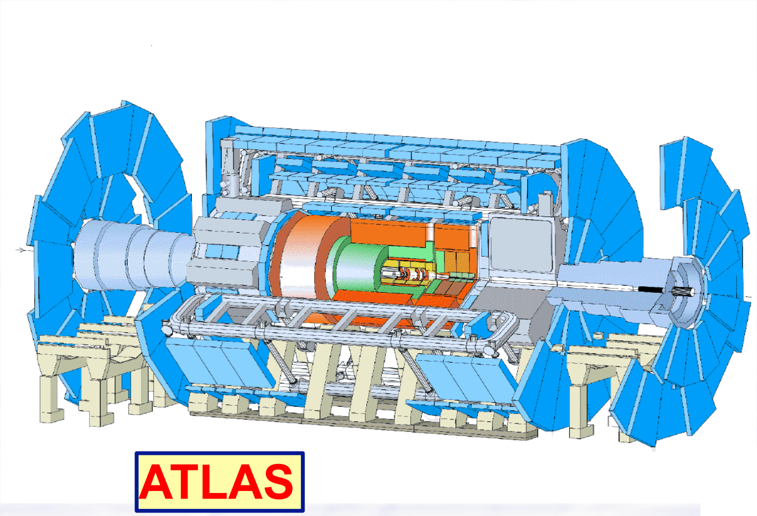
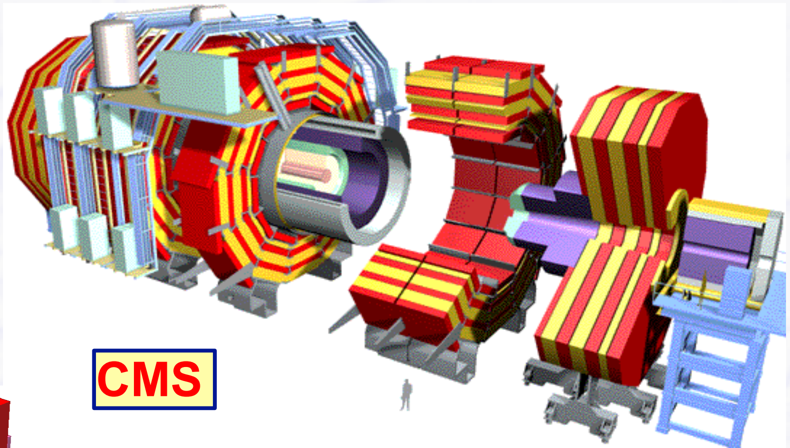
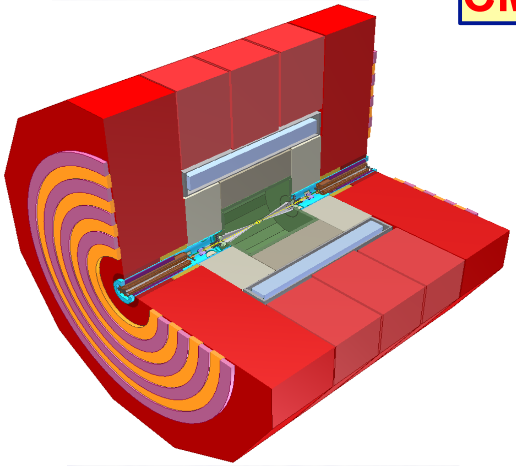
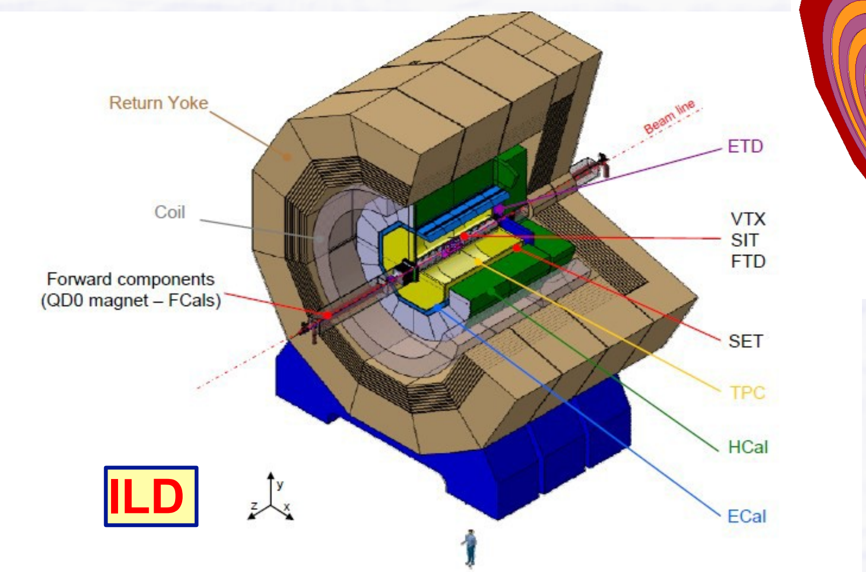
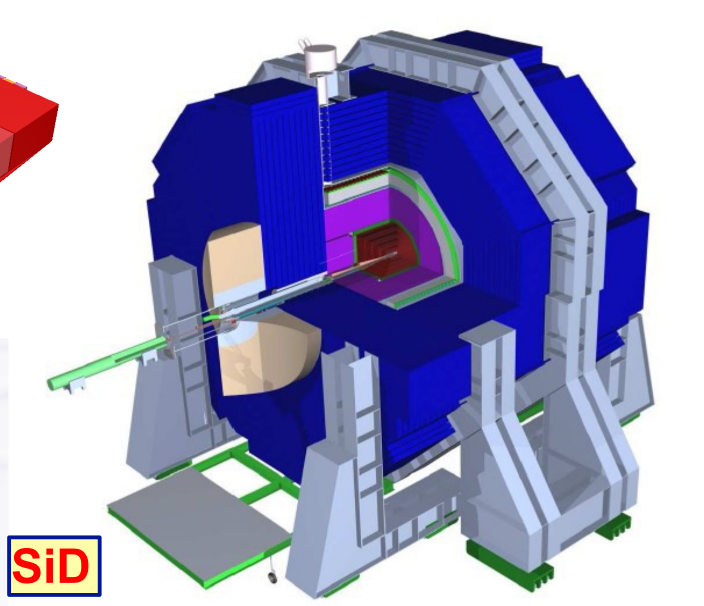
Detector Concepts





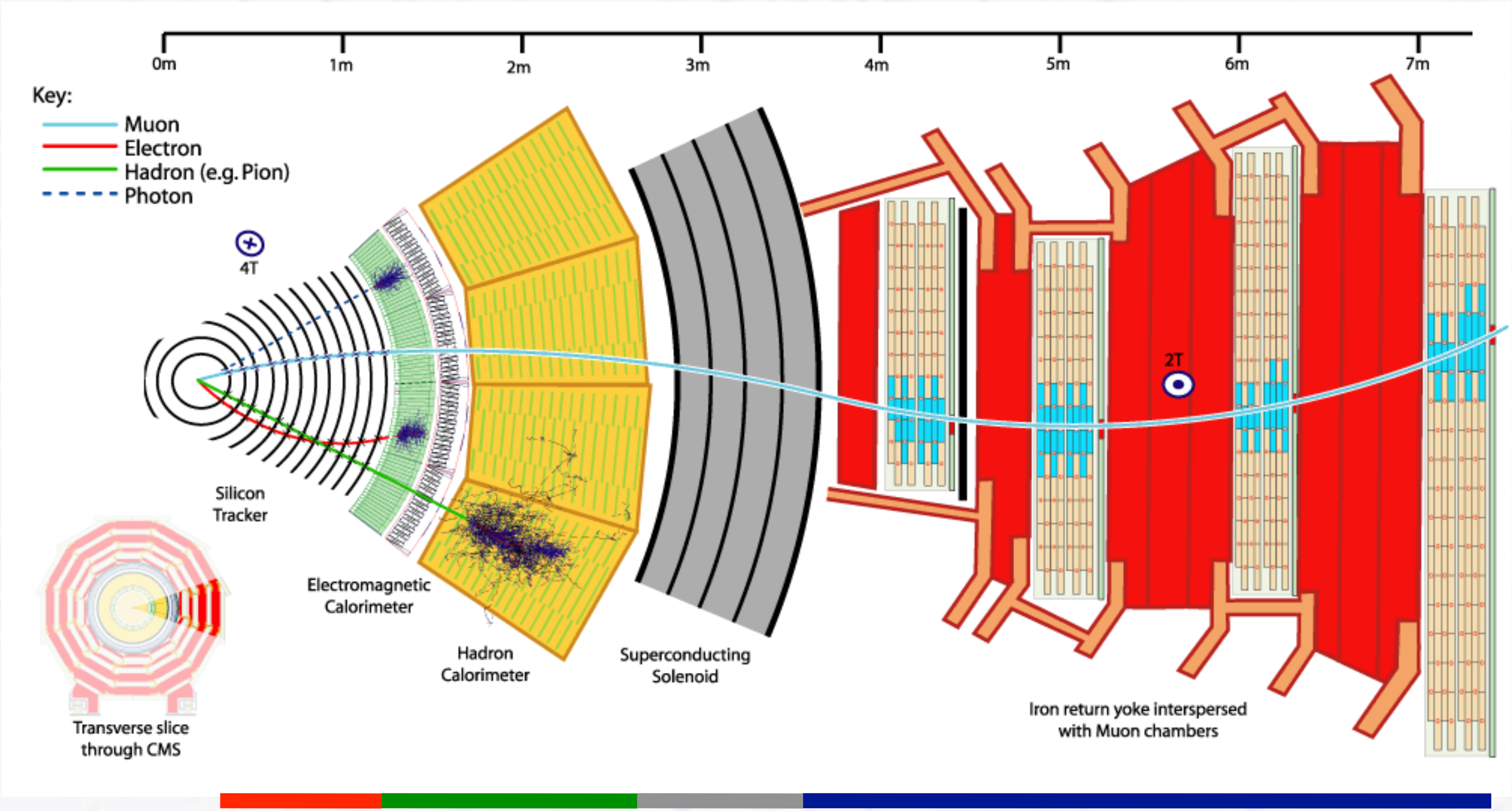






A typical Particle Detector

- **Cut-away view of CMS**



Tracker	Calorimeter	Coil	Muon Detector and iron return yoke
p	E		muon identification + p for muons

High Energy Collider Detectors

- **Tracking Detector (or Tracker) = momentum measurement**
  - **closest to interaction point: vertex detector (often silicon pixels)**
    - **measures primary interaction vertex and secondary vertices from decay particles**
  - **main or central tracking detector**
    - **measures momentum by curvature in magnetic field**
- **Calorimeters = energy measurement**
  - **electro-magnetic calorimeters (light particles: e^-, e^+, γ)**
    - **measures energy of light EM particles (electrons, positrons, photons) based on electro-magnetic showers by bremsstrahlung and pair production**
    - **two concepts: homogeneous (e.g. CMS) or sampling (e.g. ATLAS, ILD, SiD, CLIC)**
  - **hadron calorimeters (heavy hadronic particles: π, K, p, n)**
    - **measures energy of heavy (hadronic) particles (pions, kaons, protons, neutrons) based on nuclear showers created by nuclear interactions**
- **Muon Detectors = momentum measurement for muons (more precise)**
  - **outermost detector layer, basically a tracking detector**

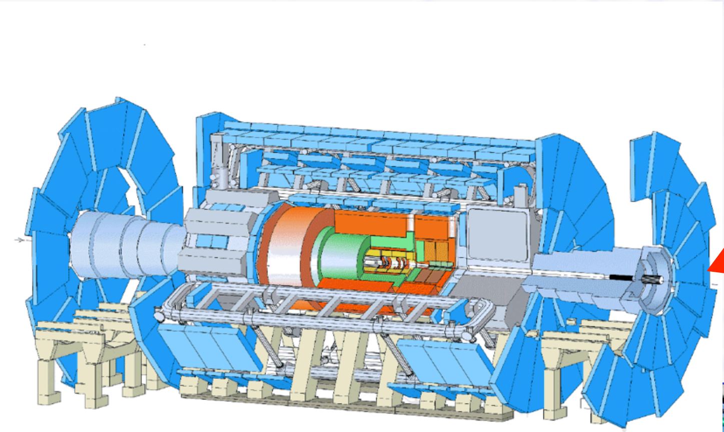
Detector Challenges at LHC

- High energy collisions
  - sufficiently high momentum resolution up to TeV scale
- High luminosity (high interaction rate)
  - high rate capabilities, fast detectors (25 ns bunch crossing rate)
- High particle density
  - high granularity, sufficiently small detector cells to resolve particles
- High radiation (lots of strongly interacting particles)
  - radiation mainly due to particles emerging from collisions, not machine background
  - radiation-hard detectors and electronics (have to survive ~10 years)

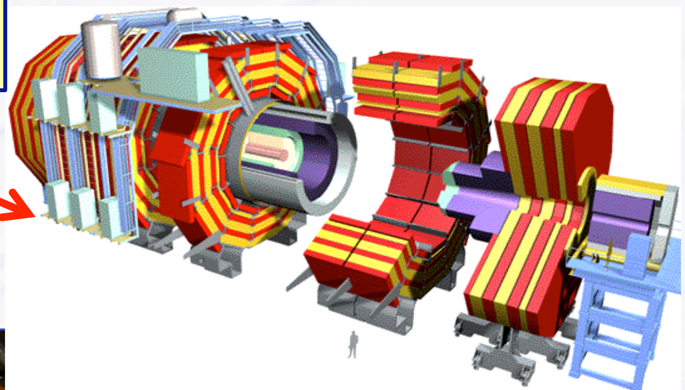
- LARGE collaborations!!!
  - ~O(3000) physicists for ATLAS and CMS each
  - communication, sociological aspects
    - exponential raise of meetings, phone + video conferences...

LHC Detectors

General purpose detectors (good for everything...)

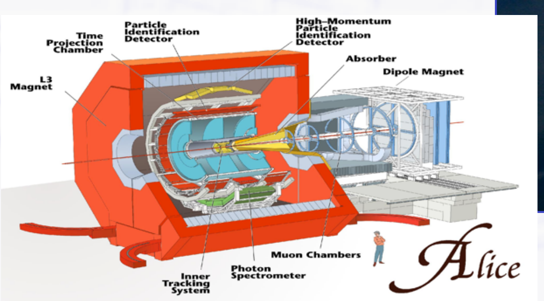


ATLAS

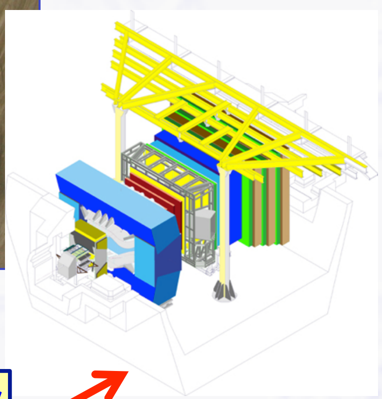


CMS

ALICE



LHCb



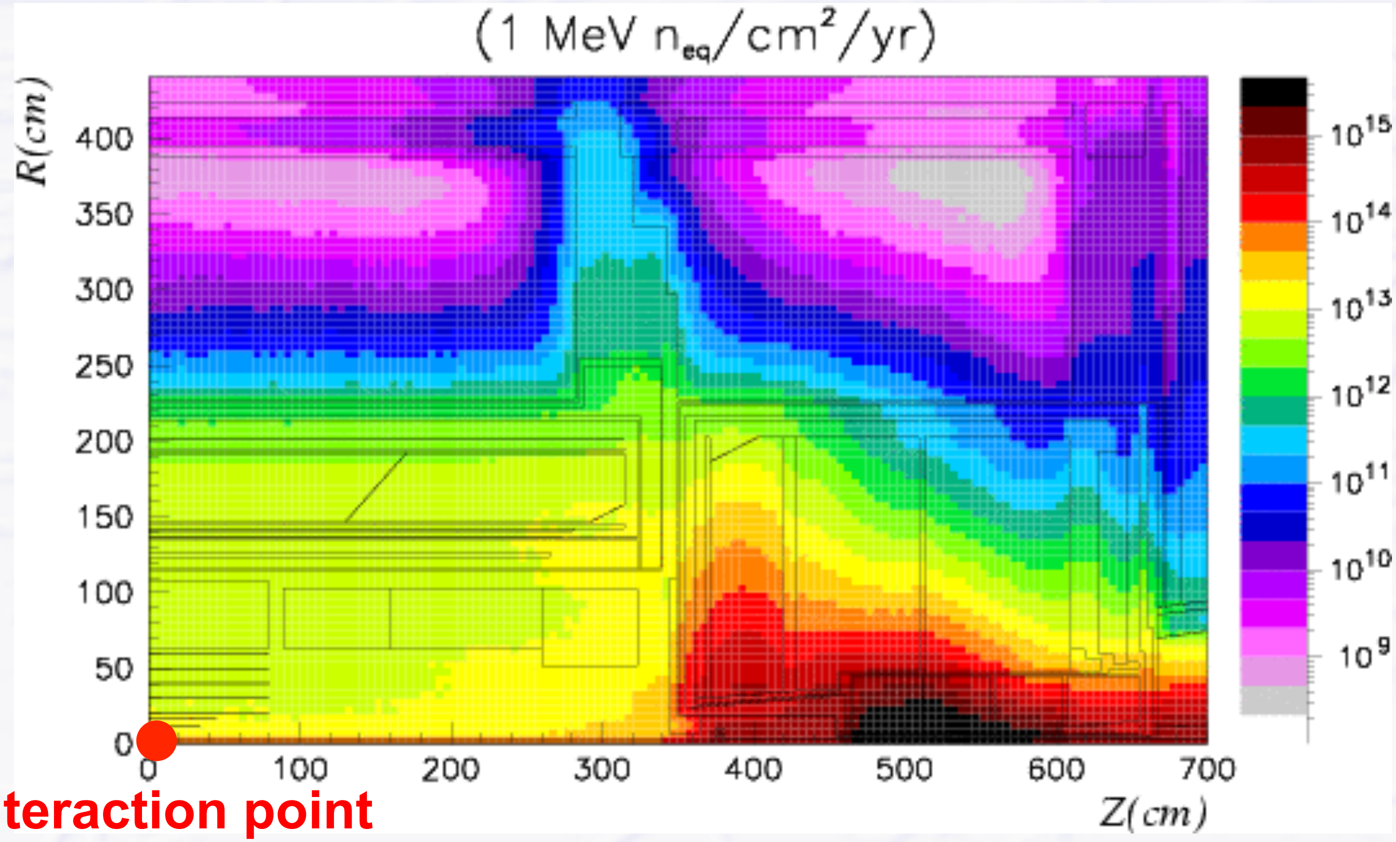
dedicated for Heavy Ion collisions

dedicated for b-physics

Radiation Doses at LHC

200 MRad

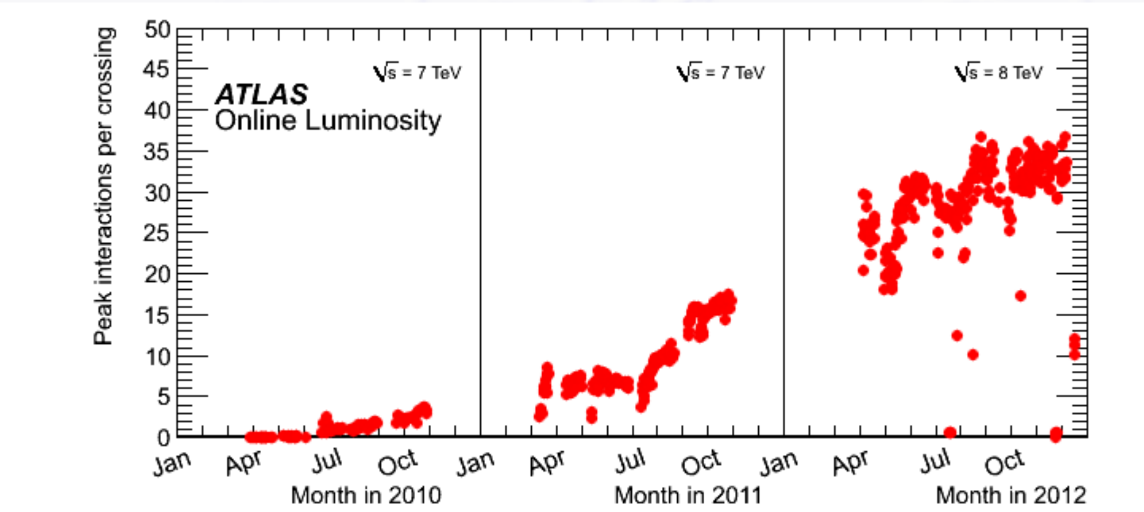
- ~ 2 x 10^6 Gray / r_T^2 / year at LHC design luminosity
  - where r_T [cm] = transverse distance to the beam
- Lots of R&D over >10 years to develop rad.-hard silicon detectors, gaseous detectors and electronics

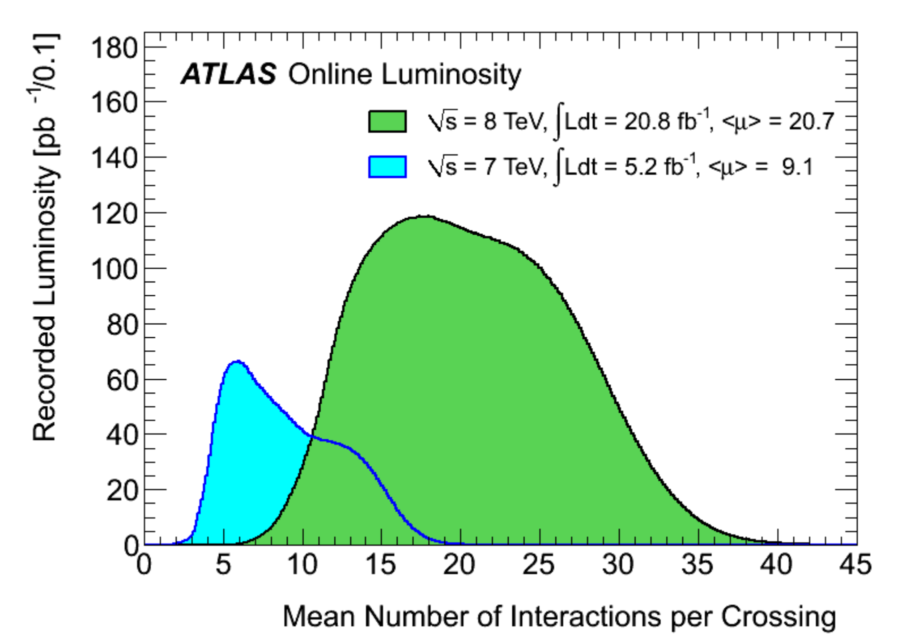


interaction point

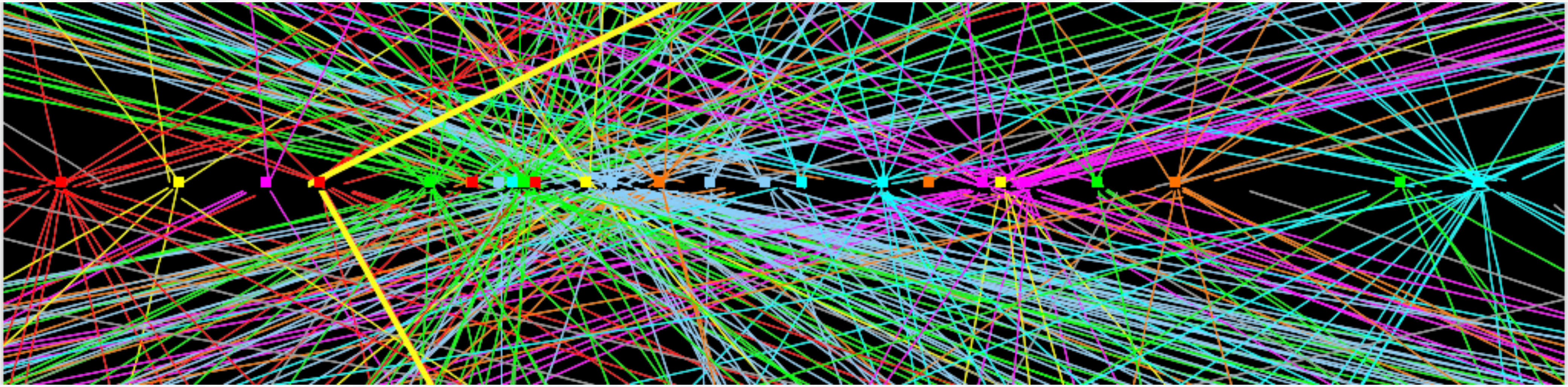
ATLAS neutron fluences

Challenging Conditions: Pile-up





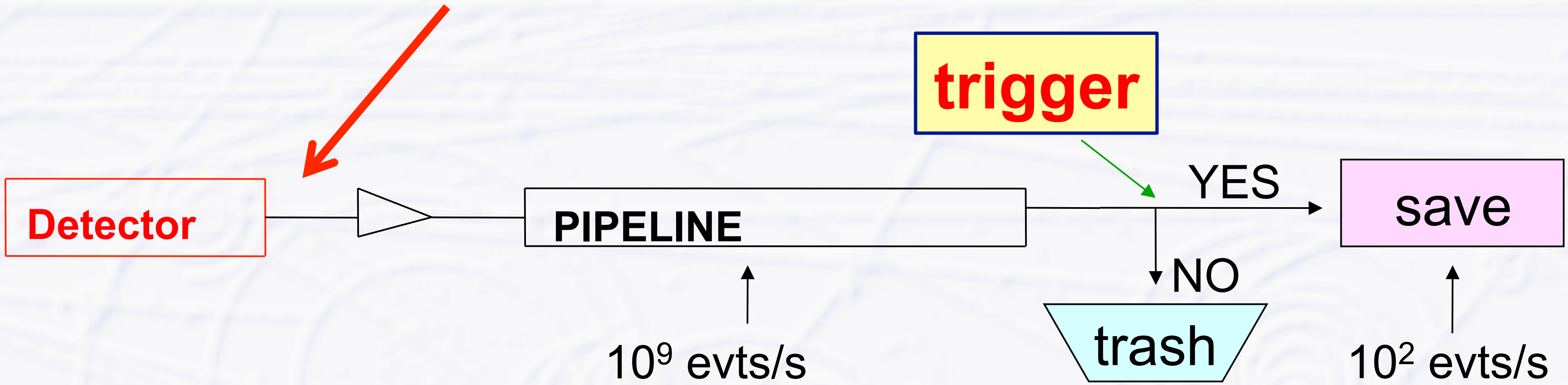
2012 event with pile-up: 25 reconstructed primary vertices



~7 cm

How to Select Interesting Events?

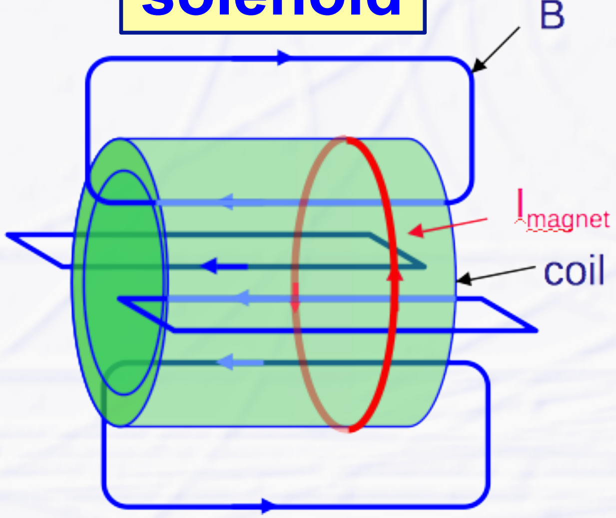
- **Bunch crossing rate: 40 MHz, ~20 interactions per BX** (10^9 evts/s)
  - can only record ~300 event/s (1.5 MB each), still ~450 MB/s data rate
- **Need highly efficient and highly selective TRIGGER**
  - raw event data (1 PB/s) are stored in pipeline until trigger decision



- **ATLAS trigger has 3 levels (CMS similar with 2 levels)**
  - Level-1: hardware, ~3 μs decision time, 40 MHz → 75 kHz
  - Level-2: software, ~40 ms decision time, 75 kHz → 2 kHz
  - Level-3: software, ~4 s decision time, 2 kHz → 300 Hz

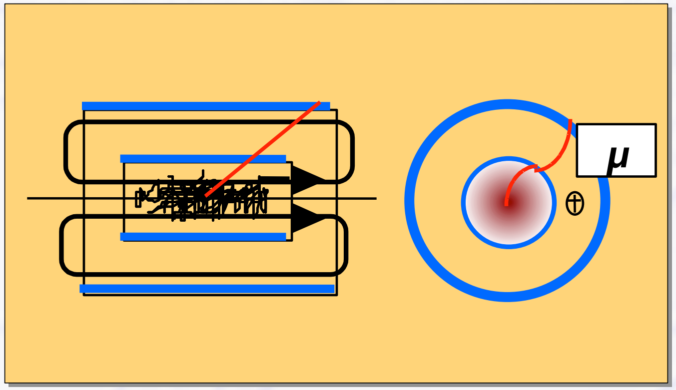
Magnet Concepts at LHC experiments

solenoid

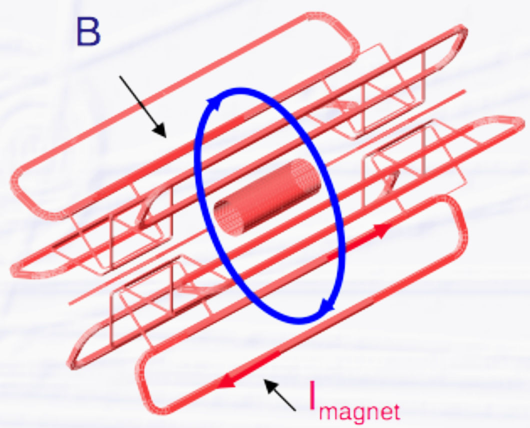


+ large homogenous field inside coil
- needs iron return yoke (magnetic shortcut)
- limited size (cost)
- coil thickness (radiation lengths)

CMS, ALICE, LEP detectors

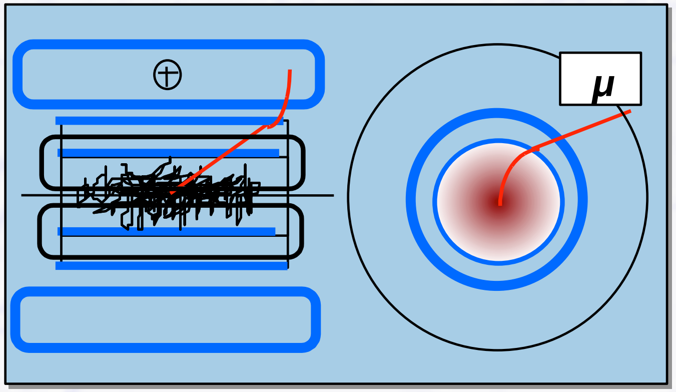


(air-core) toroid

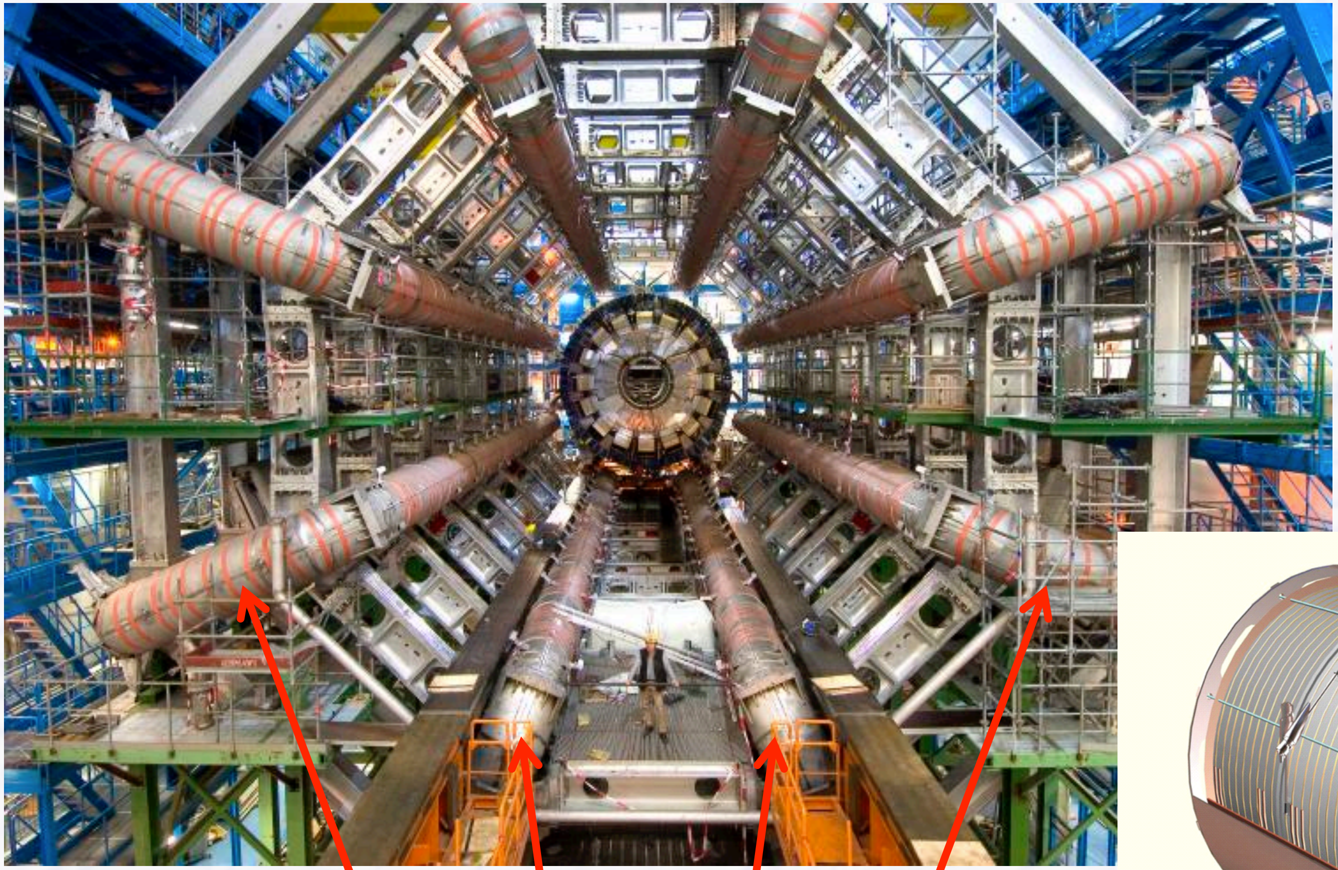


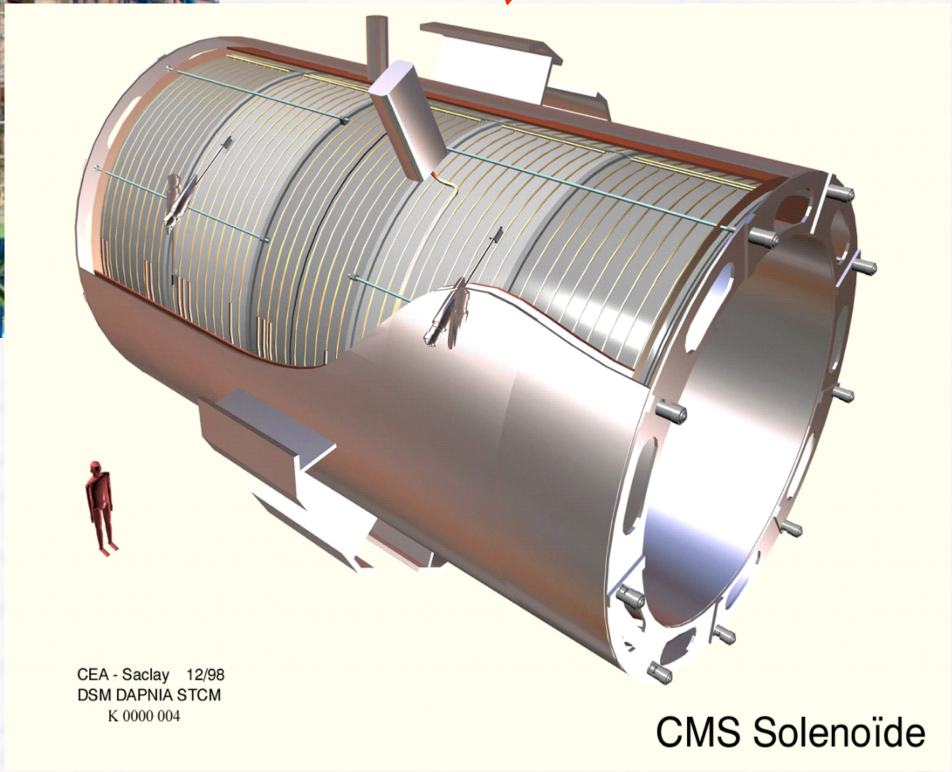
+ can cover large volume
+ air core, no iron, less material
- needs extra small solenoid for general tracking
- non-uniform field
- complex structure

ATLAS



ATLAS and CMS Coils





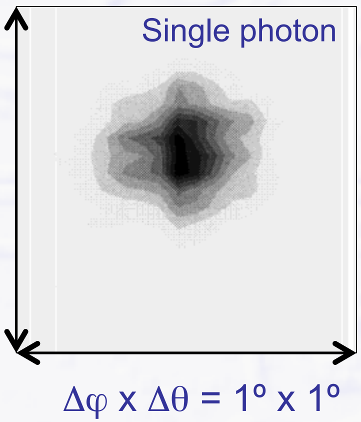
CMS solenoid (5 segments)

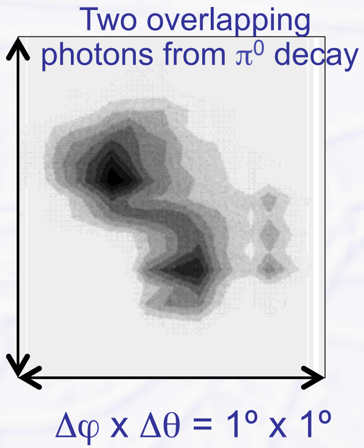
ATLAS barrel toroid coils

autumn 2005

CMS: Homogeneous EM Calorimeter

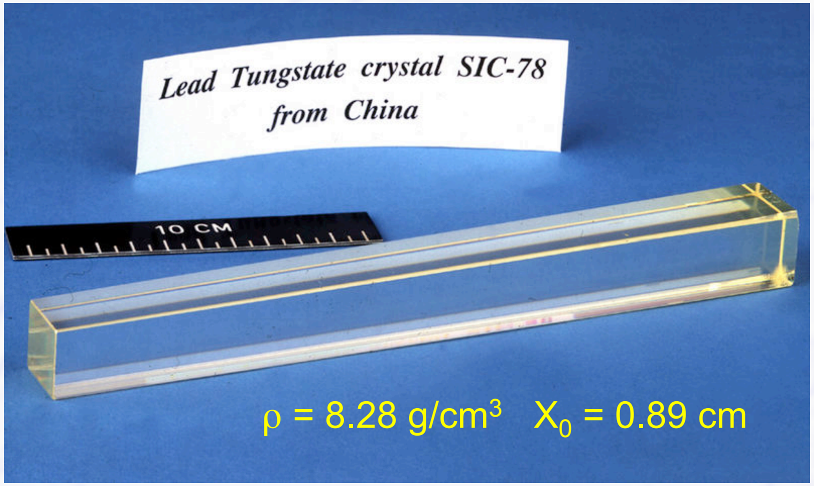
- **Clear advantage: good energy resolution**
  - **the entire shower is kept in active detector material**
    - **no shower particle is lost in passive absorber**
- **Disadvantages**
  - **limited granularity, no information on shower shape in longitudinal direction (along particle flight direction)**
    - **position information is useful to resolve near-by energy clusters, e.g. single photons versus two photons from π^0 decay**





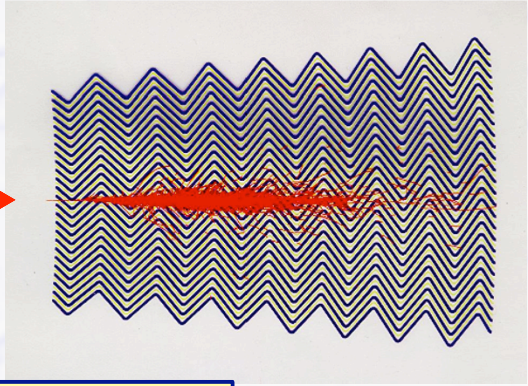
dense, transparent materials needed with short radiation length and high light yield

CMS $PbWO_4$ crystal



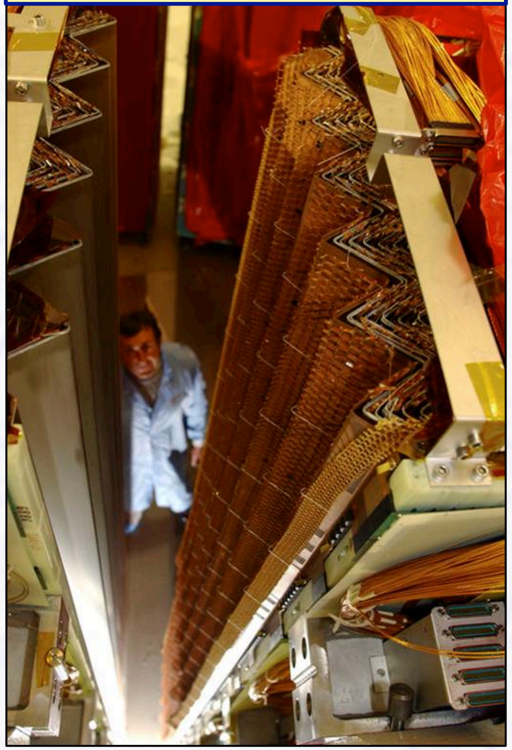
ATLAS: Sampling EM Calorimeter

- Typical sampling calorimeters use iron or lead absorber material, variety of detectors in between possible
  - gas detectors (MWPCs), plastic scintillators, liquid noble gases (LAr, LKr)
- ATLAS is using LAr with "acordeon" shaped steel absorbers
  - LAr is ionized by charged shower particles
  - Charge collected on pads
    - ionization chamber, no "gas" amplification
    - pads can be formed as needed → high granularity
  - acordeon structure helps to avoid dead zones (cables etc.)



simulated shower

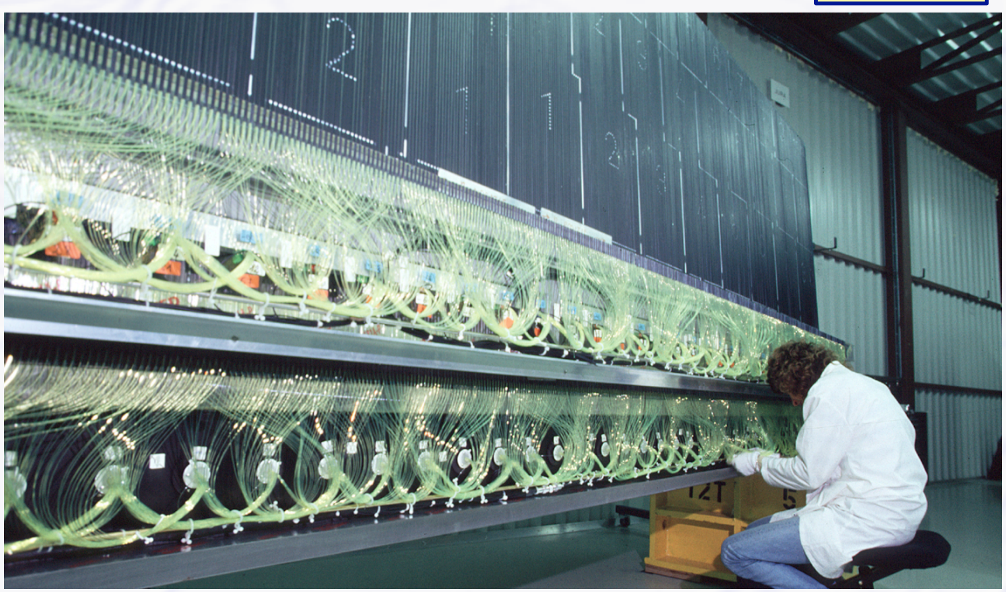
ATLAS LAr calorimeter



ATLAS/CMS Hadron Calorimeters

- **Energy resolution much worse than for electromagnetic calorimeters**
  - **larger fluctuations in hadronic shower**
  - **usually only a few nuclear interactions length deep (5 – 6 λ_I)**
- **Both ATLAS and CMS use scintillators as detector material**
  - ➔ **need many optical fibers to transport light from scintillators to photo detectors**

ATLAS



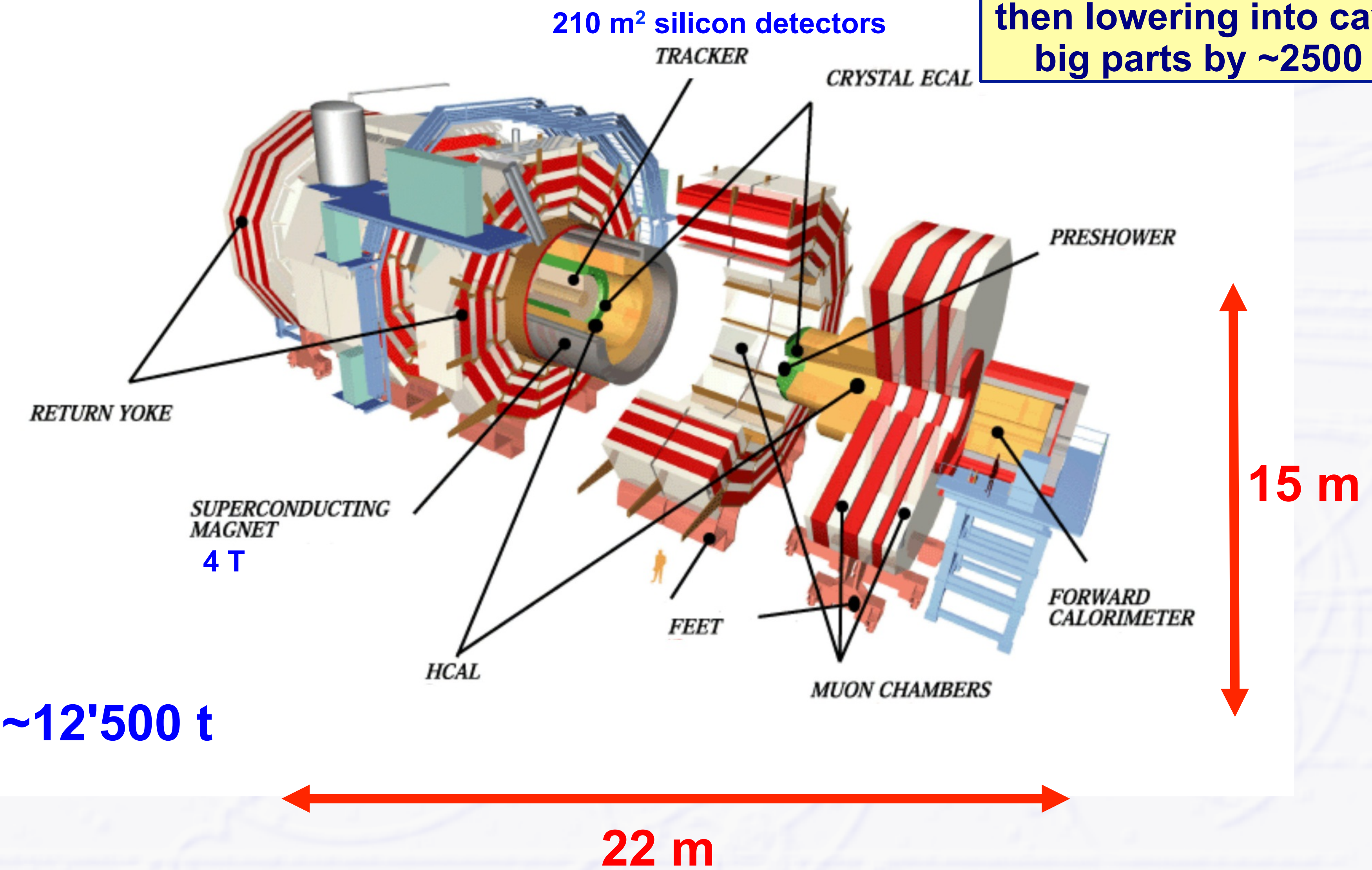
CMS

ATLAS/CMS in detail

	ATLAS	CMS
Tracker or Inner Detector	Silicon pixels, Silicon strips, Transition Radiation Tracker, 2 T magnetic field (small solenoid)	Silicon pixels, Silicon strips, 4 T magnetic field (large solenoid)
Electromagnetic calorimeter	Lead plates as absorbers with liquid argon as the active medium	Lead tungstate ($PbWO_4$) crystals both absorb and respond by scintillation
Hadronic calorimeter	Iron absorber with plastic scintillating tiles as detectors in central region, copper and tungsten absorber with liquid argon in forward regions.	Stainless steel and copper absorber with plastic scintillating tiles as detectors
Muon detector	Large air-core toroid magnets with muon chamber form outer shell of the whole ATLAS	Muon chambers inserted in the magnet return yoke

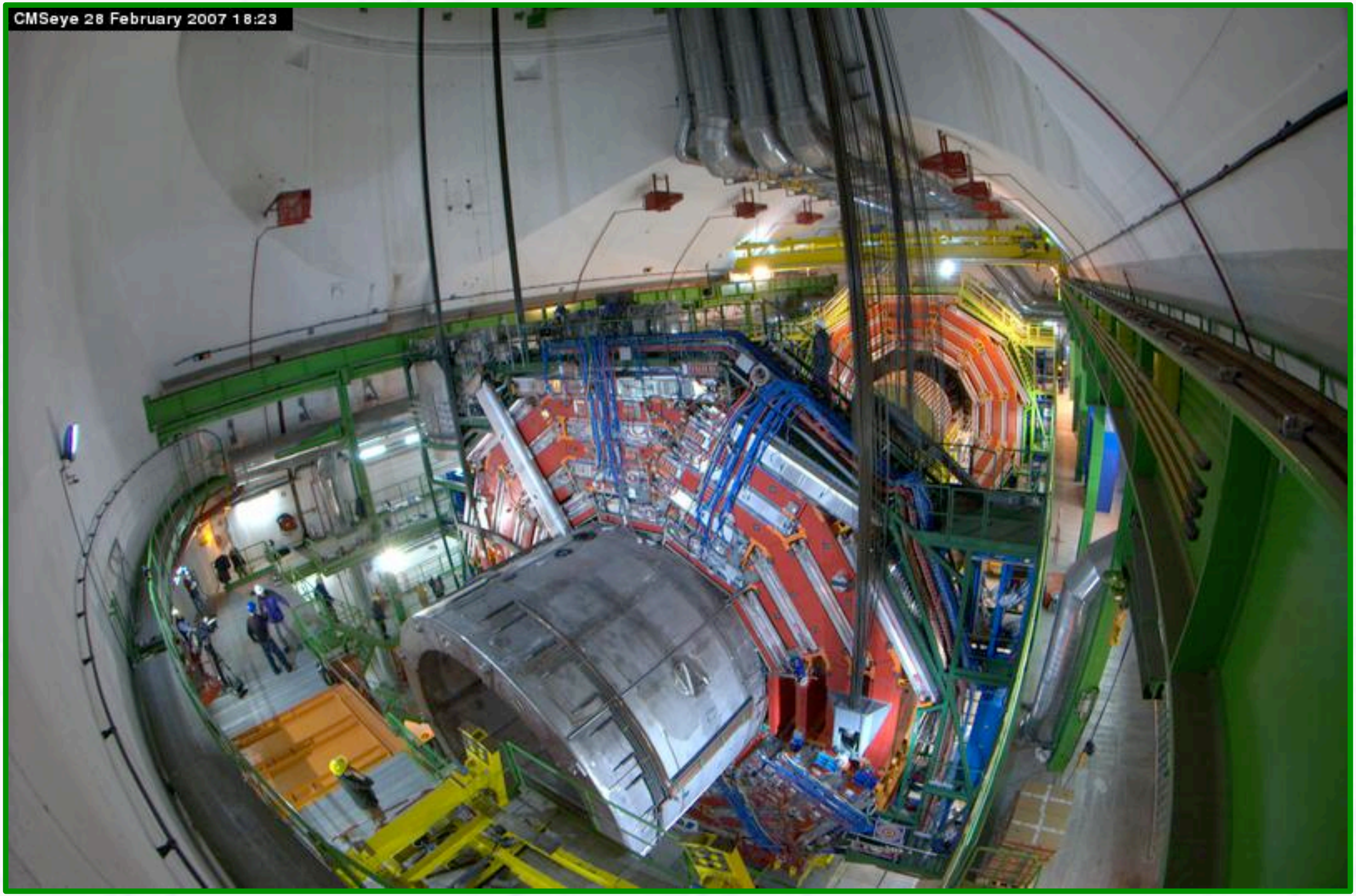
CMS (Compact Muon Spectrometer)

main assembly on surface, then lowering into cavern in 5 big parts by ~2500 t crane

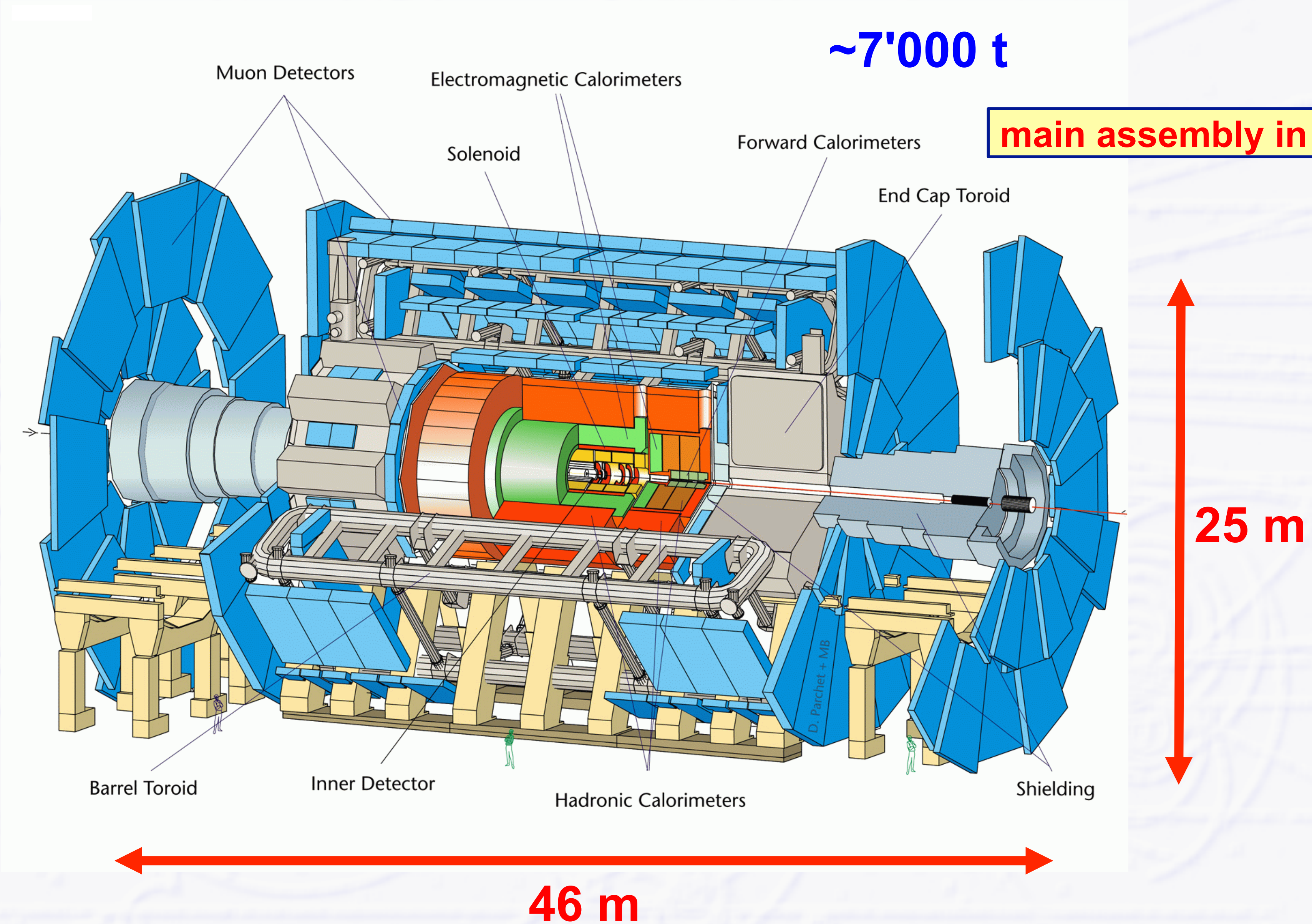


~12'500 t

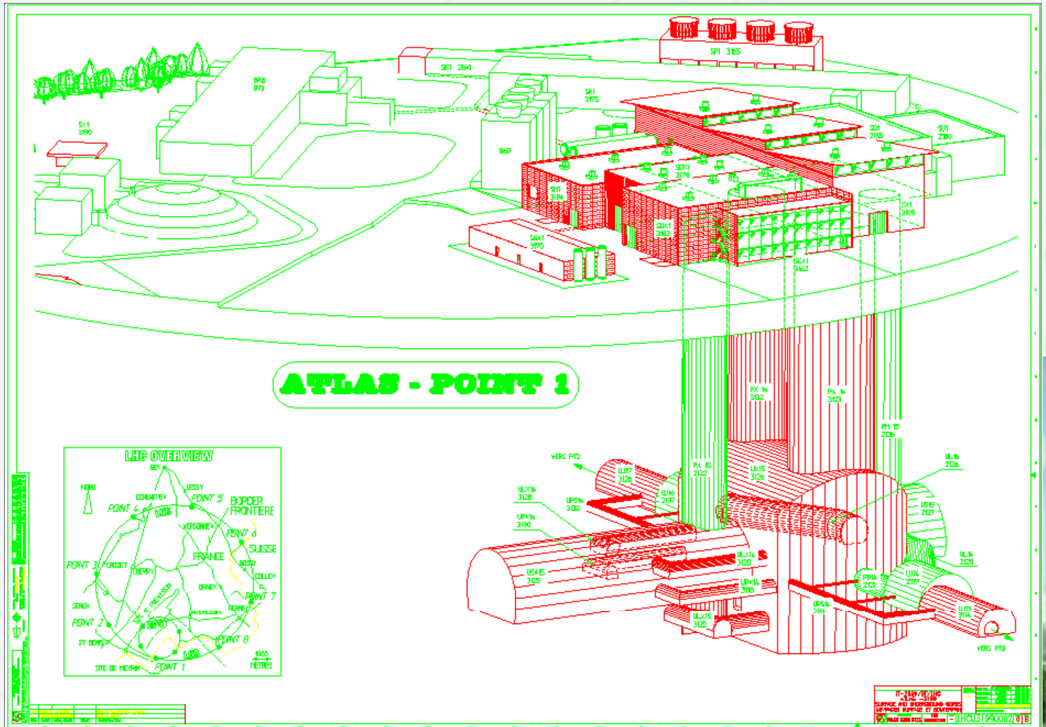
CMS Lowering of 2000 t Central Part



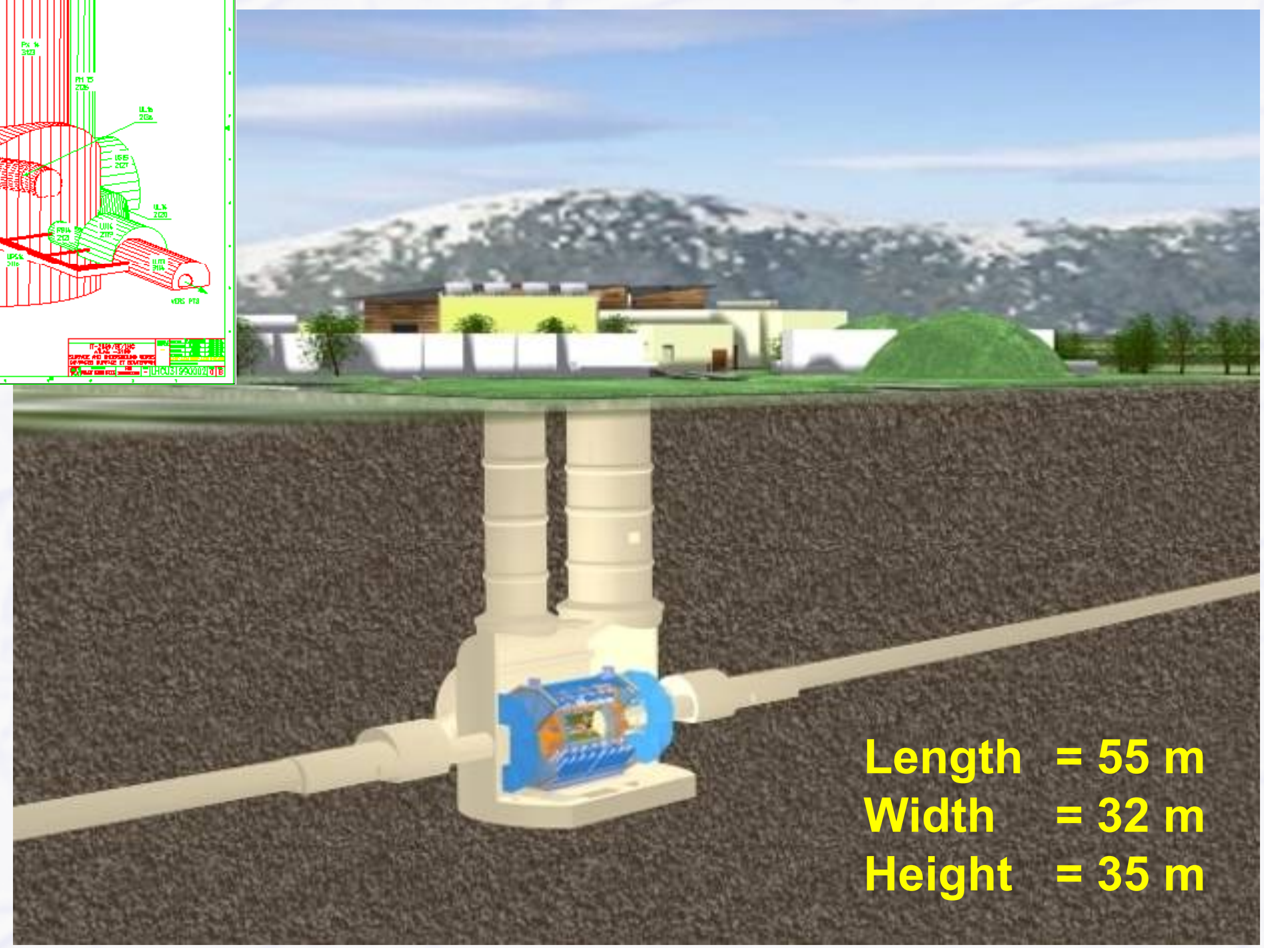
ATLAS (A Toroidal LHC ApparatuS)



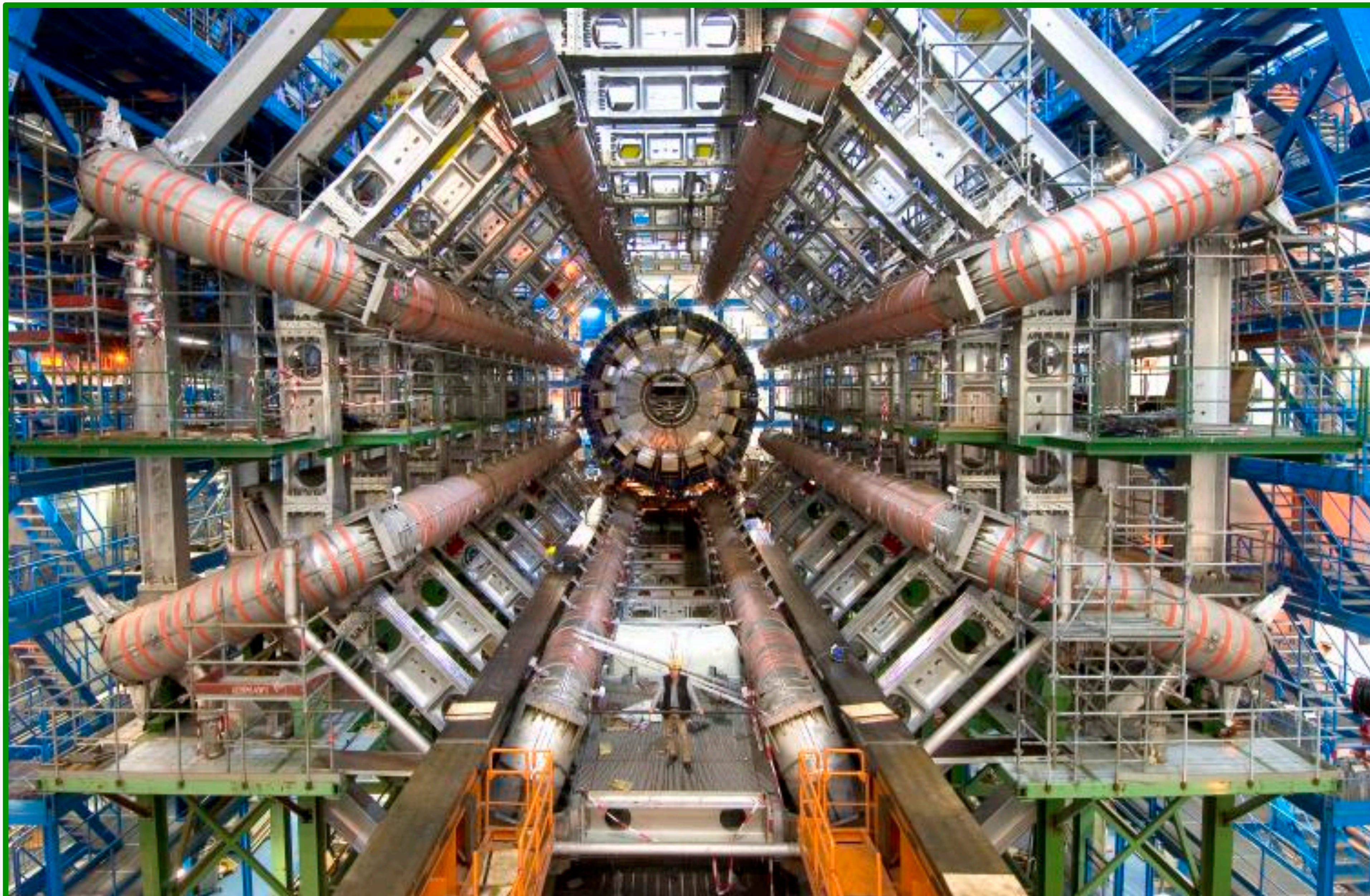
ATLAS Underground Cavern



huge cavern + surface buildings,
2 access shafts 18m + 12m Ø,
2 small shafts for elevators + stairs



ATLAS Barrel Toroid Complete (Nov 2005)



Detector Technology and Arts

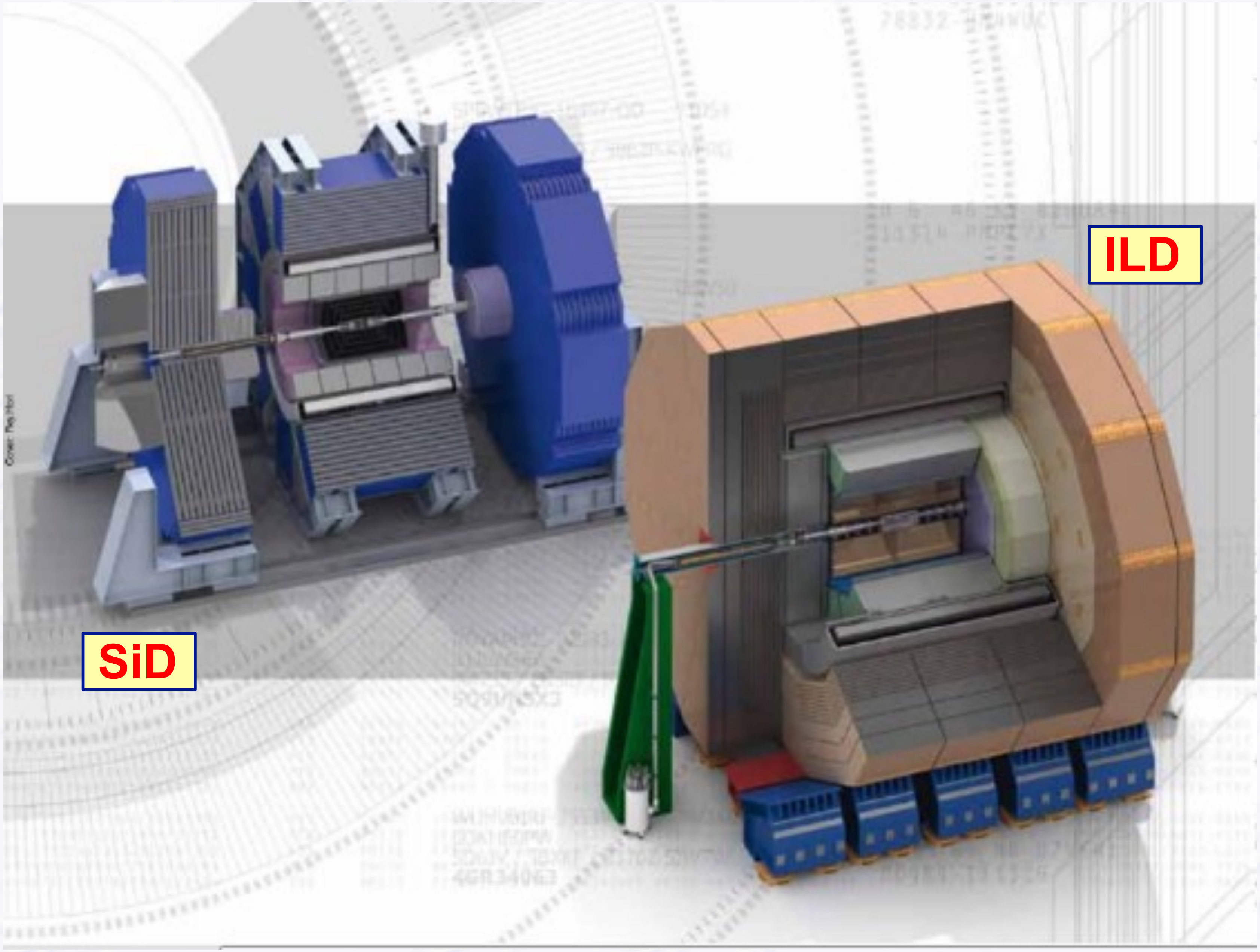
ATLAS/CMS Concept Overview

- The two large LHC detectors have somewhat different concepts
  - ATLAS
    - small inner tracker with moderate field (small 2 T solenoid)
    - electron identification by transition radiation tracker
    - sampling calorimeter with high granularity outside solenoid
    - air-core toroid system for good muon momentum measurement

      emphasis on granular calorimeter and good muon measurement
  - CMS
    - large inner tracker with high B-field (large 4 T solenoid)
    - no dedicated particle identification detector
    - homogeneous crystal calorimeter with good energy resolution inside solenoid

      emphasis on good general tracking and good energy resolution
- However, both detector concepts have very similar performance for Higgs physics (efficiency, mass resolution…)

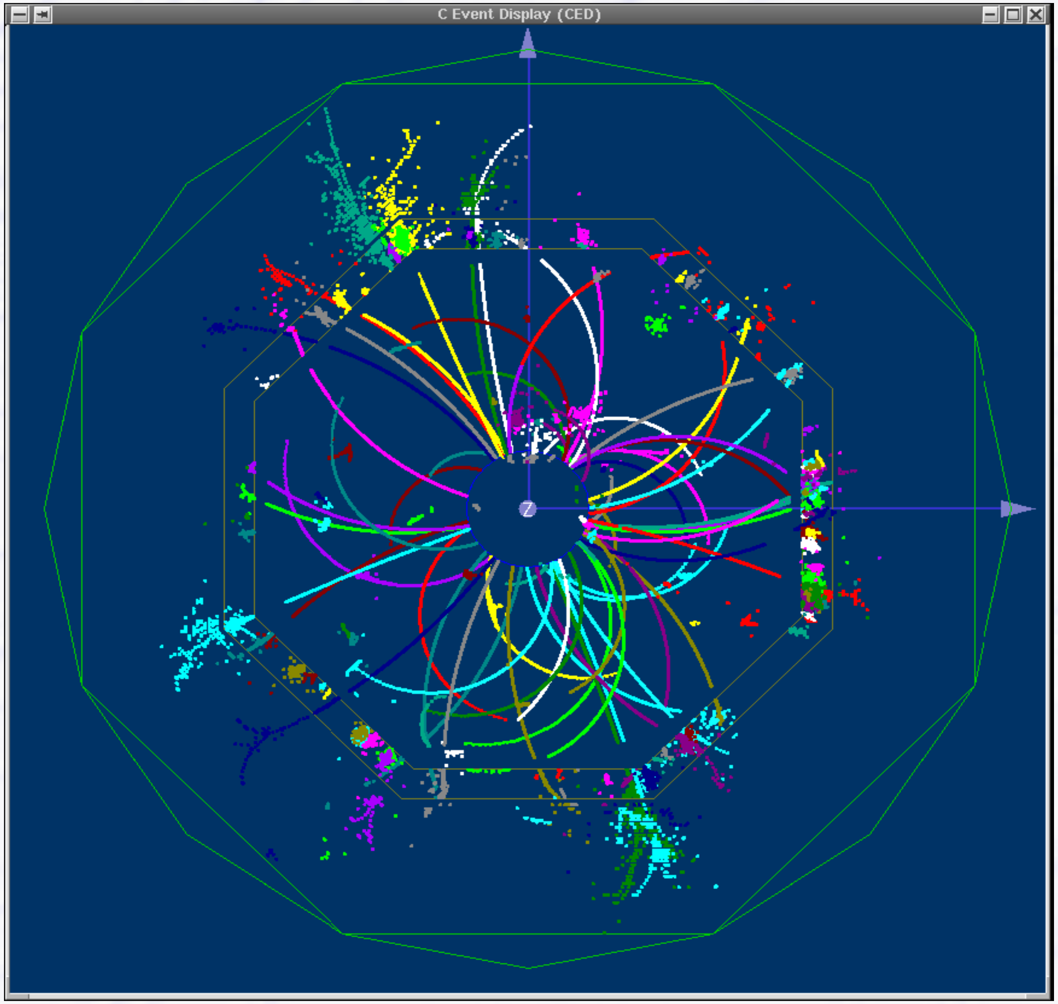
ILC Detector Concepts



Physics Events at the ILC

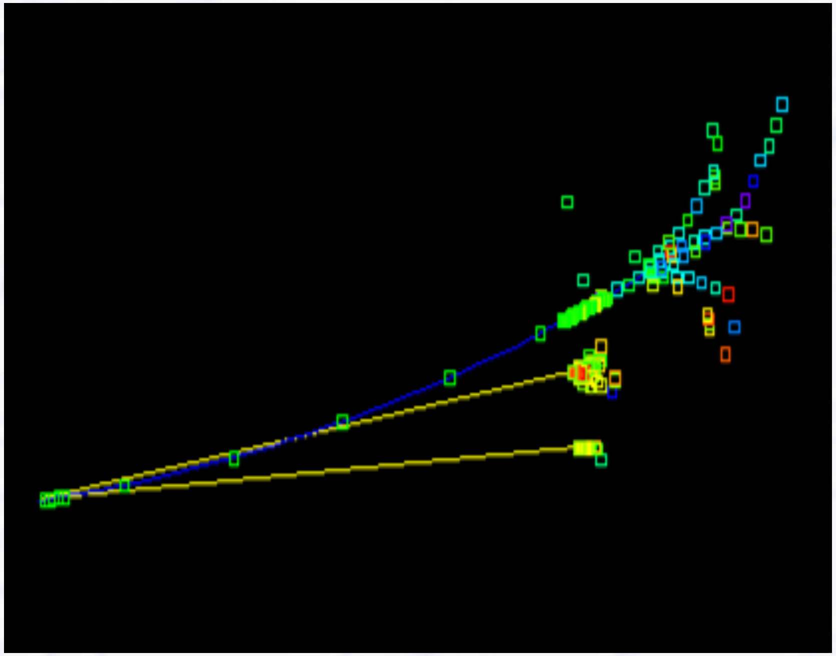
- **Event characteristics**
  - **multi jet final states**
  - **leptons, often in jets**
  - **forward going physics**
  - **jet energy reconstruction plays a central role at the ILC**
    - **need as good jet energy resolution as possible**

tt event at the ILC (ILD model)



ILC Detector – Design Philosophy

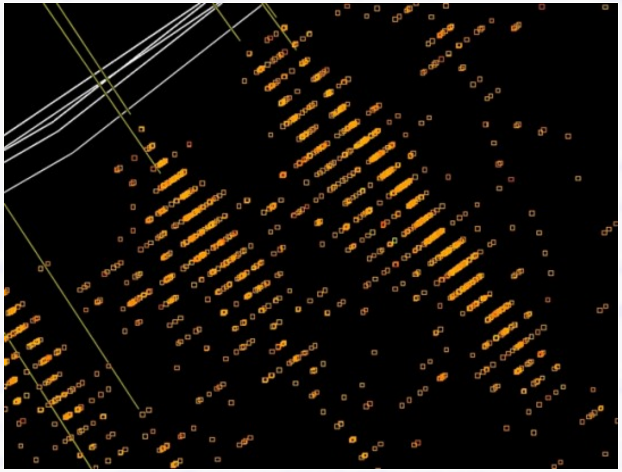
- **Particle flow as main reconstruction technique for jet energy**
  - Imaging Calorimeters (CALICE)
  - Extreme granularity wins over energy resolution, in particular in the HCAL
    - Sampling EM calorimeter
- **High power tracking**
  - High efficiency, robust tracking in dense environments
  - High precision vertexing for heavy flavour physics
    - (very) many pixels



ILC Detector - Performance Needs

- Challenging detector performance dictated by physics
  - Jet energy resolution 2 x LEP
  - Momentum resolution 10 x LEP
  - Impact parameter resolution 3 x LEP
  - Vtx detector hit resolution 3 x LEP
- NOT a simple copy of a LEP detector
- NOT a typical LHC detector
  - → LHC detector
    - focus on radiation hardness, (low) occupancy
    - trackers have large amount of material

ILC Detectors – Challenges w.r.t. LHC



- **Calorimeter granularity**
  - factor of ~200 better than LHC
- **Pixel size**
  - factor ~20 smaller than LHC
- **Material Budget**
  - as low material budget as possible, lots of photons from beamstrahlung
    - factor ~10 less than LHC (barrel)
    - factor ~100 less than LHC (forward tracking)

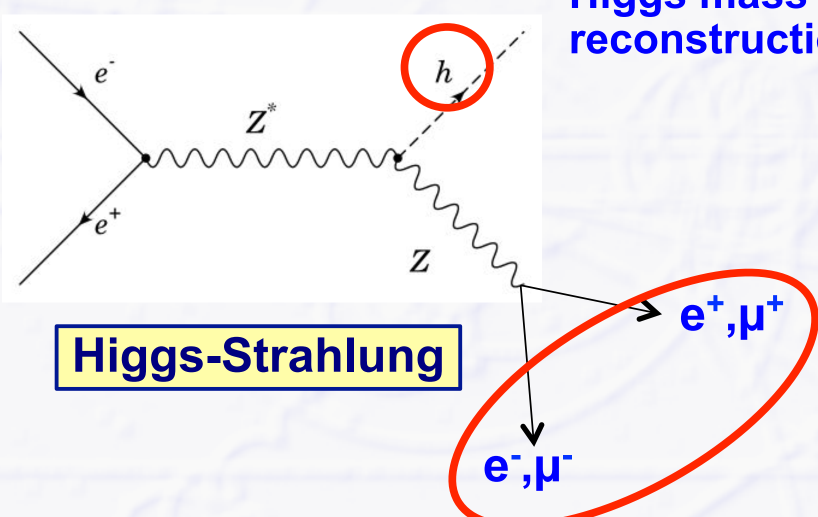
- **Requirements for timing, data rate and radiation**
  - very modest compared to LHC
    - “no” radiation issues
    - “no” trigger, keep all data of a single bunch train, decide later…
    - no pile-up, no overlaying physics events in a single bunch crossing

Momentum Resolutions

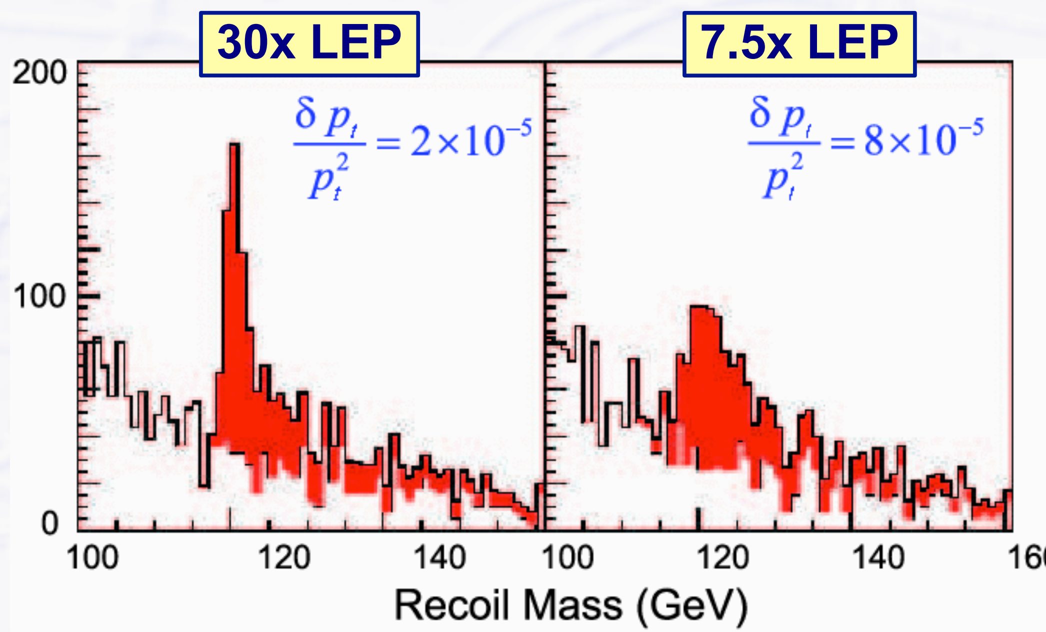
	ALEPH	DELPHI	OPAL	ILD
main tracker	TPC	TPC	Jet Chamber	TPC
size (Ø x L) [m]	3.6 x 4.4	2.4 x 2.7	3.6 x 4.0	3.2 x 4.3
magnetic field [T]	1.5	1.23	0.435	4.0
points/track	21	16	159	200
point resolution [μm]	173	250	135	100
pressure [bar]	1	1	4	1
dE/dx resolution [%]	4.5	5.5	2.8	4.3
dp_t/p_t^2 [1/GeV]				
main tracker	1.2×10^{-3}	n.a.	1.4×10^{-3}	1.3×10^{-4}
full tracking system	0.6×10^{-3}	0.6×10^{-3}	1.25×10^{-3}	**5×10^{-5}**

requires high B + many high resolution points

Higgs mass reconstruction

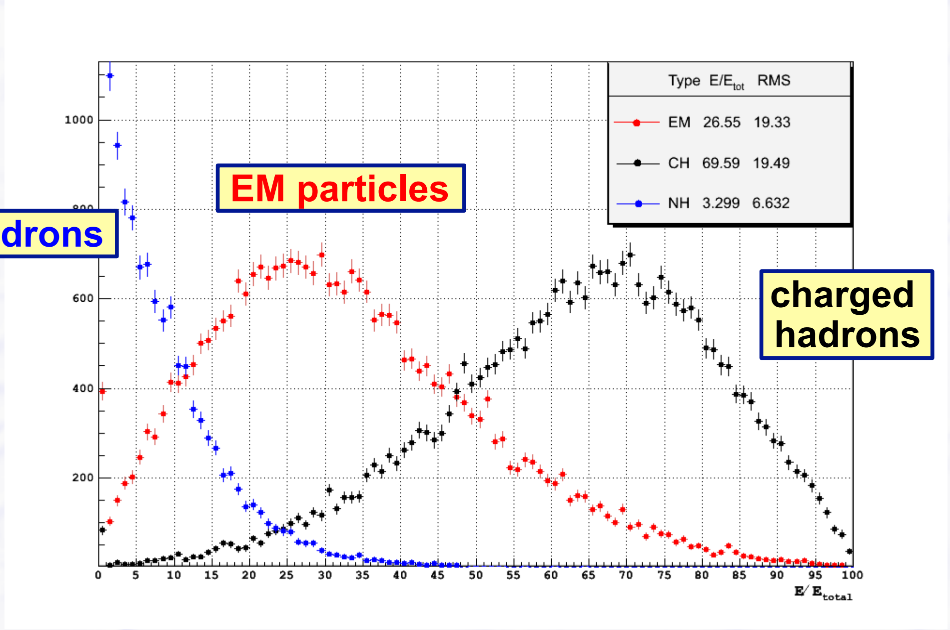


Higgs-Strahlung



Particle Flow (Algorithm) - PFA

- **Most precise event reconstruction**
  - **Individual particles are reconstructed: charged and neutrals**
- **Fundamental problem: fluctuations in the calorimeter**
  - **use tracker as much as possible for charged particles**
    - **replace information in calorimeter by tracker information**
  - **use calorimeter for neutral particles (photons, neutral hadrons)**
- **Pushes requirements for calorimeter**
  - **excellent segmentation**
    - **energy resolution is of lesser importance**
- **Goal**
  - **jet energy resolution 3-4% (below 100 GeV)**



Particle Flow

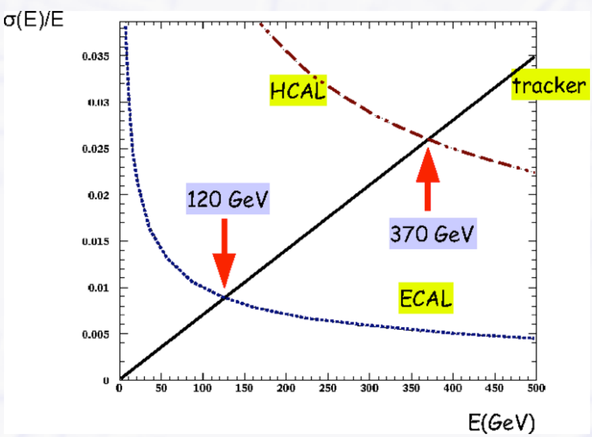
- **Many physics signatures have complicated multi-jet final states 6 – 8 jets**
  - good jet energy resolution required (2x better than at LEP)
    - LEP: $\sigma(E_{jet}) \approx 60\%/\sqrt{E_{jet}}$ ILC: $\sigma(E_{jet}) \approx 30\%/\sqrt{E_{jet}}$
  - use combined information of tracker, ECAL + HCAL to obtain better jet energy resolution

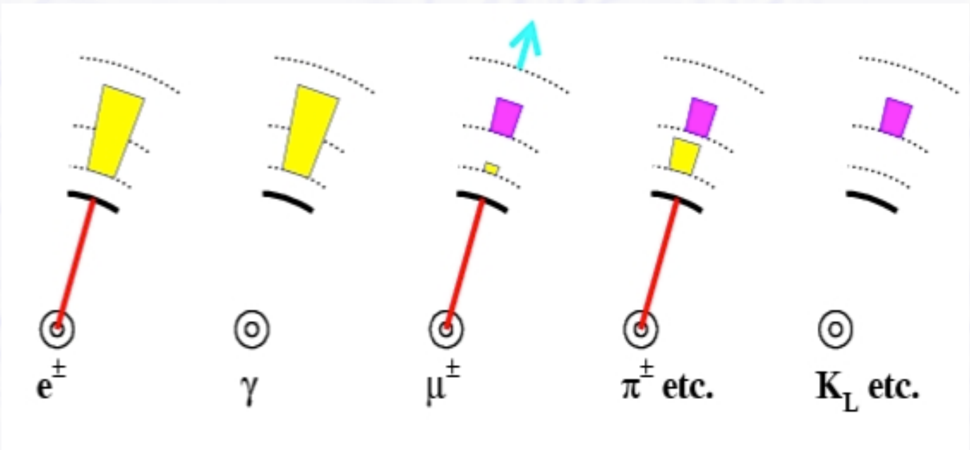
keep these as small as possible

- **"Particle Flow" concept** (simple but challenging)

$$\sigma^2(E_{jet}) = \sigma^2_{charged\ particles} + \sigma^2_{photons} + \sigma^2_{neutral\ hadrons} + \sigma^2_{confusion} + \sigma^2_{threshold}$$

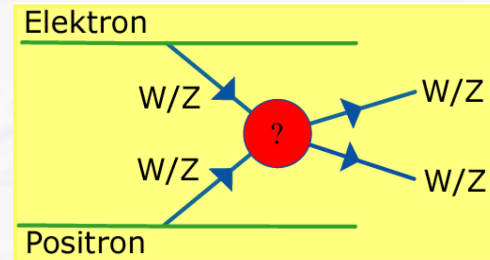
Tracker 65% | ECAL 25% | HCAL 10% ← contributions to E_{jet}



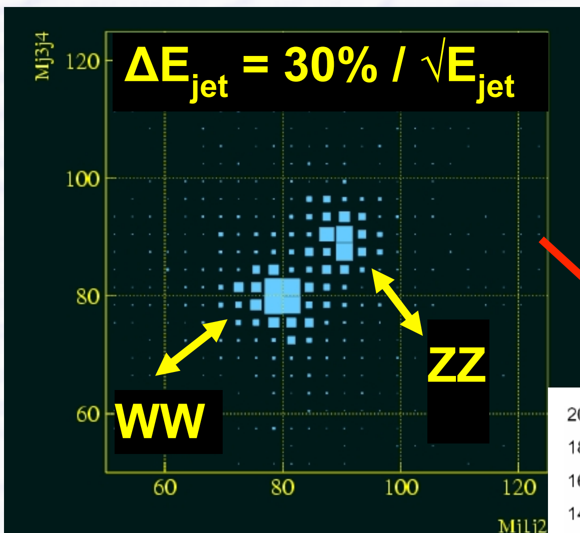


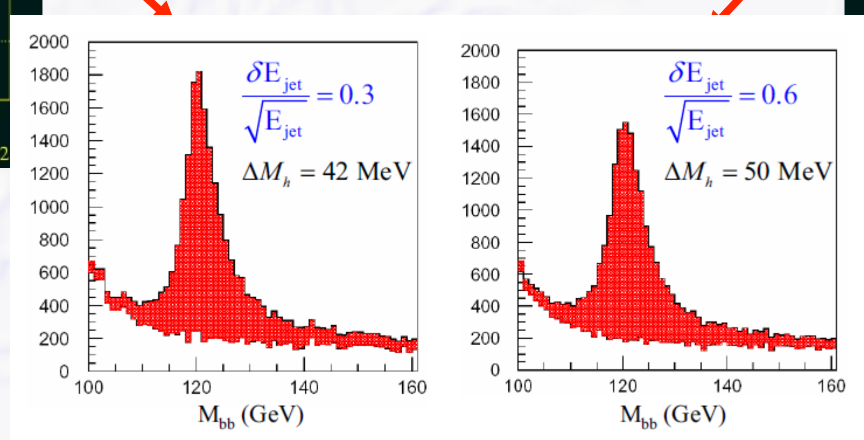
Jet Energy Resolution

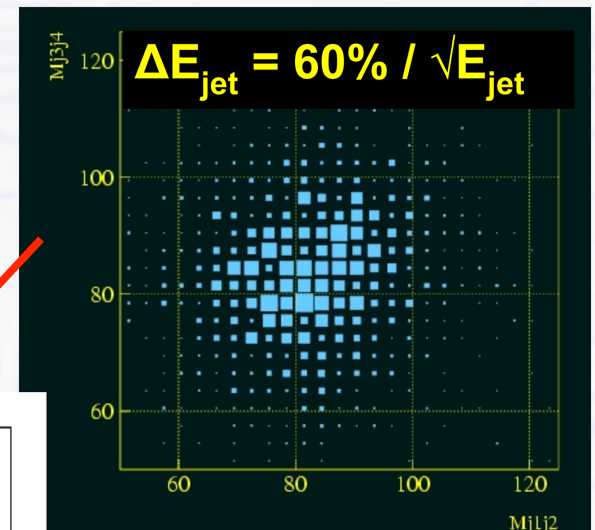
- Need enough resolution to separate Z and W decaying into jets: e+e- → νν + WW/ZZ → jets



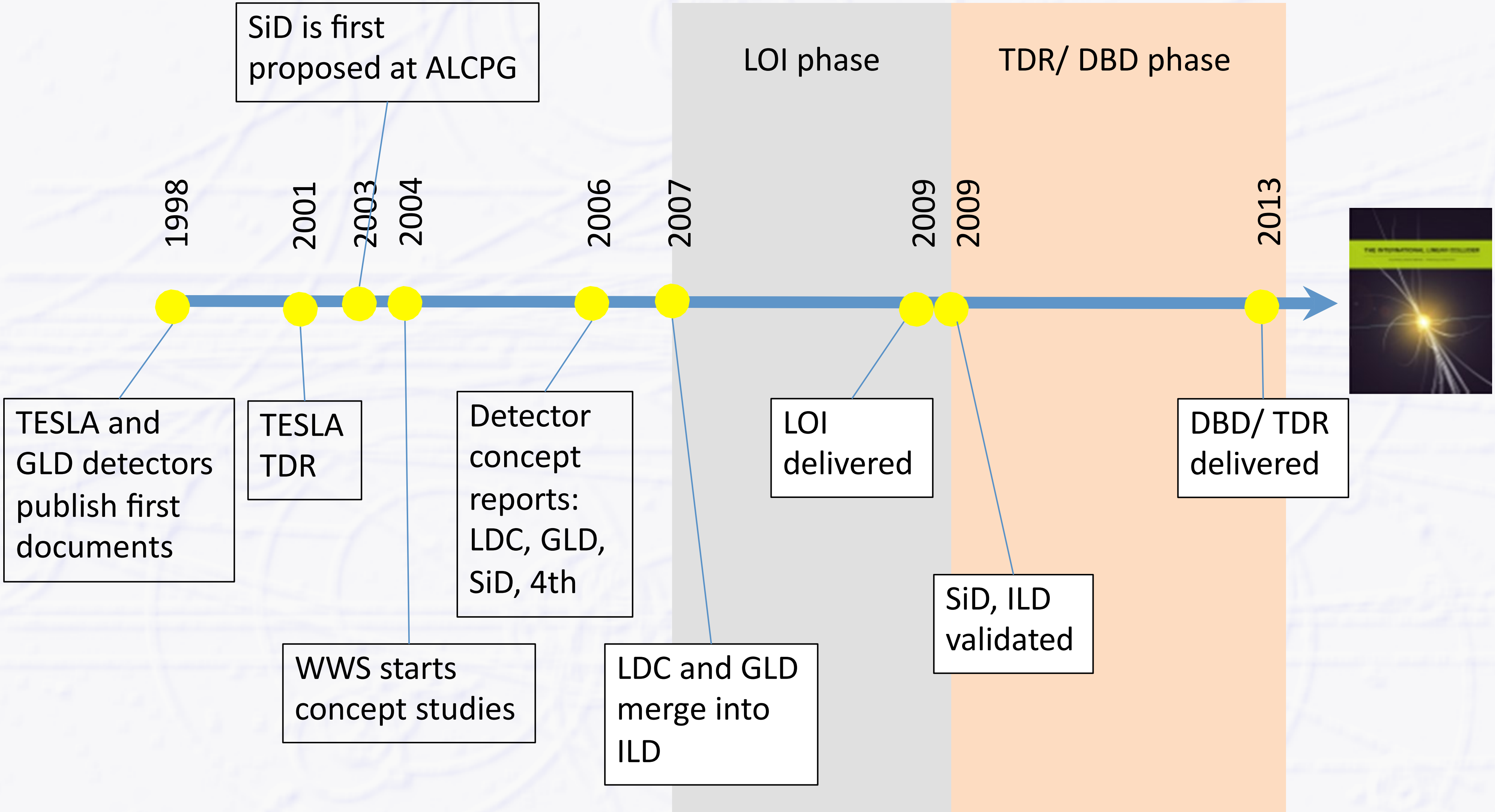
- Improvement of σ_E/E from 60%/√E to 30%/√E
  - equivalent to ~40% luminosity gain in $\sigma(M_h)$
    - similar luminosity gain in ΔBR(H → WW*), Δghhh







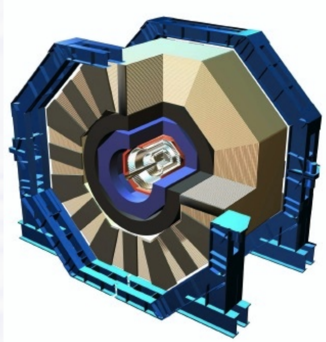
ILC Detector Concepts History



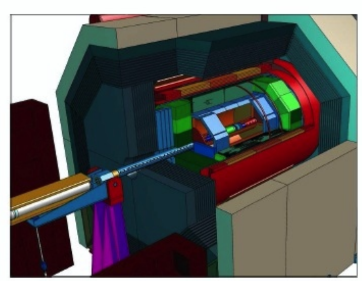
ILC Detector Concept Studies

- **started in 1990ies, up to 4 different concepts in 2006 (CDRs)**
  (3 old concepts under new names + 1 new concept)

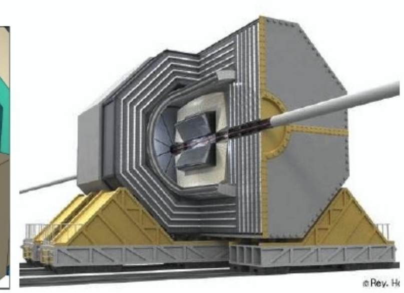
	SiD (former US small detector concept)	**LDC** (former European TESLA concept)	**GLD** (former Asian/Japanese concept)	**“4th”** (new concept)
Main Tracker	**Full Si Tracker**	**TPC (GEMs/MicroMegas)**	**TPC (GEMs/MicroMegas)**	**TPC (GEMs/MicroMegas)**
outer tracker radius	1.3 m	1.7 m	2.1 m	1.4 m
magnetic field	5 T	4 T **(CMS design)**	3 T	3.5 T **(dual solenoids)**
ECAL (inside coil)	**Si – W**	**Si – W**	Scintillator – W	Crystals
HCAL (inside coil)	RPC – W	Scintillator – Fe	Scintillator – Pb	**Fibers (Scin./Quartz) – W**



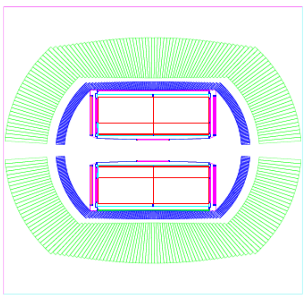
SiD



LDC



GLD



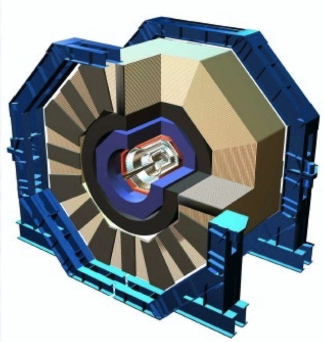
4th

- **~180 institutes + ~500 authors world-wide (~30% Europe)**

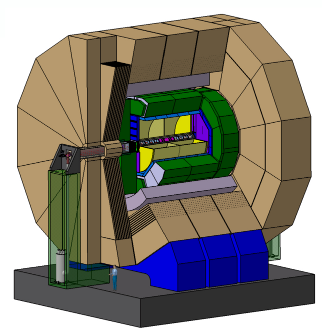
ILC Detector Concept Studies

- **2 concepts left after LoI validation process finished in 2009**
  - **SiD and ILD**

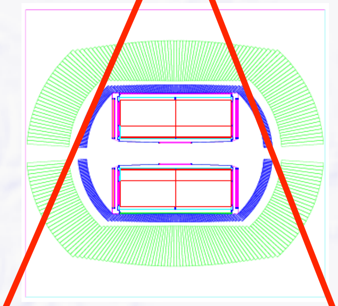
	SiD (former US small detector concept)	**ILD** (merger of LDC and GLD since August 2007)	**"4th"** (new concept)
Main Tracker	**Full Si Tracker**	**TPC (GEMs/MicroMegas)**	**TPC (GEMs/MicroMegas)**
outer tracker radius	1.3 m	2.0 m	1.4 m
magnetic field	5 T	3.5 T **(CMS design)**	3.5 T **(dual solenoids)**
ECAL (inside coil)	**Si – W**	**Si – W**	Crystals
HCAL (inside coil)	RPC – W	Scintillator – Fe; Scintillator – Pb	**Fibers (Scin./Quartz) – W**



SiD



LDC + GLD = ILD



4th

ILD and SiD Detector Philosphies

ILD	SiD
Particle flow is the fundamental paradigm for both ILD and SiD	
Precision vertexing very close to the IP	
Tracking with high redundancy many space points for excellent pattern recognition and background tolerance	Tracking with a focus on few high precision points for robust, stable and easy to calibrate tracking, precision compensates for problems in pattern recognition.
Highly granular calorimeter, similar pixel sizes, similar level of topological reconstruction	
Large size improves the separation between charged and neutral particles in the shower	High B-field opens charged shower component and is more cost efficient, some loss of performance in particular at higher energies

ILD and SiD Main Parameters

	SiD	ILD
R(in) Vertex	14 mm	16 mm
R(out) tracker	1221 mm	1808 mm
N(tracker hits)	<12>	<228>
X(0) until ECAL	12% (barrel), 20% (EC)	12% (barrel), 42% (EC)
R(out) HCAL	2493 mm	3973 mm
Λ (until end of HCAL	4.5	7 (min), 8.5 (max)
Coil inner radius	2591 mm	3440 mm
B(coil)	5 T	3.5 T
Outer Radius	6042 mm	7755 mm
Total length	5673 mm	6620 mm

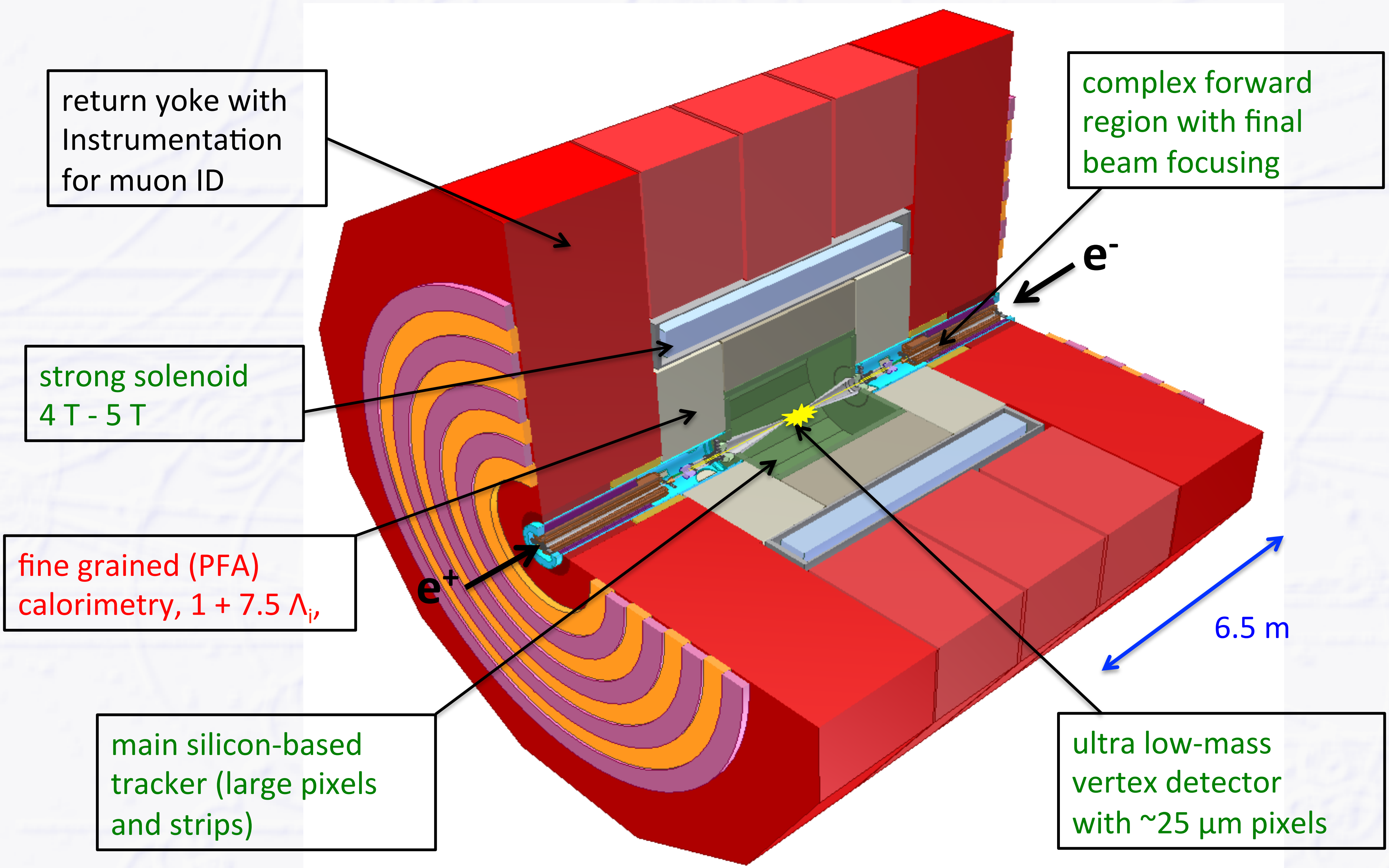
- **SiD**
  - **more compact (full silicon tracker), shorter, higher B-field**
- **ILD**
  - **larger (TPC), thicker, lower B-field**

ILC Detector Concepts - Status

- Both ILD and SiD:
  - mature designs, internationally reviewed
- Intense R&D on sub-systems technologies
  - R&D collaborations like CALICE or LCTPC, LCFI, etc.
  - Major test beam and prototyping campaigns, in Europe supported through programs like EUDET and AIDA
- Developments of integrated systems
  - First level engineering (looking for show stoppers)
  - “Reality checks” have been applied
- Costing
  - Cost models have been developed
  - Some cost optimization has taken place

CLIC Detector Concept

… adapted from ILC detector concepts …



CLIC Detector Study

- CLIC detector study has started in 2008 at CERN
  - starting point: existing SiD and ILD concepts and simulations
  - had to modify/adjust concepts to CLIC needs
- CLIC detector = “90% ILC detector” + “10% CLIC specifics”
  - CLIC has profited a lot from ILC detector R&D and design studies
  - but ILC also profits from CLIC studies
    - CLIC detector = “extreme” ILC detector → win – win situation for both communities
    - common work on Particle Flow Algorithms
    - engineering studies (push – pull), also foreseen at CLIC
- CDR prepared in 2012
  - detector and physics studies
    - “SiD-like concept” @ CLIC @ 3 TeV = CLIC_SiD
    - “ILD-like concept” @ CLIC @ 3 TeV = CLIC_ILD

CLIC_ILD and CLIC_SiD

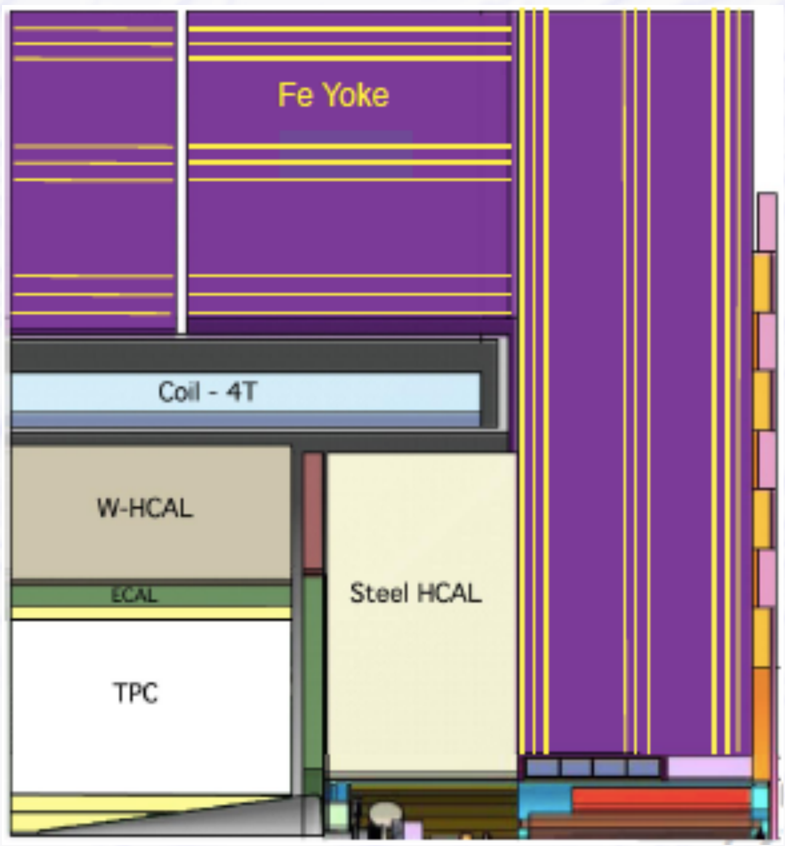
Two general-purpose CLIC detector concepts

Based on initial ILC concepts (ILD and SiD)

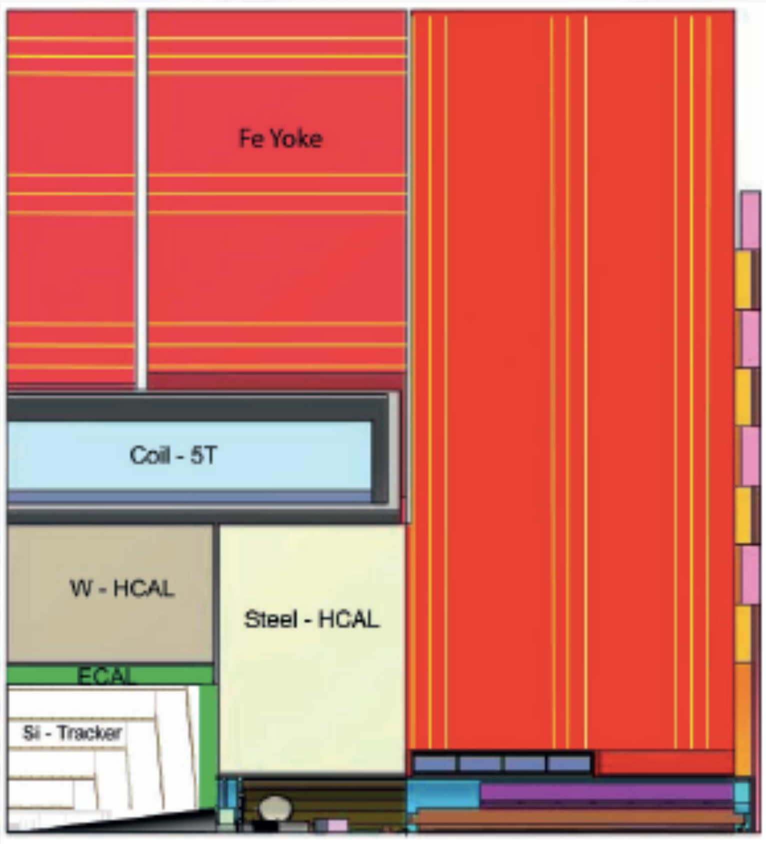
Optimised and adapted to CLIC conditions

CLIC_ILD

7 m

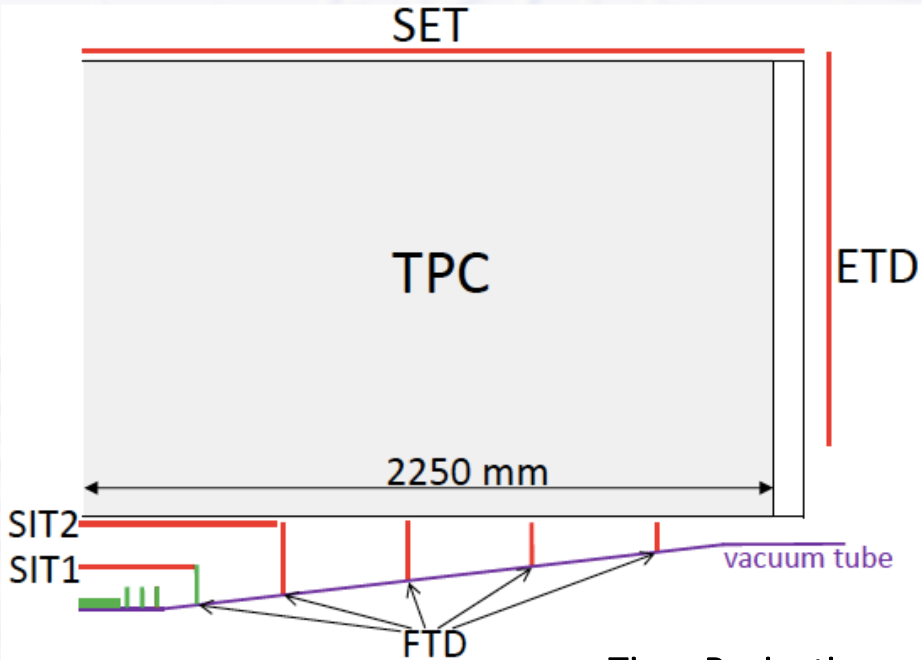


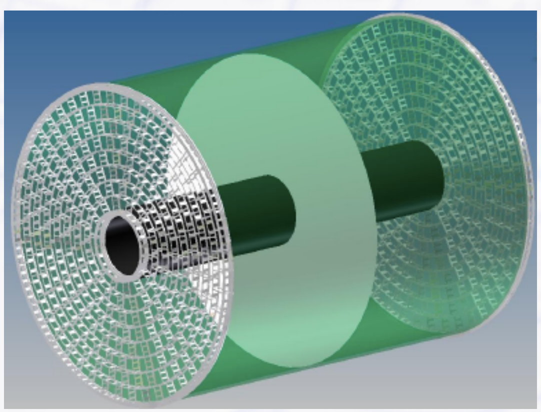
CLIC_SiD



CLIC_ILD ↙ and CLIC_SiD ↘ tracker

TPC + silicon tracker in 4 Tesla field



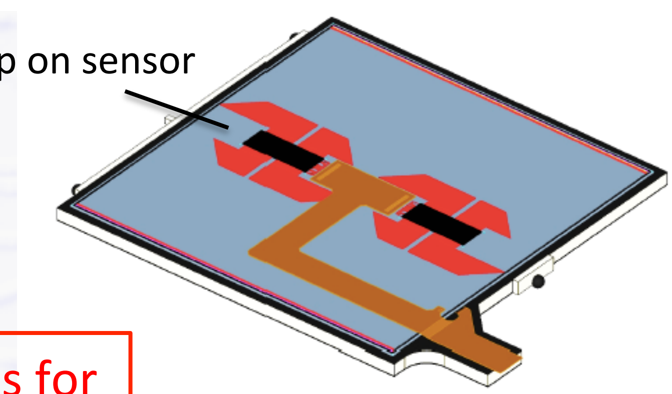


Time Projection Chamber (TPC) with MPGD readout

All-silicon tracker in 5 Tesla field

1.3 m

chip on sensor



Silicon-based tracking studies for new CLIC detector model starting

CLIC Bunch Spacing

- **CLIC study started at CERN about ~20 years ago**
  - major revision of CLIC parameters made in summer 2007
- **Basic changes**
  - 30 GHz -> 12 GHz RF frequency
    - close to old NLC frequency (11.424 GHz)
      - easier to adapt NLC work and experience
    - lower frequency allows more relaxed alignment tolerances
  - 150 MV/m -> 100 MV/m
    - reduces breakdown rate and surface damages in RF accelerating structures
    - 50 km long LINAC allows 2 x 1.5 TeV = 3 TeV CM energy (was 5 TeV)
  - 0.5 ns bunch spacing, 312 bunches (= 156 ns bunch trains), 50 Hz (3 TeV)
    - optimized for maximum luminosity
    - was subject of various changes in the past:
      0.667 ns -> 0.267 ns -> 0.667 ns -> 0.5 ns
- **Conceptional design report in 2012**

detector challenge

ILC + CLIC Parameters

Luminosity at
500 GeV similar to ILC

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

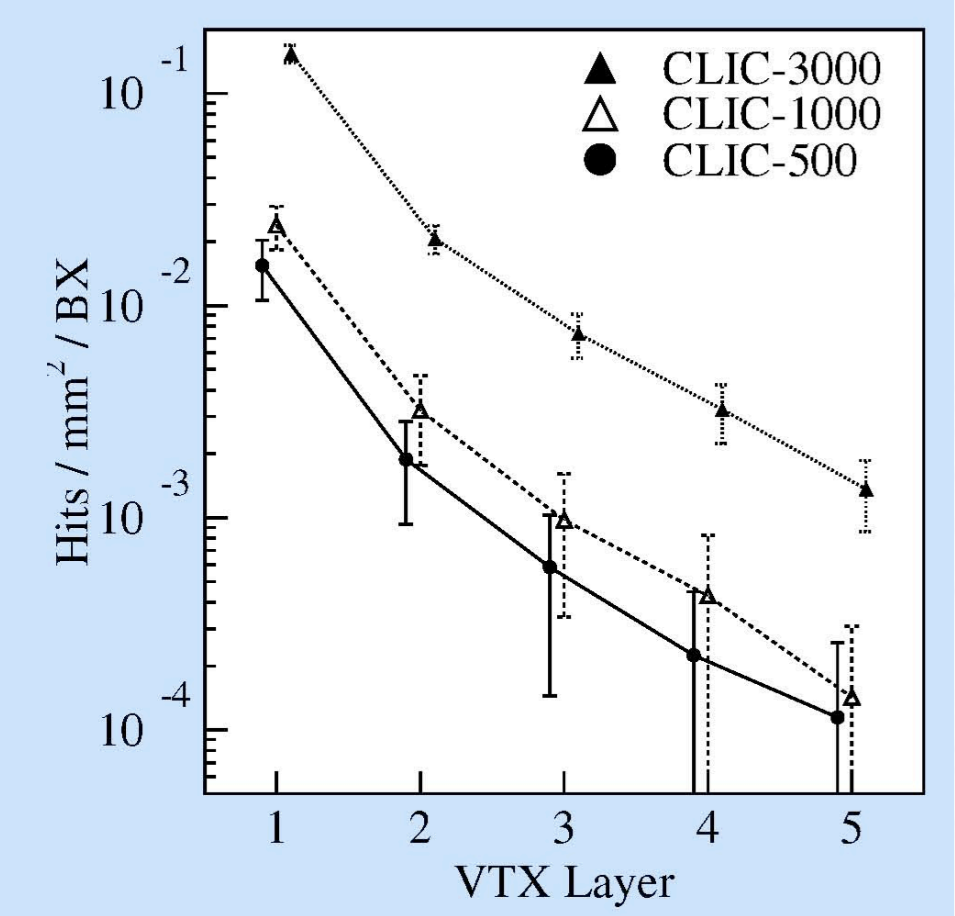
Crossing Angle 20 mrad (ILC 14 mrad)

Main CLIC – ILC differences

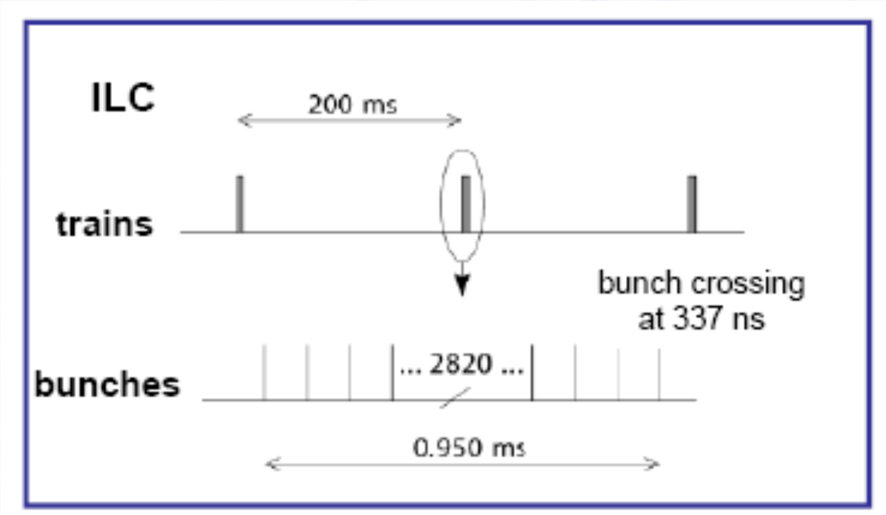
- **Higher energy → more dense particle jets** (independent on machine concept)
  - → need tracker with better double track resolution
    - TPC with good double hit resolution (GEMs, MicroMegas) reconsidered again as CLIC main tracker as alternative to full Si tracker but too much occupancy for a TPC@CLIC
  - → need calorimeters with larger thickness and higher granularity
    - Particle Flow concept requires to identify individual calorimeter EM and hadronic clusters
    - alternatively: forget particle flow, build calorimeter with (hardware) compensation = DREAM concept
- **Much shorter bunch spacing: 0.5 ns (CLIC) vs 337 ns (ILC)**
  - → need "time-stamping": identification of tracks from individual bunch crossings
    - if no time-stamping → overlay of physics events with hadronic background from beamstrahlung
  - → general time structure also has consequences for pulsed electronics
- **Smaller beam sizes + higher E → more (severe) background**
  - → need to move innermost layers further out

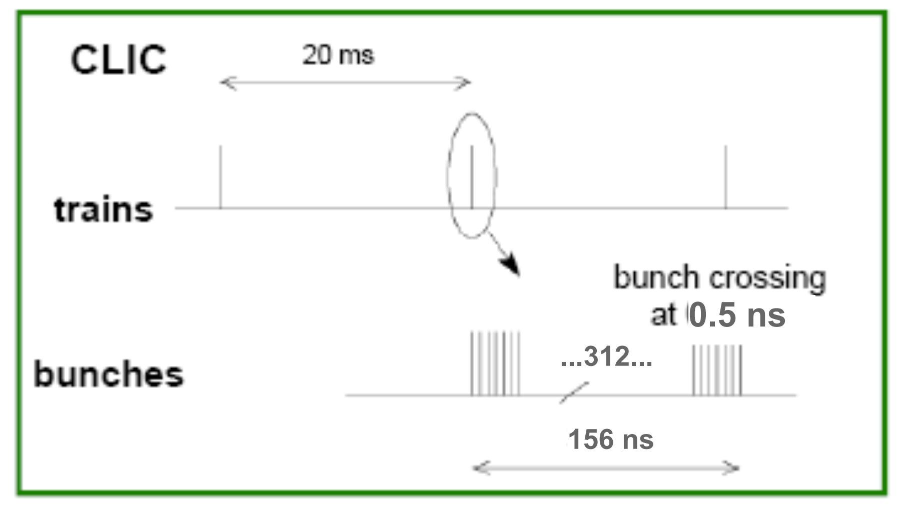
Extrapolation ILC → CLIC

- **Full LDC detector simulation at 3 TeV**
  - simulation of e^+e^- pairs from beamstrahlung
- **Conditions**
  - ILC: 100 BX used (1/20 bunch train)
  - CLIC: 312 BX used (full bunch train)
- **Conclusions (compared to ILC)**
  - CLIC VTX
    - O(10) times more background
  - CLIC TPC
    - O(30) times more background



CLIC Time Structure

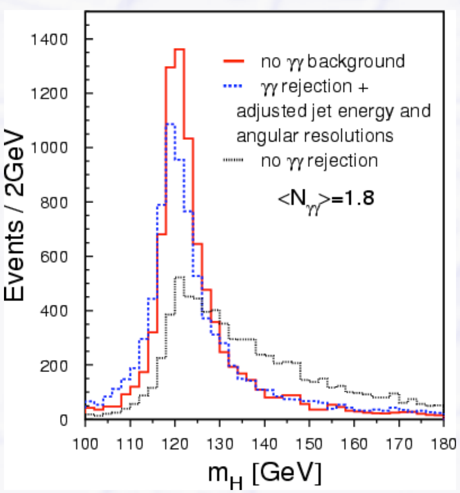




- **Bunch Spacing**
  - **ILC: 337 ns, enough time to identify events from individual BX**
  - **CLIC: 0.5 ns, extremely difficult to identify events from individual BX**
    - **need short shaping time of pulses**
    - **power cycling with 50 Hz instead 5 Hz at ILC**
    - **larger power dissipation?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

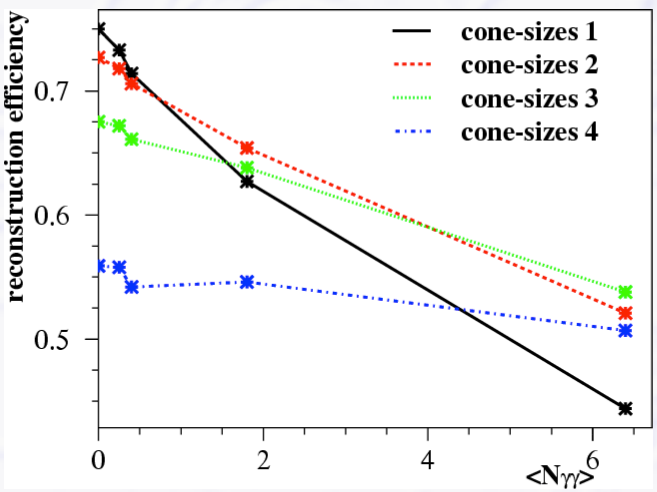
Why Time Stamping?

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



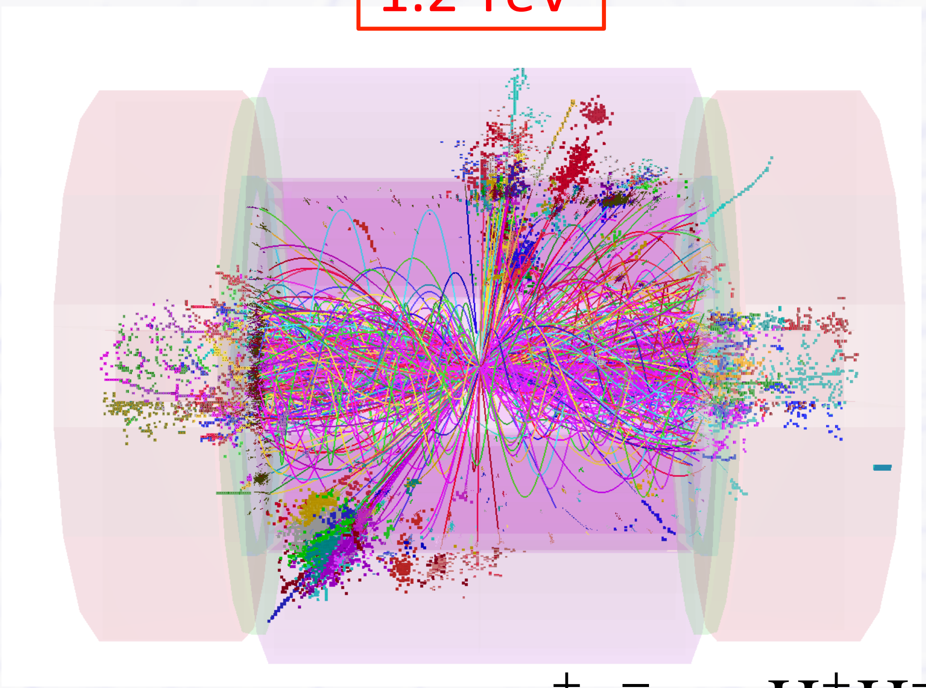
Higgs mass reconstruction from $HZ \rightarrow b\bar{b}q\bar{q}$

reconstruction of $H \rightarrow \tau^+\tau^-$

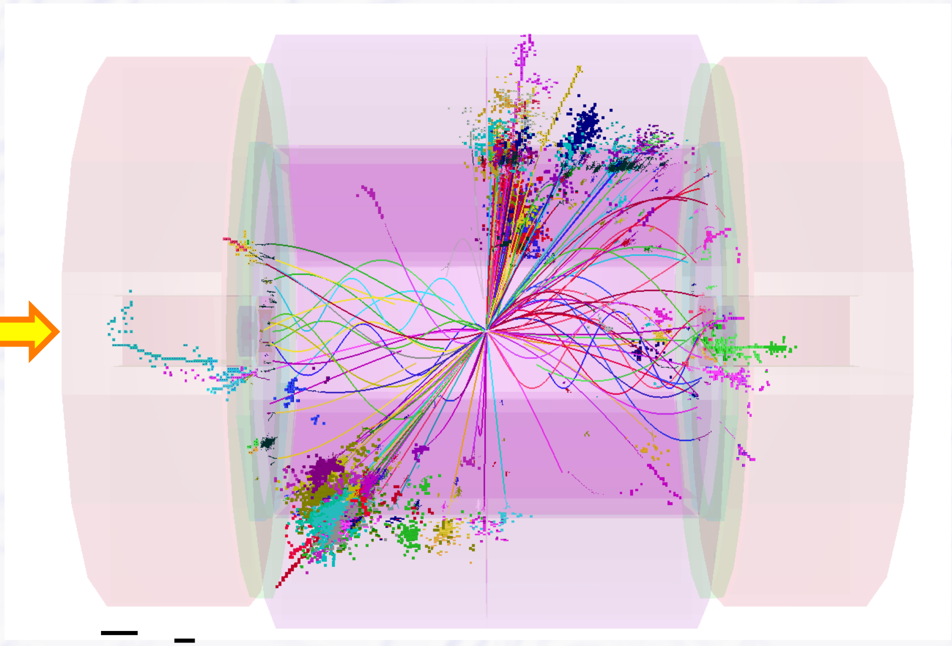


CLIC Combined p_T and Timing Cuts

1.2 TeV



100 GeV



$$e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}b\bar{t} \rightarrow 8 \text{ jets}$$

1.2 TeV background in reconstruction time window

100 GeV background after tight cuts

Summary

- **LHC detector concepts rather complementary**
  - main challenges: radiation damage, high occupancy (40 MHz BX rate)
  - ATLAS: focus on large muon spectrometer, sampling LAr calorimeter
  - CMS: large silicon tracker, homogeneous calorimeter
- **ILC detector concepts**
  - both concepts based on particle flow reconstruction
    - "imaging" sampling calorimeters
  - ILD: TPC as main (gaseous) tracker
  - SiD: all silicon tracker
- **CLIC**
  - similar to ILC concepts: CLIC_ILD, CLIC_SiD
    - time stamping required to reduce hadronic background