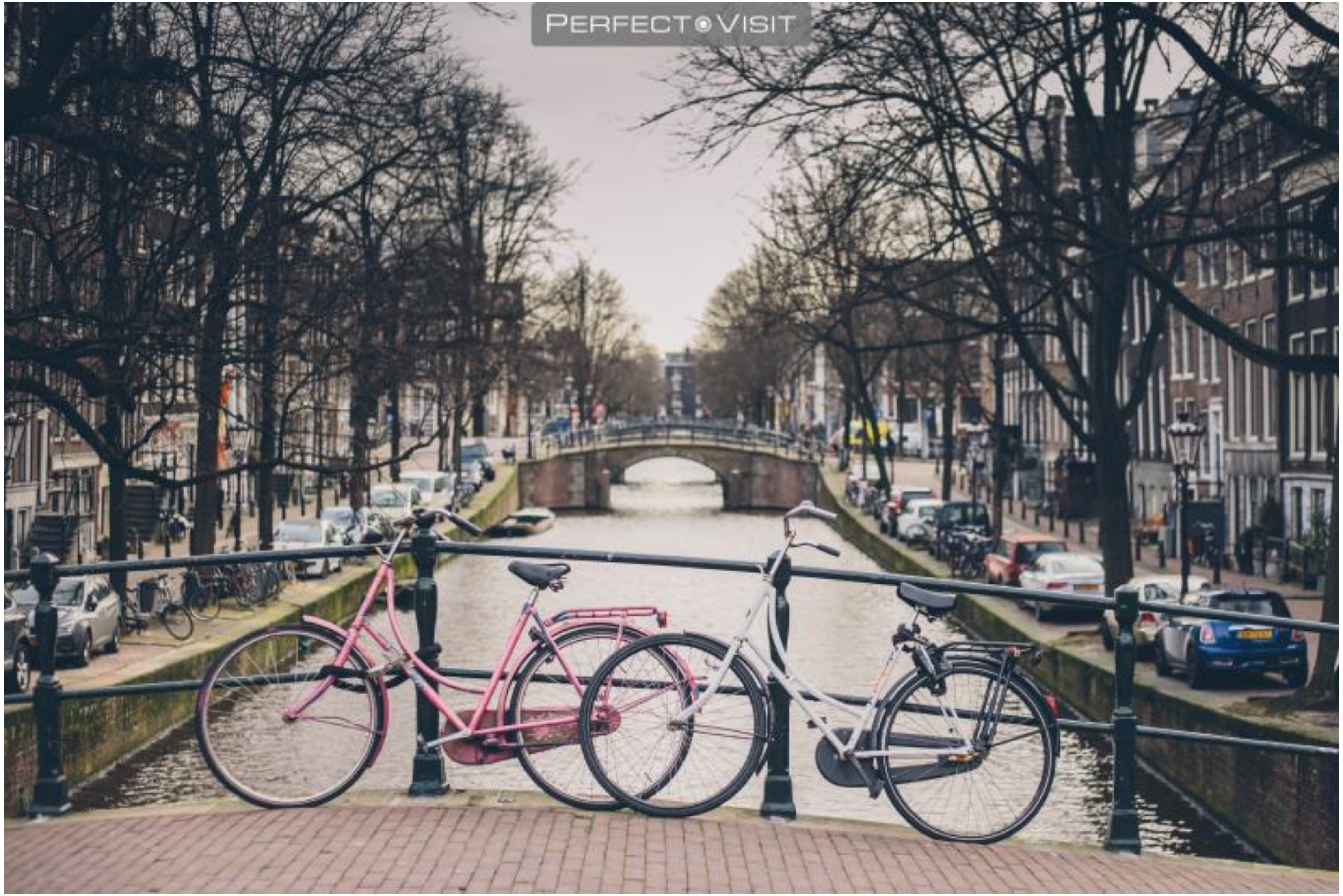
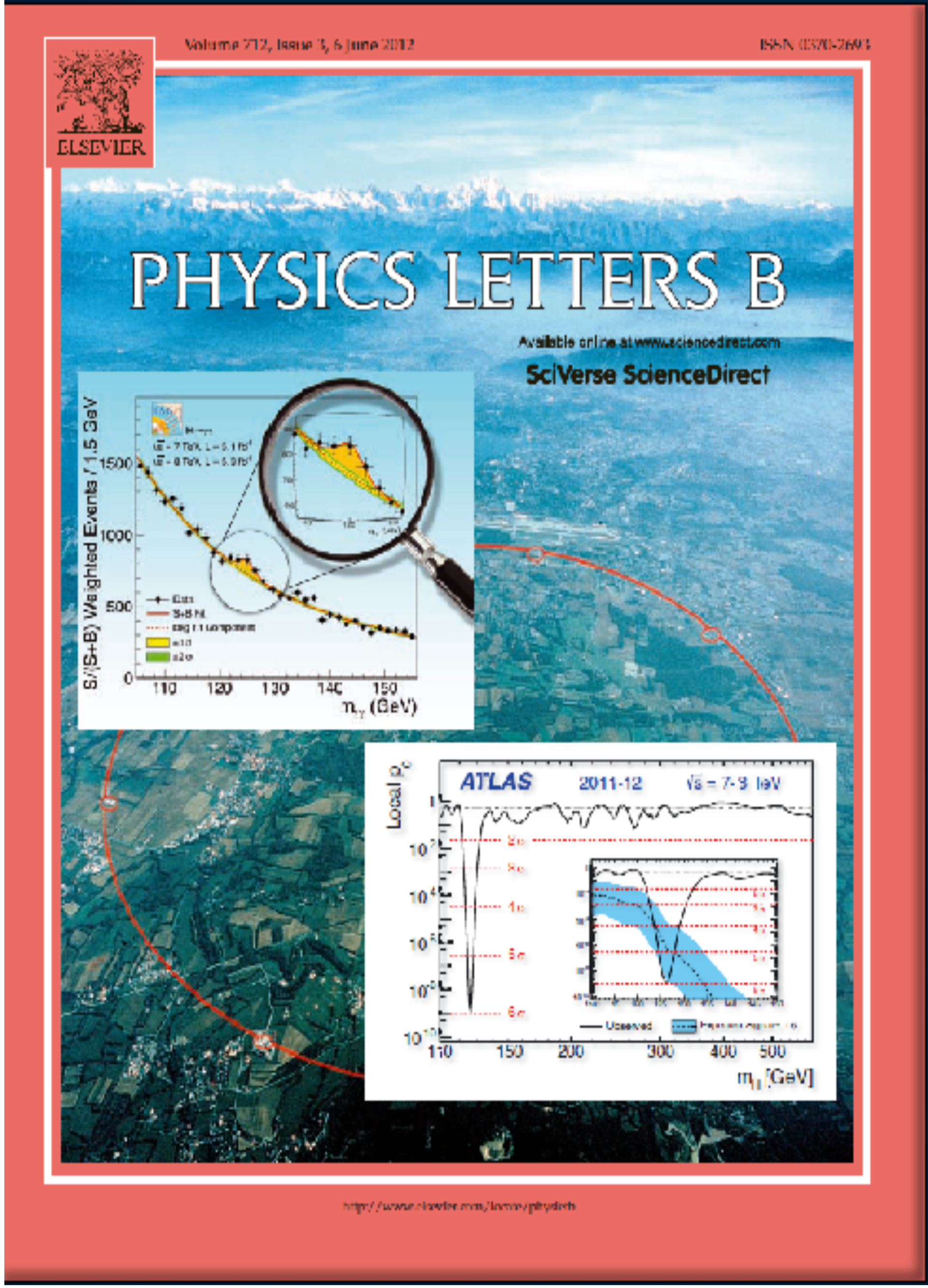
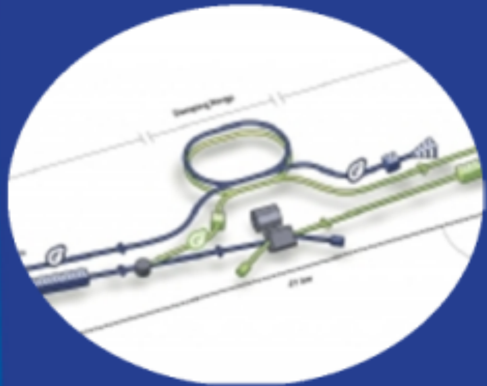
HIGGS FACTORIES



THREE YEARS ALREADY



Linear Colliders



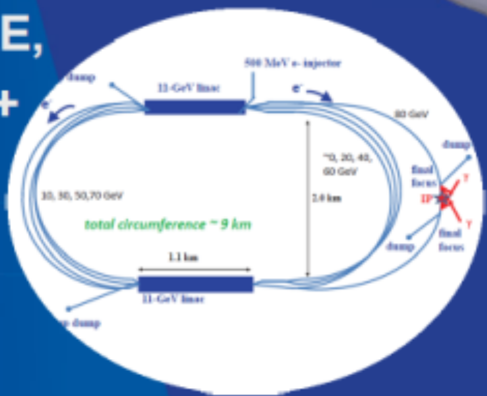
ILC
CLIC
SLC-type
Adv. Concepts

Circular e^+e^- Colliders

LEP3
TLEP
Super-Tristan
FNAL Site-filler
IHEP, +
CEPC
FCC-ee

Higgs Factories

γ-γ Colliders

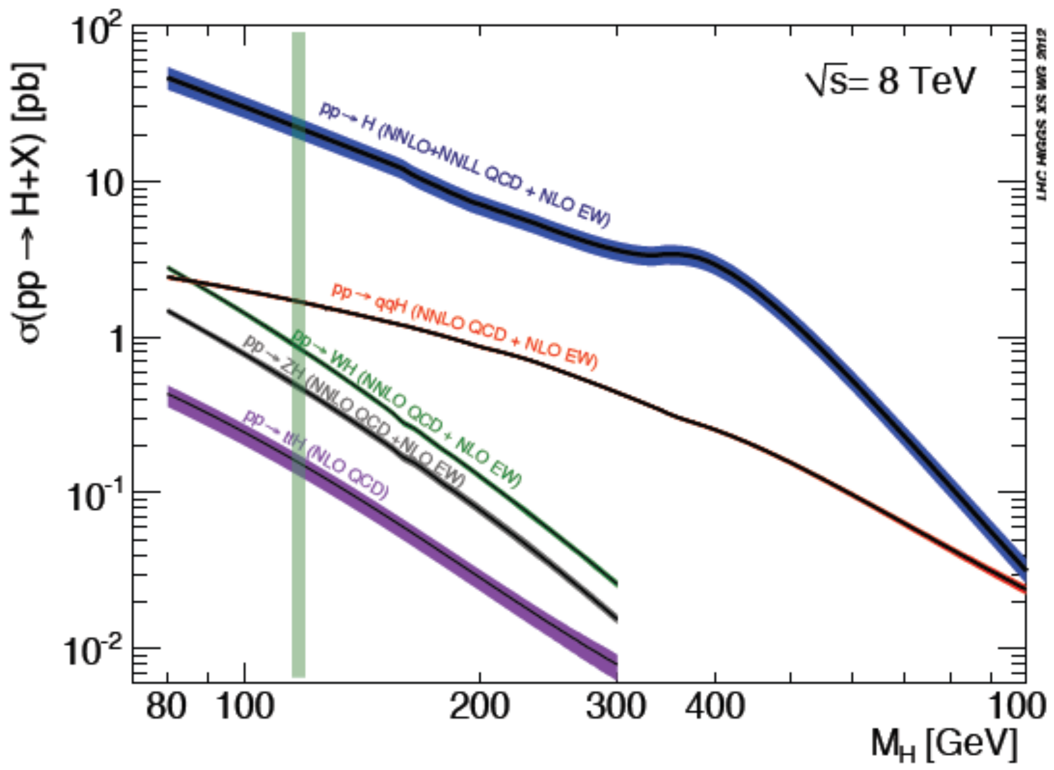


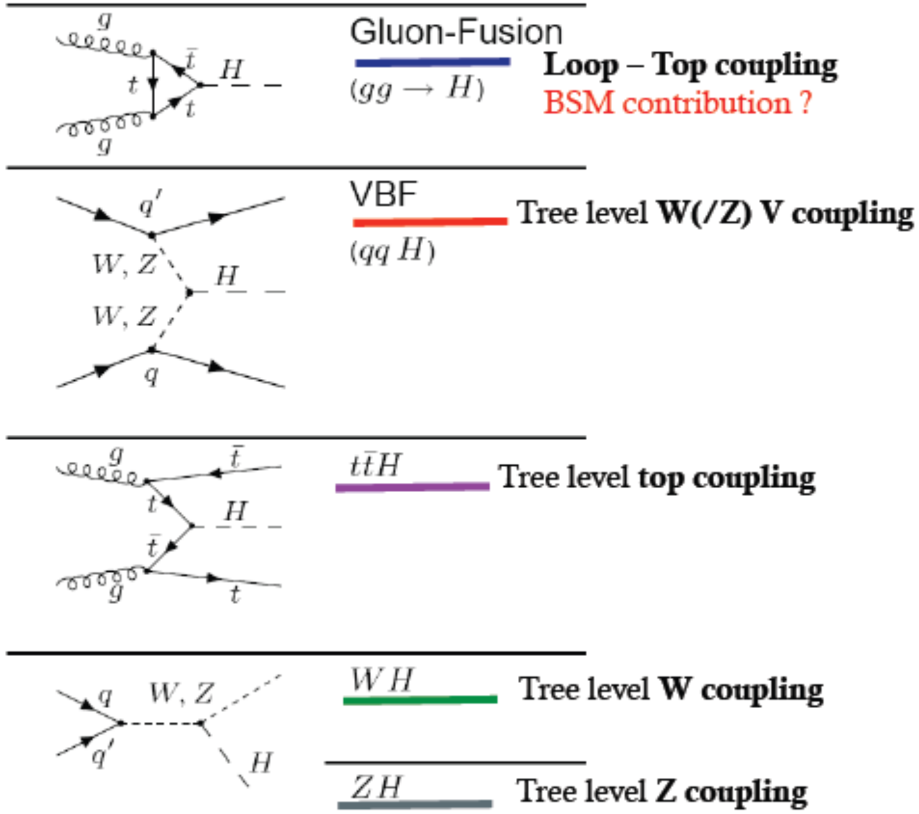
SAPPHIRE,
CLICHÉ, +
…

Muon Colliders

2

Fermilab





THE LHC is a Higgs Factory

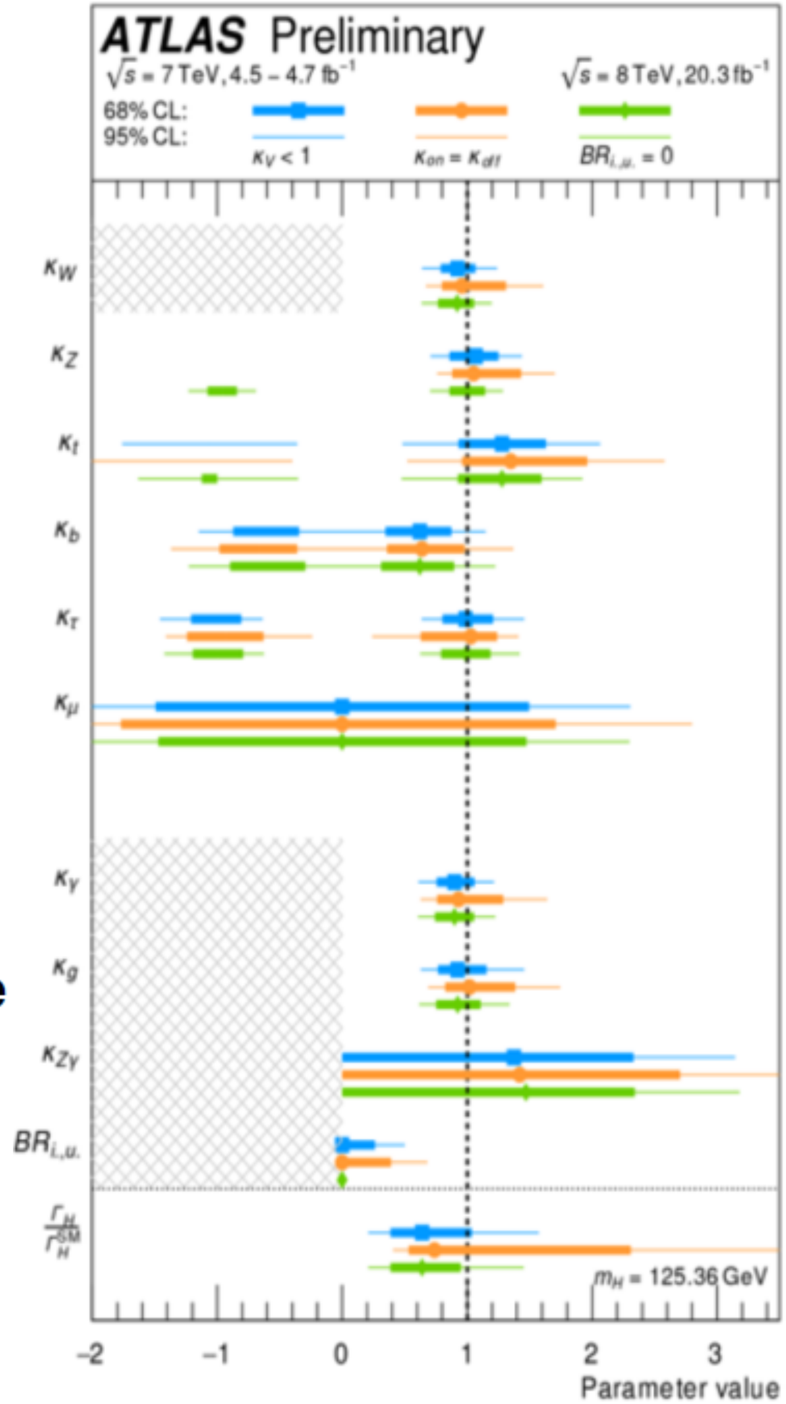
several Million Higgs already produced – more than most Higgs factory projects.
15 Higgs bosons / minute – and more to come (gain factor 3 going to 13 TeV)

Difficulties: several production mechanisms to disentangle and significant systematics in the production cross-sections σ_{prod} .
Challenge will be to reduce systematics by measuring related processes.

$\sigma_{i \to f}^{\text{observed}} \propto \sigma_{prod} \frac{(g_{Hi})^2 (g_{Hf})^2}{\Gamma_H}$ extract couplings to anything you can see or produce from if i=f as in WZ with H→ ZZ → absolute normalization

THE LHC is a Higgs Factory

- **Fantastic progress in last 3 years**
  - Observation in three boson channels
  - Evidence for fermion couplings
  - Precision mass measurements: 125.09 ± 0.24 GeV (ATLAS+CMS)
  - Spin/parity determined
  - Higgs total width from off-shell production
  - First results on differential cross sections
- **New particle looks more and more like the SM Higgs boson**
  - No evidence for non-SM decays
  - No evidence for additional Higgs bosons



THE LHC(13) and HL-LHC as Higgs Factory

CMS Projection for precision of Higgs coupling measurement

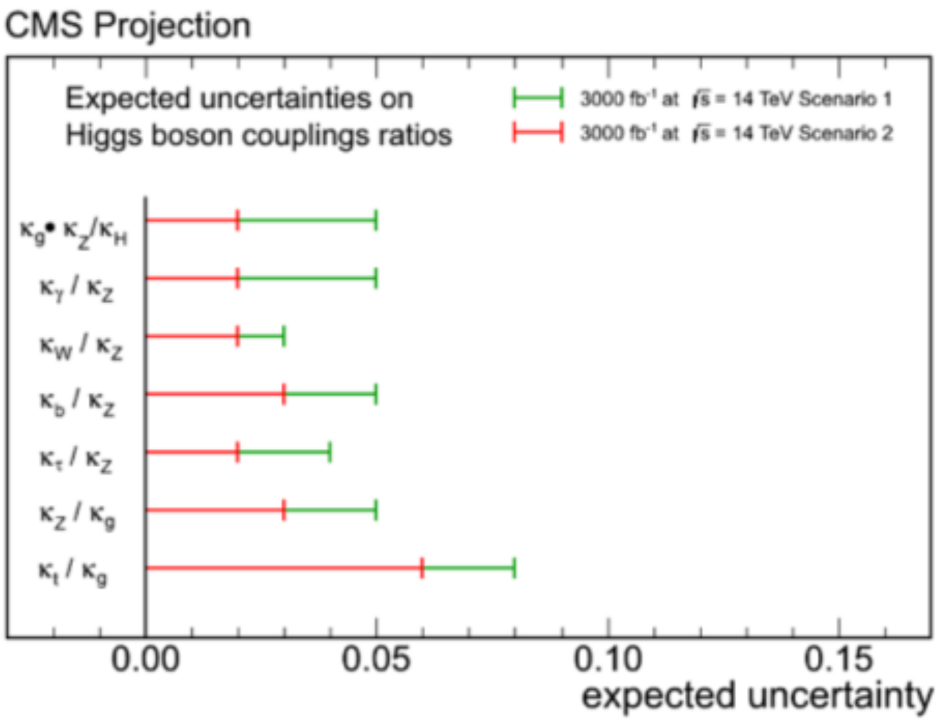
Rare-decays

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

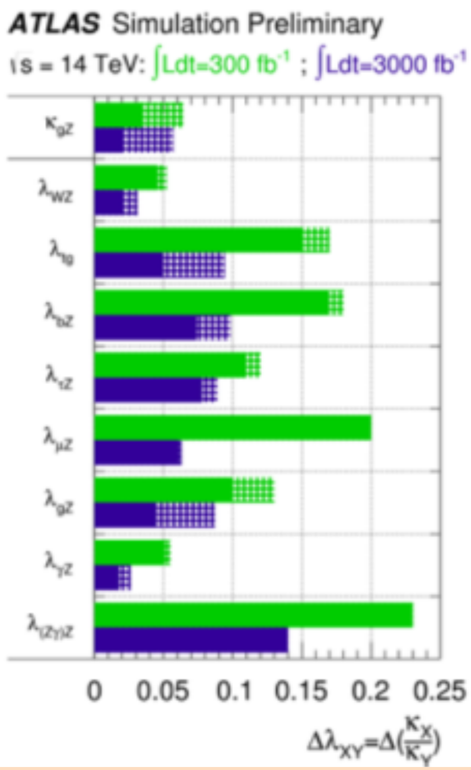
Coupling precision 2-10 %
factor 2-3 improvement from HL-LHC

Key question is the
evolution systematic uncertainty

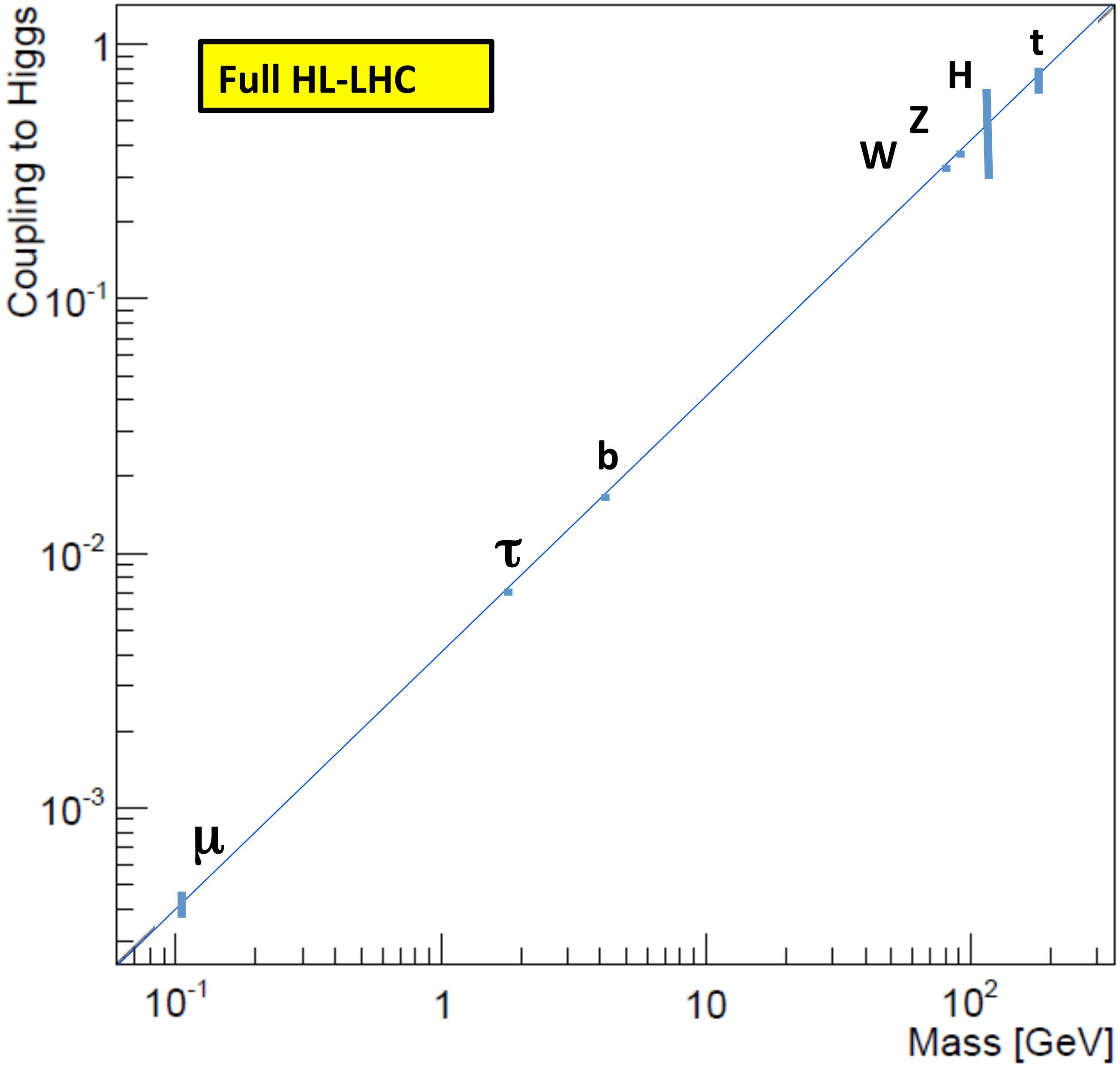
Snowmass Whitepaper for CMS - http://arxiv.org/abs/1307.7135



4

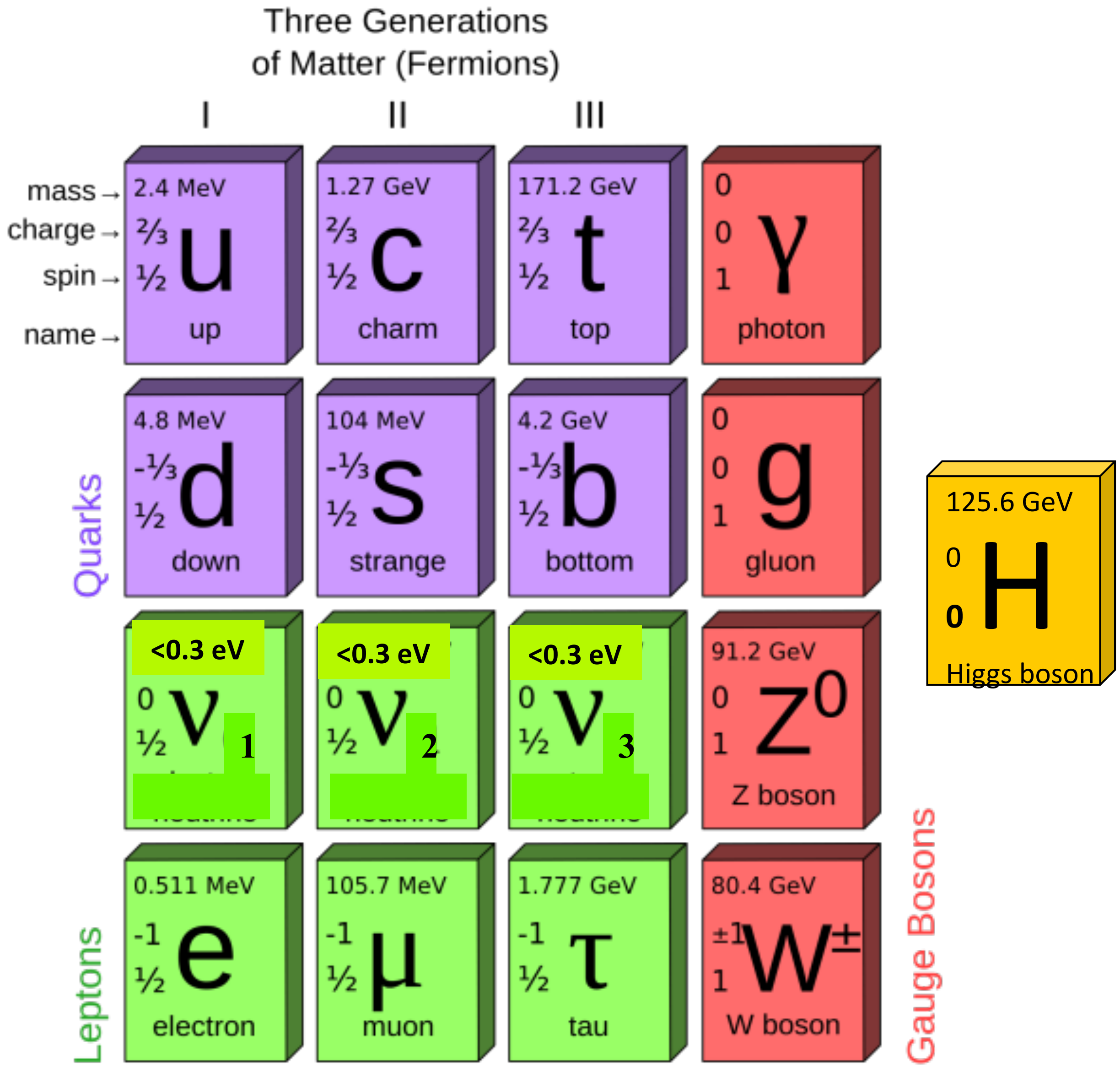


Results from 13 TeV run will be very instructive from this point of view!


Full HL-LHC
Coupling to Higgs
1
10^{-1}
10^{-2}
10^{-3}
μ
τ
b
W
Z
H
t
10^{-1}
1
10
10^{2}
Mass [GeV]


naive views...

THE STANDARD MODEL CONSTRUCTION



2012

1897

What now?

Question 1: is the H(125) The Higgs boson?

-- do/will we know well enough from LHC?

-- how precisely do we need to know before we are convinced?

Question 2: is the SM closed? or is there something else in sight?

-- known unknown facts need answer:

neutrino masses, (Dirac, and/or Majorana, sterile and right handed, CPV, MH..)

non baryonic dark matter,

Accelerated expansion of the Universe

Matter-antimatter Asymmetry

-- can the Higgs be used as search tool for new physics that answer these questions?

-- precision measurements sensitive to the existence of new particles through loops?

-- prepare highest possible reach

-- how precisely do we need to know before we are convinced?

Question 3: which Higgs factories ?

-- HL-LHC

-- (V)HE-LHC

-- mu+mu-

-- gamma-gamma

-- e+e- : linear (ILC or CLIC?) or circular (TLEP)

A: As precisely as we possibly can

a 125 GeV SM scalar is

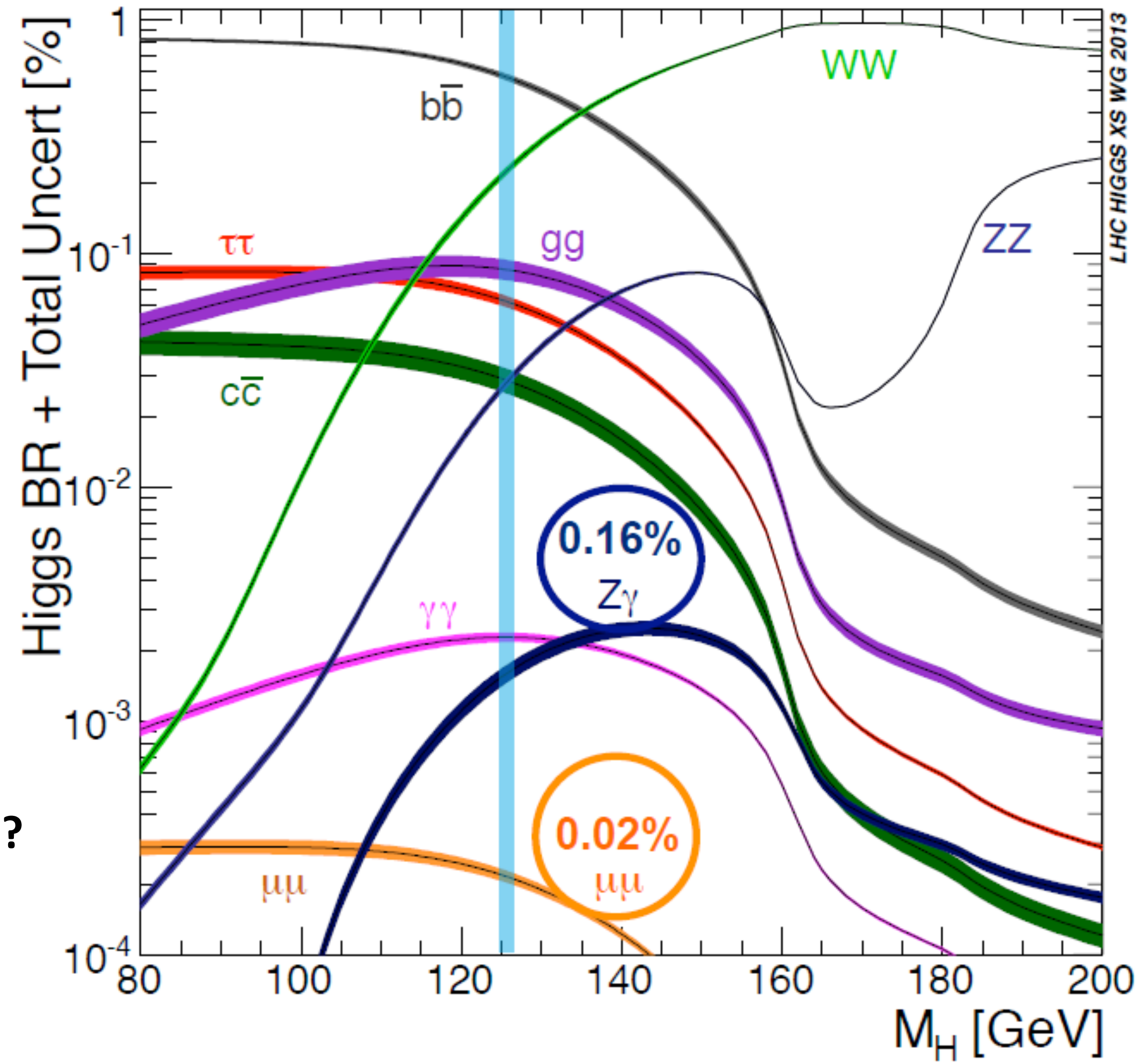
-- a new object!

-- quite narrow
Γ_H = (4.2 MeV)

-- decays into bb (57%)

-- and many other things!

What would we learn
from these measurements?



ee : 10^{-8}

Recommendations concerning Higgs Factories

European Strategy:

There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded.

(up to which energy?)

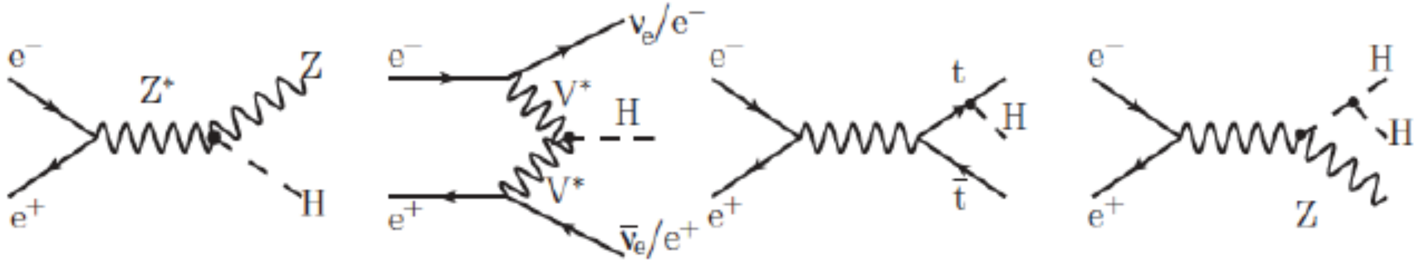
US P5 Report

An e+e- collider can provide the next outstanding opportunity [after LHC/HL-LHC] to investigate the properties of the Higgs in detail. [...] the physics case is extremely strong.

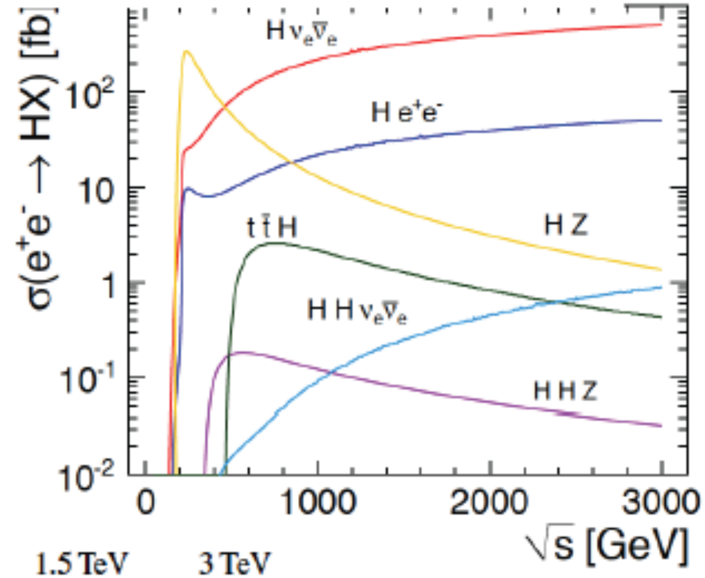
LINEAR or CIRCULAR?

At the time of the definition of these strategies, ILC was proposed by Japanese physicists to their governments and welcoming statements were added. Situation has been reviewed in Japan since. Likely to wait for results from LHC13. Issues of physics, manpower, cost, spinoffs, have been raised.

Higgs in e^+e^-



Many studies performed using full Geant-based MC

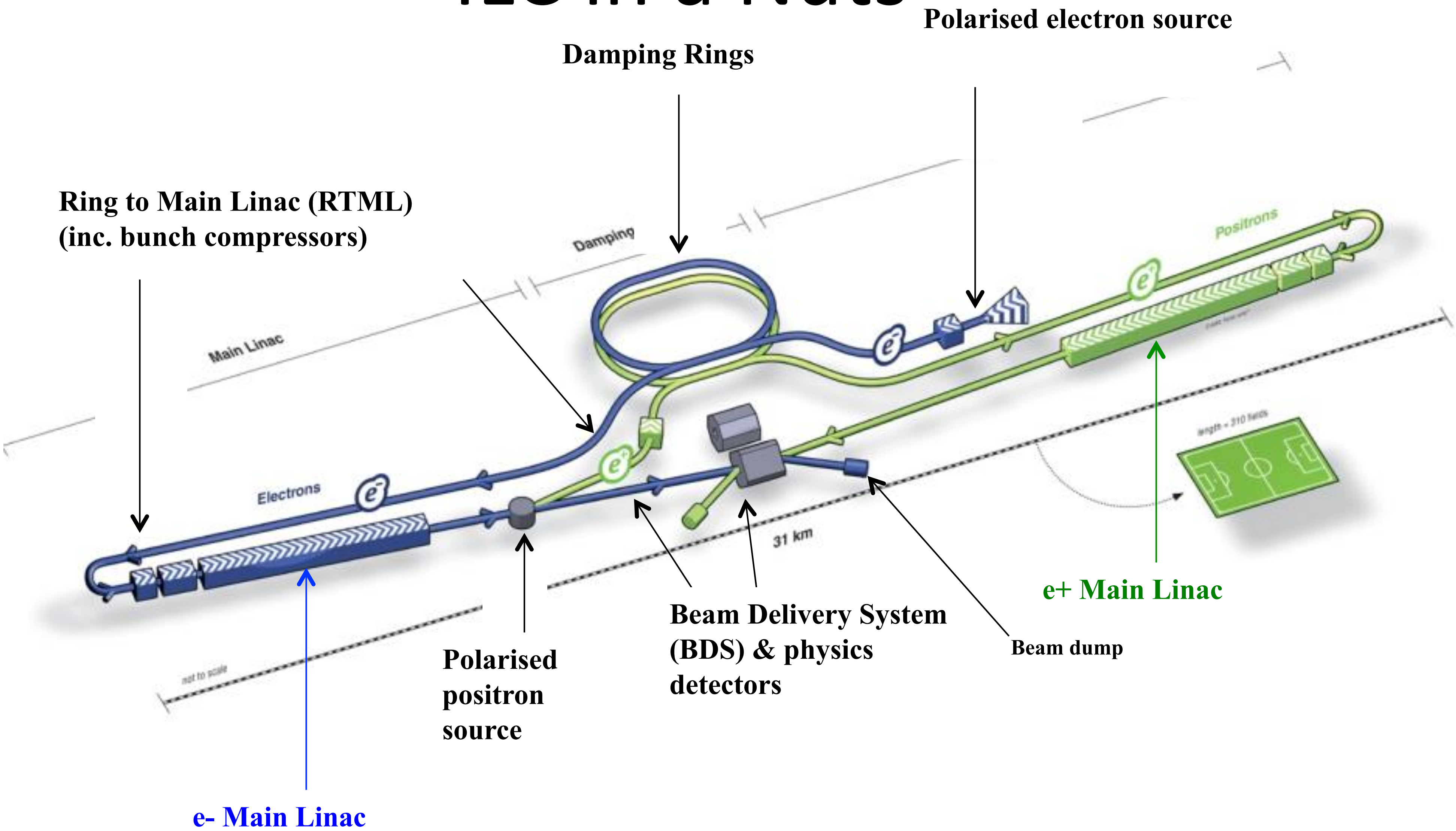


Integrated luminosity and numbers of events expected for initial 5 years running at each value of E_{cm}

	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

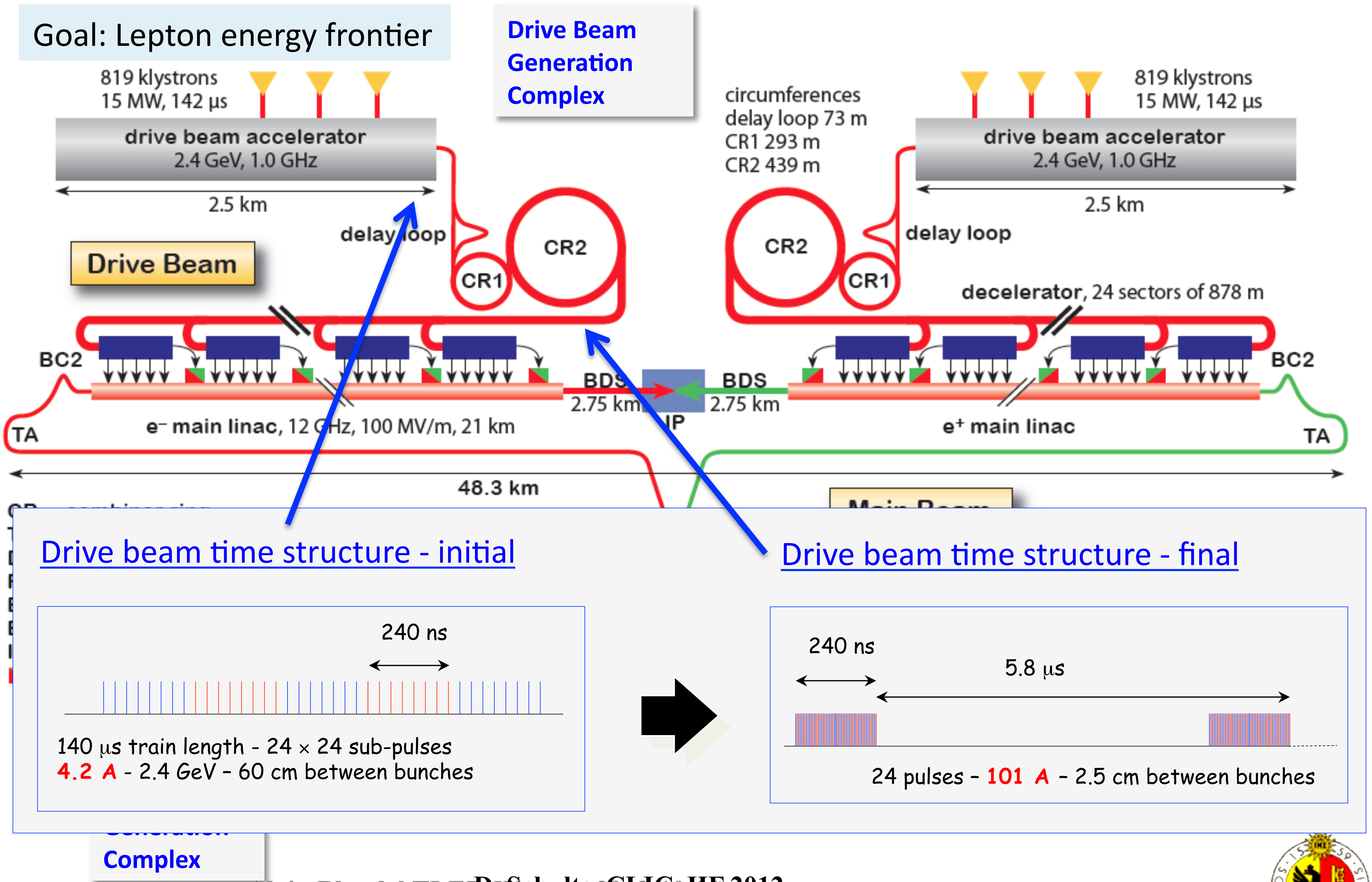
ILC in a Nutshell



not too scale

ILC Scheme | © www.form-one.de

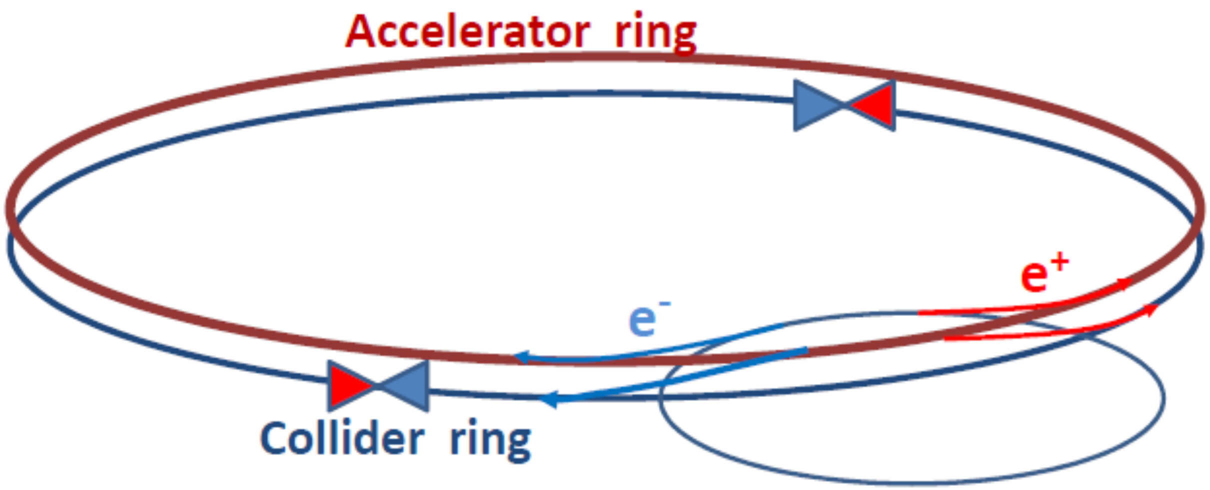
CLIC Layout at 3 TeV



D. Schulte, CLIC, HF 2012, November 2012

LEP3, CEPC and TLEP/FCC-ee

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



AB, F. Zimmermann
Dec. 13 2011

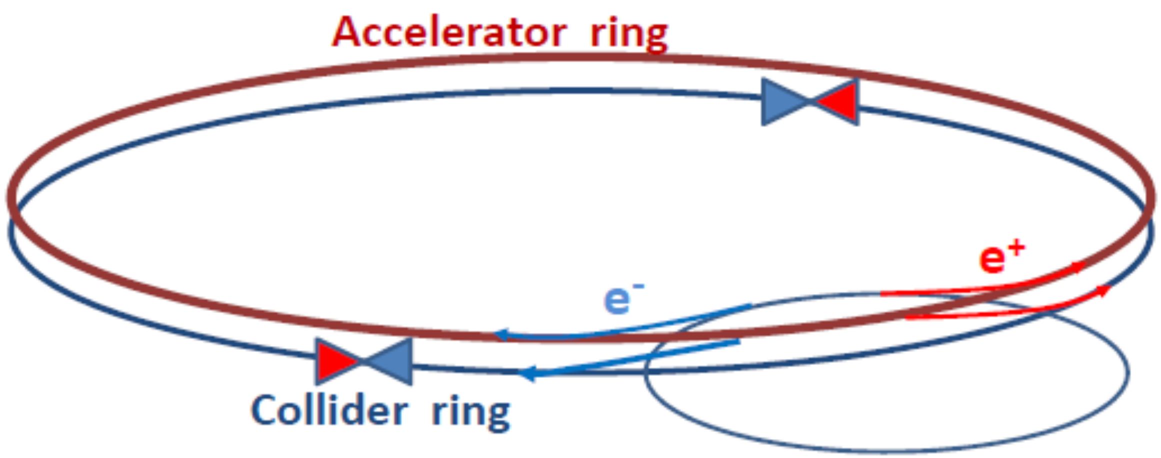
Original motivation (end 2011): now that m_H and m_top are known, explore EW region with a high precision, affordable, high luminosity machine

➔ Discovery of New Physics in rare phenomena or precision measurements

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

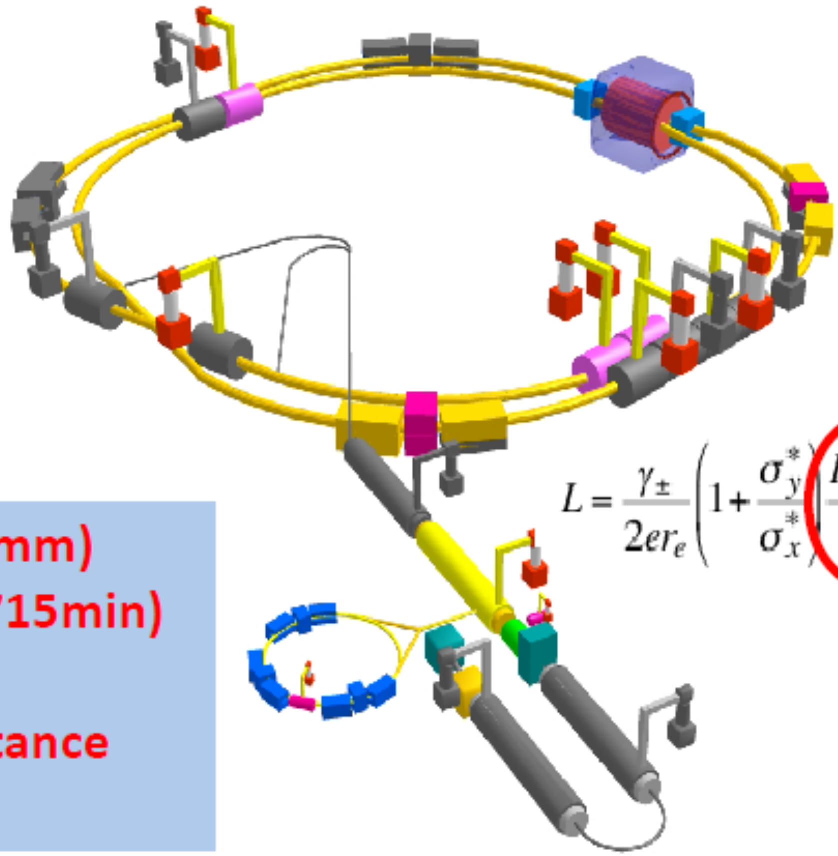
Answer is in the B-factory design: a low vertical emittance ring with
higher intrinsic luminosity, and small β^*_y (1mm vs 5cm at LEP) 50
Electrons and positrons have a much higher chance of interacting
➔ much shorter lifetime (few minutes)
➔ top up continuously with booster ==> increase operation efficiency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

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



SuperKEKB – TLEP demonstrator!

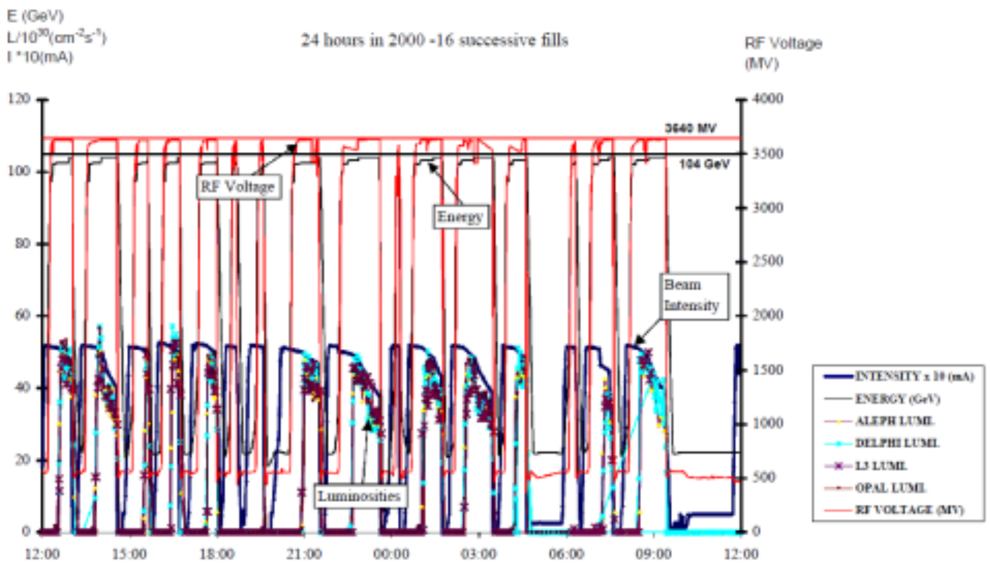
beam commissioning will start in early **2016**

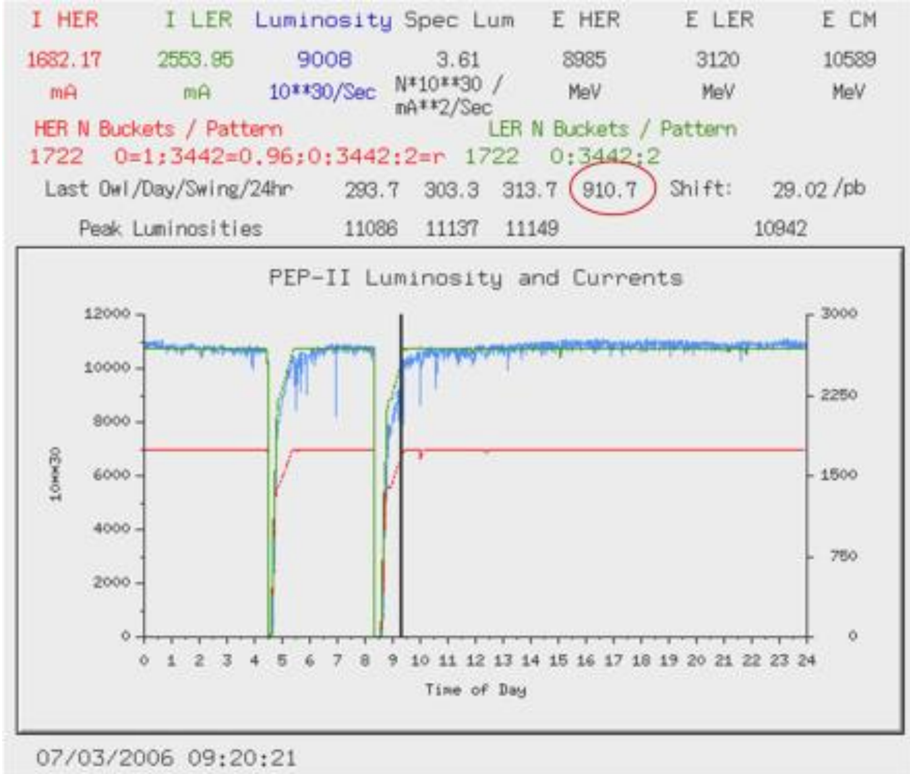


$$L = \frac{\gamma_{\pm}}{2 e r_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{\pm}\xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

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

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





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

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

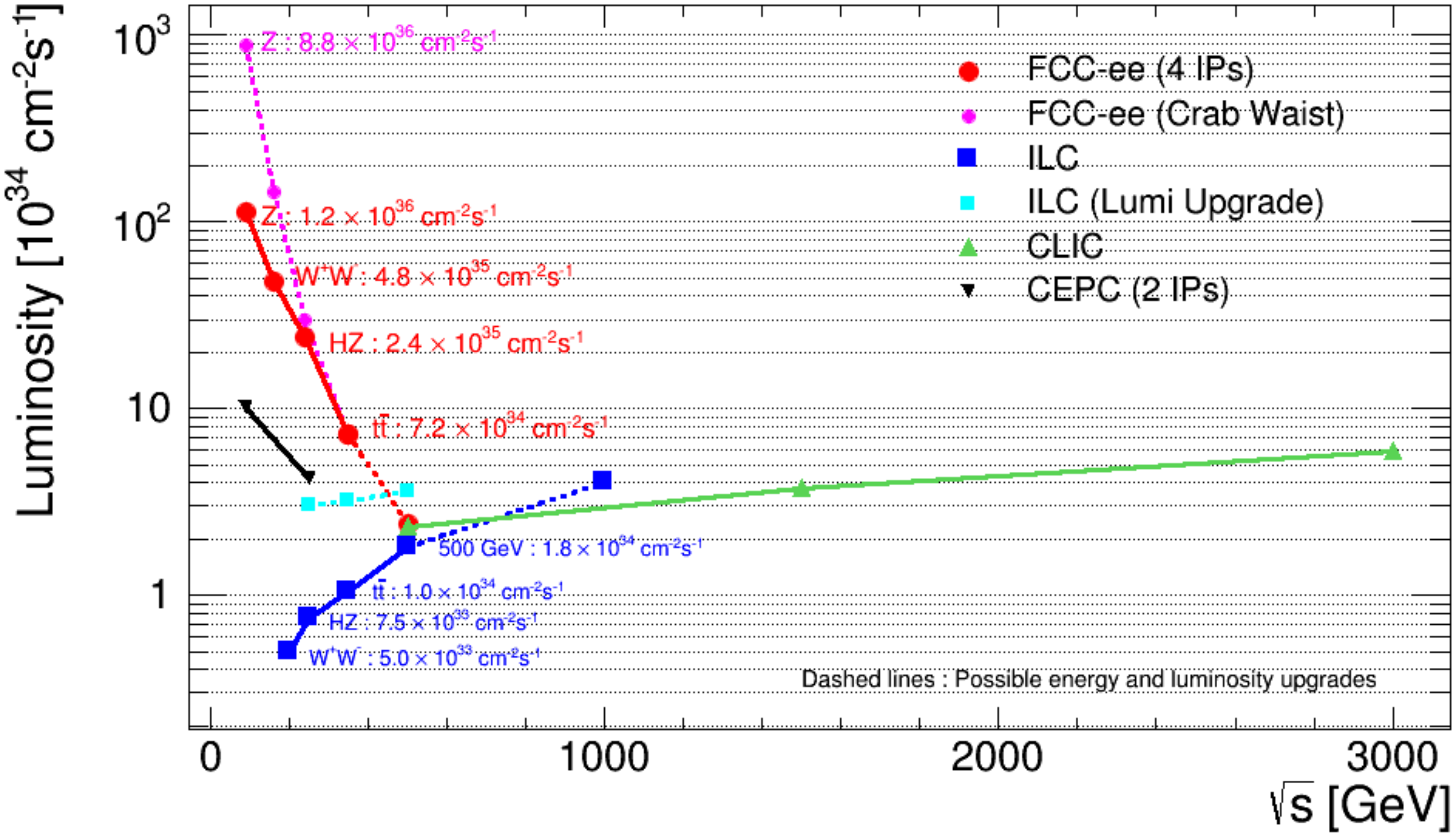
The Higgs at a e+e- Collider has been studied for many years (Tesla, ILC, CLIC)

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

--specifics:

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

-- detectors are likely to be very similar



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

FCC-ee: PARAMETERS & STATISTICS

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

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

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

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First look at the physics case of TLEP

PUBLISHED

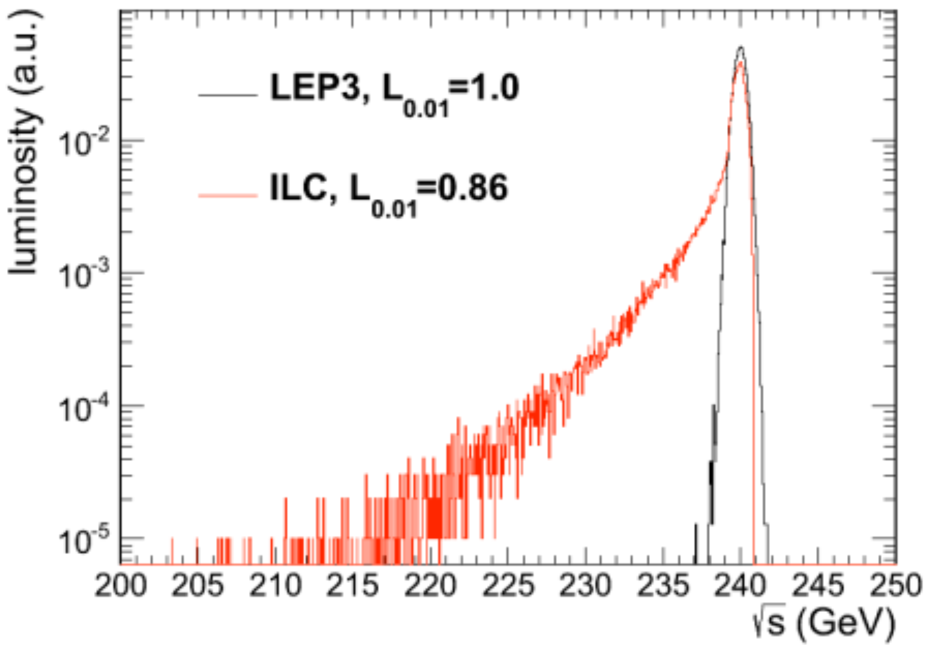
The TLEP Design Study Working Group

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

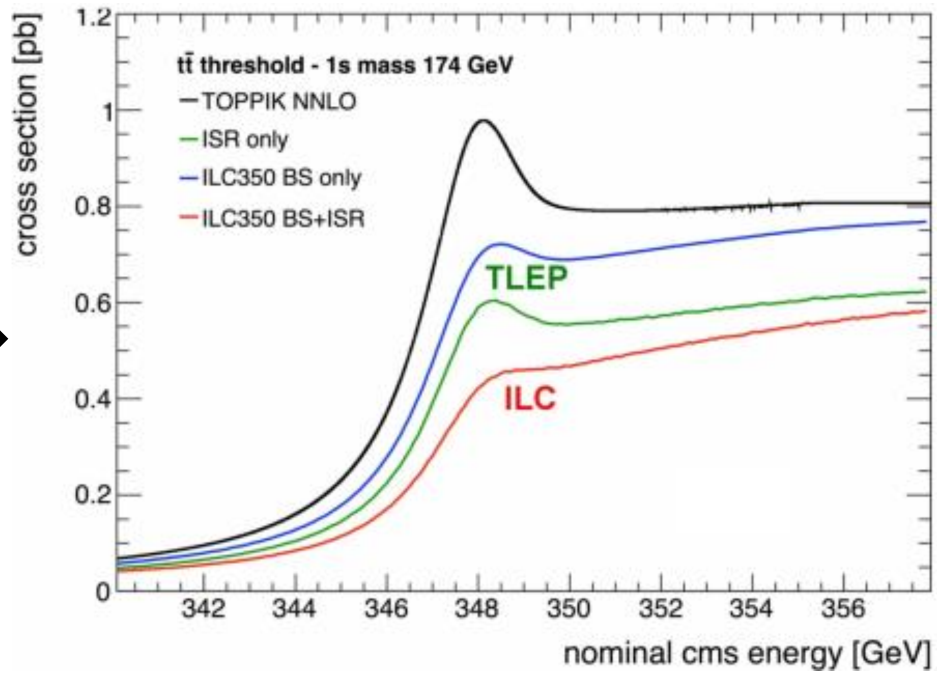
BEAMSTRAHLUNG

Luminosity *E* spectrum



➔

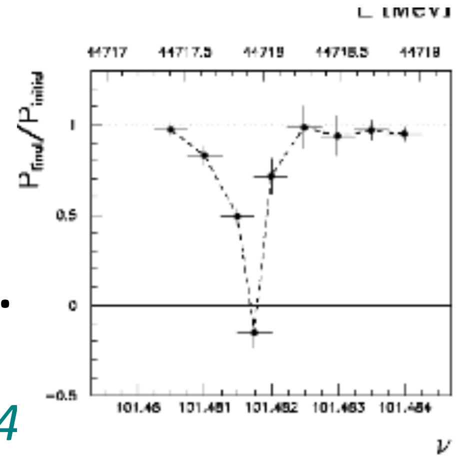
Effect on top threshold



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.

Beam polarization and E-calibration @ TLEP



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

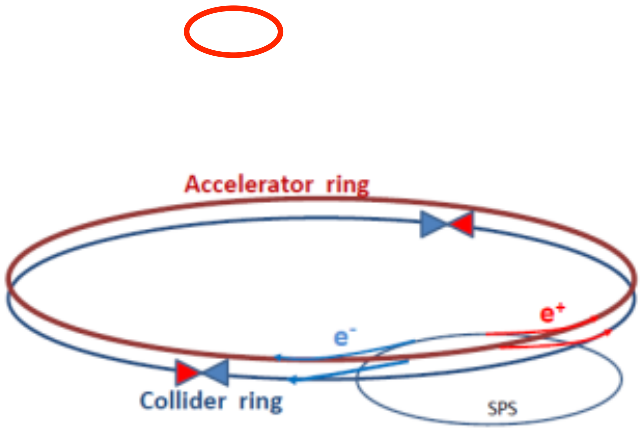
At LEP transverse polarization was achieved routinely at Z peak.
instrumental in 10^{-3} measurement of the Z width in 1993
led to prediction of top quark mass (179+- 20 GeV) in March 1994

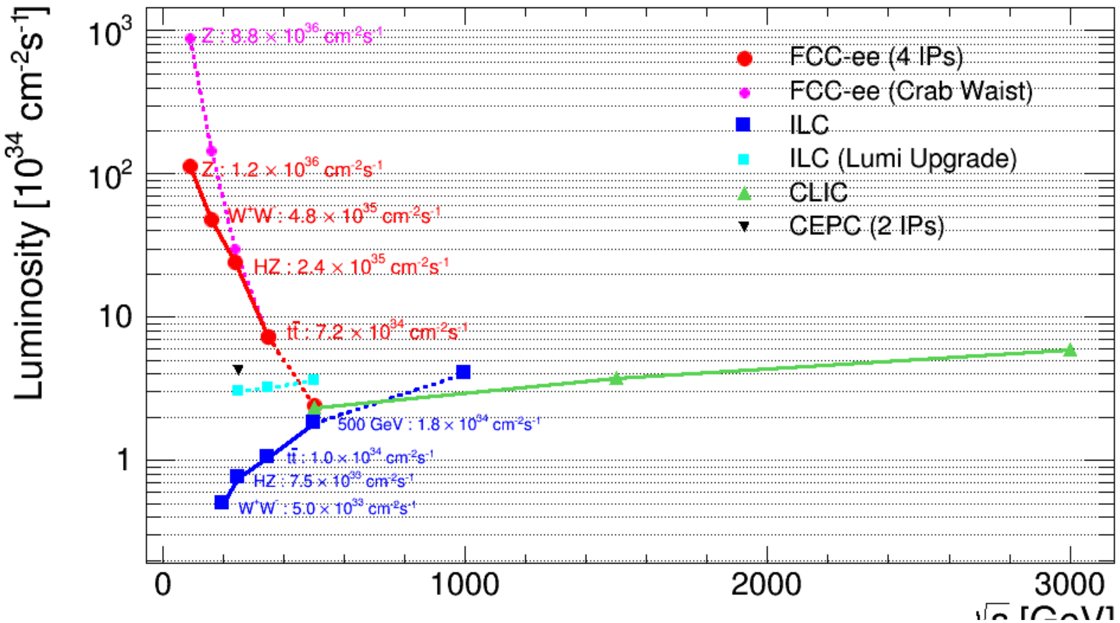
Polarization in collisions was observed *(40% at BBTS = 0.04)*

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

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

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





First look at the physics case of TLEP, arXiv:1308.6176v3 scoped the precision measurements:
-- Model independent Higgs couplings and invisible width
-- Z mass (0.1 MeV), W mass (0.5 MeV) top mass (~10 MeV), $\sin^2{}_W^{eff}$, R_b, N_ν etc...

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

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

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

Snapshot of novelties appeared in recent workshops

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

➔ sensitivity to right handed (sterile) neutrinos

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

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

➔ discovery potential for very small couplings

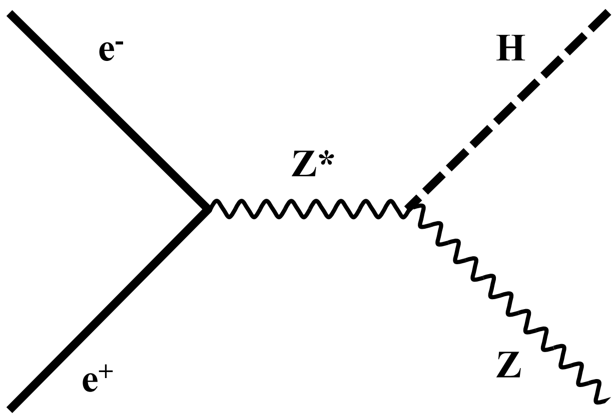
➔ precision event generators (Jadach et al)

Higgs production mechanism

"higgstrahlung" process close to threshold

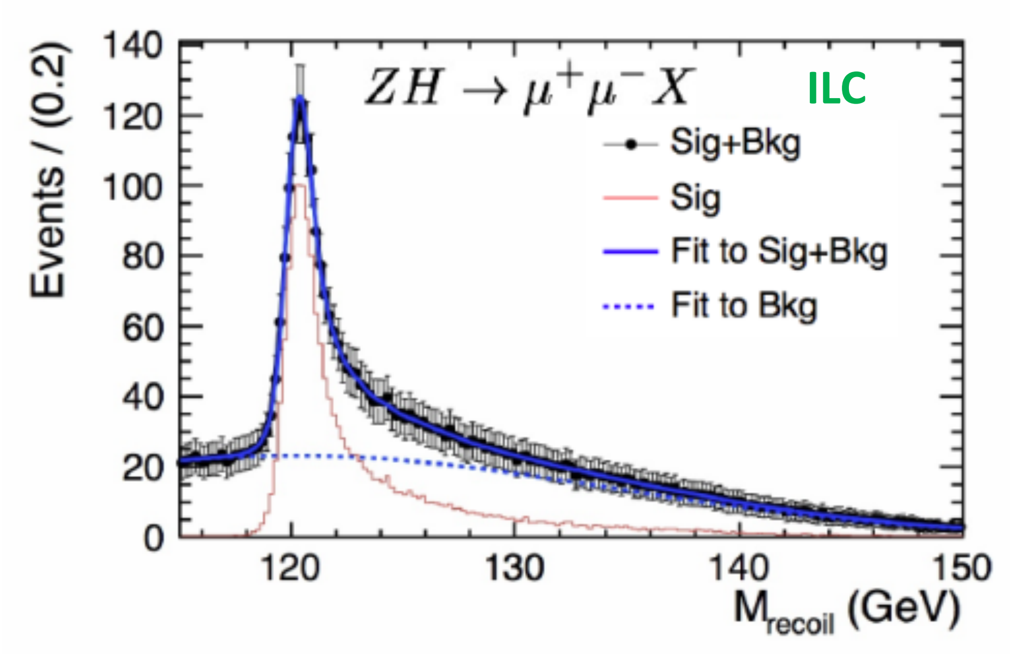
Production xsection has a maximum at near threshold ~200 fb

$10^{34}/cm^2/s$ ➔ 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 ∝ g_{HZZ}^2

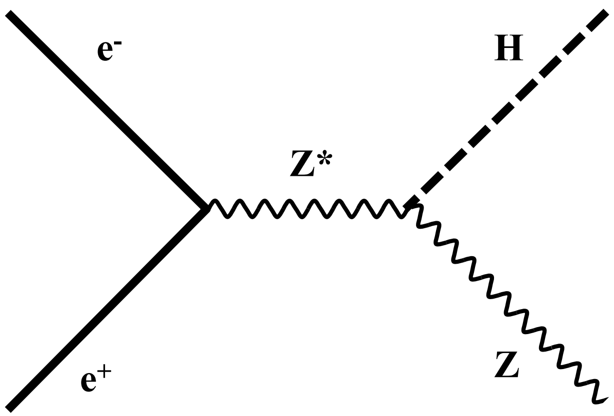
ZZZ final state ∝ g_{HZZ}^4 / Γ_H

➔ measure total width Γ_H

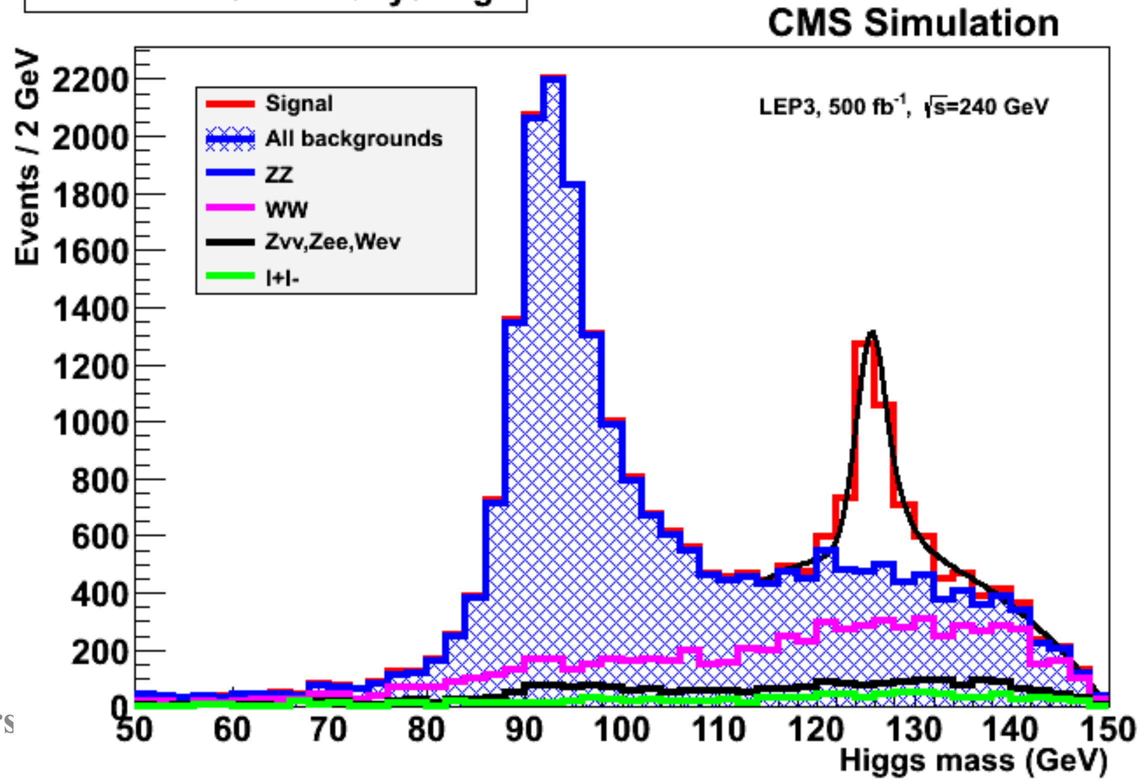
empty recoil = invisible width

'funny recoil' = exotic Higgs decay

easy control below theshold



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



Alain Blondel TLEP Wars

Higgs factory

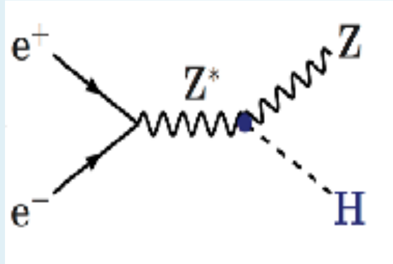
(constrained fit including 'exotic')

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

➔ total width **<1%**

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

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



2 10^6 ZH events in 5 years

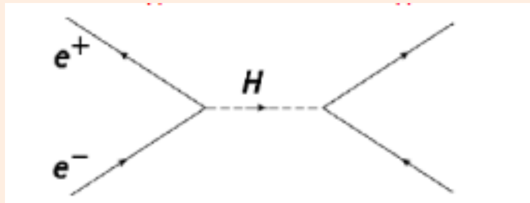
«A tagged Higgs beam».

sensitive to new physics in loops

incl. invisible = (dark matter?)

A big challenge, but unique:

Higgs s-channel production at $\sqrt{s} = m_H$



10^4 events per year.

Very difficult because huge background and beam energy spread ~ 10 x Γ_H

limits or signal? monochromators?

Aleksan, D'Enterria, Woijcik

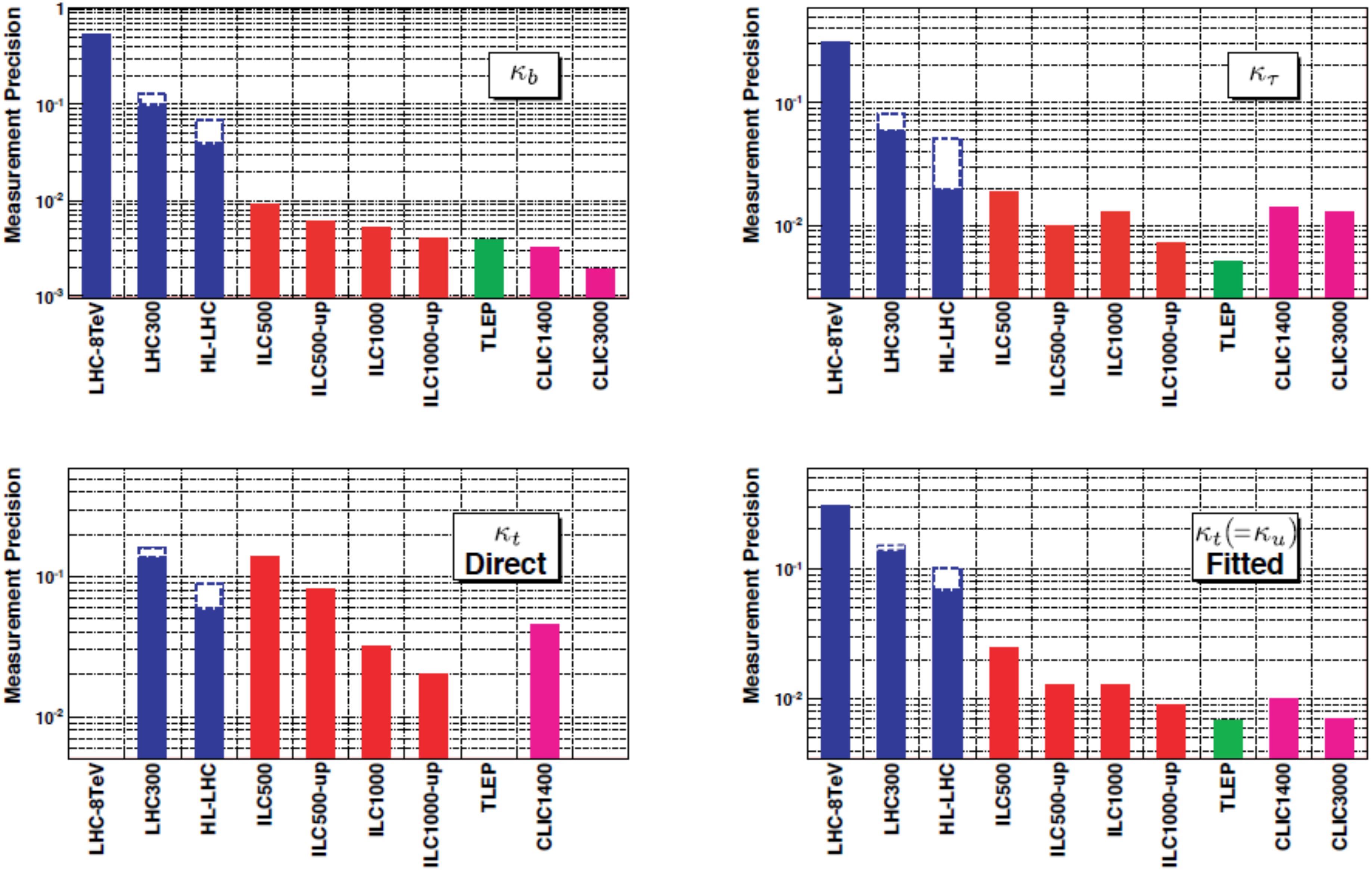


Figure 1-4. *Measurement precision on κ_b, κ_τ, and κ_t measured both directly via $t\bar{t}H$ and through global fits at different facilities.*

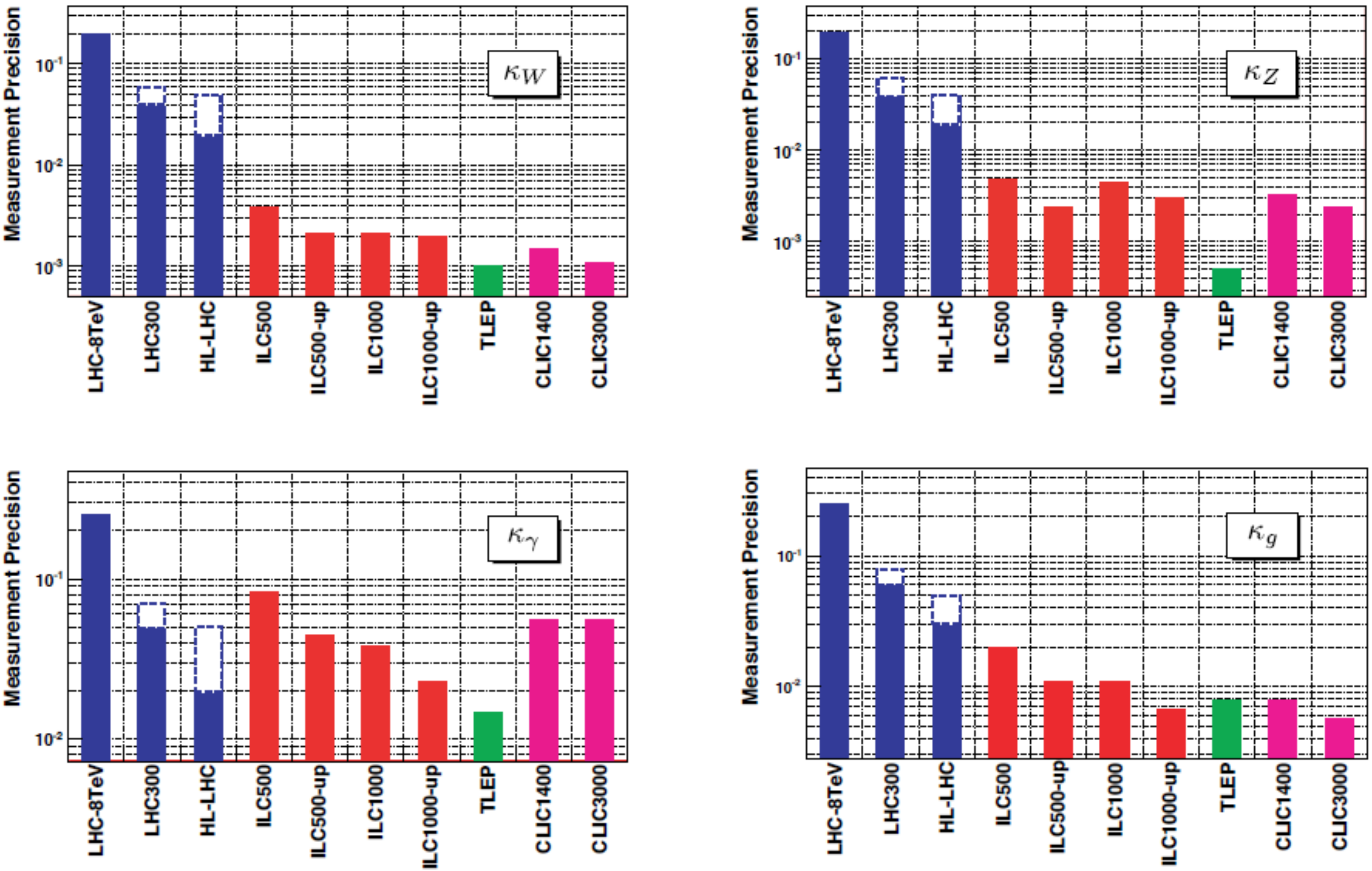
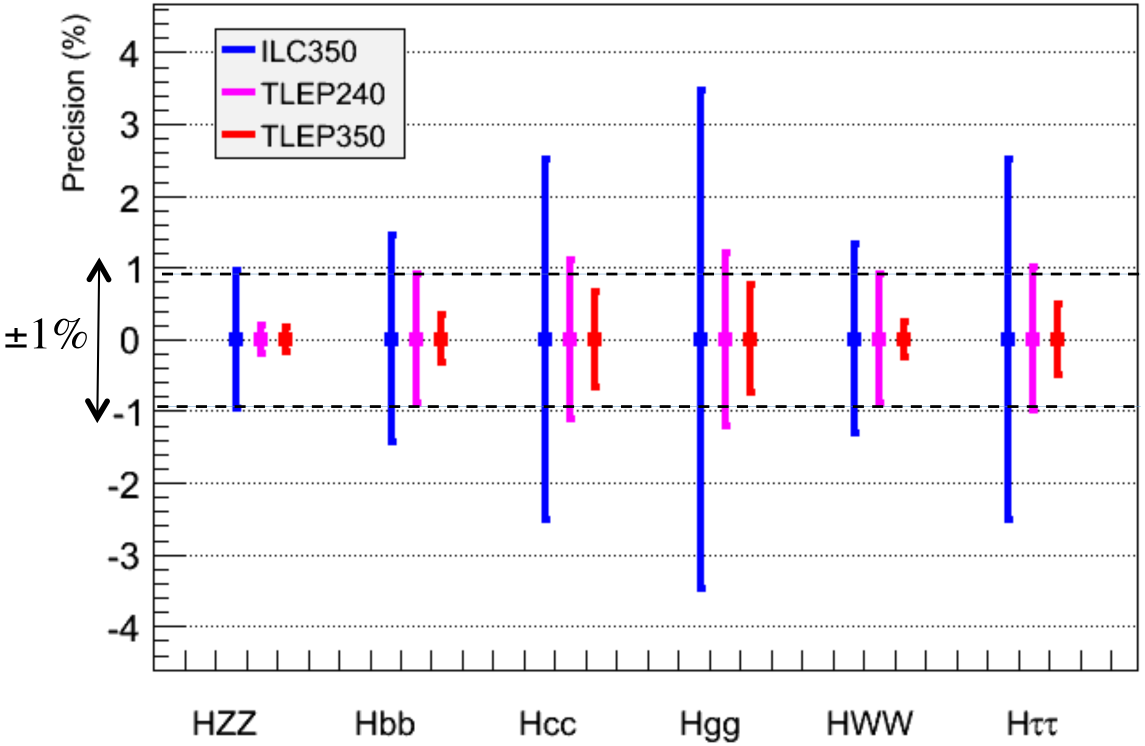


Figure 1-3. *Measurement precision on κ_W, κ_Z, κ_γ, and κ_g at different facilities.*

Performance Comparison

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

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

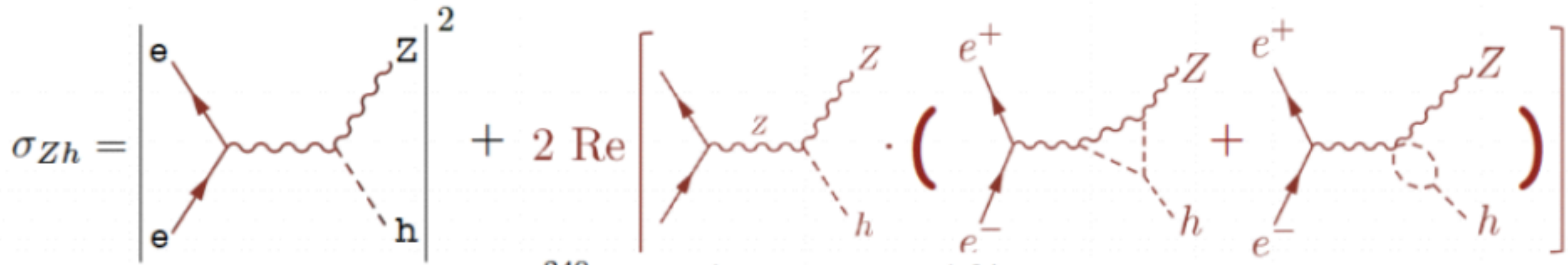


Expected precision on the total width

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

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

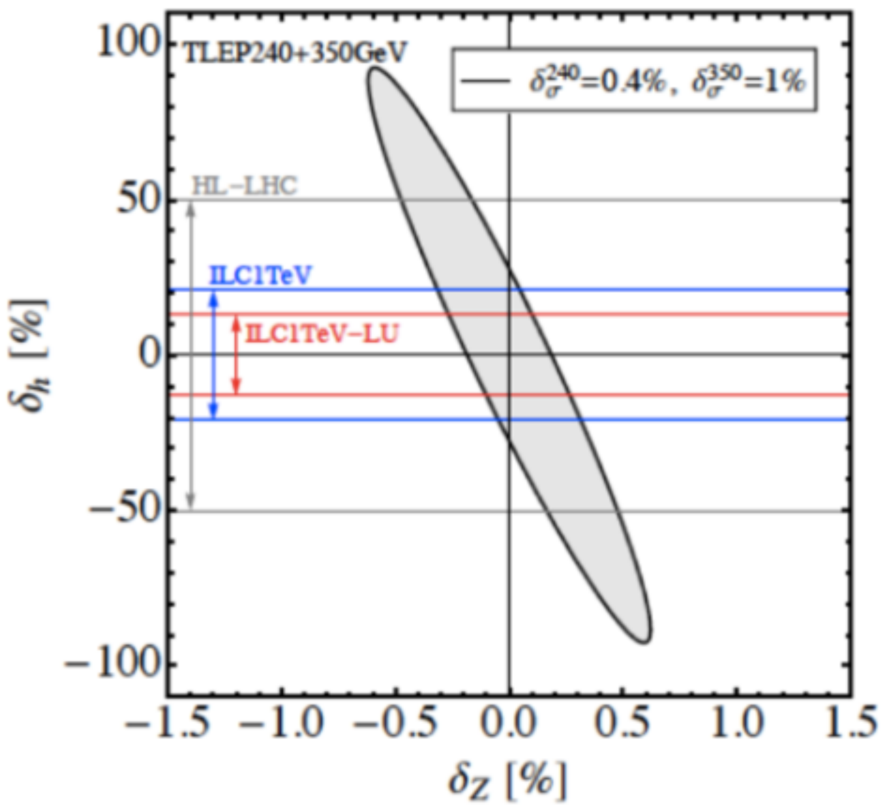
very accurate precision on threshold cross-section sensitive to loop corrections



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

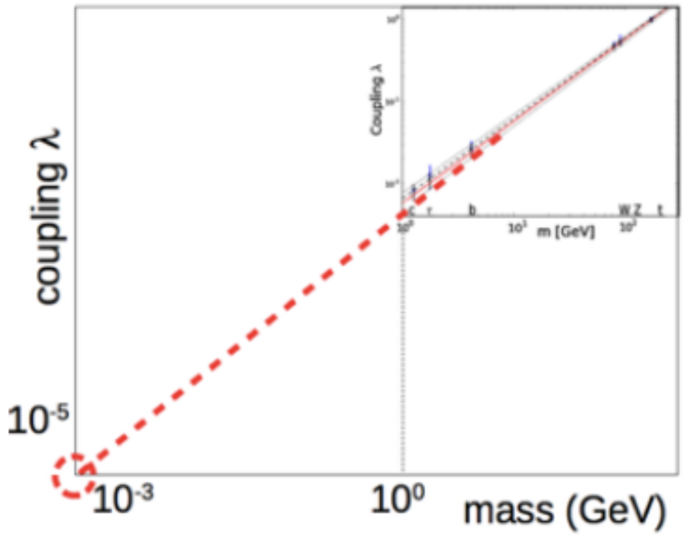
arxiv:1312.3322

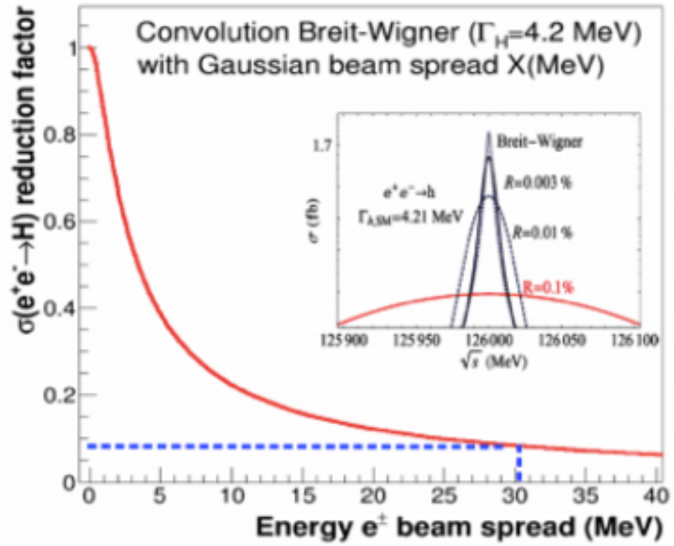
- ➡ Very large datasets at high energy allow extreme precision g_{ZH} measurements
- ➡ Indirect and model-dependent probe of Higgs self-coupling
- ➡ Note, the time axis is missing from the plot



First generation couplings

- ➡ **s-channel Higgs production**
  - Unique opportunity for measurement close to SM sensitivity
  - Highly challenging; $\sigma(ee \rightarrow H)$ = 1.6fb; 7 Higgs decay channels studied





Preliminary Results

L = 10 ab^{-1}

κ_e < 2.2 at 3σ

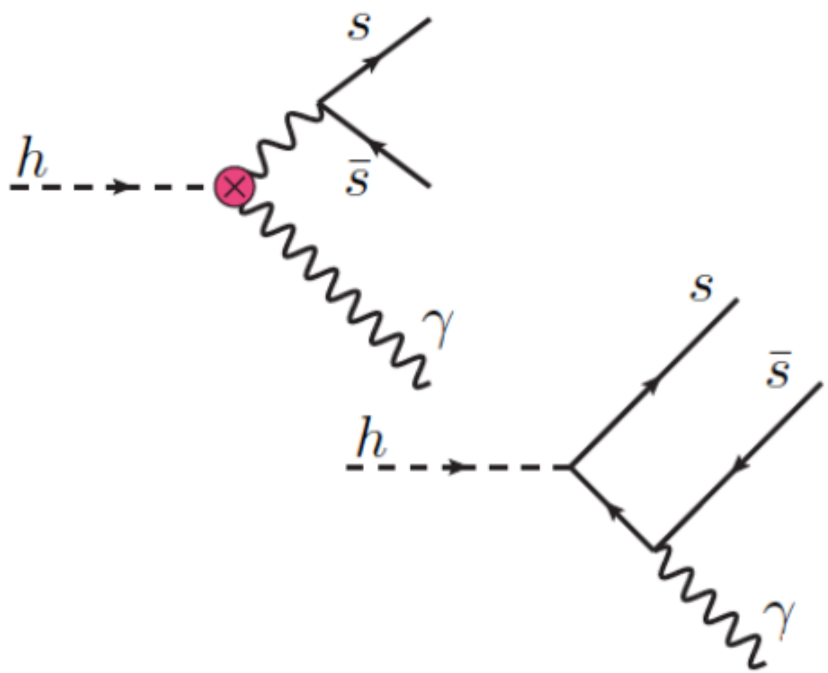
- ➡ **Work in progress**
  - How large are loop induced corrections? How large are BSM effects?
  - Do we need an energy scan to find the Higgs?
  - How much luminosity will be available for this measurement? By how much is the luminosity reduced by monochromators?

Exclusive Higgs boson decays

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

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

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



H → J/Ψ γ ➡ y_c

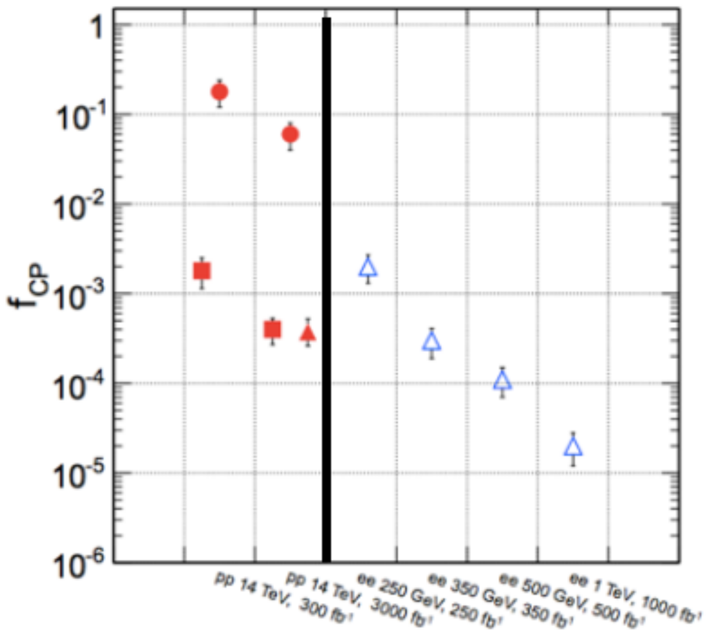
H → ϕ γ ➡ y_s

H → **ρ** γ
H → ω γ ➡ y_u, y_d

CP Measurements

- ➡ CP violation can be studied by searching for CP-odd contributions; CP-even already established
- ➡ Snowmass Higgs paper http://arxiv.org/abs/1310.8361
- ➡ Higgs to Tau decays of interest
- ➡ More detailed presentation by Felix Yu http://arxiv.org/abs/1308.1094

for HVV couplings



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

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

Rare and Exotics Higgs Bosons

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

$h \to \not{E}_T$

$h \to 4b$

$h \to 2b2\tau$

$h \to 2b2\mu$

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

$h \to 4j$

$h \to 2\gamma 2j$

$h \to 4\gamma$

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

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

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

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

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

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

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

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

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

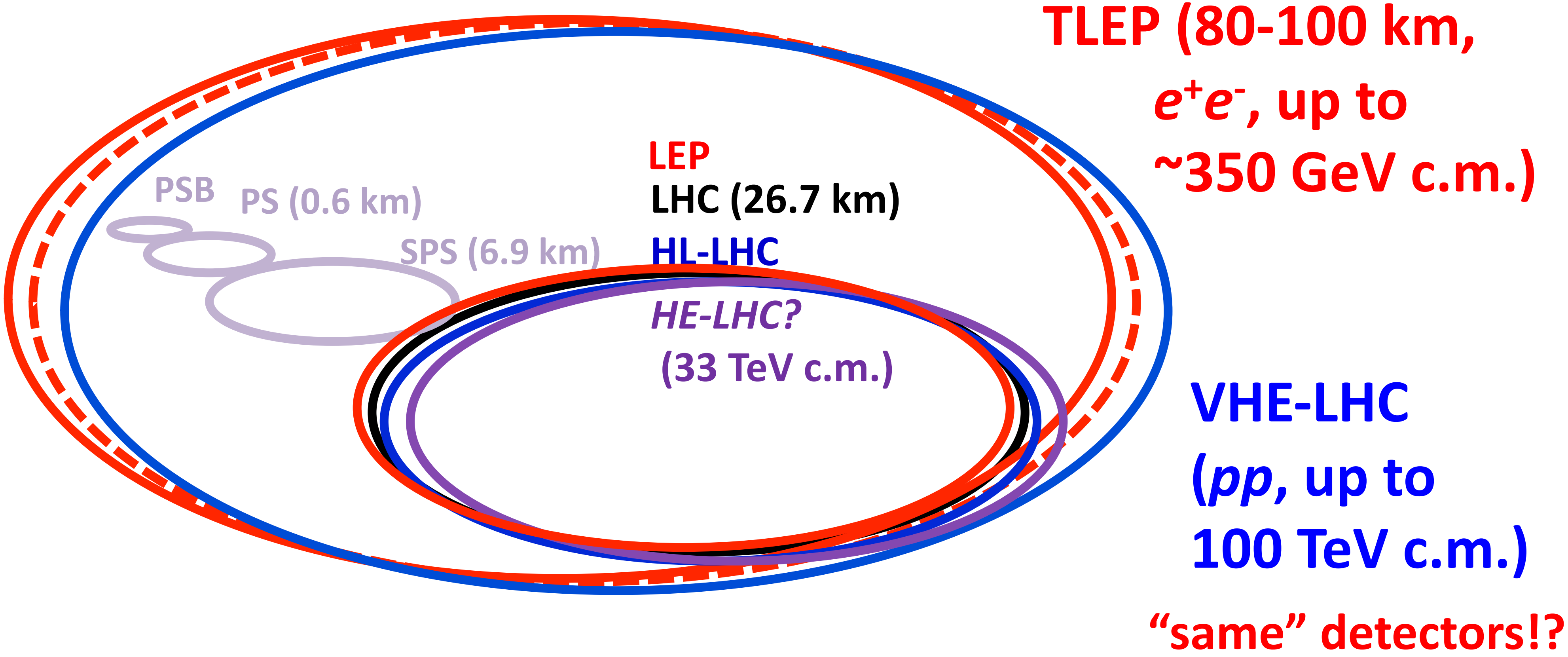
$h \to \tau^+\tau^- + \not{E}_T$

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

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

the 10B$ ILC

possible long-term strategy



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

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

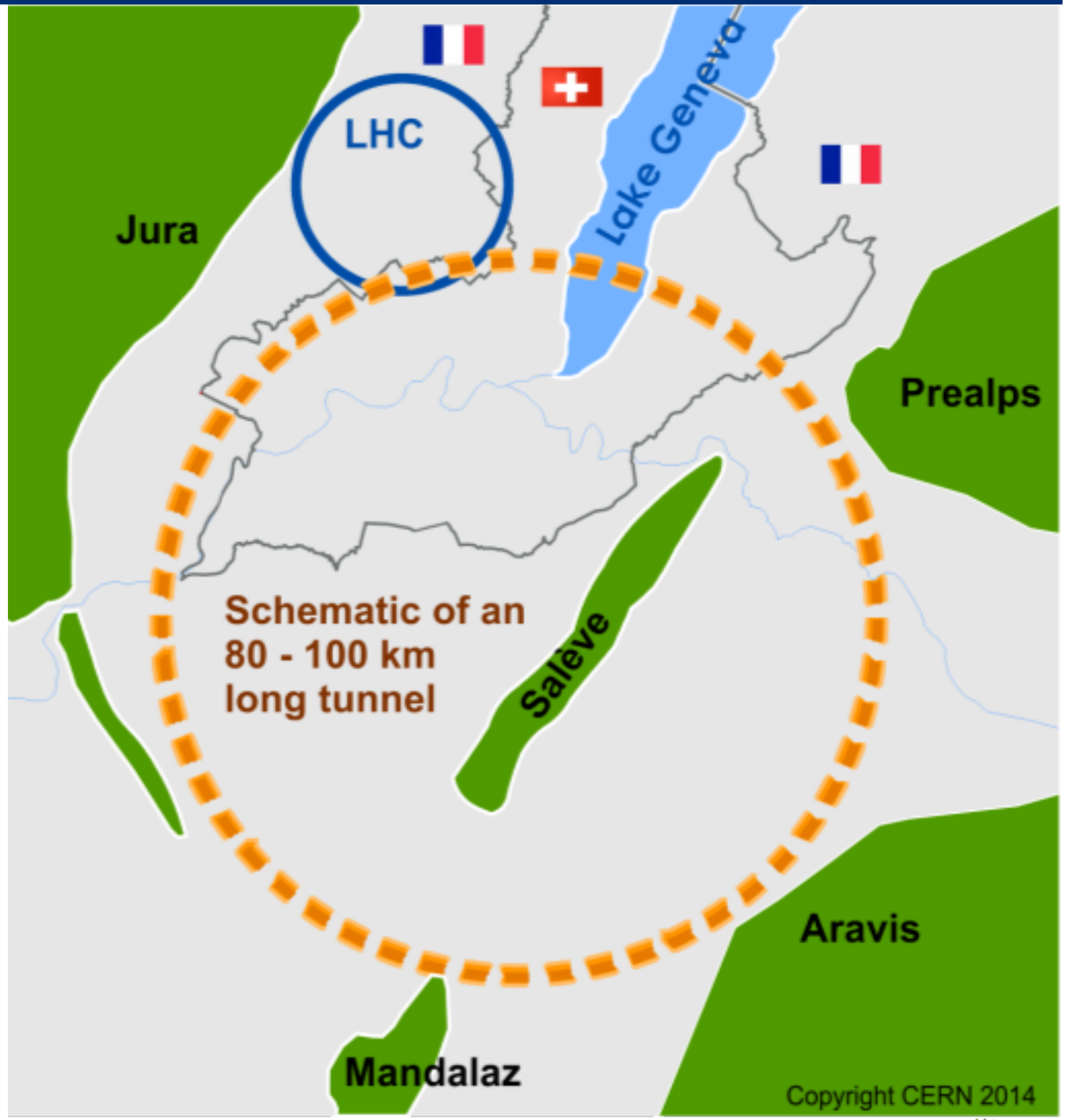
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

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 – starting point

Energy	**100 TeV c.m.**
Dipole field	**~ 16 T (Nb_3Sn), [20 T option HTS]**
Circumference	**~ 100 km**
#IPs	**2 main (tune shift) + 2**
Luminosity/IP_{main}	**5 10^{34} [2.5×10^{35}] $cm^{-2}s^{-1}$**
Stored beam energy	**8.2 GJ/beam**
Synchrotron radiation	**26 W/m/aperture** (filling fact. ~78% in arc)
Long. emit damping time	**0.5 h**
Bunch spacing	**25 ns [5 ns option]**
Bunch population (25 ns)	1×10^{11} p
Transverse emittance	2.2 micron normalized
#bunches	10500
Beam-beam tune shift	0.01 (total)
β^*	1.1 m (HL-LHC: 0.15 m)

} already available from SPS for 25 ns

Ongoing discussion : should we go to $10^{36}cm^{-2}s^{-1}$?

parameter	LHC	HL-LHC	FCC-hh
c.m. energy [TeV]	14		100
dipole magnet field [T]	8.33		16 (20)
circumference [km]	26.7		100 (83)
luminosity [10^{34} cm^{-2}s^{-1}]	1	5	5 [→20?]
bunch spacing [ns]	25		25 {5}
events / bunch crossing	**27**	**135**	**170 {34}**
bunch population [10^{11}]	1.15	2.2	1 {0.2}
norm. transverse emitt. [μm]	3.75	2.5	2.2 {0.44}
IP beta-function [m]	0.55	0.15	1.1
IP beam size [μm]	16.7	7.1	6.8 {3}
synchrotron rad. [W/m/aperture]	0.17	0.33	28 (44)
critical energy [keV]	0.044		4.3 (5.5)
total syn.rad. power [MW]	**0.0072**	**0.0146**	**4.8 (5.8)**
longitudinal damping time [h]	**12.9**		**0.54 (0.32)**

FCC-hh baseline parameters defined in EDMS No. 1342402, FCC-ACC-SPC-0001

- preliminary -

FCC-hh: some design challenges

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

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

*"….an **ambitious** post-LHC accelerator project at CERN"*

Parameters - choices for initial machine relatively conservative
- a few more aggressive choices where cost savings balance the risks

--> **establishing a credible baseline**

- potential for evolution in performance
- as design process incl R & D proceeds
- as planned machine upgrade

important parameters for detectors	baseline 2014	considered (2015)
Energy	**100 TeV**	
Lumi	**5×10^{34} (p-p)**	**up to 2.5×10^{35} (p-p)**
	3×10^{27} (Pb-Pb)	
Bunch spacing	**25ns**	**5 ns**
Pile-up	**170**	**34 - 340**
Bunch-length	8 cm	increased
% circumference filled	80 %	
L *	46m	38m
β^*	0.8m	0.3m
transverse beam size at ip	6.8mm	3mm
optimum run time	12 hrs	

93km "optimised" racetrack

PRELIMINARY

Alignment | **Shaft Tools**

Choose alignment option

93km quasi-circular ▼

Tunnel depth at centre: 206mASL

Gradient Parameters

Azimuth (°): -15

Slope Angle x-x(%): .3

Slope Angle y-y(%): 0

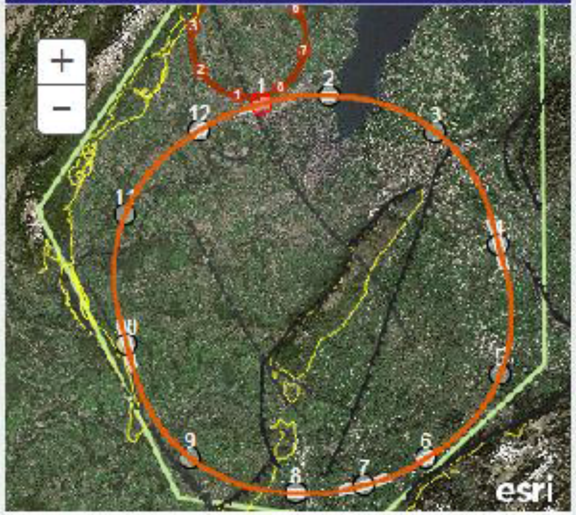
CALCULATE

Alignment centre

X: 2493923 Y: 1106695

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

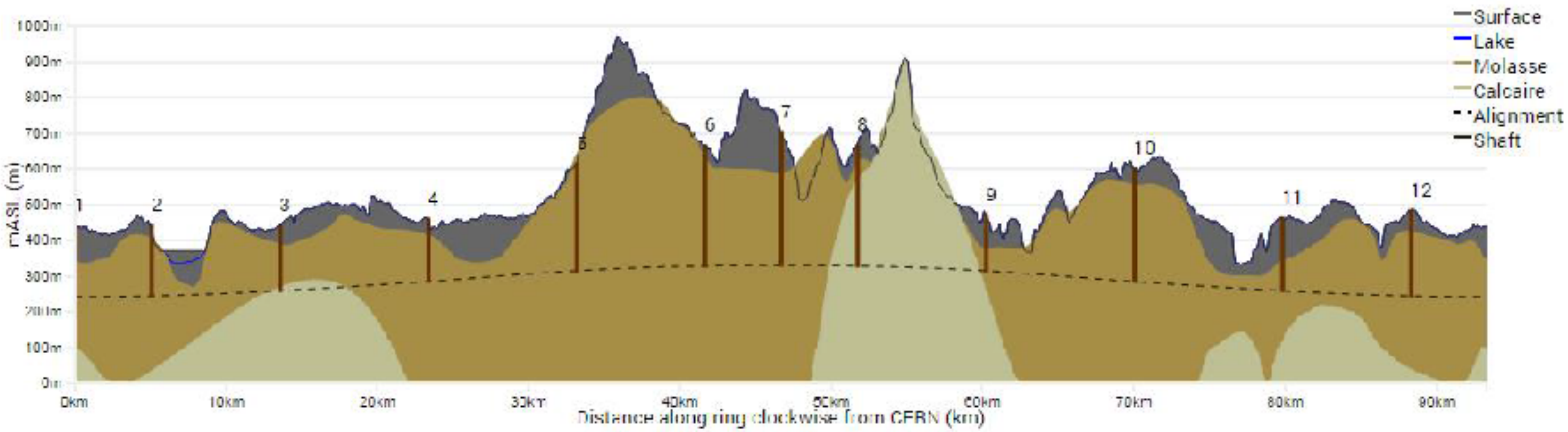
Alignment Location



Geology Intersected by Shafts | **Shaft Depths**

Shaft	Shaft Depth (m) Actual	Min	Mean	Max	Geology (m) Moraine	Molasse	Calcaire
1	200	195	197	200	92	108	0
2	196	143	181	211	34	162	0
3	183	176	184	194	63	121	9
4	174	146	166	178	44	130	0
5	299	286	311	350	0	325	0
6	336	325	339	350	35	302	0
7	374	349	377	412	119	256	0
8	337	318	341	356	44	56	237
9	155	131	145	157	94	61	0
10	315	305	320	336	46	269	0
11	203	199	202	204	122	81	0
12	239	229	238	243	58	181	0
Total	3014	2801	3001	3211	741	2062	247

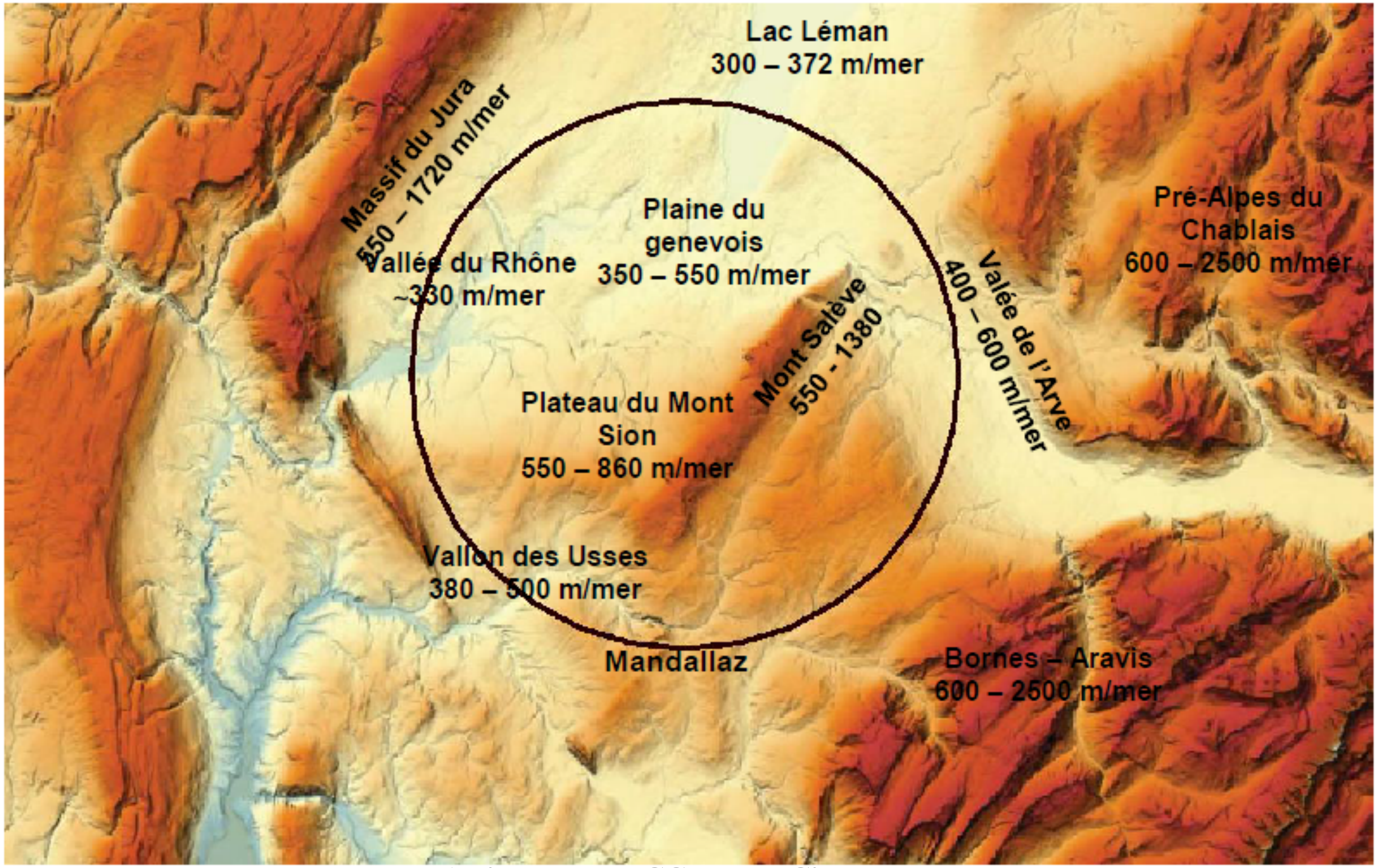
Alignment Profile



J. Osborne & C. Cook

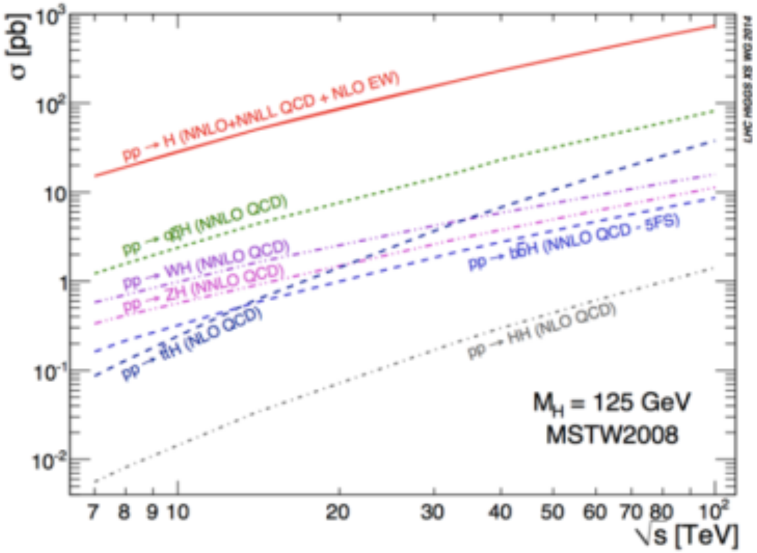
Tunnel location: topography [1/3]

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



HIGGS AT FCC-pp

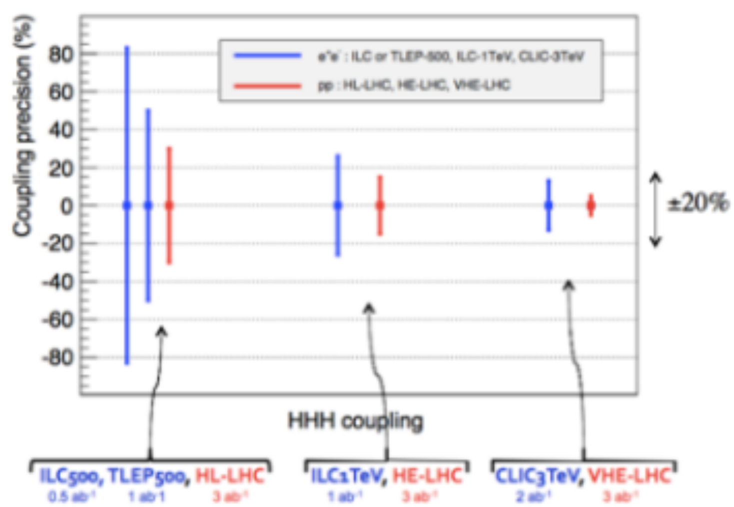
Process	8 TeV	14 TeV	100 TeV
gF	0.38	1	14.7
VBF	0.38	1	18.6
WH	0.43	1	9.7
ZH	0.47	1	12.5
ttH	0.21	1	61
bbH	0.34	1	15
gF to HH	0.24	1	42



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

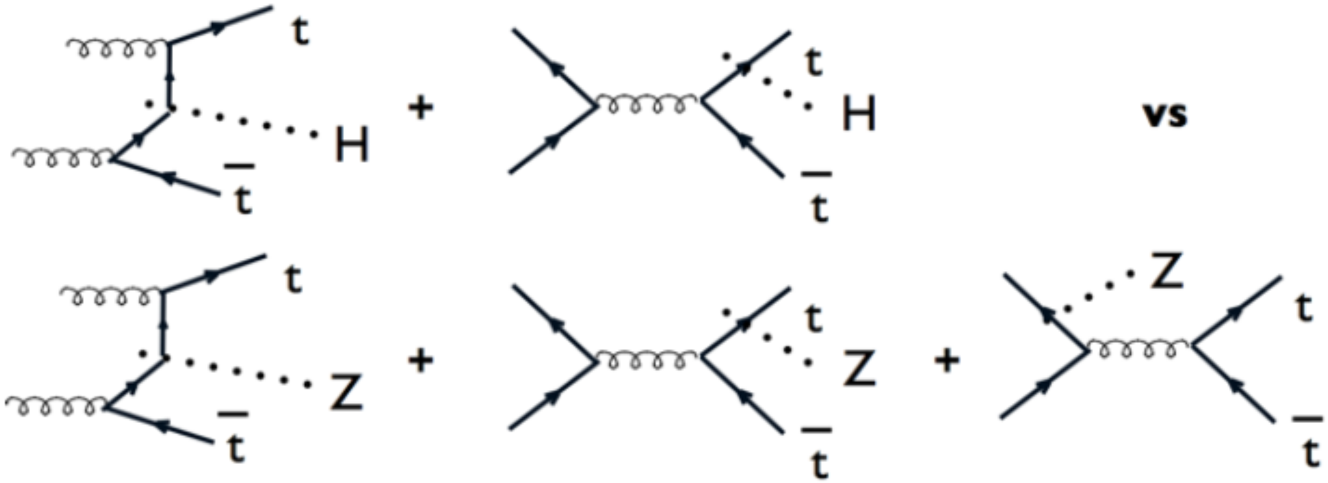
	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L}dt$ (fb^{-1})	3000	3000	3000
$\sigma \cdot \mathrm{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

arXiv:1310.8361



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

ttH / ttZ



➡ Theoretical uncertainties cancel mostly

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

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

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

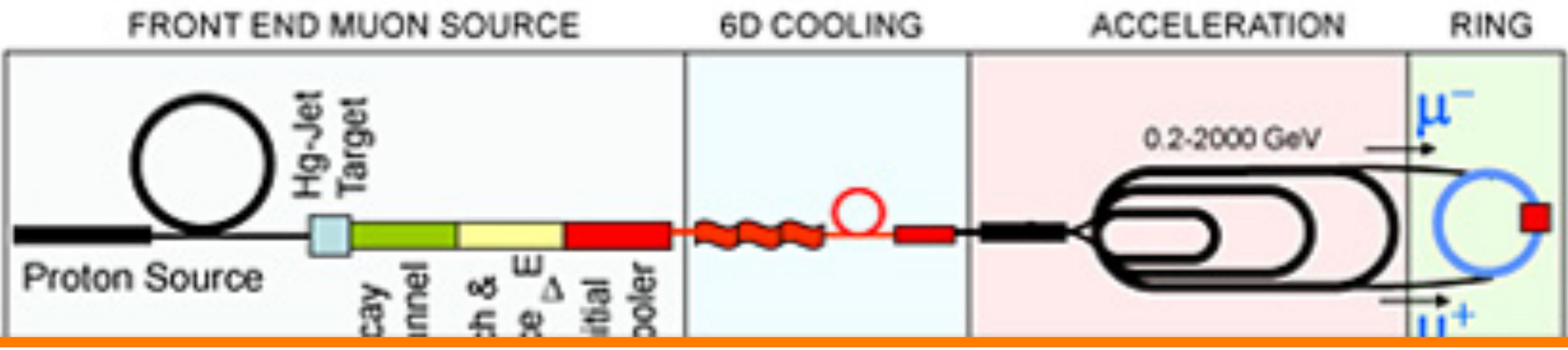
- Both lepton and 100 TeV pp colliders are vital for this effort!

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

Higgs invisible decays

Right handed Neutrinos
etc.. etc..

Muon Collider



The numbers then (1999)

Table 9: Baseline parameters for high- and low-energy muon colliders. Higgs/year assumes a cross-section σ = 5×10^4 fb; a Higgs width $\Gamma = 2.7$ MeV; 1 year = 10^7 s. From the Muon Collider Collaboration [16]

CoM energy (TeV)	3	0.4	0.1		
p energy (GeV)	16	16	16		
p/bunch	2.5×10^{13}	2.5×10^{13}	5×10^{13}		
Bunches/fill	4	4	2		
Rep. rate (Hz)	15	15	15		
$1/\tau_\mu$ (Hz)	32	240	960		
p power (MW)	4	4	4		
μ/bunch	2×10^{12}	2×10^{12}	4×10^{12}		
μ power (MW)	28	4	1		
Wall power (MW)	204	120	81		
Collider circum. (m)	6000	1000	350		
$\langle B \rangle$ (T)	5.2	4.7	3		
$\delta p/p(\%)$	0.16	0.14	0.12	0.01	0.003
6-D $\epsilon_{6,N}$ $(\pi \mathrm{m})^3$	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}
Rms ϵ_n (π mm-mrad)	50	50	85	195	290
β^* (cm)	0.3	2.6	4.1	9.4	14.1
σ_z (cm)	0.3	2.6	4.1	9.4	14.1
σ_r spot (μm)	3.2	26	86	196	294
σ_θ IP (mrad)	1.1	1.0	2.1	2.1	2.1
Tune shift	0.044	0.044	0.051	0.022	0.015
$n_{\mathrm{turns}}^{\mathrm{effective}}$	785	700	450	450	450
Luminosity ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	7×10^{34}	10^{33}	1.2×10^{32}	2.2×10^{31}	10^{31}
Higgs/year			1.9×10^3	4×10^3	3.9×10^3

$\mu^+\mu^-$ 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

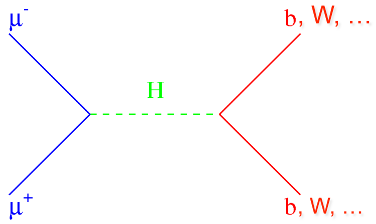
$$\sigma(\mu^+\mu^- \to H) \approx 40000 \times \sigma(e^+e^- \to H)$$ [σ_{peak} = 70 pb at tree level]

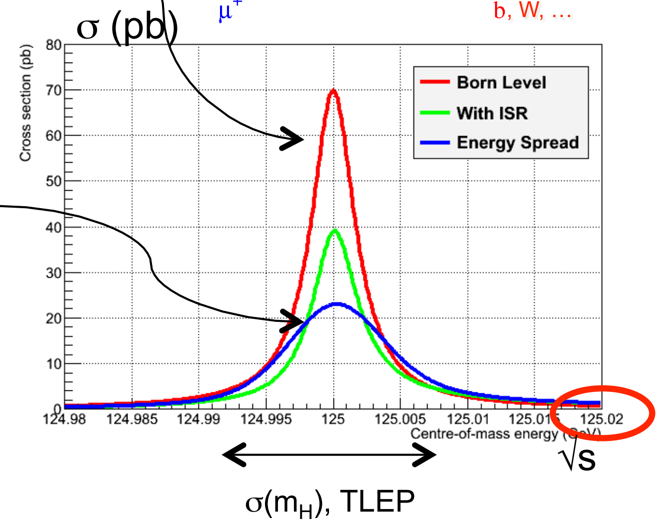
  - Beam energy spread $\delta E/E$ may be reduced to 3×10^{-5}
    - 6D Cooling, no beamstrahlung, ~no bremsstrahlung
    - For $\delta E/E$ = 0.003% (δE ~ 3.6 MeV, Γ_H ~ 4 MeV)
      - ➨ Corresponding luminosity ~ 10^{31} cm^{-2}s^{-1}

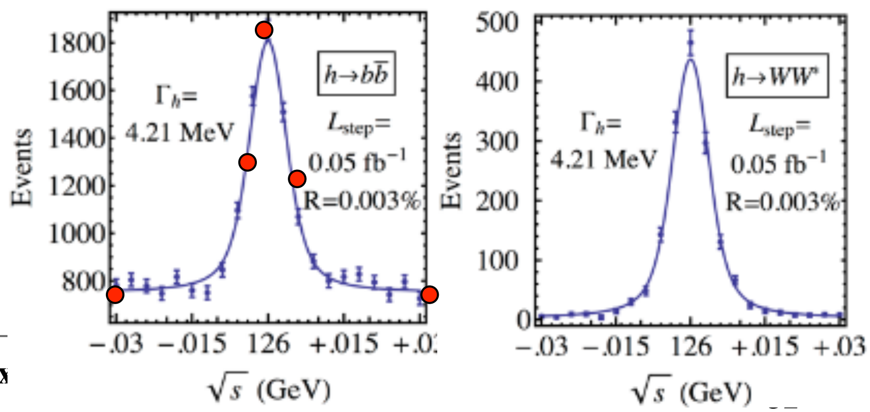
Expect 2300 Higgs events in 100 pb^{-1}/ year

  - 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%







Muon collider is the best way to reach lepton ccoliisions above 3 TeV ECM. MUCH R&D remain in cooling!
Muon collider is a very pretty Higgs factory but not necessarily the one we need for H(125)

-- if it is a single particle we will know more from the e+e- collider with ZH tag
muon collider can do this but high luminosity is necessary.

-- except ig the Higgs boson is constituted of several nearby peaks.

-- such a situation can occur in MSSM for H,A doublet with different CP parities
in which case only the muon collider can isolate the two peaks.

-- neutrino factory is the ultinmate neutrino oscillation tool and a 'baby neutrino factory' nustorm is
a necessary step to ensure the measurements of cross-sections needed for the long baseline search of CP violation

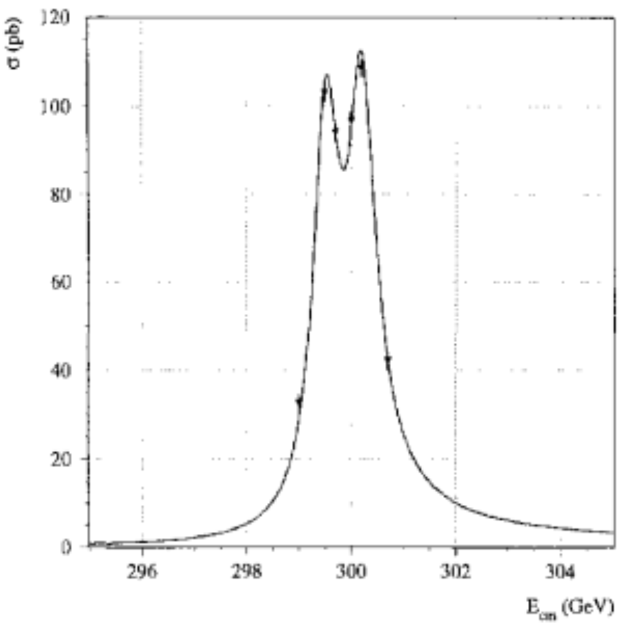
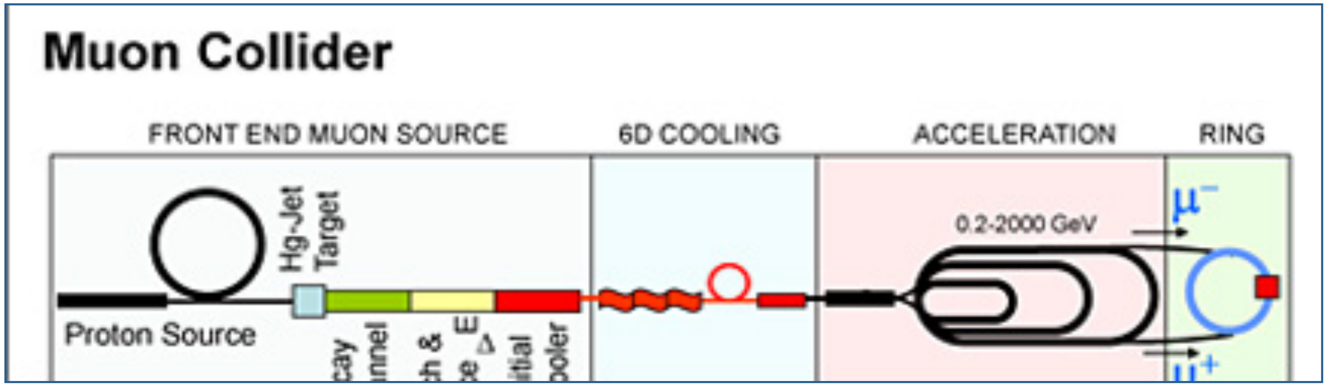
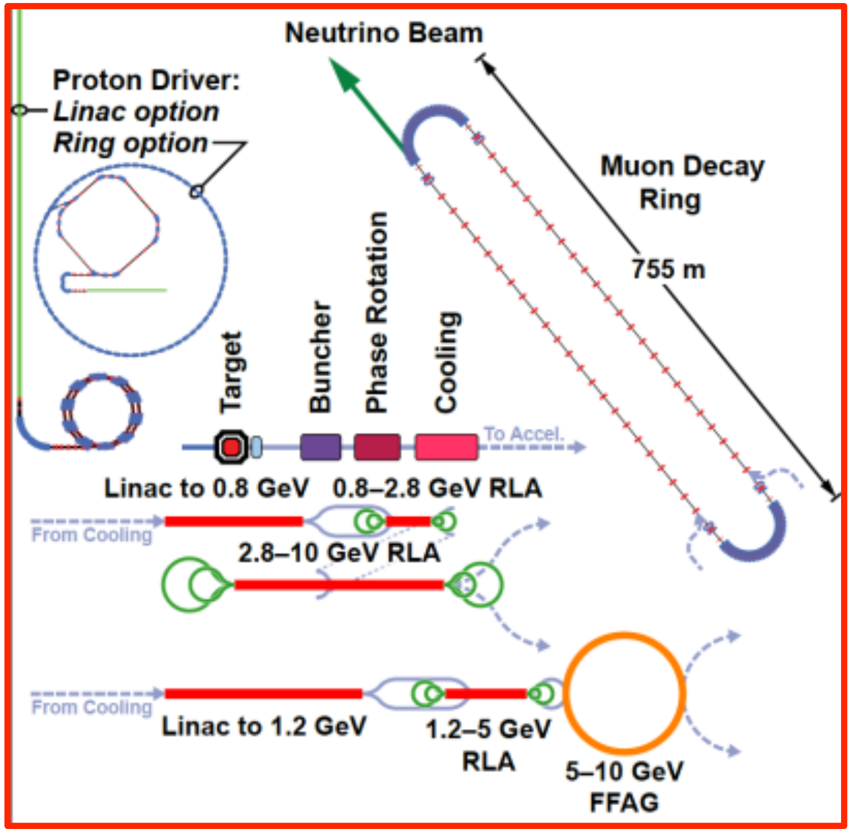


Fig. 39: Production cross-section of H and A via $\mu^+\mu^- \rightarrow H, A \rightarrow b\bar{b}$ as a function of the centre-of-mass energy for $m_A = 300$ GeV/c^2 and $\tan\beta = 10$, with a centre-of-mass energy relative spread of 3×10^{-5}. The triangles with error bars represent a simulated six-energy-point scan, with 25 pb^{-1} per point.

Alai

Neutrino Factory





MICE is one of the critical R&D experiments towards neutrino factories and muon colliders

With the growing importance of neutrino physics + the possibility of a light Higgs (115-130 GeV) physics could be turning this way very fast!

Cooling and more generally the initial chain capture, buncher, phase rotation and cooling rely on complex beam dynamics and technology, such as

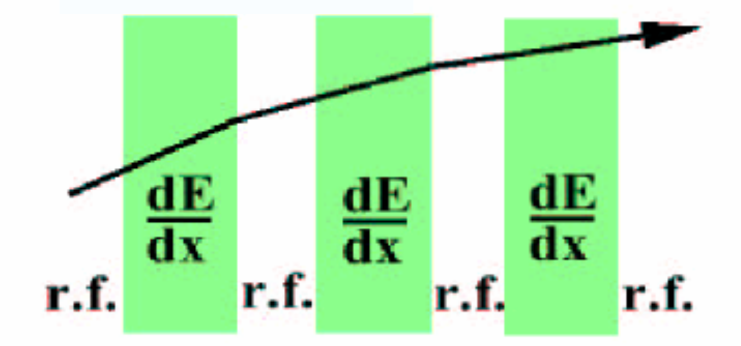
High gradient (~>12 MV/m) RF cavities embedded in strong (>2T) solenoidal magnetic field

MANY CHALLENGES!

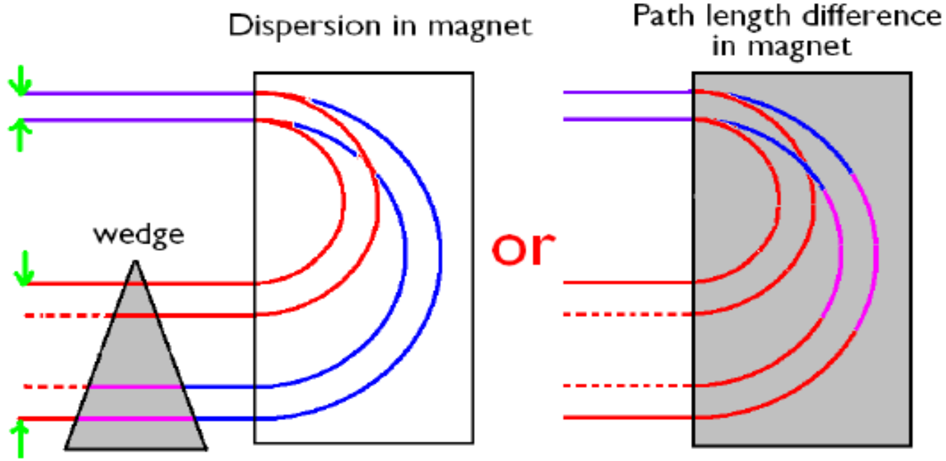
MUON COOLING ➔ HIGH INTENSITY NEUTRINO FACTORY
HIGH LUMINOSITY MUON COLLIDER

COOLING -- Principle is straightforward

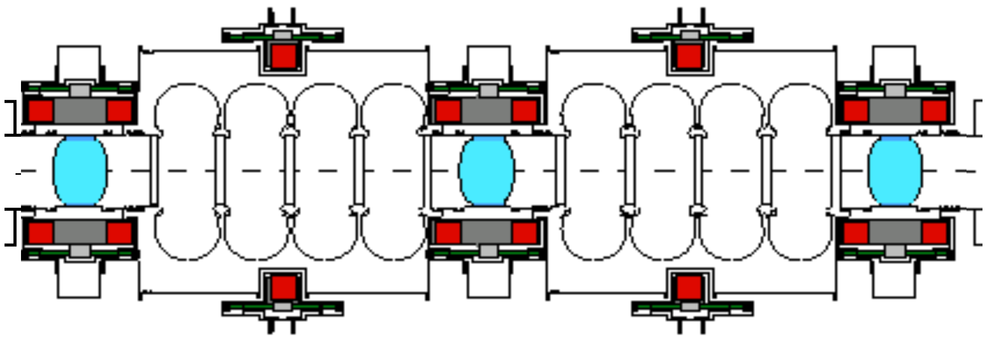
Transverse:



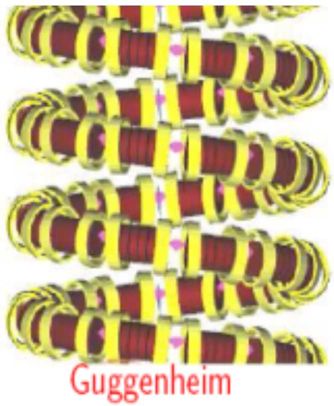
Longitudinal:

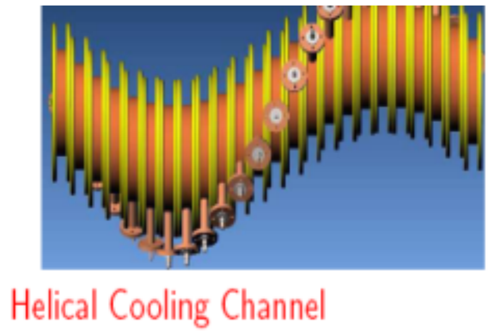


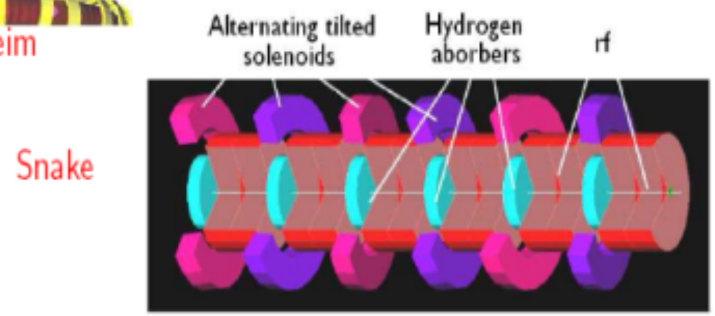
Practical realization is not!



MICE cooling channel (4D cooling)







6D candidate cooling lattices

MICE the Muon Ionization Cooling Experiment

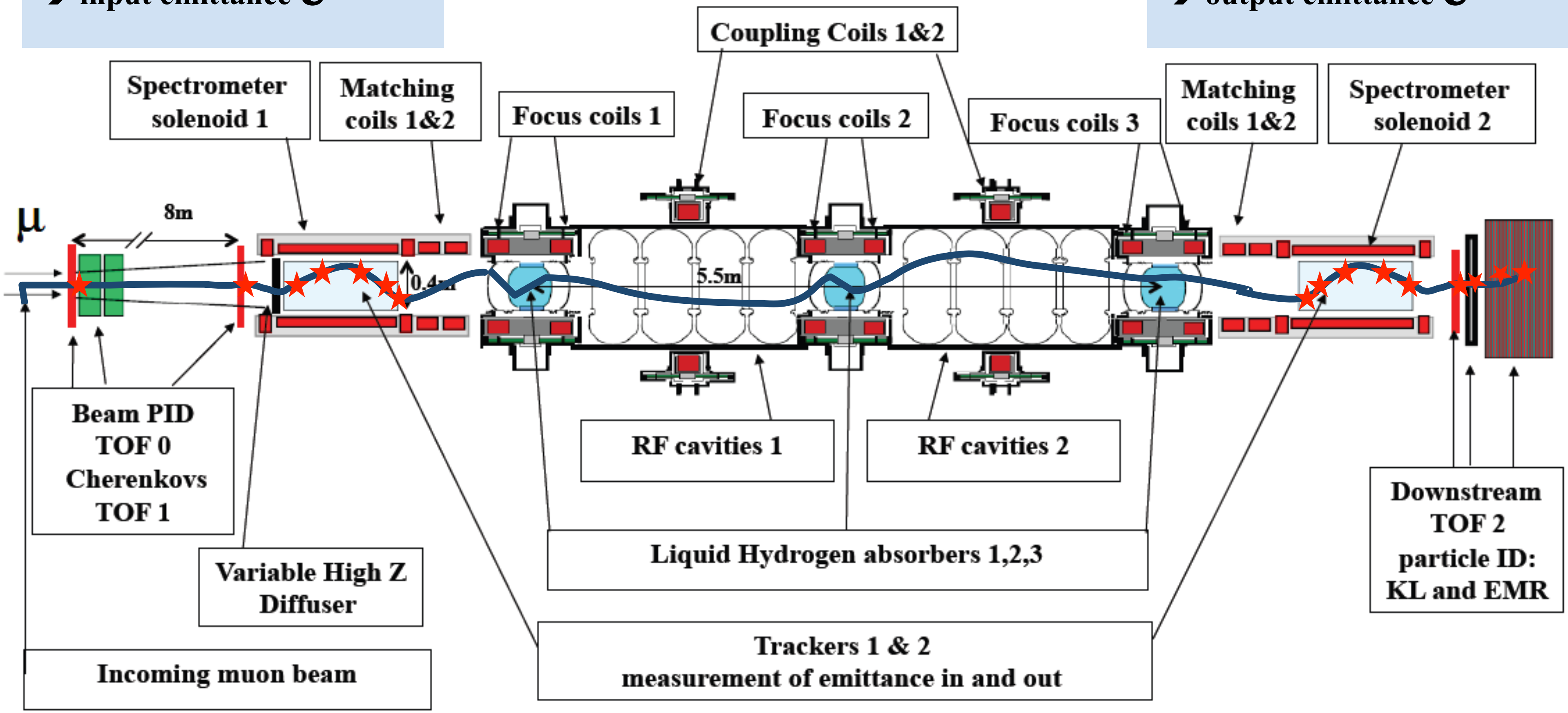
Measure input particle
x,x',y,y', t, t'=E/Pz

→ input emittance ε^{in}

COOLING CHANNEL

Measure output particle
x,x',y,y', t, t'=E/Pz

→ output emittance ε^{out}

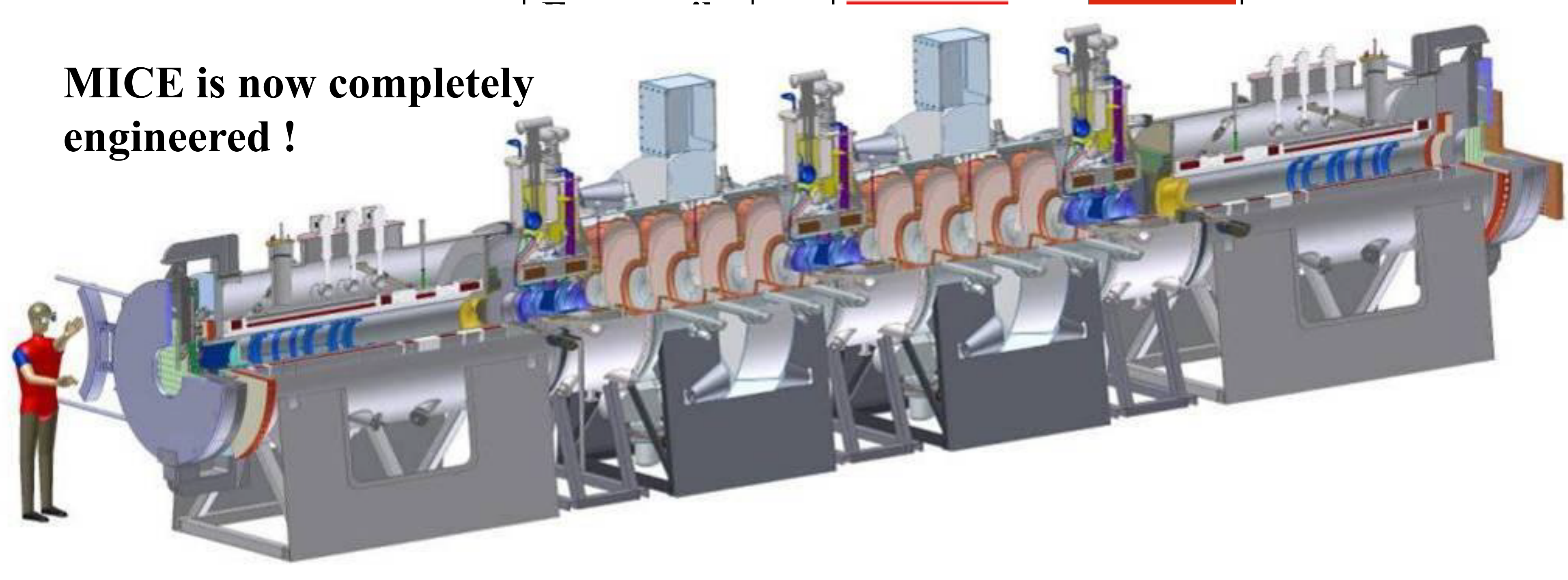


Particle by particle measurement, then accumulate few 10^5 muons
→ $\Delta[(\varepsilon^{in} - \varepsilon^{out})/\varepsilon^{in}] = 10^{-3}$

MICE Collaboration across the planet

Coupling Coils 1&2

MICE is now completely engineered !



Cherenkovs

Diffuser

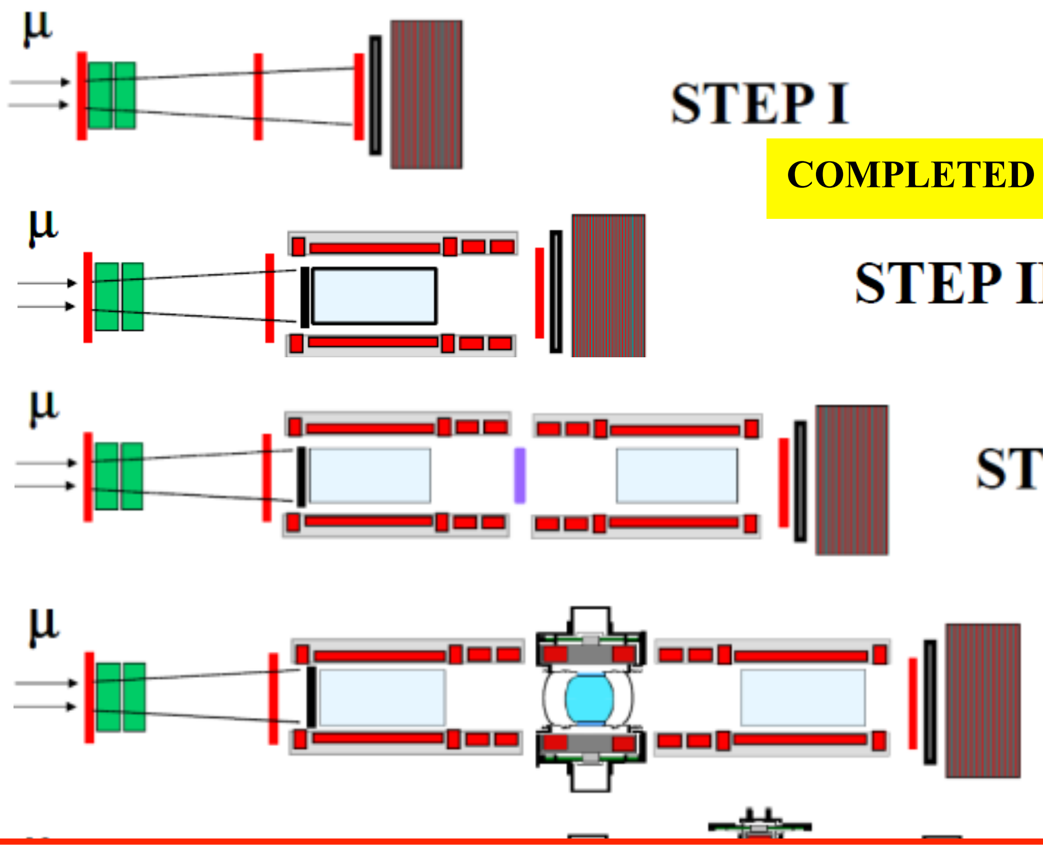
Liquid Hydrogen absorbers 1,2,3

TOF 2, KL
EMR

Incoming muon beam

Trackers 1 & 2

MICE



STEP I

COMPLETED

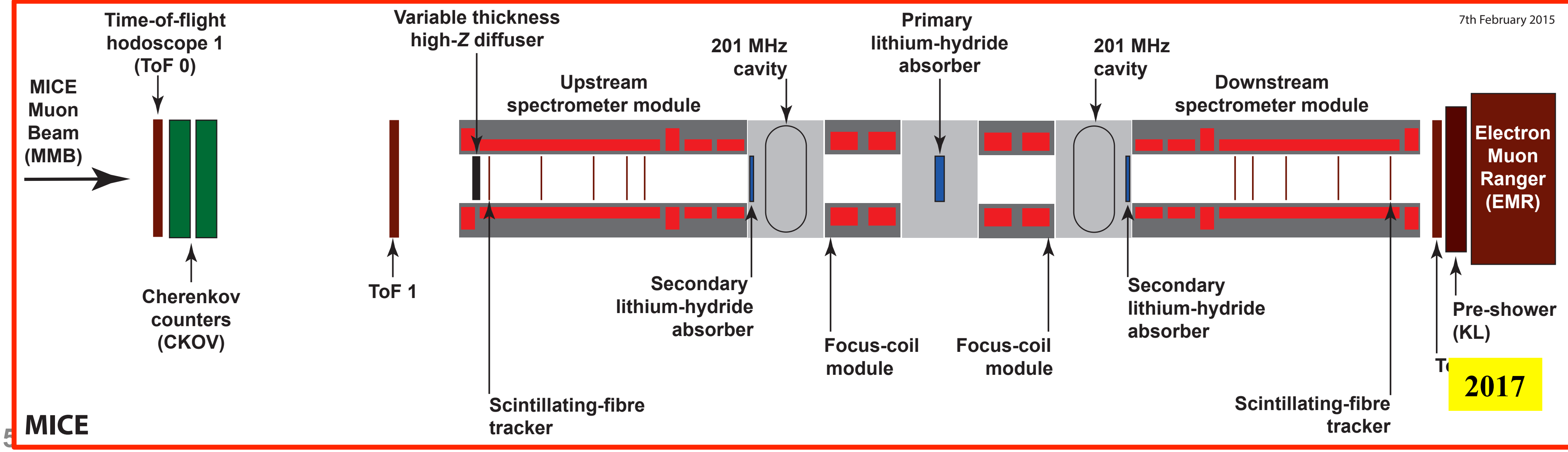
STEP II

STEP III

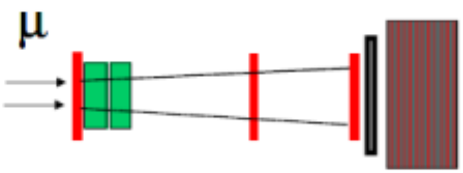
STEP IV

2015

Both for funding and science reasons MICE is executed in Steps …. Originally we had 6 Steps
We will probably only have 3 steps step I, step IV, and the final step (P5)



2017



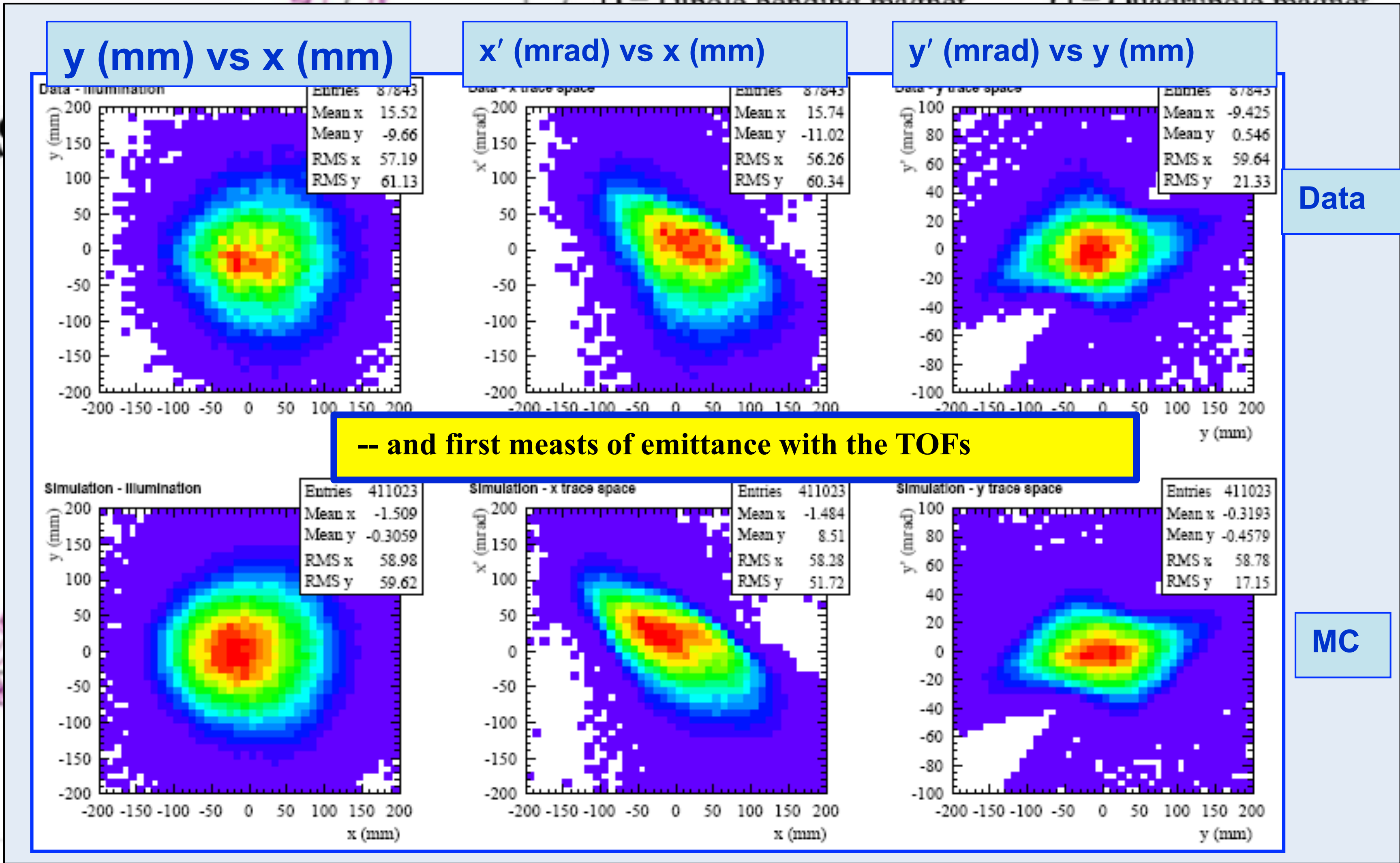
Beam commissionning

STEP I

Completed and published!

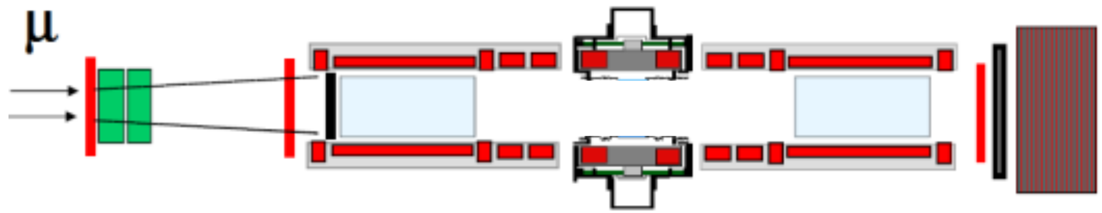
Main results:

- **-- It all works!**
- **-- TOF resolution s: 50 ps and 1cm**
- **-- ~100 muons per second**



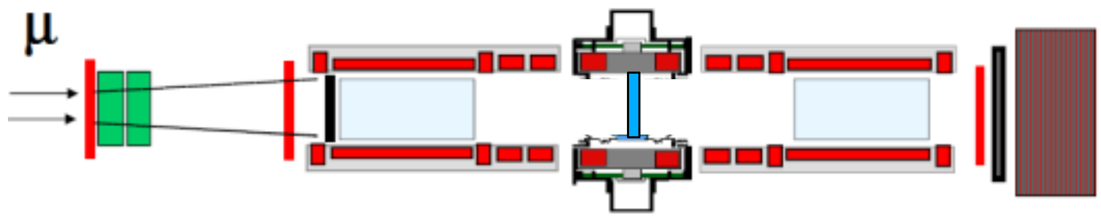
-- and first measts of emittance with the TOFs

STEP IV EXPERIMENTS (2013)



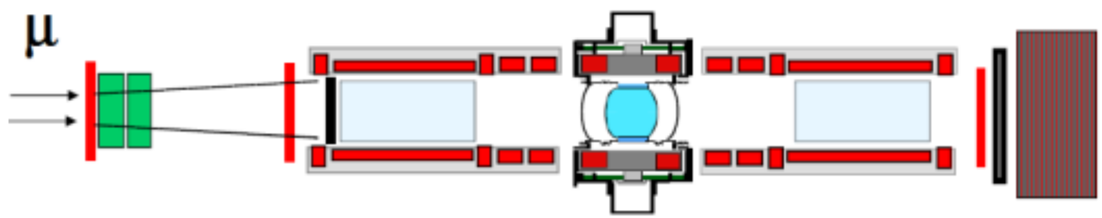
STEP IV

No absorber
Alignment
Optics studies



STEP IV

Solid absorber(s)
LiH



STEP IV

Liq H_2 absorber
(full/empty)

Multiple scattering
Energy loss
→ Cooling

There is a very strong motivation to study the Higgs boson thoroughly
-- first time we see an elementary scalar!

The FCC-ee+FCC-hh combination is 'invincible'
most precise and most complete.

CERN has launched a study of this 'ambitious post-LHC project' , the FCC
Join us!

Muon storage rings remain very specific and quite unique for neutrino studies and precise high energy colliders.

Much R&D remains to be done

MICE at RAL is <u>the</u> concrete R&D that is taking place.
Although it has been delayed significantly since the beginning of the effort in 2001, it is now about to take thecrucial muon cooling data in 2015.

The final 'sustainable cooling' will be tested in 2017.