Challenges, Current Developments and Future Possibilities for Detectors in High Energy Physics

Joint Instrumentation Seminar

DESY

February 5, 2010

Joachim Mnich

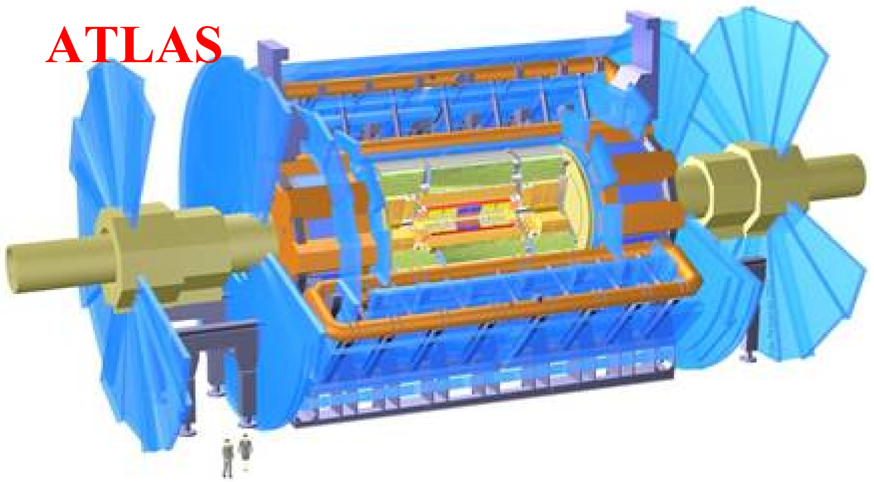
Future of Experimental Particle Physics

- Future directions in particle physics very much depends on LHC

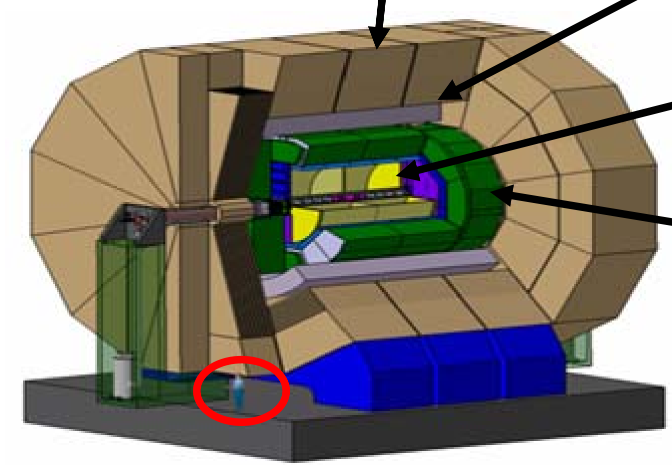
- Energy frontier:
  - LHC and upgrades (sLHC)
  - Linear Collider (ILC) or CLIC

- Other projects
  - Super b-factories
  - Neutrino physics

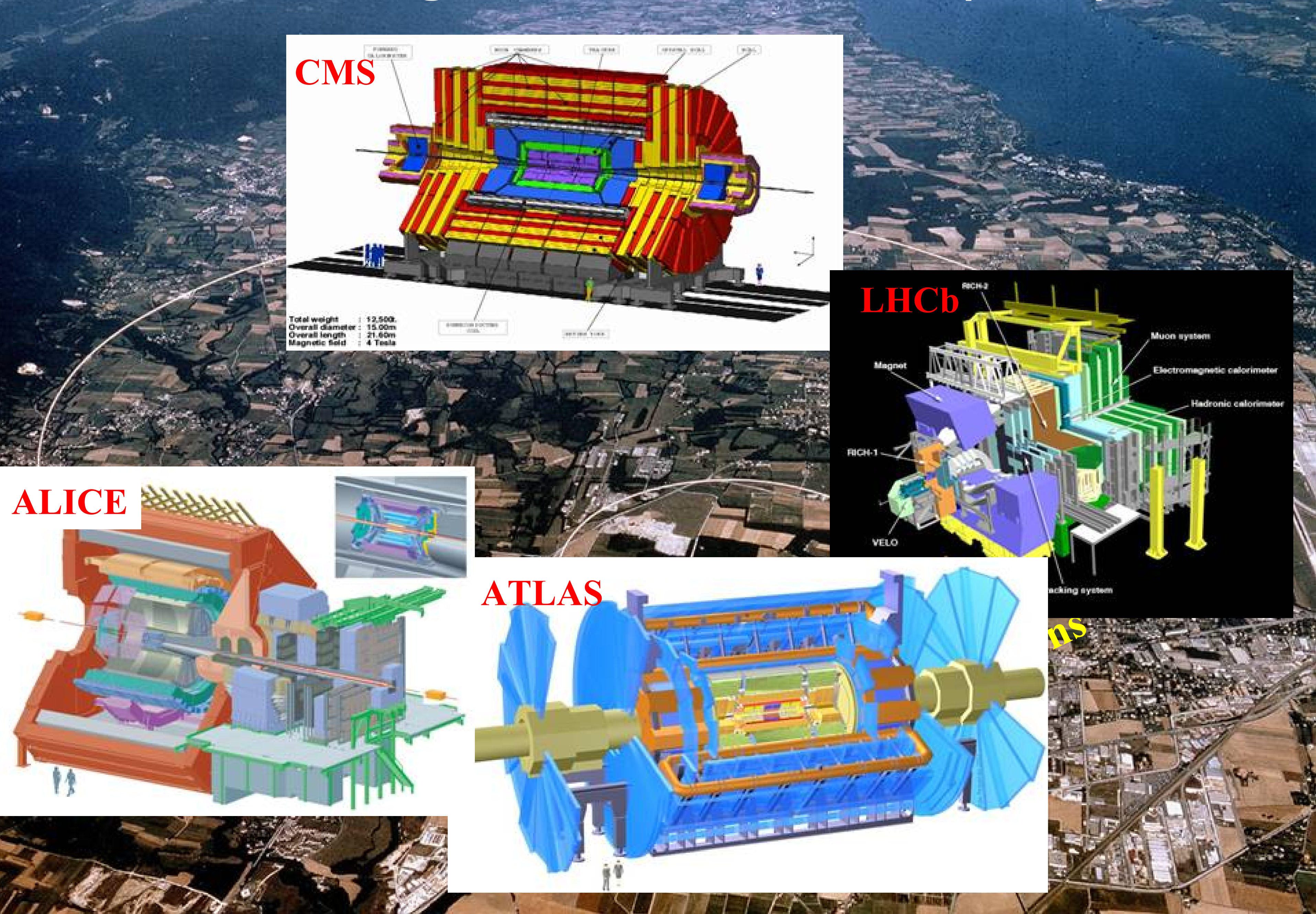
- Here: concentrate on energy frontier



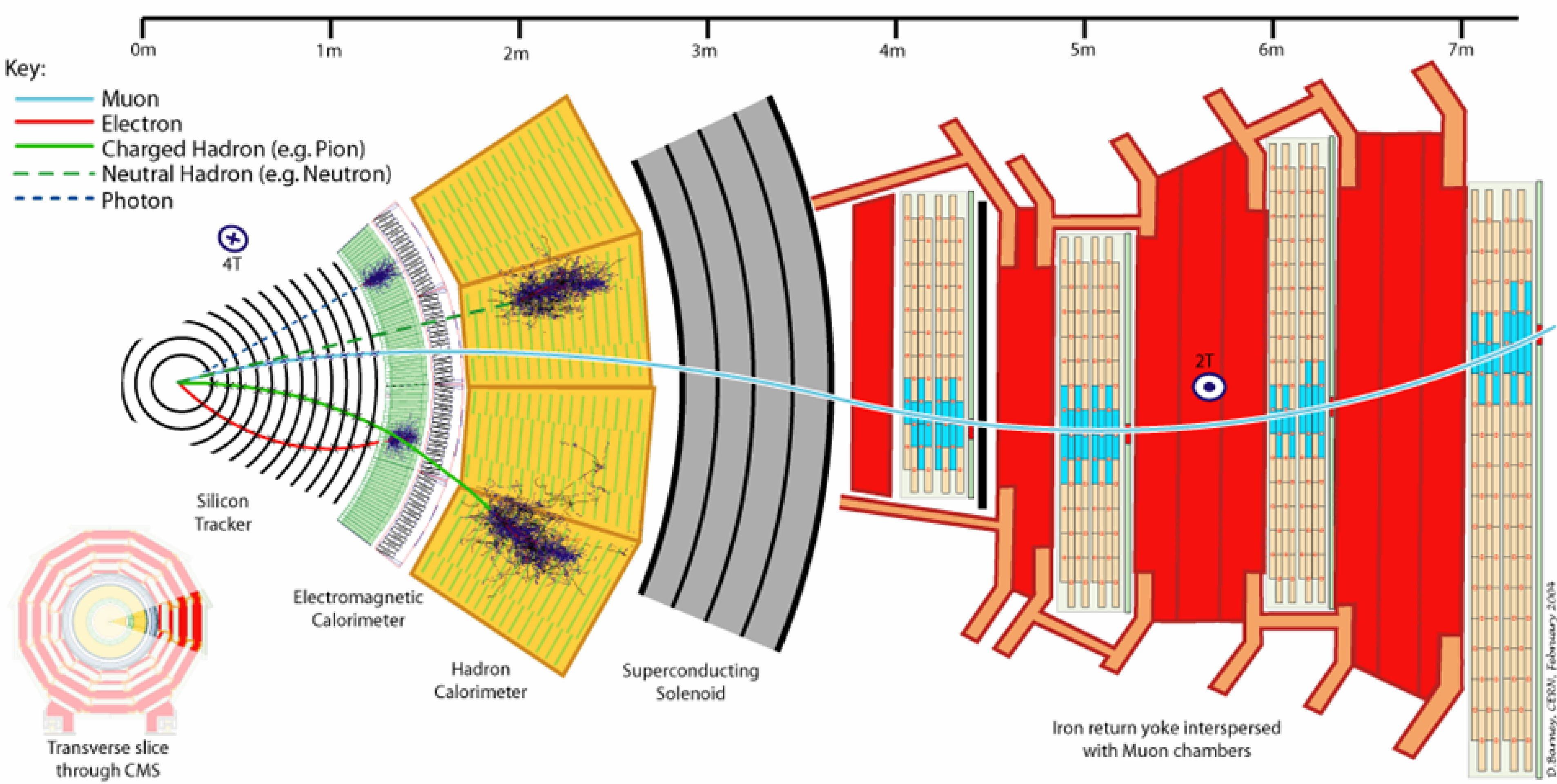
ILD concept



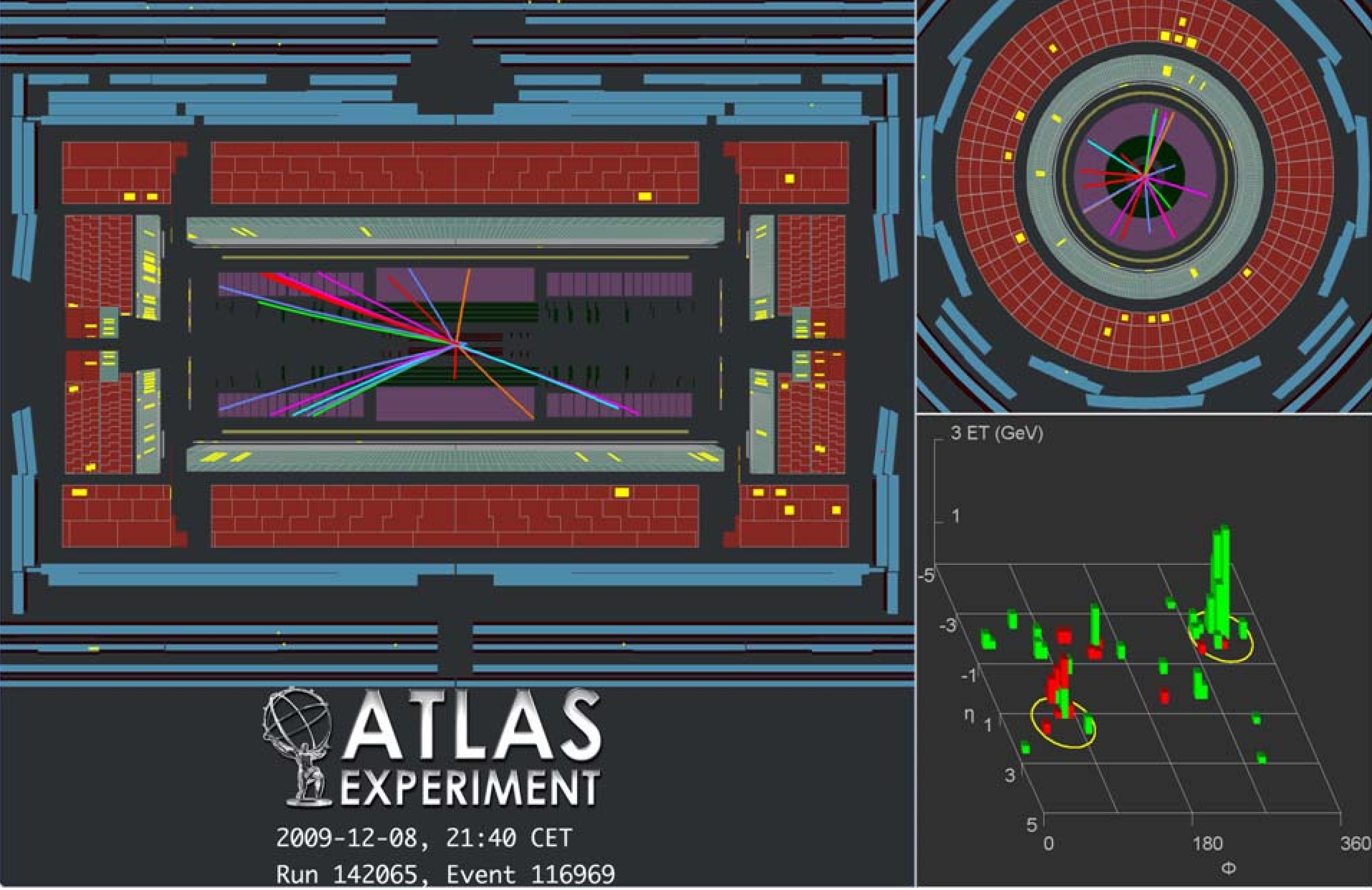
The Large Hadron Collider (LHC)



Transverse Slice Through Detector (CMS)

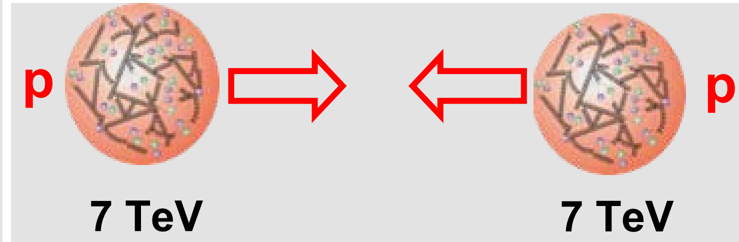


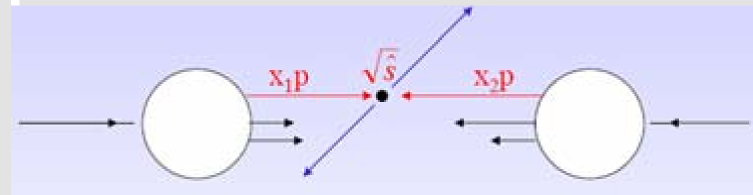
2-Jet Event at 2.36 TeV

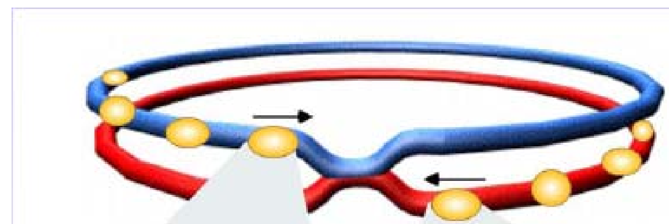


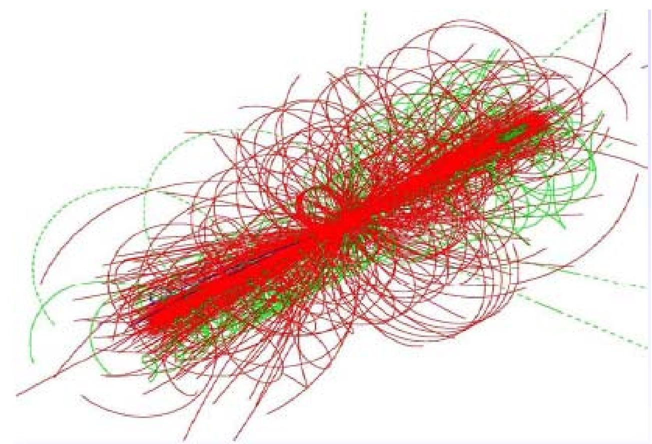
Challenges for LHC Detectors

- **Protons are composite particles**
  - **Bags filled with quarks and gluons**
  - **Quark-quark and gluon-gluon collisions are the fundamental processes**
  - **Screened by interactions of other quarks & gluons**
- **LHC is filled with 2835 + 2835 proton bunches**
  - **Collisions every 25 ns**
    40 MHz crossing rate
- **10^{11} protons per bunch**
  - **25 pp interactions per crossing (pile-up)**
  - **Each bunch collision produces ≈ 1600 charged particles**









Cross Section of Various SM Processes

Þ Low luminosity phase

$10^{33}/cm^2/s = 1/nb/s$

approximately

- 10^8 pp interactions
- 10^6 bb events
- 200 W-bosons
- 50 Z-bosons
- 1 tt-pair

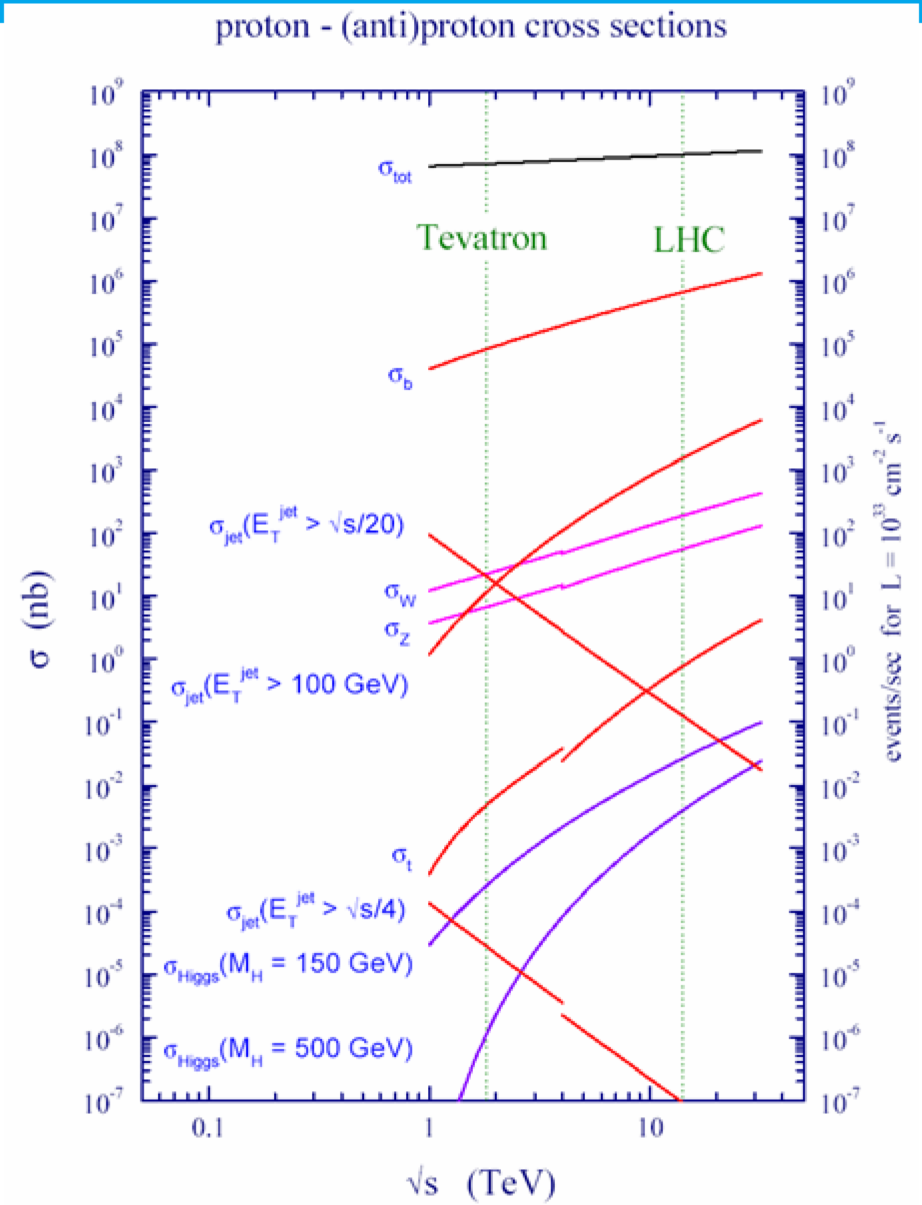
will be produced per second and

- 1 light Higgs

per minute!

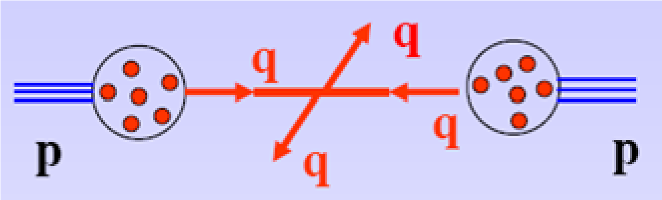
The LHC is a b, W, Z, top, Higgs, … factory!

The problem is to detect the events!



Experimental Signatures

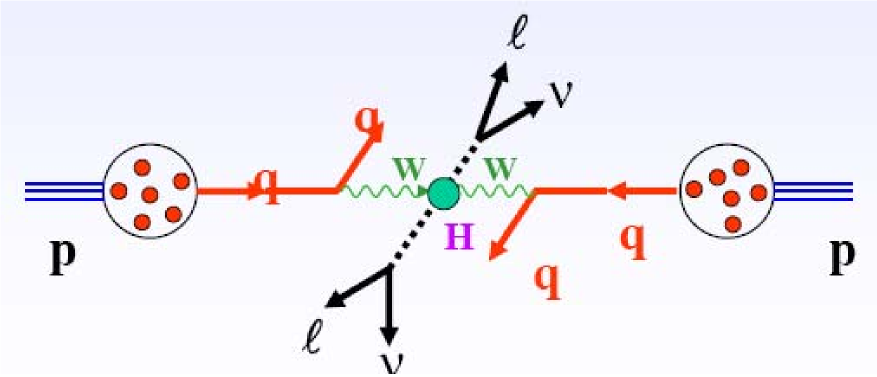
1. Hadronic final states, e.g. quark-quark



no high p_T leptons or photons in the final state

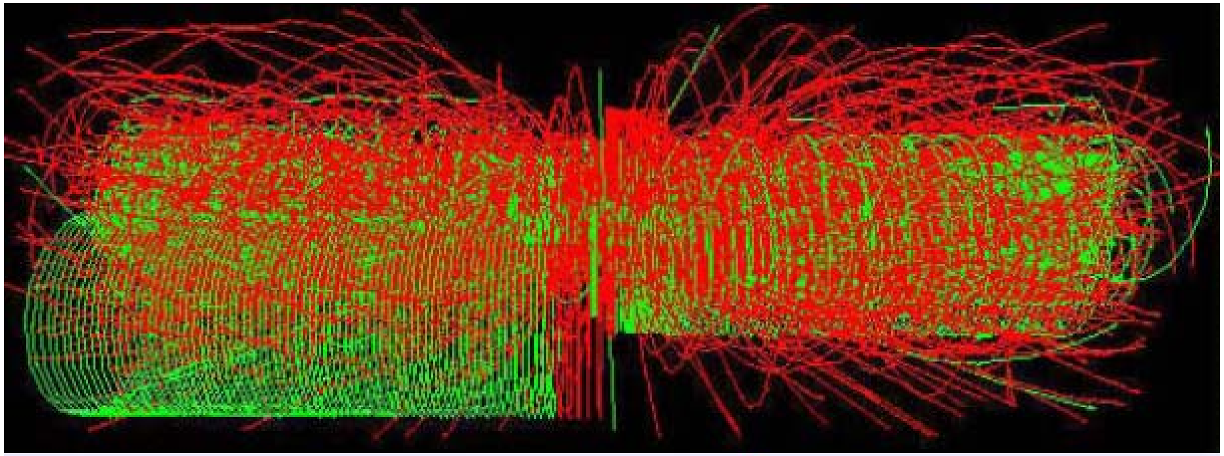
holds for the bulk of the total cross section

2. Lepton/photons with high p_T, example Higgs production and decay

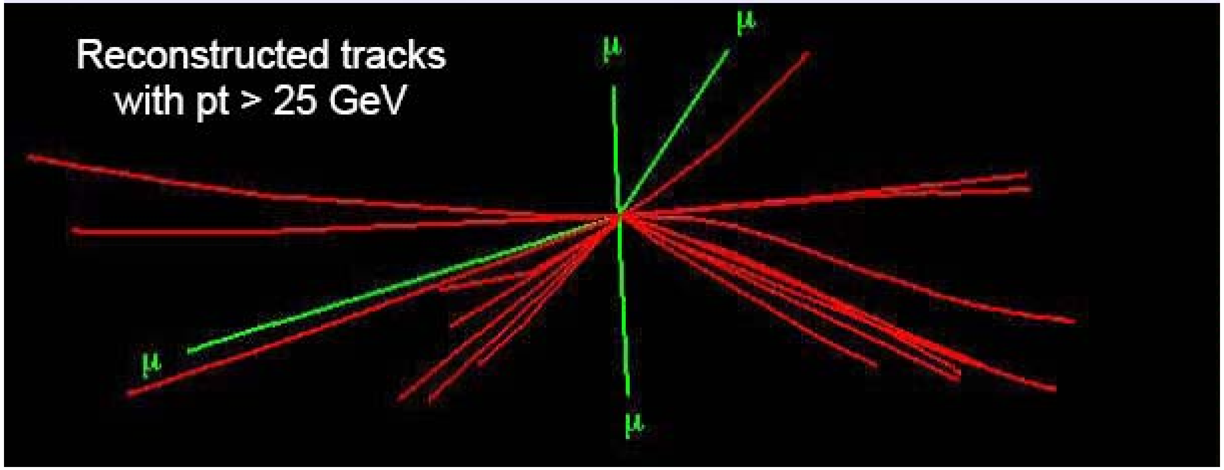


Important signatures for interesting events:
- leptons and photons
- missing transverse energy

Suppression of Background



with 25 pile-up events



removing tracks with $p_T < 25$ GeV

- requires high granularity (many channels)
- good position, momentum and energy resolution

LHC Detector Design Aspects

- **good measurement of leptons (high p_T)**
  muons: large and precise muon chambers
  electrons: precise electromagnetic calorimeter and tracking

- **good measurement of photons**

- **good measurement of missing transverse energy (E_T^{miss})**
  requires in particular good hadronic energy measurements
  down to small angles, i.e. large pseudo-rapidities ($\eta \approx 5$, i.e. $\theta \approx 1°$)

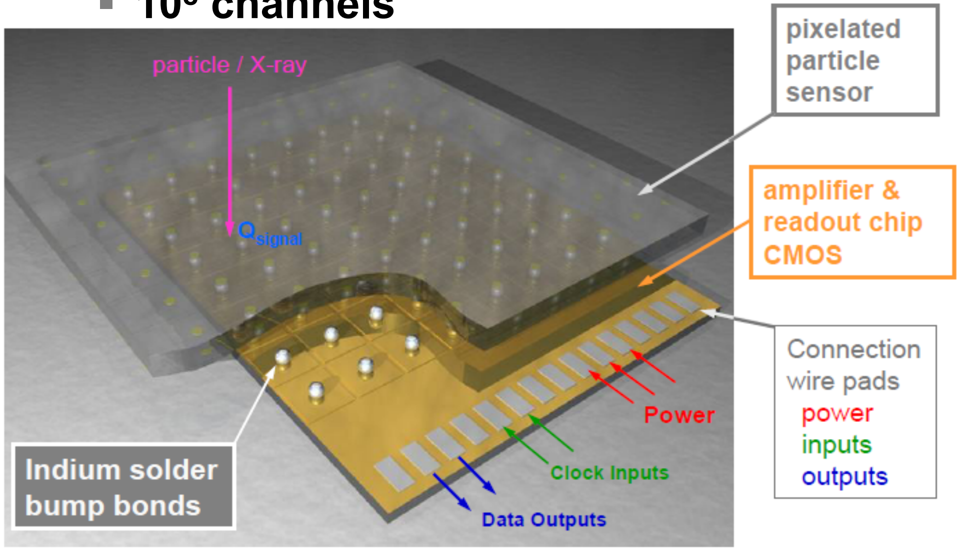
- **in addition identification of b-quarks and τ-leptons**
  precise vertex detectors (Si-pixel detectors)

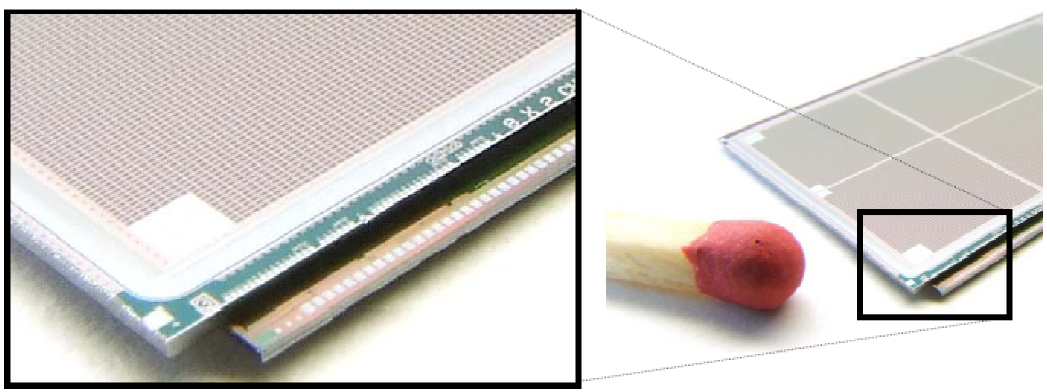
Very important: radiation hardness
e.g. flux of neutrons in forward calorimeters
10^{17} n/cm^2 in 10 years of LHC operation

Vertex Detector

> Hybrid pixel detector

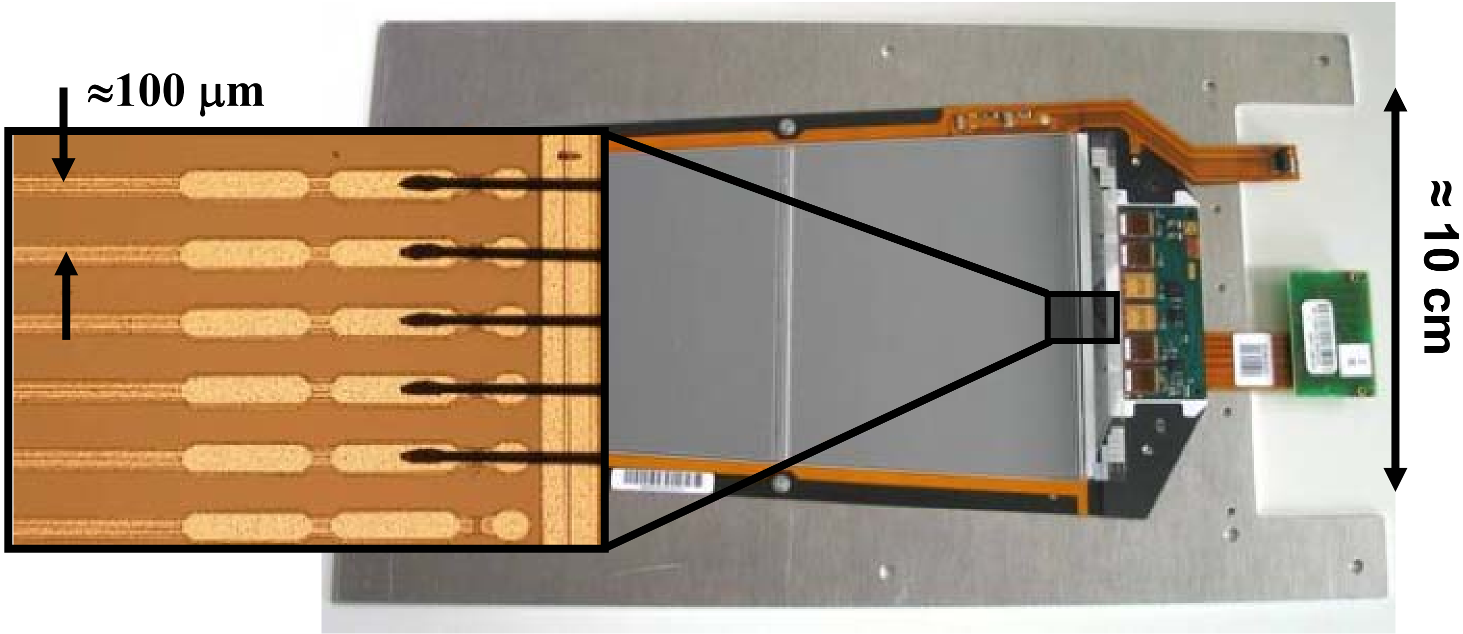
- 100 µm x 150 µm
- 10^8 channels



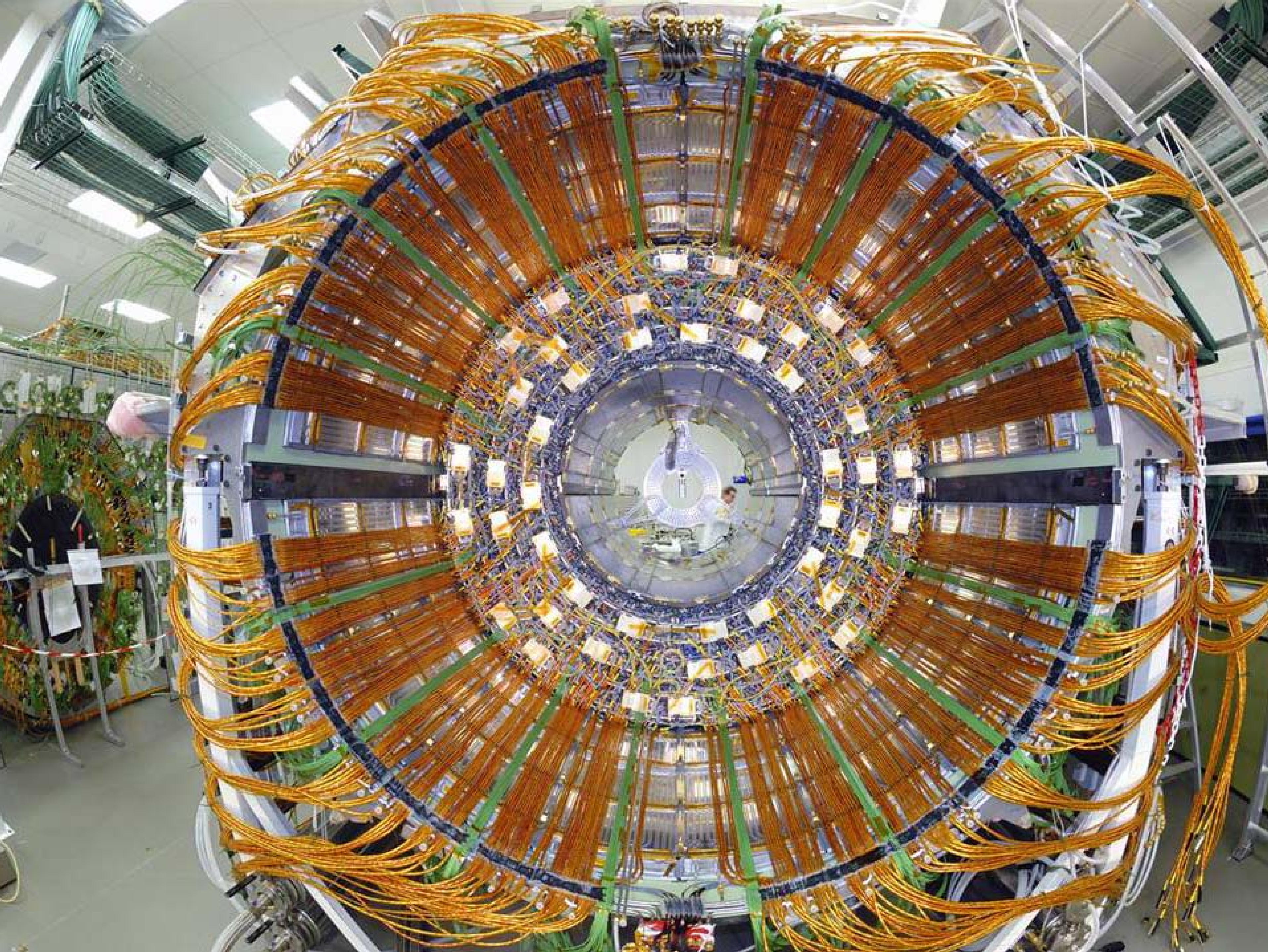


Tracking Detector

> Silicon strip detector



> 16000 such modules built
> 220 m² of silicon surface (almost a tennis court…)
> Largest silicon detector ever built



Online Trigger

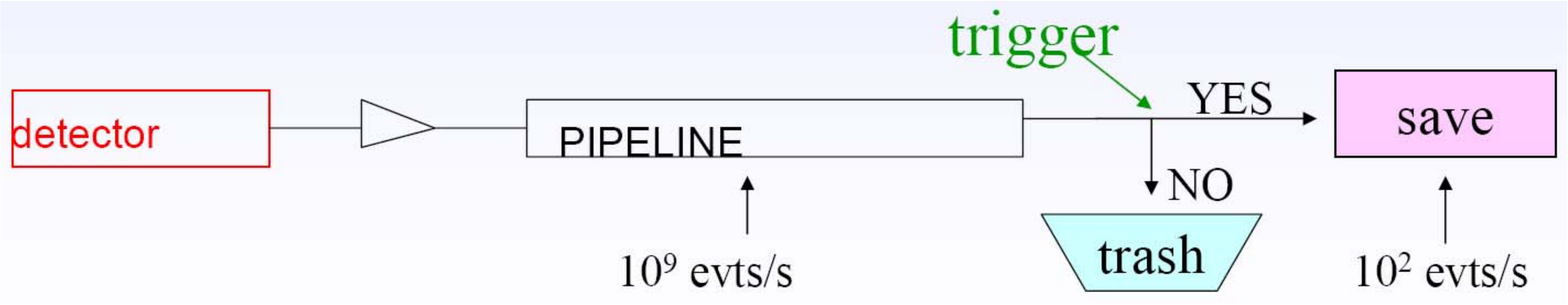
Trigger of interesting events at the LHC is much more complicated than at e^+e^- machines

- **interaction rate: ≈ 10^9 events/s**
- **max. record rate: ≈ 100 events/s** **event size ≈ 1 MByte ⇒ 1000 TByte/year of data**

⇒ trigger rejection ≈ 10^7

- **collision rate is 25 ns (corresponds to 5 m cable delay)**
- **trigger decision takes ≈ a few µs**

⇒ store massive amount of data in front-end pipelines while special trigger processors perform calculations



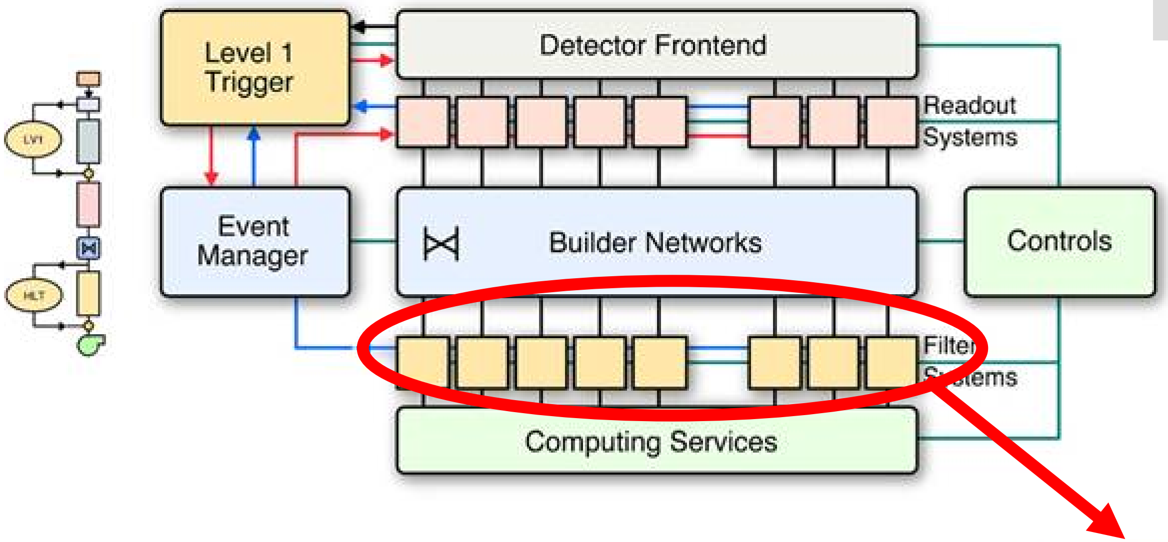
Trigger & DAQ system

Similar design for ATLAS & CMS

Example CMS:

Collision rate	40 MHz
Level-1 max. trigger rate	100 kHz†
Average event size	≈ 1 Mbyte

† 50 kHz at startup (DAQ staging)



40 MHz

10^5 Hz

1 Tb/s

10^2 Hz

Filter farm:

- approx. 2000 CPUs
- easily scaleable
- staged (lower lumi & saves money)
- uses offline software

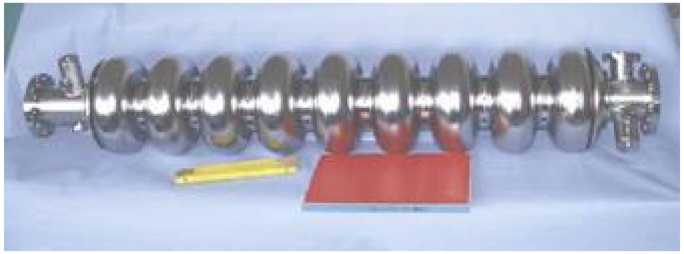
Future Challenges at the LHC

> **Super-LHC (sLHC)**

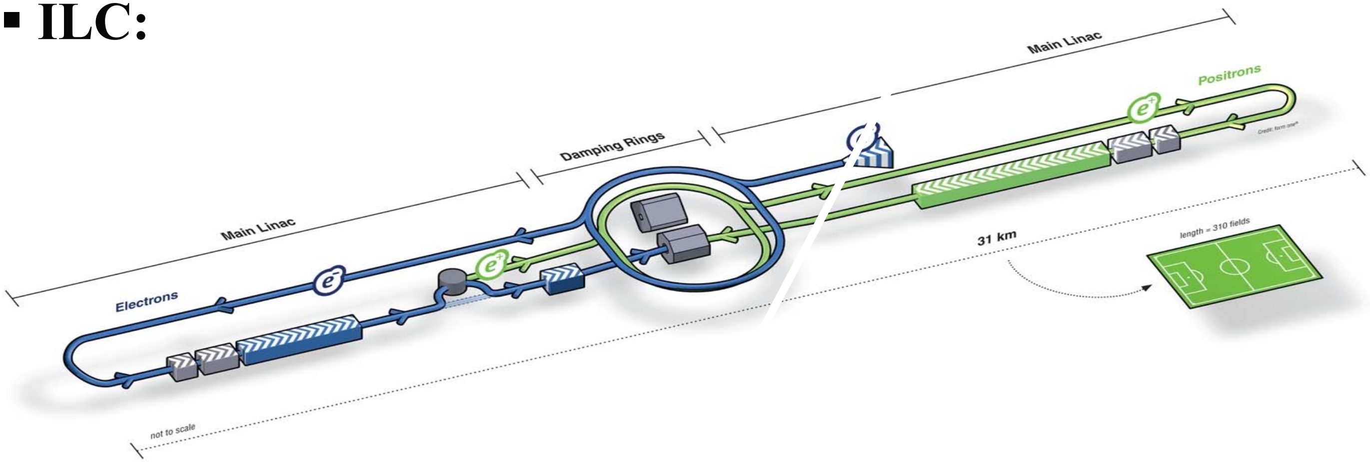
- **Increase luminosity by factor 10, i.e. $10^{35}/cm^2/s$ in steps until ≈ 2020**
- **Higher collision rates ≈ few hundred pile-up events**
- **Increased radiation hardness (inner detectors)**
- **Higher granularity pixel, strixel, strips**
- **Improved 1st level trigger high p_T leptons & jets**
- **Less material in inner detectors**
- **…**

The International Linear Collider (ILC)

- 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



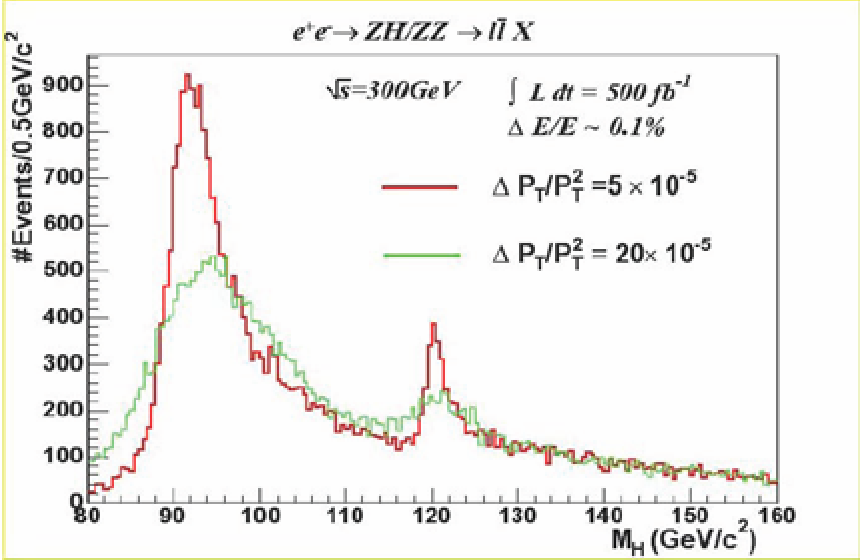
- ILC:



ILC 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
    $O(20\times20\ \mu m^2)$
- Tracking:
  - superb momentum resolution
    to select clean Higgs samples
  - ideally limited only by Γ_Z

  $\rightarrow \Delta(1/p_T) = 5\cdot10^{-5}$ /GeV
  (whole tracking system)
  3 times better than CMS



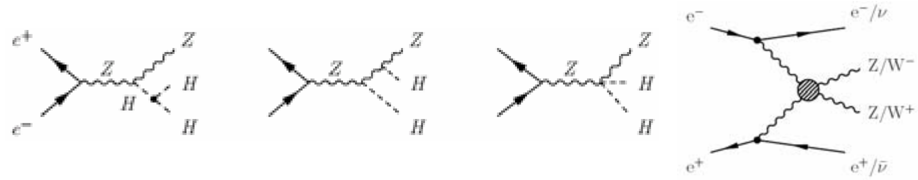
Options considered:
- Large silicon trackers (à la ATLAS/CMS)
- Time Projection Chamber with ≈ 100 µm point resolution

Impact on ILC Detector Design

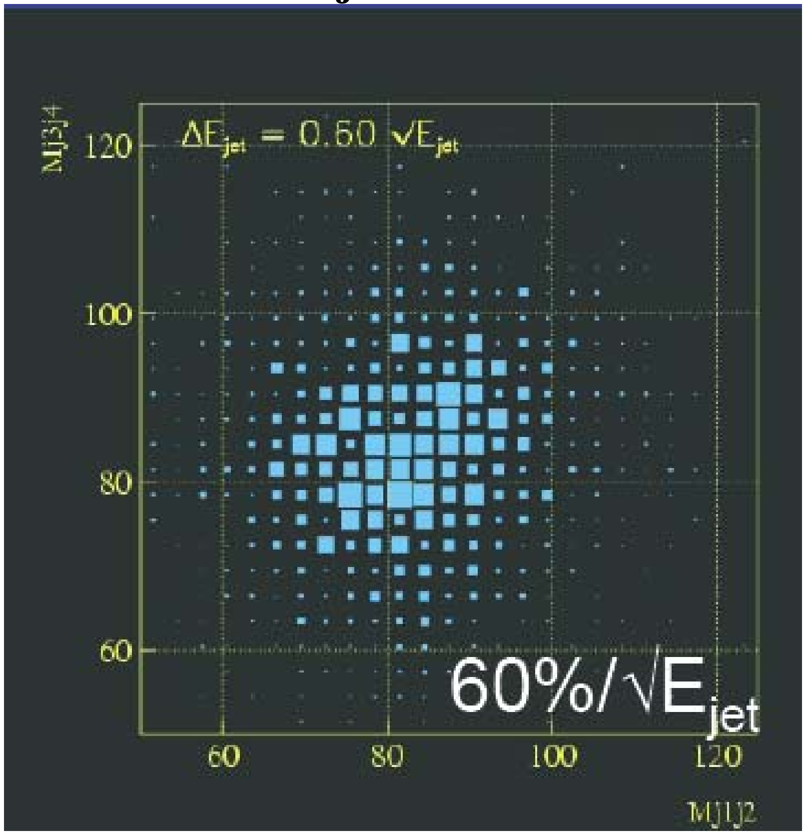
- **Calorimeter: distinguish W- and Z-bosons in their hadronic decays**

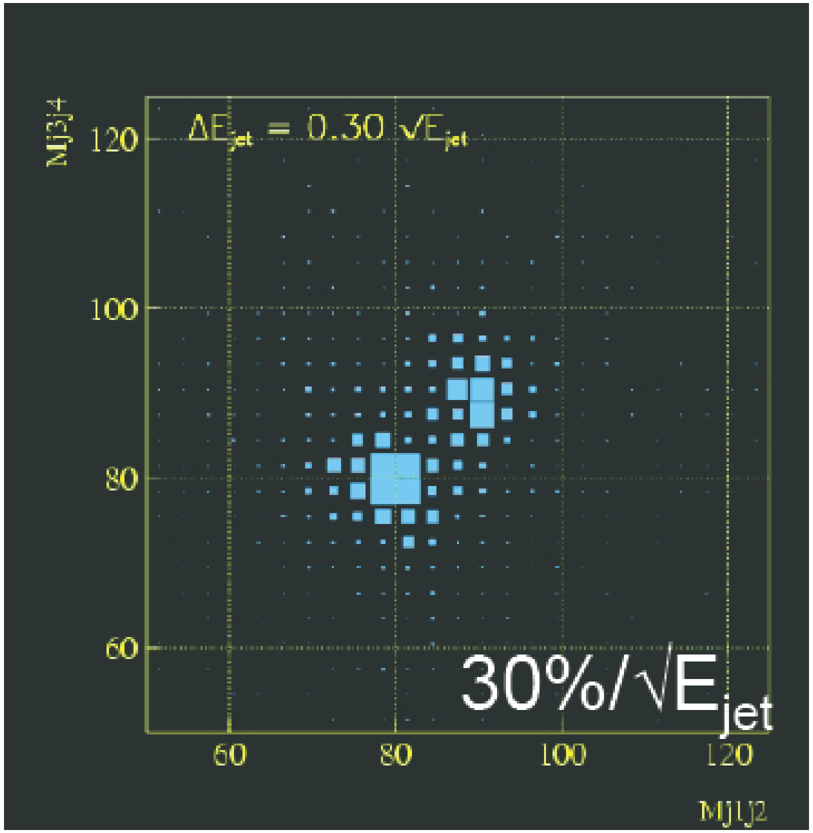
→ 30%/√E jet resolution!

2 times better than ZEUS



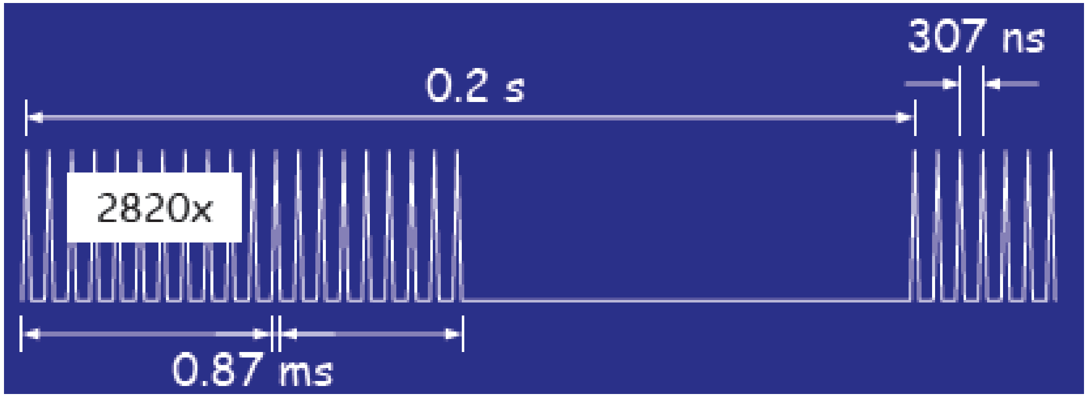
- **WW/ZZ → 4 jets:**



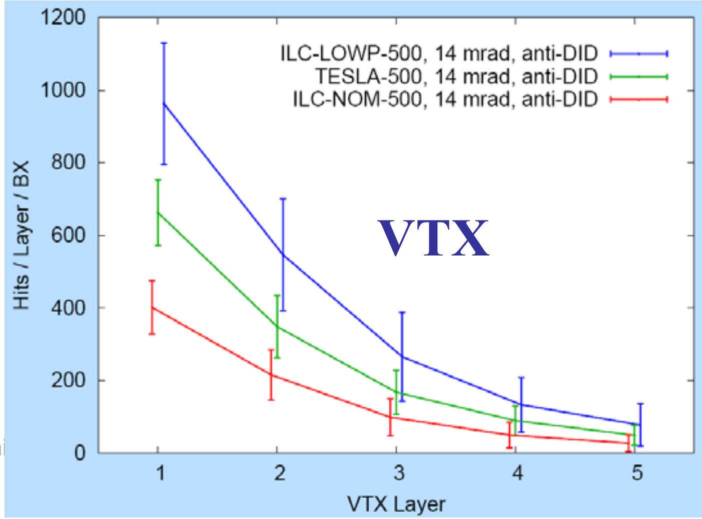


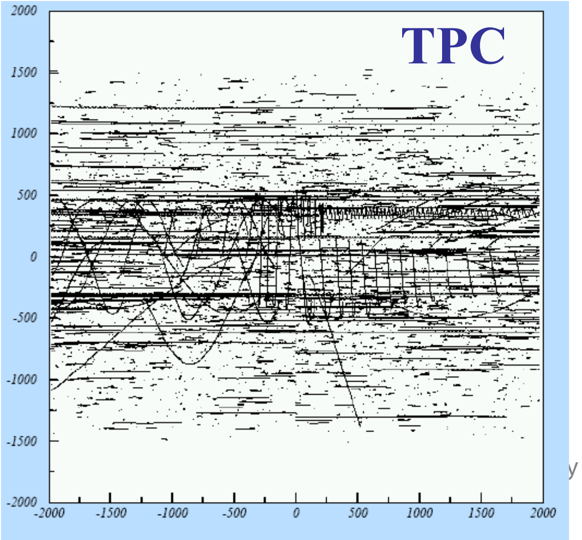
Detector Challenges at the ILC

- **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





The CLIC Two Beam Scheme

Two Beam Scheme

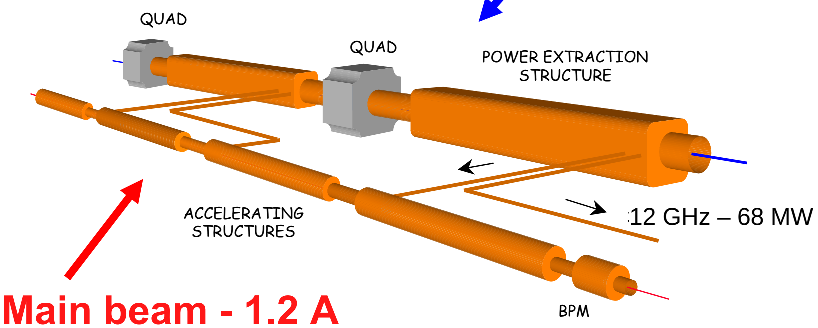
Drive Beam supplies RF power

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

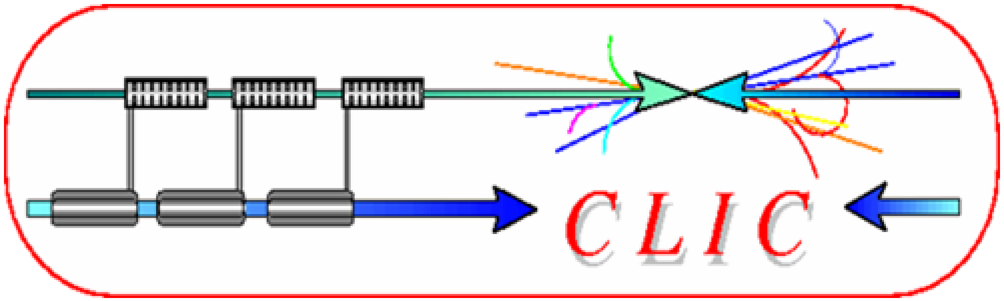
Main beam for physics

- 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)

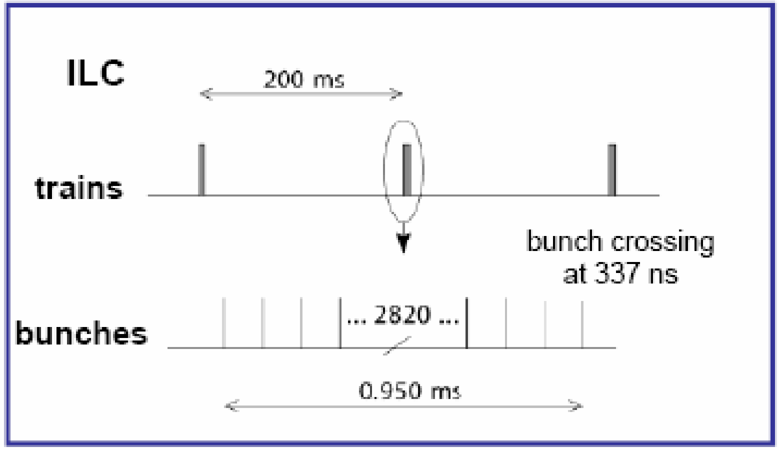


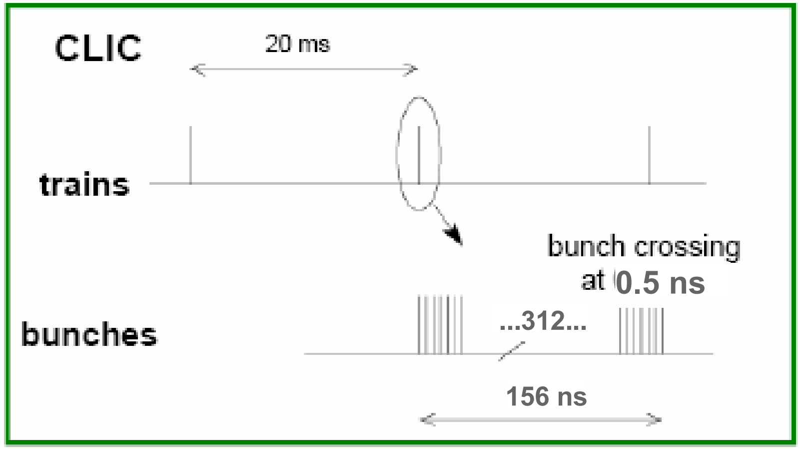
Main beam - 1.2 A
from 9 GeV -> 1.5 TeV



- **Higher gradient: 100 MV/m**
- **Higher cms energy: 3 TeV**

CLIC Time Structure





> Bunch Spacing

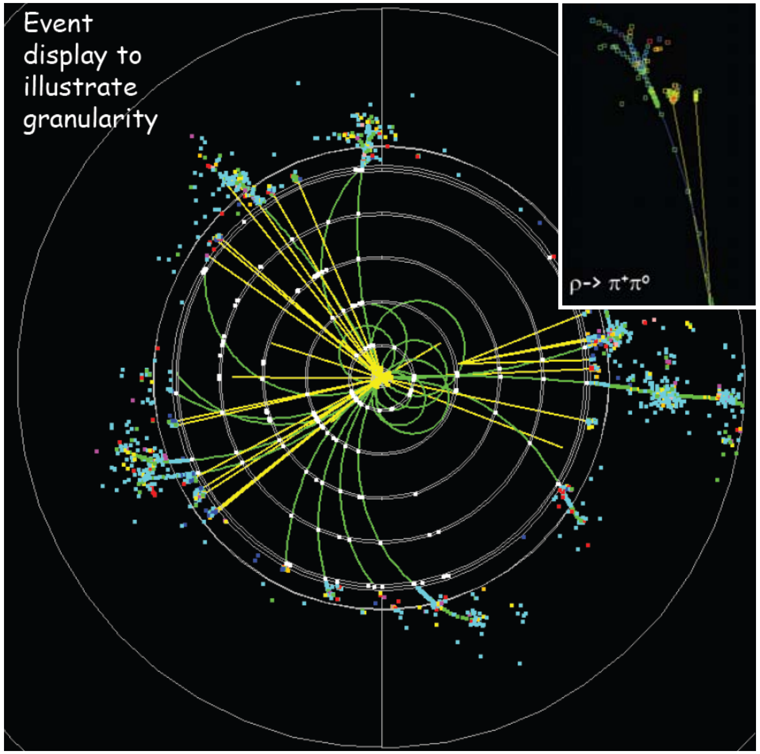
- **ILC: 337 ns, enough time to identify events from individual BX**
- **CLIC: 0.5 ns, extremely difficult to identify events from individual BX**
- **need short shaping time of pulses**
- **power cycling with 50 Hz instead 5 Hz at ILC**

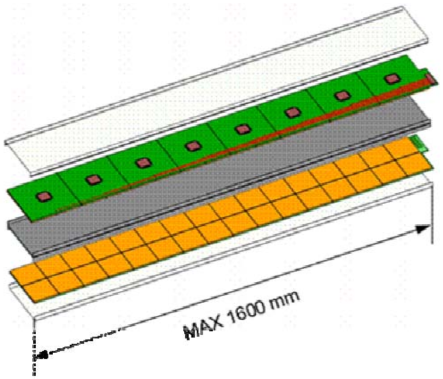
Main Differences CLIC as compared to ILC

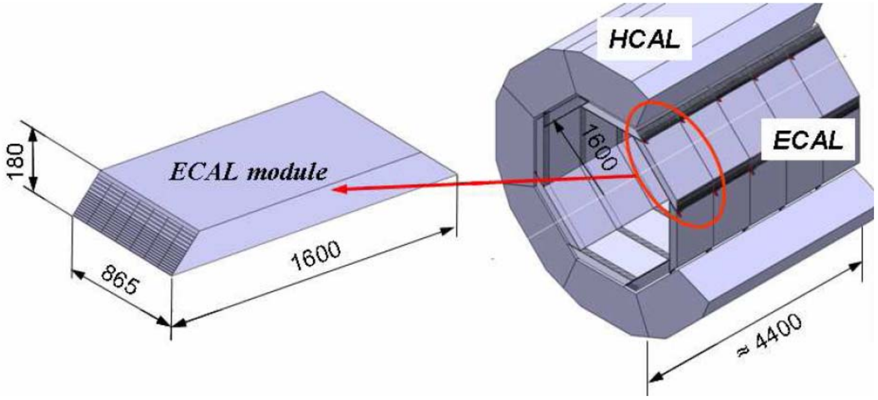
- Higher energy results in more dense particle jets
  - Improved double track resolution
  - Calorimeters with larger thickness and higher granularity
- Much shorter bunch spacing
  - CLIC 0.5 ns wrt. ILC 337 ns
  - Requires time stamping
  - Impact on pulsed power electronics
- Smaller beam sizes and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

Calorimetry at a Linear Collider

- Try to reconstruct every particle in a jet
  Particle Flow
- High granularity
  huge number of readout channels
- E.g. SiW ECAL
  - 23 X0 depth
  - 0.6 X0 – 1.2 X0 long. segmentation
  - 5×5 mm^2 cells
  - electronics integrated in detector







Summary

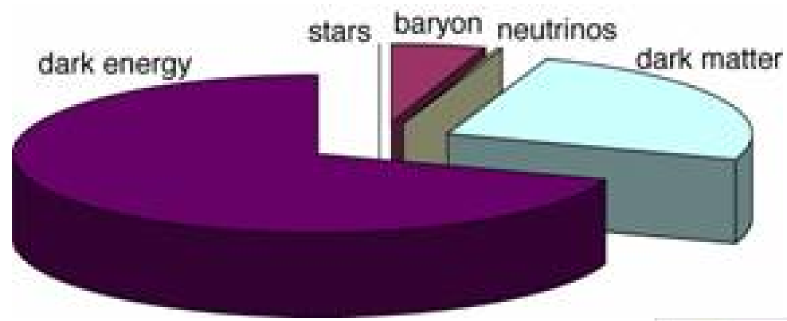
> **Trends in particle physics**
- **Radiation hardness**
- **Increasing resolution (space & time)**
- **Higher granularity, increased number of channels**

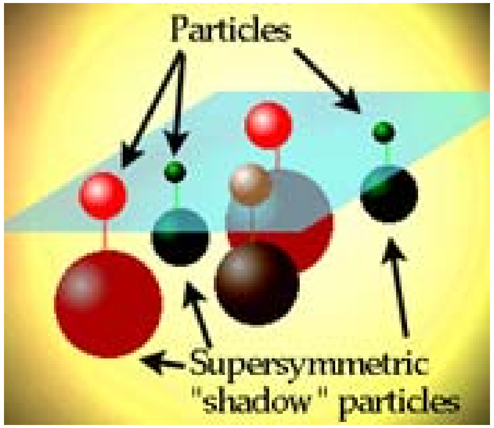
> **Synergy with other fields**
- **Silicon technology**
- **Readout and DAQ**
- **Time stamping**

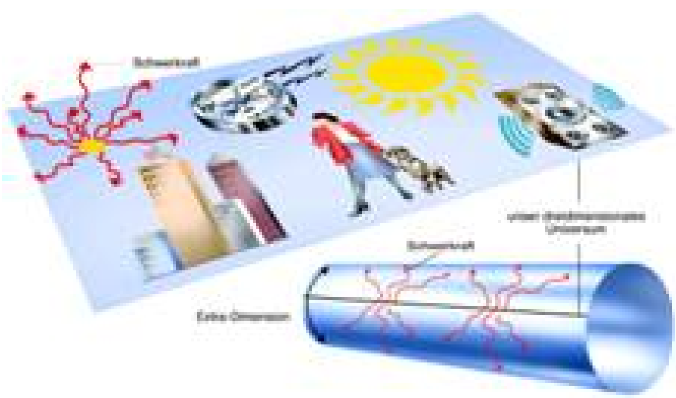
> **DESY is the ideal place to develop detector technologies across science fields**

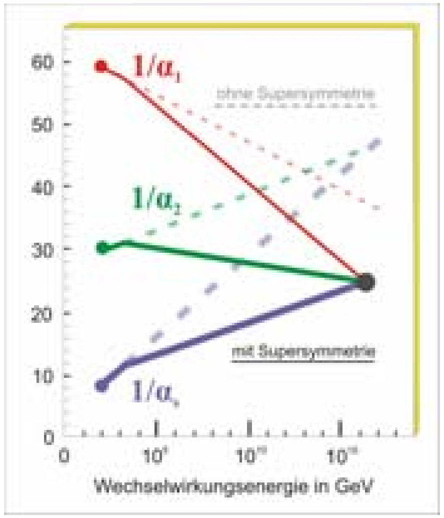
Backup

- **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

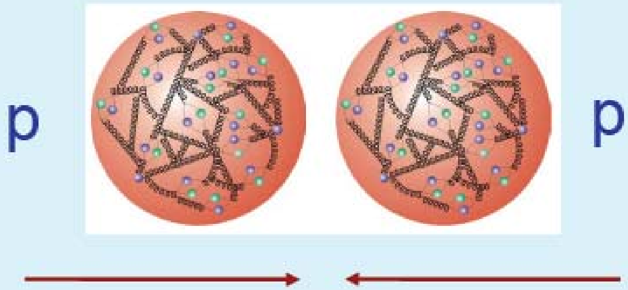




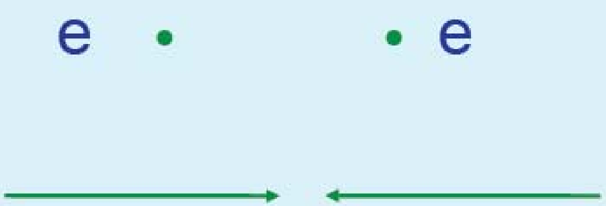




Comparison Proton and Electron Colliders



- 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

Colliders for the Terascale

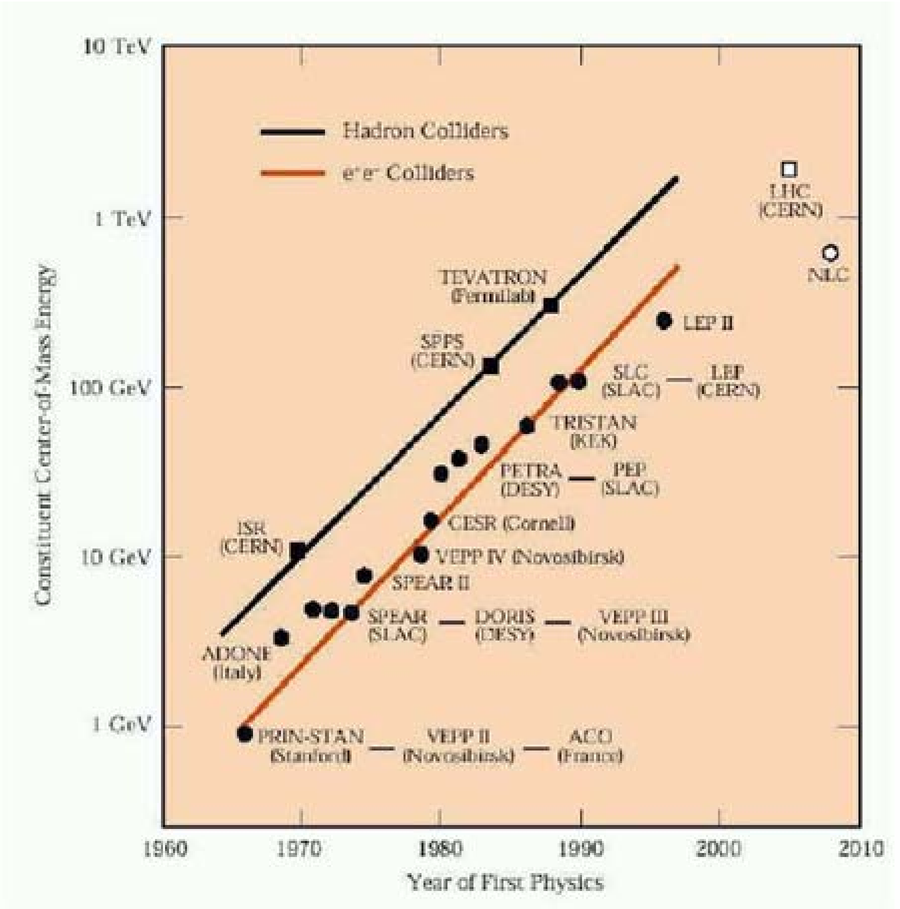
> **Proton-(anti)proton collider**

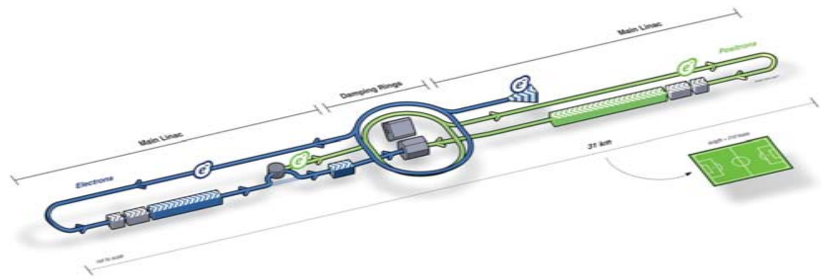
- **Higher energy reach limited by magnet bending power**
- **But much harder for experiments**

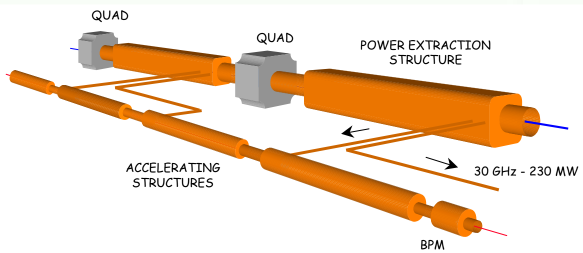
> **Electron-Positron Collider**

- **Like DORIS & PETRA at DESY or LEP at CERN**
- **Point-like particles**
- **But limited in energy by synchrotron radiation**

➔ Linear Colliders



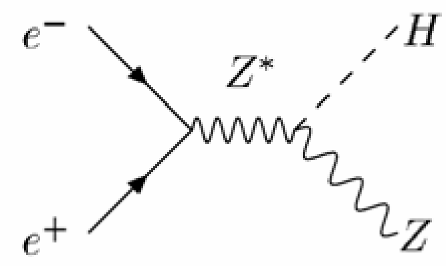


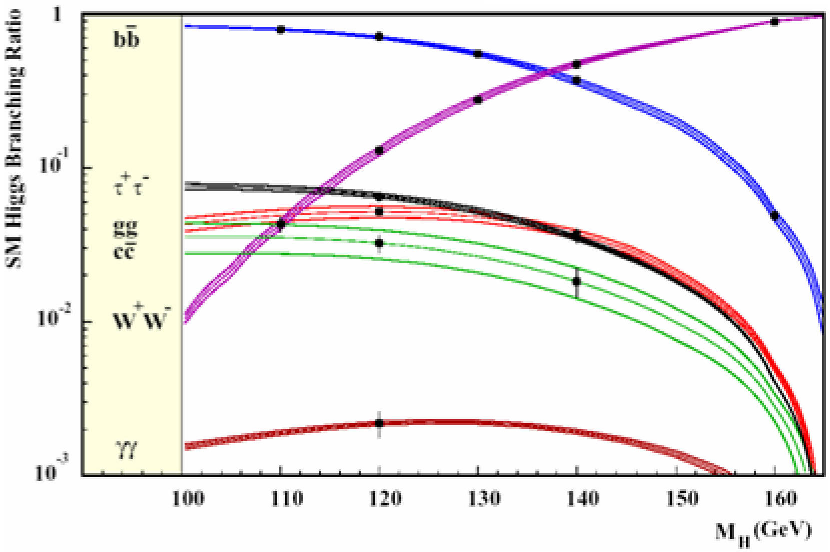


ILC Physics Motivation

- ILC will complement LHC discoveries by precision measurements

- Here just one example: Higgs
  - 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

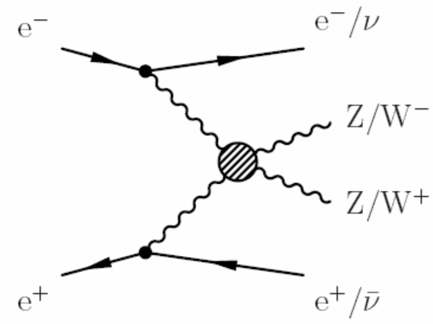




- Distinguish W and Z bosons in their hadronic decays!

  BR (W/Z $\rightarrow$ hadrons) = 68% / 70%

- Requires exquisit jet energy resolution

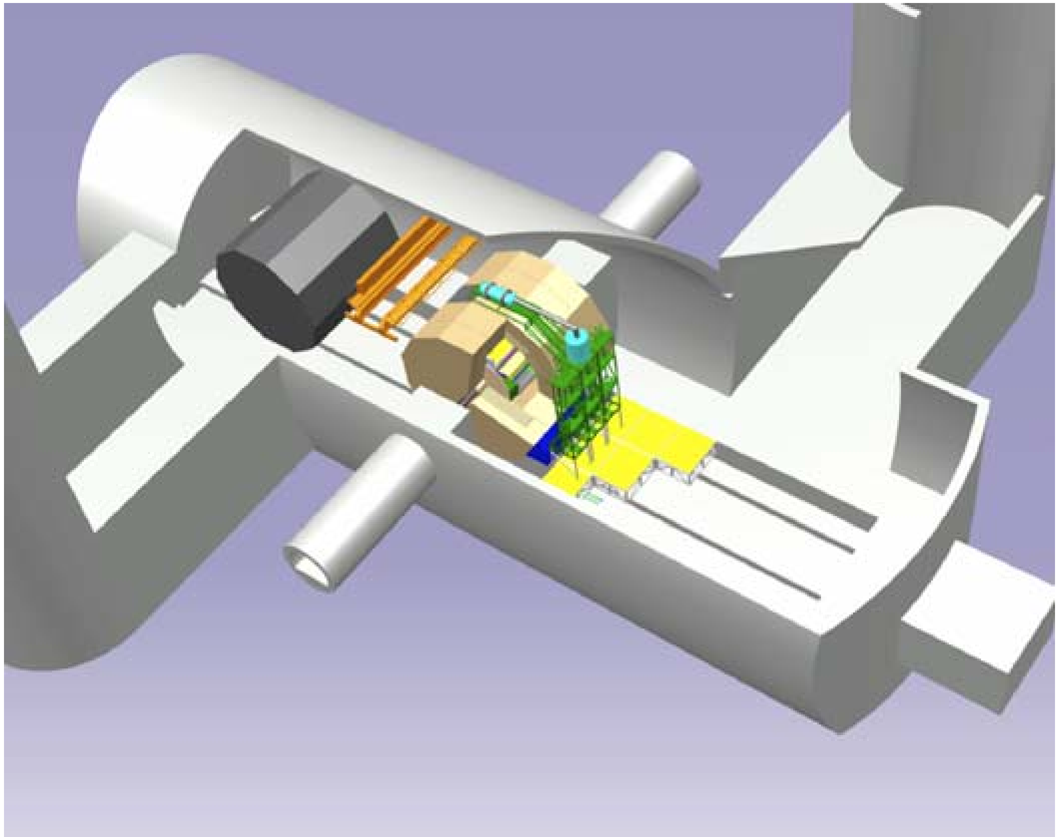


Two Detectors: Push Pull

Additional complication:

One interaction region,
but two detectors:

push pull operation anticipated



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)