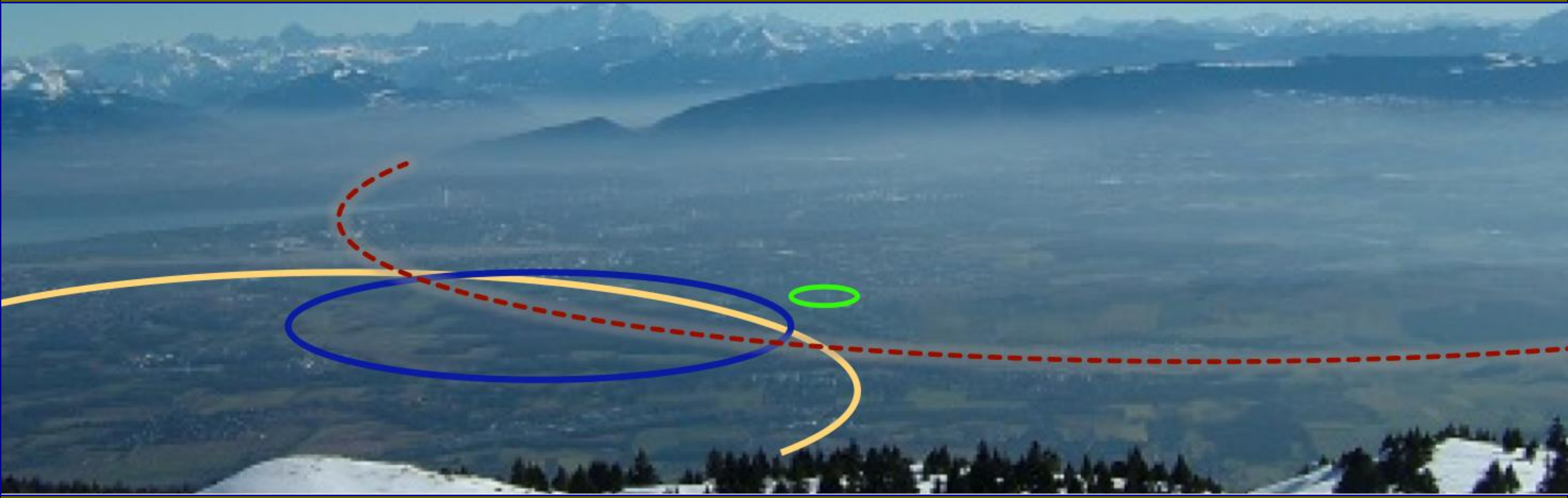
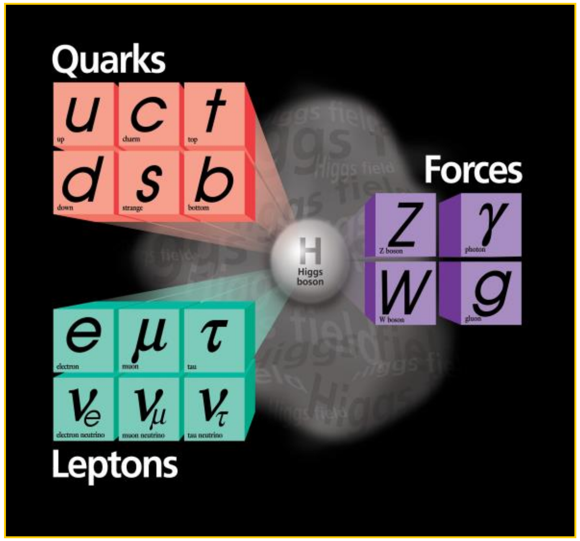
Physics prospects at the HL-LHC and beyond

- ☐ Main outstanding questions in particle physics
- ☐ Main options for future high-E/high-L colliders
- ☐ Physics potential of the HL-LHC and future colliders



Fabiola Gianotti (CERN)
5th Joint HiLumi LHC – LARP Annual Meeting, 29/10/2015

What did we accomplish so far in particle physics ?



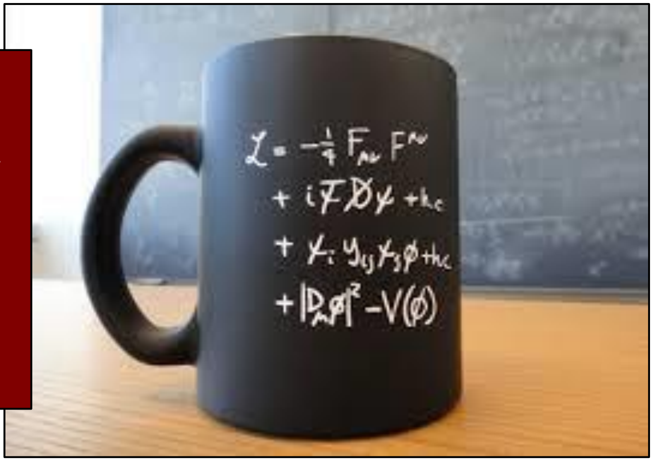
With the discovery of the Higgs boson,
we have completed the Standard Model
(> 50 years of theoretical and experimental efforts !)

Note: fermions (c, b, t, τ) discovered at accelerators in the US, bosons (g, W, Z, H) in Europe …

We have tested the Standard Model with very high precision (wealth of measurements since early '60s, in particular at accelerators)

→ it works BEAUTIFULLY (puzzling …)

→ no significant deviations observed (but difficult to accommodate non-zero neutrino masses)



However: SM is not a complete theory of particle physics, as several outstanding questions remain (raised also by precise experimental observations) that cannot be explained within the SM.

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?

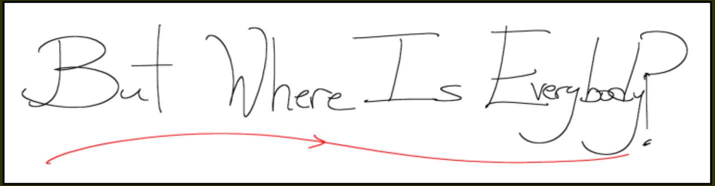
What is the origin of neutrino masses and oscillations ?

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

What is the cause of the Universe's accelerated expansion (today: dark energy ? primordial: inflation ?)

Why is Gravity so weak ?

However: NO direct evidence for new particles (yet…) from the LHC and other facilities



N. Arkani-Hamed

I.e.: 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 advances in accelerator and detector technologies): particle colliders, neutrino experiments (solar, short/long baseline, reactors, $0\nu\beta\beta$ 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
H, EWSB	x	x		x	
Neutrinos	x (ν_R)		x	x	x
Dark Matter	x			x	x
Flavour, CP, matter/antimatter	x	x	x	x	x
New particles, forces, symmetries	x	x		x	
Universe acceleration					x

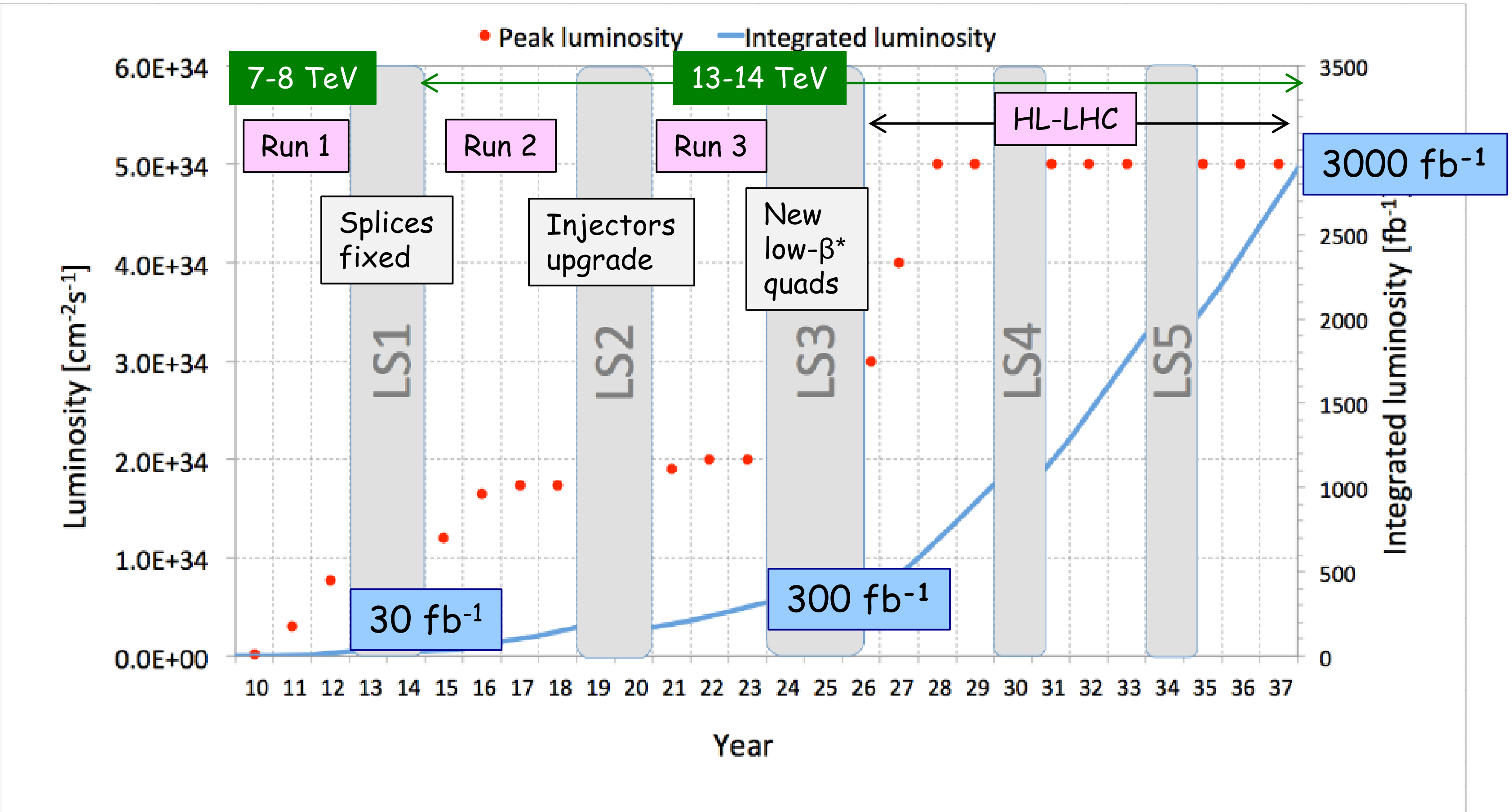
Combination of these complementary approaches is crucial to explore the largest range of E scales (directly and indirectly) and couplings, and properly interpret signs of new physics → hopefully build a coherent picture of the underlying theory.

Options for future high-E/high-L colliders

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

Disclaimer: due to time limitation, I will not discuss other opportunities (ep, γγ, ion colliders)

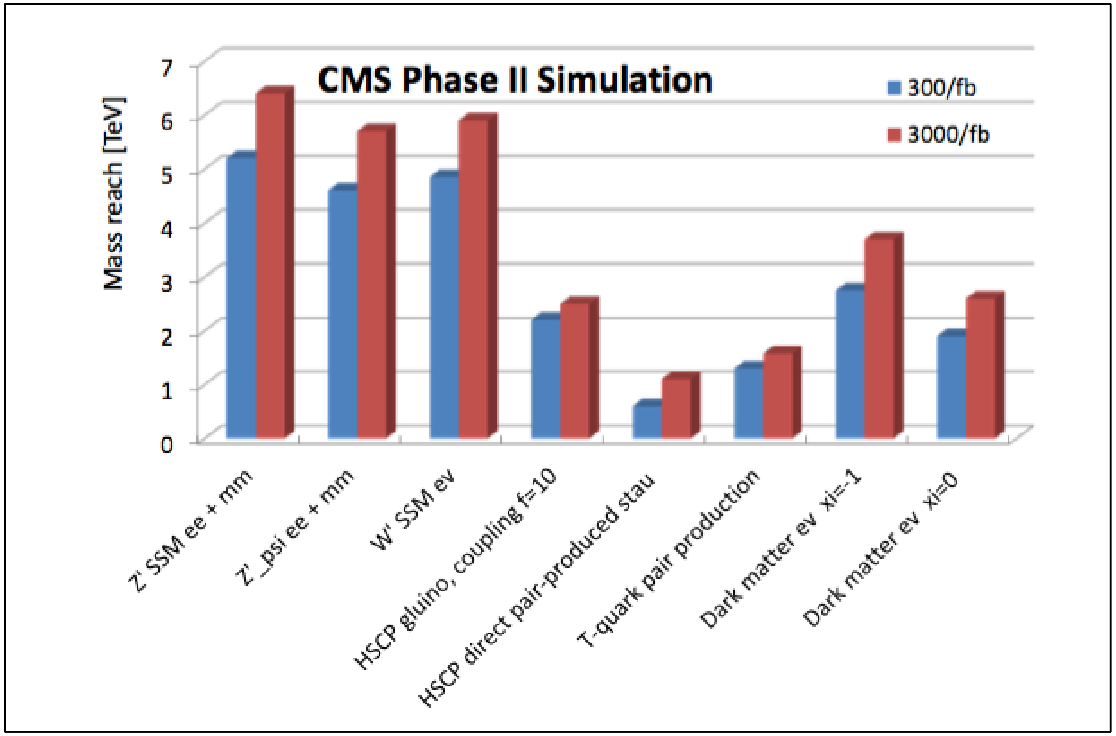
The future starts NOW : LHC and HL-LHC



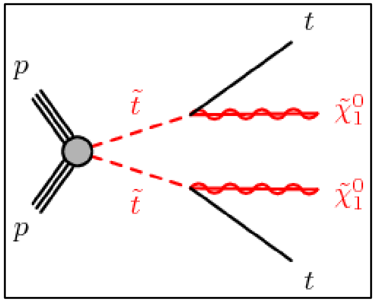
LHC is highest-E, highest-L operational collider → full exploitation (√s ~ 14 TeV, 3000/fb) is mandatory:

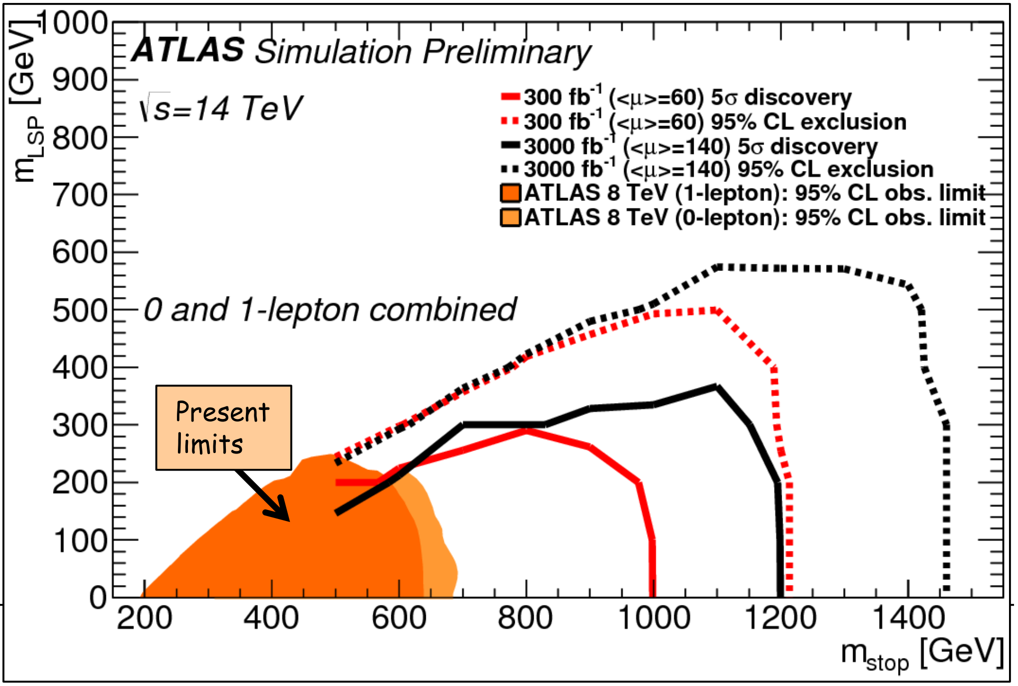
- ❑ If new physics discovered in Run 2-3:
  → first detailed exploration of new physics with well understood machine and experiments
- ❑ If no new physics in Run 2-3:
  → extend direct discovery potential by ~ 20-30% (up to m ~ 8 TeV)

In either case: measure H couplings to few percent (including 2nd generation: Hμμ)



Stop quark searches

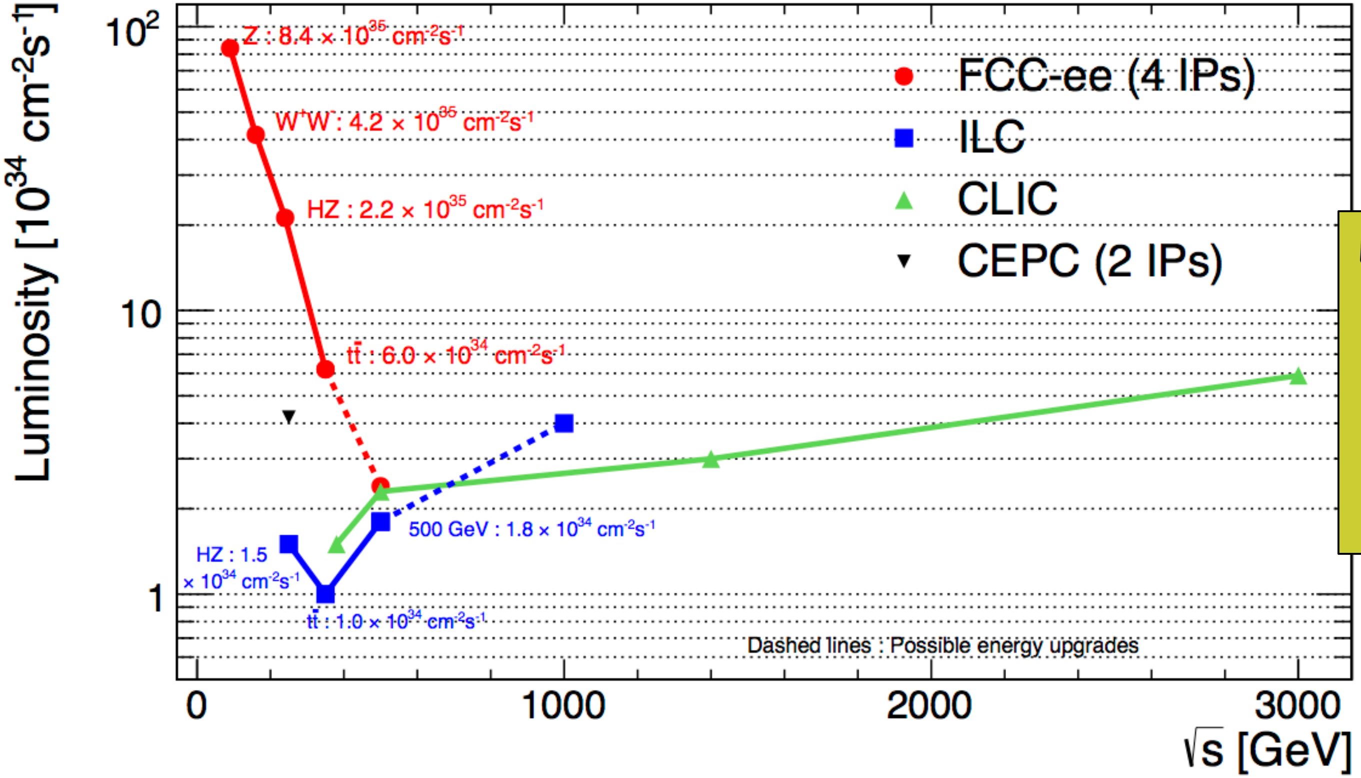


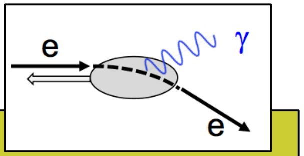


With 3000 fb^{-1} most interesting mass range for naturalness arguments will be covered

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	H precision physics (HZ)
~350	H (HZ, Hνν) and top (mass, couplings) precision physics
500-3000	ttH, HH (self-couplings), direct searches for new physics



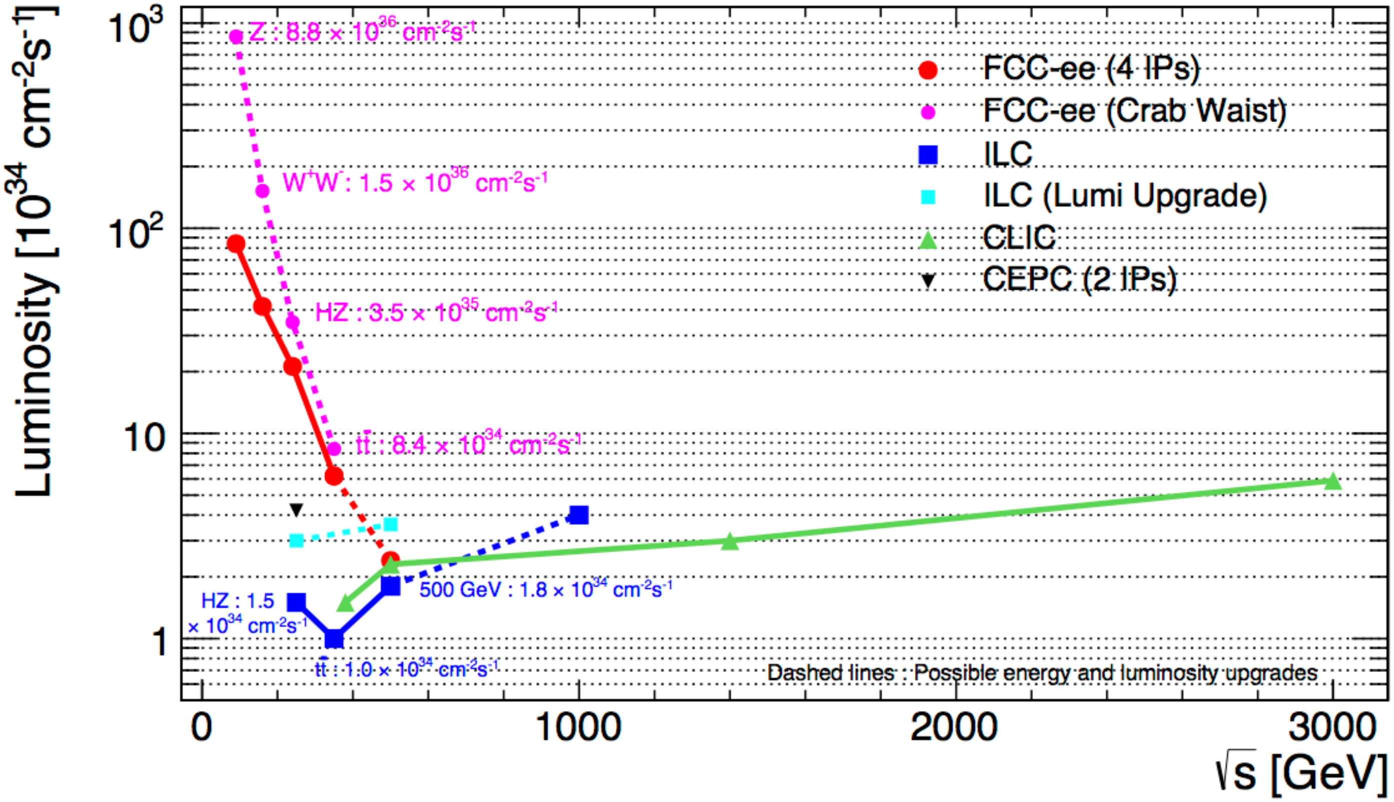


Linear:

- ☐ 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 → spare RF power used to accelerate more bunches). Note: need top-up injection ring to compensate fast L burn-off (lifetime ~ 30′)
- ☐ Several interaction regions possible
- ☐ Precise E-beam measurement from resonant depolarization



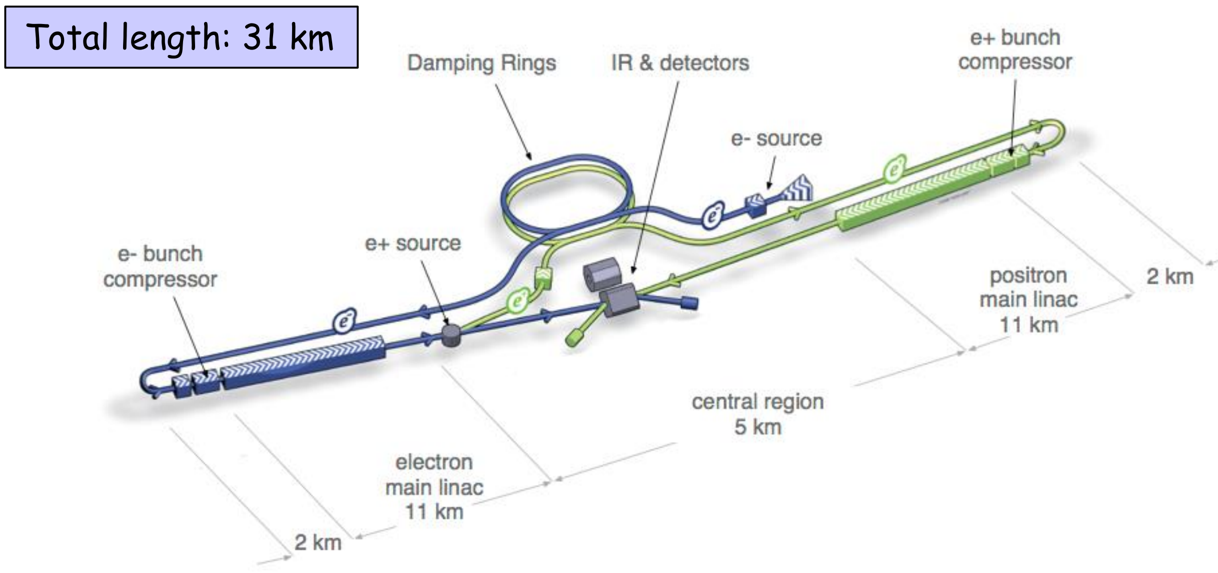
FCC-ee with crab waist scheme

ILC upgrade: 1312→ 2625 bunches per pulse

International Linear Collider (ILC)

Technical Design Report June 2013

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



- ☐ 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, several cavities reach 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)

Most recent operating scenarios (~ 20 year programme):

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

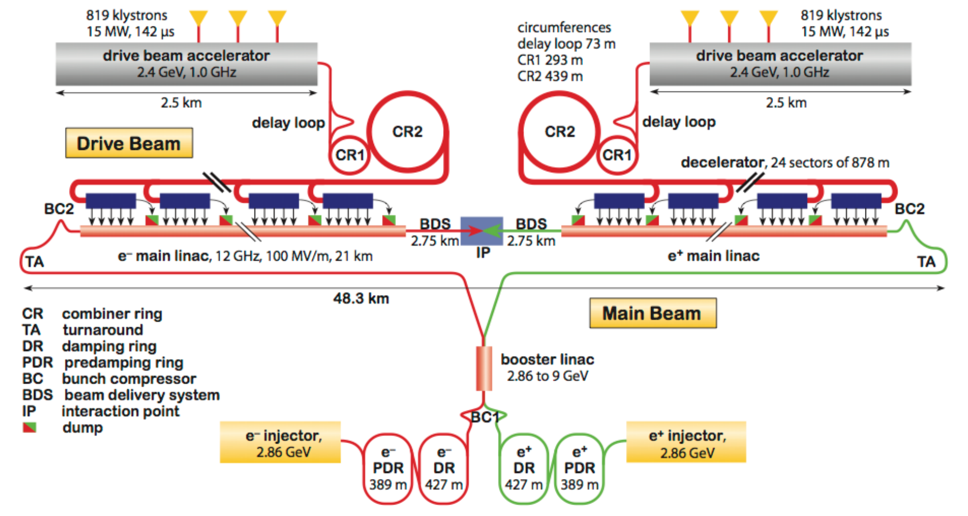
- ☐ Japan interested to host → decision based also on ongoing international discussions
- ☐ Construction could technically start as soon as decision taken, duration ~10 years
  → physics could start ~2030

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}cm^{-2}s^{-1}	1.5	5.9
Luminosity above 99% of √s	10^{34}cm^{-2}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

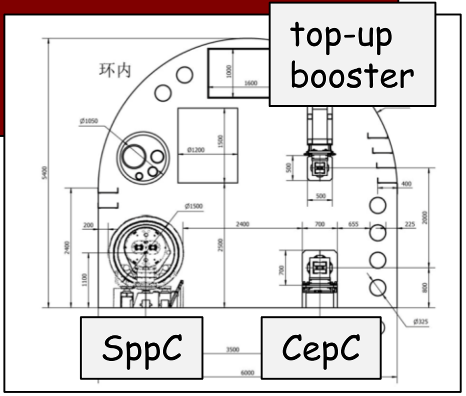
- ❑ Most recent operating scenario: start at √s=380 GeV for H and top physics
- ❑ If decision to proceed in ~ 2019 → construction could technically start ~2025, duration ~6 years for √s ~ 380 GeV (11 km Linac) → physics could start before 2035

Circular colliders: the Chinese CepC, SppC

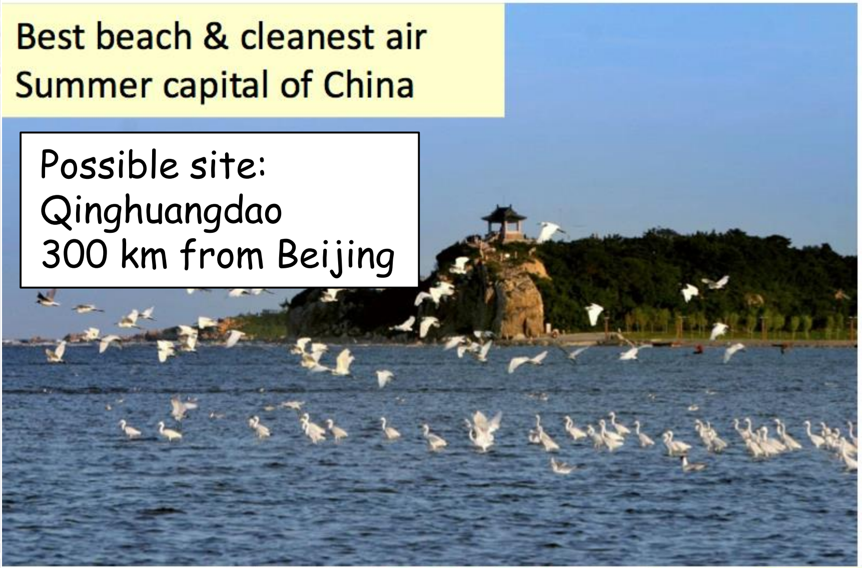
http://cepc.ihep.ac.cn/preCDR/volume.html

Baseline: 54 km ring
- ❑ CepC: e^+e^- $\sqrt{s}$=240 GeV; L=2×10^{34}; 2 IP; data-taking 2028-2035 ?
- ❑ SppC: pp , $\sqrt{s}$ = 70 TeV (20T magnets); L=1.2×10^{35}; 2 IP; data-taking 2052-2055 ?

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 March 2015: 160 M$ R&D funds request to Chinese government (5-year plan 2016-2020)



Best beach & cleanest air
Summer capital of China

Possible site:
Qinghuangdao
300 km from Beijing

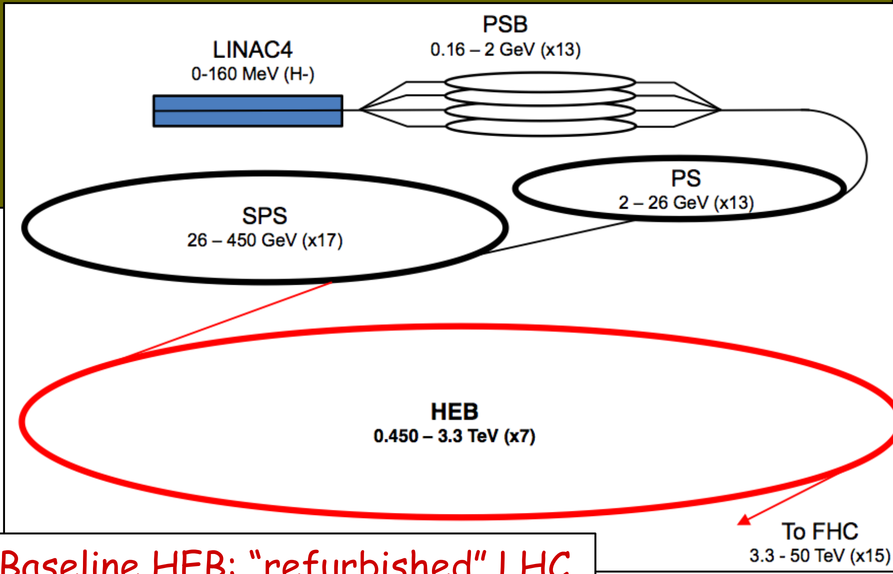
Circular colliders: the CERN FCC project

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

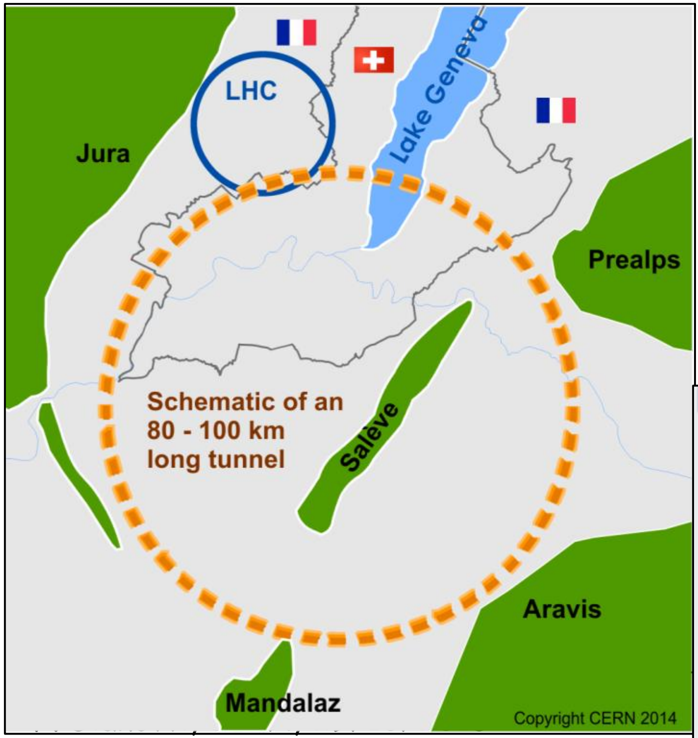
- ☐ goal: pp, $\sqrt{s}$ = 100 TeV (FCC-hh), $L\sim2\times10^{35}$; 4 IP
- ☐ possible intermediate step: e^+e^-, $\sqrt{s}$=90-350 GeV (FCC-ee), $L=2\times10^{36}-2\times10^{34}$, 2-4 IP
- ☐ option: ep, $\sqrt{s}$= 3.5 TeV (FCC-eh), $L\sim10^{34}$

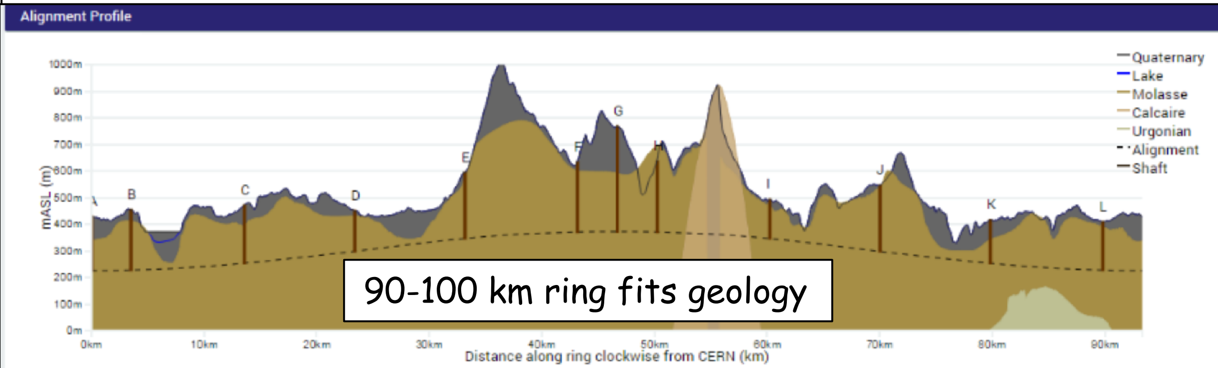
Goal of the study: CDR in ~2018

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)



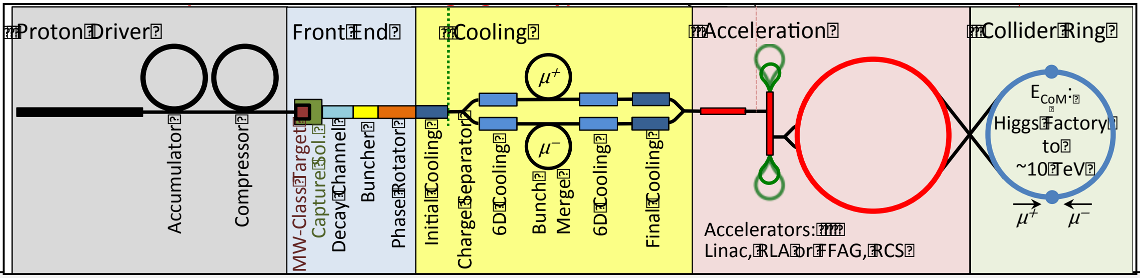
Baseline HEB: "refurbished" LHC





90-100 km ring fits geology

Muon colliders



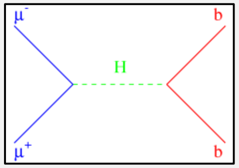
Synergies with neutrino factories

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 $\sqrt{s}$ = 125 GeV, 4.5 km for $\sqrt{s}$ = 3 TeV

→ negligible beamstrahlung → much smaller E spread

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



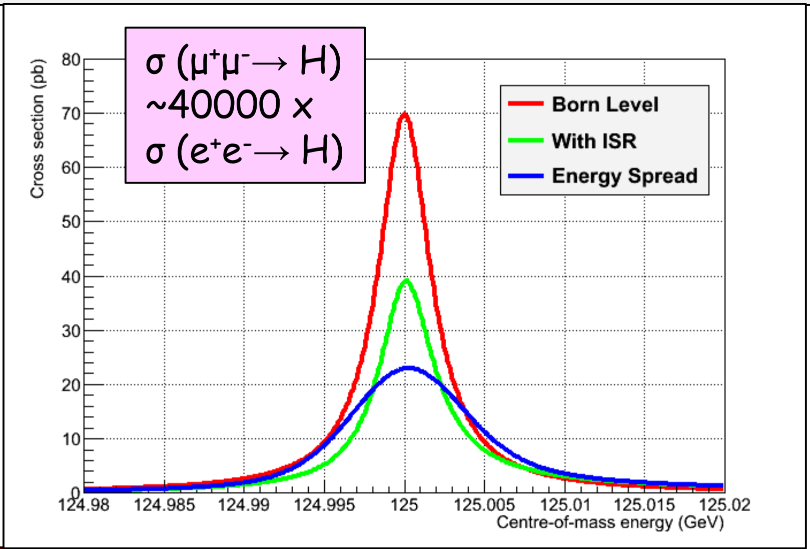
Main challenge: produce high-intensity, low E-spread beams:

☐ $m_\mu \sim 200\ m_e$ → SR damping does not work → novel cooling methods (dE/dx based) needed to reach beam energy spread of $\sim 3\times10^{-5}$ (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 $\sim 3\times10^{-5}$ would allow Γ_H measurement from line shape to 5% (0.2 MeV) → resolve (possible) resonances

However, with currently projected L ($\sim10^{32}$): ~ 20000 H/year → not competitive with e^+e^- colliders for coupling measurements (except Hμμ ~ 1%)



$\sigma(\mu^+\mu^- \to H) \sim 40000 \times \sigma(e^+e^- \to H)$

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

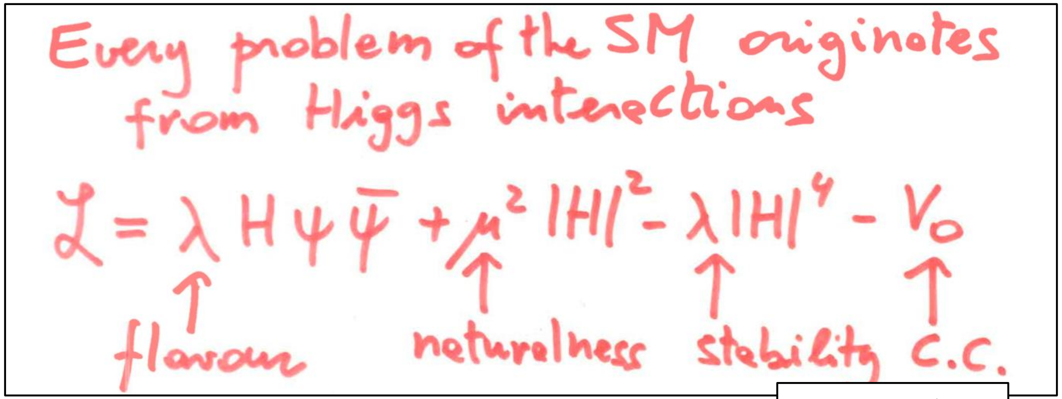
Physics motivations and potential of HL-LHC and future colliders

- ☐ H boson measurements
- ☐ Direct and indirect sesrches or new physics

The H 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

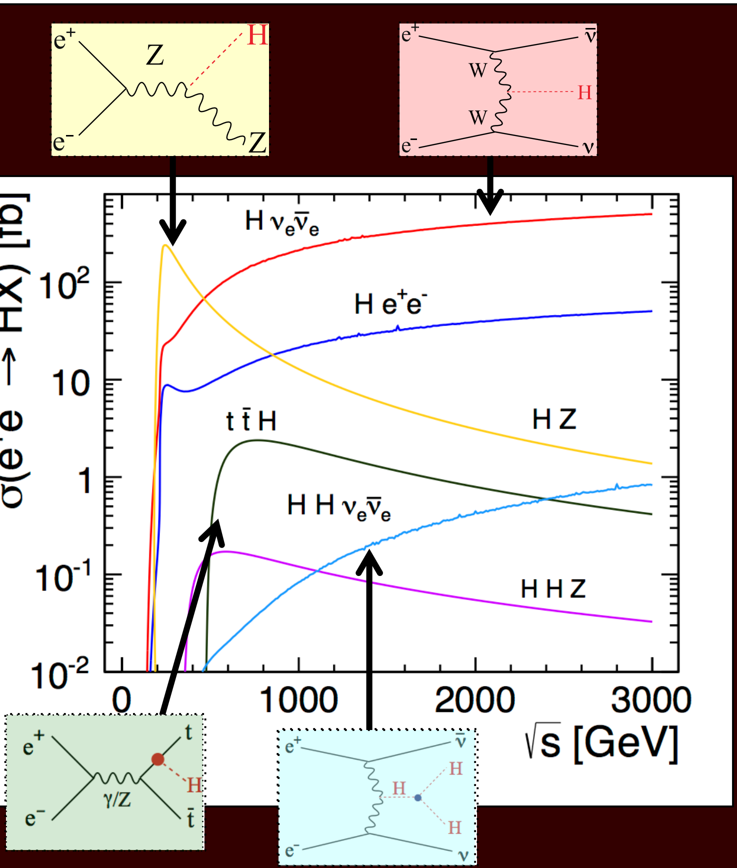
$$\mathcal{L} = \underset{\overset{\uparrow}{\text{flavour}}}{\lambda} H \psi \bar{\psi} + \underset{\overset{\uparrow}{\text{naturalness}}}{\mu^2} |H|^2 - \underset{\overset{\uparrow}{\text{stability}}}{\lambda} |H|^4 - \underset{\overset{\uparrow}{\text{C.C.}}}{V_0}$$

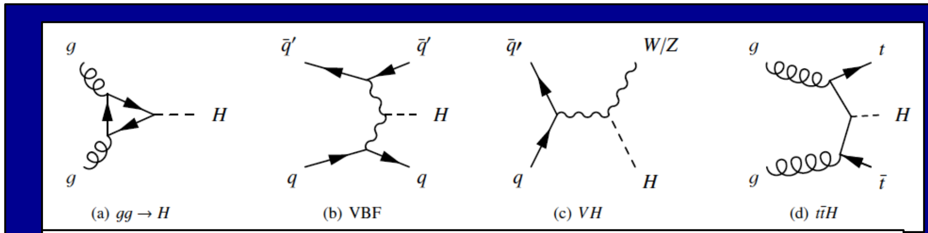
G.F. Giudice

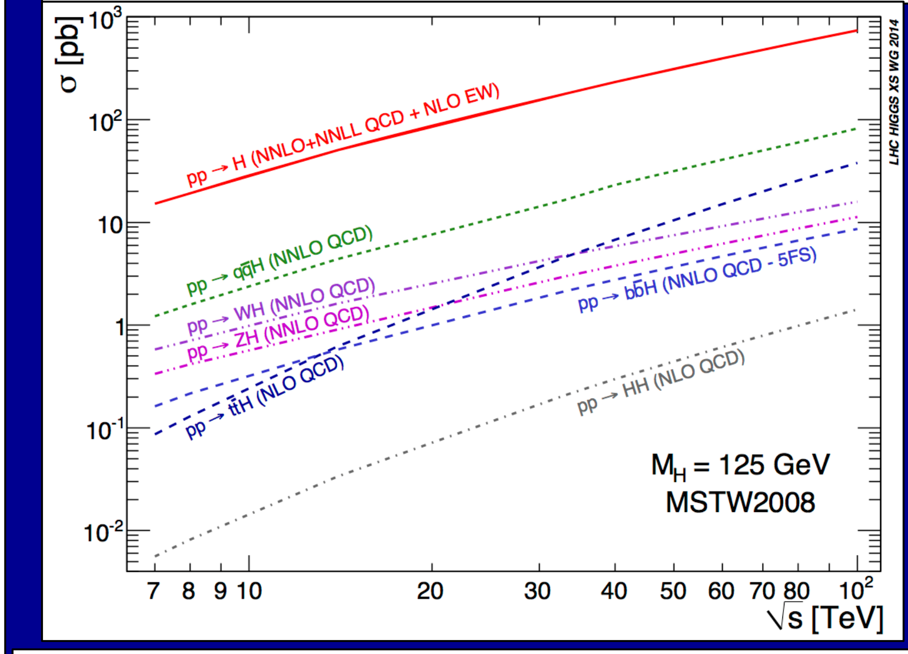
- Precision measurements of couplings (as many generations as possible, loops, …)
- Forbidden and rare decays (e.g. H→ τμ) → flavour structure and source of fermion masses
- H potential (HH production, self-couplings):
  - → EWSB mechanism (strong dynamics ?)
  - → EW phase transition → baryogenesis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

e^+e^- colliders

pp colliders



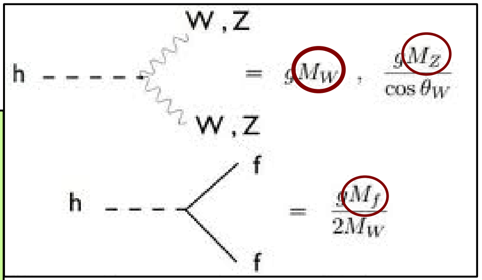




- Low backgrounds → all decay modes (hadronic, invisible, exotic) accessible
- Model-indep. coupling measurements: σ(HZ) and Γ_H from data (ZH → μμ/qq+X recoil, Hνν →bbνν)
- ttH and HH require √s ≥ 500 GeV

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

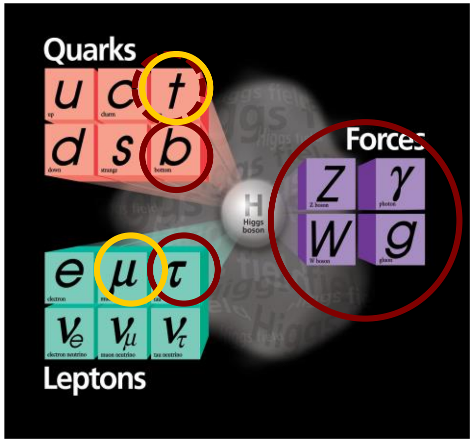
The Higgs boson as a door into new physics ?



Impact of New Physics on Higgs couplings to fermions and bosons

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

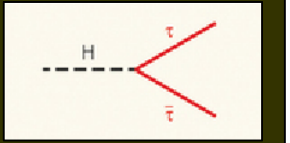
Scenarios exist with no new particles observable at LHC
→ New Physics would appear only through deviations to H couplings
→ 0.1-1% experimental precision needed for discovery

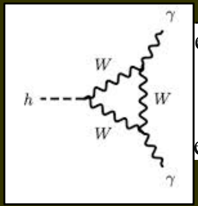


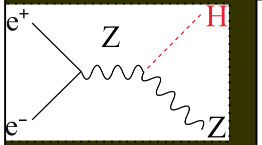
Higgs couplings from studies of:

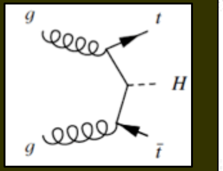
- ☐ decays (direct or via loops): H→ZZ, WW, γγ(loop), bb, ττ, cc, μμ
- ☐ production: WH, ZH, ttH, gg → H (loop)

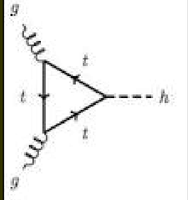
In addition: self couplings H→ HH

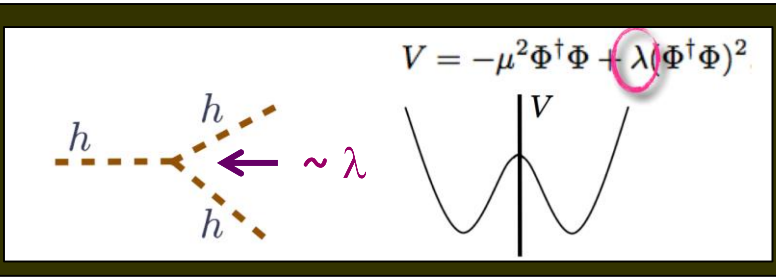












LHC Run-1: ~20% precision on couplings to bosons and 3rd generation fermion (ttH indirect)
LHC 14 TeV, 300 fb^{-1} (~2025): ~10% precision

HL-LHC (3000 fb^{-1}):

- ☐ 2-5% for most couplings
- ☐ first direct observation of couplings to 2nd family fermions (H→ μμ)
- ☐ Higgs self-coupling ?

Projected integrated luminosities for current operating scenarios

Integrated luminosities (ab^{-1})

$\sqrt{s}$	90	~240	350-380	500	1.4	3	70	100	Total $\int L\,dt$ at $\sqrt{s}$>240 GeV	# of years	# H events at production
	GeV				TeV						
FCC-ee	90	10	3						13	~7-15	2 M
CepC		5							5	~10	1 M
ILC		2	0.2	4					6.2	~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

(*) 4x10^{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

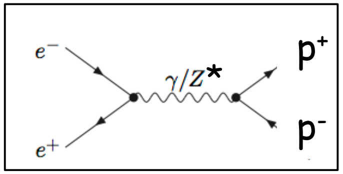
Note: different definitions of "year" across projects → assumed physics data-taking time varies over 0.5-1.6x10^7 s/year
Cfr: LHC 2012: 0.6x10^7 s of machine operation in physics with stable beams

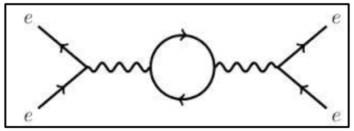
Couplings to W, Z, g, c, b, τ: best measurements: 0.2-0.8% at FCC-ee (luminosity)
Couplings to top: best measurements: few % ILC, CLIC, FCC-hh (heavy final state → energy)
Self-couplings HH: best measurements: ~10 % at CLIC, FCC-hh (heavy final state → energy)

Direct and indirect sensitivity to new (heavy) physics

e^+e^- colliders

- Direct: discovery potential for new particles coupling to Z/γ* up to m ~ √s/2 →
- Indirect: via precise measurements →
  → ILC/CLIC/FCC-ee can probe up to Λ_{NP}~O(100) TeV





HL-LHC (3000 fb^{-1}) :

- Direct: discovery potential up to m~8 TeV for single particles (~30% larger than 300 fb^{-1})
- Indirect sensitivity up to ~50 TeV (e.g. quark compositeness scale)

A 100 TeV pp collider is the instrument to explore the 10-50 TeV E-scale directly

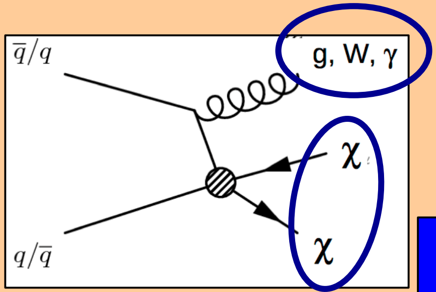
Examples:

Discovery potential for excited quarks q* (expected if quarks are composite): m ~ 50 TeV

Discovery potential for Z' (expected if additional forces exist): m ~ 30 TeV

Discovery potential for SUSY squarks and gluinos (pair produced): m ~ 15 TeV

SUSY has excellent candidate for dark matter (lightest neutralino χ^0): discovery reach up to ~ 4 TeV → cover most of region allowed by cosmology

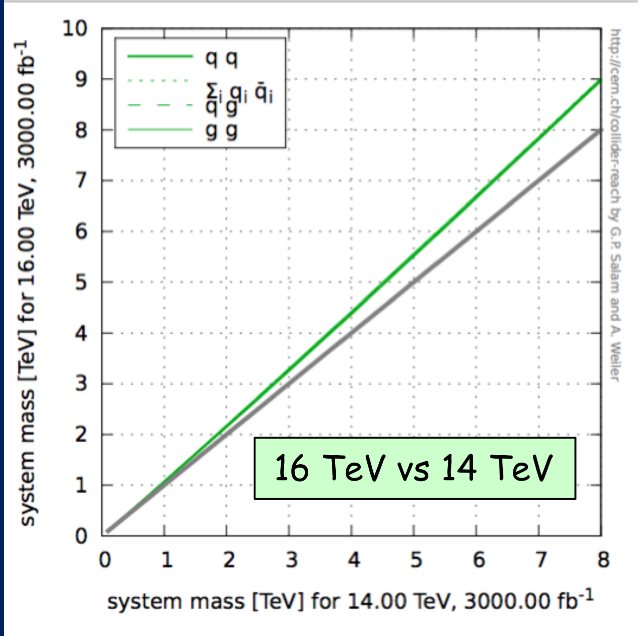


Mono-jet/γ/W from initial-state radiation provides trigger

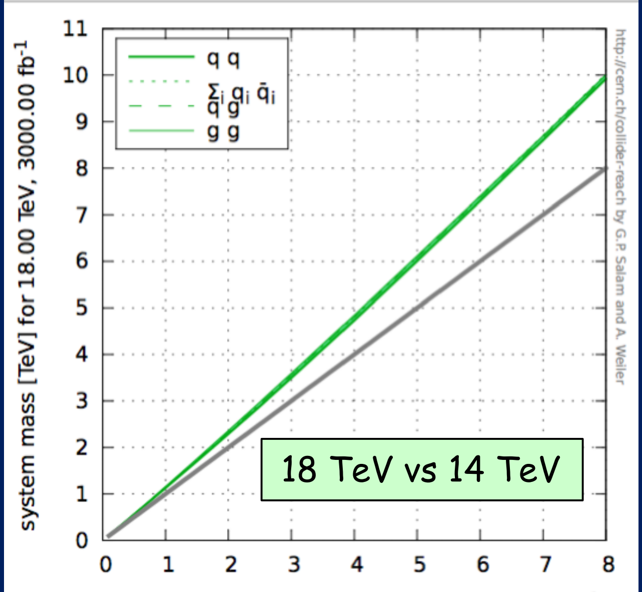
χ^0 are invisible → missing E

SUSY would also explain why Higgs mass is so light ("naturalness" problem)

Higher √s in the LHC tunnel ?



16 TeV vs 14 TeV



18 TeV vs 14 TeV

Various options, with increasing amount of HW changes, technical challenges, cost, and physics reach

1) Pushing present dipoles to ultimate performance (→ √s ~15.5 TeV ?)
2) 1) + replacing 30% of present dipoles with higher-field magnets:
   B=11 T → √s ~ 16.5 TeV
   B=14 T → √s ~ 18.5 TeV

☐ HE-LHC: filling existing 16-20 T magnets → √s = 26-33 TeV
  -- strongly motivated if new physics discovered at the LHC/HL-LHC
  -- demonstration of technology in view of future higher-E pp colliders
  -- would capitalize on existing tunnel and infrastructure
  -- magnets might be reused in a bigger tunnel ??

These options are being studied (physics case, technical feasibility, cost, time scale) in time for next round of European Strategy (~2018/2019)

Conclusions

The extraordinary success of the LHC is the result of the ingenuity, vision and perseverance of the worldwide HEP community (accelerator, experiments, computing, theory) and of more than 20 years of talented, dedicated work → the demonstrated strength of the community is an asset also for future, even more ambitious, projects.

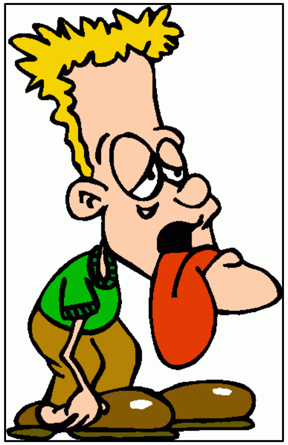
With the discovery of a Higgs boson, after > 50 years of superb theoretical and experimental work the SM is now complete. However major questions remain.

The full exploitation of the LHC, and more powerful future accelerators, will be needed to address them and to advance our knowledge of fundamental physics.
N.B. historically, accelerators have been our most powerful tool for exploration in particle physics

No doubt that future high-E colliders are extremely challenging projects

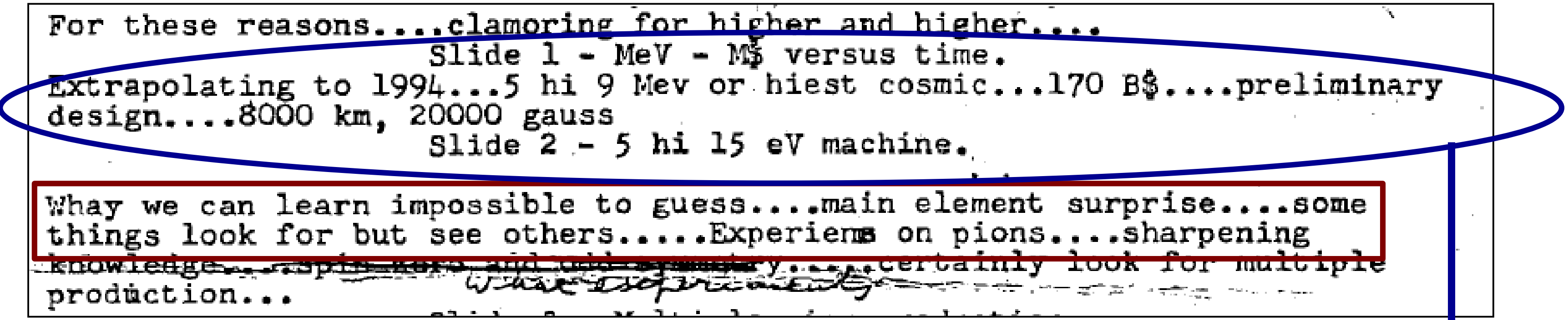
However: the correct approach, as scientists, is not to abandon our exploratory spirit, nor give in to financial and technical challenges. The correct approach is to use our creativity to develop the technologies needed to make future projects financially and technically affordable

THANK YOU !



EXTRAS

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



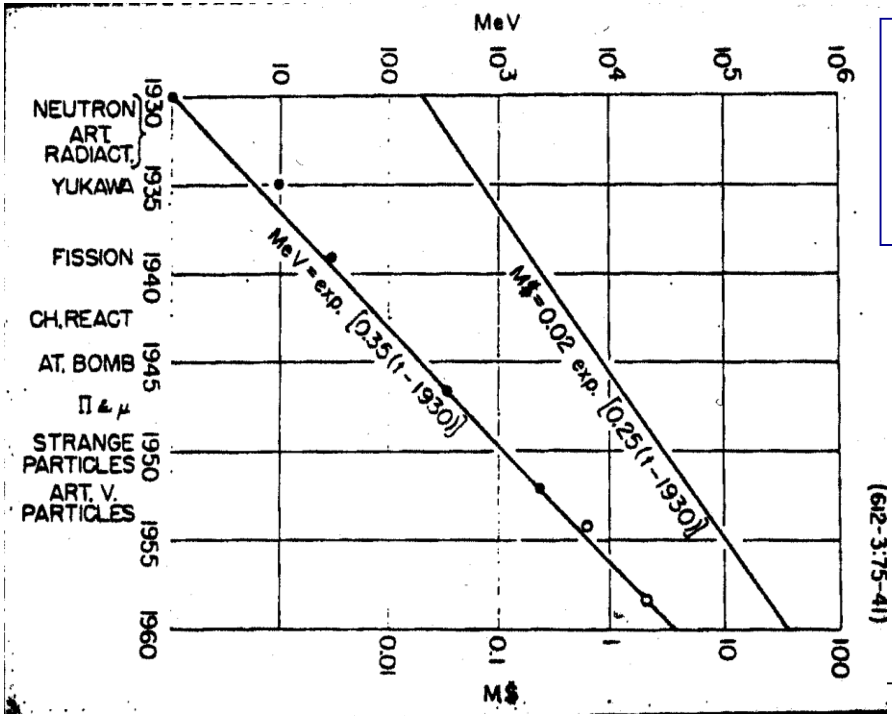
For these reasons....clamoring for higher and higher....

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 zero and odd symmetry~~.....certainly look for multiple production...



Fermi’s extrapolation to year 1994:
E_{beam} ~ 5×10^3 TeV, 2T magnets → R=8000 km
Note: fixed target accelerator → √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

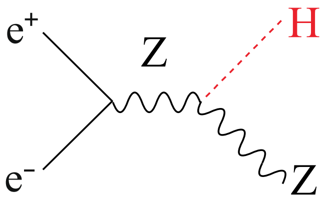
F. Gianotti, CERN, 29/10/2015

3 main complementary ways to search for (and study) new physics at accelerators

Direct

production of a given (new or known) particle

e.g.: Higgs production at future e^+e^- linear/circular colliders at $\sqrt{s}$ ~ 250 GeV through the HZ process
→ need high E and high L

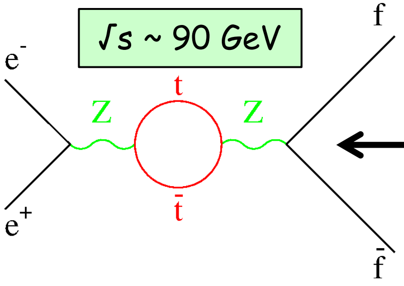


Indirect

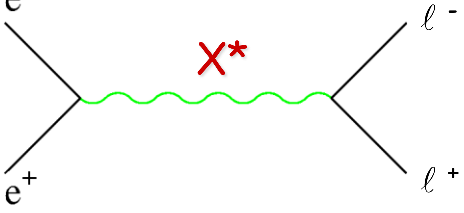
precise measurements of known processes

→ look for (tiny) deviations from SM expectation from quantum effects (loops, virtual particles)
→ sensitivities to E-scales Λ>> $\sqrt{s}$ → need high E and high L

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \frac{C_{\mathrm{NP}}}{\Lambda^2} O_{ij}$$



E.g. top mass predicted by LEP1 and SLC in 1993: m_{top} = 177 ± 10 GeV; first direct evidence at Tevatron in 1994: m_{top} = 174 ± 16 GeV

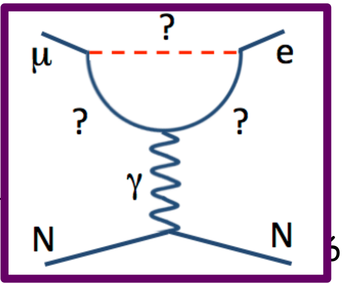


Rare processes

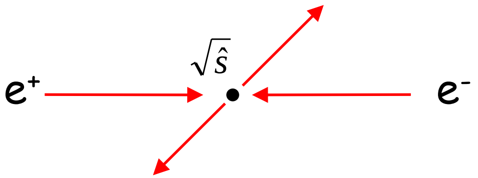
suppressed in SM → could be enhanced by New Physics

e.g. neutrino interactions, rare decay modes → need intense beams, ultra-sensitive (massive) detectors ("intensity frontier")

E.g. transitions between charged leptons of different families with Lepton-Flavour-Violation: μ→eγ (MEG@PSI), μ→e (COMET@JPARC, Mu2e@FNAL). Suppressed in SM, can occur if new physics
Note: flavour violation observed for ν (e.g. $\nu_\mu \rightarrow \nu_e$) and quarks (e.g. t→ Wb)



e^+e^- colliders vs pp colliders

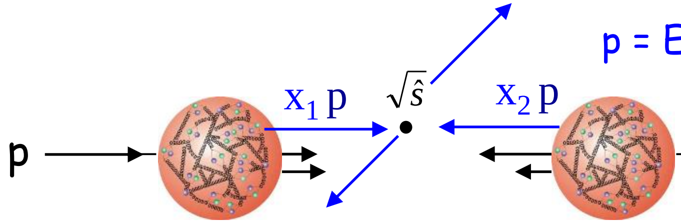


$E_{beam}=\sqrt{s}/2$

Energy of elementary interaction known

→ strong constraint for final-state reconstruction

$$\sqrt{\hat{s}} = E(e^-) + E(e^+) = \sqrt{s}$$



$p = E_{beam}=\sqrt{s}/2$

Energy of elementary interaction not known

$$\sqrt{\hat{s}} = \sqrt{x_1 x_2 s} < \sqrt{s}$$

Only two elementary particles collide

→ clean final states

Elementary interaction (hard) + interaction of “spectator” q,g (soft) overlap in detector

---

Mainly EW processes → “democratic” production of all kinematic accessible particles coupling to Z/γ*

EW processes suffer from huge backgrounds from strong processes → detector performance!

In rings √s limited by e± synchrotron radiation:

$$E_{loss} \sim \frac{E^4{}_{beam}}{R}\,\frac{1}{m_e{}^4}$$

E_{loss} ~ 2.5 GeV/turn

LEP2 (E_{beam}~ 100 GeV)

Synchrotron radiation is ~ $(m_p/m_e)^4$ ~ 10^{13} smaller

⬇

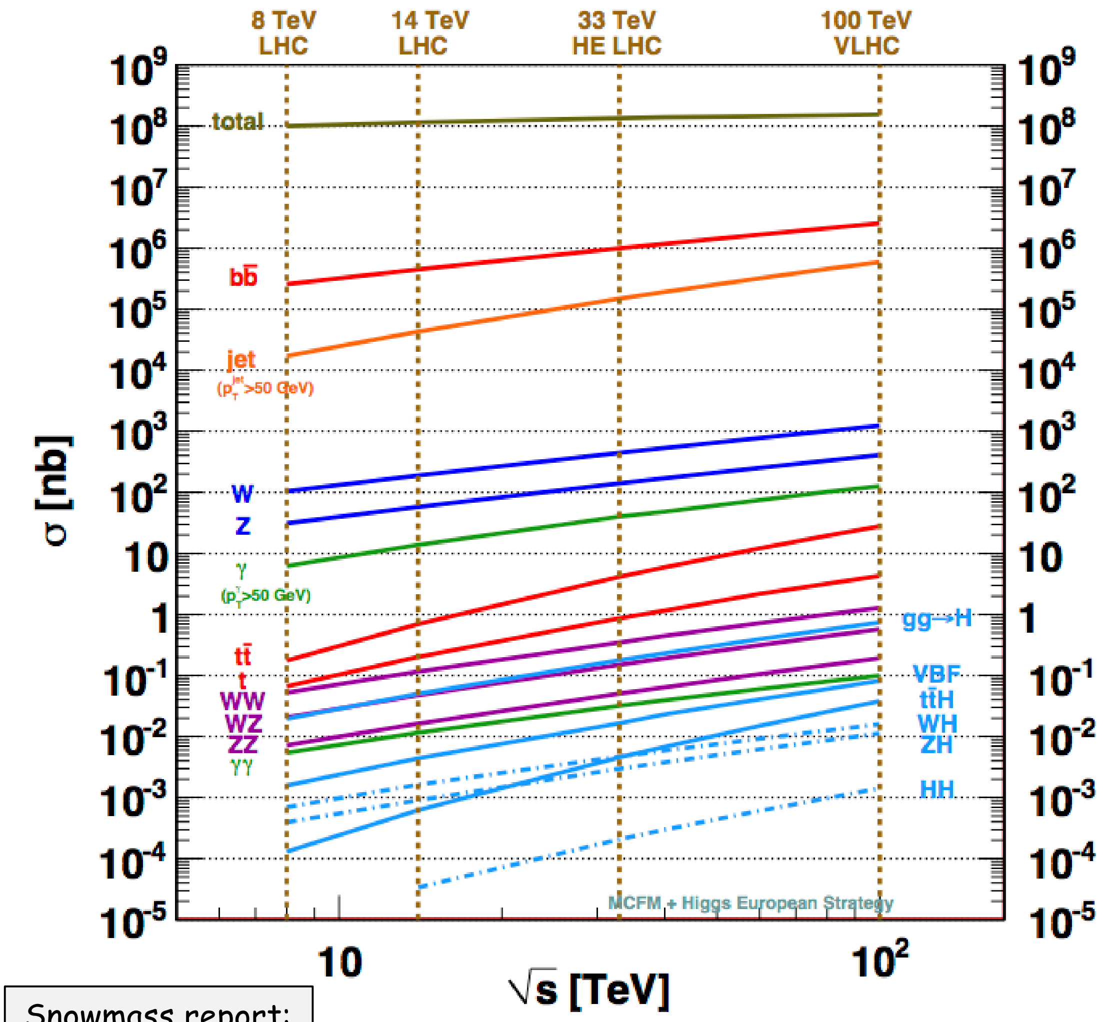
clean environment → precision measurements are optimal

⬇

high energy easier to achieve → ideal machines for discovery at energy frontier

Note: this is an oversimplified picture ! Many discoveries at e^+e^- machines (τ-lepton, gluon, etc.) and beautiful precision measurements at hadron colliders (W mass, B-physics, etc.)

Cross sections vs √s



Snowmass report:
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 10000/fb at √s=100 TeV expect: 10^{12} top, 10^{10} Higgs bosons, 10^8 m=1 TeV stop pairs, …

Units are %

Coupling √s (TeV)→ L (fb^{-1}) →	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

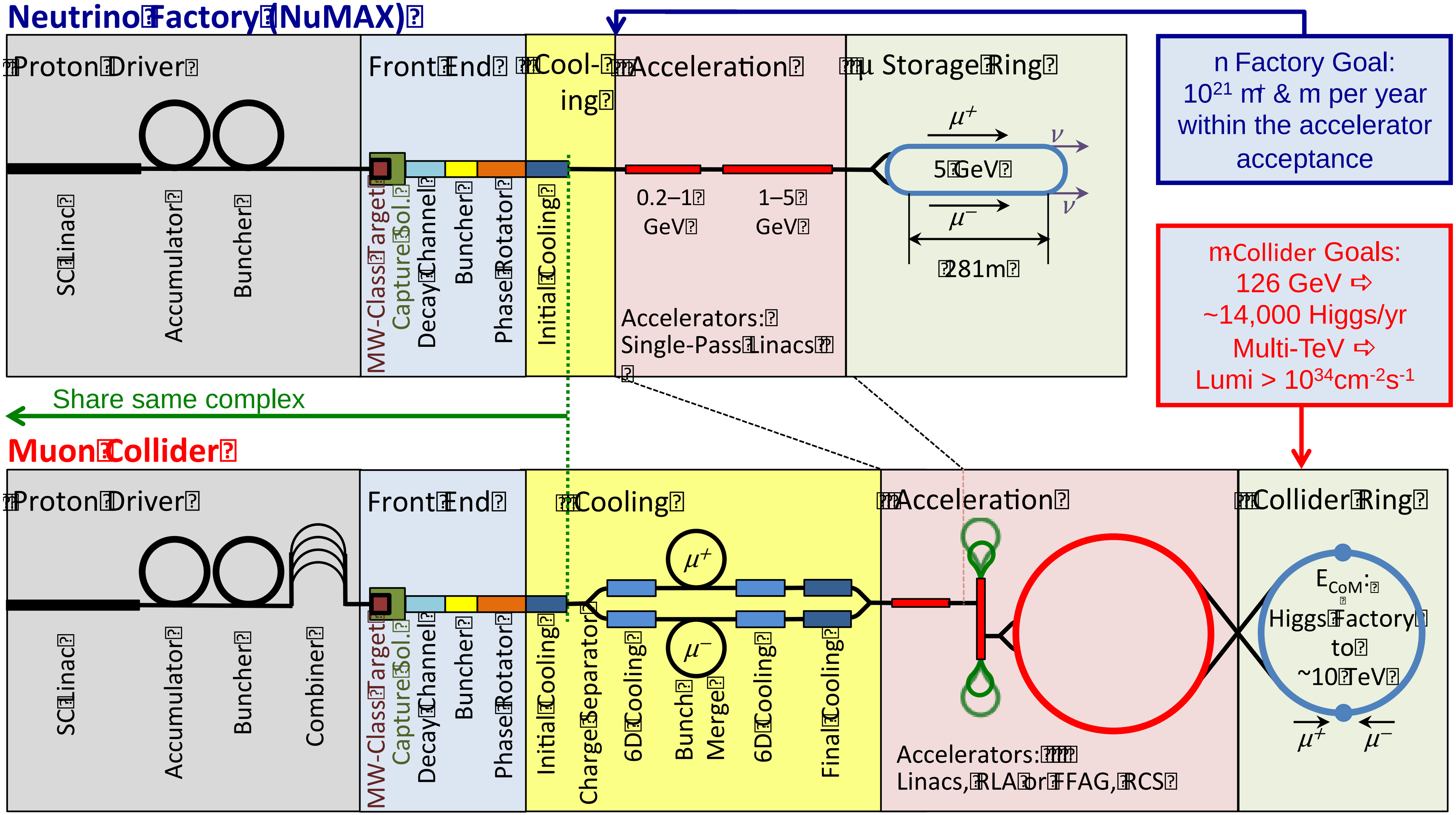
❑ HL-LHC: -- first direct observation of couplings to 2nd generation (H→ μμ)
-- model-independent ratios of couplings to 2-5%

❑ 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

Neutrino Factory & Muon Collider

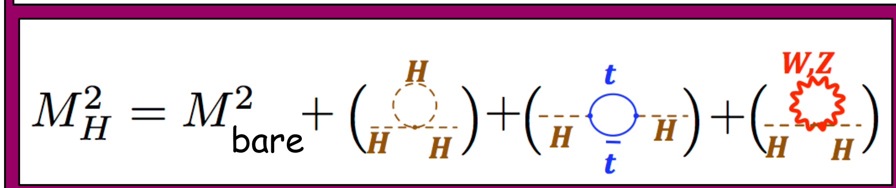


n Factory Goal:
10^{21} m+ & m per year
within the accelerator
acceptance

m-Collider Goals:
126 GeV ⇨
~14,000 Higgs/yr
Multi-TeV ⇨
Lumi > 10^{34} cm^{-2}s^{-1}

The problem of the stability of the Higgs mass a.k.a "naturalness" problem

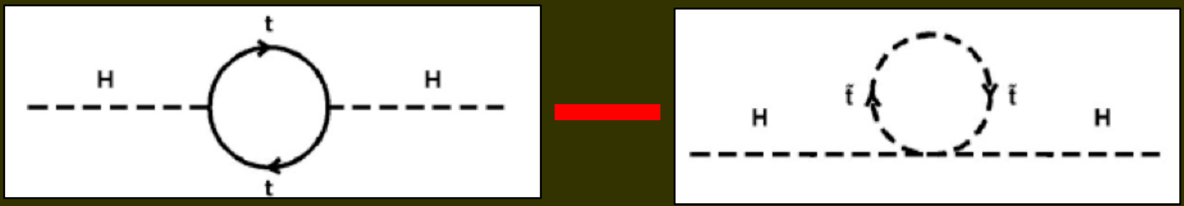
As any other particle ($e^{\pm}$, …) in quantum mechanics Higgs mass receives radiative corrections



Mostly small, except top contribution: ~ $m_t^2\Lambda^2$
Λ^2 = energy scale up to which the SM is valid (or, equivalently, new physics sets in)

2 solutions

1) "Naturalness": Higgs mass stabilized by new physics that cancel the divergences.
E.g. SUSY: the contribution of the supersymmetric partner of the top (stop) gives rise to the same contribution with opposite sign → cancellation

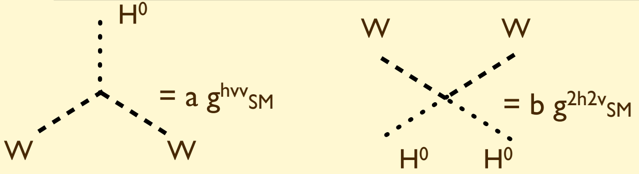


BUT: cancellation only works if stop mass not much larger than top mass → this is one of most compelling motivations for SUSY (or new physics) at TeV scale

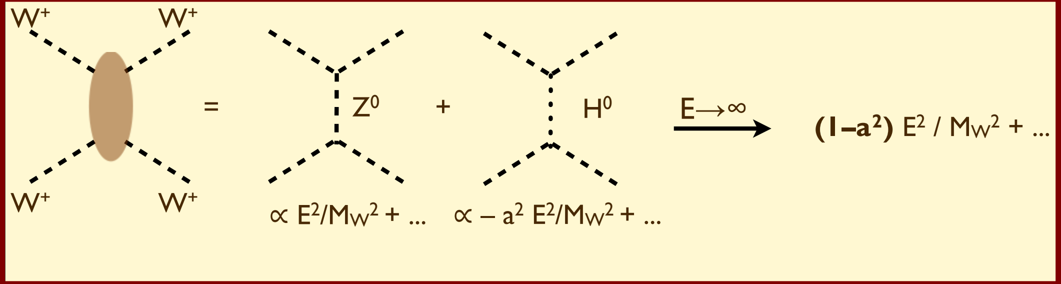
2) "Fine tuning": the bare mass cancels the radiative corrections → this becomes more and more "acrobatic" the higher the scale Λ up to which SM is valid (w/o new physics)

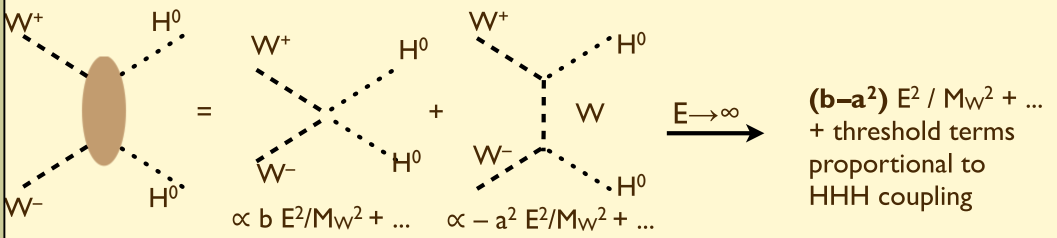
E.g. Λ = 10 TeV → M^2 (rad. corr) = 8265625 GeV² → need fine-tuned M_{bare}^2 = 8281250 GeV²
to get M_H^2= (125 GeV)² = 15262 GeV²
Λ= 10^{19} GeV → need fine tuning of M_{bare} to the 33rd digit !! → UNNATURAL

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





$(b-a^2)\, E^2 / M_W^2 + \ldots$
+ threshold terms
proportional to
HHH coupling

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

V_LV_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

Future pp colliders

Pioneering work started in the US in 1998 with VLHC: http://vlhc.org/vlhc/

	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 If enough funds	54 100	70 100-140	20	Nb_3Sn with HTS inserts	12
FCC-hh	100	100	16	Nb_3Sn (with NbTi)	5-20

5×10^{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

* 5 ns considered for $L=2\times10^{35}$ to mitigate pile-up

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