Future High Energy Collider Options and Physics Prospects

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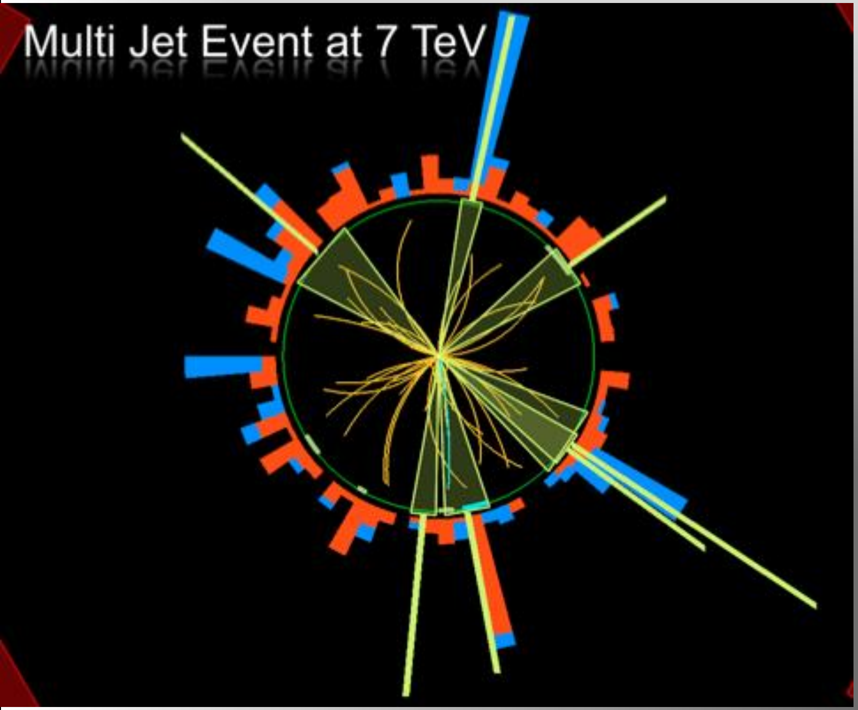
ASTROPARTICLE PHYSICS 2014

A joint TeVPA/IDM conference

CERN

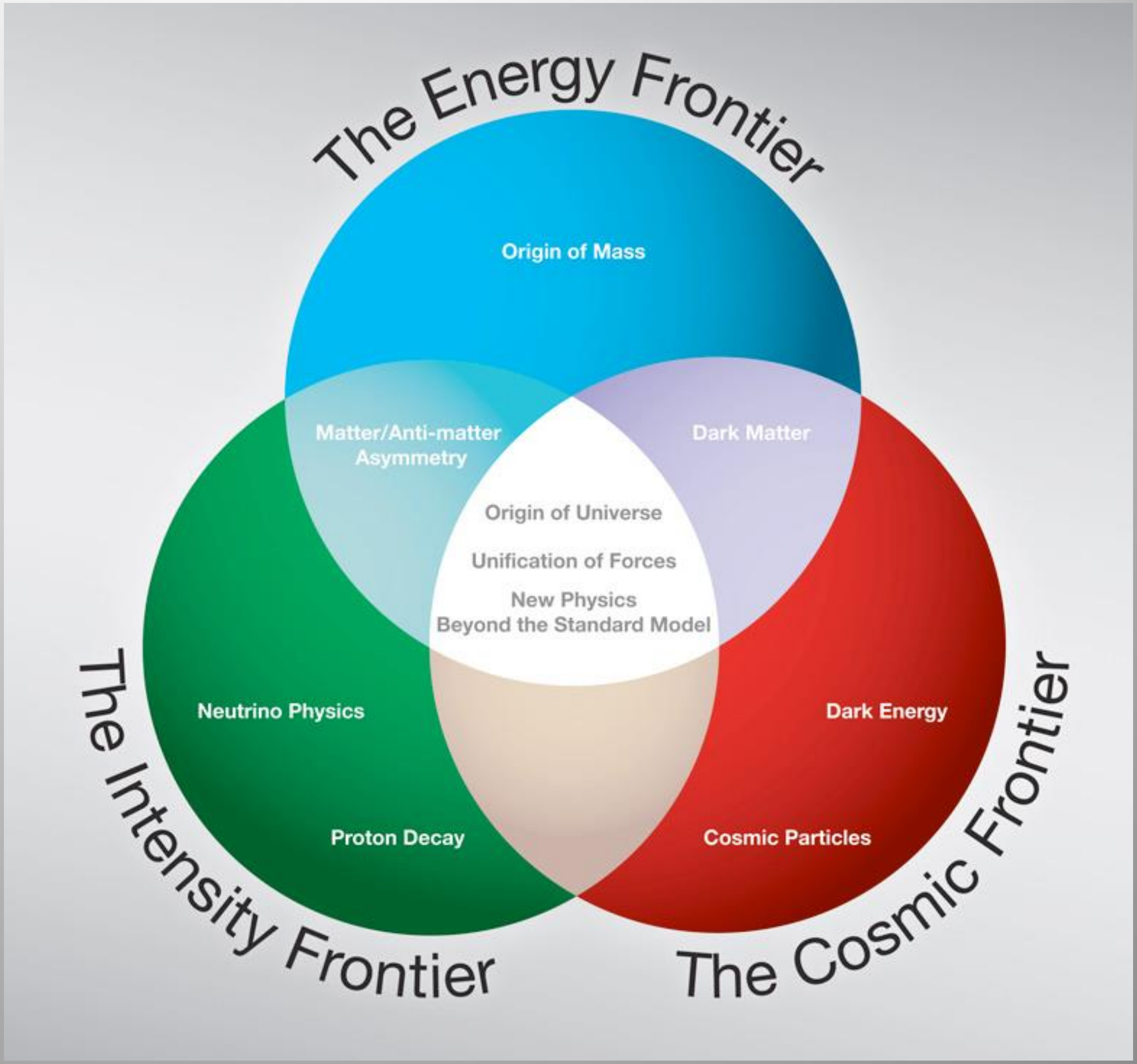


Outline

- Introduction: Discussion on the Future.
- LHC schedule for the next years of operation
- LHC upgrade plans/projects
- Beyond the LHC: where do we go from here?
- Conclusion

The Three Frontiers

Evaluated in all regions: Europe Asia, the Americas



2012-2014

- European strategy group
- Snowmass study and P5
- Japan strategy group

Recent released P5 report much in accord with Europe

Will concentrate here on the Energy Frontier

Projects Discussed in 2012/2013

pp colliders

	Years	E_{cm} TeV	Luminosity $10^{34}cm^{-2}s^{-1}$	Int. Luminosity 300 fb^{-1}
Design LHC	2014-21	14	1-2	300
HL-LHC	2024-30	14	5	3000
HE-LHC	>2035	26-33*	2	100-300/y
V-LHC**	>2035	42-100		

e+e- colliders

	Years	E_{cm} GeV	Luminosity $10^{34}cm^{-2}s^{-1}$	Tunnel length km
ILC 250	<2030	250	0.75	
ILC 500		500	1.8	~30
ILC 1000		1000		~50
CLIC 500	>2030	500	2.3(1.3)	~13
CLIC 1400		1400(1500)	3.2(3.7)	~27
CLIC 3000		3000	5.9	~48
LEP3	>2024	240	1	LEP/LHC ring
TLEP	>2030	240	5	80 (ring)
TLEP		350	0.65	80 (ring)

+ proposals for photon colliders, muon collider,..

Europe Strategy Group and P5

European Strategy for Particle Physics

- Update formally adopted by CERN council at the European Commission in Brussels on 30 May 2013
- The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme.
- *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

European Strategy
Update

Last Spring: European Strategy Group

Last Month: P5

Recommendation 10: Complete the LHC phase-1 upgrades and continue the strong collaboration in the LHC with the phase-2 (HL-LHC) upgrades of the accelerator and both general-purpose experiments (ATLAS and CMS). The LHC upgrades constitute our highest-priority near-term large project.

First recommendation on the list that is naming a project

The LHC Schedule

LHC roadmap to achieve full potential

2009 — LHC startup, √s 900 GeV

2010–2012 — √s=7+8 TeV, L~6x10[33]cm[-2]s[-1], bunch spacing 50ns — Run 1 ~25 fb[-1]

2013–2014 LS1 — Go to design energy, nominal luminosity - Phase 0

2015–2017 — √s=13~14 TeV, L~1x10[34]cm[-2]s[-1], bunch spacing 25ns — ~75-100 fb[-1]

2018 LS2 — Injector + LHC Phase I upgrade to ultimate design luminosity

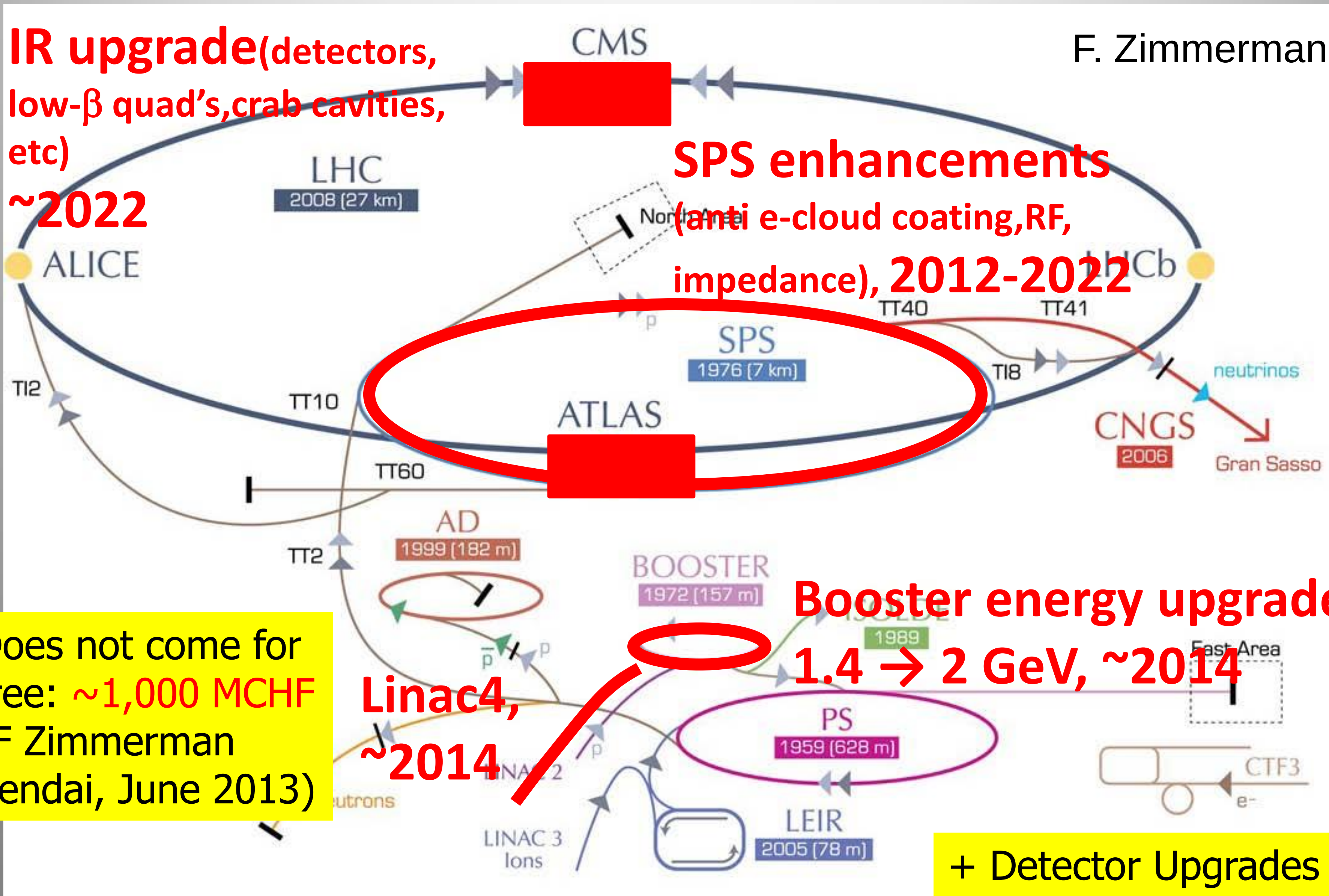
2019–2021 — √s=14 TeV, L~2x10[34]cm[-2]s[-1], bunch spacing 25ns — ~350 fb[-1]

2022 LS3 — HL-LHC Phase II upgrade: Interaction Region, crab cavities?

2023 … 2030? — √s=14 TeV, L~5x10[34]cm[-2]s[-1], luminosity levelling — ~3000 fb[-1]

High Luminosity LHC (HL-LHC)

F. Zimmerman



IR upgrade (detectors, low-β quad's, crab cavities, etc) **~2022**

SPS enhancements (anti e-cloud coating, RF, impedance), **2012-2022**

Booster energy upgrade 1.4 → 2 GeV, ~2014

Linac4, ~2014

Does not come for free: ~1,000 MCHF (F Zimmerman Sendai, June 2013)

+ Detector Upgrades

Beyond the LHC

- Proton-proton machines at higher energy…
- Electron-positron machines for high precision…
- Both? And allowing for electron-proton collisions..?

New projects will take 10-20 years before they turn into operation, hence need a vision & studies now!

From the European Strategy Group

European Strategy for Particle Physics

…."to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update":

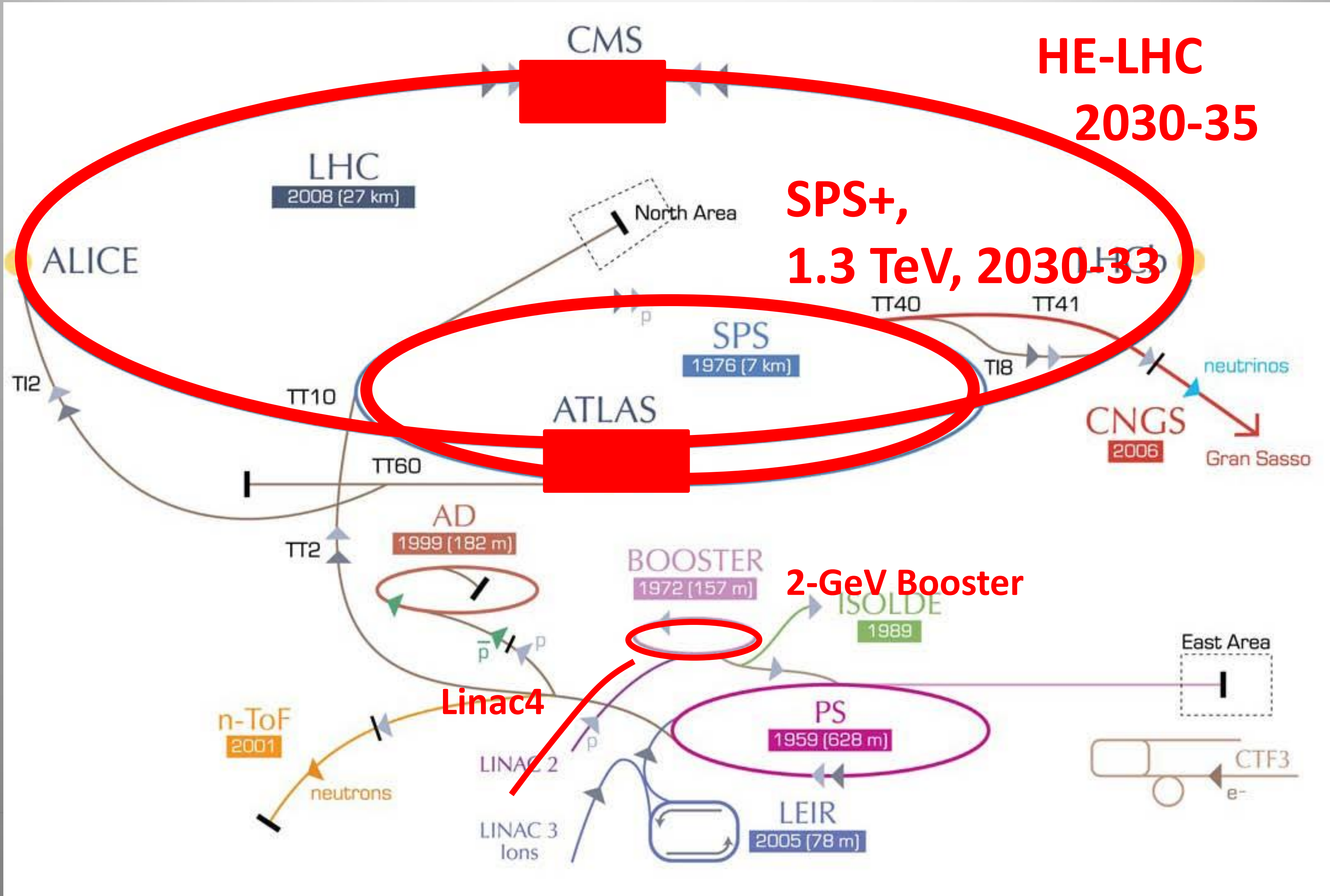
d) ***CERN should undertake design studies for accelerator projects in a global context,***

- *with emphasis on **proton-proton and electron-positron high-energy frontier machines**.*
- *These design studies should be coupled to a vigorous accelerator **R&D programme, including high-field magnets and high-gradient accelerating structures**,*
- ***in collaboration with national institutes, laboratories and universities worldwide.***

- http://cds.cern.ch/record/1567258/files/esc-e-106.pdf

Similar recommendation from the Snowmass studies in the US

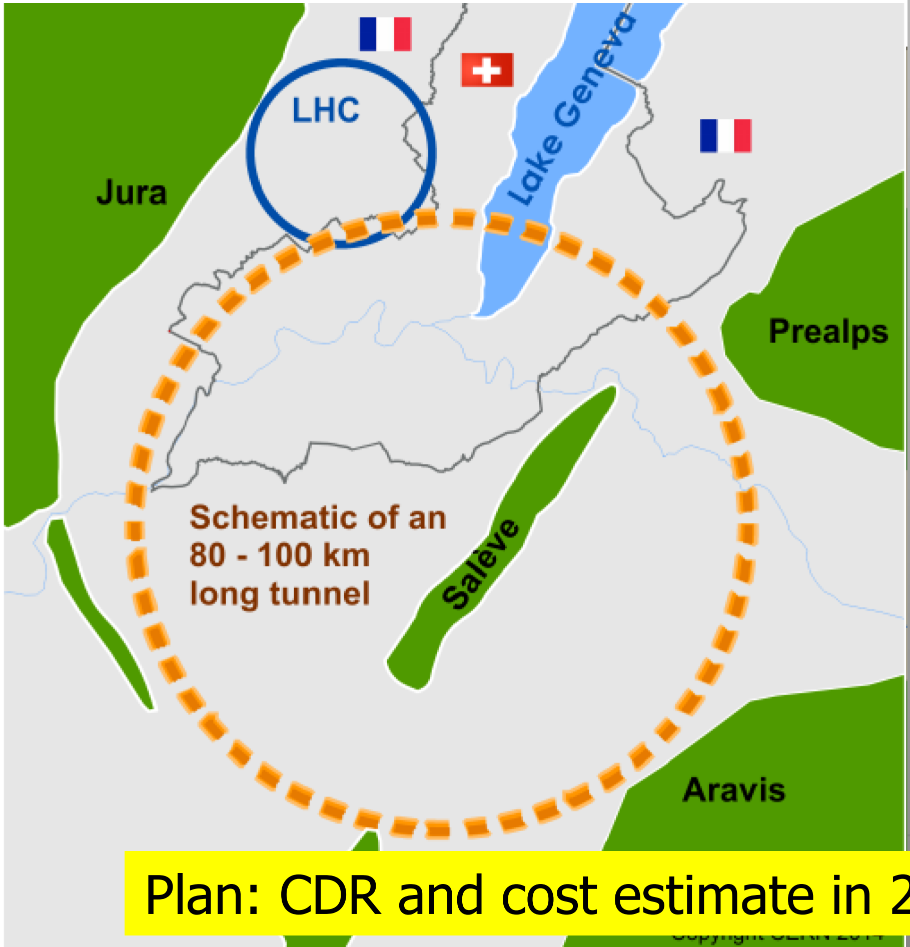
High Energy LHC (HE-LHC)



Recent CERN Initiative: FCC

Future Circular Colliders:

80-100 km tunnel infrastructure in Geneva area – design driven by pp-collider requirements (FCC-hh)
with possibility of e+-e- (FCC-ee) and p-e (FCC-he)



Plan: CDR and cost estimate in 2018

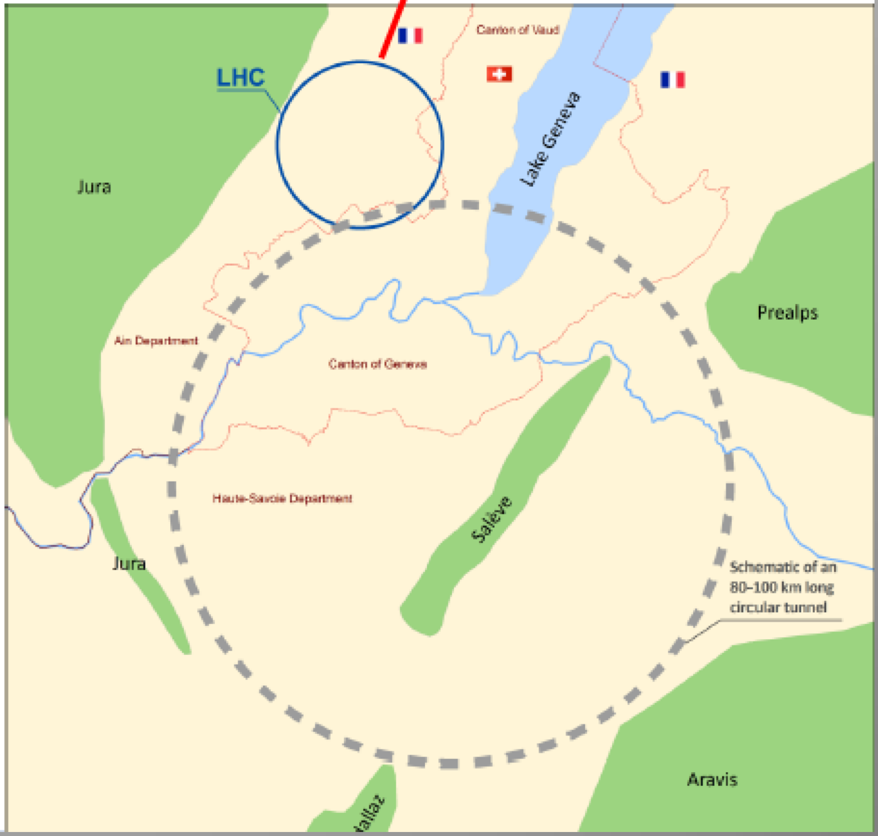
FCC-hh: a Proton-Proton Collider

"High Energy LHC"

HE-LHC :33 TeV with 20T magnets

First studies on a new 80 km tunnel in the Geneva area

- **42 TeV with 8.3 T using present LHC dipoles**
- **80 TeV with 16 T based on Nb_3Sn dipoles**
- **100 TeV with 20 T based on HTS dipoles**



FCC-ee: the Electron-Positron Option

- In July 2011 a proposal was made to (re)install a 120 GeV / beam e^+e^- collider in the LEP-LHC tunnel – named LEP3. Work on LEP3 started in a series of workshops.
- The 80 km TLEP machine appeared in 2012 in parallel with the feasibility study for a 80 km ring for a future hadron collider around CERN. TLEP and LEP3 were presented in September 2012 at the European Strategy meeting in Krakow.
- In October 2013 TLEP was integrated into the FCC study and is now known as FCC-ee.

Circular e+e- collider with √s energy in the range of 90-350 GeV

Can serve 4 experiments simultaneously!

Challenging but no showstoppers!! (2 rings)
Energy loss/turn ~ 11 GeV

√s (GeV)	<L >(ab-1/year)*	Rate (Hz) ee—>hadrons	Years	Statistics
90	5.6	2 10^4	1	2 10^{11} Z decays
160	1.6	25	1-2	2 10^7 W pairs
240	0.5	3	5	5 10^5 HZ events
350	0.13	1	5	2 10^5 ttbar

* each interaction point

Tera-Z, Giga-W, Mega-H, Mega-top

The Physics Case includes

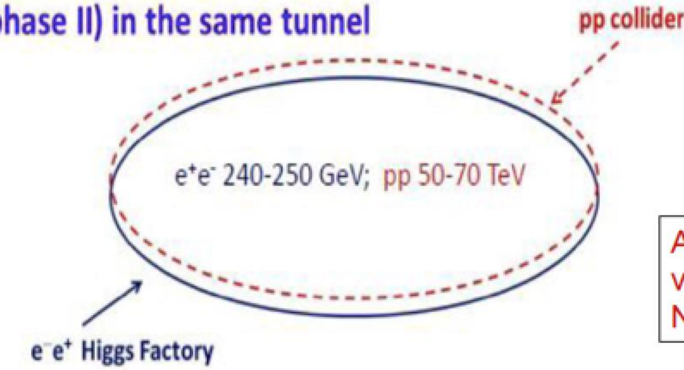
- Precise measurement (0.1% to 1%) of the Higgs Couplings
- Improve precision (statistics x 10^5) on the measurements of the Z parameters [M_Z, Γ_Z , R_ℓ, R_b, R_c, Asymmetries & weak mixing angle]. Z rare decays.
- Scan W threshold (aiming at 0.5 MeV precision). W rear decays
- Scan ttbar threshold (aiming at 10 MeV)

World Interest: in Particular in China…

China expressed an interest in the construction of a new large accelerator, first as an e+e- Higgs factory and then as a high energy pp machine.
Aim: design completed in 2020

Contribute to the world effort

- Circular Higgs factory (phase I) + super pp collider (phase II) in the same tunnel



A 50-70 km tunnel is very affordable in China NOW

"Center for Future High Energy Physics (CFHEP)"

Possible site: Qinhuangdao
(1 hr by train from Beijing)

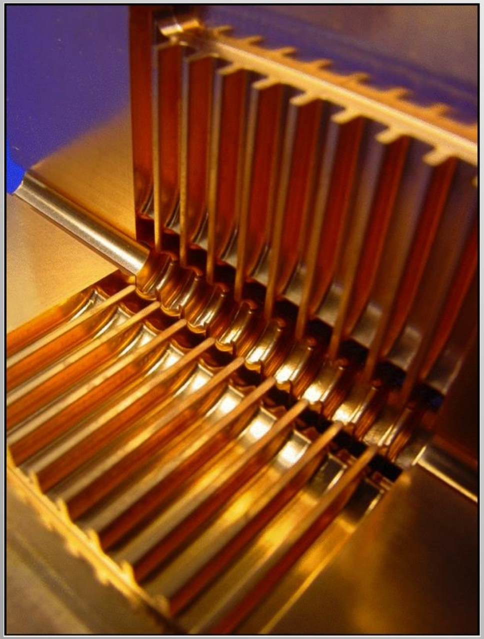
Linear e+e- Colliders

Electron-positron machines for high precision and possibly high energy (few TeV) …
Avoid Synchrotron radiation from a circular machine

Studies and R&D work on linear colliders started in the '90's and they have achieved a very high level of maturity now…

Linear e+e- Colliders: ILC and CLIC

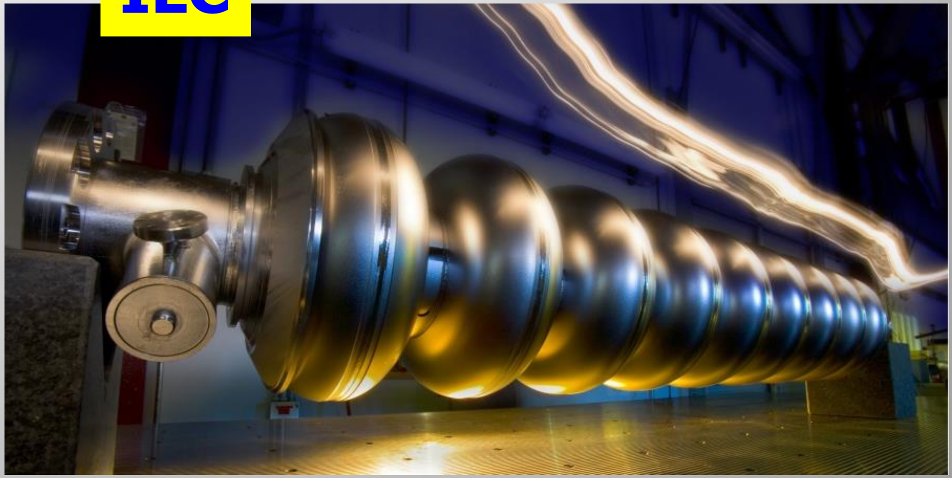
CLIC



- 2-beam acceleration scheme at room temperature
- Gradient 100 MV/m
- $\sqrt{s}$ up to 3 TeV
- Physics + Detector studies for 350 GeV - 3 TeV

Linear e^+e^- colliders
Luminosities: few 10^{34} $cm^{-2}s^{-1}$

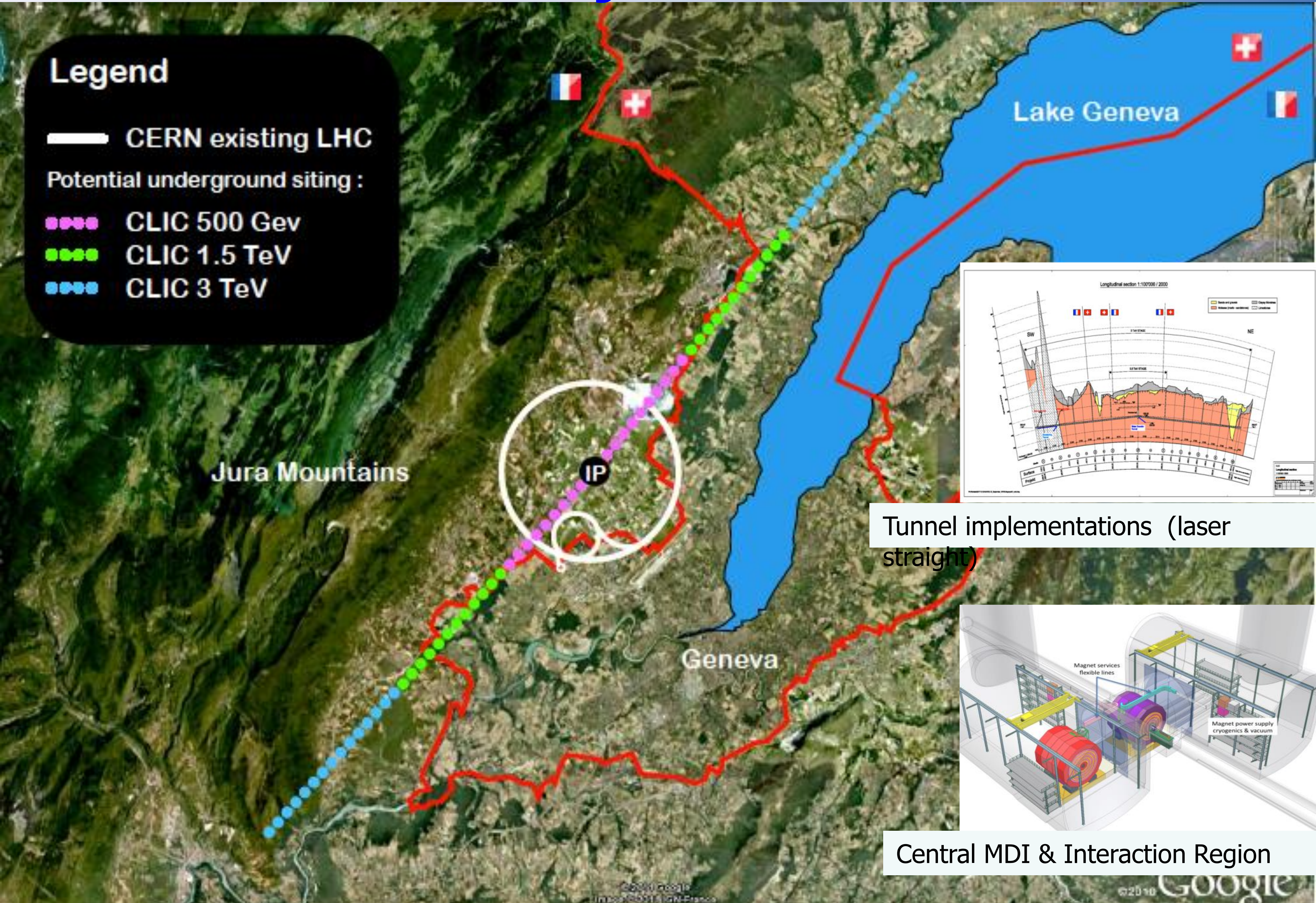
ILC



- Superconducting RF cavities (like XFEL)
- Gradient 32 MV/m
- $\sqrt{s} \leq 500$ GeV (1 TeV upgrade option)
- Focus on ≤ 500 GeV, physics studies also for 1 TeV

The ILC is basically ready to be build now!

CLIC Layout @ CERN

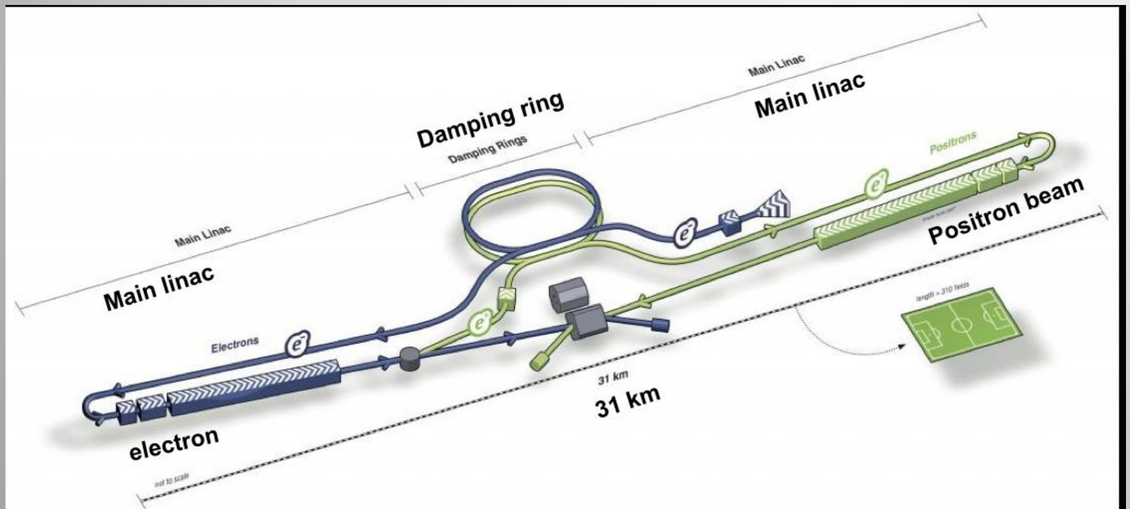


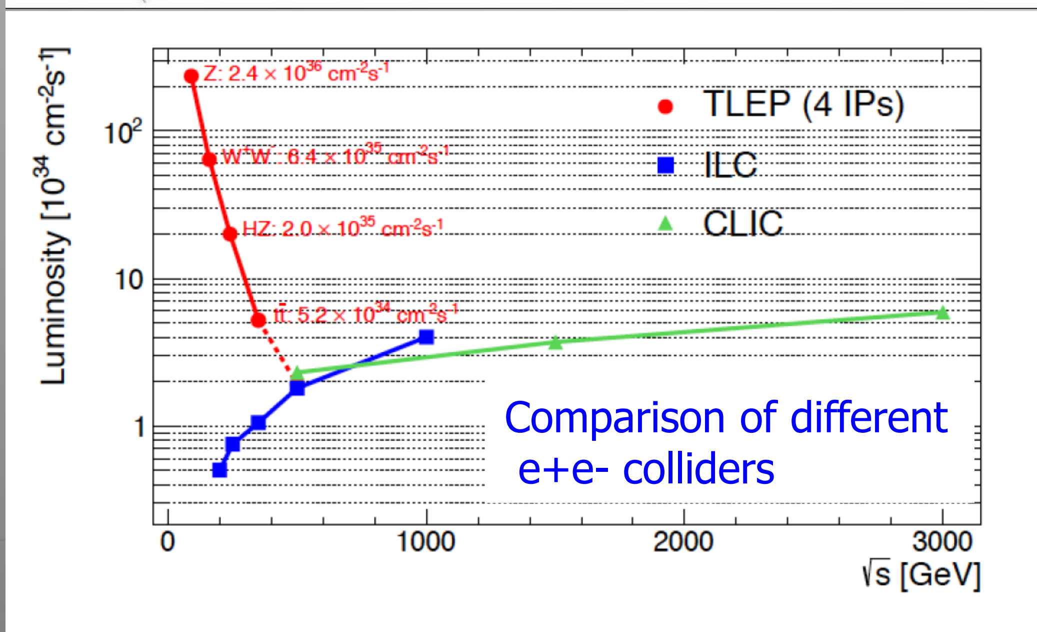
Tunnel implementations (laser straight)

Central MDI & Interaction Region

ILC Layout

Japan has expressed a strong interest to host this collider! Under discussion…





Note: in 2013 ILC produced a plan to double the luminosity
(not included in the figure)

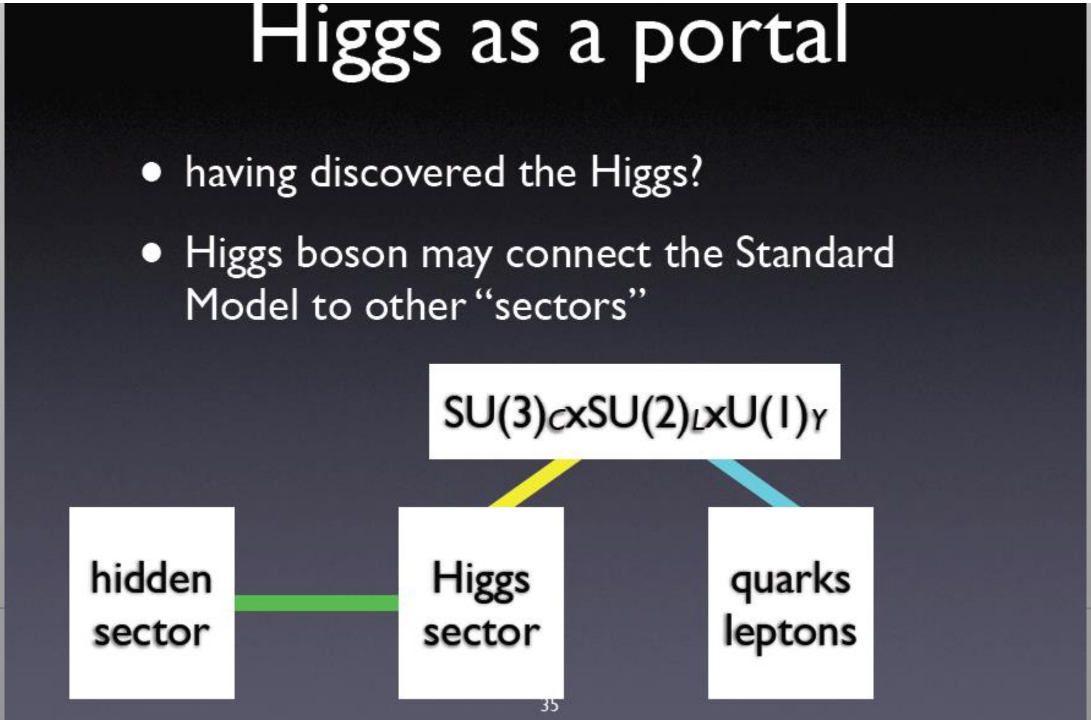
The Physics at the Future Colliders

- Studies for linear colliders documented in TDRs since ~ 15 years, regularly updated
- HL-LHC studies started in 2012, ongoing
- FCC-ee studies started in 2012, ongoing
- FCC-hh and FCC-he studies started end of last year

Apart from LC studies, most of the future collider studies are just at the beginning. (-> volunteers welcome!!)

Next Questions to be Addressed

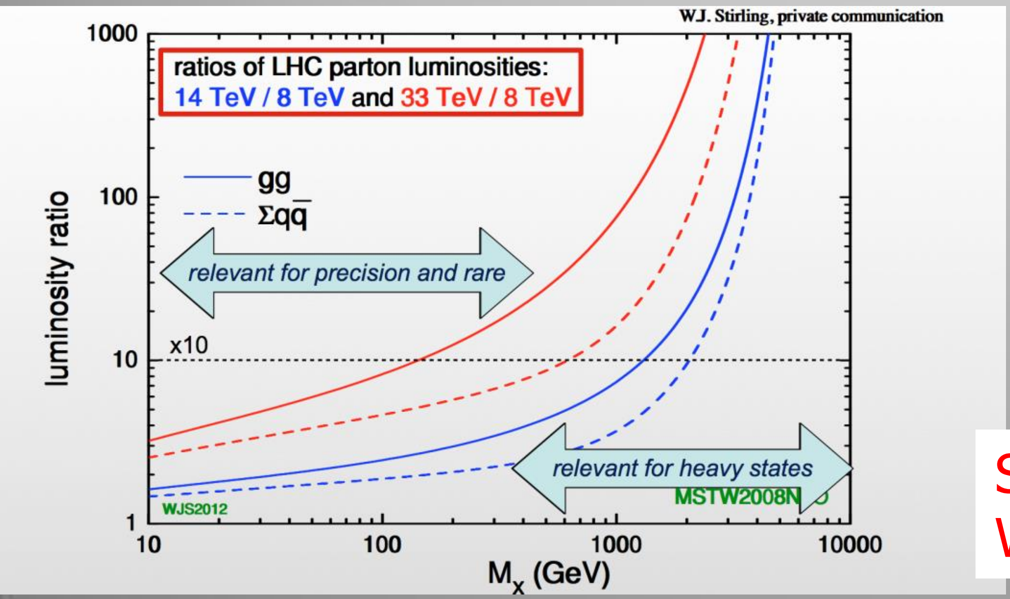
- Is it THE Standard Model Higgs or a messenger of New Physics ?
- How can we explain a Higgs mass ~ 126 GeV? What stabelizes its mass? New Physics e.g. Supersymmetry?
- What explains the mass pattern of the particles we observe?
- What is Dark Matter and Dark energy?
- Neutrino masses and properties?
- Where is the antimatter in the Universe? How did it disappear??



Physics Program: Key Topics

- Properties of the new Higgs boson, precise determination of its characteristics
- High mass reach for new particles and interactions
- Precision measurements
- Rare process

-> However, no “no-loose theorem” know, as yet.



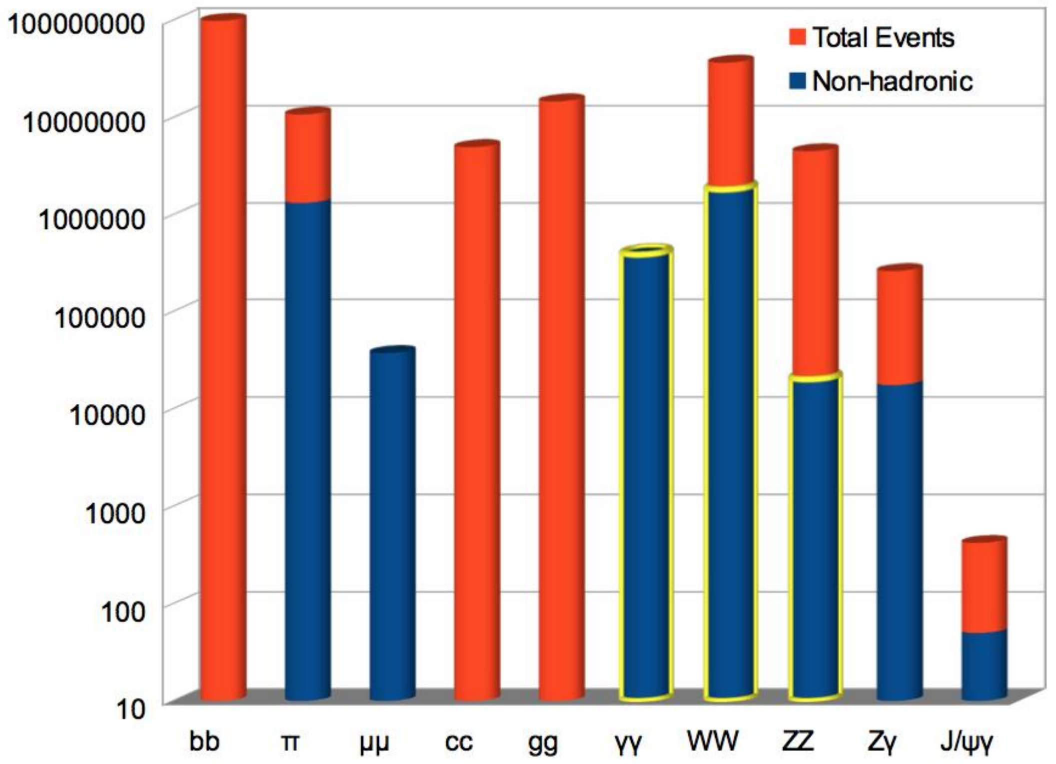
- Higgs mass precisions
  ~ 100-200 MeV enough?
- Higgs self-coupling precision
  Better than 20% needed?
- Higgs couplings? Few %? Better?
  (J. Wells et al., arXiv:1305.6397)

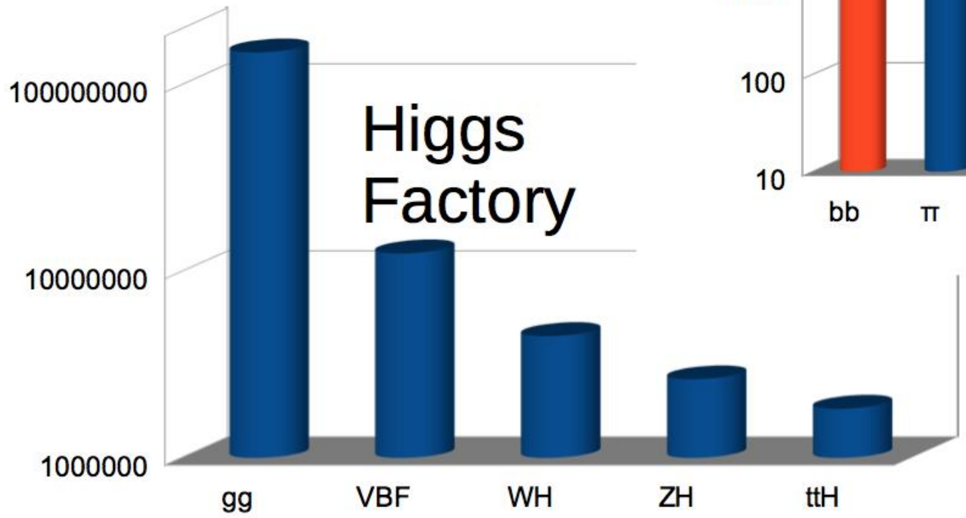
Studies for future FCC options ongoing
Working group meetings every month

High Luminosity LHC

Number of Higgs Bosons produced with 3000 fb^{-1}

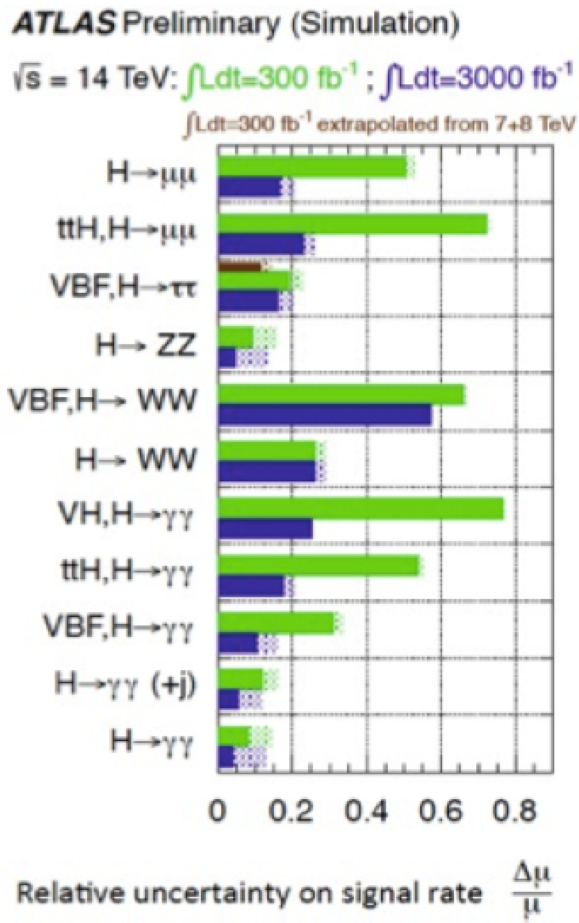
- Over 100M Higgs bosons
- 20K $H \to ZZ \to llll$
- 400K $\gamma\gamma$
- 50 $H \to J/\psi\gamma$

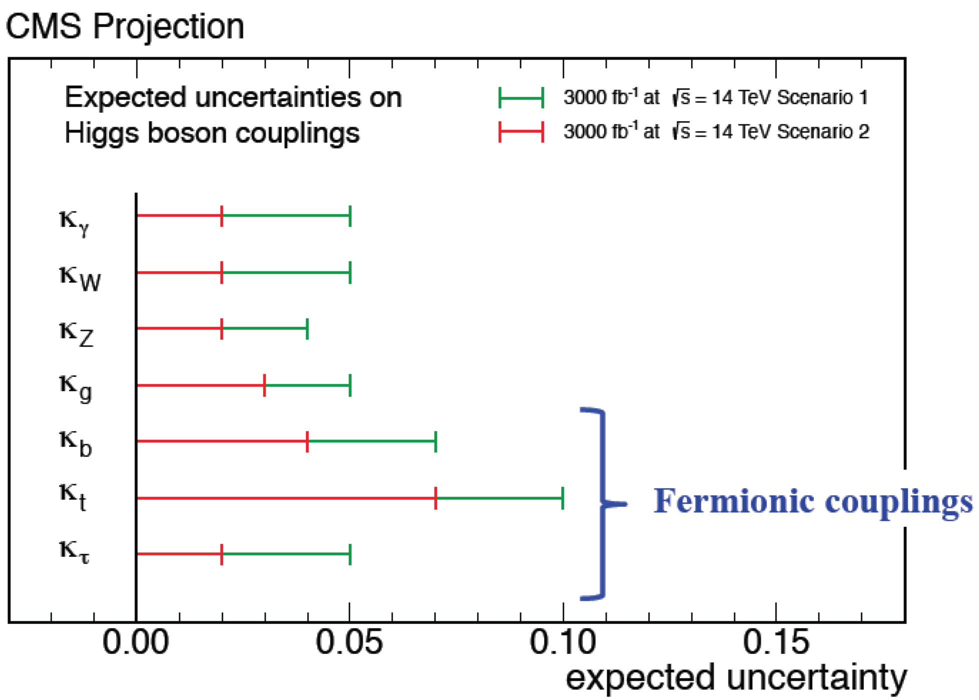




- Over 1M in all major production modes

High Luminosity LHC Precision





Assumptions on systematic uncertainties
Scenario 1: no change
Scenario 2: Δ theory / 2, rest ∝ 1/√L

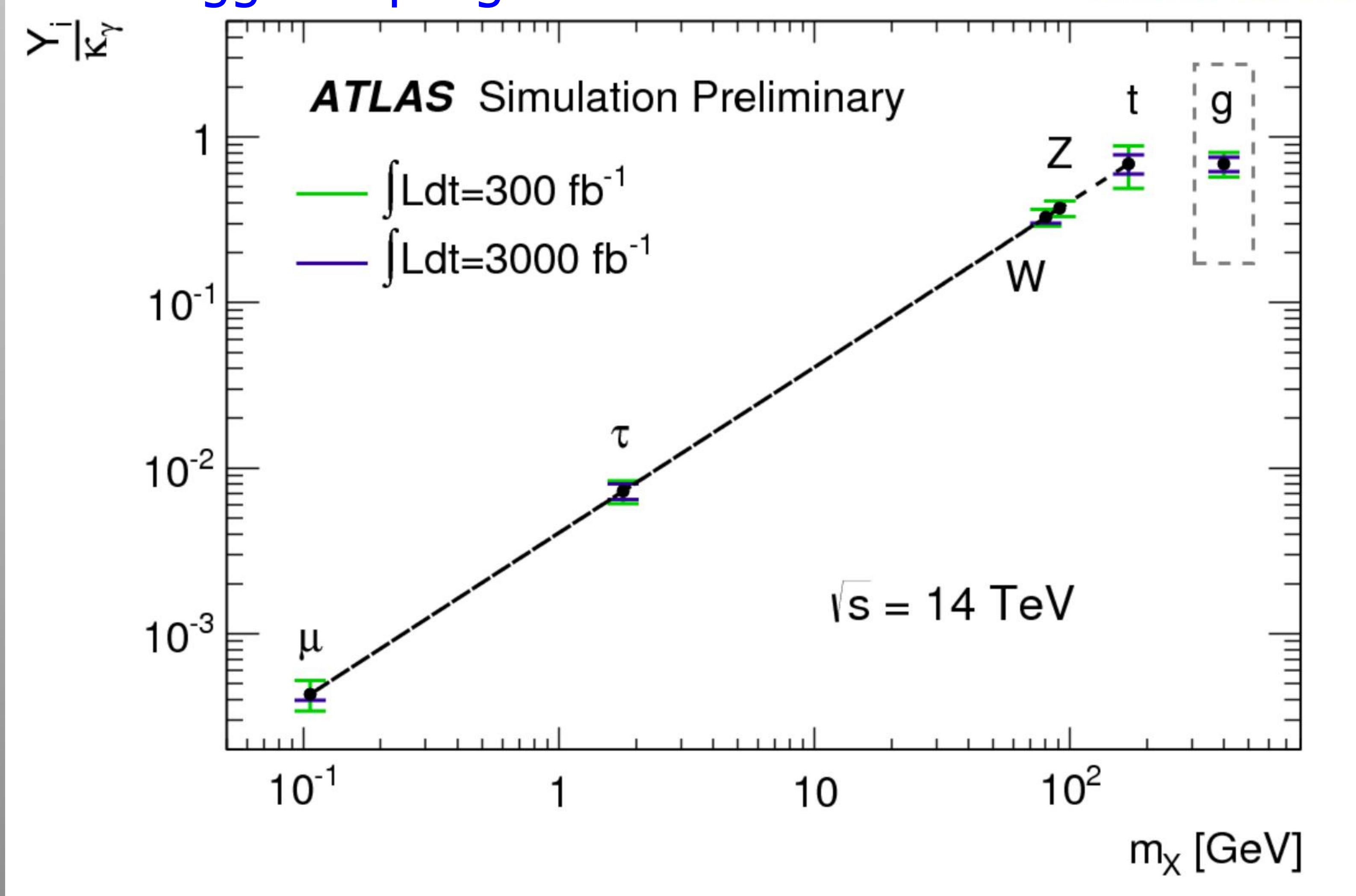
Based on parametric simulation

Extrapolated from 2011/12 results

Determine the Higgs couplings to a few % precision…

High Luminosity LHC Precision

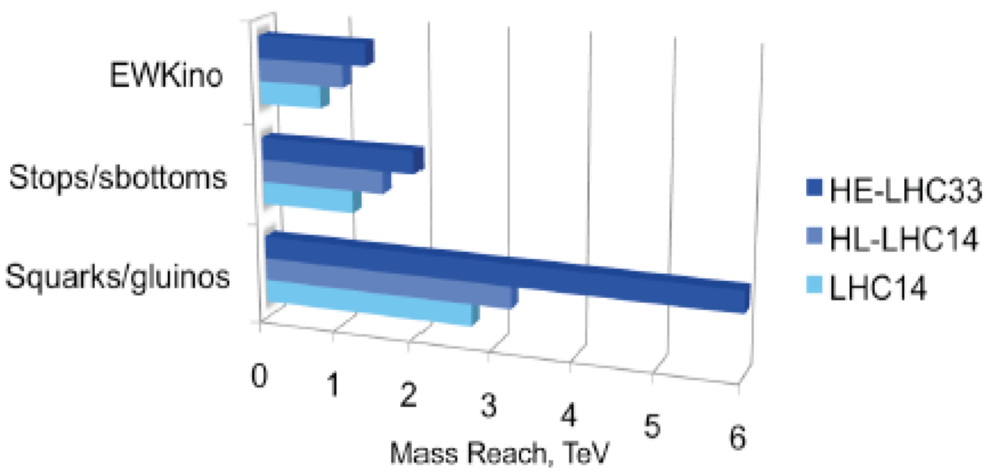
Higgs couplings: ....



Determine the Higgs couplings to a few % precision...

Searches for New Particles in pp

Searches for pair produced SUSY particles



E.g. 2HDM in SUSY

$m_h, m_H, m_A, m_{H^\pm}$ $\tan\beta \equiv \langle\Phi_2\rangle / \langle\Phi_1\rangle$

FIne tuning and naturalness: (N.Craig, BSM@100 Wshop)

$\Delta \approx \sin^2(2\beta)\frac{m_H^2}{m_h^2}$ $\Delta(\tan\beta = 50) \leq 1 \rightarrow m_H \lesssim 3.1$ TeV

Extra H can be heavy, well above LHC reach, but cannot be arbitrarily heavy

FCC-hh (100 TeV)

- Reach sparticle masses search up to about 20 TeV for squarks of light quarks and 6 TeV for stops
- Excited quarks searches probe the structure of quarks down to 4×10^{-21} m
- Discovery of resonances up to masses of 40 TeV

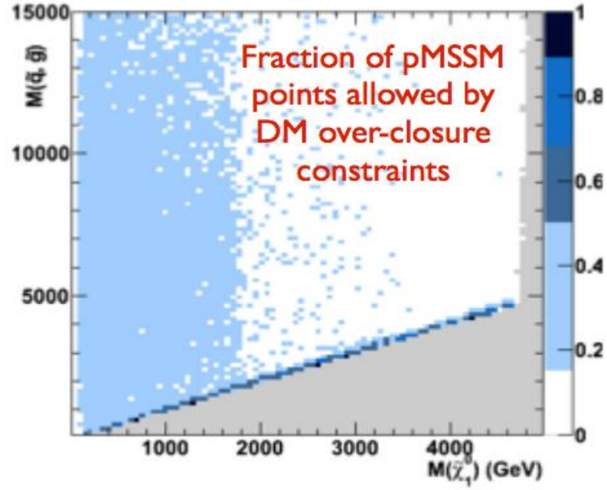
Upper limit for higher Higgs mass in 2HDM models?

- **Why 100 TeV ?**
  - Need for O(100 TeV) in the cards since the SSC days: fully explore EWSB, probing in particular unitarization of WW scattering at m(WW)> TeV, and explore dynamics well above EWSB

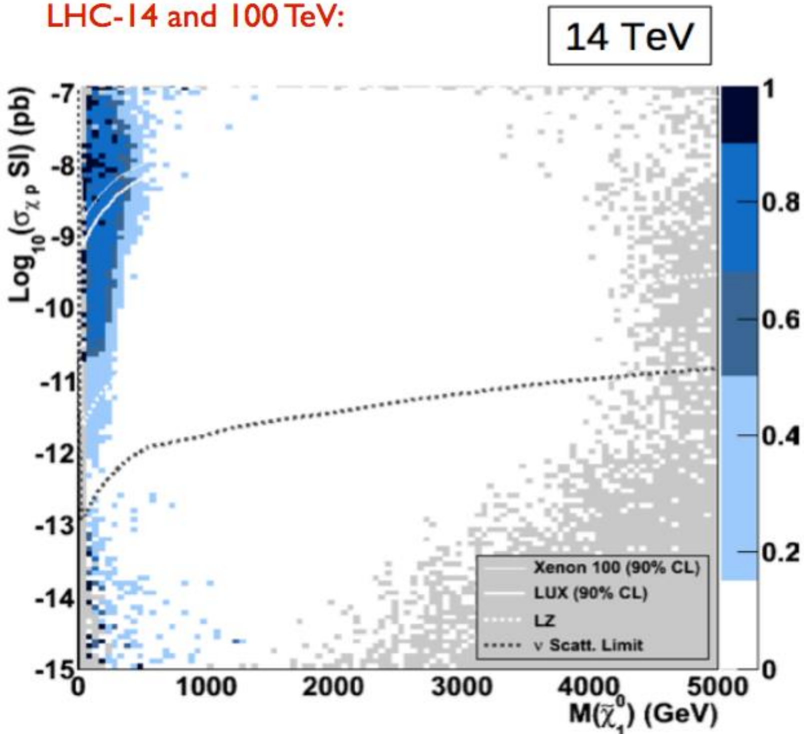
Dark Matter Coverage: pp @ 100 TeV

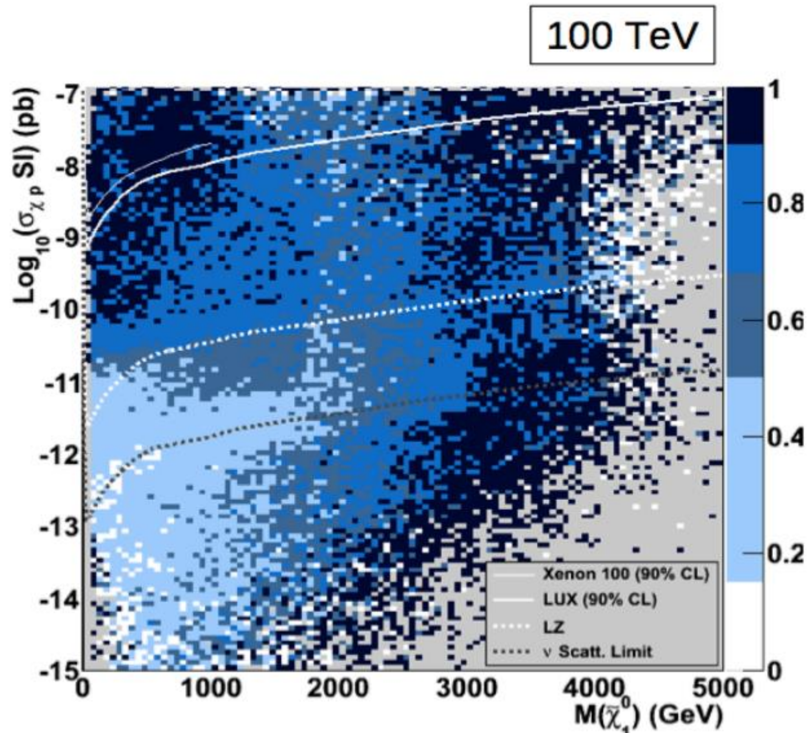
Coverage of pMSSM parameter space using DM constraints and direct searches at 14 and 100 TeV

Arbey, **Battaglia**, Mahmoudi



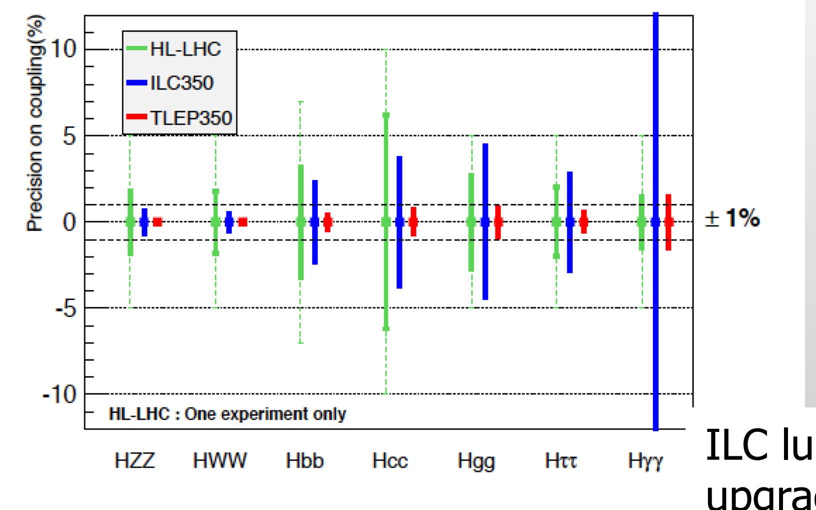
Fraction of pMSSM points that can be excluded at LHC-14 and 100 TeV:





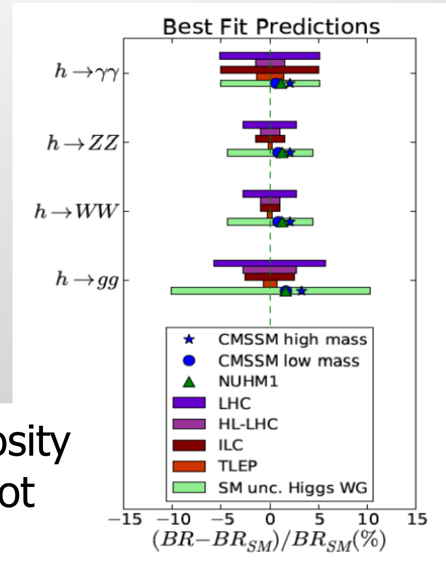
Physics at e+e- Colliders

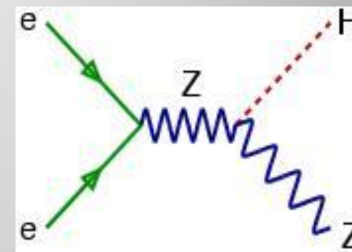
Higgs Boson Couplings



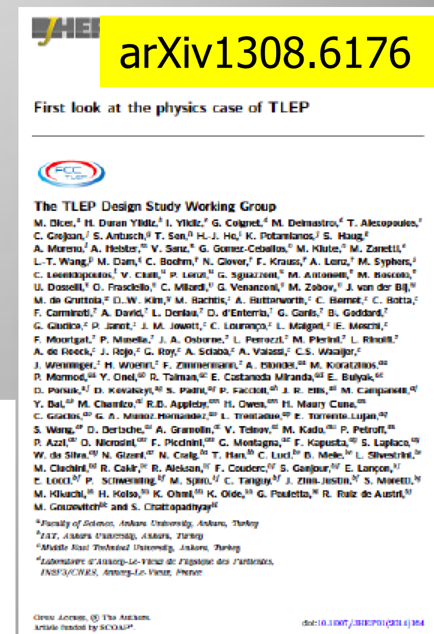
ILC luminosity upgrade not included

Higgs Boson decays

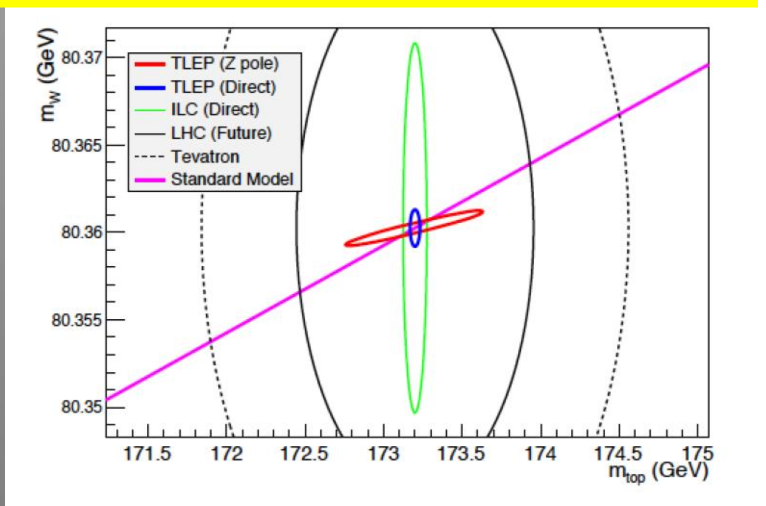




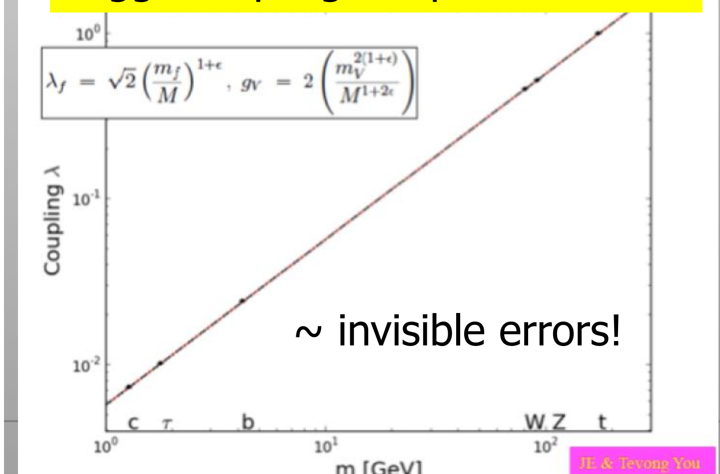
arXiv1308.6176



Fit to all EWK precision measurements



Higgs couplings vs particle mass



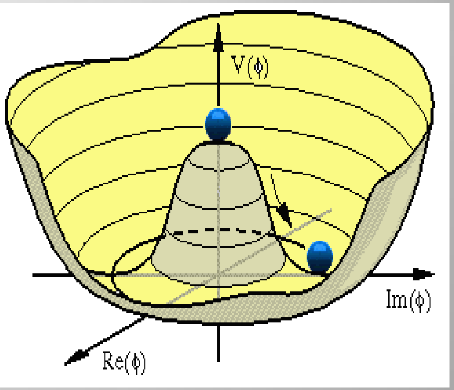
~ invisible errors!

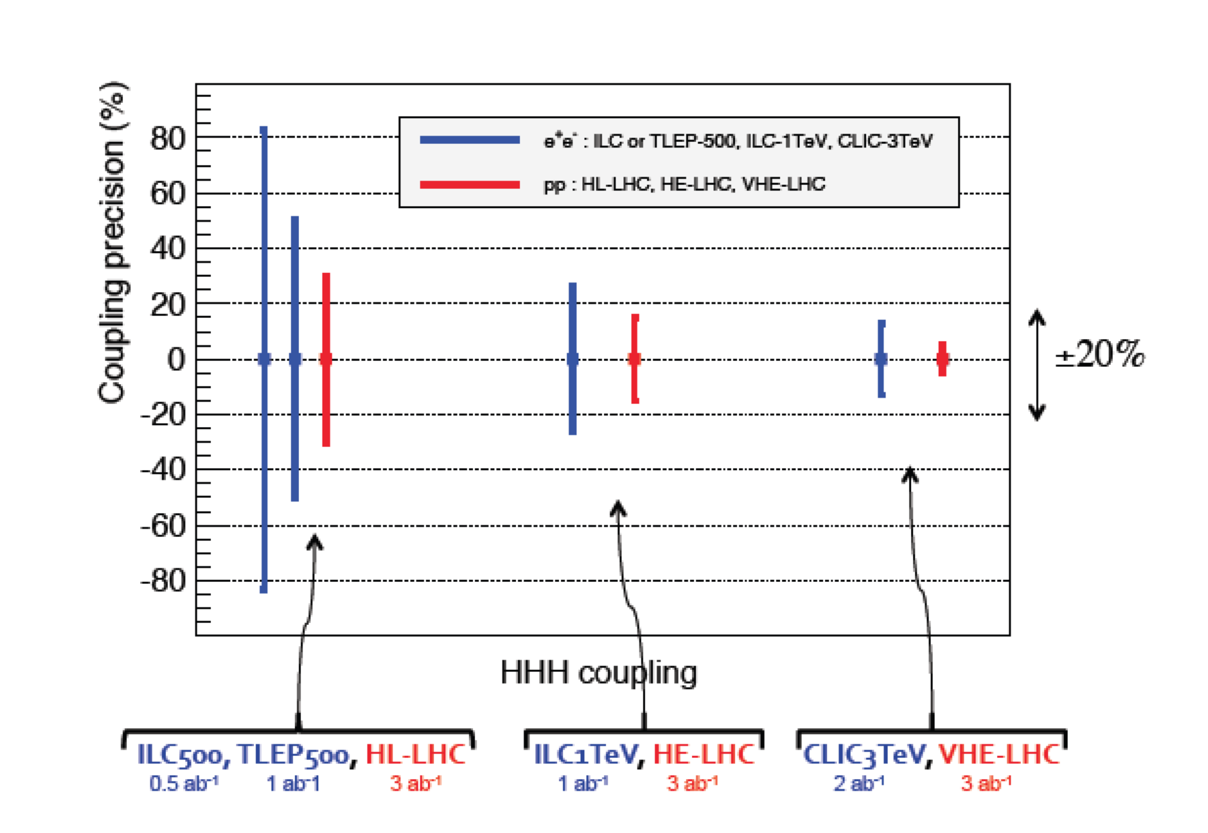
FCC-ee delivers very precise measurements

The Higgs Self Coupling!

A key measurement for our understanding of the Higgs field potential!

in pp





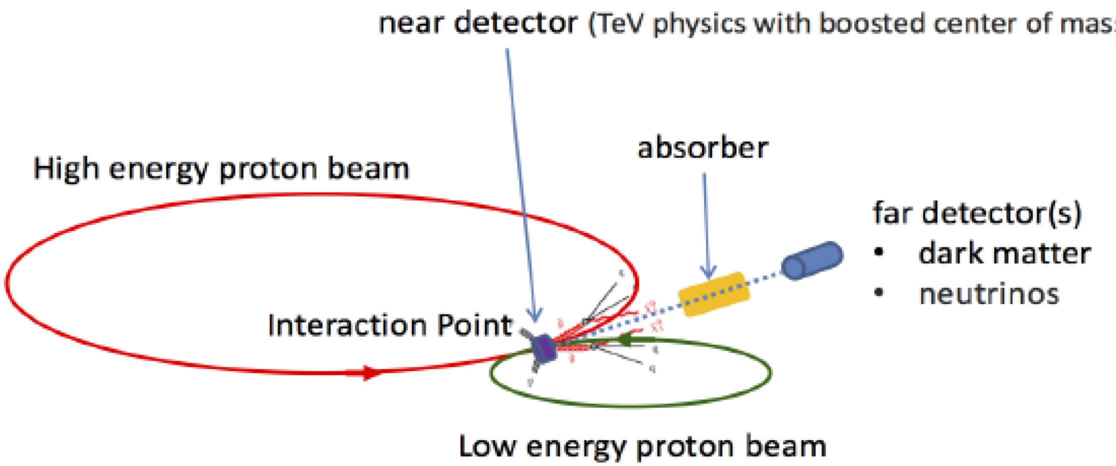
Difficult measurements!!:
Evaluation till ongoing
for HL-LHC sensitivity

e+e- machines with
sufficient energy and
FCC-hh can measure
this process

Room for Blue Sky Thinking!

Example: If we produce Dark Matter particles candidates, can we be sure it is really DM? Check the interaction with matter in a detector!!

DM Beam from Asymmetric Collider



	E_{high} $[TeV]$	E_{low} $[TeV]$	E_{cm} $[TeV]$	
FHC→Fixed Target	50	0.001	0.3	← insufficient E_{cm}
FHC↔LHC	50	7.000	37.4	promising!
FHC↔Super-SPS	50	3.000	24.5	

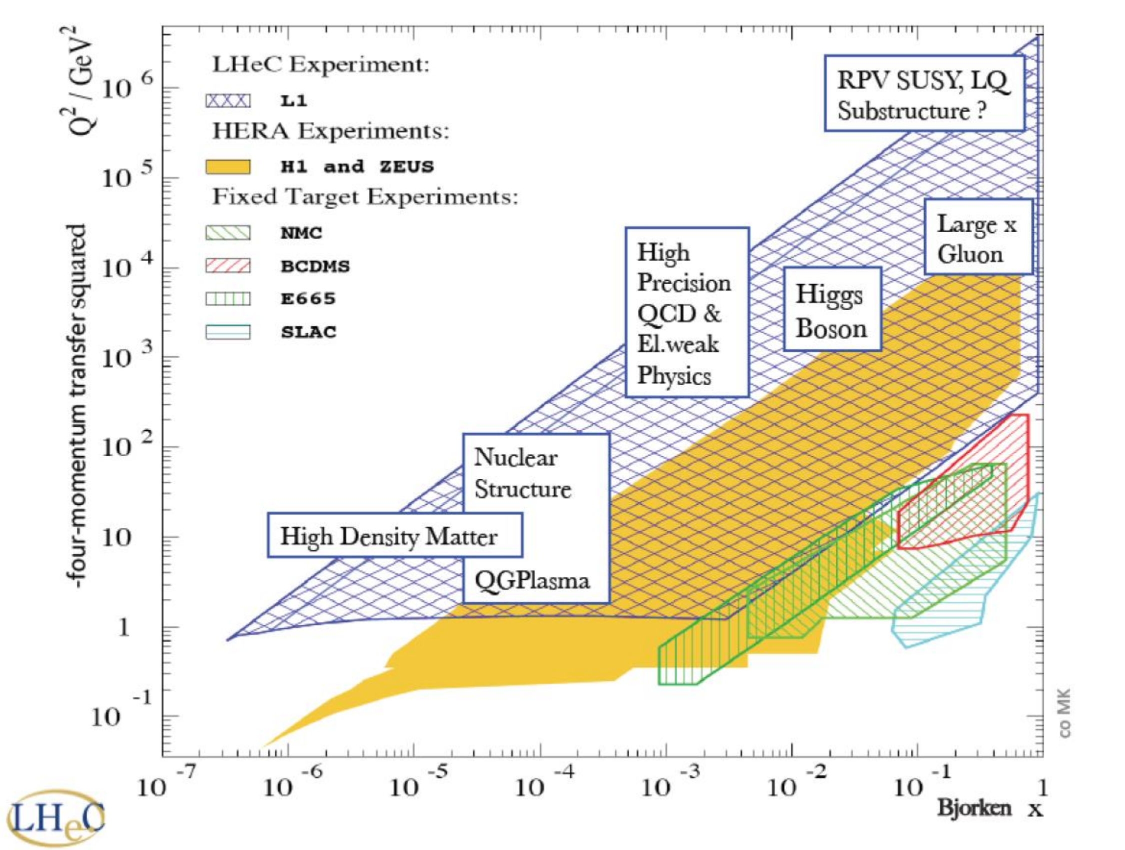
Long timescales: Time to explore new ideas!!

Conclusion

- In 2012 we found a Higgs Boson at the LHC. Next LHC run @ 14 TeV will hopefully reveal even more.
- The Higgs has started a new paradigm: Study the Higgs in detail. (HE-)LHC will be able to do a lot but very likely not everything.
- e+e- Higgs factories are being discussed & studied
- High energy pp colliders, eg at 100 TeV, will extend the reach for new particles and interactions
- A large international effort is coming together on the study for the high energy frontier, FCCs and LCs
- The path for new machines is long, and benefits for society (technology) will play an important role.

Electron-Proton Collider

Always a useful complement to a hadron collider
eg via measurement parton distribution functions



Breaking of Factorisation

Free Quarks

Unconfined Color

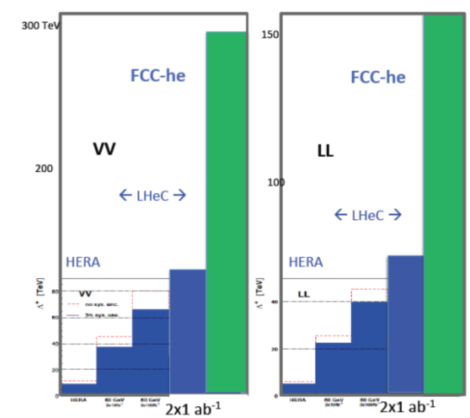
New kind of coloured matter

Quark substructure

New symmetry embedding QCD

QCD may break .. (Quigg DIS13)

Reach for CI (eeqq) at FCC-he



- Very preliminary scaling from LHeC
- Reach about O(100) TeV, expected to be competitive with FHC

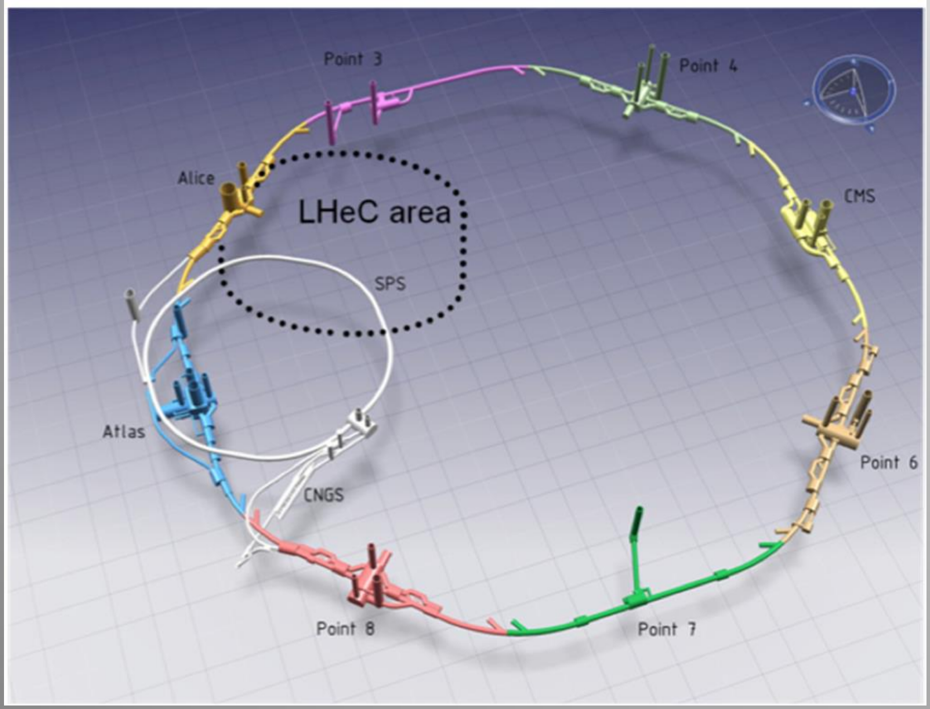
•Access to specific Higgs couplings
•Reach for new physics eg Leptoquarks, CIs…

FCC-he: the Electron-Proton Option

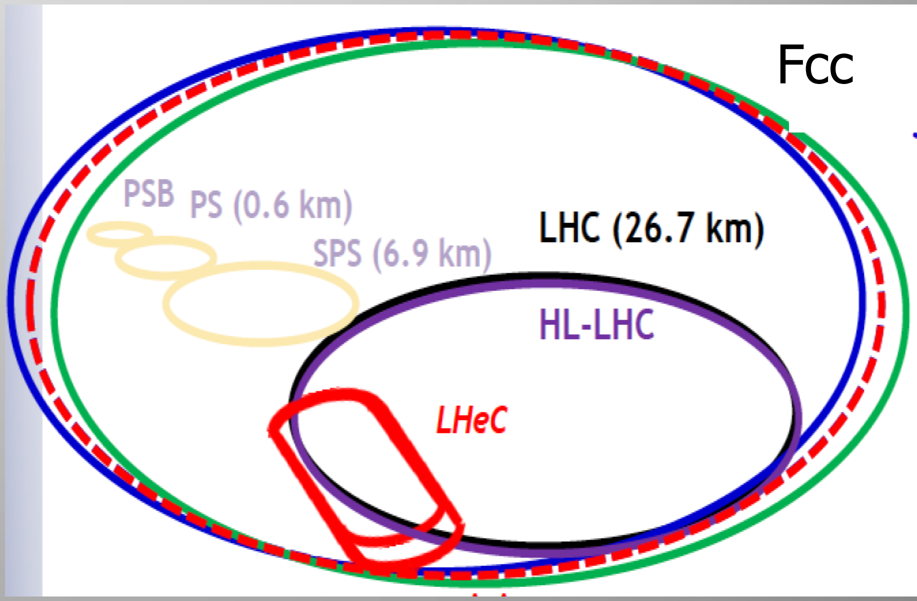
- Future possible hadron and lepton colliders will be excellent QCD explorers
- High luminosity (10^{34}-10^{35}) and/or energy lepton-hadron colliders

->Dedicated facilitie studies include the LHeC (Europe) and EIC (US) projects and now FCC-he

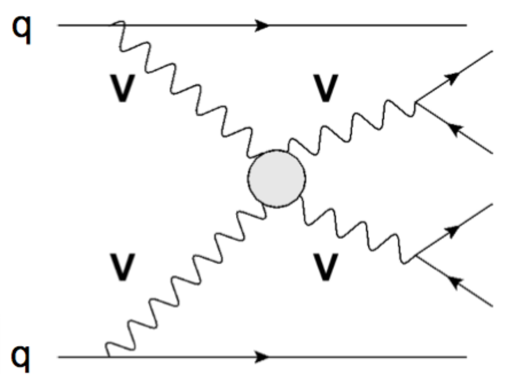
ep: 60 GeV x 7 TeV



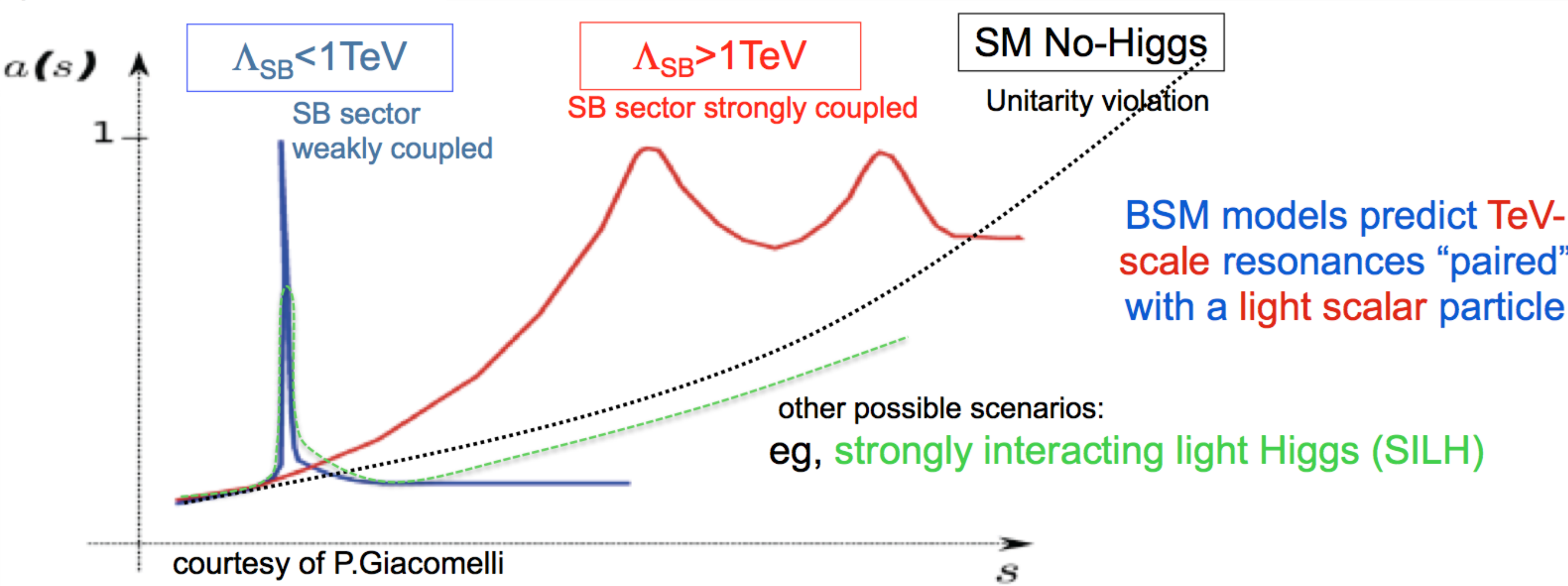
ep: 60-175 GeV x 50 TeV



Use FCC-ee ring or Energy Recovery Linac



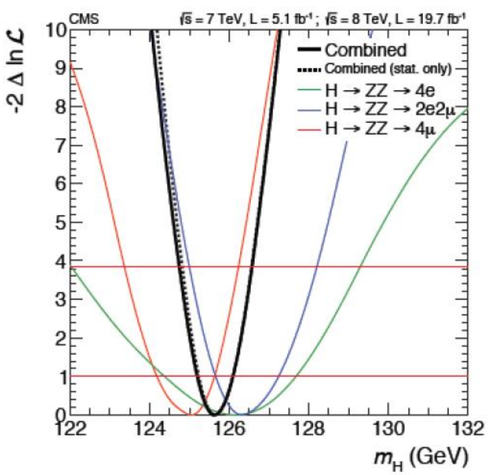
-unitarity restoration in VBS amplitudes strictly linked to EWSB mechanism.
-a SM Higgs does the job exhaustively.
-a non-SM Higgs needs further mechanism (heavy VV resonances ?)

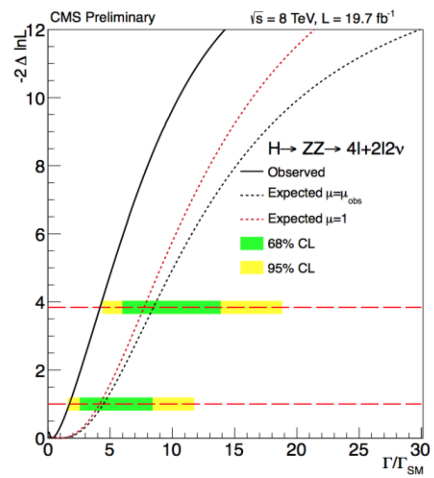


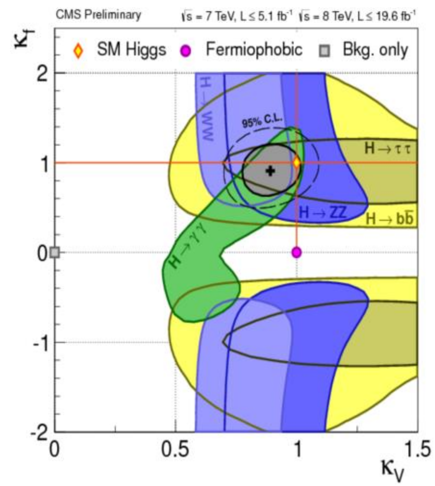
Challenging ! both for TH (interferences with qq→6f amplitudes) and EXP.s (small yields, wide y coverage, many channels) !!!

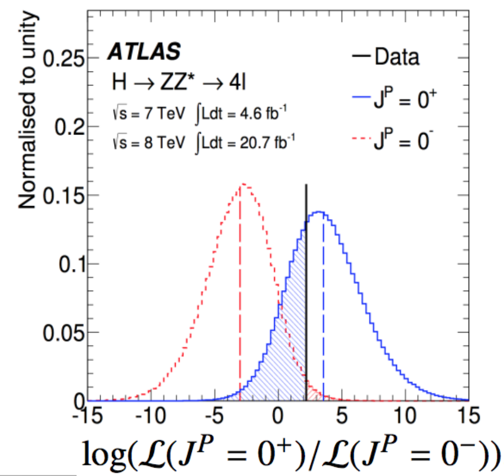
A Higgs…

We know already a lot on this Brand New Higgs Particle!!









Mass =
125.5 ±0.5 GeV

Width =
< 22 MeV
(95%CL)

Couplings are
within 20% of
the SM values

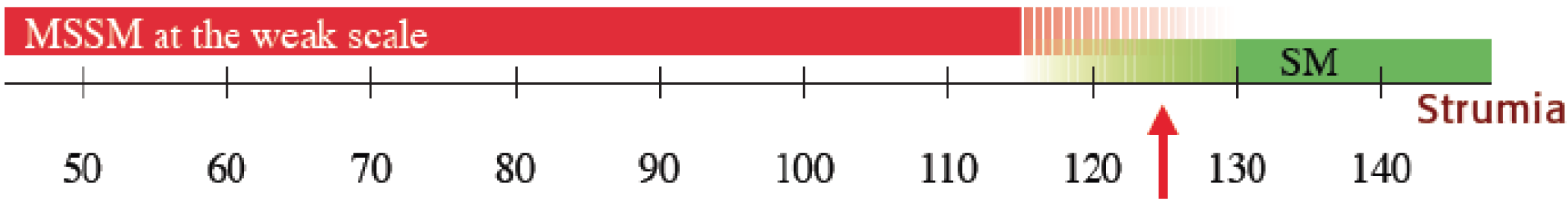
Spin =
0^+ preferred
over 0^-,1,2

Note: the LHC is a Higgs Factory: 1 Million Higgses already produced
15 Higgses/minute with present lumi.

A Higgs…

A malicious choice!

$m_H = 125.6 \pm 0.4$ GeV



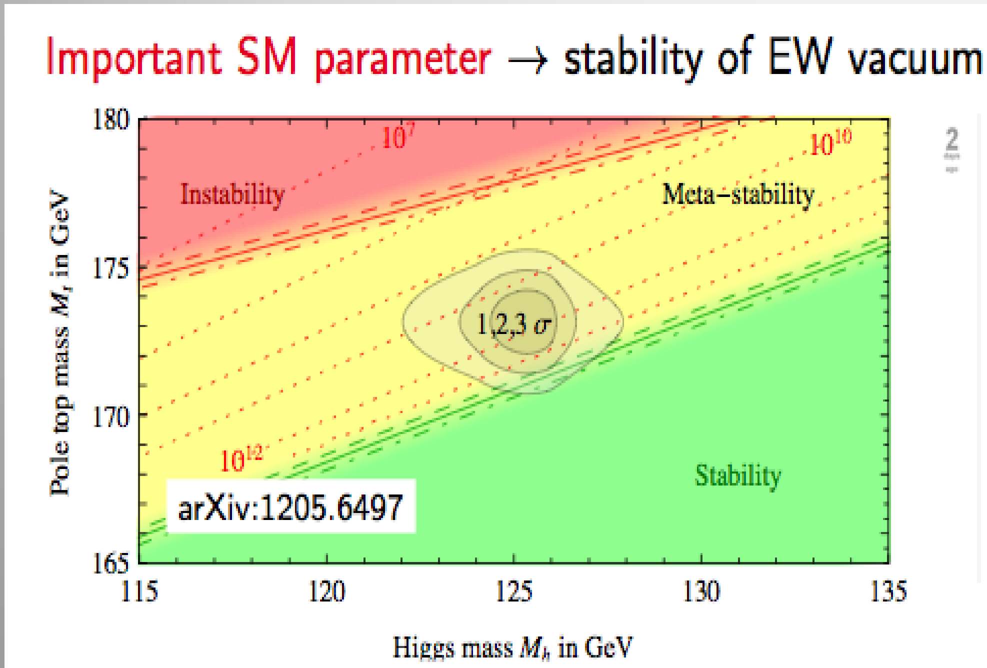
The Higgs:
so simple yet so unnatural

Guido Altarelli

Stockholm Nobel Symposium
May 2013

But there there still a lot of questions…

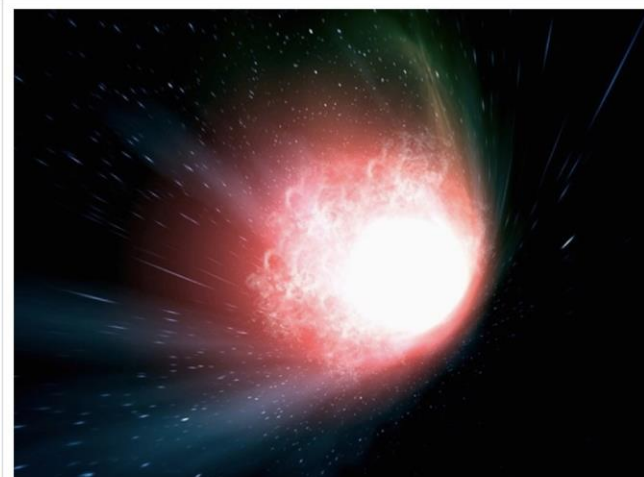
Consequences for our Universe?



Precise measurements of the top quark and first measurements of the Higgs mass:

Our Universe meta-stable ?
Will the Universe disappear in a Big Slurp? (NBCNEWS.com)

Will our universe end in a 'big slurp'? Higgs-like particle suggests it might



New Physics inevitable?
But at which scale/energy?