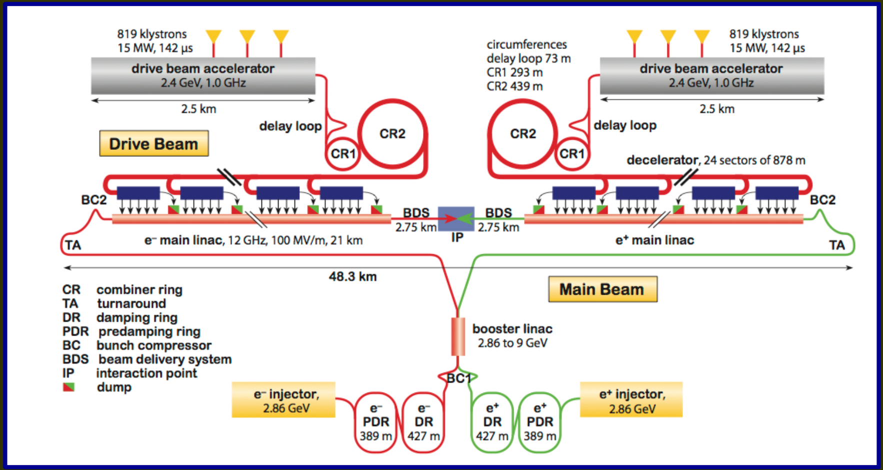
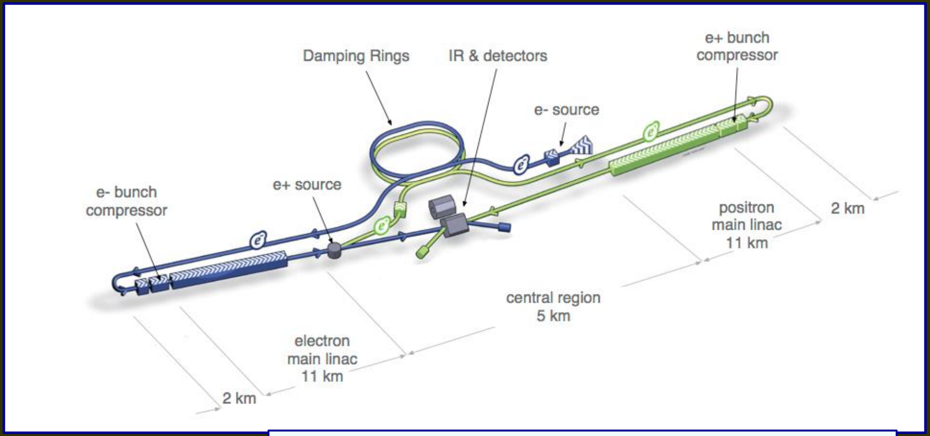
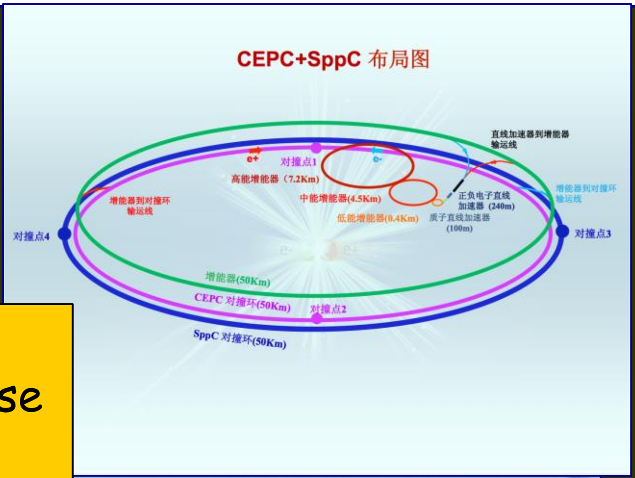
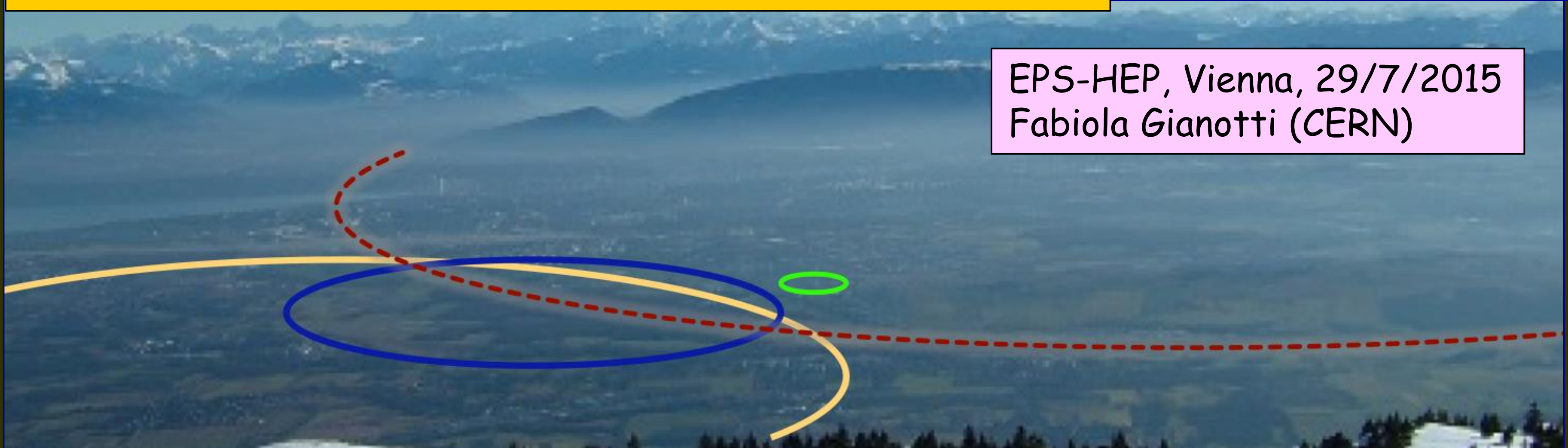






Outlook: physics prospects at high-E colliders

- ☐ Introduction
- ☐ Main options for future colliders and their physics case
- ☐ Final remarks



EPS-HEP, Vienna, 29/7/2015
Fabiola Gianotti (CERN)

With the discovery of a Higgs boson, a triumph for particle physics and high-E colliders, the SM has been completed. Technically, it works up to the Planck scale

However: many crucial questions, raised also by experimental observations, remain open. They cannot be explained within the SM. The Higgs boson itself is related to some of the deepest questions

These questions require NEW PHYSICS

Main questions in today's particle physics (a non-exhaustive list ..)

Why is the Higgs boson so light (so-called "naturalness" or "hierarchy" problem) ?

What is the origin of the matter-antimatter asymmetry in the Universe ?

Why 3 fermion families ? Do neutral leptons, charged leptons and quarks behave similarly?

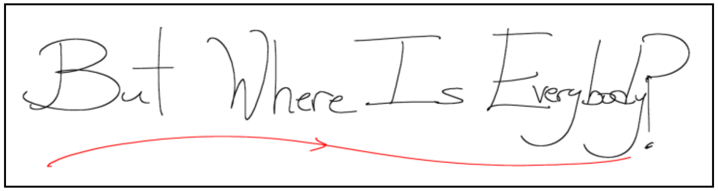
What is the origin of neutrino masses and oscillations ?

What is the composition of dark matter (23% of the Universe) ?

What is the cause of the Universe's accelerated expansion (today, primordial) ?

Why is Gravity so weak ?

However: we have NO evidence of new physics (yet ….) from LHC and other facilities (except neutrino masses)



But Where Is Everybody?

N. Arkani-Hamed

In other words: at what E scale(s) are the answers to these questions ?

The outstanding questions are compelling, difficult and interrelated→ can only be successfully addressed through the variety of approaches we have developed (thanks also to strong advancements in accelerator and detector technologies): particle colliders, neutrino experiments (solar, short/long baseline, reactors, 0νββ decays, …), cosmic surveys, dark matter direct and indirect detection, precision measurements of rare processes, dedicated searches (e.g. axions, dark-sector particles), …

Main questions and main approaches to address them

	High-E colliders	Dedicated high-precision experiments	Neutrino experiments	Dedicated searches	Cosmic surveys
Higgs , EWSB	x	x		x	
Neutrinos	x (HNL)		x	x	x
Dark Matter	x			x	x
Flavour, CP, matter/antimatter	x	x	x	x	x
New particles and forces	x	x		x	
Universe acceleration					x

Combination of these complementary approaches is crucial to explore the largest range of E scales (directly and indirectly) and couplings, and properly interpret signs of new physics → hopefully build a coherent picture of the underlying theory.

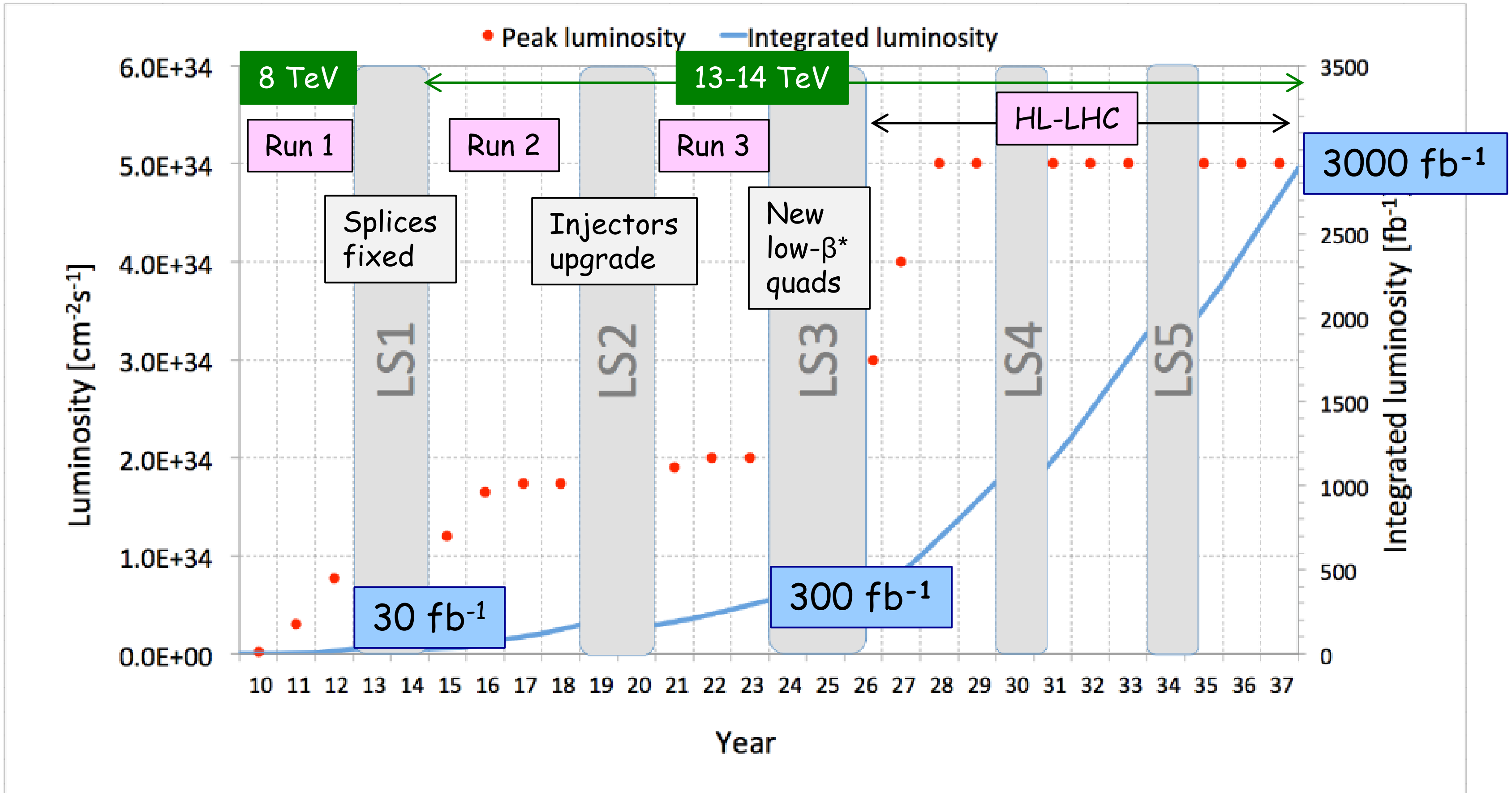
Options for future high-E (and high-L) colliders

Discussed here:

- ☐ Linear and circular e^+e^- colliders
- ☐ Very high-E proton-proton colliders
- ☐ Muon colliders (few words)

Disclaimer: due to time limitation, I will not discuss other options: e.g. ep, γγ, ion colliders

The present and near/medium-term future: LHC and HL-LHC



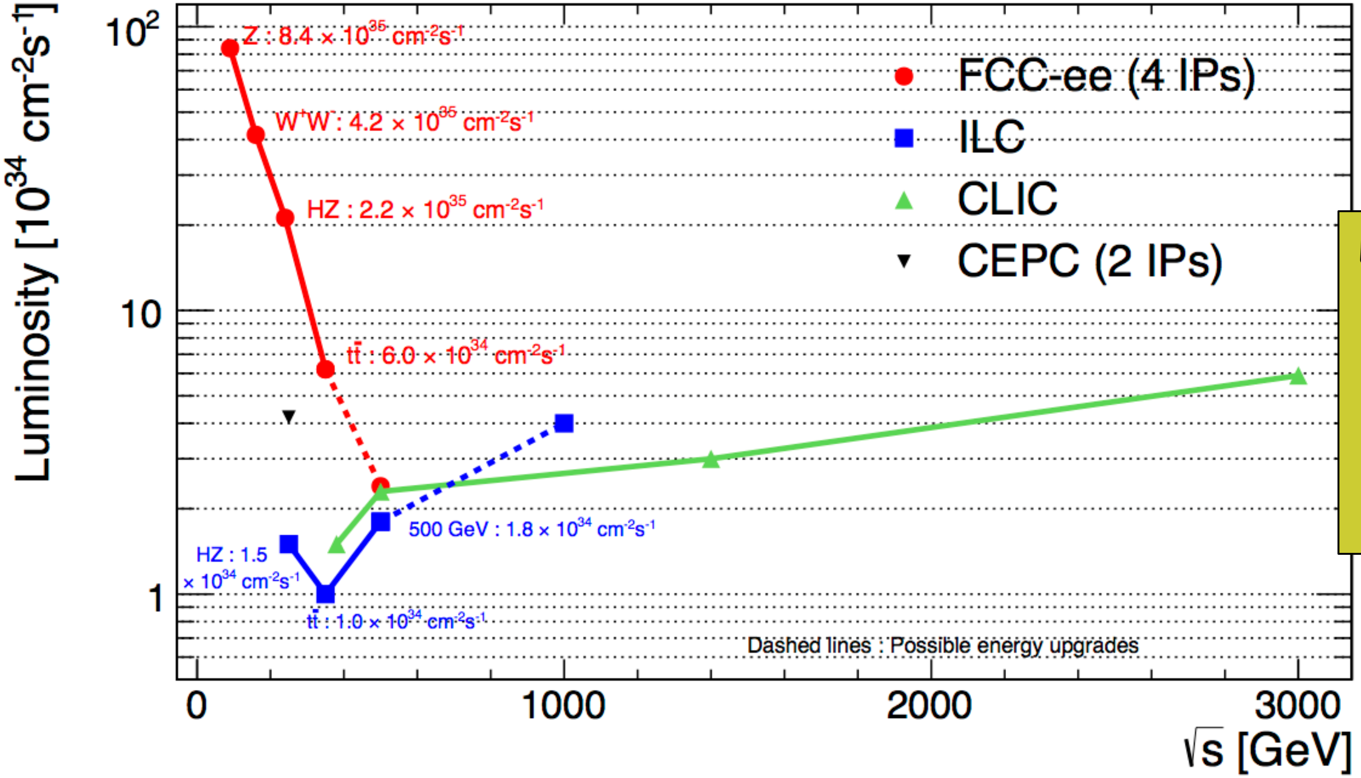
LHC is highest-E, highest-L operational collider → full exploitation (√s ~ 14 TeV, 3000/fb is mandatory:

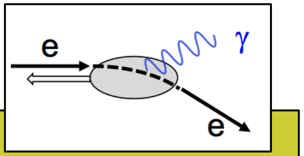
- ❑ If new physics discovered in Run 2-3:
  → first detailed exploration of new physics with well understood machine and experiments
- ❑ If no new physics in Run 2-3:
  → extend direct discovery potential by ~ 20-30% (up to m ~ 8 TeV)

In either cases: measure Higgs couplings to few percent (including 2nd generation: Hμμ !)

Future e^+e^- colliders

√s (GeV)	Main physics goals
90	Z-pole precision EW measurements beyond LEP, SLC
160	WW precision physics (mass at threshold)
250	Higgs precision physics (HZ)
~350	Higgs (HZ, Hvv) and top (mass, couplings) precision physics
500-3000	ttH, HH (self-couplings), direct searches for new physics



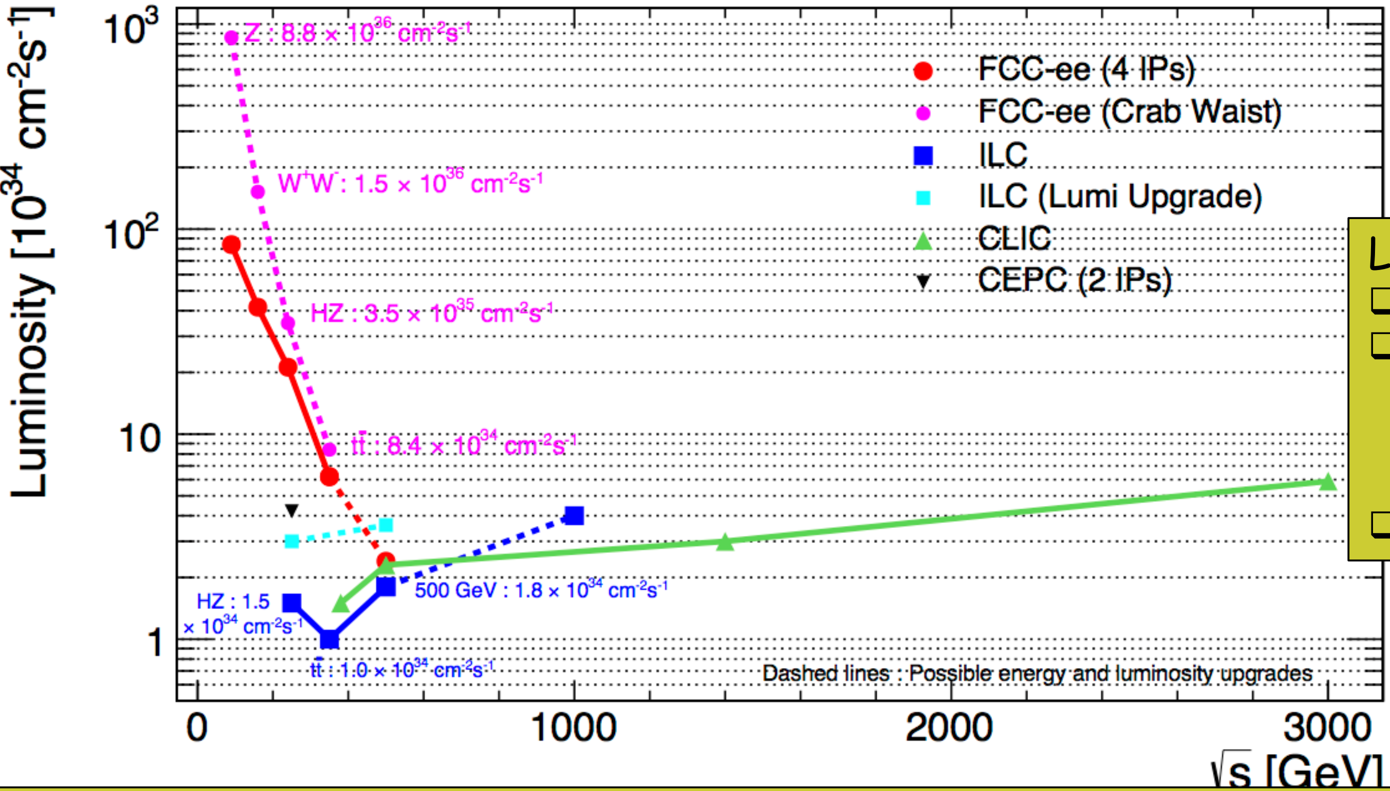


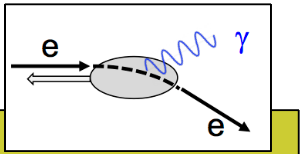
Linear:
- ☐ Larger √s reach
- ☐ Low repetition rate
  - → L from nm size beams
  - → large beamstrahlung
  - → larger E-spread
- ☐ Long. polarization easier

Circular:
- ☐ √s limited by SR ~ E^4_{beam}/R
- ☐ Large number of circulating bunches → high L (increases at lower √s as less SR → more RF power available)
- ☐ Need top-up injection ring to compensate L burn-off (lifetime ~ 30')
- ☐ Several interaction points possible
- ☐ Precise E-beam measurement from resonant depolarization

Future e^+e^- colliders

$\sqrt{s}$ (GeV)	Main physics goals
90	Z-pole precision EW measurements beyond LEP, SLC
160	WW precision physics (mass at threshold)
250	Higgs precision physics (HZ)
~350	Higgs (HZ, Hνν) and top (mass, couplings) precision physics
500-3000	tt̄H, HH (self-couplings), direct searches for new physics





Linear:

- ☐ Larger $\sqrt{s}$ reach
- ☐ Low repetition rate
  - → L from nm size beams
  - → large beamstrahlung
  - → larger E-spread
- ☐ Long. polarization easier

Circular:

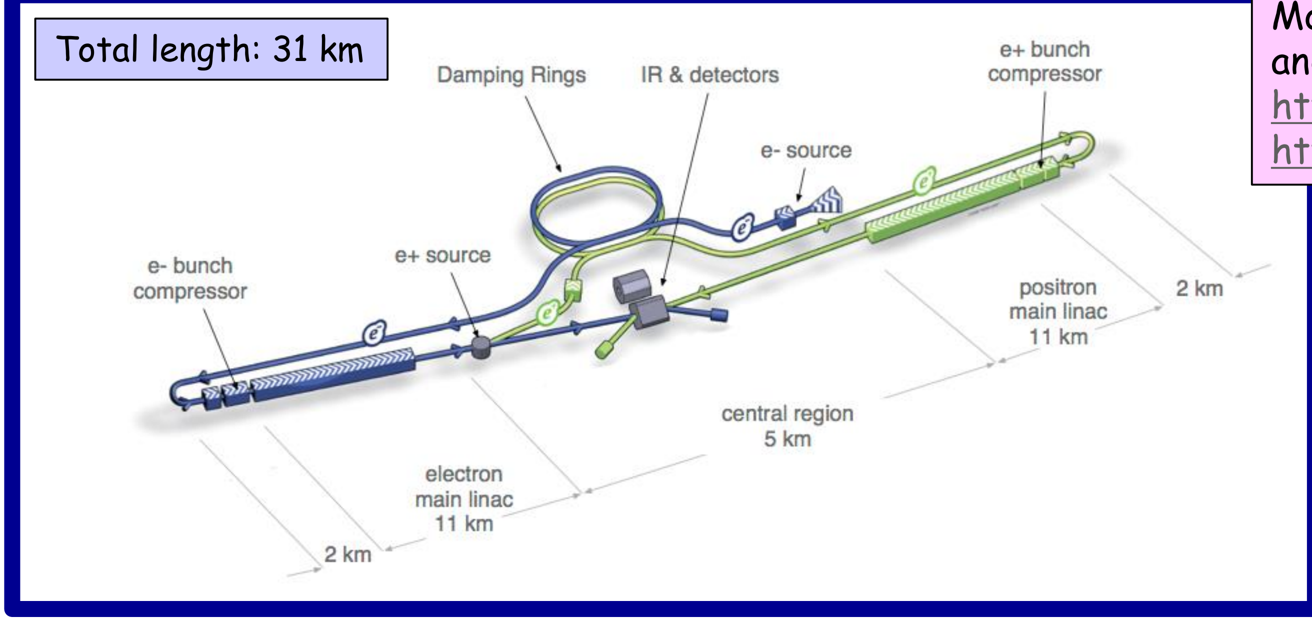
- ☐ $\sqrt{s}$ limited by SR ~ E^4_{beam}/R
- ☐ Large number of circulating bunches → high L (increases at lower $\sqrt{s}$ as less SR → more RF power available)
- ☐ Need top-up injection ring to compensate L burn-off (lifetime ~ 30')
- ☐ Several interaction points possible
- ☐ Precise E-beam measurement from resonant depolarization

International Linear Collider (ILC)

Technical Design Report June 2013

Most recent operation scenarios and physics results:
http://arxiv.org/abs/1506.07830
http://arxiv.org/abs/1506.05992

Total length: 31 km



Most recent operating scenarios (~ 20 year programme):

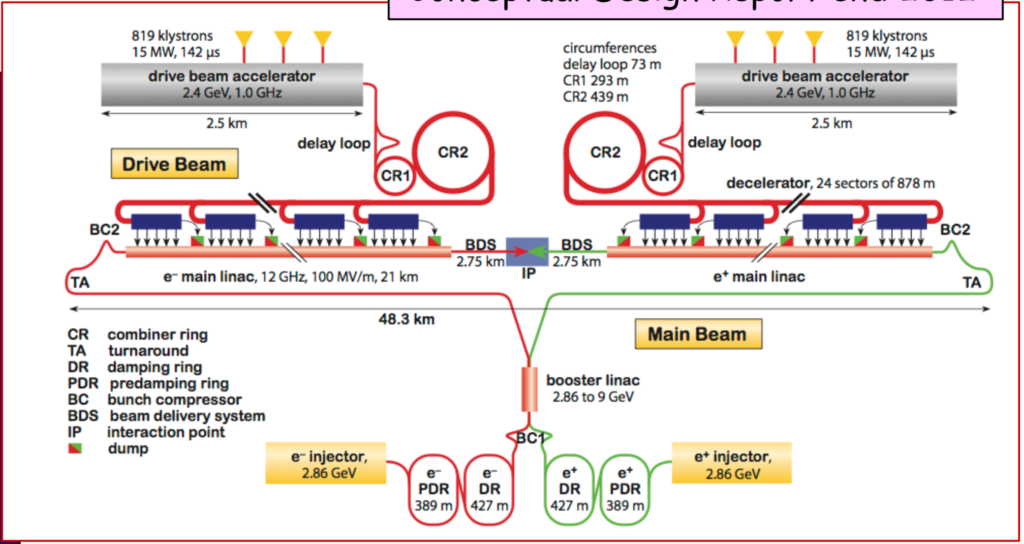
- ☐ start at $\sqrt{s}$= 500 (500 fb^{-1}), then 350 (200 fb^{-1}), then 250 (500 fb^{-1}) GeV
- ☐ L upgrade (double # of bunches): add 3500 (1500) fb^{-1} at 500 (250) GeV

- ☐ 500 GeV machine: ~ 15000 SCRF cavities, 31.5 MV/m
  Mature technology (20 years of R&D experience worldwide). European xFEL at DESY is 5% -scale "ILC prototype" (needed gradient 24 MV/m, most cavities > 30 MV/m)
- ☐ 1 TeV machine requires extension of main Linacs (50 km) and 45 MV/m
- ☐ Challenges: positron source; final focus (squeeze and collide nm-size beams)

- ☐ Japan interested to host → decision based also on ongoing international discussions
- ☐ Construction could technically start as soon as decision taken (~2019 ?), duration ~10 years → physics could start ~2030
- ☐ Cost of 500 GeV accelerator (w/o L upgrade): ~ 8 B$ (material)

Compact Linear Collider (CLIC)

Conceptual Design Report end 2012



Main challenges:

☐ 100 MV/m accelerating gradient needed for compact (50 km) multi-TeV (up to 3 TeV) collider

☐ Keep RF breakdown rate small

☐ Short (156 ns) beam trains → bunch spacing 0.5 ns to maximize luminosity

☐ 2-beam acceleration (new concept): efficient RF power transfer from low-E high-intensity drive beam to (warm) accelerating structures for main beam

☐ Power consumption (600 MW at 3 TeV): reduction under investigation

☐ nm size beams; final focus

☐ Detectors: huge beamstrahlung (20 TeV per train in calorimeters at 3 TeV) → 1-10 ns time stamps needed

Parameter	**Unit**	**380 GeV**	**3 TeV**
Centre-of-mass energy	TeV	0.38	3
Total luminosity	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.5	5.9
Luminosity above 99% of √s	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.9	2.0
Repetition frequency	Hz	50	50
Number of bunches per train		352	312
Bunch separation	ns	0.5	0.5
Acceleration gradient	MV/m	72	100

☐ Most recent operation scenario: start at √s=380 GeV for Higgs and top physics

☐ If decision to proceed in ~ 2019 → construction could technically start ~2025, duration ~6 years for √s ~ 380 GeV (11 km Linac) → physics could start before 2035

☐ Cost (material): ~6-7 BCHF for 380 GeV machine (cost optimisation underway), +~4 BCHF/TeV for next E step

Circular colliders: the Chinese CepC, SppC

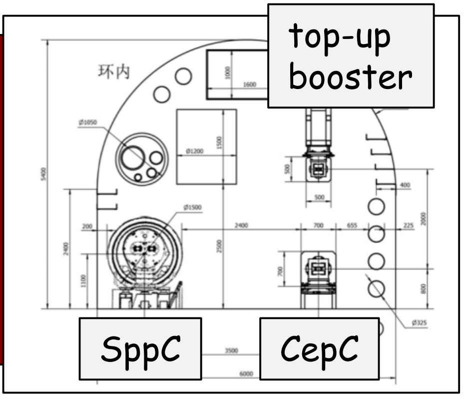
http://cepc.ihep.ac.cn/preCDR/volume.html

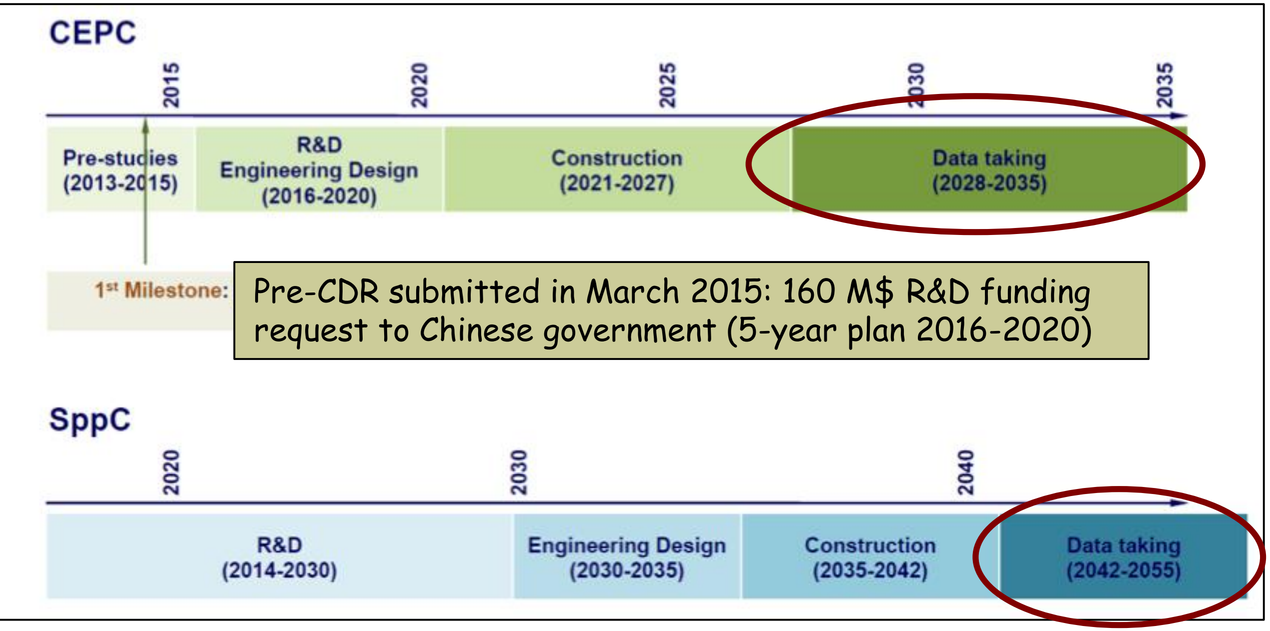
Baseline: 54 km ring

- CepC: $\sqrt{s}$=240 GeV e^+e^- ; L=2x10^{34}; 2 IP
- SppC: $\sqrt{s}$ = 70 TeV pp collider; L=1.2x10^{35}; 2 IP

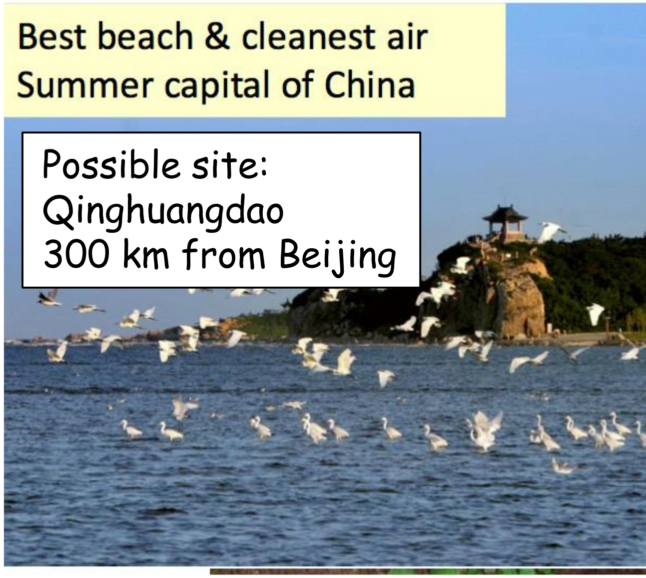
CepC cost (including tunnel and 2 experiments): ~3.5 BCHF (material)

If more funding: 100 km ring (→ 100-140 TeV pp) and/or separate pipes for e+/e-beams (→ not limited to 50 bunches/beam → higher L)





Pre-CDR submitted in March 2015: 160 M$ R&D funding request to Chinese government (5-year plan 2016-2020)



Best beach & cleanest air
Summer capital of China

Possible site:
Qinghuangdao
300 km from Beijing

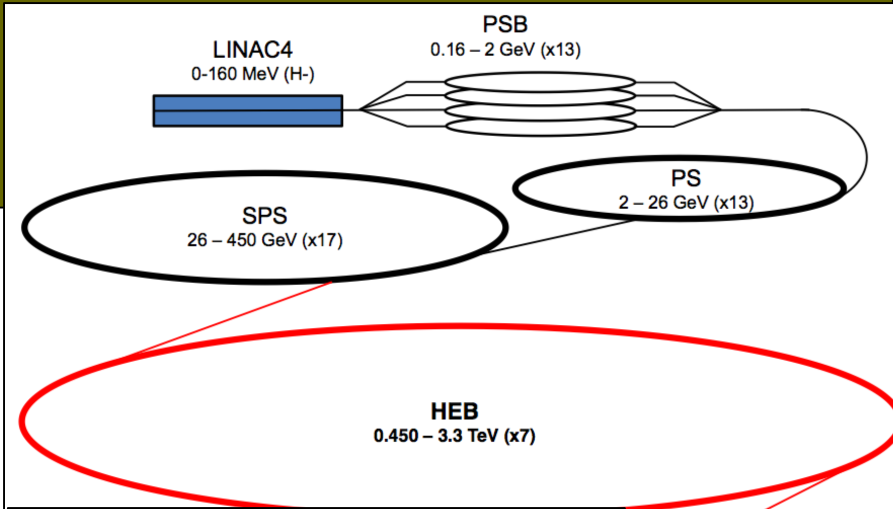
Circular colliders: the CERN FCC project

International conceptual design study for Future Circular Colliders in a ~100 km ring:

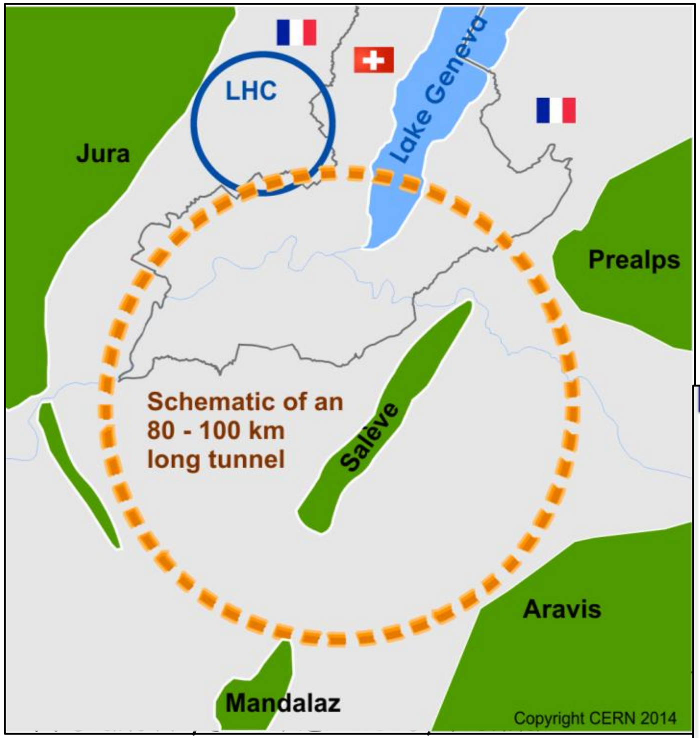
- ❑ goal: pp, $\sqrt{s}$ = 100 TeV (FCC-hh), $L\sim2.5\mathrm{x}10^{35}$; 4 IP (some general-purpose, some specific)
- ❑ possible intermediate step: e^+e^-, $\sqrt{s}$=90-350 GeV (FCC-ee), $L=2\mathrm{x}10^{36}-2\mathrm{x}10^{34}$, 2-4 IP
- ❑ option: ep, $\sqrt{s}$= 3.5 TeV (FCC-eh), $L\sim10^{34}$

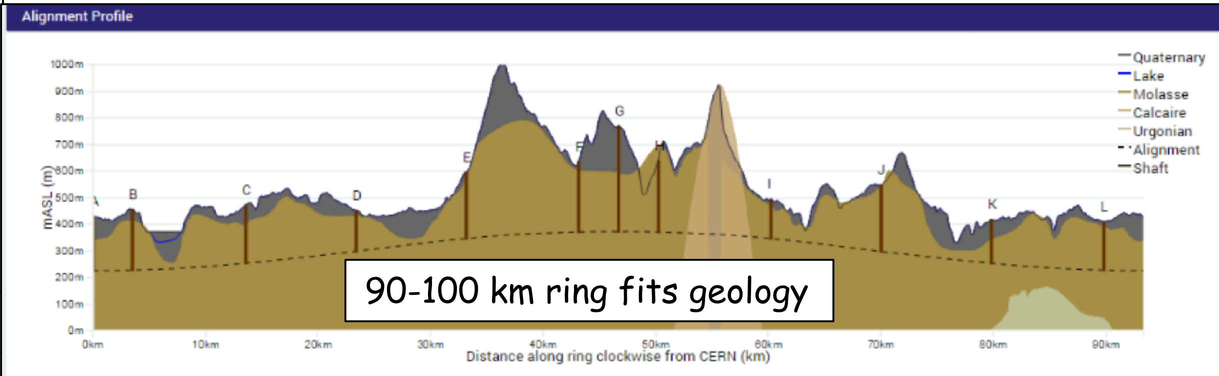
Goal of the study: CDR in ~2018

Machine studies are site-neutral.
However, FCC at CERN would greatly benefit from existing infrastructure (e.g. FCC-hh injector chain would be based on existing accelerator complex)



Baseline HEB: "refurbished" LHC





90-100 km ring fits geology

Future pp colliders

	Ring (km)	$\sqrt{s}$ (TeV)	Field (T)	Magnet technology	L (10^{34})
LHC (for comparison)	27	14	8.3	NbTi	up to 5
HE-LHC	27	26-33	16-20		~5
SppC	54	70	20	$NbSn_3$ with HTS inserts	12
If enough funds	100	100-140			
FCC-hh	100	100	16	$NbSn_3$ (with NbTi)	5-20

$5x10^{34}$ operation	HL-LHC	FCC-hh
Bunch spacing	25	25*
N. of bunches	2808	10600
Pile-up.x-ing	140	170
E-loss/turn	7 keV	5 MeV
SR power/ring	3.6 kW	2.5 MW
Interaction Points	4	4
Stored beam energy	390 MJ	8.4 GJ

Many big challenges: technology of bending dipoles (Nb_3Sn ok up to ~16T, HTS needed for 20T), SR and beam screen, stored beam energy, radiation, …

* 5 ns considered for $L=2x10^{35}$ to mitigate pile-up

Projected integrated luminosities for current operating scenarios

Integrated luminosities (ab^{-1})

√s	90	240	350-380	500	1.4	3	70	100	Total	# years	# of H at production
	GeV				TeV						
FCC-ee	90$^{(*)}$	10	3						90+13	~7-15	2 M
CepC		5							5	~10	1 M
ILC		2	0.2	4					6	~20	1.6 M
CLIC			0.5		1.5	2			4	~20	1.5 M
SppC							30		30	~10	30 B
FCC-hh								40	40	~25	40 B

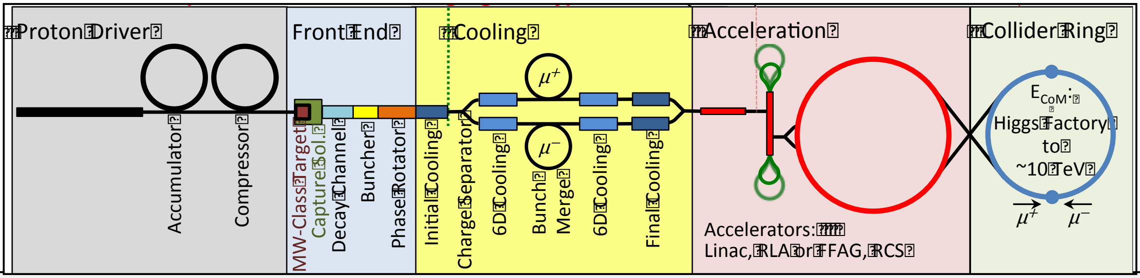
(*) 4×10^{12} Z

2 experiments assumed for CepC, SppC and FCC-hh, 2-4 for FCC-ee
L upgrade assumed for ILC and crab waist option for FCC-ee
FCC-ee plans include run at 160 GeV

Note:

- Scenarios (revised after H discovery) will evolve based also on future LHC results
- Different definitions of "year" across projects: 1-1.6x10^7 s/year assumed for physics data taking in most cases.
  Cfr: LHC in 2012 (end of Run 1): 0.6x10^7 s of machine operation in physics with stable beams
- pp colliders: usable H events are ~ 10% of total cross-section due to large backgrounds

Muon colliders



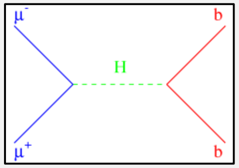
Synergies with neutrino factories

Main advantage compared to e+e- colliders: $m_\mu \sim 200\ m_e$

→ negligible SR → can reach multi-TeV with (compact !) circular colliders: 300 m ring for √s = 125 GeV, 4.5 km for √s = 3 TeV

→ negligible beamstrahlung → much smaller E spread

→ $\sigma\ (\mu\mu \to H) \sim 20$ pb (s-channel resonant production) → Higgs factory



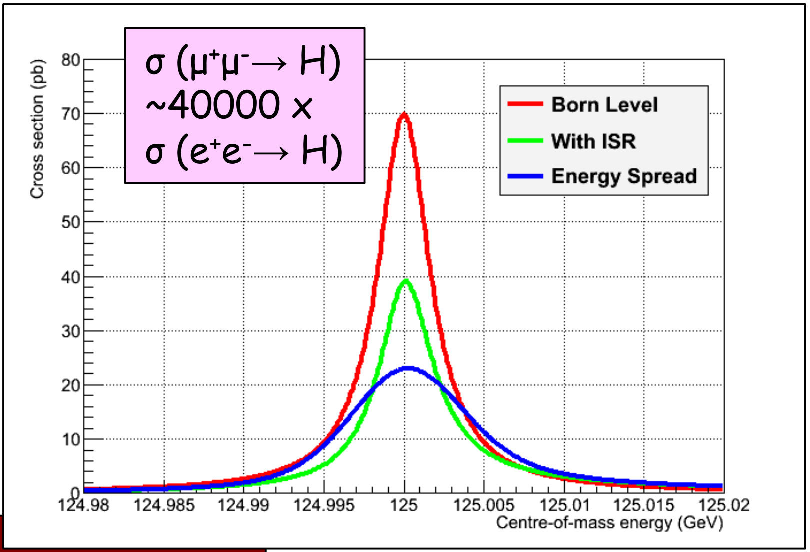
Disadvantages:

☐ $m_\mu \sim 200\ m_e$ → SR damping does not work → novel cooling methods (dE/dx based) needed to reach beam energy spread of ~ 3×10^{-5} (for precise line shape studies) and high L

☐ $\tau_\mu \sim 2.2\ \mu s$ → production, collection, cooling, acceleration, collisions within ~ ms

Beam spread of ~ 3×10^{-5} would allow Γ_H measurement from line shape to 5% (0.2 MeV) → resolve (possible) resonances

However, with currently projected L (~10^{32}): ~ 20000 Higgs/year → not competitive with e^+e^- colliders for coupling measurements (except Hμμ ~ 1%)



$\sigma\ (\mu^+\mu^- \to H)$
~40000 x
$\sigma\ (e^+e^- \to H)$

More R&D needed in particular on cooling:
linear system (MICE at RAL), rings (recently re-ignited by C.Rubbia)

Physics motivations and potential

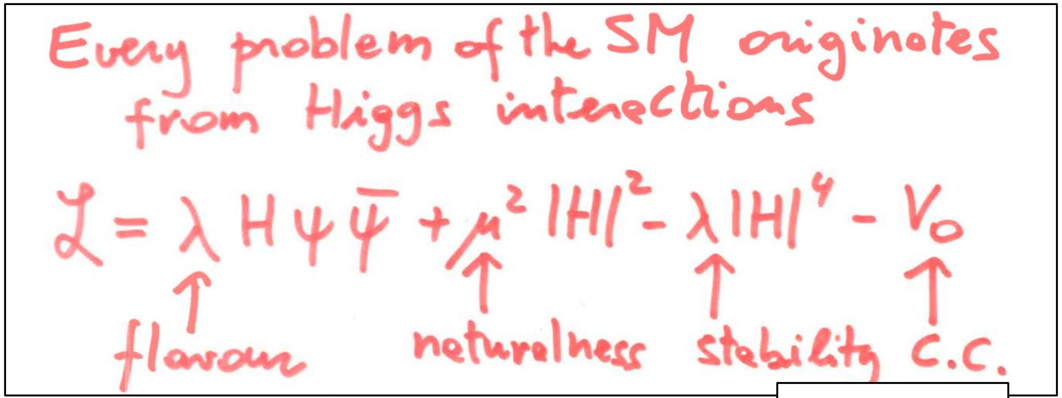
- ☐ Higgs boson measurements
- ☐ Direct and indirect sensitivity to new physics
- ☐ Additional remarks

The Higgs boson is not just … "yet another particle"

- ❑ Profoundly different from all elementary particles discovered so far
- ❑ Related to the most obscure sector of SM
- ❑ Linked to some of the deepest structural questions (flavour, naturalness, vacuum, ..)

↓

Its discovery opens new paths of exploration, and a very broad and challenging experimental programme



Every problem of the SM originates from Higgs interactions

$$\mathcal{L} = \underset{\overset{\uparrow}{\text{flavour}}}{\lambda} H\psi\bar{\psi} + \underset{\overset{\uparrow}{\text{naturalness}}}{\cancel{\mu}^2}|H|^2 - \underset{\overset{\uparrow}{\text{stability}}}{\lambda}|H|^4 - \underset{\overset{\uparrow}{\text{C.C.}}}{V_0}$$

G.F. Giudice

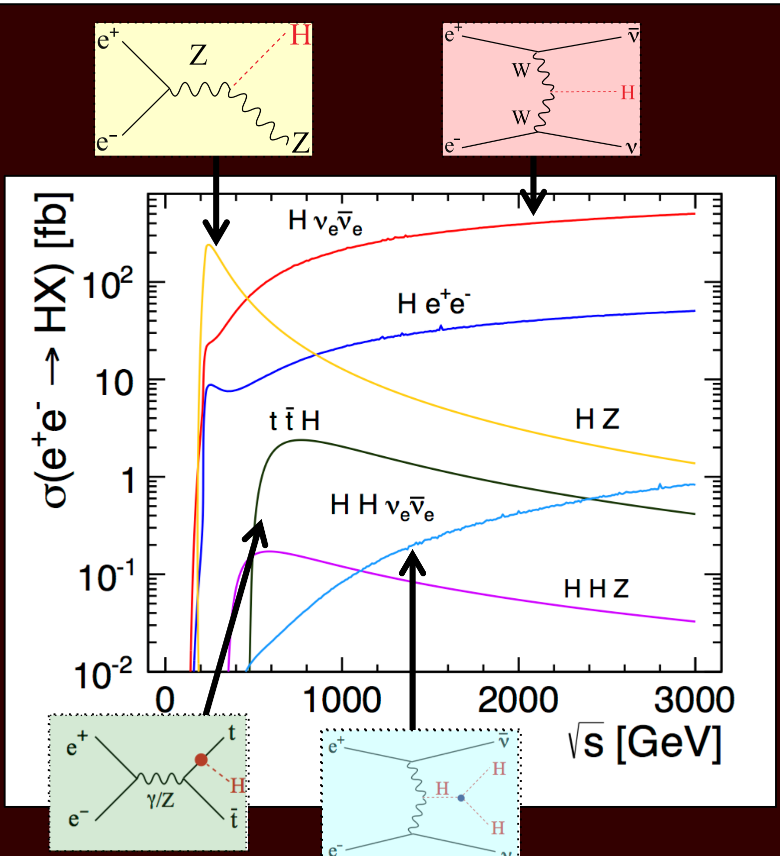
- ❑ Precision measurements of couplings (as many generations as possible, loops, …)
- ❑ Forbidden and rare decays (e.g. H→ τμ)
  → flavour structure and source of fermion masses
- ❑ Higgs potential (HH production, self-couplings):
  → EWSB mechanism (strong dynamics ?)
  → EW phase transition → baryogenesis ?
- ❑ Exotic decays (e.g. H→ E_T^{miss}) → new physics ?
- ❑ Other Higgs properties (width, CP, …)
- ❑ Searches for additional Higgs bosons
- ❑ …

Impact of New Physics on couplings:

$\Delta\kappa/\kappa \sim 5\%/\Lambda^2_{NP}$ (Λ_{NP} in TeV)

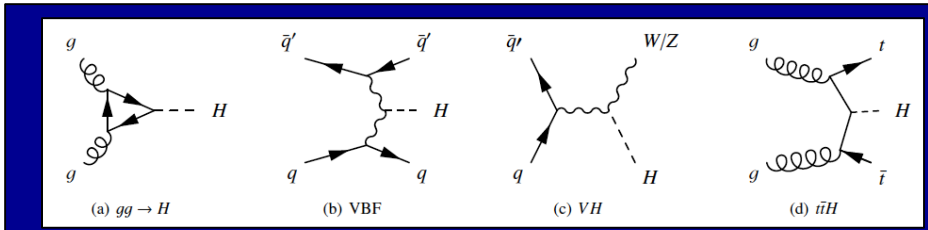
→ 0.1-1% exp. precision needed

e^+e^- colliders

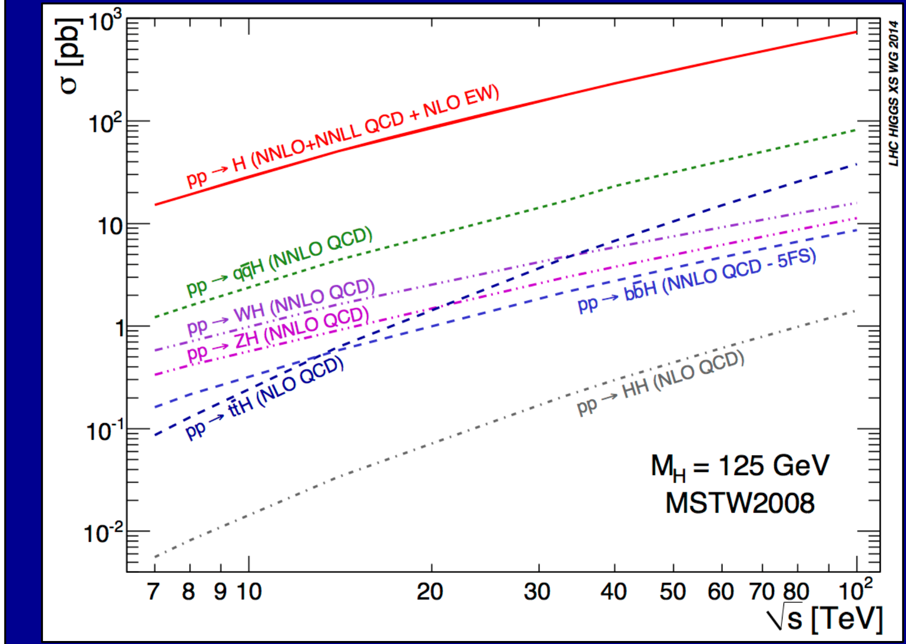


- Low backgrounds → all decay modes (hadronic, invisible, exotic) accessible
- ttH and HH require $\sqrt{s} \geq 500$ GeV
- Model-indep coupling measurements: σ(HZ) and Γ_H from data (ZH → μμ/qqX recoil, Hνν →bbνν)

pp colliders



(a) gg → H (b) VBF (c) VH (d) tt̄H



- Huge backgrounds → not all channels accessible
- High energy, huge cross-sections → optimal for (clean) rare decays and heavy final states (ttH, HH)
- Model-dep. coupling measurements: Γ_H and σ (H) from SM

Units are %

Coupling $\sqrt{s}$ (TeV)→ L (fb^{-1}) →	HL-LHC 14 3000(1 expt)	CepC 0.24 5000	FCC-ee 0.24 +0.35 13000	ILC 0.25+0.5 6000	CLIC 0.38+1.4+3 4000	FCC-hh 100 40000
K_W	2-5	1.2	0.19	0.4	0.9	
K_Z	2-4	0.26	0.15	0.3	0.8	
K_g	3-5	1.5	0.8	1.0	1.2	
K_γ	2-5	4.7	1.5	3.4	3.2	< 1
K_μ	~8	8.6	6.2	9.2	5.6	~ 2
K_c	--	1.7	0.7	1.2	1.1	
K_τ	2-5	1.4	0.5	0.9	1.5	
K_b	4-7	1.3	0.4	0.7	0.9	
$K_{Z\gamma}$	10-12	n.a.	n.a.	n.a.	n.a.	
Γ_h	n.a.	2.8	1%	1.8	3.4	
BR_{invis}	<10	<0.28	<0.19%	<0.29	<1%	
K_t	7-10	--	13% ind. tt scan	6.3	<4	~1
K_{HH}	?	35% from K_Z model-dep	20% from K_Z model-dep	27	11	5-10

Few preliminary estimates available SppC : similar reach

← from K_γ/K_Z, using K_Z from FCC-ee

rare decays → pp competitive/better

← from ttH/ttZ, using ttZ and H BR from FCC-ee

- ☐ LHC: ~20% today → ~ 10% by 2023 (14 TeV, 300 fb^{-1}) → ~ 5% HL-LHC
- ☐ HL-LHC: -- first direct observation of couplings to 2nd generation (H→ μμ)
  -- model-independent ratios of couplings to 2-5%
- ☐ Best precision (few 0.1%) at FCC-ee (luminosity !), except for heavy states (ttH and HH) where high energy needed → linear colliders, high-E pp colliders
- ☐ Complementarity/synergies between ee and pp

Theory uncertainties (presently few percent e.g. on BR) need to be improved to match expected superb experimental precision

New physics: hiding well or beyond present reach ?

The virtues of e+e- colliders:

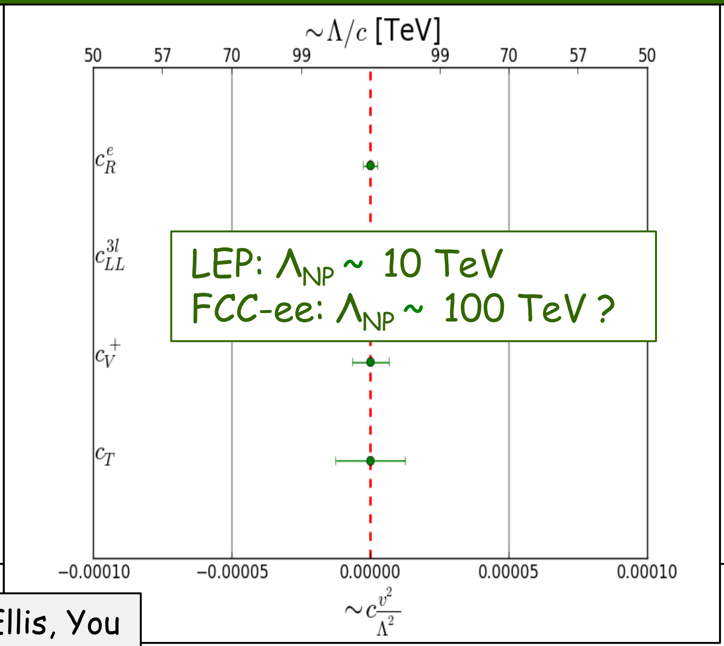
- Direct, model-independent searches for new particles coupling to Z/γ^* up to $m \sim \sqrt{s}/2$; precise measurements of the new particles and theory
- Clean environment → can fill possible “blind spots” in searches at pp colliders
- Indirect sensitivity to high-E scale → CepC,FCC-ee, ILC, CLIC can probe $\Lambda \sim O(100)$ TeV
- Sensitivity to very weakly coupled physics
- Polarised beams: powerful tool to constrain underlying theory

Example: FCC-ee (assuming matching th. precision)

- 10^{12} Z → x 20-100 higher precision on EW observables
- 10^8 WW → $\Delta m_W < 1$ MeV; 10^6 tt → $\Delta m_t \sim 10$ MeV

→ probe higher-dimensional operators from new physics

$$L_{\rm eff} = \sum_n \frac{c_n v^2}{\Lambda^2} O_n$$



LEP: $\Lambda_{NP} \sim$ 10 TeV
FCC-ee: $\Lambda_{NP} \sim$ 100 TeV ?

Ellis, You

New physics: hiding well or beyond present reach ?

The virtues of e+e- colliders:

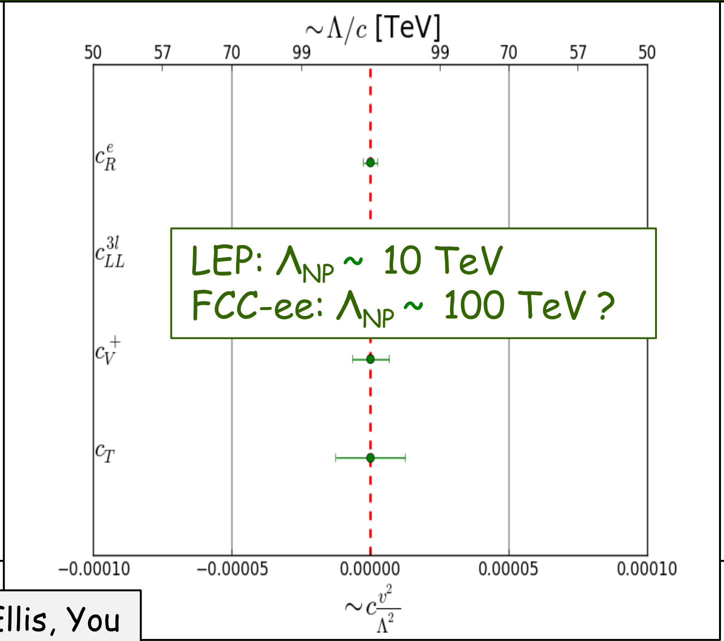
- ❑ Direct, model-independent searches for new particles coupling to Z/γ* up to m ~ √s/2; precise measurements of the new particles and theory
- ❑ Clean environment → can fill possible “blind spots” in searches at pp colliders
- ❑ Indirect sensitivity to high-E scale → CepC,FCC-ee, ILC, CLIC can probe Λ~O(100) TeV
- ❑ Sensitivity to very weakly coupled physics
- ❑ Polarised beams: powerful tool to constrain underlying theory

Example: FCC-ee (assuming matching th. precision)

- ❑ 10^{12} Z → x 20-100 higher precision on EW observables
- ❑ 10^8 WW → $\Delta m_W < 1$ MeV; 10^6 tt → $\Delta m_t \sim 10$ MeV

→ probe higher-dimensional operators from new physics

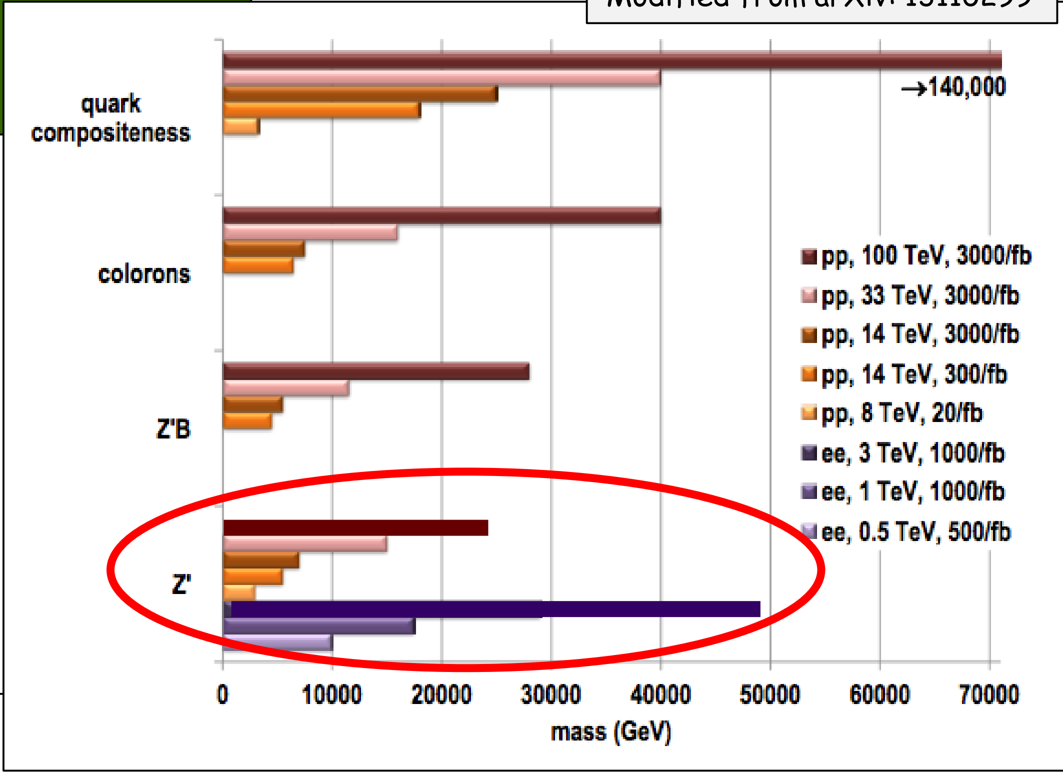
$$L_{\text{eff}} = \sum_n \frac{c_n v^2}{\Lambda^2} O_n$$



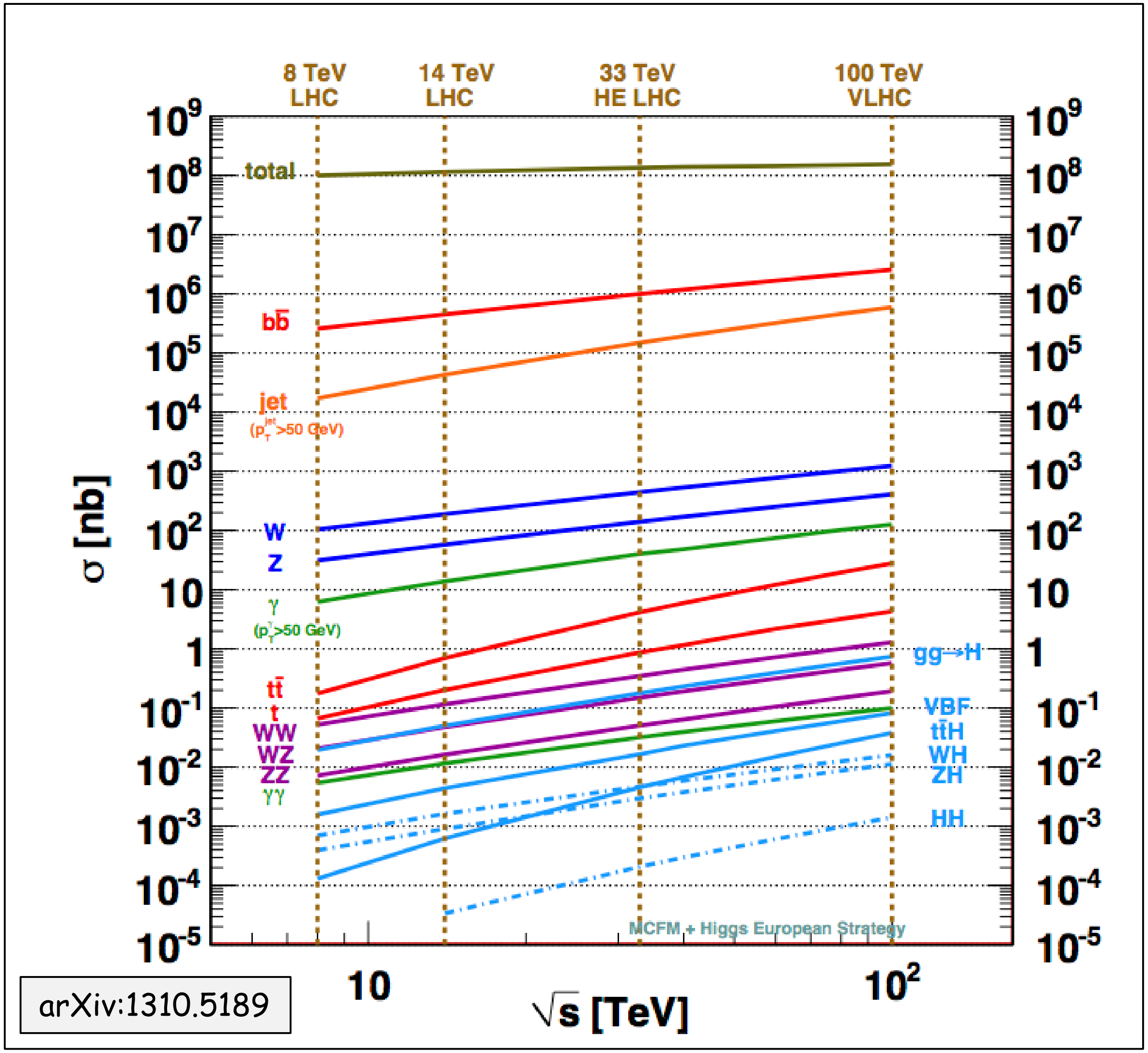
LEP: $\Lambda_{NP} \sim$ 10 TeV
FCC-ee: $\Lambda_{NP} \sim$ 100 TeV ?

Ellis, You

Modified from arXiv: 13110299



Hadron colliders: direct exploration of the “energy frontier”



arXiv:1310.5189

Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10^3

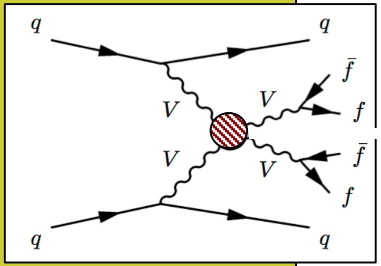
With 40/ab at √s=100 TeV expect: ~10^{12} top, 10^{10} Higgs bosons, 10^5 m=8 TeV gluino pairs, …

If new (heavy) physics discovered at the LHC → completion of spectrum is a “no-lose” argument for future ~ 100 TeV pp collider: extend discovery potential up to m~50 TeV

Other (equally strong) arguments: capability of addressing "structural questions"

Few examples from preliminary estimates

Probe SM in regime where EW symmetry is restored ($\sqrt{\hat{s}} \gg v=246$ GeV)
→ conclusive elucidation of EWSB mechanism

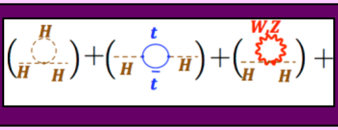


$V_L V_L$ scattering violates unitarity at m_{VV} ~TeV without Higgs

- ❑ H regularizes the theory fully → a crucial "closure test" of the SM
- ❑ Else: new physics shows up: anomalous quartic couplings (VVVV, VVhh) and/or new heavy resonances

100 TeV pp: direct discovery potential of new resonances in the O(10 TeV) range

Naturalness:

$\Delta M_H^2 \sim$  ··· $\sim \Lambda^2$

- ❑ If no new physics at end of LHC → ~ 1% fine-tuning
- ❑ 100 TeV pp: direct sensitivity to stops and other top partners up to m~ 10 TeV → fine-tuning pushed to 10^{-4}

(Distinguished) theorist 1: "Never seen 10^{-4} level of tuning in particle physics: qualitatively new, mortal blow to naturalness". (Distinguished) theorist 2: "Naturalness is a fake problem"

Nature of EW phase transition → if first order (faster than in SM) could give rise to baryogenesis → need modification of the Higgs potential, e.g. by adding a scalar singlet:

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - c_\phi v h \phi^2$$

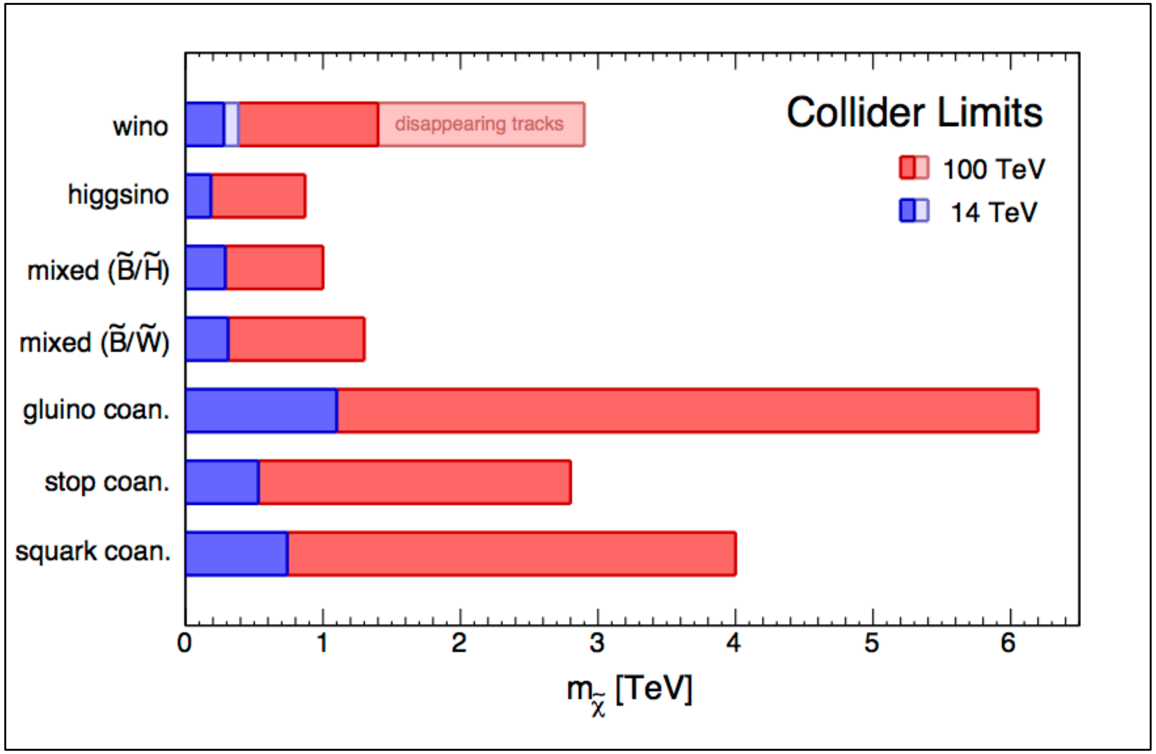
→ this (difficult) model can be constrained from precise measurements of HZ coupling at e+e- and H self-coupling at 100 TeV pp, and direct searches for new (invisible) particles at 100 TeV pp.

CepC-SppC http://cepc.ihep.ac.cn/preCDR/volume.html; see also Curtin et al., arXiv:1409.0005v4

Definitive exploration of heavy WIMP dark matter ?

From relic density, to avoid universe's overclosure:

$$M_{\rm DM} \lesssim 1.8\ {\rm TeV} \left(\frac{g_{\rm eff}^2}{0.3}\right)$$



Low, Wang
arXiv:1404.0682v2

… and of course exploration of unknown territory …

Conclusions

The full exploitation of the LHC, as well as future high-energy/intensity colliders, are necessary to advance our knowledge of fundamental physics

↓

❑ Highest-precision studies of the Higgs boson, conclusive exploration of EWSB, investigation of related issues: vacuum stability (the fate of the universe !), naturalness, EW baryogenesis, …

❑ Addressing outstanding questions (the "known unknowns"): dark matter, flavour problem, matter-antimatter asymmetry, etc.

❑ Exploration, via direct and indirect probes, of uncharted territories (the highest E-scales and smallest couplings) to look for "unknown unknowns" and the new physics that we know MUST be somewhere

Future LHC results (Run-2 and beyond) will hopefully (!!) provide some of the answers and indications of the future path: e.g if new (heavy) physics is discovered →completion of spectrum and more detailed measurements of new physics likely require multi-TeV energies

Regardless of the detailed scenario, and even in the absence of new physics from (HL)-LHC and of theoretical/experimental preference for a specific E scale, the main lines are clear:

❑ highest precision → to probe the highest E-scales indirectly and the smallest couplings

❑ highest E → to explore directly new energies and interpret results from indirect probes

N.B. historically, accelerators have been most powerful tool for exploration in particle physics

Thanks also to great technology progress, many scientifically strong opportunities for high-intensity/high-energy future colliders are available → decision on how to proceed, and the time profile of the projects, depends on science (e.g. LHC results), technology maturity, cost and funding availability, global (worldwide) perspective.

None of these opportunities is easy, none is cheap.

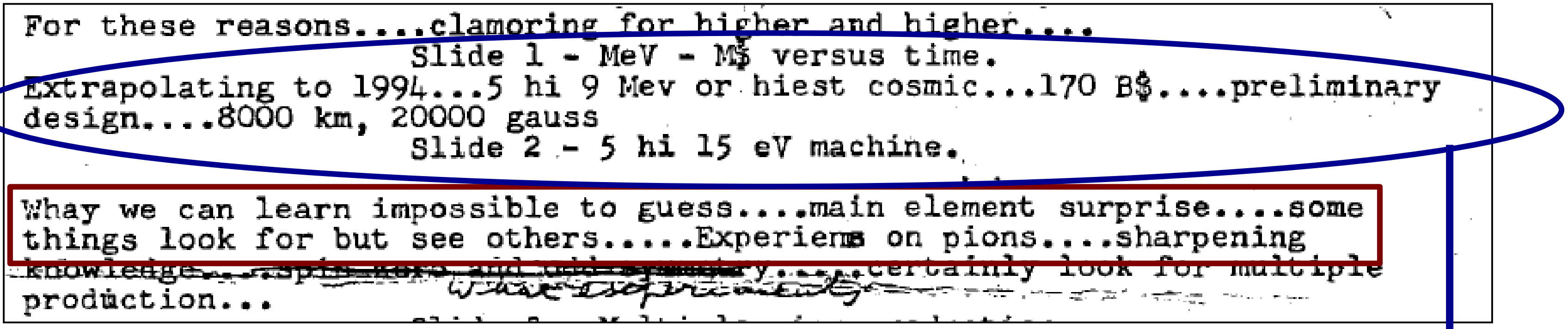
HOWEVER

1) The extraordinary success of the LHC (result of ingenuity, vision and perseverance of the <u>worldwide HEP community</u> and > 20 years of talented, dedicated work) demonstrates strength of the community (<u>accelerator, experiments, theory</u>)
→ asset in view of future, even more ambitious, projects.

2) the correct approach, as scientists, is not to abandon our exploratory spirit, nor give up to financial and technical challenges. The correct approach is to use our creativity to develop the technologies needed to make future projects financially and technically affordable

We did so in the past already … →

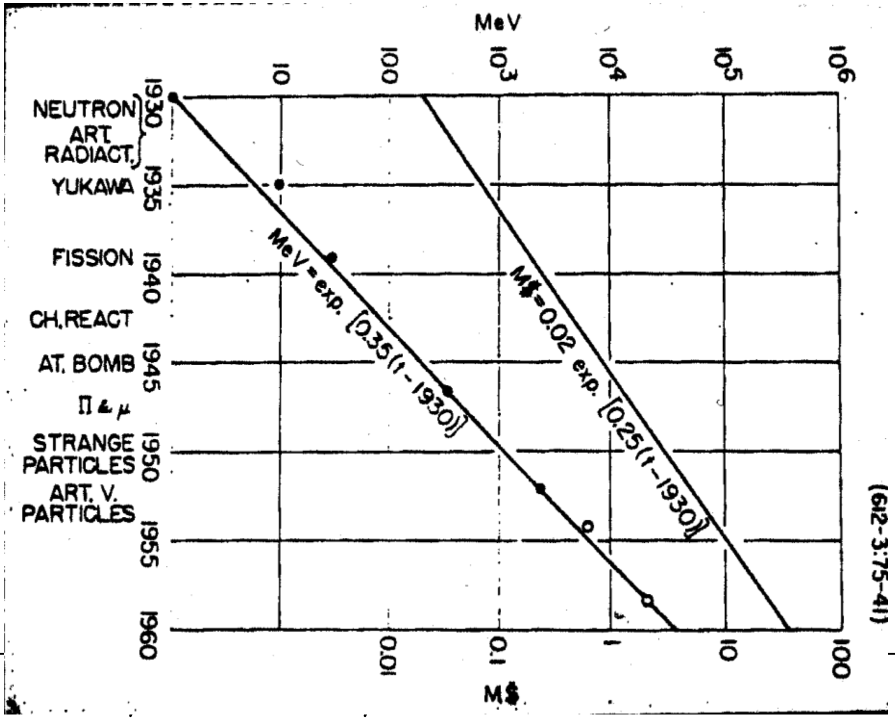
From E. Fermi, preparatory notes for a talk on
"What can we learn with High Energy Accelerators ? "
given to the American Physical Society, NY, Jan. 29th 1954



For these reasons....clamoring for higher and higher....
Slide 1 - MeV - M$ versus time.
Extrapolating to 1994...5 hi 9 Mev or hiest cosmic...170 B$....preliminary design....8000 km, 20000 gauss
Slide 2 - 5 hi 15 eV machine.

Whay we can learn impossible to guess....main element surprise....some things look for but see others.....Experiems on pions....sharpening knowledge....~~spin kors and odd symmetry~~....certainly look for multiple production...

[illegible]



F.

Fermi's extrapolation to year 1994:
2T magnets, R=8000 km (fixed target !),
E_{beam} ~ 5×10^3 TeV → $\sqrt{s}$ ~ 3 TeV
Cost : 170 B$

Was that hopeless ??

We have found the solution:
we have invented colliders
and superconducting magnets …
and built the Tevatron and the LHC

MANY THANKS TO …

THE ORGANISERS

and

C. Grojean, P.Janot, L.Linssen, M.Mangano, A.Nisati, P.Roloff, L.Rossi, D.Schulte, F.Simon, S.Stapnes, G.Wilkinson, F.Zimmermann

EXTRAS

Hard, challenging work for everybody to make the "impossible" possible !

Accelerator R&D (few examples …):

- High-field, accelerator-quality Nb_3Sn superconducting magnets ready for massive industrial production starting mid-end next decade. Continue to push HTS for farther-term future.
- Normal- and super-conducting high-Q RF cavities reaching higher field at lower cost (great progress recently in SCRF)
- Higher-efficiency RF sources
- Novel ideas to reach GV/m acceleration gradients, allowing factor ~10 shorter Linacs: e.g. laser- and beam-driven plasma wakefield acceleration (FACET@SLAC, BELLA@LBNL, AWAKE@CERN, LAOLA@DESY, FLAME@LNF)
- MW-class proton sources and high-power targets for longer-term opportunities (muon colliders, …)

Detectors (few examples …):

- ultra-light, ultra-fast, ultra-granular, rad-hard, low-power Si trackers
- 10^8 channel imaging calorimeters (power consumption and cooling at high-rate machines,..)
- big-volume 5-6 T magnets (~2 x magnetic length and bore of ATLAS and CMS, ~50 GJ stored energy) to reach momentum resolutions of ~10% for p~20 TeV muons

Theory: improved theoretical calculations (higher-order EW and QCD corrections) needed to match present and future experimental precision on EW observables, Higgs mass and branching ratios. Work together with experiments on model-independent analyses in framework of Effective Field Theory

Main outstanding questions in today's particle physics

Higgs boson and EWSB:
- m_H natural or fine-tuned ?
  - → if natural: what new physics/symmetry?
- does it regularize the divergent $V_L V_L$ cross-section at high $M(V_L V_L)$? Or is there a new dynamics ?
- elementary or composite Higgs ?
- are there other Higgs bosons ?
- origin of couplings to fermions ?
- coupling to dark matter ?
- does it violate CP ?
- is EW phase transition responsible for baryogenesis ?

Neutrinos:
- ν masses and and their origin
- what is the role of H(125) ?
- Majorana or Dirac ?
- CP violation
- additional species ? sterile ν ?
- leptogenesis

Dark matter:
- composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- one type or more ?
- only gravitational or other interactions ?

The two epochs of Universe's accelerated expansion:
- primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
- today: dark energy (why is Λ so small?) or gravity modification ?

Quarks and leptons:
- why 3 families ?
- masses and mixing in q and l sectors
- CP violation in the lepton sector
- matter and antimatter asymmetry
- baryon and charged lepton number violation

Physics at the highest E-scales:
- how is gravity connected with the other forces ?
- do forces unify at high energy ?

At what E scale(s) are the answers ?

Some typical energy points

	Size km	$\sqrt{s}$ GeV	RF MV/m	L per IP 10^{34}	Bunch/train x-ing rate(Hz)	σ_x μm	σ_y nm	Lumi within 1% of $\sqrt{s}$	Long. polarisation e^-/e^+
CEPC	54	240	15	2	3×10^5	70	150	>99%	considered
FCC-ee	100	240	9	6	4×10^6	22	40	>99%	considered
ILC	31	250	14.7	1.5	10	0.7	7.7	87%	80%/30%
ILC	31	500	31.5	1.8	5	0.5	5.9	58%	80%/30%
CLIC	15	380	72	1.5	50	0.14	3	60%	80%/considered
CLIC	48	3000	100	6	50	0.04	1	33%	80%/considered

CepC-SppC pre-CDR

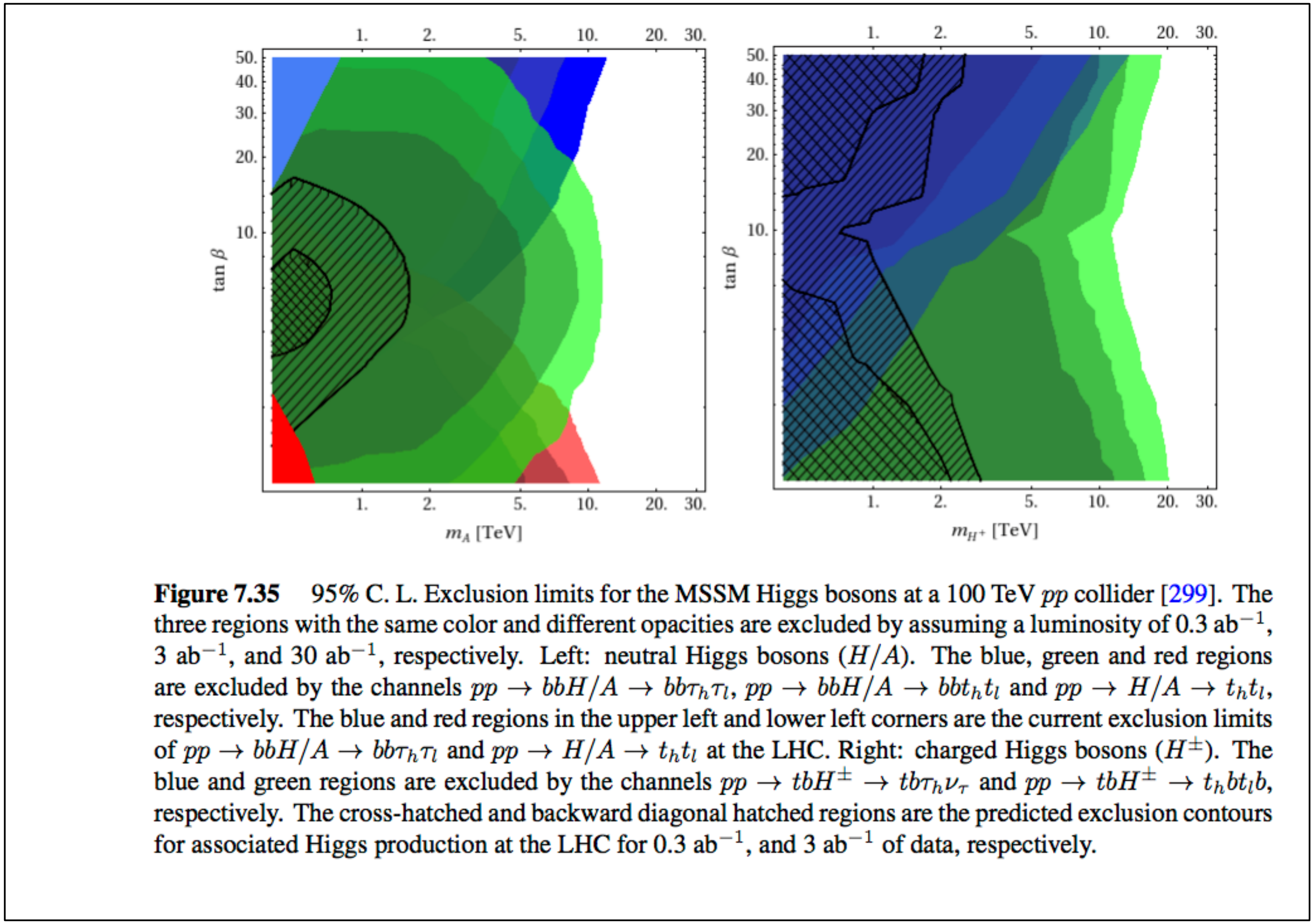
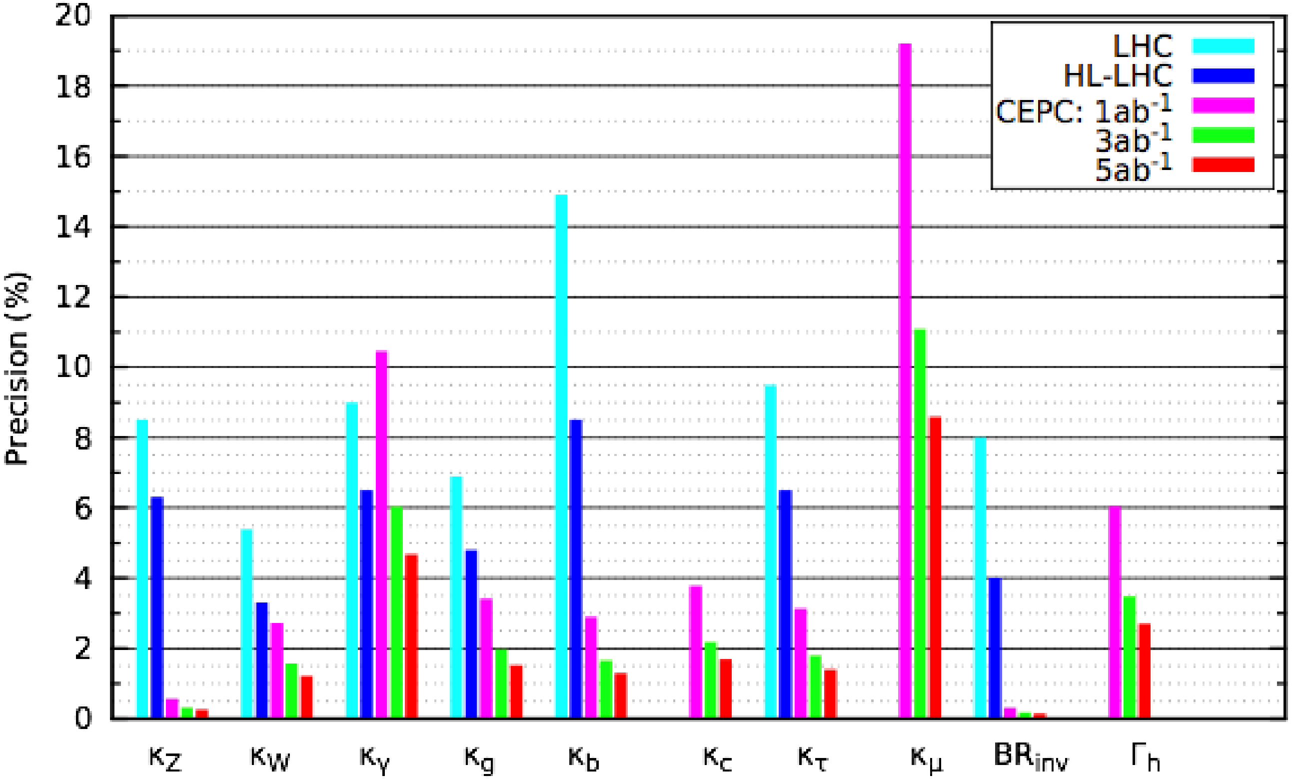


Figure 7.35 95% C. L. Exclusion limits for the MSSM Higgs bosons at a 100 TeV pp collider [299]. The three regions with the same color and different opacities are excluded by assuming a luminosity of 0.3 ab^{-1}, 3 ab^{-1}, and 30 ab^{-1}, respectively. Left: neutral Higgs bosons (H/A). The blue, green and red regions are excluded by the channels $pp \to bbH/A \to bb\tau_h\tau_l$, $pp \to bbH/A \to bbt_ht_l$ and $pp \to H/A \to t_ht_l$, respectively. The blue and red regions in the upper left and lower left corners are the current exclusion limits of $pp \to bbH/A \to bb\tau_h\tau_l$ and $pp \to H/A \to t_ht_l$ at the LHC. Right: charged Higgs bosons ($H^\pm$). The blue and green regions are excluded by the channels $pp \to tbH^\pm \to tb\tau_h\nu_\tau$ and $pp \to tbH^\pm \to t_hbt_lb$, respectively. The cross-hatched and backward diagonal hatched regions are the predicted exclusion contours for associated Higgs production at the LHC for 0.3 ab^{-1}, and 3 ab^{-1} of data, respectively.


20
18
16
14
12
10
8
6
4
2
0
Precision (%)
LHC
HL-LHC
CEPC: 1ab^{-1}
3ab^{-1}
5ab^{-1}
κ_Z
κ_W
κ_γ
κ_g
κ_b
κ_c
κ_τ
κ_μ
BR_{inv}
Γ_h

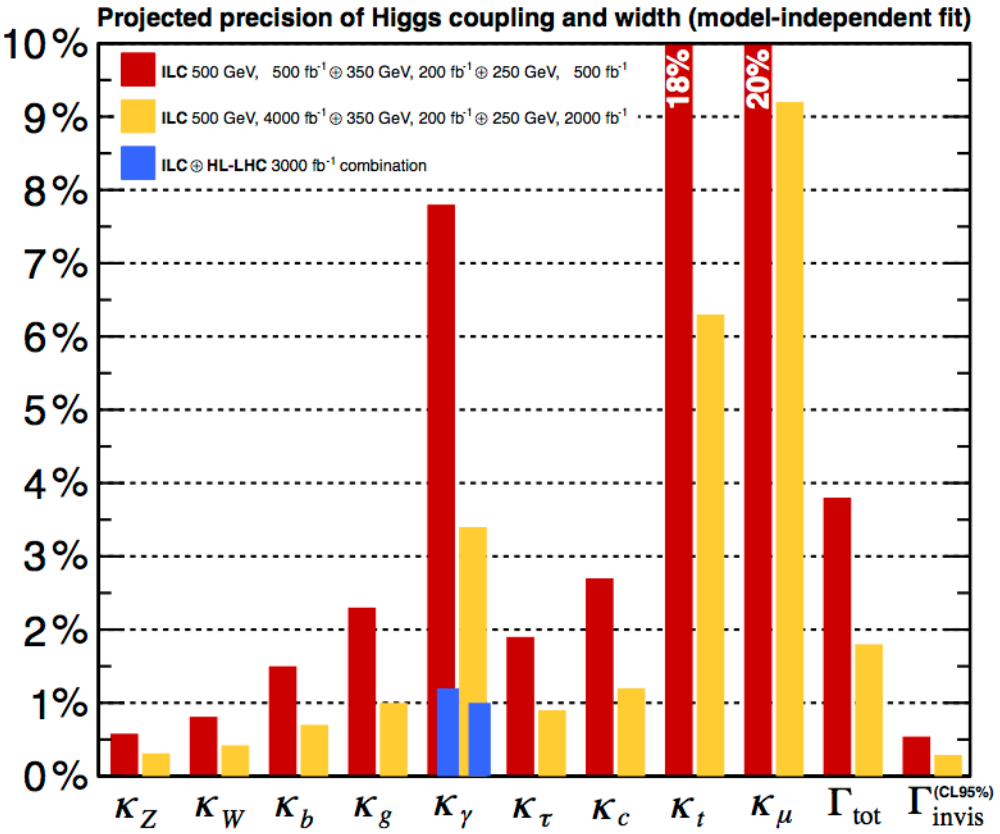
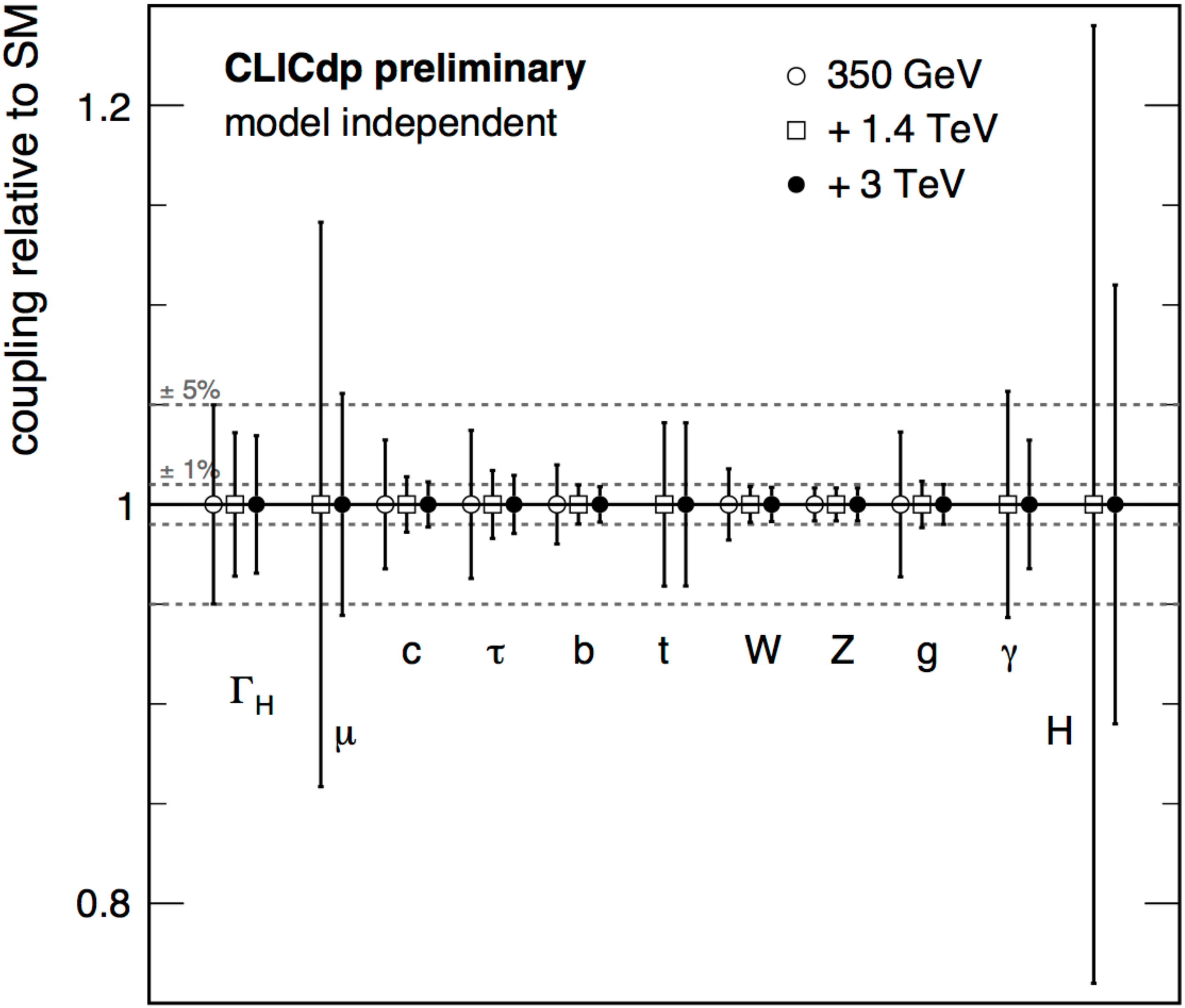
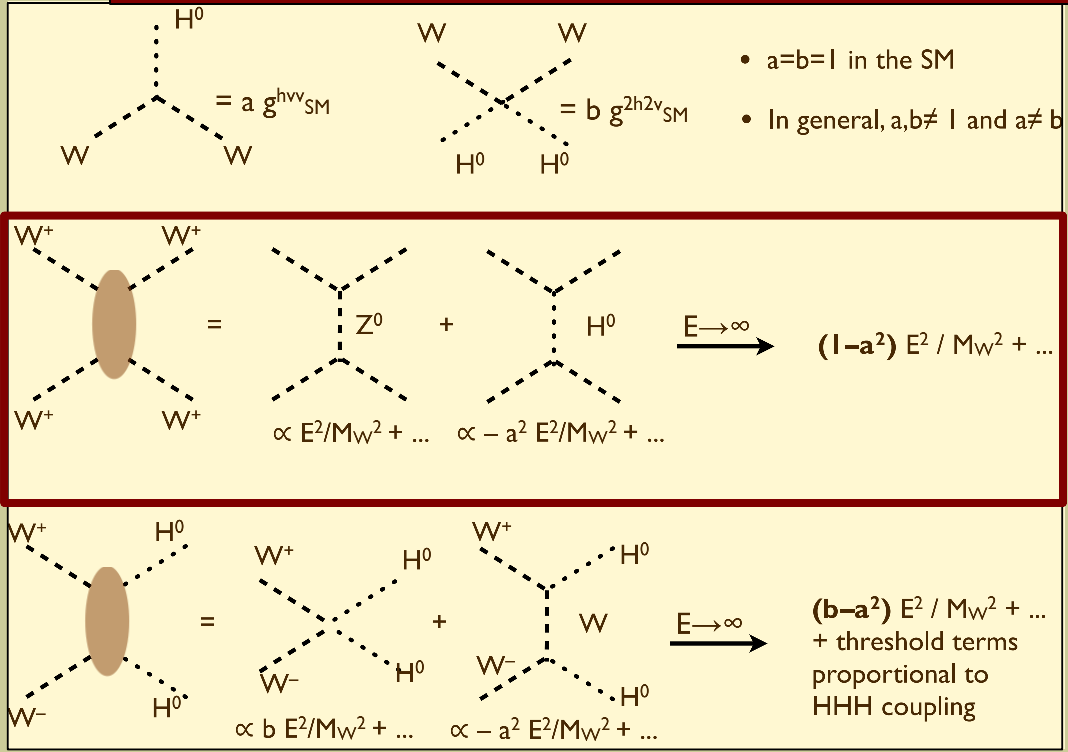


Figure 5: Relative precisions for the various Higgs couplings extracted from a model-independent fit to expected data from the ILC. The notation is as in Fig. 4.


coupling relative to SM
1.2
1
0.8
CLICdp preliminary
model independent
○ 350 GeV
□ + 1.4 TeV
● + 3 TeV
± 5%
± 1%
Γ_H
μ
c
τ
b
t
W
Z
g
γ
H

SPARES

A 100 TeV pp collider would allow a definitive exploration of EWSB



- a=b=1 in the SM
- In general, a,b≠ 1 and a≠ b

By providing direct access
to EW theory in the unbroken regime
($\sqrt{\hat{s}}$ >> v=246 GeV)

$V_L V_L$ scattering violates unitarity
at m_{VV} ~TeV without Higgs
exchange diagrams

KEYWORD: ENERGY !

Important to verify that:

- ☐ H (125) regularizes the theory → a crucial "closure test" of the SM
- ☐ Or, else: observe deviations in VV production compared to SM expectation → anomalous quartic (VVVV) gauge couplings and/or new heavy resonances → new physics
  (Note: several models predict SM-like Higgs but different physics at high E)

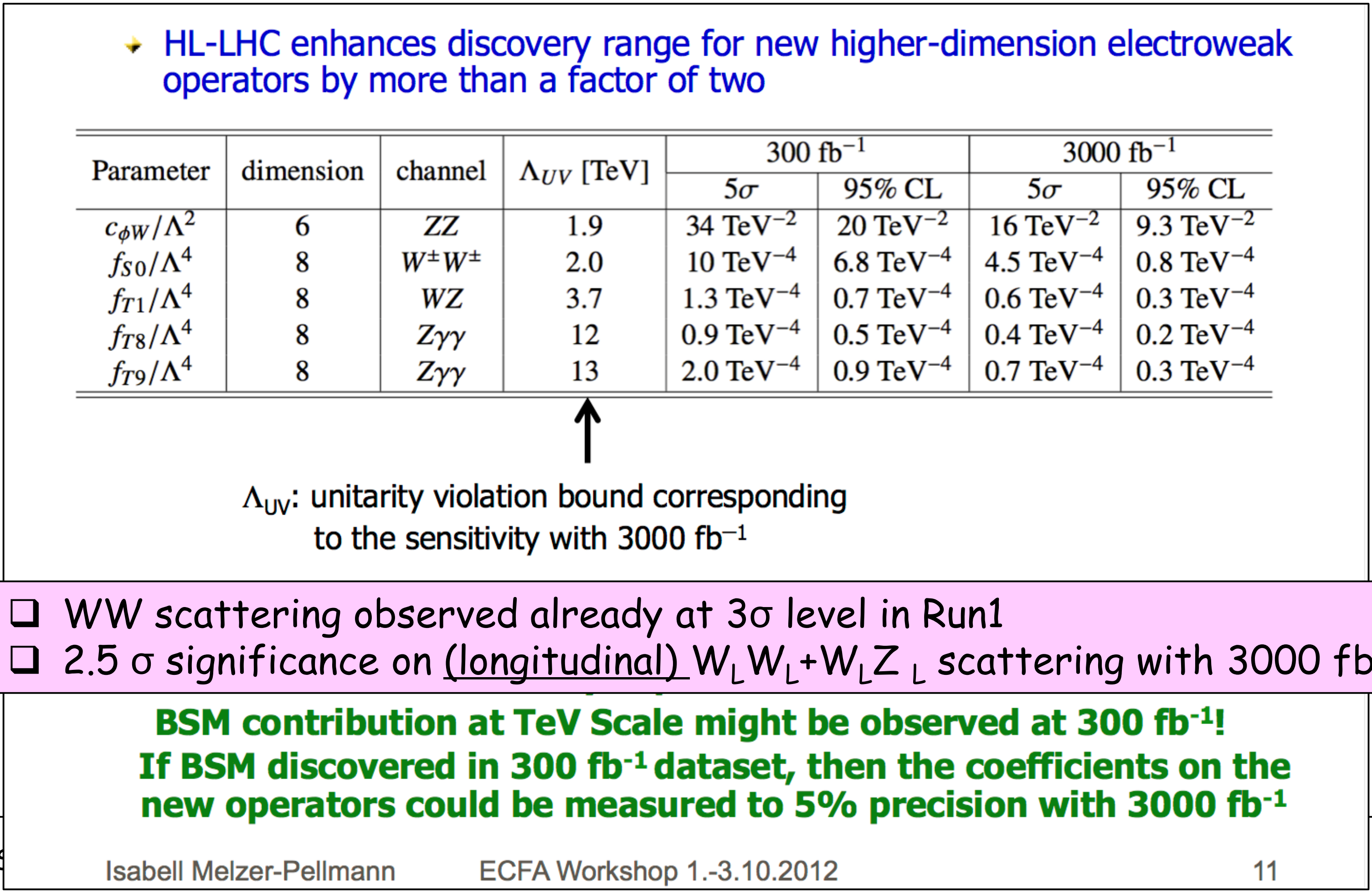
- ☐ HL-LHC: measure SM EW cross-section to 5-10%; x2 higher sensitivity to anomalous couplings than LHC@300 fb^{-1}, ~5% precision on parameters if new physics observed at LHC@300 fb^{-1}
- ☐ ILC 1 TeV, 1 ab^{-1} : indirect sensitivity to new resonances up to m~6 TeV (exploit $e^\pm$ polarization)
- ☐ CLIC 3 TeV, 2 ab^{-1} : indirect sensitivity to composite Higgs scale Λ~70 TeV from VV→ h, hh
- ☐ 100 TeV pp: huge cross-sections at high-mass: σ ~ 100 fb m_{WW}> 3 TeV; σ ~ 1 fb m_{HH} > 2 TeV

→ detailed direct studies

VBS

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \left[\frac{a_i}{\Lambda} \mathcal{O}_i^{(5)} + \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \frac{e_i}{\Lambda^4} \mathcal{O}_i^{(8)} \cdots \right]$$

Observation of **anomalous quartic gauge coupling** would indicate **new physics in the electroweak symmetry breaking sector!**



- HL-LHC enhances discovery range for new higher-dimension electroweak operators by more than a factor of two

Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1}		3000 fb^{-1}	
				5σ	95% CL	5σ	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	34 TeV^{-2}	20 TeV^{-2}	16 TeV^{-2}	9.3 TeV^{-2}
f_{S0}/Λ^4	8	$W^\pm W^\pm$	2.0	10 TeV^{-4}	6.8 TeV^{-4}	4.5 TeV^{-4}	0.8 TeV^{-4}
f_{T1}/Λ^4	8	WZ	3.7	1.3 TeV^{-4}	0.7 TeV^{-4}	0.6 TeV^{-4}	0.3 TeV^{-4}
f_{T8}/Λ^4	8	$Z\gamma\gamma$	12	0.9 TeV^{-4}	0.5 TeV^{-4}	0.4 TeV^{-4}	0.2 TeV^{-4}
f_{T9}/Λ^4	8	$Z\gamma\gamma$	13	2.0 TeV^{-4}	0.9 TeV^{-4}	0.7 TeV^{-4}	0.3 TeV^{-4}

↑

Λ_{UV}: unitarity violation bound corresponding to the sensitivity with 3000 fb^{-1}

- ☐ WW scattering observed already at 3σ level in Run1
- ☐ 2.5 σ significance on (longitudinal) $W_L W_L + W_L Z_L$ scattering with 3000 fb^{-1}

BSM contribution at TeV Scale might be observed at 300 fb^{-1}!
If BSM discovered in 300 fb^{-1} dataset, then the coefficients on the new operators could be measured to 5% precision with 3000 fb^{-1}

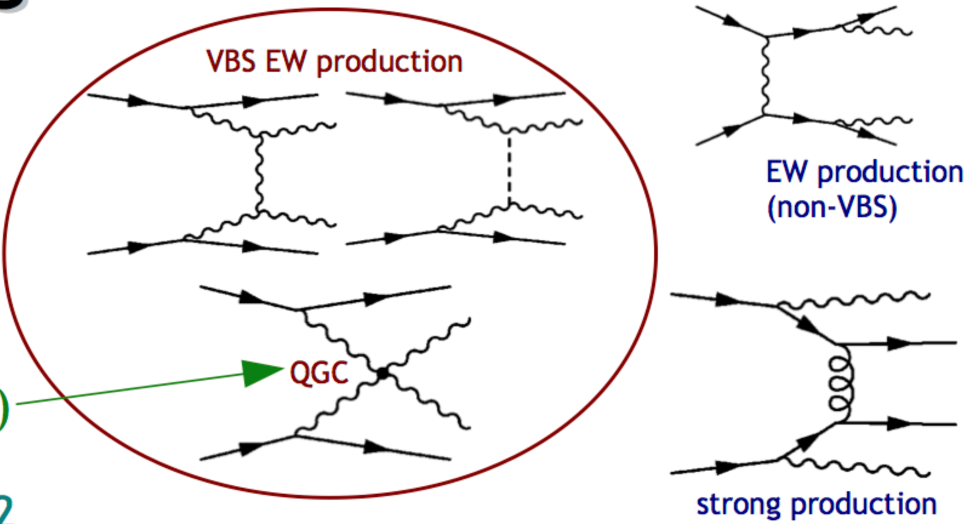
Isabell Melzer-Pellmann ECFA Workshop 1.-3.10.2012 11

Vector boson scattering $W^{\pm}W^{\pm} \rightarrow W^{\pm}W^{\pm}$

At high energies, WW → WW and ZZ → ZZ processes test if the Higgs fully explains electroweak symmetry-breaking: vector boson scattering (VBS) processes

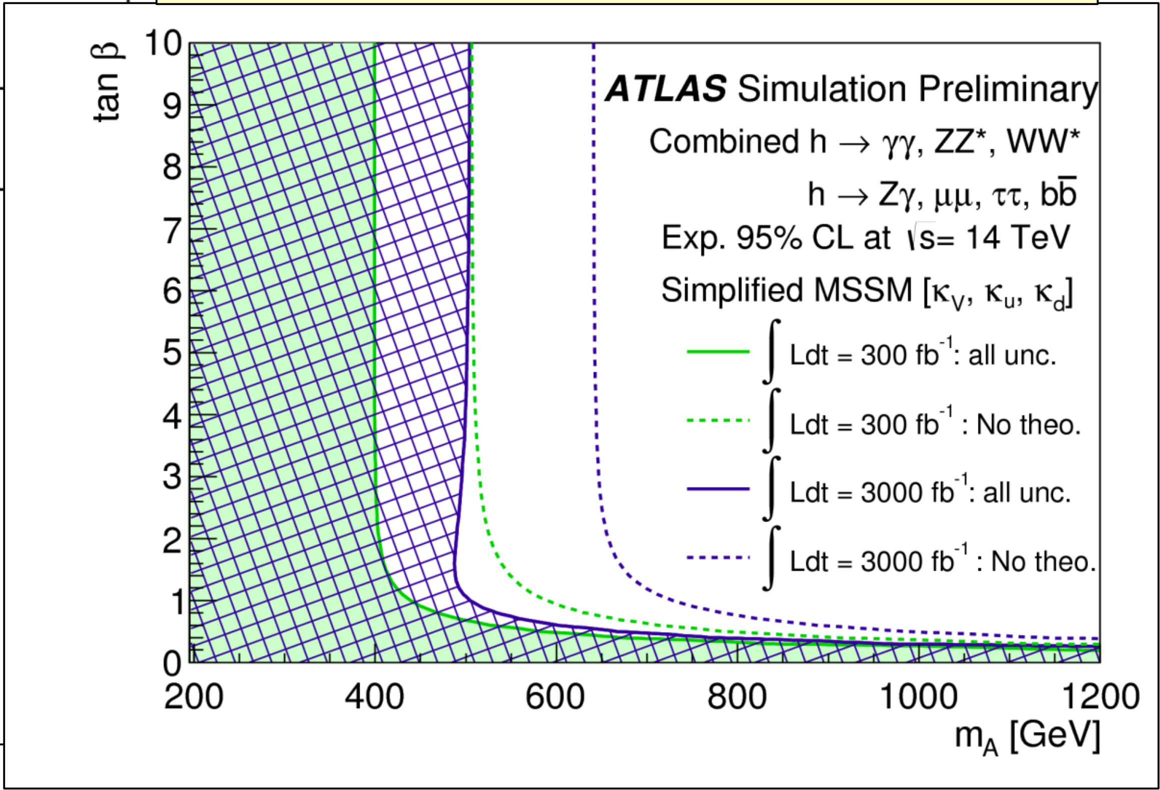
Sensitive to anomalous four-gauge boson interactions (quartic gauge coupling, QGC)

Search for $W^{\pm}W^{\pm}jj$ production in dilepton+2 jet final states, m(jj)>500 GeV

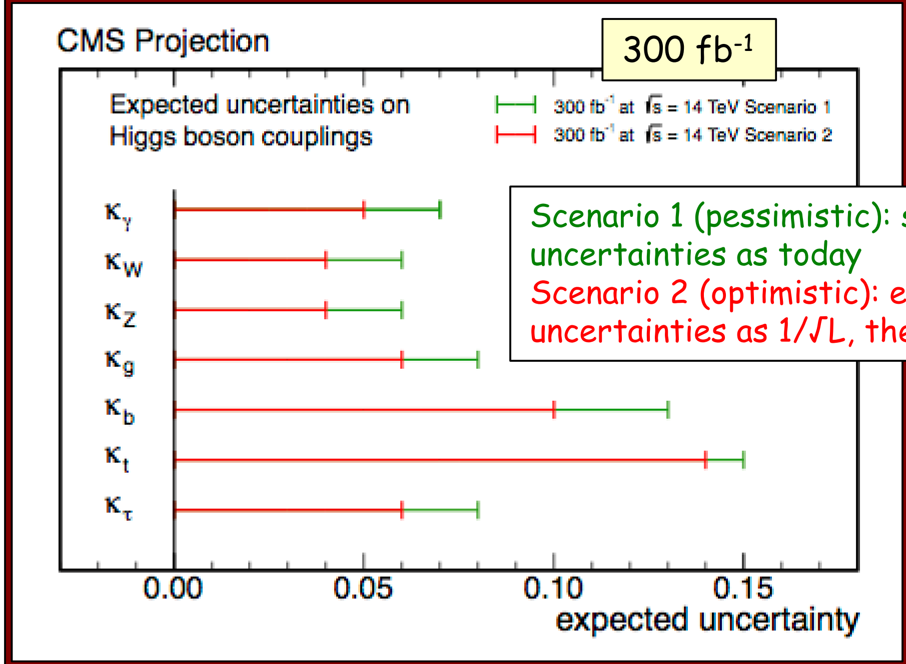


	Higgs bosons at $\sqrt{s}$=14TeV
HL-LHC, 3000fb^{-1}	170M
VBF (all decays)	13M
ttH (all decays)	1.8M
H->Zγ	230k
H->μμ	37k
HH (all)	121k

Exclusion from h coupling measurements only

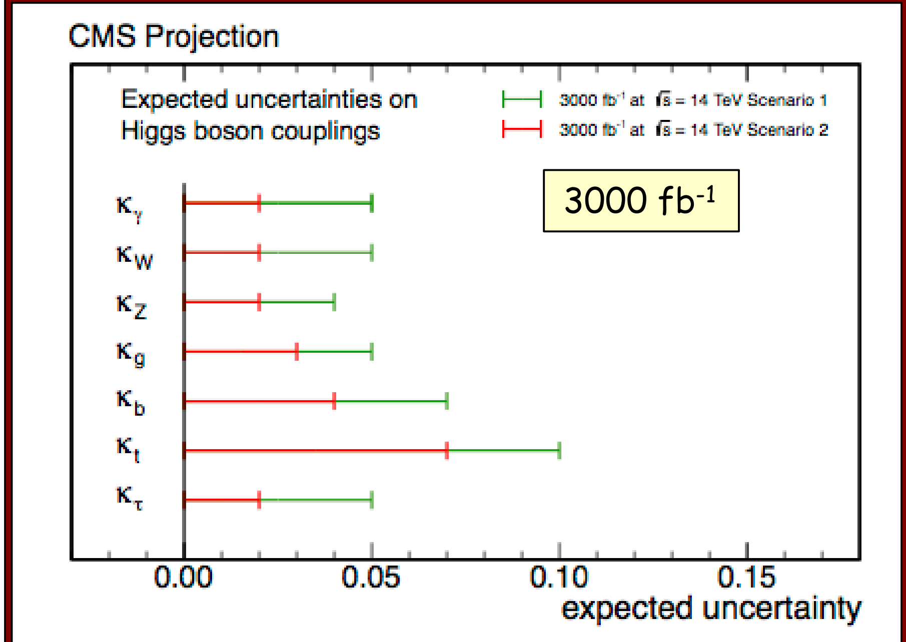


Measurements of Higgs couplings



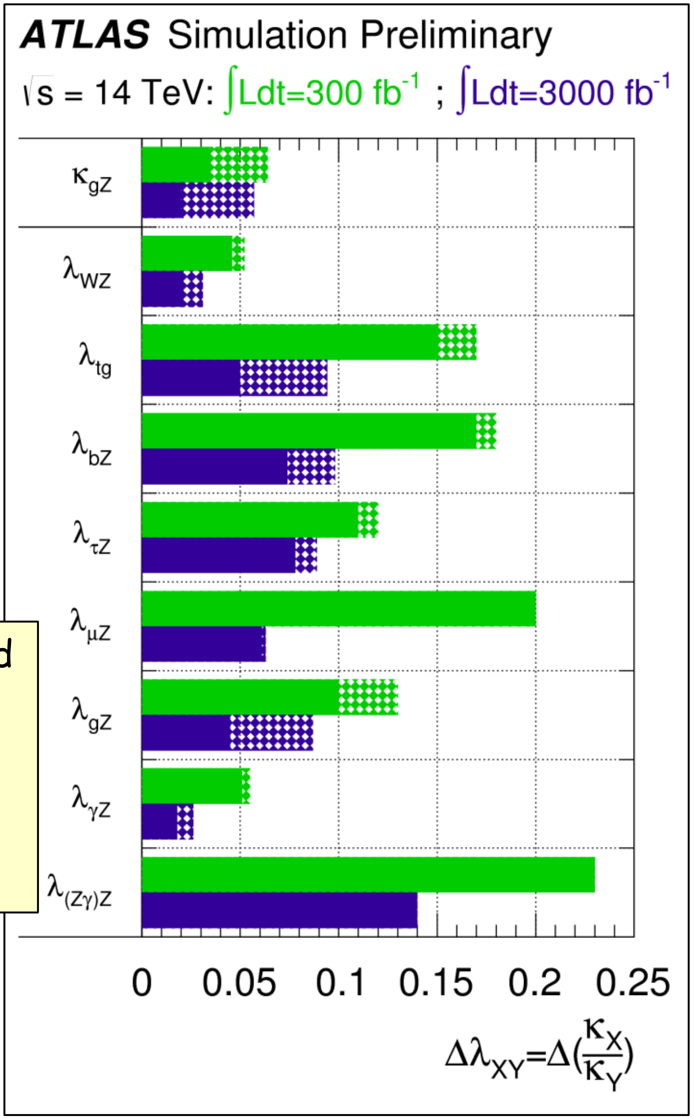
300 fb^{-1}

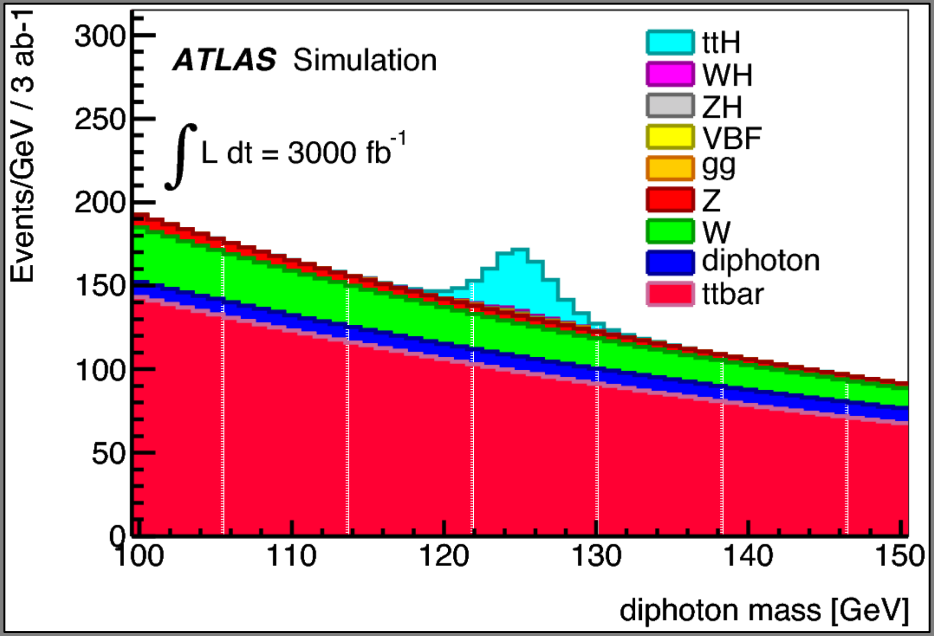
Scenario 1 (pessimistic): systematic uncertainties as today
Scenario 2 (optimistic): experimental uncertainties as $1/\sqrt{L}$, theory halved



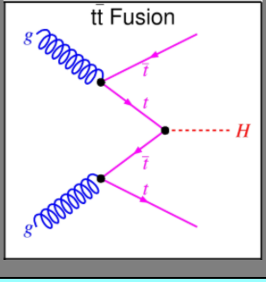
3000 fb^{-1}

k_i= measured coupling normalized to SM prediction
$\lambda_{ij}=k_i/k_j$

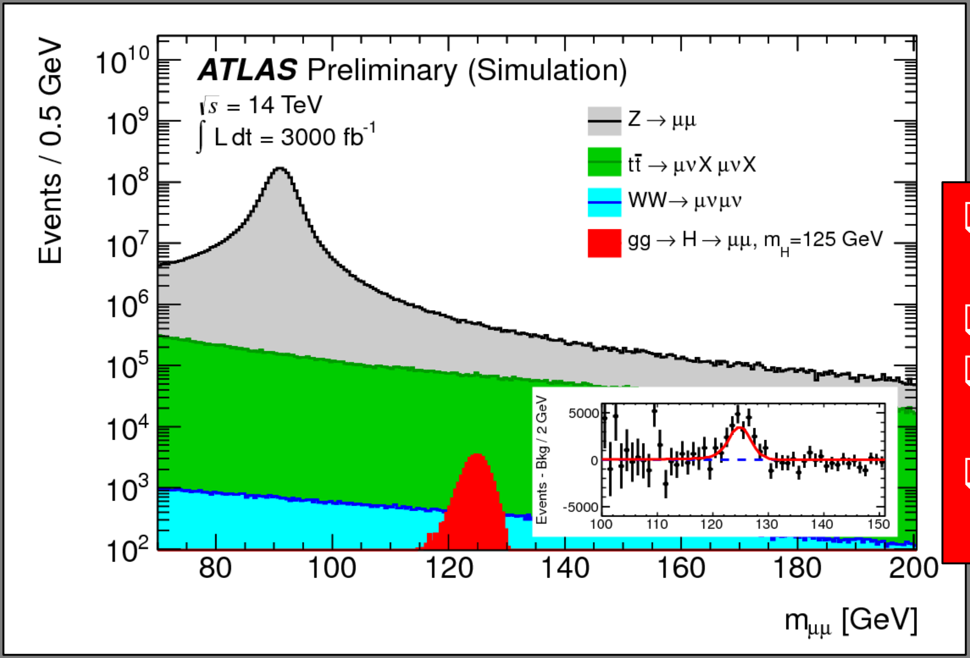




ttH production with H → γγ

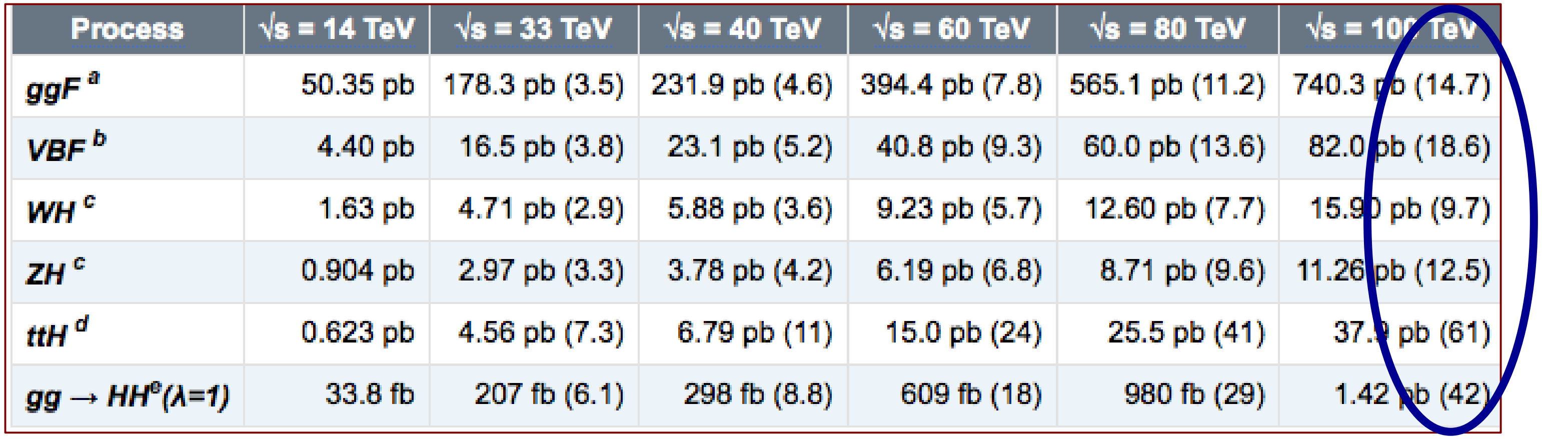


- ❑ Gives direct access to Higgs-top coupling (intriguing as top is heavy)
- ❑ With 3000 fb^{-1} expect 200 signal events (S/B ~ 0.2) and > 5σ
- ❑ Higgs-top coupling can be measured to about 10%



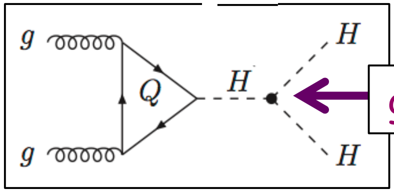
H →μμ

- ❑ Gives direct access to Higgs couplings to fermions of the second generation.
- ❑ Today's sensitivity: 7xSM cross-section
- ❑ With 3000 fb^{-1} expect 17000 signal events (but: S/B ~ 0.3%) and ~ 7σ significance
- ❑ Higgs-muon coupling can be measured to about 10%



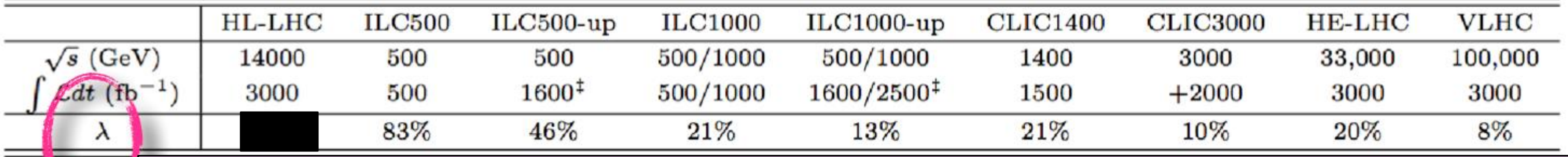
Process	√s = 14 TeV	√s = 33 TeV	√s = 40 TeV	√s = 60 TeV	√s = 80 TeV	√s = 100 TeV
ggF [a]	50.35 pb	178.3 pb (3.5)	231.9 pb (4.6)	394.4 pb (7.8)	565.1 pb (11.2)	740.3 pb (14.7)
VBF [b]	4.40 pb	16.5 pb (3.8)	23.1 pb (5.2)	40.8 pb (9.3)	60.0 pb (13.6)	82.0 pb (18.6)
WH [c]	1.63 pb	4.71 pb (2.9)	5.88 pb (3.6)	9.23 pb (5.7)	12.60 pb (7.7)	15.90 pb (9.7)
ZH [c]	0.904 pb	2.97 pb (3.3)	3.78 pb (4.2)	6.19 pb (6.8)	8.71 pb (9.6)	11.26 pb (12.5)
ttH [d]	0.623 pb	4.56 pb (7.3)	6.79 pb (11)	15.0 pb (24)	25.5 pb (41)	37.9 pb (61)
gg → HH[e]***(λ=1)***	33.8 fb	207 fb (6.1)	298 fb (8.8)	609 fb (18)	980 fb (29)	1.42 pb (42)

Higgs cross sections (LHC HXS WG)



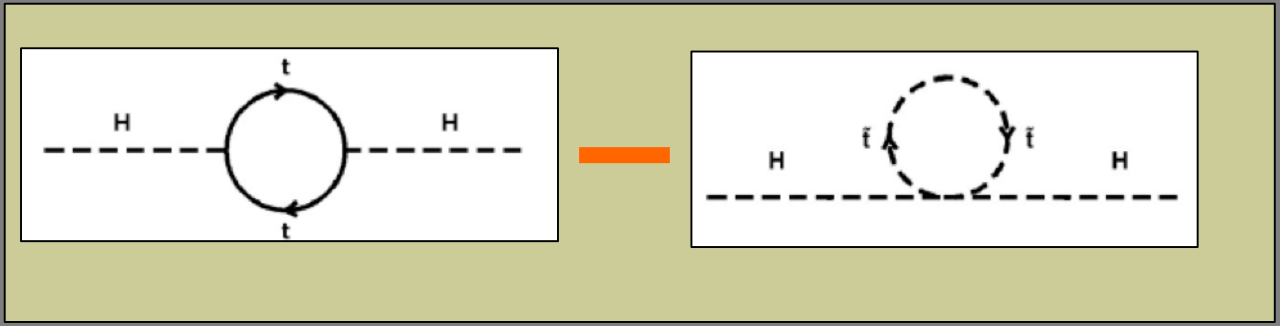
$g_{HHH} \sim \lambda v$

Higgs self-couplings difficult to measure at any facility (energy is mainly needed ..)

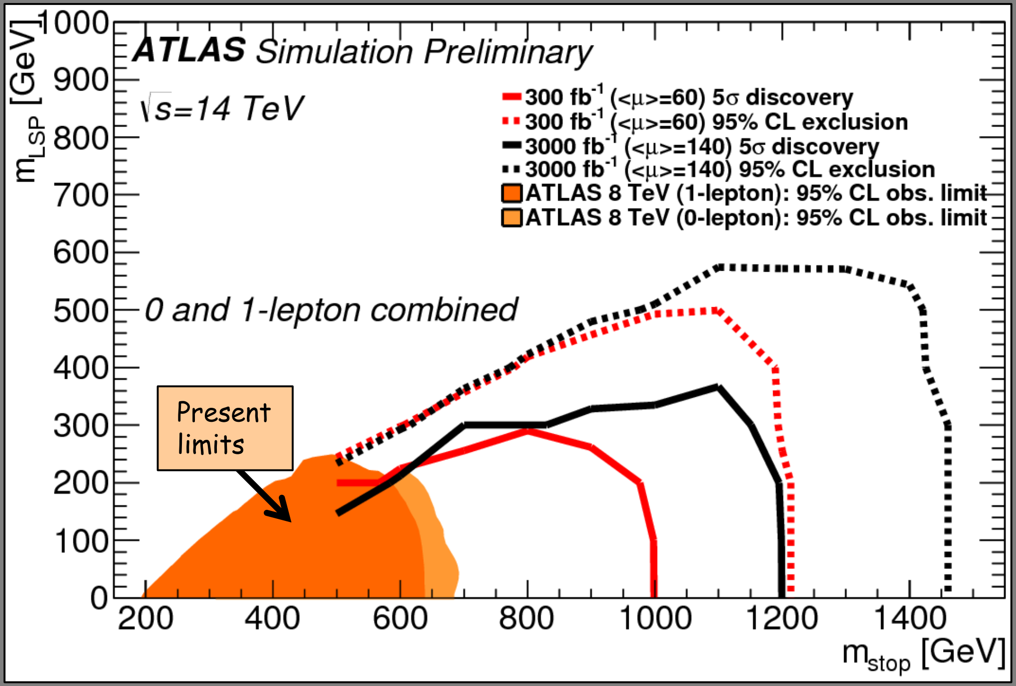


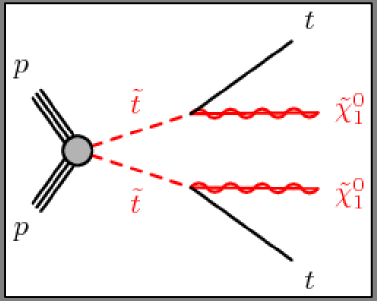
	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000	500	1600‡	500/1000	1600/2500‡	1500	+2000	3000	3000
λ	[redacted]	83%	46%	21%	13%	21%	10%	20%	8%

HL-LHC studies not completed yet … ~30% precision expected, but need 3000 fb^{-1}



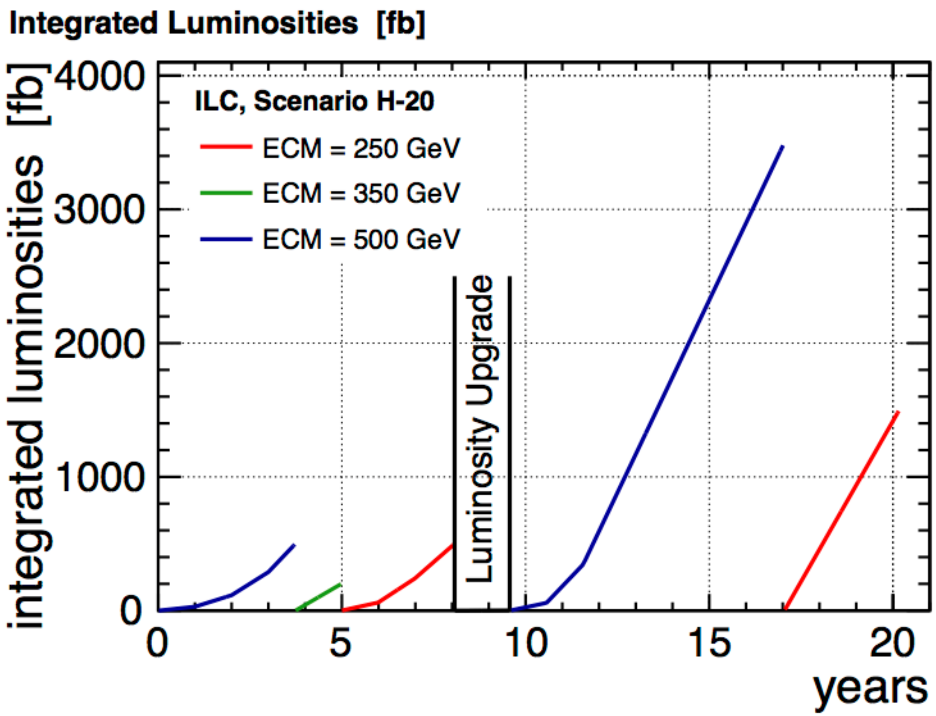
To stabilize the Higgs mass (without too much fine-tuning), the stop should not be much heavier than ~ 1-1.5 TeV (note: the rest of the SUSY spectrum can be heavier)





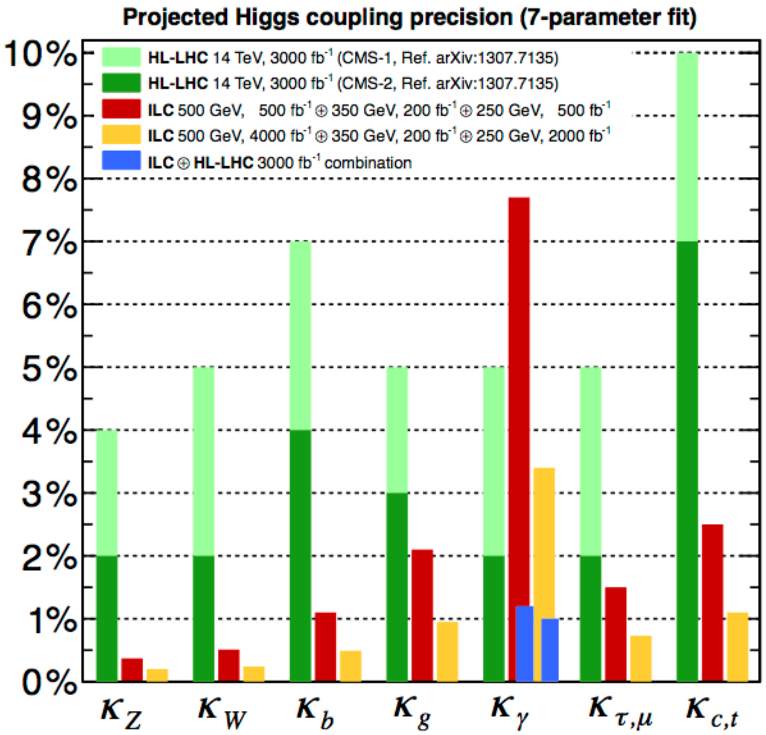
Mass reach extends by ~ 200 GeV from 300 to 3000 fb^{-1}

→ most of best motivated mass range will be covered at HL-LHC



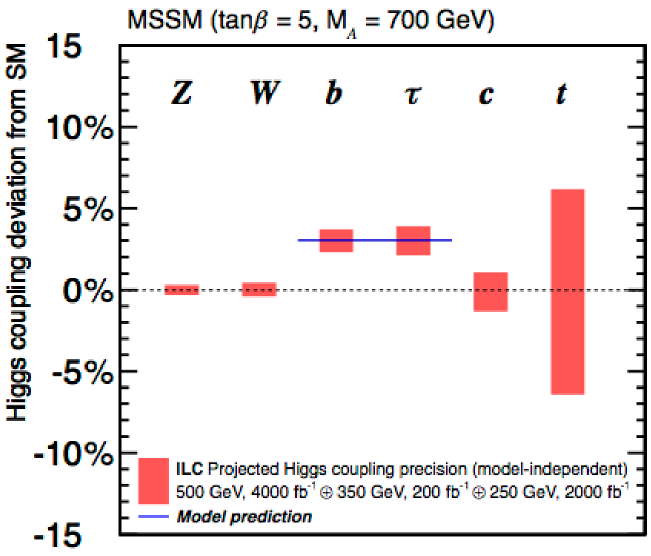
	$\sqrt{s}$	$\int \mathscr{L} dt$	L_{peak}	Ramp				T	T_{tot}	Comment
	[GeV]	[fb^{-1}]	[fb^{-1}/a]	1	2	3	4	[a]	[a]	
Physics run	500	500	288	0.1	0.3	0.6	1.0	3.7	3.7	TDR nominal at 5 Hz
Physics run	350	200	160	1.0	1.0	1.0	1.0	1.3	5.0	TDR nominal at 5 Hz
Physics run	250	500	240	0.25	0.75	1.0	1.0	3.1	8.1	operation at 10 Hz
Shutdown								1.5	9.6	Luminosity upgrade
Physics run	500	3500	576	0.1	0.5	1.0	1.0	7.4	17.0	TDR lumi-up at 5 Hz
Physics run	250	1500	480	1.0	1.0	1.0	1.0	3.2	20.2	lumi-up operation at 10 Hz

Table 7: Scenario H-20: Sequence of energy stages and their real-time conditions.

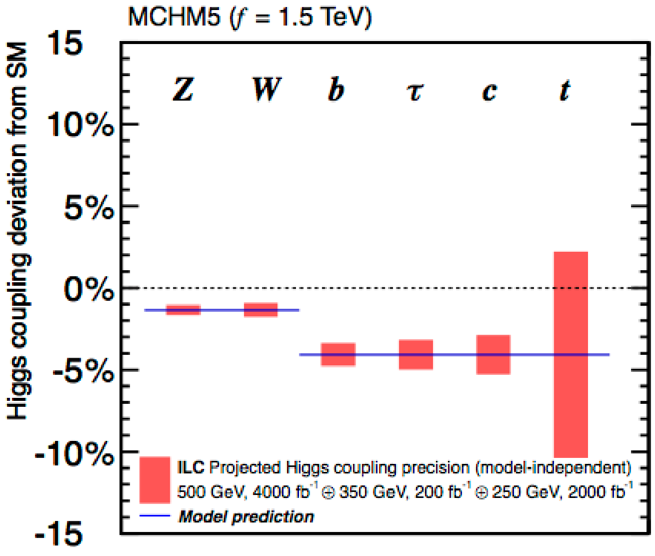


To compare with LHC:
-- ratio of couplings to SM expectation
-- assumption on SM width and
k_c=k_t, k_μ=k_τ i.e. similar deviations from SM expectation

Figure 4: Relative precisions for the various Higgs couplings extracted using the model-dependent fit used in the Snowmass 2013 study [18], applied to expected data from the High-Luminosity LHC and from the ILC. Here, κ_A is the ratio of the $A\bar{A}h$ coupling to the Standard Model expectation. The red bands show the expected errors from the initial phase of ILC running. The yellow bands show the errors expected from the full data set. The blue bands for κ_γ show the effect of a joint analysis of High-Luminosity LHC and ILC data.



MSSM ($\tan\beta = 5$, $M_A = 700$ GeV)

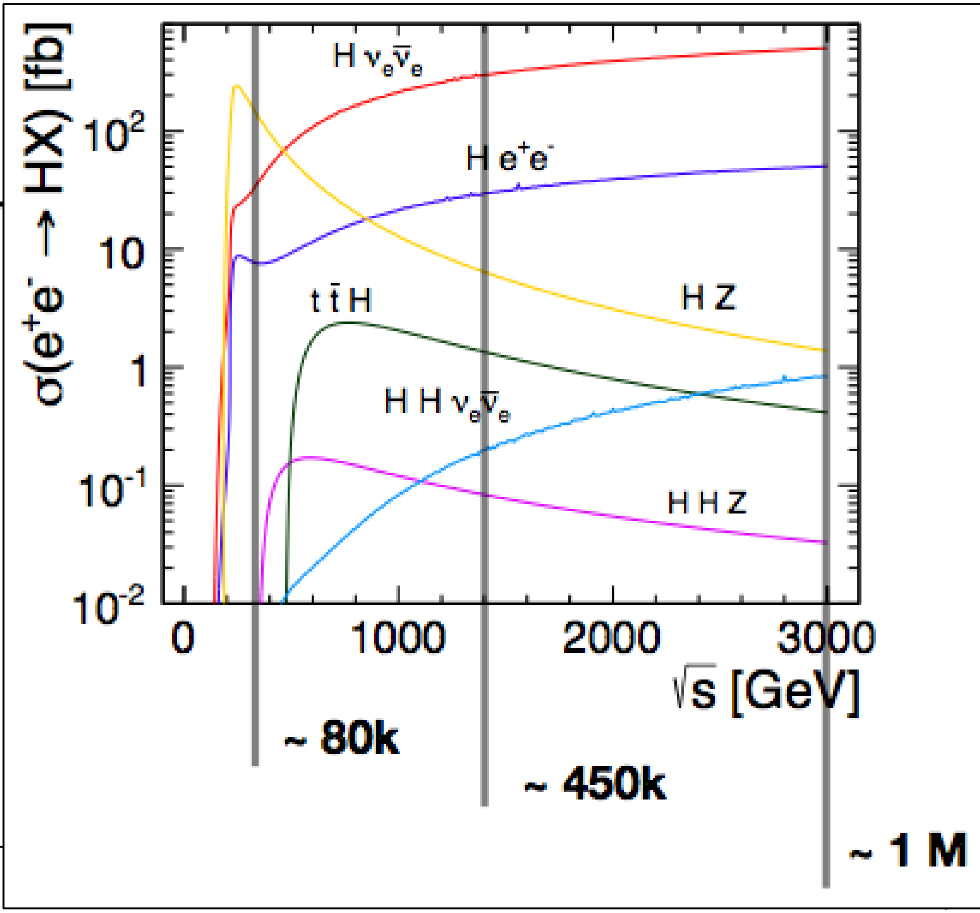


MCHM5 (f = 1.5 TeV)

CLIC

	350 GeV	1.4 TeV	3 TeV
$\mathcal{L}_{\text{int}}$	500 fb^{-1}	1.5 ab^{-1}	2 ab^{-1}
# ZH events	68 000	20 000	11 000
# $H\nu_e\bar{\nu}_e$ events	17 000	370 000	830 000
# He^+e^- events	3 700	37 000	84 000

	1.4 TeV	3 TeV
$\mathcal{L}_{\text{int}}$	1.5 ab^{-1}	2 ab^{-1}
# $t\bar{t}H$ events	2400	1400
# $HH\nu_e\bar{\nu}_e$ events	225	1 200



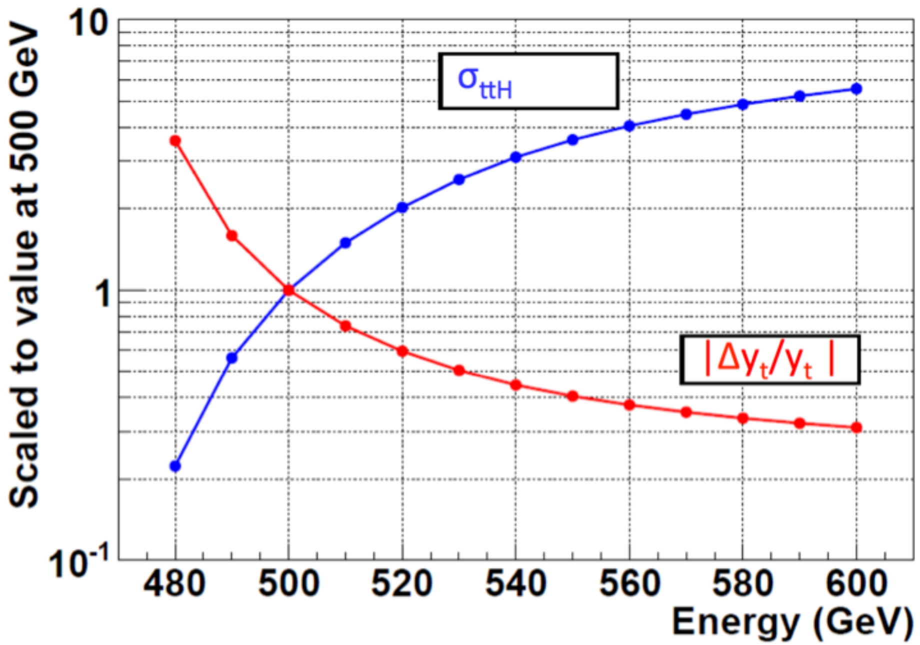
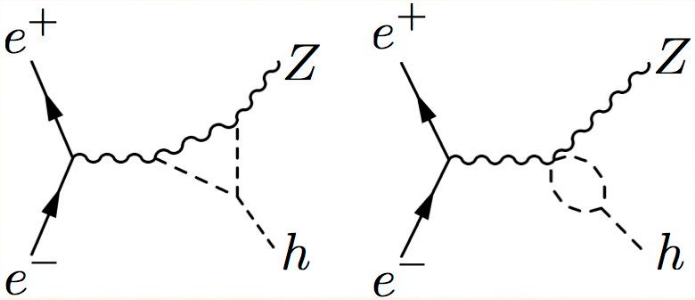
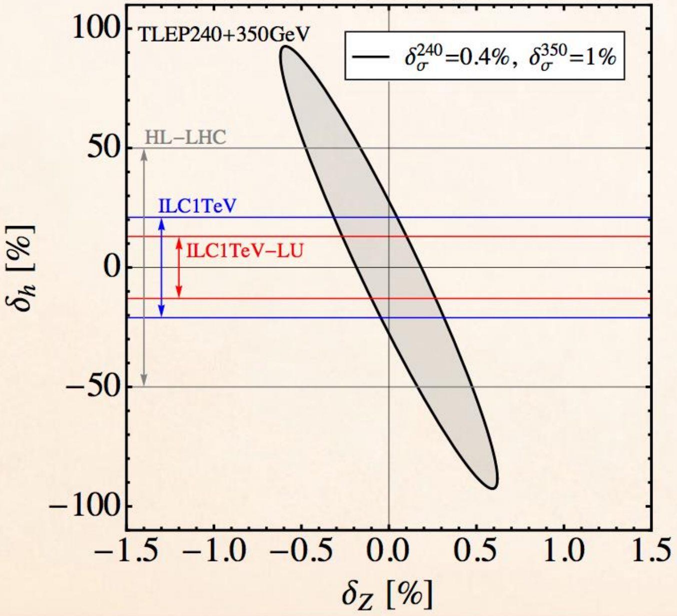


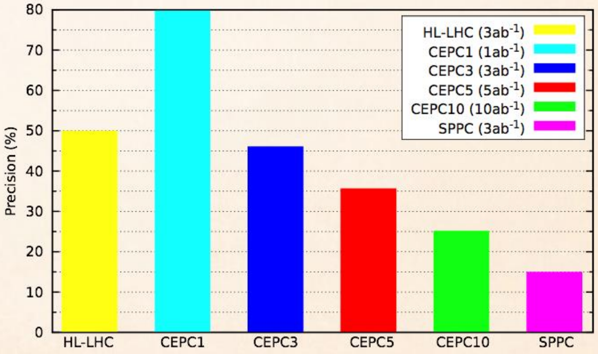
Figure 20: Relative cross section and top Yukawa coupling precision versus centre-of-mass energy, extrapolated based on scaling of signal and main background cross-sections.

Higgs self-coupling: indirectly inferred from limit on κ_Z with some assumptions McCullough 2014



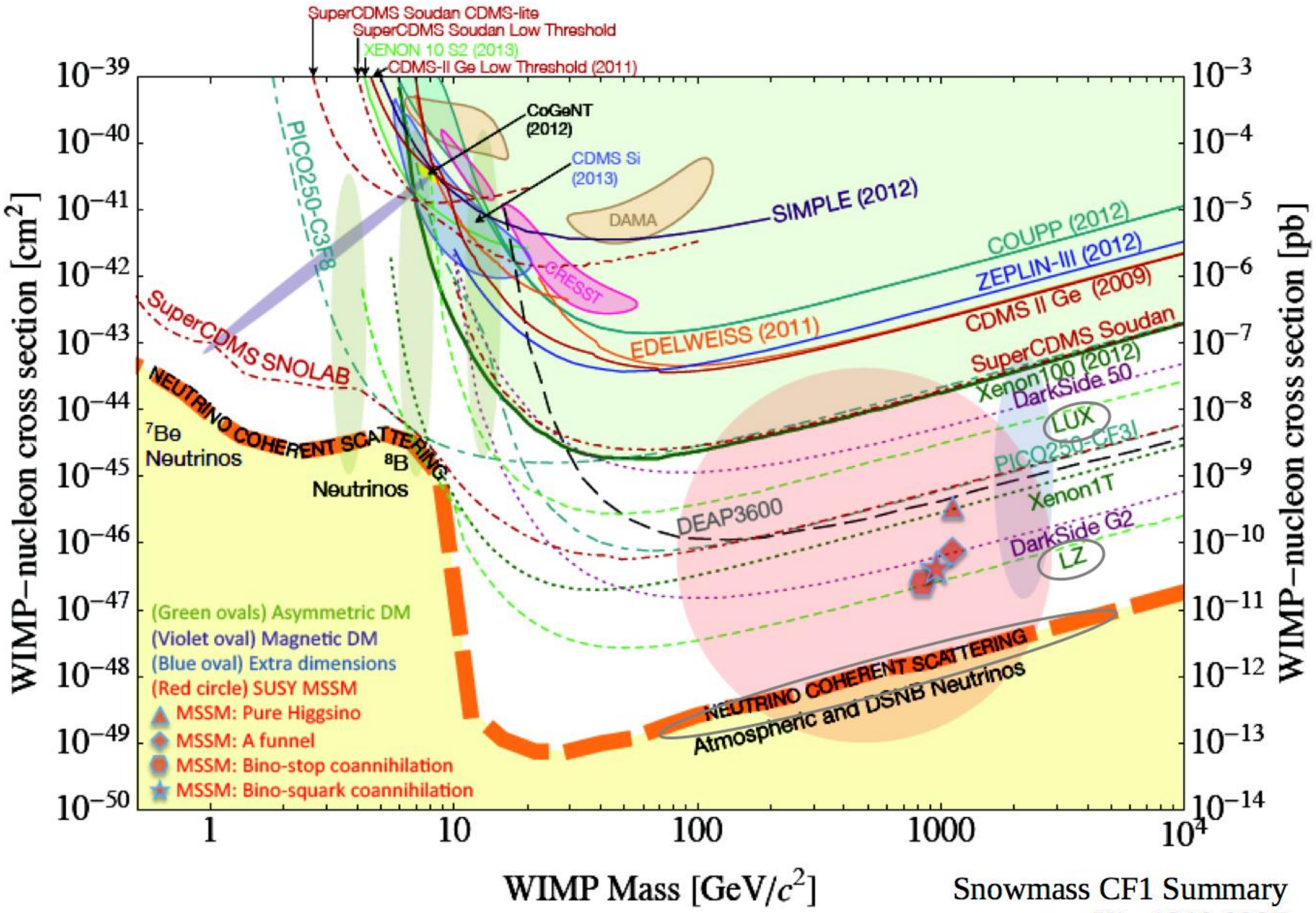
$$\Delta\sigma_{Zh} = \frac{\sigma_{Zh}}{\sigma_{Zh}^{\mathrm{SM}}} - 1 = 2\Delta_{\kappa_Z} + 0.014\Delta_{\lambda_{hhh}}.$$



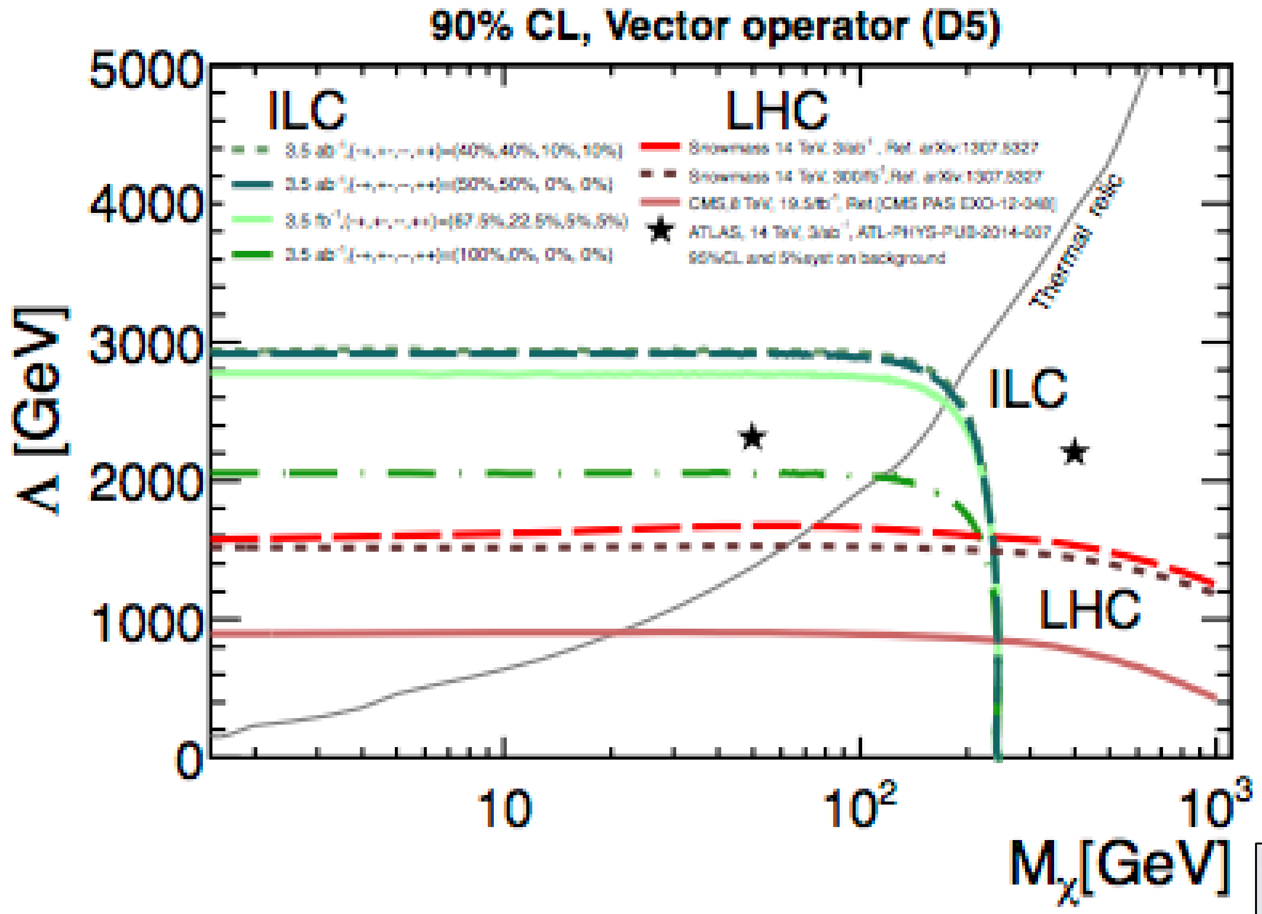


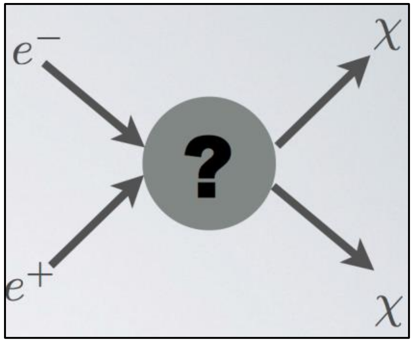
CEPC/SppC preCDR

Dark Matter Direct Detection Experiments: Limits and Future Sensitivity



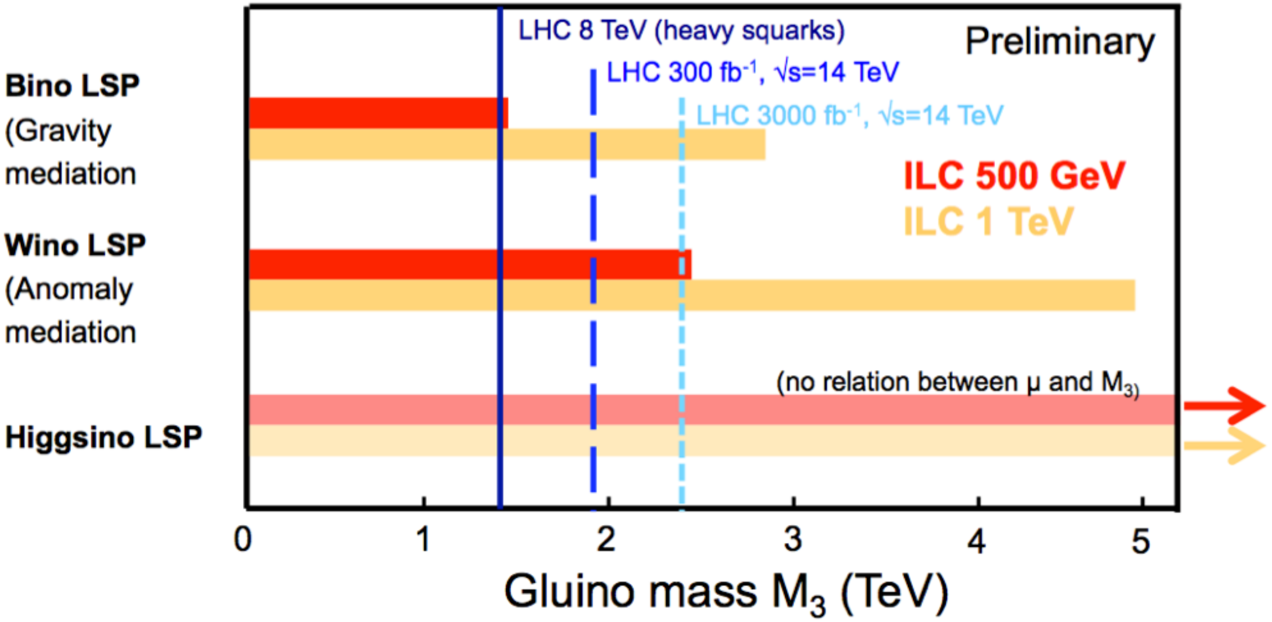
Snowmass CF1 Summary
arXiv:1310.8327

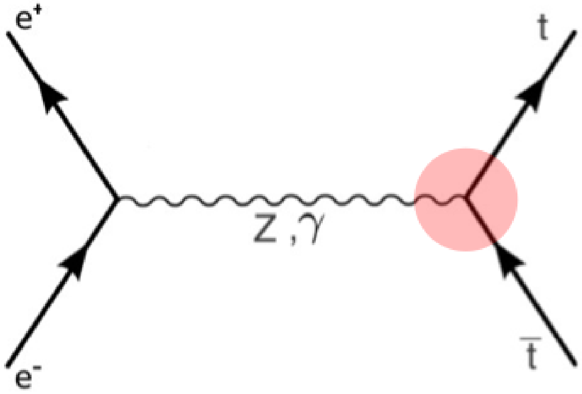




Contact interaction type with scale Λ (EFT).
From ISR (gluon for LHC, γ for ILC)

Complementarity/synergies



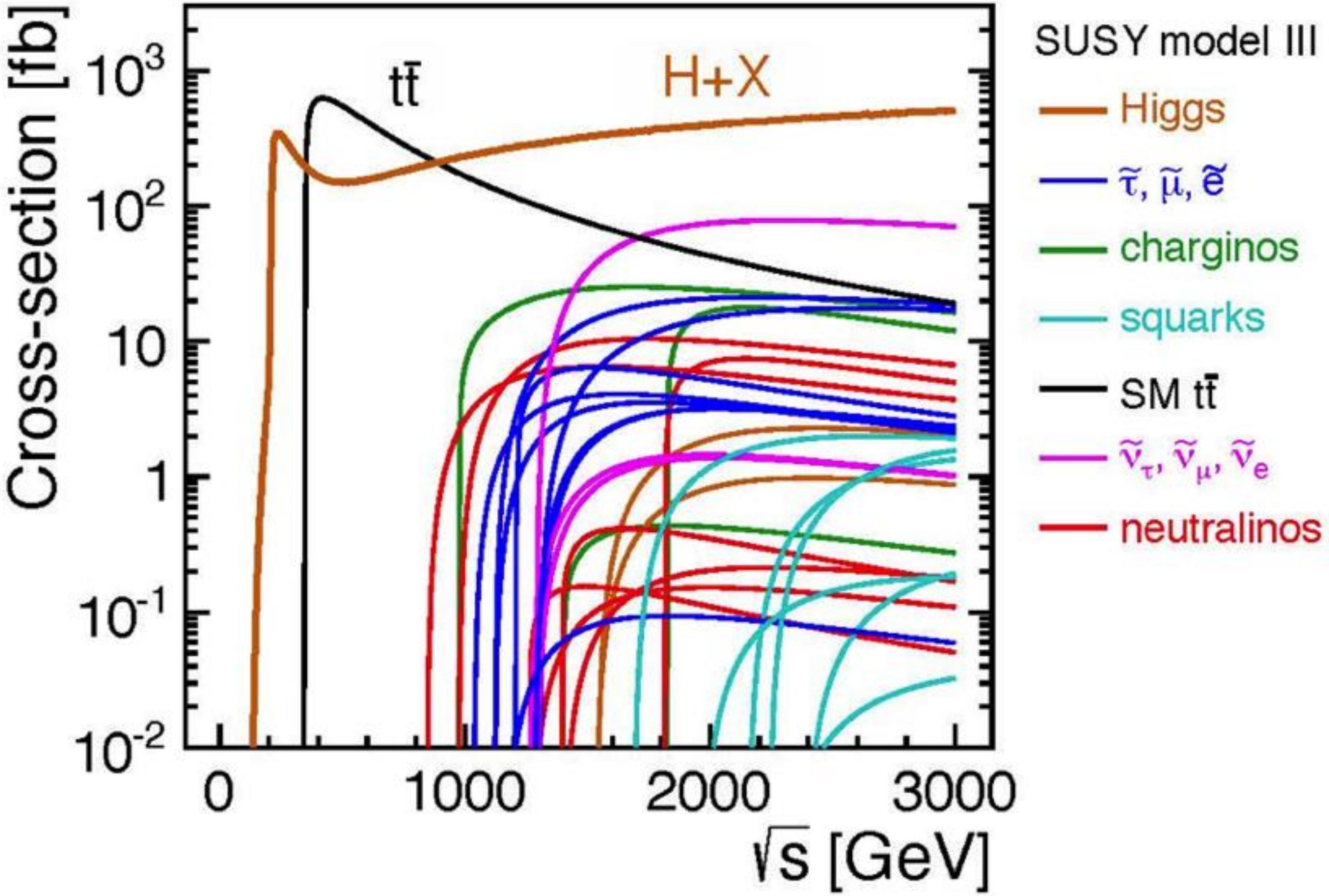


Form factors:

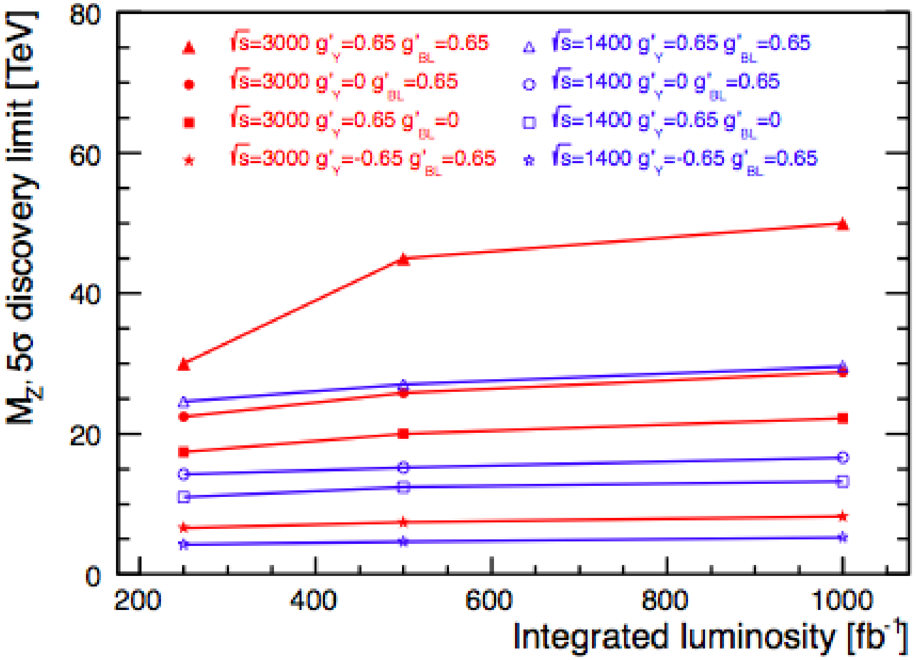
$$\Gamma^{\mu}_{t\bar{t}} = ie\left[\gamma^{\mu}\left(\tilde{F}^{\gamma,Z}_{1V} + \tilde{F}^{\gamma,Z}_{1A}\gamma^{5}\right) + \frac{(p_{t} - p_{\bar{t}})^{\mu}}{2m_{t}}\left(\tilde{F}^{\gamma,Z}_{2V} + \tilde{F}^{\gamma,Z}_{2A}\gamma^{5}\right)\right]$$

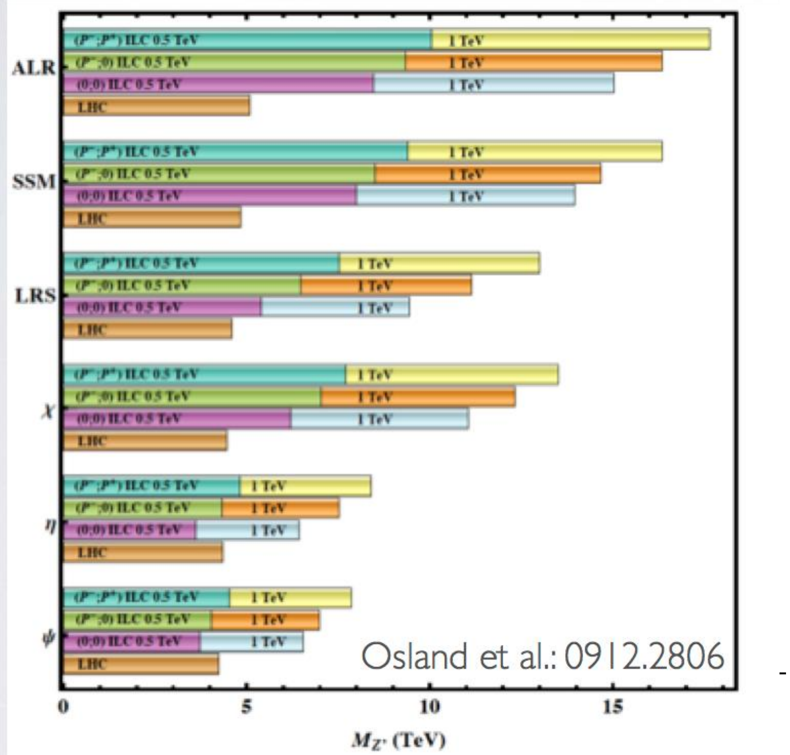
or **Effective higher dimensional operators:**

$$\mathcal{L}_{\mathrm{eff}} = \ldots + \frac{C_i}{\Lambda^2} O_i + \ldots$$



Scan over all accessible states





Osland et al.: 0912.2806

Among the main targets for the coming months: identify experimental challenges, in particular those requiring new concepts and detector R&D

The two main goals

- Higgs boson measurements beyond HL-LHC (and any e^+e^- collider)
- exploration of energy frontier

are quite different in terms of machine and detector requirements

Exploration of E-frontier → look for heavy objects up to m ~30-50 TeV, including high-mass $V_L V_L$ scattering:

- requires as much integrated luminosity as possible (cross-section goes like 1/s)

→ may require operating at higher pile-up than HL-LHC (~140 events/x-ing)

- events are mainly central → "ATLAS/CMS-like" geometry is ok
- main experimental challenges: good muon momentum resolution up to ~ 50 TeV; size of detector to contain up to ~ 50 TeV showers; forward jet tagging; pile-up

Precise measurements of Higgs boson:

- would benefit from moderate pile-up
- light object → production becomes flatter in rapidity with increasing $\sqrt{s}$
- main experimental challenges: larger acceptance for precision physics than ATLAS/CMS → tracking/B-field and good EM granularity down to $|\eta|$~4-5; forward jet tagging; pile-up

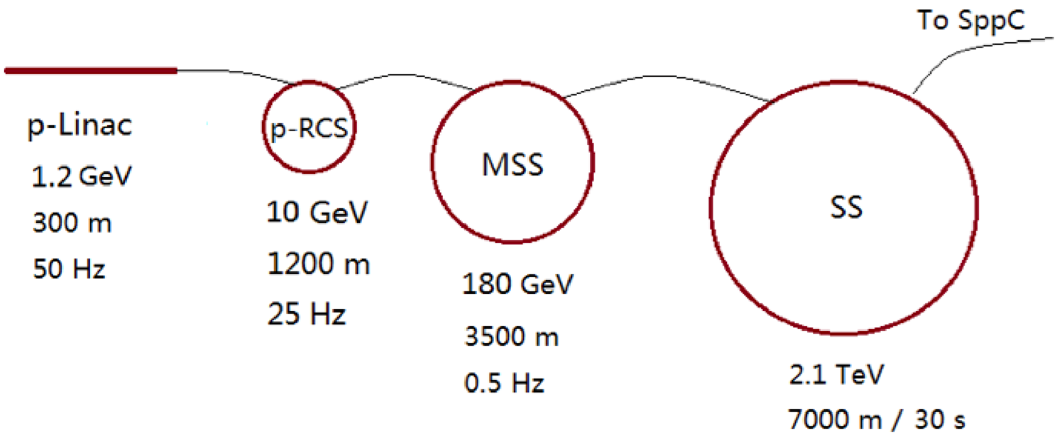
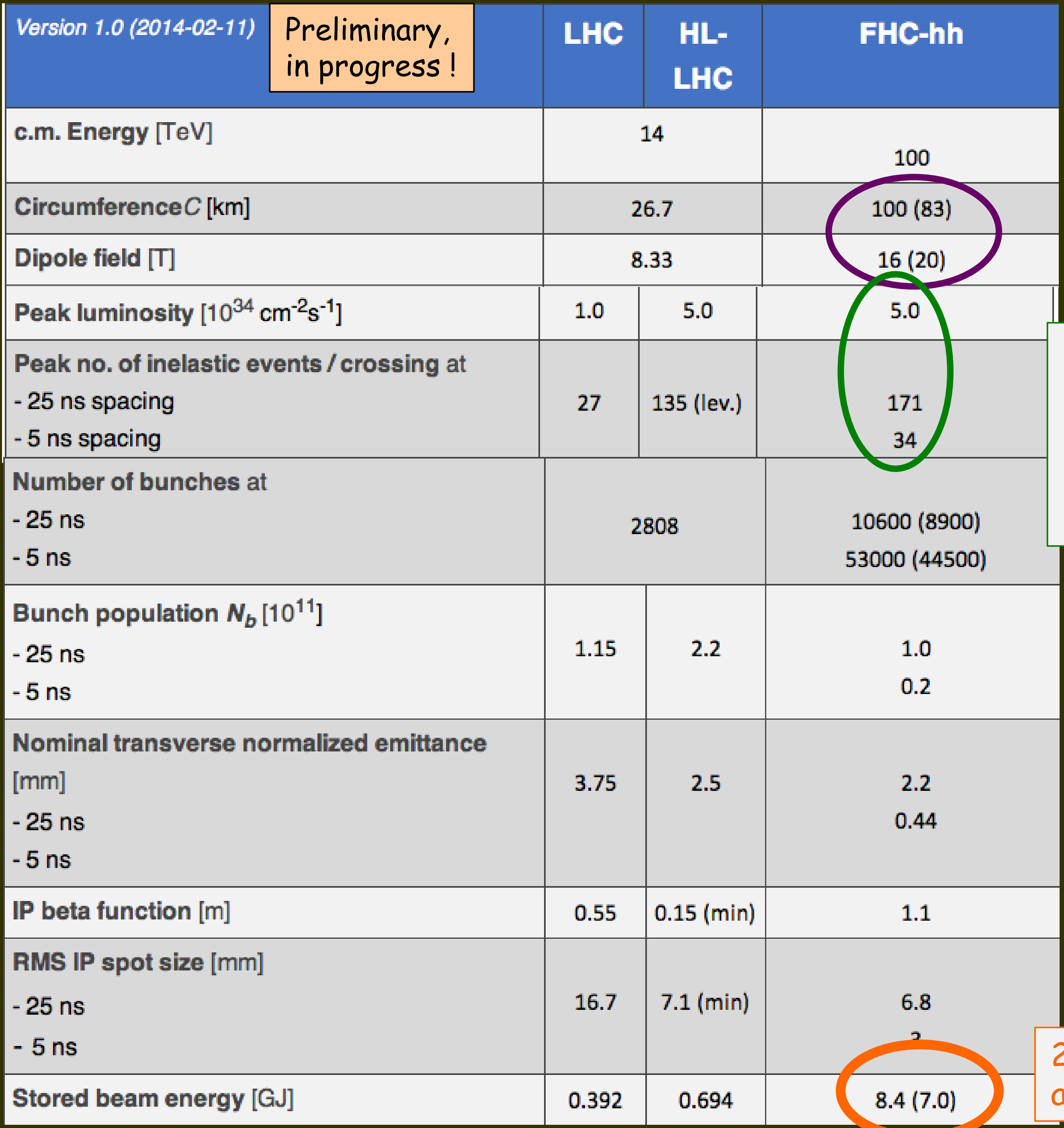


Figure 7.4.1: Injector chain for the SPPC

Parameters of a ~ 100 TeV pp collider



Preliminary, in progress !

Version 1.0 (2014-02-11)	**LHC**	**HL-LHC**	**FHC-hh**
c.m. Energy [TeV]	14		100
Circumference C [km]	26.7		100 (83)
Dipole field [T]	8.33		16 (20)
Peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	5.0	5.0
Peak no. of inelastic events / crossing at - 25 ns spacing - 5 ns spacing	 27	 135 (lev.)	 171 34
Number of bunches at - 25 ns - 5 ns	2808		 10600 (8900) 53000 (44500)
Bunch population N_b [10^{11}] - 25 ns - 5 ns	 1.15	 2.2	 1.0 0.2
Nominal transverse normalized emittance [mm] - 25 ns - 5 ns	 3.75	 2.5	 2.2 0.44
IP beta function [m]	0.55	0.15 (min)	1.1
RMS IP spot size [mm] - 25 ns - 5 ns	 16.7	 7.1 (min)	 6.8 3
Stored beam energy [GJ]	0.392	0.694	8.4 (7.0)

Nb_3Sn ok up to 16 T;
20 T needs HTS

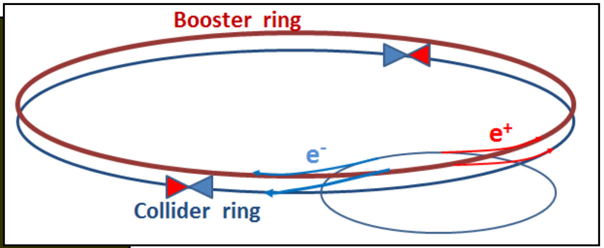
Largest integrated luminosity needed for heavy physics
→ L=10^{35} may be reached
→ bunch-spacing 5 ns to mitigate pile-up and e-cloud

25 x LHC ! 1 Airbus 380 at full speed

	CepC	FCC-ee		
Ring (km)	54	100		
$\sqrt{s}$ (GeV)	240	240	350	90
E loss per turn (GeV)	3	1.7	7.5	0.03
Total RF voltage (GV)	6.9	5.5	11	2.5
Beam current (mA)	16.6	30	6.6	1450
N. of bunches	50 (one ring!)	1360	98	16700
L (10^{34} cm^{-2} s^{-1})/IP	1.8	6	1.8	28
$e^{\pm}$/bunch (10^{11})	3.7	0.46	1.4	1.8
σ_y/σ_x at IP (μm)	0.16/74	0.045/22	0.045/45	0.25/121
Interaction Points	2	4	4	4
Lumi lifetime (min)	60	21	15	213
SR power/beam	50 MW	50 MW		

Main challenges:

- ☐ FCC ring size
- ☐ Synchrotron radiation → 100 MW RF system with high efficiency
- ☐ Beam polarization for beam energy calibration at Z-pole and WW threshold to <100 keV to measure m_Z, m_W to < MeV at FCC-ee
- ☐ Machine design with large energy acceptance over full $\sqrt{s}$ span



Note: Super-KEKB is an excellent "prototype", with more stringent requirements on positron rate, momentum acceptance, lifetime, β_y^*