14:00

Detectors for Future Colliders (25' + 5') *Joao Barreiro Guimaraes Da Costa*
Korea Advanced Institute of Science and Technology (KAIST) 14:00 - 14:30

New developments in tracking (15' + 5') *Daniela Bortoletto*
Korea Advanced Institute of Science and Technology (KAIST) 14:30 - 14:50

Calorimeters inside Detectors at Colliders (15' + 5') *John Michael Hauptman*
15:00
Korea Advanced Institute of Science and Technology (KAIST) 14:50 - 15:10

Computing in HEP and future developments (15' + 5') *Jae Yu*
Korea Advanced Institute of Science and Technology (KAIST) 15:10 - 15:30

17:00

Instrumentation for underground physics in Korea (20' + 5') *Yeongduk Kim*
Korea Advanced Institute of Science and Technology (KAIST) 17:00 - 17:25

Collaboration of Korean HEP community and the capabilities of Korean industry for future experiments (25' + 5') *In Kyu Park*

Detector plan for Korea Neutrino Observatory (15' + 5') *Kyung Kwang Joo*
18:00
Korea Advanced Institute of Science and Technology (KAIST) 17:50 - 18:10

Detection of wave messengers of the universe (15' + 5') *Il-Heung Park*
Korea Advanced Institute of Science and Technology (KAIST) 18:10 - 18:30

Discussions: next steps on Instrumentation + Computing
Korea Advanced Institute of Science and Technology (KAIST) 18:30 - 19:00

Detectors for Future Colliders

KAIST-KAIX Workshop for Future Particle Accelerators

Korea Advanced Institute of Science and Technology (KAIST)
8-19 July 2019

João Guimarães da Costa

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Are there more forces? particles? symmetries?

Explain mass and relative strengths of the fundamental forces

Are there extra dimensions? What is the structure of spacetime?

What is the structure and fate of the Universe?

What is the right description of gravity, and where does it become relevant for particle physics?

Is there unification of all forces? What breaks it?

What breaks electroweak symmetry? What is the origin of mass?

What is the physics beyond the SM? New particles? New interactions?

Flavor puzzles:
Can we understand the masses, and fermions mixing?Why 3 families?
Where does CP violation come from?

Can we explain the universe?
Is it matter dominated?
Cosmological constant?
What is dark-matter?

pp collider 100 TeV

Muon collider

e^+e^- collider multi-TeV

pp collider LHC 14 TeV

e^+e^- collider Higgs factory

e^+e^- collider Z factory

Neutrino factory

B, τ, charm factories

Particle astrophysics

Adapted from: Maury Tigner; *Physics Today* 54, 36-40 (2001) — Originally from Persis Drell

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The highest **energy** possible

The highest **luminosity** possible

As **low backgrounds** as possible

After the Higgs boson discovery, no other new physics found
Need to also pursue outstanding precision

- PRECISION IS ESSENTIAL -

High Energy Colliders

Hadron Colliders

LHC, HL-LHC 2026-2036

HE-LHC: pp 27 TeV

pp 100 TeV, 100 km collider
40/50 TeV?
SppC, FCC-hh

Lepton Colliders

Electron-positron Colliders

Linear machines

ILC, CLIC

Circular machines

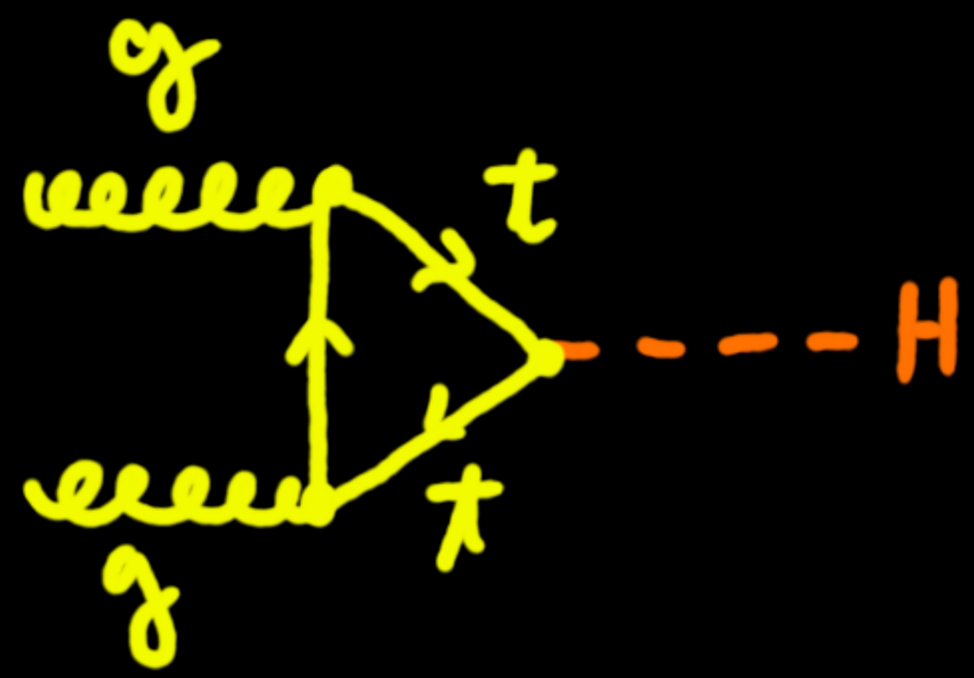
CEPC, FCC-ee

Muon Colliders

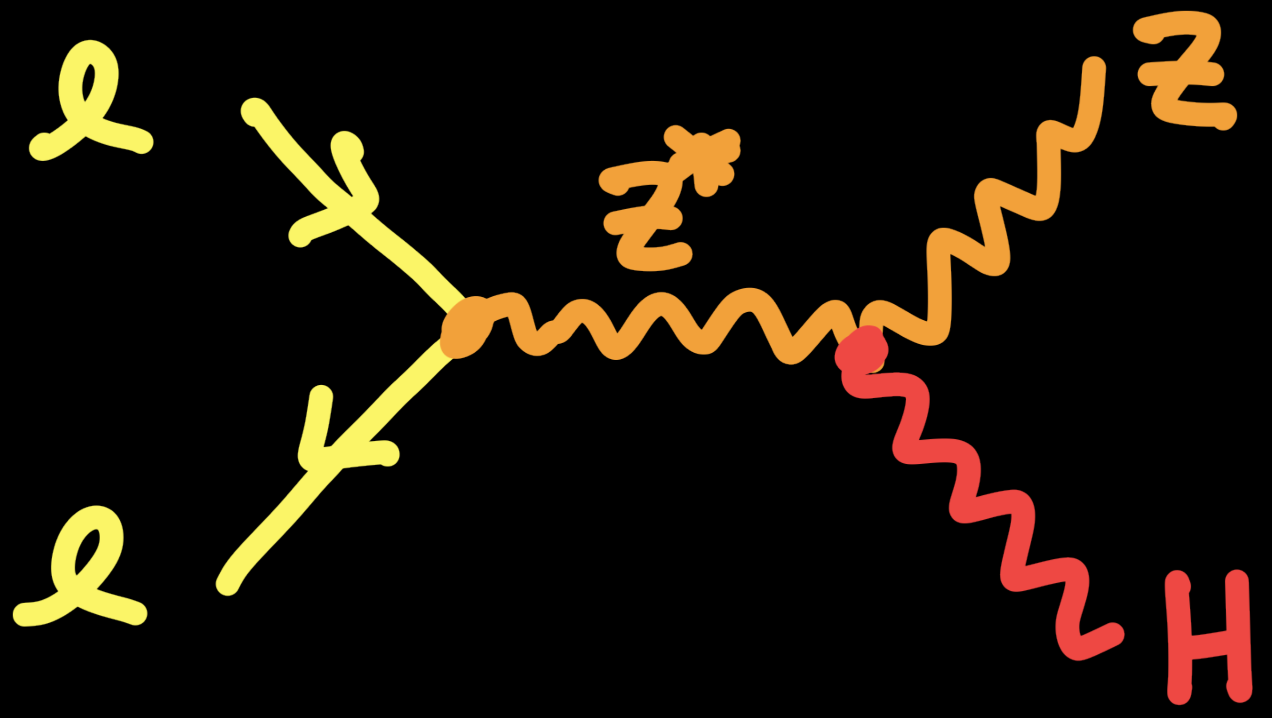
Proton driver (MAP)
Low emittance (LEMMA)

EIC, LHeC, FCC-eh and VHEeP: e-hadron scattering — precision PDF

Hadron versus lepton colliders

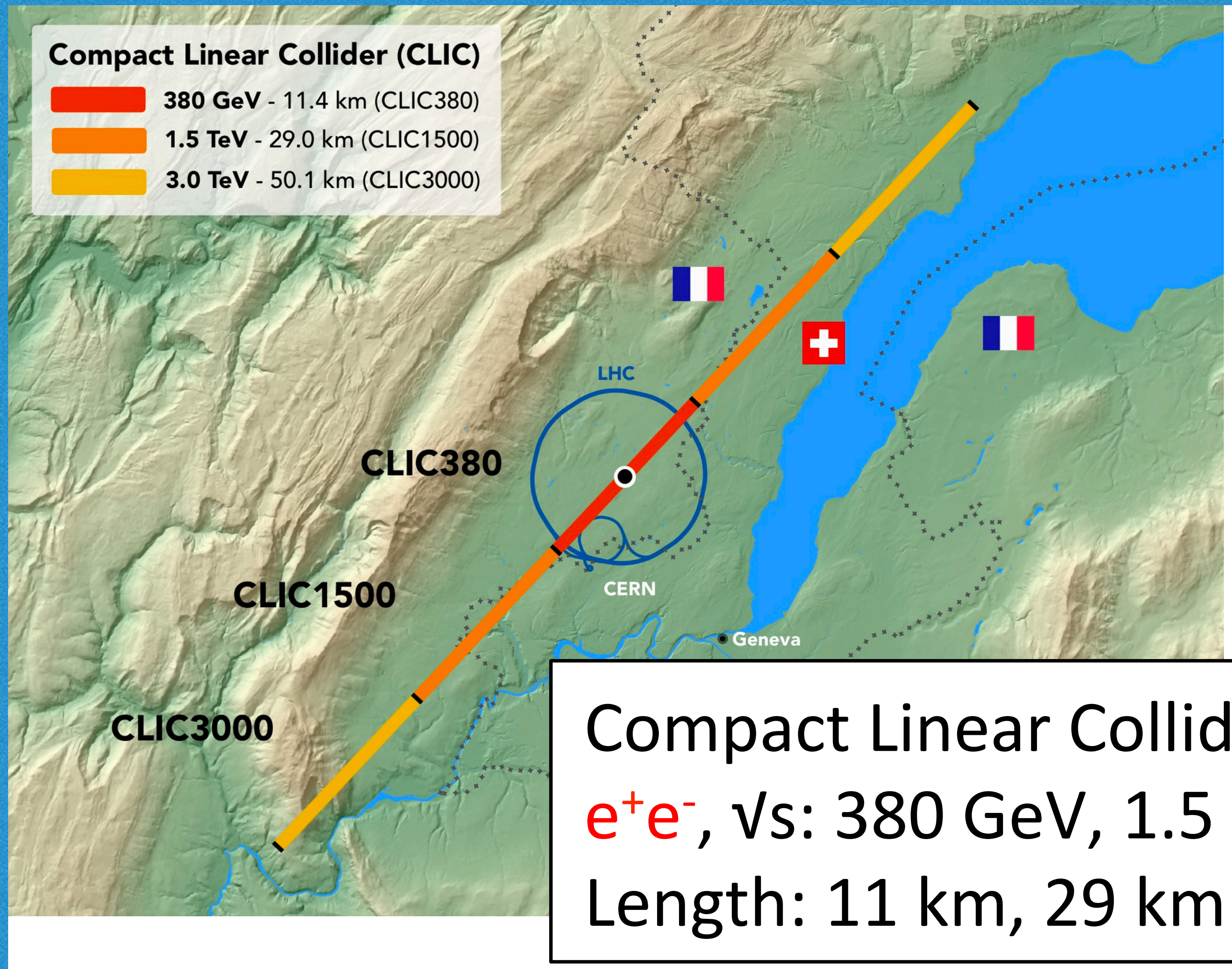


1. Proton are compound objects
   - Initial state unknown (particle and momentum)
   - Limits achievable precision
2. High rates of QCD background S/B ~ 10^{-10}
   - Complex triggers
   - High levels of radiation
     - Detector design focus on radiation hardness of many sub-detectors
3. Very high-energy circular colliders feasible

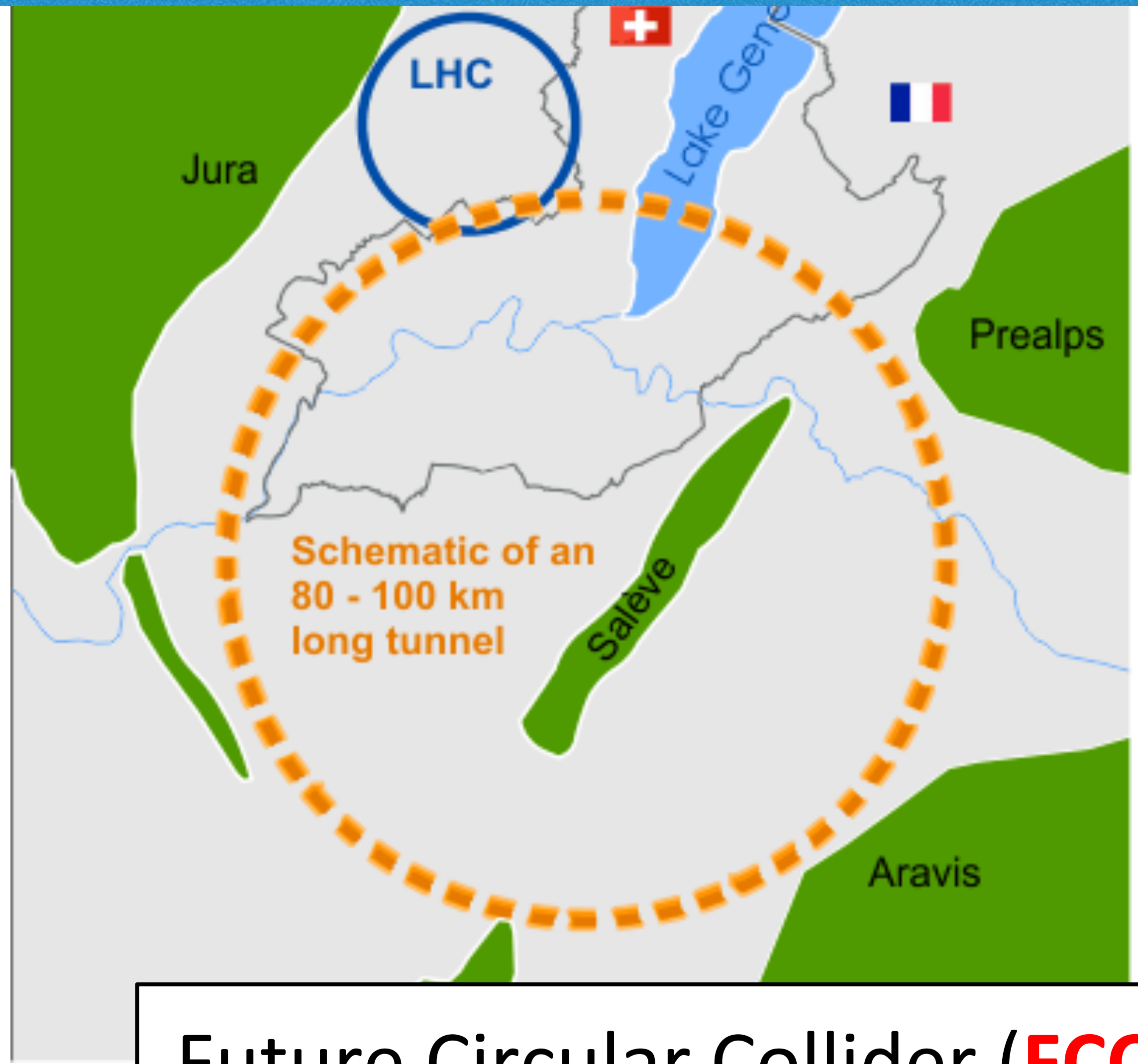


1. Electrons are point-like particles
   - Initial state well-defined (particle, energy, polarization?)
   - High-precision measurements
2. Clean experimental environment S/B ~ 10^{-3}
   - No (less) need for triggers
   - Lower levels of radiation
3. Very high-energies require linear colliders

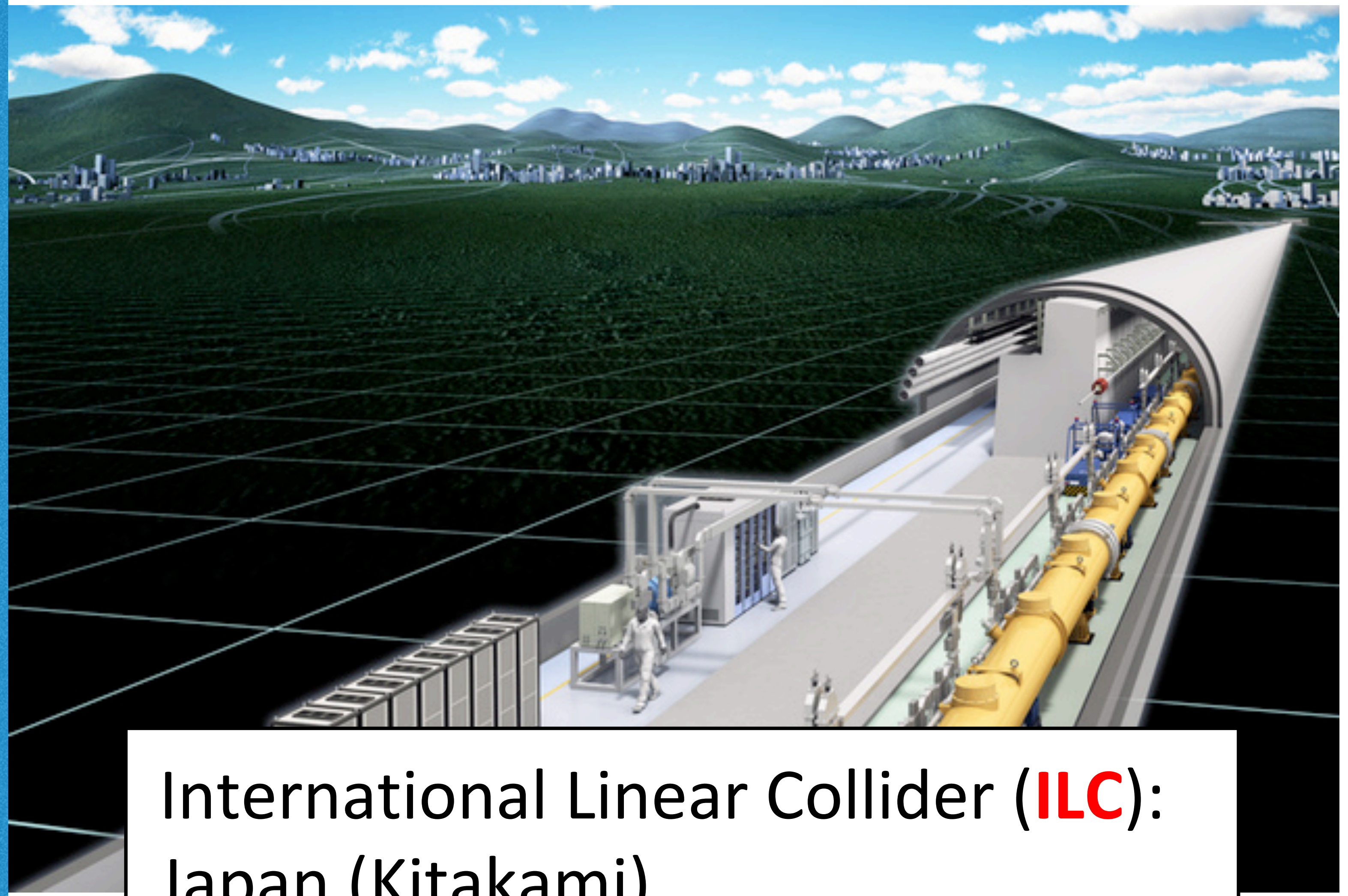
High-energy e^+e^- collider projects



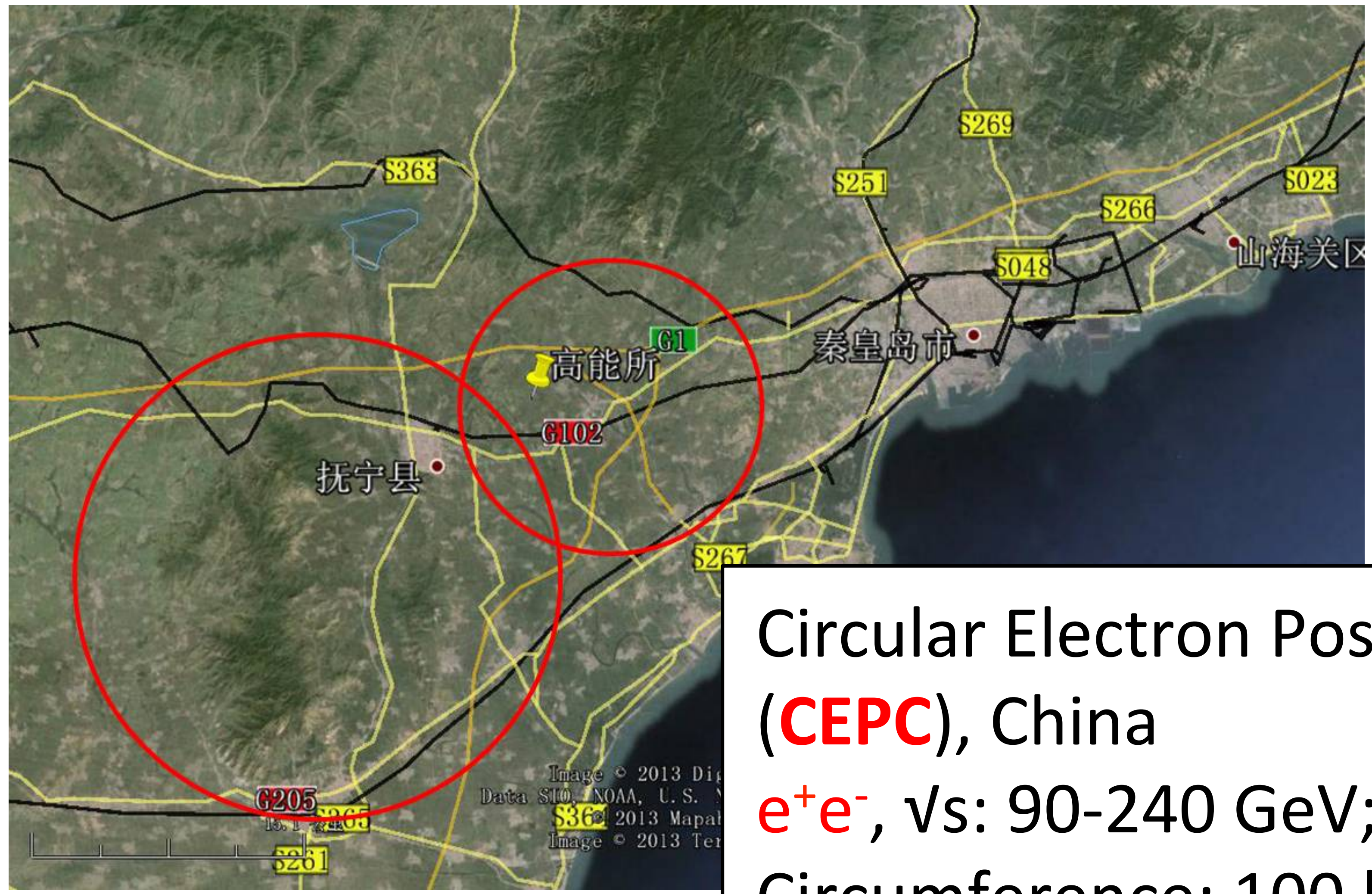
Compact Linear Collider (**CLIC**): CERN
e^+e^-, $\sqrt{s}$: 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km , 50 km



Future Circular Collider (**FCC-ee**): CERN
e^+e^-, $\sqrt{s}$: 90 - 350 (365) 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)



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

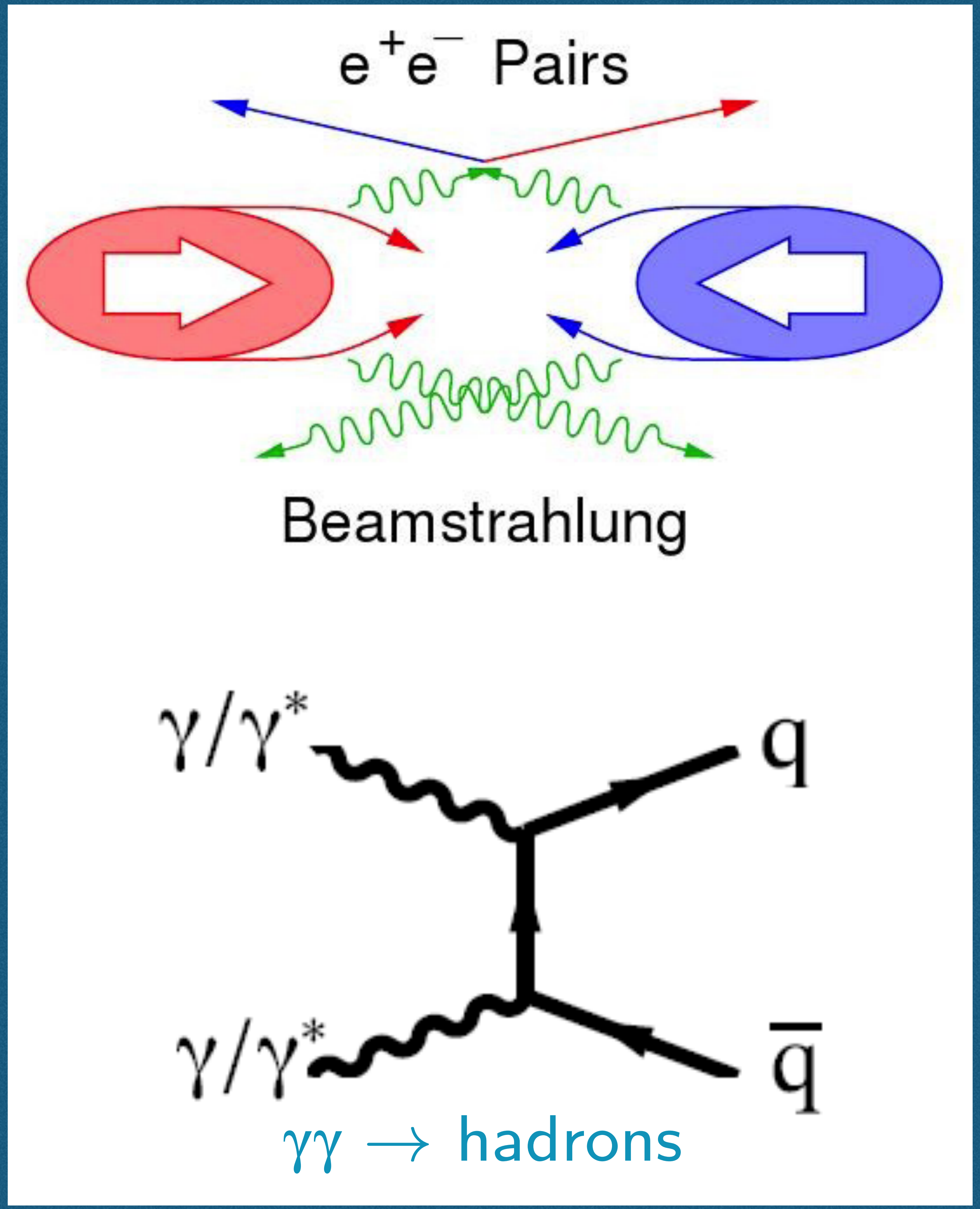
Experimental conditions in linear and circular colliders

Impact on detector design

Beam-induced backgrounds

Linear collider: Achieve high luminosities by using extremely small beam sizes

3 TeV CLIC: Bunch size: $\sigma_{x:y:z}$ = {40 nm; 1 nm; 44 μm} → beam-beam interactions



Main Backgrounds (p_T > 20 MeV, θ > 7.3°)

Incoherent e^+e^- pairs:

- 19k particles/bunch train at 3 TeV
- High occupancies

  → Impact on detector granularity

$\gamma\gamma$ → hadrons:

- 17k particles/bunch train at 3 TeV
- Main background in calorimeters and trackers

  → Impact on detector granularity and physics

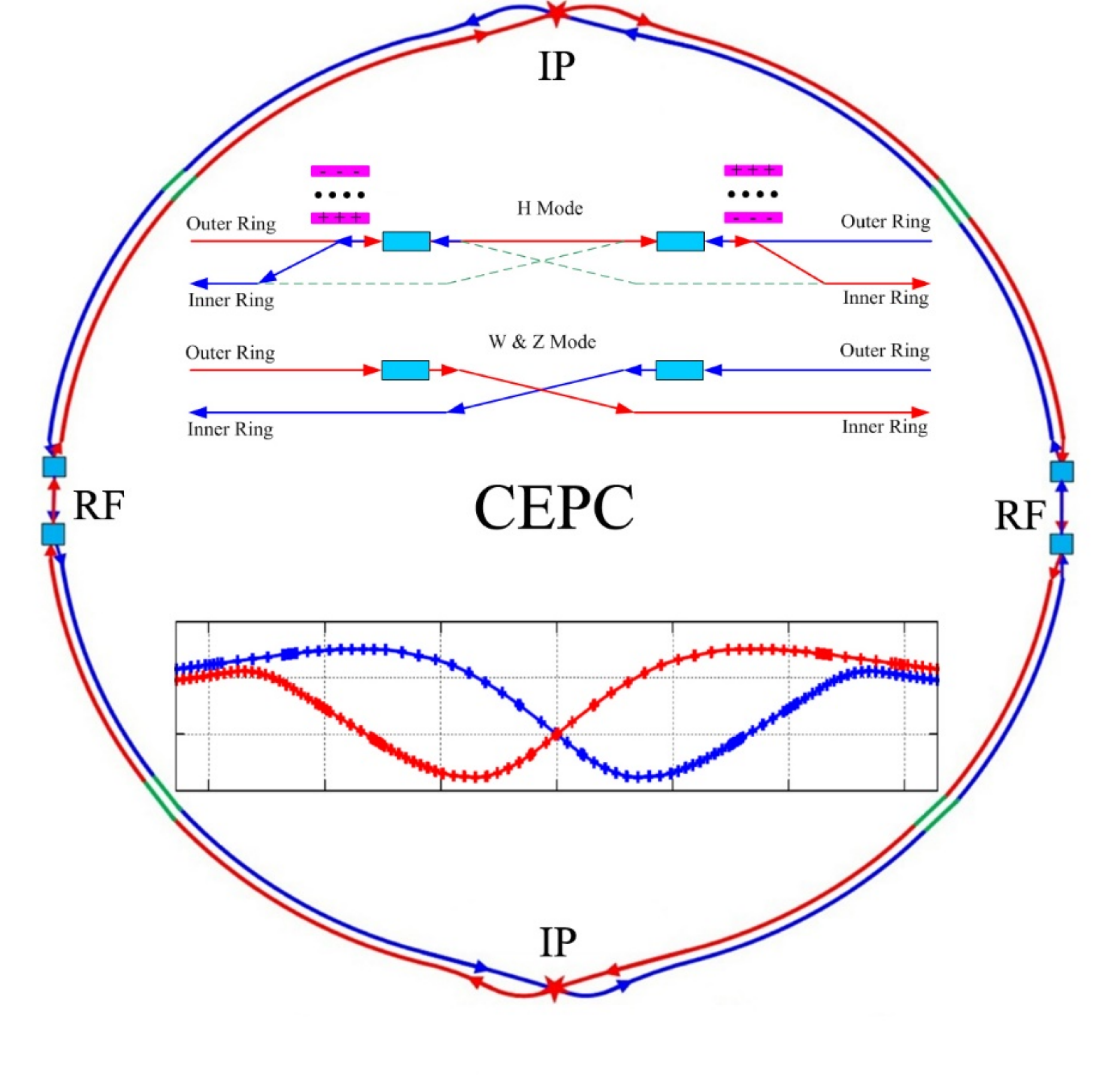
Circular collider: same processes but to much low extent, plus synchrotron radiation

Synchrotron radiation in circular colliders

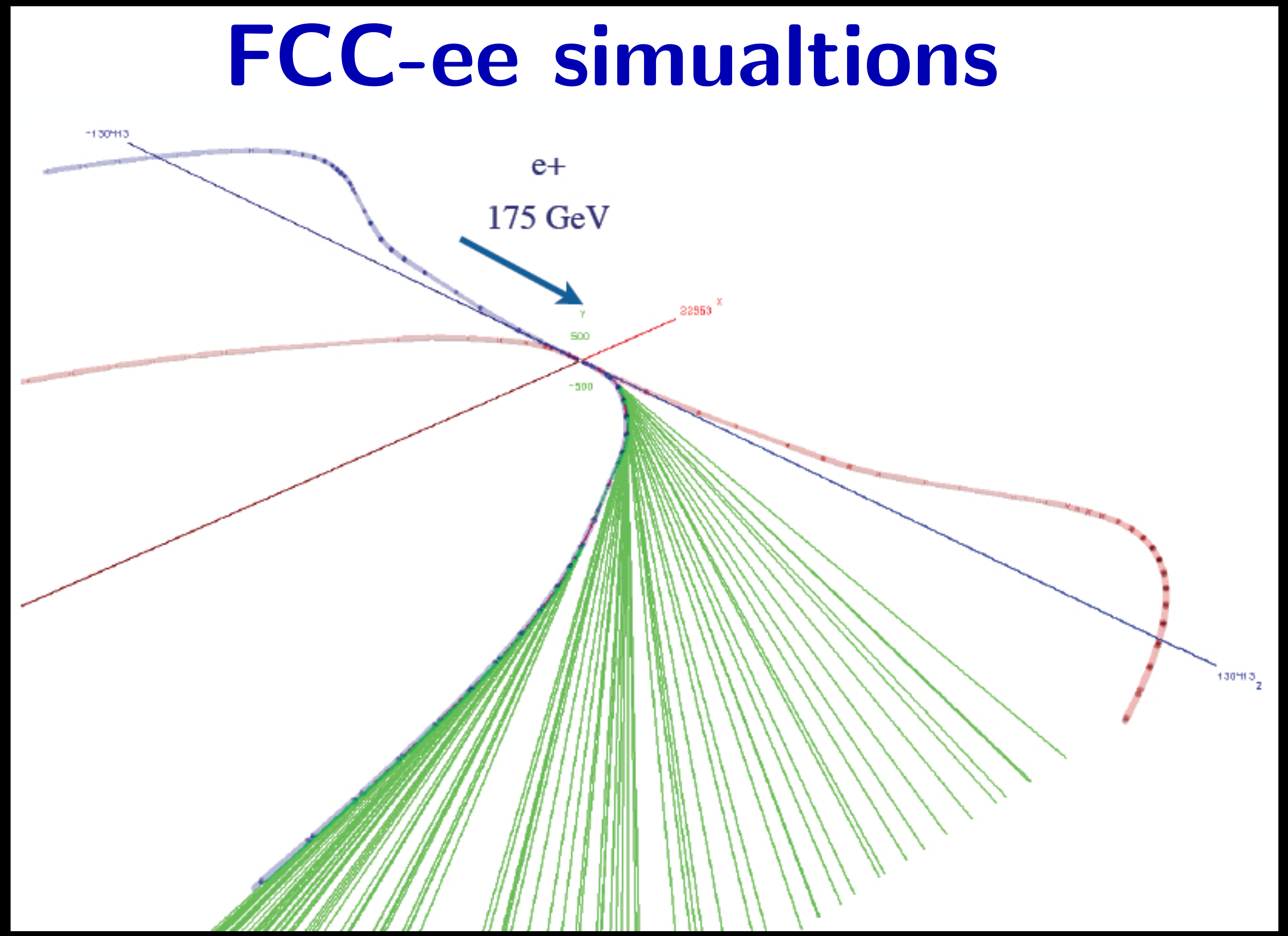
Synchrotron radiation:

$$\sim \frac{E_{beam}^4}{m_e^4 \times r}$$

2.75 GeV/turn lost at LEP at E = 105 GeV
(0.09 GeV/turn at E = 45 GeV)

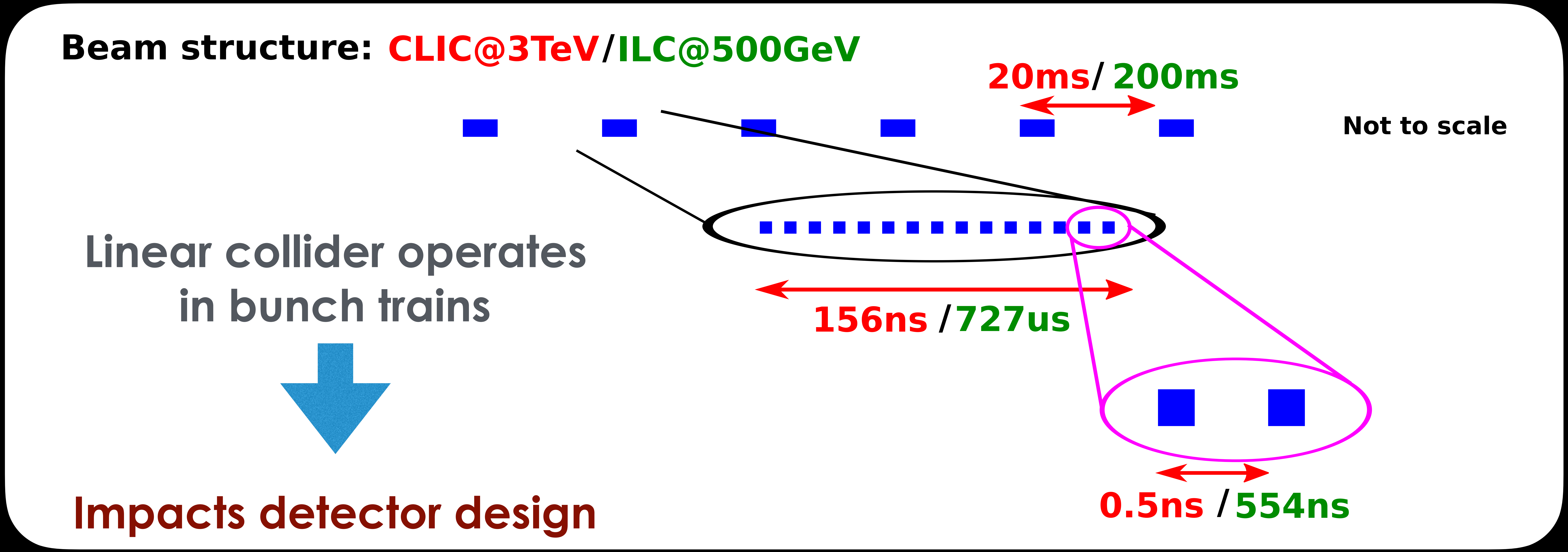


asymmetric layout



Property	FCC-ee (100 km)				CEPC (100 km)		
Beam energy (GeV)	**45.6**	**80**	**120**	**175**	**45.6**	**80**	**120**
Energy loss/turn (GeV)	0.03	0.33	1.67	7.55	0.036	0.34	1.73

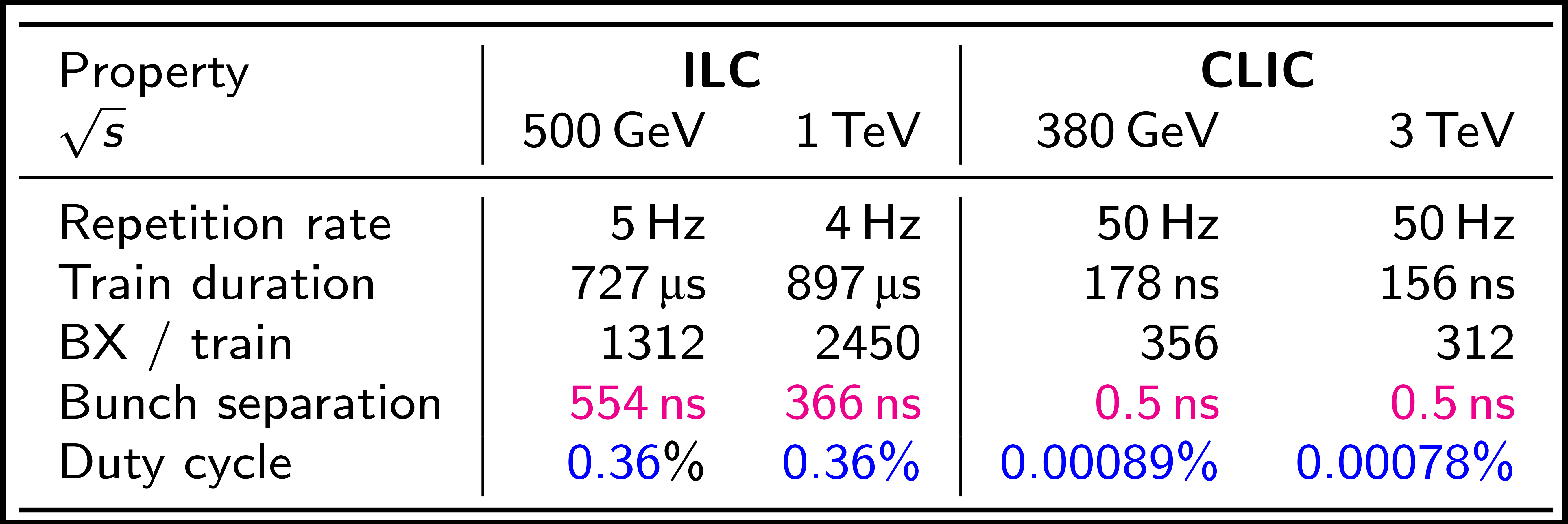
Duty cycle and bunch separation in linear colliders



Beam structure: CLIC@3TeV/ILC@500GeV

Linear collider operates in bunch trains

Impacts detector design



Property $\sqrt{s}$	ILC 500 GeV	 1 TeV	CLIC 380 GeV	 3 TeV
Repetition rate	5 Hz	4 Hz	50 Hz	50 Hz
Train duration	727 µs	897 µs	178 ns	156 ns
BX / train	1312	2450	356	312
Bunch separation	554 ns	366 ns	0.5 ns	0.5 ns
Duty cycle	0.36%	0.36%	0.00089%	0.00078%

→ Low duty cycle

→ Possibility to power pulse the detectors

ILC 250 GeV similar specs

High luminosities in circular colliders

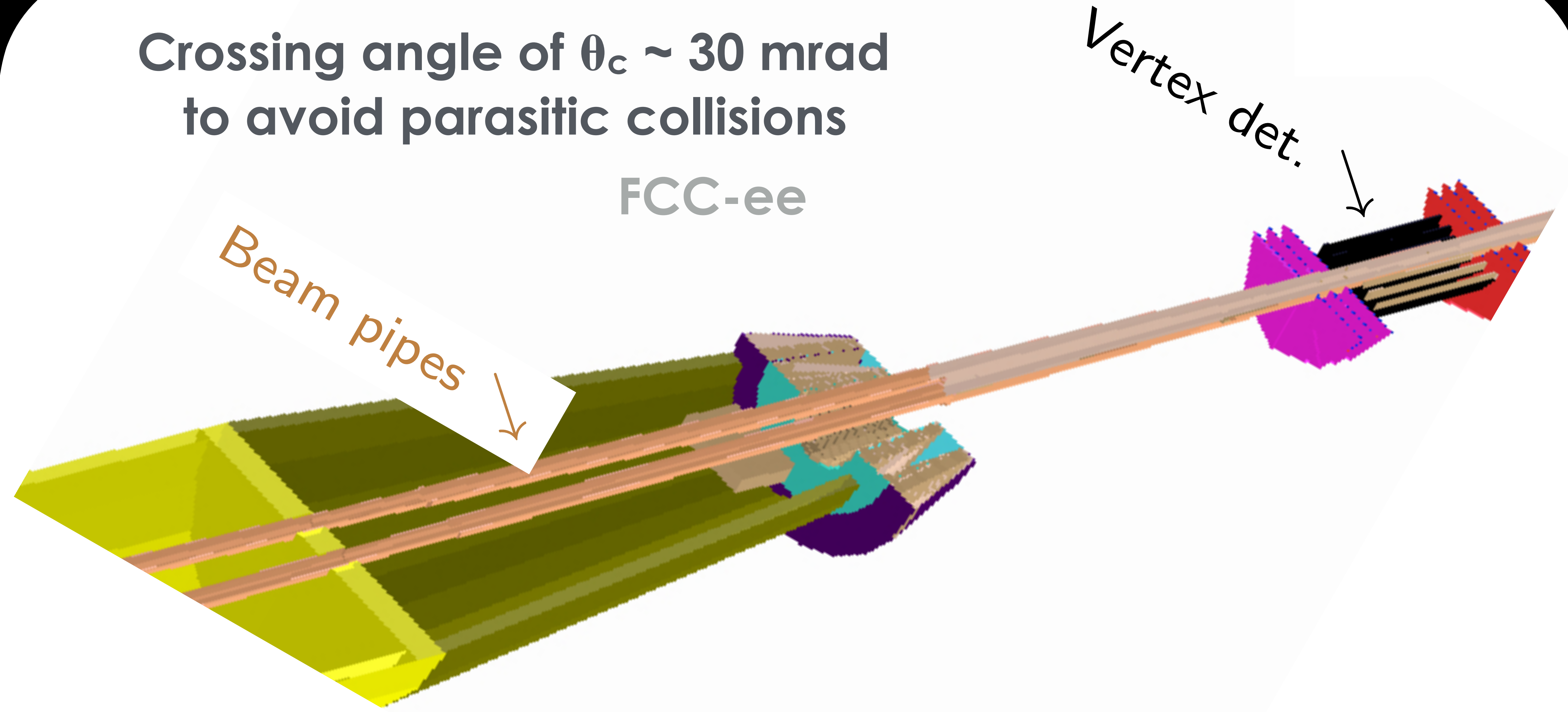
Property	FCC-ee (100 km)				CEPC (100 km)		
Beam energy (GeV)	**45.6**	**80**	**120**	**175**	**45.6**	**80**	**120**
Luminosity/IP (10^{34}cm^{-2}s^{-1})	230	28	8.5	1.5	32	10	3
Bunches/beam	16640	2000	393	48	12000	1524	242
Bunch separation (ns)	20	160	830	8300	25	260	680

Luminosity up to ~ 10^{36} cm^{-2}s^{-1}

Large number of bunches

Consequences for detector design

Crossing angle at IP
Bunch separation impacts overall designs
No power pulsing of detectors



Crossing angle of θ_c ~ 30 mrad
to avoid parasitic collisions

Detector requirements from physics

Momentum resolution :

- Higgs recoil mass, Higgs coupling to muons, smuon endpoint

$\sigma_{p_T}/p_T^2 \sim 2\times10^{-5}\mathrm{GeV}^{-1}$ **for high-p_T**

Impact parameter resolution:

- c/b-tagging, Higgs branching ratios

$\sigma_{r\phi} \sim a \oplus b/(p[\mathrm{GeV}]\sin^{\frac{3}{2}}\theta)\ \mu\mathrm{m}$

a = 5 μm, b = 10-15 μm

Jet energy resolution:

- Separation of W/Z/H in di-jet modes

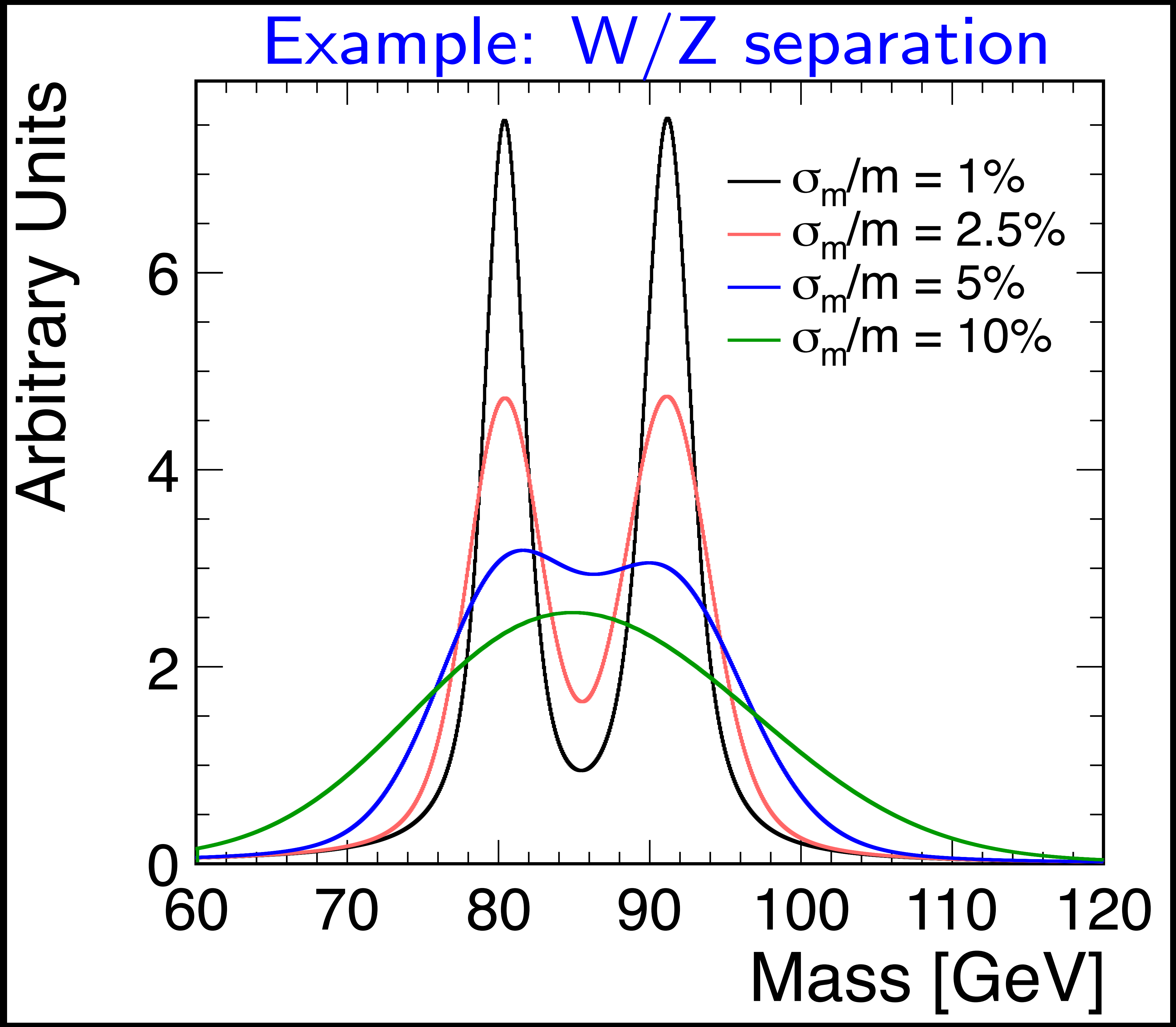
$\sigma_E/E \sim 3.5\,\%$ **for jets above 50 GeV**

Large angular coverage

- Forward electron and photon tagging

Requirements from beam environment

- Solenoid field, beam structure, beam induced backgrounds



Generic detector requirements for high-energy e^+e^- colliders

Precision measurements

Require excellent momentum resolution and flavor tagging

Low-mass vertex and tracking detectors, high granularity

Require excellent energy resolution

Employ excellent calorimeters (particle flow, dual readout)

No major concerns about radiation hardness, unless for very forward detectors and inner most layer of vertex detector

Complementary subsystems

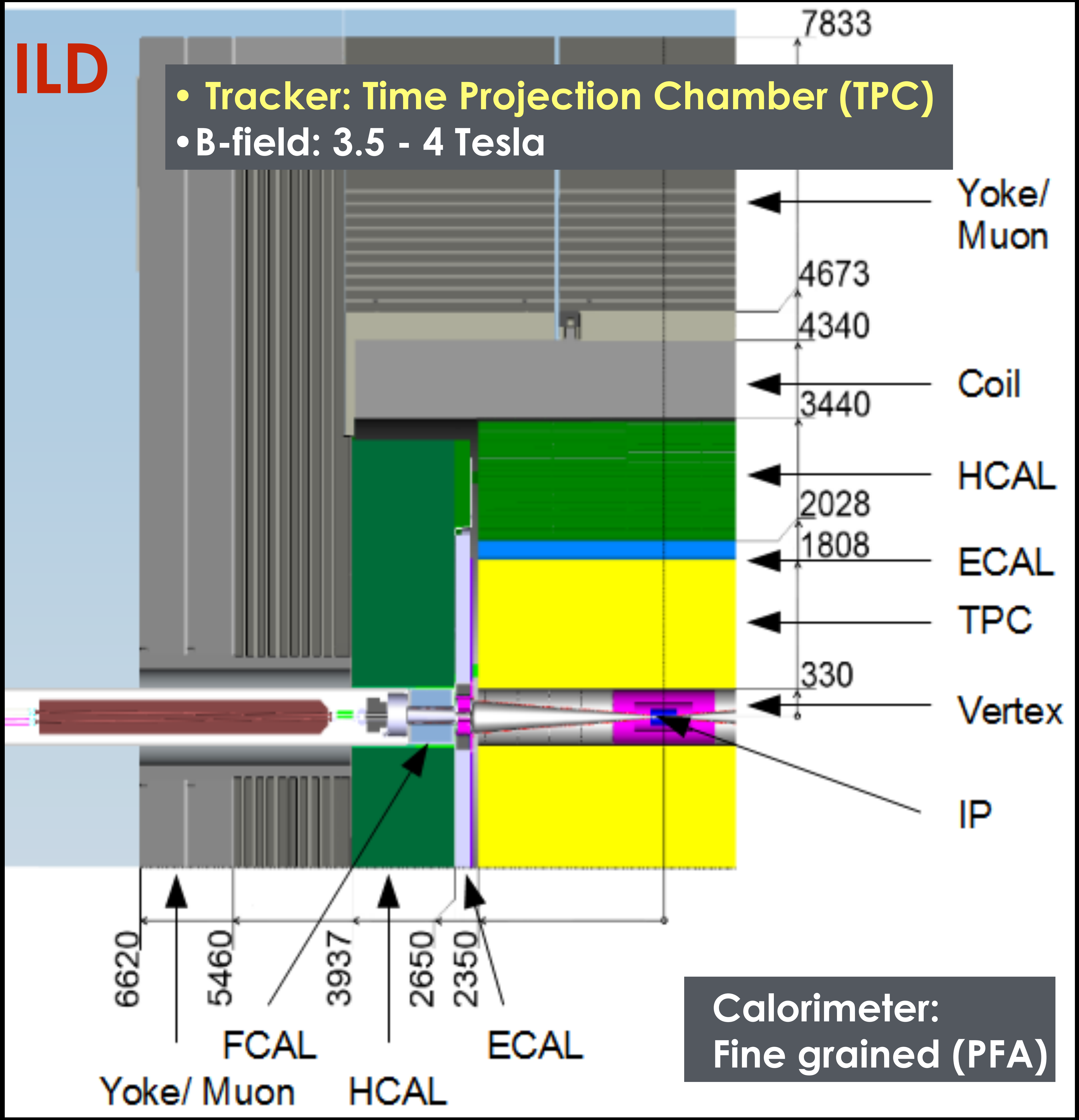
Subsystem	Measurement
Vertex detector	vertex position
	impact parameter → helps determine flavor
	track momenta of charged particles
Tracking detector	track momenta of charged particles
ECAL: electromagnetic calorimeter	energy of γ, $e^{\pm}$ and hadrons
HCAL: hadronic calorimeter	energy of hadrons (including neutrals)
Magnet system	bend charged particles → momentum measurement
Muon system	identify muons
Hermicity	missing energy (e.g. ν)
Luminosity detectors	luminosity

Detector Concepts

ILC Detectors

ILD

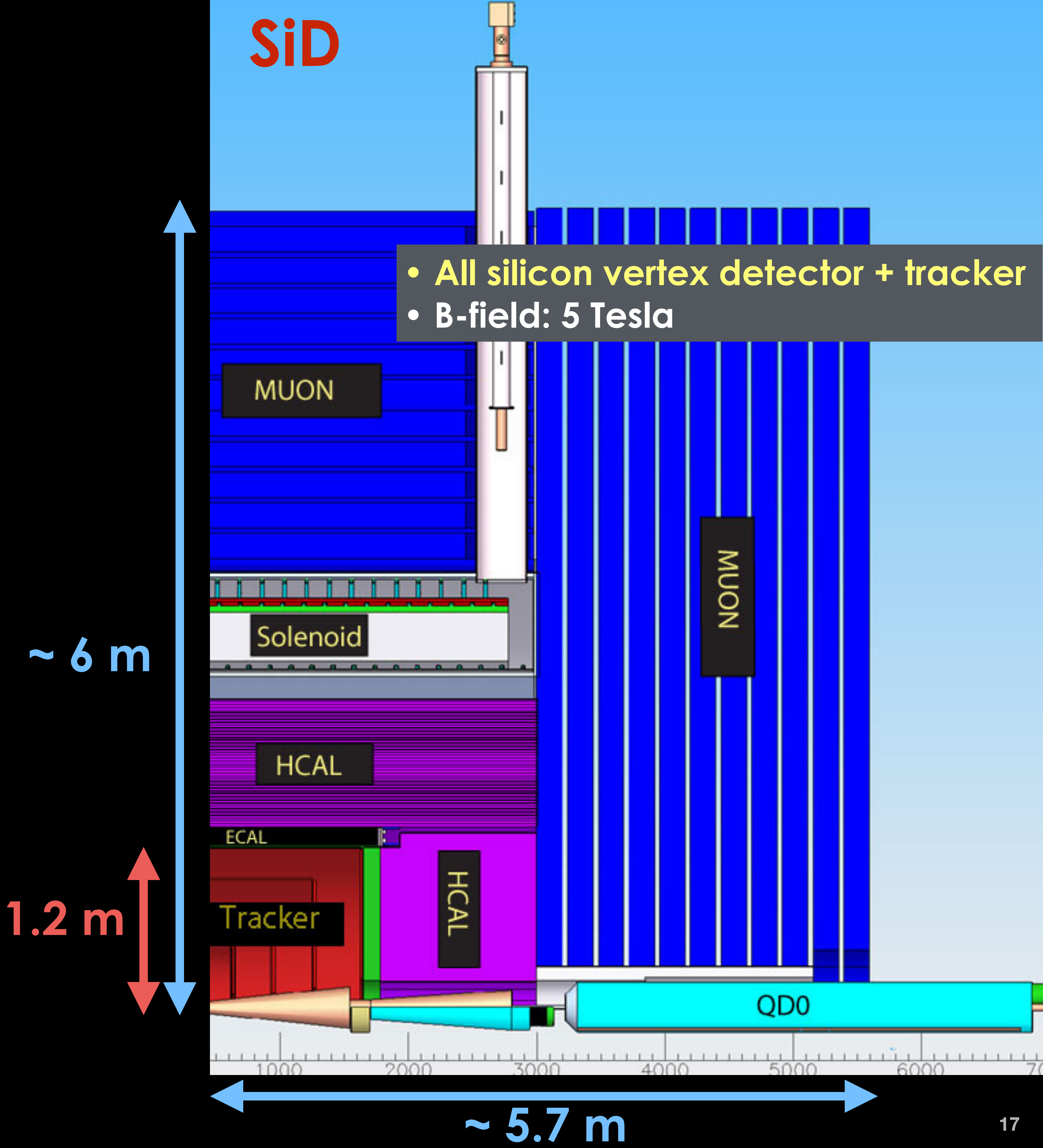
- Tracker: Time Projection Chamber (TPC)
- B-field: 3.5 - 4 Tesla



Calorimeter:
Fine grained (PFA)

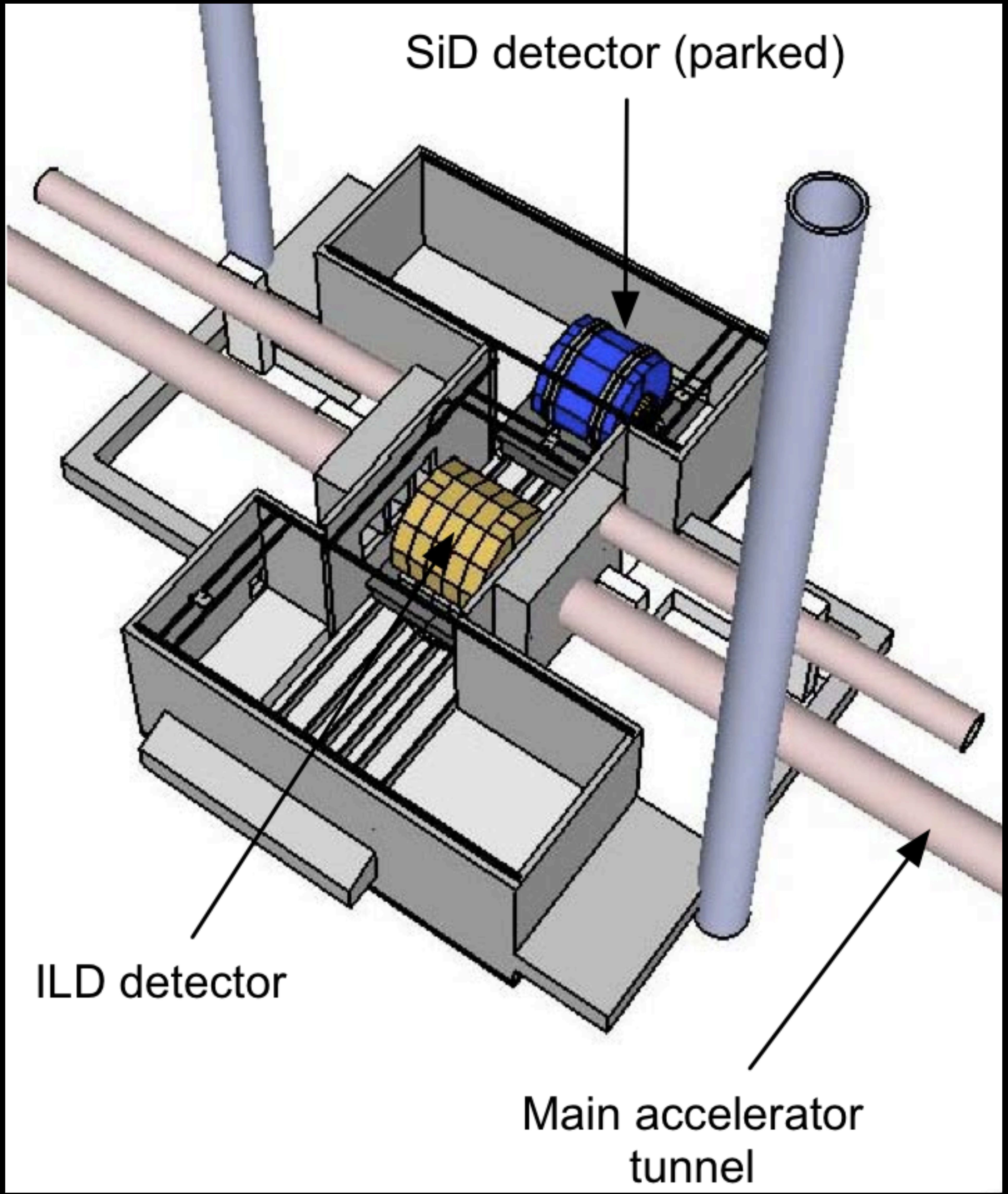
SiD

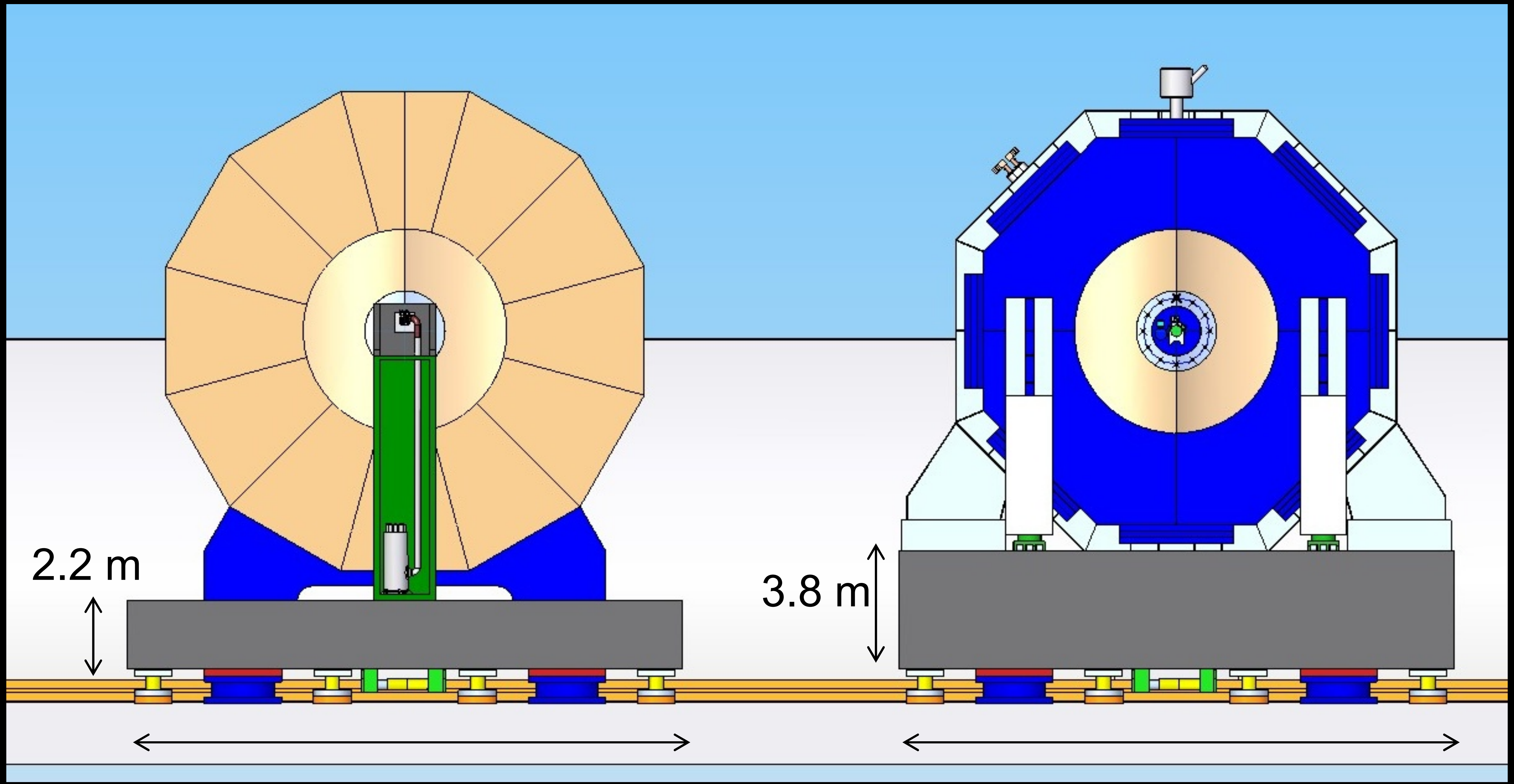
- All silicon vertex detector + tracker
- B-field: 5 Tesla



ILC detectors: Push-Pull (SiD <—> ILD)

Only one interaction point at a linear collider → Swap detectors IN and OUT



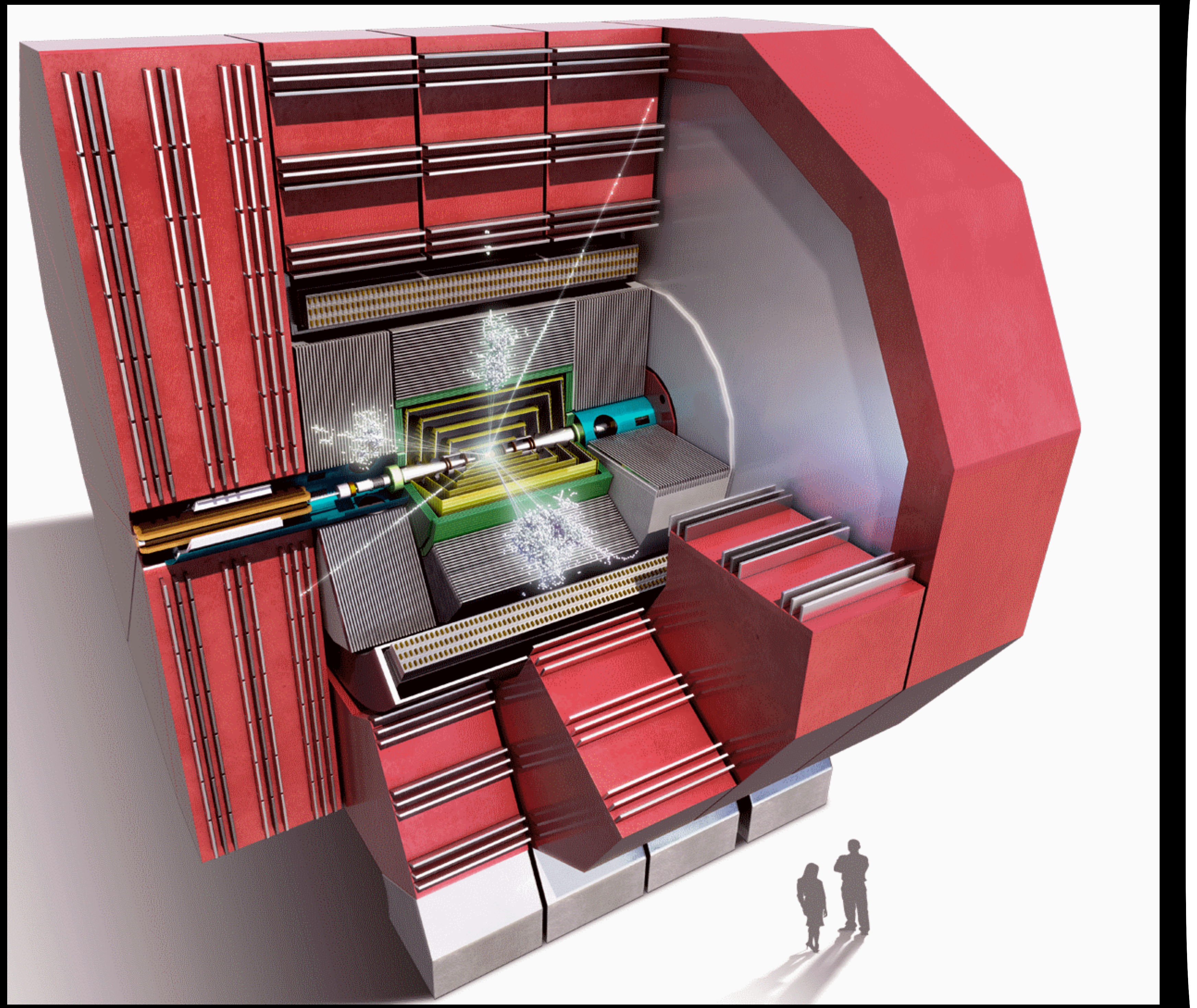


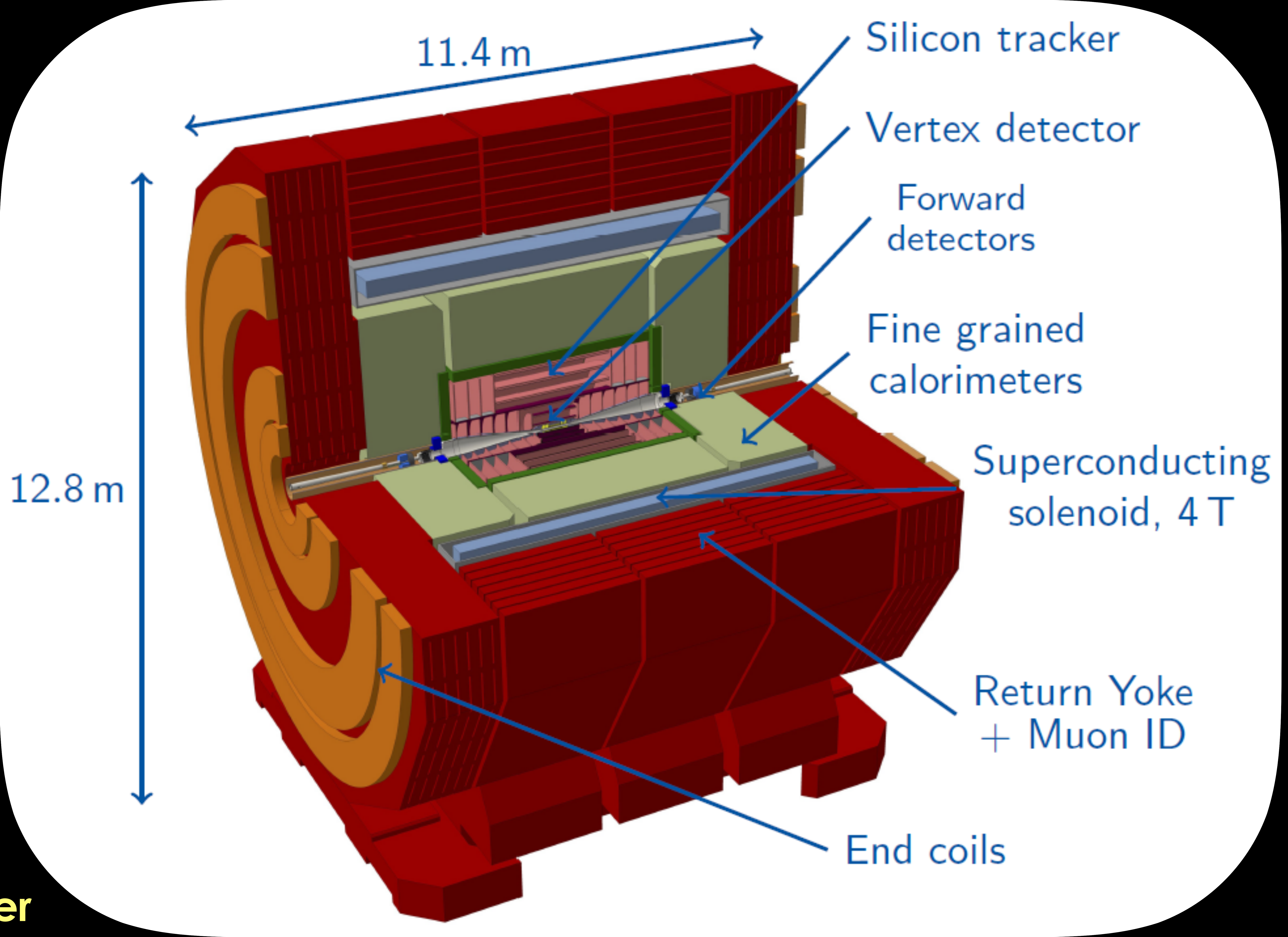
Movable platforms, keeping services connected and allowing fast re-alignment

Full process to take about two days

CLIC: CLICdet

SiD/ILD inspired detector





- Silicon vertex detector + tracker
  - R = 1.5 m
- B-field: 4 Tesla
- Calorimeter: Fine grained — particle flow analysis

Final focus magnets (QD0) outside detector:
→ increase HCAL forward acceptance

FCC-ee: CLD – CLIC inspired detector

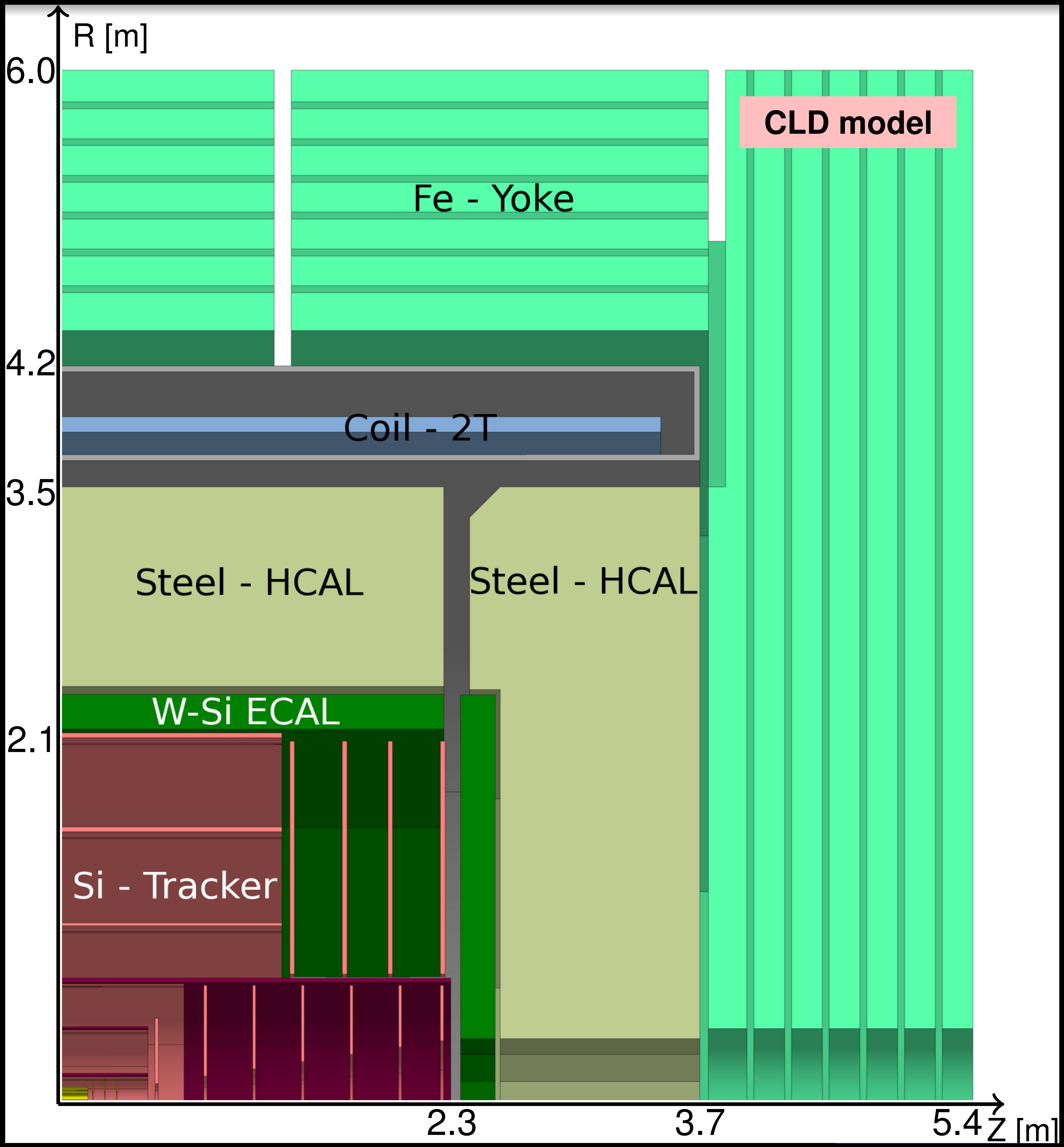
Final focus magnet inside detector: L* = 2.2 m

Lower magnetic field to not disturb beam

Larger tracker radius

Smaller radius HCAL, given lower √s

	CLICdet		CLD
VTX Barrel	31-60 mm	$\Longrightarrow$	17-59 mm
VTX Endcap	Spirals	$\Longrightarrow$	Disks
Tracker radius	1486 mm	$\Longrightarrow$	2100 mm
ECAL thickness	40 layers, 22 X_0	$\Longrightarrow$	40 layers, 22 X_0
HCAL thickness	60 layers, 7.5 λ_I	$\Longrightarrow$	44 layers, 5.5 λ_I
Yoke thickness	1989 mm	$\Longrightarrow$	1521 mm
MDI (forward region)		$\Longrightarrow$	$<$ 150 mrad
Solenoid field	4 Tesla	$\Longrightarrow$	2 Tesla

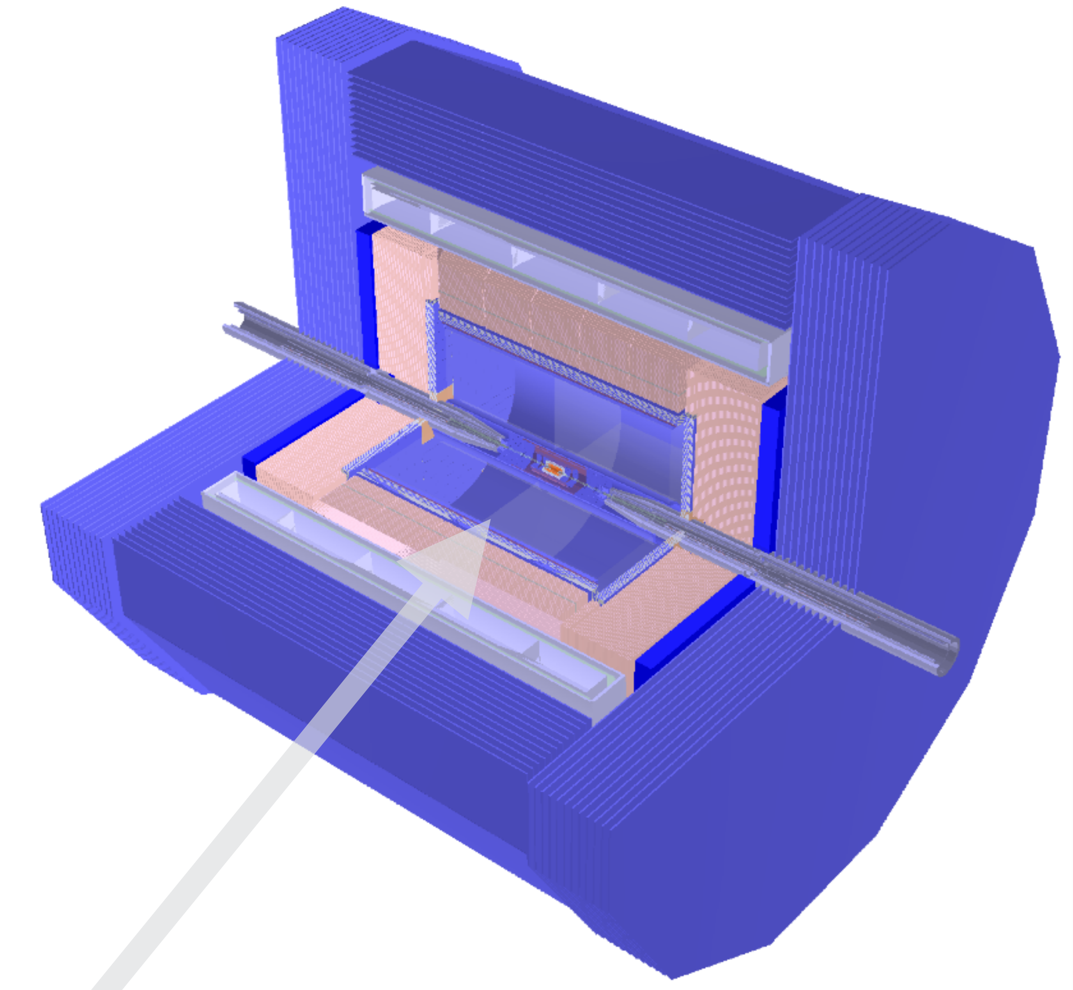


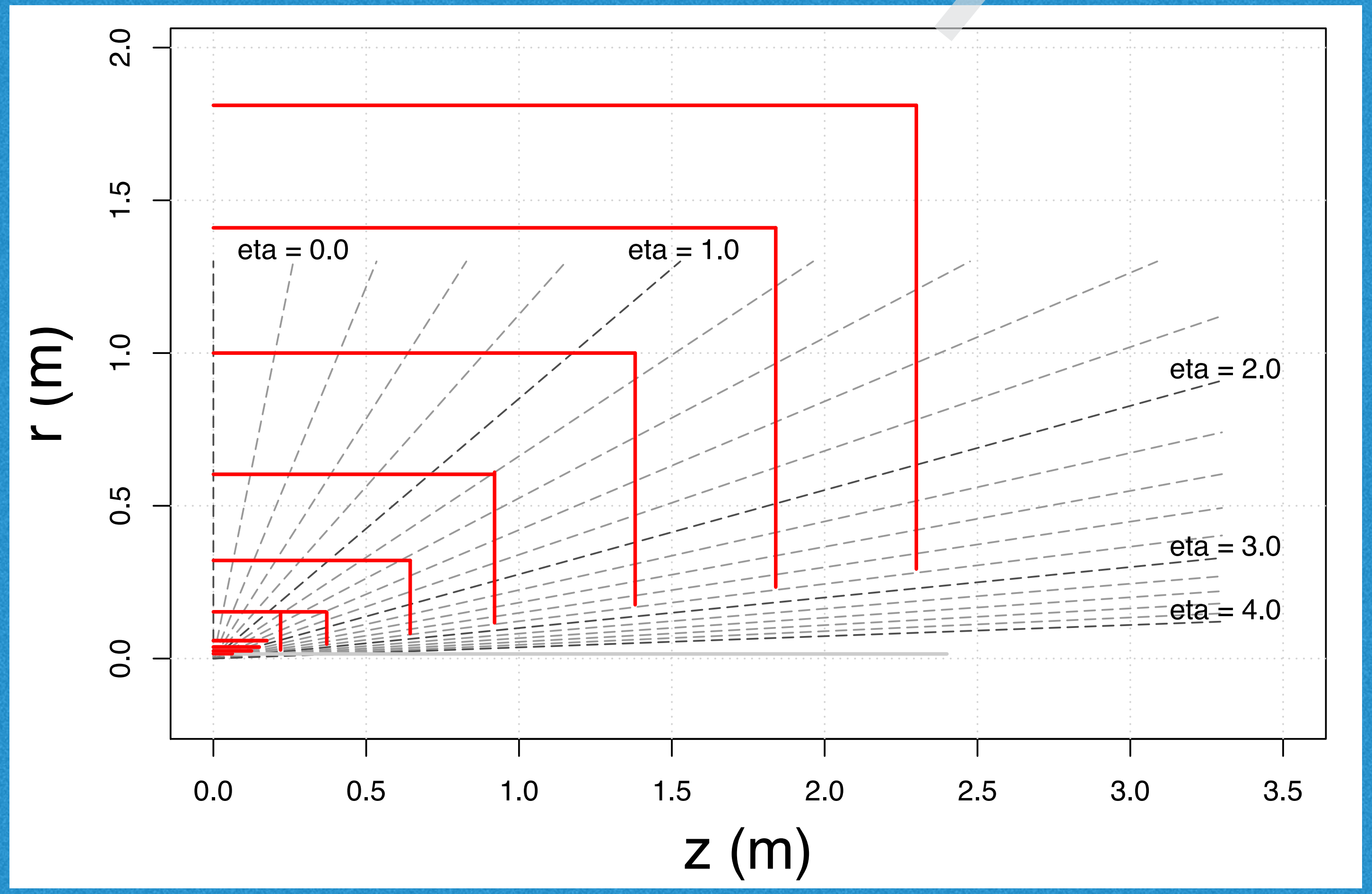
Post-CDR: beam pipe at IP radius reduced from 15 mm to 10 mm

CEPC: 2.5 detector concepts

Particle Flow Approach

Baseline detector
ILD-like
(3 Tesla)

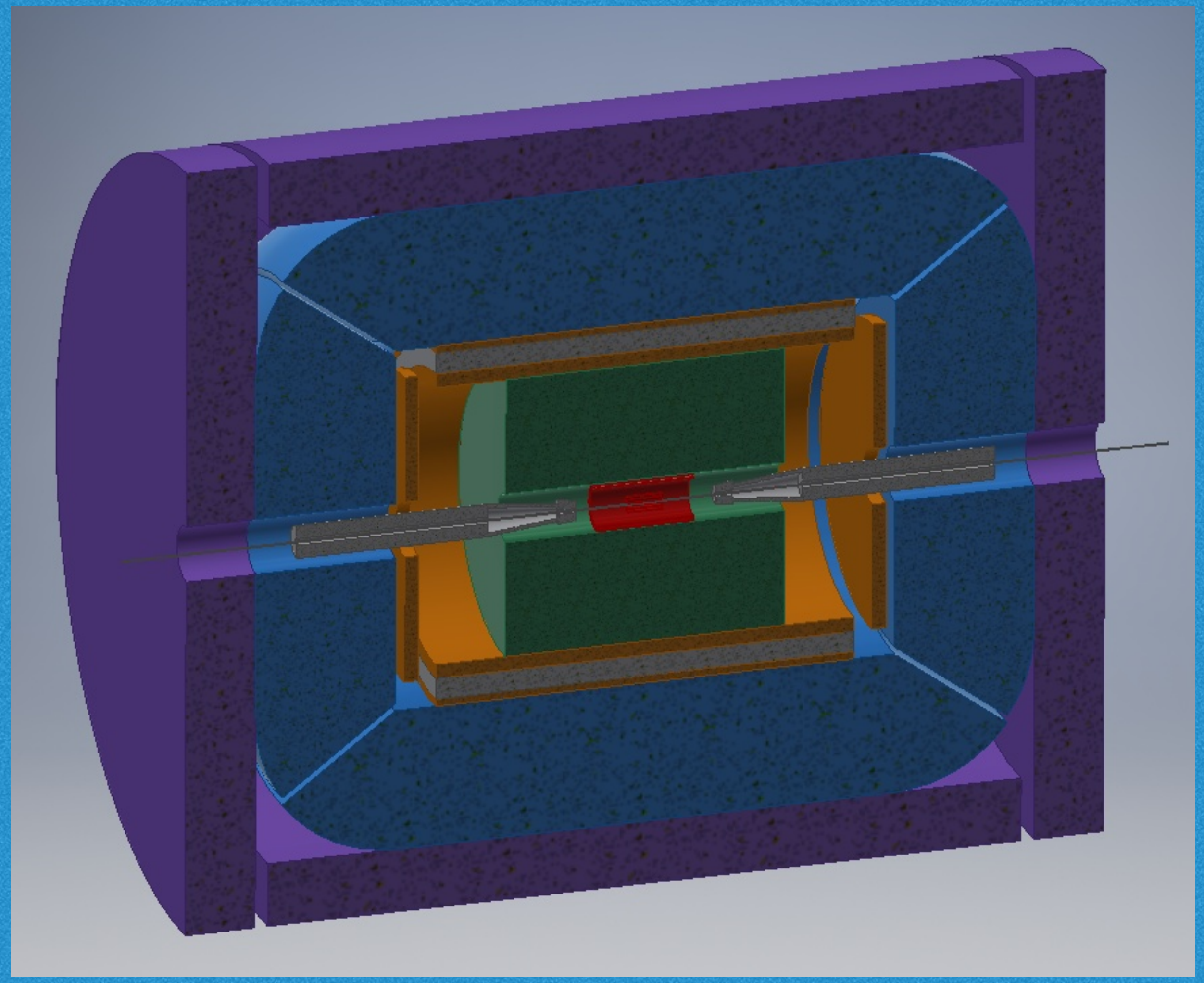




Full silicon
tracker
concept

CEPC plans for
2 interaction points

Low
magnetic field
concept
(2 Tesla)

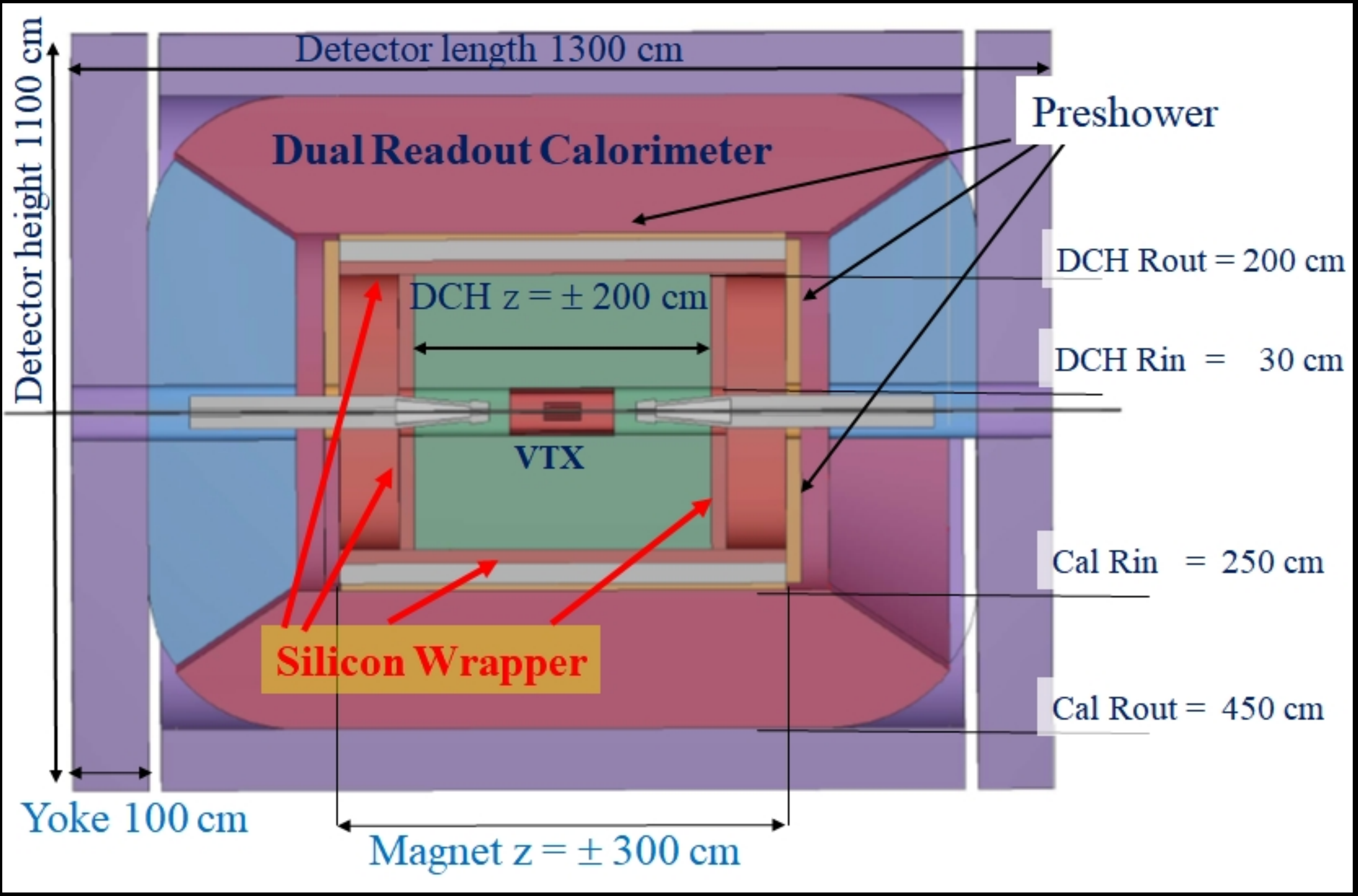


IDEA - also proposed for FCC-ee

Final two detectors likely to be a mix and match of different options

CEPC + FCC-ee: IDEA

Only concept with calorimeter outside the coil



Magnet: 2 Tesla, 2.1 m radius

Thin (~ 30 cm), low-mass (~0.8 X_0)

Vertex: Similar to CEPC default

- **Drift chamber:** 4 m long; Radius ~30-200 cm, ~ 1.6% X_0 , 112 layers

Preshower: ~1 X_0

- **Dual-readout calorimeter:** 2 m/8 λ_{int}

- (yoke) muon chambers (MPGD)

Detector Challenges

Machine–detector interface (MDI) in circular colliders

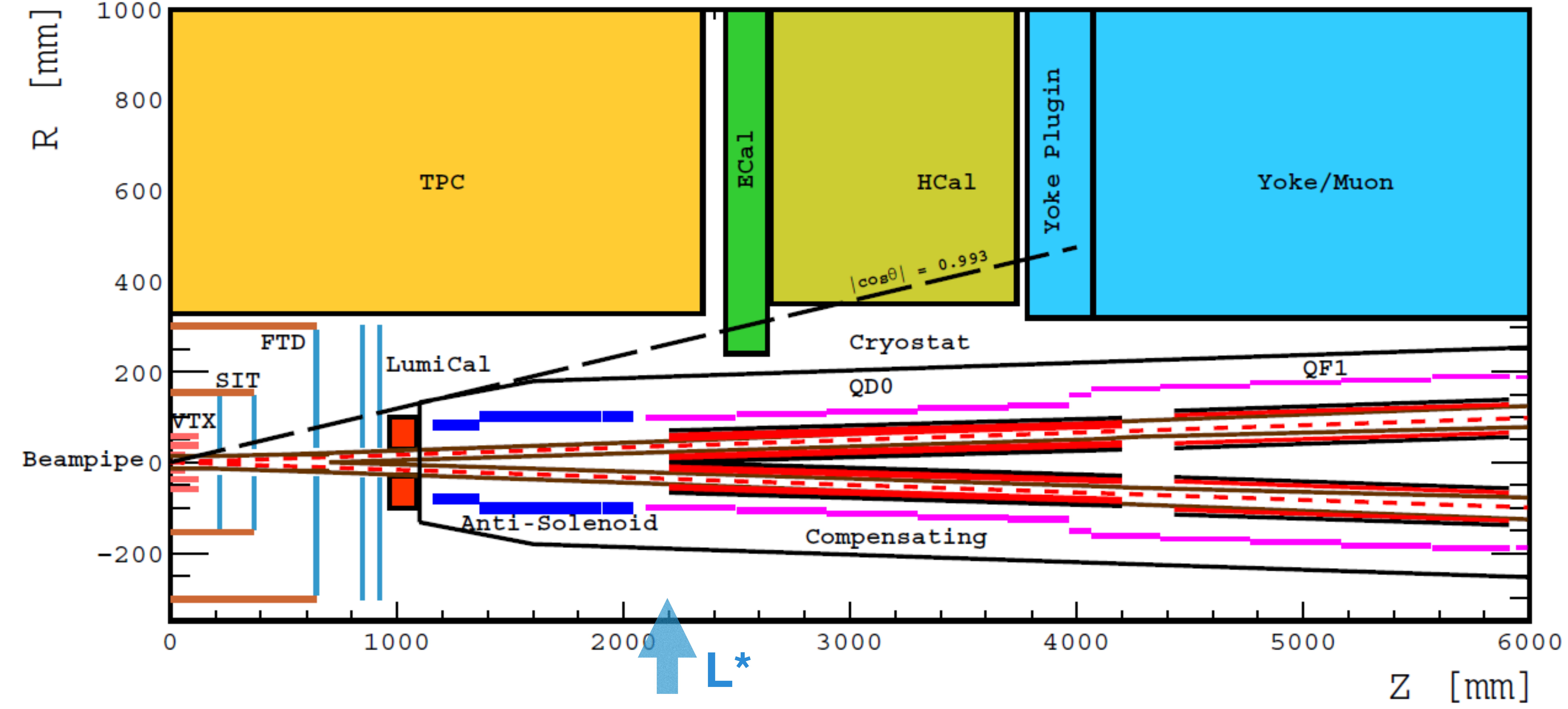
High luminosities ➡ Final focusing quadrupole (QD0) needs to be very close to IP

L* = 2.2 m at FCC-ee and CEPC

Detector acceptance:
> ± 150 mrad

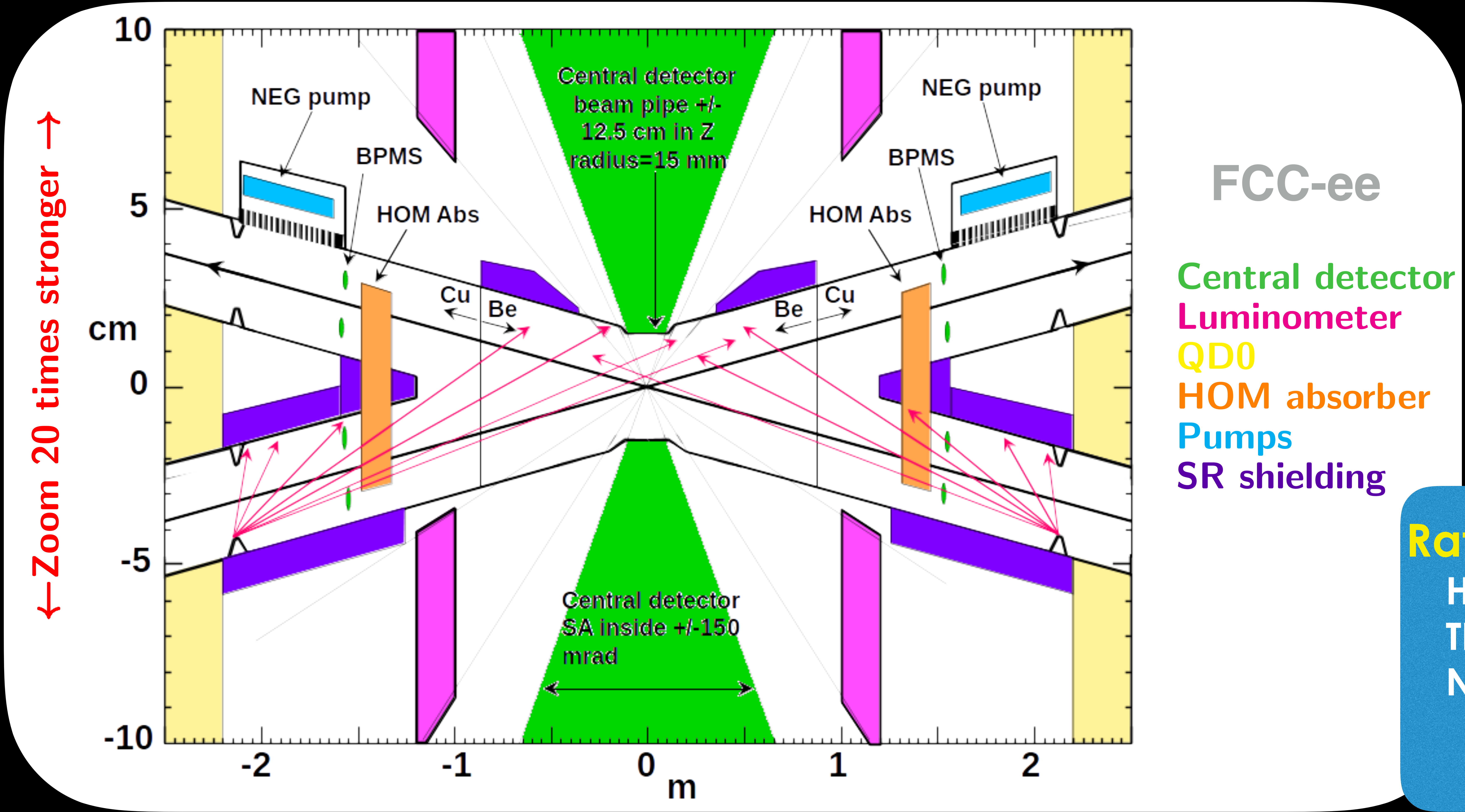
Solenoid magnetic field limited:
2-3 Tesla

due to beam emittance blow up



Synchroton radiation in circular colliders: Shielding

Shielding added to prevent synchrotron radiation/secondary radiation to enter the detector



Rates at the inner layer (16 mm):

Hit density: ~2.5 hits/cm²/BX
TID: 2.5 MRad/year
NIEL: 10^{12} 1MeV n_{eq}/cm²

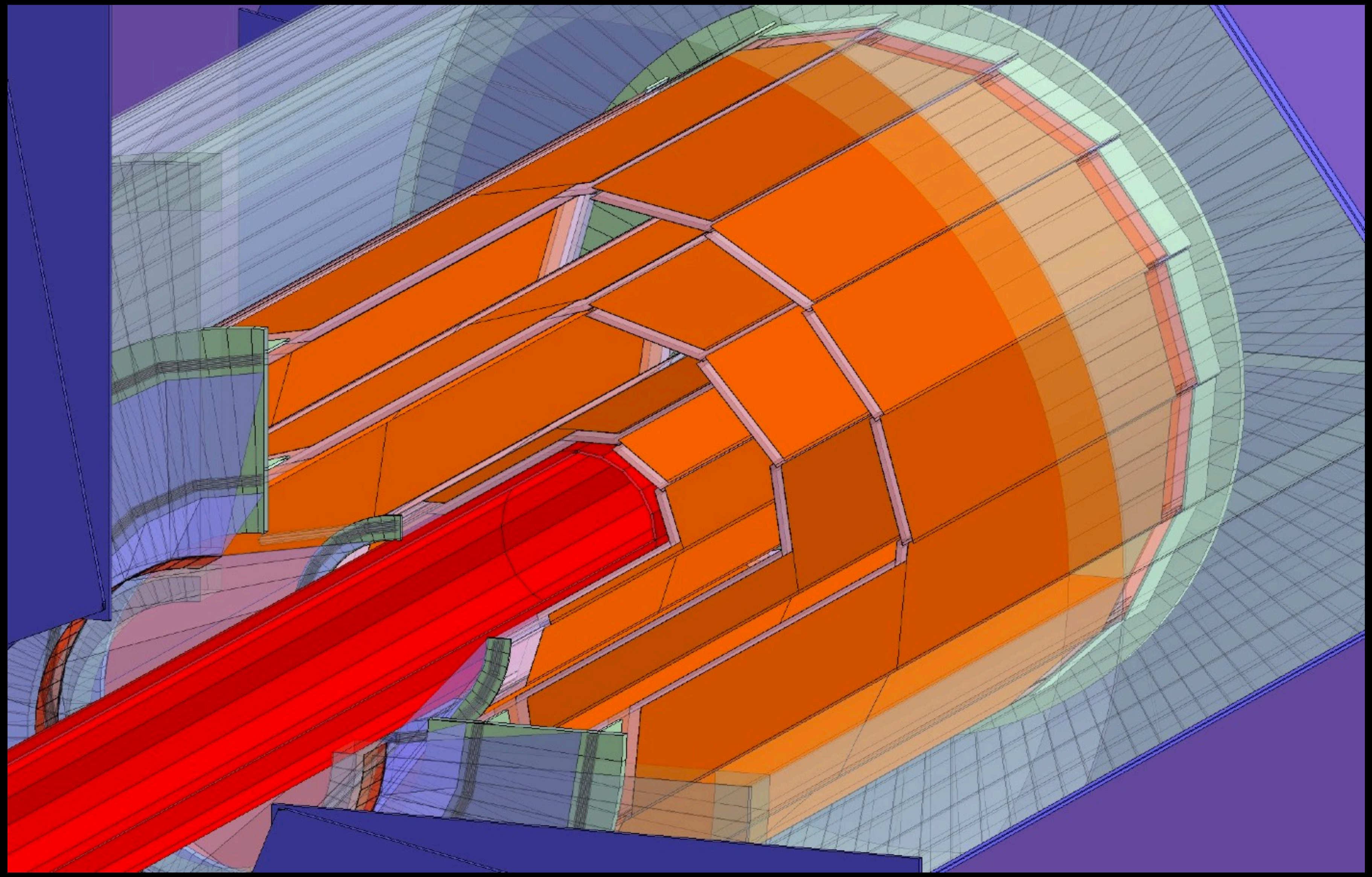
(Safety factors of 10 applied)

Cooling of beampipe needed → increases material budget near the interaction point (IP)

Challenges in vertex detectors

Vertex detector design driven by needs of flavor tagging

- Extremely accurate/precise
- Extremely light



Large surfaces: ~ 1 m^2

Single point resolution $\sigma < 3 - 5\ \mu m$ → Pixel pitch $\sim 16 - 25\ \mu m$

Low material budget $< 0.1 — 0.3\% X_0$ per layer → Thin sensors and ASICs, Light-weight support

Low material budget $< 0.1 — 0.3\% X_0$ per layer → Power pulsing (LC), Air cooling → Low power dissipation $\leq 50\ mW/cm^2$

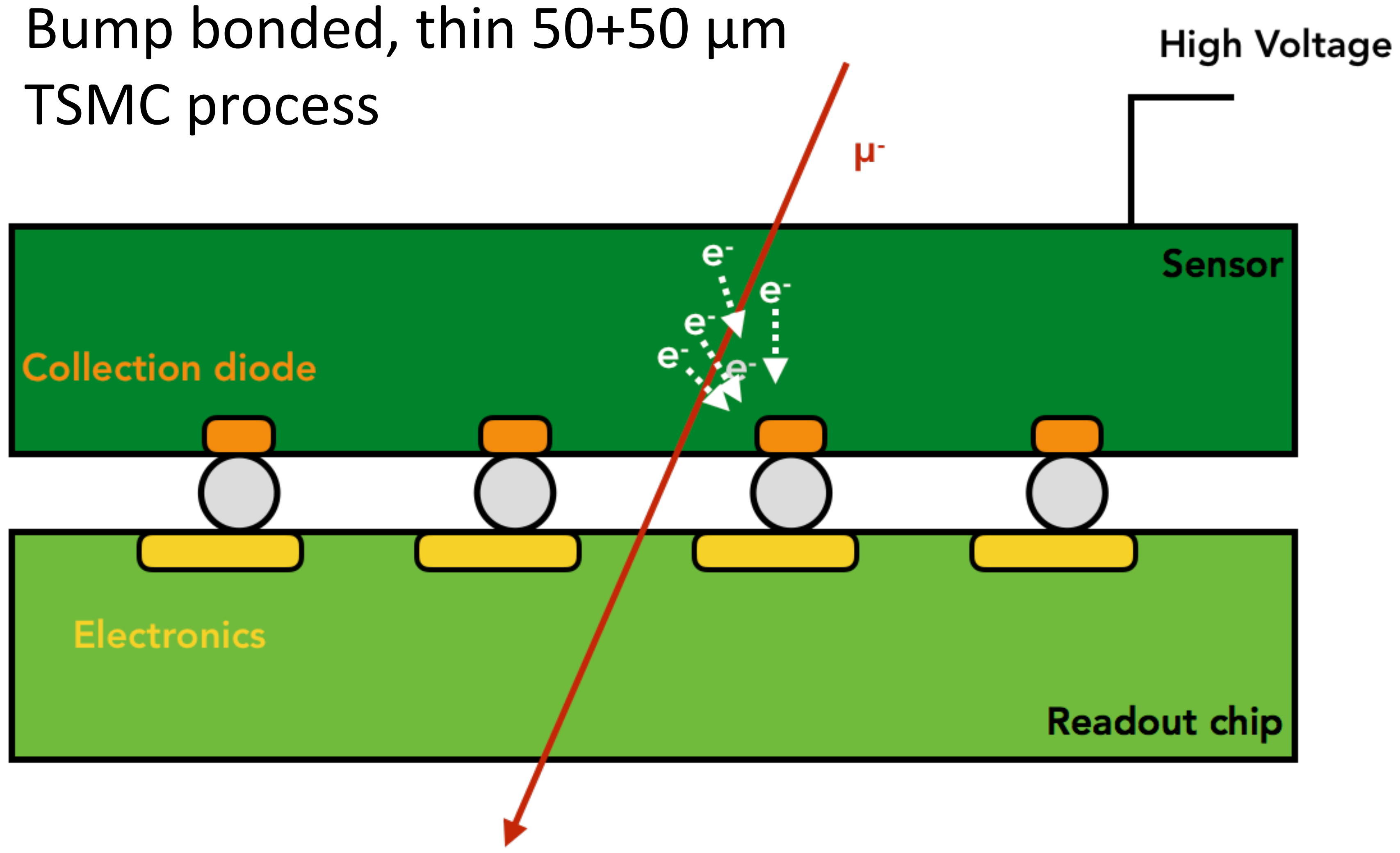
Time stamping
~10 ns (CLIC)
~30 ns — μs (ILC/CC)

Circular colliders: continuous operation → more cooling → more material

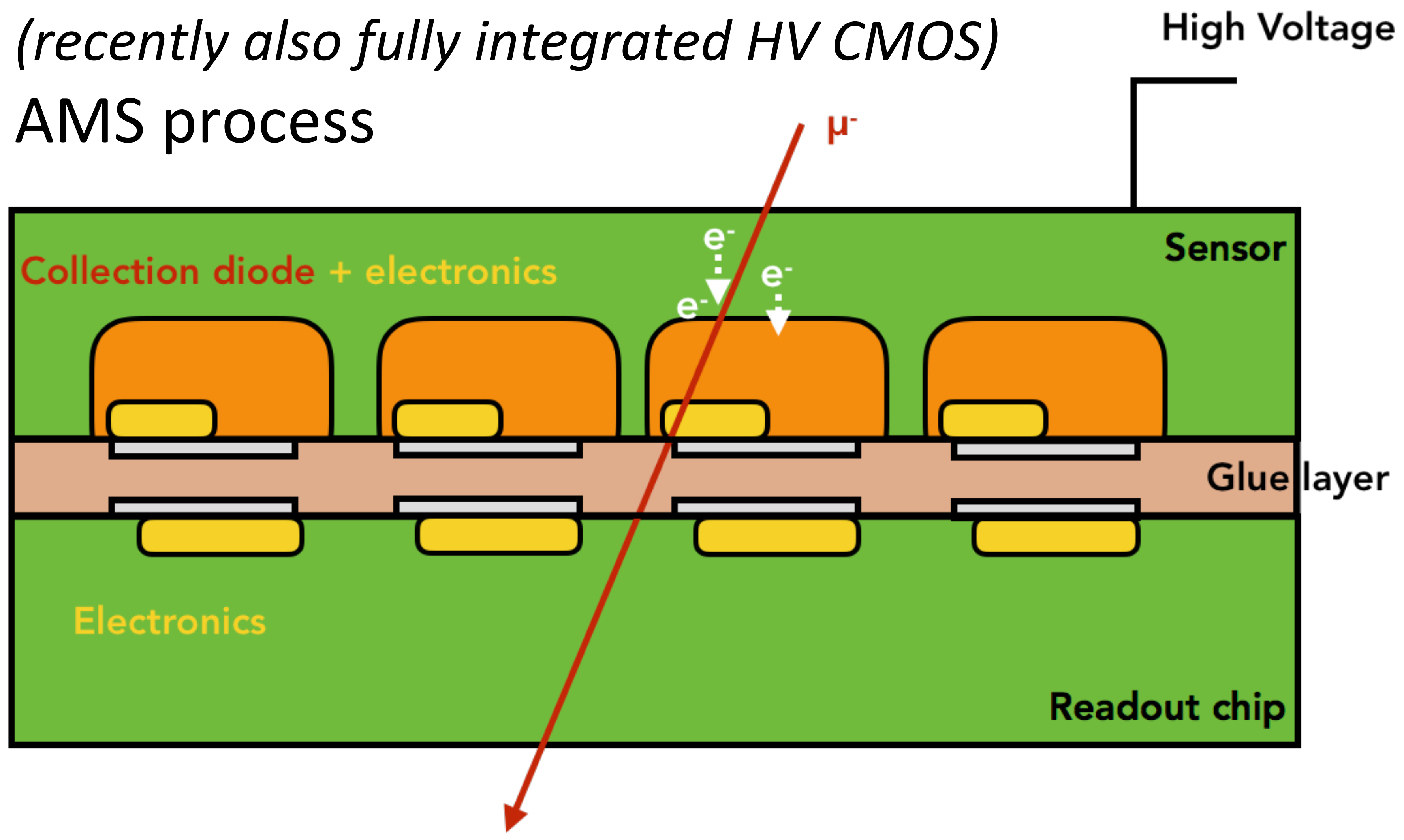
Silicon pixel–detector technologies

CLICpix
HV-CMOS
hybrid

Hybrid: Si sensor + ASIC (65 nm)
Bump bonded, thin 50+50 μm
TSMC process

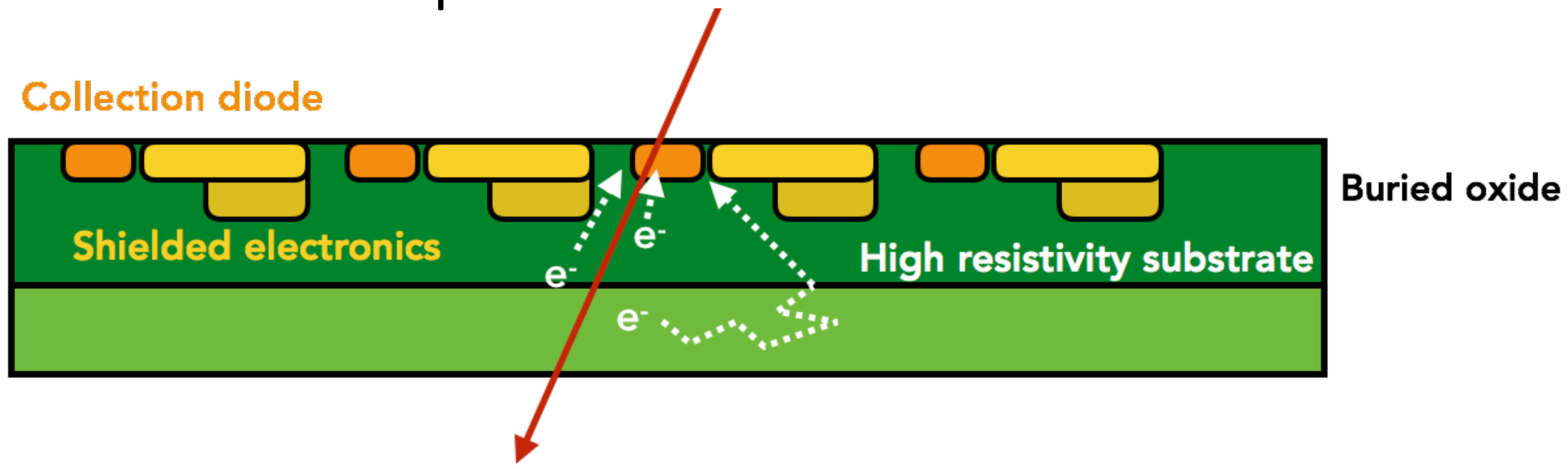


Hybrid: HV CMOS active sensor + ASIC (65 nm)
Capacitive coupling (glue)
(recently also fully integrated HV CMOS)
AMS process

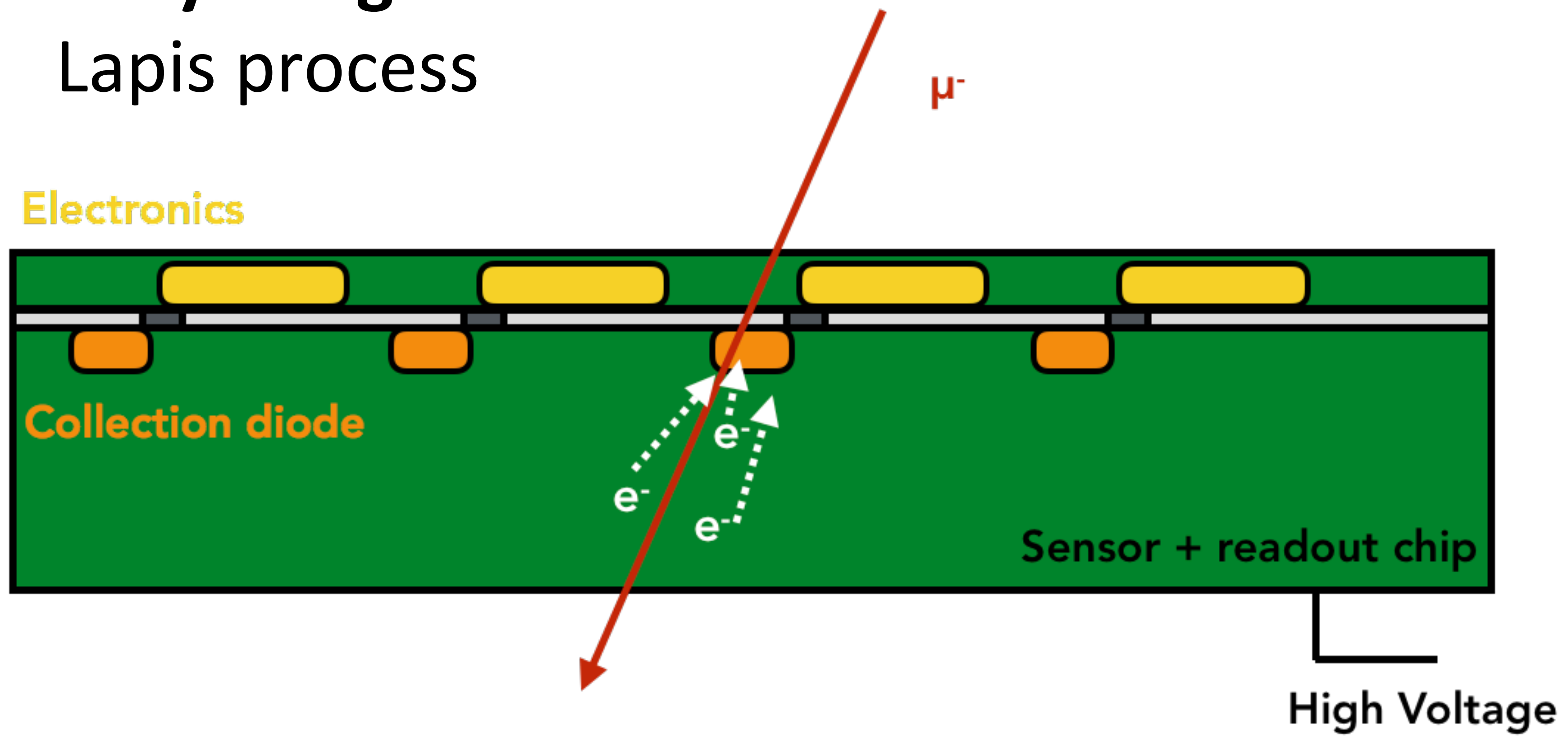


MAPS
HV-CMOS
HR-CMOS
Mimosa CPS

Fully integrated: HR CMOS
TowerJazz process



Fully integrated: SOI
Lapis process



SOI
Silicon
-On
-Insulator

Systematics R&D studies have focused on Pixel implementation, with Pixel sizes around 25×25 μm^2
Studies equally valid for the main tracker, even though it will have larger cell sizes

Monolithic Active Pixel Sensor (MAPS)

Fully Integrated CMOS Technology

- ✦ CMOS Image Pixel Sensors —> benefit from industrialization
  - ➡ Commercial process (8” or 12” wafers)
  - ➡ Multiple vendors
  - ➡ Potentially cheaper interconnection processes available
  - ➡ Thin sensor (50–100 um) have less material

Early Generations

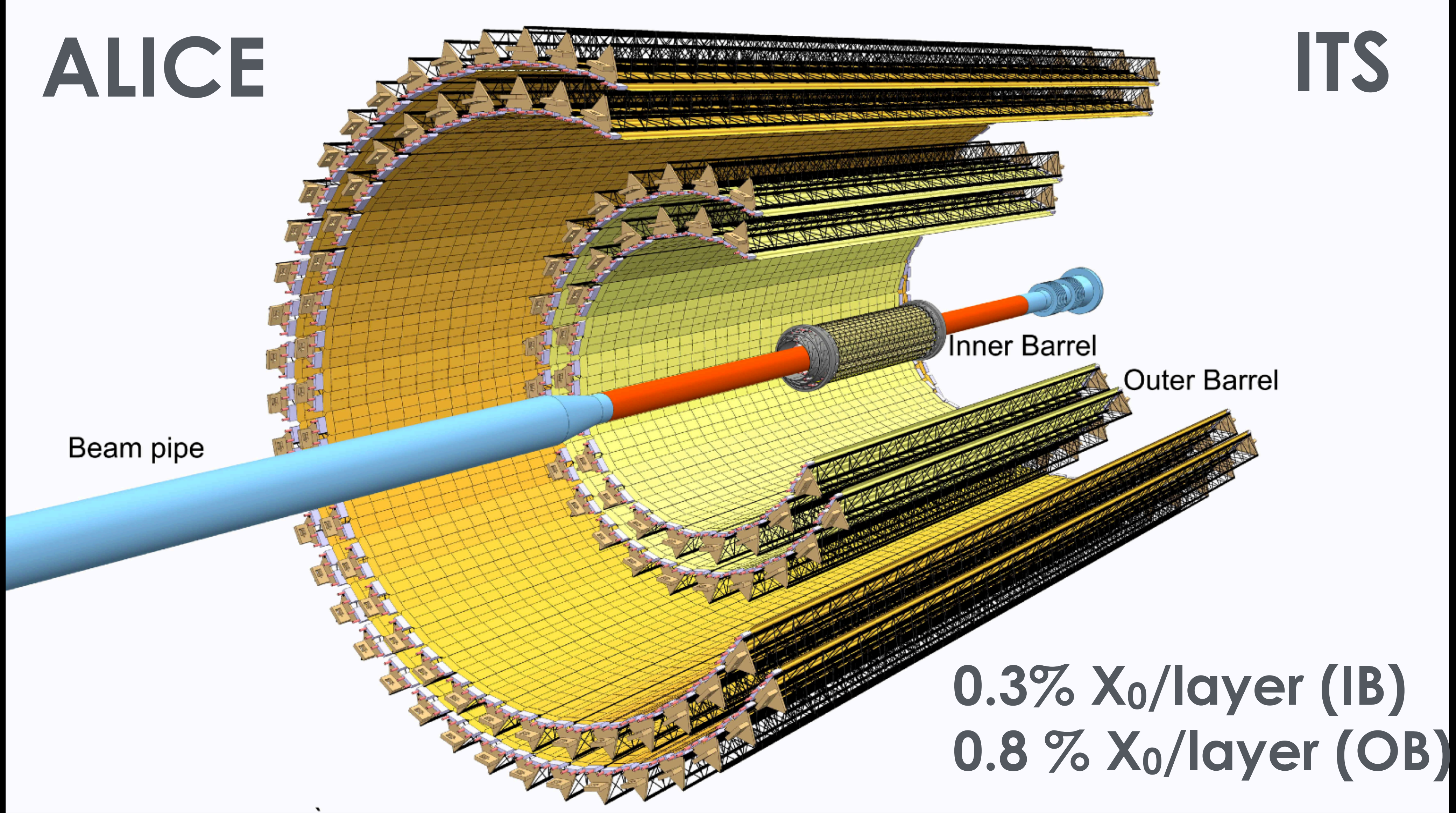
- ✦ Charge collection mainly by diffusion
- ✦ Timing limited by rolling-shutter readout (μs)

Recent advances

- ✦ Moving towards smaller feature size (TowerJazz 180 nm)
- ✦ Promising timing performance

Successfully deployed in HEP, with increasingly demanding requirements:

- Test-beam telescopes
- STAR @ RHIC
- CBM MVD @ FAIR
- ALICE ITS upgrade
- Baseline technology for ILD VTX, under study for CEPC and CLIC

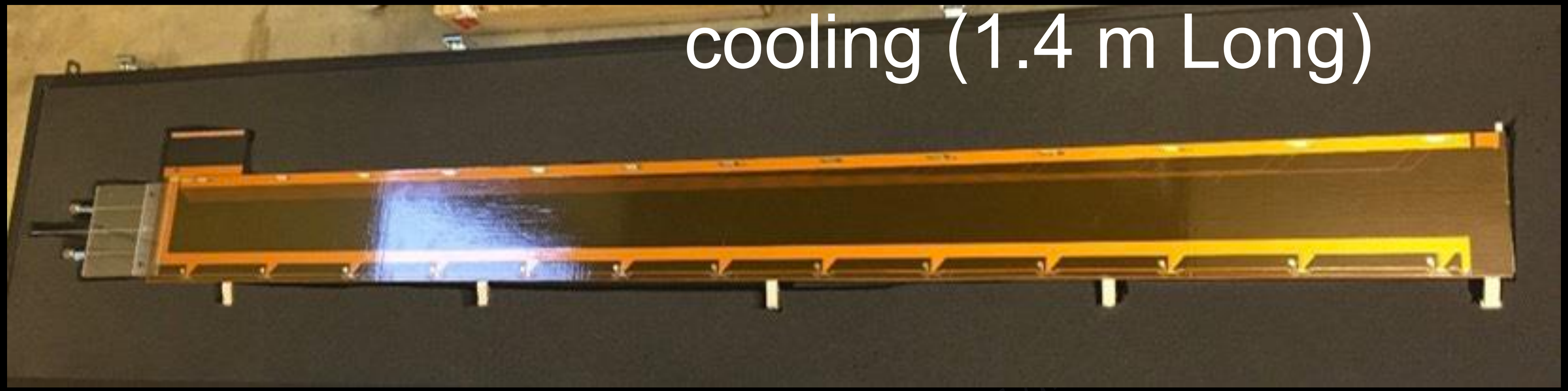


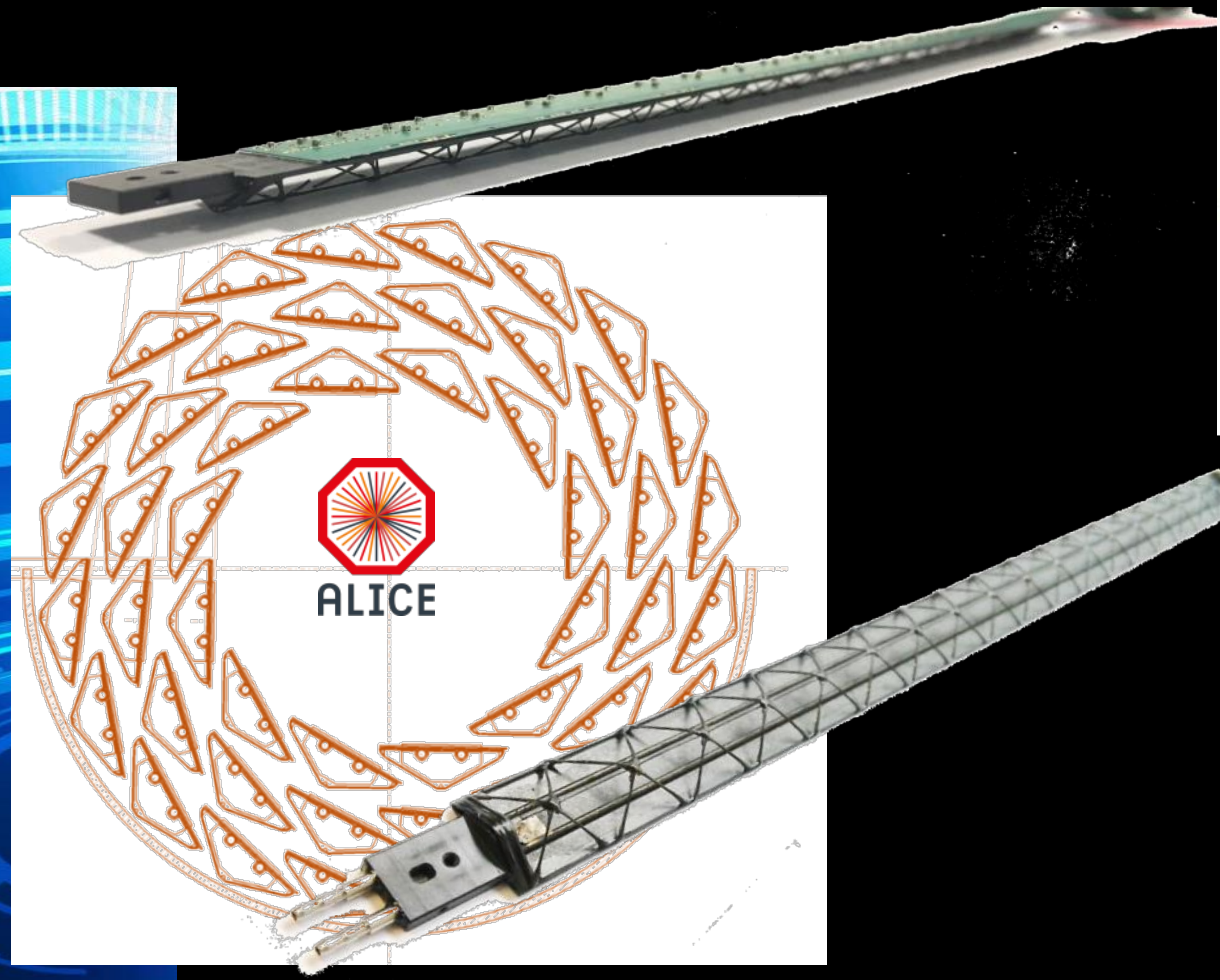
0.3% X_0/layer (IB)
0.8 % X_0/layer (OB)

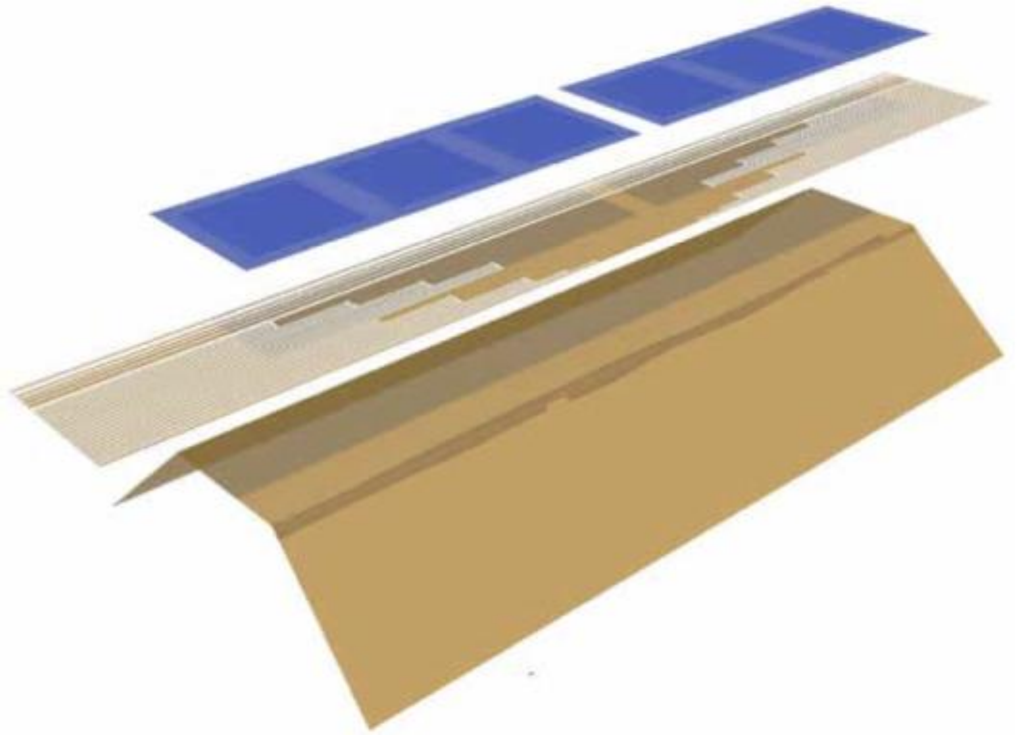
MATERIAL REDUCTION

- Non conventional use of Carbon Fibre Reinforced Plastic (CFRP) materials for Vertex Detectors to match the requirement of minimum material budget, high rigidity, thermal management.

ATLAS ITK module support structure with copper-Kapton co-cured tape and embedded CO2 cooling (1.4 m Long)





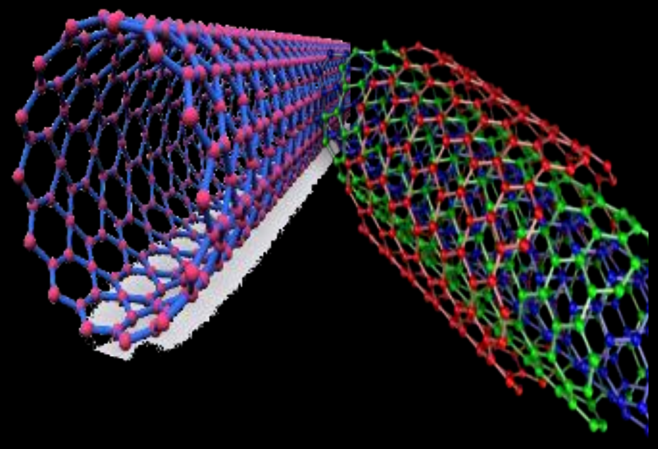


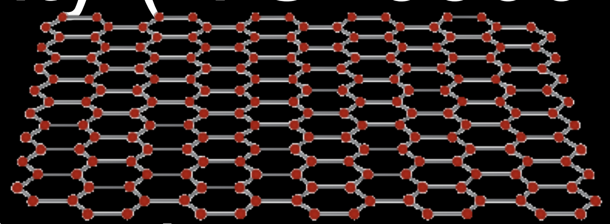
- 50 µm DMAPS
- 25 µm Kapton Flexprint
- 50 µm Kapton support frame
- < 1‰ Radiation length


Mu3e

Carbon Nanotubes

Allotrope of carbon with a cylindrical nanostructure
Very high Therma Conductivity (TC=3500 W/mK)





Graphene

One atomic-layer thin film of carbon atoms in honeycomb lattice. Graphene shows outstanding thermal performance, the intrinsic TC of a single layer is 3000-5000 W/mK

Challenges in tracking detectors

Goal: very good momentum resolution, with preferably good PID capabilities

Different detectors, each with large B × R^2

- **SiD, CLICdet, CEPC**: all silicon tracker
- **ILD, IDEA, CEPC**: silicon + gaseous tracking

Silicon tracker challenges

Large surface area of O(100 m^2)

Solution: Integrated sensors with large pixels/strips (~ 30 µm × 1-10 mm)

Maintain efficiency and good timing

(despite large detector area)

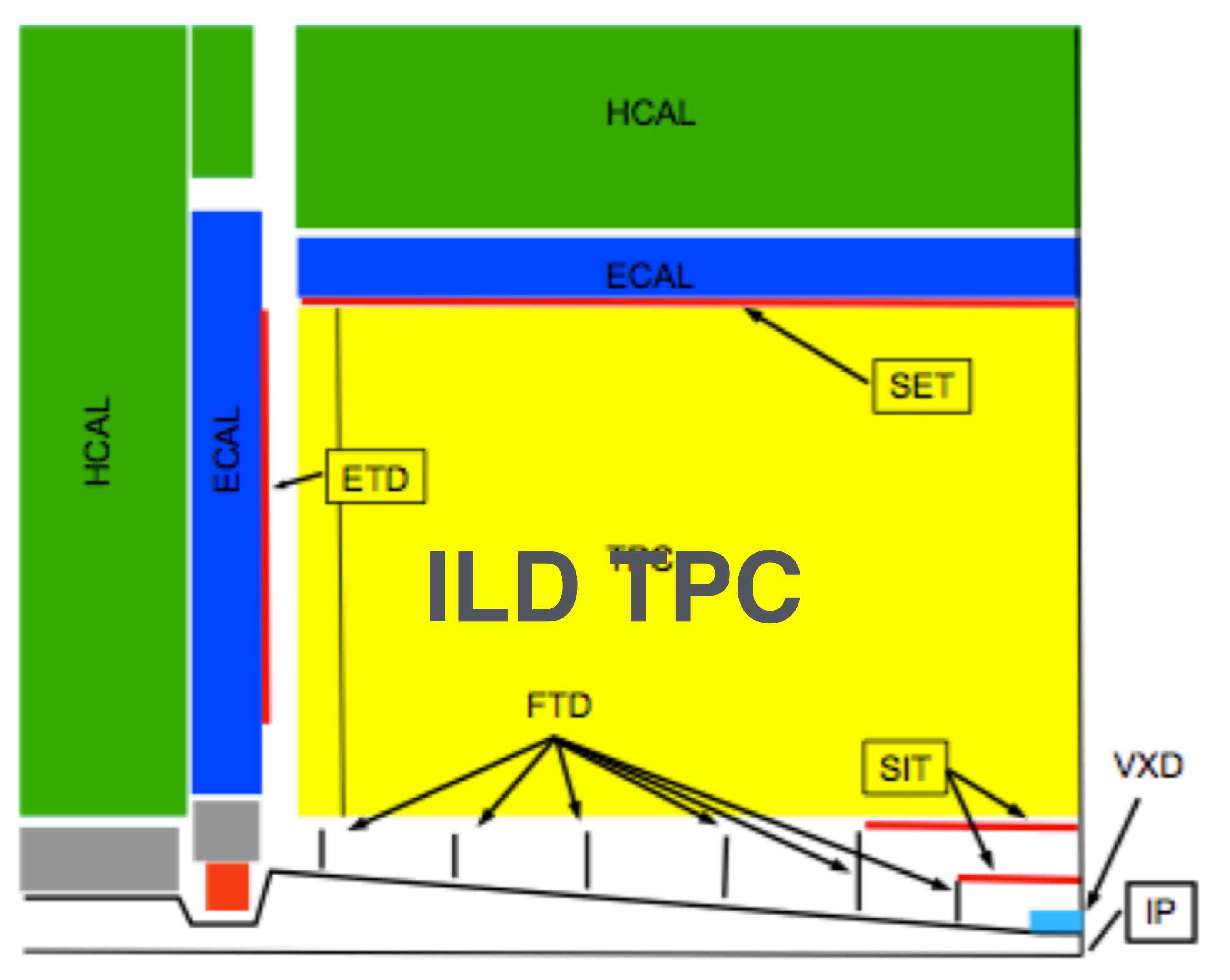
Mechanical stiffness with low-mass materials

Light-weight cooling methods

Gas detector challenges

Hit timing and momentum resolution

Solution: Silicon wrapper around detectors



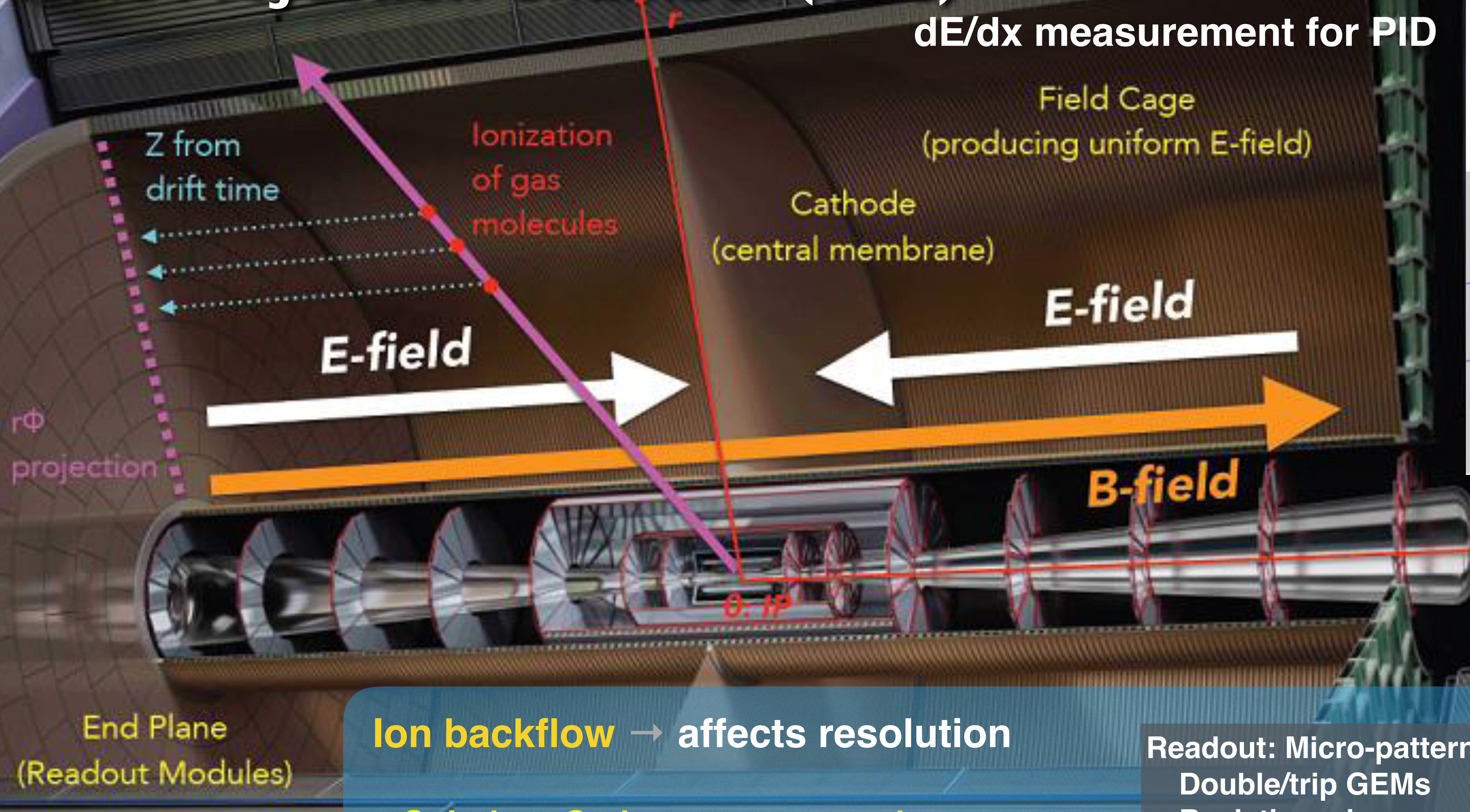
Occupancies at high event rates

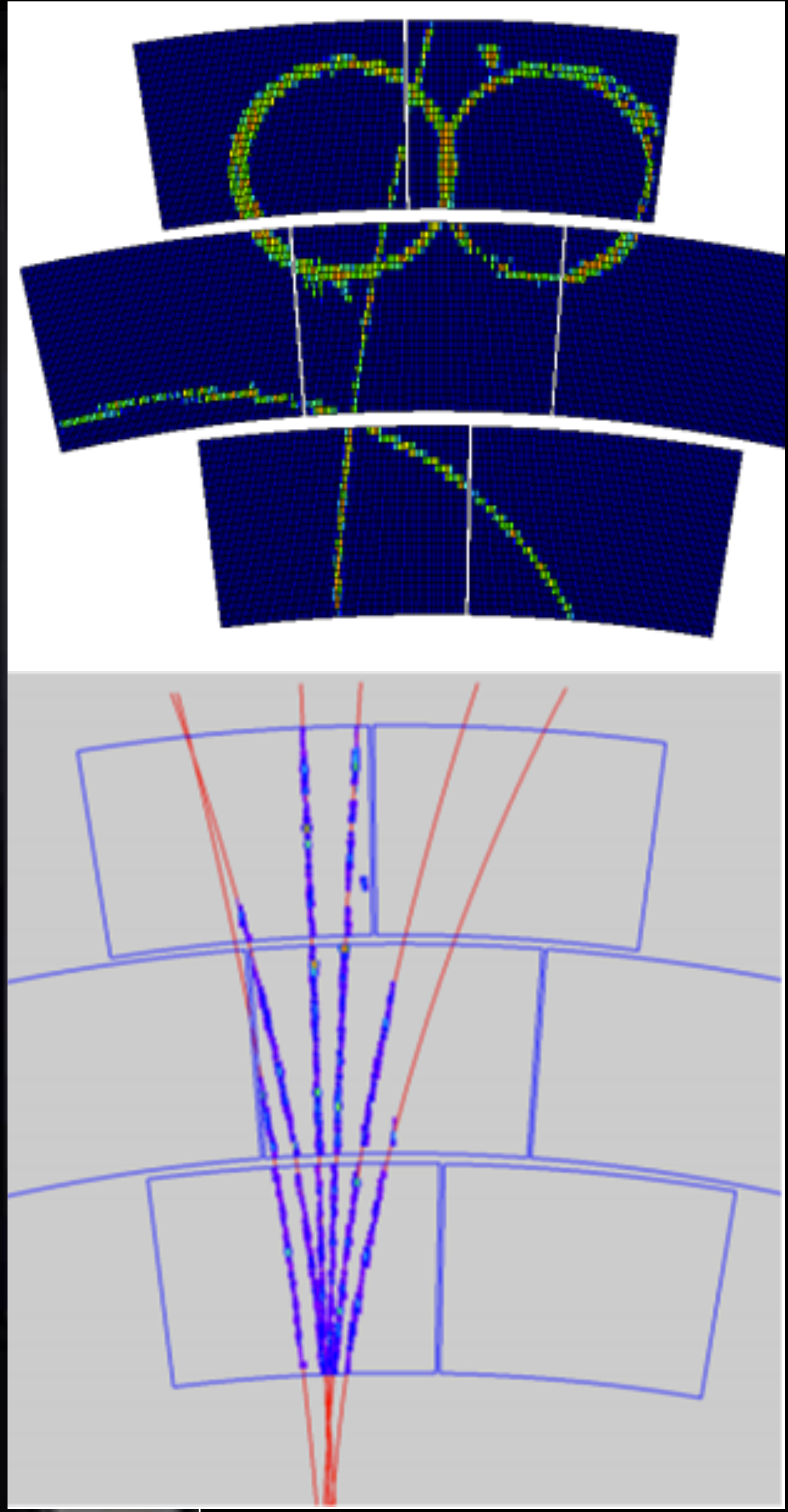
Meets requirements for ILC

Under study for Z-pole running at CEPC

Time Projection Chamber (TPC)

dE/dx measurement for PID





Ion backflow → affects resolution

Solution: Gating concepts and new readout modules under study

Readout: Micro-pattern gas detectors
- **Double/trip GEMs**
- **Resistive micromegas**
- **Integrated pixel readout**

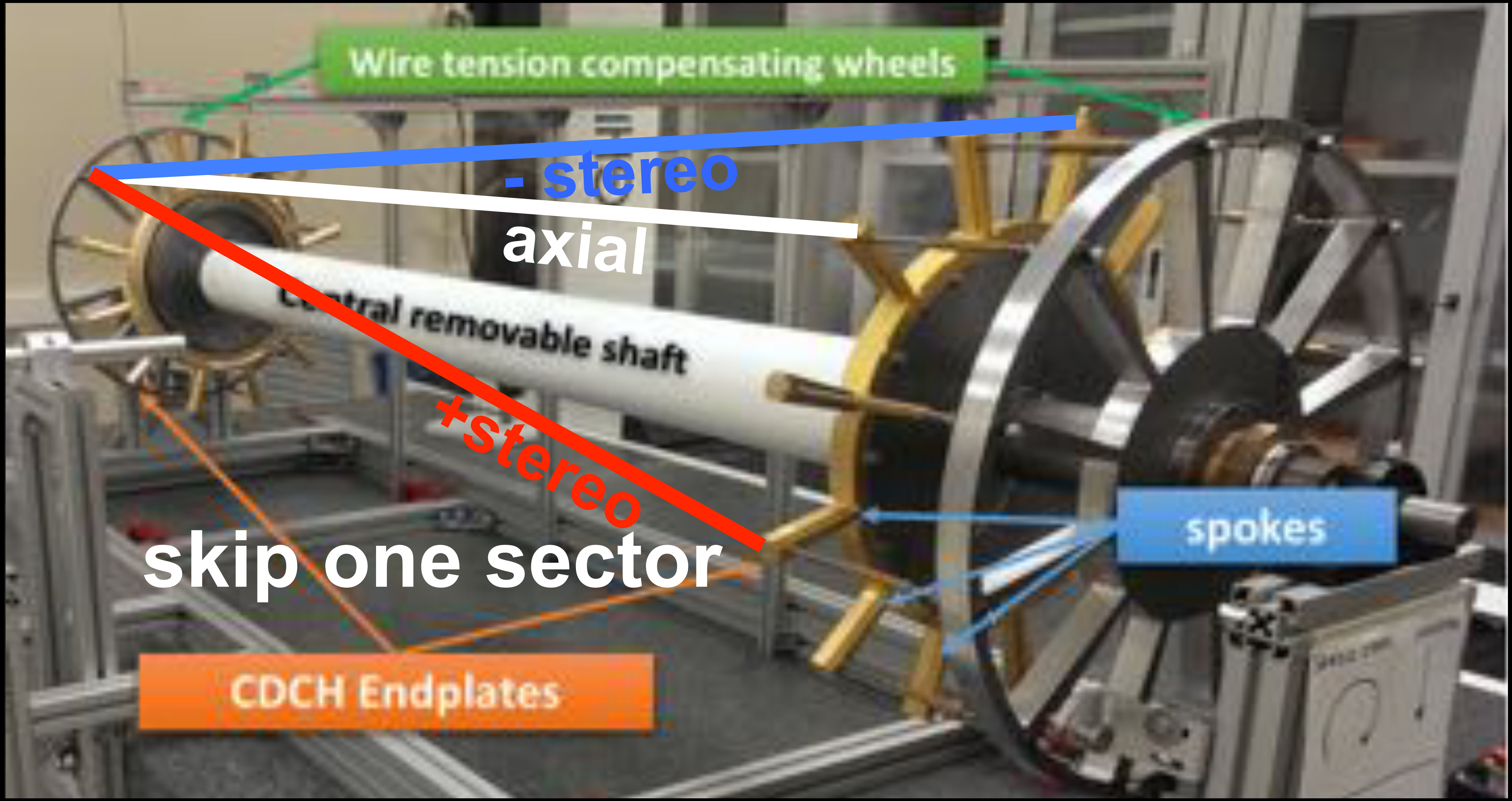
Drift Chamber

160 kg/spoke

IDEA: Ultra-light drift chamber

KLOE → MEG2 → IDEA

- 4 m long
- Radius ~30-200 cm
- 112 layers
- cell size: ~ 1.4 mm²



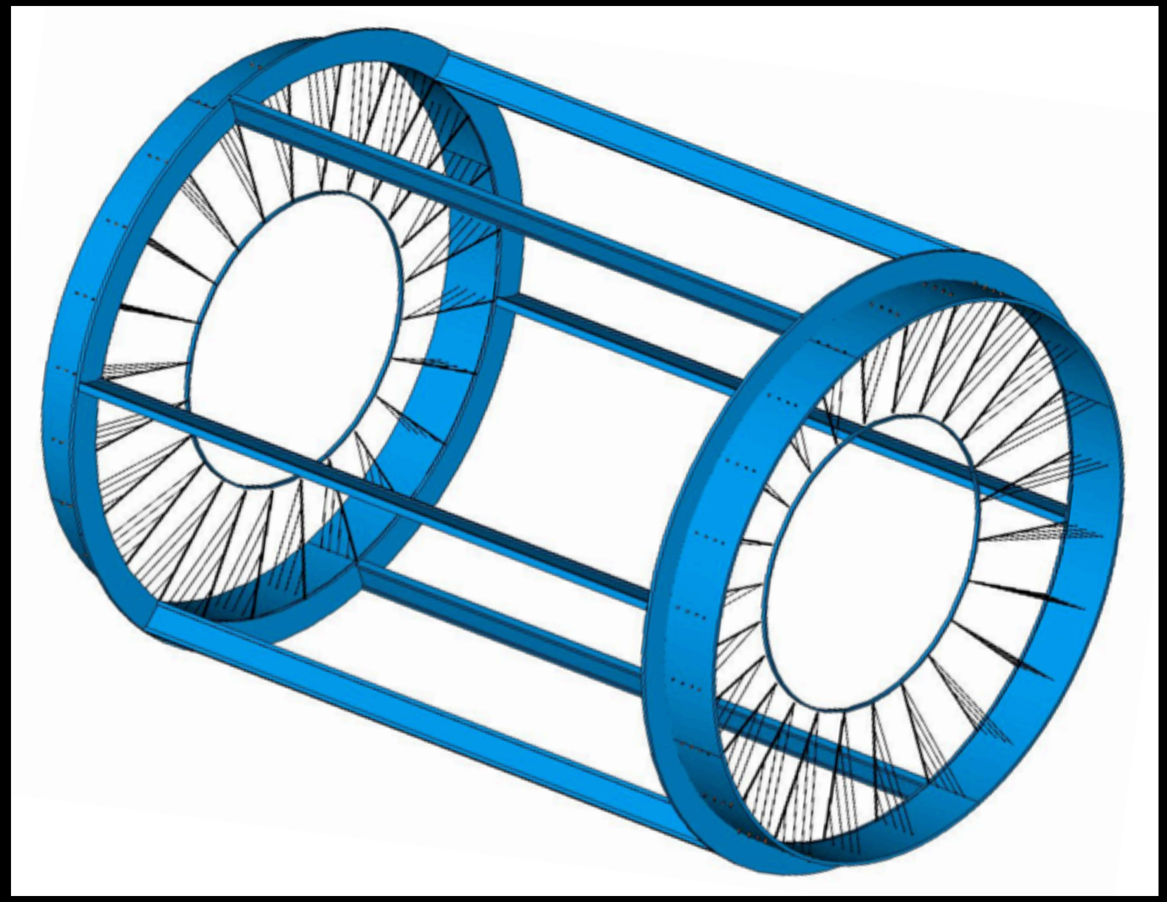
Material

	inner wall	gas	wires	outer wall	service area
thickness [mm]	0.2	1000	1000	20	250
X_0 [%]	0.08	0.07	0.13	1.2	4.5

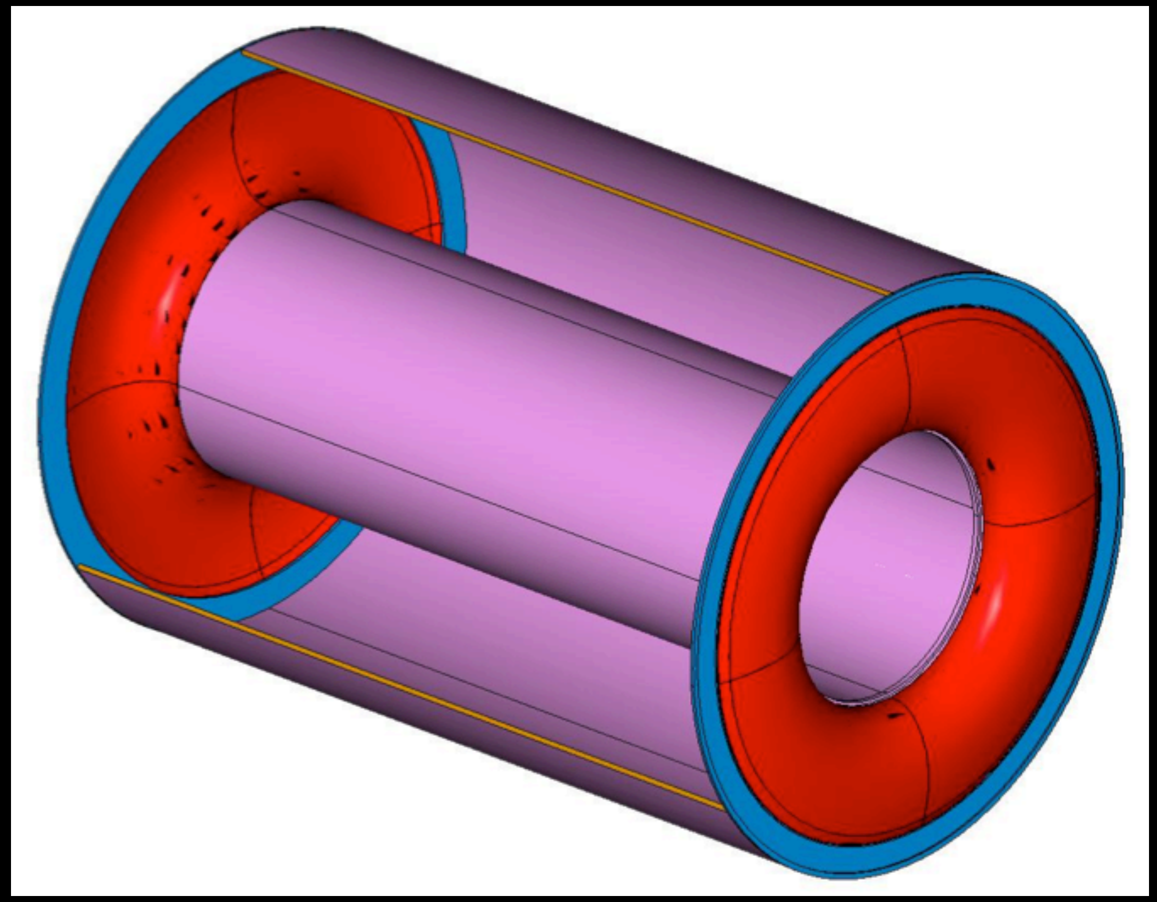
central: ~ 1.6% X_0

endcap ~ 5% X_0

Wire support



Gas containment



Particle flow calorimeters (ILC, CLIC, CEPC and FCC-ee)

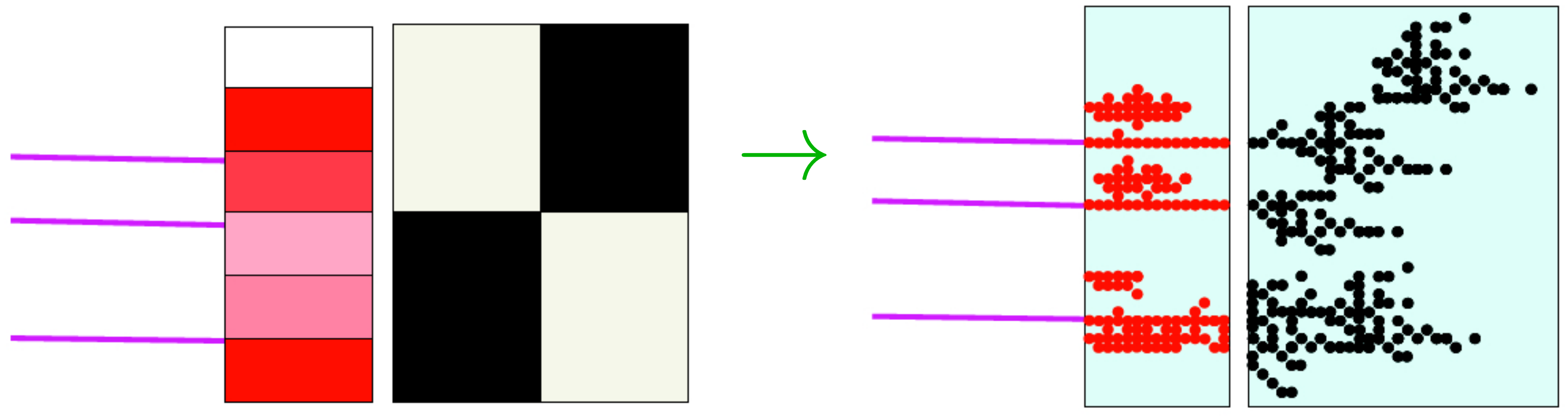
3%-4% jet energy resolution reachable with Particle Flow Analysis (PFA)

Average jet composition		**Use best information**
60% charged particles	→	60% tracker
30% photons	→	ECAL
10% neutral hadrons	→	HCAL

Full detector solution

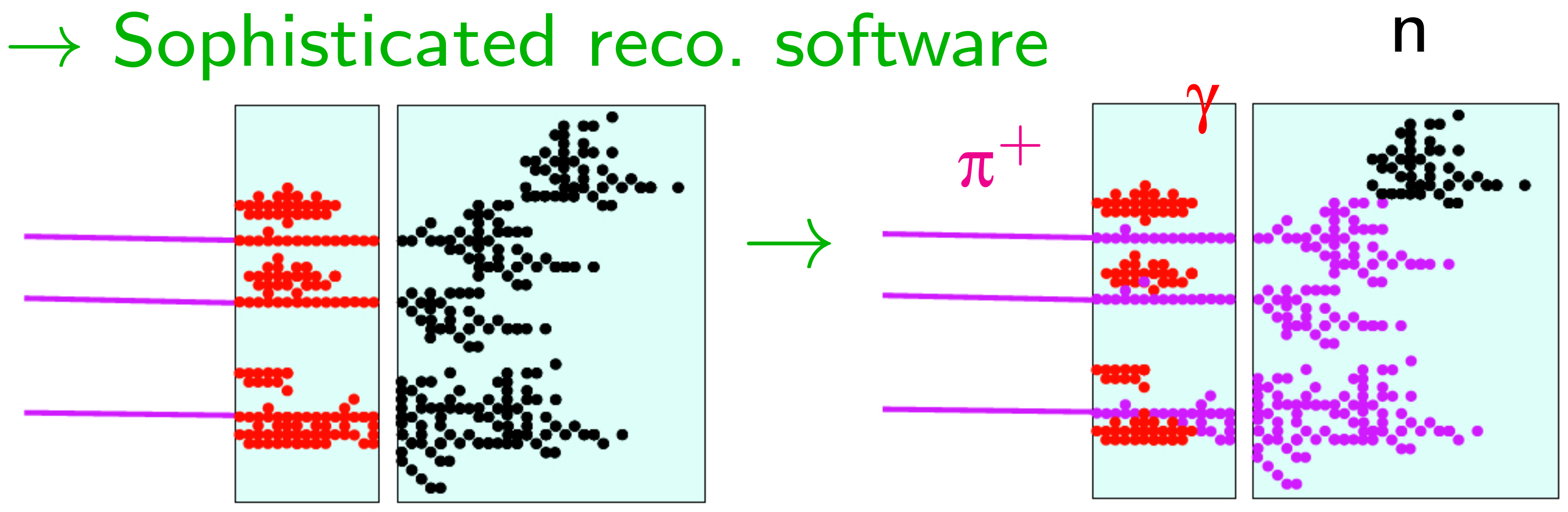
Particle Flow Analysis: Hardware + Software

- Hardware: Resolve energy deposits from different particles
  → High granularity calorimeters



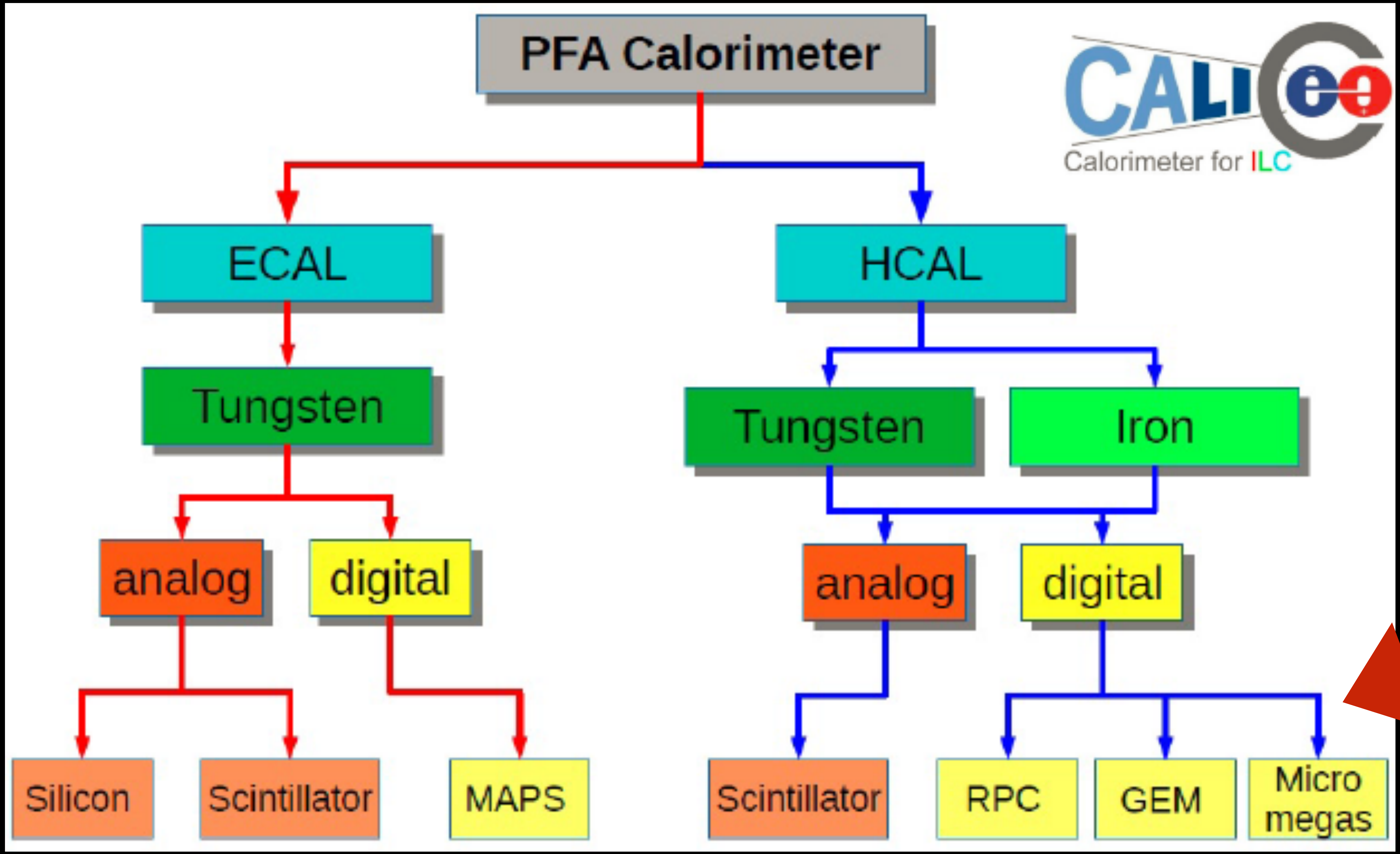
$E_{jet} = E_{ECAL} + E_{HCAL}$

- Software: Identify energy deposits from each individual particle
  → Sophisticated reco. software



$E_{jet} = E_{track} + E_{\gamma} + E_{n}$

Particle Flow calorimeter options



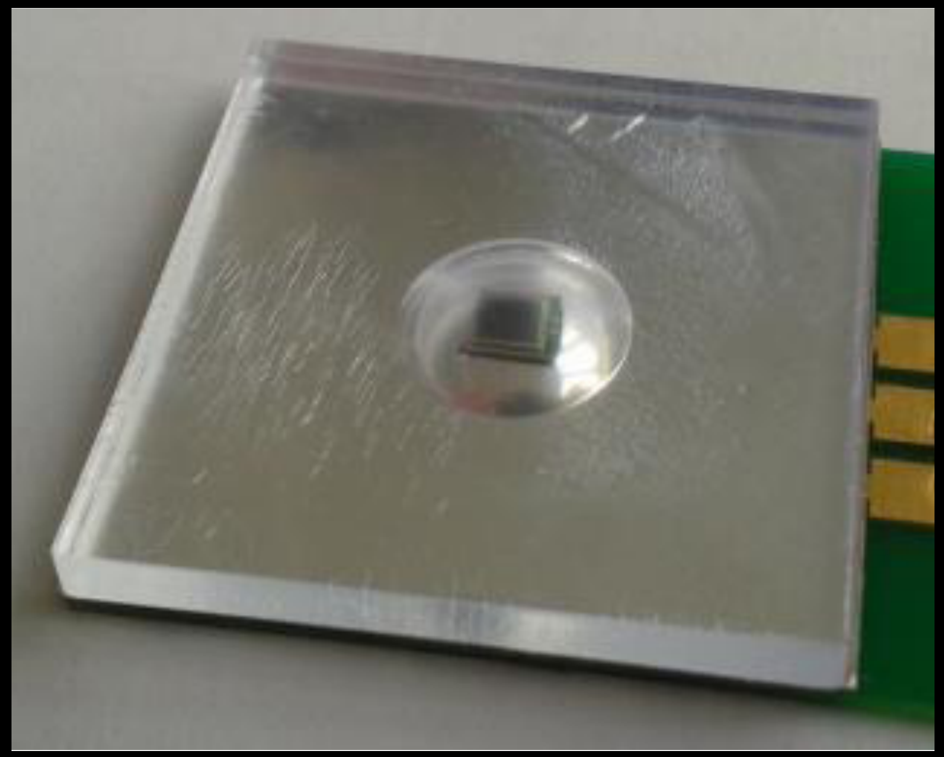
- PFA Calorimeter
  - ECAL
    - Tungsten
      - analog
        - Silicon
        - Scintillator
      - digital
        - MAPS
  - HCAL
    - Tungsten
    - Iron
      - analog
        - Scintillator
      - digital
        - RPC
        - GEM
        - Micro megas

CALICE
Calorimeter for ILC

Detector challenges:

- Compact design
- Calibration of channels
- Cooling
- Cost

Scintillator tiles/strips
(here 3 × 3 cm²) + SiPMs



Test beam experiments at DESY, CERN, FNAL: 2006 - 2015
First physics prototypes of up to ~1 m³, ~ 2 m³ (with Tail Catcher Muon Tracker)

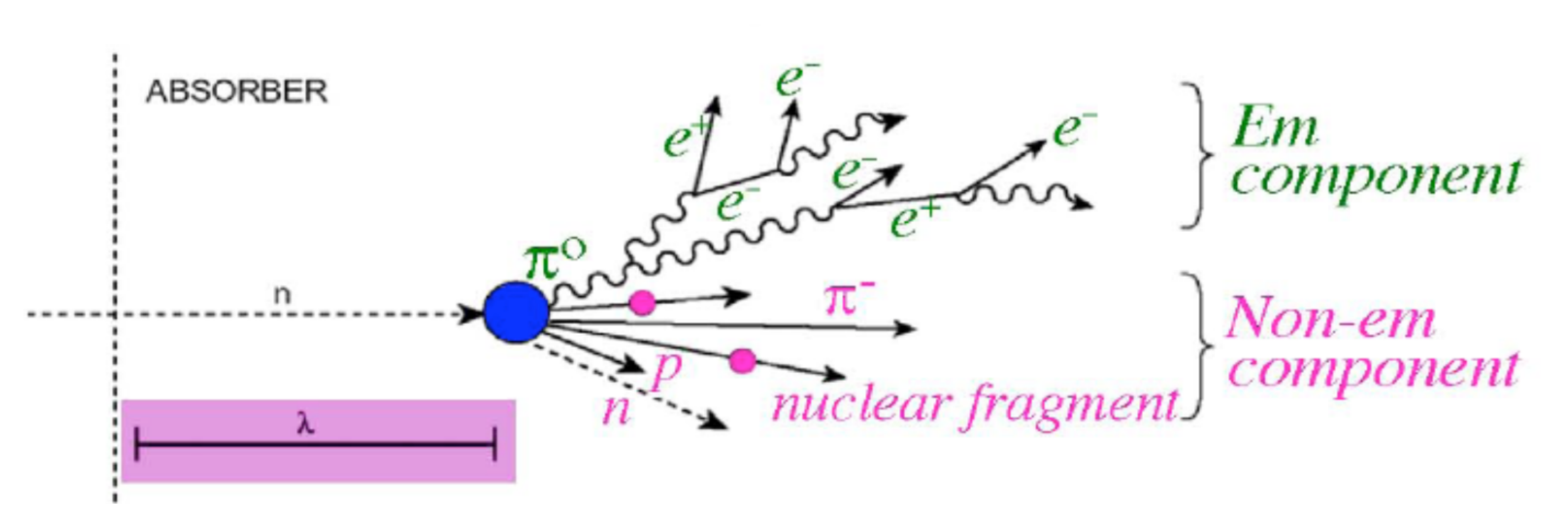
Studies started on a Crystal (LYSO:Ce + PbWO) ECAL/ Dual readout calorimetry

Dual Readout Calorimeter

Based on the DREAM/RD52 collaboration

Dual readout (DR) calorimeter measures both:

- Electromagnetic component
- Non-electromagnetic component



Fluctuations in event-by-event calorimeter response affect the energy resolution

Measure simultaneously:

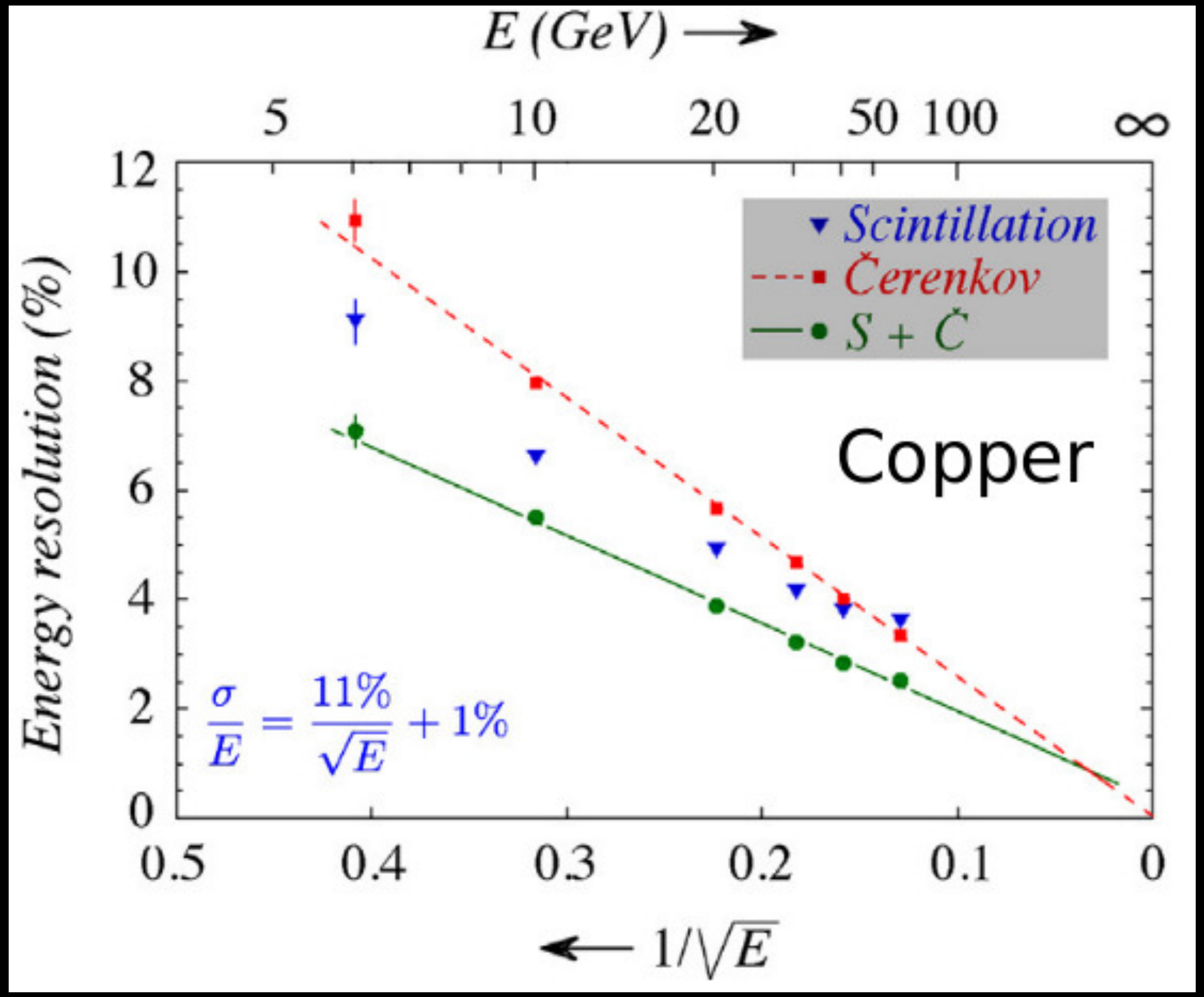
Cherenkov light (sensitive to relativistic particles)
Scintillator light (sensitive to total deposited energy)

Expected resolution:

EM: ~10%/sqrt(E)
Hadronic: 30-40%/sqrt(E)

Several prototypes from RD52 have been built

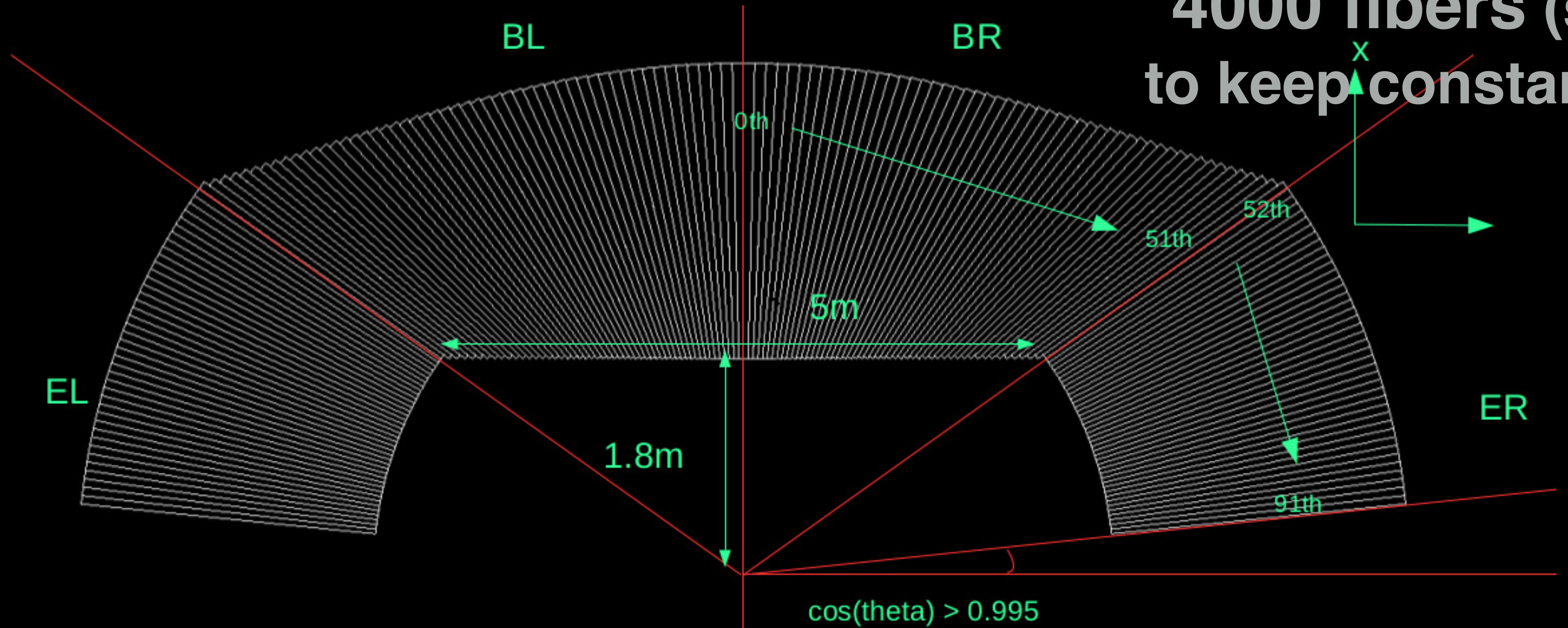
Energy resolution for electrons



Dual Readout Calorimeter

Based on the DREAM/RD52 collaboration

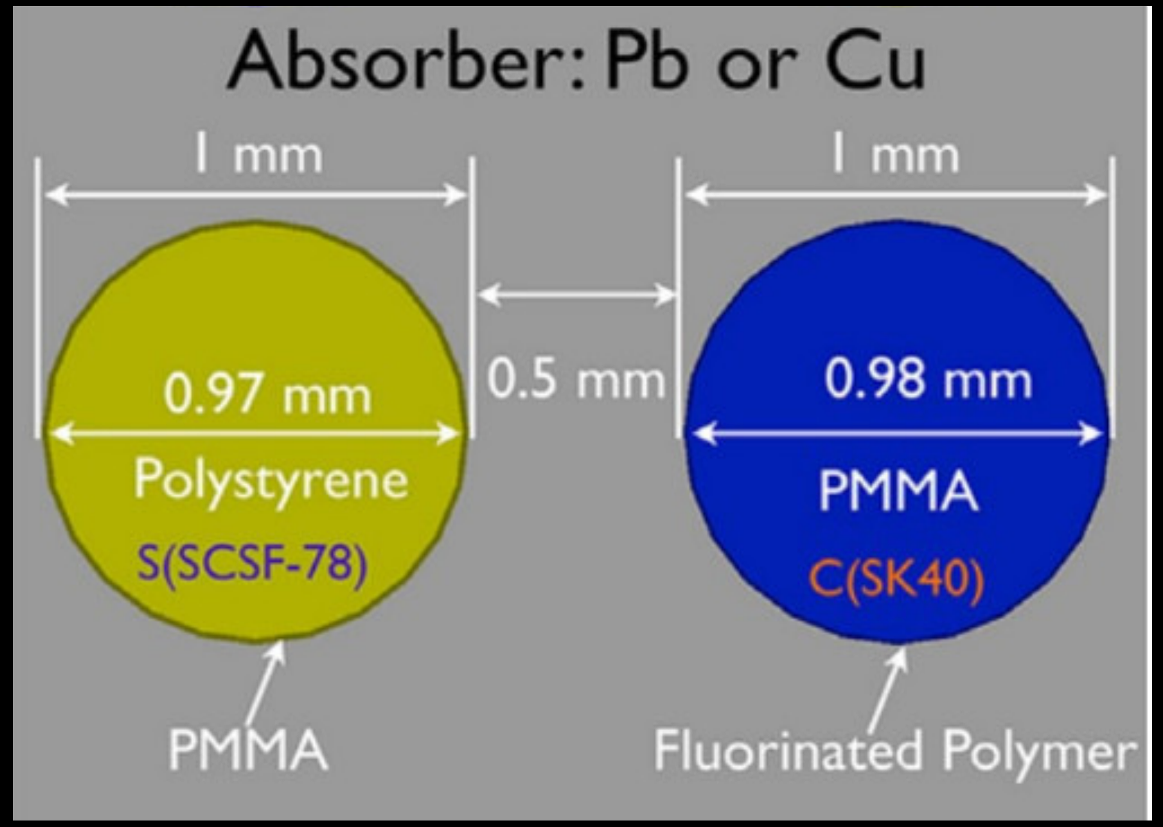
Projective 4π layout implemented into CEPC simulation
(based on 4th Detector Collaboration design)



4000 fibers (start at different depths to keep constant the sampling fraction)

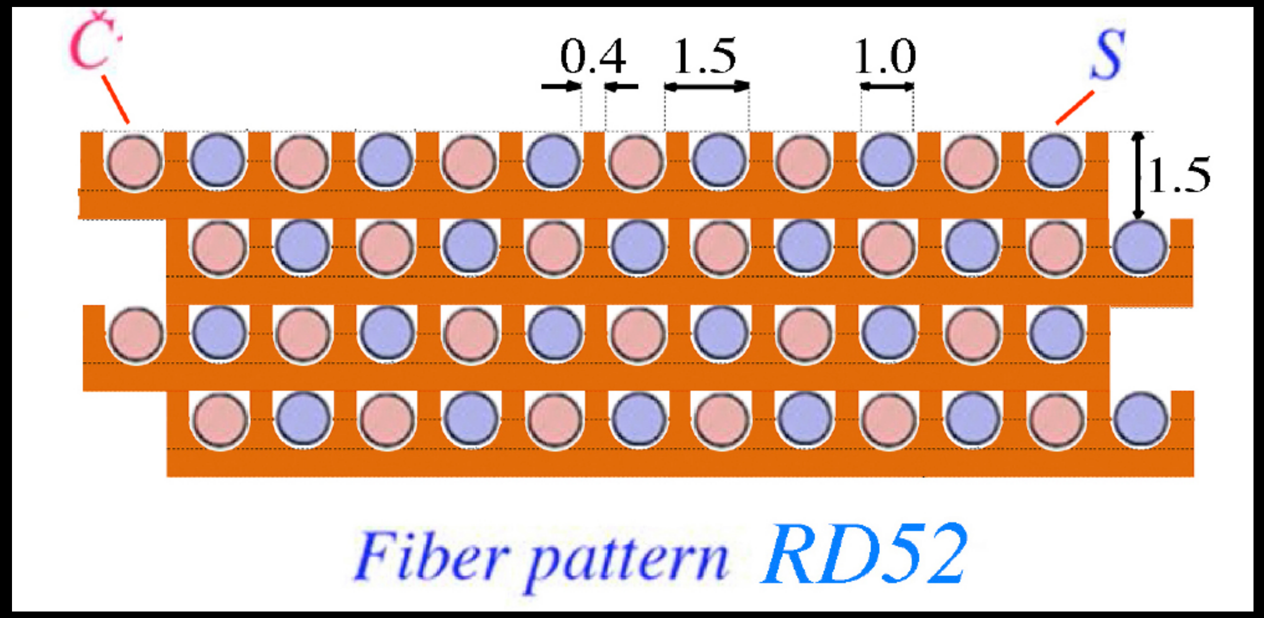
Covers full volume up to |cos(θ)| = 0.995

Expected resolution:
EM: ~10%/sqrt(E)
Hadronic: 30-40%/sqrt(E)



Demonstration in test beam experiments

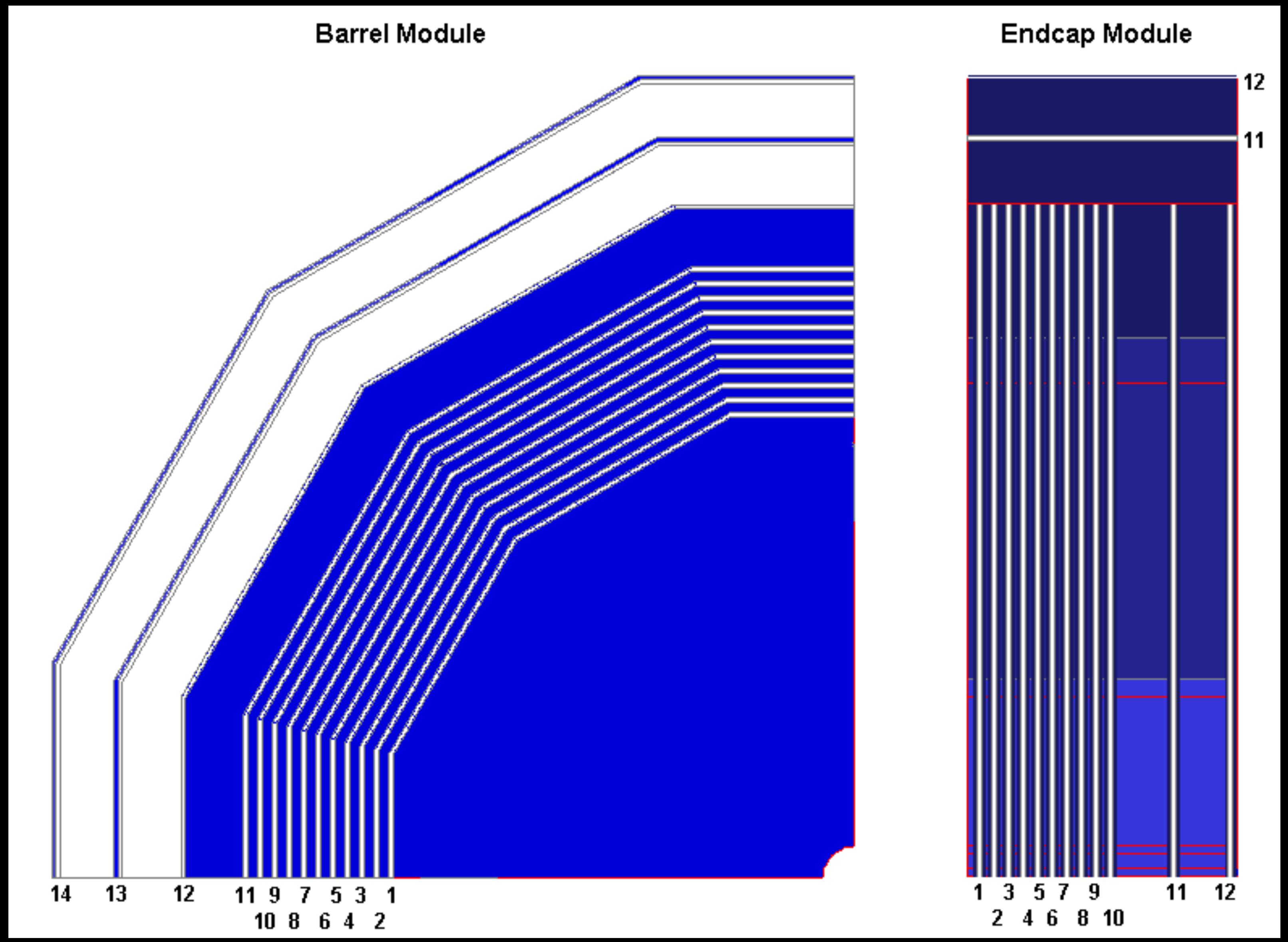
Studying different readout schemes
PMT vs SiPM



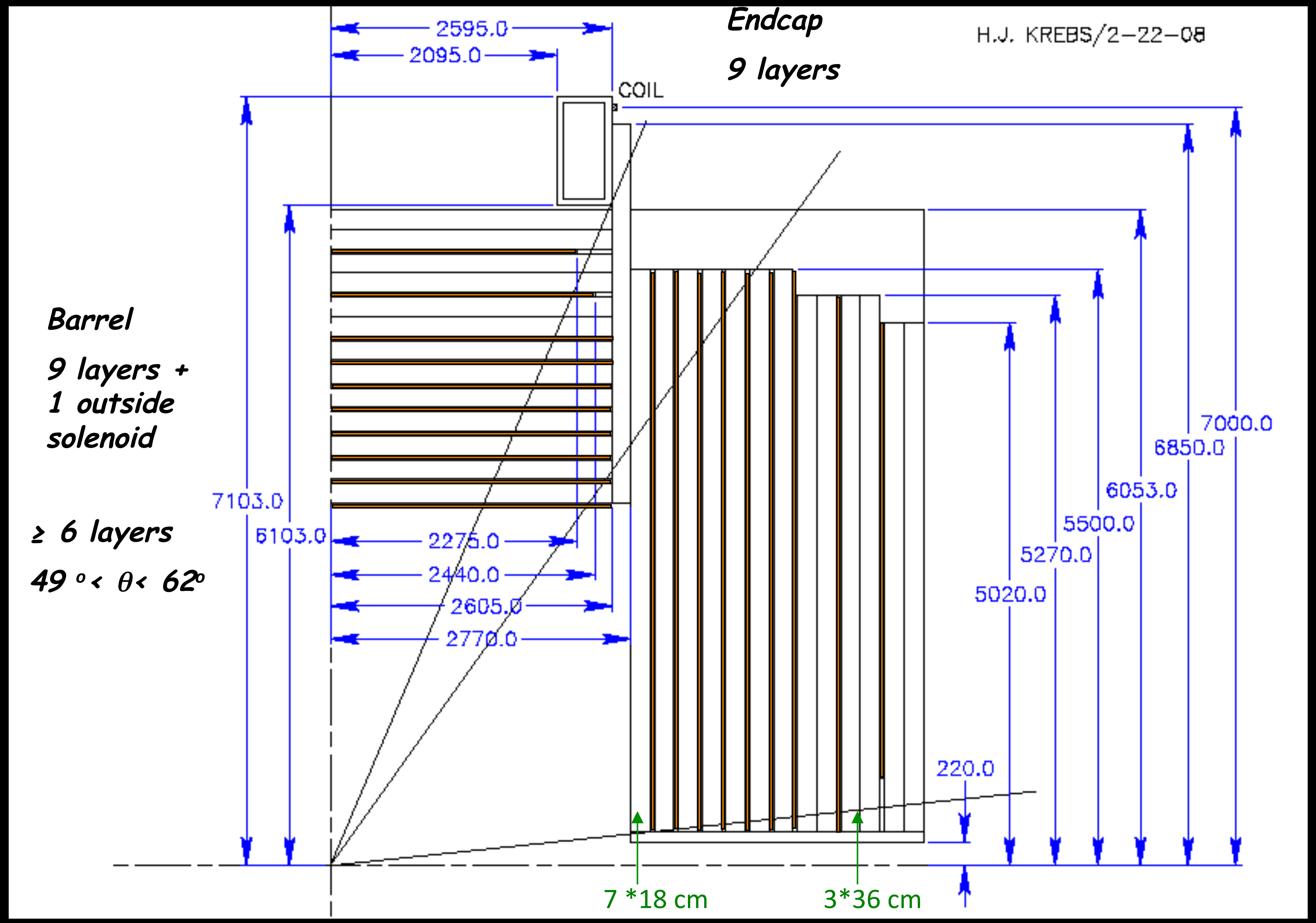
NEED: large size prototype that could contain full hadronic shower

Muon Systems

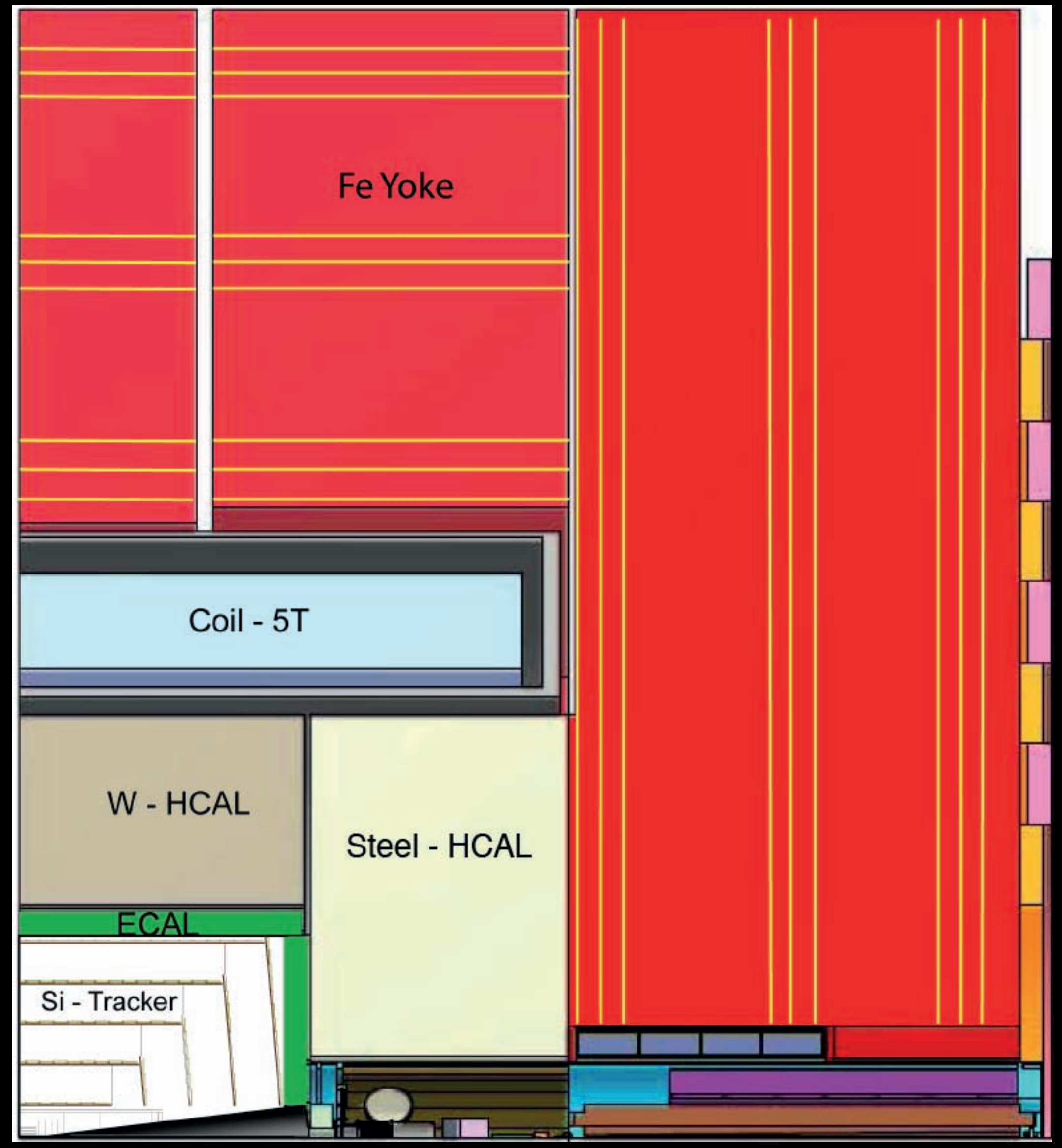
ILD: 12-14 sensitive layers



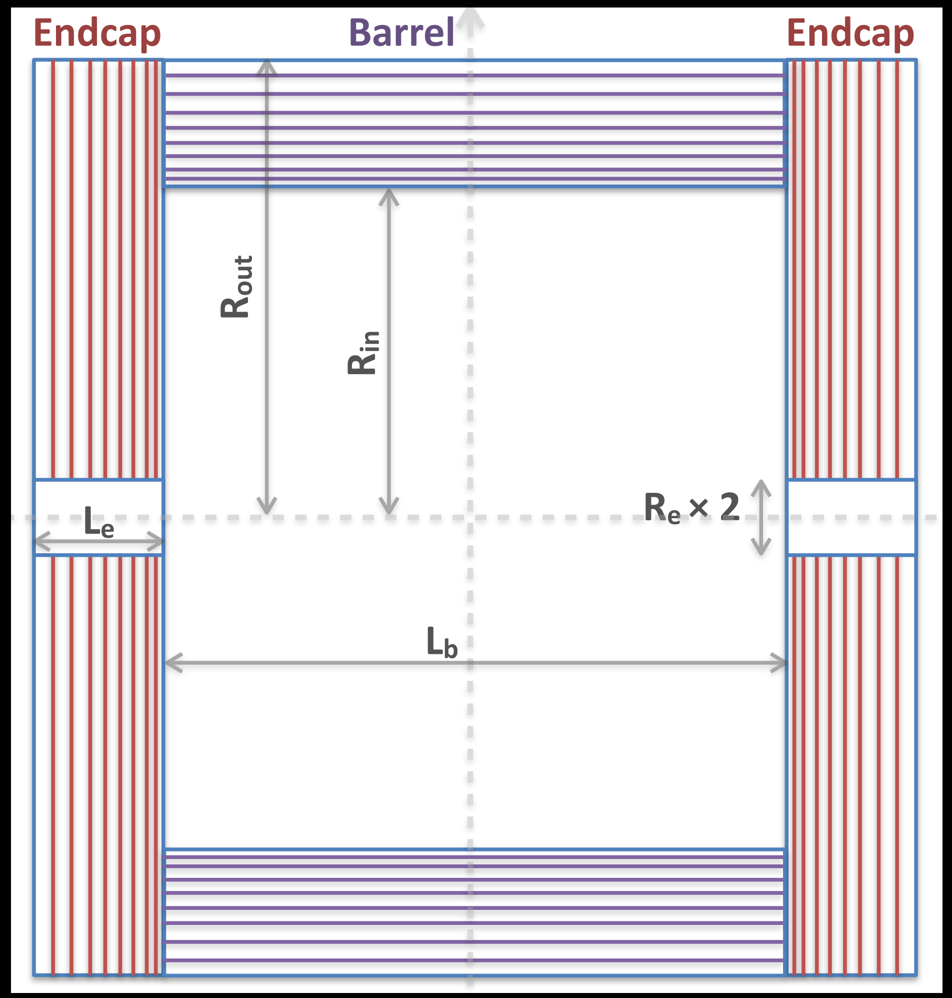
SiD: 9-10 sensitive layers



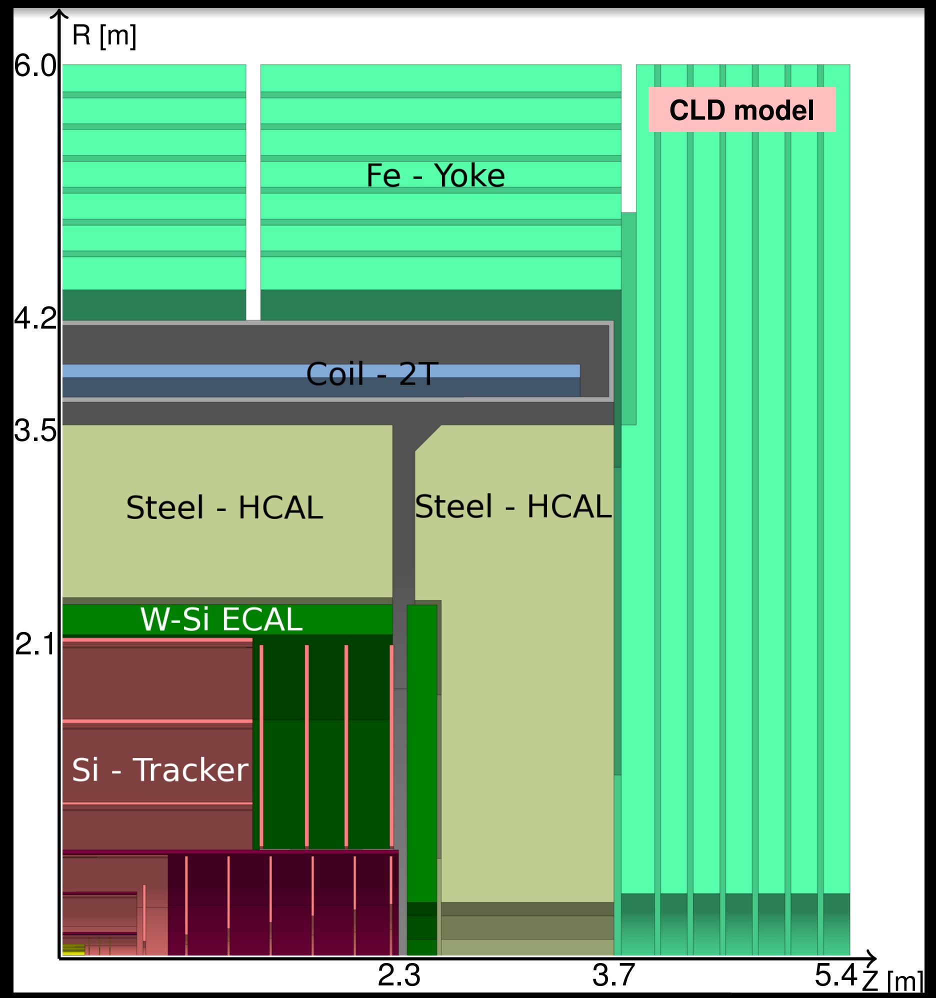
CLICdet: 9 sensitive layers



CEPC: 8 sensitive layers



FCC-ee - CLD: 6+1 sensitive layers



Technologies considered

Resistive Plate Chambers (RPC)
Thin Gap Chambers (TGC)
Micromegas
Gas Electron Multiplier (GEM)
Scintillator Strips
μRwell

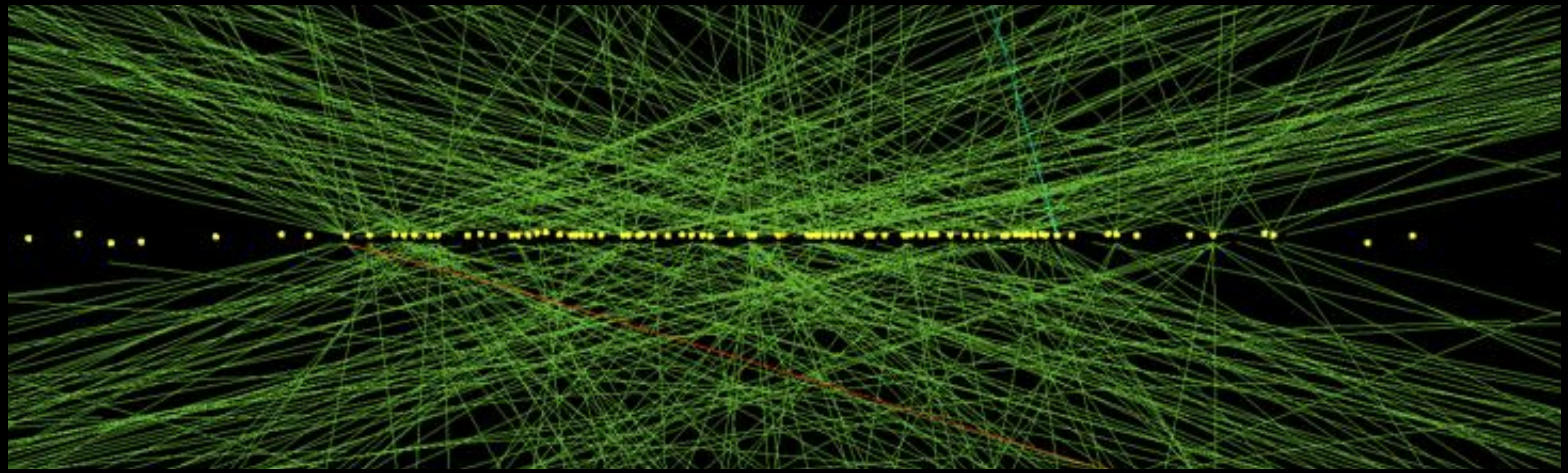
Detector for FCC-hh

100 km, ~100 TeV, pp collider

Pileup: number of pp collisions per bunch crossing (BC)

LHC: 30 collisions/BC

HL-LHC: 140 collisions/BC

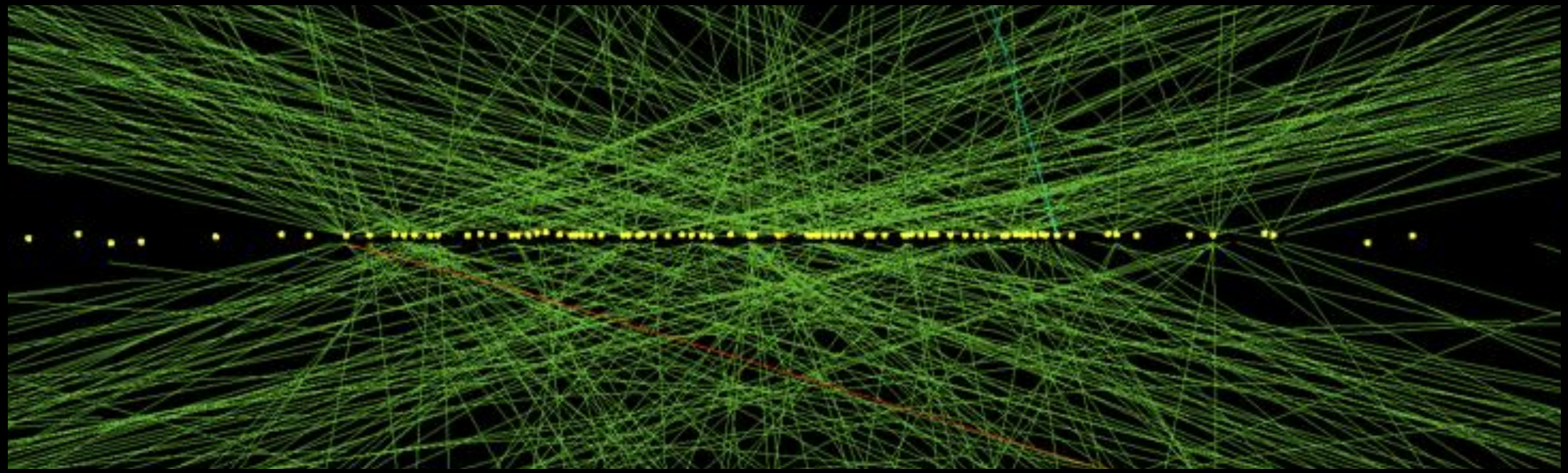


FCC-hh: 1000 collisions/BC

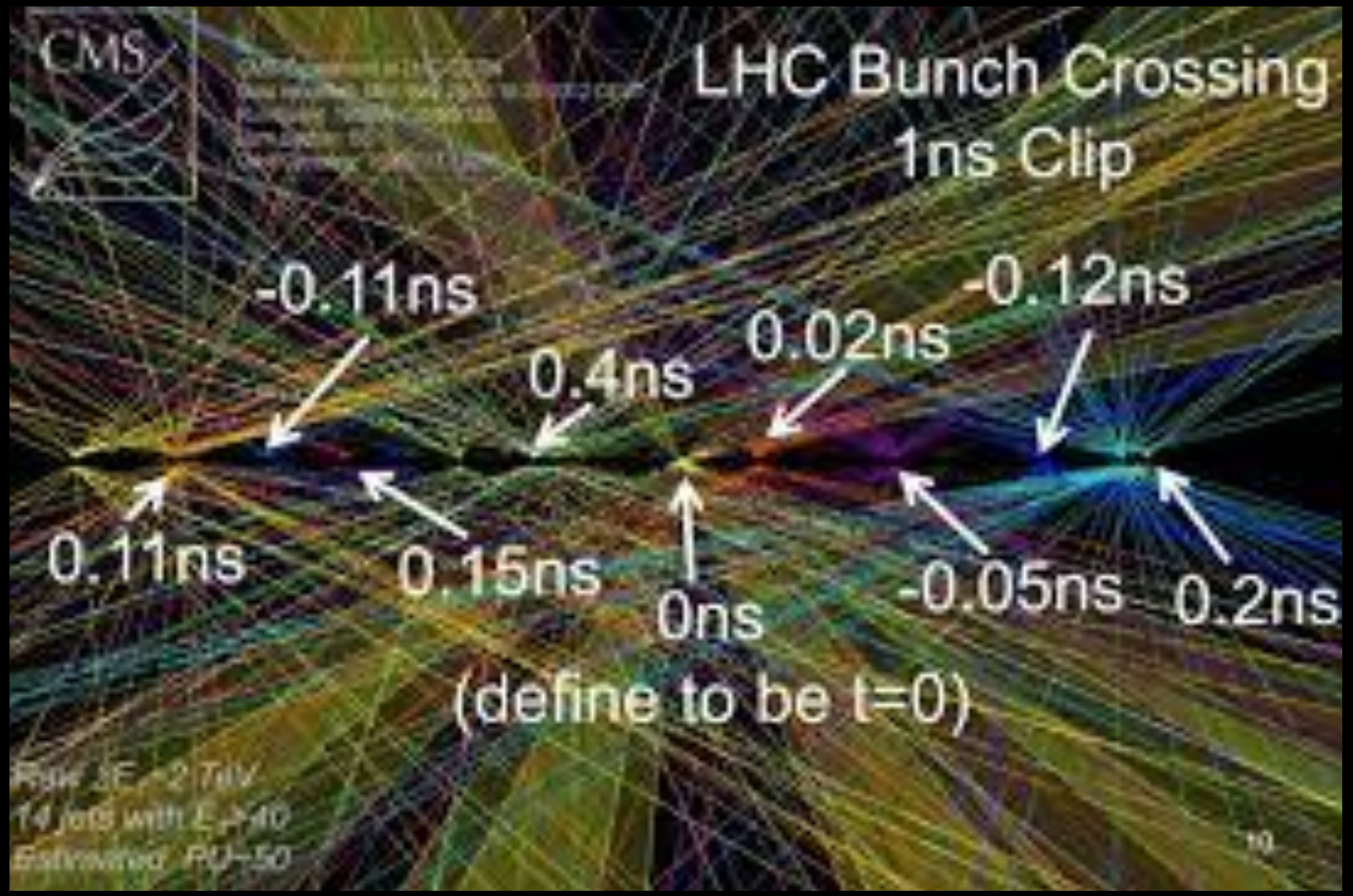
Pileup: number of pp collisions per bunch crossing (BC)

LHC: 30 collisions/BC

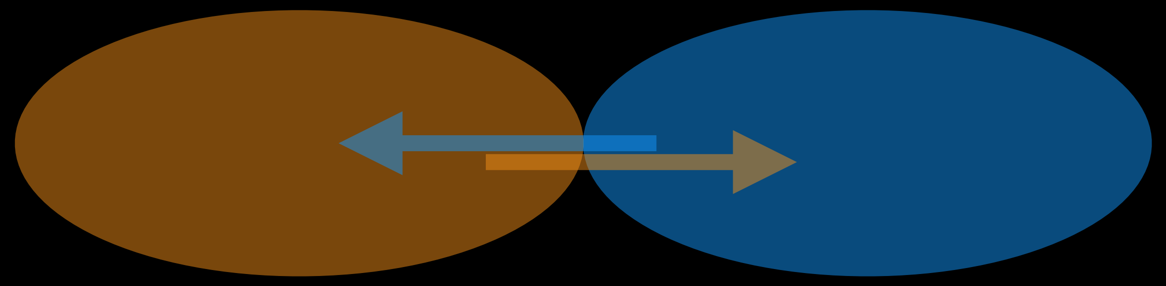
HL-LHC: 140 collisions/BC



FCC-hh: 1000 collisions/BC



Timescale difference of collisions within BC used for identification/reconstruction

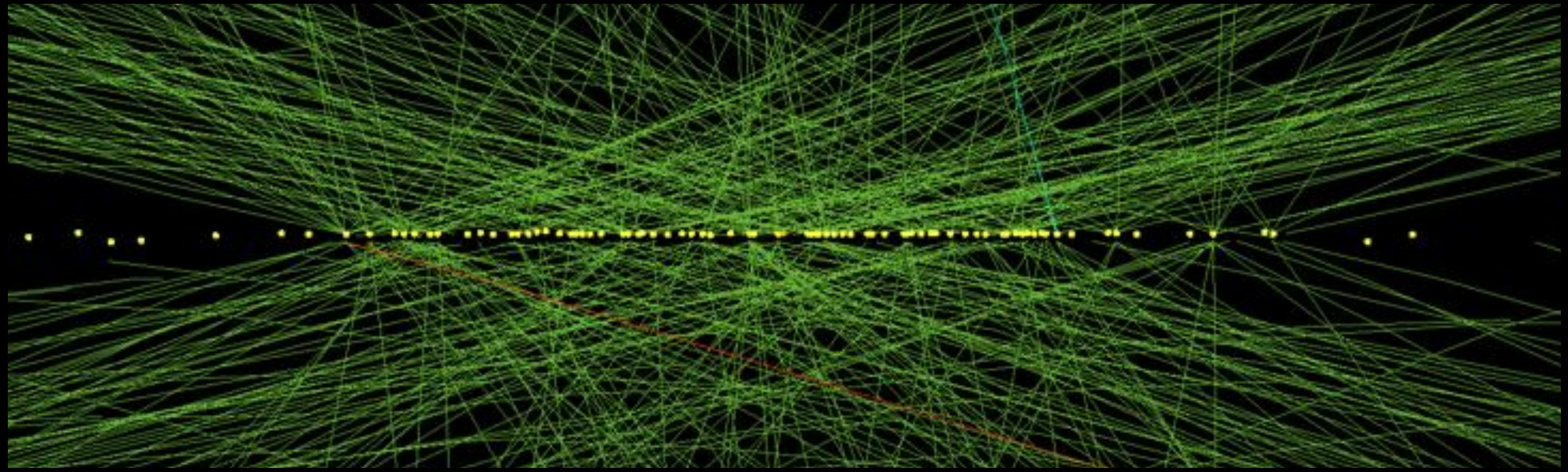


10-20 ps time resolution required

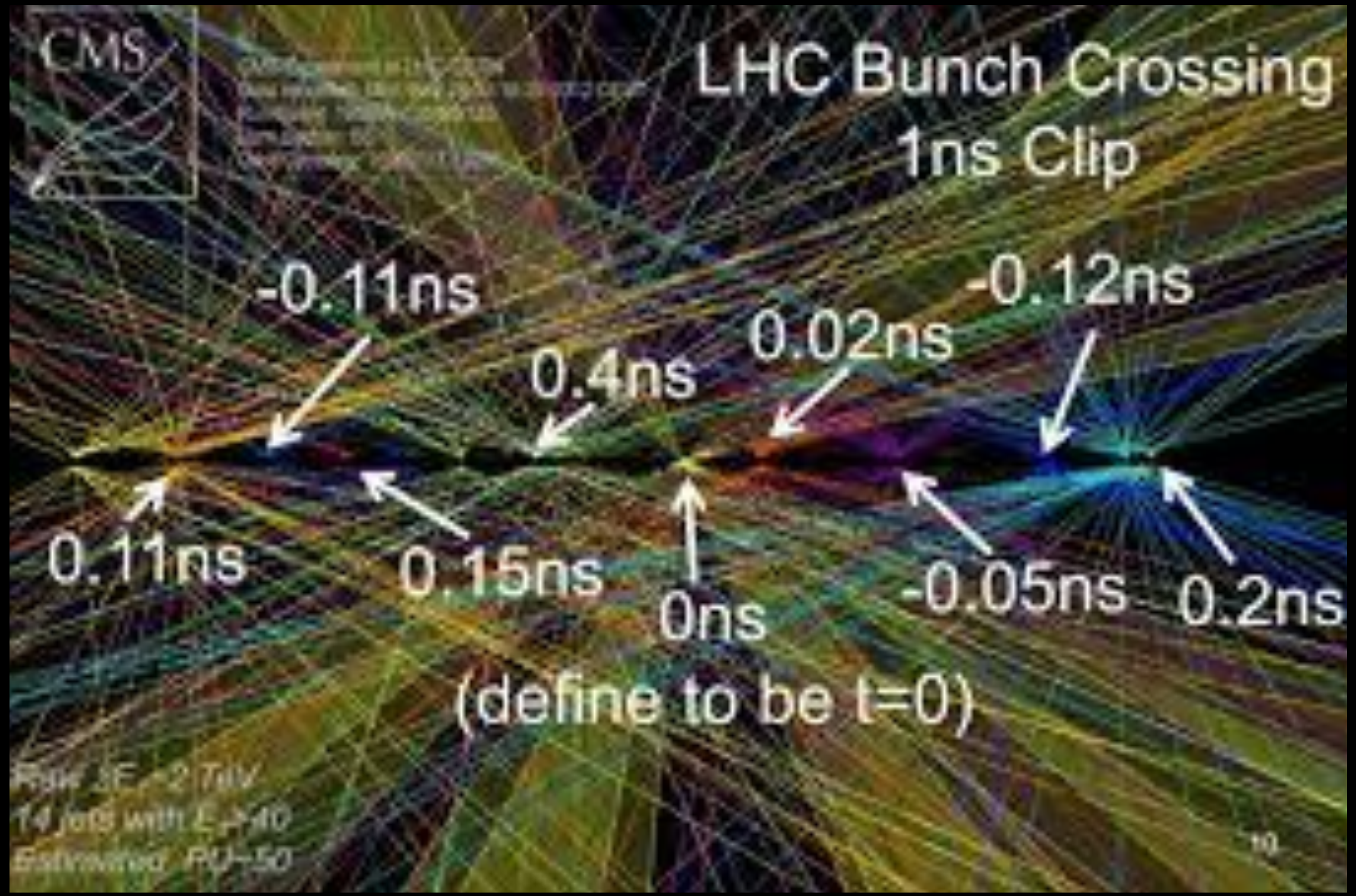
Pileup: number of pp collisions per bunch crossing (BC)

LHC: 30 collisions/BC

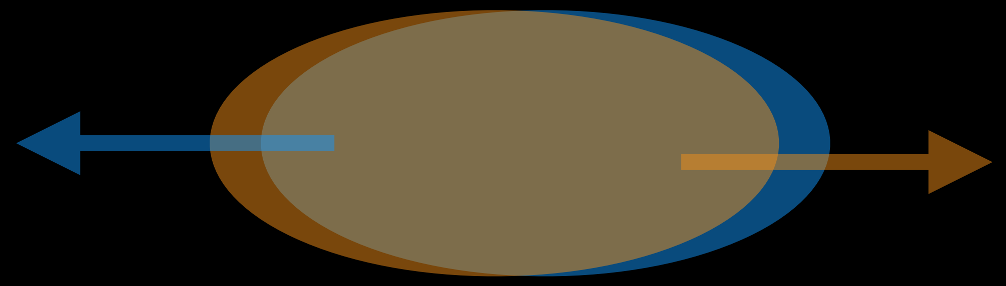
HL-LHC: 140 collisions/BC



FCC-hh: 1000 collisions/BC



Timescale difference of collisions within BC used for identification/reconstruction



10-20 ps time resolution required

Pileup: number of pp collisions per bunch crossing (BC)

LHC: 30 collisions/BC

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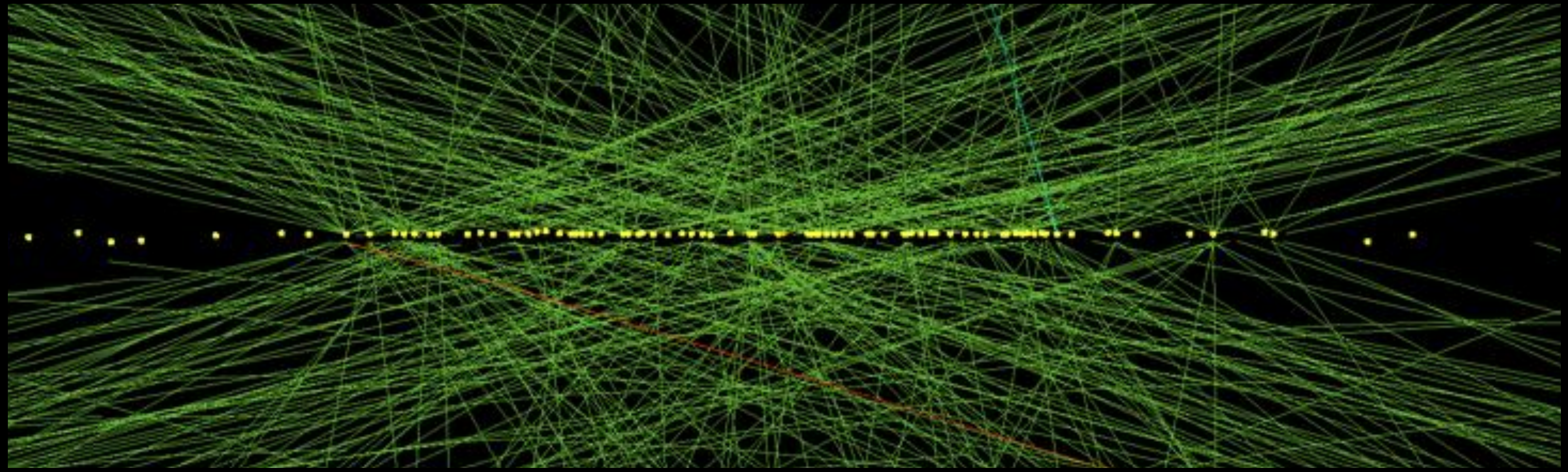
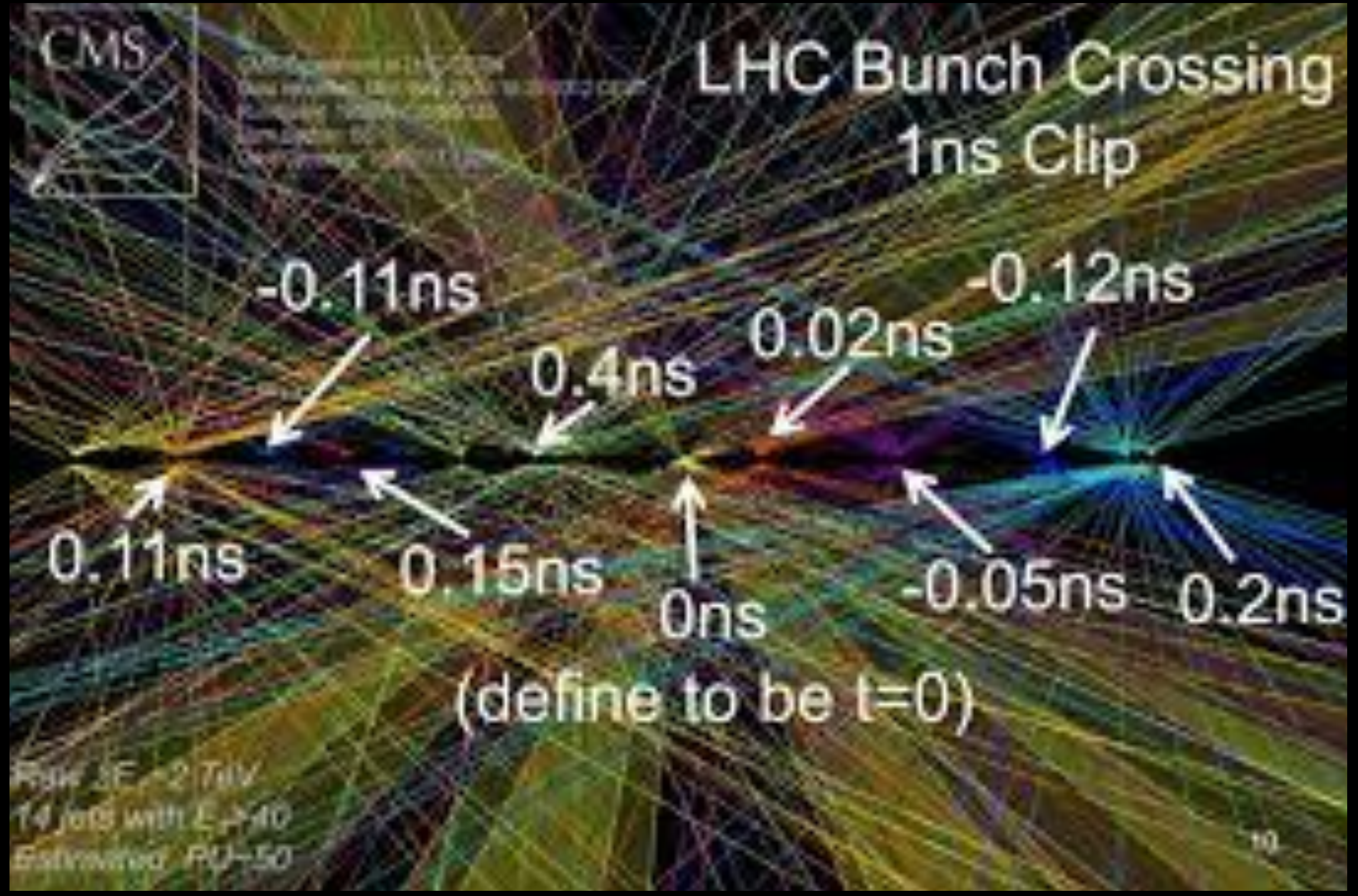
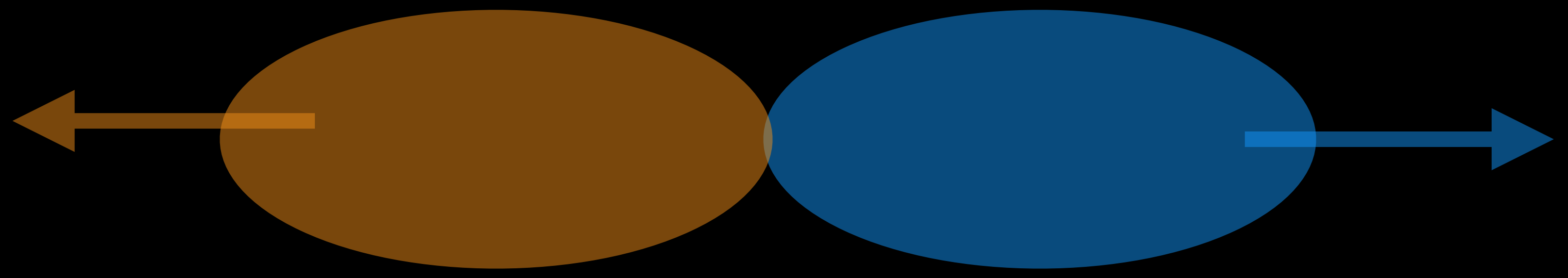


FCC-hh: 1000 collisions/BC

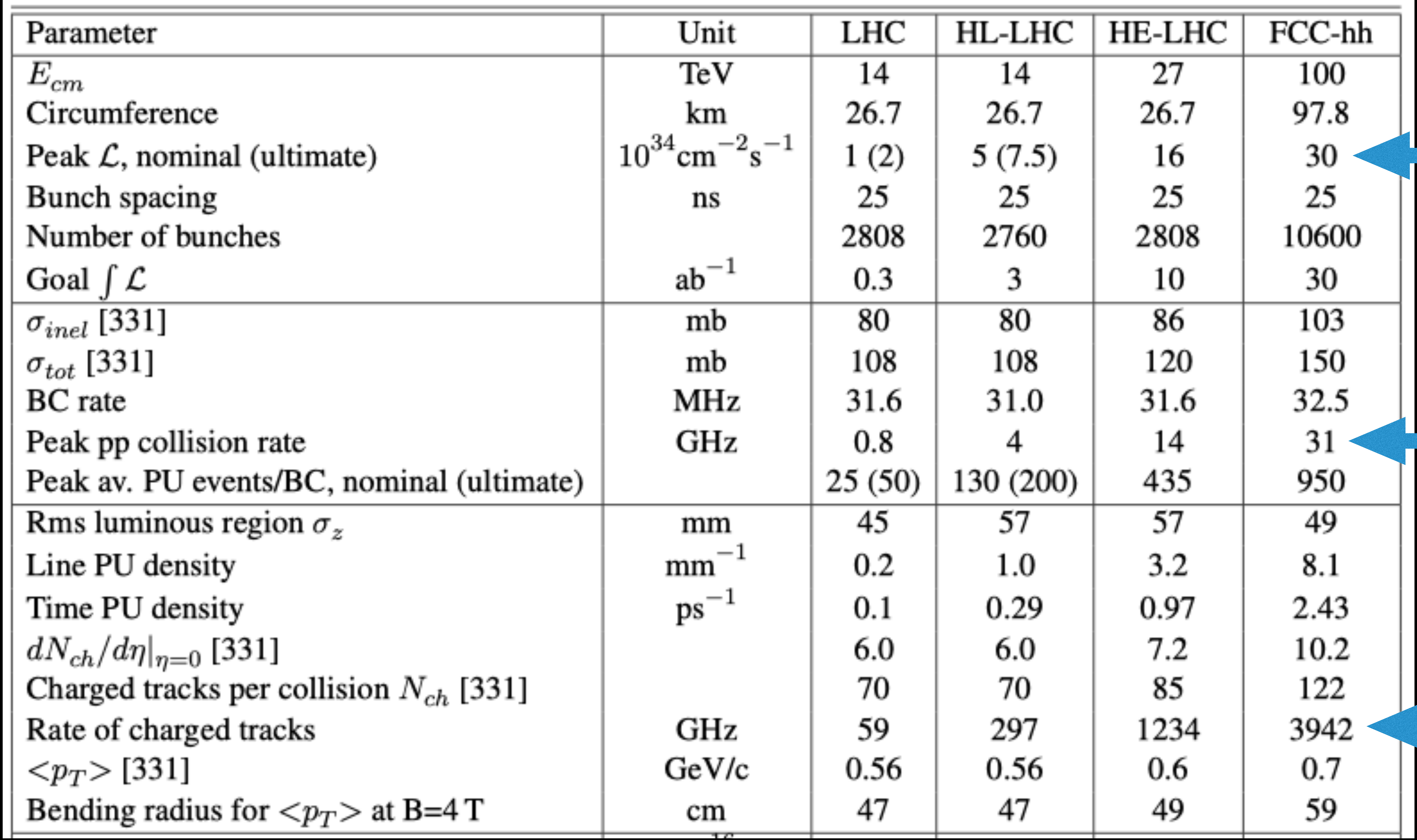


Timescale difference of collisions within BC used for identification/reconstruction



10-20 ps time resolution required

Parameter table



Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
Circumference	km	26.7	26.7	26.7	97.8
Peak $\mathcal{L}$, nominal (ultimate)	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1 (2)	5 (7.5)	16	30
Bunch spacing	ns	25	25	25	25
Number of bunches		2808	2760	2808	10600
Goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel} [331]	mb	80	80	86	103
σ_{tot} [331]	mb	108	108	120	150
BC rate	MHz	31.6	31.0	31.6	32.5
Peak pp collision rate	GHz	0.8	4	14	31
Peak av. PU events/BC, nominal (ultimate)		25 (50)	130 (200)	435	950
Rms luminous region σ_z	mm	45	57	57	49
Line PU density	mm^{-1}	0.2	1.0	3.2	8.1
Time PU density	ps^{-1}	0.1	0.29	0.97	2.43
$dN_{ch}/d\eta\vert_{\eta=0}$ [331]		6.0	6.0	7.2	10.2
Charged tracks per collision N_{ch} [331]		70	70	85	122
Rate of charged tracks	GHz	59	297	1234	3942
$<p_T>$ [331]	GeV/c	0.56	0.56	0.6	0.7
Bending radius for $<p_T>$ at B=4 T	cm	47	47	49	59

$30 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
Luminosity

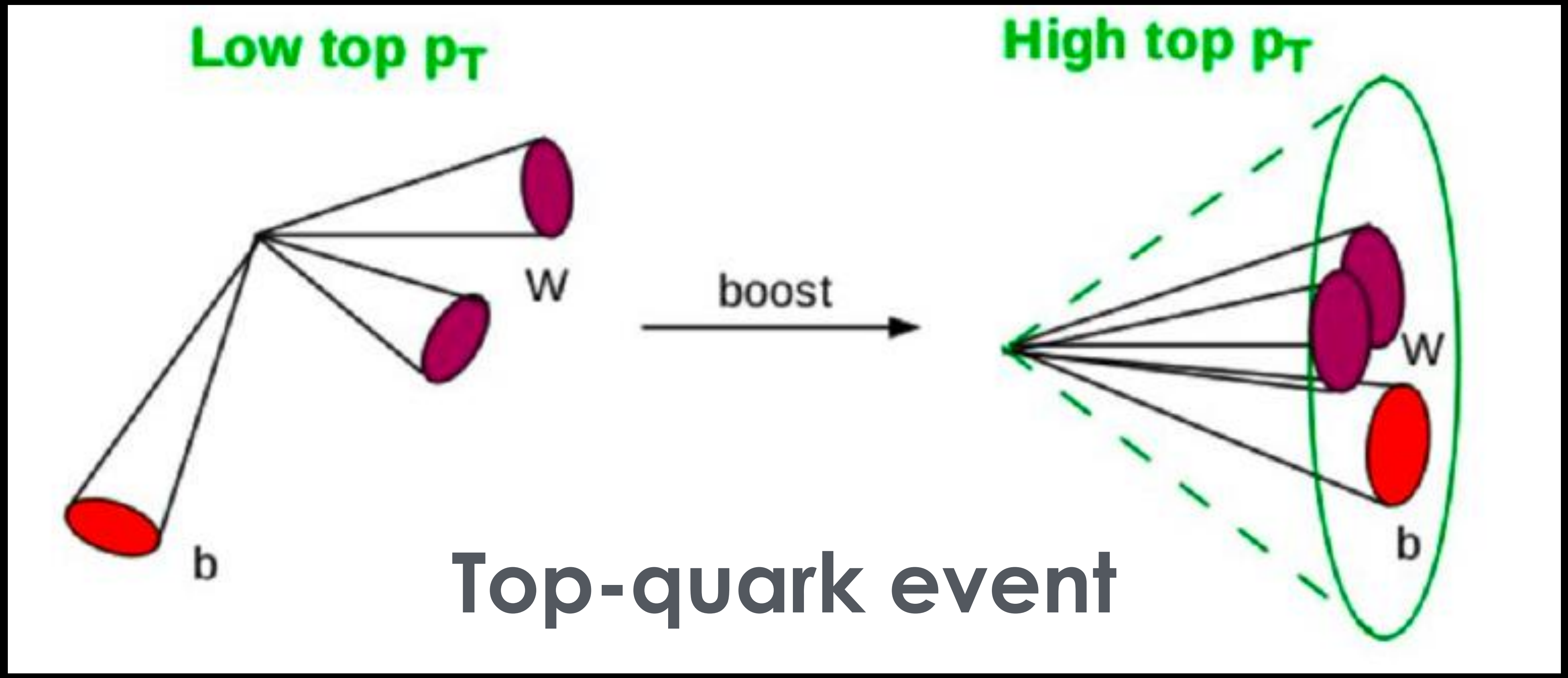
31 GHz
collision rate

4 THz
track rate

Physics requirements

100 TeV Collisions → Physics Objects will be more boosted

Overlapping physics objects



Requirements of high granularity (both in tracker and calorimeters)

Long-lived particles travel longer

5 TeV τ-lepton can travel 10 cm before decaying

5 TeV *b*-hadron can travel 50 cm before decaying

Requirement of extensive precise tracking/vertexing systems

Physics requirements

100 TeV Collisions → Physics Objects will be more boosted

Tracking

Tracks target resolution:
$\sigma(p_T)/p_T$ = (10 - 20) % @ 10 TeV
10% @ 1 TeV at LHC

$\sigma(p_T)/p_T$ < 1% for low p_T tracks
(multiple scattering limit)

Muons target resolution:
$\sigma(p)/p$ = 5 % @ 10 TeV (η ~ 0)

Calorimeter

Keep constant term as small as possible

Electron/photon target resolution:
$\sigma(E)/E = 10\%/\sqrt{E} \oplus 1\%$

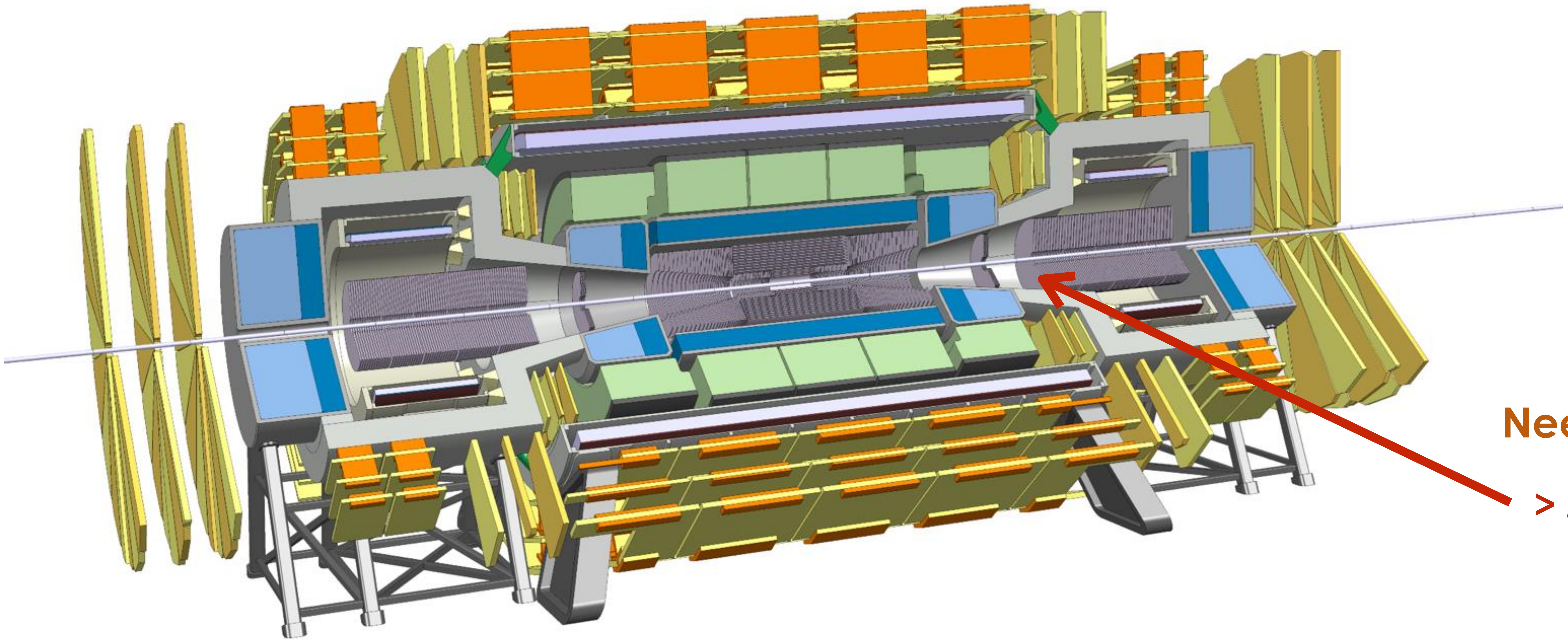
Jets target resolution:
$\sigma(E)/E = (50 - 60)\%/\sqrt{E} \oplus 3\%$

Transverse granularity 4× better than ATLAS and CMS

Reference detector for FCC-hh

Challenging radiation levels

HL-LHC muon system should work for most of FCC-hh detector areas



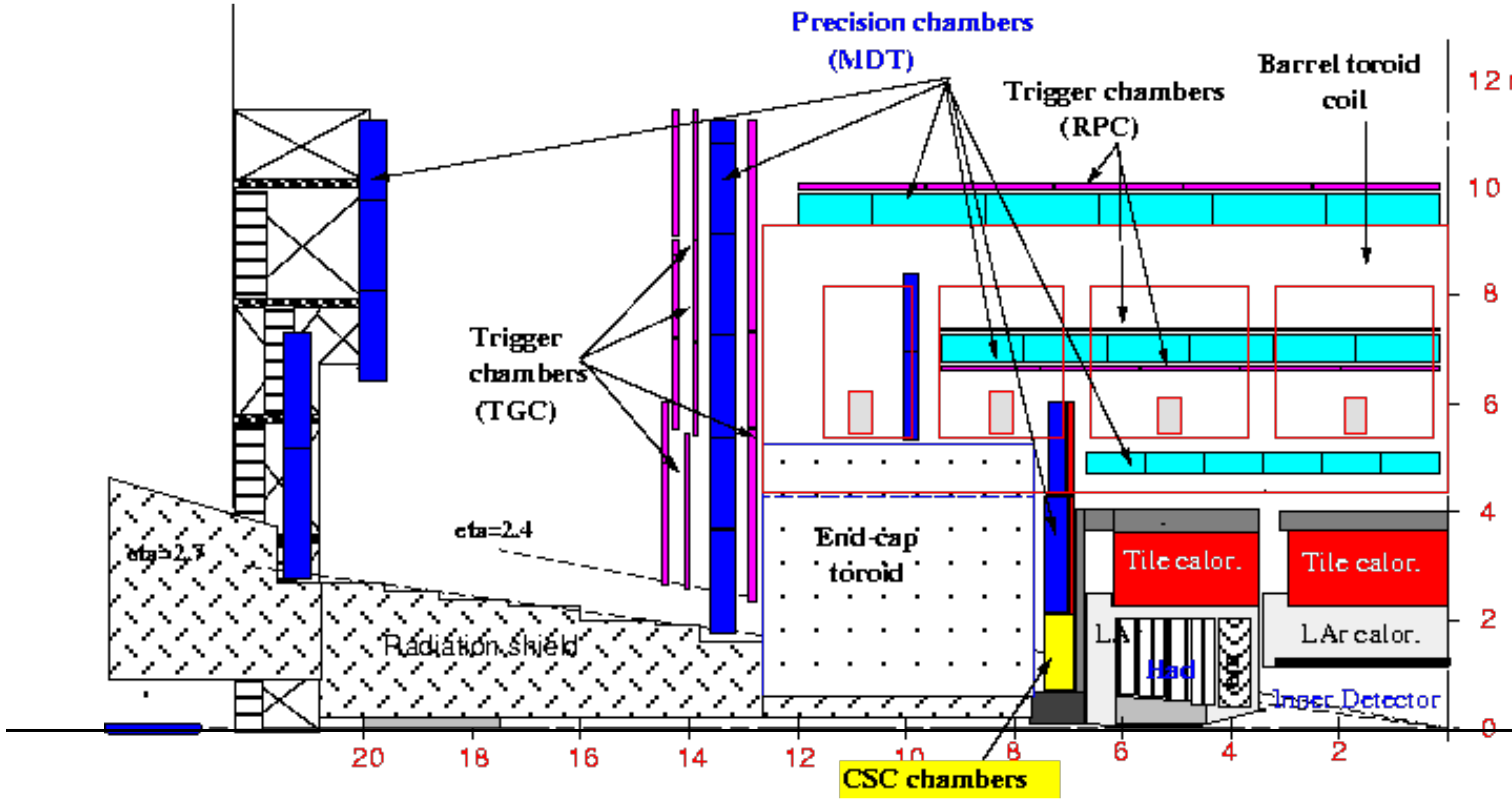
- 4T 10m solenoid
- Forward solenoids
- Silicon tracker
- Barrel ECAL Lar
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

Need high-granularity

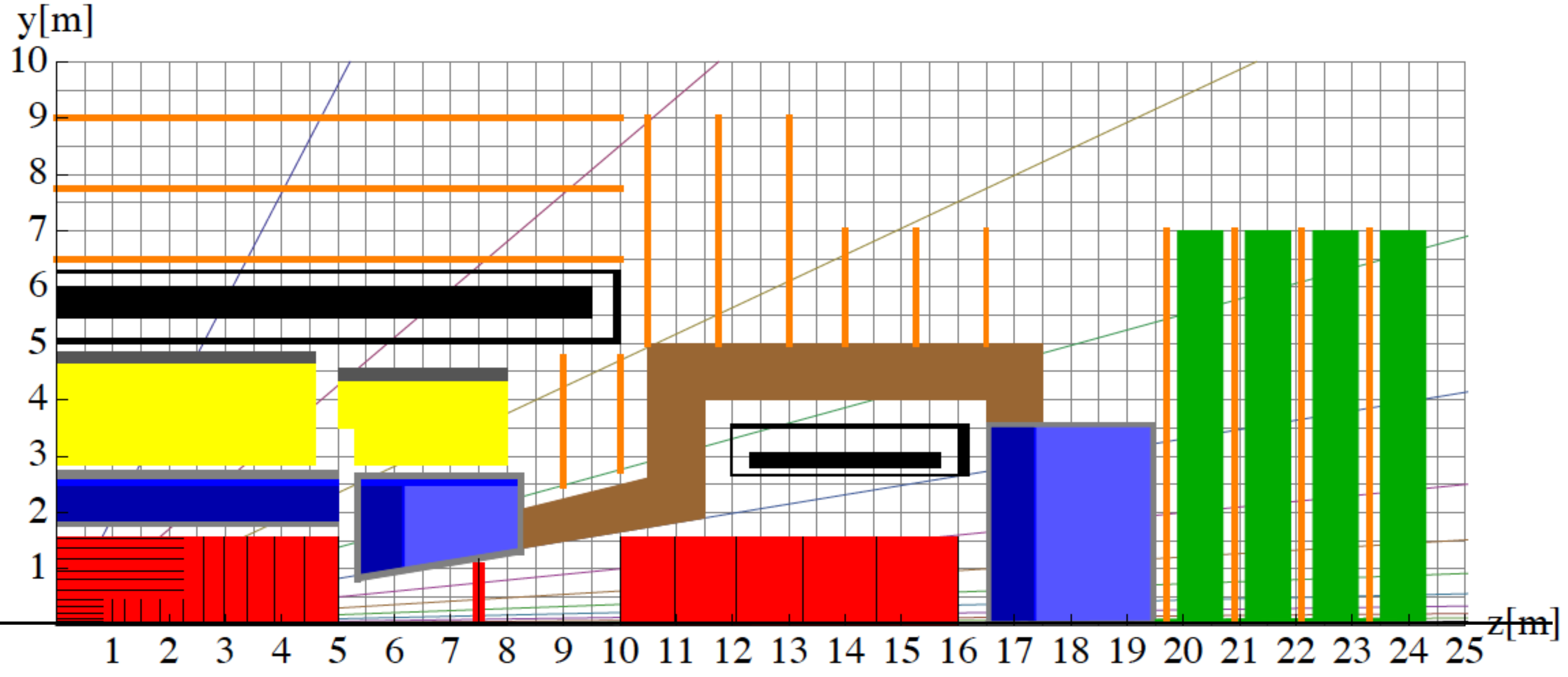
> 20 tracker disks

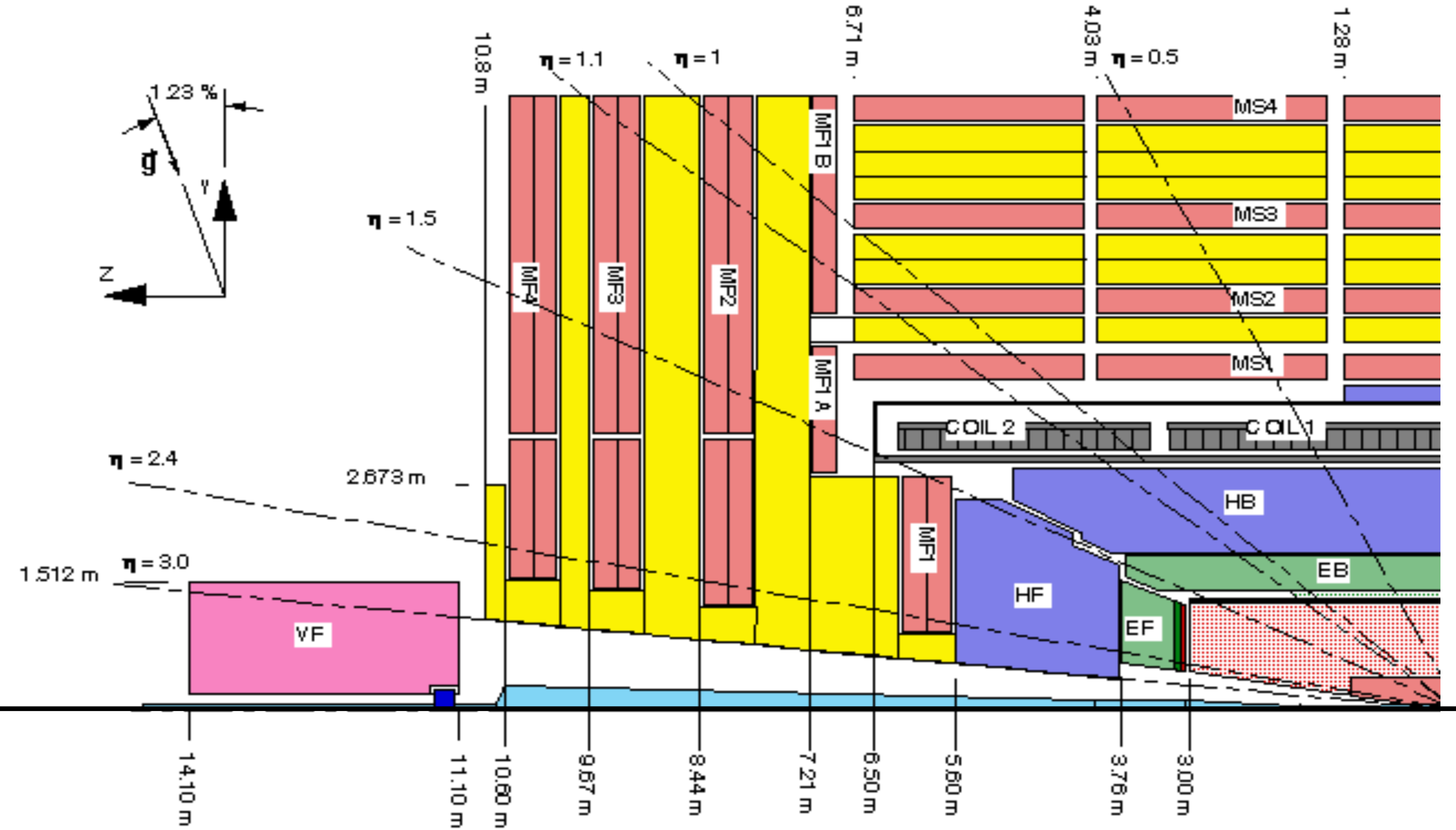
L* ~ 40 m in contrast to ~2m for FCC-ee/CEPC

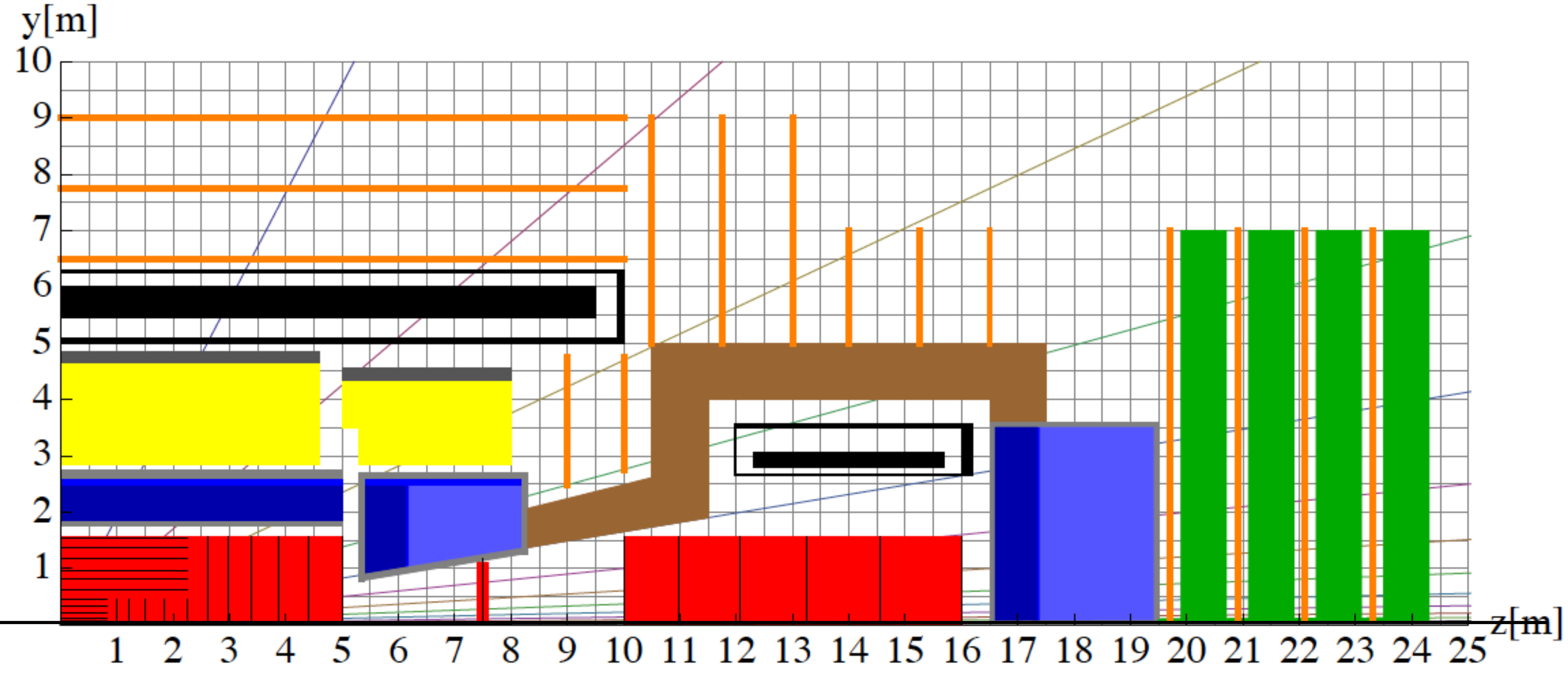
Comparison with ATLAS and CMS



50 m length, 20 m diameter







Major Technology R&D for Future Experiments

Silicon detectors

Gas detectors

Calorimetry

Detector magnets

Major Technology R&D for Future Experiments

Silicon detectors	LGAD sensor Monolithic CMOS sensors
Gas detectors	Large area gaseous detector Novel materials and fabrication techniques
Calorimetry	Silicon based calorimetry Scintillators+SiPM based detectors Liquid Argon detectors Dual Readout calorimetry
Detector magnets	Reinforced super conductors Ultra-light cryostat Advanced magnet powering systems

Major Technology R&D for Future Experiments

- Silicon detectors
- Gas detectors
- Calorimetry
- Detector magnets

- Detector mechanics
- IC technologies
- High speed electronics
- Software

Major **Technology R&D** for Future Experiments

Silicon detectors

Low-mass mechanical structures
High performance cooling

Detector mechanics

Gas detectors

Mainstream CMOS technologies (28/16 nm)

IC technologies

Calorimetry

ASICs for up to 56 Gb/s data links
High performance FPGAs
Optoelectronics

High speed electronics

Detector magnets

Faster simulation
Heterogeneous computing frameworks (GPUs, FPGA)
Efficient analysis facilities
Efficient resource sharing across experiments

Software

https://ep-dep.web.cern.ch/rd-experimental-technologies

Final remarks

The discovery of the Higgs at 125 GeV make e^+e^- circular machines possible,

in addition to linear e^+e^- colliders

Precision machines push for new technological advances in detectors

Hadronic machines continue to be tool for the exploration of the highest energies

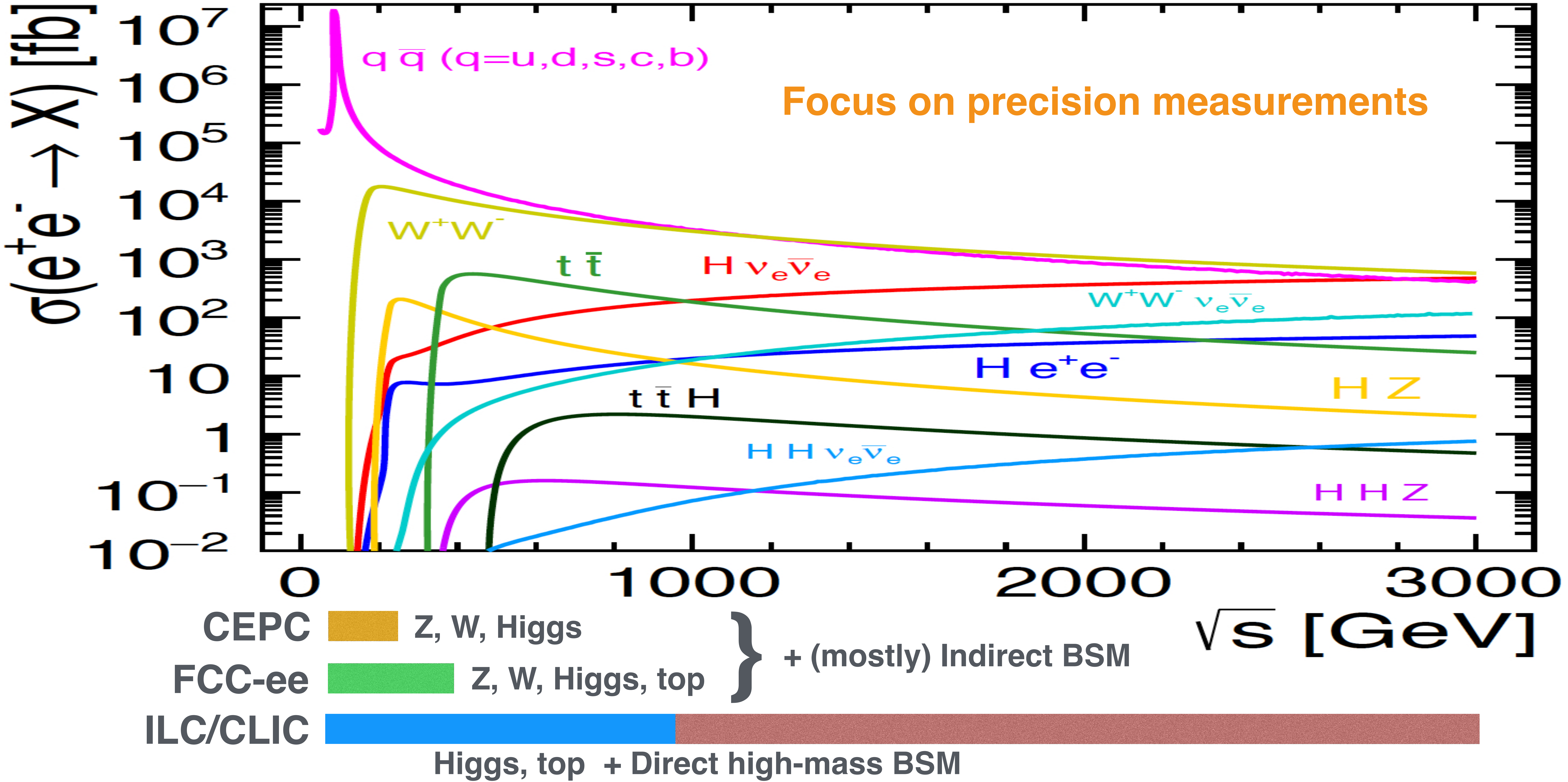
Detector challenges associated with the large event rates and radiation levels

There are currently many concurrent studies on detector concepts with demanding requirements from physics goals and experimental conditions

Large synergies between collider projects and already approved experiments

Active detector collaborations and R&D spin-offs

Physics programs — depending on energy reach



Focus on precision measurements

CEPC Z, W, Higgs

FCC-ee Z, W, Higgs, top

} + (mostly) Indirect BSM

ILC/CLIC

Higgs, top + Direct high-mass BSM

Tracking systems at e^+e^- colliders

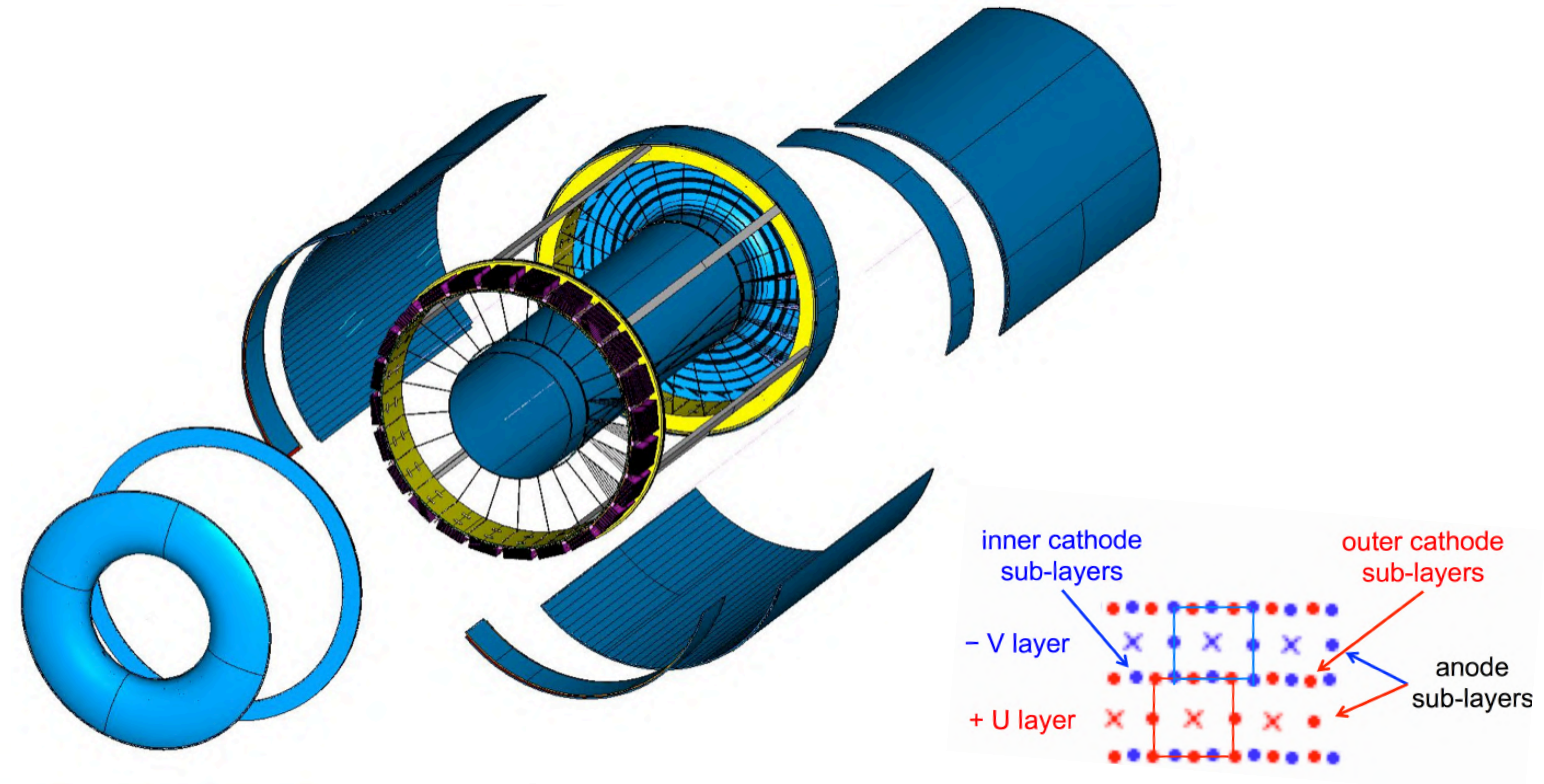
recent past

LEP	ALEPH	TPC
	DELPHI	TPC
	L3	Si + TEC
	OPAL	Drift Chamber
SLC	MARK2	Drift Chamber
	SLD	Drift Chamber
DAPHNE	KLOE	Drift Chamber
VEPP2000	CMD-2	Drift Chamber
PEP2	BaBar	Drift Chamber
KEKB	Belle	Drift Chamber
CESR	CLEO3	Drift Chamber
BEPC2	BES3	Drift Chamber

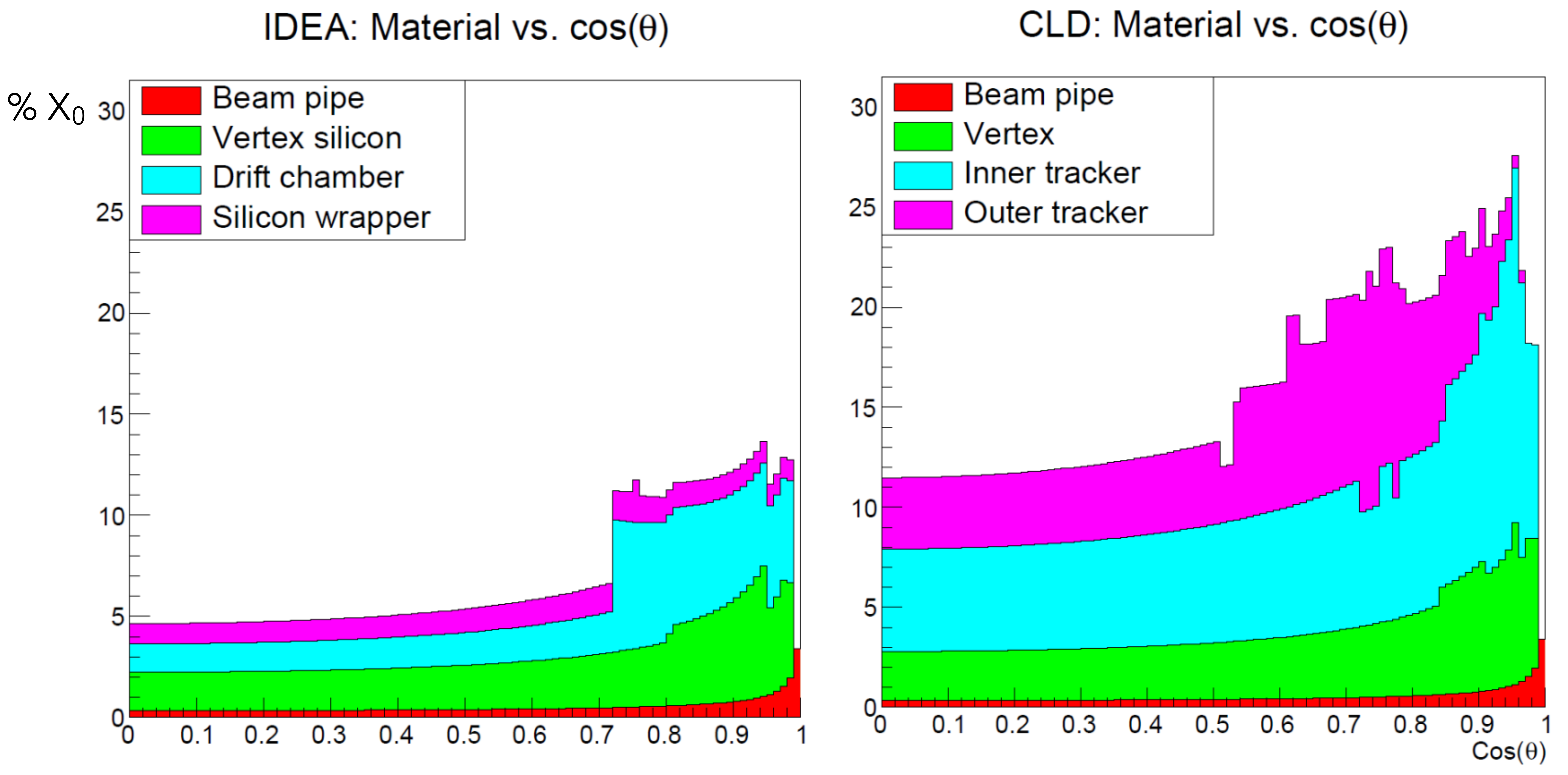
future

ILC	ILD	TPC	
	SiD	Si	
CLIC	CLIC	Si	
FCC-ee	CLD	Si	
	IDEA	Drift Chamber	
CEPC	Baseline	TPC	Si
	IDEA	Drift Chamber	
KEKB	Belle2	Drift Chamber	
SCTF	BINP	Drift Chamber	
STCF	HIEPA	Drift Chamber	

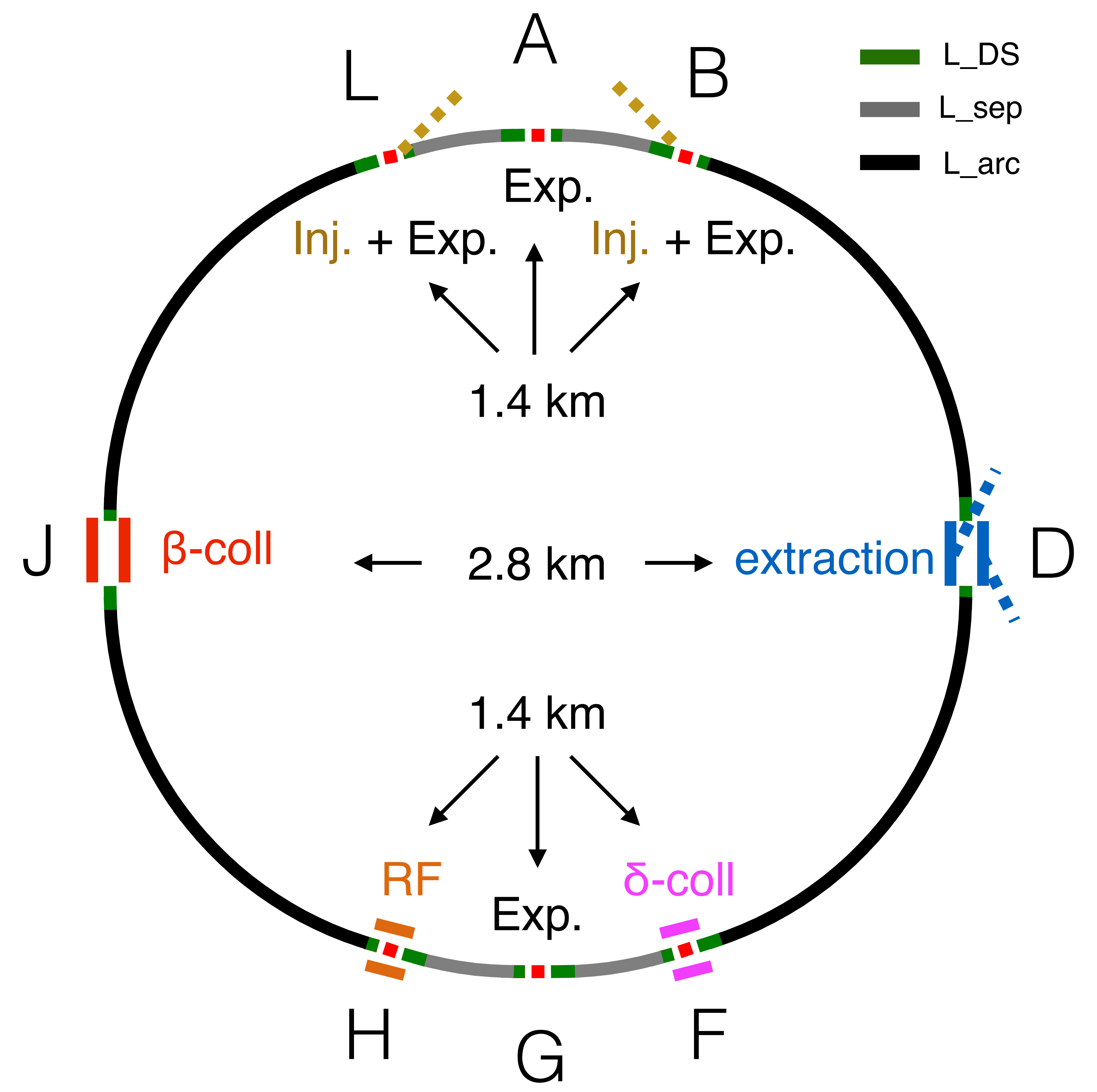
IDEA Drift Chamber



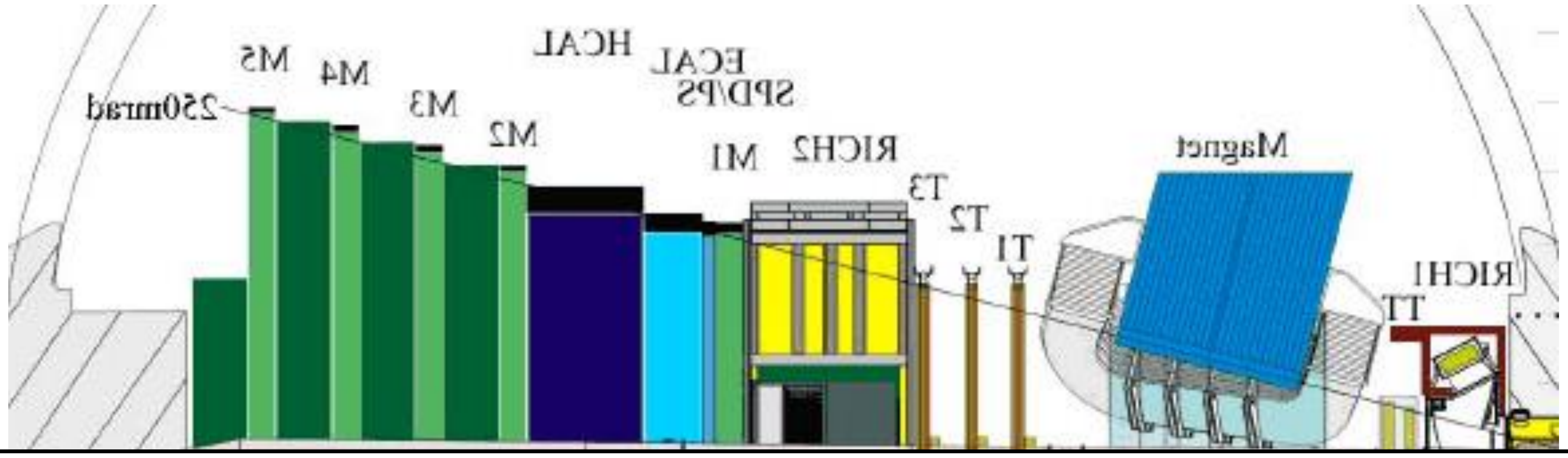
Estimate of full-tracker material budget

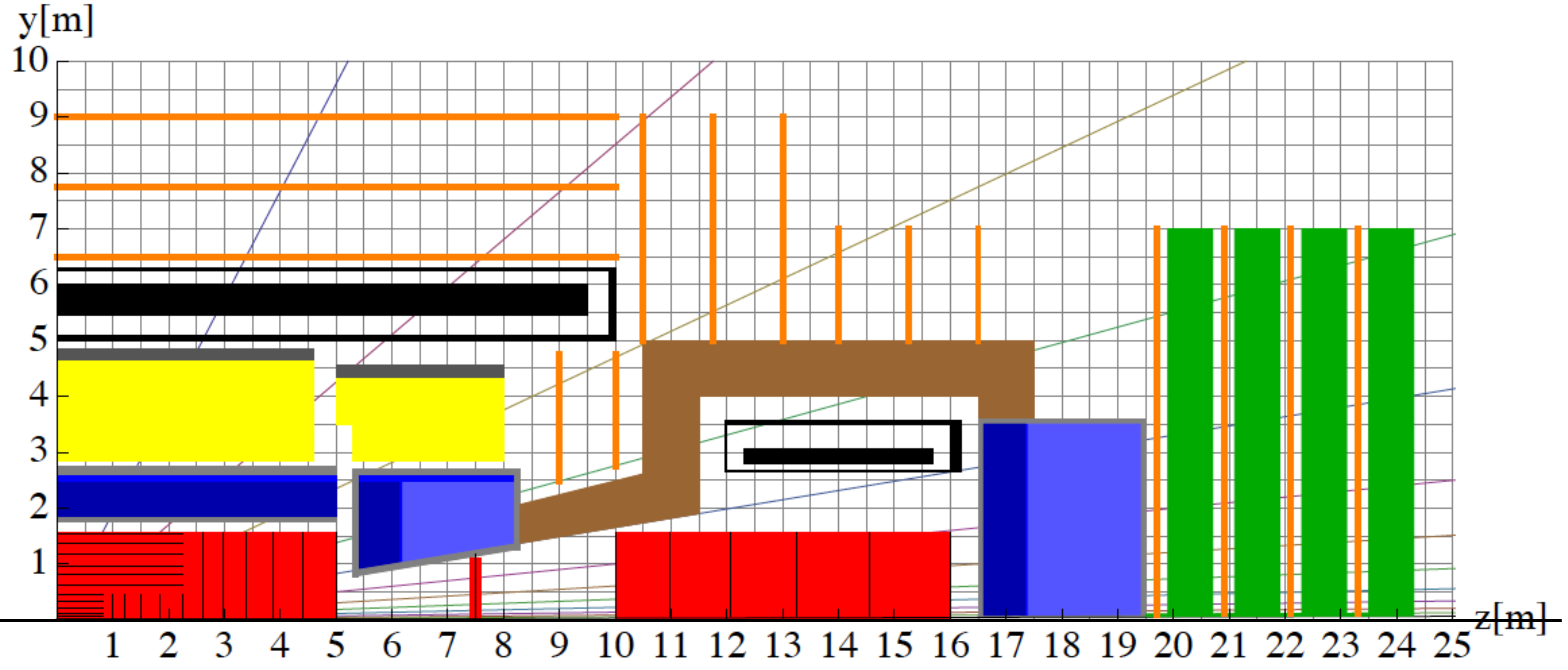


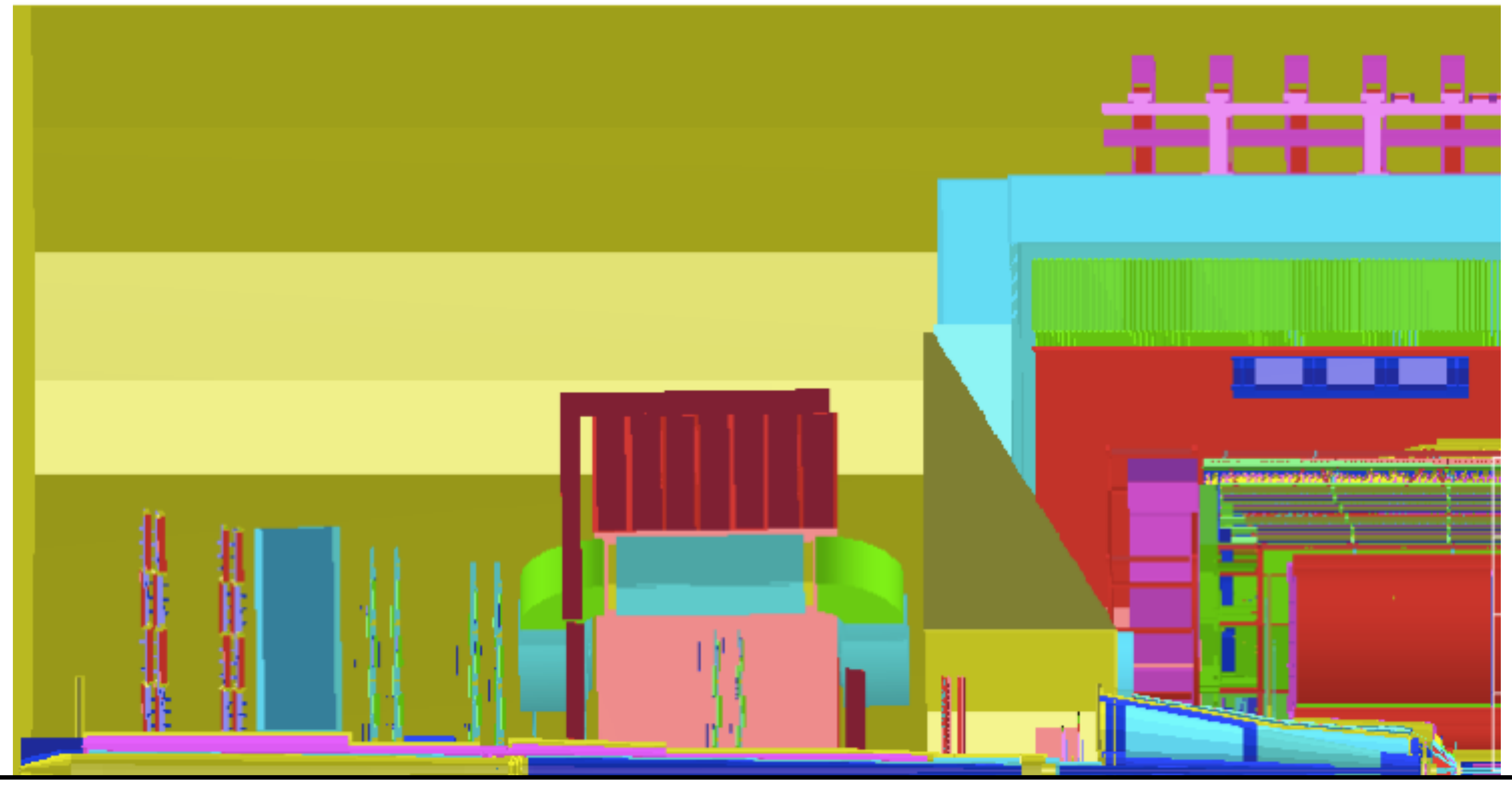
FCC-hh Collider Ring and Experiments

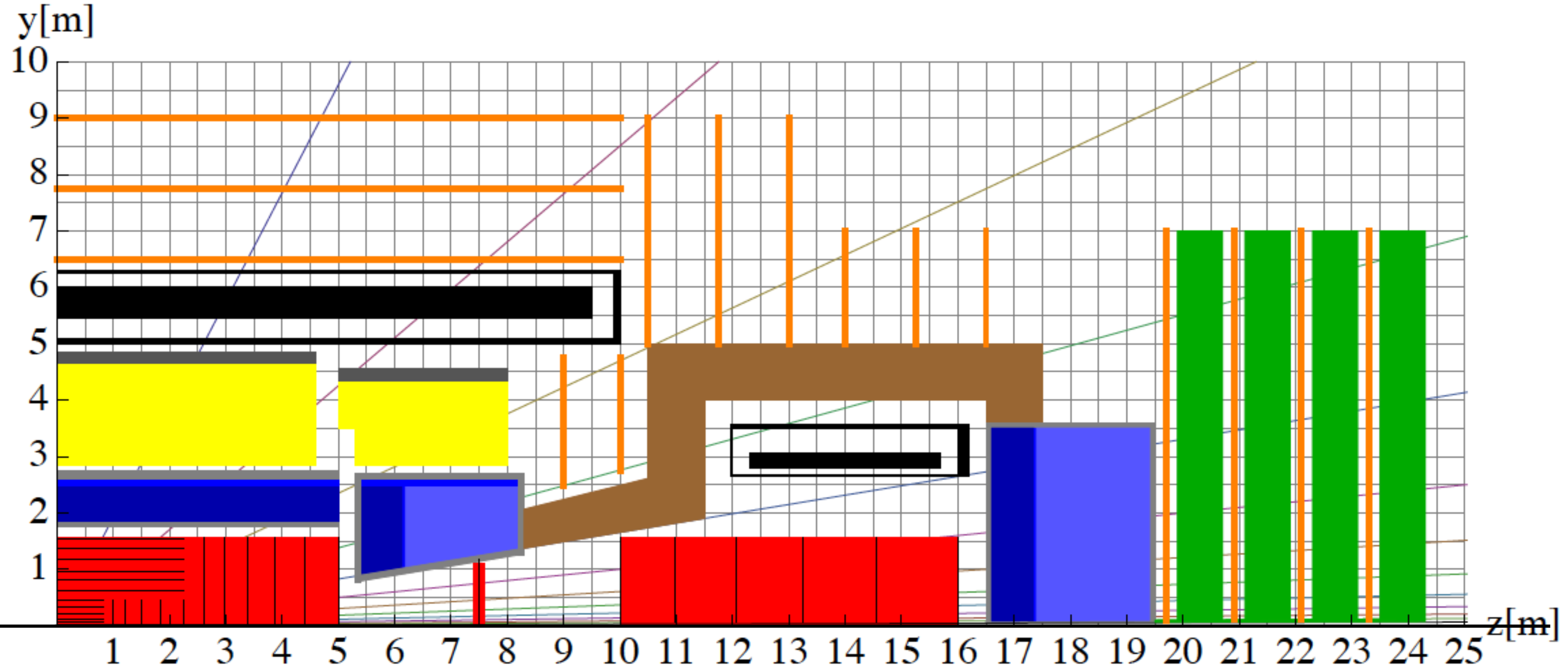


Comparison with LHCb and ALICE









Interaction region: Machine Detector Interface

Machine induced backgrounds

- Radiative Bhabha scattering
- Beam-beam interactions
- Synchrotron radiation
- Beam-gas interactions

Studies for new configuration being finalized

Higgs operation
(E_{cm} = 240 GeV)

Rates at the inner layer (16 mm):

Hit density: ~2.5 hits/cm²/BX
TID: 2.5 MRad/year
NIEL: 10^{12} 1MeV n_{eq}/cm²

(Safety factors of 10 applied)