking in detail

Lumi detection angles



M. Sullivan

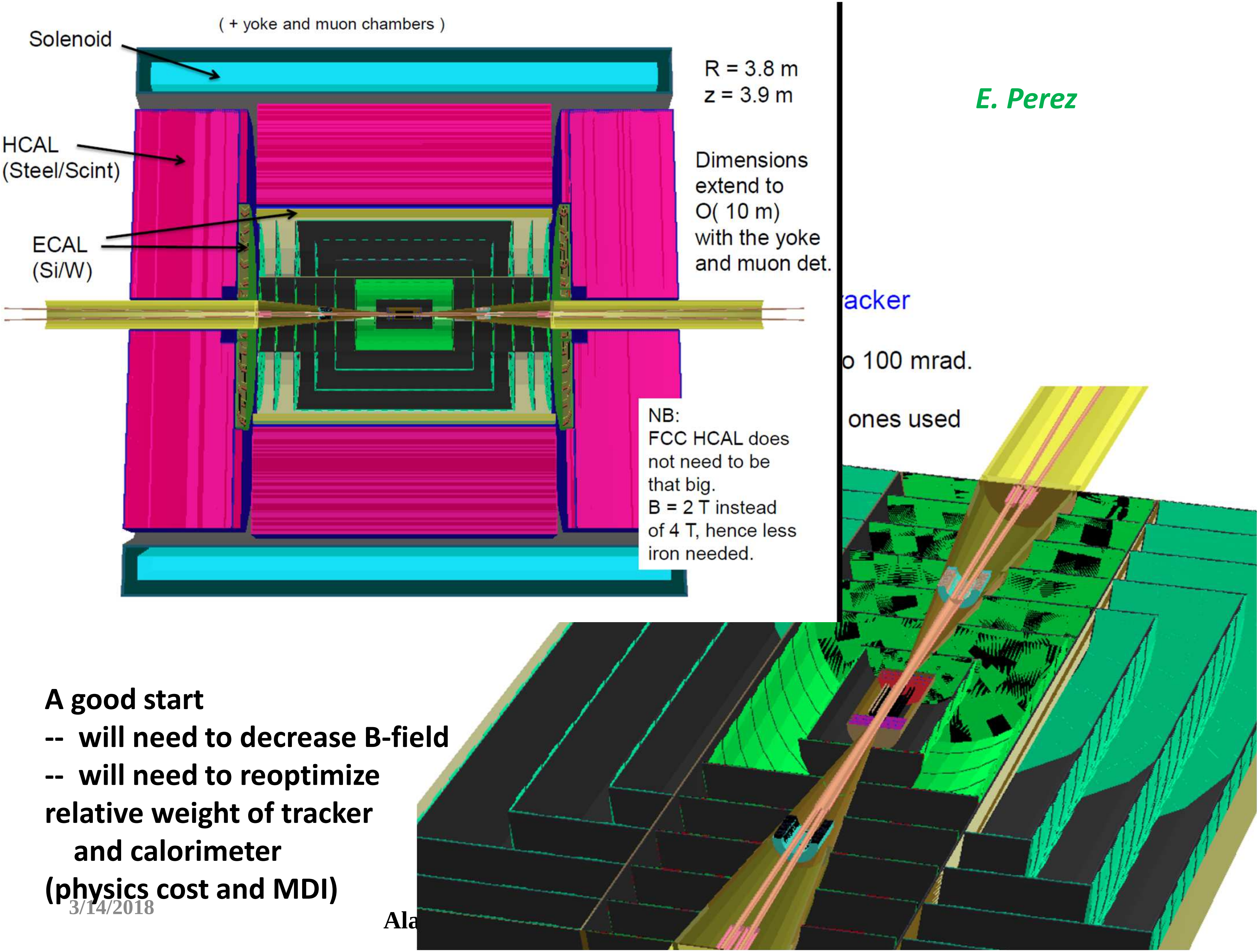
Started from hardest (tt machine)

What to do next

- Do a forward scatter simulation ✓
- Look at Z machine parameters ✓
- Check what a higher field soft bend does
  - Try this at the Z

Looks like it should be fine

- Look at Higgs machine parameters



R = 3.8 m
z = 3.9 m

Dimensions extend to O(10 m) with the yoke and muon det.

NB:
FCC HCAL does not need to be that big.
B = 2 T instead of 4 T, hence less iron needed.

E. Perez

acker

o 100 mrad.

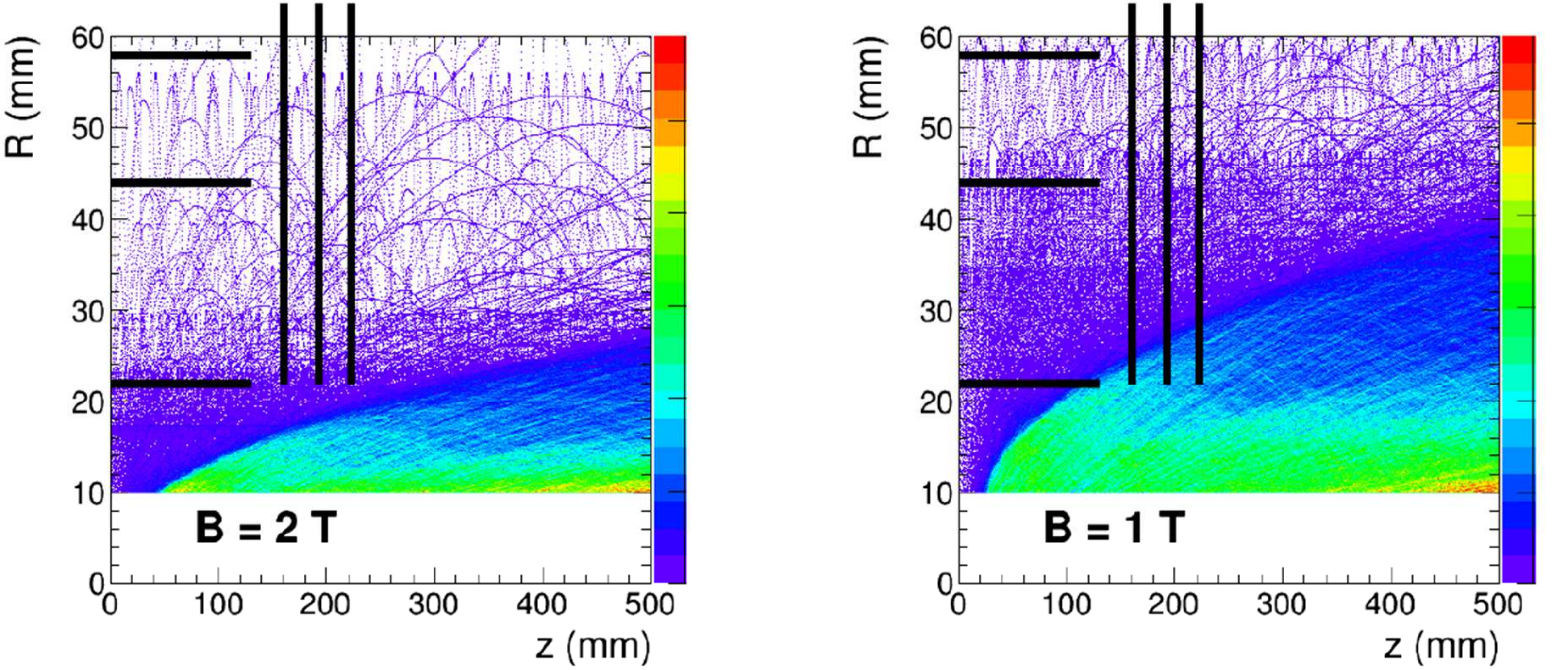
ones used

A good start
-- will need to decrease B-field
-- will need to reoptimize relative weight of tracker and calorimeter
(physics cost and MDI)

Conclusions similar to M. Sullivan: VTX detector at ~2cm from IP.

Trajectories of e+/- pairs in the 2T field

Helicoidal trajectories of the e+/- pairs in the field of the experiment :



With the nominal value of B = 2 T and innermost layer of VXD at 2.2 cm :
VXD avoids the hot region

Luminosity measurement

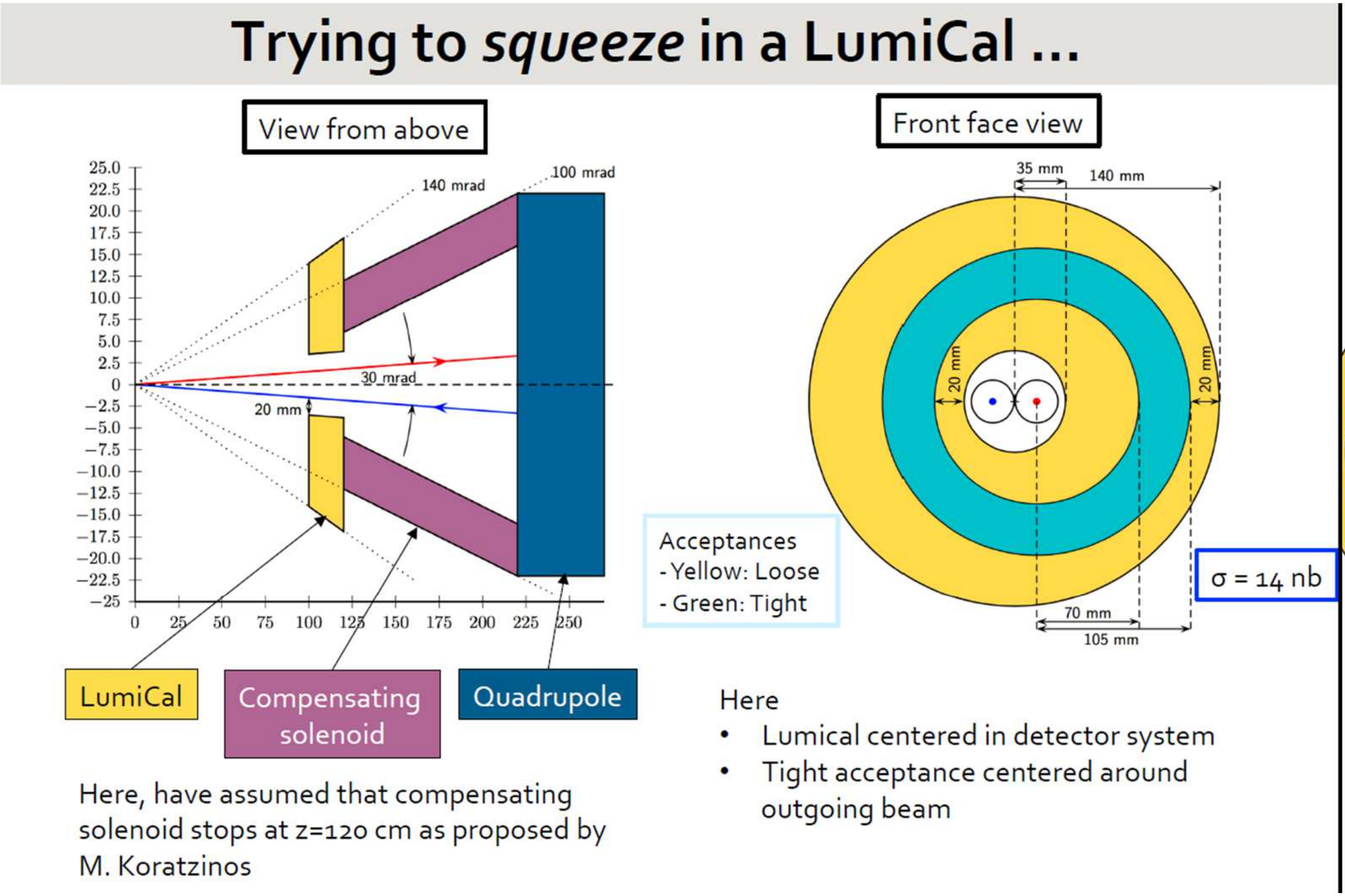
M. Dam

-- thanks to high luminosity can use two large angle QED processes

e+e- → γγ and e+e → e+e-

-- need theoretical evaluation of e+e- → γγ @ 10^{-4} precision

-- at and around Z pole need low angle Bhabha :

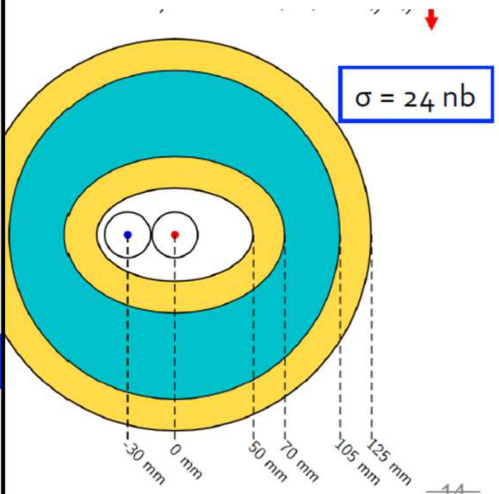


Trying to *squeeze* in a LumiCal ...

Acceptances
- Yellow: Loose
- Green: Tight

Here, have assumed that compensating solenoid stops at z=120 cm as proposed by M. Koratzinos

Here
- Lumical centered in detector system
- Tight acceptance centered around outgoing beam



α_s from hadronic W decays at FCC-ee

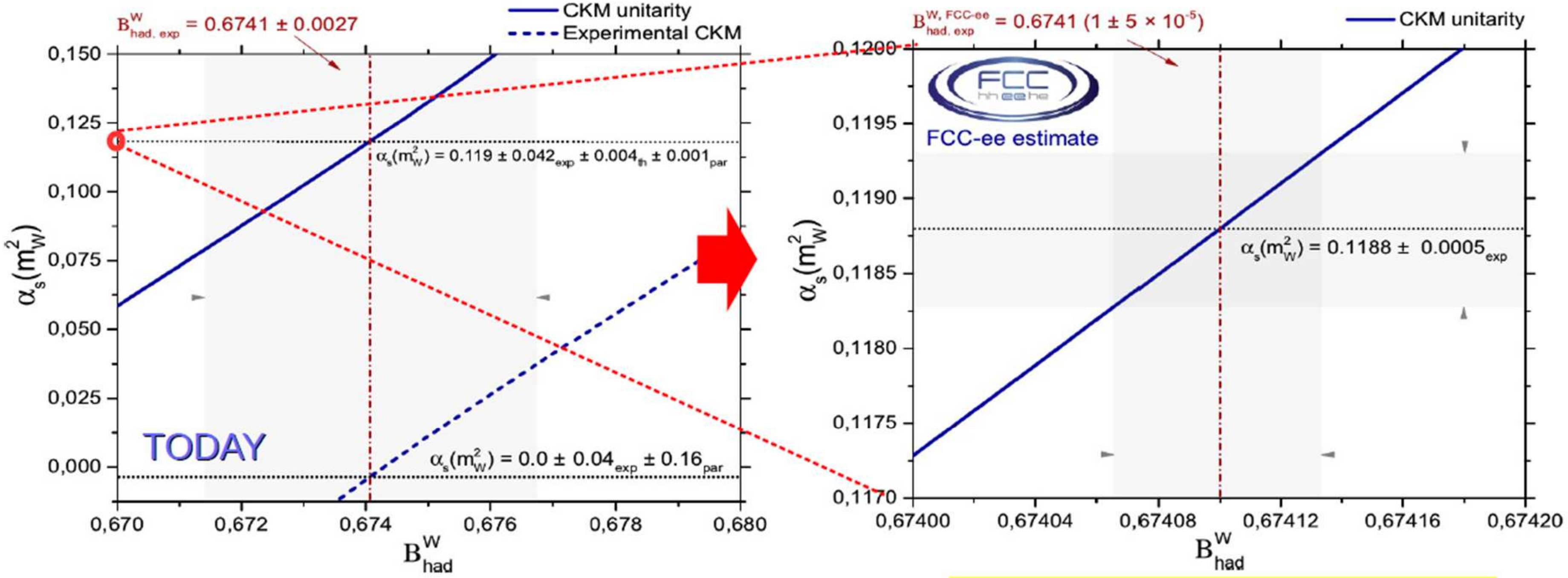
[d'Enterria,Srebre, arXiv:1603.06501]

- Hadronic W width (BR) known at N^{3}LO (NNLO). Sensitivity to α_s (only beyond Born) requires exquisite experimental uncertainties:

$$\Gamma_{\mathrm{W,had}} = \frac{\sqrt{2}}{4\pi} G_{\mathrm{F}} m_{\mathrm{W}}^3 \sum_{\mathrm{quarks\ i,j}} |V_{\mathrm{i,j}}|^2 \left[1 + \sum_{\mathrm{k=1}}^{4} \left(\frac{\alpha_{\mathrm{s}}}{\pi} \right)^k + \delta_{\mathrm{electroweak}}(\alpha) + \delta_{\mathrm{mixed}}(\alpha\alpha_{\mathrm{s}}) \right]$$

- Current Γ_W measurement yields poor extraction: $\delta\alpha_s$~25%

- FCC-ee prospects: Huge $e^+e^- \to WW$ stats (10^8, $\times 10^3$ LEP): $\delta\alpha_s < 0.2\%$



$\alpha_s(M_Z) = 0.117 \pm 0.030_{(\mathrm{exp})}$
$\pm\ 0.003_{(\mathrm{th})} \pm 0.001_{(\mathrm{par,CKM=1})}$

$\alpha_s\ (M_Z) = 0.1188 \pm 0.0002_{(\mathrm{exp})}$

$R_W \equiv \mathcal{B}^W_{\mathrm{had}}/\mathcal{B}^W_{\mathrm{lep}} = \mathcal{B}^W_{\mathrm{had}}/(1 - \mathcal{B}^W_{\mathrm{had}})$ in three $e^+e^- \to W^+W^-$ final states ($\ell\nu\ \ell\nu$, $\ell\nu$ qq, qq qq)

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:

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

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

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

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

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

Combining the two above, a realistic target precision would be

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

Present W.A.

$\alpha_s(M_Z)= 0.1181 \pm 0.0013$

D. Enterria

Workshop on α_S sept 2015

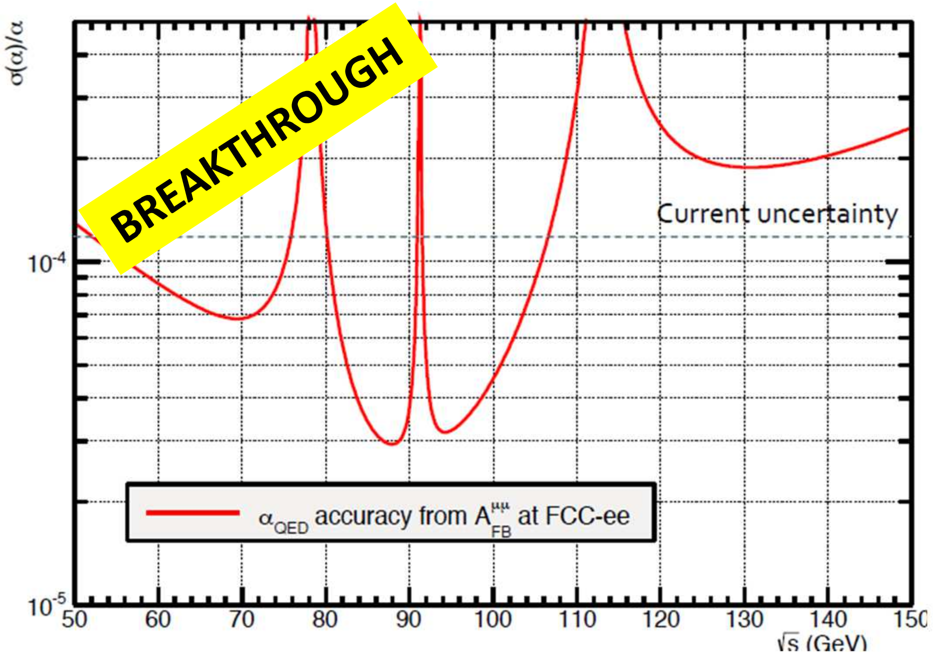
D. d'Enterria, P.Z. Skands (eds.)

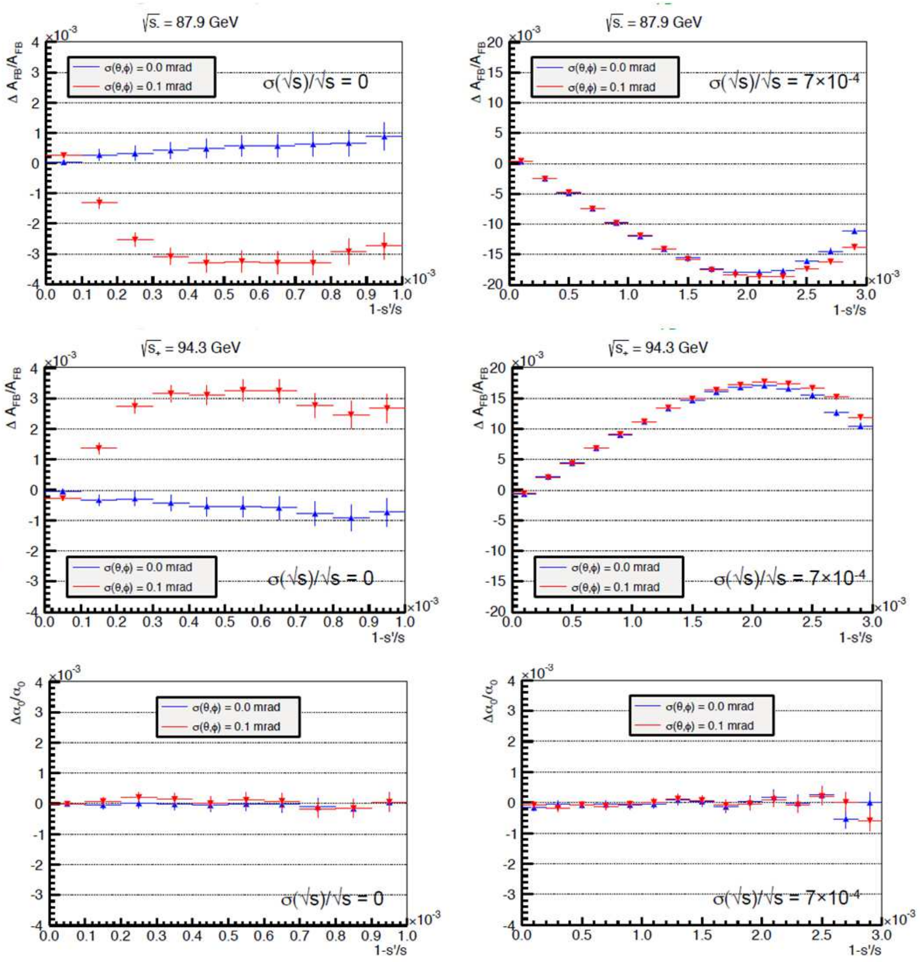
arXiv:1512.05194

Unwanted error

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

Physics discoveries





- Total bias on $\alpha_{QED}(m_Z^2)$ of the order of 8×10^{-6}

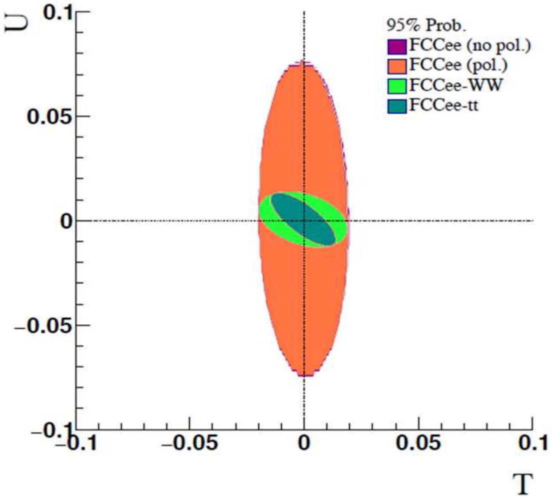
P. Janot discovered that one can measure $\Delta\alpha_{QED}(m_z)$ from measuring $A_{FB}^{\mu\mu}$ at +- 3 GeV from the Z peak. (Nice Z lineshape scan)

Further studies with S. Jadach shows error cancellation of +3 vs -3 points.

DO WE NEED LONGITUDINAL POLARIZATION?

A.Blondel

	$A_{FB}^{\mu\mu}$ @ FCC-ee		A_{LR} @ ILC
visible Z decays	10^{12}	visible Z decays	10^{9}
muon pairs	10^{11}	beam polarization	90%
$\Delta A_{FB}^{\mu\mu}$ (stat)	$3\ 10^{-6}$	ΔA_{LR} (stat)	$4.2\ 10^{-5}$
Δ E_{cm} (MeV)	0.1		2.2
$\Delta A_{FB}^{\mu\mu}$ (E_{CM})	$9.2\ 10^{-6}$	ΔA_{LR} (E_{CM})	$4.1\ 10^{-5}$
$\Delta A_{FB}^{\mu\mu}$	$1.0\ 10^{-5}$	ΔA_{LR}	$5.9\ 10^{-5}$
$\Delta\sin^2\theta^{lept}_W$	$5.9\ 10^{-6}$		$7.5\ 10^{-6}$



J. De Blas

	from $A_{FB}^{\mu\mu}$	LEP 2.10^7Z	SLC, 5.10^5 Z	$\Delta\alpha$= 0.00035	$\Delta\alpha$= 0.00003
$\Delta\sin^2\theta^{lept}_W$		$5.3\ 10^{-4}$	$2.6\ 10^{-4}$	$1.2\ 10^{-4}$	$1.\ 10^{-5}$
			W.A. $1.6\ 10^{-4}$		

All exceeds the limitation given by $\Delta\alpha(m_Z)$ (310^{-5}) or the needed precision for comparison with m_W (500keV)

But this precision on $\Delta\sin^2\theta^{lept}_W$ can only be exploited at FCC-ee!

At FCC-ee longitudinal polarization is more difficult and implies a significant reduction of luminosity. As far as we can tell today it is not justified

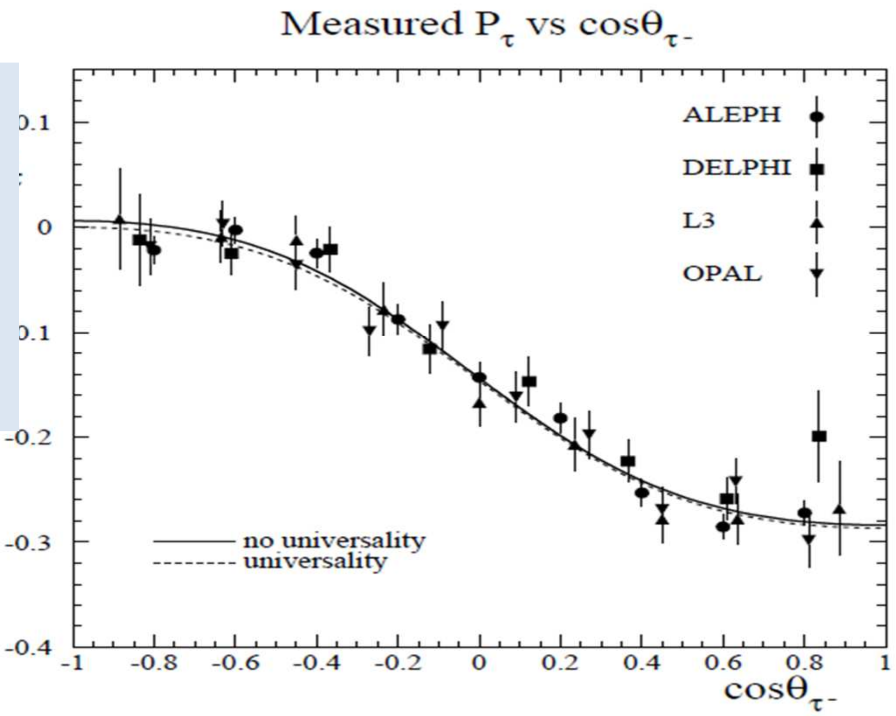
(similar conclusion by J. De Blas in pheno session)

The forward backward tau polarization asymmetry is very clean.
Dependence on E_{CM} same as A_{LR} negl.
At FCC-ee

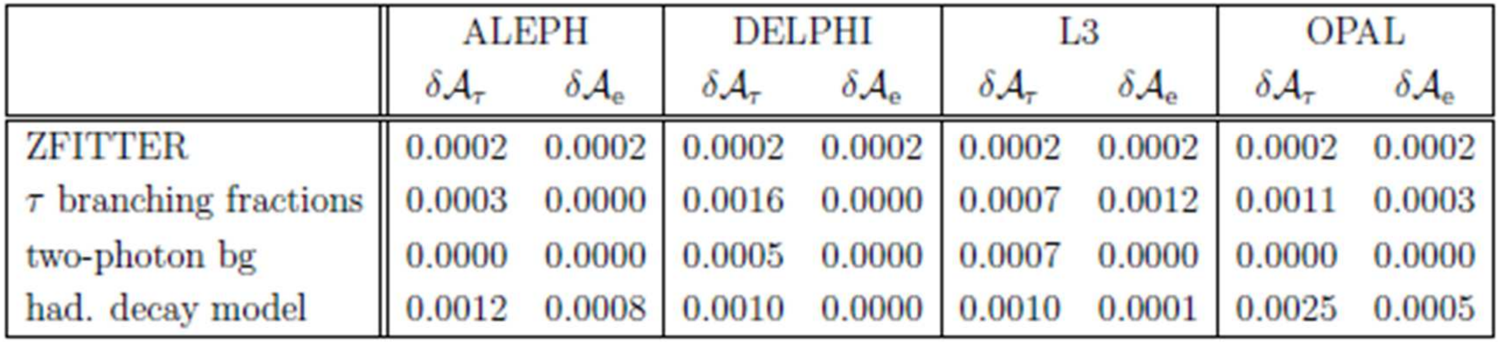
ALEPH data 160 pb^{-1} (80 s @ FCC-ee !)

Already syst. level of 610^{-5}on $\sin^2\theta_W$

much improvement possible
by using dedicated selection
e.g. tau→ π v to avoid had. model



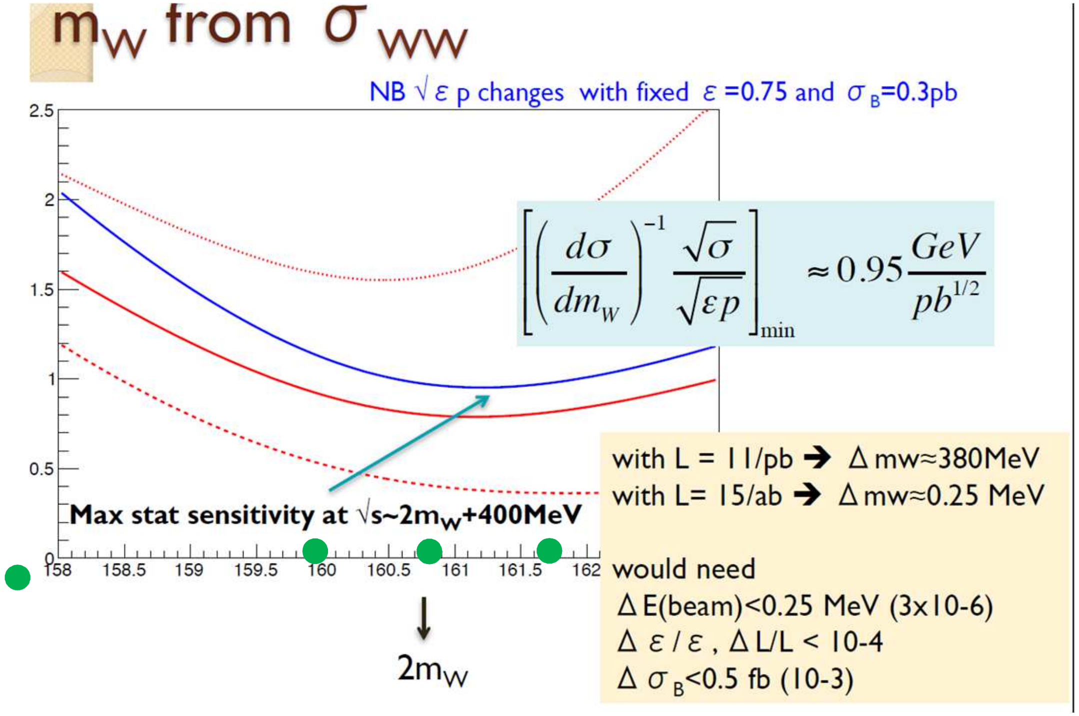
ure 4.7: The values of $\mathcal{P}_\tau$ as a function of $\cos\theta_{\tau^-}$ as measured by each of the LEP ex- riments. Only the statistical errors are shown. The values are not corrected for radiation, interference or pure photon exchange. The solid curve overlays Equation 4.2 for the LEP values of $\mathcal{A}_\tau$ and $\mathcal{A}_e$. The dashed curve overlays Equation 4.2 under the assumption of lepton universality for the LEP value of $\mathcal{A}_\ell$.



	ALEPH		DELPHI		L3		OPAL	
	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$
ZFITTER	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
τ branching fractions	0.0003	0.0000	0.0016	0.0000	0.0007	0.0012	0.0011	0.0003
two-photon bg	0.0000	0.0000	0.0005	0.0000	0.0007	0.0000	0.0000	0.0000
had. decay model	0.0012	0.0008	0.0010	0.0000	0.0010	0.0001	0.0025	0.0005

Table 4.2: The magnitude of the major common systematic errors on $\mathcal{A}_\tau$ and $\mathcal{A}_e$ by category for each of the LEP experiments.

P. Azzuri started optimizing
The W threshold scan
for measurement of
m_W and Γ_W
Smooth, plenty of points
with half integer spin tunes ●



m_W from σ_{WW}

NB $\sqrt{\varepsilon p}$ changes with fixed ε =0.75 and σ_B=0.3pb

$$\left[\left(\frac{d\sigma}{dm_W}\right)^{-1}\frac{\sqrt{\sigma}}{\sqrt{\varepsilon p}}\right]_{\min}\approx 0.95\frac{GeV}{pb^{1/2}}$$

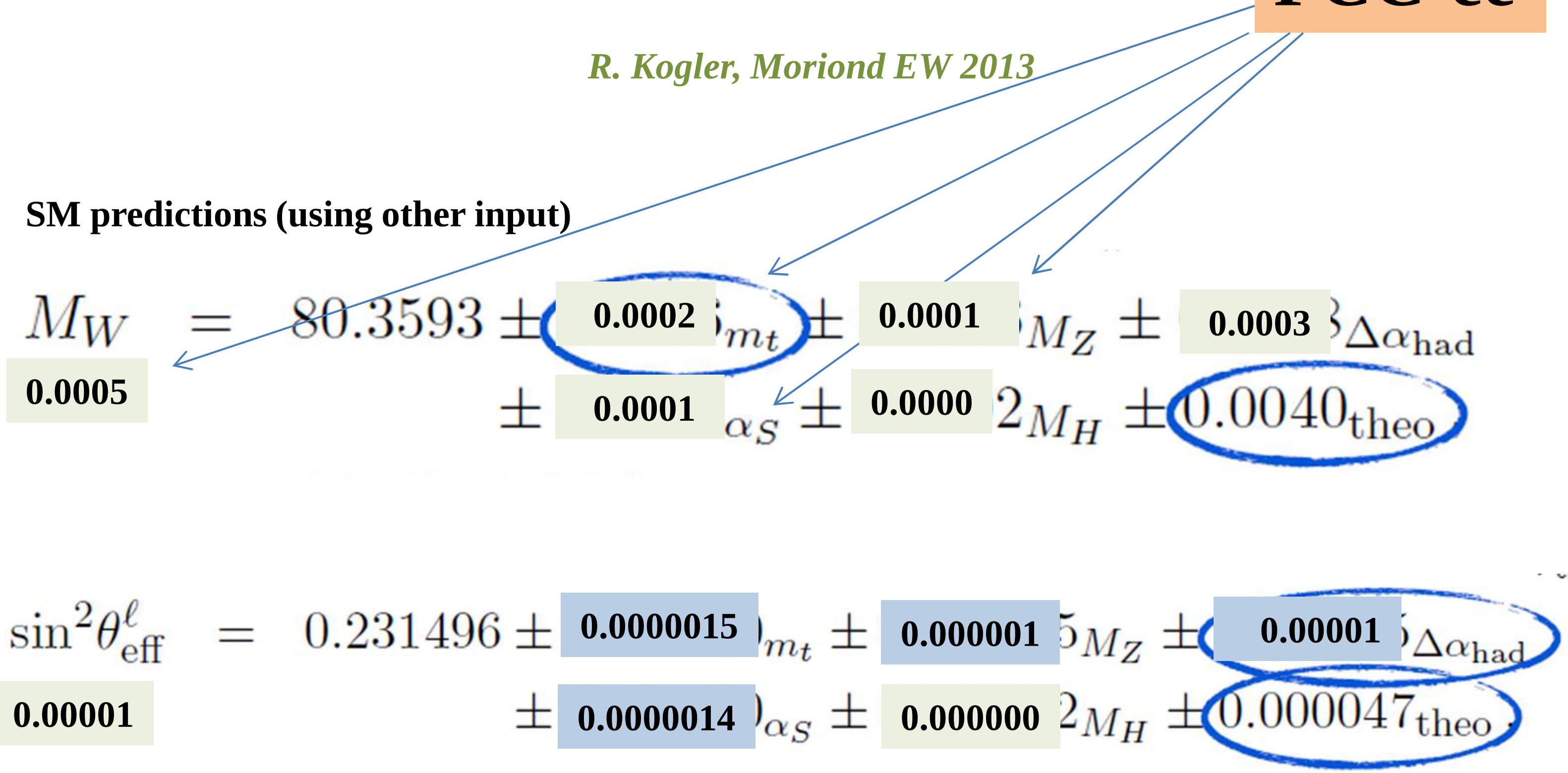
Max stat sensitivity at $\sqrt{s}$~$2m_W$+400MeV

with L = 11/pb → Δ mw≈380MeV
with L= 15/ab → Δ mw≈0.25 MeV

would need
Δ E(beam)<0.25 MeV (3x10-6)
Δ ε / ε , Δ L/L < 10-4
Δ σ_B<0.5 fb (10-3)

Statistical error on m_W will be O(300 keV)
next: background and *signal* cross-sections!

Theoretical limitations



FCC-ee

R. Kogler, Moriond EW 2013

SM predictions (using other input)

$$M_W = 80.3593 \pm 0.0002_{m_t} \pm 0.0001_{M_Z} \pm 0.0003_{\Delta\alpha_{\mathrm{had}}} \pm 0.0001_{\alpha_S} \pm 0.0000\,2_{M_H} \pm 0.0040_{\mathrm{theo}}$$

0.0005

$$\sin^2\theta^{\ell}_{\mathrm{eff}} = 0.231496 \pm 0.0000015_{m_t} \pm 0.000001\,5_{M_Z} \pm 0.00001_{\Delta\alpha_{\mathrm{had}}} \pm 0.0000014_{\alpha_S} \pm 0.000000\,2_{M_H} \pm 0.000047_{\mathrm{theo}}$$

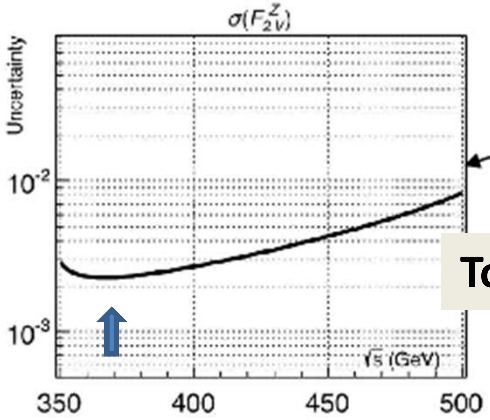
0.00001

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

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

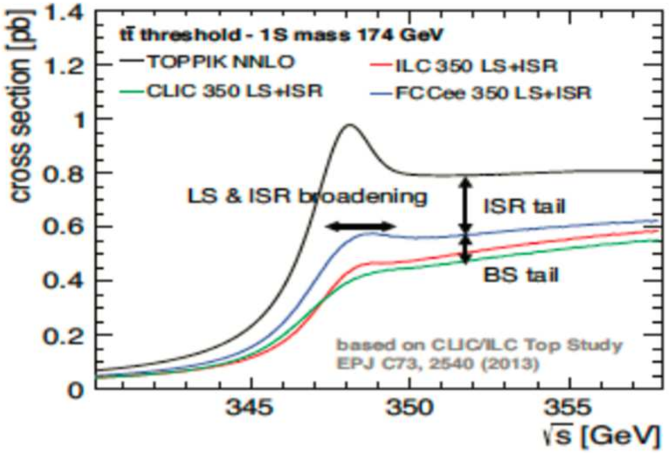
Top physics *Moftaba*

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



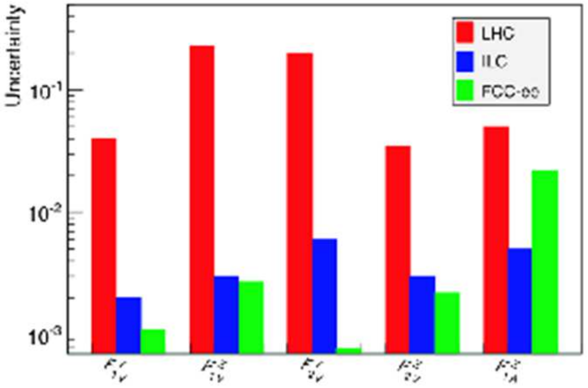
Typically best sensitivity just above production threshold

Top beam energy is 185 GeV



Top mas can be measured to O(10 MeV)
Beam energy calibration from WW, γZ, ZZ
Reduce th. errors due α_S meast @FCC-ee

Also:
CKM measurements
FCNC decays down to 10^{-6}
All luminosity can be used!



Patrick Janot
arXiv:1503.01325v2

FCC-ee discovery potential

Of course discovery depends on the goodwill of nature.
A few things that FCC-ee could discover if is there :

EXPLORE 10 TeV energy scale (and beyond) with Precision Measurements

-- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass)
$m_{Z,}$ m_W, m_{top} , $\sin^2 \theta_w^{eff}$, R_b , α_{QED} (m_z) α_s (m_z), Higgs and top couplings

DISCOVER a violation of flavour conservation
-- ex FCNC (Z --> $\mu\tau$, $e\tau$) in 5 10^{12} Z decays.
+ flavour physics (10^{12} bb events)

DISCOVER dark matter as «invisible decay» of H or Z

DISCOVER very weekly coupled particle in 5-100 GeV energy scale
such as: Right-Handed neutrinos, Dark Photons etc…

…..

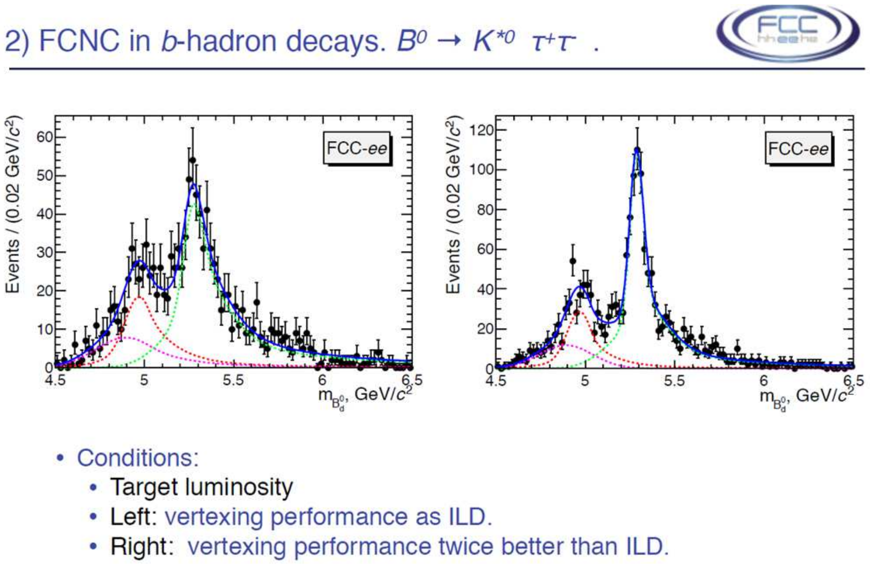
S. Monteil

Leptonic FCNCs

SM from neutrino oscillations:

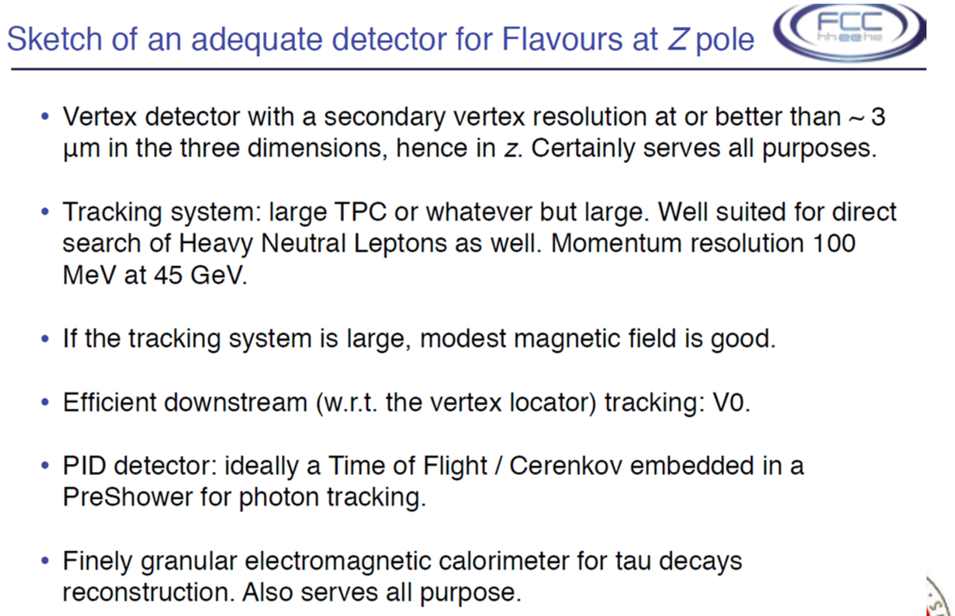
$$\mathcal{B}(Z \to e^{\pm}\mu^{\mp}) \sim \mathcal{B}(Z \to e^{\pm}\tau^{\mp}) \sim 10^{-54} \text{ and } \mathcal{B}(Z \to \mu^{\pm}\tau^{\mp}) \sim 4.10^{-60}$$

FCC-ee is highly competitive for $Z \to e\tau, \mu\tau.$
potential sensitivity 10^{-12} How far can we go?
First investigation of backgrounds. Z→ ππ Z→ W*W
Backgrounds at level of 10^{-8} , but do not have life time (unlike taus)
Further analysis will need simulation.



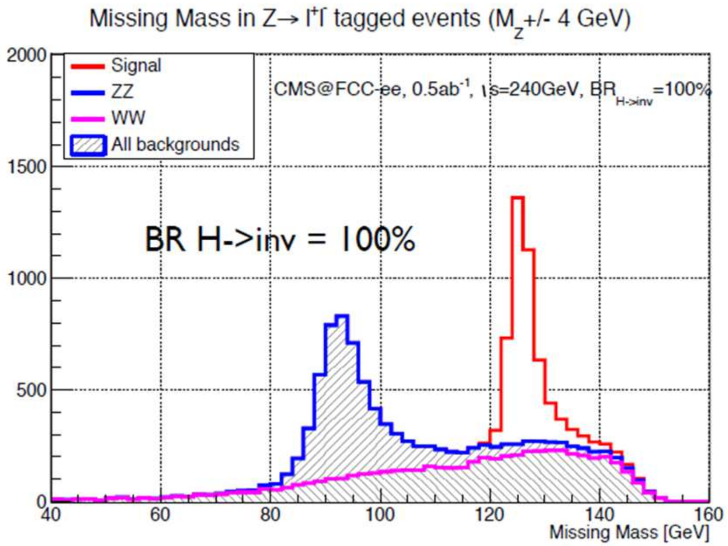
2) FCNC in *b*-hadron decays. $B^0 \to K^{*0}\ \tau^+\tau^-$.

- Conditions:
  - Target luminosity
  - Left: vertexing performance as ILD.
  - Right: vertexing performance twice better than ILD.



Sketch of an adequate detector for Flavours at *Z* pole

- Vertex detector with a secondary vertex resolution at or better than ~ 3 µm in the three dimensions, hence in *z*. Certainly serves all purposes.
- Tracking system: large TPC or whatever but large. Well suited for direct search of Heavy Neutral Leptons as well. Momentum resolution 100 MeV at 45 GeV.
- If the tracking system is large, modest magnetic field is good.
- Efficient downstream (w.r.t. the vertex locator) tracking: V0.
- PID detector: ideally a Time of Flight / Cerenkov embedded in a PreShower for photon tracking.
- Finely granular electromagnetic calorimeter for tau decays reconstruction. Also serves all purpose.



M. De Gruttola

The Higgs invisible width

Potential: discovery of Dark Matter

Target: limit at 10^{-3} level

UNIQUE to e+e- : ability to tag event as ZH even if do not see the Higgs decay

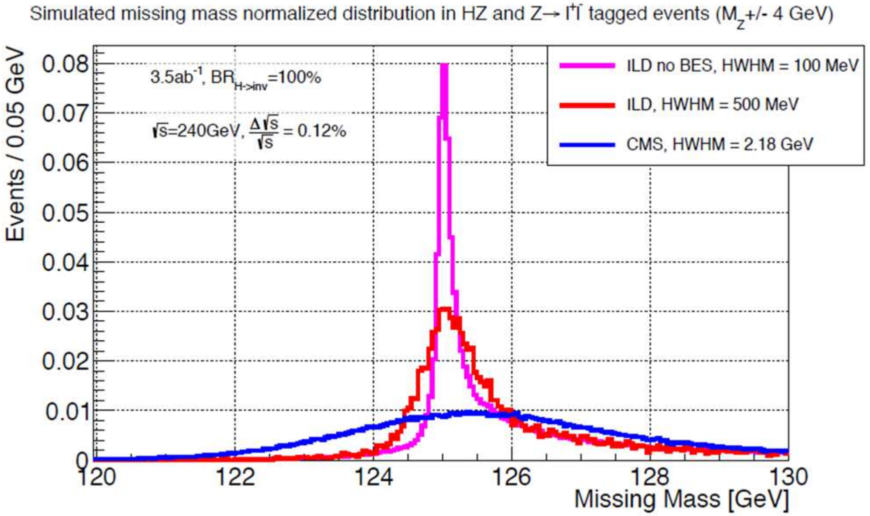
Started with Z-> leptons

Studied the effect of detector resolution

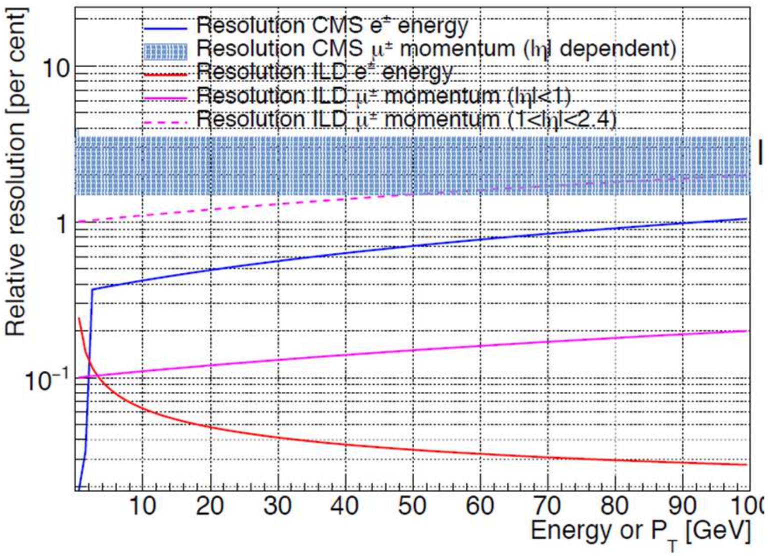
Compare CMS with ILD

Study effect of beam energy spread

Next step : look at Z→ qq tag (evts X 20)



CMS vs ILD (2)



Main conclusions

MDI acc-exp working group started and *working* !

-- asymmetric beam crossing has brought SR problem back to real axis
-- soon will be in position to attack magnet integration
-- Luminosity measurement requires attention but problem is well posed
-- detector simulation study (with great help from CLIC work!) started

Detectors and experiments will take usefully all luminosity the machine can give (pile-up< 10^{-3})

-- «baseline» is a good start, more welcome (we won't do anything that prevents it!)
-- discovery potential is in precision measurements, rare decays, invisible width (detector!)
-- top beam energy needs to be set to 185 GeV for top couplings measurements

Continuous beam energy calibration at O(10^{-6}) precision @ Z and W (resonant depolarization)

➔ central to precision measurements
➔ need a joint acc-exp working group to converge on strategy.

No obvious need identified so far for longitudinal polarization at any energy

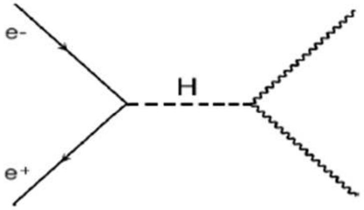
-- top quark couplings can be measured well using top quark polarization
-- high statistics @ Z (and e.g. final state polarization (tau))
should allow precision on $\sin^2\theta^{lept}{}_W$ with more than adequate precision < 10^{-5}
-- high luminosity brings much much more $\Delta\alpha_{QED}(m_z)$ @ 310^{-5} , $\Delta\alpha_S(m_z)$ @ ~10-^{4}

Monochromatization for s-channel e+e- → Higgs @ 125.2 GeV looks promising (off sessions)

Electron Yukawa via s-channel $e^+e^- \to H$ at FCC-ee

[d'Enterria, Wojcik, Aleksan]

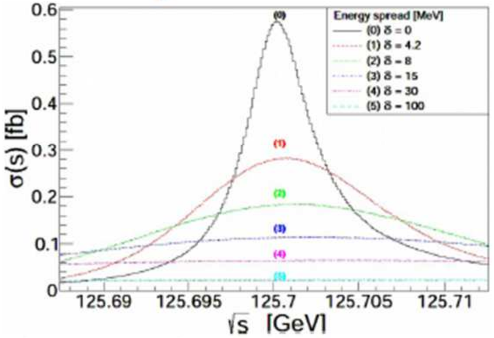
- Resonant s-channel Higgs production at $\sqrt{s}$ = 125 GeV has tiny cross sections:



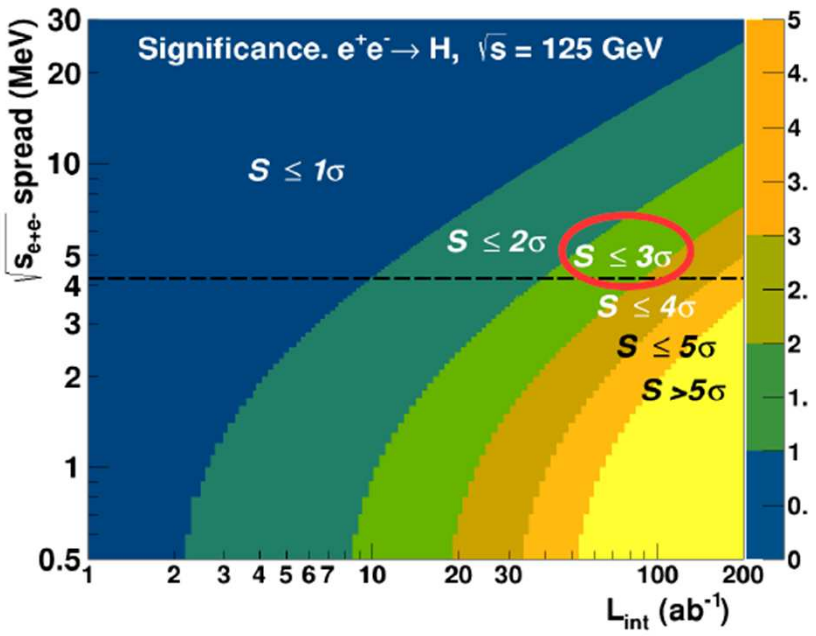
$\sigma(e^+e^-\to H)_{\text{Breit-Wigner}}$ = 1.64 fb

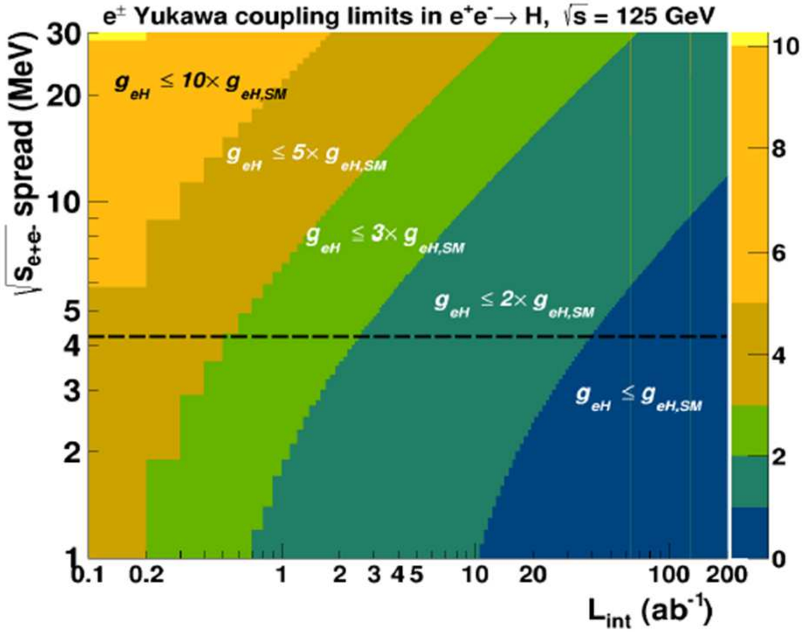
$\sigma(e^+e^-\to H)_{\text{visible}}$ = 290 ab (including ISR + $\sqrt{s}_{\text{spread}} = \Gamma_H$ = 4.2 MeV)

Mono-chromatization required to achieve $\sqrt{s}_{\text{spread}} \sim \Gamma_H$



- Preliminary study for signal + backgrounds in 10 Higgs decay channels.
- Significance & limits on e-Yukawa coupling:





3σ observation requires $L_{\text{int}} = 90\ \text{ab}^{-1}$

$L_{\text{int}} = 10\ \text{ab}^{-1}$: $S \approx 0.7$, $\text{BR(Hee)} < 2.8\times\text{BR}_{\text{SM}}$

$g_{eH} < 1.7\times g_{eH,SM}$ (95% CL)