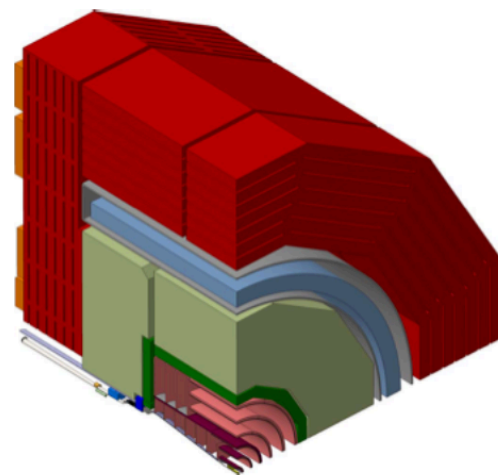
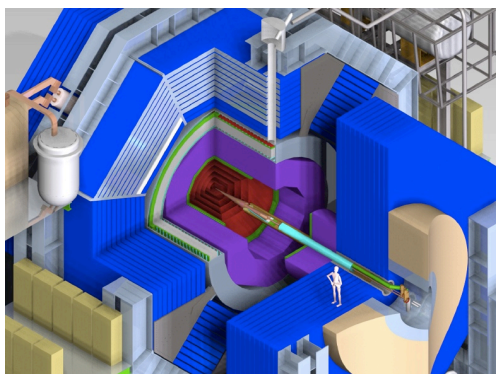
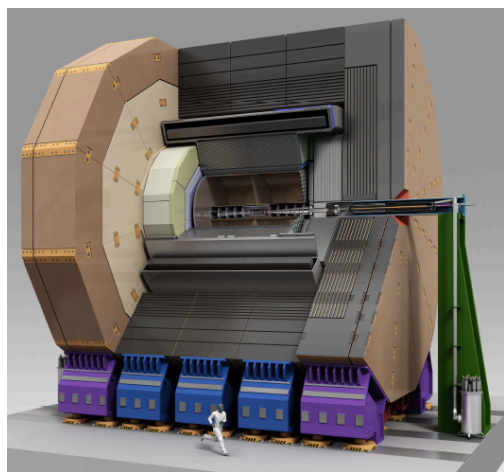
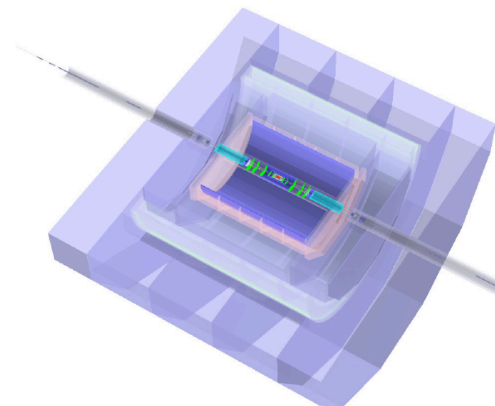
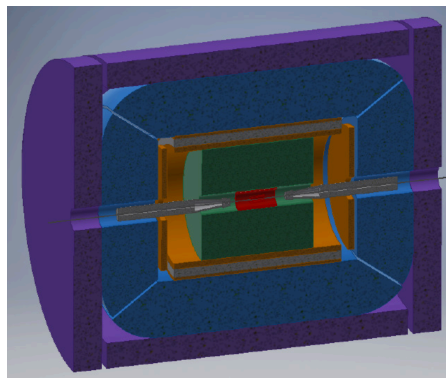
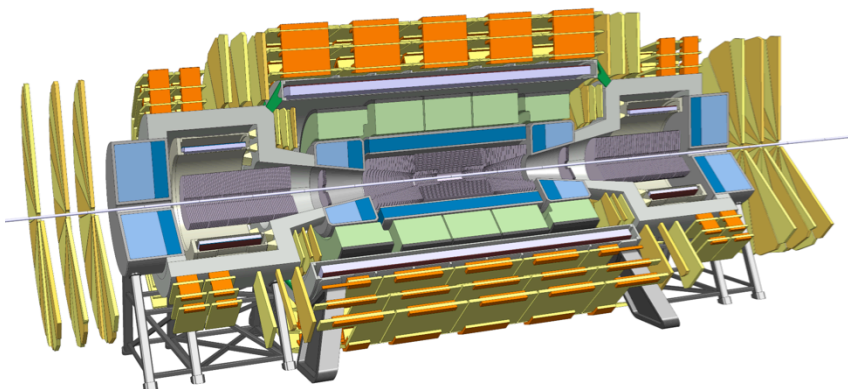


detectors for future collider experiments



Lucie Linssen, CERN

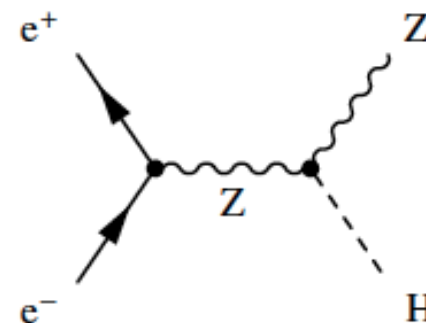
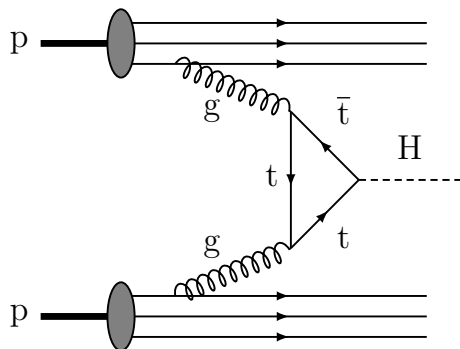
Many thanks for slide material from several persons, in particular Werner Riegler and Eva Sicking

outline

- Intro to high-energy e^+e^- and pp colliders
- Experimental conditions
- Requirements for the detectors
- Detector concepts for future facilities
- Detector technology R&D
- Summary

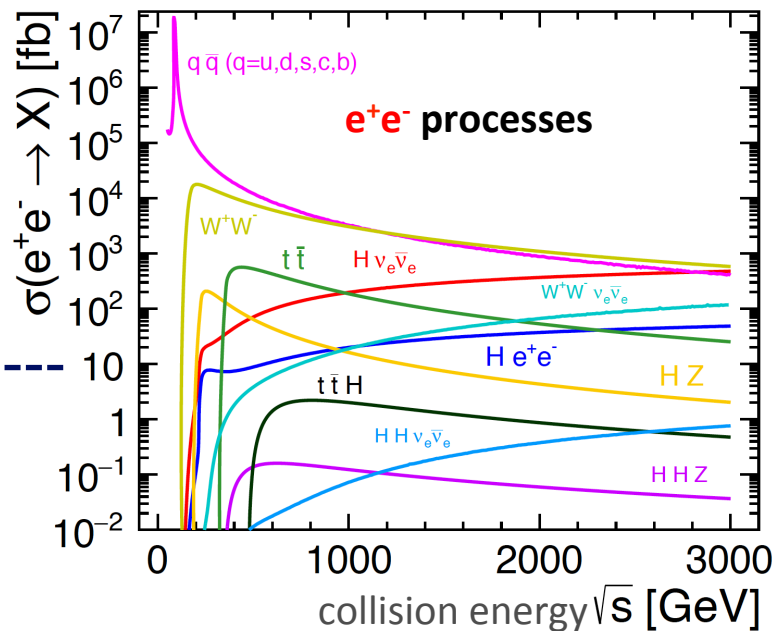
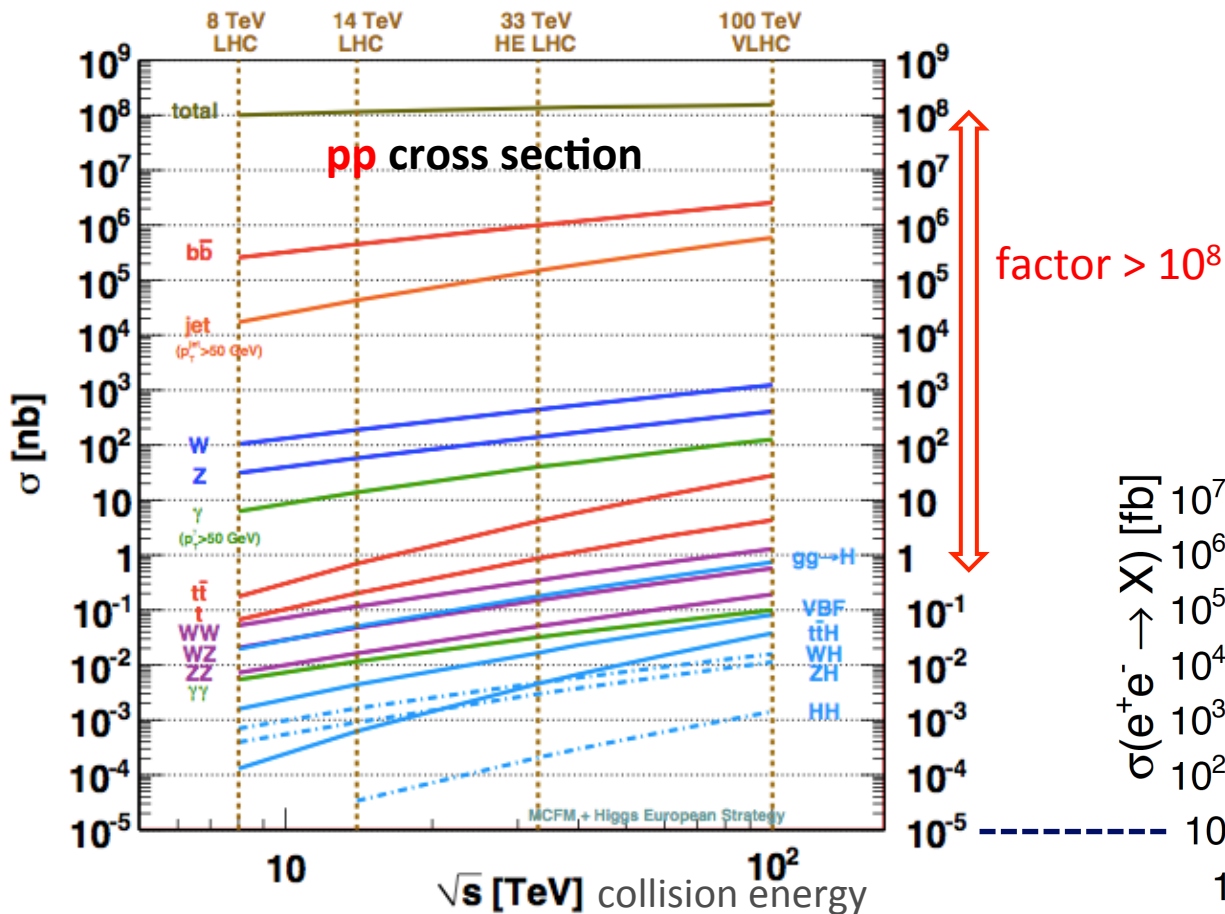
pp collisions / e^+e^- collisions

to tackle the open questions in particle physics



p-p collisions	e^+e^- collisions
Proton is compound object → Initial state unknown → Limits achievable precision	e^+/e^- are point-like → Initial state well defined (Vs / opt: polarisation) → High-precision measurements
High rates of QCD backgrounds → Complex triggering schemes → High levels of radiation	Cleaner experimental environment → Less / no need for triggers → Lower radiation levels
High cross-sections for colored-states	Superior sensitivity for electro-weak states
Very high-energy circular pp colliders feasible	High energies ($>\approx 350$ GeV) require linear collider

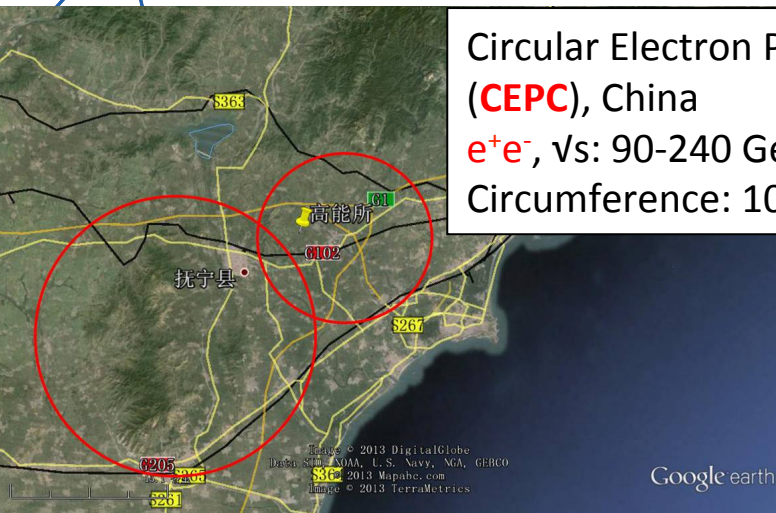
pp collisions / e^+e^- collisions



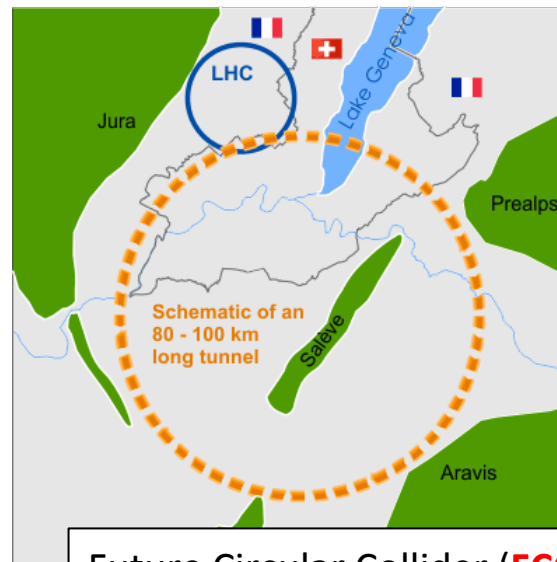
- In pp interesting events need to be found within a huge number of collisions

- e^+e^- events are more “clean”

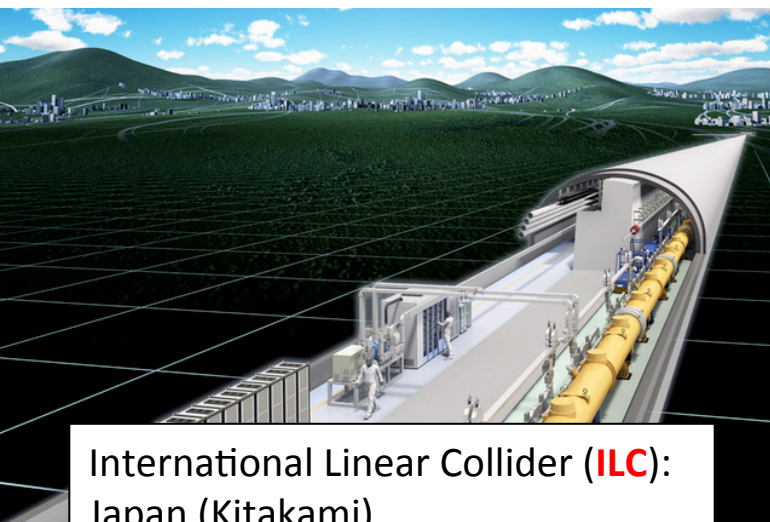
studies of high-energy e^+e^- colliders



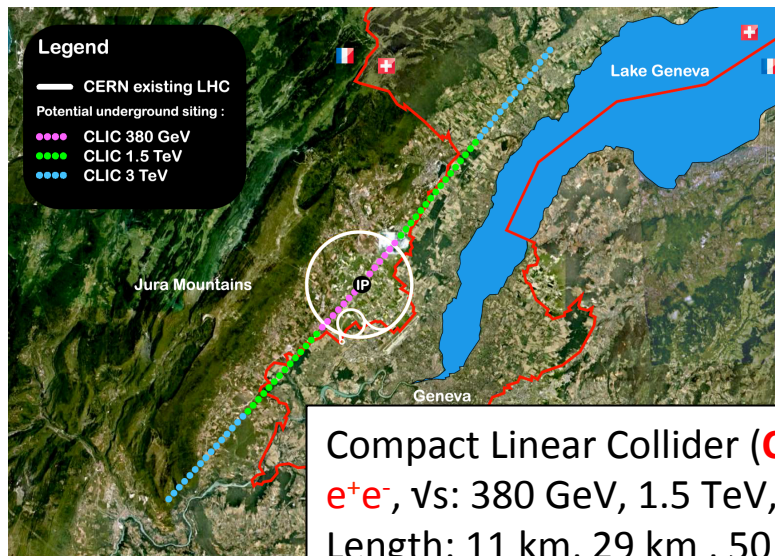
Circular Electron Positron Collider (**CEPC**), China
 e^+e^- , $\sqrt{s}$: 90-240 GeV; SPPC pp,
 Circumference: 100 km



Future Circular Collider (**FCC-ee**): CERN
 e^+e^- , $\sqrt{s}$: 90 - 350 GeV; FCC-hh pp
 Circumference: 97.75 km

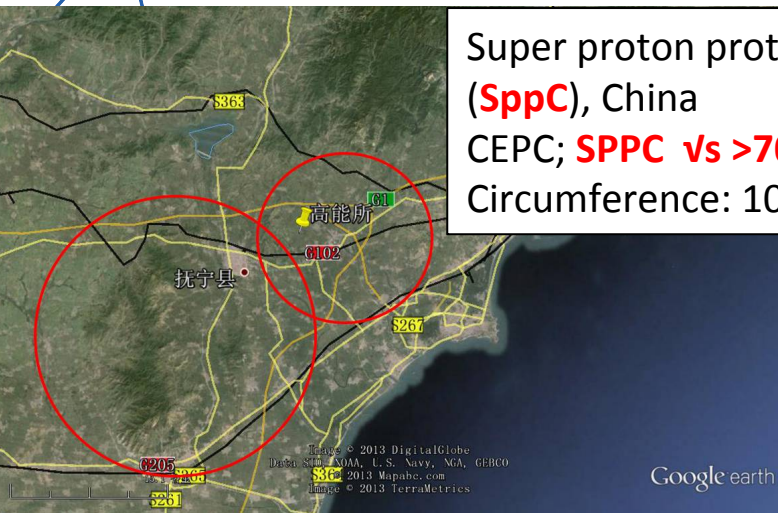


International Linear Collider (**ILC**):
 Japan (Kitakami)
 e^+e^- , $\sqrt{s}$: 250 – 500 GeV (1 TeV)
 Length: 17 km, 31 km (50 km)

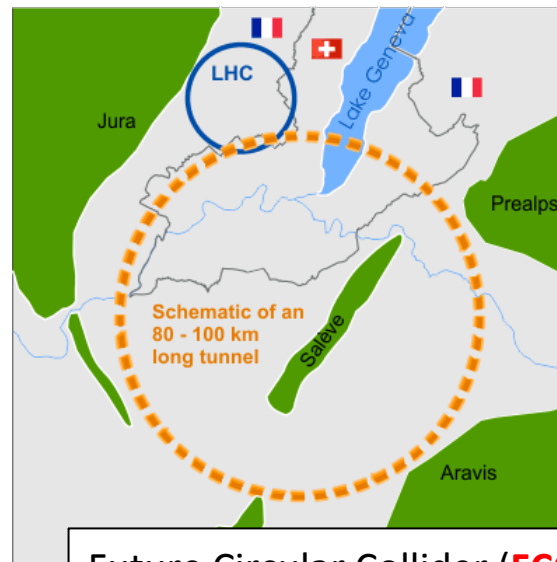


Compact Linear Collider (**CLIC**): CERN
 e^+e^- , $\sqrt{s}$: 380 GeV, 1.5 TeV, 3 TeV
 Length: 11 km, 29 km, 50 km

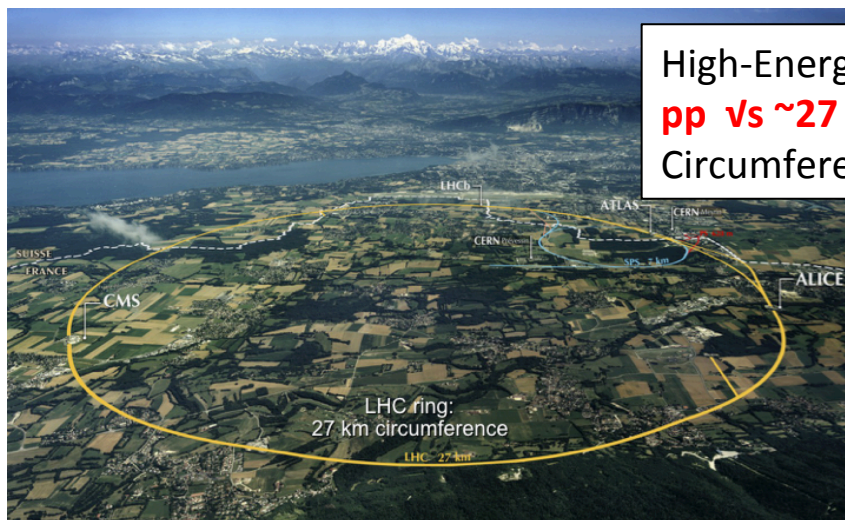
studies of high-energy **pp** colliders



Super proton proton Collider (**SppC**), China
CEPC; **SPPC vs >70 TeV**
Circumference: 100 km



Future Circular Collider (**FCC-hh**): CERN
FCC-ee; **FCC-hh vs ~100 TeV**
Circumference: 97.75 km



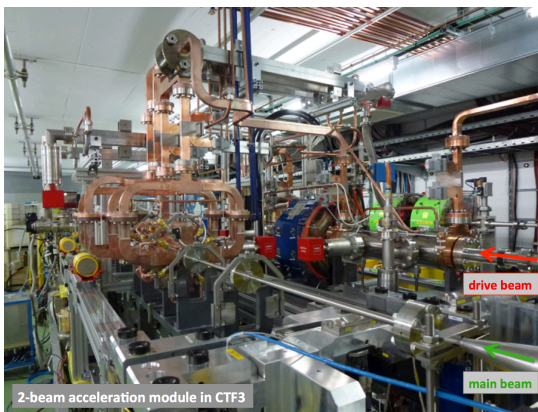
High-Energy LHC (**HE-LHC**): CERN
pp vs ~27 TeV
Circumference: 27 km

status of the projects

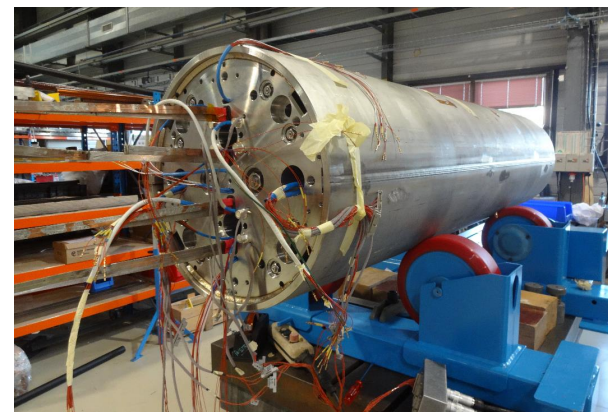
Facility	Status
ILC	- TDR/DBD in 2013 - European XFEL in operation using similar accelerator technology
CLIC	- CDR in 2012 - Staging baseline document in 2016 - Project Implementation Plan foreseen for 2018
CEPC-SppC	- Pre-CDR in 2015 - CDR planned for 2017
FCC-ee, FCC-hh, HE-LHC	CDR planned for 2018
HE-LHC	- Existing LHC tunnel - Prospect to use FCC-hh magnet technology



XFEL in operation since Dec 2016



CLIC 2-beam acceleration, 100 MV/m

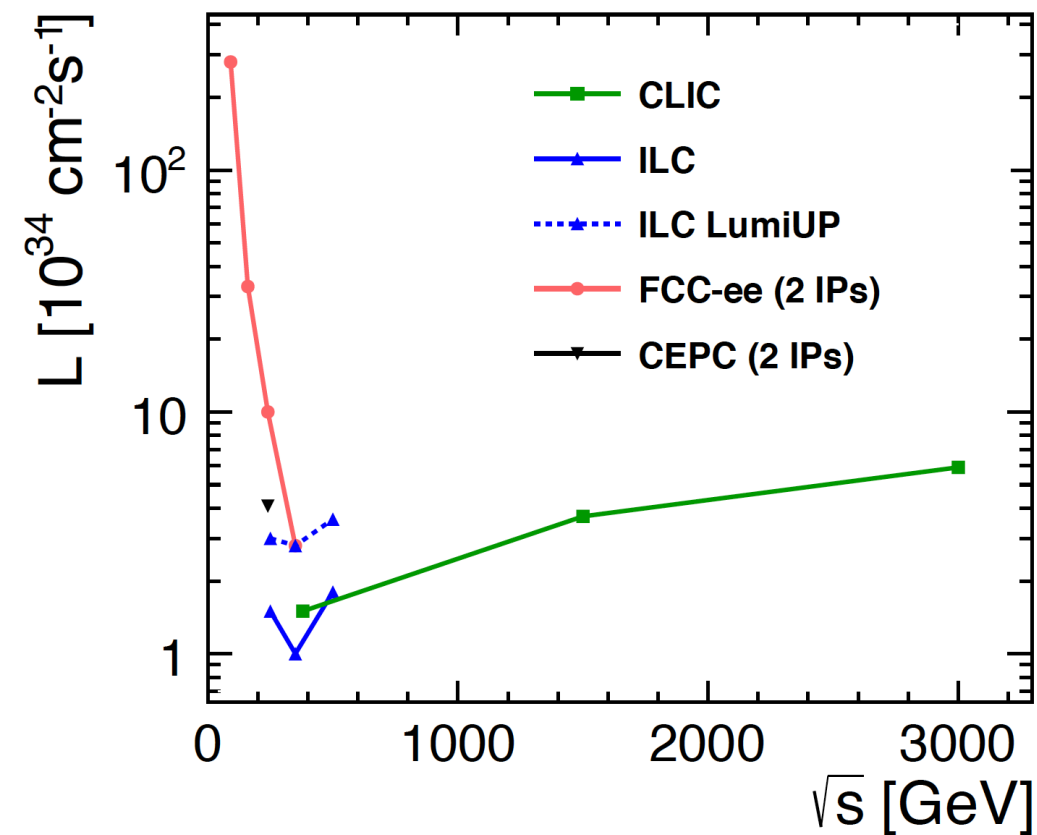


11 T superconducting dipole prototype

future high-energy e^+e^- colliders

and their experimental conditions

luminosity performance e^+e^- colliders



Linear colliders:

- Can reach much higher energies
- Luminosity rises with energy
- Beam polarisation at all energies

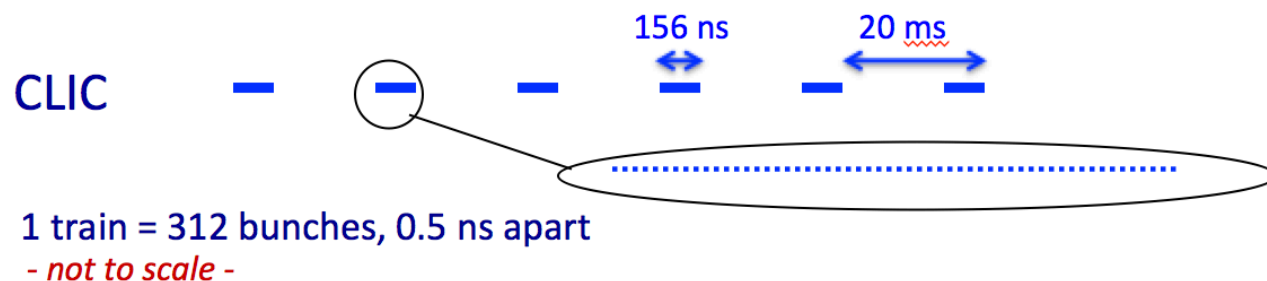
Circular colliders:

- Huge luminosity at lower energies
- Luminosity decreases with energy

Note: Peak luminosity at LEP2 (209 GeV) was $\sim 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

linear e^+e^- accelerator parameters

Parameter	ILC		CLIC		
	250 GeV (next stage)	500 GeV	380 GeV	1.5 TeV	3 TeV
Luminosity $\mathcal{L}$ ($10^{34}\text{cm}^{-2}\text{sec}^{-1}$)	1.5	1.8	1.5	3.7	5.9
$\mathcal{L}$ above 99% of $\sqrt{s}$ ($10^{34}\text{cm}^{-2}\text{sec}^{-1}$)	1.3	1.0	0.9	1.4	2.0
Accelerator gradient (MV/m)	31.5	31.5	72	72/100	72/100
Site length (km)	~17	31	11.4	29	50
Repetition frequency (Hz)	10	5	50	50	50
Bunch separation (ns)	554	554	0.5	0.5	0.5
Number of bunches per train	1312	1312	352	312	312
Beam size at IP σ_x/σ_y (nm)	729/7.7	474/5.9	150/2.9	~60/1.5	~40/1
Beam size at IP σ_z (μm)	300	300	70	44	44



FCC-ee parameters:

parameter	Z	W	H (ZH)	ttbar
$\sqrt{s}$ [GeV]	91	160	240	350
Beam current [mA]	1400	147	29	6.4
Number of bunches	71000	7500	740	62
Bunch intensity [10^{11}]	0.4	0.4	0.8	2.1
Bunch spacing [ns]	2.5 / 5.0	40	400	5000
SR energy loss / turn [GeV]	0.036	0.34	1.71	7.72
Total RF voltage [GV]	0.25	0.8	3.0	9.5
Long. damping time [turns]	1280	235	70	23
Bunch length with SR & BS [mm]	4.1	2.3	2.2	2.9
Luminosity / IP [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	130	16	5	1.4

Note on CEPC:

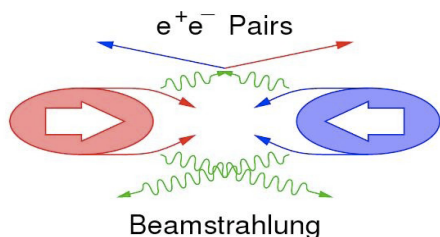
- pre-CDR 2015, 54 km ring
- CDR expected in 2017, 100 km ring → parameters @ H (HZ), W, Z under study *(see next slide)*

Parameters of CEPC Double ring

	<i>Higgs</i>	<i>W</i>	<i>Z</i>
Number of IPs	2	2	2
Energy (GeV)	120	80	45.5
SR loss/turn (GeV)	1.67	0.33	0.034
Half crossing angle (mrad)	16.5	16.5	16.5
Piwinski angle	3.19	5.69	4.29
N_e/bunch (10^{11})	0.968	0.365	0.455
Bunch number	412	5534	21300
Beam current (mA)	19.2	97.1	465.8
SR power /beam (MW)	32	32	16.1
Bending radius (km)	11	11	11
Momentum compaction (10^{-5})	1.14	1.14	4.49
β_{IP} x/y (m)	0.171/0.002	0.171 /0.002	0.16/0.002
Emittance x/y (nm)	1.31/0.004	0.57/0.0017	1.48/0.0078
Transverse σ_{IP} (um)	15.0/0.089	9.9/0.059	15.4/0.125
$\xi_x/\xi_y/\text{IP}$	0.013/0.083	0.0055/0.062	0.008/0.054
RF Phase (degree)	128	126.9	165.3
V_{RF} (GV)	2.1	0.41	0.14
f_{RF} (MHz) (harmonic)	650	650 (217800)	650 (217800)
Nature σ_z (mm)	2.72	3.37	3.97
Total σ_z (mm)	2.9	3.4	4.0
HOM power/cavity (kw)	0.41(2cell)	0.36(2cell)	1.99(2cell)
Energy spread (%)	0.098	0.065	0.037
Energy acceptance (%)	1.5		
Energy acceptance by RF (%)	2.1	1.1	1.1
n_y	0.26	0.15	0.12
Life time due to beamstrahlung (min)	52		
F (hour glass)	0.96	0.98	0.96
L_{max}/IP ($10^{34}\text{cm}^{-2}\text{s}^{-1}$)	2.0	5.15	11.9

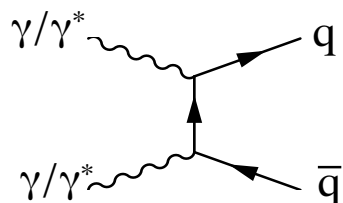
e^+e^- beam-induced background

Linear colliders: very small beam sizes needed to achieve high luminosities
e.g. CLIC bunch sizes at 3 TeV $\sigma_{x,y,z} = \{40 \text{ nm}, 1 \text{ nm}, 44 \mu\text{m}\} \Rightarrow$ **beamstrahlung**



Main backgrounds ($p_T > 20 \text{ MeV}$, $\theta > 7.3^\circ$):

- **Incoherent e^+e^- pairs**
 - 19k particles per bunch train at 3 TeV
 - High occupancies
 $\Rightarrow$ **Impact on detector granularity**
- **$\gamma\gamma \Rightarrow$ hadrons**
 - 17k particles per bunch train at 3 TeV
 - Main background in calorimeters and trackers
 $\Rightarrow$ **Impact on detector granularity and physics**



*At ILC or at lower CLIC energies, beamstrahlung effect is less strong
 $\Rightarrow$ nevertheless a driver for the detector design*

Circular colliders: **beamstrahlung** (less pronounced) + **synchrotron radiation**

Background levels and impact on the detector depend on the v s and on the bunch separation $\Rightarrow$ *studies still ongoing*

calorimetry and PFA

Jet energy resolution + background suppression for optimal detector design

=> => fine-grained calorimetry + Particle Flow Analysis (PFA)

What is PFA?

Typical jet composition:
60% charged particles
30% photons
10% neutral hadrons



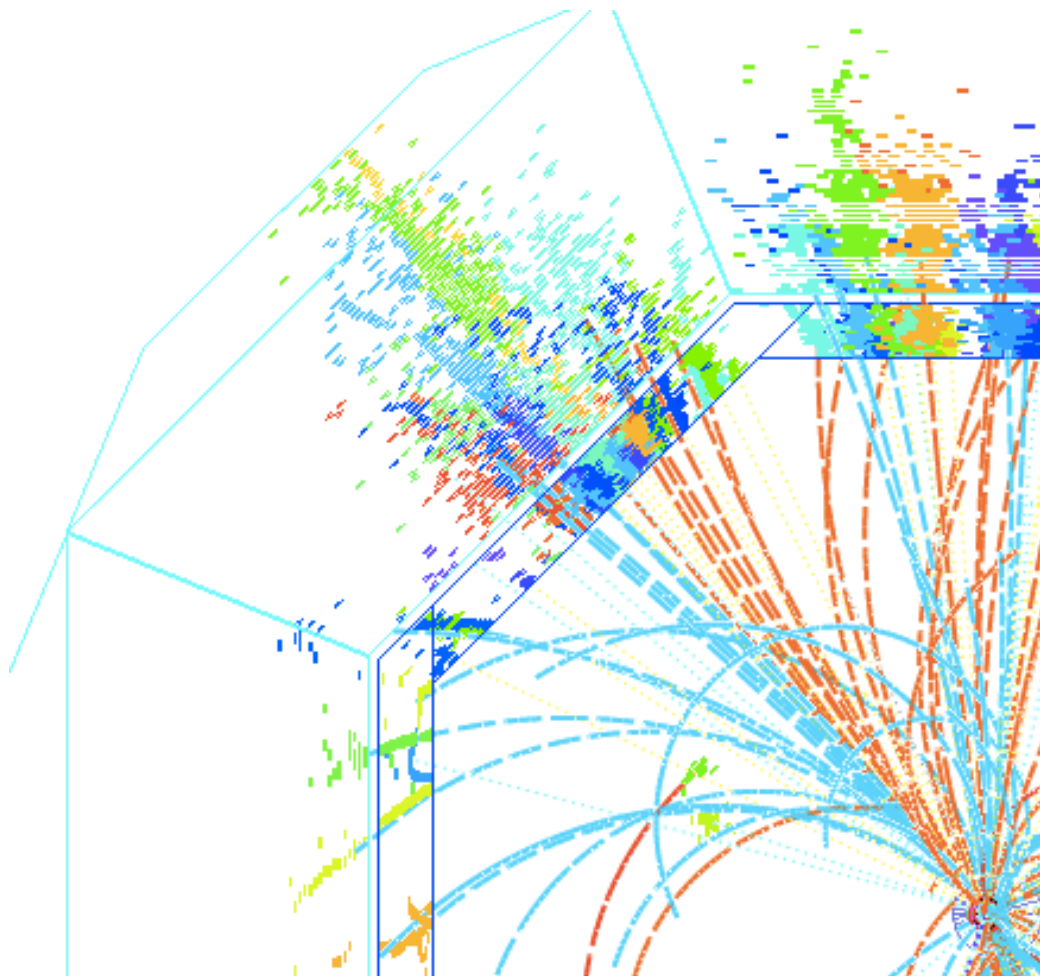
Always use the best info you have:

60% => tracker 😊 😊

30% => ECAL 😊

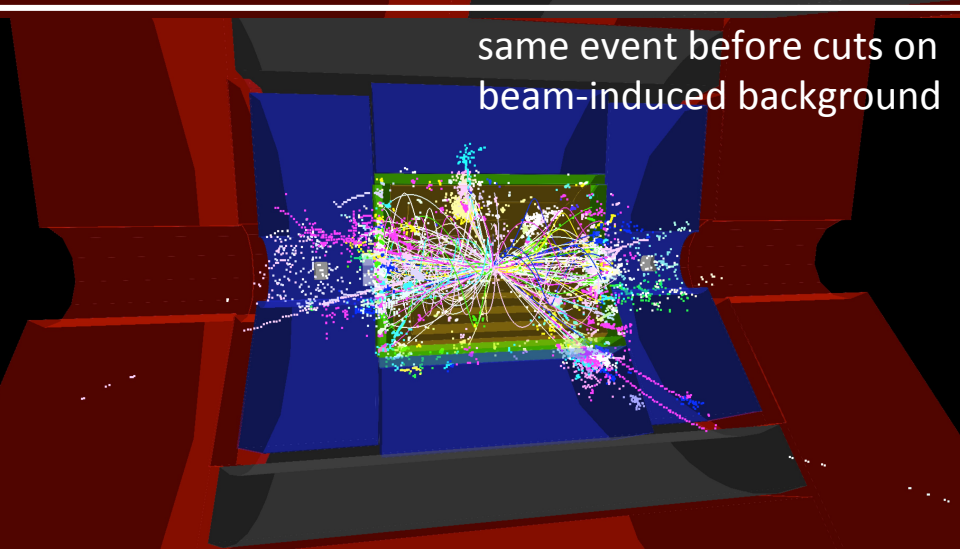
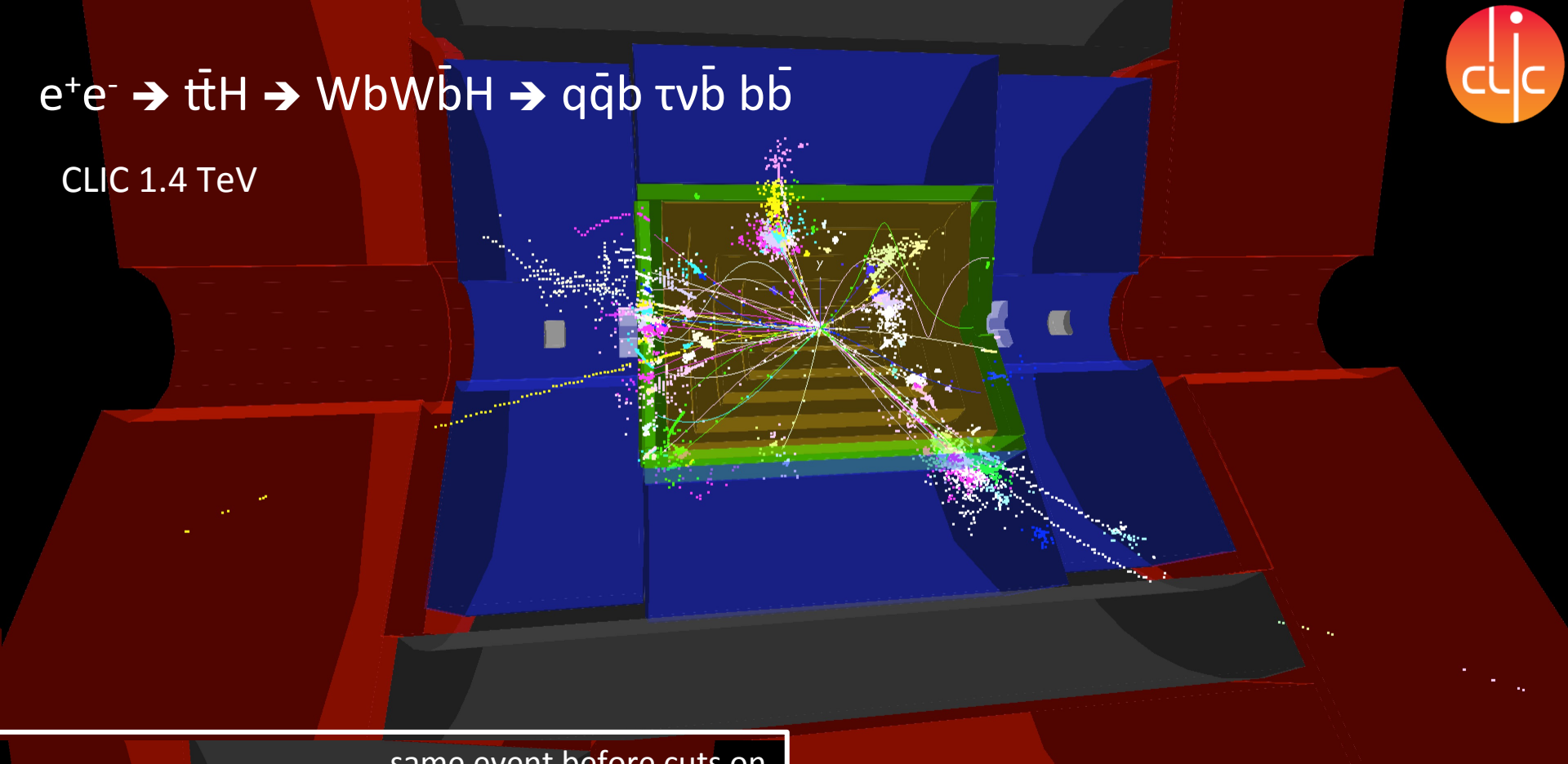
10% => HCAL 😞

Hardware + software !



$e^+e^- \rightarrow t\bar{t}H \rightarrow WbW\bar{b}H \rightarrow q\bar{q}b\tau\nu\bar{b}b\bar{b}$

CLIC 1.4 TeV



same event before cuts on
beam-induced background

Highly granular calorimetry + precise hit timing



Very effective in suppressing backgrounds
for fully reconstructed particles



General trend for e^+e^- and pp options
(e.g. CMS endcap calorimetry for HL-LHC)

experimental conditions e^+e^-

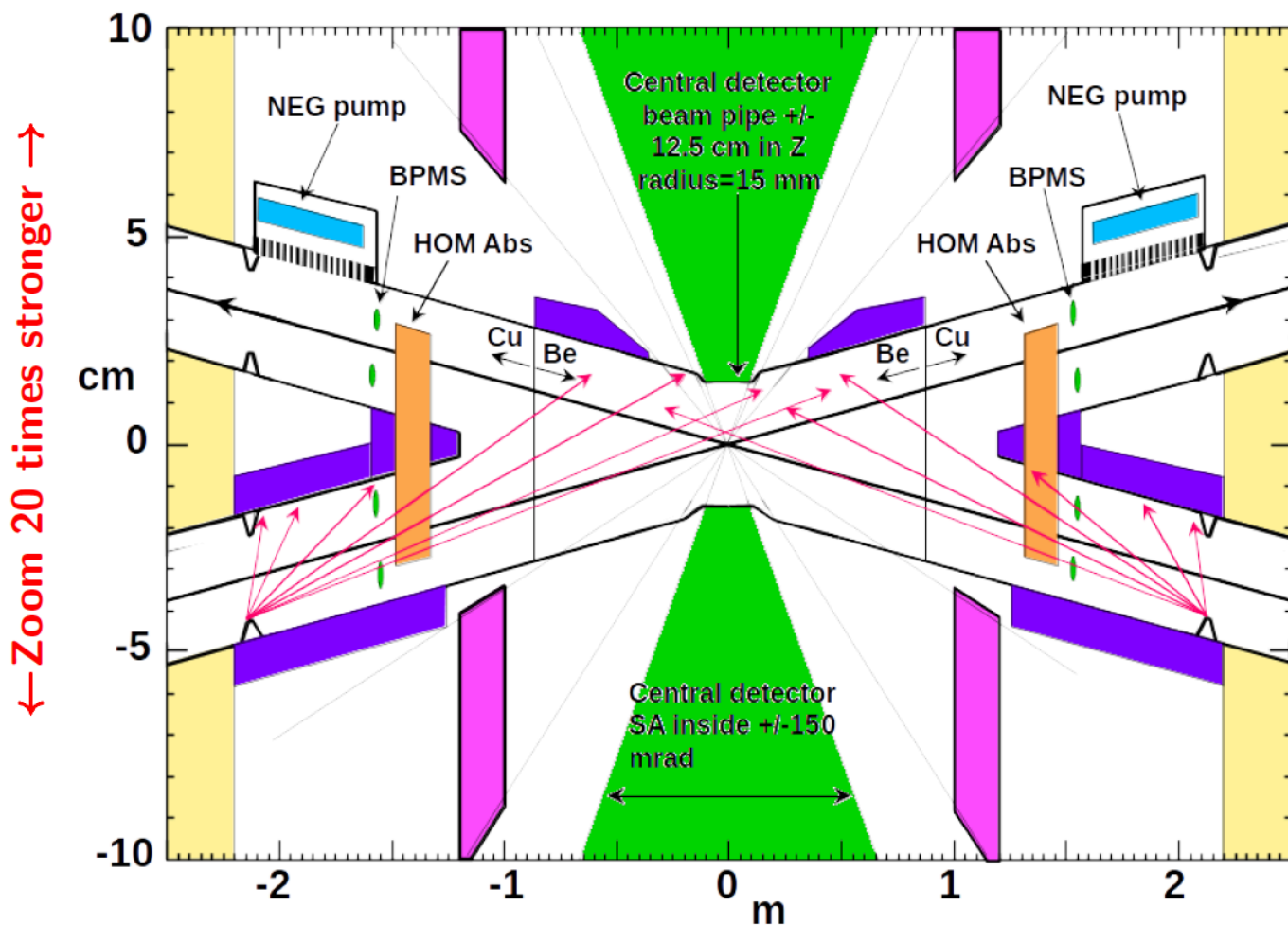
Linear Colliders

- **Beam-induced background:**
 - $\Rightarrow$ vertex inner radius ~ 15 mm (ILC), 31 mm (CLIC 3 TeV)
 - Small granularity (e.g. pixel size 25×25 μm in vertex detector), PFA
 - Hit timing required at CLIC (~ 10 ns in vertex/tracker, ~ 1 ns on calo hits)
- Beam crossing angle 14 mrad (ILC), 20 mrad (CLIC)
- Due to **low duty cycle** $\Rightarrow$ power pulsing of electronics possible
 - $\Rightarrow$ low mass in vertex/tracker, better compactness in calorimeters

Circular Colliders

- **Beam-induced background** $\Rightarrow$ *see next slide for impact on layout*
- **Circulating beams**
 - Beam crossing angle 30 mrad
 - Maximum detector solenoid field of 2 T $\Rightarrow$ need to increase tracker radius
 - Complex magnet shielding schemes
 - Beam focusing quadrupole closer to IP (~ 2 m)
 - $\Rightarrow$ limits detector acceptance $\Rightarrow$ starts at 150 mrad from beam
- **High luminosity and many bunches at Z pole**
 - $\Rightarrow$ requires triggering schemes and information on hit time

Circular e^+e^- collider => interaction point



FCC-ee

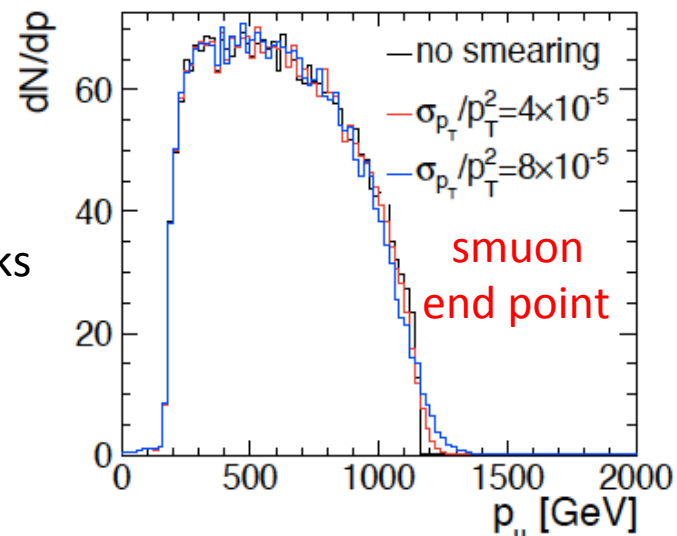
Central detector
Luminometer
QD0
HOM absorber
Pumps
SR shielding

e^+e^- detector requirements (from physics)

★ momentum resolution:

e.g. ZH with $Z \rightarrow \mu\mu$, Smuon endpoint

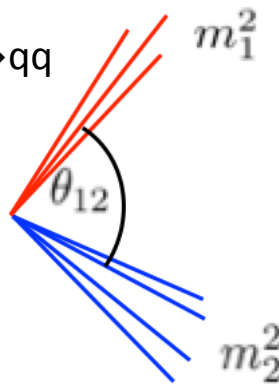
$$\sigma_{p_T} / p_T^2 \sim 2 \times 10^{-5} \text{ GeV}^{-1} \quad \text{for high } p_T \text{ tracks}$$



★ jet energy resolution:

e.g. W/Z/H di-jet mass separation, ZH with $Z \rightarrow qq$

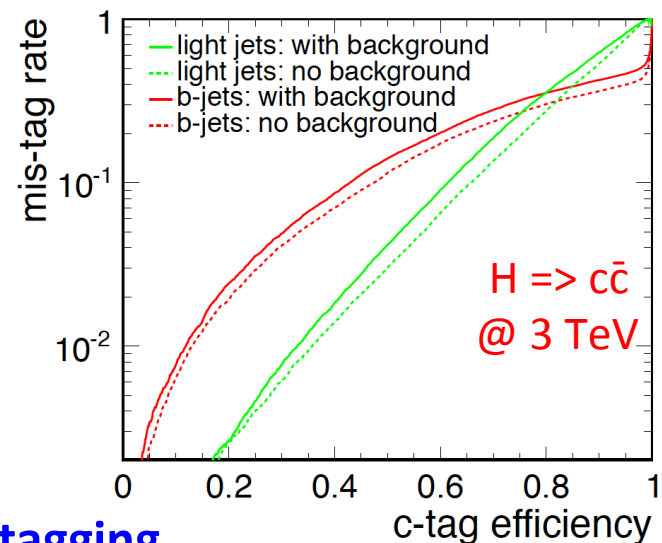
$$\frac{\sigma_E}{E} \sim 3.5 - 5 \% \quad (\text{for high-E jets, light quarks})$$



★ impact parameter resolution:

e.g. c/b-tagging, Higgs BR

$$\sigma_{r\phi} = 5 \oplus 15 / (p[\text{GeV}] \sin^{\frac{3}{2}} \theta) \mu\text{m}$$



★ angular coverage, very forward electron/photon tagging

+ requirements from CLIC experimental conditions

future high-energy pp colliders

and their experimental conditions

FCC-hh, HE-LHC, HL-LHC, LHC parameters

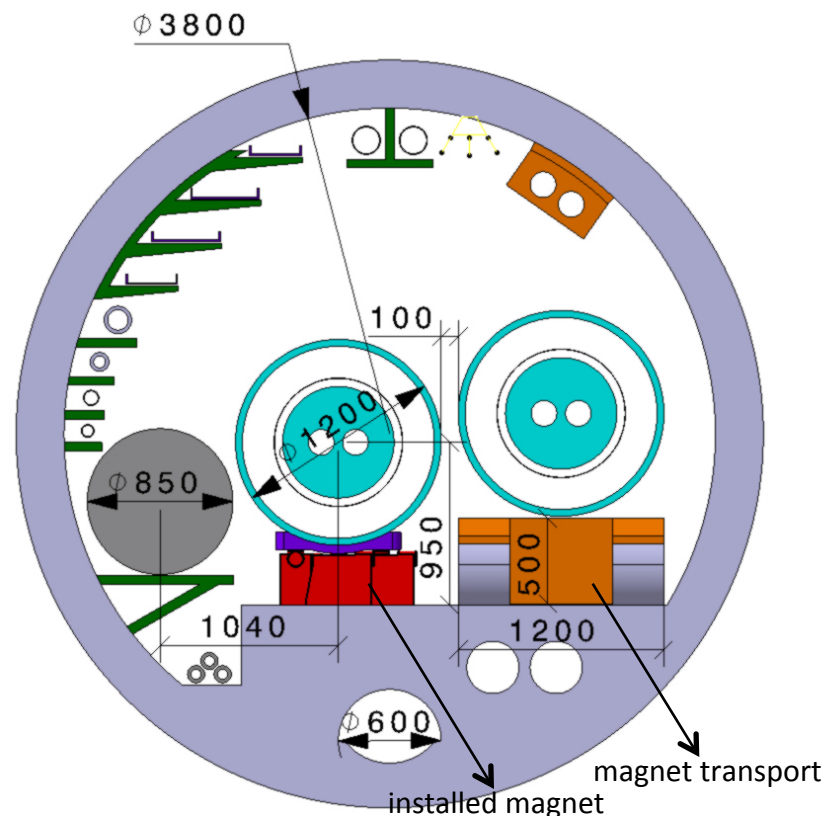
parameter	New tunnel		LHC tunnel		
		FCC-hh	HE-LHC	HL-LHC	LHC
$\sqrt{s}$ [TeV]		100	27	14	14
Dipole field [T]		16	16	8.33	8.33
Circumference [km]		97.75	26.7	26.7	26.7
Beam current [A]		0.5	1.12	1.12	0.58
Bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	2.2	1.15
Bunch spacing [ns]	25	25 (5)	25 (5)	25	25
Synchr. rad. power / ring [kW]		2400	101	7.3	3.6
SR power / length [W/m/ap.]		28.4	4.6	0.33	0.17
Long. emit. damping time [h]		0.54	1.8	12.9	12.9
Peak luminosity [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	5	30	25	5	1
events/bunch crossing	170	~1000 (200)	~800 (160)	135	27

Use the FCC-hh magnet technology for a proton-proton collider in the LHC tunnel

- **$\sqrt{s}=27$ TeV** ($=14$ TeV * 16 T / 8.33 T)
- **Luminosity 4 times higher than HL-LHC** ($1/E^2$)
- Constraint on external diameter of magnet cryostat, 1.2 m, for LHC tunnel compatibility

Key ingredients:

- FCC-hh magnet technology
- FCC-hh vacuum system
- HL-LHC crab waist scheme
- HL-LHC electron lens
- HL-LHC/LIU beam parameters (25 ns bunch structure, 5 ns option)



SppC parameters

Parameter	Unit	Value		
		PreCDR	CDR	Ultimate
Circumference	km	54.4	100	100
C.M. energy	TeV	70.6	75	125-150
Dipole field	T	20	12	20-24
Injection energy	TeV	2.1	2.1	4.2
Number of IPs		2	2	2
Nominal luminosity per IP	cm ⁻² s ⁻¹	1.2e35	1.0e35	-
Circulating beam current	A	1.0	0.7	-
Bunch separation	ns	25	25	-
Bunch population		2.0e11	1.5e11	-
SR power per beam	MW	2.1	1.1	-
SR heat load per aperture @arc	W/m	45	13	-

SppC aims for full iron-based HTS dipole technology (12 T baseline, 20-24 T upgrade)

Table presented at the [FCC week, Berlin](#), May 2017



experimental conditions future **pp** colliders

Experimental conditions for a ~ 75 -100 TeV pp collider have much in common with conditions as we know them from HL-LHC.

Challenge: preserve overall detector performance, despite huge pile up, high energies and high radiation conditions

A few extra remarks:

- Compared to HL-LHC, **radiation levels** increase in proportion to the luminosity
- Particles (e.g. Higgs) have more **forward boost**:
 - $\Rightarrow$ precision tracking needed down $\eta=4$, $\theta=2^\circ$ ($\eta=2.5$, 2.5° at LHC)
 - $\Rightarrow$ calorimetry down to $\eta=6$, $\theta \approx 0.5^\circ$
- Aim for track resolution of 10-15% up to p_T of 10 TeV
 - $\Rightarrow$ central solenoid 4 T with inner radius 5 m, track hit resolution $\sim 10 \mu\text{m}$
 - Forward solenoids are needed to increase angular coverage

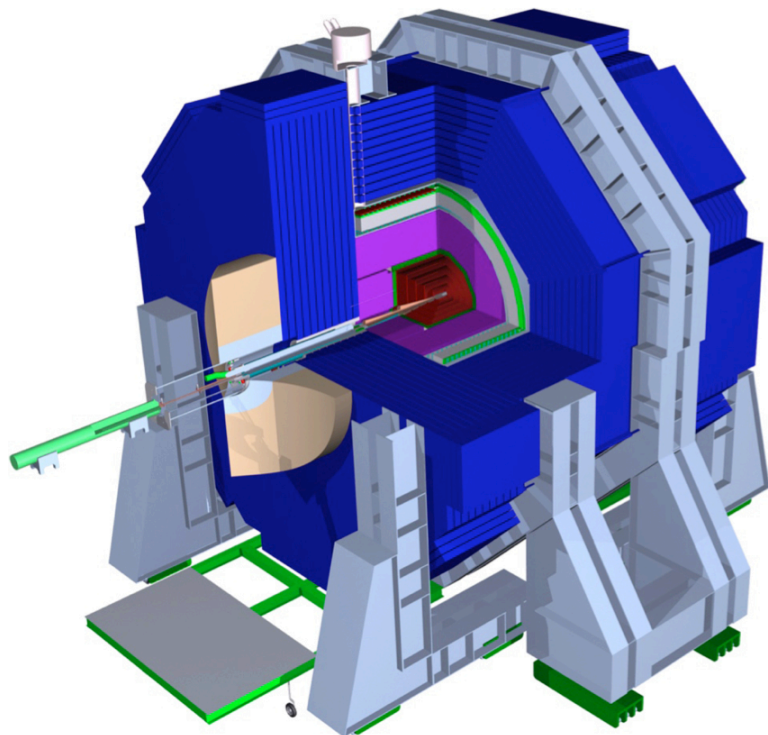
Pile up of 1000 events?

- FCC-hh average distance at $z=0$ between events is $170 \mu\text{m}$, 0.5 ps (1mm, 3 ps at HL-LHC)
- For tracks at $\eta > 1.7$, multiple scattering effect due to 0.8 mm Be beam pipe is larger than average distance between two interaction vertices !
- Fine grained calorimetry required to help resolving pile up
- Excellent time (few ps) resolution required

better ask accelerator
for 5 ns bunch spacing

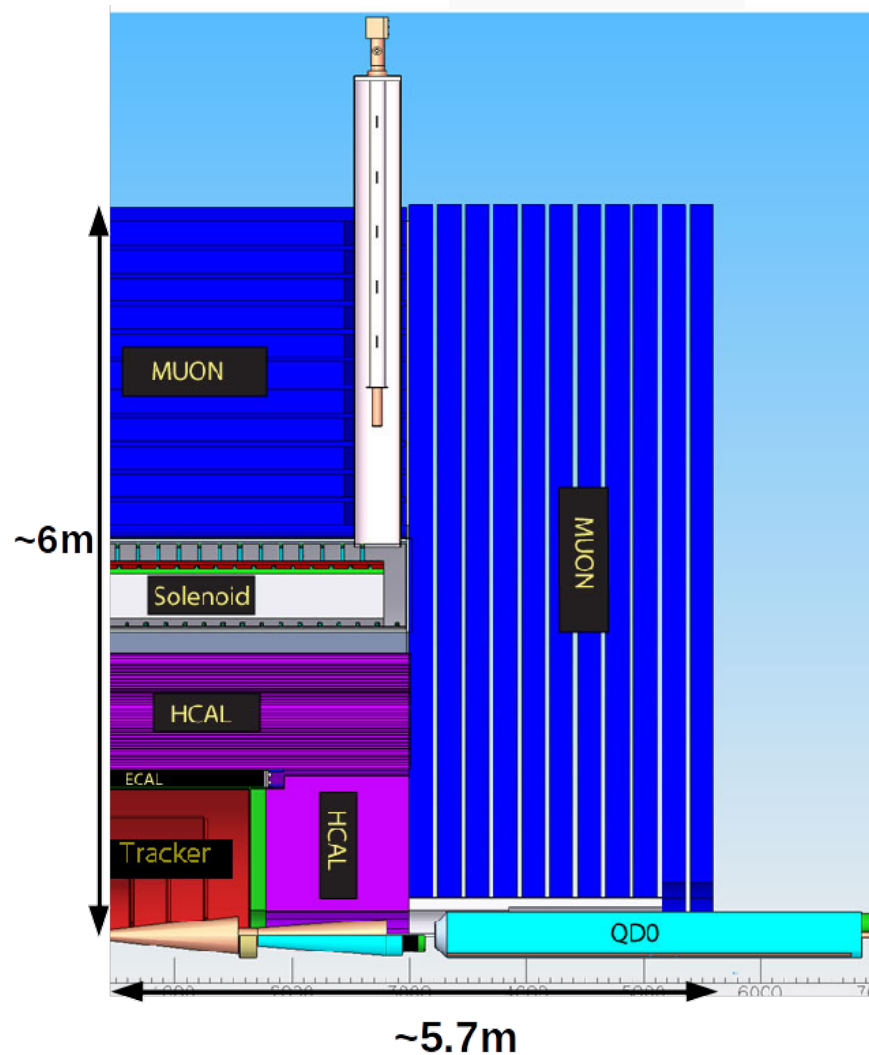
future high-energy e^+e^- colliders

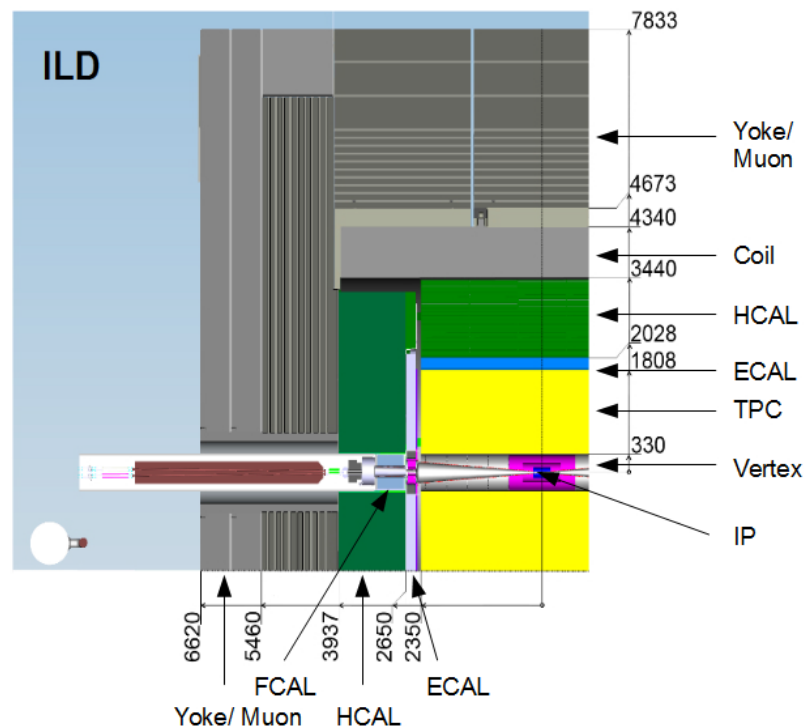
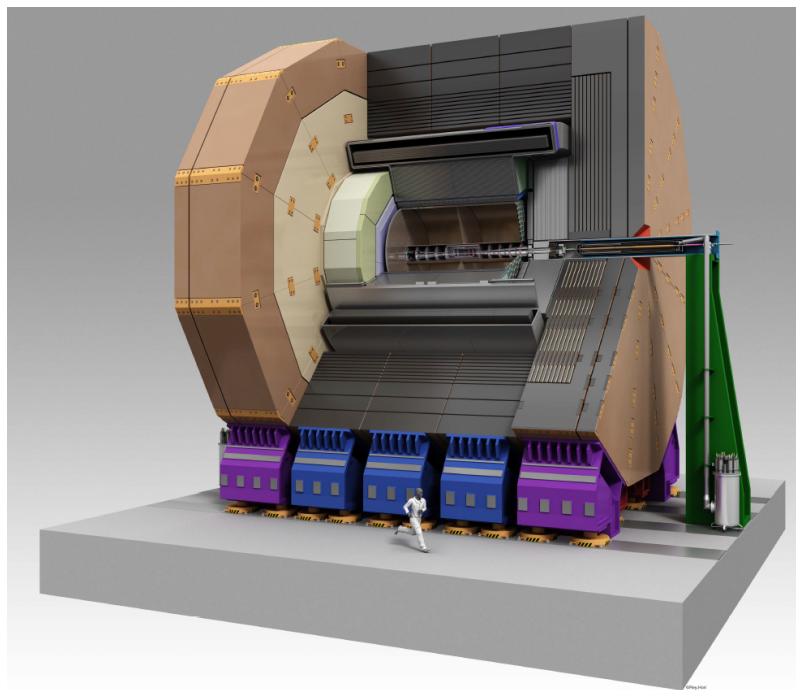
current detector concepts



SiD: "Silicon Detector"

- 5 T solenoid
- All-silicon vertex detector + tracker
- Fine-grained calorimetry (PFA)
- Compact design (1.2m tracker radius)
- Final focus quadrupoles inside the detector



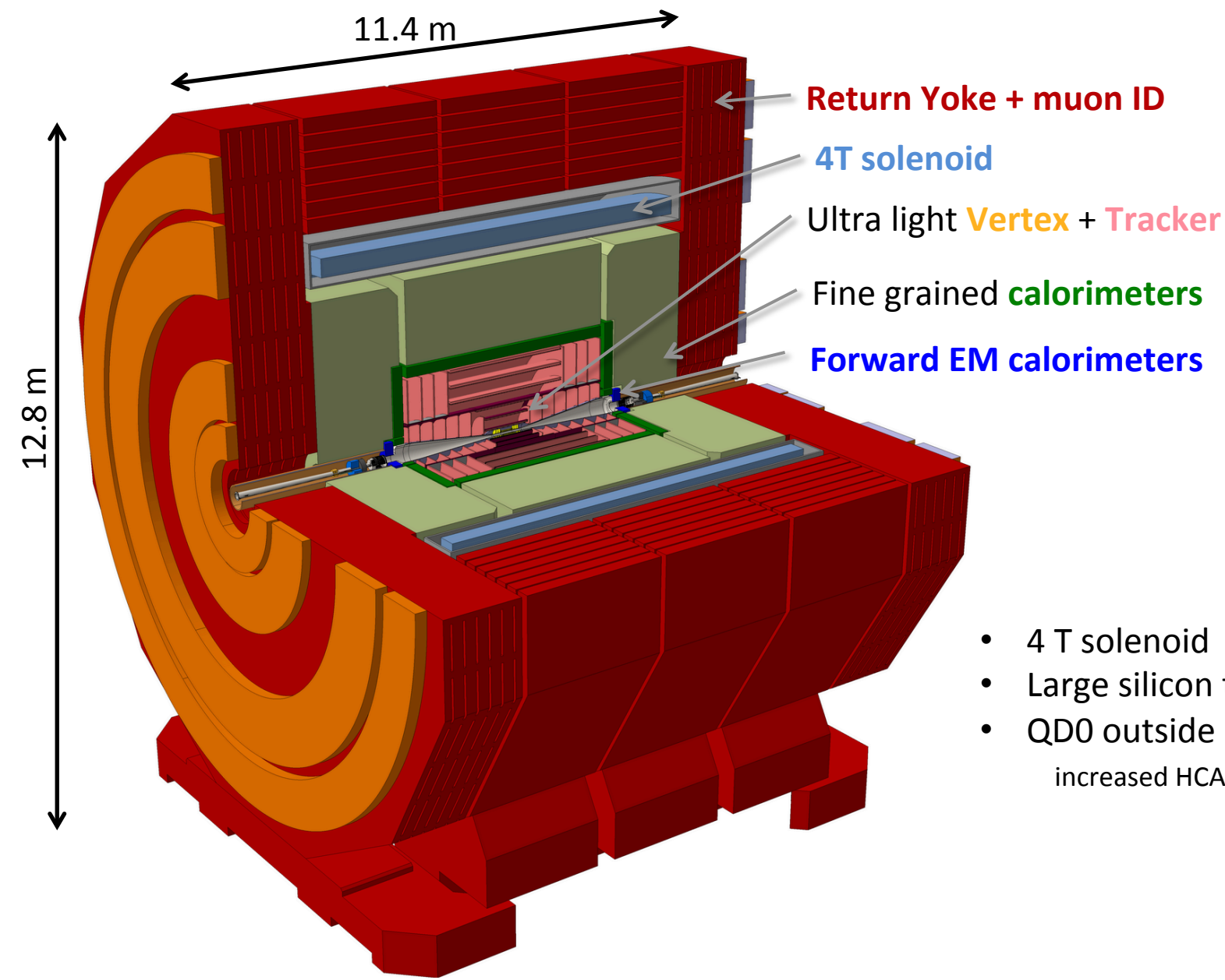


ILD: "International Large Detector"

- Silicon vertex detector
- Time Projection Chamber as tracker
- ... surrounded by Silicon envelope
- Fine-grained calorimetry (PFA)
- Large (L) and small (S) options under study
- Final focus quadrupoles inside the detector

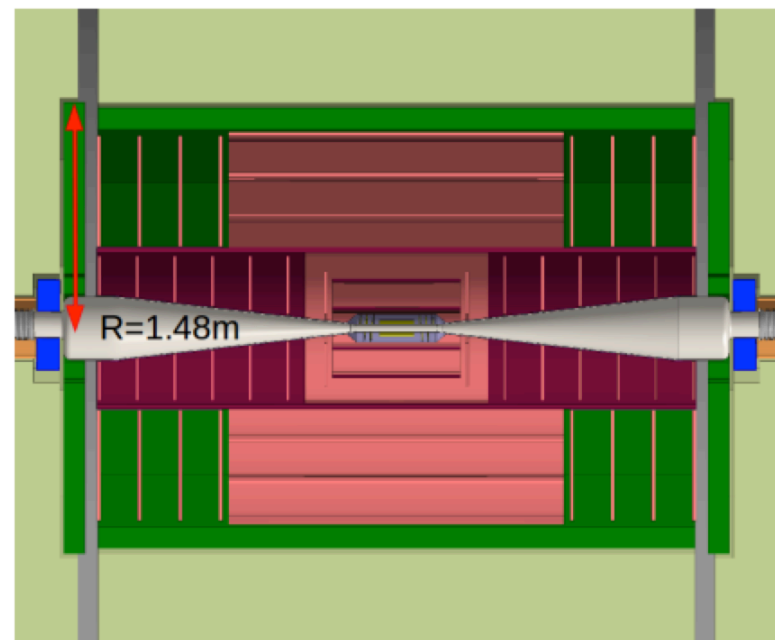
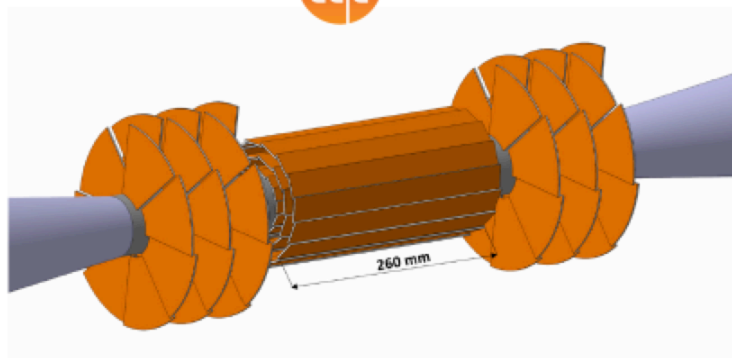
	ILD-L	ILD-S
	(DBD)	
B-field	3.5 T	4 T
TPC outer radius	180 cm	146 cm
Coil inner radius	344 cm	310 cm

“CLICdet” at CLIC



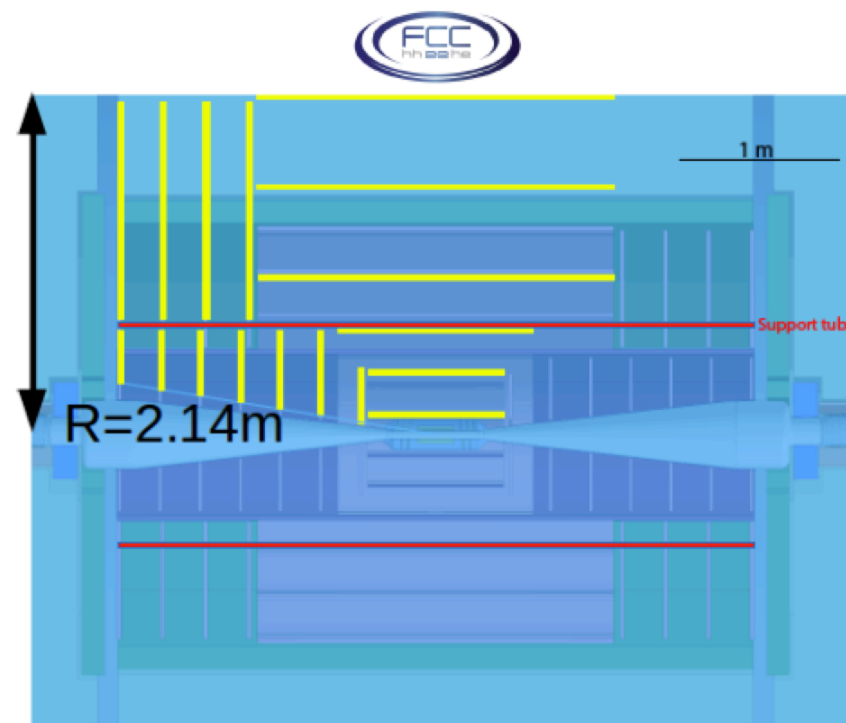
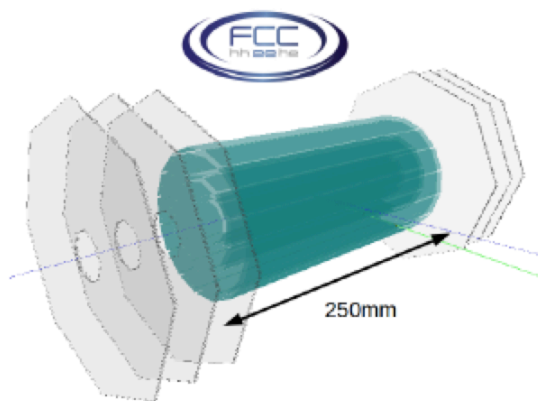
- 4 T solenoid
- Large silicon tracker ($R=1.5\text{m}$)
- QD0 outside detector
increased HCAL forward acceptance

- **CLICdet-inspired** detector concept
 - Complex forward region
 - smaller magnetic field of $B=2\text{ T}$
 - larger tracker radius (keep similar momentum resolution)
 - HCAL less deep → lower $\sqrt{s}$
 - Vertex detector endcap without spirals (no air cooling)



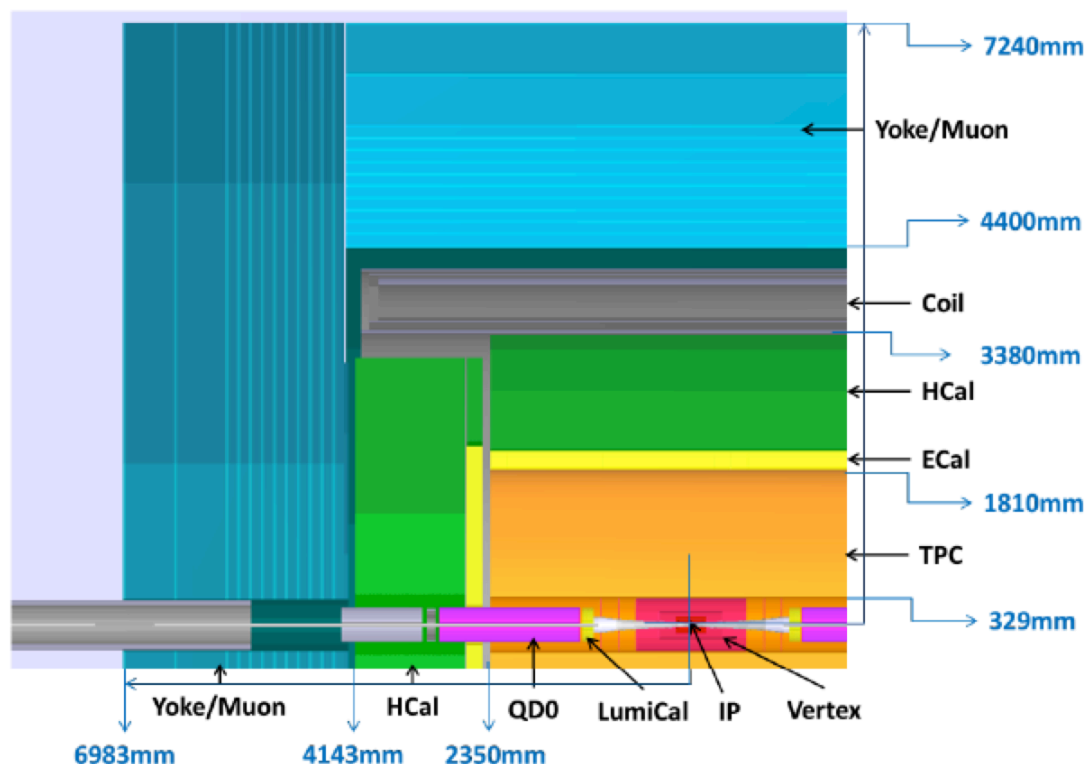
- To be further optimised for different
 - Physics goals
 - Backgrounds
 - Detector cooling requirements

- **CLICdet-inspired** detector concept
 - Complex forward region
 - smaller magnetic field of $B=2\text{ T}$
 - larger tracker radius (keep similar momentum resolution)
 - HCAL less deep → lower $\sqrt{s}$
 - Vertex detector endcap without spirals (no air cooling)



- To be further optimised for different
 - Physics goals
 - Backgrounds
 - Detector cooling requirements

- **ILD-L-inspired** detector concept studied for pre-CDR



- Shorter L^* of 1.5 m
→ QD0 inside tracker
- Increased cooling infrastructure due to continuous operation
- Thickness of return yoke reduced for both barrel and endcap

Towards CDR:

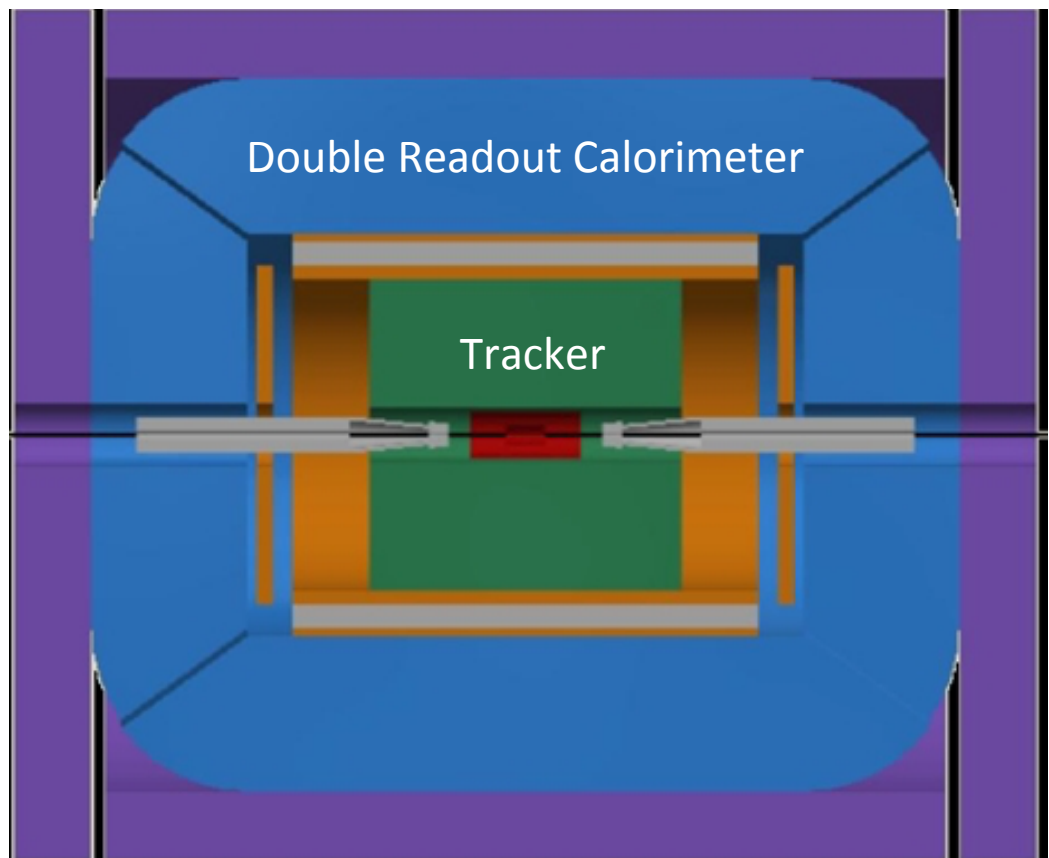
- Study 2+ detector concepts
- ILD-like / SiD-like concepts, novel concept (→ "IDEA")

“IDEA” concept for CEPC/FCC-ee (option 2)



IDEA “International Detector for Electron-positron Accelerator”

- Vertex detector, MAPS
 - Ultra-light drift chamber with PID
 - Pre-shower counter
 - Double read-out calorimetry
 - 2 T solenoid (possibly instrumented)
 - return yoke
- or
- possibly surrounded by large tracking volume ($R \approx 8\text{m}$) for long-lived particles

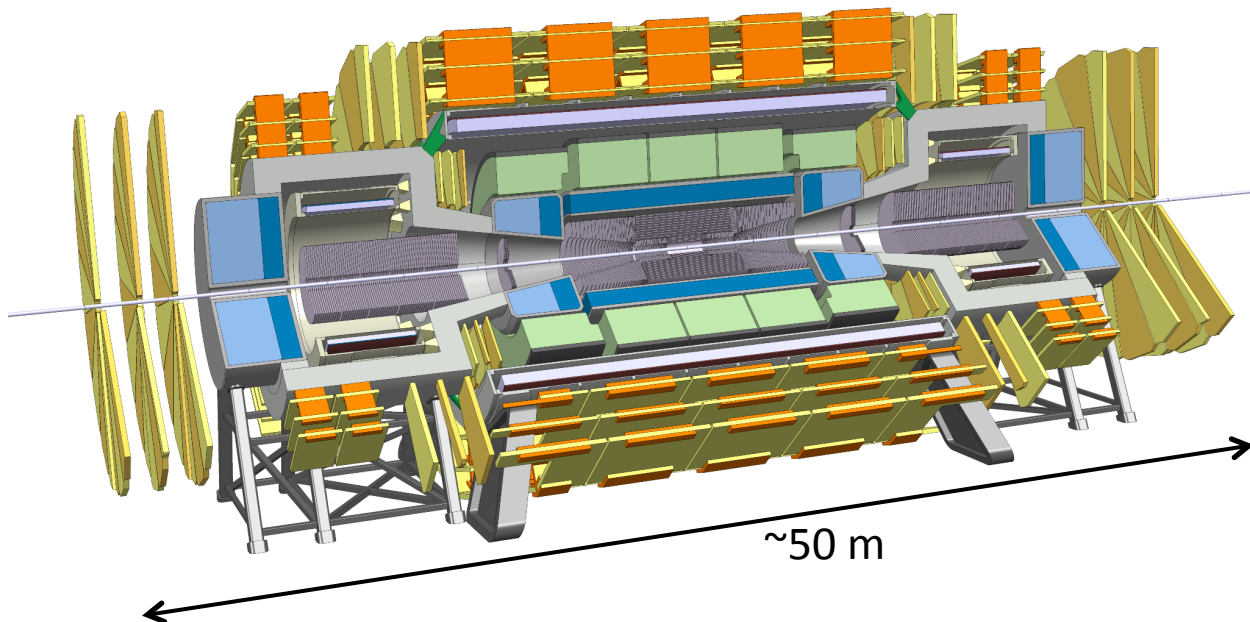


Two options: solenoid inside or outside calorimeter

future high-energy pp colliders

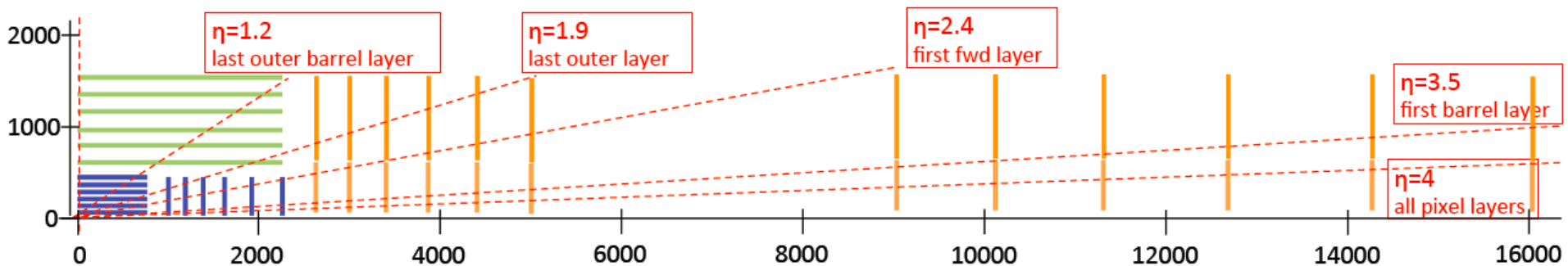
current detector concepts

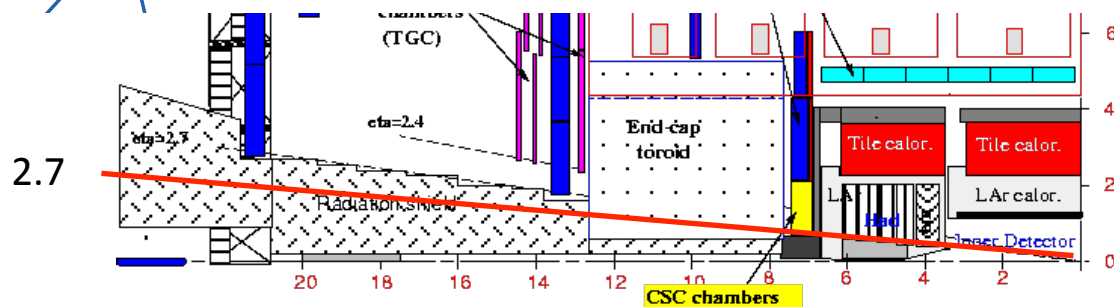
FCC-hh detector concept



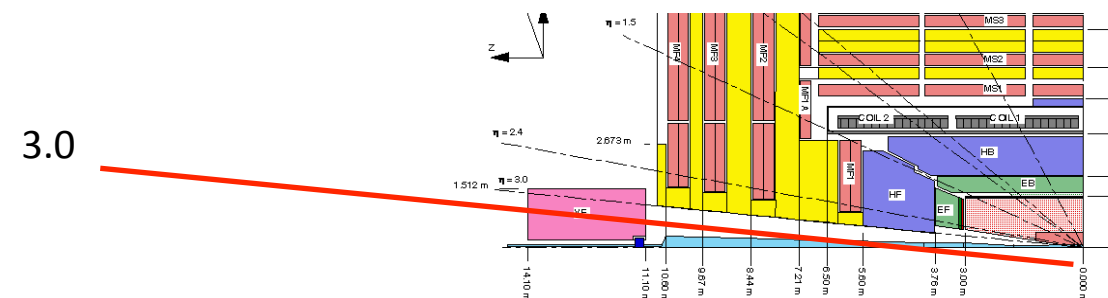
- 4T, 10 m diam. solenoid
- Forward solenoids
- Silicon tracker
- Barrel ECAL LAr
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

FCC tracker layout

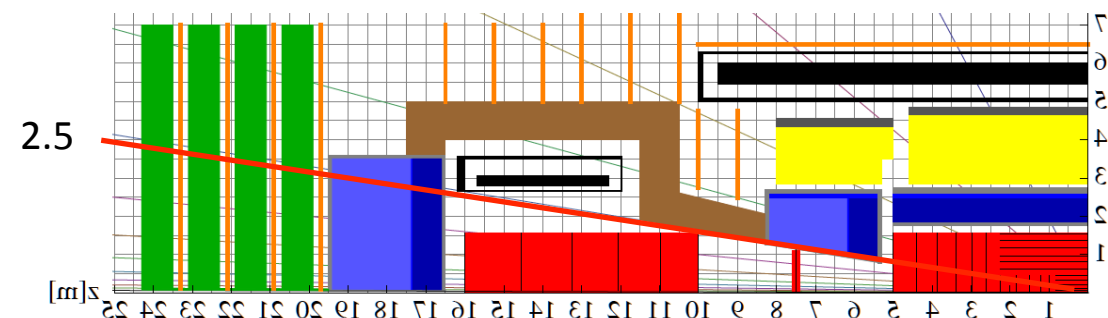




ATLAS



CMS



FCC-hh

(cavern length of 70 m required)

Compared to ATLAS / CMS, the forward calorimeters are moved far out in order to reduce radiation load and increase granularity.

→ A large shielding (brown) needed to stop neutrons from escaping to cavern and muon syst.

a few words on detector technologies

detectors at future e^+e^- and pp collider face strong challenges

Vertex/tracker

Property	e^+e^-	pp
Position resolution (3 μm – 10 μm)	***	***
Small cell sizes (down to 20*20 μm)	***	***
Very thin materials	***	**
Excellent timing (ps-ns scale)	**	***
Large surfaces, low cost	**	***
Radiation hardness	*	****

despite differences,
many challenges in
common



Calorimetry

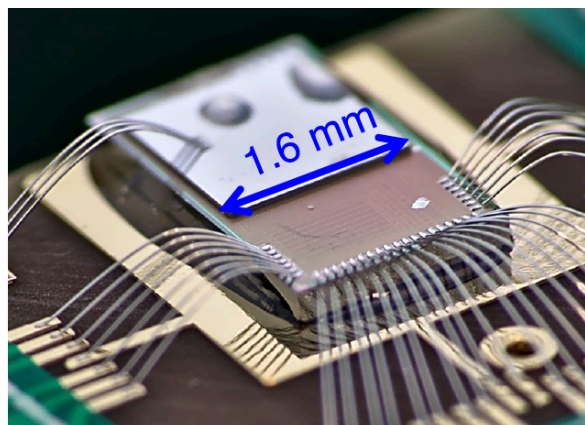
Property	e^+e^-	pp
High granularity (few cm^2 cells)	**	**
Excellent timing (ps-ns scale)	**	***
Compactness (thin active layers)	***	**
Large surfaces, low cost	**	***
Radiation hardness	*	****

much (not all)
of the required R&D
points at advanced
silicon /
microelectronics
technologies

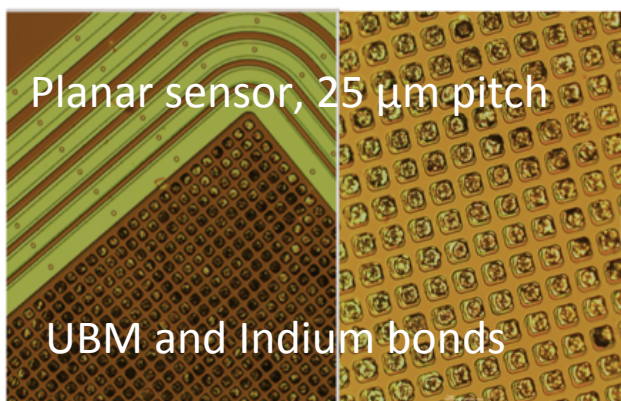
+ large area muon detection + DAQ/trigger + large superconducting solenoids + ...

silicon vertex and tracker R&D (1)

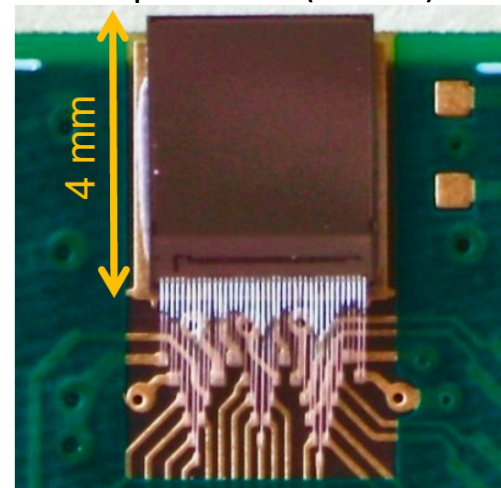
CLICpix (65 nm) + 50 μm sensor



Bump-bonding, 25 μm pitch



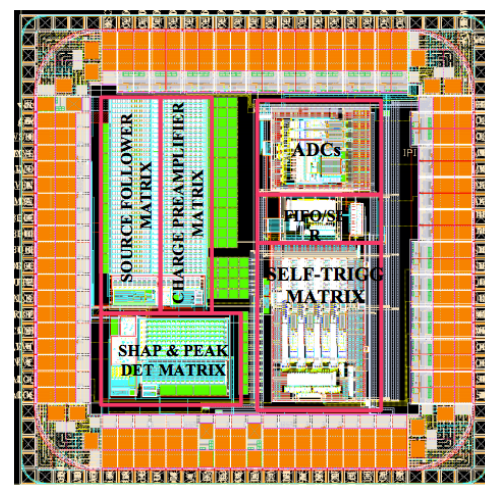
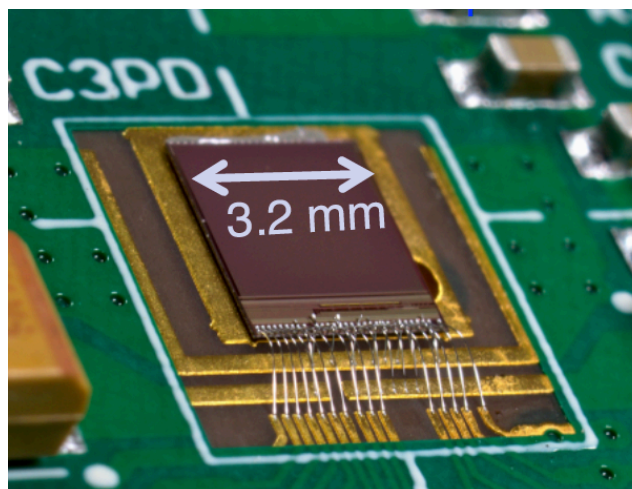
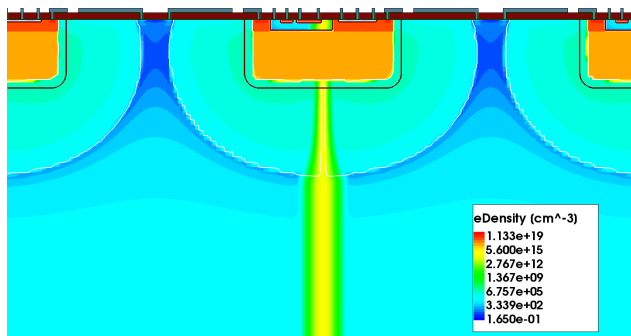
CLICpix2 ASIC (65 nm)



C3PD HV-CMOS sensor, thinned 50 μm

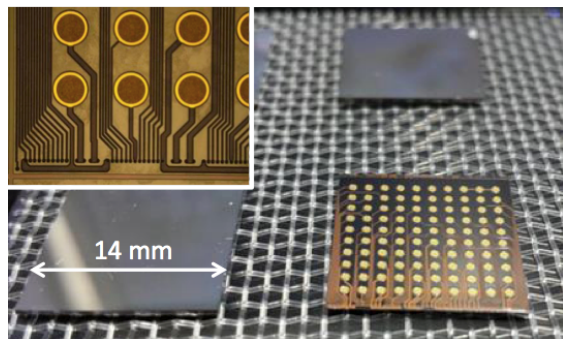
SOI sensor design

TCAD simulations, HV-CMOS sensor

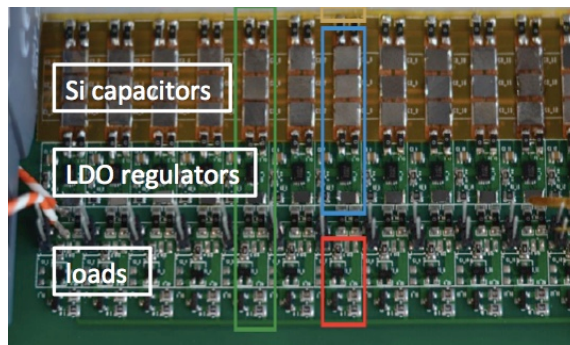


silicon vertex and tracker R&D (2)

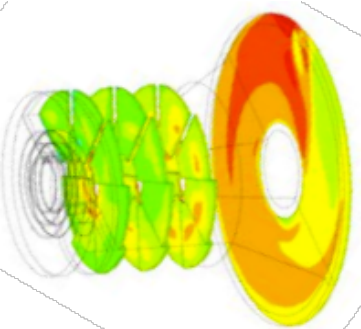
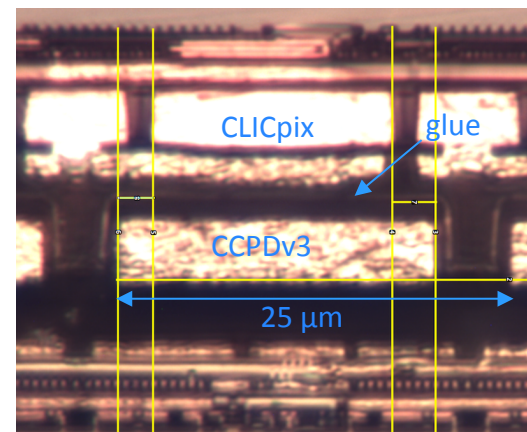
TSV interconnect technology



power delivery + pulsing

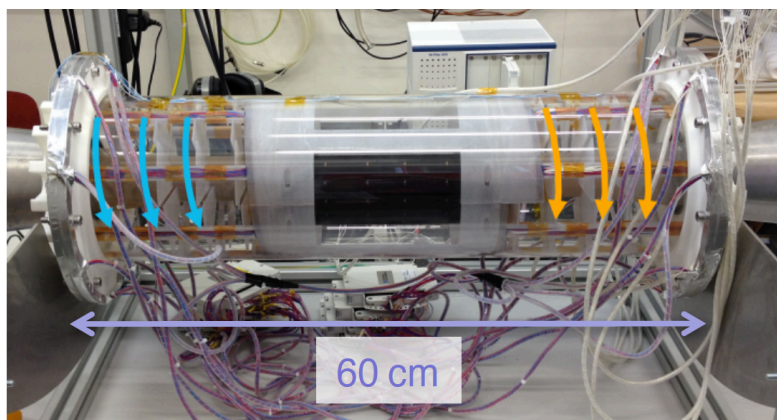
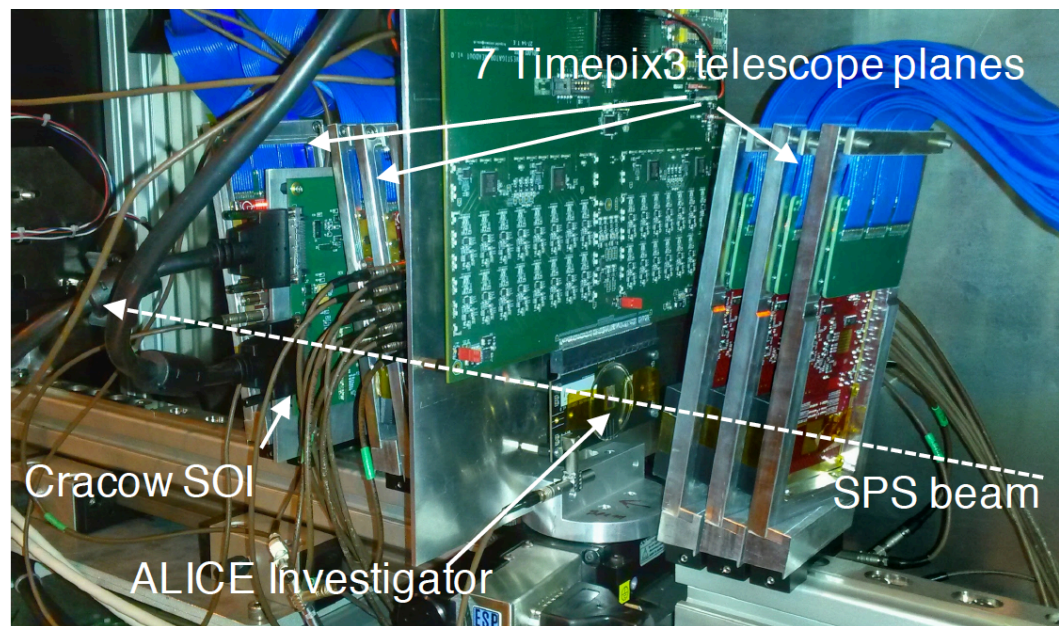


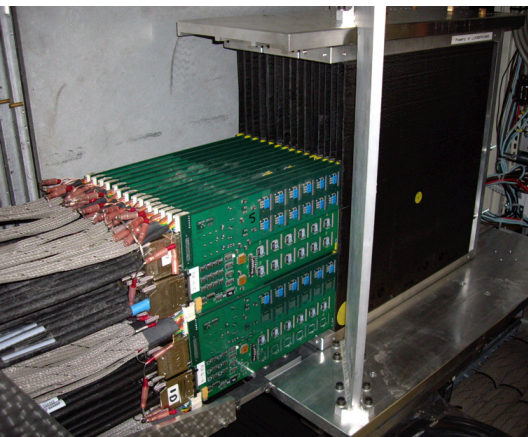
Flip-chip gluing (AC-coupling)



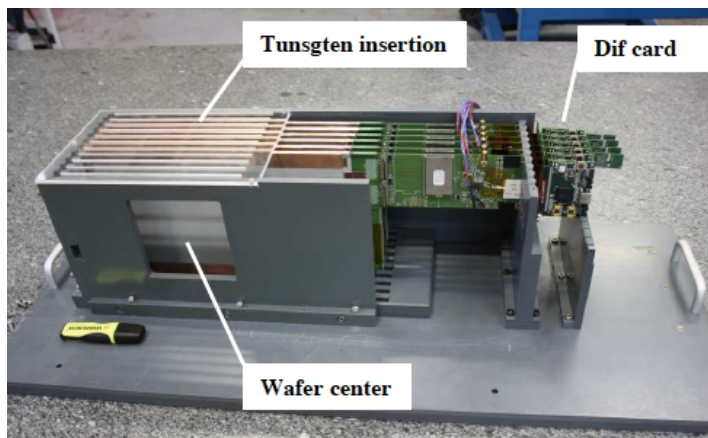
Air cooling simulation and 1:1 scale test set up

LCD Timepix3 telescope at 2016 SPS test beam

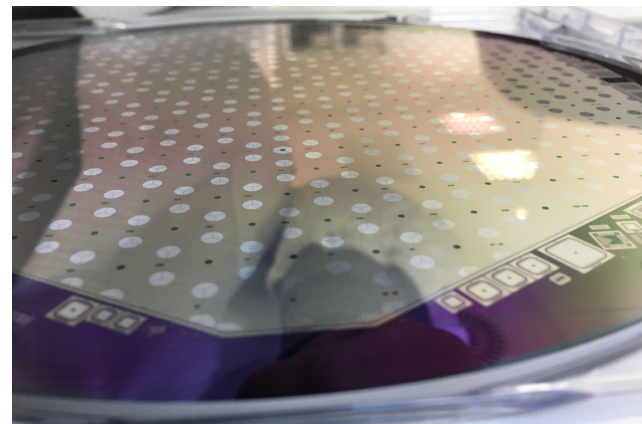




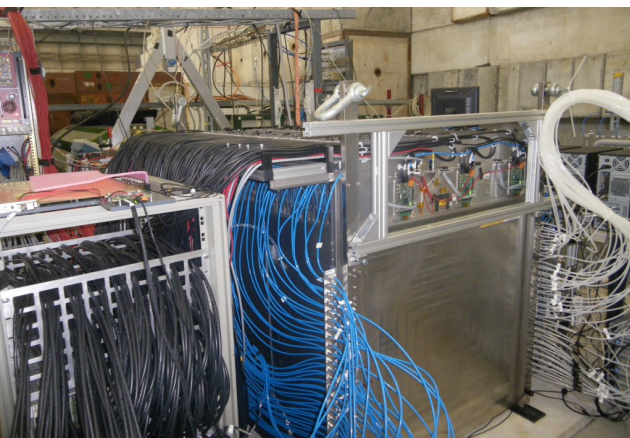
Silicon-tungsten ECAL



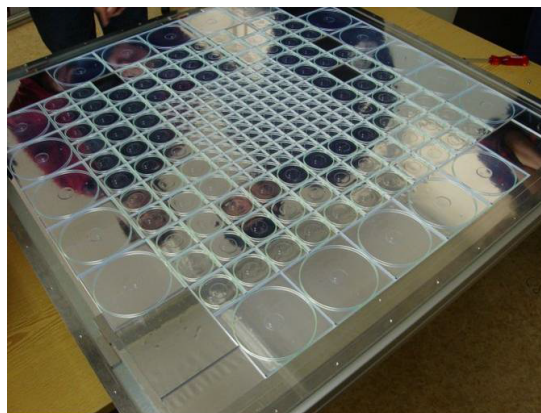
Silicon-tungsten ECAL



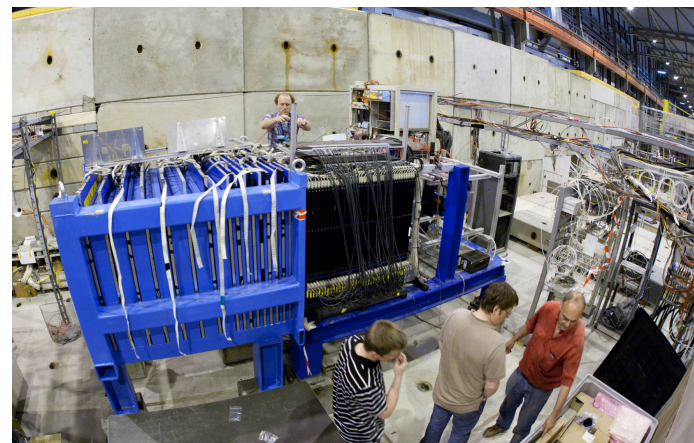
CMS HGCal 8" silicon wafer



RPC-steel SDHCAL



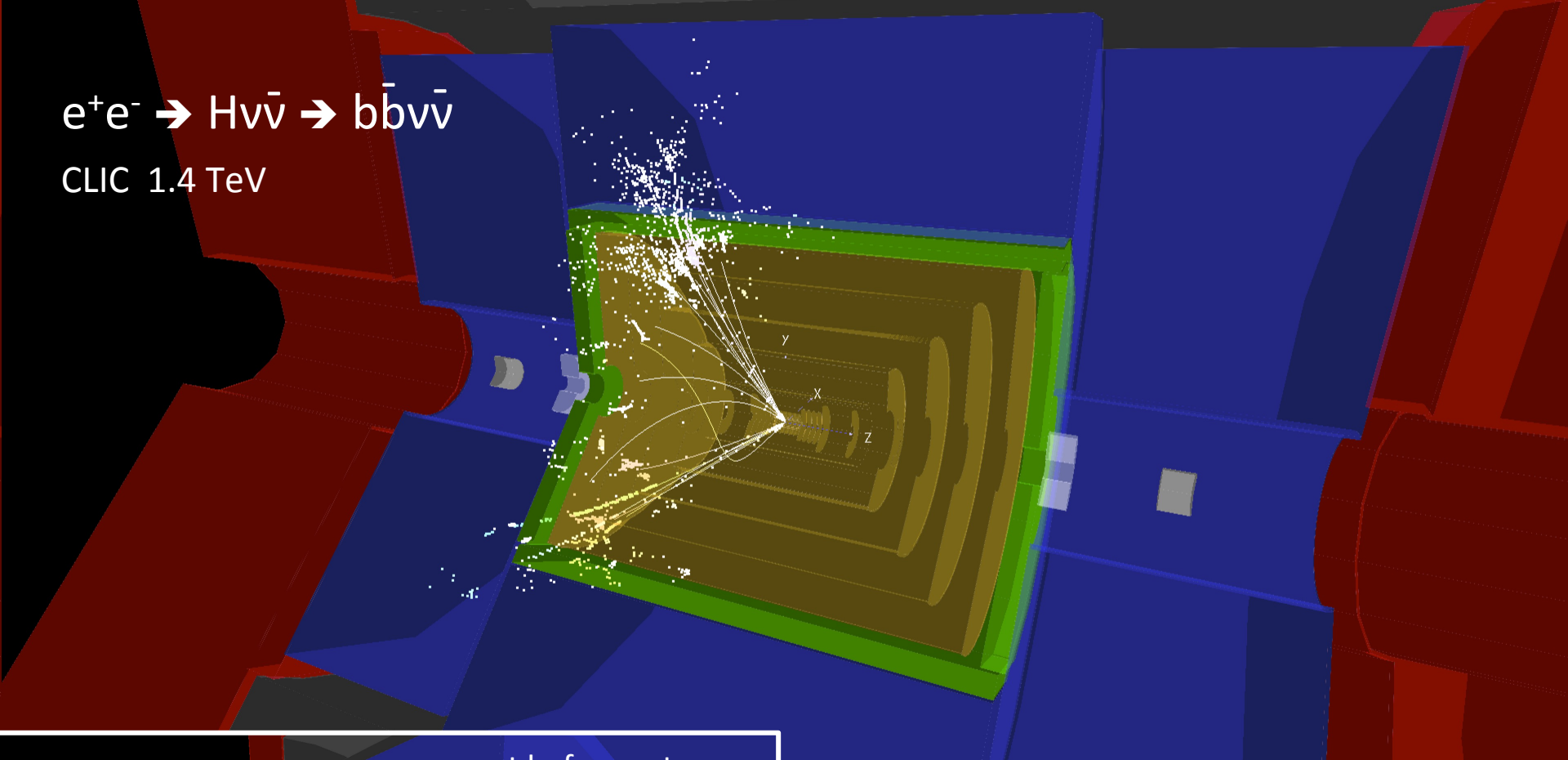
Scintillator HCAL plane



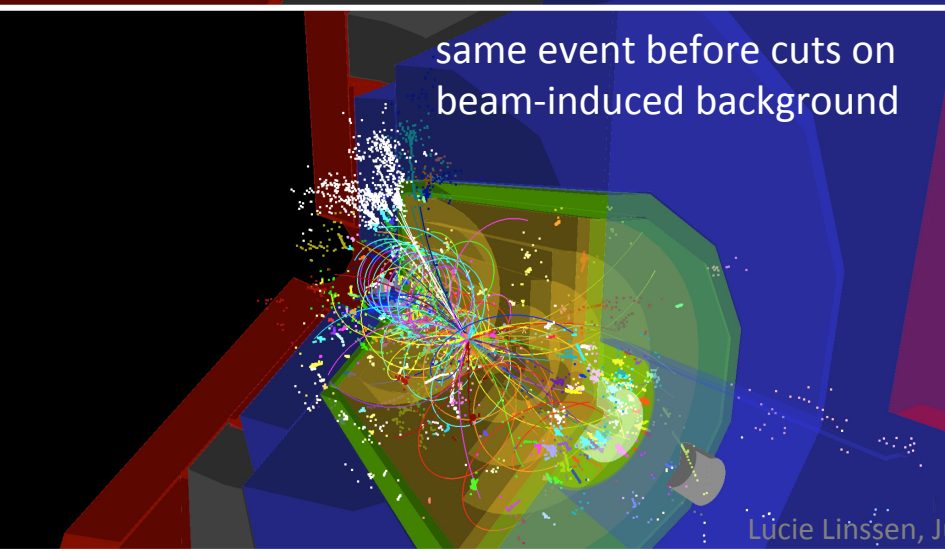
Scintillator-tungsten HCAL

$$e^+e^- \rightarrow H\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$$

CLIC 1.4 TeV



same event before cuts on
beam-induced background



thank you !