Experimental Challenges and Techniques for Future Accelerators

XI ICFA School on Instrumentation in Elementary Particle Physics

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DESY

Outline

> ## Lecture 1

- Future particle physics at the energy frontier: case for a Linear Collider
- Linear Collider Concepts
- Experimental Challenges
- Detector Concepts

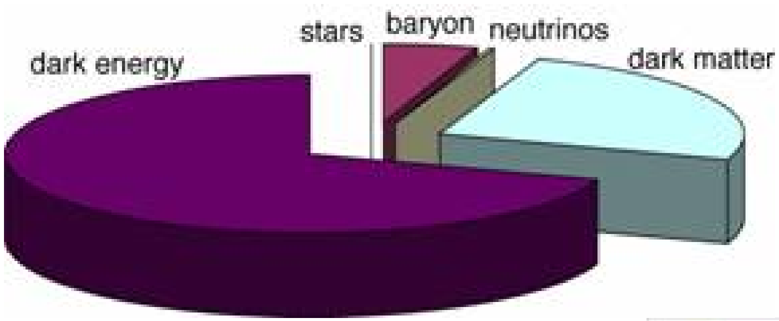
> ## Lecture 2

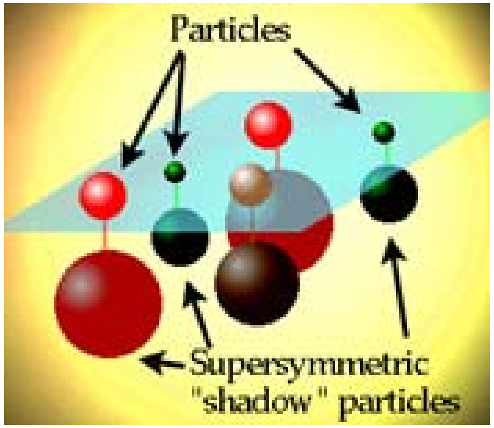
- R&D for detector components
- Vertex detector
- Tracking detectors
- Calorimeters

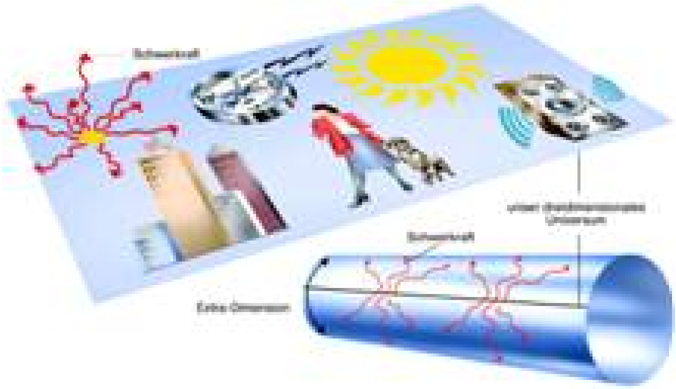
Elementary Particle Physics: Challenges and Visions

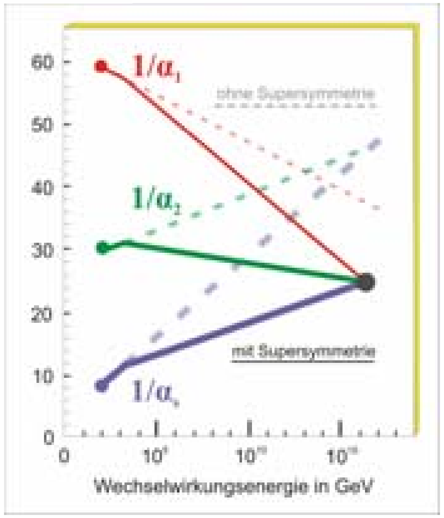
> **Particle Physics entering Terascale**
  - Start of the Large Hadron Collider (LHC) at CERN

> **Expect answers to fundamental questions**
  - Origin of mass (Higgs)
  - Mystery of Dark Matter
  - Supersymmetry
  - Extra space dimensions
  - Grand Unification





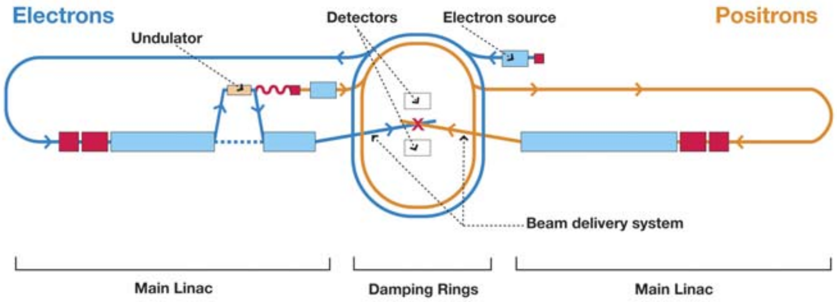




Future of Particle Physics at the Energy Frontier

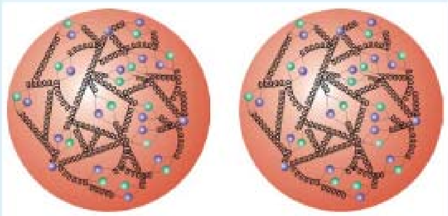
> **LHC and its upgrades**
- **Luminosity**
- **Energy (?)**

> **Electron-Positron Linear Collider**
- **ILC (supra-conducting technology)**
- **CLIC (two-beam acceleration)**
- **Muon collider (?)**



> **Here: emphasis on detector challenges for Linear Collider**

Comparison Proton and Electron Colliders



p p

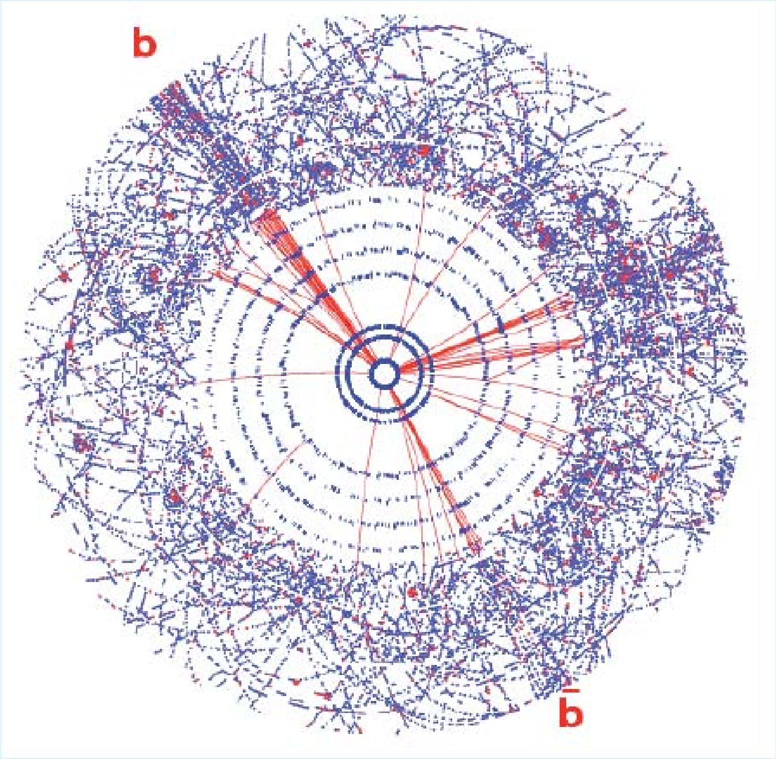
e e

- Proton (anti-) proton colliders:
  - Energy range higher (limited by magnet bending power)
  - Composite particles, different initial state constituents and energies in each collision
  - Hadronic final states difficult
- Discovery machines
- Excellent for some precision measurements

- Electron positron colliders:
  - Energy range limited (by RF power)
  - Point-like particles, exactly defined initial state quantum numbers and energies
  - Hadronic final states easy
- Precision machines
- Discovery potential

- **Precision is main motivation for a new electron positron collider**
- **Complementarity to proton machines, e.g. SppS/Tevatron and LEP**

Comparison Proton and Electron Colliders



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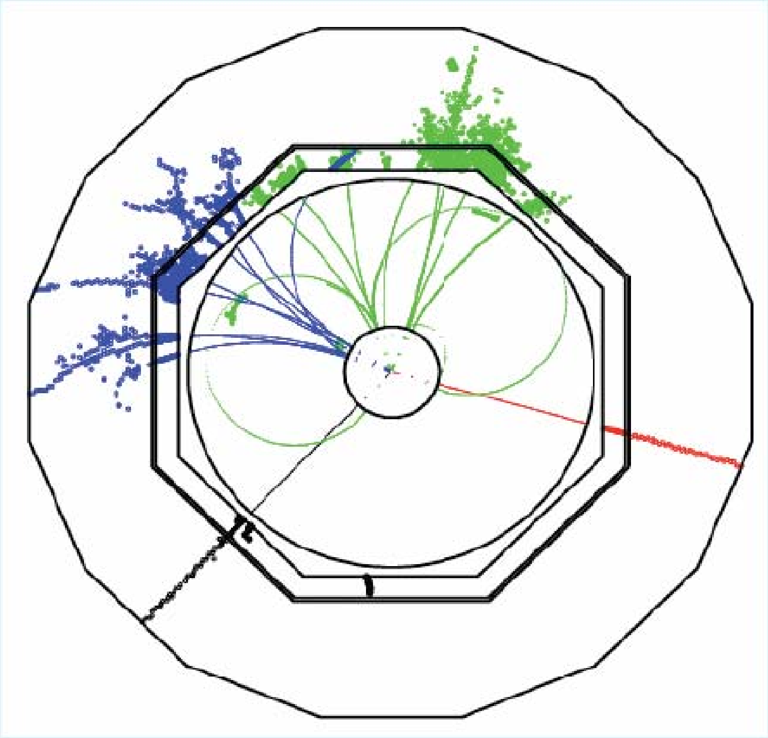
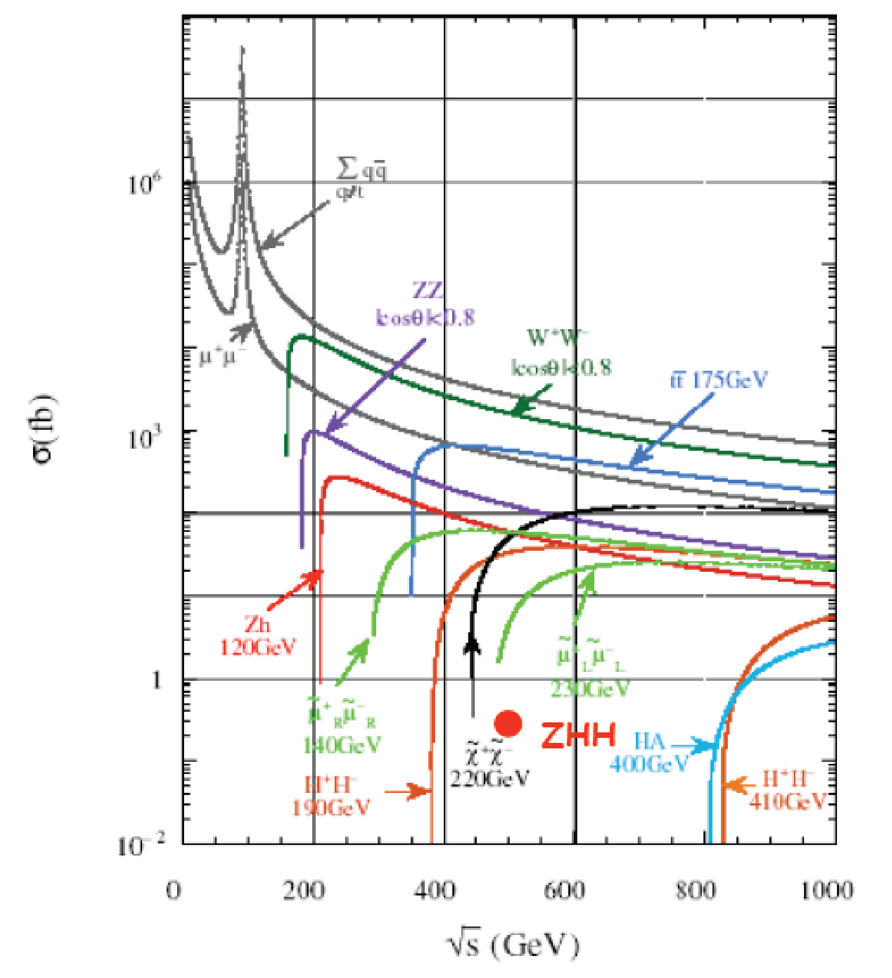


e^+e^- → HZ

Electron Positron Collider

- The e^+e^- cross section drops $\sim 1/\sqrt{s}$
- The key parameters for a competitive e^+e^- machine are
  - energy reach
  - luminosity

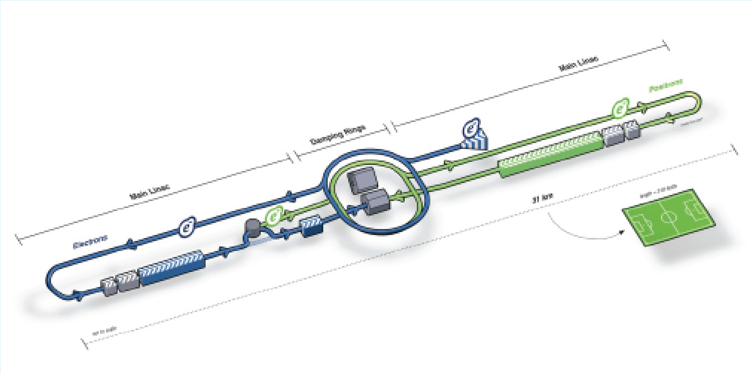
strive for few $10^{34}/cm^2/s$ (comparable to LHC)



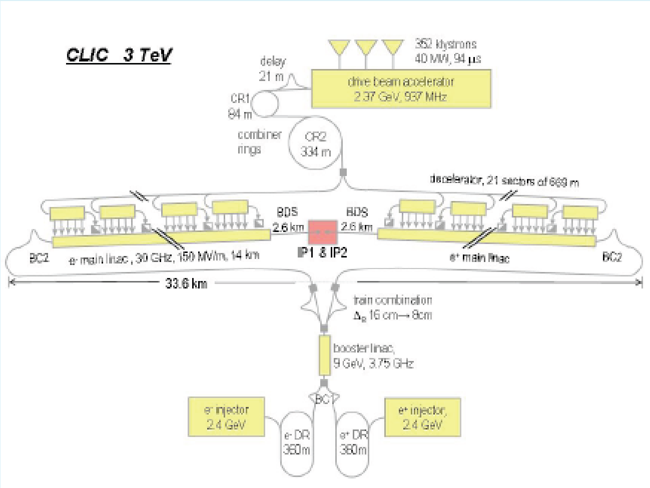
Recall: $10^{34}/cm^2/s$ corresponds to 100 fb^{-1} per year

Linear Collider Concepts

- International Linear Collider ILC
  - superconducting acceleration
  - 31.5 MeV/m, 1.3 GHz
  - advanced design (c.f. XFEL)
  - 500 GeV (→ 1TeV)
  - Luminsosity: 2 x 10^{34} cm^{-2} s^{-1}

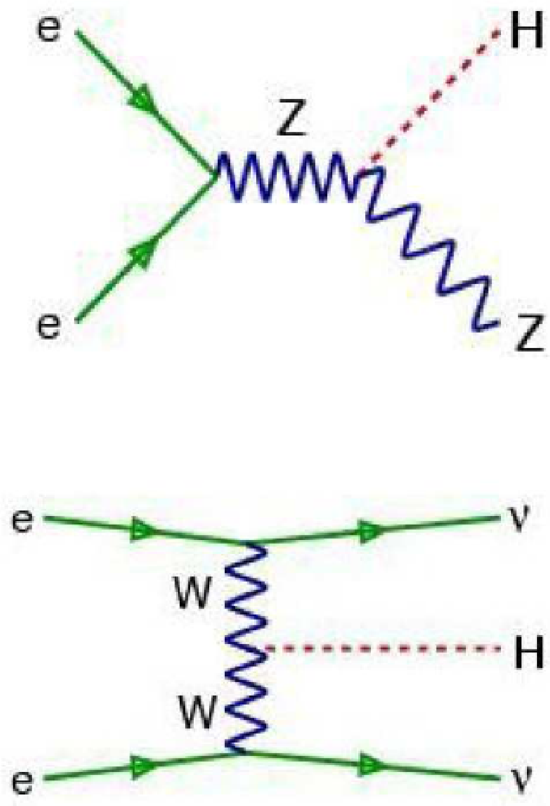


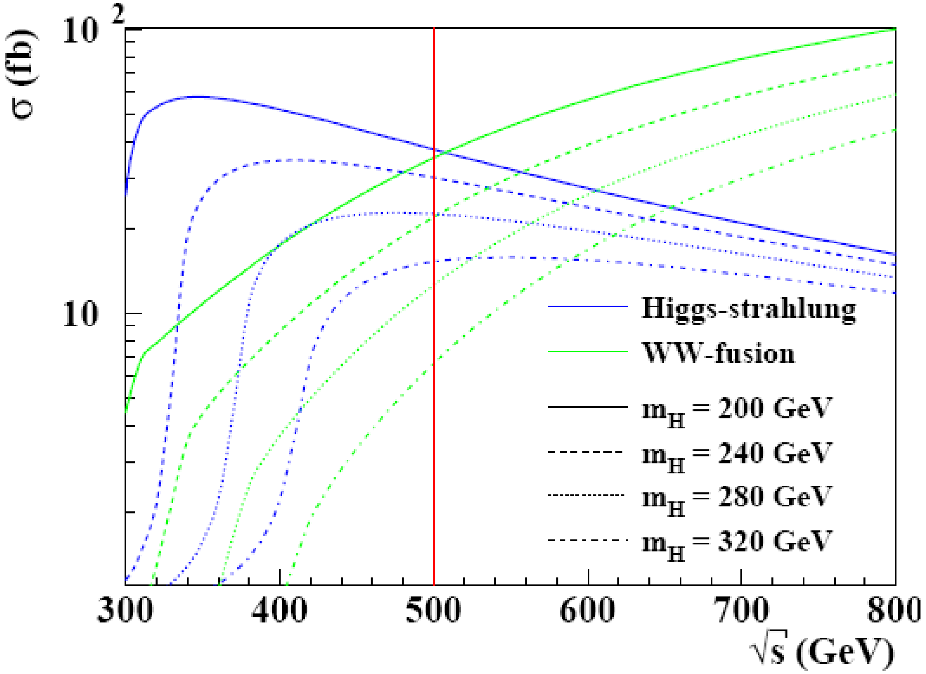
- Compact Linear Collider CLIC
  - normalconducting acceleration
  - 100 MeV/m, 12 GHz
  - two-beam acceleration principle
  - up to several TeV
  - still in fundamental R&D phase



- **Summary:**
  - **ILC ready to go ahead, but limited in energy reach (≤ 1 TeV)**
  - **CLIC in very early state, but may pave the way for higher energy**

SM Higgs Production at the ILC

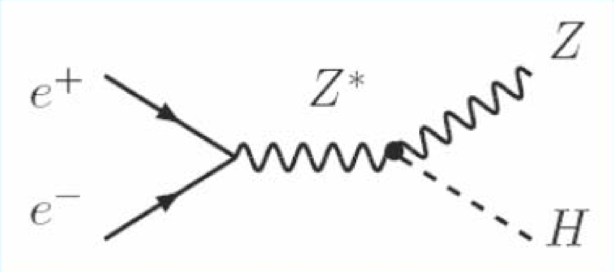


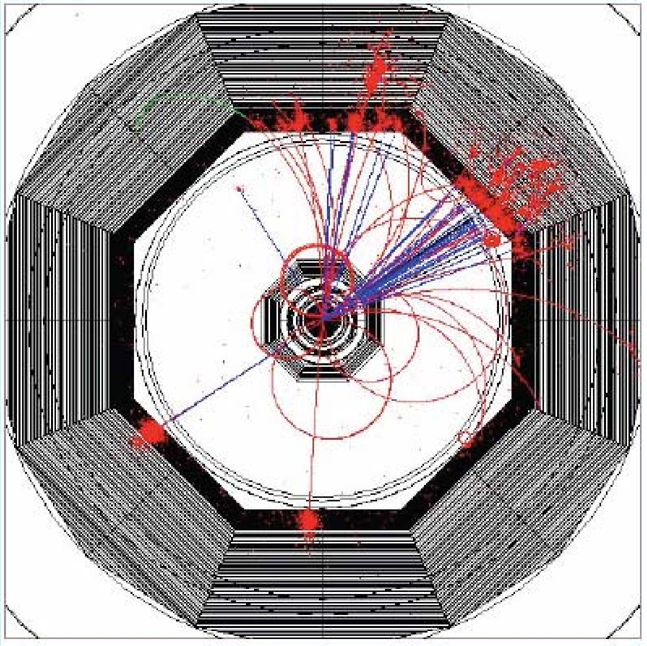


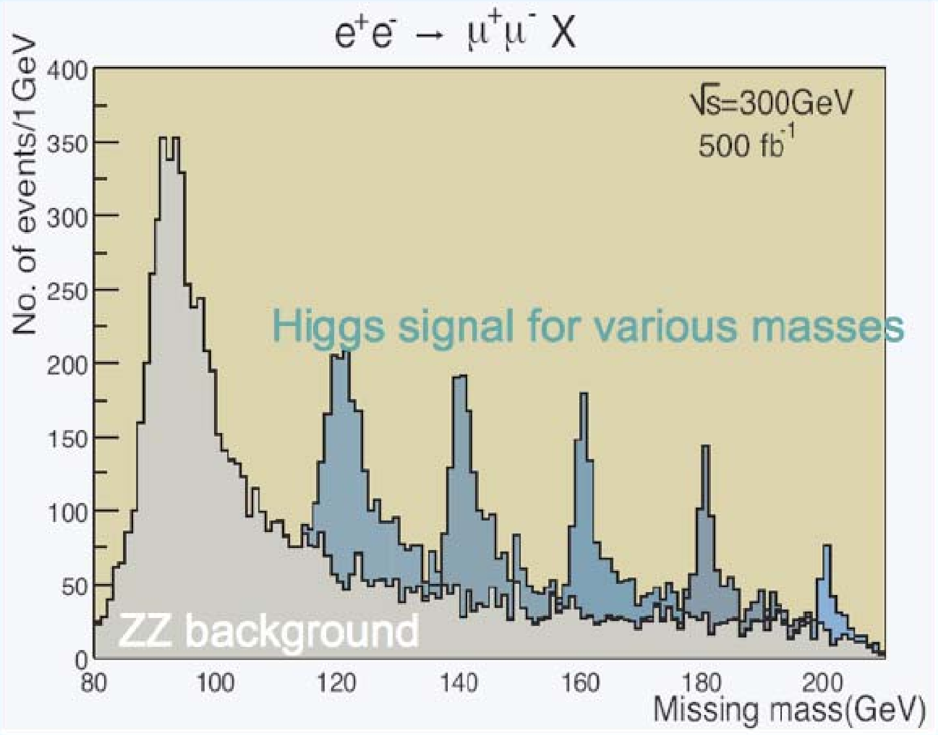
- Dominant production mechanisms: Higgsstrahlung and WW-fusion

Higgs

- Model independent Higgs measurement

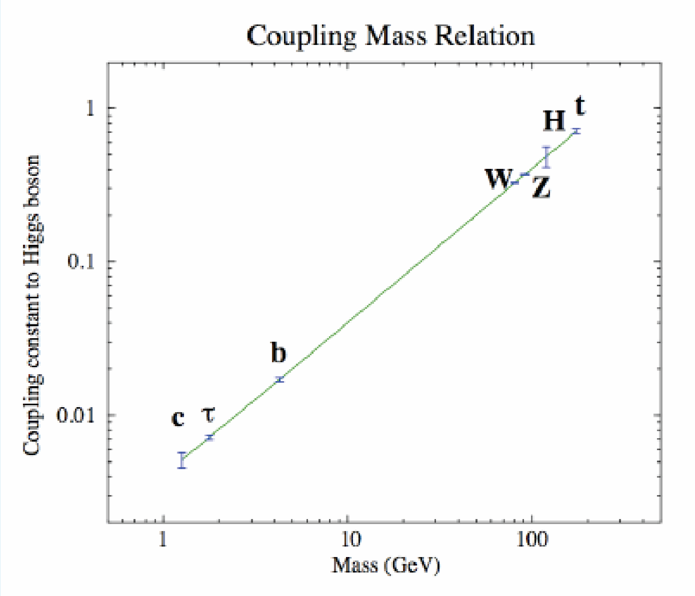


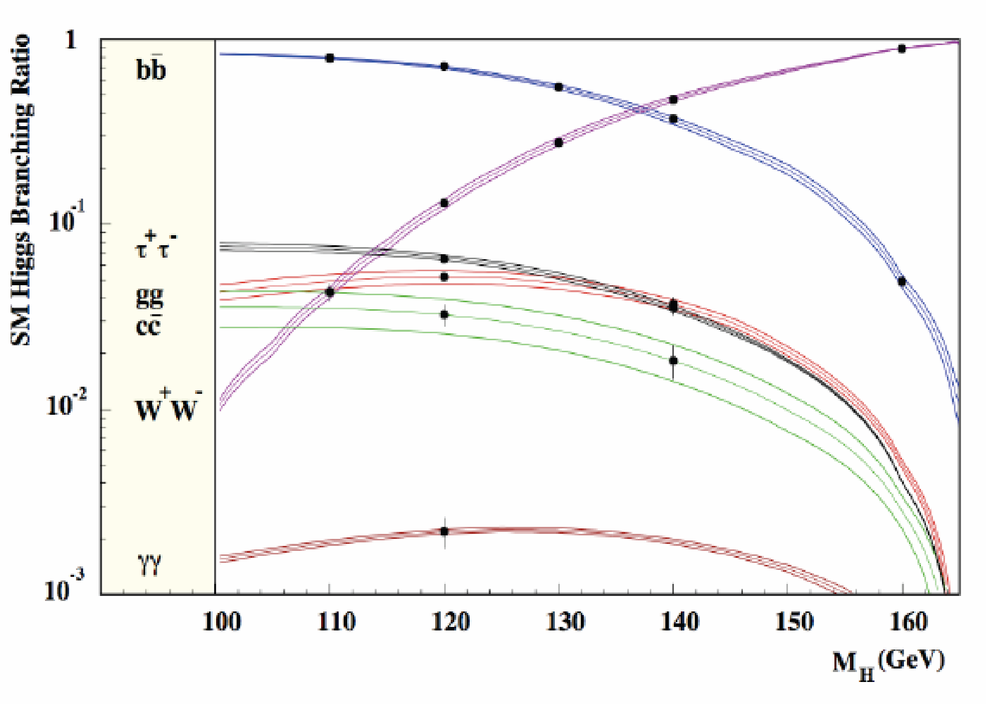




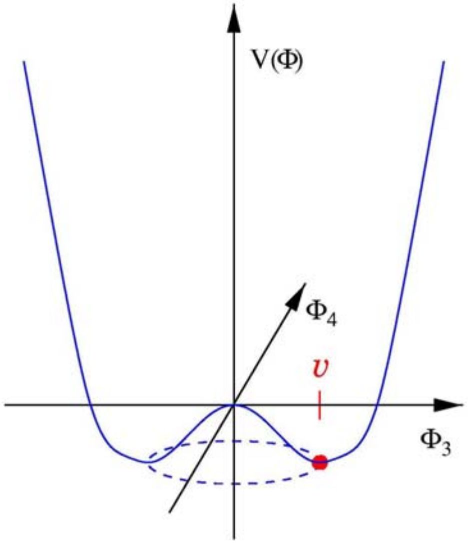
Higgs Couplings

- Measuring the couplings of the Higgs to massive particle
- Check coupling-mass relation
  - The smoking gun!





Verification of the Higgs Potential

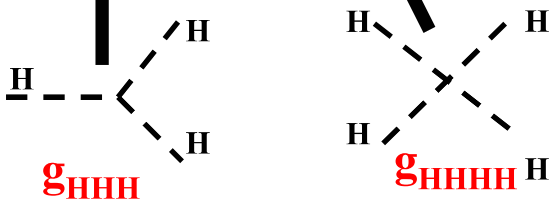


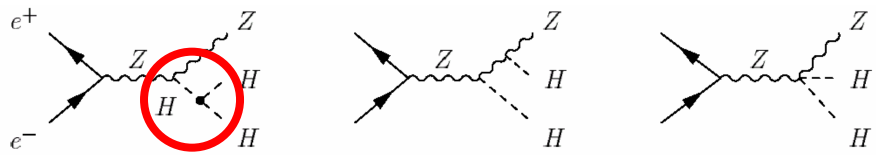
$$V(\Phi) = \mu^2 |\Phi|^2 + \lambda |\Phi|^4 \qquad \mu^2 < 0 \quad \lambda > 0$$

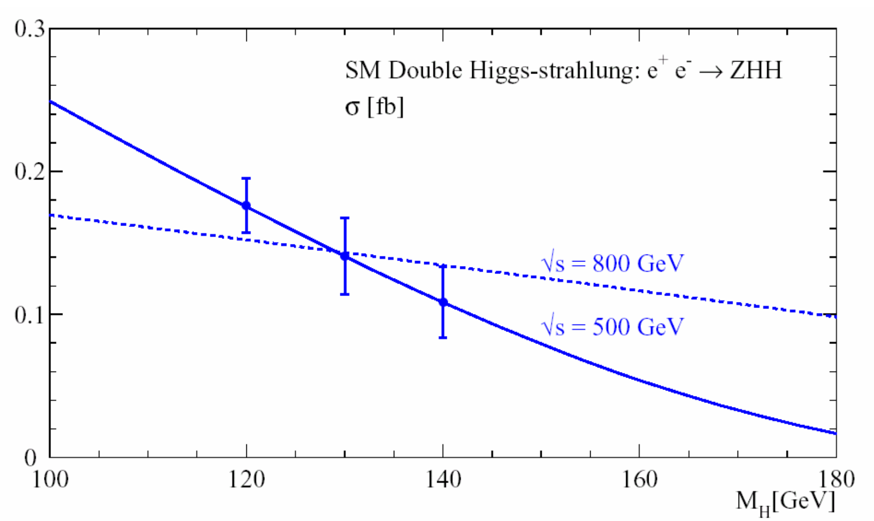
Vacuum expectation value $v = \sqrt{-\mu^2/\lambda}$

$$V(H) = \lambda v^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$$

$$m_H = \sqrt{2\lambda} v$$







- **Measurement of double Higgs-strahlung: $e^+ e^- \rightarrow HHZ$**

  $\Delta g_{HHH} / g_{HHH} = 0.22$

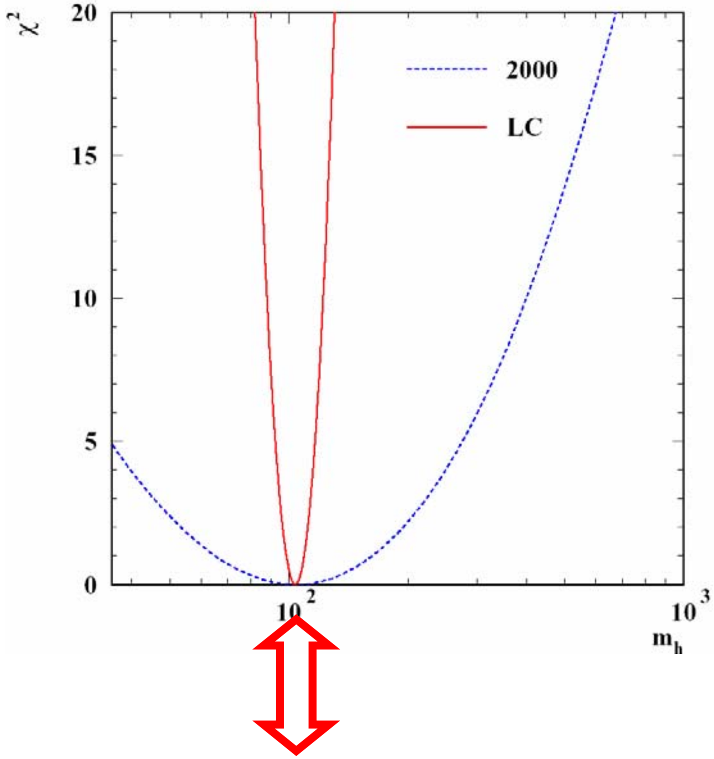
- **Measurement of g_{HHHH} not possible**

Giga-Z

- Production of 10^9 Z-Bosonen at $\sqrt{s}$ = 91 GeV
  - 100-fold LEP I statistics
  - polarisation (as SLC)
  - 30 fb^{-1} = 1/2 year

	LEP/SLC/Tevatron	Giga-Z
m_Z	91 187,5 ± 2,1 MeV	---
$\sin^2\vartheta_W$	0,23153 ± 0,00016	± 0,000013
A_b	0,899 ± 0,013	± 0,001
R_b	0,21629 ± 0,00066	± 0,00014
m_W	80 392 ± 29 MeV	± 6 MeV

Comparison today's SM-Fits with Giga-Z:



Comparison to direct Higgs mass measurement

Supersymmetry

- **If m_{SUSY} < 2 TeV ⇒ Discovery at the LHC**

SUSY will be the New Standard Model

- **Scalar partners of fermions**

$$\tilde{e}_R, \tilde{e}_L, \tilde{\mu}_R, \tilde{\mu}_L, \ldots, \tilde{t}_1, \tilde{t}_2$$

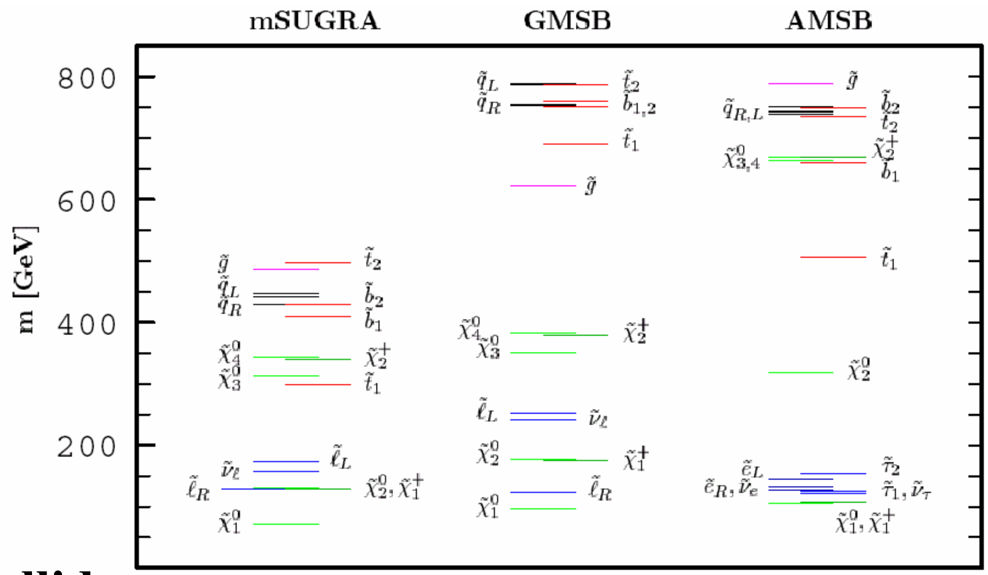
- **Fermionic partners of bosons**

$$\tilde{\chi}^{\pm}, \tilde{\chi}^0_1, \cdots, \tilde{\chi}^0_4, \tilde{g}$$

- **≥ 2 Higgs-doublets**

$$h, H, A, H^{\pm}$$

Template mass spectra:



Advantages of an electron positron collider:

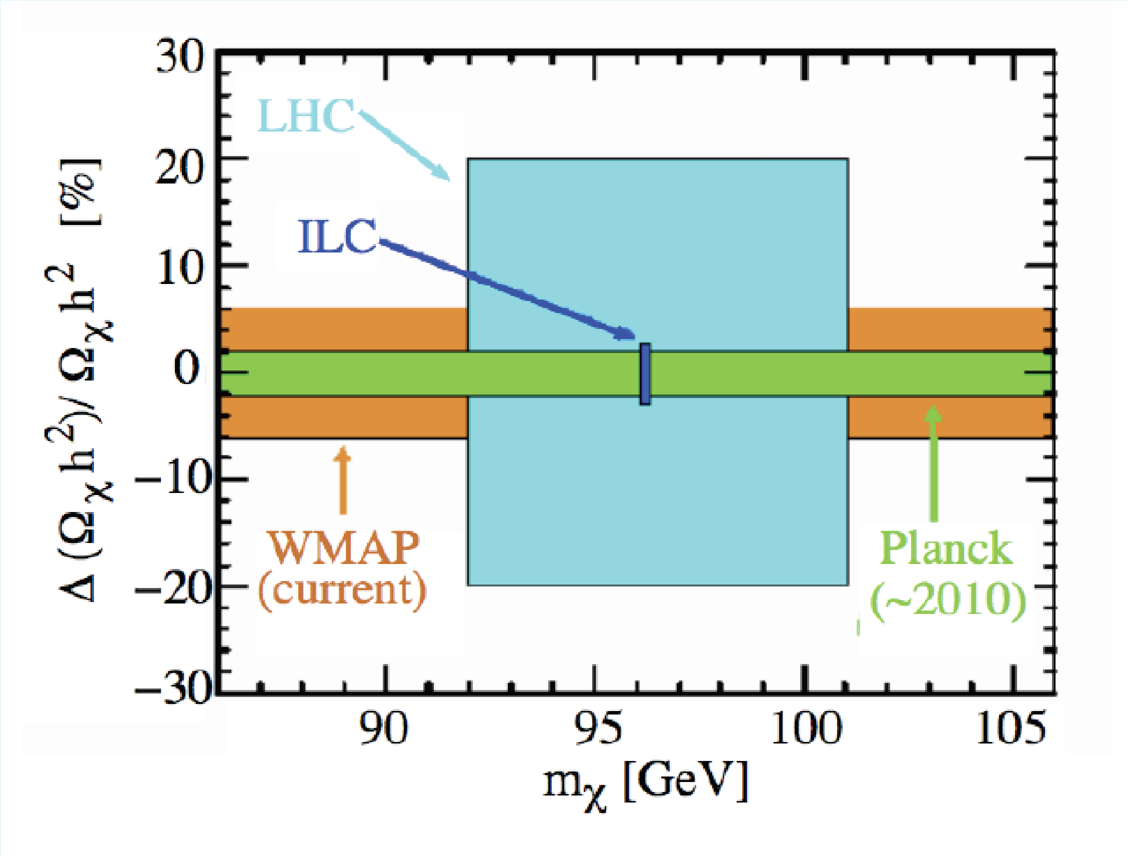
- **tune cms energy: turn on SUSY particles one-by one**
- **mass measurement at the kinematic threshold**
- **polarisation of electrons and positrons**

separation of SUSY partners, e.g.:

$$e^+_L e^-_L \rightarrow \tilde{e}^+_L \tilde{e}^-_L \qquad e^+_R e^-_R \rightarrow \tilde{e}^+_R \tilde{e}^-_R$$

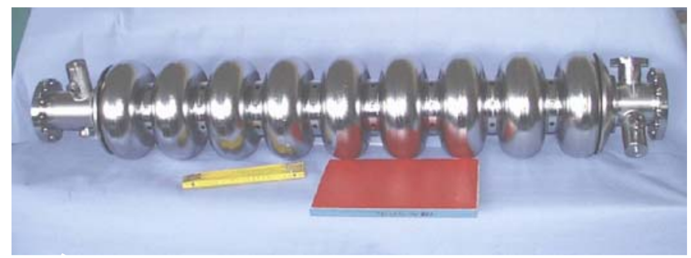
The Cosmological Connection

- Could SUSY particles be the Cold Dark Matter?
- Astrophysics experiments measure just densities
- ILC could close the loop

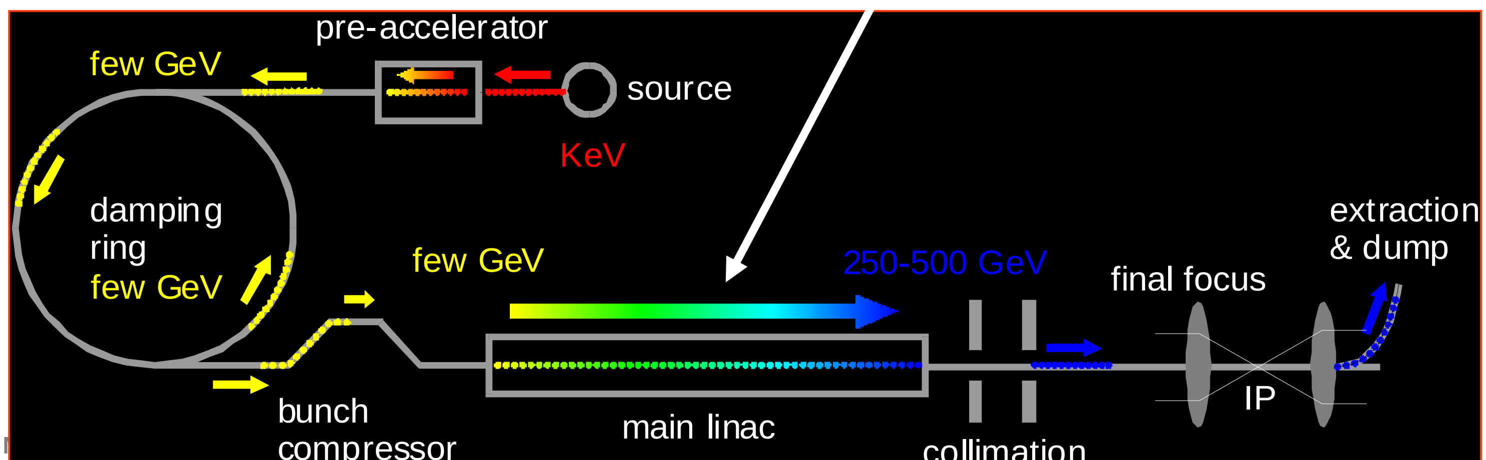


The International Linear Collider

- Electron-positron collider
  - centre-of-mass energy up to 1 TeV centre-of-mass energy
  - luminosities $> 10^{34}/cm^2/s$
- Designed in a global effort
- Accelerator technology: supra-conducting RF cavities



- Elements of a linear collider:



International Linear Collider (ILC)

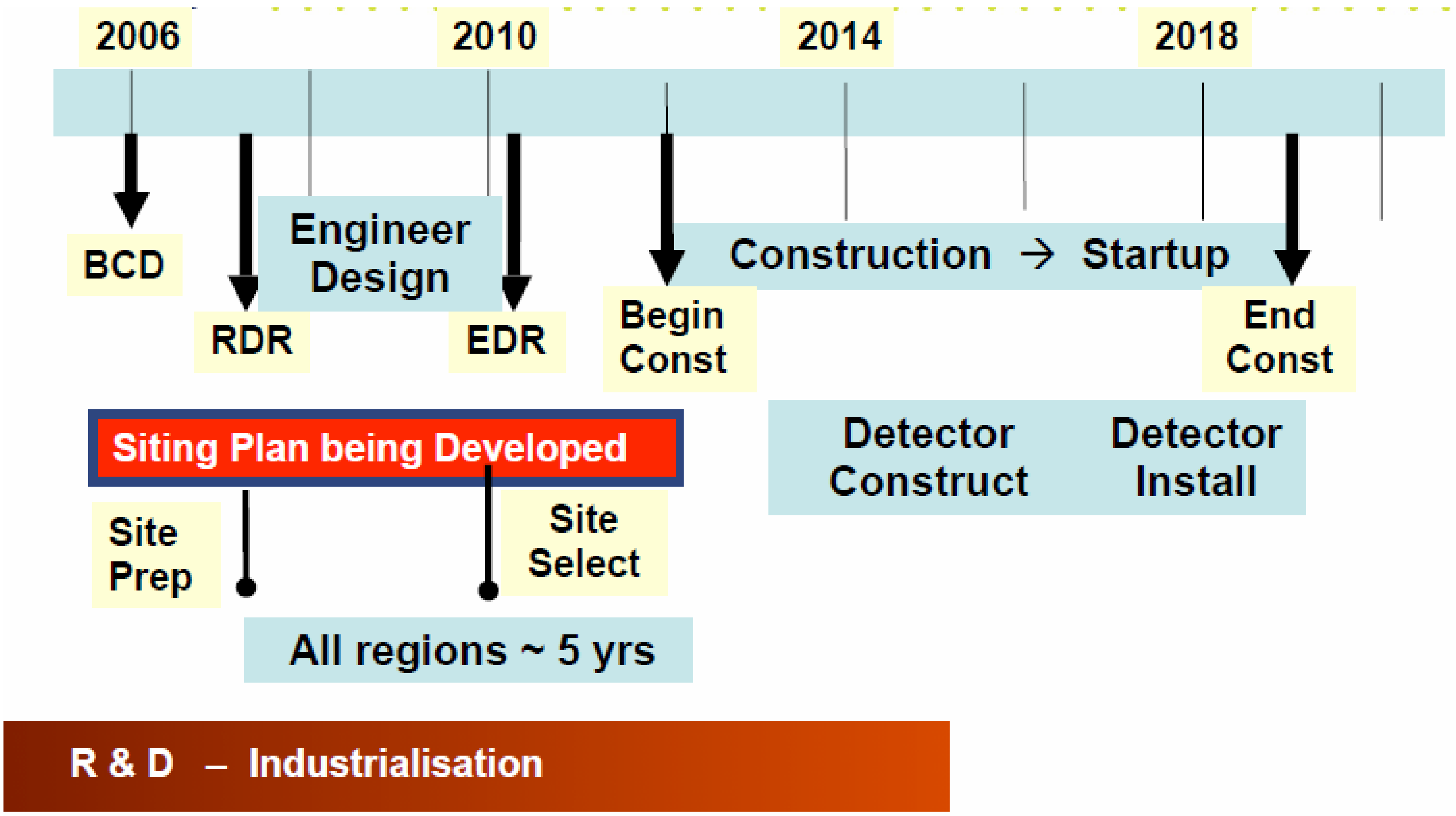
- E_{cm} adjustable from 200 – 500 GeV
- Luminosity $\int L dt = 500\ fb^{-1}$ in 4 years
  (corresponds to $2 \times 10^{34}\ cm^{-2}s^{-1}$ with a start-up profile)
- Ability to scan between 200 and 500 GeV
- Energy stability and precision below 0.1%
- Electron polarisation of at least 80%

Positron polarisation

- The machine must be upgradeable to 1 TeV!

ILC Time Schedule

- 2006: Baseline Configuration Document
- 2007: Reference Design Report



Challenges

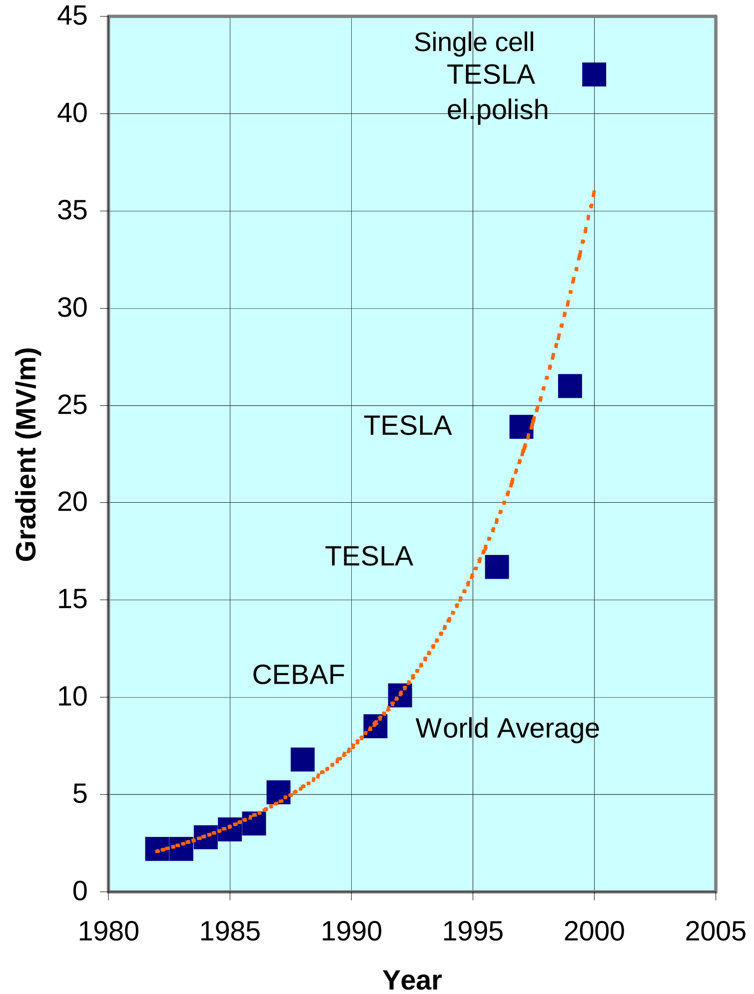
- Quest for the highest possible accelerator gradient
- ILC goal: 35 MV/m

- Huge progress over the last 15 years
- 25-fold improvement in perfomance/cost

- Major impact on next generation light sources:
  - XFEL designed for ≥ 25 MV/m
    10% prototype for ILC

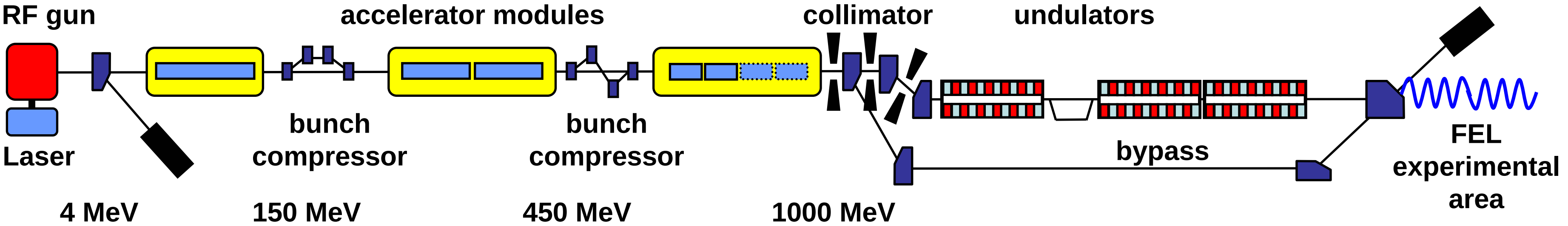
- Recall: LEP II used 7 MV/m

Development (schematic) of gradient in SCRF cavities



FLASH: Prototype for XFEL and ILC

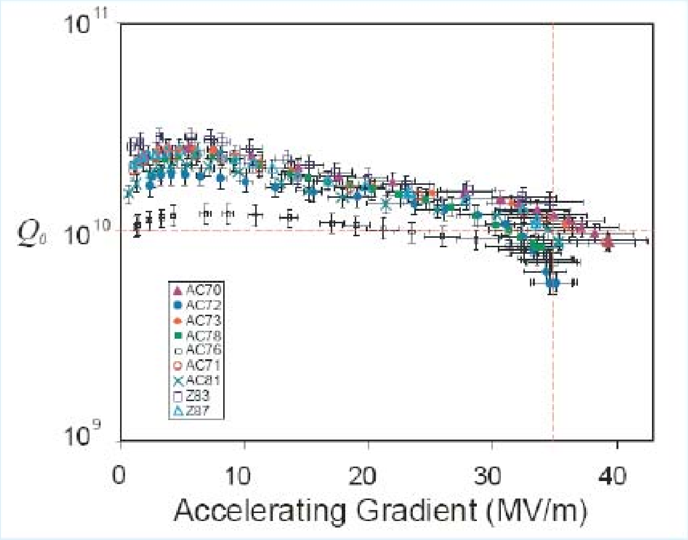
- 1 GeV electron LINAC based on SCRF
- used for ILC studies and as light source (free electron laser)

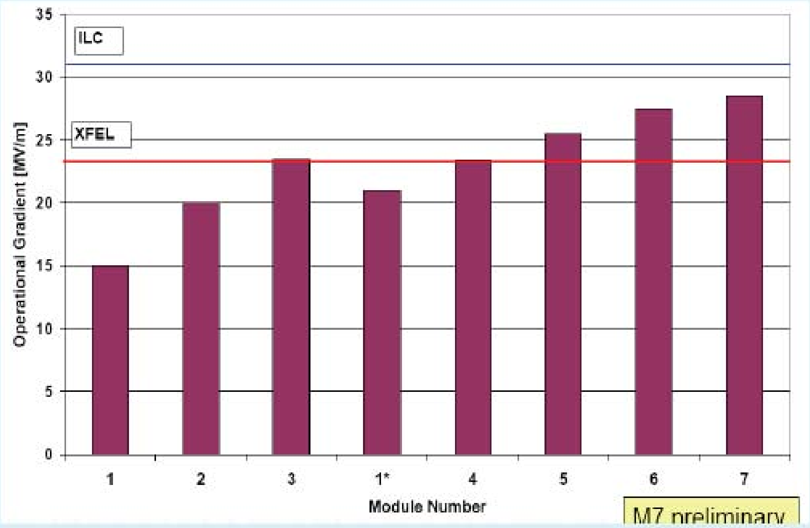


Challenges

- **Getting to 35 MV/m:**

  - Acceleration gradient goal:
    - 35 MV/m in 9-cell cavities with production yield >80%
    - 50 MV/m have been reached with single cavities
    - Mass production reliability is the key problem





Cavity Quality (Q value)

- Superconducting cavity: $Q > 10^{10}$
- A church bell (300 Hz) with $Q = 5 \times 10^{10}$ would ring – once excited – longer than one year!

Challenges

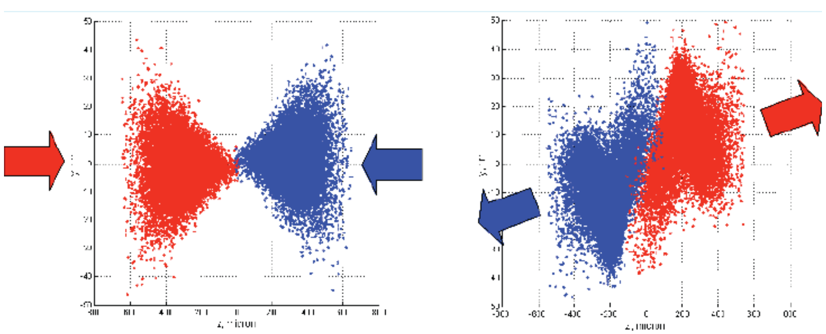
- **Luminostity:**

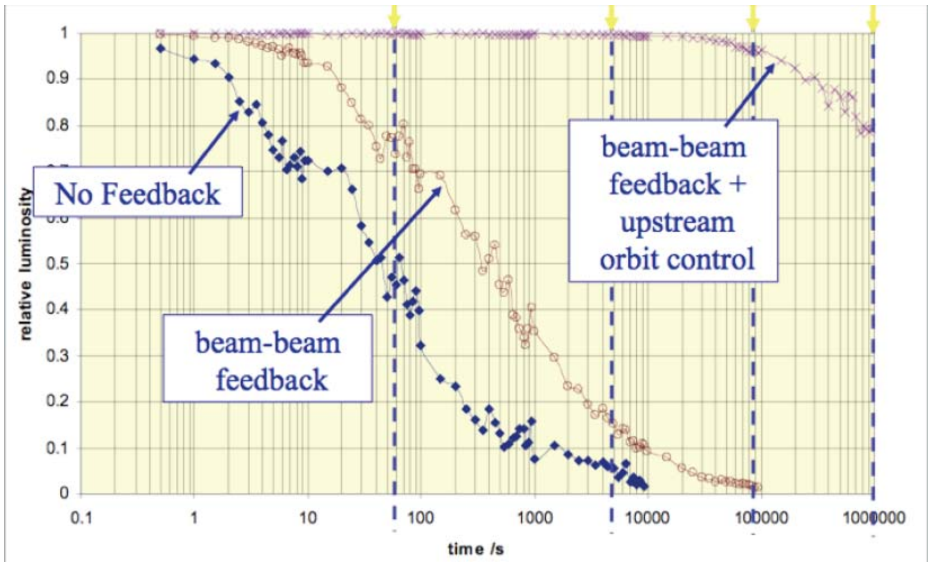
$$L = \frac{n_b N_e^2 f_{rep}}{4\pi \sigma_x^* \sigma_y^*} \times H_D$$

n_b	number of bunches per pulse
N_e	number of electrons (positrons) per bunch
f_{rep}	pulse repetition frequency
H_D	disruption enhancement factor (≈ 2)
$\sigma^*_{x(y)}$	beam dimensions at interaction point

- **make beams as small as possible at IP**
  6 nm × 600 nm

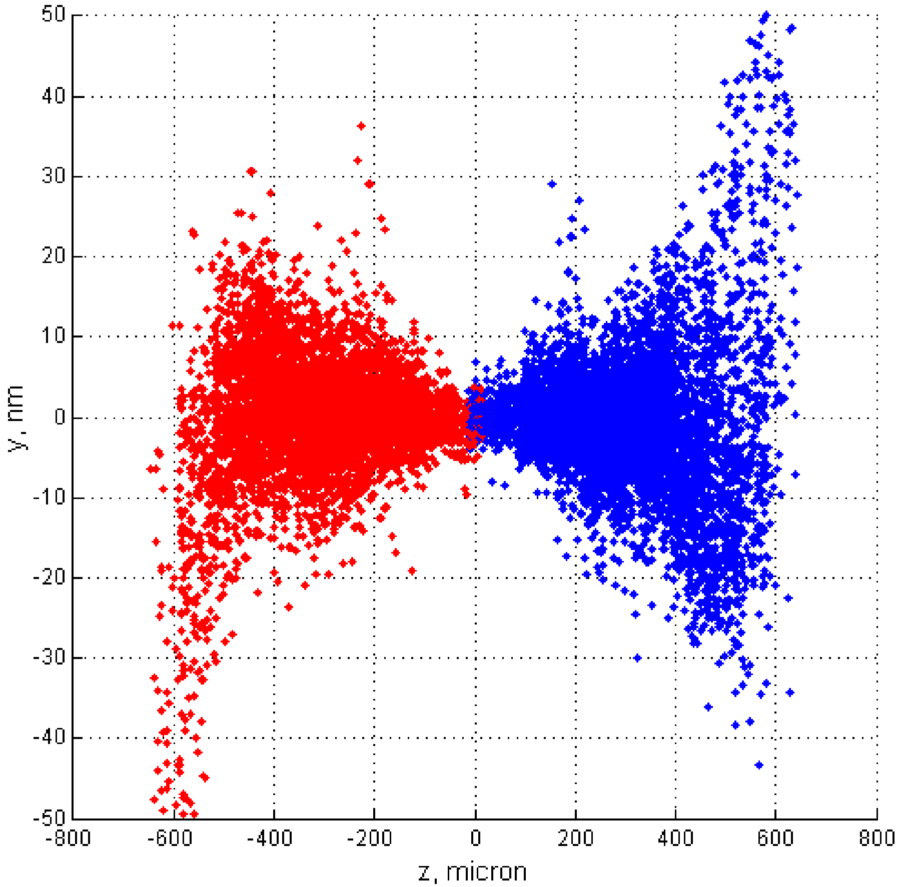
- **and make them collide!!!**





Beam Beam Interactions

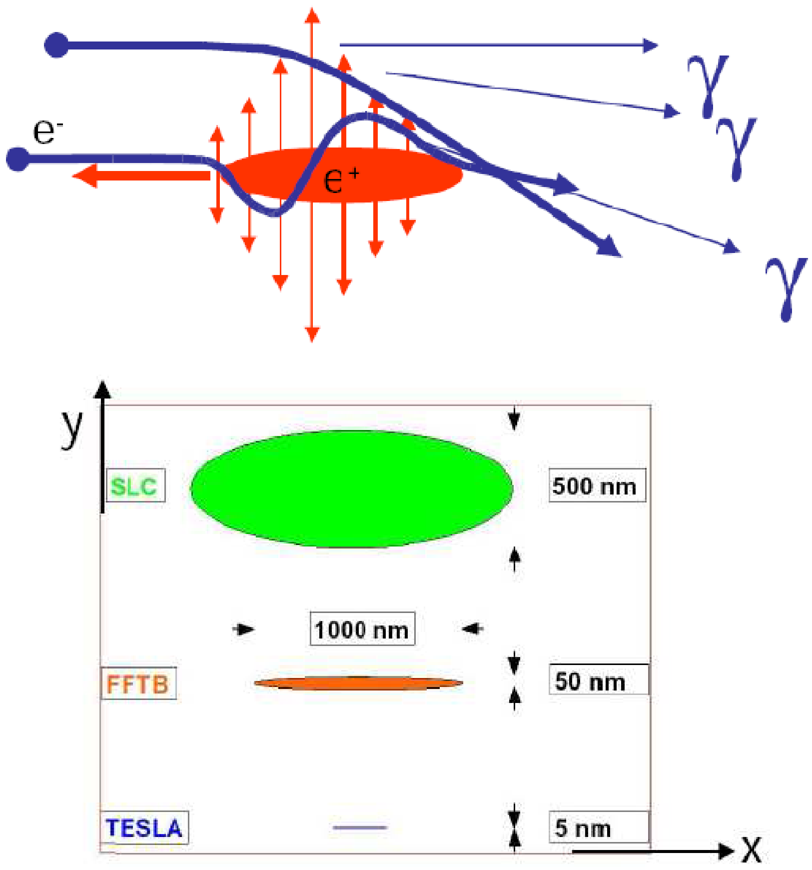
Simulation of two LC bunches as they meet each other



Andrei Sergey, SLAC

Challenges

Beamstrahlung



- Energy loss in collision due to Beamstrahlung:

$$\delta_{BS} = \frac{\Delta E}{E} = \frac{E_{CM}}{\sigma_Z} \left(\frac{N}{\sigma_x + \sigma_y} \right)^2$$

- But: $\mathcal{L} \sim 1/\sigma_x \sigma_y \Rightarrow$ choose flat beams
- 1.5 % energy loss on average
- $\approx 100\,000\,\gamma\gamma$ pairs per BX!
- Intense backgrouns in the forward direction, need high B field to control e^+e^- pairs

Comparison LHC and ILC

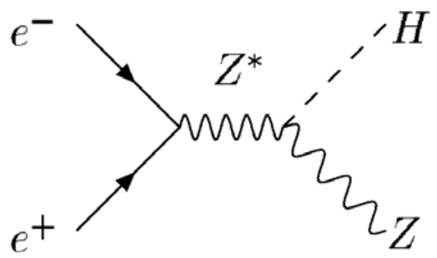
	LHC	ILC
total energy	14 TeV	0.5-1 TeV
usable energy	a fraction	full
beam	composite	point-like
signal rate	high	low
background	very high	low
analysis	specific modes	nearly all modes
reconstruction	loose along beam	full event
status	soon to start	design to be completed

ILC Physics Motivation

- ILC will complement LHC discoveries by precision measurements

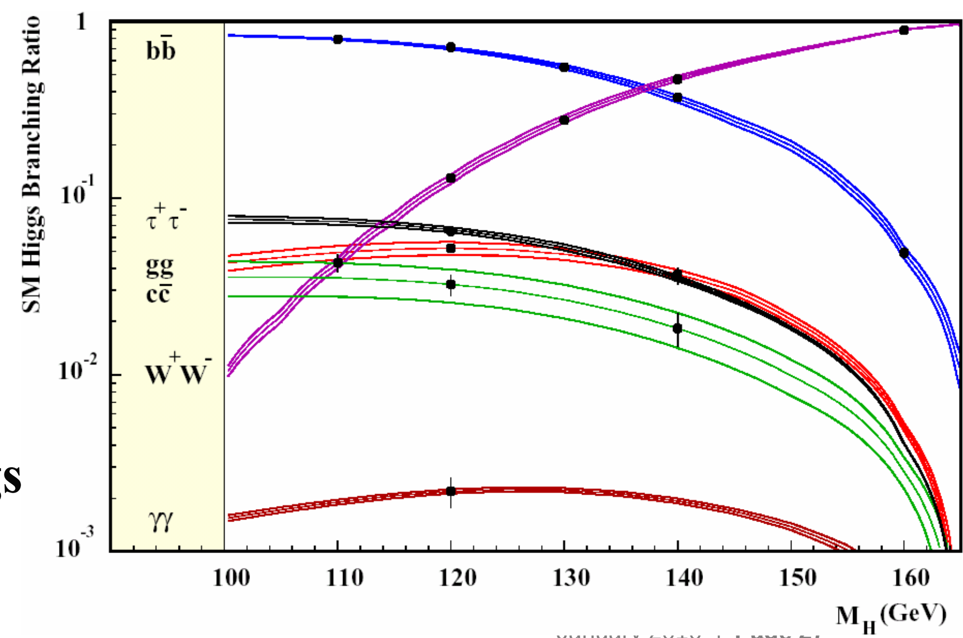
- Here just two examples:

1) There is a Higgs, observed at the LHC
   - e^+e^- experiments can detect Higgs bosons without assumption on decay properties Higgs-Strahlungs process (à la LEP)



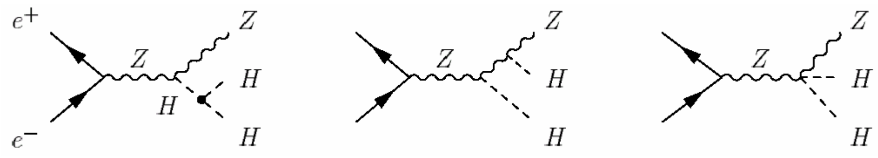
   - identify Higgs events in $e^+e^- \rightarrow ZH$ from $Z \rightarrow \mu\mu$ decay

   - count Higgs decay products to measure Higgs BRs
   - and hence (Yukawa)-couplings



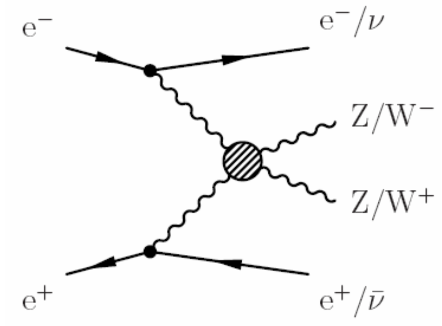
ILC Physics Motivation

- **Measure Higgs self-couplings $e^+e^- \to ZHH$ to establish Higgs potential**
  Note: small signal above large QCD background



2) There is NO Higgs (definite answer from LHC!)

- **something else must prevent e.g. WW scattering from violating unitarity at O(1 TeV)**
- **strong electroweak symmetry breaking?**
  → study $e^+ e^- \to WW\nu\nu$, $Wze\nu$ and $ZZee$ events



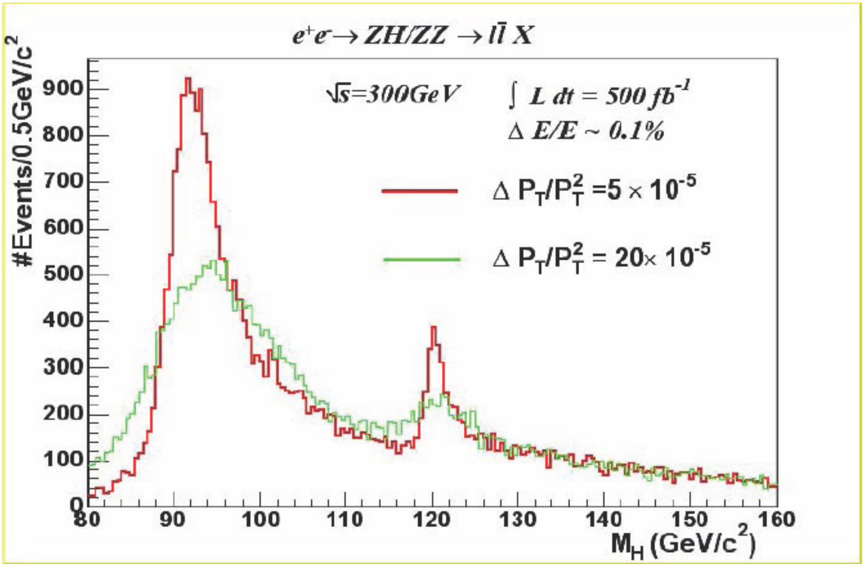
- **need to select and distinguish W and Z bosons in their hadronic decays!**
  BR (W/Z → hadrons) = 68% / 70%

- **Many other physics cases: SM, SUSY, new phenomena, …**
  Need ultimate detector performance to meet the ILC physics case

Impact on Detector Design

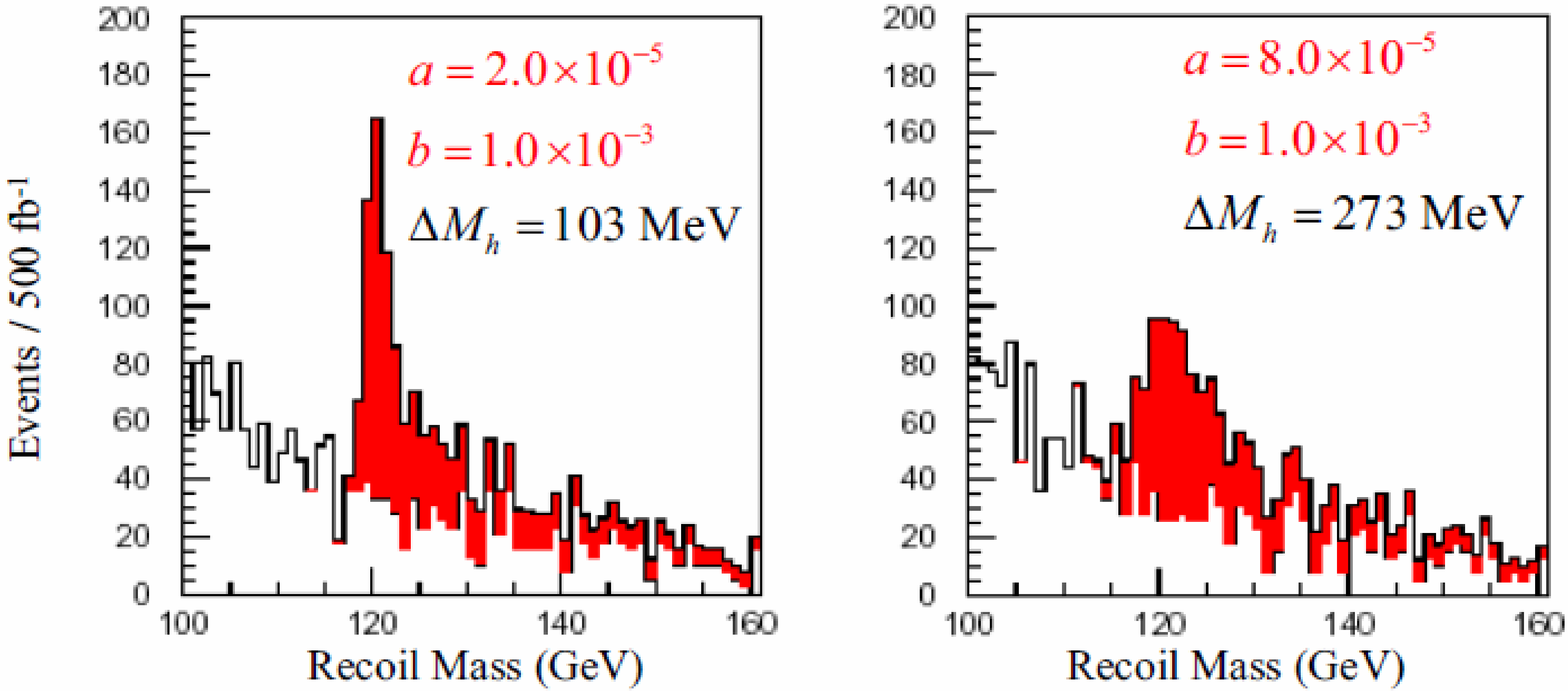
- Vertex detector:
  e.g. distinguish c- from b-quarks
  - goal impact parameter resolution
    $\sigma_{r\varphi} \approx \sigma_z \approx 5 \oplus 10/(p \sin \Theta^{3/2})$ µm   3 times better than SLD
  - small, low mass pixel detectors, various technologies under study
    O(20×20 µm²)
- Tracking:
  - superb momentum resolution
    to select clean Higgs samples
  - ideally limited only by Γ_Z

  $\rightarrow \Delta(1/p_T) = 5 \cdot 10^{-5}$ /GeV
  (whole tracking system)
  3 times better than CMS



Options considered:
- Large silicon trackers (à la ATLAS/CMS)
- Time Projection Chamber with ≈ 100 µm point resolution
  (complemented by Si–strip devices)

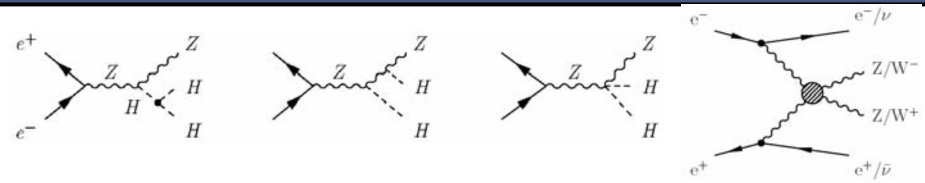
Tracker Resolution



Tracker resolution matters

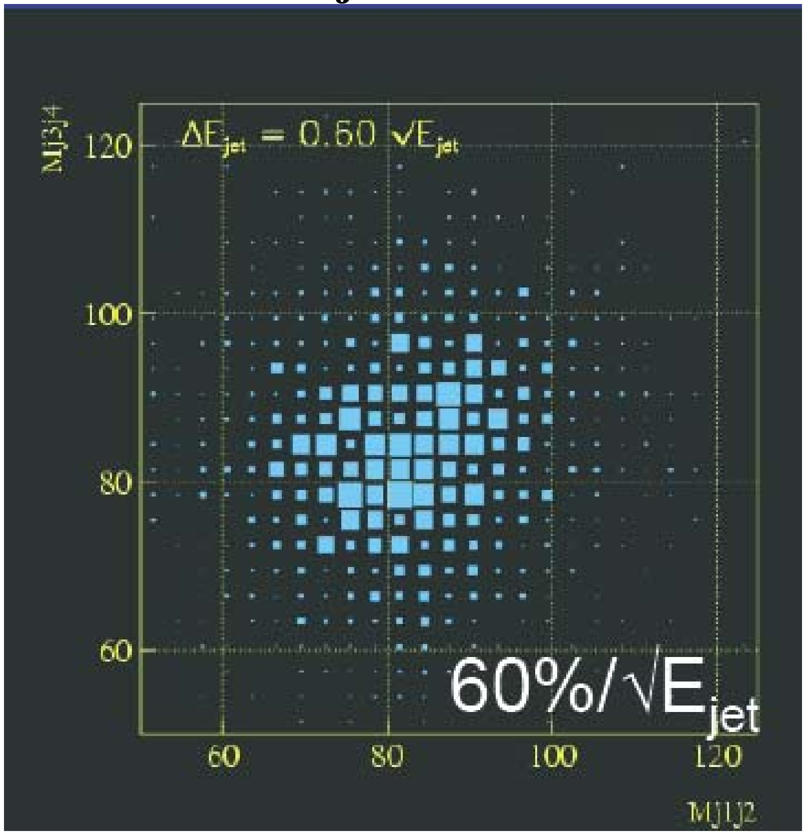
Impact on Detector Design

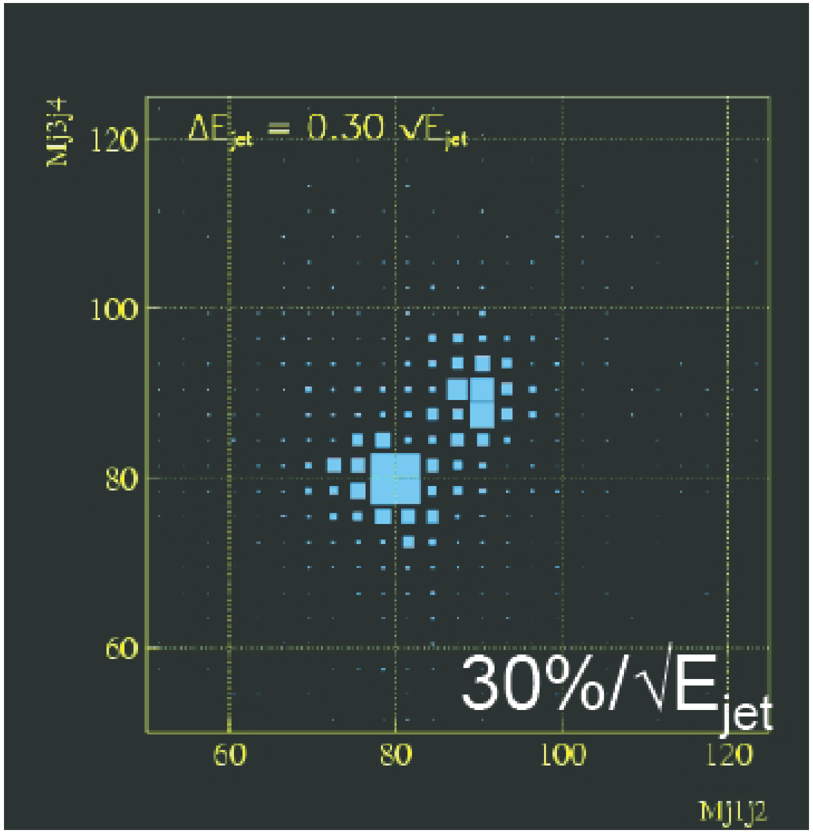
- **Calorimeter:**
  distinguish W- and Z-bosons in their hadronic decays
  → 30%/√E jet resolution!



2 times better than ZEUS

- **WW/ZZ → 4 jets:**

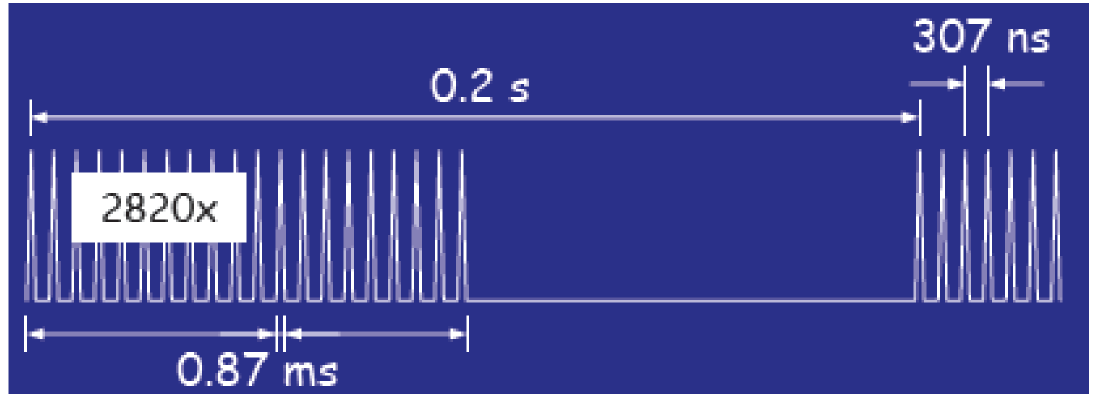




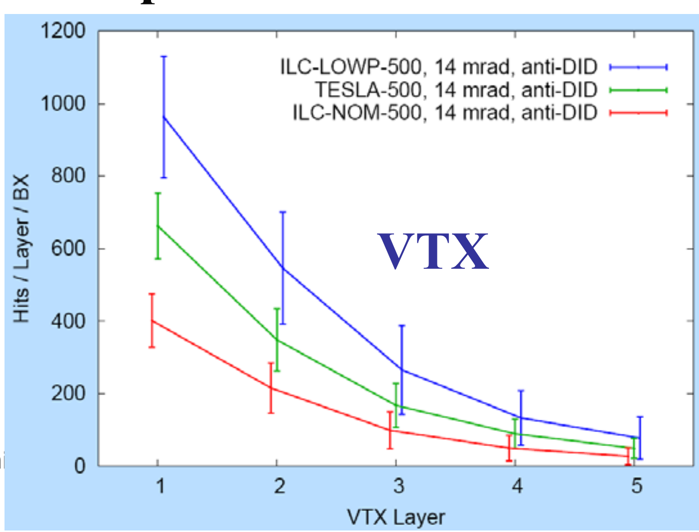
→ Particle Flow or Dual Readout calorimeter

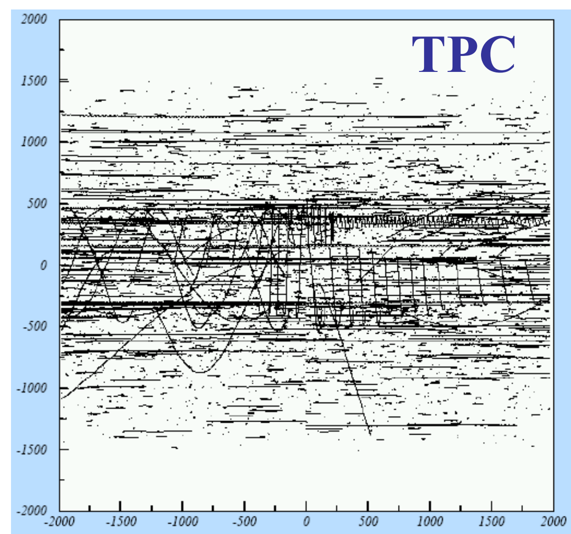
Detector Challenges at the ILC

- Bunch timing:
  - 5 trains per second
  - 2820 bunches per train separated by 307 ns
    - no trigger
    - power pulsing
    - readout speed
- 14 mrad crossing angle
- Background:
    - small bunches
    - create beamstrahlung → pairs



backgound not as severe as at LHC but much more relevant than at LEP

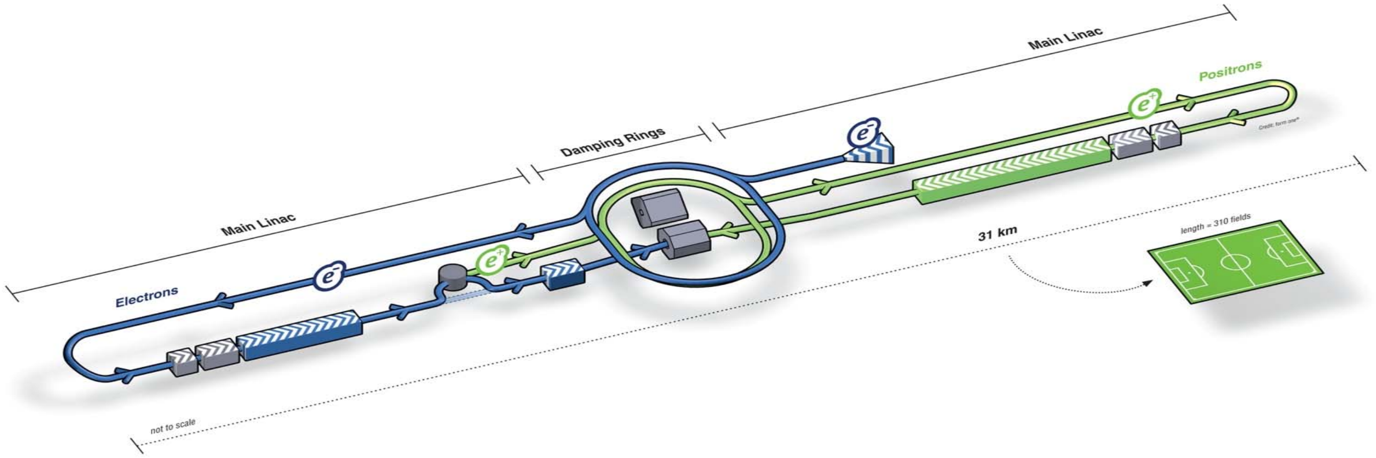




Two Detectors

Additional complication:

One interaction region,
but two detectors:

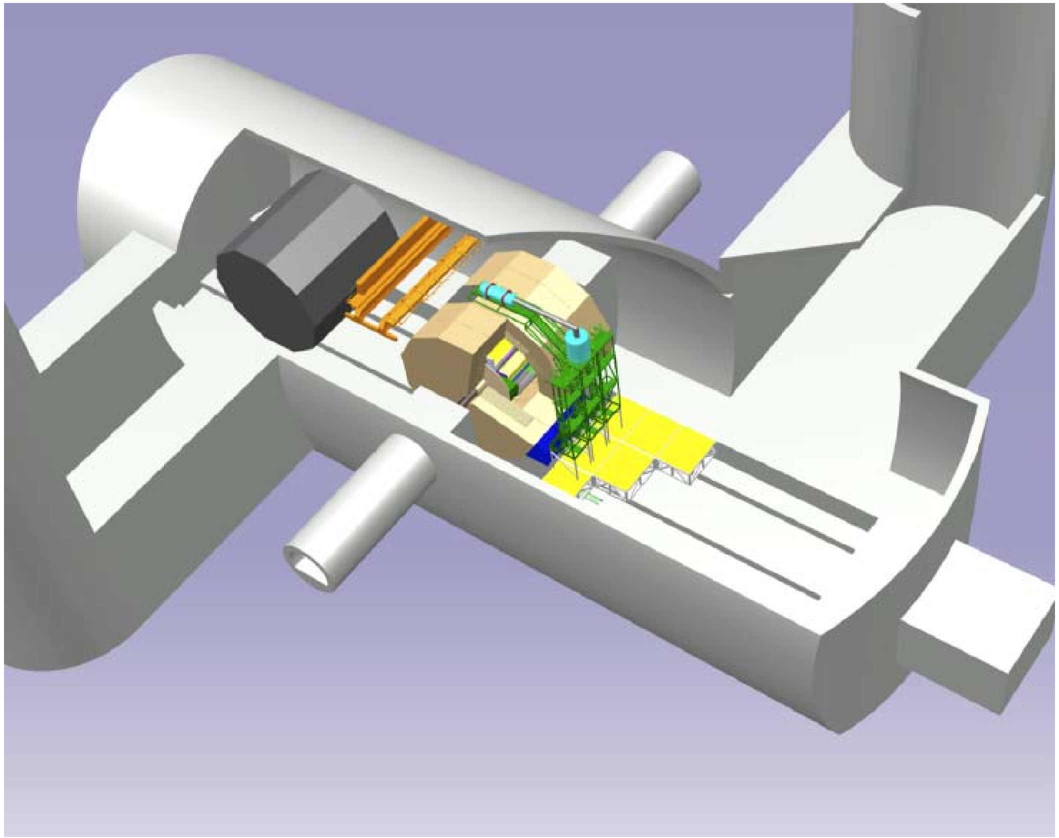


Two Detectors: Push Pull

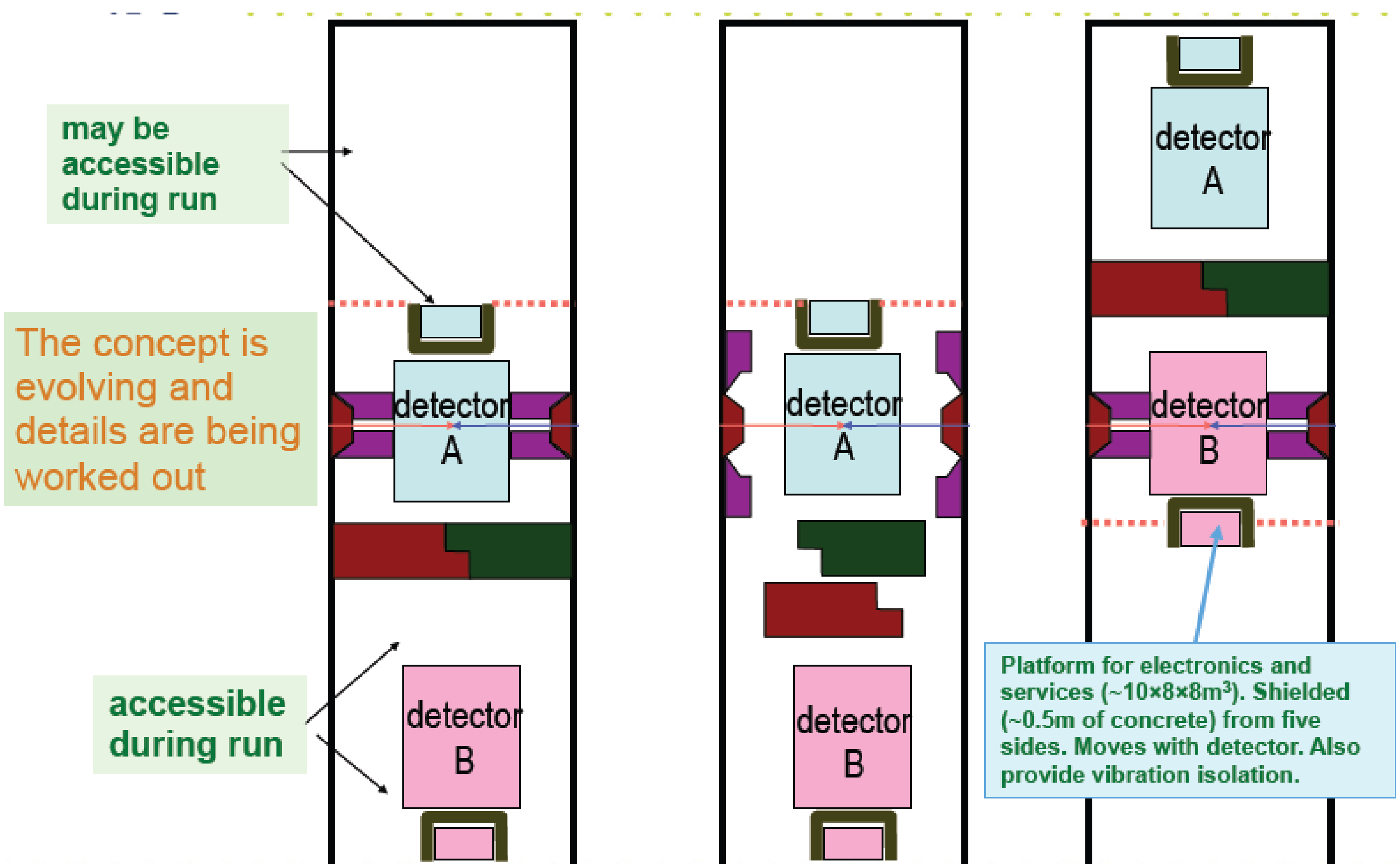
Additional complication:

One interaction region,
but two detectors:

push pull operation anticipated



Detector Push-Pull



The CLIC Two Beam Scheme

Two Beam Scheme

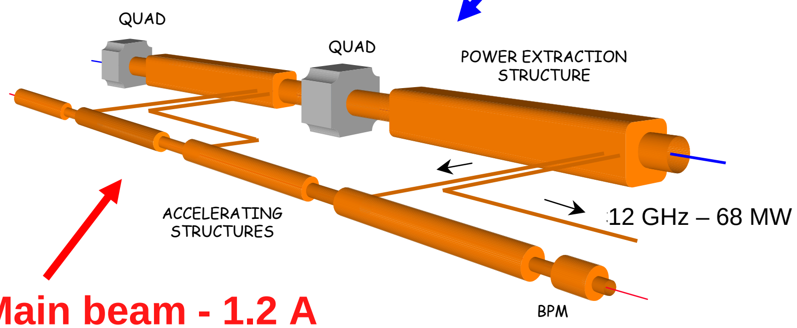
Drive Beam supplies RF power

- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

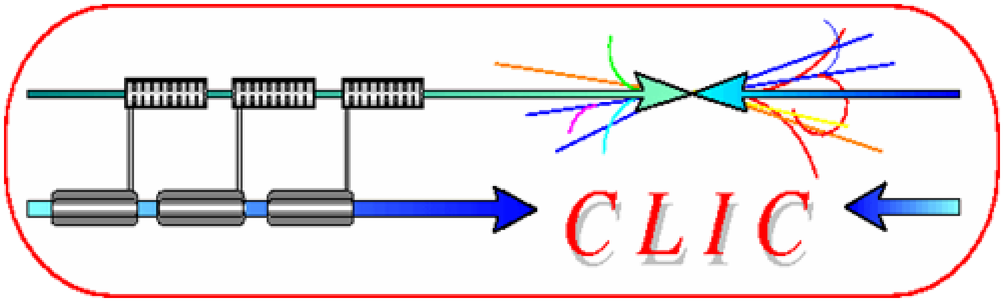
Main beam for physics

- high energy (9 GeV – 1.5 TeV)
- current 1.2 A

Drive beam - 100 A from 2.4 GeV -> 240 MeV (deceleration by extraction of RF power)



Main beam - 1.2 A from 9 GeV -> 1.5 TeV

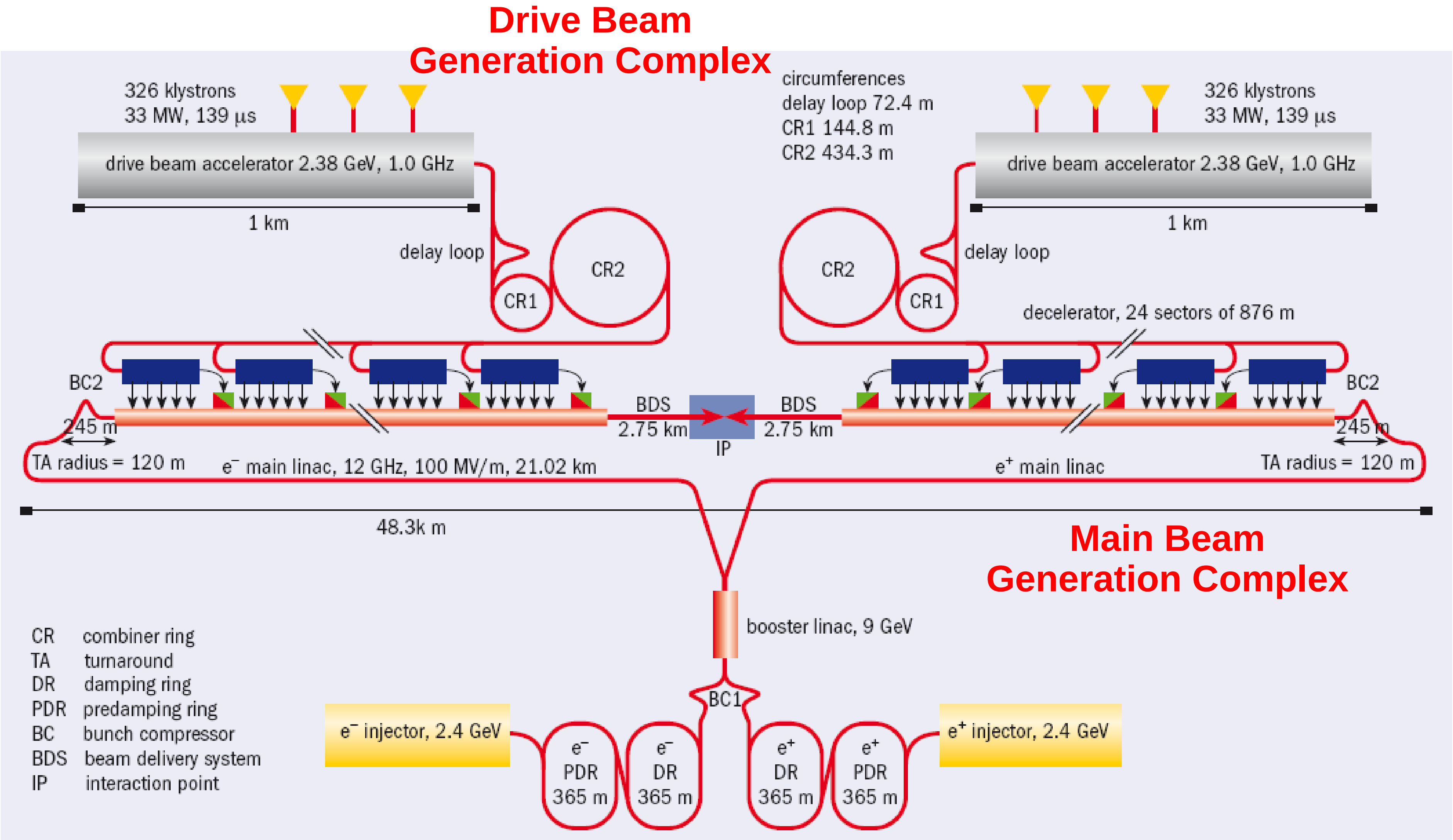


No individual RF power sources

->

CLIC itself is basically a ~50 km long klystron...

CLIC 3 TeV Overall Leyout

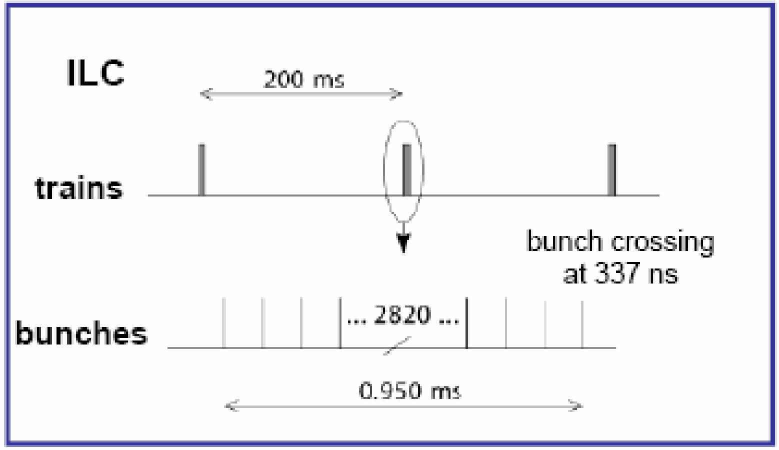


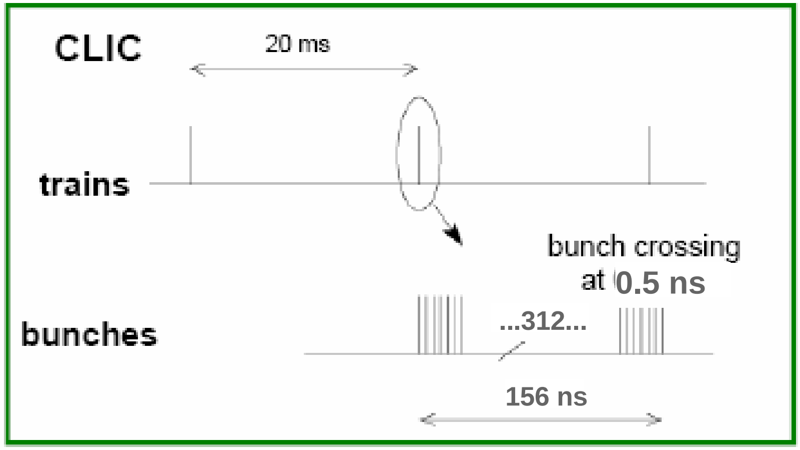
Comparison ILC and CLIC

Center-of-mass energy	ILC 500 GeV	CLIC 500 GeV	CLIC 3 TeV
Total (Peak 1%) luminosity [$\cdot 10^{34}$]	2(1.5)	2.3 (1.4)	5.9 (2.0)
Repetition rate (Hz)	5	50	
Loaded accel. gradient MV/m	32	80	100
Main linac RF frequency GHz	1.3	12	
Bunch charge [$\cdot 10^9$]	20	6.8	3.7
Bunch separation (ns)	370	0.5	
Beam pulse duration (ns)	950μs	177	156
Beam power/beam (MWatts)		4.9	14
Hor./vert. IP beam size (nm)	600 / 6	200 / 2.3	40 / 1.0
Hadronic events/crossing at IP	0.12	0.2	2.7
Incoherent pairs at IP	$1 \cdot 10^5$	$1.7 \cdot 10^5$	$3 \cdot 10^5$
BDS length (km)		1.87	2.75
Total site length km	31	13	48
Total power consumption MW	230	130	415

Crossing Angle 20 mrad (ILC 14 mrad)

CLIC Time Structure





> Bunch Spacing

- **ILC: 337 ns, enough time to identify events from individual BX**
- **CLIC: 0.5 ns, extremely difficult to identify events from individual BX**
- **need short shaping time of pulses**
- **power cycling with 50 Hz instead 5 Hz at ILC**
- **larger power dissipation? does silicon tracker need to be cooled? (not cooled in SiD)**

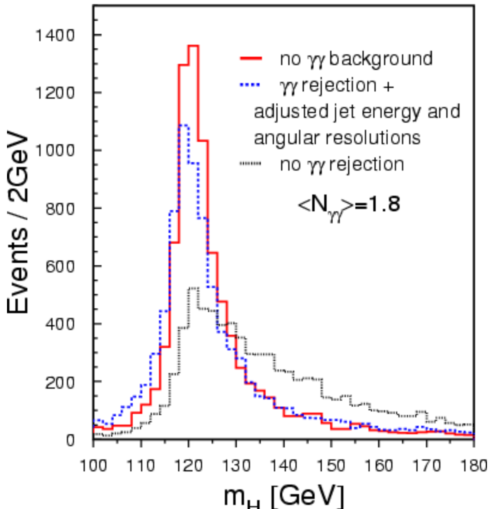
Why Time Stamping?

> **Overlay of physics events with background events from several bunch crossings**

- **degradation of physics performance**

> **Main background sources from beamstrahlung**

- **e+e- pairs from beamstrahlung photons**
  low pT, can be kept inside beam pipe with high magnetic field, B > 3 T
- **hadrons from 2-photon collisions (beamstrahlung photons)**
  can have high pT, reach main tracker and confuses jet reconstruction
  typically ~O(1) hadronic background event per BX with pT > 5 GeV tracks



Higgs mass reconstruction from HZ -> $b\bar{b}q\bar{q}$

Summary of CLIC Challenges + R&D

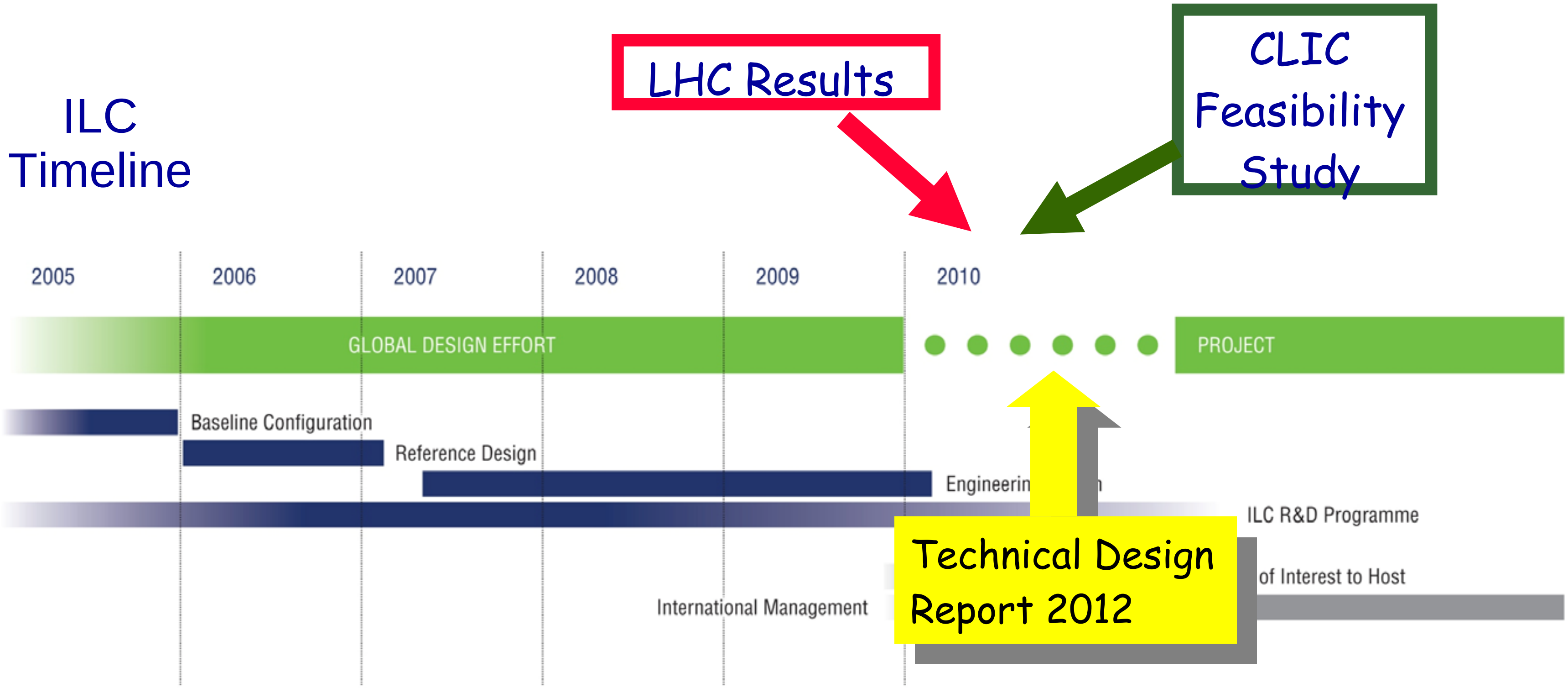
- **Time stamping**
  - most challenging in inner tracker/vertex region
  - trade-off between pixel size, amount of material and timing resolution
- **Power pulsing and other electronics developments**
  - in view of CLIC time structure
- **Hadron calorimetry**
  - dense absorbers to limit radial size (e.g. tungsten)
  - PFA studies at high energy
  - alternative techniques, like dual/triple readout
- **Background**
  - innermost radius of first vertex detector layer
  - shielding against muon background more difficult at higher E
- **Alignment and stability**

Main Differences CLIC as compared to ILC

- Higher energy results in more dense particle jets
  - Improved double track resolution
  - Calorimeters with larger thickness and higher granularity
- Much shorter bunch spacing
  - CLIC 0.5 ns wrt. ILC 337 ns
  - Requires time stamping
  - Impact on pulsed power electronics
- Smaller beam sizes and higher energy
  - Result in more severe background

Time Lines

ILC
Timeline



End of Lecture 1