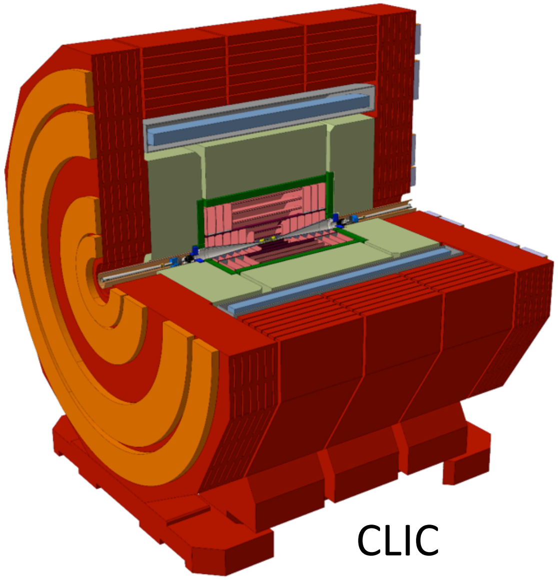
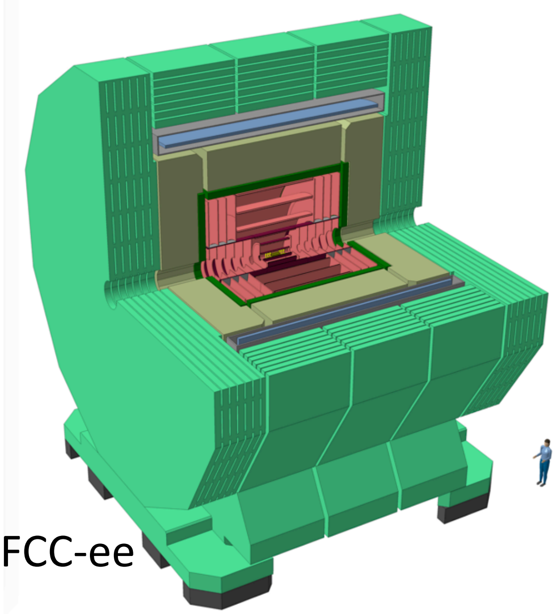
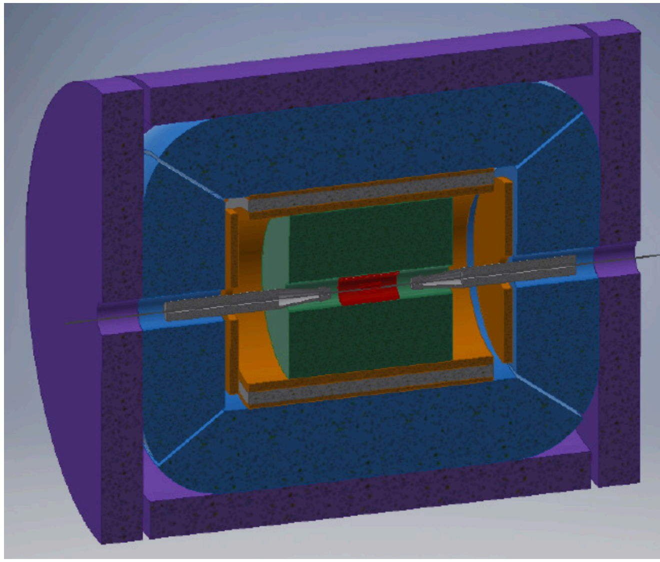
detector requirements for future e^+e^- colliders


CLIC

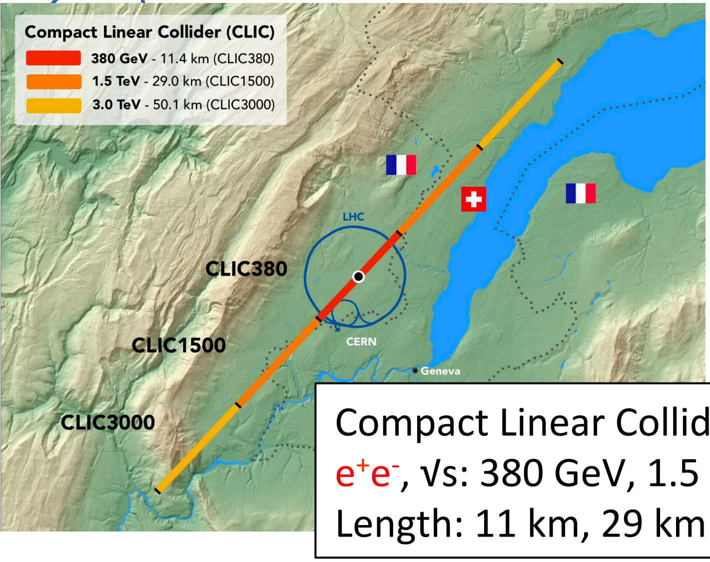

FCC-ee


FCC-ee

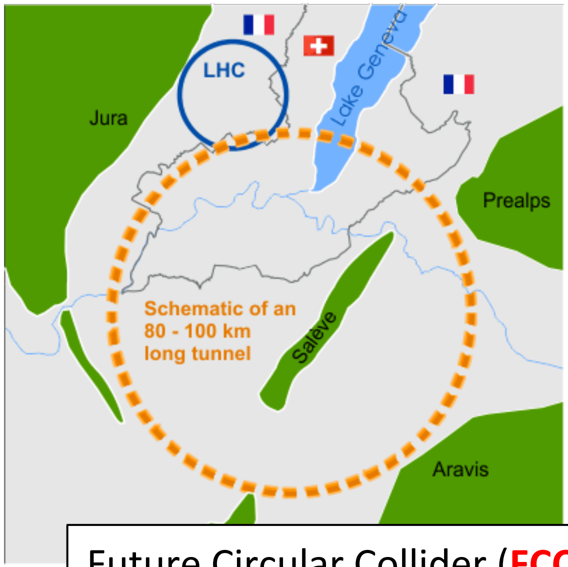
Patrick Janot, Lucie Linssen
EP R&D kick-off meeting
November 20th 2017

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

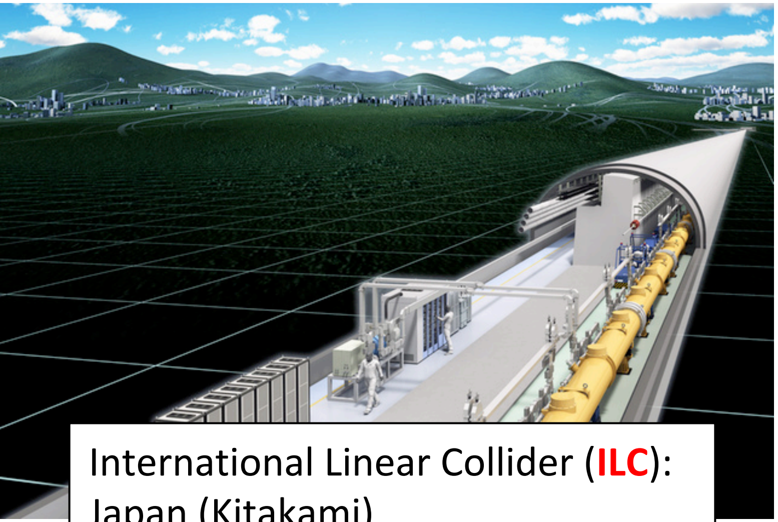
high-energy e^+e^- collider projects



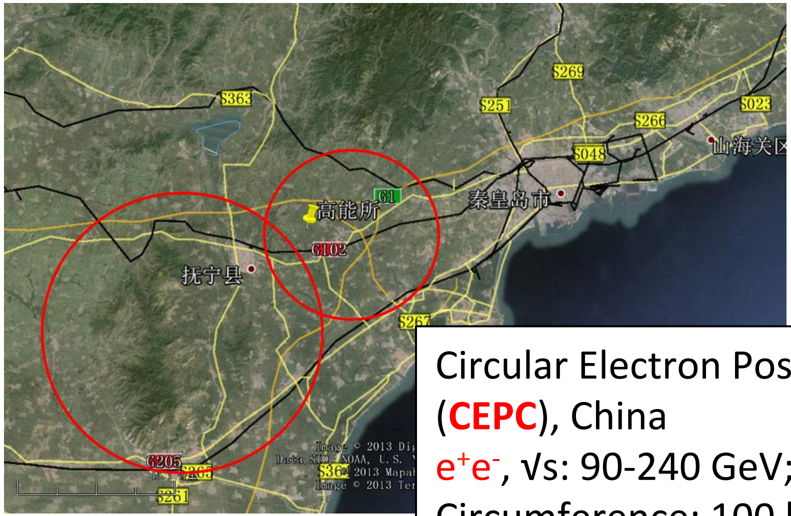
Compact Linear Collider (**CLIC**): CERN
e^+e^-, $\sqrt{s}$: 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km , 50 km



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

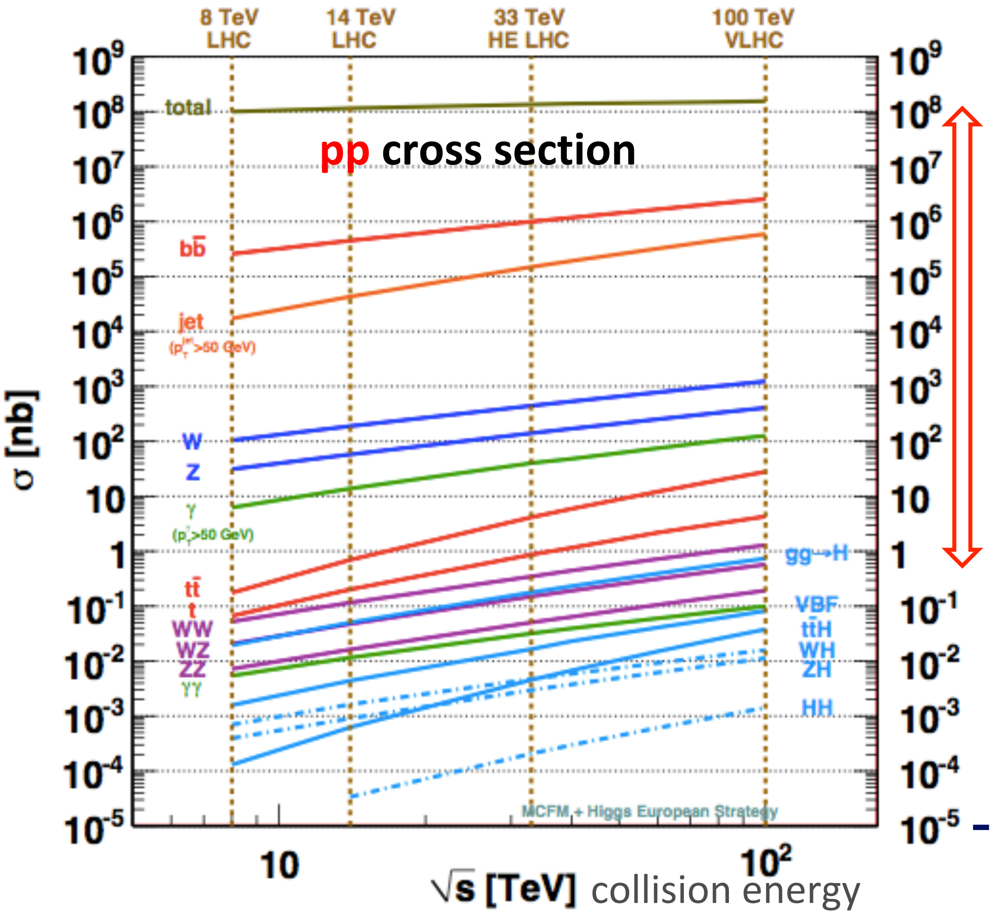


International Linear Collider (**ILC**):
Japan (Kitakami)
e^+e^-, $\sqrt{s}$: 250 – 500 GeV (1 TeV)
Length: 17 km, 31 km (50 km)



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

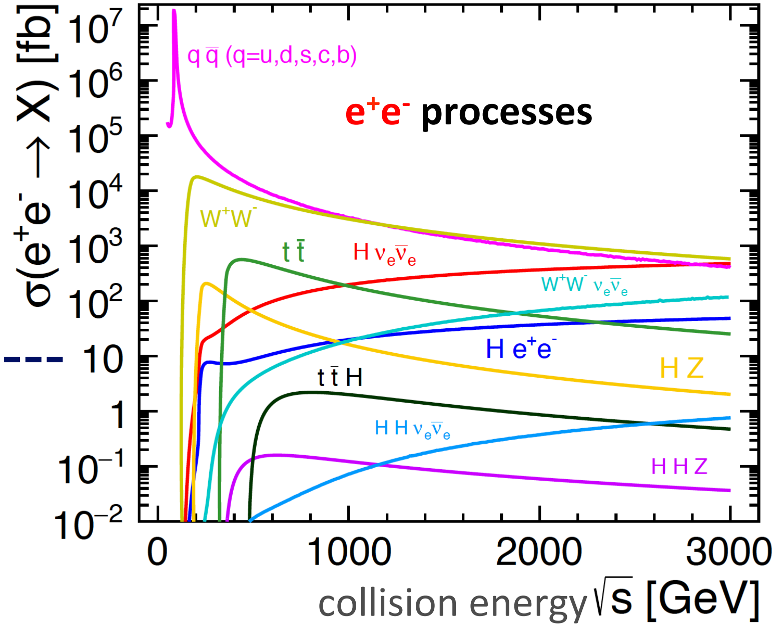
pp collisions / e^+e^- collisions



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

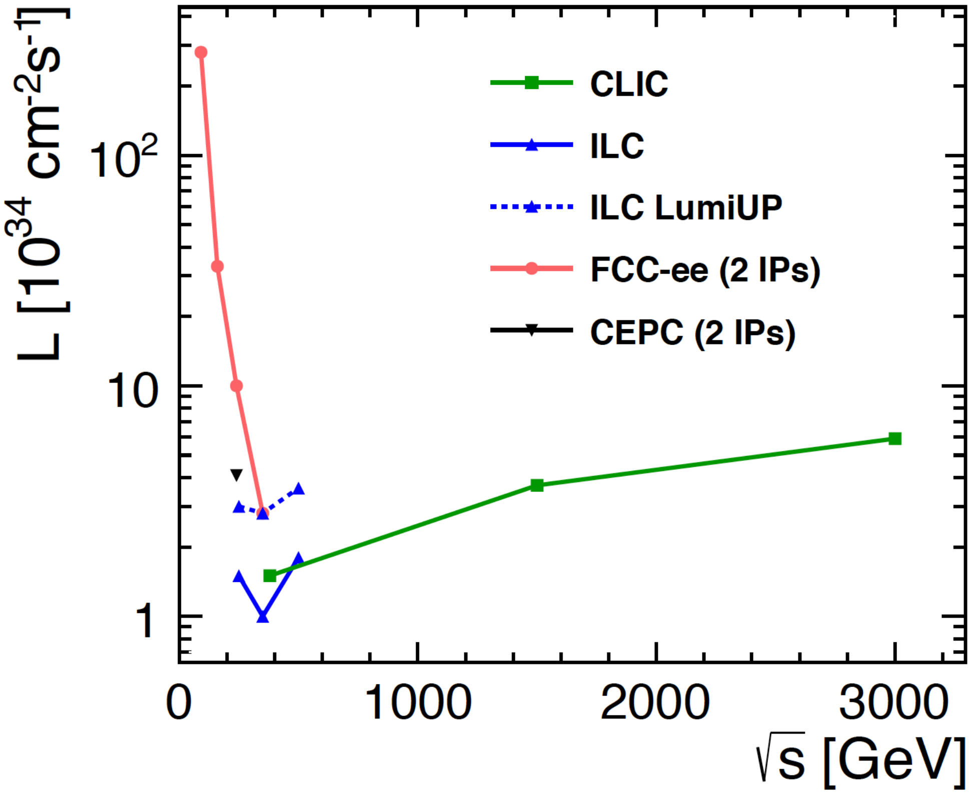
factor > 10^8

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



- e^+e^- events are more "clean"

luminosity performance e^+e^- colliders



Linear colliders:

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

Circular colliders:

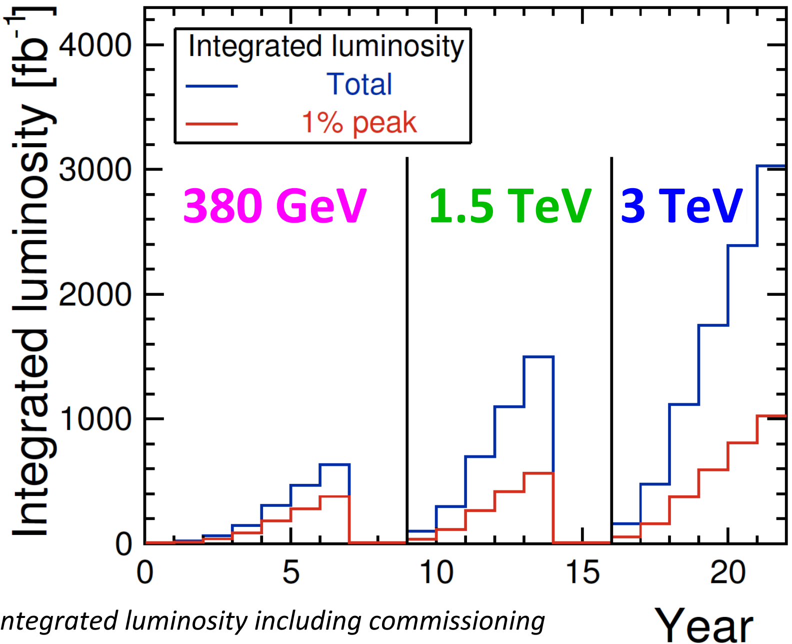
- Luminosity increases with decreasing energy
- Huge luminosity at lower energies

Note: Latest adjustments (FCC-ee, ILC, CEPC) not included in this plot

Peak luminosity at LEP2 (209 GeV) was ~10^{32} cm^{-2}s^{-1}

CLIC physics and staging scenario

The CLIC program builds on energy stages:



Integrated luminosity including commissioning with beam and stops for energy upgrades

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

Dedicated to top mass threshold scan

CERN-2016-004

- **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

Staging scenario can be adapted, e.g. to new results from (HL-)LHC
CLIC is extendable. May profit from even more advanced technologies for high-E stages

CLIC accelerator parameters

Parameter	**380 GeV**	**1.5 TeV**	**3 TeV**
Luminosity ℒ (10^{34}cm^{-2}sec^{-1})	**1.5**	**3.7**	**5.9**
ℒ above 99% of √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
Estimated power consumption* (MW)	252	364	589

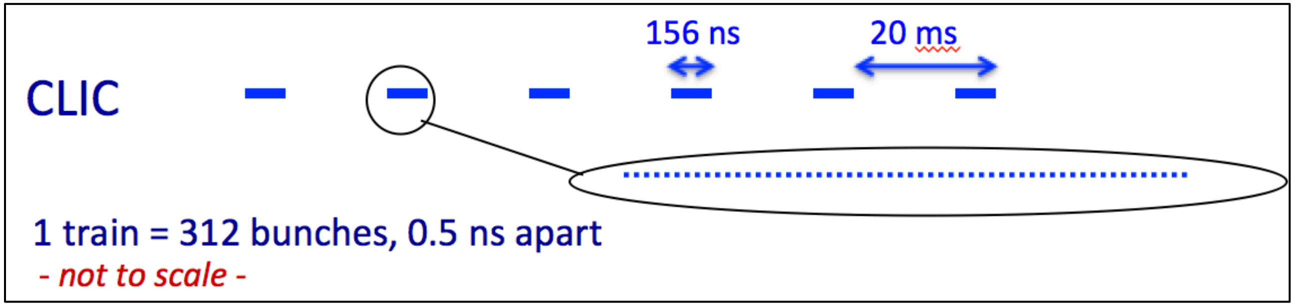
Drives timing requirements for CLIC detector

Very small beam

scaled from CDR, with room for improvement

Crossing angle 20 mrad

allows for trigger-less readout



1 train = 312 bunches, 0.5 ns apart

- not to scale -

CERN-2016-004

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 10-1000 TeV energy scale via precision measurements

⇒ Search for (very) weakly coupled particles

working point	**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**

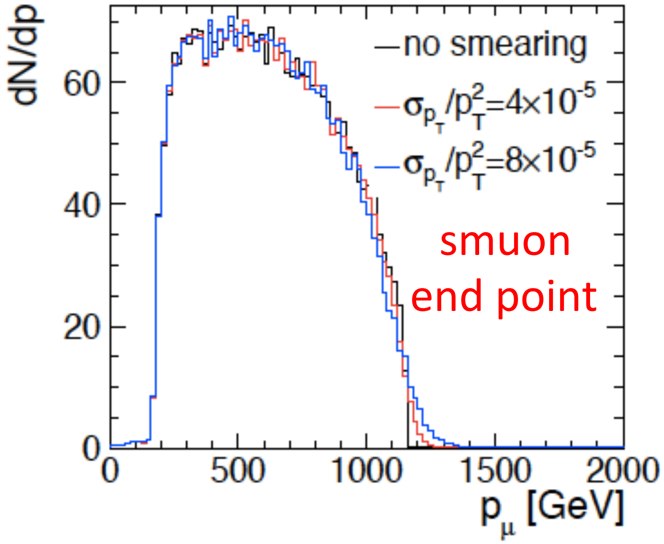
$\Rightarrow$ This also drives requirement on **data rates**

CLIC detector requirements (from physics)

★ **momentum resolution:**

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

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

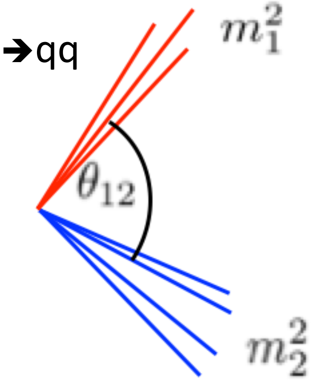


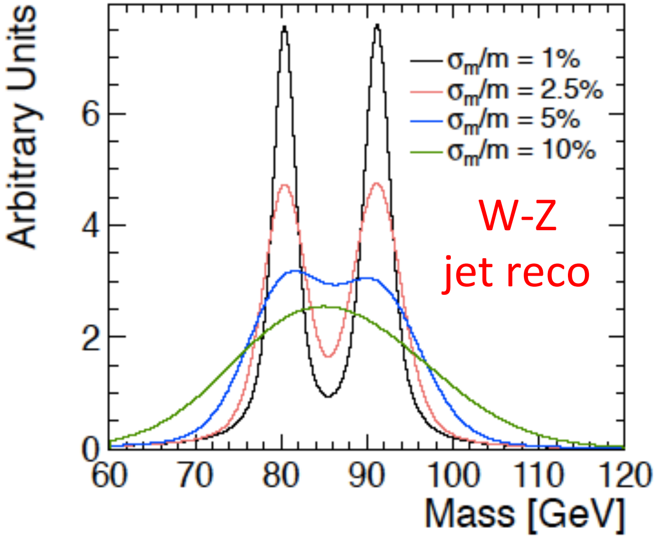
★ **jet energy resolution:**

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:**

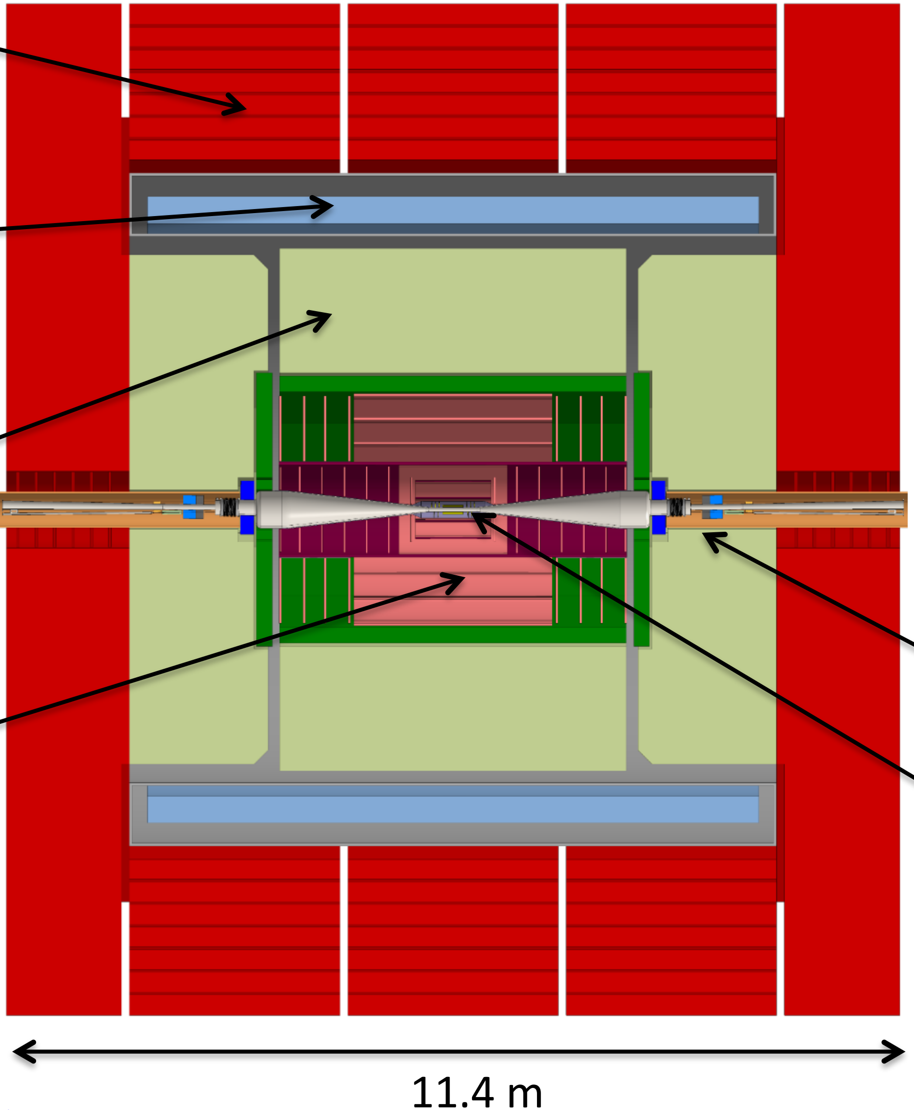
e.g. c/b-tagging, Higgs BR

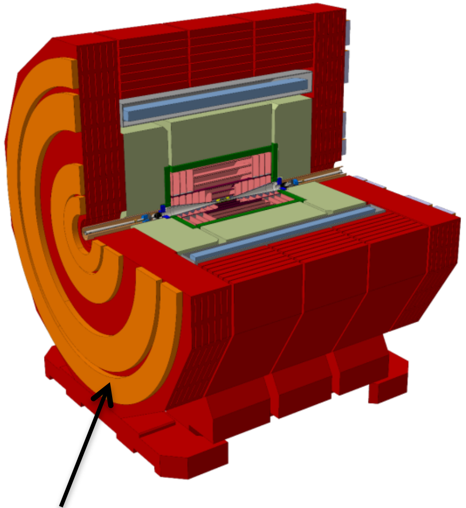
$$\boxed{\sigma_{r\phi} = 5 \oplus 15/(p[\mathrm{GeV}]\sin^{\frac{3}{2}}\theta)\,\mu\mathrm{m}}$$

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

+ requirements from CLIC experimental conditions

the (new) 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)

end-coils for field shaping

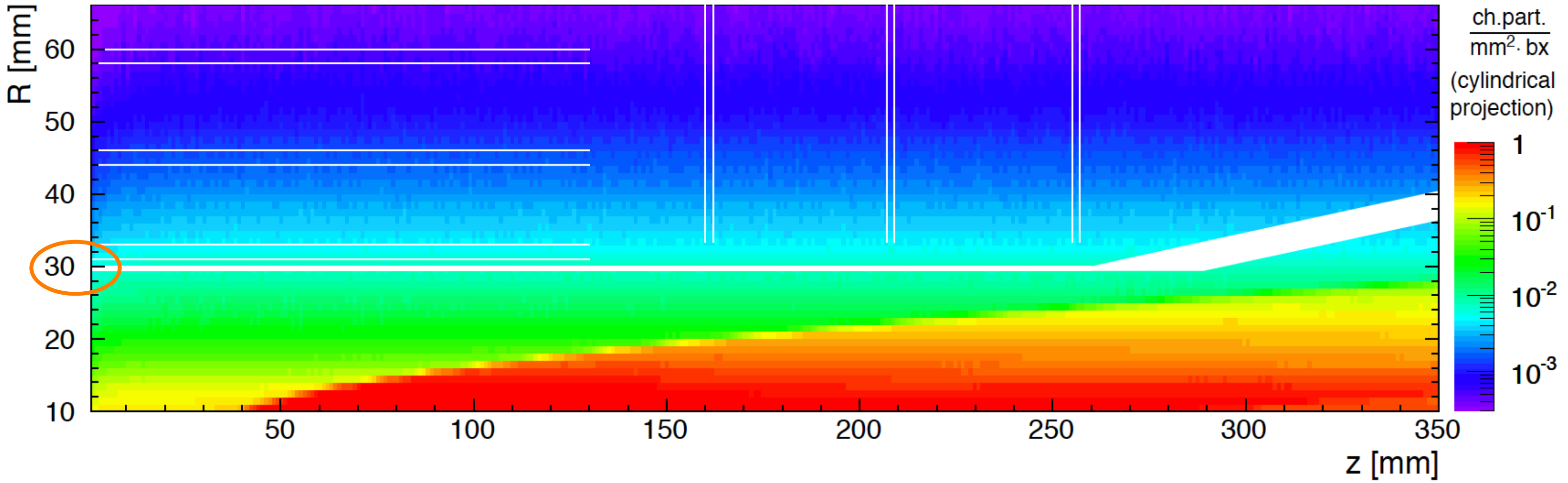
forward region with compact forward calorimeters

low-mass vertex detector, ~25 µm pixels

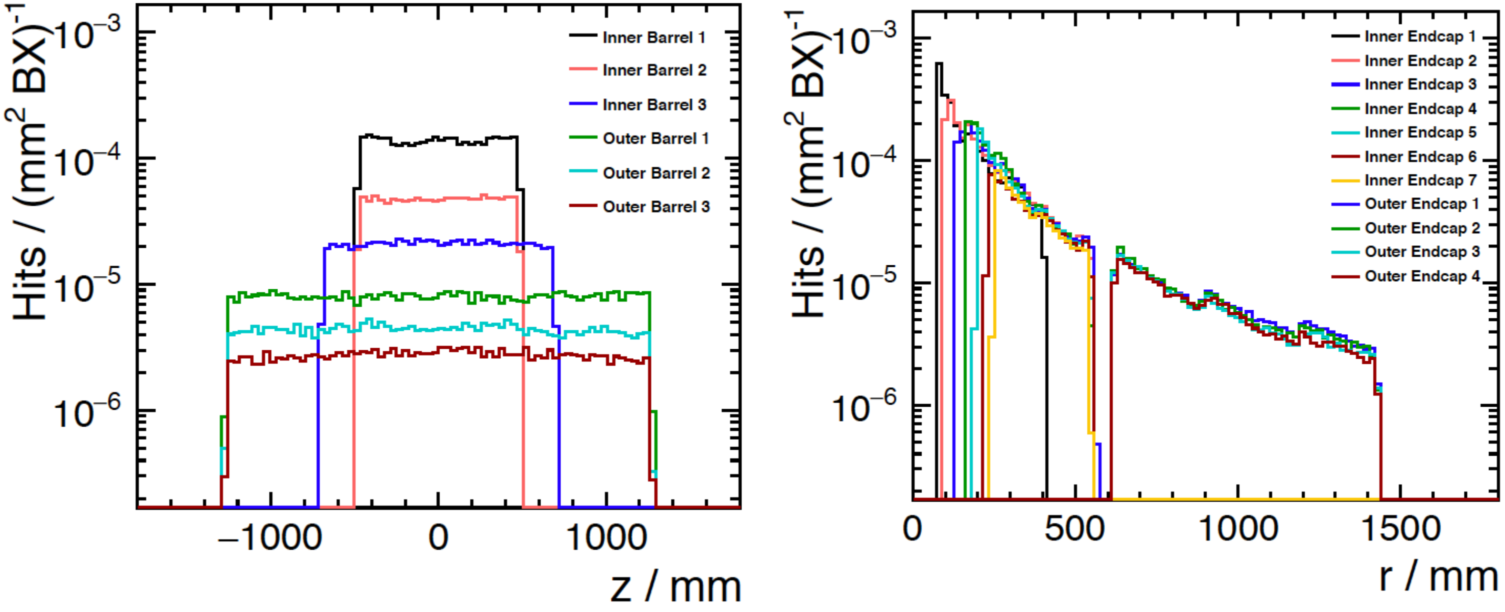
Final beam focusing is outside the detector

CLICdp_Note_2017_001

CLIC detector occupancies from beam-induced backgrounds



CLIC Vertex detector at 3 TeV



CLIC tracker at 3 TeV

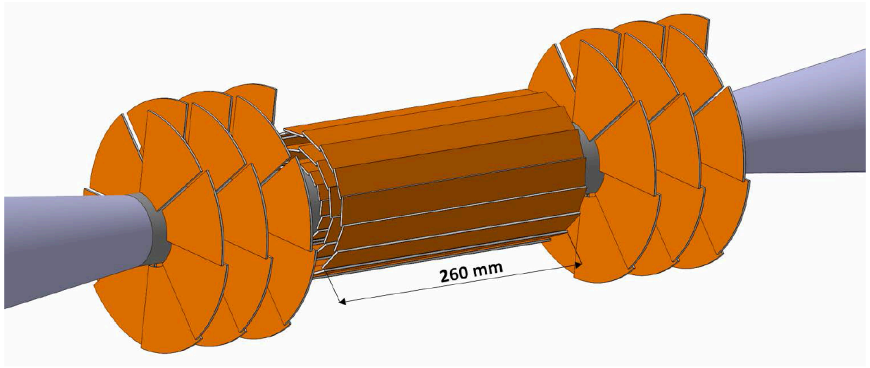
Charged particles: incoherent pairs + γγ→hadrons

CLIC vertex requirements: CERN-2012-003
CLIC tracker readout requirements: CLICdp-Note-2017-002

CLIC silicon pixel R&D (vertex and tracker)

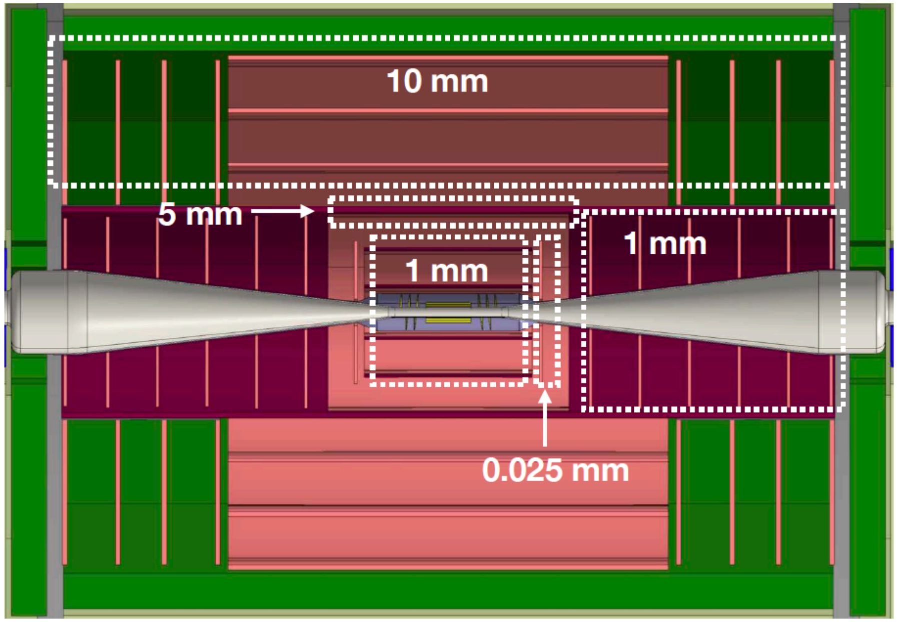
Parameter	vertex	tracker
Hit position resolution (μm)	3	7
Time stamping (ns per slice)	10	10
Material per layer (X_0)	<0.2%	<1-1.5%
Silicon thickness (μm)	~100 (50+50)	~200
Power (mW/cm^2, incl. power pulsing)	<50	<150
Radiation level NIEL (n_{eq} cm^{-2}/yr)	$<4\times10^{10}$	$<10^{10}$
Radiation level 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)

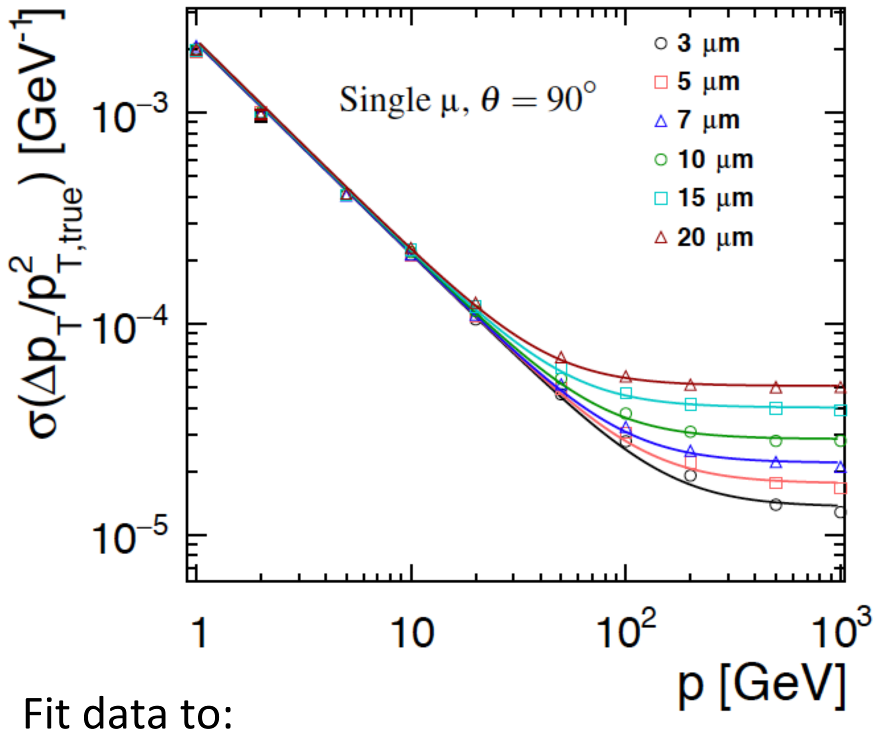
Layout of the CLIC tracker
Tracker radius ~1.5 m, maximum strip lengths indicated (assuming 50 μm strip width) taking into account occupancies from beam-induced background)



CLIC tracking performances

Geant4-based simulation and event reconstruction

Varying **position resolution in tracker**



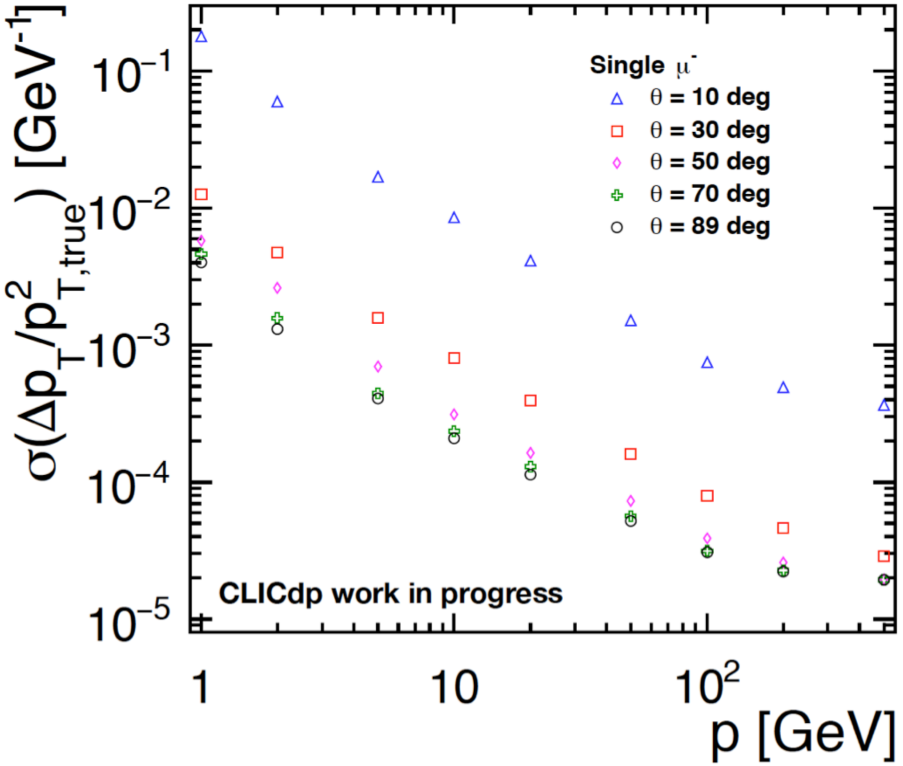
Fit data to:

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

Shows that 7 μm in tracker is needed

CLICdp-Note-2017-002

CLICdet with nominal performances



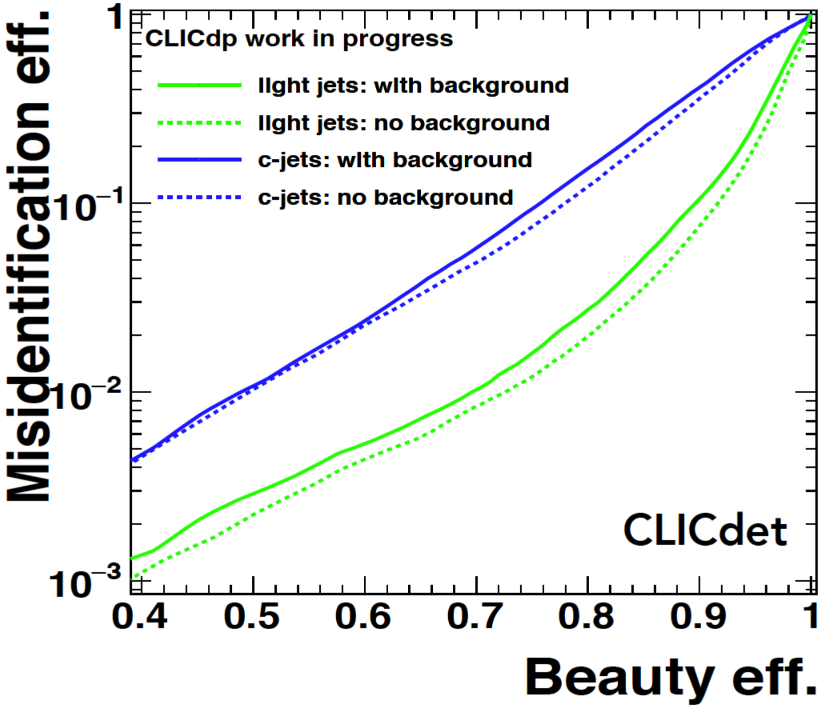
Momentum resolution for muons.
~2×10^{-5} GeV^{-1} achieved in central part

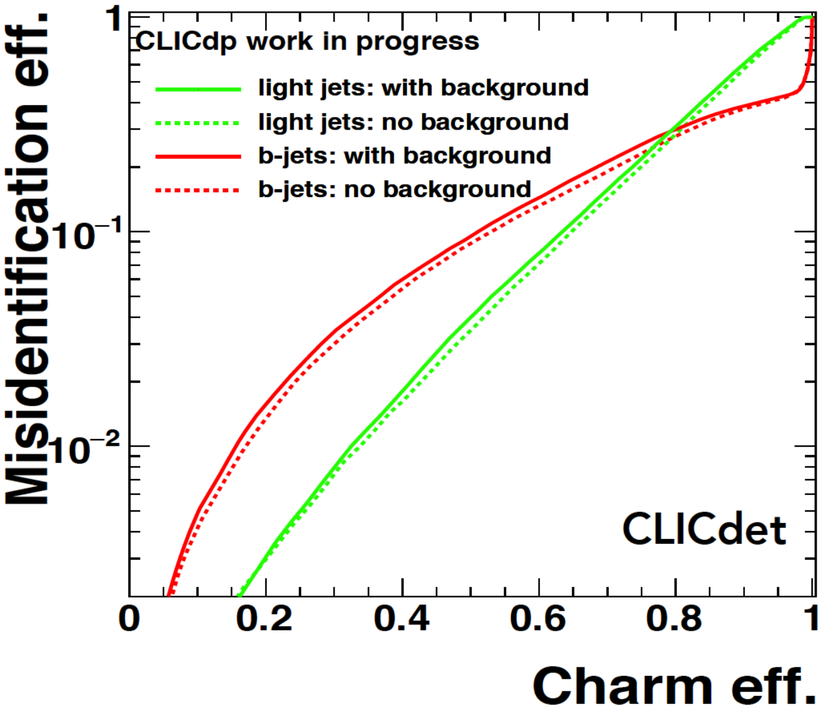
E.Leogrande @ LCWS17

CLIC flavour tagging

Geant4-based simulation and event reconstruction

CLICdet with nominal performances



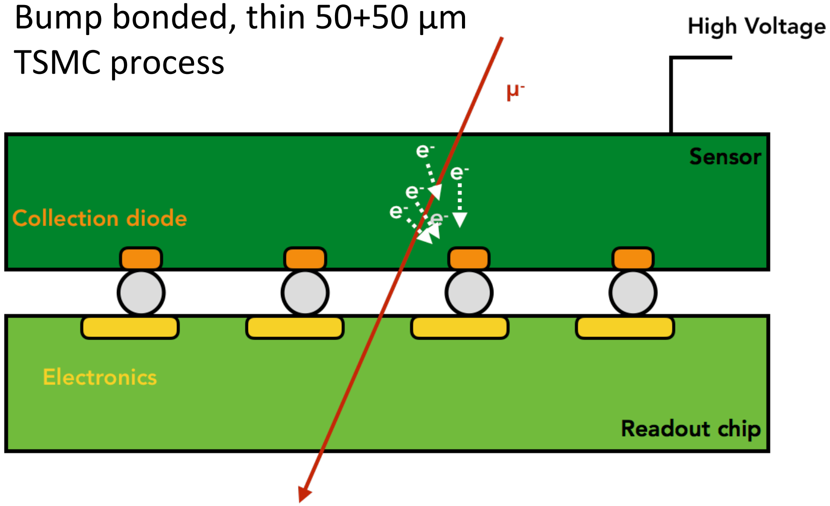


See also: CLICdp-Note-2014-002 and CLICdp-Note-2017-001 for dependence of flavour-tagging performance on vertex detector parameters (single point resolution, amount of material) and vertex detector layout.

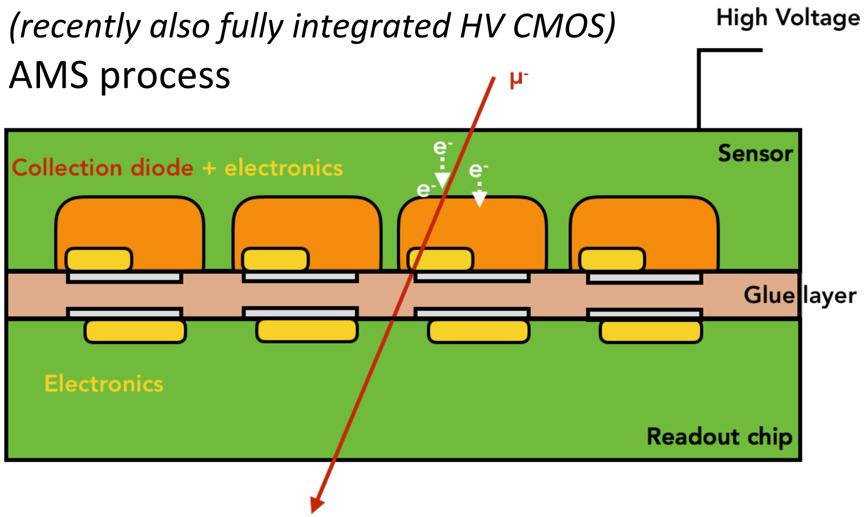
=> **Vertex detector: 3 µm position resolution is needed, low material budget is very important**

Si technologies pursued in CLIC R&D

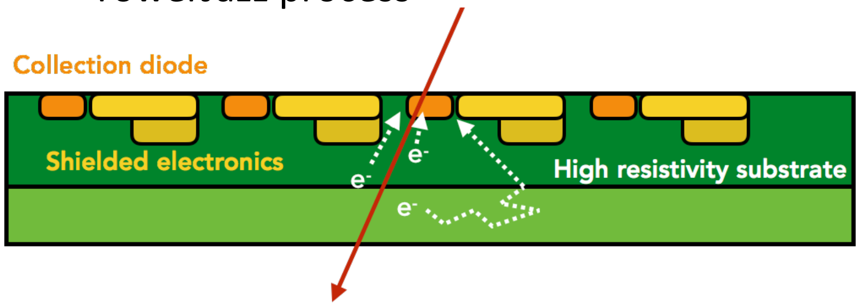
Hybrid: Si sensor + ASIC (65 nm)
Bump bonded, thin 50+50 µm
TSMC process



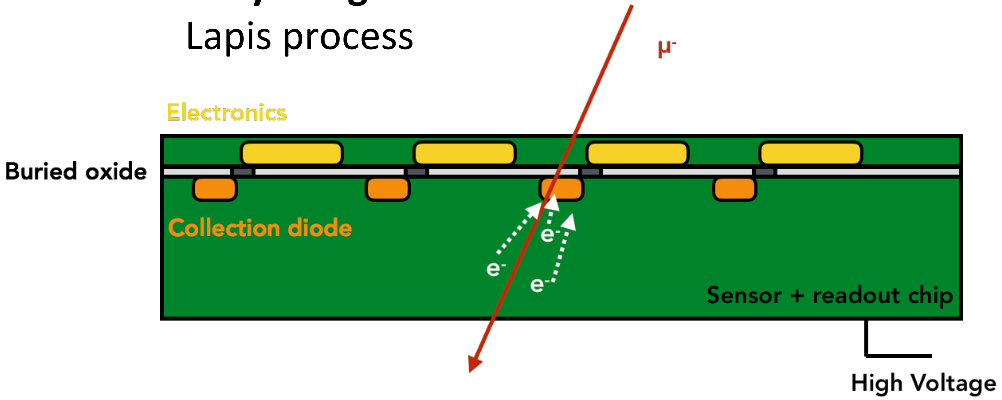
Hybrid: HV CMOS active sensor + ASIC (65 nm)
Capacitive coupling (glue)
(recently also fully integrated HV CMOS)
AMS process



Fully integrated: HR CMOS
TowerJazz process



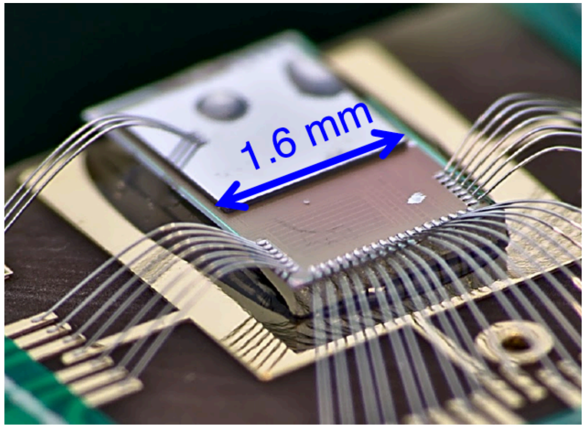
Fully integrated: SOI
Lapis process



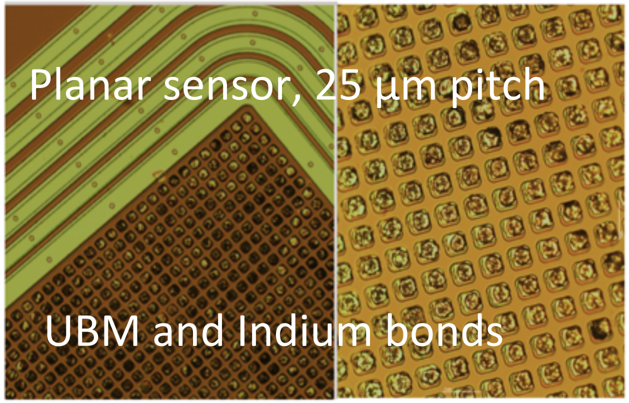
Systematics R&D studies have focused on Pixel implementation, with Pixel sizes around 25×25 µm^2
Studies equally valid for the main tracker, even though it will have larger cell sizes

CLIC silicon vertex and tracker R&D (1)

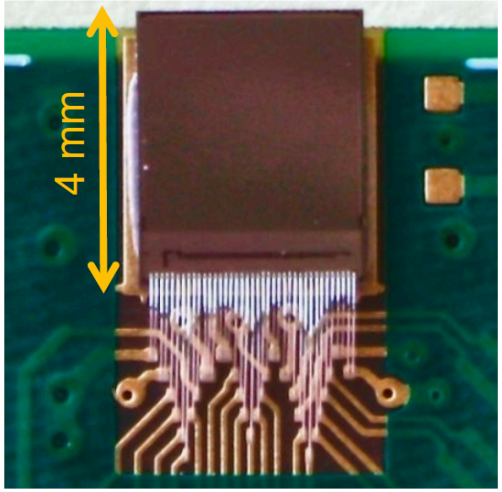
CLICpix (65 nm) + 50 µm sensor



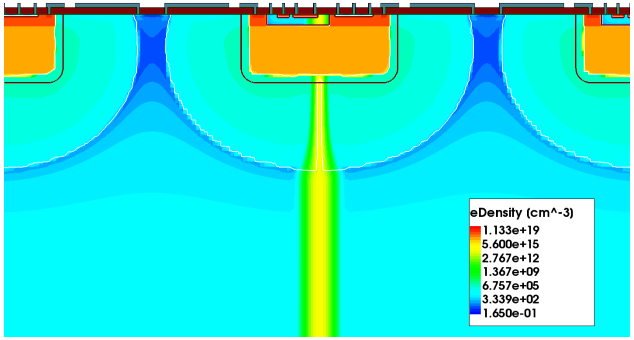
Bump-bonding, 25 µm pitch



CLICpix2 ASIC (65 nm)



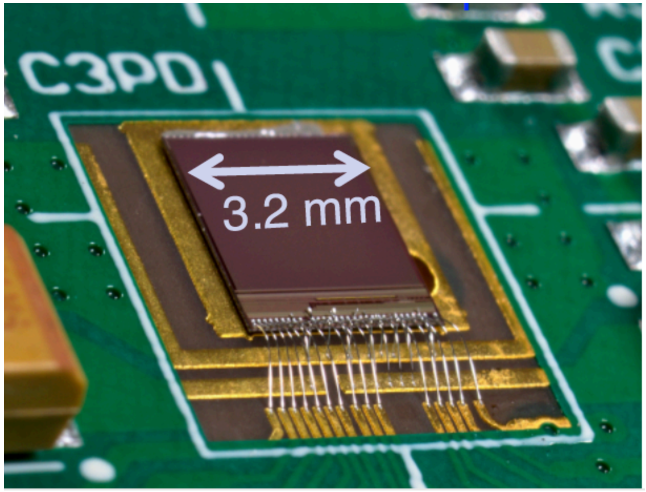
TCAD simulations, HV-CMOS sensor



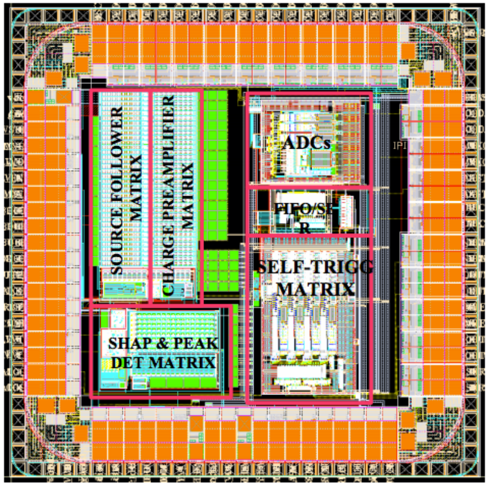
[Recent presentation on vertex R&D]

[Recent presentation on tracker R&D]

C3PD HV-CMOS sensor, thinned 50 µm

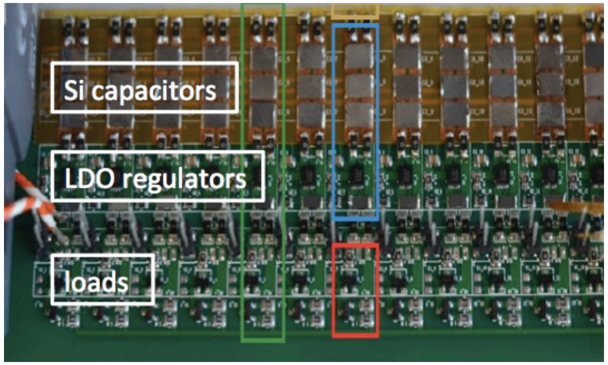


SOI sensor design

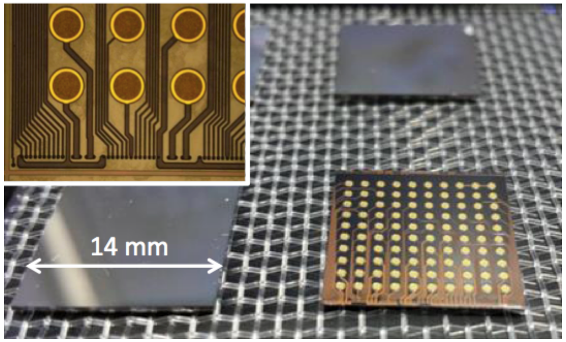


CLIC silicon vertex and tracker R&D (2)

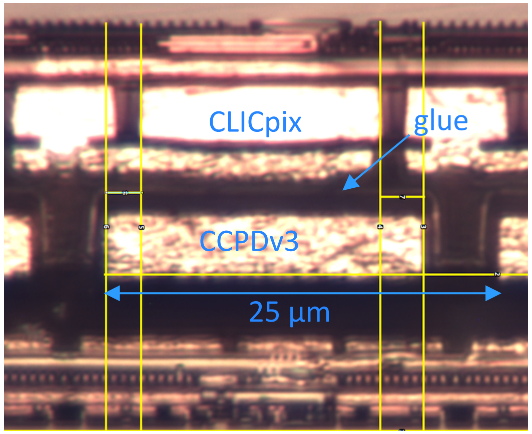
power delivery + pulsing

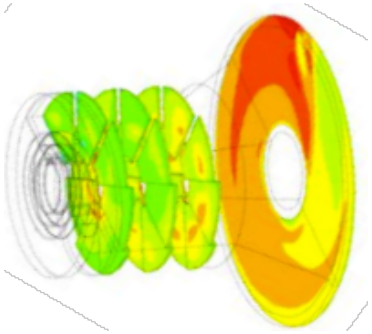


TSV interconnect technology

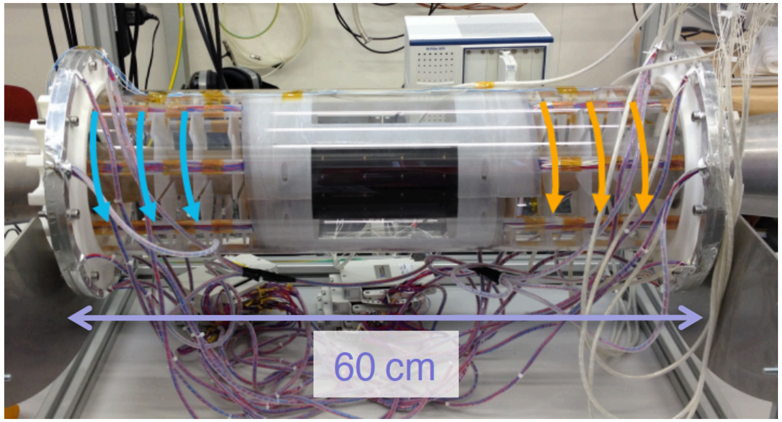


Flip-chip gluing (AC-coupling)

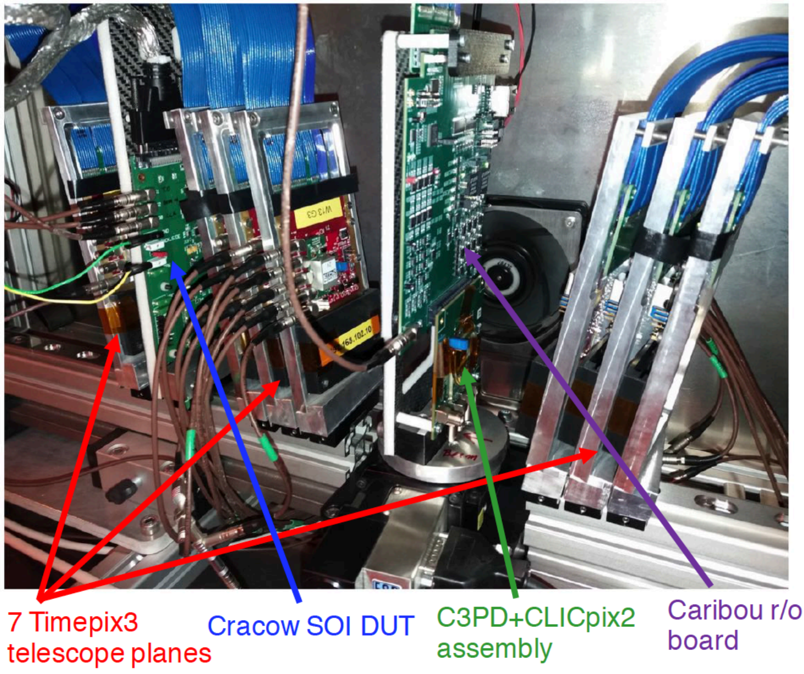




Air cooling simulation
and
1:1 scale test set up



SOI and C3PD+CLICpix2 in Timepix3 telescope at SPS



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

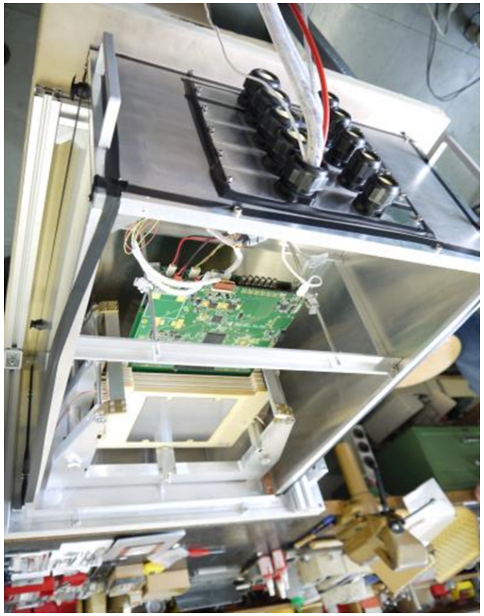
	layers	cell sizes	active material
ECAL	40	5×5 mm^2	silicon
HCAL	60	3×3 cm^2	scintillator+SiPM

1 ns time resolution, 16 bit readout

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

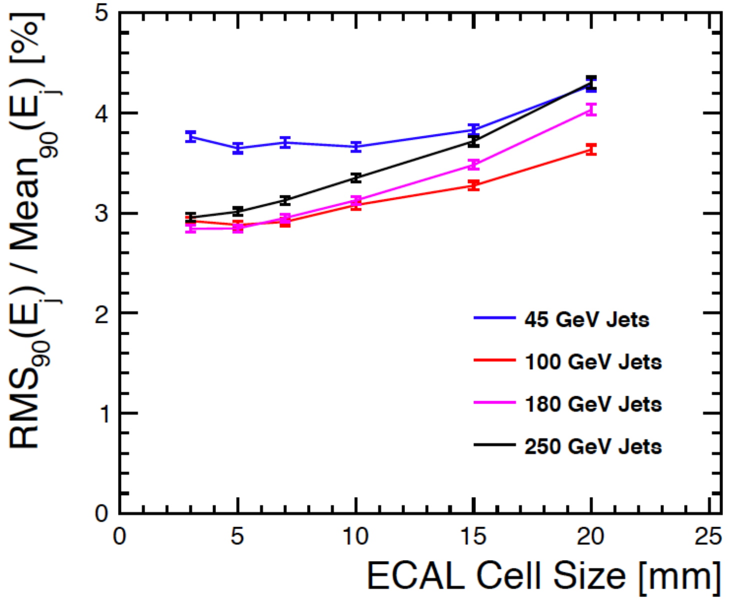
5 ns time resolution, 32 bit readout

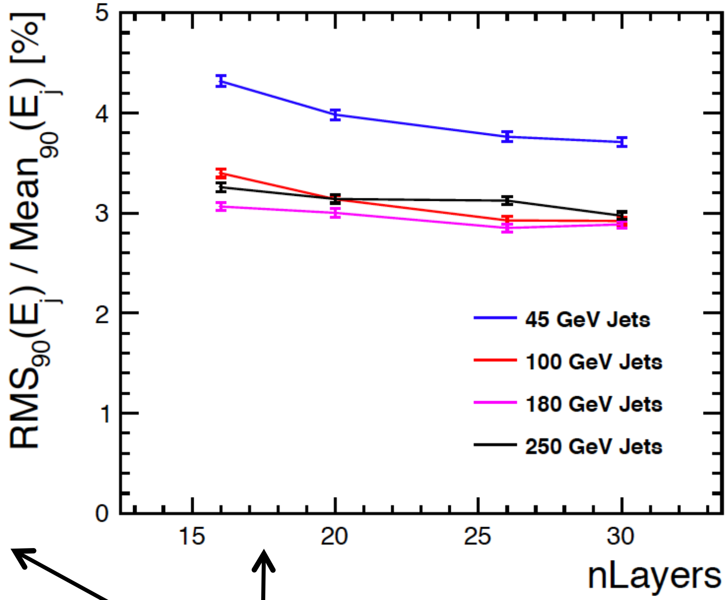
Developments and beam tests of CMS HGCal are an important test bed for CLIC



FCAL calorimeter module

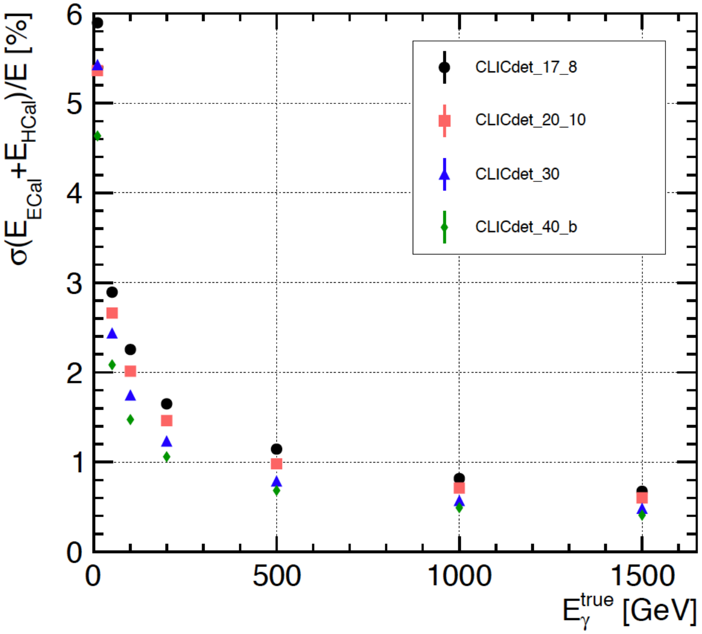
CLIC ECAL optimisation study





Jets

5×5 mm cell size motivated by jet energy resolution



Single photons

40 layers in depth motivated by single photon resolution

CLICdp-Note-2017-001

FCC-ee detector occupancy

Dominant backgrounds

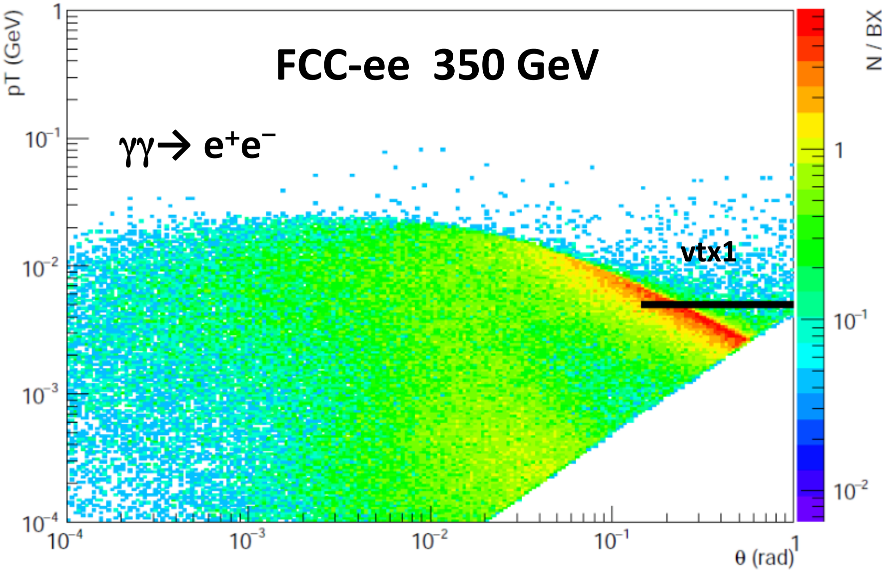
- **Synchrotron radiation**
- Interactions between γs from **beamstrahlung**
  - $\gamma\gamma \to e^+e^-$ (#particles / BX: see figure)
  - $\gamma\gamma \to$ hadrons (0.005 event / BX)

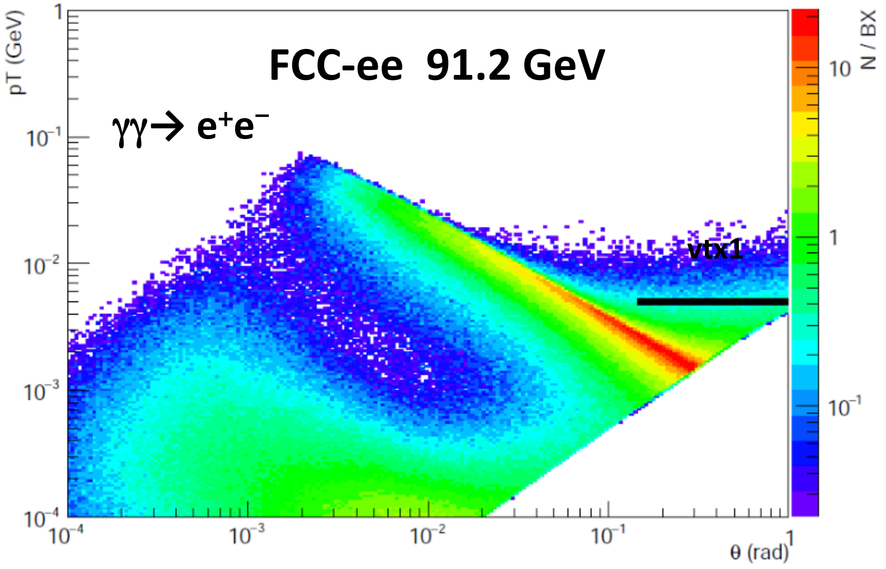
Effects on first detector layer

- Reasonable assumptions
  - Silicon pixel detector
  - **Radius : 17 mm**
  - **Pixel pitch : $25\times25\ \mu m^2$**
  - 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**

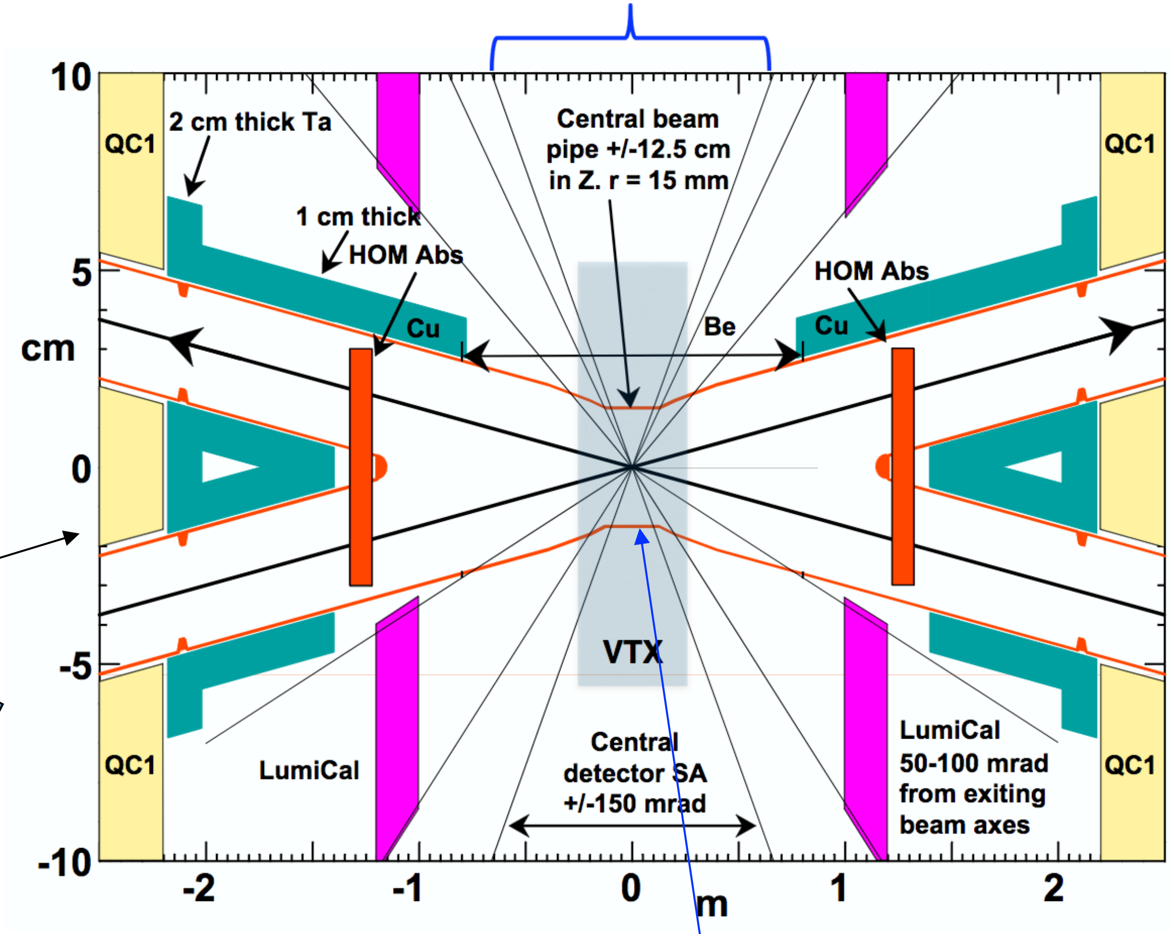




FCC-ee interaction region

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

Note different x/z scales !



Incoming beam

SR γs

Crossing angle 30 mrad

Beam pipe radius : 15 mm

- FF quads
- LumiCal
- Tantalum
- HOM Abs.
- Vertex det

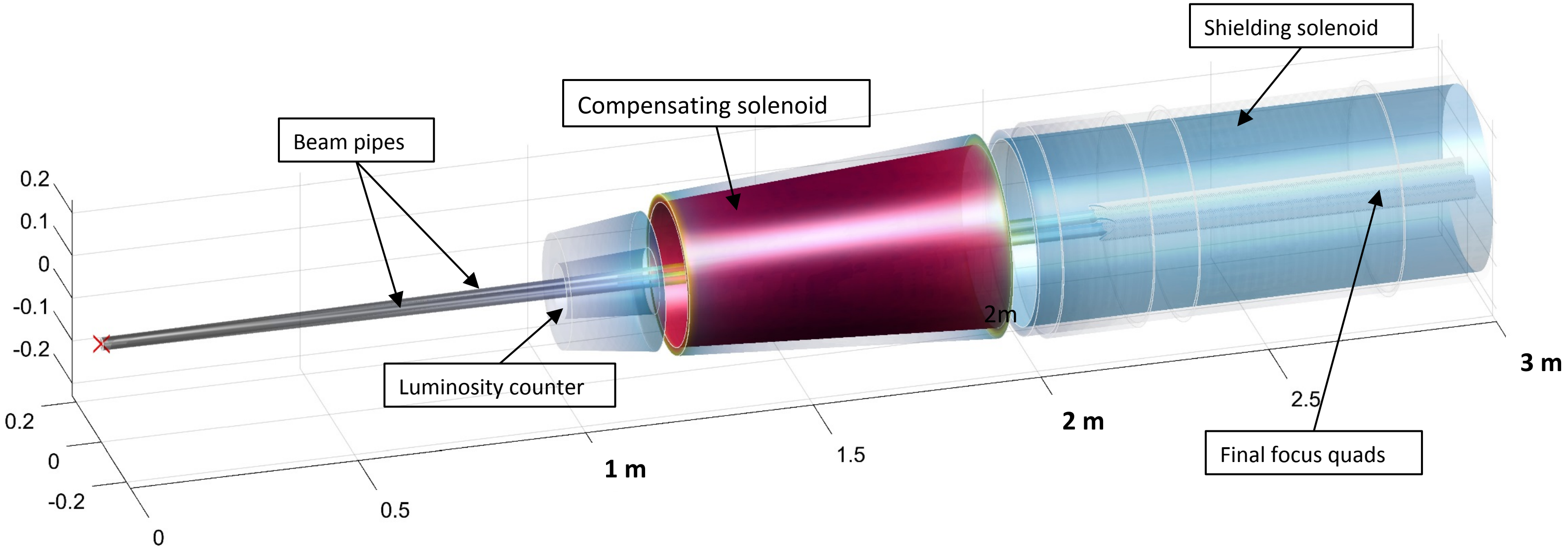
L* = 2.2 m

FCC-ee interaction region

30 mrad beam crossing angle
Emittance blow-up from detector magnetic field
Final focusing quadrupoles embedded in the detector

- **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- ➔ e+e-), front face at 1.2 m from IP



FCC-ee tracking accuracy

Precision mostly driven by physics at the Z-peak

Aim:

- Several 10^{-5} to 10^{-6} type of precision measurements
  - $\sin^2 q_W$, to 6×10^{-6}, $a_{QED}(m_Z)$ to 3×10^{-5}, m_Z to 100 keV, Γ_Z to 100 keV
  - (also m_W to 500 keV, …)

- Beam energy spread (0.13% at the Z pole) to be measured with relative precision of a few per mille (using $\mu^+\mu^-$ events).

$\Rightarrow$ Stringent constraints on the accuracy of the tracker

- **Angular resolution $\sigma(\theta)$, $\sigma(\varphi) \leq 0.1$ mrad for 45 GeV muons**
- **Momentum resolution $\sigma(1/p)$ of ~2-3 10^{-5} GeV^{-1}**
- **The tracker needs to be as light as possible**

(continuous operation impacts on the cooling and thus on material budget)

Options:

- **Silicon technology**
- **Wire Chamber technology**
- ~~TPC not compatible with 20 ns bunch crossing frequency~~

more on FCC-ee tracking accuracy

$\sqrt{s}$ = 365 GeV:

Top quark couplings from lepton angular and momentum distributions

=> Momentum resolution $\sigma(1/p)$ must be better than 10^{-4} GeV^{-1}

$\sqrt{s}$ = 240 GeV:

A factor ~1.5 can be gained on the **HZ cross-section and the HZZ coupling** precisions if the resolution is improved to 3×10^{-5} GeV^{-1}

$\sqrt{s}$ = 91 GeV:

Further improvement, to about 1-2 $\times10^{-5}$ GeV^{-1} could bring even better (faster) accuracy to measurement of **beam energy spread at the Z pole**.
(would require larger B-field, larger tracker radius, smaller Si pitch).

FCC-ee calorimetry requirements

Particle-flow capabilities and energy resolution:

- **Transverse segmentation ~few cm** : separate clusters from different particles in jets
- **Longitudinal segmentation** : identify or even track electron/photon and hadron showers
- σ(E) stochastic term **~10%√E for e, γ and ~30%√E for pions**
- Inside solenoid coil (or alternatively, extremely thin coil <1 X_0)

Balloon experiment magnet

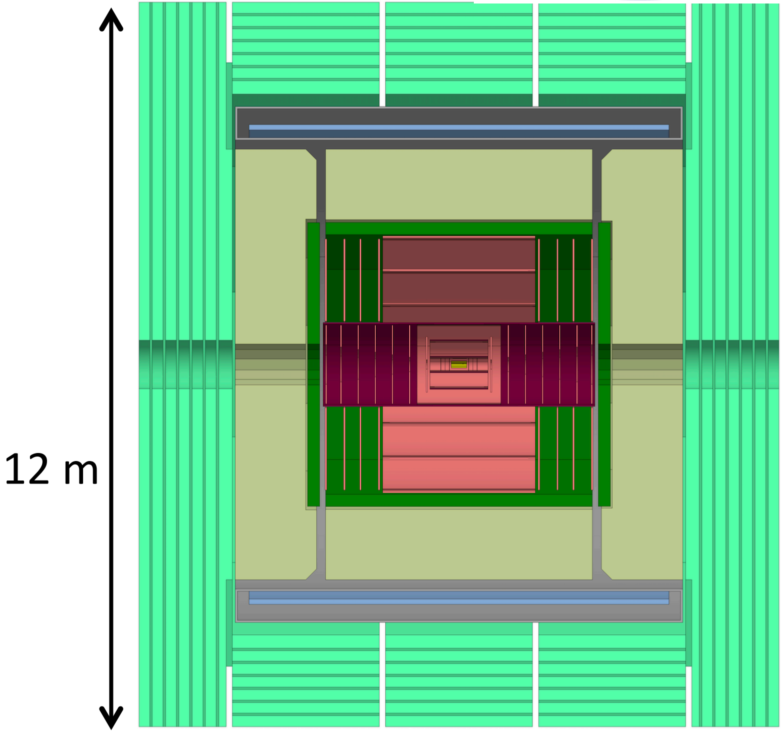
Detector options currently under study:

- **Fine-grained calorimeter à la CALICE**
  - Si-W ECAL
  - HCAL (currently same Scintillator+SiPM/steel option as CLIC)
- **Dual readout calorimetry**
  - Would require R&D for longitudinal separation (wrt present RD52 Dual Readout R&D)

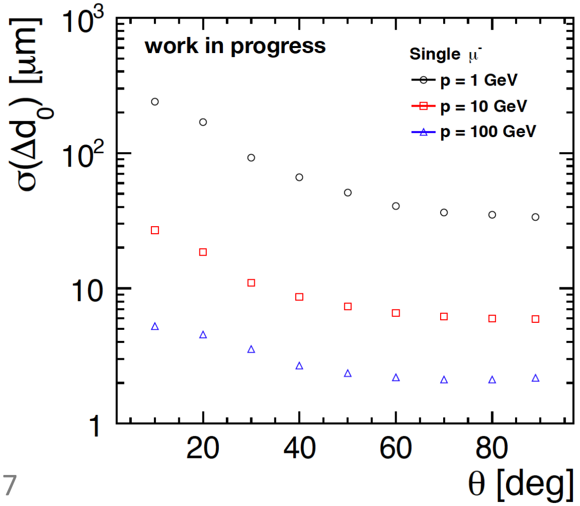
FCC-ee detector design #1 : all Silicon

Adaptation of the CLIC detector for FCC-ee

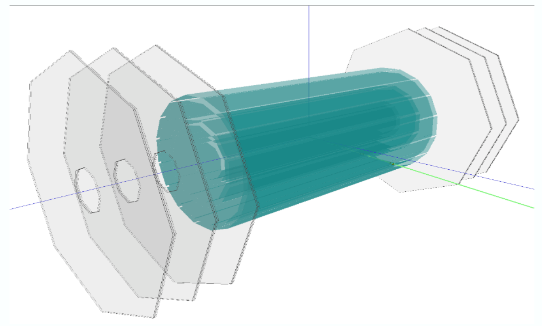
- Instrumentation up to ±150 mrad
- Smaller beam pipe radius (15 mm)
  - => Inner pixel layer closer to IP (radius 17 mm)
- Solenoid field 2 T
  - => Larger tracker radius (1.5 → 2.2 m)
- Lower energies
  - Thinner HCAL (4.2 m → 3.7 m)
- Continuous operation => increased cooling
  - => Thicker pixel layers (~+50%)
  - => Flat pixel discs (no spirals)
  - => Reduced calorimeter granularity



☆ d0 resolution



Performance validation ongoing



FCC-ee detector design #2 : IDEA

🟥 **Vertex Si detector**
With light MAPS technology
7 layers, up to 35 cm radius

🟩 **Ultra light wire drift chamber**
4m long, 2 m radius, 0.4% X_0
112 layers with Particle ID

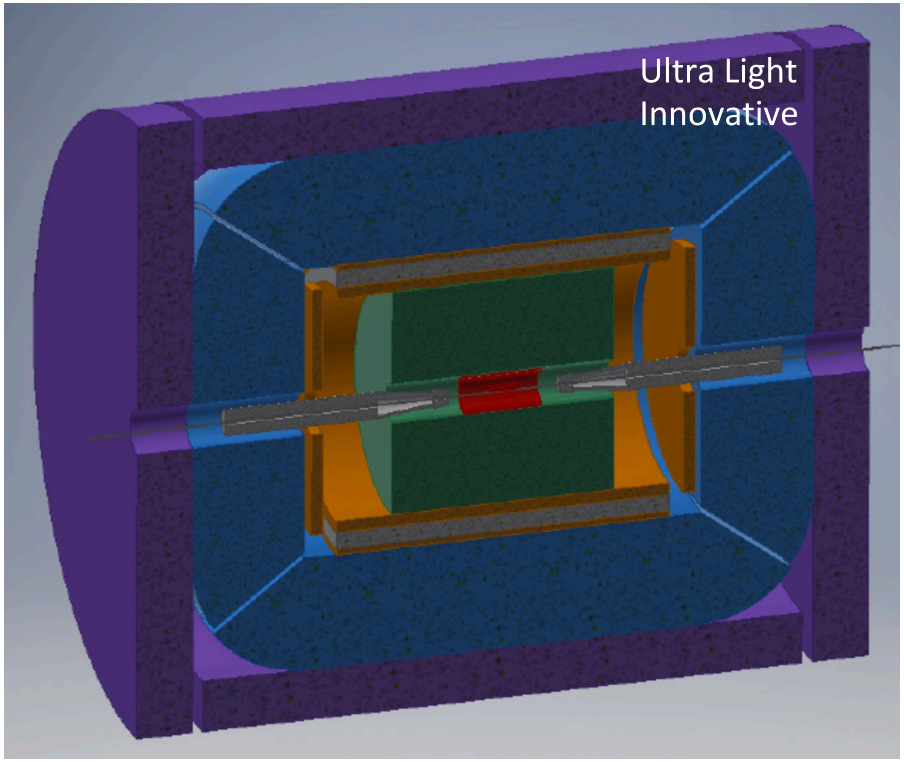
🟧 **One Si layer for acceptance determination**
Precise tracking with large lever arm
barrel and end-caps

⬜ **Ultra-thin 20-30 cm solenoid (2T)**
Acts as preshower (1 X_0)
or 1 X_0 Pb if magnet outside calo

🟧 **Two μ-RWell layers**
Active preshower measurement

🟦 **Dual readout fibre calorimeter**
2m thick, longitudinal segmentation

🟪 **Instrumented return yoke**



√s = 91 GeV:
Drift chamber may drive
requirements linked to large data flow.

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

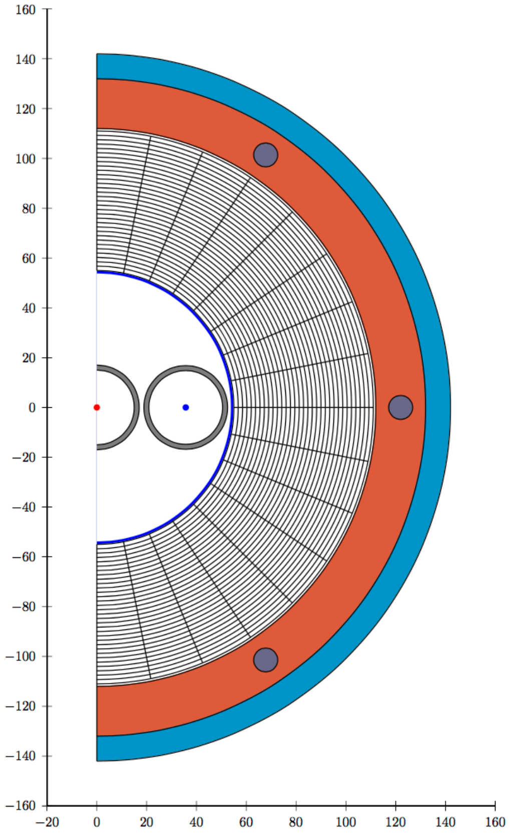
- Placed closer to the IP (z < 1.2 m) and made smaller
- Centred around the outgoing beam

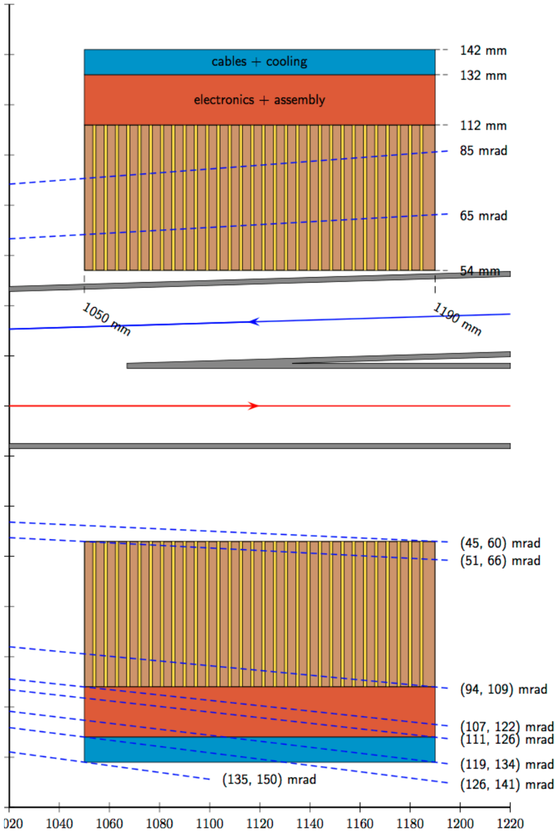
Depth 10 cm (1.05 to 1.15 m)
Radius from 5.4 to 14.2 cm
30 layers ($1X_0$) of 3.5 mm W + 1 mm Si
32 × 32 Si pads in (R,ϕ): 3×10^4 channels

Positioned with 1 μm accuracy

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

P.Janot, Acad.Training, Oct 2017





FCC-ee flavour tagging and particle ID

√s = 91 GeV:

~10^{12} Z →bb events at the FCC-ee

⇒ large potential for heavy flavour physics

⇒ e.g. b to sττ transition, to study the possible low-significance LHC_b effects with large statistics, or $Bs\rightarrow\tau^+\tau^-$ measurement with 100,000 events.

⇒ **Particle ID** (π, K, p, e) becomes an important feature for the tracker (wire chamber OK, not sure about Si Tracker).

√s = 240 GeV, √s = 350 (365) GeV:

Aim for per-mille precision of Hbb, Hcc, and Hgg couplings

=> excellent **flavour tagging** required

- currently beam pipe radius of 1.5 cm
- currently pixel pitch 25×25 μm^2 assumed

⇒ **might need to improve further**

Do not forget the software tools

Design of future experiments requires:

Flexible software infrastructure for Geant4-based simulation and full reconstruction

Components of FCC (ee, hh, eh) and iLCSoft software frameworks

	LC software	**FCC software**
Framework	Marlin framework	GaudiHive
Event data format	LCIO	PODIO
Geometry description	DD4hep	DD4hep
Simulation	Geant4	Geant4
Track reconstruction	Custom silicon tracking	ACTS
Particle flow reconstruction	PandoraPFA	??
Flavour tagging	LCFIplus	-
Grid production	iLCDirac	iLCDirac

Future: bring the CLIC and FCC software tools closer together

Requires high-level reconstruction

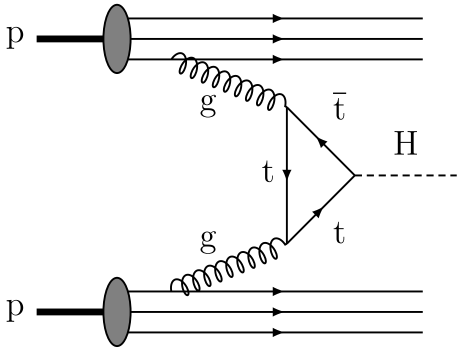
- Track reconstruction
- Particle flow reconstruction with fine-grained calorimetry
- Flavour tagging

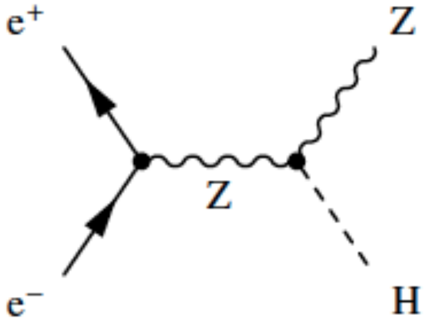
Challenges generally larger for FCC-hh than for CLIC/FCC-ee

THANK YOU

pp collisions / e^+e^- collisions

to tackle the open questions in particle physics

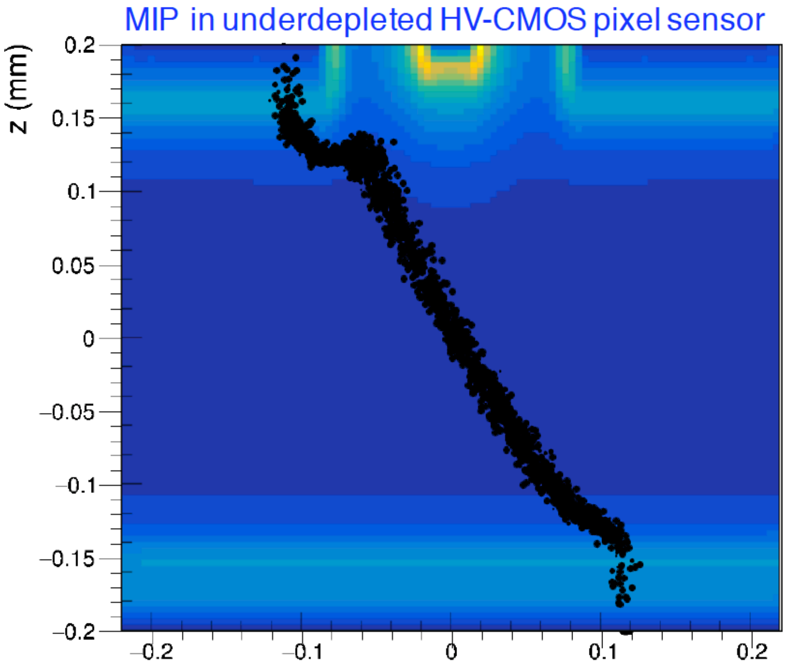


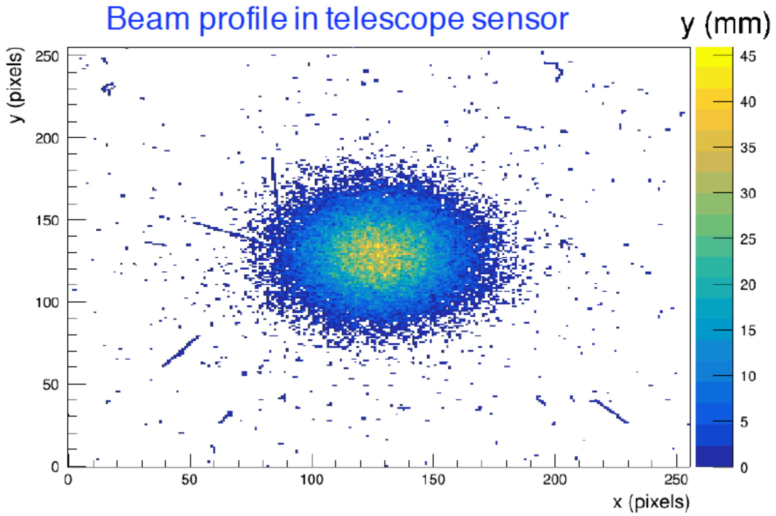


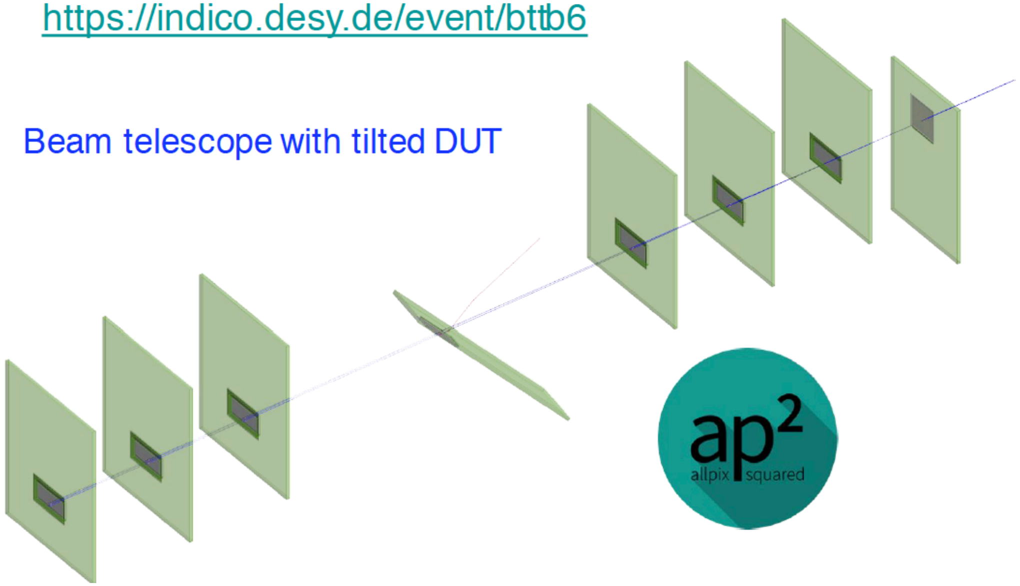
p-p collisions	e^+e^- collisions
Proton is compound object → Initial state unknown → Limits achievable precision	**e^+/e^- are point-like** → Initial state well defined (√s / opt: polarisation) → High-precision measurements
High rates of QCD backgrounds → Complex triggering schemes → High levels of radiation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

Allpix^2 silicon simulation framework

- Modular simulation framework for silicon tracking detectors
- Simulates full chain from incident radiation to digitized hits
- Modern and well-documented C++ code
- Easy-to-use description of detector models, supports full beam telescope setups
- Full Geant4 simulation of charge deposition
- Fast charge propagation using drift-diffusion model, can import electric fields in the TCAD DF-ISE format
- Simulation of HV-CMOS sensors with capacitive coupling
- Easy to add new modules for new digitizers, other output formats, etc.
- For Introduction, User manual and code reference visit: https://cern.ch/allpix-squared
- Allpix^2 tutorial at BTTB Zurich (January 16-19, 2018): https://indico.desy.de/event/bttb6


MIP in underdepleted HV-CMOS pixel sensor

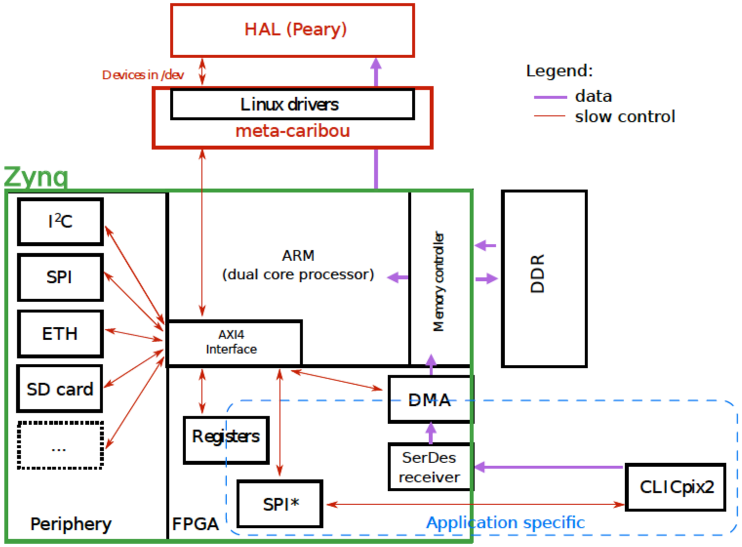

Beam profile in telescope sensor


Beam telescope with tilted DUT

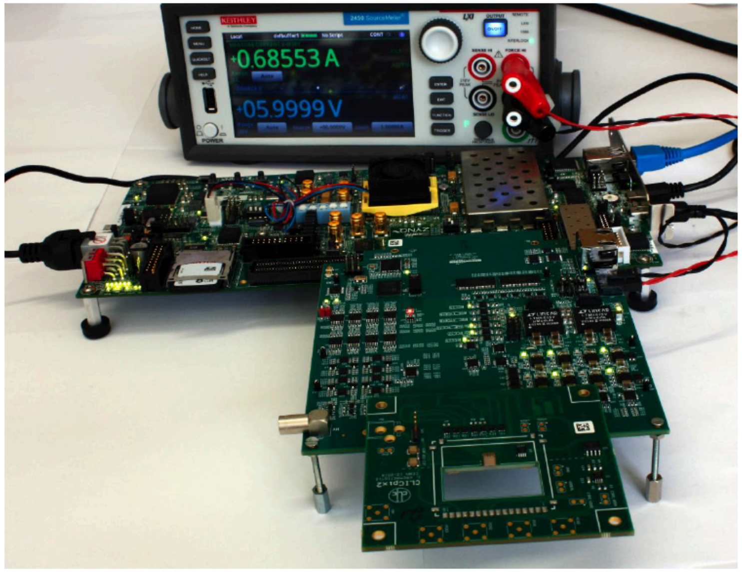
Caribou multi-chip modular r/o system

- Caribou universal r/o system (BNL, UniGE, CERN)
- Target: laboratory and high-rate test-beam measurements
- Generic DAQ Software Peary
- Modular concept:
  - Xilinx FPGA evaluation board ZC706 with ARM Cortex-A9 processor → FPGA code reduced to minimum → System-on-Chip (SoC) runs full Linux stack and actual Peary DAQ software, easily customizable
  - Generic periphery board (CaR) → Stable voltages, various communication standards, ADCs for monitoring
  - Project specific chip boards: currently supporting CLICpix2, C3PD, FEI4, H35Demo, ATLASPIX → cheap, minimum functionality: routing, chip-specific buffers
- Open hardware / firmware / software: https://gitlab.cern.ch/Caribou/

CaRIBOu DAQ System schematics



CaRIBOu with CLICpix2 r/o ASIC



CLIC readout electronics requirements

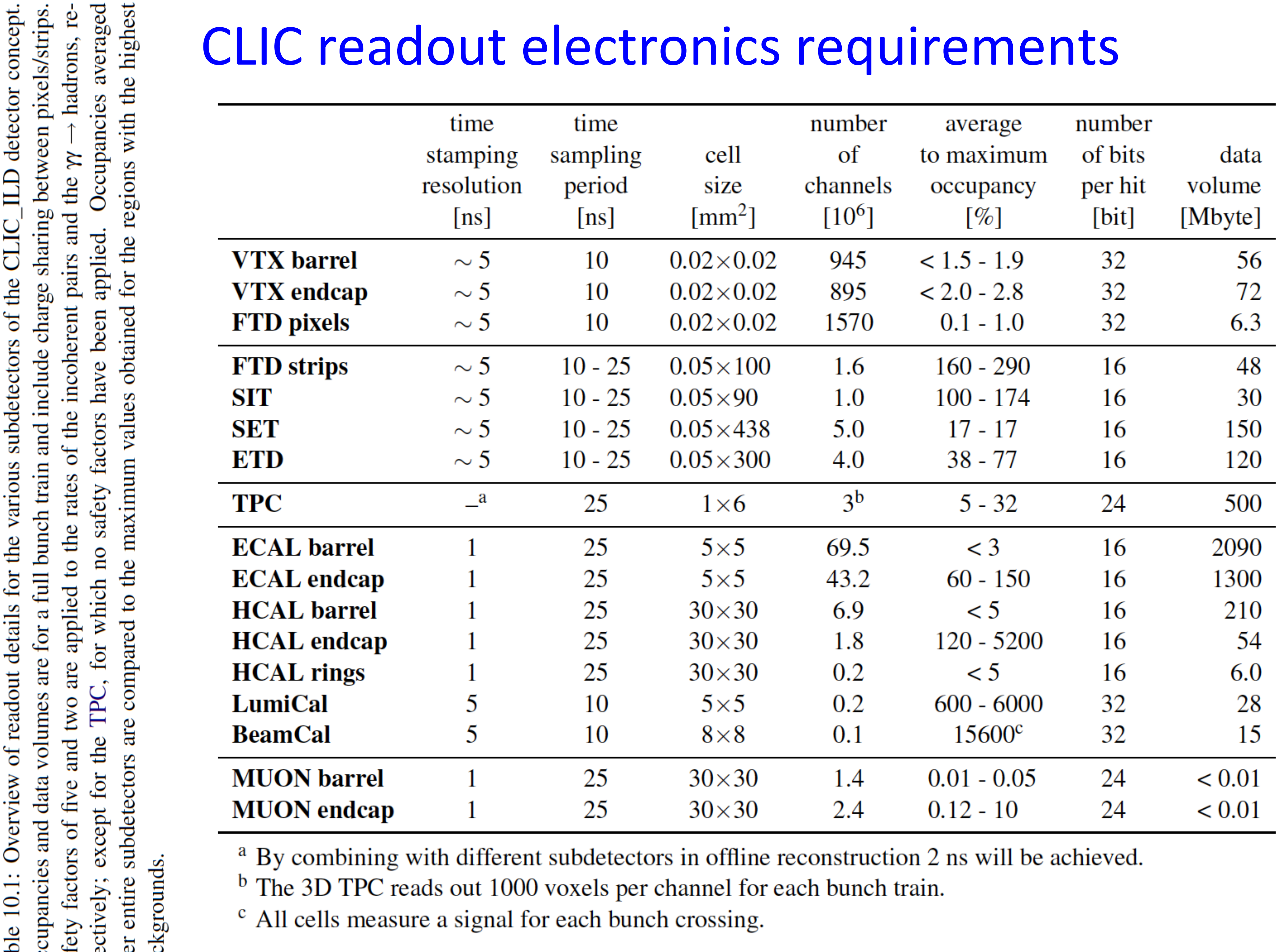


Table 10.1: Overview of readout details for the various subdetectors of the CLIC_ILD detector concept. Occupancies and data volumes are for a full bunch train and include charge sharing between pixels/strips. Safety factors of five and two are applied to the rates of the incoherent pairs and the $\gamma\gamma \rightarrow$ hadrons, respectively; except for the TPC, for which no safety factors have been applied. Occupancies averaged over entire subdetectors are compared to the maximum values obtained for the regions with the highest backgrounds.

	time stamping resolution [ns]	time sampling period [ns]	cell size [mm^2]	number of channels [10^6]	average to maximum occupancy [%]	number of bits per hit [bit]	data volume [Mbyte]
VTX barrel	~ 5	10	0.02×0.02	945	< 1.5 - 1.9	32	56
VTX endcap	~ 5	10	0.02×0.02	895	< 2.0 - 2.8	32	72
FTD pixels	~ 5	10	0.02×0.02	1570	0.1 - 1.0	32	6.3
FTD strips	~ 5	10 - 25	0.05×100	1.6	160 - 290	16	48
SIT	~ 5	10 - 25	0.05×90	1.0	100 - 174	16	30
SET	~ 5	10 - 25	0.05×438	5.0	17 - 17	16	150
ETD	~ 5	10 - 25	0.05×300	4.0	38 - 77	16	120
TPC	–[a]	25	1×6	3[b]	5 - 32	24	500
ECAL barrel	1	25	5×5	69.5	< 3	16	2090
ECAL endcap	1	25	5×5	43.2	60 - 150	16	1300
HCAL barrel	1	25	30×30	6.9	< 5	16	210
HCAL endcap	1	25	30×30	1.8	120 - 5200	16	54
HCAL rings	1	25	30×30	0.2	< 5	16	6.0
LumiCal	5	10	5×5	0.2	600 - 6000	32	28
BeamCal	5	10	8×8	0.1	15600[c]	32	15
MUON barrel	1	25	30×30	1.4	0.01 - 0.05	24	< 0.01
MUON endcap	1	25	30×30	2.4	0.12 - 10	24	< 0.01

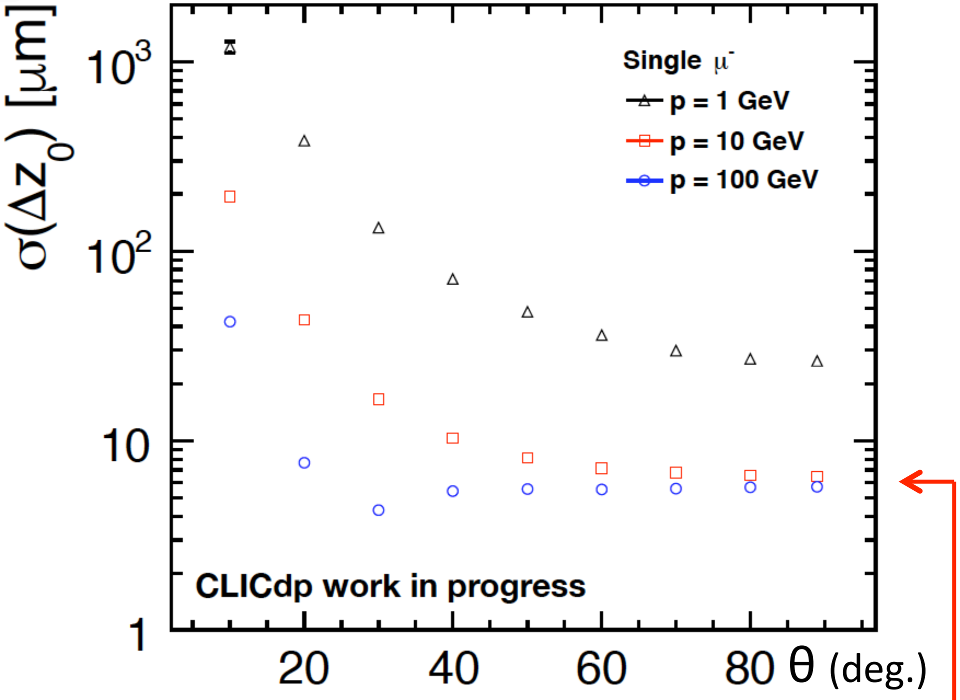
[a] By combining with different subdetectors in offline reconstruction 2 ns will be achieved.

[b] The 3D TPC reads out 1000 voxels per channel for each bunch train.

[c] All cells measure a signal for each bunch crossing.

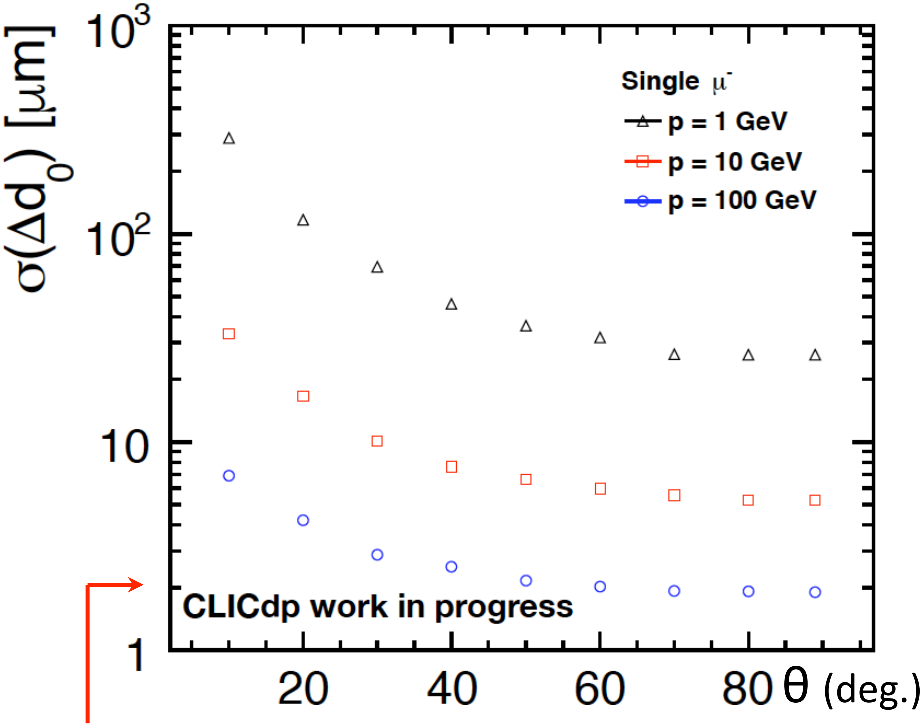
CLIC impact parameter resolution

☆ z0 resolution



~6 μm

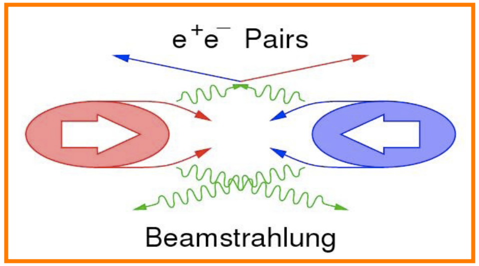
☆ d0 resolution



2 μm

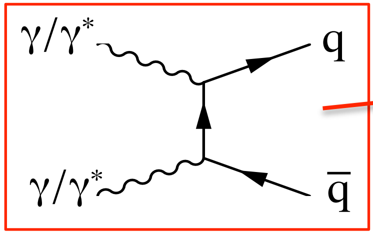
E.Leogrande @ LCWS17

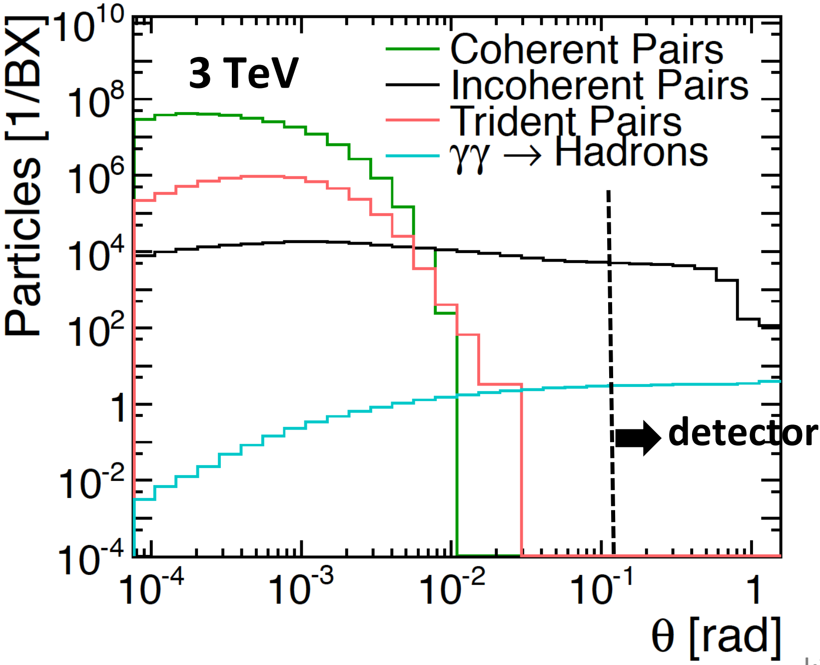
CLIC accelerator environment

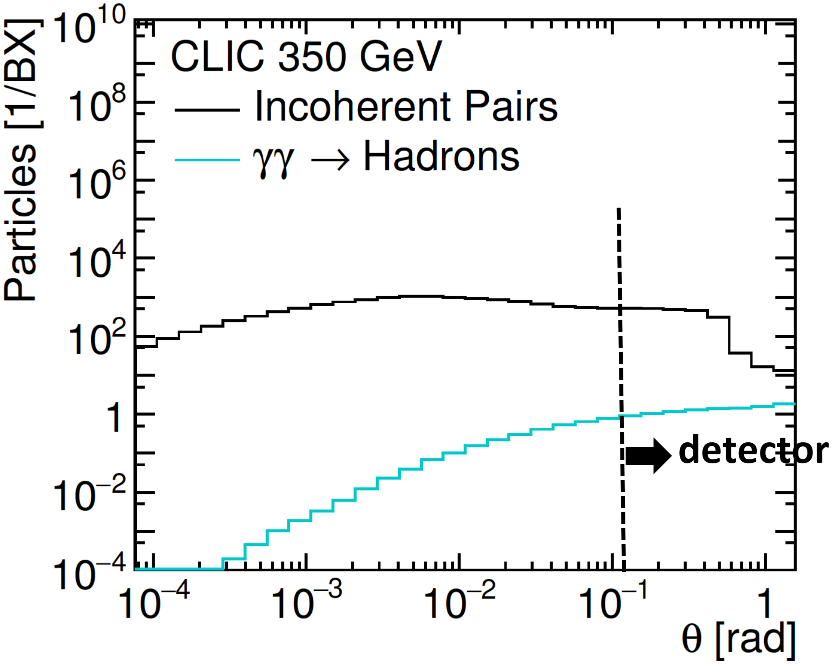


Beam-beam background at IP:

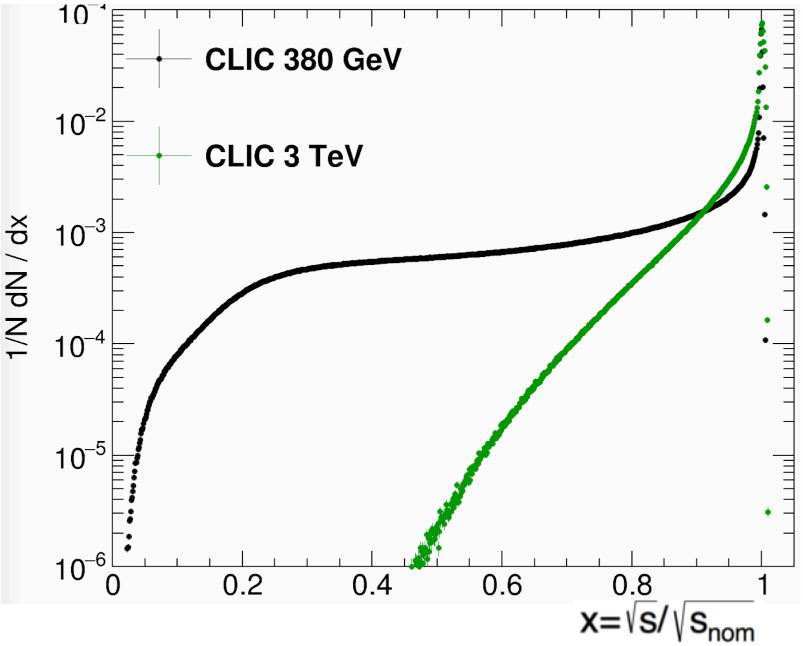
- Small beams => very high E-fields
  - **Beamstrahlung**
  - **Pair-background** → Simplified picture: **Design issue** (small cell sizes)
    - High occupancies
  - **γγ to hadrons** → Impacts on the physics **Needs suppression in data**
    - Energy deposits







luminosity spectrum



Beamstrahlung ➔ important energy losses right at the interaction point

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

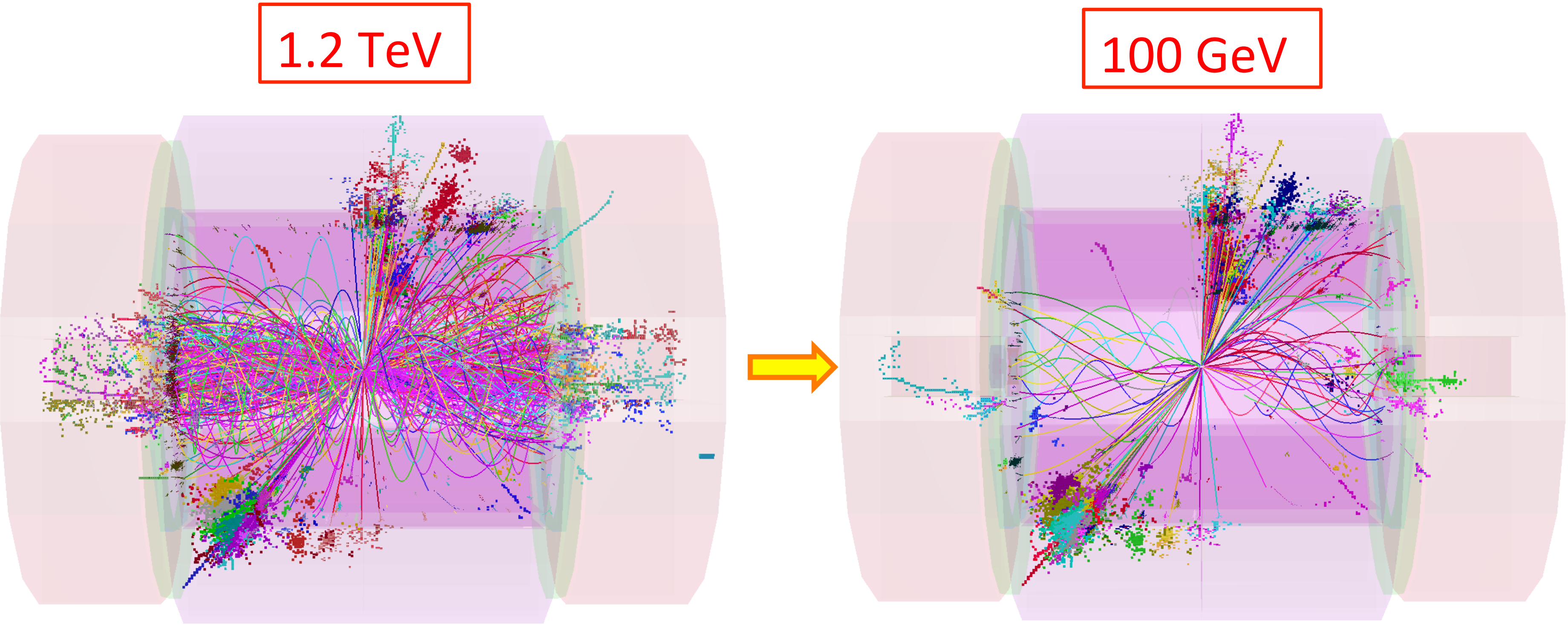
Luminosity spectrum can be measured in situ using large-angle Bhabha scattering events, to 5% accuracy at 3 TeV

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%

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)



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

1.2 TeV background in reconstruction window (>=10 ns) around main physics event

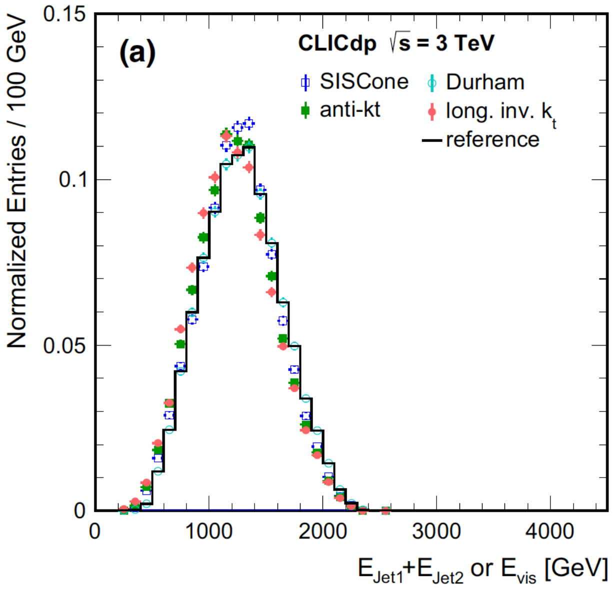
100 GeV background after tight cuts

beam-induced background rejection (2)

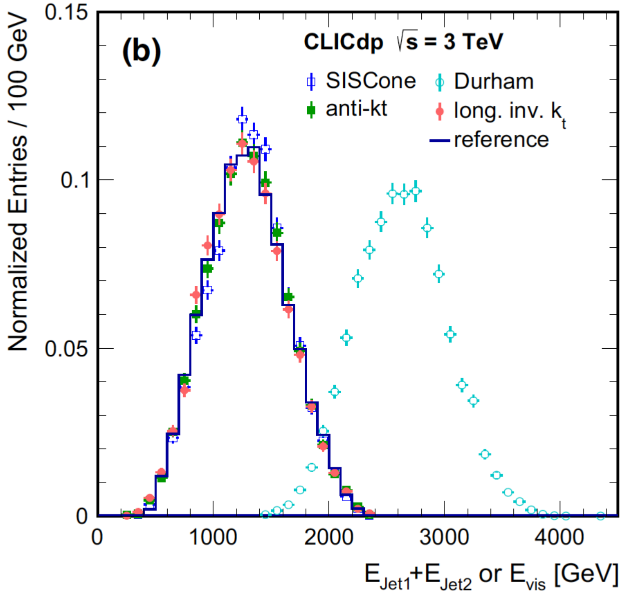
Beam-induced background from γγ ➔ hadrons is further reduced by applying **adapted jet reconstruction algorithms**

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

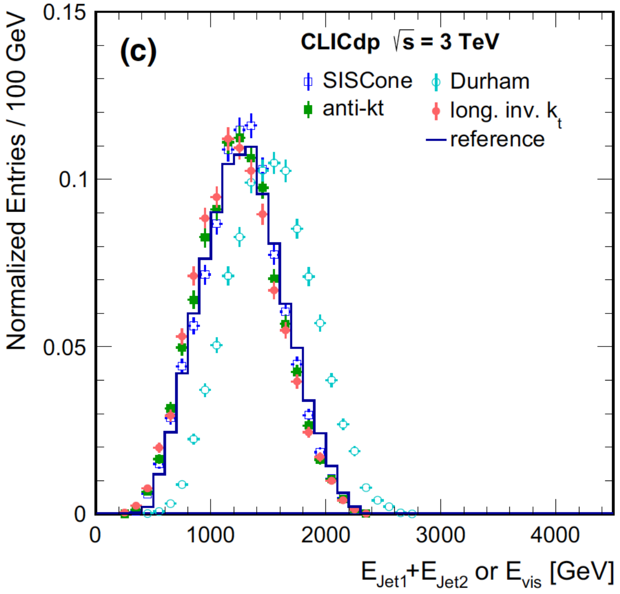
$$e^+e^- \rightarrow \tilde{q}_R\tilde{q}_R \rightarrow q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$$



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

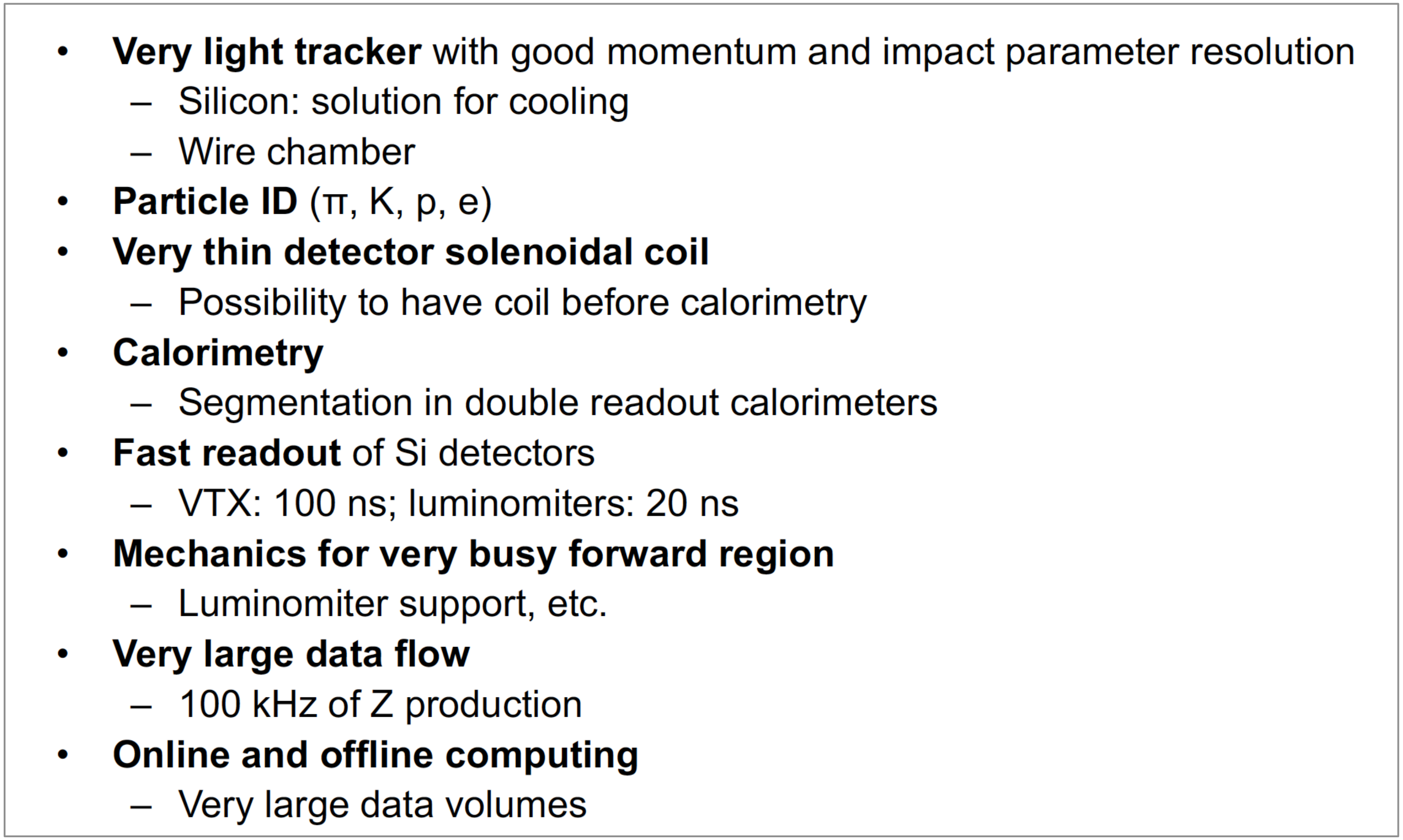
From Eur.Phys.J. C75 (2015) no.8, 379, see also arXiv:1607.05039

The FCC-ee central detector

- With 100,000 Z / second / detector, expect more than 2×10^{12} Z / year
  - Statistical accuracies on cross sections, asymmetries, etc. of 10^{-5} or better
    - Experimental uncertainties must be controlled at this level too
      - Demands state-of-the-art performance for all detector subsystems
- Vertex detector
  - Excellent b- and c-tagging capabilities : few μm precision for charged particle origin
    - Small pitch, thin layers, limited cooling, first layer as close as possible from IP
- Tracker
  - State-of-the-art momentum and angular resolution for charged particles.
    - Typically $\sigma(1/p) \sim 2 - 3 \times 10^{-5}\,\mathrm{GeV}^{-1}$ and $\sigma(\theta, \phi) \sim 0.1$ mrad for 45 GeV muons
    - Almost transparent to particles (as little material as possible)
  - Particle ID is a valuable additional ability
- Calorimeters
  - Good particle-flow capabilities and energy resolution
    - Transverse segmentation ~ cm : separate clusters from different particles in jets
    - Longitudinal segmentation : identify or even track electron/photon and hadron showers
    - $\sigma(E) \sim 10\%\sqrt{E}$ for e, γ and $\sim 30\%\sqrt{E}$ for pions
    - Inside solenoid coil, or alternatively, extremely thin coil
- Instrumented return yoke OR large tracking volume outside the calorimeters
  - Muon identification and long-lived particle reconstruction

… from FCC-ee meeting 15/11

Francesco Grancagnolo (INFN) , Mogens Dam (University of Copenhagen (DK):



- **Very light tracker** with good momentum and impact parameter resolution
  - Silicon: solution for cooling
  - Wire chamber
- **Particle ID** (π, K, p, e)
- **Very thin detector solenoidal coil**
  - Possibility to have coil before calorimetry
- **Calorimetry**
  - Segmentation in double readout calorimeters
- **Fast readout** of Si detectors
  - VTX: 100 ns; luminomiters: 20 ns
- **Mechanics for very busy forward region**
  - Luminomiter support, etc.
- **Very large data flow**
  - 100 kHz of Z production
- **Online and offline computing**
  - Very large data volumes