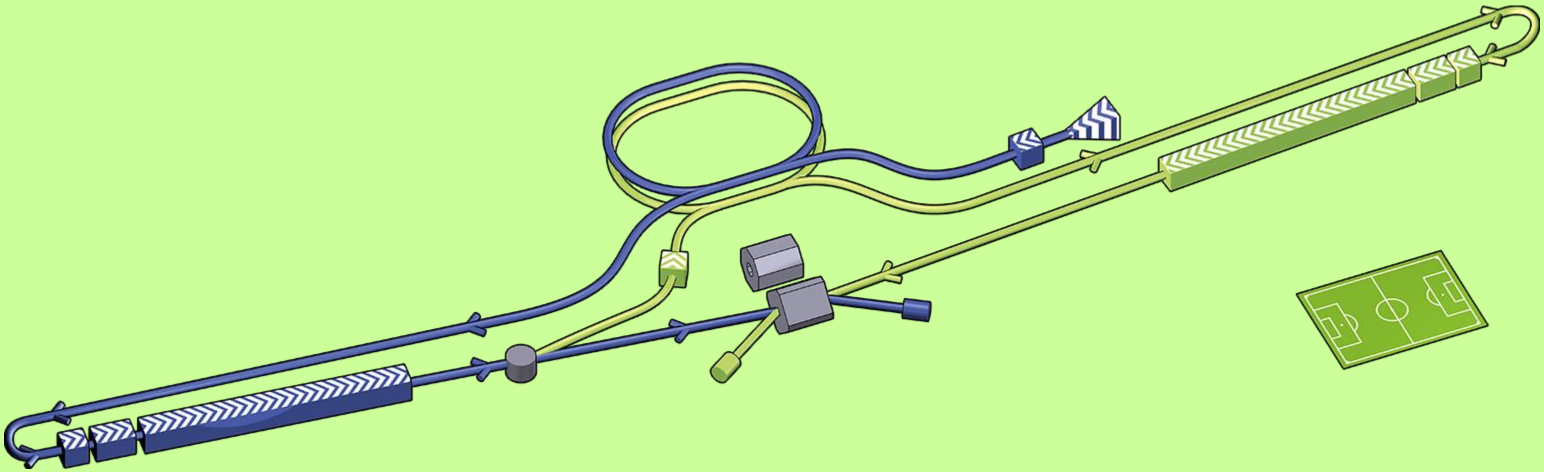
The Future of Particle Accelerators

The International Linear Collider



Barry C Barish – Caltech

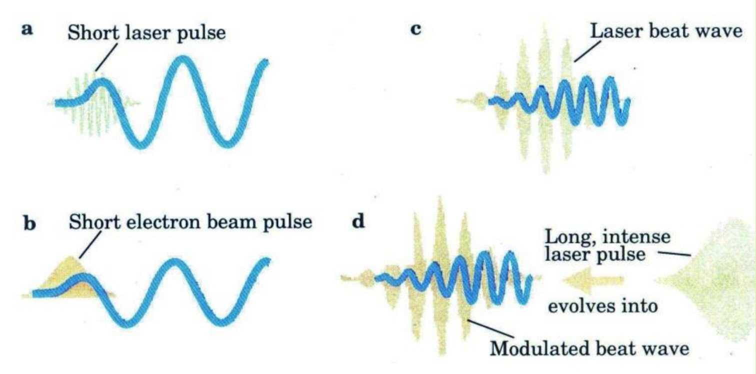
Tohoku Forum for Creativity
Particle Physics and Cosmology after the discovery of the Higgs Boson
21-25 October 2013

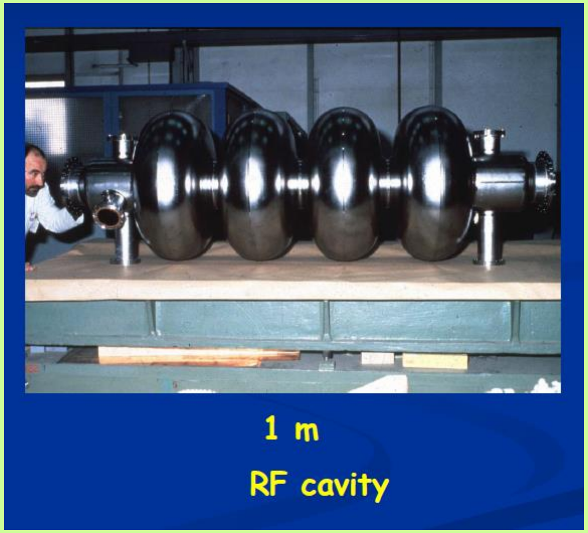
Future of Accelerator Based Particle Physics?

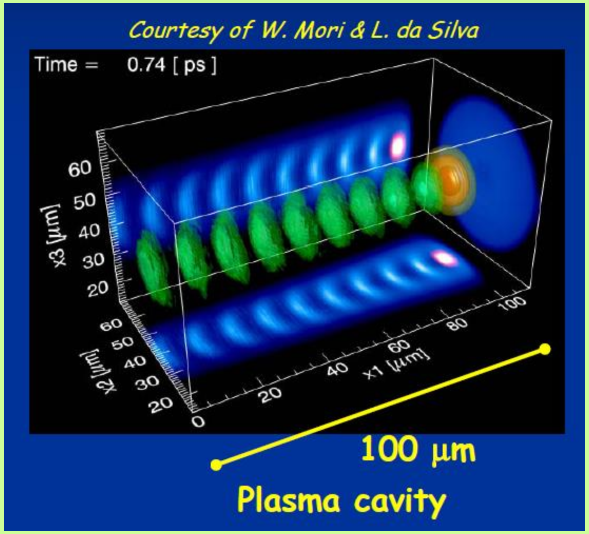
Future of Accelerators (eliminate materials!)

Plasma/Laser

Wakefield Acceleration



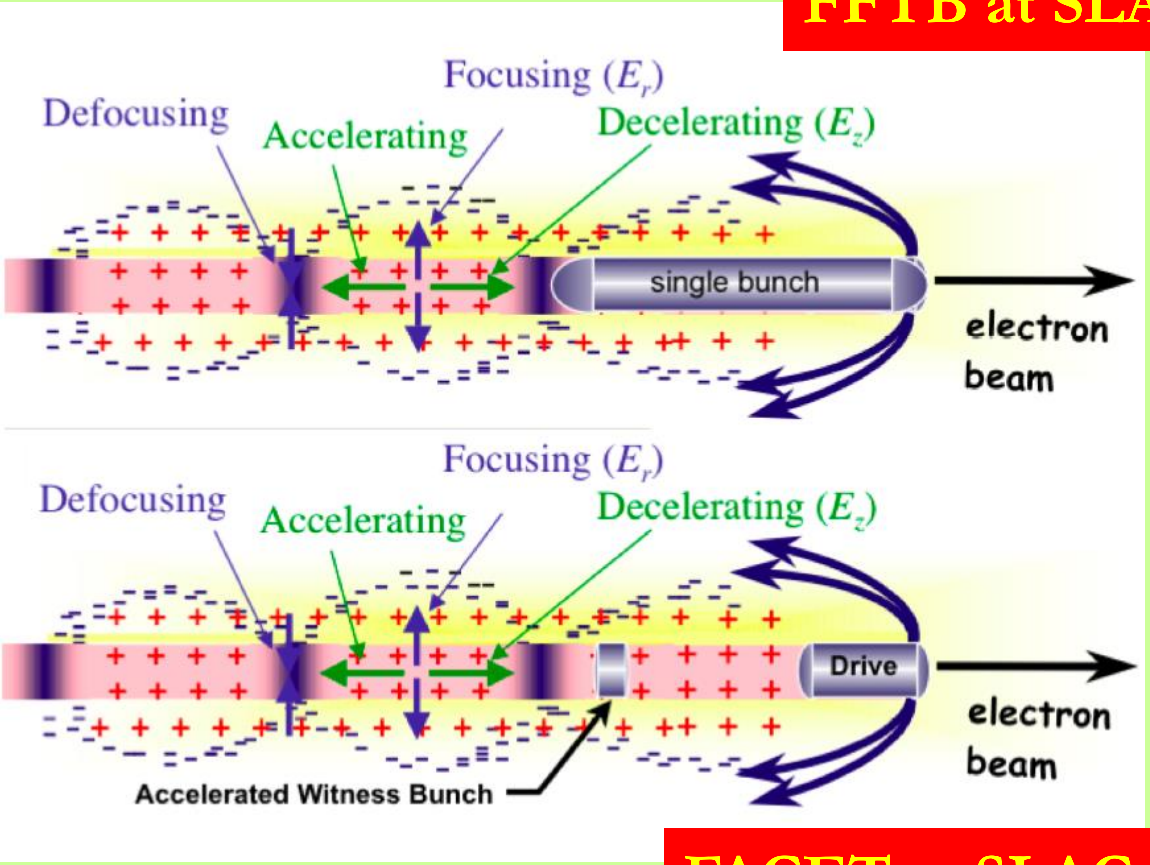


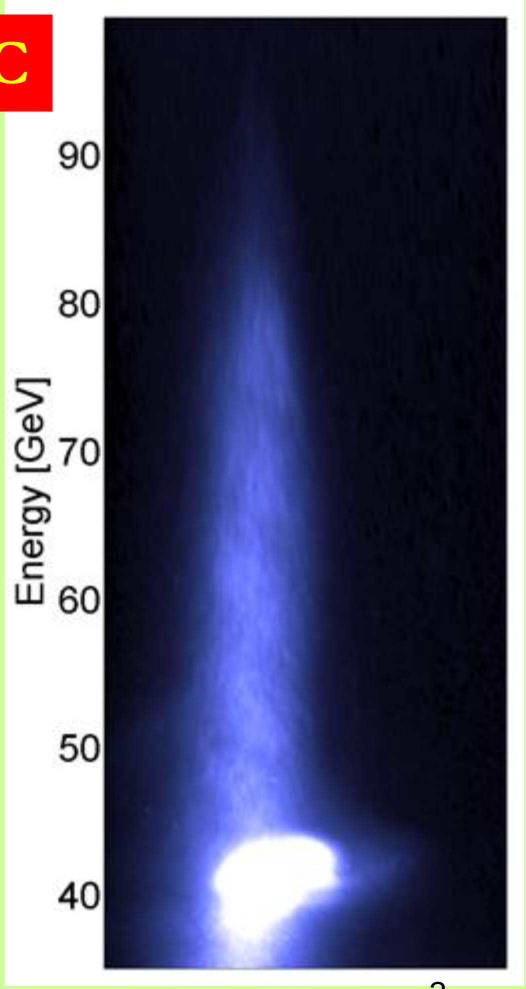


Compact Acceleration

50 GeV/meter has been achieved

FFTB at SLAC

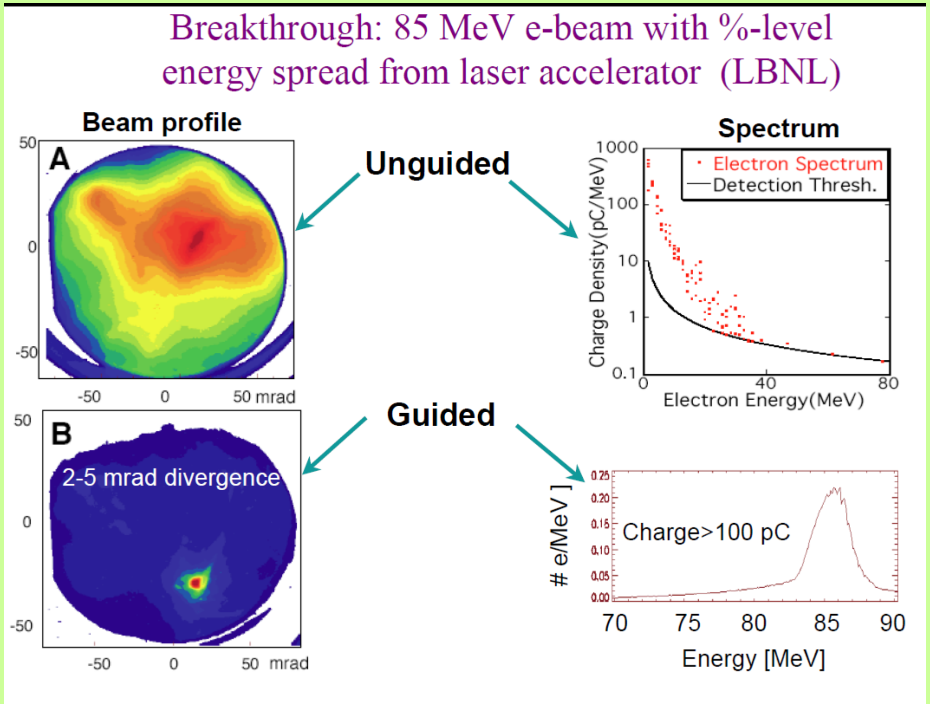




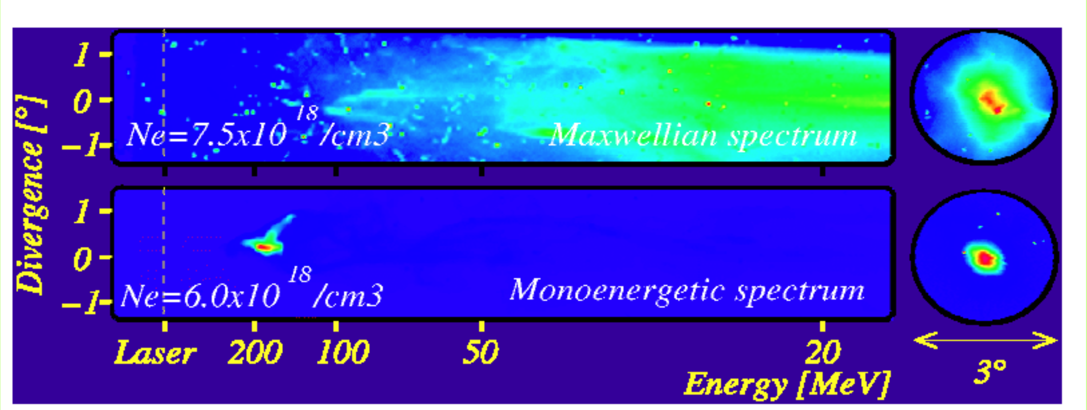
FACET at SLAC

Controlling the beams

LBNL



Reducing energy spread to ~ percent level



Reducing angular divergence (< 1 degree)

Advanced Accelerator R&D projects

FACET

Location
SLAC National Accelerator Laboratory

Creates electron wake using an electron beam in a plasma

Based on previous experiments that doubled the energies of a few electrons—from 42 billion to 85 billion electron volts—in 84 centimeters

Stimulus funds
$14.5 million

Next step/midterm goal:
is to create tighter electron bunches and accelerate them from 23 billion to 46 billion electronvolts in 40 centimeters

BELLA

Location
Lawrence Berkeley National Laboratory

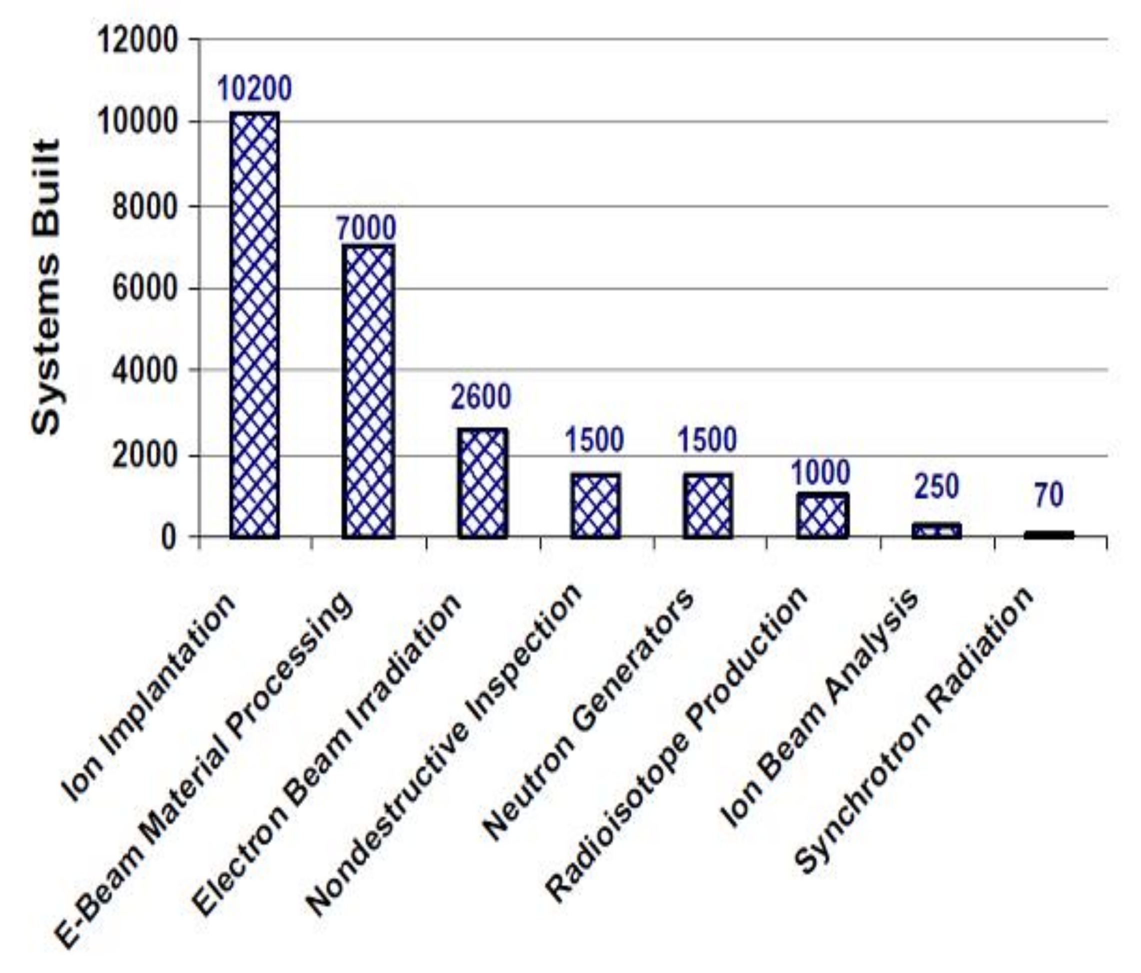
Creates electron wake using a laser beam in a plasma

Based on previous experiments that accelerated tightly packed electron bunches—the kind needed for physics experiments—from zero to 1 billion electron volts in 3 centimeters

Stimulus funds
$20 million

Next step/midterm goal:
is to accelerate already-tight electron bunches to higher energies, from zero to 10 billion electron volts in 80 centimeters

Accelerators: Economic Impact

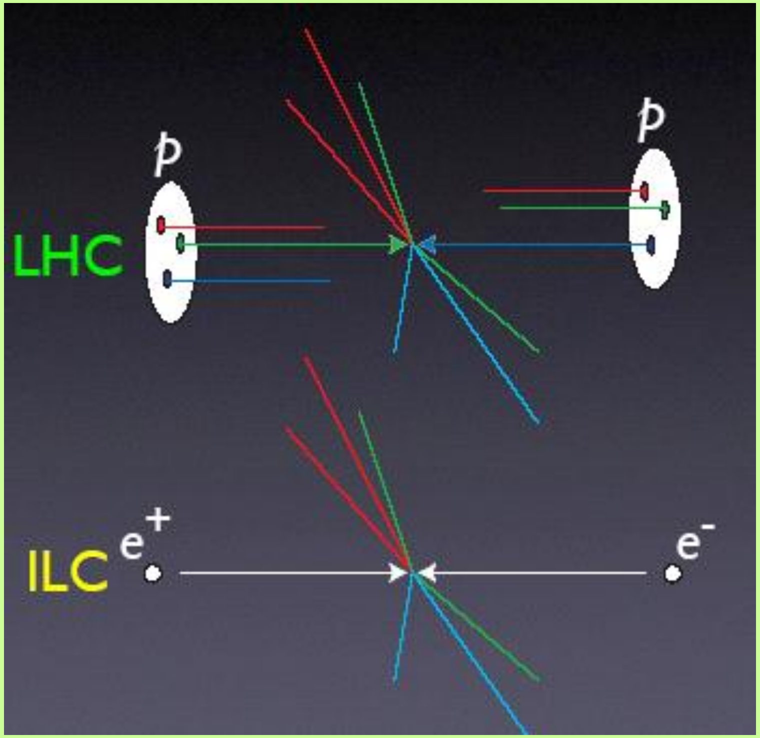


- Total built to date >24 000, with >18 000 in operation
- Sales increasing ~10% per year
- Presently >70 accelerator vendors worldwide
- Vendors primarily in US, Europe and Japan, but growing in China, Russia and India
- Equipment sales ~$3B per year worldwide

All the products that are processed, treated or inspected by particle beams have an annual value exceeding $500B

Exploring the Terascale
the tools

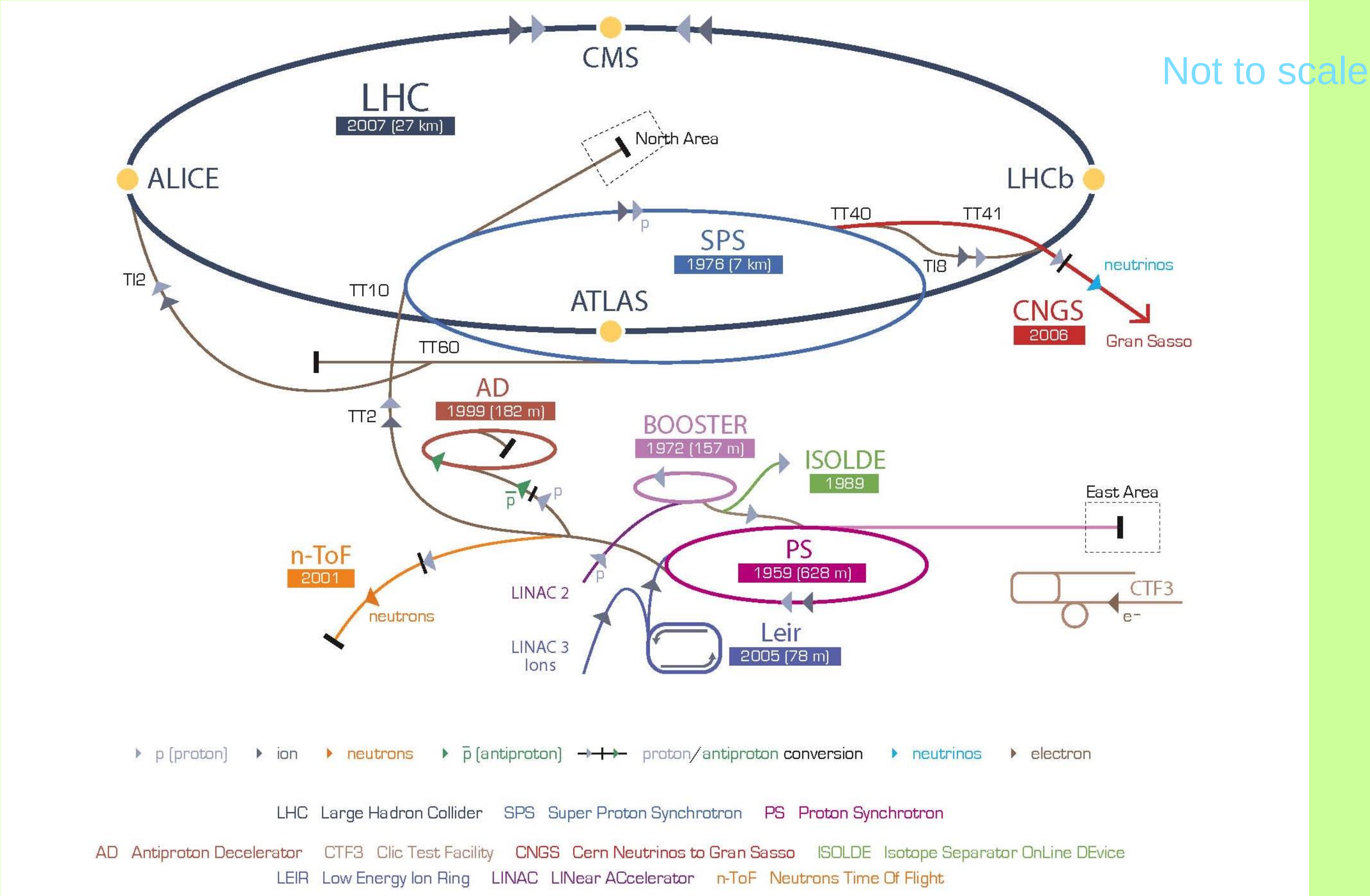
- The LHC
  - » It is leading the way and has large reach
  - » Quark-quark, quark-gluon and gluon-gluon collisions at 0.5 - 5 TeV
  - » Broadband initial state



- A Lepton Collider (e.g. ILC or ?)
  - » A second view with 'high precision'
  - » Electron-positron collisions with fixed energies
  - » Well defined initial state

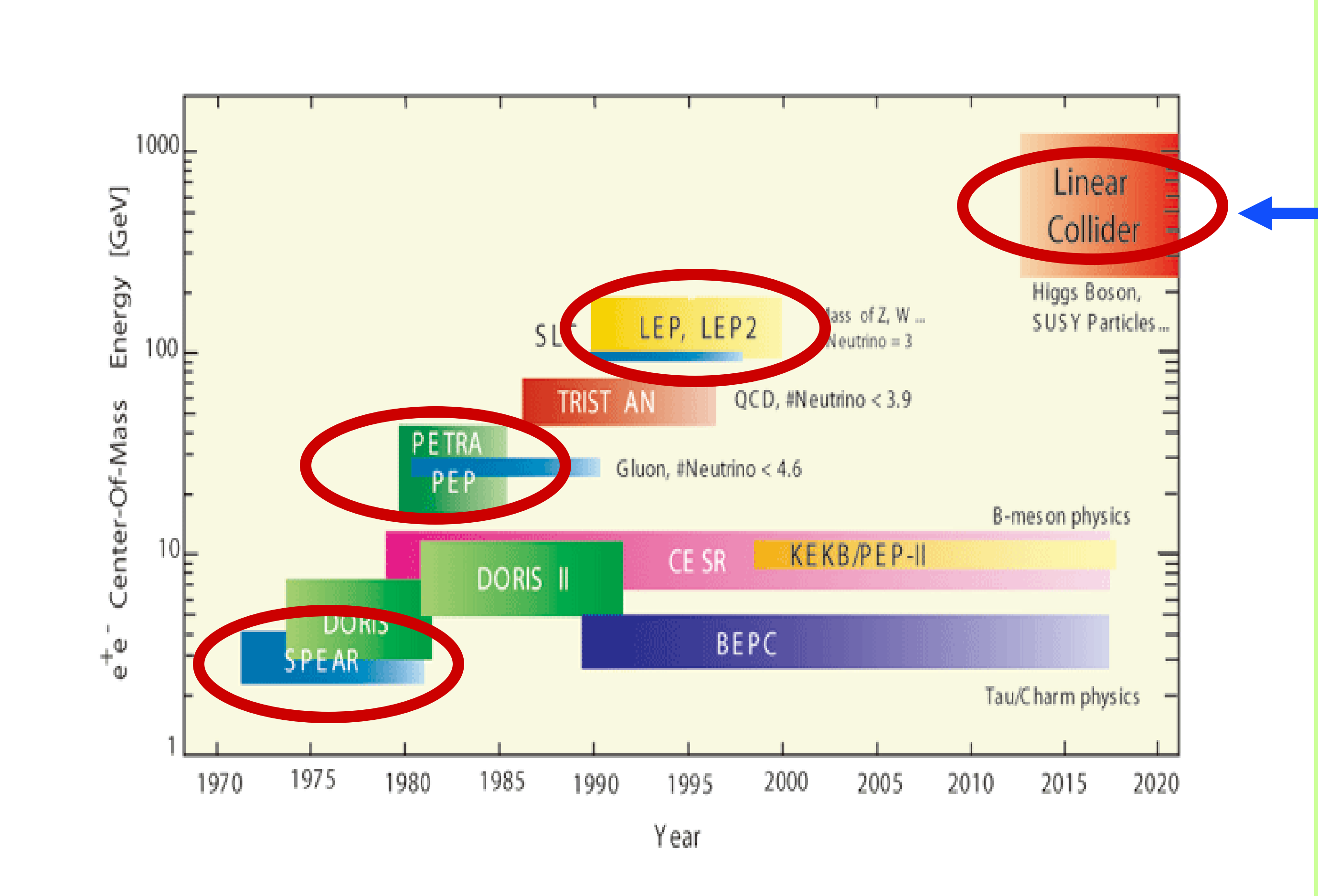
- Together, these two types of accelerators are our tools for uncovering physics at the terascale

LHC – CERN Accelerator Complex



Three Generations of e^+e^- Colliders

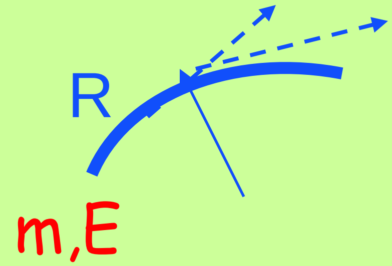
The Energy Frontier



Fourth Generation?

Circular or Linear Collider?

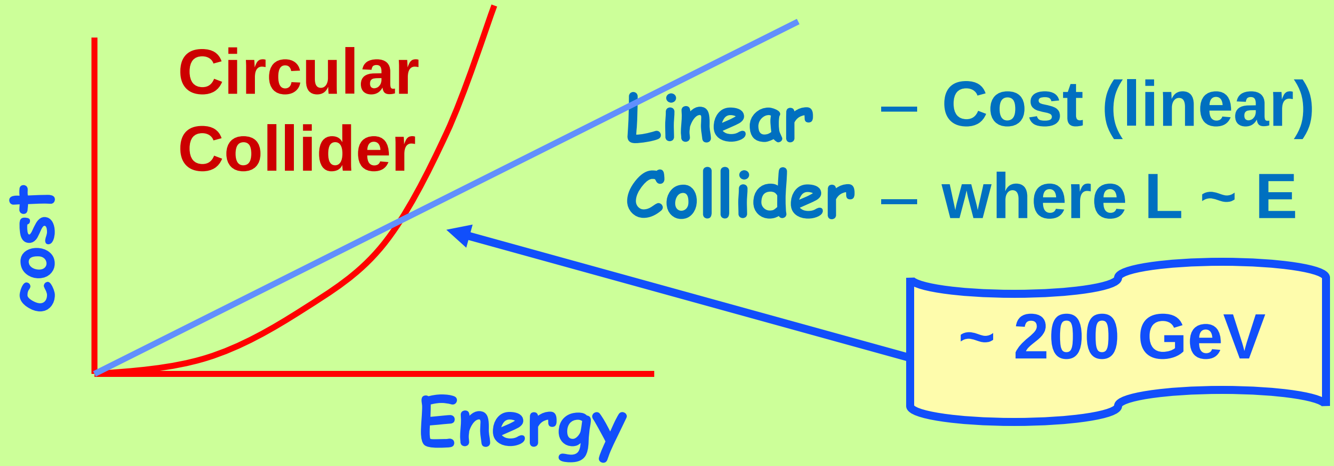
- **Circular Machine**



Synchrotron Radiation

  - $\Delta E \sim (E^4 / m^4 R)$
  - Cost $\sim a R + b \Delta E$

    $\sim a R + b (E^4 / m^4 R)$
  - **Optimization : $R \sim E^2$ $\Rightarrow$ Cost $\sim c E^2$**



  - Cost (linear) $\sim a' L$
  - where $L \sim E$

A Global Initiative for an ILC

International Committee for Future Accelerators (ICFA) representing major particle physics laboratories worldwide.

- Determined ILC physics design parameters
- Chose ILC accelerator technology (SCRF)
- Formed Global Design Effort and Mandate (TDR)

ILCSC/ICFA Parameters Studies

physics driven input

Key Parameters

- » Luminosity → $\int L dt = 500\ \mathrm{fb}^{-1}$ in 4 years
- » E_{cm} adjustable from 200 – 500 GeV
- » Ability to scan between 200 and 500 GeV
- » Energy stability and precision below 0.1%
- » Electron polarization of at least 80%

Options

- – The machine must be upgradeable to 1 TeV
- – Positron polarization desirable as an upgrade

Luminosity & Beam Size

$$L = \frac{n_b N^2 f_{rep}}{2\pi\sigma_x\sigma_y} H_D$$

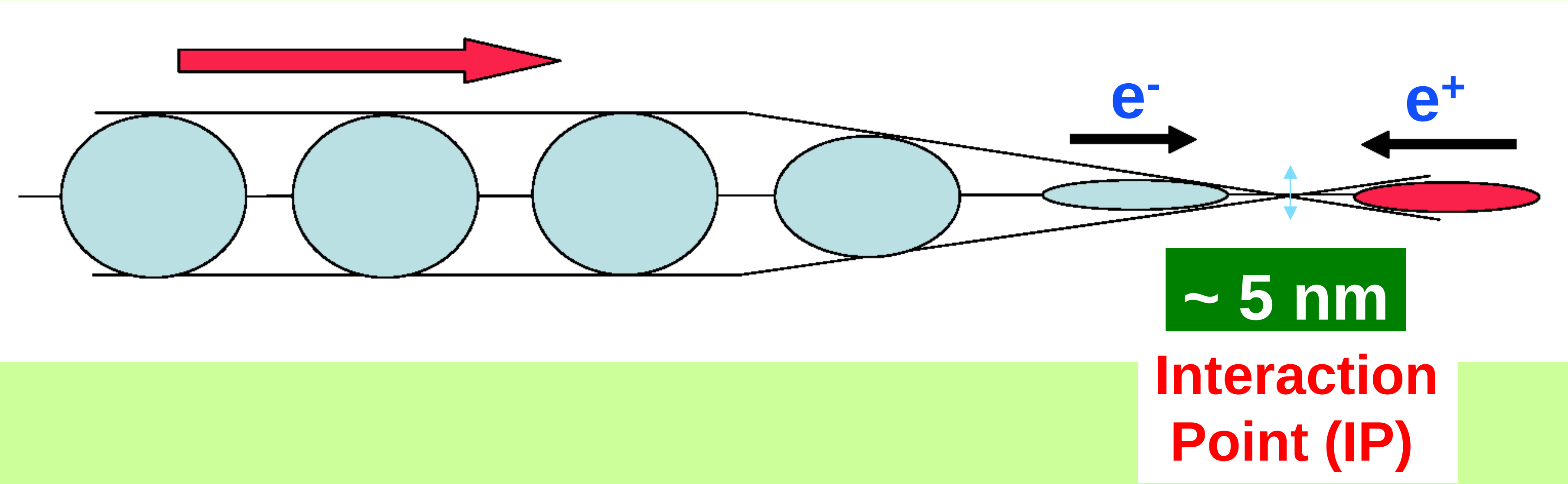
- f_{rep} * n_b tends to be low in a linear collider

	L	f_{rep} [Hz]	n_b	N [10^{10}]	σ_x [μm]	σy [μm]
ILC	2×10^{34}	5	3000	2	0.5	0.005
SLC	2×10^{30}	120	1	4	1.5	0.5
LEP2	5×10^{31}	10,000	8	30	240	4
PEP-II	1×10^{34}	140,000	1700	6	155	4

- Achieve luminosity with spot size and bunch charge

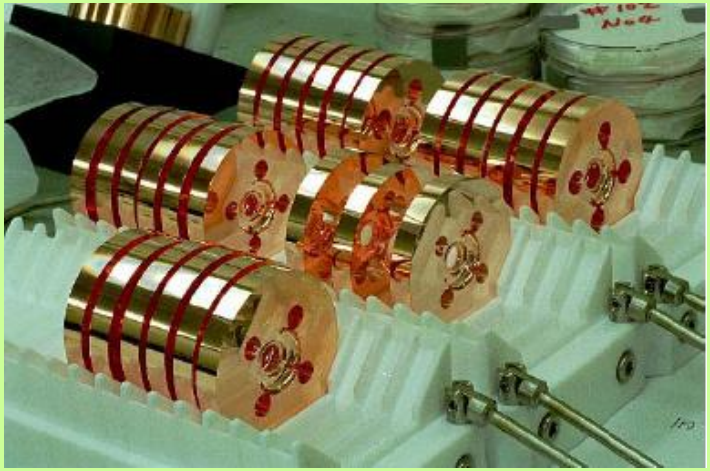
Achieving High Luminosity

- **Low emittance machine optics**
- **Contain emittance growth**
- **Squeeze the beam as small as possible**



HEP Lab-driven R&D programs

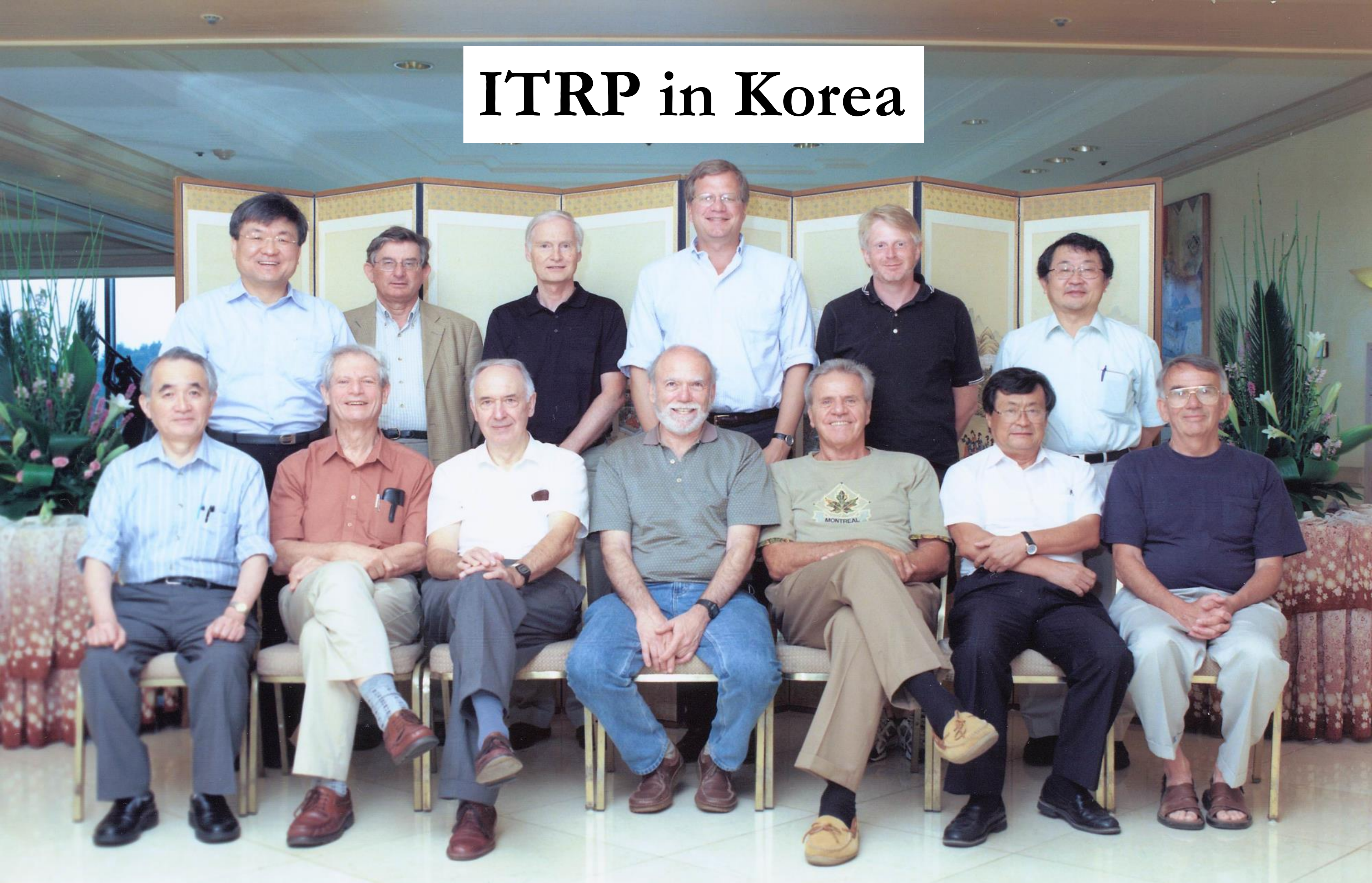
- Room temperature copper structures (KEK and SLAC)



OR

- Superconducting RF cavities (DESY)

ITRP in Korea



International Technology Recommendation Panel Meeting
August 11 ~ 13, 2004. Republic of Korea

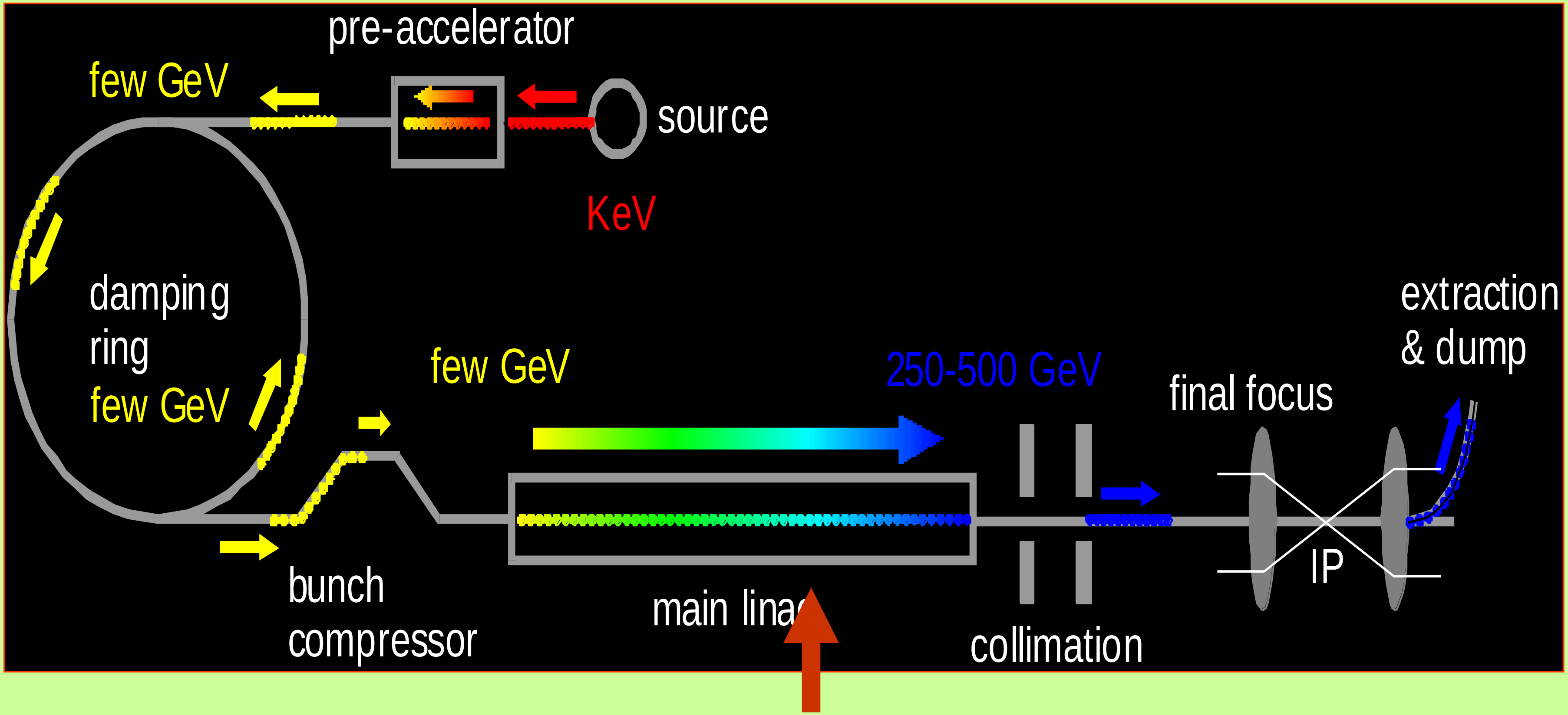
GDE – Mandate (7-Feb 06)

Global Design Effort

– The Mission of the GDE
- Produce a design for the ILC that includes a detailed design concept, performance assessments, reliable international costing, an industrialization plan , siting analysis, as well as detector concepts and scope.
- Coordinate worldwide prioritized proposal driven R & D efforts (to demonstrate and improve the performance, reduce the costs, attain the required reliability, etc.)

7-Feb-06 GDE Report to ILCSC 2

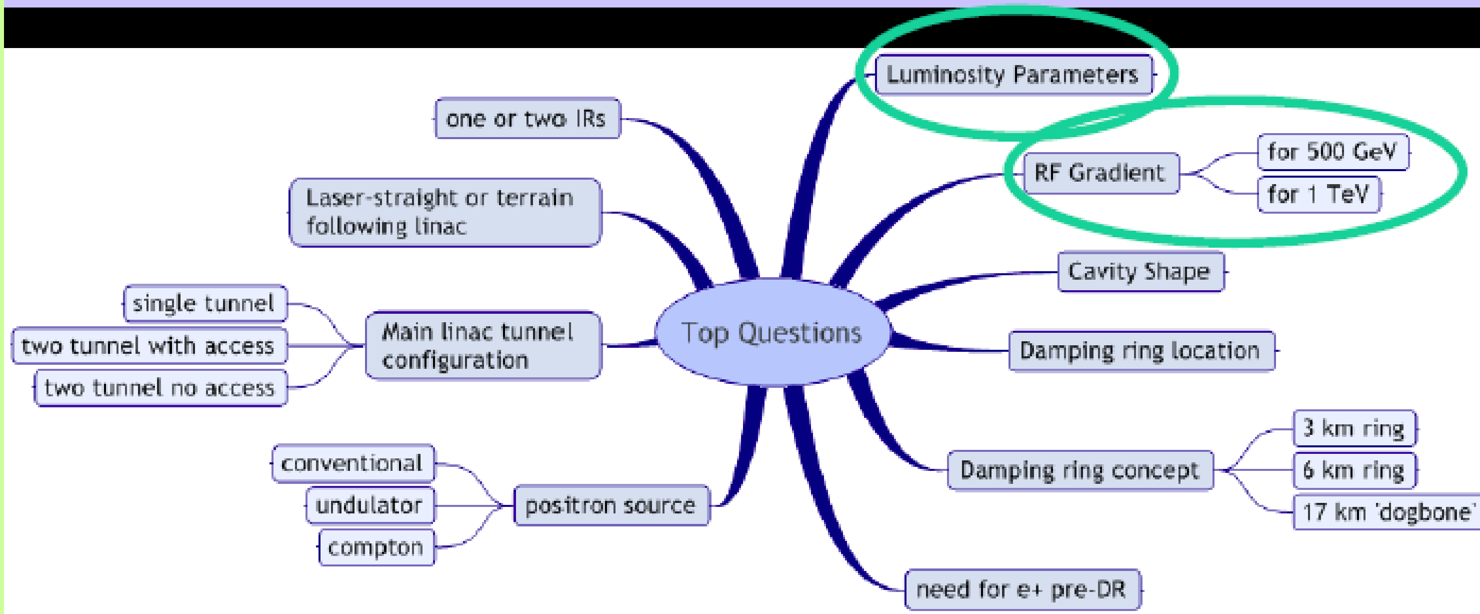
GDE -- Design a Linear Collider



Superconducting RF Main Linac

Design decisions accepted globally!

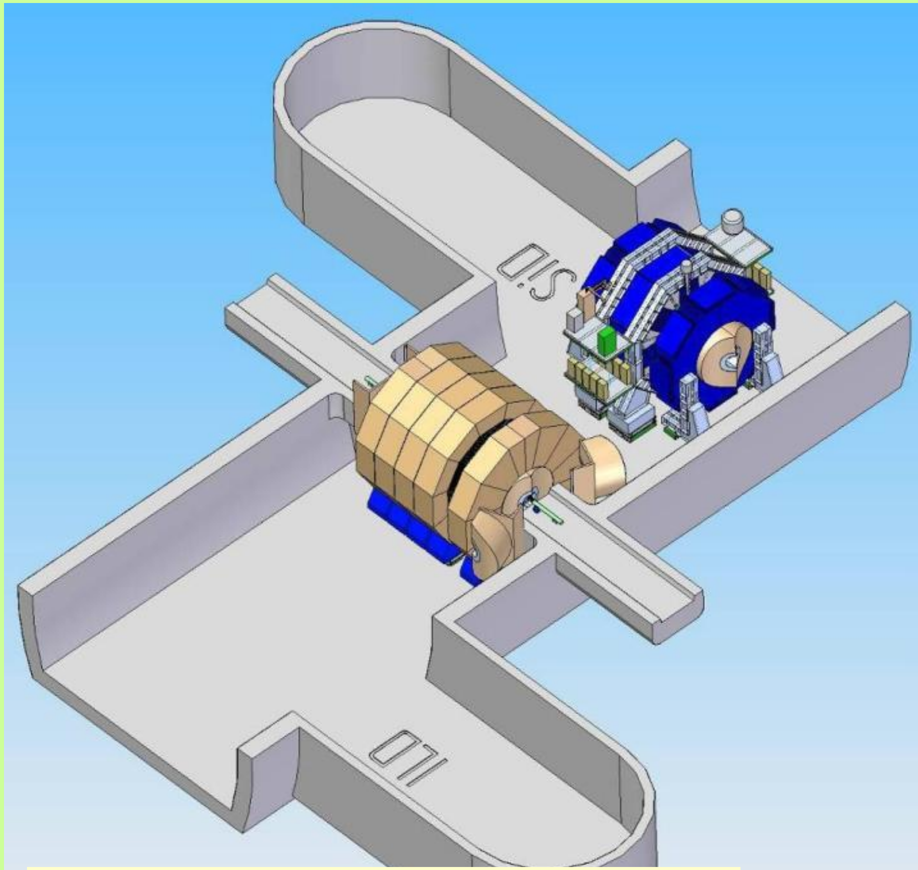
The Key Decisions



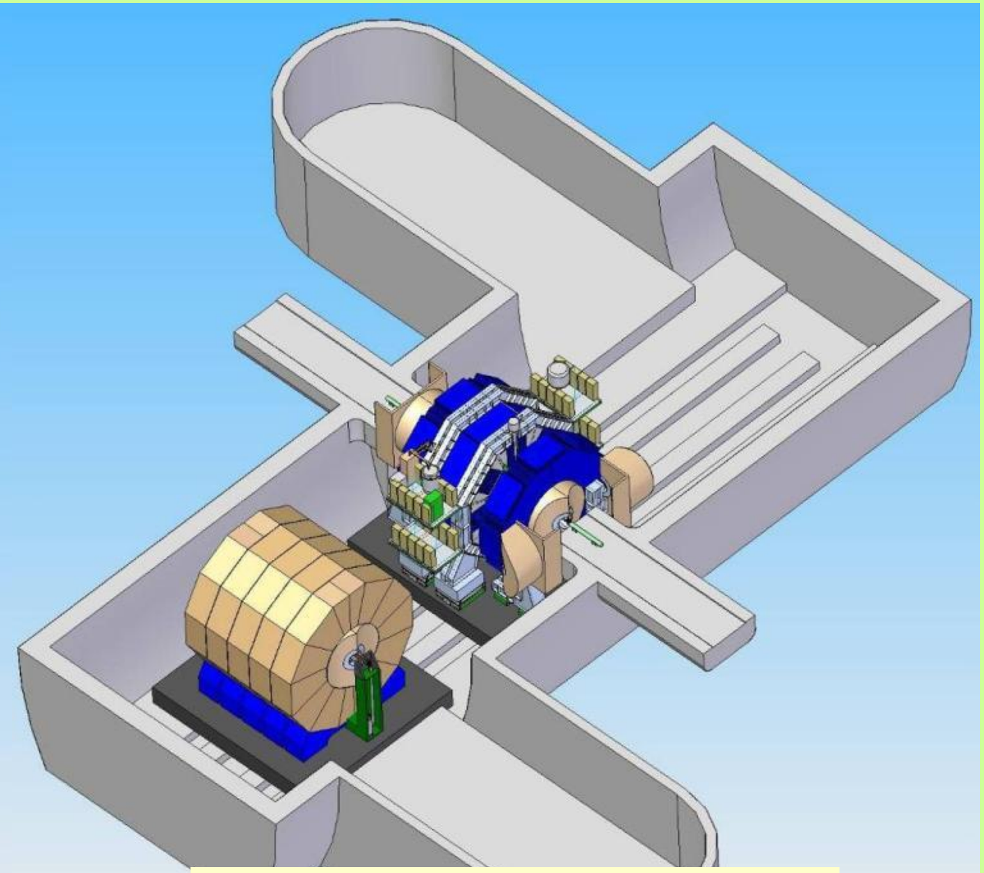
Critical choices: luminosity parameters & gradient

7-Feb-06 GDE Report to ILCSC 7

Push – Pull Detector Concept



Both detectors without platforms



Both detectors with platforms

- Vibration stability will be one of the major criteria in eventual selection of a motion system design

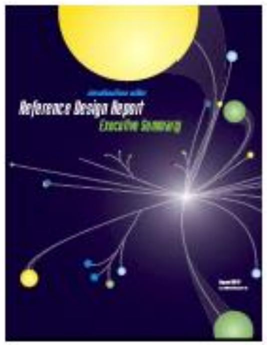
RDR Design Parameters

Max. Center-of-mass energy	500	GeV
Peak Luminosity	$\sim 2 \times 10^{34}$	$1/cm^2 s$
Beam Current	9.0	mA
Repetition rate	5	Hz
Average accelerating gradient	31.5	MV/m
Beam pulse length	0.95	ms
Total Site Length	31	km
Total AC Power Consumption	~ 230	MW

Reference Design - 2008

RDR Reports

- Reference Design Report (4 volumes)



Executive Summary

Physics at the ILC

Accelerator

Detectors

11-Feb-08
ILCSC

Global Design Effort

5

Major R&D Goals for Technical Design

SCRF

- High Gradient R&D - globally coordinated program to demonstrate gradient by 2010 with 50%yield; improve yield to 90% by TDR (end 2012)
- Manufacturing: plug compatible design; industrialization, etc.
- Systems tests: FLASH; plus NML (FNAL), STF2 (KEK) post-TDR

Test Facilities

- ATF2 - Fast Kicker tests and Final Focus design/performance EARTHQUAKE RECOVERY
- CesrTA - Electron Cloud tests to establish damping ring parameters/design and electron cloud mitigation strategy
- FLASH – Study performance using ILC-like beam and cryomodule (systems test)

1.3 GHz Superconducting RF Cavity

- solid niobium
- standing wave
- 9 cells
- operated at 2K (LHe)

- 35 MV/m
- $Q_0 \geq 10^{10}$

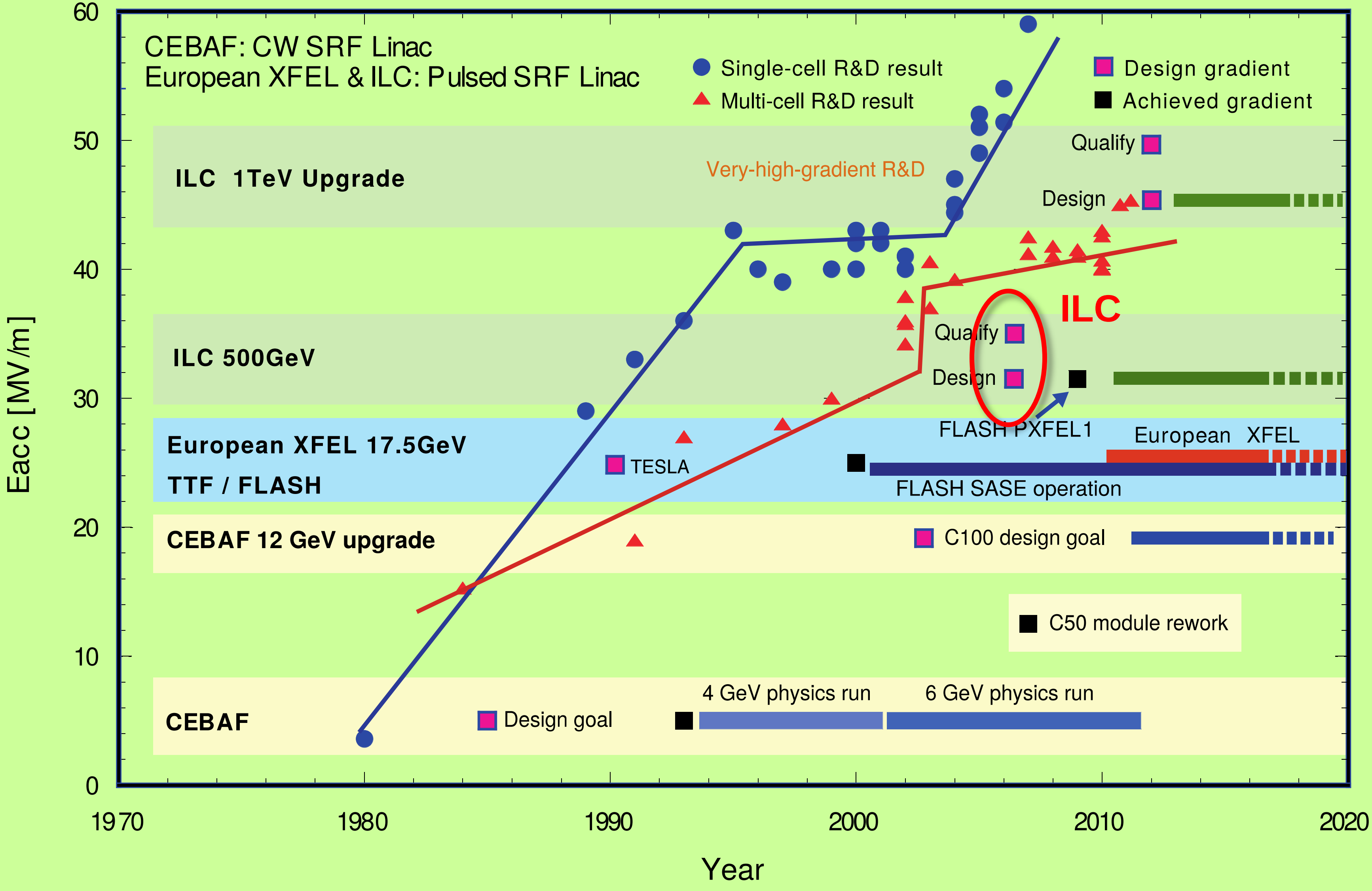
Globally Coordinated SCRF R&D

Figure 1.2-1: A TESLA nine-cell 1.3 GHz superconducting niobium cavity.

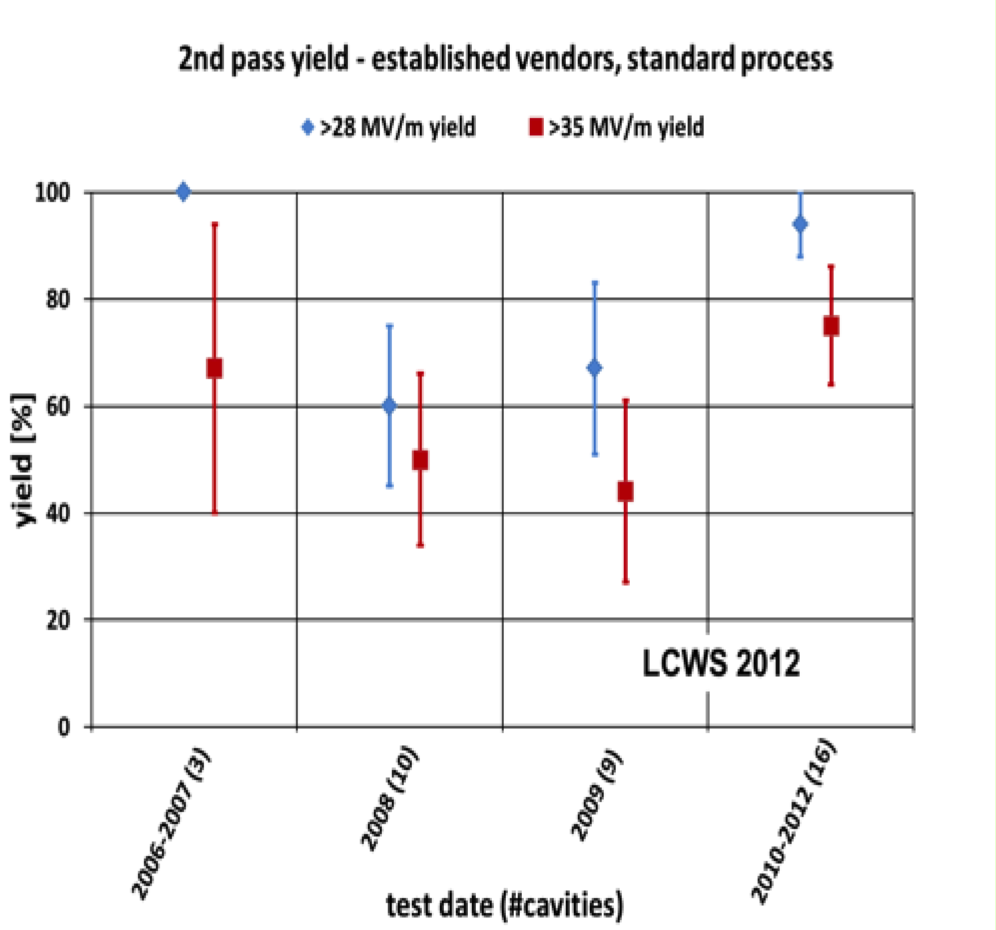
- Achieve high gradient (35MV/m); develop multiple vendors; make cost effective, etc

- Focus is on high gradient; production yields; cryogenic losses; radiation; system performance

The Quest for Higher Gradient



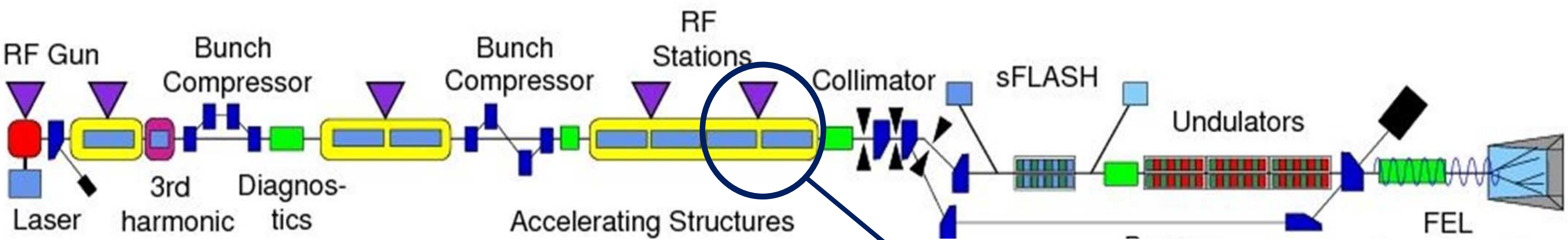
Progress in Cavity Gradient Yield



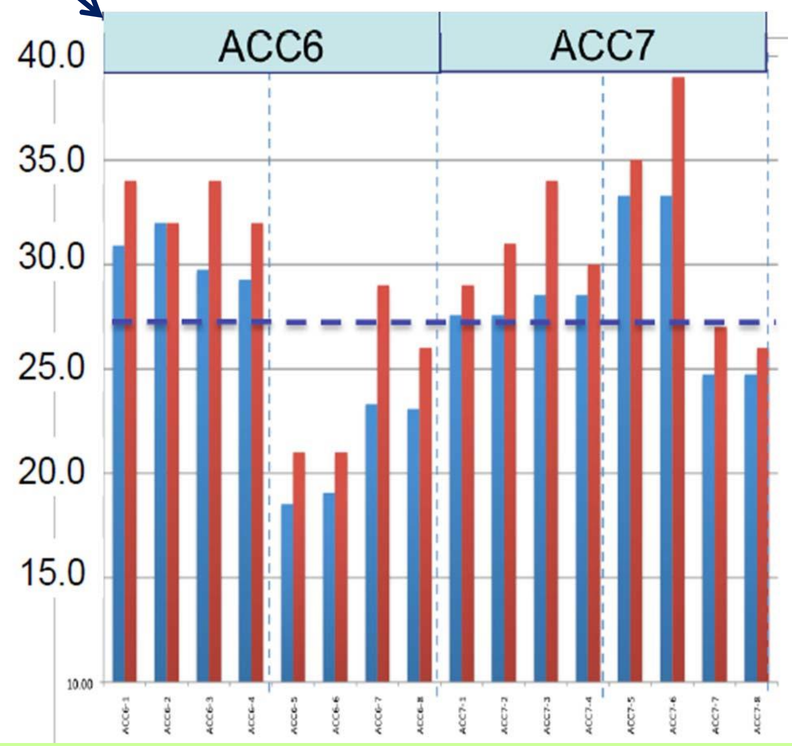
Production yield: 94 % at > 28 MV/m,

Average gradient: 37.1 MV/m

FLASH at DESY: 9mA Experiment



		XFEL	ILC (upg.)	FLASH design	9mA studies
Bunch charge	nC	1	3.2	1	3
# bunches		3250	2625	7200*	2400
Pulse length	μs	650	970	800	800
Current	mA	5	9	9	9



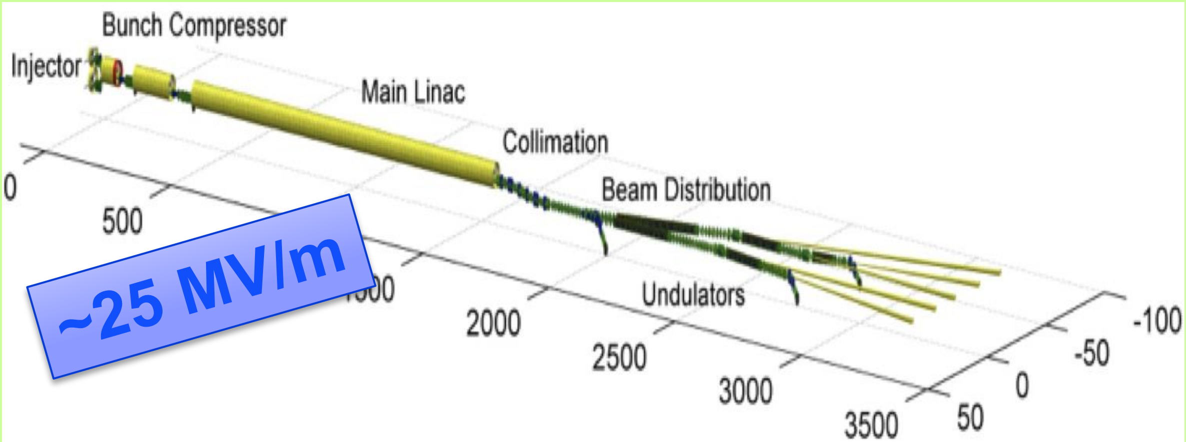
Many basic demonstrations:

- heavy beam loading with long bunch trains
- operation close to quench limits
- klystron overhead etc.

Development (LLRF & controls):

- tuning algorithms
- automation
- quench protection etc.

European XFEL at DESY



Largest deployment of this technology to date

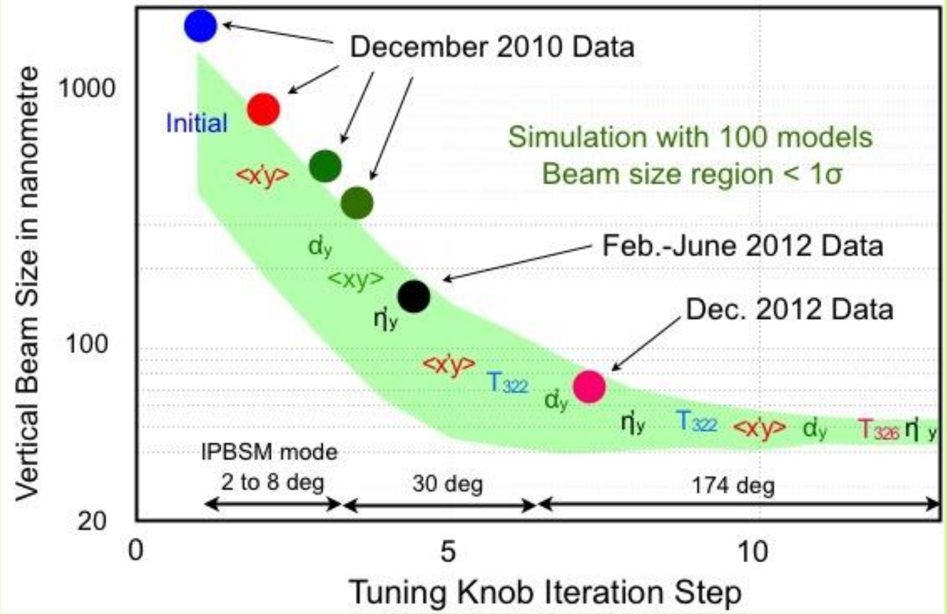
- 100 cryomodules
- 800 cavities
- 17.5 GeV



The ultimate ‘integrated systems test’ for ILC.
Commissioning with beam 2^{nd} half 2015

ATF-2 – final focus tests

March 2013 <65 nm achieved

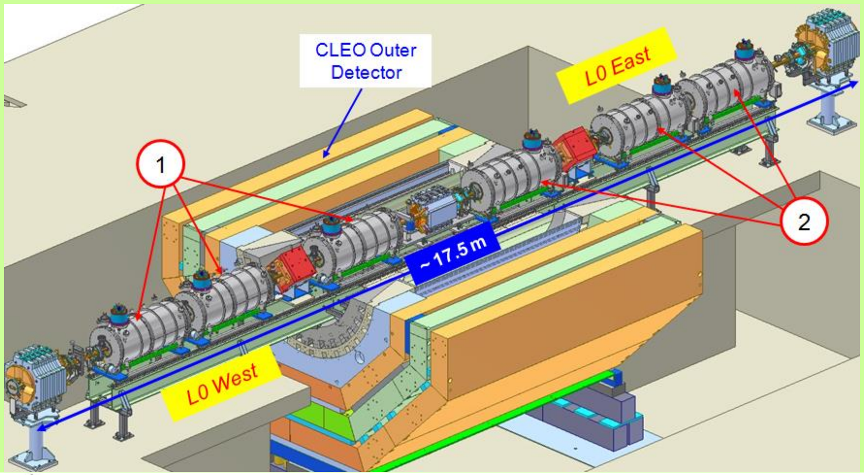


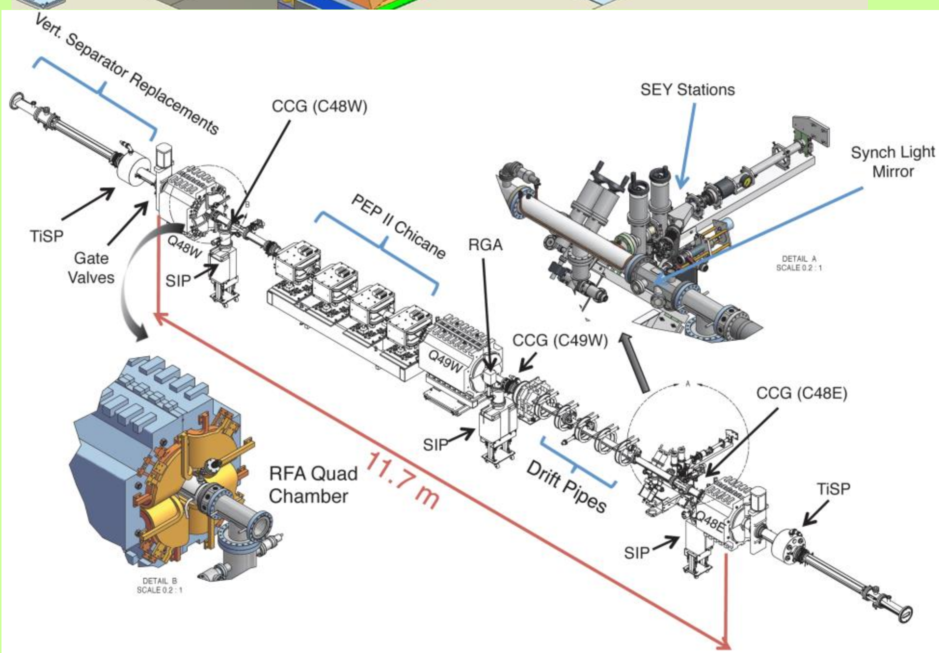
Test bed for ILC final focus optics

- strong focusing and tuning (37 nm)
- beam-based alignment
- stabilisation and vibration (fast feedback)
- instrumentation

Critical R&D: Electron Cloud

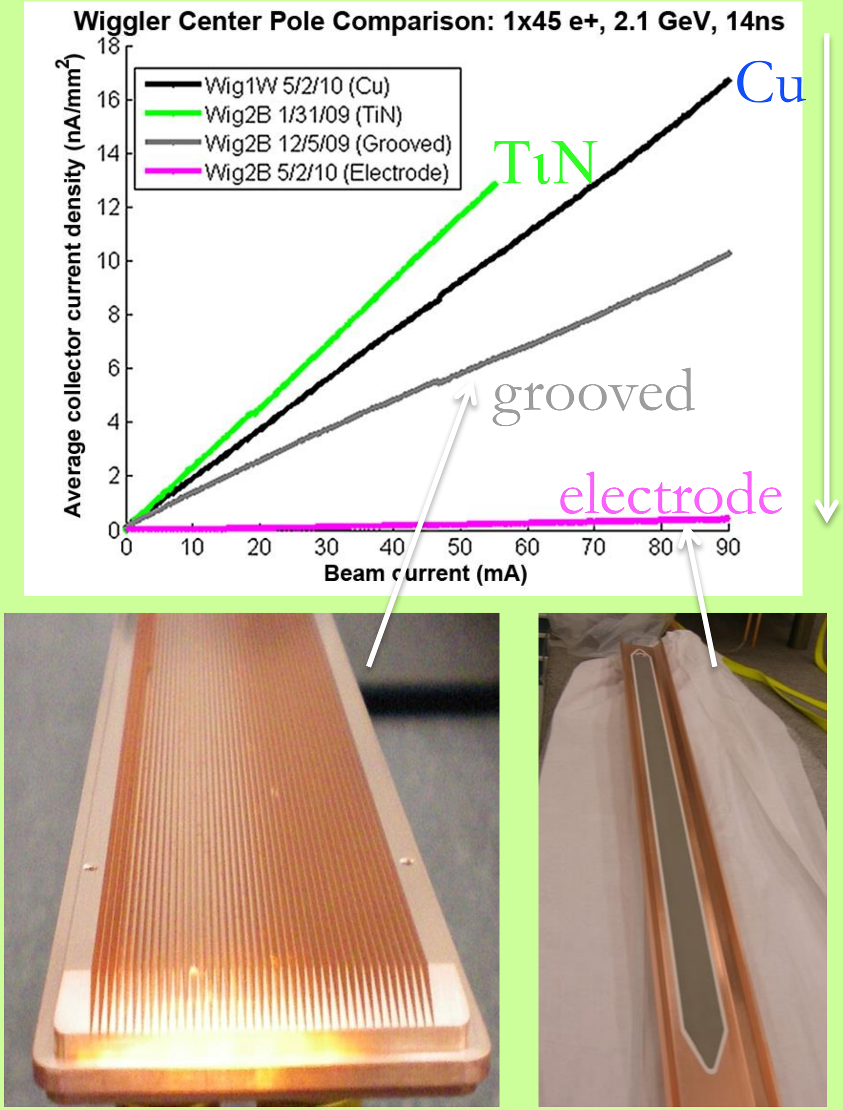
3840511-040





- **Extensive R&D program at CESR, Cornell (CesrTA)**
- **Instrumentation of wiggler, dipole and quad vacuum chambers for e-cloud measurements**
- **low emittance lattice with goal: reliable extrapolations to ILC**

Critical R&D: Electron Cloud



- Extensive R&D programme at CESR, Cornell (CesrTA)
- Instrumentation of wiggler, dipole and quad vacuum chambers for e-cloud measurements
- low emittance lattice
- Example: wiggler vacuum chamber
- Benchmarking of simulation codes
  - » cloud build-up
  - » beam dynamics (head-tail instabilities)

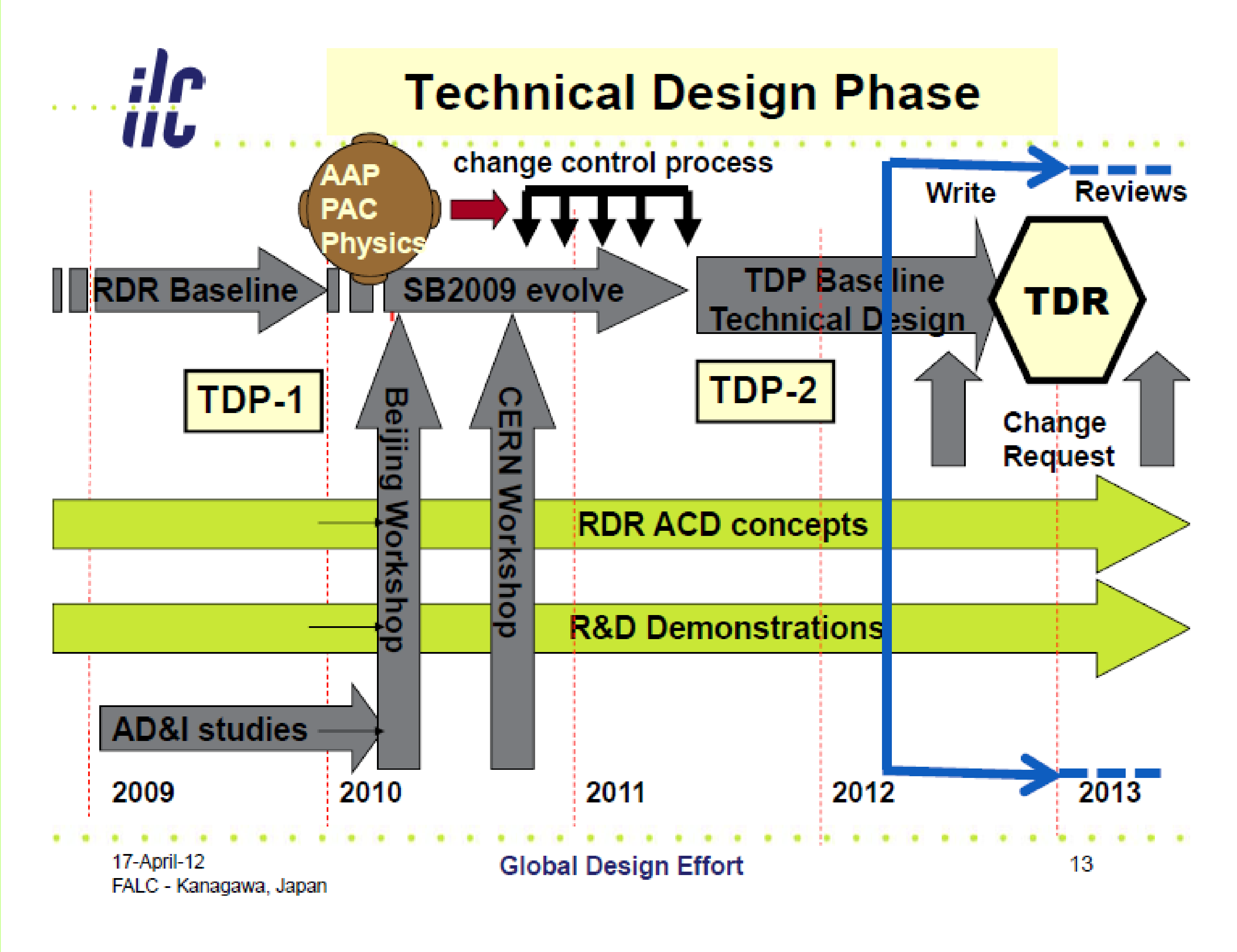
Baseline Mitigation Plan

EC Working Group Baseline Mitigation Recommendation				
	Drift*	**Dipole**	**Wiggler**	**Quadrupole***
Baseline Mitigation I	**TiN Coating**	**Grooves with TiN coating**	**Clearing Electrodes**	**TiN Coating**
Baseline Mitigation II	**Solenoid Windings**	**Antechamber**	**Antechamber**	
Alternate Mitigation	**NEG Coating**	**TiN Coating**	**Grooves with TiN Coating**	**Clearing Electrodes or Grooves**

*Drift and Quadrupole chambers in arc and wiggler regions will incorporate antechambers

- Preliminary CesrTA results and simulations suggest the presence of *sub-threshold emittance growth*
  - Further investigation required
  - May require reduction in acceptable cloud density ⇨ reduction in safety margin
- An aggressive mitigation plan is required to obtain optimum performance from the 3.2km positron damping ring and to pursue the high current option

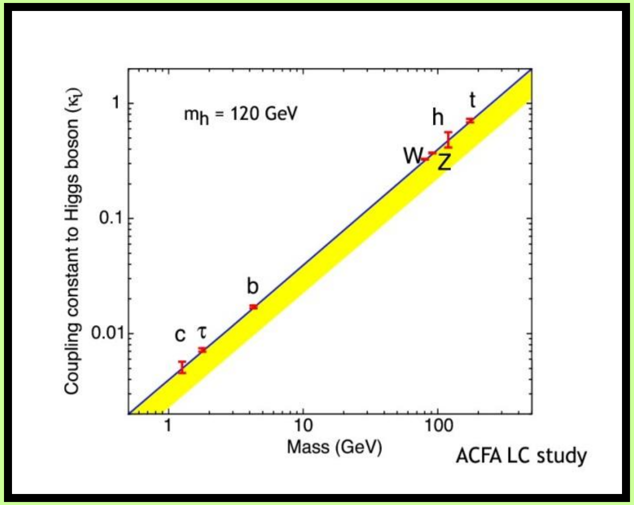
Baseline for the TDR



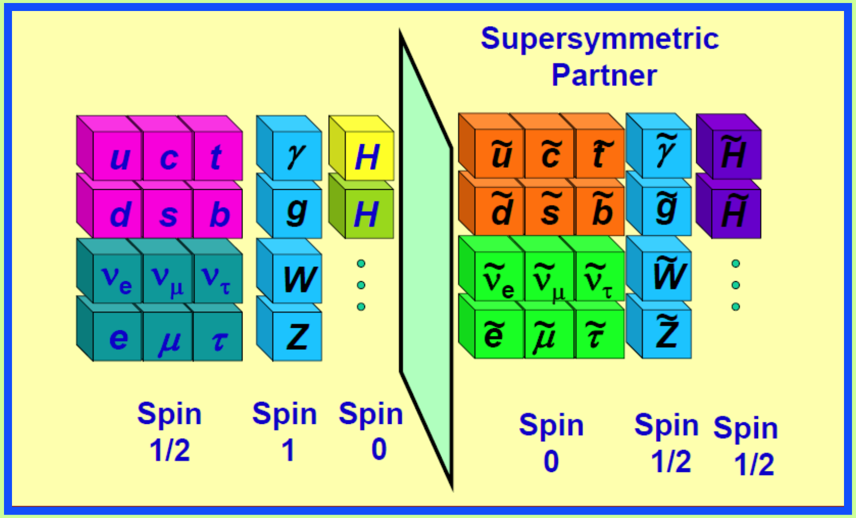
LHC

The Higgs has been discovered.
What about supersymmetry?

- **Higgs**



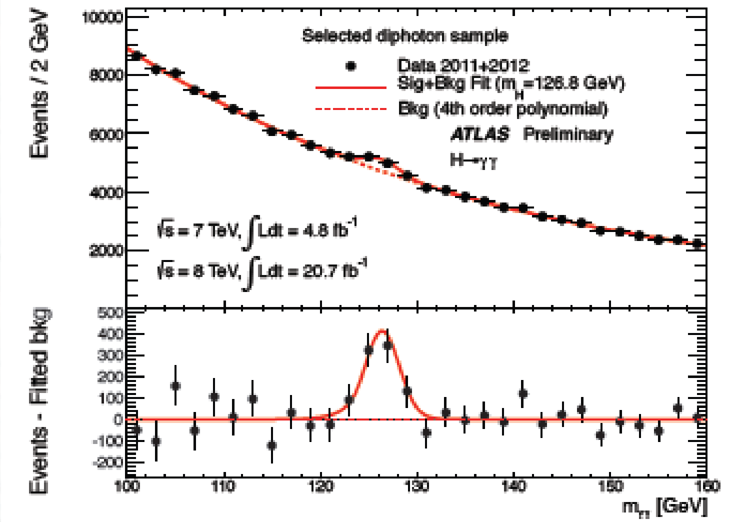
- **Supersymmetry**



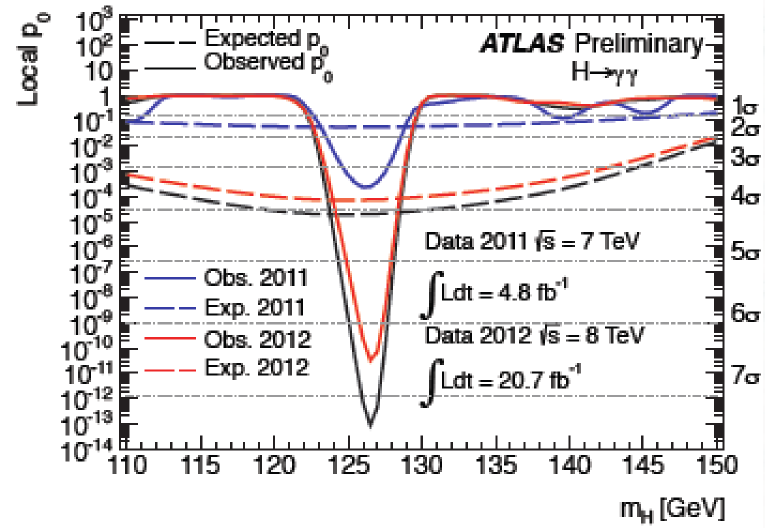
ATLAS: Higgs Evidence (γγ)

Result of the ATLAS search for H → γγ

Full dataset ATLAS-CONF-2013-012



ATLAS-CONF-2013-012



- p_0 value for consistency of data with background-only: $\sim 10^{-13}$ (7.4σ observed) for the combined 7 TeV and 8 TeV data; (4.3σ expected) (minimum found at $m_{\gamma\gamma}$ = 126.5 GeV)
- Establishes the discovery of the new particle in the γγ channel alone

How about the other Higgs characteristics?

- Spin (must be spin 0)
- Coupling (couples to mass)
- Are there more Higgs particles?
- What is the self-coupling
- etc

These questions will be a major focus of the LHC program after the upgrade; but so far, LHC results are consistent with a simple Higgs

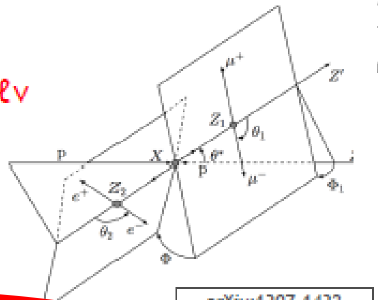
ATLAS: Spin 0?

Spin-parity

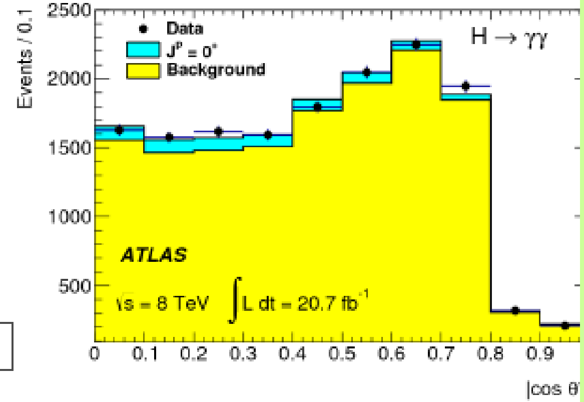
Use $H\to\gamma\gamma$, $H\to 4\ell$, $H\to WW\to \ell\nu\ell\nu$

Variables sensitive to decay angles

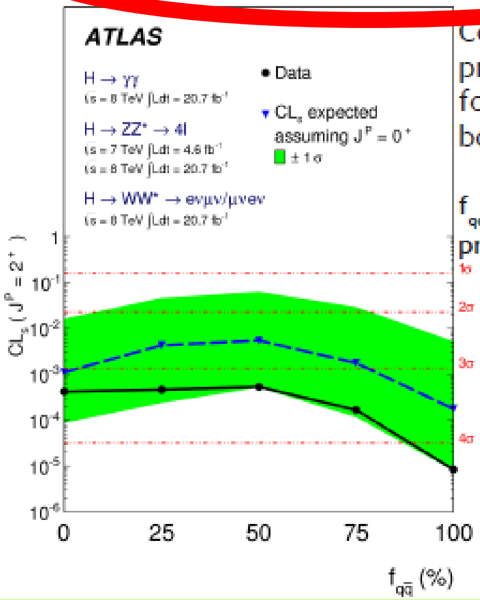
Make pairwise hypothesis tests J^P vs 0^+



arXiv:1307.1432
accepted by PLB



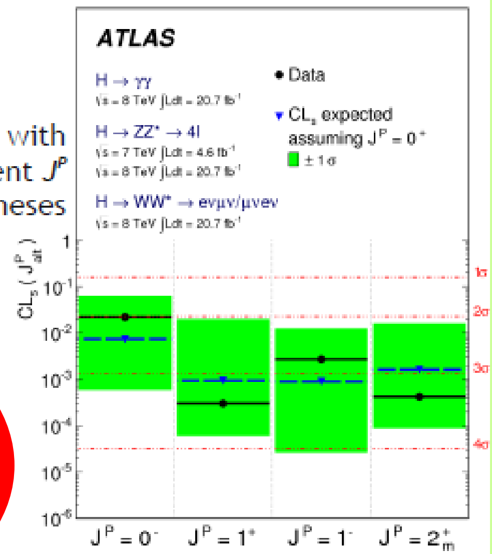
Data are consistent with 0^+ on every test



Compare with a range of production hypotheses for a spin-2 graviton-like boson

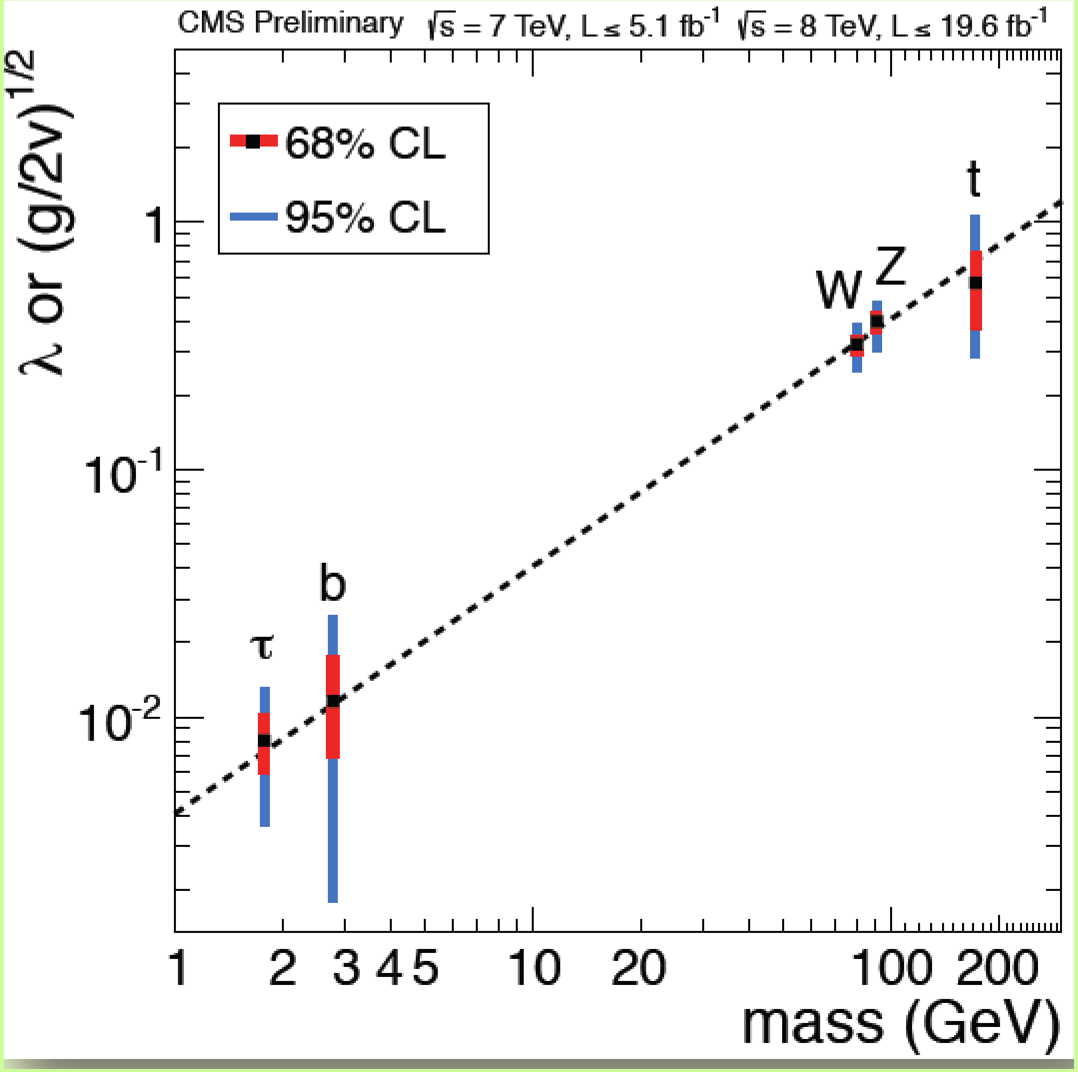
f_{qq} = fraction of qq production (rather than gg)

Compare with different J^P hypotheses

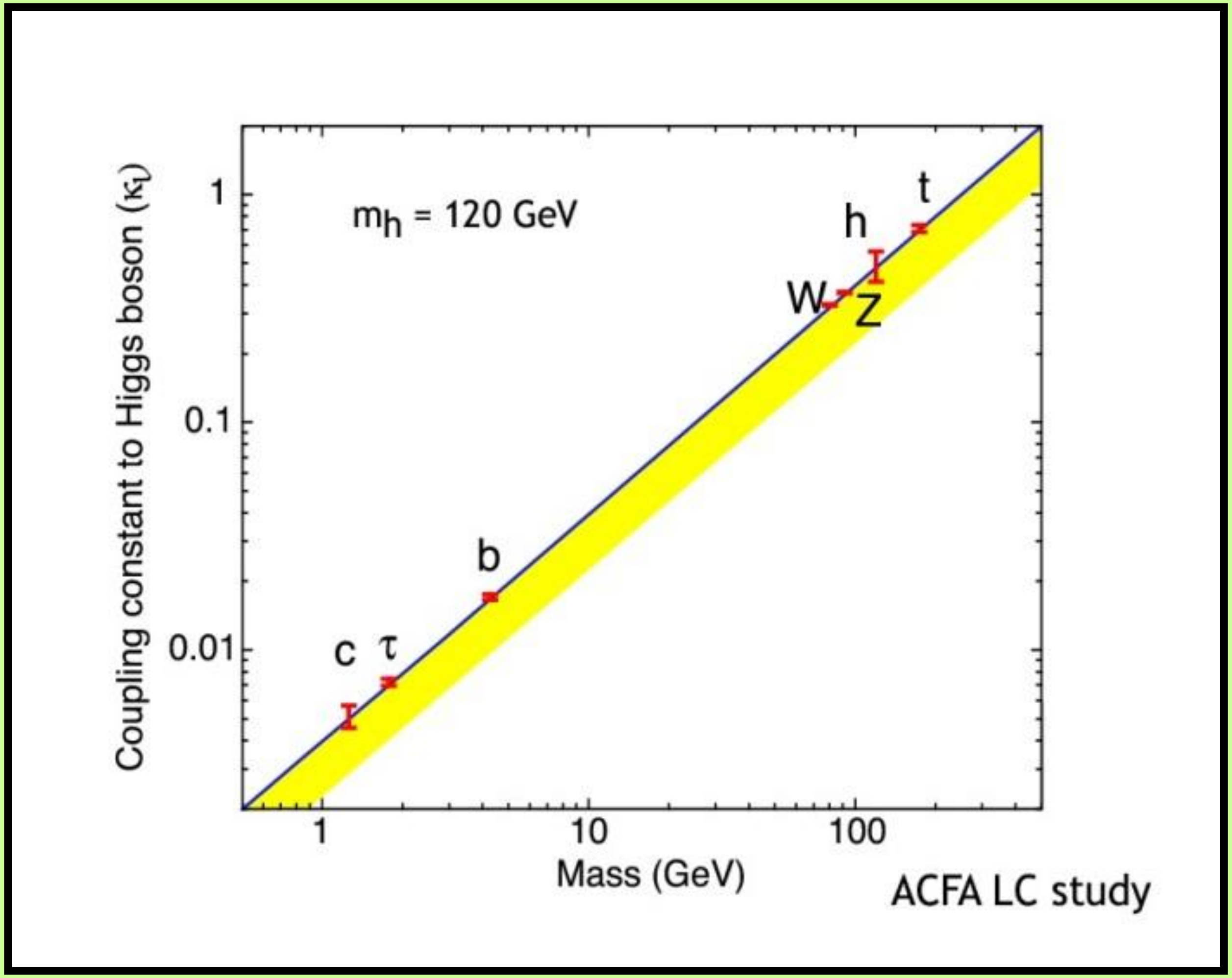


All alternative hypotheses disfavoured at >97.8% CL

CMS: Higgs coupling vs mass



Higgs couples to mass !



Is there a high mass Higgs?

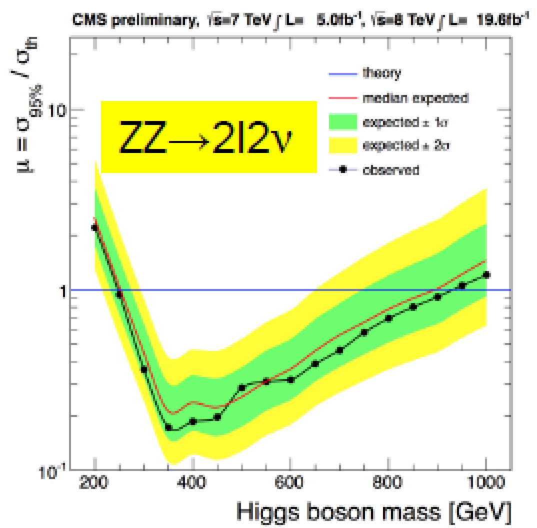
High Mass Higgs Searches

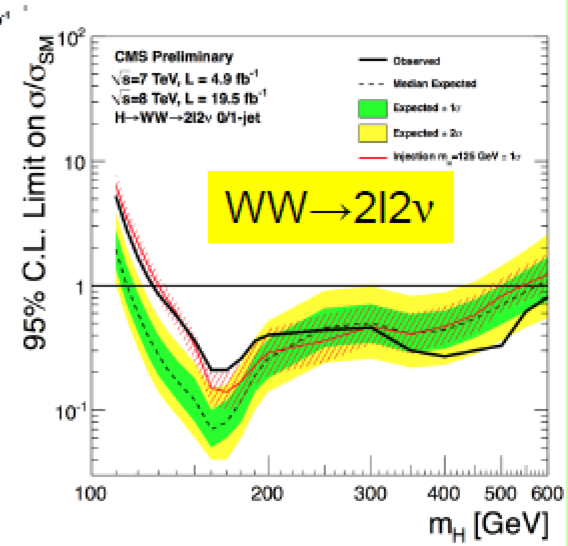
High mass Higgs searches with SM channels WW, ZZ updated with 2012 Statistics

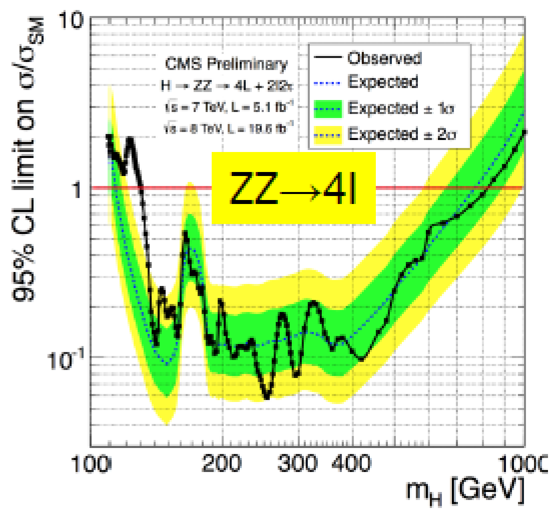
Sensitivity reaches now up to ~ 1 TeV

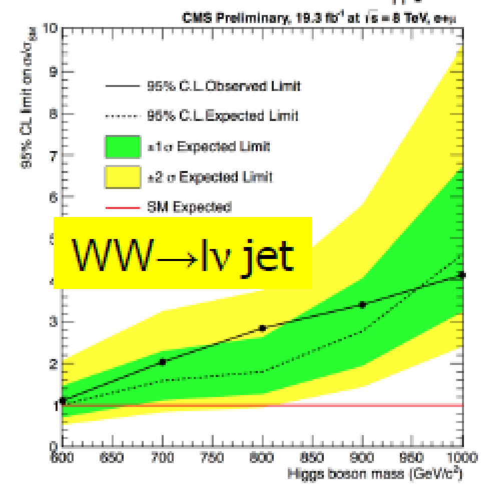
Interpretation of the data in eg EW-singlet models; Benchmark models proposed by the LHC XS WG:

See CMS-PAS-13-008
CMS-PAS-13-014

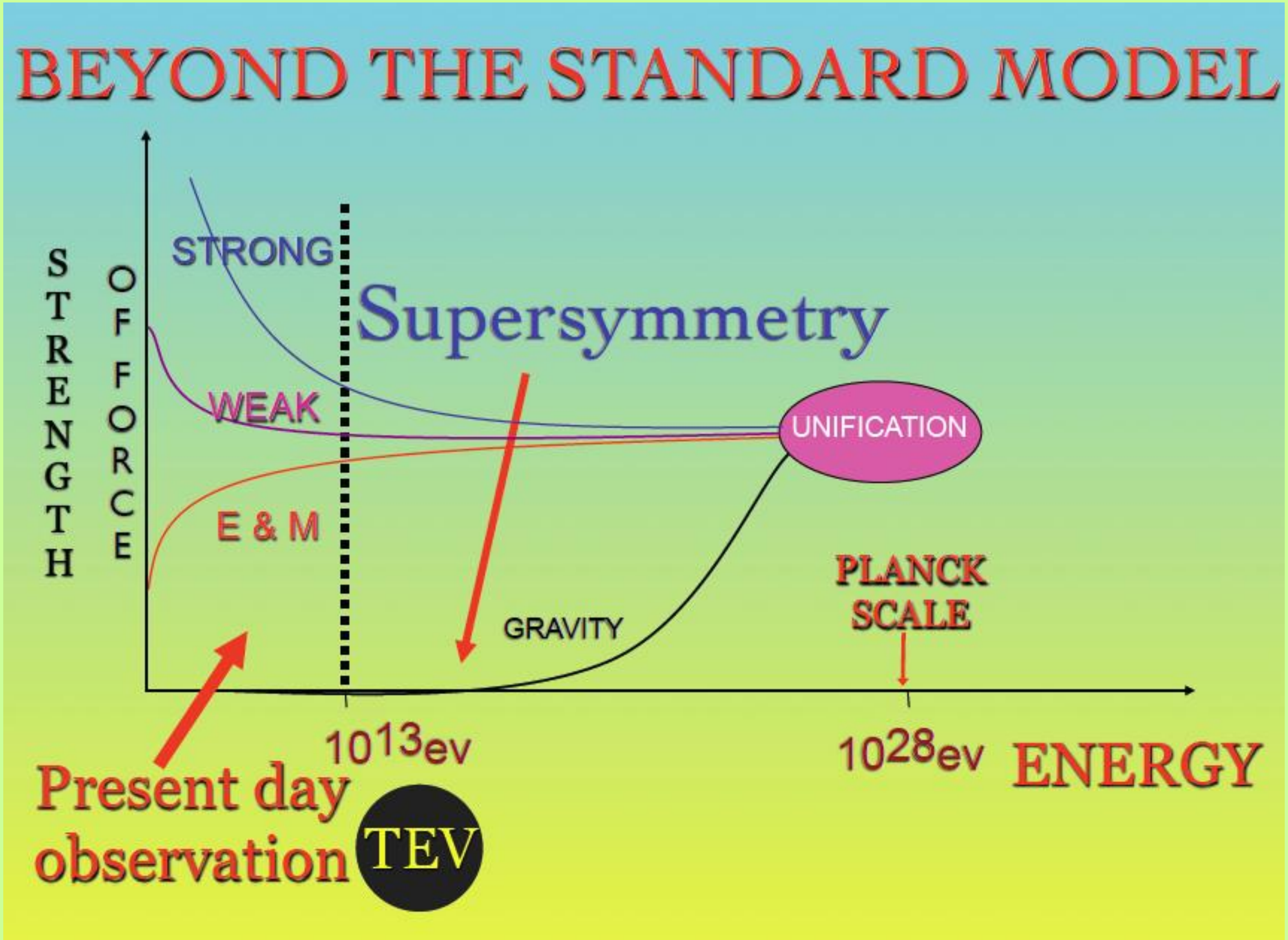




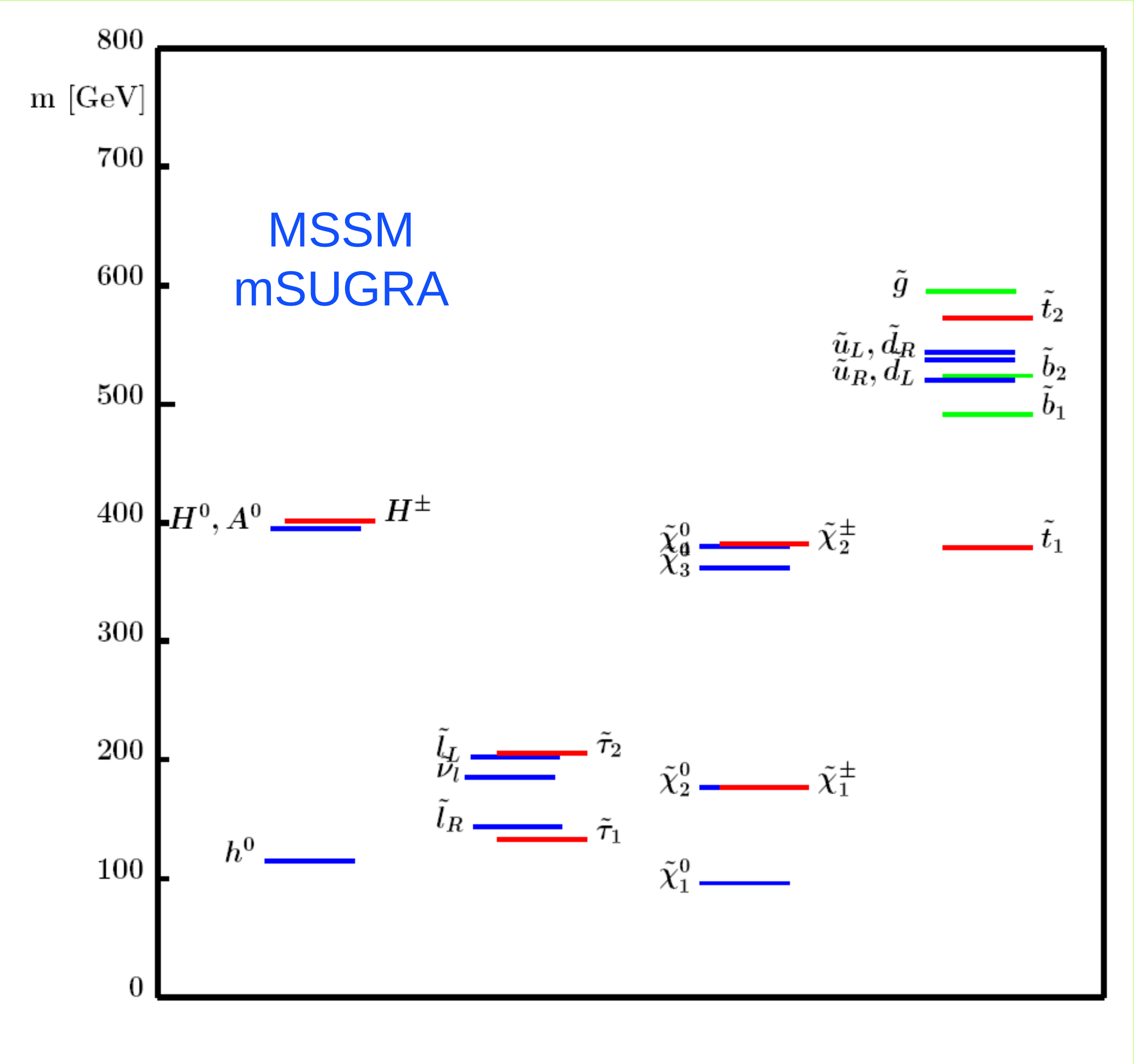




What about supersymmetry?



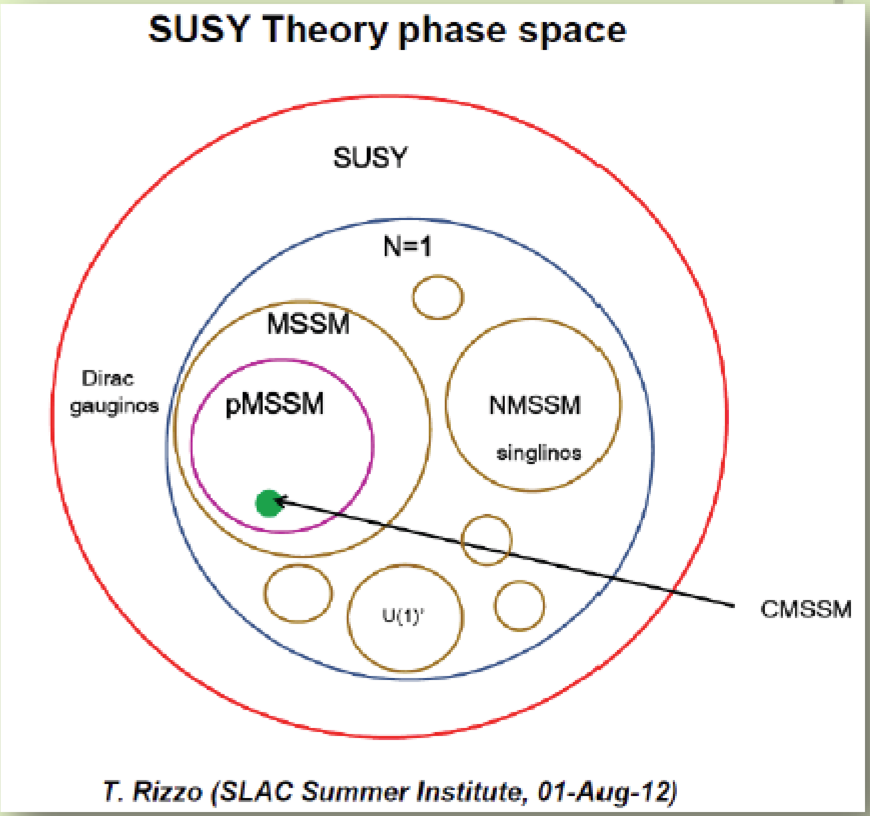
We expect a rich spectrum of new particle



squarks and sgluons heavy yielding long decay chains ending with LSP neutrilino

Supersymmetric Particles <u>NOT</u> ruled out

CMSSM in context



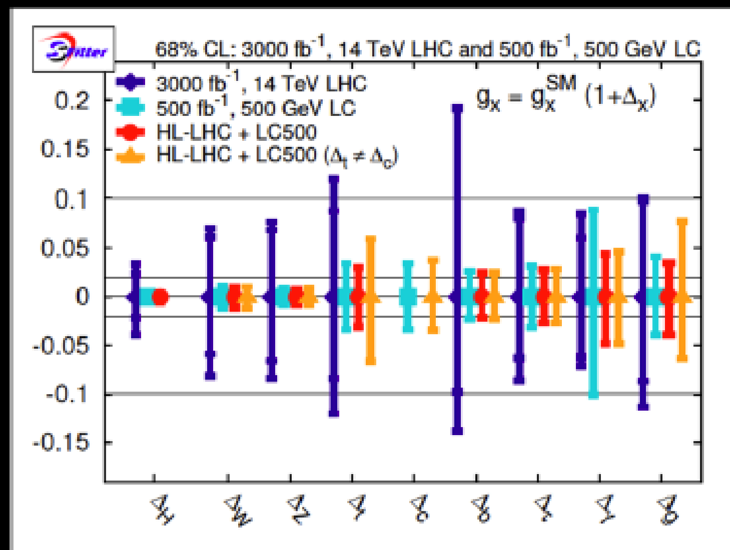
- LHC excludes squarks and gluinos > 1 TeV and > 1.8 TeV respectively in the CMSSM
    - But, this is only really probing a tiny part of a large parameter space

Incandela

ILC Physics Potential

Measurement errors of Higgs couplings

LHC 14 TeV 3000 fb-1 and ILC 500 GeV 500 fb-1



Klute et al
arXiv:1301/1322v2

500 fb^{-1} of ILC@500 GeV
1.8 E34/cm^{2}s : ~3 years
(1 yr = 1E7 s)

Apart from γ, ILC errors are 1/3~1/10 of LHC
(statistical equivalent: 1~2 orders of magnitude more- at about the same cost)

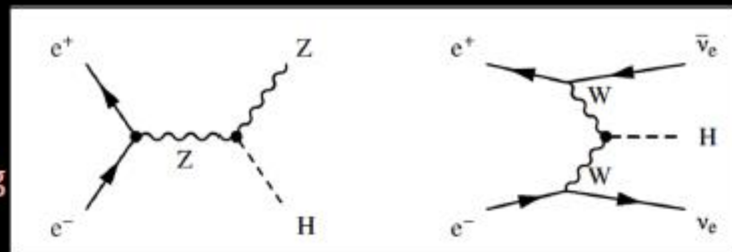
- LHC may improve systematics (both theoretical and experimental)
- ILC by full simulation with bkgs. May improve analysis methods

Great prospect for HEP : ILC and LHC running in parallel!

ILC Physics Potential

ILC @1 TeV

Higgsstrahlung



W fusion

	250 GeV	350 GeV	500 GeV	1 TeV
$\sigma(e^+e^- \to ZH)$	240 fb	129 fb	57 fb	13 fb
$\sigma(e^+e^- \to H\nu_e\bar{\nu}_e)$	8 fb	30 fb	75 fb	210 fb
Int. $\mathcal{L}$	250 fb^{-1}	350 fb^{-1}	500 fb^{-1}	1000 fb^{-1}
# ZH events	60,000	45,500	28,500	13,000
# $H\nu_e\bar{\nu}_e$ events	2,000	10,500	37,500	210,000

Luminosity
each energy for ~3 years

- At higher Ecm
  - W fusion dominant
  - More Higgs
  - New particles !

- Good for Higgs self coupling

  $e+e- \to \nu\nu HH$

  - Effect of irreducible diagrams less important

  $\delta\lambda/\lambda = 0.76\ \delta\sigma/\sigma$ @ 1 TeV

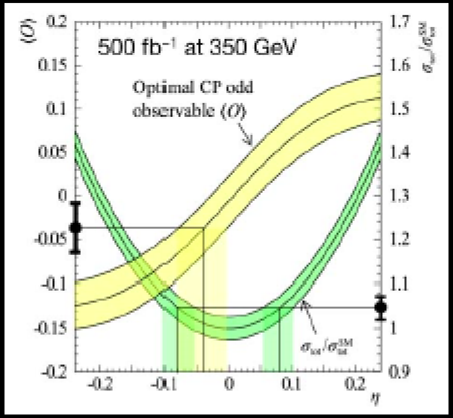
  ($\delta\lambda/\lambda = 1.66\ \delta\sigma/\sigma$ @500 GeV)

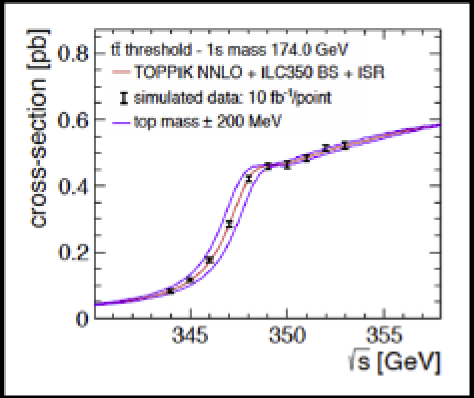
  □ $\delta\lambda/\lambda = 17\%$ (2 ab^{-1} @ 1 TeV)

ILC Physics Potential

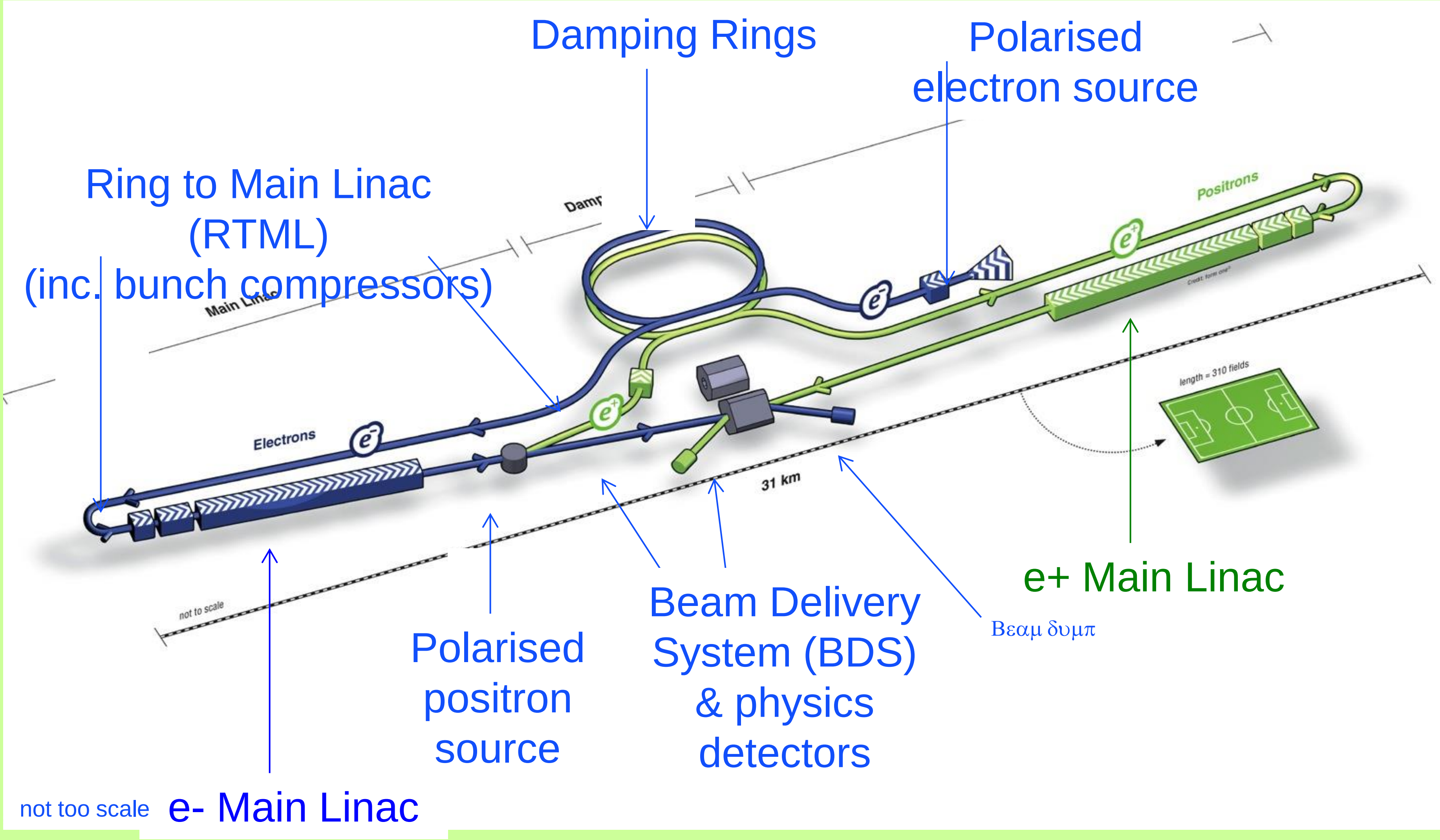
ILC 250~500 GeV

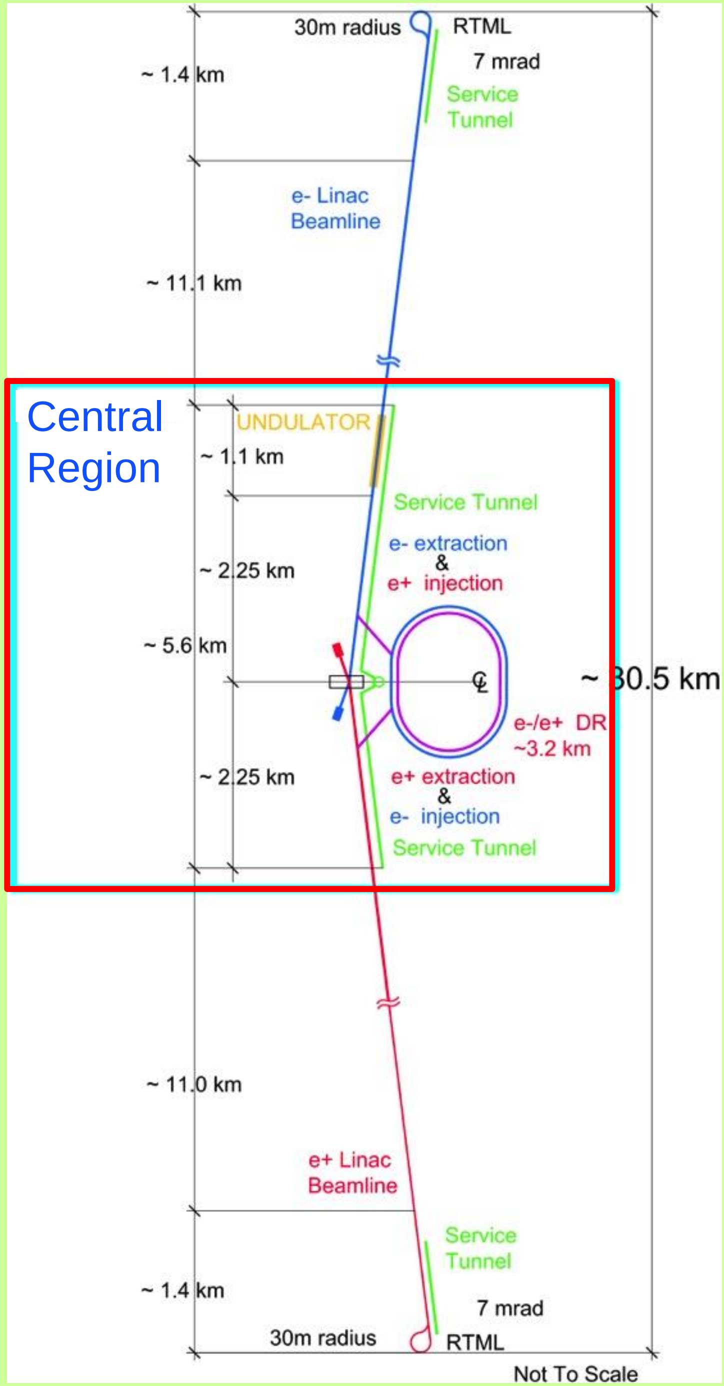
- Higgs
  - Generate ~30K Higgs every year (w/ pol)
    - 5 σ Higgs discovery sensitivity in ~ 1 day
  - Higgs Brs (table later)
    - $H \rightarrow cc$, invisible; & model independent
  - Γ_{tot} to 5%
    - $Br(H \rightarrow WW)$ & g(HWW) by e+e- $\rightarrow \nu\nu H$
    - $Br(H \rightarrow ZZ)$ & g(HZZ) by e+e- $\rightarrow$ HZ
  - CP to 3~4% (on mixing coeff)
- top
  - m_t(msbar) to 100 MeV
  - Anomalous ttZ, tbW, ttg coupl
- New physics through SM
  - Composite Higgs scale to 45 TeV
  - Anomalous WWV coupl
- New unexpected particles!





ILC Technical Design Report Layout

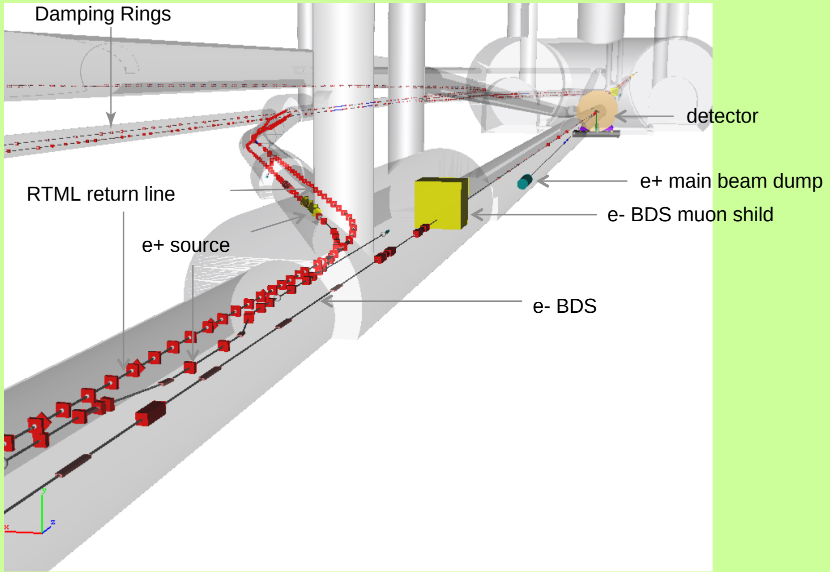




Central Region

- 5.6 km region around IR
- Systems:
  - » electron source
  - » positron source
  - » beam delivery system
  - » RTML (return line)
  - » IR (detector hall)
  - » damping rings

  (electron source through IR (detector hall): **common tunnel**)
- Complex and crowded area



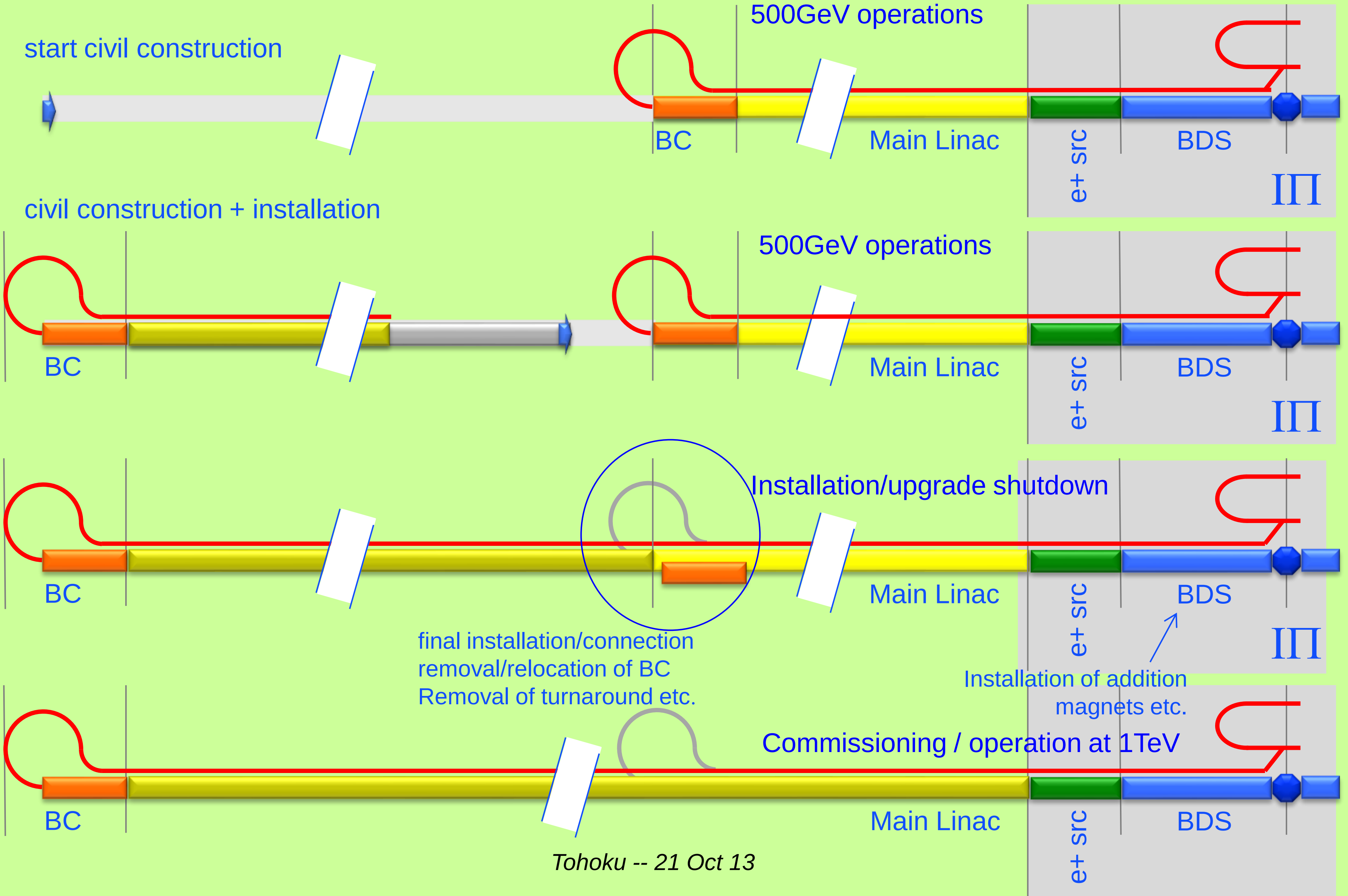
Luminosity Upgrade

- **Concept: increase n_b from 1312 → 2625**
  - » **Reduce linac bunch spacing 554 ns → 336 ns**

- **Doubles beam power → ×2 L = 3.6×10^{34} cm^{-2}s^{-1}**

- **AC power: 161 MW → 204 MW (est.)**
  - » **shorter fill time and longer beam pulse results in higher RF-beam efficiency (44% → 61%)**

Energy (TeV) upgrade



Upgrades - Energy

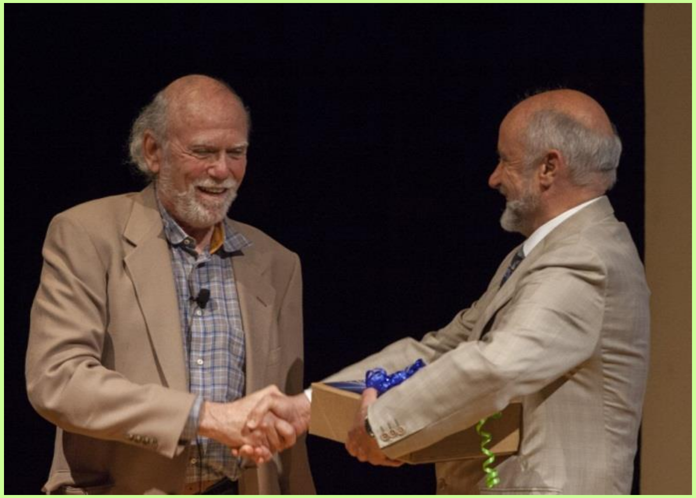
Energy upgrade scenarios – Chapter 12

		500 GeV Baseline	TeV Upgrade			
			Scenario A	Scenario B		Scenario C
				upgrade	base	
Energy range	GeV	15–250	15–500	15–275	275–500	15–500
Gradient	MV/m	31.5	31.5	45	31.5	45
Num. of cavities		7400	15 280	8190	7090	10 700
				total cavities: 15280		
Linac length	km	12	25	9.5	11.5	17.5
				total length: 21.0		

- Upgrading the beam energy will require extending the main SCRF linacs to provide the additional 250 GeV per beam.
- The beam current for the TeV upgrade (7:6 mA), less than that for the luminosity upgrade (8:8 mA)
- The cost of an energy upgrade is completely dominated by the extension of the main linacs and the time-dependent choice of accelerating gradient. (present three scenarios)

The International Linear Collider

- International Consensus for the next energy frontier particle accelerator (eg. TeV scale e+e-)
- ICFA – Determined the physics goals to complement LHC; chose the technology superconducting RF; oversaw the design effort
- Mature technical design; cost; technical readiness – June 2013
- Lyn Evans (CERN LHC
- Project Director) became
- ILC project leader



Higgs Factory - Staged ILC

250 GeV (Higgs Factory) → 500 GeV baseline → 1 TeV

- **TDR Table 12.1** presents primary parameters for a 250 GeV CM first stage, the luminosity upgrade for the 500 GeV baseline machine, and the two parameter sets for the TeV upgrade: low Beamstrahlung (A) and high Beamstrahlung (B). The baseline 500 GeV parameters are included for reference.

- The initial 250 GeV stage (Light Higgs Factory) needs a re-evaluation of machine parameters for cost-performance optimization at that energy.

Japanese plans: ILC and a "Science City"

Staged ILC – Higgs Factory

- **Staged proposal, beginning as a Higgs factory, increases to top, 500 GeV, 1 Tev**