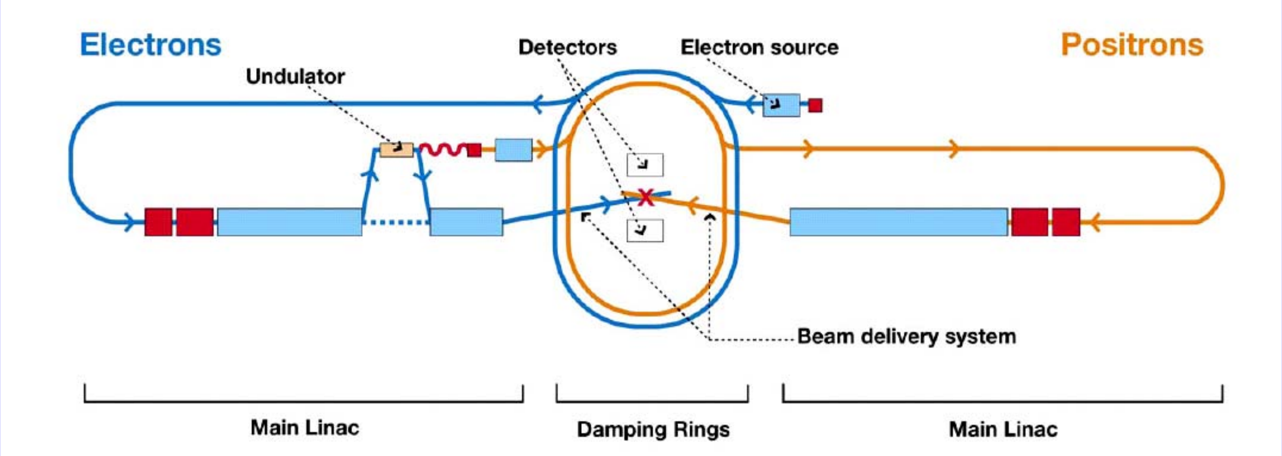
The Art and Science of Planning for the *International Linear Collider*



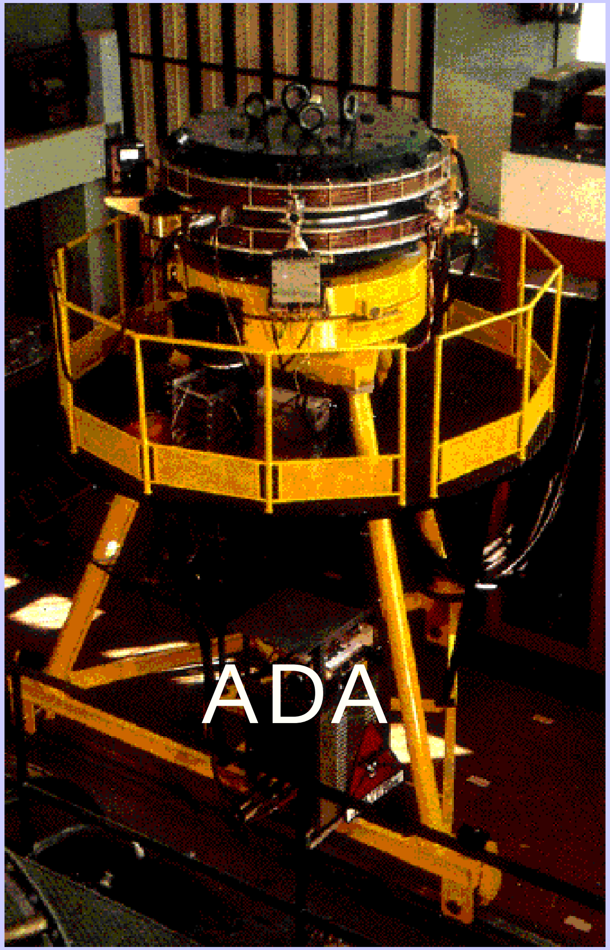
Barry Barish
Caltech

CERN Colloquium
13-Nov-07

Exploring the Terascale
the tools

- **LHC**
  - It will lead the way and has large reach
  - Quark-quark, quark-gluon and gluon-gluon collisions at 0.5 - 5 TeV
  - Broadband initial state
- **Lepton Collider**
  - A second view with high precision
  - $\ell^+\ell^-$ collisions with fixed energies, adjustable between 0.1 and 1.0 TeV (or higher??)
  - Well defined initial state
- **Together, these are our tools for the terascale**

Electron-Positron Colliders

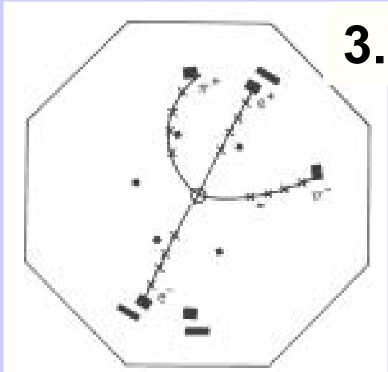


Bruno Touschek built the first successful electron-positron collider at Frascati, Italy (1960)

Eventually, went up to 3 GeV

But, not quite high enough energy ....

SPEAR at SLAC

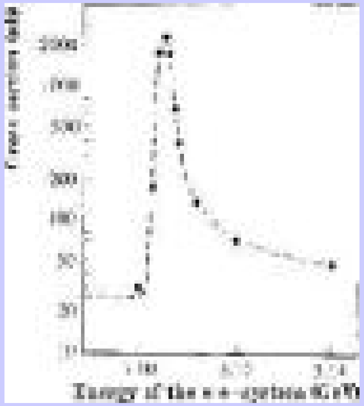


3.1 GeV

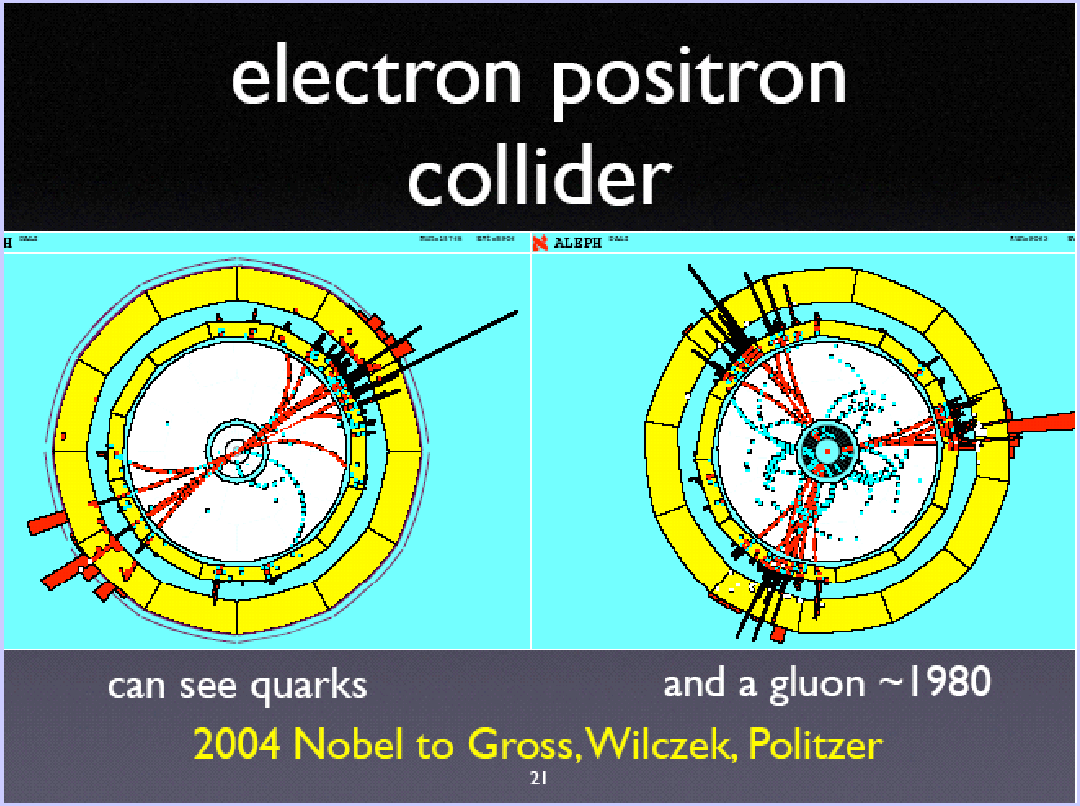
Burt Richter
Nobel Prize

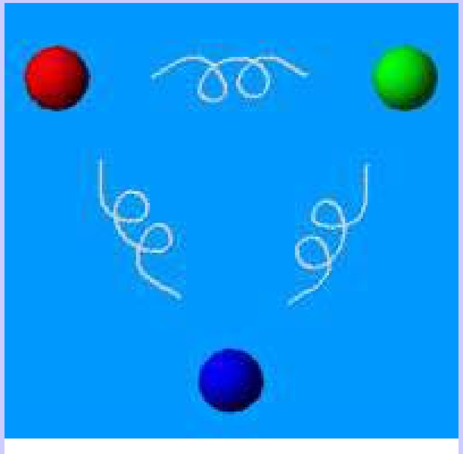
and

Discovery
Of
Charm
Particles



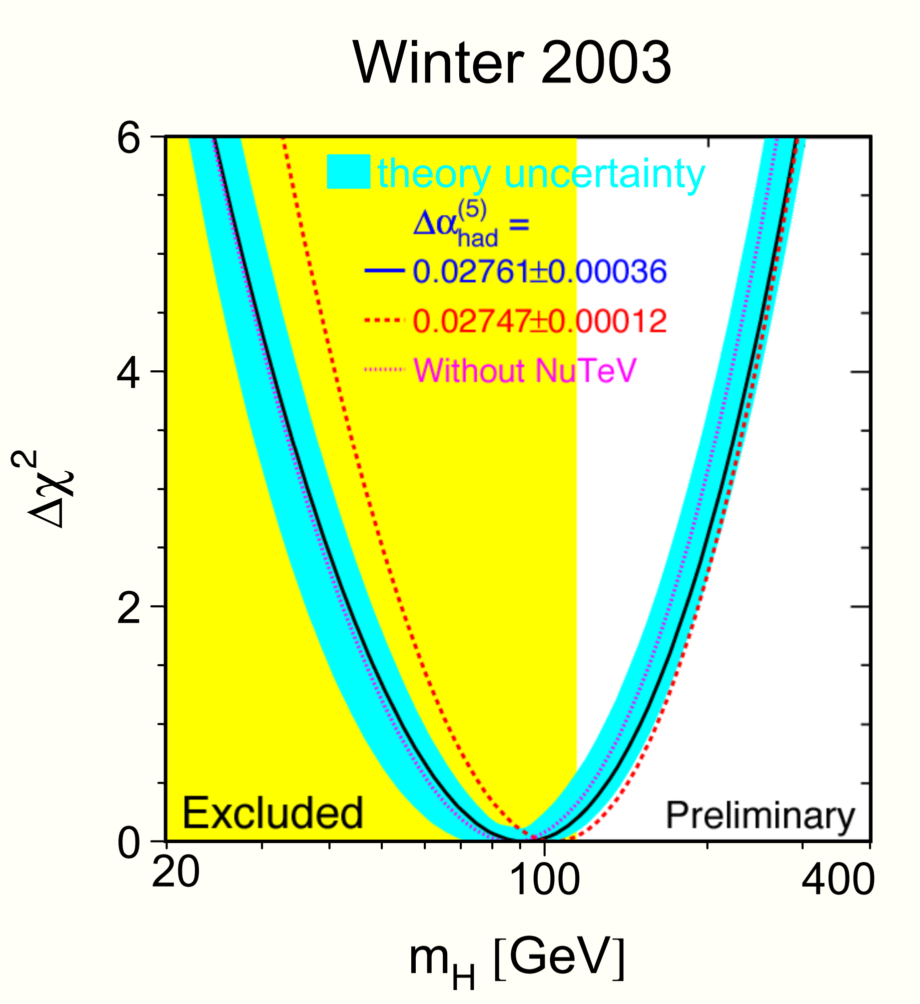
The rich history for e^+e^- continued as higher energies were achieved …





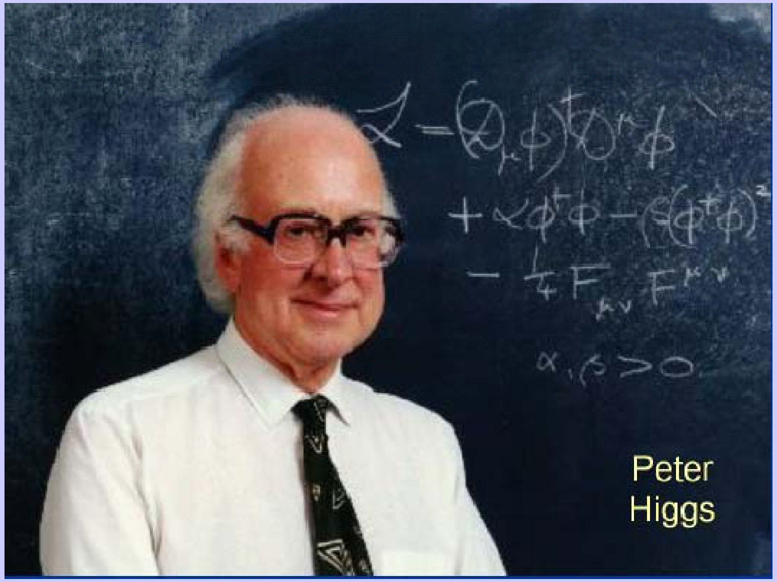
DESY PETRA Collider

And also at LEP, where the stage has been set for the terascale



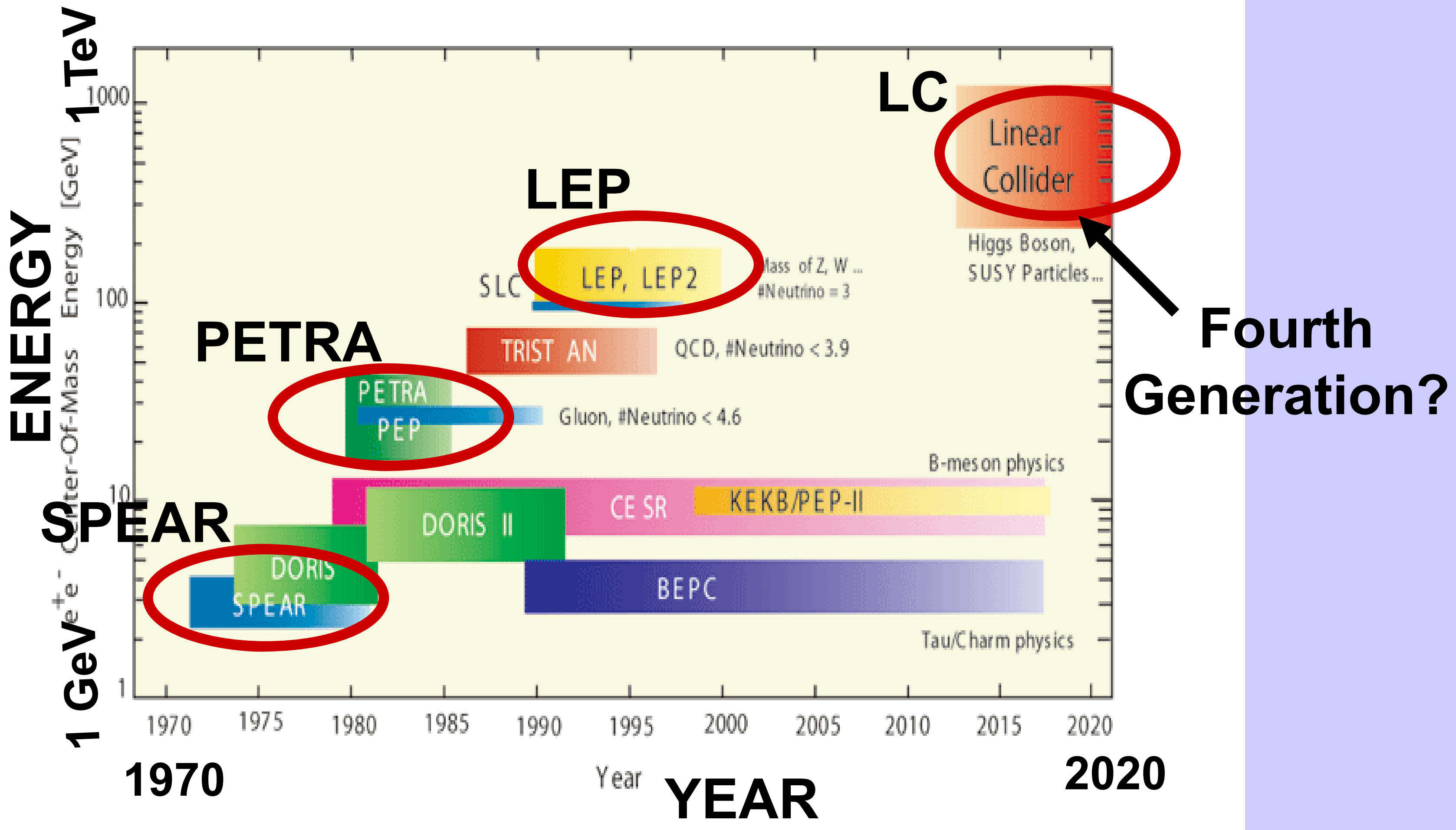
What causes mass??

The mechanism – Higgs or alternative appears around the corner



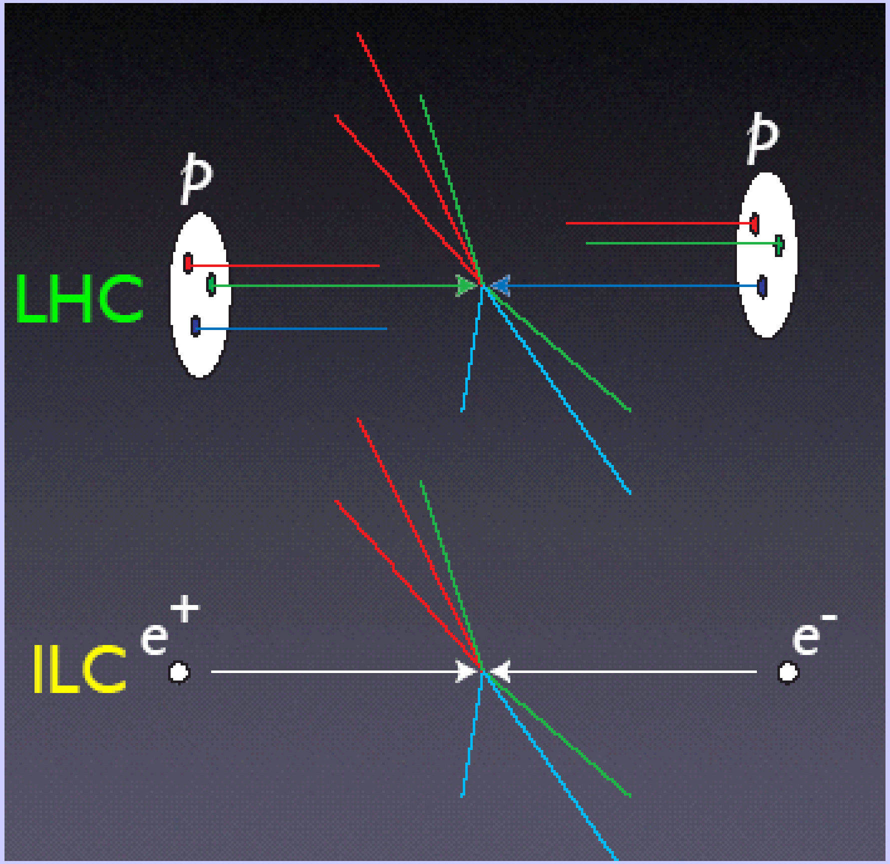
Three Generations of Lepton Colliders

The Energy Frontier



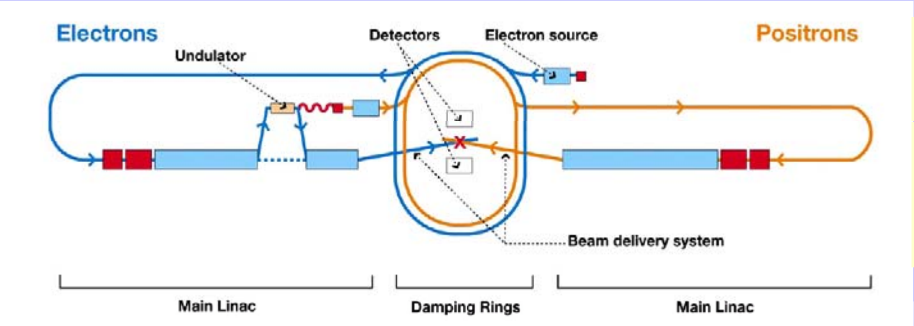
Why a Lepton Collider?

- elementary particles
- well-defined
  - energy,
  - angular momentum
- uses full COM energy
- produces particles democratically
- can mostly fully reconstruct events



Possible TeV Scale Lepton Colliders

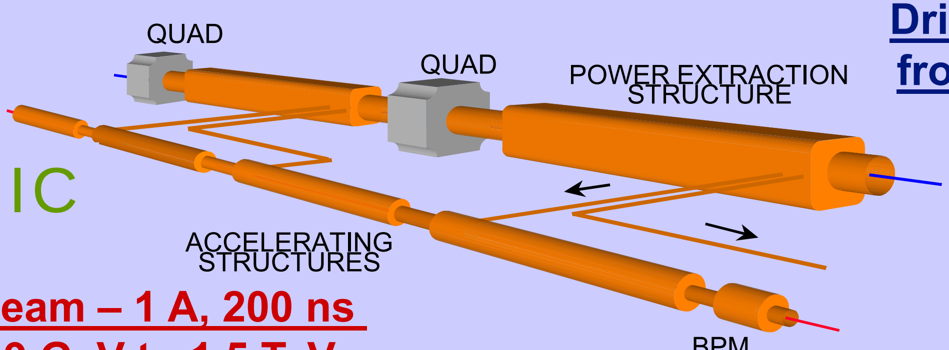
ILC



ILC < 1 TeV
Technically possible
~ 2019

Drive beam - 95 A, 300 ns
from 2.4 GeV to 240 MeV

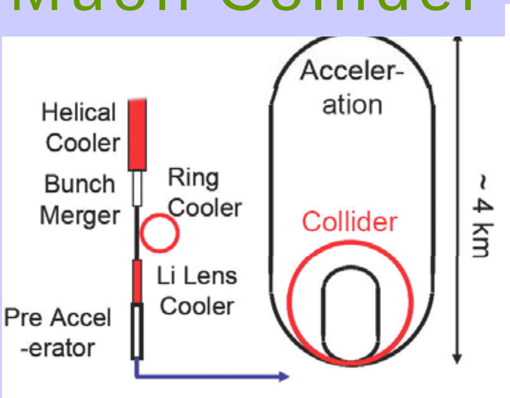
CLIC



Main beam – 1 A, 200 ns
from 9 GeV to 1.5 TeV

CLIC < 3 TeV
Feasibility?
ILC + 5-10 yrs

Muon Collider



Much R&D Needed
- **Neutrino Factory R&D +**
- **bunch merging**
- **much more cooling**
- **etc**

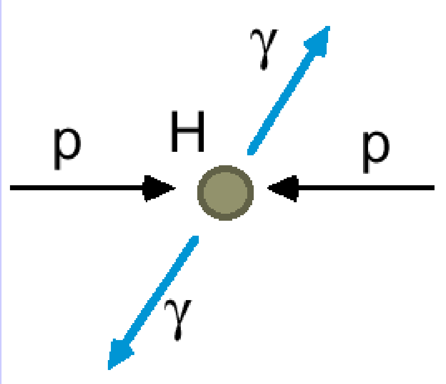
Muon Collider
< 4 TeV
FEASIBILITY??
ILC + 15 yrs?

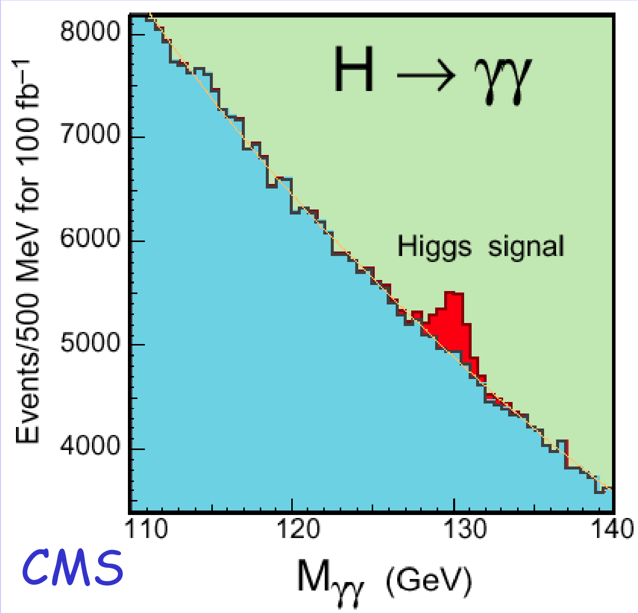
Strategies toward TeV Scale Lepton Collider

- **Assuming LHC reveals the new physics we all anticipate,**
  - **We will want complementary lepton collider for precision measurements**
- **Time scales dictate vigorously investing toward that goal now**
  - **If LHC physics justifies a < 1 TeV machine, ILC can be ready to build as the next big HEP machine**
  - **If LHC physics demands a > 1 TeV machine, CLIC may be the answer with a longer time scale, depending on "feasibility"**
  - **The alternative muon collider is also a long term possibility, if "FEASIBLE"**

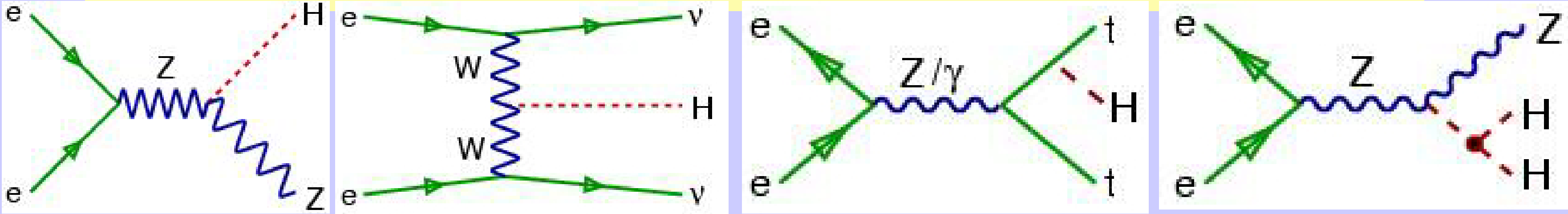
LHC: Low mass Higgs: $H \to \gamma\gamma$
$M_H < 150\ GeV/c^2$

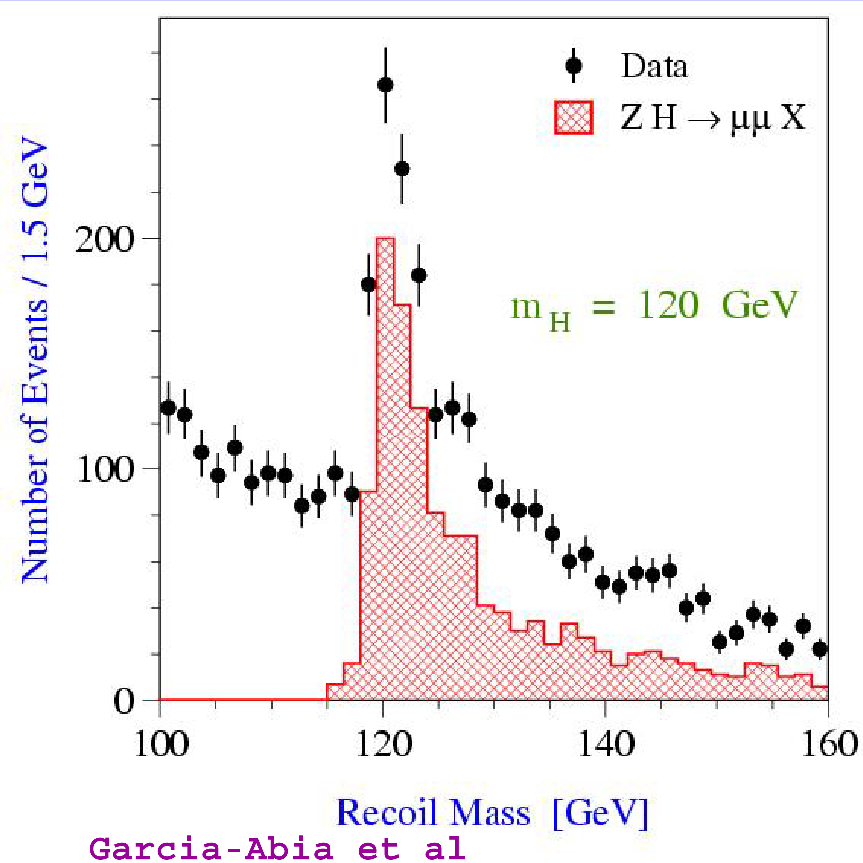
- **Rare decay channel: BR ~ 10^{-3}**
- **Requires excellent electromagnetic calorimeter performance**
  - **acceptance, energy and angle resolution,**
  - **γ/jet and γ/π^0 separation**
  - **Motivation for LAr/$PbWO_4$ calorimeters for CMS**
- **Resolution at 100 GeV: $\sigma \approx 1$ GeV**
- **Background large: S/B ≈ 1:20, but can estimate from non signal areas**





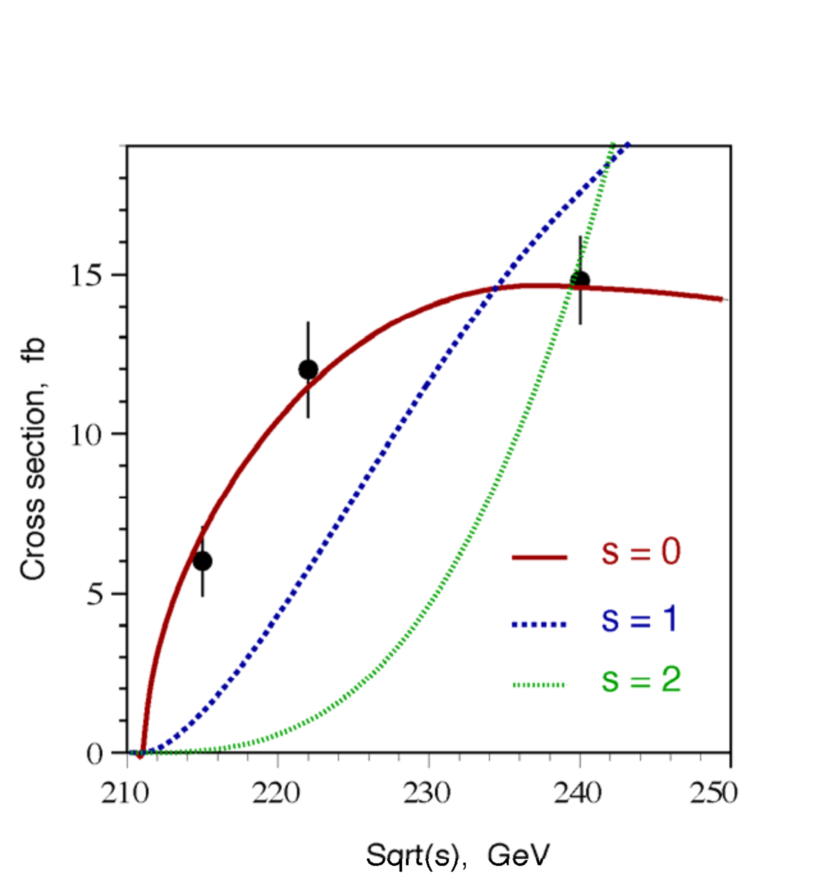
ILC: Precision Higgs physics





- **Model-independent Studies**
  - **mass**
  - **absolute branching ratios**
  - **total width**
  - **spin**
  - **top Yukawa coupling**
  - **self coupling**
- **Precision Measurements**

How do you know you have discovered the Higgs ?

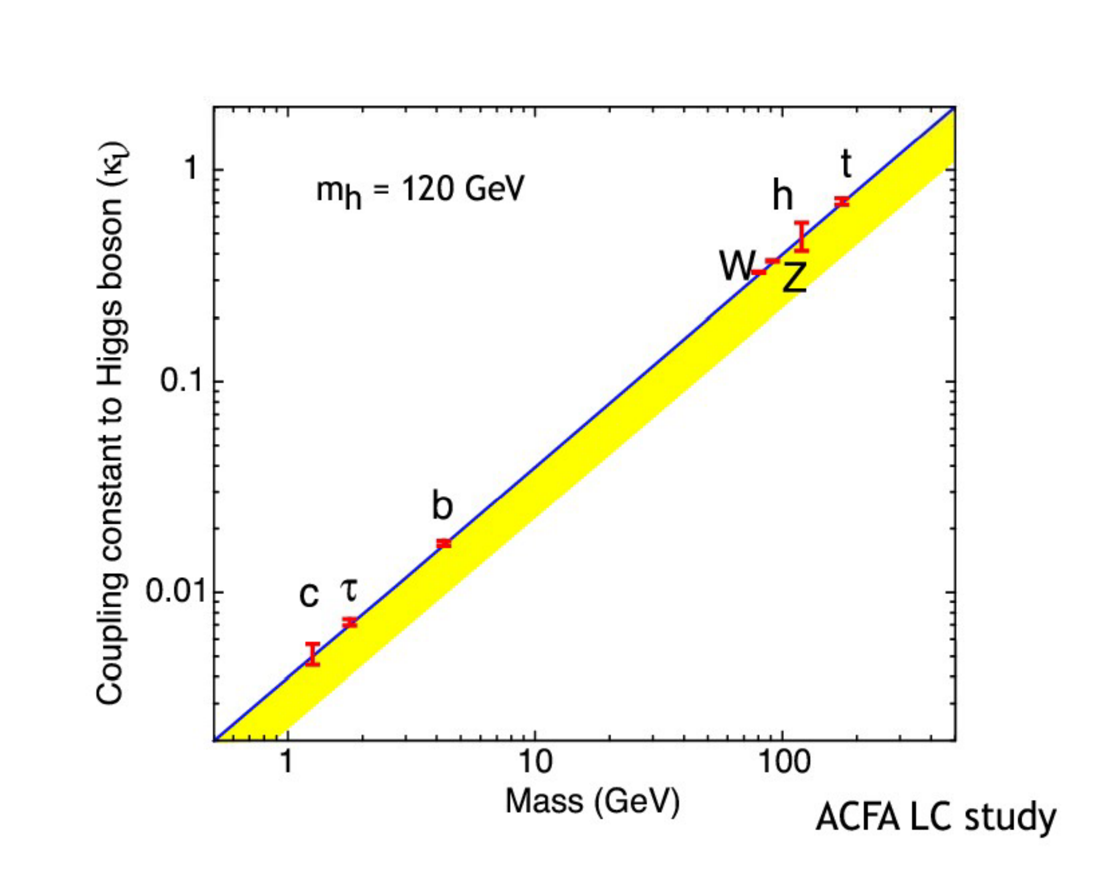


Measure the quantum numbers. The Higgs must have spin zero !

The linear collider will measure the spin of any Higgs it can produce by measuring the energy dependence from threshold

What can we learn from the Higgs?

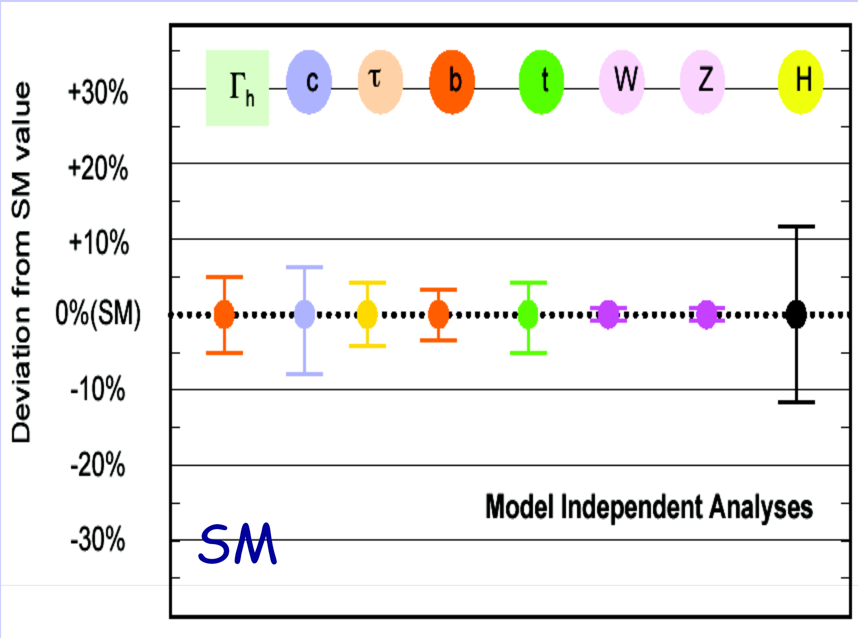
Precision measurements of Higgs coupling



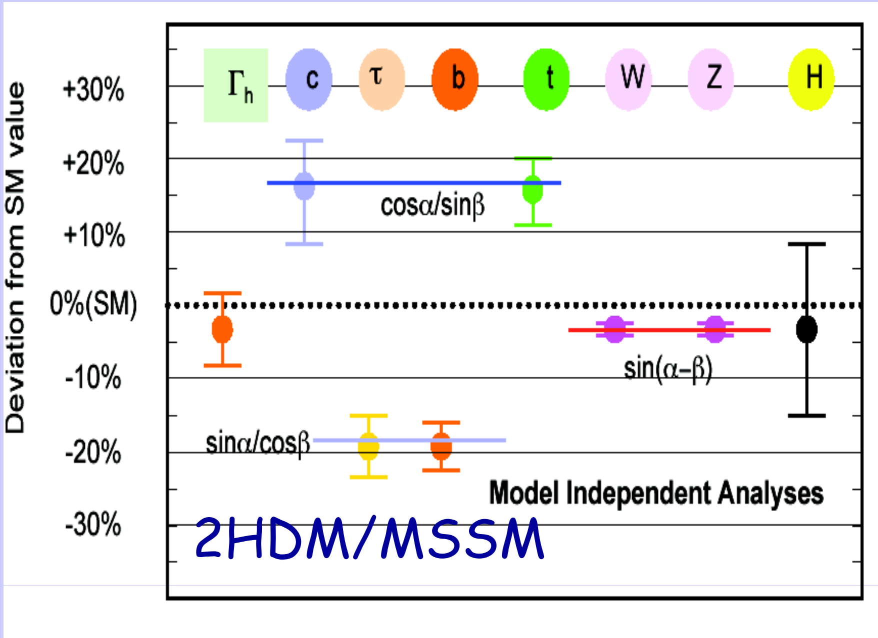
Higgs Coupling strength is proportional to Mass

e^+e^- : Studying the Higgs

determine the underlying model



Yamashita et al

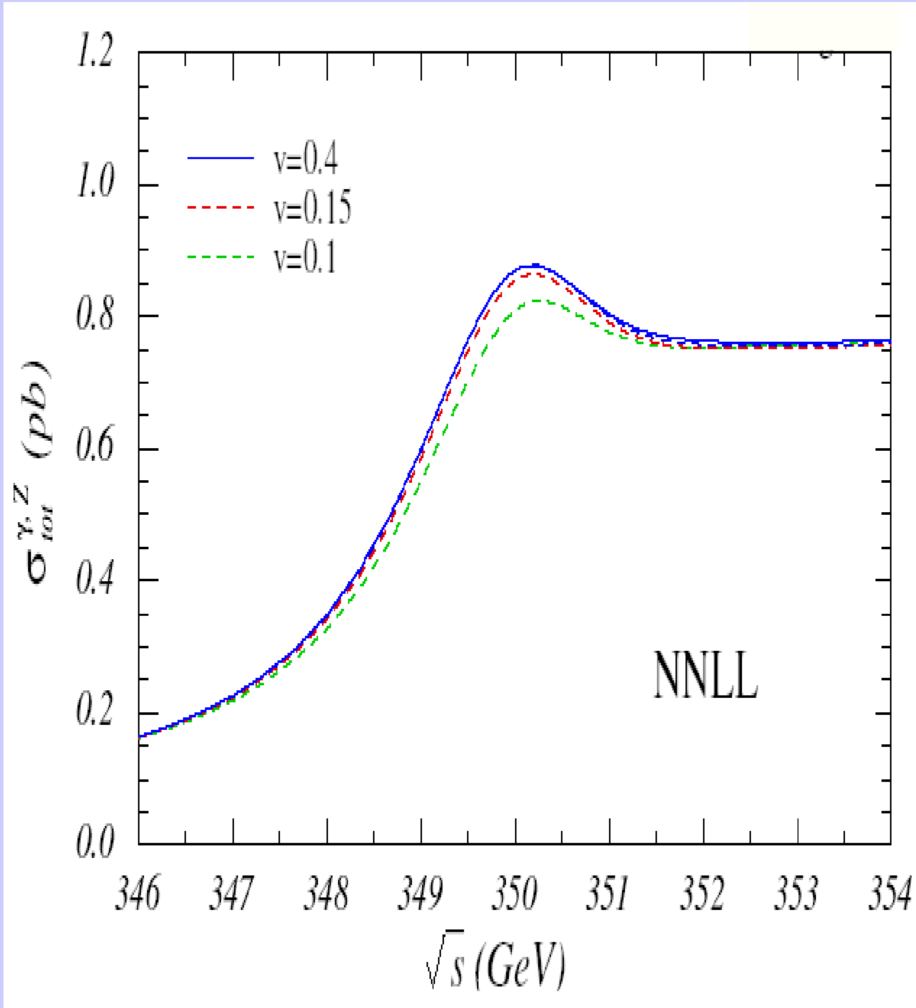


Zivkovic et al

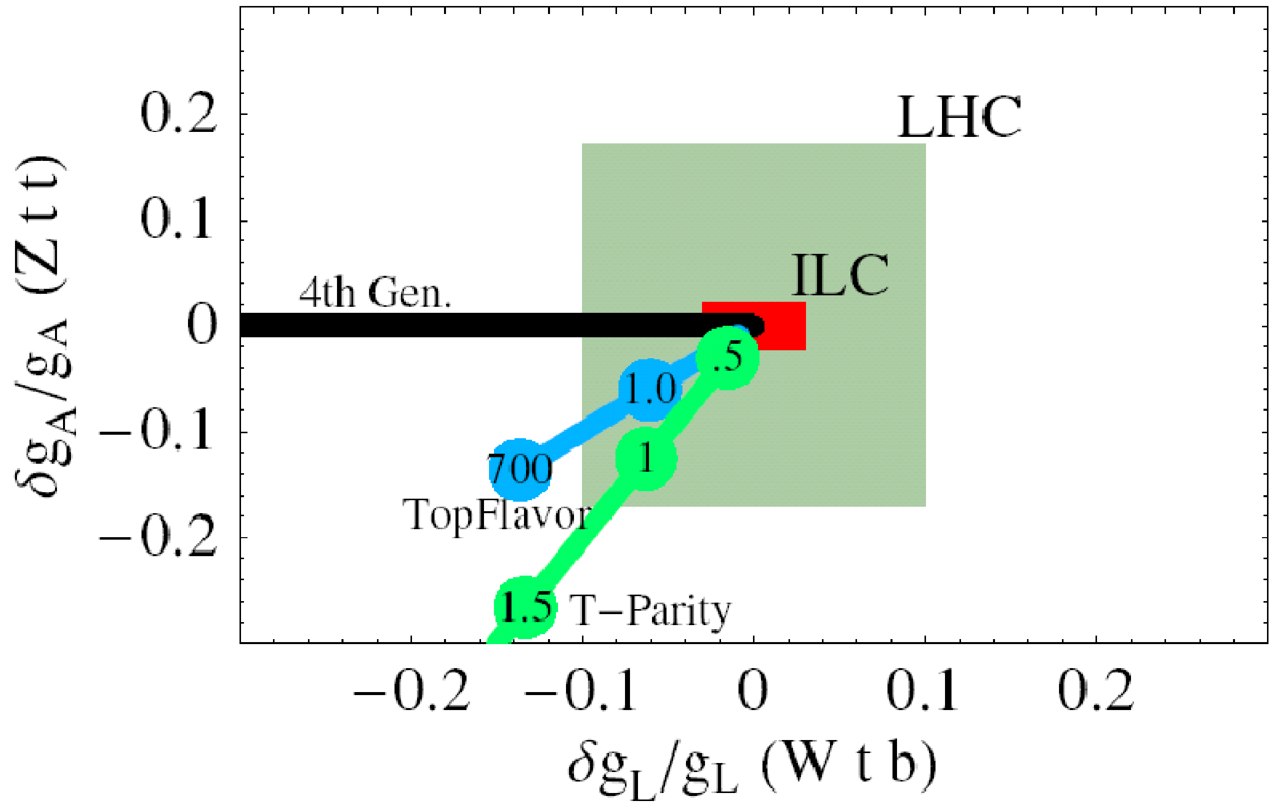
Top Quark Measurements

Threshold scan provides mass measurement

Theory (NNLL) controls m_t(MS) to 100 MeV

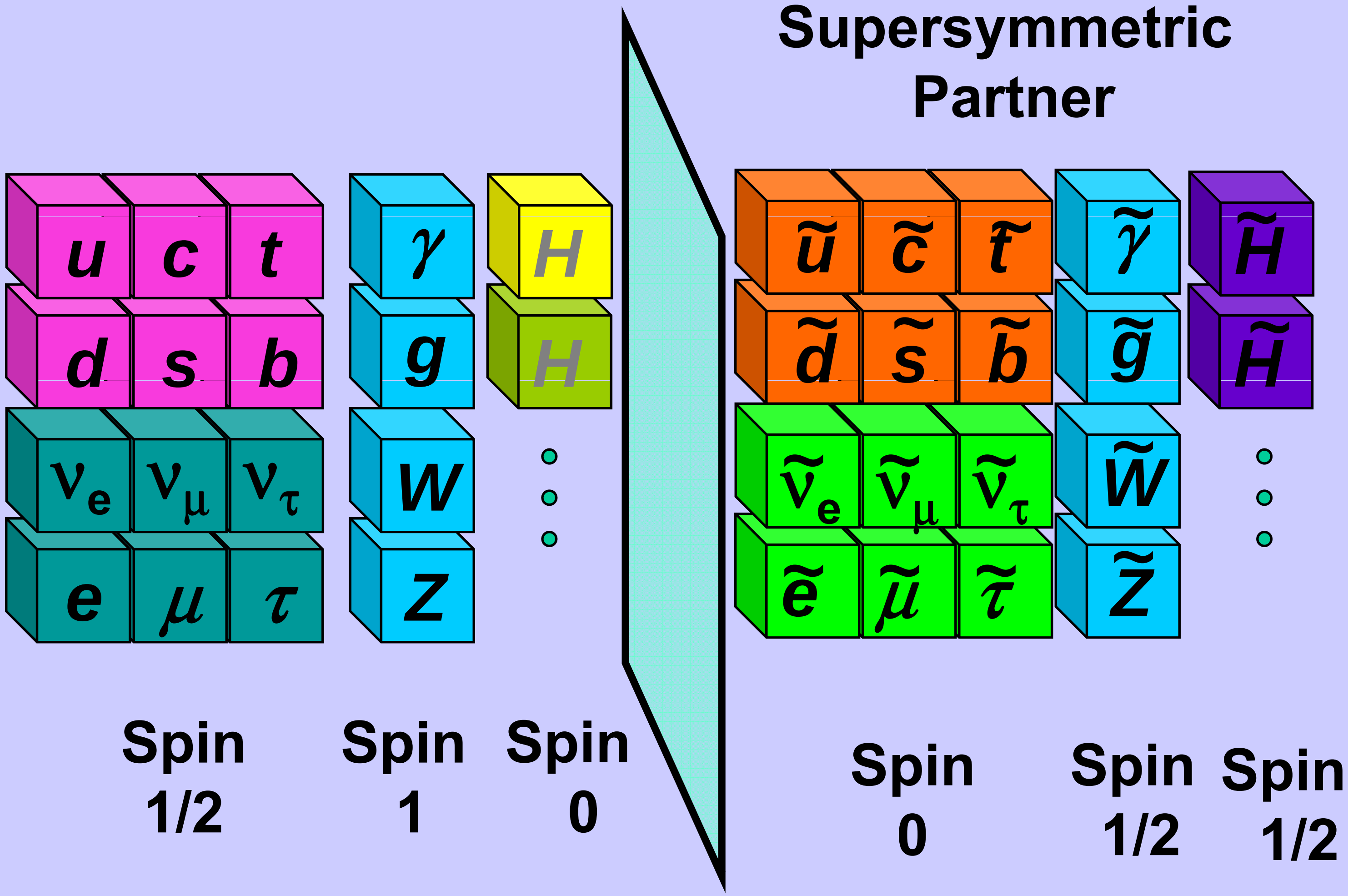


Top Quark Measurements



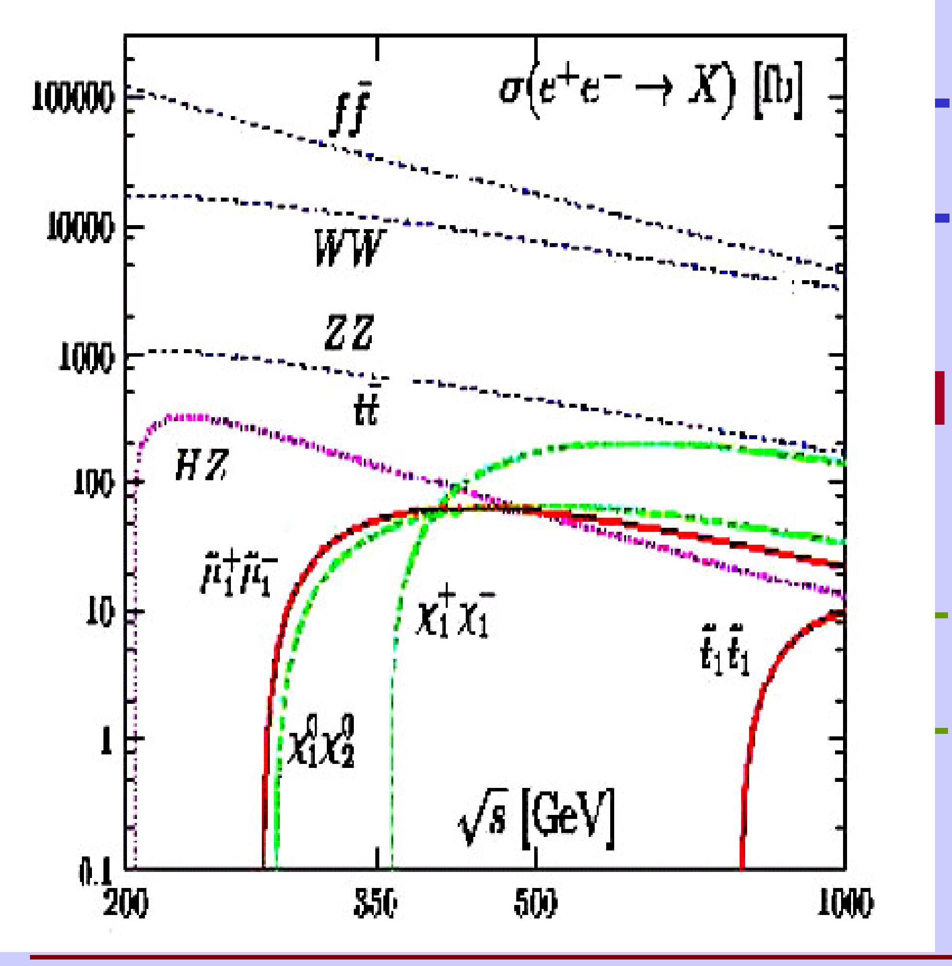
Bounds on axial ttbarZ and left handed tbW for LHC and ILC compared to deviations in various models

Supersymmetry



Supersymmetry

e^+e^- production crosssections



- Measure quantum numbers
- Is it MSSM, NMSSM, …?
- How is it broken?

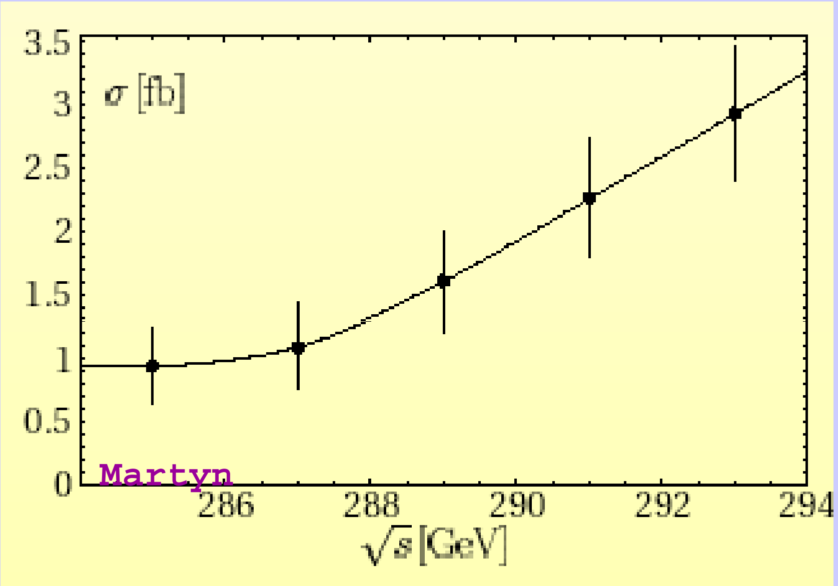
ILC can answer these questions!

- tunable energy
- polarized beams

Supersymmetry

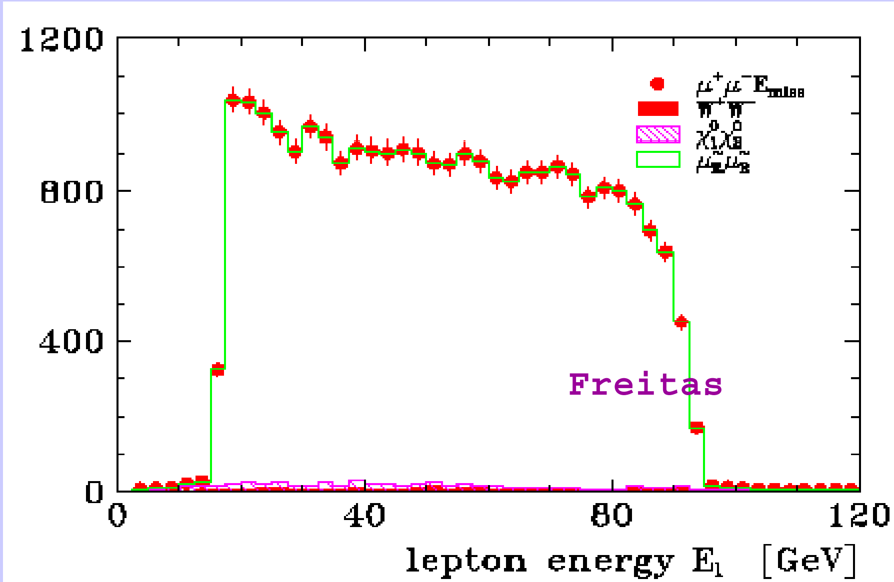
Two methods to obtain absolute sparticle masses:

Kinematic Threshold:



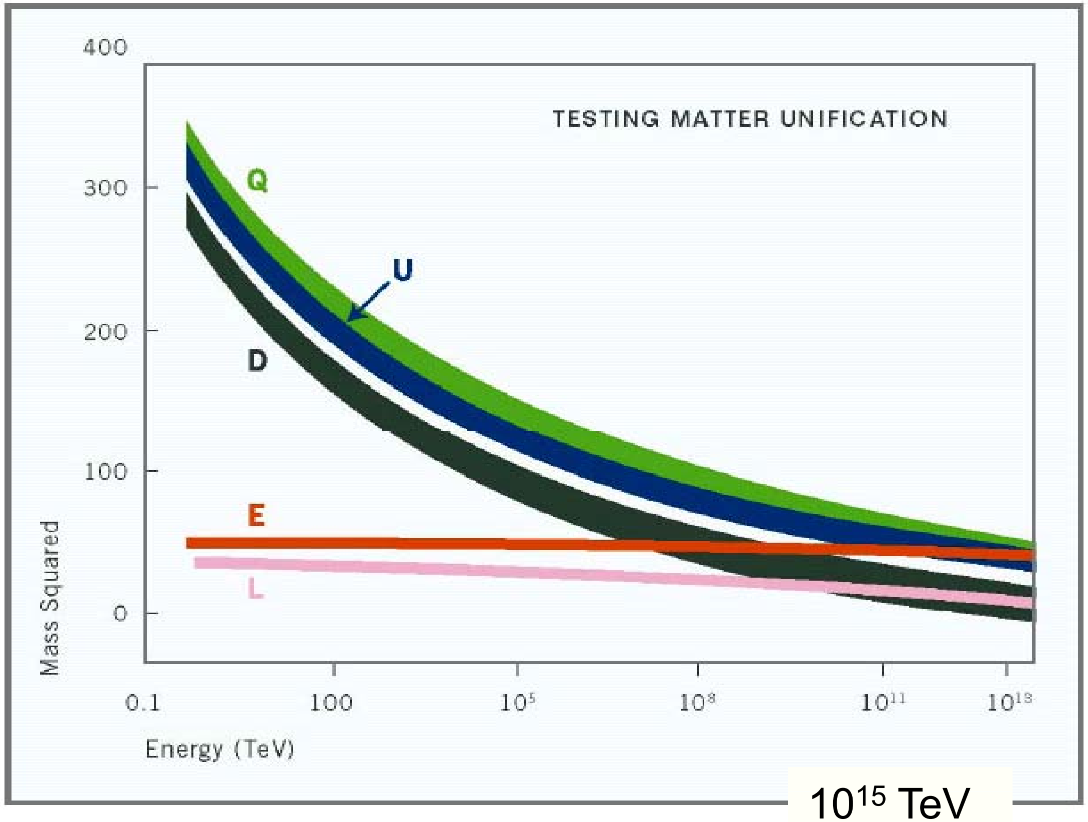
Determine SUSY parameters without model assumptions

In the continuum



Minimum and maximum determines masses of primary slepton and secondary neutralino/chargino

Supersymmetry
quark and lepton unification

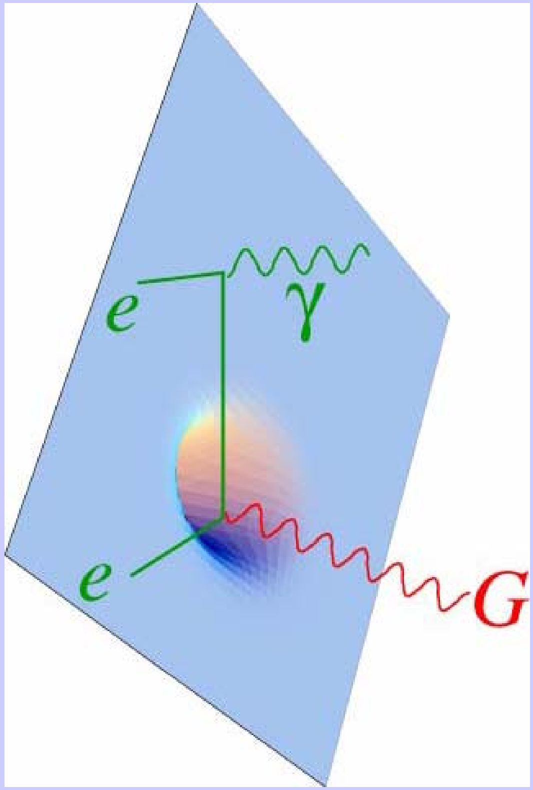


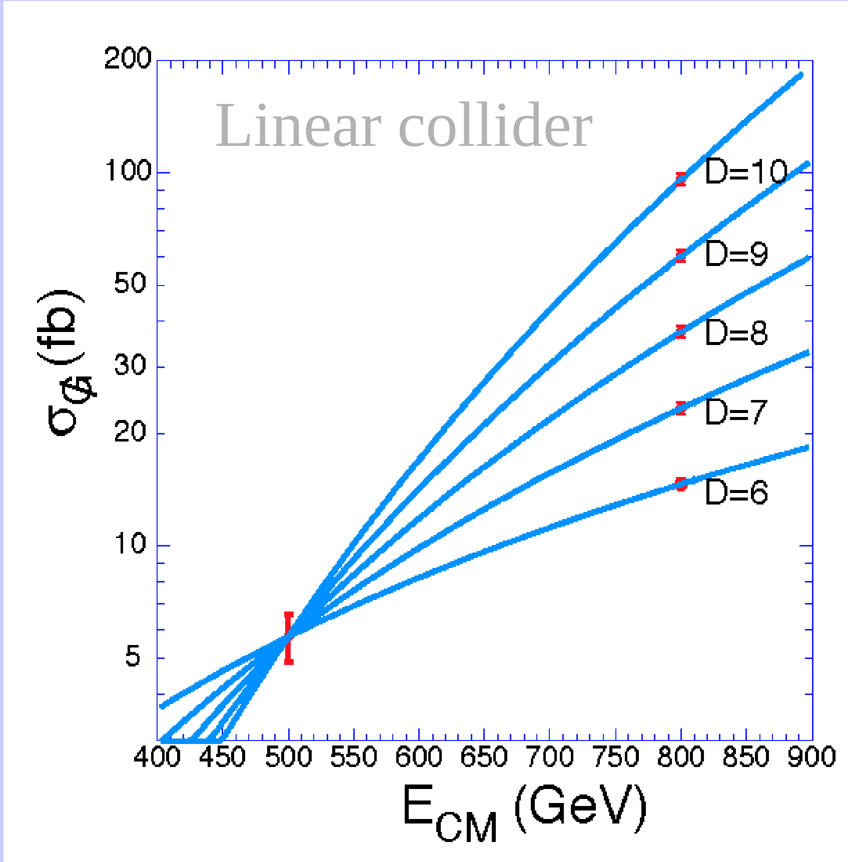
10^{15} TeV

Do Quarks and Leptons also Unify?

- **Predicted in most models**
- **Can be tested at the ILC**

Direct production from extra dimensions ?

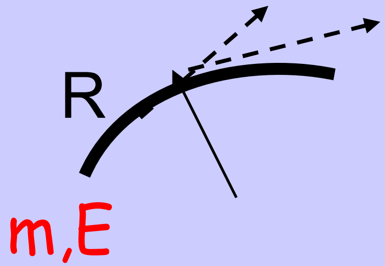




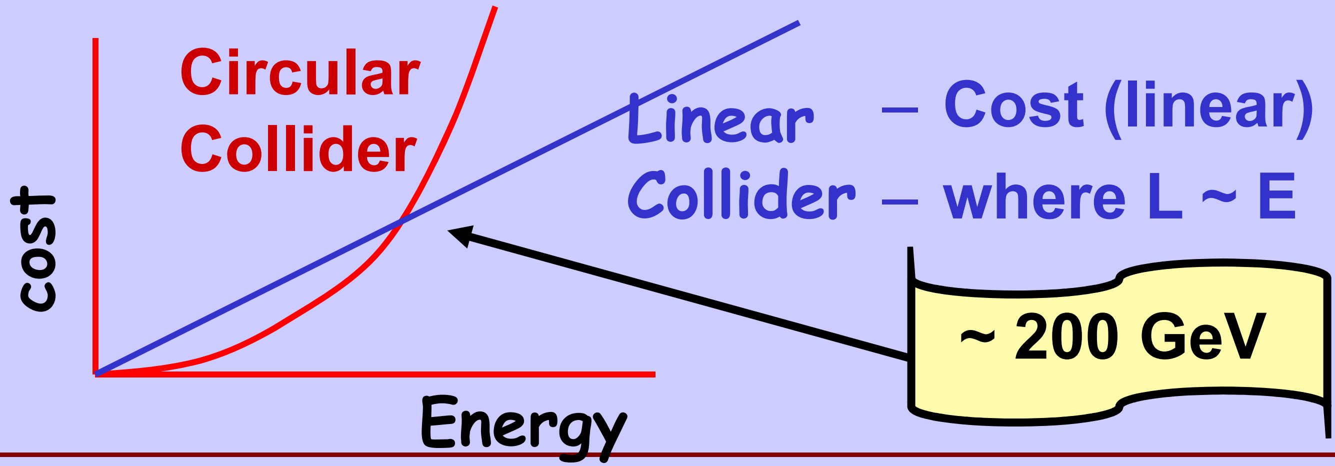
New space-time dimensions can be mapped by studying the emission of gravitons into the extra dimensions, together with a photon or jets emitted into the normal dimensions.

Why Linear?

- **Circular Machine**
  - $\Delta E \sim (E^4 / m^4 R)$
  - Cost ~ a R + b ΔE
    ~ a R + b $(E^4 / m^4 R)$
  - Optimization : $R \sim E^2$ ⇒ Cost ~ c E^2



Synchrotron Radiation



– Cost (linear) ~ a′ L
– where L ~ E

How the physics defines the ILC

Parameters for the Linear Collider

September 30, 2003

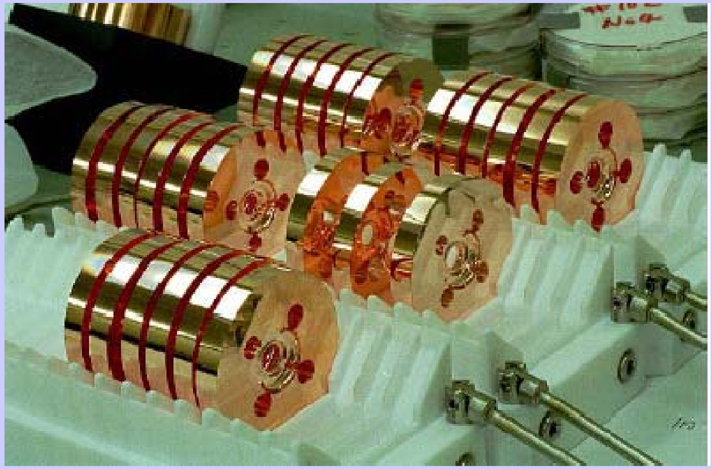
Parameters for the ILC

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

- The machine must be upgradeable to 1 TeV

ILC – Underlying Technology

- **Room temperature copper structures**



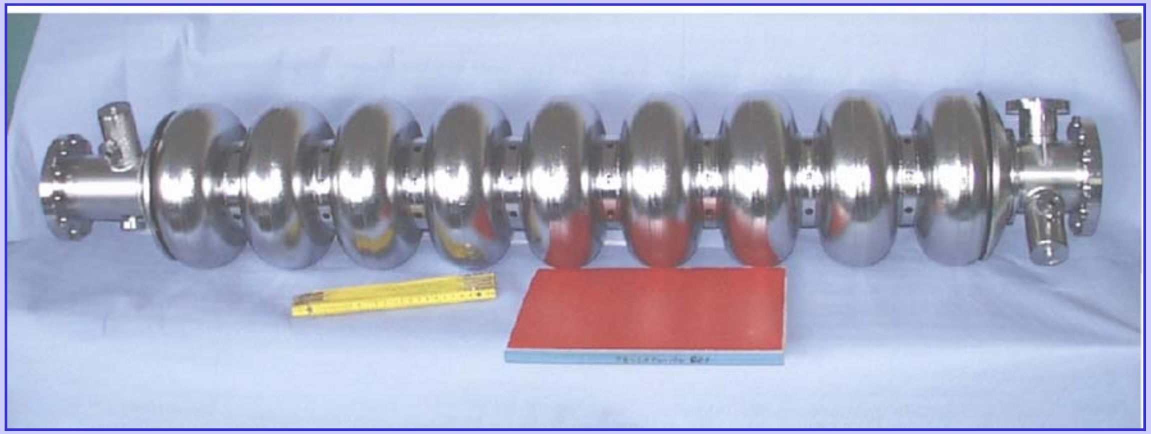
OR

- **Superconducting RF cavities**

SCRF Technology Recommendation

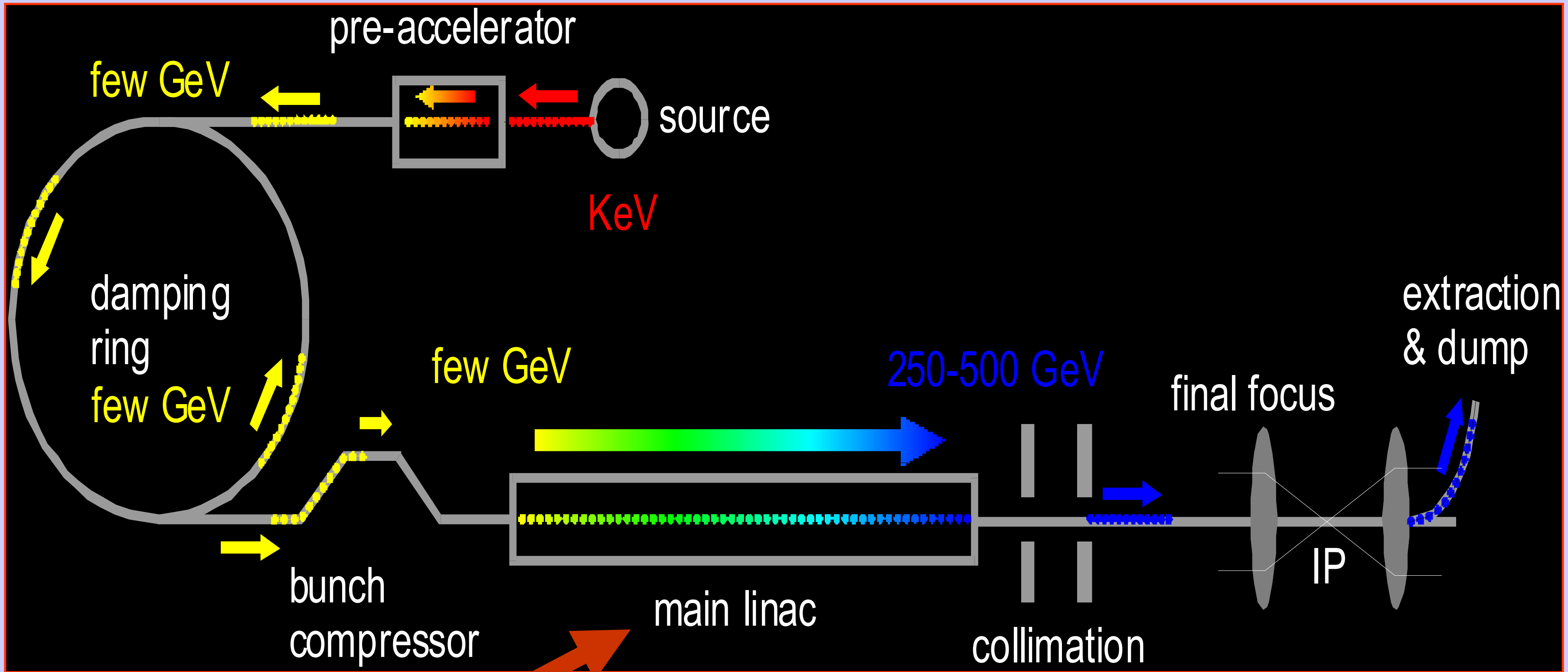
- **The recommendation of ITRP was presented to ILCSC & ICFA on August 19, 2004 in a joint meeting in Beijing.**
- **ICFA unanimously endorsed the ITRP's recommendation on August 20, 2004**

Superconducting RF Technology



- **Forward looking technology for the next generation of particle accelerators: particle physics; nuclear physics; materials; medicine**
- **The ILC R&D is leading the way for Superconducting RF technology**
  - **high gradients; low noise; precision optics**

Designing a Linear Collider



Superconducting RF Main Linac

Luminosity & Beam Size

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

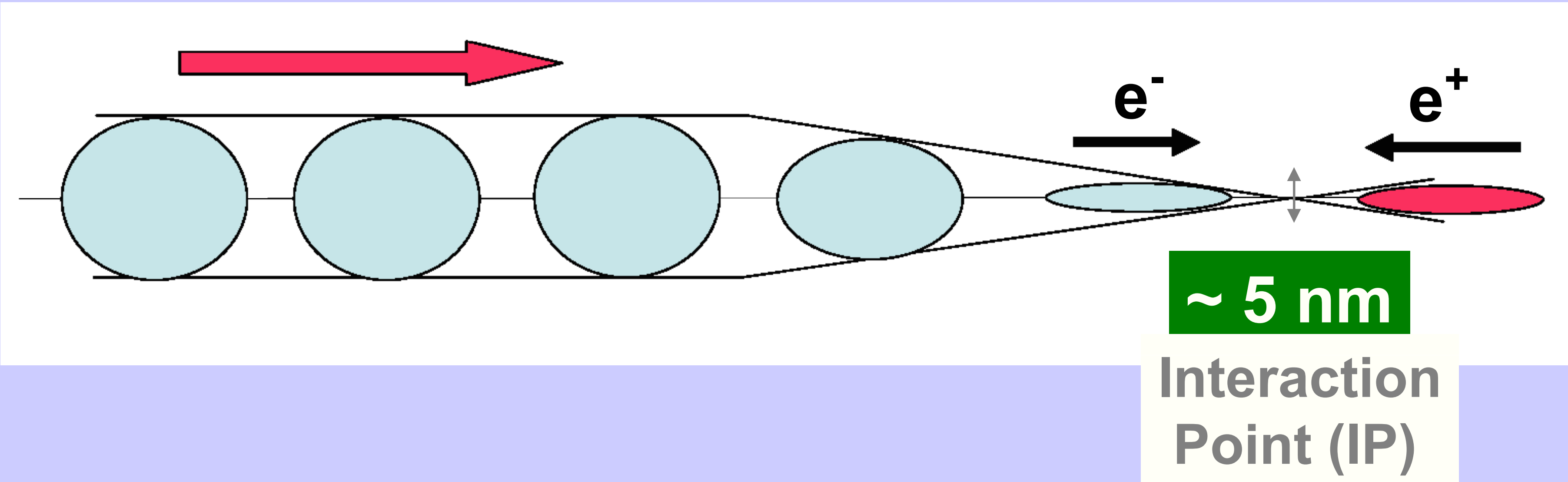
- f_{rep} * n_b tends to be low in a linear collider

	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

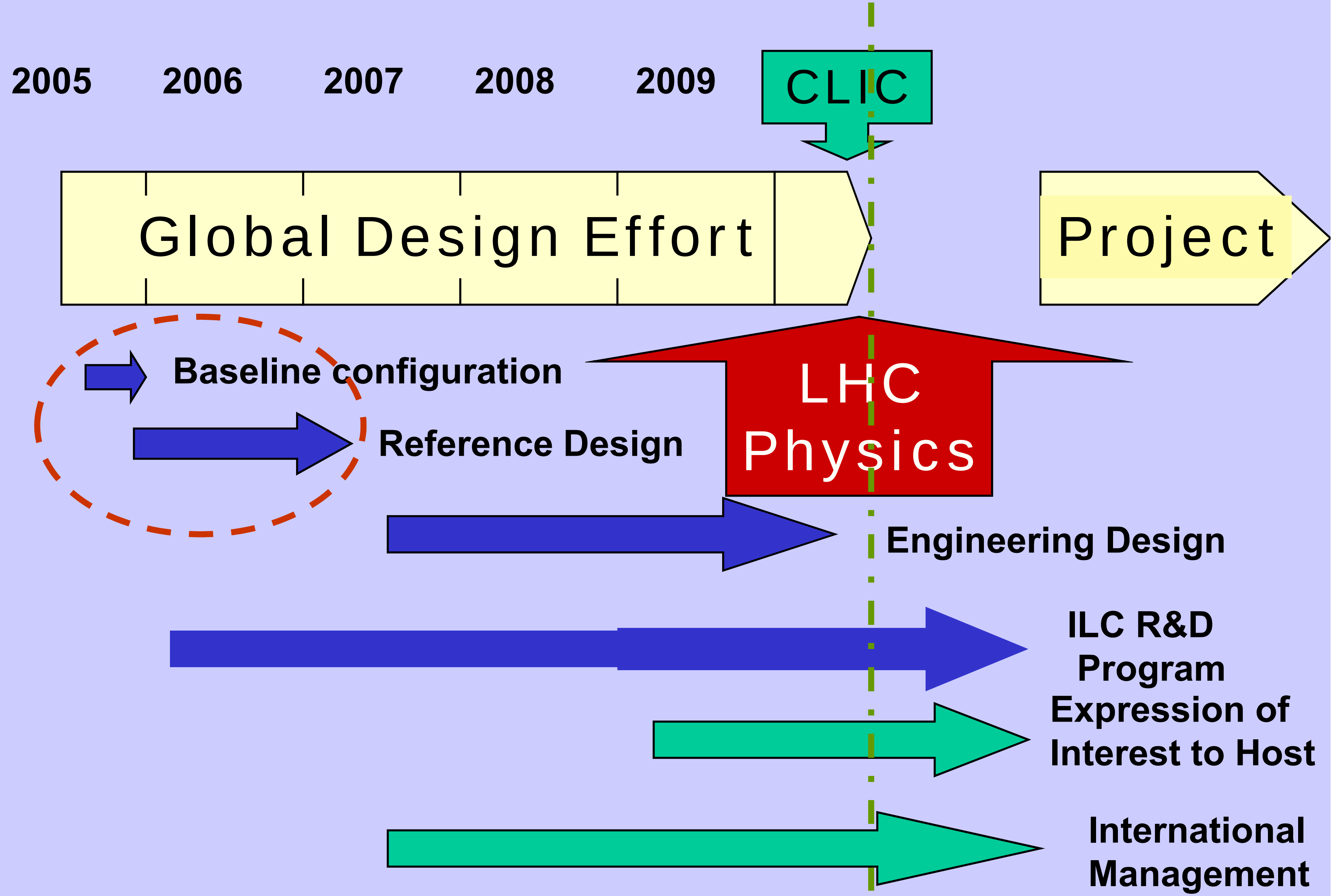
- Achieve luminosity with spot size and bunch charge

Achieving High Luminosity

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

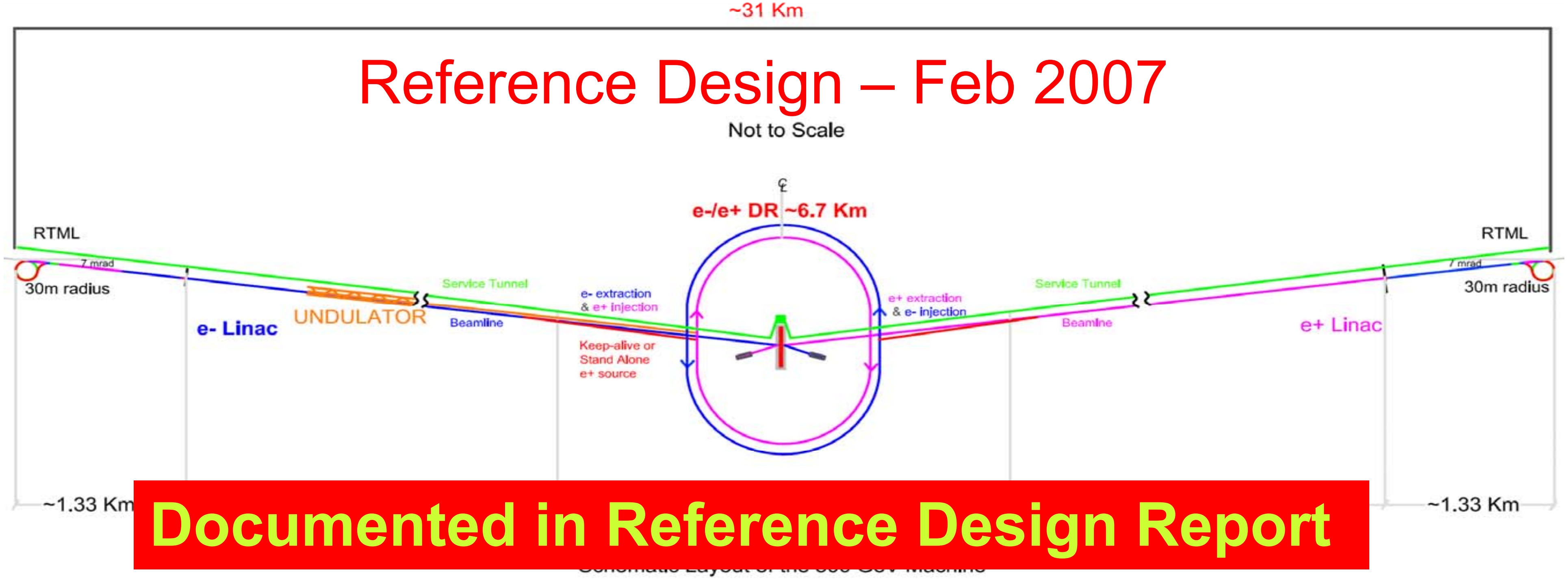


ILC – Global Design Phase



ILC Reference Design

- 11km SC linacs operating at 31.5 MV/m for 500 GeV
- Centralized injector
  - Circular damping rings for electrons and positrons
  - Undulator-based positron source
- Single IR with 14 mrad crossing angle
- Dual tunnel configuration for safety and availability



Documented in Reference Design Report

RDR Design Parameters

Max. Center-of-mass energy	500	GeV
Peak Luminosity	$\sim 2\times10^{34}$	$1/cm^2s$
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

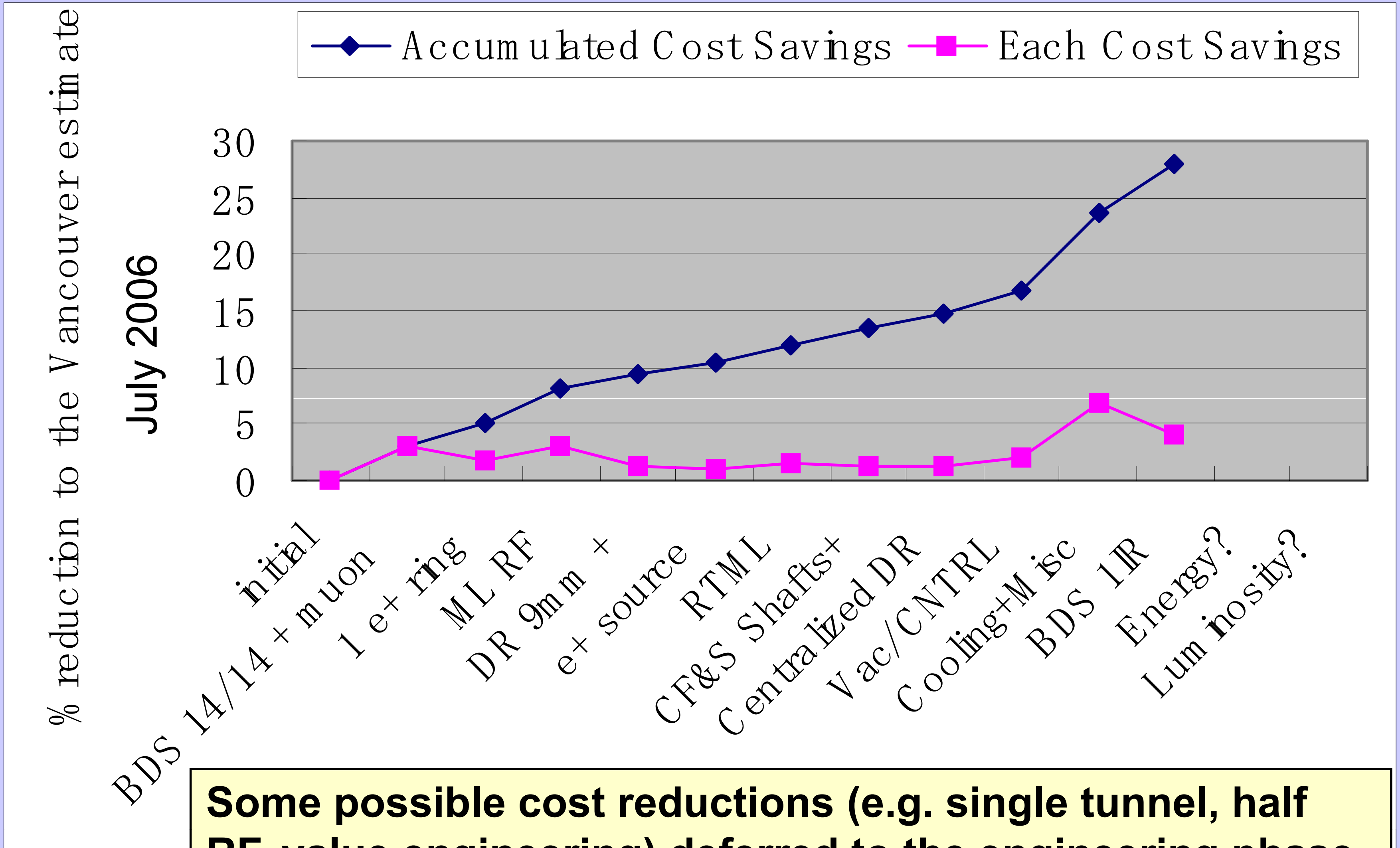
RDR Cost Estimating

- **"Value" Costing System: International costing for International Project**
  - **Provides basic agreed to "value" costs**
  - **Provides estimate of "explicit" labor (man-hr)]**

- **Based on a call for world-wide tender:**
  lowest reasonable price for required quality

- **Classes of items in cost estimate:**
  - **Site-Specific: separate estimate for each sample site**
  - **Conventional: global capability (single world est.)**
  - **High Tech: cavities, cryomodules (regional estimates)**

Evolving Design → Cost Reductions



Some possible cost reductions (e.g. single tunnel, half RF, value engineering) deferred to the engineering phase

RDR Design & “Value” Costs

The reference design was “frozen” as of 1-Dec-06 for the purpose of producing the RDR, including costs.

It is important to recognize this is a snapshot and the design will continue to evolve, due to results of the R&D, accelerator studies and value engineering

The value costs have already been reviewed three time

- 3 day “internal review” in Dec
- ILCSC MAC review in Jan
- International Cost Review (May)

Σ Value = 6.62 B ILC Units

Summary
RDR “Value” Costs

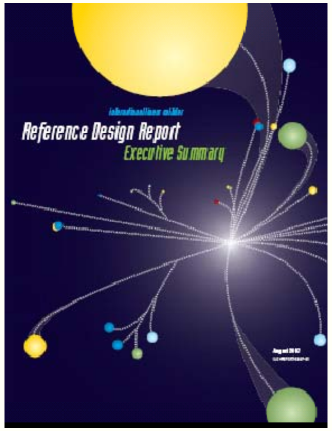
Total Value Cost (FY07)
4.80 B ILC Units Shared
+
1.82 B Units Site Specific
+
14.1 K person-years
(“explicit” labor = 24.0 M person-hrs @ 1,700 hrs/yr)
1 ILC Unit = $ 1 (2007)

Assessing the RDR

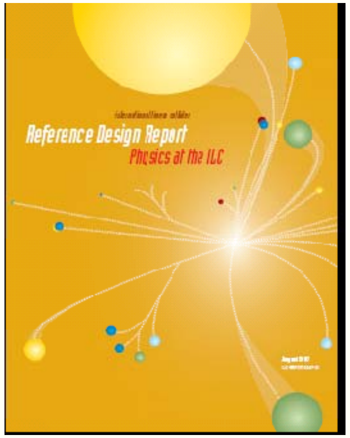
- **Reviews (5 major international reviews + regional)**
  - **The Design:** "The MAC applauds that considerable evolution of the design was achieved … the performance driven baseline configuration was successfully converted into a cost conscious design."
  - **The R&D Plan:** "The committee endorses the approach of collecting R&D items as proposed by the collaborators, categorizing them, prioritizing them, and seeking contact with funding agencies to provide guidelines for funding.
  - **International Cost Review (Orsay):** Supported the costing methodology; considered the costing conservative in that they identify opportunities for cost savings; etc.
- **Final Step**
  - The final versions of Executive Summary, Reference Design Report and Companion Document were submitted to FALC (July), ILCSC and ICFA (August).
- **The Reference Design is now official**

RDR Complete

- Reference Design Report (4 volumes)

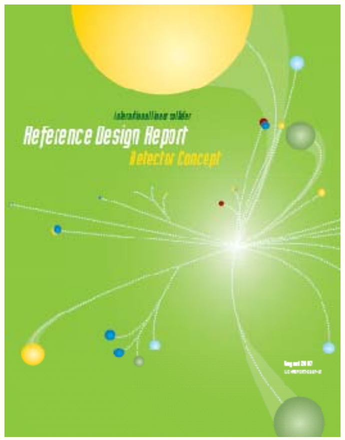


Executive Summary



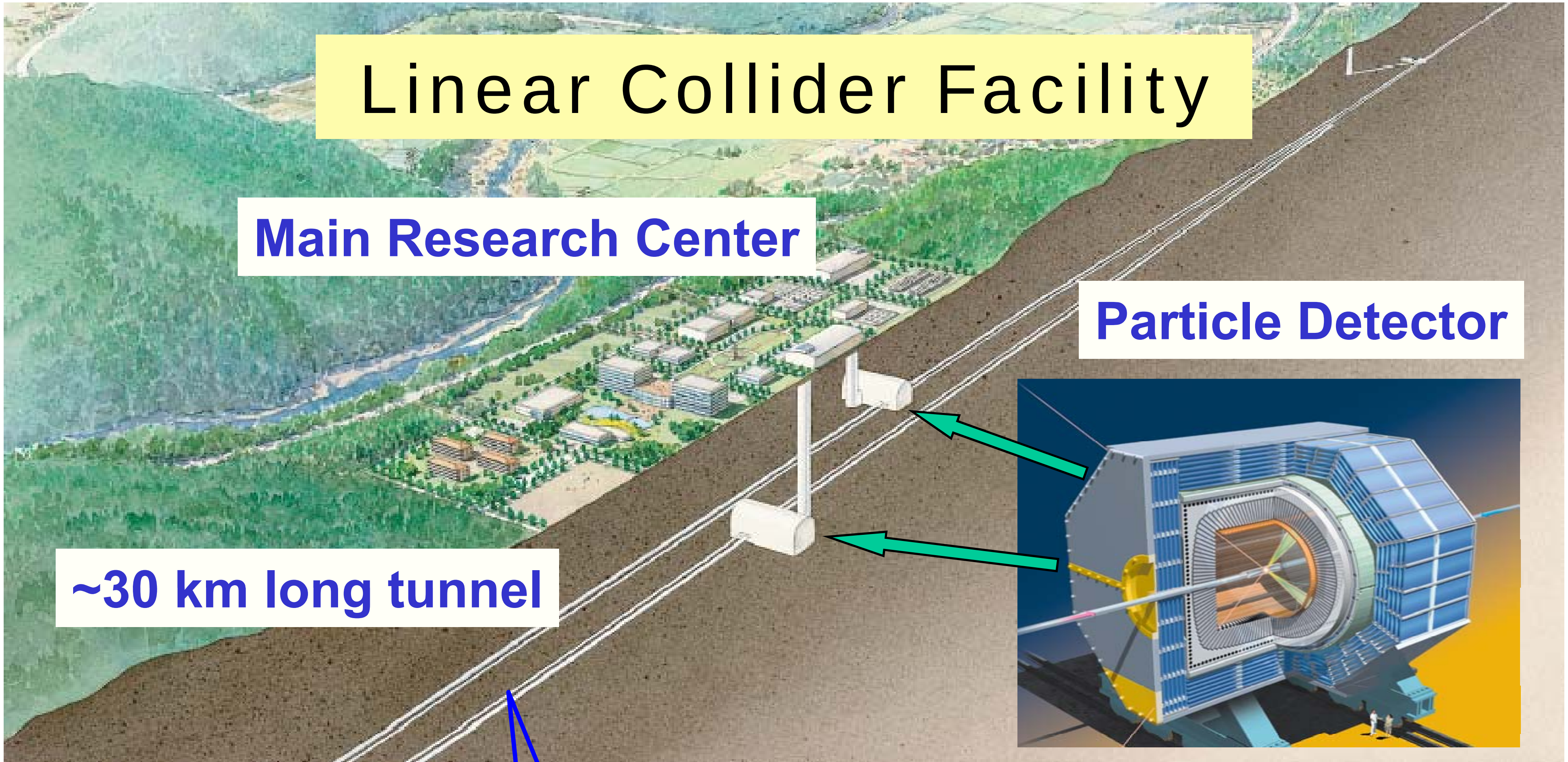
Physics at the ILC

Accelerator



Detectors

Linear Collider Facility



Two tunnels

- accelerator units
- other for services - RF power

Conventional Facilities

72.5 km tunnels ~ 100-150 meters underground

13 major shafts ≥ 9 meter diameter

443 K cu. m. underground excavation: caverns, alcoves, halls

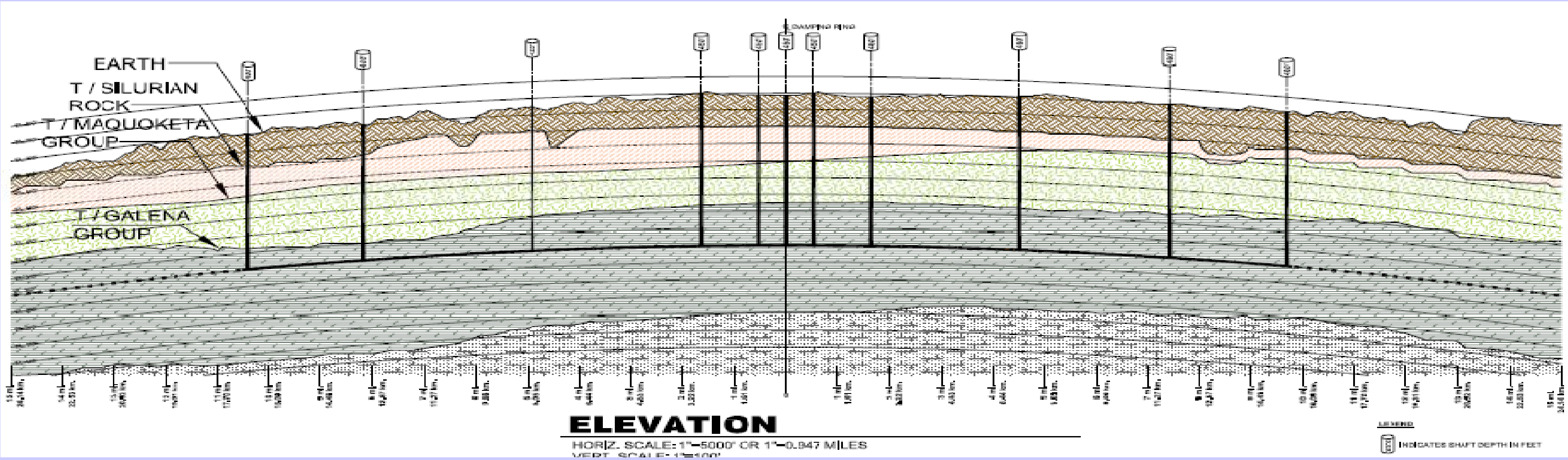
92 surface “buildings”, 52.7 K sq. meters = 567 K sq-ft

Americas Fermilab Sample Site

*Situation : i**n solid rock, close to existing institute, close to the city of Chicago and international airport, close to railway and highway networks.***

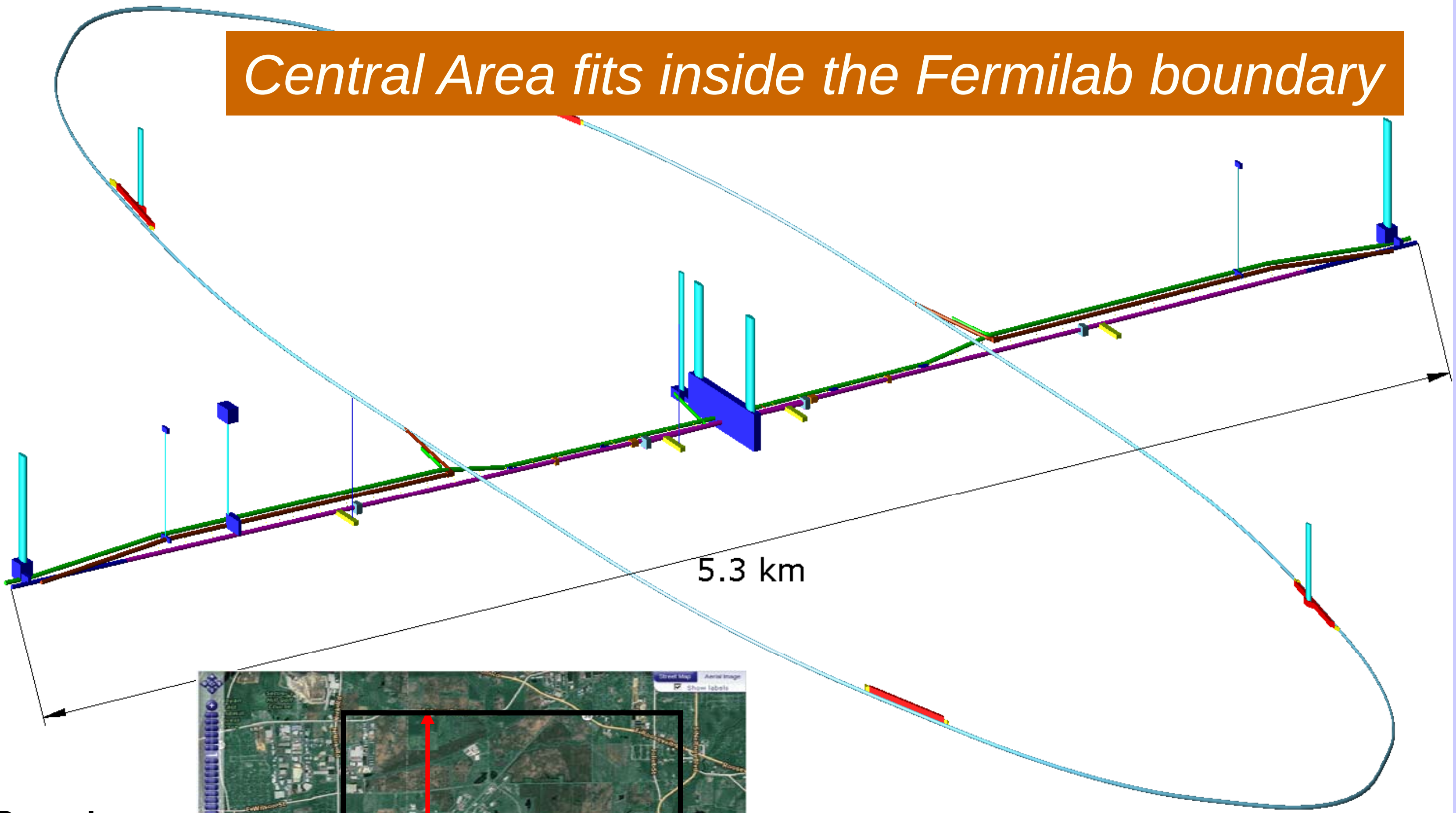
*Geology : **Glacially derived deposits overlaying Bedrock. The concerned rock layers are from top to bottom the Silurian dolomite, Maquoketa dolomitic shale, and the Galena-Platteville dolomites.***

*Depth of main tunnels : **Average ~ 135 m***

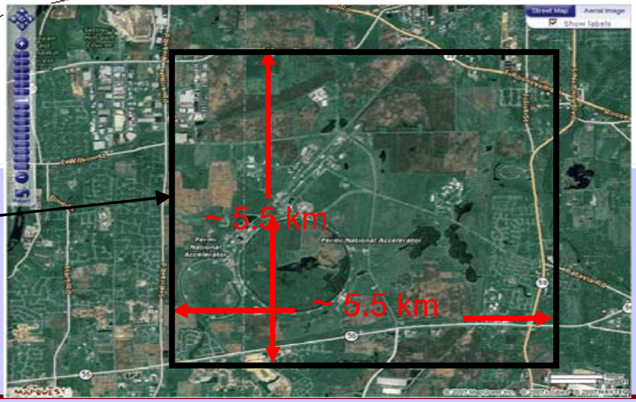


Preconstruction Plan for Fermilab

Central Area fits inside the Fermilab boundary



~ Boundary of Fermilab

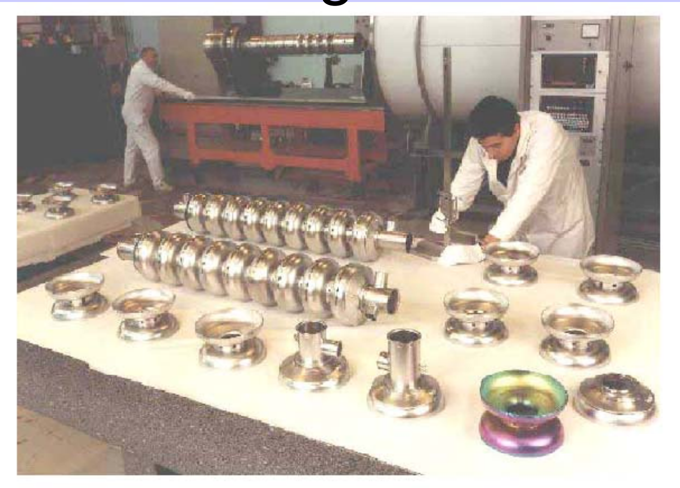


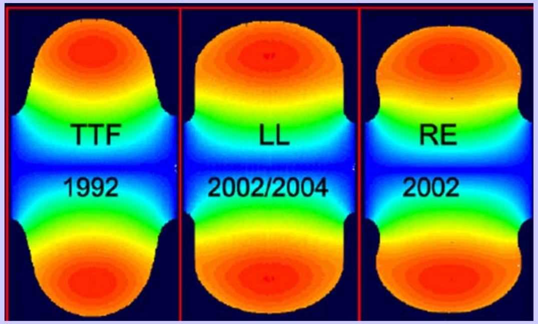
Site Characterization of the Central Area can be done

Superconducting RF Cryomodule

ILC Reference Design and Plan

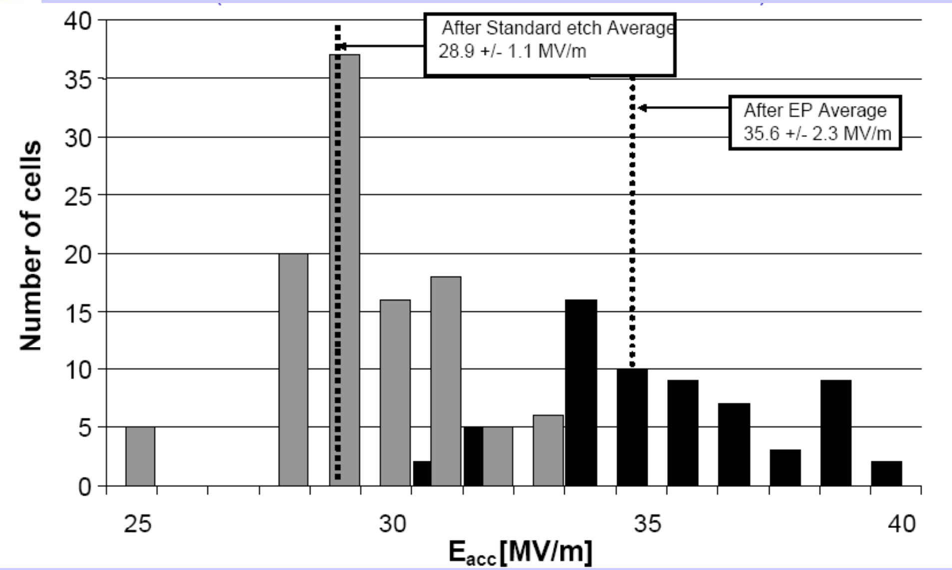
Producing Cavities



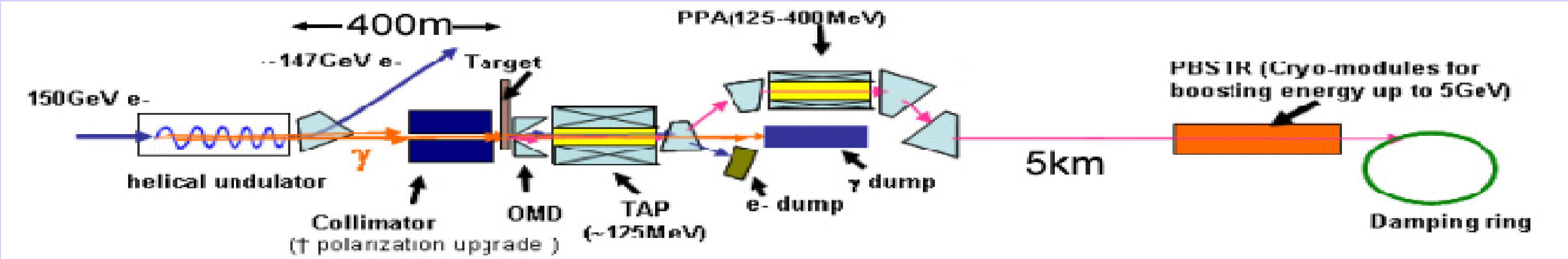


Cavity Shape

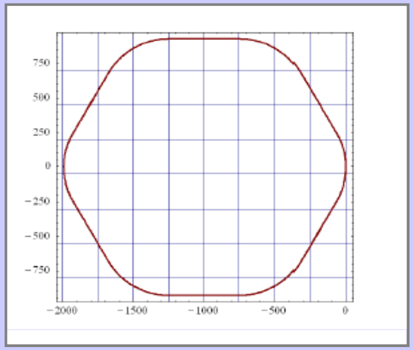
Obtaining Gradient



ILC Reference Design and Plan

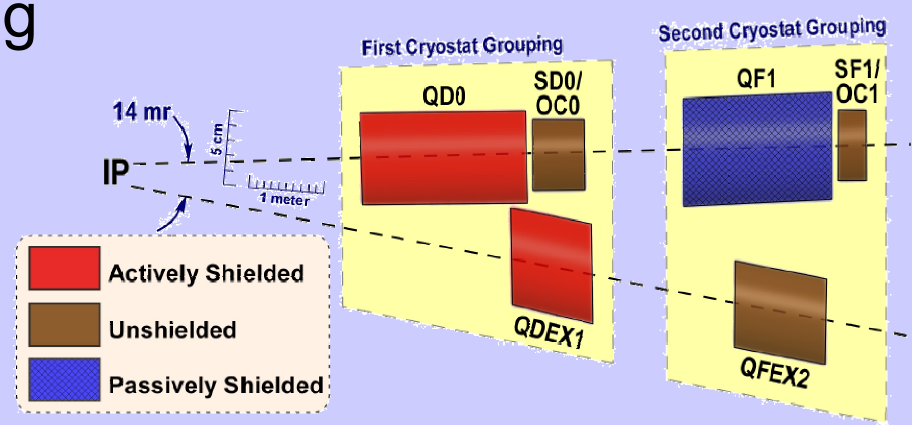


Making Positrons

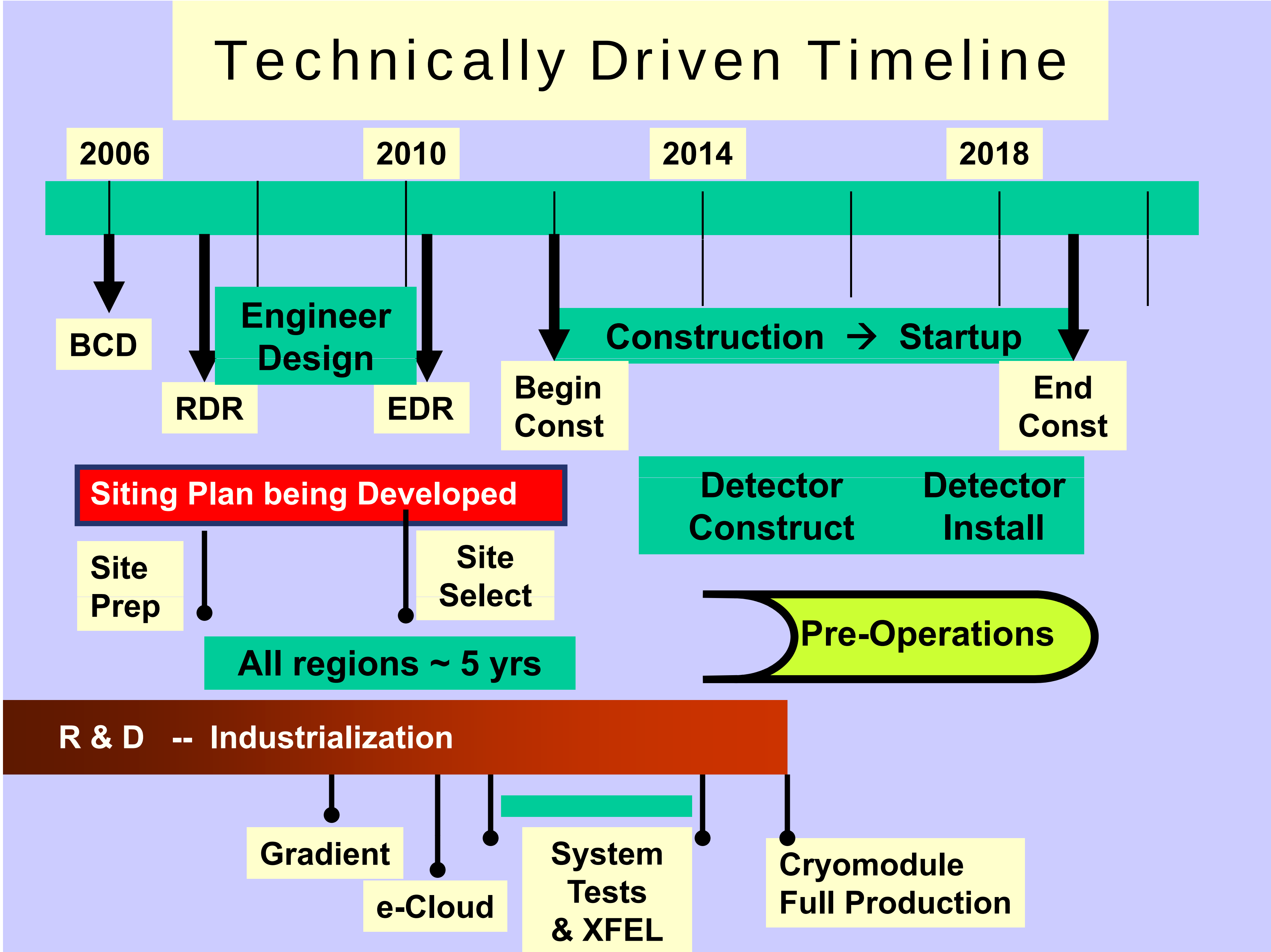


6km Damping Ring

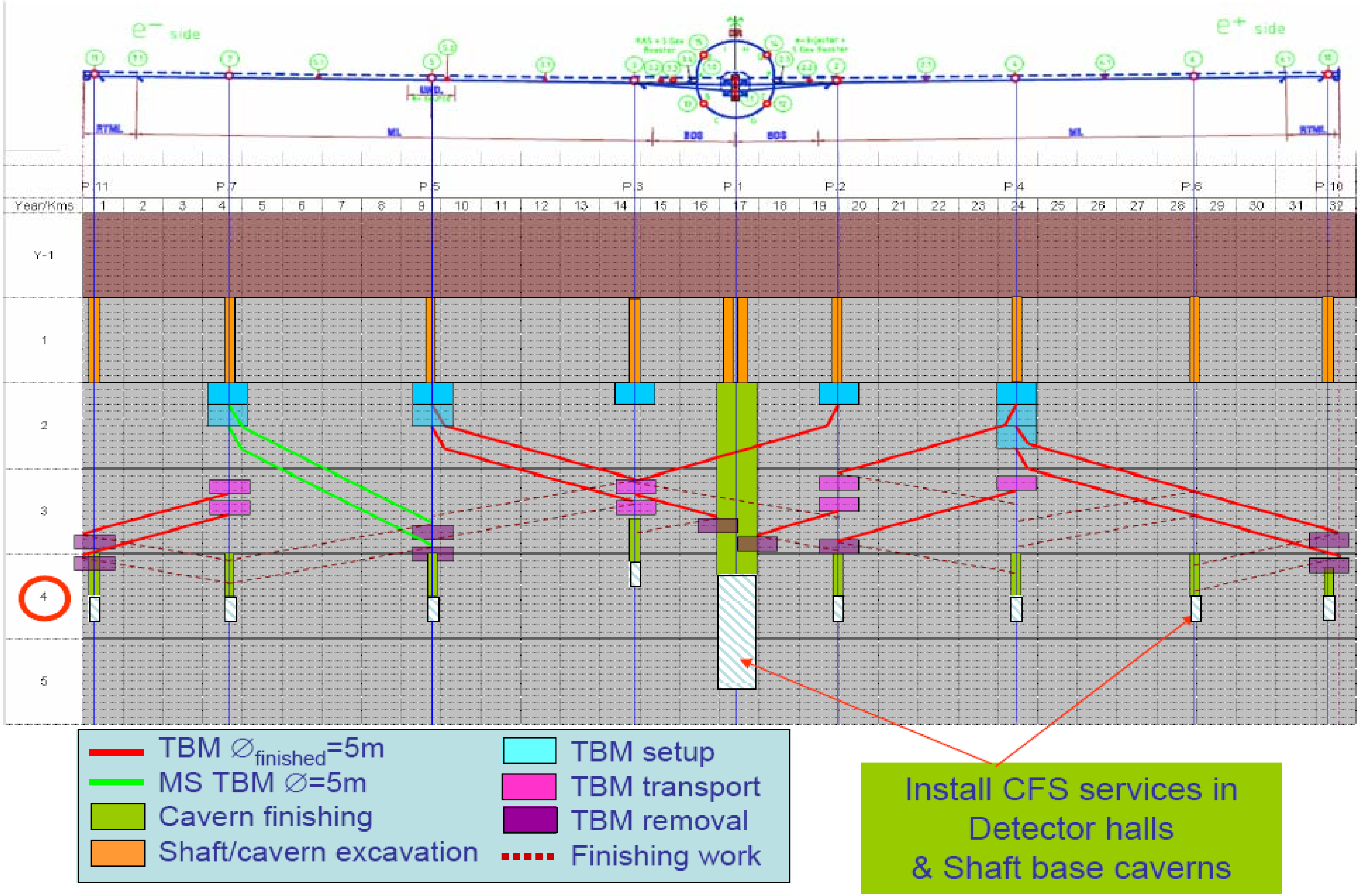
10MW Klystrons



Beam Delivery and Interaction Point

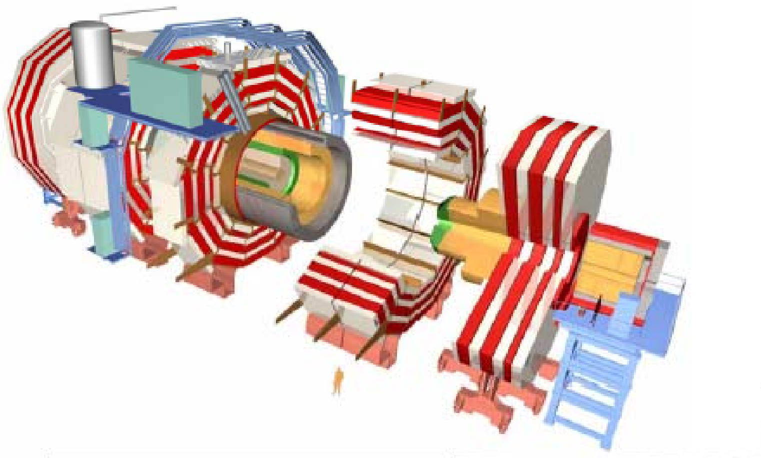

Technically Driven Timeline
2006
2010
2014
2018
BCD
RDR
Engineer Design
EDR
Construction → Startup
Begin Const
End Const
Siting Plan being Developed
Site Prep
Site Select
All regions ~ 5 yrs
Detector Construct
Detector Install
Pre-Operations
R & D -- Industrialization
Gradient
e-Cloud
System Tests & XFEL
Cryomodule Full Production

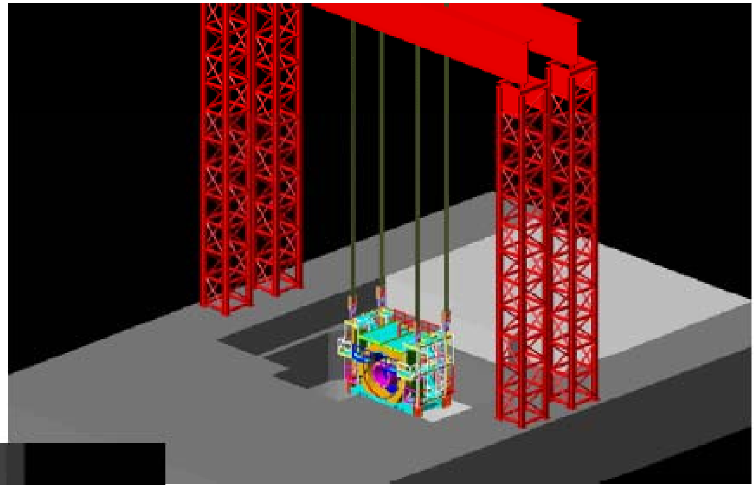
Civil Construction Timeline

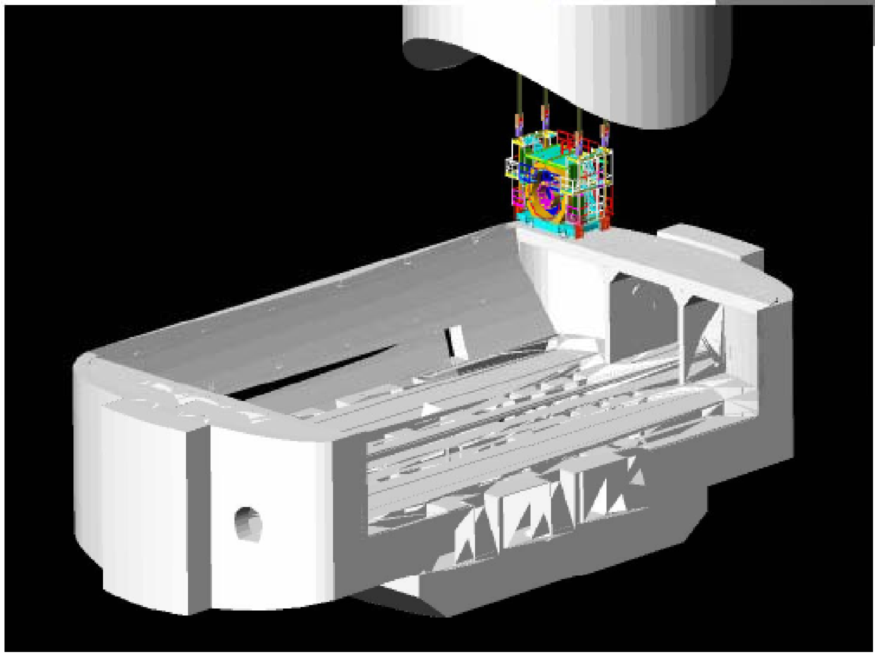


On-surface Detector Assembly

CMS approach







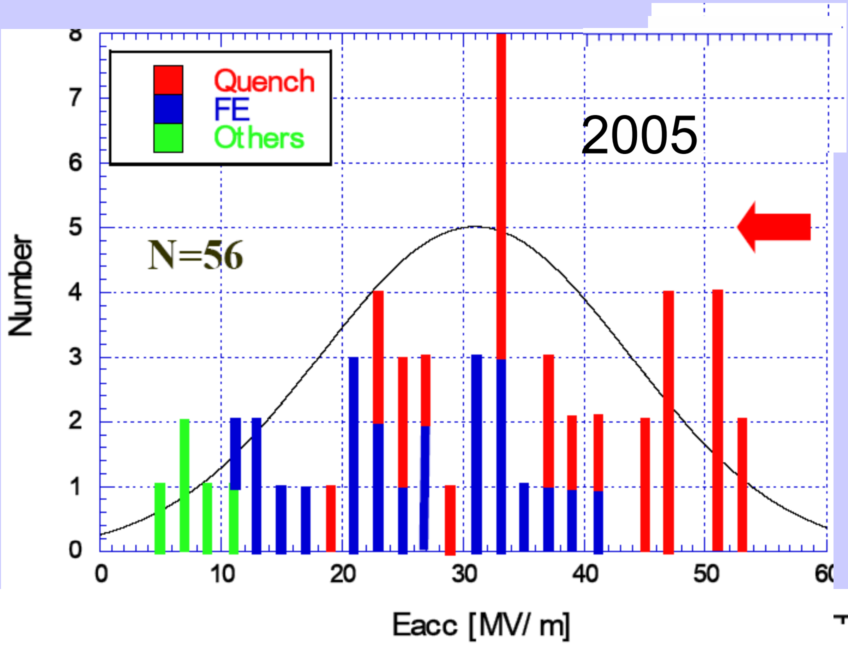
CMS assembly approach:

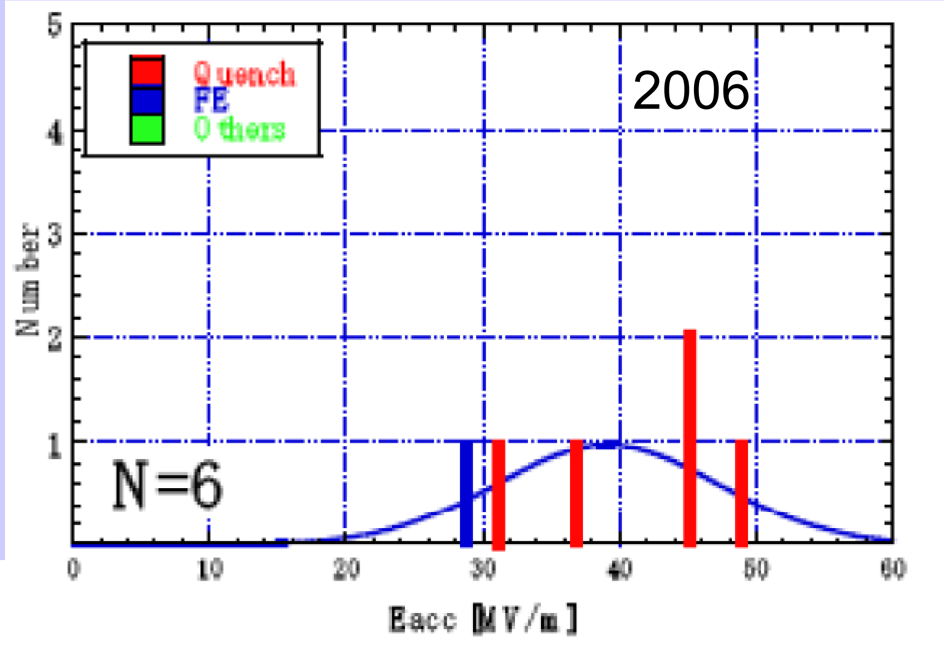
- **Assembled on the surface in parallel with underground work**
- **Allows pre-commissioning before lowering**
- **Lowering using dedicated heavy lifting equipment**
- **Potential for big time saving**
- **Reduces size of required underground hall**

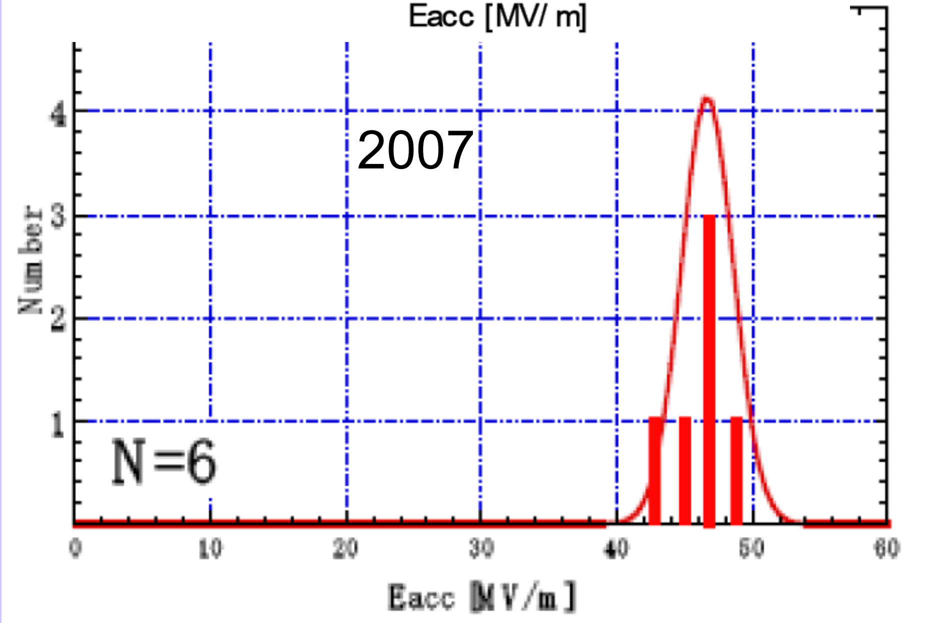
Cavity Gradient – Goal

- **Current status: Nine 9 cell cavities have been produced with gradients > 35 MeV/m. Not reproducible and needs several attempts at final processing.**
- **Goal: After a viable cavity process has been determined through a series of preparations and vertical tests on a significant number of cavities, achieve 35 MV/m at $Q_0 = 10^{10}$ in a sufficiently large final sample (greater than 30) of nine-cell cavities in the low power vertical dewar testing in a production-like operation e.g. all cavities get the same treatment.**
  - **The yield for the number of successful cavities of the final production batch should be larger than 80% in the first test. After re-processing the 20 % underperforming cavities the yield should go up to 95%. This is consistent with the assumption in the RDR costing exercise.**

Cavity Gradient – Results





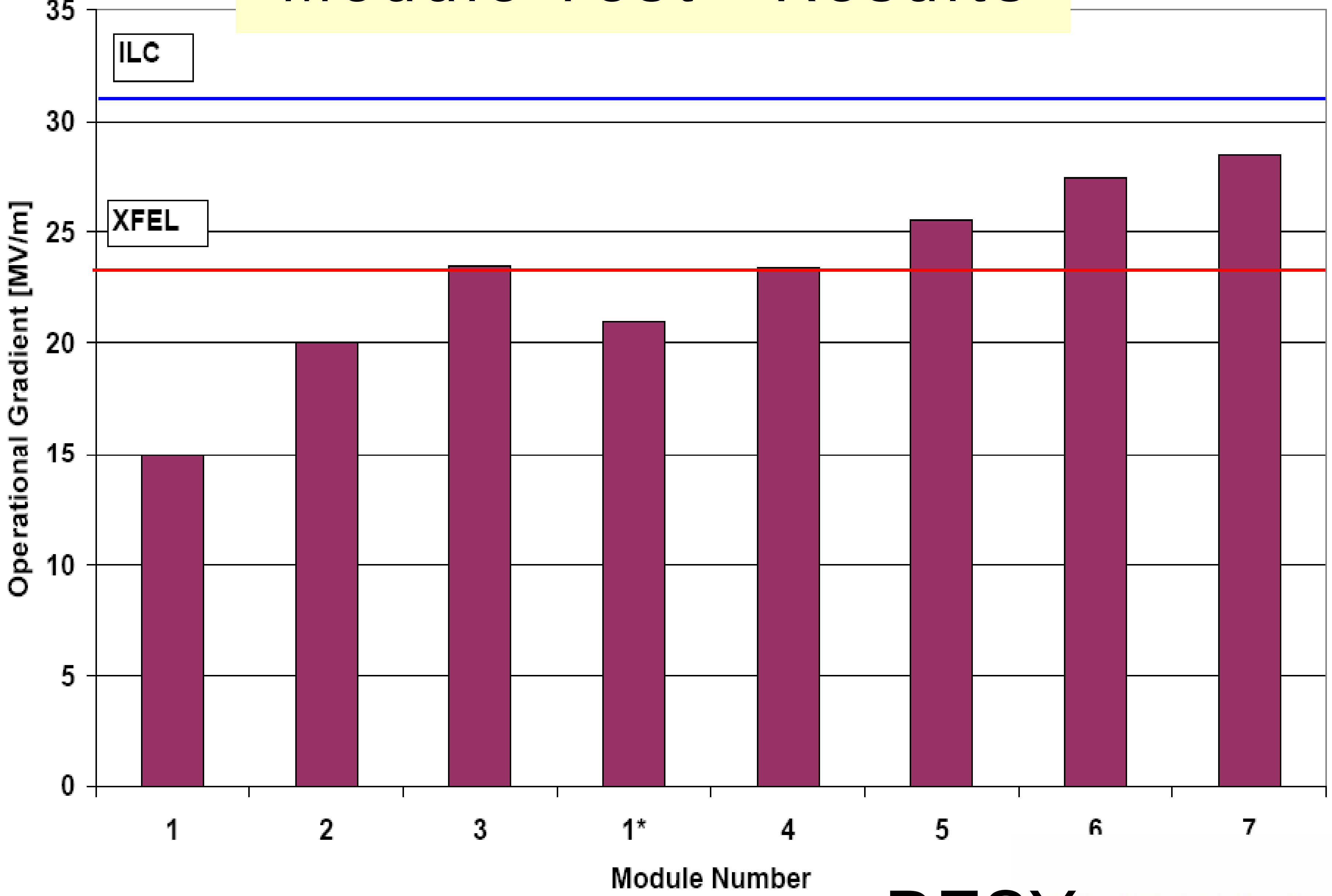


KEK single cell results:
2005 – just learning
2006 – standard recipe
2007 – add final 3 µm fresh acid EP
Note: multi-cells are harder than singles

Module Test – Goal

- **Intermediate goal**
  - Achieve 31.5 MV/m average operational accelerating gradient in a single cryomodule as a proof-of-principle. In case of cavities performing below the average, this could be achieved by tweaking the RF distribution accordingly.
  - Auxiliary systems like fast tuners should all work.
- **Final goal**
  - Achieve > 31.5 MeV/m operational gradient in 3 cryomodules.
  - The cavities accepted in the low power test should achieve 35 MV/m at $Q_0 = 10^{10}$ with a yield as described above (80% after first test, 95% after re-preparation).
  - It does not need to be the final cryomodule design

Module Test – Results

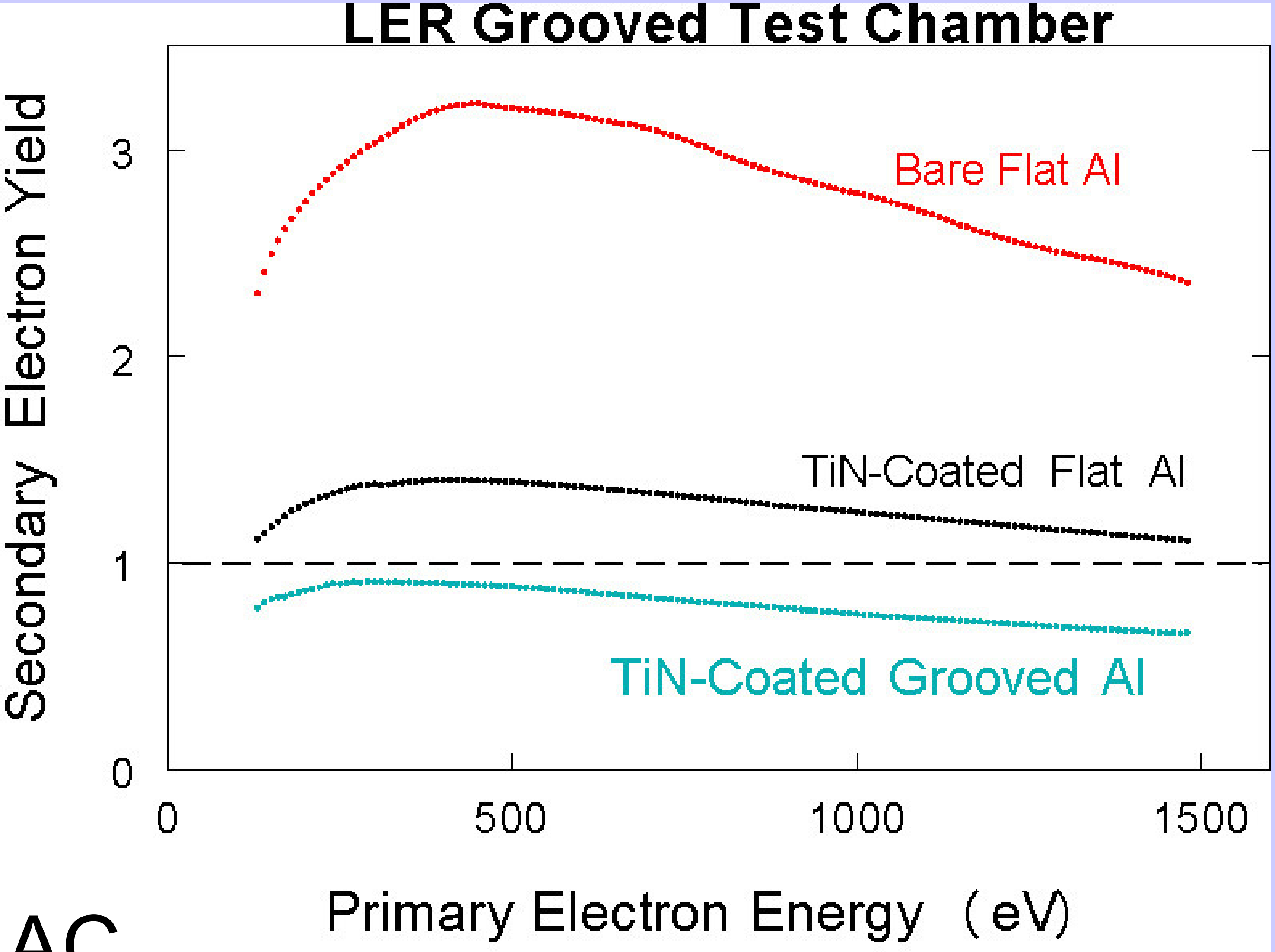


DESY

Electron cloud – Goal

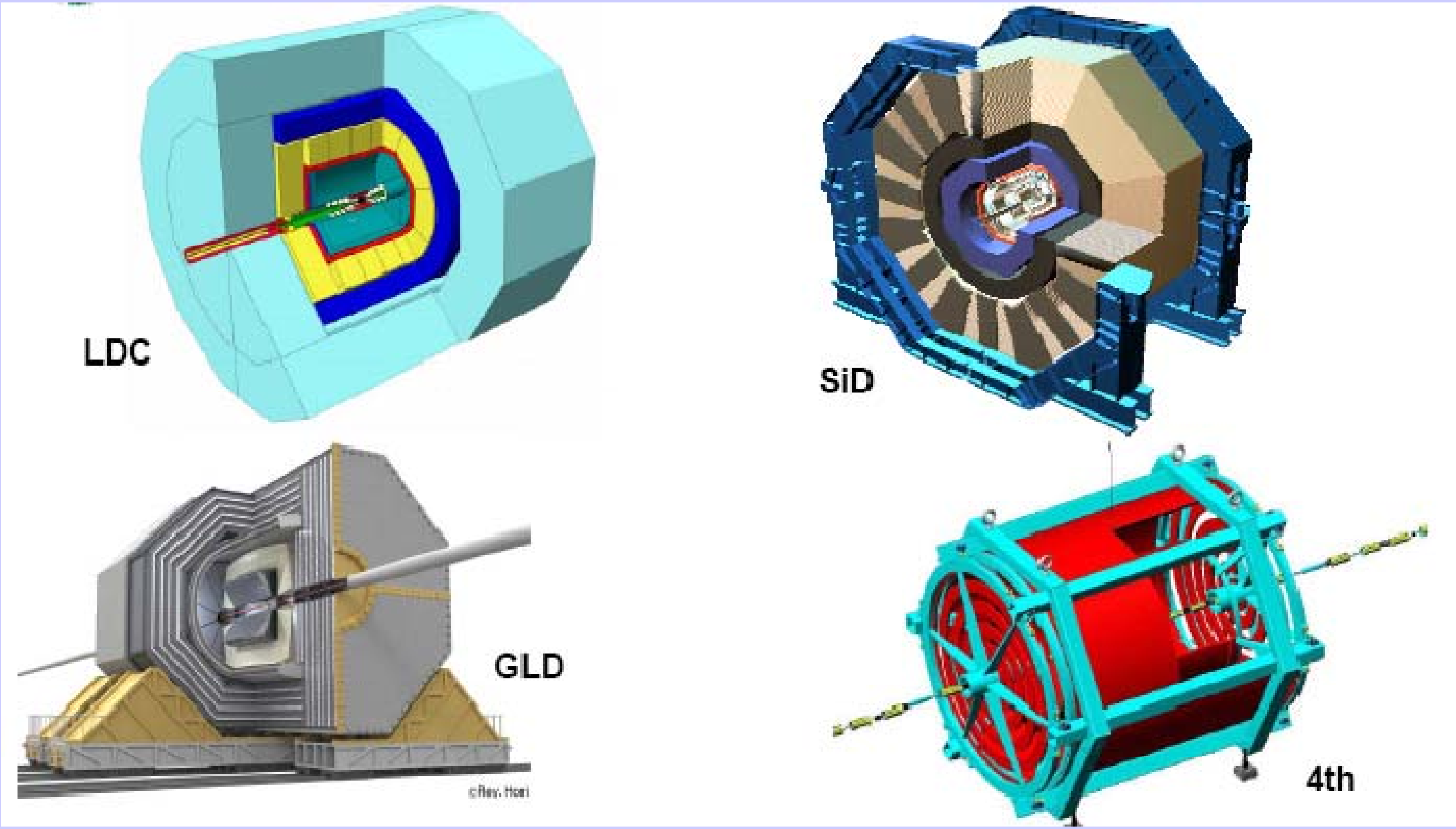
- **Ensure the e- cloud won't blow up the e+ beam emittance.**
  - **Do simulations (cheap)**
  - **Test vacuum pipe coatings, grooved chambers, and clearing electrodes effect on e-cloud buildup**
  - **Do above in ILC style wigglers with low emittance beam to minimize the extrapolation to the ILC.**

E Cloud – Results



SLAC

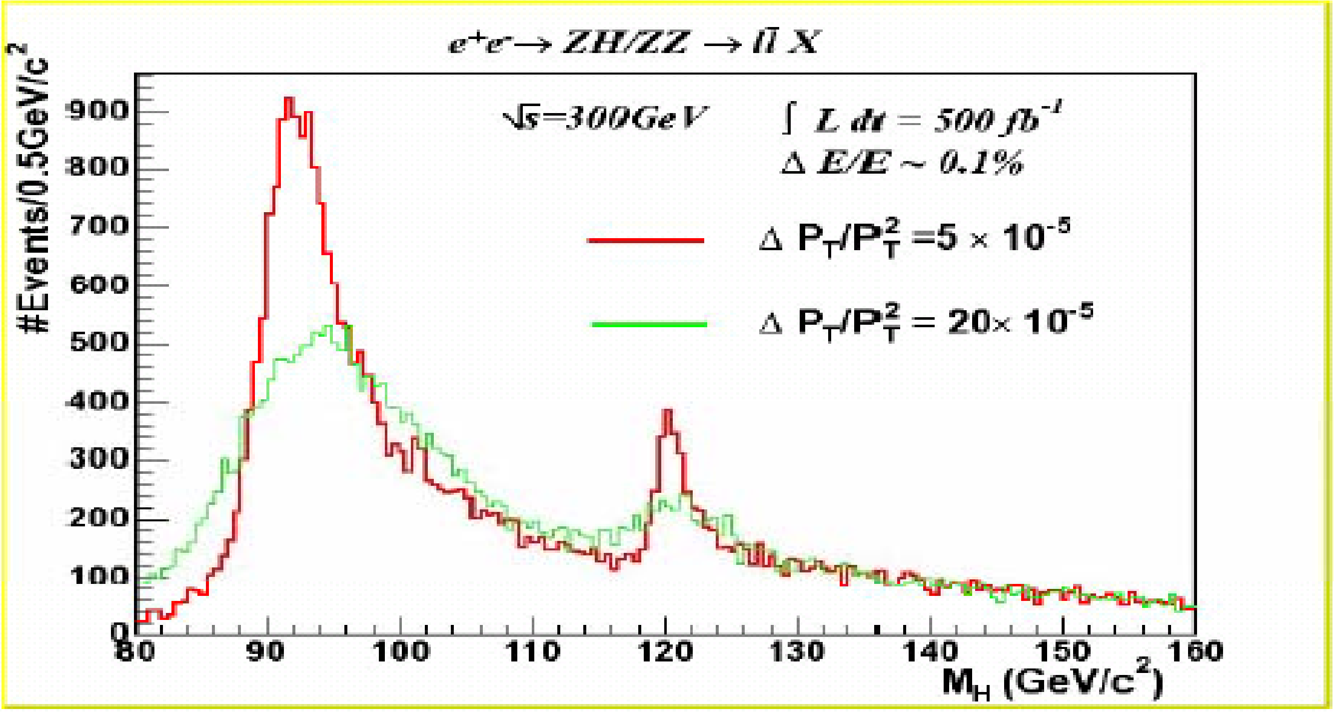
Detector Concepts Report



Detector Performance Goals

e.g: The Higgs tagging mode

$e^+e^- \rightarrow ZH, \quad Z \rightarrow \ell^+\ell^-$



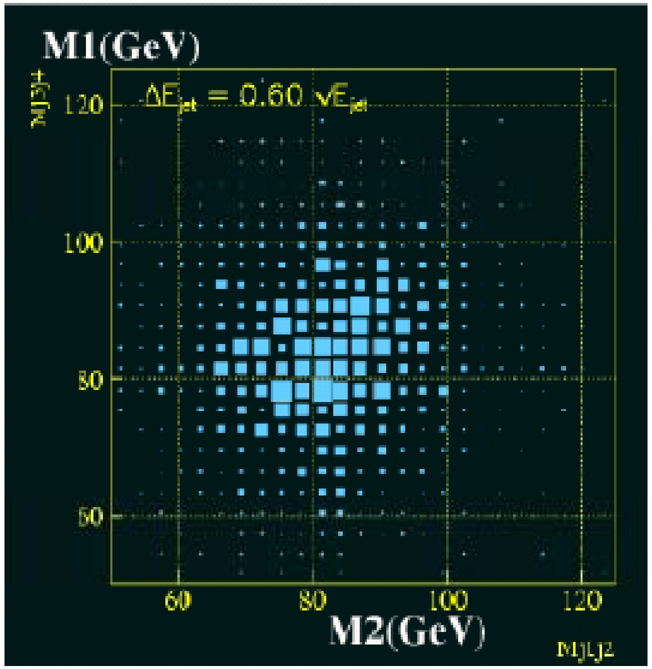
$\sigma_p/p^2 \sim 5 \times 10^{-5}$ is "necessary"

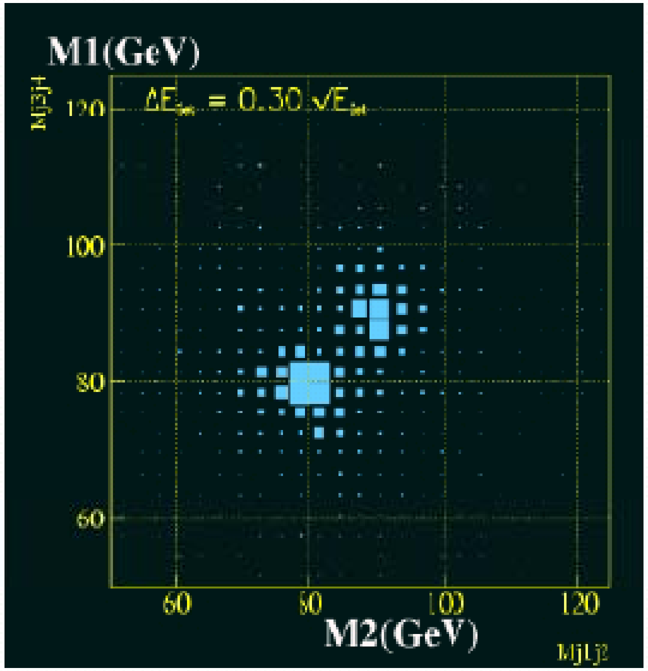
Detector Performance Goals

e.g: Separation of WW and ZZ

$$e^+e^- \to \nu\bar{\nu}W^+W^-, \nu\bar{\nu}ZZ\,, \quad W, Z \to 2\text{jets}$$

$$\frac{\sigma_E}{E} = \frac{0.6}{\sqrt{E}} \qquad\qquad \frac{\sigma_E}{E} = \frac{0.3}{\sqrt{E}}$$





$\frac{\sigma_E}{E} \sim \frac{0.3}{\sqrt{E}}$ is 'needed'. For jets !!!!

Detector Performance Goals

- ILC detector performance requirements and comparison to the LHC detectors:
  - Inner vertex layer ~ 3-6 times closer to IP
  - Vertex pixel size ~ 30 times smaller
  - Vertex detector layer ~ 30 times thinner

  Impact param resolution $\Delta d = 5\ [\mu m] \oplus 10\ [\mu m] / (p[GeV] \sin 3/2\theta)$

  - Material in the tracker ~ 30 times less
  - Track momentum resolution ~ 10 times better

  Momentum resolution $\Delta p / p^2 = 5 \times 10^{-5}\ [GeV^{-1}]$ **central region**

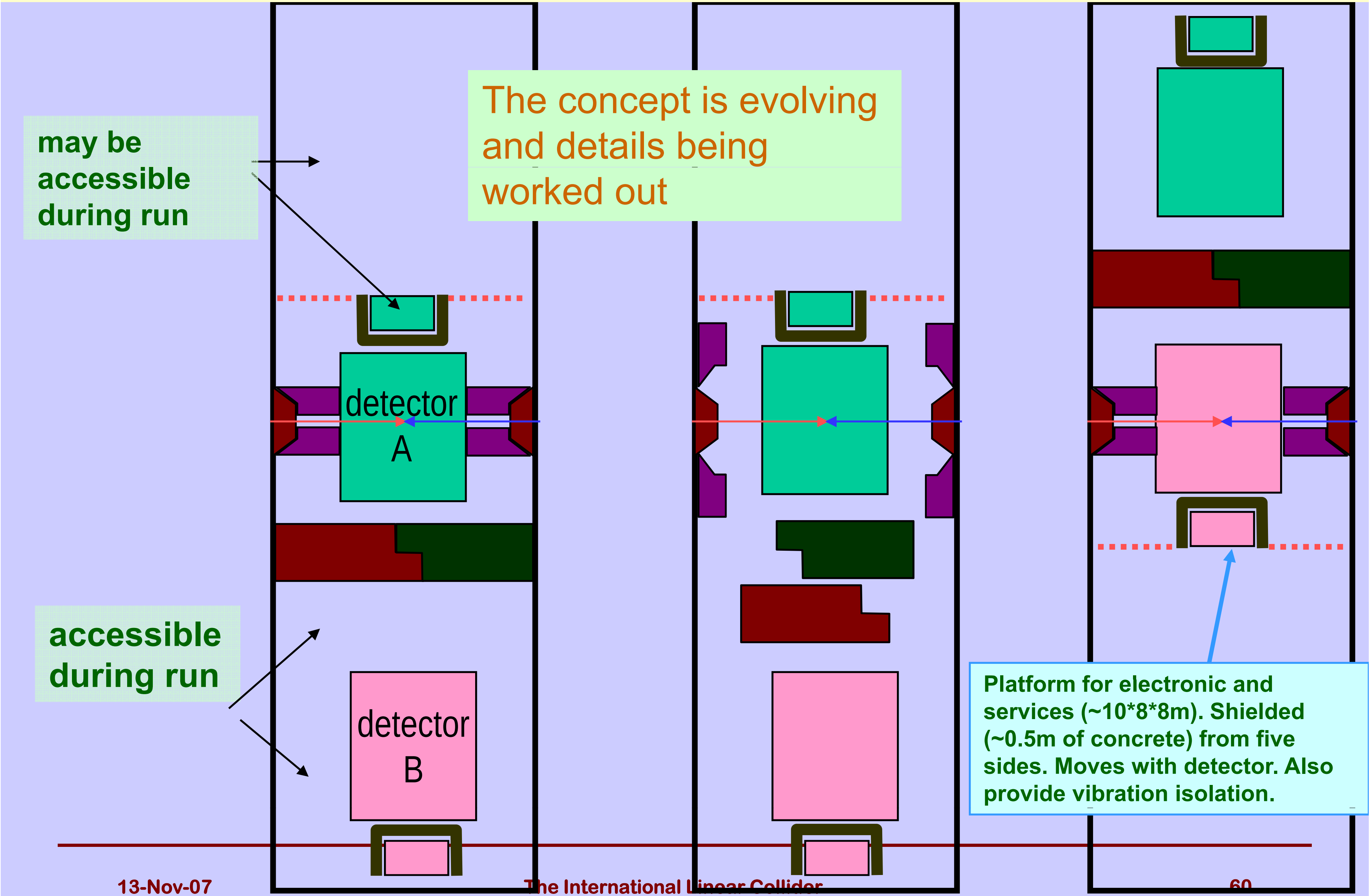
  $\Delta p / p^2 = 3 \times 10^{-5}\ [GeV^{-1}]$ **forward region**

  - Granularity of EM calorimeter ~ 200 times better

  Jet energy resolution $\Delta E_{jet} / E_{jet} = 0.3 / \sqrt{E_{jet}}$

  Forward Hermeticity down to θ = 5-10 [mrad]

Concept of IR hall with two detectors



Final Reflections

- **We have come a long way, and the connecting theme has been a strong physics case, coupled with the development of a coherent concept for the accelerator and the R&D technology demonstrations**

- **This provides a strong base for the future, but there are many hurdles ahead: costs, LHC results, international management, determining a host and site, funding.**

- **Many elements should converge early in the next decade and our aim is to be ready with the strongest construction proposal possible on that time scale.**