R&D challenges of a CLIC vertex detector

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CERN LCD

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Outline

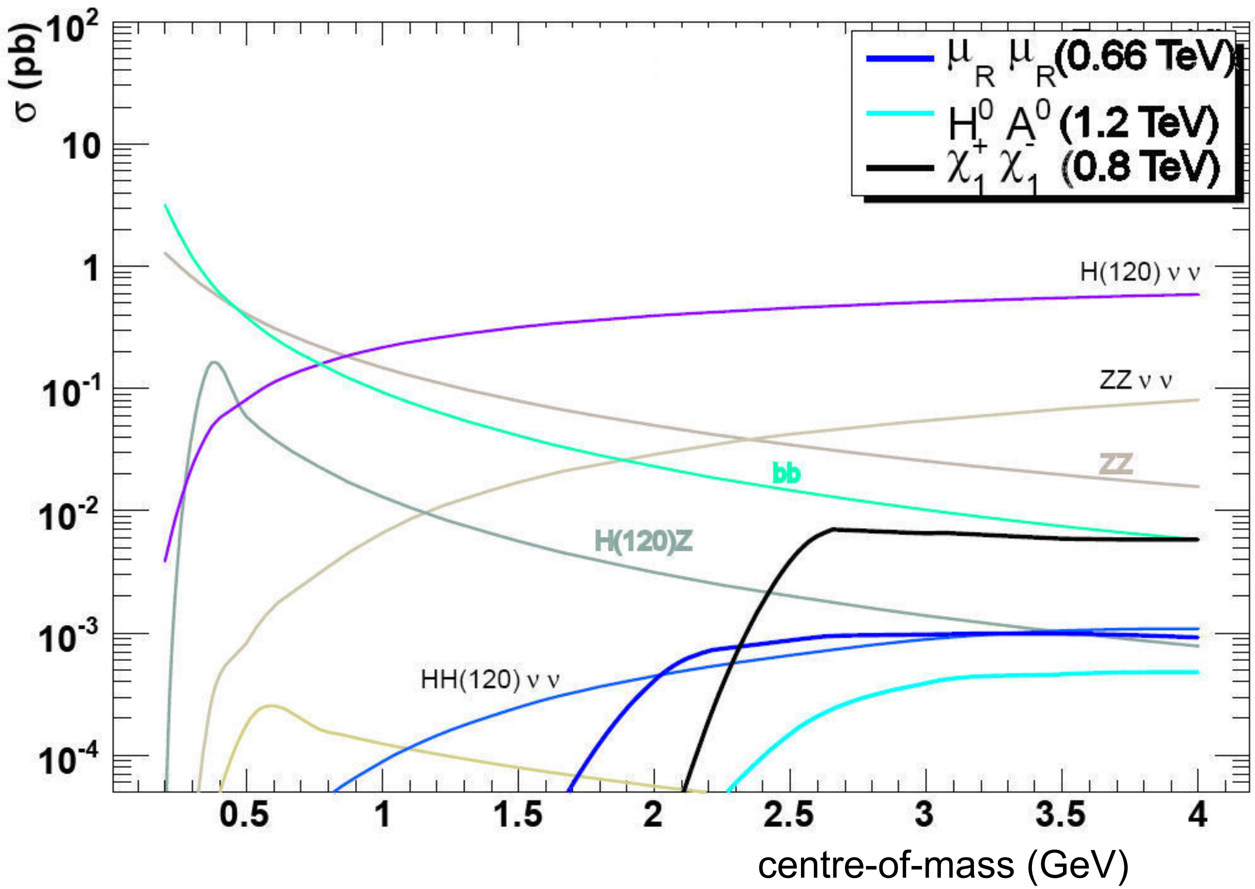
- Physics at multi-TeV e^+e^-
- Introduction CLIC
  - Multi-TeV e^+e^- collisions
- ➢ Linear collider detector concepts

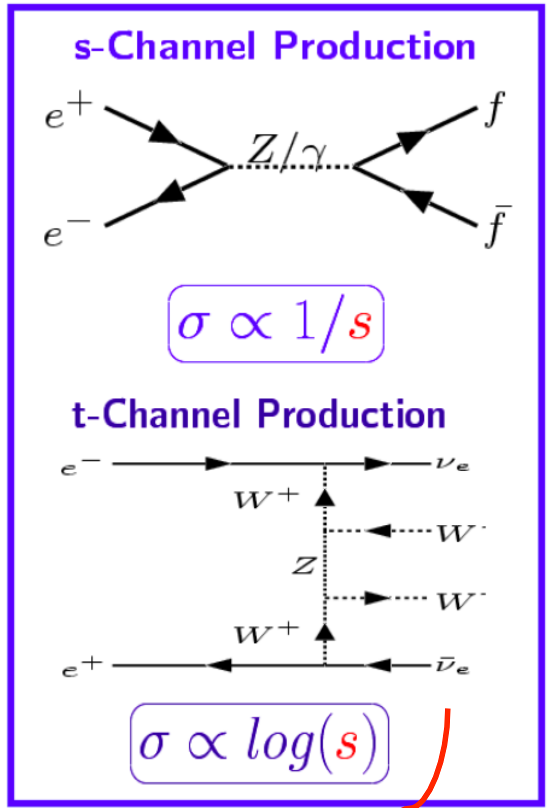
- ➢ Vertex detector requirements
  - Time resolution
  - Position resolution
  - Material budget
  - Power pulsing
  - …

Preliminary

Physics at a few TeV

- Refine LHC physics & explore energy frontier
- What's different: many interesting channels in forward region

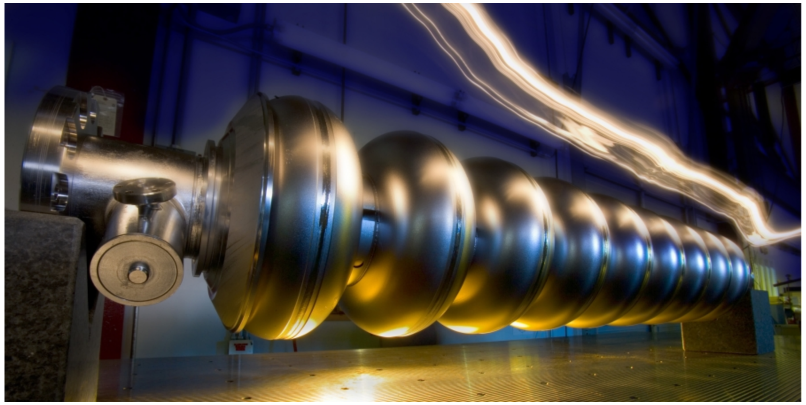




Forward region

ILC and CLIC

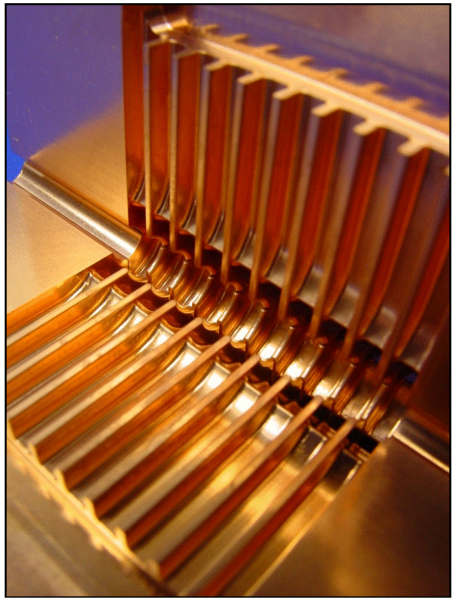
linear collider, producing e^+e^- collisions



ILC

- Based on superconducting RF cavities
- Gradient 32 MV/m
- Energy: 500 GeV, upgradeable to 1 TeV
- (+ lower energies: ttbar resonance,…)
- Detector studies focus mostly on 500 GeV

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



CLIC

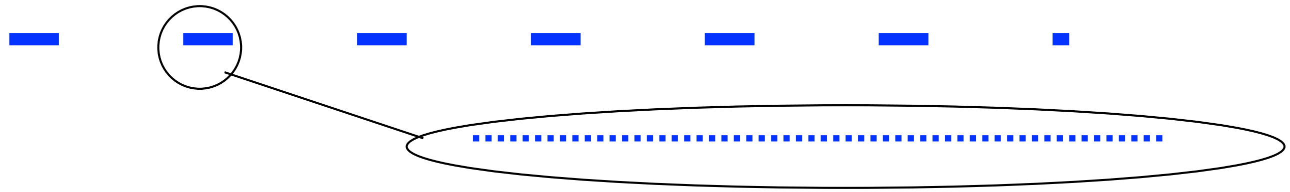
- Based on 2-beam acceleration scheme
- Gradient 100 MV/m
- Energy: 3 TeV, though will probably start at lower energy (~0.5 TeV)
- Detector study focuses on 3 TeV

CLIC parameters

Train repetition rate 50 Hz

Not to scale

CLIC

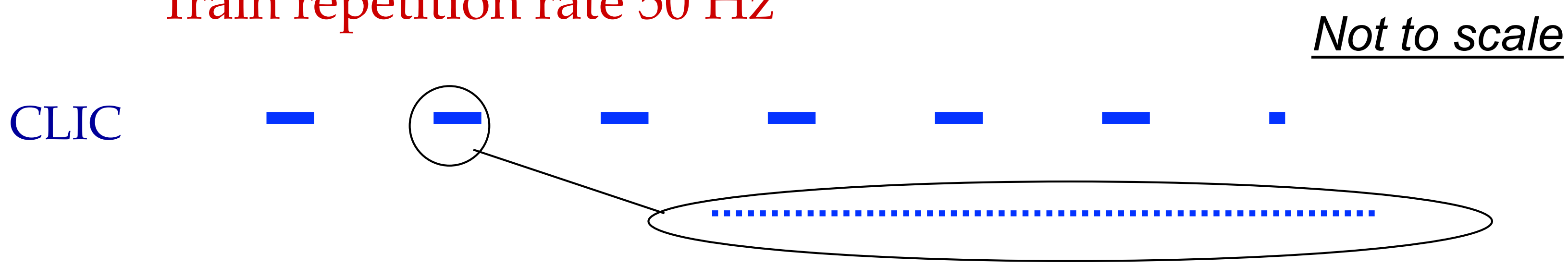


CLIC: 1 train = 312 bunches, 0.5 ns apart trains at 50 Hz

ILC: 1 train = 2820 bunches, 308 ns apart trains at 5 Hz

CLIC parameters

Train repetition rate 50 Hz



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

ILC: 1 train = 2820 bunches, 308 ns apart trains at 5 Hz

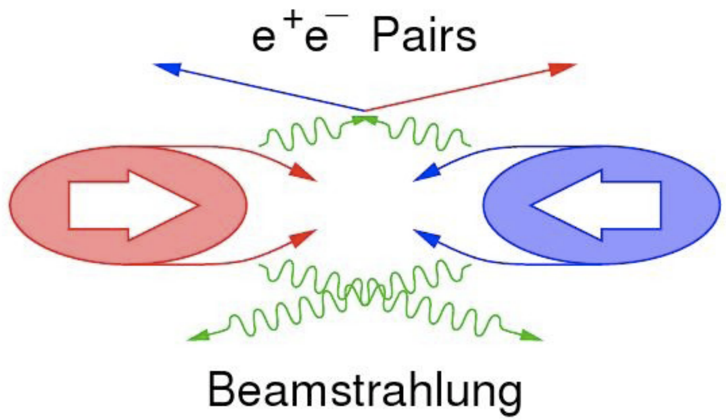
	LEP 2	ILC 0.5 TeV	CLIC 3 TeV
L [cm^{-2}s^{-1}]	5×10^{31}	2×10^{34}	6×10^{34}
Crossing angle		14 mrad	20 mrad
BX separation	~22 μs	308 ns	0.5 ns
IP size in x / y / z direction [nm]	250 μm / 5 μm / 10 mm	600nm / 6nm / 10mm	45 nm / 1 nm / 40 μm
# (γγ→hadrons) / BX	negligible	0.2	3.0
#Incoherent pairs / BX	negligible	1×10^5	3×10^5

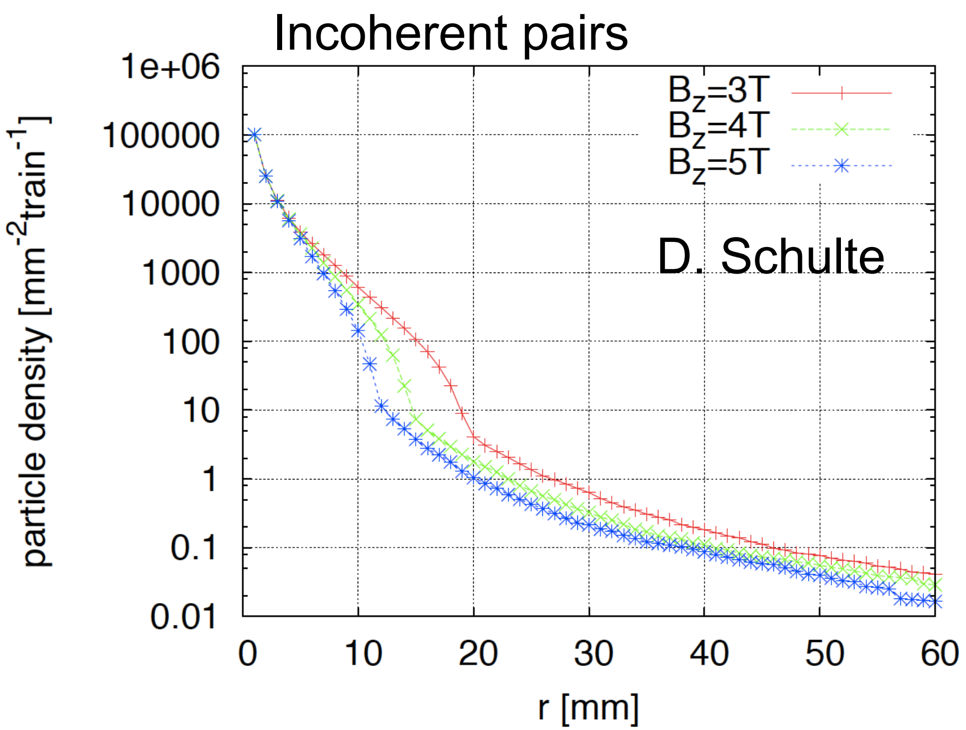
Beamstrahlung at 3 TeV

$\Delta E/E = 29\%$ ($10\times ILC_{value}$)

- **Coherent pairs**
  3.8×10^{8} per BX
  ~ disappear in beam pipe
- **Incoherent pairs**
  3.0×10^{5} per BX
  ~ reduced by strong solenoid-field
  main source of background in vertex detector

- Large impact on detector concepts:
  - ➢ Conical beampipe.
  - ➢ Inner radius of vertex detector to be larger at CLIC: 3 cm.



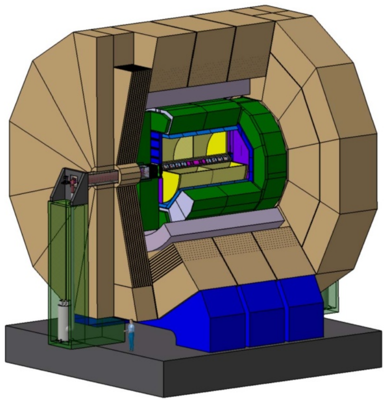


CLIC detector concepts

- Based on ILC validated concepts, modified to CLIC requirements

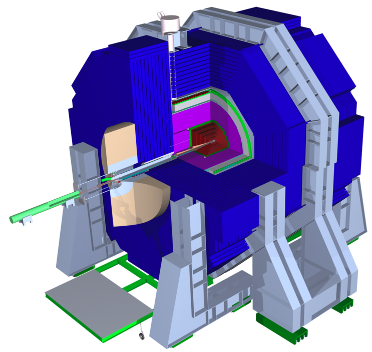
CLIC_ILD: International Large Detector

"Large":	tracker radius 1.8 m
B-field:	4 T solenoid
Tracker:	TPC + Si-strip layer
Vertex:	Si-pixel



CLIC_SiD: Silicon Detector

"Small":	tracker radius 1.3 m
B-field:	5 T solenoid
Tracker:	Silicon
Vertex:	Si-pixel

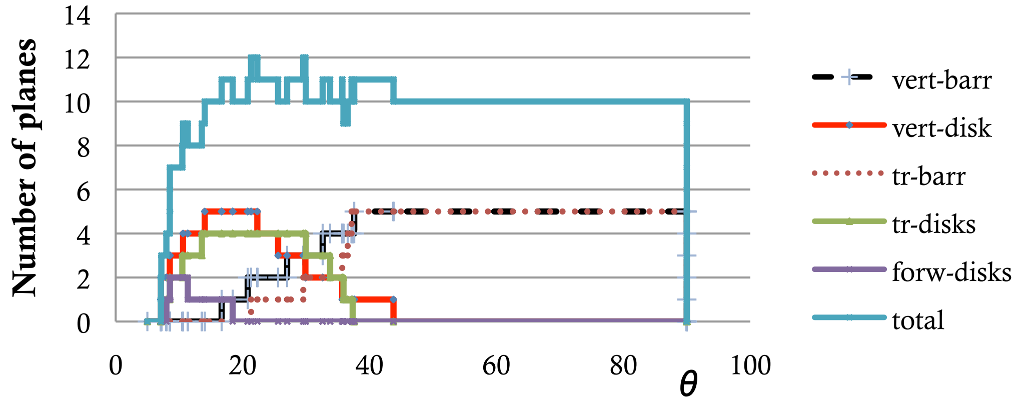


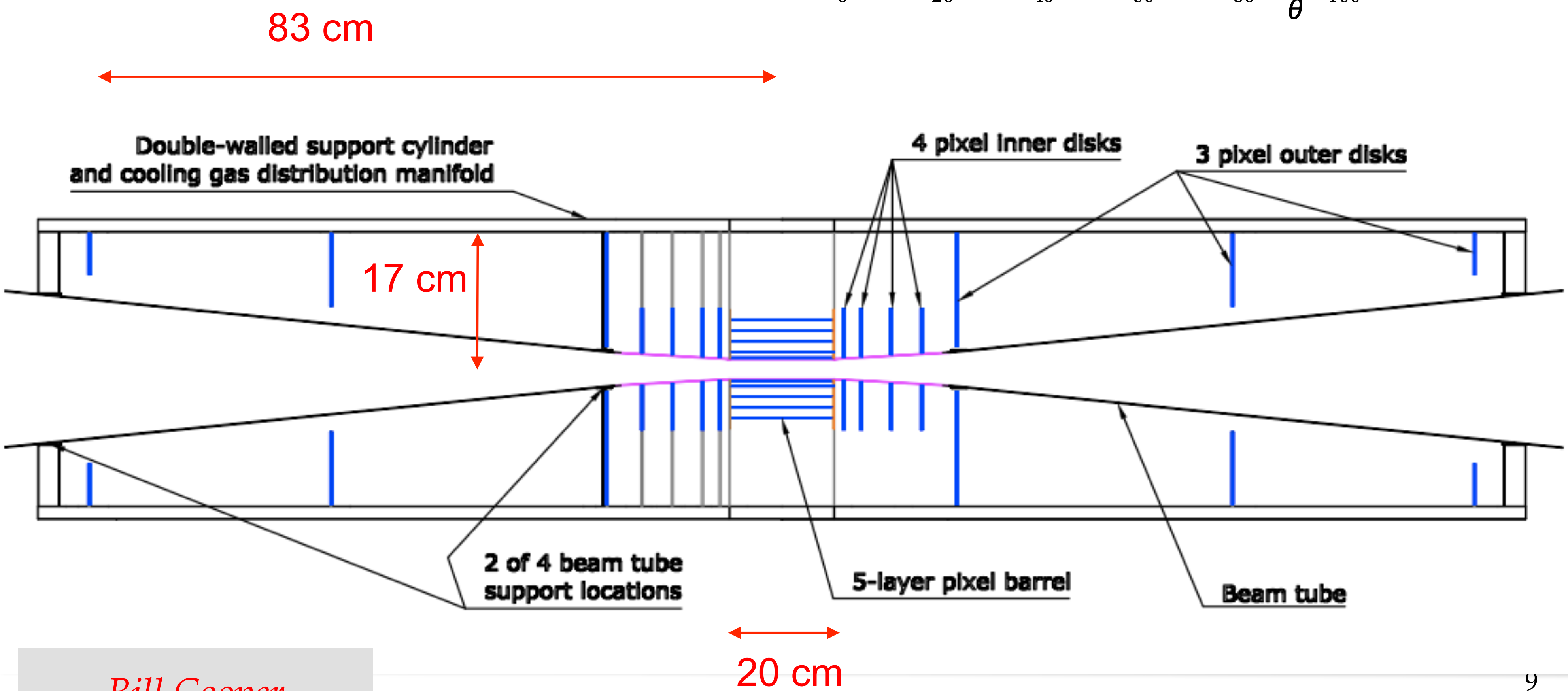
Both have ECAL+HCAL inside solenoid with high granularity

CLIC_SiD vertex and forward tracker

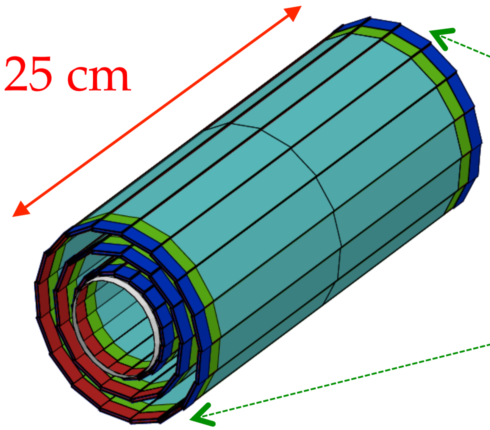
First design:

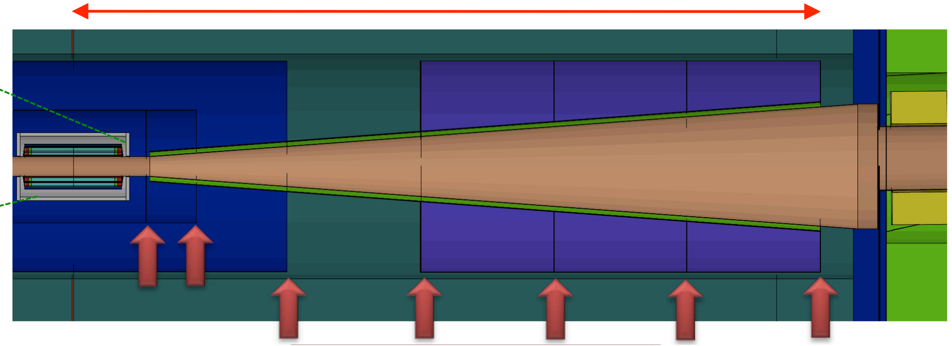
5 barrel layers and 7 disks



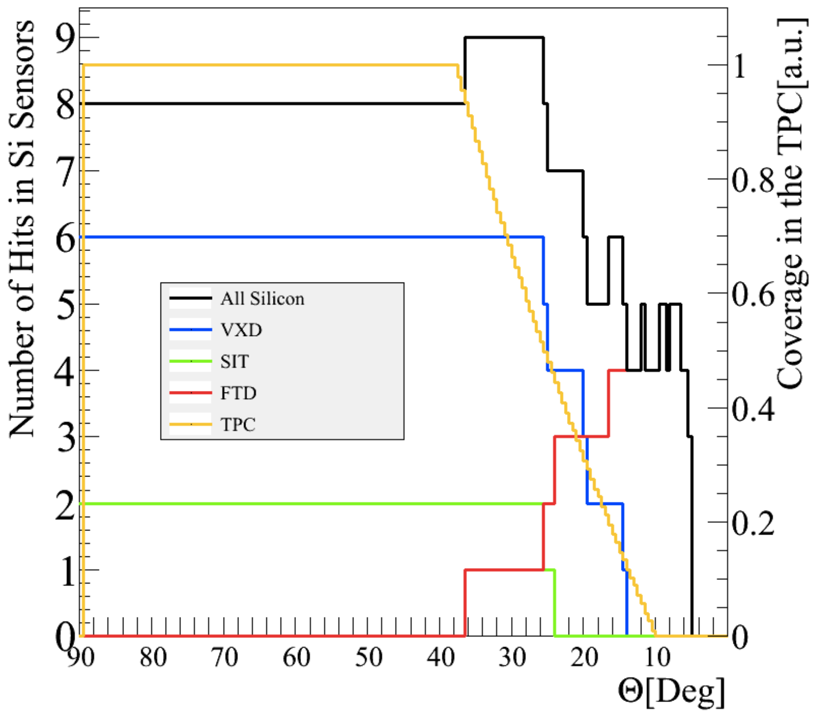


Bill Cooper





2 inner + 5 forward disks



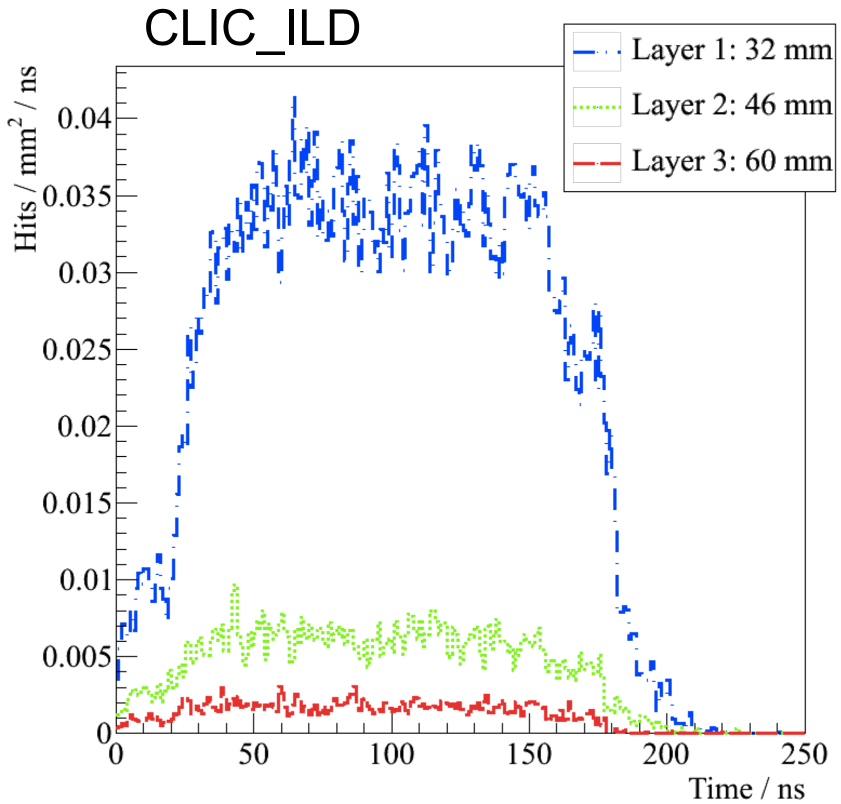
'long barrel': 25 cm

- Three double-sided barrel ladders
- Interplay between acceptance and amount of material
- short barrel + disks or long barrel?
  - Double/single sided?
- Material for services, cooling options?

Occupancy in vertex detector

- Because of 0.5 ns BX spacing background of several BX will overlap
- Clear separation between direct and back-scattered hits
- 2/3 coming from back-scatters; somewhat reducible with forward region design

➢ Need high granularity in time for read out to reduce background.
➢ Inhomogeneous distribution in azimuthal angle: up to 5x more.



Averaged over ϕ

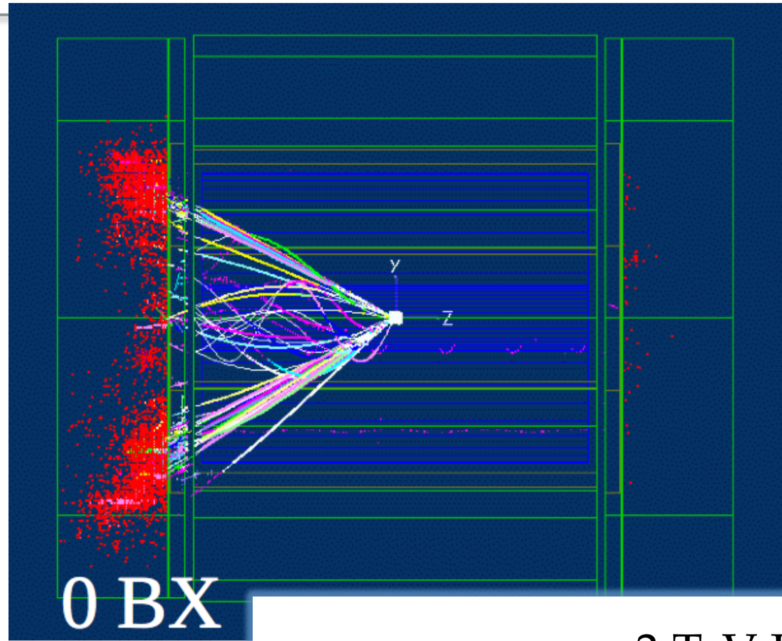
- With for example 20x20 μm pixels, 5-10pix/cluster:

0.04 hits / mm² / ns in Layer 1 → ~1-2% average occupancy during train.
x5 for hot spots.
→ Need multi-hit readout electronics

Jets at √s = 3 TeV

Forward region:

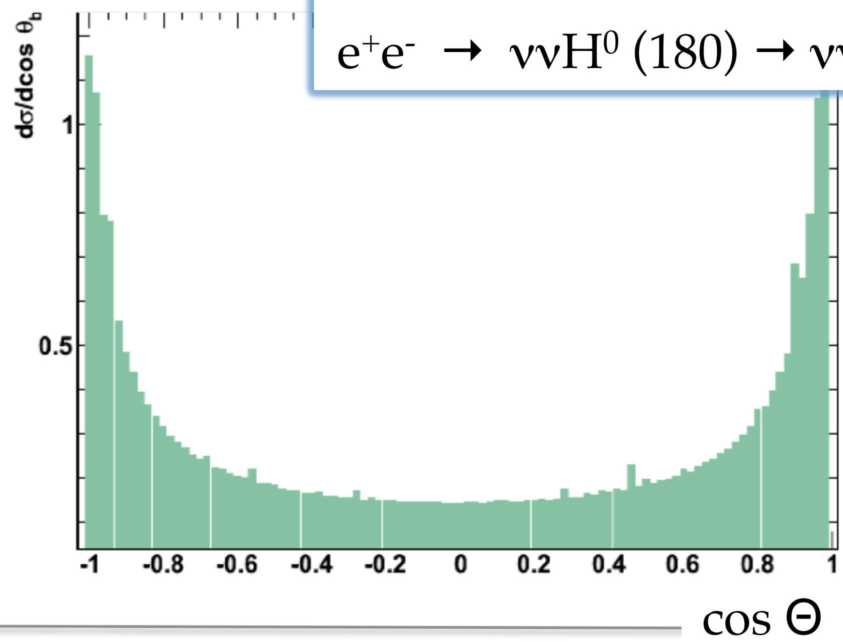
- many interesting physics channels
- worse resolution (more material)
- more background



3 TeV ILD

$e^+e^- \rightarrow \nu\nu H^0\ (180) \rightarrow \nu\nu bb$

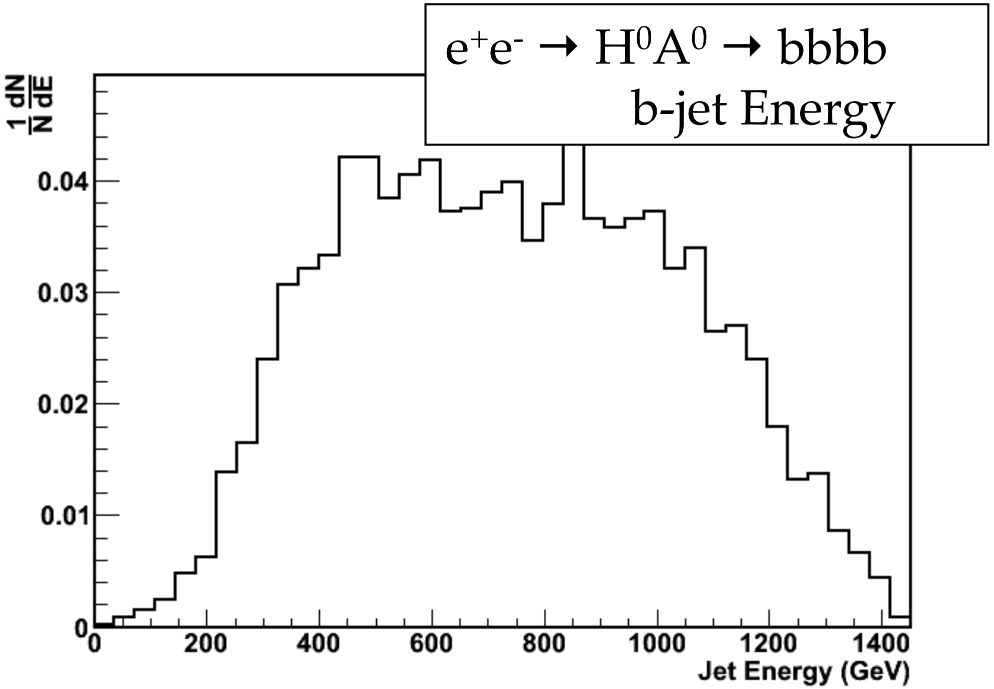
b-jet angular distribution →

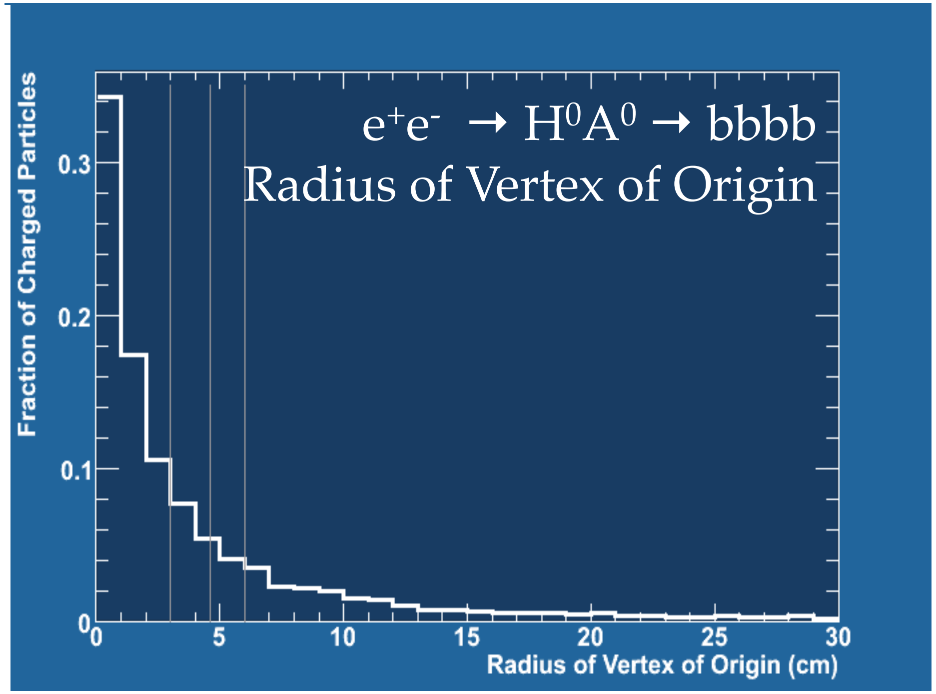


$0.9 < \cos\theta < 0.995$ ~

$6° < \theta < 30°$ or $1.5 < |\eta| < 3$

Jets at $\sqrt{s}$ = 3 TeV





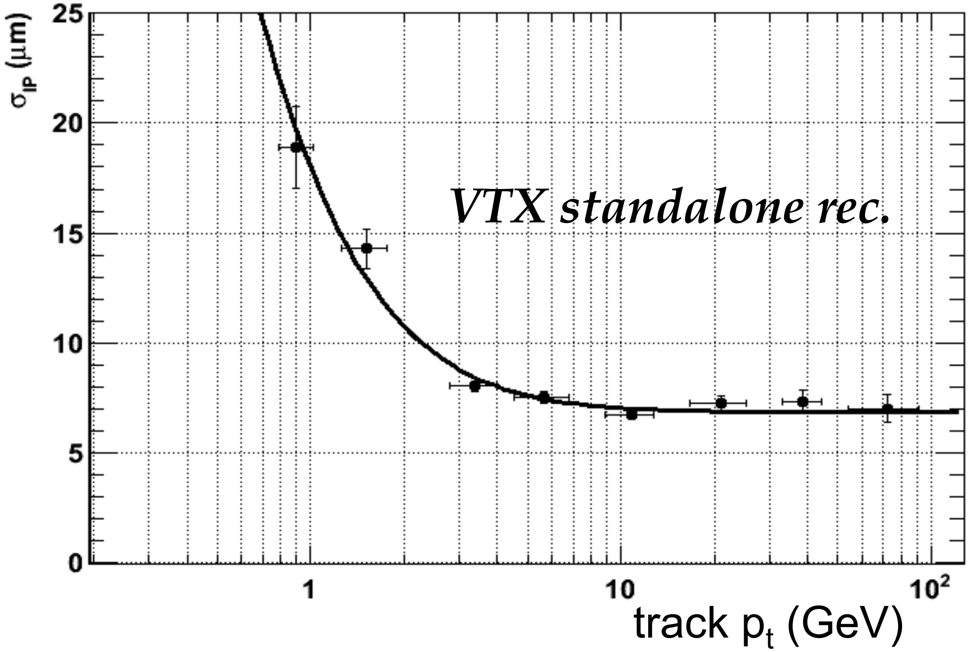
- Broad range of b-jet energies of interest:

  ~0.05 - 1.5 TeV.

- Long lived hadrons in b-jets acquire significant flight distance:

  with four jets, over 1/3 of charged particles with $p > 1$ GeV decay after first vertex detector layer.

Impact parameter Resolution



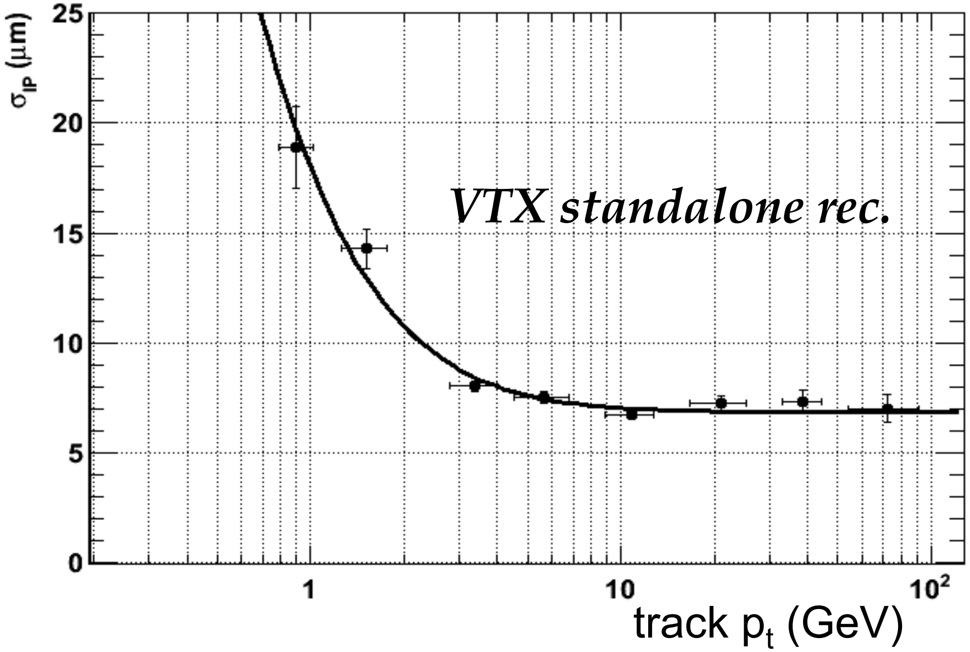
5-layered barrel VTX with:

- R_{in} = 30 mm, R_{out} = 60 mm
- 15 μm pixels, 3 μm single point resolution
- 50 μm Silicon, with total layer thickness of 0.12% X_0

Material budget in detector concepts: ~0.1%X_0 per layer, to keep contribution of multiple scattering to σ_{IP} low.

$\sigma_{\text{point}} = 3\mu\text{m}$	$\sigma_{IP} = 6.5 \oplus \frac{16.7}{p_t}\,\mu\text{m}$
$\sigma_{\text{point}} = 5\mu\text{m}$	$\sigma_{IP} = 9.2 \oplus \frac{18.6}{p_t}\,\mu\text{m}$

Impact parameter Resolution



$\sigma_{point} = 3\mu m$	$\sigma_{IP} = 6.5 \oplus \frac{16.7}{p_t} \mu m$
$\sigma_{point} = 5\mu m$	$\sigma_{IP} = 9.2 \oplus \frac{18.6}{p_t} \mu m$

$$\sigma_{IP} \simeq 5\ \mu m \oplus \frac{15\ \mu m}{p_t(GeV)}$$

Given CLIC constraints this can be achieved with:

- a multi-layered VTX with single point resolution ~3µm, i.e. a ~10µm binary pixel or a 15-20 µm analog pixel with charge interpolation.
- Single-layer material thickness ~0.1% X_0 to keep the multiple scattering low.

R&D issues

Technology domains	Issues
Sensor technology & Alignment	Low expected radiation damage. IP size (x/y/z): 45nm / 1nm / 40 µm → Requires high time & position resolution: 3µm point resolution
Readout electronics	Time binning ~10ns, multi-hit capability within 156ns train; high & inhomogeneous occupancy.
Power dissipation and cooling, Power delivery	readout in less than ~200-400 µs, power pulsing, DC-DC or serial
Small pitch interconnect and seamless coverage	Hybrid, integrated technologies, 3D/TSV (through-silicon-vias)
Low-mass engineering	~0.1% X_0 per layer

Summary

R&D for CLIC vertex detector will touch upon many technical domains.

- Some issues have overlap with R&D for ILC and R&D for sLHC. However, the combination of (technically conflicting) requirements for CLIC make it a challenging R&D on its own.

- Forward region deserves more attention: expect more of the interesting physics, more background, worse resolution.

- We're currently still in the phase where we try to understand the extent of the challenge and try to bring it in relation with "what's on the market".

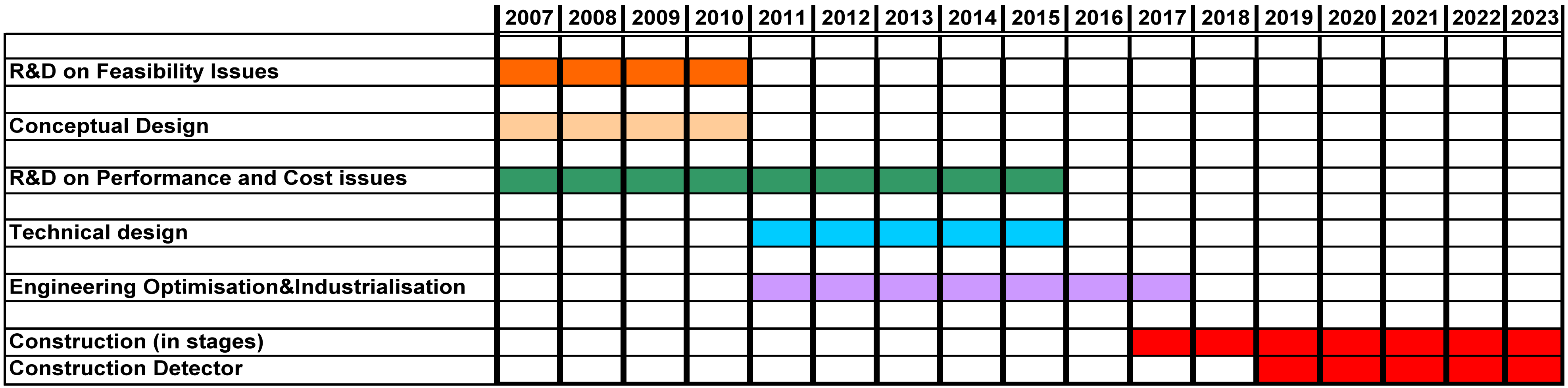
➢ CLIC CDR to be published April 2011

LCD homepage: http://lcd.web.cern.ch/lcd/
Indico agenda:
- Track and vertex reconstruction WG
- Vertex Detector WG

Backup slides

Tentative long-term CLIC scenario

Technology evaluation and Physics assessment based on LHC results for a possible decision on Linear Collider with staged construction starting with the lowest energy required by Physics



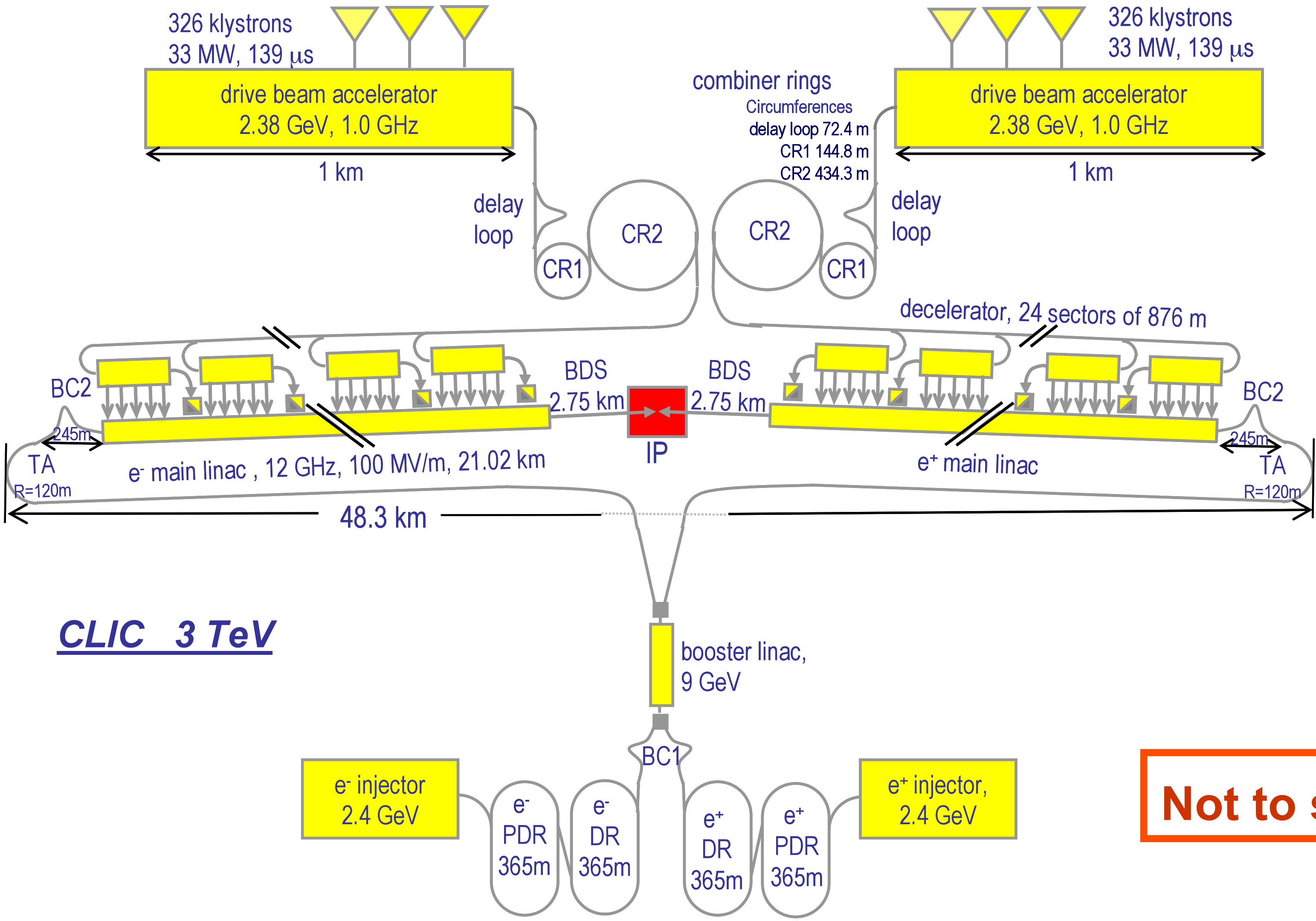
Conceptual Design Report (CDR)

Technical Design Report (TDR)

Project approval ?

First Beam?

The full CLIC scheme

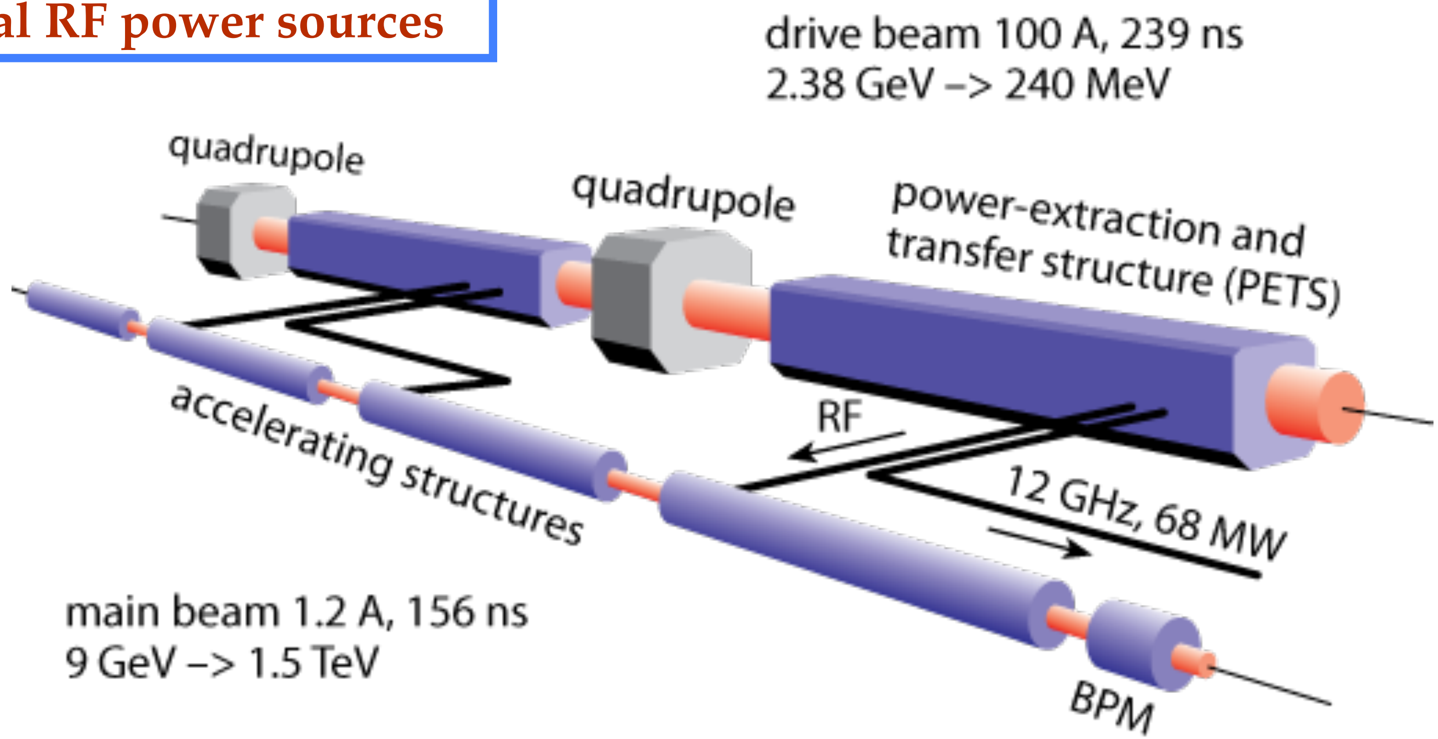


CLIC 3 TeV

Not to scale!

CLIC acceleration

No individual RF power sources



Two Beam Scheme:

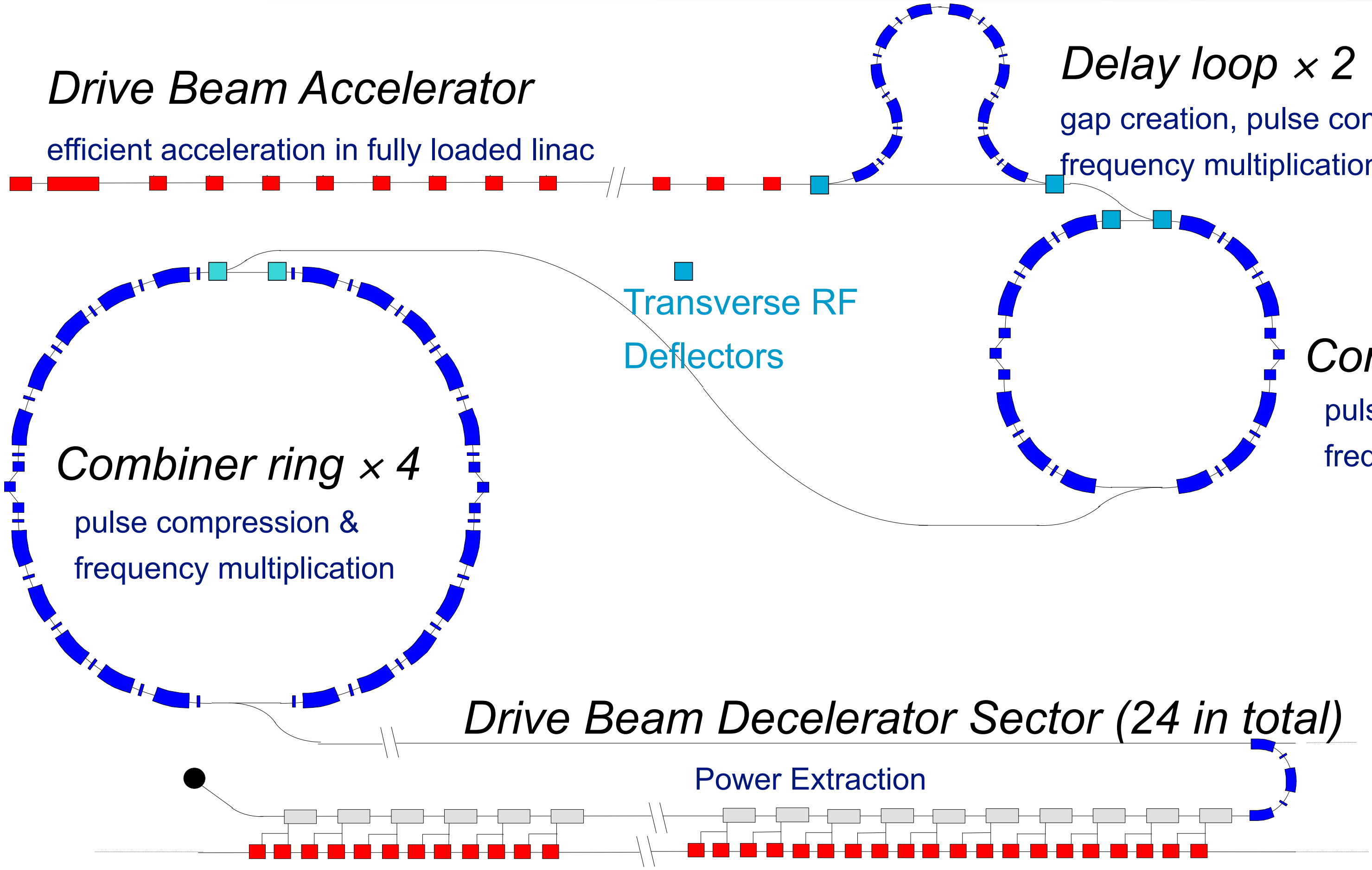
Drive Beam supplies RF power

- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

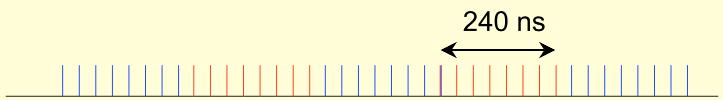
Main beam for physics

- high energy (9 GeV – 1.5 TeV)
- current 1.2 A

RF power source

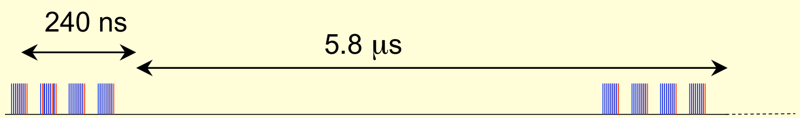


Drive beam time structure - initial



140 μs total length - 24 × 24 sub-pulses - 4.2 A
2.4 GeV - 60 cm between bunches

Drive beam time structure - final



24 pulses – 100 A – 2.5 cm between bunches

CLIC acceleration

CLIC parameters:

Accelerating gradient: 100 MV/m

RF frequency: 12 GHz

Basic accelerating structure of 23.3cm active length

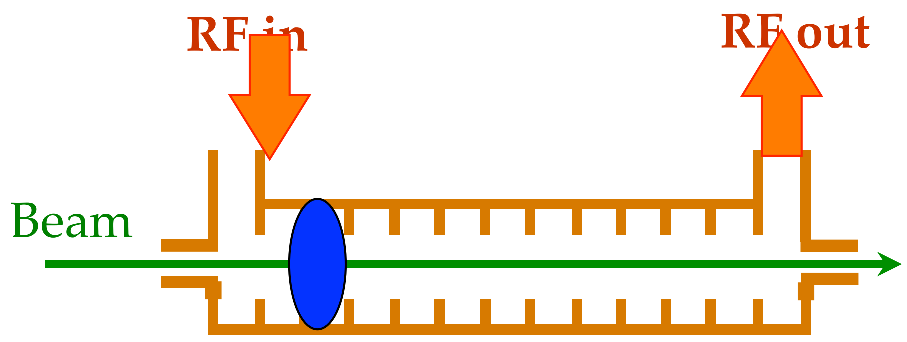
total active length for 1.5 TeV: **15'000 m**

The 12 GHz is a higher frequency than the 0.5ns between BXs.

-There is time needed between the BXs, not to have them interfere & for the RF to come back to nominal.

The RFs cannot continuously be operated, hence the 'long' deadtime between trains.

Acceleration in travelling wave structures:

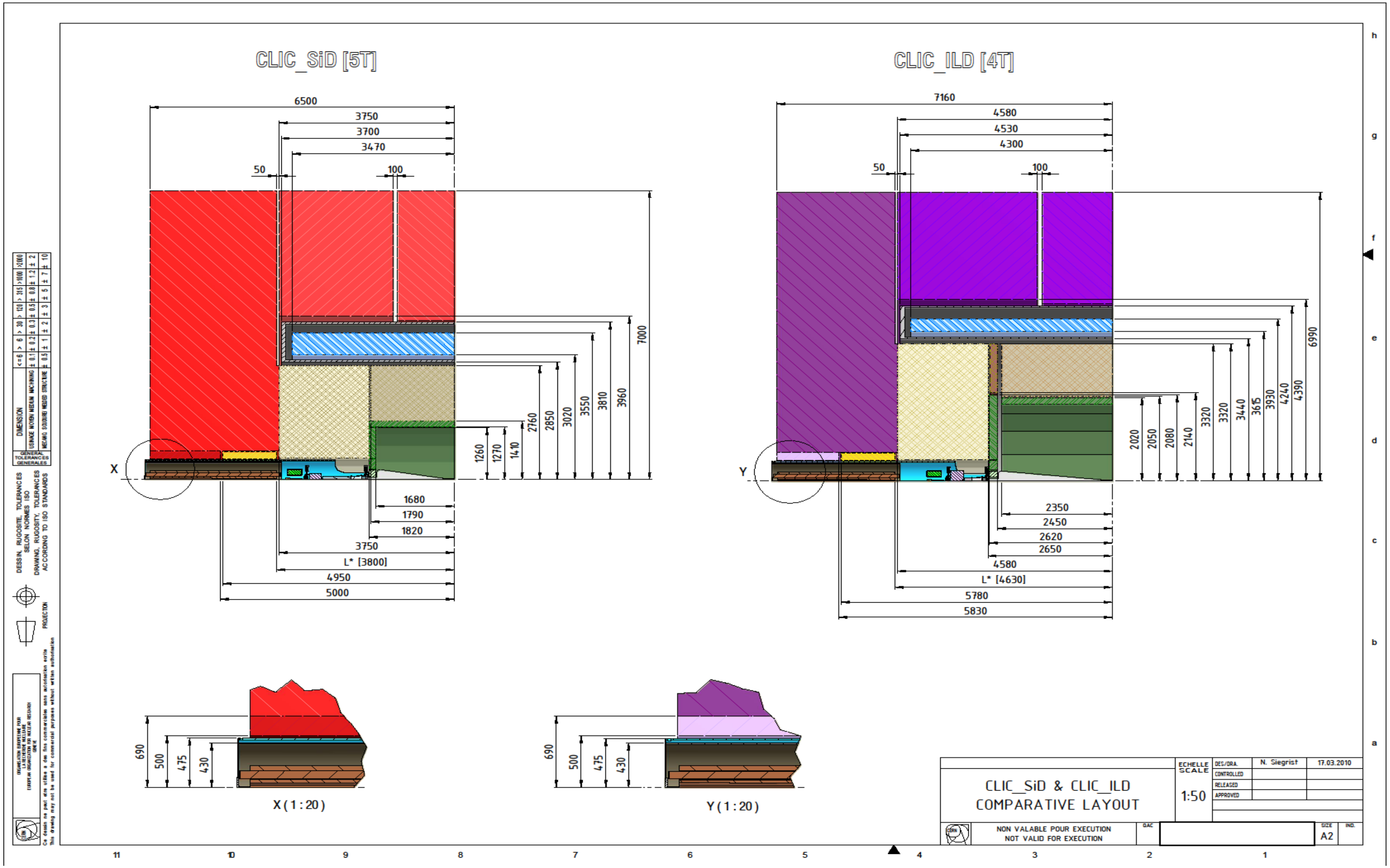


CLIC parameters

Center-of-mass energy	ILC 500 GeV	CLIC 500 GeV	CLIC 3 TeV
Total (Peak 1%) luminosity [$\cdot 10^{34}$]	2(1.5)	2.3 (1.4)	5.9 (2.0)
Repetition rate (Hz)	5	50	
Loaded accel. gradient MV/m	32	80	100
Main linac RF frequency GHz	1.3	12	
Bunch charge [$\cdot 10^{9}$]	20	6.8	3.7
Bunch separation (ns)	370	0.5	
Beam pulse duration (ns)	950μs	177	156
Beam power/beam (MWatts)		4.9	14
Hor./vert. IP beam size (nm)	600 / 6	200 / 2.3	40 / 1.0
Hadronic events/crossing at IP	0.12	0.2	2.7
Incoherent pairs at IP	$1 \cdot 10^{5}$	$1.7 \cdot 10^{5}$	$3 \cdot 10^{5}$
BDS length (km)		1.87	2.75
Total site length km	31	13	48
Total power consumption MW	230	130	415

Crossing Angle 20 mrad (ILC 14 mrad)

Parameter drawing of CLIC Detectors



Occupancy in vertex detector

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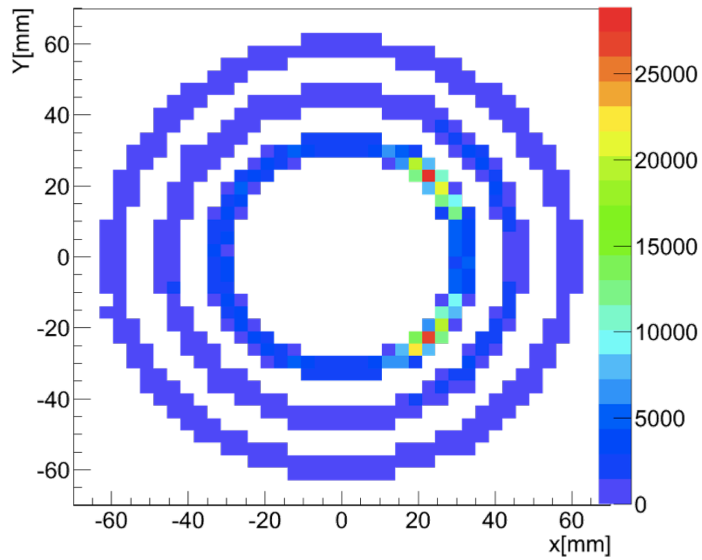
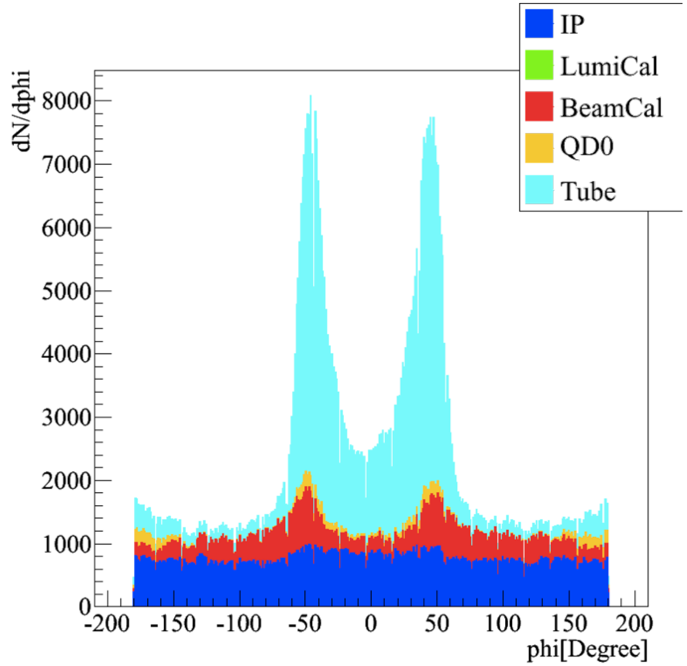
- Clear separation between direct and back-scattered hits
- 2/3 coming from back-scatters; somewhat reducible with forward region design



- Inhomogeneous distribution of hits in phi for the first layer of the VXD
  - Due to 20 mrad crossing angle
  - Intensity ~5x higher at two spots



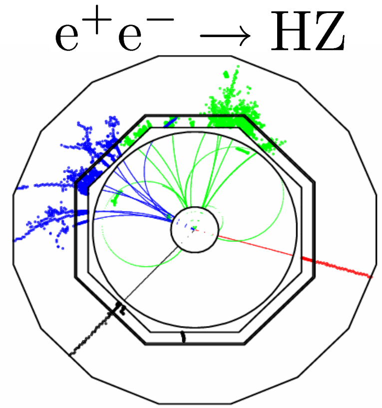
André Sailer

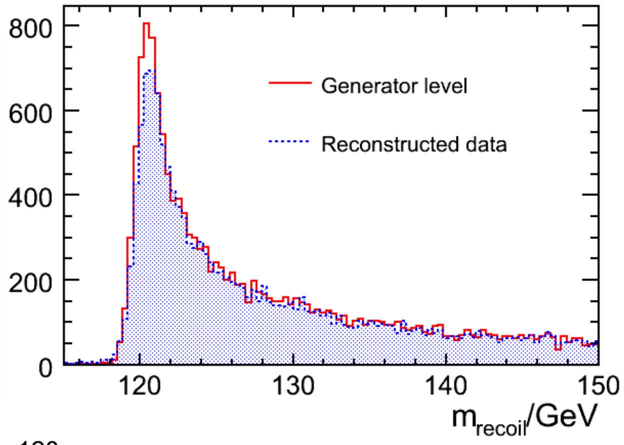
Overall detector requirements

★ **momentum:** (1/10 x LEP)

e.g. Muon momentum
Higgs recoil mass

$$\sigma_{1/p} < 5 \times 10^{-5}\,\mathrm{GeV}^{-1}$$

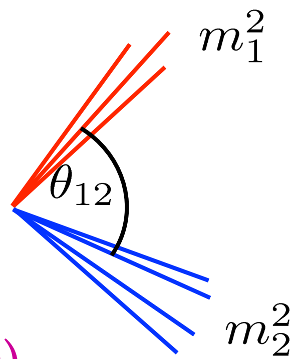


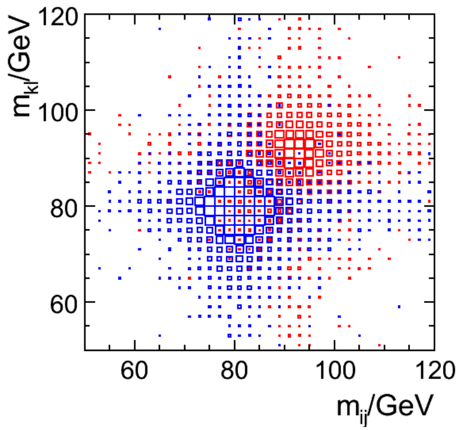


★ **jet energy:** (1/3 x LEP/ZEUS)

e.g. W/Z di-jet mass separation
EWSB signals

$$\frac{\sigma_E}{E} \approx 3-4\,\%$$

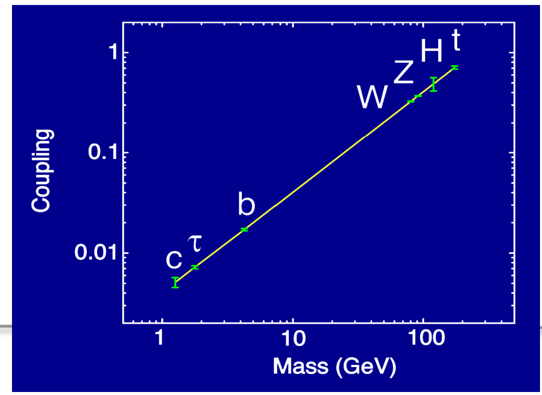




★ **impact parameter:** (1/3 x SLD)

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

$$\sigma_{r\phi} = 5 \oplus 10/(p \sin^{\frac{3}{2}}\theta)\,\mu\mathrm{m}$$



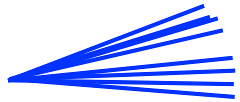
★ **hermetic:** down to θ = 5 mrad

e.g. missing energy signatures in SUSY

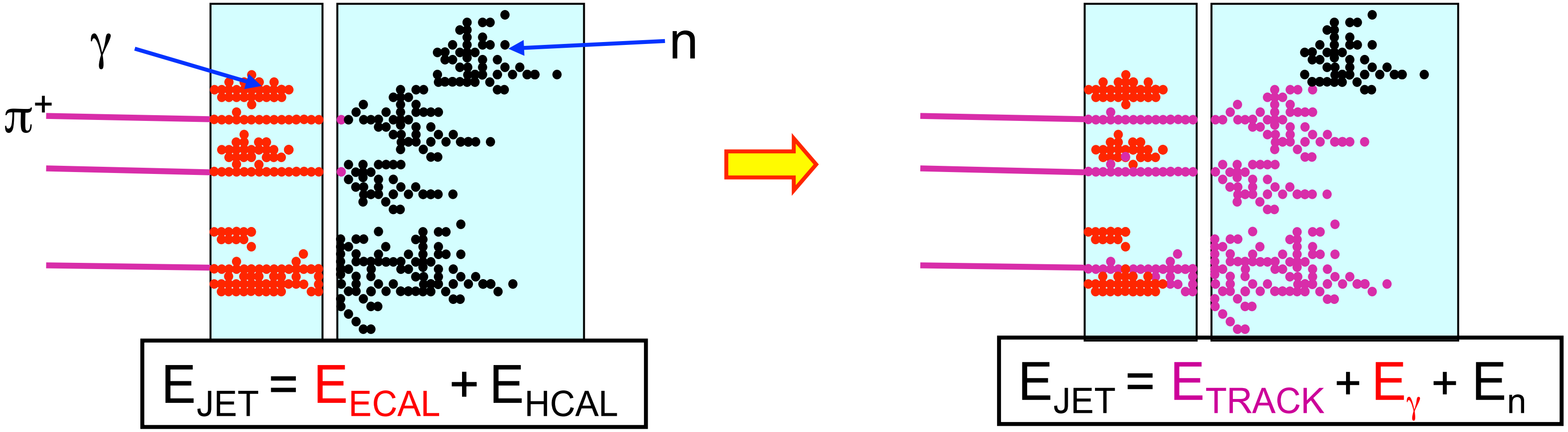
See talk by M. Thomson – CLIC'09

Particle Flow Calorimetry

- In a typical jet :
  - 60 % of jet energy in charged hadrons
  - 30 % in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
  - 10 % in neutral hadrons (mainly n and K_L)



- Traditional calorimetric approach:
  - Measure all components of jet energy in ECAL/HCAL !
  - ~70 % of energy measured in HCAL: $\sigma_E/E \approx 60\,\%/\sqrt{E(\mathrm{GeV})}$
  - Intrinsically “poor” HCAL resolution limits jet energy resolution



- 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

Physics reach

	LHC 100 fb^{-1}	ILC 800 GeV 500 fb^{-1}	SLHC 1000 fb^{-1}	CLIC 3 TeV 1000 fb^{-1}	CLIC 5 TeV 1000 fb^{-1}
Squarks [TeV]	2.5	0.4	3	1.5	2.5
Sleptons [TeV]	0.34	0.4		1.5	2.5
New gauge boson Z′ [TeV]	5	8	6	22	28
Excited quark q* [TeV]	6.5	0.8	7.5	3	5
Excited lepton l* [TeV]	3.4	0.8		3	5
Two extra space dimensions [TeV]	9	5–8.5	12	20-35	30–55
Strong $W_L W_L$ scattering	2σ	-	4σ	70σ	90σ
Triple-gauge Coupling (95%)	.0014	0.0004	0.0006	0.00013	0.00008

Integrated luminosities used are 100 fb–1 for the LHC, 500 fb–1 for the 800 GeV LC, and 1000 fb–1 for the SLHC and CLIC. Most numbers given are TeV, but for strong WLWL scattering the numbers of standard deviations, and pure numbers for the triple gauge coupling (TGC).

Frederic Teubert

Example: looking for heavy neutralinos

$$\tilde{\chi}_j^0 \rightarrow \ell^\pm \tilde{\ell}^\mp \rightarrow \ell^+ \ell^- \tilde{\chi}_1^0$$

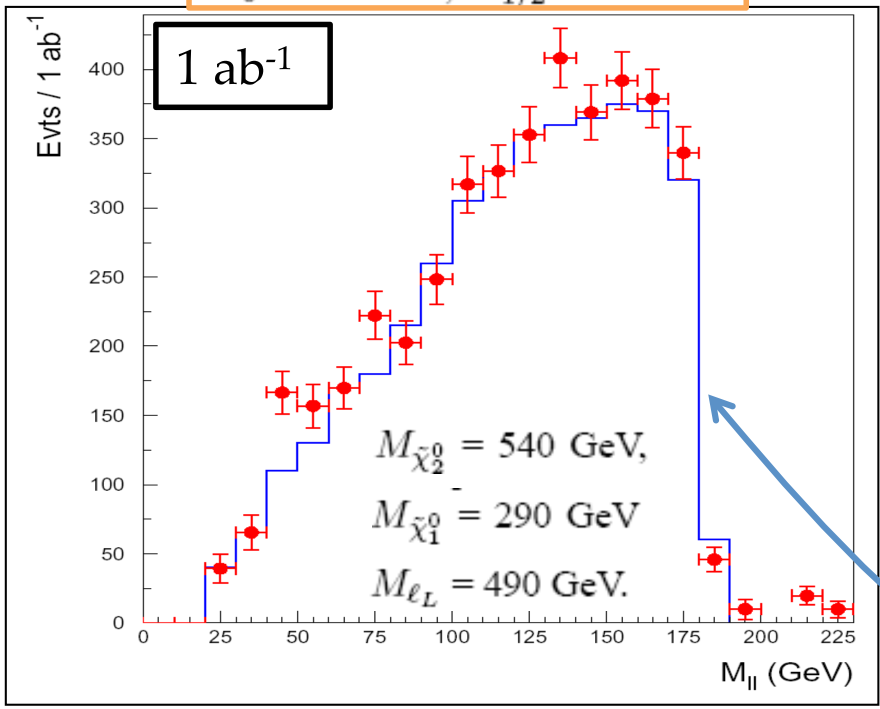
Gives an excess of events in the l^+l^- invariant mass distribution. A simultaneous fit of the *slepton* and $\chi_{1,2}$ mass gives ~2% precision with 1 ab^{-1}. The precision is dominated by the correlation between parameters.

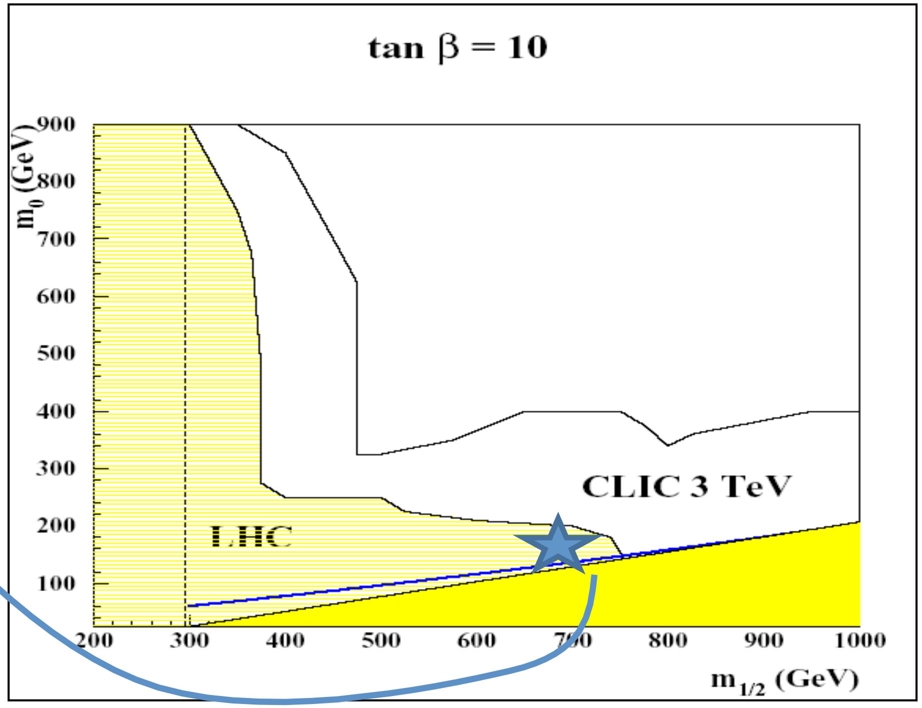
$$\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_{1,2}^0 Z^0$$

$$\tilde{\chi}_4^0 \rightarrow \tilde{\chi}_{1,2}^0 h^0$$

Also $\chi_{3,4}$ are accessible in a multi-TeV LC.

m_0 = 150 GeV, $m_{1/2}$ = 700 GeV

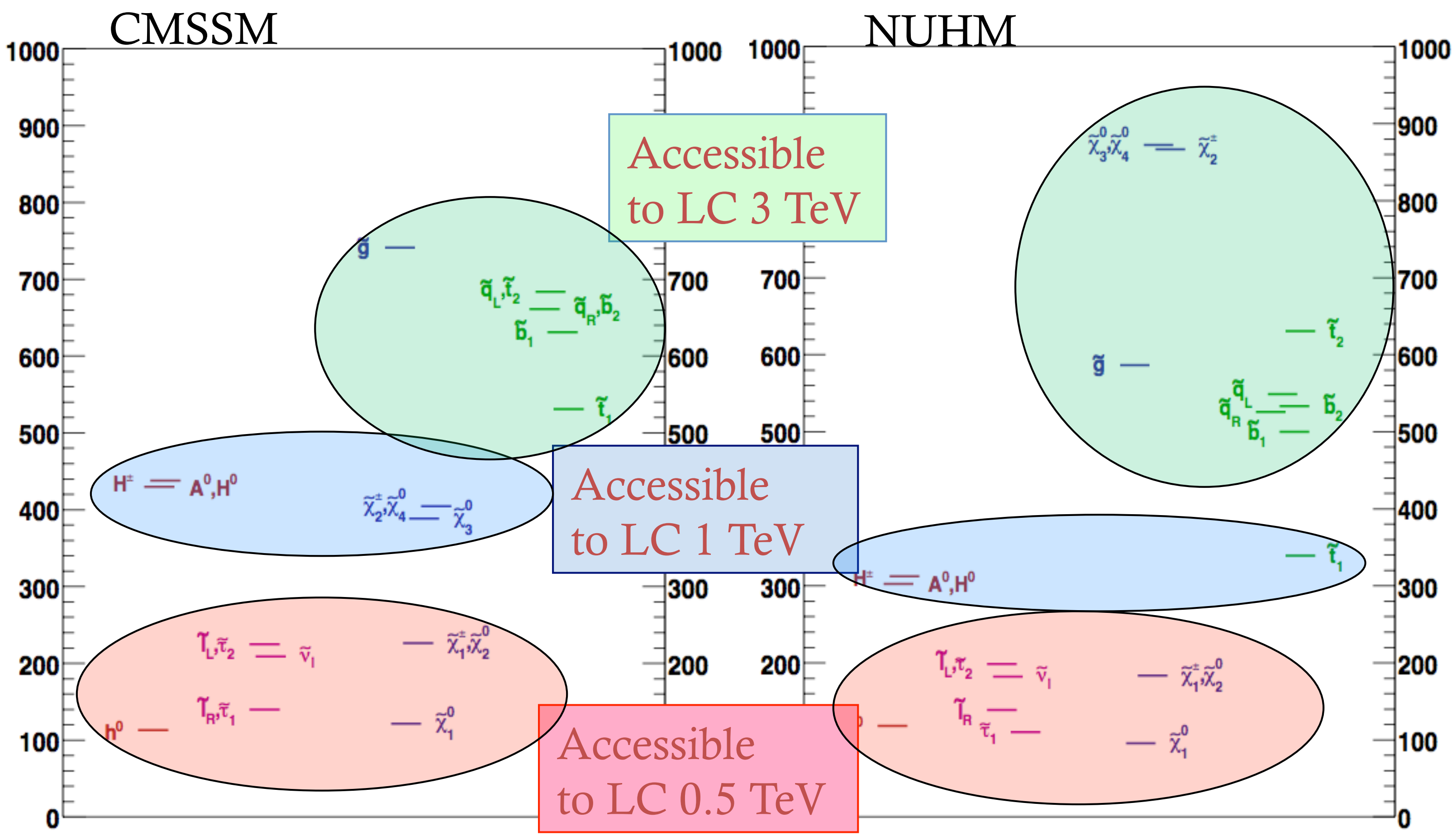




Frederic Teubert

Supersymmetry with different accelerators

Within a SUSY model (CMSSM, NUHM, etc..) we can use low energy measurements, in particular $b \rightarrow s\gamma$, the limit on M_h and g_μ-2, to evaluate the most probable mass spectra, see for instance *arXiv 0808.4128.*

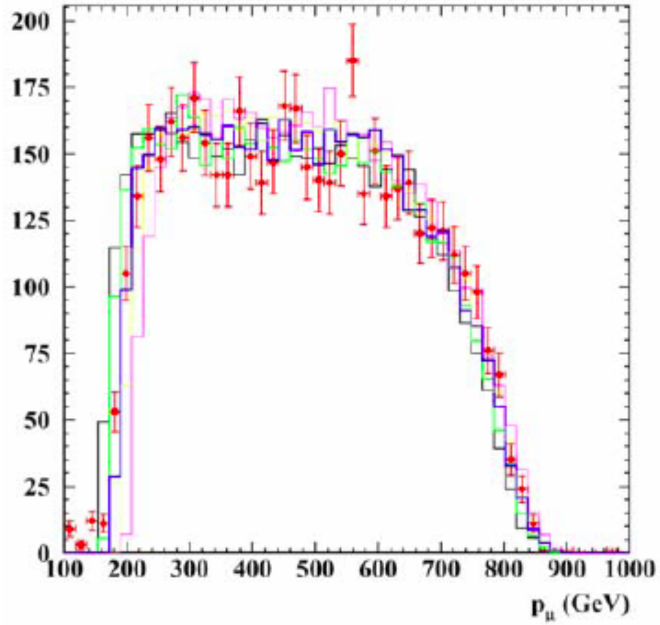


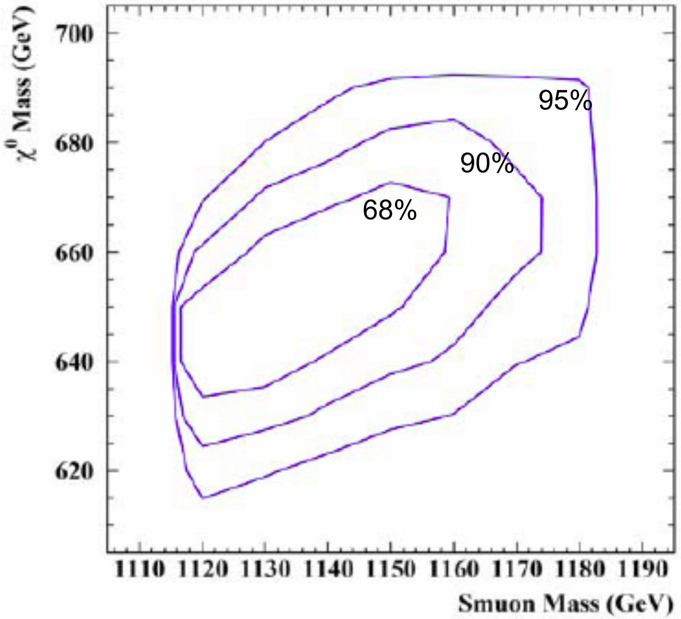
Example of SUSY study

Mass determinations: $e^+e^- \to \tilde{\mu}_L^+ \tilde{\mu}_L^- \to \mu^+ \chi_1^0 \mu^- \chi_1^0$

- If $\sqrt{s} >> 2\tilde{m}_\mu$, μ spectrum end points

$$E_{\min,\max} = \frac{\sqrt{s}}{4}\left(1-\tilde{m}_\chi^2/\tilde{m}_\mu^2\right)\left(1 \pm \sqrt{1-4\tilde{m}_\mu^2/s}\right)$$





$\tilde{m}_\chi = (652 \pm 22)\,\text{GeV}$ 3%

$\tilde{m}_\mu = (1145 \pm 25)\,\text{GeV}$ 2%

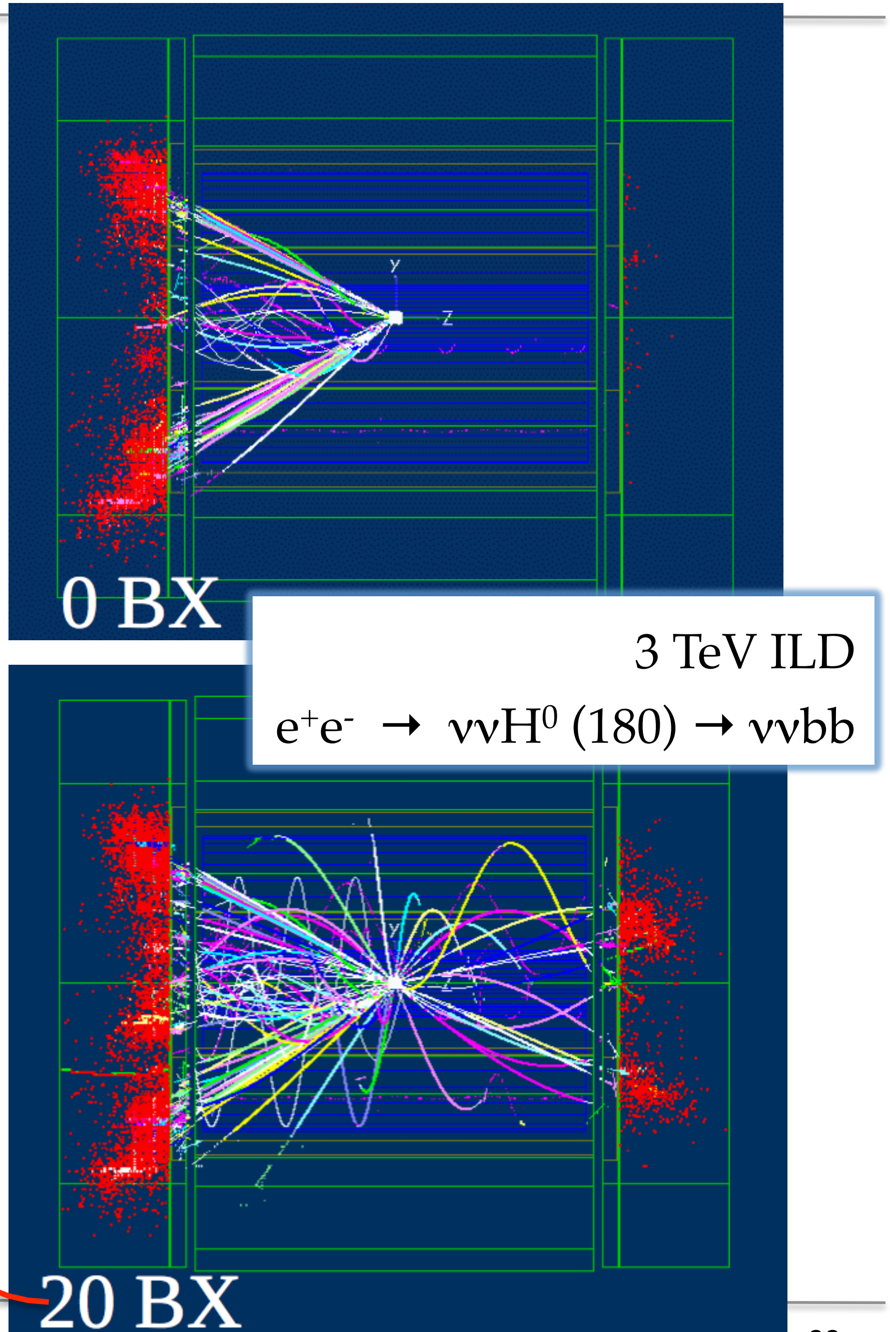
After LHC, mass determinations can be improved with CLIC.

- Allows for better identification of susy breaking mechanism.

CLIC Tracking

Vertex and Tracking issues:

- With overlapping BX, time stamping might be necessary.
  - For tracker & vertex detector, or only for tracker?
- Narrow jets at high energy
  - 2-track separation is an issue for the tracker/vertex detector
  - Track length may have to increase (fan-out of particles within jet)



Overlapping with $\gamma\gamma \rightarrow$ hadrons

$\mathcal{O}$(3) hadron events per BX