TLEP/VHELHC: an exciting vision for Particle Physics

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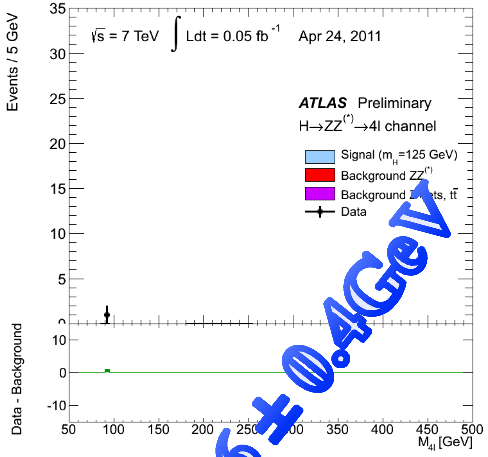
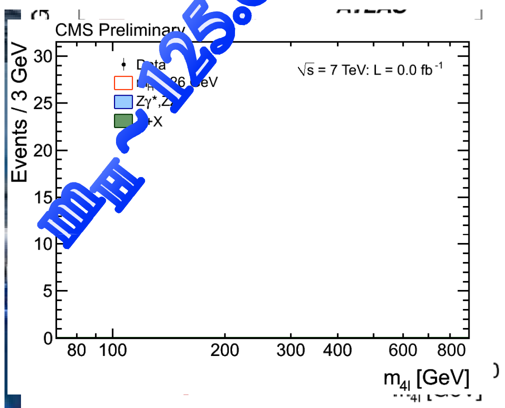
Corfu2013

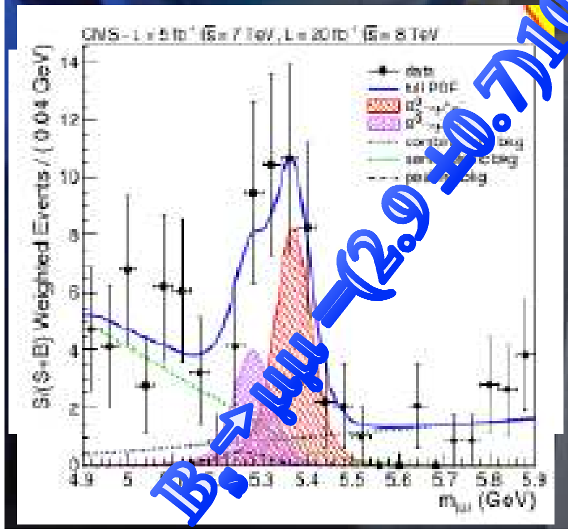
- The Frontiers of PP
- What to do Next and which Strategy
- Next Accelerator Technology Challenges for PP
- Conclusion

High Precision Measurements
Very High Energy Reach
High Intensity ν Beams

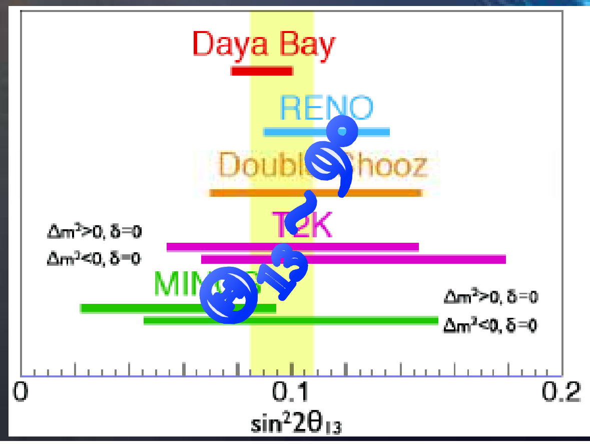




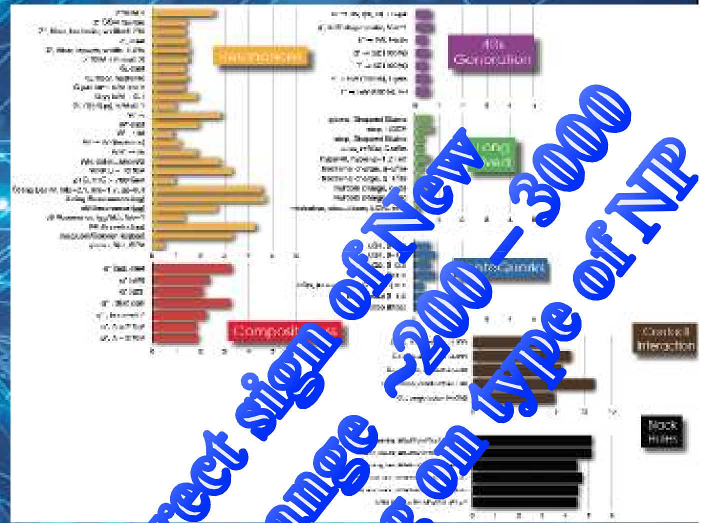
$m_H \sim 125.6 \pm 0.4$GeV

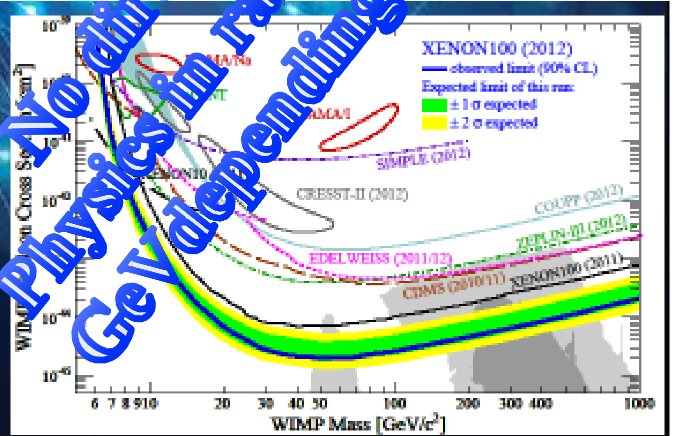


$B_s \to \mu\mu = (2.9 \pm 0.7)10^{-9}$



$\theta_{13} \sim 9°$





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

Possible Strategy

1. Mesuring the electroweak sector with the HIGHEST possible precision with e^+e^- collisions
2. Observation of deviations from the SM providing indications on the scale of New Physics
3. Exploring this New Physics directly with pp collisions
4. If needed, complement the studies with other types of collisions
   - $e^{+/-}p$ collisions
   - $\gamma\gamma$ collisions
   - $\mu^+\mu^-$ collisons

A « >50-year » programme !

Possible Scenarii (cont'd)

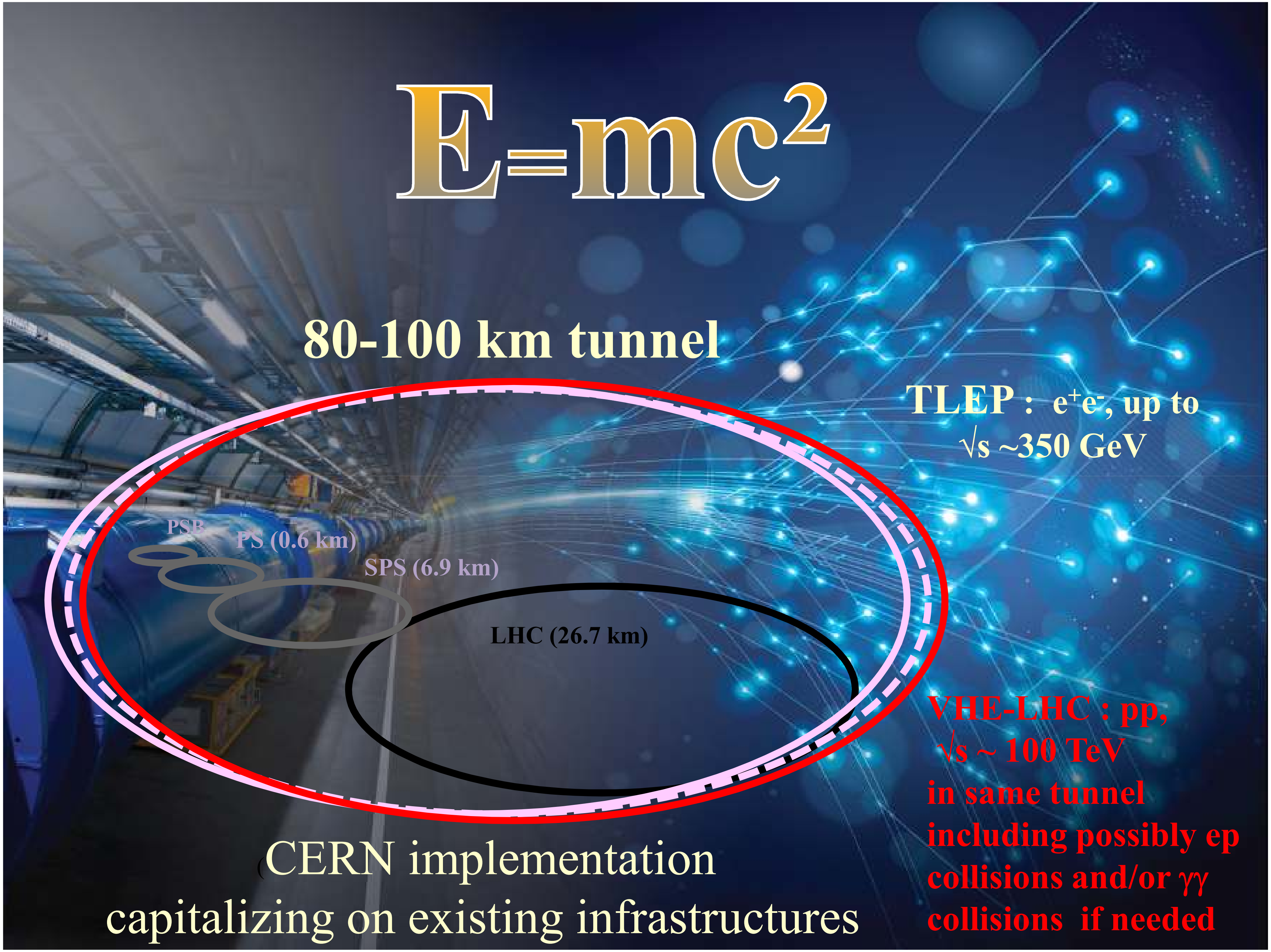
When | **What**

When	Standard Higgs	Non-standard Higgs / new physics
after LHC @14 TeV	Standard Higgs and nothing else	Non standard Higgs and/or new physics
Decision in 2018	e^+e^- Collider : e.g. TLEP	Depending of NP scale e^+e^- and/or pp : CLIC or TLEP+VHE-LHC or VHE-LHC directly
	VHE-LHC (pp 100 TeV) or $\mu\mu$ collider (if new physics hints <5 TeV)	

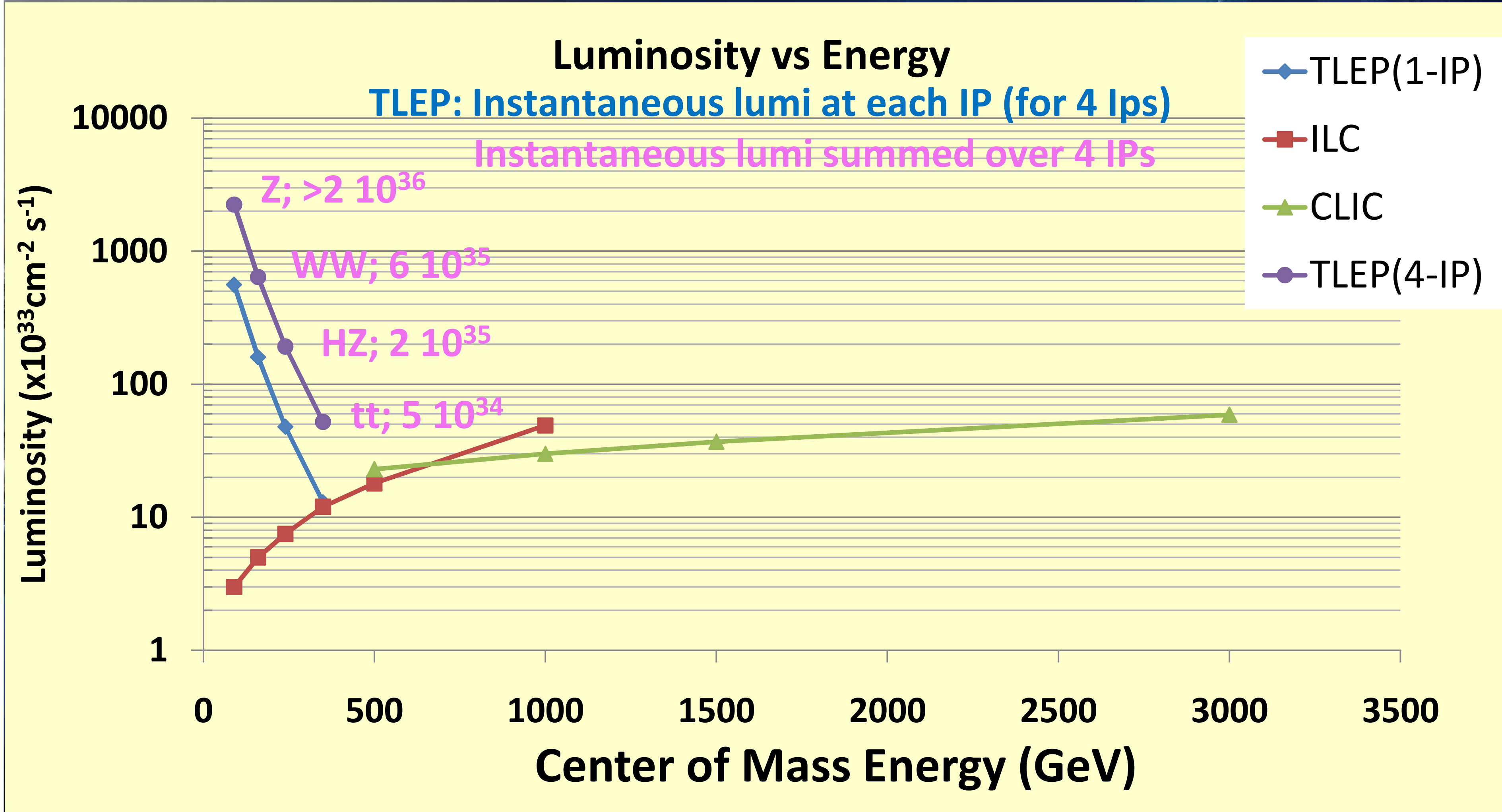
We should develop a strategy toward very High Energy …

…possibly with the same complex?


Can one do this all in one?
Make
E=mc²
Extended Multiprobe
Collider Complex



E=mc²
80-100 km tunnel
TLEP : e⁺e⁻, up to
√s ~350 GeV
PSB
PS (0.6 km)
SPS (6.9 km)
LHC (26.7 km)
VHE-LHC : pp,
√s ~ 100 TeV
in same tunnel
including possibly ep
collisions and/or γγ
collisions if needed
CERN implementation
capitalizing on existing infrastructures



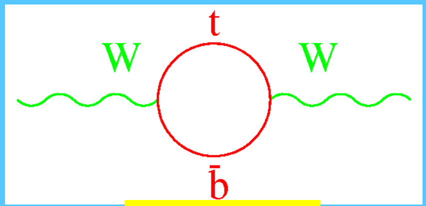
If you want to know more about TLEP see

arXiv:1308.6176v1 [hep-ex] 28 Aug 2013

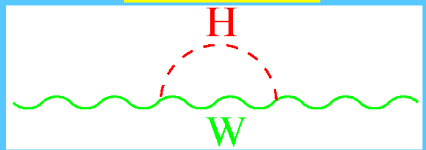
Website: http://tlep.web.cern.ch/

…WHY e^+e^-…

Improve further the consistency tests of the Standard Model

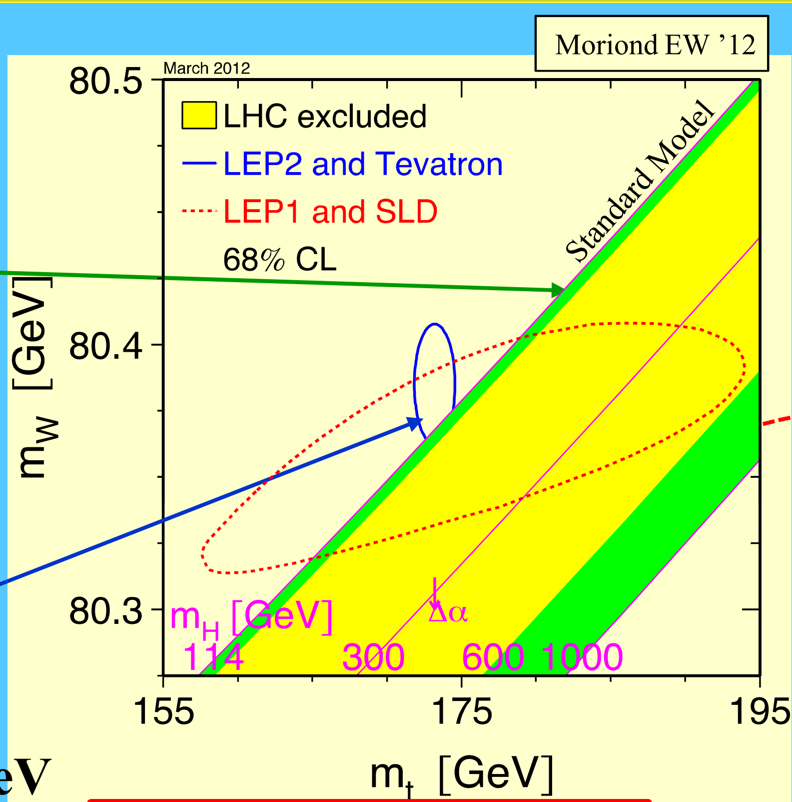


$\propto M_t^2$

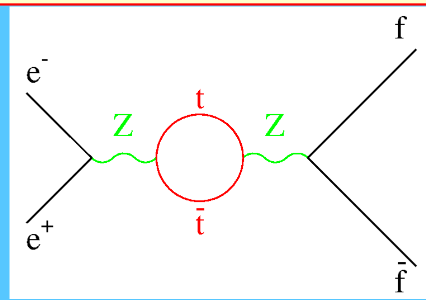


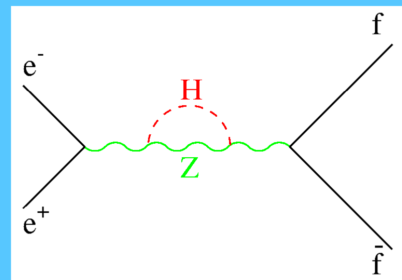
$\propto \ln(M_H)$

Direct m_W, m_{top} measurements



Z pole measurements





M_W = 80.385 ± 0.015 GeV

M_t = 173.5 ± 1.0 GeV

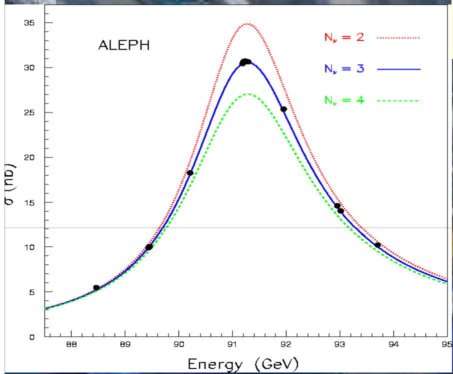
$M_H = 93 \pm ^{26}_{20}$ GeV

Affects Z lineshape, Asymmetries, Cross section Decay Rates…

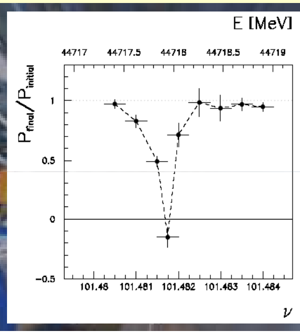
Need to improve

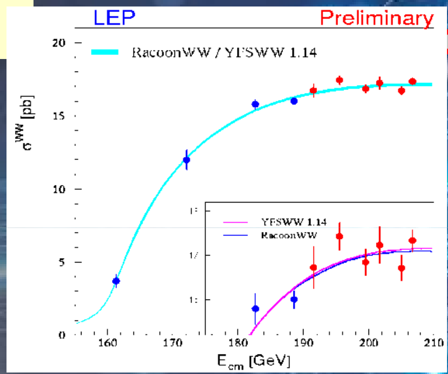
- **Measurement @Z-pole**
- **M_w and M_t (@threshold)**
- **M_H**

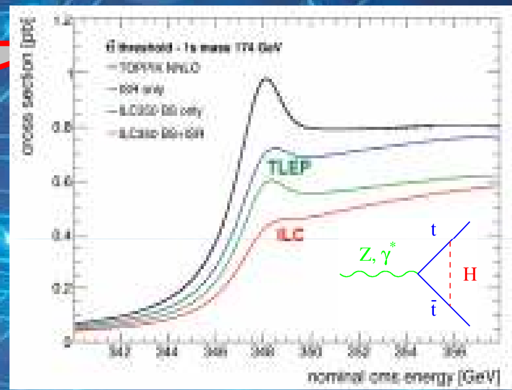
TLEP instant. luminosity ($cm^{-2}s^{-1}$)	$5.6\ 10^{35}$ @Z-pole	$1.6\ 10^{35}$ @161 GeV	$5\ 10^{34}$ @240 GeV	$1.3\ 10^{34}$ @~350 GeV
TLEP Programme	**#Z in 1 year @Z-pole**	**#W in 1 year @161 GeV**	**#H in 5 years @240 GeV**	**#top in 5 years @~350 GeV**
# events@TLEP with 4 detectors	**$\sim 10^{12}$**	**$\sim 5\ 10^{7}$**	**$\sim 2\ 10^{6}$**	**$> 10^{6}$**



Beam E cal. with reson. depolar.



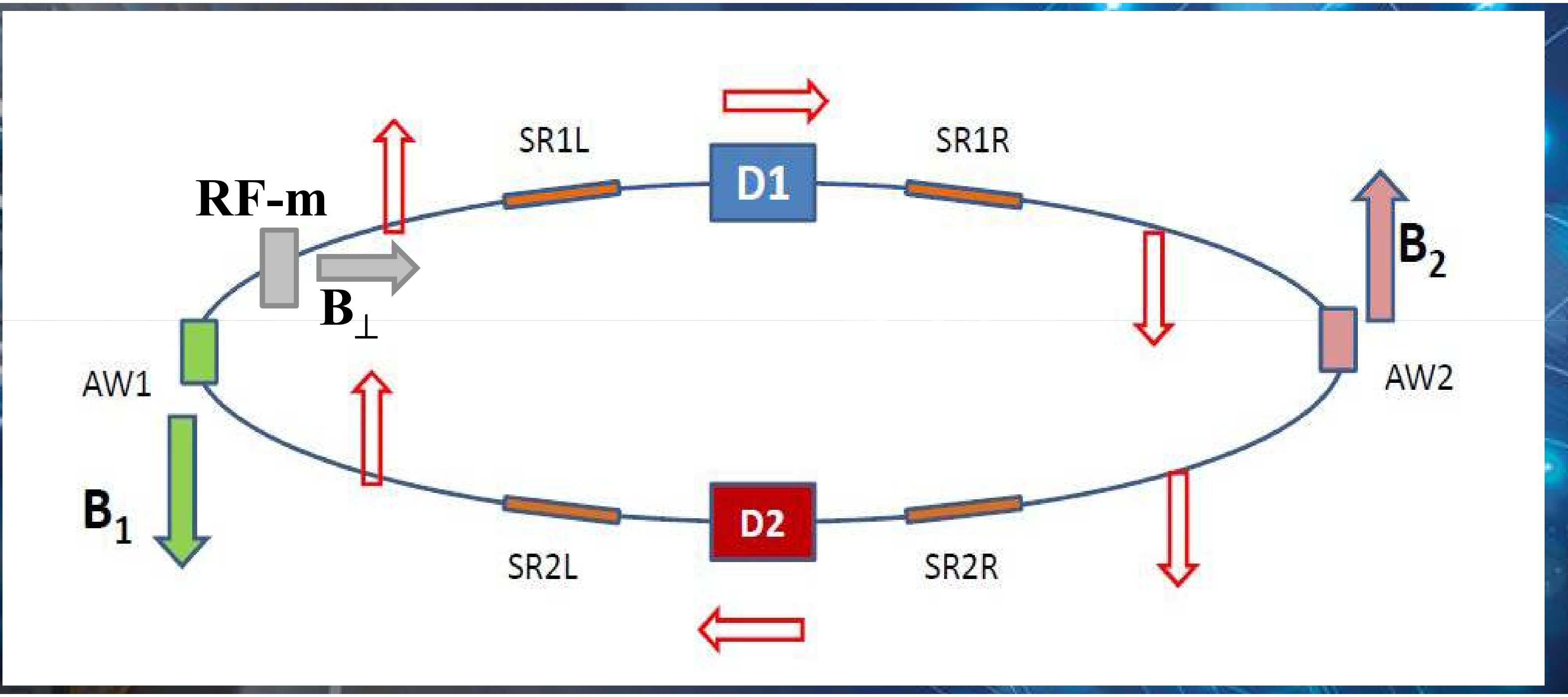




	LHC(300)	LHC (3000)	ILC programme	TLEP programme	Comment/caveat
Δm_W (MeV)	~10	~10	~7	<0.5	Theor. limited
Δm_t (MeV)	800-1000	500-800	34	10	~100 from theo.
Δm_H (GeV) indirect	-25	~20	~5	~1.4	Theor. errors should match!
Δm_H (MeV) direct	~100	~50	~35	~7	Overkill for now

Polarization at circular colliders

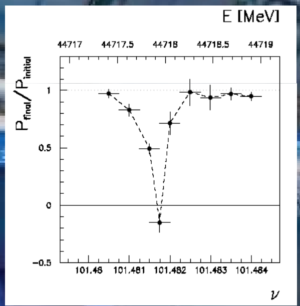
- $e^-(e^+)$ spin naturally align along dipole magnetic field
- Transverse polarization builds up by synchrotron radiation emission (or if needed using wigglers)
- Transverse to longitudinal polarization is achieved with Spin Rotators

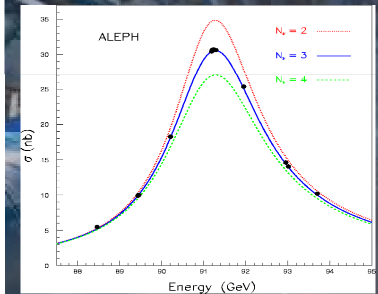


- Resonant depolarization is achieved with small field (perpendicular to dipole field) RF-magnet with frequency in phase with precession frequency. (Precession period is proportional to beam energy)
- Depolarizing RF-magnet frequency measures beam energy with <0.1 MeV

High precisions at Z pole and WW and top thresholds

Quantity	Physics	Present precision		Statistical uncertainty	Systematic uncertainty	Challenge
m_Z (keV)	Input	91187500 ± 2100	Z Line shape scan	5 keV	< 100 keV	QED corrections
Γ_Z (keV)	$\Delta\rho$ (not $\Delta\alpha_{had}$)	2495200 ± 2300	Z Line shape scan	8 keV	< 100 keV	QED corrections
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	0.0001	< 0.001	QED corrections
N_ν	PMNS Unitarity, ...	2.984 ± 0.008	Z Peak	0.00008	< 0.004	Bhabha scat.
N_ν	... and sterile ν's	2.92 ± 0.05	$Z\gamma$, 161 GeV	0.001	< 0.001	
R_b	δ_b	0.21629 ± 0.00066	Z Peak	0.000003	< 0.000060	Hemisphere correlations
A_{LR}	$\Delta_\rho, \epsilon_3, \Delta\alpha_{had}$	0.1514 ± 0.0022	Z peak, polarized	0.000015	< 0.000015	Design experiment
m_W (MeV)	$\Delta\rho$, $\epsilon_3, \epsilon_2, \Delta\alpha_{had}$	80385 ± 15	WW threshold scan	0.3 MeV	< 0.5 MeV	QED corrections
m_{top} (MeV)	Input	173200 ± 900	$t\bar{t}$ threshold scan	10 MeV	< 10 MeV	Theory interpretation

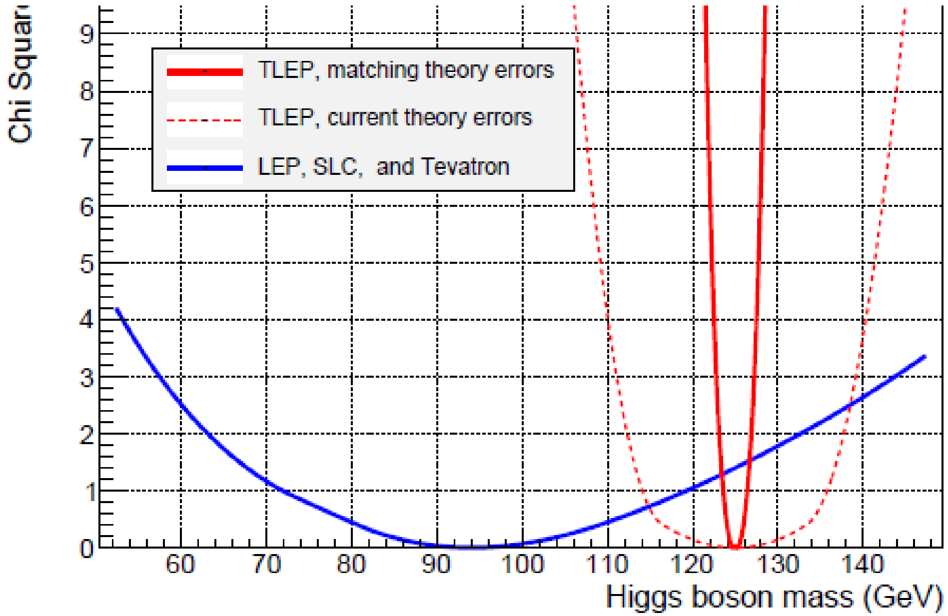




Indirect m_H measurement error

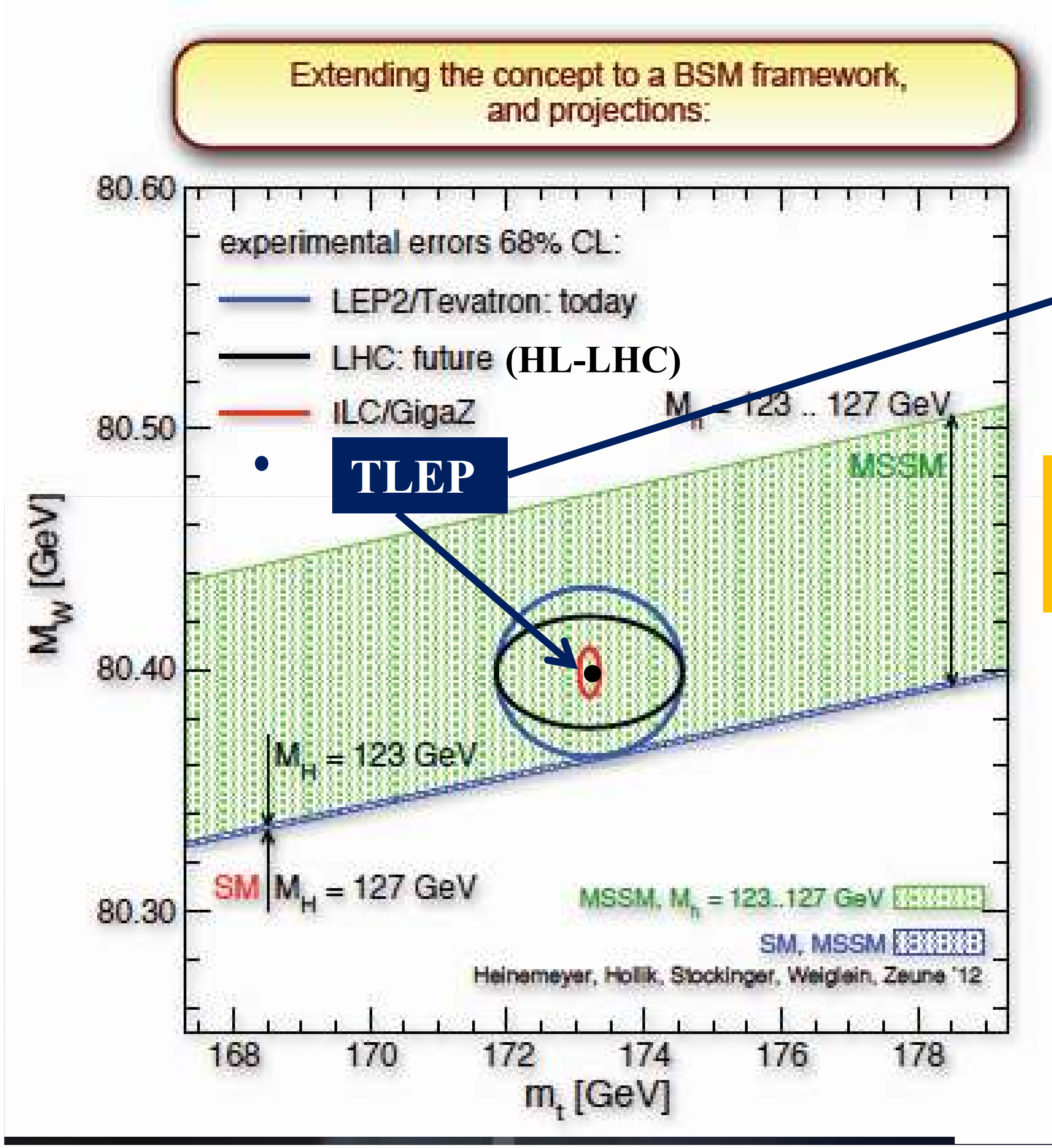
TLEP + matching theory ➩ $\delta m_H \pm 1.4$ GeV

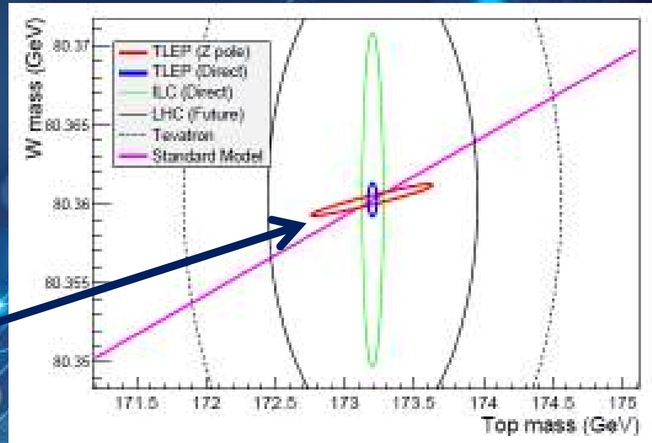
TLEP + present theory ➩ $\delta m_H \pm 11$ GeV



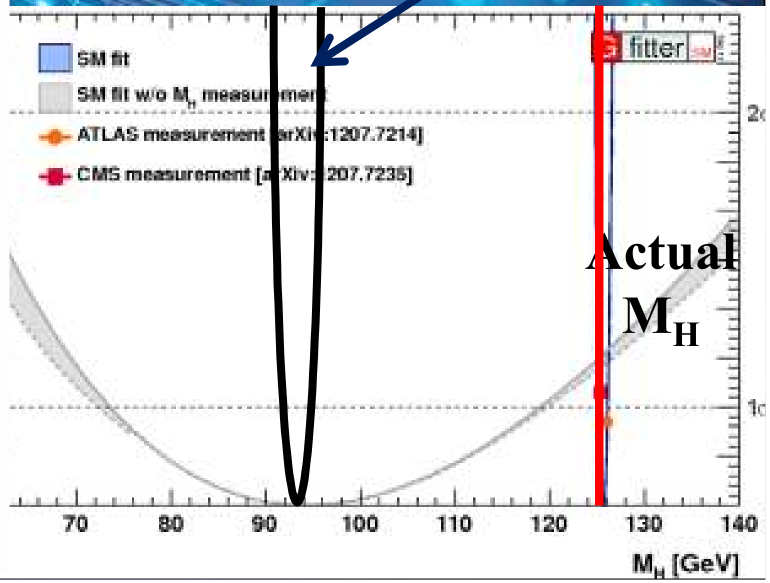
E_{beam} calibration with resonant depolarization unique to circular collider ➩ $\delta E_{beam} < 0.1$ MeV should be possible @TLEP

High precisions at Z pole and WW and top thresholds





Indirect: M_H=94.0 ± 1.4
Direct: M_H=125.500 ±0.007



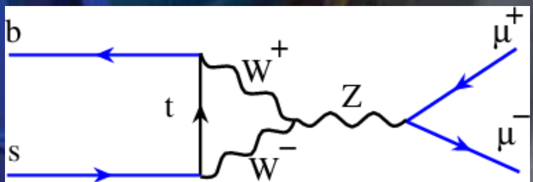
High precisions at Z-pole

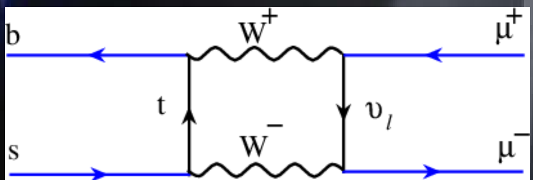
Many other measurements would benefit from Tera-Z production

Channels	Production/year	Physics
$\tau^+\tau^-$	$3\ 10^{10}$ pairs	Rare decays, conservation laws…
c or b quarks	$> 2\ 10^{11}$	CP violation, rare decays…
	e.g. $> 3\ 10^{10}\ B_s$	Large B_s sample with clean environment within SM, $> 1000\ B_s \rightarrow \tau^+\tau^-$ detected

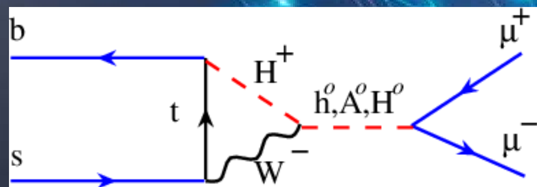
Complement to $B_s \rightarrow \mu^+\mu^-$ for NP search

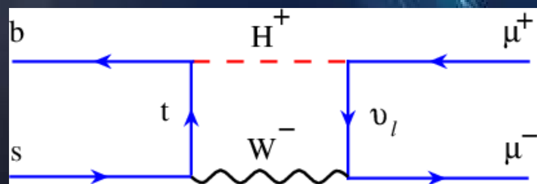
SM





Example of non-SM



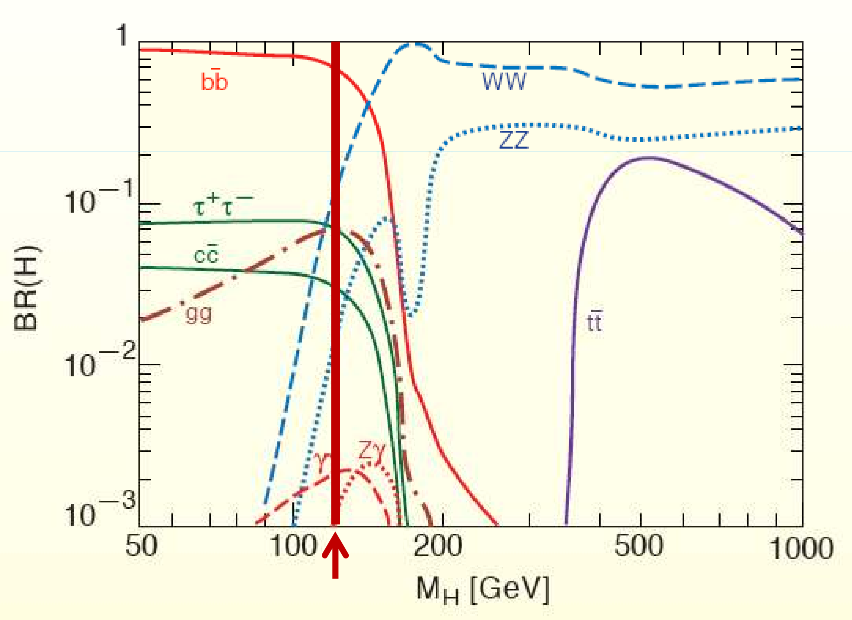


… or any NP loop process favoring 3rd generation

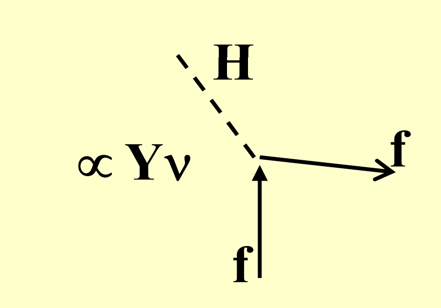
Study further the Higgs properties and couplings

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

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



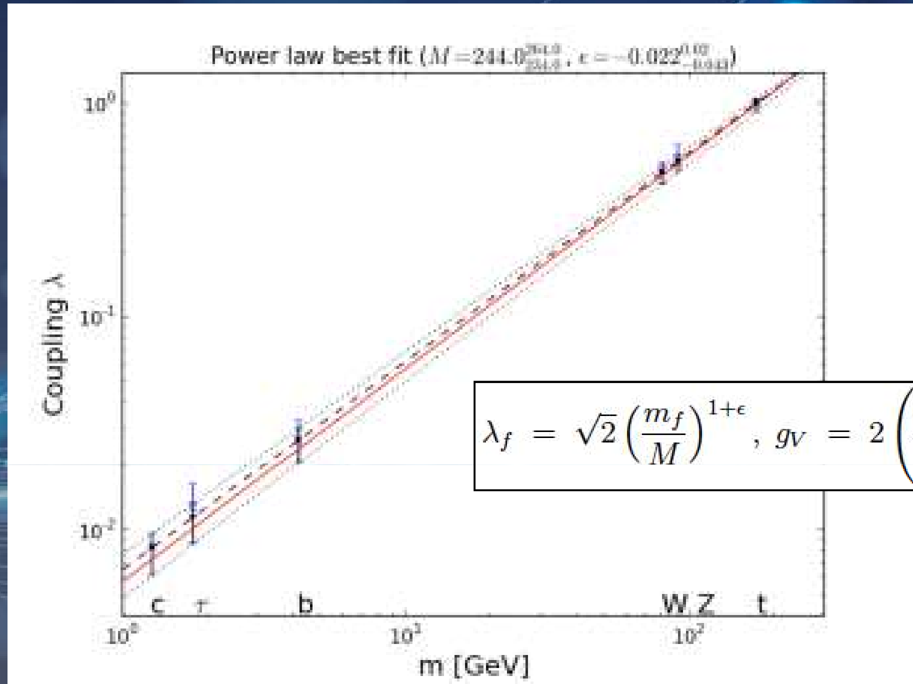
H coupling to fermions $\propto m_f$



High precisions physics at H threshold

LHC is the benchmark Higgs Factory

Accelerator → Physical quantity ↓	LHC $300 fb^{-1}$ /exp	HL-LHC $3000 fb^{-1}$ /exp
Approx. date	2021	2030-35?
N_H	1.7×10^7	1.7×10^8
Δm_H (MeV)	100	**50**
$\Delta\Gamma_H/\Gamma_H$	--	--
$\Delta\Gamma_{inv}/\Gamma_H$	18 – 14%	11 – **7%**
$\Delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$	7 – 5%	5 – **2%**
$\Delta g_{Hgg}/g_{Hgg}$	8 – 6%	5– **3%**
$\Delta g_{Hww}/g_{Hww}$	6– 4%	5 – **2%**
$\Delta g_{HZZ}/g_{HZZ}$	6– 4%	4 – **2%**
$\Delta g_{HHH}/g_{HHH}$	--	**< 30% ?** (2 exp.)
$\Delta g_{H\mu\mu}/g_{H\mu\mu}$	~30%	**~10%**
$\Delta g_{H\tau\tau}/g_{H\tau\tau}$	8 –6%	5 – **2%**
$\Delta g_{Hcc}/g_{Hcc}$	--	**~7%**
$\Delta g_{Hbb}/g_{Hbb}$	13 – 10%	7 – **4%**
$\Delta g_{Htt}/g_{Htt}$	15 – 14%	10 – **7%**
Δm_t (MeV)	800-1000	**500-800**
Δm_W (MeV)		**~10**



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

Coupling measurements with precisions:

- **in the range 4-15% with 300 fb^{-1} per exp.**
- **in the range 2-7% with 3000 fb^{-1} per exp.**

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)

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

$$\boldsymbol{v = 246\ GeV}$$

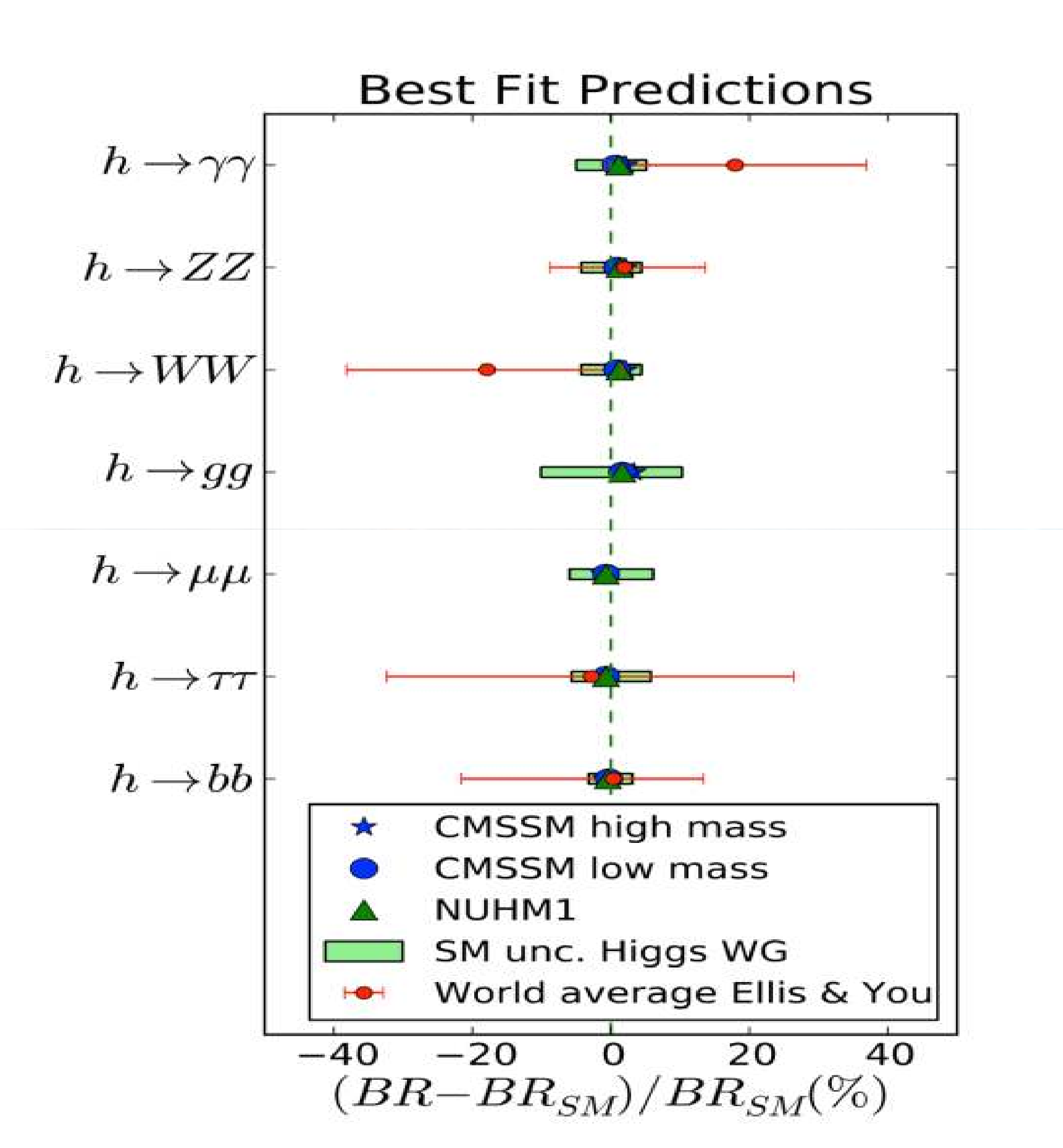
Compositness

All couplings reduced according to compositness scale

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

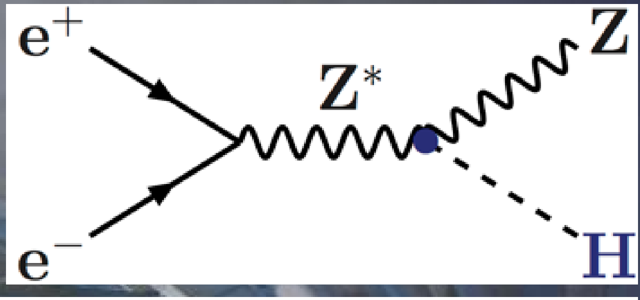
Higgs couplings should be measured as precisely as possible!

High precisions at H threshold



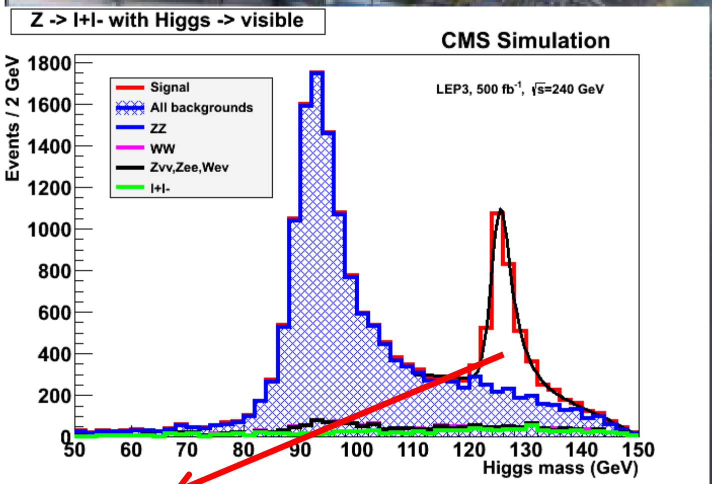
<u>Sub % sensitivities</u> on couplings to Higgs are highly desirable to probe new physics at and above the TeV scale

High precisions Higgs couplings at 240 GeV and 350 GeV



- Reconstruct Z
- Determine recoil mass

(thanks to be beam-energy constraint)



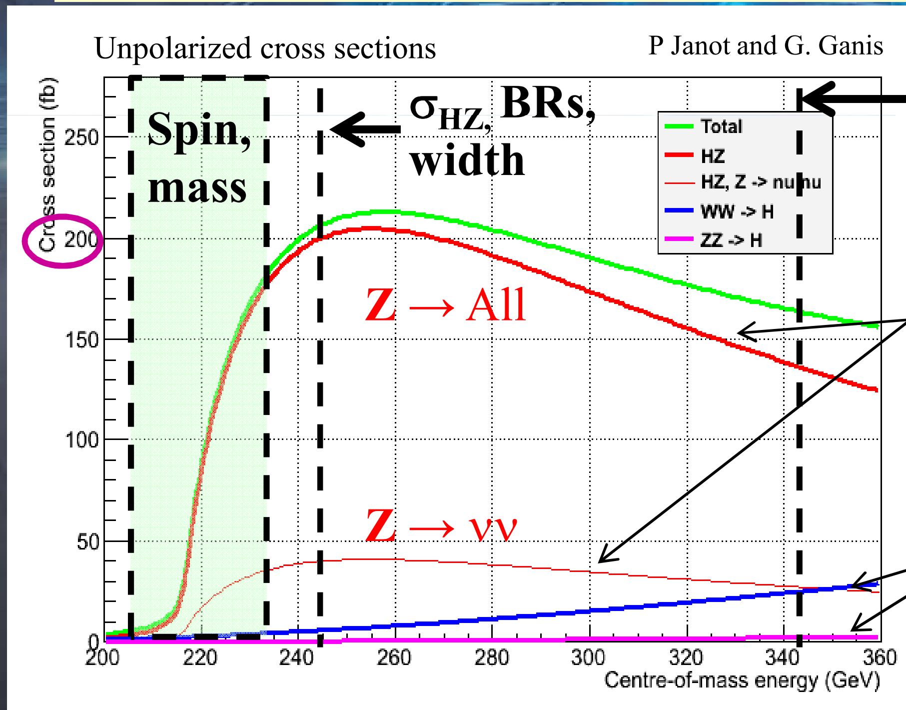
$\delta(\sigma_{HZ}) = 0.4\%$

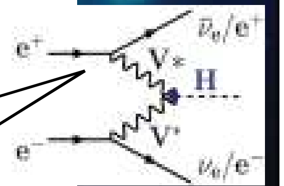
Great e$^+$e$^-$ asset: Tagged Higgs sample

- ⇨ **Total Higgs decay width**
- ⇨ **Individual branching ratios to sub %**
- ⇨ **Invisible and exotic decays**

But …

Cross section modest ⇨ very large luminosity

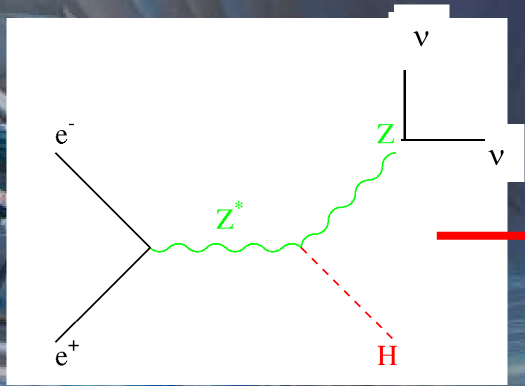


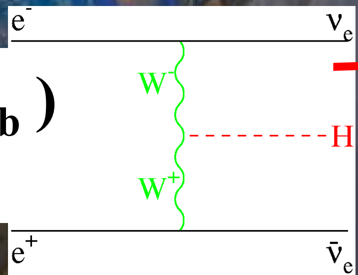


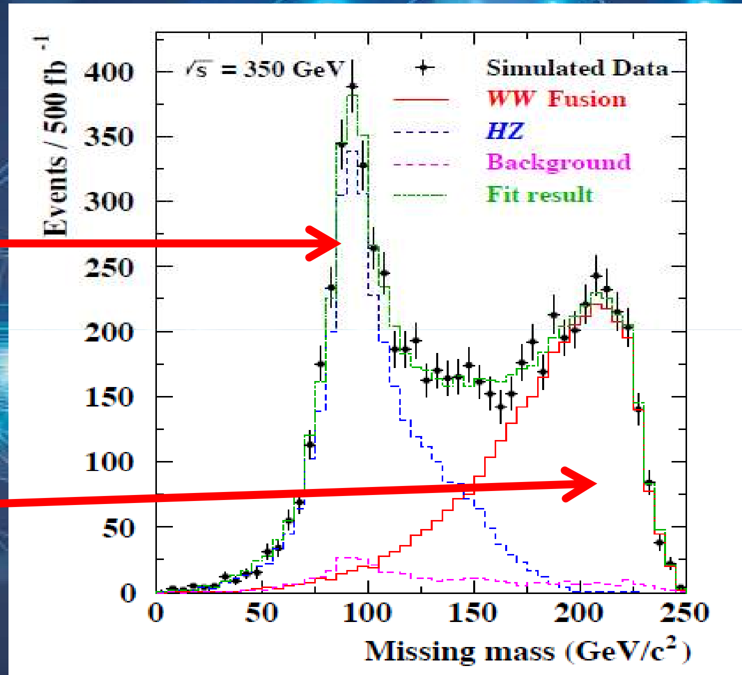
$\sigma_{HZ} \propto g_{HZZ}^2$, and $\sigma_{HZ} \times BR(H \to ZZ) \propto g_{HZZ}^4 / \Gamma_H$ ⇨ $\boxed{\Gamma_H \propto \sigma_{HZ}^2 / \sigma_{HZ} \times BR(H \to ZZ)}$

Total Higgs decay width can also be extracted from W-fusion

$$\Gamma_H \propto \sigma_{WW\to H} / \mathrm{BR}(H \to WW) = \boxed{\sigma_{WW\to H\to bb} / \mathrm{BR}(H \to WW) \times \mathrm{BR}(H \to bb)}$$







$\delta(\sigma_{WW\to H\to bb}) = 0.6\%$

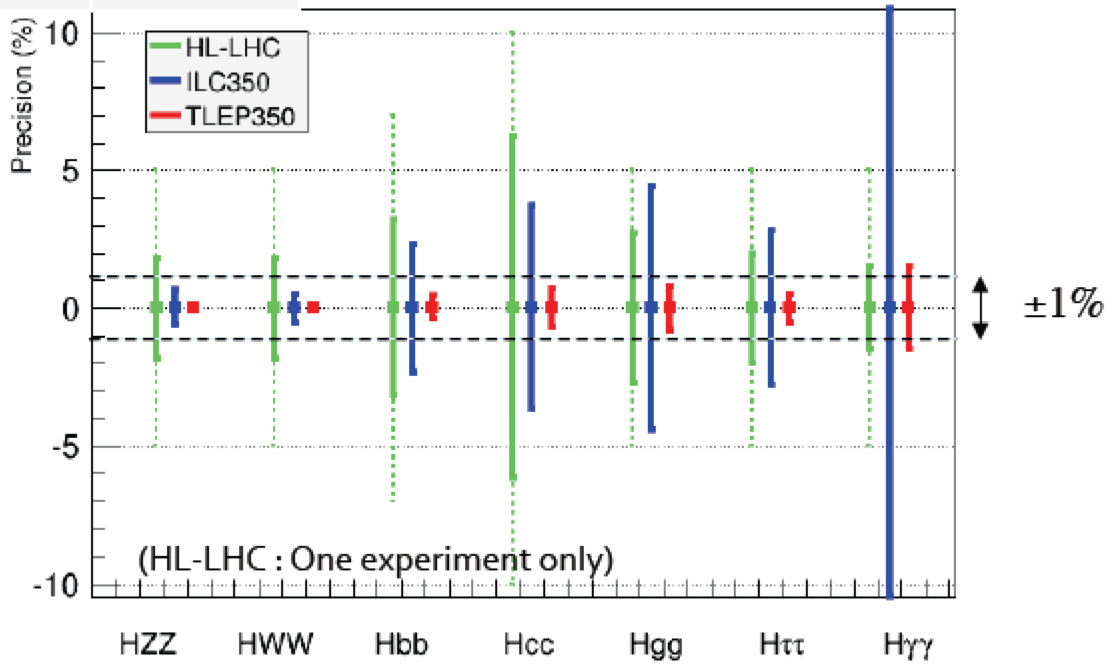
$\Delta\Gamma_H/\Gamma_H$

Process and final state	TLEP	ILC
$e^+e^- \to HZ$ with $H \to ZZ$	3.1%	20%
$WW \to H$ with $H \to b\bar{b}$ at 240 GeV	2.4%	12%
$WW \to H$ with $H \to b\bar{b}$ at 350 GeV	1.2%	7%
Combined	1.0%	6.0%

Accelerator → Physical quantity ↓	HL-LHC 3000fb^{-1} /exp	ILC (250+350)	TLEP 240 +350 4 IP
$\Delta\Gamma_{H}/\Gamma_{H}$	--	6.0%	**1.0%**
$\Delta\Gamma_{inv}/\Gamma_{H}$	~7%	2.9%	**0.45%**
$\Delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$	2.0%	14.5%	**1.5%**
$\Delta g_{Hgg}/g_{Hgg}$	3.0%	4.4%	**0.8%**
$\Delta g_{Hww}/g_{Hww}$	2.0%	0.5%	**0.19%**
$\Delta g_{HZZ}/g_{HZZ}$	2.0%	0.9%	**0.15%**
$\Delta g_{H\mu\mu}/g_{H\mu\mu}$	<10%	45%	**6.2%**
$\Delta g_{H\tau\tau}/g_{H\tau\tau}$	2.0%	2.9%	**0.54%**
$\Delta g_{Hcc}/g_{Hcc}$	~7%	3.8%	**0.71%**
$\Delta g_{Hbb}/g_{Hbb}$	4.0%	2.4%	**0.42%**

Sensitivity to Higgs Coupling at TLEP using data at 240 and 350 GeV (5 years at each energy)

Comparison with of TLEP sensitivities with HL-LHC and ILC



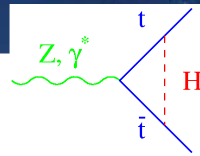
Sensitivity to Higgs Coupling at TLEP using data at 240 GeV (5 years, 4 detectors)

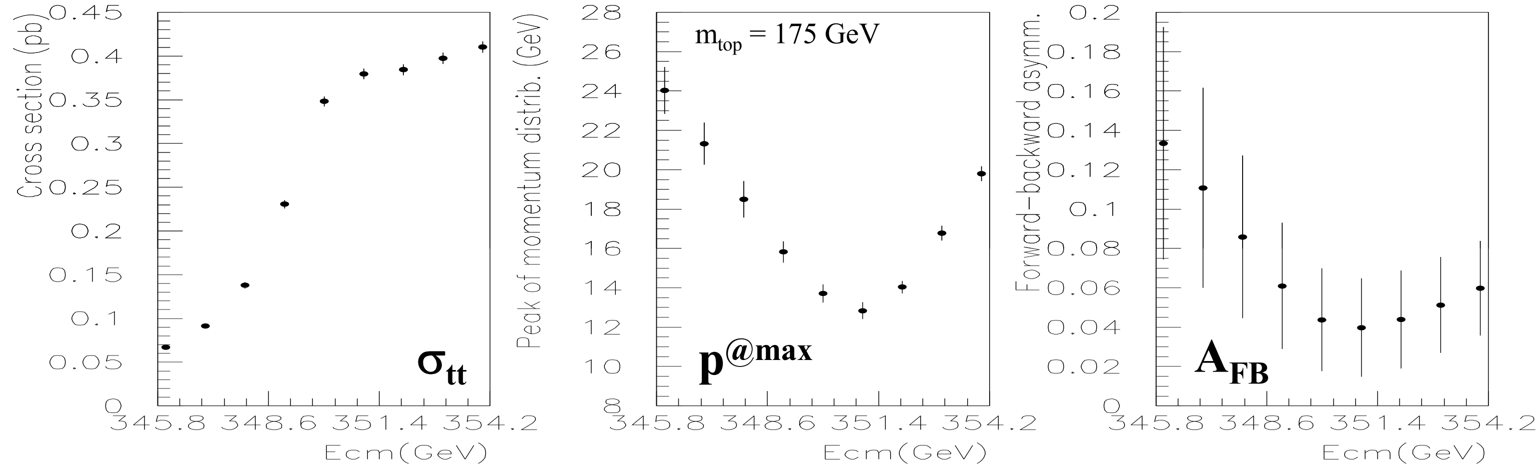
Collider	TLEP 240	ILC 250
σ_{HZ}	0.4%	2.5%
$\sigma_{HZ} \times BR(H \to b\bar{b})$	0.2%	1.1%
$\sigma_{HZ} \times BR(H \to c\bar{c})$	1.2%	7.4%
$\sigma_{HZ} \times BR(H \to gg)$	1.4%	9.1%
$\sigma_{HZ} \times BR(H \to WW)$	0.9%	6.4%
$\sigma_{HZ} \times BR(H \to \tau\tau)$	0.7%	4.2%
$\sigma_{HZ} \times BR(H \to ZZ)$	3.1%	19%
$\sigma_{HZ} \times BR(H \to \gamma\gamma)$	3.0%	35%
$\sigma_{HZ} \times BR(H \to \mu\mu)$	13%	100%

Coupling	TLEP-240
g_Z	0.16%
g_W	0.85%
g_b	0.88%
g_c	1.0%
g_g	1.1%
g_τ	0.94%
g_μ	6.4%
g_γ	1.7%
BR_{exo}	0.48%

High precisions at ttbar threshold

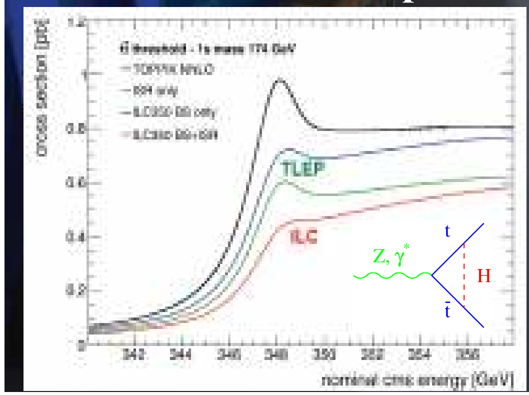
- Scan of the tt threshold
  - Observables σ_{tt}, A_{FB} and <$p^{@max}$> sensitive to m_{top}, Γ_{top}, and λ_{top} (ttH Yukawa coupling)
    - Experimental precision for ILC with 100,000 tt events
      - No beamstrahlung and 500,000 tt events at TLEP





M. Martinez and R. Miquel, 2003

- Expected sensitivity for TLEP (full study to be done) and ILC



	Δm_{top}	$\Delta\Gamma_{top}$	$\Delta\lambda_{top}/\lambda_{top}$
TLEP	10 MeV	11 MeV	13%
ILC	31 MeV	34 MeV	40%

Study of the Higgs properties, its couplings and the potential

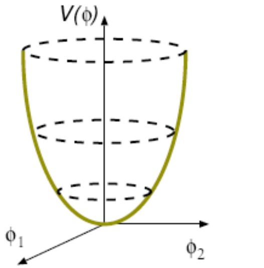
$$V_{Higgs} = -\mu^2\, \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

field self coupling

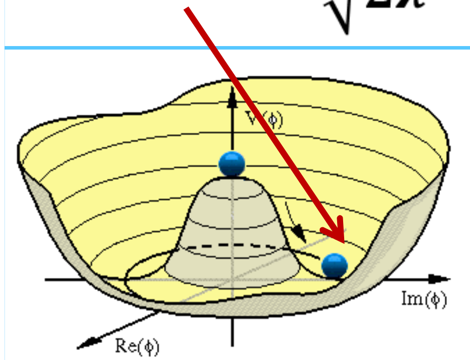
H potential

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

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

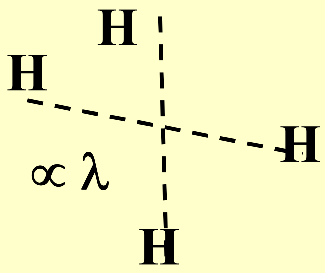


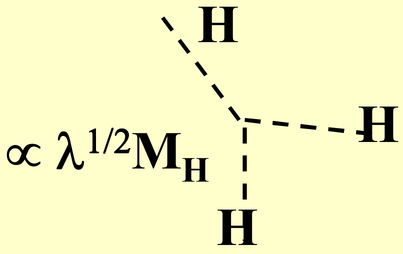
$$\phi_{min} = v = \sqrt{\frac{\mu^2}{2\lambda}}\, e^{-i\delta}$$



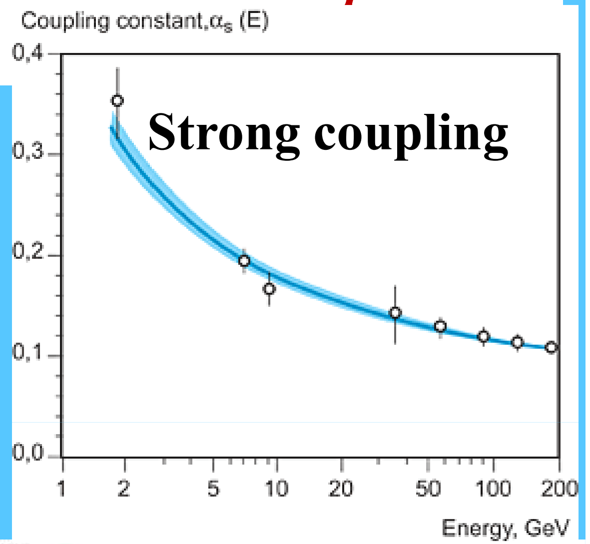
$$v = 246\ GeV$$

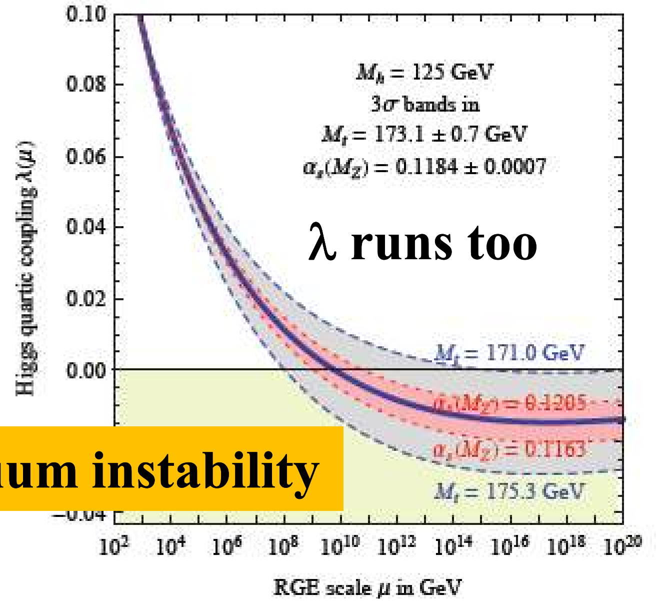
$$M_H = \sqrt{2\lambda v^2}$$





Consistency Check





Vaccuum instability

Do we have the technology to carry out these measurements?

	LHC(300)	LHC (3000)	ILC (250+350)	TLEP (240+350)	Comment
Δm_H (MeV)	~100	~50	~30	~7	Overkill for now
$\Delta\Gamma_H/\Gamma_H\,(\Delta\Gamma_{inv})$	--(14)	--(7)	6(2.9)%	1.0(0.45)%	
H spin	✓	✓	✓	✓	
Δm_W (MeV)	~10	~10	~7	<0.5	Theo. limits
Δm_t (MeV)	800-1000	500-800	31	10	~100 from theo.
$\Delta g_{HVV}/g_{HVV}$	4-7%*	2%*	0.5-14.5%	0.15-1.5%	
$\Delta g_{Hff}/g_{Hff}$	6-13%*	2- 7%*	2-2.5%	0.2-0.7%	
$\Delta g_{Htt}/g_{Htt}$	14%*	7%*	~40%	~13%	
$\Delta g_{HHH}/g_{HHH}$	--	~30%	44%**	--	Insufficient ?

Could be significantly improved at VHE-LHC

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

**Sensibility with $2ab^{-1}$ at 500 GeV

Recommendations from European Strategy Group (cont'd)

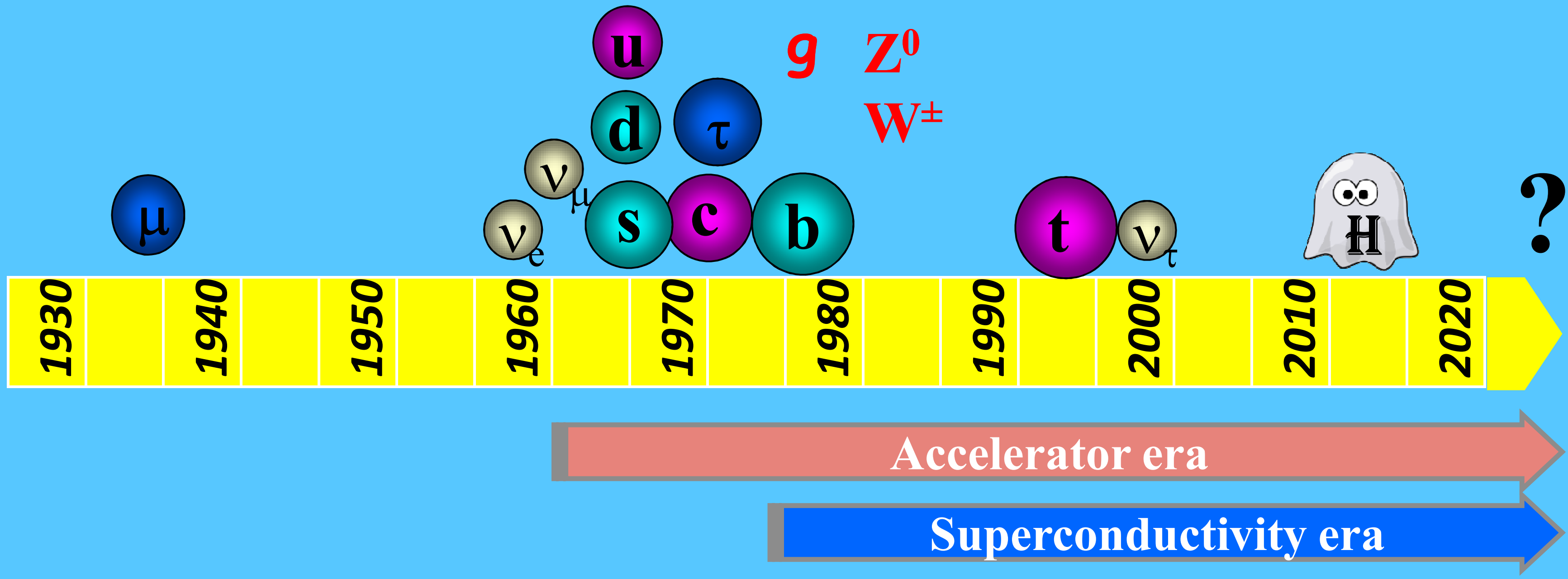
High-priority large-scale scientific activities (2)

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.

Indeed, most of the fundamental particles (13/17) have been *discovered thanks to accelerators*



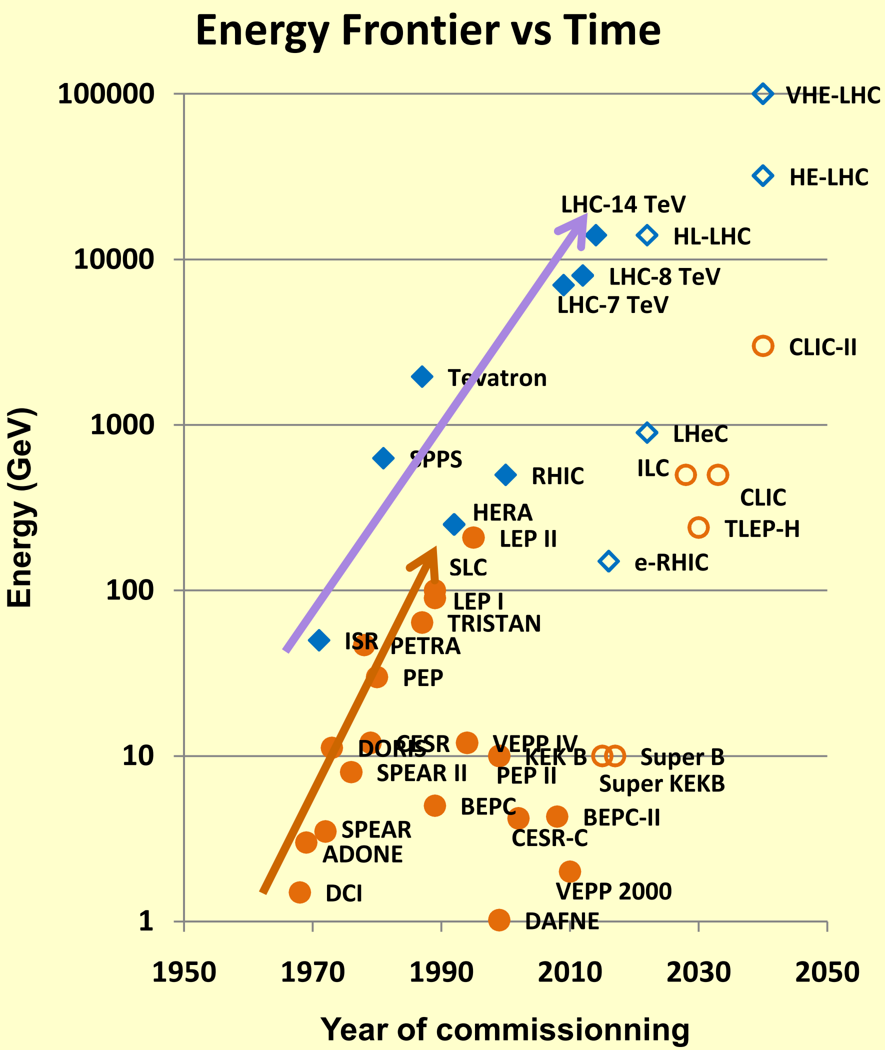
Both energy and intensity frontiers had to be challenged in past 50 Years

Today
E_{max}=8 TeV @ LHC(pp collider)
L_{max}=2x10^{34} cm^{-2}s^{-1} @ KEKB (ee collider)

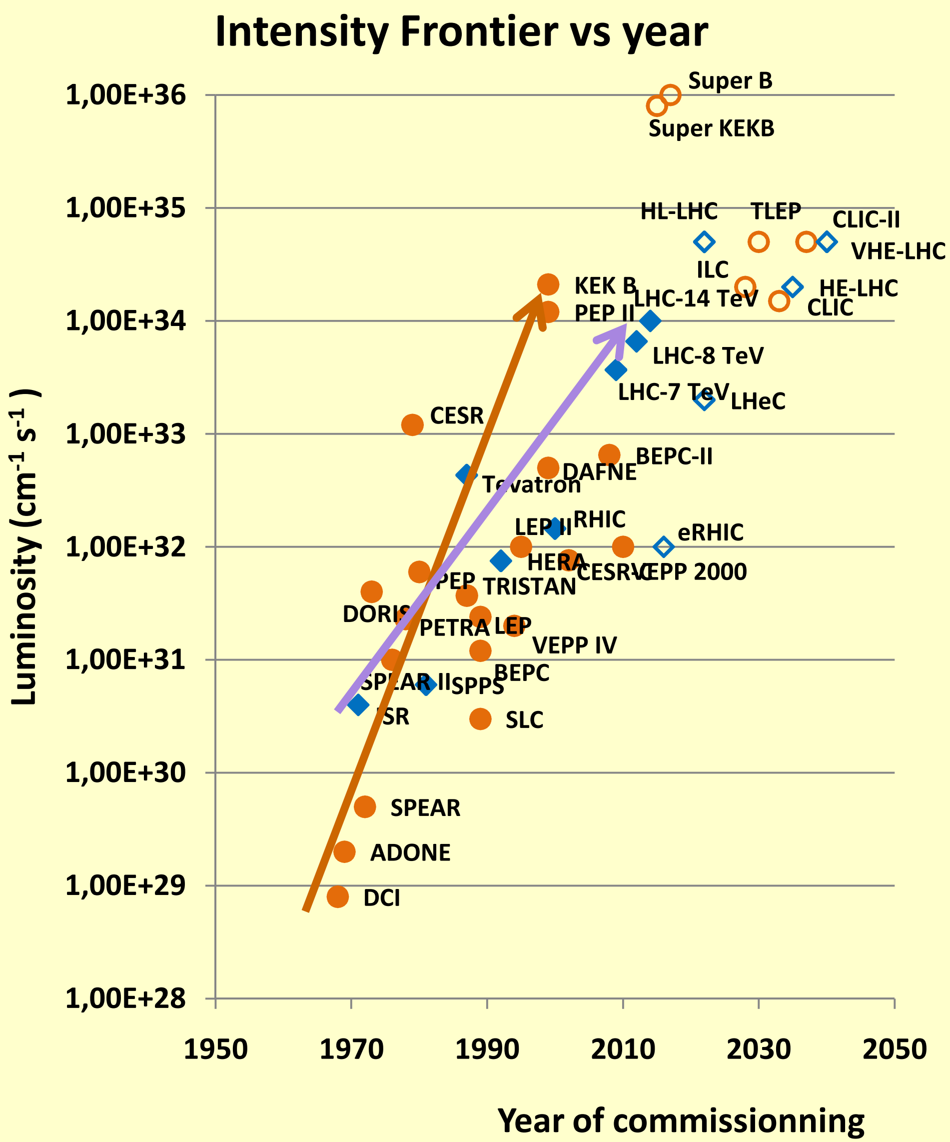
$$L = f_{rev} n_b \frac{N_1 N_2}{s(cm^2)}$$

$$S = 4\pi\sigma_x\sigma_y$$

From past … toward new frontiers



>2(3) orders of magnitude in Energy in e(p) colliders



>5 (3) orders of magnitude in Luminosity for e (p) colliders

Accelerator issues


PS 19MHz cavity

Get highest possible accelerating gradient

$$P_{sr} \propto I \left(\frac{E}{m}\right)^4 B$$

Make B small! Possibly 0 or use large m particles


First PS dipole


PS 19MHz cavity

$$\rho(\mathrm{m}) = \frac{P(GeV)}{0.3qB(T)}$$

Make B as large as possible

Beamstrahlung: $\propto \left(\frac{E}{m}\right) \frac{dQ}{dS}$

- **Get large momentum acceptance**
- **Make flat beams**
- **High top-up rate**

SC has enabled great progress

Two main areas: Magnets and RF cavities

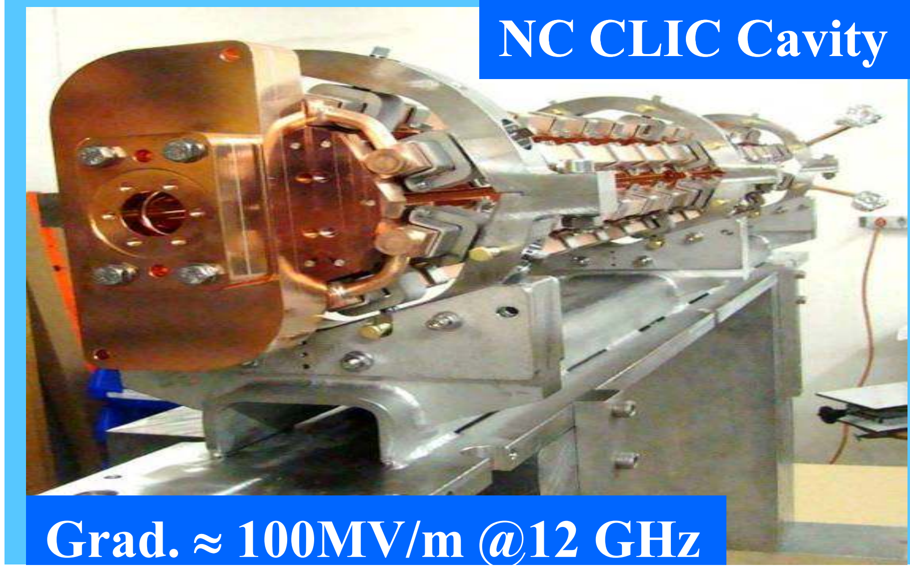
LHC dipole

B ≈ 8.3 T

LHC Cavity cryomodule

XFEL Cavity

G rad. ≈ 40MV/m @1.3 GHz



NC CLIC Cavity

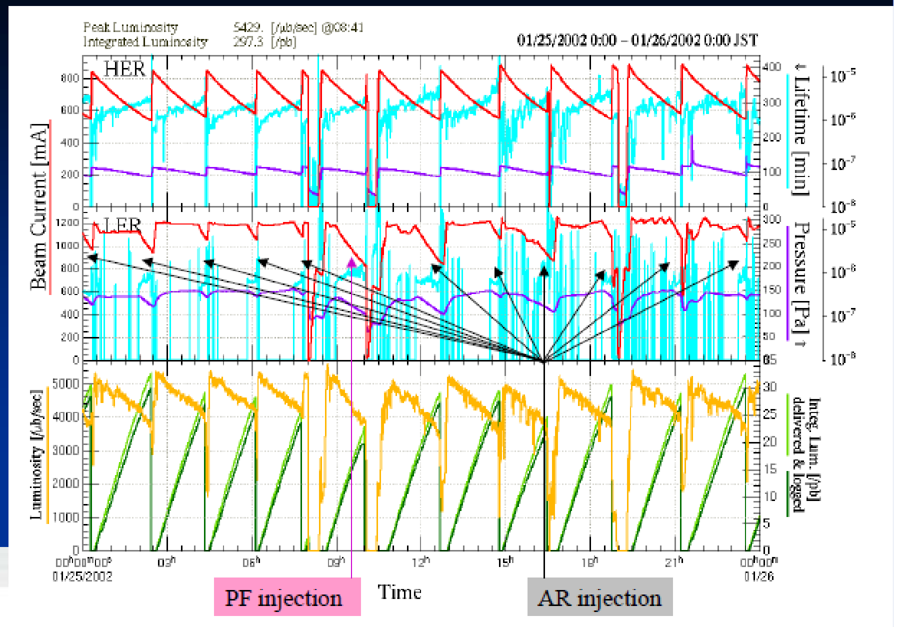
Grad. ≈ 100MV/m @12 GHz

ESS type elliptical & spoke Cavities

The « revolution » of circular e^+e^- colliders

The Top up scheme

Continuous High luminosity



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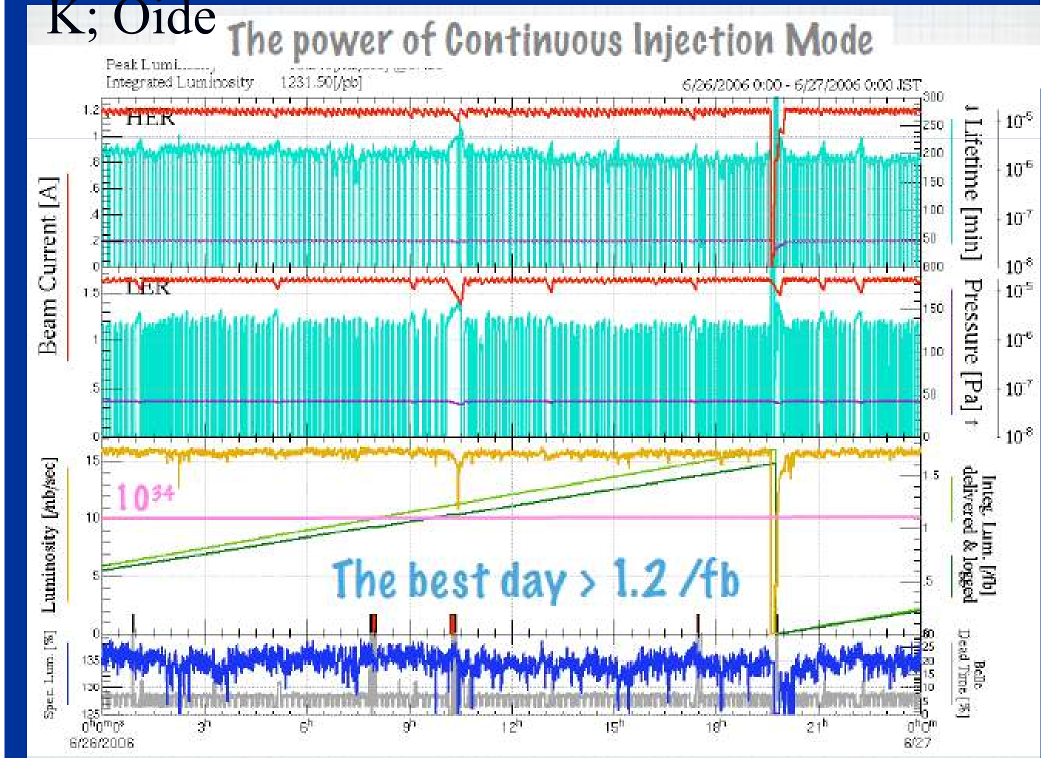
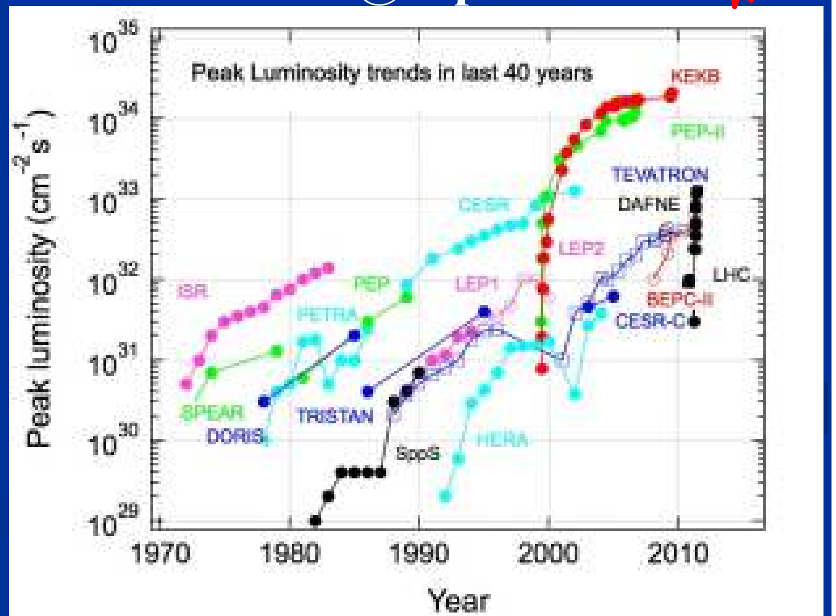
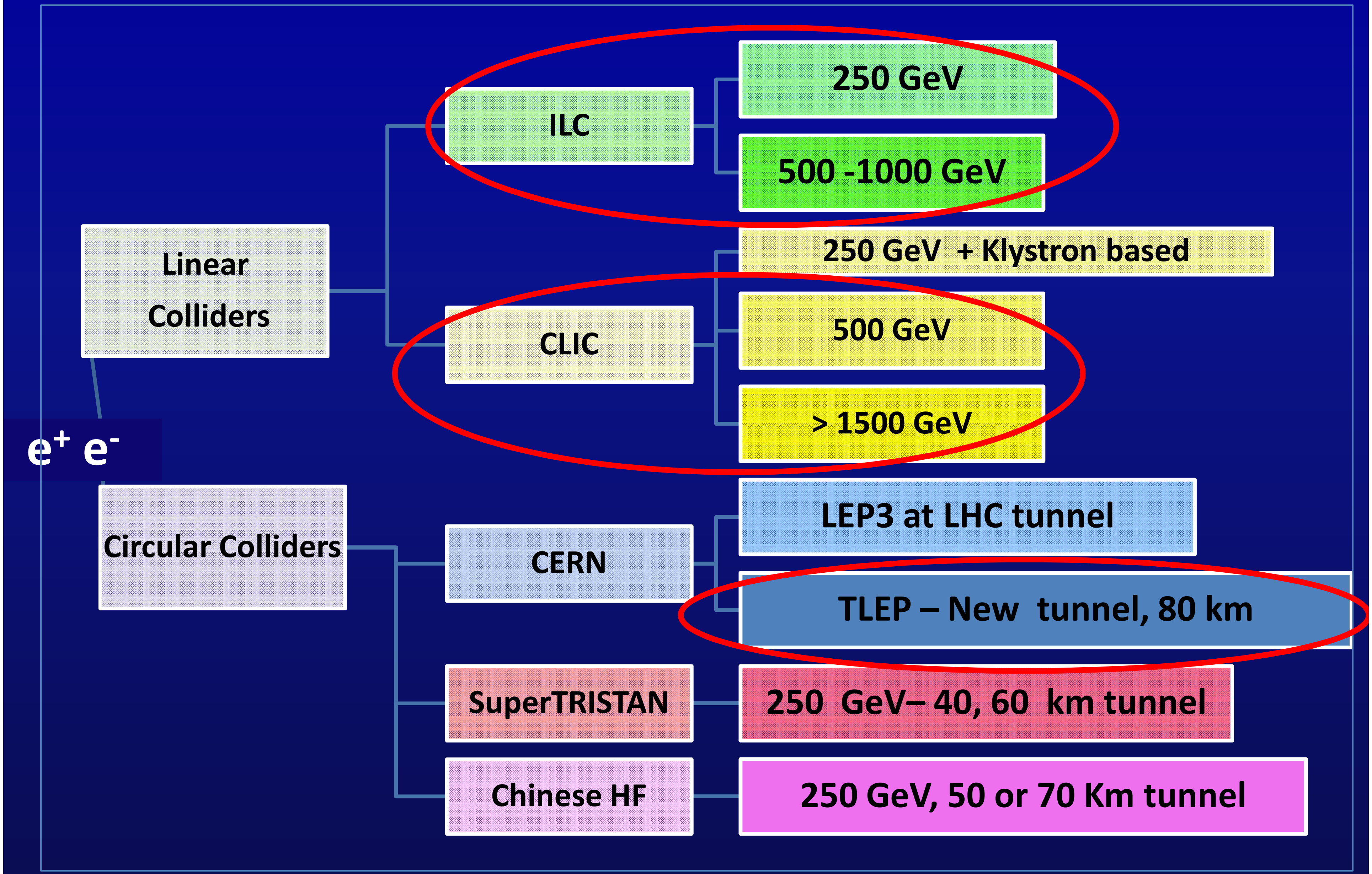


8x10^{35}@superKEKB

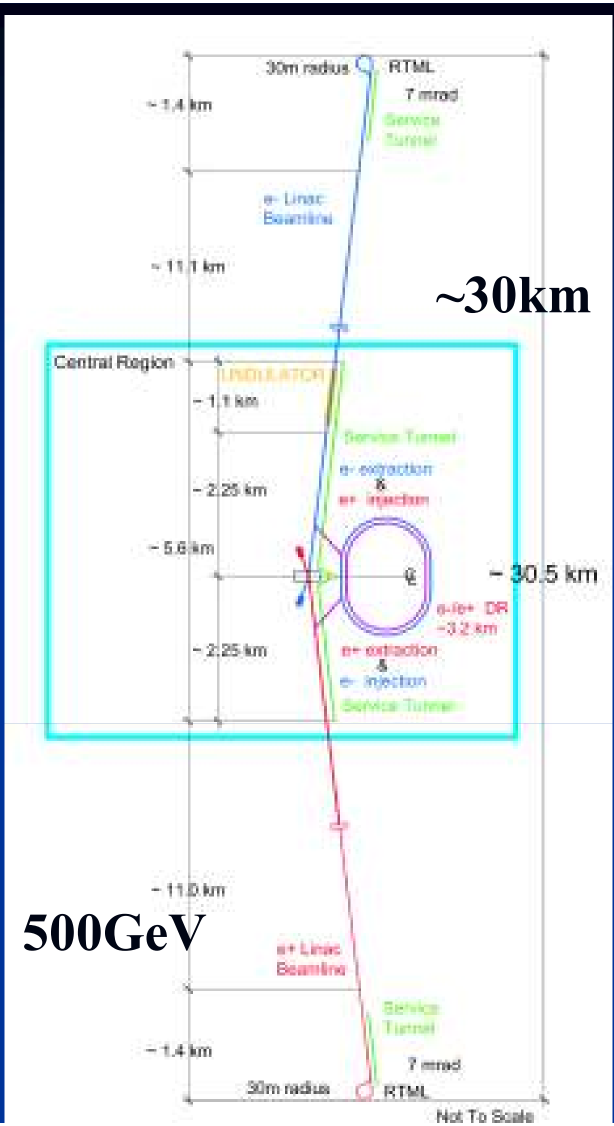


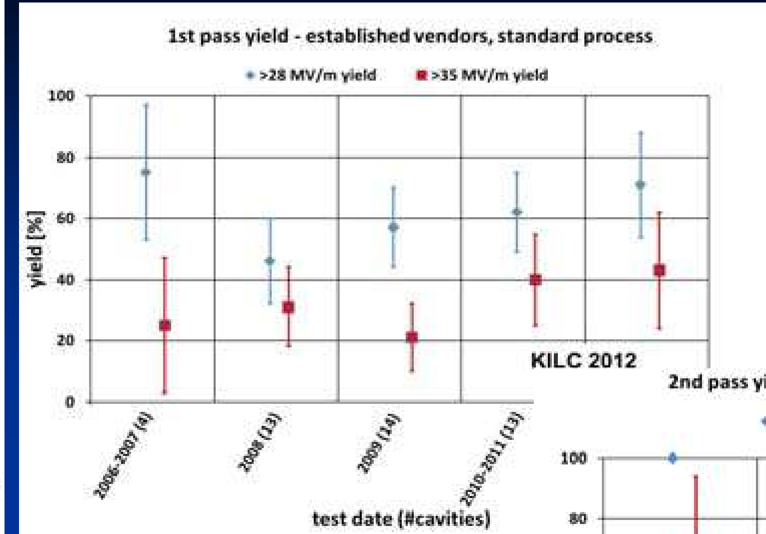
e^+e^- colliders «clean HIGGS FACTORIES»

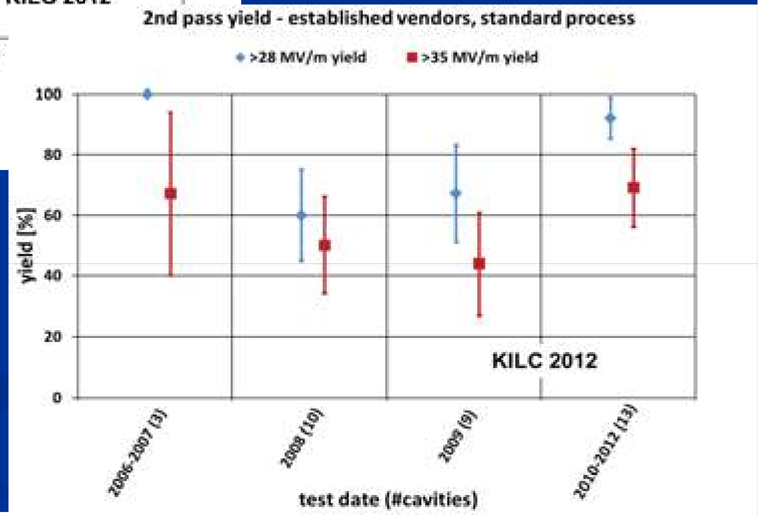


ILC

Gradient Range Yield Gain







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

Some further ILC challenges

- **Achieving and maintaining nano beam size (σ_y =6-8nm) with 2×10^{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 bunch intensity (2×10^9 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**

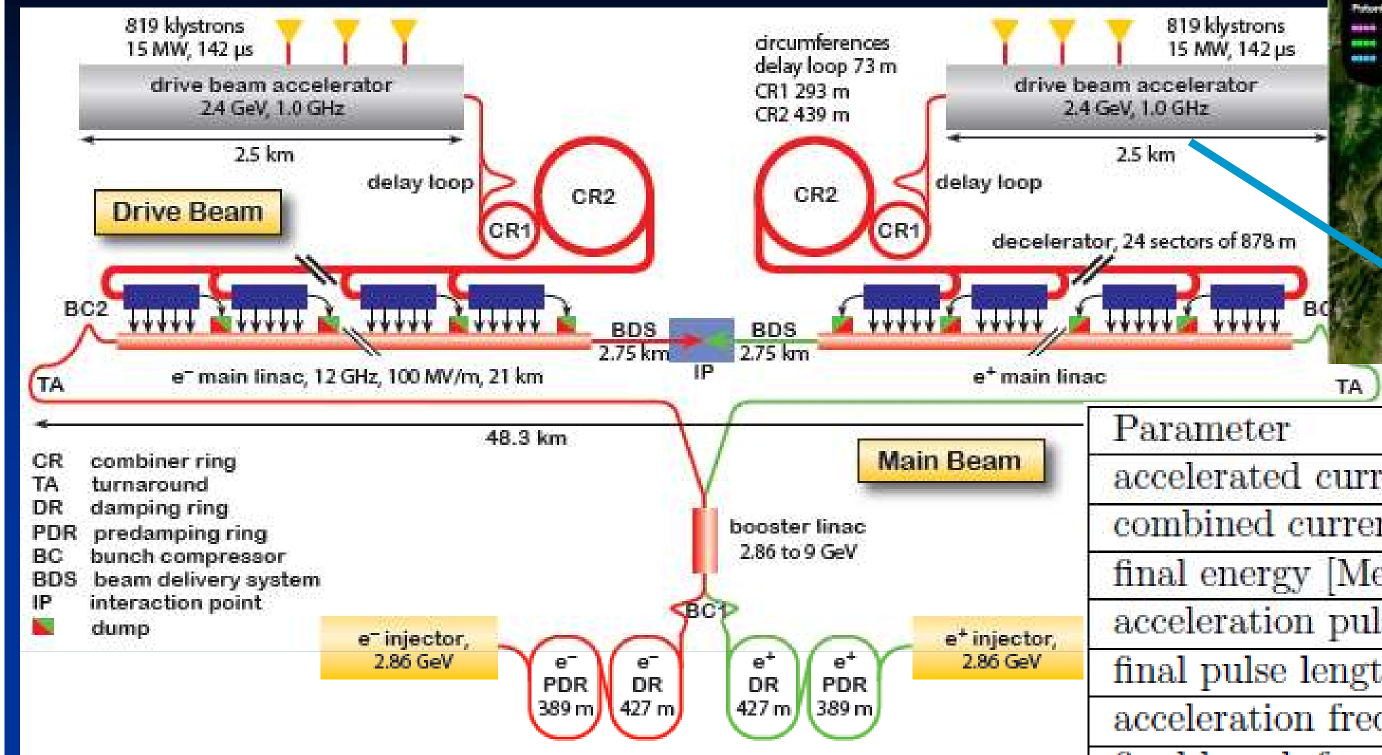
  ➡ **XFEL =5% of ILC**

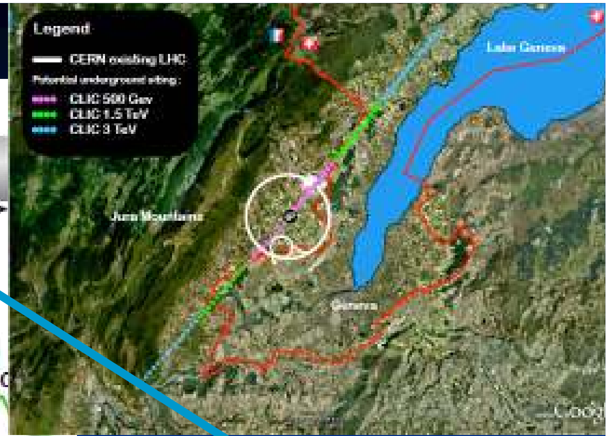
- ***Strong R&D on these issues is on-going***
- ***Carried out by international collaborative***
- ***Several issues still being addressed***
- ***Proposal from the Japanese physics community***

Two Candidate Sites in Japanese mountainous locations

Japanese HEP community proposes to host ILC based on the "staging scenario" to the Japanese Government.

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 ($<10^{-6}$)

International collaboration around CFT3 @CERN

➡ Demonstrated with a few cavities

Energy CM (GeV)	500	3000
Luminosity ($\times 10^{34} cm^{-2} s^{-1}$)	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: ~60% cost

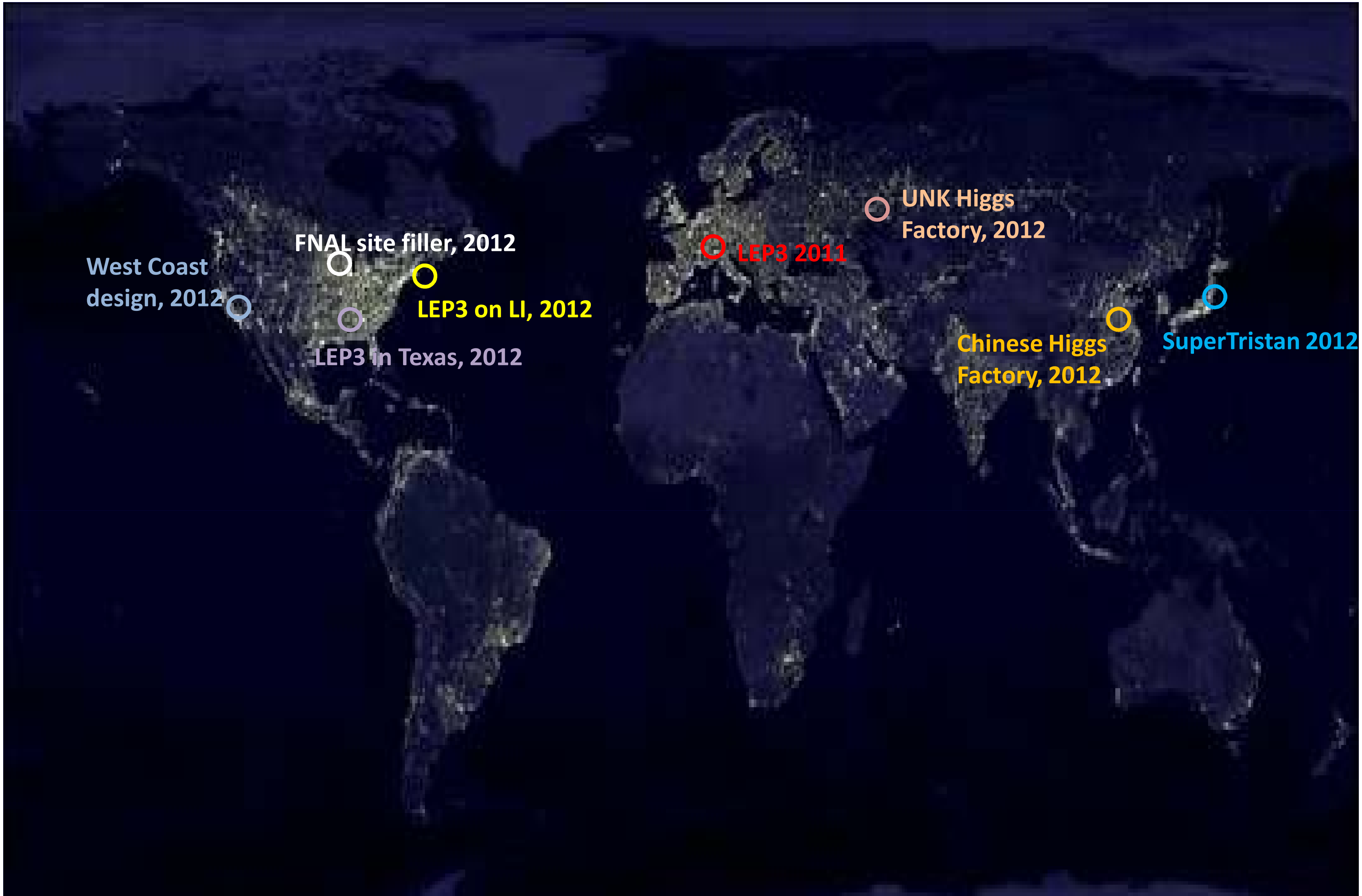
Building on existing technologies and experience (LEP, KEKB, PEPII…)

Using SC cavities

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

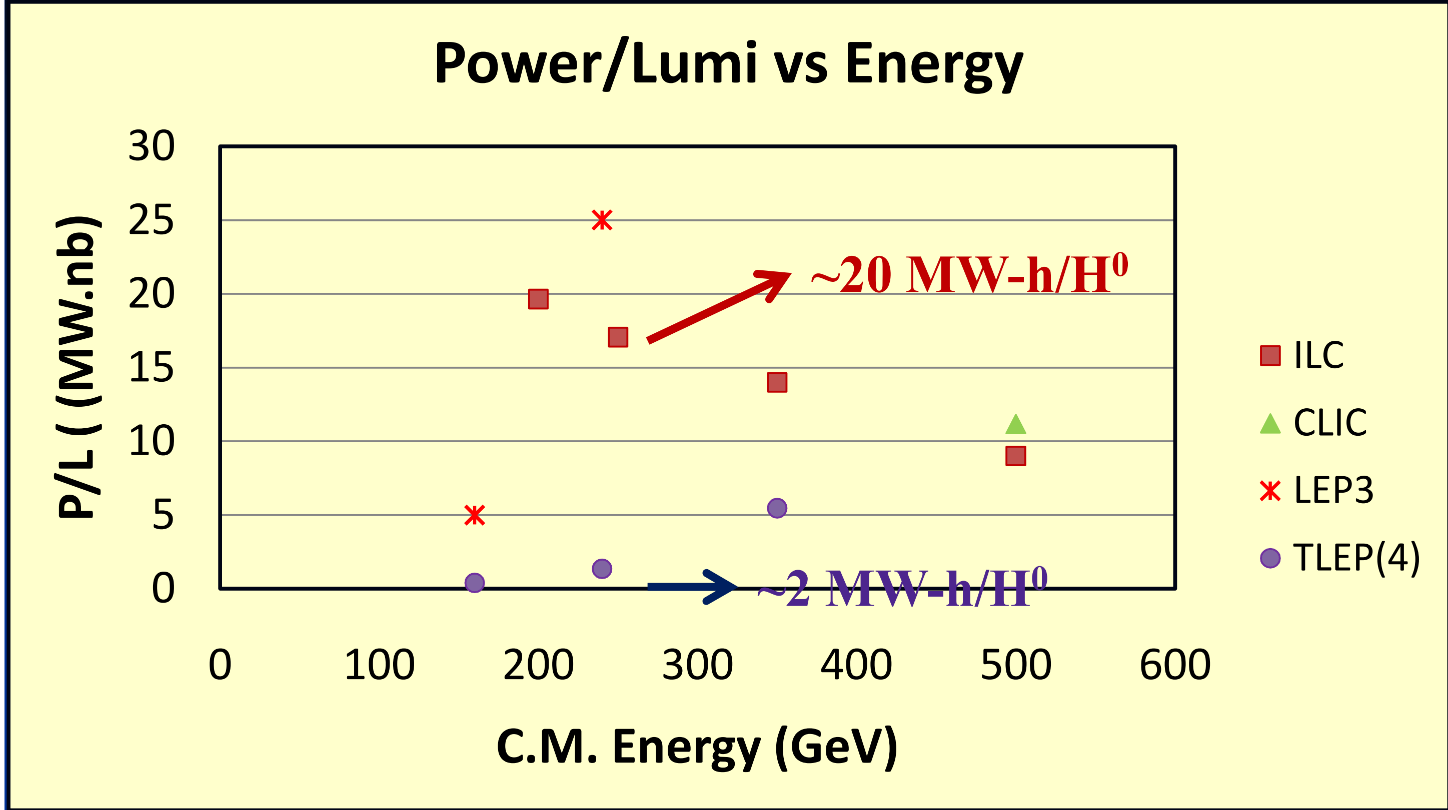
Energy CM (GeV)	90	160	240	350
Luminosity ($x10^{34}cm^{-2}s^{-1}$)/IP	56	16	~5	~1.3
Cavity Gradient (MV/m)	20	20	20	20
#5-cell SC cavities	600	600	600	600
Beam lifetime (mn)	67	25	16	20
Total AC power (MW)	250	250	260	284

Most parameters have been achieved or are planned at SuperKEKB

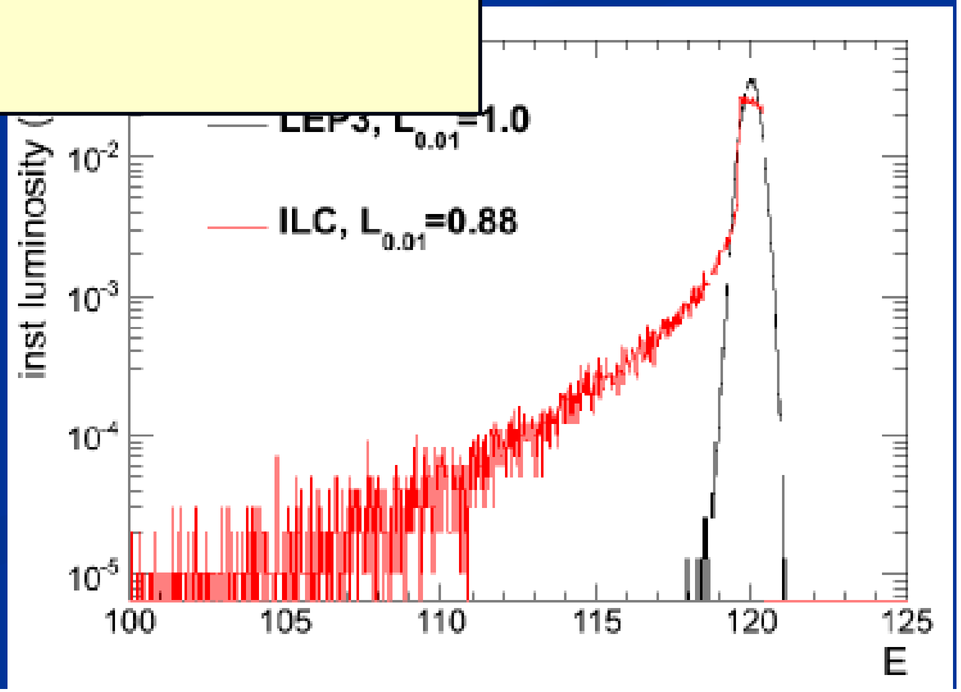


circular Higgs factories around the world

An important parameter is the power per unit of luminosity



*Luminosity not corrected for peak 1% factor



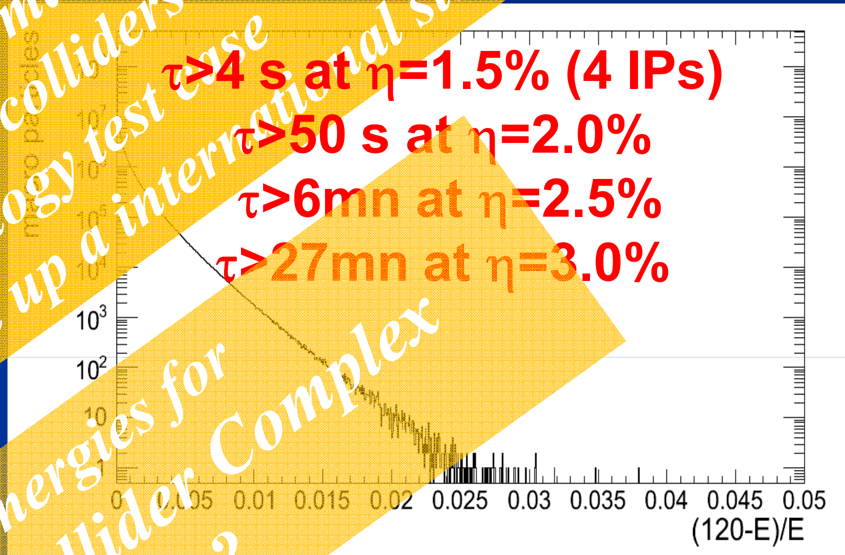
Although based on strong experience in building circular collider, several challenges have to be overcome:

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

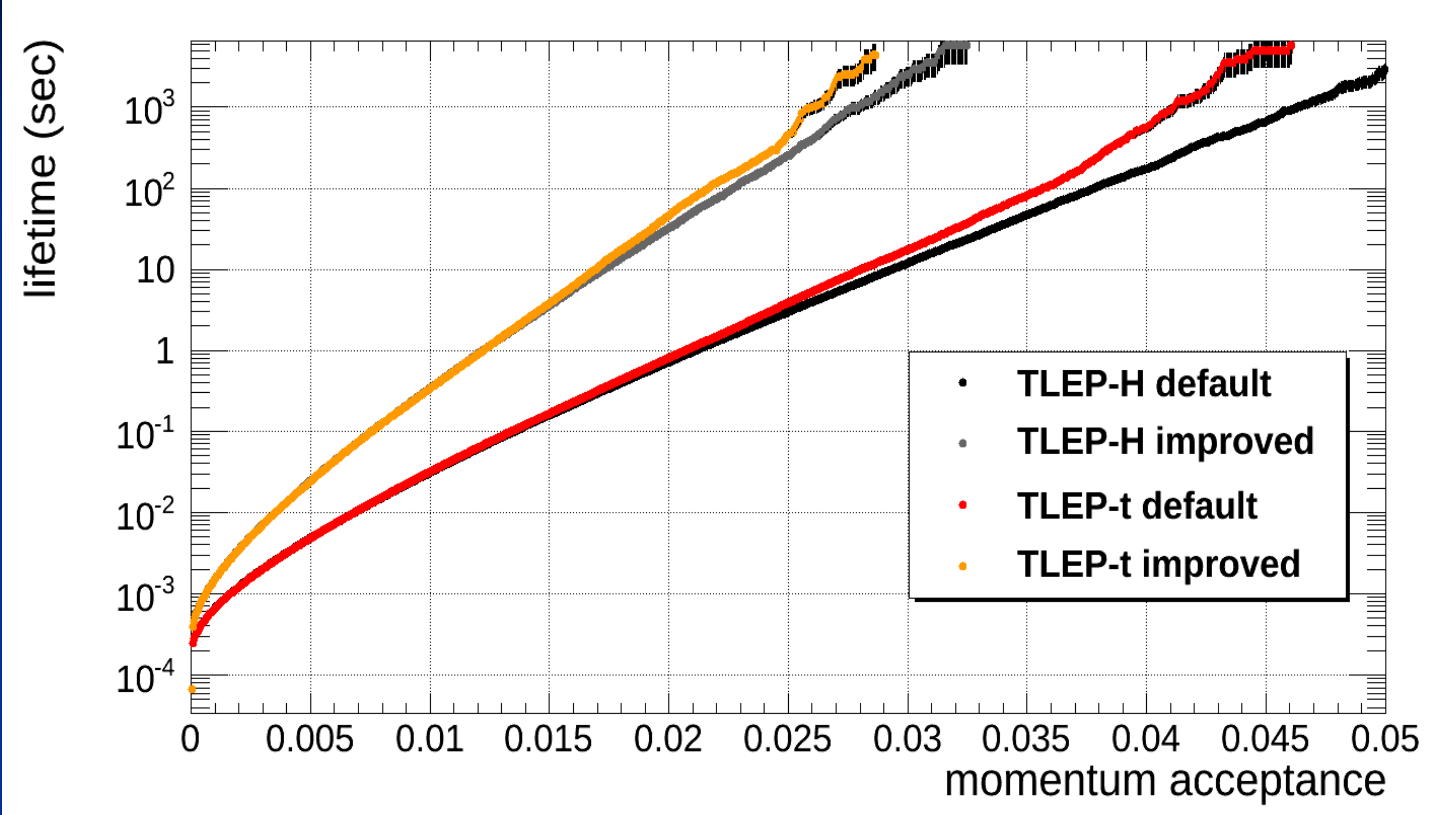
➢ *Idea is rather new triggered by low Higgs mass but based on long and mature experience in circular colliders*

➢ *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?

Example of beam lifetime simulation with Beamstrahlung



TLEP parameters -1

soon at SuperKEKB:
β_x^*=0.03 m, β_Y^*=0.03 cm

	LEP2	sKEKB LER/HER	LHeC	TLEP -Z	TLEP -W	TLEP -H	TLEP -t
beam energy E_b [GeV]	104.5	4/7	60	45.5	80	120	175
circumference [km]	26.7	3	26.7	80	80	80	80
beam current [A]	0.004	3.6/2.6	0.1	1.18	0.124	0.0243	0.0054
#bunches/beam	4	2500	2808	4400	600	80	12
#e−/beam [10^{12}]	2.3	226/163	56	1960	200	40.8	9.0
horizontal emittance [nm]	48	3.2	5	30.8	9.4	9.4	10
vertical emittance [nm]	0.25	0.0081	2.5	0.07	0.02	0.02	0.01
bending radius [km]	3.1	16/104	2.6	9.0	9.0	9.0	9.0
Momentum comp. α_c [10^{-5}]	18.5		8.1	9.0	2.0	1.0	1.0
SR power/beam [MW]	11		44	50	50	50	50
β^*_x [m]	1.5	0.032	0.18	0.5	0.5	0.5	1
β^*_y [cm]	5	0.027	10	0.1	0.1	0.1	0.1
σ^*_x [µm]	270	10	30	124	78	68	100
σ^*_y [µm]	3.5	0.047	16	0.27	0.14	0.14	0.1
hourglass F_{hg}	0.98		0.99	0.71	0.75	0.75	0.65
ΔE^{SR}_{loss}/turn [GeV]	3.41	$1/3\times10^{-3}$	0.44	0.04	0.4	2.0	9.2

SuperKEKB: $\varepsilon_y/\varepsilon_x$=0.25%

TLEP parameters -2

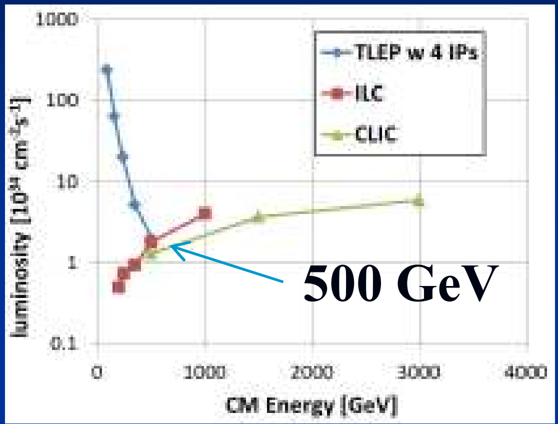
LEP2 was not beam-beam limited

	LEP2	sKEKB LER/HER	LHeC	TLEP -Z	TLEP -W	TLEP -H	TLEP -t
$V_{RF,tot}$ [GV]	3.64	0.0094/0.015	0.5	2.0	2.0	6.0	12.0
$\delta_{max,RF}$ [%]	0.77		0.66	4.0	5.5	9.4	4.9
ξ_x/IP	0.025	0.0028/0.0012	N/A	0.07	0.10	0.10	0.10
ξ_y/IP	0.065	0.0881/0.0807	N/A	0.07	0.10	0.10	0.10
f_s [kHz]	1.6		0.65	1.29	0.45	0.44	0.43
E_{acc} [MV/m]	7.5		11.9	3	3	10	20
eff. RF length [m]	485		42	600	600	600	600
f_{RF} [MHz]	352		721	700	700	700	700
δ^{SR}_{rms} [%]	0.22		0.12	0.06	0.10	0.15	0.22
$\sigma^{SR}_{z,rms}$ [cm]	1.61	0.6/0.5	0.69	0.19	0.22	0.17	0.25
L/IP[10^{32}cm^{-2}s^{-1}]	1.25	8000	N/A	5600	1600	480	130
number of IPs	4	1	1	4	4	4	4
b.lifetime [min]	360	10	N/A	67	25	16	20

Lifetime at superKEKB = 10 min

LEP data for 94.5 - 101 GeV consistently suggest a beam-beam limit of ~0.115

TLEP will enable to probe further the SM with very high precision, search for rare processes and new light particles (<~200 GeV)



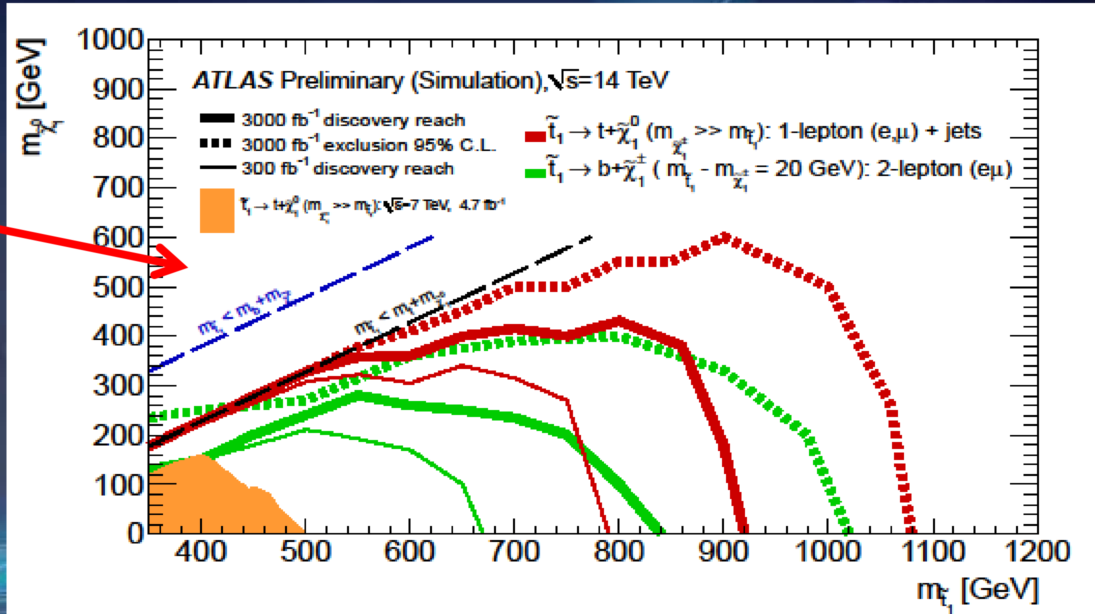
If deemed necessary, the c.m. energy could be pushed to 400-500 GeV, but to reach much higher scales hadron colliders is necessary (on-going study to determine E_{max} with $L=10^{34}$ with 4 detectors)

We need a tool to search for direct production of new particles up to energy scale in the 10 TeV range

Why not repeating the success story of LEP/LHC with TLEP/VHE-LHC!

LHC + HL-LHC: Great tool to Search for new particles/phenomena

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

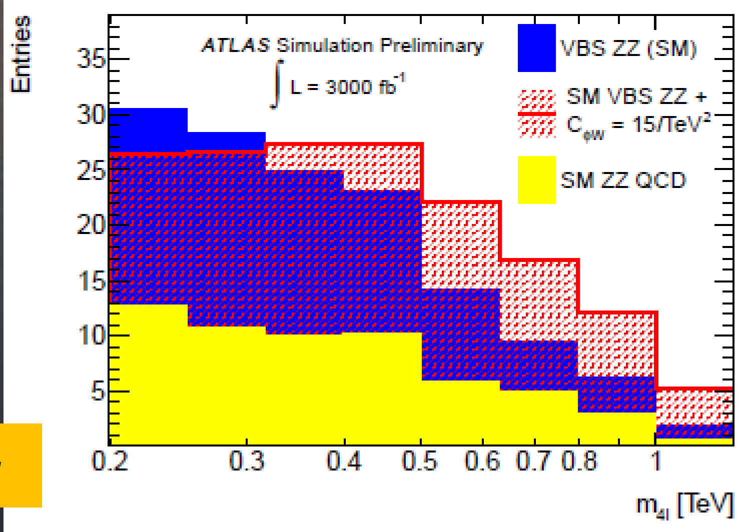


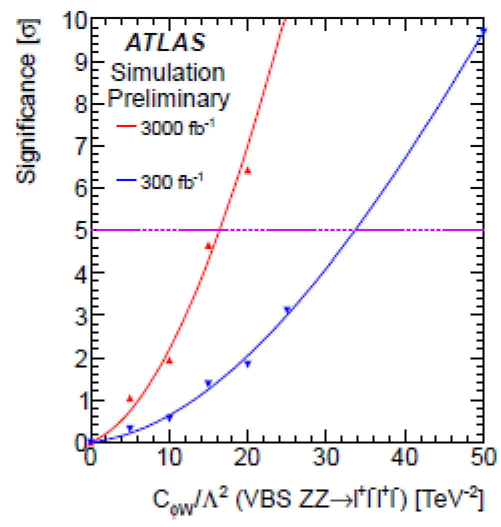
- High energy and luminosity are necessary to probe the $V_L V_L$ scattering and verify that unitarity is preserved, thanks to the « Higgs » discovered

Example: ZZ VBS on top of the SM VBS contribution (i.e. VV+ 2 forward jets):

$$\mathcal{L}_{\phi W} = \frac{c_{\phi W}}{\Lambda^2} \mathrm{Tr}(W^{\mu\nu} W_{\mu\nu}) \phi^\dagger \phi.$$

>5σ for $C_{\phi W}/\Lambda^2$ >15 TeV^{-2}





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*

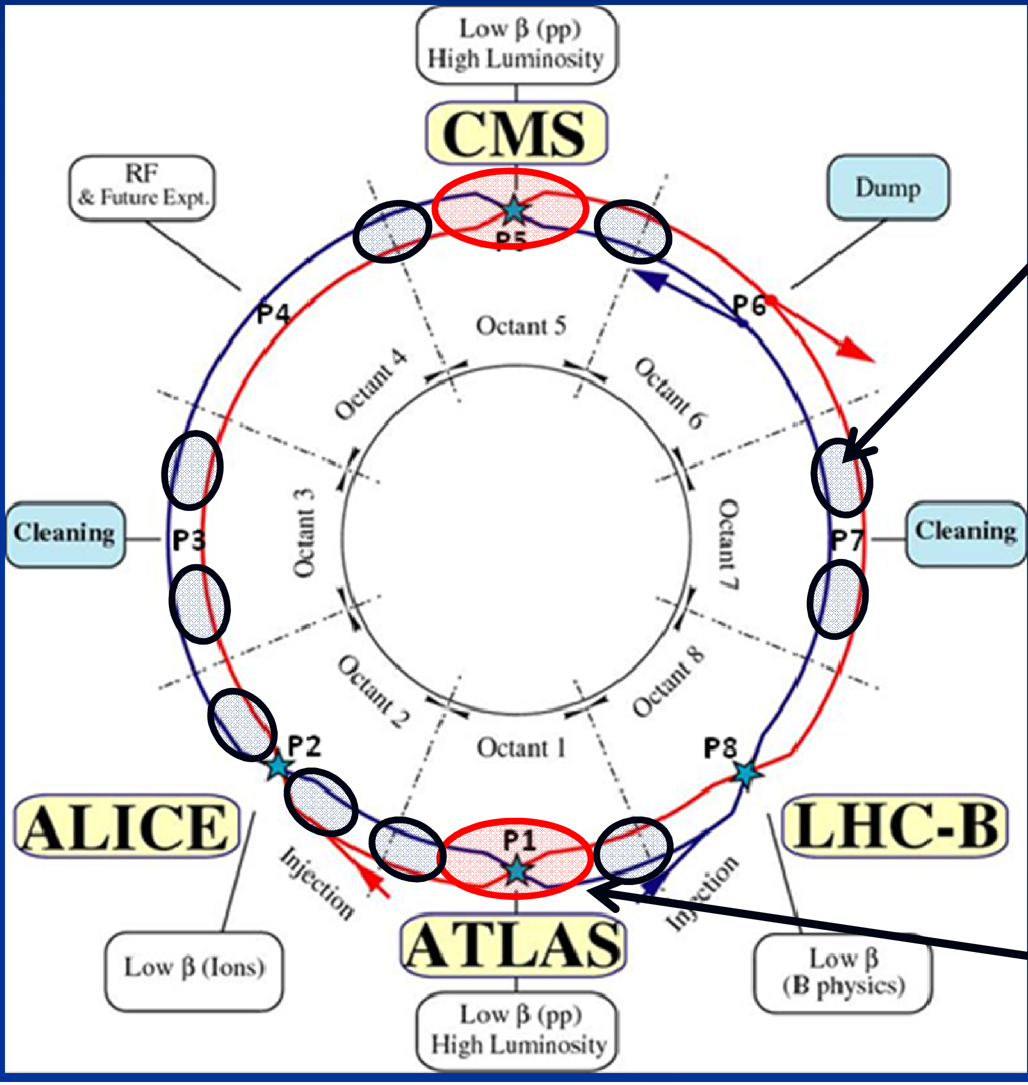
- **Improve and adjust the luminosity with beam overlap control**

  ⇨ 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***

Upgrading LHC luminosity early 2020's

- Increase beam current ⇨ protect SC dipole (diffracted protons)
- Reduce beam size at IP ⇨ Stronger focussing quads near IP



8T-15m ⇨ 11T-11m dipoles

5.5 m Nb_3Sn	3.5 m Collim	5.5 m Nb_3Sn

Fermilab/CERN Collaboration
Demo single bore 11T , 2m
Test: very good to 10.4 T
Next model twin-bore by beginning of 2013

Change Quadrupole Triplets
200T/m, 70mm (~8T, <6m>)
⇨ 140T/m, 150mm (13T, 8m)

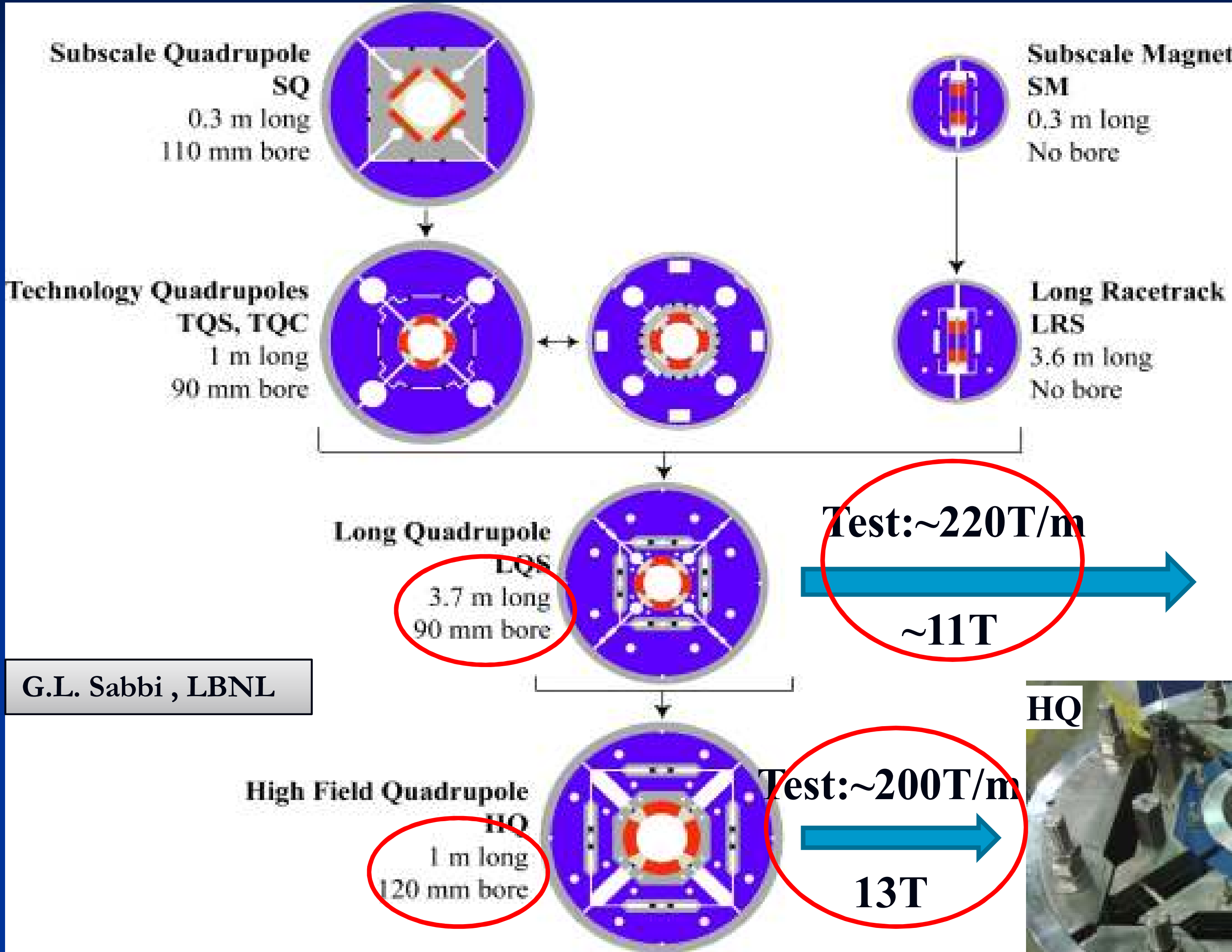
Target parameters for HL-LHC run

Efficiency is defined as the ratio between the annual luminosity target of 250 fb^{-1} over the potential luminosity that can be reached with an ideal cycle run time with no stop for 150 days: $t_{run}=t_{lev}+t_{dec}+t_{turn}$. The turnaround time after a beam dump is taken as 5 hours, t_{decay} is 3 h while t_{lev} depends on the total beam current

Parameter	Nom. 25 ns	Target 25 ns	Target 50 ns	LIU 25 ns	LIU 50 ns
N_b [10^{11}]	1.15	2.0	**3.3**	1.7	2.5
n_b	2808	2808	1404	2808	1404
I [A]	0.56	**1.02**	0.84	0.86	0.64
θc [μrad]	300	475	445	480	430
β* [m]	0.55	**0.15**	**0.15**	**0.15**	**0.15**
ε_n [μm]	3.75	**2.5**	**2.0**	**2.5**	**2.0**
ε_s [eV s]	2.5	2.5	2.5	2.5	2.5
IBS h [h]	111	25	**17**	25	**10**
IBS l[h]	65	21	**16**	21	**13**
Piwinski	0.68	2.5	2.5	2.56	2.56
F red.fact.	0.81	0.37	0.37	0.37	0.36
b-b/IP[10^{-3}]	3.1	3.9	**5**	3	**5.6**
L_{peak}	1	7.4	8.4	5.3	**7.2**
Crabbing	no	**yes**	**yes**	**yes**	**yes**
$L_{peak\ virtual}$	1	20	22.7	14.3	19.5
Pileup $L_{lev}=5L_0$	19	95	190	95	190
Eff.† 150 days	=	0.62	0.61	0.66	0.67

baseline

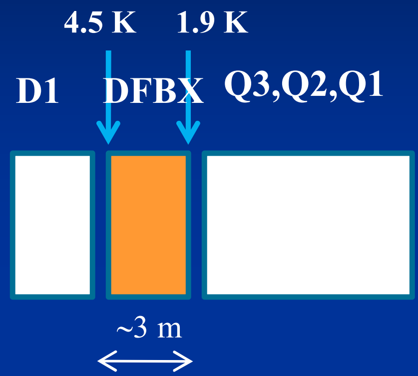
LARP (US LHC program) Magnets



G.L. Sabbi , LBNL

HTS links
Protection of Electrical Distribution Feedbox's (DFBX)

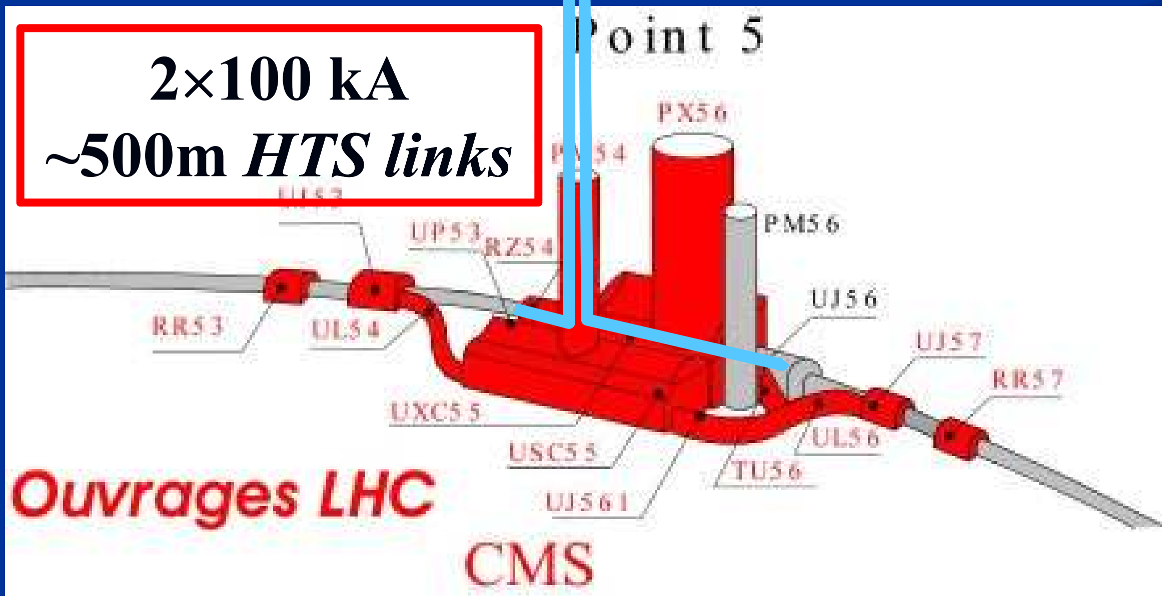
In the tunnel, feed power from room temperature power converters to the « cold world » of LHC. Actual LHC use short Nb-Ti links.



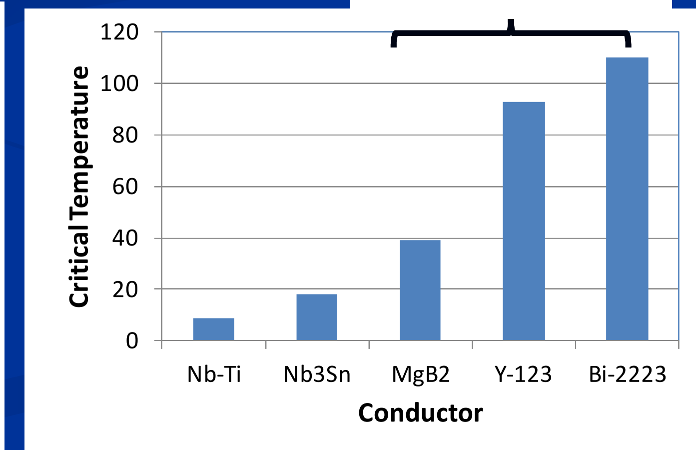
IP5

Need to be protected against radiation and provide easier access

➡ **Move DFBX on surface**



To be decided

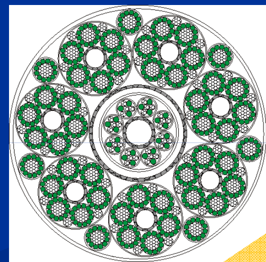


Note: LHC uses 1400 Bi-2223 current leads

On going HTS link test at CERN

2m long MgB_2 cables tested at 2x4500A

Possible cable configuration for high current :
7 × 14 kA, 7 × 3 kA and 8 × 0.6 kA cables
Itot~**120 kA @ 30 K**



Φ = 62 mm

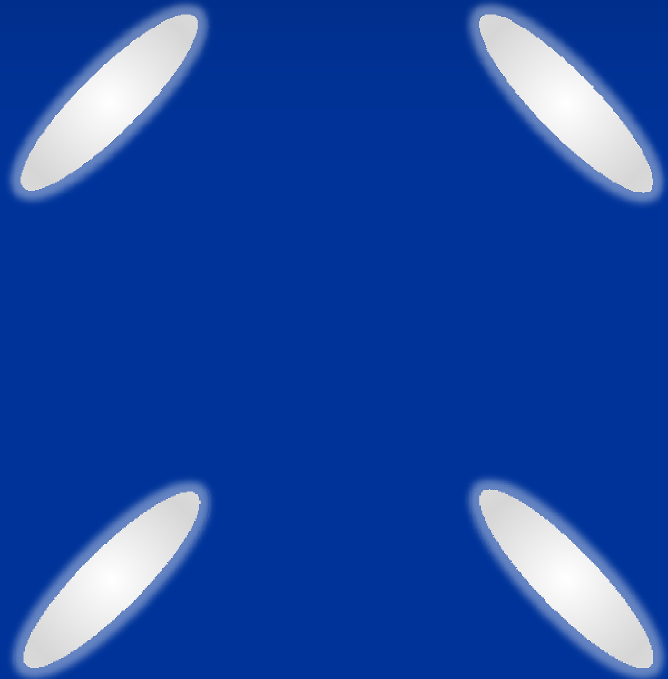
Nexan Cryoflex® line (20 m long semi-flexible cryostat of link) procured and installed in the CERN SM-18 laboratory
20 kA – 4 to 80 K test

MgB_2, YBCO… tests started end 2012

- ***Very encouraging results:***
- ***16kA reached with MgB_2 in 20m cryostat***

« Crab » Crossing

Improving further the luminosity by better overlap of the 2 beams

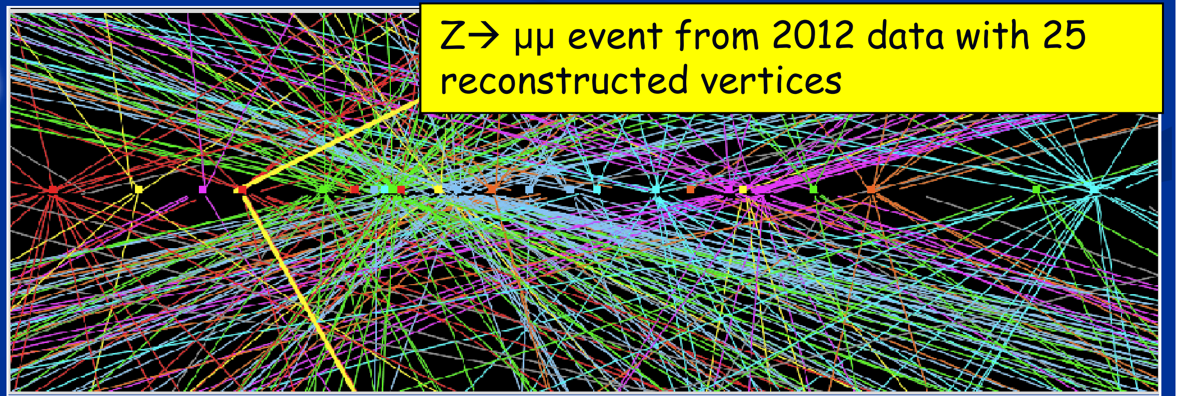


SC RF «Crab» Cavity, for p-beam rotation at fs level!

Technology pioneered successfully on KEKB, Japan

- **Effort at SLAC-ODO and in BNL, USA**
- **Effort in Daresbury (Cockcroft Institute and STCF) with CERN.**

Also help to adjust the luminosity to ease experiments' life (Luminosity levelling)



Z→ μμ event from 2012 data with 25 reconstructed vertices

Progress in SC « Crab » Cavities

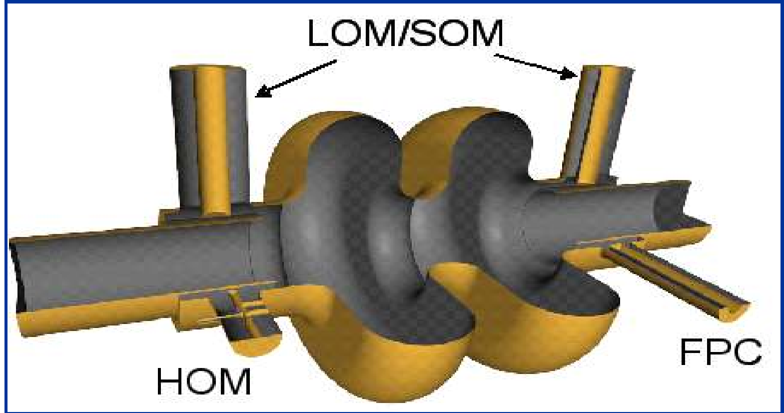
UK - Cockcroft

Several types of prototypes being designed and made…

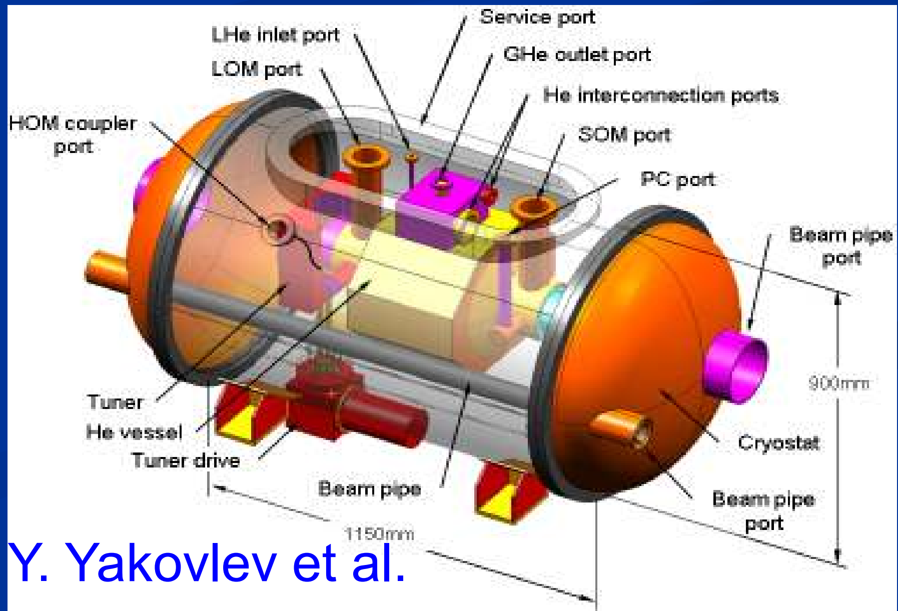
USA (ODU)

… as well as cryomodule

L. Xiao et al.



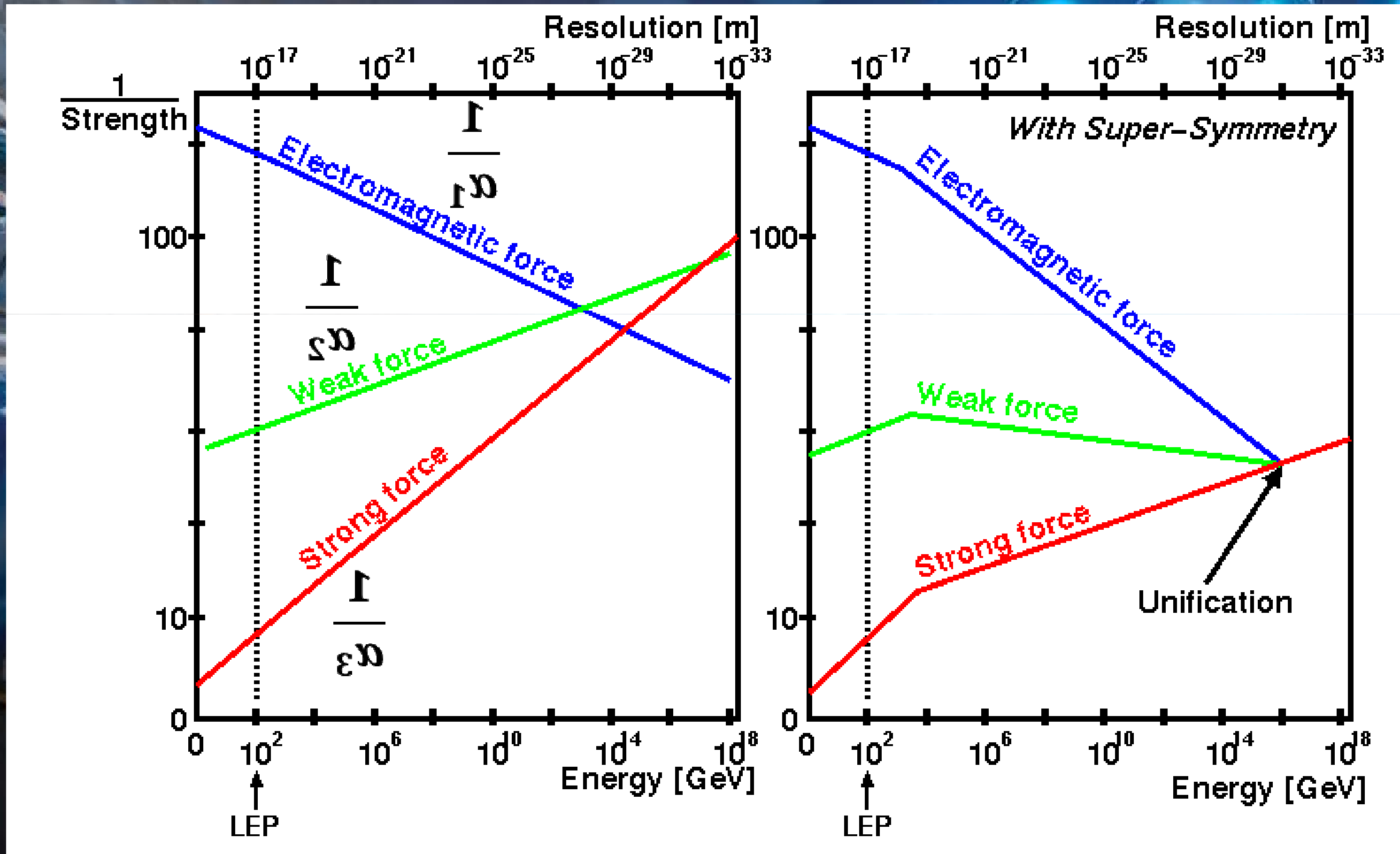
~250 mm outer radius



Y. Yakovlev et al.

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

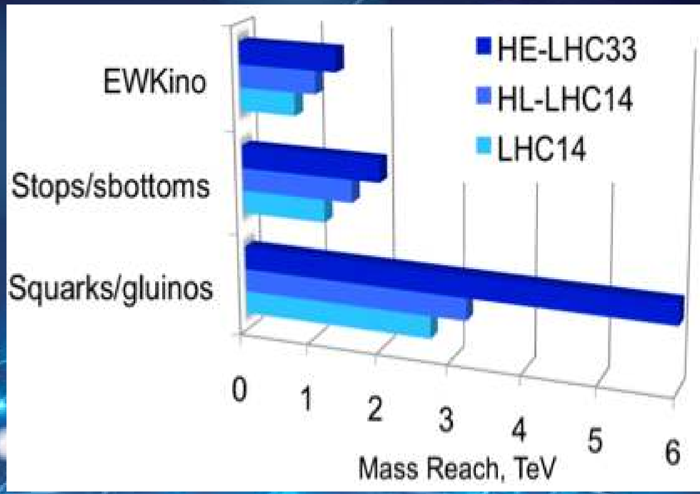


Need to explore higher energy regions (up to ~10 TeV)

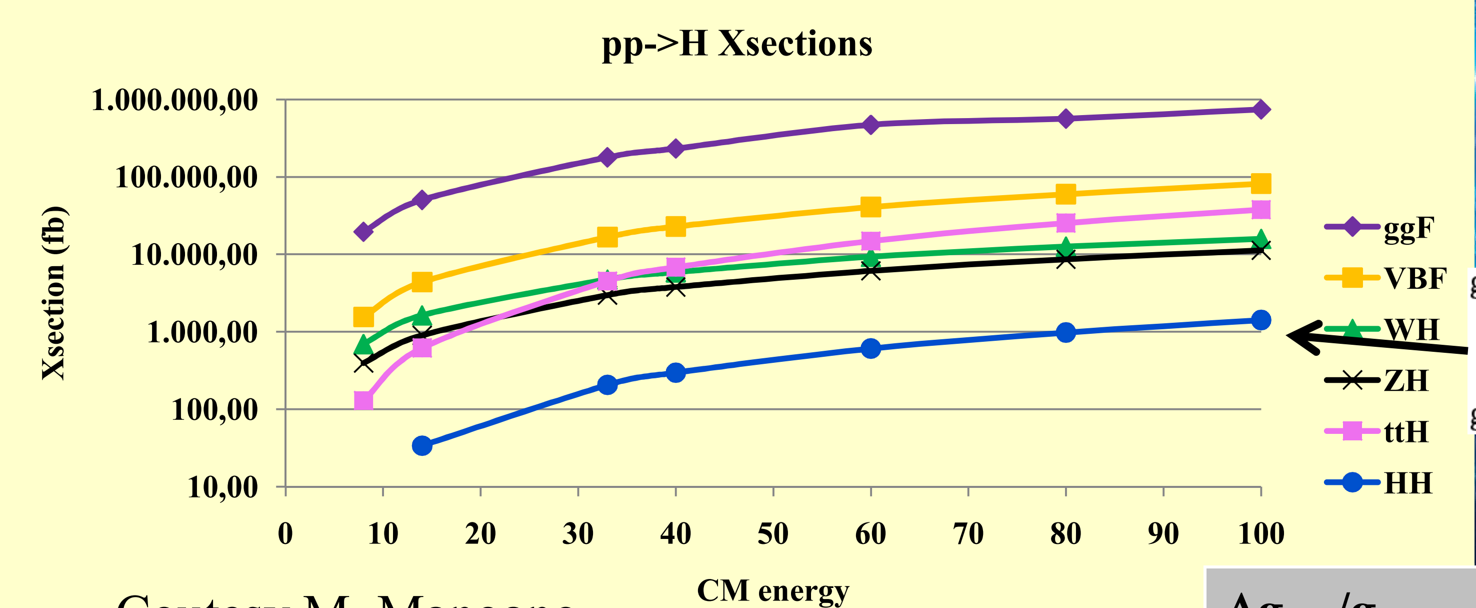
Whatever is found or not, reaching higher energies is unavoidable

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

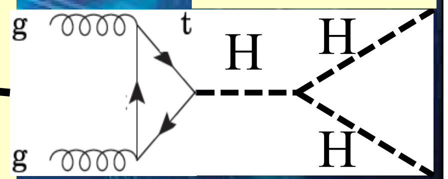
To probe $V_L V_L$ scattering up to 10 TeV region, very high energy is necessary



It will also allow more precise SM measurements



$\propto \lambda^{1/2} M_H$



Coutesy M. Mangano

VHE-LHC is THE tool for Htt and HHH couplings

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

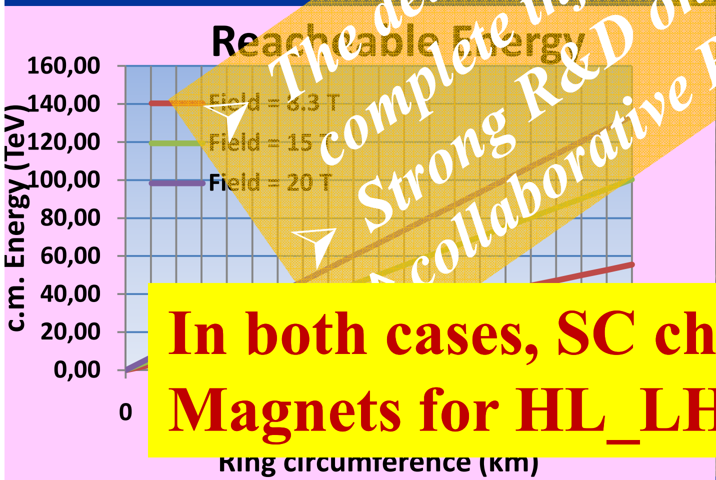
LEP: Construct. | Physics | Upgr

LHC: Design, R&D | Proto | Construct. | Physics

HL-LHC: Design, R&D | Construct. | Physics

HE-LHC: Design, R&D | Proto | Construct. | Physics | VHE

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



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*

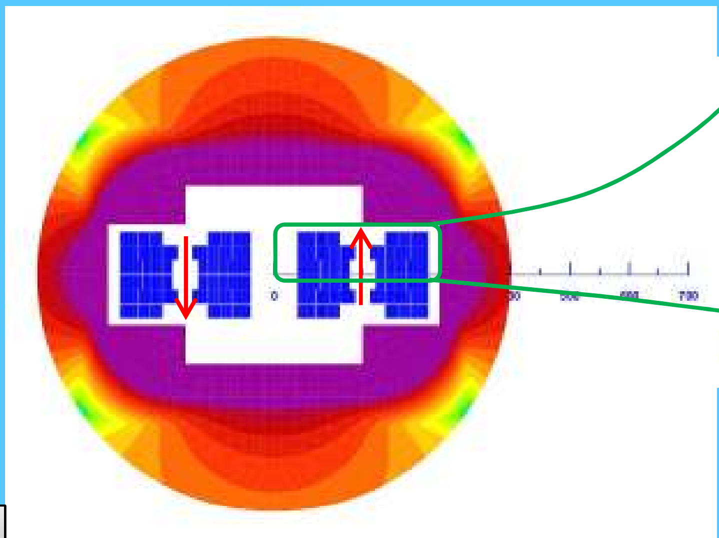
Or build (or reuse) a 80-100 km tunnel to reach 80-130 TeV collisions VHE-LHC

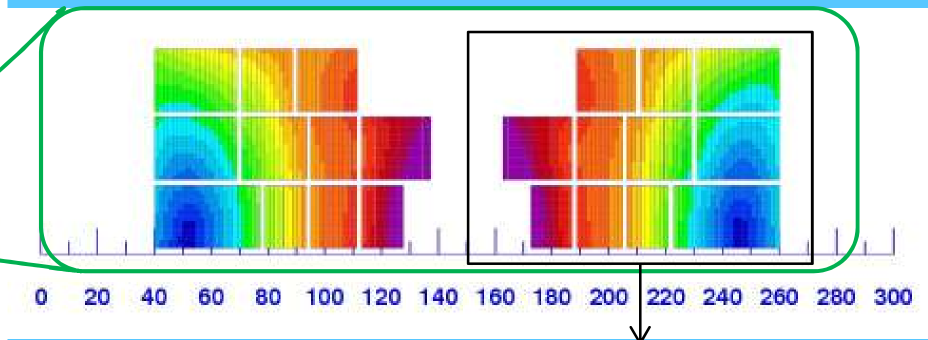
⇨ **more detailed study of such a tunnel starting**

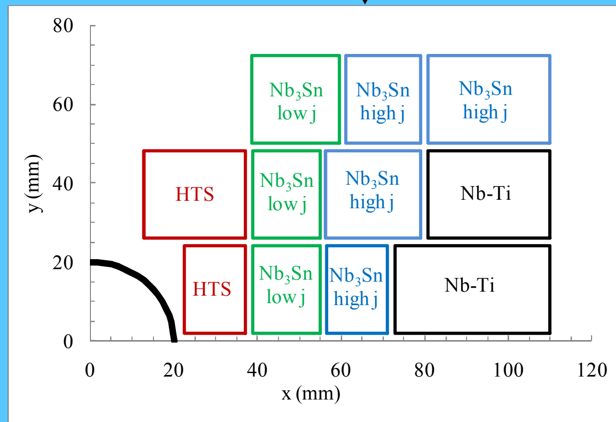
In both cases, SC challenge to develop 16-20 Tesla magnets!
Magnets for HL_LHC is an indispensible first step

First consistent conceptual design

Using multiple SC material







L. Rossi

Material	N. turns	Coil fraction	Peak field	$J_{overall}$ (A/mm^2)
Nb-Ti	41	27%	8	380
Nb3Sn (high Jc)	55	37%	13	380
Nb3Sn (Low Jc)	30	20%	15	190
HTS	24	16%	20.5	380

15 T

20 T field!

Magnet design: 40 mm bore (depends on injection energy: > 1 Tev)
Approximately 2.5 times more SC than LHC: 3000 tonnes! (~4000 long magnets)
Multiple powering in the same magnet for FQ (and more sectioning for energy)
Only a first attempt: cosϑ and other shapes needs to be also investigated

Parameter	LHC	HL-LHC	HE-LHC	VHE-LHC
c.m. energy [TeV]	14		33	100
circumference C [km]	26.7			80
dipole field [T]	8.33		20	20
dipole coil aperture [mm]	56		40	≤ 40
beam half aperture [cm]	2.2 (x), 1.8 (y)		1.3	≤ 1.3
injection energy [TeV]	0.45		>1.0	>3.0
no. of bunches	2808			8420
bunch population [10^{11}]	1.15	2.2	0.94	0.97
init. transv. norm. emit. [μm]	3.75	2.5	1.38	2.15
initial longitudinal emit. [eVs]	2.5		3.8	13.5
no. IPs contributing to tune shift	3	2		
max. total beam-beam tune shift	0.01	0.021	0.01	0.01
beam circulating current [A]	0.584	1.12	0.478	0.492
RF voltage [MV]	16		16	22
rms bunch length [cm]	7.55			
IP beta function [m]	0.55	0.15 (min.)	0.35	1.1
rms IP spot size [μm]	16.7	7.1 (min.)	5.2	6.7
full crossing angle [μrad]	285	590	171	71
Piwinski angle	0.65	3.13 (0)	1.5	0.5
geometric luminosity loss	0.84	> 0.9	0.55	0.89
stored beam energy [MJ]	362	694	701	6610
SR power per ring [kW]	3.6	7.3	96.2	2900
arc SR heat load [W/m/aperture]	0.17	0.33	4.35	43.4
energy loss per turn [keV]	6.7		201.3	5857
critical photon energy [eV]	44		575	5474
photon flux [10^{17}/m/s]	1.0	2.0	1.9	2.0
longit. SR emit. damping time [h]	12.9		1.0	0.32
horiz. SR emit. damping time [h]	25.8		2.0	0.64
init. longit. IBS emit. rise time [h]	57	23.3	40	396
init. transv. IBS emit. rise time [h]	103	20.4	20	157
peak events per crossing	27	135 (lev.)	147	171
total/inelastic cross section [mb]	111 / 85		129 / 93	153 / 108
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	5.0	5.0	5.0
beam lifetime due to burn off [h]	45	15.4	5.7	14.8
optimum run time [h]	15.2	10.2	5.8	10.7
opt. av. int. luminosity / day [fb^{-1}]	0.47	2.8	1.43	2.08

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

Main Conclusion

An 80-100 km complex (TLEP and VHE-LHC) would provide a FANTASTIC post-LHC physics programme

A TLEP Design study has started

- Ambitious milestones have been 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 technically possible timeline (to be confirmed by the DS)

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