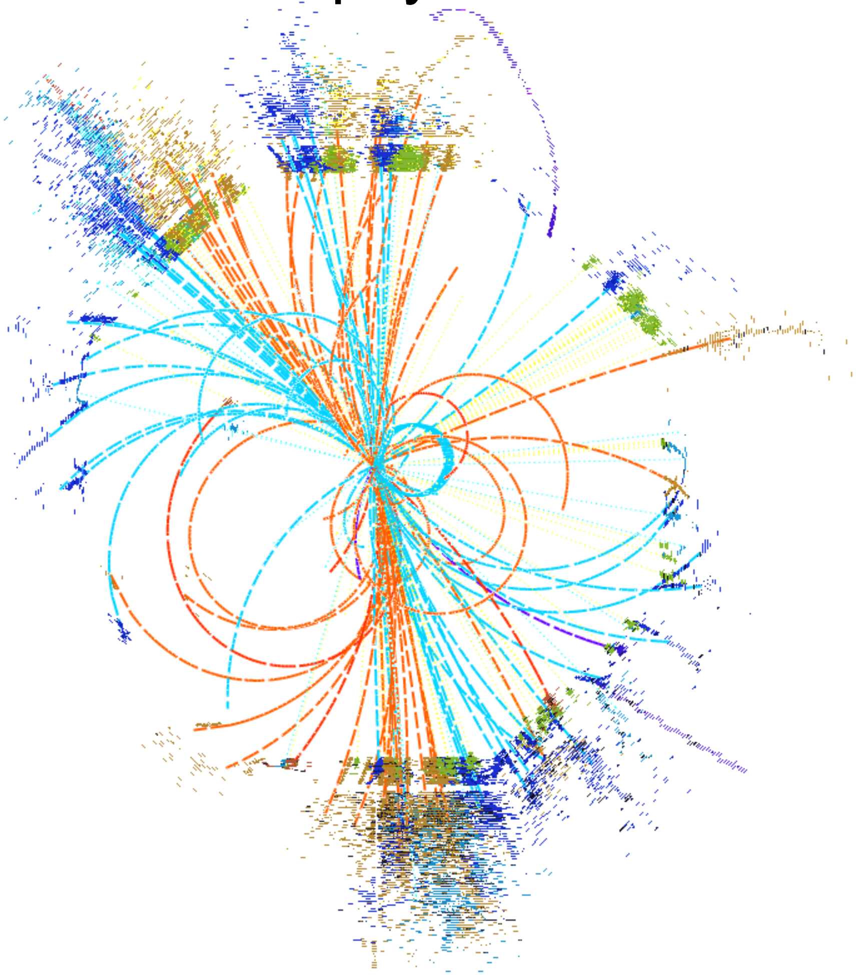
Detectors at CLIC

Philipp Roloff (CERN)
on behalf of the CLIC physics and detector study



Joint Instrumentation Seminar, DESY Hamburg, 20/01/2012

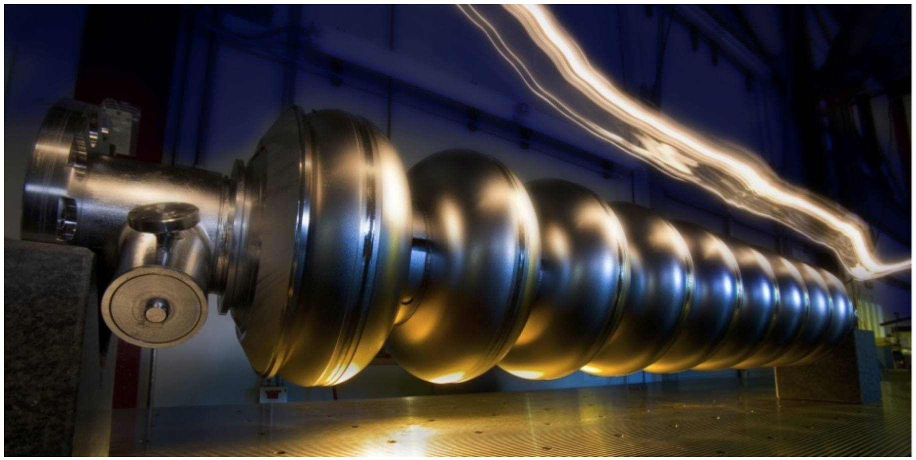
Outline

- The CLIC accelerator
- Physics at CLIC
- Detector requirements
- The CLIC_ILD and CLIC_SiD detectors
  - Vertex detectors
  - Tracking
  - Calorimetry
- Background suppression and event reconstruction

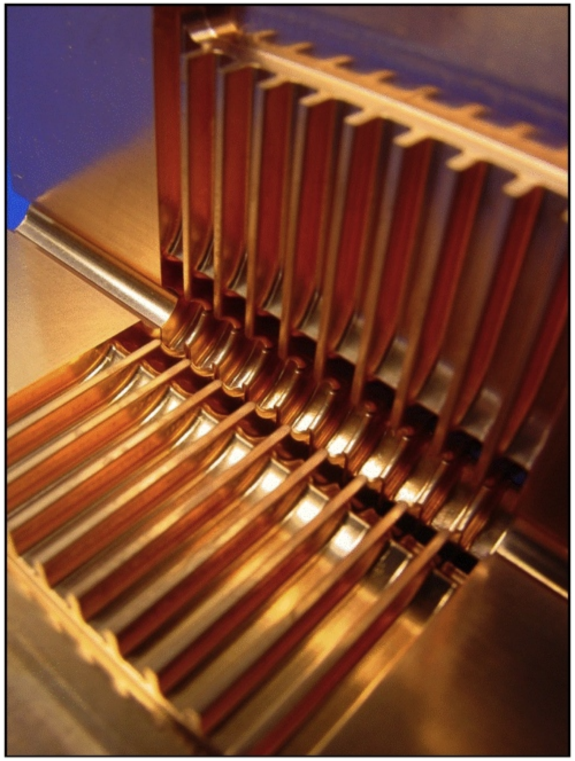
The CLIC accelerator

CLIC and ILC

e^+e^- collisions at high energies → linear accelerators



International Linear Collider (ILC):
- Based on superconducting RF cavities (like XFEL)
- Gradient: 32 MV/m
- Energy: 500 GeV, upgradable to 1 TeV
- Detector studies focussed mostly on up to 500 GeV, work for 1 TeV ongoing



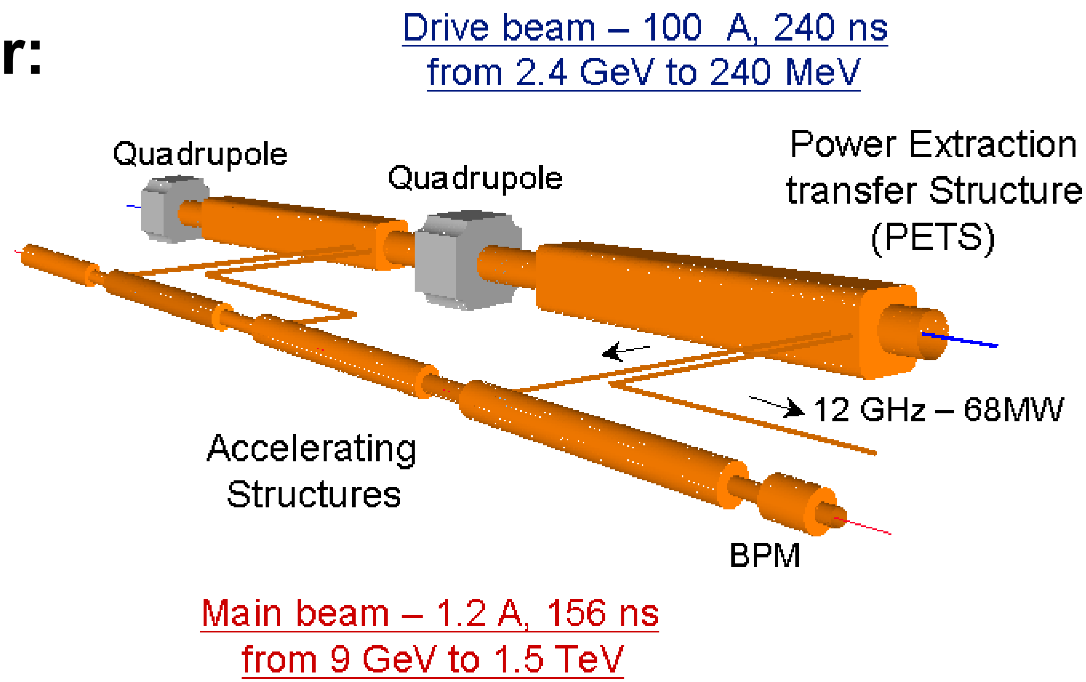
Compact Linear Collider (CLIC):
- Based on 2-beam acceleration scheme
- Operated at room temperature
- Gradient: 100 MV/m
- Energy: 3 TeV, staged construction in steps starting from few hundred GeV possible
- Detector study focusses on 3 TeV, lower energies will be studies soon

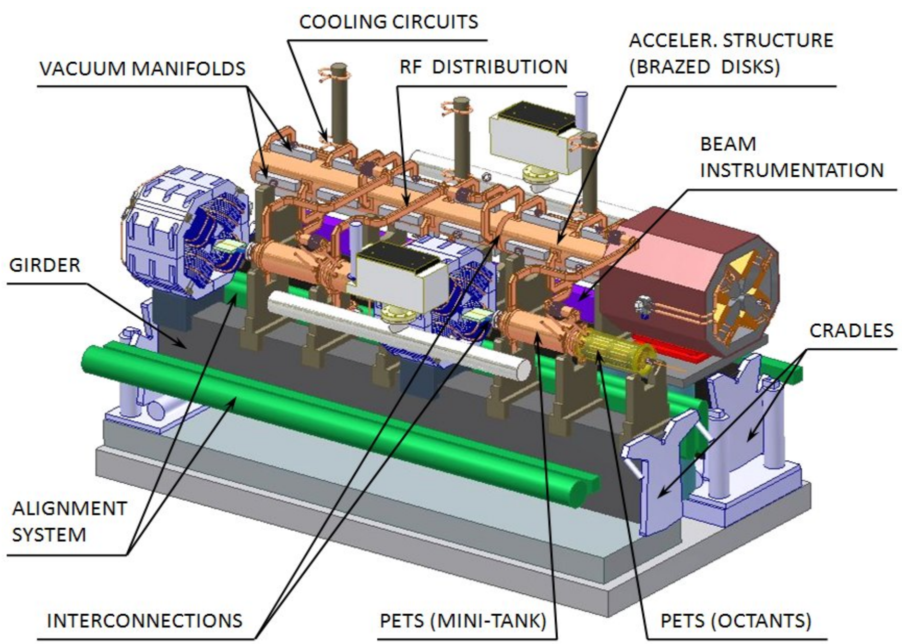
Luminosities: few 10^{34} $cm^{-2}s^{-1}$

2-beam acceleration scheme

Drive beam supplies RF power:
- 12 GHz bunch structure
- Low energy:

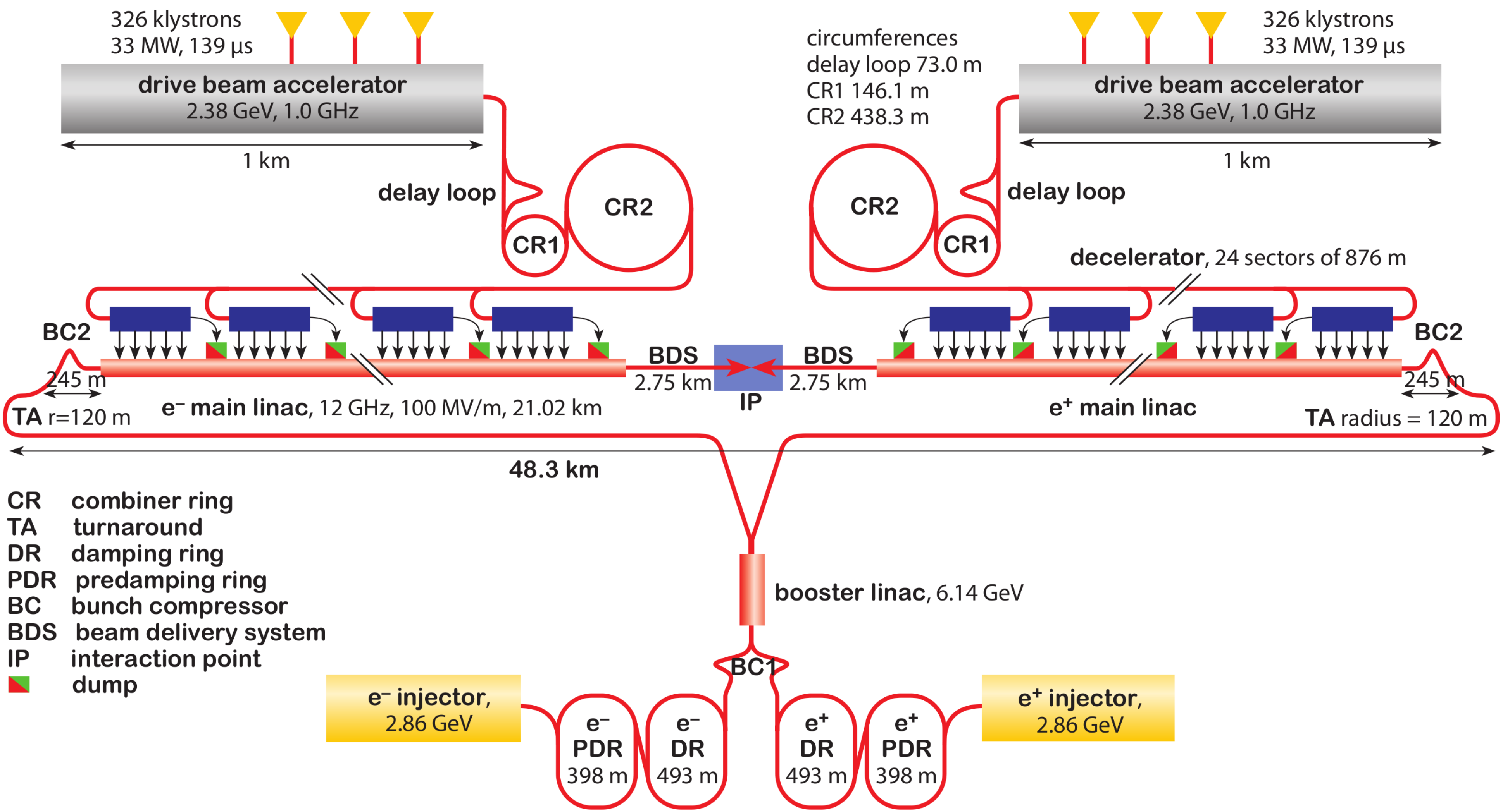
2.4 GeV – 240 MeV
- High current: 100 A





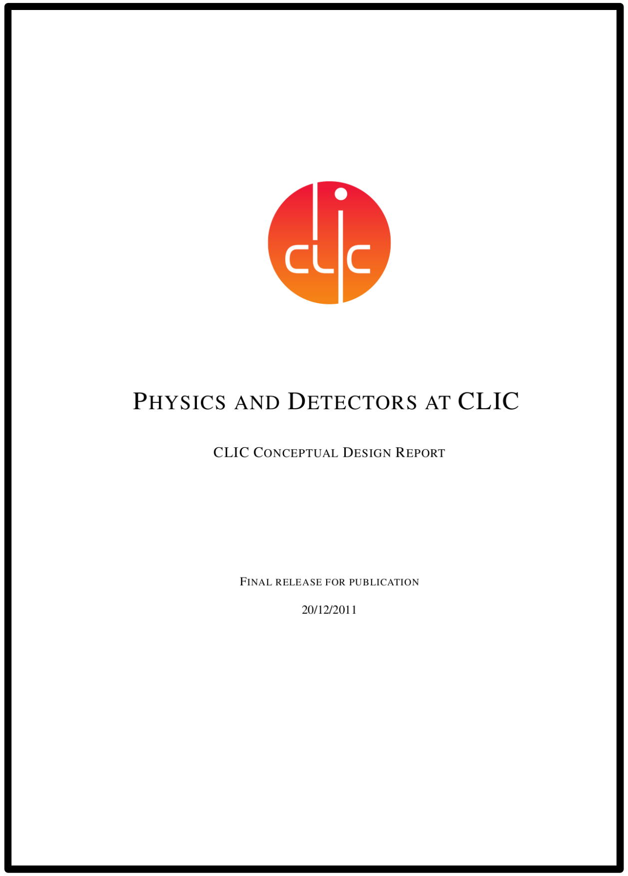
Main beam for physics:
- High energy: 9 GeV – 1.5 TeV
- Current: 1.2 A

CLIC accelerator complex



CLIC physics and detector CDR

CLIC provides the potential for e+e- collisions up to $\sqrt{s}$ = 3 TeV:
Challenging machine environment
→ detailed detector studies are needed


PHYSICS AND DETECTORS AT CLIC

CLIC CONCEPTUAL DESIGN REPORT

FINAL RELEASE FOR PUBLICATION

20/12/2011

CLIC physics and detector CDR:

- Physics potential
- Demonstrate that the physics can be measured at CLIC

Release of the CDR text (20.12.2011):
https://edms.cern.ch/document/1177771

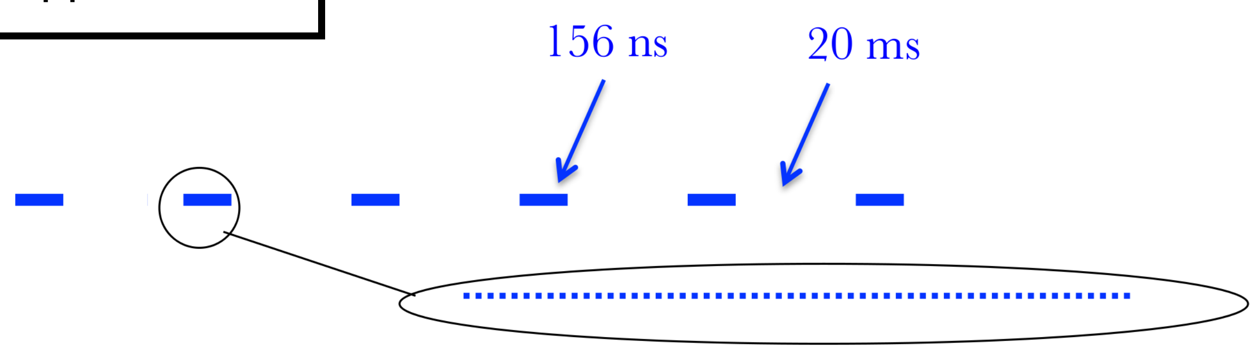
Review in October 2011:
https://indico.cern.ch/conferenceTimeTable.py?confId=146521

Selected CLIC parameters

	CLIC at 3 TeV
L ($cm^{-2}s^{-1}$)	$5.9 \cdot 10^{34}$
Bunch separation	0.5 ns
#Bunches / train	312
Train duration	156 ns
Train rep. rate	50 Hz
Crossing angle	20 mrad
Particles / bunch	$3.72 \cdot 10^{9}$
σ_x/σ_y (nm)	≈ 45 / 1
σ_z (μm)	44

Drive timing requirements for CLIC detector

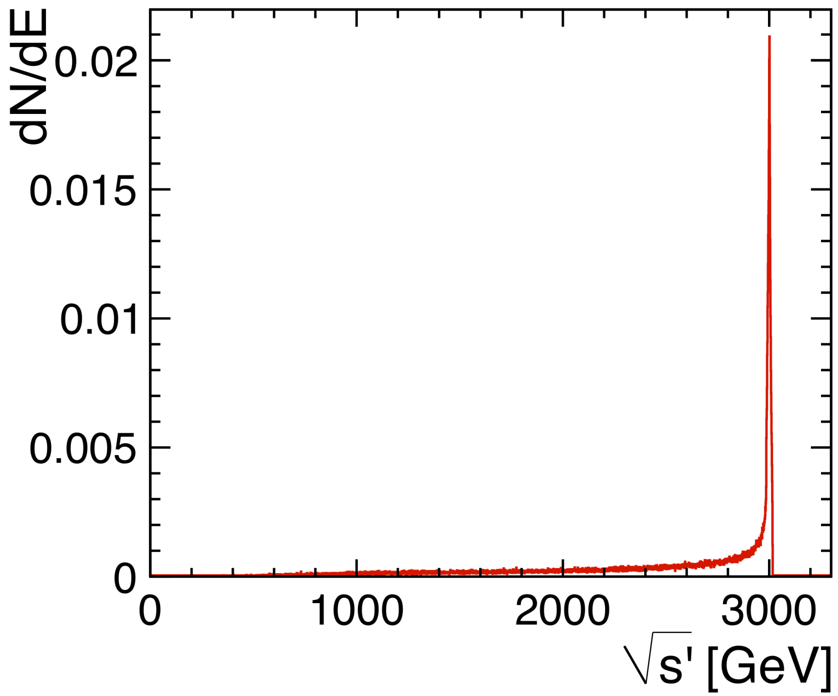
Very small beam profile at the interaction point



CLIC: trains at 50 Hz, 1 train = 312 bunches, 0.5 ns apart

Luminosity spectrum

Significant energy loss at the interaction point due to Beamstrahlung

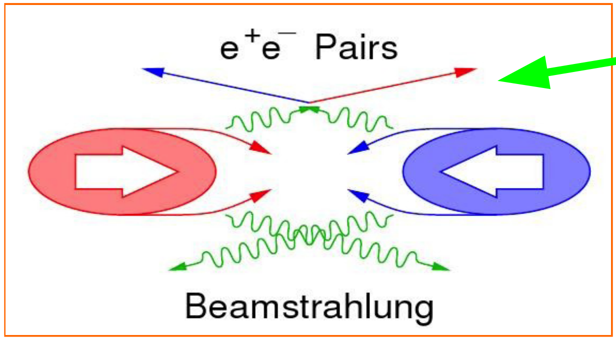


Full luminosity: $L = 5.9 \cdot 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
In the most energetic 1% ("peak luminosity"):
$L_{0.01} = 2.0 \cdot 10^{34}\ \mathrm{cm^{-2}s^{-1}}$

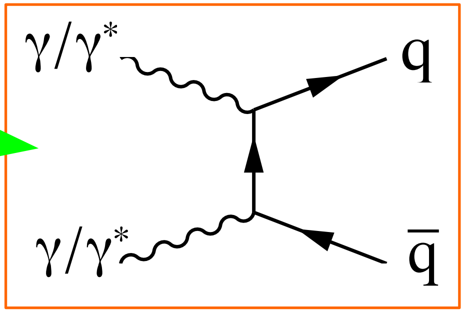
Most physics processes are studies well above the production threshold
→ Profit from (almost) full luminosity

$$\sqrt{s'} = \sqrt{4 \cdot E_1 \cdot E_2}$$

Beam related backgrounds



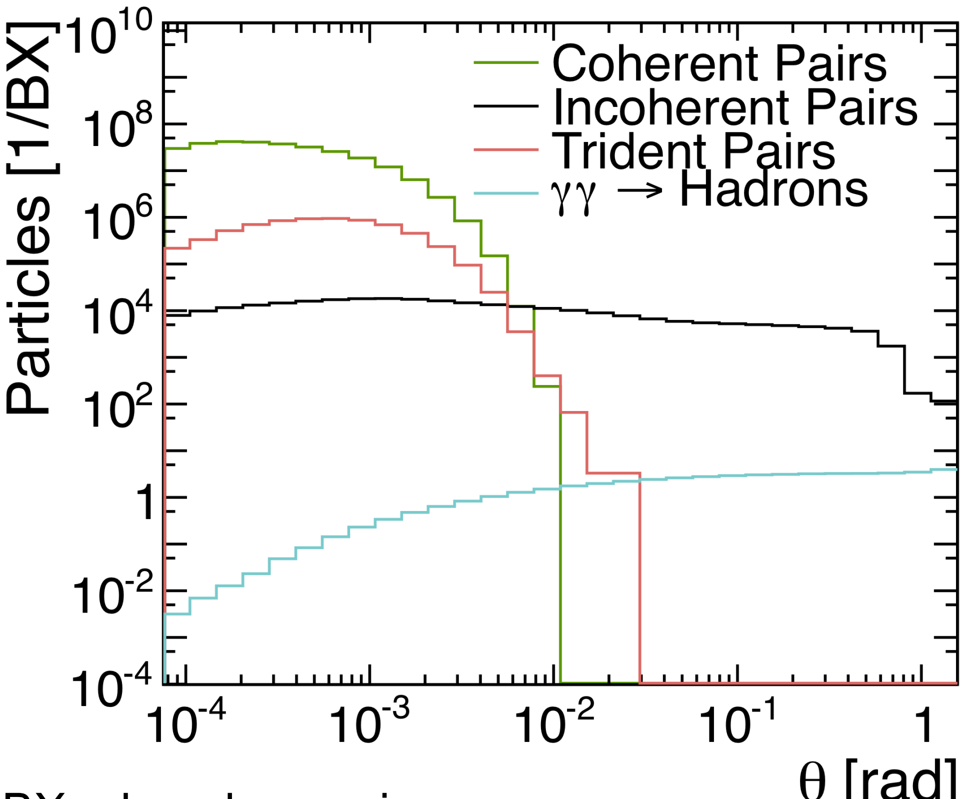
- e^+e^- pairs
- $\gamma\gamma \to$ hadrons
- Beam halo muons



Coherent e^+e^- pairs:
$7 \cdot 10^8$ per BX, very forward
Incoherent e^+e^- pairs:
$3 \cdot 10^5$ per BX, rather forward
→ Detector design issue
(high occupancies)

$\gamma\gamma \to$ hadrons
- "Only" 3.2 per BX
- Main background

in calorimeters and trackers
→ Impact on physics



BX = bunch crossing

Physics at CLIC

CLIC physics potential

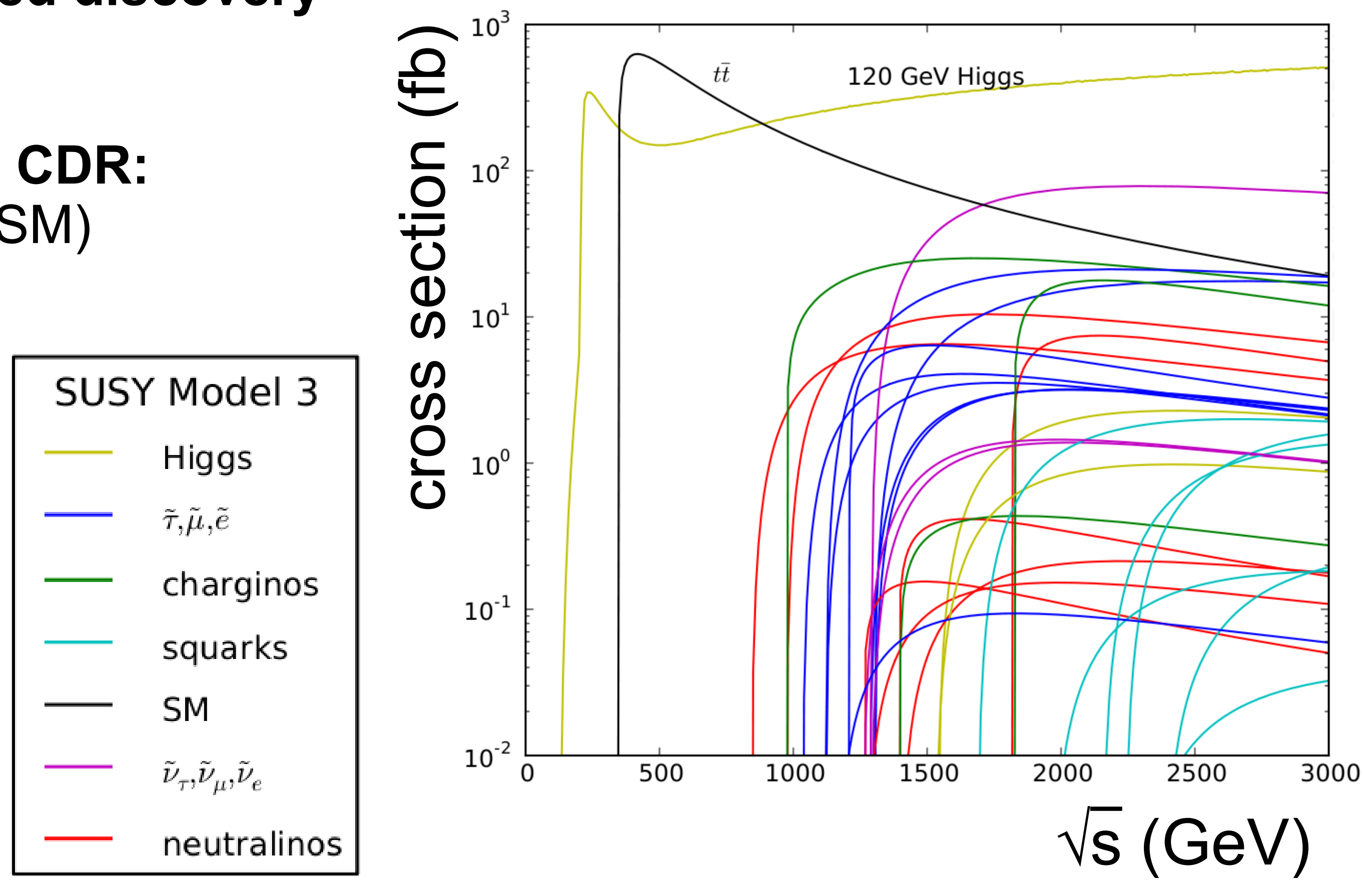
Advantage of e^+e^- collisions:

- Defined initial state
- Precision measurements possible due to clean conditions
- Well suited for weakly interacting states (e.g. sleptons, gauginos)
- Polarised (electron) beam

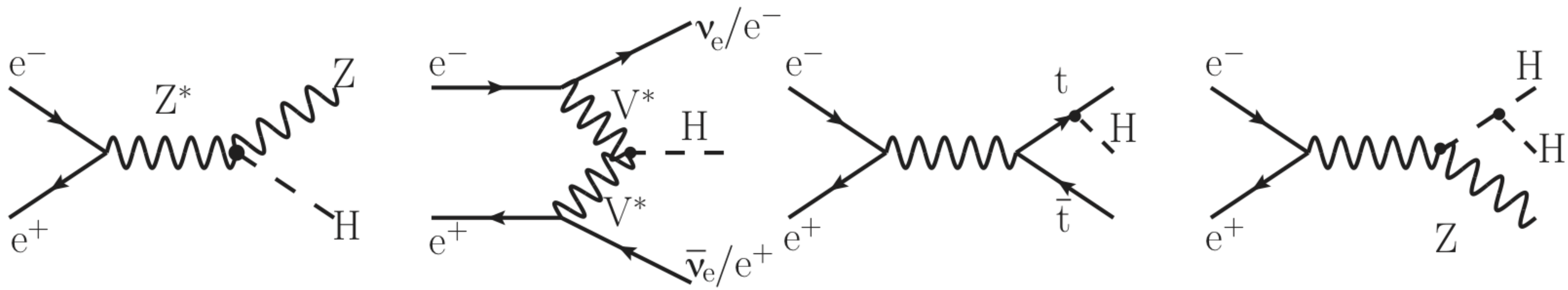
→ Complementary / enhanced discovery reach compared to the LHC

Examples highlighted in the CDR:

- Higgs physics (SM and non-SM)
- Top physics
- SUSY
- Higgs strong interactions
- Z'
- Contact interactions
- Extra dimensions
- ...



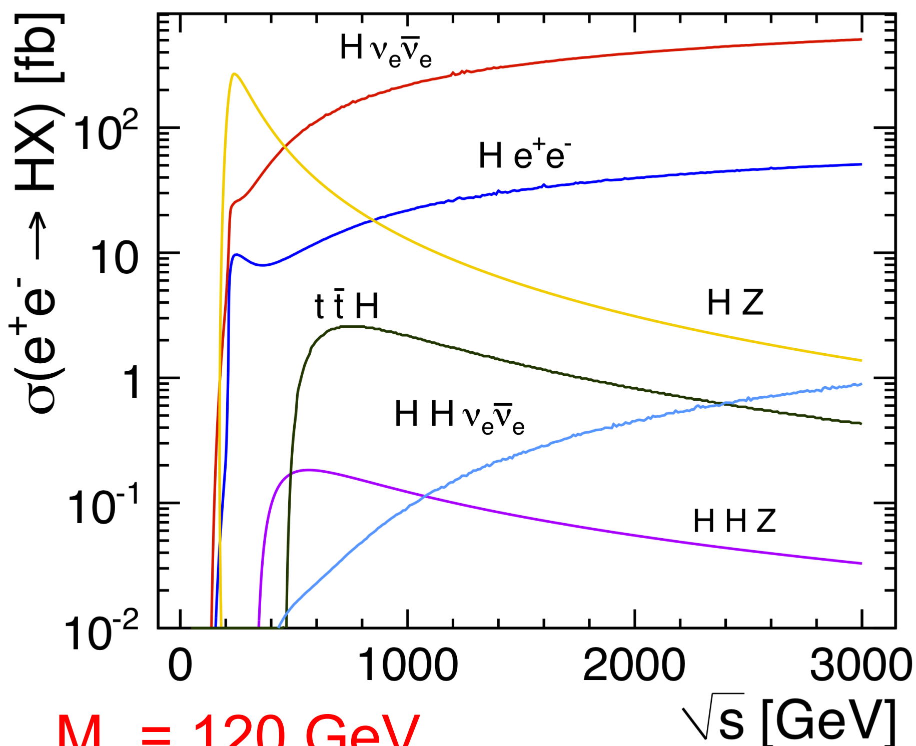
SM Higgs production



s-channel: ~ 1/s

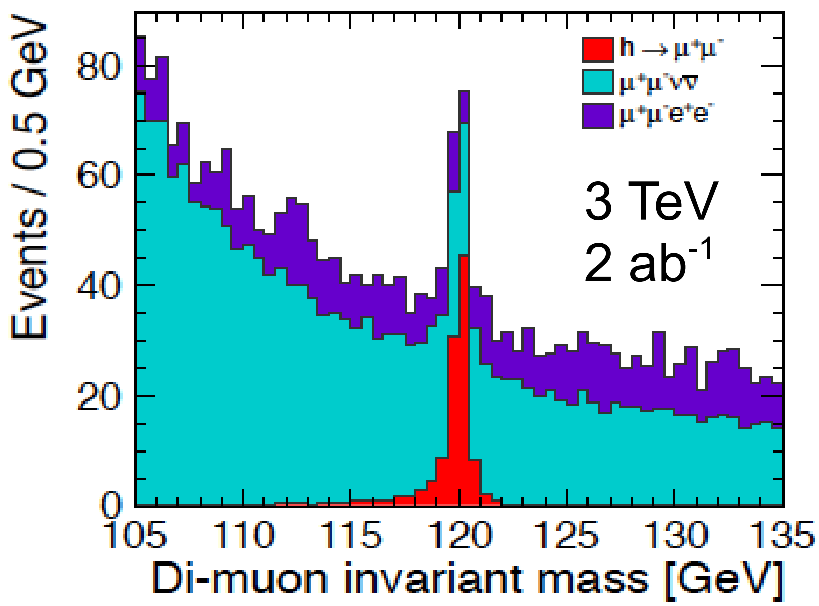
t-channel: ~ log(s)

At $\sqrt{s}$ = 3 TeV: WW fusion ($e^+e^- \rightarrow H\nu_e\bar{\nu}_e$) dominant

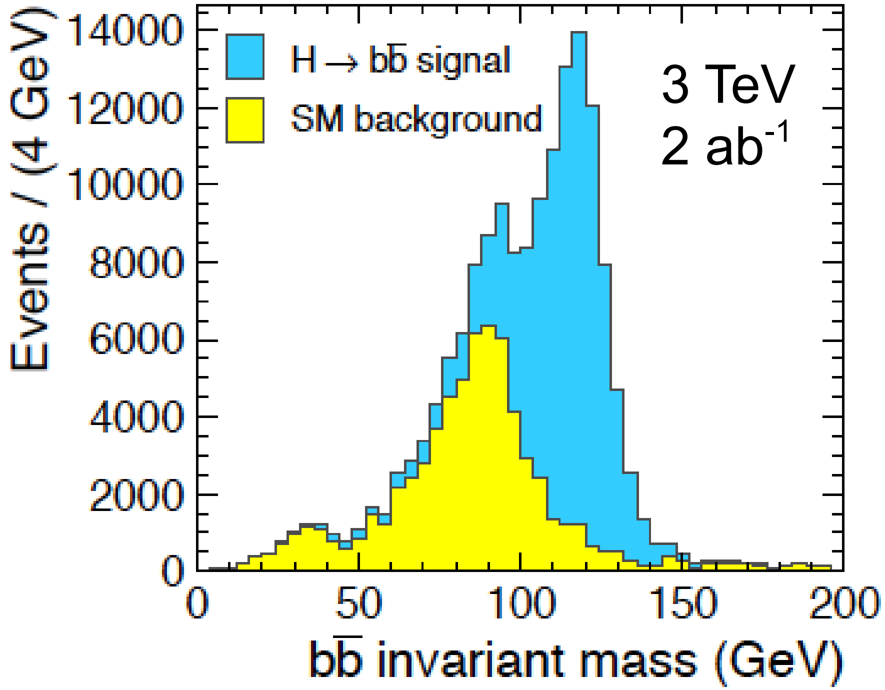


M_h = 120 GeV

Example Higgs observables



$\sigma(h \to \mu^+\mu^-) \to \pm 15\%$ (stat.)



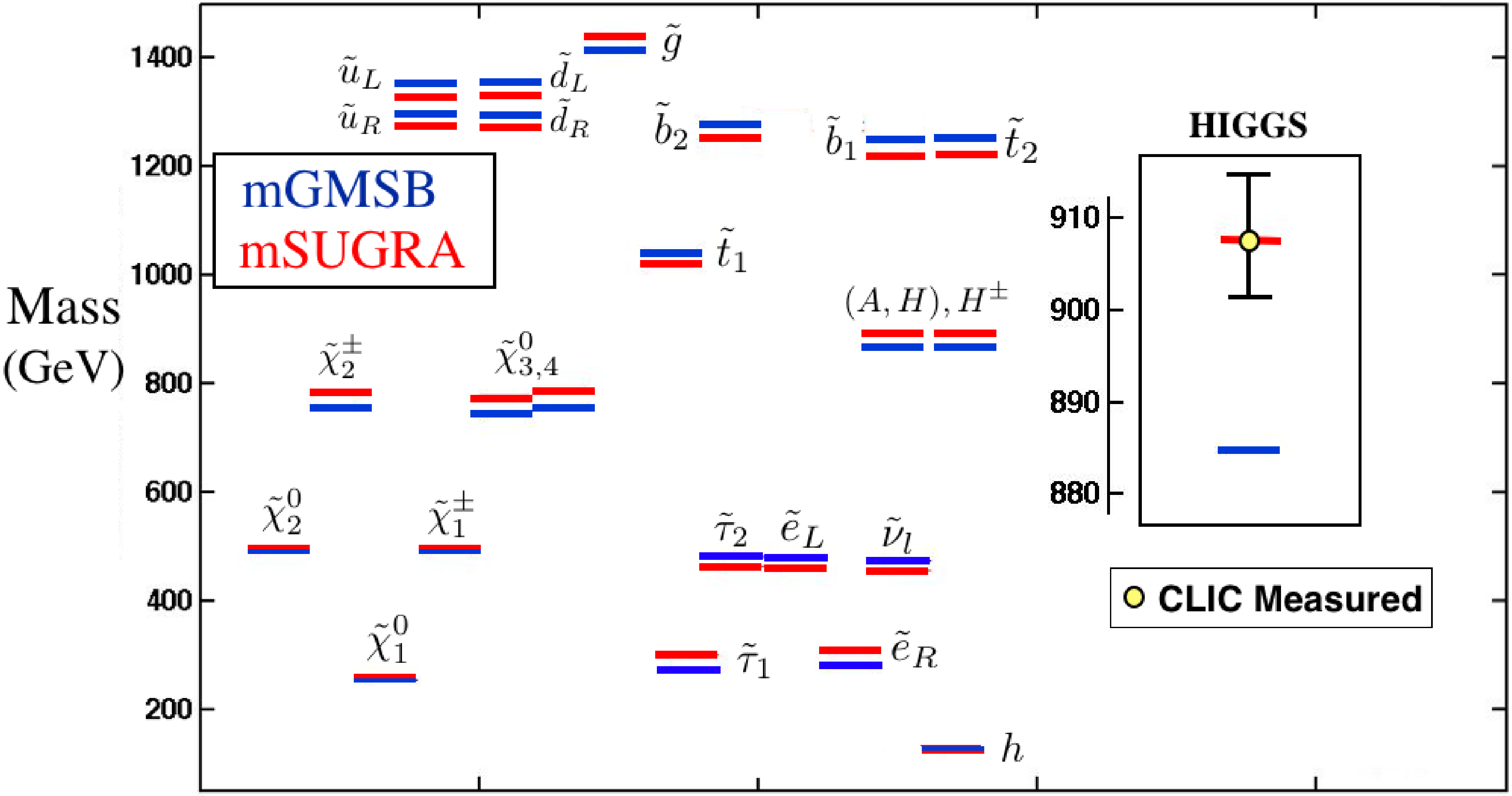
$\sigma(h \to b\bar{b}) \to \pm 0.22\%$ (stat.)

	Coupling determination(%)	Sensitivity to SM deviation (%)
Hbb	2	4
Hcc	3	6
$H\mu\mu$	15	15

Resolving new physics models

Precision measurements at CLIC allow to discriminate between new physics models, e.g. following first observations at the LHC

Example: SUSY breaking models with nearly degenerate mass spectra

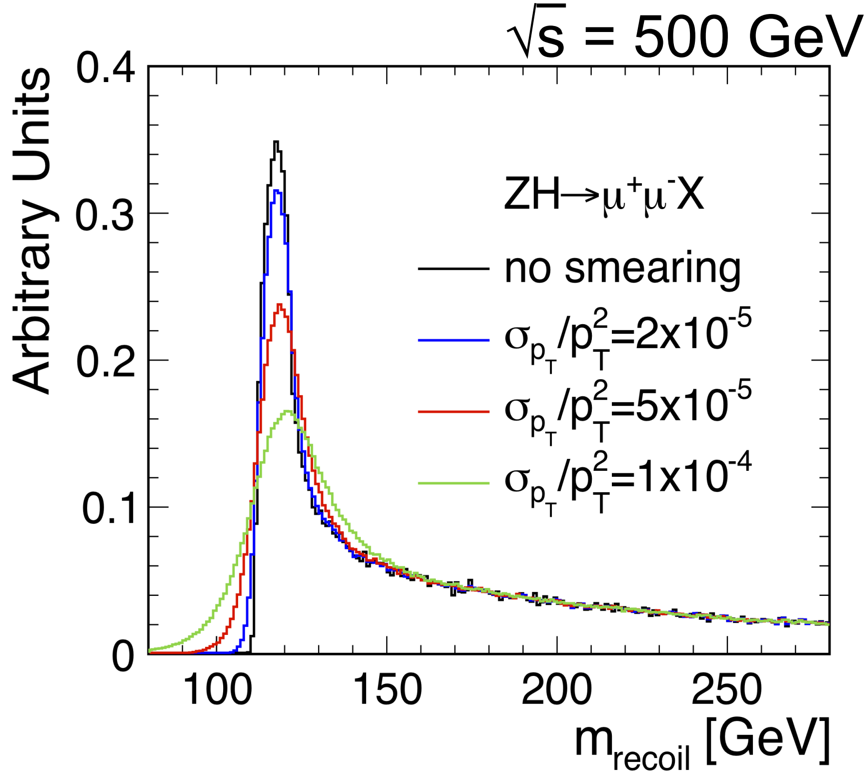


Detector requirements

Physics aims → detector needs

- **Momentum resolution**
(e.g. Higgs recoil mass, h → $\mu^+\mu^-$, leptons from BSM processes)

$$\frac{\sigma(p_T)}{p_T^2} \sim 2\times10^{-5}\,GeV^{-1}$$



- **Jet energy resolution**
(e.g. W/Z/h separation)

$$\frac{\sigma(E)}{E} \sim 3.5-5\%\ for\ E=1000-50\,GeV$$

- **Impact parameter resolution**
(b/c tagging, e.g. Higgs couplings)

$$\sigma(d_0)=\sqrt{a^2+b^2\cdot GeV^2/(p^2\sin^3\theta)},\ a\approx5\,\mu m,\ b\approx15\,\mu m$$

- **Lepton identification, very forward electron tagging**

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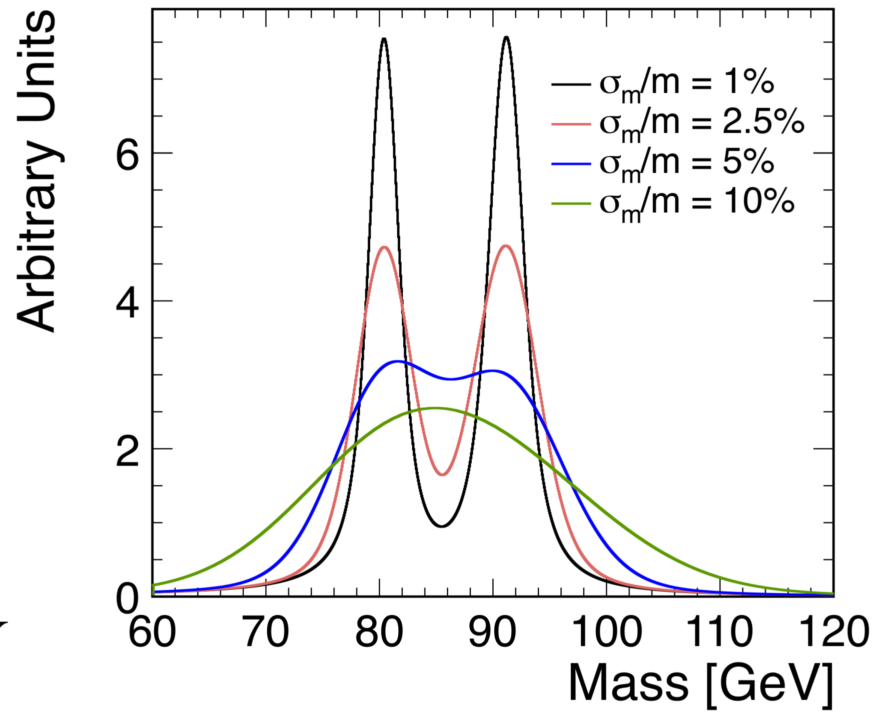

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Physics aims → detector needs

- **Momentum resolution**
(e.g. Higgs recoil mass, h → μ⁺μ⁻, leptons from BSM processes)

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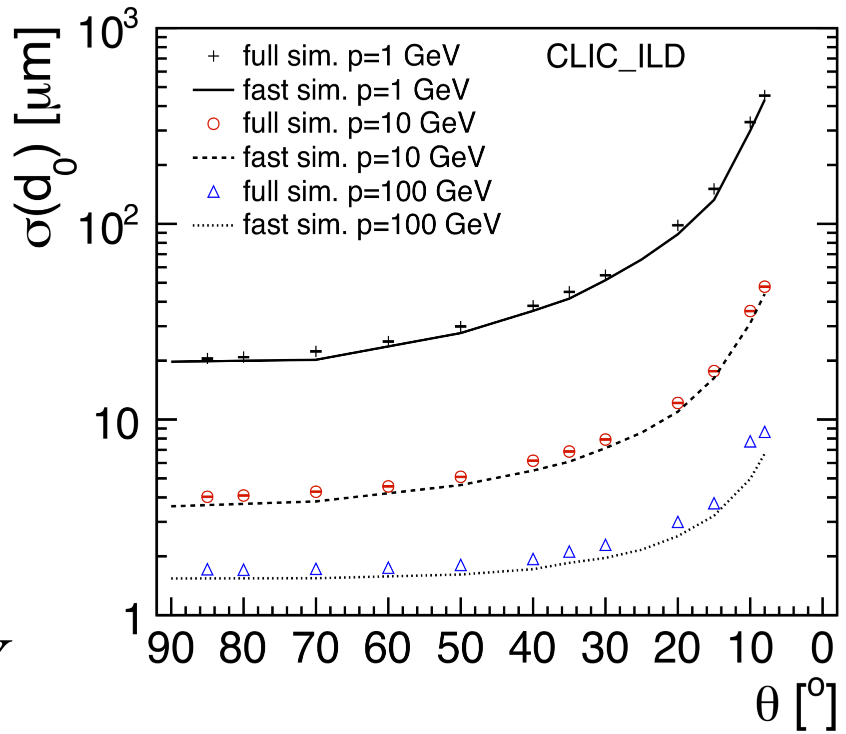

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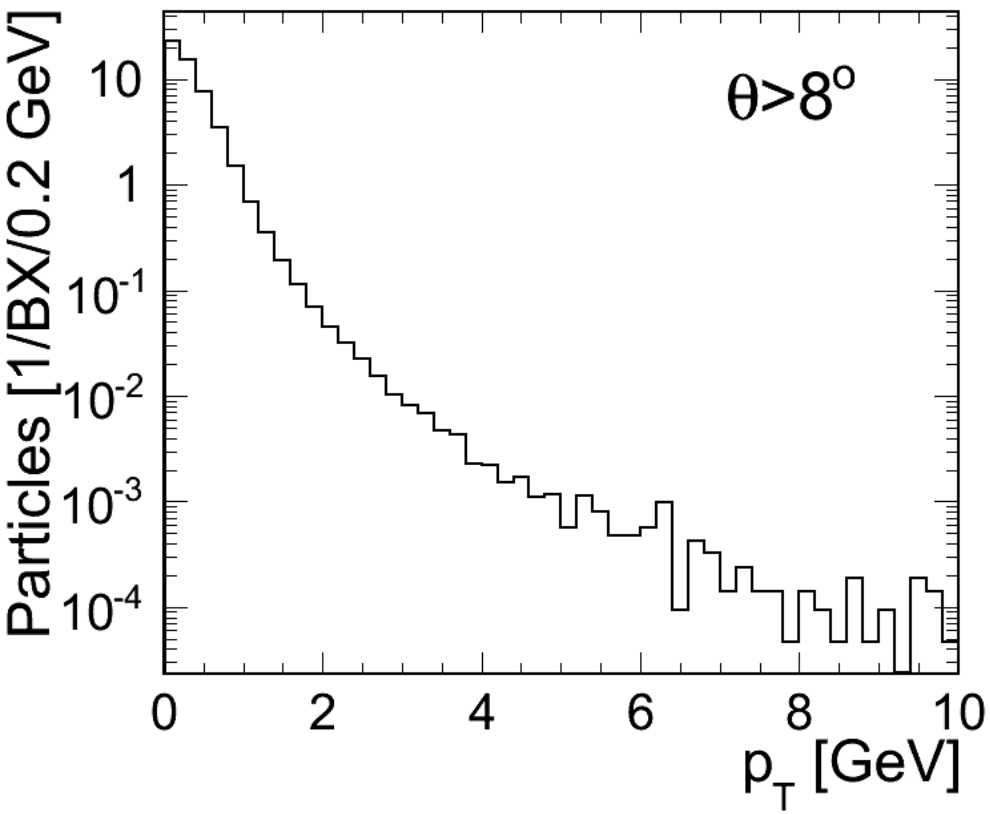
- **Lepton identification, very forward electron tagging**

General readout considerations

3.2 γγ → hadr. Interactions per bunch crossing:

- 19 TeV in the calorimeters per 156 ns bunch train

- 5000 tracks with a total momentum of 7.3 TeV



Triggerless readout of full bunch train:
- Time-stamping in tracking detectors and calorimeters
- Multi-hit storage / readout
- Filtering algorithms at reconstruction level (→ later)

The CLIC_ILD and CLIC_SiD detectors

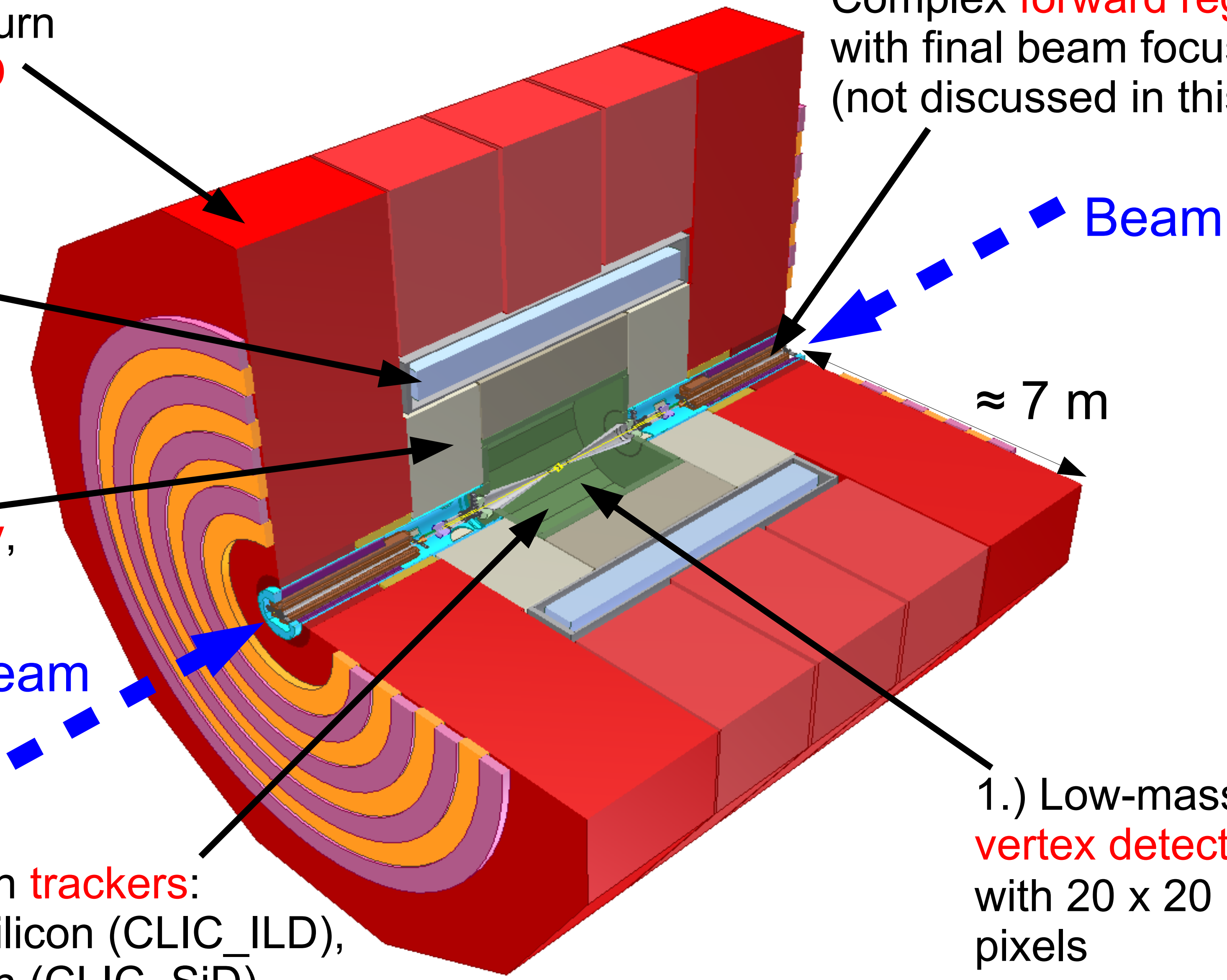
Detector overview

Instrumented return yoke for muon ID

Strong solenoids (4-5 T)

3.) Fine grained (PFA) calorimetry, 1+7.5 λ

Complex forward region with final beam focusing (not discussed in this talk)

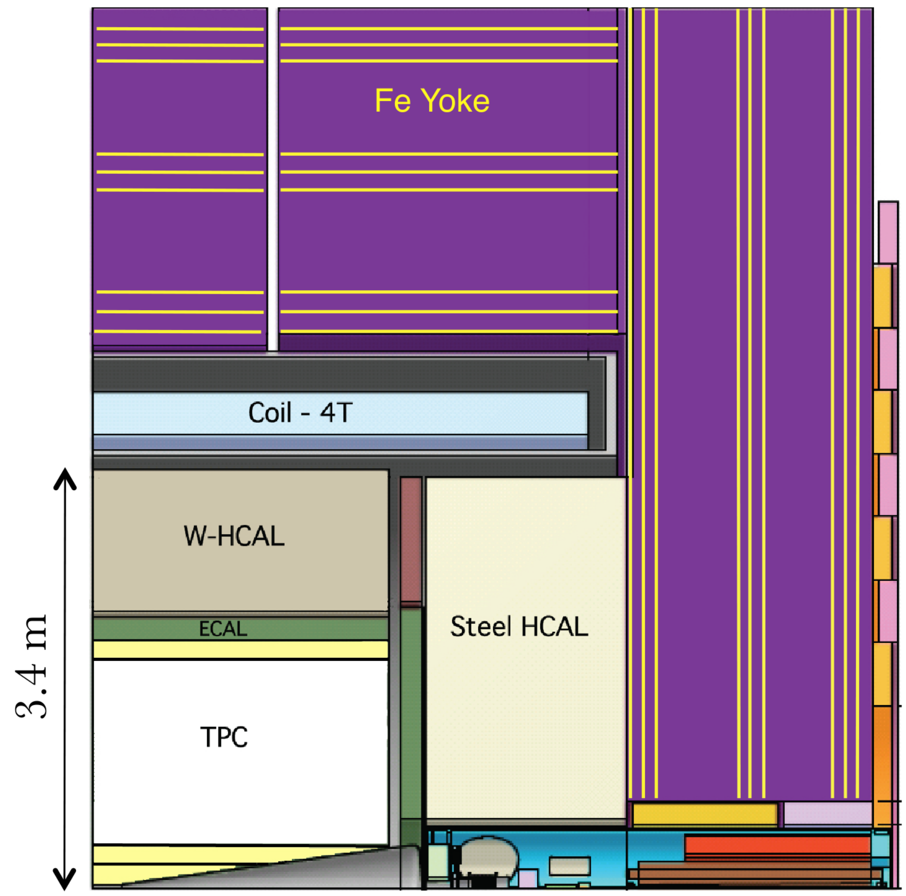


2.) Main trackers: TPC+silicon (CLIC_ILD), all-silion (CLIC_SiD)

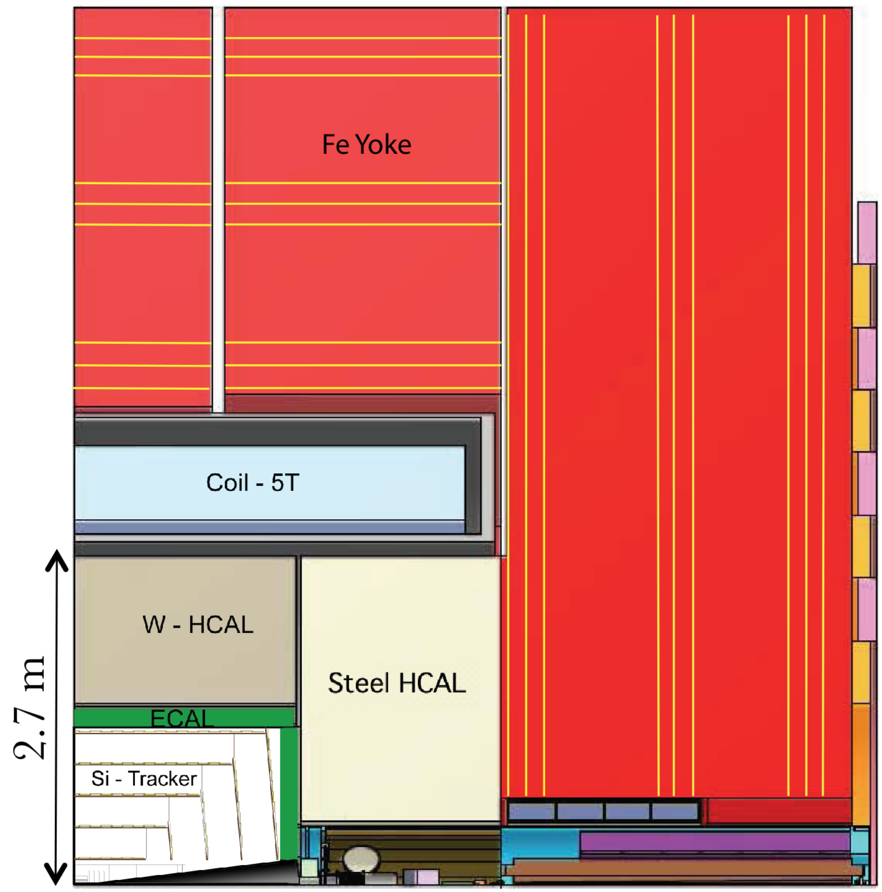
1.) Low-mass vertex detector with 20 x 20 μm^2 pixels

CLIC detector concepts

Based on validated ILC designs, adapted and optimised to the CLIC conditions:
- Denser HCAL in the barrel (Tungsten, 7.5 λ)
- Redesign of the vertex and forward detectors (backgrounds)



CLIC_ILD



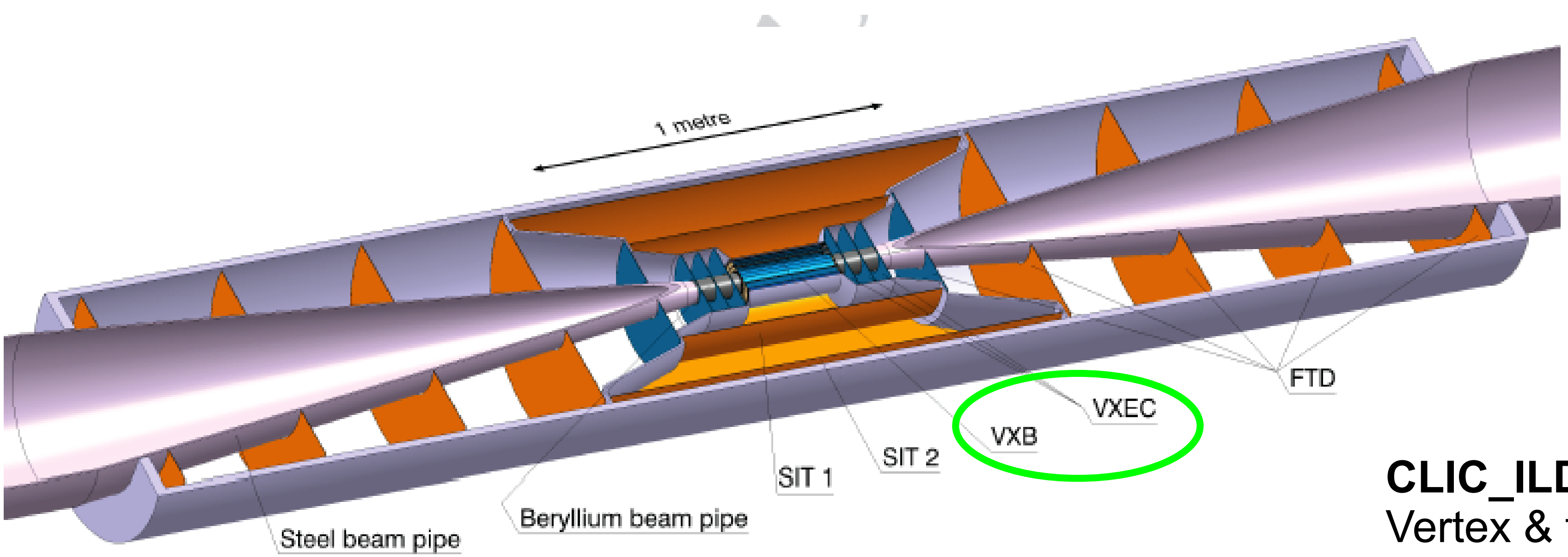
CLIC_SiD

Vertex detectors

Vertex detector

Requirements:

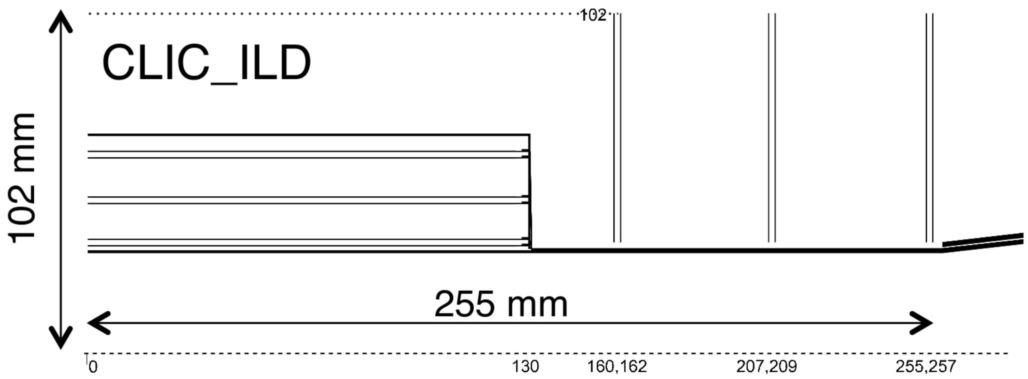
- 20 x 20 μm^2 pixel size
- Material: 0.2% X_0 per layer:
  - Very thin materials / sensors
  - Low-power design, power pulsing, low-mass cooling
- Time stamping precision: 5 - 10 ns (to reject backgrounds)
- Radiation level: $\approx 10^{10}$ n_{eq} /cm^2 /yr (10^{-4} of LHC)

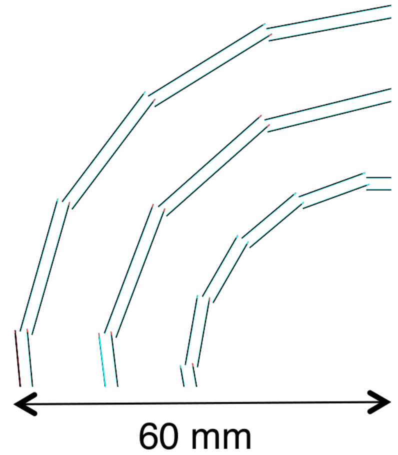


CLIC_ILD:
Vertex & forward tracking

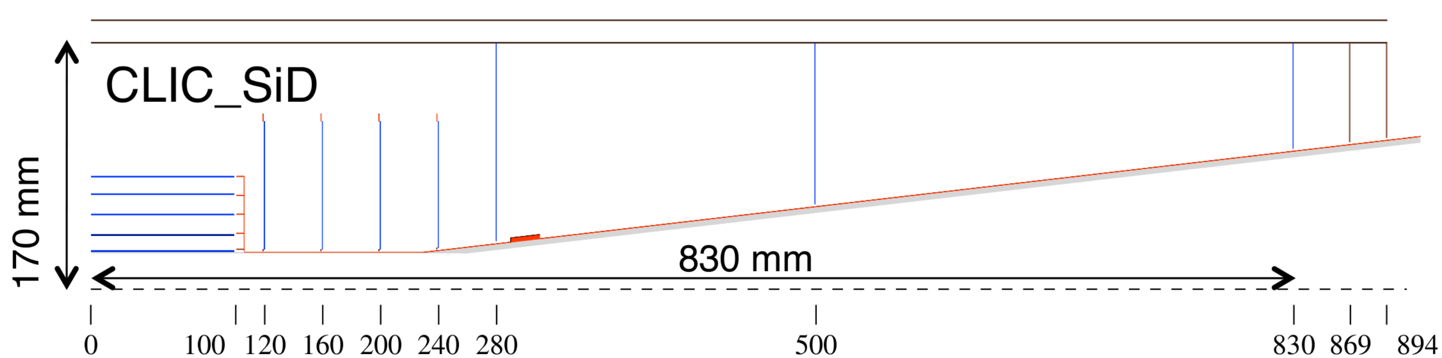
Vertex detector layouts

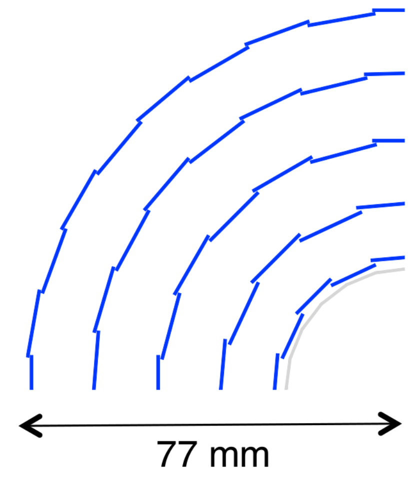
CLIC_ILD: 3 double layers, 1.84 · 10^9 pixels





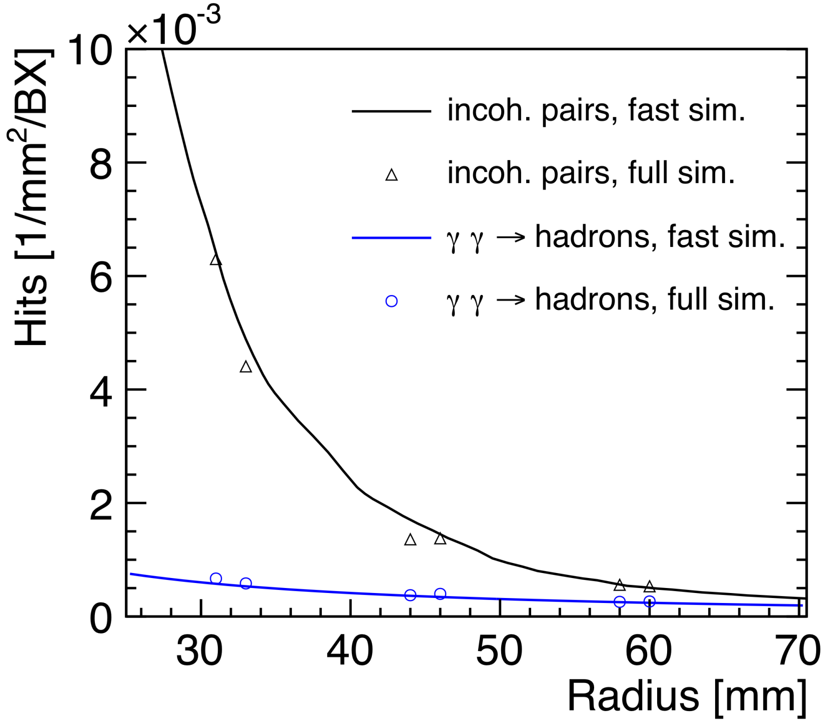
CLIC_SiD: 5 single layers, 2.76 · 10^9 pixels



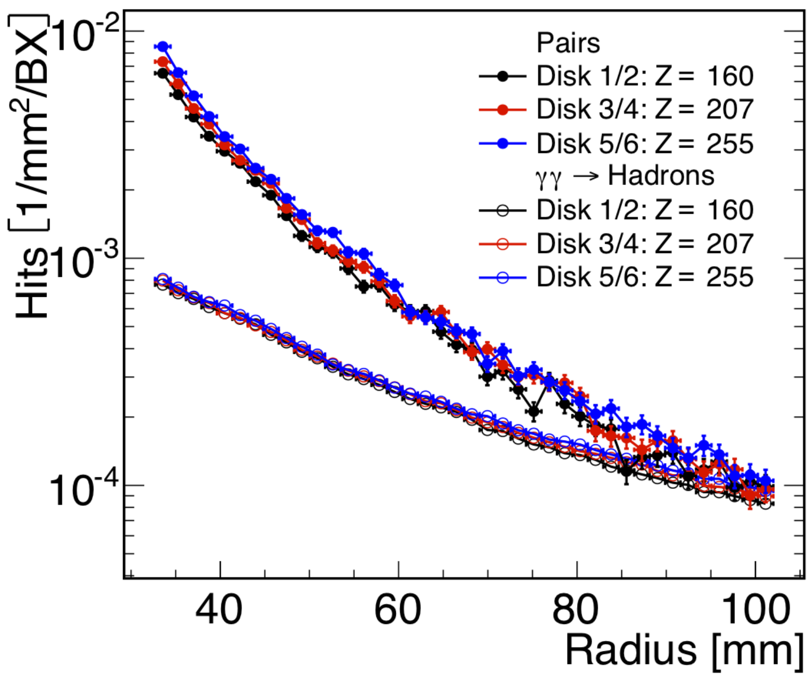


Occupancies in the CLIC_ILD vertex region

Barrel cylinder layers



Forward disk layers



- Direct hits from incoherent e^+e^- pairs dominate
- Barrel: up to 1.9% train occupancy / pixel
- Forward: up to 2.9% train occupancy / pixel

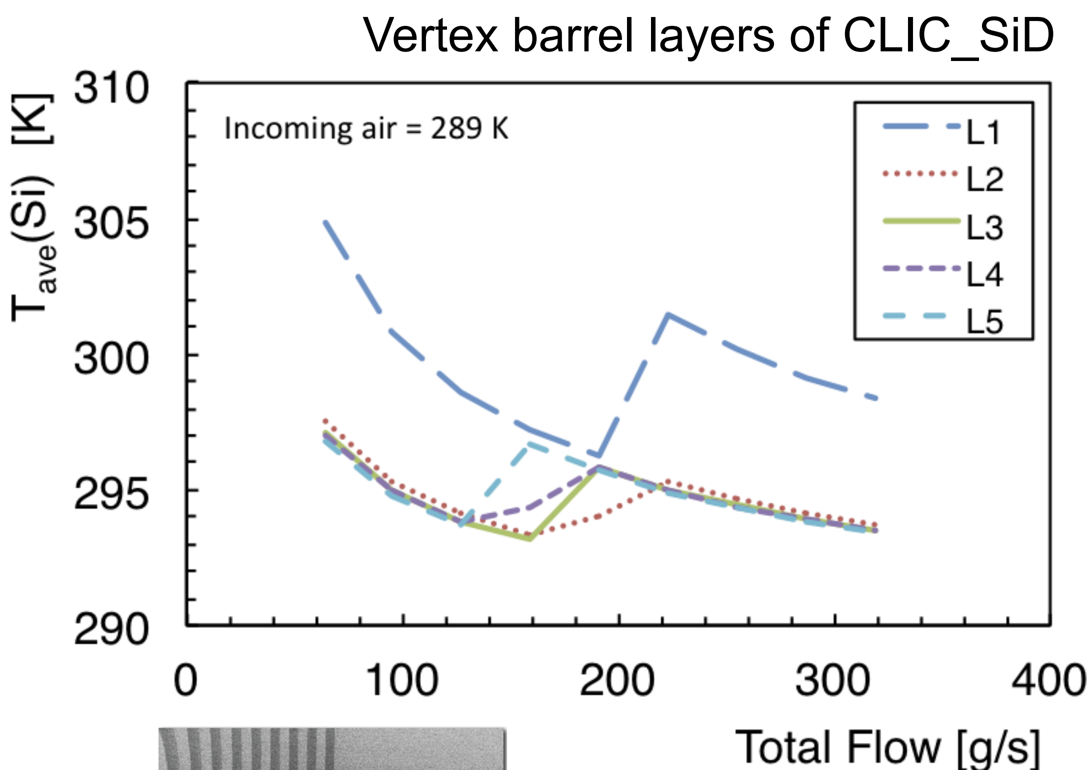
(including safety factors for simulation uncertainty and clustering)

Vertex detector cooling

Vertex detector: P ≈ 500 W → need low mass cooling solutions

Forced (dry) air flow:
- Baseline for barrel region
- No extra material
- Up to 240 liter/s flow,

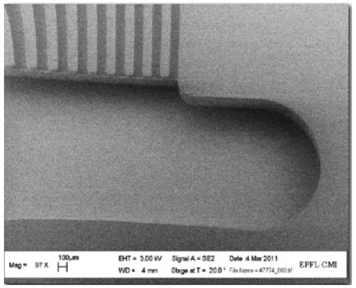
≈ 40 km/h flow velocity



Options in forward disks:
- Evaporative CO_2 cooling

(high pressure → thick tubes)
- Water cooling (sub-atmospheric pressure)

Micro-channel cooling:
- Ongoing R&D (e.g. NA62 upgrade)
- Integrate cooling channels in Silicon



- May be suitable for regions where sufficient air flow can not be established

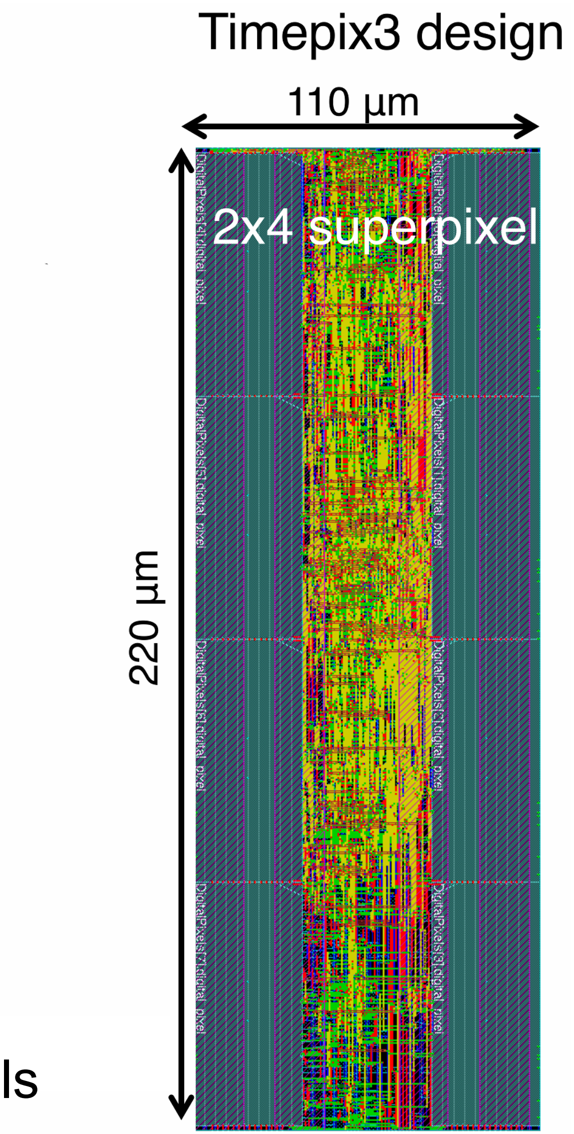
Pixel sensor options I

1.) **Hybrid technologies**:

- Thinned high-resistivity fully depleted sensors
- Fast, low-power highly integrated readout chip
- Low mass interconnects

Pros: - Factorisation of sensor + readout R&D
→ Readout chips profit fully from advancing industry standards

Cons: - Interconnect difficult / expensive → needs R&D
- Harder to reduce material



- **Thinned high-resistivity fully depleted sensors:**
  - 50 µm active thickness
  - ALICE pixel upgrade → meets CLIC goals
- **Fast low-power readout chips:**
  - Timepix3 (2012) in 130 nm IBM CMOS:
  - 55 x 55 µm^2 pixels
  - 1.5 ns time resolution → exceeds CLIC goals
  - P ≈ 10 µW / pixel
  - CLICPix (prototypes ≈2014) in 65 nm, 20 x 20 µm^2 pixels

Pixel sensor options II

2.) **Integrated technologies**:

- Sensor and readout combined in one chip
- Charge collection in epitaxial layer

Pros: - Allows for very low material solutions
- Synergy with R&D for ILC detectors

Cons: - Harder to achieve good time resolution and sufficient S/N

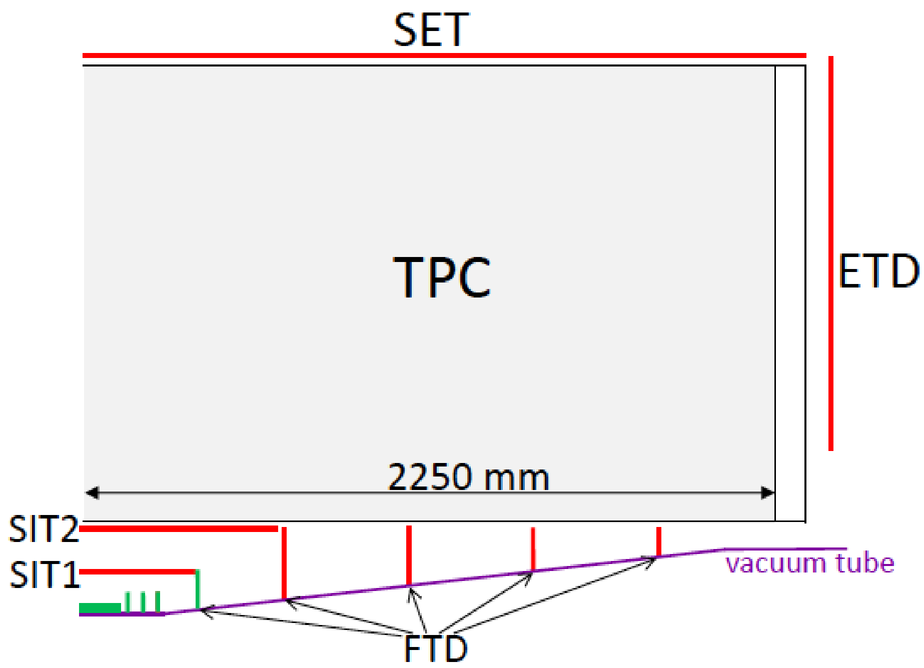
- Several active R&D programs (targeted to ILC requirements)
- Attempts to reach faster signal collection and ns time-stamping capability (compatible with CLIC requirements):
  - MIMOSA CMOS with high-resistivity epitaxial layers
  - Chronopixel CMOS
  - INMAPS
  - High voltage CMOS

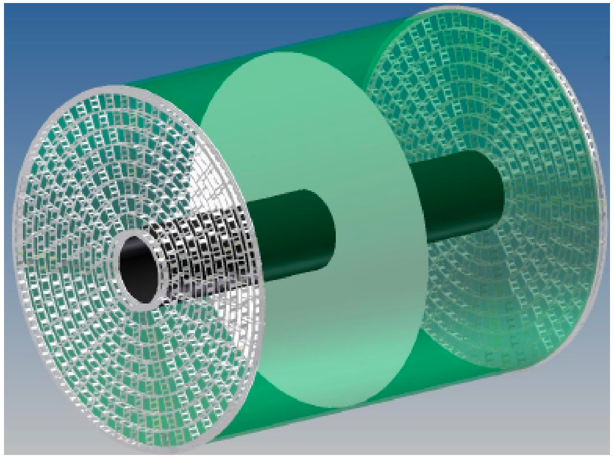
3.) **New technologies**:
- Silicon-On-Insulator (SOI)
- Full 3D-integrated pixel sensors

Tracking

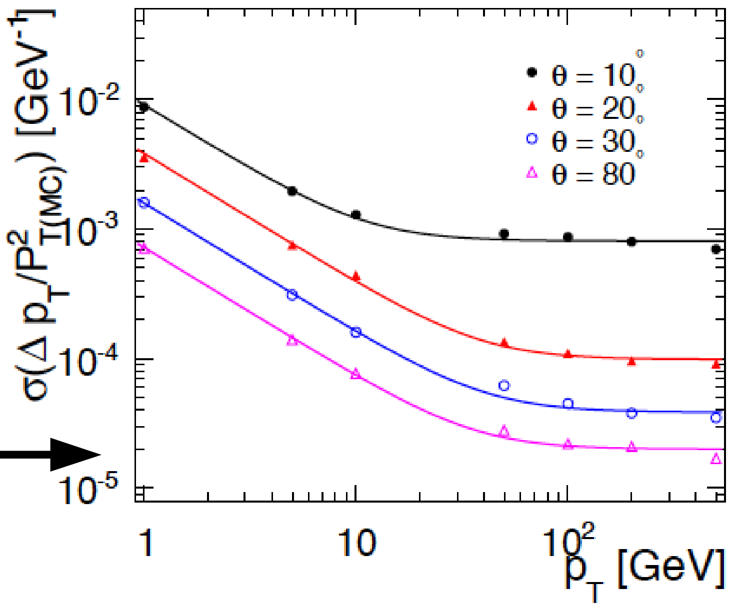
Tracking in CLIC_ILD

TPC + silicon tracking in 4T field





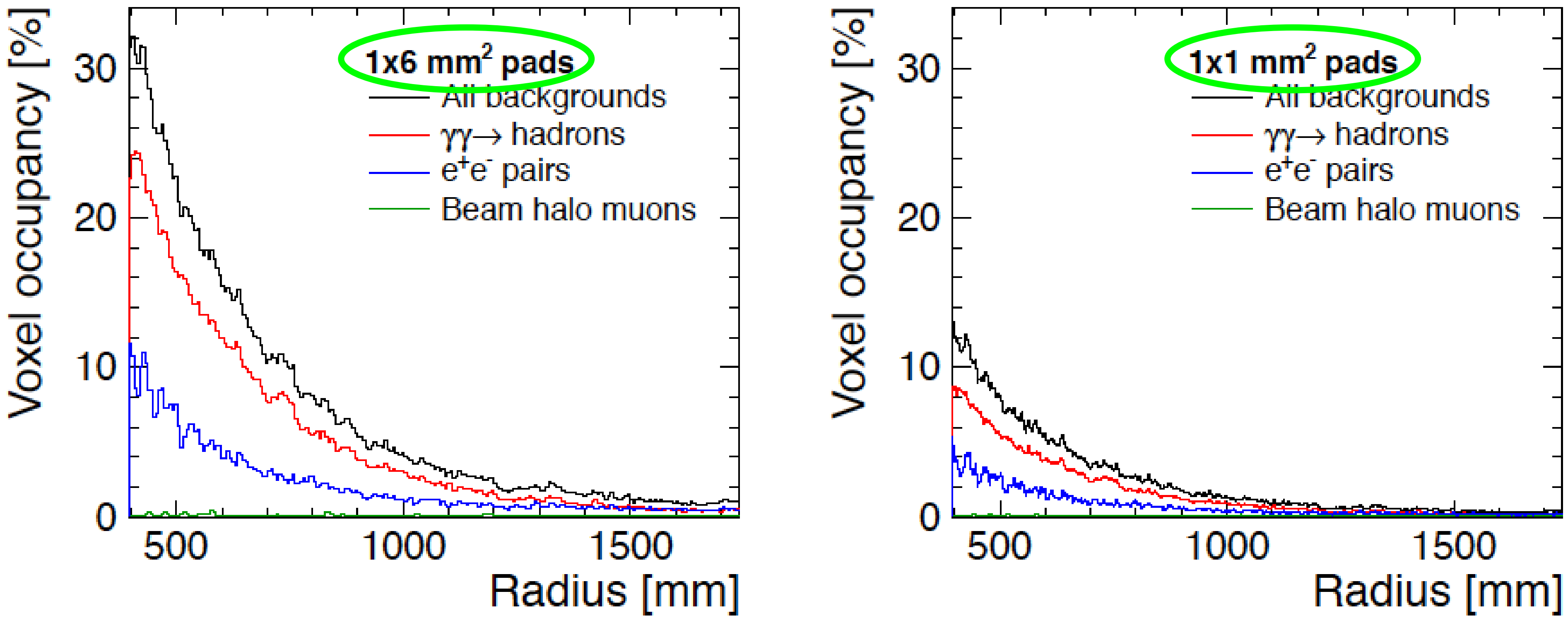
Time projection chamber (TPC)



Performance goal on momentum resolution achieved

Occupancies in the TPC

The readout time of the TPC is much longer than a CLIC bunch train
→ The TPC integrates the background of a full train at CLIC



Plots are for Gas Electron Multiplier (GEM) + Pad readout, voxels of 25 ns

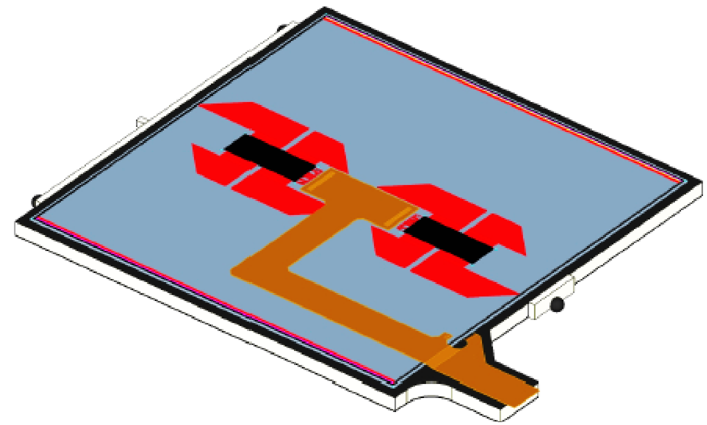
→ A TPC at CLIC may need a larger inner radius or very small pads
Similar study with micromegas + pixel readout is starting

Tracking in CLIC_SiD

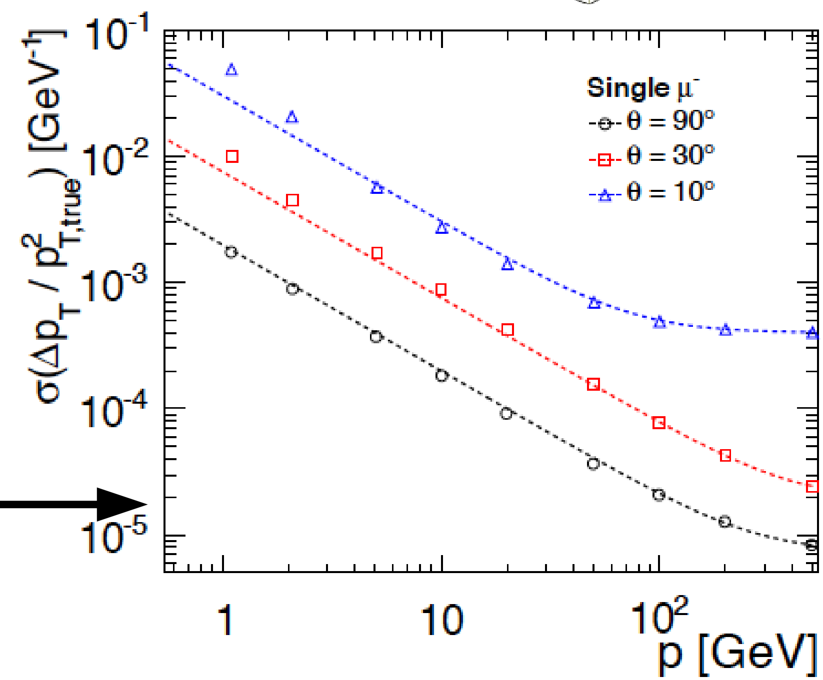
All silicon tracker in 5T field:

- Vertex detector and tracker viewed as one system
- Combined seeding and tracking

Two readout (KPiX) chips bump bonded to the sensor



Performance goal on momentum resolution achieved



Calorimetry

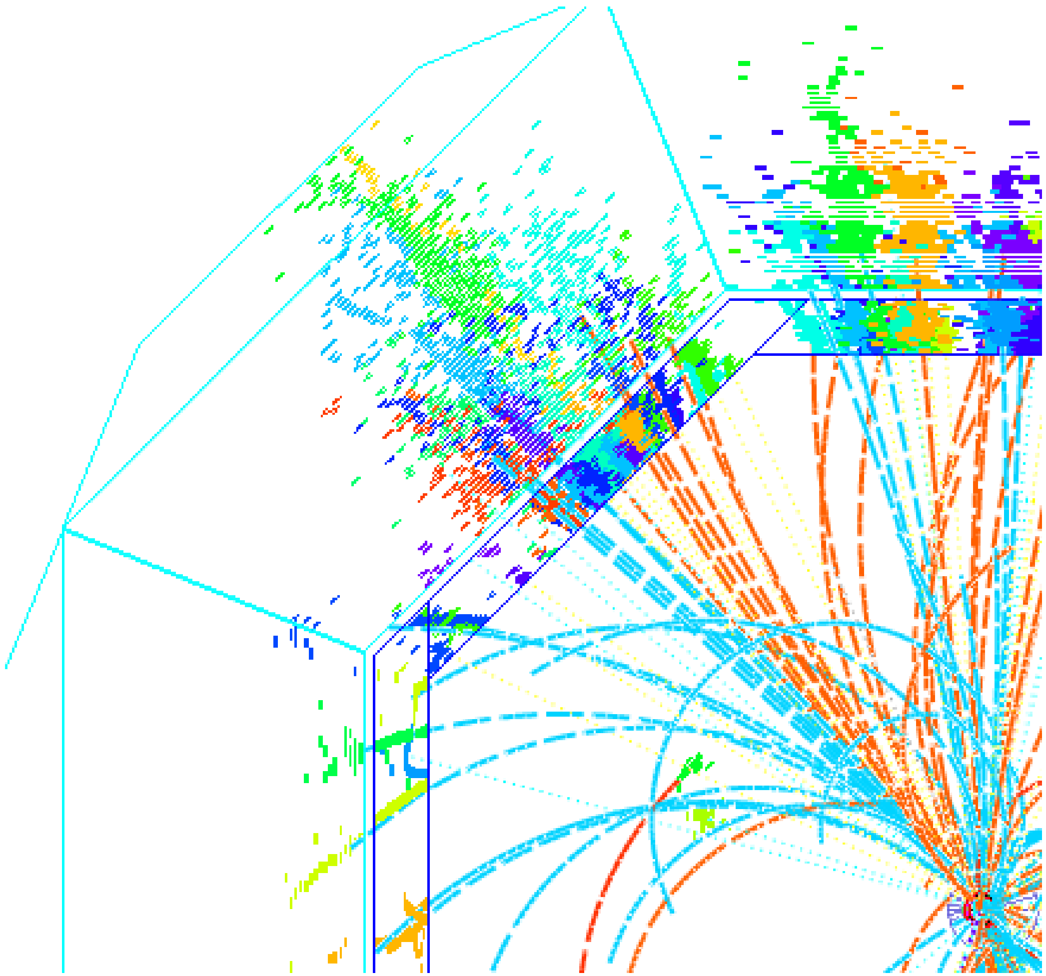
Calorimetry and PFA

Detector design driven by jet energy resolution and background rejection
→ 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 available measurement:
- charged particles
→ tracking detectors: 🙂 🙂
- photons → ECAL: 🙂
- neutrals → HCAL: 🙁

Hardware and software!

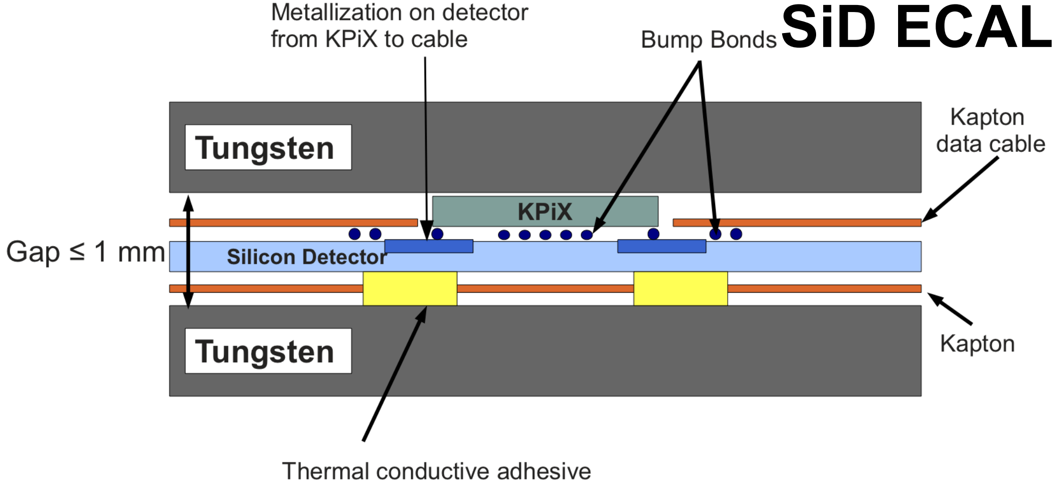


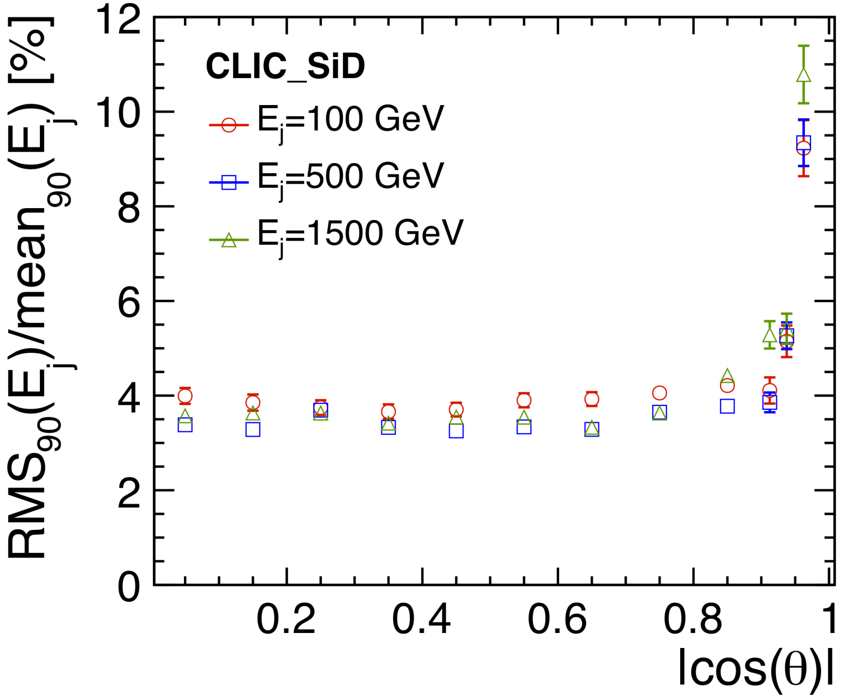
Calorimetry: technology

ECAL:
- Silicon pads or scintillator
- Tungsten absorber
- Cell sizes: 25 mm^2 (CLIC_ILD)
  11 mm^2 (CLIC_SiD)
- 30 layers in depth
- 23 X_0 and 1 λ

HCAL:
- Several options for sensors
- Tungsten (barrel), steel (forward)
- Cell sizes: 9 cm^2 (analog)
  1 cm^2 (digital)
- 60 - 75 layers in depth
- 7.5 λ

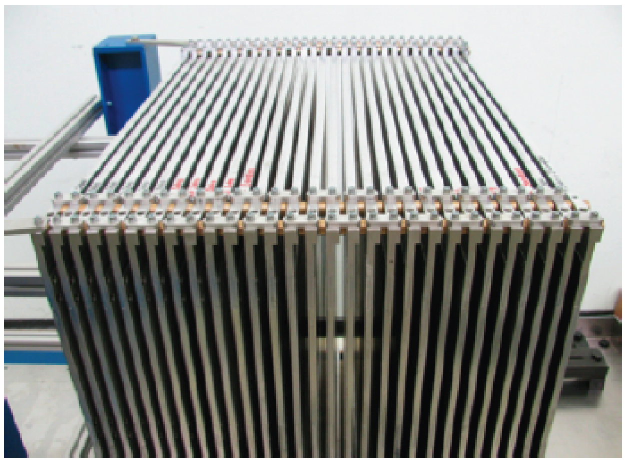
SiD ECAL

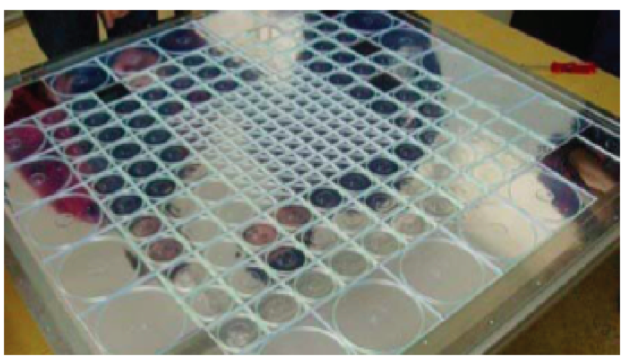




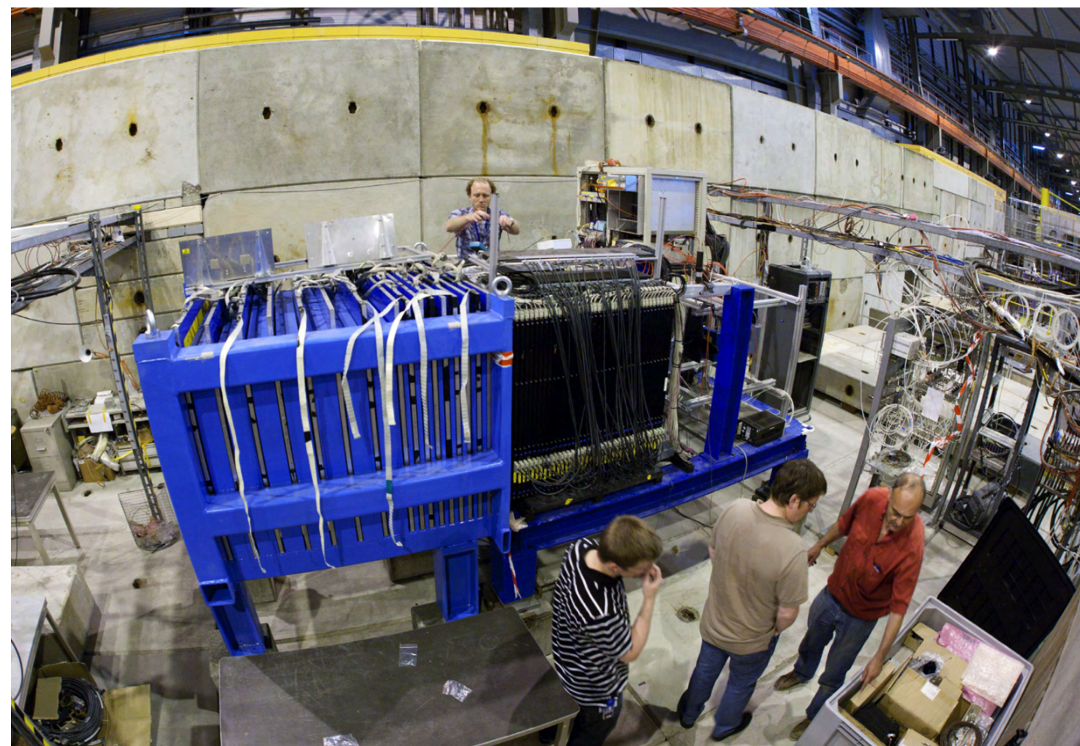
Tungsten HCAL prototype

Main purpose: Validation of Geant4 simulation for hadronic showers in tungsten





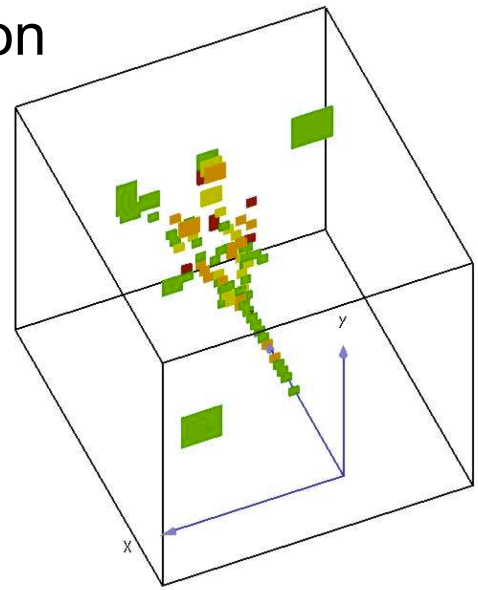
Data taken 2010/11 at CERN-PS/SPS, mixed beams 1-300 GeV

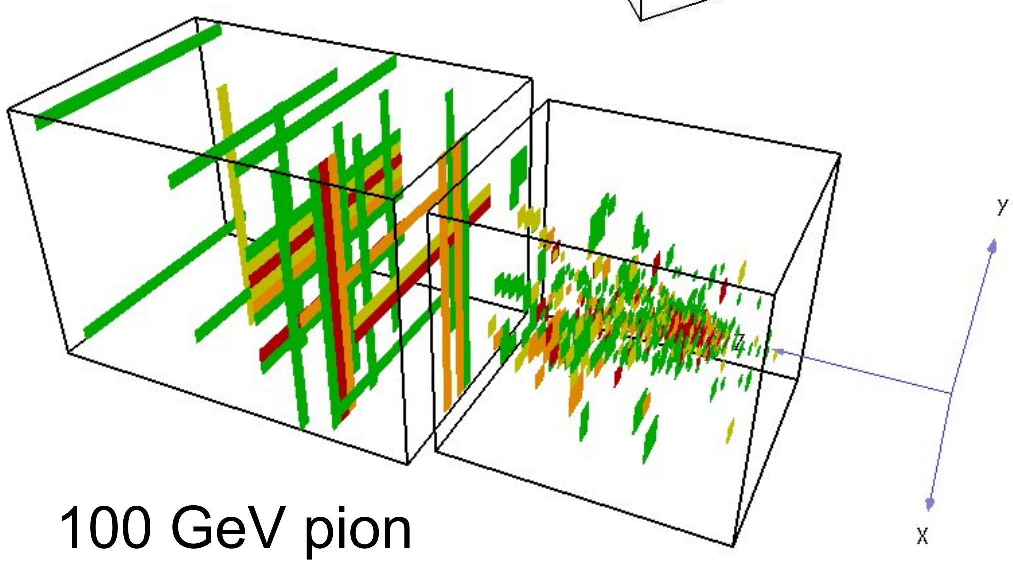


Scintillator tiles 3x3 cm^2
Read out by SiPM

Analog HCAL testbeam

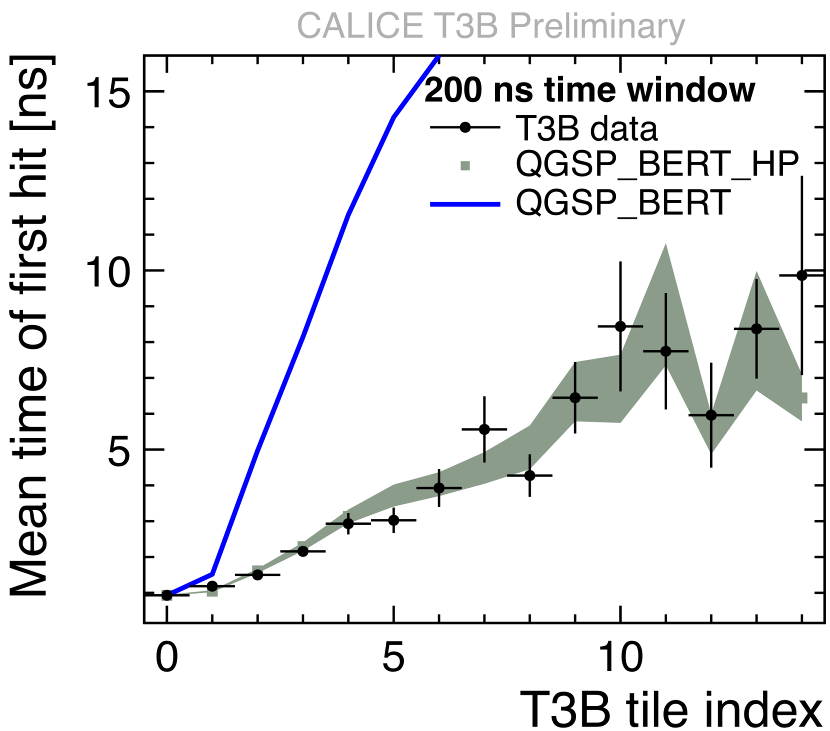
10 GeV pion





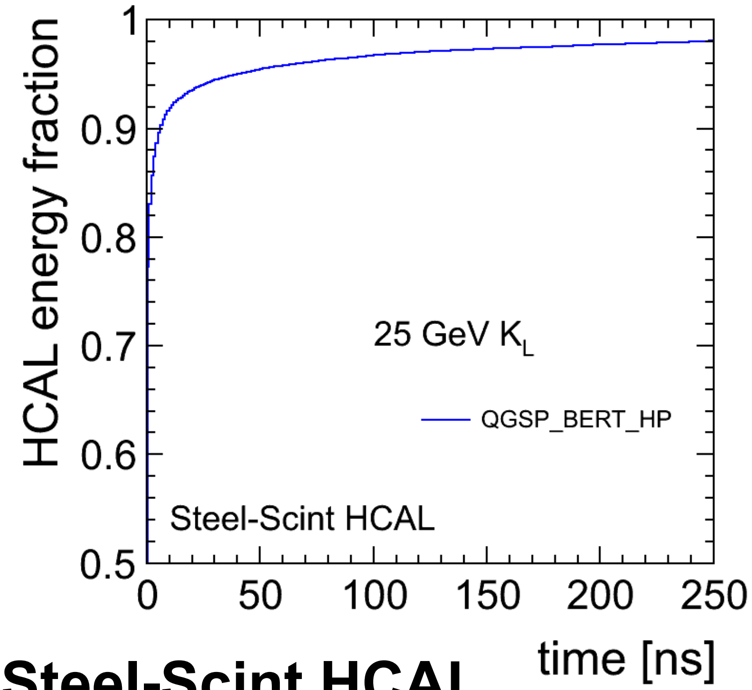
100 GeV pion

Time structure of the showers:

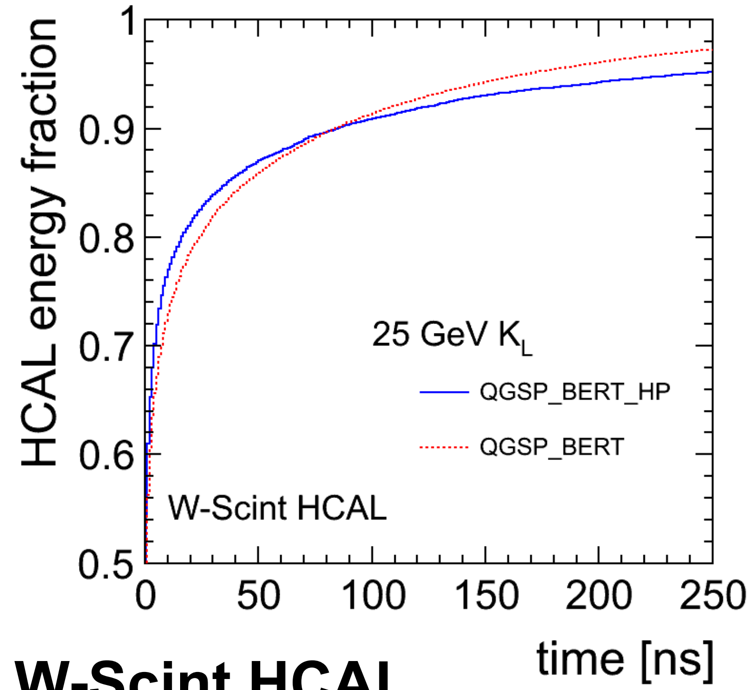


More details:
Talk by Frank Simon
on 24/06/2011

Time development in hadronic showers



Steel-Scint HCAL



W-Scint HCAL

- In steel 90% of the energy is recorded within 6 ns (corrected for time-of-flight)
- In tungsten only 82% of the energy is deposited within 25 ns:

(much larger component of the energy in nuclear fragments)

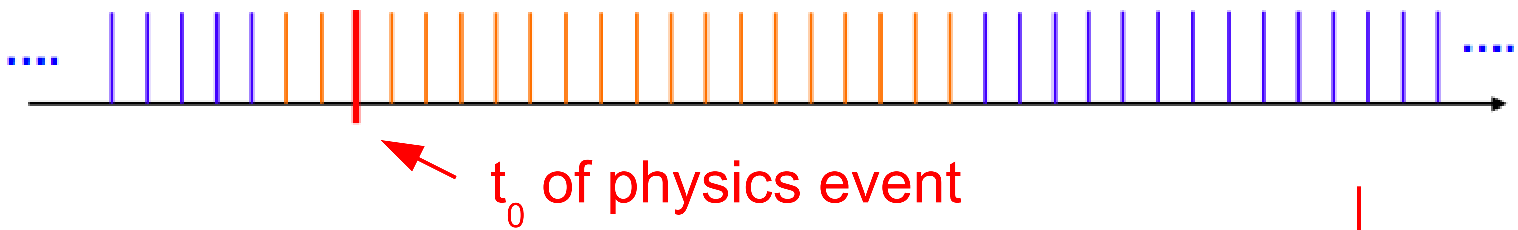
→ Energy resolution degrades if not the majority of calorimeter hits is read

→ Need to integrate over ≈100 ns in the reconstruction, keeping the background level low

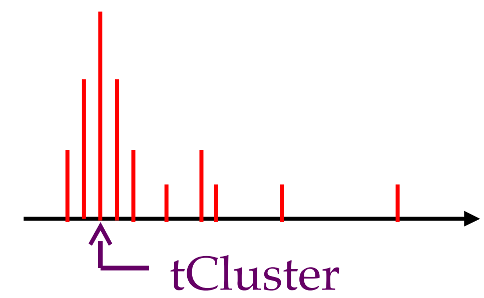
Background suppression and event reconstruction

Background suppression

Triggerless readout of full bunch train:



1.) **Identify t_0 of physics event in offline event filter**



- Define reconstruction window around t_0
- All hits and tracks in this window are passed to the reconstruction

→ Physics objects with precise p_T and cluster time information

2.) **Apply cluster-based timing cuts**

- Cuts depend on particle-type, p_T and detector region

→ Protects physics objects at high p_T

Time windows and hit resolutions

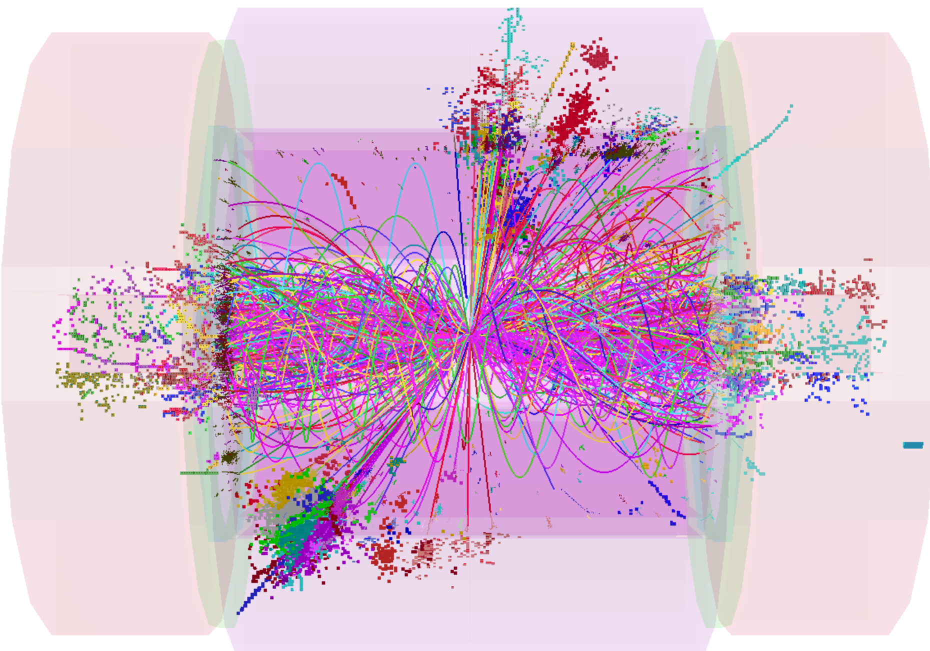
Used in the reconstruction software for CDR simulations:

Subdetector	Reconstruction window	hit resolution
ECAL	10 ns	1 ns
HCAL Endcaps	10 ns	1 ns
HCAL Barrel	100 ns	1 ns
Silicon Detectors	10 ns	$10/\sqrt{12}$ ns
TPC	entire bunch train	n/a

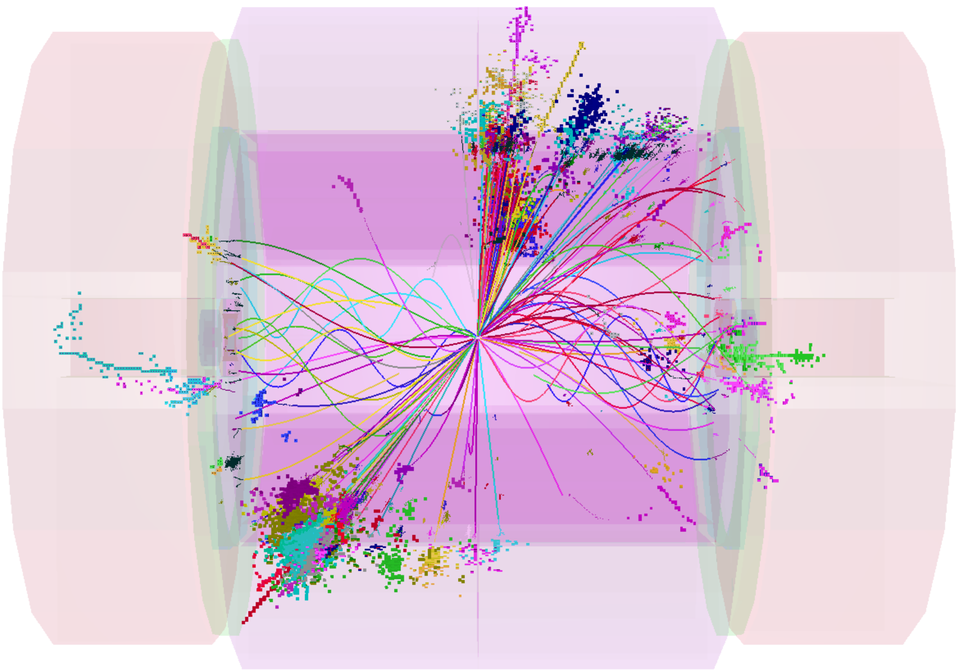
- CLIC hardware requirements
- Achievable in the calorimeters with a sampling every ≈ 25 ns

Impact of the timing cuts

$e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}b\bar{t}$ (8 jet final state)

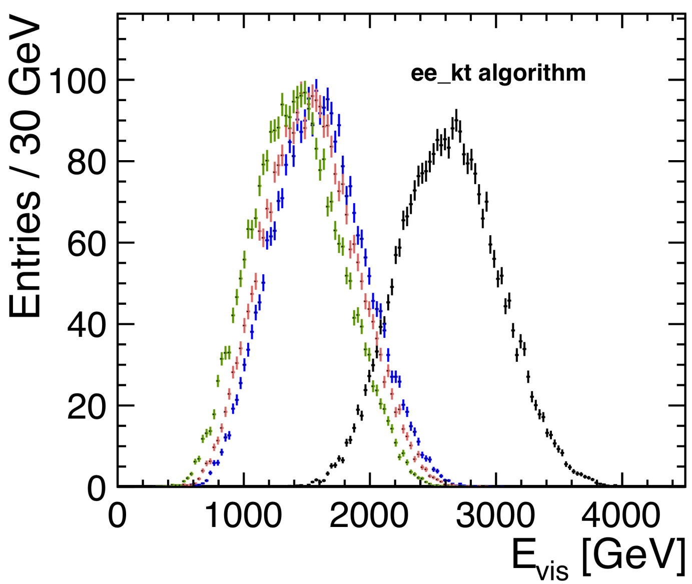


1.2 TeV background
in the reconstruction window



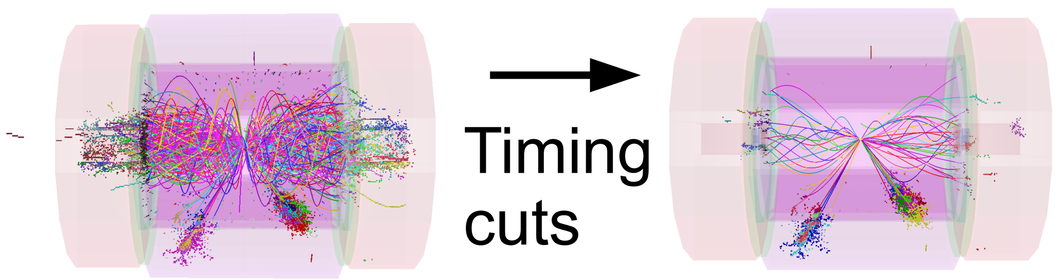
100 GeV background
after (tight) timing cuts

Jet reconstruction at CLIC I



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

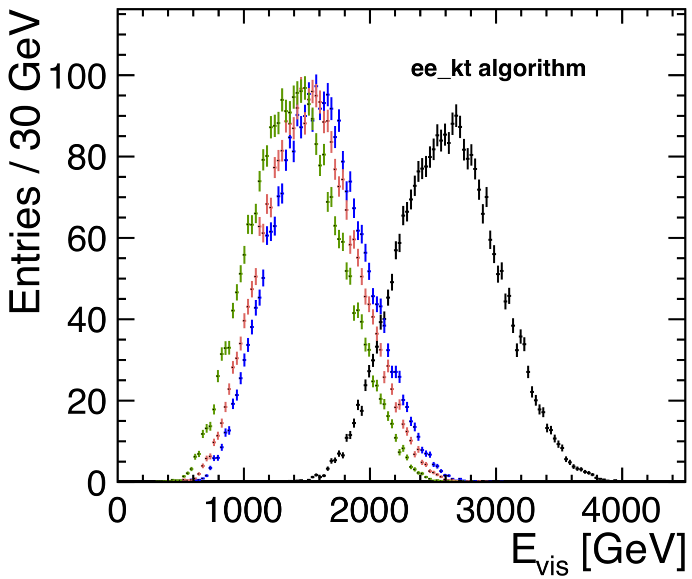
Two jets + missing energy

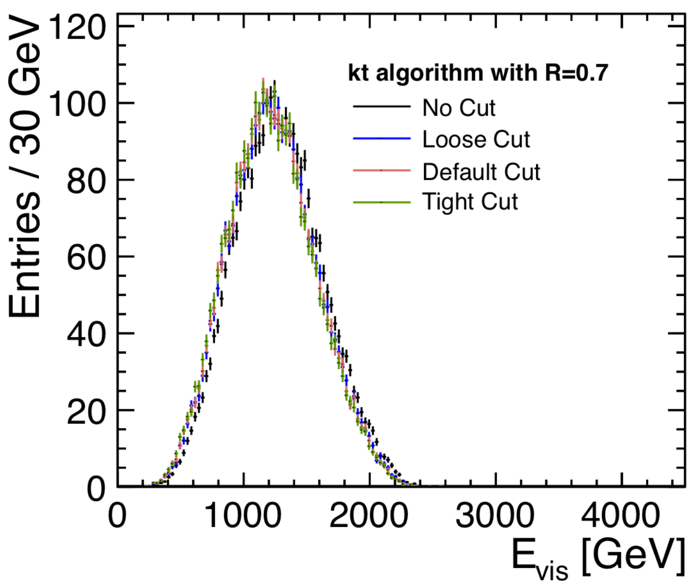


- Using Durham k_T à la LEP

→ Timing cuts are effective, but not sufficient

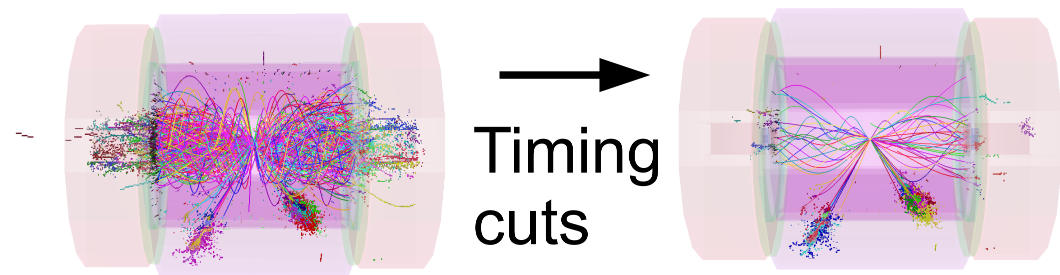
Jet reconstruction at CLIC II





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

Two jets + missing energy



- Using Durham k_T à la LEP

→ Timing cuts are effective, but not sufficient

- "hadron collider" k_T, R = 0.7

→ Background significantly reduced further

→ **Need timing cut + jet finding for background reduction**

Test of the di-jet mass reconstruction

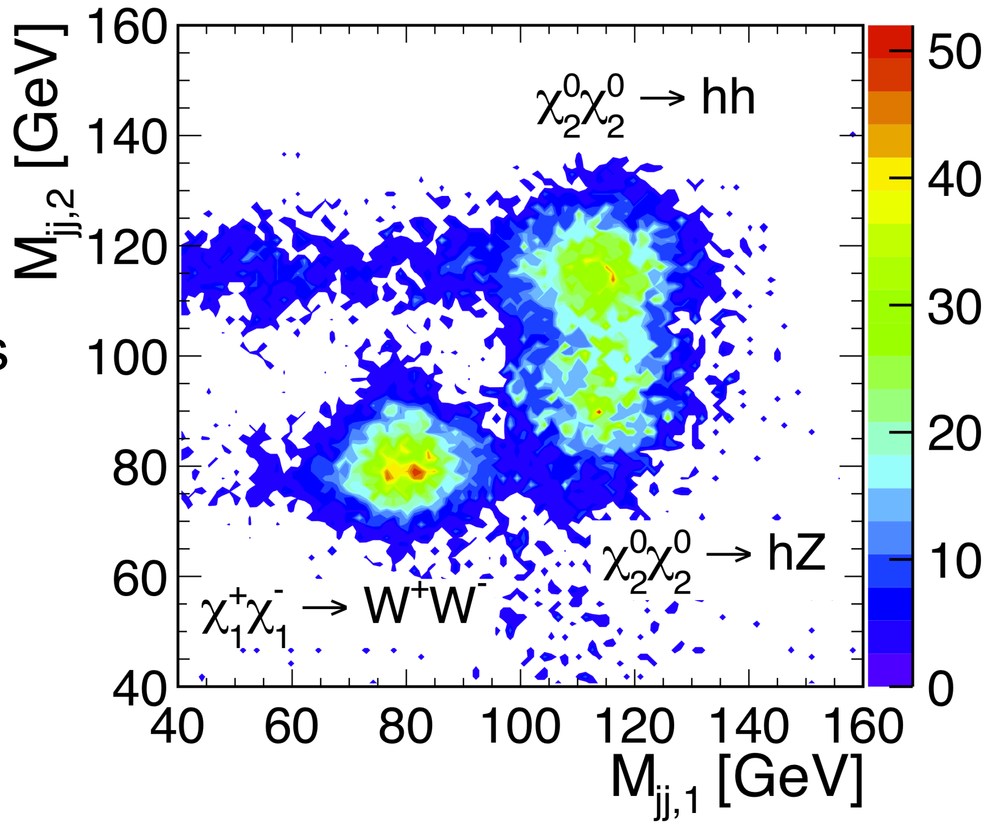
Chargino and neutralino pair production:

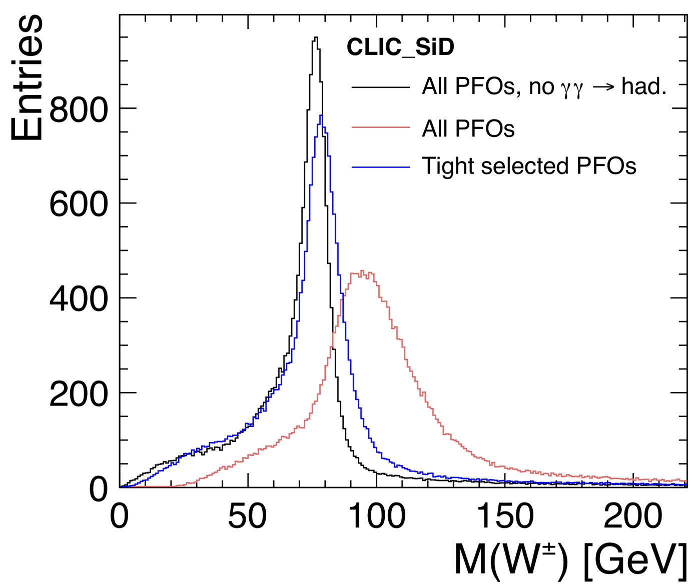
$$e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$$

$$e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow hh\,\tilde{\chi}_1^0\tilde{\chi}_1^0 \quad 82\%$$

$$e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow Zh\,\tilde{\chi}_1^0\tilde{\chi}_1^0 \quad 17\%$$

Reconstruct $W^\pm/Z/h$ in hadronic decays
→ four jets and missing energy





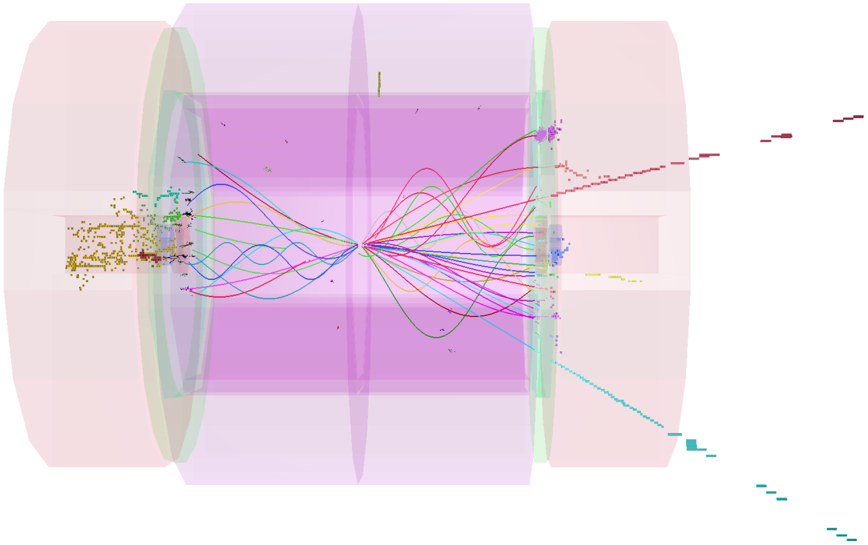
Test of the lepton reconstruction

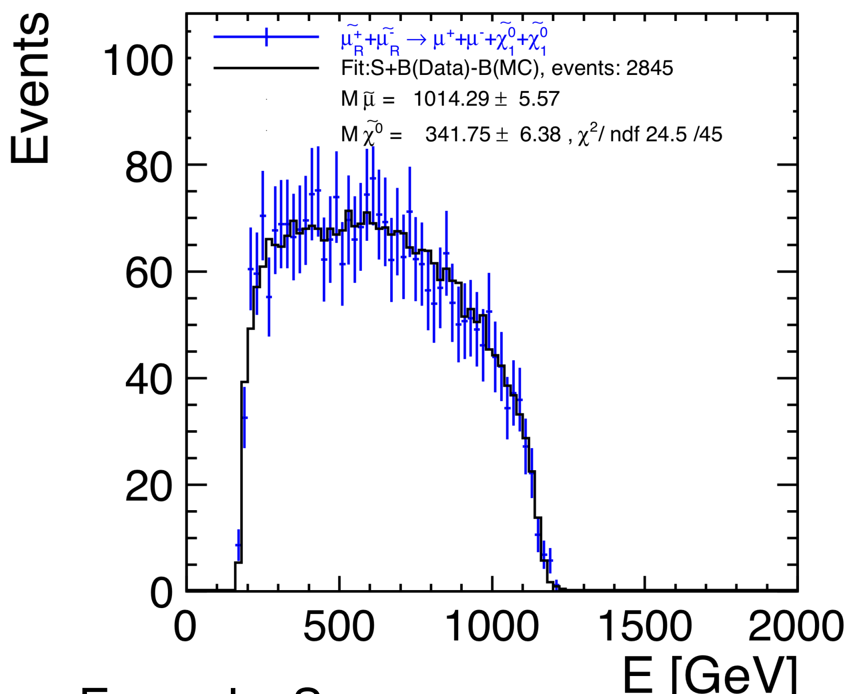
- Slepton production very clean at CLIC
- SUSY “model II”: slepton masses ≈ 1 TeV
- Investigated channels include:

$$e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^- \rightarrow \mu^+\mu^- \, \tilde{\chi}_1^0 \, \tilde{\chi}_1^0$$

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

$$e^+e^- \rightarrow \tilde{\nu}_e\tilde{\nu}_e \rightarrow e^+e^- W^+W^- \, \tilde{\chi}_1^0 \, \tilde{\chi}_1^0$$





Example: Smuons

- Leptons and missing energy
- Masses from endpoints of energy spectra

$$m(\tilde{\mu}_R) \; : \; \pm 5.6 \,\text{GeV}$$

$$m(\tilde{e}_R) \; : \; \pm 2.8 \,\text{GeV}$$

$$m(\tilde{\nu}_e) \; : \; \pm 3.9 \,\text{GeV}$$

$$m(\tilde{\chi}_1^0) \; : \; \pm 3.0 \,\text{GeV}$$

$$m(\tilde{\chi}_1^\pm) \; : \; \pm 3.7 \,\text{GeV}$$

More detector benchmarks

- Full physics simulation and reconstruction with pileup from beam background ($\gamma\gamma \rightarrow$ hadr.)

- Seven channels chosen to cover various crucial aspects of detector performance (jet measurements, missing energy, isolated leptons, flavour tagging, ...)

Summary and outlook

- Main message of the CLIC physics and detector CDR:
Physics at a 3 TeV CLIC e^+e^- collider can be measured with high precision, despite challenging background conditions

- Backgrounds studied in detail:
  - Require high granularity in space and time
  - Define detector requirements and guide future R&D

- Next project phase (5 years):
  - CLIC detector R&D (within the international LC R&D program)
  - Further physics studies (LHC input) + detector optimisation

- Signatories to support the physics case and R&D towards a future linear collider based on CLIC technology are currently collected here:

  https://indico.cern.ch/conferenceDisplay.py?confId=136364

Backup slides

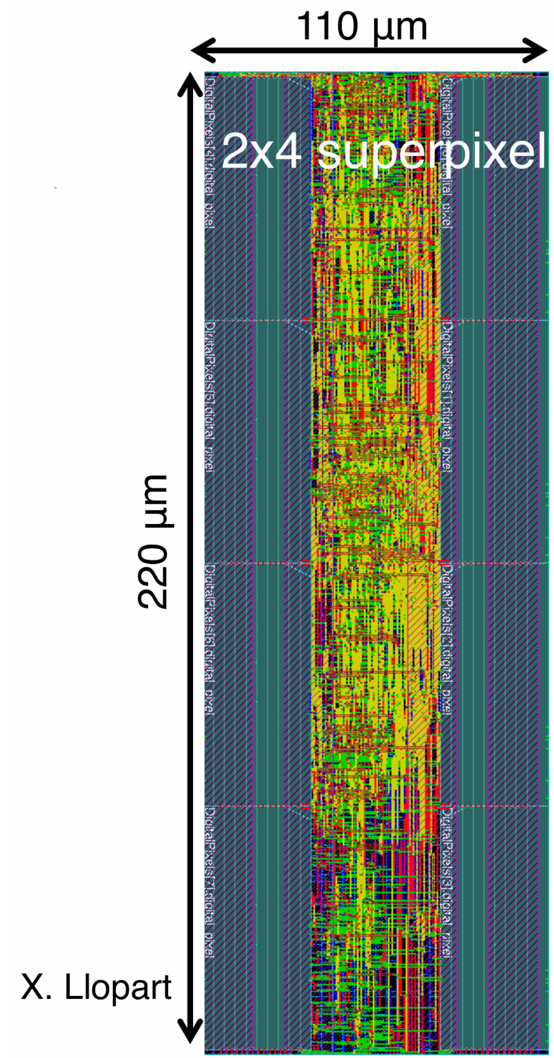
Examples for hybrid approach

Thinned high-resistivity fully depleted sensors:
- 50 μm active width
- Example: ALICE pixel upgrade → meets CLIC goals

Fast low-power readout chips:
- Timepix3 (2012) in 130 nm IBM CMOS:
  - 55 x 55 μm^2 pixels
  - 1.5 ns time resolution → exceeds CLIC goals
  - P ≈ 350 mW / cm^2 → meets CLIC goals (with power pulsing)
- CLICPix (prototypes ≈2014) in 65 nm:
  - 20 x 20 μm^2 pixels

Low-mass interconnects between senor+readout:
- Cost driver → needs further R&D
- Technologies: Through-Silicon Vias (TSV), 3D interconnects, edgeless sensors, stitching of CMOS arrays

Timepix3 design

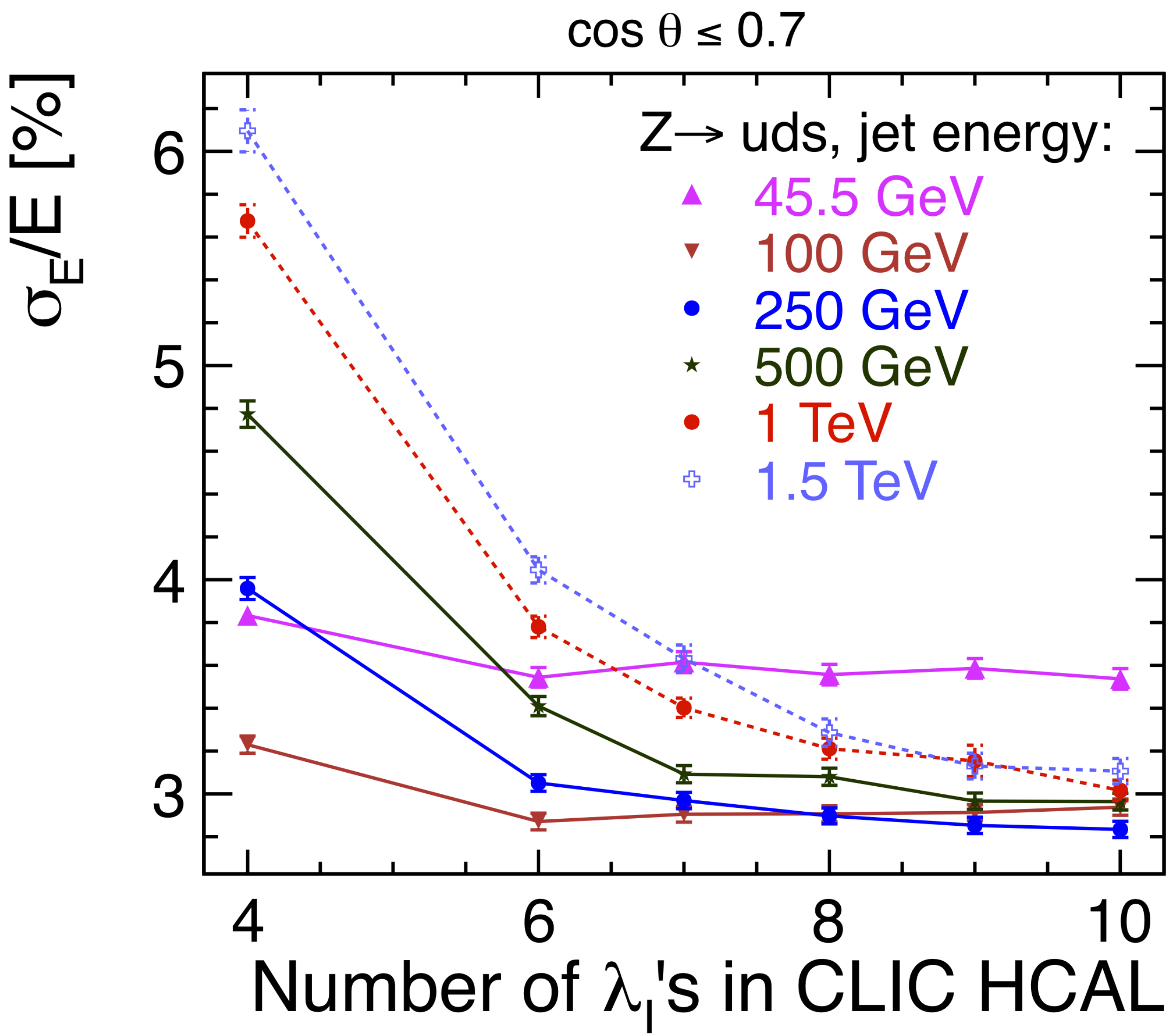


Examples for integrated approach

- Several active R&D programs (targeted to ILC requirements)

- Attempts to reach faster signal collection and ns time-stamping capability (compatible with CLIC requirements):
  - **MIMOSA CMOS** chip family (currently 350 nm): developing high-resistivity epitaxial layers, smaller feature sizes
  - **Chronopixel CMOS** sensors with fully depleted epitaxial layer
  - **INMAPS** technology: deep p-well barrier protects n-well charge collector, improves charge collection, allows for high-resistivity epitaxial layer and full featured CMOS MAPS technology
  - **High voltage CMOS:** CMOS signal processing electronics embedded in reverse-biased deep n-well that acts as signal collecting electrode
  - **Silicon-On-Insulator (SOI)**: ≈200 nm SiO_2 isolation layer separates charge collection and readout functionality
  - **Full 3D-integrated pixel sensors:** Thinned high-resistivity sensitive tier coupled to additional tiers with advanced analog+digital functionality

HCAL resolution

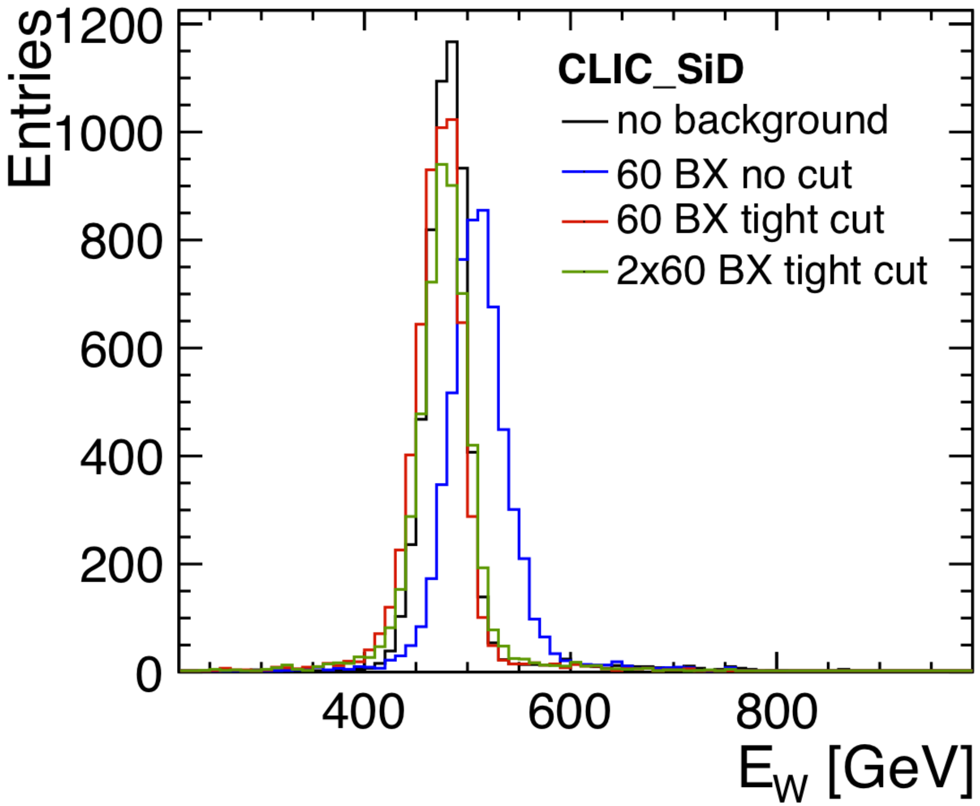


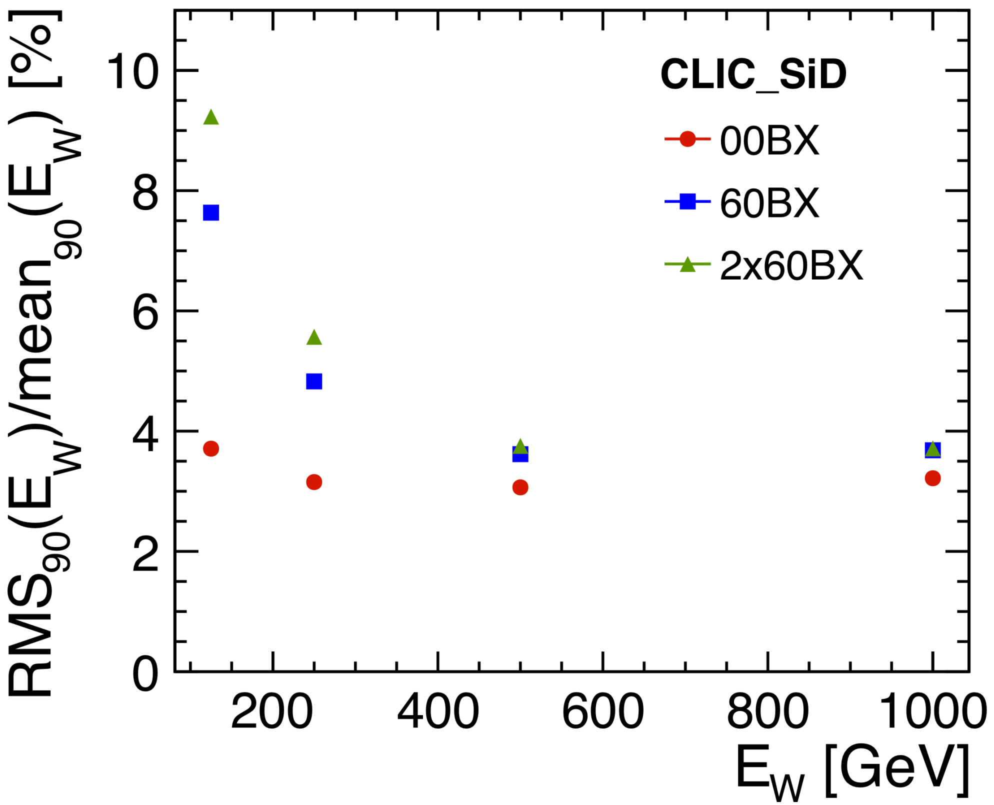
PFO based timing cuts

Region	p_t *range*	Time cut
Photons		
central ($\cos\theta \leq 0.975$)	$0.75\ \text{GeV} \leq p_t < 4.0\ \text{GeV}$	$t < 2.0$ nsec
	$0\ \text{GeV} \leq p_t < 0.75\ \text{GeV}$	$t < 1.0$ nsec
forward ($\cos\theta > 0.975$)	$0.75\ \text{GeV} \leq p_t < 4.0\ \text{GeV}$	$t < 2.0$ nsec
	$0\ \text{GeV} \leq p_t < 0.75\ \text{GeV}$	$t < 1.0$ nsec
Neutral hadrons		
central ($\cos\theta \leq 0.975$)	$0.75\ \text{GeV} \leq p_t < 8.0\ \text{GeV}$	$t < 2.5$ nsec
	$0\ \text{GeV} \leq p_t < 0.75\ \text{GeV}$	$t < 1.5$ nsec
forward ($\cos\theta > 0.975$)	$0.75\ \text{GeV} \leq p_t < 8.0\ \text{GeV}$	$t < 2.0$ nsec
	$0\ \text{GeV} \leq p_t < 0.75\ \text{GeV}$	$t < 1.0$ nsec
Charged PFOs		
all	$0.75\ \text{GeV} \leq p_t < 4.0\ \text{GeV}$	$t < 3.0$ nsec
	$0\ \text{GeV} \leq p_t < 0.75\ \text{GeV}$	$t < 1.5$ nsec

- Track-only minimum p_t: 0.5 GeV
- Track-only maximum time at ECAL: 10 nsec

Influence of pileup





W^+W^- and ZZ

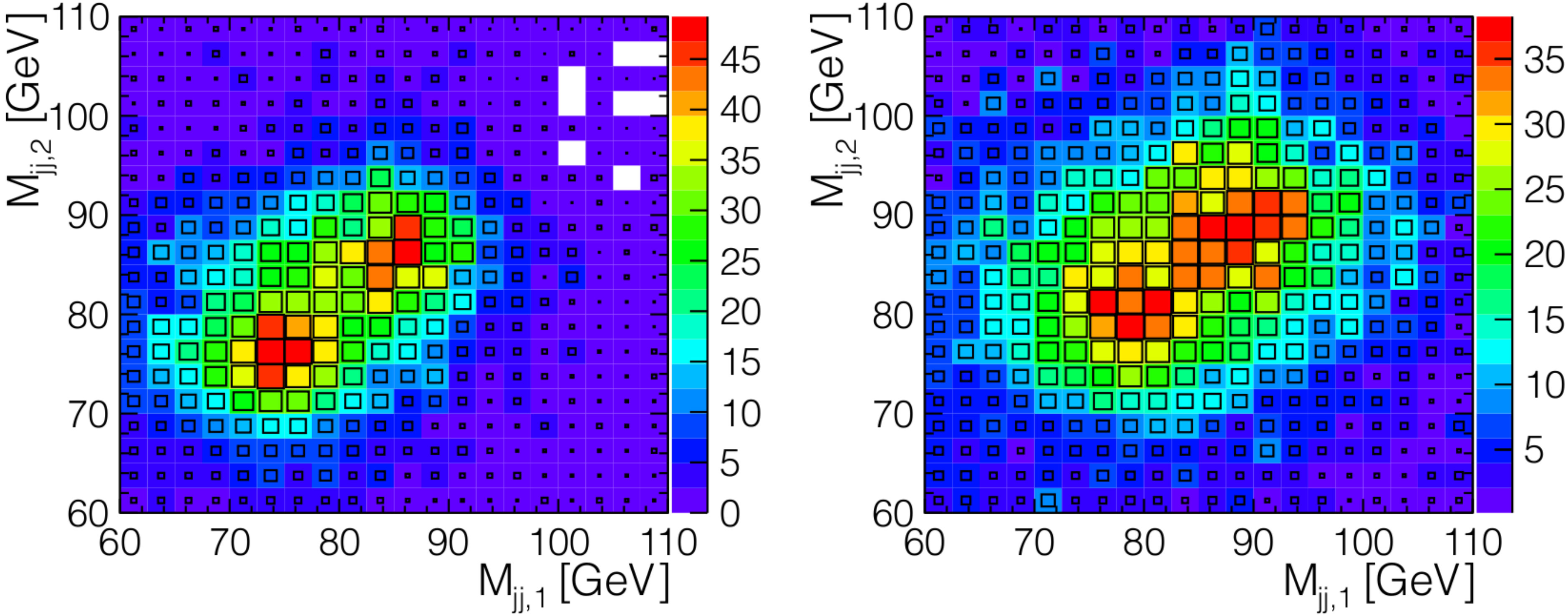


Figure 19: Separation of *W* and *Z* from the chargino decay without overlay (left) and with 60 BX of background (right) for CLIC_SiD.