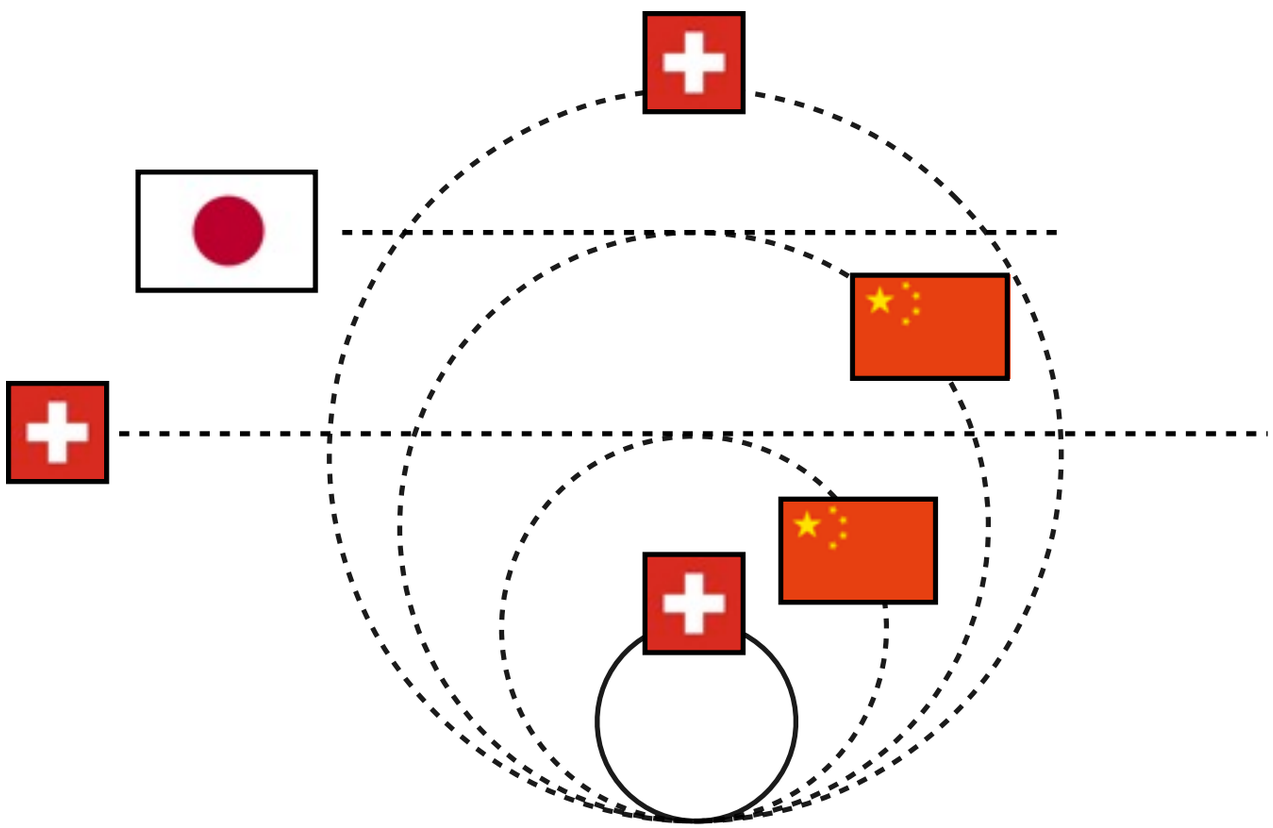
Higgs measurements
at Future Circular Colliders

SUSY 2016

Melbourne, July 3-8, 2016



Christophe Grojean

DESY (Hamburg)

(christophe.grojean@desy.de)

Which Machine(s)?

Hadrons

- large mass reach ⇛ exploration?
- S/B ~ 10^{-10} (w/o trigger)
- S/B ~ 0.1 (w/ trigger)
- requires multiple detectors
  (w/ optimized design)
- only pdf access to $\sqrt{\hat{s}}$
- ⇛ couplings to quarks and gluons

Leptons

- S/B ~ 1 ⇛ measurement?
- polarized beams
  (handle to chose the dominant process)
- limited (direct) mass reach
- identifiable final states
- ⇛ EW couplings

Circular

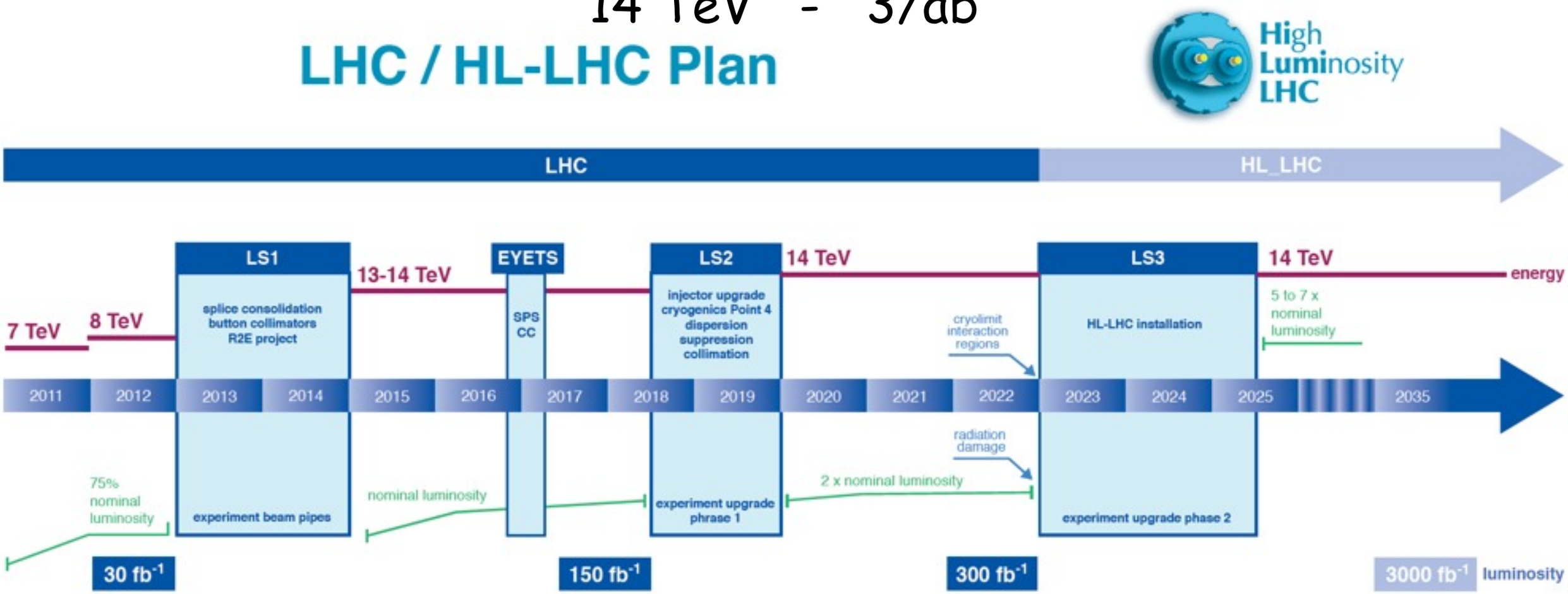
- $\sqrt{s}$ limited by synchroton radiation
- higher luminosity
- several interaction points
- precise E-beam measurement
  (O(0.1MeV) @ FCC-ee via resonant depolarization)

Linear

- easier to upgrade in energy
- easier to polarize beams
- large beamsthralung
- greener: less power consumption

HL-LHC (2023-2035)

14 TeV - 3/ab

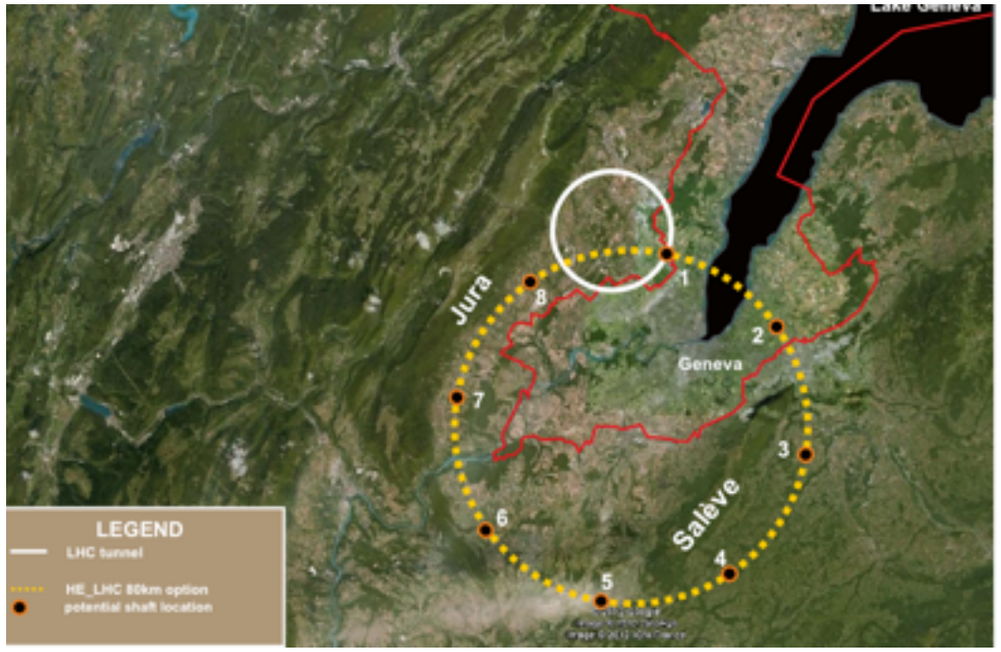


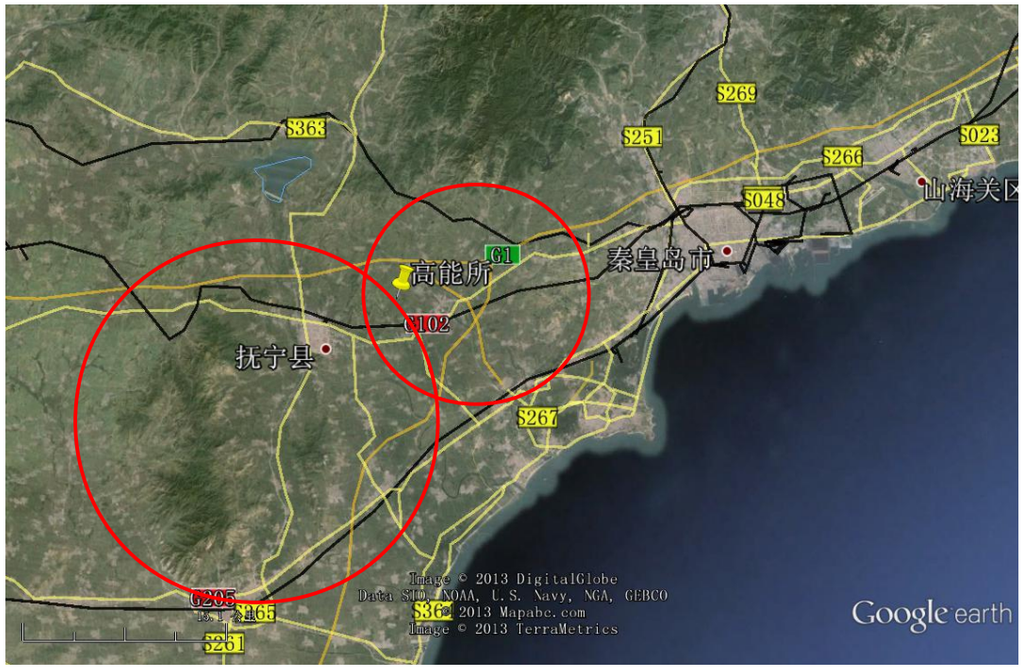
	Higgs bosons at √s=14TeV
HL-LHC, 3000fb^{-1}	170M
VBF (all decays)	13M
ttH (all decays)	1.8M
H->Zγ	230k
H->μμ	37k
HH (all)	121k

		K_γ	K_W	K_Z	K_g	K_b	K_t	K_τ	$K_{Z\gamma}$	K_μ
300fb^{-1}	ATLAS	[9,9]	[9,9]	[8,8]	[11,14]	[22,23]	[20,22]	[13,14]	[24,24]	[21,21]
300fb^{-1}	CMS	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000fb^{-1}	ATLAS	[4,5]	[4,5]	[4,4]	[5,9]	[10,12]	[8,11]	[9,10]	[14,14]	[7,8]
3000fb^{-1}	CMS	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

FCC-ee (x=post HL-LHC - x+20)/CepC (??-??)

240/350/(500) - 10/ab





FCC-ee (x=post HL-LHC - x+20)/CepC (??-??)

240/350/(500) - 10/ab

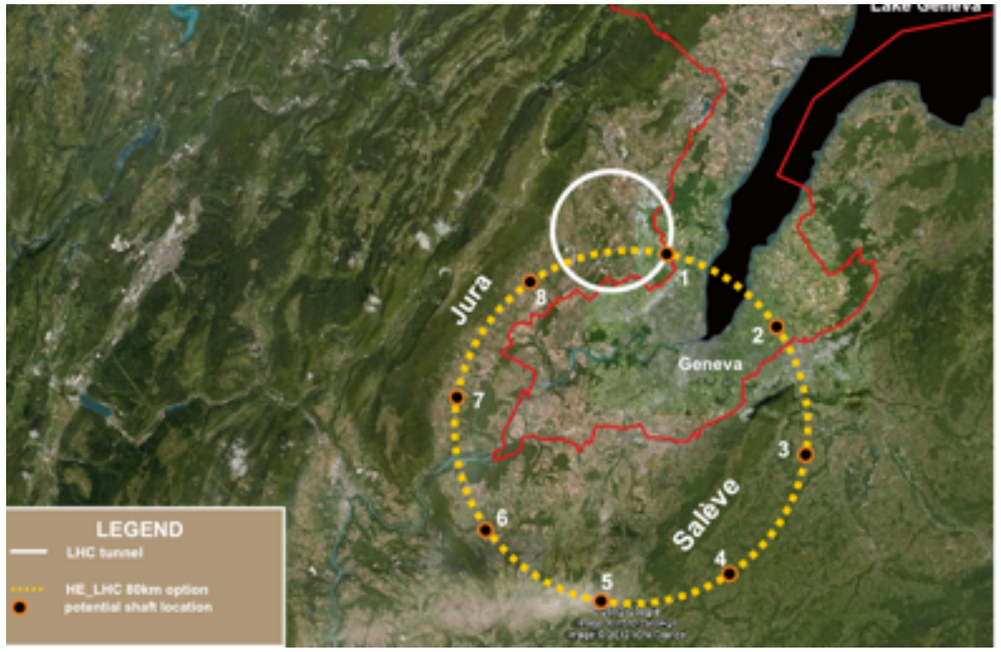
parameter	FCC-ee			CEPC	LEP2
energy/beam [GeV]	**45**	**120**	**175**	**120**	105
bunches/beam	13000-60000	500-1400	51- 98	50	4
beam current [mA]	1450	30	6.6	16.6	3
luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	**21 - 280**	**5 - 11**	**1.5 - 2.6**	**2.0**	0.0012
energy loss/turn [GeV]	0.03	1.67	7.55	3.1	3.34
synchrotron power [MW]	100			103	22
RF voltage [GV]	0.2-2.5	3.6-5.5	11	6.9	3.5

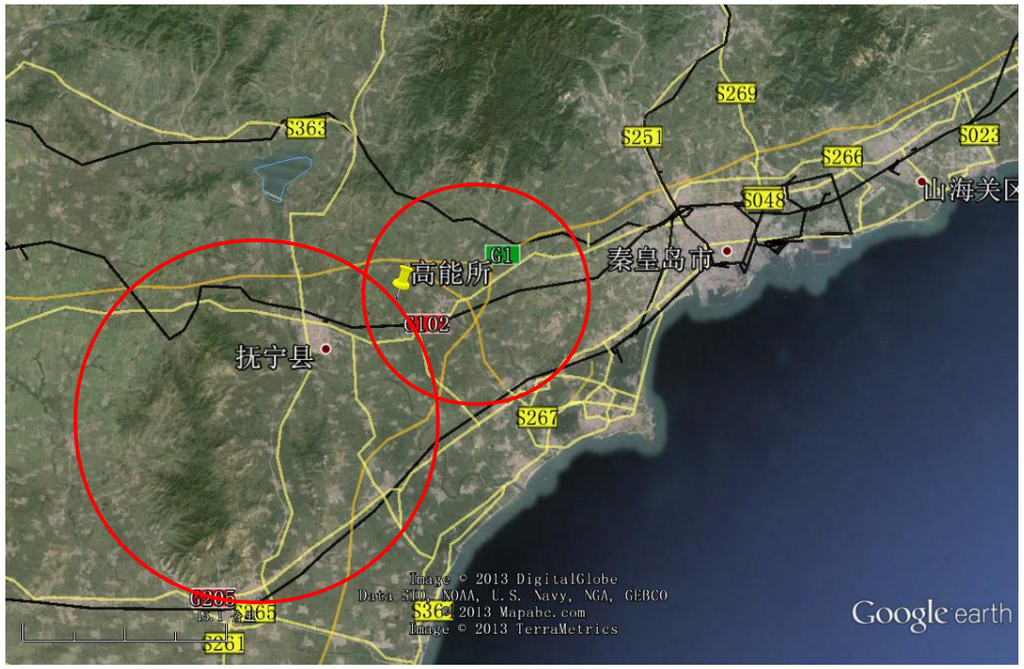
@FCC-ee

- 10^6 H
- 10^{12} Z possible upgrade to 10^{13} Z (line-shape, mass & width, probe rare (FCNC) decays)
- 10^8 W (mass)
- 3×10^{10} tau/muon pairs
- 2×10^{11} b/c quarks $\Rightarrow$ >20'000 $B_s\to\tau^+\tau^-$
- TLEP@340/500: 10^6 top pairs (pole mass, probe FCNC decays, top Yukawa)

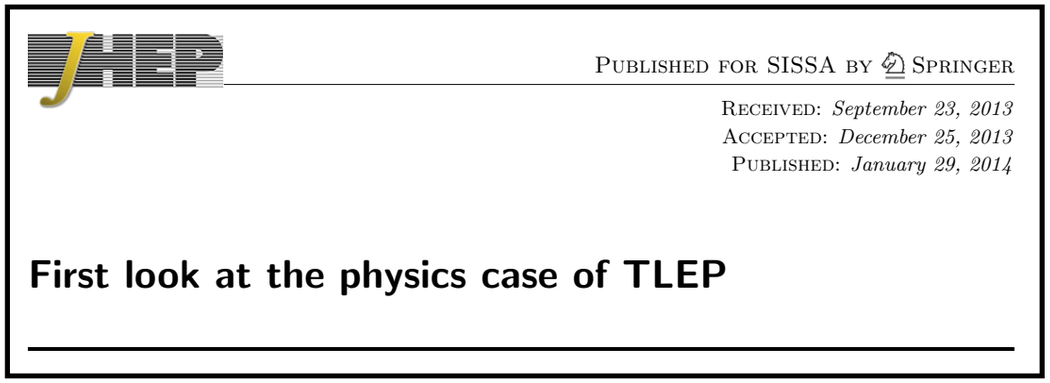
FCC-ee (x=post HL-LHC - x+20)/CepC (??-??)

240/350/(500) - 10/ab





- physics case: JHEP01(2014)164 arXiv:1308.6176
- CDR and cost review due in 2018



JHEP

PUBLISHED FOR SISSA BY SPRINGER

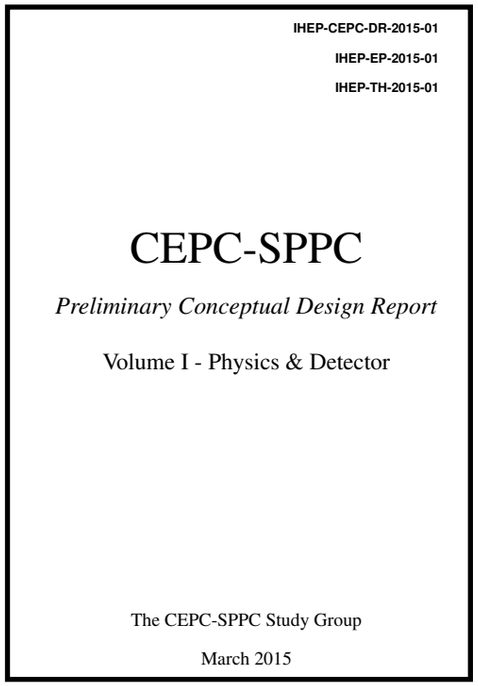
RECEIVED: *September 23, 2013*
ACCEPTED: *December 25, 2013*
PUBLISHED: *January 29, 2014*

First look at the physics case of TLEP

The FCC and CepC are essentially equivalent proposals with different emphasis; FCC – hadrons via e+e-, CepC – e+e- then hadrons

Mike Harrison , SPC meeting Sept. 2015

pre-CDR:



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

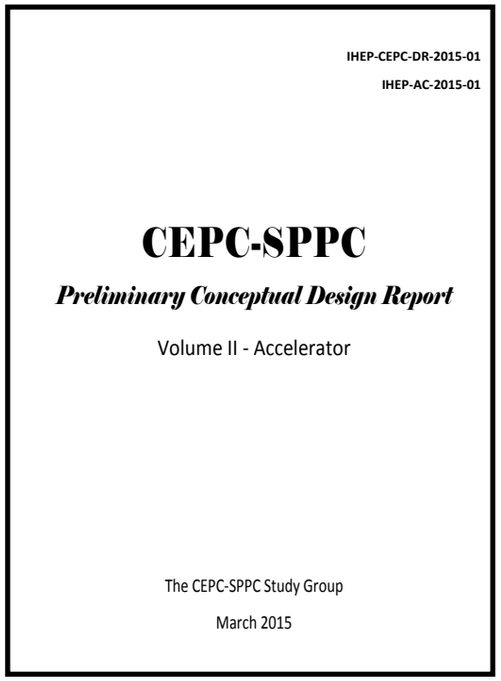
CEPC-SPPC

Preliminary Conceptual Design Report

Volume I - Physics & Detector

The CEPC-SPPC Study Group

March 2015



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

CEPC-SPPC

Preliminary Conceptual Design Report

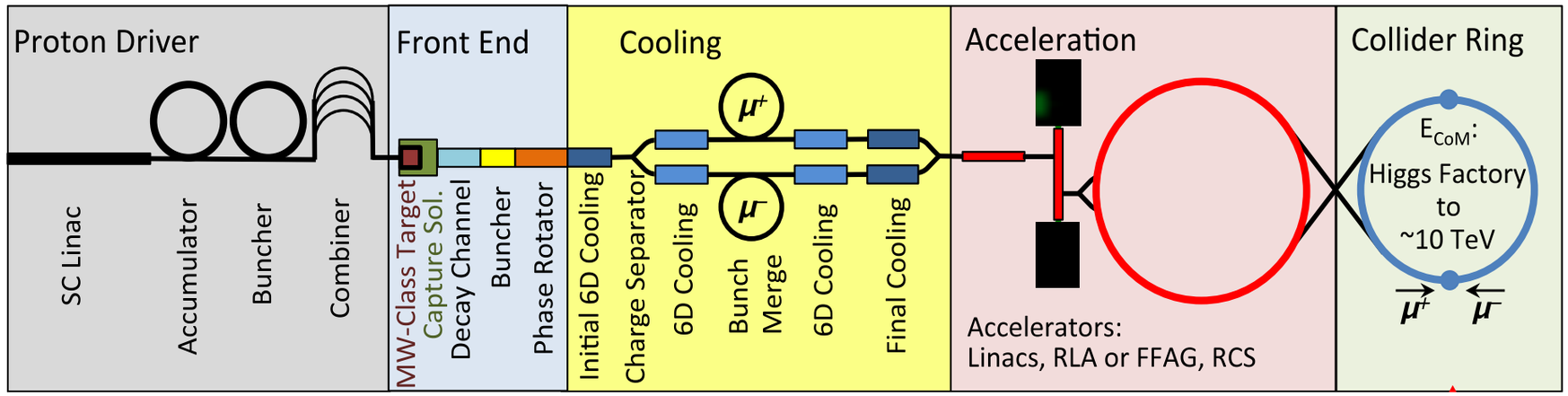
Volume II - Accelerator

The CEPC-SPPC Study Group

March 2015

μ collider aka project X (TBD: ?-?)

126/1'000/10'000 GeV - O(1)/ab



M. Palmer, CERN '15

Physics Frontiers

- **Intense and cold muon beams ⇨ unique physics reach**
  - Tests of Lepton Flavor Violation
  - Anomalous Magnetic Moment (g-2)
  - Precision sources of neutrinos
  - Next generation lepton collider

$$m_\mu = 105.7\, MeV/c^2$$
$$\tau_\mu = 2.2\mu s$$

Colliders

- **Opportunities**
  - s-channel production of scalar objects
  - Strong coupling to particles like the Higgs
  - Reduced synchrotron radiation ⇨ multi-pass acceleration feasible
  - Beams can be produced with small energy spread
  - Beamstrahlung effects suppressed at IP
- ***BUT* accelerator complex/detector must be able to handle the impacts of μ decay**

$$\lhd \left(\frac{m_\mu^2}{m_e^2}\right) \cong 4\times 10^4$$

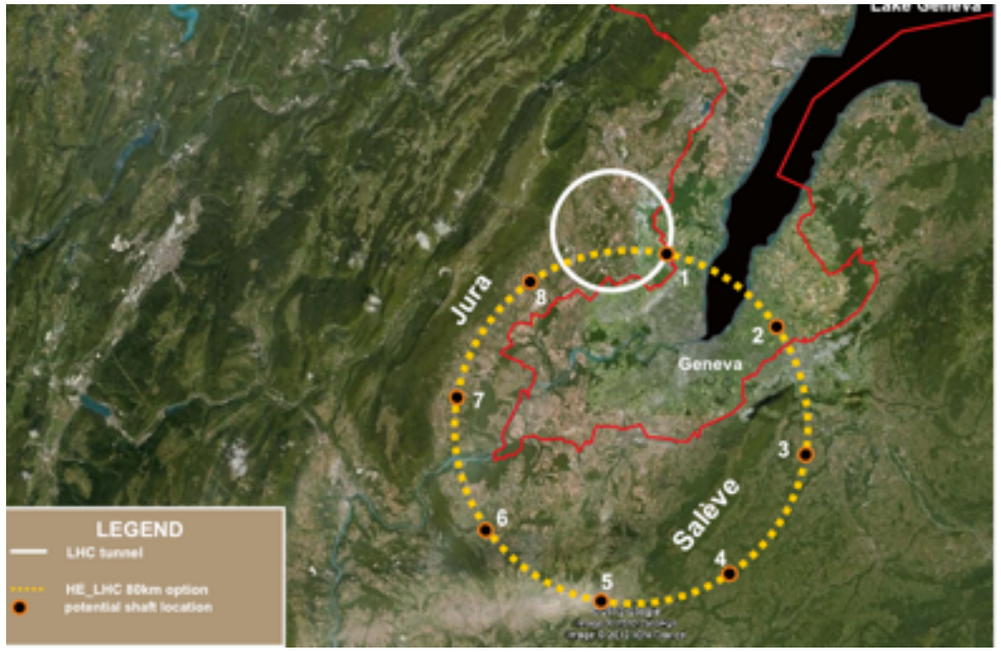
Collider Synergies

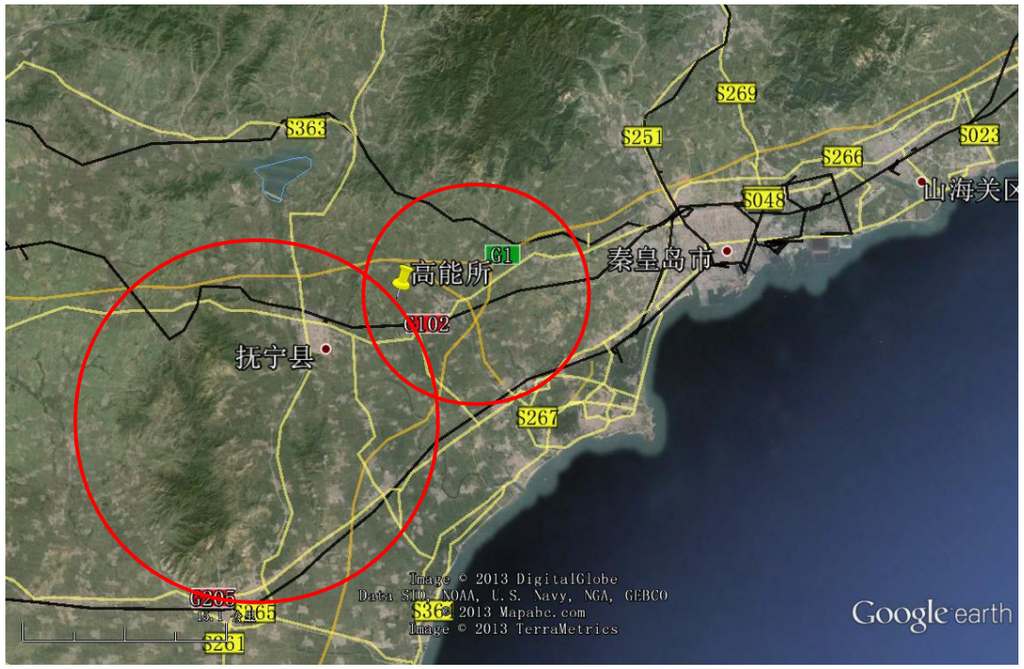
- High intensity beams required for a long-baseline Neutrino Factory are readily provided in conjunction with a Muon Collider Front End
- Such overlaps offer unique staging strategies to guarantee physics output while developing a muon accelerator complex capable of supporting collider operations

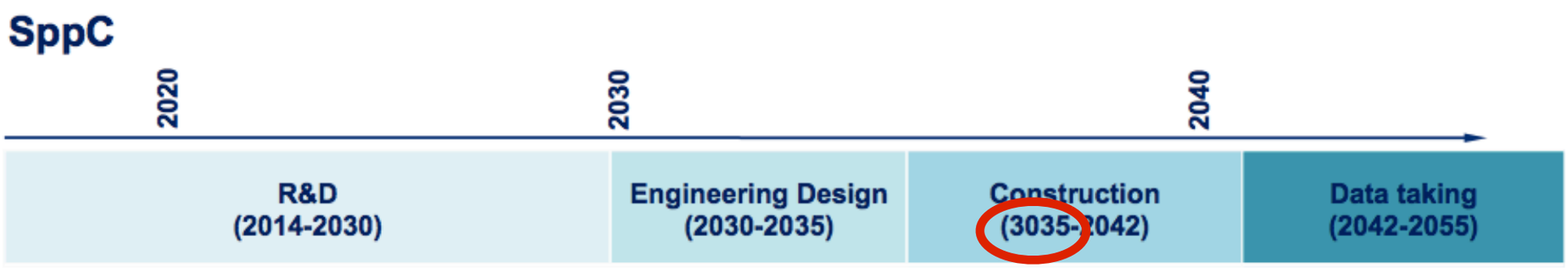
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

FCC-hh/SppC (TBC: 2035-2060)

80/100 TeV - 30/ab

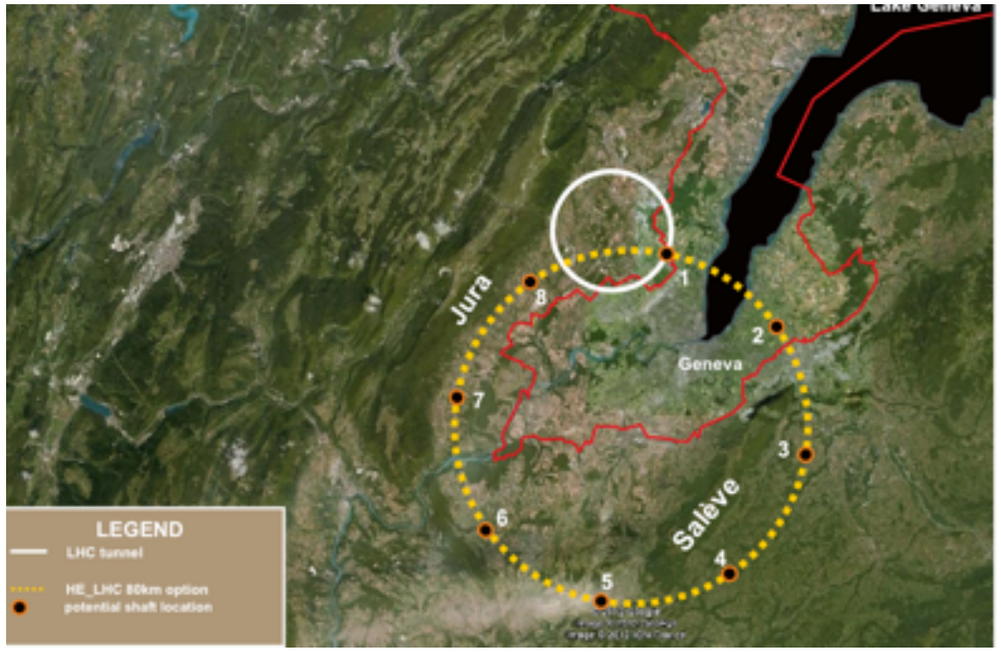


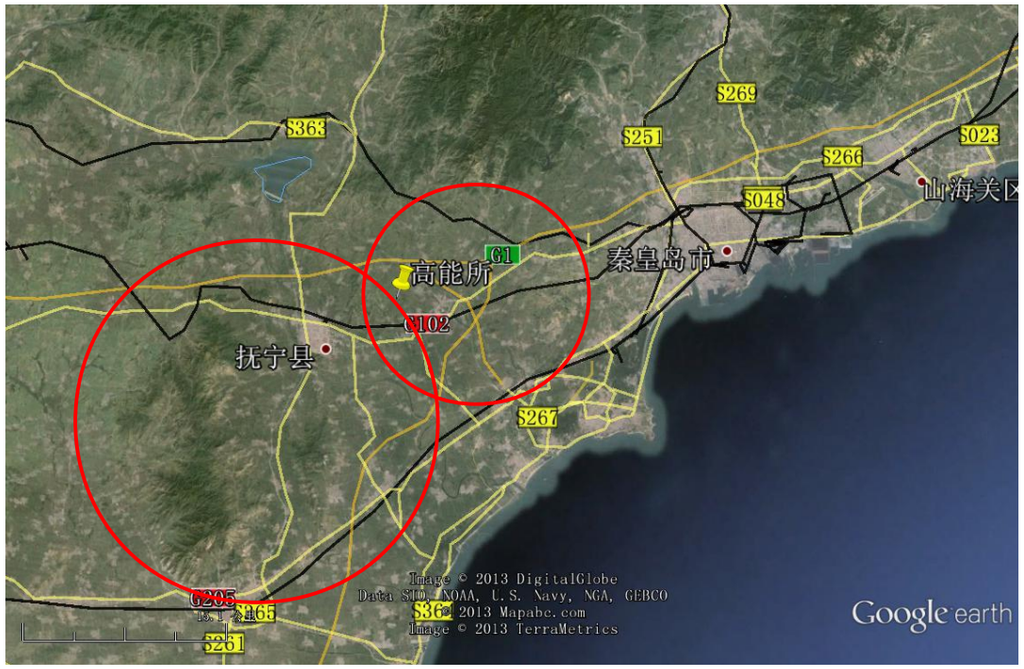




FCC-hh/SppC (TBC: 2035-2060)

80/100 TeV - 30/ab





Parameter	FCC-hh		SPPC	LHC	HL LHC
collision energy cms [TeV]	100		71.2	14	
dipole field [T]	16		20	8.3	
# IP	2 main & 2		2	2 main & 2	
bunch intensity [10^{11}]	1	1 (0.2)	2	1.1	2.2
bunch spacing [ns]	25	25 (5)	25	25	25
luminosity/Ip [10^{34} $cm^{-2}s^{-1}$]	5	25	12	1	5
events/bx	170	850 (170)	400	27	135
stored energy/beam [GJ]	8.4		6.6	0.36	0.7
synchr. rad. [W/m/apert.]	30		58	0.2	0.35

Higgs as a particular object to study

Preamble

- W/Z discovered in '83. Still discussing today how to improve the measurement of their properties! Hadron colliders played, are playing and will continue playing a key role in this game
  - reasonable to expect the same will be true for the Higgs 30-40 yrs after 2012
- Precision measurements of Higgs properties are the guaranteed deliverable of any future energy-frontier facility
  - set performance benchmarks, and allow cross-comparisons among facilities
  - little we know of physics at the TeV scale!! (see the 750 GeV excitement)
- Higgs will soon become an analysis tool, if not a background, like W/Z and like the top quark
  - need to learn how to deal with and optimize the exploitation of large samples
- pp@100 TeV vs e^+e^- (LC or CC): complementarity, synergy and more ....

M. Mangano, KUST'16

Higgs programme at future colliders

more energy + more luminosity = more Higgses

# of Higgses in 3 ab^{-1}

100 TeV > 2 billion

33 TeV > 500 million

14 TeV > 150 million

In comparison, O(million) Higgs at Higgs factories

@ 100 TeV

	σ	N / $10ab^{-1}$
gg→H	740 pb	7.4 G
VBF	82 pb	0.8 G
WH	16 pb	160 M
ZH	11 pb	110 M
ttH	38 pb	380 M
gg→HH	1.4 pb	14 M

M. Mangano, HXSWG '15

Statistical precision:

- O(100 - 500) better w.r.t Run 1
- O(10 - 20) better w.r.t HL-LHC

- better measurements of Higgs properties: mass, width
- precision measurements of Higgs couplings
- access to rare decay modes
- access at rare production modes/kinematical distributions
- discovery of extended Higgs sectors

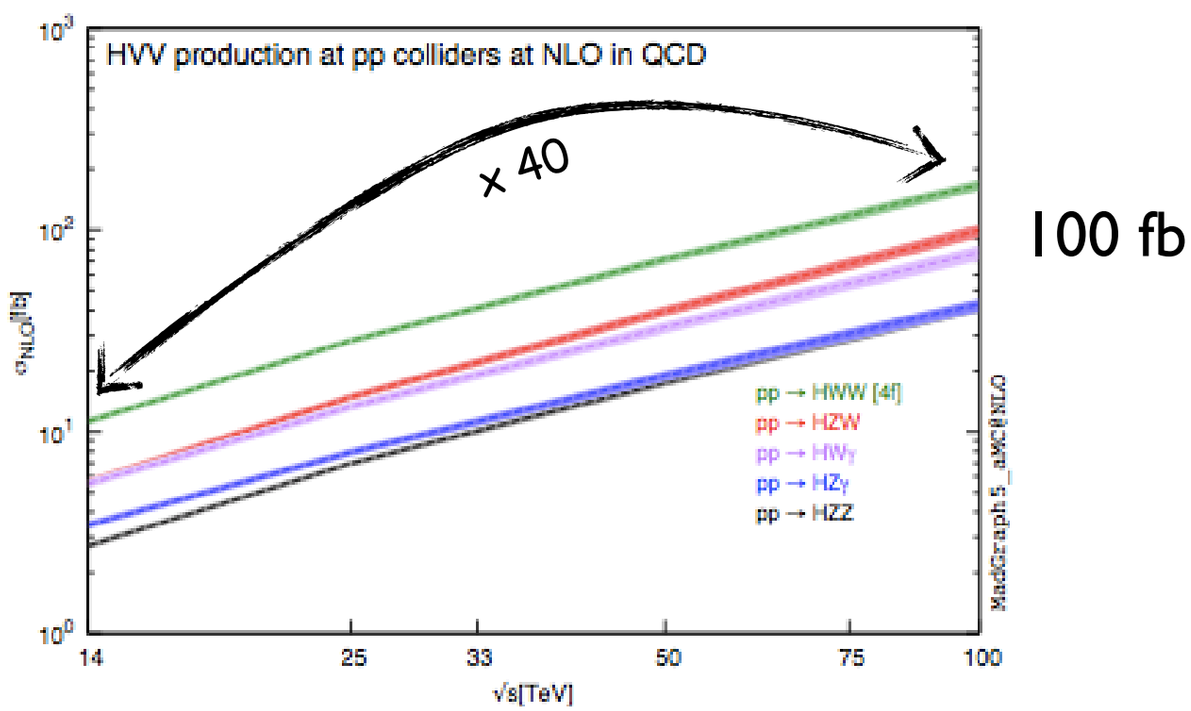
H production @ FCC-hh

	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

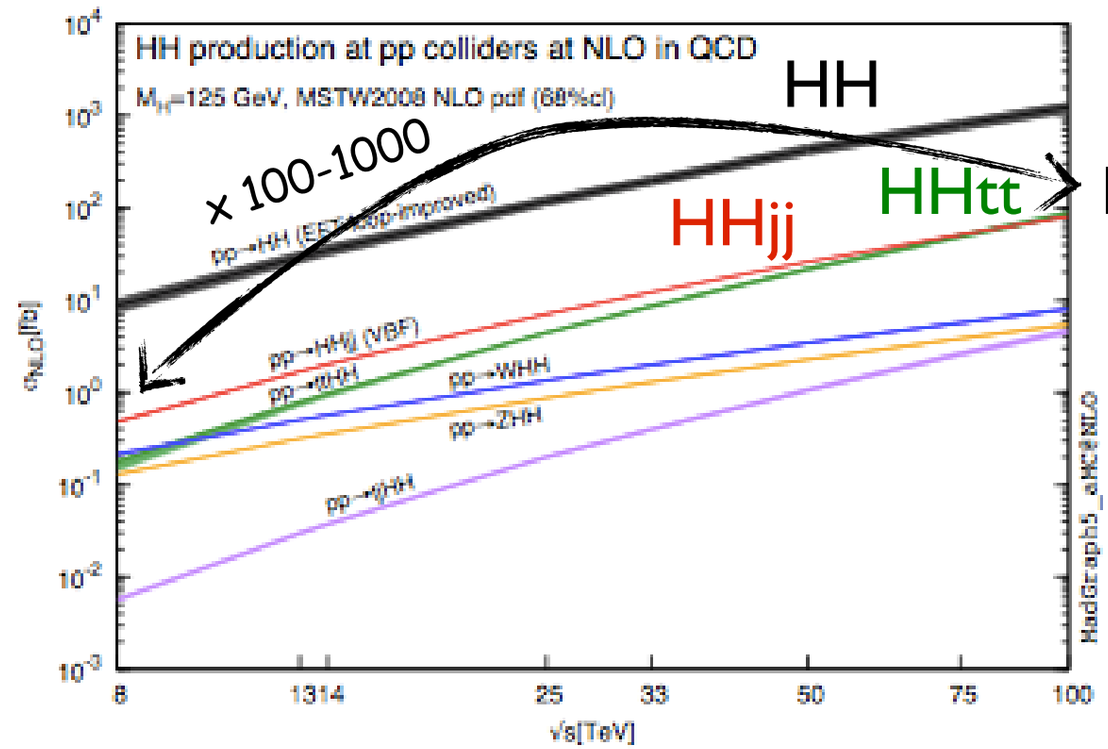
relative importance of production modes modified in favor of VBF and ttH

FCC-hh = H+X factory

Higgs-diboson associated production



Higgs-pair associated production

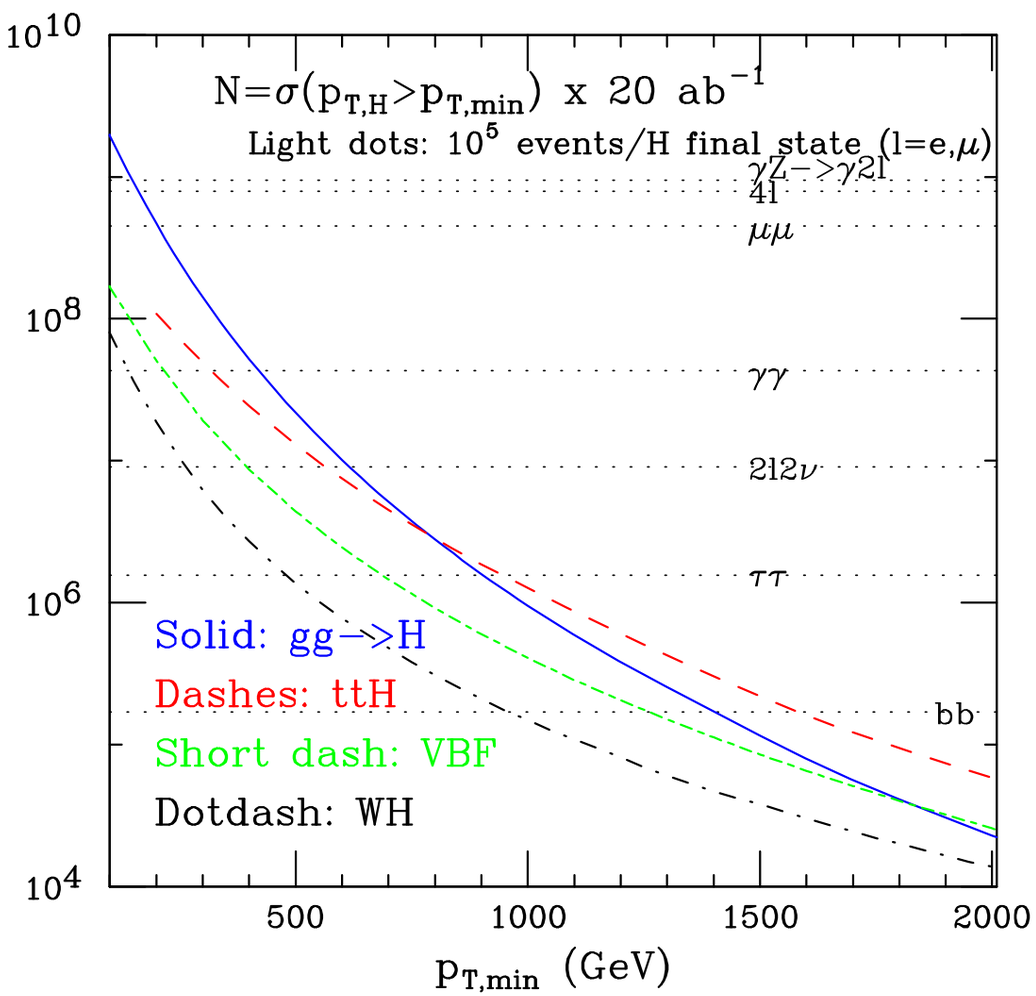


(Plots from P. Torrielli and MLM, CERN'14)

Rare Higgs production/decay

FCC-hh =
probe extreme kinematic regimes

FCC-hh = H+X factory



	Process	$\sigma_{\rm NLO}$(8 TeV) [fb]	$\sigma_{\rm NLO}$(100 TeV) [fb]	ρ
$pp \to$	Htj	$2.07 \cdot 10^1 \,^{+2\%}_{-1\%}\,^{+2\%}_{-2\%}$	$5.21 \cdot 10^3 \,^{+3\%}_{-5\%}\,^{+1\%}_{-1\%}$	252
$pp \to$	HW^+W^- (4FS)	$4.62 \cdot 10^0 \,^{+3\%}_{-2\%}\,^{+2\%}_{-2\%}$	$1.68 \cdot 10^2 \,^{+5\%}_{-6\%}\,^{+2\%}_{-1\%}$	36
$pp \to$	$HZW^\pm$	$2.17 \cdot 10^0 \,^{+4\%}_{-4\%}\,^{+2\%}_{-2\%}$	$9.94 \cdot 10^1 \,^{+6\%}_{-7\%}\,^{+2\%}_{-1\%}$	46
$pp \to$	$HW^\pm\gamma$	$2.36 \cdot 10^0 \,^{+3\%}_{-3\%}\,^{+2\%}_{-2\%}$	$7.75 \cdot 10^1 \,^{+7\%}_{-8\%}\,^{+2\%}_{-1\%}$	33
$pp \to$	$HZ\gamma$	$1.54 \cdot 10^0 \,^{+3\%}_{-2\%}\,^{+2\%}_{-2\%}$	$4.29 \cdot 10^1 \,^{+5\%}_{-7\%}\,^{+2\%}_{-2\%}$	28
$pp \to$	HZZ	$1.10 \cdot 10^0 \,^{+2\%}_{-2\%}\,^{+2\%}_{-2\%}$	$4.20 \cdot 10^1 \,^{+4\%}_{-6\%}\,^{+2\%}_{-1\%}$	38

e.g. $h \to Z_D Z_D \to 4l$

e.g. $h \to 2a \to 4b$ or even $h \to$ jets

	E (Tev)	lumi (/fb)	N_{higgs} (all)	N_{higgs} (clean)	Br sensitivity for very **conspicuous** decays	Br sensitivity for very **difficult** decays
LHC run 1	7,8	25	500k	0	10^{-4}	O(1) or worse
LHC run 2	14	300	10 million	0	10^{-5}	O(0.1) - O(1)
HL-LHC	14	3000	100 million	0	10^{-6}	?
ILC	0.25 - 1	7000	1 million	40k	10^{-4} - 10^{-5}	10^{-2}
TLEP	0.25ish	10000	3 million	300k	10^{-5}	10^{-3}
100 TeV	100	3000	few billion	0	10^{-7} - 10^{-8}	10^{-2} ????

ee colliders vs. hh colliders

~~ significant steps in precision study of Higgs properties ~~

(1) Higgs kinematic parameters: m_H and Γ_H

- ↠ reduce parametric uncertainties in xs and BR
- ↠ control the fate of EW vacuum within the SM
- ↠ constrain new physics models (e.g. MSSM)

(2) Precise and model-independent access to Higgs couplings

- ↠ 1% level
- ↠ identification of correlation patterns among deviations
- ↠ indirect test of extended Higgs sectors/composite nature
- ↠ ultimate test of naturalness

(3) Access to decays modes that are background dominated @ LHC

- ↠ bb/cc/gg
- ↠ exotic decay modes (↳ portal models of Dark Matter)

(4) Constraints on Higgs flavor violating couplings

- ↠ shed light on the origin of fermion masses and flavors

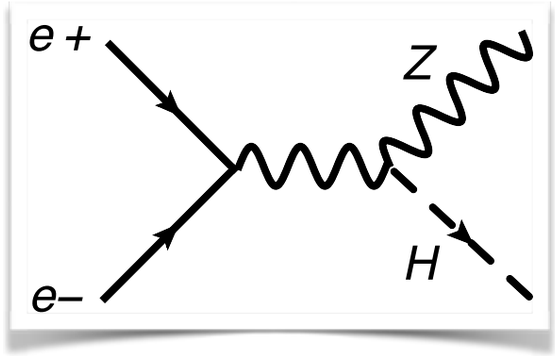
ee colliders vs. hh colliders

(1) Higgs kinematic parameters: m_H and Γ_H

(2) Precise and model-independent access to Higgs coupling

- Lepton colliders provide a unique opportunity to make model independent measurements of Higgs couplings via the measurement of $\sigma(e^+e^- \to ZH)$
- Z is reconstructed independently of Higgs decay
- 4-momentum of the Higgs obtained from

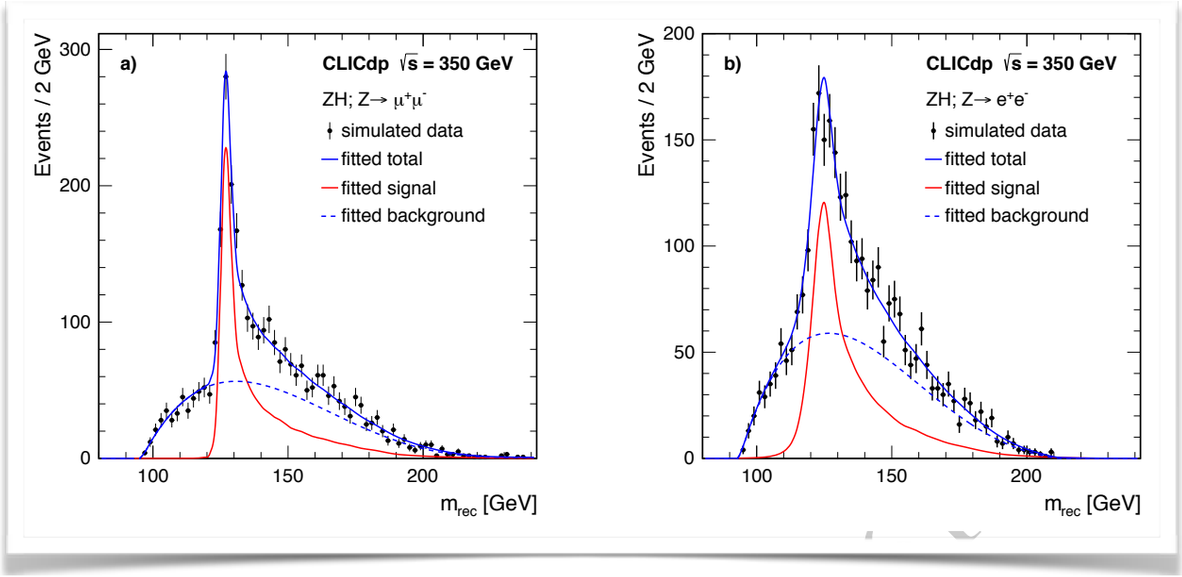
$$E_{rec} = \sqrt{s} - E_Z \qquad \vec{p}_{rec} = -\vec{p_Z}$$



- Obtain a model independent measurement of g_{ZZ} of ~1%
- Higgs mass from recoil mass

H. Gray LHCP'16

	ILC	CLIC	FCC-ee	CEPC
Δm_H (MeV)	150	44	-	5.9
Γ_H	1.8%	3.6%	1%	2.8%

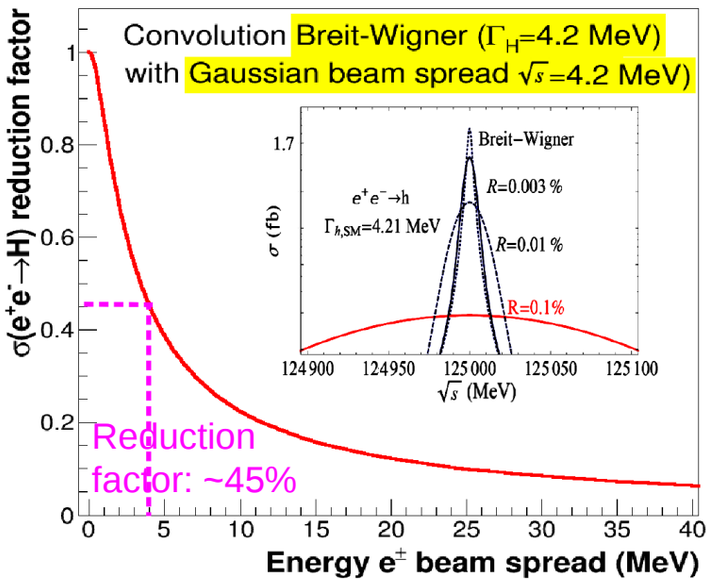


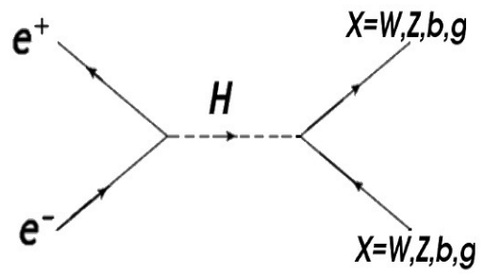
Higgs couplings to electrons (unique to FCC-ee)

- Higgs-e$^{\pm}$ Yukawa g_{Hee} unobservable via decay: BR($H\to e^+e^-$)~5.3·10^{-9}
- Resonant s-channel production considered so far only for μμ collider ($\sigma_{\mu\mu\to H}$ ~ 70 pb). $\frac{g_{H\mu\mu}}{g_{Hee}} \propto \frac{m_\mu^2}{m_e^2} = 4.28\times 10^4$ ⇒ Tiny σ(ee→H)

$$\sigma(e^+e^-\to H) = \frac{4\pi\Gamma_H^2 Br(H\to e^+e^-)}{(\hat{s}-M_H^2)^2+\Gamma_H^2 M_H^2} \simeq 1.6\ \text{fb}$$

Analysis of 7 Higgs decay channels:
L_{int} = 10 ab^{-1}, S=0.65:
BR(Hee) < 4.6×BR$_{SM}$ (3σ)
g_{hee} < 2.2 × $g_{Hee,SM}$ (3σ)



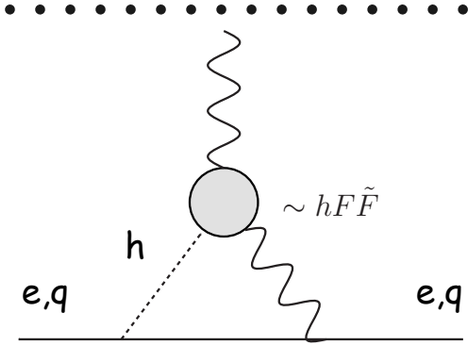


Including ISR + $\sqrt{\sigma_{spread}}$ ~ Γ_H = 4.2 MeV:

σ(ee→H) = 280 ab

- invaluable info on mass generation of light particles
- indirect stringent bounds on Higgs CP-violating couplings

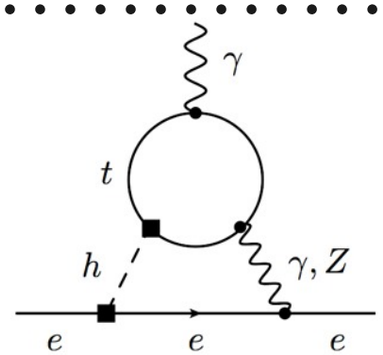
operators with γ:
already severely constrained by e and q EDMs
McKeen, Pospelov, Ritz '12



$$\tilde{\kappa}_{\gamma\gamma} \sim \tilde{\kappa}_{\gamma Z} \leq 10^{-4}$$

$\Lambda_{\not{CP}}$ > 25 TeV

operators with top:
already severely constrained by e and q EDMs
Brod, Haisch, Zupan '13



$$\delta\tilde{g}_{htt} \leq 0.01$$

$\Lambda_{\not{CP}}$ > 2.5 TeV

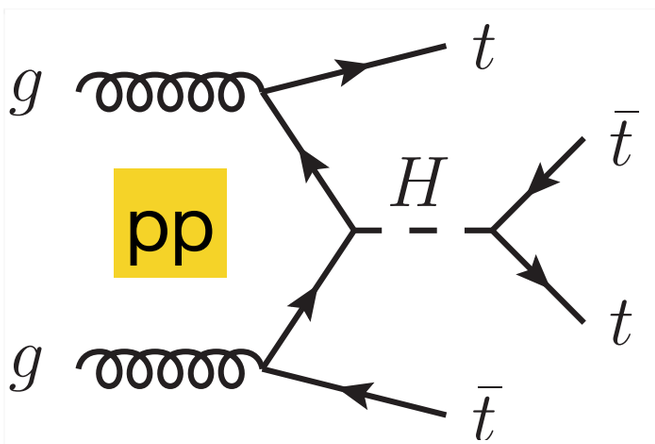
d'Enterria Lomonosov '15

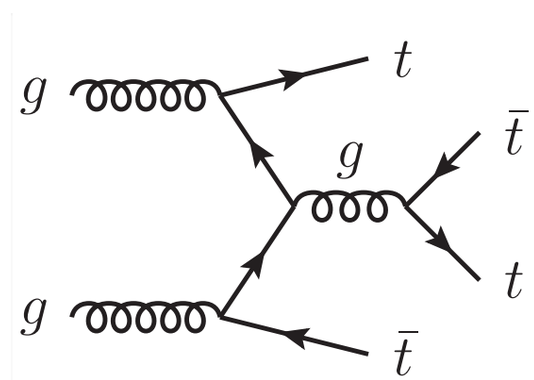
Top Yukawa coupling measurement

important quantity that controls
EW vacuum stability, Higgs mass hierarchy
limited (~10%) sensitivity @ HL-LHC

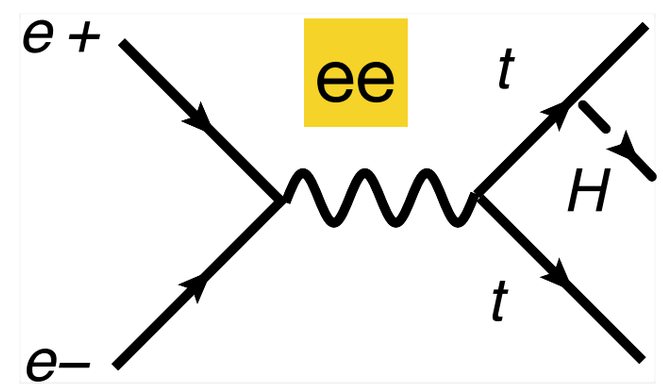
hadron

lepton





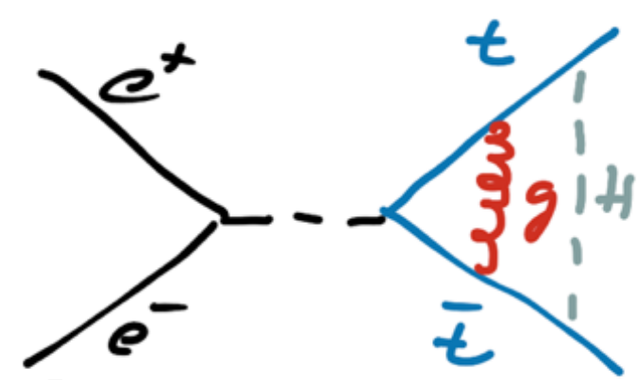
independent of Higgs width



not an option for circular machines

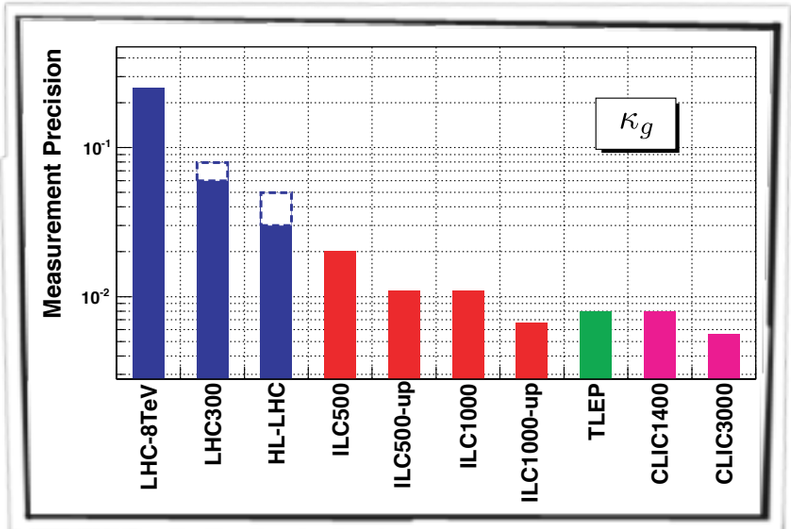
- also from H+jet by resolving lop

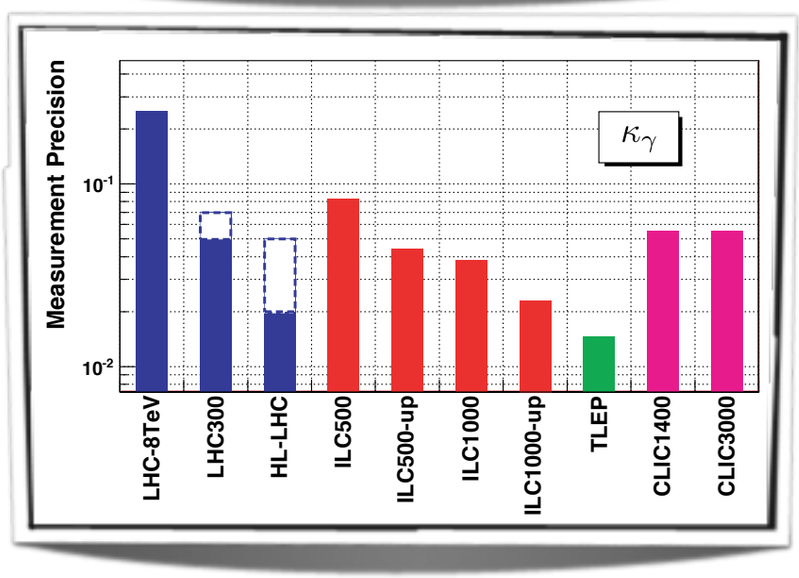
→ large increase in rate from 13 to 100 TeV
(afford aggressive cut on Higgs pT to reduce background)
→ ratio ttH/ttZ to cancel theory uncertainties

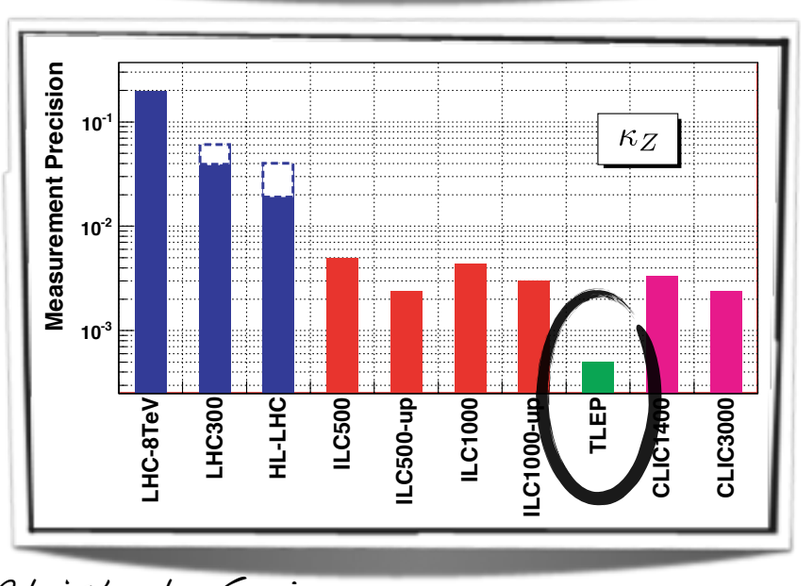


threshold for $t\bar{t}$ production around 350 GeV = "hydrogen atom for strong interactions", i.e. bound state free of nonperturbative quark confining interactions

Higgs coupling measurements







unique superb measurement of ZH xs production

g_{HXY}	FCC-ee	FCC-hh
ZZ	0.16%	
WW	0.19%	
γ γ	1.7%	<1% ?
Zγ	?	1% ?
tt		1% ?
bb	0.42%	
τ τ	0.54%	
cc	1.0%	
ss	H→Vγ, in progr.	
μμ	6.4%	2% ?
uu,dd	H→Vγ, in progr.	
ee	e^+e^-→H, in progr.	
HH		5% ?
BR_{exo}	0.48%	$< 10^{-6}$?

adapted from M. Mangano, HXSWG '15

Higgs self-couplings

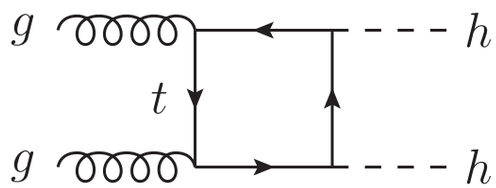
The Higgs self-couplings plays important roles

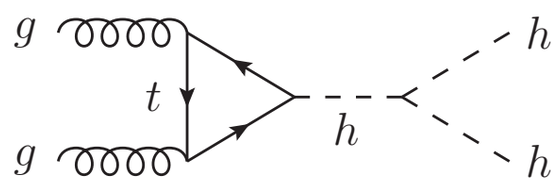
(1) controls the stability of the EW vacuum

(2) dictates the dynamics of EW phase transition and potentially conditions the generation of a matter-antimatter asymmetry via EW baryogenesis

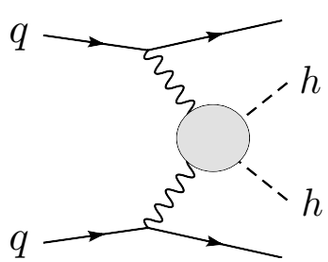
hadron

Gluon Fusion (GF)

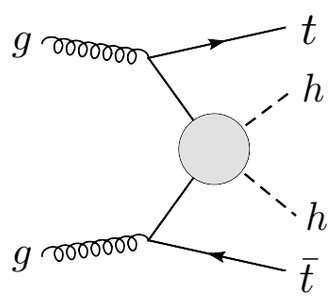




Vector Boson Fusion (VBF)



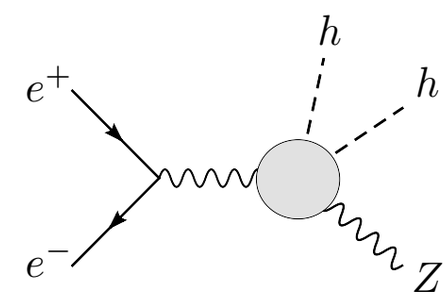
tthh associated production



lepton

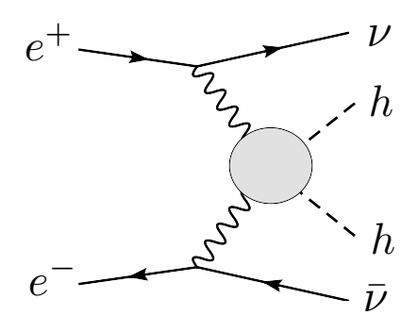
not an option for circular machines

Double HiggsStrahlung (DHS)



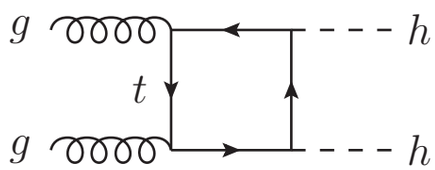
relevant 350GeV<E<1TeV

Vector Boson Fusion (VBF)

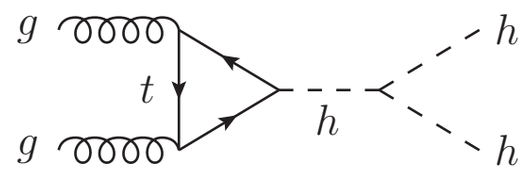


relevant E>1TeV

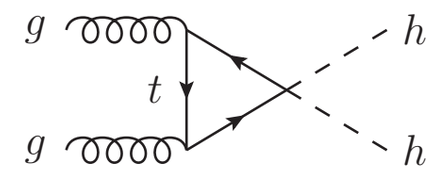
HH production as a probe of HE couplings



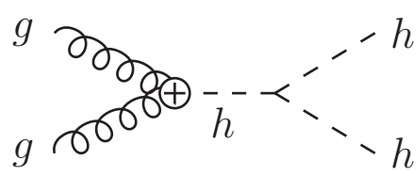
$\sim c_t^2 \times const.$



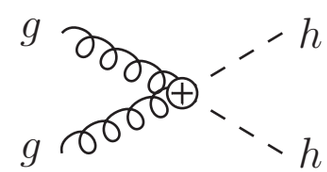
$\sim c_t c_3 \times \frac{m_h^2}{\hat{s}} \log^2\left(\frac{m_t^2}{\hat{s}}\right)$



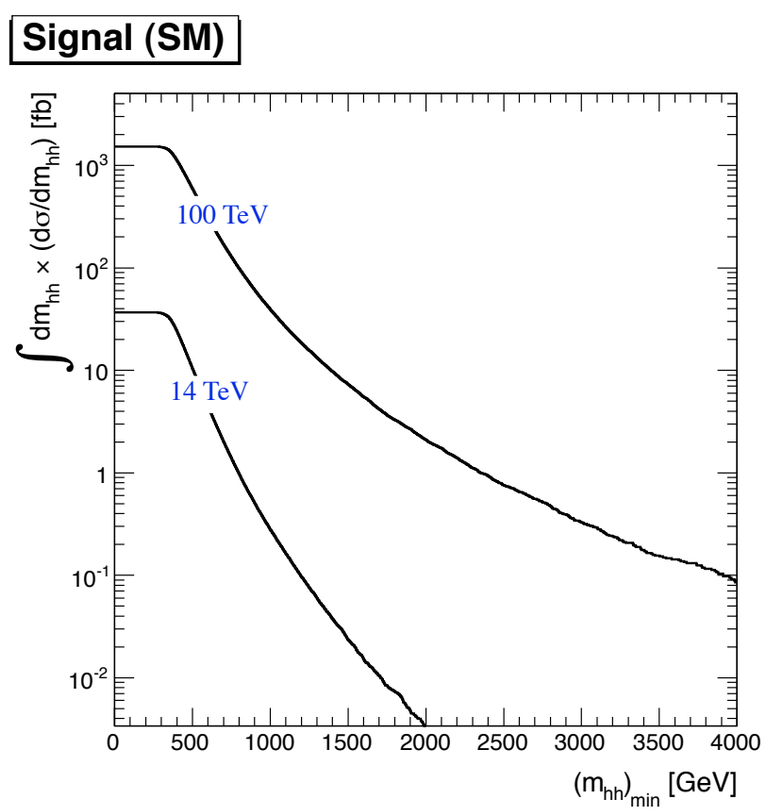
$\sim c_{2t} \times \log^2\left(\frac{m_t^2}{\hat{s}}\right)$

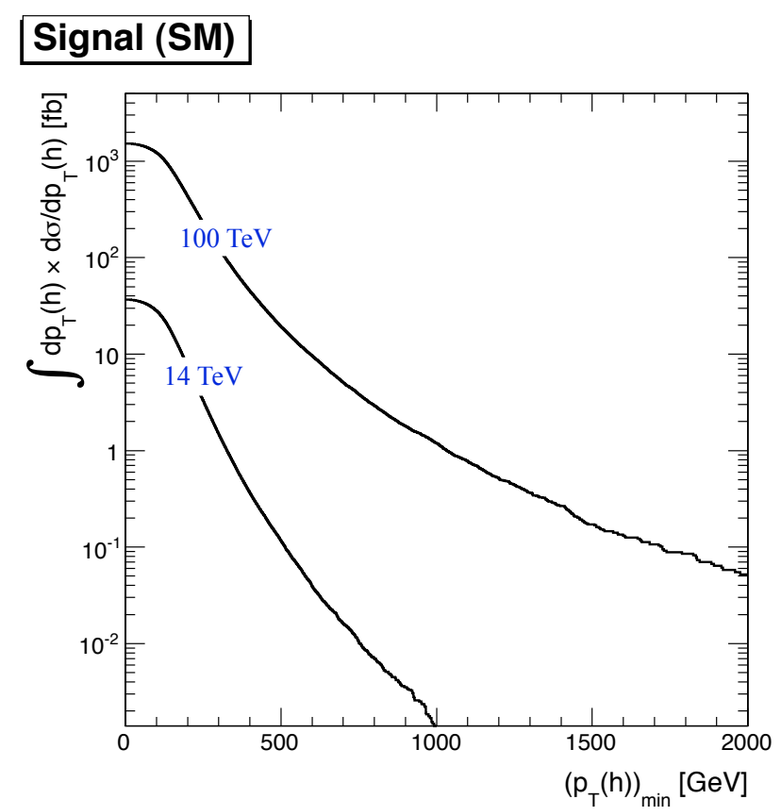


$\sim c_g c_3 \frac{\alpha_s}{4\pi} \times const.$



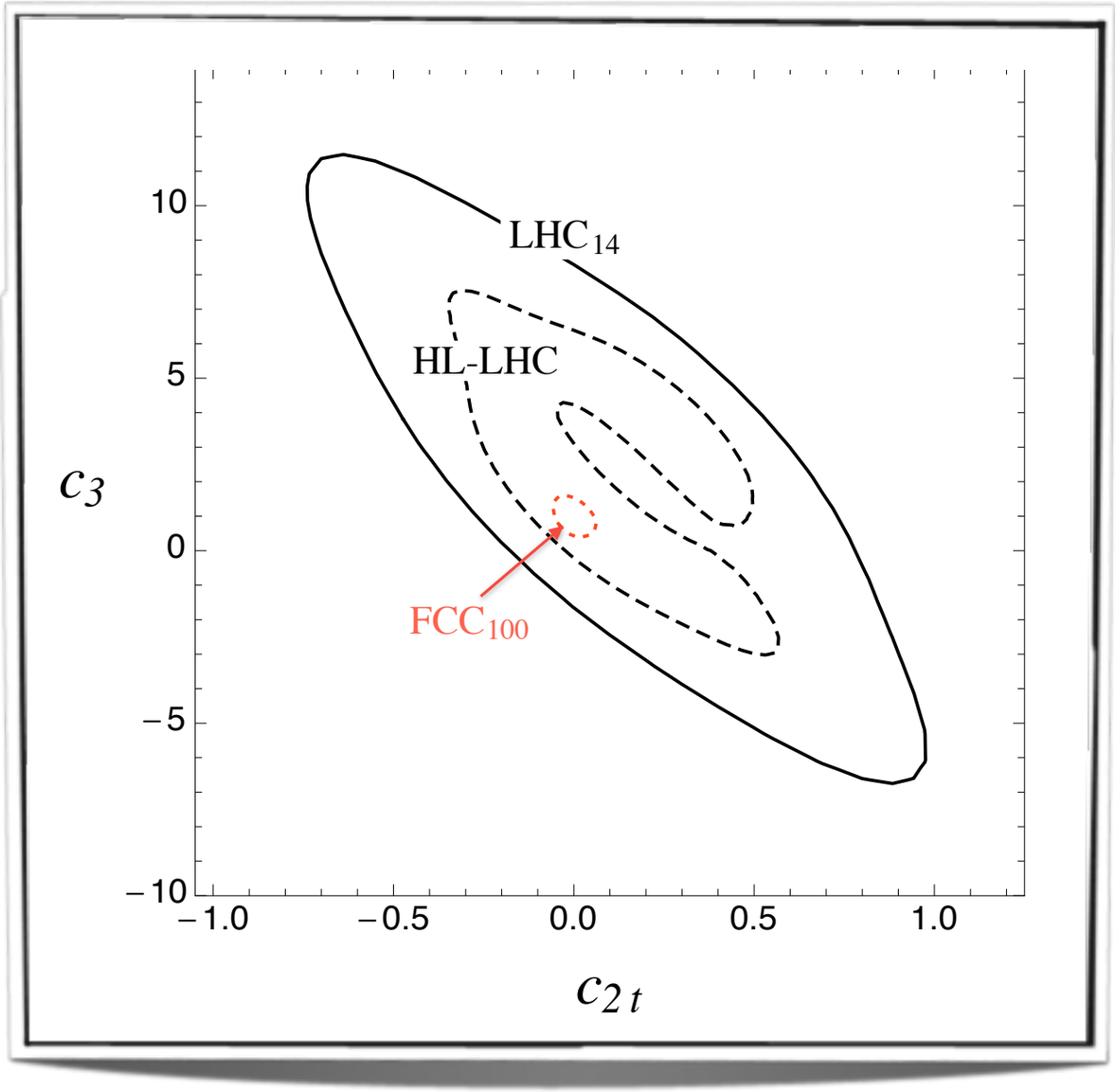
$\sim c_{2g} \frac{\alpha_s}{4\pi} \frac{\hat{s}}{v^2}$

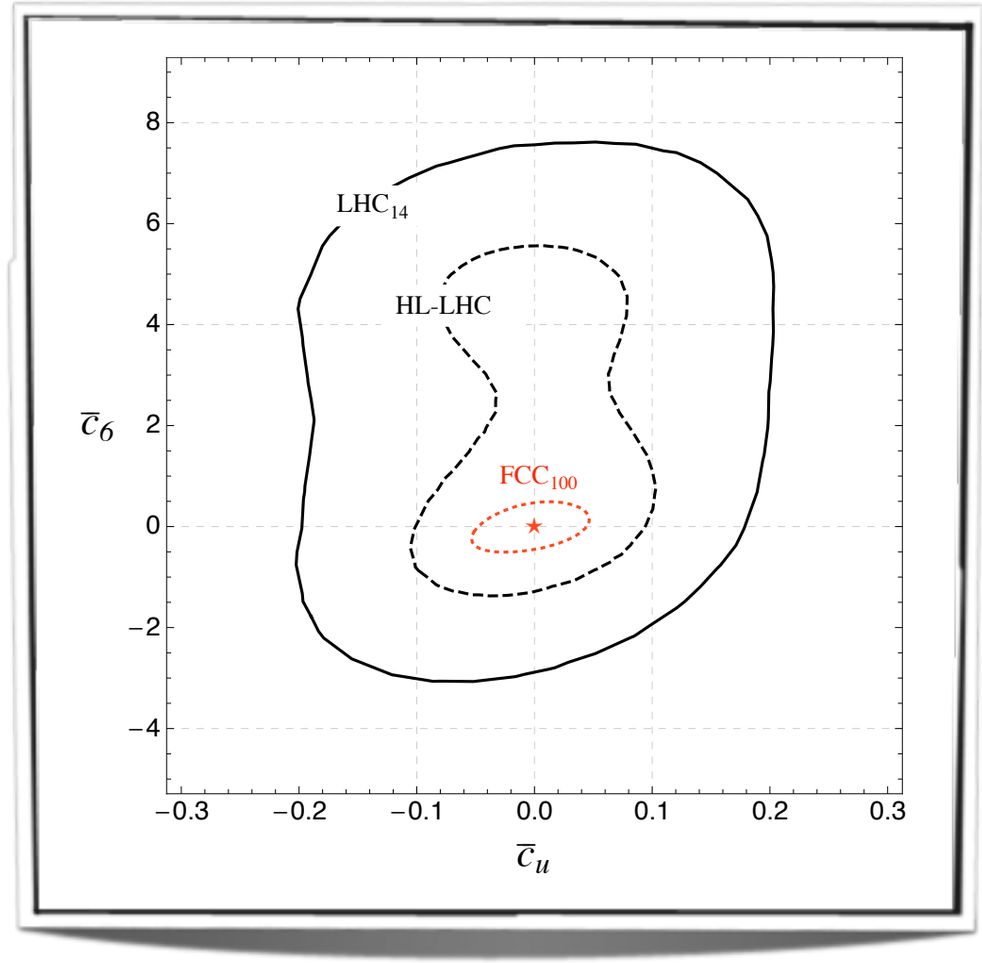




Azatov, Contino, Panico, Son '15

HH production as a probe of HE couplings





Azatov, Contino, Panico, Son '15
see also Goertz, Papaefstathiou, Yang, Zurita '14

Remarks:

- unique access to c_3 but sensitivity is limited (within the validity of EFT?).
- statistically limited, with more luminosity
  - ⇛ access to distribution
  - ⇛ discriminating power c_3 vs. c_{2t} vs c_g

Searches for extended Higgs sectors

Extended Higgs sectors are a prediction of many BSM scenarios.
They may play a role in the following open questions:

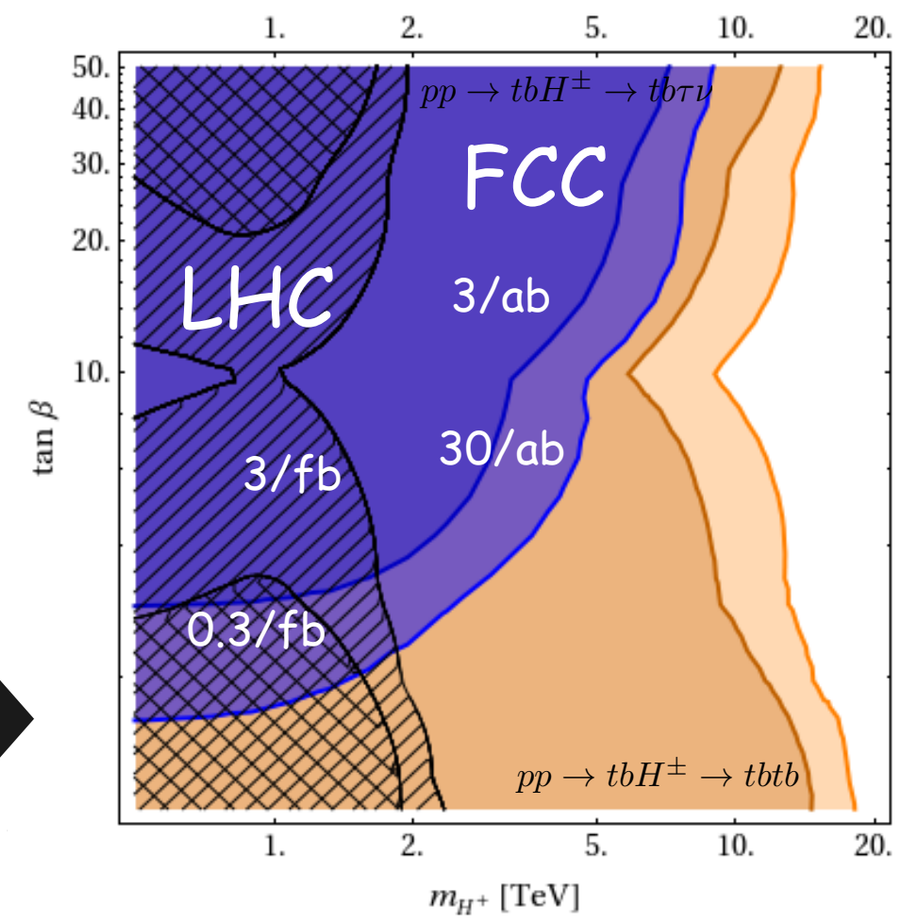
- (EW) Baryogenesis → Modified scalar potential can lead to a 1st order EW phase transition
- Identity of Dark Matter → Scalar DM with TeV mass; Scalar mediators in hidden-sector DM coupled to Higgs portal
- Smallness of the neutrino masses → Type-II see-saw through extra scalars
- Naturalness of the EW scale → Extended scalar sectors follows in natural theories:
  i) SUSY
  ii) Neutral Naturalness

☞ A 100TeV pp collider offers the unique opportunity to discover EW-charged or SM-singlet scalars with a few TeV mass

Contino FCC@Rome '16

just one example
for illustration:
charged Higgs 95%CL exclusion

J. Hajer et al '15



Conclusions: breaking the HEP frontiers

new machines much wanted to

~~ open new horizons beyond LHC ~~

no lack of theoretical motivations

plenty of physics issues outside the SM frame

from deep QFT questions

to pressing phenomenological puzzles

synergy fuels progress

⇓ ⇓ ⇓

* no BSM major discovery without a thorough understanding of SM background

* challenge: control theoretical uncertainty to the level of experimental sensitivity

* the cosmic/intensity/energy frontiers might be very much intertwined

* complementarity and synergy of electron and hadron machines

Conclusions: breaking the HEP frontiers

new machines much wanted to

~~ open new horizons beyond LHC ~~

no lack of theoretical motivations

plenty of physics issues outside the SM frame

from deep QFT questions

to pressing phenomenological puzzles

synergy fuels progress

H. Gray, FCC-ee Higgs workshop '15

Observable	FCC-hh	FCC-ee
Extra Higgs States		
Rare Higgs Decays		
EW Precision Observables		
Higgs Couplings		
ZH cross-section		
Higgs self-coupling		

To know more

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

CERN-TH-2016-113

Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies

Editors:
R. Contino[1,2], D. Curtin[3], A. Katz[1,4], M. L. Mangano[1], G. Panico[5], M. J. Ramsey-Musolf[6,7], G. Zanderighi[1]

Contributors:
C. Anastasiou[8], W. Astill[9], G. Bambhaniya[21], J. K. Behr[10,11], W. Bizon[9], P. S. Bhupal Dev[12], D. Bortoletto[10], D. Buttazzo[22] Q.-H. Cao[13,14,15], F. Caola[1], J. Chakrabortty[16], C.-Y. Chen[17,18,19], S.-L. Chen[15,20], D. de Florian[23], F. Dulat[8], C. Englert[24], J. A. Frost[10], B. Fuks[25], T. Gherghetta[26], G. Giudice[1], J. Gluza[27], N. Greiner[28], H. Gray[29], N. P. Hartland[10], V. Hirschi[30], C. Issever[10], T. Jeliński[27], A. Karlberg[9], J. H. Kim[31,32,33], F. Kling[34], A. Lazopoulos[8], S. J. Lee[35,36], Y. Liu[13], G. Luisoni[1], O. Mattelaer[37], J. Mazzitelli[23,38], B. Mistlberger[1], P. Monni[9], K. Nikolopoulos[39], R. N Mohapatra[3], A. Papaefstathiou[1], M. Perelstein[40], F. Petriello[41], T. Plehn[42], P. Reimitz[42], J. Ren[43], J. Rojo[10], K. Sakurai[37], T. Schell[42], F. Sala[44], M. Selvaggi[45], H.-S. Shao[1], M. Son[31], M. Spannowsky[37], T. Srivastava[16], S.-F. Su[34], R. Szafron[46], T. Tait[47], A. Tesi[48], A. Thamm[49], P. Torrielli[50], F. Tramontano[51], J. Winter[52], A. Wulzer[53], Q.-S. Yan[54,55,56], W. M. Yao[57], Y.-C. Zhang[58], X. Zhao[54], Z. Zhao[54,59], Y.-M. Zhong[60]

Eur. Phys. J. C manuscript No.
(will be inserted by the editor)

Physics at the e^+e^- Linear Collider

Editors: G. Moortgat-Pick[a,1,2], H. Baer[3], M. Battaglia[4], G. Belanger[5], K. Fujii[6], J. Kalinowski[7], S. Heinemeyer[8], Y. Kiyo[9], K. Olive[10], F. Simon[11], P. Uwer[12], D. Wackeroth[13], P.M. Zerwas[2]
Specific Contributions: A. Arbey[38,39,40], M. Asano[14], J. Bagger[45,55], P. Bechtle[15], A. Bharucha[16,53], J. Brau[46], F. Brümmer[17], S.Y. Choi[18], A. Denner[19], K. Desch[15], S. Dittmaier[20], U. Ellwanger[21], C. Englert[22], A. Freitas[23], I. Ginzburg[24], S. Godfrey[25], N. Greiner[11,2], C. Grojean[2,26], M. Grünewald[27], J. Heisig[28], A. Höcker[29], S. Kanemura[30], K. Kawagoe[48], R. Kogler[31], M. Krawczyk[7], A.S. Kronfeld[50,54], J. Kroseberg[15], S. Liebler[1,2], J. List[2], F. Mahmoudi[38,39,40], Y. Mambrini[21], S. Matsumoto[32], J. Mnich[2], K. Mönig[2], M.M. Mühlleitner[33], R. Pöschl[43], W. Porod[19], S. Porto[1], K. Rolbiecki[7,34], M. Schmitt[35], P. Serpico[5], M. Stanitzki[2], O. Stål[36], T. Stefaniak[4], D. Stöckinger[37], G. Weiglein[2], G.W. Wilson[41], L. Zeune[42]
LHC contacts: F. Moortgat[29], S. Xella[44]
Advisory Board: J. Bagger[45,55], J. Brau[46], J. Ellis[47,29], K. Kawagoe[48], S. Komamiya[49], A.S. Kronfeld[50,54], J. Mnich[2], M. Peskin[51], D. Schlatter[29], A. Wagner[2,31], H. Yamamoto[52]

Physics Opportunities of a 100 TeV Proton-Proton Collider

Nima Arkani-Hamed[a], Tao Han[b], Michelangelo Mangano[c], Lian-Tao Wang[d]

[a] *Institute for Advanced Study, Princeton, NJ, 08540, USA*
[b] *Department of Physics and Astronomy, Univ. of Pittsburgh, Pittsburgh, PA 15260, USA and Department of Physics, Tsinghua University, Beijing 100086, China*
[c] *Physics Department, TH Group, CERN, CH-1211 Genve 23, Switzerland*
[d] *Enrico Fermi Institute, Department of Physics, and Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637-1434, USA*