Physics and Detectors at CLIC

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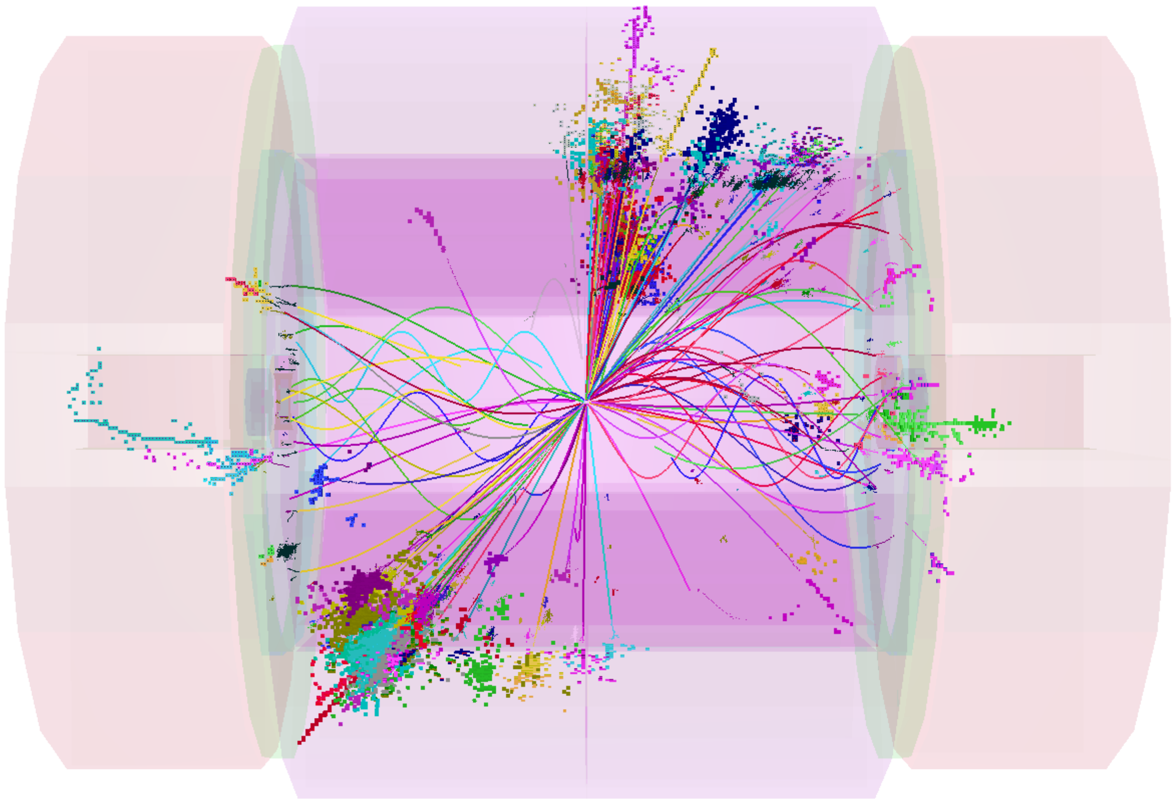


Overview

This talk:

- Introduction to the CLIC Accelerator
- Physics at CLIC
- Experimental Conditions at CLIC
- The CLIC Detector Concepts
- Background Suppression at CLIC
- Physics Benchmark Studies
- Beyond the CDR
- Summary/Conclusions

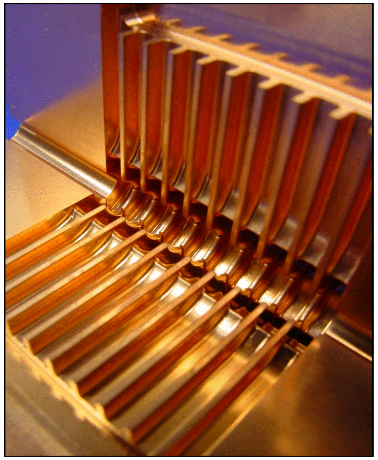
A Brief Introduction to CLIC

CLIC in a Nutshell

CLIC = Compact Linear Collider

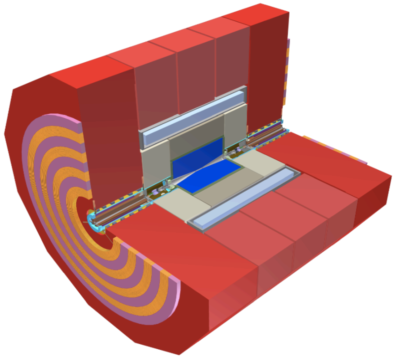
Accelerator:

- ★ High luminosity, high energy e^+e^- linear collider
- ★ Based on 2-beam acceleration scheme
  - Gradient of 100 MV/m (warm technology)
  - Strong accelerator R&D programme at CERN
- ★ Energy:
  - From a few-hundred GeV
  - Upgradable in steps to 3 TeV



Detector:

- ★ Two detector concepts CLIC_ILD and CLIC_SiD
  - based on concepts developed for ILC
- ★ Studies have focussed on 3 TeV requirements

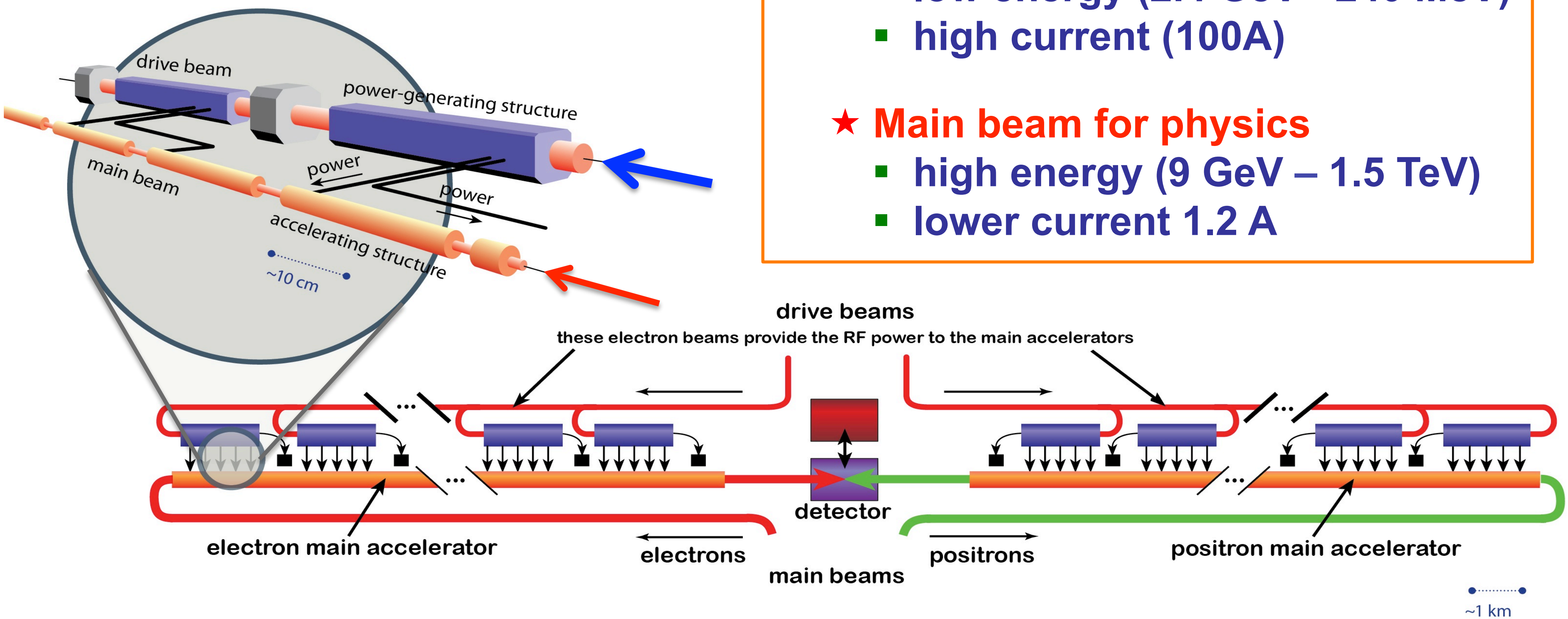


Accelerating gradient: 100 MV/m
⇨ **"compact"**

Two beam scheme:

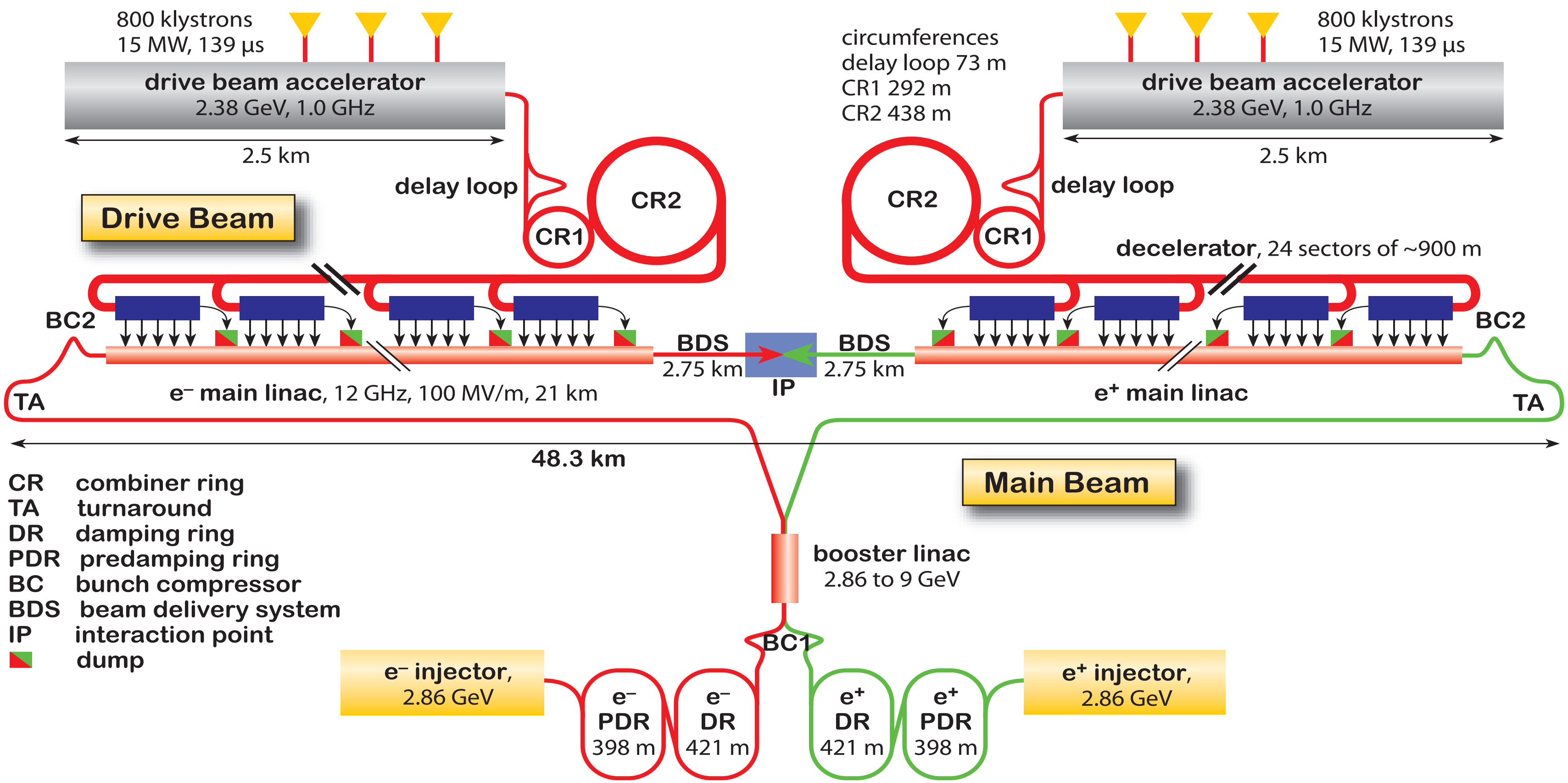
★ **Drive Beam supplies RF power**
- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

★ **Main beam for physics**
- high energy (9 GeV – 1.5 TeV)
- lower current 1.2 A



CLIC Layout at 3 TeV

★ **CLIC is a complex machine**
- effectively two accelerators
- a number of technical challenges
- nevertheless, very promising progress on R&D at **CTF3** (CLIC Test Facility)



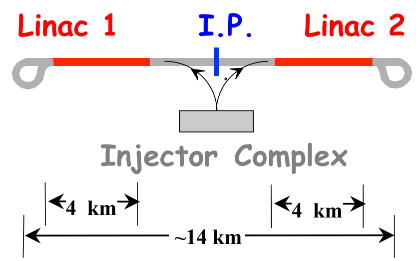
Drive Beam Generation Complex

Main Beam Generation Complex

CLIC Staging

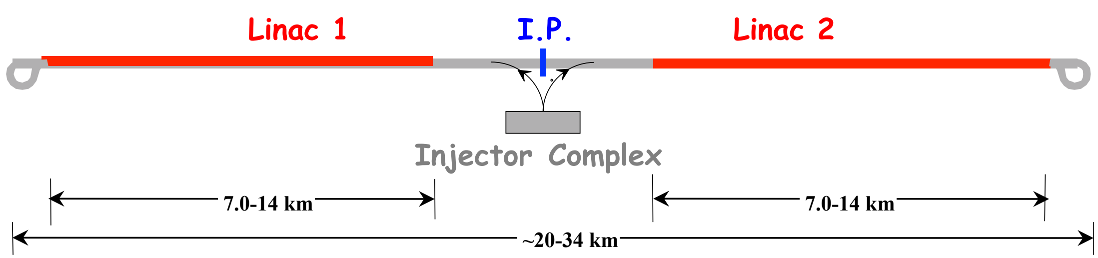
★ **Currently foreseen that CLIC construction would be staged**
- compatible with two beam scheme compatible
- lower energy machine running during most of construction of next stage
- details of staging will depends on LHC physics results and/or CLIC goals.

0.5 TeV Stage

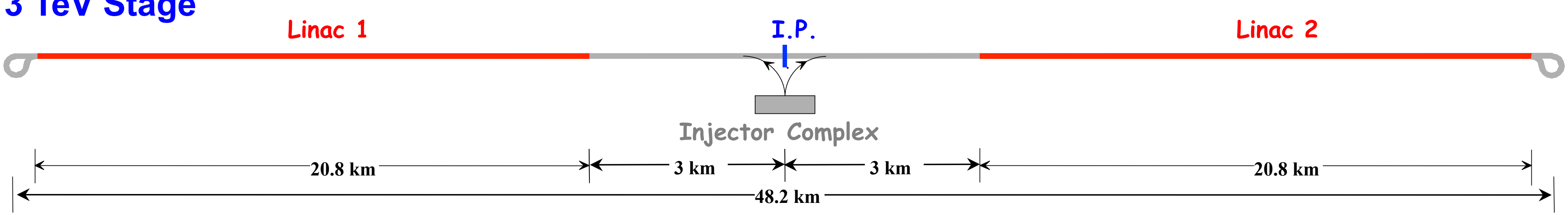


14 km

1-2 TeV Stage



3 TeV Stage

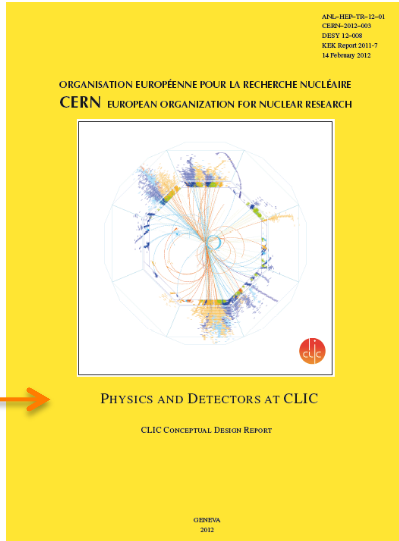


CLIC Status

- ★ Currently at Conceptual Design Report (CDR) Stage
- ★ Moving towards the technical design phase

The three volumes of the CLIC CDR:

- ★ **Accelerator**
  - No show-stoppers identified
  - Accelerating gradient in reach
  - Officially presented to CERN SPC, final text editing ongoing
  - http://clic-study.org/accelerator/CLIC-ConceptDesignRep.php
- ★ **Physics and Detectors - published**
  - http://arxiv.org/abs/1202.5940
- ★ **Strategic CDR volume (energy staging, cost, ...)**
  - In progress, ready summer 2012



Signatories list of the **CLIC CDR**

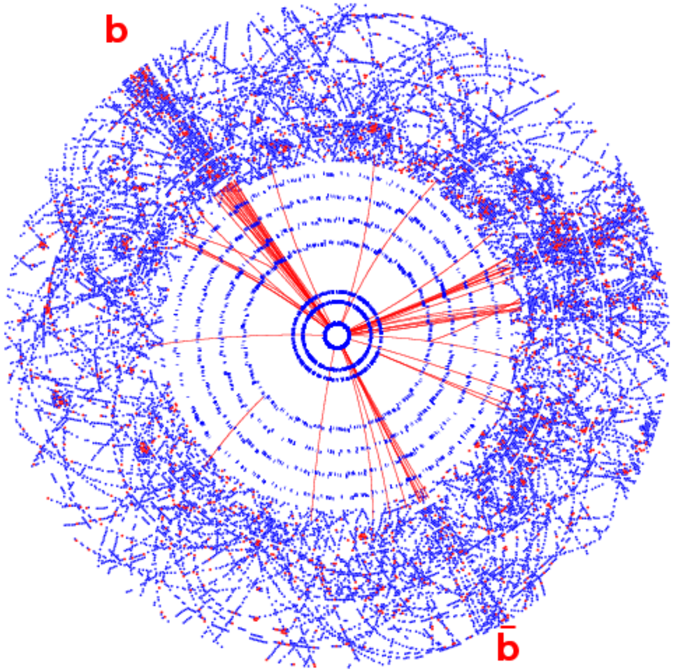
https://indico.cern.ch/conferenceDisplay.py?confId=136364

Currently 1377 signatories

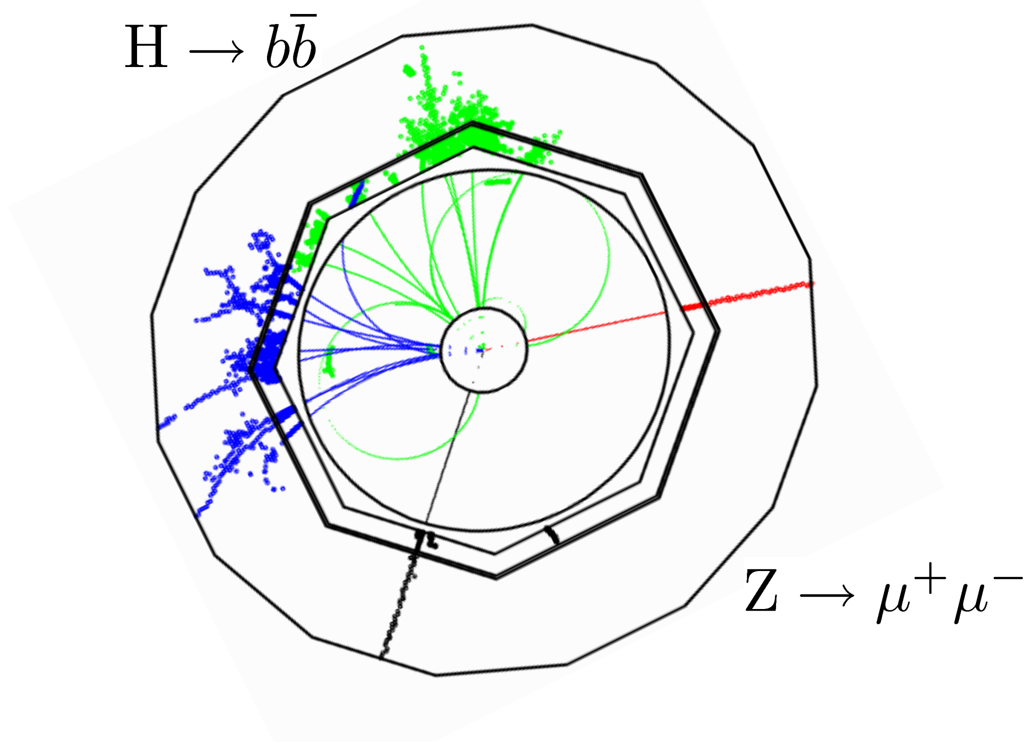
CLIC Physics Potential

★ **Electron-positron colliders provide clean environment for precision physics**

The LHC $\mathrm{pp} \rightarrow \mathrm{H} + X$



Future Linear Collider $\mathrm{e^+e^-} \rightarrow \mathrm{HZ}$



★ **At an electron-positron collider, the observed final state corresponds to the underlying physics interaction**

CLIC Physics Potential

★ CLIC physics potential is complementary to that of the LHC / HL LHC

★ **In particular, electron-positron collisions bring**
- clean experimental conditions
- precision Higgs physics (SM and BSM)
- access to weakly coupled BSM states, e.g. sleptons, gauginos

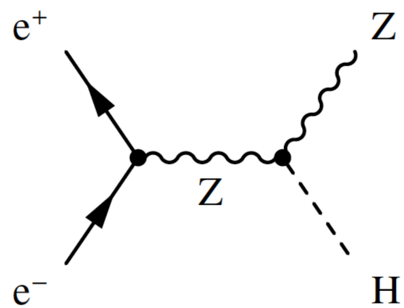
★ Physics highlighted in CDR include
- Higgs (discussed in following slides)
- Top
- SUSY (discussed later in context of benchmark studies)
- Z'
- Contact interactions
- Extra dimensions
- …

★ Experimental sensitivities are now well understood, many studies based on
- Full simulation/reconstruction (see later)
- Including pile-up of background

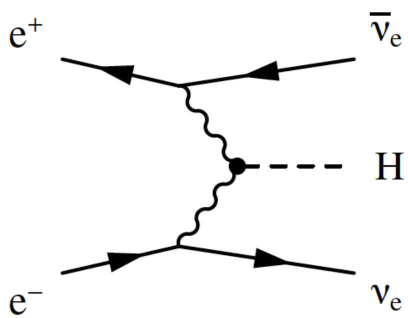
Standard Model Higgs

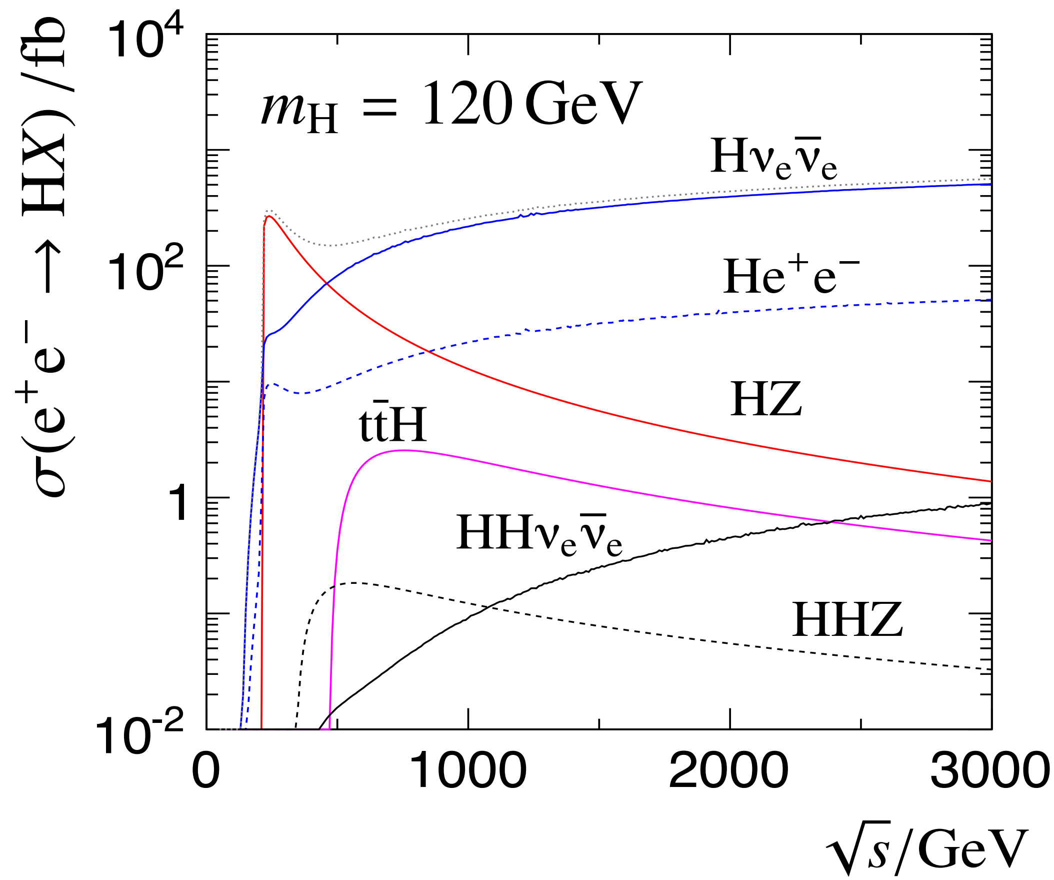
★ A number of SM Higgs processes accessible at CLIC

★ Below √s = 500 GeV
Higgs-strahlung dominates



★ Above √s = 500 GeV
WW fusion dominates

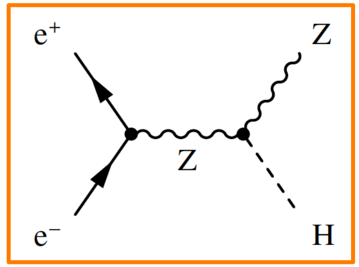


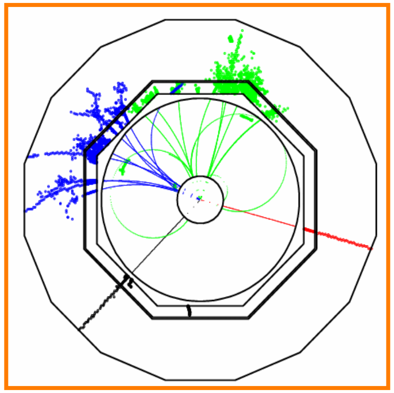


★ CLIC energy stages, provide a rich program of precision Higgs physics

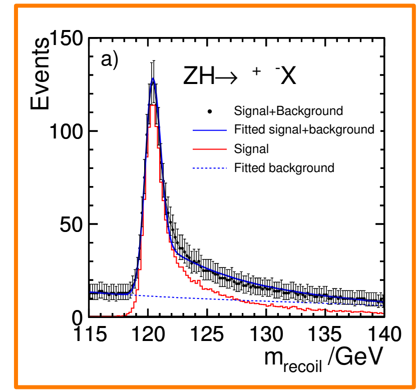
Higgs-strahlung

★ During first stage of CLIC (or at the ILC) study Higgs-strahlung process





★ **Model independent analysis**
- Select Higgs based on mass recoiling against leptonically decaying Z
- Measure Higgs BRs



★ Measure Higgs production cross section **independent of Higgs decay**
- Sensitive to invisible Higgs decay modes
- **Absolute** measurement of HZ coupling

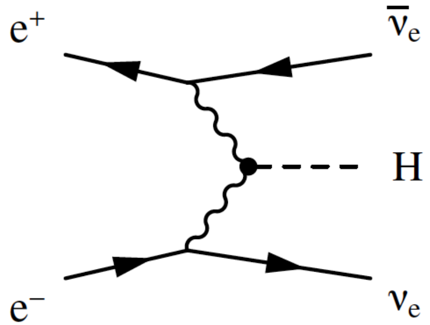
★ e.g. 250 fb^{-1} at $\sqrt{s}$ = 350 GeV

$$\frac{\Delta(\sigma)}{\sigma} \sim 4\,\% \quad \Rightarrow \quad \frac{\Delta(g_{\mathrm{HZZ}})}{g_{\mathrm{HZZ}}} \sim 2\,\%$$

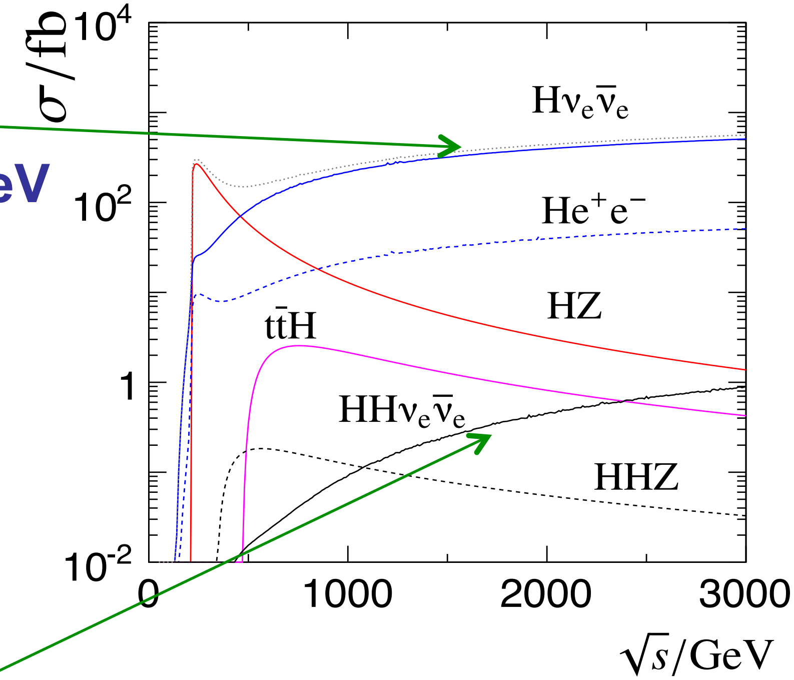
Higgs at High energies

★ **In a higher energy stage of CLIC…**

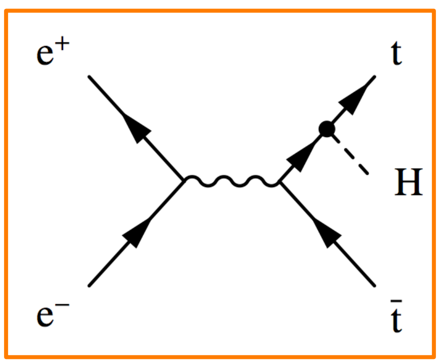
- **Fusion cross section becomes large**
- **x3 larger peak luminosity at 3 TeV vs 500 GeV**
- **Large numbers of $H\nu_e\bar{\nu}_e$ events**

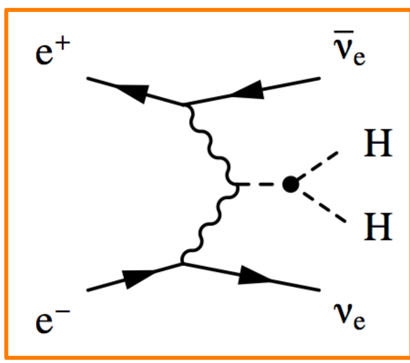


	√s = 3 TeV
Int Lumi [fb]	2000
Cross section [fb]	510
N(Hνν) Events	10^6



- **Precise BR measurements**



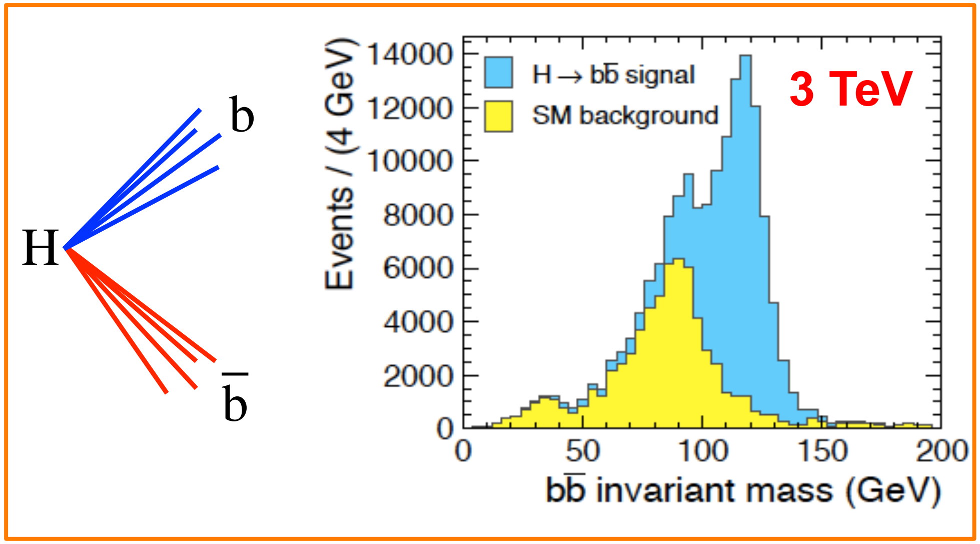


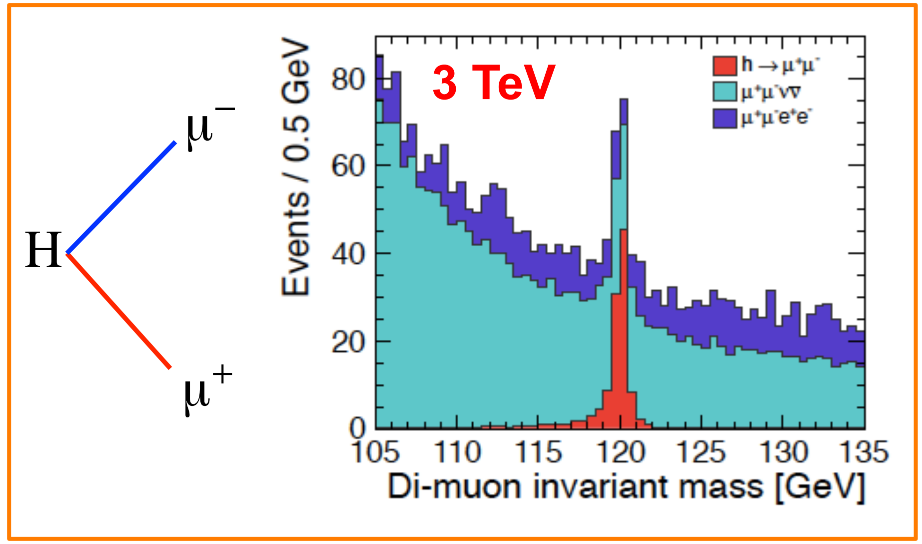
★ **+ Rarer processes give access to**

- **top Yukawa coupling**
- **Higgs self-couplings**

BRs and Self-Couplings

★ **Full detector simulation/reconstruction studies at 3 TeV with pile-up**

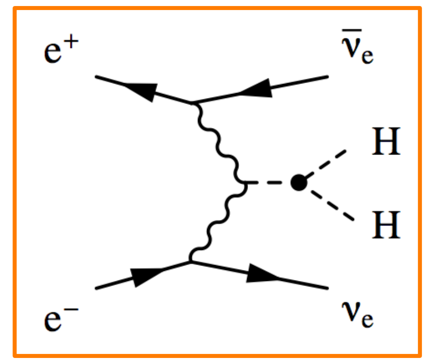




⇒ $\sigma(H \to b\bar{b}) \sim \pm 0.2\,\%$ | $\sigma(H \to c\bar{c}) \sim \pm 3\,\%$ | $\sigma(H \to \mu^+\mu^-) \sim \pm 15\,\%$

★ **Initial studies of HH production achieve sensitivities to Higgs self-coupling of**

$\Delta\lambda/\lambda < 20\,\%$ (at 1.4 TeV) $\Delta\lambda/\lambda < 25\,\%$ (at 3.0 TeV)

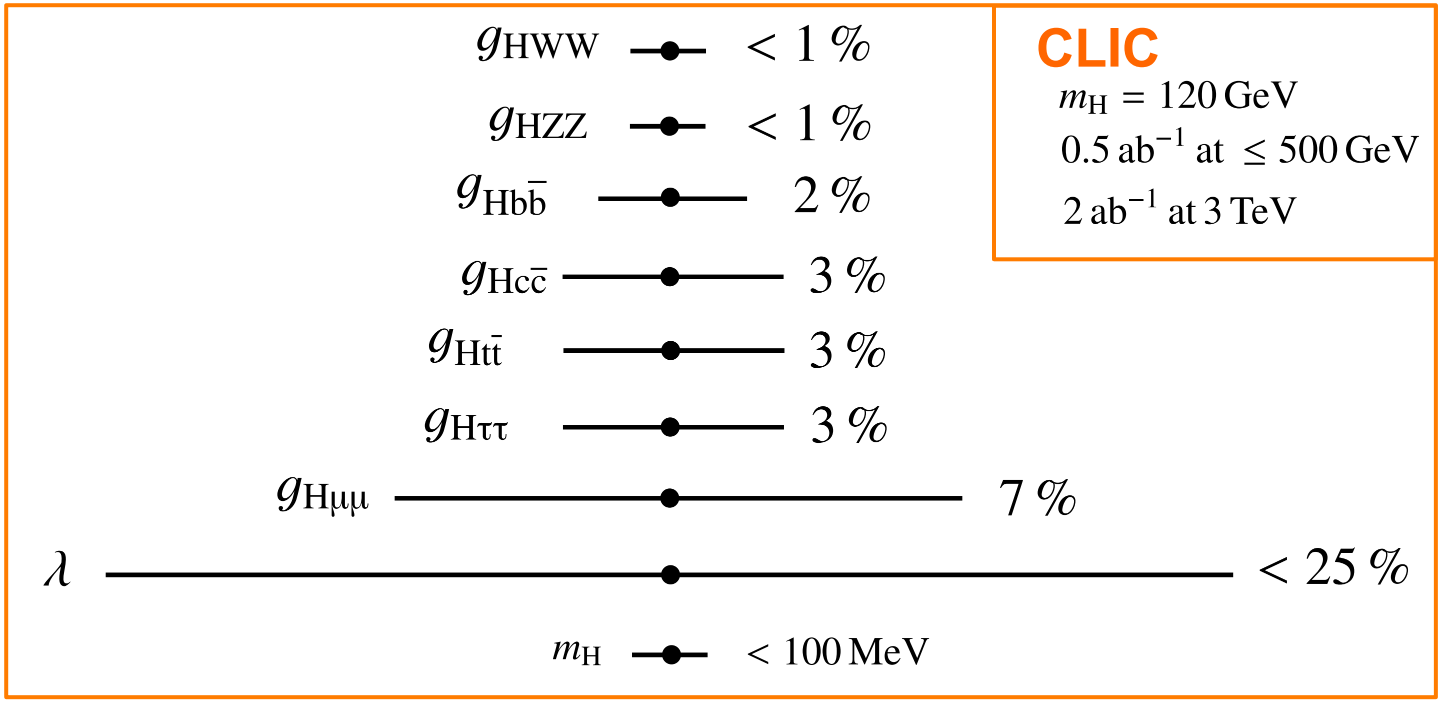


★ **Direct probe of Higgs potential !**

SM-like Higgs Summary

★ **Current understanding of "SM-like" Higgs precision at CLIC**

*still work in progress, e.g. top coupling extrapolated from ILC study

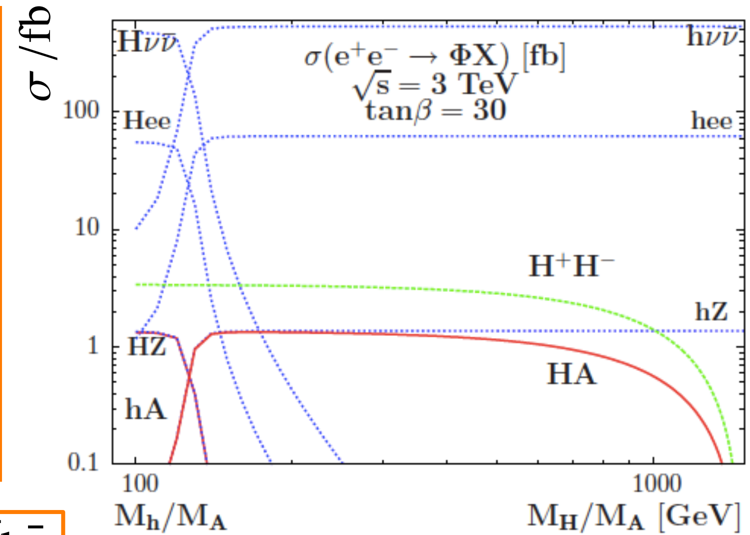


★ **Such precise measurements would pin down Higgs sector, e.g.**

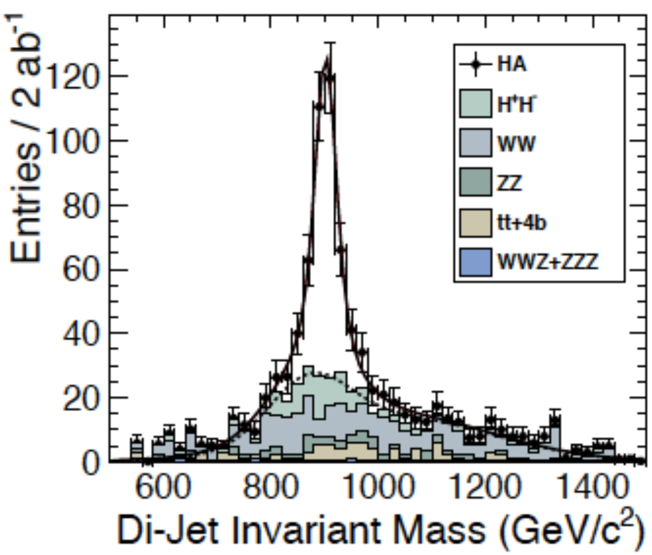
- **SM vs 2HDM**
- **+ probe Higgs potential itself**

BSM Higgs

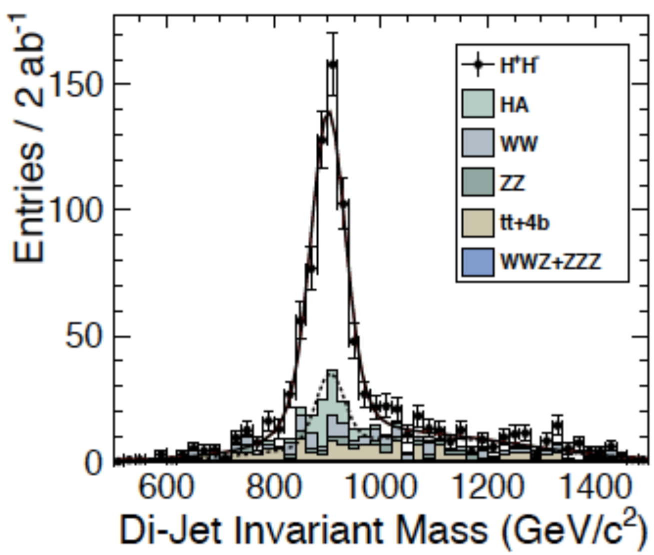
- ★ **In MSSM have extended Higgs sector**
  - **5 Higgs states from 2 Higgs doublets**
  - **gives rise to heavy states**
  - **in CDR studied models with 750 GeV and 900 GeV (near degenerate) heavy Higgs**
  - **cross sections significant at $\sqrt{s}$ = 3 TeV**
  - **multi-jet final states**



$e^+e^- \to H^0A^0 \to b\bar{b}b\bar{b}$



$e^+e^- \to H^+H^- \to t\bar{b}b\bar{t}$



2 ab^{-1}

m_{A^0/H^0} : ± 2.8 GeV

$m_{H^\pm}$: ± 2.4 GeV

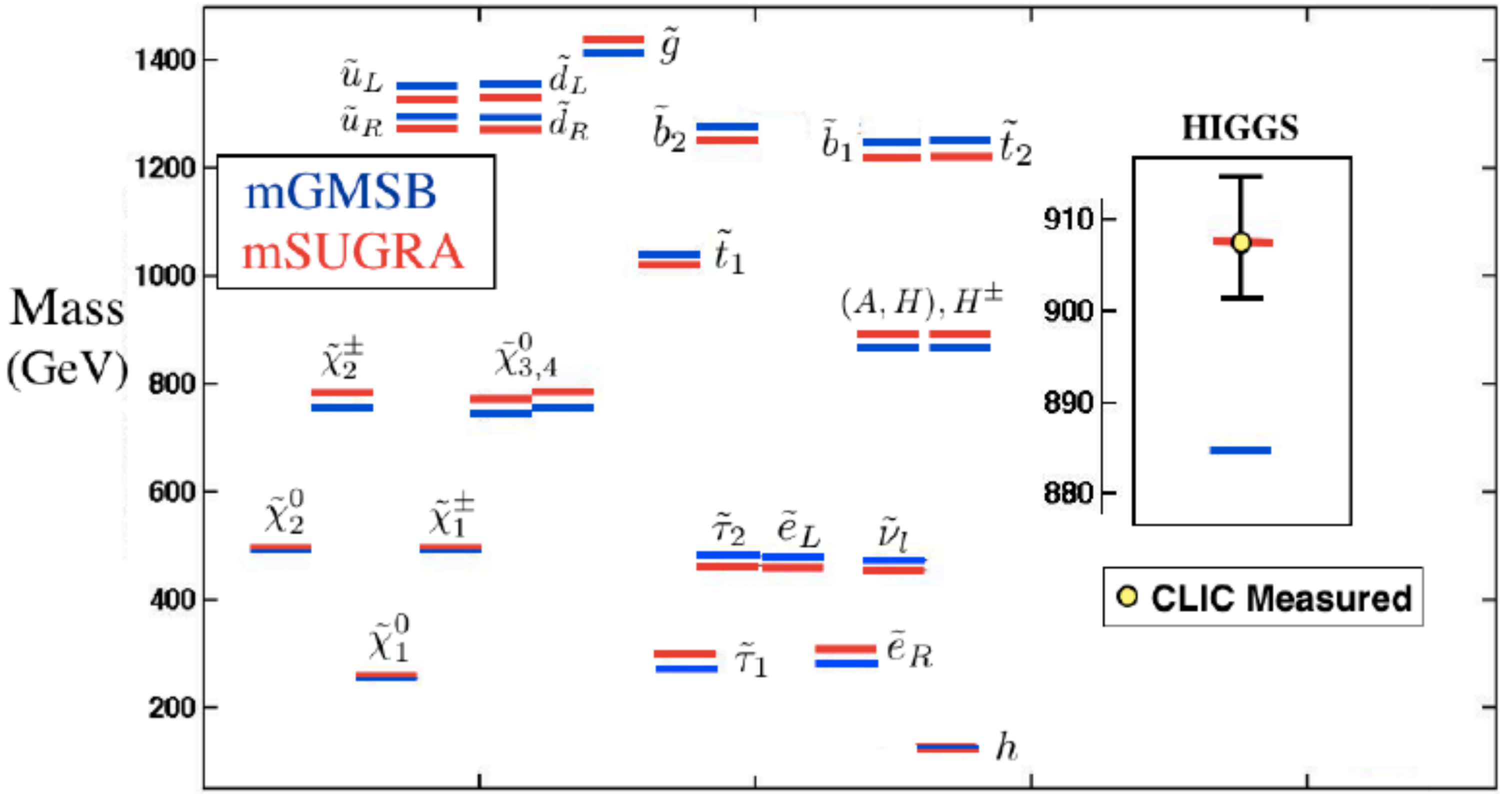
Sensitivity upto

$m_A \sim 1.4$ TeV

Power of precision

Precision measurements at CLIC allow one to distinguish between models of new physics, e.g. following first observations at LHC

e.g. CLIC resolving power for SUSY breaking models



★ **Have just scratched the surface of Higgs physics at CLIC**
★ **Rely on making precision physics in CLIC environment…**

Experimental Conditions at CLIC

CLIC Machine Environment

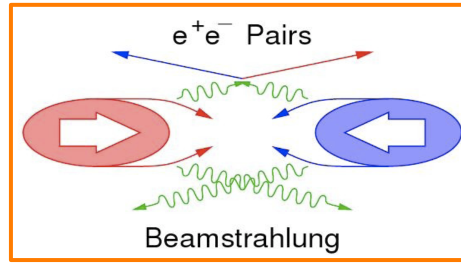
★ CLIC machine environment much more challenging than, e.g. LEP

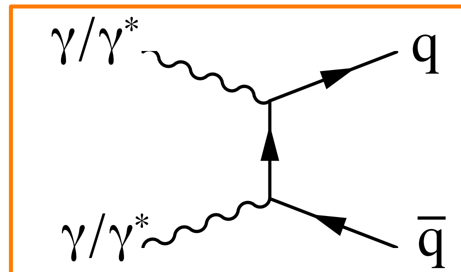
	LEP 2	CLIC at 3 TeV
L ($cm^{-2}s^{-1}$)	5×10^{31}	5.9×10^{34}
BX separation	247 ns	0.5 ns
#BX / train	4	312
Train duration	1 μs	156 ns
Rep. rate	50 kHz	50 Hz
σ_x / σ_y	240/4 μm	≈ 45 / 1 nm
σ_z		44 μm

Drives timing Requirements for CLIC detector

★ Beam related background:

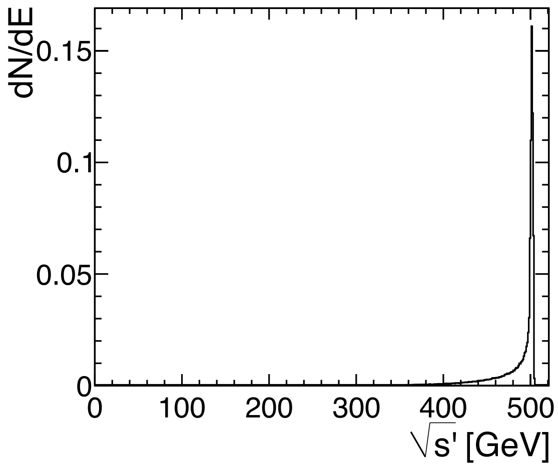
- Small beam profile at IP leads very high E-field:
  - Beamsstrahlung
  - Pair-background
- Interactions of real and virtual photons:
  - $\gamma\gamma \rightarrow$ hadrons "mini-jets"

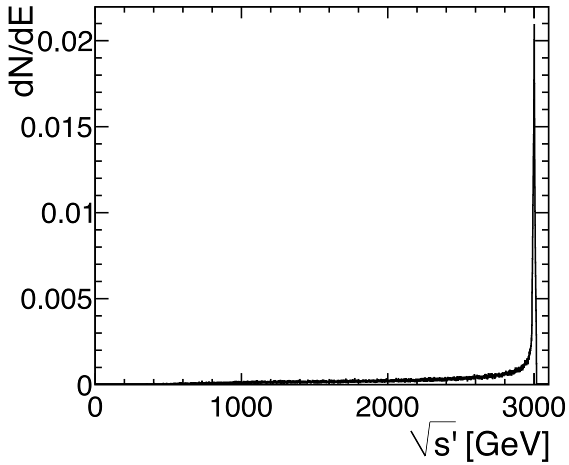




Beamsstrahlung

★ Beamsstrahlung results in a distribution of centre-of-mass energies
- Large effect at CLIC due to small beam size, $\sqrt{s'} > 99\,\%\ \sqrt{s}$
    - 62 % at 500 GeV
    - 35 % at 3 TeV





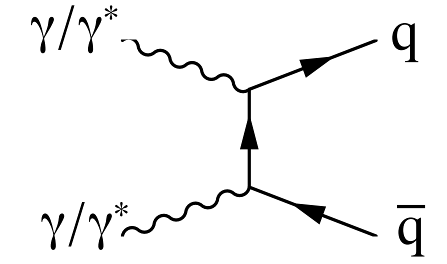
$\sqrt{s'}/\sqrt{s}$	0.5 TeV	3 TeV
> 99 %	62 %	35 %
> 90 %	89 %	54 %
> 70 %	99 %	76 %
> 50 %	~100 %	88 %

★ **Impact on physics** – depends on final state
- Reduces effective luminosity at nominal centre-of-mass energy
    - not so important for processes well above threshold
- Well above threshold, boost along beam axis
    - can distort kinematic edges, e.g. in SUSY searches

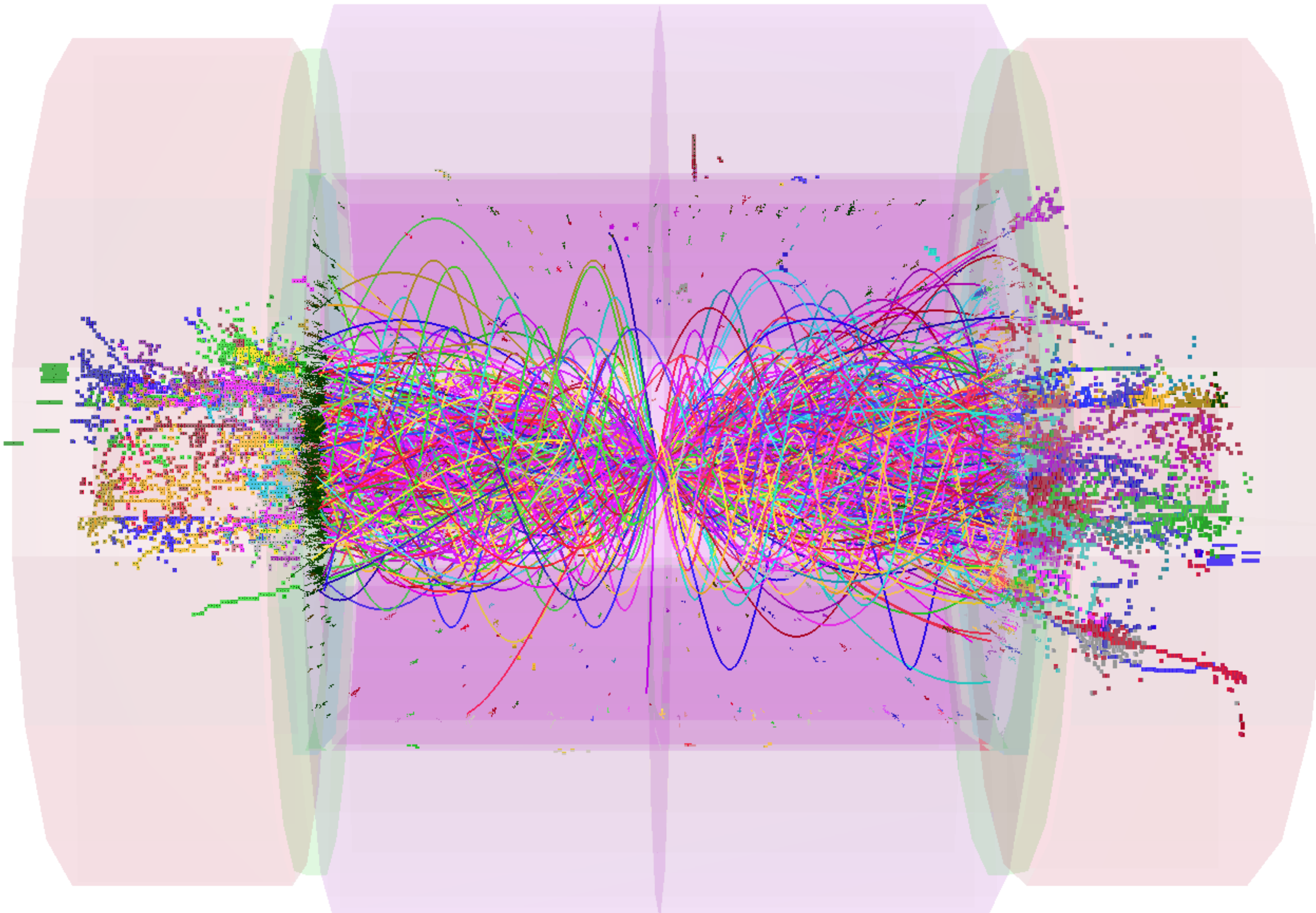
Impact of Background

- ★ Large backgrounds from interactions of real (Beamsstrahlung) and virtual photons
  - Coherent e^+e^- pairs (real)
    - 7×10^8 per bunch crossing (BX) at 3 TeV
    - but mainly collinear with beams – impacts design of forward region
  - Incoherent e^+e^- pairs
    - 3×10^5 per BX (low p_T)
    - mostly low angle, impact design of low angle tracking/beam pipe
  - $\gamma\gamma \rightarrow$ hadrons (real and virtual) - "pile-up of mini-jet events"
    - 3.2 events per bunch crossing at 3 TeV
    - main background in central tracker/calorimeters

- ★ Bunch train structure ⇨ pile-up of "mini-jets"
  - CLIC: BX separation 0.5 ns
    - Integrate over multiple BXs of $\gamma\gamma \rightarrow$ hadrons
    - 19 TeV visible energy per 156 ns bunch train



20 BXs = 10 ns of $\gamma\gamma \rightarrow$ hadrons



CLIC Detector Concepts

Detector Considerations

★ **A detector at CLIC must**

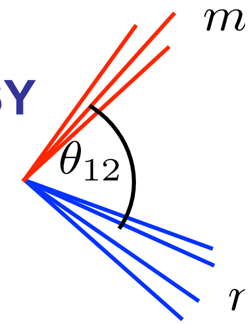
- **meet stringent performance requirements to deliver precision physics**
- **cope with the machine background**
  - **forward region – pair background**
  - **central region –** $\gamma\gamma \rightarrow \text{hadrons}$
- **cope with 0.5 ns CLIC bunch structure**

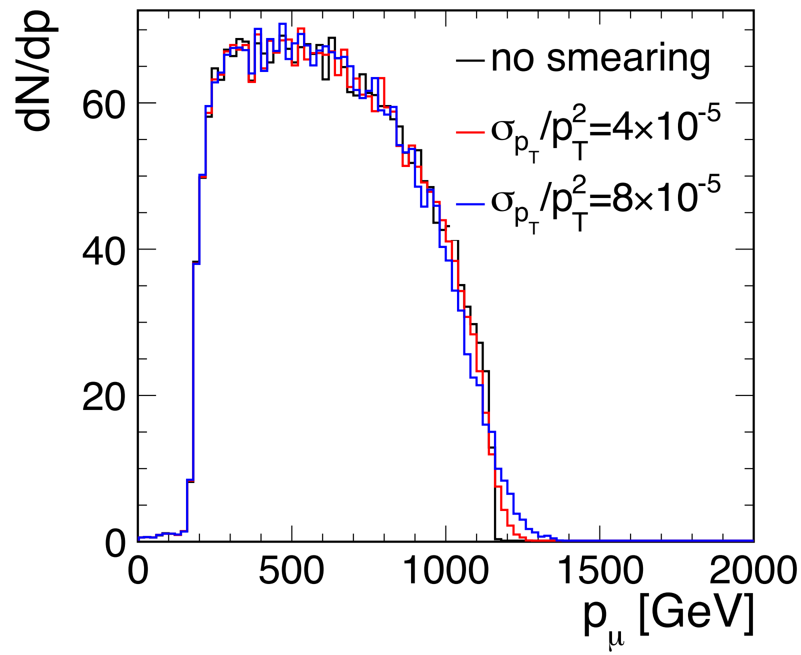
- ★ **momentum: (1/10 x LEP)**
  e.g. Smuon endpoint, Higgs recoil mass

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

- ★ **jet energy: (1/3 x LEP/ZEUS)**
  e.g. W/Z di-jet mass separation, SUSY

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





- ★ **impact parameter: (1/3 x SLD)**
  e.g. c/b-tagging, Higgs BR

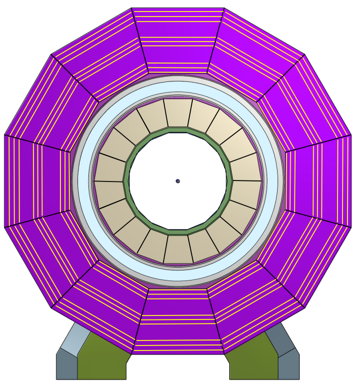
$$\sigma_{r\phi} = 5 \oplus 15/(p[\mathrm{GeV}]\sin^{\frac{3}{2}}\theta)\,\mu\mathrm{m}$$

- ★ **hermetic:** e.g. missing energy signatures in SUSY
- ★ **granularity:** in space and time to mitigate background

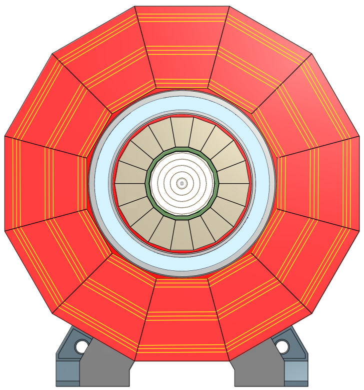
CLIC Detector Concepts

★ **Considered two possible general purpose detector concepts**
- **based on ILD and SiD concepts for ILC**
- **adapted for CLIC conditions**

★ **For studies define two detector models: CLIC_ILD and CLIC_SiD**



	CLIC_ILD	CLIC_SiD
Tracker	TPC, r = 1.8 m	Silicon, r = 1.2 m
B-field	4 T	5 T
ECAL	SiW	SiW
HCAL barrel	W-Scint	W-Scint
HCAL endcap	Steel-Scint	Steel-Scint



★ **Detailed GEANT 4 simulation**
★ **Studied using full reconstruction with background**

CLIC Detectors in a Nutshell

Instrumented return yoke for muon ID

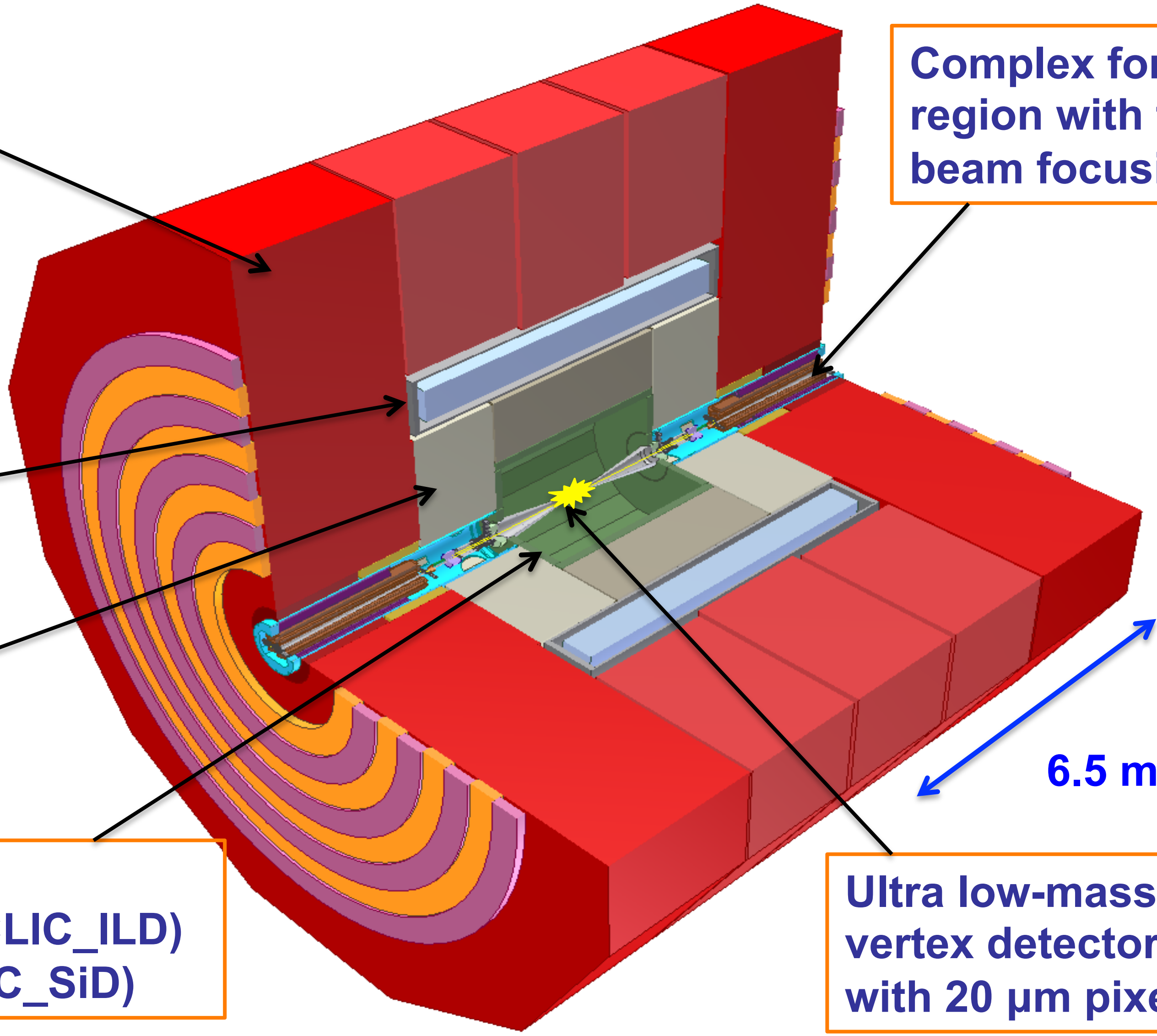
Strong SC solenoid 4 T or 5 T

Fine grained calorimeters for PFA: 1 + 7.5 λ_{int}

Tracking:
- TPC+silicon (CLIC_ILD)
- all-silicon (CLIC_SiD)

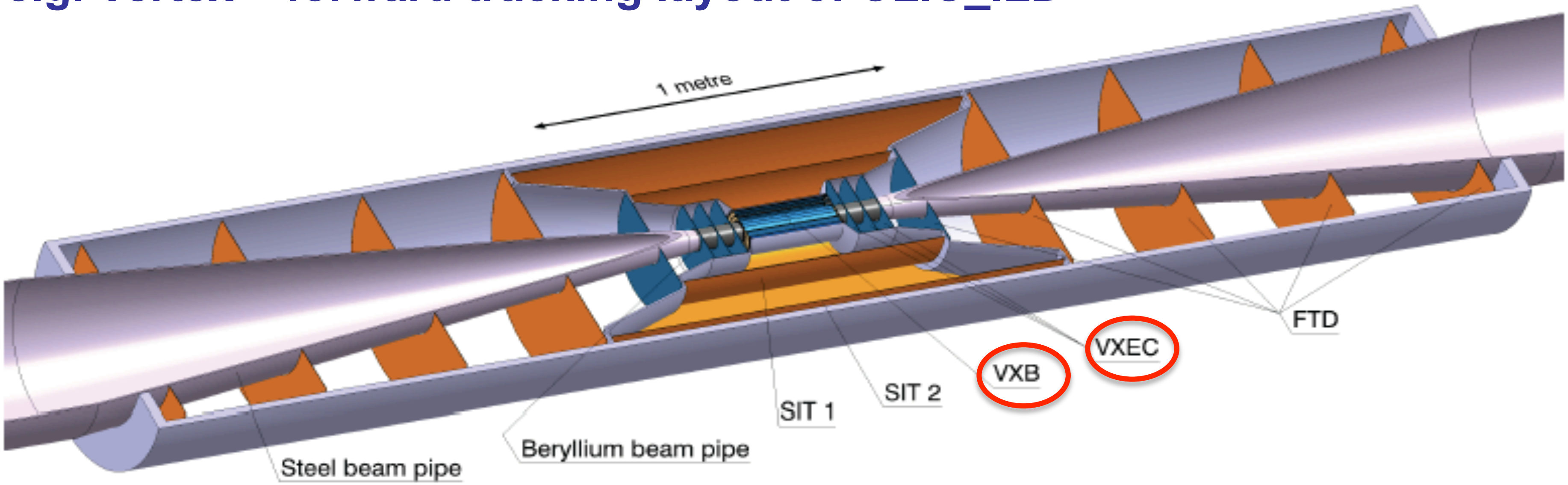
Complex forward region with final beam focusing

Ultra low-mass vertex detector with 20 μm pixels



Vertex detector

e.g. Vertex + forward tracking layout of CLIC_ILD



- ★ ~20×20 μm pixel size
- ★ 0.2% X_0 material par layer - very thin !
  - Very thin materials/sensors
  - Low-power design, power pulsing, air cooling
- ★ Time stamping 10 ns
- ★ Radiation level $<10^{11}\ n_{eq}\ cm^{-2}\ year^{-1}$ - 10^4 lower than LHC

Challenging ongoing R&D project

Vertex detector

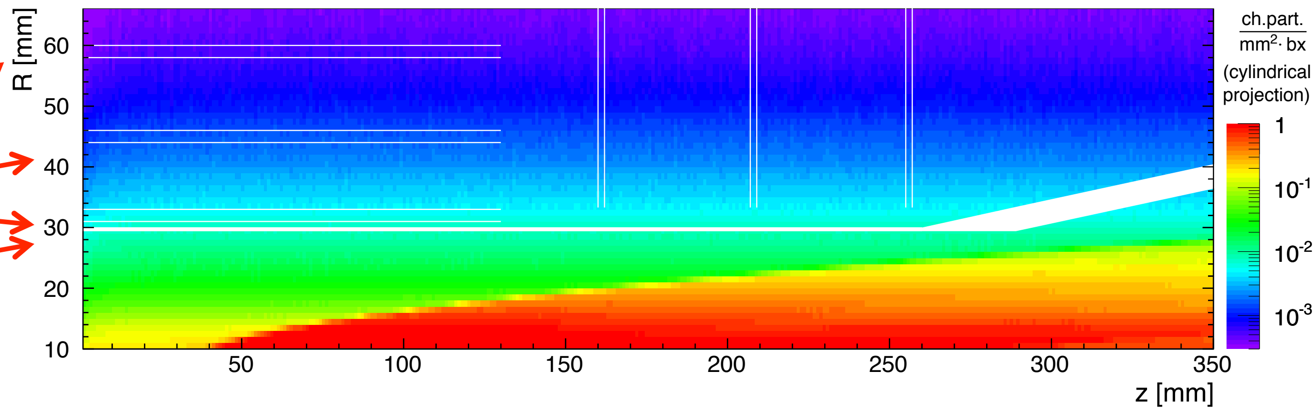
★ **Core of incoherent pair background determine:**

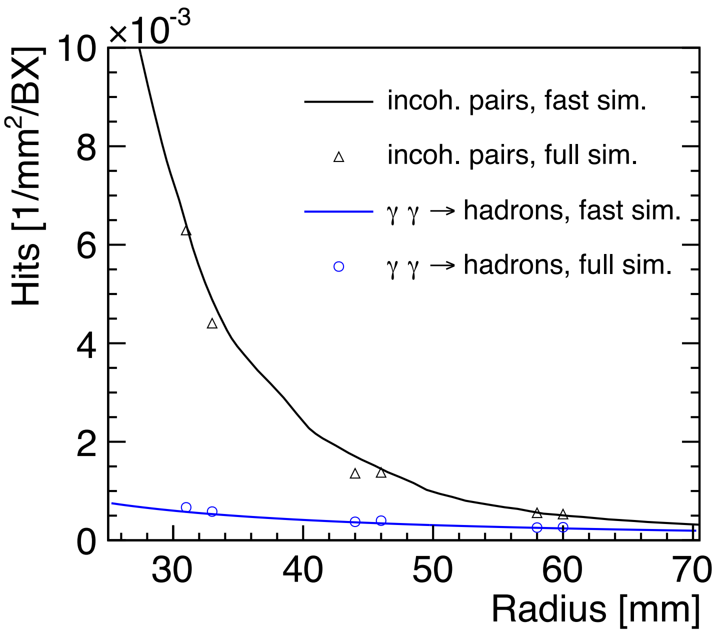
- **location of vertex detector; forward tracking discs; design of beam pipe…**

e.g. CLIC_ILD

VTX

Beampipe





★ **Pair background mostly at low radii**

★ **Inner radius of barrel vertex detector**

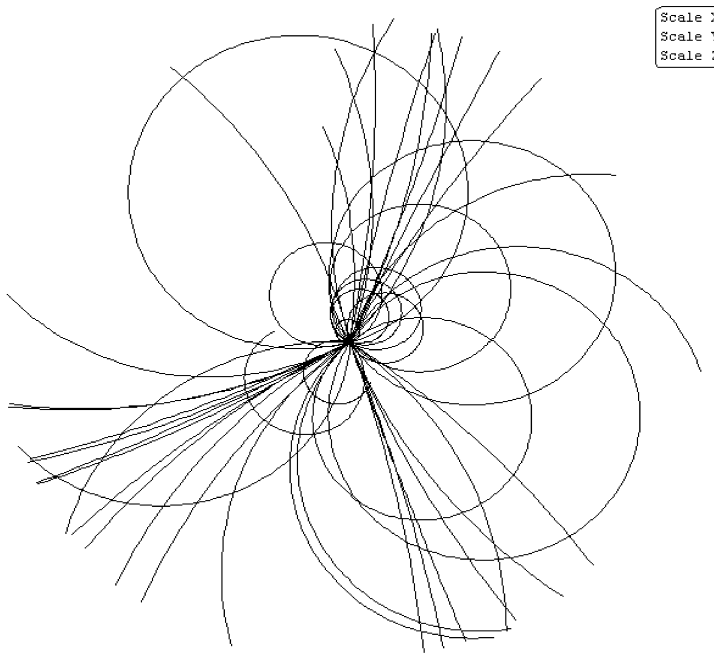
- **CLIC_ILD: 31 mm**
- **CLIC_SiD: 27 mm**

★ **Maximum occupancy**

- **1.9 % per bunch train**
  (assumes safety factor 5)

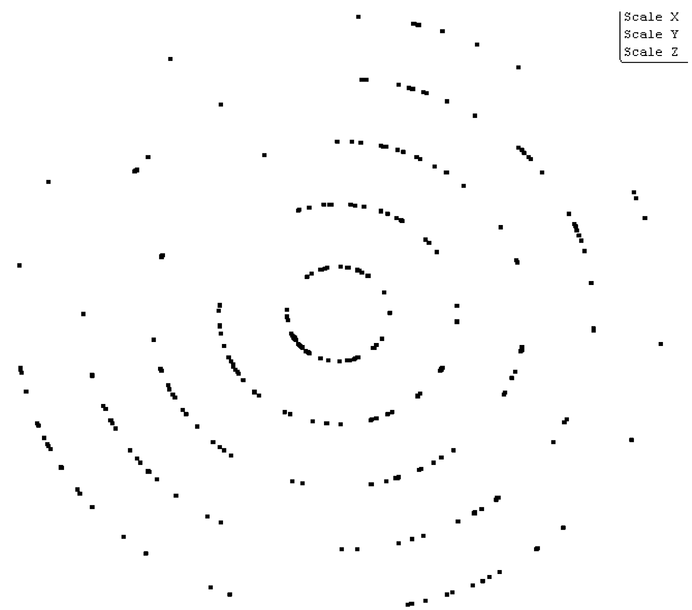
The two options considered:

- CLIC_ILD: Time Projection Chamber



- Large number of samples

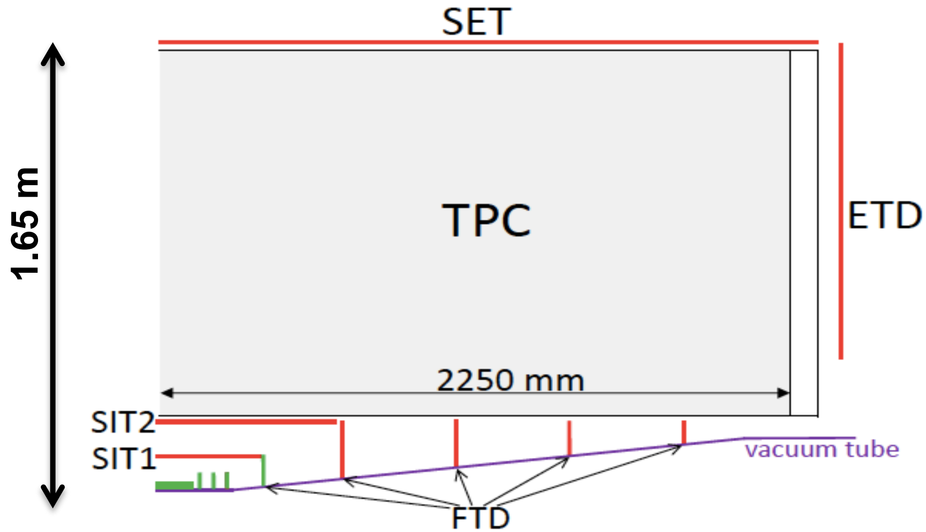
- CLIC_SiD: Silicon tracker (5 layers)

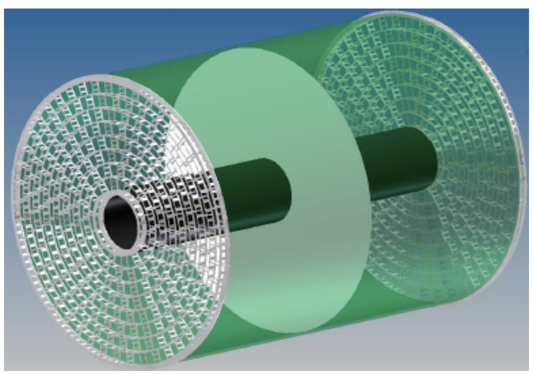


- Few very well measured points

Tracking at CLIC

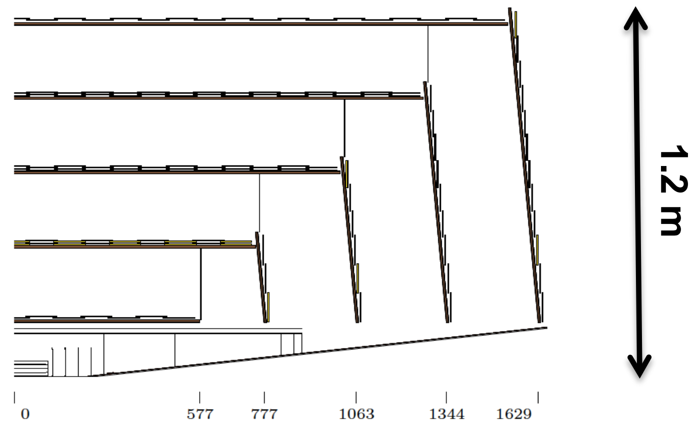
TPC + silicon tracker in 4 Tesla field



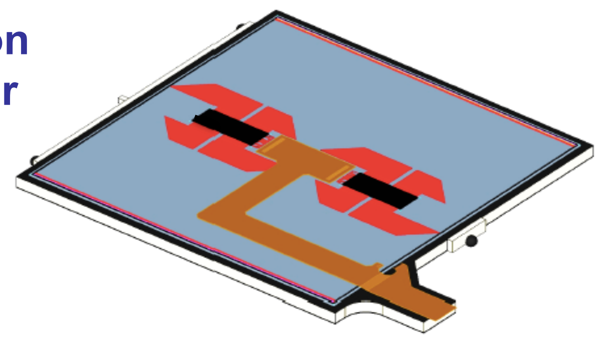


TPC with MPGD readout (GEMs or MicroMegas)

Si tracker in 5 Tesla field



chip on sensor



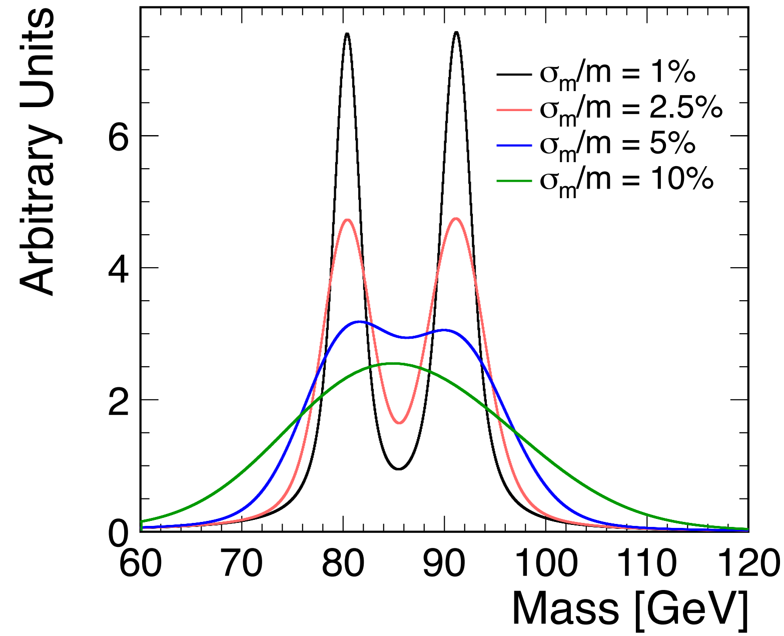
$$\sigma_{p_T} / p_T^2 \sim 2 \times 10^{-5}\ \mathrm{GeV}^{-1}$$

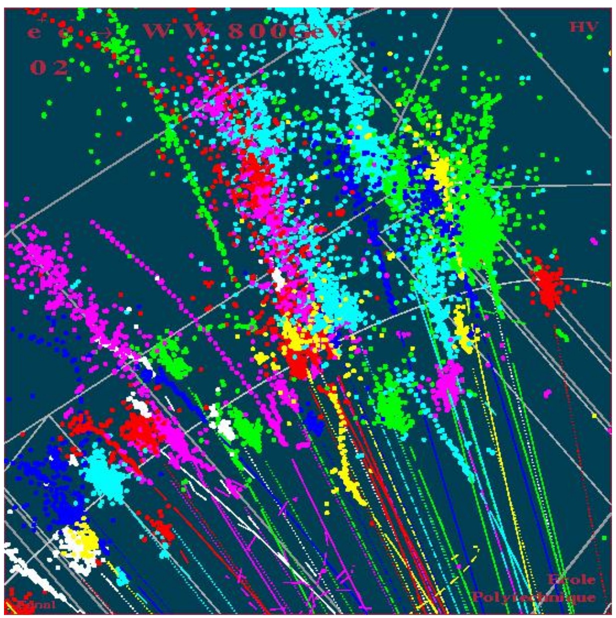
Calorimetry at CLIC

★ **Requirement: separate hadronic decays of W and Z**

$$\Rightarrow \quad \frac{\sigma_E}{E} \sim \frac{\sigma_m}{\sqrt{2}m} \sim 3.5 - 5\,\%$$

over wide range of jet energies:
50 GeV – 1 TeV





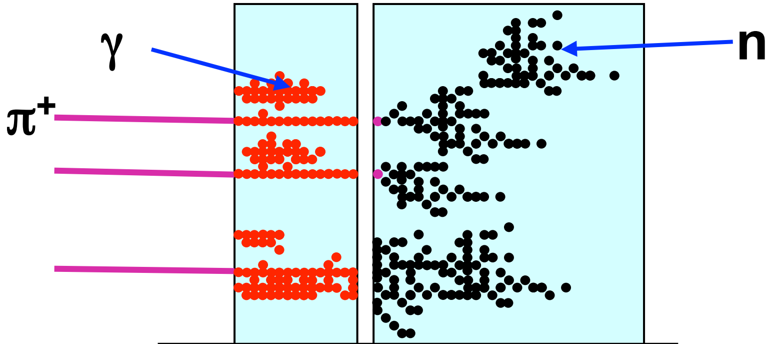
★ **Very hard (may not be possible) to achieve this with a traditional calorimetry; limited by HCAL resolution of > 55%/√E(GeV)**

Solution:

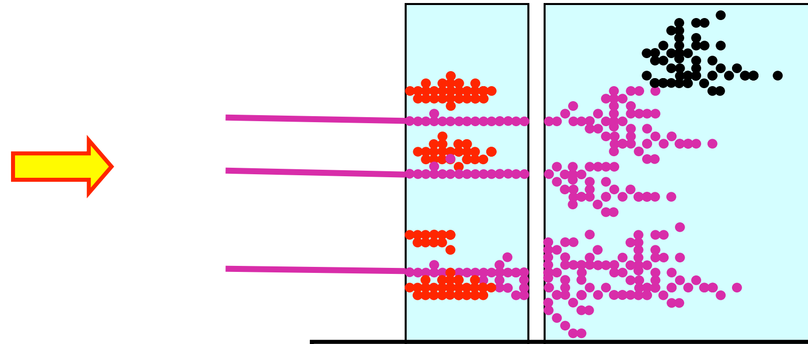
★ **High granularity particle flow calorimetry**
★ **Also motivated by background conditions**

Particle Flow Basics

- In a typical jet, energy is :
  - 60 % charged hadrons, 30 % in photons, 10 % in neutral hadrons
- Traditional calorimetric approach:
  - Measure all components of jet energy in ECAL/HCAL
  - ~70 % of energy measured in HCAL, limits jet energy resolution



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



$$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$$

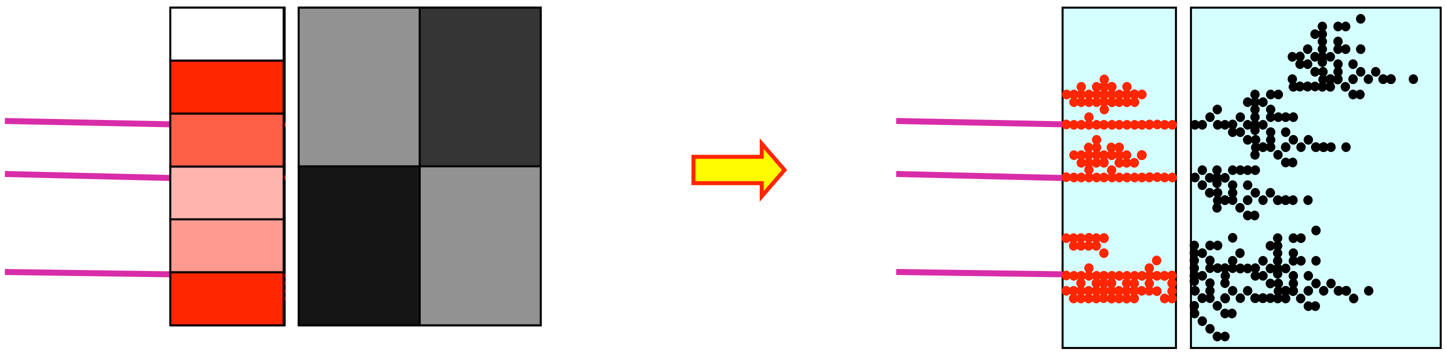
- Particle Flow Calorimetry paradigm:
  - charged particles measured in tracker (essentially perfectly)
  - Photons in ECAL: $\sigma_E/E < 20\,\%/\sqrt{E(\mathrm{GeV})}$
  - Neutral hadrons (ONLY) in HCAL
  - Only 10 % of jet energy from HCAL ⟹ much improved resolution

Particle Flow Basics

Hardware:

★ Need to be able to resolve energy deposits from different particles

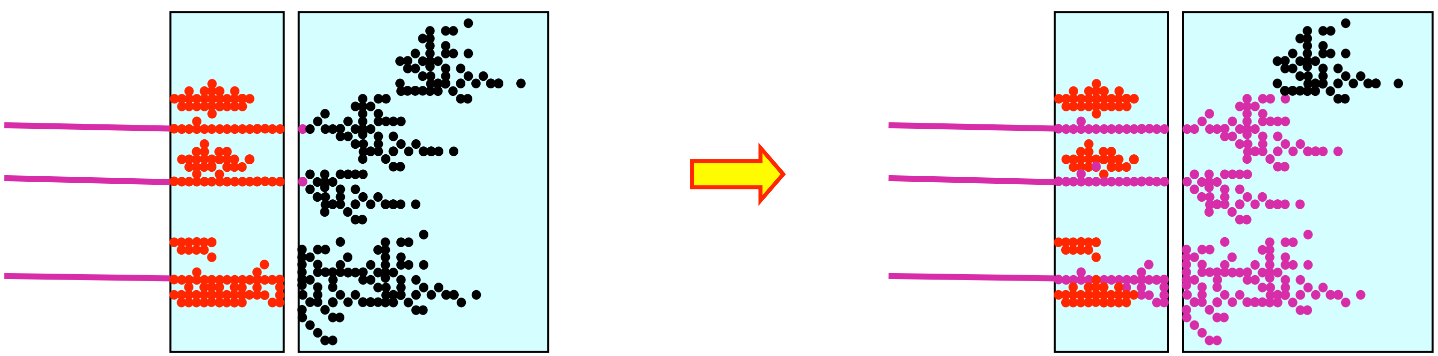
➡ Highly granular detectors (as studied in CALICE)



Software:

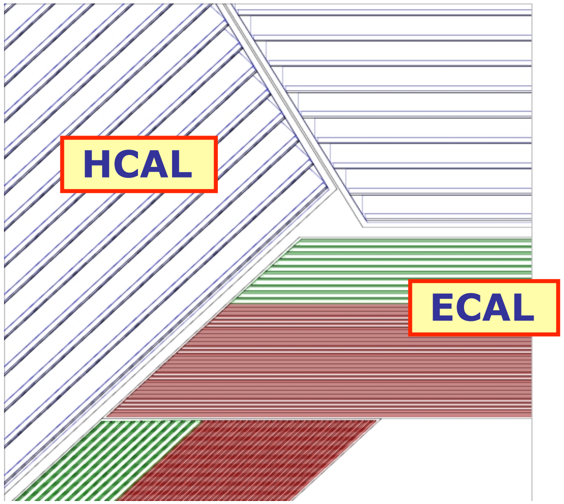
★ Need to be able to identify energy deposits from individual particles

➡ Sophisticated reconstruction software



Calorimeters for CLIC

★ Calorimeters inside Solenoid (for particle flow)
- require “compact” barrel HCAL



ECAL:

- SiW sampling calorimeter
- Tungsten: X_0/λ_{had} = 1/25, $R_{Mol.}$ ~ 9mm
  - → Narrow EM showers
  - → longitudinal sep. of EM/had. Showers
- Longitudinal segmentation: 30 layers
- Transverse segmentation: ~5x5 mm^2 pixels

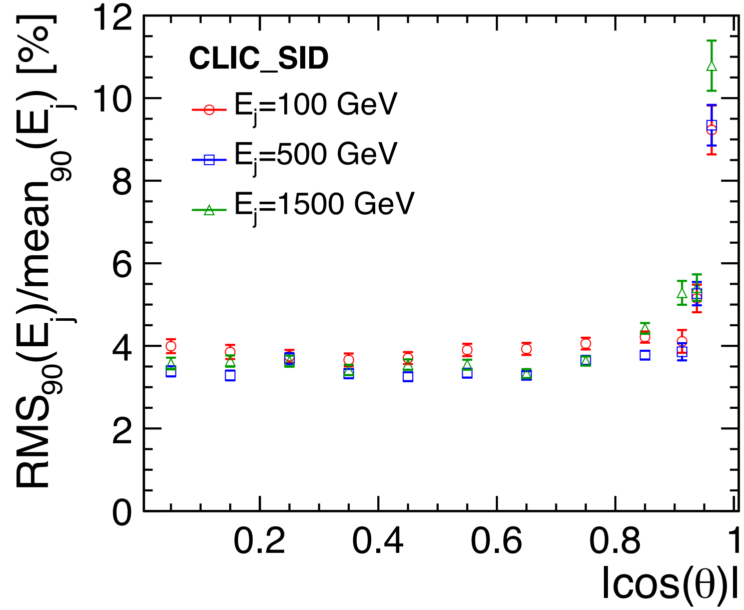
HCAL:

- Sampling calorimeter
- Absorber: tungsten (barrel), steel (endcap)
- Longitudinal segmentation: ~70 layers (7.5 interaction lengths)
- Transverse segmentation: 3x3 cm^2 scintillator tiles (analogue)
  or 1x1 cm^2 RPC pads (digital)

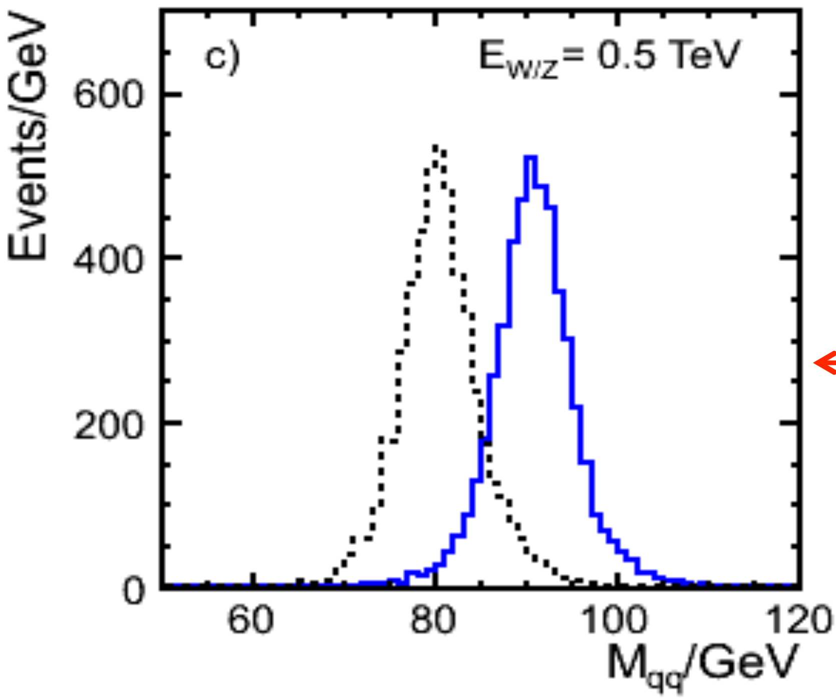
Underlying Pflow Performance

★ **Studied using full GEANT 4 simulation + full particle flow reconstruction**

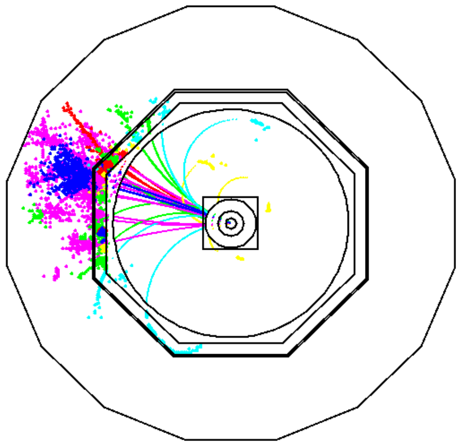
Jet energy resolution



W/Z Separation



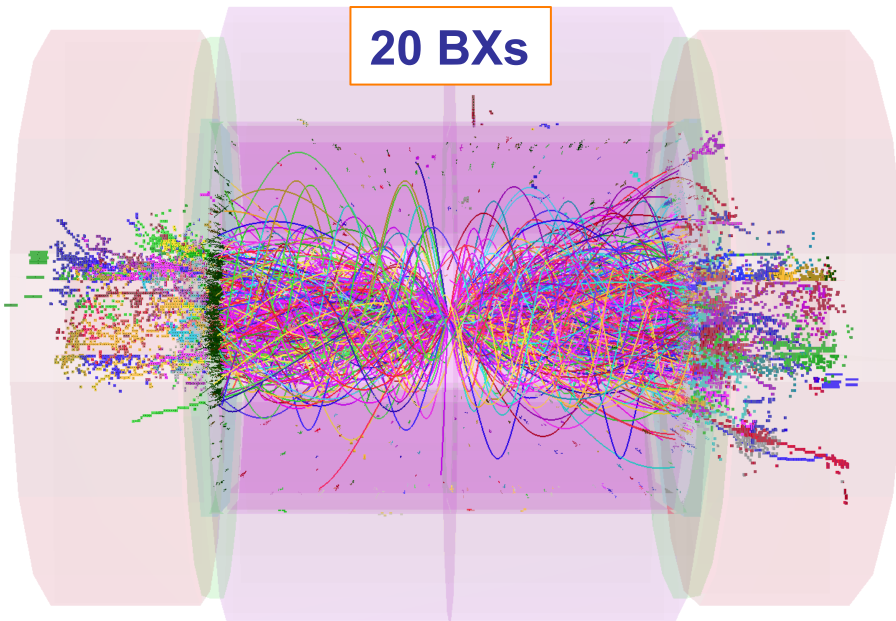
e.g. 500 GeV Z

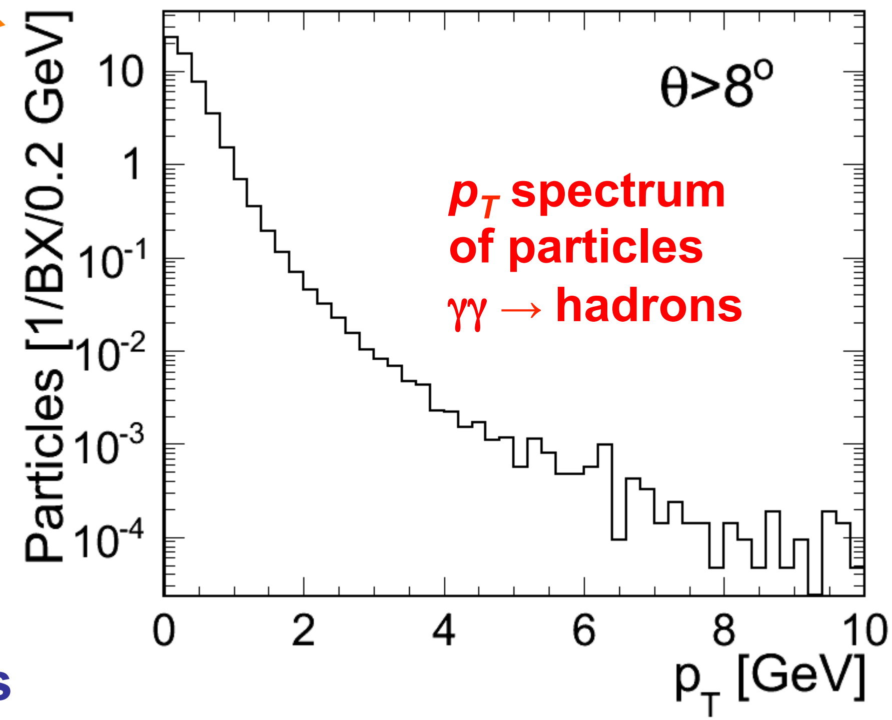


Background Suppression at CLIC

Background from $\gamma\gamma \rightarrow$ hadrons

- ★ Background in calorimeters and central tracker dominated by $\gamma\gamma \rightarrow$ hadrons "mini-jets"
- ★ For an entire bunchtrain at 3 TeV:
  - 5000 tracks giving total track momentum : 7.3 TeV
  - Total calorimetric energy (ECAL + HCAL) : 19 TeV
- ★ Largely low p_T particles

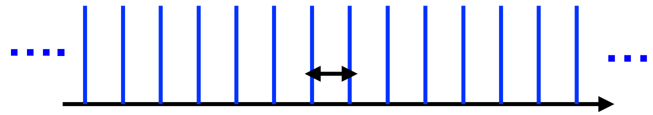




- ★ Irreducible background – it is physics

Backgrounds in the Calorimeters

- ★ Calorimeter backgrounds per bunch-crossing are manageable, ~ 60 GeV
- ★ Want to integrate over as few as possible BXs
- ★ Tight timing requirements !

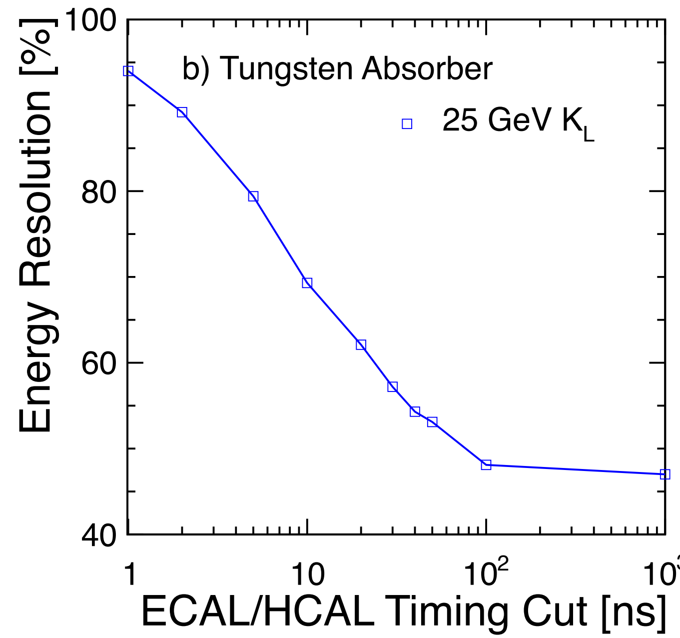


0.5 ns

- ★ But can't make calorimeter time window arbitrarily short…
- ★ Time needed to accumulate all calorimetric energy (due to low energy particles, nuclear break-up etc.) significant compared to 0.5 ns Bx
- ★ HCAL resolution depends on time window

Tungsten (Barrel): ~100 ns

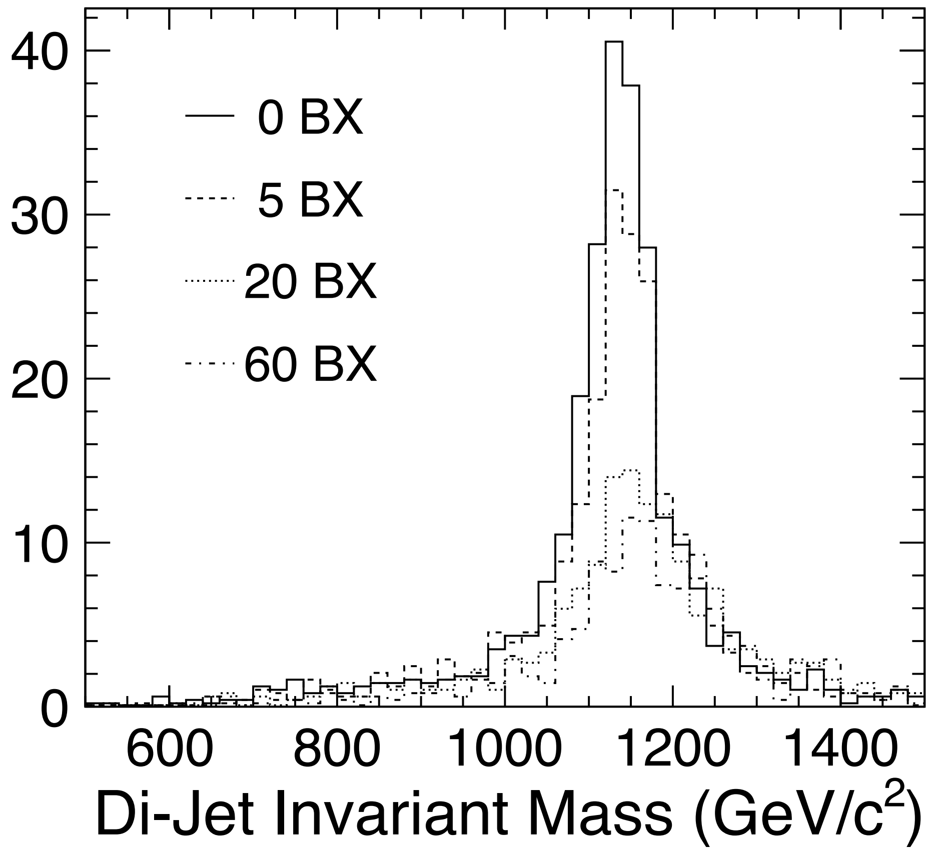
Steel (Endcap): ~10 ns



CLIC Timing cont.

★ Tension between maximising calorimeter integration time and minimizing number of BXs of $\gamma\gamma \rightarrow$ **hadrons** background

- e.g. reconstructed di-jet mass in $e^+e^- \rightarrow H^0A^0 \rightarrow b\bar{b}b\bar{b}$

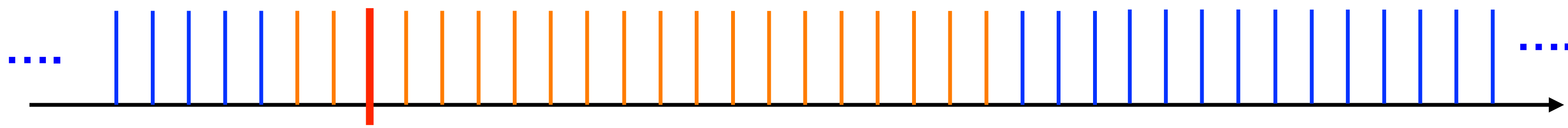


⇨ **< 5 BX**

But < 2.5 ns not long enough for calorimetry

A CLIC Detector in Time

- ★ Based on trigger-free readout of detector hits all with time-stamps
  - assume multi-hit capability of 5 hits per bunch train
- ★ Assume can identify t0 of physics event in offline trigger/event filter
  - define "reconstruction" window around t0



- ★ Hits within window passed to track and particle flow reconstruction

Subdetector	Reco Window	Hit Resolution
ECAL	10 ns	1 ns
HCAL Endcap	10 ns	1 ns
HCAL Barrel	100 ns	1 ns
Silicon Detectors	10 ns	$10/\sqrt{12}$
TPC (CLIC_ILD)	Entire train	n/a

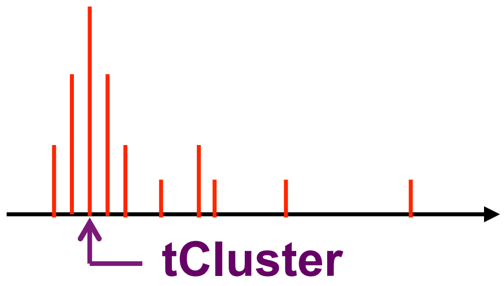
Sufficient calorimeter integration window

CLIC hardware requirements

- ★ Still 1.2 TeV reconstructed background per event

Reconstruction in Time

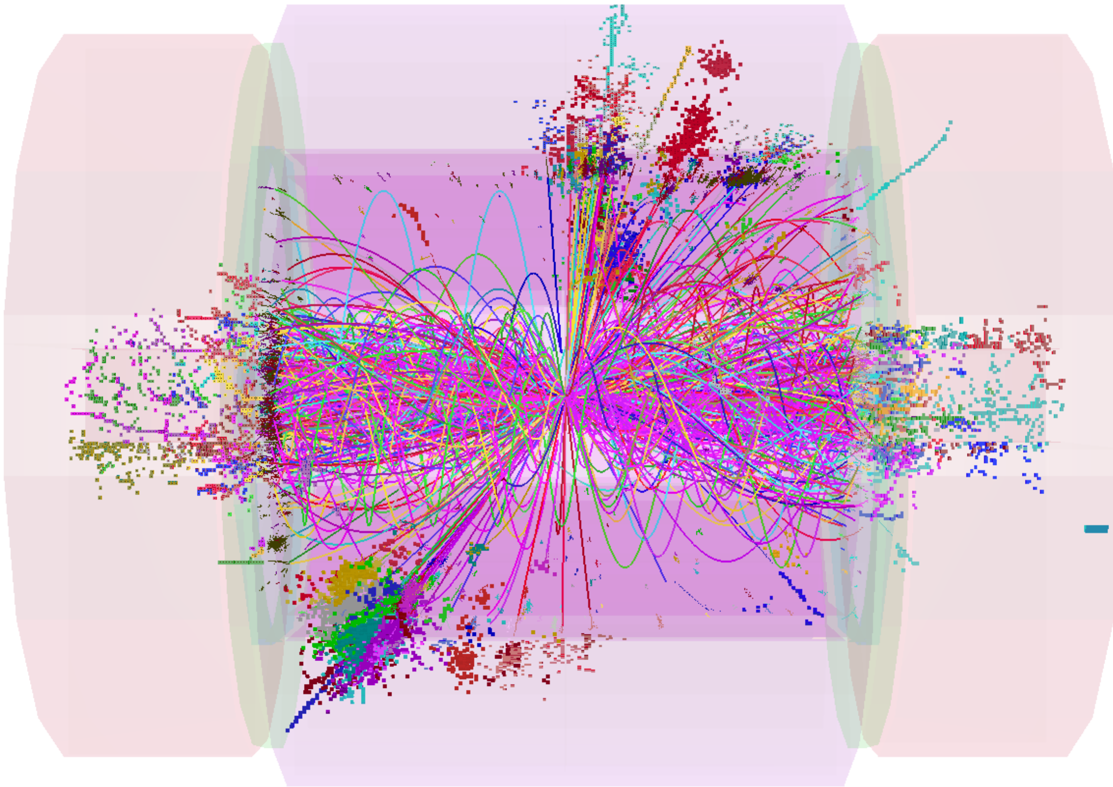
- ★ Tighter time cuts then applied at reconstructed particle flow object level
- ★ Using mean cluster time can cut at 1-2 ns level (not applied to high p_T particles)



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

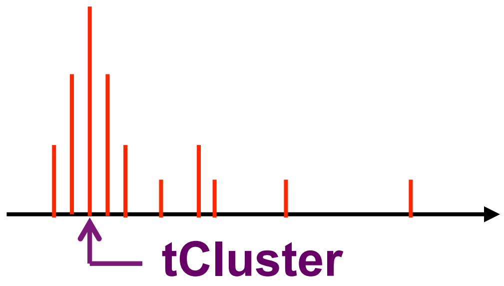
In reco. window

1.2 TeV



Reconstruction in Time

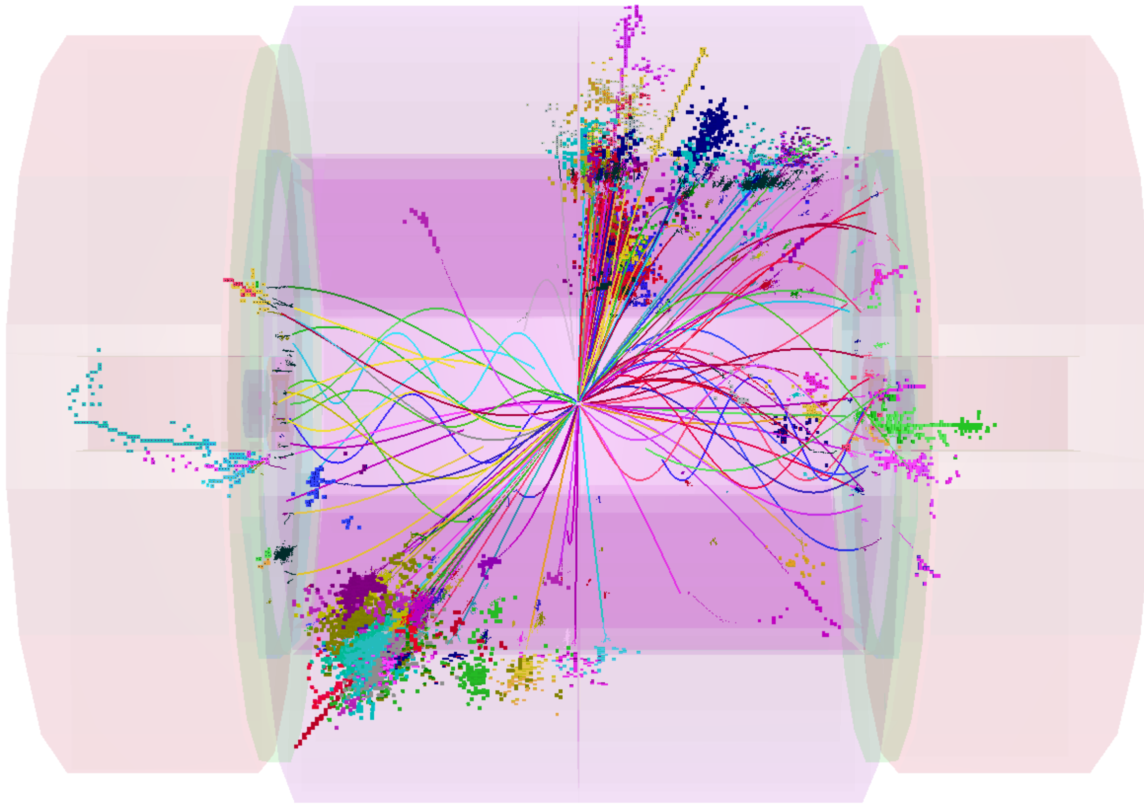
- ★ Tighter time cuts then applied at **reconstructed** particle flow object level
- ★ Using mean cluster time can cut at **1-2 ns** level (not applied to high p_T particles)



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

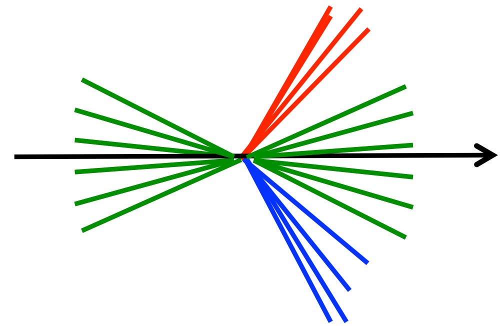
After cluster time

100 GeV



Jet Finding at CLIC

★ At **LEP**, preferred jet-finding algorithm: **Durham k_T**
- **all particles** in event clustered into the jets
- not appropriate for **CLIC**



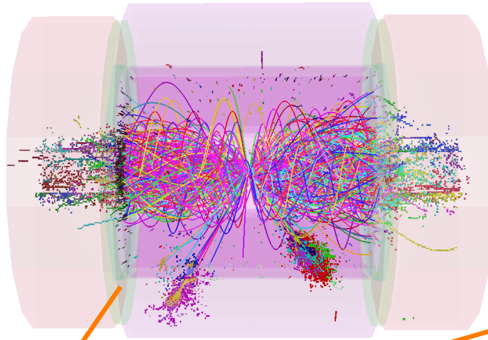
★ Events at **CLIC**
- significant background from **forward-peaked** $\gamma\gamma \rightarrow$ **hadrons**
- are often boosted along beam axis (beamsstrahlung)
- "hadron collider" type algorithms more appropriate

★ Jet finding at **CLIC**
- studied for benchmark physics analyses (FASTJET package)
- preferred option "k_T" with distance measure $\Delta R^2 = \Delta\eta^2 + \Delta\phi^2$
  - invariant under longitudinal boosts
- particles either combined with existing jet or beam axis
  - reduces sensitivity to $\gamma\gamma \rightarrow$ **hadrons**

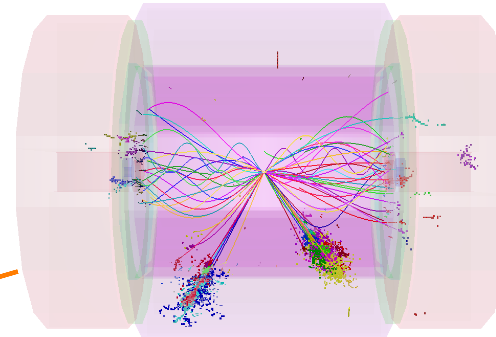
Jet Finding at CLIC

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

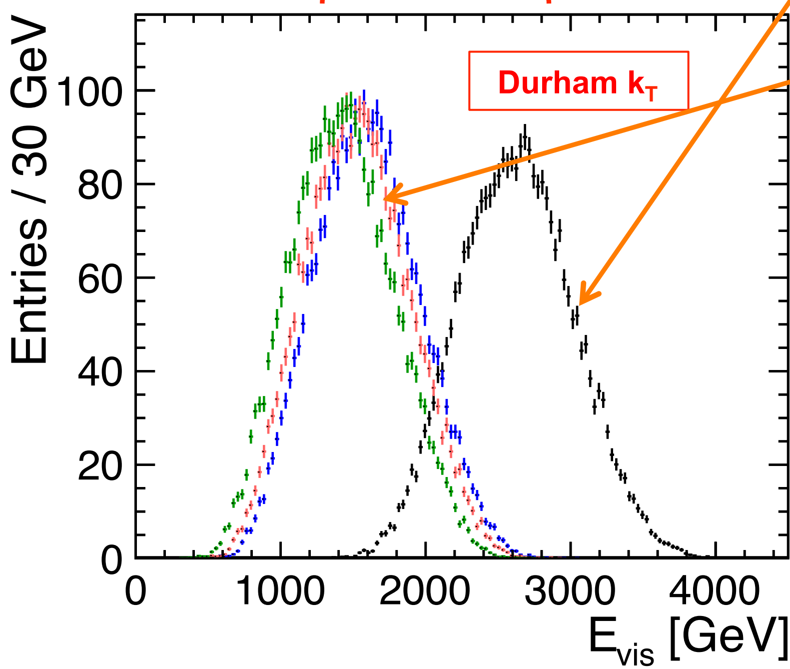
- two jets + missing energy

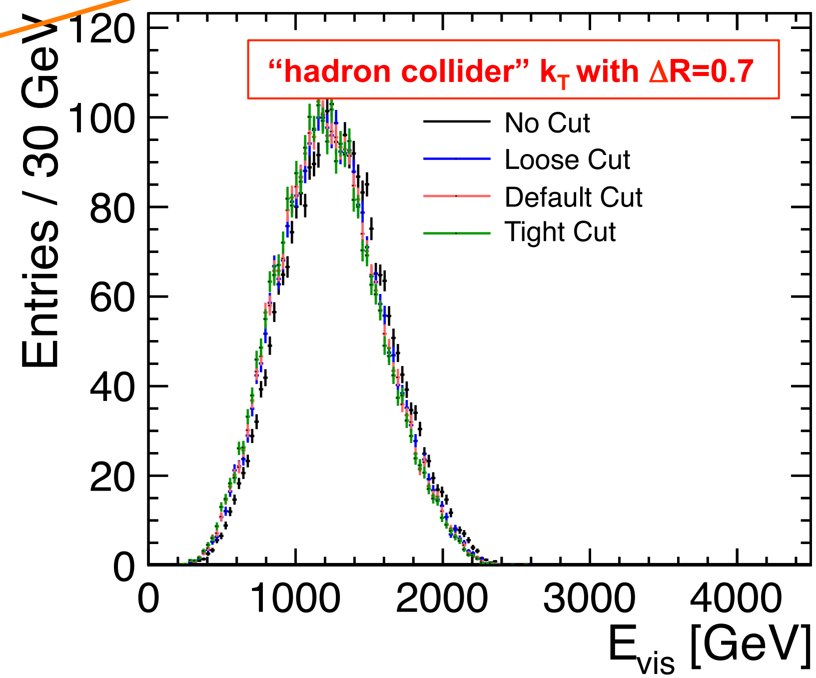


timing ⇒



All particles clustered





★ Two "weapons" against background: timing cuts + jet finding

Background Summary

★ Background conditions much more extreme than LEP

But combination of:

- ★ With high granularity calorimetry,
- ★ good time resolution
- ★ hadron-collider motivated jet algorithms

⇒ No major impact on physics, even at 3 TeV

Demonstrated with Physics Benchmark channels

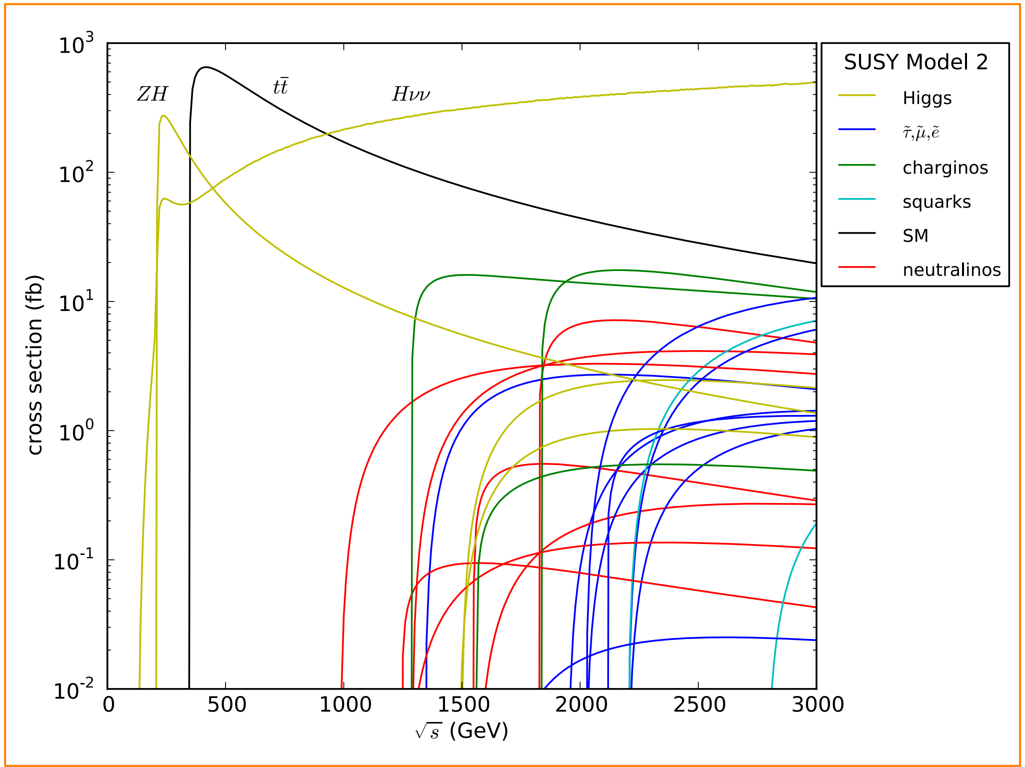
- ★ All full simulation, full reconstruction
- ★ All with background pile-up
- ★ Mostly focussed on worst case of 3 TeV

Physics Benchmarks

CLIC Benchmarks

★ **In the CDR, the benchmarks were chosen to demonstrate aspects of detector performance**

- **e.g. Light Higgs (120 GeV) – some results shown previously**
- **e.g. Two SUGRA SUSY points with non-unified gaugino masses – chosen to emphasise detector performance**



***SUSY Model 2**

$$m(\tilde{\chi}_1^0) = 340\,\mathrm{GeV}$$

$$m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^+) \approx 643\,\mathrm{GeV}$$

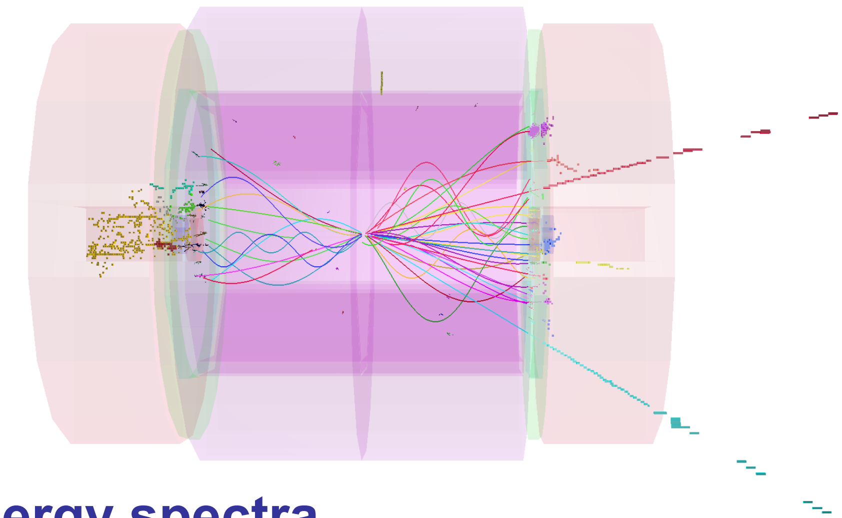
$$m(\tilde{e}_R) = m(\tilde{\mu}_R) = 1010\,\mathrm{GeV}$$

$$m(\tilde{\nu}_L) = 1097\,\mathrm{GeV}$$

$$m(\tilde{e}_L) = m(\tilde{\mu}_L) = 1100\,\mathrm{GeV}$$

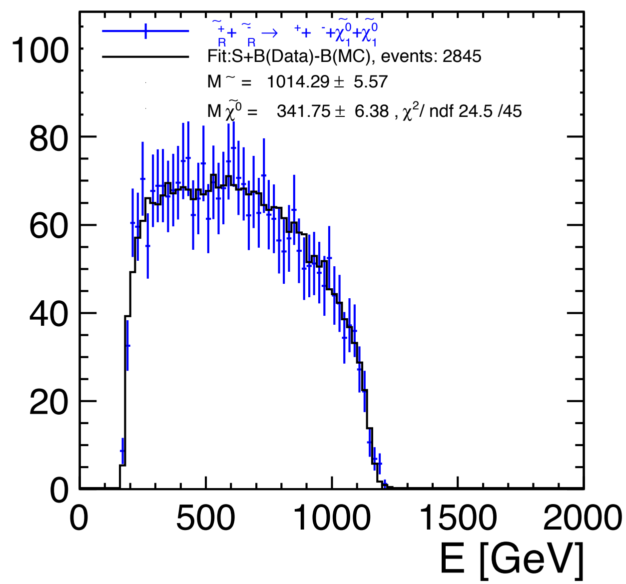
*for details see CDR

Slepton Production at 3 TeV



- ★ **Slepton production at CLIC very clean**
- ★ **Channels studied include**
  - $e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^- \rightarrow \mu^+\mu^- \tilde{\chi}_1^0\tilde{\chi}_1^0$
  - $e^+e^- \rightarrow \tilde{e}_R^+\tilde{e}_R^- \rightarrow e^+e^- \tilde{\chi}_1^0\tilde{\chi}_1^0$
  - $e^+e^- \rightarrow \tilde{\nu}_e\tilde{\nu}_e \rightarrow e^+e^-W^+W^- \tilde{\chi}_1^0\tilde{\chi}_1^0$
- ★ **Acoplanar leptons and missing energy**
- ★ **Masses from analysis of endpoints of energy spectra**

e.g. smuon production



All channels combined ⇒

$$m(\tilde{\mu}_R) : \pm 5.6\,\text{GeV}$$
$$m(\tilde{e}_R) : \pm 2.8\,\text{GeV}$$
$$m(\tilde{\nu}_e) : \pm 3.9\,\text{GeV}$$
$$m(\tilde{\chi}_1^0) : \pm 3.0\,\text{GeV}$$
$$m(\tilde{\chi}_1^\pm) : \pm 3.7\,\text{GeV}$$

Gaugino Pair Production

★ **Test of particle flow reconstruction of boosted low mass (EW scale) state**

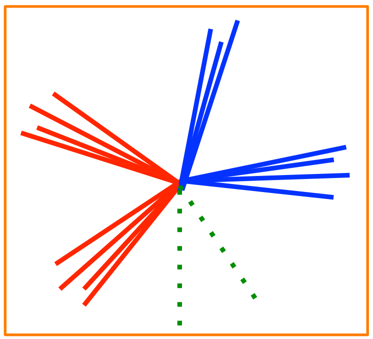
★ **Pair production and decay:**

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

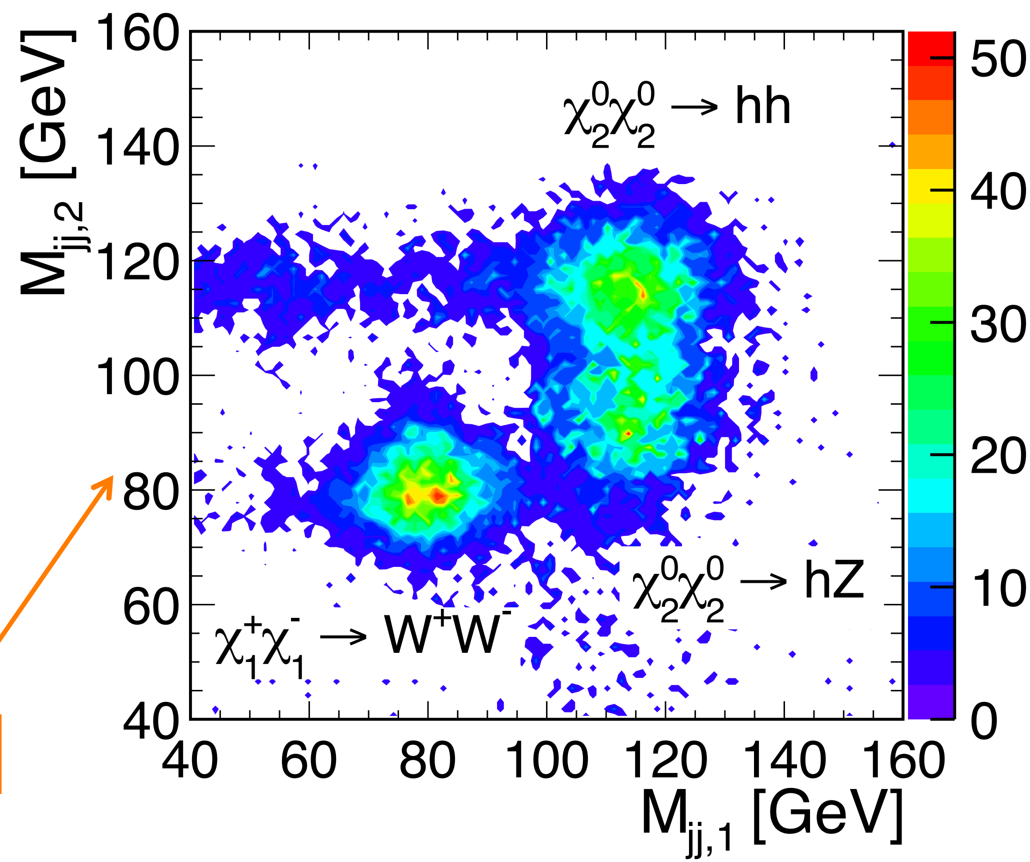
$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow hh\, \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad \textbf{82 \%}$$

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

★ **Largest decay BR has same topology for all final states**



Full Simulation with background



★ **Separate using di-jet invariant masses**

$$m(\tilde{\chi}_1^{\pm}) : \pm 7\,\text{GeV}$$
$$m(\tilde{\chi}_2^0) : \pm 10\,\text{GeV}$$

★ **e.g. CLIC potential* for "Model 2" of CDR**

Particle	Mass	Stat. acc.
$\tilde{\chi}^0_1$	340.3	±3.3
$\tilde{\chi}^0_2$	643.1	±9.9
$\tilde{\chi}^0_3$	905.5	±19.0*
$\tilde{\chi}^0_4$	916.7	±20.0*
$\tilde{\chi}^\pm_1$	643.2	±3.7
$\tilde{\chi}^\pm_2$	916.7	±7.0*
$\tilde{e}_R^\pm$	1010.8	±2.8
$\tilde{\mu}_R^\pm$	1010.8	±5.6
$\tilde{\nu}_1$	1097.2	±3.9

Particle	Mass	Stat. acc.
h	118.5	±0.1*
A	742.0	±1.7
H	742.0	±1.7
$H^\pm$	747.6	±2.1

Quantity	Value	Stat. acc.
$\Gamma(A)$	22.2	±3.8
$\Gamma(H^\pm)$	21.4	±4.9

Particle	Mass
$\tilde{\tau}_1$	670
$\tilde{\tau}_2$	974
$\tilde{t}_1$	1393
$\tilde{t}_2$	1598
$\tilde{b}_1$	1544
$\tilde{b}_2$	1610
$\tilde{u}_R$	1818
$\tilde{u}_L$	1870
$\tilde{g}$	1812

*note: 3 TeV is not optimal for a number of these measurements

Benchmark Summary

★ **Wide range of channels studied**

- **Excellent physics performance achieved in all**
- **Both CLIC_ILD and CLIC_SiD concepts are viable options**
- **For more details refer to CDR…**

Beyond the CDR

What next ?

★ CDR phase detector and physics studies complete

- now starting work for next phase, aligned with machine

Main focus

★ Physics studies

- Follow up on 8 TeV and 14 TeV LHC results
- Full exploration of SM physics potential (Higgs, top)
- More detailed understanding of reach for new physics
- Refinement of strategy for CLIC energy staging

★ Detector optimisation

- Optimisation + simulation studies in close relation with detector R&D

★ **Detector R&D**

- Address main hardware issues for CLIC detector
- Strong overlap with ILC detector R&D programme

Detector R&D

Rich programme of detector R&D with many generic aspects

- ★ **Vertex detector**
  - Demonstration module that meets the material/power requirements
- ★ **Main tracker**
  - Demonstration modules, including coping with occupancies
- ★ **Calorimeters**
  - Demonstration modules, technological prototypes + cost mitigation
- ★ **Electronics**
  - Demonstrators, in particular in view of power pulsing
- ★ **Magnet systems**
  - Demonstrate conductor technology, safety systems, etc.
- ★ **Engineering and detector integration**
  - Engineering design and detector integration harmonized with hardware R&D demonstrators

Considered feasible in a 5-year R&D program

Summary/Conclusions

Summary/Conclusions

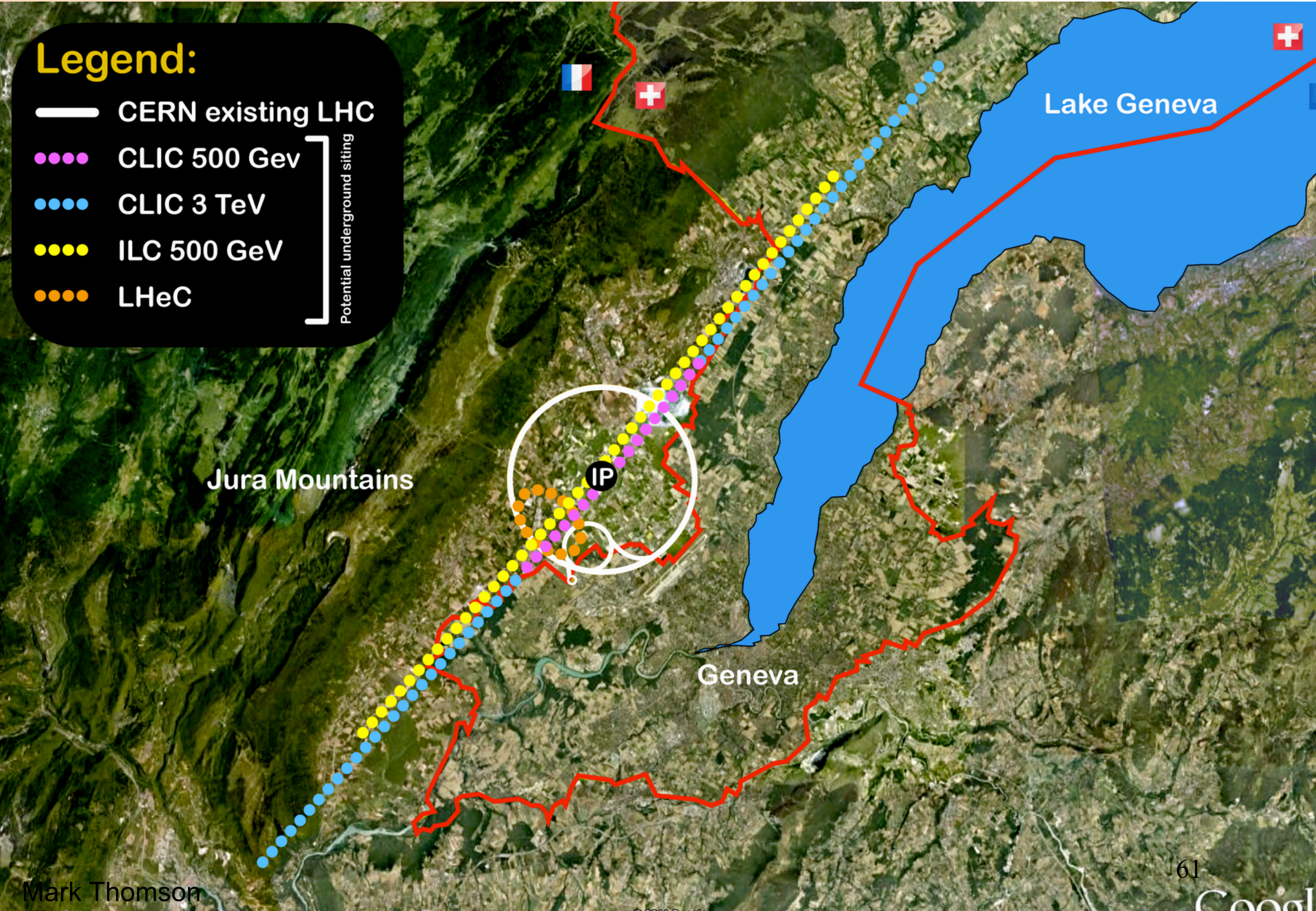
★ **CLIC is an attractive option for a future energy frontier machine**
- **Complementary to the LHC**
- **Staged approach ⟹ large potential for SM and BSM physics**
- **Defined detector requirements which will guide future R&D**

★ **Understanding of Detectors at CLIC has made great progress**
- **Have demonstrated precision physics in CLIC environment**
- **Defined detector requirements which will guide future R&D**

★ **Strong future programme**
- **Physics and detector studies**
- **Detector R&D**

Many thanks

to all those who worked on the CLIC CDR – too many names to acknowledge individually


Legend:
CERN existing LHC
CLIC 500 Gev
CLIC 3 TeV
ILC 500 GeV
LHeC
Potential underground siting
Lake Geneva
Jura Mountains
IP
Geneva

Backup Slides

Possible Staging Scenario

★ **A number of possible staging scenarios**

- **details, currently being worked out, e.g.**

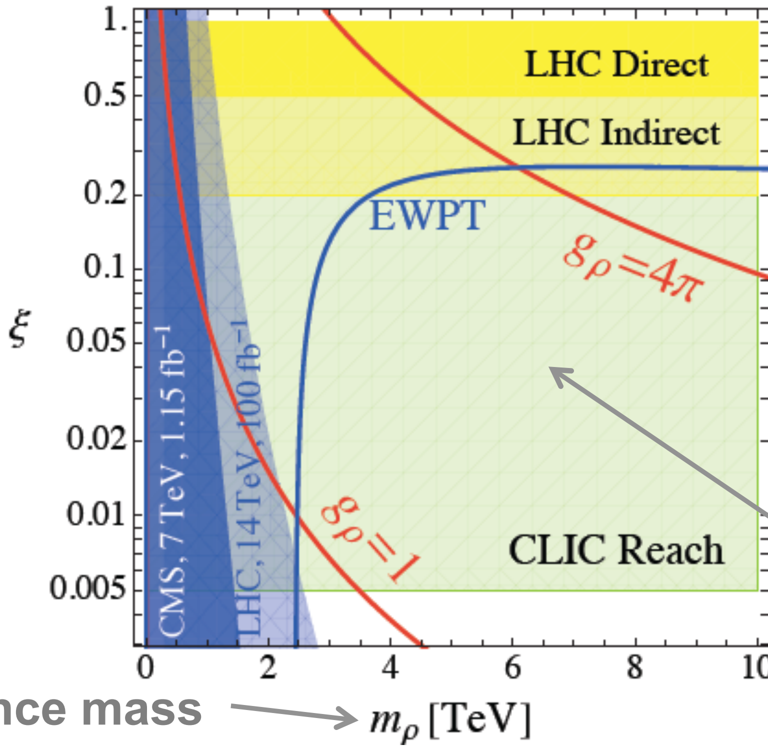
parameter	symbol			
centre of mass energy	E_{cm} [GeV]	500	1400	3000
luminosity	$\mathcal{L}$ [10^{34} cm^{-2}s^{-1}]	2.3	3.2	5.9
luminosity in peak	$\mathcal{L}_{0.01}$ [10^{34} cm^{-2}s^{-1}]	1.4	1.3	2
gradient	G [MV/m]	80	80/100	100
site length	[km]	13	28	48.3
charge per bunch	N [10^9]	6.8	3.7	3.7
bunch length	σ_z [μm]	72	44	44
IP beam size	σ_x/σ_y [nm]	200/2.26	$\approx$ 60/1.5	$\approx$ 40/1
norm. emittance	ϵ_x/ϵ_y [nm]	2400/25	660/20	660/20
bunches per pulse	n_b	354	312	312
distance between bunches	Δ_b [ns]	0.5	0.5	0.5
repetition rate	f_r [Hz]	50	50	50
est. power cons.	P_{wall} [MW]	271	361	582

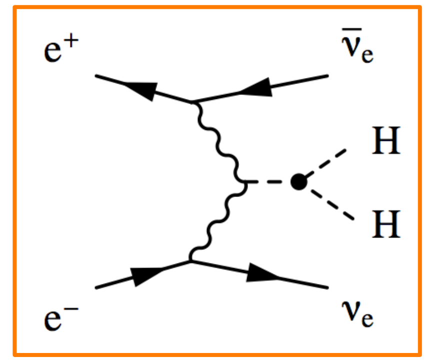
Composite Higgs

★ In some scenarios, a light Higgs is a bound state of new strongly interacting dynamics at the TeV scale   e.g. Giudice et al., JHEP 06 (2007) 045

- sensitivity from double Higgs production via WW fusion at CLIC

Dimensionless Scale parameter





Region favoured by EW precision tests

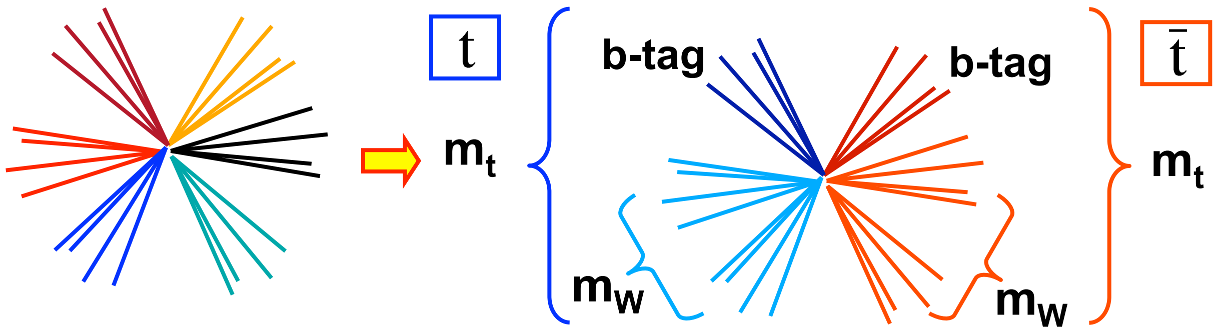
Vector resonance mass

★ Probe Higgs compositeness at the 30 TeV scale for 1 ab^{-1} at 3 TeV

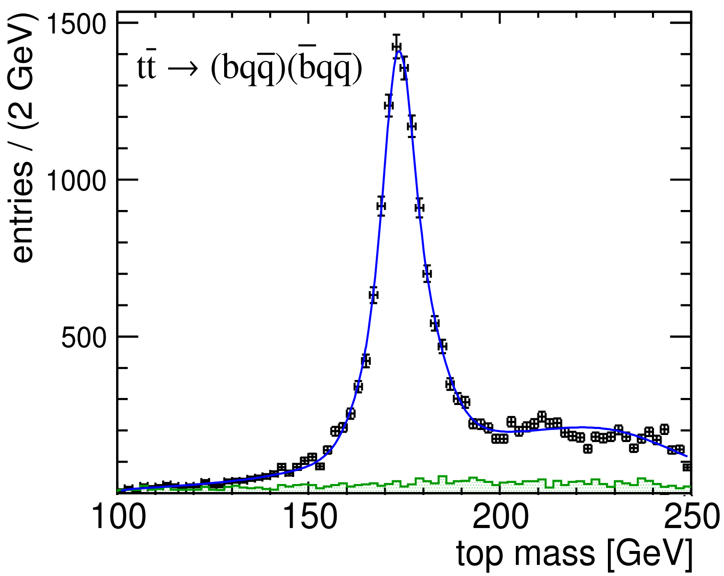
(60 TeV scale if combined with precise measurements from single Higgs production)

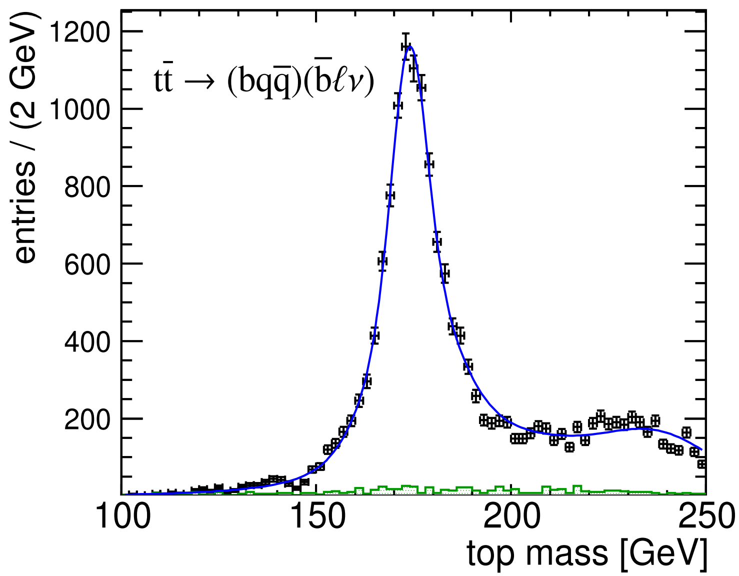
+ Top mass at 500 GeV

★ Study top production at $\sqrt{s}$ = **500 GeV** under CLIC background conditions
- fully hadronic $t\bar{t} \to (bq\bar{q})(\bar{b}q\bar{q})$ and semi-leptonic $t\bar{t} \to (bq\bar{q})(\bar{b}\ell\nu)$
- complex analysis, e.g. jet combinatorics



Use:
- b-tagging
- Invariant masses
- Kinematic fits





100 fb^{-1}

m_t : ± 60 MeV