Detectors for High Energy Colliders
+ Machine Detector Interface

Lucie Linssen (CERN)

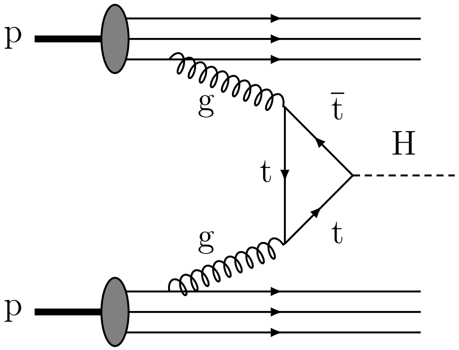
CAS school on beam dynamics and
technologies for future colliders

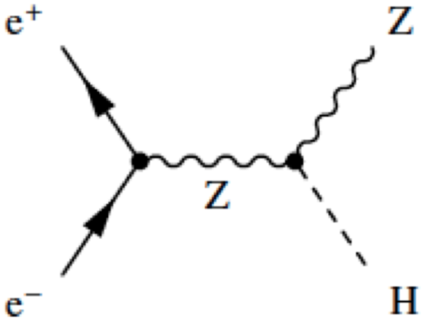
February 23rd 2018

With many thanks to my CLICdp, ILC, FCC-ee and FCC-hh colleagues for presentation material

pp collisions / e^+e^- collisions

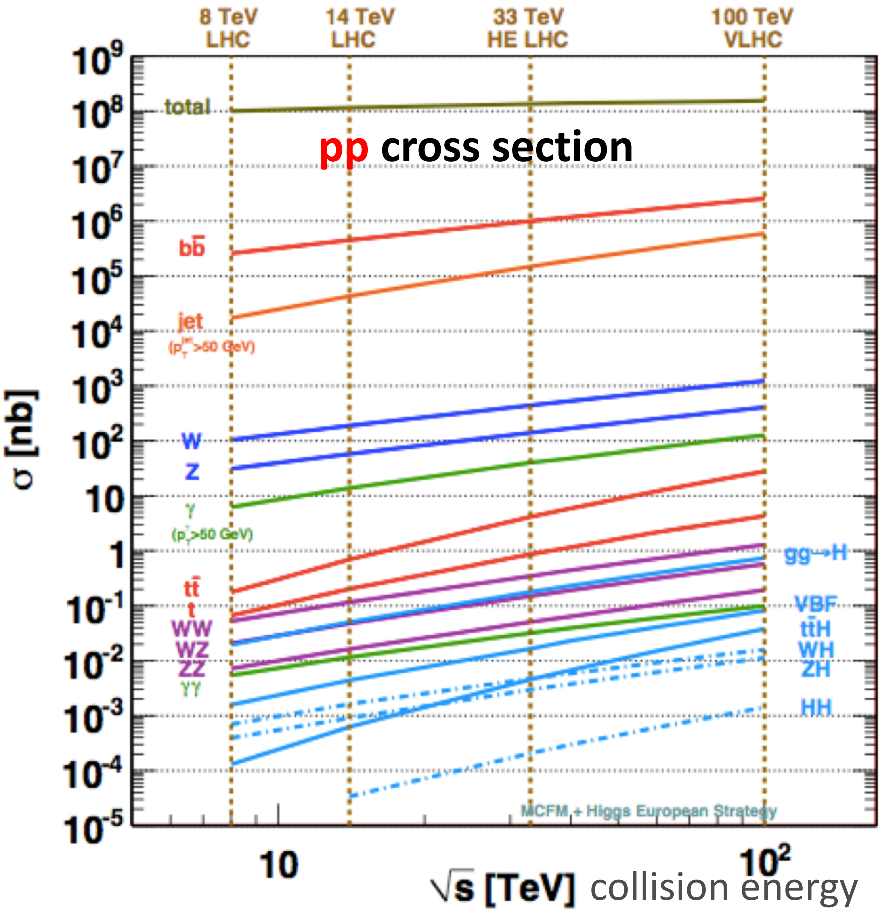
to tackle the open questions in particle physics





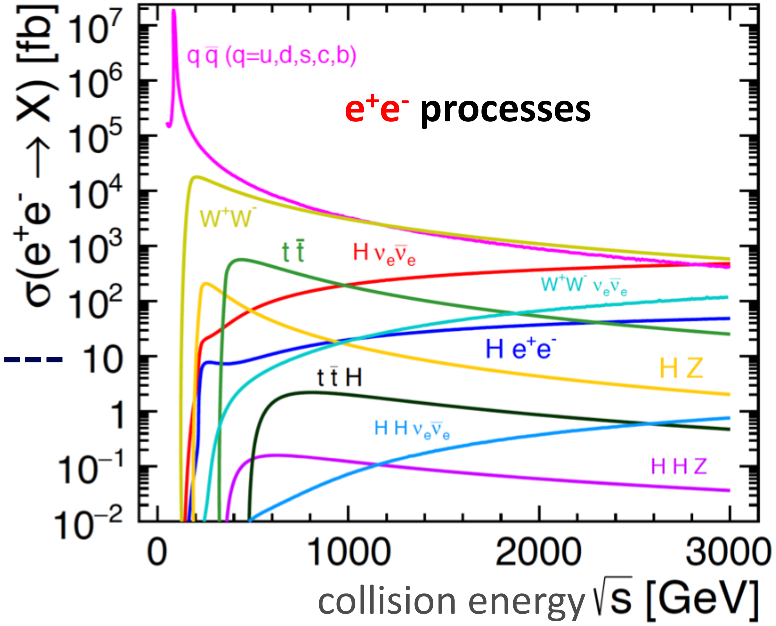
p-p collisions	**e^+e^- collisions**
Proton is compound object → Initial state unknown → Limits achievable precision	**e^+/e^- are point-like** → Initial state well defined (√s / opt: polarisation) → High-precision measurements
High rates of QCD backgrounds → Complex triggering schemes → High levels 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 (>≈350 GeV) require **linear** collider

pp collisions / e$^+$e$^-$ collisions



factor > 10^8

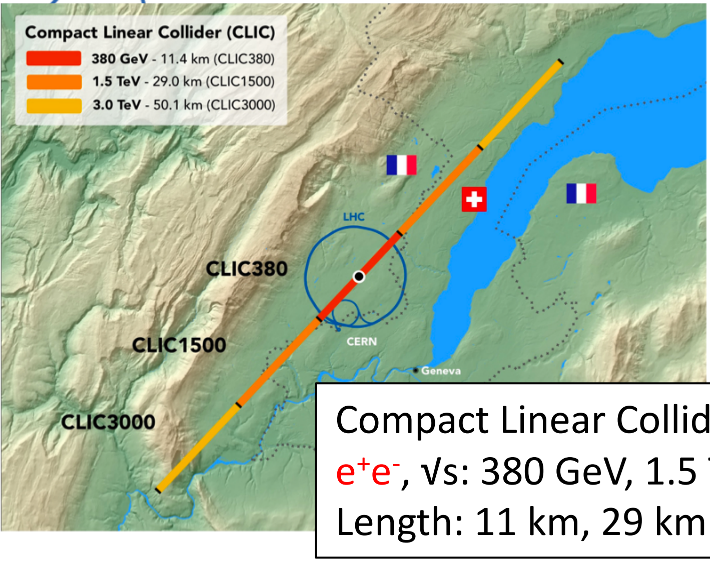
pp and e$^+$e$^-$ collisions
provide complementary physics information
=> important for our field to have both !



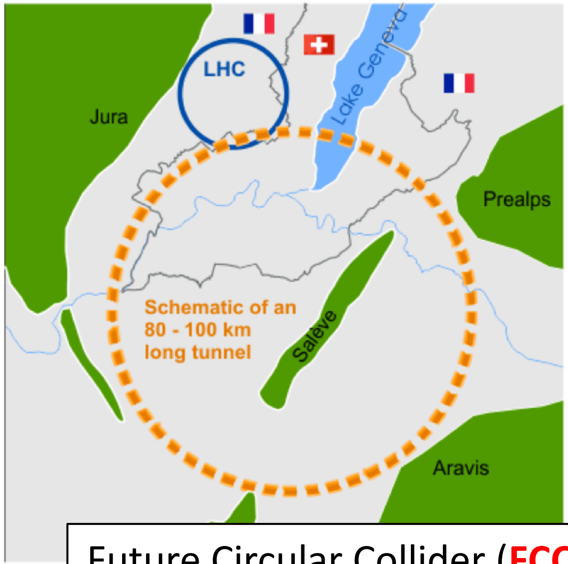
- Interesting pp events need to be found within a huge number of collisions

- e$^+$e$^-$ events are more “clean”

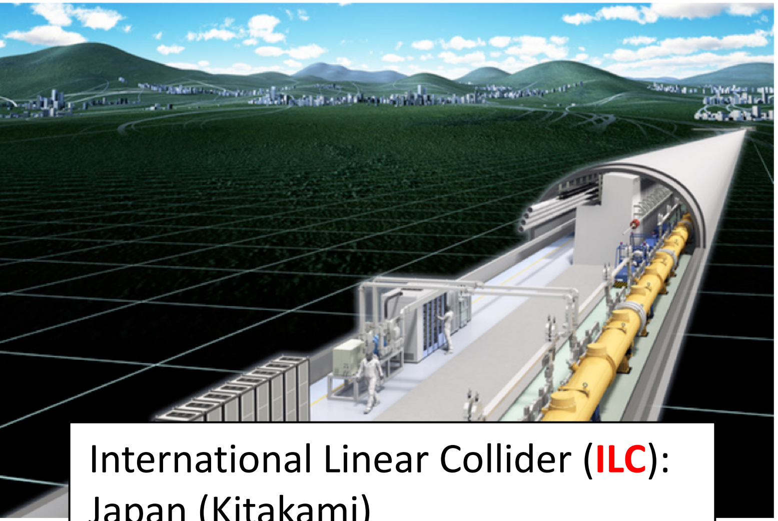
high-energy e^+e^- collider studies



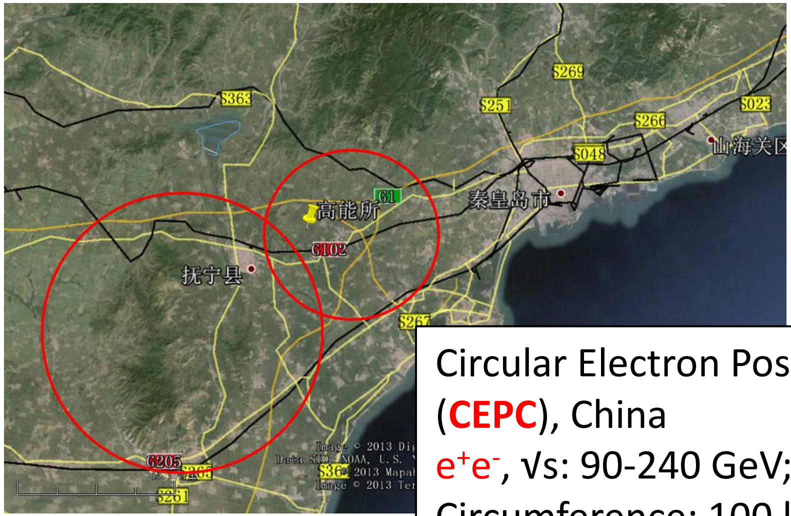
Compact Linear Collider (**CLIC**): CERN
e^+e^-, $\sqrt{s}$: 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km , 50 km



Future Circular Collider (**FCC-ee**): CERN
e^+e^-, $\sqrt{s}$: 90 - 350 (365) GeV; FCC-hh pp
Circumference: 97.75 km

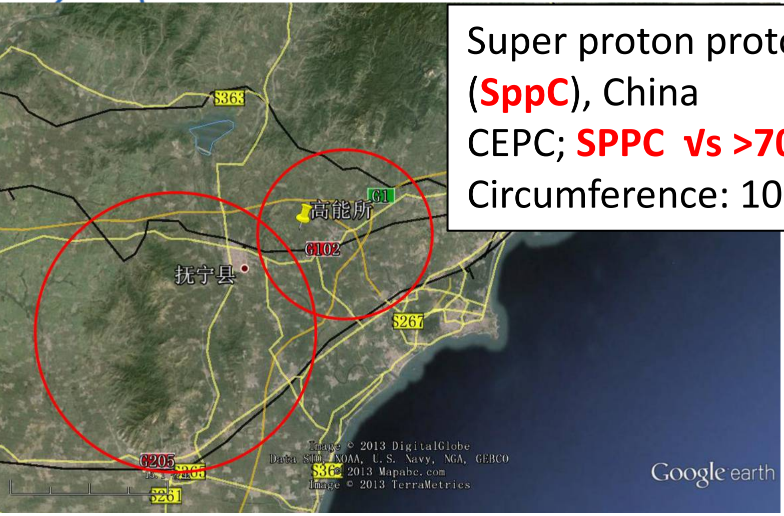


International Linear Collider (**ILC**):
Japan (Kitakami)
e^+e^-, $\sqrt{s}$: 250 – 500 GeV (1 TeV)
Length: 17 km, 31 km (50 km)

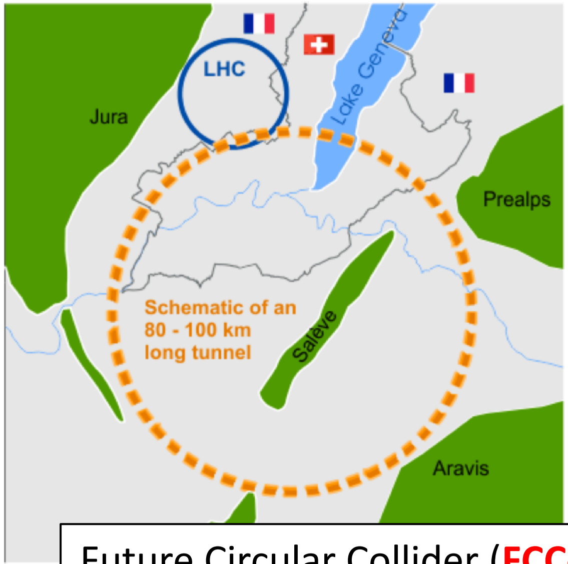


Circular Electron Positron Collider (**CEPC**), China
e^+e^-, $\sqrt{s}$: 90-240 GeV; SPPC pp,
Circumference: 100 km

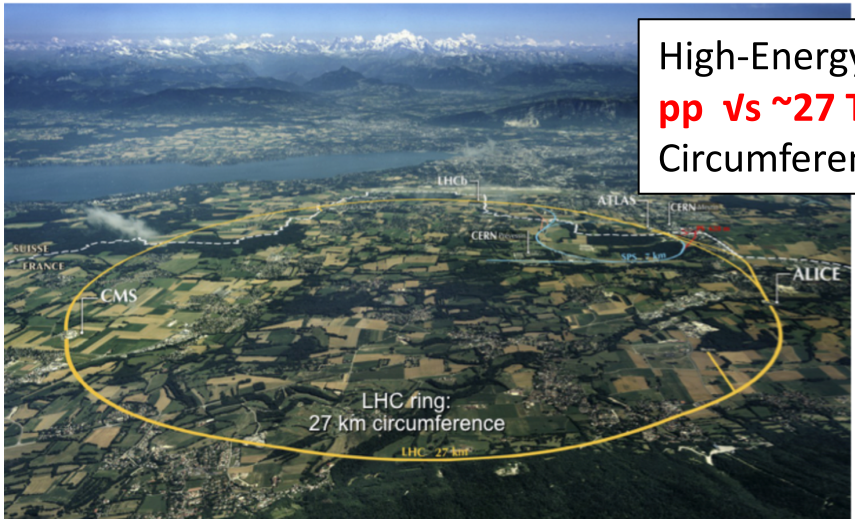
high-energy pp collider studies



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



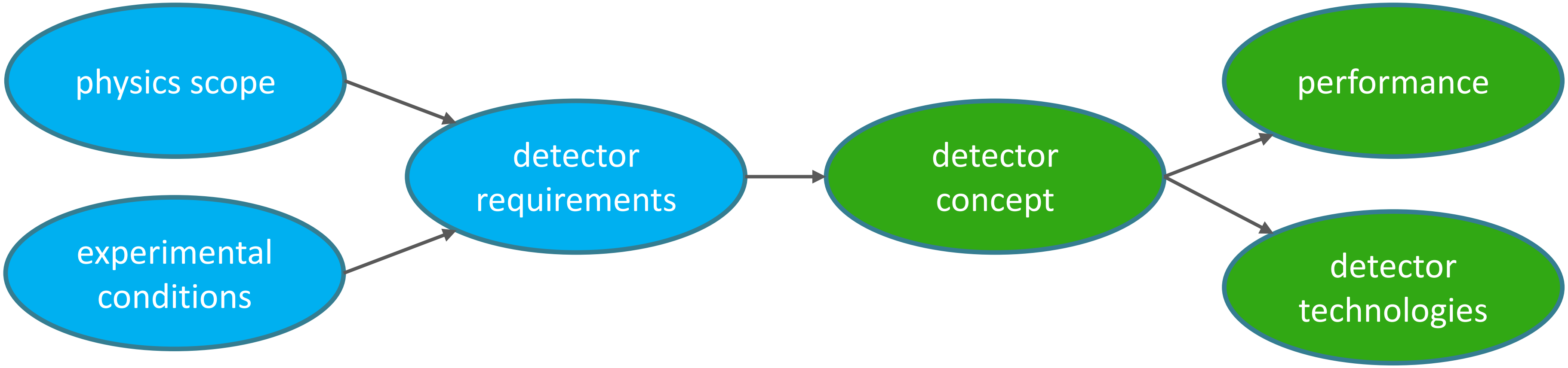
Future Circular Collider (**FCC-hh**): CERN
FCC-ee; **FCC-hh √s ~100 TeV**
Circumference: 97.75 km



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

Scope of the lectures

For both **e^+e^-** and **pp**:


physics scope

experimental conditions

detector requirements

detector concept

performance

detector technologies

Principally explained on the basis of CERN-hosted studies:

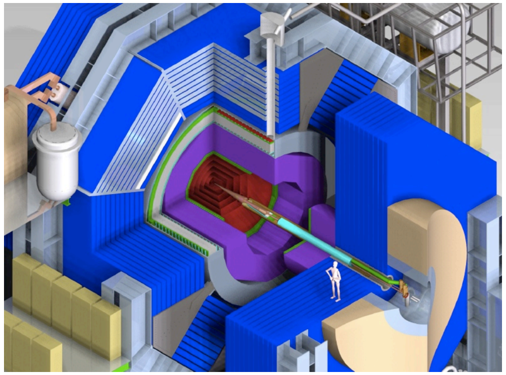
Future **e^+e^- linear** collider => CLIC
Future **e^+e^- circular** collider => FCC-ee
Future **pp circular** collider => FCC-hh

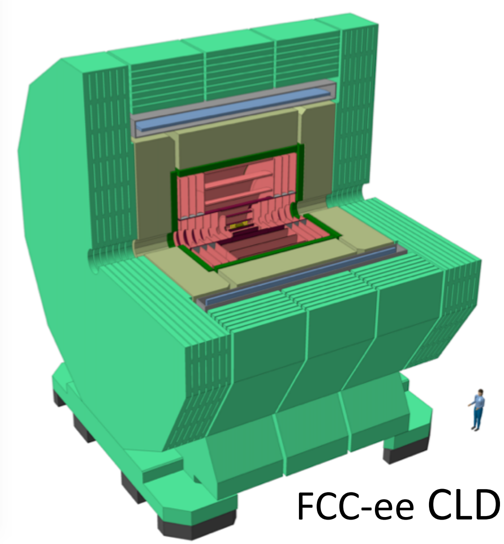
General detector concepts also presented for

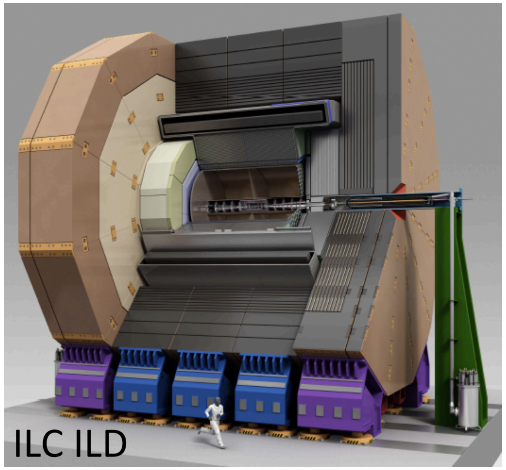
Future **e^+e^- linear** collider => ILC
Future **e^+e^- circular** collider => CEPC

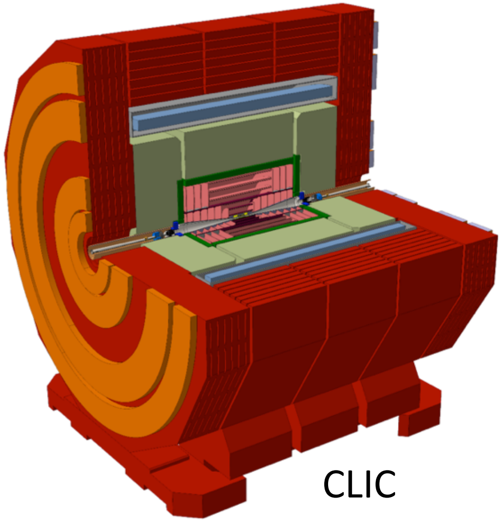
Part 1

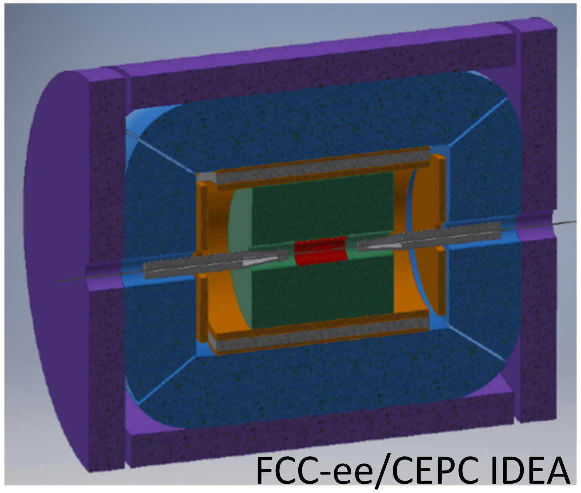
e^+e^- detectors


ILC SiD


FCC-ee CLD


ILC ILD


CLIC


FCC-ee/CEPC IDEA

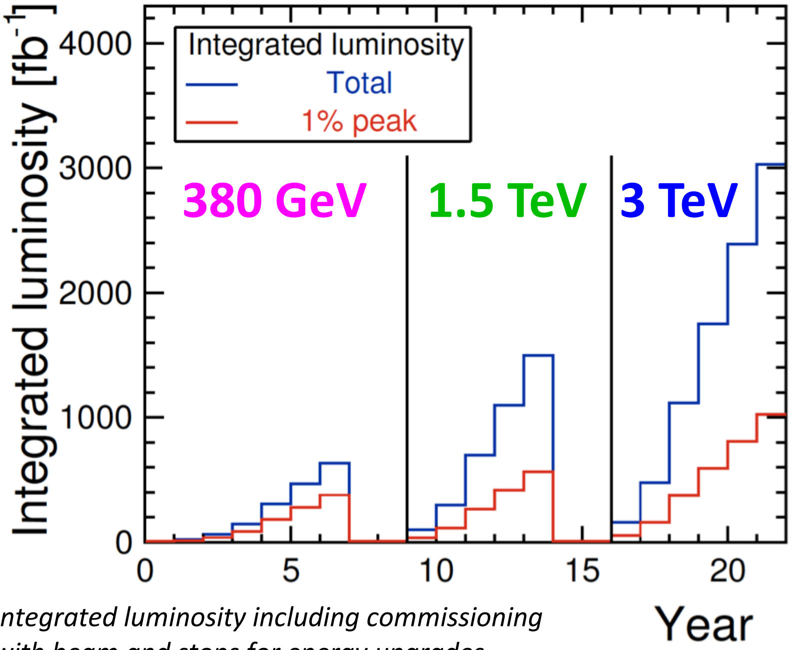
With many thanks to CLICdp, ILC and FCC-ee colleagues for presentation material

CLIC physics scope and staging scenario

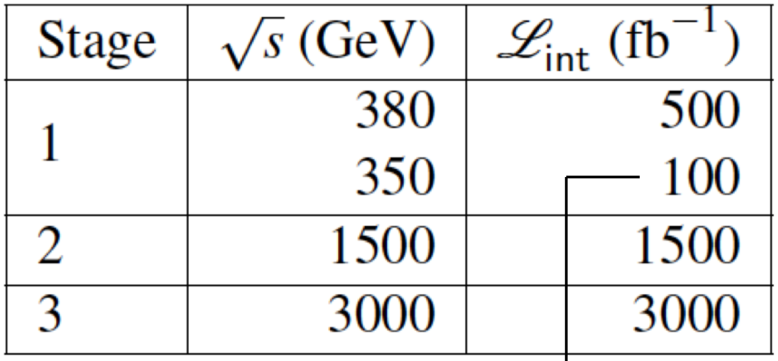
The CLIC program builds on energy stages:

- **380 GeV (350 GeV)**, 600 fb^{-1} : **precision Higgs and top physics**
- **1.5 TeV, 1.5 ab^{-1} :** **BSM searches, precision Higgs, ttH, HH, top physics**
- **3 TeV, 3 ab^{-1} :** **BSM searches, precision Higgs, HH, top physics**

BSM searches: direct (up to ~1.5 TeV), indirect (>> TeV scales)



Integrated luminosity including commissioning with beam and stops for energy upgrades



Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{\text{int}}$ (fb^{-1})
1	380 350	500 100
2	1500	1500
3	3000	3000

Dedicated to top mass threshold scan

CERN-2016-004

Staging scenario can be adapted, e.g. to new results from (HL-)LHC

CLIC accelerator parameters

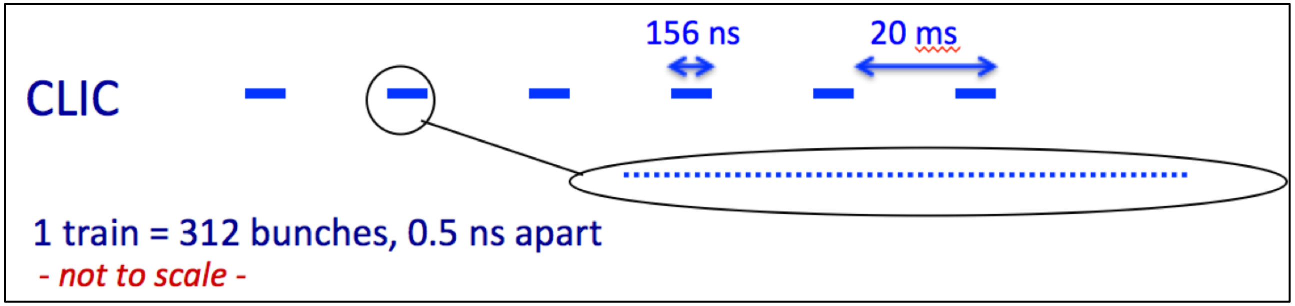
Parameter	**380 GeV**	**1.5 TeV**	**3 TeV**
Luminosity $\mathcal{L}$ (10^{34}cm^{-2}sec^{-1})	**1.5**	**3.7**	**5.9**
$\mathcal{L}$ above 99% of $\sqrt{s}$ (10^{34}cm^{-2}sec^{-1})	0.9	1.4	2.0
Accelerator gradient (MV/m)	72	72/100	72/100
Site length (km)	11.4	29	50
Repetition frequency (Hz)	50	50	50
Bunch separation (ns)	0.5	0.5	0.5
Number of bunches per train	352	312	312
Beam size at IP σ_x/σ_y (nm)	150/2.9	~60/1.5	~40/1
Beam size at IP σ_z (μm)	70	44	44

Drives timing requirements for CLIC detector

Very small beam

Crossing angle 20 mrad, electron polarization ±80%

Very low duty cycle
Allows for:
- Triggerless readout
- Power pulsing



CERN-2016-004

linear e$^+$e$^-$ accelerator parameters

Parameter	ILC 250 GeV	ILC 500 GeV	CLIC 380 GeV	CLIC 1.5 TeV	CLIC 3 TeV
Luminosity $\mathscr{L}$ (10^{34}cm^{-2}sec^{-1})	**1.35**	**1.8**	**1.5**	**3.7**	**5.9**
$\mathscr{L}$ above 99% of √s (10^{34}cm^{-2}sec^{-1})	**1.2**	**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) →	5	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**

ILC: Crossing angle 14 mrad, electron polarization ±80%, positron polarization ±30%

Comparing experimental conditions ILC with CLIC

- Larger beam sizes and lower energies => less beamstrahlung
- Longer bunch trains (~1 ms)

} Detectors do not need ns-level timing capabilities to reject background

[Shin Michizono, HEP conf 2018]

FCC-ee physics and staging scenario

Energy stages $\sqrt{s}$ = 91 GeV **Z**, 160 GeV **W**, 240 GeV **H**, 350 (365) GeV **top**

m_Z, m_W, m_{top}, $\sin^2\theta_W^{eff}$, R_b, $\alpha_{QED}(m_Z)$, $\alpha_s(m_Z\ m_W)$, Higgs and top quark couplings

$\Rightarrow$ Very high precision measurements of electroweak parameters

$\Rightarrow$ Exploration of very high energy scale (>> TeV) via precision measurements

$\Rightarrow$ Search for (very) weakly coupled particles

	luminosity/IP [10^{34} cm^{-2}s^{-1}]	**total luminosity (2 IPs)/ yr**	**physics goal**	**run time [years]**
Z first 2 years	100	26 ab^{-1}/year	150 ab^{-1}	4
Z later	200	52 ab^{-1}/year		
W	30	7.8 ab^{-1}/year	10 ab^{-1}	1
H	7.0	1.8 ab^{-1}/year	5 ab^{-1}	3
machine modification for RF installation & rearrangement: 1 year				
top 1st year (350 GeV)	0.8	0.2 ab^{-1}/year	0.2 ab^{-1}	1
top later (365 GeV)	1.3	0.34 ab^{-1}/year	1.5 ab^{-1}	4

total program duration: 14 years - *including machine modifications*

phase 1 (*Z, W, H*): 8 years, phase 2 (top): 6 years

P.Janot, Acad.Training, Oct 2017

M. Benedikt, Nov 2017

FCC-ee accelerator parameters

	Z	**W**	**H (ZH)**	**ttbar**
beam energy [GeV]	**45.6**	**80**	**120**	**182.5**
SR energy loss / turn (GeV)	0.036	0.34	1.72	9.21
SR total power [MW]	100	100	100	100
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.153	0.099 / 0.151	0.15 / 0.20
bunch length (SR / BS) [mm]	3.5 / 12.1	3.3 / 7.65	3.15 / 4.9	2.5 / 3.3
bunch intensity [10^{11}]	1.7	1.5	1.5	2.8
no. of bunches / beam	16640	2000	393	39
Bunch crossing separation (ns)	**20**	160	830	8300
luminosity [10^{34} cm^{-2}s^{-1}] per IP	**230**	32	7.8	1.5

Beam transverse polarisation => beam energy can be measured to very high accuracy (~50 keV)

At Z-peak very high luminosities and high cross section

⇒ Statistical accuracies at 10^{-5} level (e.g. cross sections, asymmetries)

⇒ This drives the **detector performance**

⇒ This also drives requirement on **data rates**

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

★ **momentum resolution:**

e.g, HZ, $g_{H\mu\mu}$, Smuon endpoint

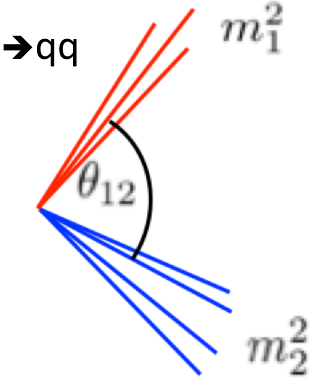
$$\boxed{\sigma_{p_T}/p_T^2 \sim 2\times 10^{-5}\,\mathrm{GeV}^{-1}}$$

★ **jet energy resolution:**

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

$$\boxed{\frac{\sigma_E}{E} \sim 3.5-5\,\%}$$

(for high-E jets, light quarks)



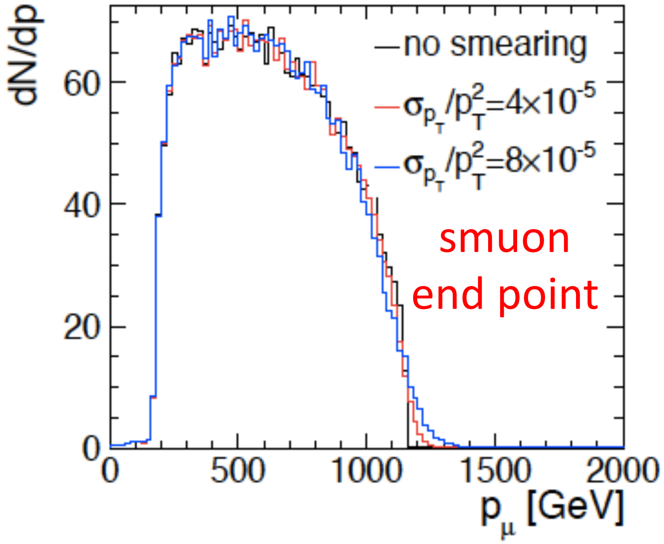
★ **impact parameter resolution:**

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

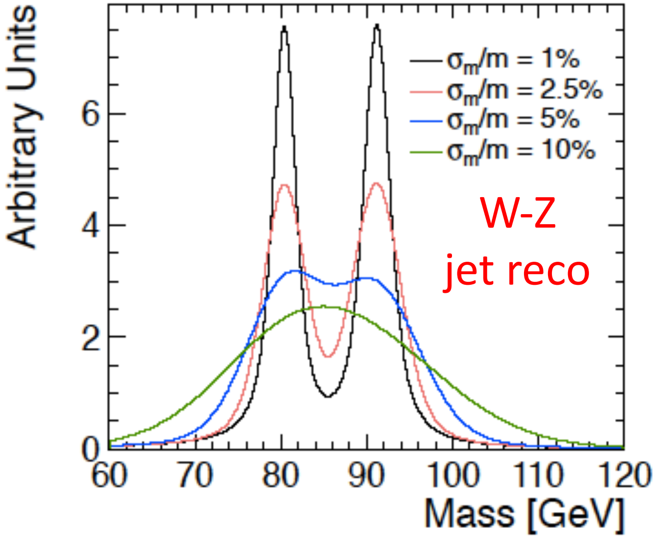
$$\boxed{\sigma_{r\phi} = 5 \oplus 15/(p[\mathrm{GeV}]\sin^{\frac{3}{2}}\theta)\,\mu\mathrm{m}}$$

★ **angular coverage, very forward electron tagging**

+ requirements from experimental conditions



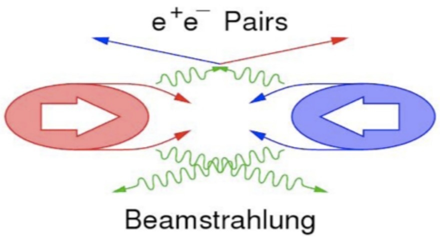
smuon end point

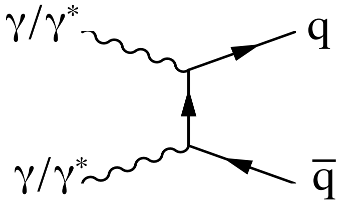


W-Z jet reco

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 nm, 1 nm, 44 µm} => **beamstahlung**





Main backgrounds (p_T>20 MeV, θ>7.3°):

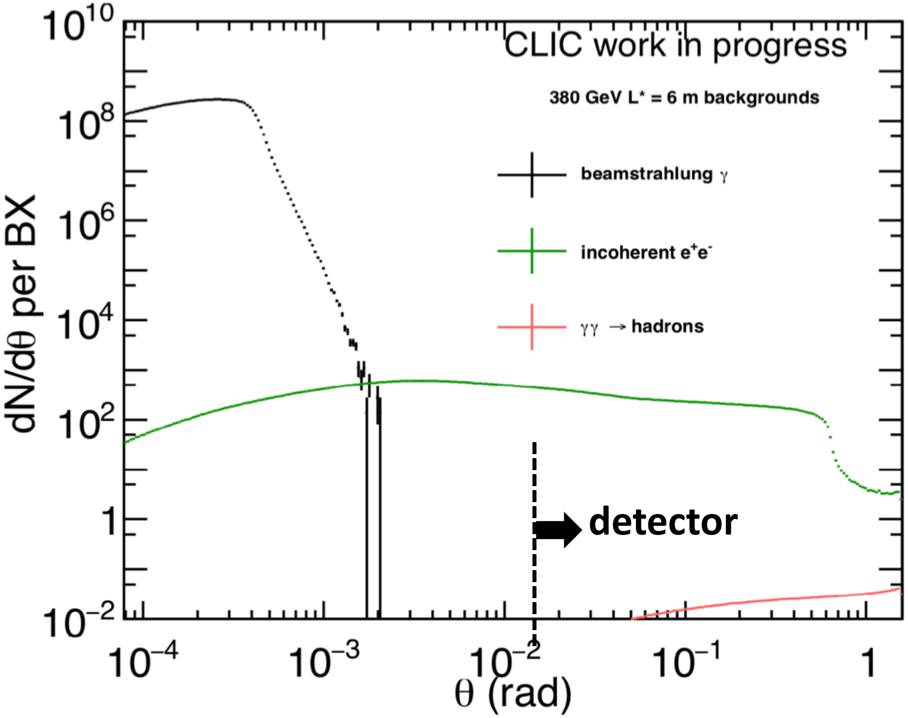
- **Incoherent e+e- pairs**
  - 19k particles per bunch train at 3 TeV
  - High occupancies
    => **Impact on detector granularity**
- **γγ => hadrons**
  - 17k particles per bunch train at 3 TeV
  - Main background in calorimeters and trackers
    => **Impact on detector granularity and physics**

Note: at ILC or at lower CLIC energies, beamstrahlung effect is less strong
=> nevertheless a driver for the detector design

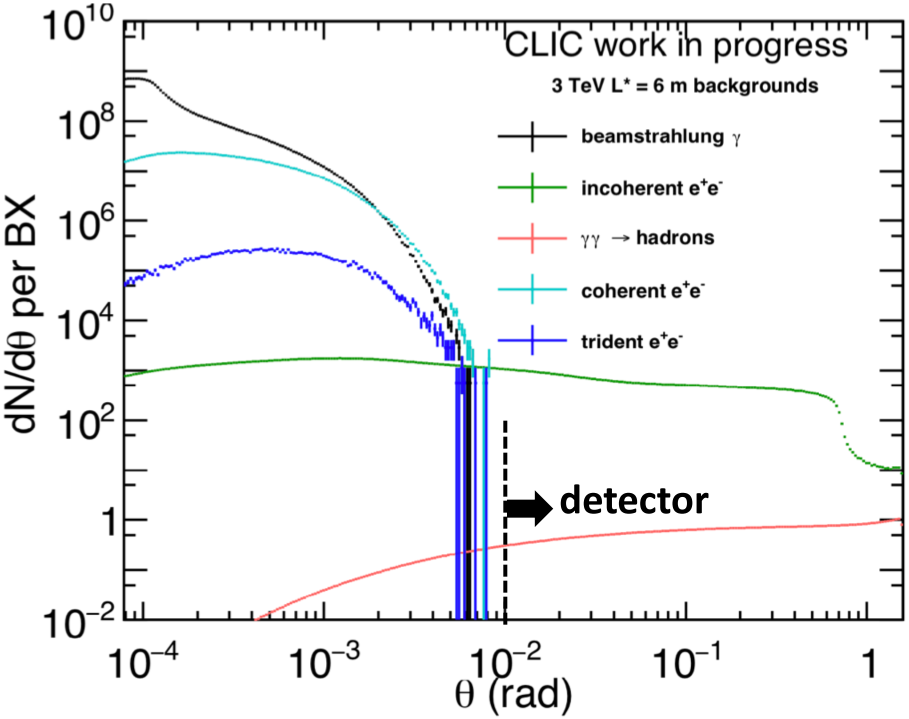
Circular colliders: beamstrahlung (BS) (*less pronounced*) + synchrotron radiation (SR)
Strongest effects at 365 GeV. Recent studies show that SR can be reduced below BS level.

CLIC beam-induced background

CLIC 380 GeV



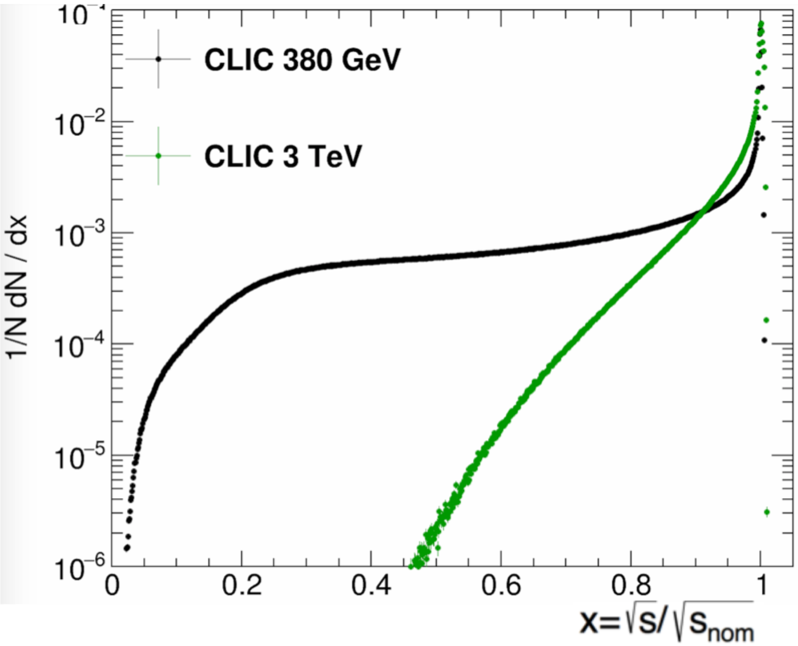
CLIC 3 TeV



In the detector region, the relevant backgrounds are incoherent pairs and $\gamma\gamma \rightarrow$ hadrons

Dominik Arominski, CLIC2018

luminosity spectrum



Beamstrahlung ➔ important energy losses right at the interaction point

Most physics processes are studied well above production threshold => profit from full spectrum

Luminosity spectrum can be measured in situ using large-angle Bhabha scattering events, to 5% accuracy at 3 TeV
Eur.Phys.J. C74 (2014) no.4, 2833

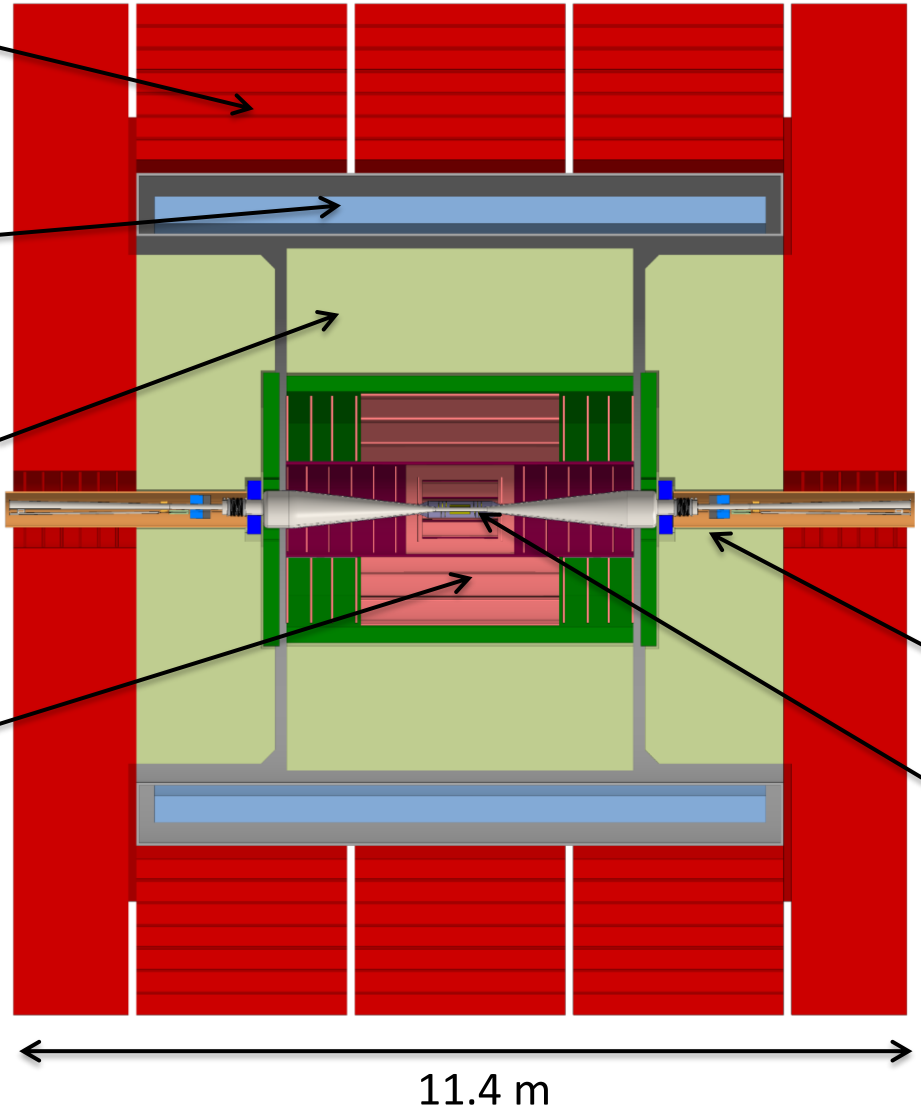
Fraction $\sqrt{s}/\sqrt{s_{nom}}$	380 GeV	3 TeV
>0.99	63%	36%
>0.9	91%	57%
>0.8	98%	68%
>0.7	99.5%	77%
>0.5	~100%	88%

experimental conditions linear e^+e^-

Linear Colliders

- **Beam-induced background**:
  - Beamstrahlung (incoherent pairs and $\gamma\gamma \rightarrow$ hadrons)
  - High occupancies in the detector => small readout cells needed
  - Precise (ns-level) timing required at CLIC
- **Low duty cycle**
  - Power pulsing of electronics possible
  - Triggerless readout
- **Beam crossing angle** 14 mrad (ILC), 20 mrad (CLIC)

CLIC detector model



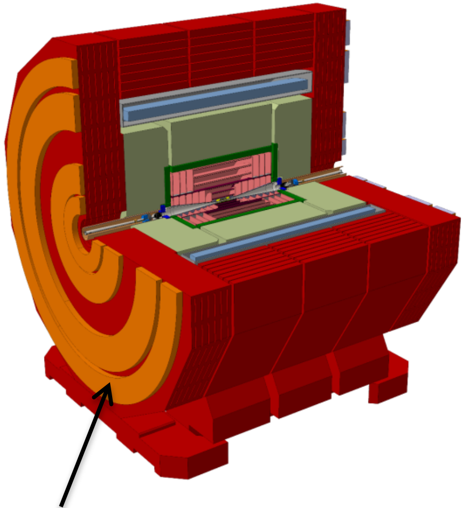
return yoke (Fe) with muon-ID detectors

superconducting solenoid, 4 Tesla

fine grained (PFA) calorimetry, 1 + 7.5 Λ_i, Si-W ECAL, Sc-FE HCAL

silicon tracker, (large pixels / short strips)

Final beam focusing is outside the detector



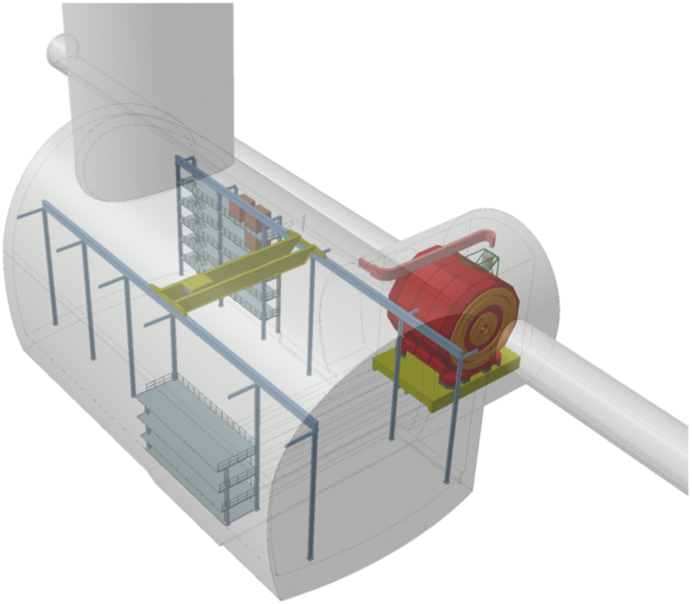
end-coils for field shaping

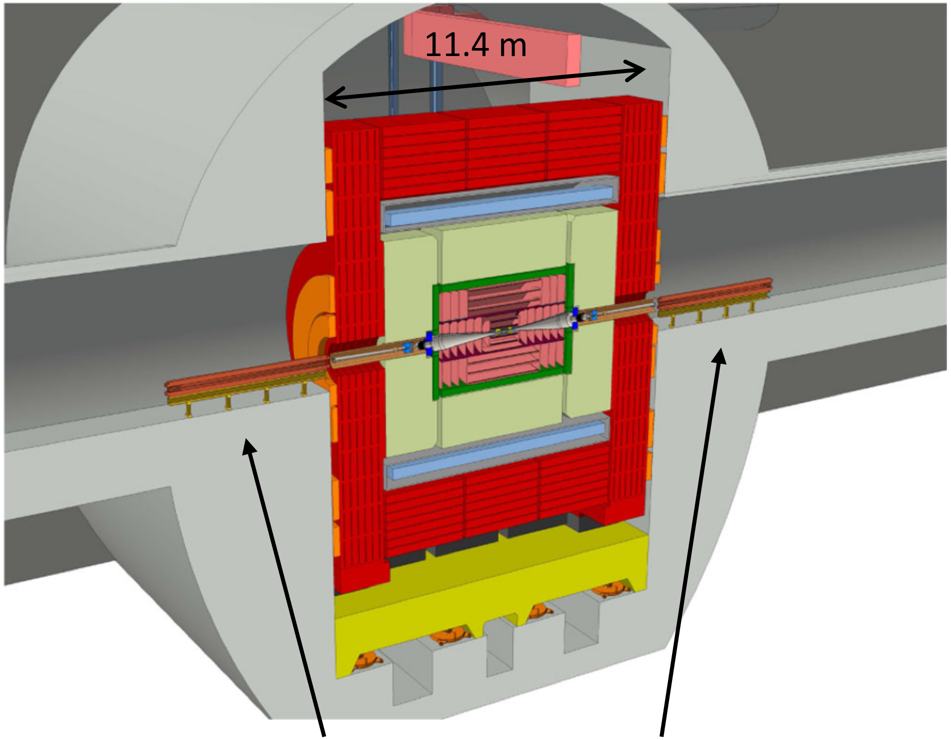
forward region with compact forward calorimeters

low-mass vertex detector, ~25 µm pixels

CLICdp-Note-2017-001

CLIC detector





Experiment kept short along beam line
Still maximising acceptance for forward-going particles

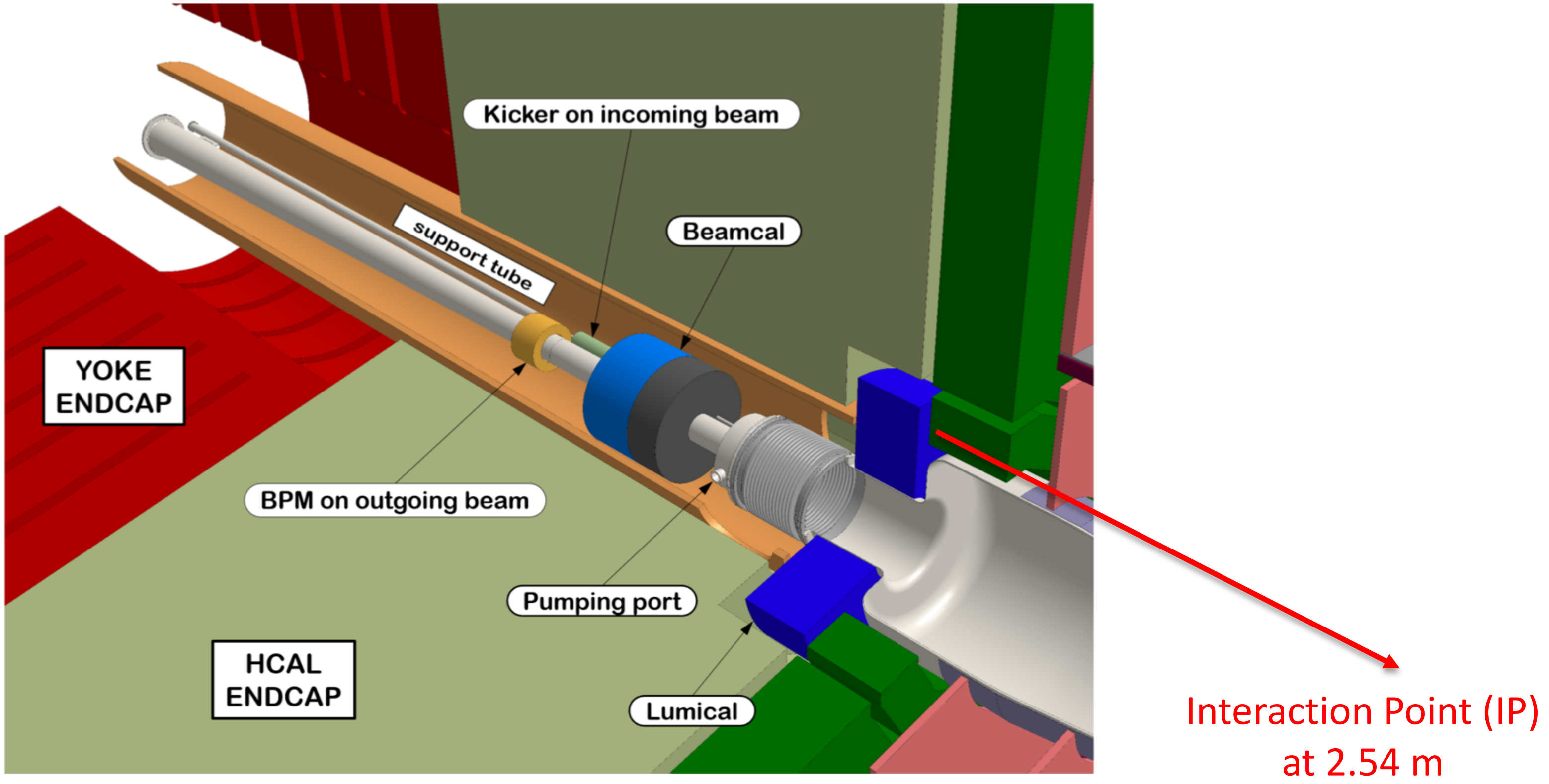
Recent CLIC MDI publication

final focus quadrupoles
in accelerator tunnel
L*=6m

QD0 B-field 201.4 T/m
aperture radius 4 mm

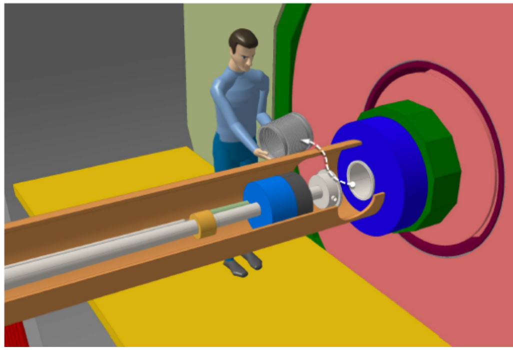
Note: ILC detectors have final focus elements inside the detector (L is 3.4 m)*

CLIC forward detector region

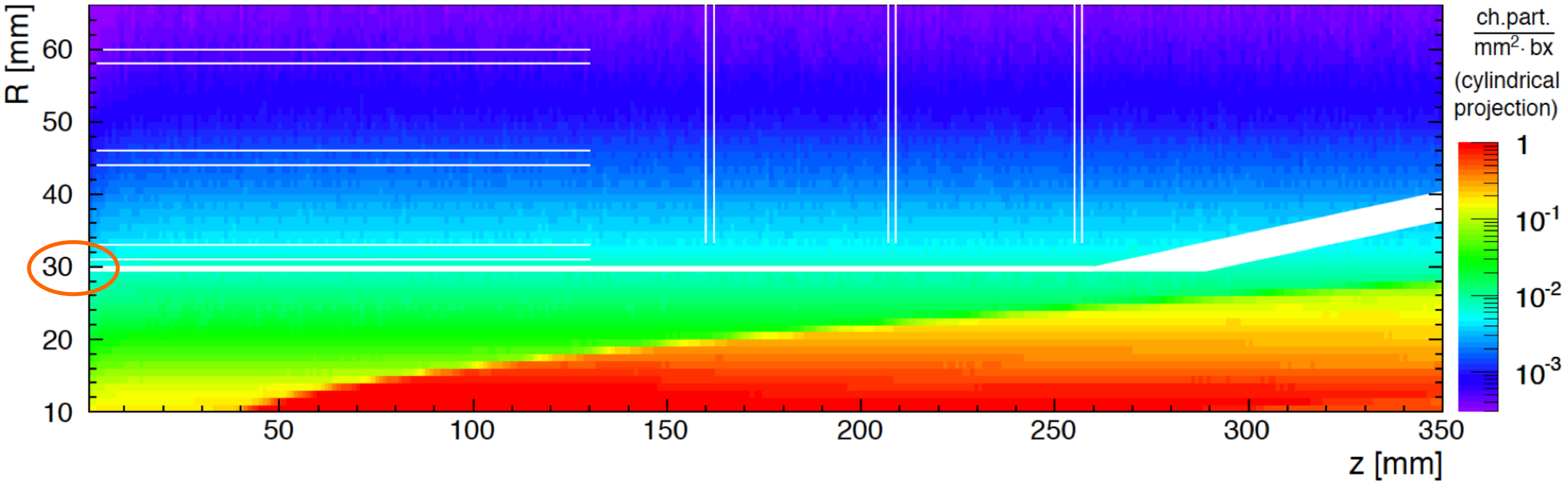


Includes 2 compact forward calorimeters: Lumical + Beamcal

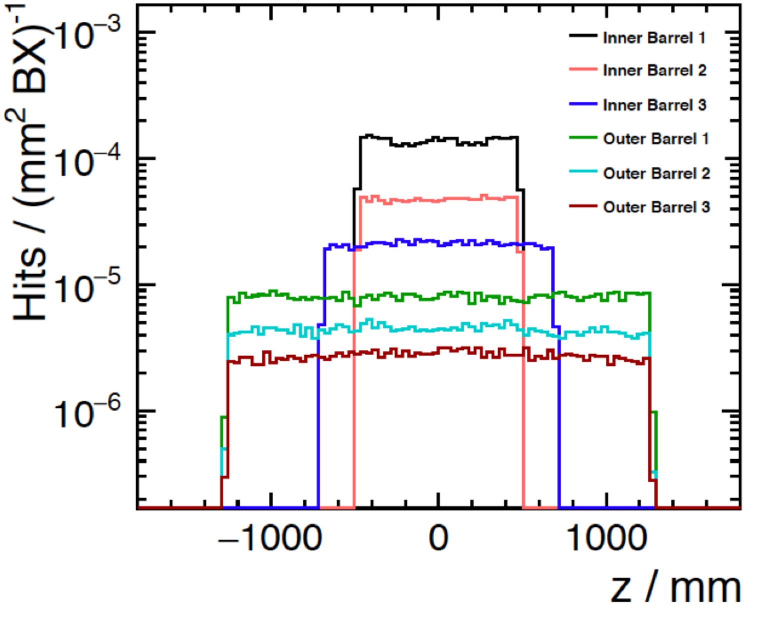
- e/γ acceptance to small angles
- Luminosity measurement (using Bhabha scattering)
- (possibly beam feedback)

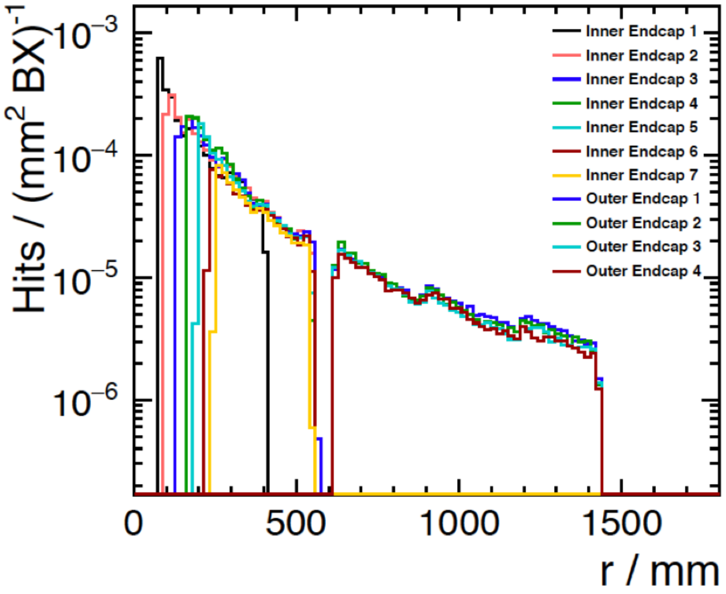


CLIC detector occupancies from beam-induced backgrounds



CLIC Vertex detector at 3 TeV





CLIC tracker at 3 TeV

Charged particles: incoherent pairs + γγ→hadrons

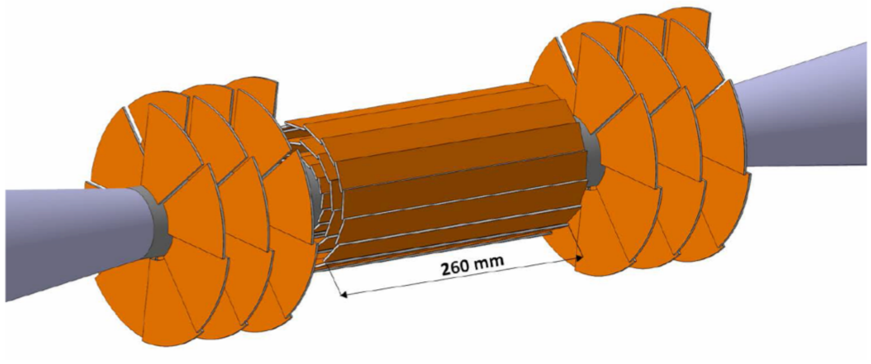
CLIC vertex requirements: CERN-2012-003

CLIC tracker readout requirements: CLICdp-Note-2017-002

CLIC silicon pixel R&D (vertex and tracker)

Parameter	vertex	tracker
Hit position resolution (µm)	3	7
Time stamping (ns per slice)	10	10
Material per layer (X_0)	<0.2%	<1-1.5%
Silicon thickness (µm)	~100 (50+50)	~200
Power (mW/cm^2, incl. power pulsing)	<50	<150
Radiation level NIEL (n_{eq} cm^{-2}/yr)	<4×10^{10}	<10^{10}
Radiation level TID (Gy/yr)	<200	<1

Performance requirements for the CLIC tracking system



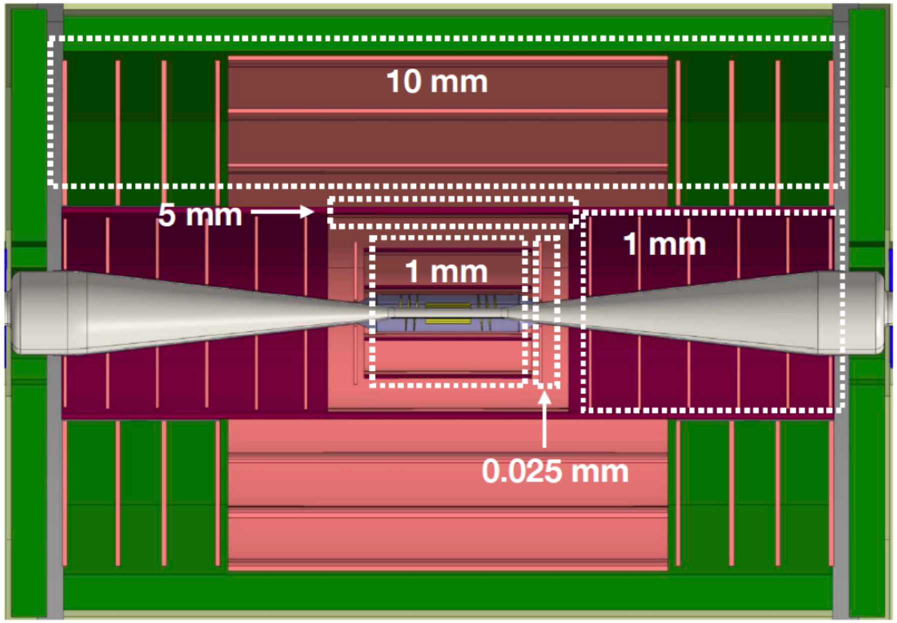
Layout of the CLIC vertex detector

(with spiraling discs for air cooling purposes)

First layer at ~30 mm (3 TeV), ~25 mm (380 GeV)

Layout of the CLIC tracker

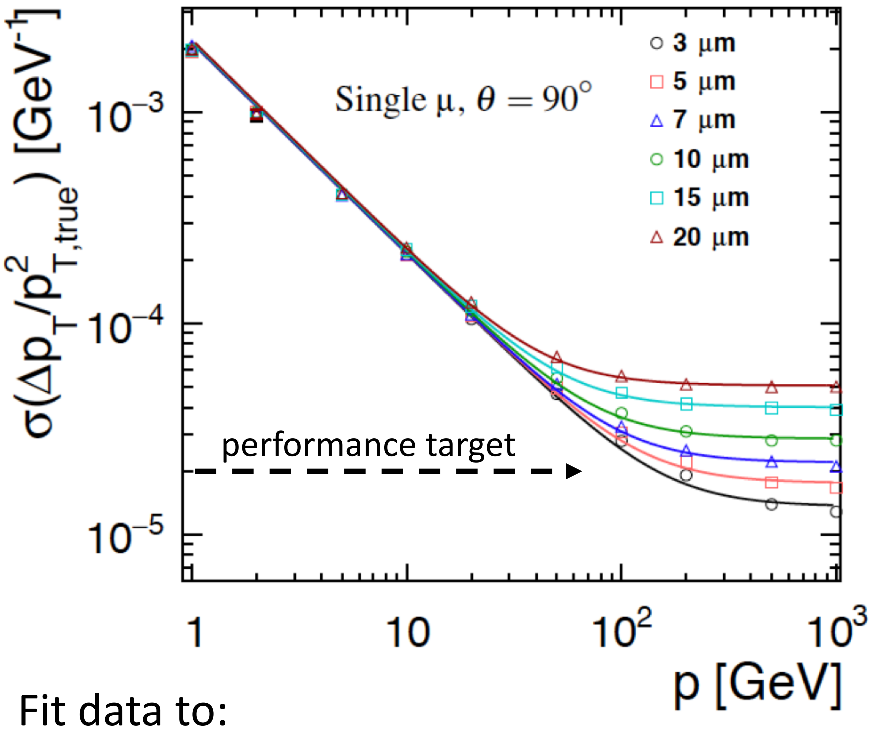
Tracker radius ~1.5 m, maximum strip lengths indicated (assuming 50 µm strip width) taking into account occupancies from beam-induced background)



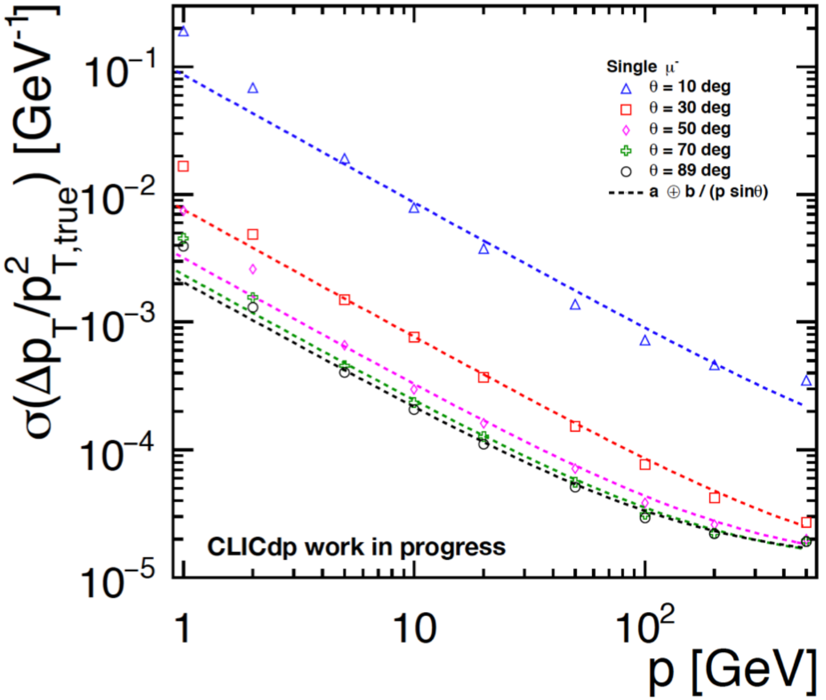
CLIC tracking performances

Geant4-based simulation and event reconstruction

Varying position resolution in tracker



CLICdet with nominal performances



Fit data to:

$$\sigma\left(\Delta_{p_\mathrm{T}}/p_\mathrm{T}^2\right) = a \oplus \frac{b}{p\sin\theta}$$

Shows that 7 μm in tracker is needed

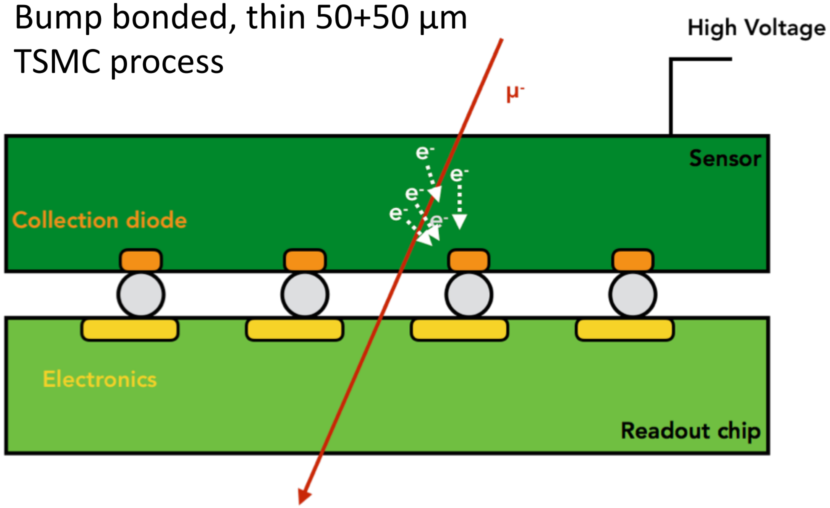
Geant4 simulation + reconstruction momentum resolution for muons ~2×10^{-5} GeV $^{-1}$ achieved in central part

E.Leogrande @ CLIC18

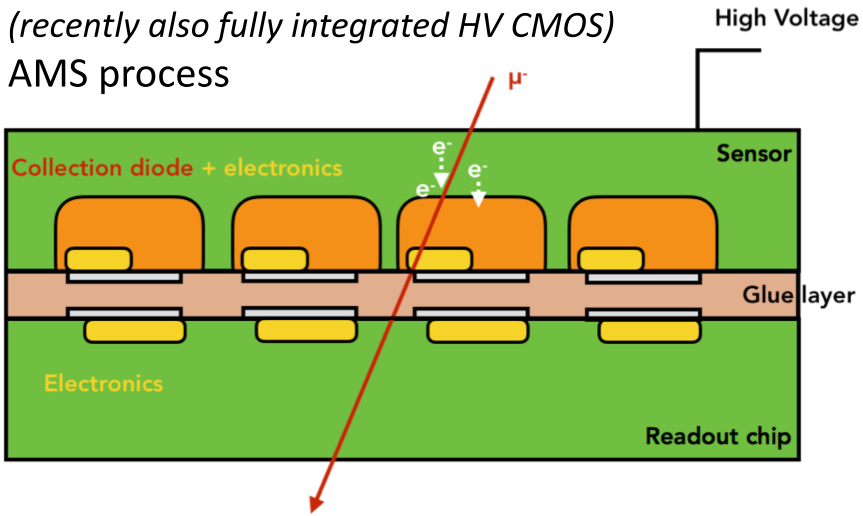
CLICdp-Note-2017-002

Si technologies pursued in CLIC R&D

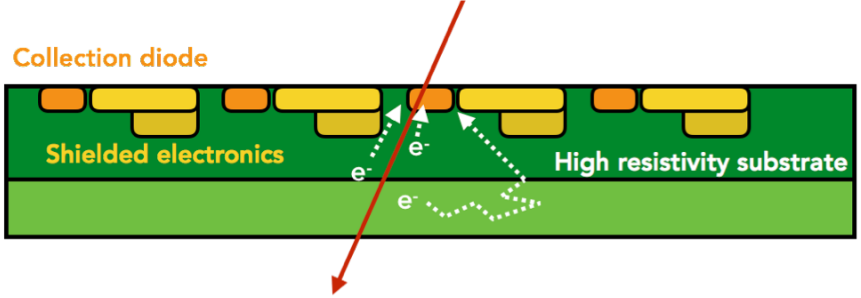
Hybrid: Si sensor + ASIC (65 nm)
Bump bonded, thin 50+50 μm
TSMC process



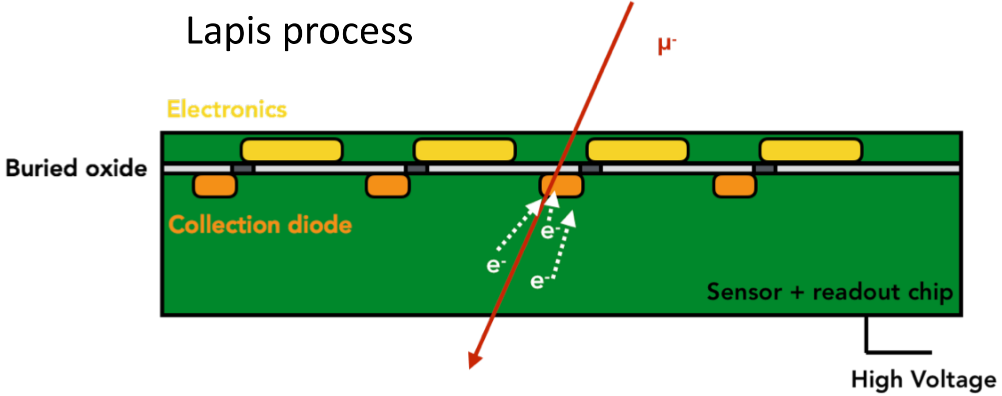
Hybrid: HV CMOS active sensor + ASIC (65 nm)
Capacitive coupling (glue)
(recently also fully integrated HV CMOS)
AMS process



Fully integrated: HR CMOS
TowerJazz process



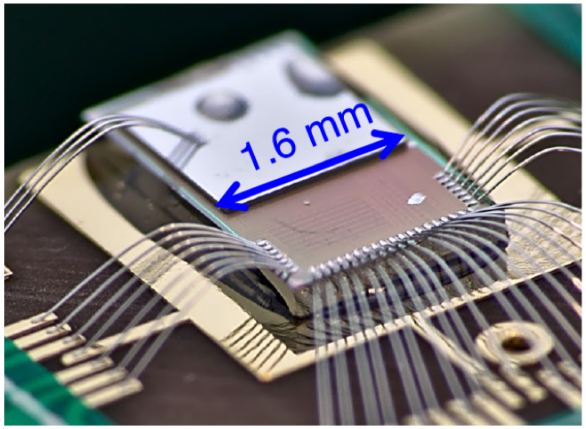
Fully integrated: SOI
Lapis process



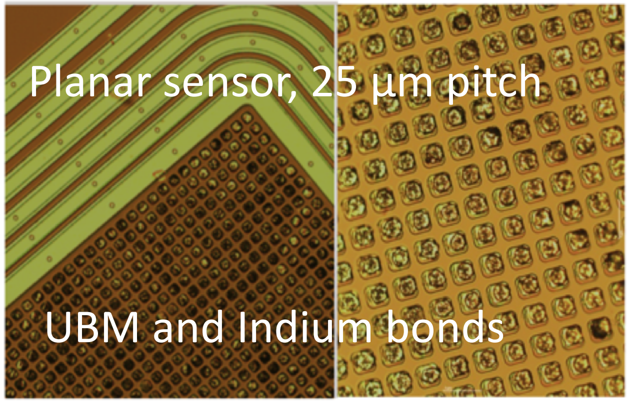
Systematics R&D studies have focused on Pixel implementation, with Pixel sizes around 25×25 μm^2
Studies equally valid for the main tracker, even though it will have larger cell sizes

CLIC silicon vertex and tracker R&D (1)

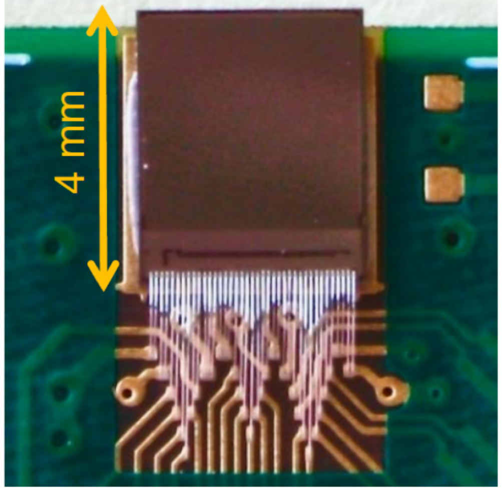
CLICpix (65 nm) + 50 µm sensor



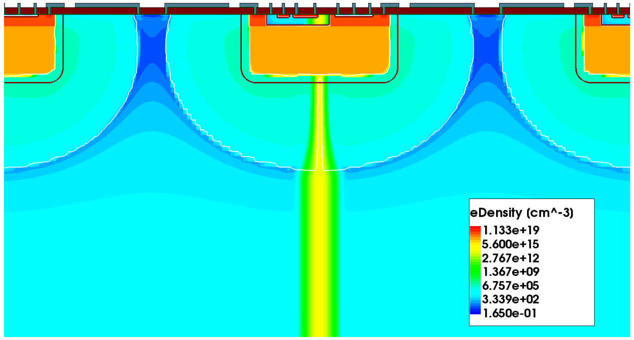
Bump-bonding, 25 µm pitch



CLICpix2 ASIC (65 nm)



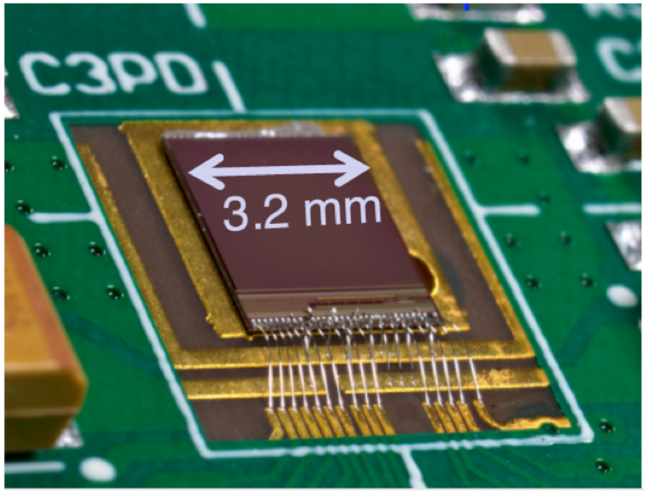
TCAD simulations, HV-CMOS sensor



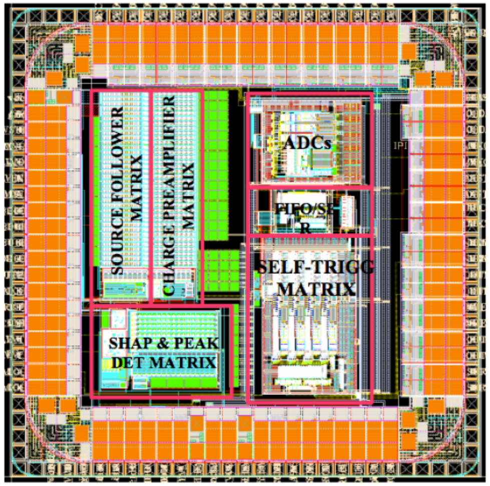
[Recent presentation on vertex R&D]()

[Recent presentation on tracker R&D]()

C3PD HV-CMOS sensor, thinned 50 µm

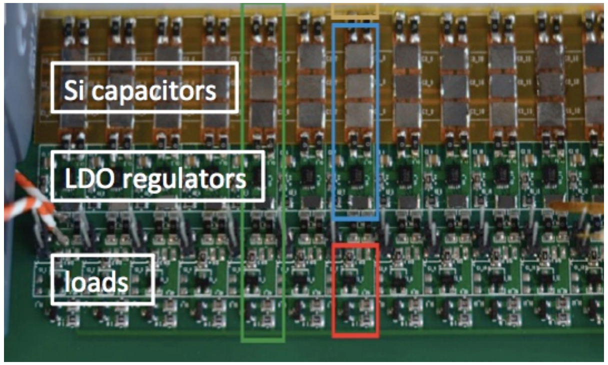


SOI sensor design

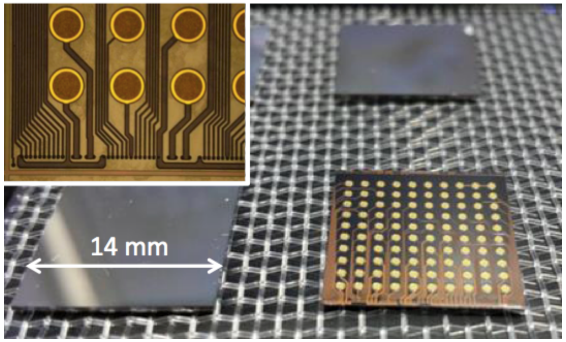


CLIC silicon vertex and tracker R&D (2)

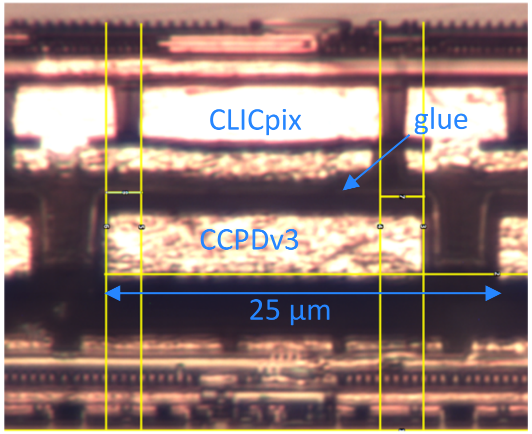
power delivery + pulsing

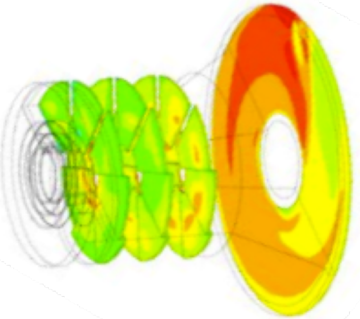


TSV interconnect technology

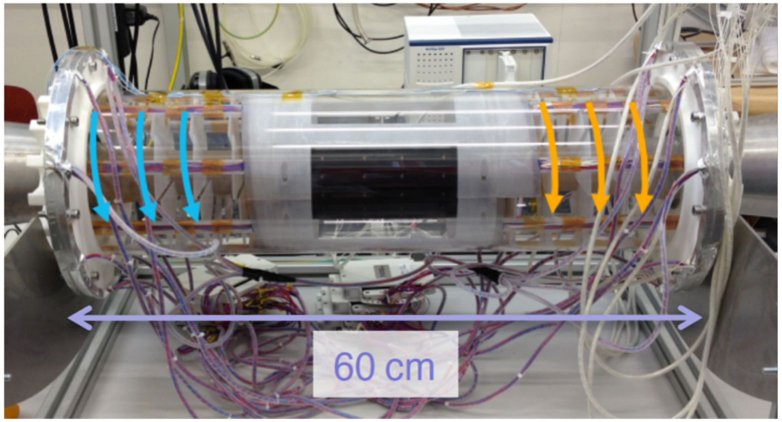


Flip-chip gluing (AC-coupling)

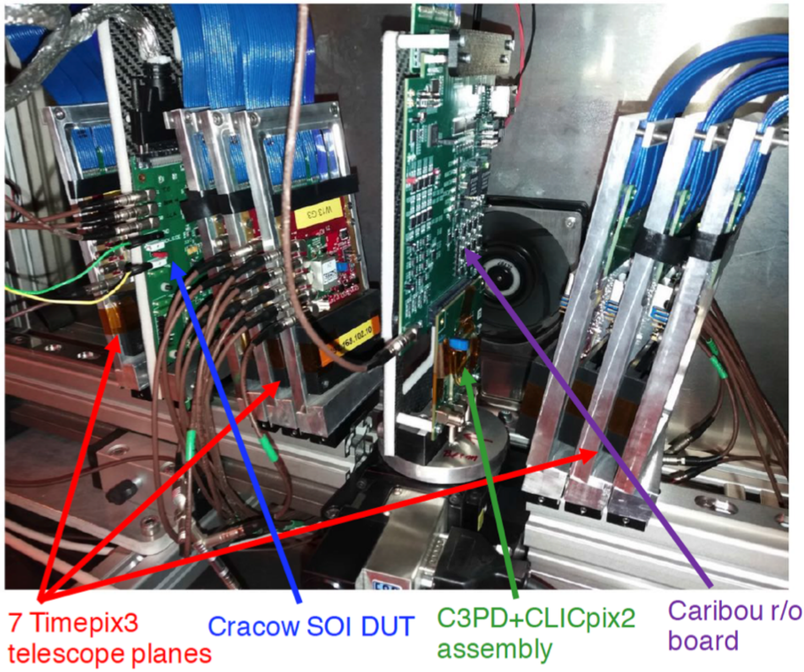




Air cooling simulation
and
1:1 scale test set up



SOI and C3PD+CLICpix2 in Timepix3 telescope at SPS



calorimetry and PFA

Jet energy resolution + background suppression for optimal detector design

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

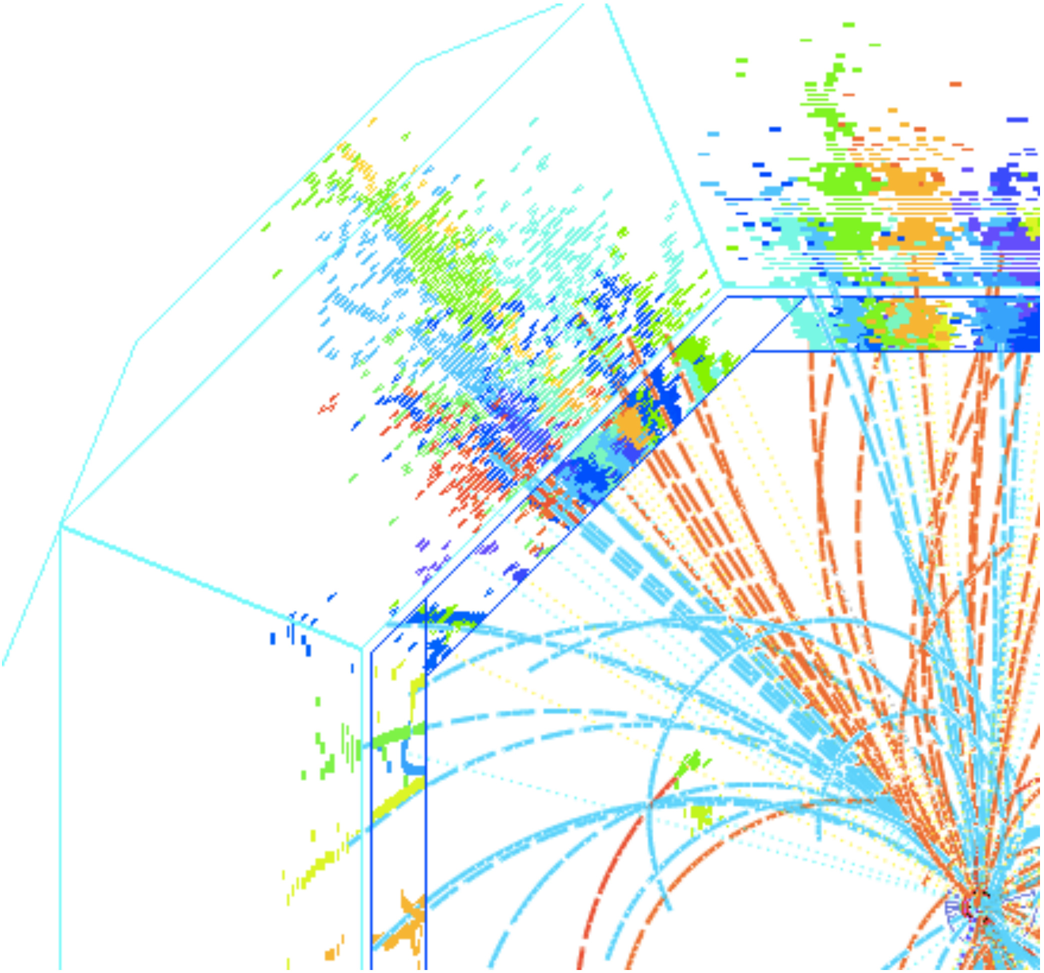
What is PFA?

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

↓

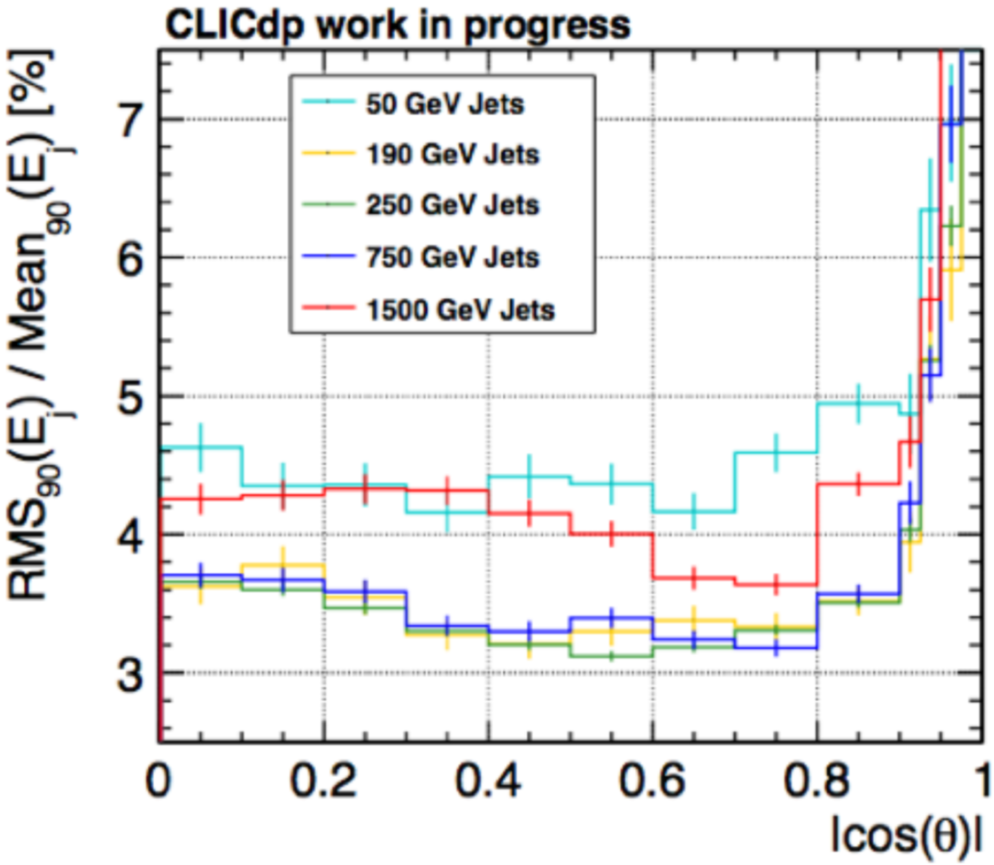
Always use the best info you have:
- 60% => tracker 🙂 🙂
- 30% => ECAL 🙂
- 10% => HCAL 🙁

Hardware + software !



Particle flow performance

Jet energy resolution



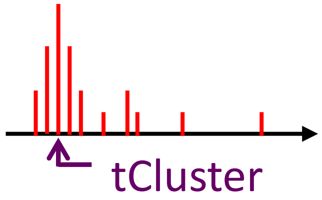
Full Geant4-based simulation + reconstruction using particle flow
Such a plot requires a lot of calibration/tuning efforts for all detector regions

Beam-induced background suppression

Triggerless readout of full train

t_0 physics event (offline)

- **Full event reconstruction + PFA analysis with background overlaid**
  - => physics objects with precise p_T and cluster time information
  - Time corrected for shower development and TOF
- **Then apply cluster-based timing cuts**
  - Cuts depend on particle-type, p_T and detector region
  - Allows to protect high-p_T physics objects

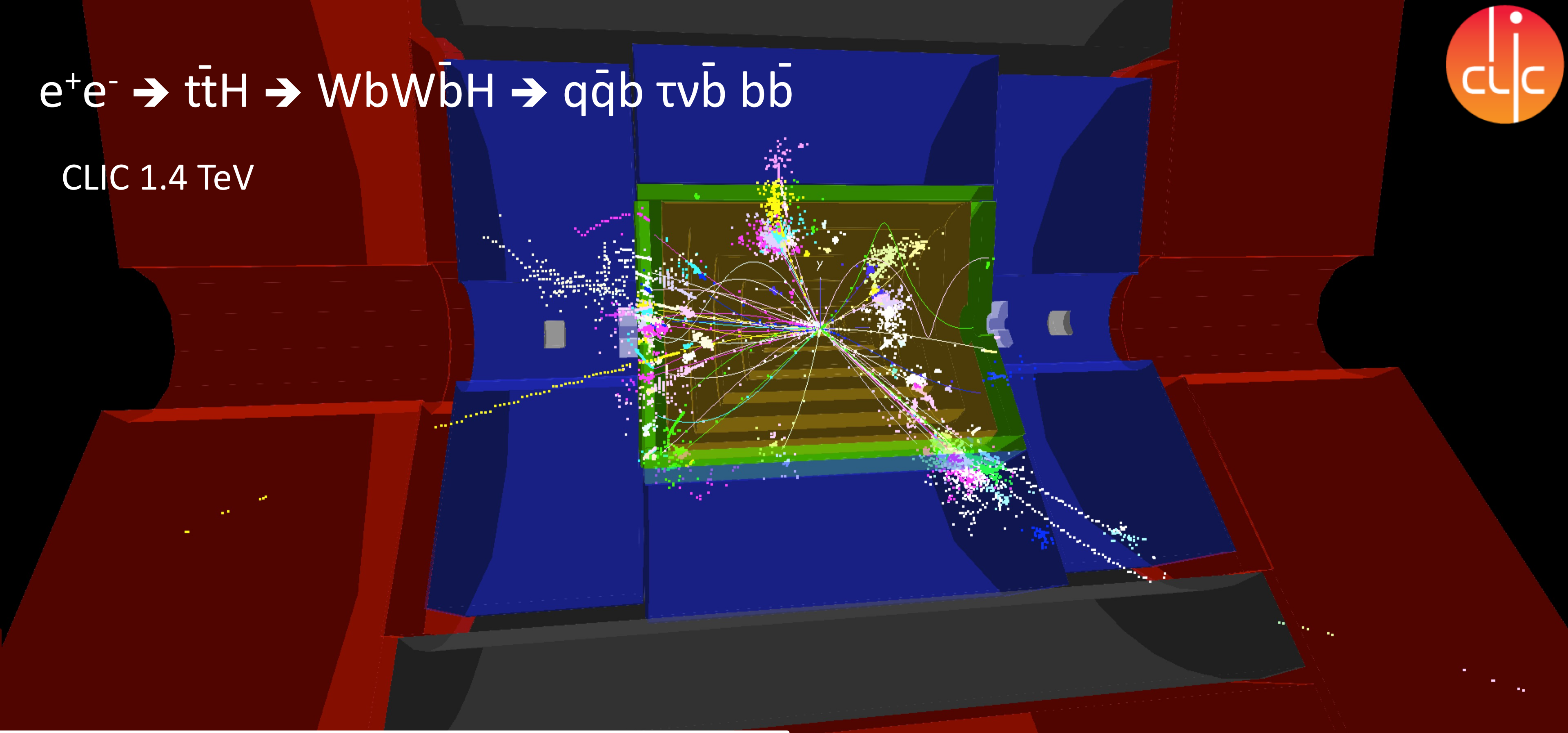


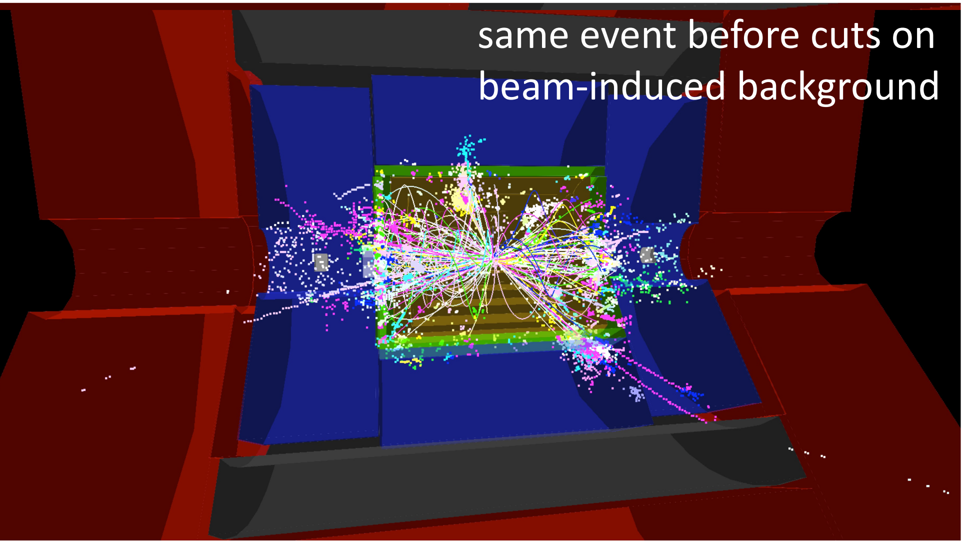
+

- **Use well-adapted jet clustering algorithms**
  - Making use of LHC experience (e.g FastJet k_t or e^+e^- adapted VLC algorithm)

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

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)

CLIC fine-grained calorimetry requirements

Fine-grained calorimetry: ECAL, HCAL, LumiCal, BeamCal

R&D for CLIC is carried out by the **CALICE** and **FCAL** collaborations

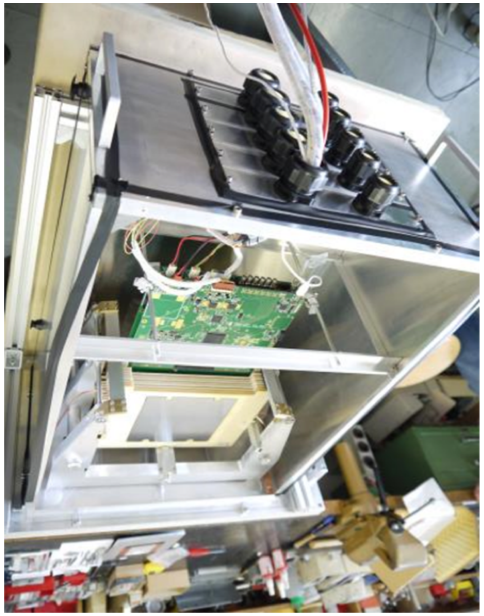
	layers	cell sizes	active material
ECAL	40	5×5 mm^2	silicon
HCAL	60	3×3 cm^2	scintillator+SiPM

1 ns time resolution, 16 bit readout

	layers	Θ mrad	active material
LumiCal	40	38 - 110	silicon
BeamCal	40	10 - 40	GaAs (tbc)

5 ns time resolution, 32 bit readout

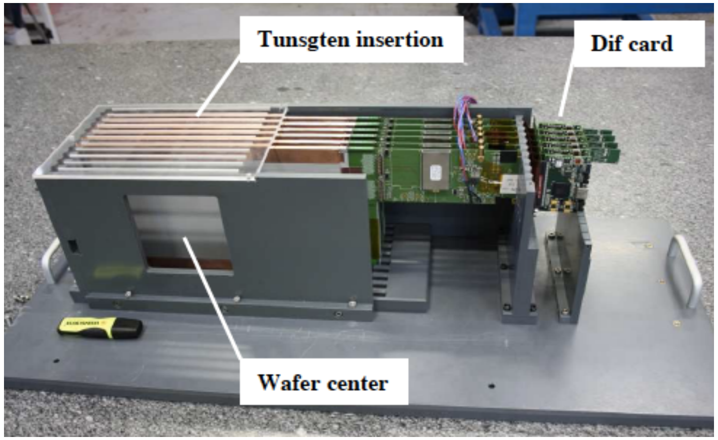
Developments and beam tests of CMS HGCal are an important test bed for Linear Collider



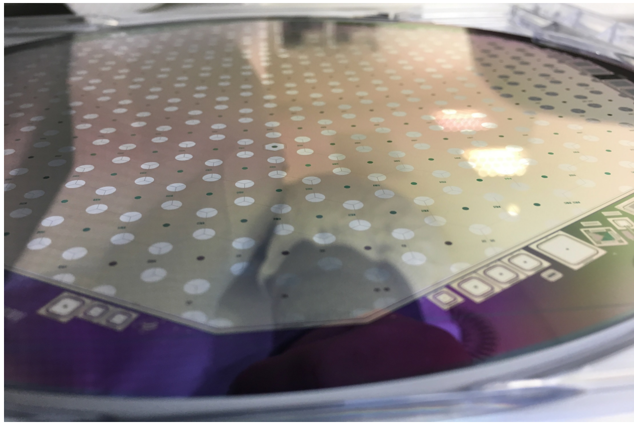
FCAL calorimeter module

high-granularity calorimetry

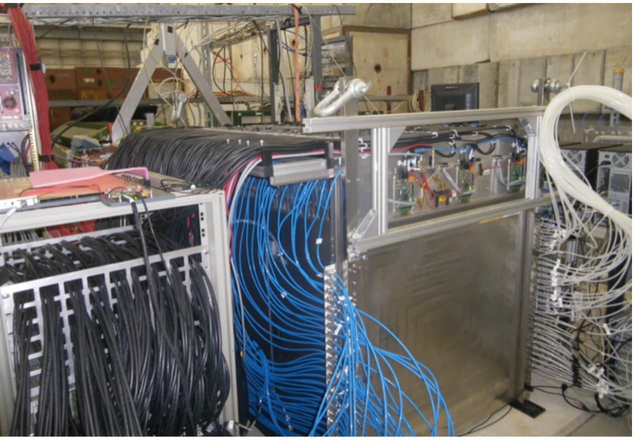
Silicon-tungsten ECAL



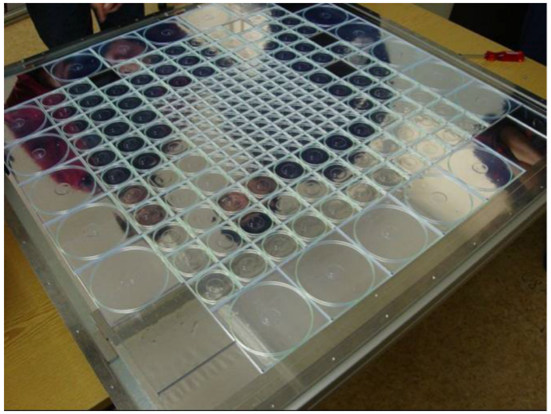
Silicon-tungsten ECAL



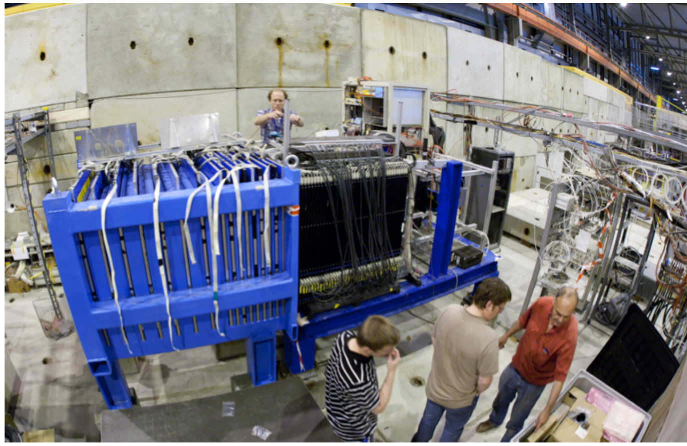
CMS HGCal 8” silicon wafer



RPC-steel SDHCAL

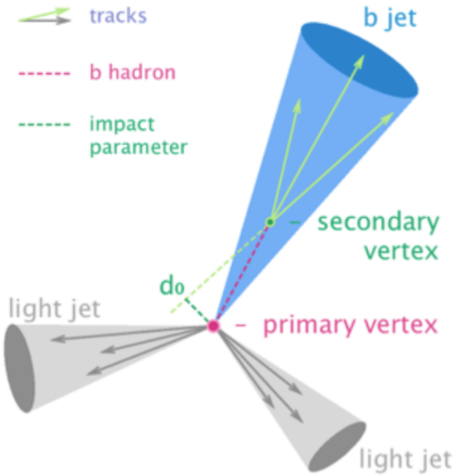


Scintillator HCAL plane



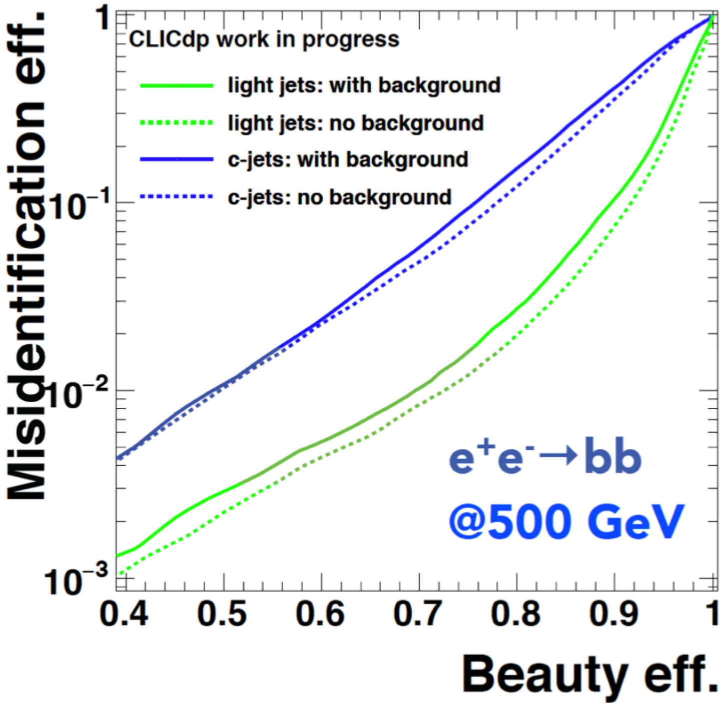
Scintillator-tungsten HCAL

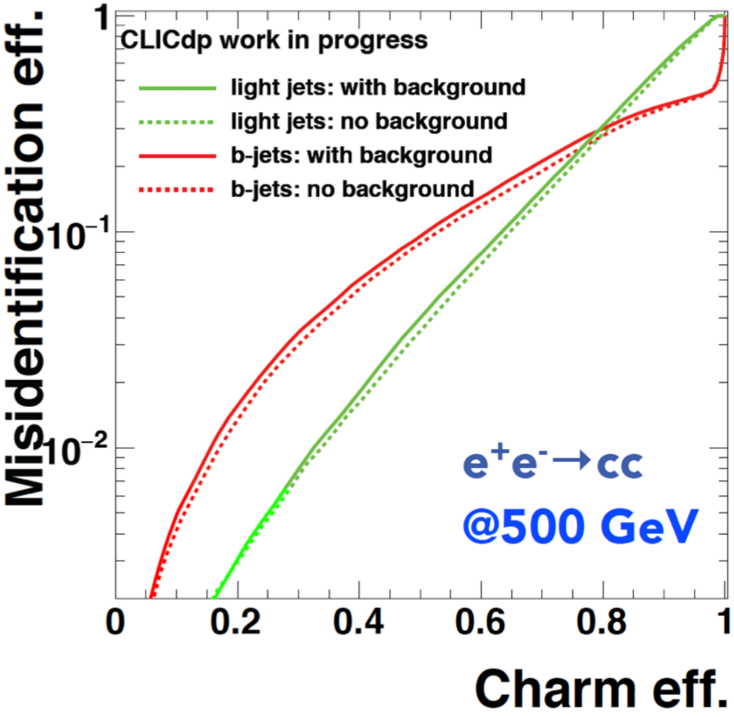
Jet flavour tagging



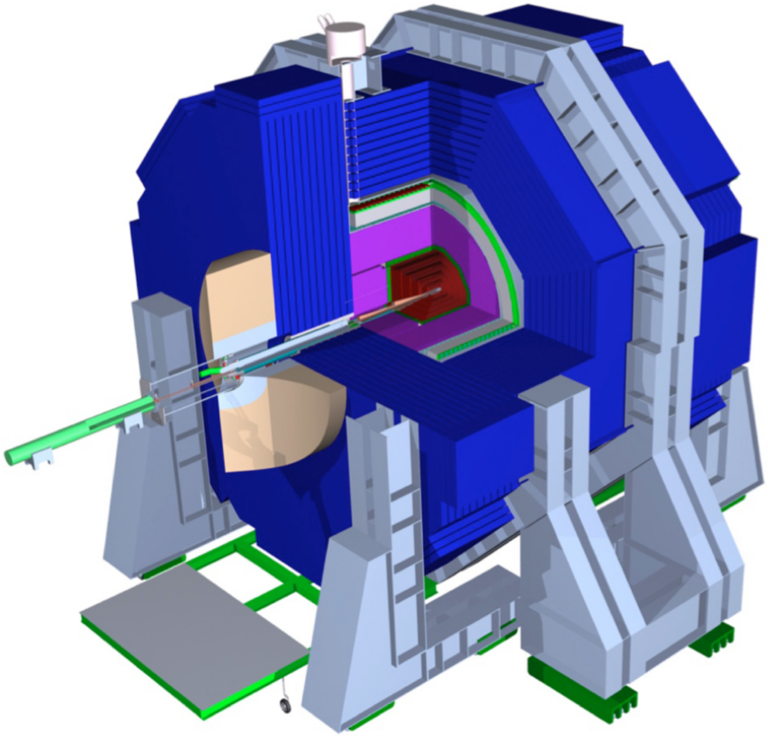
c-quark and and b-quark jets involve secondary decays

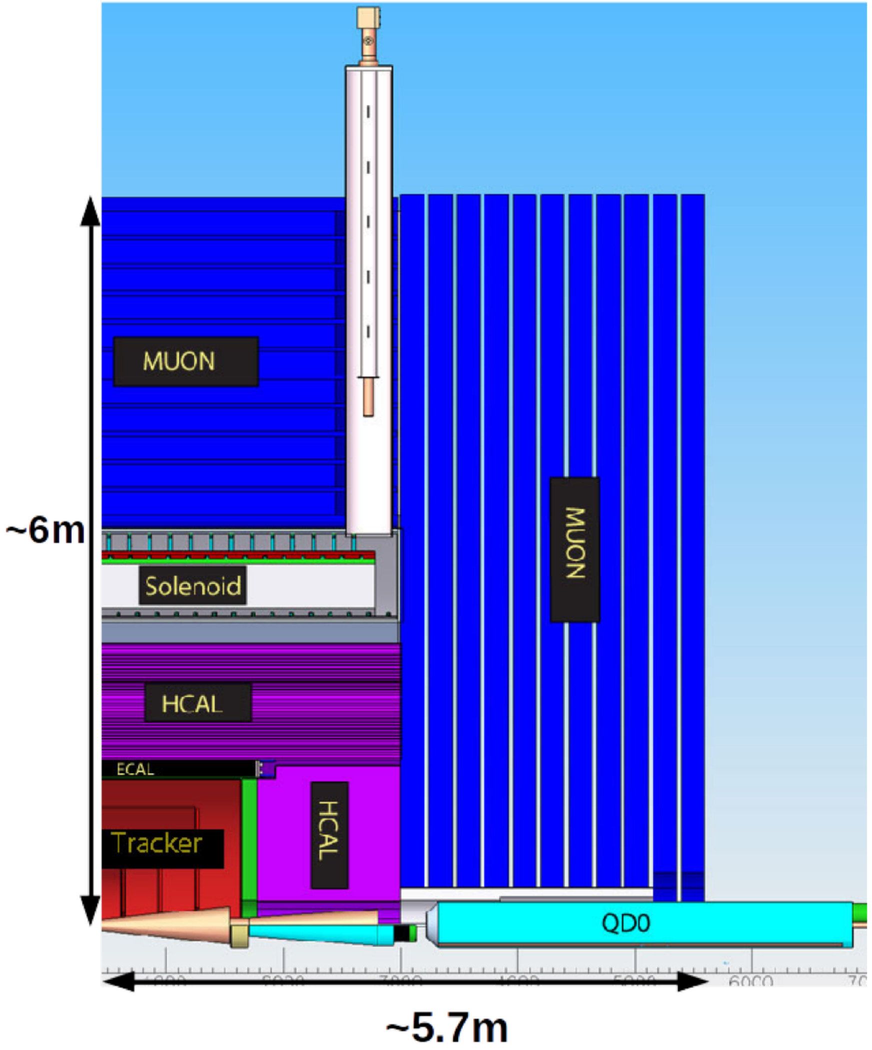
- Look for displaced (secondary) vertices within jets
- Vertex detector performance is very important
- Multi-parameter identification, uses the entire detector





SiD detector at ILC

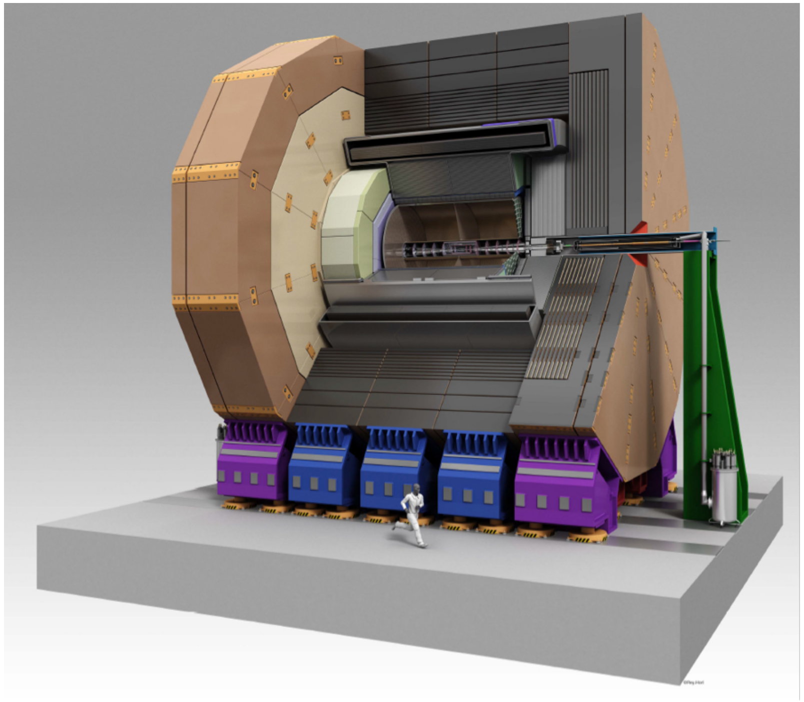


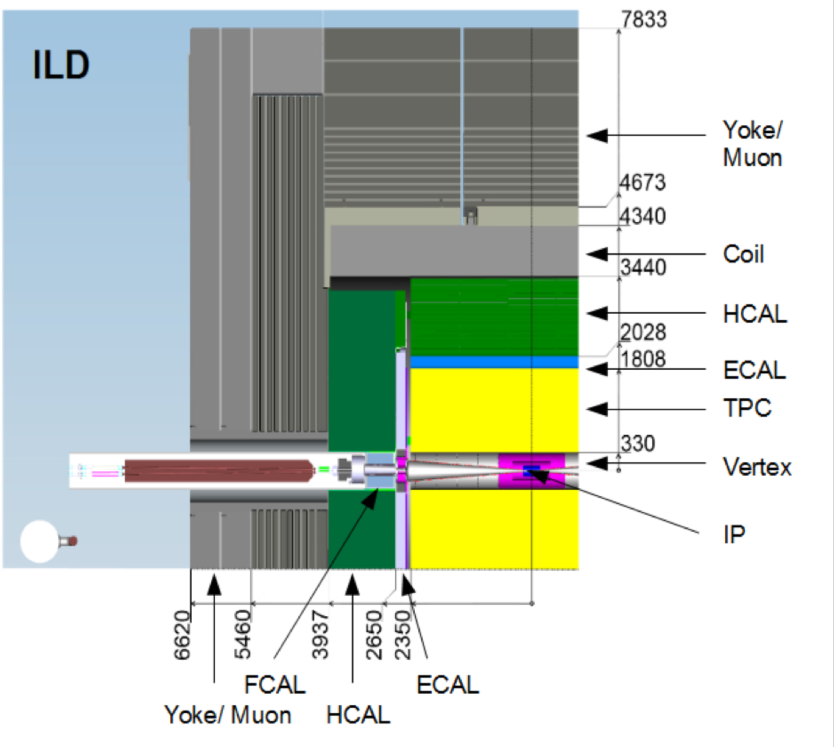


SiD: “Silicon Detector”

- 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 detector at ILC





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

circular e^+e^-

FCC-ee physics and staging scenario

Energy stages √s = 91 GeV **Z**, 160 GeV **W**, 240 GeV **H**, 350 (365) GeV **top**

m_Z, m_W, m_{top}, $\sin^2\theta_W^{eff}$, R_b, $\alpha_{QED}(m_Z)$, $\alpha_s(m_Z\ m_W)$, Higgs and top quark couplings

⇒ Precision measurements of electroweak parameters

⇒ Exploration of very high energy scale (>> TeV) via precision measurements

⇒ Search for (very) weakly coupled particles

	luminosity/IP [10^{34} cm^{-2}s^{-1}]	**total luminosity (2 IPs)/ yr**	**physics goal**	**run time [years]**
Z first 2 years	100	26 ab^{-1}/year	150 ab^{-1}	4
Z later	200	52 ab^{-1}/year		
W	30	7.8 ab^{-1}/year	10 ab^{-1}	1
H	7.0	1.8 ab^{-1}/year	5 ab^{-1}	3
machine modification for RF installation & rearrangement: 1 year				
top 1st year (350 GeV)	0.8	0.2 ab^{-1}/year	0.2 ab^{-1}	1
top later (365 GeV)	1.3	0.34 ab^{-1}/year	1.5 ab^{-1}	4

total program duration: 14 years - *including machine modifications*

phase 1 (*Z*, *W*, *H*): 8 years, phase 2 (top): 6 years

P.Janot, Acad.Training, Oct 2017

M. Benedikt, Nov 2017

FCC-ee accelerator parameters

	Z	**W**	**H (ZH)**	**ttbar**
beam energy [GeV]	**45.6**	**80**	**120**	**182.5**
SR energy loss / turn (GeV)	0.036	0.34	1.72	9.21
SR total power [MW]	100	100	100	100
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.153	0.099 / 0.151	0.15 / 0.20
bunch length (SR / BS) [mm]	3.5 / 12.1	3.3 / 7.65	3.15 / 4.9	2.5 / 3.3
bunch intensity [10^{11}]	1.7	1.5	1.5	2.8
no. of bunches / beam	16640	2000	393	39
Bunch crossing separation (ns)	**20**	160	830	8300
luminosity [10^{34} $cm^{-2}s^{-1}$] per IP	**230**	32	7.8	1.5

Beam transverse polarisation => beam energy can be measured to very high accuracy (~50 keV)

At Z-peak very high luminosities and high cross section

$\Rightarrow$ Statistical accuracies at 10^{-5} level (e.g. cross sections, asymmetries)

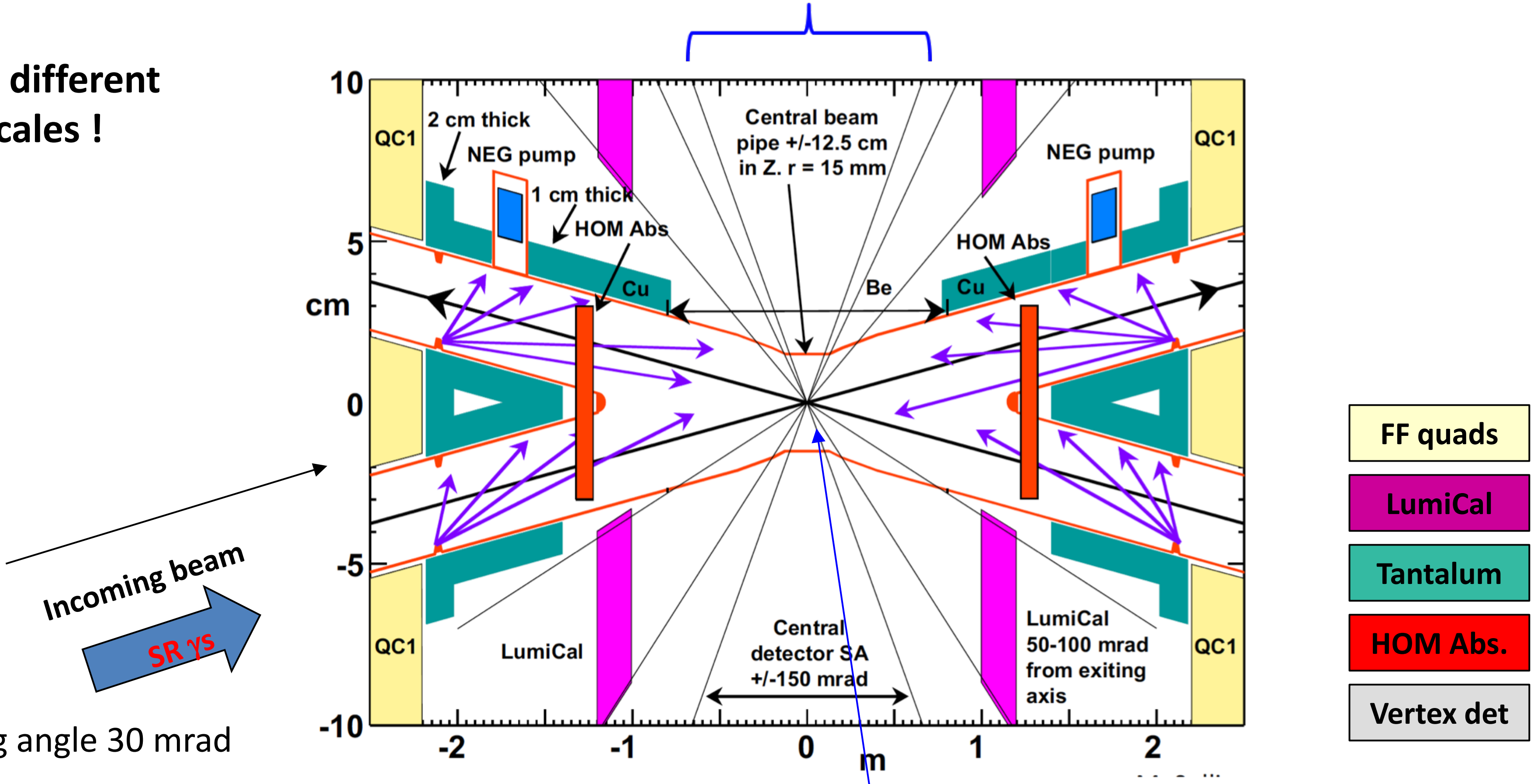
$\Rightarrow$ This drives the **detector performance**

$\Rightarrow$ This also drives requirement on **data rates**

FCC-ee interaction region

central detector down to ±150 mrad (θ ±8.6 deg)

Note different x/z scales !



Crossing angle 30 mrad

Beam pipe radius : 15 mm

L* = 2.2 m

Design valid for all FCC-ee centre-of-mass energies. Tantalum shield needed at highest energy.
Mask tips at +/-2.1m to protect central chamber from photons generated at 100 m from IP

FCC-ee forward region

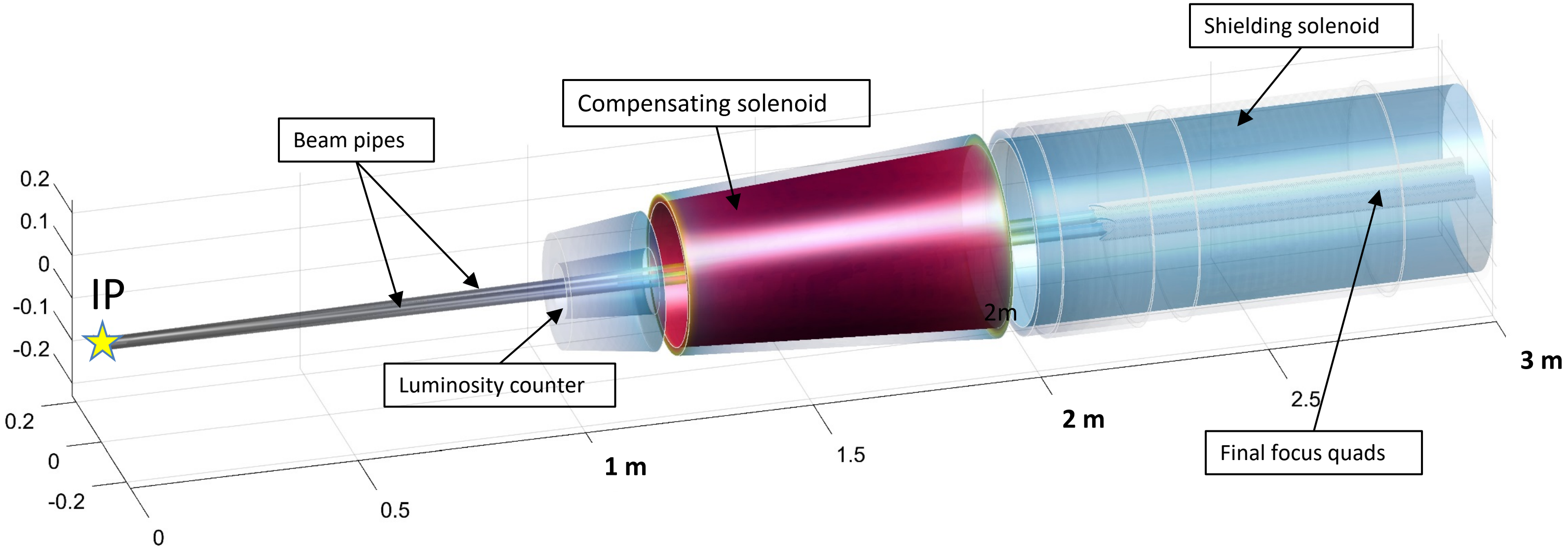
30 mrad beam crossing angle

Final focusing quadrupoles embedded in the detector

Emittance blow-up from detector magnetic field

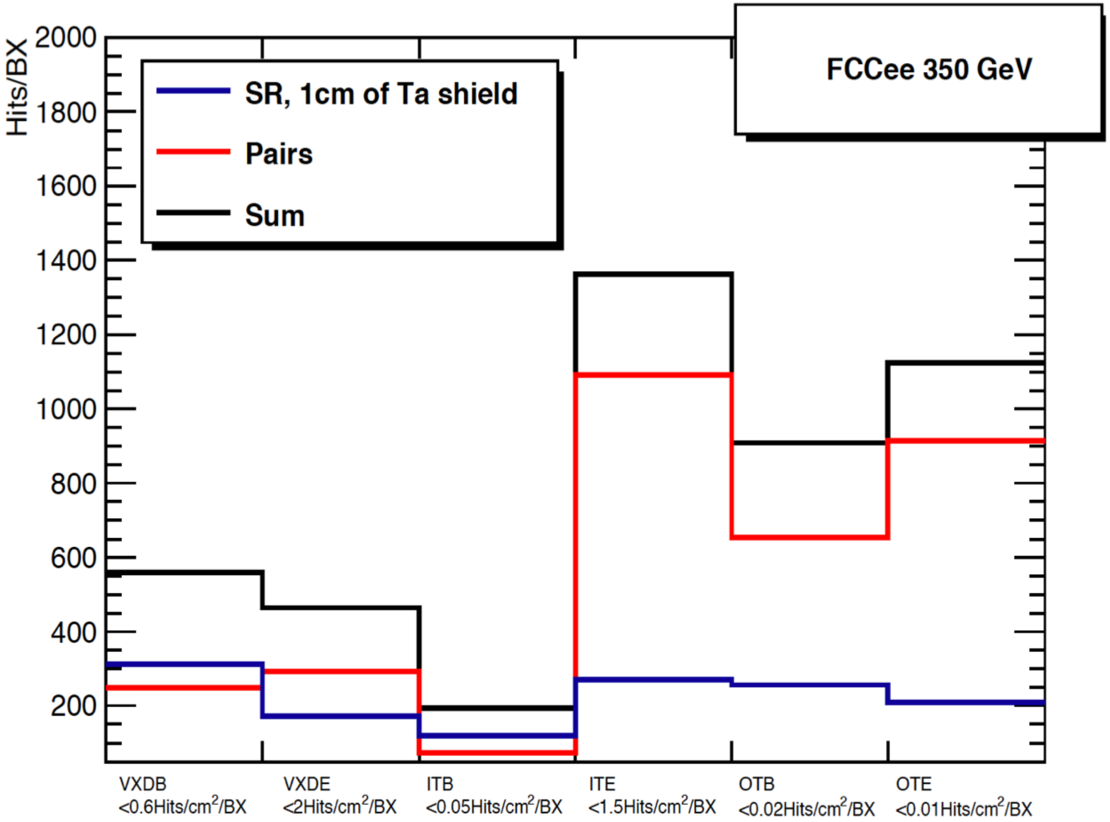
- **Detector magnetic field limited to max. 2T**
- Compensating solenoid close to the IP
- Magnetic shielding around the final focus quads

Luminosity counter (makes use of Bhabha $e^+e^- \rightarrow e^+e^-$), front face at 1.0 m from IP



FCC-ee occupancy from background particles

Occupancy in the various sub-detectors
from synchrotron radiation and incoherent pairs



vertex detector inner tracker outer tracker

Maximum hit density in the hottest area of each subdetector per bunch crossing
=> Synchrotron radiation can be suppressed efficiently

FCC-ee detector occupancy

Dominant backgrounds

- **Synchrotron radiation**
- **Beamstrahlung**

$\gamma\gamma \rightarrow e^+e^-$ (shape of distribution in figure)

$\gamma\gamma \rightarrow$ hadrons (0.005 event / BX)

=> First detector layer

Reasonable assumptions

Silicon pixel detector

Radius : **17 mm**

Pixel pitch : **25×25 μm^2**

(includes safety factor 3)

Full simulation (GuineaPig, GEANT)

Estimated occupancy ~ 5×10^{-4} / BX

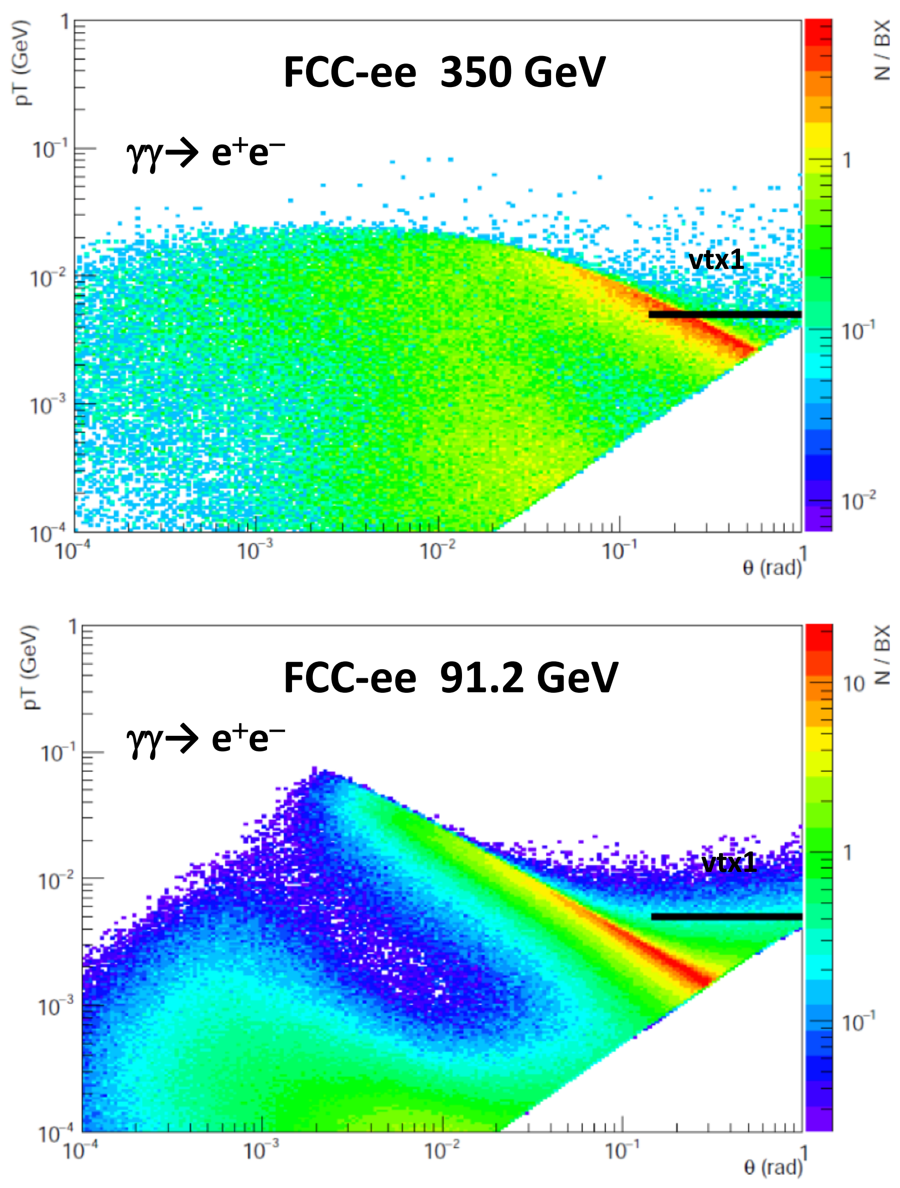
Both at the top and the Z

Needs for fast electronics ?

At the Z, one bunch crossing every 20 ns

Keep occupancy below 1% with electronics

integration time < 0.4 μs



P.Janot, Acad.Training, Oct 2017

experimental conditions e^+e^-

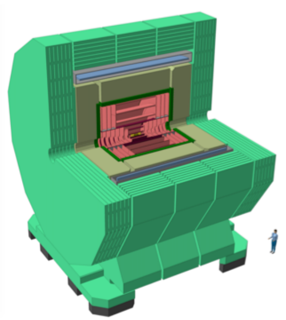
Linear Colliders

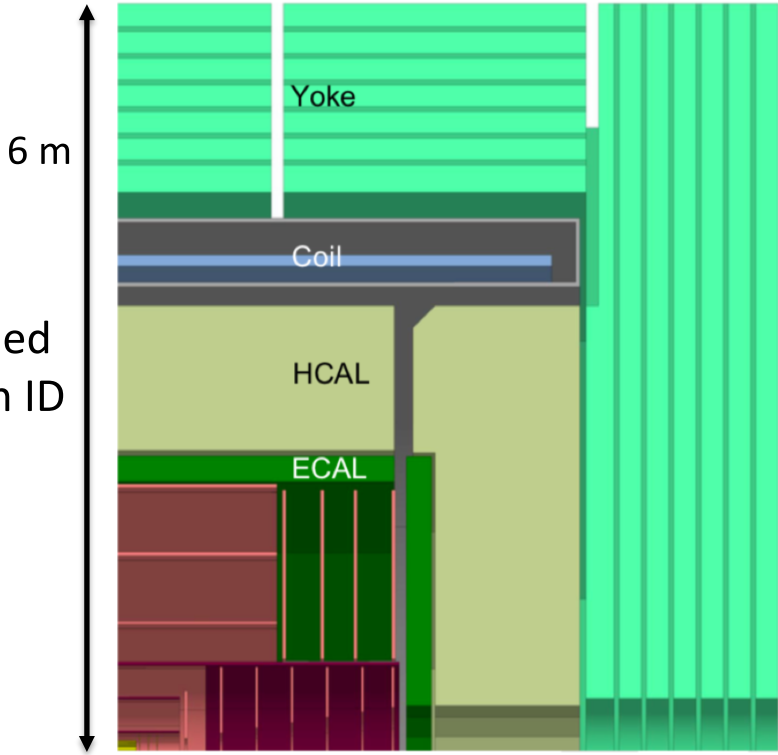
- **Beam-induced background**:
    - Beamstrahlung (incoherent pairs and $\gamma\gamma \rightarrow$ hadrons)
    - High occupancies in the detector => small readout cells needed
    - Precise (ns-level) timing required at CLIC
- **Low duty cycle**
    - Power pulsing of electronics possible
    - Triggerless readout
- **Beam crossing angle** 14 mrad (ILC), 20 mrad (CLIC)

Circular Colliders

- **Beam-induced background**
    - Beamstrahlung (incoherent pairs and $\gamma\gamma \rightarrow$ hadrons)
    - Synchrotron radiation
- **Circulating beams**
    - Maximum detector solenoid field of 2 T => need to increase tracker radius
    - Complex magnet shielding schemes
    - Beam focusing quadrupole closer to IP (~2.2m)
    - No power pulsing
- **High luminosity and many bunches at Z pole**
    - Moderate requirements on detector timing, high data rates

CLD detector for FCC-ee





CLD is derived from the CLIC detector model

Silicon pixel vertex detector + Silicon tracker

Silicon-tungsten Ecal, Scintillator-steel HCal <= fine-grained

Superconducting solenoid, yoke with detectors for muon ID

Constraints from MDI at FCC-ee

Detector solenoidal field ↓ 2 T (4 T for CLIC)

Outer tracker radius ↑ 2.15 m (1.5 m for CLIC)

Beam pipe radius ↓ 15 mm (29 mm for CLIC)

Inner vertex radius ↓ 17 mm (31 mm for CLIC)

Max collision energy ↓ 365 GeV (3 TeV for CLIC)

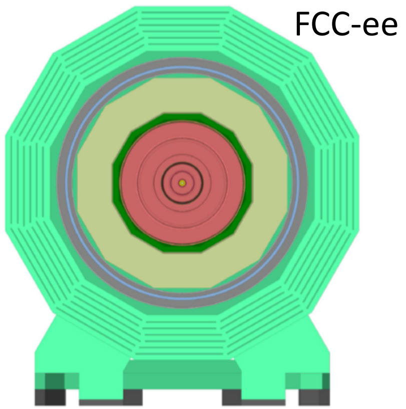
Hadronic calorimeter depth ↓ 5.5 λ_I (7.5 λ_I for CLIC)

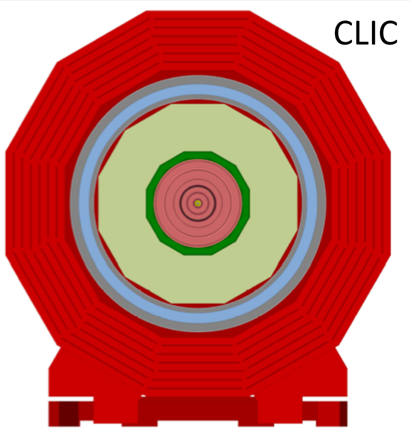
Layout respects the ±150 mrad cone for detector

Constraints from FCC-ee continuous operation

Power pulsing not possible

Increased tracker "mass" in simulation model

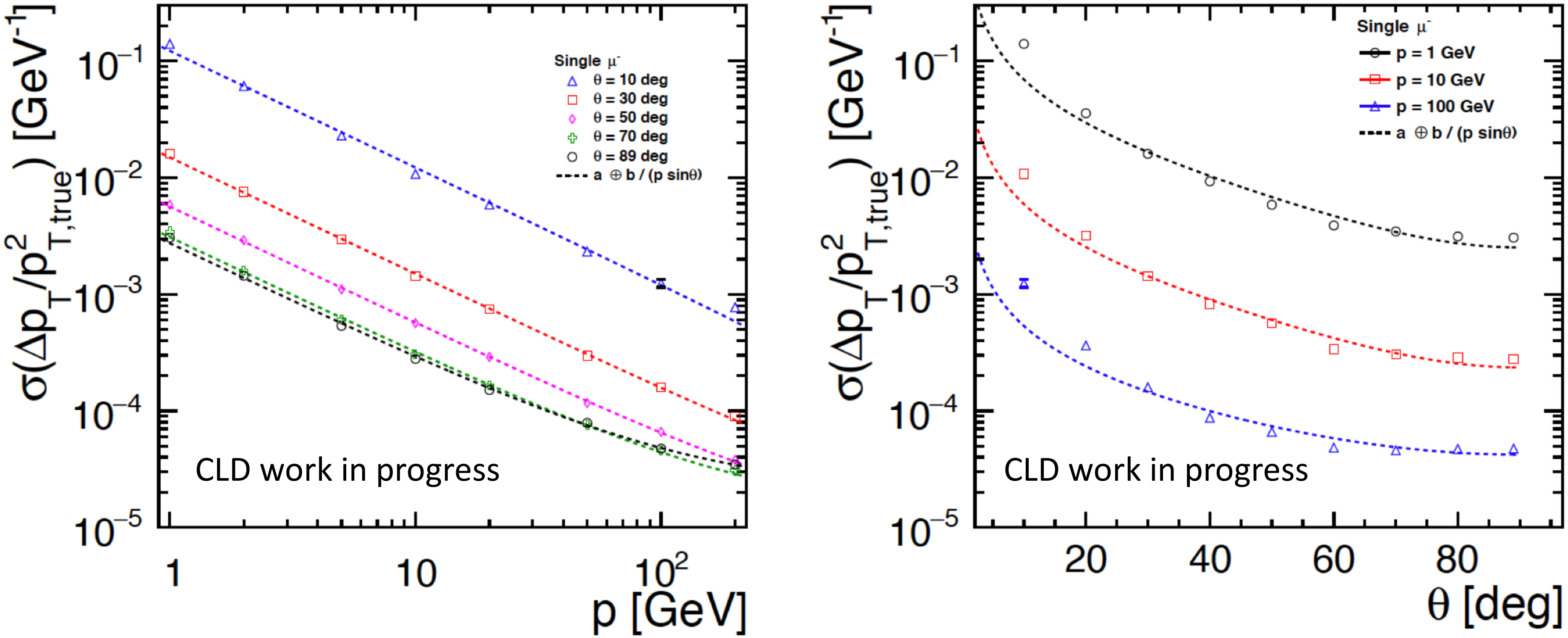




FCC-ee CLD detector performance

Track resolution for single muons

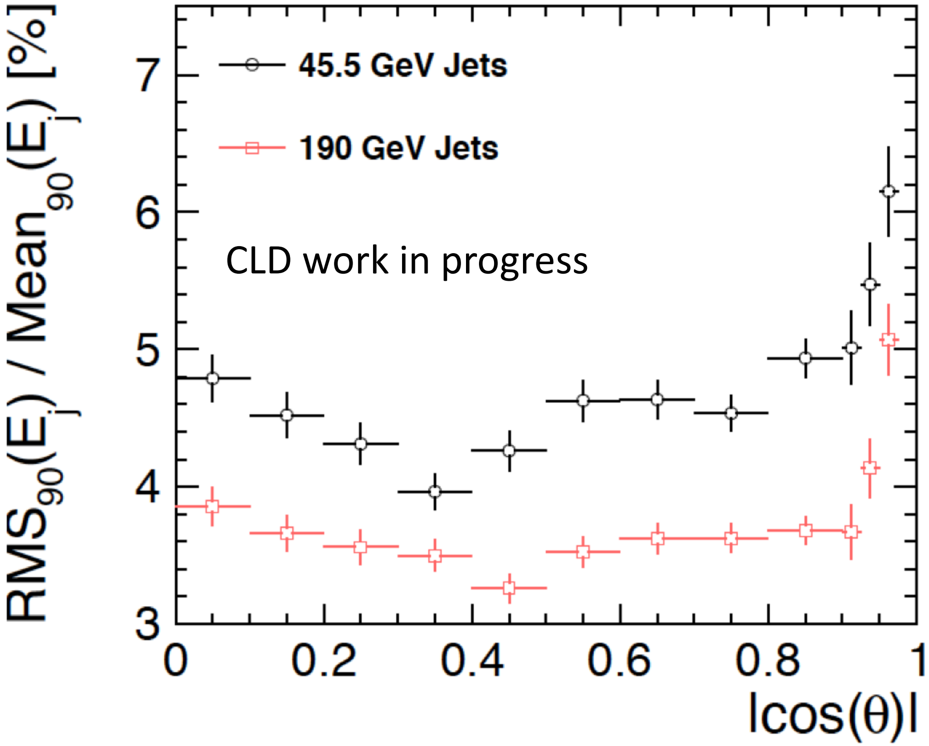
CLD work in progress !!!



FCC-ee CLD detector performance

Jet energy resolution

CLD work in progress !!!

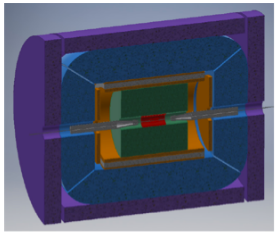


Full Geant4-based simulation + reconstruction using particle flow
Such a plot requires a lot of calibration/tuning efforts for all detector regions

"IDEA" concept for FCC-ee/CEPC

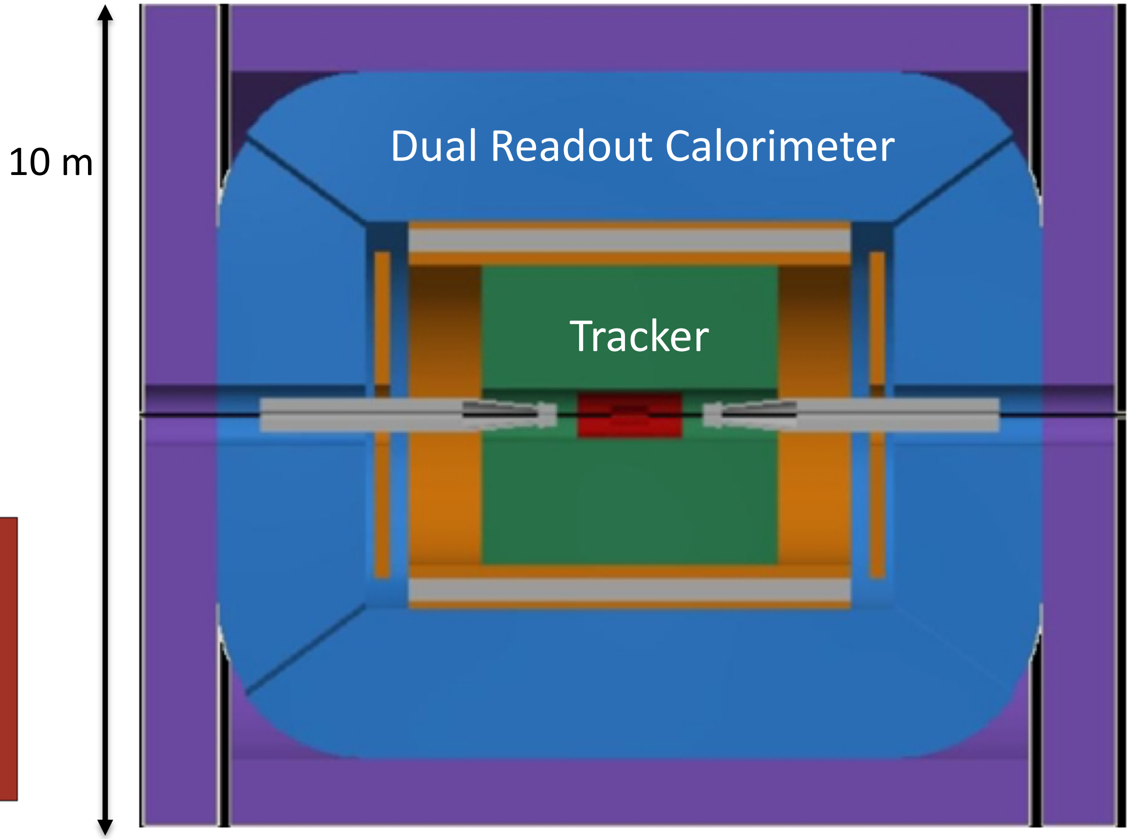
IDEA "International Detector for Electron-positron Accelerator"

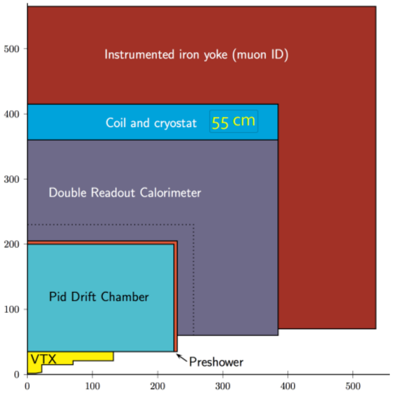
- Vertex detector, MAPS, R_{in}=15mm
- Ultra-light drift chamber with PID
- Outer silicon layer
- Thin superconducting solenoid 2T, R=2m
- Pre-shower
- Dual read-out calorimetry, 2m deep
- Instrumented return yoke

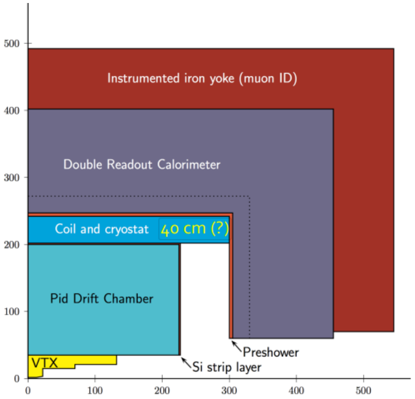


Optionally solenoid outside/inside calorimeter:

a. Classical 2T solenoid around the calorimeter, 7.2m bore, 8m long
b. Ultra light 2T solenoid around tracker, 4.0m bore, 6m long

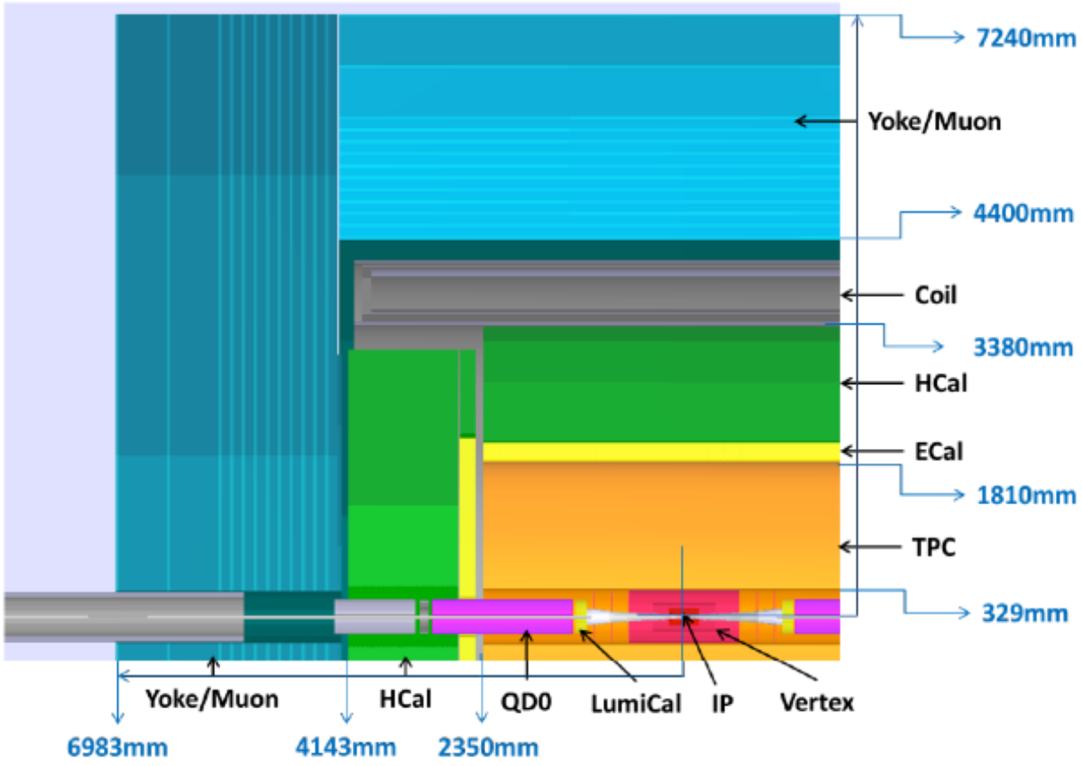






CEPC detector

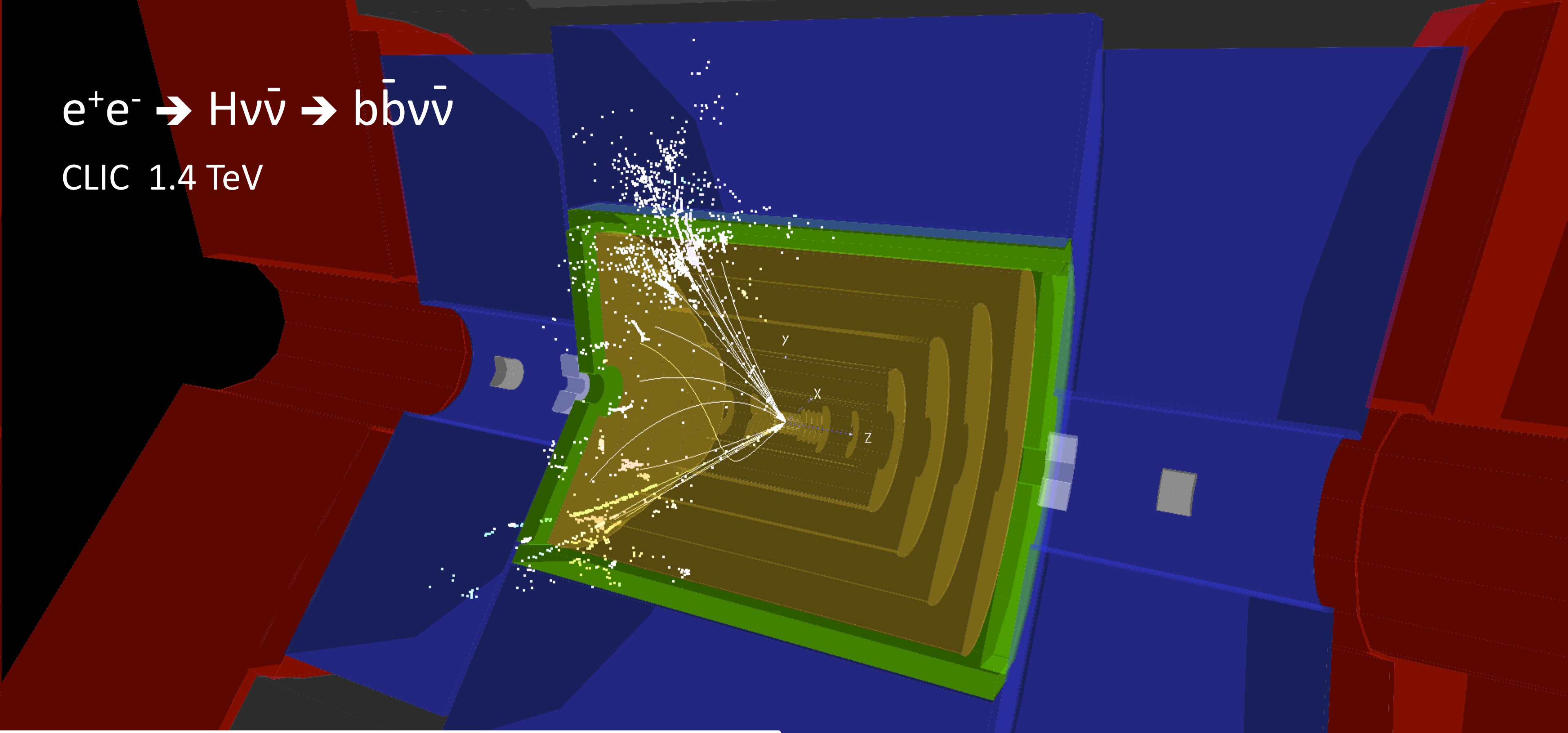
- ILD-L-inspired detector concept studied for pre-CDR



- 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

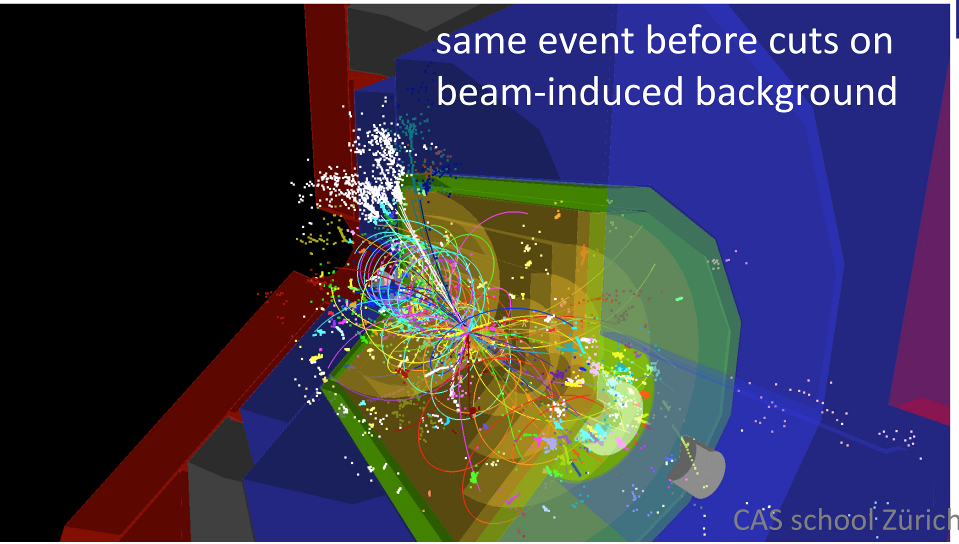
Towards CDR:

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



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

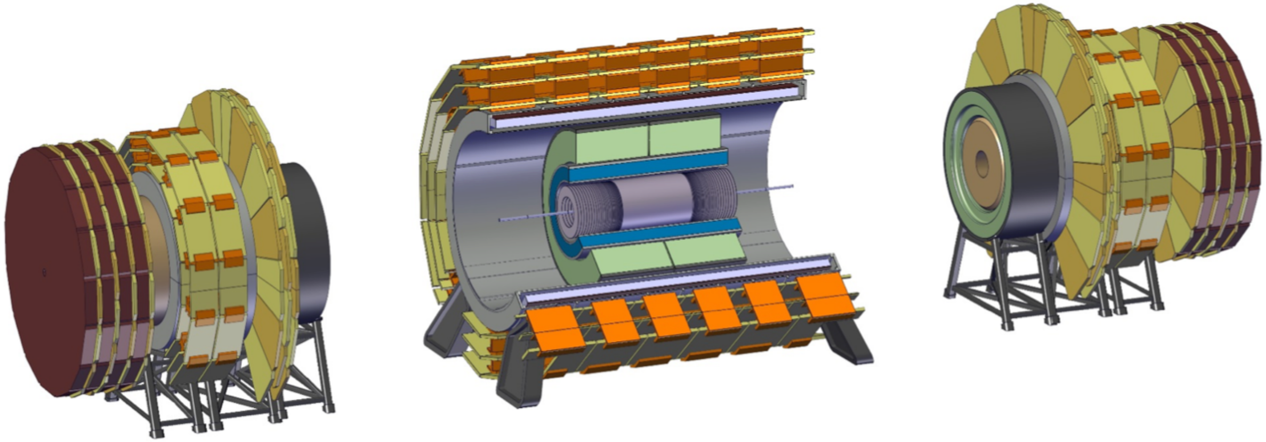
CLIC 1.4 TeV



same event before cuts on beam-induced background

end of the e^+e^- lecture part

Detectors for High Energy Colliders
Machine Detector Interface
part 2
future pp colliders



With many thanks to my FCC-hh colleagues
Particular thank you to Werner Riegler, most of the material is ***his***

W. Riegler, Acad.Training, Oct 2017

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

M. Benedikt, CAS, Zürich, 2018

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		25	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.27	(1.12) 0.58
bunch intensity $[10^{11}]$	1 (0.2)	1 (0.2)	2.5	(2.2) 1.15
bunch spacing [ns]	25 (5)	25 (5)	25 (5)	25
IP $\beta^*_{x,y}$ [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} cm^{-2}s^{-1}]	5	30	34	(5) 1
peak #events/bunch crossing	170	1020 (204)	1070 (214)	(135) 27
stored energy/beam [GJ]	8.4		1.4	(0.7) 0.36
synchrotron rad. [W/m/beam]	30		4.1	(0.35) 0.18

FCC-hh and HE-LHC have very similar detector requirements (resolution and radiation hardness) !!!

FCC-hh physics scope

How to specify detectors for such a collider ?

The **Higgs** is still a key benchmark for the FCC-hh detector,
=> Highly forward boosted features (100 TeV, 125 GeV Higgs)

ATLAS and CMS are general purpose detectors that were benchmarked with the 'hypothetical' Higgs in different mass regions with tracking up to η = 2.5 ($\theta \approx 10°$)

Many other physics goals (see lectre by Michelangelo), for example:
Higgs self-coupling (λ), precision Standard Model, heavy resonances, SUSY, etc.

FCC detectors must be 'general general' purpose detectors
with very large η acceptance and extreme granularity

Detector acceptance goal set:
Muon detection up to η = 4 ($\theta \approx 2°$)
Calorimetry up to η = 6 ($\theta \approx 0.5°$)

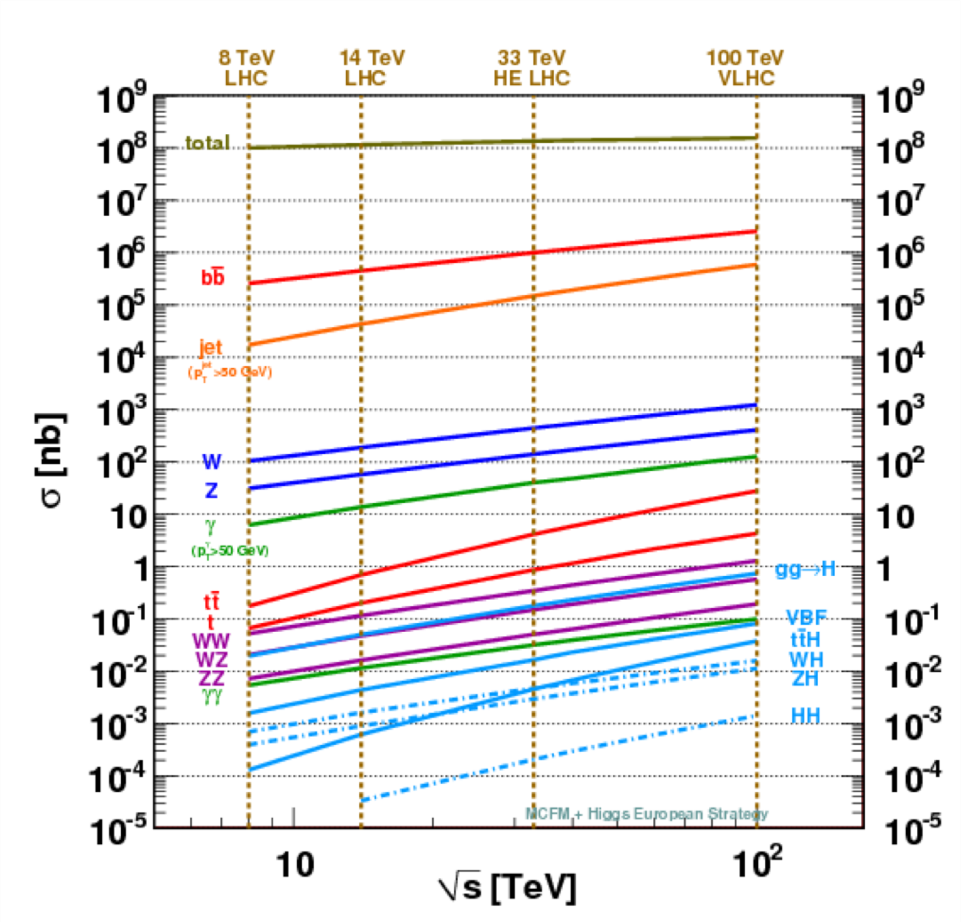
$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

W. Riegler, Acad.Training, Oct 2017

FCC-hh physics scope

The present working hypothesis:

- peak luminosity baseline: 5×10^{34}, integrated luminosity ~250 fb^{-1}/yr
- peak luminosity ultimate: $\leq 30 \times 10^{34}$, integrated luminosity ~1000 fb^{-1}/yr



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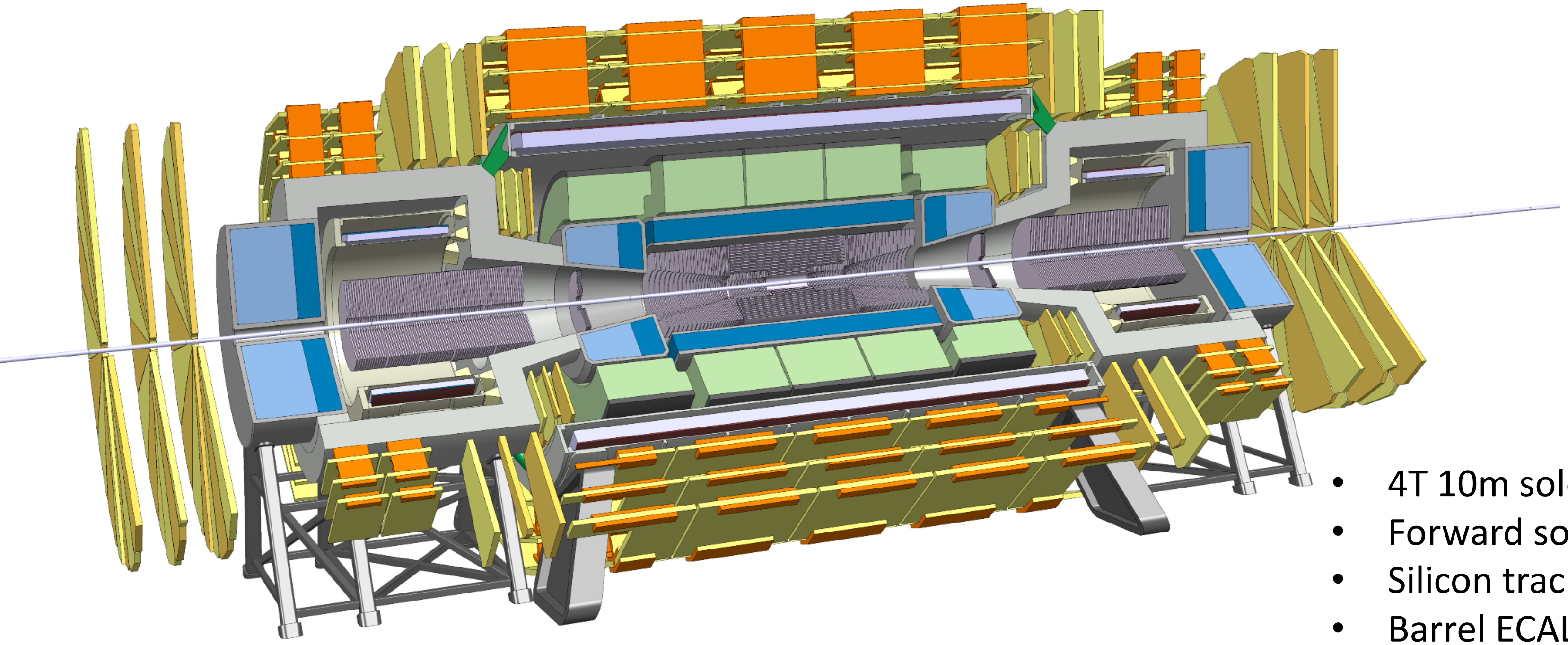
Total cross section and Minimum Bias multiplicity => modest increase from LHC to FCC-hh.

The cross section for interesting processes => significant increase !

→ **Interesting stuff is sticking out more !!**

Going from **pileup of 140 at HL-LHC** to **pileup of 1000 at FCC-hh** however reduces this possible advantage (e.g. triggering)

FCC-hh reference detector for the CDR

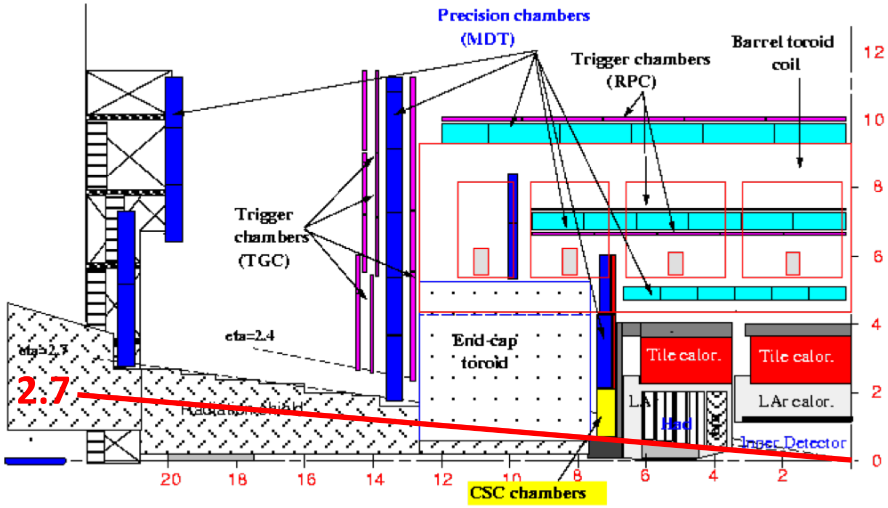


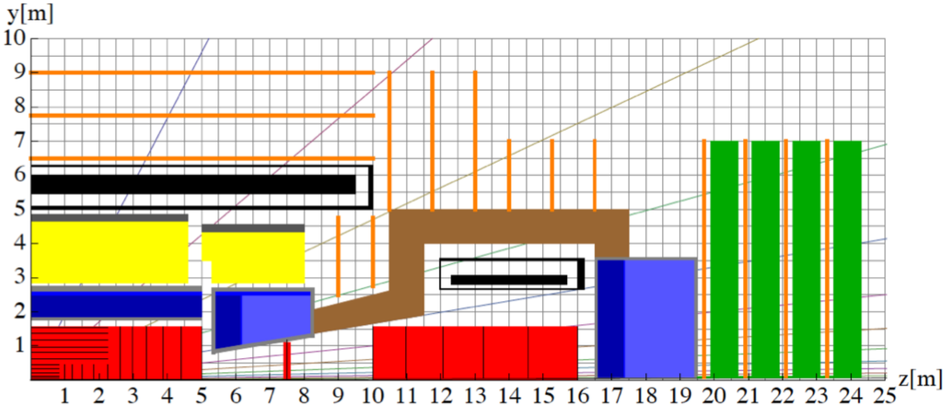
- 4T 10m solenoid
- Forward solenoids
- Silicon tracker
- Barrel ECAL Lar
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

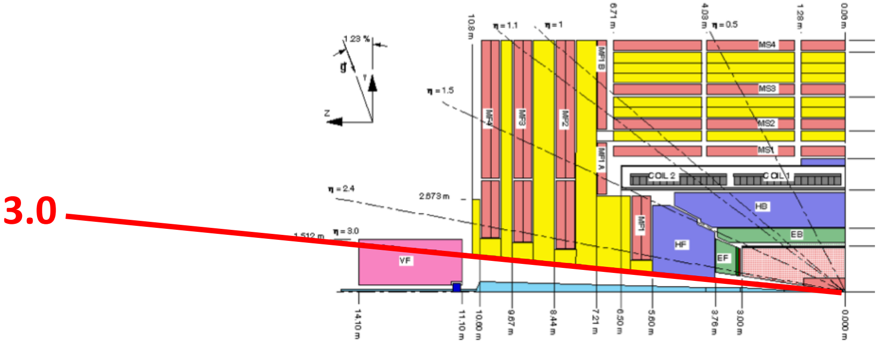
This is a reference detector that ‘can do the job’ and that is used to define the challenges.
The question about the specific strategy for detectors at the two IPs is a different one.

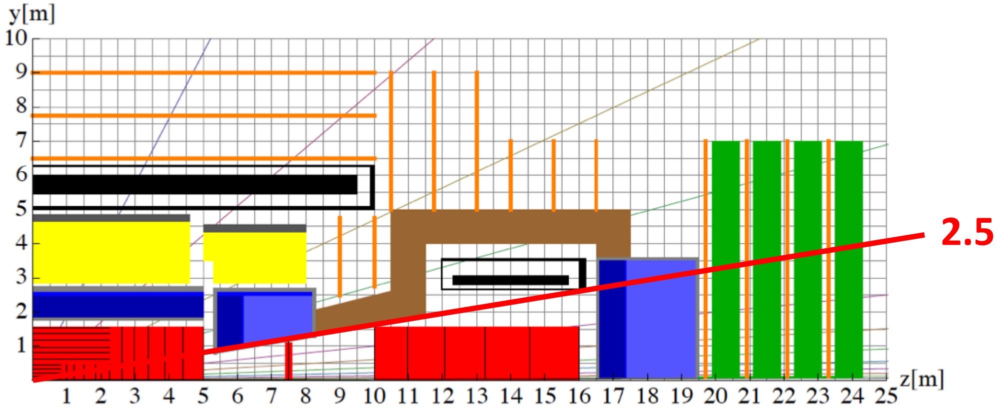
W. Riegler, Acad.Training, Oct 2017

Comparison to ATLAS and CMS





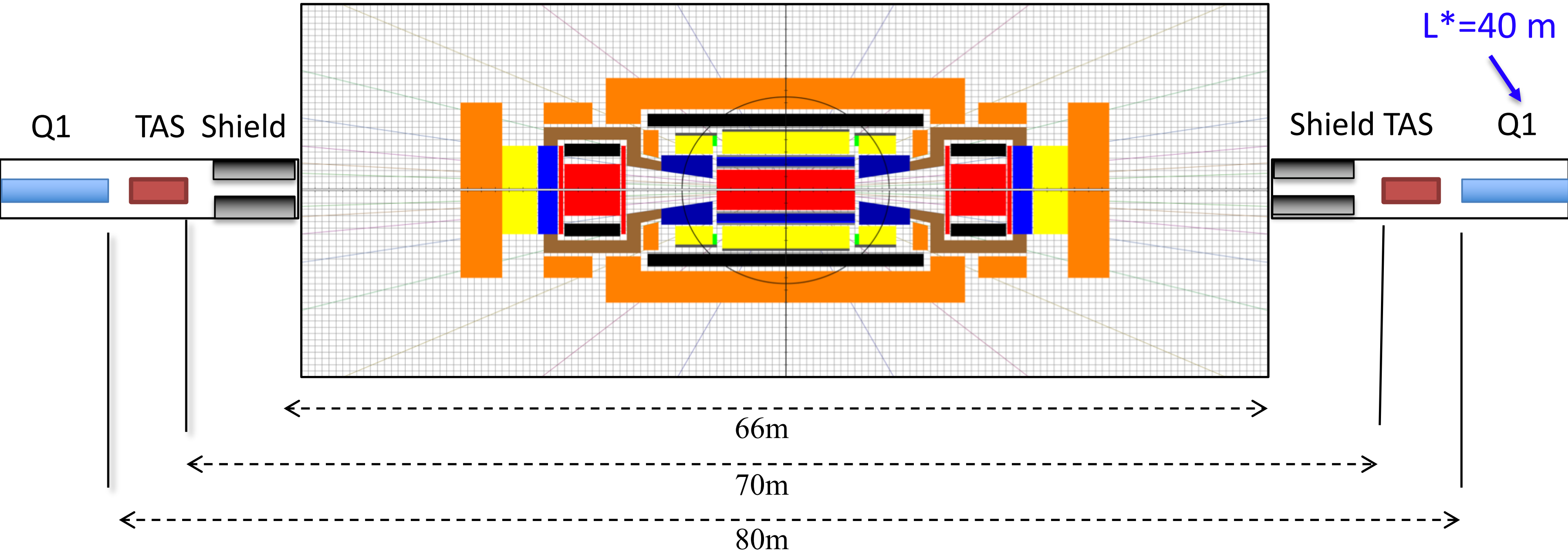




- Compared to ATLAS / CMS, the forward calorimeters are moved far out in order to reach larger η, reduce radiation load and increase granularity.
- Forward solenoid adds about 1 unit of η to tracking acceptance.
- A large shielding (brown) stops neutrons from escaping to cavern and muon system

W. Riegler, Acad.Training, Oct 2017

FCC-hh cavern dimension

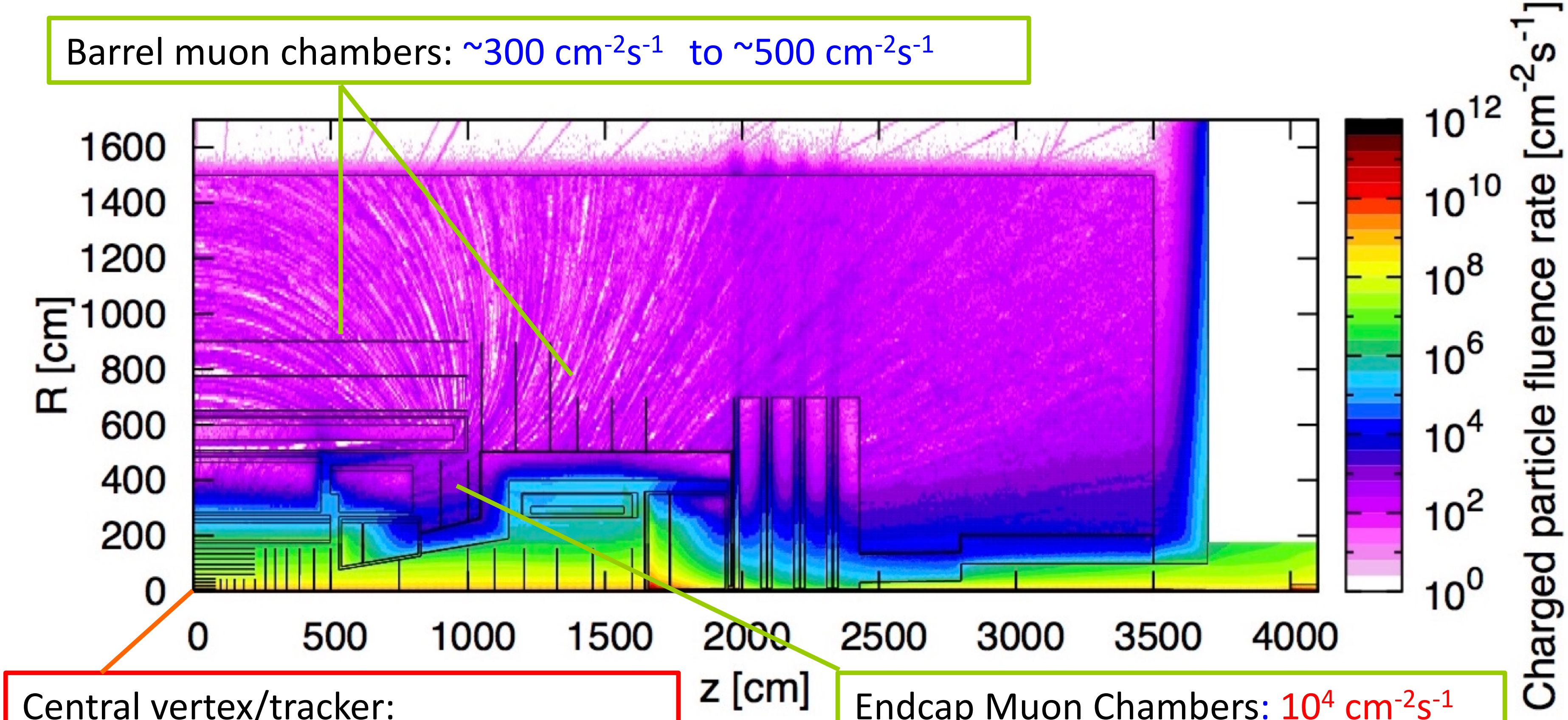


Cavern length of 66 m => compatible with the opening scenario of the present detector
Cavern diameter of 20 m => similar to ATLAS cavern

W. Riegler, Acad.Training, Oct 2017

Charged particle fluence at L=30×10^{34}cm^{-2}s^{-1}

Barrel muon chambers: ~300 cm^{-2}s^{-1} to ~500 cm^{-2}s^{-1}



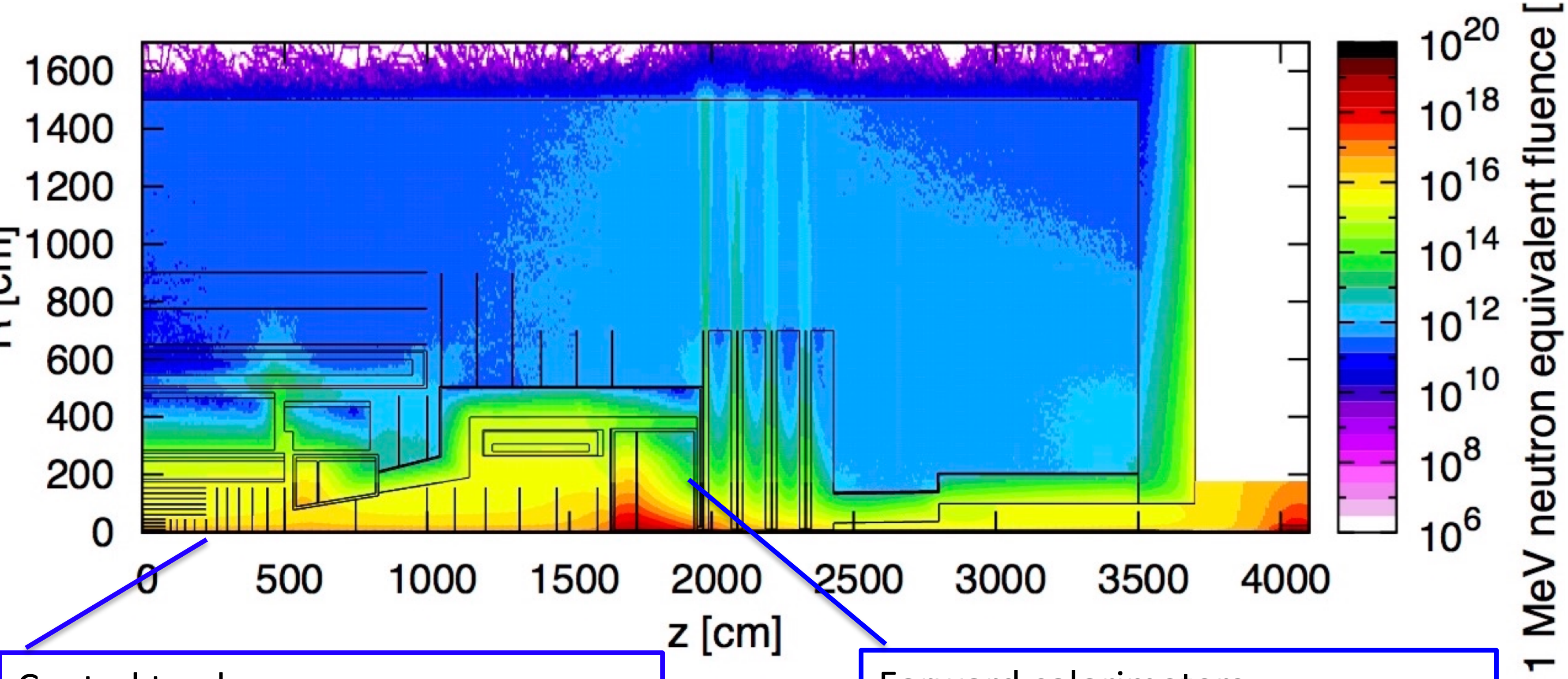
Central vertex/tracker:
- first IB layer (2.5 cm): ~1.2×10^{10} cm^{-2}s^{-1}
- external part: 3×10^{6} cm^{-2}s^{-1}

Endcap Muon Chambers: 10^{4} cm^{-2}s^{-1}

R > 1m: 5×10^{5} cm^{-2}s^{-1}

W. Riegler, Acad.Training, Oct 2017

1 MeV neutron equivalent fluence for 30 ab^{-1}



M.I. Besana, FCC week 2017

Central tracker:

first IB layer (2.5 cm): ~5-6×10^{17} cm^{-2}
external part: ~5×10^{15} cm^{-2}

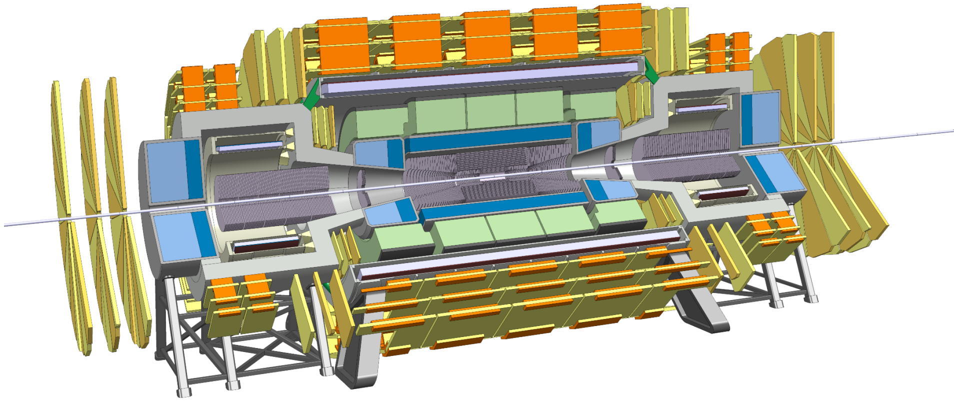
Forward calorimeters:

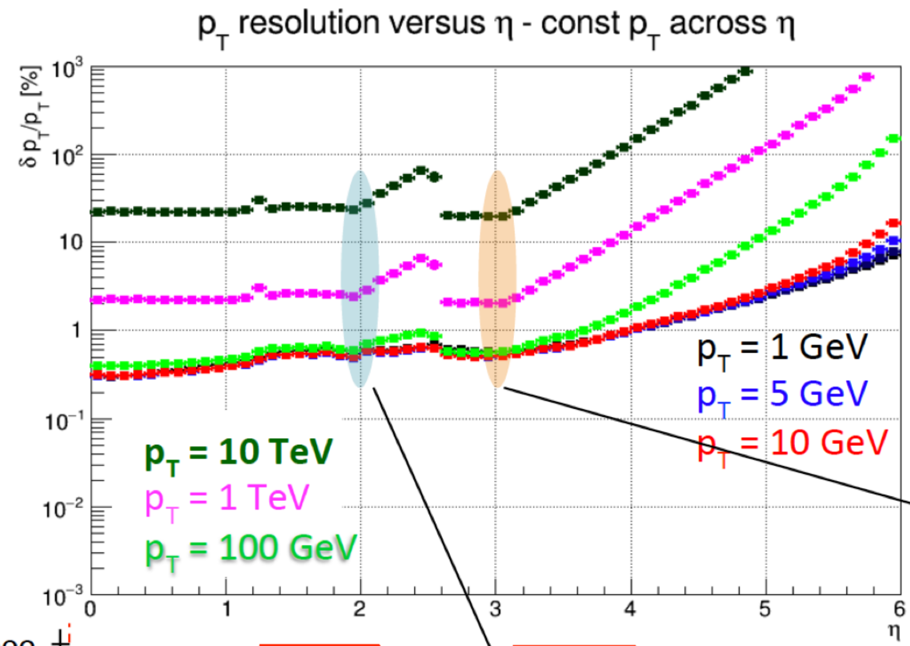
maximum at ~5×10^{18} cm^{-2} for both the EM and the HAD-calo
10^{16} cm^{-2} at R=2 m

W. Riegler, Acad.Training, Oct 2017

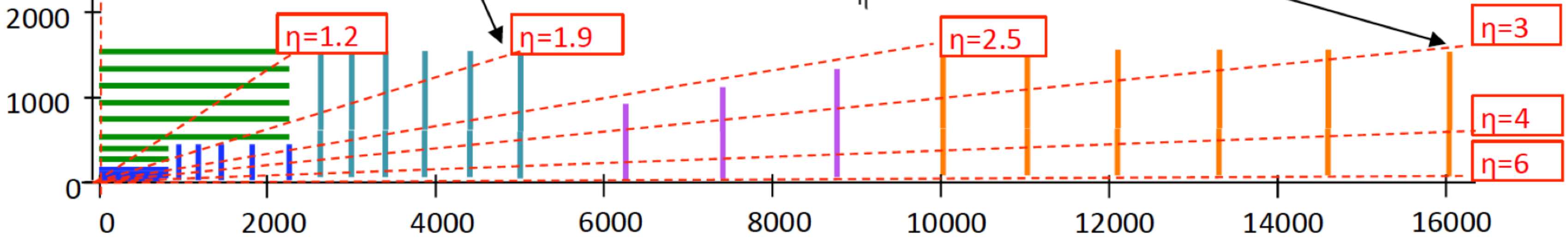
FCC-hh tracker

Tracker radius 1.6 m, half-length 16 m
Hit position resolution ~10 μm in R-ϕ





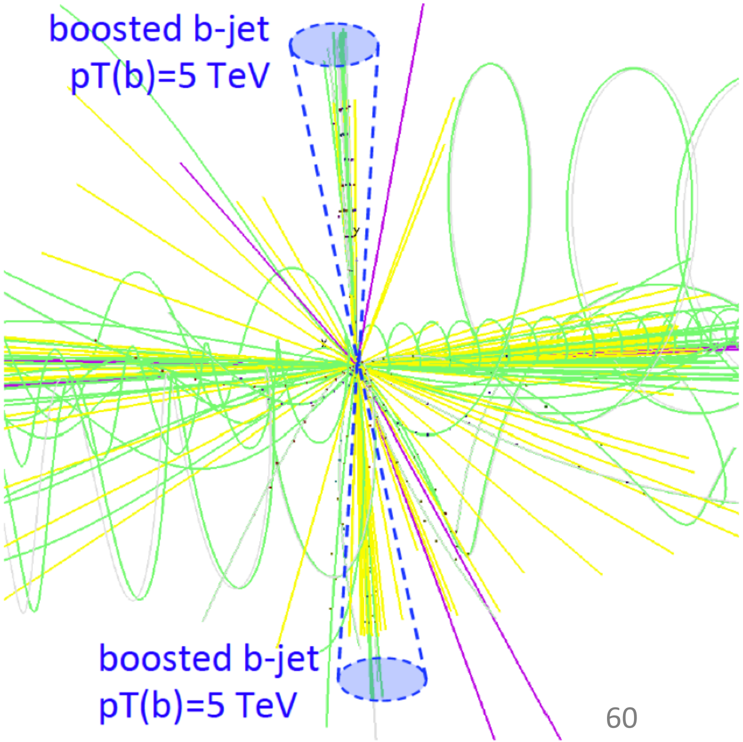
Note: resolution improves as $1/\sqrt{N_{layers}}$, material budget increases as N_{layers}
→ **12 barrel layers, 20 endcap disks**



W. Riegler, Acad.Training, Oct 2017

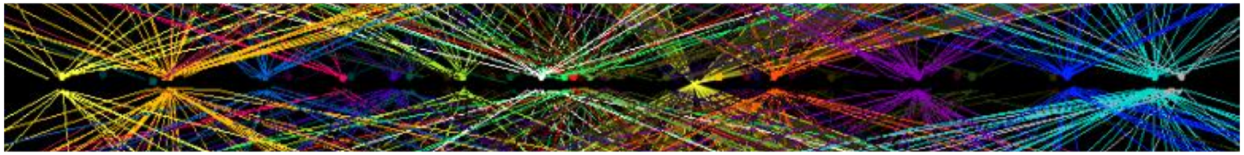
FCC-hh tracker considerations

- A 1.6m x 16m long detector with 10 µm single point resolution in R-ϕ can achieve a 20% **dpT/pT resolution** for 10 TeV tracks
- **Timing information** will be essential to identify the primary vertex within the 1000 pile-up events.
- **Tilted layout** would be very advantageous to reduce multiple scattering for pattern recognition
- **Beampipe material** is the limiting factor for z_0 resolution at $|\eta|>1.7$
- Tracking performance in **boosted objects** is limited by detector granularity
- A significant fraction of **displaced vertices** will be out of detector acceptance



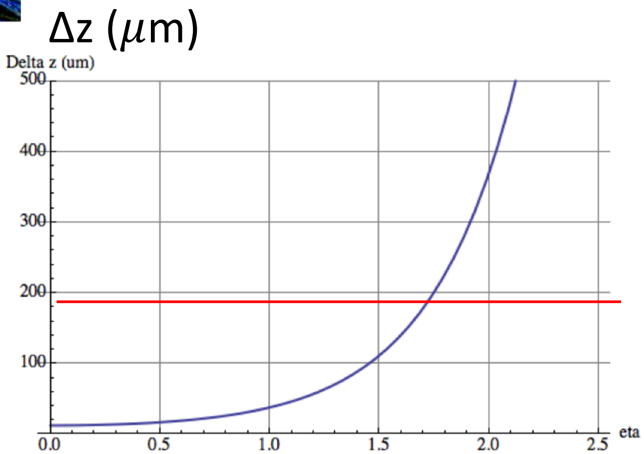
E. Perez Codina, HEP Valparaiso, 2018

Pile up and beam pipe



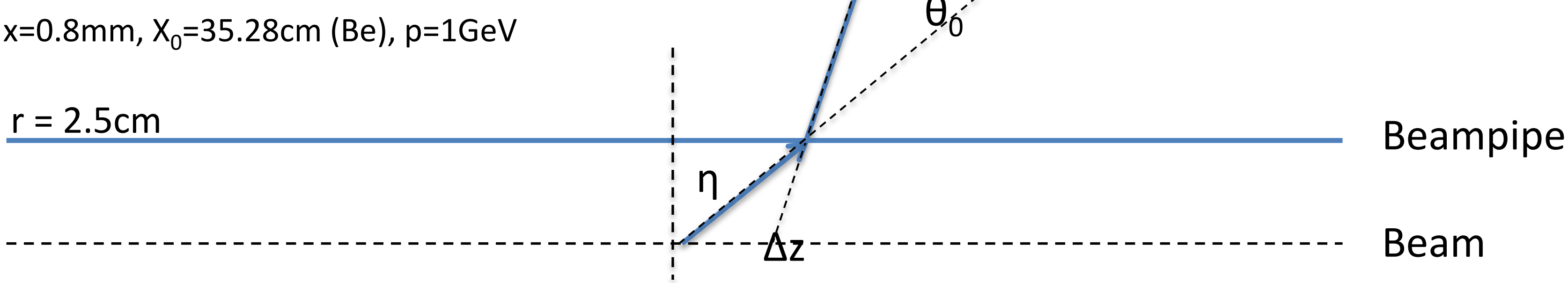
HL-LHC average distance between vertices at z=0 is
≈ 1mm in space and 3ps in time

For 6 times higher luminosity at FCC-hh (and HE-LHC)
≈ 170µm in space and 0.5ps in time



$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038\ln(x/X_0)\Big]$$

x=0.8mm, X_0=35.28cm (Be), p=1GeV



For η > 1.7 the error due to multiple scattering in beampipe is larger than average vertex distance !

Timing and very clever new are ideas are needed …

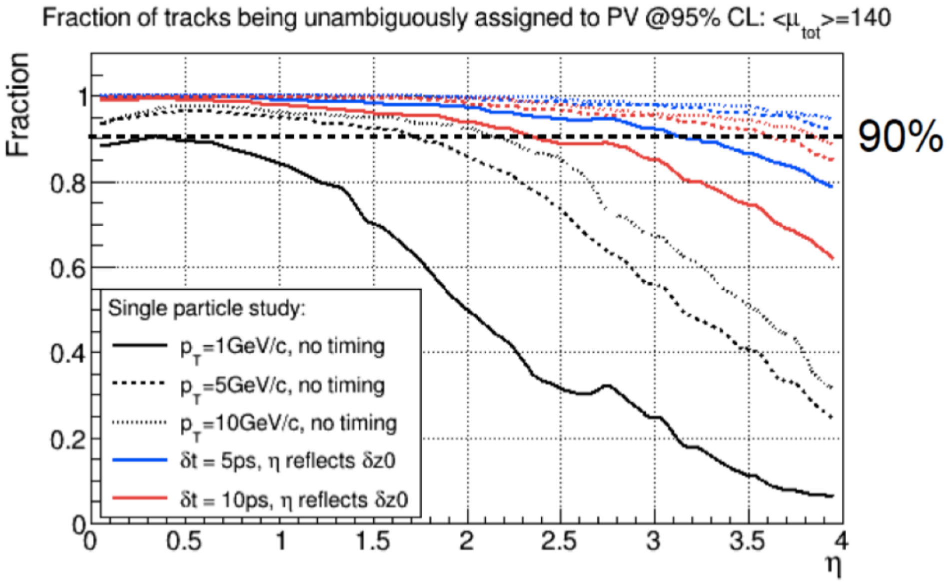
W. Riegler, Acad.Training, Oct 2017

primary vertex reconstruction and pile up

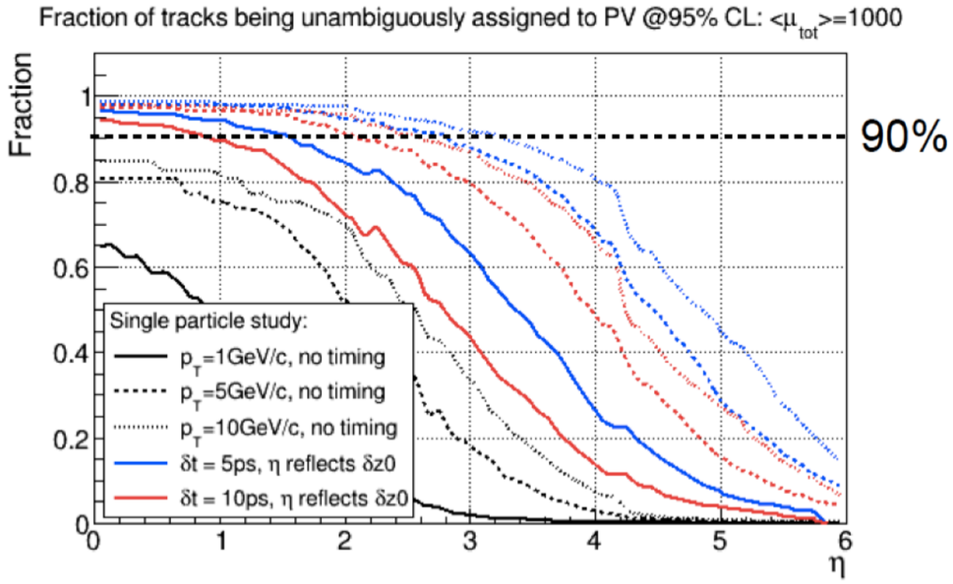
Fraction of events correctly assigned to the primary vertex
No timing, 5 ps timing, 10 ps timing

→ Compare FCC-hh scenario to HL-LHC conditions (PU~140), using e.g. CMS Ph2 upgrade layout

HL-LHC scenario @ PU=140
CMS Ph2 Upgr. tracker



FCC-hh scenario @ PU=1000
Tilted layout



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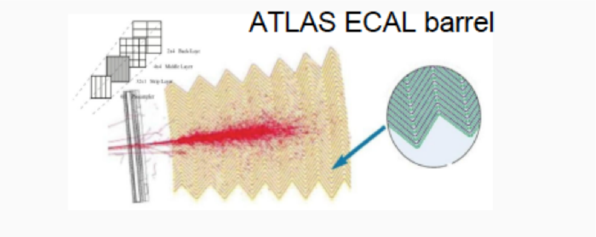
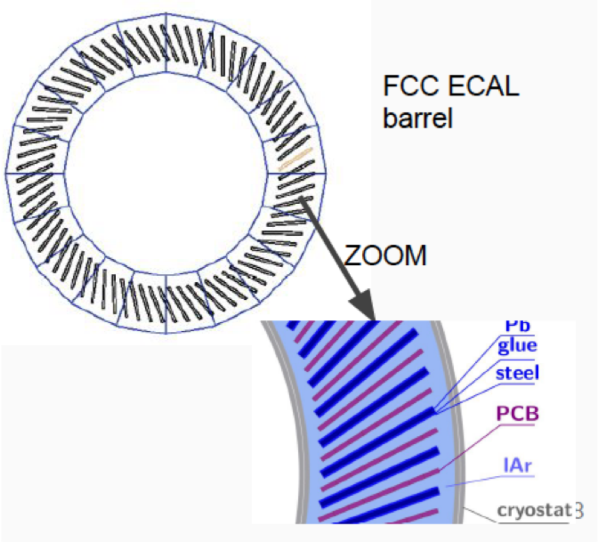
FCC-hh calorimetry

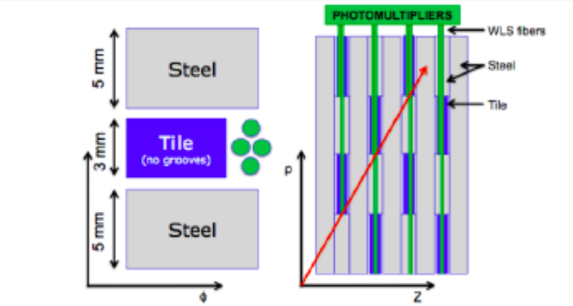
Overall 2-4x better granularity than e.g. ATLAS

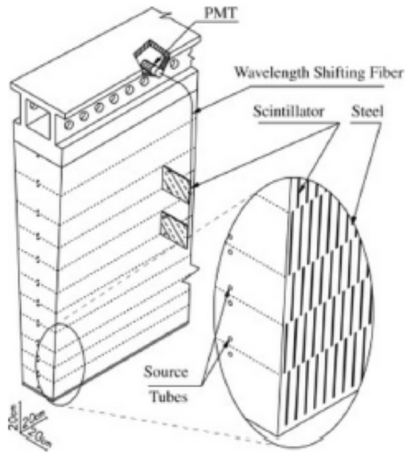
barrel HCAL Fe/Scintillator similar to ATLAS Tilecal

barrel ECAL, endcap ECAL/HCAL, forward ECAL/HCAL are in LAr technology, intrinsically radiation hard









$\sim 11\,\lambda$ FCC-hh HCAL, pion resolution:

$\sigma E/E = 43\,\%/\sqrt{E} \oplus 2.7\%$

Note : Silicon ECAL and ideas for digital ECAL with MAPS are also being discussed

W. Riegler, Acad.Training, Oct 2017

muon system considerations

Compare 3 options:

1. Tracker only with identification in the muon system
2. Muon system only by measuring the muon angle where it exits the coil
3. Tracker combined with the position of the muon where it exists the coil

Assume (at η=0) :

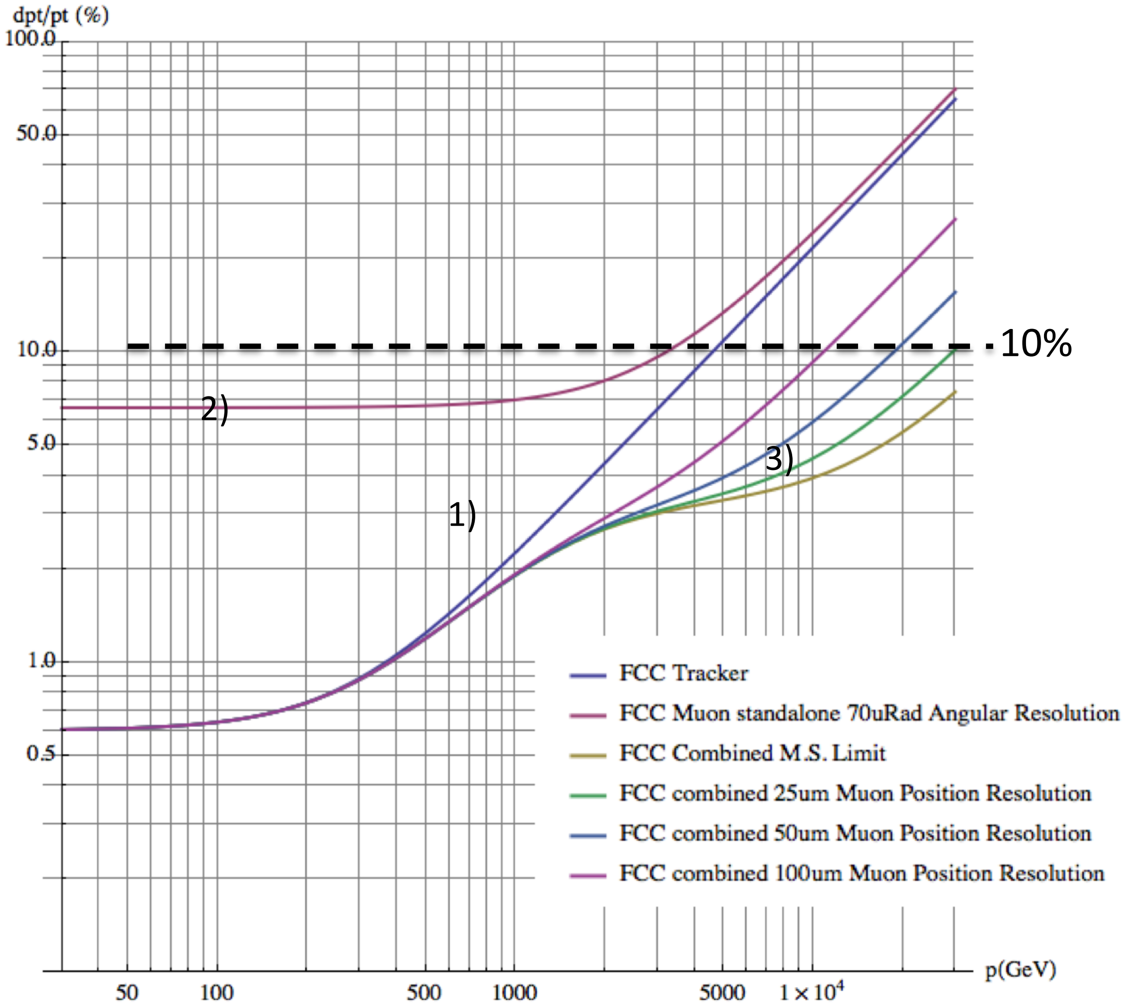
- 50µm position resolution
- 70µRad angular resolution

⬇

<10% standalone momentum resolution up to 3TeV/c

<10% combined momentum resolution up to 20TeV

within reach of 'standard' muon system technology



W. Riegler, Acad.Training, Oct 2017

experimental conditions future pp colliders

Experimental conditions for a ~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, very forward-going physics 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**:
  - => precision tracking needed down $\eta=4$, $\theta=2°$ ($\eta=2.5$, 2.5° at LHC)
  - => calorimetry down to $\eta=6$, $\theta\approx0.5°$
- Aim for track resolution of 10-15% up to p_T of 10 TeV
  - => central solenoid 4 T with inner radius 5 m, track hit resolution ~10 µm
  - Forward solenoids are needed to increase angular coverage

Pile up of 1000 events?

- FCC-hh average distance at z=0 between events is 170 µm, 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

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	*	****

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	*	****

despite differences, many challenges in common

↓

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

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

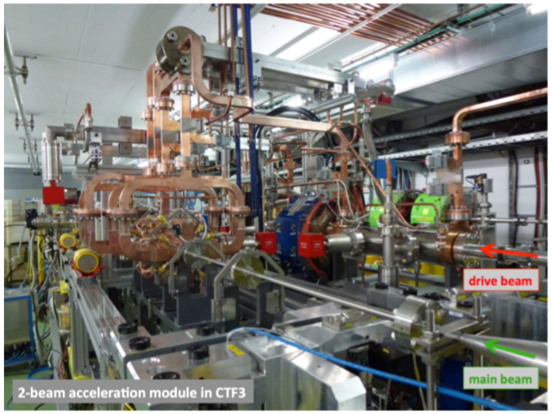
THANK YOU !

SPARE SLIDES

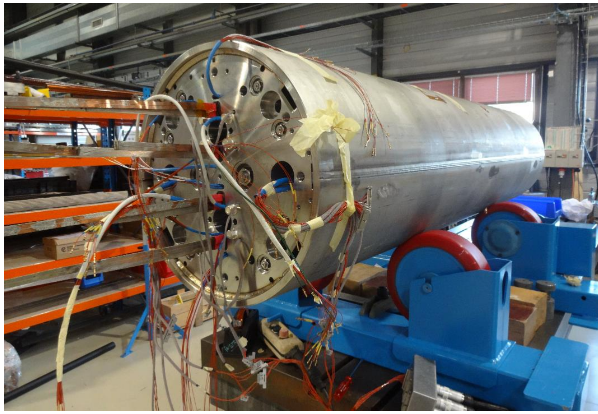
status of the projects

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

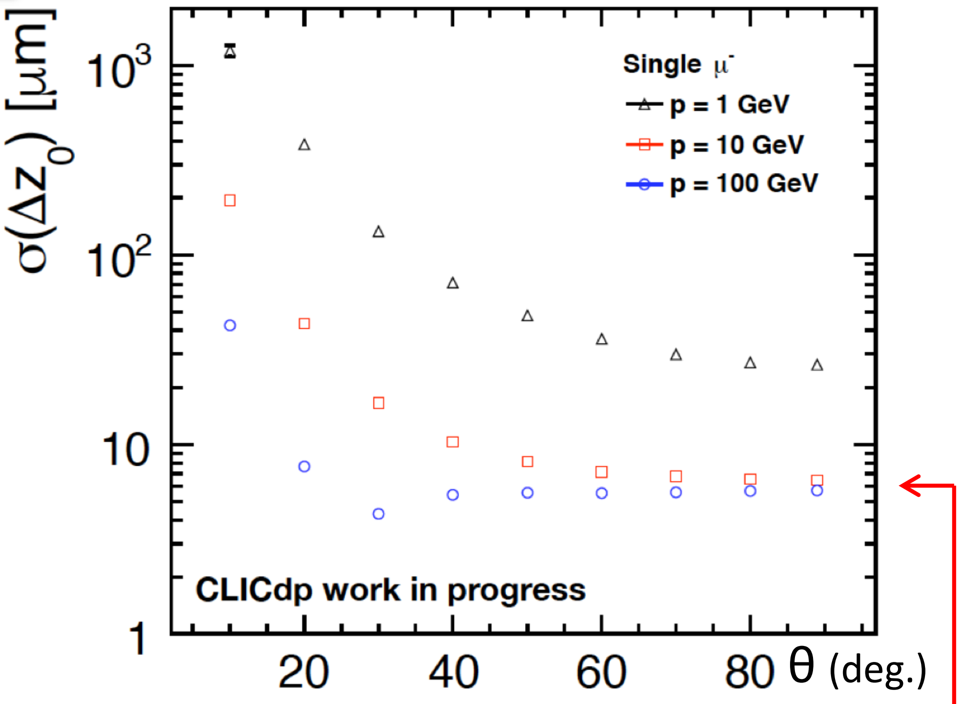


CLIC 2-beam acceleration, 100 MV/m


11 T superconducting dipole prototype

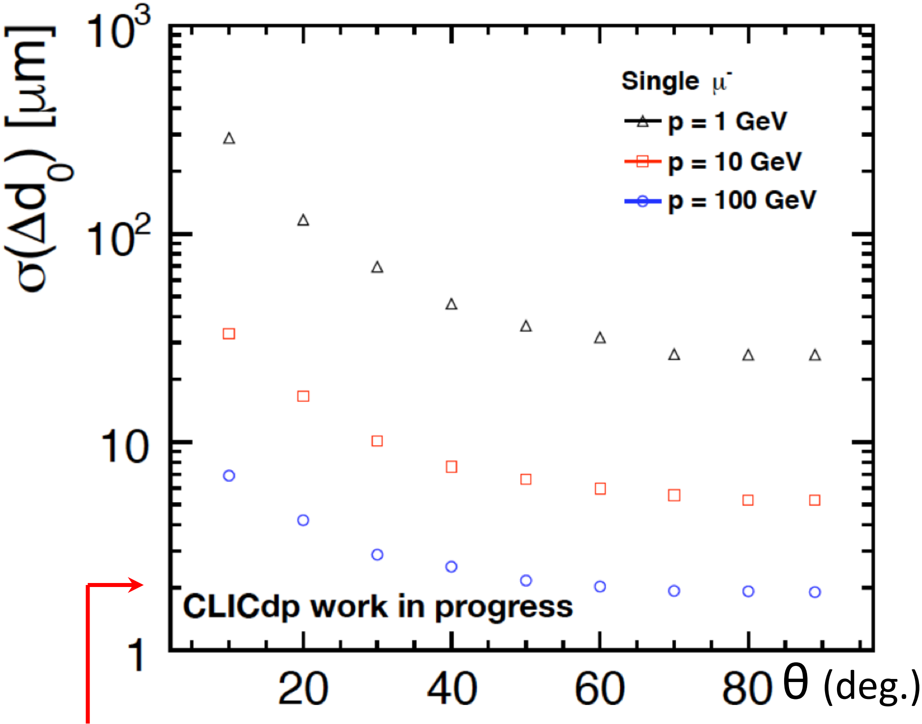
CLIC impact parameter resolution

☆ z0 resolution



~6 µm

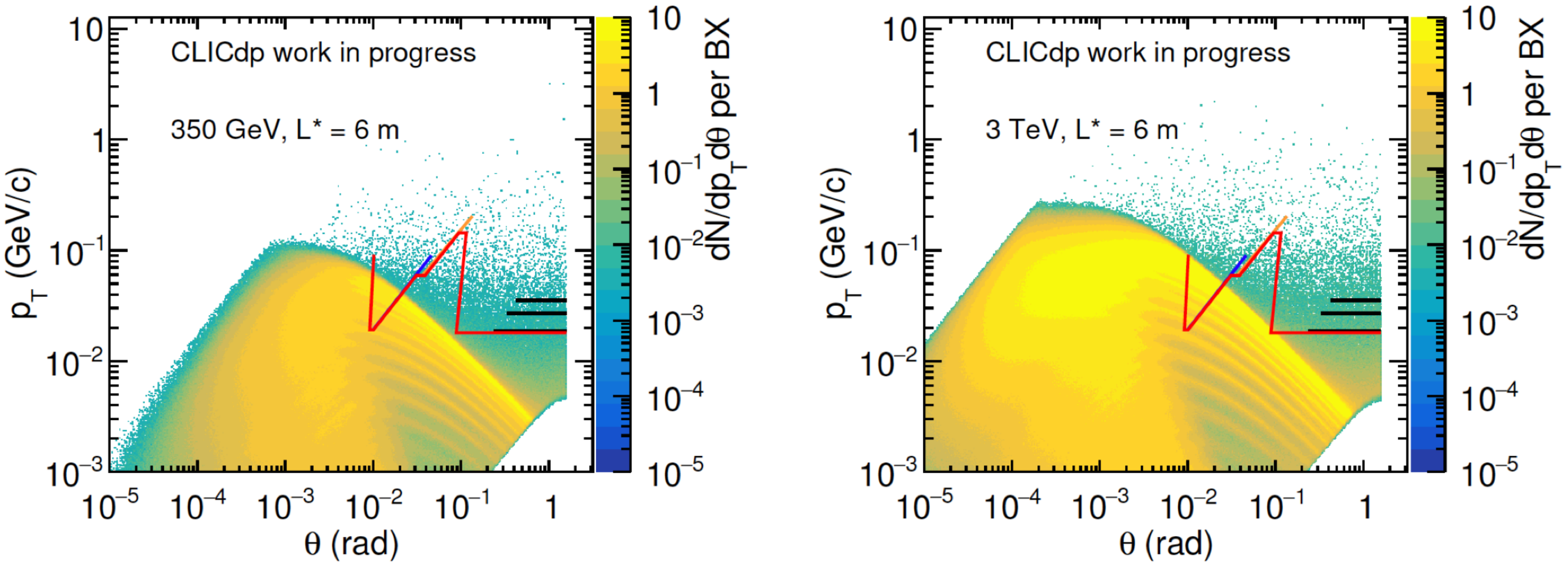
☆ d0 resolution



2 µm

E.Leogrande @ LCWS17

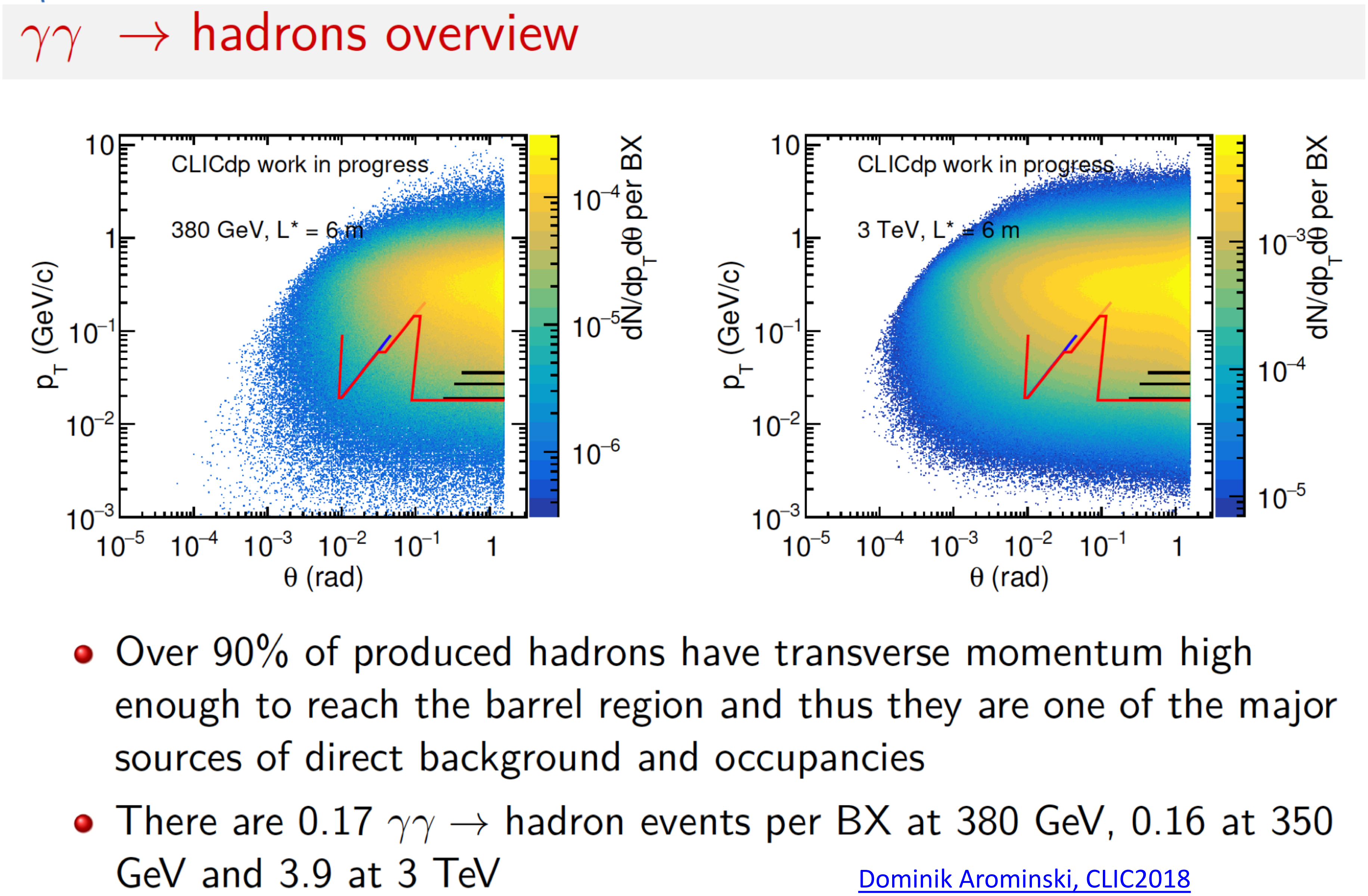
Incoherent e^+e^- pairs



- There are on average 84k incoherent pairs per bunch crossing at 380 GeV, 74k at 350 GeV, and 290k at 3 TeV
- In all cases only around 10% of the incoherent pairs are a source of direct background, mostly in the forward detector region, irradiating BeamCal and LumiCal subdetectors

Dominik Arominski, CLIC2018

$\gamma\gamma$ => hadrons



$\gamma\gamma \rightarrow$ hadrons overview

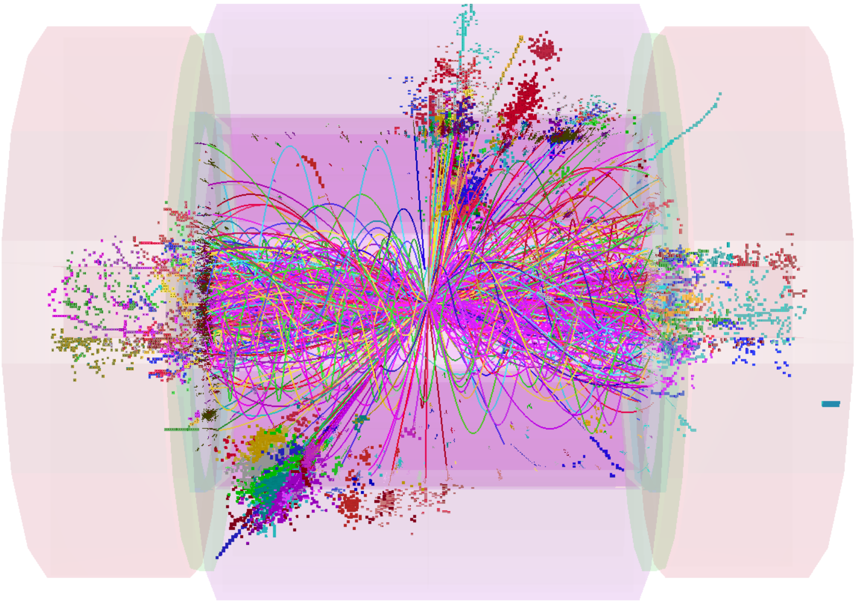
- Over 90% of produced hadrons have transverse momentum high enough to reach the barrel region and thus they are one of the major sources of direct background and occupancies
- There are 0.17 $\gamma\gamma \rightarrow$ hadron events per BX at 380 GeV, 0.16 at 350 GeV and 3.9 at 3 TeV

Dominik Arominski, CLIC2018

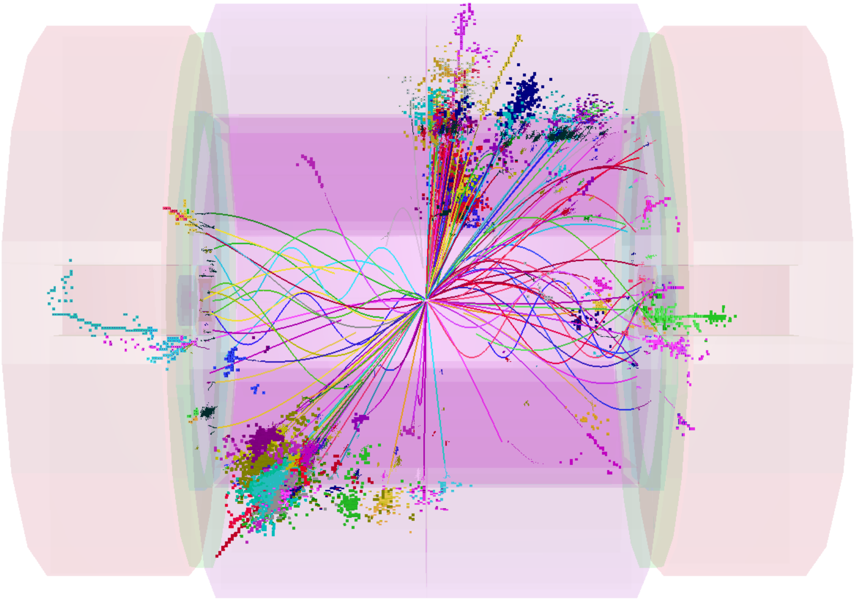
beam-induced background rejection (1)

Beam-induced background from γγ ➔ hadrons can be efficiently suppressed by applying **p_t cuts and timing cuts on individually reconstructed particles** (particle flow objects)

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 window (>=10 ns) around main physics event

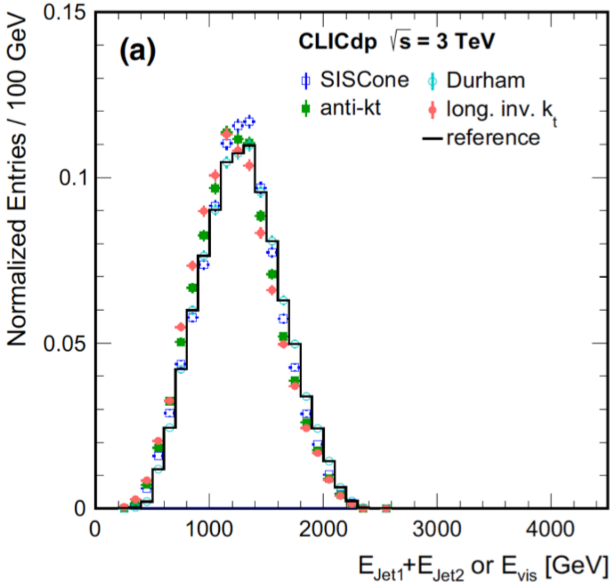
100 GeV background after tight cuts

beam-induced background rejection (2)

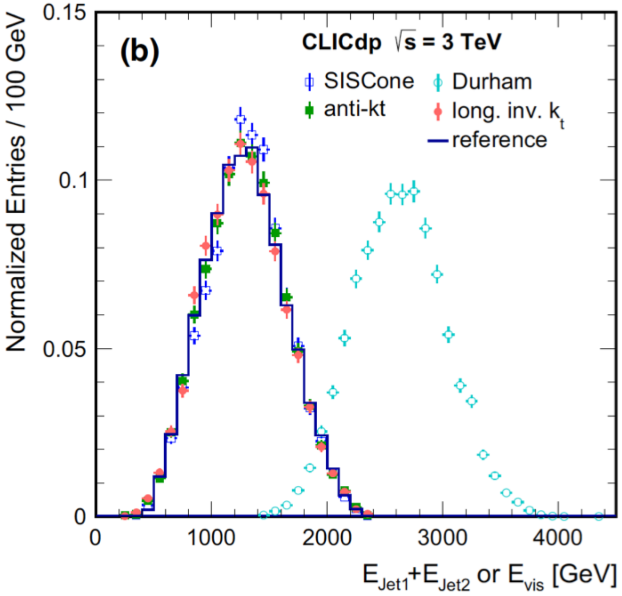
Beam-induced background from γγ ➔ hadrons is further reduced by applying **adapted jet reconstruction algorithms**

Example: ***squark study*** at √s = 3 TeV (with assumed squark mass of 1.1 TeV)

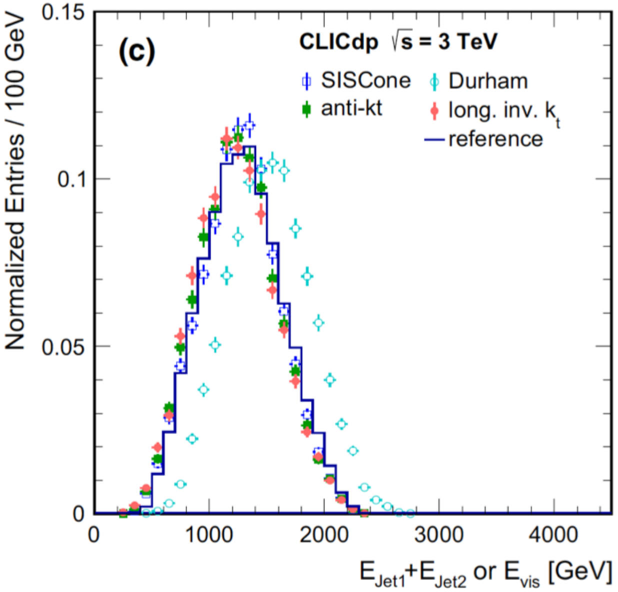
$$e^+e^- \rightarrow \tilde{q}_R\tilde{q}_R \rightarrow q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$$



No γγ ➔ hadrons background



With γγ ➔ hadrons bkg from 60 bunch crossings



With γγ ➔ hadrons bkg from 60 bunch crossings + use of p_t and timing cuts

Traditional Durham-ee jet algorithm inadequate <=> use of "LHC-like" jet algorithms effective

From Eur.Phys.J. C75 (2015) no.8, 379, see also arXiv:1607.05039

FCC-ee forward luminosity calorimeter

Luminosity needs to be measured to very high accuracy

- Few 10^{-5} at the Z pole
- Few 10^{-4} at the tt threshold

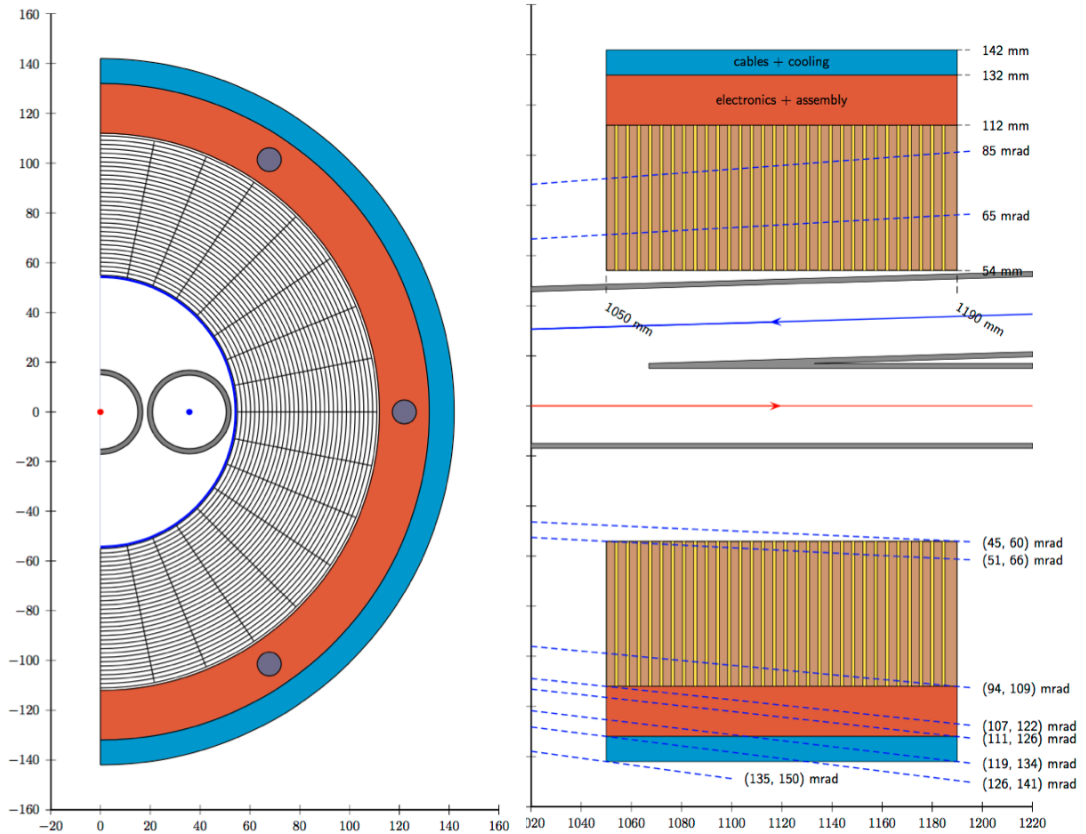
Forward calorimeter to measure Bhabha scattering, adapted from ILC/CLIC design

- Placed closer to the IP (z < 1.2 m) and made smaller
- Centred around the outgoing beam

Depth 10 cm (1.05 to 1.15 m)
Radius from 5.4 to 14.2 cm
30 layers ($1X_0$) of 3.5 mm W + 1 mm Si
32 × 32 Si pads in (R,ϕ): 3×10^4 channels

Positioned with 1 µm accuracy

Total angular coverage: 45-95 mrad
Loose acceptance: 63-83 mrad
Tight acceptance: 68-78 mrad
$\sigma(e^+e^- \rightarrow e^+e^-)$ = 6-13 nb



P.Janot, Acad.Training, Oct 2017

FCC-hh three solenoids