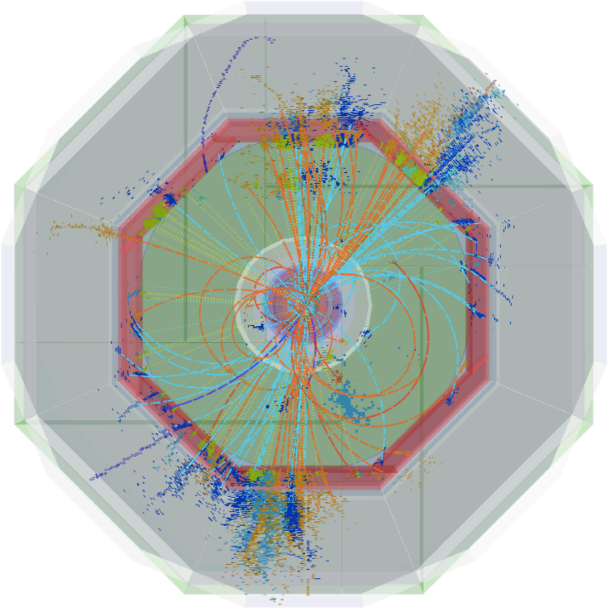
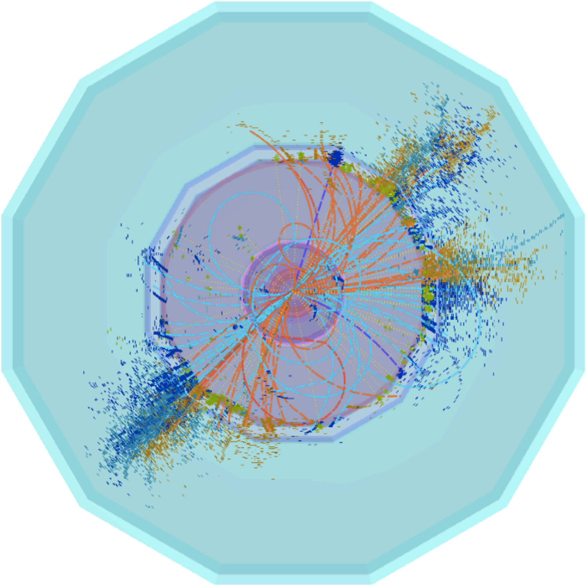
CLIC CDR
“detector part”





Lucie Linssen, CERN

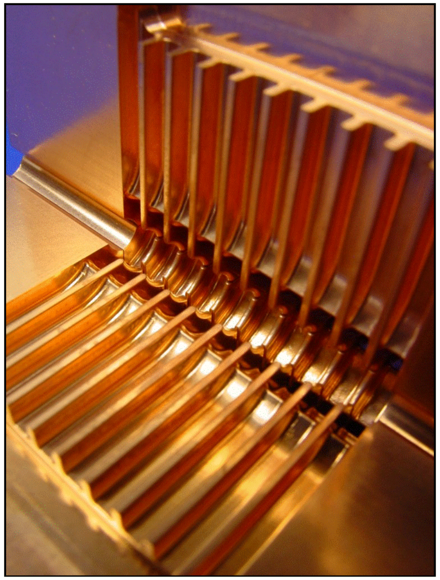
on behalf of the CLIC physics and detector study

Outline

- CLIC (ILC) accelerator introduction
- CLIC conceptual design report
- Experimental conditions
- Detector requirements
- Detector concepts CLIC_SiD and CLIC_ILD
- Background suppression at CLIC
- Detector benchmark studies
- Outlook (R&D) and summary

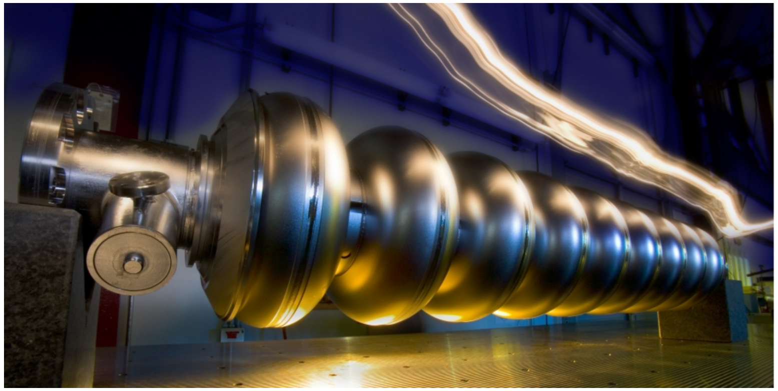
CLIC and ILC, in just a few words

linear collider, e^+e^- collisions



CLIC

ILC



- Based on superconducting RF cavities
- Gradient 32 MV/m
- Energy: from few-hundred GeV to 500 GeV, upgradable to 1 TeV: R&D has focused on 500 GeV
- Detector study focused mostly on few-hundred GeV to 500 GeV; 1 TeV studies now ongoing

- Based on 2-beam acceleration scheme
- Gradient 100 MV/m
- Energy: from few-hundred GeV upgradable in steps up to 3 TeV; R&D has focused on 3 TeV
- Detector study focuses on 3 TeV, lower $\sqrt{s}$ energies under study

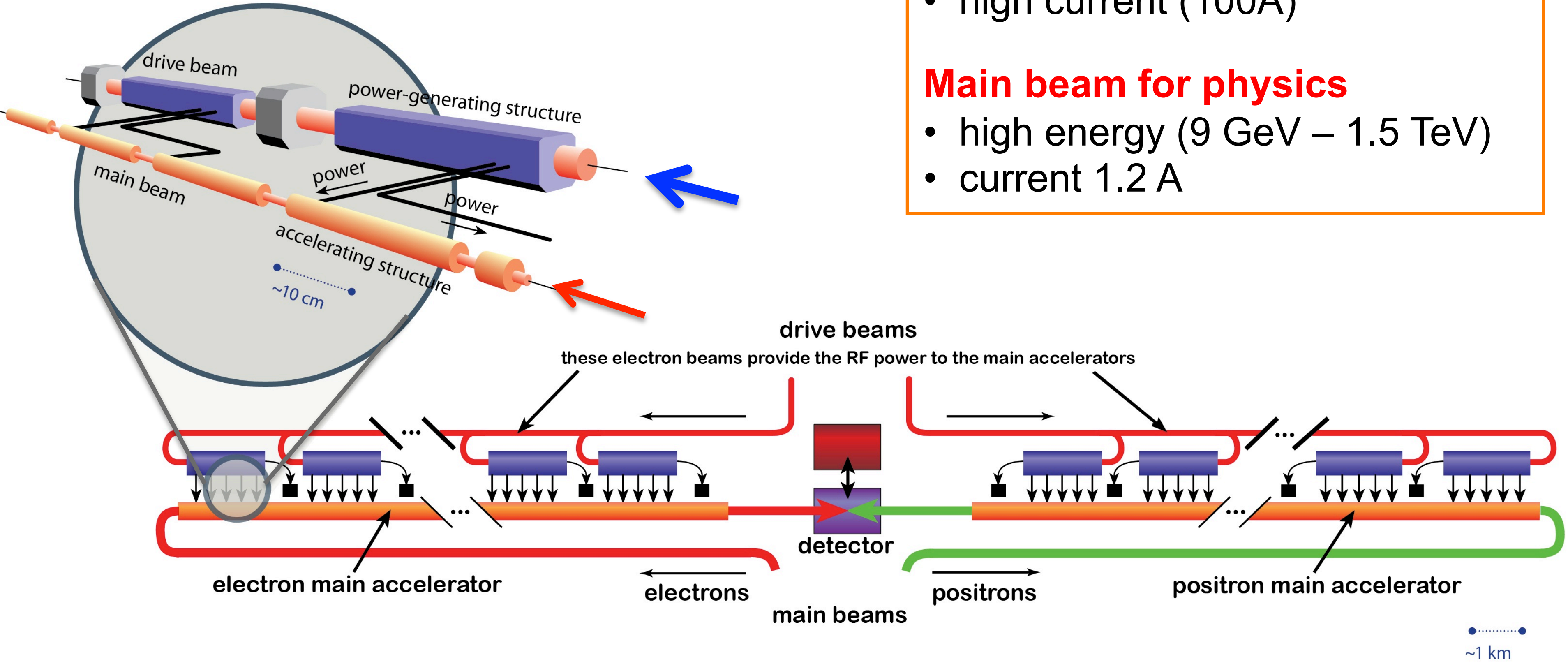
Luminosities: few 10^{34} $cm^{-2}s^{-1}$

2-beam acceleration scheme

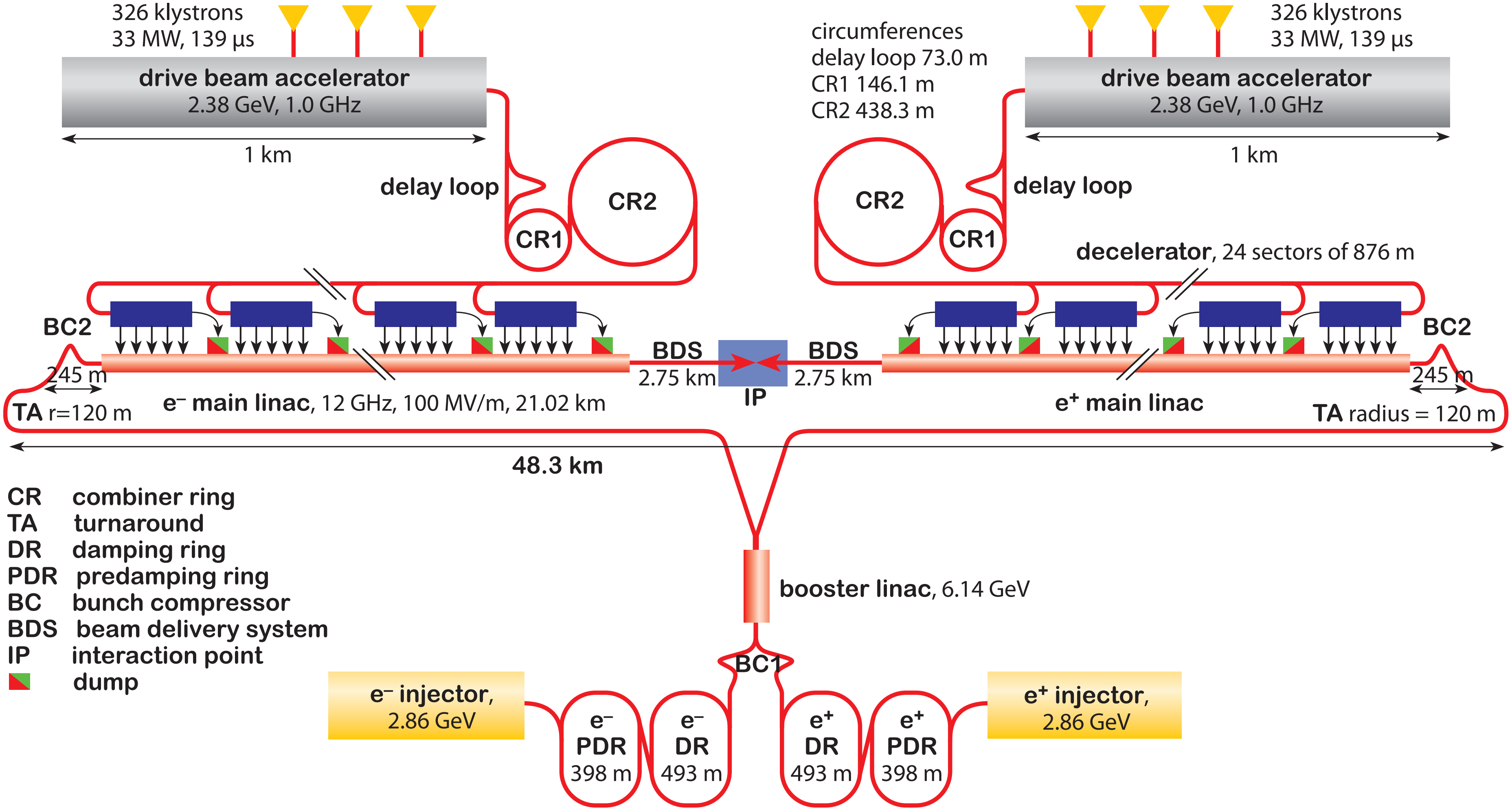
Two Beam Scheme:

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)
- current 1.2 A



CLIC accelerator complex

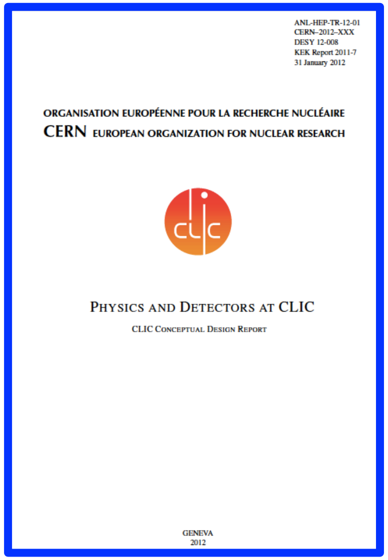


CR	**combiner ring**
TA	**turnaround**
DR	**damping ring**
PDR	**predamping ring**
BC	**bunch compressor**
BDS	**beam delivery system**
IP	**interaction point**
◩	**dump**

CLIC physics and detector CDR

CLIC conceptual design report (CDR):

1. Accelerator
   text nearly complete
2. Physics and Detectors => finished
   http://lcd.web.cern.ch/LCD/CDR/CDR.html
3. Strategic CDR volume (energy staging, cost, power...)
   foreseen summer 2012



ANL-HEP-TR-12-01
CERN–2012–XXX
DESY 12-008
KEK Report 2011-7
31 January 2012

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PHYSICS AND DETECTORS AT CLIC

CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012

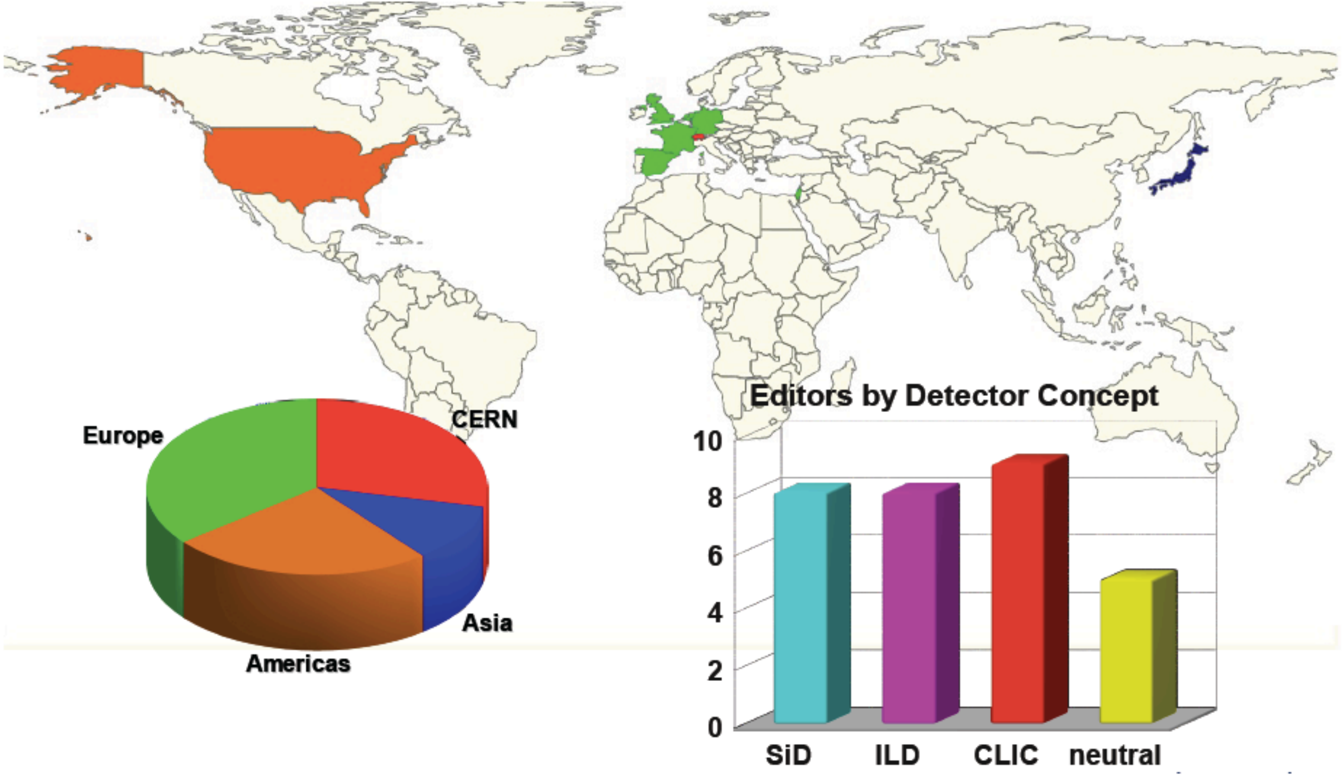
The main purpose of the CLIC Physics and Detector Conceptual Design Report:

- What is the CLIC physics potential ? <= talk of James Wells
- Show how the physics can be measured with good precision <= this talk

The physics & detector CDR was reviewed in October 2011:
https://edms.cern.ch/document/1172721

CLIC CDR detector studies => who?

CLIC physics & detector CDR studies were carried out within a broad international **Linear Collider physics and detector effort**, drawing on existing ILC (etc.) studies



↙ 36 editors

In CERN-PH:

PH-LCD group
+
members from
PH-TH, PH-ESE,
PH-DT, PH-SFT,
PH-CMD, PH-LBD,
PH-ADP, PH-ADO,
PH-AID

http://lcd.web.cern.ch/LCD/CDR/CDR.html

centre-of-mass energy choice

CDR Studies:

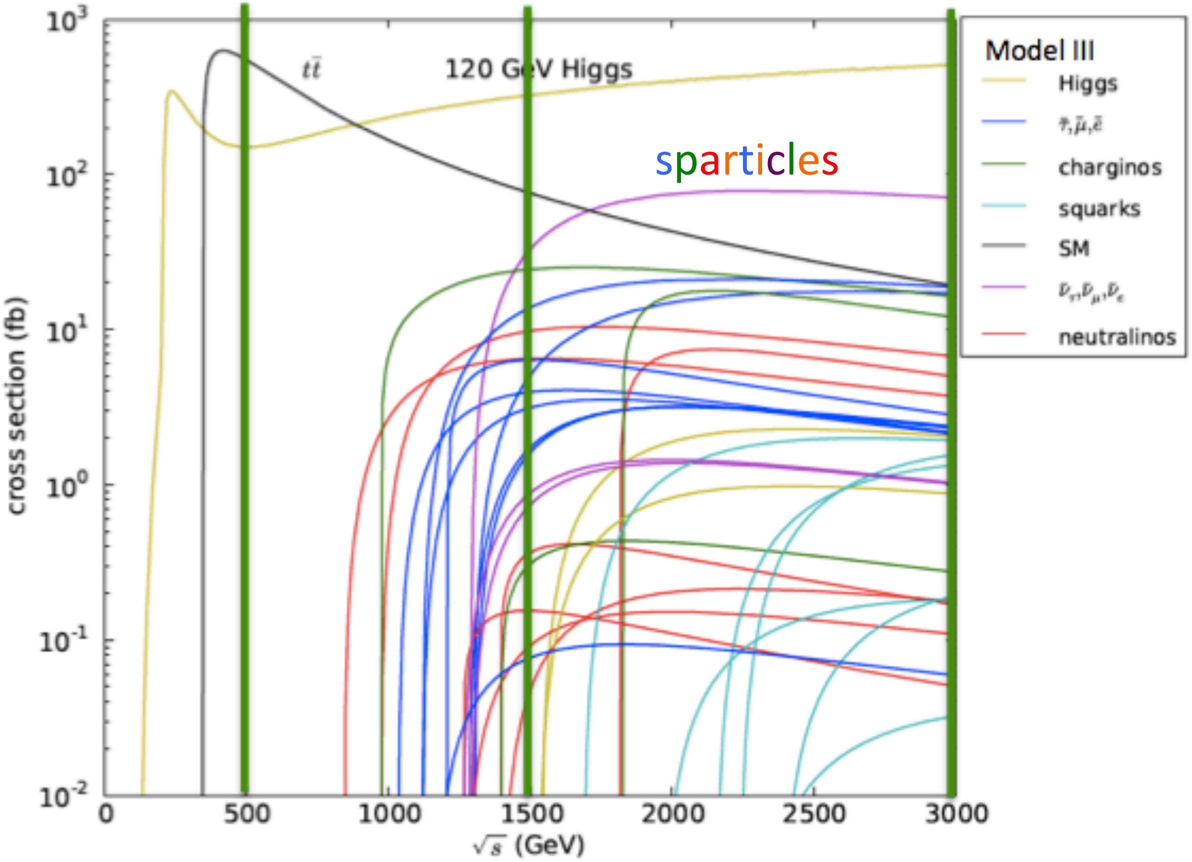
- Majority performed at √s = 3.0 TeV
  - most challenging for beam-induced backgrounds in the detector
  - ultimate physics reach
- Majority based on full Geant4 detector simulations including background

↓

this talk concentrates on 3 TeV

although…

CLIC can be staged in energy

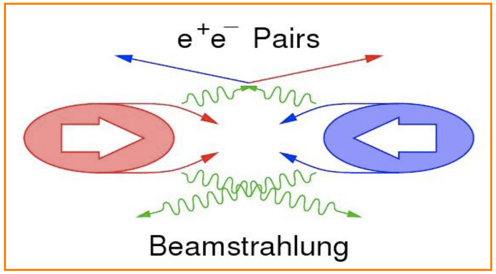


CLIC machine environment (1)

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

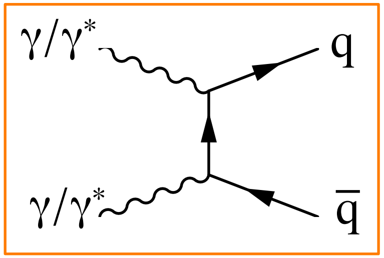
Drives timing requirements for CLIC detector

very small beam size



Beam related background:

- Small beam profile at IP leads very high E-field
  - **Beamsstrahlung**
    - Pair-background
    - γγ to hadrons



CLIC machine environment (2)

Beamstrahlung ➔ important energy losses right at the interaction point

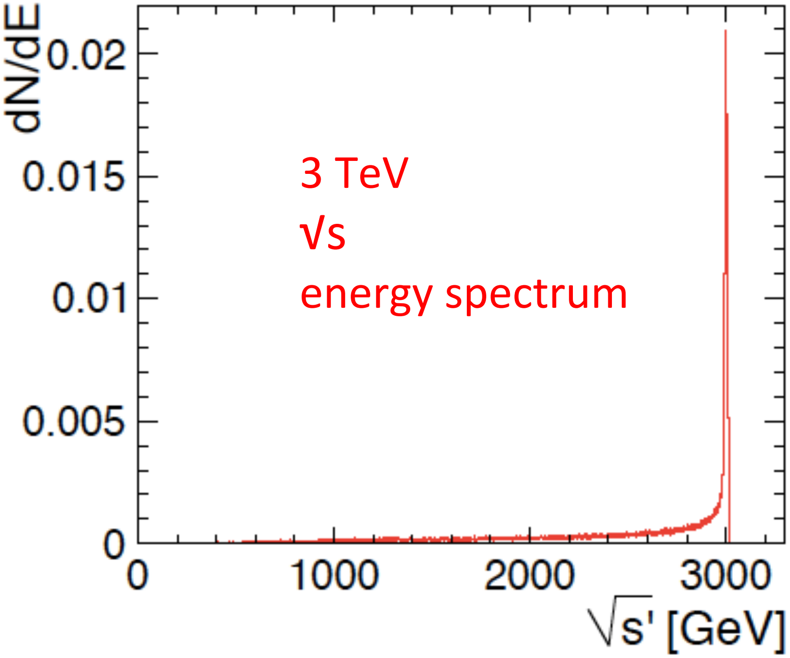
Full luminosity:

5.9×10^{34} cm^{-2}s^{-1}

Of which in the 1% most energetic part:

2.0×10^{34} cm^{-2}s^{-1}

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



Coherent e$^+$e$^-$ pairs

- 7 x 10^8 per BX, very forward

Incoherent e$^+$e$^-$ pairs

- 3 x 10^5 per BX, rather forward

γγ→ hadrons

- 3.2 evts. per BX
- main background in calorimeters

➔

Simplified view:

Pair background

- Design issue (high occupancies)

γγ → hadrons

- Impacts on the physics
- Needs suppression in data

physics aims => detector needs

★ momentum resolution:

e.g. Smuon endpoint

Higgs recoil mass, Higgs coupling to muons

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

★ jet energy resolution:

e.g. W/Z/h di-jet mass separation

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

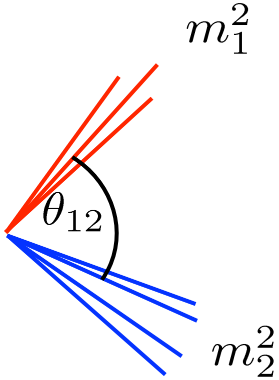
(for high-E jets)

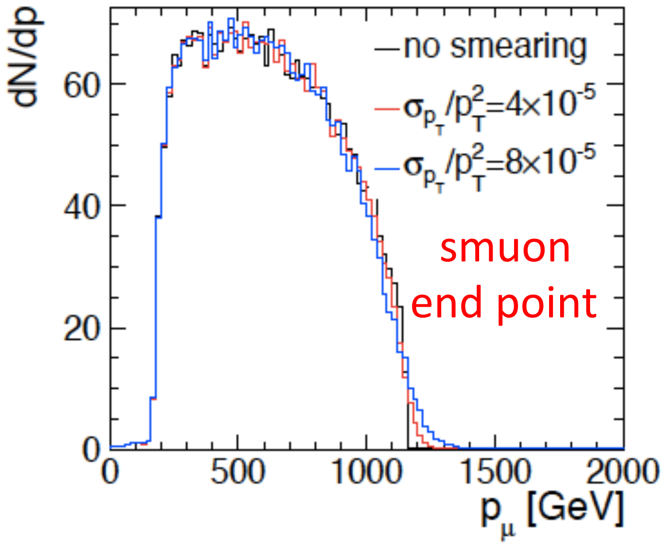
★ impact parameter resolution:

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

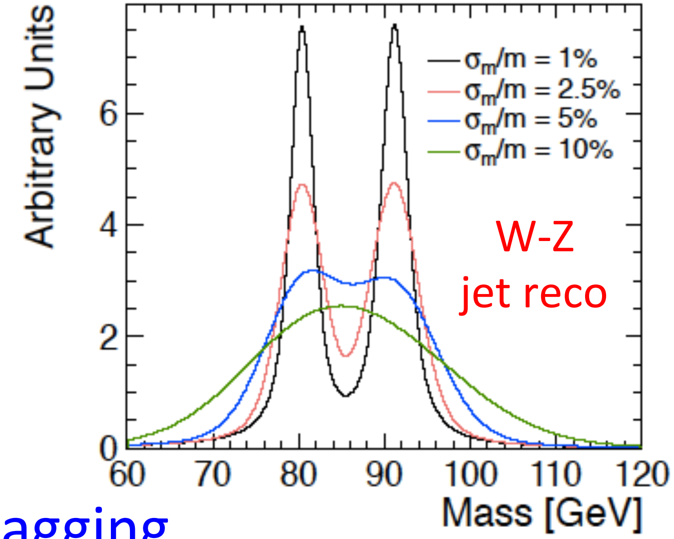
$$\boxed{\sigma_{r\phi} = 5 \oplus 15/(p[\mathrm{GeV}]\sin^{\frac{3}{2}}\theta)\ \mu\mathrm{m}}$$

★ angular coverage, very forward electron tagging





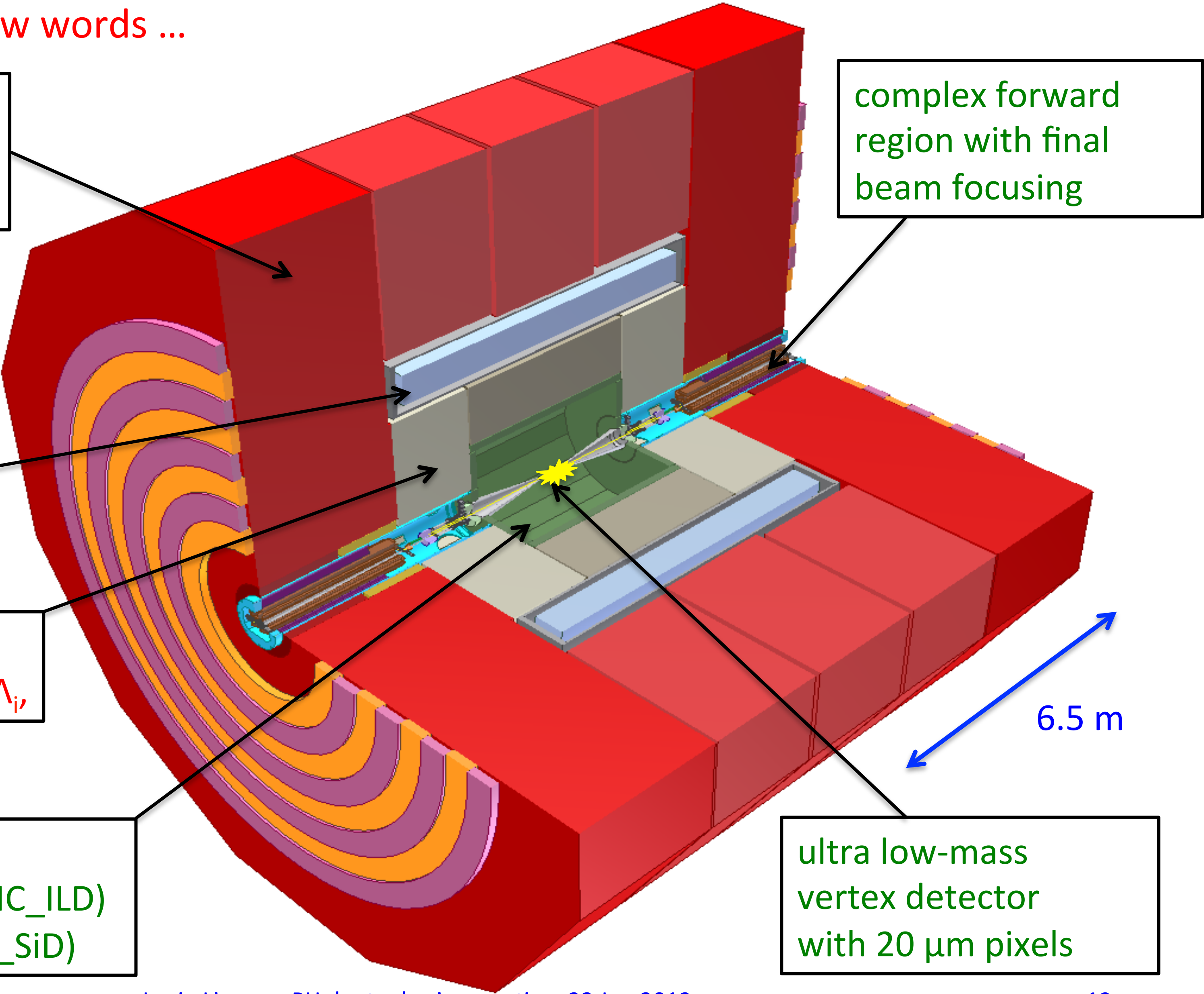
smuon end point



W-Z jet reco

detector concepts

... in a few words ...



return yoke with
Instrumentation
for muon ID

complex forward
region with final
beam focusing

strong solenoids
4 T and 5 T

fine grained (PFA)
calorimetry, 1 + 7.5 Λ_i,

main trackers:
TPC+silicon (CLIC_ILD)
all-silicon (CLIC_SiD)

ultra low-mass
vertex detector
with 20 μm pixels

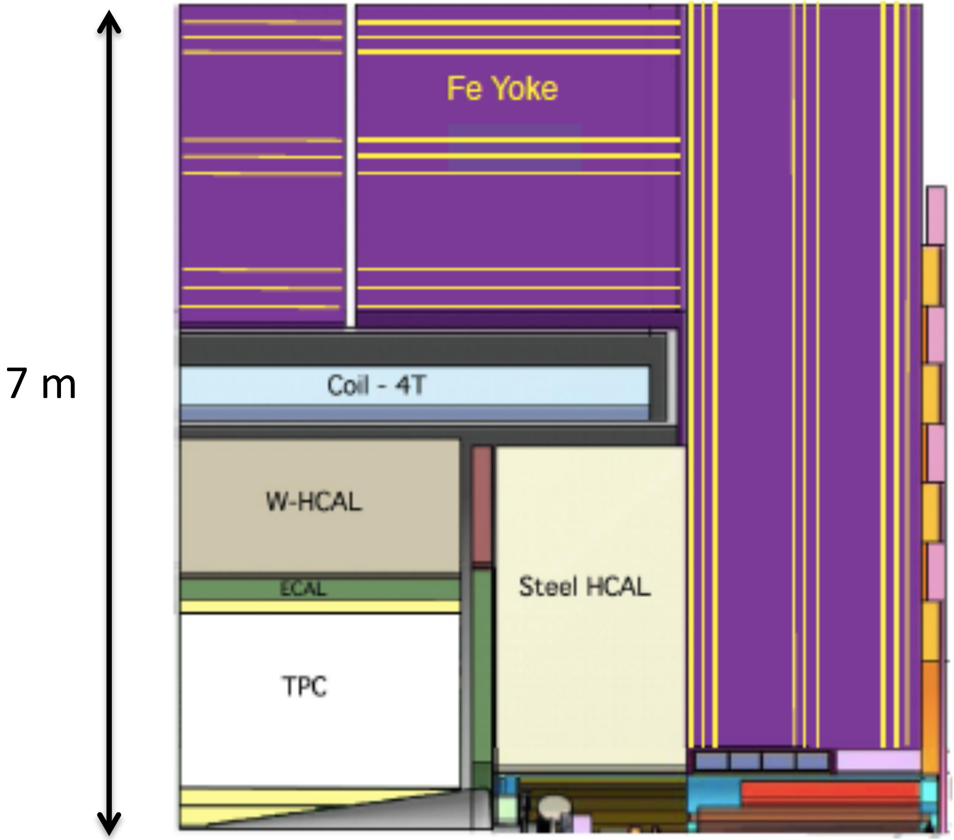
CLIC_ILD and CLIC_SiD

Two general-purpose CLIC detector concepts

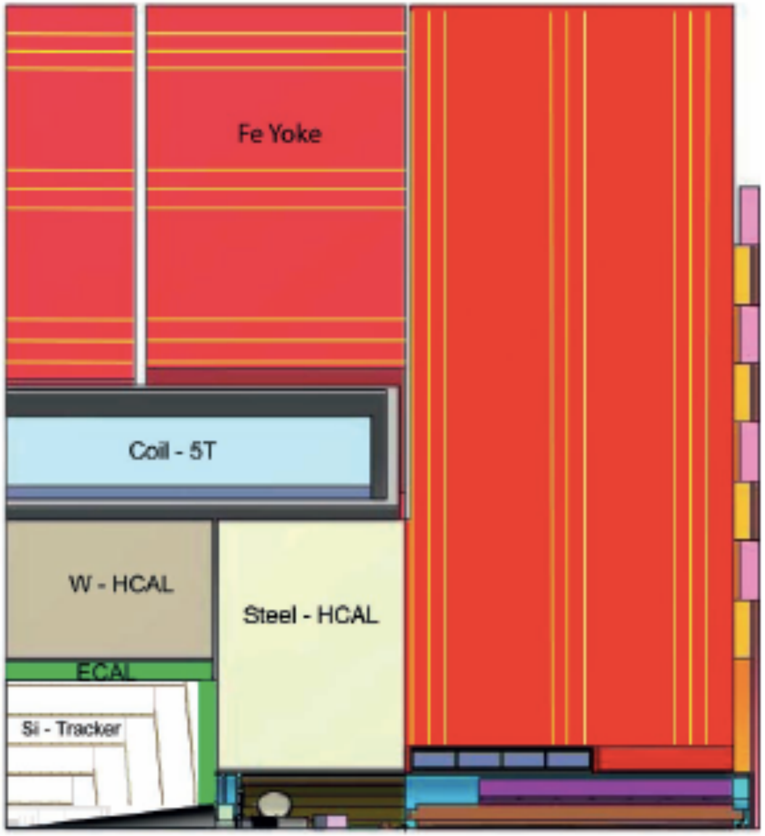
Based in initial ILC concepts (ILD and SiD)

Optimised and adapted to CLIC conditions

CLIC_ILD

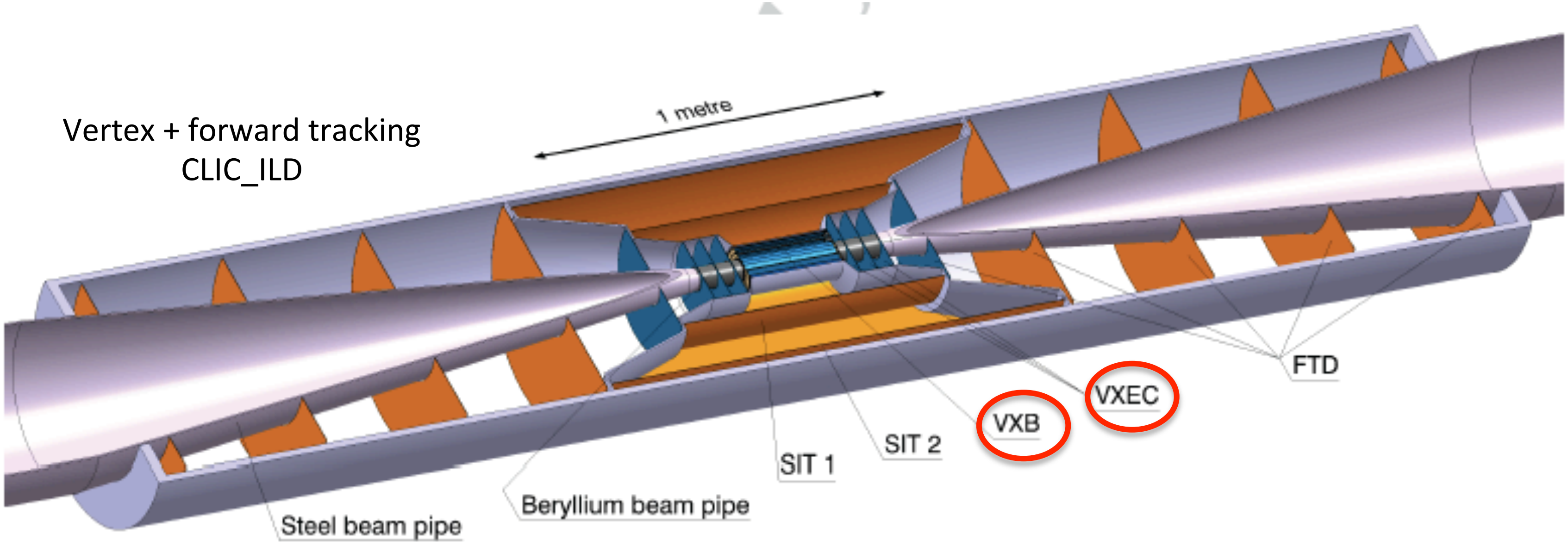


CLIC_SiD



vertex detector

Vertex + forward tracking
CLIC_ILD

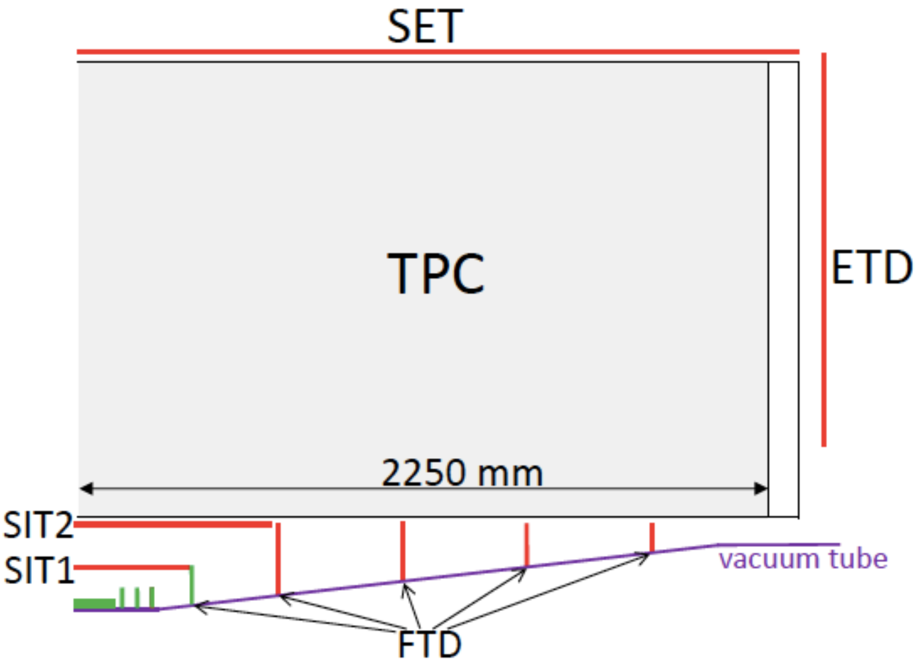


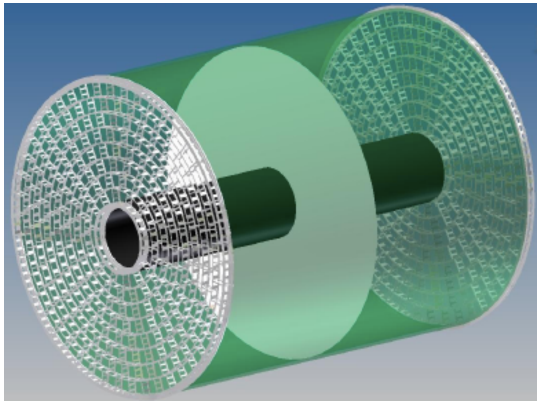
- 20×20 µm pixel size
- 0.2% X_0 material par layer <= very thin !
  - Very thin materials/sensors
  - Low-power design, power pulsing, air cooling
- Time stamping 10 ns
- Radiation level <10^{11} $n_{eq}cm^{-2}year^{-1}$ <= 10^4 lower than LHC

Challenging R&D project

CLIC_ILD ↙ and CLIC_SiD ↘ tracker

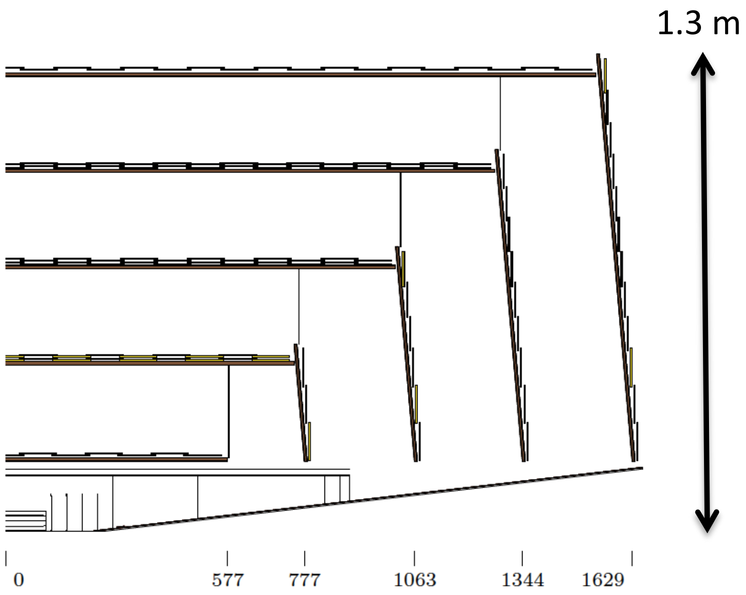
TPC + silicon tracker in 4 Tesla field

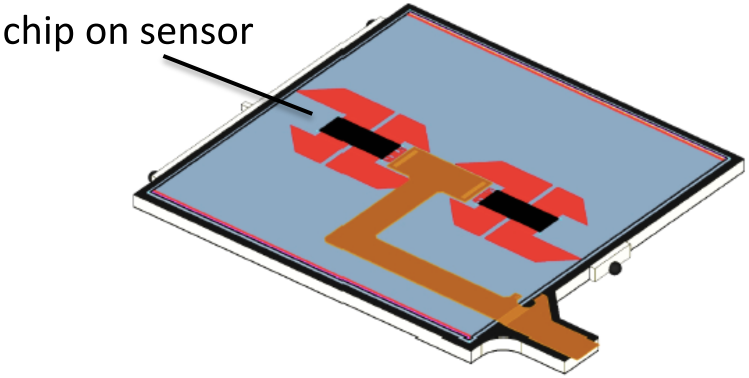




Time Projection Chamber (TPC) with MPGD readout

all-silicon tracker in 5 Tesla field





calorimetry and PFA

Jet energy resolution and **background rejection** drive the overall detector design

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

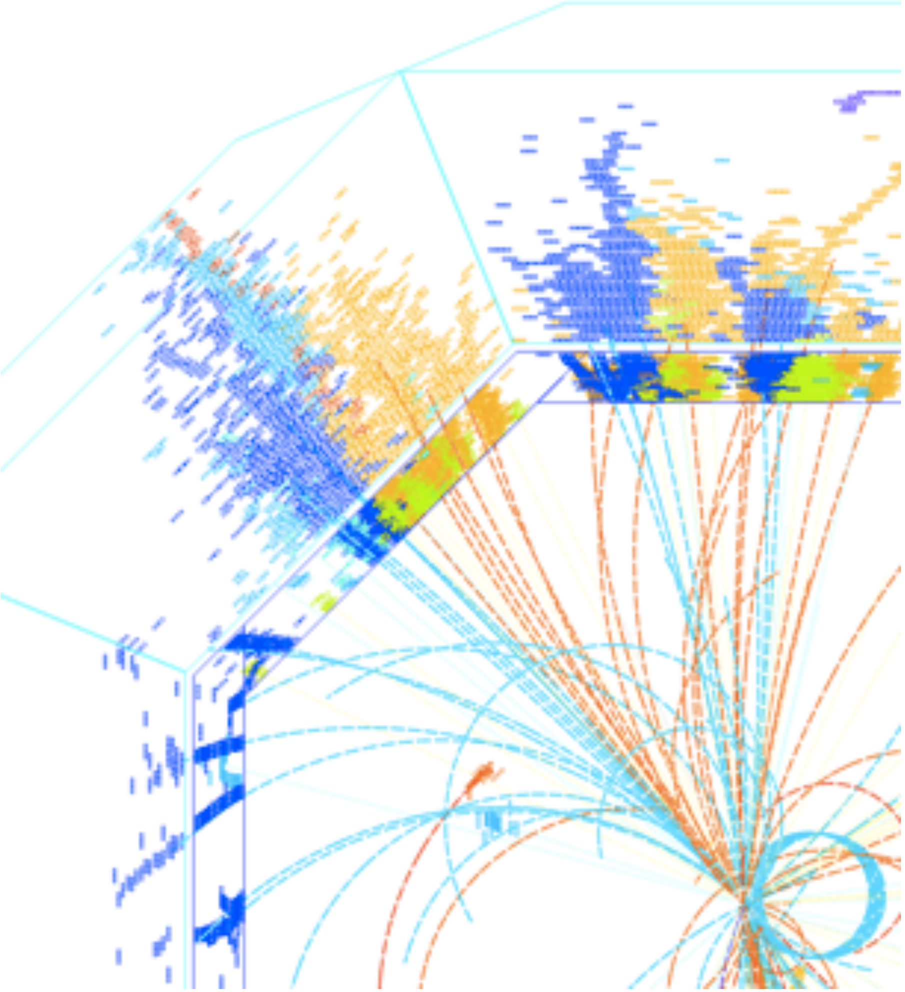
What is PFA?

Typical jet composition:
60% charged particles
30% photons
10% neutrons

↓

Always use the best info you have:
60% => tracker ☺ ☺
30% => ECAL ☺
10% => HCAL ☹

Hardware + software !



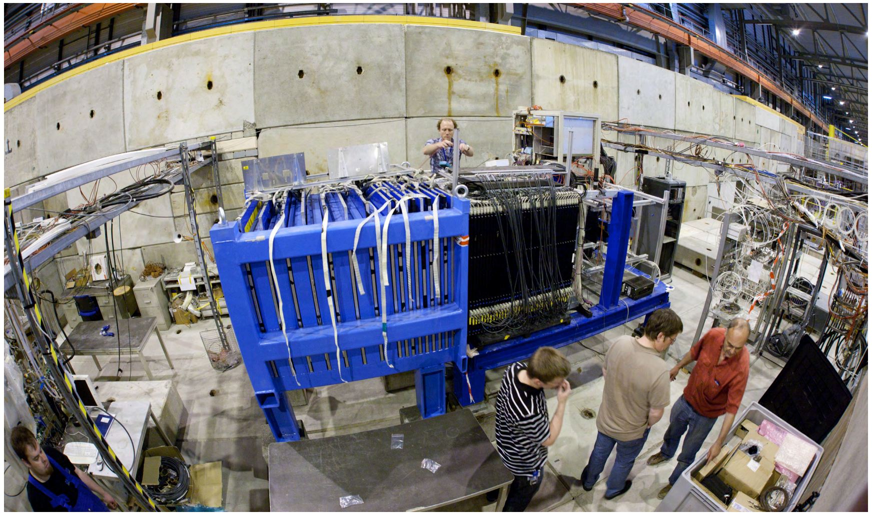
Lucie Linssen, PH dept. physics meeting, 23 Jan 2012

calorimetry and PFA

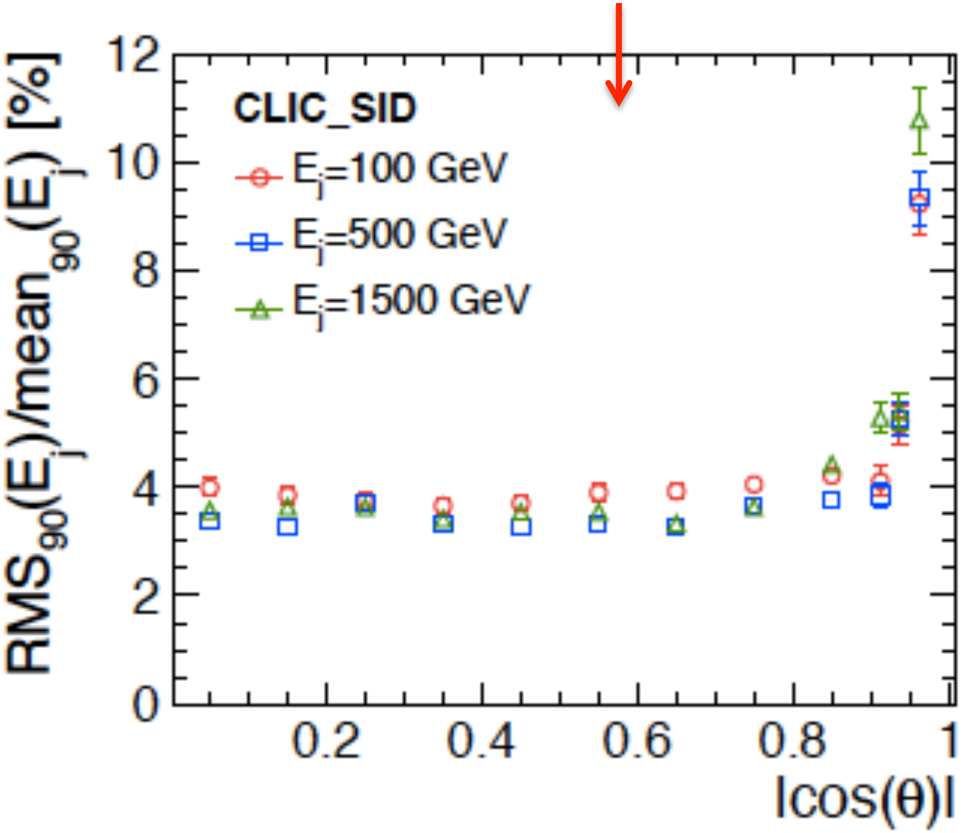
ECAL:
Si or Scint. (active) + Tungsten (absorber)
cell sizes 13 mm^2 or 25 mm^2
30 layers in depth

HCAL:
Several technology options
Tungsten (barrel), steel (endcap)
cell sizes 9 cm^2 (analog) or 1 cm^2 (digital)
60-75 layers in depth
Total depth 7.5 Λ_i

← technology

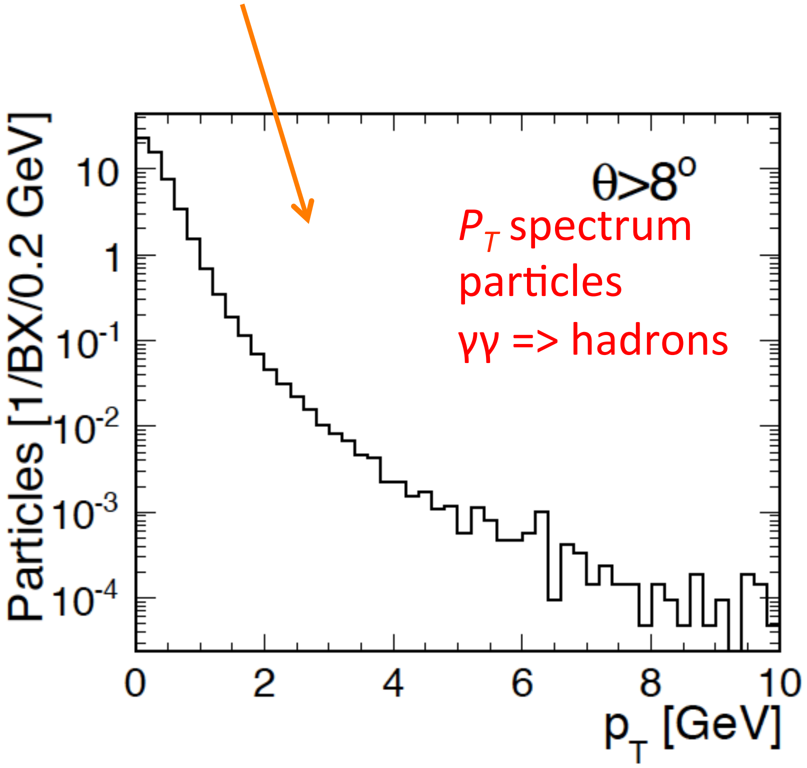


jet energy resolution



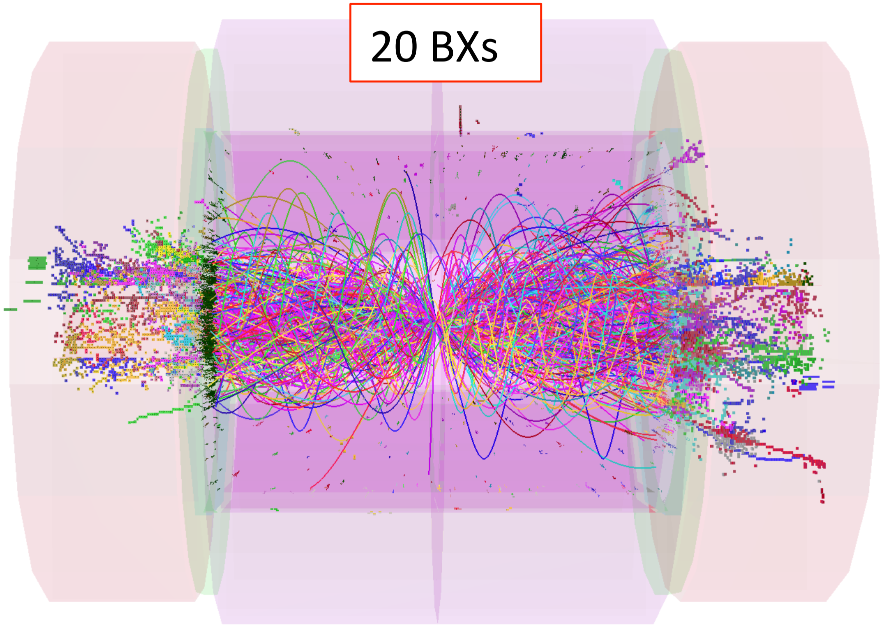
impact of γγ → hadrons

- Dominating background
- For entire bunch-train (312 BXs)
  - 5000 tracks giving total track momentum : 7.3 TeV
  - Total calorimetric energy (ECAL + HCAL) : 19 TeV
- Mostly low p_T particles



P_T spectrum particles

γγ => hadrons

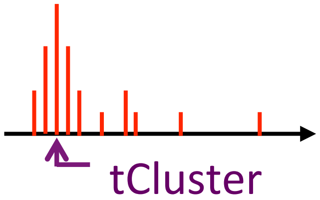

20 BXs

background suppression at CLIC

Triggerless readout of full train

t_0 physics event (offline)

- **Full event reconstruction + PFA analysis with background overlaid**
  - => physics objects with precise p_T and cluster time information
  - Time corrected for shower development and TOF



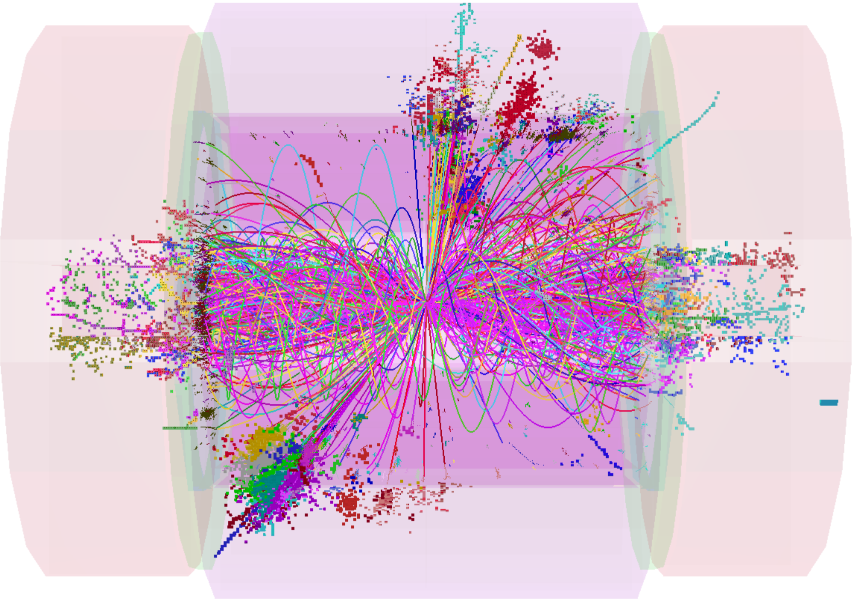
- **Then apply cluster-based timing cuts**
  - Cuts depend on particle-type, p_T and detector region
  - Allows to protect high-p_T physics objects

+

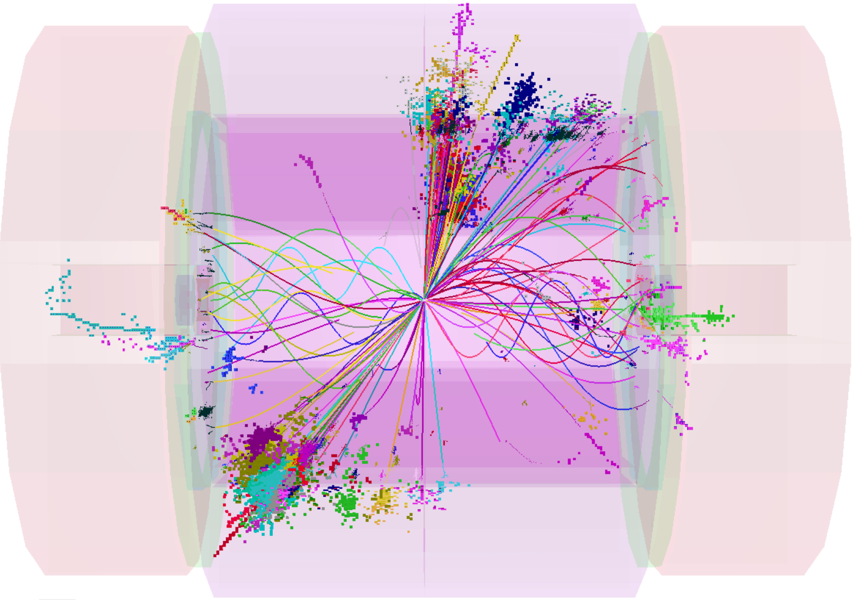
- **Use well-adapted jet clustering algorithms**
  - Making use of LHC experience (FastJet)

combined p_T and timing cuts

1.2 TeV



100 GeV



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

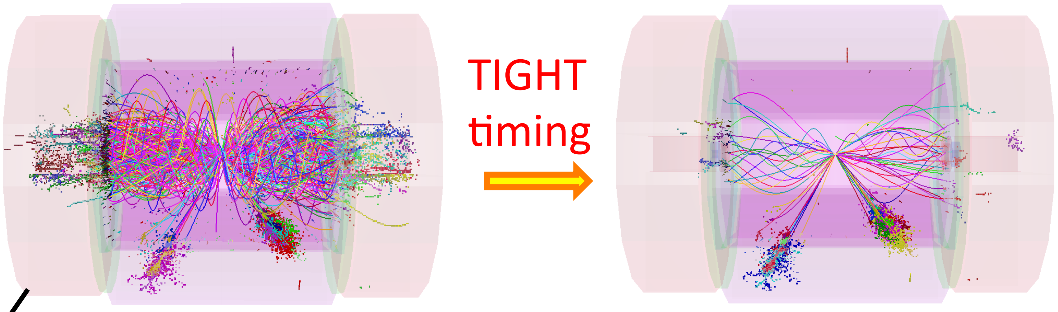
1.2 TeV background in reconstruction time window

100 GeV background after tight cuts

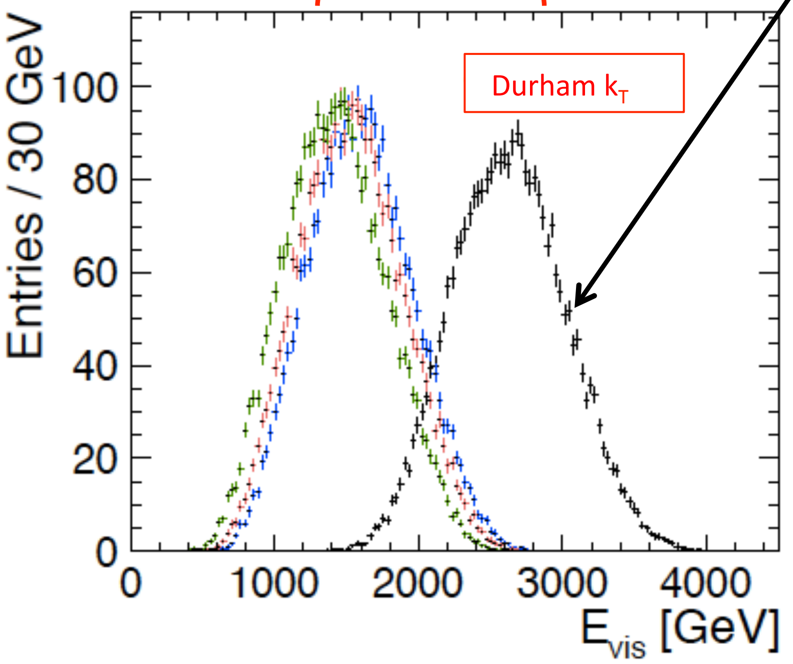
jet clustering (example)

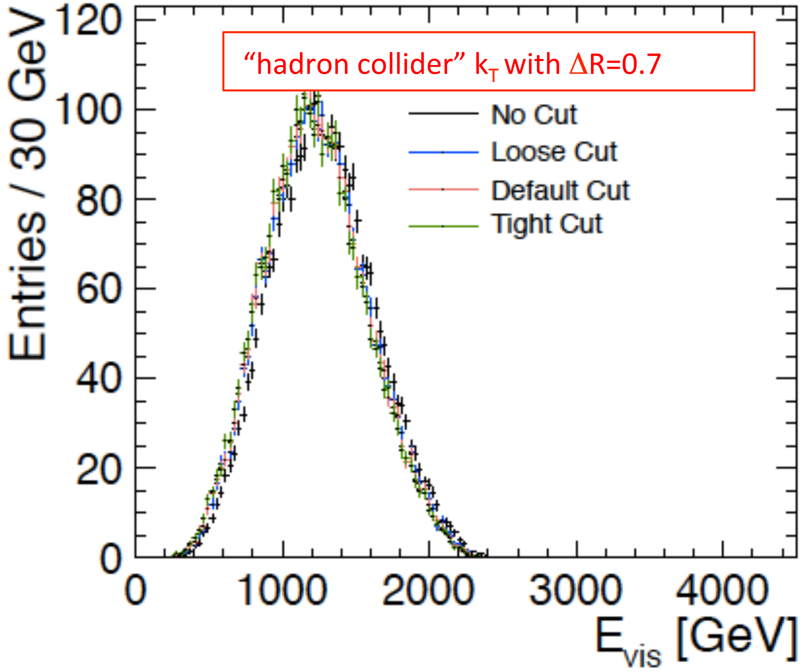
e.g. $e^+e^- \to \tilde{q}_R\tilde{q}_R \to q\bar{q}\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$

- for squark mass ~1.1 TeV
- two jets + missing energy


TIGHT timing

All particles clustered





Result of this detector benchmark study: $m_{\tilde{q}_R}$: $\pm 6\,\mathrm{GeV}$

detector benchmark studies for CDR

Full physics simulation and reconstruction studies with beam background overlay ($\gamma\gamma$ => hadrons)

Choose six channels, with emphasis on mapping various crucial aspects of detector performance (jet measurement, missing energy, isolated leptons, flavour tagging etc.)

3 TeV

- $e^+e^- \to h\nu_e\bar{\nu}_e$ ★
- $e^+e^- \to H^+H^- / H^0A$ ★
- $e^+e^- \to \tilde{q}_R\bar{\tilde{q}}_R$ ★
- $e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-$ ★
- $e^+e^- \to \tilde{\chi}_i^+\tilde{\chi}_i^- / \tilde{\chi}_i^0\tilde{\chi}_i^0$ ★

500 GeV

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

slepton production

Slepton production at CLIC very clean

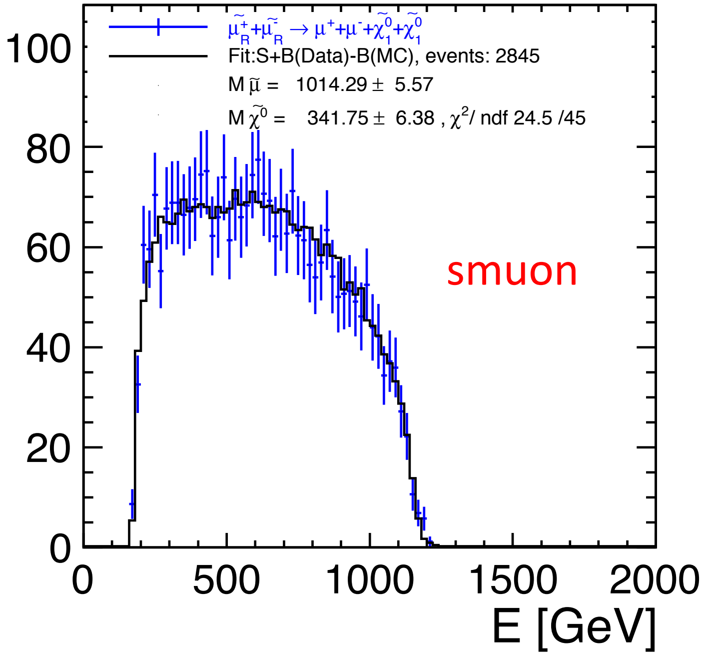
SUSY “*model II*”: slepton masses ~ 1 TeV

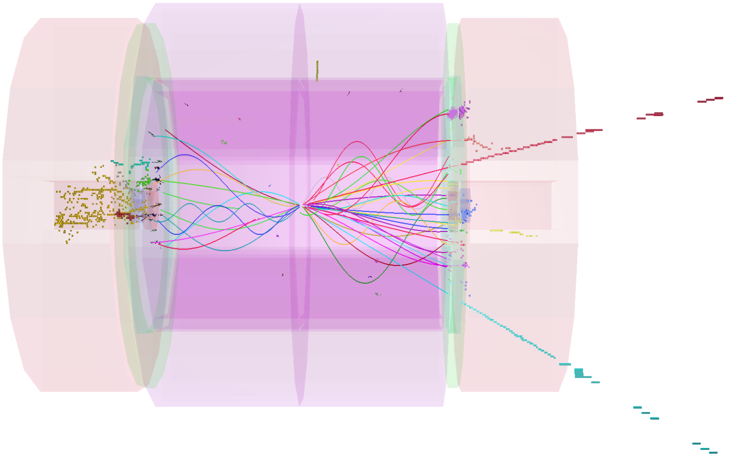
Channels studied include

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

Leptons and missing energy

Masses from analysis of endpoints of energy spectra





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

SUSY "*model II*": $m(\tilde{\chi}_1^0) = 340\,\mathrm{GeV} \quad m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^+) \approx 643\,\mathrm{GeV}$

Pair production and decay:

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

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

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

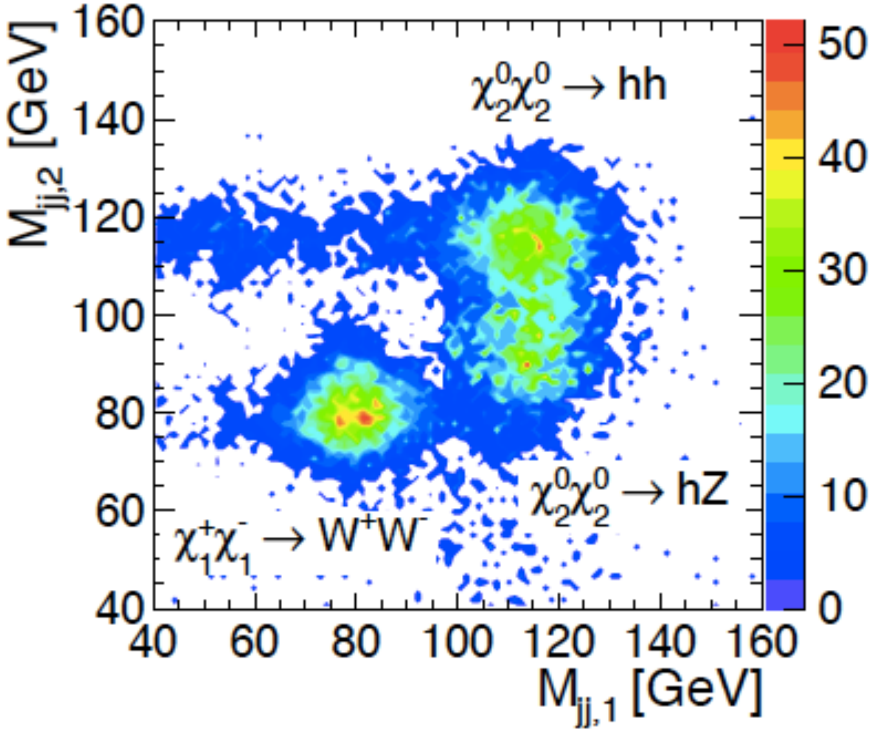
$m(\tilde{\chi}_1^\pm)$: ± 7 GeV

$m(\tilde{\chi}_2^0)$: ± 10 GeV

use slepton study result

$m(\tilde{\chi}_1^0)$: ± 3 GeV

Separation using di-jet invariant masses (test of PFA)



activities in the next project phase

Challenging detector technologies, considered feasible in a 5-year R&D program

- Physics studies
  - CLIC at various energies, follow up on LHC results
- Simulation studies and Detector optimisation
  - General detector optimisation, incl. link to detector R&D
- Detector R&D and engineering
  - Vertex detector
    - Ultra-thin (0.2 X_0/layer), very small pixels (20 μm), 10 ns hit time-stamping
  - Tracking detectors
    - Very thin integrated designs (TPC and Silicon)
  - Calorimetry
    - High-grained, very compact active layers, 1 ns hit time resolution
  - Electronics
    - High readout functionality, precise timing
    - Low power, power delivery and power pulsing (=> air cooling)
  - Engineering and magnet R&D
    - Reinforced superconductor, moveable services
    - Forward region integration, detector movements, calorimetry, alignment…

summary and outlook

Main message from 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

* * *

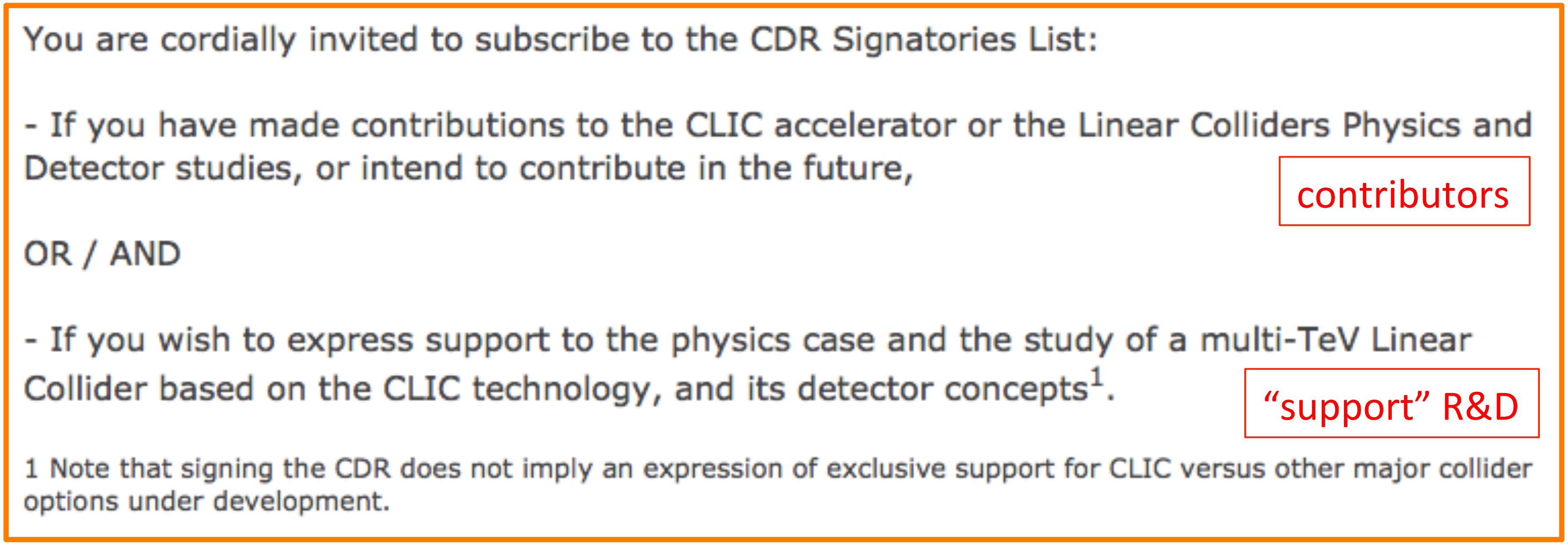
This gives CLIC a very large physics potential, that can be exploited in a staged $\sqrt{s}$ energy approach.

The CLIC physics potential complements LHC at the energy frontier

CLIC CDR signatories list

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



You are cordially invited to subscribe to the CDR Signatories List:

- If you have made contributions to the CLIC accelerator or the Linear Colliders Physics and Detector studies, or intend to contribute in the future,

OR / AND

- If you wish to express support to the physics case and the study of a multi-TeV Linear Collider based on the CLIC technology, and its detector concepts[1].

[1] Note that signing the CDR does not imply an expression of exclusive support for CLIC versus other major collider options under development.

contributors

"support" R&D

currently ~630 names

Signatories => no engagement, non-exclusive support for R&D at energy frontier

SPARE SLIDES

comparison CLIC ⇔ LHC detector

In a nutshell:

CLIC detector:

- **High precision:**
  - Jet energy resolution
    - => fine-grained calorimetry
  - Momentum resolution
  - Impact parameter resolution

- **Overlapping beam-induced background:**
  - High background rates, medium energies
  - High occupancies
  - Cannot use vertex separation
  - Need very precise timing (1ns, 10ns)

- **“No” issue of radiation damage (10^{-4} LHC)**

- **Beam crossings “sporadic”**

- **No trigger, read-out of full 156 ns train**

LHC detector:

- **Medium-high precision:**
  - Very precise ECAL (CMS)
  - Very precise muon tracking (ATLAS)

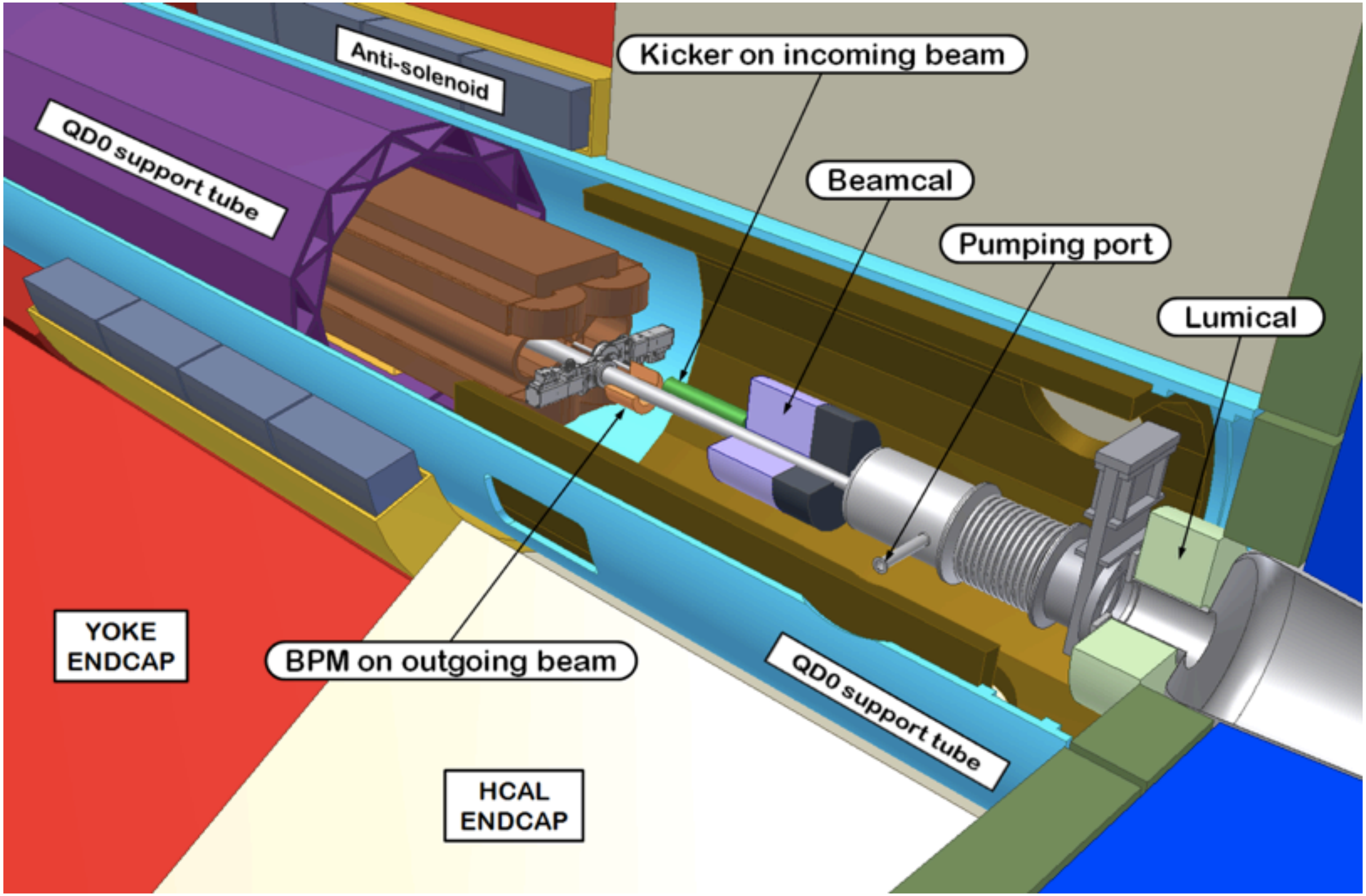
- **Overlapping minimum-bias events:**
  - High background rates, high energies
  - High occupancies
  - Can use vertex separation in z
  - Need precise time-stamping (25 ns)

- **Severe challenge of radiation damage**

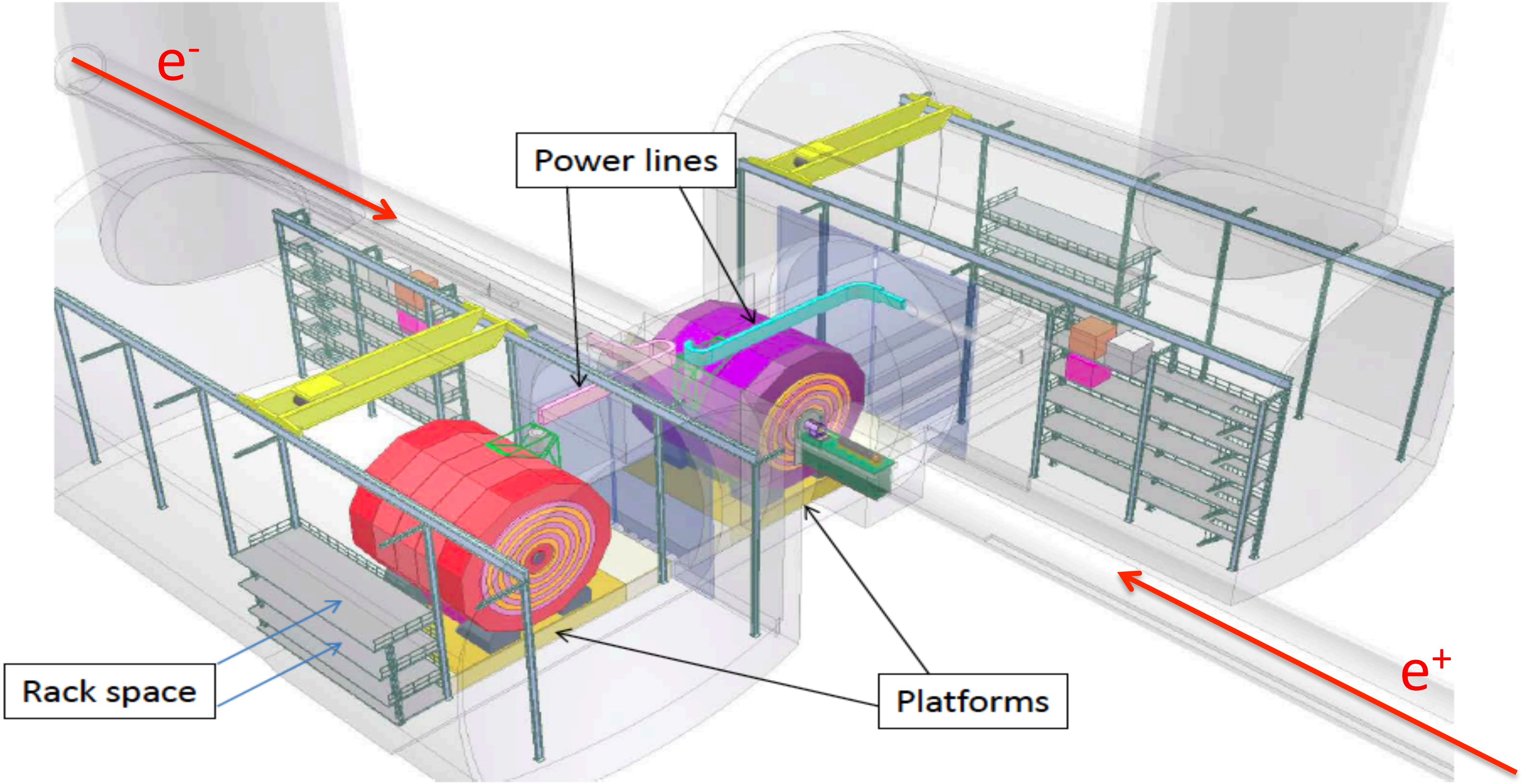
- **Continuous beam crossings**

- **Trigger has to achieve huge data reduction**

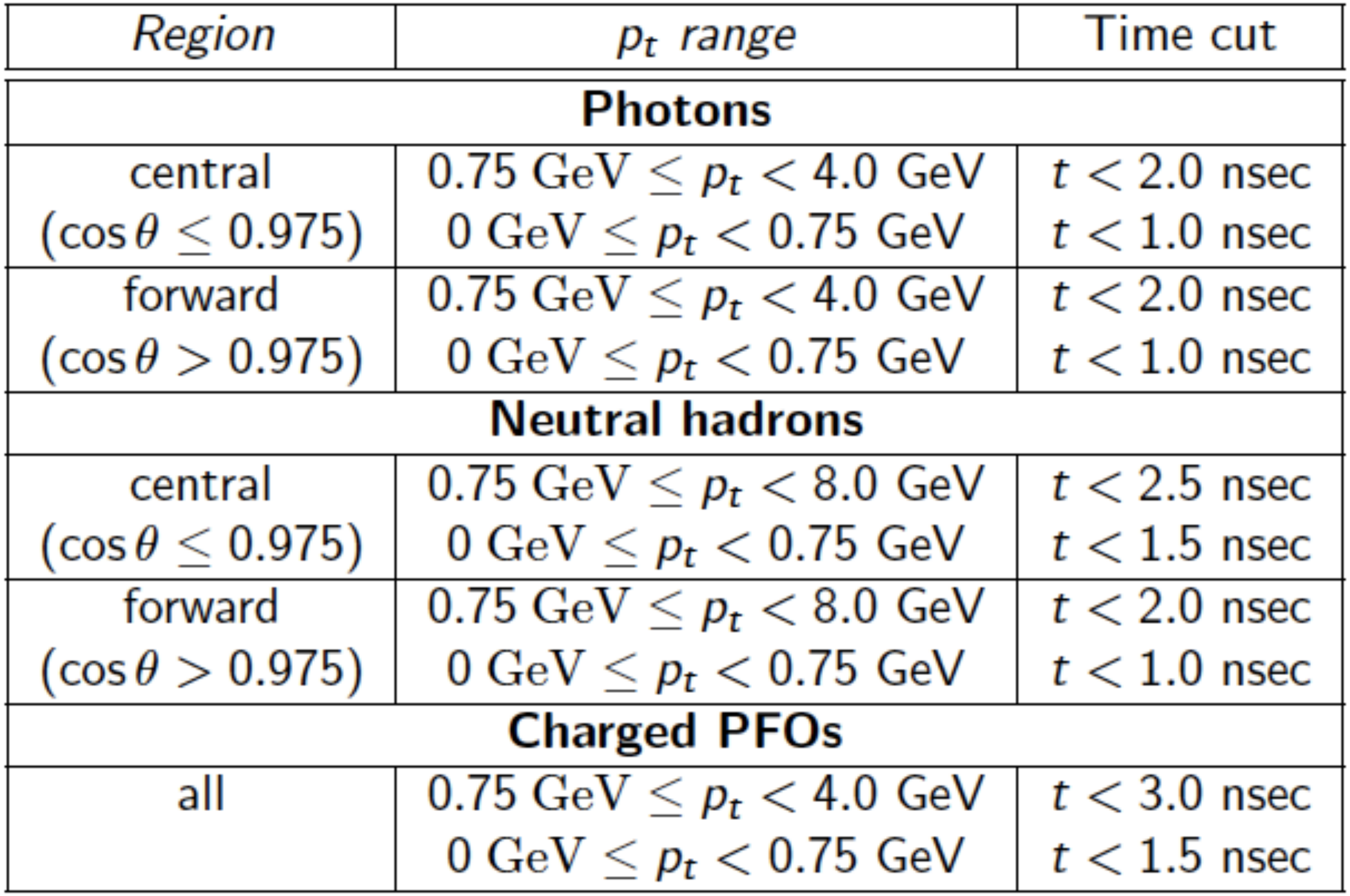
details of forward detector region



two experiments in push-pull



PFO-based timing cuts

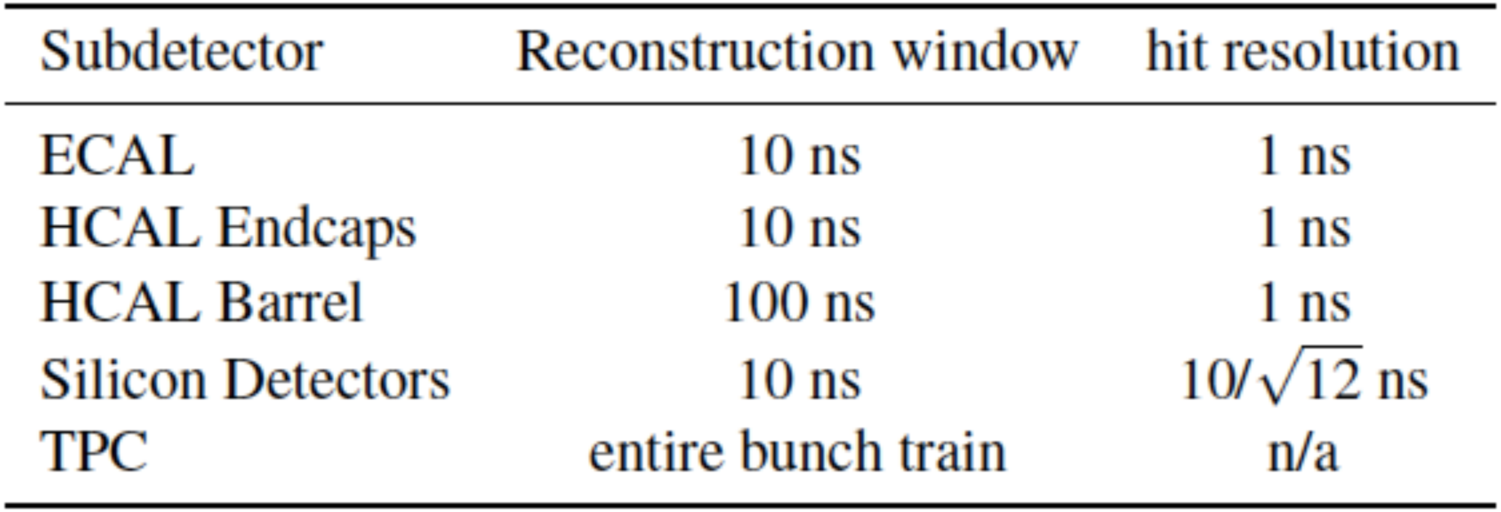


Region	p_t *range*	Time cut
Photons		
central ($\cos\theta \leq 0.975$)	$0.75\text{ GeV} \leq p_t < 4.0\text{ GeV}$ $0\text{ GeV} \leq p_t < 0.75\text{ GeV}$	$t < 2.0$ nsec $t < 1.0$ nsec
forward ($\cos\theta > 0.975$)	$0.75\text{ GeV} \leq p_t < 4.0\text{ GeV}$ $0\text{ GeV} \leq p_t < 0.75\text{ GeV}$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

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

time window / time resolution

The reconstruction software uses:



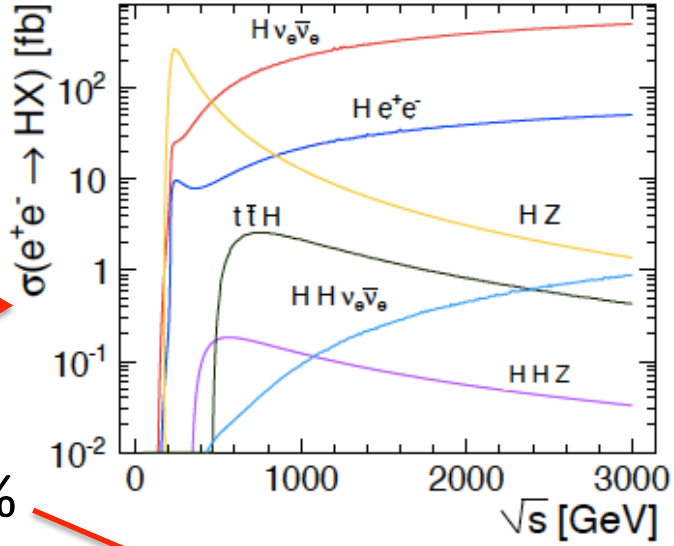
Subdetector	Reconstruction window	hit resolution
ECAL	10 ns	1 ns
HCAL Endcaps	10 ns	1 ns
HCAL Barrel	100 ns	1 ns
Silicon Detectors	10 ns	$10/\sqrt{12}$ ns
TPC	entire bunch train	n/a

Translates in precise timing requirements of the sub-detectors

SM Higgs

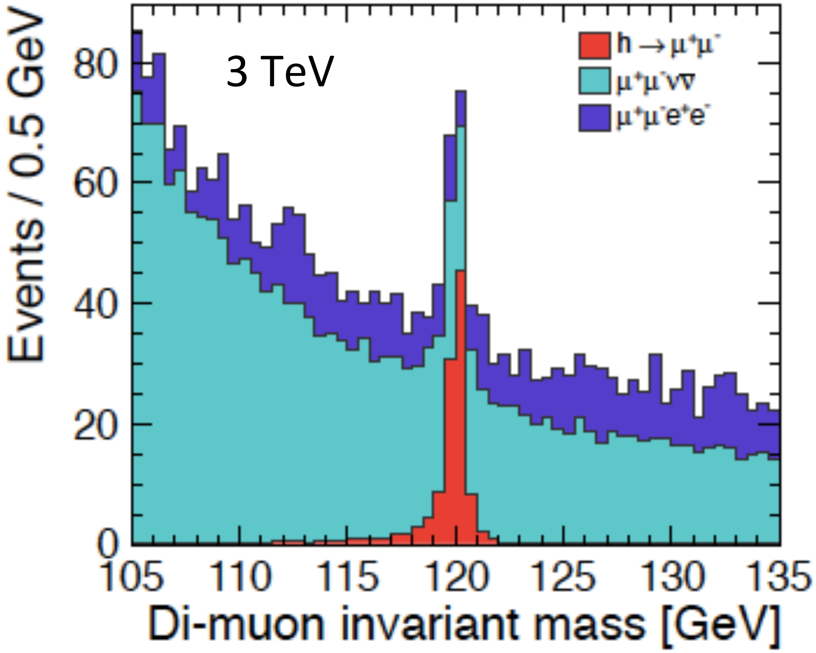
Standard model Higgs (example 120 GeV)

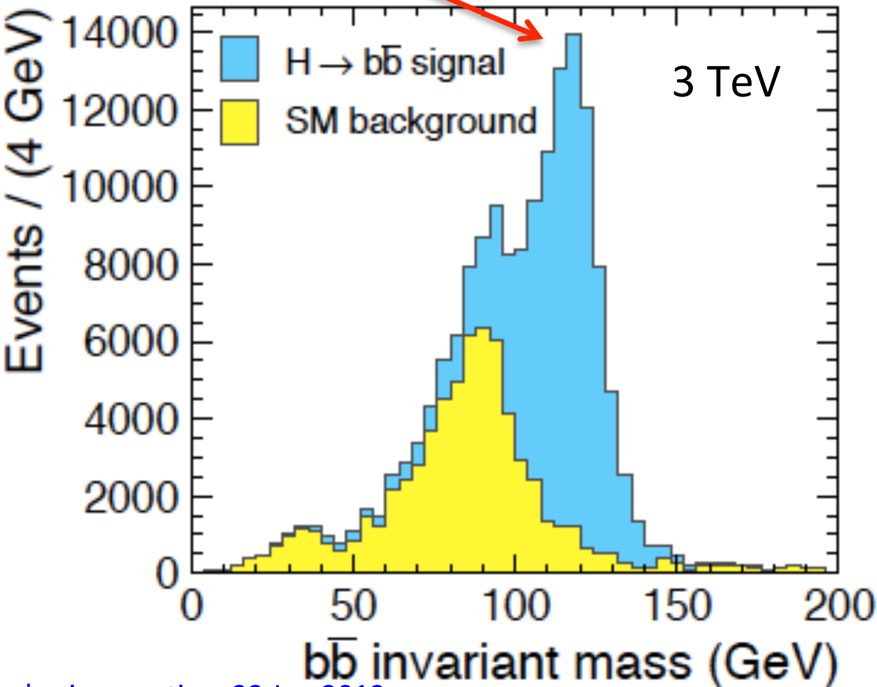
CLIC √s range give access to a wealth of Higgs studies



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

$\sigma(h \to b\bar{b}) \to \pm 0.2\%$



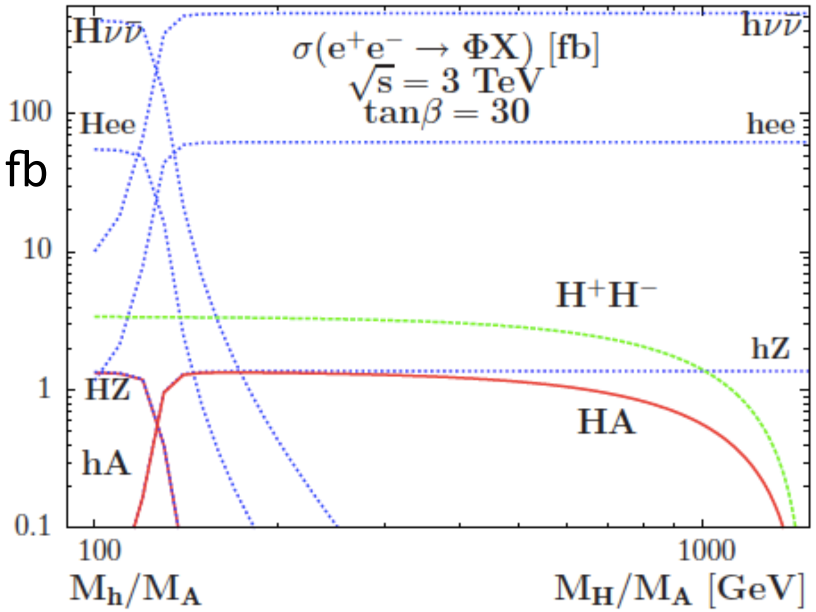


heavy Higgs, non-SM

Non-SM Higgs

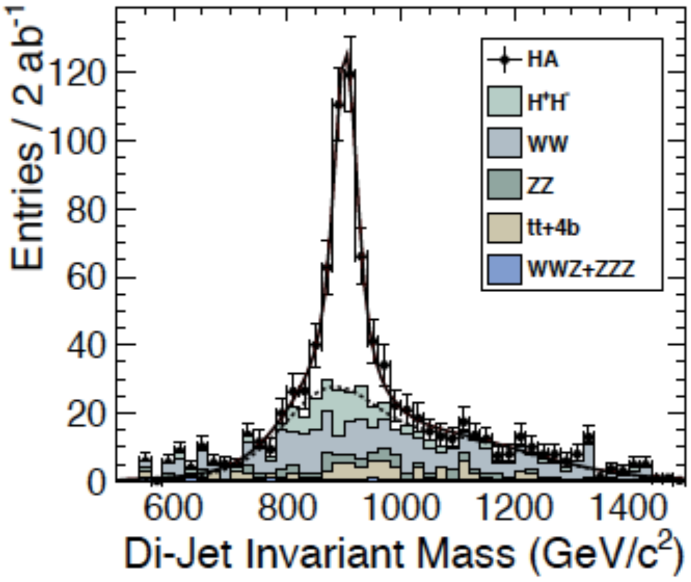
e.g. SUSY heavy Higgs →

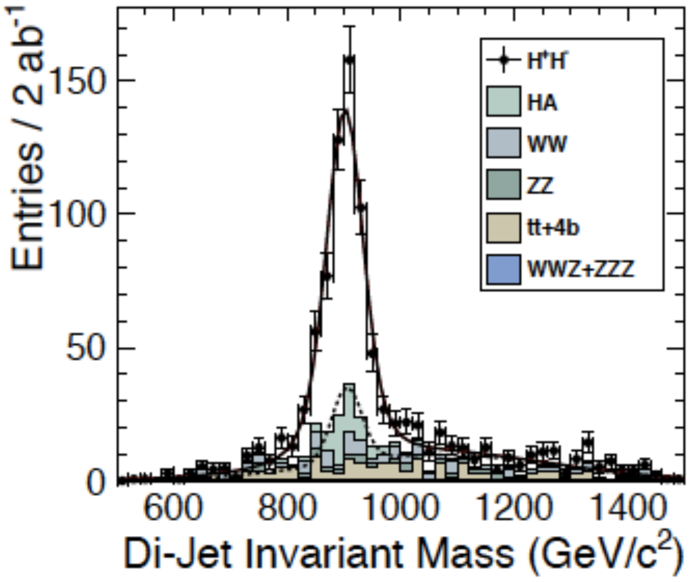
MSSM
3 TeV CM



m_{A^0/H^0} : ± 2.8 GeV

$m_{H^\pm}$: ± 2.4 GeV

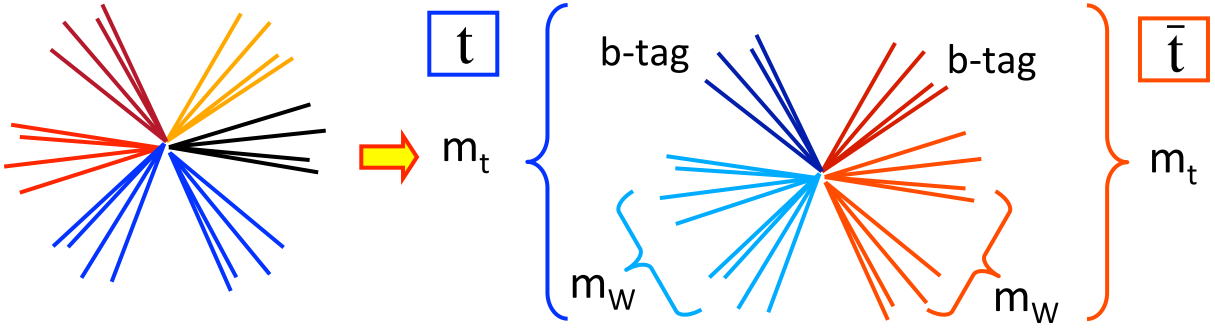




top mass at √s 500 GeV

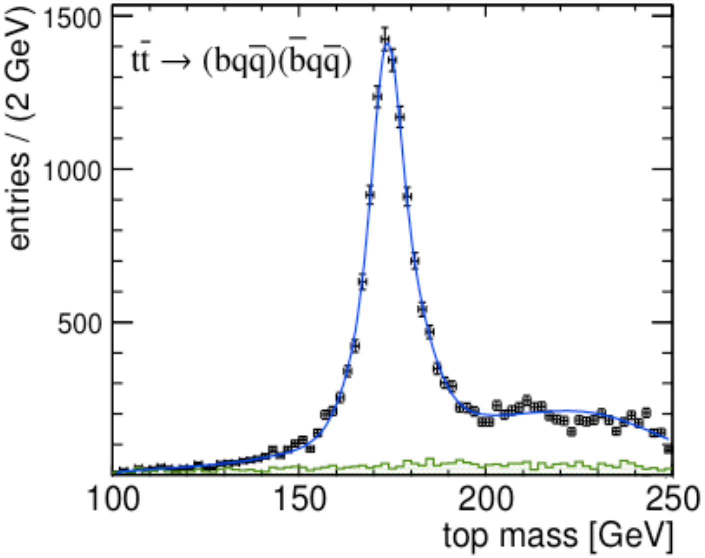
Study top production at √s = 500 GeV under CLIC background conditions

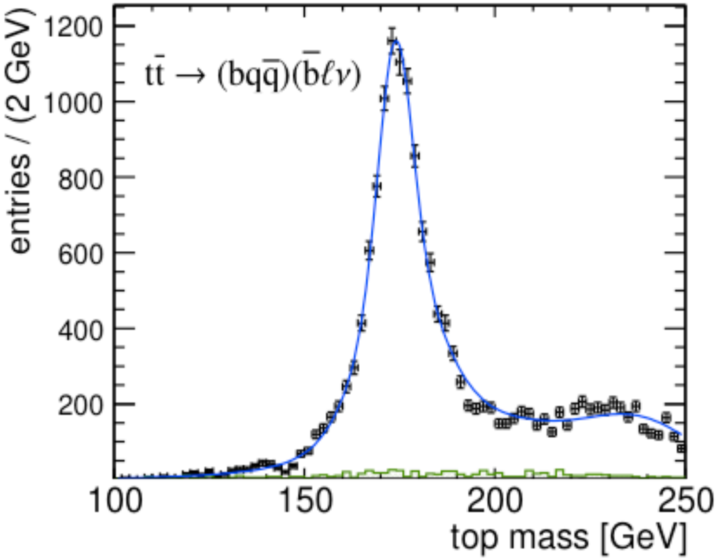
- fully hadronic $t\bar{t} \rightarrow (bq\bar{q})(\bar{b}q\bar{q})$ and semi-leptonic $t\bar{t} \rightarrow (bq\bar{q})(\bar{b}\ell\nu)$



Use:

- b-tagging
- Invariant masses
- Kinematic fits





100 fb^{-1}

↓

$$\boxed{m_t \ : \ \pm 60\,\text{MeV}}$$

Summary of benchmark studies (1)

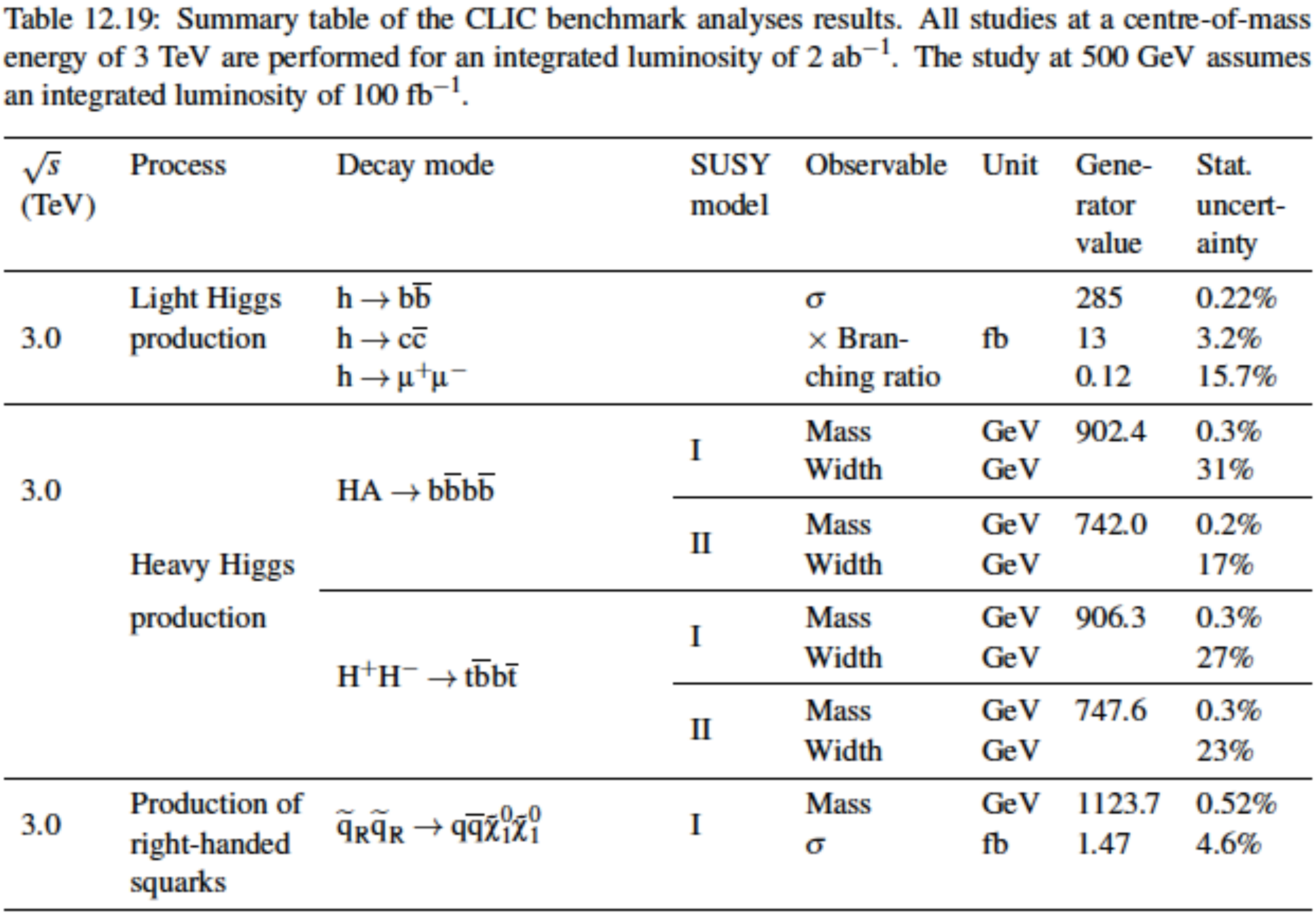
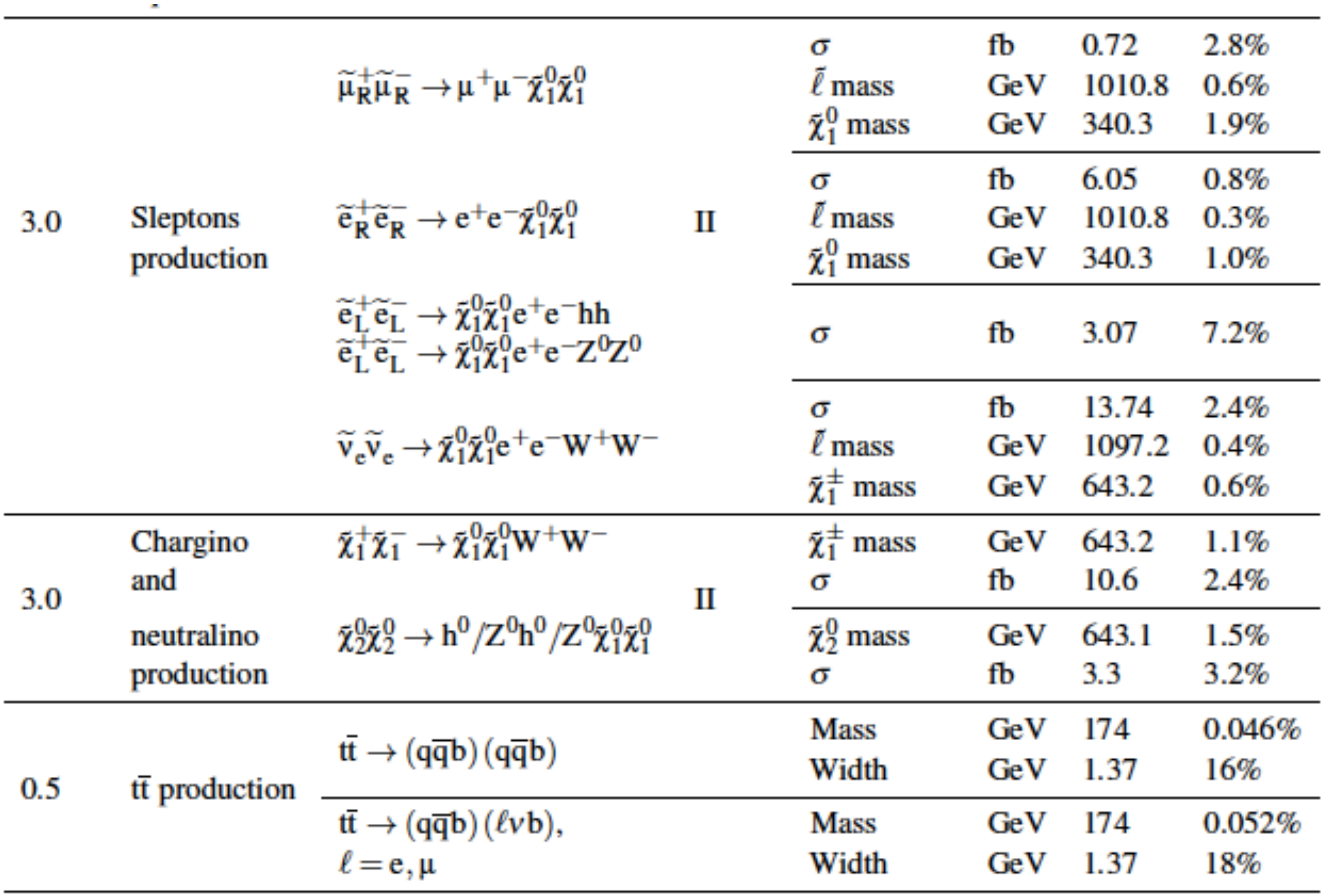


Table 12.19: Summary table of the CLIC benchmark analyses results. All studies at a centre-of-mass energy of 3 TeV are performed for an integrated luminosity of 2 ab^{-1}. The study at 500 GeV assumes an integrated luminosity of 100 fb^{-1}.

$\sqrt{s}$ (TeV)	Process	Decay mode	SUSY model	Observable	Unit	Generator value	Stat. uncertainty
3.0	Light Higgs production	$h \rightarrow b\bar{b}$		$\sigma \times$ Branching ratio	fb	285	0.22%
		$h \rightarrow c\bar{c}$				13	3.2%
		$h \rightarrow \mu^+\mu^-$				0.12	15.7%
3.0	Heavy Higgs production	$HA \rightarrow b\bar{b}b\bar{b}$	I	Mass	GeV	902.4	0.3%
				Width	GeV		31%
			II	Mass	GeV	742.0	0.2%
				Width	GeV		17%
		$H^+H^- \rightarrow t\bar{b}b\bar{t}$	I	Mass	GeV	906.3	0.3%
				Width	GeV		27%
			II	Mass	GeV	747.6	0.3%
				Width	GeV		23%
3.0	Production of right-handed squarks	$\tilde{q}_R\tilde{q}_R \rightarrow q\bar{q}\tilde{\chi}^0_1\tilde{\chi}^0_1$	I	Mass	GeV	1123.7	0.52%
				σ	fb	1.47	4.6%

Summary of benchmark studies (2)



3.0	Sleptons production	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	II	σ	fb	0.72	2.8%
				$\tilde{\ell}$ mass	GeV	1010.8	0.6%
				$\tilde{\chi}_1^0$ mass	GeV	340.3	1.9%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		σ	fb	6.05	0.8%
				$\tilde{\ell}$ mass	GeV	1010.8	0.3%
				$\tilde{\chi}_1^0$ mass	GeV	340.3	1.0%
		$\tilde{e}_L^+\tilde{e}_L^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^- hh$ $\tilde{e}_L^+\tilde{e}_L^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^- Z^0Z^0$		σ	fb	3.07	7.2%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^- W^+W^-$		σ	fb	13.74	2.4%
				$\tilde{\ell}$ mass	GeV	1097.2	0.4%
				$\tilde{\chi}_1^\pm$ mass	GeV	643.2	0.6%
3.0	Chargino and neutralino production	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	II	$\tilde{\chi}_1^\pm$ mass	GeV	643.2	1.1%
				σ	fb	10.6	2.4%
		$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h^0/Z^0 h^0/Z^0 \tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	GeV	643.1	1.5%
				σ	fb	3.3	3.2%
0.5	$t\bar{t}$ production	$t\bar{t} \to (q\bar{q}b)(q\bar{q}b)$		Mass	GeV	174	0.046%
				Width	GeV	1.37	16%
		$t\bar{t} \to (q\bar{q}b)(\ell\nu b)$, $\ell = e, \mu$		Mass	GeV	174	0.052%
				Width	GeV	1.37	18%