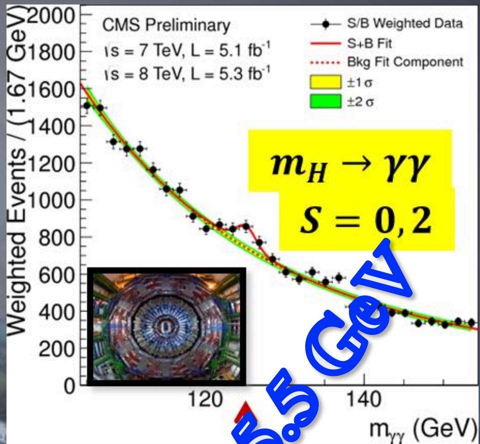
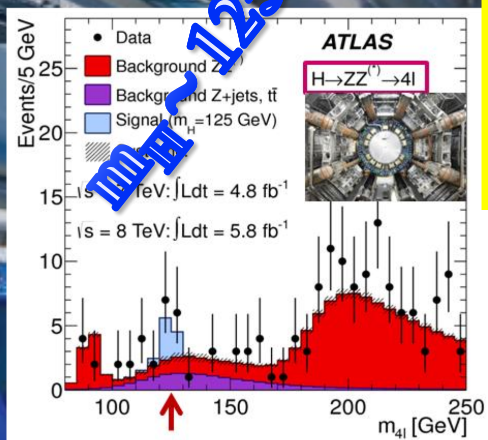
Future Accelerator Projects

Roy Aleksan
Nobel Symposium
May 13-17, 2013

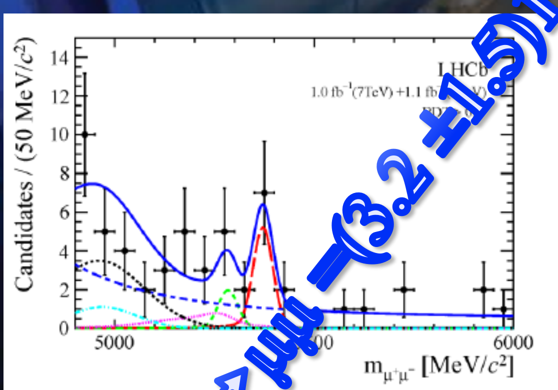
- The Frontiers of PP; what to do next?
- Strategy
- Next Accelerator Technology Challenges for PP
- Conclusion



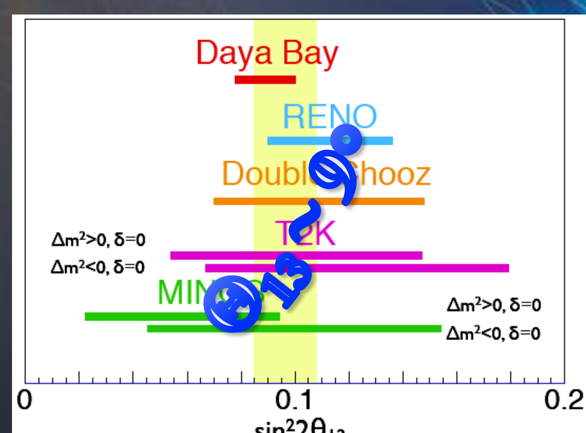
$m_H \sim 125.5$ GeV



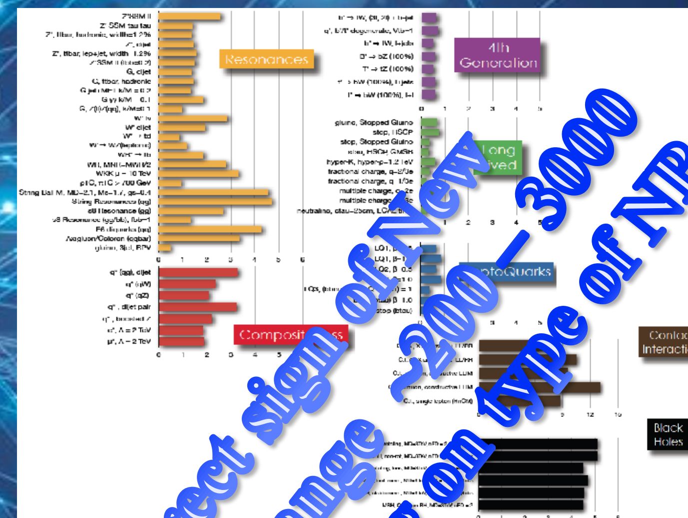
High Precision Measurements
Very High Energy Reach
High Intensity ν Beams

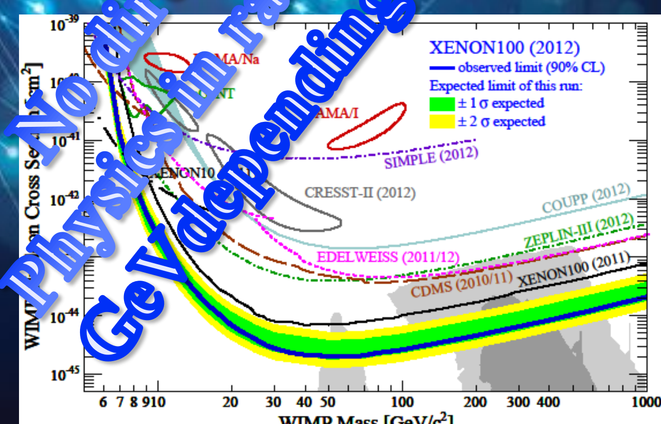


$B_s \to \mu\mu = (3.2 \pm 1.5)10^{-9}$



$\theta_{13} \sim 9°$





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

Questions

- **What parameters should we measure for probing BSM physics and what precison levels should we aim at?**

- **What energy scale should we aim at exploring to have a reasonable chance to find BSM physics?**

- **What neutrino beam (E and I) should we aim at building**

If we cannot do all of the above right away, what is THE priority for the next accelerator

Projects discussed/mentioned in the talk

- ***High Precision Measurements***
  - ***HL-LHC, LC(ILC/CLIC), TLEP, μ–Coll, $\gamma\gamma$-coll***
- ***Very High Energy Reach***
  - ***HE-LHC:VHE-LHC, CLIC, μ–Coll***
- ***High Intensity ν Beams***
  - ***Multi-MW superBeam, ν-Factories***

Projects not discussed in the talk

Projects already approved

- ***LHC@14TeV, SuperKEKB, T2K, NuMI…***

ElectroWeak Symmetry Breaking precision measurements

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

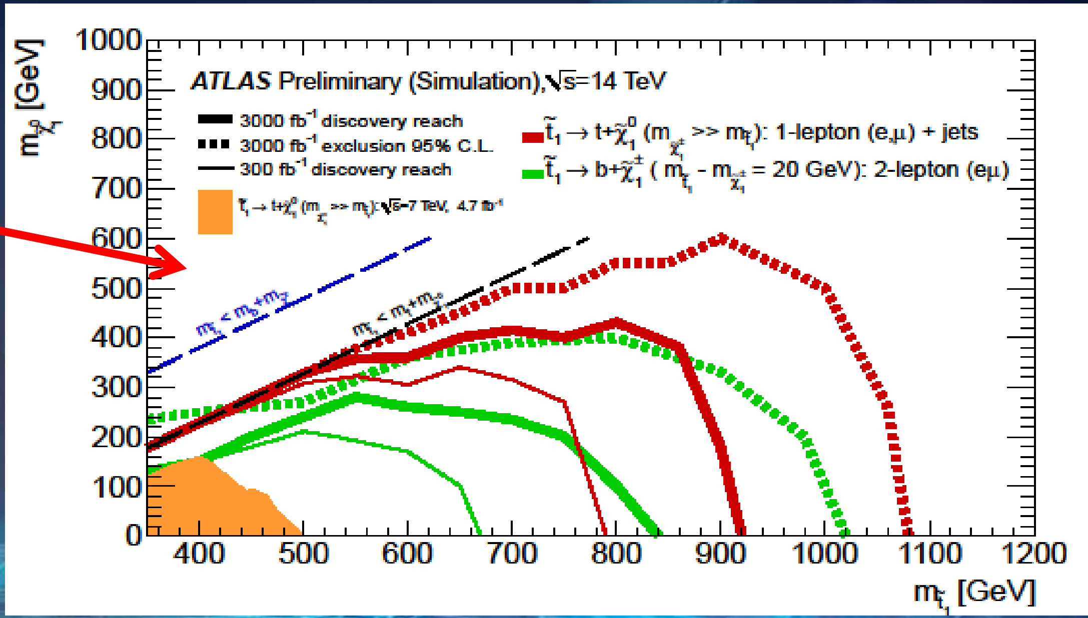
	LHC(300)	LHC (3000)	ILC (250+350+500)	TLEP (240+350)	Comment
Δm_H (MeV)	~100	~50	~30	~7	Overkill for now
$\Delta\Gamma_H/\Gamma_H (\Delta\Gamma_{inv})$			5.5(1.2)%	1.1(0.3)%	
H spin	✓	✓	✓	✓	
Δm_W (MeV)	~10	~10	~6	<1	Theo. limits
Δm_t (MeV)	800-1000	500-800	20	15	~100 from theo.
$\Delta g_{HVV}/g_{HVV}$	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 systemaical 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

Search of new particles

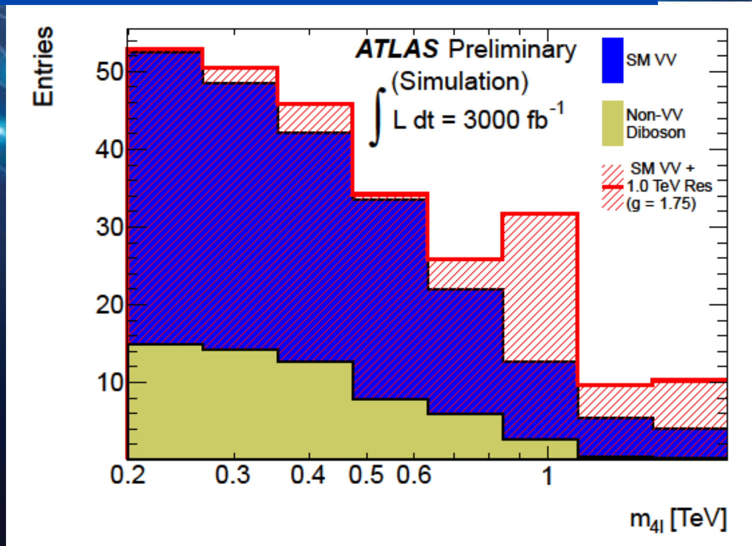
- Sensitivity on SUSY can be signicantly improved … in particular for stop



- 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}
$m_{\text{resonance}} = 500$ GeV, $g = 1.0$	2.4 σ	7.5 σ
$m_{\text{resonance}} = 1$ TeV, $g = 1.75$	1.7 σ	5.5 σ
$m_{\text{resonance}} = 1$ TeV, $g = 2.5$	3.0 σ	9.4 σ



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***

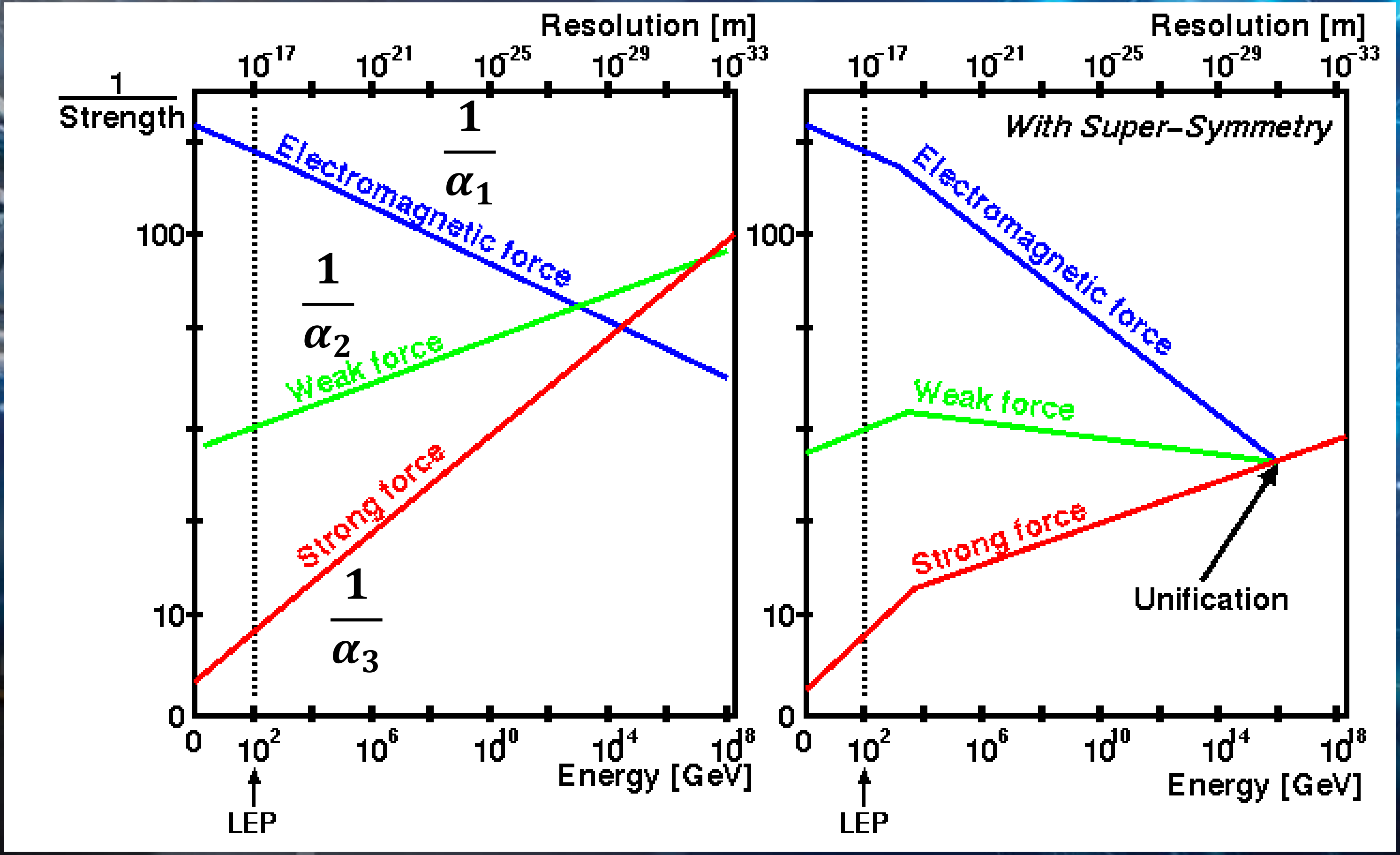
- Improve and adjust the luminosity with beam overlap control

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

- *Strong R&D on these issues is necessary*
- *Very substantial programme ⇨ collaborative R&D needed*
- *All this work is a first step toward higher energy*

Grand unification of Interactions (Strong, Weak, Electromagnetic)

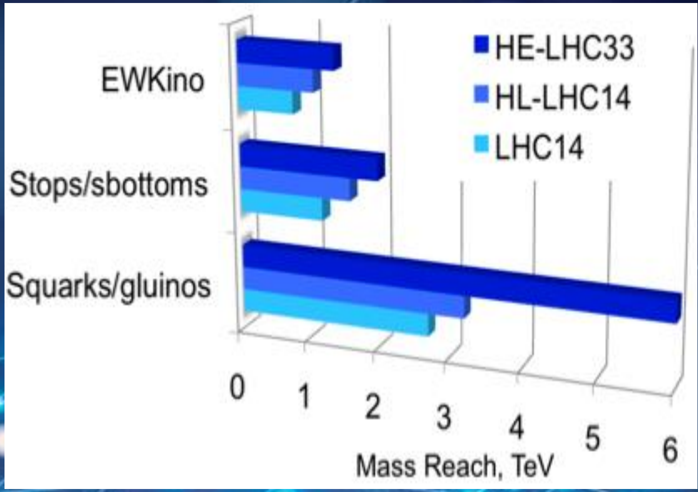
Additionnal particles (such as supersymmetric partners) with energy scales of TeVs affect the running of the coupling constants



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

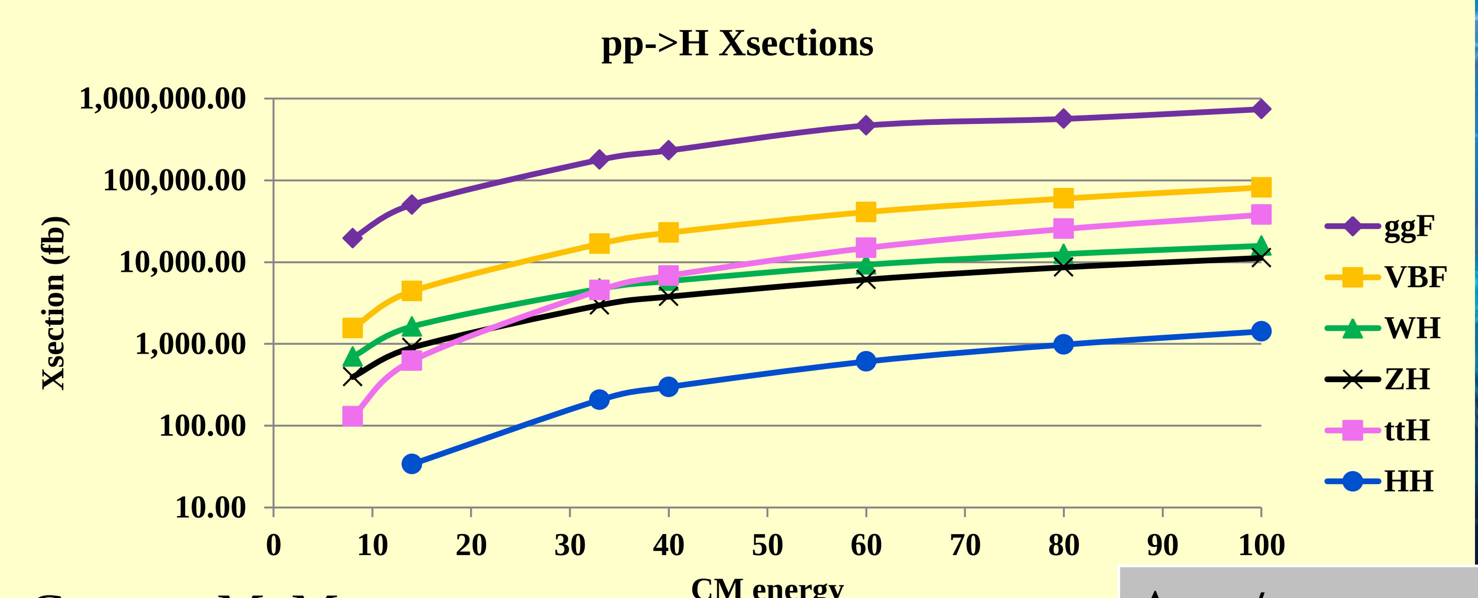
Whatever is found or not, reaching higher energies is unavoidable

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



Coutesy M. Mangano

$\Delta g_{Htt}/g_{Htt}$	<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

The detailed study of such a machine is needed, including the complete injection chain (no major difficulties expected)

➢ Strong R&D on these new very high field magnet is necessary

⇨ collaborative R&D needed

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

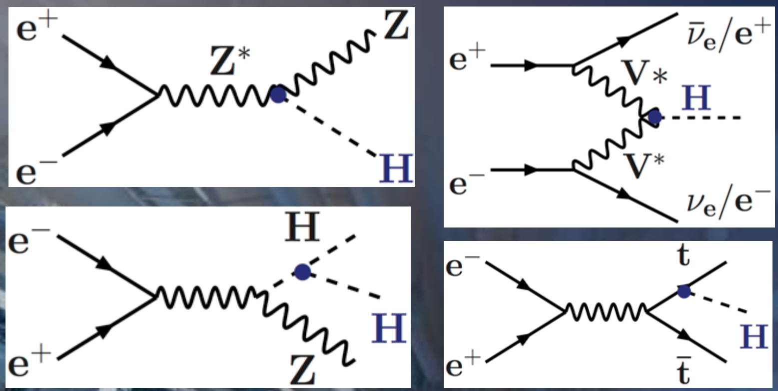
⇨ more detailed study of such a tunnel needed

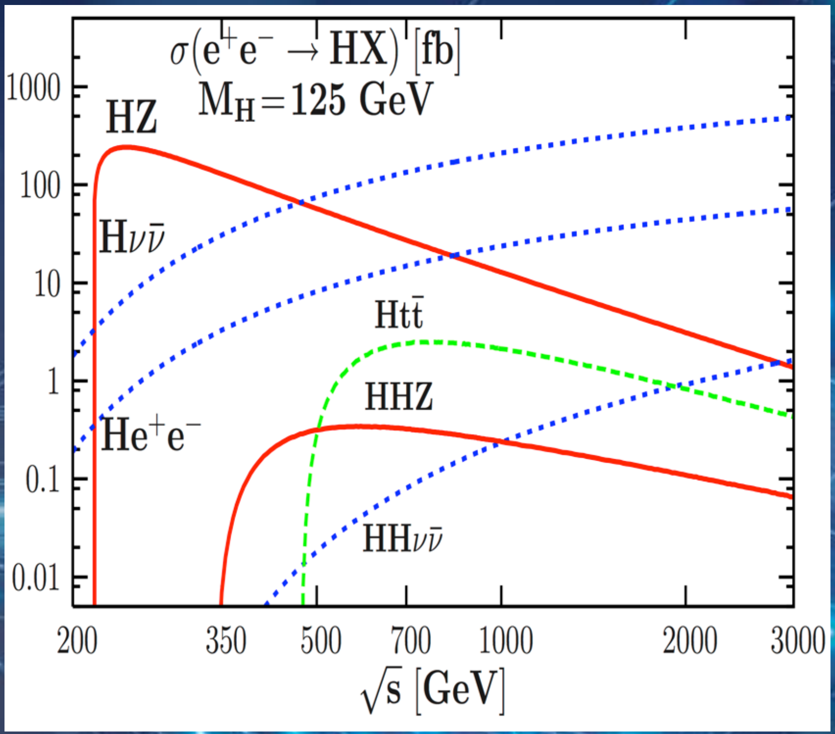
In both cases, SC challenge to develop 16-20 Tesla magnets!

Magnets for HL_LHC is an indispensible first step

ElectroWeak Symmetry Breaking precision measurements

Lepton colliders allows clean absolute measurements!





At 240 GeV, σ_{HZ}~250 fb^{-1}

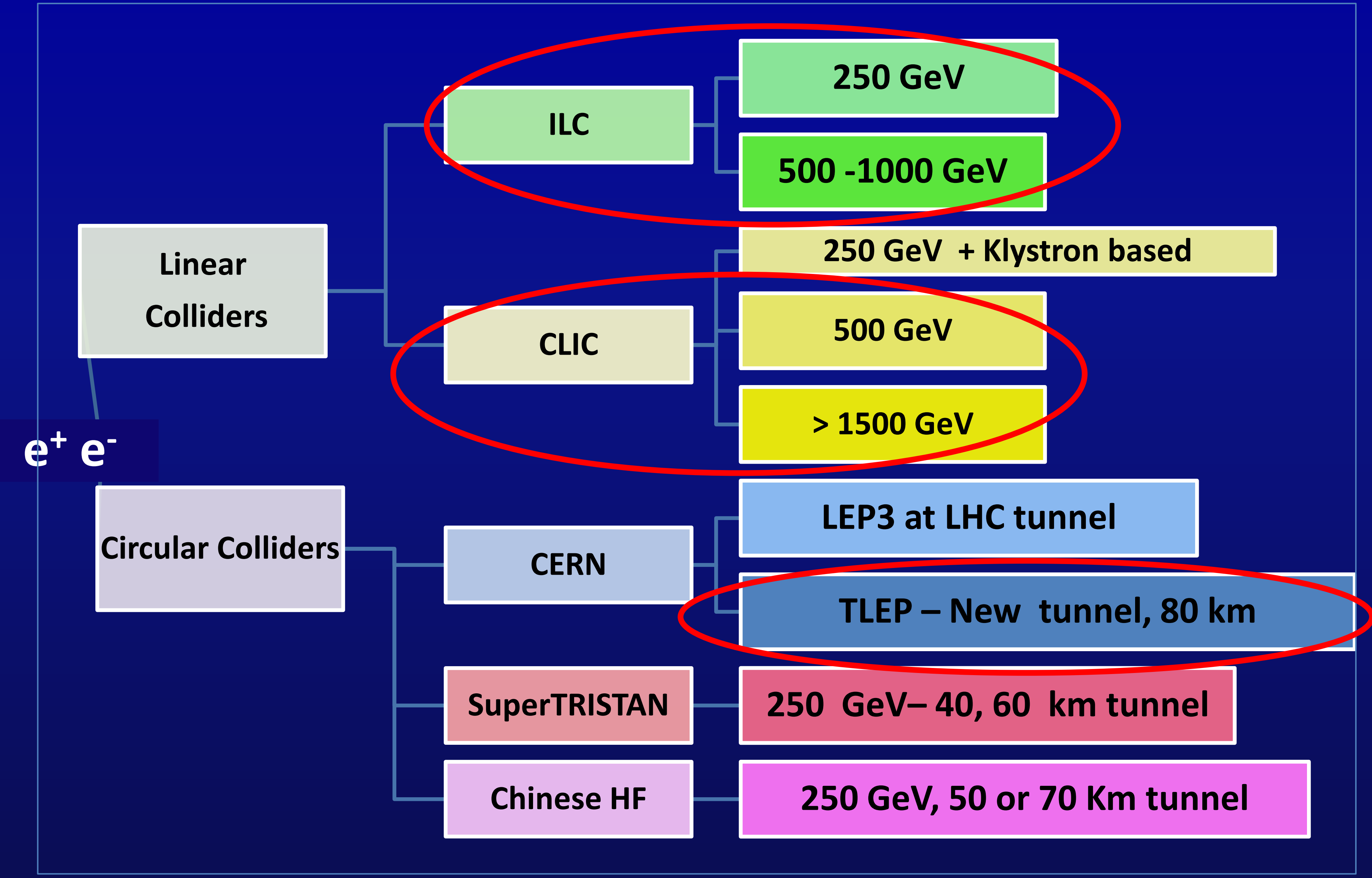
- Tagged Higgs, largest cross section
- Individual branching ratios to a few %
- Invisible and exotic decays
- Possibly total Higgs decay width

@Lepton colliders, coupling measurements with precisions:

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

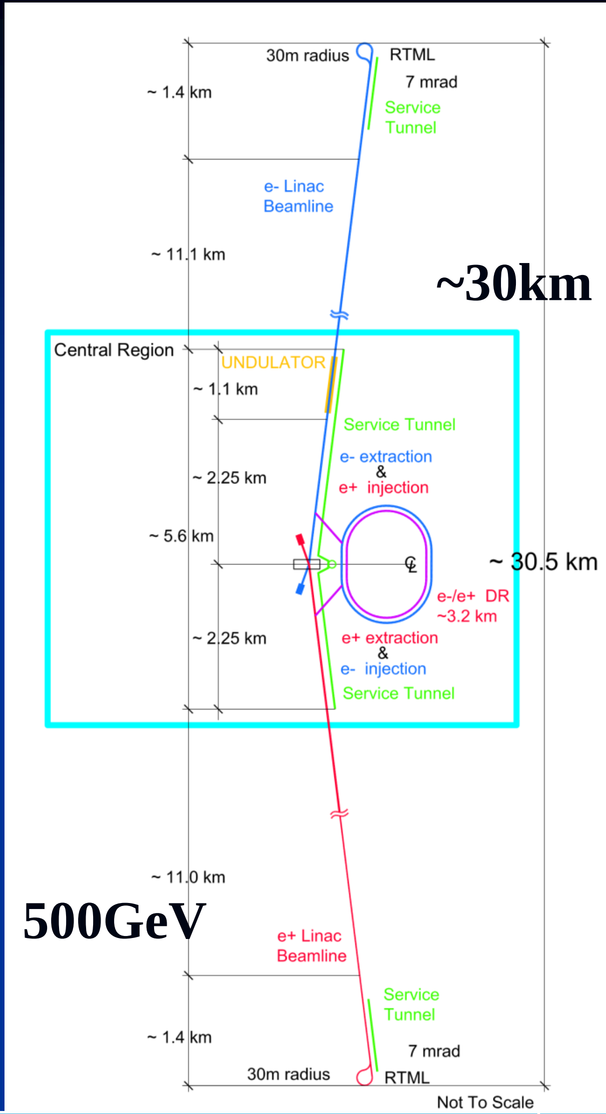
Note: σ (μμ→H) @ 125GeV = ~20pb

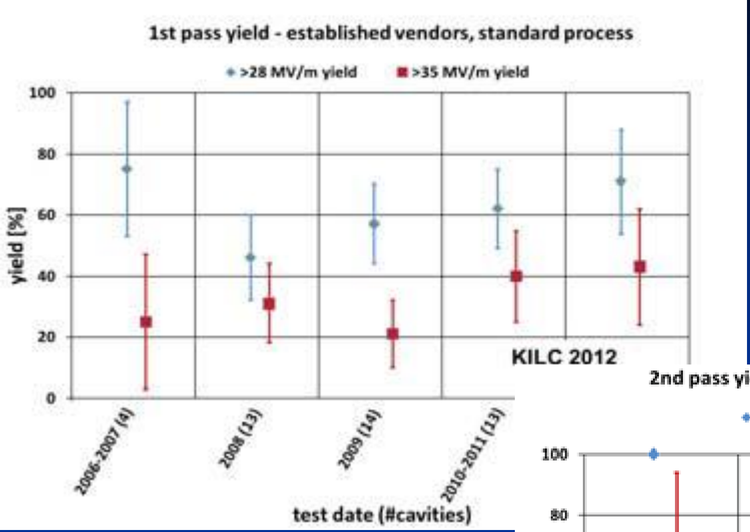
e^+e^- colliders «clean HIGGS FACTORIES»

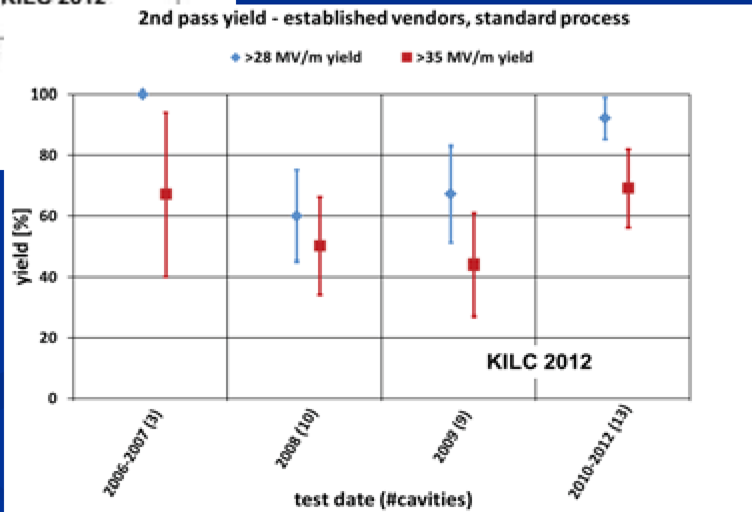


ILC

Gradient Range Yield Gain







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

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

Some further ILC challenges

- **Achieving and maintaining nano beam size (σ_y =6-8nm) with $2x10^{10}$ e/bunch**

➡ **ATF2 operating since 2009 at KEK objective: 37nm @1.28 GeV**

February 2012 σ_y=166±7 nm
Dec. 2012 σ_y=72±5 nm with low b. intensity ($2x10^9$ e/bunch)

- **Realization of very low emittance damping rings with ultra fast kickers for extraction**

➡ **TIARA collaboration with SLS @PSI (<1pm @2.86 GeV)**

- **Achieving the required positron rate**

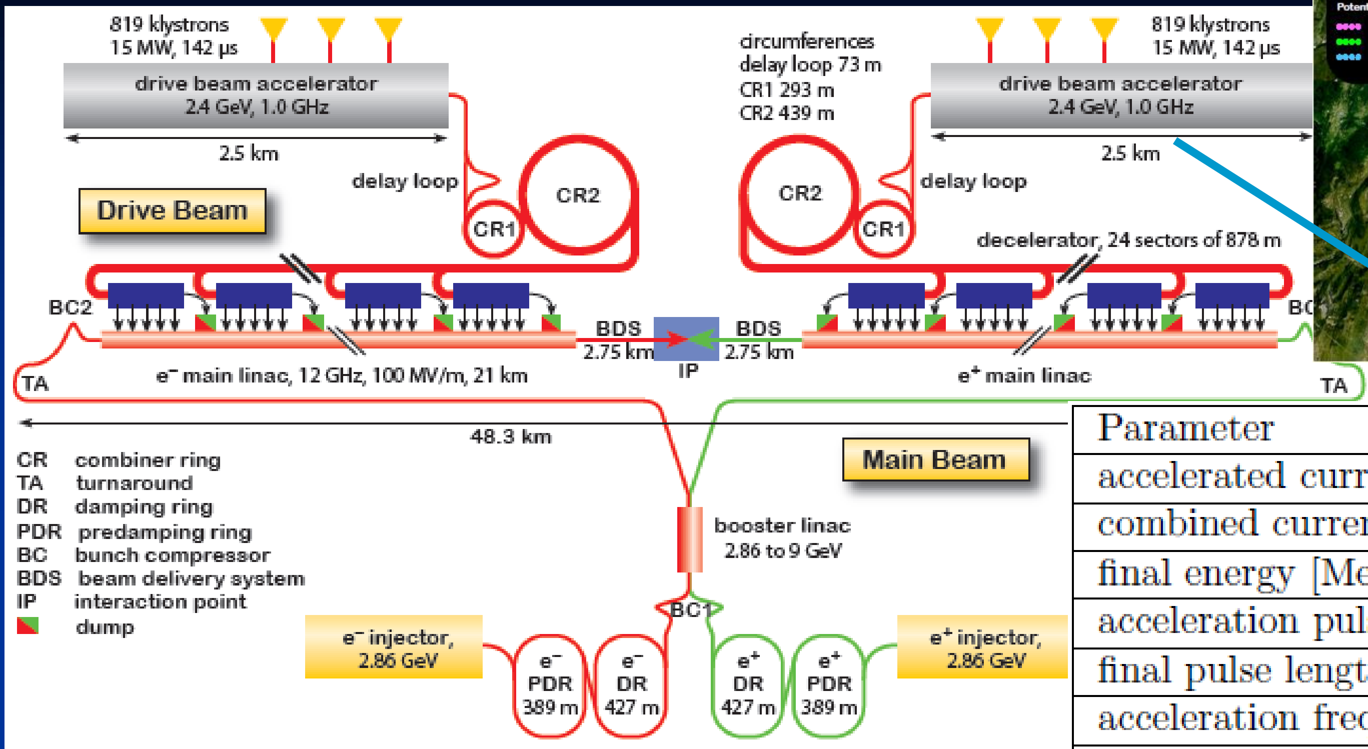
➡ **photons from 150 GeV beam through 150m of small-aperture SC undulator or 125 GeV beam through 250 m of SC undulators**

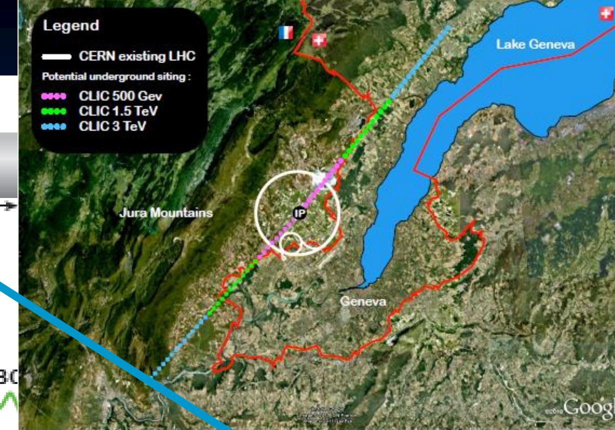
- **Industrialization of technology at very high scale**

➡ **XFEL =5% of ILC**

- ***Strong R&D on these issues is on-going***
- ***Carried out by international collaborative***
- ***Several issues still being addressed***
- ***Proposal from the Japanese physics community***

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

Some further CLIC challenges

- Same type of difficulties as for ILC though more severe, e.g.
  - smaller beam size (~1nm)
  - Shorter bunch length (150ns)
  - Normalized y emittance ~20nm and its preservation
    - Ultra precise alignment and magnet stabilization

- Some difficulties are specific to CLIC, e.g.
  - Production of RF power
  - Stable deceleration of drive beam
  - And main beam acceleration

- *Strong R&D on these issues is on-going*
- *Developed by international collaborative*

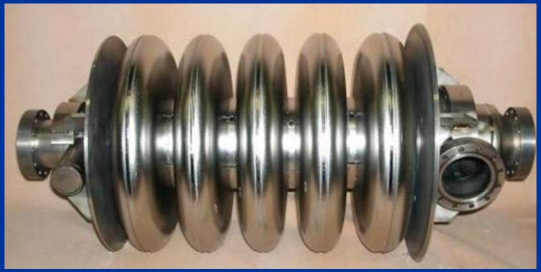
Although a lot of progress have been achieved, still a lot of R&D needed to deliver a TDR

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

Tunnel: ~2/3 cost

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

Using SC cavities

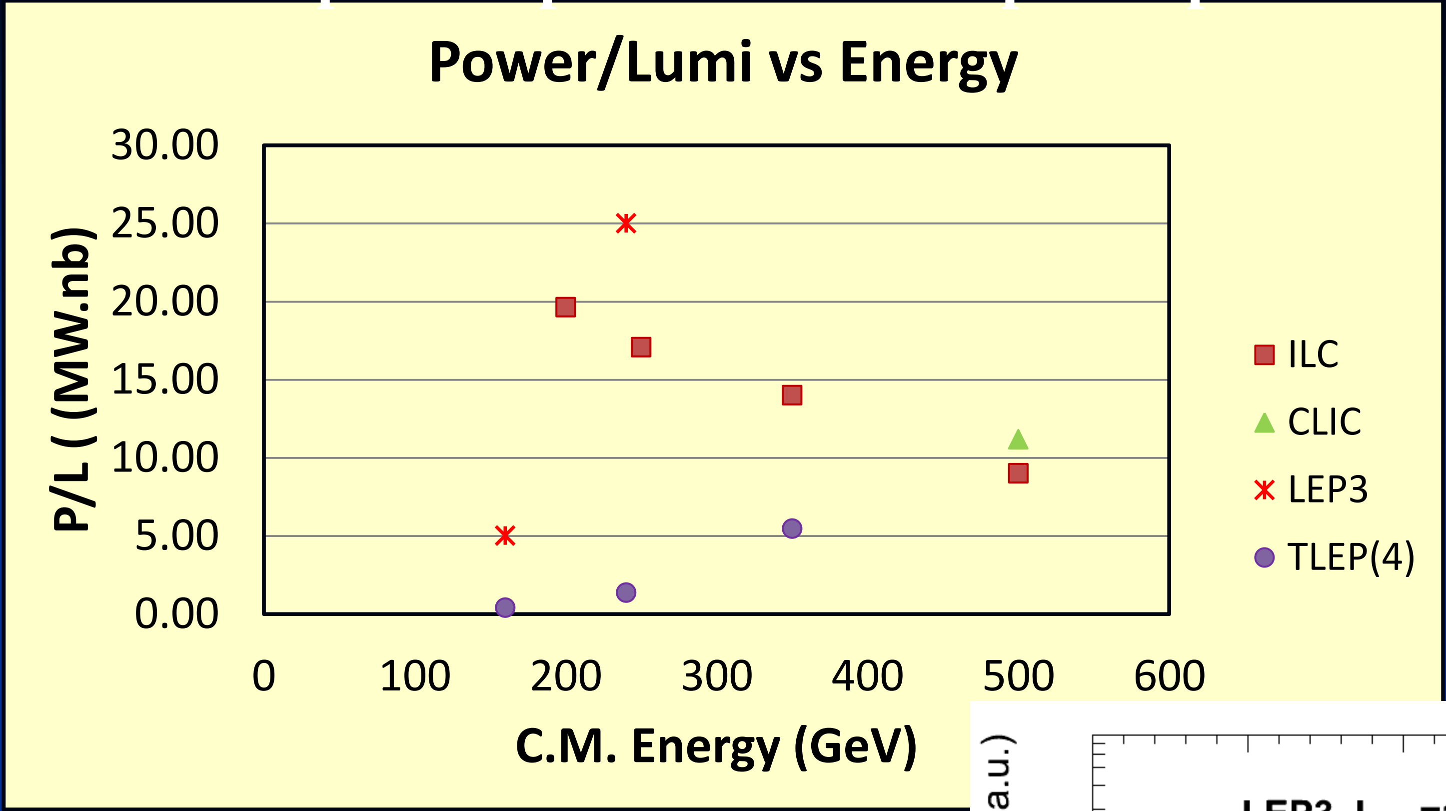


Could cover a wide range of energy up to 350 Gev collision energy.

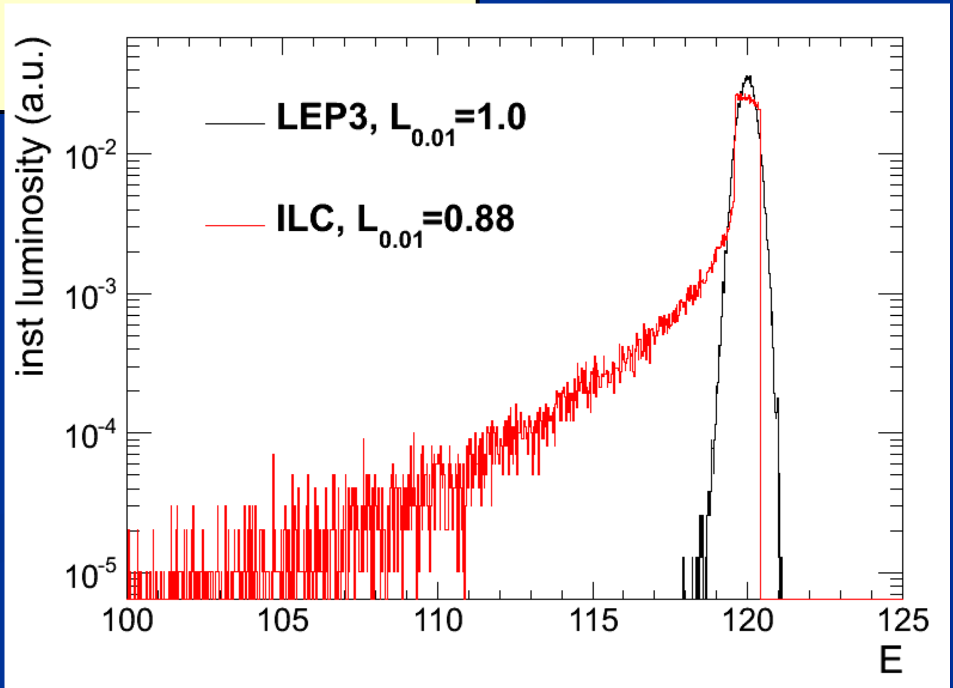
Energy CM (GeV)	90	160	240	350
Luminosity ($x10^{34}cm^{-2}s^{-1}$)/IP	56	16	~5	~1.3
Cavity Gradient (MV/m)	20	20	20	20
#5-cell SC cavities	600	600	600	600
Beam lifetime (mn)	67	25	16	27
Total AC power (MW)	250	250	260	284

Most parameters have been achieved or are planned at SuperKEKB

An important parameter is the power per unit of luminosity



*Luminosity not corrected for peak1% factor



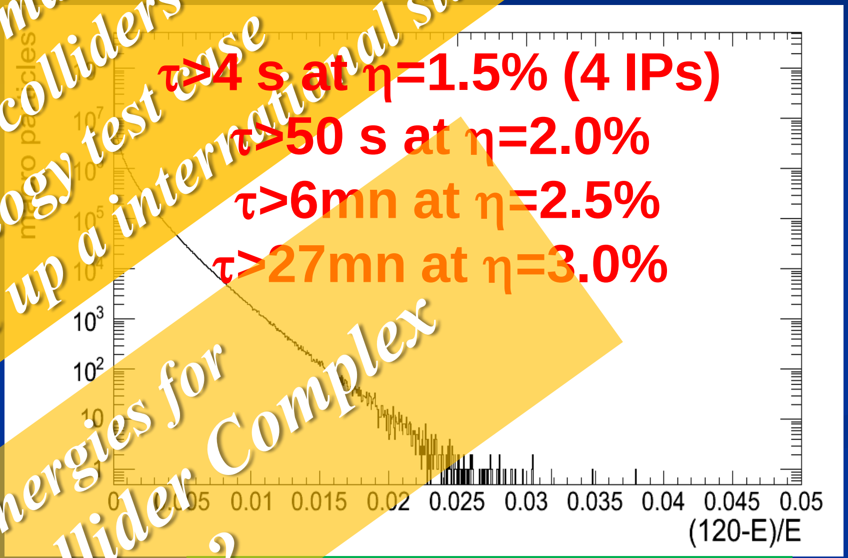
Although based on strong experience in building circular collider, several challenges have to be overcome:

Beamstrahlung:

⇨ Beam lifetime reduction (should not be much smaller than bhabha scattering limits

⇨ Need to study the energy acceptance of the collider (>2.5%)

⇨ optic design is challenging



τ>10mn at superKEKB

Bremstrahlung:

⇨ Need to study heat extraction and radiation damage and shielding issues

Top up ring:

⇨ Need to study the injection system

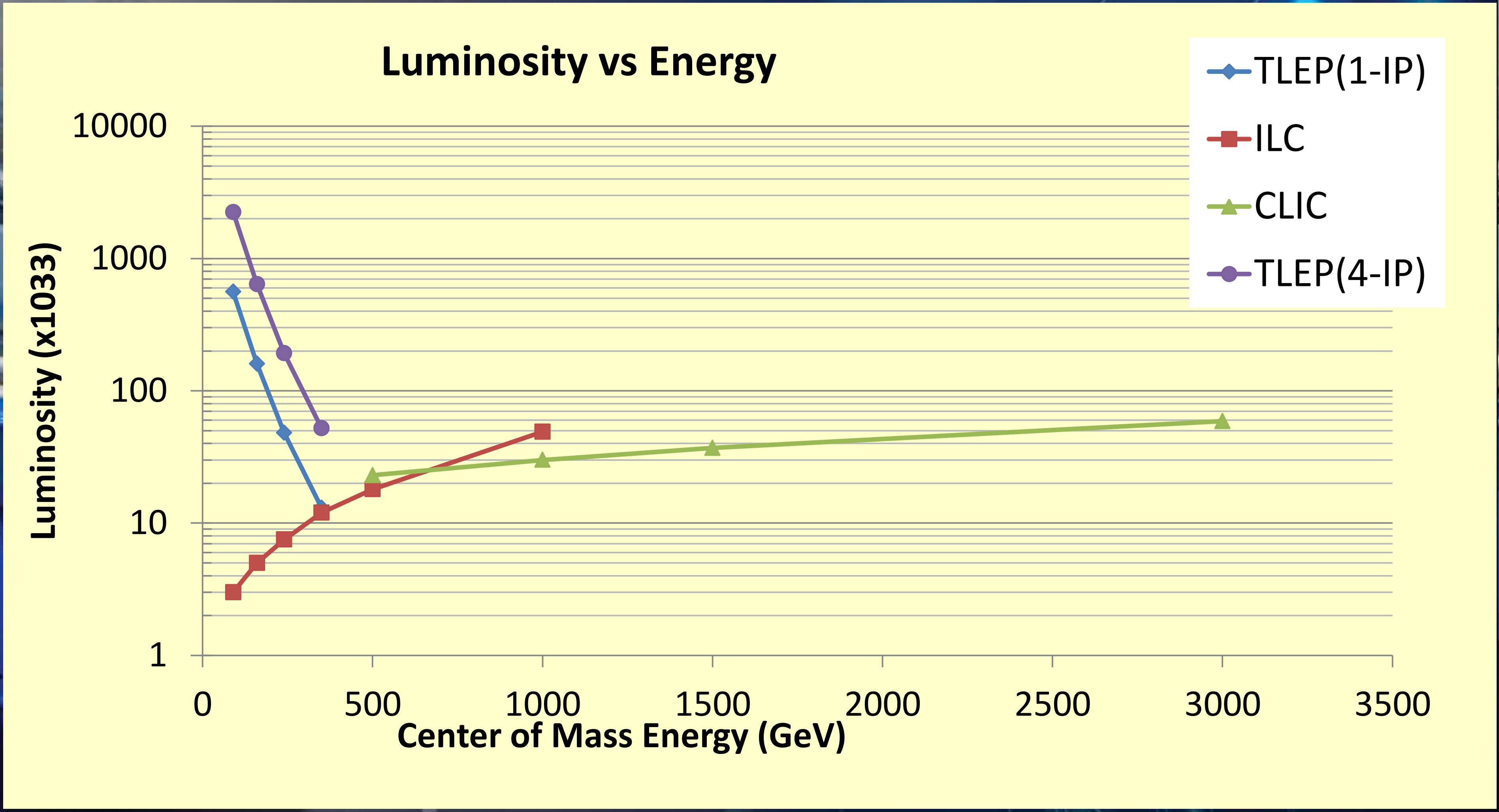
➢ *Idea is rather new triggered by low Higgs mass but based on long and mature experience in circular colliders*

➢ *superKEKB is a very effective technology test case*

➢ *Promising possibility ⇨ need to set up a international study*

Explore synergies for a Very Large Collider Complex e^+e^-, pp, ep?

ElectroWeak Symmetry Breaking precision measurements require very high luminosity



ElectroWeak Symmetry Breaking precision measurements

Accelerator →Physical quantity ↓	HL-LHC $3000fb^{-1}$ /exp	ILC (250) 250 fb^{-1}	ILC (250+350+1000)	LEP3 240 4 IP	TLEP 240 +350 4 IP
Approx. date	2030-35	2030-35?	>2045?	2035?	2035?
N_H	1.7 x 10^8	5 10^4 ZH	(10^5 ZH) ($1.4\ 10^5$ Hvv)	4 10^5ZH	2 10^6 ZH
Δm_H (MeV)	50	35	35	26	7
$\Delta\Gamma_{H}/\Gamma_H$	--	10%	3%	4%	1.3%
$\Delta\Gamma_{inv}/\Gamma_H$	Indirect (?)	1.5%	1.0%	0.35%	0.15%
$\Delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$	1.5%	--	5%	3.4%	1.4%
$\Delta g_{Hgg}/g_{Hgg}$	2.7%	4.5%	2.5%	2.2%	0.7%
$\Delta g_{Hww}/g_{Hww}$	1.0%	4,3%	1%	1.5%	0.25%
$\Delta g_{HZZ}/g_{HZZ}$	1.0%	1.3%	1.5%	0.65%	0.2%
$\Delta g_{HHH}/g_{HHH}$	< 30% (2 exp.)	--	~30%	--	--
$\Delta g_{H\mu\mu}/g_{H\mu\mu}$	<10%	--	--	14%	7%
$\Delta g_{H\tau\tau}/g_{H\tau\tau}$	2.0%	3,5%	2.5%	1.5%	0.4%
$\Delta g_{Hcc}/g_{Hcc}$	--	3,7%	2%	2.0%	0.65%
$\Delta g_{Hbb}/g_{Hbb}$	2.7%	1.4%	1%	0.7%	0.22%
$\Delta g_{Htt}/g_{Htt}$	3.9%	--	15%	--	30%
Δm_t (MeV)	500-800	--	20	--	15
Δm_W (MeV)	~10	--	~6	--	< 1

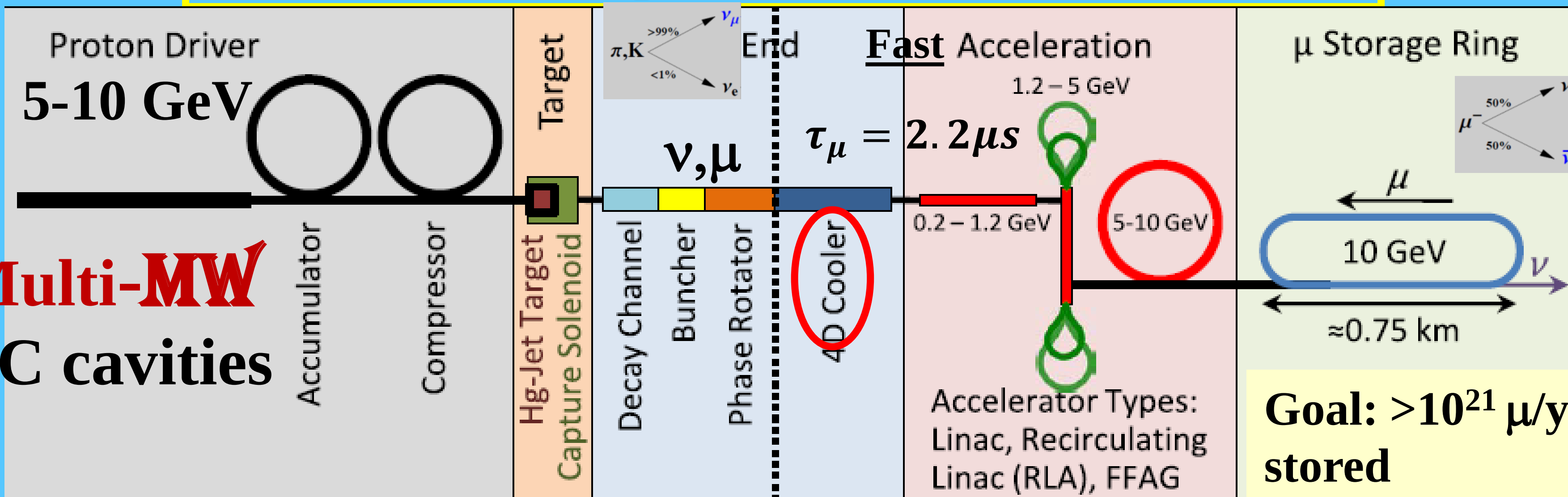
Many other accelerator R&D topics have not been discussed here e.g. e-p collider, γγ collider, μ collider, plasma acceleration… They should not be forgotten…

…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

Higgs Factories	Linear Collider	Plasma Wakefield	Circular Collider	Muon Collider	γ–γ Collider
Technical Maturity Proj launch/First beam	☺ 2018/2027	☹☹ ?	☺☺ 2020/2030	☹ ?	😐 2025/2035
Engineered design readiness	☺☺ ILC	☹☹	☹	☹☹	☹☹
Size (km)	☹ 13-50	☺ 2.5	☹ 20-80	☺ 1.5(0.3)	☺ 10
Cost (BCHF)	☹ 8-10	😐 ?	😐☹ 6-7	😐 ?	😐 ?
Power (MW) Consumption	☺ 128-235	☺ 133	☹ 280	😐 200	😐 ?
Energy Resolution	☹ 10^{-2}	☹☹ Few 10^{-2}	😐☺ 10^{-3}-10^{-6}	☺☺ 10^{-5}	☹ ?
Polarisation	☺☺ 80/30	☹ ?/?	☺☹ @low E only	😐 15-15	😐 ?/?
MDI	😐	😐	😐	☹ background	☹ laser
Energy (TeV) Upgradability	☺ 1-3	☺☺ 3	☹☺☺ 0.35e-/100 p+	☺☺ 3-6	☺ 1-2
Power @ Emax	~300-600	~320	~200	~280	?

From neutrino superBeams toward ν-factories

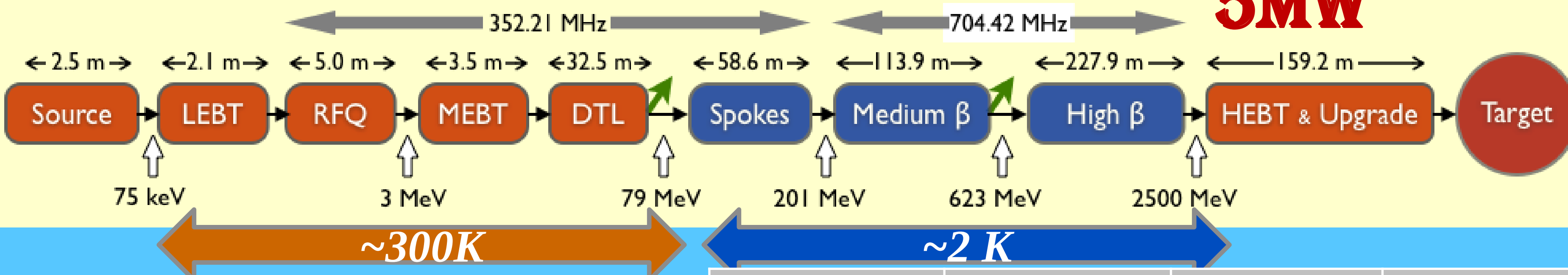


Multi-MW
SC cavities

Goal: >10[21] μ/year stored

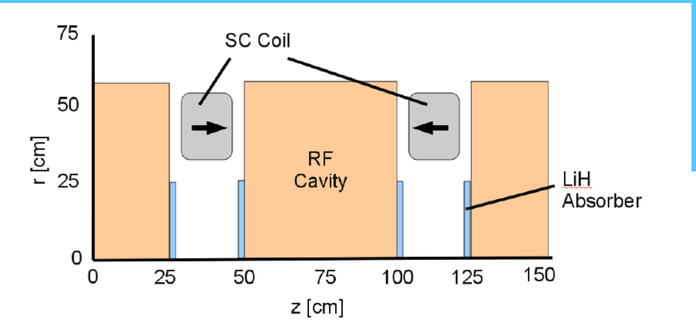
➢ **Do we have technology for multiMW proton driver ?**

Indeed, see for example **ESS** **5MW**



Cavity type	Gradient	#cav.(cell)	#cryomod.
Spoke	8 MV/m	48(2)	16
Ellip. 1	~14 MV/m	36(5)	9
Ellip. 2	~21 MV/m	112(5)	14

The key issue : beam cooling

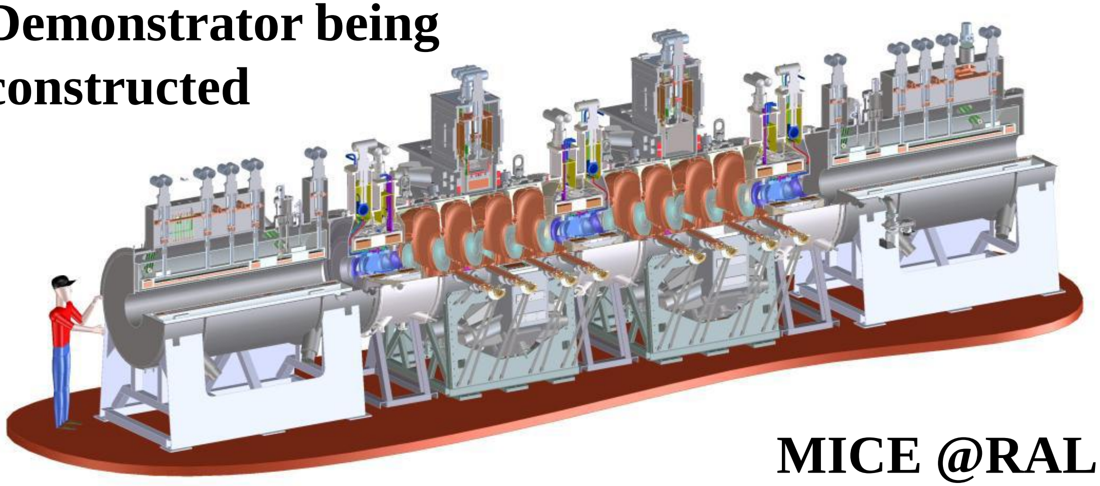


Ionization cooling

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

- **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)**

Demonstrator being constructed

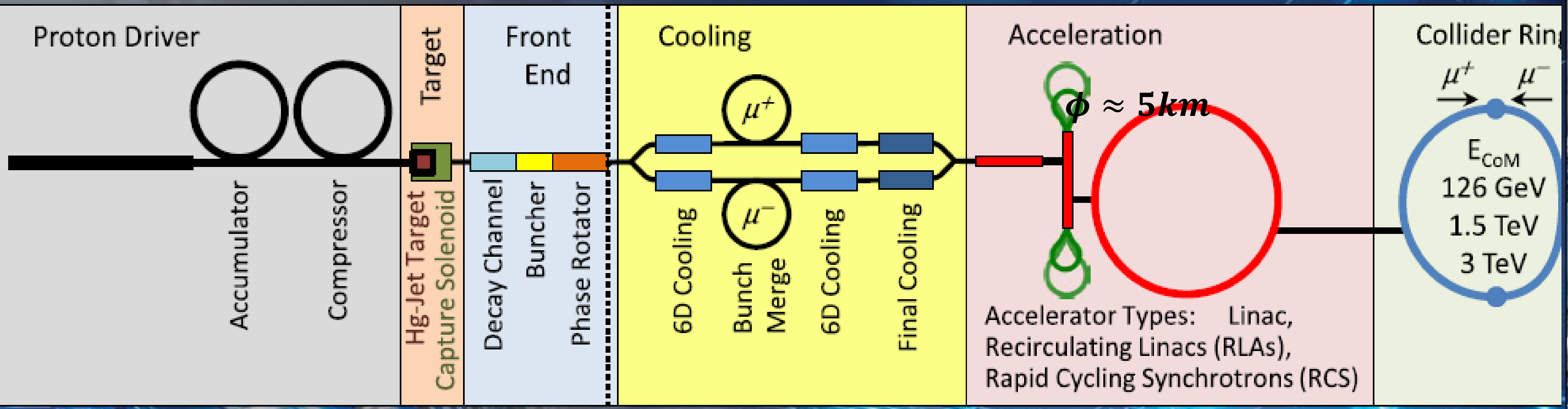


MICE @RAL

- ***On-going R&D by international collaborative***
- ***Maintaining a Strong R&D on these issues is important***
- ***A project like nuStorm is also an interesting idea to test muon storing and decays to ν***

However, thanks to large θ_{13} value, conventional beam based on high power proton beam (~1MW) can be used

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



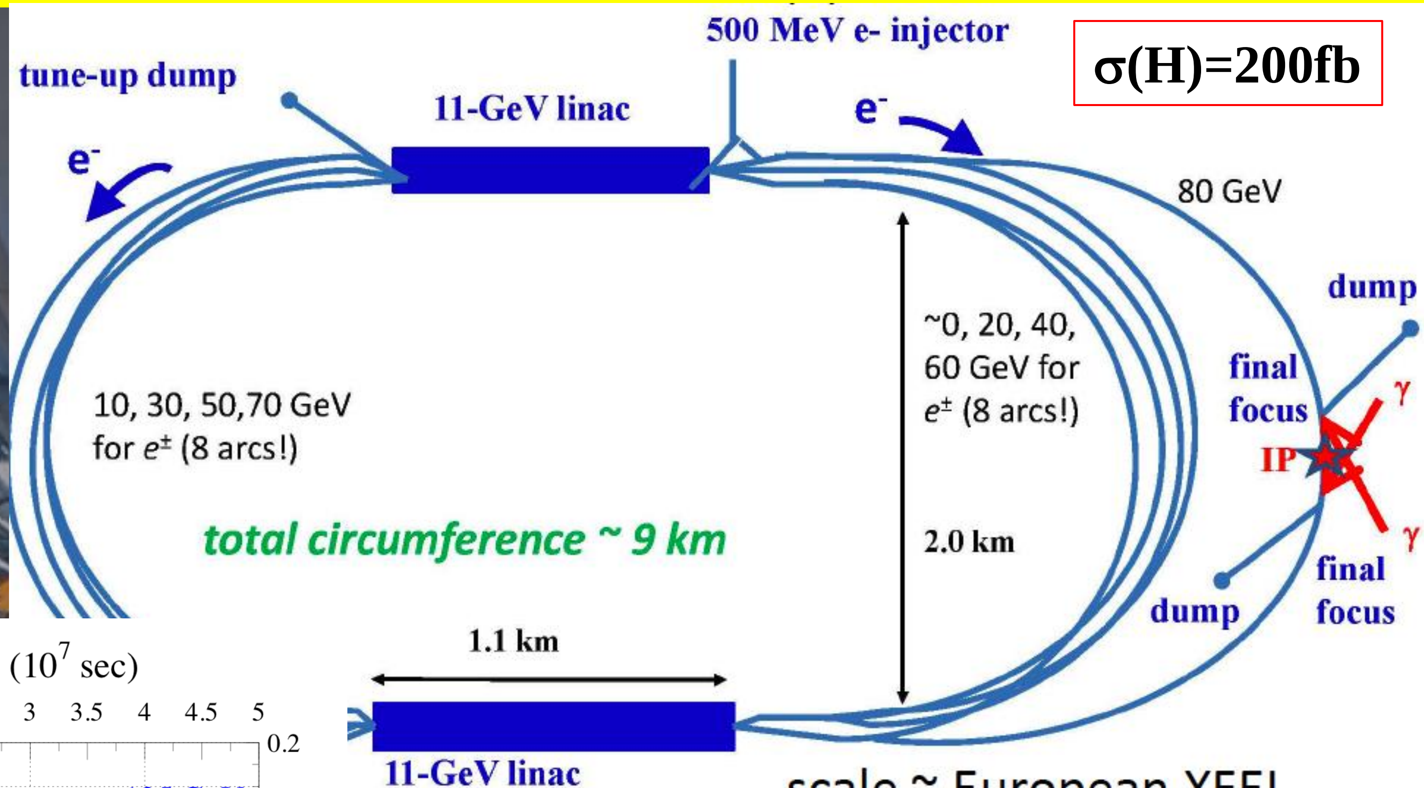
Require much smaller beam size (i.e. lower emittance)
→ Very efficient cooling

Some ultra-challenging components:
- **Very high field solenoids (20-30T)**
- **High gradient cavities in multi-Tesla field**

1-2x10^4 H/Year

If cooling demonstrated!

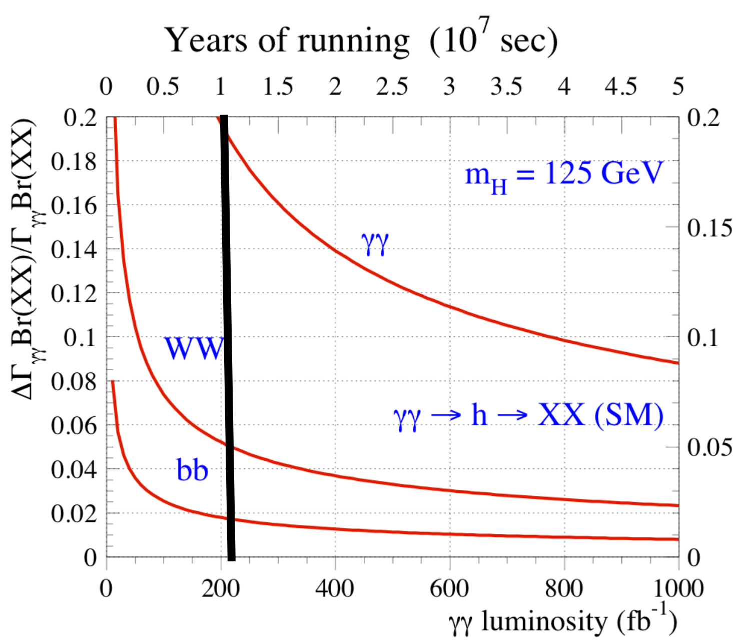
From e^+e^- Higgs factory to $e^-e^-/\gamma\gamma$ collider



σ(H)=200fb

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)

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

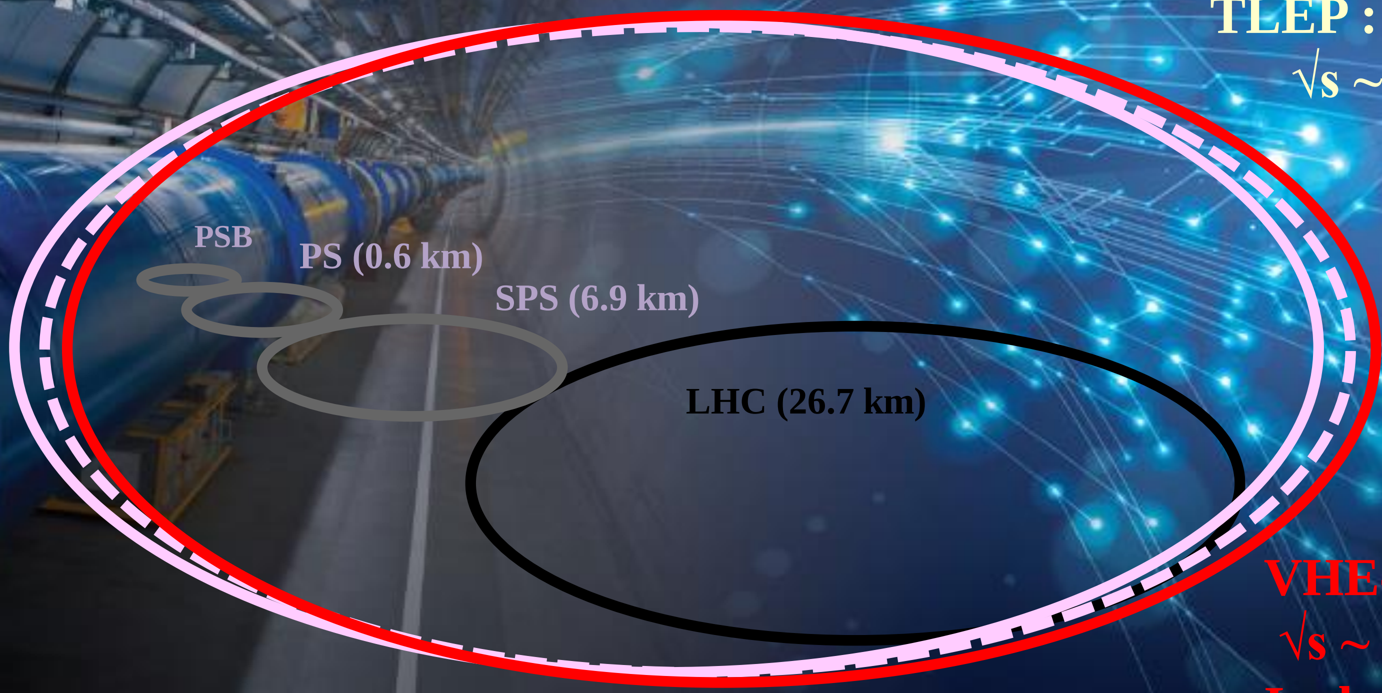
$E=mc^2$

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

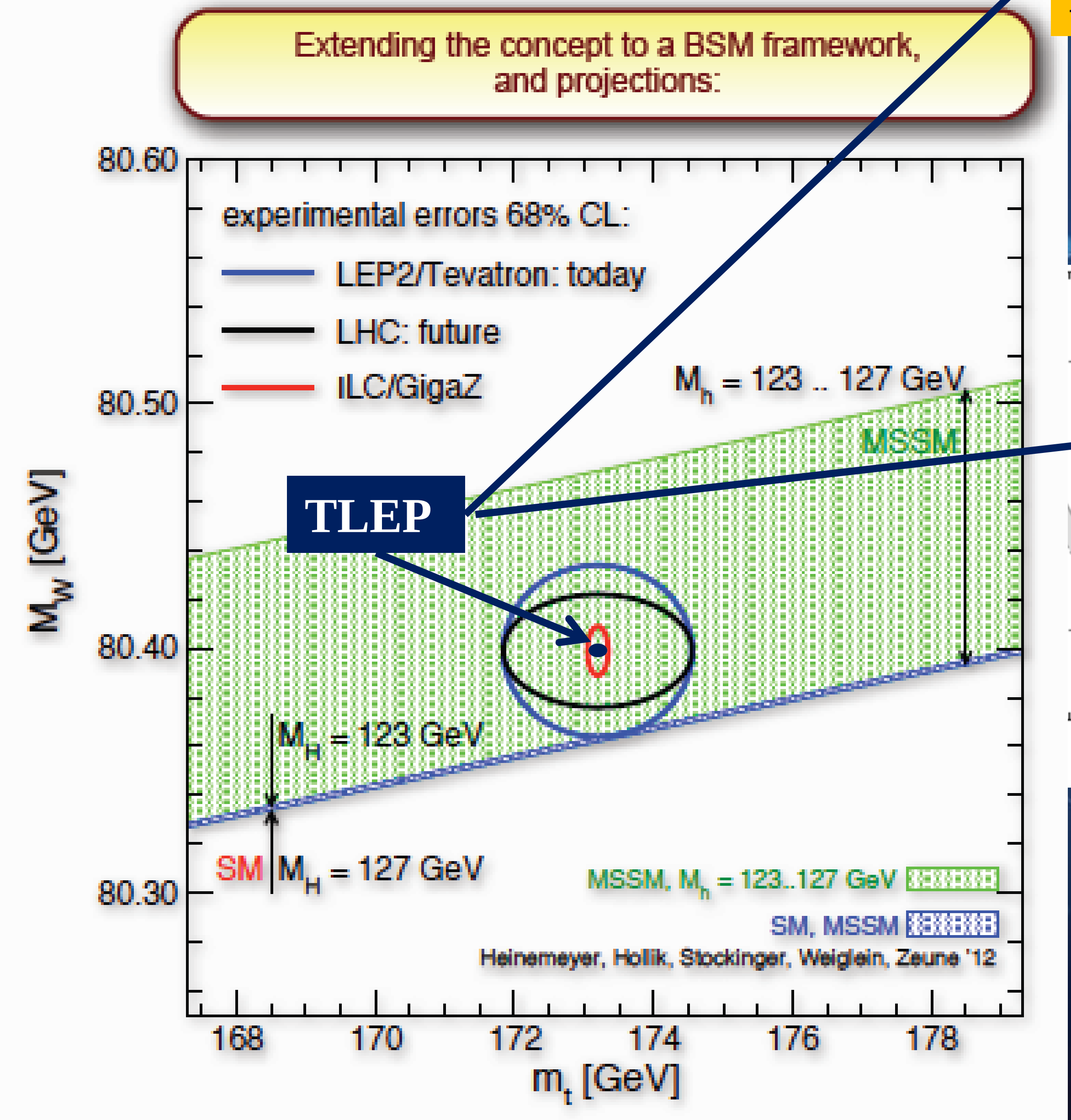
- Ambitious milestones should be set up
  - CDR in 2 years
  - TDR in 5 years, in a timely fashion with an update of the European Strategy in 2017-18, after the first round of operation of the LHC@13-14 TeV
- A possible timeline should be discussed

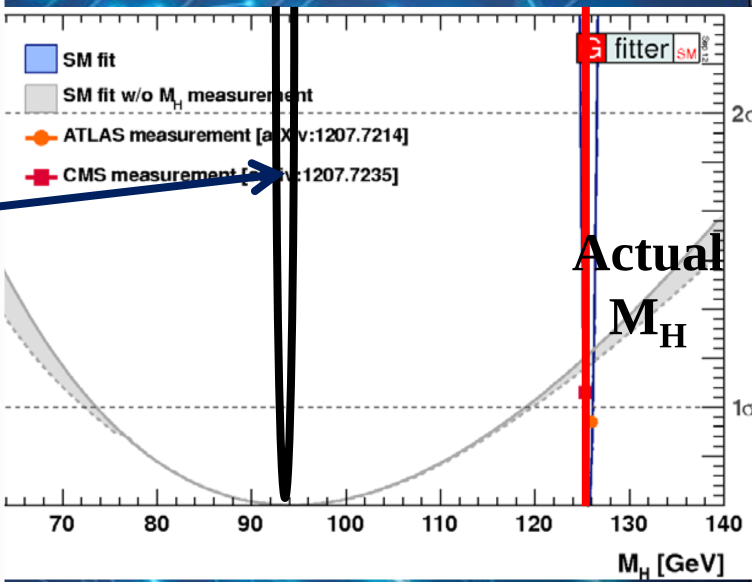
	2010	2015	2020	2025	2030	2035	2040
LHC							
HL-LHC		R&D + constr					
TLEP*			Design + R&D + construction				
VHE-LHC*			Design + R&D + construction				
ILC			Design + R&D + construction				

*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