PHYSICS at the NEXT ELECTRON-POSITRON MACHINE (an introductary and conceptual view)

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INFIERI School
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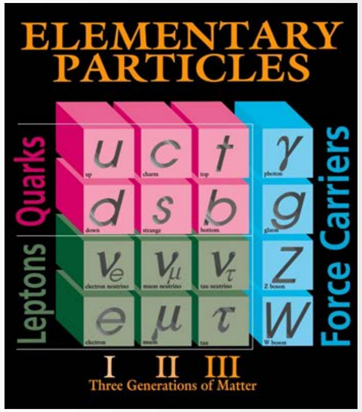
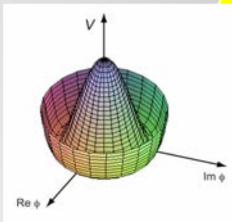
Standard Model

$$\mathcal{L}_{SM} = \mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}$$

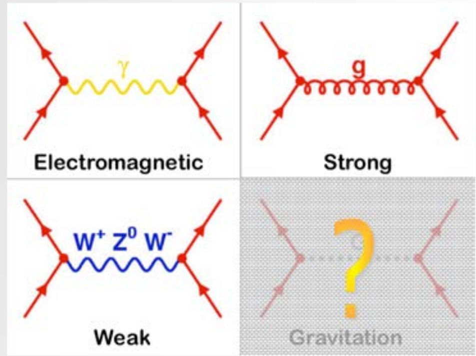
(~1980)

Symmetry





Higgs: EWSB



Particles

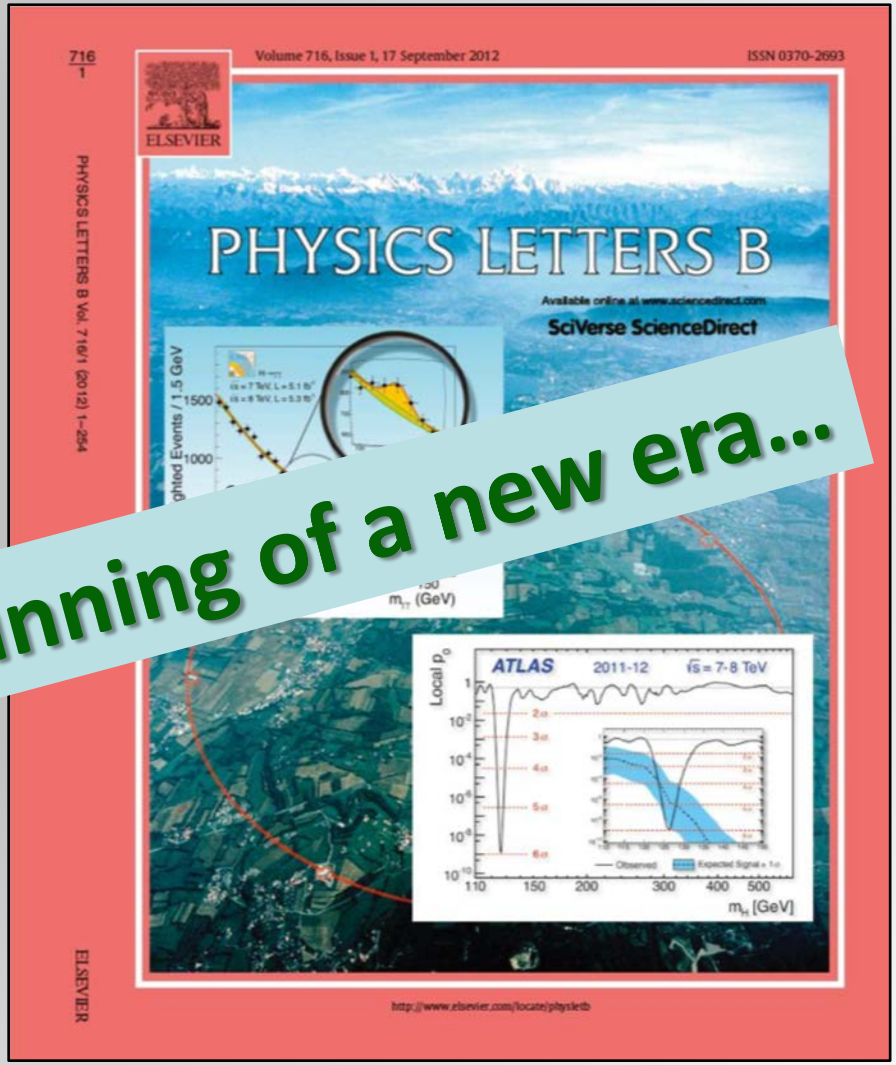
Interactions/Forces

ATLAS y CMS

"Higgs-H(125) discovery"

Phys. Lett. B716 (2012)

Physics Letters B cover



… this was the beginning of a new era…

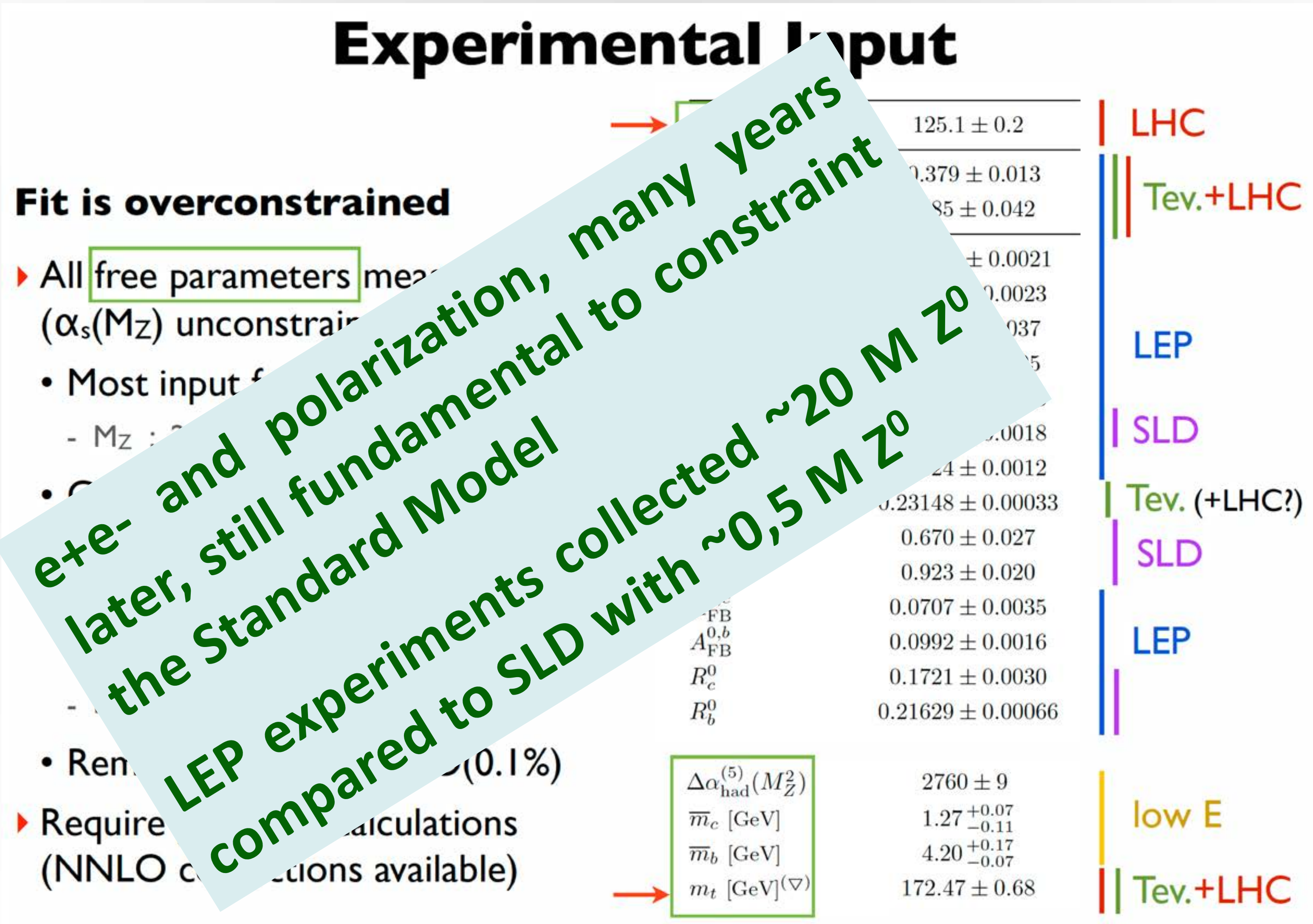
The Standard Model: Experimental pillars

Roman Kogler 2020,

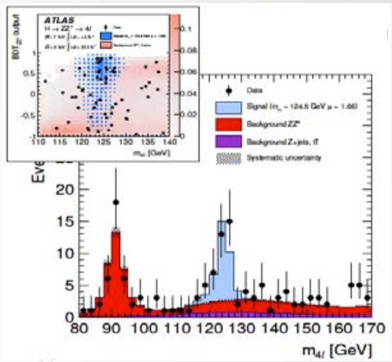
arXiv: 1509.00672;1708.06355;1803.01853

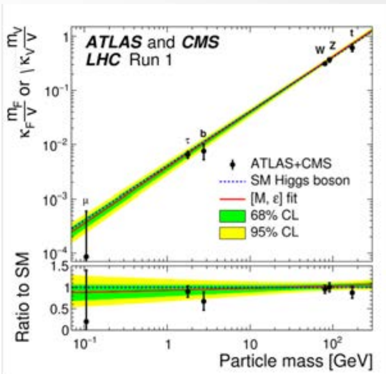
Gfitter group

http://project-gfitter.web.cern.ch/project-gfitter/Standard_Model/



Courtesy of Carmen García





The open questions about the "H(125)" :

1. **is it the boson of the (minimal) Standard Model ?**
2. **is it an elementary or composite particle ?**
3. **is it unique/solitary ?**
4. **is it natural ?**
5. **is it the first supersymmetric particle ever observed ?**
6. **is it really "responsible" for the masses of all elementary particles ?**
7. **is it mainly produced by top quarks or by new heavy vector-like particles ?**
8. **is it at the origin of the matter-antimatter asymmetry ?**
9. **has it driven the inflationary expansion of the Universe ?**

Need for precision and model independent tests

New Physics require precise measurements

Effects are seen as "low scale new physics" => modification of Higgs properties !

- different patterns of deviations from SM prediction for different NP models
- size of deviations depends on NP scale

Tiny differences between best fit and SM. In general precision at ~% or better is required

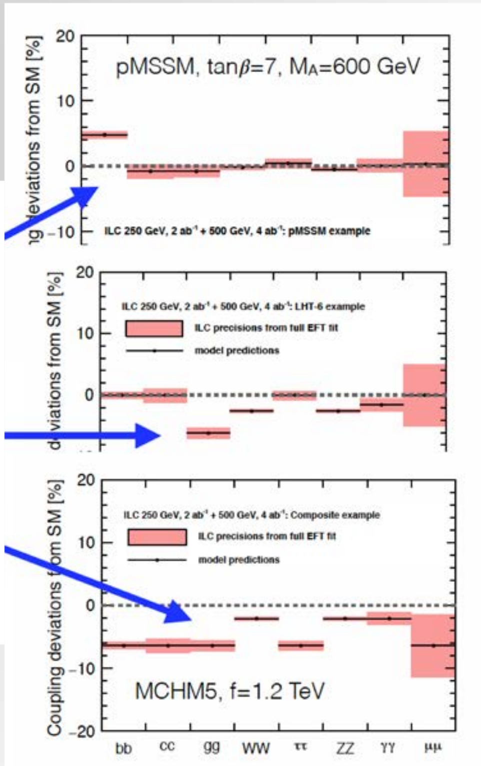
Supersymmetry: $g(\tau)/SM = 1 + 10\% \left(\frac{400\ \mathrm{GeV}}{m_A}\right)^2$

$g(b)/SM = g(\tau)/SM + (1-3)\%$

Little Higgs: $g(g)/SM = 1 + (5-9)\%$

$g(\gamma)/SM = 1 + (5-6)\%$

Composite Higgs: $g(f)/SM = 1 + (3-9)\% \cdot \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$



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New Physics require precise measurements

Effects are seen as "low scale new physics" => modification of Higgs properties !

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-

Not only the values are important (~%)
but also the pattern of the deviations
(to distinguish models)

Tiny dif … uired

Supersymmetry: $g(\tau)/SM = 1 + 10\% \left(\frac{400\ \mathrm{GeV}}{m_A}\right)^2$

$g(b)/SM = g(\tau)/SM + (1-3)\%$

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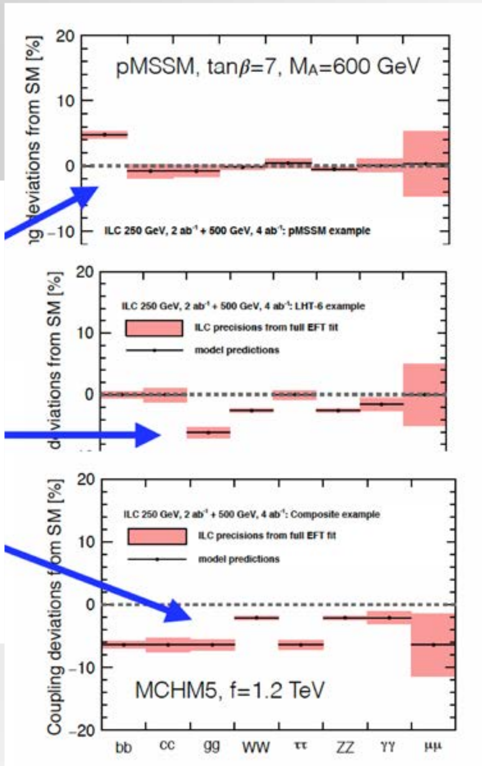

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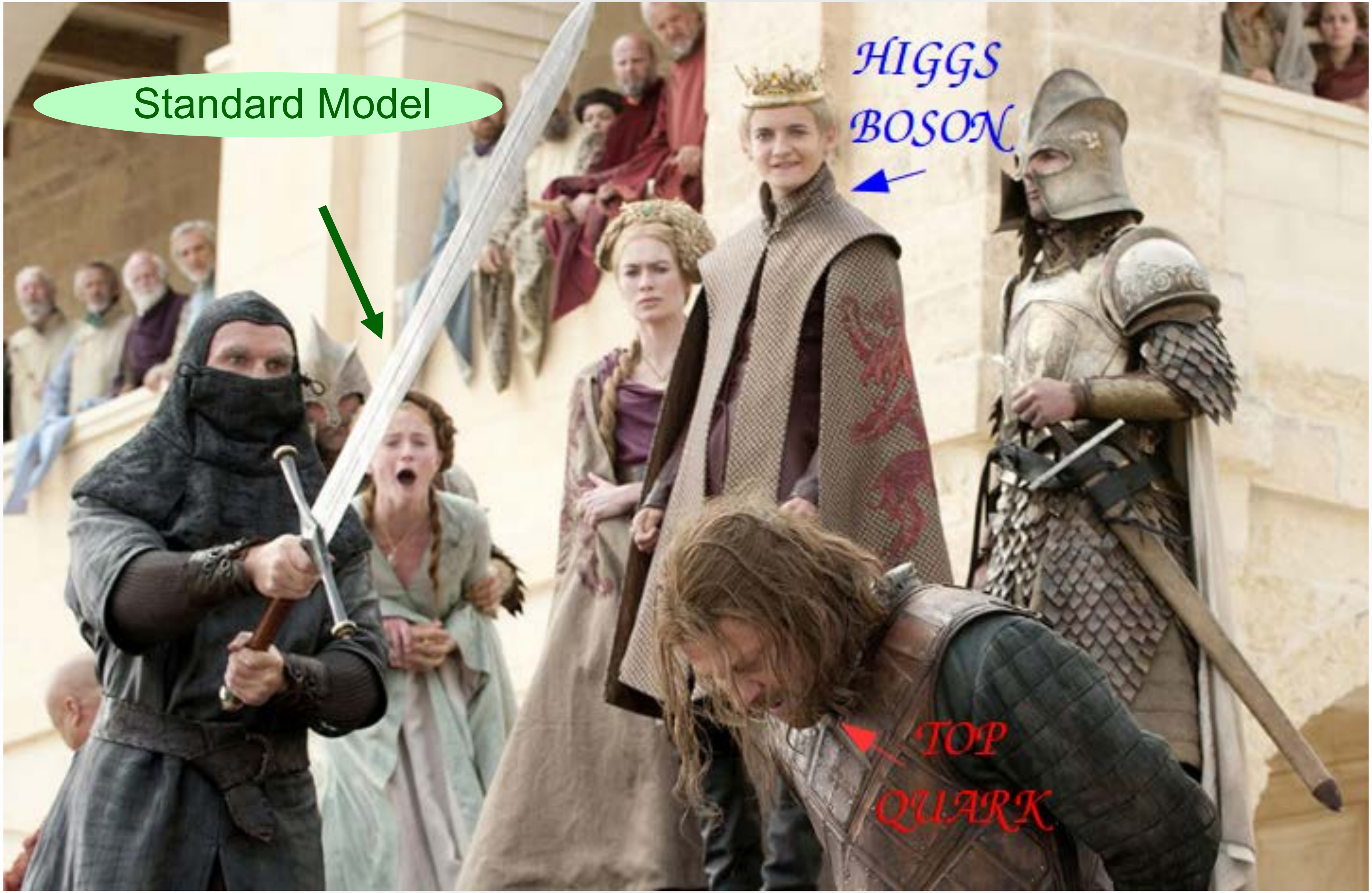
But not only the H(125) !!!

But not only the H(125) !!!



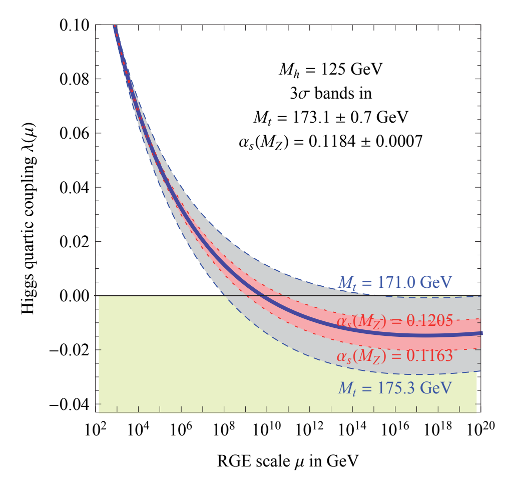
Stability of the Higgs potential (a personal, biased example)

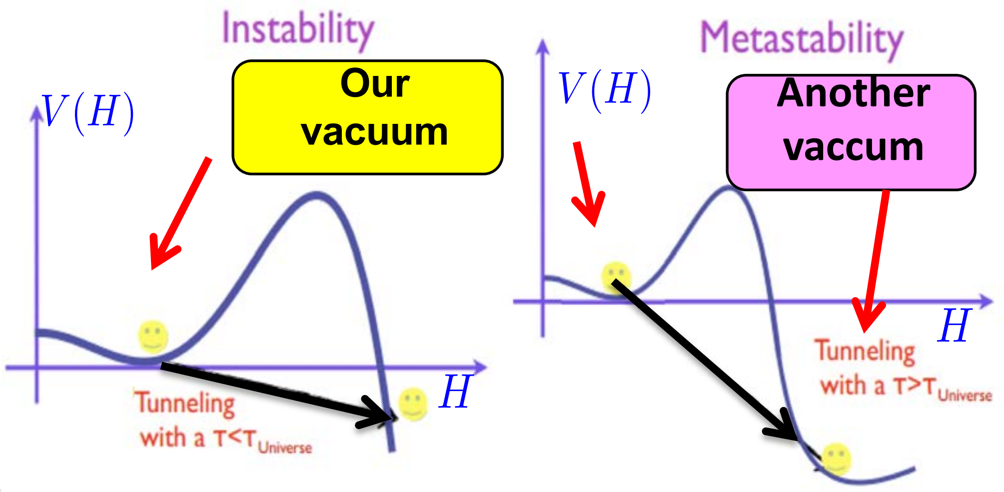
Vacuum Stability ($\lambda(\Lambda) \geq 0$)

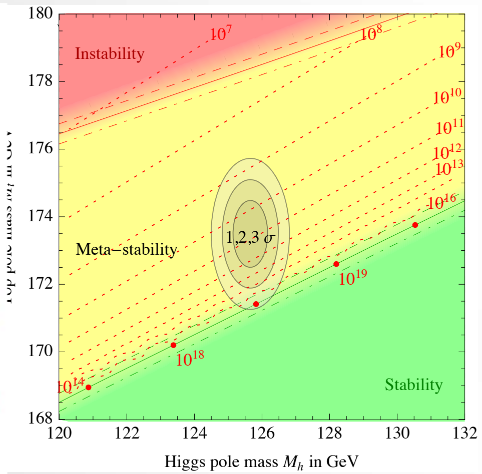
$\lambda(\Lambda)$ the $\overline{\text{MS}}$ quartic Higgs Coupling

Degrassi et al, JHEP 1208 (2012) 098

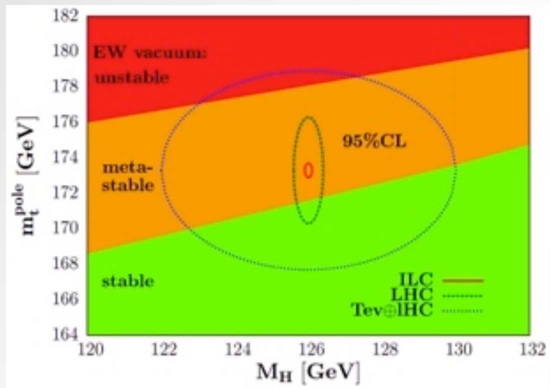
Butazzo et al, 1307.3536 (2013)







Alekhin et al, Phys.Lett. B716 (2012) 214

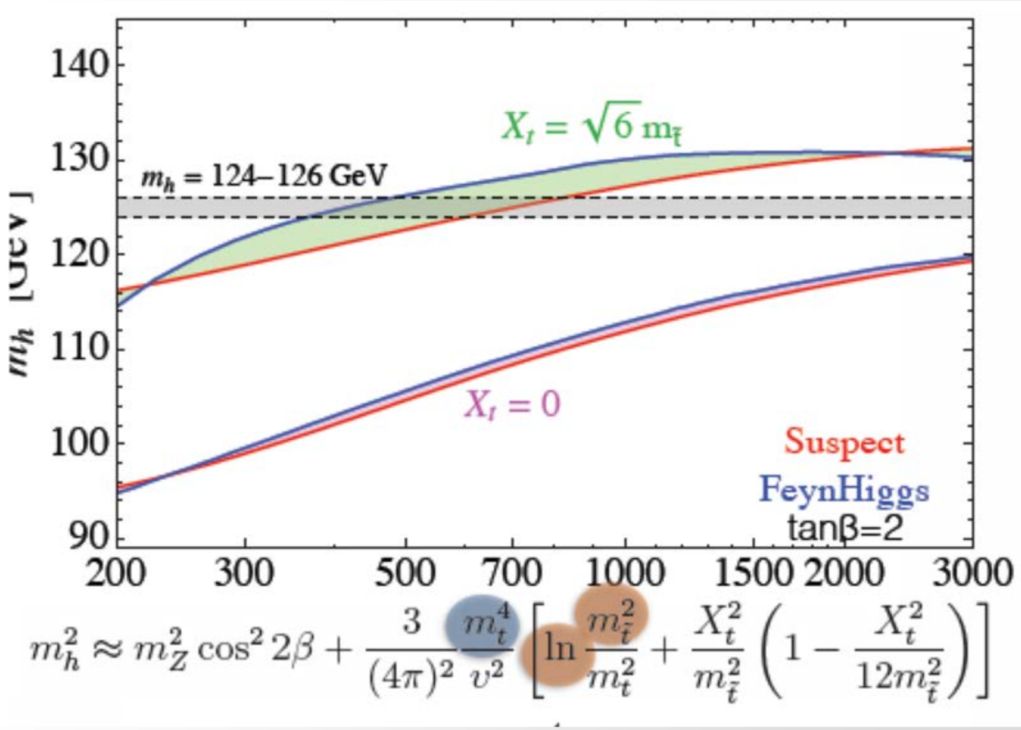


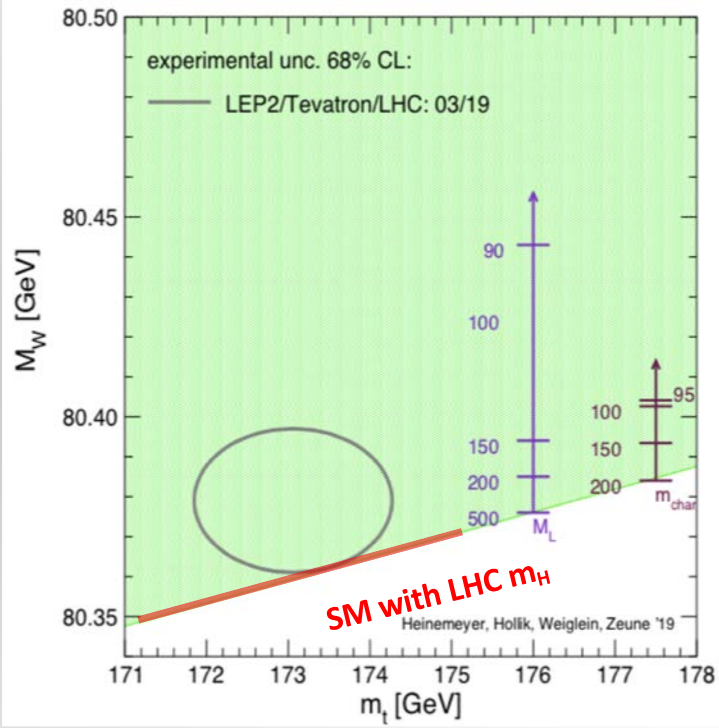
Need to measure m_t with very high accuracy:

$\Delta m_t < 100$ MeV

(The existence of New Physics would change the scenario)

Top mass and W mass (a personal, biased example)





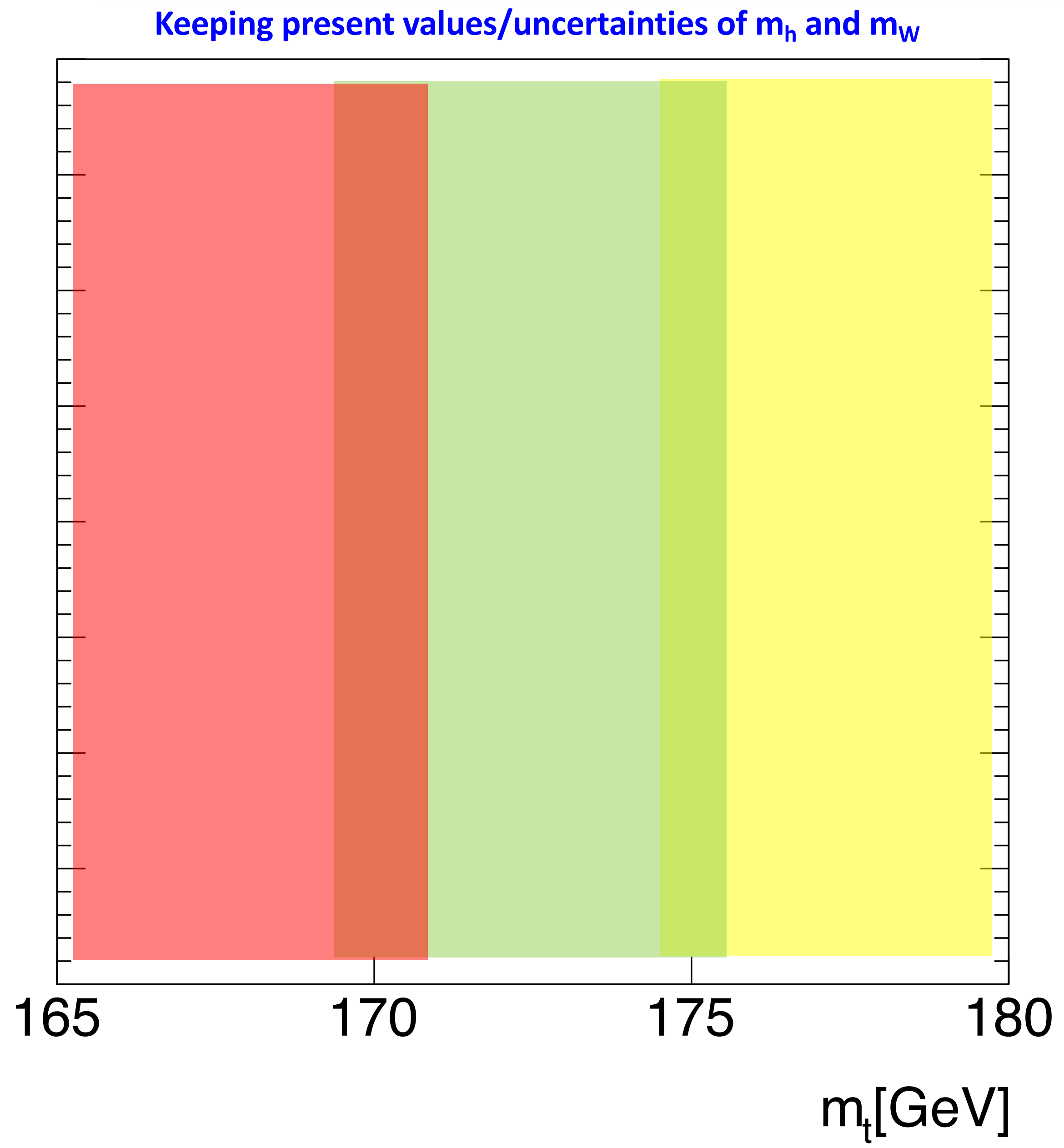
Roberto Franceschini (IFIC seminar, Valencia)

[www.ifca.unican.es/users/heinemey/uni/plots]

Large mass ⟺ **Sizeable effects**

Low values of the top-quark mass ⟺ **less SM**

Top mass and Higgs Mass relation (a personal, biased example)



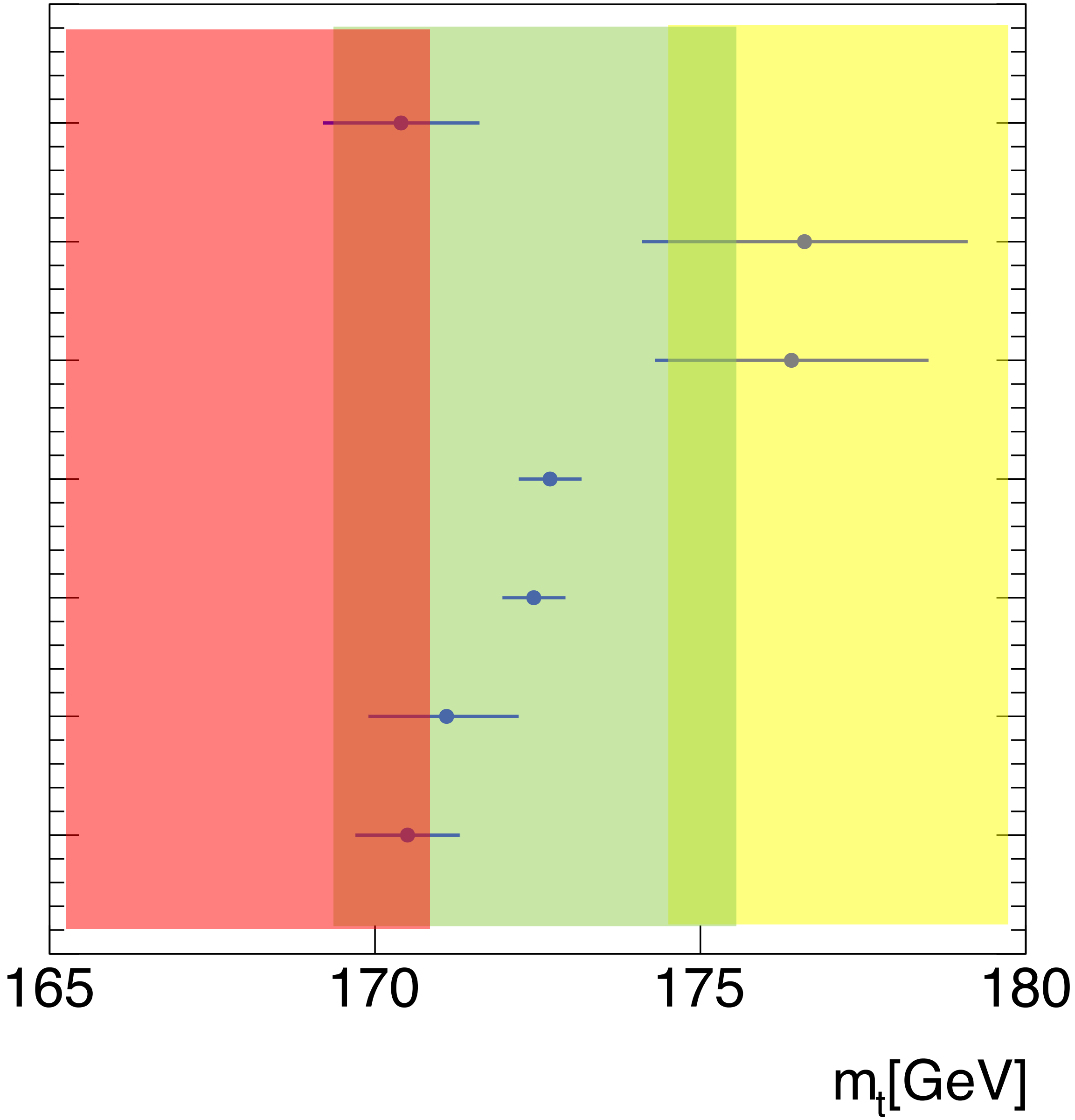
New Physics at Low EW Energy Scales (Heinemmeyer et al.)

Need for New Physics @ Large Energy Scales
Vacuum Stability: Meta-stable Universe

Need for New Physics @ Large Energy Scales
Vacuum Stability: Unstable Universe

Top mass and Higgs Mass relation (a personal, biased example)

Keeping present values/uncertainties of m_h and m_W



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Global Fit – NNLO QCD

EW- Fits: HEPfit. & Gfitter

ATLAS & CMS

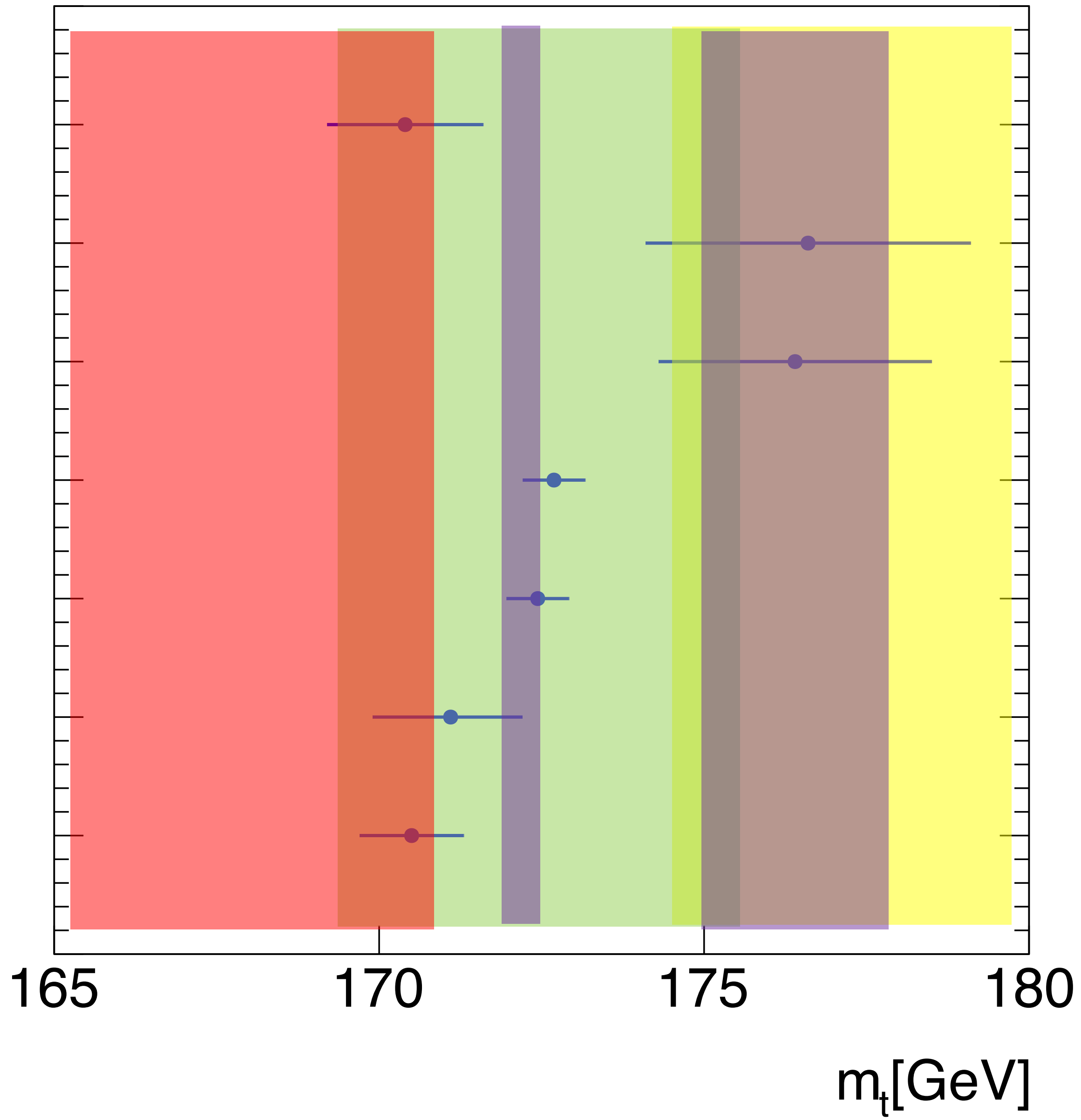
Combinations of "Direct Measurements"

ATLAS & CMS

Total & Differential Cross-Sections
3D and tt+1jet

Top mass and Higgs Mass relation (a personal, biased example)

Keeping present values/uncertainties of m_h and m_W



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HL-LHC

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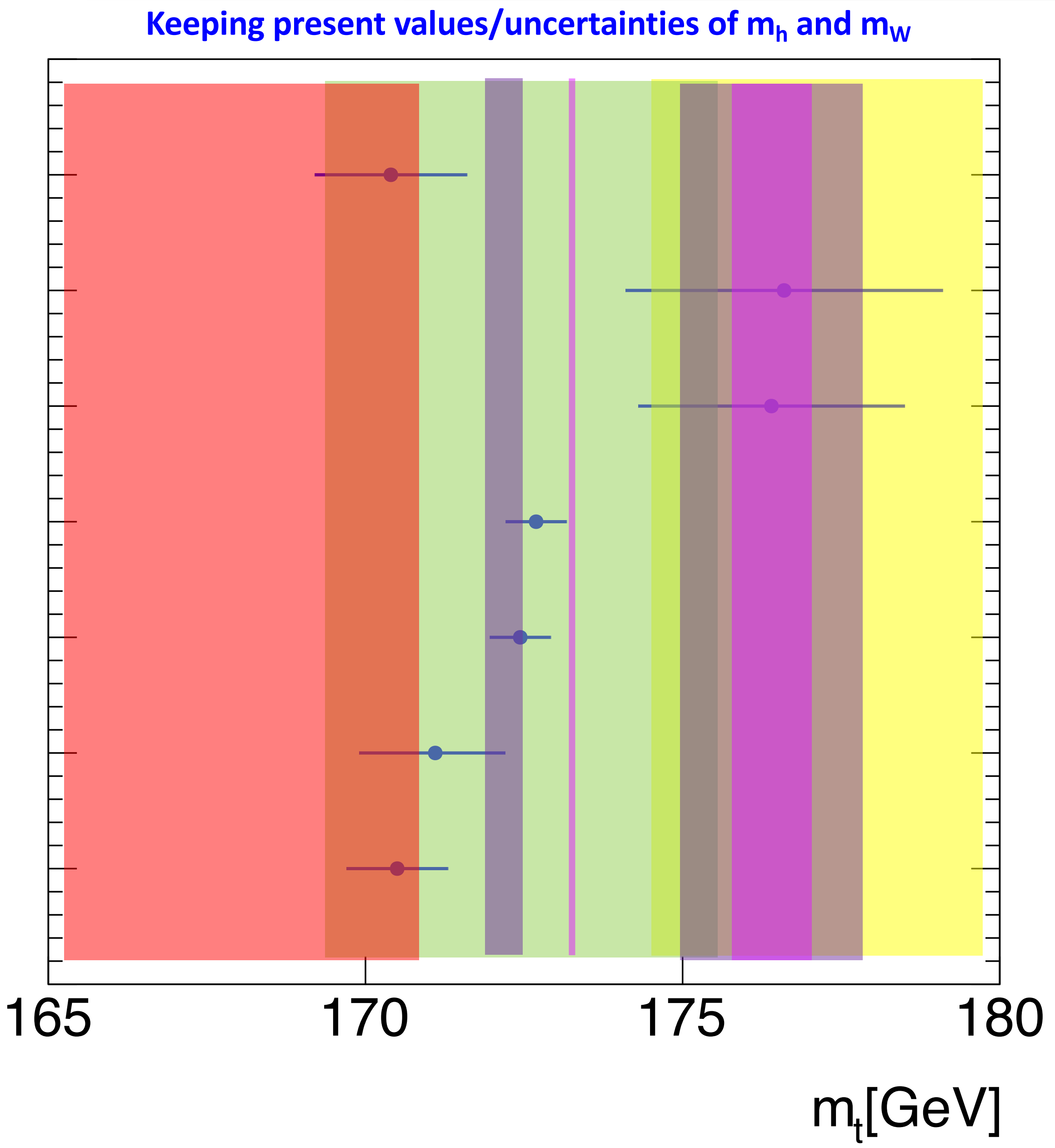

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Combinations of "Direct Measurements"

ATLAS & CMS

Total & Differential Cross-Sections

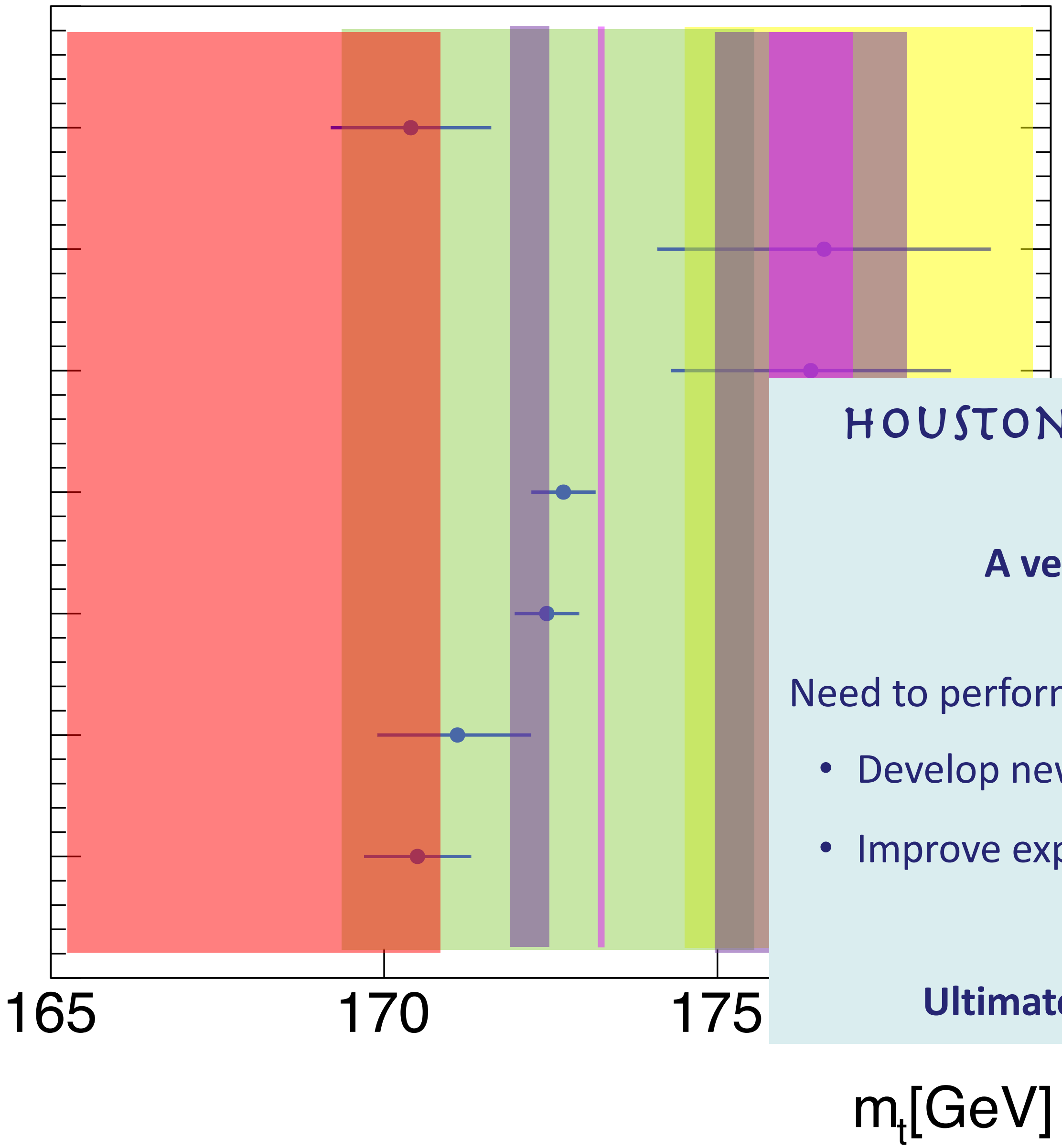
3D and tt+1jet

HL-LHC

Future e+e- Collider

Top mass and Higgs Mass relation (a personal, biased example)

Keeping present values/uncertainties of m_h and m_W



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Need for New Physics @ Large Energy Scales Vacuum Stability: Meta-stable Universe

Need for New Physics @ Large Energy Scales Vacuum Stability: Unstable Universe

HOUSTON WE HAVE A CHALLENGE !!!

A very interesting challenge in fact

Need to perform highly precise m_t / m_W measurements:

- Develop new calculations/observables
- Improve experimental methods

Ultimate precision at e+e- future colliders

Dark Matter

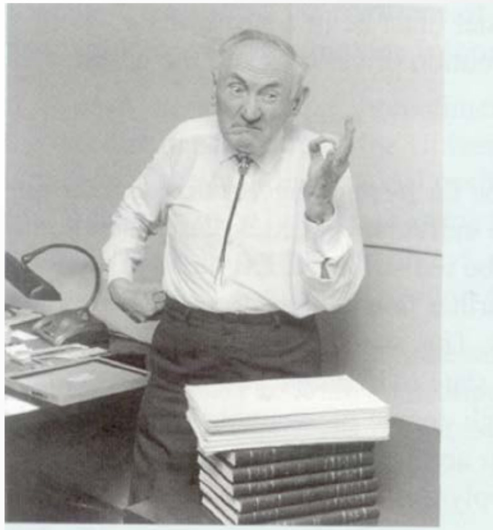
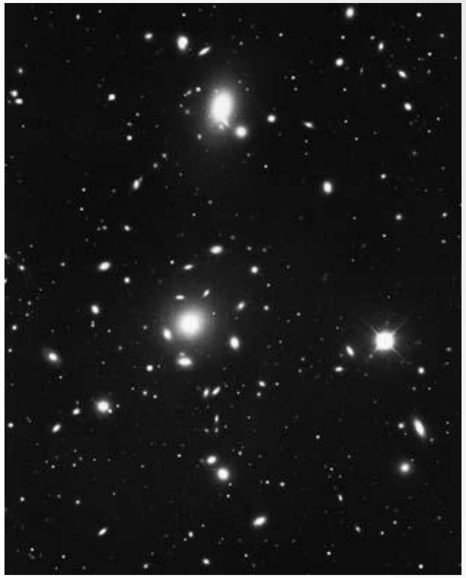


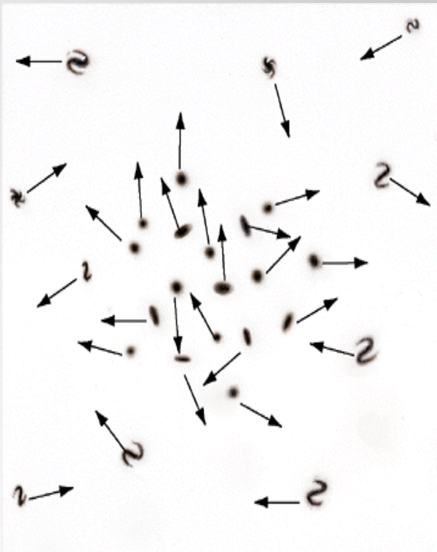
Figure 4.6 Fritz Zwicky (1898 – 1974). (California Institute of Technology)

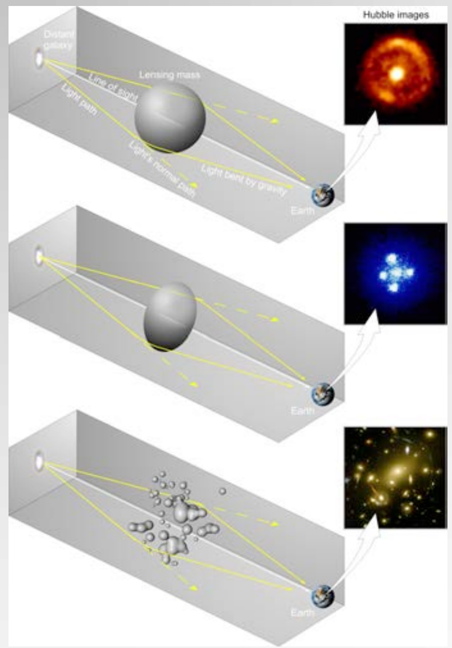
1930s: Fritz Zwicky, studied the Coma galaxy cluster infering the existence of unseen matter, which he referred to as *dunkle Materie* “Dark Matter”.

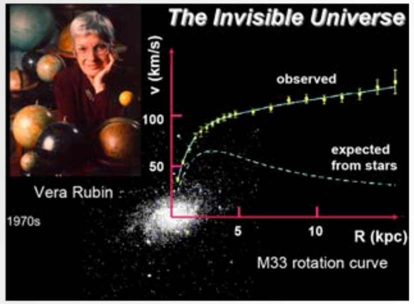
Since then many other observations confirm the existence of “Dark Matter” (gravitational lenses).

No candidate for “Dark Matter” in the SM

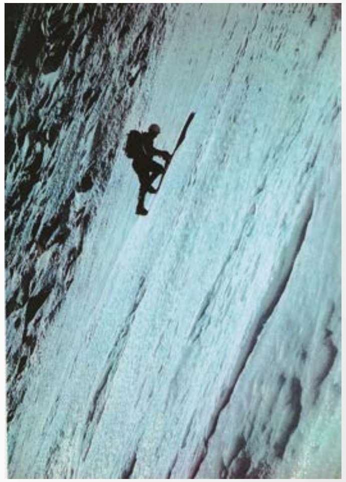






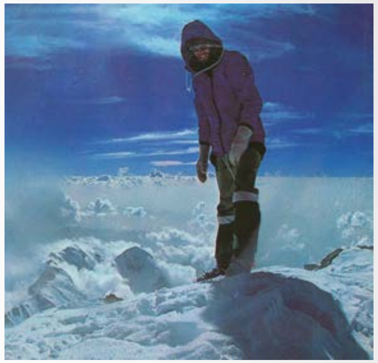


H(125) discovered and new challenges appear



Long and successful scientific programme, many studies, resources, and investigations during years of research in theory and experiment (PETRA, PEP, Babar, Belle, HERA, LEP, Tevatron, LHC, etc..) have led to build up the Standard Model

Reinhold Messner



Culminated with the discovery of H(125)

But.. this is just one more “step” which allows us to have a “better view” of what is next.

- One question answered, H(125)
- Many old questions remain (DM, etc..)
- New questions open

H(125) discovered and new challenges appear

Fundamental questions to answer:

- What establishes the Higgs mass ?, is it elementary/composite ?
- Which is the mechanism behind electroweak symmetry breaking ? (one or more Higgs)
- What is the nature of Dark Matter ?
- What drives inflation ?
- Why the Universe is made out of matter ?

Our (main) tools in High Energy Physics:

- H(125)

- Top quark, b/c quarks,
- W/Z bosons

- Searches for new physics – new particles

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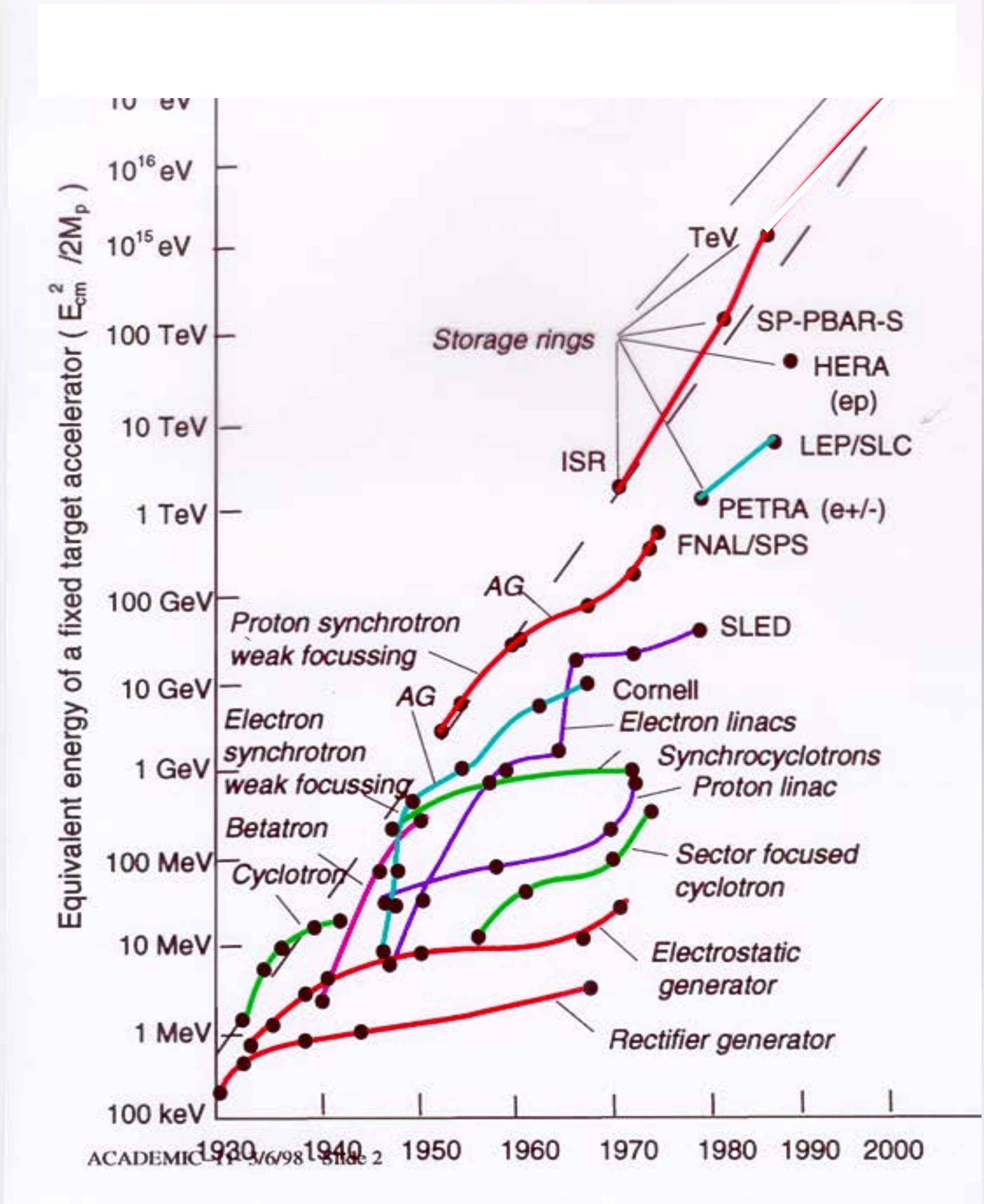
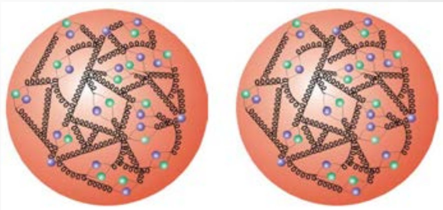
Our Instruments: The accelerators



- Continuous development last 90 years
- New technologies have been necessary to overcome saturation of past technologies bringing new ranges of energy
- Superconductivity is now the basic technology but cannot be the last. PLASMA acceleration can be the future (potential improvement factor of 1000 accelerating power)
- **Challenges in Circular Colliders:**
  - ✓ Ultra-high field magnets
  - ✓ Synchrotron radiation
- **Challenges in Linear Colliders:**
  - ✓ High gradient acceleration
  - ✓ Use of nano-beams

See talks: Angeles Faus-Golfe & Ralf Wolfgang

Our Instruments: The accelerators landscape

p  p

LHC

In Operation

2011-15 ~29 fb^{-1} @ 7/8 TeV

~2020 ~160 fb^{-1} @ 13 TeV

~2035 3000 fb^{-1} @ 14 TeV HL-LHC

Proposals

FCC-hh @100 TeV & SppC @ 50-70 TeV

e^+ • • e^-

Linear Colliders:

ilc **250...500...1000 GeV**

clic **250...1500...3000 GeV**

Cirrcular Colliders:

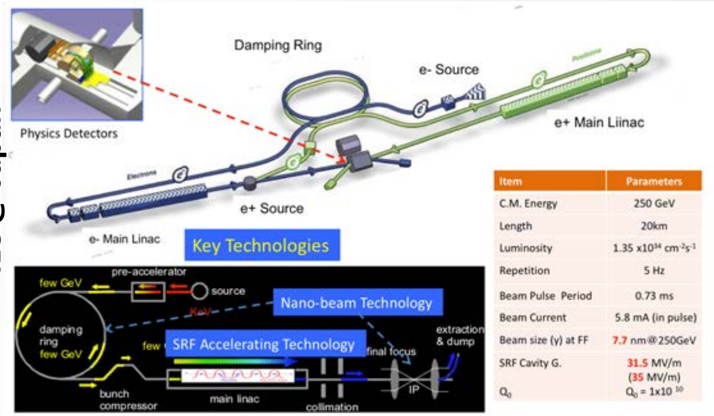
CepC 90..250 GeV

FCC-ee 240..350 GeV

(Others: $\gamma\gamma \rightarrow H$, $ep \rightarrow H+X$, $\mu\mu \rightarrow H$)

Our instruments: e+e- Higgs Factories proposals

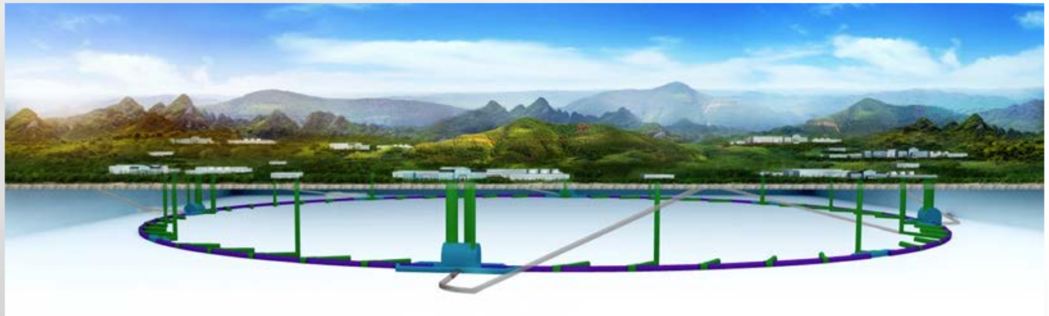
ILC @ Japan



Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35×10^{34} $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G.	31.5 MV/m (35 MV/m)
Q_0	$Q_0 = 1 \times 10^{10}$

ILC: e+e- @ 250 GeV - 500 GeV – 1 TeV
Polarized beams (e- 80%, e+ 30%)
Technical Design Rep. in 2013
Staging proposal 2017: start at 250 GeV
Summer 2020: ICFA installed International Development Team
Now: preparing funding proposal for 4 years of pre-laboratory

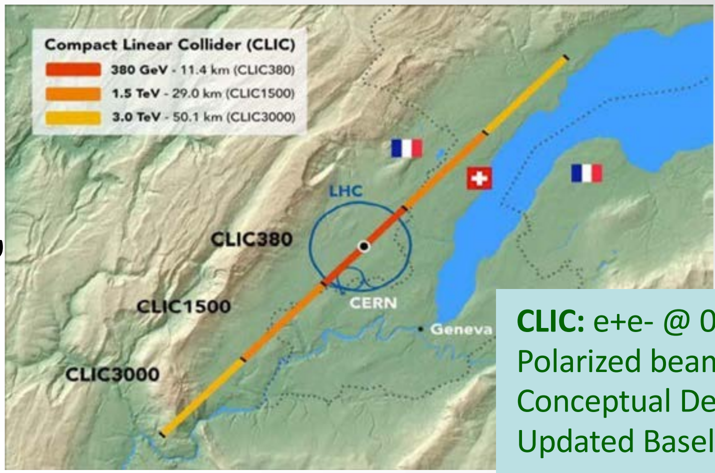
CEPC@China



CEPC: e+e- @ 240 GeV & pp @ 50-70 GeV
Conceptual Design Report published 2017
Technical Design by 2022
SppC: pp@ 50-70 GeV

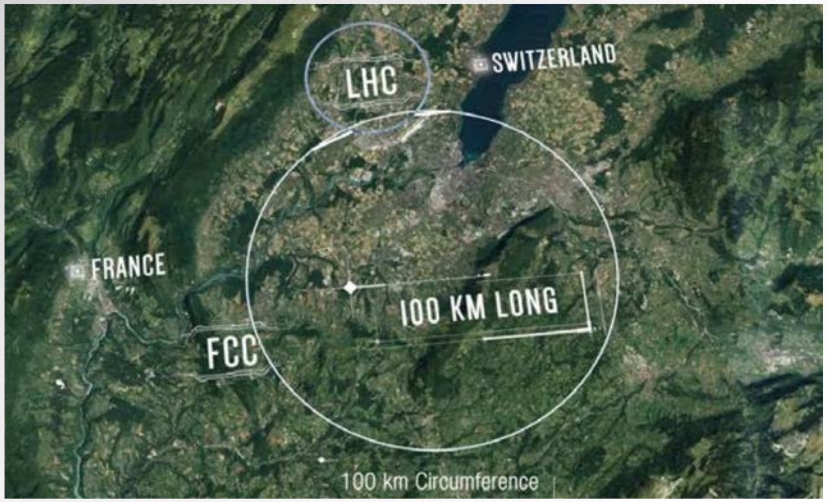
FCC: e+e- @ 90-350 GeV & pp @ 100 TeV
Conceptual Design Report published 2017

CLIC @ CERN

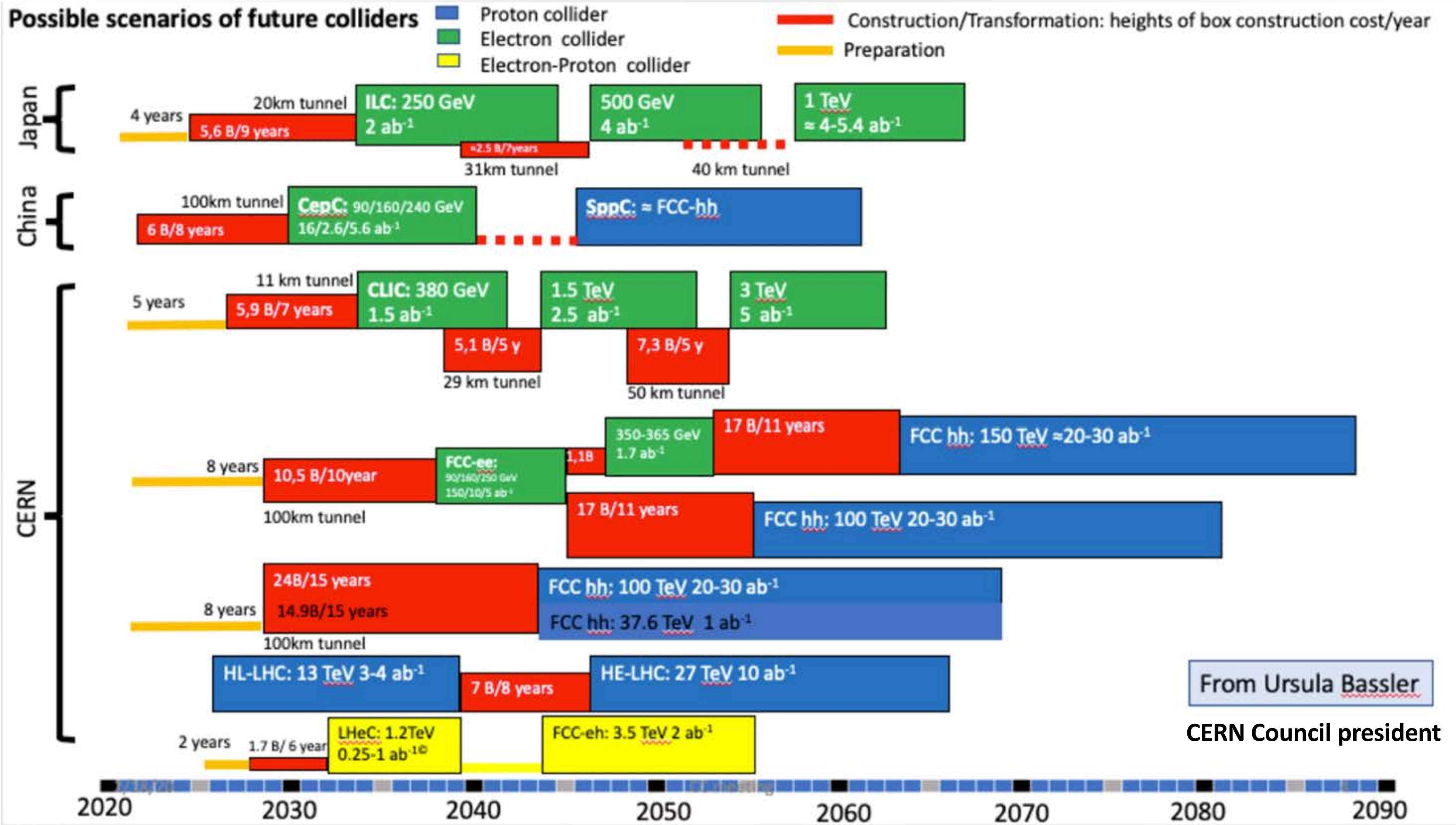


CLIC: e+e- @ 0,38,1,4 TeV, 3 TeV
Polarized beams (e- 80%, e+ 0%)
Conceptual Design Report 2012
Updated Baselien 2017

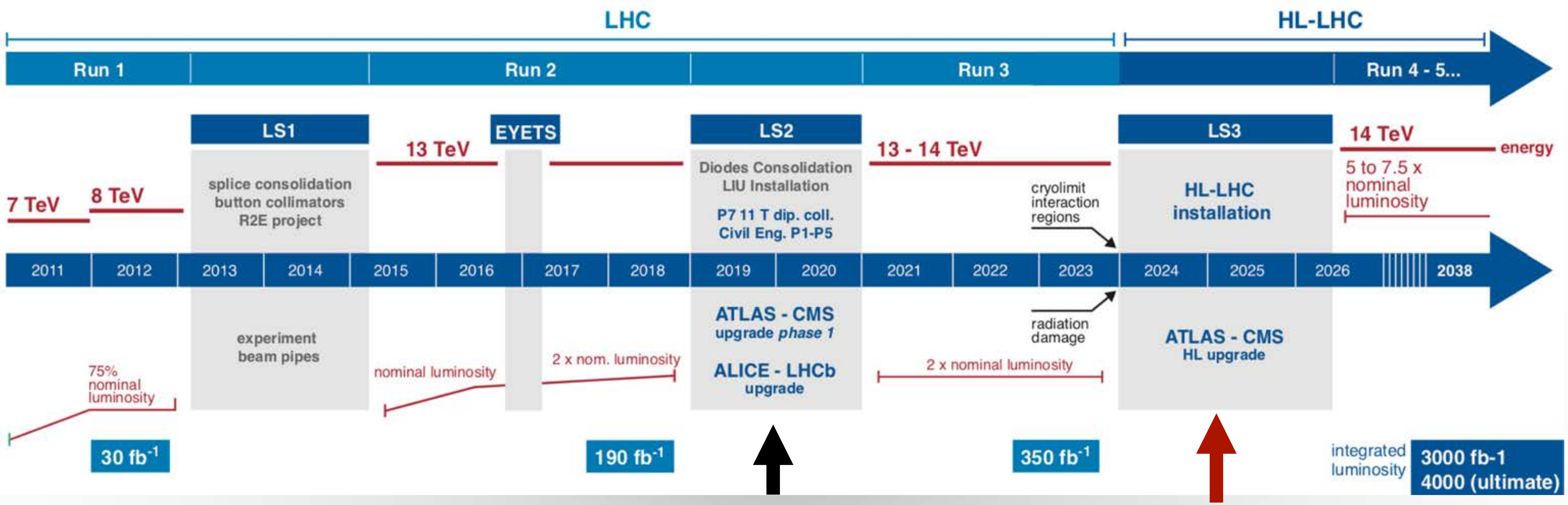
FCC-ee @ CERN



Timeline and possible scenarios for future colliders



LHC and HL-LHC programme



LS2 (2019-2020):

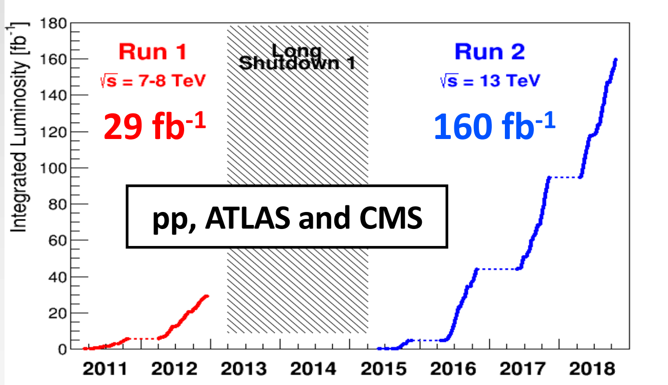
- ❑ **LHC Injectors Upgrade (LIU)**
- ❑ **Civil engineering for HL-LHC equipment P1, P5**
- ❑ **Installation of (part of) 11T Nb_3Sn dipoles for HL-LHC**
- ❑ **Phase-1 upgrade of LHC experiments**

LS3 (2024-2026):

- ❑ **HL-LHC installation**
- ❑ **Phase-2 upgrade of ATLAS and CMS**

Run 1 + Run 2:

ATLAS, CMS: ~189 fb^{-1} (goal was 150); LHCb: ~10 fb^{-1}



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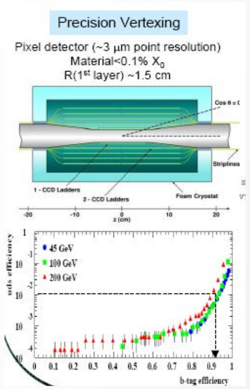
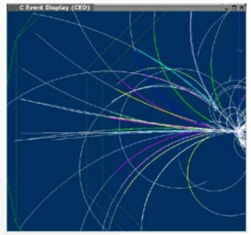


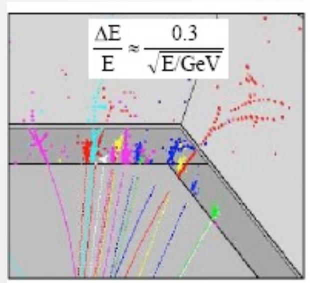


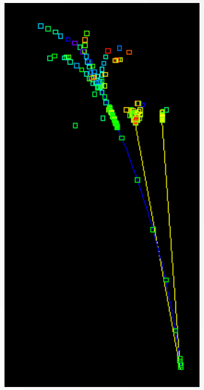
- **Vertex, "flavour tag"** $(h \to b\bar{b}, c\bar{c}, \tau^+\tau^-)$

  ~1/5 $r_{beampipe}$, ~1/30 pixel size (ILC wrt LHC), vtx 1-2 cm

  vtx 2-3 cm (CLIC wrt ILC)

$$\sigma_{ip} = 5\mu m \oplus 10\mu m / p\sin^{3/2}\theta$$





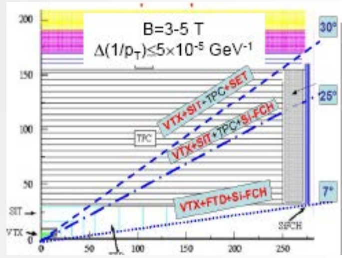
- **Tracking, "recoil mass"**

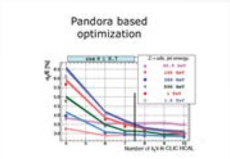
$$(e^+e^- \to Zh \to \ell^+\ell^- X; \text{incl. } h \to \text{nothing})$$

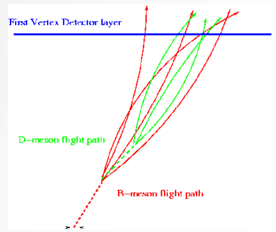
  ~1/6 material, ~1/7 resolution (ILC wrt LHC),

  B=4-5 T (CLIC and ILC)

$$\sigma(1/p) = 5\times10^{-5}/\text{GeV}$$





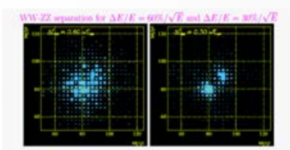


- **Particle Flow, Jet Energy Rec. → Tracker+Calorimetry**
- **Di-jet mass Resolution, Event Reconstruction, Hermiticity, coverage**

  ~1/2 resolution (ILC wrt LEP),

  Redesign Forward Region, HCAL 7,5 l (CLIC wrt ILC)

$$\sigma_E / E = 0.3/\sqrt{E(\text{GeV})}$$

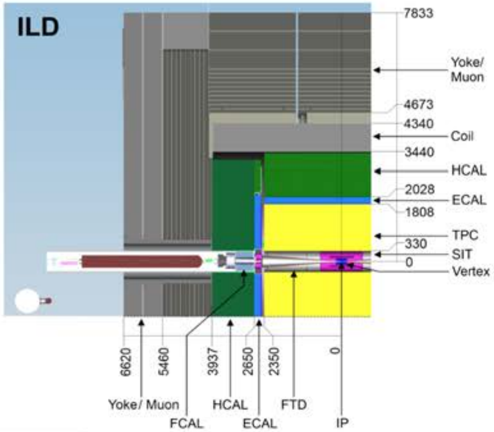


Our Instruments: The detectors for Linear Colliders

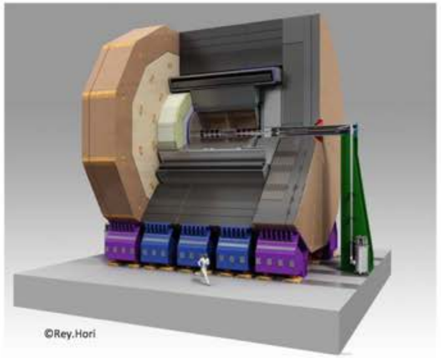
ILD: a multi purpose detector for the ILC

- Excellent vertexing very close to the IP
- Hybrid tracking system optimized for excellent resolution at high energies and ultimate efficiency over a broad momentum range
- Particle flow as the key design driver

Up to HCAL, all inside solenoidal coil of 3-4 T



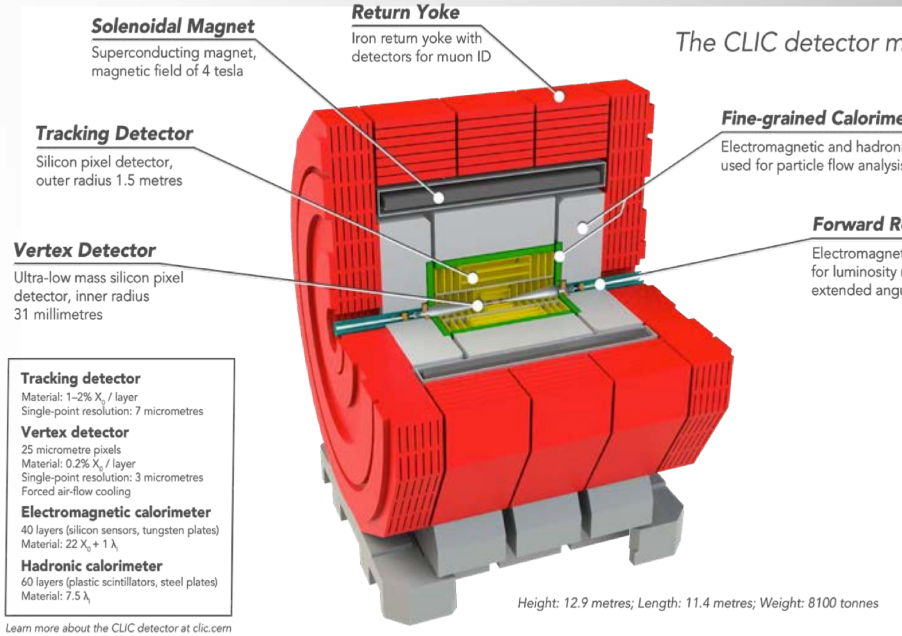
~15 m



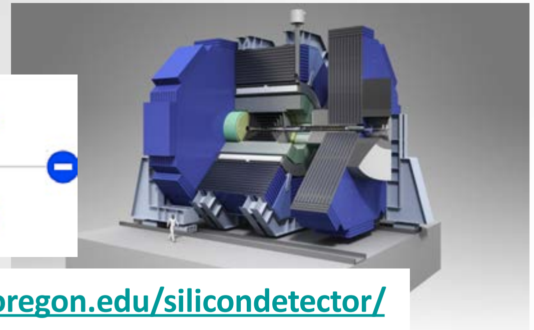
https://www.ilcild.org/

ILCX2021 ILC Workshop on Potential Experiments

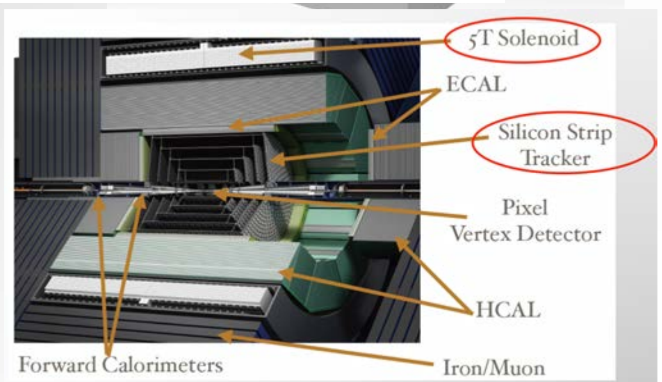
https://agenda.linearcollider.org/event/9211/



https://clicdp.web.cern.ch/



https://pages.uoregon.edu/silicondetector/



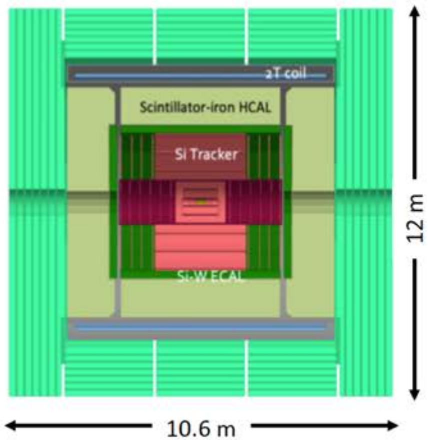
J. Fuster

Our Instruments: The detectors for Circular Colliders

"Proof of principle concepts"
- Not necessarily matching (all) detector requirements, which are still being spelled out

Mogens Dam
ECFA detector R&D Roadmap
(Feb, 2021)

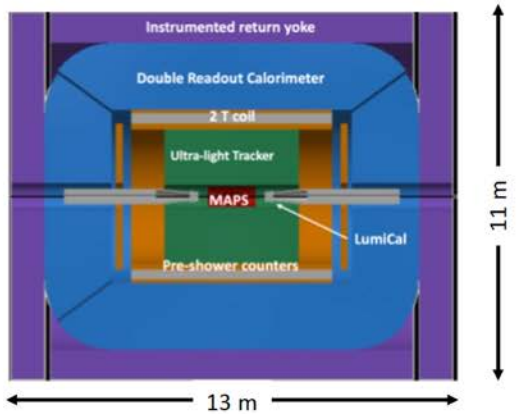
CLD



- Based on CLIC detector design; profits from technology developments carried out for LCs (c.f. F.Simon's talk)
  - All silicon vertex detector and tracker
  - 3D-imaging highly-granular calorimeter system
  - Coil *outside* calorimeter system

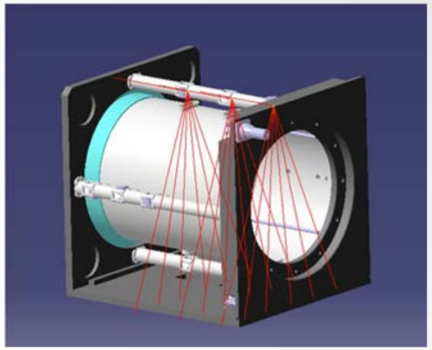
https://arxiv.org/abs/1911.12230, https://arxiv.org/abs/1905.02520

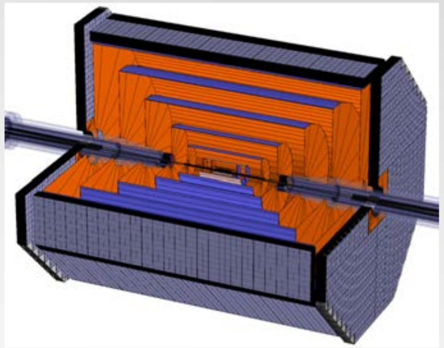
IDEA

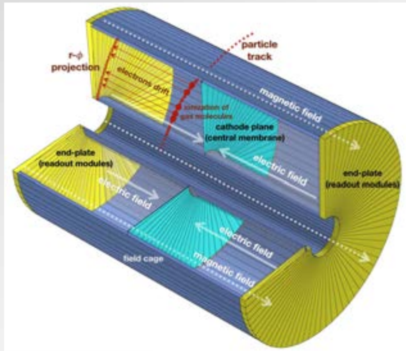


- New, innovative, possibly more cost-effective concept
  - Silicon vertex detector
  - Short-drift, ultra-light wire chamber
  - Dual-readout calorimeter
  - Thin and light solenoid coil *inside* calorimeter system

https://pos.sissa.it/390/

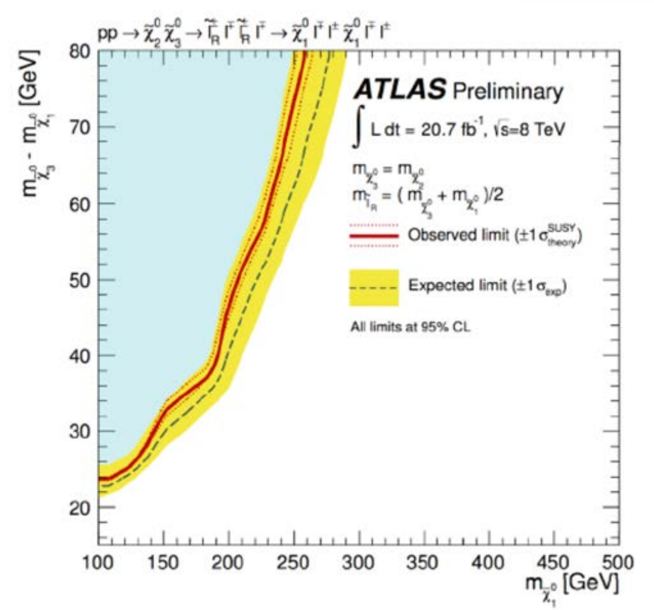


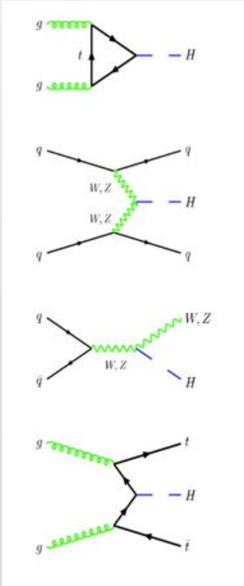


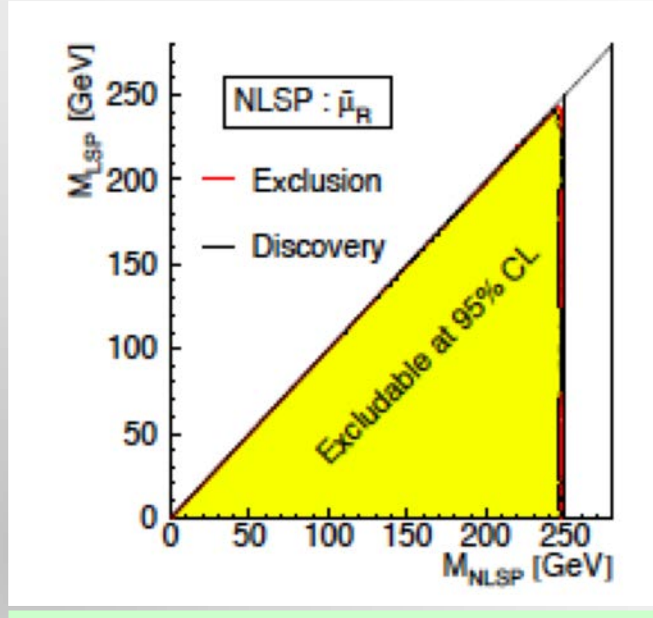


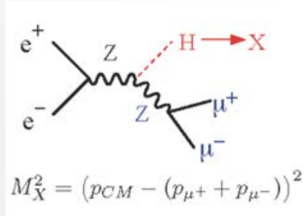
CEPC CDR
arXiv:1811.10545

Conceptual differences: pp vs. e+e-









pp (LHC, HL-LHC, FCC-hh):

Higher energy, higher statistics

e+e- (ILC, CLIC, FCC-ee, CEPC:

Higher sensitivity, higher precision

- pp reaches higher energies and higher statistics but can miss important effects due to larger backgrounds and systematics. Tevatron could not observe a clear signal of the Higgs boson though more than 20000 Higgs events were produced at the collider.
- e+e- allows to measure the Higgs properties in an easy and model-independent way at ~250 GeV.
- Signal/background events in pp collisions are produced through process which differ in various orders (higher backfgrounds) whereas in e+e- all process are produced at similar rates.

The European Strategy 2020

1

HL-LHC (highest priority):

The successful completion of the high-luminosity upgrade of the machine and detectors should remain the focal point of European particle physics. The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma.

Europe, and CERN through the Neutrino Platform:

Continue to support long baseline experiments in Japan and the United States. In particular, they should continue to collaborate with the United States and other international partners towards the successful implementation of the Long-Baseline Neutrino Facility (LBNF) and the Deep Underground Neutrino Experiment (DUNE).

2

General Considerations:

This Strategy update should be implemented to ensure Europe's continued scientific and technological leadership.

The particle physics community must further strengthen the unique ecosystem of research centres in Europe. In particular, cooperative programmes between CERN and these research centres should be expanded and sustained with adequate resources in order to address the objectives set out in the Strategy update.

The implementation of the Strategy should proceed in strong collaboration with global partners and neighbouring fields.

3

Future Colliders:

An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.

⋮

5

The European Strategy 2020: Future Colliders

3

High-priority future initiatives

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

· the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;

· Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

B. Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. ***The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.***

- **Highest priority:** Higgs Factory
- **R&D effort in accelerator technology** and in particular to develop high field
- **Explore and investigate the possibility to build** a future hadron collider of 100 TeV with an e+e- collider as first stage which operate at Z^0, Higgs and Top-quark thresholds
- **Timely realization** of the International Linear Collider in Japan is compatible with the European strategy thus including European

ECFA statement (endorsed at the Plenary ECFA meeting on 13 July 2020)

- *ECFA recognizes the need for the experimental and theoretical communities involved in physics studies, experiment designs and detector technologies at future Higgs factories to gather.* ***ECFA supports a series of workshops with the aim to share challenges and expertise, to explore synergies in their efforts and to respond coherently to this priority in the European Strategy for Particle Physics (ESPP).***

  Goal: bring the entire e^+e^- Higgs factory effort together, foster cooperation across various projects, collaborative research programs are to emerge

---

- Setting up an **International Advisory Committee (IAC)** was agreed to be the next step with involvement of some RECFA members and European leaders of possible future Higgs factories. In addition the (HL)-LHC community should be represented.
  (discussed in Nov. 2020 RECFA meeting)

K. Jakobs (RECFA meeting, 2021)

ECFA
European Committee for Future Accelerators

RECFA meeting, 12th March 2021 2

The European Strategy 2020: Implementation

International Advisory Committee

- International Advisory Committee
  - ECFA-chair would act as chair: Karl Jakobs
  - From RECFA: Jean-Claude Brient, Tadeusz Lesiak, Chiara Meroni
  - With (HL-)LHC experience: Jorgen D'Hondt, Max Klein, Aleandro Nisati, Roberto Tenchini
  - For theory: Christophe Grojean, Andrea Wulzer
  - For Linear Colliders: Steinar Stapnes, Juan Fuster, Frank Simon, Aidan Robson
  - For Circular Colliders: Alain Blondel, Mogens Dam, Patrick Janot, Guy Wilkinson
  - For CERN: Joachim Mnich
- Objective to have a first meeting in January 2021

Meetings on: 7 Jan, 25 Jan, 9 Feb, and 3 March

K. Jakobs (RECFA meeting, 2021)

ECFA
European Committee for Future Accelerators

RECFA meeting, 12th March 2021

The European Strategy 2020: Implementation

Physics, Experiments & Detector studies for an e^+e^- Higgs factory

- More detailed **mandates** for possible Working Groups 1 and 2 have been prepared (linked to Agenda page, next pages)

- Possible names for conveners have been discussed and the IAC agreed on the following proposal:

  WG 1: Juan Alcaraz (Madrid), Jenny List (DESY)
  James Wells (Michigan), Fabio Maltoni (Louvain / Bologna)

  WG 2: Patrizia Azzi (Padova / CERN), Dirk Zerwas (IJCLab)
  Fulvio Piccinini (Pavia)

K. Jakobs (RECFA meeting, 2021)

ECFA
European Committee for Future Accelerators

RECFA meeting, 12th March 2021 7

Let's take a glance to the physics programme

Roman soldiers were making fun of a spartan as

he was a lame person and was going to a battle

His answer was:

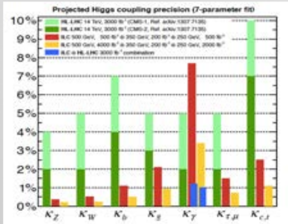
"my mission is to fight not to flee"

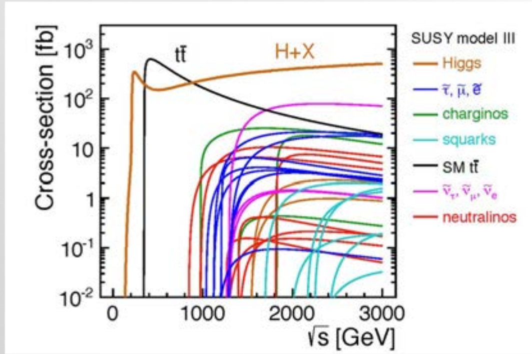
Valerio Máximo, year 31st aC

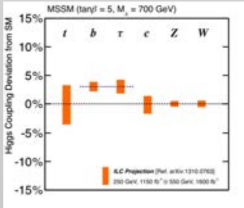
Factorum et dictorum memorabilium

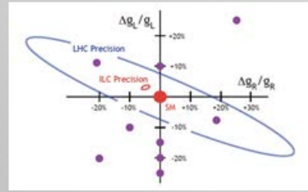
physics potential for e+e- colliders

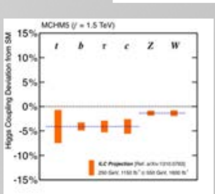
- **Physics case:**
  - **Higgs physics (SM and non-SM)**
  - **Top**
  - **SUSY**
  - **Dark matter**
  - **New Z' sector**
  - **Contact interactions**
  - **Extra dimensions**
  - **….**

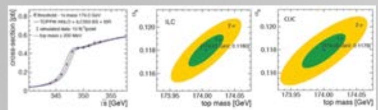


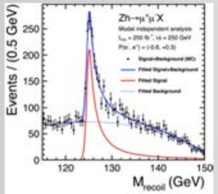


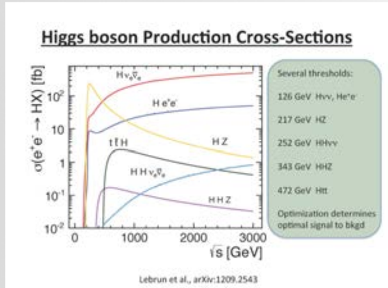


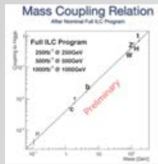


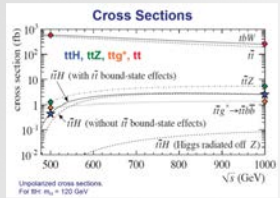












- **Physics programme very similar to all machines within the same energy range**

FCC-ee	FCC-ee: The Lepton Collider: Future Circular Collider Conceptual Report, Volume 2 CER-ACC-2018-0057
CEPC	CEPC Conceptual Design Report: Volume 2, Physics & Detector arXiv:1811.10545
CLIC	CLIC CDR, arXiv:1202.5940,1209.2543; Updated baseline for a staged Compact Linear Collider arXiv:1608.07537
ILC	ILC Technical Design Report, Volume 2, arXiv:1306.6352; The International Linear Collider: A Global Project arXiv1903.01629

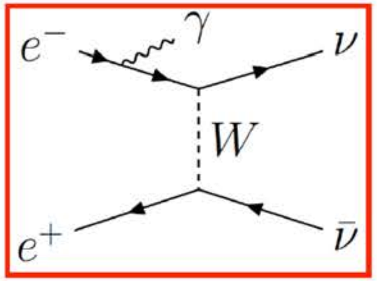
J. Fuster

Using polarized beams means…

The magic of polarization: *more observables & in some cases higher cross sections*

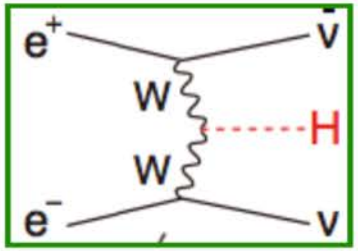
background suppression:

- $e^+e^- \to WW / \nu\nu$ strongly P-dependent since t-channel only for $e^-_L e^+_R$



signal enhancement:

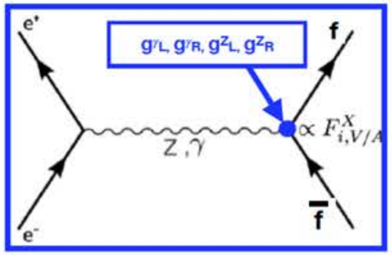
- Higgs production in WW fusion
- many BSM processes



have strong polarisation dependence => higher S/B

chiral analysis:

- SM: Z and γ differ in couplings to left- and right-handed fermions



- BSM: chiral structure unknown, needs to be determined!

redundancy & control of systematics:

- "wrong" polarisation yields "signal-free" control sample
- flipping *positron* polarisation controls nuisance effects on observables relying on *electron* polarisation
- essential: fast helicity reversal for *both* beams!

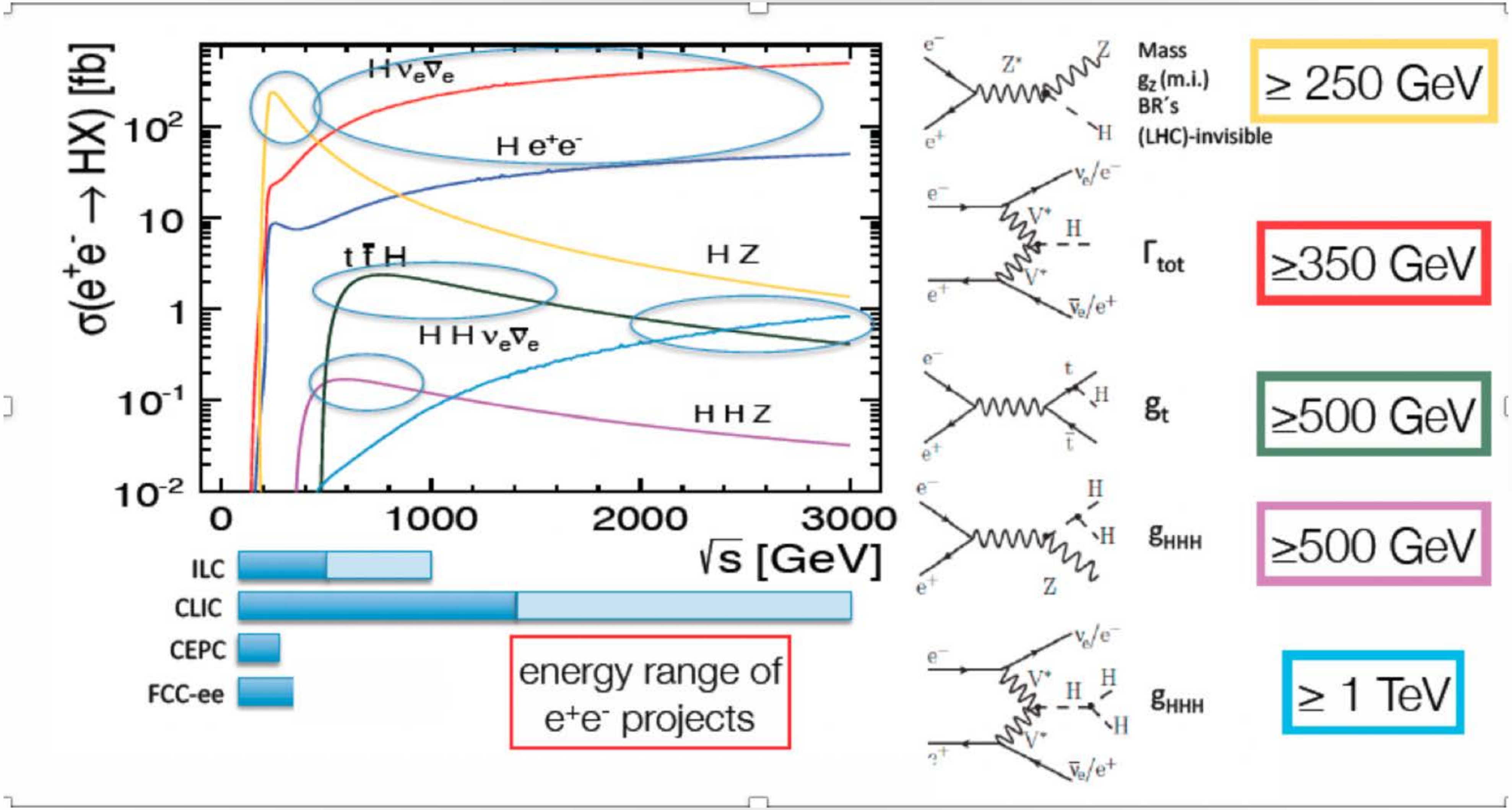
General references on polarised e+e– physics:

K, Fuji et al., arXiv:1801.02840

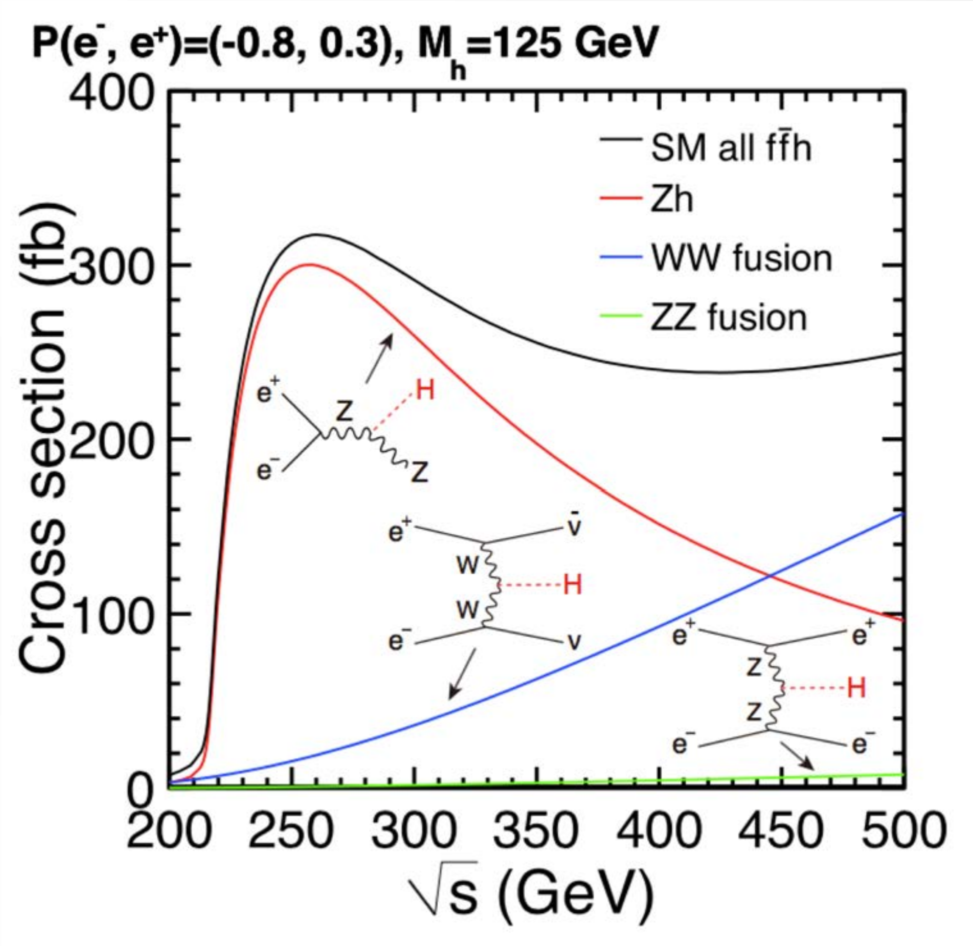
G Moortgat-Pick et al., Phys. Rept. 460 (2008) 131-243

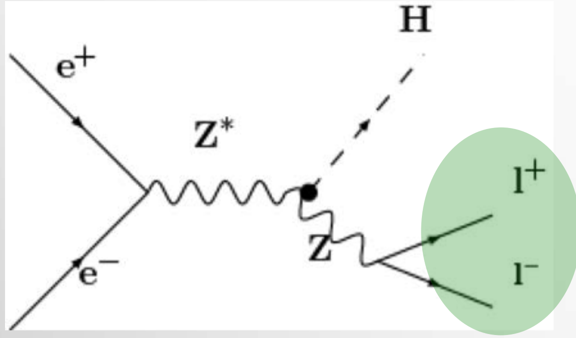
J. List IFIC-seminar , April 2021

e+e- Higgs Physics



Model independent tests @ 240-250 GeV





$$M_H^2 = \ M_{recoil}^2 \ = s + M_Z^2 - 2E_Z\sqrt{s}$$

Production dominated by Zh
(ILC with 2 ab-1 => ~600 000 Zh events)

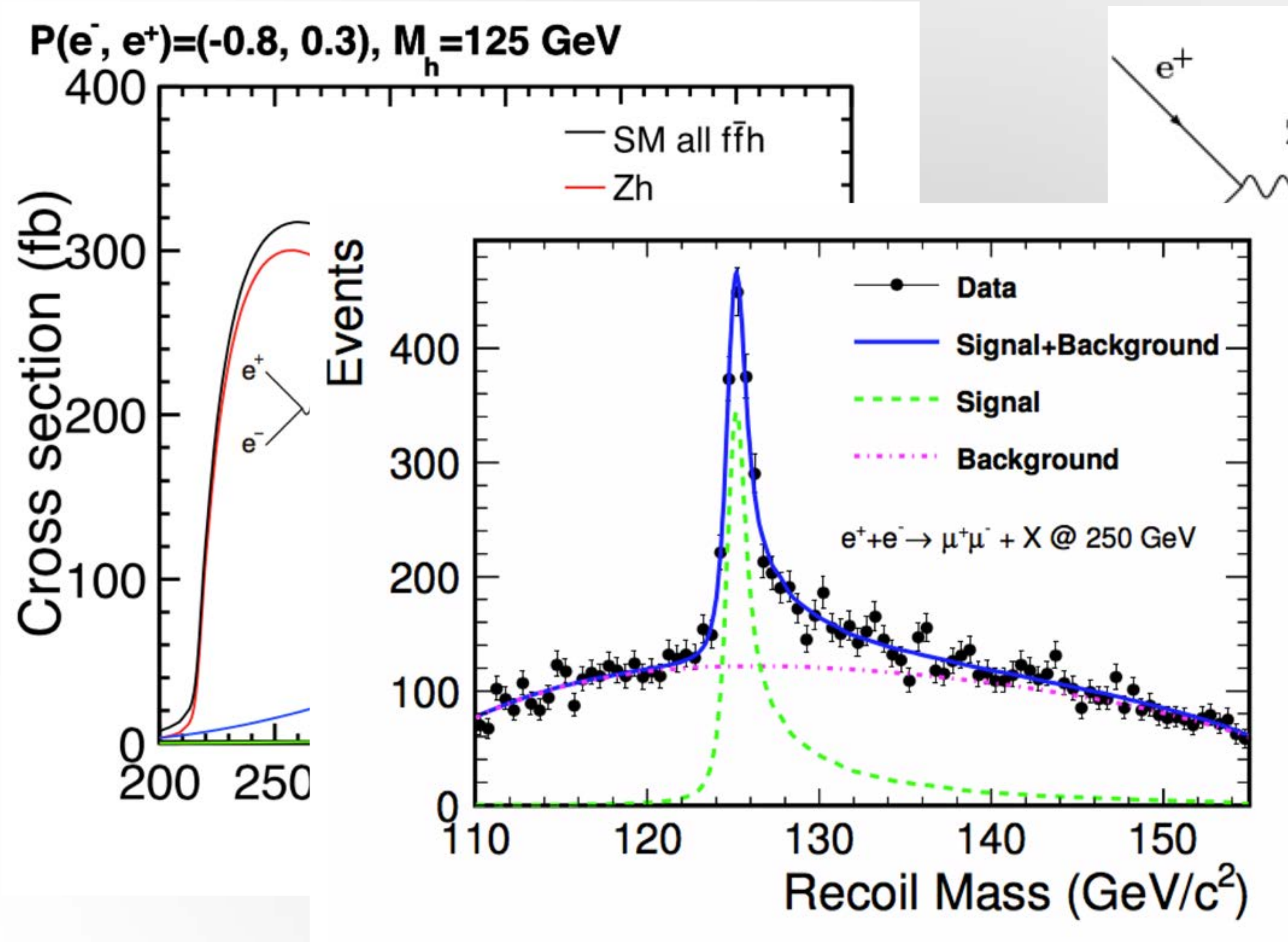
Measurements/Observables:

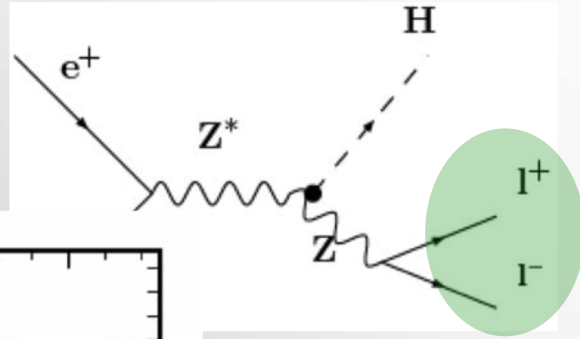
- (recoil) mass
- total Zh cross section: the key to model-independent
- h-> invisible (Dark Matter!):
  expected limit < 0.3% @ 95%
- all kinds of branching ratios
- CP properties of h-fermion coupling
- CP properties of Zh coupling

ILC prospects as an example but similar to all e+e- colliders options
For detailed precision see arXiv:1708.08912

J. Fuster

Model independent tests @ 240-250 GeV





$$\ldots_{oil} = s + M_Z^2 - 2E_Z\sqrt{s}$$

l by Zh

)0 000 Zh events)

vables:

ction: the key to model-

rk Matter!):

0.3% @ 95%

ching ratios

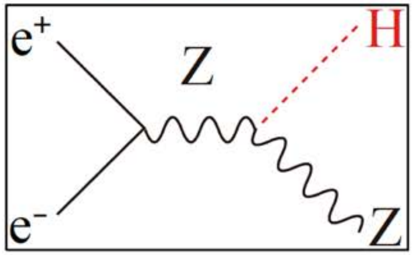
- CP properties of h-fermion coupling
- CP properties of Zh coupling

ILC prospects as an example but similar to all e+e- colliders options
For detailed precision see arXiv:1708.08912

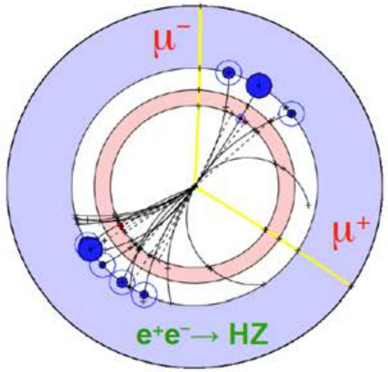
Model independent tests @ 240-250 GeV

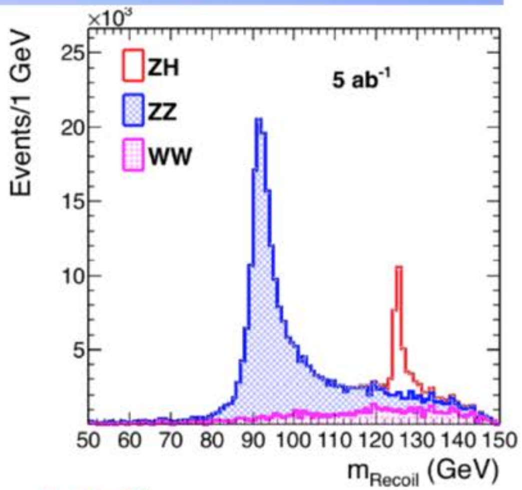
Absolute coupling and width measurement

- Higgs tagged by a Z, Higgs mass from Z recoil



$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$





- Total rate $\propto g_{HZZ}^2$ → measure g_{HZZ} to 0.2%
- ZH → ZZZ final state $\propto g_{HZZ}^4 / \Gamma_H$ → measure Γ_H to a couple %
- ZH → ZXX final state $\propto g_{HXX}^2\, g_{HZZ}^2 / \Gamma_H$ → measure g_{HXX} to a few per-mil / per-cent
- Empty recoil = invisible Higgs width; Funny recoil = exotic Higgs decays

- Note: The HL-LHC is a great Higgs factory (10^9 Higgs produced) but …
  - $\sigma_{i\to f}^{(observed)} \propto \sigma_{prod}\,(g_{Hi})^2\,(g_{Hf})^2 / \Gamma_H$
    - Difficult to extract the couplings : σ_{prod} is uncertain and Γ_H is largely unknown
      - Must do physics with ratios or with additional assumptions.

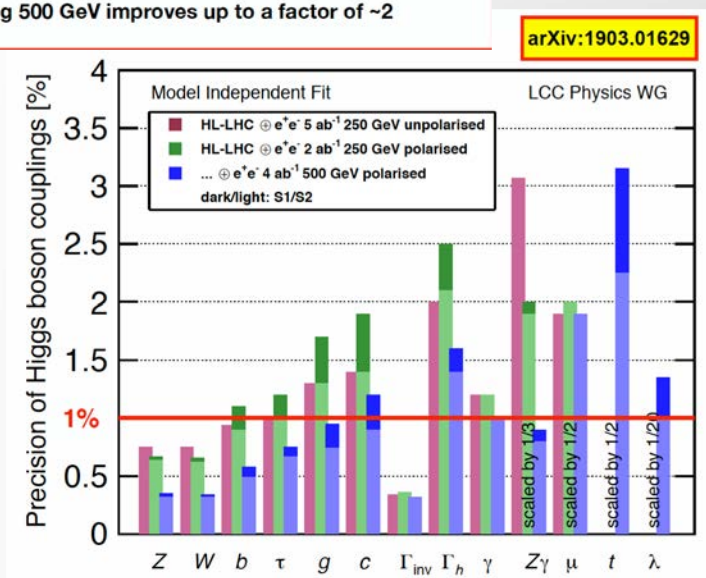
FCC-ee prospects, Patrick Janot, FCC-ee workshop, CERN Jan. 2019

Higgs couplings

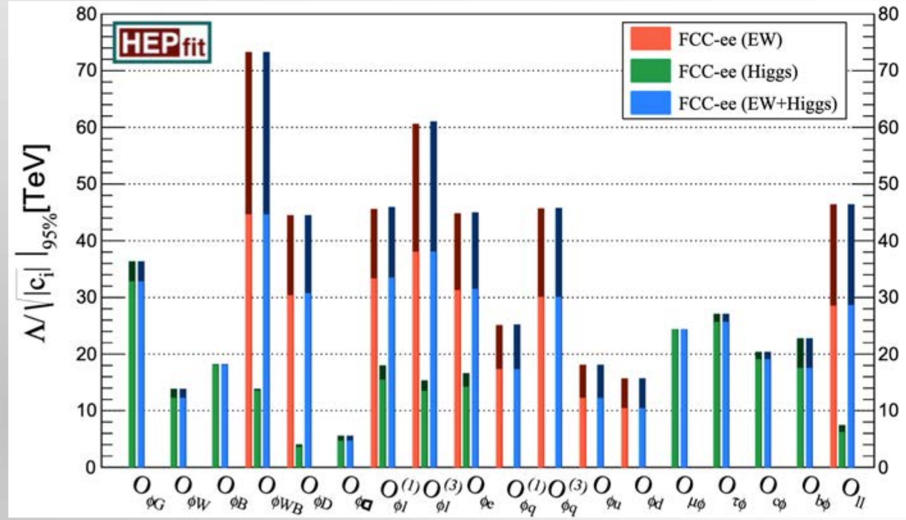
ILC Model independent tests

★ 2 ab⁻¹ polarised ≈ 5 ab⁻¹ unpolarised

★ adding 500 GeV improves up to a factor of ~2



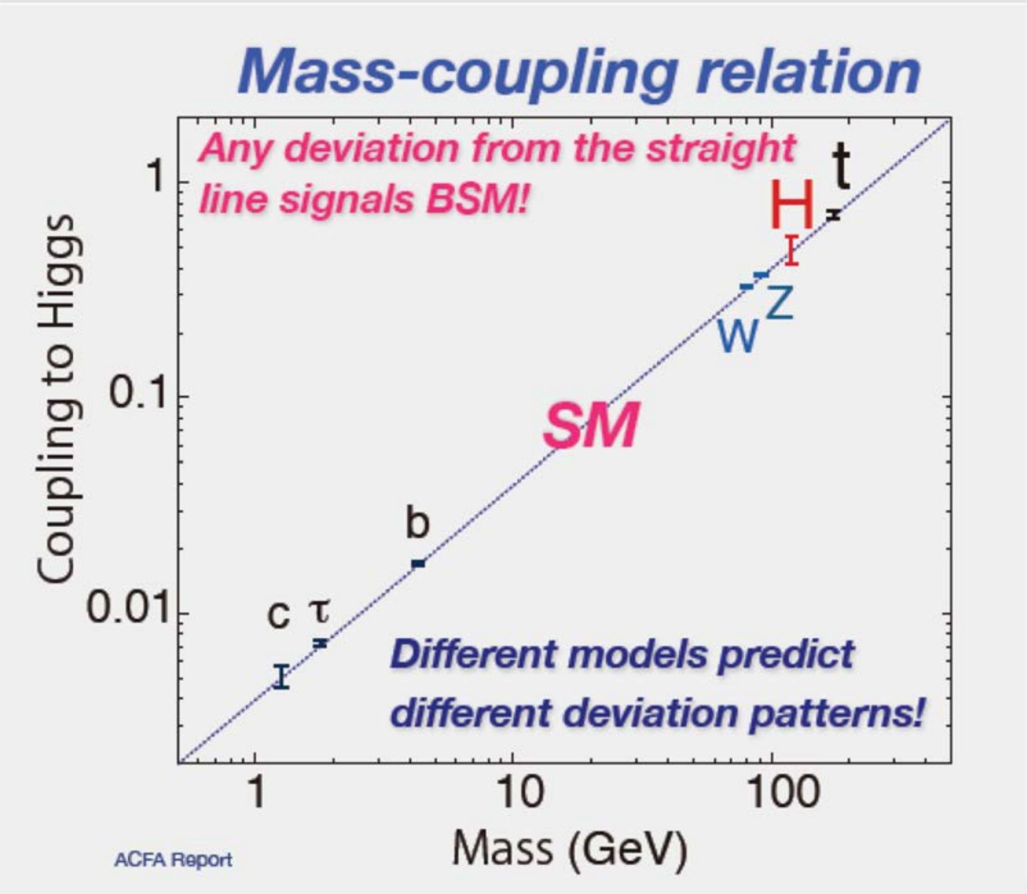
A. Blondel et al., arXiv2106,13885



Model Independent tests allow for:

- No assumption for generation universality, unitarity, nor on BSM
- Apart from γ, t, μ, accuracy is ~1 % or less (level that is meaningful in distinguishing models)
- The total Higgs width is extracted with a few percent uncertainty
- H->invisible with high accuracy
- Several channels (e.g.: H→cc, gg) very difficult in hadron collisions
- Coupling to the photon benefits from combination with HL-LHC which would provide Γ(H→γγ)/Γ(H→ZZ*)

Deviations in Higgs couplings



New Physics at 1 TeV imply Δ~10%

%-level precision needed and HL-LHC not enough.

Only e+e- colliders can do it.

K. Fujii 2016, Paris

Decoupling Theorem

When new physics at scale *M* are large, low energy theory is the SM. Up to m^2/M^2 [O(1-10)% for *M*=TeV]

i.e., 1% precision will mean M=3 TeV

(M. Peskin)

example 1: **Minimal SUSY**

(MSSM : tanβ=5, radiative correction factor ≈ 1)

$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \text{TeV}}{m_A}\right)^2$$

heavy Higgs mass

example 2: **Minimal Composite Higgs Model**

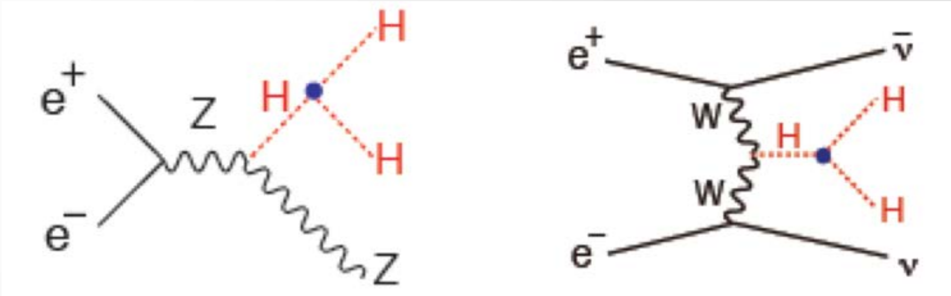
$$\frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 8.3\% \left(\frac{1\ \text{TeV}}{f}\right)^2$$

composite scale

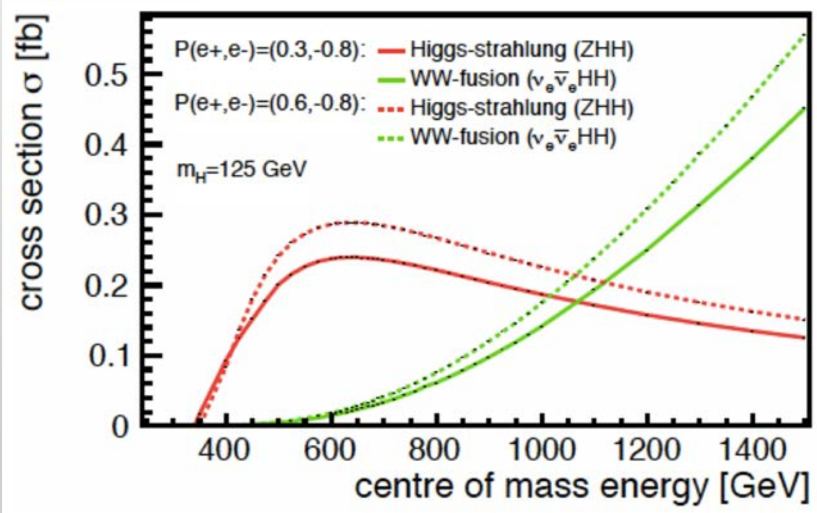
J. Fuster

Higgs self coupling

The Higgs self-coupling is at the heart of EWSB



Challenging channel (low cross-section and presence of irreducible backgrounds)



arXiv:1310.0763	ILC500	ILC500-up	ILC1000	ILC1000-up
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000
$\int \mathcal{L}dt$ (fb^{-1})	500	1600‡	500+1000	1600+2500‡
$P(e^-, e^+)$	(−0.8, 0.3)	(−0.8, 0.3)	(−0.8, 0.3/0.2)	(−0.8, 0.3/0.2)
$\sigma(ZHH)$	42.7%		42.7%	23.7%
$\sigma(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%
λ	83%	46%	21%	13%

27% (H20)

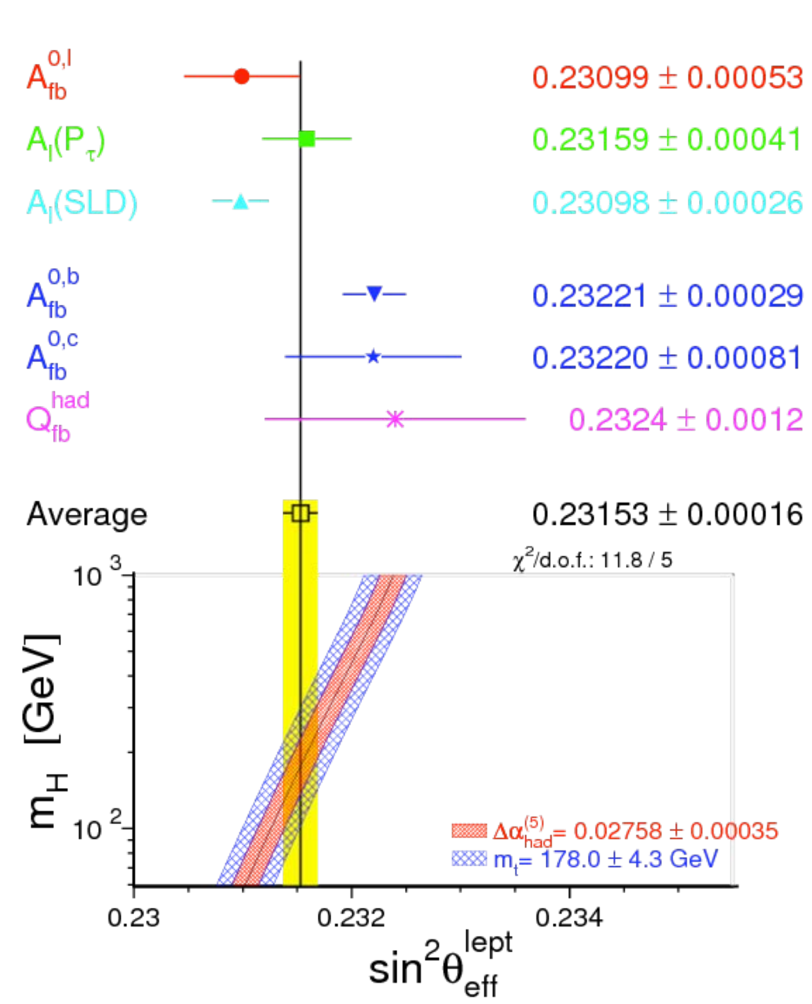
CLIC (arXiv: 1307.5288)

1.4 TeV (1.5 ab^{-1})	+3 TeV (2 ab^{-1})
21%	10%

On-going studies (full detector simulation) show the possibility to have Δ ~ O(10%)

K. Fujii, 2016

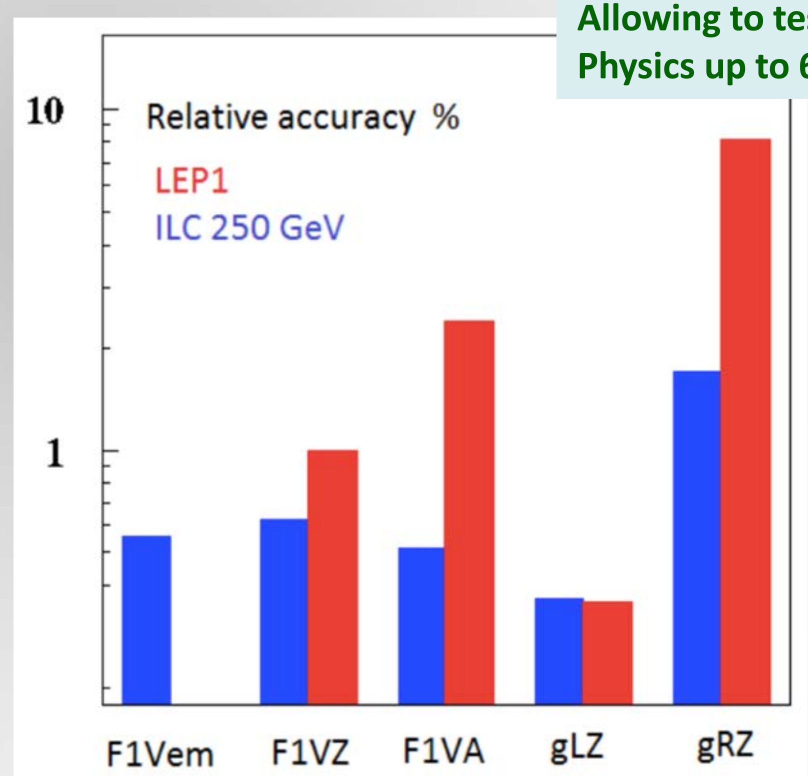
Bottom physics at Higgs Factory



b_R compositeness could explain e.g. long-standing tension between two most precise determinations of sin2ϑeff- one of them from A_b^{FB}(MZ) •

Remeasure couplings of b_R and A_b^{FB}(250GeV) and improve on LEP1?

Allowing to test New Physics up to 60 TeV



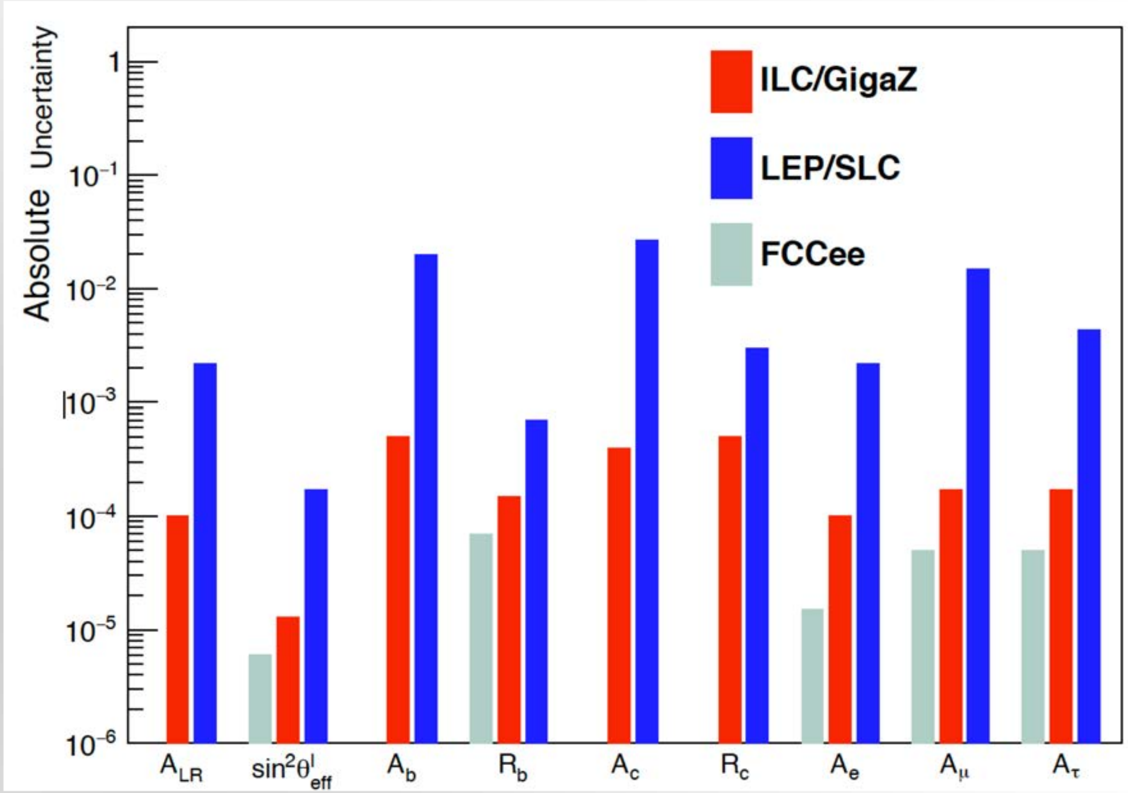
S. Bilokin, arXiv 1709.04289

Polarization and electroweak studies @ Z-pole

At least factor 10, often ~50 improvement over LEP/SLC

Note in particular A_c is nearly 100 x better thanks to excellent charm/anti-charm tagging:

- ultra-precise vertex detector
- Tiny beam spot
- Kaon-ID using DE/dX /in ILD´s TPC)



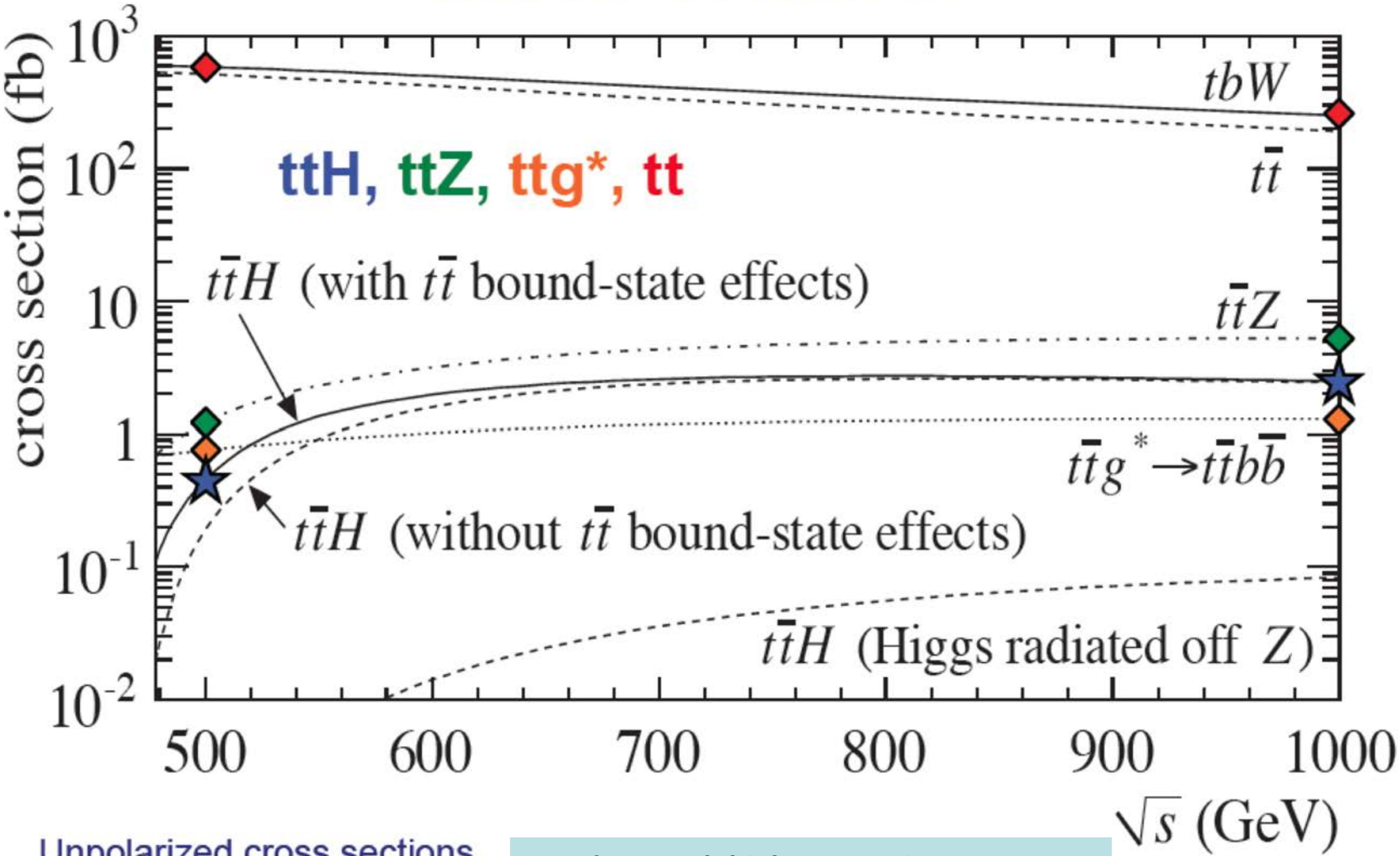
K. Fuji et al, arXiv1908,11299

ILC/GigaZ is 2-3 less precise than FCCee's unpolarised TeraZ

Use of polarization accounts for a factor of ~100 in luminosity

J. Fuster

Cross Sections



Unpolarized cross sections.
For ttH: m_H = 120 GeV

Need to reach higher energies > 350 GeV

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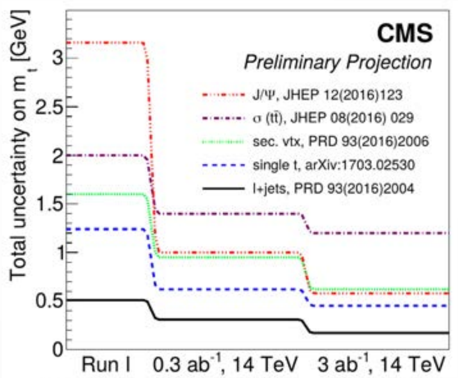
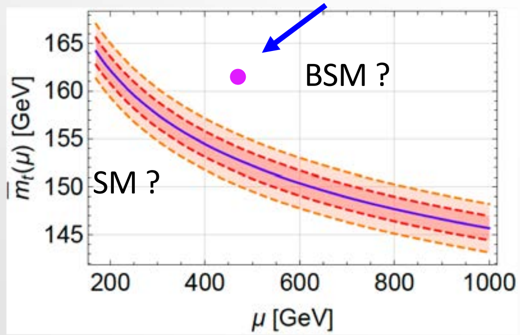
Top-quark physics at e+e- colliders: the mass



Method	Statistical	Systematic	Total (GeV)
$t\bar{t}$ lepton+jets	0.17	0.02	0.17
single-t t-channel	0.45	0.06	0.45
m_{svl}	0.62	0.02	0.62
J/ψ	0.24	0.53	0.58
$\sigma_{t\bar{t}}$	0.4% (exp)	0.4% (theory)	1.2

Standard Model Physics at the HL-LHC and HE-LHC, arXiv:1902.04070

Z.Z. Xing et al. et al, Phys.Rev. D72 (2008) 113016



HL-LHC (higher statistics):

- Possibility to use rare decays (J/Y)
- Restrict phase space regions
- Better control of systematics/modelling

- **Expected accuracy: 200-300 MeV**

- Need to develop further present theory calculations/predictions
- New observables or/and use of different mass definitions. To be explored

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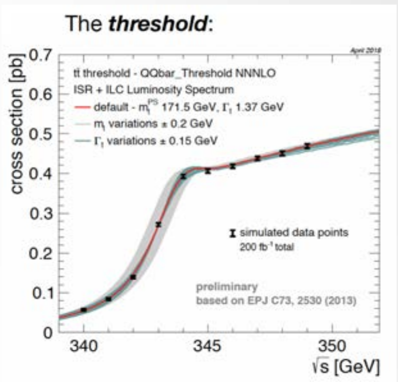
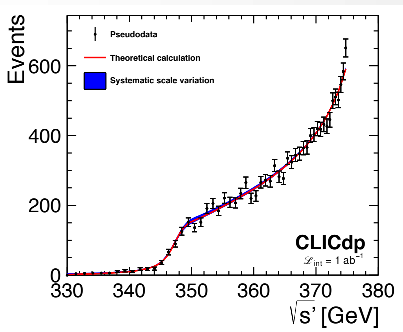


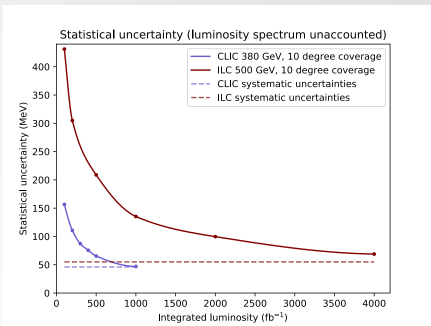
Collider e+e- (at top threshold): H. Abramowicz et al., CLICdp Collab., arXiv:1807.02441

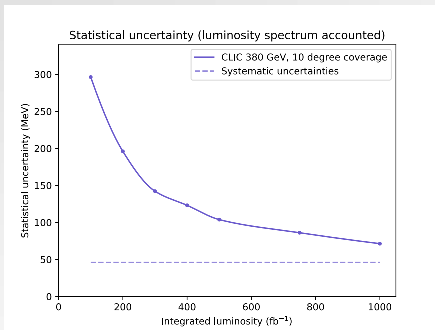
- Well-defined mass scheme
- Access to top-width and Yukawa coupling
- **Expected accuracy: m_t~ 40-75 MeV; Γ_t~100 MeV; y_t~15%**

Collider e+e- (at continuum above top threshold):

- Well-defined mass scheme
- After 1-2 years data taking better accuracy than LHC/HL-LHC complete programme
- **Expected accuracy: m_t~ 100-150 MeV**







$$s' = s\left(1 - \frac{2E_\gamma}{\sqrt{s}}\right)$$

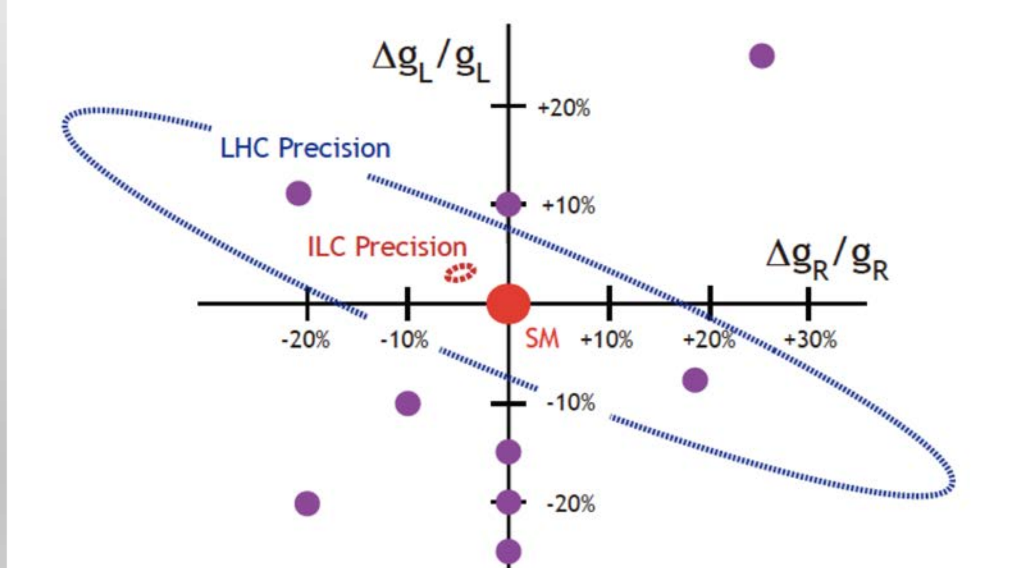
J. Fuster

Top-quark physics at e+e- colliders: Anomalous top couplings

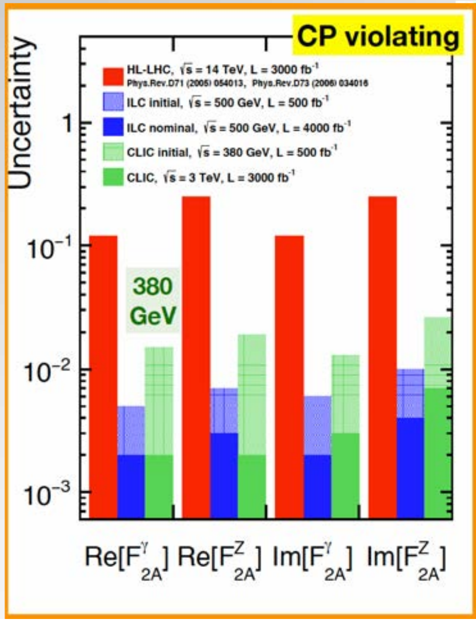
BSM: Anomalous top couplings @ >500 GeV

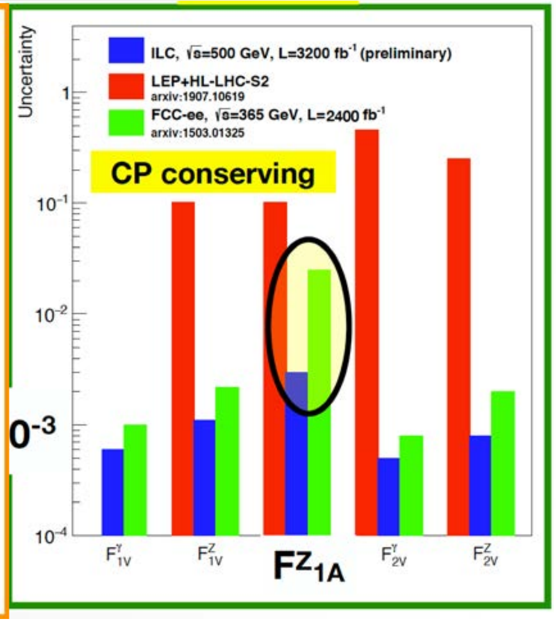
Top anomalous couplings:

- Distinguish variety of BSM models.
- Use beam polarization (separates γ and Z, R and L)
- Sensitivity up to 20 TeV

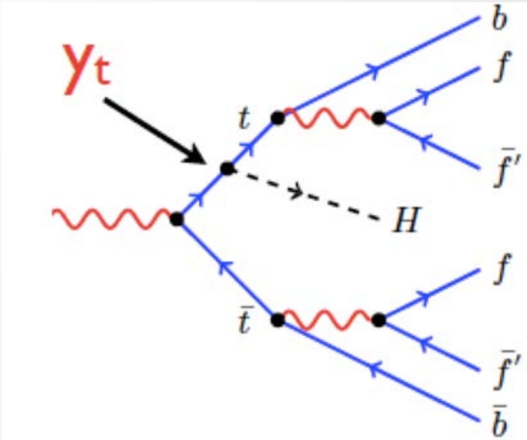


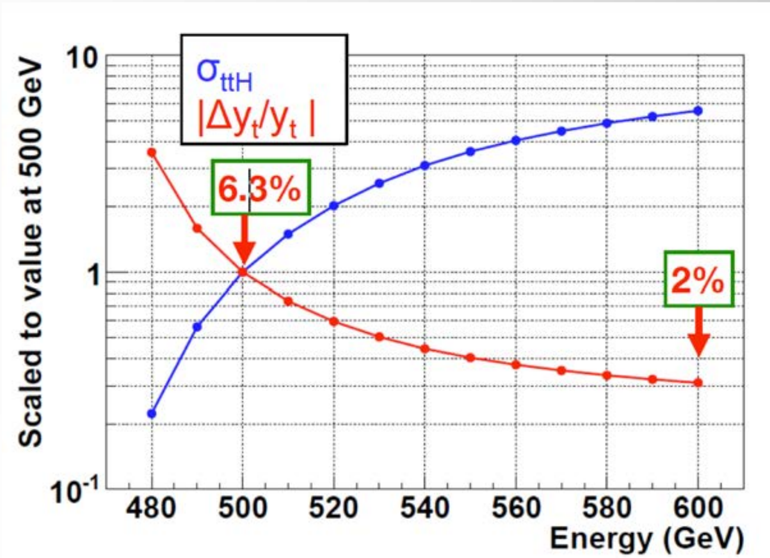
ILD-PHYS-PUB-2019-007, arXiv:1908.11299, Eur.Phys.J. C78 (2018) 2, 155





Top-quark physics at e+e- colliders: Yukawa coupling





Phys.Rev. D84 (2011) 014033 & arXiv:1506.07830

Production threshold at 475 GeV

SM s(ttH) = 0.45fb @ 500 GeV

ILC running scenario Δy_t = 6.3%

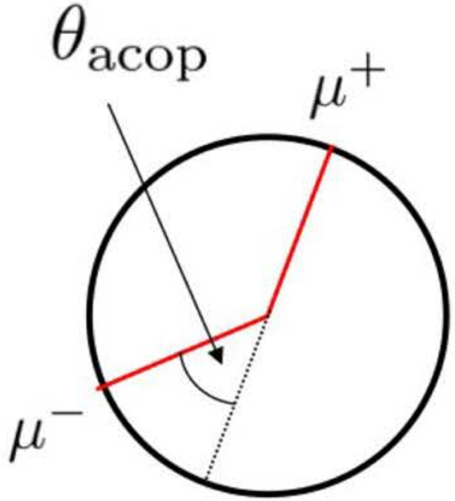
(@550 GeV Δy_t = 2.5%)

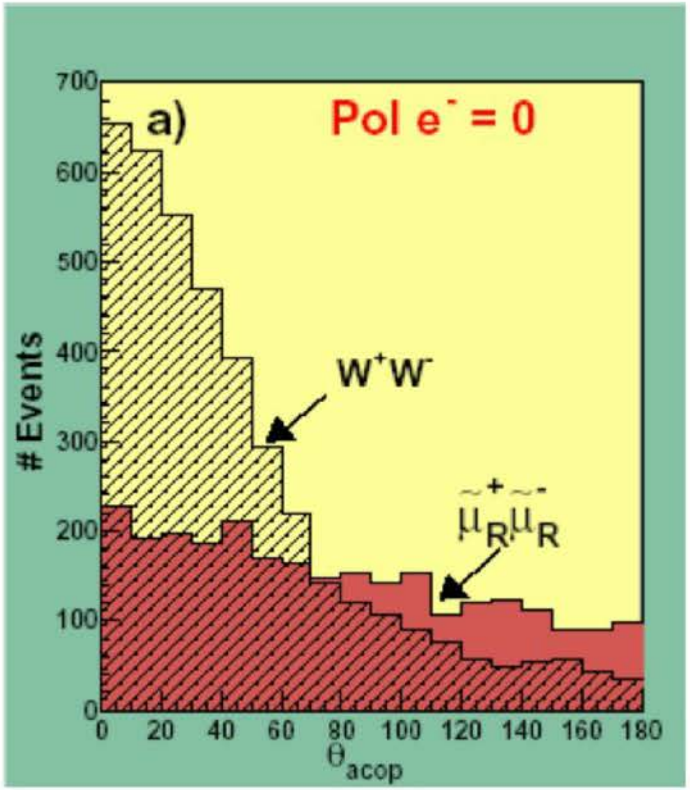
(strong dependence on the CMS energy)

@ 1 TeV and 4ab^{-1}; Δy_t = 1.4% (ILC)

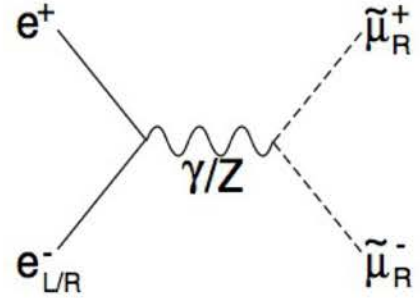
@ 1.4 TeV and 1.5ab^{-1}; Δy_t = 4.4% (CLIC)

New Physics: direct searches (power of beam polarization)

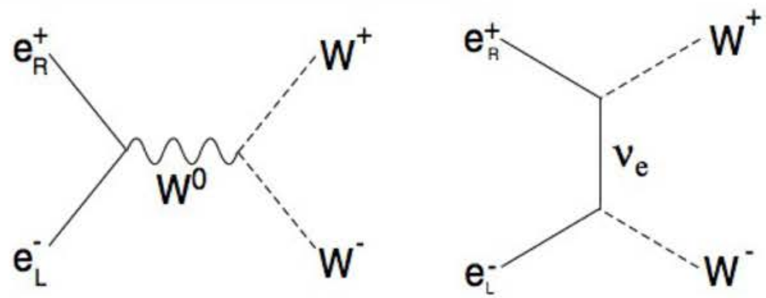




signal



SM background



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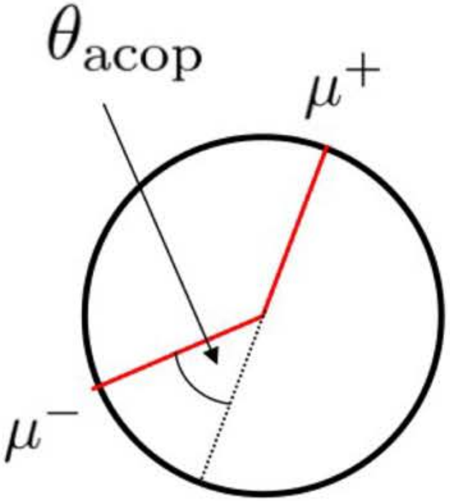
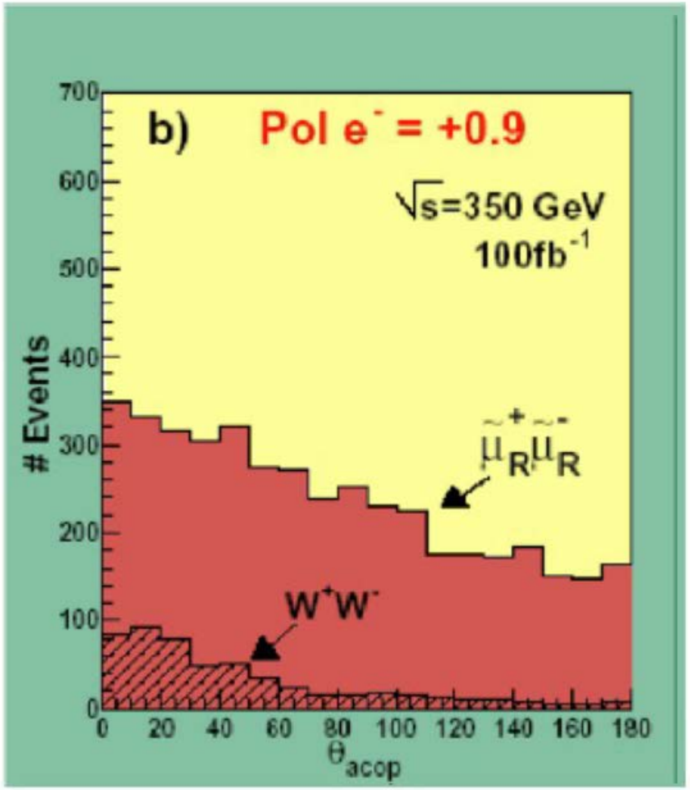
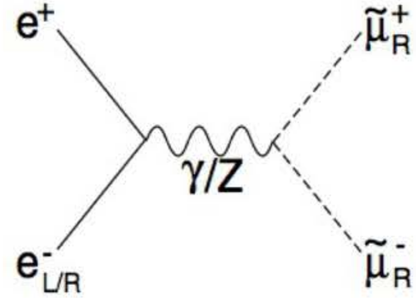
New Physics: direct searches (power of beam polarization)

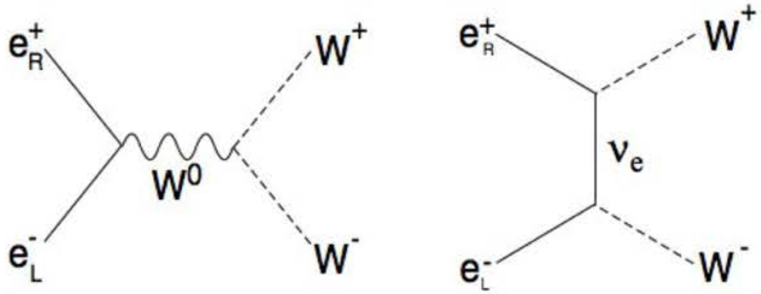




signal

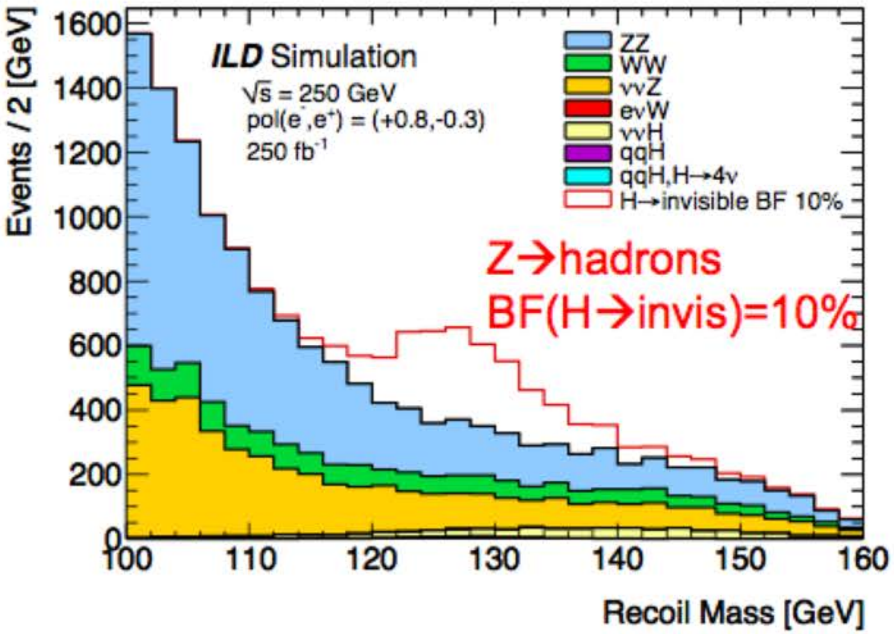


SM background



WIMP searches at colliders are complementary to direct/indirect searches.
Examples at the ILC:

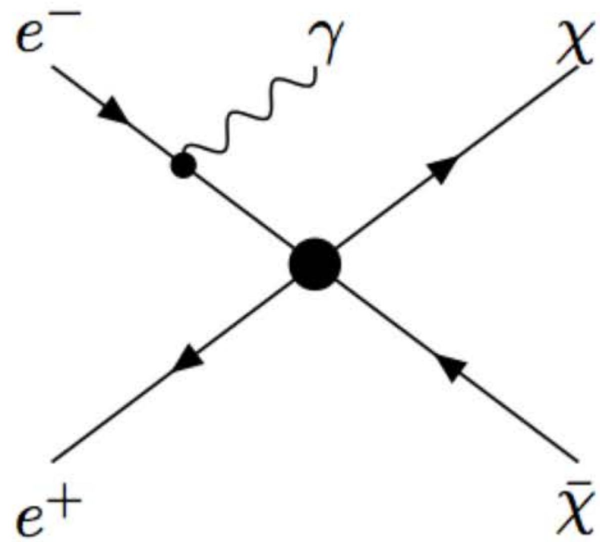
Higgs Invisible Decays



BR(H→invis.) < 0.4% at 250 GeV, 1150 fb^{-1}

Impact of jet energy resolution

Monophoton Searches

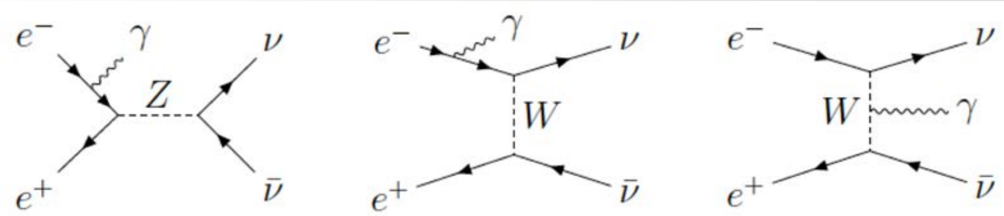


→ DM mass sensitivity nearly half √s

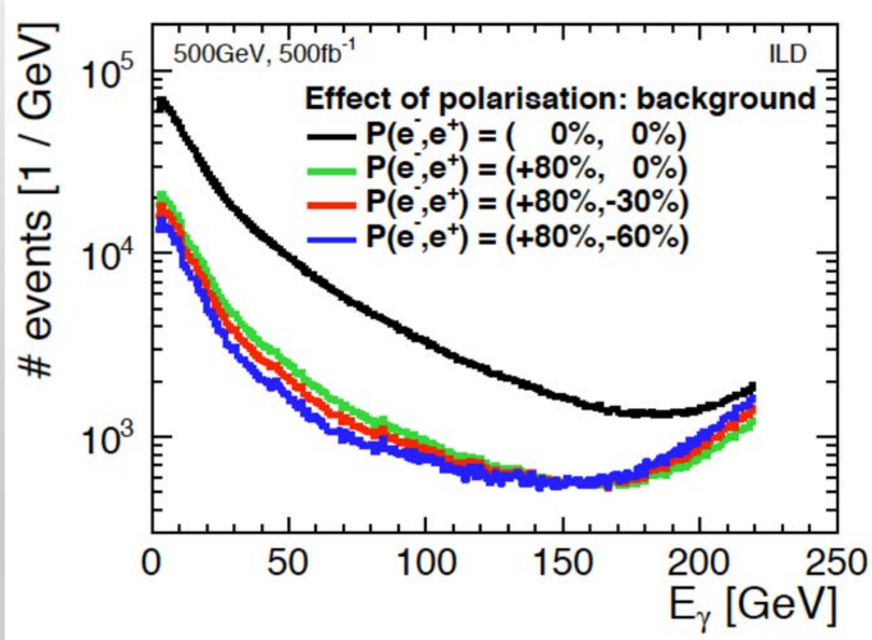
Soft photons, forward detectors

J. Fuster

mono-photon search e+e–→$\chi\chi\gamma$



Main SM background: e+e–→$\nu\nu\gamma$

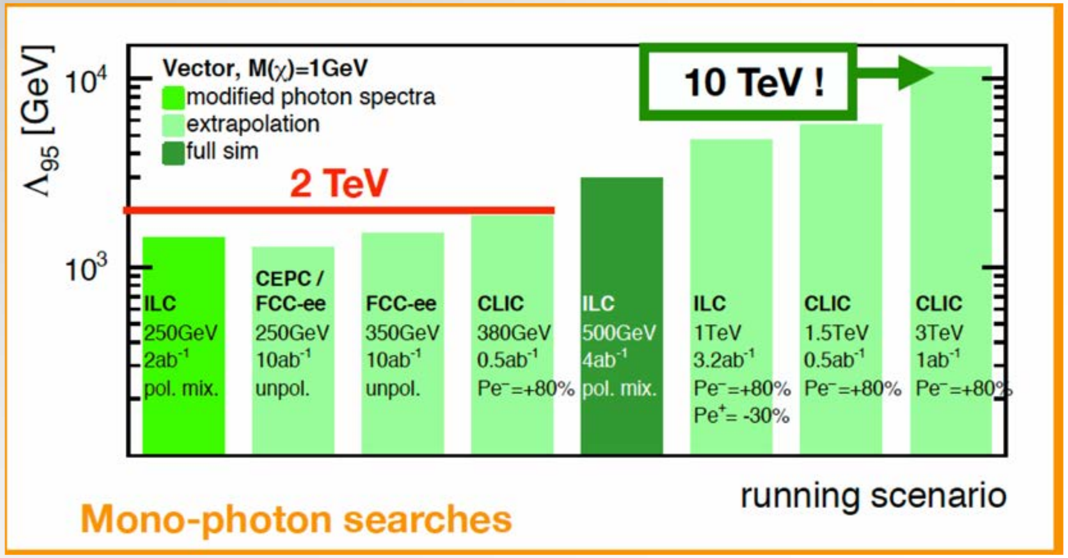


Polarization: Background reduction of ~10x

Dark matter search in e+e-:

- Polarization: Reduces background
- CMS energy: Improves sensitivity as it increases

M. Habermehl et al., Phys. Rev. D 101 (2020) 7



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Conclusion, 1st part

Interesting and busy times to come:

- **HL-LHC a compelling physics programme to be accomplished**
- **e+e- Higgs factory the next collider**

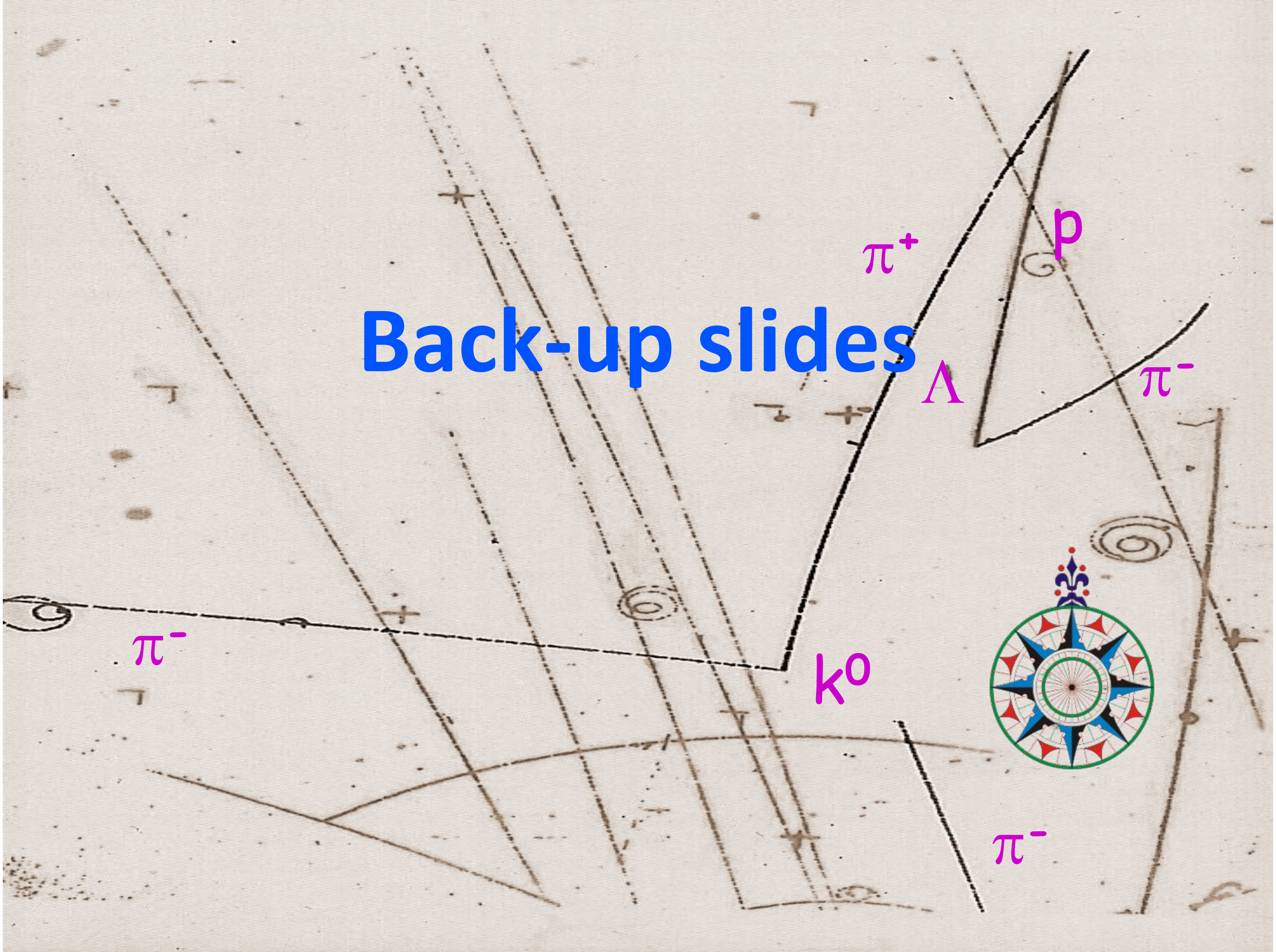
Higgs factory proposals:

- **@ 250 GeV all (circular vs linear) have similar performance (statistics vs polarization)**
- **Energy range, technical readiness, timescales are the main issue**

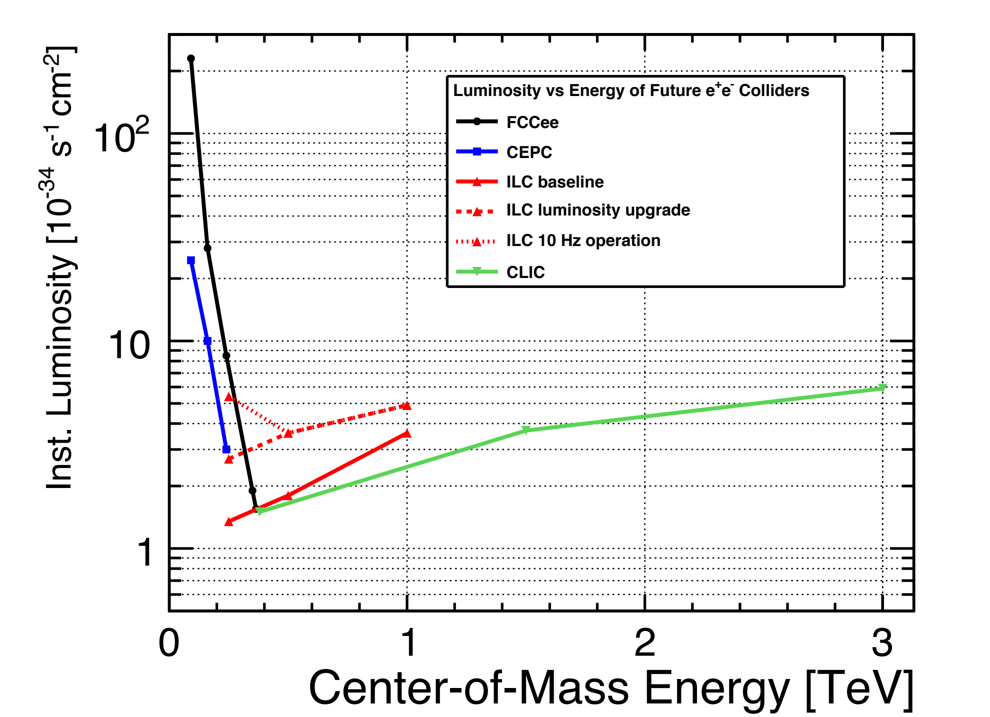
Sense títol, 2009

“ An expert has told me that only the largest and most aggressive will survive”

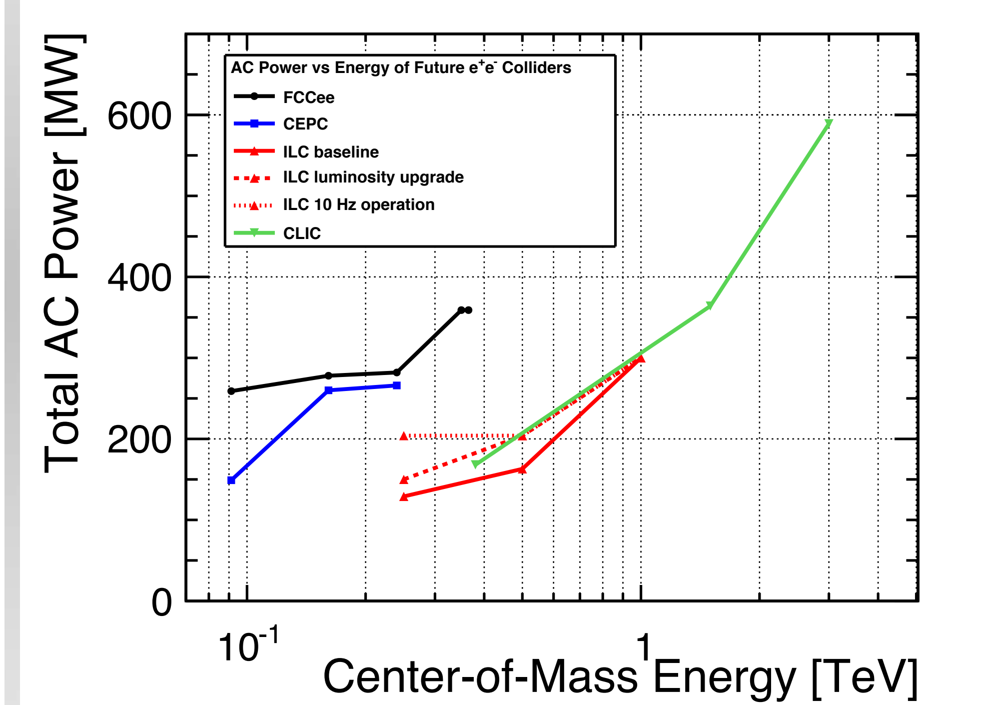
Back-up slides



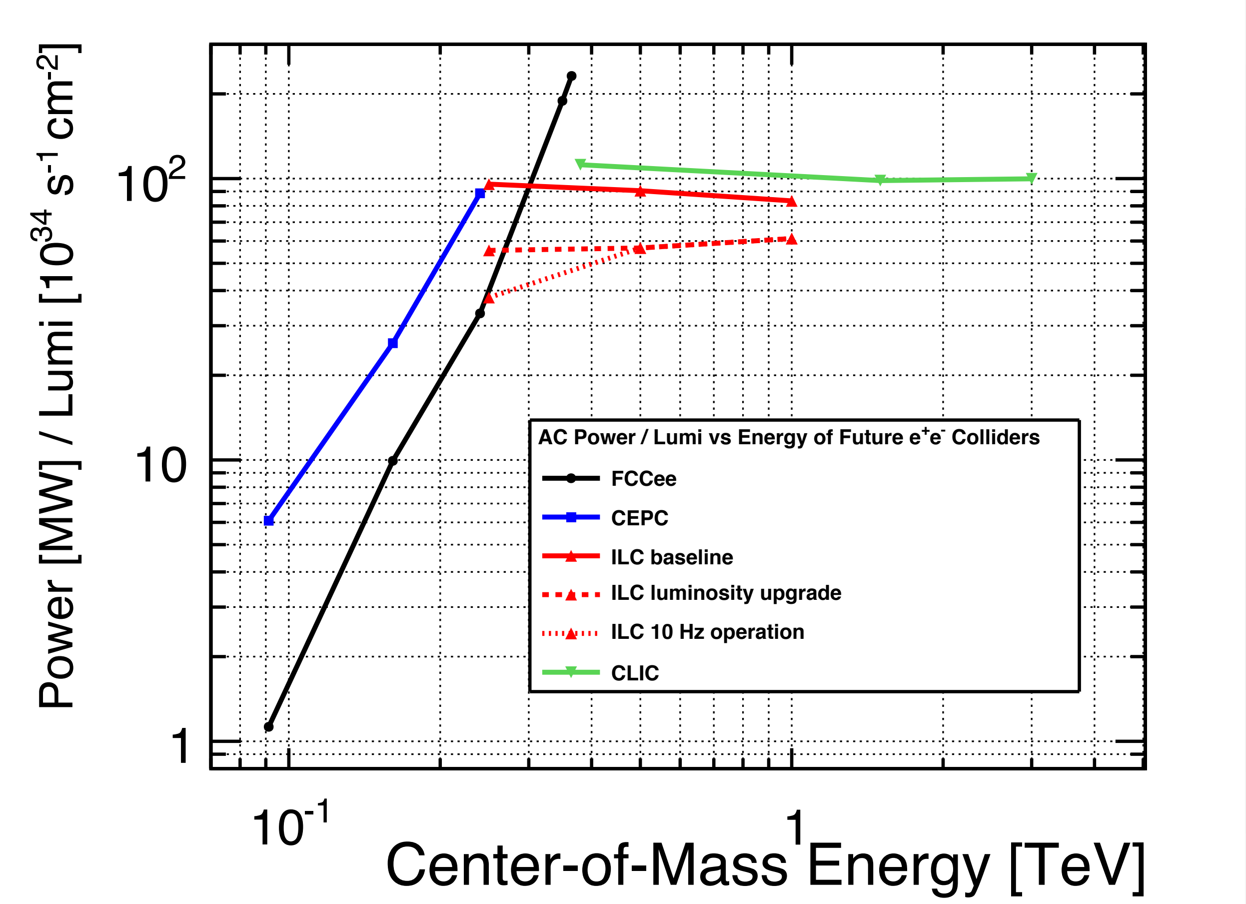
Luminosity



Consumption



Consumo/Luminosidad

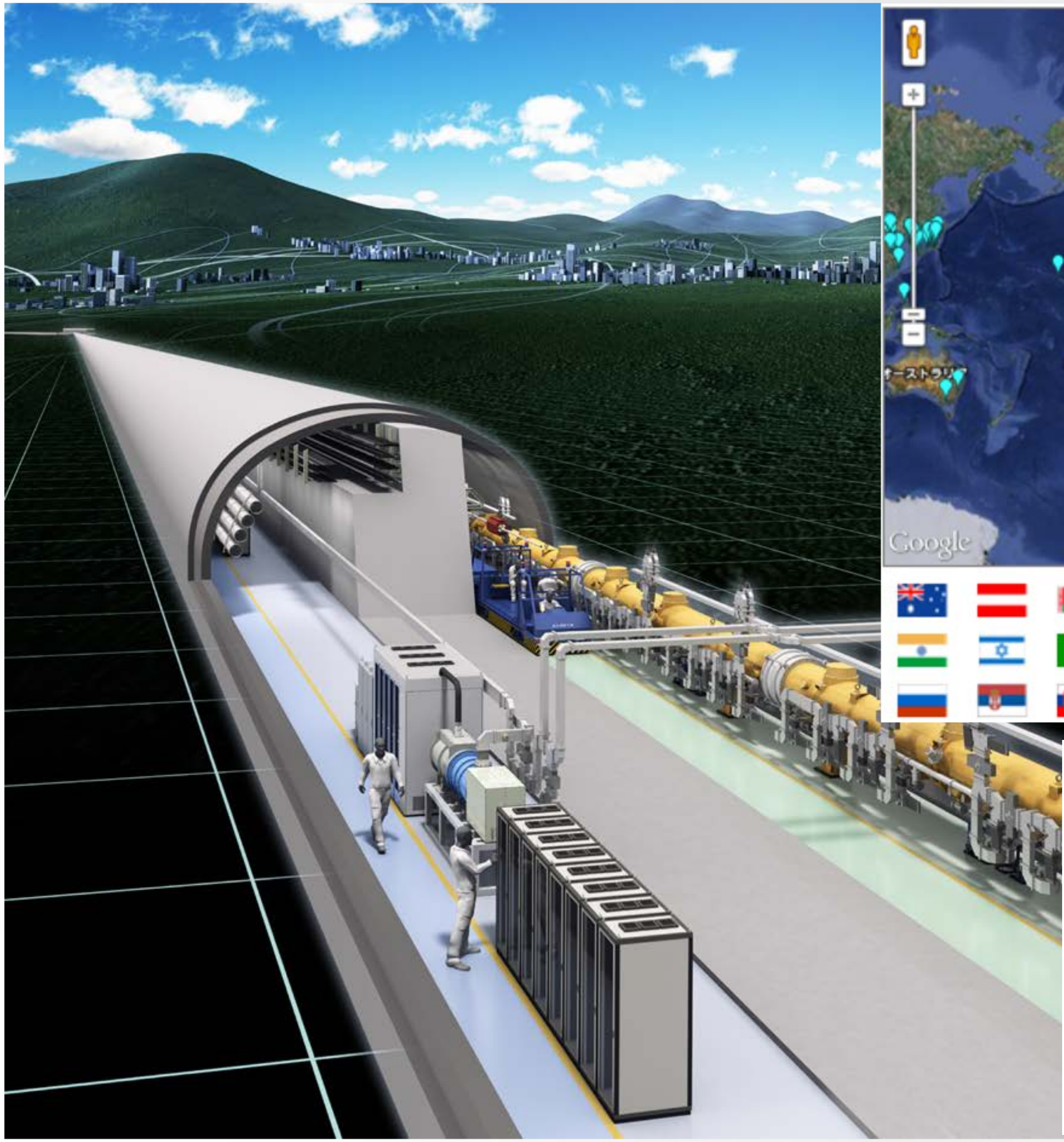


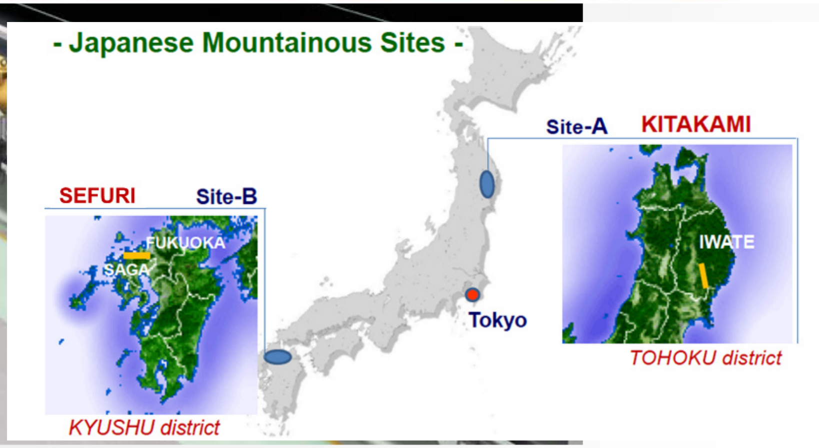
Polarización >80% e$^-$, 30-40% e$^+$: aumenta un factor 2.5 en luminosidad (no visualizado en el gráfico)

Lineal: no tiene perdida energética debido a radiación sincrotrón ($\Delta E \sim (E/m)^4 R^{-1}$) ---> Menor consumo

Circular: mayor luminosidad a bajas energías (<250 GeV). Lineal necesario alcanzar nano-haces

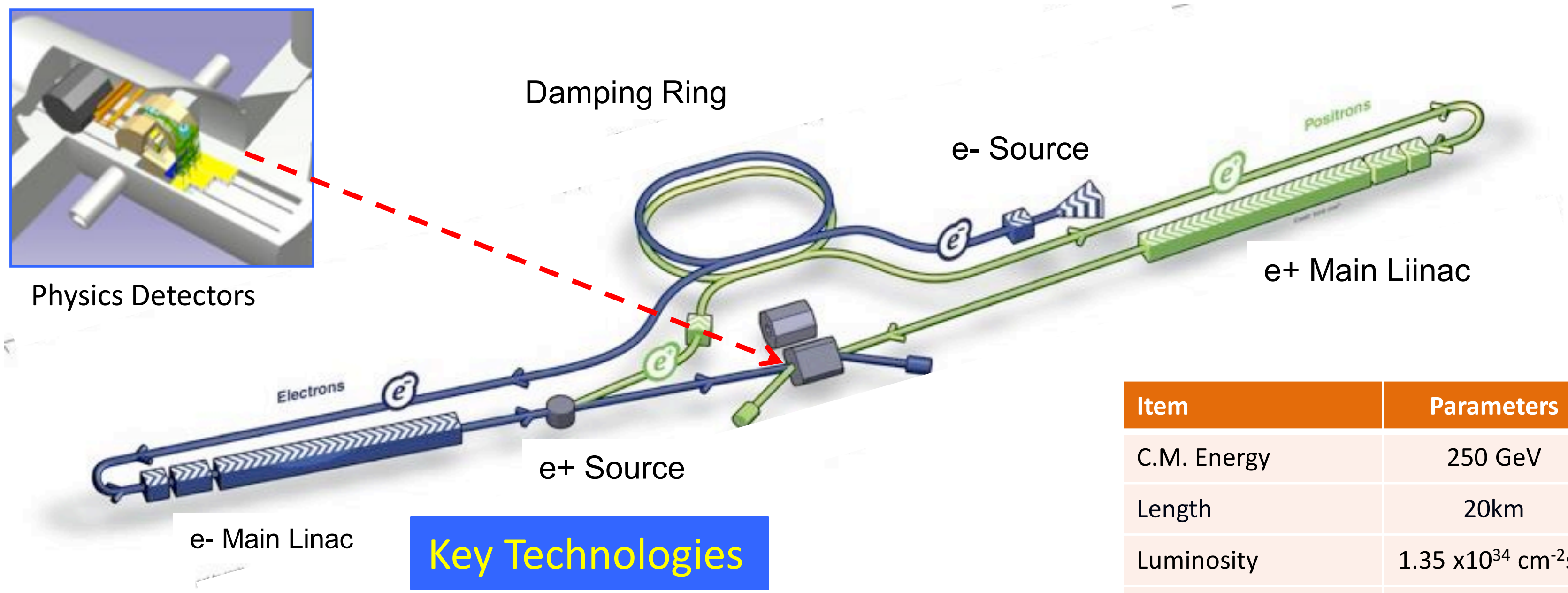
El Colisionador Lineal Internacional (ILC) en Japón

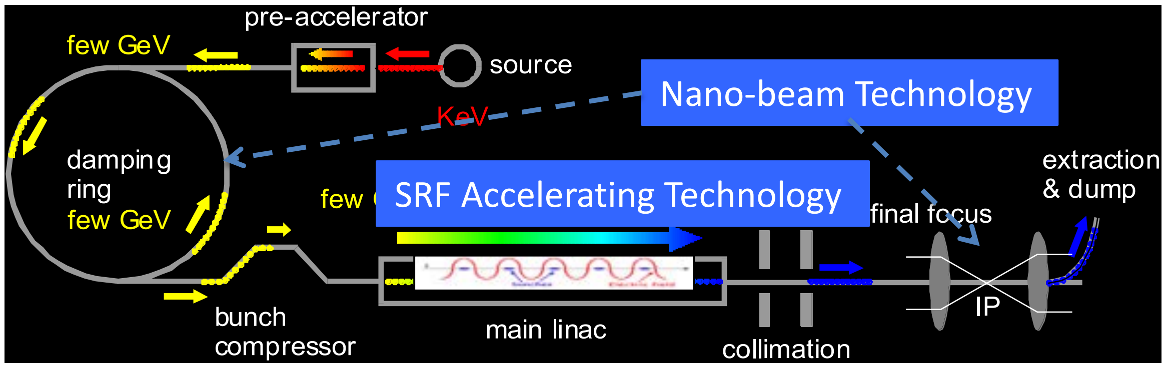




ILC250 Acc. Design Overview

S. Michizono (LCWS21, 2021)



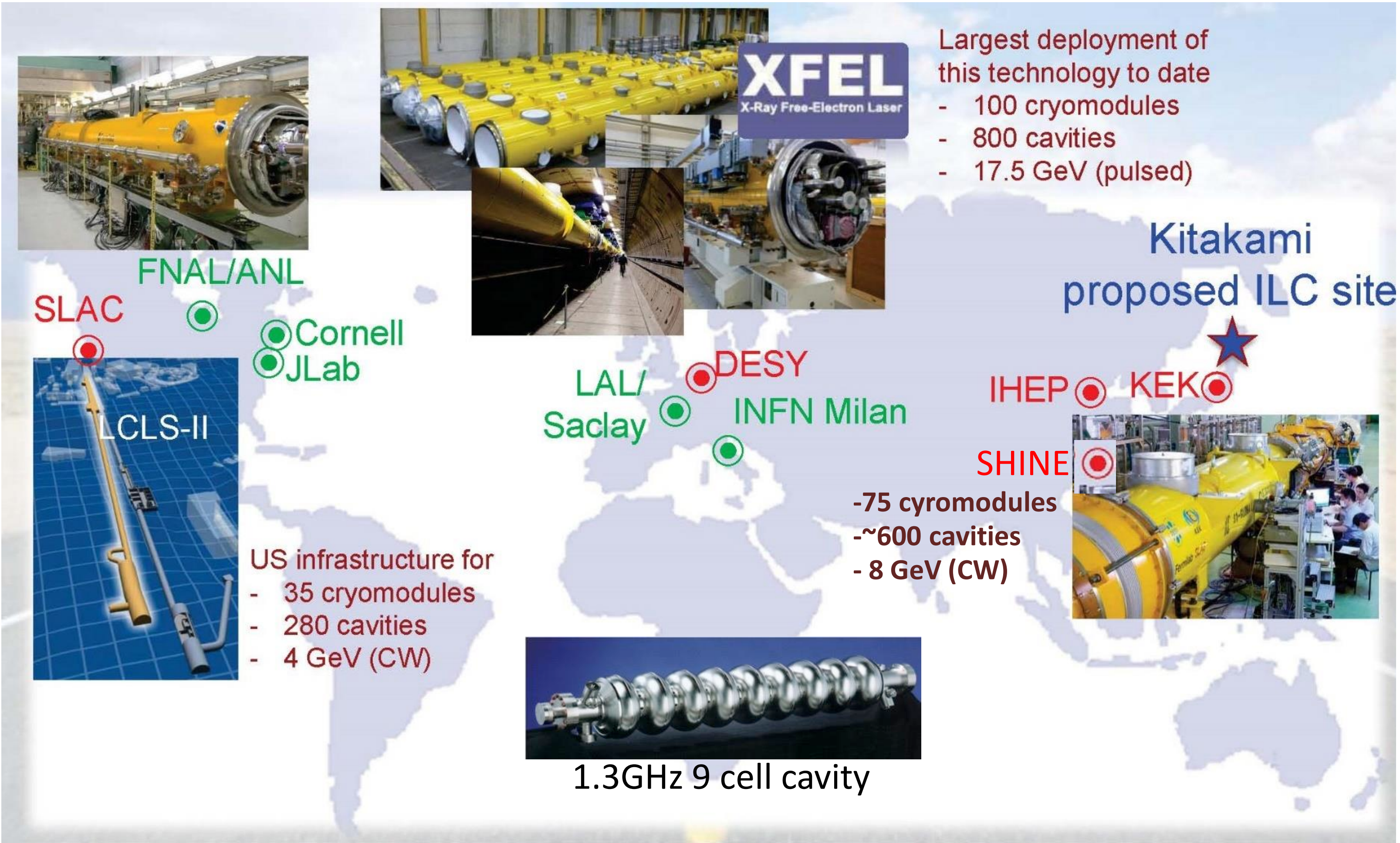


Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 x10^{34} $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G. Q_0	31.5 MV/m (35 MV/m) Q_0 = 1x10^{10}

LC community meeting (Apr. 8,2019)
Shin MICHIZONO

ILC: Capacidad de construcción/experiencia a nivel mundial

SRF accelerators in the world



Tecnología madura e industrialización probada

ATF-2 nano-beam collaboration

	CERN	France		Germany	Spain	UK	
		LAL	LAPP	DESY	IFIC	Oxford	RHUL
Goal 1 Small beam							
Very-low β	✔						
Ultra-low β	✔						
Halo control		✔			✔		
Wakefield/Intensity	✔				✔	✔	✔
Instrumentation	✔	✔			✔	✔	✔
Ground motion	✔		✔			✔	
Background				✔			✔
Goal 2 Beam stabilization							
Stabilisation/Feedback		✔				✔	

ILC: plan de trabajo y construcción

ILC IDT (~1.5 years)

Prepare the work and deliverables of the ILC Pre-laboratory and work out, with national and regional laboratories, a scenario for their contributions

Prepare a proposal for the organisation and governance of the ILC Pre-laboratory

ILC Pre-laboratory (~4 years)

Complete all the technical preparation necessary to start the ILC project (infrastructure, environmental impact and accelerator facility)

Prepare scenarios for the regional contributions to and organisation for the ILC.

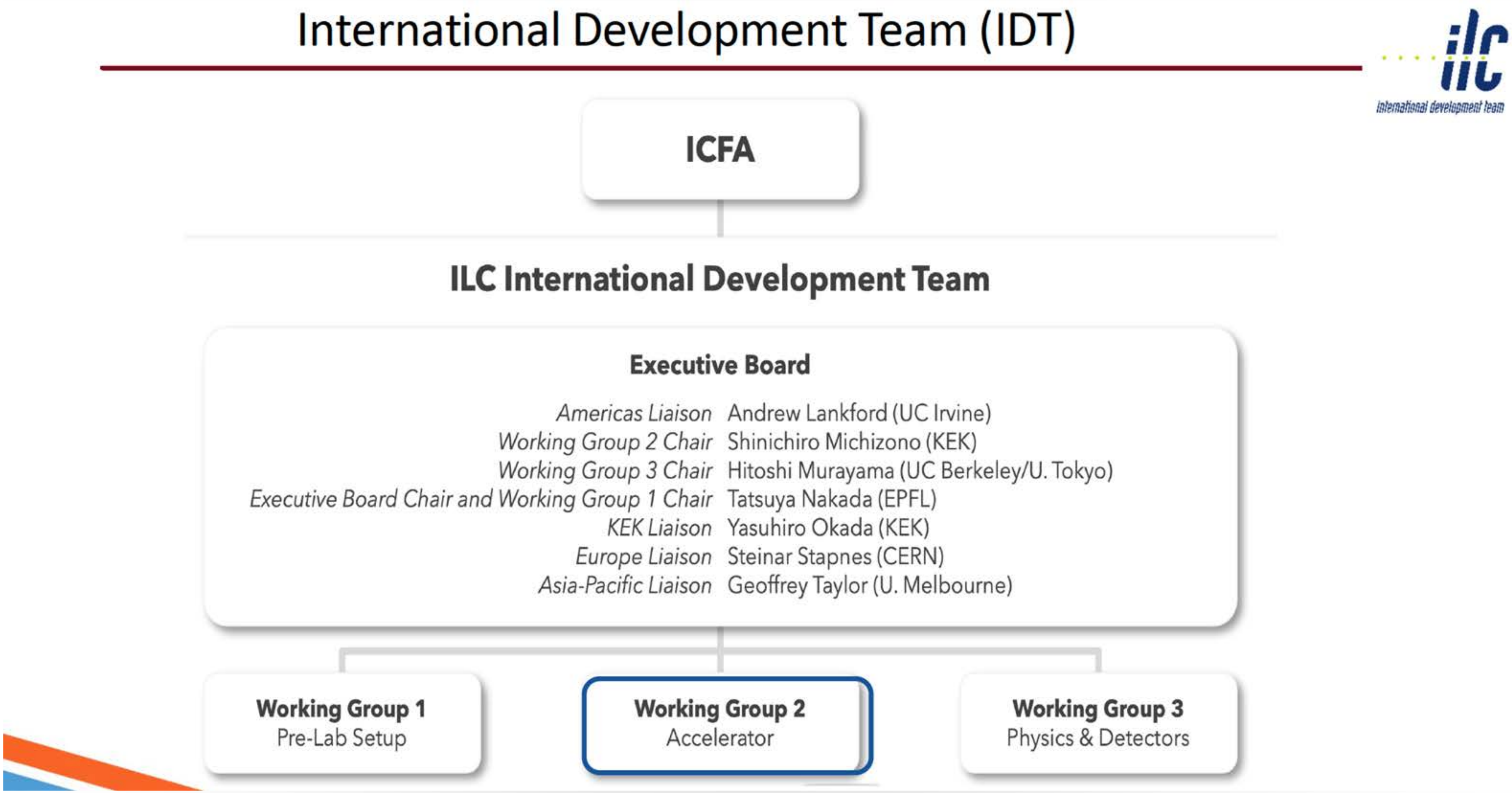
ILC laboratory

Construction and commissioning of the ILC (~9-10 years)

Followed by the operation of the ILC

Managing the scientific programme of the ILC

Steinar Stapnes PECFA – 19 Nov 2020



Contribución española importante y visible en todos los grupos de trabajo

ILC Project: perspectiva europea, arXiv:1901.09825

European ILC project plans

I. Introduction
II. Accelerator
  A. ILC accelerator competence in Europe
  B. ILC accelerator Preparation Phase activities in Europe
  C. ILC accelerator in-kind contributions from Europe during the ILC Construction Phase
  D. Organisation of the accelerator activities

The International Linear Collider
A European Perspective

Prepared by: Philip Bambade[1], Ties Behnke[2], Mikael Berggren[2], Ivanka Bozovic-Jelisavcic[3], Philip Burrows[4], Massimo Caccia[5], Paul Colas[6], Gerald Eigen[7], Lyn Evans[8], Angeles Faus-Golfe[1], Brian Foster[2,4], Juan Fuster[9], Frank Gaede[2], Christophe Grojean[2], Marek Idzik[10], Andrea Jeremie[11], Tadeusz Lesiak[12], Aharon Levy[13], Benno List[2], Jenny List[2], Joachim Mnich[2], Olivier Napoly[6], Carlo Pagani[14], Roman Poeschl[1], Francois Richard[1], Aidan Robson[15], Thomas Schoerner-Sadenius[2], Marcel Stanitzki[2], Steinar Stapnes[8], Maksym Titov[6], Marcel Vos[9], Nicholas Walker[2], Hans Weise[2], Marc Winter[16].

[1]LAL-Orsay/CNRS, [2]DESY, [3]INN VINCA, Belgrade, [4]Oxford U., [5]U. Insubria, [6]CEA/Irfu, U. Paris-Saclay, [7]U. Bergen, [8]CERN, [9]IFIC, U. Valencia-CSIC, [10]AGH, Kraków, [11]LAPP/CNRS, [12]IFJPAN, Kraków, [13]Tel Aviv U., [14]INFN, [15]U. Glasgow, [16]IPHC/CNRS.

	Germany	France	Italy	Poland	Russia	Spain
Linac						
Cryomodules	✓	✓	✓	✓		
SCRF Cavities	✓		✓	✓		
Couplers and Tuners	✓	✓		✓		
Cold Vacuum	✓				✓	
Cavity String Assembly	✓	✓				
SC Magnets	✓			✓		✓
Infrastructure						
Accelerator Module Test Facility (AMTF)	✓			✓	✓	
Cryogenics	✓					
Sites & Buildings						
AMTF hall	✓					

TABLE I. Responsibility matrix for cryomodule production and testing for the European XFEL. More details and a similar matrix can be found in [2] concerning construction of SCRF modules for the ESS linac.

	SCRF	HLRF	Sources	Damping Rings	Instru-mentation	Beam Dynamics	Beam Delivery System	Cryogenics
CERN		C,O	O	G,C,O	C,G	C,G	C,G	O
France	X,E,G		G		A,G	G	C,G	
Germany	X,G	X	G	G	X	G		X,O
Italy	X,E,G			G				
Poland	X,E		O		E,O			X,E,O
Russia	X		G					
Spain	X,E				A		C,G	
Sweden	E						G	
Switzerland					X,C			
UK	E		G	G	A,C,G	C,G,A	C,G,A	

TABLE III. European expertise relevant for ILC accelerator construction, based on experience in the recent past. This is based on two major construction projects, the E-XFEL (X) and the ESS (E), several more R&D oriented efforts namely the GDE/LCC (G), ATF-2 (A), CLIC (C) and experience in other accelerator projects (O)

European ILC project plans

Documento sugiere una contribución europea:

20% of (stage 1) ILC = 1.0-1.5 B CHF = coste 10%-15% of FCC-ee CDR

B. ILC accelerator Preparation Phase activities in Europe
C. ILC accelerator in-kind contributions from Europe during the ILC Construction Phase
D. Organisation of the accelerator activities

Steinar Stapnes, Maksym Titov, Marcel Vos, Nicholas Walker, Hans Weise, Marc Winter.

[1]LAL-Orsay/CNRS, [2]DESY, [3]INN VINCA, Belgrade, [4]Oxford U., [5]U. Insubria, [6]CEA/Irfu, U. Paris-Saclay, [7]U. Bergen, [8]CERN, [9]IFIC, U. Valencia-CSIC, [10]AGH, Kraków, [11]LAPP/CNRS, [12]IFJ PAN, Kraków, [13]Tel Aviv U., [14]INFN, [15]U. Glasgow, [16]IPHC/CNRS.

Estrategia Europea:

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

Cryogenics	✓					
Sites & Buildings						
AMTF hall	✓					

TABLE I. Responsibility matrix for cryomodule production and testing for the European XFEL. More details and a similar matrix can be found in [2] concerning construction of SCRF modules for the ESS linac.

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CLIC Collaborations

https://clic.cern

CLIC accelerator:
- ~50 institutes from 28 countries
- CLIC accelerator studies, design and development
- Construction + operation of CLIC Test Facility, CTF3

CLIC detector and physics (CLICdp):
- 30 institutes from 18 countries
- Physics prospects & simulation studies
- Detector optimisation + R&D for CLIC

Ph. Burrows (LCWS21, 2021)

- e^+e^- collisions $\sqrt{s}$ up to 3 TeV
- Luminosity: a few 10^{34} $cm^{-2}s^{-1}$
- Physics operation 350 GeV - 3 TeV
- 2-beam acceleration scheme
- At room temperature
- Gradient 100 MV/m
- Conceptual Design Report published in 2012

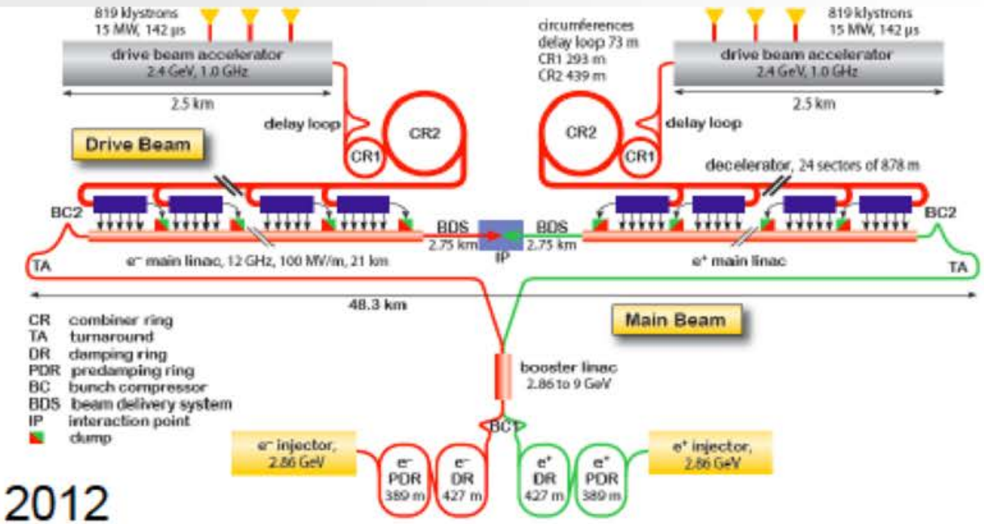
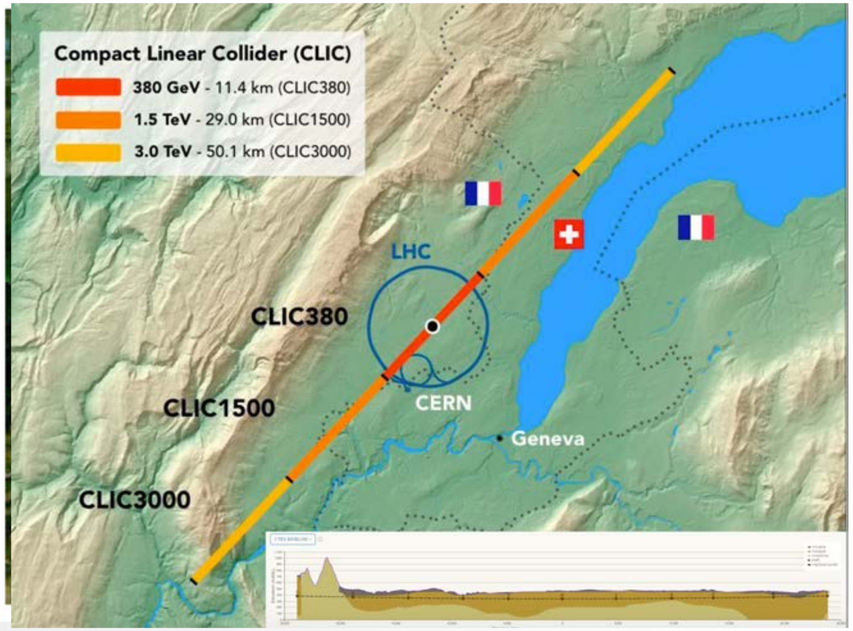


Fig. 3.1: Overview of the CLIC layout at $\sqrt{s} = 3$ TeV.

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 $\sqrt{s}$	$10^{34}cm^{-2}s^{-1}$	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
Site length	km	11	48



CLIC overview

- **Timeline:** e+e- linear collider at CERN for the era beyond HL-LHC
- **Compact:** novel and unique two-beam accelerating technique based on high-gradient room temperature RF cavities:

  first stage: 380 GeV, ~11km long, 20,500 cavities
- **Expandable:** staged collision energies from 380 GeV (Higgs/top) up to 3 TeV

- Conceptual Design Report published in 2012
- Project Implementation Plan released 2018

  Cost: 5.9 BChF for 380 GeV (stable w.r.t. CDR)

  Power: 168 MW at 380 GeV (significantly reduced since CDR)

- Comprehensive Detector and Physics studies

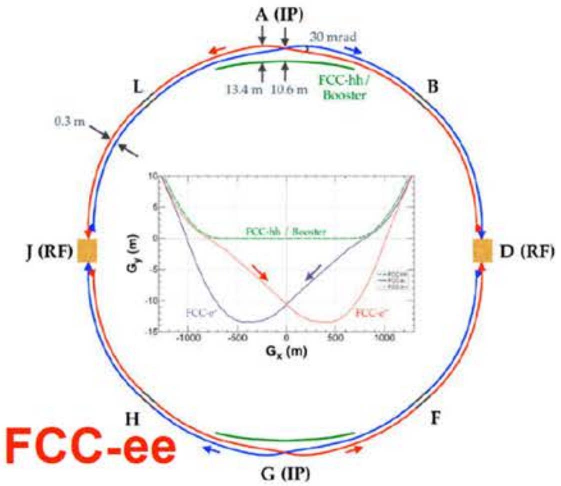
Ph. Burrows (LCWS21, 2021)

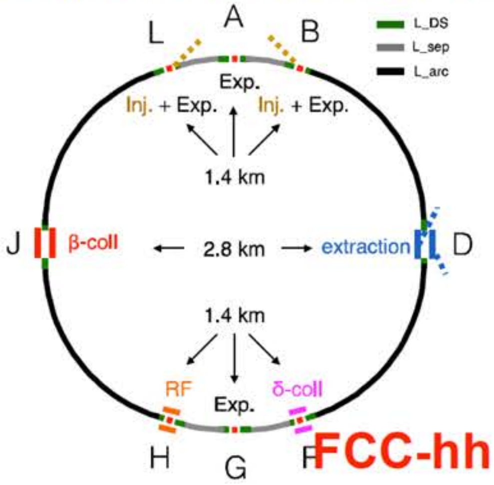
El Futuro Colisionador Circular (FCC-ee)

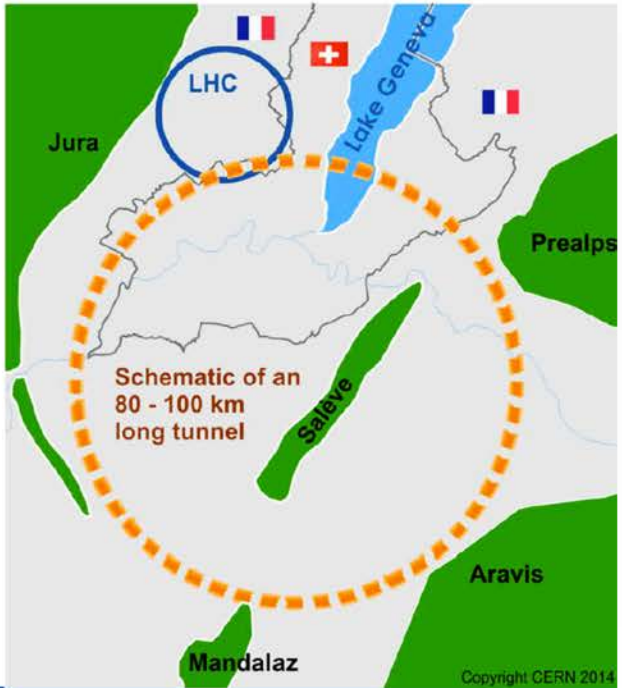
The FCC integrated program inspired by successful LEP – LHC programs at CERN

Comprehensive cost-effective program maximizing physics opportunities

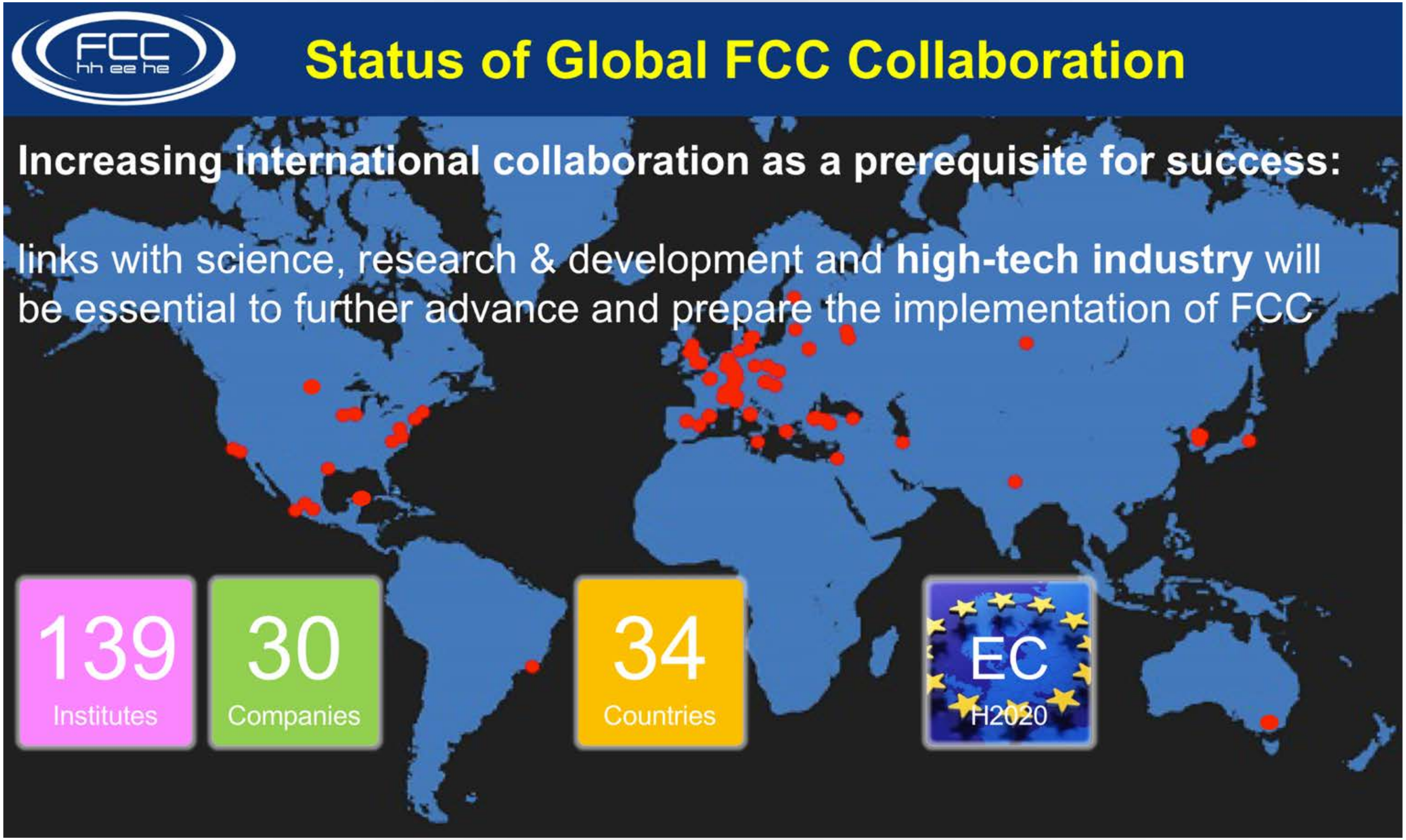
- **Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & and top factory at highest luminosities**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- Complementary physics
- Common civil engineering and technical infrastructures
- Building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after HL-LHC



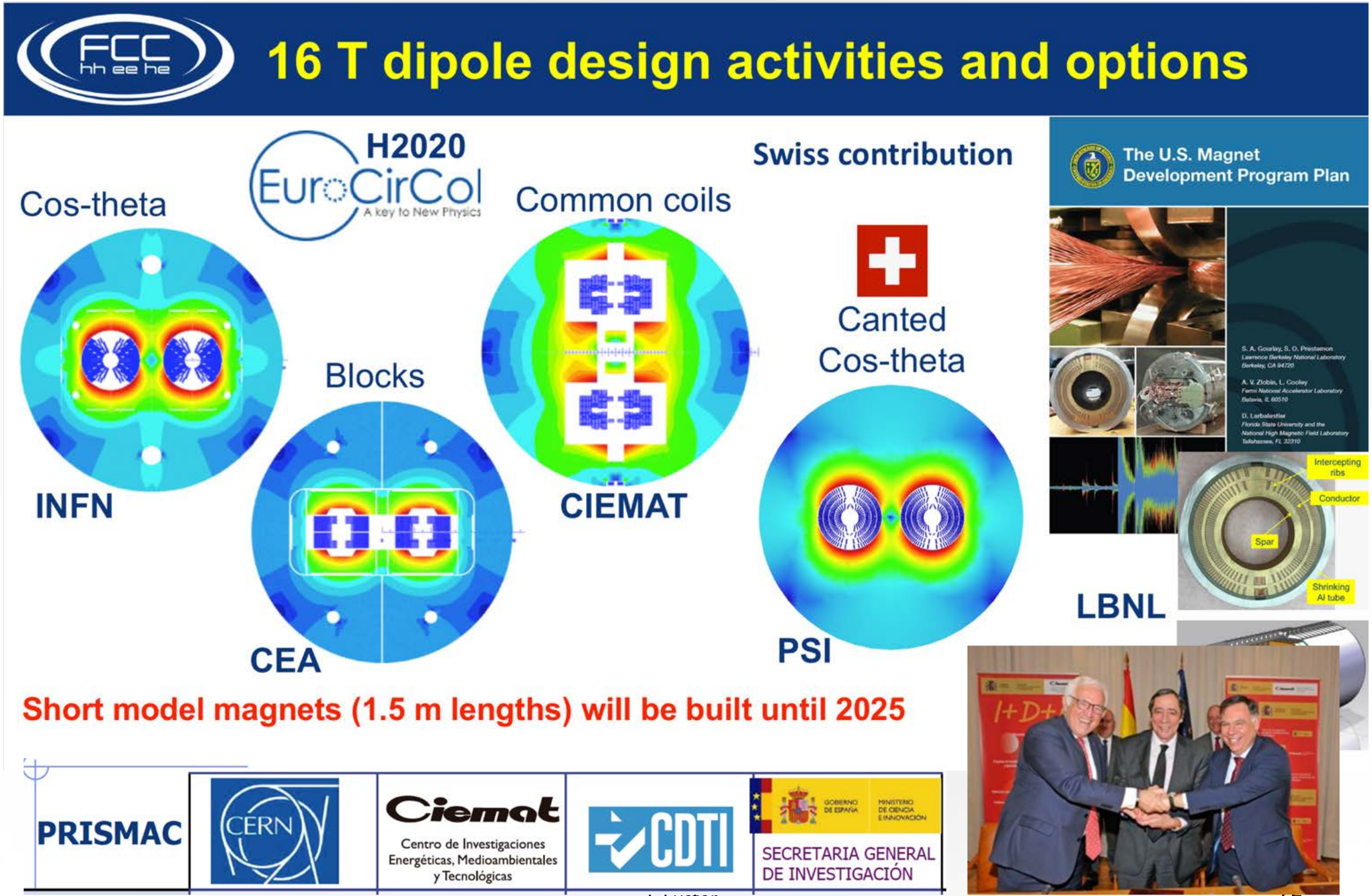




El Futuro Colisionador Circular (FCC-ee)



El Futuro Colisionador Circular (FCC-ee)

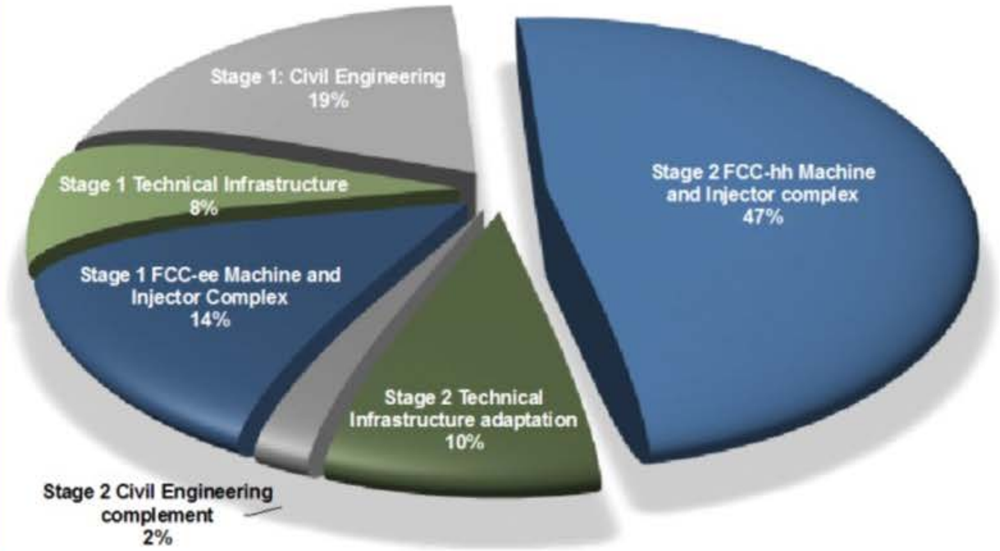


FCC-ee Collider Parameters

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	230	28	8.5	1.55
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

FCC-integrated project cost estimate

Domain	Cost in MCHF
Stage 1 - Civil Engineering	5,400
Stage 1 - Technical Infrastructure	2,200
Stage 1 - FCC-ee Machine and Injector Complex	4,000
Stage 2 - Civil Engineering complement	600
Stage 2 - Technical Infrastructure adaptation	2,800
Stage 2 - FCC-hh Machine and Injector complex	13,600
TOTAL construction cost for integral FCC project	**28,600**



Total construction cost FCC-ee (Z, W, H) amounts to 10,500 MCHF & 1,100 MCHF (tt).

Total construction cost for subsequent FCC-hh amounts to 17,000 MCHF.

(FCC-hh stand alone cost would be 25 BCHF)

El Colisionador Electrón Positrón Circular (CEPC) en China

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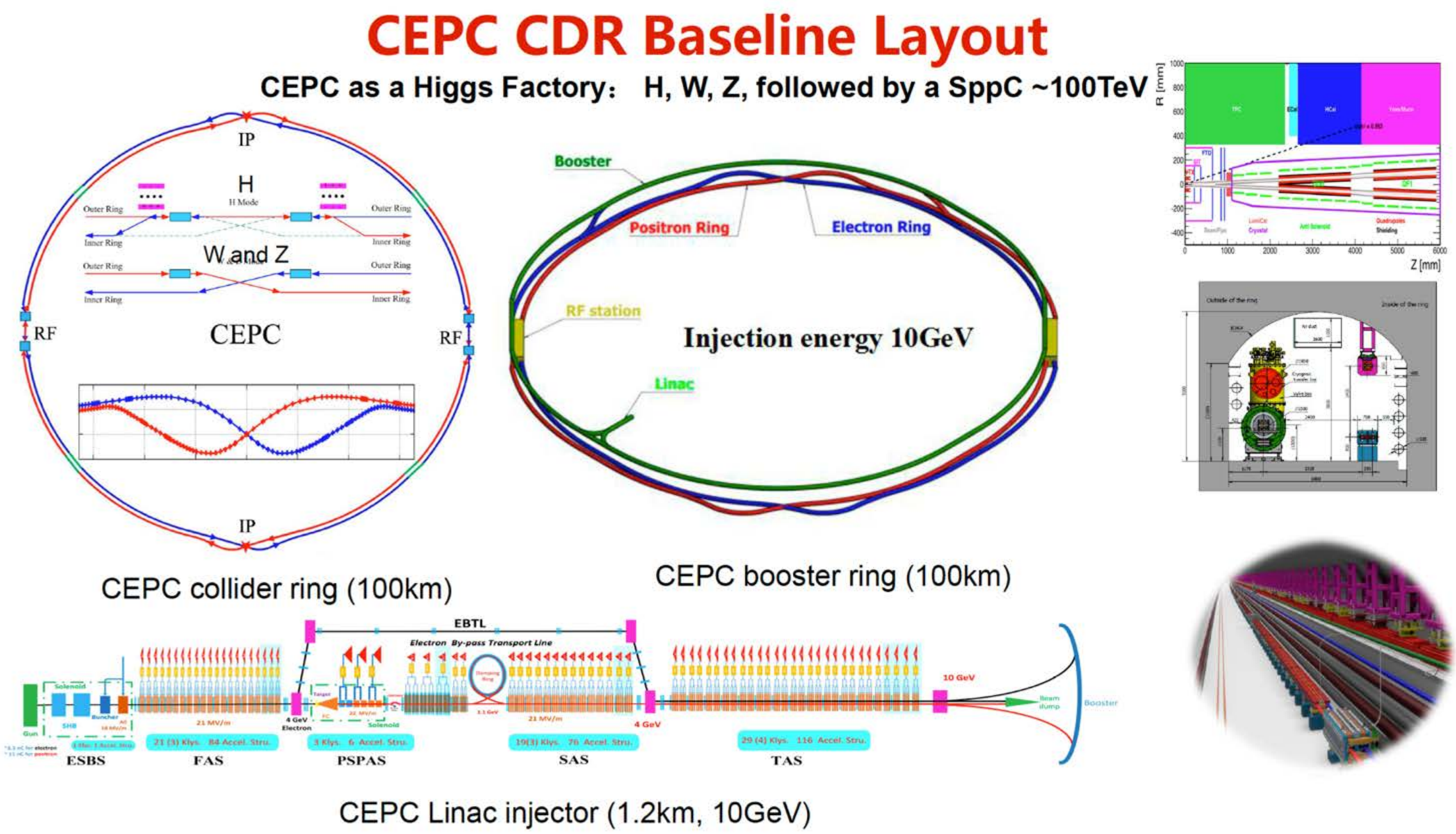
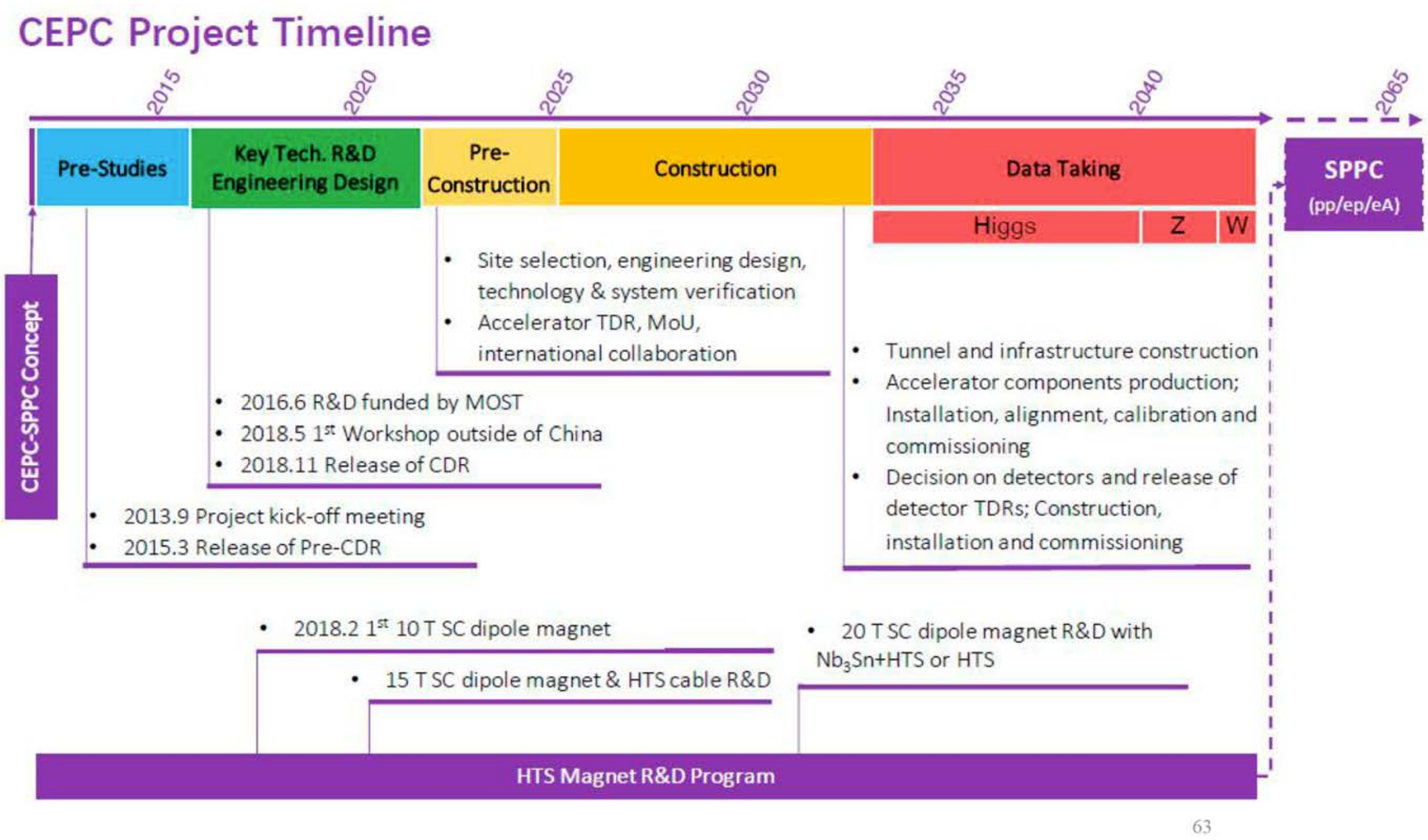


El Colisionador Electrón Positrón Circular (CEPC) en China



El Colisionador Electrón Positrón Circular (CEPC) en China

CEPC High Luminosity Parameters after CDR

	tt	*Higgs*	*W*	*Z*	
Number of IPs	2	2	2	2	
Energy (GeV)	180	120	80	45.5	
Circumference (km)	100	100	100	100	
SR loss/turn (GeV)	8.53	1.73	0.33	0.036	
Half crossing angle (mrad)	16.5	16.5	16.5	16.5	
Piwinski angle	1.16	4.87	9.12	24.9	
N_e/bunch (10^{10})	20.1	16.3	11.6	15.2	
Bunch number (bunch spacing)	37 (4.45μs)	214 (0.7us)	1588 (0.2μs)	3816 (86ns)	11498 (26ns)
Beam current (mA)	3.5	16.8	88.5	278.8	839.9
SR power /beam (MW)	**30**	**30**	**30**	**10**	**30**
Bending radius (km)	10.7	10.7	10.7	10.7	
Phase advance of arc cell	90°/90°	90°/90°	90°/90°	60°/60°	
Momentum compaction (10^{-5})	0.73	0.73	0.73	1.48	
β_{IP} x/y (m)	1.0/0.0027	0.33/0.001	0.33/0.001	0.15/0.001	
Emittance x/y (nm)	1.45/0.0047	0.68/0.0014	0.28/0.00084	0.27/0.00135	
Transverse σ_{IP} (um)	37.9/0.11	15.0/0.037	9.6/0.029	6.36/0.037	
ξ_x/ξ_y/IP	0.076/0.106	0.018/0.115	0.014/0.13	0.0046/0.131	
V_{RF} (GV)	9.52	2.27	0.47	0.1	
f_{RF} (MHz) (harmonic)	650 (216816)	650 (216816)	650 (216816)	650 (216816)	
Nature bunch length σ_z (mm)	2.23	2.25	2.4	2.75	
Bunch length σ_z (mm)	2.66	4.42	5.3	9.6	
HOM power/cavity (kw)	**0.45 (5cell)**	**0.48 (2cell)**	**0.79 (2cell)**	**2.0 (2cell)**	**3.02 (1cell)**
Energy spread (%)	0.17	0.19	0.11	0.12	
Energy acceptance requirement (DA) (%)	2.0	1.7	1.2	1.3	
Energy acceptance by RF (%)	2.61	2.5	1.83	1.48	
Lifetime (hour)	0.59	0.35	1.3	1.7	1.4
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	**0.5**	**5.0**	**18.7**	**35.0**	**105.5**

Factorías de Higgs: Madurez, consumo, coste

- ***F1* "Technology Readiness" :**

Green	- TDR
Yellow	- CDR
Red	- R&D

- ***F2* "Energy Efficiency"**

Green	: 100-200 MW
Yellow	: 200-400 MW
Red	: > 400 MW

- ***F3* "Cost" :**

Green	: < LHC
Yellow	: 1-2 x LHC
Red	: > 2x LHC

Vladimir Shiltsev (Fermilab)

EPPSU 2019 Future Colliders, Granada

Factorías de Higgs: Madurez, consumo, coste

Higgs Factories	Readiness	Power-Eff.	Cost
ee Linear *250 GeV*			
ee Rings *240GeV/tt*			
μμ Collider *125 GeV*			*
Highest Energy			
ee Linear *1-3TeV*			
pp Rings *HE-LHC*			
FCC-hh/SppC			
μμ Coll. *3-14 TeV*			*

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EPPSU 2019 Future Colliders, Granada