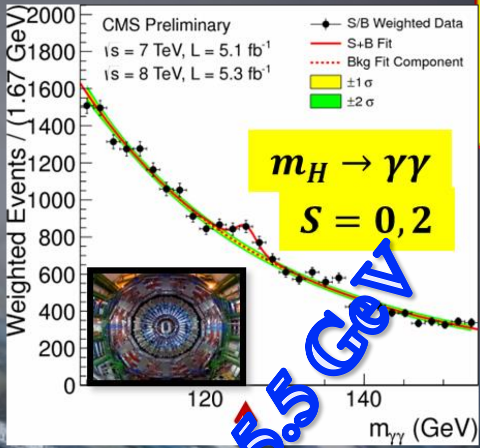
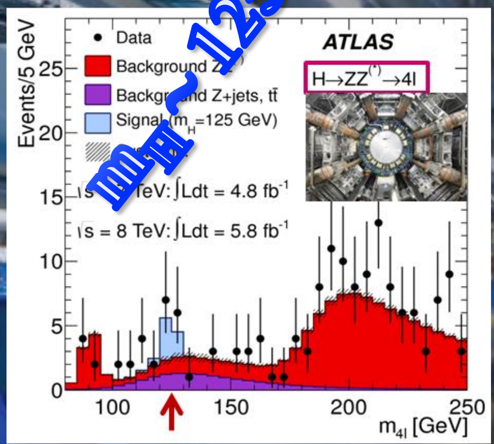
Physique à la frontière en énergie et à la frontière en luminosité

Roy Aleksan
Congrès SFP
1-5 Juillet 2013

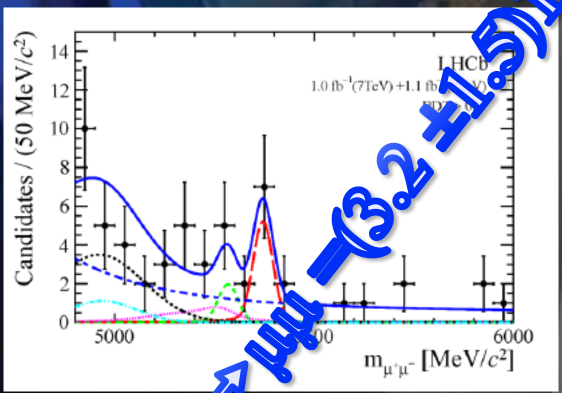
- The Frontiers of PP
- What to do Next and which Strategy
- Next Accelerator Technology Challenges for PP
- Conclusion

High Precision Measurements
Very High Energy Reach
High Intensity ν Beams

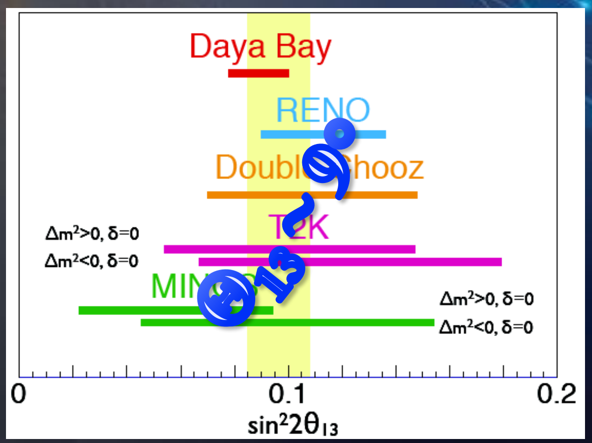




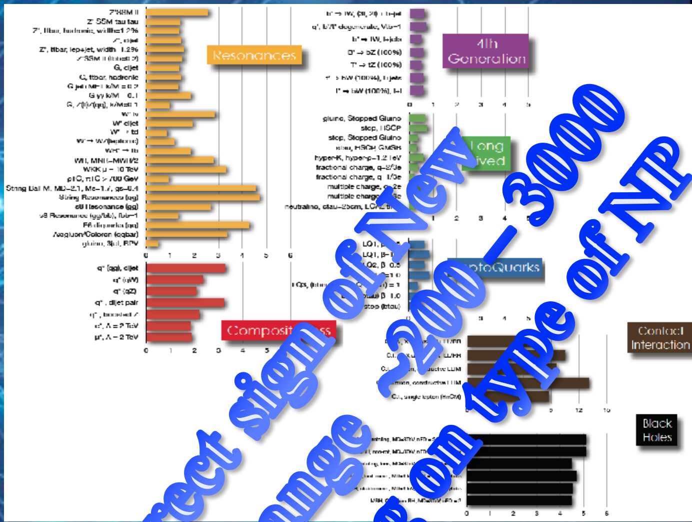
$m_H \sim 125.5$ GeV

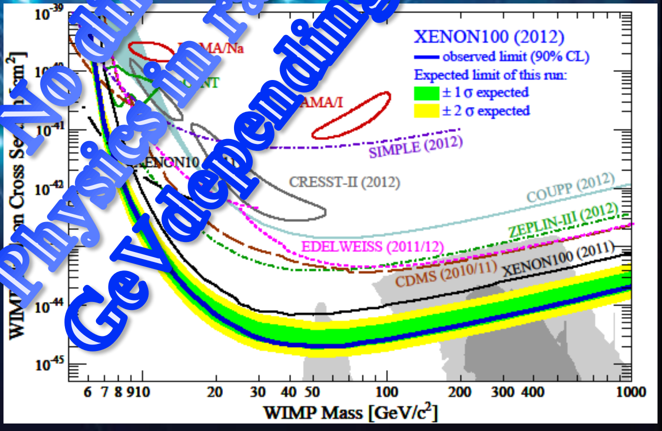


$B_s \to \mu\mu = (3.2 \pm 1.5) 10^{-9}$



$\theta_{13} \sim 9°$

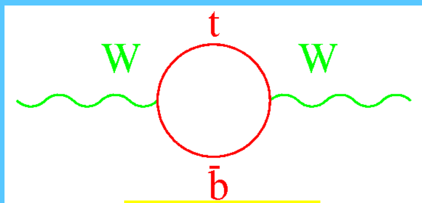




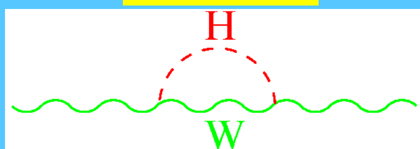
No direct sign of New Physics in range ~200 – 3000 GeV depending on type of NP

…WHAT NEXT

Improve further the consistency of the Standard Model

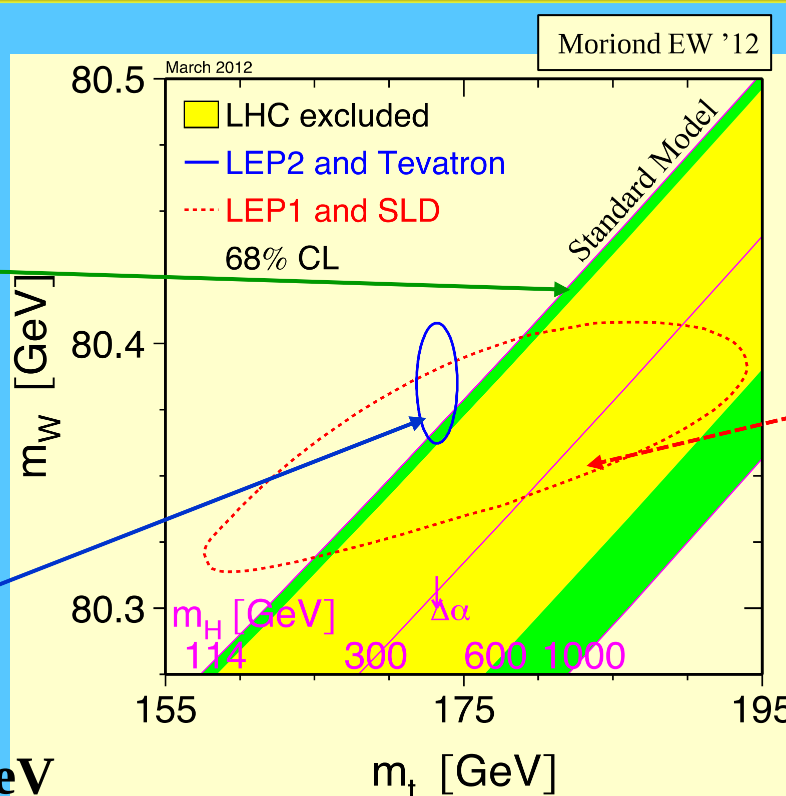


$\propto M_t^2$



$\propto \ln(M_H)$

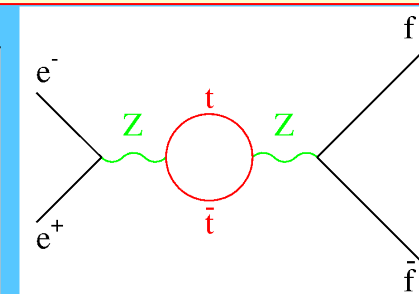
Direct m_W, m_{top} measurements

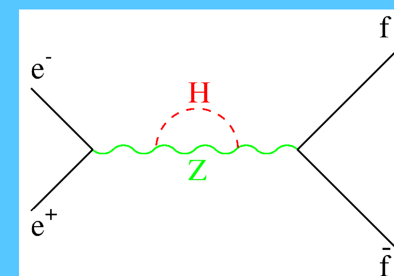


M_W= 80.385 ± 0.015 GeV

M_t= 173.5 ± 1.0 GeV

Z pole measurements



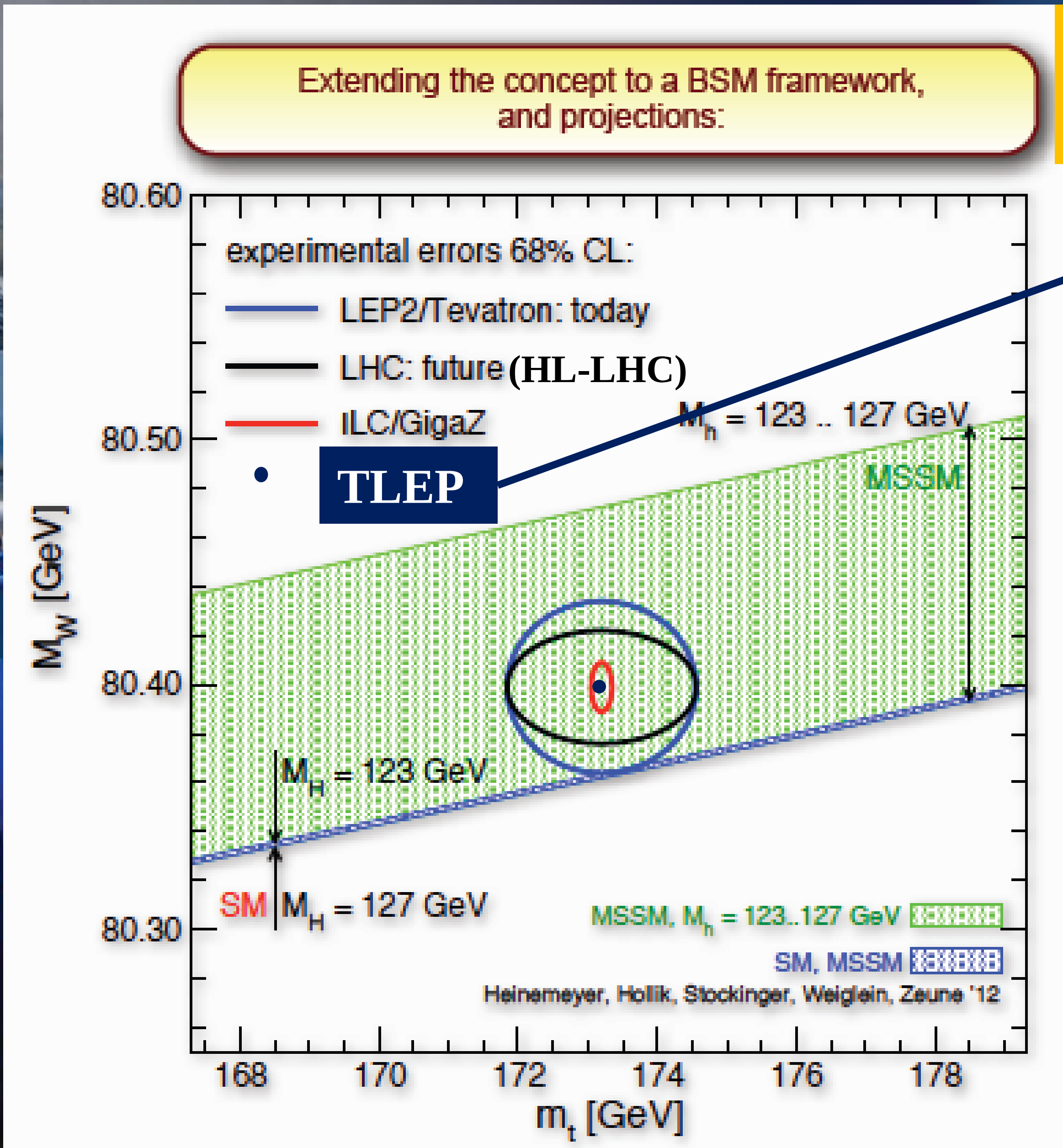


Affects Z lineshape, Asymmetries, Cross section Decay Rates…

Need to improve

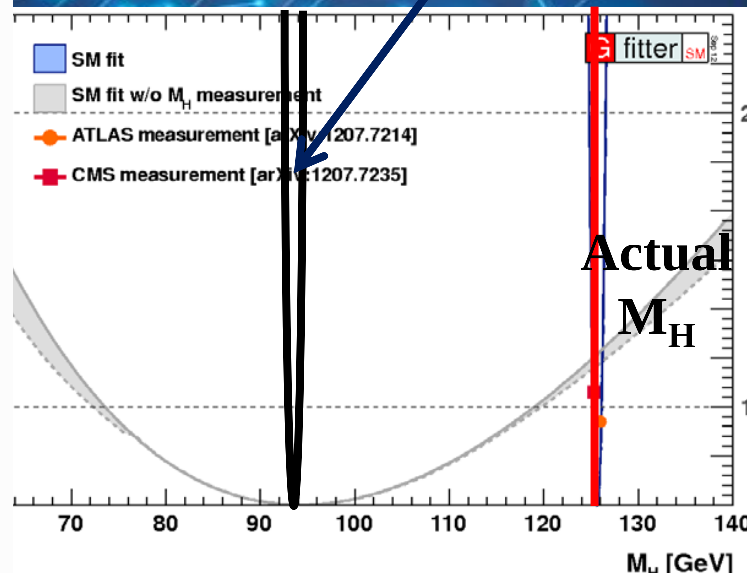
- **Measurement @Z-pole**
- **M_w and M_t (@threshold)**
- **M_H**

High precisions at Z pole and WW and top thresholds



Indirect: M_H=94.0 ± 1.5

Direct: M_H=125.500 ±0.007



Note: This is indicative, a careful analysis still to be carried out

Study of the Higgs properties, its couplings and the potential

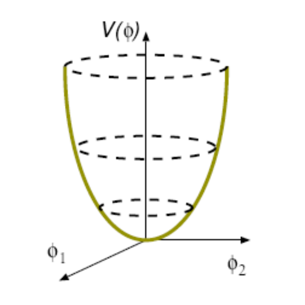
$$V_{Higgs} = -\mu^2\, \phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

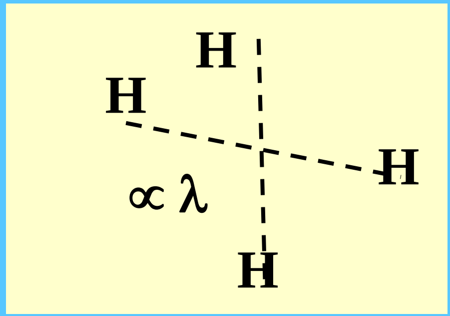
field self coupling

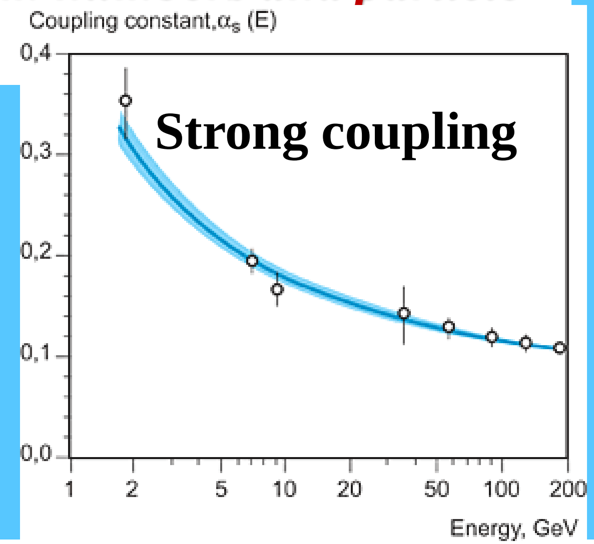
H potential

Interaction strength varies with energy scale, depends on quantum numbers and particle species

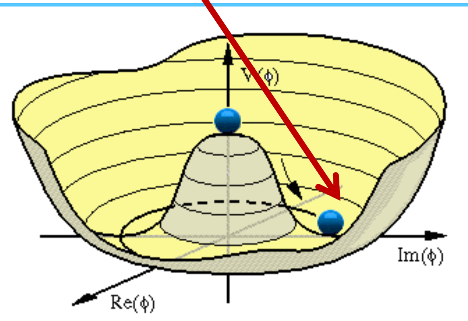
$$\phi_{min} = v = 0$$

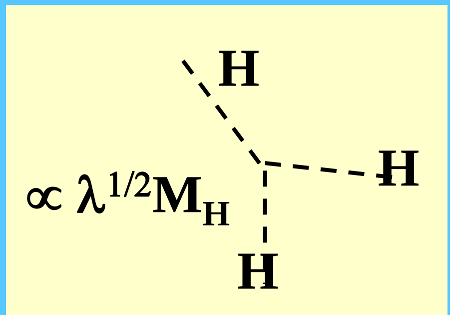


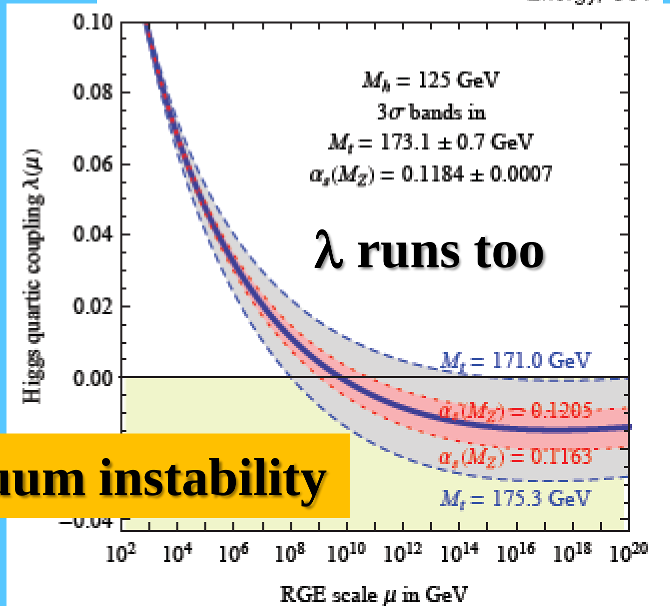




$$\phi_{min} = v = \sqrt{\frac{\mu^2}{2\lambda}}\, e^{-i\delta}$$







$$v = 246\ GeV$$

$$M_H = \sqrt{2\lambda v^2}$$

Consistency Check

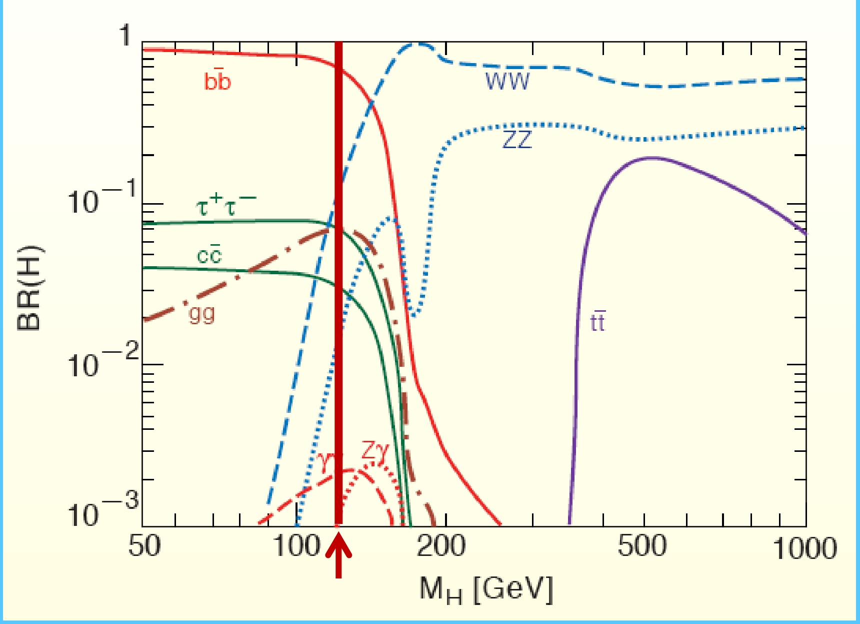
Vaccuum instability

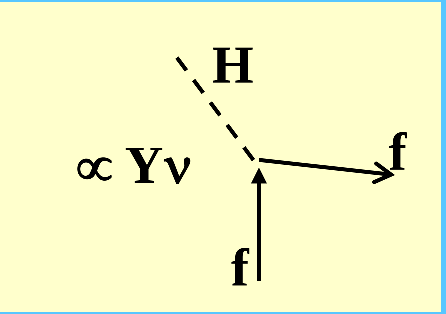
Study further the Higgs properties and couplings

$$V_{Higgs} = -\mu^2 \phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 + [\overline{\psi_{Li}} Y_{ij} \psi_{Rj}\phi + h.c.]$$

$$m_{ij} \equiv Y_{ij} v$$

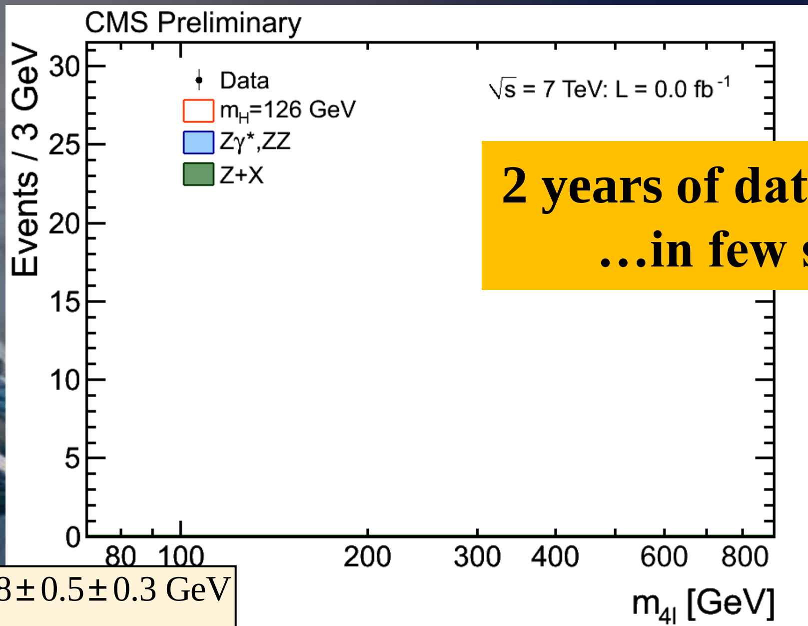
H coupling to fermions $\propto$ m_f



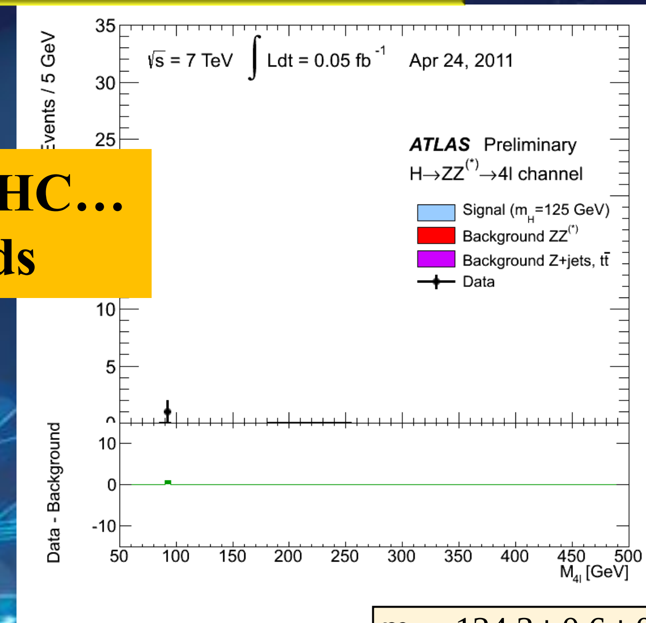


High precisions at H threshold

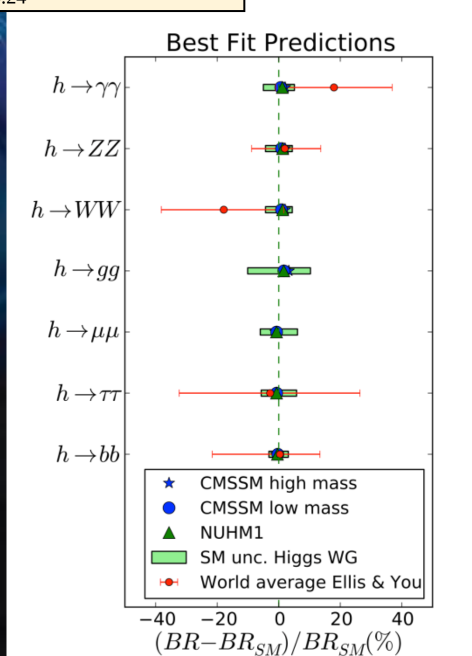
2 years of data @LHC…
…in few seconds

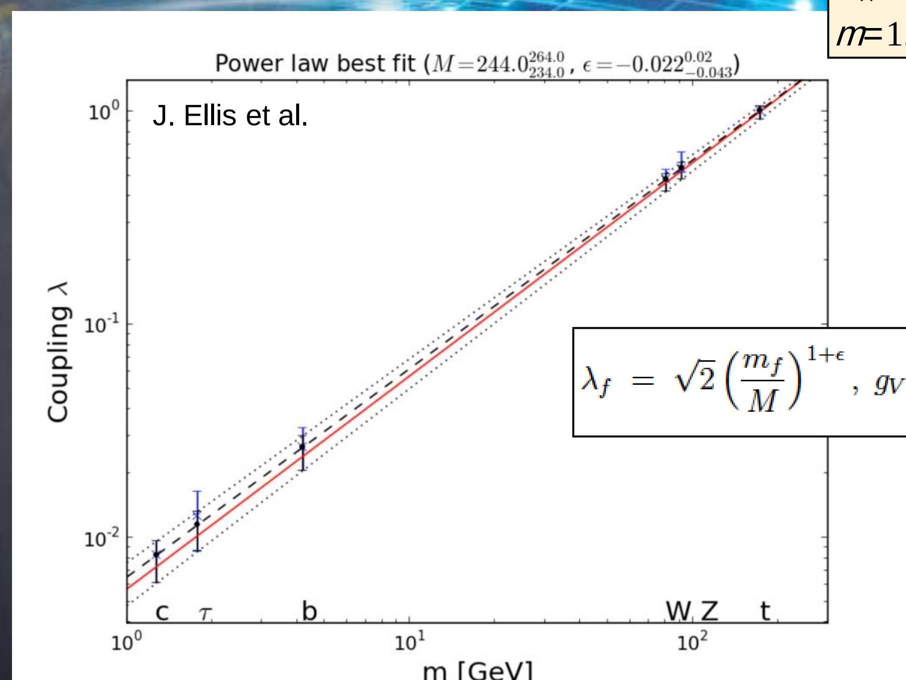


$m_H = 125.8 \pm 0.5 \pm 0.3$ GeV
$\mu = 0.91^{+0.30}_{-0.24}$



$m_H = 124.3 \pm 0.6 \pm 0.4$ GeV
$\mu = 1.5 \pm 0.4$ (at 125.5 GeV)





$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \quad g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$

ElectroWeak Symmetry Breaking precision measurements

Example : Precision for Higgs couplings

SUSY modifies tree-level couplings

e.g. Pseudo-scalar A is difficult to find for **moderate tanβ=5**

H. Baer, M. Peskin et al.

Largest effet expected for bb, ττ

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

e.g. light stop is an important search (hierarchy problem)

$$\frac{g_{hgg}}{g_{h_{SM}gg}} \approx 1 + 11.6\% \left(\frac{0.5\,TeV}{m_T}\right)^2$$

$$\frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \approx 1 - 3.2\% \left(\frac{0.5\,TeV}{m_T}\right)^2$$

Compositness

All couplings reduced according to compositness scale

$$\frac{g_{hff}}{g_{h_{SM}ff}} \approx \frac{g_{hVV}}{g_{h_{SM}VV}} \approx 1 - 3\% \left(\frac{1\,TeV}{f}\right)^2$$

Higgs couplings should be measured as precisely as possible!

→ one should aim at sub-percent measurements

ElectroWeak Symmetry Breaking precision measurements

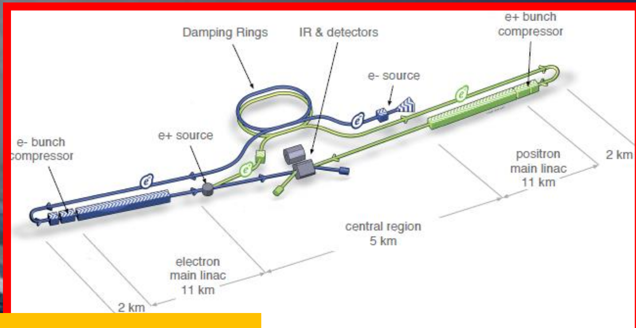
Do we have the technology to study the electroweak sector and Higgs properties with very high precisions

1. **Upgrade LHC luminosity (factor ~10)**
   - **Improve current and focussing**
2. **Build a dedicated « Higgs factory » (factor ~10!)**
   - **e^+e^- circular or linear colliders**
   - **$\gamma\gamma$ colliders**
   - **$\mu^+\mu^-$ colliders**
3. **Build (V)HE-frontier colliders (factor ~10!)**
   - **pp circular colliders**
   - **e^+e^- linear colliders**
   - **$\mu^+\mu^-$ colliders**
   - **Plasma acceleration colliders**

Future large scale accelerators discussed/mentioned in the talk

From Higgs studies and electroweak high precision tests…

Linear Colliders
(ILC, CLIC)



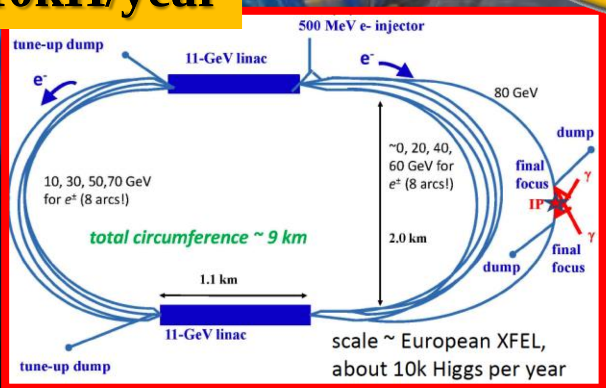
~14kH/year

Circular e^+e^- Colliders
(TLEP, super TRISTAN, IHEP…)

~400kH/year (4 det.)

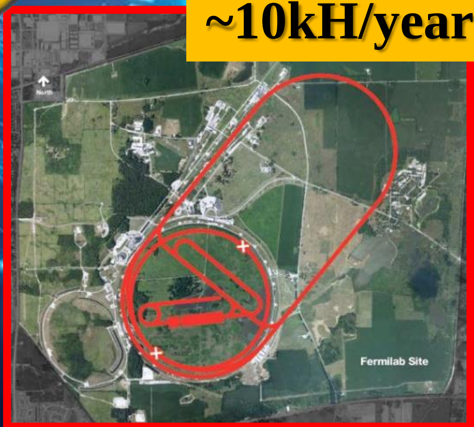
Higgs Factories

~10kH/year



γγ Colliders
(SAPPHIRE, SILC, CLICHE, HFiTT)

~10kH/year (2det.)



Muon Colliders
(ν-Fact. as possible 1st step

ElectroWeak Symmetry Breaking precision measurements

- With M_H all parameters of SM are known! What do we need to measure now?

	LHC(300)	LHC (3000)	ILC (250+350+500)	TLEP (240+350)	Comment
Δm_H (MeV)	~100	~50	~30	~7	Overkill for now
$\Delta\Gamma_H/\Gamma_H (\Delta\Gamma_{inv})$			5.5(1.2)%	1.1(0.3)%	
H spin	✓	✓	✓	✓	
Δm_W (MeV)	~10	~10	~6	<1	Theo. limits
Δm_t (MeV)	800-1000	500-800	20	15	~100 from theo.
$\Delta g_{HVV}/g_{HVV}$	2.7-5.7%*	1-2.7%*	1-5%	0.2-1.7%	
$\Delta g_{Hff}/g_{Hff}$	5.1-6.9%*	2- 2.7%*	2-2.5%	0.2-0.7%	
$\Delta g_{Htt}/g_{Htt}$	8.7%*	3.9%*	~15%	~30%	
$\Delta g_{HHH}/g_{HHH}$	--	~30%	15-20%**	--	Insufficient ?

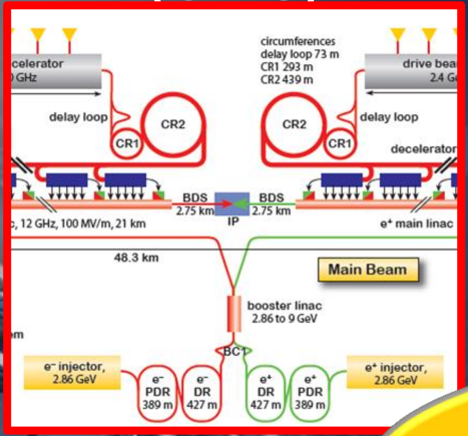
*Assuming systematical errors scales as statistical and theoretical errors divided by 2 compared to now

**Sensibility with $2ab^{-1}$ at 500 GeV (TESLA TDR) and needs to be comfirmed by on-going more detailed studies

Future large scale accelerators discussed/mentioned in the talk

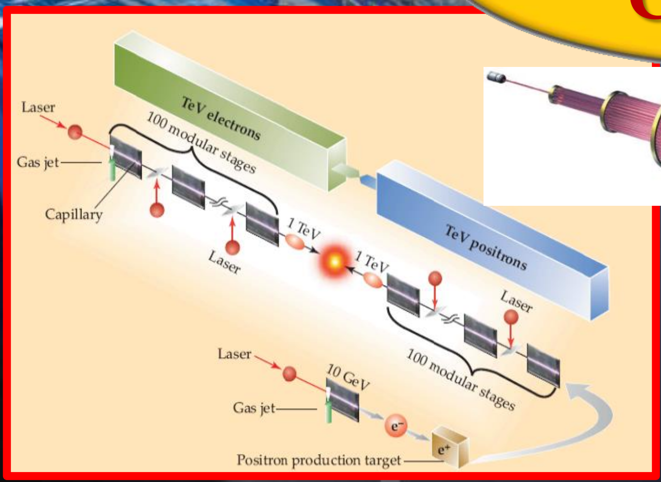
…to HE-physics and -Frontier exploration

Linear Colliders (CLIC)



pp Colliders (HE-LHC, VHE-LHC,…)

HE-Frontier Colliders



Plasma Colliders

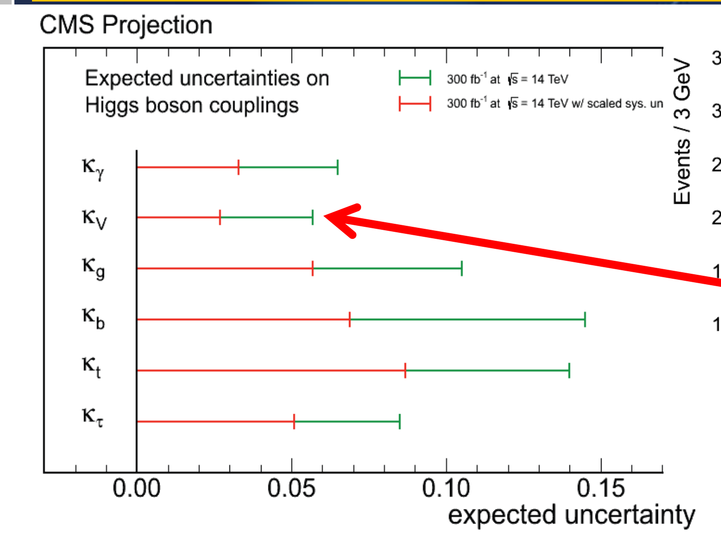
Muon Colliders

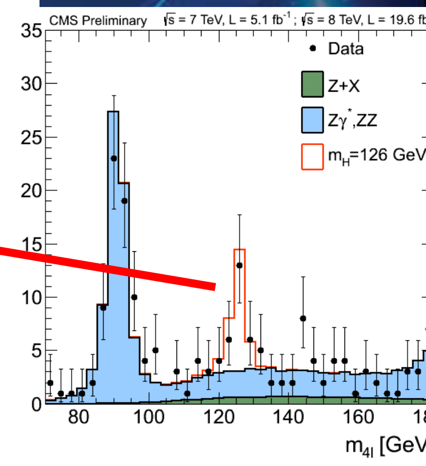
(ν-Fact. as possible 1st step

ElectroWeak Symmetry Breaking precision measurements

Accelerator → Physical quantity ↓	LHC 300fb^{-1} /exp	HL-LHC 3000fb^{-1} /exp
Approx. date	2021	2030-35?
N_H	1.7 x 10^7	1.7 x 10^8
Δm_H (MeV)	100	**50**
$\Delta\Gamma_{H}/\Gamma_H$	--	--
$\Delta\Gamma_{inv}/\Gamma_H$	Indirect (?)	Indirect (?)
$\Delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$	6.5 – 5.1%	5.4 – **1.5%**
$\Delta g_{Hgg}/g_{Hgg}$	11 – 5.7%	7.5 – **2.7%**
$\Delta g_{Hww}/g_{Hww}$	5.7 – 2.7%	4.5 – **1.0%**
$\Delta g_{HZZ}/g_{HZZ}$	5.7 – 2.7%	4.5 – **1.0%**
$\Delta g_{HHH}/g_{HHH}$	--	**< 30%** (2 exp.)
$\Delta g_{H\mu\mu}/g_{H\mu\mu}$	<30%	<10%
$\Delta g_{H\tau\tau}/g_{H\tau\tau}$	8.5 – 5.1%	5.4 – **2.0%**
$\Delta g_{Hcc}/g_{Hcc}$	--	--
$\Delta g_{Hbb}/g_{Hbb}$	15 – 6.9%	11 – **2.7%**
$\Delta g_{Htt}/g_{Htt}$	14 – 8.7%	8.0 – **3.9%**
Δm_t (MeV)	800-1000	**500-800**
Δm_W (MeV)		**~10**

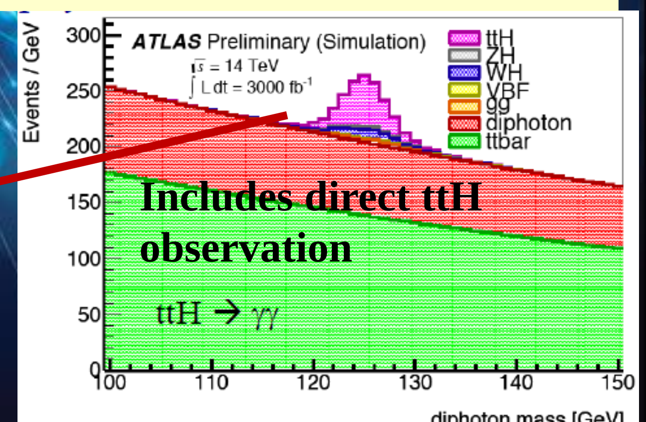
LHC is the benchmark Higgs Factory





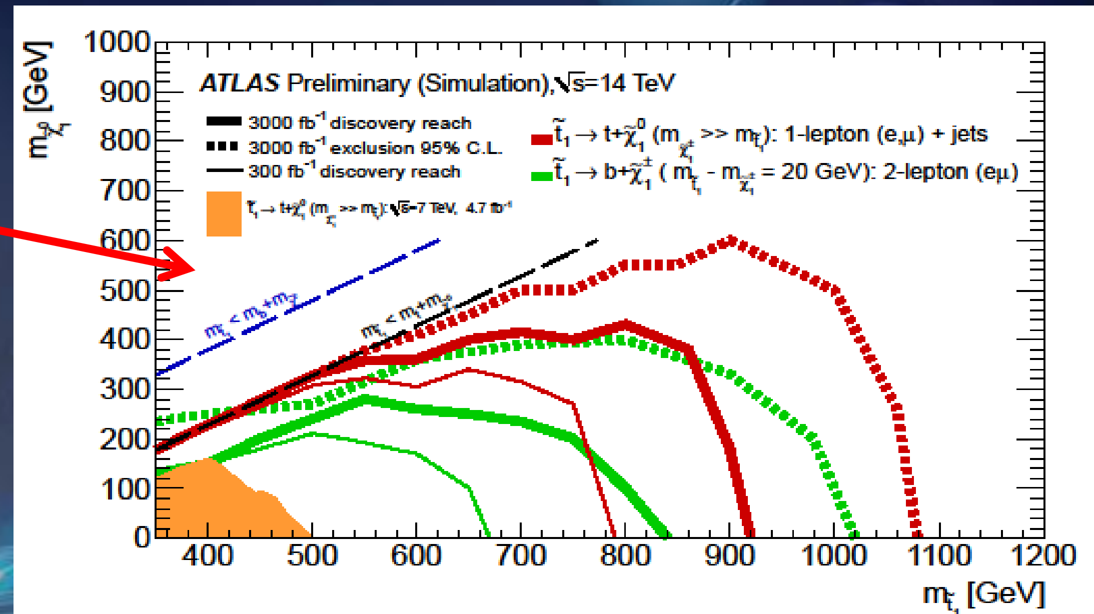
Coupling measurements with precisions:

- in the range 6-15% with 300 fb^{-1}
- in the range 1-4% with 3000 fb^{-1b}



Search of new particles

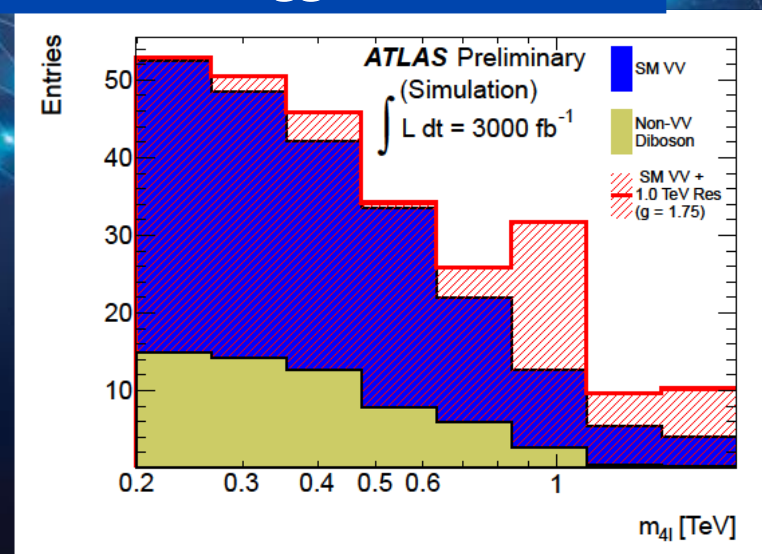
- Sensitivity on SUSY can be signicantly improved … in particular for stop



- High energy and luminosity are necessary to probe the $V_L V_L$ scattering and verify that unitarity is preserved, thanks to the « Higgs » discovered

A statistical presicion of 15% on the SM VBS contribution (i.e. VV+ 2 forward jets) can be obtained with HL-LHC

Model	300 fb^{-1}	3000 fb^{-1}
$m_{\mathrm{resonance}} = 500$ GeV, $g = 1.0$	2.4 σ	7.5 σ
$m_{\mathrm{resonance}} = 1$ TeV, $g = 1.75$	1.7 σ	5.5 σ
$m_{\mathrm{resonance}} = 1$ TeV, $g = 2.5$	3.0 σ	9.4 σ



Recommendations from European Strategy Group

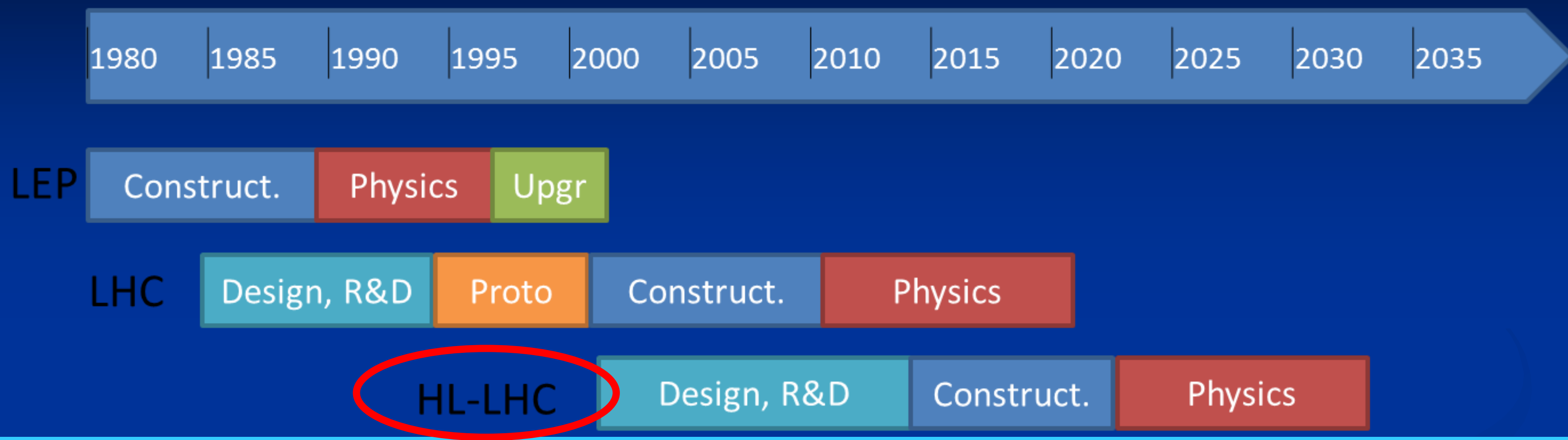
High-priority large-scale scientific activities (1)

Recommendation #1

c) 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.

The super-exploitation of the CERN complex: Injectors, LEP/LHC tunnel, infrastructures



- **Increase beam current ⇨ protect SC dipole (diffracted protons)**

  8T-15m (20 magnets) ⇨ 11T-2x5.5 m dipoles

- **Reduce beam size at IP ⇨ Larger aperture quads near IP**

  Change Quadrupole Triplets ⇨ 140T/m, 150mm (13T, 8m)

- **Protect Electrical Distribution Feedbox's (DFBX)**

  ⇨ 2×100 kA ~500m *HTS links*

- **Improve and adjust the luminosity with beam overlap control**

  ⇨ SC RF «Crab» Cavity, for p-beam rotation at fs level!

Recommendations from European Strategy Group (cont'd)

High-priority large-scale scientific activities (2)

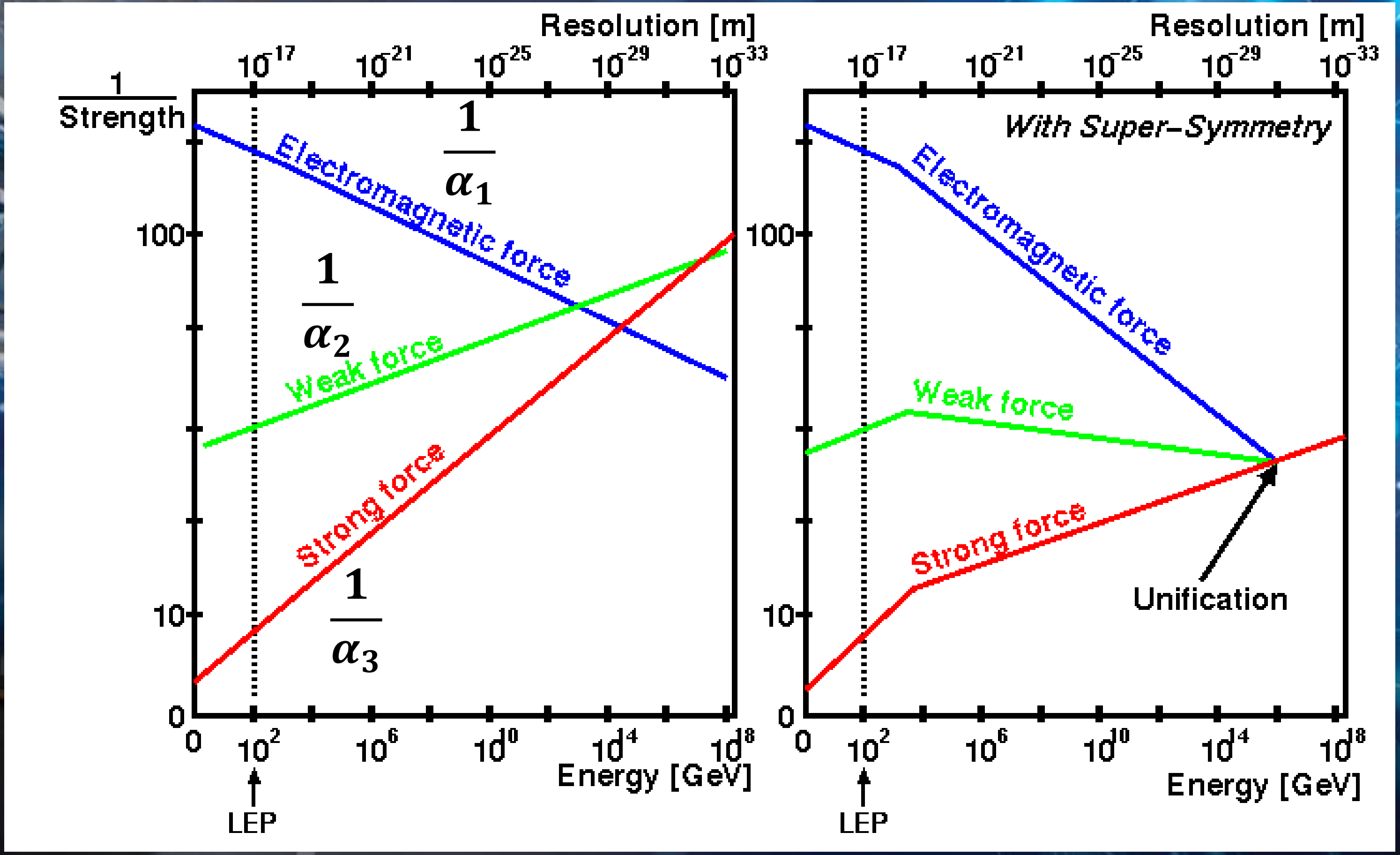
Recommendation #2

d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available.

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.

Grand unification of Interactions (Strong, Weak, Electromagnetic)

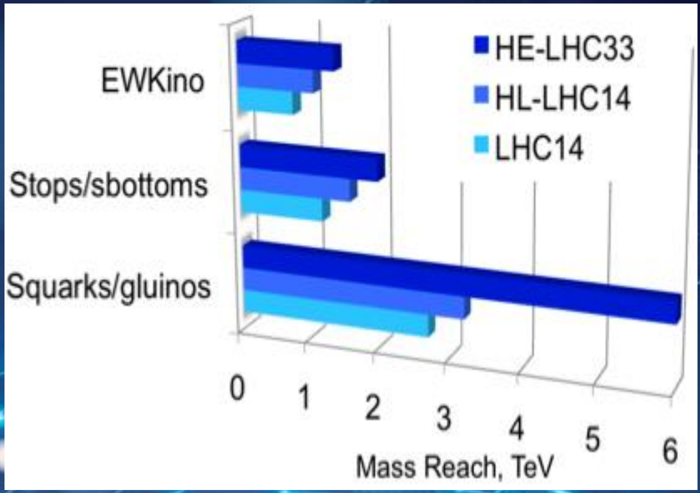
Additionnal particles (such as supersymmetric partners) with energy scales of TeVs affect the running of the coupling constants



Need to explore higher energy regions (up to ~10 TeV)

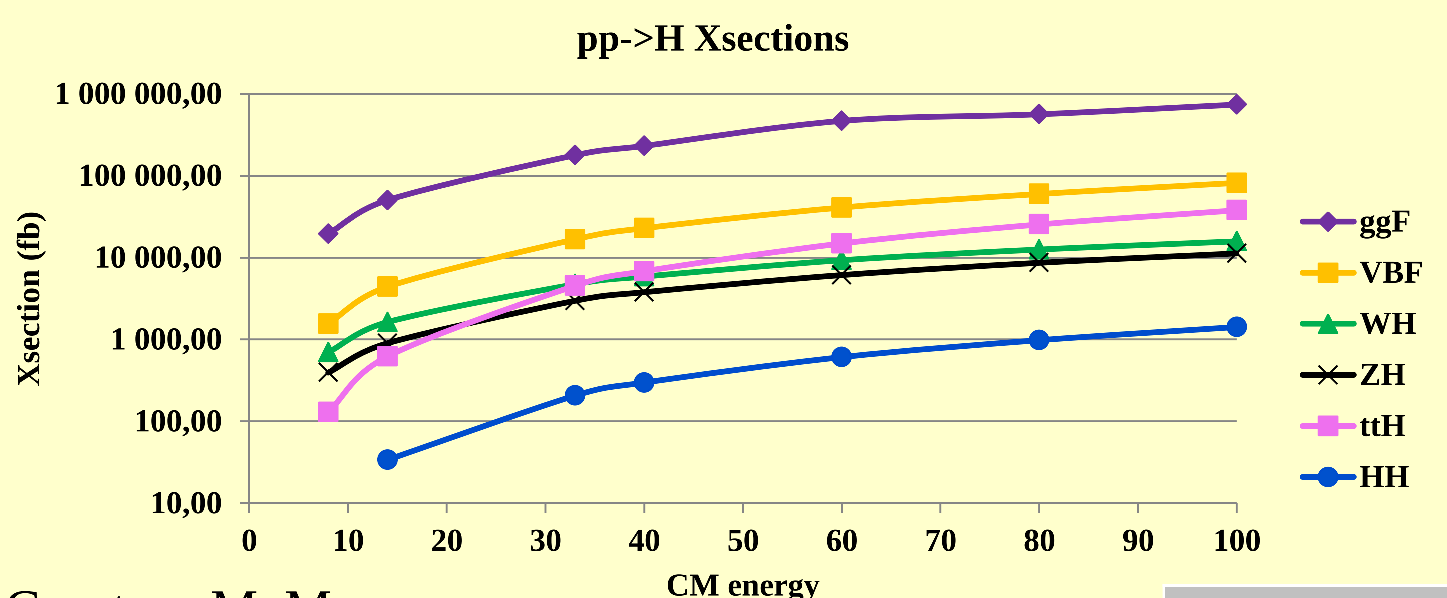
Whatever is found or not, reaching higher energies is unavoidable

To search for new particles up to 10 TeV, very high energy (>50TeV) is necessary



To probe $V_L V_L$ scattering up to 10 TeV region, very high energy is necessary

It will also allow more precise SM measurements



Courtesy M. Mangano

VHELHC is also a very precise higgs study machine

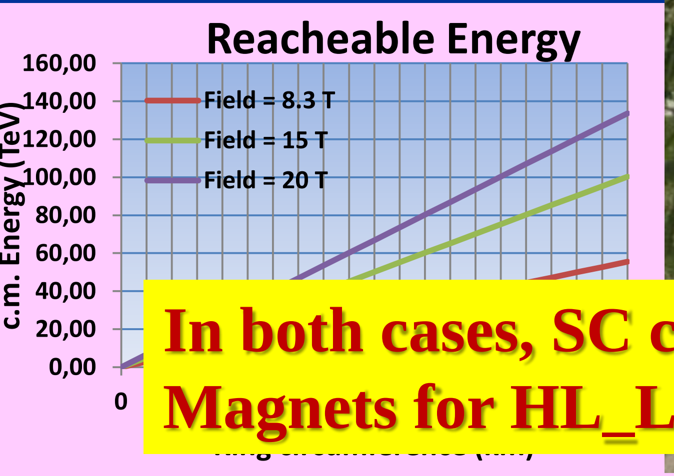
$\Delta g_{Htt}/g_{Htt}$	<1%
$\Delta g_{HHH}/g_{HHH}$	<5%

The super-exploitation of the CERN complex: Injectors, LEP/LHC tunnel, infrastructures

	1980	1985	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035

- **LEP**: Construct. → Physics → Upgr
- **LHC**: Design, R&D → Proto → Construct. → Physics
- **HL-LHC**: Design, R&D → Construct. → Physics
- **HE-LHC / VHE-LHC**: Design, R&D → Proto → Construct. → Physics → VHE

Either using existing LEP/LHC tunnel to reach 26-32 TeV collisions



Or build (or reuse) a 80km tunnel to reach 80-100 TeV collisions VHE-LHC

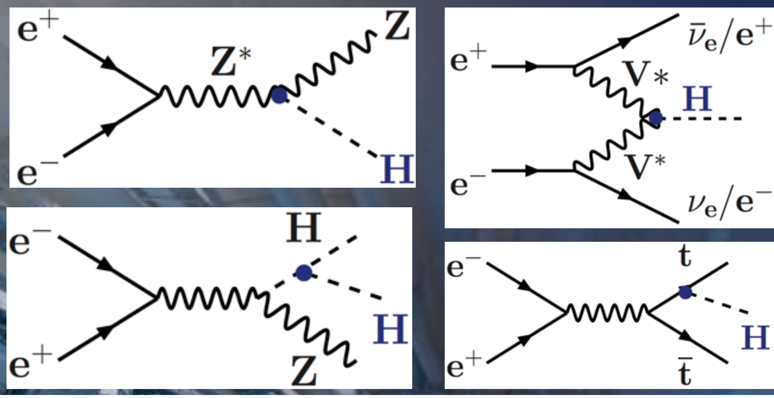
⇨ more detailed study of such a tunnel needed

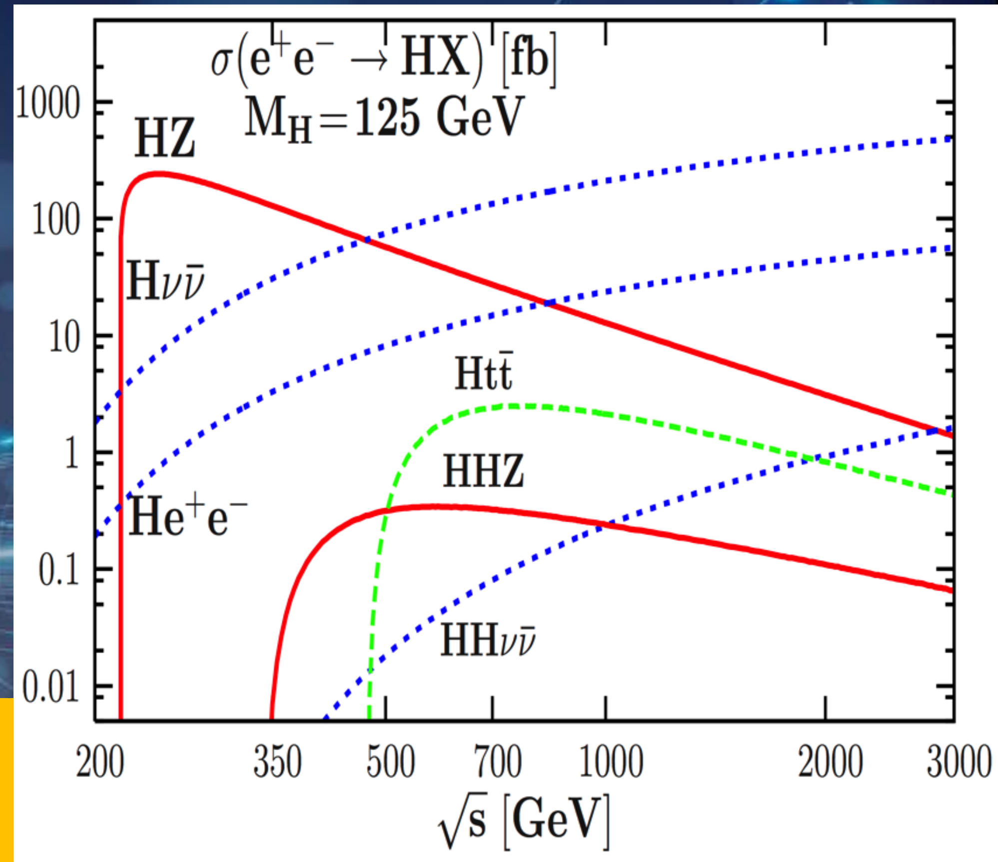
In both cases, SC challenge to develop 16-20 Tesla magnets!

Magnets for HL_LHC is an indispensible first step

ElectroWeak Symmetry Breaking precision measurements

Lepton colliders allows clean absolute measurements!





- Tagged Higgs, largest cross section
- Individual branching ratios to a few %
- Invisible and exotic decays
- Possibly total Higgs decay width

But Xsection is low:
At 240 GeV, σ_{HZ}~200 fb^{-1} only!

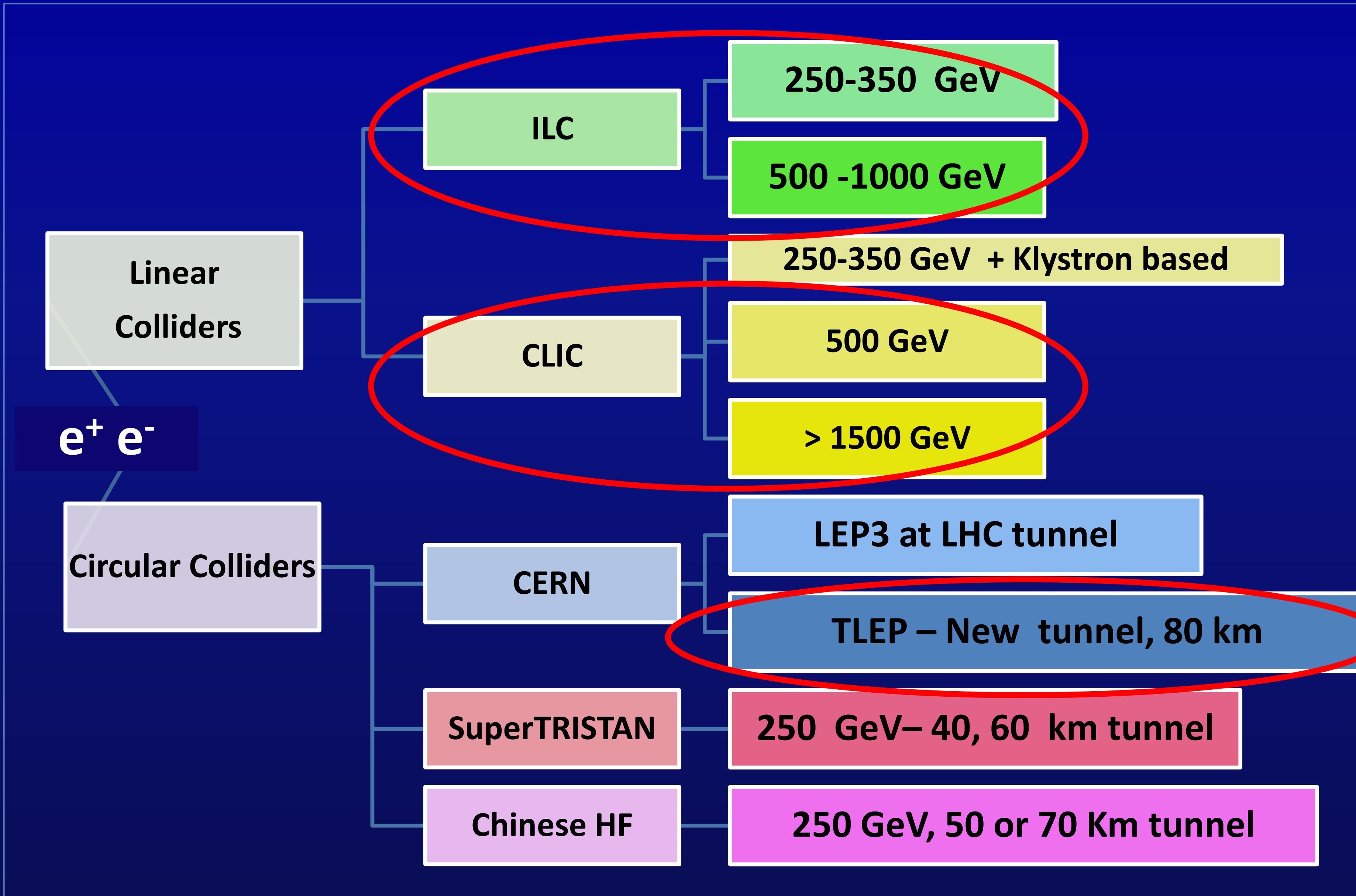
@Lepton colliders, coupling measurements with precisions:

- **in the range 1.5-4% LC**
- **in the sub% level with TLEP**

The prime focus is luminosity

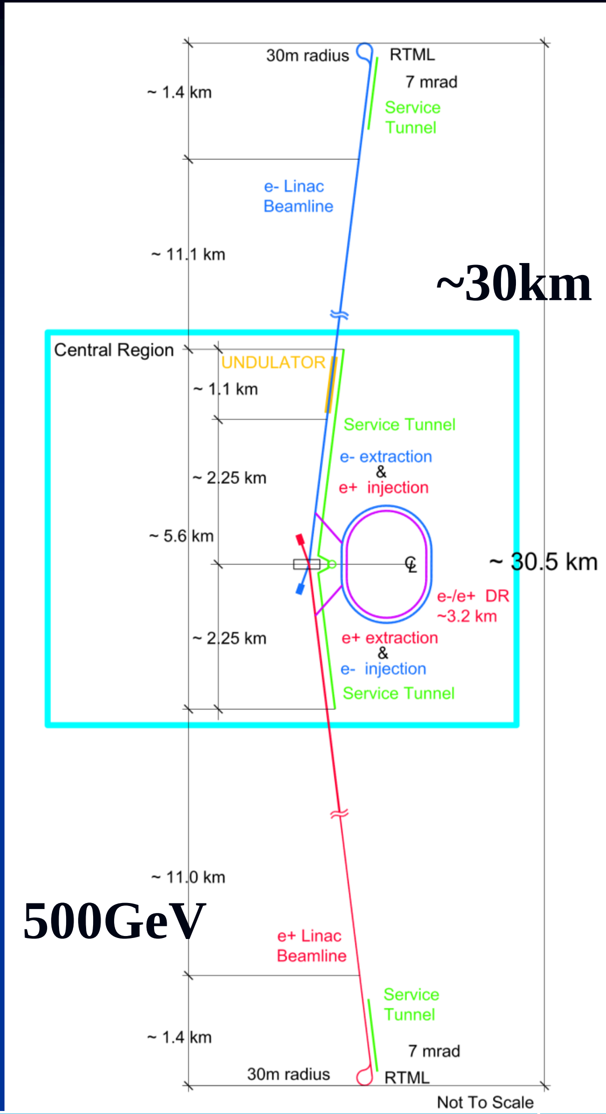
Note: σ (μμ→H) @ 125GeV = ~20pb

e^+e^- colliders «clean HIGGS FACTORIES»



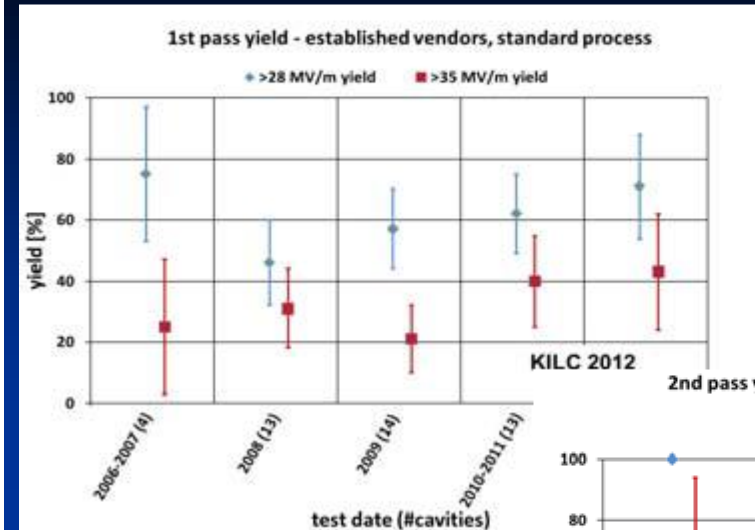
ILC

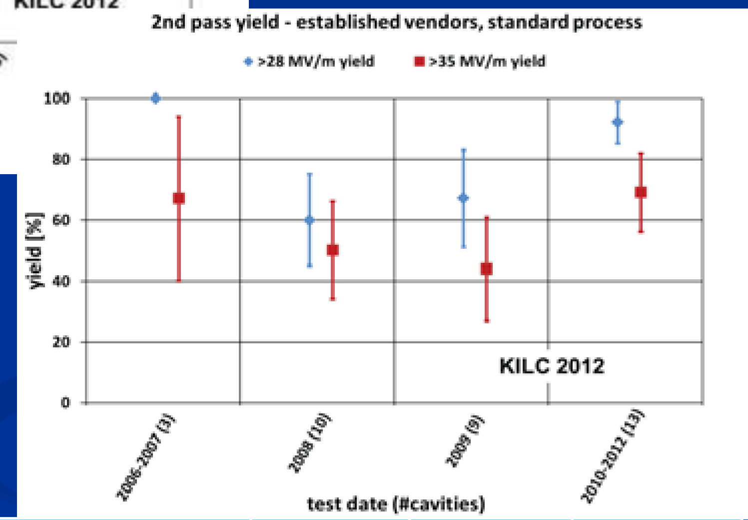
Gradient Range Yield Gain



~30km

500GeV

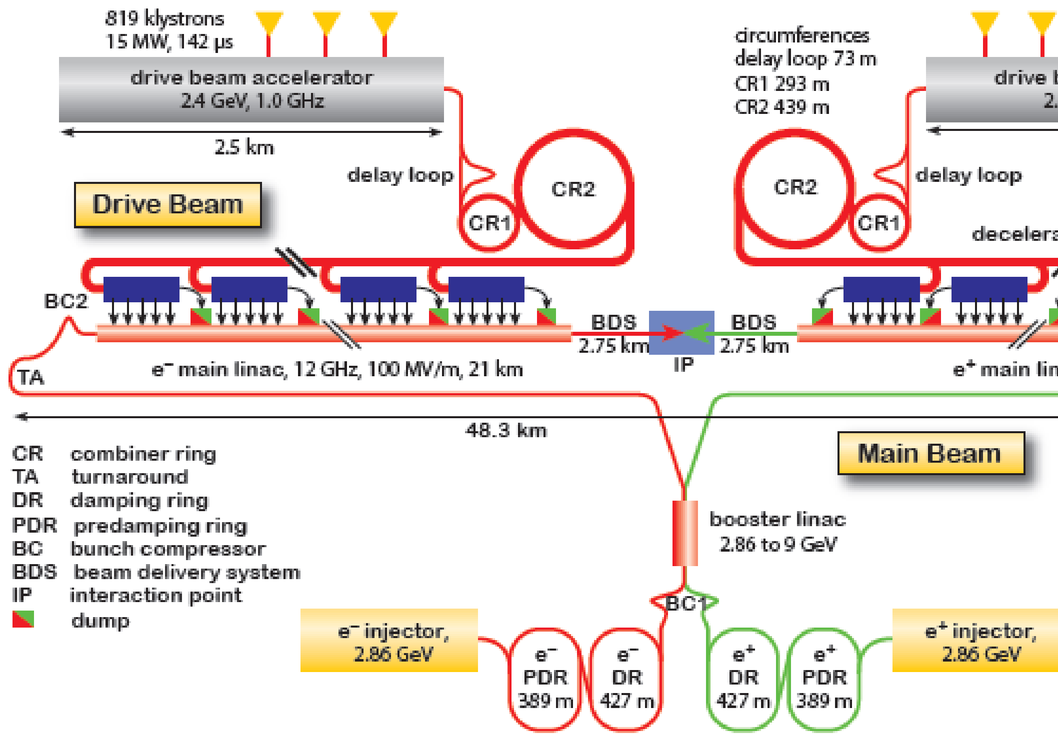


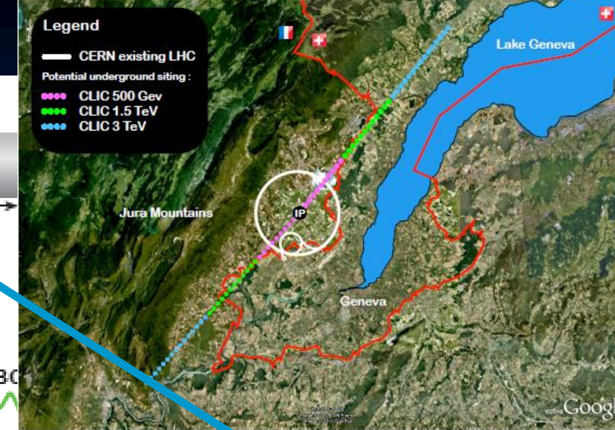


Cavity Gradient (MV/m)	31.5
#9-Cell cavities	~16000
#Cryomodules (2K)	~1800
#RF units (10MW Kly)	~560

Energy CM (GeV)	250	500	1000
Luminosity ($x10^{34}cm^{-2}s^{-1}$)	0.75	1.8	3.6
Beam size (σ_x/σ_y nm)	730/8	470/6	480/3
Pulse duration (ms)	0.75	0.75	0.9
Beam power (MW)	8.4	10.5	27.2
Total AC power (MW)	158	162	300

CLIC





Parameter	CLIC	CTF3
accelerated current [A]	4.2	3.5
combined current [A]	101	28
final energy [MeV]	2400	120
acceleration pulse length [μs]	140	1.2
final pulse length [ns]	240	149
acceleration frequency [GHz]	1	3
final bunch frequency [GHz]	12	12

- **Achieving very high gradiant (100Mv/m) with low enough breakdown rate (<10 $^{-6}$)**

➡ **Demonstrated with a few cavities**

International collaboration around CFT3 @CERN

Energy CM (GeV)	500	3000
Luminosity (x10^{34}cm^{-2}s^{-1})	2.3	5
Beam size (σ_x/σ_y nm)	202/2.3	40/1
Pulse duration (ns)	177	155
Beam power (MW)	4.9	14
Total AC power (MW)	270	589

TLEP Ring e^+e^- collider: Primary Cost Driver

Tunnel: ~2/3 cost

Building on existing technologies and experience (LEP, KEKB, PEPII…)

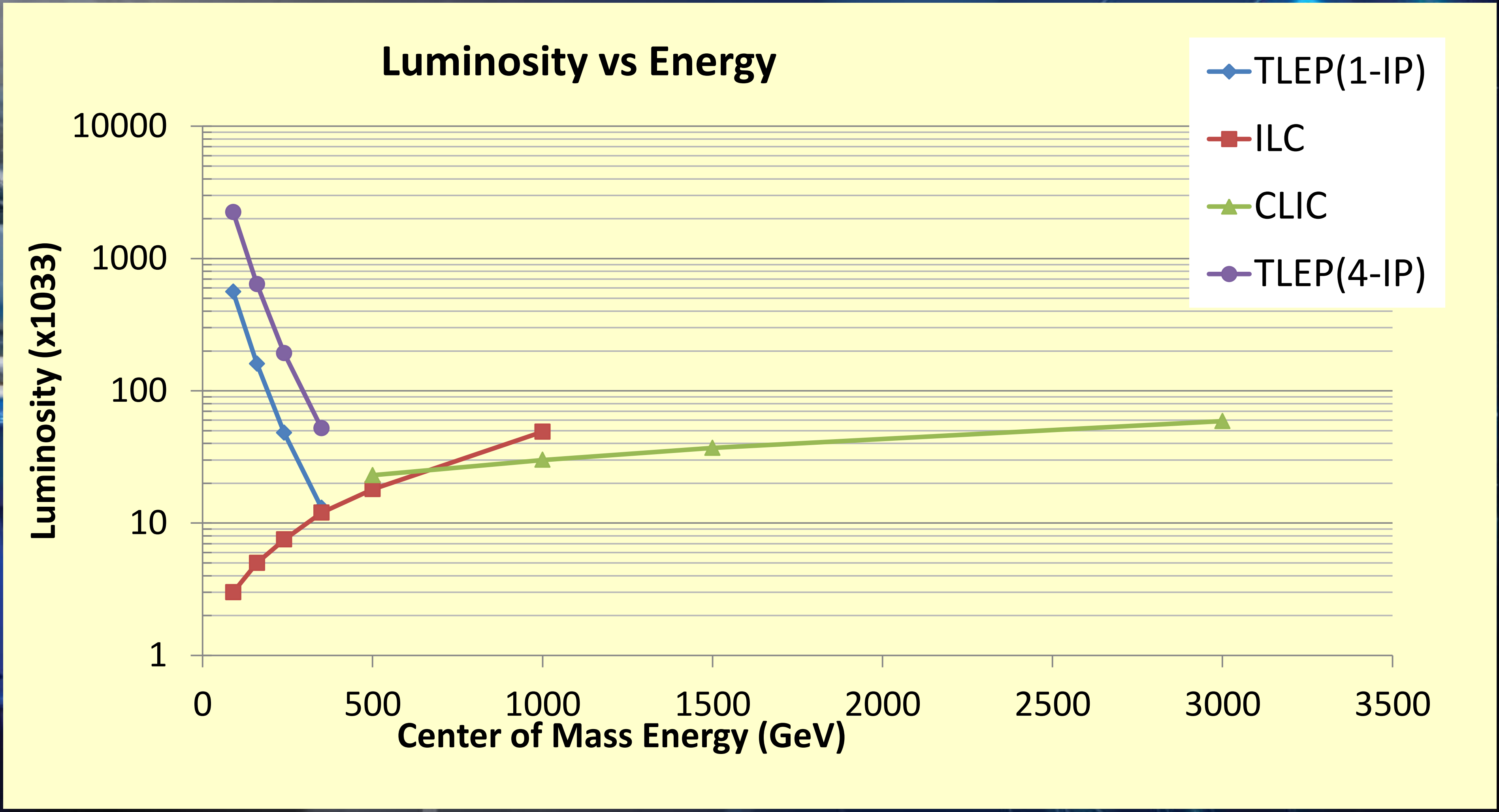
Using SC cavities

Could cover a wide range of energy up to 350 Gev collision energy.

Energy CM (GeV)	90	160	240	350
Lumin. ($\times 10^{34}$cm^{-2}s^{-1})/IP	56	16	~5	~1.3
Beam size (σ_x μm/σ_y nm)	124/270	78/140	68/140	100/100
Cavity Gradient (MV/m)	20	20	20	20
#5-cell SC cavities	600	600	600	600
Beam lifetime (mn)	67	25	16	27
Total AC power (MW)	250	250	260	284

Most parameters have been achieved or are planned at SuperKEKB

ElectroWeak Symmetry Breaking precision measurements require very high luminosity

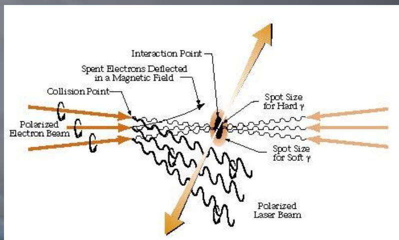


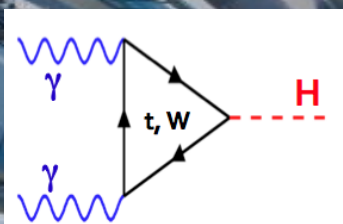
Many other accelerator R&D topics have not been discussed here e.g. e-p collider, γγ collider, μ collider, plasma acceleration… They should not be forgotten…

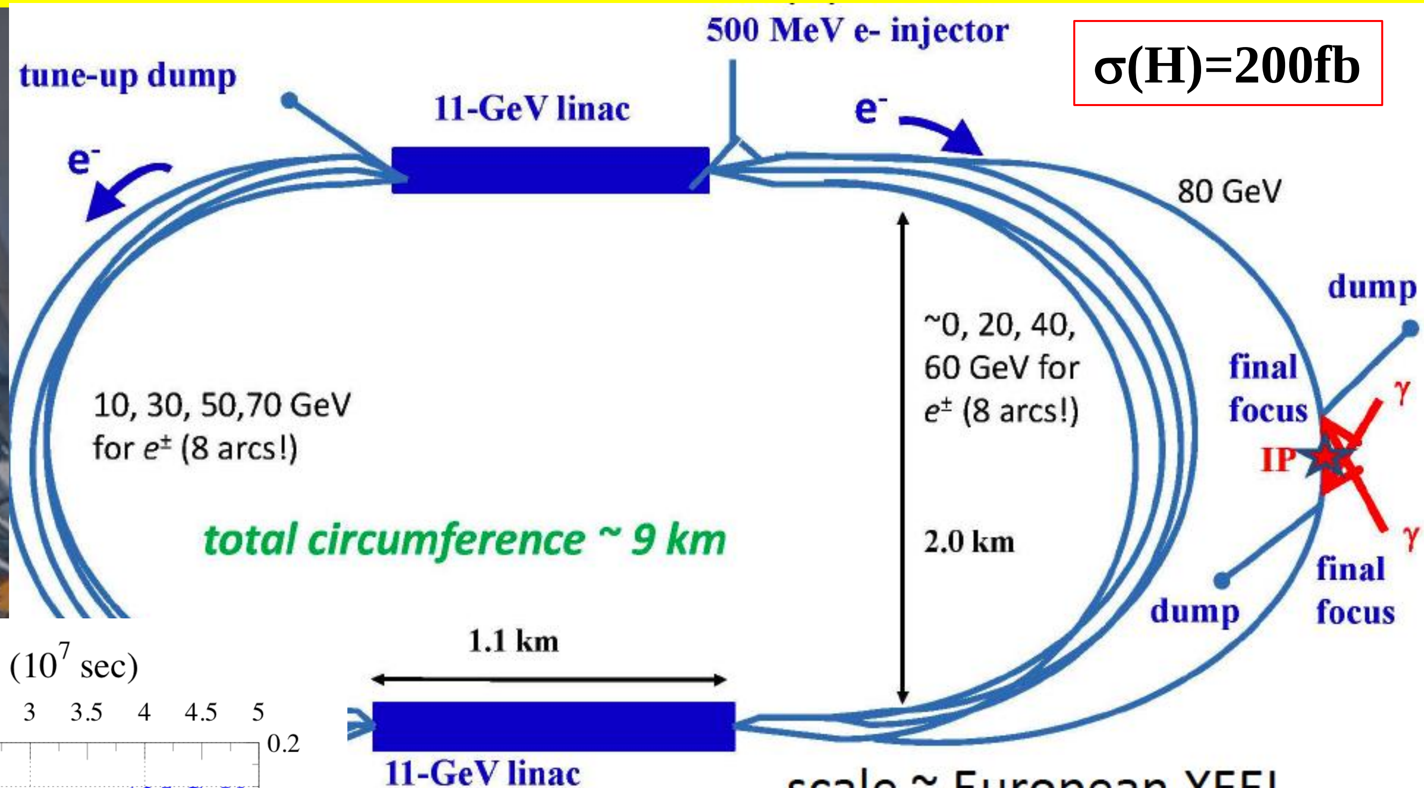
…but at present either the physics reach is deemed limited and/or lead time seems too long

→ **Proton-proton and electron-positron colliders appear as most promising/practical options**

From e^+e^- Higgs factory to $e^-e^-/\gamma\gamma$ collider

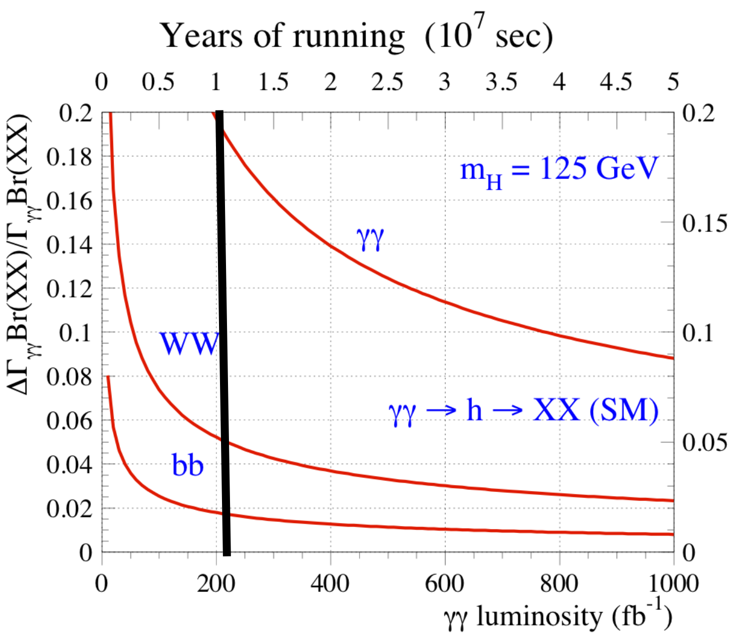






scale ~ European XFEL,

about 10k Higgs per year



Main issues:

- Laser with required power and rep. rate
- Develop the IR and the Machine Detector Interface (MDI)

Particle – antiparticle Asymmetry

Is ther any interaction able to differentiate a particle and its antiparticle?

Essential to generate a Universe dominated by matter (over antimatter)!

Phenomenon initially observed in *s* quark decays in 1964 but underlying process was not experimentally understood

Observation of dissymmetric behavior in 2001 in *b* quark decays (BaBar, Belle) ⇨ *Electroweak interactions* are responsible

$$e.g.\ B^0(\bar{b}d) \rightarrow K^+(\bar{s}u)\pi^-(\bar{u}d) \neq \bar{B}^0(b\bar{d}) \rightarrow K^-(s\bar{u})\pi^+(u\bar{d})$$

particle ≠ antiparticle

Explained through interference mechanisms because:

- **Physical quarks are superpositions of flavor states**

  e.g. $m^{phys}_{"b"} = c_1 m_b + c_2 m_s + c_3 m_d$
- **All quark masses ≠ 0**
- **∃ at least 3 families of quarks !!!**

Thanks to H

Detailed studies of Flavor physics (b, c, τ) including CP violation and rare decays are powerful means to probe further the consistency of SM and indirect search of new Physics

⇨ Flavor Factories: e.g. superKEKB (L=8 x 10^{35} cm^{-2} s^{-1})

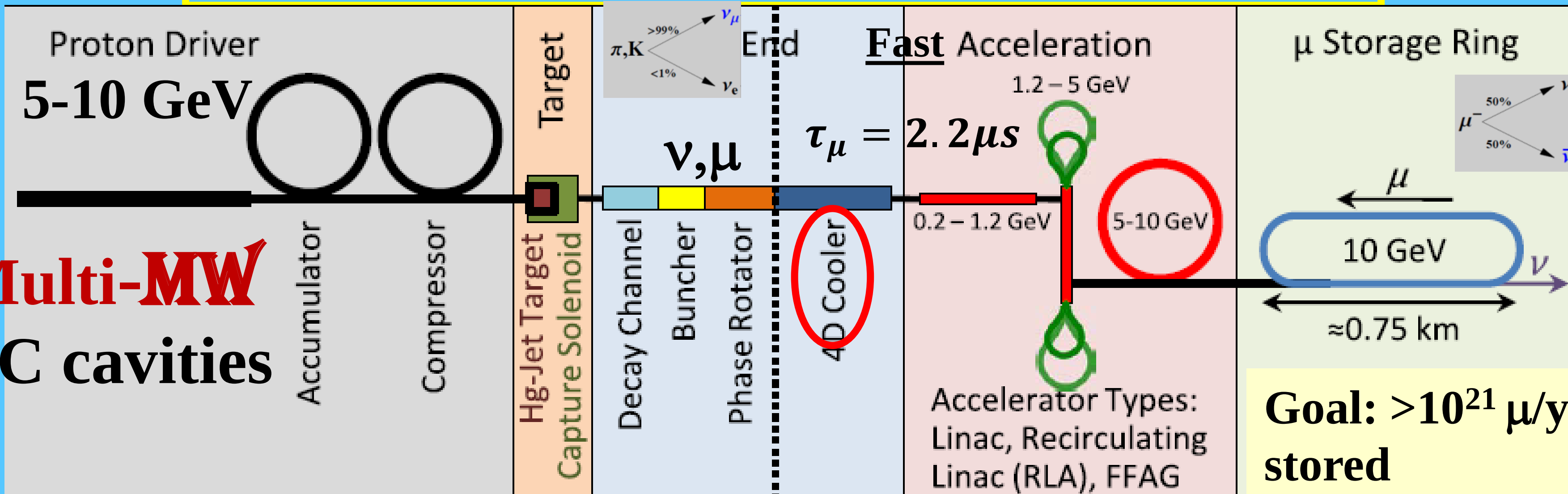
⇨ ⇨ HL-LHC, TLEP-Z…

Neutrinos : the « New (Physics!) Kids in the block »

SM	
ν_L	$\bar{\nu}_R$
I= ½	½
X 3 Families	
6 massless states 3 active neutrinos 3 active antinu's	

Mass hierarchies are all unknown except $m_1 < m_2$

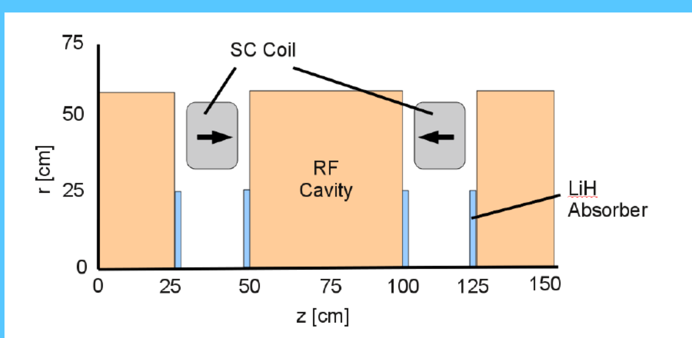
From neutrino superBeams toward ν-factories



Multi-MW
SC cavities

Goal: >10^{21} μ/year stored

The key issue : beam cooling

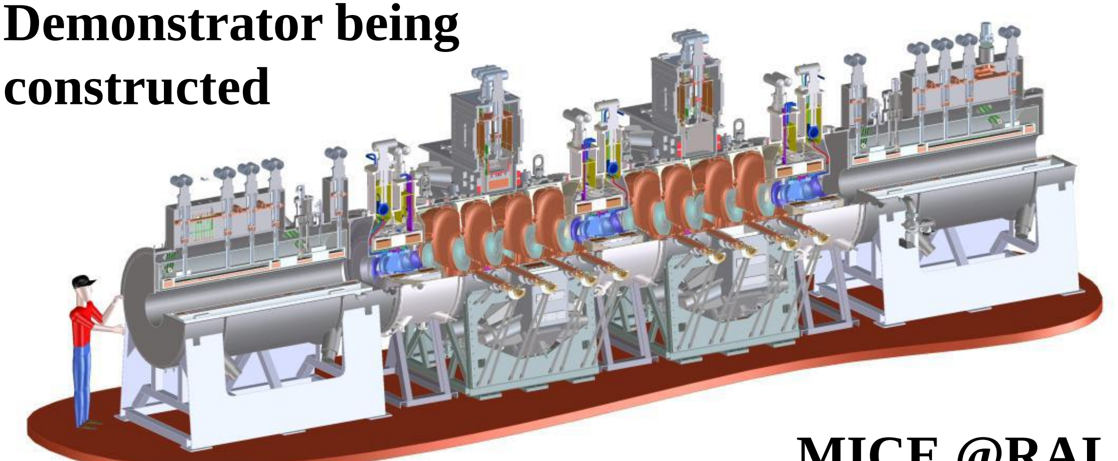


- **Cooling section consists of 100 cells 0.75m in length (total length 75m)**
- **100 RF cavities (15MV/m) operating in high magnetic field**
- **100 superconducting 0.15m coils (2.8T)**

Ionization cooling

- **Do we have technology for cooling the muons?**

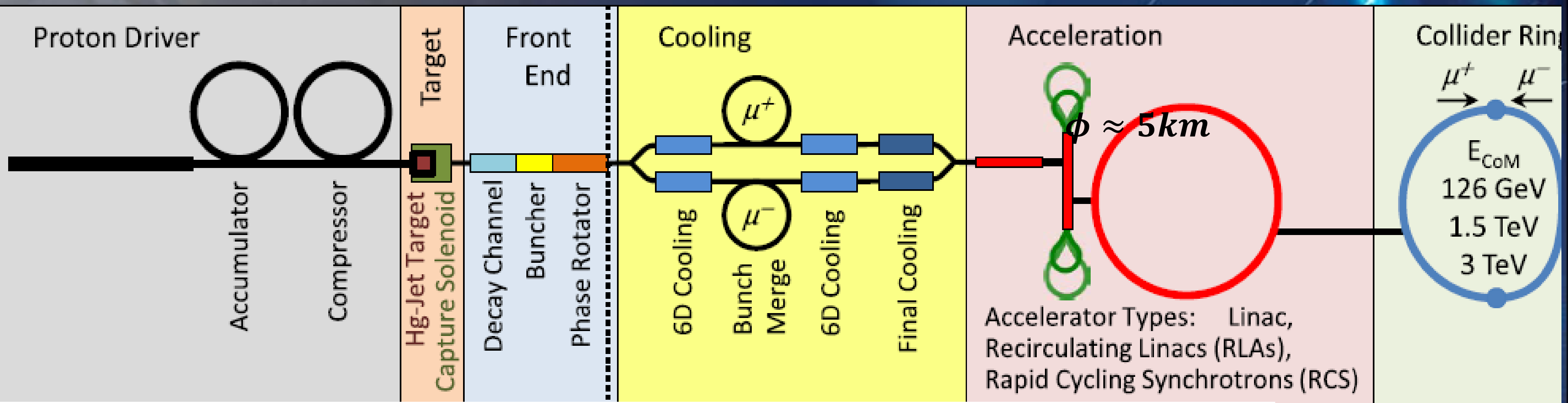
Demonstrator being constructed



MICE @RAL

From ν-factories toward the "dream" of muon collider

Higgs factory at 126GeV with ~10^4 Higgs/year **If cooling demonstrated!**



Goal: O(10^{21}) muons/year within the acceptance of an accelerator

Require much smaller beam size (i.e. lower emittance)

➡ Very efficient cooling

Some ultra-challenging components:

- **Very high field solenoids (20-30T)**
- **High gradient cavities in multi-Tesla field**

E Frontier Collider: √s = 3 TeV
Circumference = 4.5km
$L = 3\times10^{34}$ cm^{-2}s^{-1}
μ/bunch = $2\mathrm{x}10^{12}$
$\sigma(p)/p$ = 0.1%
$\varepsilon_{\perp N}$ = 25 μm, $\varepsilon_{//N}$=72 mm
β* = 5mm
Rep. Rate = 12 Hz
Power=300MW

Selected Future Projects

RF system needs

Project	Beam Type	RF freq. (MHz)	Beam Power (MW)	Pulse length (μs)	# cavity	Gradient (MV/m)
ILC 250	elect.	1300	~8	727	8000	31,5
CLIC 3000	elect.	12000	14	0,155	30000	100
TLEP	elect.	700-800	100	CW	600	20
VHELHC	prot.	400	2	CW	16	2

We do have the technologies for Higgs factories and Energy frontier up to TeV scale with e^+e^- and 60 (100) TeV with pp colliders

We do not have the technology for multi TeV lepton colliders

μ collider or « plasma acceleration » colliders may be the solution but many issues to be solved

Conclusion

- The last few years were very exciting
- Many teams have contributed to this success, they have to be ***warmly congratulated***
- Thanks to this work, ***prospects for the Future looks very promising***, with many new ideas emerging
- The European Strategy was an opportunity to bring these ideas on the table and provide ***further momentum toward*** our quest for understanding the fundamental laws of the Universe
- The Strategy is an important opportunity to open up a medium and long term ambitious vision and programme ***for Particle Physics in Europe : Top priority in the Strategy***
- Accelerator R&D is vital to enable the realization of our vision once we get the results of the LHC runs @ 13-14TeV and should remain at ***the highest priority*** within our strategy

My Conclusion

I have a Dream

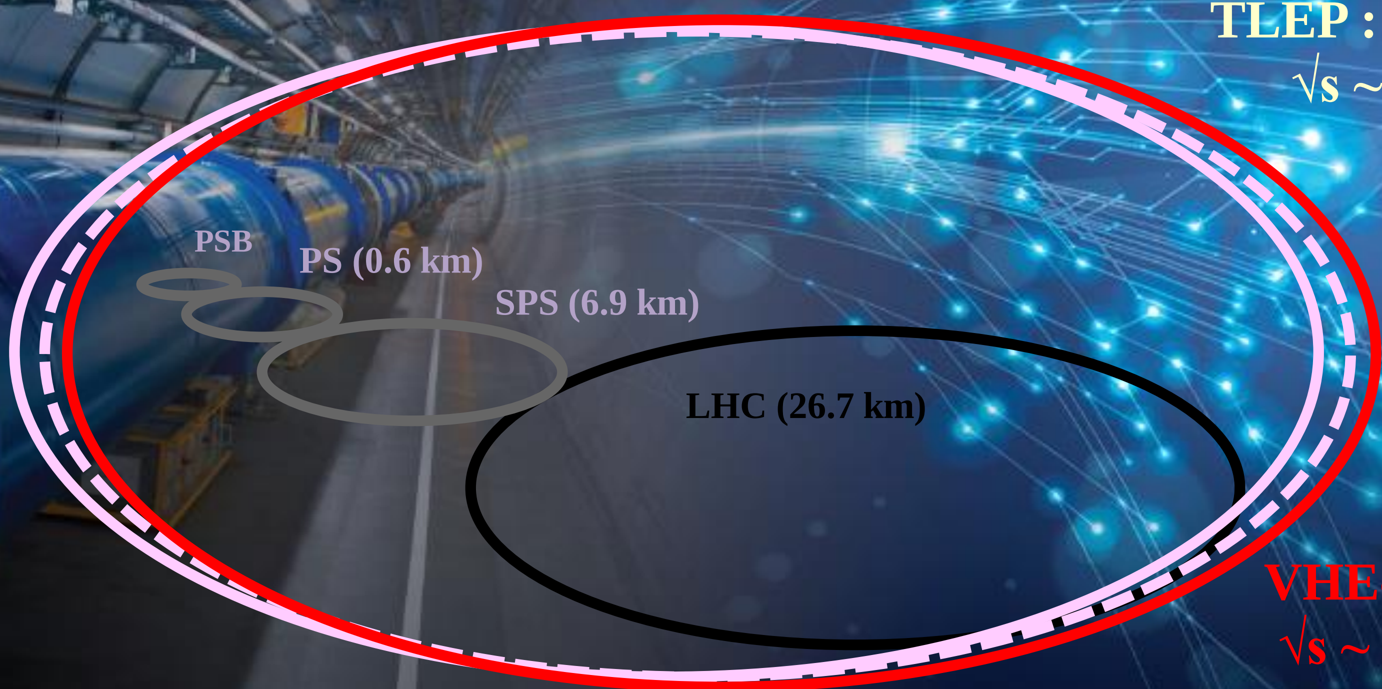
$E=mc^2$

Extended Multiprobe Collider Complex

My Conclusion

$$E=mc^2$$

TLEP : e^+e^-, up to $\sqrt{s}$ ~350 GeV



VHE-LHC : pp, $\sqrt{s}$ ~ 100 TeV Including possibly ep collisions

(CERN implementation

My Conclusion

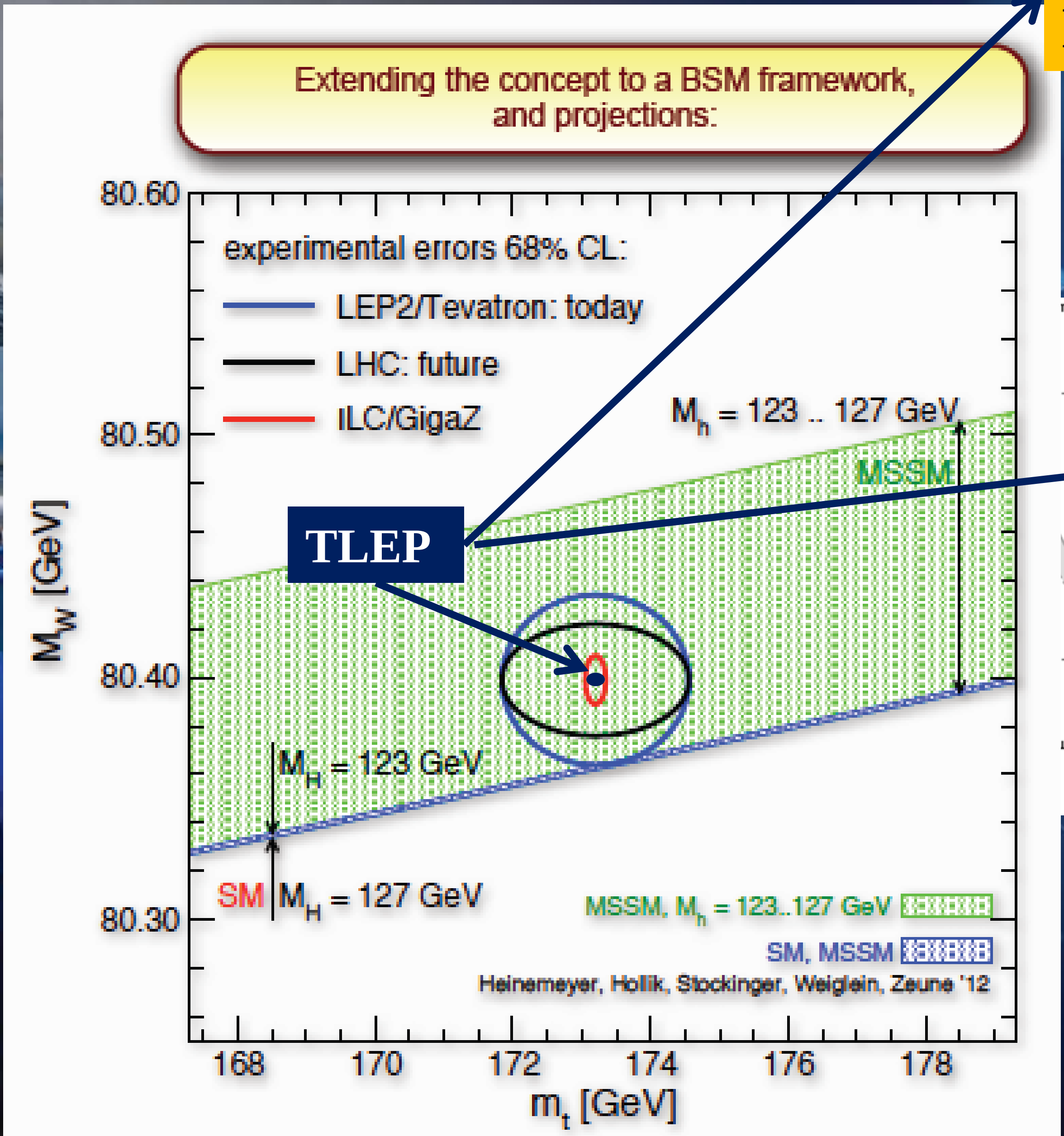
- Ambitious milestones should be set up
  - CDR in 2 years
  - TDR in 5 years, in a timely fashion with an update of the European Strategy in 2017-18, after the first round of operation of the LHC@13-14 TeV
- A possible timeline should be discussed

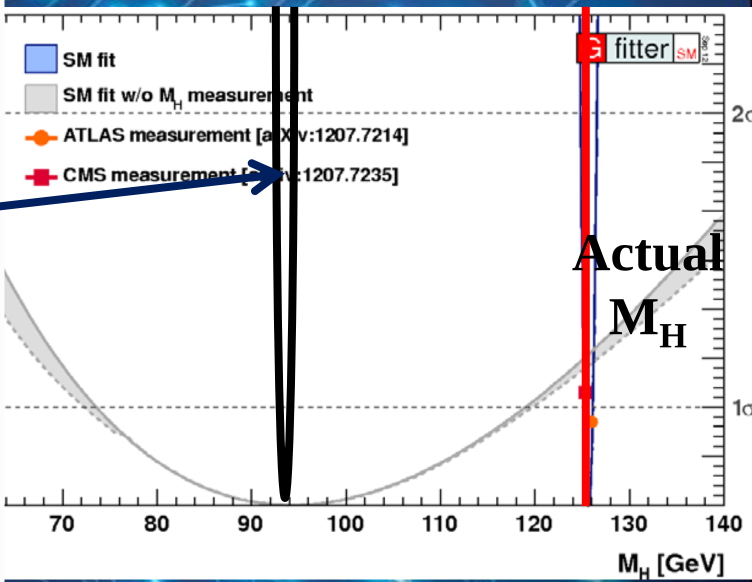
	2010	2015	2020	2025	2030	2035	2040
LHC							
HL-LHC		R&D + constr					
TLEP*			Design + R&D + construction				
VHE-LHC*				Design + R&D + construction			
ILC			Design + R&D + construction				

*tentative timeline; similar timeline applies for LEP3/HE-LHC but installation requires stopping LHC

My Conclusion

Indirect: M_H=94.0 ± 1.5
Direct: M_H=125.500 ±0.007





Note: This is indicative, a careful analysis still to be carried out